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Analytical & numerical relativity modeling of gravitational waves from neutron star mergers

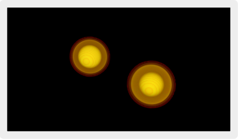
(and some highlights from binary black holes)

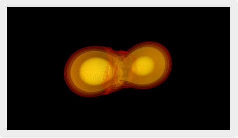
S.Bernuzzi

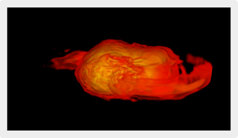
Damour Fest: Adventures in Gravitation

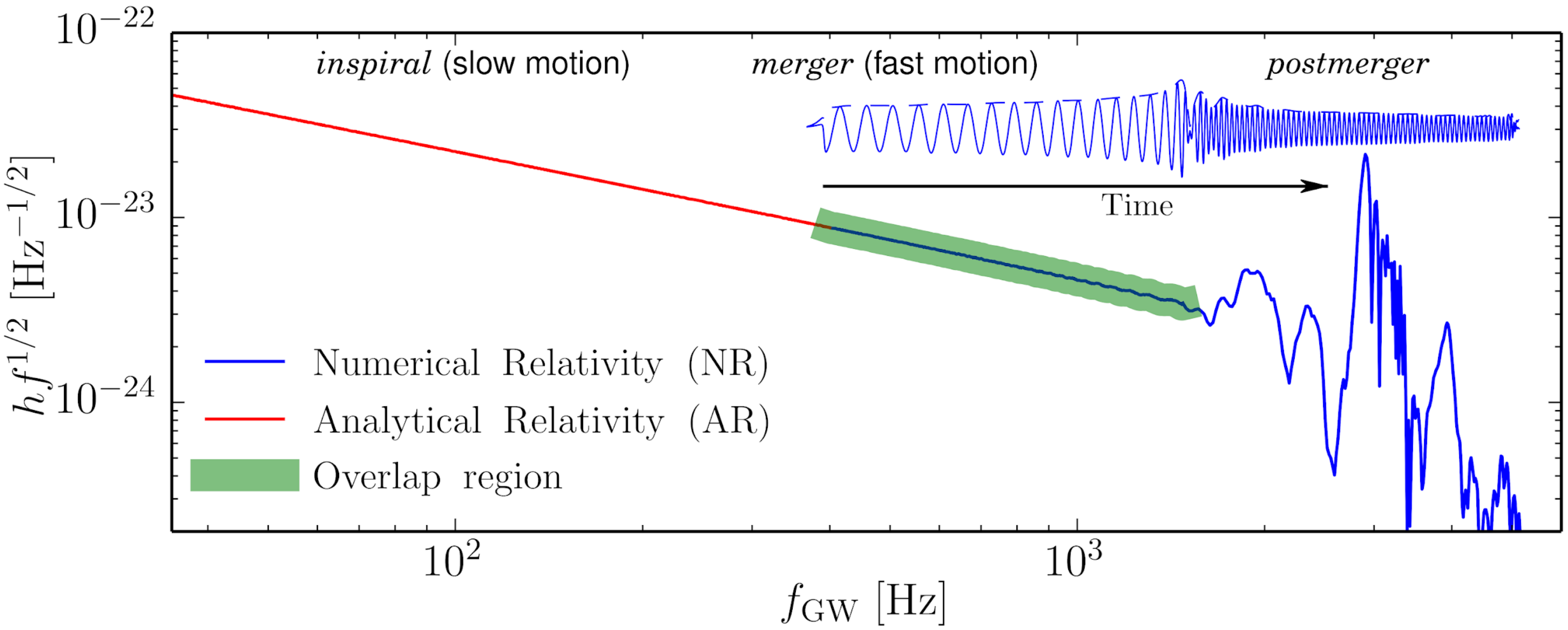
October 2021, IHES

The BNS gravitational-wave spectrum



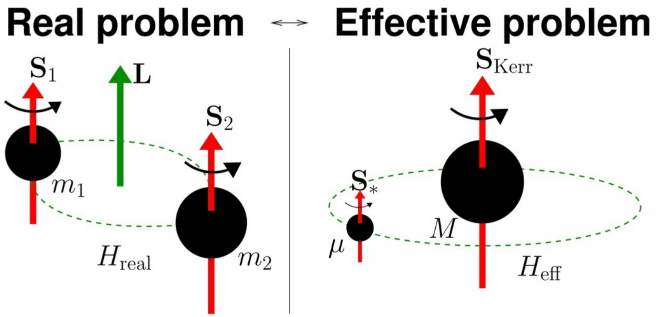






Effective-one-body framework in a nutshell

[Buonanno&Damour PRD 2000a, 2000b]



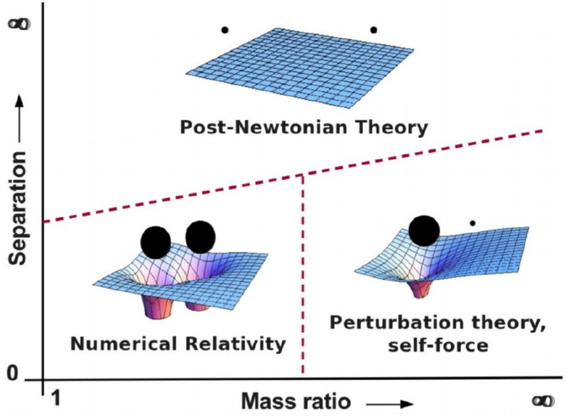
Credit: A.Taracchini/AEI

$$H_{\rm eff} \sim \mu\sqrt{A(u)(1+p_\phi^2 u^2) + p_{r*}^2}$$

$$A(u;\nu;\kappa_2^T) = A^0(u;\nu) + A^T(u;\nu;\kappa_2^T)$$

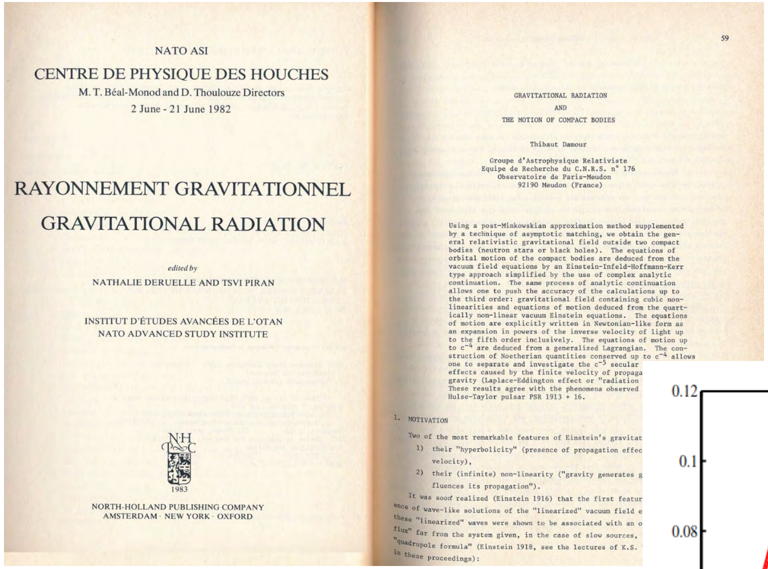
$$A^0(u;\nu) = 1 - 2u + \nu(\ldots$$

Factorized (resummed) PN waveform [Damour,Iyer,Nagar 2008]
Includes test-mass limit (i.e. particle on Schwarzschild)
Includes post-Newtonian and self-force results
Uses resummation techniques → predictive strong-field regime
Includes tidal interactions (→ BNS) [Damour&Nagar PRD 2010]
Flexible framework → NR informed



Credit: L.Barak

Love numbers depends on EOS and NS compactness



NATO ASI

CENTRE DE PHYSIQUE DES HOUCHES

M. T. Béal-Monod and D. Thoulouze Directors

2 June - 21 June 1982

RAYONNEMENT GRAVITATIONNEL

GRAVITATIONAL RADIATION

edited by

NATHALIE DERUELLE AND TSVI PIRAN

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59

GRAVITATIONAL RADIATION

AND

THE MOTION OF COMPACT BODIES

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92190 Meudon (France)

Using a post-Minkowskian approximation method supplemented by a technique of asymptotic matching, we obtain the general relativistic gravitational field outside two compact bodies (neutron stars or black holes). The equations of orbital motion of the compact bodies are deduced from the vacuum field equations by an Einstein-Infeld-Hoffmann-Kerr type approach simplified by the use of complex analytic continuation. The same process of analytic continuation allows one to push the accuracy of the calculations up to the third order: gravitational field containing cubic nonlinearities and equations of motion deduced from the quartically non-linear vacuum Einstein equations. The equations of motion are explicitly written in Newtonian-like form as an expansion in powers of the inverse velocity of light up to the fifth order inclusively. The equations of motion up to c^{-4} are deduced from a generalized Lagrangian. The construction of Noetherian quantities conserved up to c^{-4} allows one to separate and investigate the c^{-5} secular effects caused by the finite velocity of propaga gravity (Laplace-Eddington effect or "radiation These results agree with the phenomena observed Hulse-Taylor pulsar PSR 1913 + 16.

1. MOTIVATION

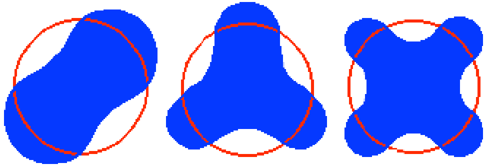
Two of the most remarkable features of Einstein's gravitat

1) their "hyperbolicity" (presence of propagation effec velocity),

2) their (infinite) non-linearity ("gravity generates g fluences its propagation").

It was soon realized (Einstein 1916) that the first featur ence of wave-like solutions of the "linearized" vacuum field e these "linearized" waves were shown to be associated with an o flux" far from the system given, in the case of slow sources, "quadrupole formula" (Einstein 1918, see the lectures of K.S. in these proceedings):

"inner problem"



$$Q_{ij} = \lambda_2 G_{ij} \sim \lambda_2 \partial_i \partial_j \phi$$

PHYSICAL REVIEW D **80**, 084035 (2009)

Relativistic tidal properties of neutron stars

Thibault Damour[1,2] and Alessandro Nagar[1,2]

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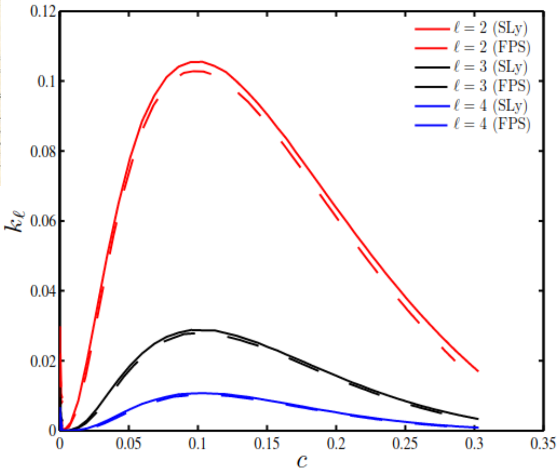
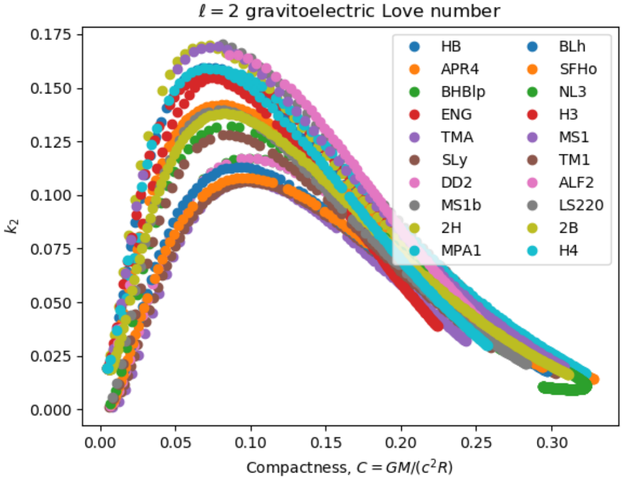
[2]*ICRANet, 65122 Pescara, Italy*

(Received 30 May 2009; published 23 October 2009)





See also Hinderer 2007, Binnington&Poisson 2009

3. DIGEST OF THE HISTORY OF THE PROBLEM OF MOTION

In 1687, I. Newton showed how the orbital motion of approximately spherical extended objects could be well-approximated by the motion of point masses. This is a very important result of Newtonian physics whose extension to General Relativity is highly non-trivial, as was pointed out by M. Brillouin (1922). M. Brillouin called this schematization of an extended body by a point mass with disappearance of all internal structure: "le principe d'effacement" ("effacing principle;" perhaps a more picturesque name would be: "the Cheshire cat principle"). In Newtonian physics the proof of this "effacing principle" makes an essential use of:

1) the linearity of the gravitational field as a function of the matter distribution (which allows one to define and separate the self-field and the external field);
2) the Action and Reaction principle (which allows one to define the center of mass and to ignore the contribution of the self-field to its motion);
3) Newton's theorem on the attraction of spherical bodies.

More specifically, for a binary system constituted of non-rotating nearly spherical bodies of masses m and m', one deduces from 1) that the main correction to the point mass idealization will come from the tidal field $Gm'd^{-3}r$ (where G is Newton's constant, r is the distance away from the center of mass of the first object m, and d is the distance between the two objects). If b denotes the radius of the first object, the tidal field will deform slightly its shape: $\delta b/b = h(m'/d^3)(b^3/m)$, where h, the first Love (1909) number, is a dimensionless quantity of order unity. This deformation induces in turn a small quadrupole moment: $Q = k\, m'b^5d^{-3}$, where k, the second Love number, is a dimensionless quantity of order unity ($h = 3/5$ and $k = 4/15$ for the Earth). Finally this tidally induced quadrupole moment will create a small correction to Newton's law for point masses: $\delta F/F \sim k\,(b/d)^5$. Therefore as long as the radii of the objects are much smaller than their mutual distances, their internal structure (if they are not rotating) will be utterly negligible. We shall show in Section 5 how this result of "effacing" can be extended to Einstein's theory even, and in fact most accurately, in the case of compact objects, i.e. when the radius $b \sim Gm/c^2$. But as we shall not be able to use 1) and 2) above, we shall need a completely different approach to show that the very strong "self field" of the compact object does not contribute to its orbital motion.

Then one can find in vacuum a decoupled second order differential equation for $H = H_0 = H_2$ for instance (Edelstein and Vishveshwara 1970 , Demianski and Grishchuk 1974):

$$\hat{R}(\hat{R}-2)d^2(H/\hat{R}(\hat{R}-2))/d\hat{R}^2 + 3(2\hat{R}-2)d(H/\hat{R}(\hat{R}-2))/d\hat{R} - (L-2)(L+3)\,H/\hat{R}(\hat{R}-2) = 0. \tag{10}$$

The general solution of this second order differential equation contains 2 arbitrary constants. For instance, when $L = 2$, one finds for the general quadrupolar H perturbation in vacuum, i.e. outside the body:

$$H = D(\hat{R}(\hat{R}-2) + k\,\hat{R}(\hat{R}-2)\int_{\hat{R}}^{\infty} 5dx/(x^3(x-2)^3)\,). \tag{11}$$

The dimensionless constant k is a relativistic generalization (Damour 1981) of the second Love number (Love 1909) which was introduced in Section 3. It is, in a sense, a dimensionless measure of the yielding of the object to an external tidal solicitation. It depends on the internal structure of the body (equations of state,...) and can be determined for an ordinary body (not a black hole) by imposing the regularity of the metric perturbation H, K, h_0 at the center of the body and when crossing the surface of the body (see e.g., Thorne and Campolattaro 1967). By our hypothesis 1) we have $\hat{R} \sim 1$ at the radius of the object, therefore as there are no other scales in the problem, k must be of order unity (like the non-relativistic one):

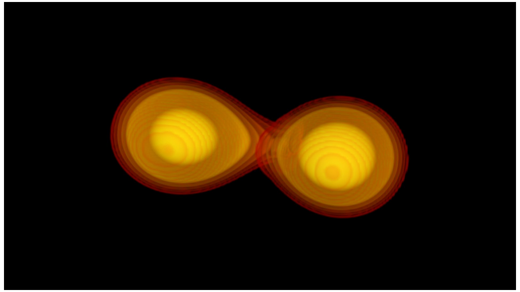
$$k \sim 1 \tag{12}$$

(More generally for non-necessarily compact objects of dimensionless radius $\hat{b}$, one will have $k \sim \hat{b}^5$ which allows one to justify the remark after hypothesis 1)). In the case of a black hole, k is determined by imposing the regularity of metric perturbation on the future horizon: in this case one finds $k = 0$ (in agreement with D'Eath 1975a). Incidently, one should not conclude from this result that there are no tidal responses of a black hole to an external solicitation: such a non-zero response is contained in the first term of the righthand side of (11): $\hat{R}\,(\hat{R} - 2)$ which differs from the usual term (in absence of any object): $\hat{R}^2$.

PHYSICAL REVIEW D **81,** 084016 (2010)

Effective one body description of tidal effects in inspiralling compact binaries

Thibault Damour and Alessandro Nagar
Institut des Hautes Etudes Scientifiques, 91440 Bures-sur-Yvette, France and ICRANet, 65122 Pescara, Italy
(Received 26 November 2009; published 8 April 2010)



$$\kappa_2^T = 2\left[\frac{X_A}{X_B}\left(\frac{X_A}{C_A}\right)^5 k_2^A + \frac{X_B}{X_A}\left(\frac{X_B}{C_B}\right)^5 k_2^B\right]$$

Tidal coupling constant (Analogous to the reduced tidal parameter $\overline{\Lambda}$ [Favata 2013])

Hamiltonian
(Newtonian limit):

$$H_{\mathrm{EOB}} \approx Mc^2 + \frac{\mu}{2}\left(\mathbf{p}^2 + A(r) - 1\right)$$

$$A(r) = 1 - \frac{2}{r} - \frac{\kappa_2^T(k_2)}{r^6}$$

Waveform:

$$h \sim Af^{-7/6}e^{-i\Psi(x(f))} = Af^{-7/6}e^{-i\Psi_{\mathrm{pp}}(x)+i39/4\,\kappa_2^T x^{5/2}}$$

PHYSICAL REVIEW D **81**, 084016 (2010)

Effective one body description of tidal effects in inspiralling compact binaries

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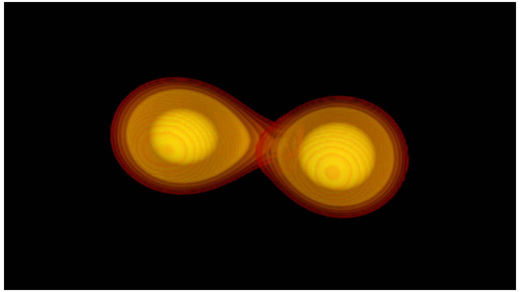

$$\kappa_2^T = 2\left[\frac{X_A}{X_B}\left(\frac{X_A}{C_A}\right)^5 k_2^A + \frac{X_B}{X_A}\left(\frac{X_B}{C_B}\right)^5 k_2^B\right]$$

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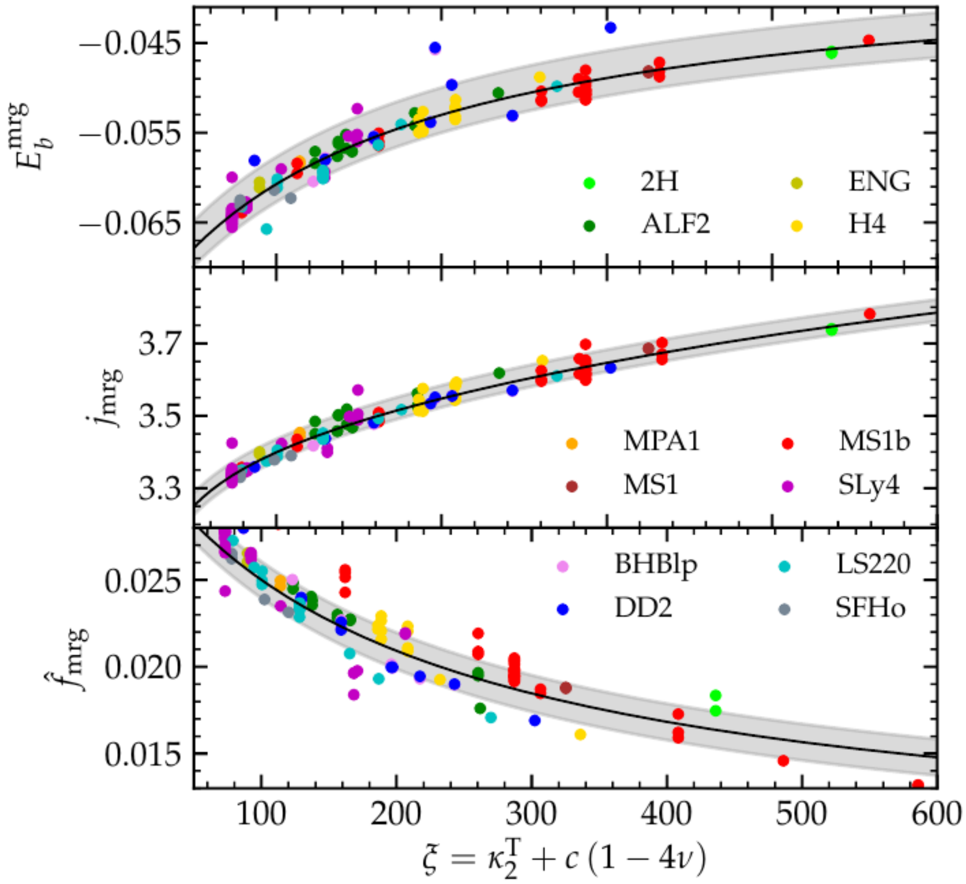
Waveform:

$$h \sim A f^{-7/6} e^{-i\Psi(x(f))} = A f^{-7/6} e^{-i\Psi_{\mathrm{pp}}(x) + i 39/4\, \kappa_2^T x^{5/2}}$$

Key point: No other binary parameter (mass, radii, etc) enter separately the formalism at LO

Merger parametrization (aka quasiuniversality)



- How to interpret numerical-relativity (NR) data?
- *Y-axis:* simulation results from multi-orbit NR simulations with different EOS, masses, mass-ratio, spins, etc.
- *X-axis:* tidal coupling constant (plus effective correction for very asymmetric binaries)

- Tidal coupling constant captures strong-field features to high precision!
  SB+ (2014) [https://arxiv.org/abs/1402.6244]

- Why useful?
  - Lower bounds for energy, angular momentum, radiated to merger (at the end of chirp)
  - GW merger frequency/amplitude (not predicted by post-Newtonian methods)
  - Peak luminosity and upper bounds for remnant's energy, ang.momentum, etc. [Zappa,SB+ (2017)]

PRL **114,** 161103 (2015) PHYSICAL REVIEW LETTERS week ending 24 APRIL 2015

Modeling the Dynamics of Tidally Interacting Binary Neutron Stars up to the Merger

Sebastiano Bernuzzi,[1,2] Alessandro Nagar,[3] Tim Dietrich,[4] and Thibault Damour[3]
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[2]*DiFeST, University of Parma, I-43124 Parma, Italy*
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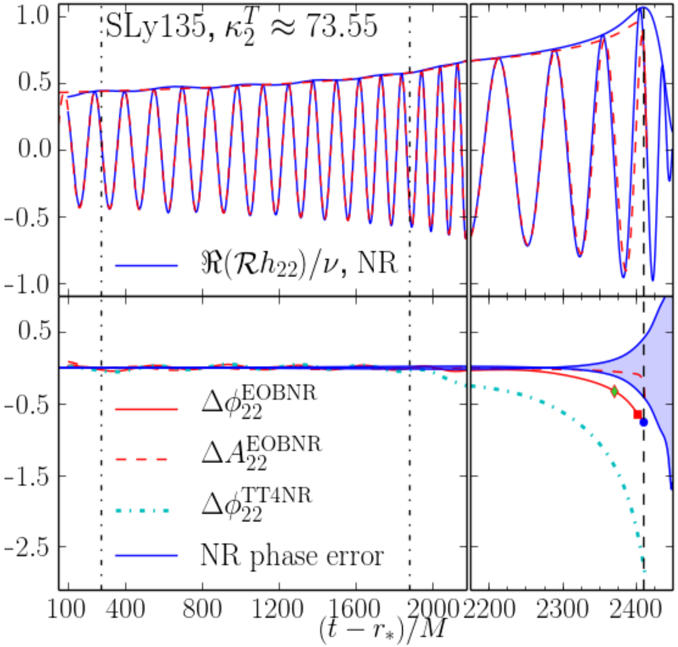
[4]*Theoretical Physics Institute, University of Jena, 07743 Jena, Germany*
(Received 15 December 2014; revised manuscript received 18 February 2015; published 23 April 2015)



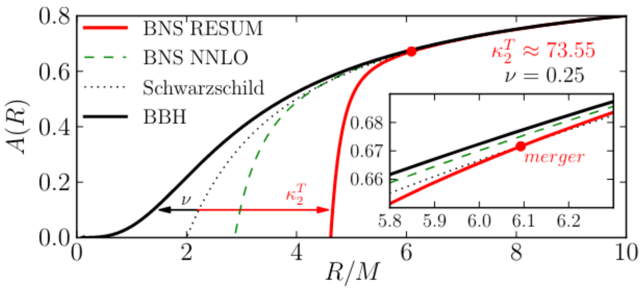


FIG. 1: The main radial gravitational potential $A(R)$ in various EOB models. Finite-mass ratio effects (ν) make the gravitational interaction less attractive than the Schwarzschild relativistic potential $A_{\rm Schw} = 1 - 2M/R$, while tides (κ_2^T, see Table I) make it more attractive (especially at short separations).

PHYSICAL REVIEW D **90,** 124037 (2014)

Gravitational self-force corrections to two-body tidal interactions and the effective one-body formalism

Donato Bini[1] and Thibault Damour[2]
[1]*Istituto per le Applicazioni del Calcolo "M. Picone," CNR, I-00185 Rome, Italy*
[2]*Institut des Hautes Etudes Scientifiques, 91440 Bures-sur-Yvette, France*
(Received 24 September 2014; published 10 December 2014)

See also Bini, Damour, Feye 2013, Dolan+ 2014
Akcay, SB+ [https://arxiv.org/abs/1812.02744]

PSR J0737-3039

Masses: 1.338 - 1.249

Spins: (0,0.0028,0.05) - (0,0,0)

Initial Grav. Wave-freq: 470 Hz

upper left panel:
density
inside level 4

upper right panel:
logarithm of the entropy
inside level 3

lower left panel:
gravitational wave for z<0
inside level 0

lower right panel:
unbound material
inside level 3

PHYSICAL REVIEW D **79**, 064004 (2009)

Improved resummation of post-Newtonian multipolar waveforms from circularized compact binaries

Thibault Damour,[1,2] Bala R. Iyer,[1,3] and Alessandro Nagar[1,2,4]
[1]*Institut des Hautes Etudes Scientifiques, 91440 Bures-sur-Yvette, France*
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(Received 13 November 2008; published 3 March 2009)

As indicated above, the resummation method we shall use here consists in: (i) decomposing the PN-correction factor $\hat{h}_{\ell m}^{(\epsilon)} = 1 + h_1 x + h_{1.5} x^{3/2} + \dots$ into the *product of four factors*, each of which has a similar PN expansion, $1 + \mathcal{O}(x)$, namely

$$\hat{h}_{\ell m}^{(\epsilon)} = \hat{S}_{\rm eff}^{(\epsilon)} T_{\ell m} e^{{\rm i}\delta_{\ell m}} \rho_{\ell m}^{\ell}, \tag{8}$$

and then (ii), resumming separately each factor.

The structure of this Hamiltonian can be clarified by introducing the (gauge-invariant) concept of "centrifugal radius" $r_c(r)$, defined so that the orbital part of the Hamiltonian ruling equatorial orbits ($\theta = \pi/2$) can be written as

$$H_{\rm orb,eq}^{\rm Kerr}(r, p_r, p_\varphi) = \sqrt{A^{\rm eq}(r)\left(\mu^2 + \frac{p_\varphi^2}{r_c^2} + \frac{p_r^2}{B^{\rm eq}(r)}\right)}, \tag{8}$$

with the usual, relativistic centrifugal energy term $\mu^2 + p_\varphi^2/r_c^2$. By comparing with Eq. (2) one obtains

$$r_c^2 \equiv \frac{\mathcal{R}^4(r)}{r^2} = r^2 + a^2 + \frac{2Ma^2}{r}. \tag{9}$$

PHYSICAL REVIEW D **90**, 044018 (2014)

New effective-one-body description of coalescing nonprecessing spinning black-hole binaries

Thibault Damour and Alessandro Nagar
Institut des Hautes Etudes Scientifiques, 91440 Bures-sur-Yvette, France
(Received 26 June 2014; published 13 August 2014)

$$r_c^2 = r^2 + \tilde{a}_Q^2\left(1 + \frac{2}{r}\right) + \frac{\delta a_{\rm NLO}^2}{r} + \frac{\delta a_{\rm NNLO}^2}{r^2} + \frac{\delta a_{\rm LO}^4}{r^2}. \tag{25}$$

EOS-dependent self-spin terms up to NNLO + bilinear, cubic, quartic nonlinear effects at LO [Nagar,SB+ 2018, Nagar+ 2018]

Source’s parameters measurement from GWs

Selected for a Viewpoint in *Physics*
PRL **119,** 161101 (2017) PHYSICAL REVIEW LETTERS week ending 20 OCTOBER 2017

GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral

B. P. Abbott *et al.**
(LIGO Scientific Collaboration and Virgo Collaboration)
(Received 26 September 2017; revised manuscript received 2 October 2017; published 16 October 2017)

PHYSICAL REVIEW D **85,** 123007 (2012)

Measurability of the tidal polarizability of neutron stars in late-inspiral gravitational-wave signals

Thibault Damour and Alessandro Nagar
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Loïc Villain
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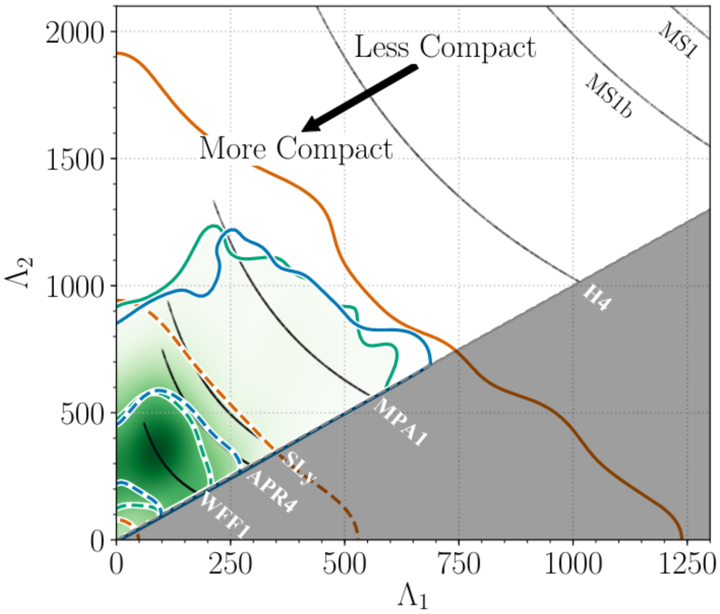
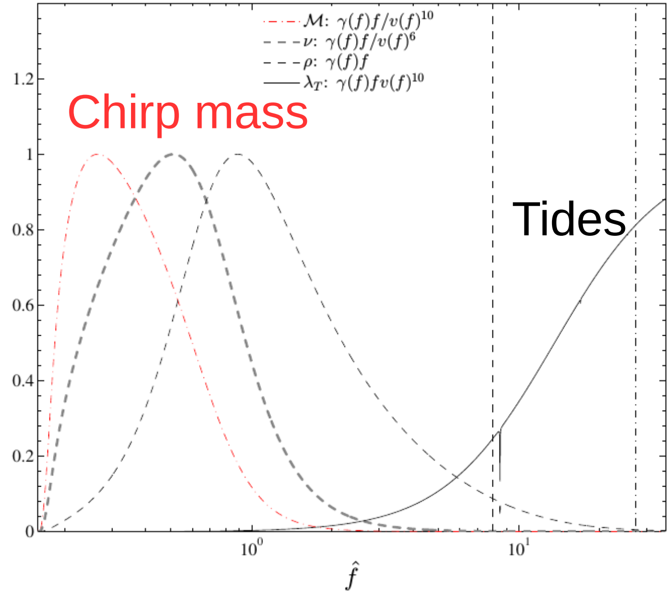
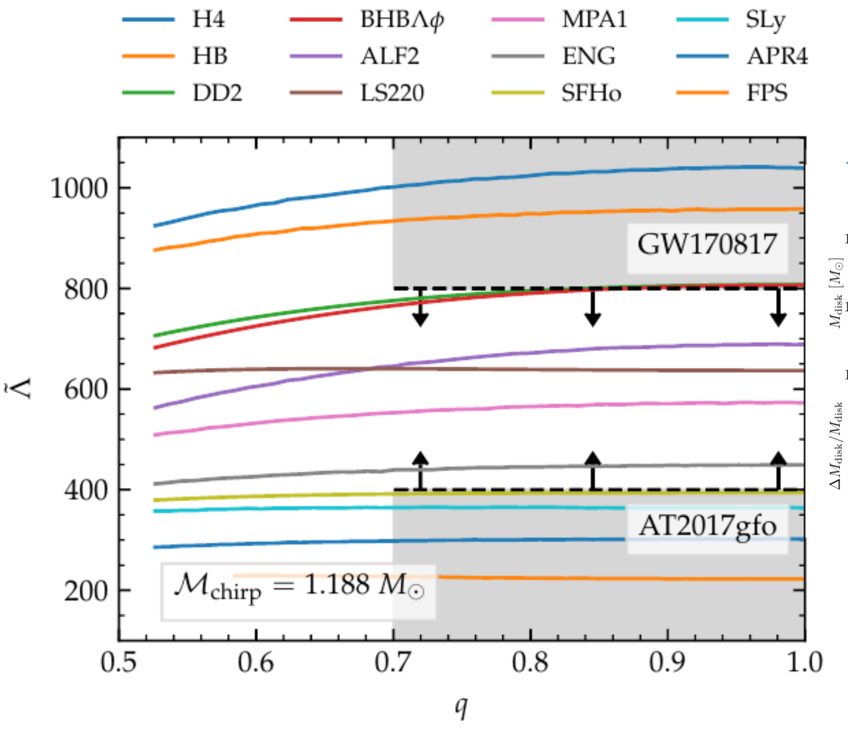
(Received 20 March 2012; published 15 June 2012)

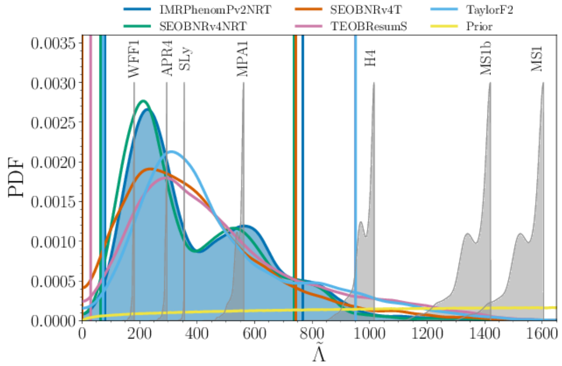


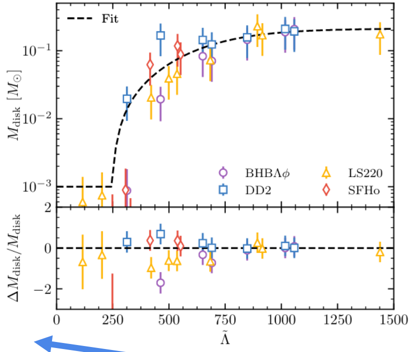


Joint analyses to maximize science output

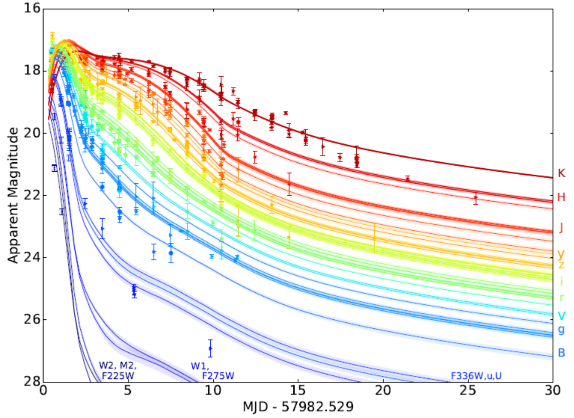


NRAR modeling
Grav. waves





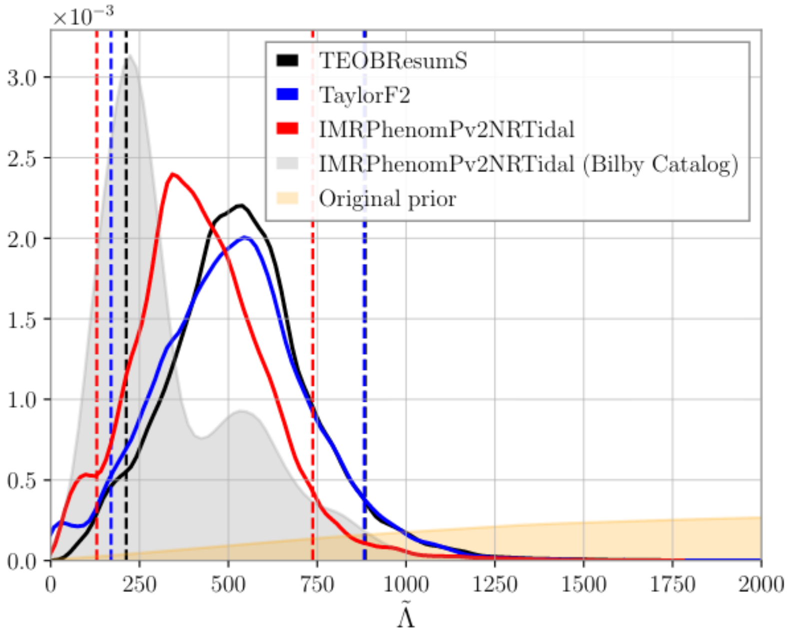
NR modeling
remnant &
counterparts



Radice,Perego,Zappa,SB [https://arxiv.org/abs/1711.03647]

Tidal parameters inference & wvf systematics

Gamba, Breschi, SB+ [https://arxiv.org/abs/2009.08467]



Updated NS radius measurement:

$R_{1.4} = 12.5^{+1.1}_{-1.8}$ km

GW170817: no “strong” wvf systematics BUT $\bar{\Lambda}$ shift & “double peaked” posteriors
1kHz cut-off removes double peaks, less wvf baises and shifts to larger $\bar{\Lambda}$ (larger radii) for comparable log-like.
Estimated <10% SNR above f > 1kHz; high-frequencies issues in $\bar{\Lambda}$-inference? (Dai+ 2018, Narikawa+ 2019)

How well we do with BNS waveforms?

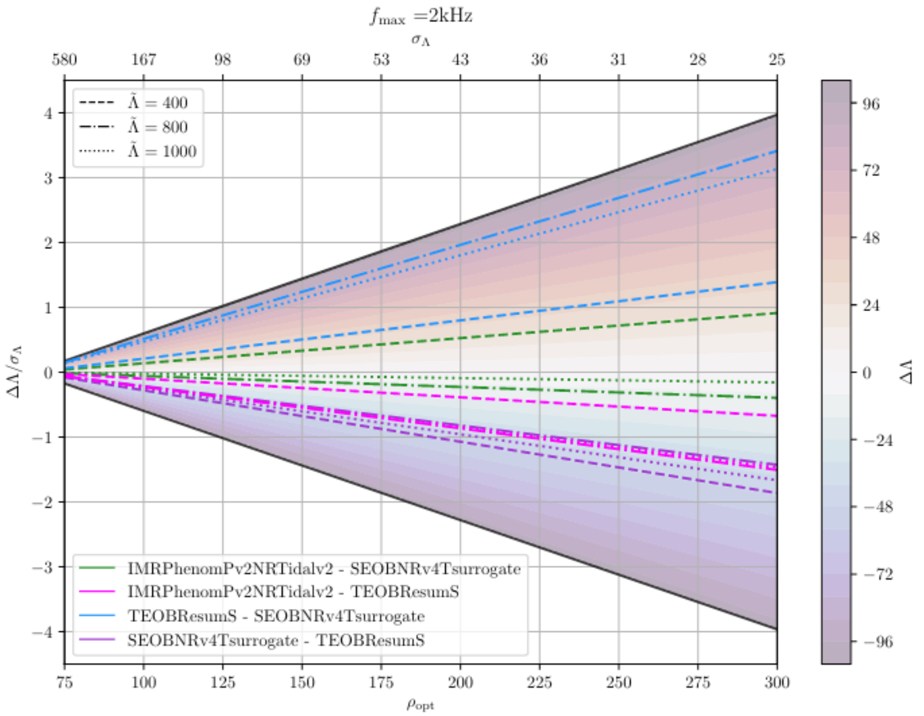


TABLE V. Faithfulness values $\mathcal{F}$ computed considering frequencies from $f_{\rm low}$ to $f_{\rm mrg}$ between simulations with the same intrinsic parameters and two different resolutions, extracted at $r/M = 1000$. The source is situated in the same sky location as GW170817, and the waveform polarizations h_+ and $h_\times$ are computed and projected on the Livingston detector. We employ the `aLIGODesignSensitivityP1200087` [22] PSD from `pycbc` [110] to compute the matches, and compare the values obtained to the thresholds $\mathcal{F}_{\rm thr}$ calculated with Eq. 19 with $\epsilon^2 = 1$ or $\epsilon^2 = N$. A tick ✓ indicates that $\mathcal{F} > \mathcal{F}_{\rm thr}$. Conversely, a cross ✗ indicates that $\mathcal{F} < \mathcal{F}_{\rm thr}$.

Sim	n[a]	$\mathcal{F}$	SNR 14		SNR 30		SNR 80	
			$N = 6$	1	$N = 6$	1	$N = 6$	1
`BAM:0011`	[96, 64]	0.991298	✓	✗	✗	✗	✗	✗
`BAM:0017`	[96, 64]	0.985917	✓	✗	✗	✗	✗	✗
`BAM:0021`	[96, 64]	0.957098	✗	✗	✗	✗	✗	✗
`BAM:0037`	[216, 144]	0.998790	✓	✓	✓	✗	✗	✗
`BAM:0048`	[108, 72]	0.983724	✗	✗	✗	✗	✗	✗
`BAM:0058`	[64, 64]	0.999127	✓	✓	✓	✗	✗	✗
`BAM:0064`	[240, 160]	0.997427	✓	✗	✓	✗	✗	✗
`BAM:0091`	[144, 108]	0.997810	✓	✓	✓	✗	✗	✗
`BAM:0094`	[144, 108]	0.996804	✓	✗	✓	✗	✗	✗
`BAM:0095`	[256, 192]	0.999550	✓	✓	✓	✓	✓	✗
`BAM:0107`	[128, 96]	0.995219	✓	✗	✗	✗	✗	✗
`BAM:0127`	[128, 96]	0.999011	✓	✓	✓	✗	✗	✗

[a] Number of grid point (linear resolution) of the finest grid refinement, roughly covering the diameter of one NS

Insufficient for SNR>80 [Gamba,Breschi,SB+ https://arxiv.org/abs/2009.08467]

Systematics will be a major issue for (high-precision) measurements (e.g. Einstein Telescope)

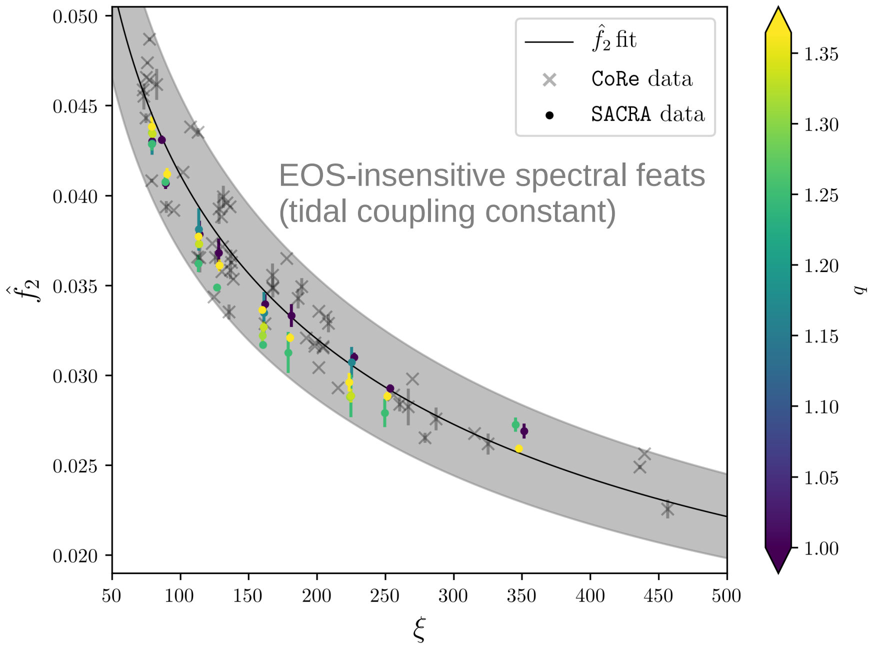
NRPM: Postmerger waveform (EOB-completion)

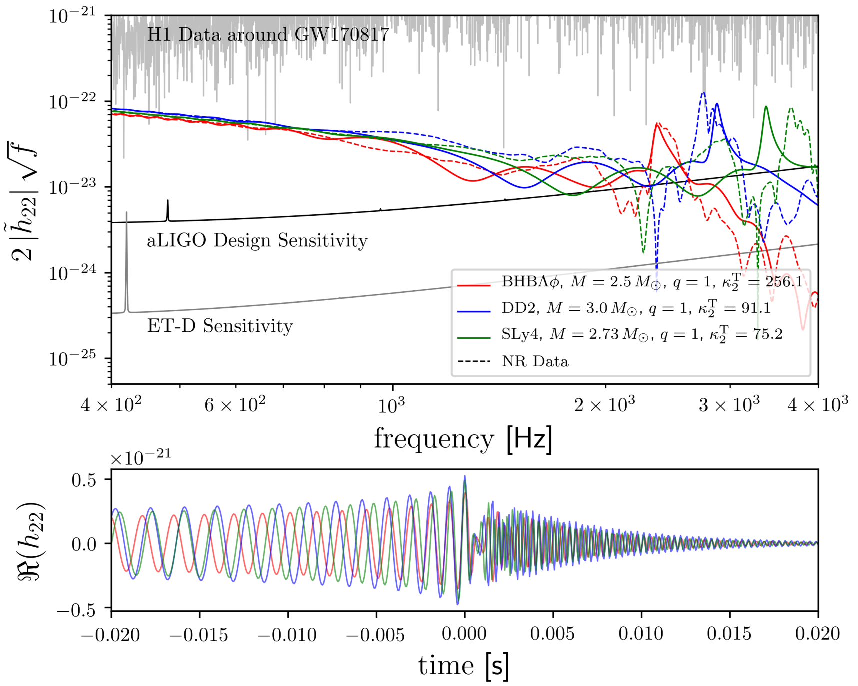
PRL 115, 091101 (2015) PHYSICAL REVIEW LETTERS week ending 28 AUGUST 2015

Modeling the Complete Gravitational Wave Spectrum of Neutron Star Mergers

Sebastiano Bernuzzi,[1,2] Tim Dietrich,[3] and Alessandro Nagar[4]
[1]*TAPIR, California Institute of Technology, 1200 East California Boulevard, Pasadena, California 91125, USA*
[2]*DiFeST, University of Parma and INFN Parma, I-43124 Parma, Italy*
[3]*Theoretical Physics Institute, University of Jena, 07743 Jena, Germany*
[4]*Institut des Hautes Etudes Scientifiques, 91440 Bures-sur-Yvette, France*
(Received 9 April 2015; revised manuscript received 11 June 2015; published 27 August 2015)

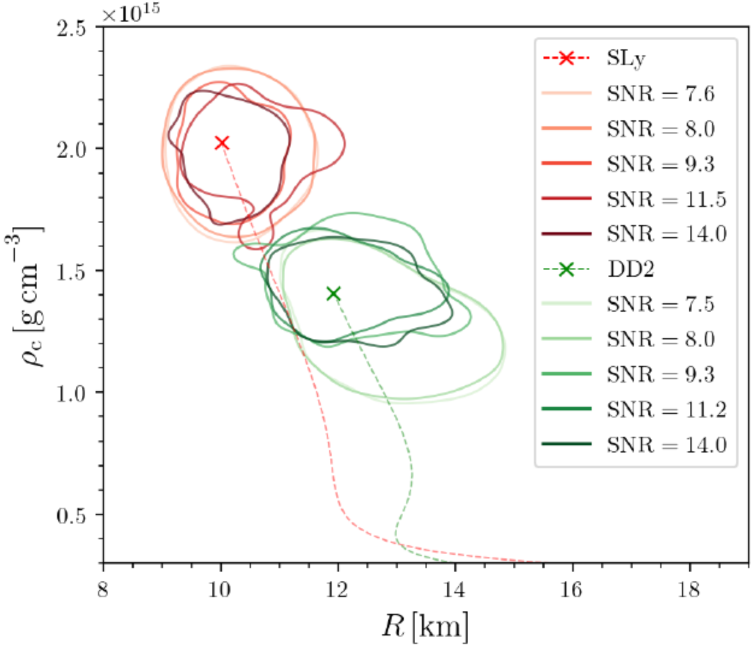
Breschi+ [https://arxiv.org/abs/1908.11418]

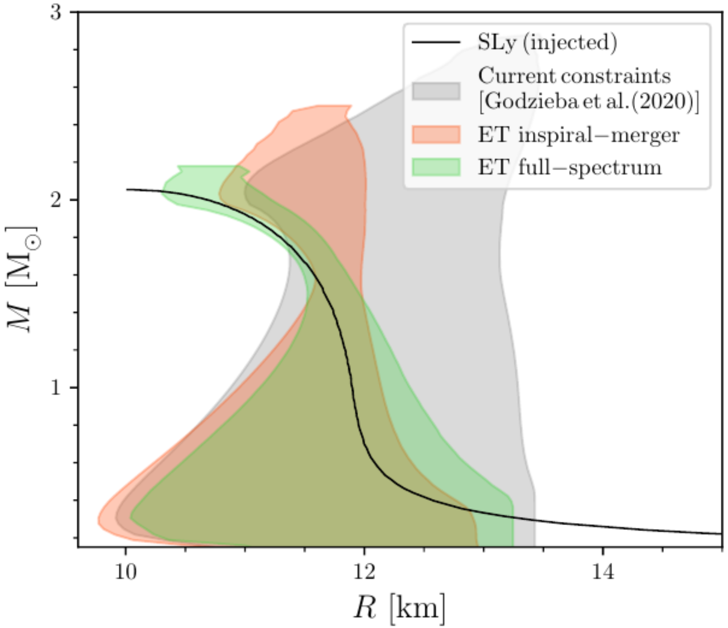




<u>Hypothesis ranking</u> to identify PM signal: min PM SNR ~ 7-9 (GW170817-like events for 3G)
(cf. e.g. Torres-Rivas+ [https://arxiv.org/abs/1811.08931])

GW constraints on NS's extreme matter





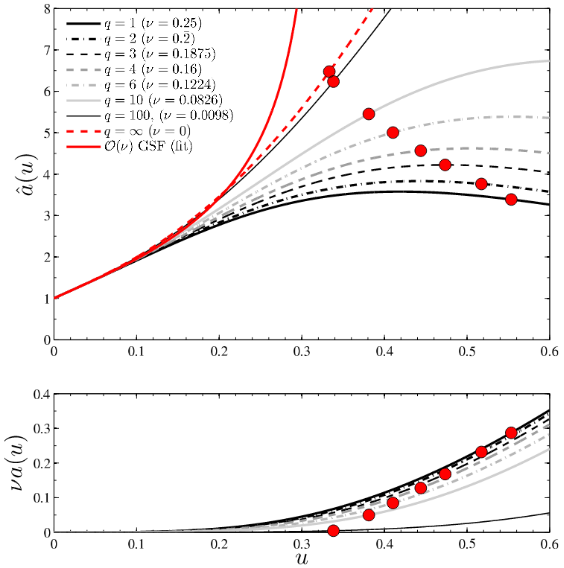
Full-spectrum (mock) analysis using Einstein Telescope sligthly above the minimum SNR threshold for a PM detection
New quasi-universal (EOS-insensitive) relation for the maximum density of an equilibrium NS
NS maximum density to 15% and maximum mass to 12% (90% confidence level)
[Breschi, SB+ To Appear (2021)]

Binary Black holes

PHYSICAL REVIEW D **87**, 084035 (2013)

Improved effective-one-body description of coalescing nonspinning black-hole binaries and its numerical-relativity completion

Thibault Damour,[1] Alessandro Nagar,[1] and Sebastiano Bernuzzi[2]
[1]*Institut des Hautes Etudes Scientifiques, 91440 Bures-sur-Yvette, France*
[2]*Theoretical Physics Institute, University of Jena, 07743 Jena, Germany*
(Received 19 December 2012; published 12 April 2013)



Pade (1,5) resummed radial 5PN-log potential [Damour (2010), Blanchet+ (2010)]

$$A^{\rm Taylor}(u) = 1 - 2u + 2\nu u^3 + \left(\frac{94}{3} - \frac{41}{32}\pi^2\right)\nu u^4$$
$$+ \nu\left[a_5^c(\nu) + a_5^{\ln}(\nu)\ln u\right]u^5 + \nu\left[a_6^c(\nu) + a_6^{\ln}(\nu)\ln u\right]u^6$$

Next-to-quasi-circular (NQC) corrections to the factorized waveform guided by test-mass limit (Regge-Wheeler-Zerilli perturbations)

See also Pan+ 2011; and Barausse+ 2012 (A log-resummed with horizon)

Binary Black holes

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Thibault Damour,[1] Alessandro Nagar,[1] and Sebastiano Bernuzzi[2]
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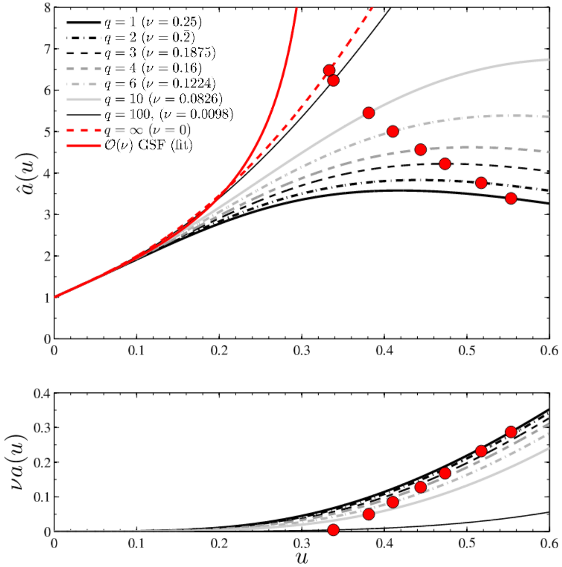


Binary black hole merger in the extreme-mass-ratio limit

Alessandro Nagar[1], Thibault Damour[2] and Angelo Tartaglia[1]

[1] Dipartimento di Fisica, Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 Torino, Italy and INFN, sez. di Torino, Via P Giuria 1, Torino, Italy
[2] Institut des Hautes Etudes Scientifiques, 35 route de Chartres, 91440 Bures-sur-Yvette, France

PHYSICAL REVIEW D **83,** 064010 (2011)

Binary black hole coalescence in the extreme-mass-ratio limit: Testing and improving the effective-one-body multipolar waveform

Sebastiano Bernuzzi,[1] Alessandro Nagar,[2] and Anıl Zenginoğlu[3]
[1]*Theoretical Physics Institute, University of Jena, 07743 Jena, Germany*
[2]*Institut des Hautes Etudes Scientifiques, 91440 Bures-sur-Yvette, France*
[3]*Theoretical Astrophysics, California Institute of Technology, Pasadena, California 91125, USA*
(Received 10 December 2010; published 8 March 2011)

RWZ and Teukolsky solutions with test-mass
Horizon-penetrating, hyperboloidal foliations of Kerr spacetime
(scri-fixing and no boundary conditions)

See also Zenginoglu 2008; SB+ 2011; Harms,SB+ 2014

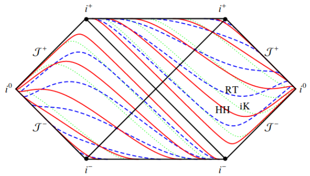
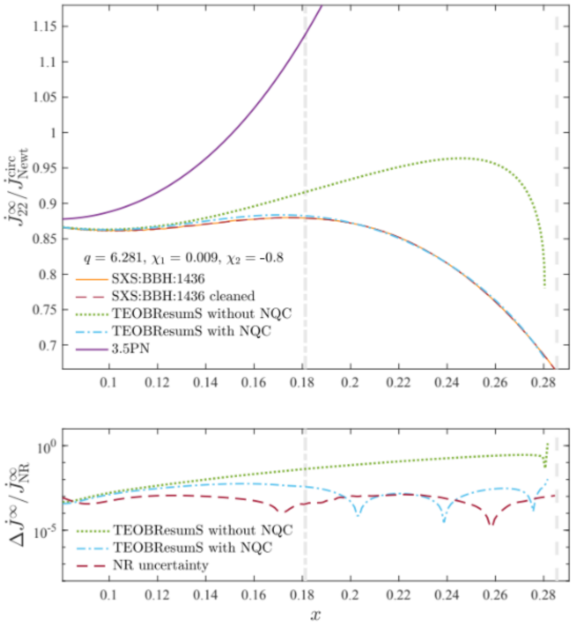
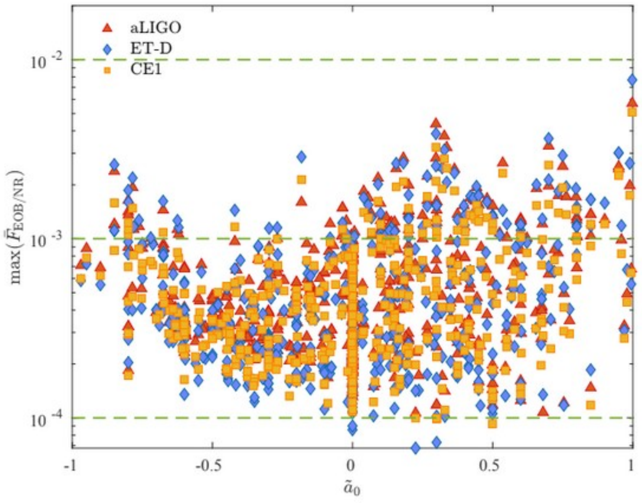


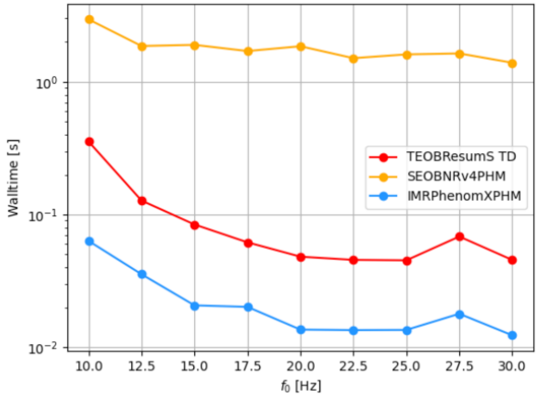
Figure 1. Foliations of Schwarzschild spacetime ($a = 0$): ingoing Kerr (iK; green dotted), Racz–Tóth (RT; blue dashed), and horizon-penetrating-hyperboloidal (HH; red solid) coordinates with $S = 10$.

TEOBResumS: Faithful & fast

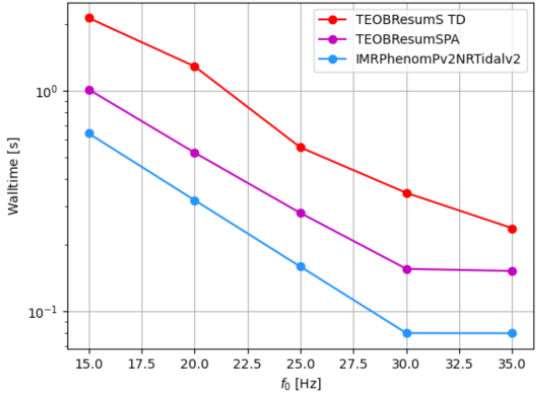




Precessing quasicircular ...



... and with tides



Flux-waveform consistency ensured via NQC tuning
NR-faithful for 3G sensitivities
Spin-precession and tidal interactions
Post-adiabatic approximation [Nagar&Rettegno 2018] and EOB-SPA [Gamba+2020]

Riemenschneider+ 2021 [https://arxiv.org/abs/2104.07533]
Albertini+ 2021 (To appear)

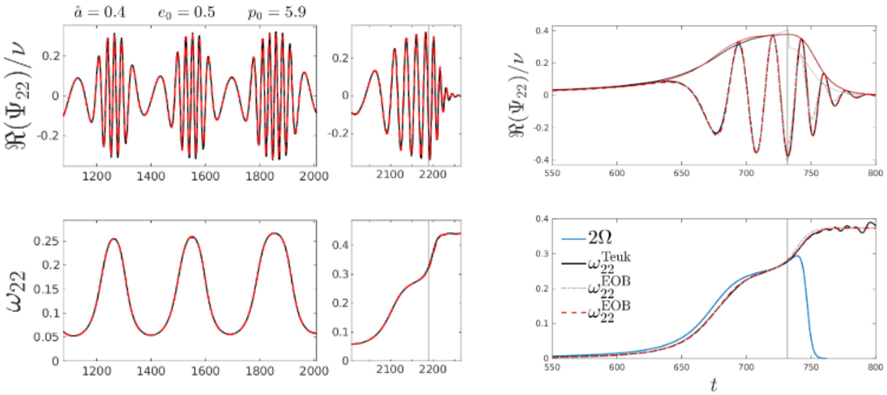
Gamba+ 2021 (To appear)

Black holes scattering & encounters

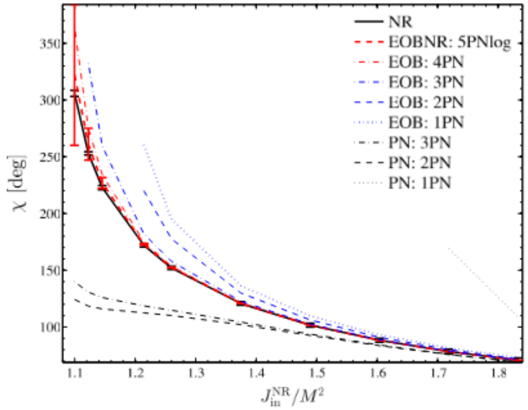
PHYSICAL REVIEW D **89**, 081503(R) (2014)

Strong-field scattering of two black holes: Numerics versus analytics

Thibault Damour,[1] Federico Guercilena,[2,3] Ian Hinder,[2] Seth Hopper,[2] Alessandro Nagar,[1] and Luciano Rezzolla[3,2]
[1]*Institut des Hautes Etudes Scientifiques, 91440 Bures-sur-Yvette, France*
[2]*Max-Planck-Institut für Gravitationsphysik, Albert-Einstein-Institut, Am Mühlenberg 1, D-14476 Golm, Germany*
[3]*Institut für Theoretische Physik, Max-von-Laue-Str. 1, D-60438 Frankfurt am Main, Germany*
(Received 28 February 2014; published 8 April 2014)



EOB vs Teukolsky wvfs highly eccentric & encounter
Albanesi, Nagar, SB 2021 [https://arxiv.org/abs/2104.10559]



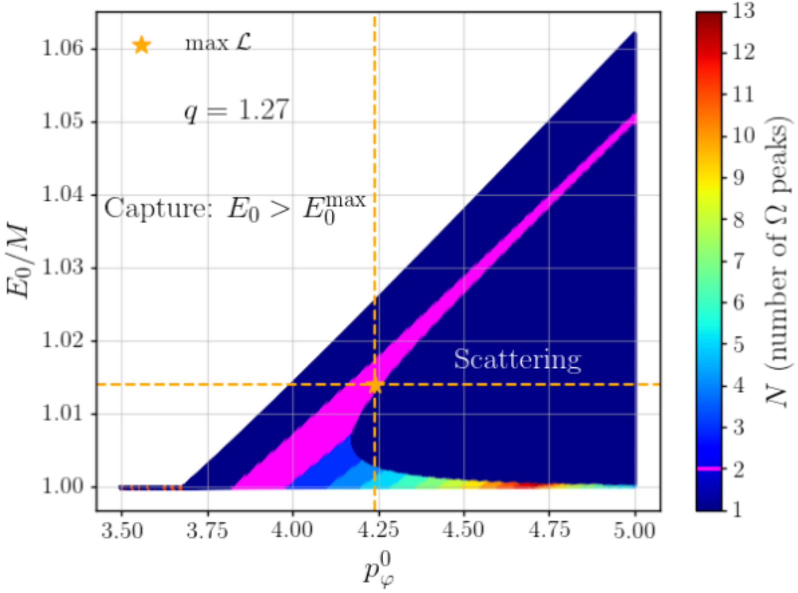
Faithful analytical effective-one-body waveform model for spin-aligned, moderately eccentric, coalescing black hole binaries

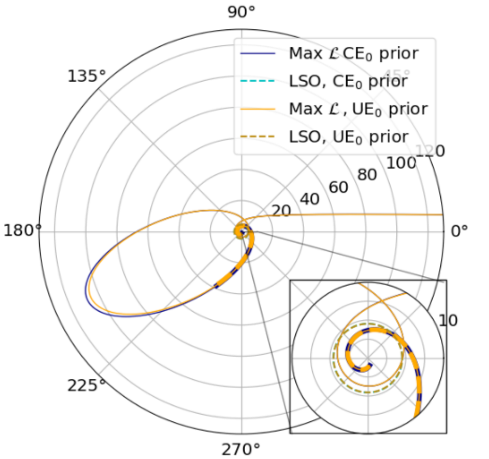
Danilo Chiaramello[1,2] and Alessandro Nagar[2,3]
[1]*Dipartimento di Fisica, Università di Torino, Via Pietro Giuria 1, 10125 Torino, Italy*
[2]*INFN Sezione di Torino, Via Pietro Giuria 1, 10125 Torino, Italy*
[3]*Institut des Hautes Etudes Scientifiques, 91440 Bures-sur-Yvette, France*

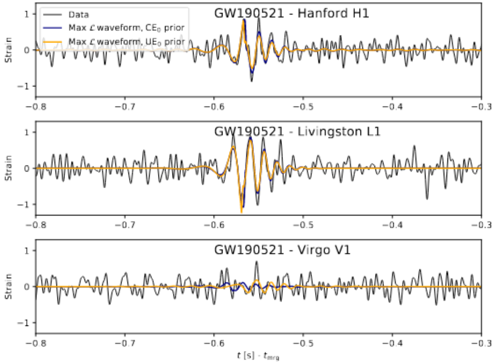
(Received 31 January 2020; accepted 27 April 2020; published 26 May 2020)

See also Nagar+ 2020 [https://arxiv.org/abs/2009.12857]
NR simulations of BBH encounters, Pretorius et al. (2009), Gold&Bruegmann (2011), ...

The strange case of GW190521



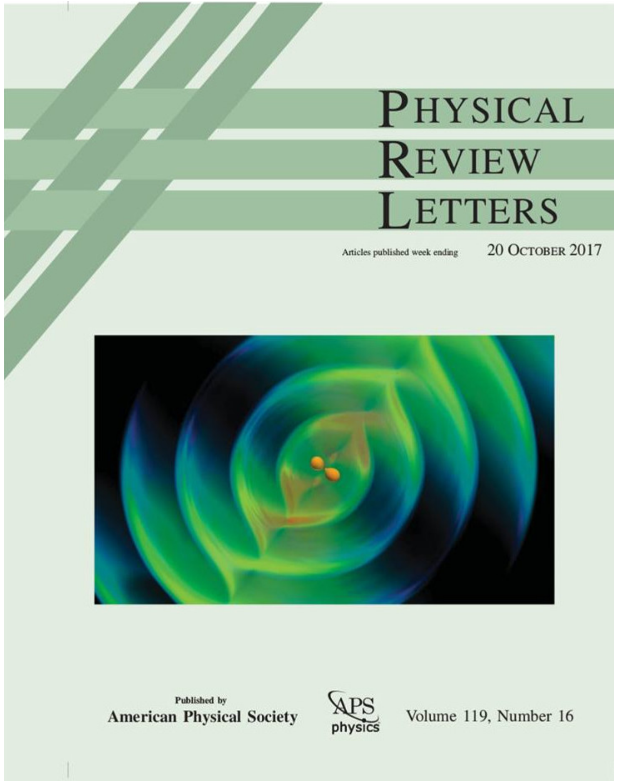


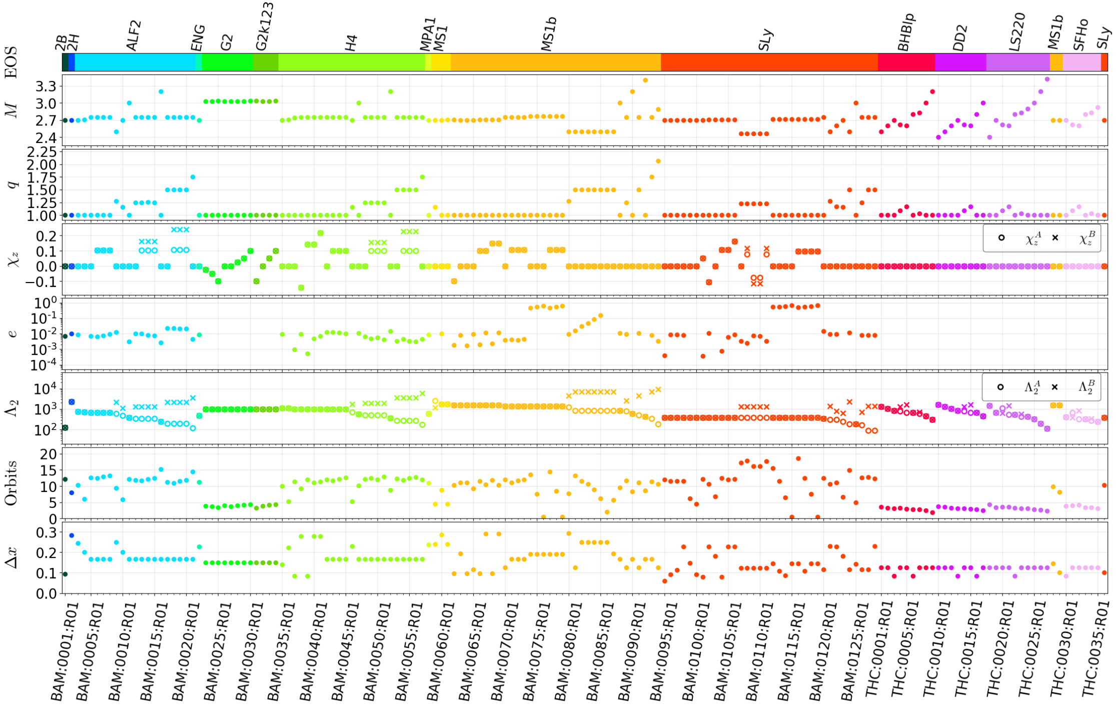


~81+52$M_\odot$ (“mass gap” ?)→ intermediate-mass BH
Two encounters and no-spin favoured w.r.t. precessing quasicircular

Gamba+ [https://arxiv.org/abs/2106.05575]

Numerical relativity

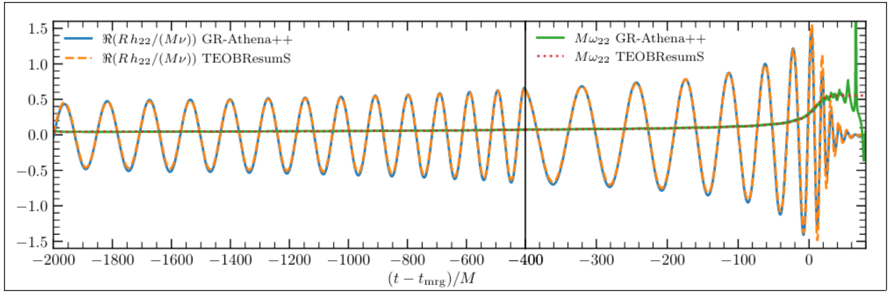


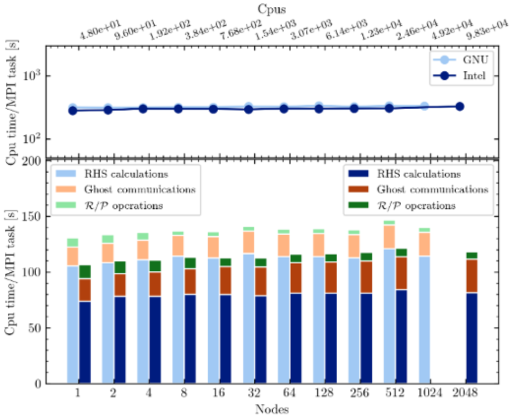


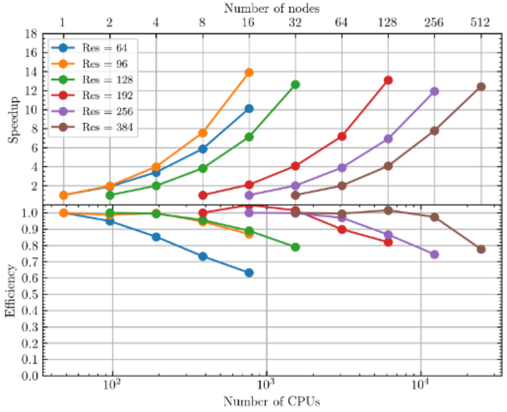
Jena's BAM code
(Bruegmann, SB, ...)

CoRe www.computational-relativity.org

Exascale computations for GW and relativistic astrophysics







GR-Athena++ code [Daszuta+ 2021]

Summary

- First complete (inspiral-merger-postmerger) BNS GW spectrum model from EOB and NR
- Application to NS matter constraints (GW170817 and beyond)
- Merger waveform systematics are an issue for high-precision measurements of tides (3G)
  - Need (even) higher precision in NR simulations
- Full signal analyses (w/ postmerger) can deliver (e.g. maximum mass)
  - Need deeper understanding of quasiuniversal relations
- TEOBResumS BBH quasi-circular waveforms are complete and robust.
  - Might be already suitable for 3G!
- TEOBResumS BBH can handle generic orbital configurations
  - GW190521 admits an interpretation as “hyperbolic merger”