Title: Modeling the Inspiral, Merger and Ringdown of Compact Binaries: Successes and Open Questions

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Abstract:

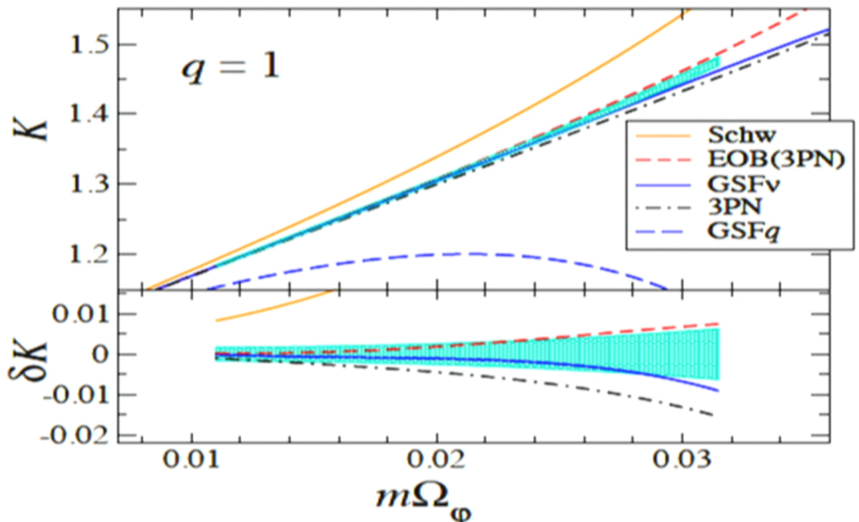
Content

- **Studies at the interface between numerical and analytical relativity** *(PN theory, gravitational self force, BH perturbation theory, and effective-one-body approach)* **are testing the consistency of these approaches, and are informing us with a universal analytical model of the two-body dynamics and gravitational-wave emission.**
- **NRAR work is crucial for ongoing and future gravitational-wave searches.**
- **Combining NRAR results within the effective-one-body formalism to build faithful templates:**
  - **Modeling for comparable, small and extreme mass-ratio black-hole binaries.**
  - **Extensions to spinning black holes and binary neutron stars.**
  - **Universal picture of the merger signal for coalescing black-hole binaries.**
- **Do we need more accurate analytical predictions? If so, in which part of the binary's parameter space?**

Periastron advance in black hole binaries

[Le Tiec, Mroué, Barack, AB, Pfeiffer, Sago & Taracchini 11]

34 orbits!



- In 1915 Einstein derived the lowest order GR angular advance per orbit:

$$\Delta\Phi = \frac{6\pi G\, M_\odot}{c^2\, a\, (1-e^2)}$$

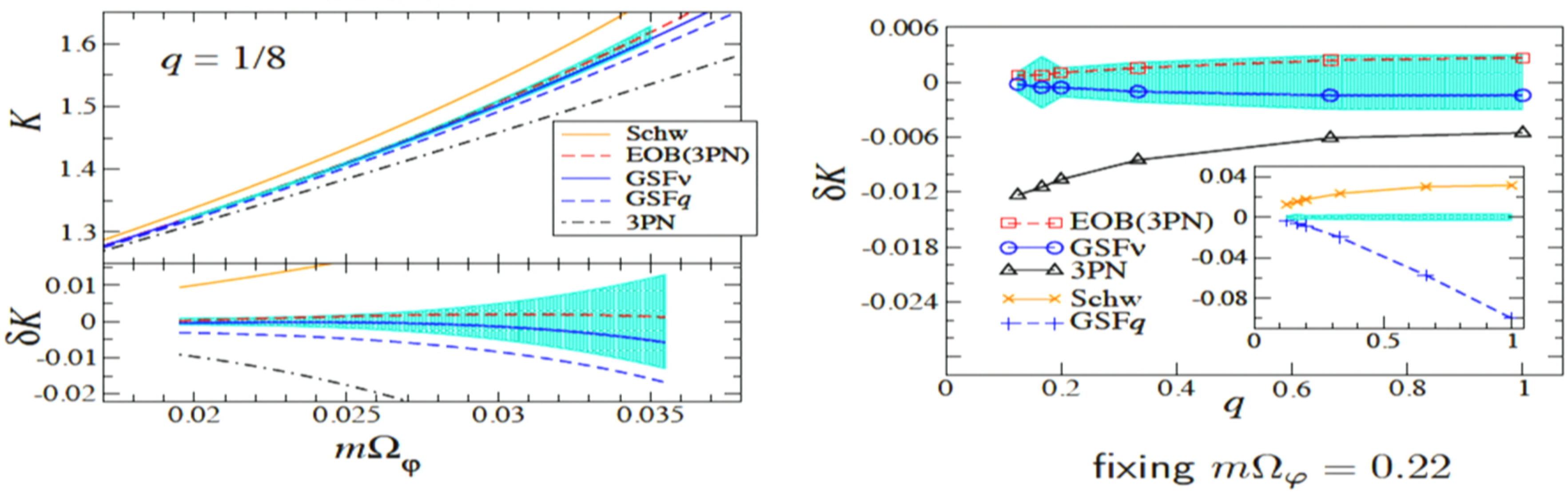
- Very accurate NR simulations
- Predictions from PN theory
- Predictions from (uncalibrated) EOB
- Predictions from gravitational self-force (GSF)

[Barack & Sago 09-11; Barack, Damour & Sago 10]

$$K = 1 + \frac{\Delta\Phi}{2\pi}, \quad K = \frac{\Omega_\varphi}{\Omega_r}$$

Periastron advance for several mass ratios

24 orbits!



fixing $m\Omega_\varphi = 0.22$

Binding energy and angular momentum computed at next-to-leading order in the mass ratio $\nu = m_1 m_2/(m_1+m_2)^2$

- **Predictions from PN theory**
- **Predictions from (uncalibrated) EOB**
- **Predictions from GSF**

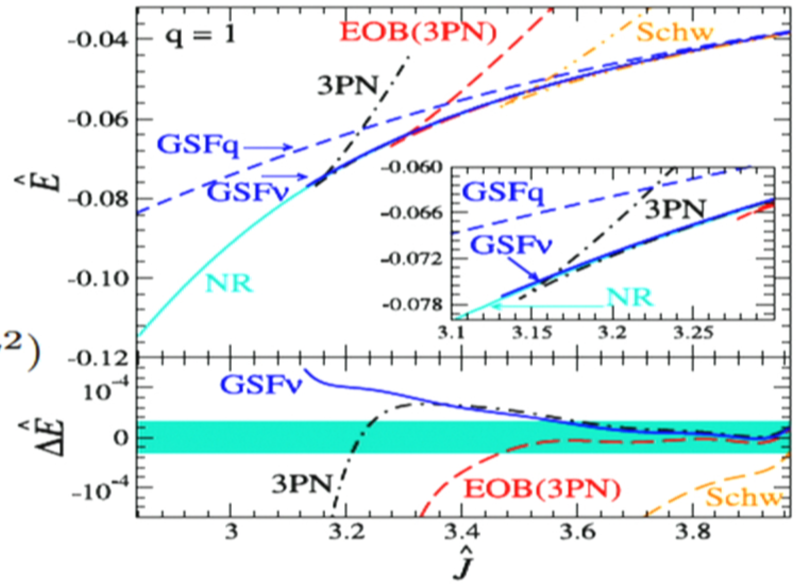
  [Le Tiec, Barausse & AB 11]

$$\hat{E} = \left(\frac{1-2x}{\sqrt{1-3x}} - 1\right) + \nu\, E_{\rm SF}(x) + \mathcal{O}(\nu^2)$$

$$\hat{J} = \frac{1}{\sqrt{x\,(1-3x)}} + \nu\, J_{\rm SF}(x) + \mathcal{O}(\nu^2)$$

- **NR result**

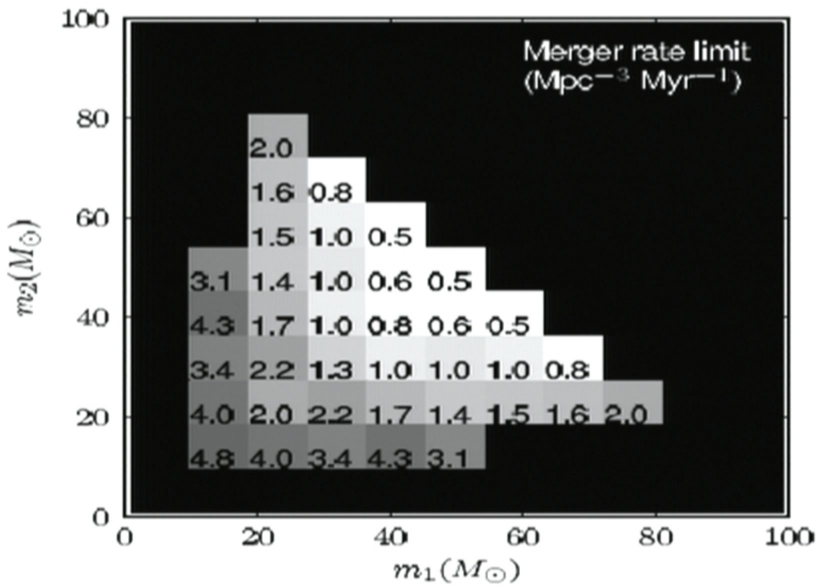
  [Damour, Nagar, Pollney & Reisswig 11]

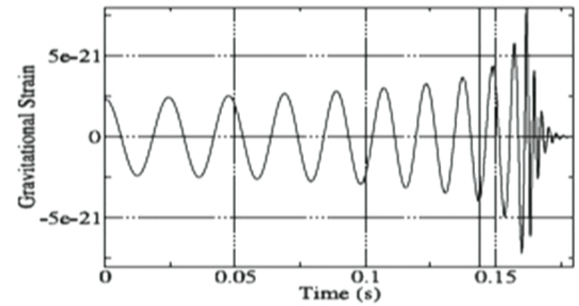


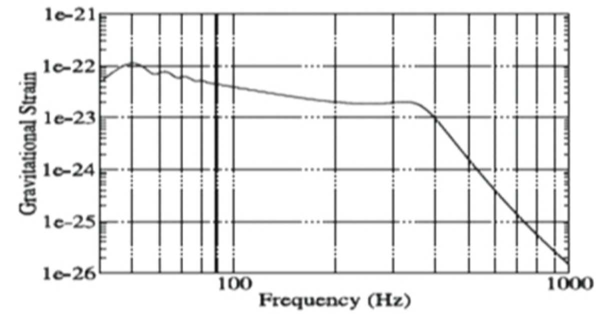
Similar results for $m_2/m_1 = 1/2, 1/3$

First search of GWs from merging compact binaries with LIGO/Virgo

[Abadie et al. 11 (The LSC/Virgo Collaboration)]

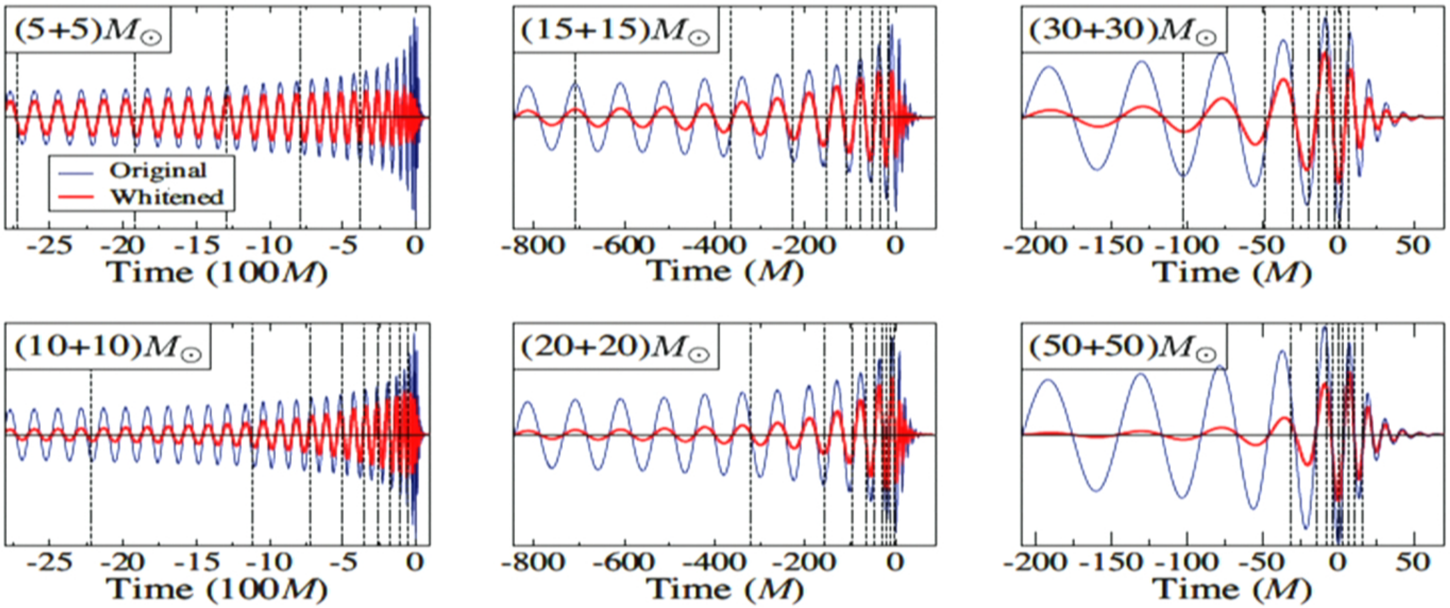




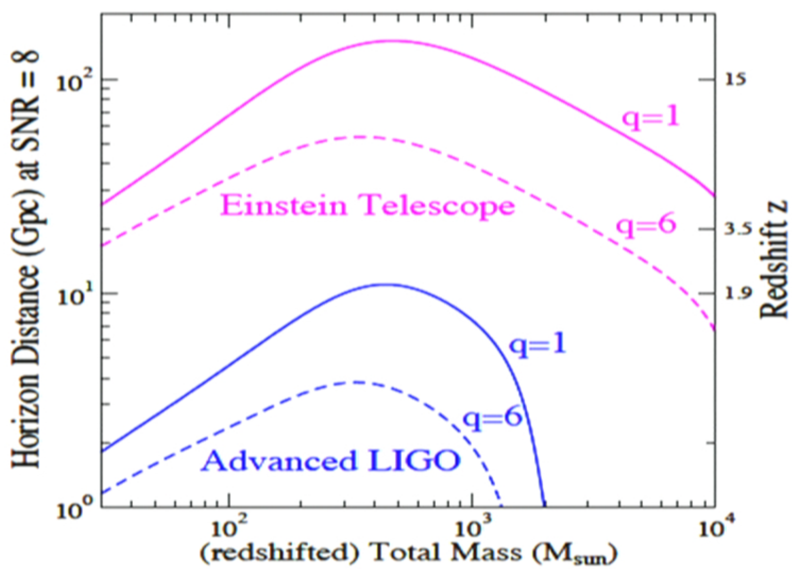


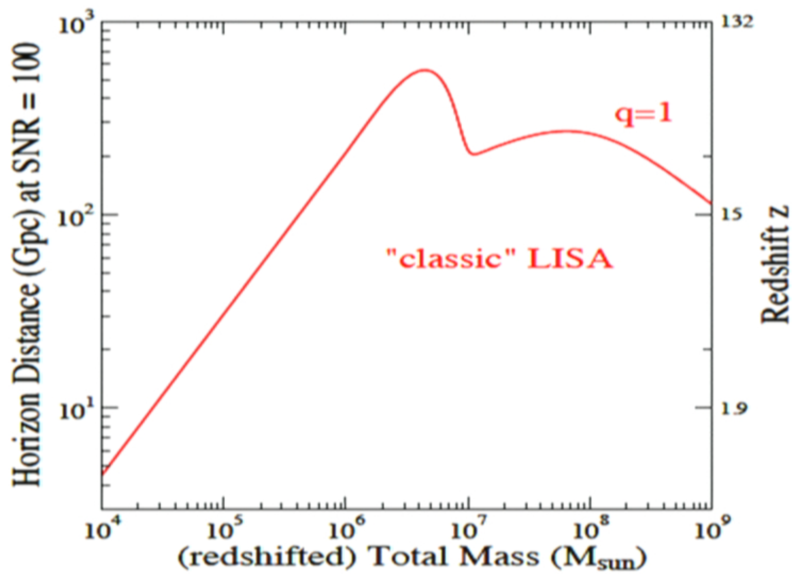
The significance of merger and ringdown signals for LIGO/Virgo

[Pan, AB, Pretorius & NASA-Goddard 07]



Inclusion of merger–ringdown: implications for advanced detectors



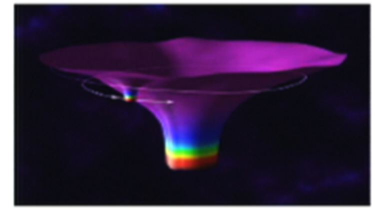


[courtesy of Yi Pan]

Why we need *analytical* waveforms, how accurate they need to be

- The high computational cost of running numerical simulations makes it difficult to generate sufficiently long and accurate waveforms that cover the parameter space of astrophysical interest.
- By *analytical* templates we mean also templates obtained by solving ordinary differential equations. This is computationally faster than running a numerical simulation.
- The requirements on the phase and amplitude accuracy depends on the use of the waveforms: detection, parameter extraction, GR tests, waveform subtraction, etc.
- Analytical modeling helps in *understanding* the numerical simulations.

One-body problem: test-particle orbiting a non-spinning black hole



- Schwarzschild metric

$$ds^2 = -\left(1-\frac{2M}{r}\right)\, dt^2 + \left(1-\frac{2M}{r}\right)^{-1} dr^2 + r^2\, d\Omega^2$$

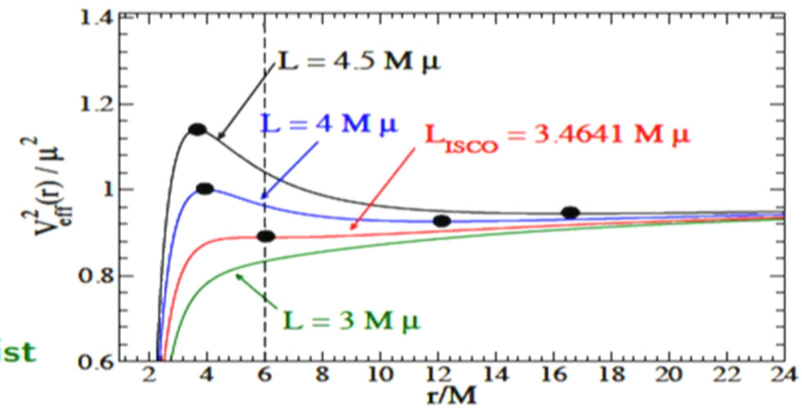
$$H_{\rm Schw}(\mathbf{r},\mathbf{p}) = \mu \sqrt{\left(1-\frac{2M}{r}\right)\left[1+\frac{\mathbf{p}^2}{\mu^2} - \frac{2M}{r}\frac{p_r^2}{\mu^2}\right]}$$

- $H_{\rm Schw}(\mathbf{r},\mathbf{p})$ describes a test-particle of mass μ orbiting a black hole of mass M

- Effective radial potential:

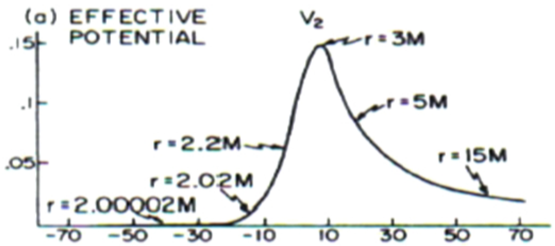
$$\frac{V^2_{\rm eff}(r)}{\mu^2} = \left(1-\frac{2M}{r}\right)\left(1+\frac{L^2}{\mu^2 r^2}\right)$$

- For $L < L_{\rm ISCO}$ circular orbits no longer exist

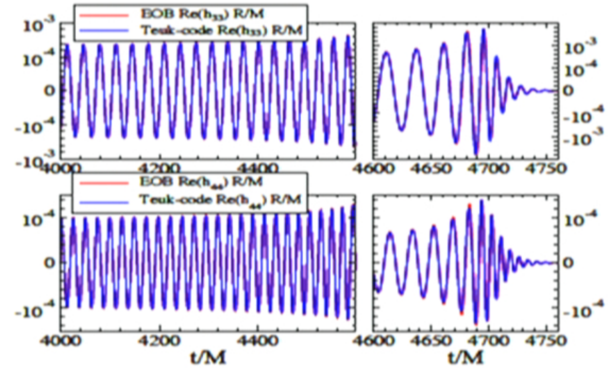


Analytical modeling of merger-ringdown in the small mass-ratio limit

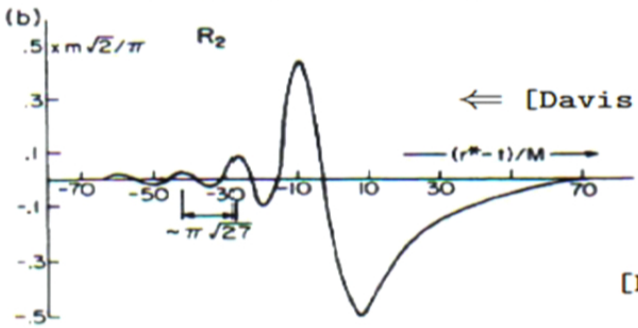
$$\frac{d^2}{dr_*^2} Z_{\ell m} + (V_\ell - \omega_{\ell m}^2)\, Z_{\ell m} = S_{\ell m}$$



⇐ Radial infall

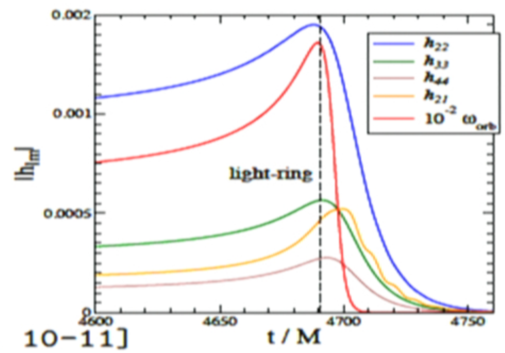


Inspiraling orbit ⇒



⇐ [Davis et al. 71-72]

[Barausse et al. 11] ⇒



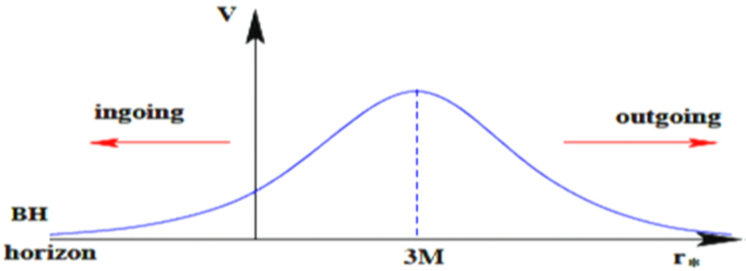
[Damour & Nagar 07; Sundararajan et al. 10; Bernuzzi et al. 10-11]

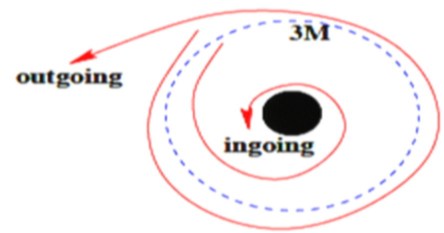
Simplicity of the merger signal

[Vishveshwara 70; Press 71; Chandrasekhar & Detweiler 75; Schutz & Will 85]

[Mashhoon 86; Ferrari & Mashhoon 87]

- Effective potential V_ℓ peaks at the light-ring or photon (graviton) orbit
- For large $\ell \sim m \quad \Rightarrow \quad \omega_{\ell m}^{\rm QNM} \sim \ell\, \omega_{\rm lr}$
- Gravitational rotating perturbations trigger the production of QNMs by resonance





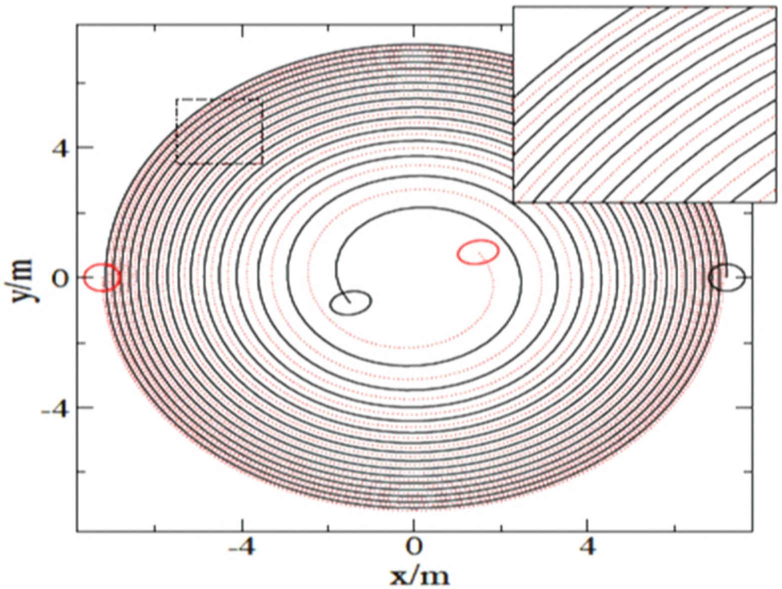
- Collapse of a star: when surface of star passes through the effective potential the gravitational perturbations are redshifted and reflected by the potential.

[Price 72; Nichols & Chen 10, 11]

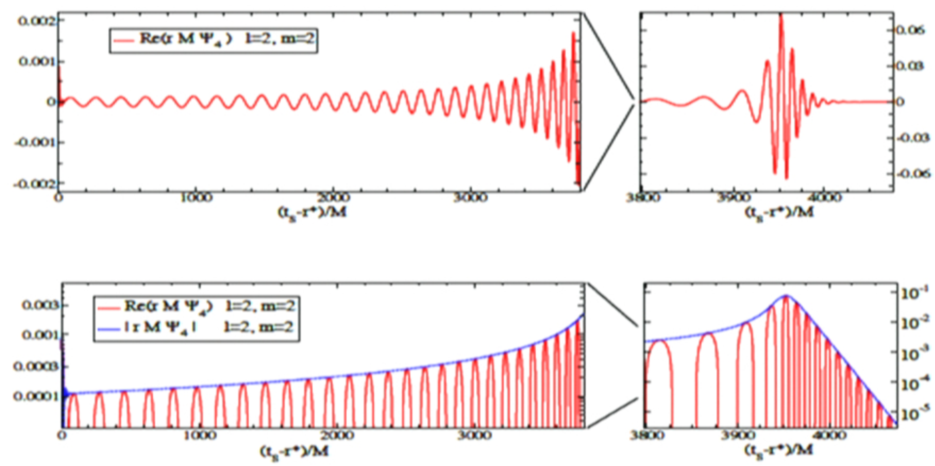
Solving Einstein equations *numerically*

- **Breakthrough in numerical relativity in 2005**

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



Inspiral-merger-ringdown waveform

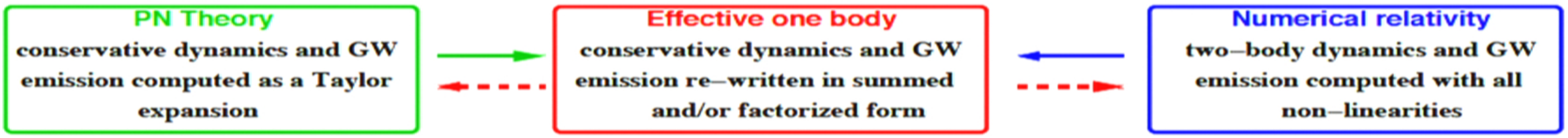


[Caltech-Cornell Collaboration 08]

Combining post-Newtonian and numerical-relativity results: the effective-one-body (EOB) approach

- **EOB approach introduced before the NR breakthrough** [AB & Damour 99, 00]

  many papers since then!



- **The EOB formalism uses the best information available in PN theory, but *sums* it in a *suitable* way to be able to describe accurately the full evolution: inspiral, merger and ringdown.**

- **The EOB formalism provides us with a *moment in time* when to switch from the two-body to the one-body description.**

The problem of motion using the EOB formalism

- **EOB effective metric**

$$ds^2_{\rm eff} = -A_\nu(r)\, c^2\, dt^2 + B_\nu(r)\, dr^2 + r^2\, d\Omega^2$$

$$\nu = \mu/M$$

$$H^\nu_{\rm eff}(\mathbf{r},\mathbf{p}) = \mu \sqrt{A_\nu(r)\, \left[1 + \frac{\mathbf{p}^2}{\mu^2} + \left(\frac{1}{B_\nu(r)} - 1\right) \frac{p_r^2}{\mu^2} + \cdots\right]}$$

- **EOB Hamiltonian**

$$H^{\rm EOB} = M \sqrt{1 + 2\nu\, \left(\frac{H^\nu_{\rm eff}}{\mu} - 1\right)}$$

- **Effective radial potential:**

$$\frac{V^2_{\rm eff}(r)}{\mu^2} = A_\nu(r)\, \left(1 + \frac{L^2}{\mu^2 r^2}\right)$$

$$A_\nu(r) = 1 - \frac{2M}{r} + \frac{2M^3\nu}{r^3} + \left(\frac{94}{3} - \frac{41}{32}\pi^2\right) \frac{M^4\nu}{r^4}$$

- **Enforce presence of ISCO, *pseudo* light-ring, horizon in $A_\nu(r)$**
- **Add possible unknown higher-order PN terms in $A_\nu(r)$**

EOB dynamics and waveforms

- **EOB dynamics**

$$\dot{\mathbf{r}} = \frac{\partial H^{\mathrm{EOB}}}{\partial \mathbf{p}}, \qquad \dot{\mathbf{p}} = -\frac{\partial H^{\mathrm{EOB}}}{\partial \mathbf{r}} + \mathbf{F}, \qquad \mathbf{F} \propto \frac{dE}{dt}, \qquad \frac{dE}{dt} = \frac{1}{16\pi} \sum_{\ell,m} |\dot{h}_{\ell m}|^2$$

$$\dot{\mathbf{S}}_1 = \frac{\partial H^{\mathrm{EOB}}}{\partial \mathbf{S}_1} \times \mathbf{S}_1, \qquad \dot{\mathbf{S}}_2 = \frac{\partial H^{\mathrm{EOB}}}{\partial \mathbf{S}_2} \times \mathbf{S}_2$$

[AB & Damour 00; Damour et al. 98; AB et al. 05; Damour et al. 07-09; AB et al. 09; Pan et al. 09]

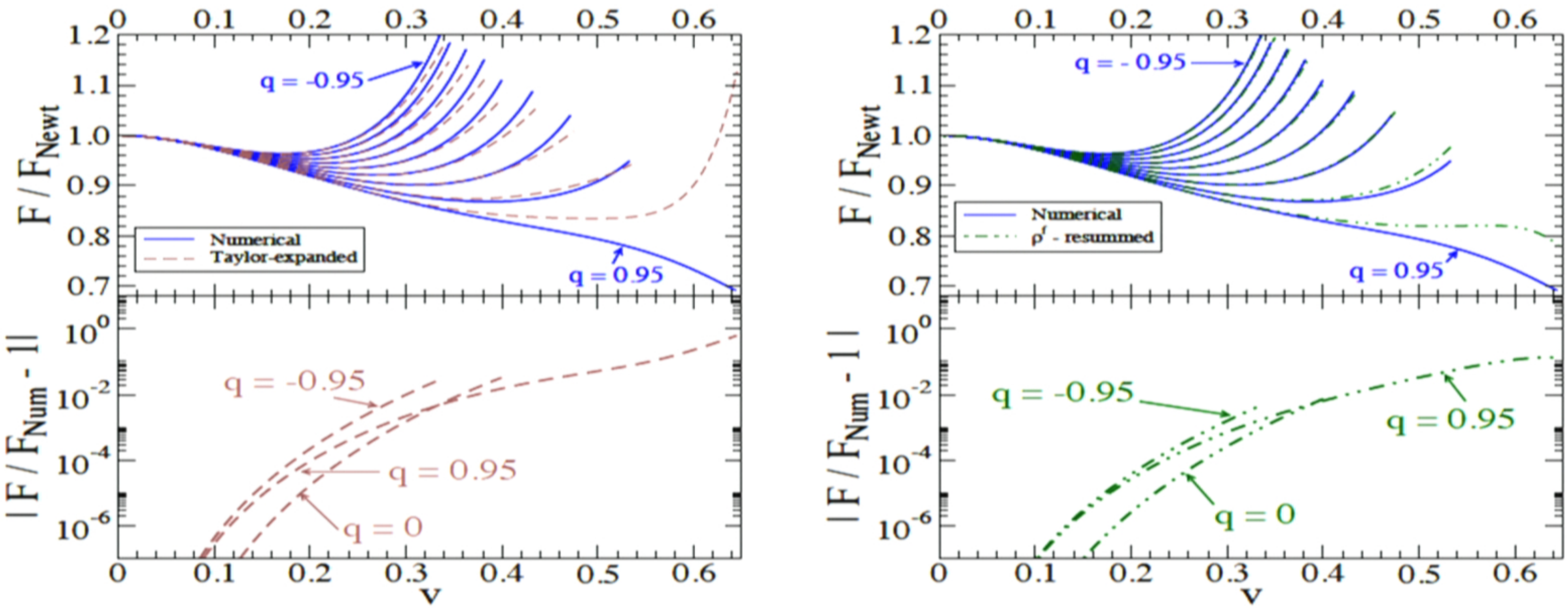
- **EOB (factorized) waveforms**

$$h_{22}(t) = -\frac{8\pi}{5}\frac{\nu M}{R} v^2 e^{-2i\Phi} \left\{1 - \left(\frac{107}{42} - \frac{55}{42}\nu\right) v^2 + \left[2\pi + 12i \log\left(\frac{v}{v_0}\right)\right] v^3 + \ldots\right\}$$

$$h_{\ell m}^{\mathrm{insp-plunge}}(t) = \hat{h}_{\ell m}^{N}\, e^{-im\Phi}\, \mathcal{S}_{\mathrm{eff}}\, T_{\ell m}\, e^{i\delta_{\ell m}}\, (\rho_{\ell m})^{\ell}\, h_{\ell m}^{\mathrm{NQC}}(a_i, b_i)$$

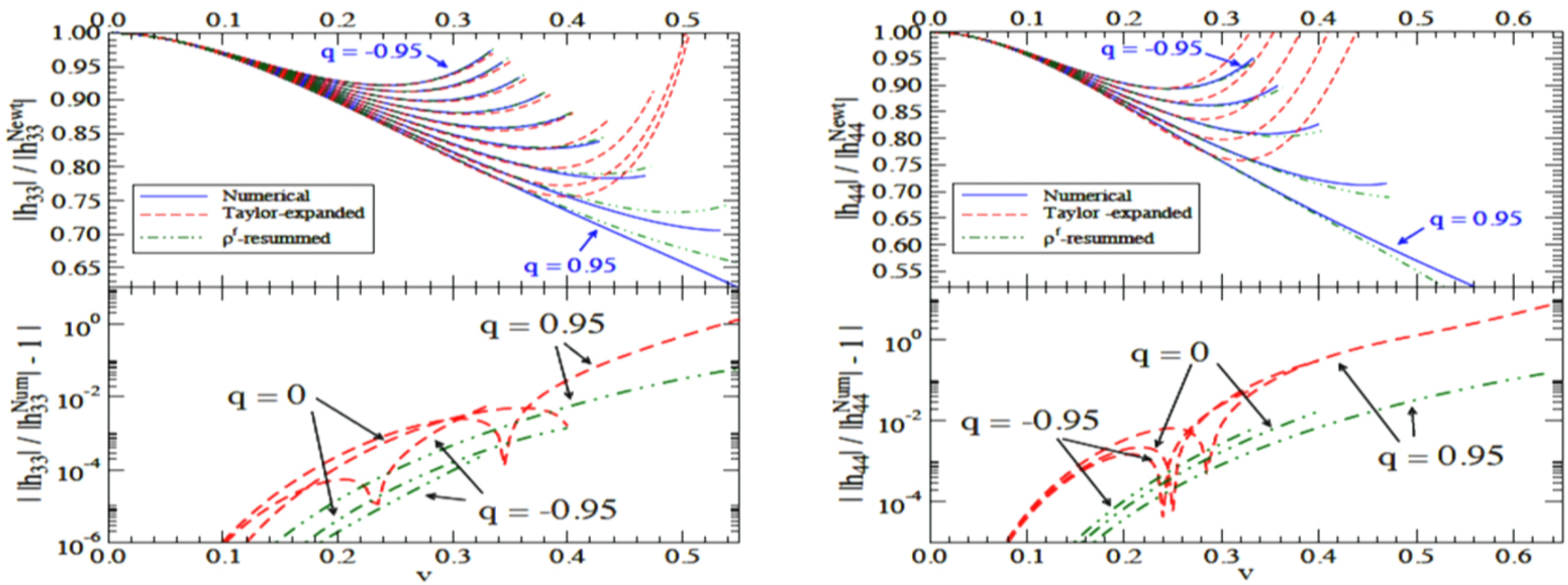
[Damour, Iyer & Nagar 09; Fujita & Iyer 10; Pan, AB, Fujita, Racine & Tagoshi 10]

Factorized energy-flux for a test-particle orbiting a spinning BH



$[q = a/M]$ [Pan, AB, Fujita, Racine & Tagoshi 10]

Factorized waveforms for a test-particle orbiting a spinning BH



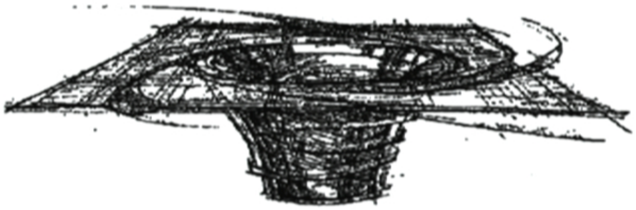
$[q = a/M]$ [Pan, AB, Fujita, Racine & Tagoshi 10]

If perturbed, black holes *ring or vibrate*: quasi-normal modes

[Vishveshwara 70; Press 71; Chandrasekhar et al. 75; Ferrari & Mashoon 84; Schutz & Will 85]

- If black hole *size* is $R_{\rm BH} = 2GM/c^2$, and $M = 1M\odot \Rightarrow R_{\rm BH} = 3\,{\rm km}$
  Travel time of spacetime *vibration* $\Rightarrow R_{\rm BH}/c = 10^{-2}\,{\rm msec}$

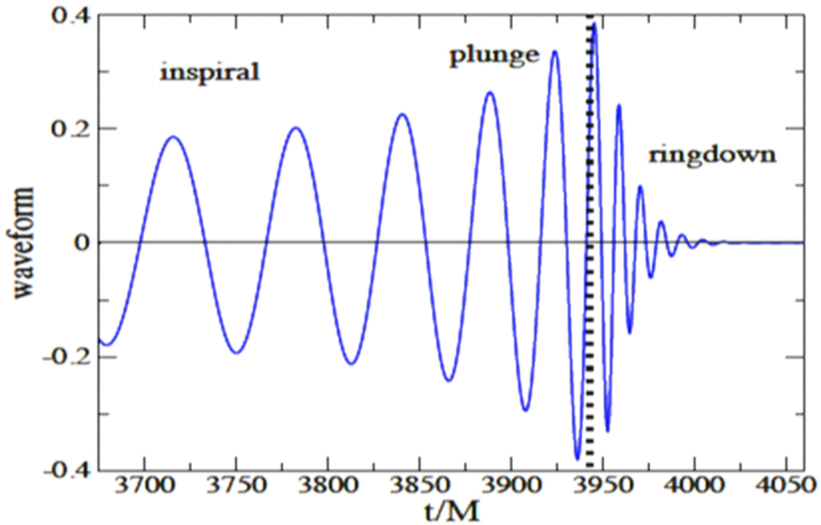
- Frequency and decay time of quasi-normal modes depend *only* on BH mass and spin
- For each $(l, m) \Rightarrow$ infinite tower of overtones

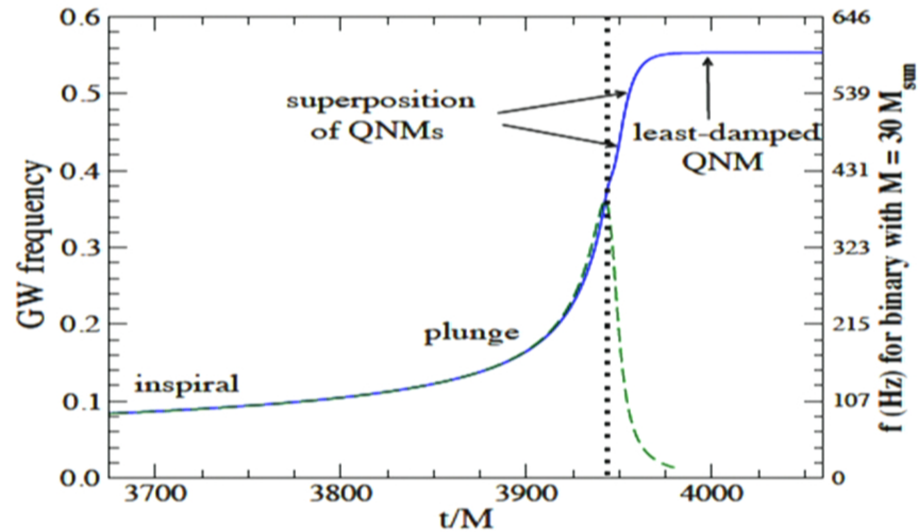


- If black hole has mass $M = 20M_\odot$, S $= 0$:
  $\omega_{200} = 604$ Hz, $\tau_{200} = 1.10$ msec
  $\omega_{201} = 560$ Hz, $\tau_{201} = 0.36$ msec
  $\omega_{202} = 486$ Hz, $\tau_{202} = 0.20$ msec
  ... ...

- Perturbations of black-hole spacetime are highly dissipative

EOB inspiral-merger-ringdown waveforms

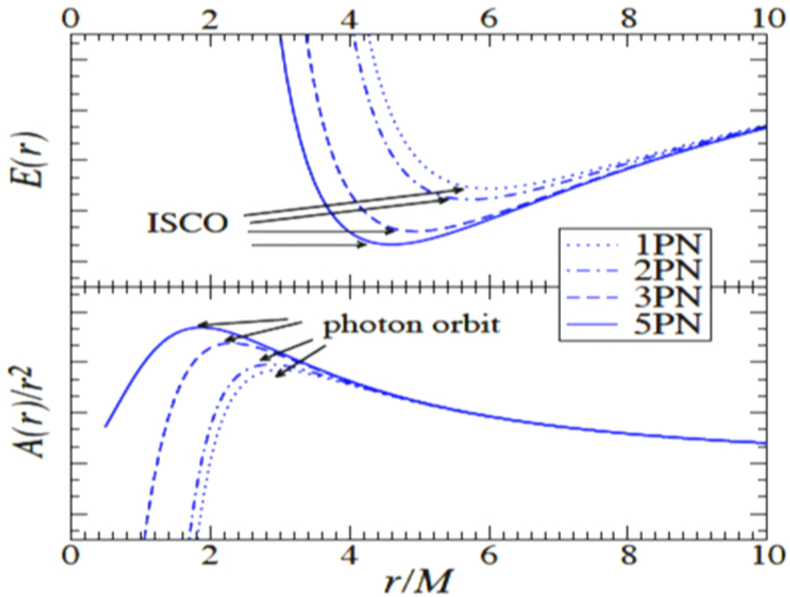




- Very *short* transition merger–ringdown
- Energy quickly released during merger

- Gravitational rotating perturbations trigger production of QNMs

Calibrating the EOB model



- **Higher order PN terms in radial potential can improve the late inspiral and plunge:**

$$A^{\mathrm{P4PN}}(r) = A^{\mathrm{3PN}}(r) + \frac{a_5(\nu)}{r^5} + \frac{a_6(\nu)}{r^6} + \cdots$$

$$E^2(r) = A(r)\left(1 + \frac{L^2(r)}{r^2}\right)$$

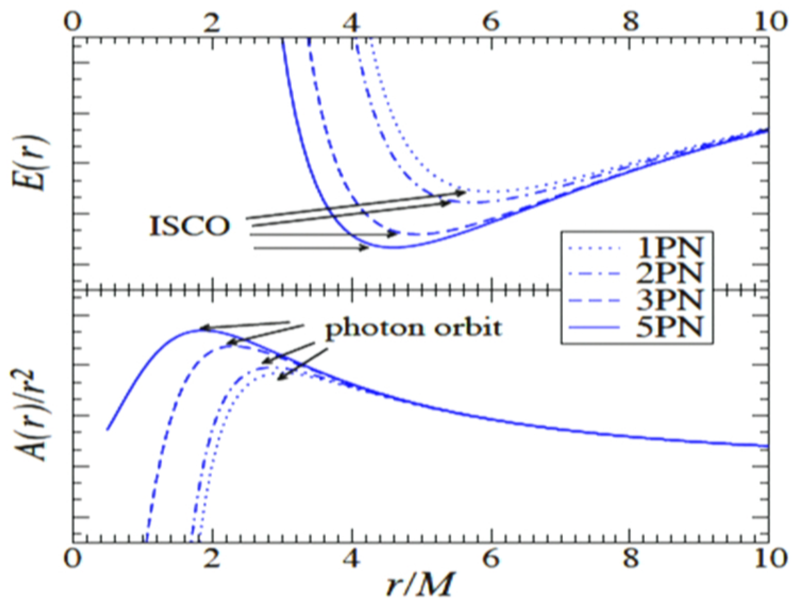
- **Padè-sum $A(r)$ to ensure an ISCO**

  [Damour, Jaranowski & Schaefer 00]

- **Log-sum $A(r)$ to ensure horizon in presence of spins**

  [Barausse & AB 09,11]

Calibrating the EOB model



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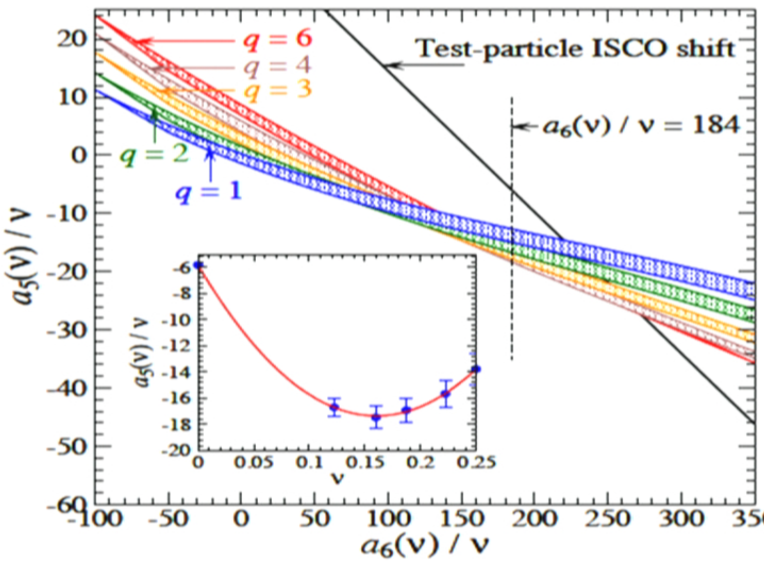
[Barausse & AB 09,11]

EOB-dynamics adjustable parameters

[AB et al. 07; Damour & Nagar 07-09; Pan et al. 09]

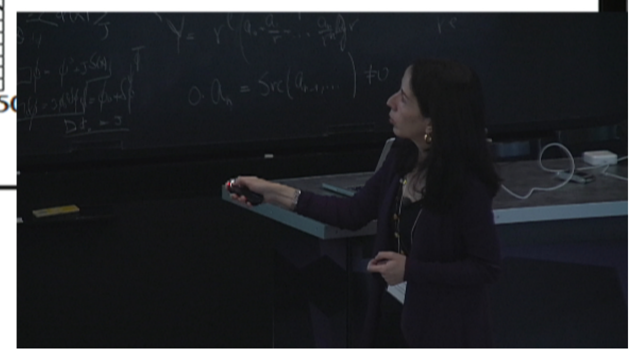
[Pan, AB, Boyle, Buchman, Kidder,Pfeiffer & Scheel 11]



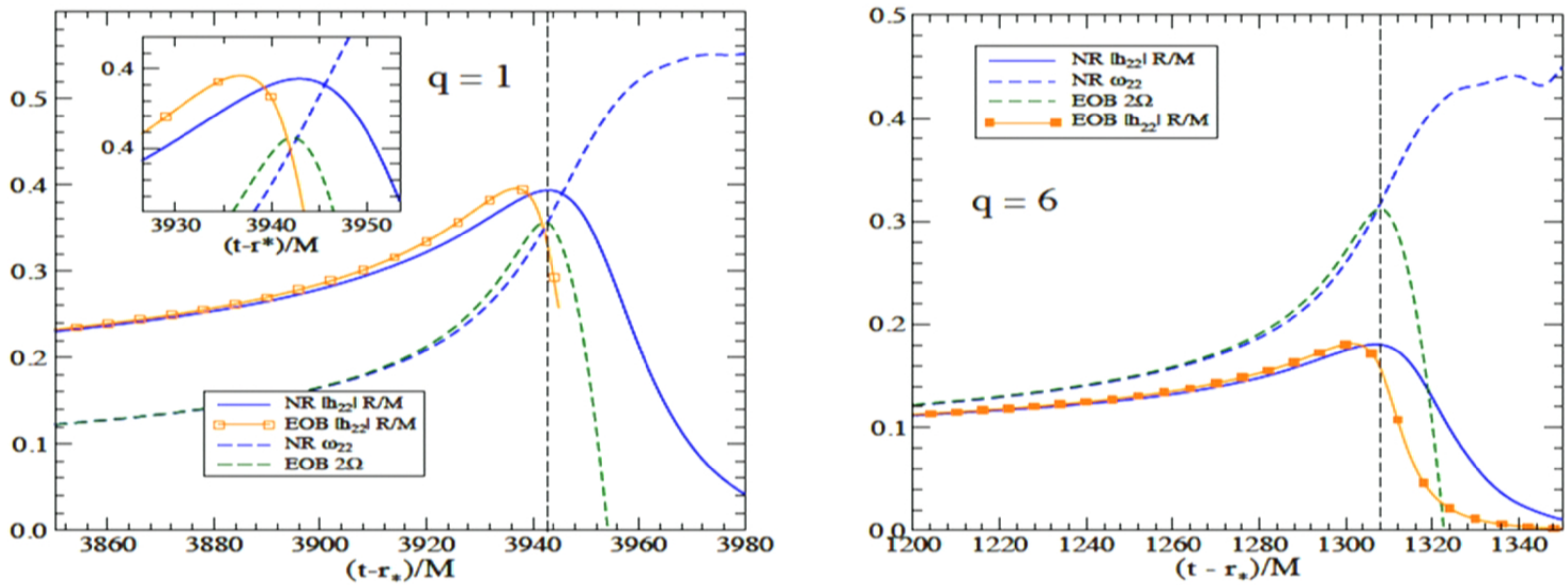
- ISCO shift

  [Barack & Sago 09]

  [Damour 10]

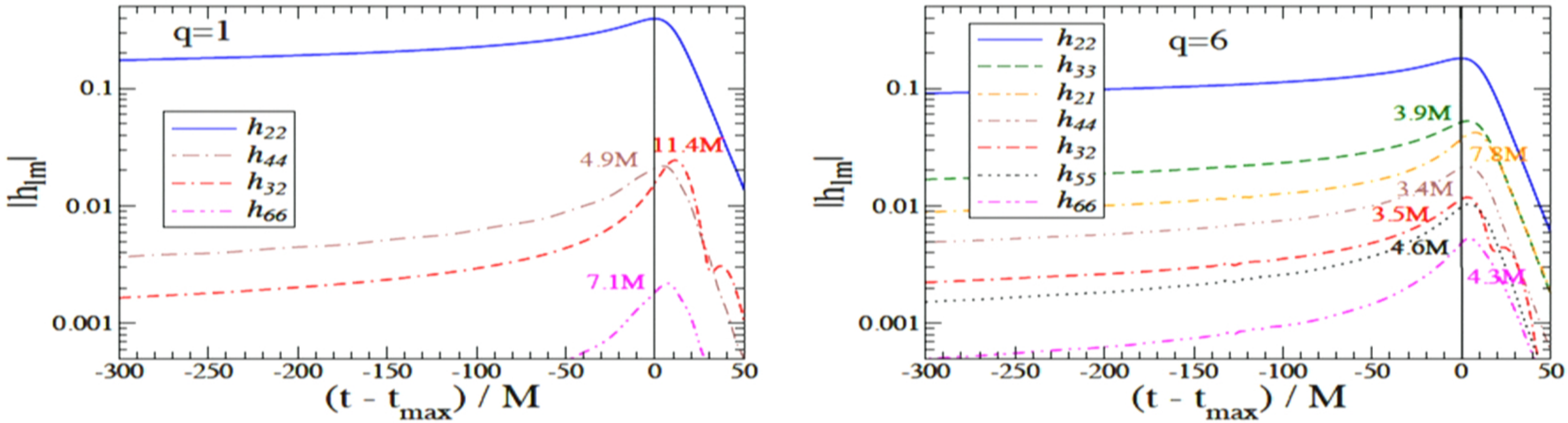


How do *factorized* waveforms compare with NR waveforms?



Amplitudes for subleading modes for $m_1/m_2 = 1$ and 6

- $h_+(\theta, \phi; t) - i h_\times(\theta, \phi) = \sum_{\ell,m} {}_{-2}Y_{\ell m}(\theta, \phi)\, h_{\ell m}(t)$



Modes's amplitudes do not peak at the same time

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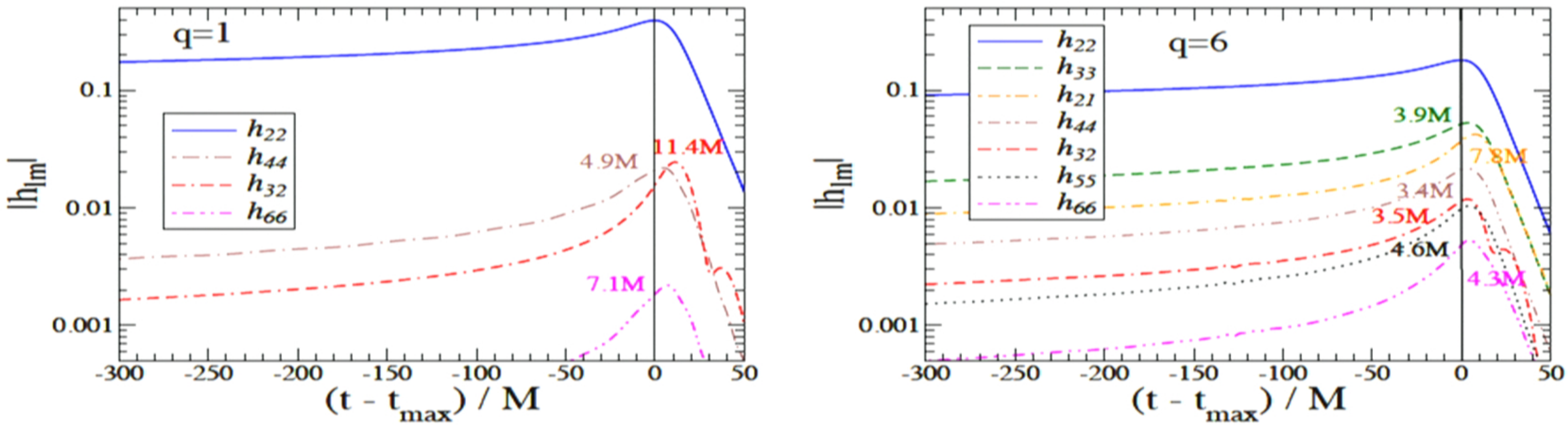
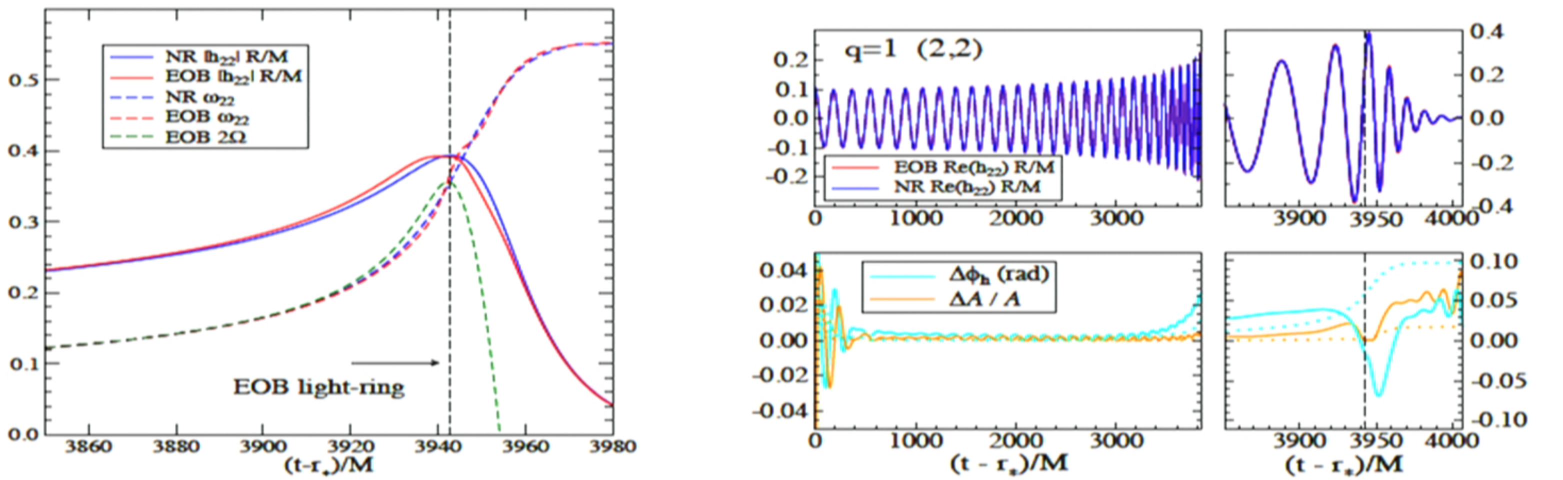


Modes's amplitudes do not peak at the same time

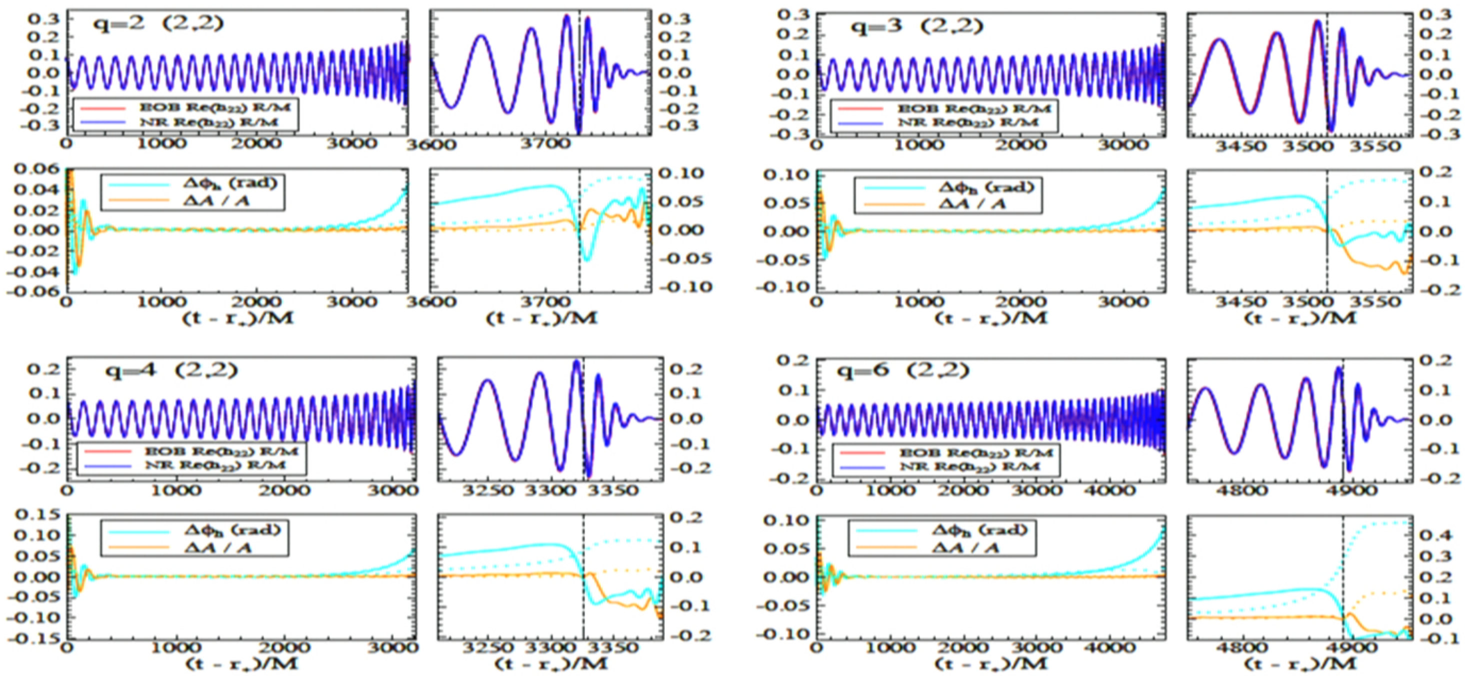
Building the EOB full waveform and comparing with NR: $m_1/m_2 = 1$

[Pan, AB, Boyle, Buchman, Kidder, Pfeiffer & Scheel 11]

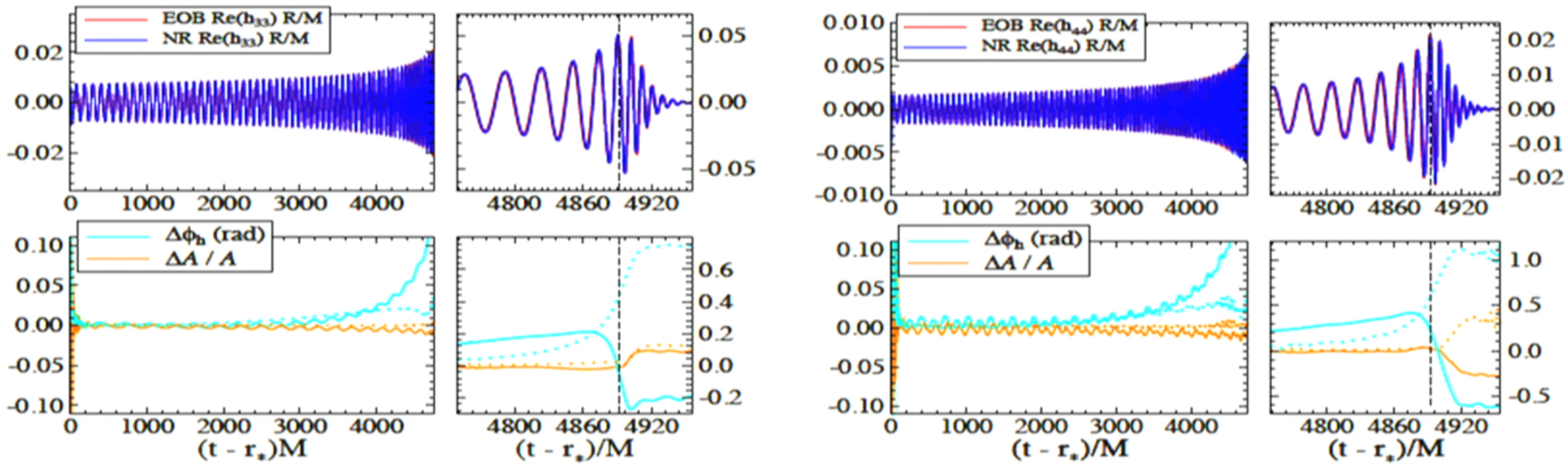


- $h_{22}^{\rm merger-RD}(t) = \sum_{n=0}^{N-1} A_{22}\, e^{-i\sigma_{22n}(t-t^{22}_{\rm match})}$ $\quad \sigma_{22n} = \omega^{\rm QNM}_{22n} - i/\tau^{\rm QNM}_{22n}$
- $h_{22}^{\rm full}(t) = h_{22}^{\rm insp-plunge}\,\theta(t^{22}_{\rm match} - t) + h_{22}^{\rm merger-RD}\,\theta(t - t^{22}_{\rm match})$

Comparing to unequal-mass binaries: $m_1/m_2 = 2, 3, 4, 6$

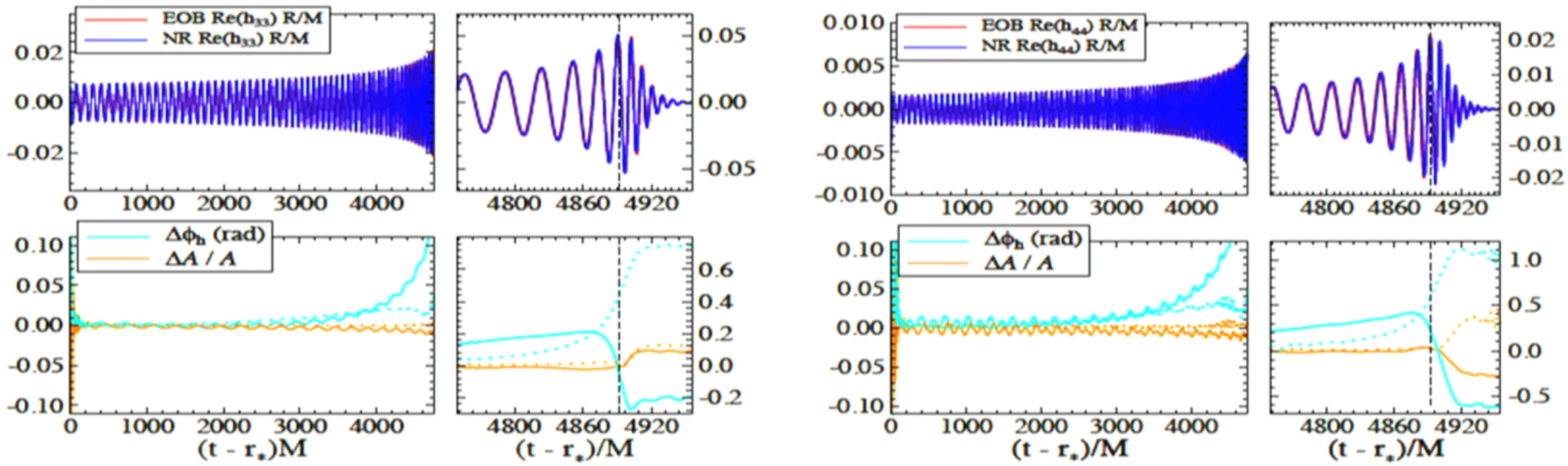


Comparing (4, 4) and (3, 3) modes for $m_1/m_2 = 6$



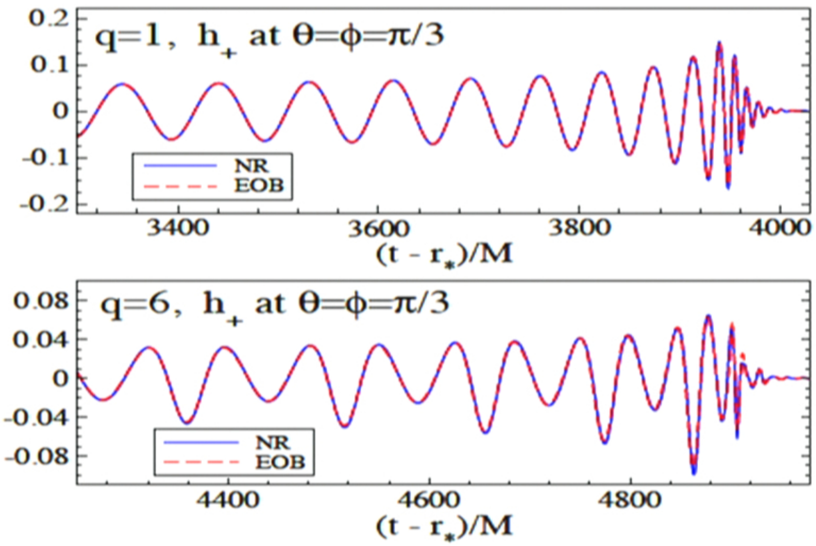
Calibrating also two higher-order PN terms in mode's amplitude/phase

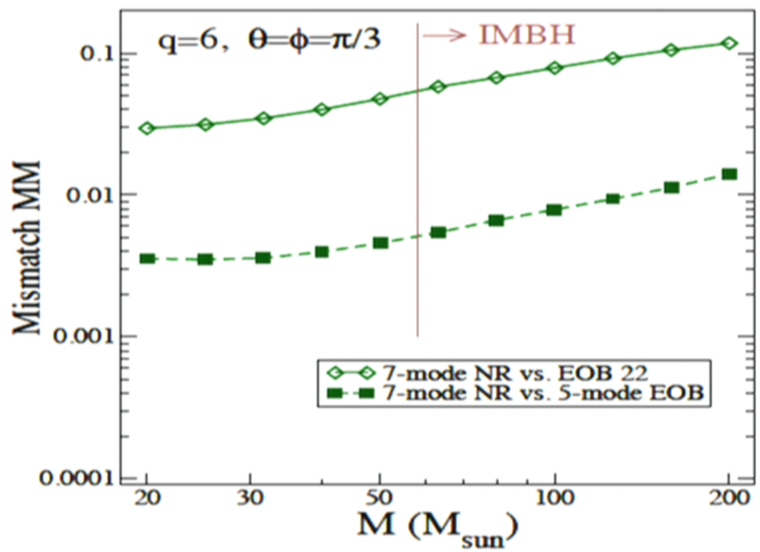
Comparing $(4,4)$ and $(3,3)$ modes for $m_1/m_2 = 6$



Calibrating also two higher-order PN terms in mode's amplitude/phase

Gravitational polarizations and detection accuracy



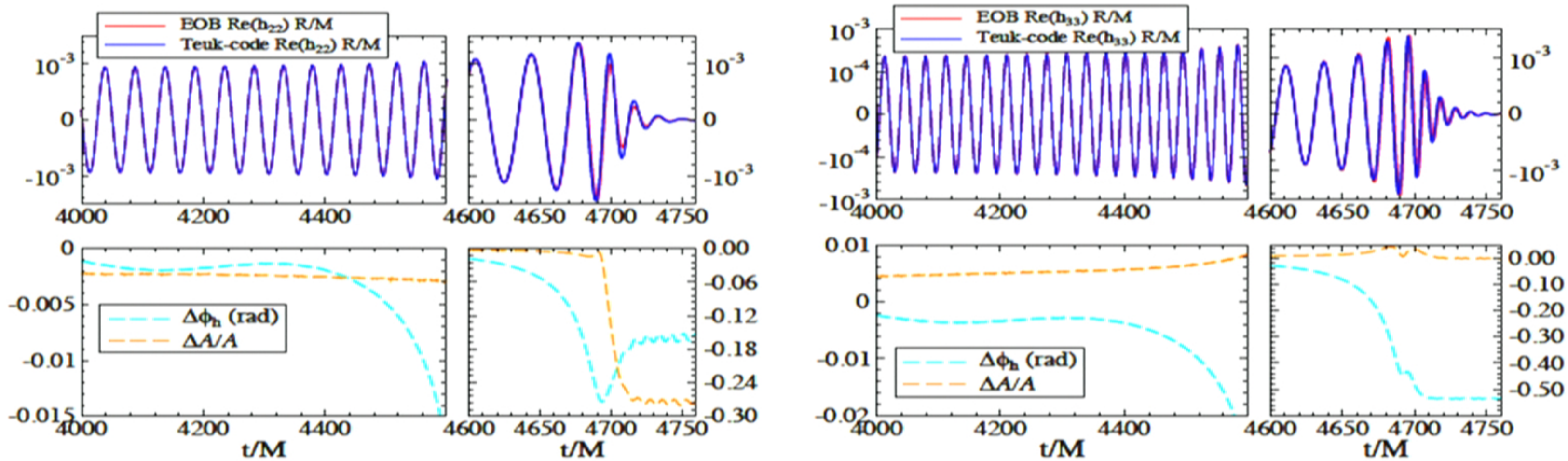


- $h_+(\theta, \phi; t) - i h_\times(\theta, \phi) = \sum_{\ell,m} {}_{-2}Y_{\ell m}(\theta, \phi)\, h_{\ell m}(t)$
- **Loss in event rates** $\propto 3\mathrm{MM}$

Comparing with small mass-ratio limit ($m_2/m_1 = 10^{-3}$) obtained with Teukolsky code

[Barausse, AB, Hughes, Khanna, O'Sullivan & Pan 11]

Using EOB trajectory to evolve time-domain Teukolsky code through merger



Without re-calibrating the EOB-dynamics and waveforms!

Complete EOB metric at linear order in ν for a certain class of EOB Hamiltonians

[Barausse, AB & Le Tiec 11]

$$\bar{D} = (A\,B)^{-1}$$

$$A(r) = 1 - \frac{2M}{r} + \nu\, A_{\rm SF}(r) + \mathcal{O}(\nu^2)\,, \qquad \bar{D}(r) = 1 + \nu\, \bar{D}_{\rm SF}(r) + \mathcal{O}(\nu^2)$$

$$A_{\rm SF}(x) = \sqrt{1-3x}\, z_{\rm SF}(x) - x\left(1 + \frac{1-4x}{\sqrt{1-3x}}\right)\,, \qquad x \equiv (M\Omega)^{2/3} = M/r + \mathcal{O}(\nu)$$

$$\bar{D}_{\rm SF}(x) = \frac{1}{1-6x}\left[\rho_{\rm SF}(x) - 4x\left(1 - \frac{1-2x}{\sqrt{1-3x}}\right) - A_{\rm SF}(x) - x\, A'_{\rm SF}(x) - \frac{x}{2}\,(1-2x)\, A''_{\rm SF}(x)\right]$$

- **The quantities $\rho_{\rm SF}(x)$ and $z_{\rm SF}(x)$ are known numerically up to $x = 1/6$ and $1/5$**

  [Blanchet et al. 10; Damour, Barack & Sago 10]

- **$A(r)$ and $\bar{D}(r)$ are also computed through 6PN and 5PN orders, respectively, including the logarithms!**

Spin effective-one-body model in a nutshell

- **EOB models with spins** [Damour 01, Damour et al. 08, Barausse & AB 09, 11; Nagar 11]
- **The PN Hamiltonian of two BHs of masses $m_{1,2}$ and spins $\mathbf{S}_{1,2}$ is mapped into the effective Hamiltonian of a spinning test-particle of mass μ and spin $\mathbf{S}^*$ moving in a deformed-Kerr spacetime with mass M and spin $\mathbf{S}_{\rm Kerr}$.**
- $H_{\rm eff} = H_{\rm NS} + H_{\rm S} - \frac{\mu}{2M\,r^3}\,S_*^2 \qquad H_{\rm NS} = \beta^i\,p_i + \alpha\,\sqrt{\mu^2 + \gamma^{ij}\,p_i\,p_j}$

  $H_{\rm S}$ **is linearly proportional to the effective particle's spin** S_*

  deformed-Kerr potential $\Delta_t = r^2\left[A(r) + \frac{a_{\rm Kerr}^2}{r^2}\right]$
- $H_{\rm EOB} = M\,\sqrt{1 + 2\nu\,\left(\frac{H_{\rm eff}}{\mu} - 1\right)}$
- **When PN expanded $H_{\rm EOB}$ reproduces known PN spin terms for comparable masses, and *all* PN terms linear in the small BH's spin in the test-particle limit, i.e., it is equivalent to the Papapetrou equation** [Barausse, Racine & AB 09]

Mapping of spin variables between real and effective descriptions

[Barausse & AB 09, 11]

- The spin variables entering the EOB Hamiltonian are

$$S^* = S_1 \frac{m_2}{m_1} + S_2 \frac{m_1}{m_2} + \frac{1}{c^2} \Delta^{(1)}(\mathbf{q}, \mathbf{p}, \mathbf{S}_1, \mathbf{S}_2, \alpha_i) + \frac{1}{c^4} \Delta^{(2)}(\mathbf{q}, \mathbf{p}, \mathbf{S}_1, \mathbf{S}_2, \beta_i)$$

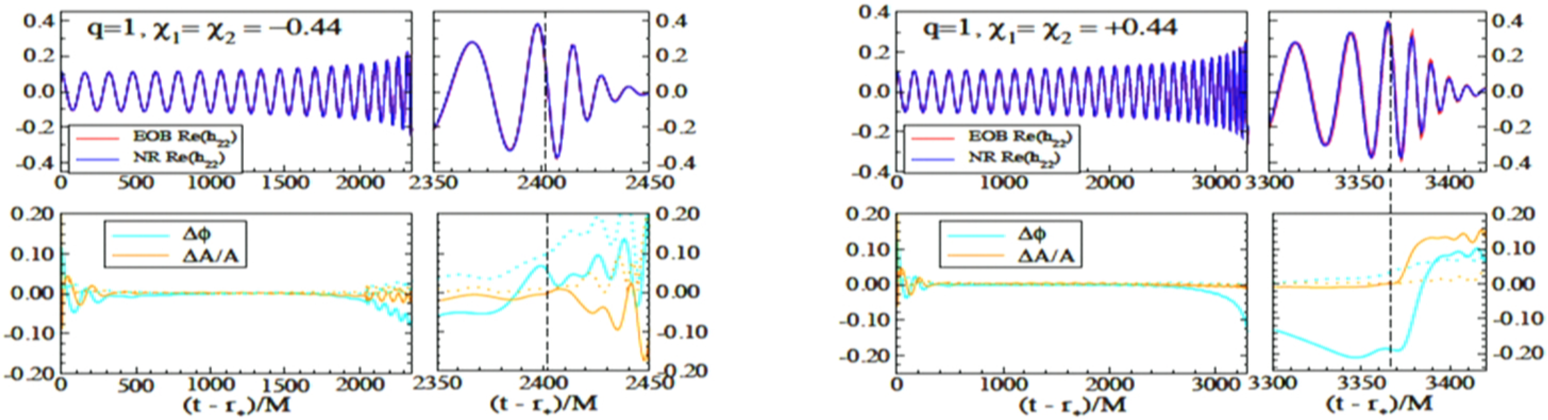
$$S_{\rm Kerr} = S_1 + S_2$$

- $\Delta^{(1,2)}$ depend on several *gauge parameters*, which are present because of the large class of canonical transformations that can map the real and effective descriptions.

- In the following we set all gauge parameters to zero.

EOB calibrations for spinning, non-precessing black-hole binaries

[Pan, AB, Buchman, Chu, Kidder, Pfeiffer & Scheel 09; Taracchini et al. (in prep)]

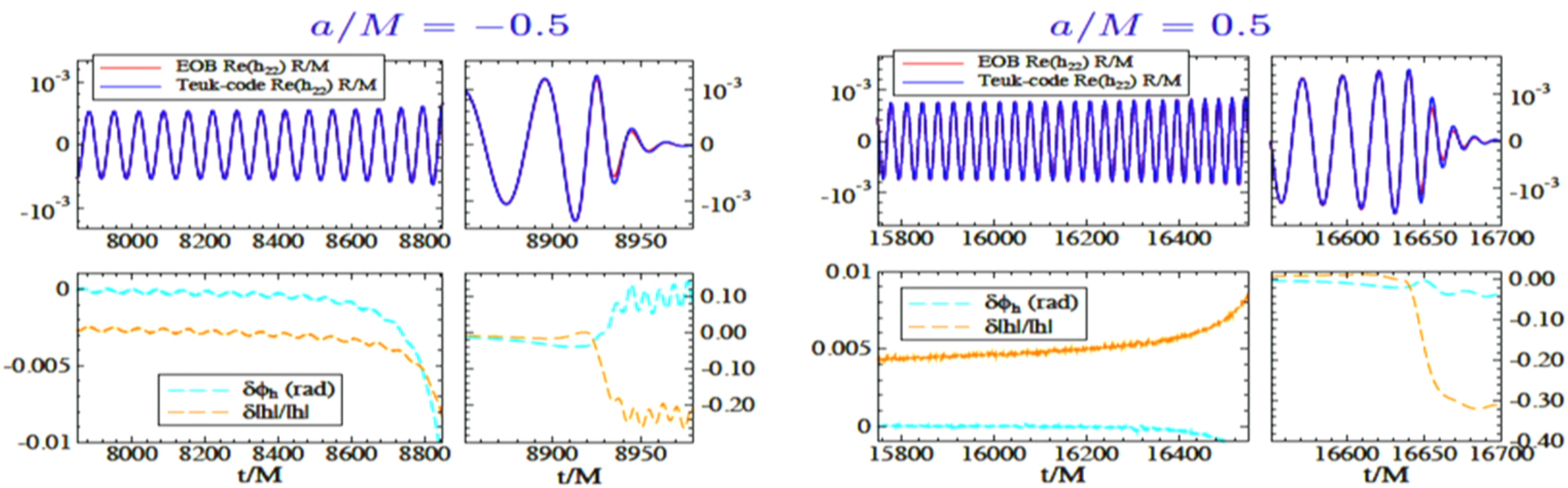


- **The calibration uses five unequal-mass, non-spinning waveforms; two equal-mass, spinning waveforms, and the small-mass ratio limit results**

Merger modeling with $m_2/m_1 = 10^{-3}$ and spin effects

[Barausse, AB, Hughes, Khanna, O'Sullivan & Pan 11]

Using spin EOB trajectory to evolve time-domain Teukolsky code through merger

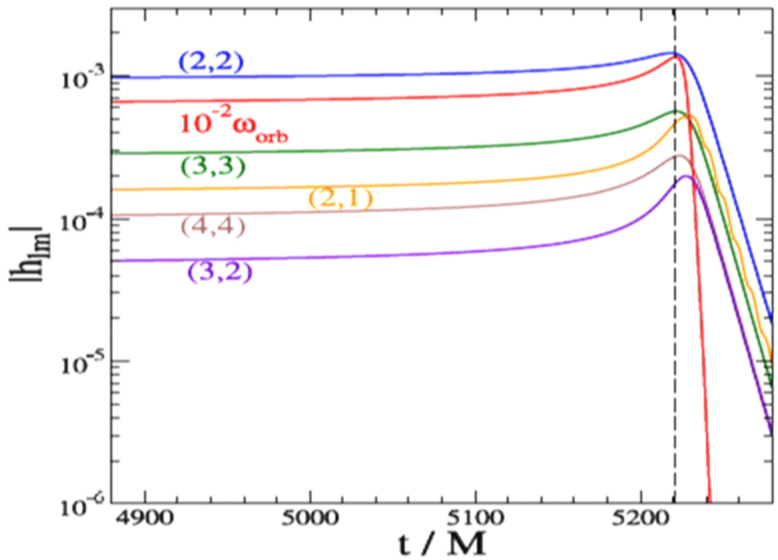


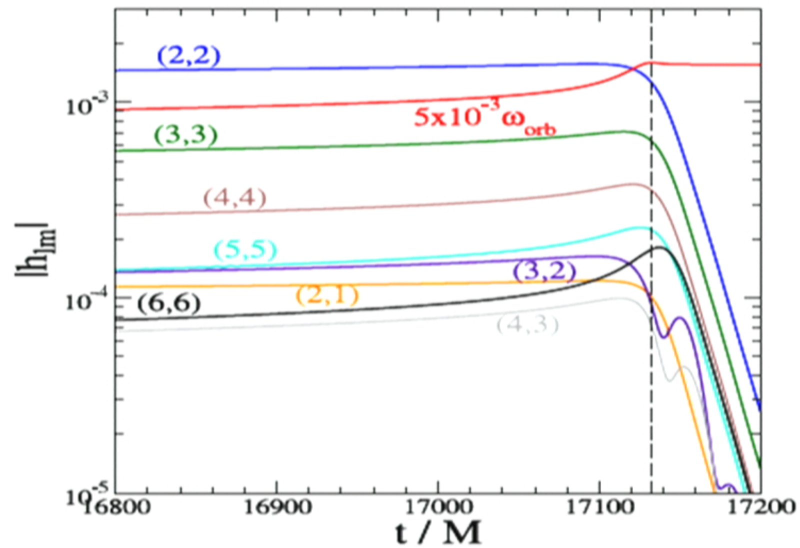
Modes and orbital frequency peak at different time

[Barausse, AB, Hughes, Khanna, O'Sullivan & Pan 11]

$m_2/m_1 = 10^{-3}$

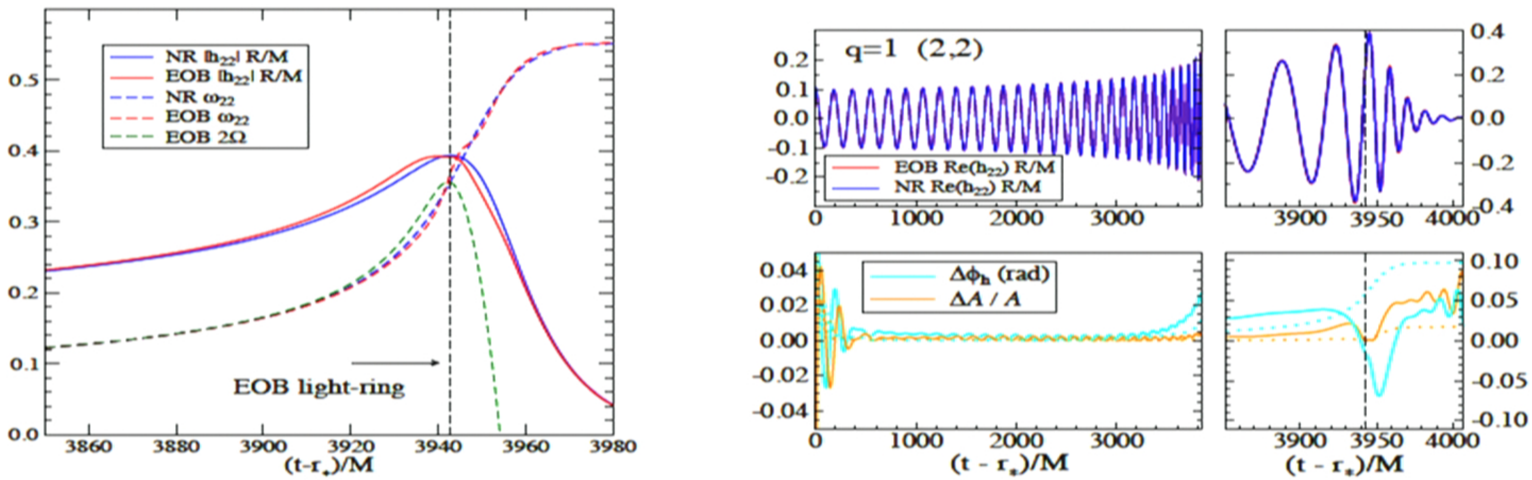
$a/M = 0$ $a/M = 0.9$





Building the EOB full waveform and comparing with NR: $m_1/m_2 = 1$

[Pan, AB, Boyle, Buchman, Kidder, Pfeiffer & Scheel 11]

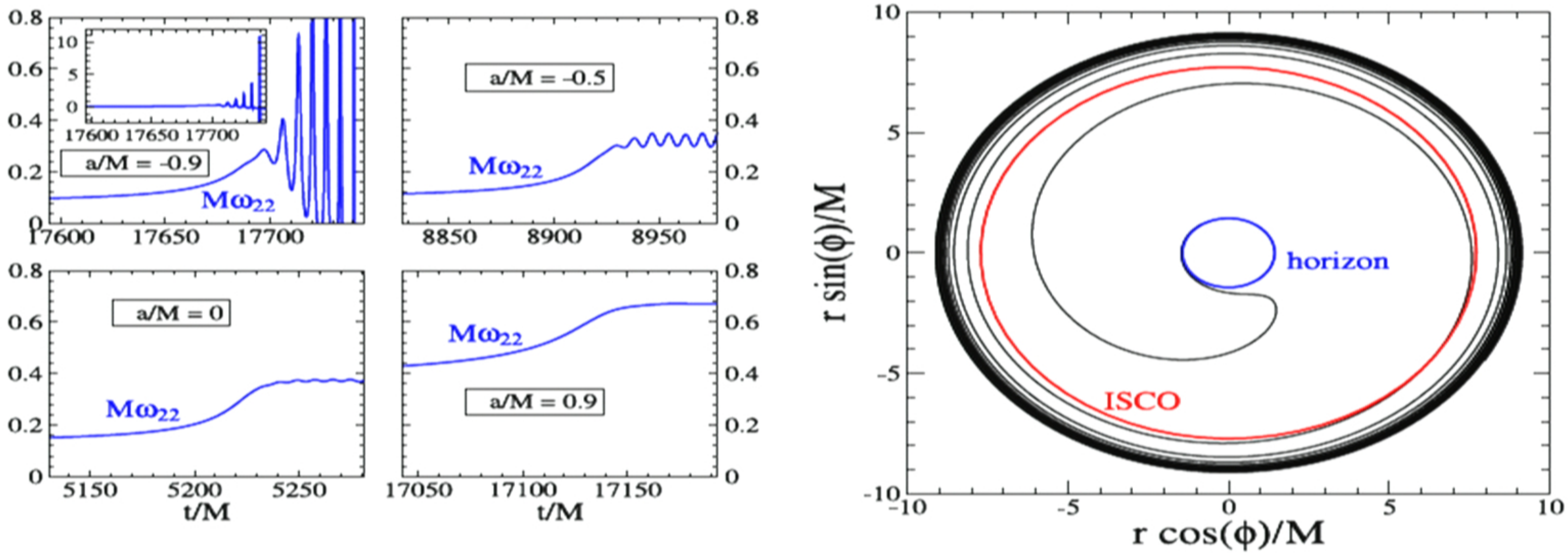


- $h_{22}^{\text{merger}-\text{RD}}(t) = \sum_{n=0}^{N-1} A_{22}\, e^{-i\sigma_{22n}(t-t_{\text{match}}^{22})}$ $\qquad \sigma_{22n} = \omega_{22n}^{\text{QNM}} - i/\tau_{22n}^{\text{QNM}}$
- $h_{22}^{\text{full}}(t) = h_{22}^{\text{insp}-\text{plunge}}\,\theta(t_{\text{match}}^{22} - t) + h_{22}^{\text{merger}-\text{RD}}\,\theta(t - t_{\text{match}}^{22})$

Presence of oscillations in GW frequency for retrograde orbits

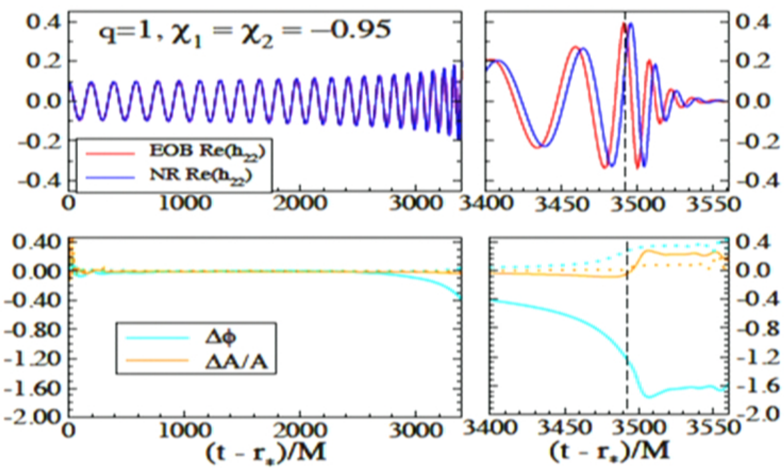
[Barausse, AB, Hughes, Khanna, O'Sullivan & Pan 11]

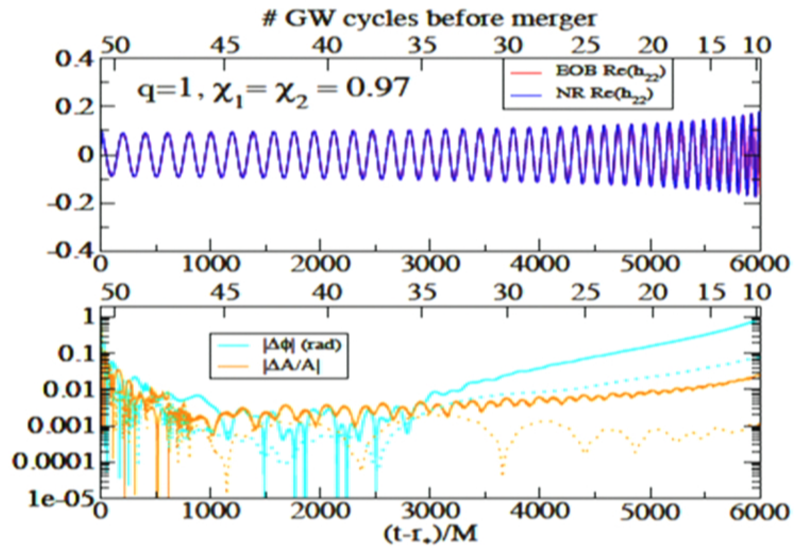
$m_2/m_1 = 10^{-3}$



First-order spin EOB model compared to extreme-spin BH binaries

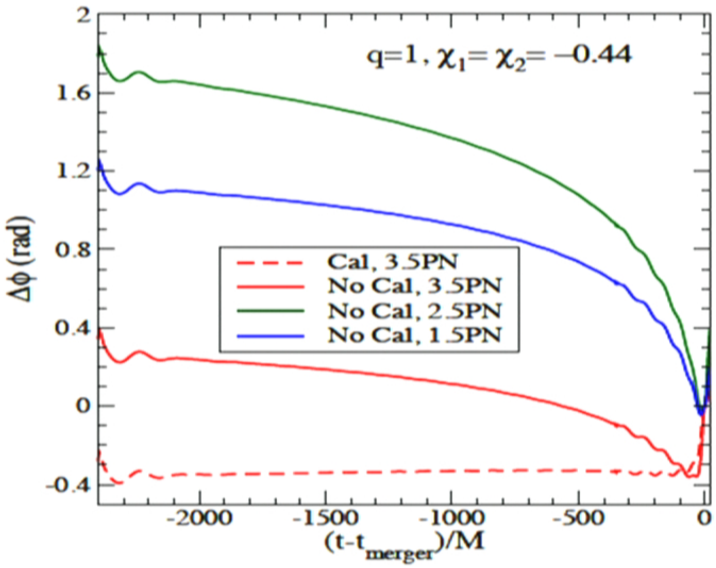
[Taracchini et al. (in prep); Lovelace, Boyle, Scheel & Szilagyi 11]

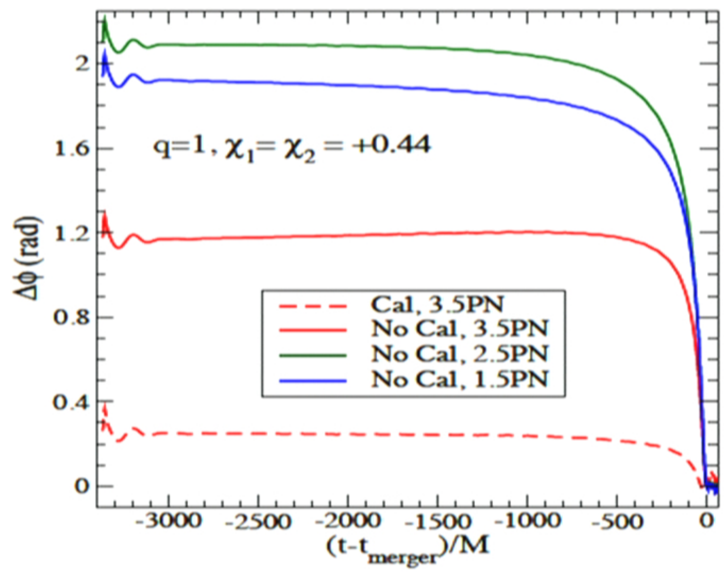




The EOB-adjustable parameters were not calibrated to the extreme-spin NR waveforms

The importance of extending spin effects at higher PN order



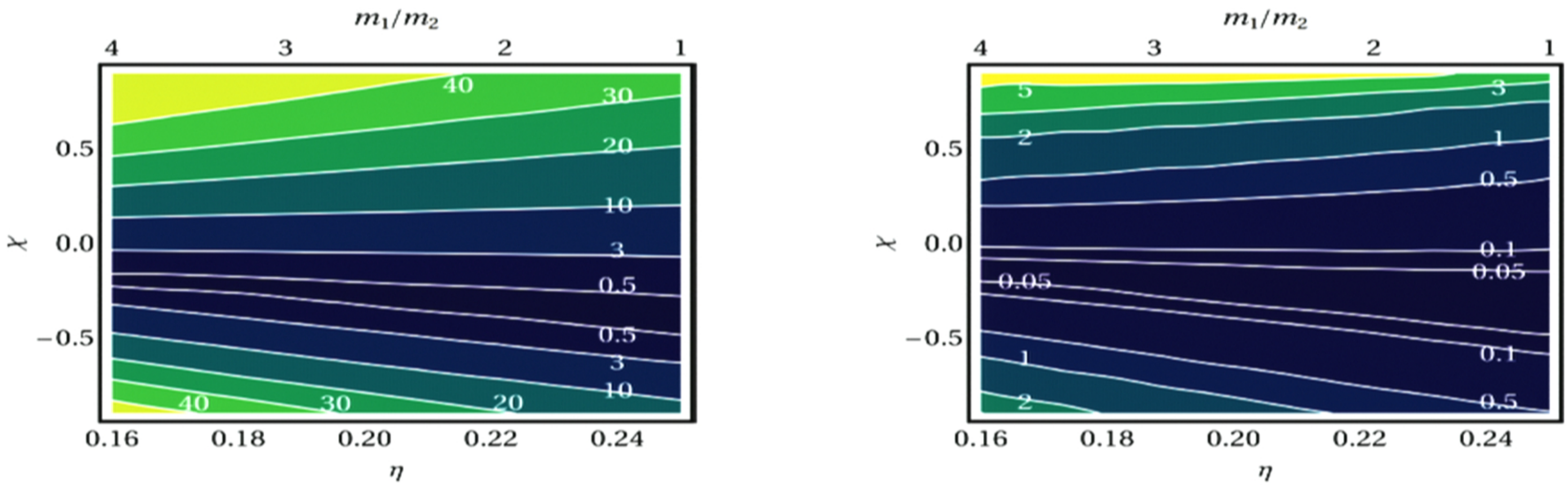


[courtesy of Andrea Taracchini]

NR length requirements: are 15 orbital cycles sufficient? Yes, if ...

[Ohme, Hannam & Husa 11; see also Damour, Nagar & Trias 11; Boyle 11; MacDonald et al. 11]

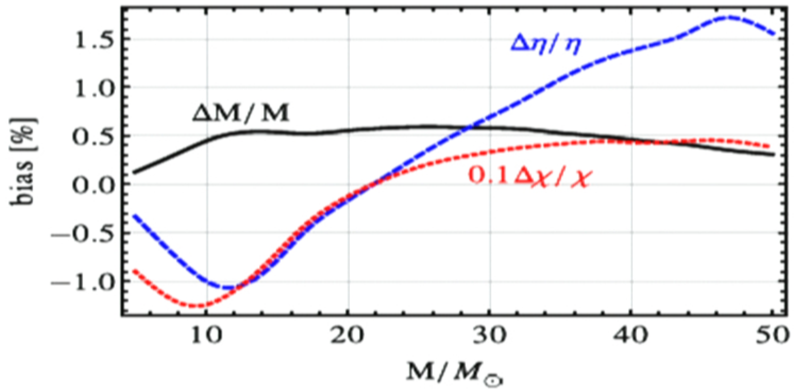
- Mismatch contours between two PN approx. using matching frequency $M\omega_m = 0.06$

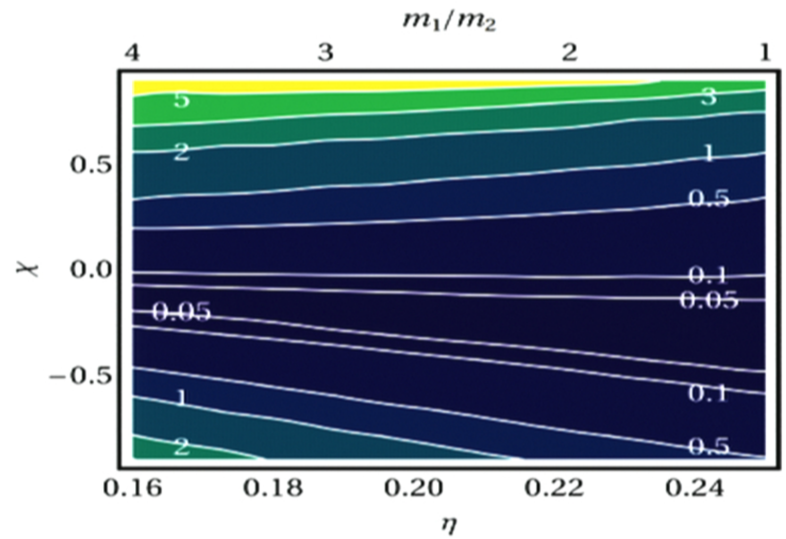


- Without maximizing on binary parameters
- Maximizing on binary parameters

Biases in the binary parameters

[Ohme, Hannam & Husa 11]



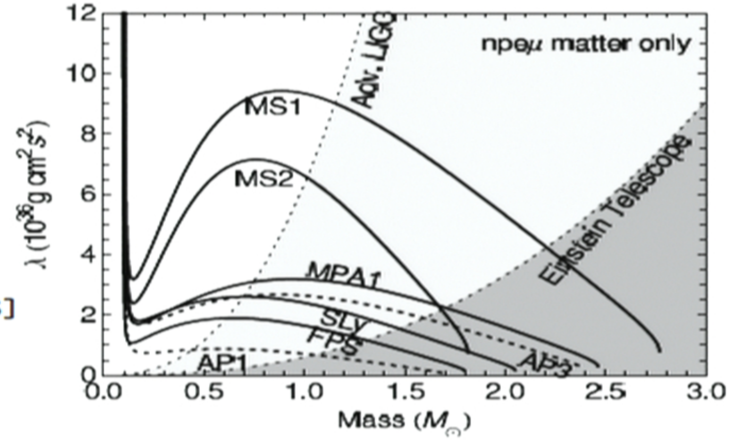


- **In this region of parameter space, biases comparable to statistical errors if SNR ~ 10**
- **What about highly spinning, precessing and unequal mass systems?**

Can aLIGO extract information on NS's equation of state using only inspiraling signals?

- The influence of star's internal structure on the waveform is characterized by a single parameter: the tidal deformability λ.

[Hinderer et al. 10]



- λ measures the star's quadrupole deformation in response to the companion perturbing tidal field: $Q_{ij} = -\lambda \, E_{ij}$
- Tidal Love number: $k_2 = \frac{3G}{2} \lambda \, R^{-5}$

  $R \rightarrow$ radius of NS $\quad k_2 = k_2(\mathcal{C}, \mathrm{EOS})$

[Kochanek 92; Bildsten & Cutler 92; Lai & Wiseman 96]

[Lai, Rasio & Shapiro 94; Flanagan & Hinderer 08;]

[Pannarale et al. 11]

- aLIGO observations of NS-NS at 100 Mpc, between 10–450 Hz, will probe only only unusually stiff EOS, but with a network of N detectors $\Delta\lambda/\sqrt{N}$, and a closer signal $\Delta\lambda/(D/100\mathrm{Mpc})$.

Successes

- The work at the interface between NR and AR (PN, EOB and self force) is providing us with new insights and remarkable results!
- Binding energy for circular orbits has been computed at next-to-leading order in ν.
- EOB approach condenses dynamics and GW emission in a few crucial functions. It can be calibrated to NR simulations, and used in LIGO/Virgo searches for GWs.
- Complete accurate EOB model for mass ratios 1, 2, 3, 4, 6, including higher harmonics. Importance of modeling higher harmonics in asymmetric systems.
- First-order EOB model with aligned/anti-aligned spins is available, but not yet calibrated to several NR simulations.
- Because of *universality* of merger signal over large mass-ratio range, it has proven very beneficial to include results from the small mass-ratio limit.
- There exist other examples of full waveforms calibrated to NR ones, such as the the *phenomenological* templates.

Open questions

- Uncertainties in the modeling process:
  - How long the NR waveforms need to be?
  - Error in the interpolation model representing the entire EOB waveforms as a function of the physical parameters.
- Do we need higher-order PN predictions, and GSF results?
  - Extend spin effects through 3.5PN order in the energy flux.
  - Extend spin effects in the modes' amplitude at high PN order and to inclined orbits, especially in the test-particle limit.
  - Compute redshift observable and periastron advance (and binding energy, angular momentum, EOB potentials, etc.) for binaries with aligned/antialigned spins.
- Spanning the parameter space with NR simulations:
  - Spinning, precessing BH simulations are needed!
  - Short, merger simulations very valuable for EOB-waveform modeling.

The NRAR Collaboration

- Produce accurate numerical-relativity simulations spanning a large region of the binary parameter space, focusing especially on spinning systems.
- Develop *in time* for the searches of gravitational waves with Advanced LIGO/ Virgo, *calibrated* template families covering the entire parameter space (binary masses and spins).
- NSF has made available 11 million CPU-hrs on the Teragrid machine Kraken.
- 13 NR groups and several AR/data-analysis groups are participating worldwide.
- Current status: building the first repository (29 waveforms) to start template-construction activity; runs for other 30 waveforms in progress.