# Status of TEOBResumS

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Time-domain effective-one-body waveforms from coalescing compact binaries with nonprecessing spins, tides and self-spin effects
arXiv:1806.01772: AN, S. Bernuzzi, W. Del Pozzo,…. S. Babak, (19 coauthors)…. and T. Damour
Complementary posters by: Gamba, Martinetti, Messina, Rettegno, Riemenschneider

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VIRGO

# What is TEOBResumS?

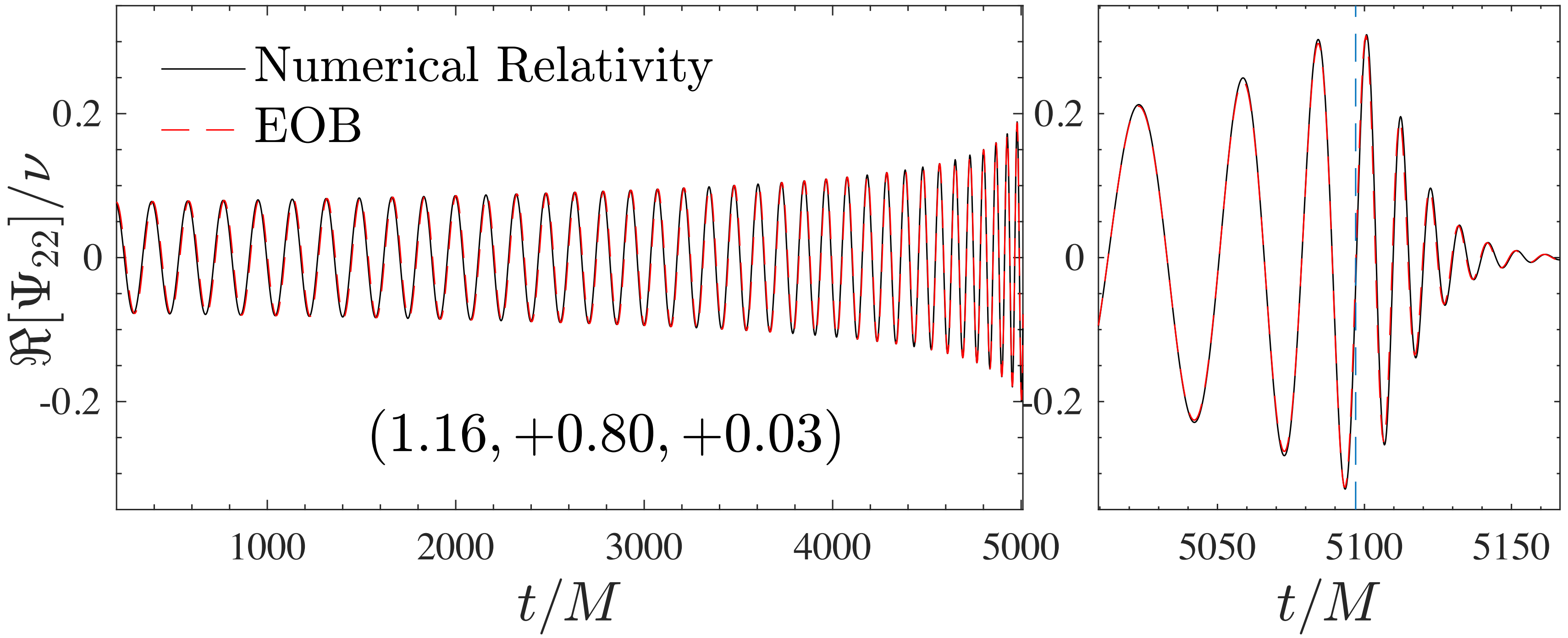
## Effective-one-body (EOB)-based waveform model for spin-aligned coalescing binaries

- BBH sector improved by Numerical-Relativity information

- BNS (tidal) sector compatible with high-accuracy NR simulations. Spin-induced quadrupole moments included

- Public stand-alone C-implementation:

  git clone https://alex_nagar@bitbucket.org/eob_ihes/teobresums.git




Challenges:
- physical completeness
- accuracy
- efficiency (AR vs NR)
- $10^7$ templates needed for a single event

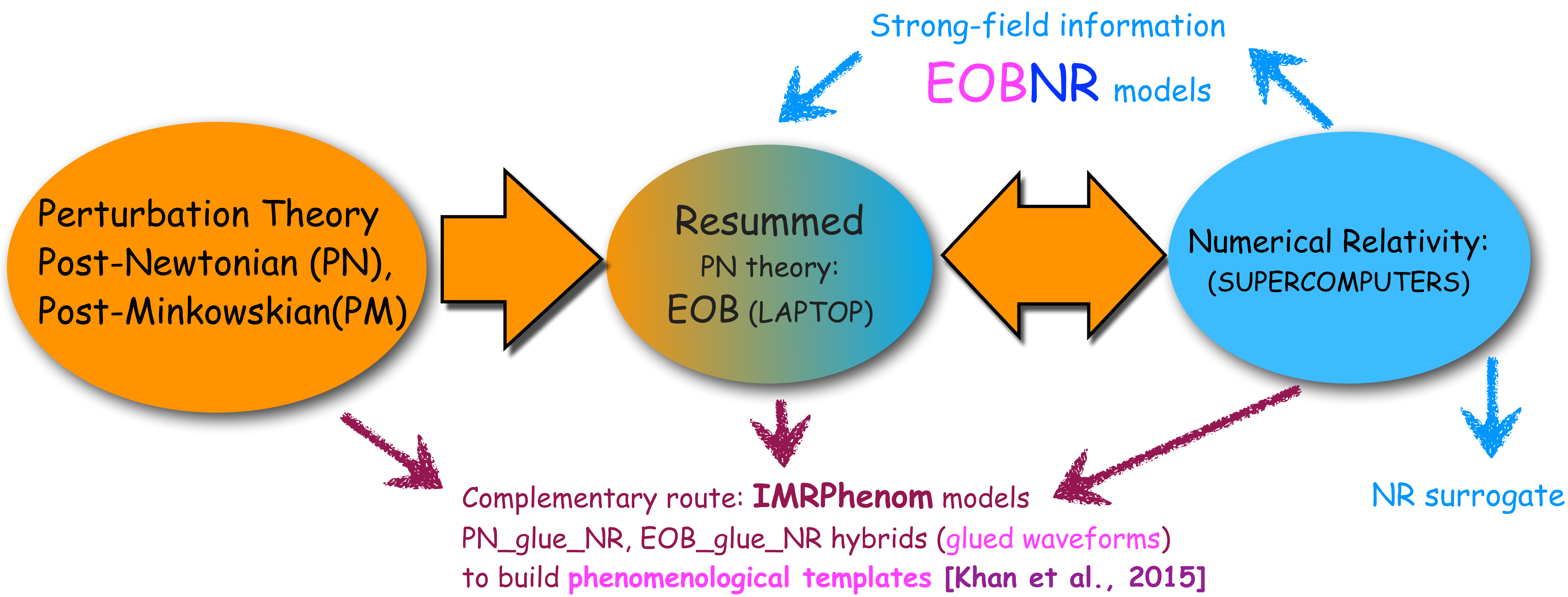
# 2-body problem in GR

Hamiltonian: conservative part of the dynamics

Radiation reaction: mechanical energy/angular momentum goes away in GWs and backreacts on the system.

The (closed) orbit CIRCULARIZES and SHRiNks with time

## Waveform



# Analytical Effective-One-Body approach

Provides a complete description of dynamics and radiation from relativistic binaries

(Buonanno-Damour 99, 00, Damour-Jaranowski-Schäfer 00, Damour 01, Damour-Nagar 07, Damour-Iyer-Nagar 08)

key ideas:

**(1)** Replace two-body dynamics $(m_1, m_2)$ by dynamics of a particle $(\mu \equiv m_1 m_2/(m_1 + m_2))$ in an effective metric $g^{\text{eff}}_{\mu\nu}(u)$, with

$$u \equiv GM/c^2 R, \quad M \equiv m_1 + m_2$$

**(2)** Systematically use RESUMMATION of PN expressions (both $g^{\text{eff}}_{\mu\nu}$ and $\mathcal{F}_{RR}$) based on various physical requirements

**(3)** Require continuous deformation w.r.t. $\nu \equiv \mu/M \equiv m_1 m_2/(m_1 + m_2)^2$ in the interval $0 \leq \nu \leq \frac{1}{4}$

$$A^{\text{Taylor}}_{\text{5PN}} = 1 - 2u + 2\nu u^3 + \left(\frac{94}{3} - \frac{41}{32}\pi^2\right)\nu u^4 + \nu[a^c_5(\nu) + a^{\ln}_5 \ln u]u^5 + \nu[a^c_6(\nu) + a^{\ln}_6 \ln u]u^6$$

1PN 2PN 3PN 4PN 5PN

# TEOBResumS: ringdown from NR

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

1. Factorize the fundamental QNM, fit what remains
2. Global fit all over parameter space
3. Del Pozzo & AN, PRD 95 (2017) 124034

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

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

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

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

$$c_2^A = \frac{1}{2}\alpha_{21},$$

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

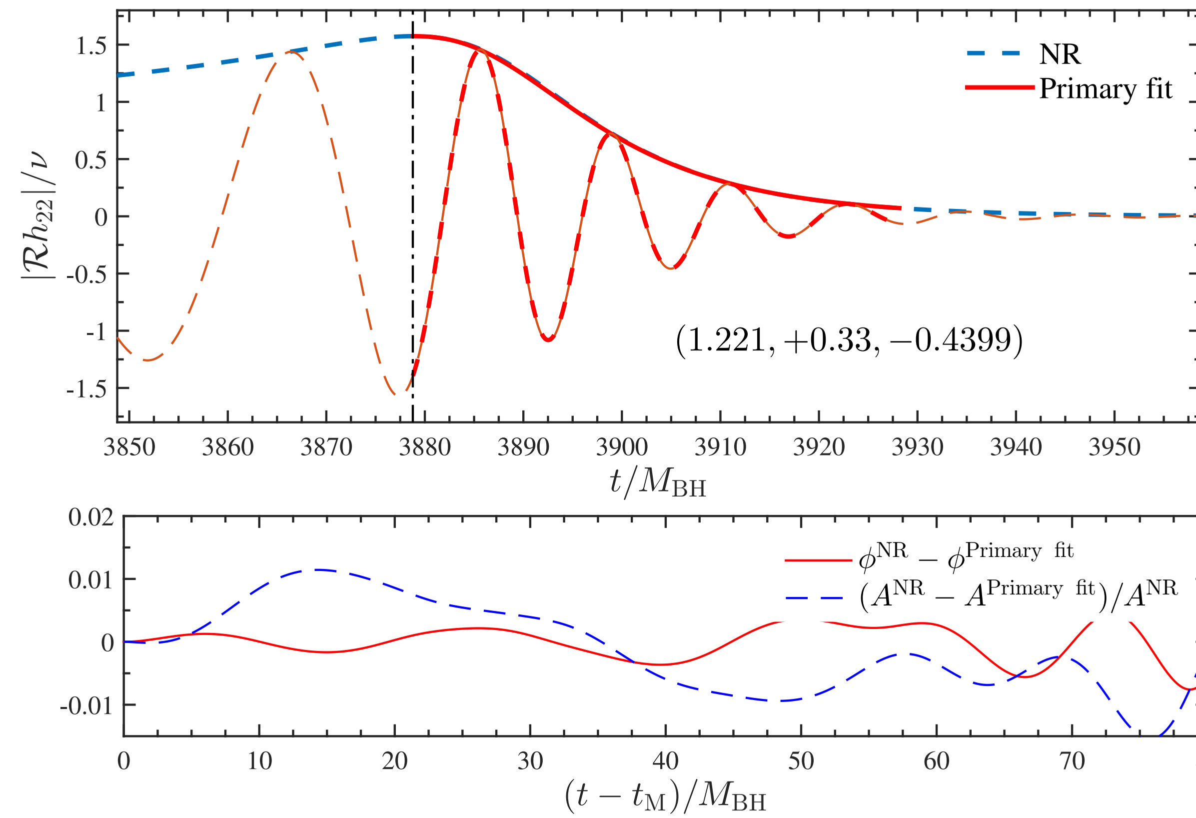
$$c_1^A = \hat{A}_{22}^{\rm mrg}\,\alpha_1 \frac{\cosh^2(c_3^A)}{c_2^A},$$

$$c_1^\phi = \Delta\omega \frac{1 + c_3^\phi + c_4^\phi}{c_2^\phi(c_3^\phi + 2c_4^\phi)},$$

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

$$\alpha_{21} = \alpha_2 - \alpha_1$$

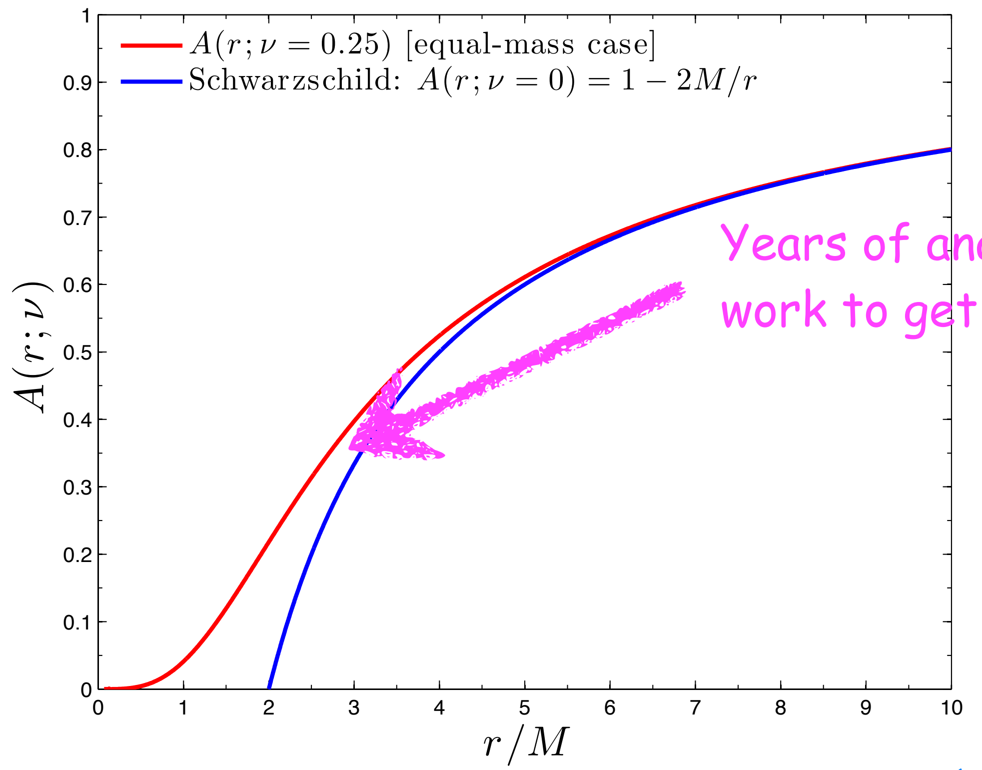
$$\Delta\omega \equiv \omega_1 - M_{\rm BH}\omega_{22}^{\rm mrg}$$




- Extended to several modes
- (2,2); (2,1); (3,3); (3,2); (4,4); (4,3); (5,5)
- Usable as stand-alone ringdown template
- Specific fits for peak quantities
- NO mode-mixing (for the moment…)

See poster
of G. Riemenschneider

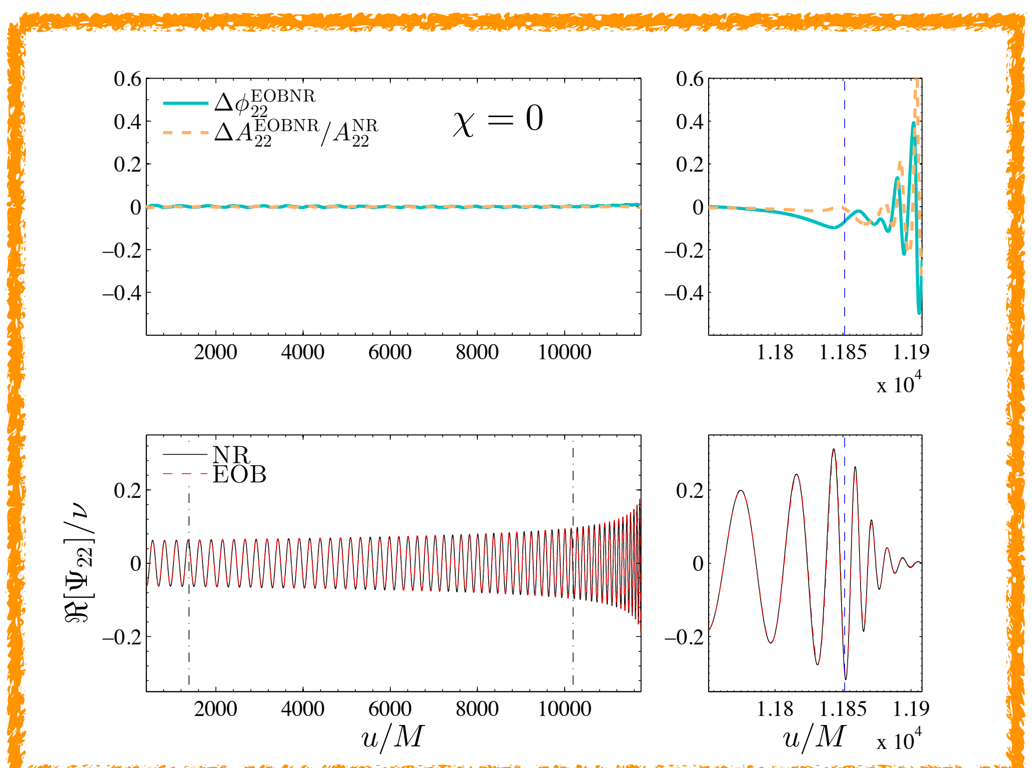
# TEOBResumS point-mass potential

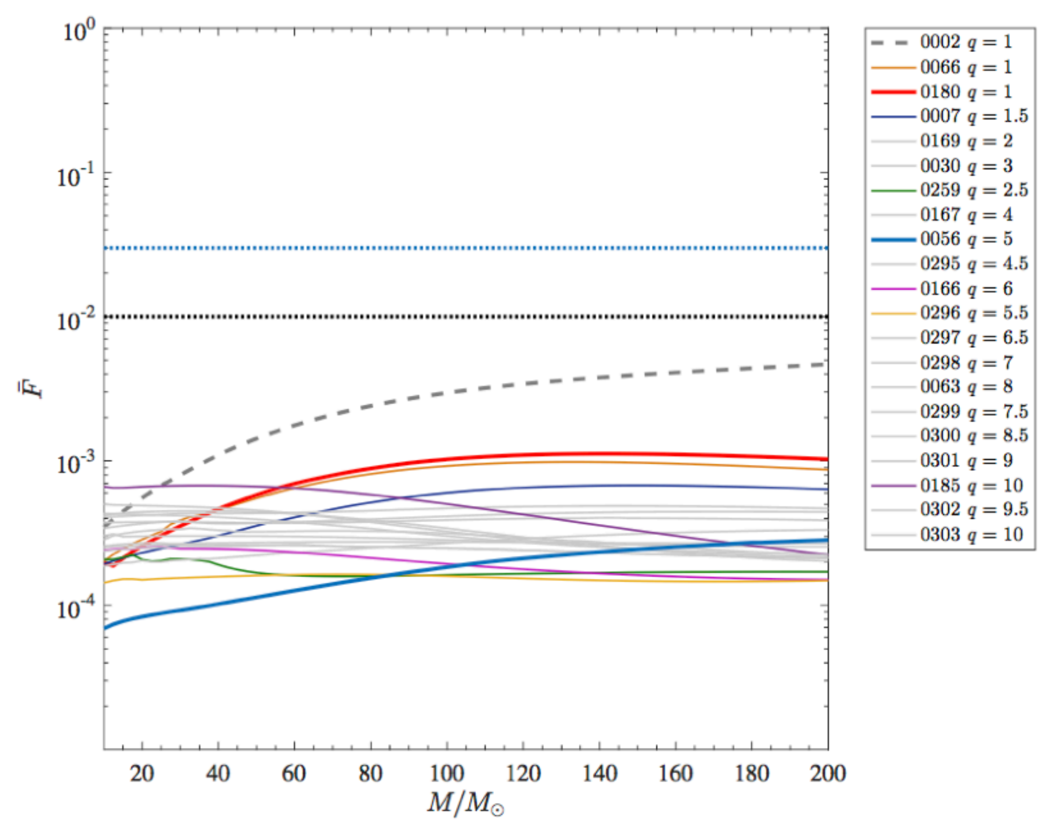



Years of analytical and numerical work to get this strong-field difference!

$$A(u;\nu,a_6^c) = P_5^1[A_{5\mathrm{PN}}^{\mathrm{Taylor}}(u;\nu,a_6^c)]$$

From EOB/NR-fitting: $a_6^c(\nu) = 3097.3\nu^2 - 1330.6\nu + 81.3804$




Nagar, Riemenschneider, Pratten 2017

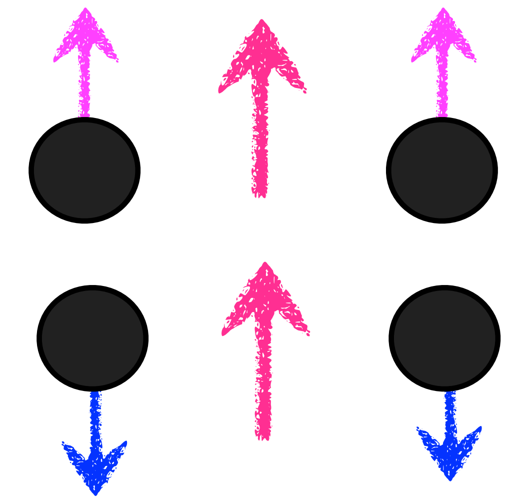
# Spinning BBHs

## Spin-orbit & spin-spin couplings

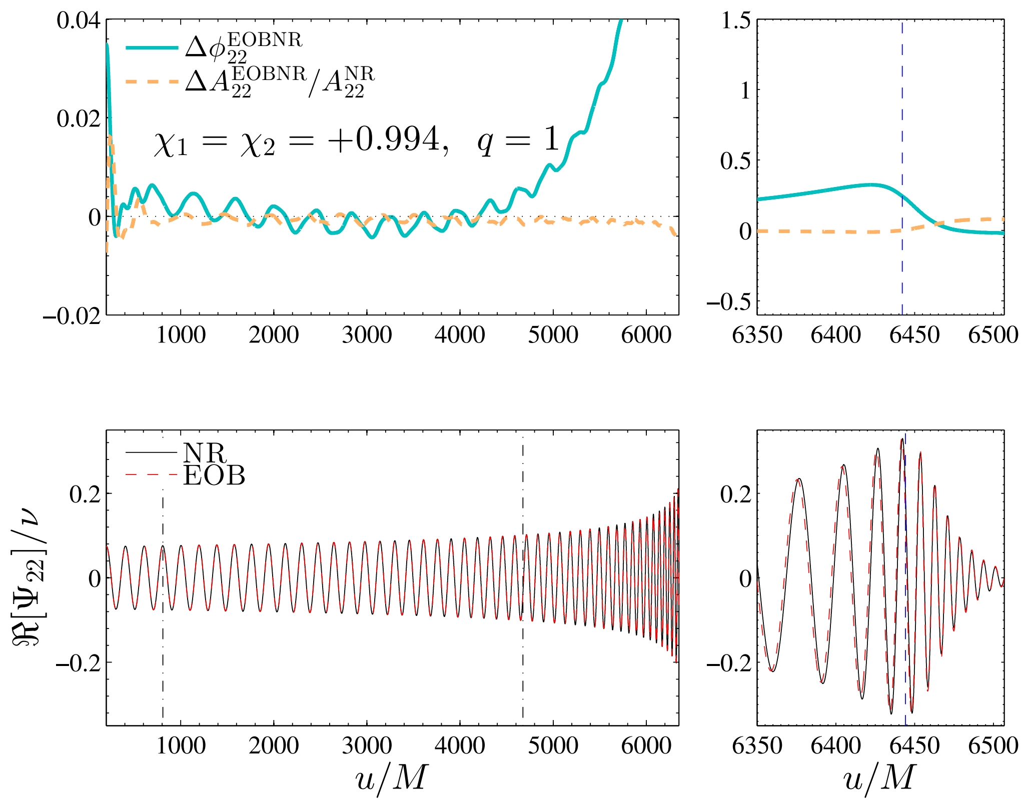
(i) Spins aligned with L: repulsive (slower) L-o-n-g-e-r INSPIRAL

(ii) Spins anti-aligned with L: attractive (faster) Shorter INSPIRAL

(iii) Misaligned spins: precession of the orbital plane (waveform modulation)



$$\chi_{1,2} = \frac{c\,\mathbf{S}_{1,2}}{G m_{1,2}^2}$$




EOB/NR agreement: sophisticated (though rather simple) model for spin-aligned binaries

Damour&AN, PRD90 (2014), 024054 (Hamiltonian)

Damour&AN, PRD90 (2014), 044018 (Ringdown)

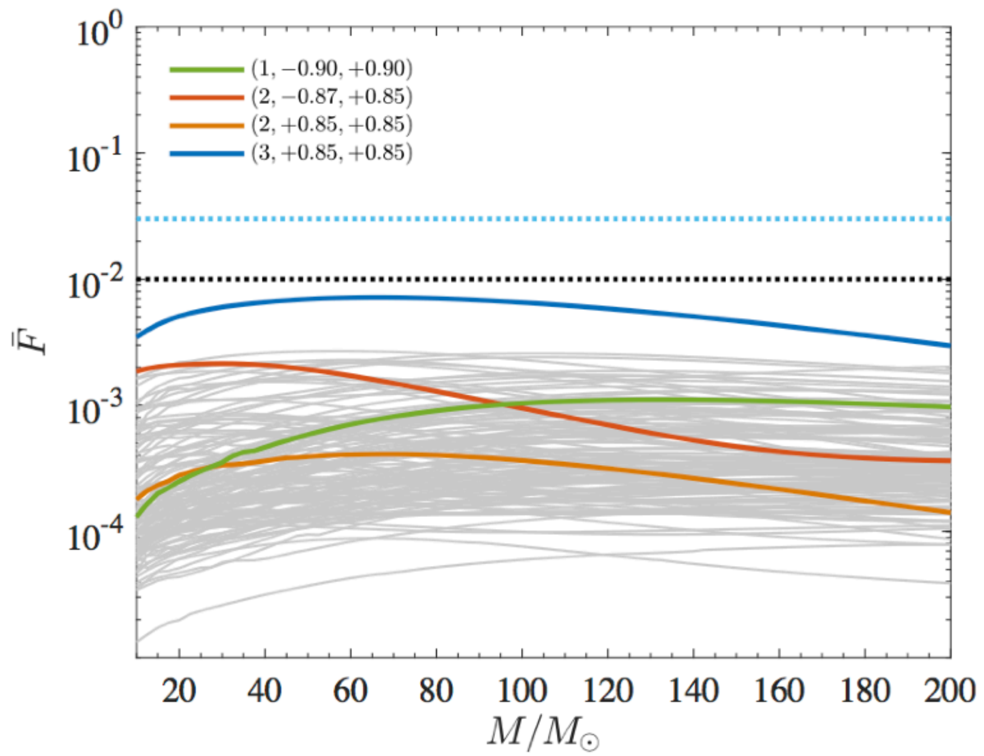
AN,Damour, Reisswig & Pollney, PRD 93 (2016), 044046

AN, Riemenschneider & Platten, PRD2017

AN, Bernuzzi, Del Pozzo et al., PRD98.104052

$$\hat{H}_{\rm eff} = \frac{g_S^{\rm eff}}{r^3}\mathbf{L}\cdot\mathbf{S} + \frac{g_{S^*}^{\rm eff}}{r^3}\mathbf{L}\cdot\mathbf{S}^* + \sqrt{A(1+\gamma^{ij}p_i p_j + Q_4(p))}$$

# TEOBResumS: spin-aligned BBH




- spin-orbit parameter informed by 30 BBH NR simulations
- BEST faithfulness with all NR available (200 simulations)
- Robust and simple
- Tides and spin-induced moment included (BNS)
- ONLY publicly available stand-alone EOB code

$$\bar{F}(M) \equiv 1 - F = 1 - \max_{t_0,\phi_0} \frac{\langle h_{22}^{\rm EOB}, h_{22}^{\rm NR}\rangle}{||h_{22}^{\rm EOB}||\,||h_{22}^{\rm NR}||},$$

Nagar, Bernuzzi, Del Pozzo et al., PRD98.104052

effective NNNLO spin-orbit "function"

$$c_3(\tilde{a}_A, \tilde{a}_B, \nu) = p_0 \frac{1 + n_1 \hat{a}_0 + n_2 \hat{a}_0^2}{1 + d_1 \hat{a}_0} + \left(p_1 \nu + p_2 \nu^2 + p_3 \nu^3\right) \hat{a}_0 \sqrt{1 - 4\nu} + p_4 \left(\tilde{a}_A - \tilde{a}_B\right) \nu^2, \quad (17)$$

$$\tilde{a}_{1,2} = X_{1,2} \chi_{1,2}$$

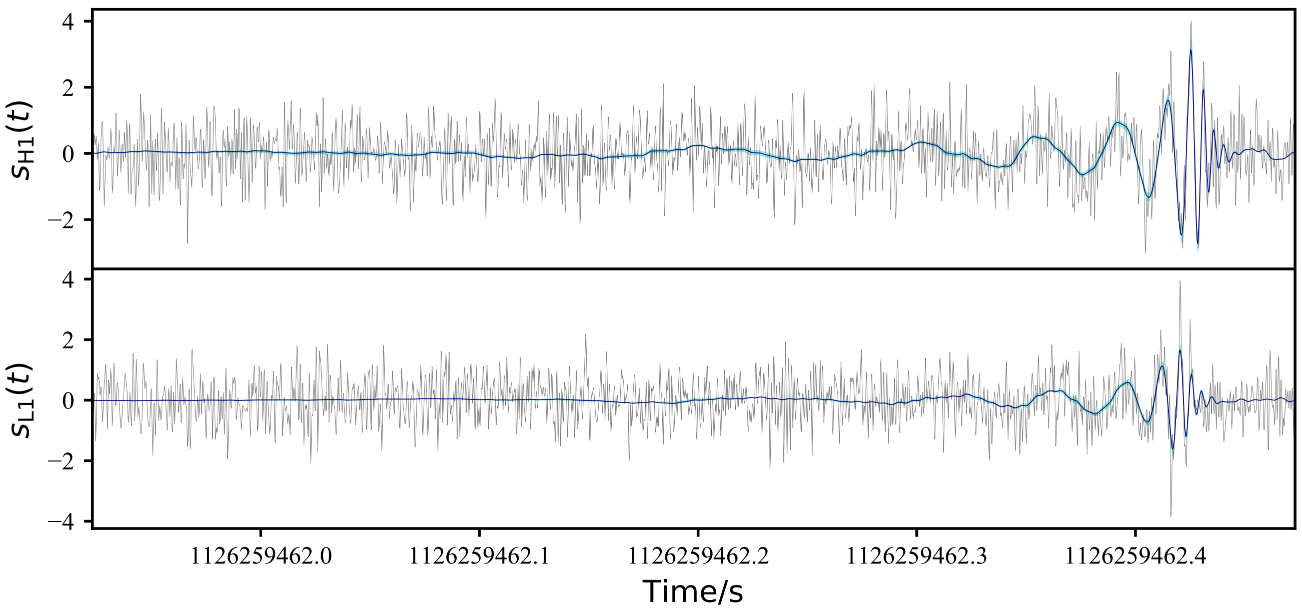
$$X_{1,2} \equiv \frac{m_{1,2}}{M}$$

$$\hat{a}_0 \equiv \frac{S + S_*}{M^2} = X_A \chi_A + X_B \chi_B = \tilde{a}_A + \tilde{a}_B$$

ONLY 2 EOBNR models
TEOBResumS
SEOBNRv4 (AEI)

Hamiltonian comparison:
see poster of F. Martinetti

# TEOBResumS on GW150914



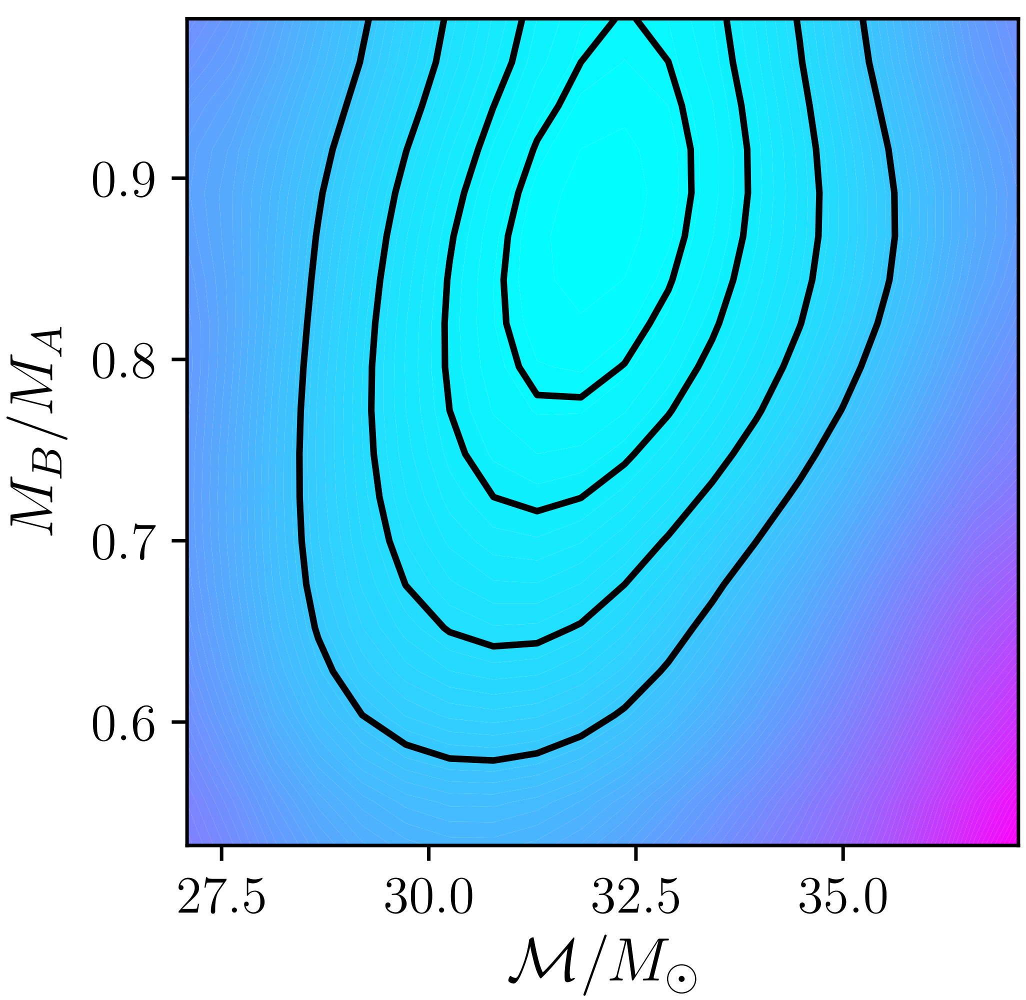
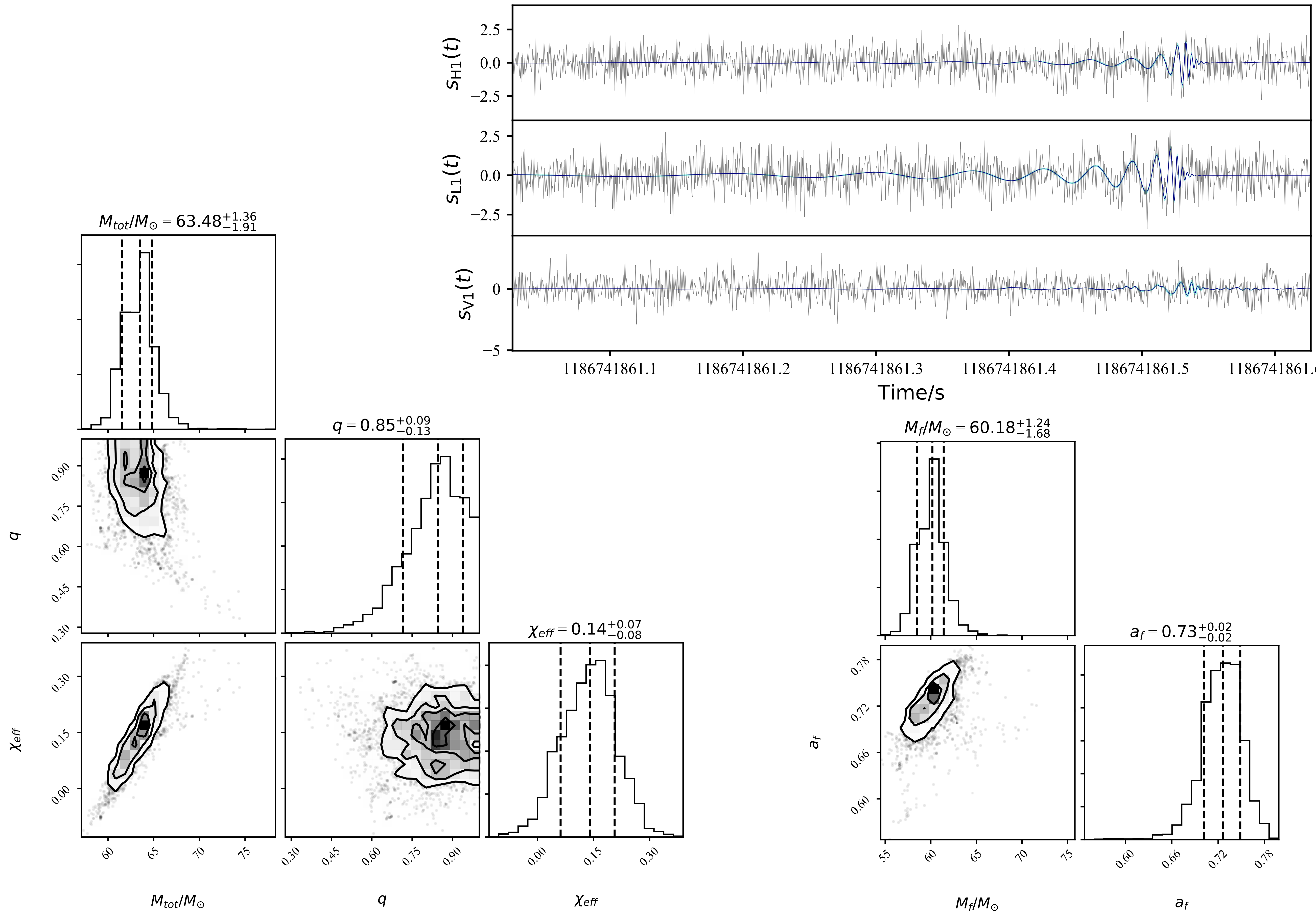




TABLE IV. Summary of the parameters that characterize GW150914 as found by **cpnest** and using **TEOBResumS** as template waveform, compared with the values found by the LVC collaboration [135]. We report the median value as well as the 90% credible interval. For the magnitude of the dimensionless spins $|\chi_A|$ and $|\chi_B|$ we also report the 90% upper bound. Note that we use the notation $\chi_{\rm eff} \equiv \hat{a}_0$ for the effective spin, as introduced in Eq. (8).

| | TEOBResumS | LVC |
|---|---|---|
| Detector-frame total mass $M/M_\odot$ | $73.6^{+5.7}_{-5.2}$ | $70.6^{+4.6}_{-4.5}$ |
| Detector-frame chirp mass $\mathcal{M}/M_\odot$ | $31.8^{+2.6}_{-2.4}$ | $30.4^{+2.1}_{-1.9}$ |
| Detector-frame remnant mass $M_f/M_\odot$ | $70.0^{+5.0}_{-4.6}$ | $67.4^{+4.1}_{-4.0}$ |
| Magnitude of remnant spin $\hat{a}_f$ | $0.71^{+0.05}_{-0.07}$ | $0.67^{+0.05}_{-0.07}$ |
| Detector-frame primary mass $M_A/M_\odot$ | $40.2^{+5.1}_{-3.7}$ | $38.9^{+5.6}_{-4.3}$ |
| Detector-frame secondary mass $M_B/M_\odot$ | $33.5^{+4.0}_{-5.5}$ | $31.6^{+4.2}_{-4.7}$ |
| Mass ratio $M_B/M_A$ | $0.8^{+0.1}_{-0.2}$ | $0.82^{+0.20}_{-0.17}$ |
| Orbital component of primary spin $\chi_A$ | $0.2^{+0.6}_{-0.8}$ | $0.32^{+0.49}_{-0.29}$ |
| Orbital component of secondary spin $\chi_B$ | $0.0^{+0.9}_{-0.8}$ | $0.44^{+0.50}_{-0.40}$ |
| Effective aligned spin $\chi_{\rm eff}$ | $0.1^{+0.1}_{-0.2}$ | $-0.07^{+0.16}_{-0.17}$ |
| Magnitude of primary spin $\|\chi_A\|$ | $\leq 0.7$ | $\leq 0.69$ |
| Magnitude of secondary spin $\|\chi_B\|$ | $\leq 0.9$ | $\leq 0.89$ |
| Luminosity distance $d_{\rm L}/{\rm Mpc}$ | $479^{+188}_{-235}$ | $410^{+160}_{-180}$ |

Nagar, Bernuzzi, Del Pozzo et al., PRD98.104052

# GW170814

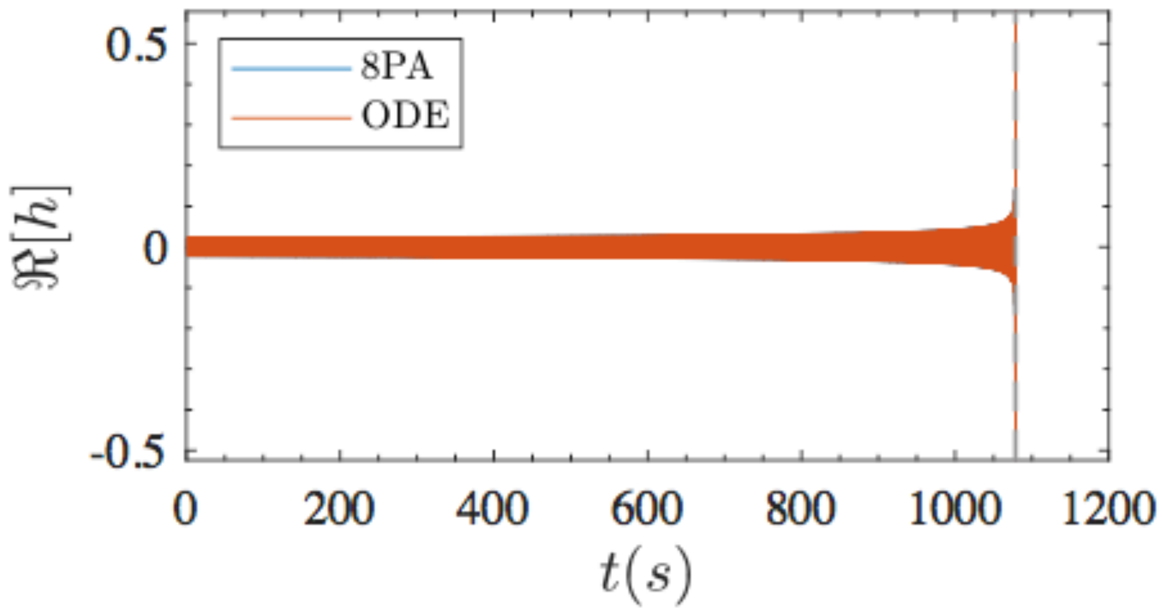


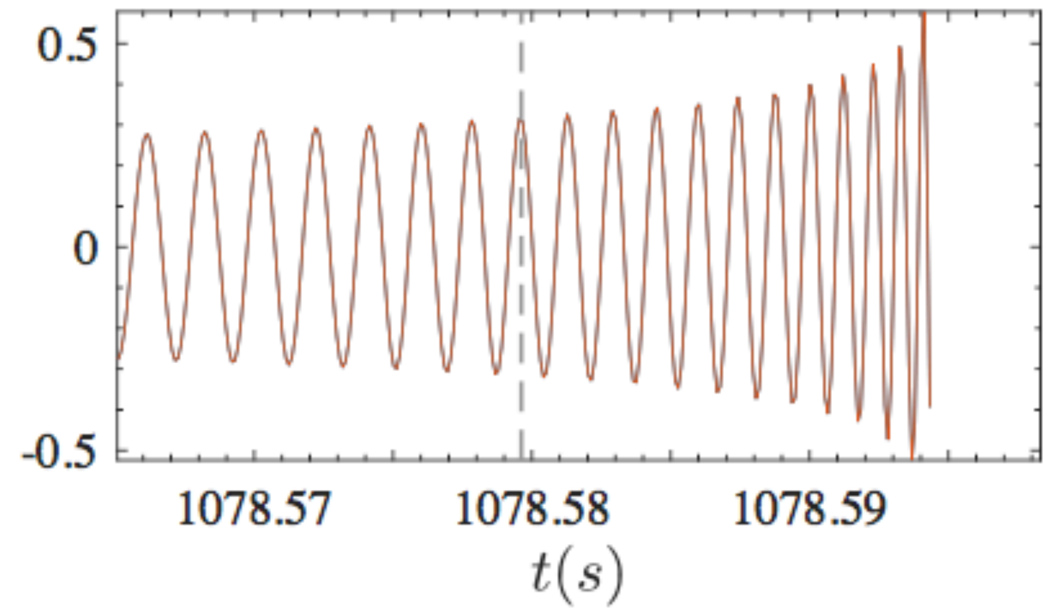
$s_{H1}(t)$
$s_{L1}(t)$
$s_{V1}(t)$
Time/s
1186741861.1
1186741861.2
1186741861.3
1186741861.4
1186741861.5
1186741861.6
$M_{tot}/M_\odot = 63.48^{+1.36}_{-1.91}$
$q = 0.85^{+0.09}_{-0.13}$
$\chi_{eff} = 0.14^{+0.07}_{-0.08}$
$M_f/M_\odot = 60.18^{+1.24}_{-1.68}$
$a_f = 0.73^{+0.02}_{-0.02}$
$M_{tot}/M_\odot$
$q$
$\chi_{eff}$
$M_f/M_\odot$
$a_f$

# Neutron stars: tides & spin

**TEOBResumS today** [AN+, PRD98, 2018,104052]

- tidal effects + nonlinear-in-spin-effects *($S^2$, $S^3$,$S^4$,…)* [AN+, PRD99, 2019,044007]
- analytically very complete model (almost final)
- l=3 GSF-informed + gravitomagnetic tides [Akcay+, PRD, 2019, in press]
- checked with (state-of-the-art but short) NR simulations up to merger
- EFFICIENT due to the post-adiabatic approximation [AN & Rettegno PRD99, 2019 021501]
- no precession (yet!)



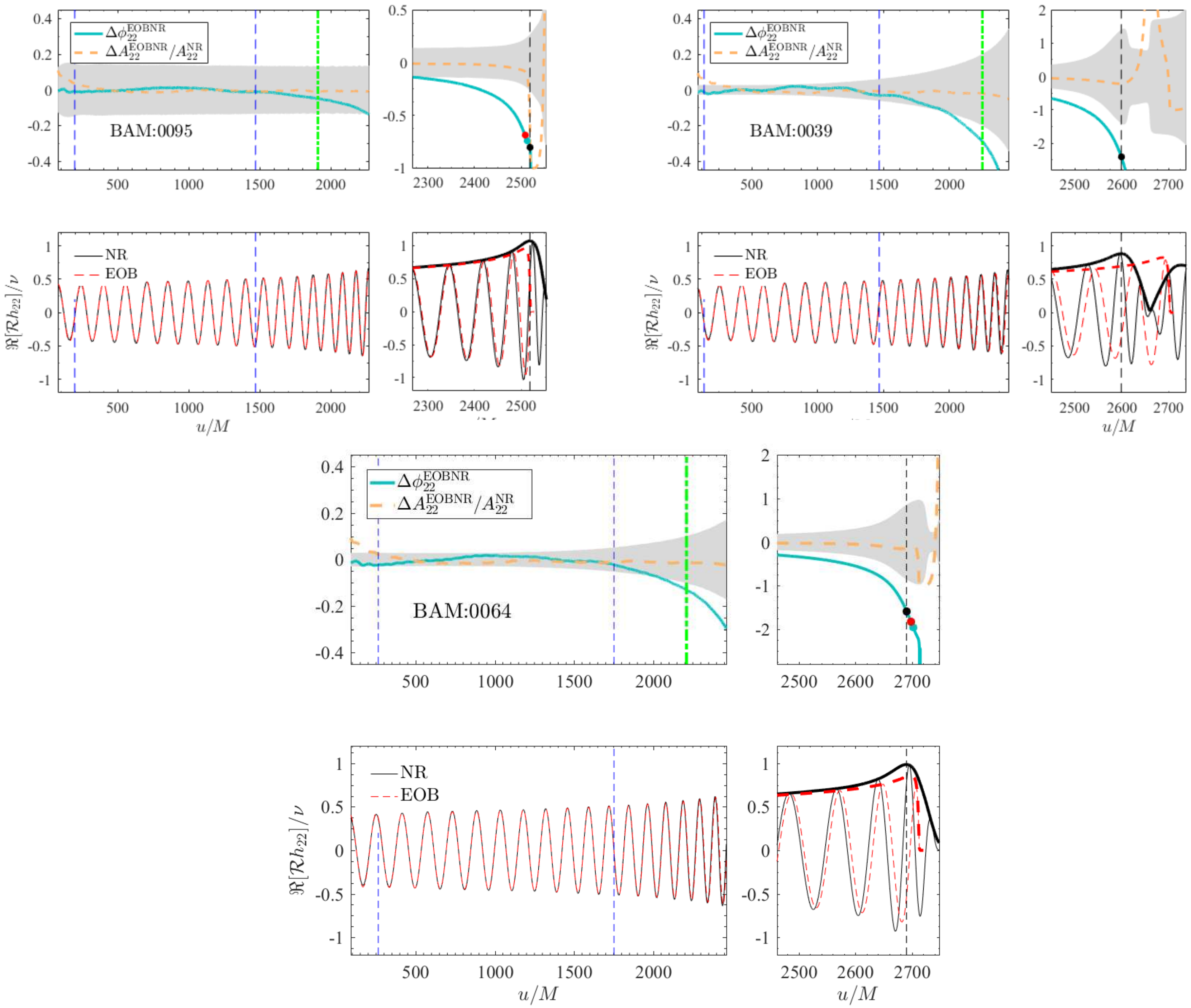

| $f_0$ [Hz] | $r_0$ | $r_{\rm min}$ | $N_r$ | $\Delta r$ | $\tau_{\rm 8PA}$ [sec] | $\tau_{\rm ODE}$ [sec] |
|---|---|---|---|---|---|---|
| 20 | 112.81 | 12 | 500 | 0.20 | 0.03 | 0.53 |
| 10 | 179.02 | 12 | 830 | 0.20 | 0.05 | 1.1 |

No real need of EOB-surrogate!

see poster of P. Rettegno

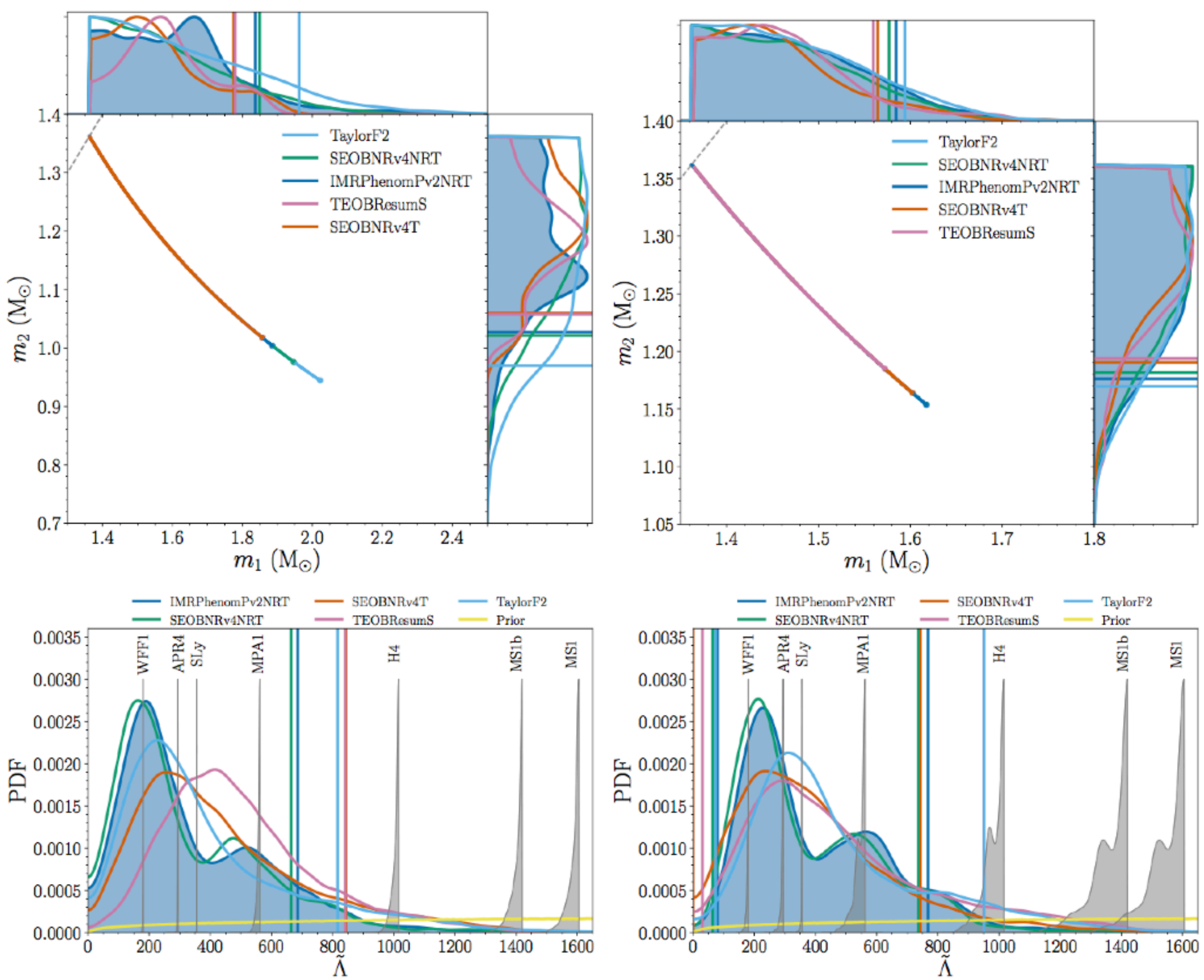
# TEOBResumS vs NR: BNS

| name | EOS | $M_{A,B}[M_\odot]$ | $C_{A,B}$ | $k_2^{A,B}$ | $\kappa_2^T$ | $\Lambda_2^{A,B}$ | $\chi_{A,B}$ | $C_{QA,QB}$ |
|---|---|---|---|---|---|---|---|---|
| BAM:0095 | SLy | 1.35 | 0.17 | 0.093 | 73.51 | 392 | 0.0 | 5.491 |
| BAM:0039 | H4 | 1.37 | 0.149 | 0.114 | 191.34 | 1020.5 | 0.141 | 7.396 |
| BAM:0064 | MS1b | 1.35 | 0.142 | 0.134 | 289.67 | 1545 | 0.0 | 8.396 |



# GW170817- Parameter Estimation (LVC)

- Only existing EOB model independent from existing waveform models in LIGO/Virgo
- PE of the binary neutron star GW170817: arXiv:1811.12907 (GWTC-1)




$$\tilde{\Lambda} = \frac{16}{13}\frac{(m_1 + 12m_2)m_1^4\Lambda_1 + (m_2 + 12m_1)m_2^4\Lambda_2}{M^5}.$$

Masses

Tidal polarizability (EOS)

see also poster of R. Gamba
on the impact of crust modelization
arXiv:1902.04616

# Tides (for GW170817)

TEOBResumS: GSF-improved tides
SEOBNRv4T: “dynamical” tides (f-mode coupling)[Hinderer+,2016]
Spin-orbit & self-spin effects (EOS-dependent)

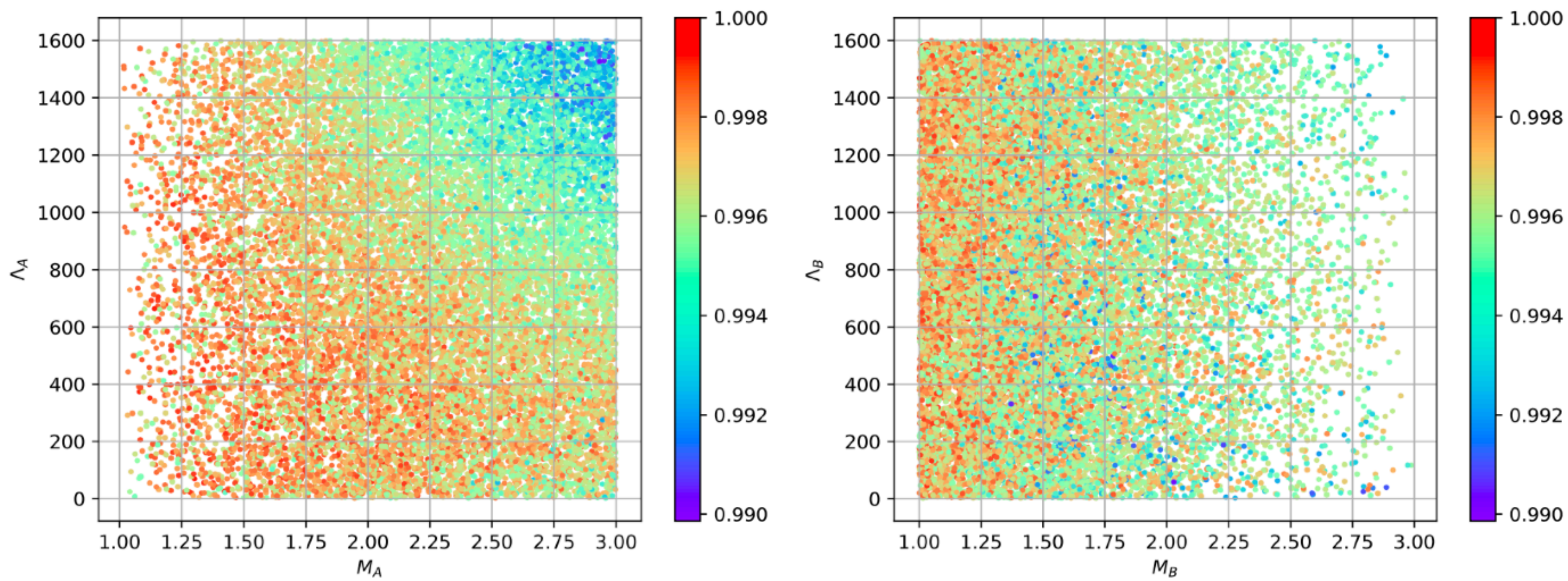
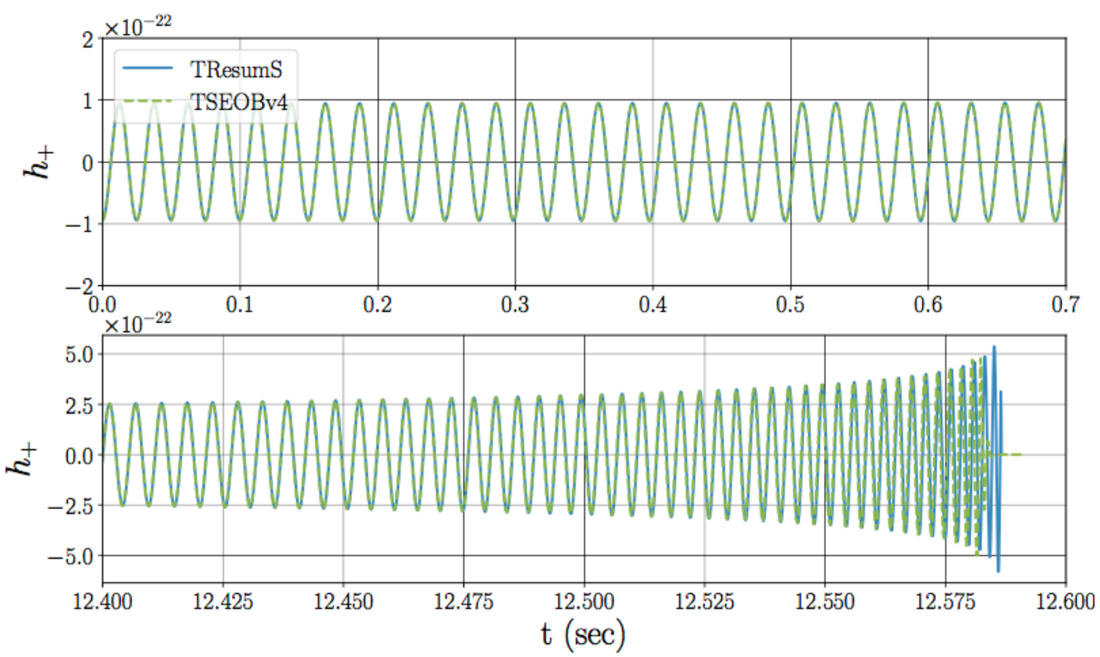



FIG. 19. The match computed between **SEOBNRv4T** and **TEOBResumS**. The match values are color-coded. Based on 17300 randomly chosen points. The plot highlights the high compatibility between the two models.




Excellent compatibility between the two models

# Higher modes

Improved resummation of waveform amplitudes [Messina+ 2018]

NR completion merger-bringdown: (2,2), (3,3),(3,2),(4,4),(4,3),(5,5)

## Nonspinning+(3,1),(4,2),(4,1)

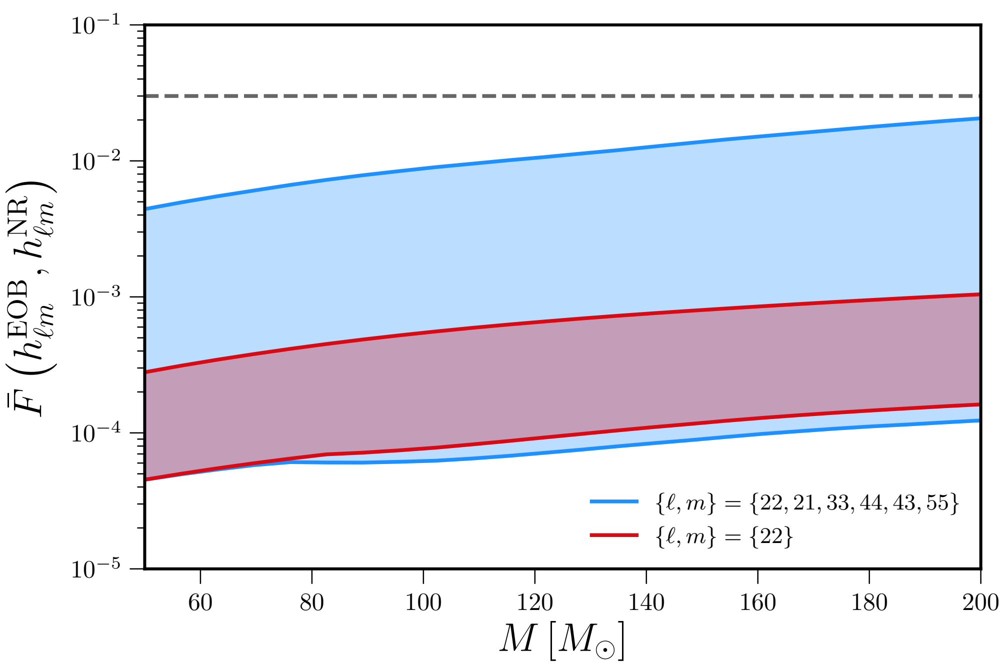
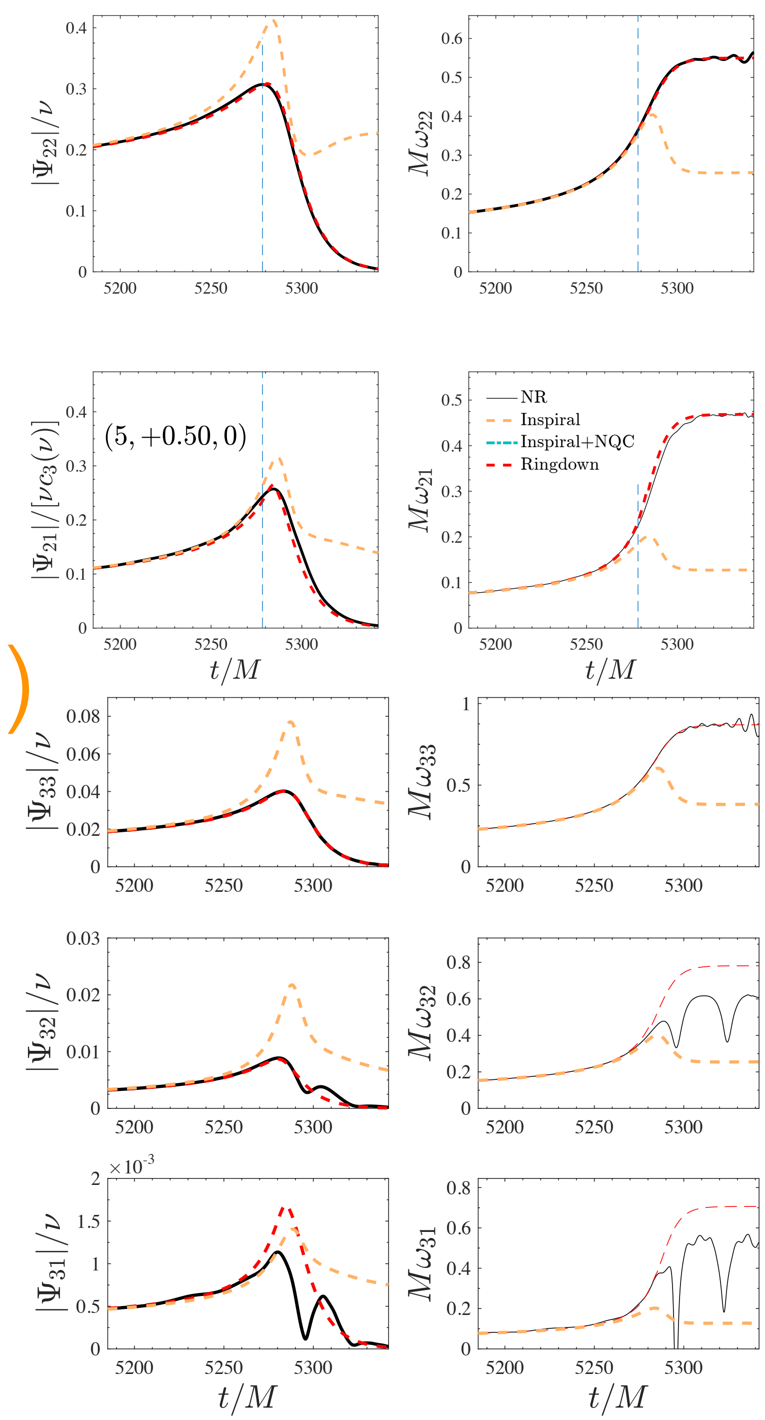



FIG. 10. Unfaithfulness between `TEOBiResumMultipoles` and SXS simulations between mass ratios $q \in \{1, 10\}$ using the zero-detuned high power Advanced LIGO design sensitivity PSD. We show the minimum and maximum unfaithfulness over all angles $(\theta, \varphi)$, demonstrating that the worst case performance is always below 3% for binaries with a total mass $M < 200 M_\odot$.

## Spin (in progress)



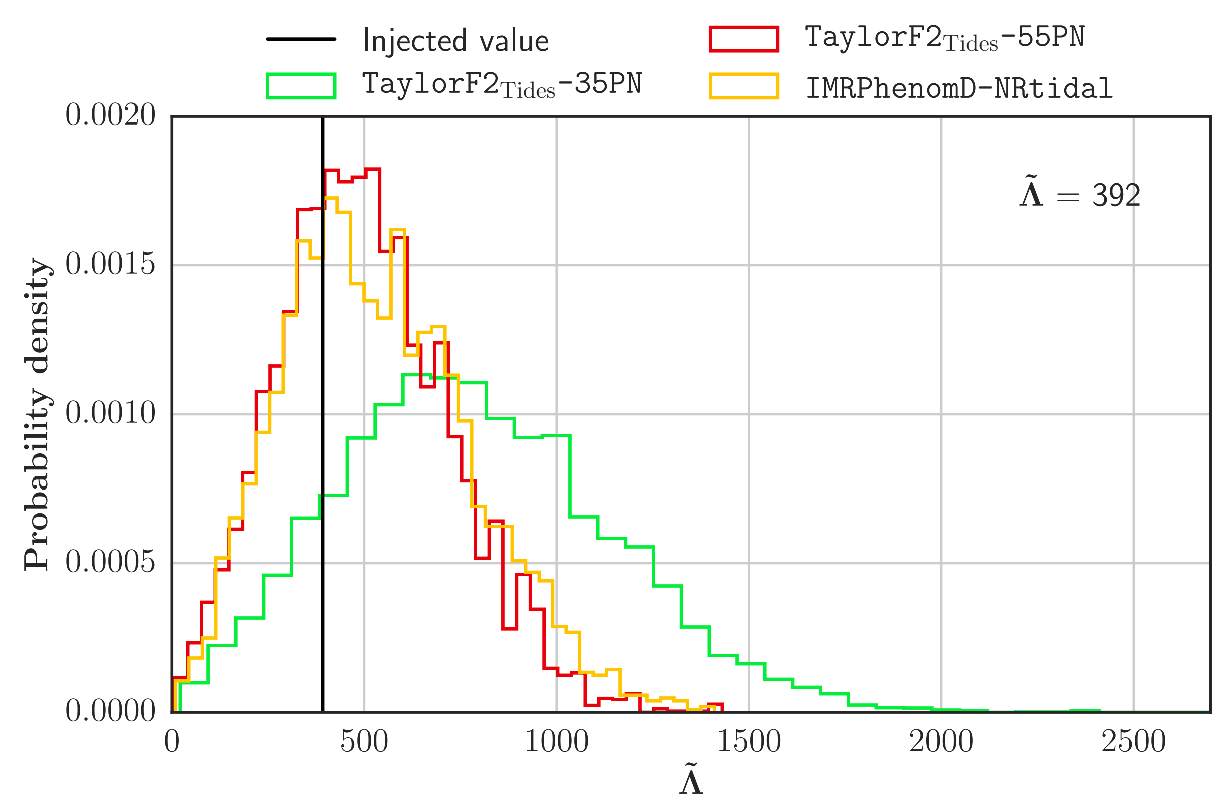

see posters of F. Messina-G. Riemenschneider

# Use of TEOBResumS

- Use as a benchmark for testing the accuracy of phenomenological tidal models, e.g IMRPhenomP_NRTidal [Dietrich et al. 2018]

- Used to test high-PN (5.5PN) approximants and to identify biases in tidal parameters due to the inaccurate point-mass baseline.
  [Dudi,Messina, Nagar & Bernuzzi in prep.]

see poster of F. Messina



# Conclusions

## What exists

- C version stand-alone: complete and working. Dimensionless units. Including both the PA implementation and the NQC iteration.

- BBH (merger+ringdown), BNS & BHNS (up to merger)

git clone https://alex_nagar@bitbucket.org/eob_ihes/teobresums.git

## What is in progress/to be released

- BBH sector: Higher modes: (2,1),(3,3),(3,2),(4,4),(4,3),(5,5): completed with NR-informed peak and postpeak part. The others are “bare” (but still have a peak). Even more modes available for the non spinning case, e.g. (3,1), (4,1), (4,2).

- BNS sector: improved with more EOS-dependent information and higher modes available. l=3 GSF-resummed tidal potential; included up to NNLO self-spin effects. Not negligible also for small spins. Current approximates underestimate these effects. EOB-controlled PN approximant to improve current PhenomPv2NRTidal model [AN+, PRD99, 2019,044007]

- LAL (LVC) version of the model in progress and will be released soon.