WFM: modeling challenges

NR challenges: G. Lovelace & C. Lousto

EOB/NR challenges: A. Nagar

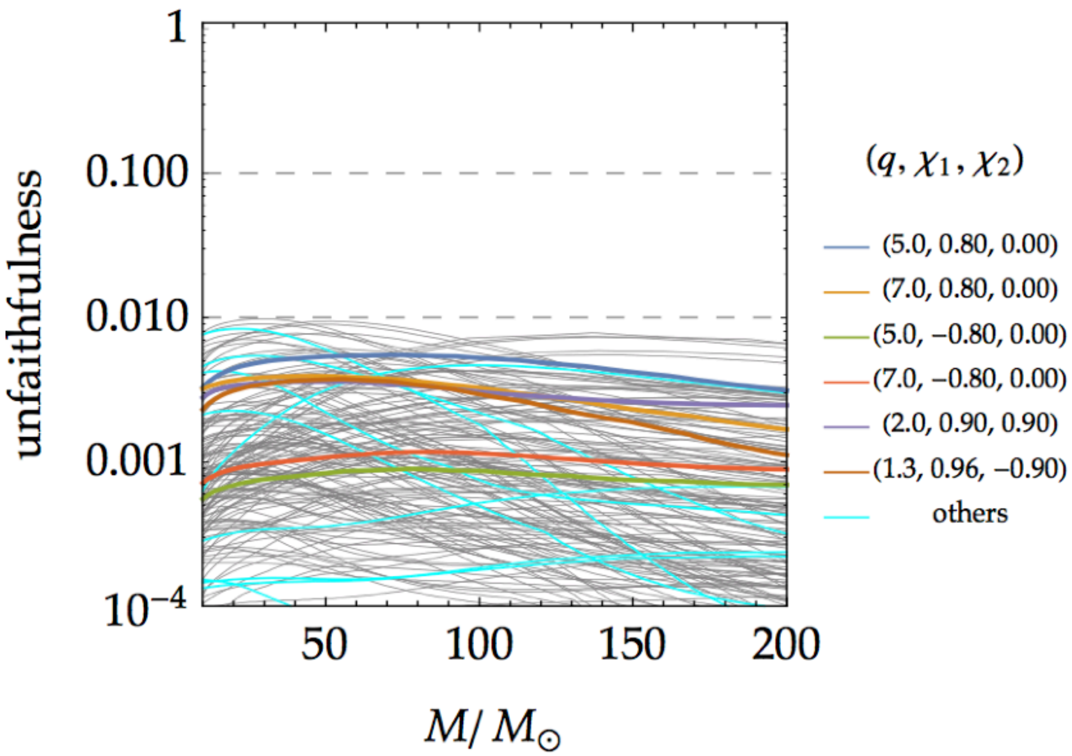
Beyond GR challenges: P. Pani

EOB waveform modeling

- EOB/NR synergy for BBH. What is used / needed?
- The role of NR: improving accuracy (also having in mind 3G)
- The role of NR: improving accurately the (sparse) coverage of parameter space. Targeted, highly accurate, simulations.

EOB/NR state of the art: spin-aligned

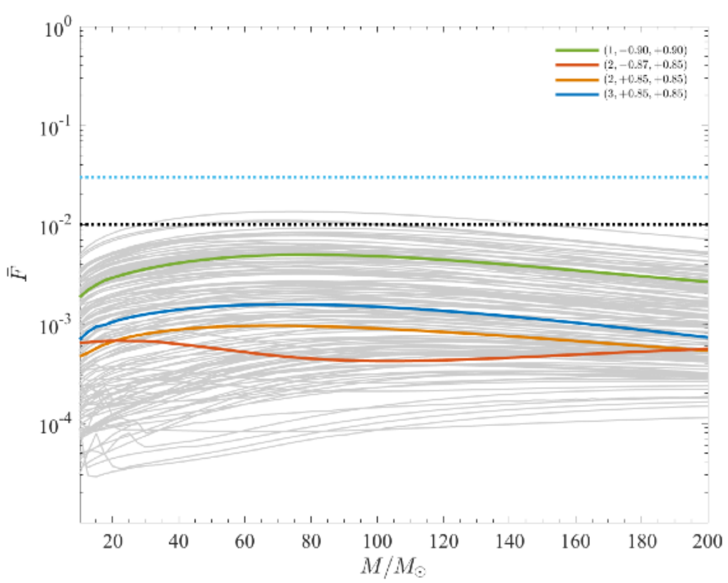
SEOBNRv4 (LAL implementation, Bohe et al. 2016)

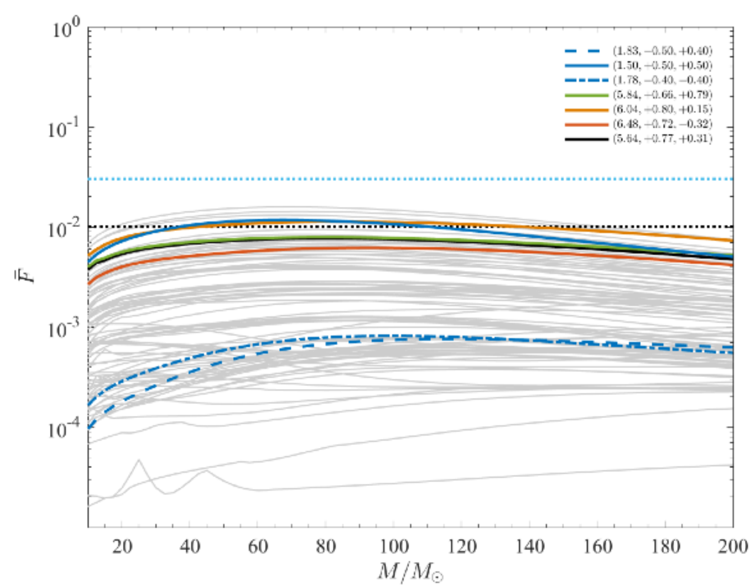


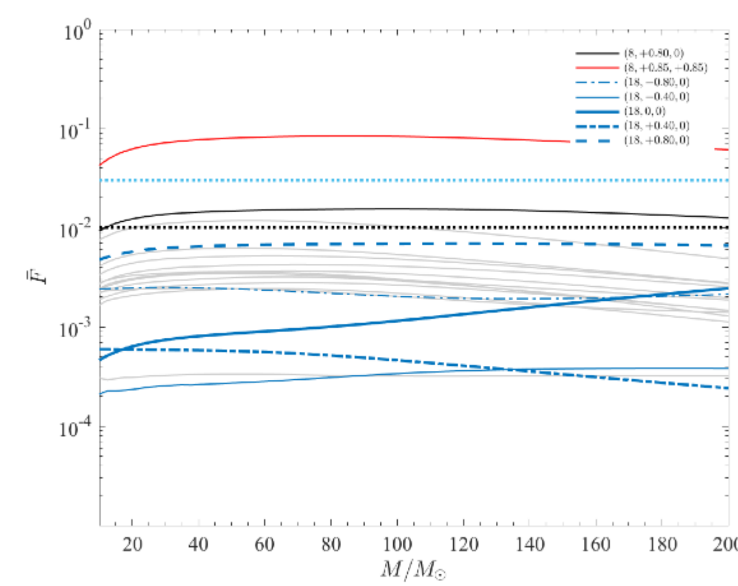
EOB/NR (SXS) unfaithfulness

TEOBResumS (LAL implementation). Nagar et al. 2017),

Improvable?

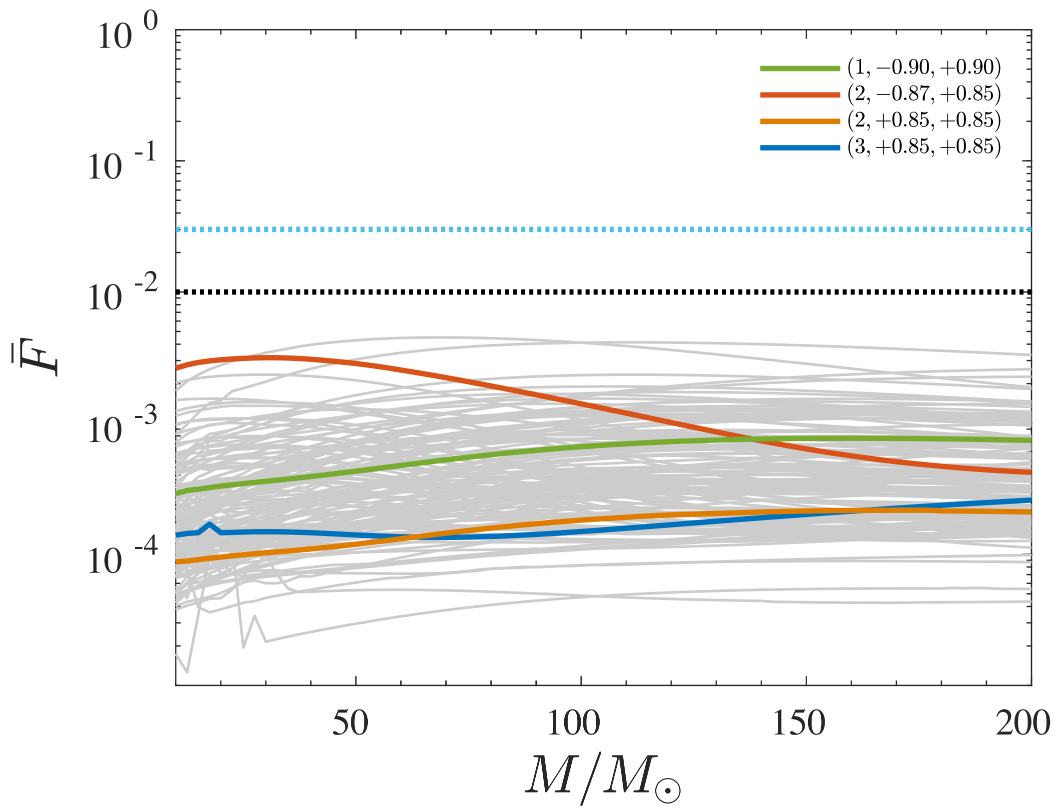


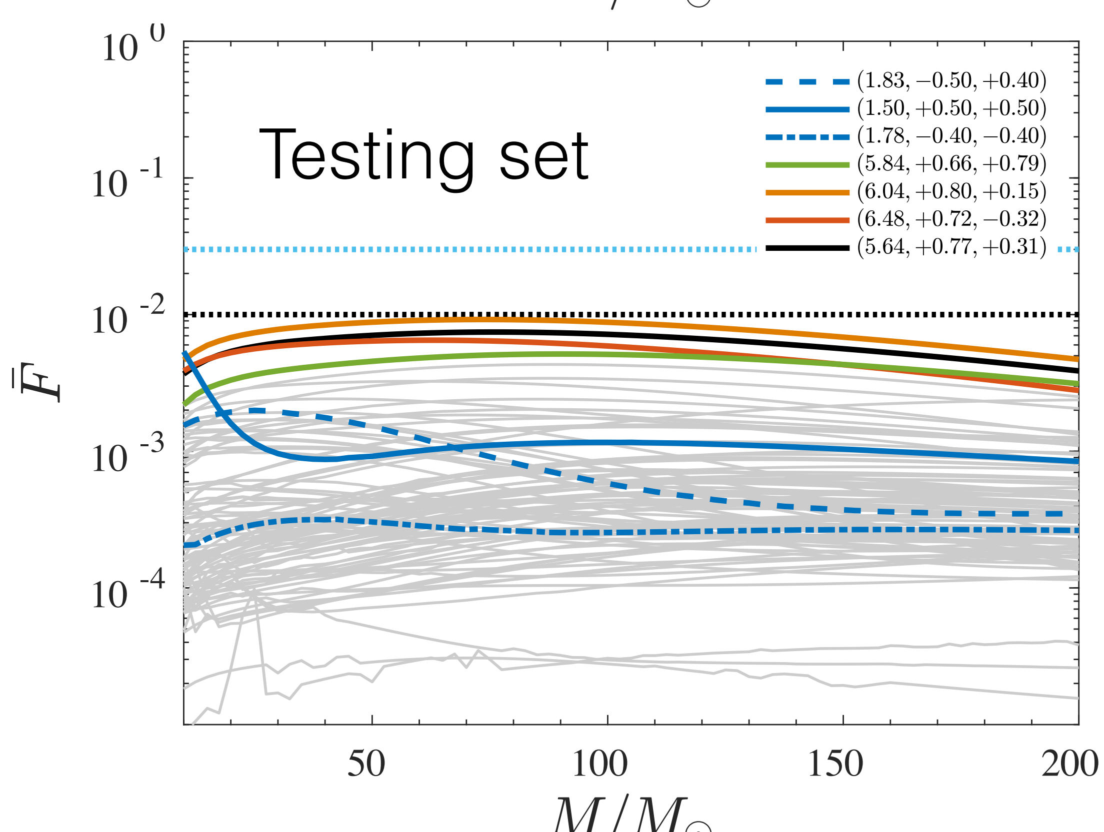


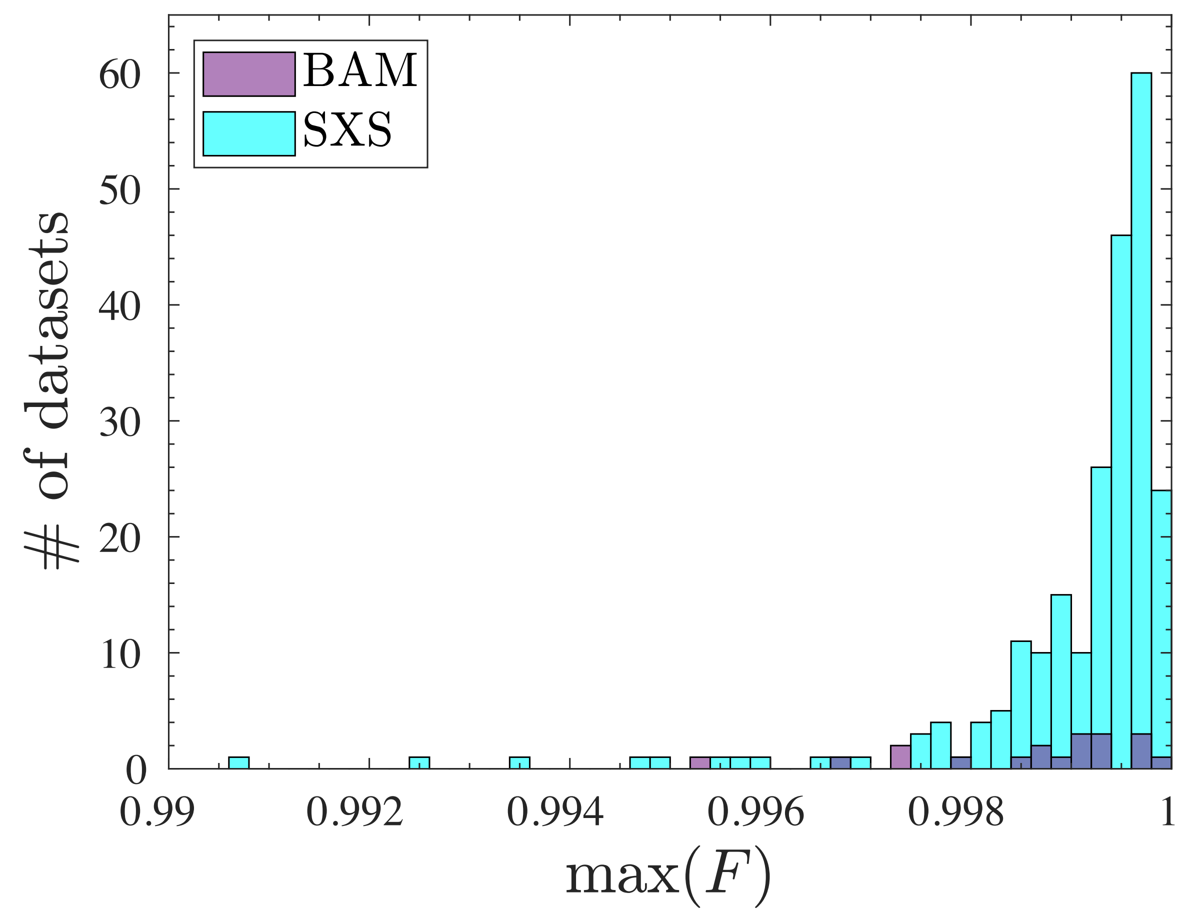


SXS catalog < 1904219

TEOBResumS/vB: spin-aligned





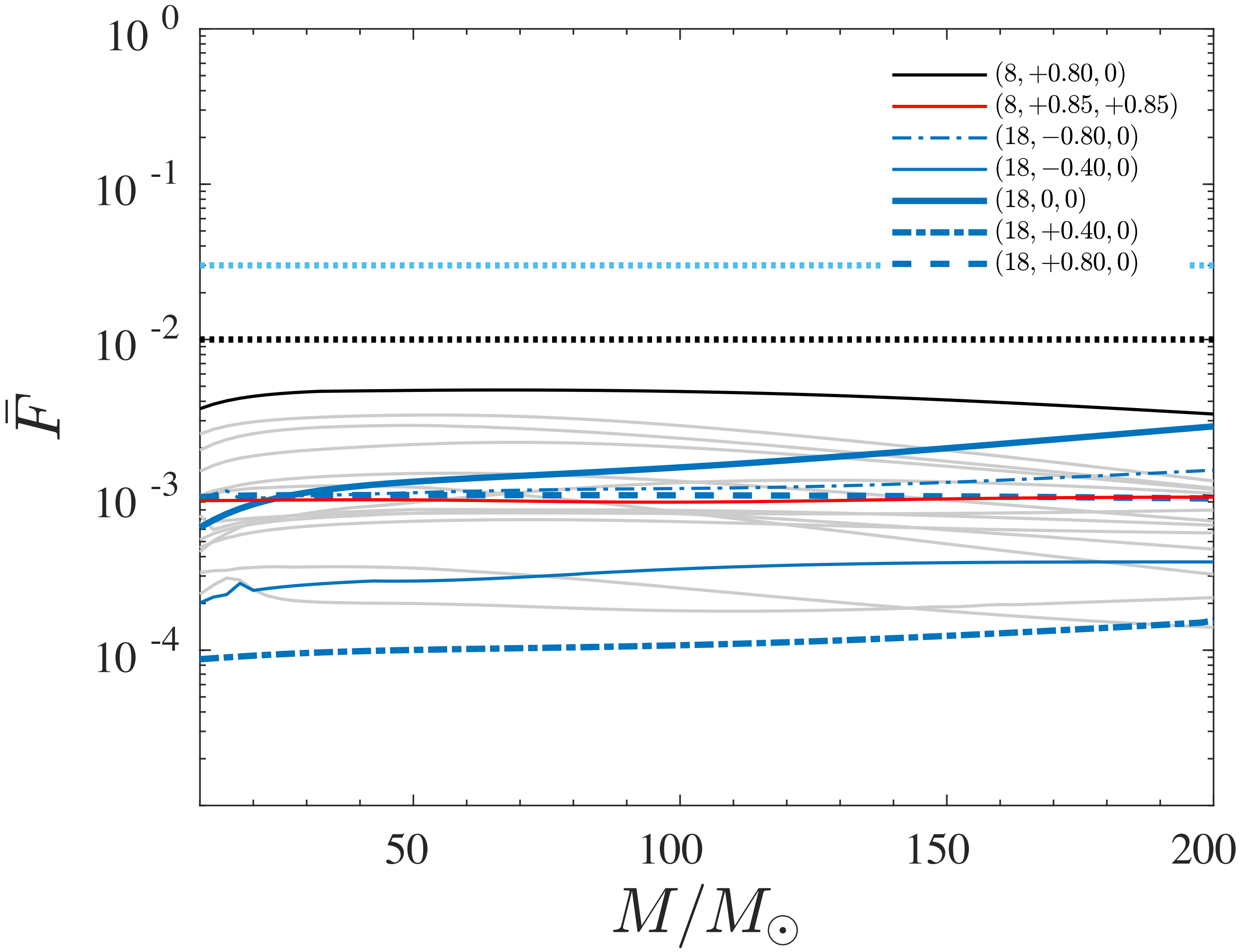


SXS catalog (<19 April 2019)
BAM waveforms
max(q) = 18 (NR)

Improvable IF needed
(more demanding NR calibration)

Riemenschneider, Nagar+ in prep., 2019

TEOBResumS/vB: large mass-ratio



Very limited checks of
the model for large-mass-ratio,
large spins

Short (10-12 cycles) waveforms

Ringdown & dynamics

Evident issues?

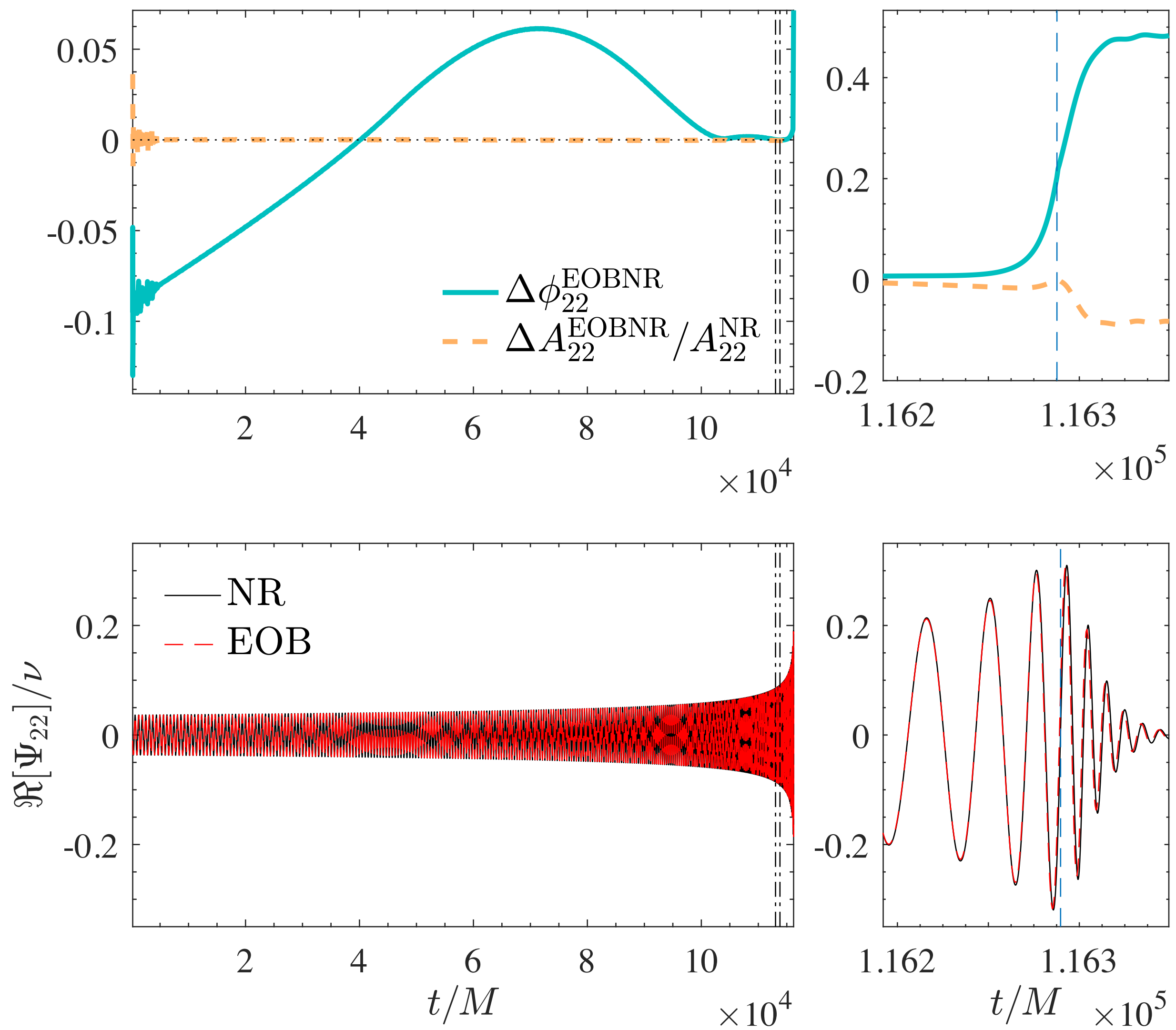


FIG. 4. EOB/NR phasing comparison for SXS:BBH:1415, $(1.5, 0.5, 0.5)$. Note that it doesn't seem possible to flatten the phase difference up to $t/M \simeq 1 \times 10^5$. The vertical lines indicate the alignment frequency region $[M\omega_L, M\omega_R] = [0.038, 0.042]$. This may explain the corresponding behavior of $\bar{F}$ in Fig. 3 and suggests that the waveform behavior might be influenced by some systematic effect.

who's right?
EOB or NR?

NR calibration: inspiral+plunge

effective spin-orbit parameter

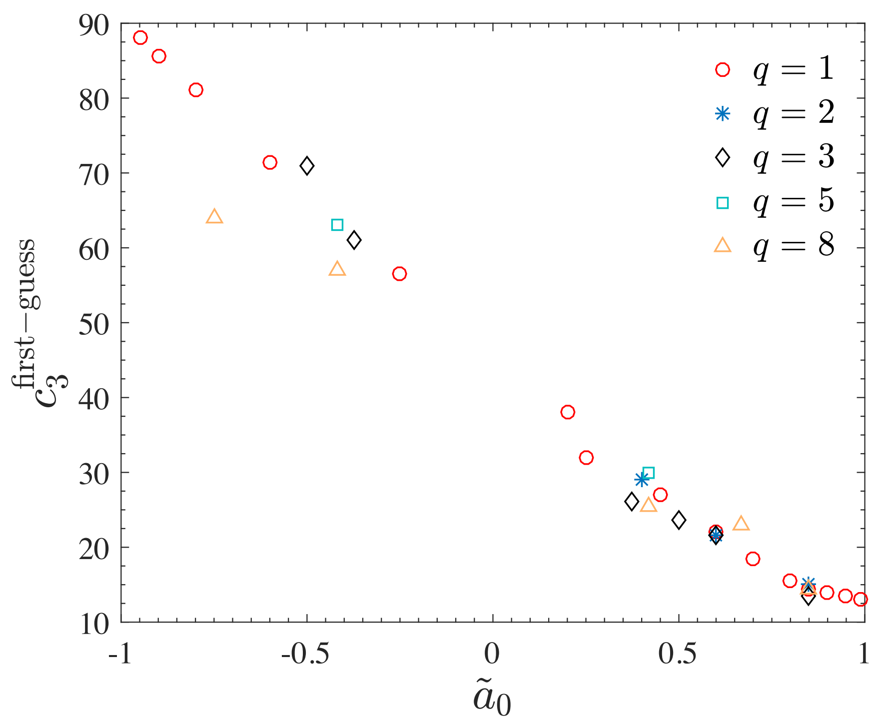


FIG. 1. The first-guess c_3 values of Table II versus the spin variable $\tilde{a}_0 \equiv S_1/(m_1 M) + S_2/(m_2 M)$. The unequal-spin and unequal-mass points can be essentially seen as a correction to the equal-mass, equal-spin values.

$$c_3(\tilde{a}_1, \tilde{a}_2, \nu) = p_0 \frac{1 + n_1 \tilde{a}_0 + n_2 \tilde{a}_0^2 + n_3 \tilde{a}_0^3 + n_4 \tilde{a}_0^4}{1 + d_1 \tilde{a}_0}$$
$$+ p_1 \tilde{a}_0 \nu \sqrt{1 - 4\nu} + p_2 \left(\tilde{a}_1 - \tilde{a}_2\right) \nu^2,$$

$a_i = S_i/(m_i M)$

32 “calibration” dataset

(+ 6 nonspinning datasets)

#	(q, χ_A, χ_B)	$c_3^{\text{first guess}}$
1	$(1, -0.95, -0.95)$	88
2	$(1, -0.90, -0.90)$	85.5
3	$(1, -0.80, -0.80)$	81
4	$(1, -0.60, -0.60)$	71.5
5	$(1, +0.20, +0.20)$	38.0
6	$(1, +0.60, +0.60)$	22.0
7	$(1, +0.80, +0.80)$	15.5
8	$(1, +0.85, +0.85)$	14.5
9	$(1, +0.90, +0.90)$	13.9
10	$(1, +0.95, +0.95)$	13.4
11	$(1, +0.99, +0.99)$	13.0
12	$(1, -0.50, 0)$	56.6
13	$(1, +0.90, 0)$	27.0
14	$(1, +0.90, +0.50)$	18.50
15	$(1, +0.50, 0)$	32
16	$(1.5, -0.50, 0)$	58.5
17	$(2, +0.60, 0)$	29.0
18	$(2, +0.60, +0.60)$	21.5
19	$(2, +0.85, +0.85)$	15.0
20	$(3, -0.50, 0)$	61.1
21	$(3, -0.50, -0.50)$	71
22	$(3, +0.50, 0)$	26.2
23	$(3, +0.50, +0.50)$	23.7
24	$(3, +0.60, +0.60)$	21.5
25	$(3, +0.85, +0.85)$	13.5
26	$(5, -0.50, 0)$	63.0
27	$(5, +0.50, 0)$	30.0
28	$(8, -0.90, 0)$	64.0
29	$(8, -0.50, 0)$	57.0
30	$(8, +0.50, 0)$	25.5
31	$(8, +0.80, 0)^*$	23
32	$(8, +0.85, +0.85)^*$	14.5

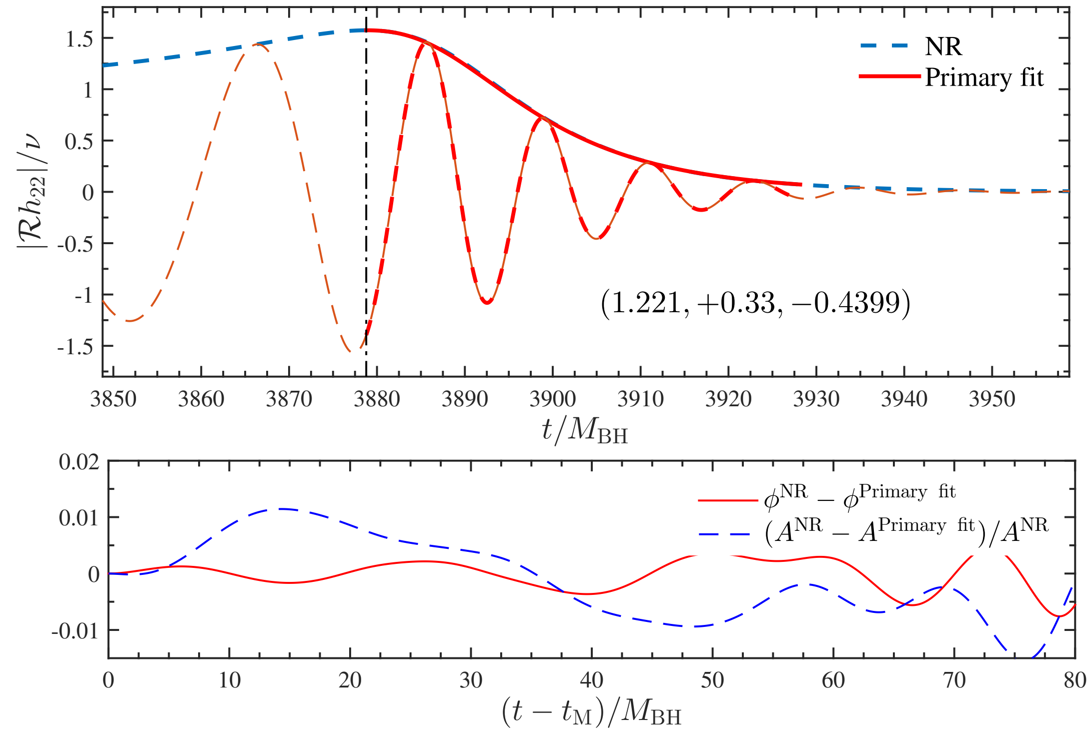
NR calibration: merger & ringdown

Damour&AN 2014: NR-based phenomenological description of postmerger phase

Factorize the fundamental QNM, fit what remains

$$h(\tau) = e^{\sigma_1 \tau - \mathrm{i}\phi_0} \bar{h}(\tau)$$

$$\bar{h}(\tau) \equiv A_{\bar{h}} e^{\mathrm{i}\phi_{\bar{h}}(\tau)}.$$



$$A_{\bar{h}}(\tau) = c_1^A \tanh(c_2^A \tau + c_3^A) + c_4^A,$$

$$\phi_{\bar{h}}(\tau) = -c_1^\phi \ln\left(\frac{1 + c_3^\phi e^{-c_2^\phi \tau} + c_4^\phi e^{-2c_2^\phi \tau}}{1 + c_3^\phi + c_4^\phi}\right)$$

$$c_2^A = \frac{1}{2}\alpha_{21}, \qquad \alpha_{21} = \alpha_2 - \alpha_1$$

$$c_4^A = \hat{A}_{22}^{\rm mrg} - c_1^A \tanh(c_3^A),$$

$$c_1^A = \hat{A}_{22}^{\rm mrg}\, \alpha_1 \frac{\cosh^2(c_3^A)}{c_2^A},$$

$$c_1^\phi = \Delta\omega \frac{1 + c_3^\phi + c_4^\phi}{c_2^\phi(c_3^\phi + 2c_4^\phi)}, \qquad \Delta\omega \equiv \omega_1 - M_{\rm BH}\omega_{22}^{\rm mrg}$$

$$c_2^\phi = \alpha_{21},$$

Good performance of primary fits (modulo details...)

Do this for various NR dataset and then build up a (simple-minded) interpolating fit

Black-list:
(1) mode mixing: not included (yet)
(2) large-mass ratios/high spin: NR input needed
(3) consistency with EMRL (to be improved)
(4) improve/check over all datasets (SXS & BAM for large mass-ratios & consistency with EMRL)
(5) Higher modes.

Special behavior: (2,1) mode

Amplitude of the (2,1) mode can develop zeros [Cotesta+ 2018].
Nearly equal-mass binaries, as well for other m=odd modes

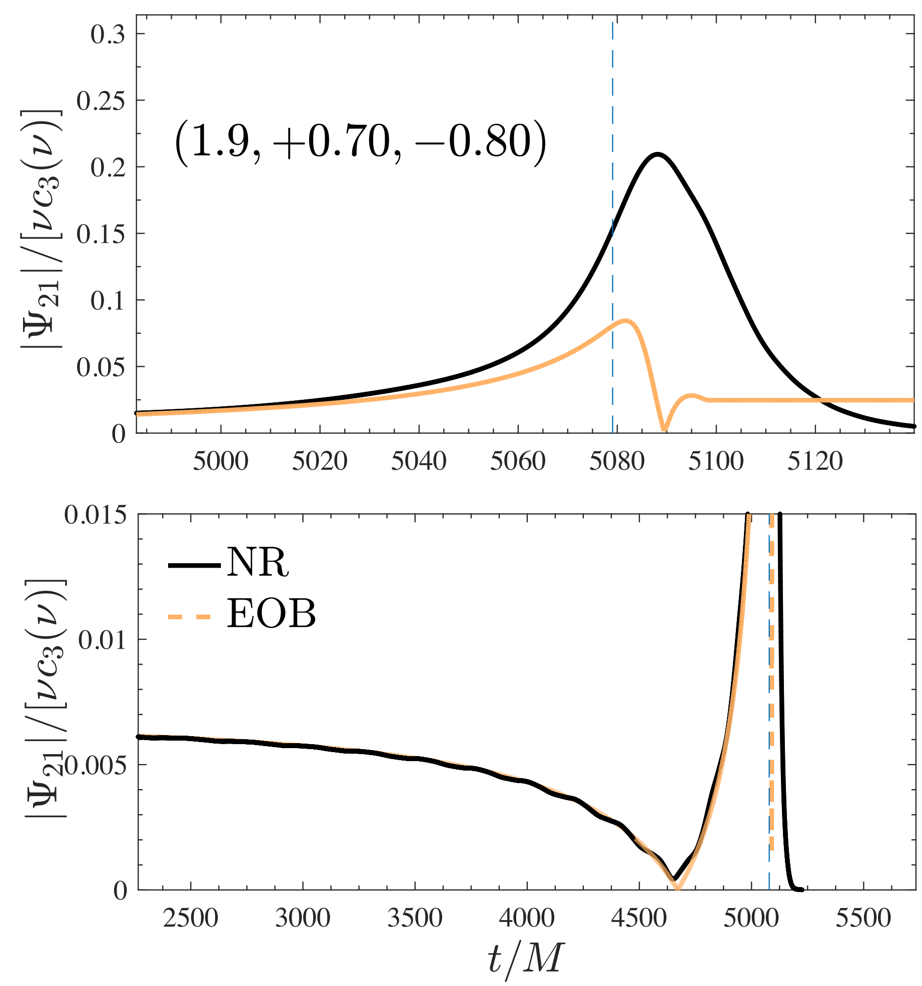
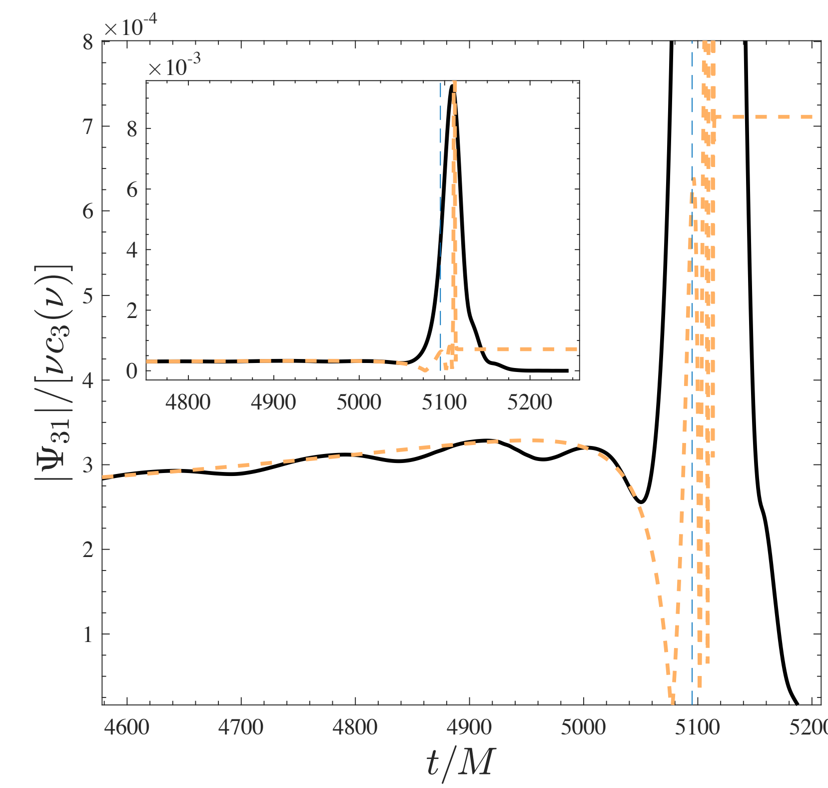


FIG. 7. PR: Line dashed in legend Mode $(2,1)$: comparison between the EOB amplitude (orange) and the corresponding NR one from dataset SXS:BBH:1466. The purely analytical EOB waveform multipole is able to accurately predict the location of the minimum (that analytically corresponds to a zero) consistently with the one found in the NR data. The excellent agreement is obtained *naturally*, without the need of calibrating any additional parameter entering the waveform amplitude.

Analytical difficulty: getting the (2,1) mode amplitude correct up to merger-ringdown

SEOBNRv4-HM: the minimum is not modeled

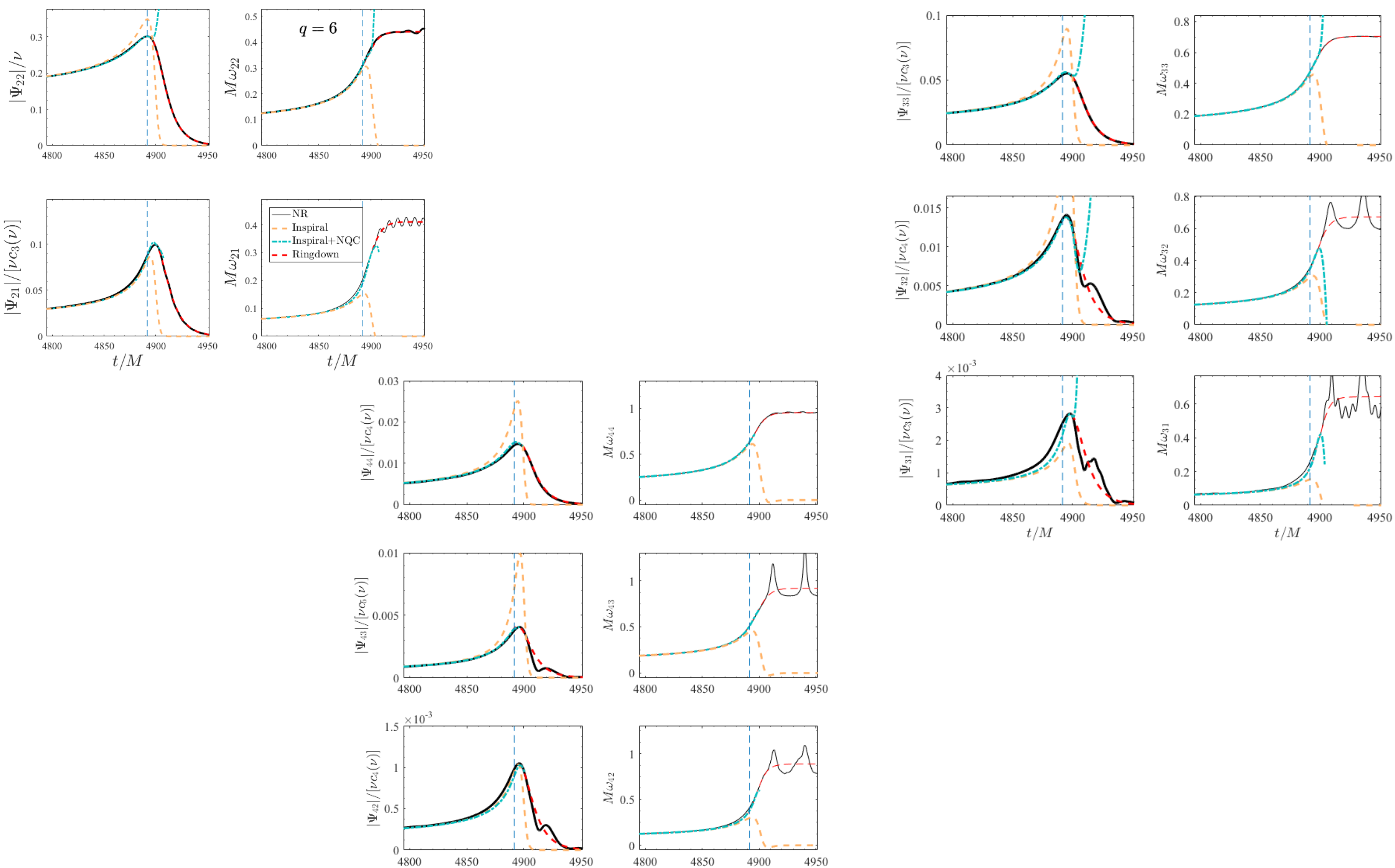


Riemenschneider, Nagar+, in prep, 2019

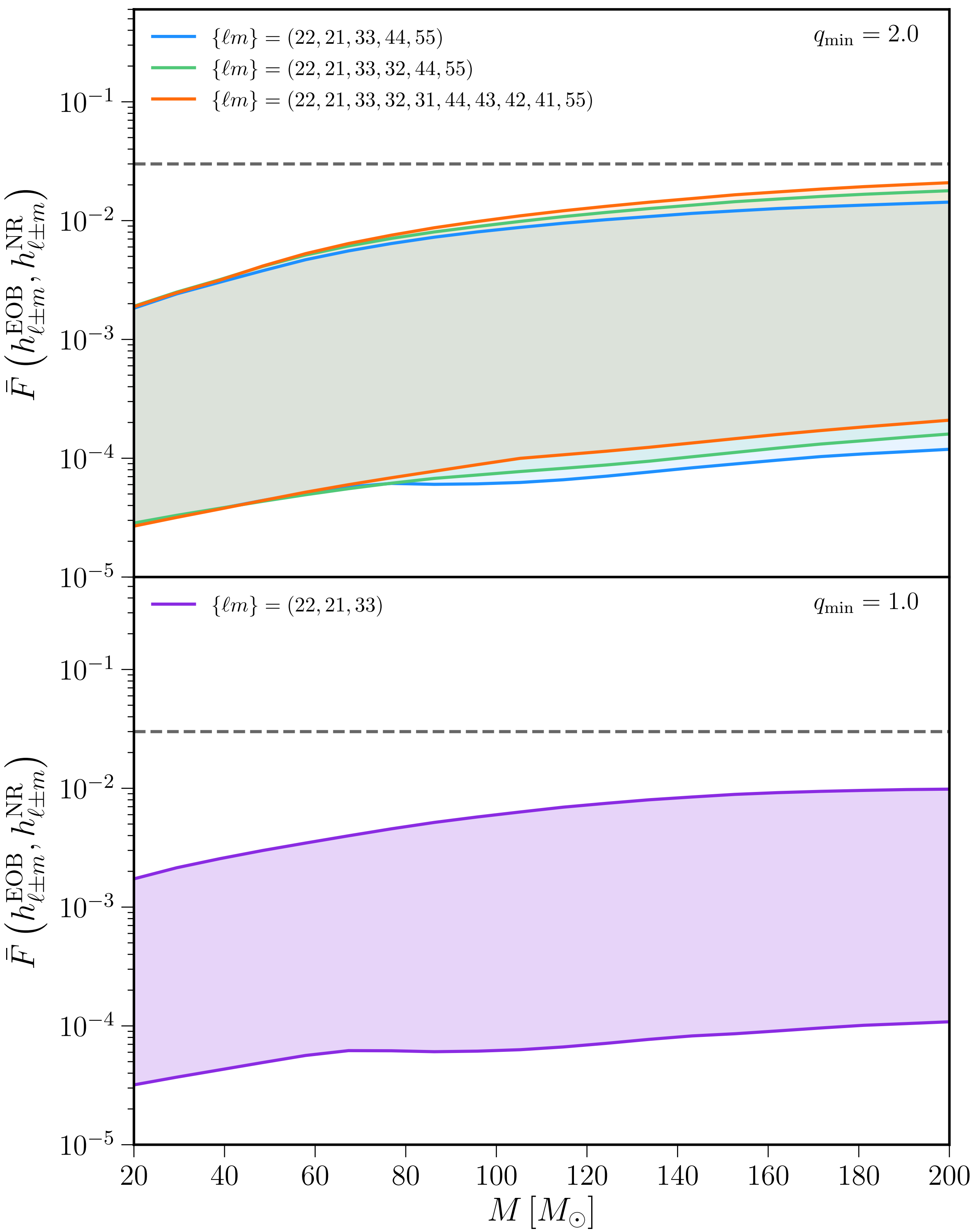
Higher modes

Cotesta+ 2018: SEOBNRv4-HM: 22,21,33,44,55 - LAL state of the art

AN, Pratten,Riemenschneider,Gamba: 1904.09550. No spin, alla modes up to (5,5)



Higher modes



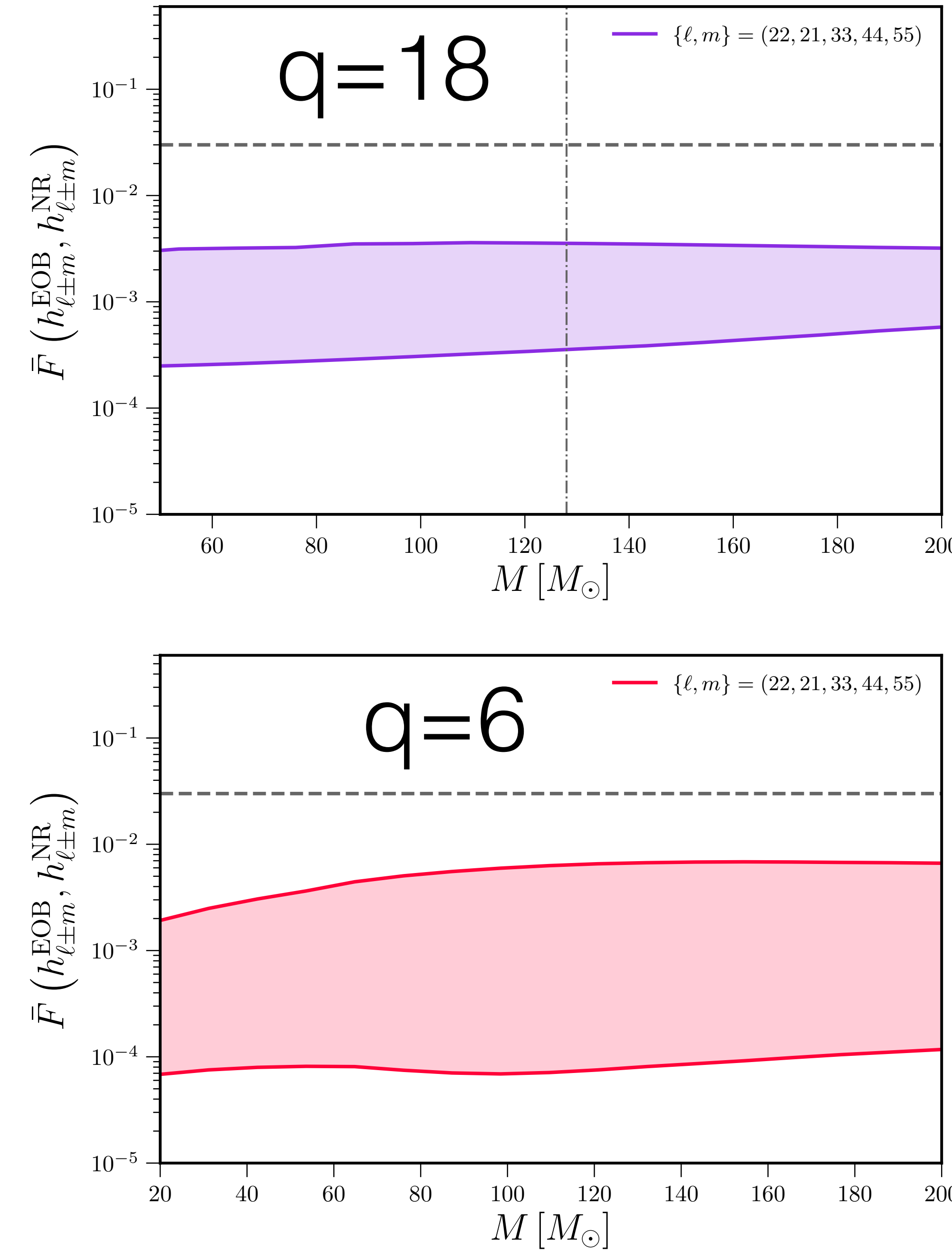
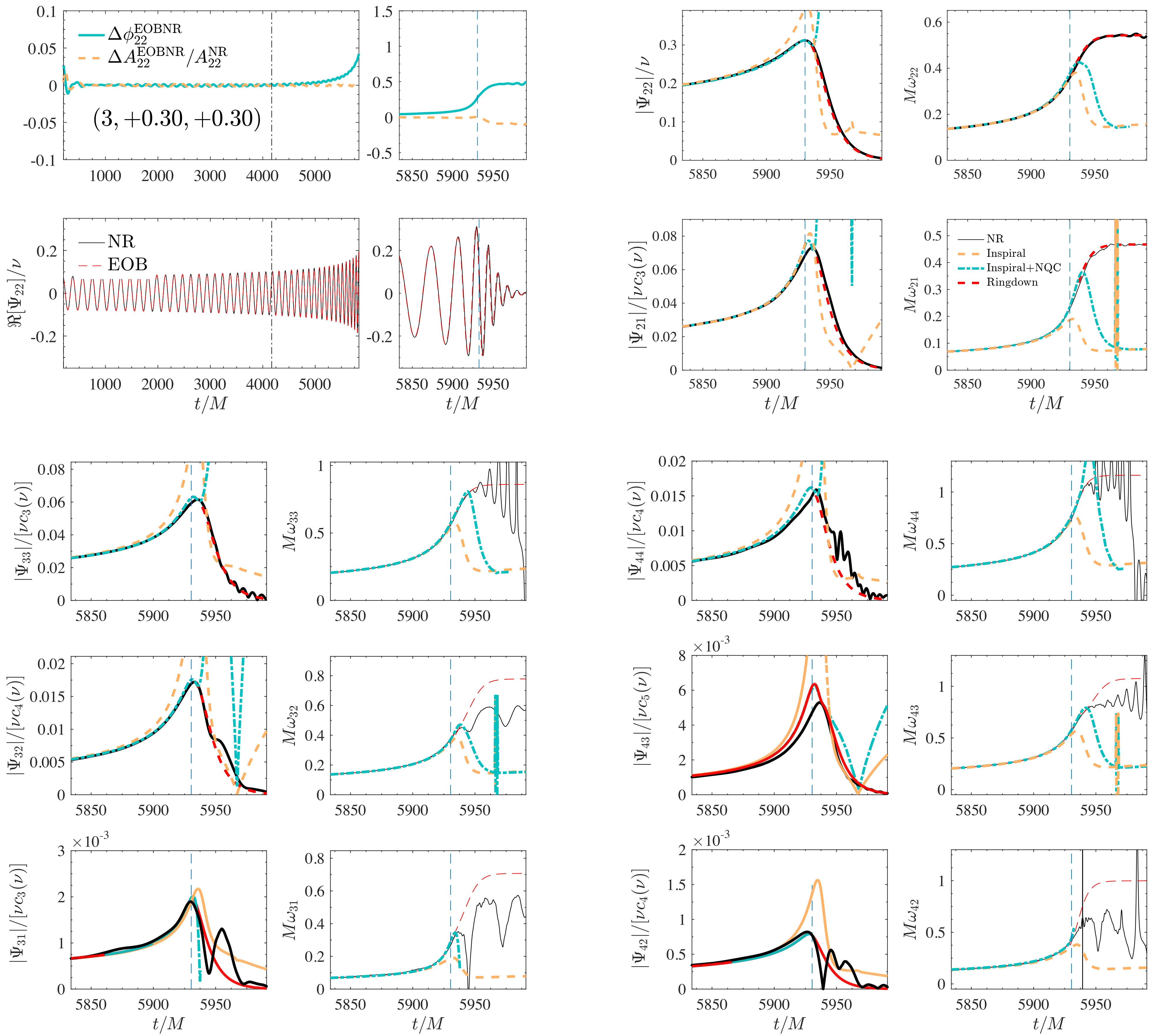


FIG. 15. Minimum and maximum unfaithfulness for TEOBiResumMultipoles model against a BAM $q = 18$ waveform [74] (top panel) and an SXS $q = 6$ simulation (bottom panel). In the top panel, the dot-dashed line shows the minimum mass for which the entire NR waveform is in band. The EOB/NR performance for $q = 6$ is comparable to (though slightly better than) SEOBNRv4HM, for the same SXS dataset, as deducible by comparison with Fig. 16 of Ref. [30].

Higher modes: spin case



Analytic systematics?

SEOBNRv4 & TEOBResumS

$$H_{\rm EOB} = M\sqrt{1+2\nu\left(\hat{H}_{\rm eff}-1\right)}.$$

TEOBResumS

$$\hat{H}^{\rm TEOB}_{\rm eff} = \sqrt{A\left(1+p_\varphi^2/r_c^2+2\nu(4-3\nu)p_{r^*}^4/r_c^2\right)+p_{r^*}^2}+ \\ +\left(G_S\hat{S}+G_{S^*}\hat{S}^*\right)p_\varphi. \qquad (2)$$

SEOBNRv4

$$\hat{H}^{\rm SEOB}_{\rm eff} = \sqrt{\mathbb{A}\left(1+p_\varphi^2/\bar{r}_c^2+2\nu(4-3\nu)p_{r^*}^4/r^2\right)+p_{r^*}^2}+ \\ +\left(\bar{G}^0_S\hat{S}+\mathbb{G}_{\mathbb{S}^*}\hat{\mathbb{S}}^*\right)p_\varphi+\hat{H}_{ss}. \qquad (3)$$

- spin-gauge (spin-orbit part)
- spin-spin part
- spinning-particle information
- deformation from the Kerr case
- NR calibration

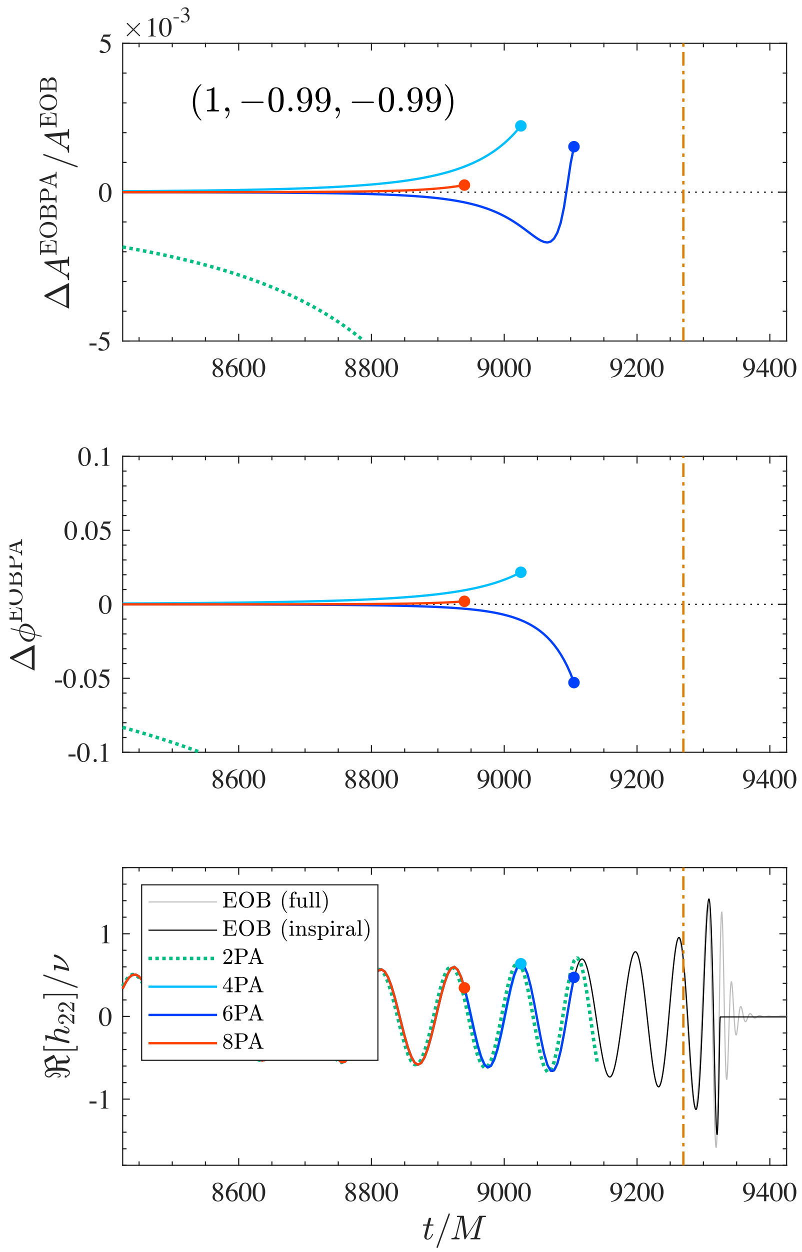
Martinetti, Nagar+, 2018, in prep.

Efficient waveform generation

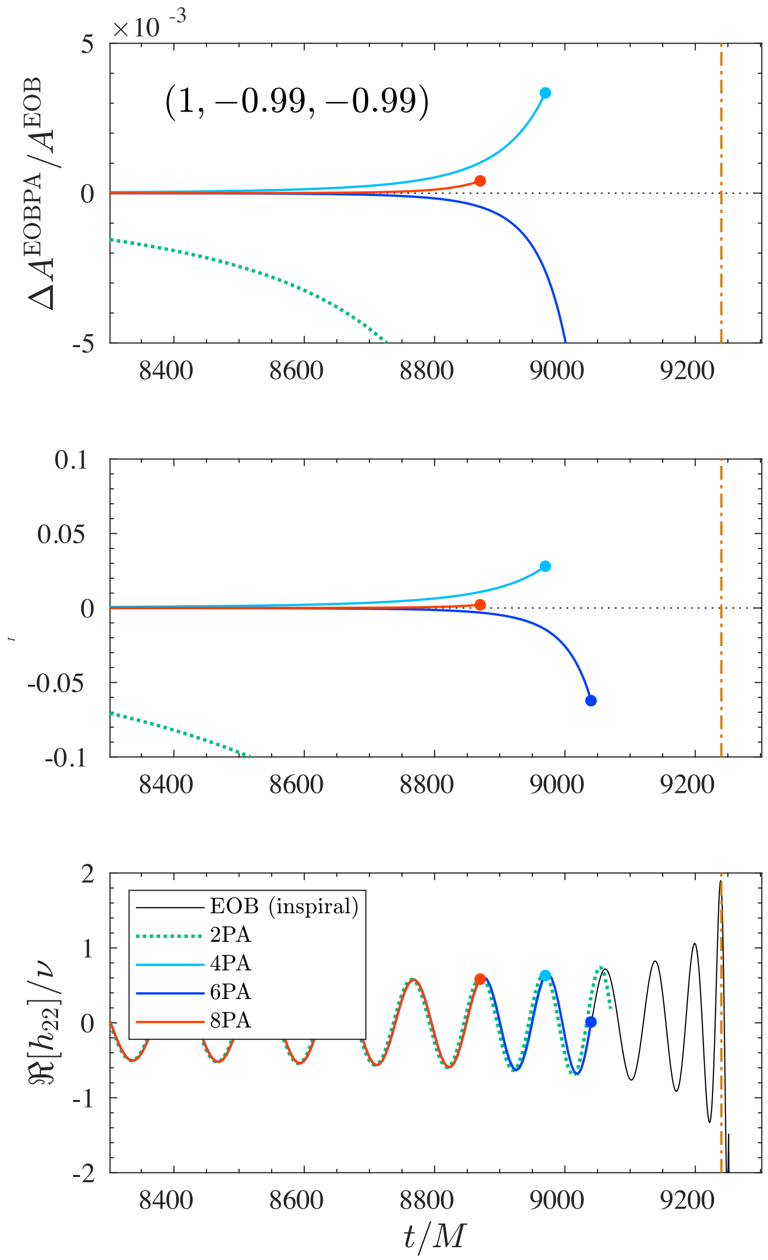
Post-adiabatic (PA) approximation for the inspiral (AN&Rettegno, 2018)

ODE vs PA. Efficient also for O3?

TEOBResumS



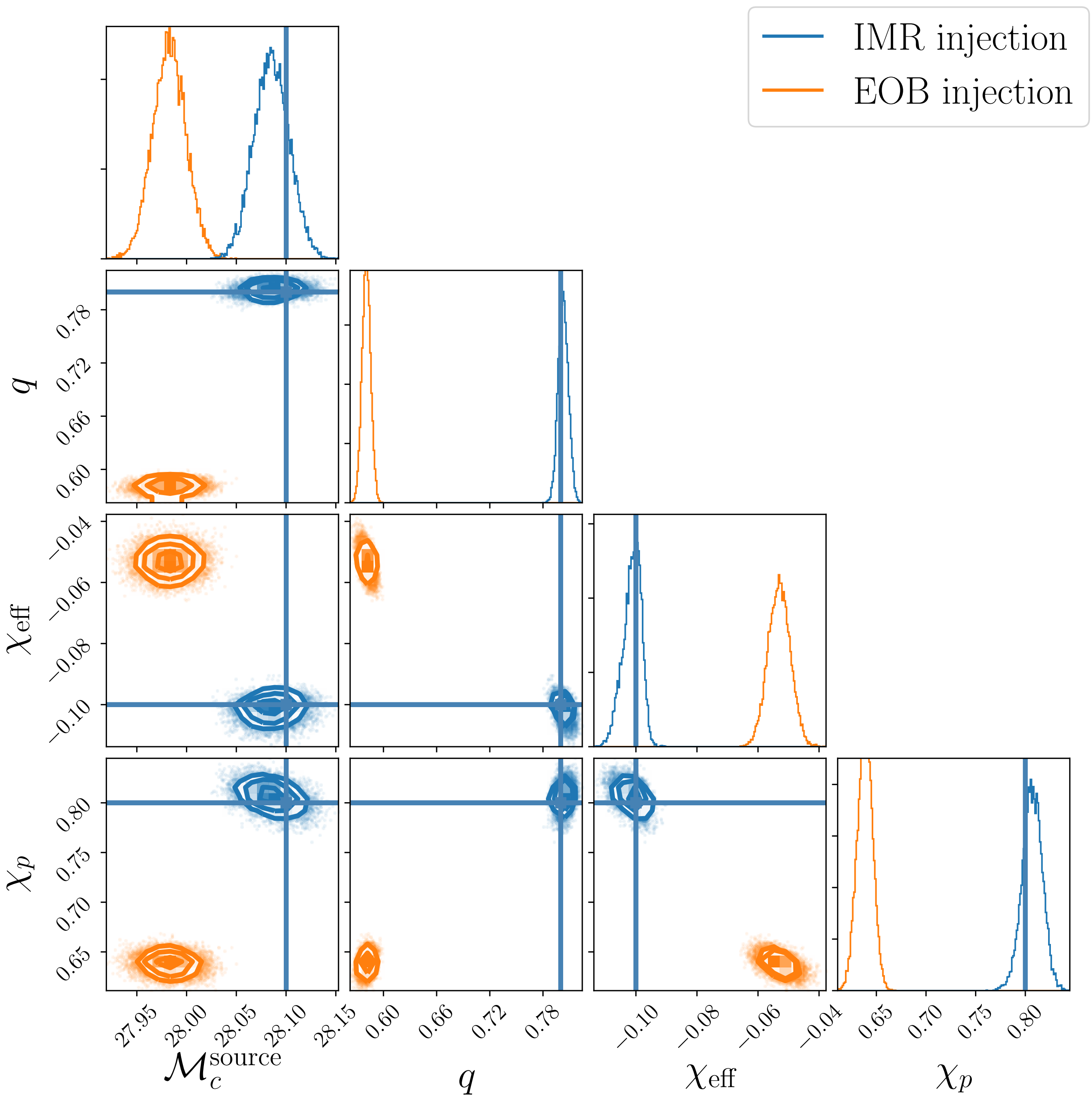
SEOBNRv4-Ham



- TEOBResumS speed comparable to Phenom speed
- No need of EOB surrogate.
- SEOBNRv4 implementation in progress (+AEI people)

Martinetti, Nagar+, 2018, in prep.

Careful with high SNR



SNR=400

theta_JN~30deg

Puerrer+, in prep

SEOBNRv3 vs IMRPhenomPv2

Open questions:

From Analytical Relativity:

- Different EOB formulation/gauges: change Hamiltonian
- Different resummation strategies
- Additional analytical information
- PM vs PN? What about GSF information?
- Proper modelization of (2,1) mode looks challenging.

From Numerical Relativity:

- Enlarge the span of NR simulations: large q, large spins.
  Targeted simulations for specific tasks.
- How accurate our analytical inspiral is/can be ?
- How accurate our analytical ringdown can be?
- Improving/testing higher modes