Prometeo (theory)

Waveform modeling for BBH/BNS: EOB/NR - **TEOBResumS**

(Torino/MiB) F. Messina, A. Nagar, P. Rettegno, G. Riemenschneider….

(Jena U) S. Bernuzzi, F. Zappa, S. Akcay…

Data analysis applications: W. Del Pozzo+

PN/GSF/EOB theory: Roma3/CNR

(D. Bini) : **new entry. The ONLY, high-level, italian PN expert.**

Noise characterization of GW detectors [mirrors]

PoliTo (Rondoni +): **new entry**

EM counterparts

MiB (Ghirlanda, Perego, Salafia, Colpi)

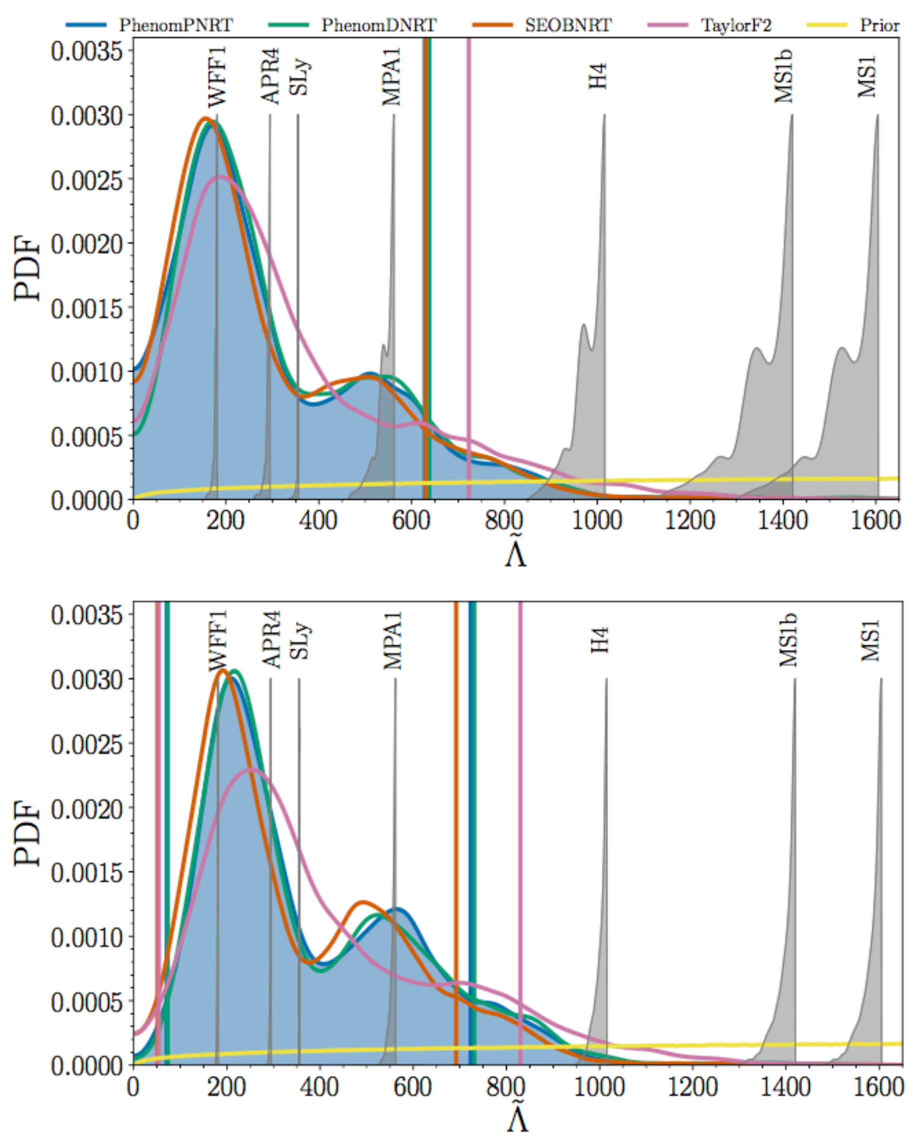
Population rates

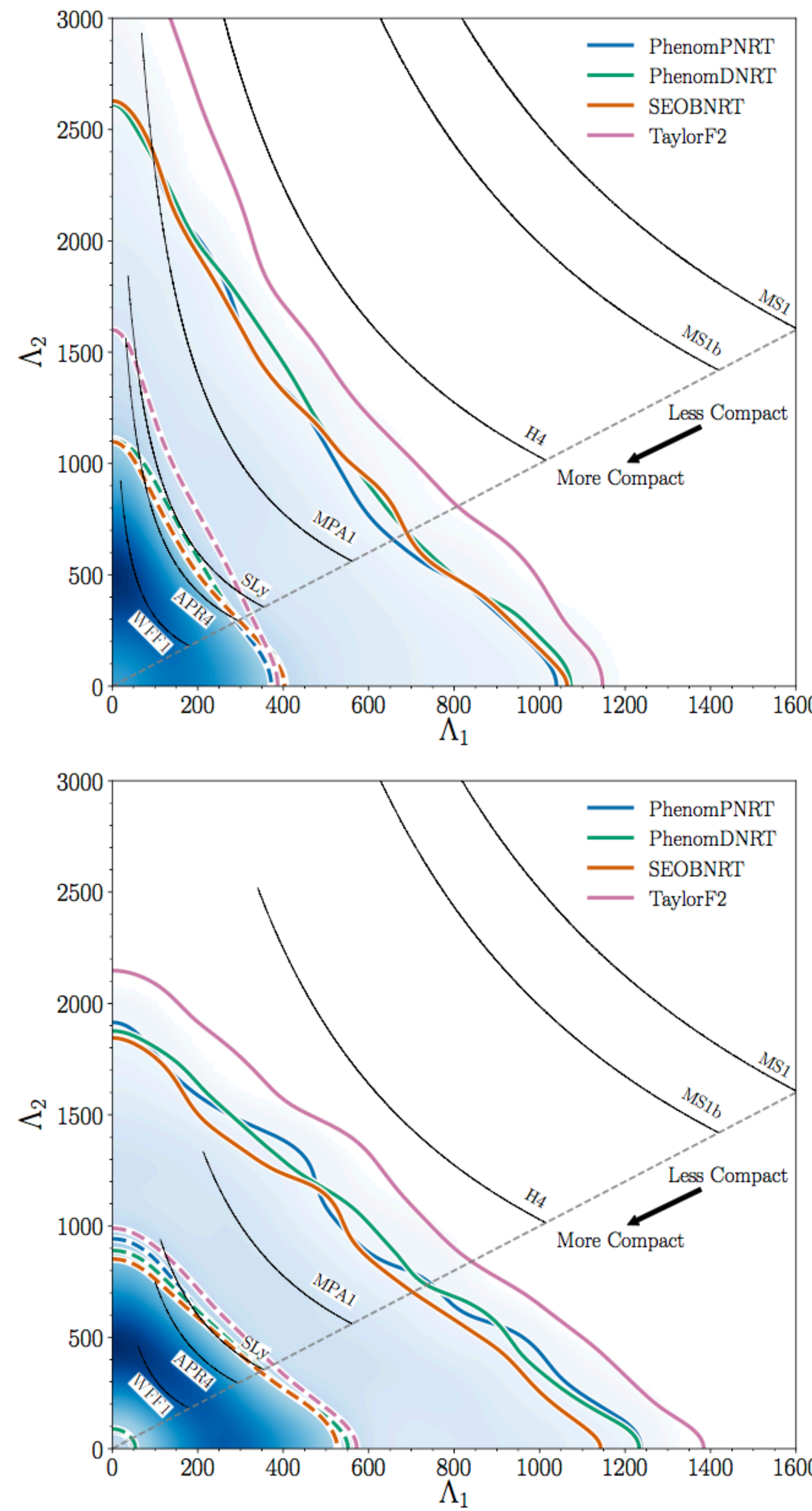
Padova (Mapelli & Spera)

Properties of the binary neutron star merger GW170817

The LIGO Scientific Collaboration and The Virgo Collaboration
(Compiled 30 May 2018)

On August 17, 2017, the Advanced LIGO and Advanced Virgo gravitational-wave detectors observed a low-mass compact binary inspiral. The initial sky localization of the source of the gravitational-wave signal, GW170817, allowed electromagnetic observatories to identify NGC 4993 as the host galaxy. In this work we improve initial estimates of the binary's properties, including component masses, spins, and tidal parameters, using the known source location, improved modeling, and re-calibrated Virgo data. We extend the range of gravitational-wave frequencies considered down to 23 Hz, compared to 30 Hz in the initial analysis. We also compare results inferred using several signal models, which are more accurate and incorporate additional physical effects as compared to the initial analysis. We improve the localization of the gravitational-wave source to a 90% credible region of 16 deg^2. We find tighter constraints on the masses, spins, and tidal parameters, and continue to find no evidence for non-zero component spins. The component masses are inferred to lie between 1.00 and 1.89 $M_\odot$ when allowing for large component spins, and to lie between 1.16 and 1.60 $M_\odot$ (with a total mass $2.73^{+0.04}_{-0.01}\,M_\odot$) when the spins are restricted to be within the range observed in Galactic binary neutron stars. Using a precessing model and allowing for large component spins, we constrain the dimensionless spins of the components to be less than 0.50 for the primary and 0.61 for the secondary. Under minimal assumptions about the nature of the compact objects, our constraints for the tidal deformability parameter $\tilde{\Lambda}$ are $(0, 630)$ when we allow for large component spins, and 300^{+420}_{-230} (using a 90% highest posterior density interval) when restricting the magnitude of the component spins, ruling out several equation of state models at the 90% credible level. Finally, with LIGO and GEO600 data, we use a Bayesian analysis to place upper limits on the amplitude and spectral energy density of a possible post-merger signal.





Low-spin prior, $\chi_i \leq 0.05$	TaylorF2	SEOBNRT	PhenomDNRT
Binary inclination $\theta_{\rm JN}$	146^{+24}_{-28} deg	146^{+24}_{-28} deg	147^{+24}_{-28} deg
Binary inclination $\theta_{\rm JN}$ using EM distance constraint [104]	149^{+13}_{-10} deg	152^{+14}_{-11} deg	151^{+14}_{-10} deg
Detector frame chirp mass $\mathcal{M}^{\rm det}$	$1.1975^{+0.0001}_{-0.0001} {\rm M}_\odot$	$1.1976^{+0.0001}_{-0.0001} {\rm M}_\odot$	$1.1975^{+0.0001}_{-0.0001} {\rm M}_\odot$
Chirp mass $\mathcal{M}$	$1.186^{+0.001}_{-0.001} {\rm M}_\odot$	$1.186^{+0.001}_{-0.001} {\rm M}_\odot$	$1.186^{+0.001}_{-0.001}$
Primary mass m_1	$(1.36,\ 1.61)\ {\rm M}_\odot$	$(1.36,\ 1.59)\ {\rm M}_\odot$	$(1.36,\ 1.60)\ {\rm M}_\odot$
Secondary mass m_2	$(1.16,\ 1.36)\ {\rm M}_\odot$	$(1.17,\ 1.36)\ {\rm M}_\odot$	$(1.17,\ 1.36)\ {\rm M}_\odot$
Total mass m	$2.73^{+0.05}_{-0.01} {\rm M}_\odot$	$2.73^{+0.04}_{-0.01} {\rm M}_\odot$	$2.73^{+0.04}_{-0.01} {\rm M}_\odot$
Mass ratio q	$(0.72,\ 1.00)$	$(0.74,\ 1.00)$	$(0.73,\ 1.00)$
Effective spin $\chi_{\rm eff}$	$0.00^{+0.02}_{-0.01}$	$0.00^{+0.02}_{-0.01}$	$0.00^{+0.02}_{-0.01}$
Primary dimensionless spin χ_1	$(0.00,\ 0.02)$	$(0.00,\ 0.02)$	$(0.00,\ 0.02)$
Secondary dimensionless spin χ_2	$(0.00,\ 0.02)$	$(0.00,\ 0.02)$	$(0.00,\ 0.02)$
Tidal deformability $\tilde{\Lambda}$ with flat prior (symmetric/HPD)	$340^{+580}_{-240}/340^{+490}_{-290}$	$280^{+490}_{-190}/\ 280^{+410}_{-230}$	$300^{+520}_{-190}/\ 300^{+430}_{-230}$

TABLE IV. Source properties for GW170817 using the additional waveform models TaylorF2, PhenomDNRT, and SEOBNRT. Conventions are the same as in Table II. The TaylorF2 results here can be directly compared with those from [3]. Note that the 90% upper limits for $\tilde{\Lambda}$ reported in Table 1 of [3] for TaylorF2 are incorrect (see Sec. III D). In [3] for the high-spin prior it should be ≤ 800 and not ≤ 700, while for the low-spin prior it should be ≤ 900 and not ≤ 800.

Low-spin prior, $\chi_i \leq 0.05$	SEOBNRv4T	TEOBResumS	PhenomDNRT
Detector frame chirp mass $\mathcal{M}^{\rm det}$	$1.1975^{+0.0001}_{-0.0001} {\rm M}_\odot$	$1.1975^{+0.0001}_{-0.0001} {\rm M}_\odot$	$1.1975^{+0.0001}_{-0.0001} {\rm M}_\odot$
Chirp mass $\mathcal{M}$	$1.186^{+0.001}_{-0.001} {\rm M}_\odot$	$1.186^{+0.001}_{-0.001} {\rm M}_\odot$	$1.186^{+0.001}_{-0.001}$
Primary mass m_1	$(1.36,\ 1.56)\ {\rm M}_\odot$	$(1.36,\ 1.53)\ {\rm M}_\odot$	$(1.36,\ 1.57)\ {\rm M}_\odot$
Secondary mass m_2	$(1.19,\ 1.36)\ {\rm M}_\odot$	$(1.22,\ 1.36)\ {\rm M}_\odot$	$(1.19,\ 1.36)\ {\rm M}_\odot$
Total mass m	$2.73^{+0.04}_{-0.01} {\rm M}_\odot$	$2.73^{+0.03}_{-0.01} {\rm M}_\odot$	$2.73^{+0.04}_{-0.01} {\rm M}_\odot$
Mass ratio q	$(0.76,\ 1.00)$	$(0.79,\ 1.00)$	$(0.76,\ 1.00)$
Effective spin $\chi_{\rm eff}$	$0.00^{+0.02}_{-0.01}$	$0.00^{+0.01}_{-0.01}$	$0.00^{+0.02}_{-0.01}$
Primary dimensionless spin χ_1	$(0.00,\ 0.03)$	$(0.00,\ 0.02)$	$(0.00,\ 0.03)$
Secondary dimensionless spin χ_2	$(0.00,\ 0.03)$	$(0.00,\ 0.03)$	$(0.00,\ 0.03)$
Tidal deformability $\tilde{\Lambda}$ with flat prior (symmetric/HPD)	$280^{+430}_{-220}/280^{+280}_{-280}$	$340^{+520}_{-260}/\ 340^{+350}_{-330}$	$310^{+510}_{-240}/\ 310^{+380}_{-290}$

TABLE V. Source properties for GW170817 produced using RapidPE for the additional waveform models SEOBNRv4T and TEOBResumS. Conventions are the same as in Table II.

Time-domain effective-one-body gravitational waveforms for coalescing compact binaries with nonprecessing spins, tides and self-spin effects

Alessandro Nagar[1,2,3], Sebastiano Bernuzzi[4,5,6], Walter Del Pozzo[7], Gunnar Riemenschneider[2,8], Sarp Akcay[4], Gregorio Carullo[7], Philipp Fleig[9], Stanislav Babak[10], Ka Wa Tsang[12], Marta Colleoni[13], Francesco Messina[14,15], Geraint Pratten[13], David Radice[16,17], Piero Rettegno[2,8], Michalis Agathos[18], Edward Fauchon-Jones[19], Mark Hannam[19], Sascha Husa[13], Tim Dietrich[9,12], Pablo Cerdá-Duran[21], José A. Font[21,22], Francesco Pannarale[19], Patricia Schmidt[23], and Thibault Damour[3]

[1] *Centro Fermi - Museo Storico della Fisica e Centro Studi e Ricerche Enrico Fermi, Rome, Italy*
[2] *INFN Sezione di Torino, Via P. Giuria 1, 10125 Torino, Italy*
[3] *Institut des Hautes Etudes Scientifiques, 91440 Bures-sur-Yvette, France*
[4] *Theoretisch-Physikalisches Institut, Friedrich-Schiller-Universität Jena, 07743, Jena, Germany*
[5] *Istituto Nazionale di Fisica Nucleare, Sezione Milano Bicocca, gruppo collegato di Parma, I-43124 Parma, Italy*
[6] *Department of Mathematical, Physical and Computer Sciences, University of Parma, I-43124 Parma, Italy*
[7] *Dipartimento di Fisica "Enrico Fermi", Università di Pisa, and INFN sezione di Pisa, Pisa I-56127, Italy*
[8] *Dipartimento di Fisica, Università di Torino, via P. Giuria 1, I-10125 Torino, Italy*
[9] *Max Planck Institute for Dynamics and Self-Organization, 37077 Göttingen, Germany*
[10] *APC, CNRS-Université Paris 7, 75205 Paris CEDEX 13, France*
[11] *Moscow Institute of Physics and Technology, Dolgoprudny, Moscow region, Russia*
[12] *Nikhef, Science Park, 1098 XG Amsterdam, The Netherlands*
[13] *Universitat de les Illes Balears, IAC3-IEEC, 07122 Palma de Mallorca, Spain*
[14] *Dipartimento di Fisica, Università degli studi di Milano Bicocca, Piazza della Scienza 3, 20126 Milano, Italy*
[15] *INFN, Sezione di Milano Bicocca, Piazza della Scienza 3, 20126 Milano, Italy*
[16] *Department of Astrophysical Sciences, Princeton University, 4 Ivy Lane, Princeton NJ 08544, USA*
[17] *Institute for Advanced Study, 1 Einstein Drive, Princeton NJ 08540, USA*
[18] *DAMTP, Centre for Mathematical Sciences, University of Cambridge, Wilberforce Road, Cambridge CB3 0WA, UK*
[19] *School of Physics and Astronomy, Cardiff University, The Parade, Cardiff CF24 3AA, UK*
[20] *Max Planck Institute for Gravitational Physics (Albert Einstein Institute), Am Mühlenberg 1, Potsdam 14476, Germany*
[21] *Departament d'Astronomia i Astrofśica, Universitat de València, Dr. Moline 50, 46100 Burjassot (Valencia)*
[22] *Observatori Astronòmic, Universitat de València, C/ Catedrático José Beltrán 2, 46980, Paterna (València), Spain and*
[23] *Department of Astrophysics/IMAPP, Radboud University Nijmegen, P.O. Box 9010, 6525 GL Nijmegen, The Netherlands*

(Dated: June 6, 2018)

We present TEOBResumS, a new effective-one-body (EOB) waveform model for nonprecessing (spin-aligned) and tidally interacting compact binaries. Spin-orbit and spin-spin effects are blended together by making use of the concept of centrifugal EOB radius. The point-mass sector through merger and ringdown is informed by numerical relativity (NR) simulations of binary black holes (BBH) computed with the SpEC and BAM codes. An improved, NR-based phenomenological description of the postmerger waveform is developed. The tidal sector of TEOBResumS describes the dynamics of neutron star binaries up to merger and incorporates a resummed attractive potential motivated by recent advances in the post-Newtonian and gravitational self-force description of relativistic tidal interactions. Equation-of-state dependent self-spin interactions (monopole-quadrupole effects) are incorporated in the model using leading-order post-Newtonian results in a new expression of the centrifugal radius. TEOBResumS is compared to 135 SpEC and 19 BAM BBH waveforms. The maximum unfaithfulness to SpEC data $\bar{F}$ – at design Advanced-LIGO sensitivity and evaluated with total mass M varying between $10M_\odot \leq M \leq 200M_\odot$ – is always below 2.5×10^{-3} except for a single outlier that grazes the 7.1×10^{-3} level. When compared to BAM data, $\bar{F}$ is smaller than 0.01 except for a single outlier in one of the corners of the NR-covered parameter space, that reaches the 0.052 level. TEOBResumS is also compatible, up to merger, to high end NR waveforms from binary neutron stars with spin effects and reduced initial eccentricity computed with the BAM and THC codes. The data quality of binary neutron star waveforms is assessed via rigorous convergence tests from multiple resolution runs and takes into account systematic effects estimated by using the two independent high-order NR codes. The model is designed to generate accurate templates for the analysis of LIGO-Virgo data through merger and ringdown. We demonstrate its use by analyzing the publicly available data for GW150914.

PACS numbers: 04.25.D-, 04.30.Db, 95.30.Sf, 97.60.Jd

TEOBResumS and GW150914

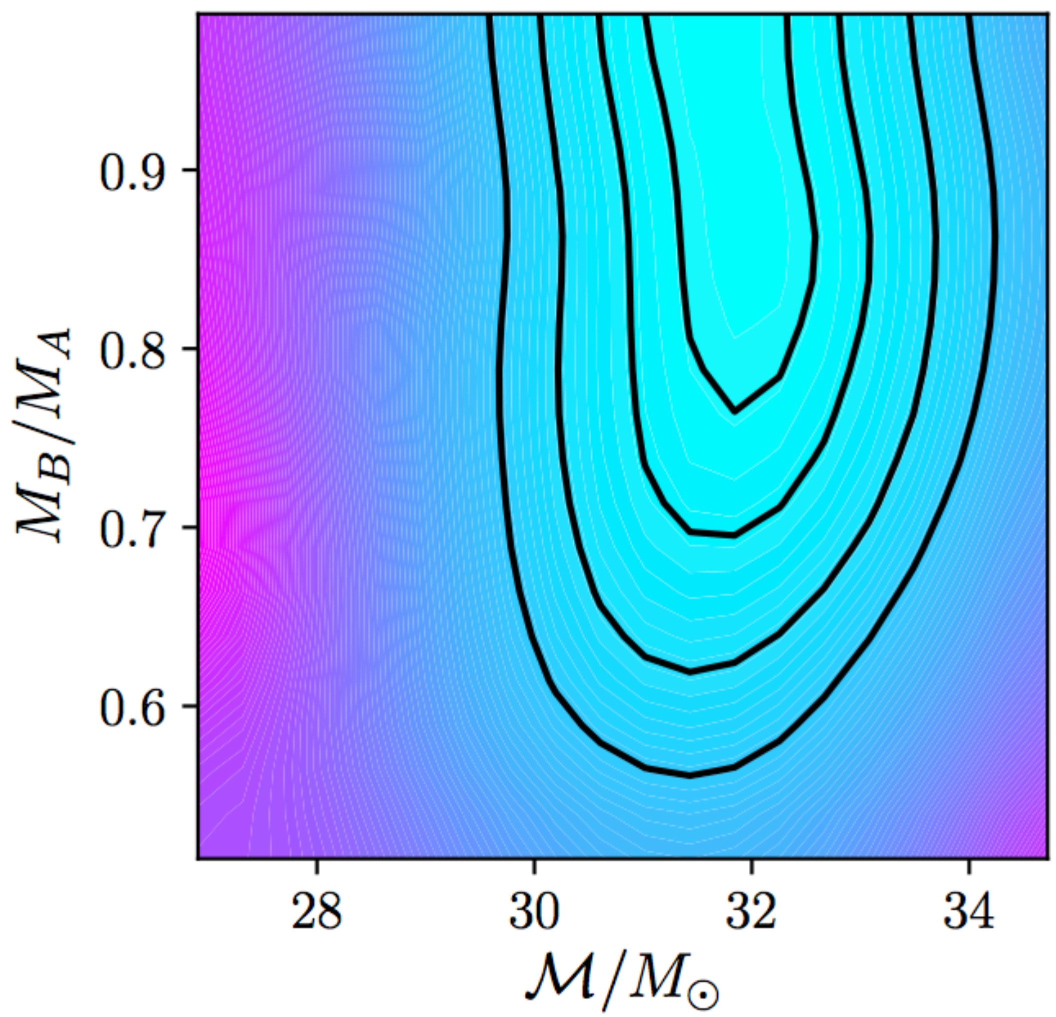


FIG. 15. Two-dimensional posterior distribution for $\mathcal{M}$ and M_B/M_A for GW150914 as inferred using **cpnest** and **TEOBResumS**. The contours indicate the regions enclosing 90%, 75%, 50% and 25% of the probability.

TABLE IV. Summary of the parameters that characterize GW150914 as found by **cpnest** and using **TEOBResumS** as template waveform, compared with the values found by the LVC collaboration [130]. We report the median value as well as the 90% credible interval. For the magnitude of the dimensionless spins $|\chi_A|$ and $|\chi_B|$ we also report the 90% upper bound.

	TEOBResumS	LVC
Detector-frame total mass $M/M_\odot$	$71.8^{+6.5}_{-8.3}$	$70.6^{+4.6}_{-4.5}$
Detector-frame chirp mass $\mathcal{M}/M_\odot$	$30.7^{+3.0}_{-3.8}$	$30.4^{+2.1}_{-1.9}$
Detector-frame remnant mass $M_f/M_\odot$	$68.3^{+5.5}_{-7.4}$	$67.4^{+4.1}_{-4.0}$
Magnitude of remnant spin $\hat{a}_f$	$0.70^{+0.08}_{-0.11}$	$0.67^{+0.05}_{-0.07}$
Detector-frame primary mass $M_A/M_\odot$	$40.3^{+7.0}_{-6.3}$	$38.9^{+5.6}_{-4.3}$
Detector-frame secondary mass $M_B/M_\odot$	$30.9^{+5.9}_{-6.3}$	$31.6^{+4.2}_{-4.7}$
Mass ratio M_B/M_A	$0.8^{+0.2}_{-0.2}$	$0.82^{+0.20}_{-0.17}$
Orbital component of primary spin χ_A	$0.1^{+0.5}_{-0.7}$	$0.32^{+0.49}_{-0.29}$
Orbital component of secondary spin χ_B	$0.1^{+0.6}_{-0.7}$	$0.44^{+0.50}_{-0.40}$
Effective aligned spin $\chi_{\rm eff}$	$0.09^{+0.23}_{-0.25}$	$-0.07^{+0.16}_{-0.17}$
Magnitude of primary spin $\lvert\chi_A\rvert$	≤ 0.6	≤ 0.69
Magnitude of secondary spin $\lvert\chi_B\rvert$	≤ 0.7	≤ 0.89
Luminosity distance d_L/Mpc	585^{+198}_{-224}	410^{+160}_{-180}

Nagar, Bernuzzi, Del Pozzo et al. 2018

TEOBResumS is simple and flexible. It delivers the highest matches with NR waveforms among all available semi-analytical waveform models

Rush the inspiral: efficient Effective One Body time-domain gravitational waveforms

Alessandro Nagar[1,2,3] and Piero Rettegno[2,4]
[1] *Centro Fermi - Museo Storico della Fisica e Centro Studi e Ricerche Enrico Fermi, Rome, Italy*
[2] *INFN Sezione di Torino, Via P. Giuria 1, 10125 Torino, Italy*
[3] *Institut des Hautes Etudes Scientifiques, 91440 Bures-sur-Yvette, France and*
[4] *Dipartimento di Fisica, Università di Torino, via P. Giuria 1, 10125 Torino, Italy*
(Dated: May 11, 2018)

Computationally efficient waveforms are of central importance for gravitational wave data analysis of inspiralling and coalescing compact binaries. We show that the post-adiabatic (PA) approximation to the effective-one-body (EOB) description of the binary dynamics, when pushed to high-order, allows one to accurately and efficiently compute the waveform of coalescing binary neutron stars (BNSs) or black holes (BBHs) up to a few orbits before merger. This is accomplished bypassing the usual need of numerically solving the relative EOB dynamics described by a set of ordinary differential equations (ODEs). Under the assumption that radiation reaction is small, the Hamilton's equations for the momenta can be solved *analytically* for given values of the relative separation. Time and orbital phase are then recovered by simple numerical quadratures. For the least-adiabatic BBH case, equal-mass, quasi-extremal spins anti-aligned with the orbital angular momentum, 6PA/8PA orders are able to generate waveforms that accumulate less than 10^{-3} rad of phase difference with respect to the complete EOB ones up to ~ 3 orbits before merger. Analogous results hold for BNSs. The PA waveform generation is extremely efficient: for a standard BNS system from 10Hz, a nonoptimized `Matlab` implementation of the `TEOBResumS` EOB model in the PA approximation is more than 100 times faster (~ 0.09 sec) than the corresponding C^{++} code based on a standard ODE solver. Once optimized further, our approach will allow to: (i) avoid the use of the fast, but often inaccurate, post-Newtonian inspiral waveforms, drastically reducing the impact of systematics due to inspiral waveform modelling; (ii) alleviate the need of constructing EOB waveform surrogates to be used in parameter estimation codes.

PACS numbers: 04.30.Db, 04.25.Nx, 95.30.Sf, 97.60.Lf

arXiv: 1805.03891

C implementation: 50ms for BNS from 10Hz

In progress: O3 target

Porting TEOBResumS into LAL (Agathos, Bernuzzi, Del Pozzo)

Spin-aligned, higher modes (Messina, Nagar, Rettegno, Riemenschneider)
In progress, almost concluded.

Improvements of TEOBResumS. Systematics?
[See also arXiv:1804.02235, the PhenomPv2_NRTidal paper..]

TEOBResumS_rush for low-latency pipelines??

Macroscopic oscillators and GWs

Rondoni, De Matteis, Degregorio (PoliTo)

We consider the effects of dissipation on the intrinsic noise of GW detectors. Gravitational wave detector are indeed characterized by noise that is neither stationary nor Gaussian, showing for instance non-Gaussian ‘tails’ in the probability distribution. If these are large, they bias the statistics thus making problematic the achievement of a given level of statistical confidence. In the past some of these unexpected noise fluctuations have been claimed as true GW signals, falsified by subsequent analysis. Because of the difficulty in distinguishing a true GW signal from a non-modeled noise fluctuation, joint GW searches are mandatory that combine data from multiple detectors with uncorrelated noise.

From the thermodynamic viewpoint, GW experiments have been commonly modeled as equilibrium systems in the past, but this is hardly correct. In interferometric detectors the fibers which suspend the interferometer mirrors are driven out of equilibrium by the thermal gradient due to the light power dissipated into the mirror substrate and coating, extracted as heat through the fibers themselves.

Our group has already shown that nonequilibrium effects can be quite dramatic on the power spectrum of different devices. we intend to continue this study refining and making more precise the theory so far developed, especially in view of the new generation of GW detectors.

Richieste TO

1 Assegnista (Nagar, 50%)
1 PO(Rondoni, 20%)
3 PhD (Riemenschneider, Rettegno, Dematteis, 100% each)
4 Tecnologi (Bagnasco, Gaido,Lusso, Vallero, 10% each)
1 RuTB (De Gregorio, 100%)

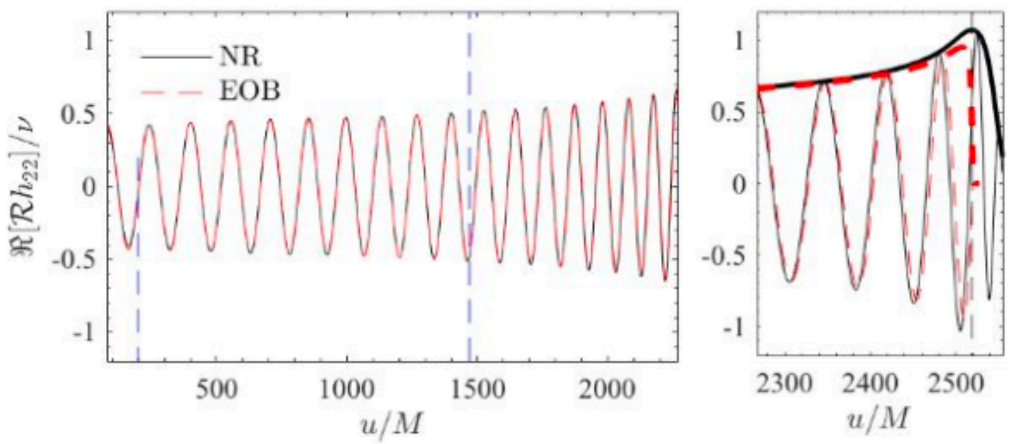
4.7 FTE

Richiesta missioni: 22k

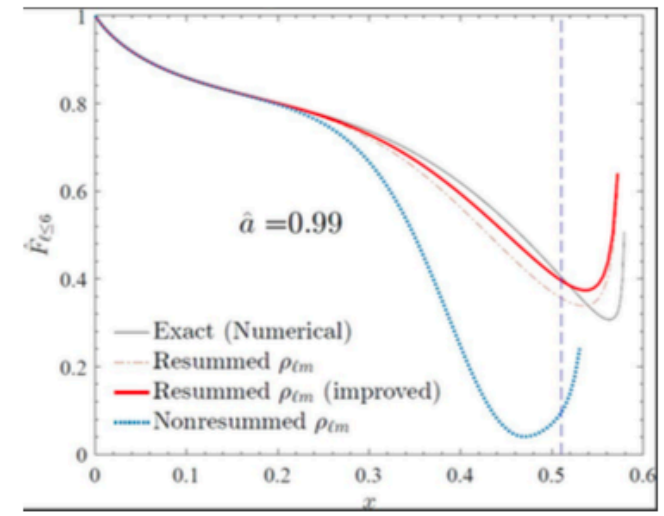
Inventariabile (storage per Tullio e ws): 4k
Licenze software (Mathematica-Maple):3k

What we have done: GW models

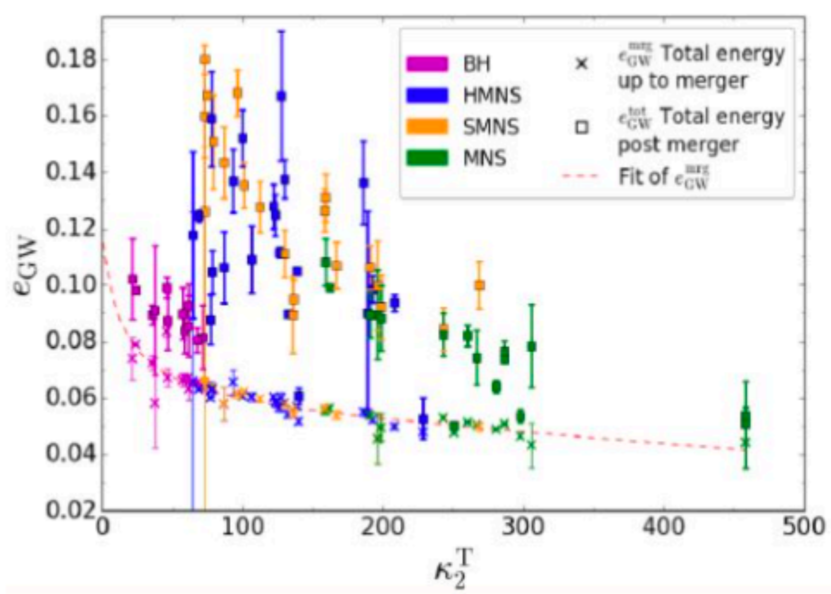
(Bernuzzi, Nagar, Zappa, Messina)



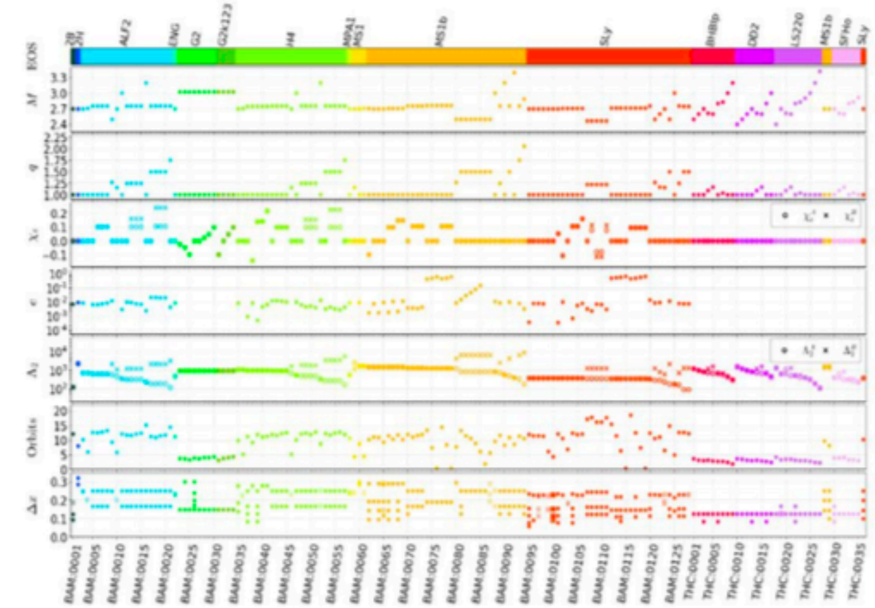
Inspiral waveform models using Effective-One-Body (EOB) and Numerical Relativity for *accurate* parameter estimation



EOB models for accurate evolution of the inspiral of Compact Binary Coalescences



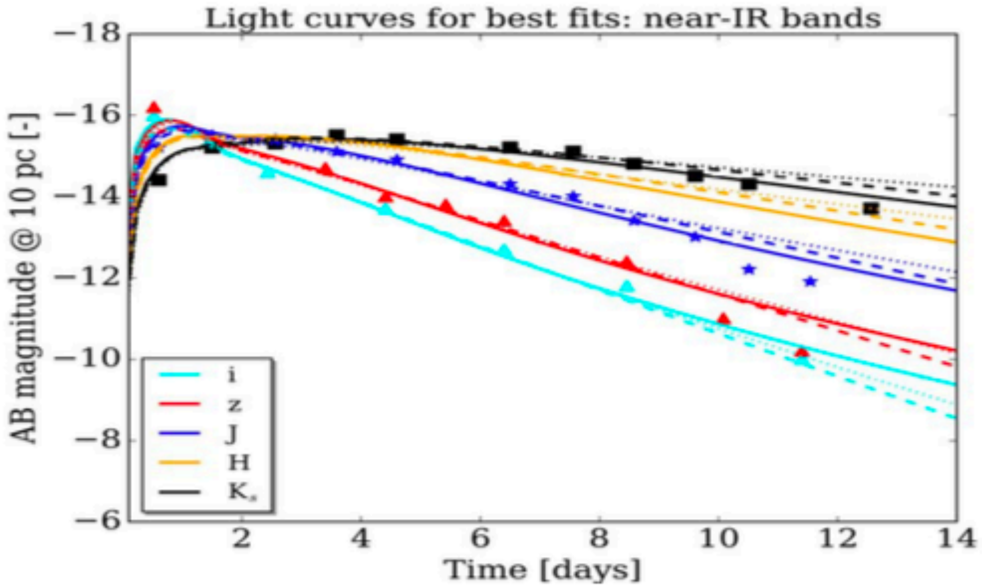
Numerical Relativity study of GW luminosity, radiated energy and remnant angular momentum



Contribution to the largest **BNS waveform database** from Numerical Relativity (CoRe collaboration: www.computational-relativity.org/)

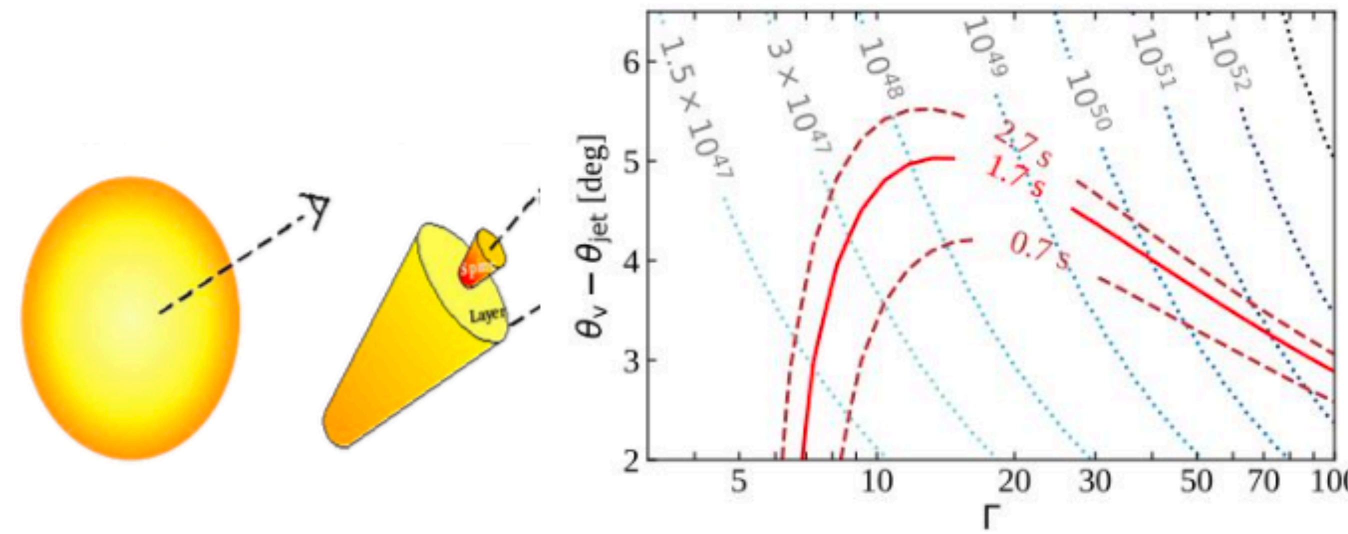
What we have done: EM counterparts

(Ghirlanda, Perego, Salafia, Colpi)



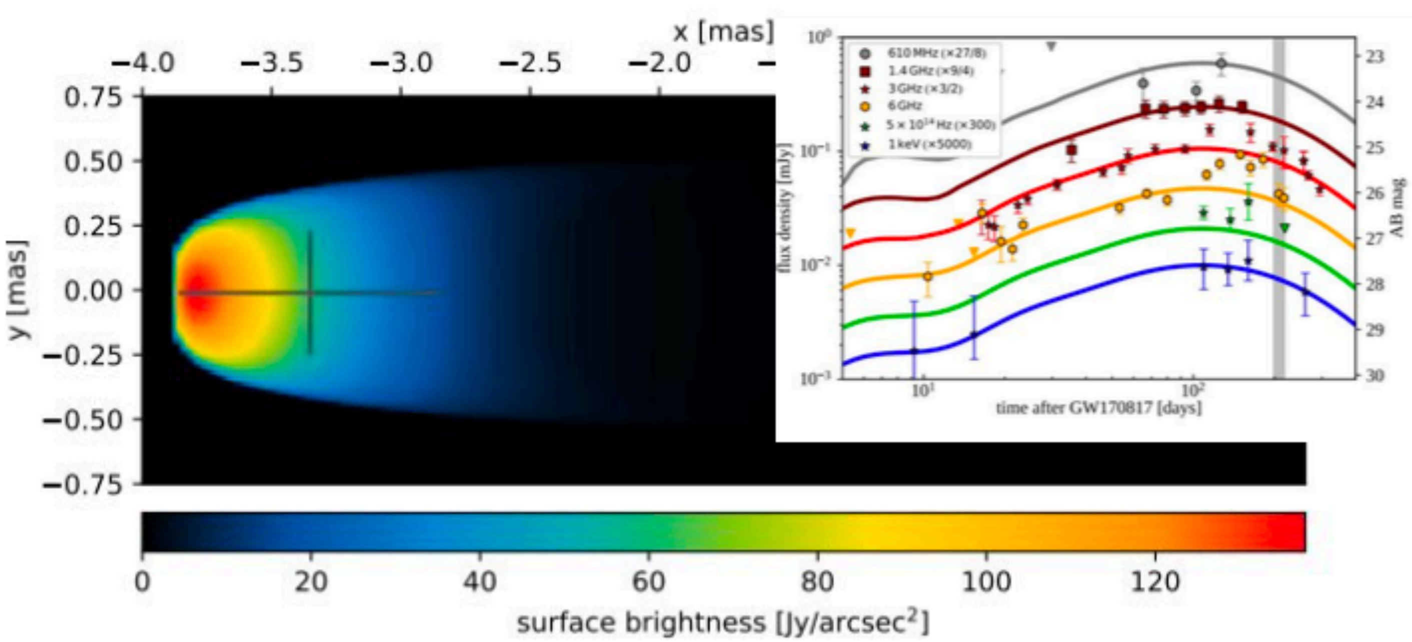
[Perego, Bernuzzi+17]

Kilonova models informed by Numerical Relativity and Radiation Hydrodynamics



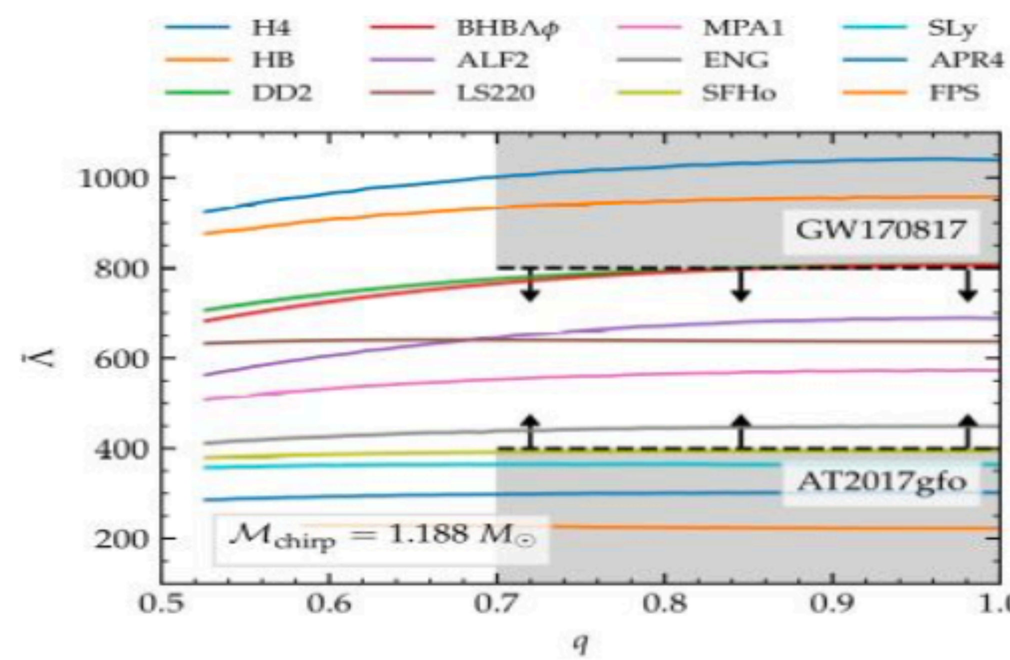
[Salafia, Ghirlanda+17,+18]

Interpretation of the gamma-ray emission following GW170817



[Ghirlanda, Salafia+18]

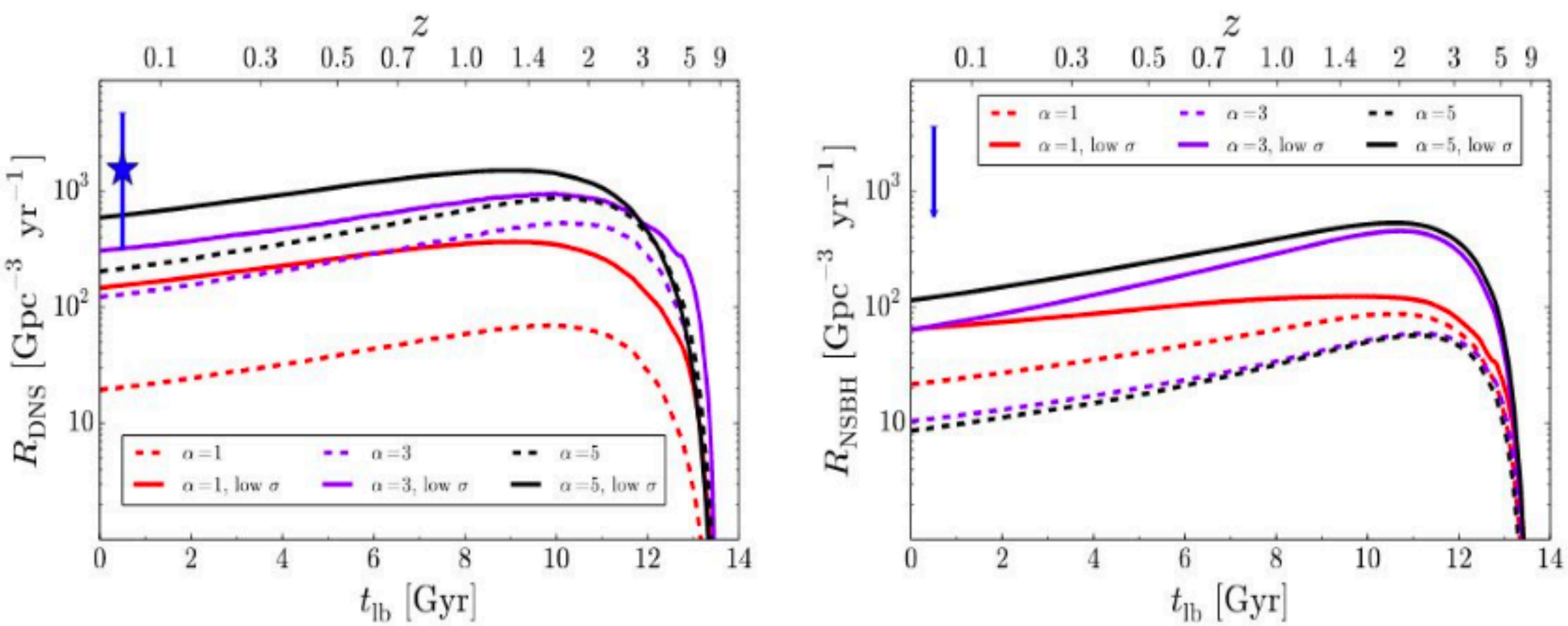
Jet afterglow lightcurves + theoretical radio image predictions for global-VLBI imaging of GW170817 (coming soon!)



[Radice, Perego, Zappa & Bernuzzi '18]

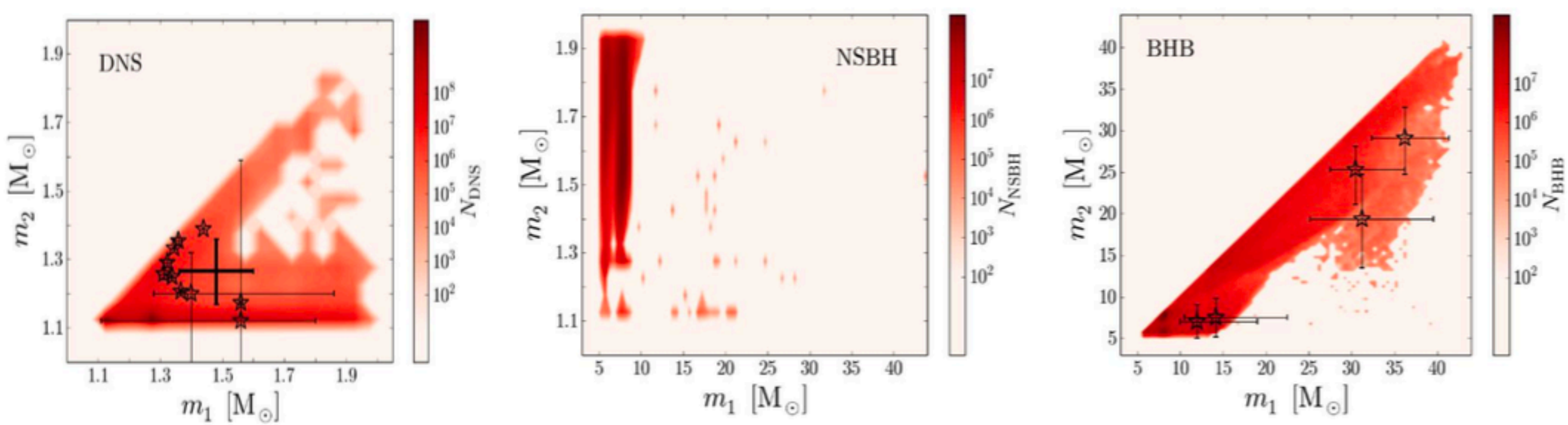
Joint GW, EM & Numerical Relativity analysis to constraint the equation of state of nuclear matter

What we have done: population and rates
(Mapelli, Spera)



Prediction of CBC rates through the cosmic history combining cosmological simulations and binary evolution models

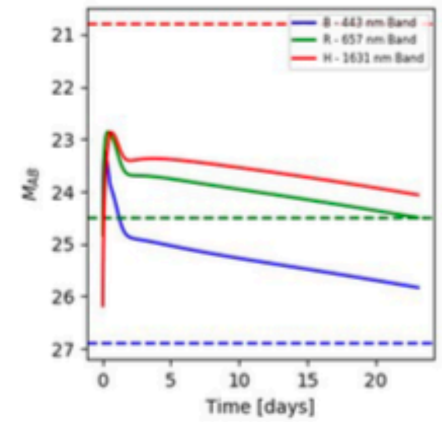
Prediction of the detected binary system mass distribution and comparison with observations

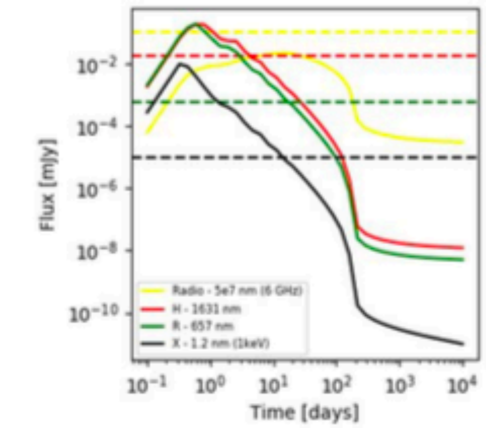


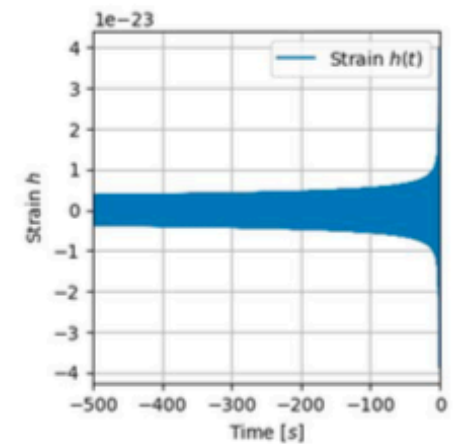
What we are doing

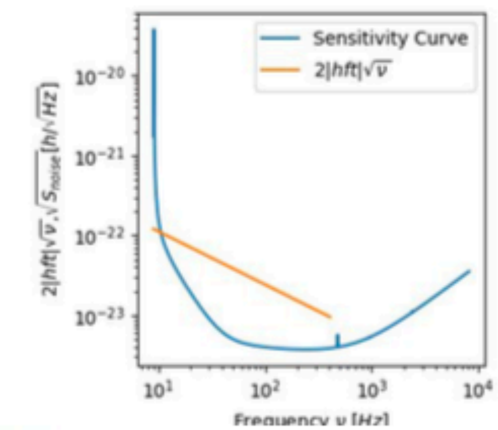
Multimessenger (GW+EM) modeling of BH-NS mergers, to achieve:

- Predictions for the rate of joint detections (GW+kilonova, GW+jet, GW+both) with various facilities and strategies
- statistical/astrophysical properties of the detected population
- coherent GW+EM parameter estimation (requires a complete description of kilonova and jet dynamics and emission, with all possible links to binary parameters!)



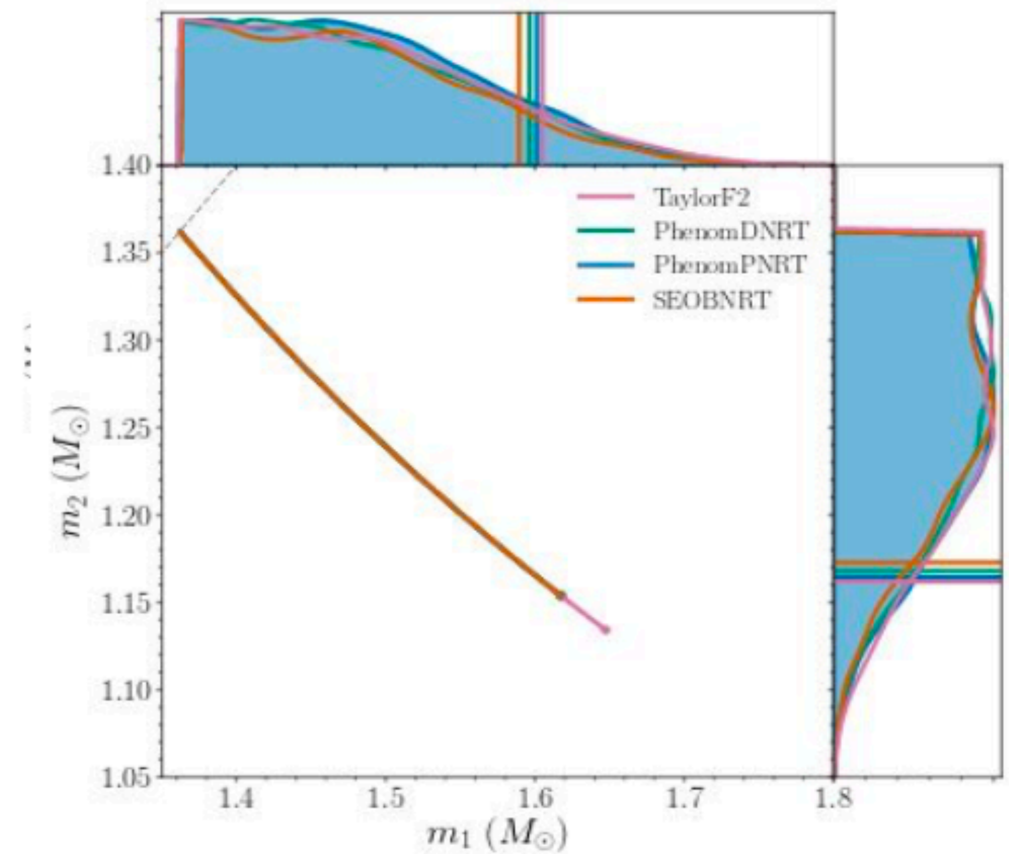






Continuing improvements **GW CBC models** using **EOB** and **Numerical Relativity → inclusion in LV** data analysis and **parameter estimation**:

- Higher PN terms
- Spin contributions
- Tidal and point mass effects



FTE and funding estimate for MiB

- NAME
  FTE (Virgo-Mib)
- Barbieri Claudio (PhD stud) 1.0 (0.5)
- Colpi Monica 0.4
- Ghirlanda Giancarlo 0.4
- Messina Francesco (PhD stud) 1.0 (0.5)
- Perego Albino 0.5
- Salafia Om Sharan 0.4
- TOTAL 3.7 (2.7)

- FUNDING ESIMATES
- Travel money: 19.0k euros (7k/FTE x 2.7 FTE)
- Software Licences: 3.0k euros