GDR “ONDES GRAVITATIONNELLES”
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A NEW PHENOMENOLOGICAL TIME-DOMAIN MODEL OF GRAVITATIONAL WAVEFORMS FOR TESTS OF GENERAL RELATIVITY IN LIGO/VIRGO

AGNOSTIC TESTS OF GENERAL RELATIVITY WITH LIGO-VIRGO BLACK HOLES

- **Current tests** are checking:
  - is the signal consistent with GR ?
  - are "ad-hoc" GR deviations compatible with the signal ?

arXiv:1903.04467

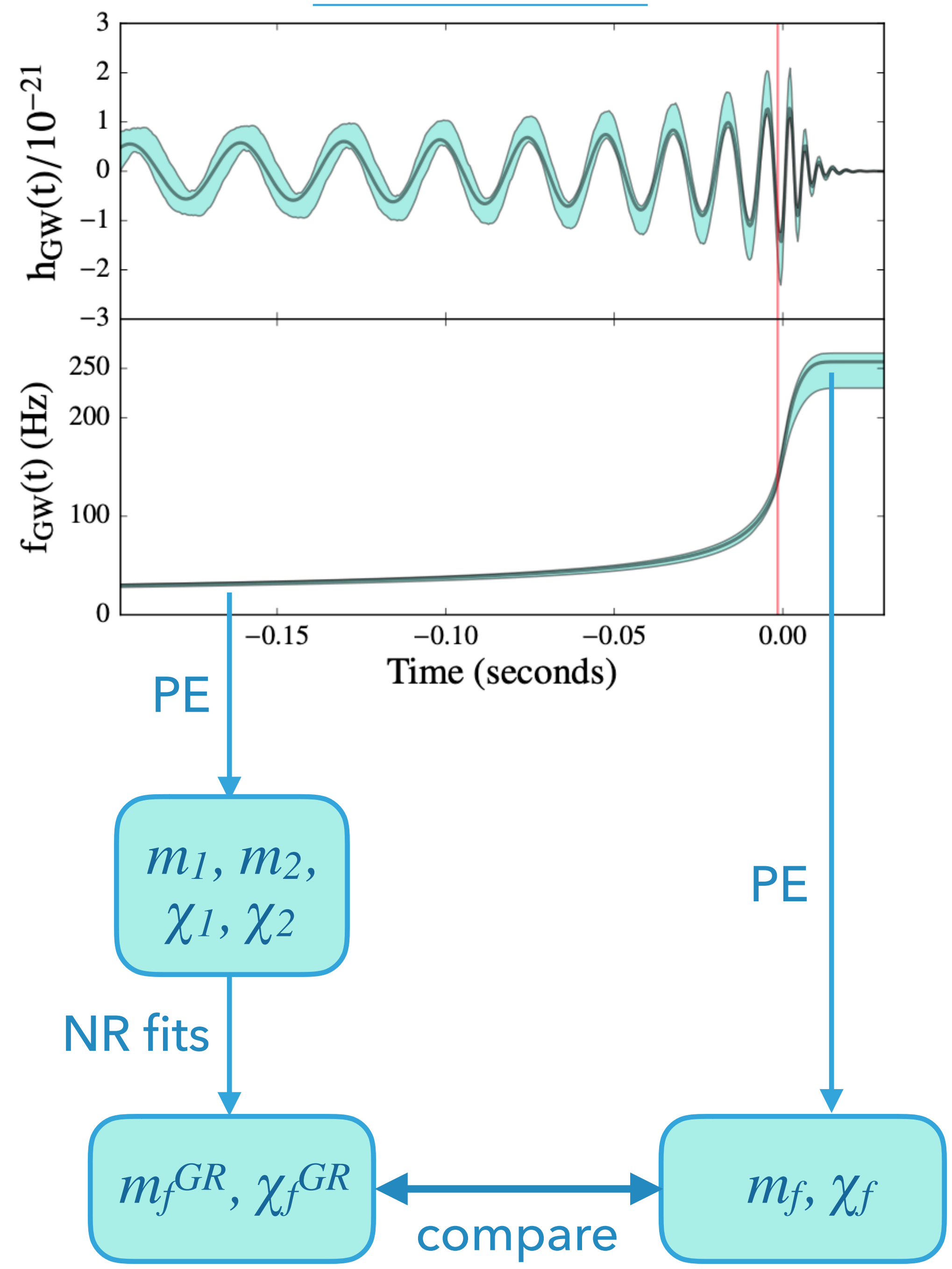
- Based on **2 models** of gravitational waveforms:
  - IMRPhenomP: phenomenological model, precession effects included, $q < 18$
  - SEOBNRv4: EOB calibrated to NR for merger, no precession, $1 < q <$ extreme mass ratio, used to check IMRPhenomP results

- **Models domains**:
  - IMRPhenomP: frequency domain from design
  - SEOBNRv4: designed in time domain but analysis uses the ROM version in the frequency domain

INSPIRAL / POST-INSPIRAL CONSISTENCY TESTS

- **Check consistency with GR** by:
  - cutting the GW signal at the inner stable circular orbit frequency f_{ISCO}
  - determining initial black holes parameters m_1, m_2, χ_1, χ_2 from inspiral signal
  - predicting remnant black hole parameters m_f^{GR}, χ_f^{GR} with fits to NR data
  - determining remnant black hole parameters m_f, χ_f from post-inspiral signal
  - Comparing m_f to m_f^{GR}, χ_f to χ_f^{GR}, to see if consistent

arXiv:1602.03841



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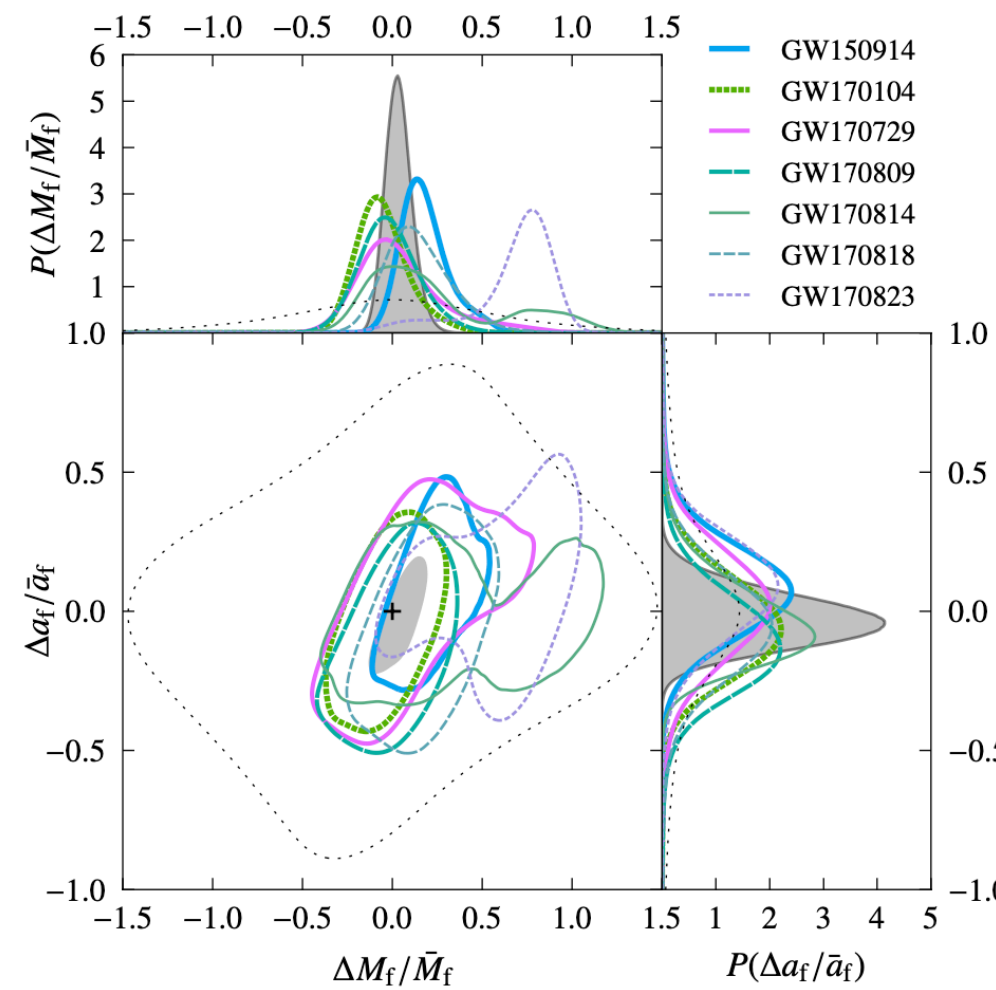
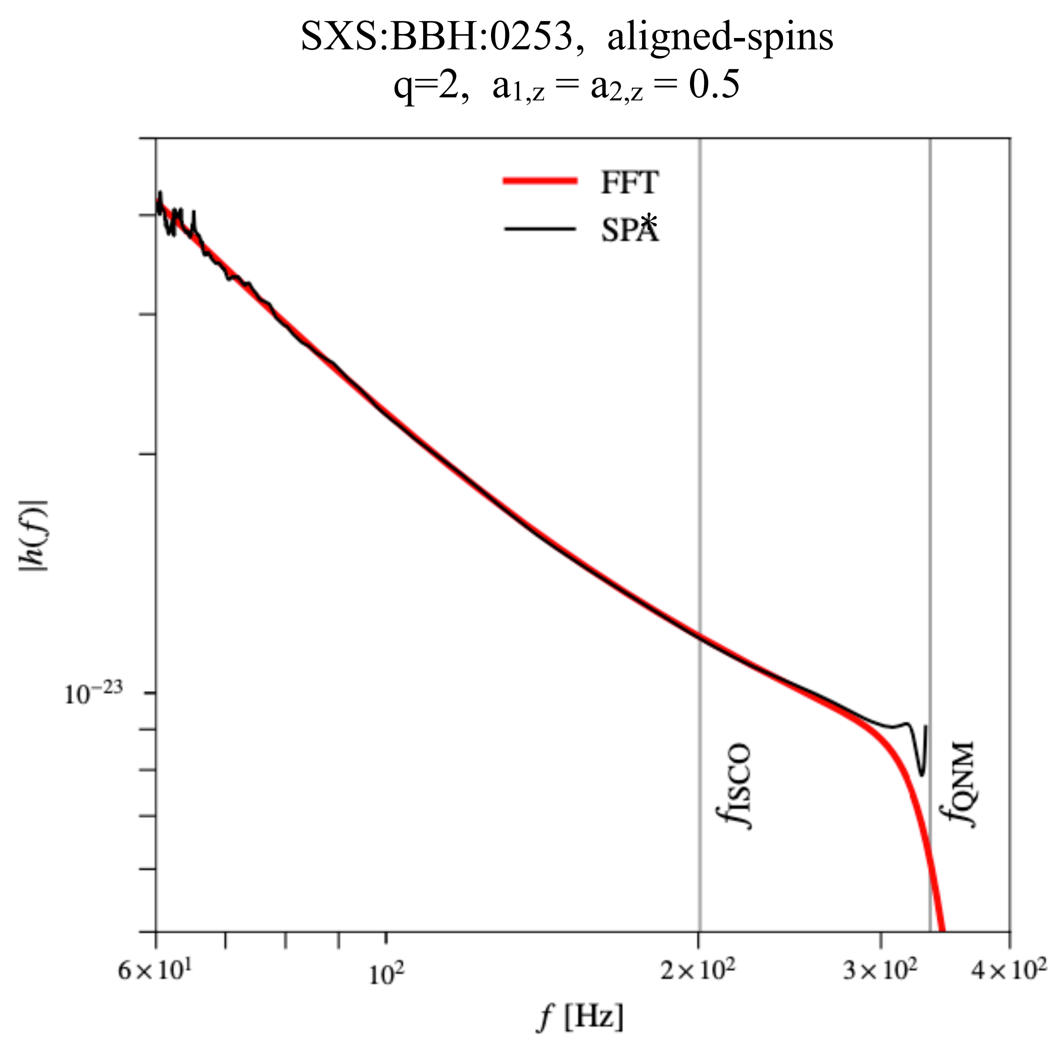


arXiv:1903.04467

INSPIRAL / POST-INSPIRAL CONSISTENCY TESTS

- **Spectral leakage ?**
  i.e. is doing the cut in the frequency domain making some power at later times "contaminating" the inspiral part ?
- **Non-precessing systems** with $f_{cut} = f_{ISCO}$:
  little-to-no leakage
- If **system strongly precessing**,
  and/or if desire to compare inspiral+merger with ringdown: might create some contamination
- In this case, the analysis should be performed in **the time domain**



arXiv:1704.06784

* Stationary Phase Approximation:
all the power at f comes from the time t_f

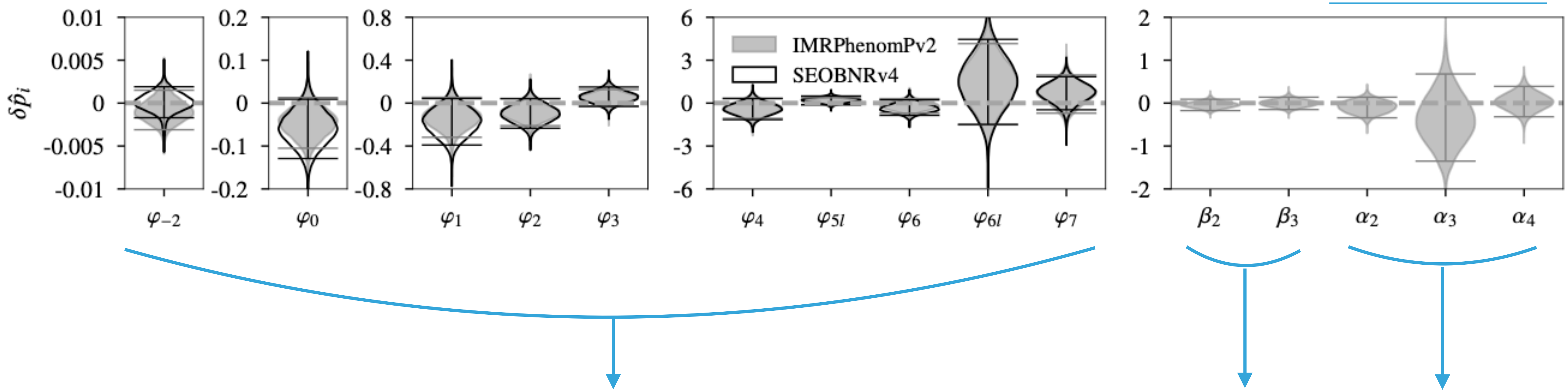
PARAMETERISED TESTS OF GW GENERATION

- **Look for modification of the black holes dynamics:**
  impact in the orbital phase $\Phi(f)$ of the gravitational waves
- **Phase evolution controlled by coefficients** in GW phenomenological models:
  - inspiral: post-Newtonian (up to 3.5 pN) + higher orders tuned to NR
  - post-inspiral : tuned to numerical relativity (NR) simulations
  → assume GR by design
- Add **free parameters encoding deviations** of the coefficients:
  - shift deviations: $\varphi_i(f) \longrightarrow (1+\delta\varphi_i)\ \varphi_i(f)$
  - IMRPhenomP: coefficients varied along all IMR waveform
  - SEOBNRv4: only pN varied (inspiral)
  - for pN, can be linked to specific alternative theories (but lots of degeneracies)

PARAMETERISED TESTS OF GW GENERATION

- **Combined results:**
  assume all black hole binaries undergo the same GR modification

arXiv:1903.04467



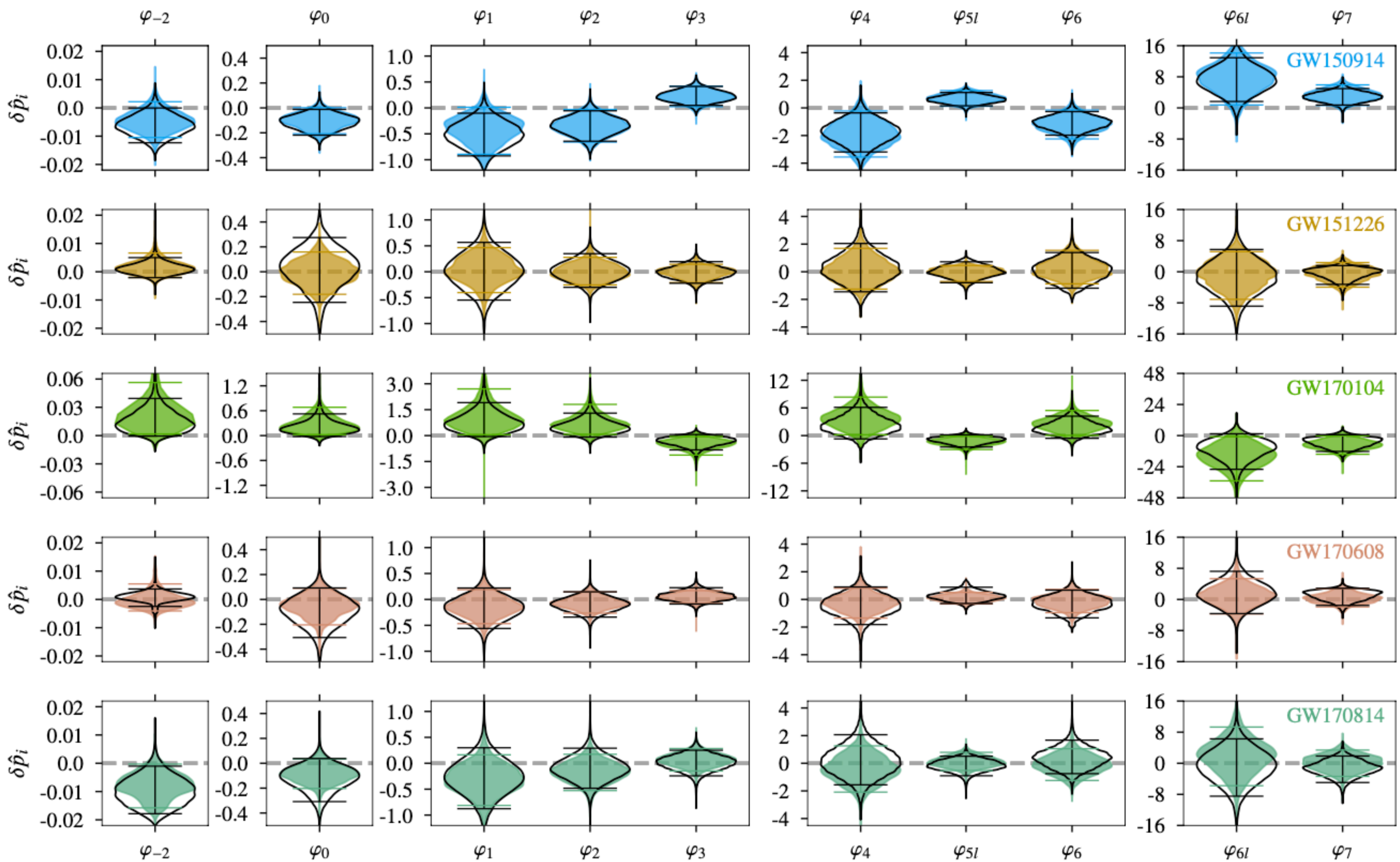
Inspiral

Intermediate

Merger-ringdown

PARAMETERISED TESTS OF GW GENERATION

- **Individual results:**



arXiv:1903.04467

PARAMETERISED TESTS OF GW GENERATION

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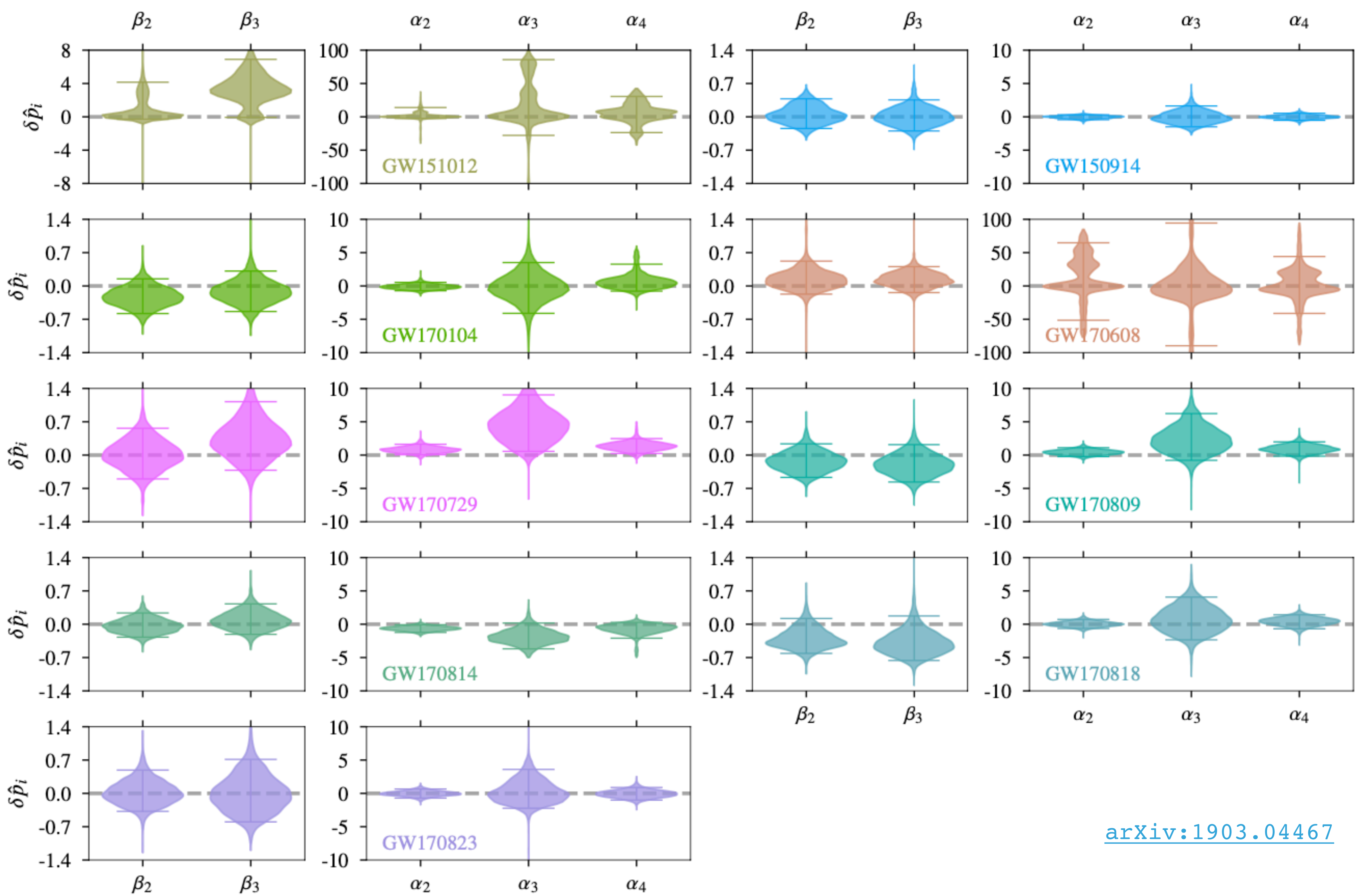

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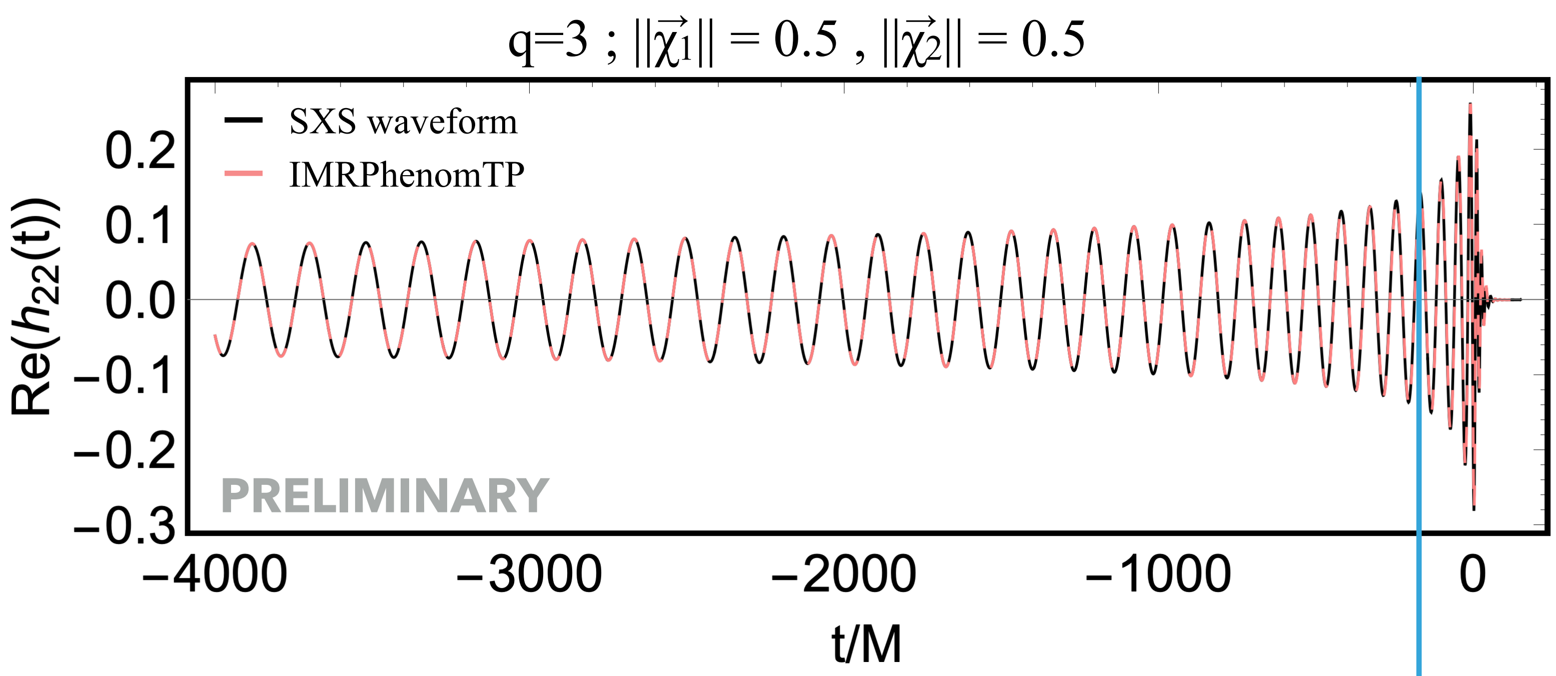
FIRST PHENOMENOLOGICAL TIME-DOMAIN GW MODEL

- **IMRPhenomTP**:
  - phenomenological model of gravitational waveform in the time domain
  - post-Newtonian + analytic functions tuned to NR simulations
  - contains main radiation mode (2,2) and precession effects
  - a lot of progress since IMRPhenomP (hierarchical modelling)

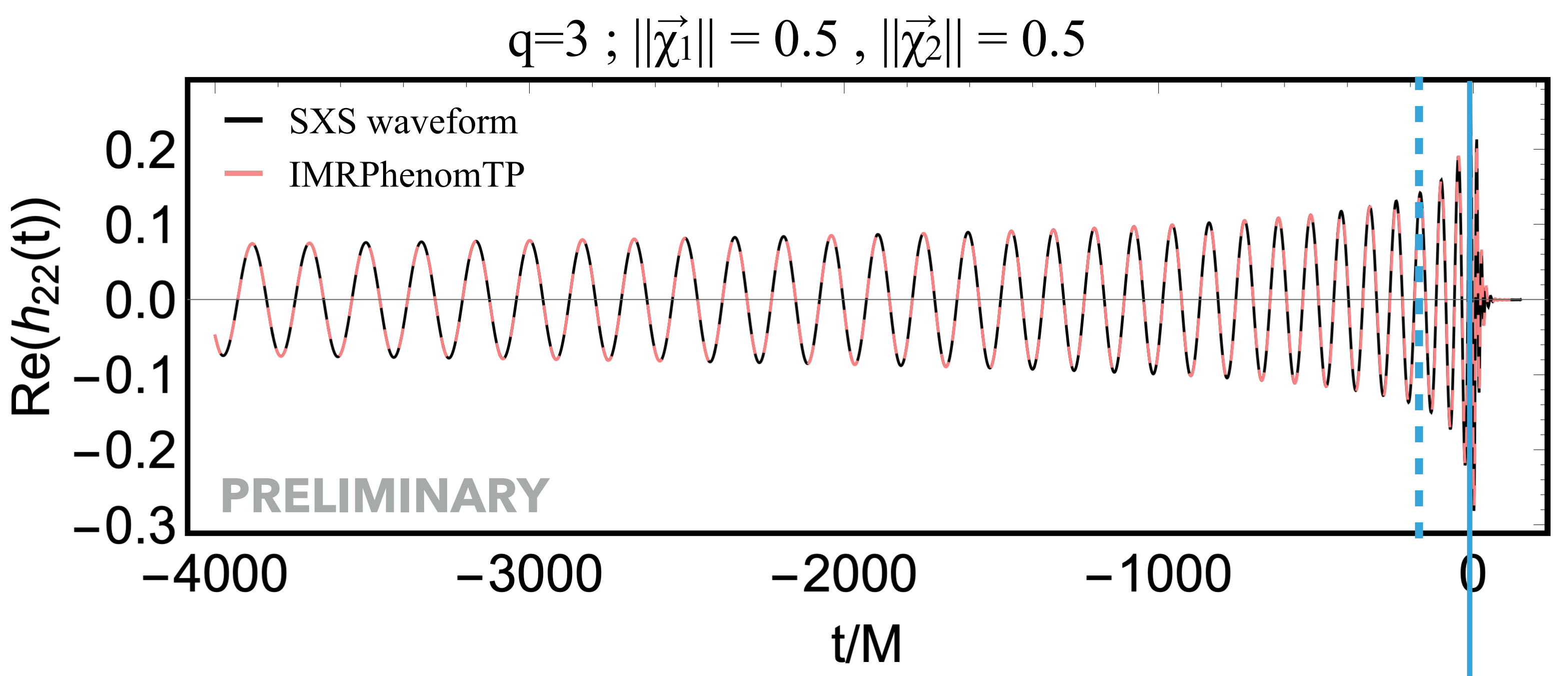
- **Status**:
  - developed at the University of Balearic Islands
  - almost finalised, preprint to be available in the next weeks
  - implementation in LALSuite to follow as soon as model is validated

FULL INSPIRAL-MERGER-RINGDOWN WAVEFORM



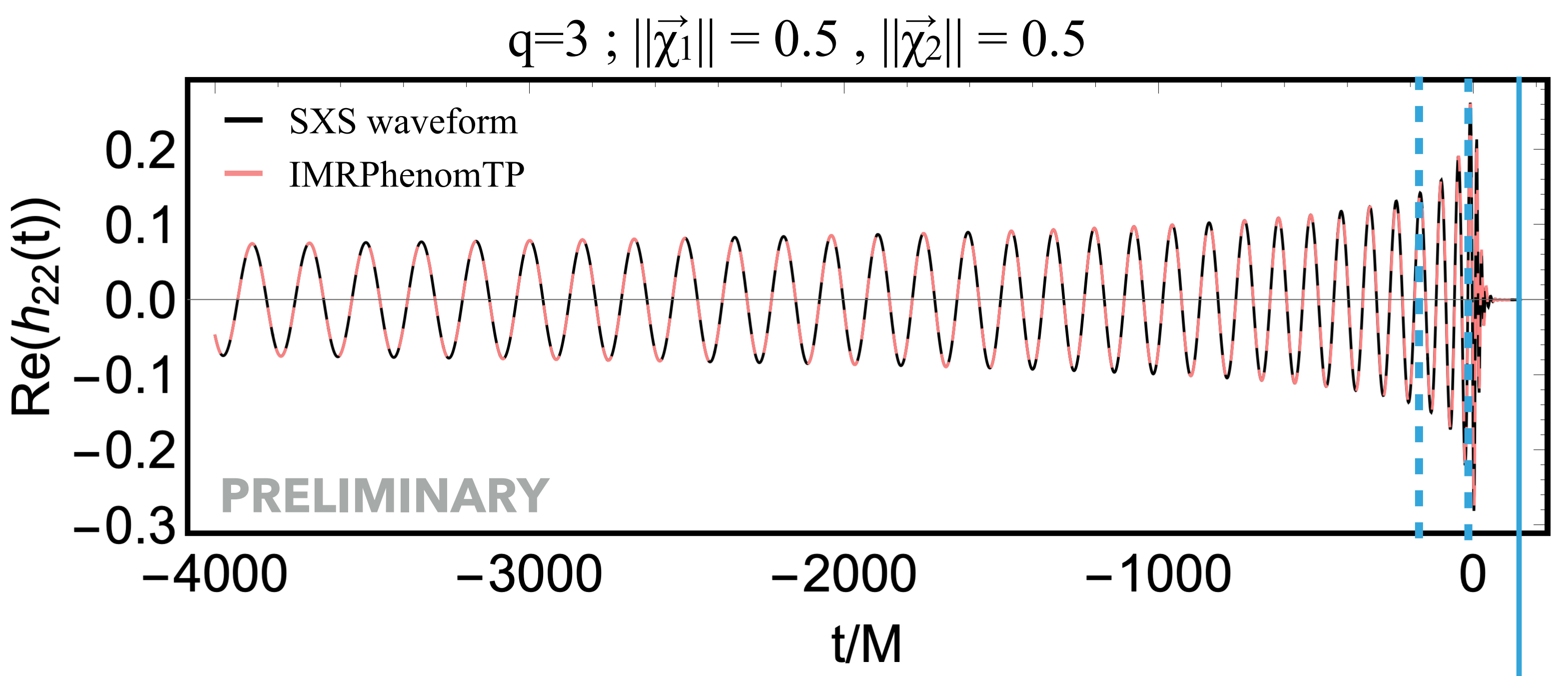
- **Inspiral**:
  - frequency obtained with 3.5 PN TaylorT3 formula + 6 pseudo-PN orders
  - amplitude obtained with 3.5 PN quadrupole formula + 3 pseudo-PN orders
  - fit the higher order coefficients by requiring exact matching of the frequency and amplitude at collocation points

FULL INSPIRAL-MERGER-RINGDOWN WAVEFORM



- **Merger**:
  - frequency modelled with hyperbolic arsin ansatz
  - amplitude modelled with polynomial + hyperbolic secant ansatz
  - fit to NR simulations and fix coefficient by requiring continuity and differentiability at t_{MECO}, t_{peak}, and collocation points

FULL INSPIRAL-MERGER-RINGDOWN WAVEFORM



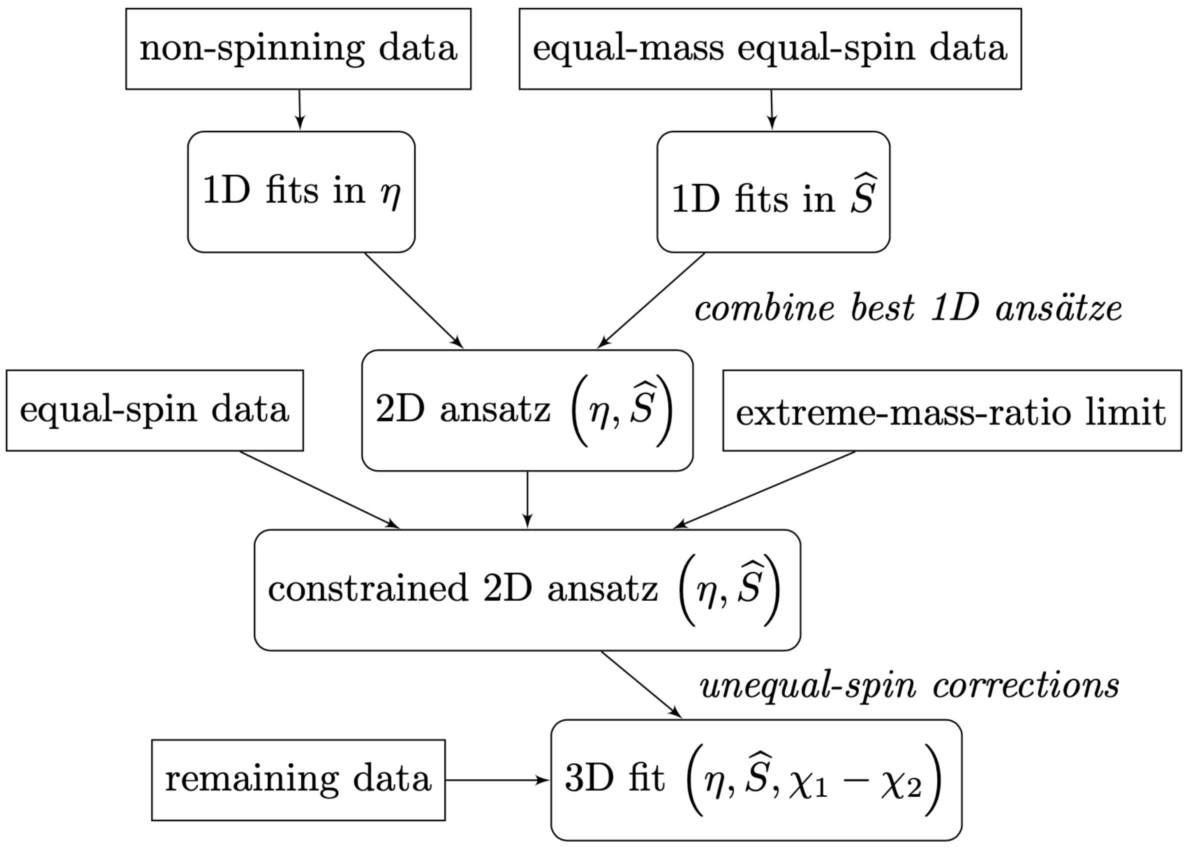
- **Ringdown**:
  - follow quasi-normal modes formalism
  - factorise the dominant ground state and model the remaining part with hyperbolic tangent-like functions

- **IMR phase**:
  - analytic primitives exist for all frequency ansatz

CALIBRATION ACROSS PARAMETER SPACE

- **Calibrated to SXS catalog**
  531 (-9) non-precessing waveforms
  $1 \leq q \leq 10$; $0 \leq |\chi_{1,2}| \leq 0.998$

- **Follow a hierarchical approach**
  to handle the fit of the parameters in the multidimensional parameters space



arXiv:1611.00332

CALIBRATION ACROSS PARAMETER SPACE

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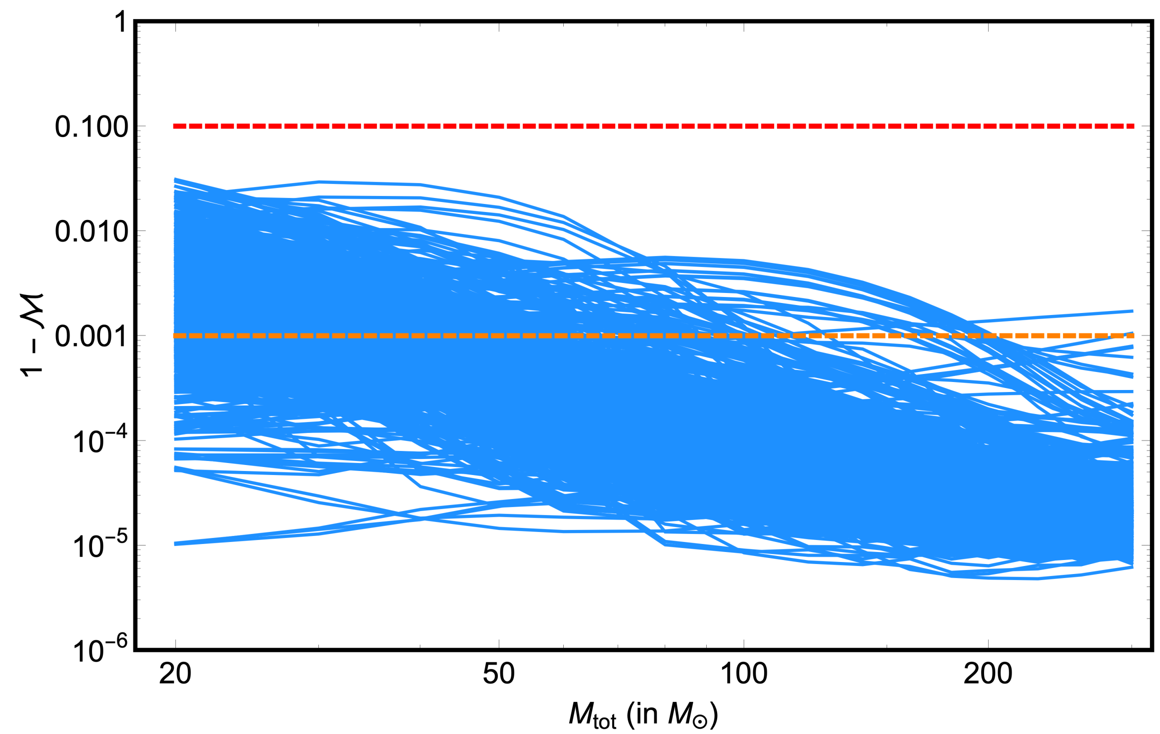
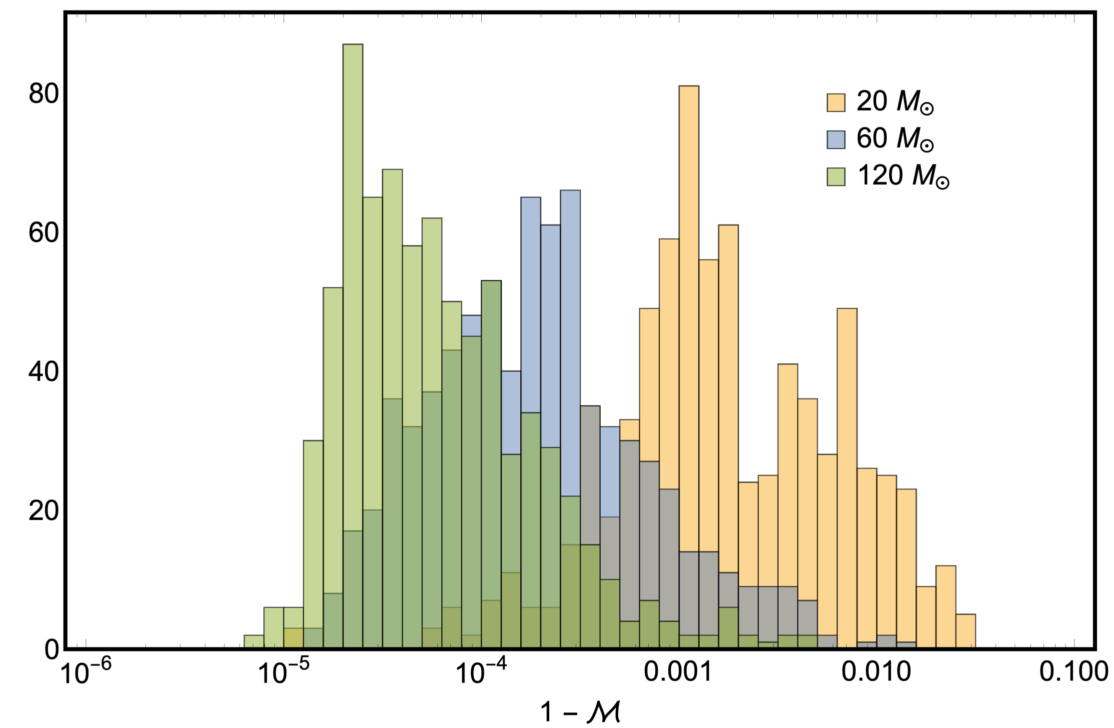
  531 (-9) non-precessing waveforms
  $1 \leq q \leq 10$; $0 \leq |\chi_{1,2}| \leq 0.998$
- **Follow a hierarchical approach**
  to handle the fit of the parameters in the multidimensional parameters space
- **Validated against EOB-NR hybrid waveforms**
  but also IMRPhenomX, SEOBNRv4 with mismatch:

$$1-\mathcal{M} = 1 - \max_{t_0,\phi_0} \frac{(h_1|h_2)}{\sqrt{(h_1|h_1)(h_2|h_2)}},$$





PRECESSION EFFECTS

- **"Twisting up" approach**
  - Take a precessing GW
  - Find a reference frame where it is similar to a non-precessing GW with same source parameters
  - Compute the rotation from the co-precessing to the inertial frame (Euler angles)
  - Apply the inverse rotation on non-precessing GW to create precession Effects on the waveform
- **Currently work in progress**

SUMMARY

- **All detections by LIGO-Virgo so far agree with General Relativity**
  but detectors sensitivities increase: expecting more events at larger distance, mass ratios, precession effects

- **Current analysis are restricted to the frequency domain**
  - IMRPhenomTP will enable to perform tests of GR in the time domain
  - New consistency tests (i.e. inspiral vs ringdown to test the area law)
  - Better understanding of constraints on parameterised deviations

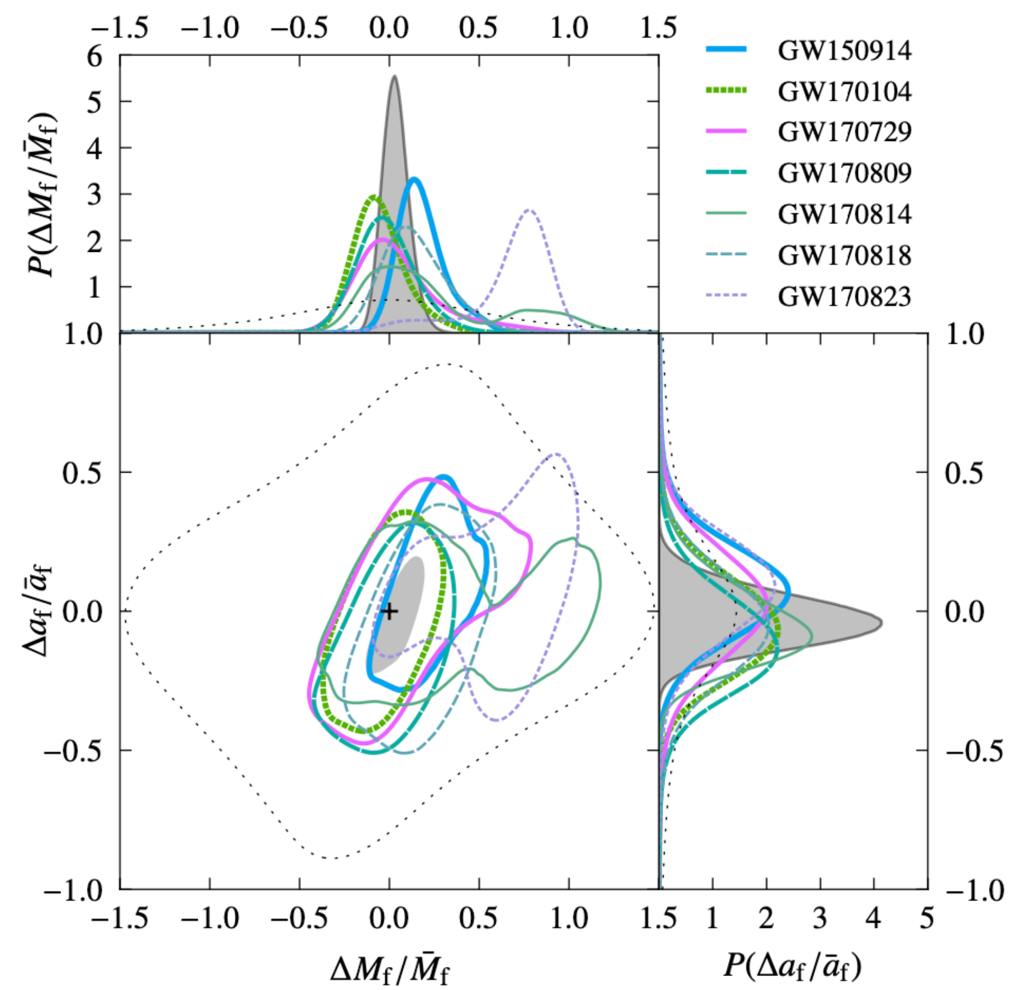
- **This is just the beginning**
  - tests of the GW propagation to be studied in the time domain
  - study the inclusion of waveform modelling systematics in the analysis
  - use alternative methods to combine results from several events (hierarchical tests…)
  - no-hair theorem: need the inclusion of higher modes and/or overtones

BACKUP

INSPIRAL / POST-INSPIRAL CONSISTENCY TESTS

arXiv:1903.04467

We see additional peaks in the posteriors estimated from GW170814 and GW170823. Detailed follow-up investigations did not show any evidence of the presence of a coherent signal in multiple detectors that differs from the GR prediction. The second peak in GW170814 is introduced by the posterior of $M_f^{\text{post-insp}}$, while the extra peak in GW170823 is introduced by the posterior of M_f^{insp}. Injection studies in real data around the time of these events, using simulated GR waveforms with parameters consistent with GW170814 and GW170823, suggest that such secondary peaks occur for ~ 10% of injections. Features in the posteriors of GW170814 and GW170823 are thus consistent with expected noise fluctuations.



PARAMETERISED TESTS OF GW GENERATION

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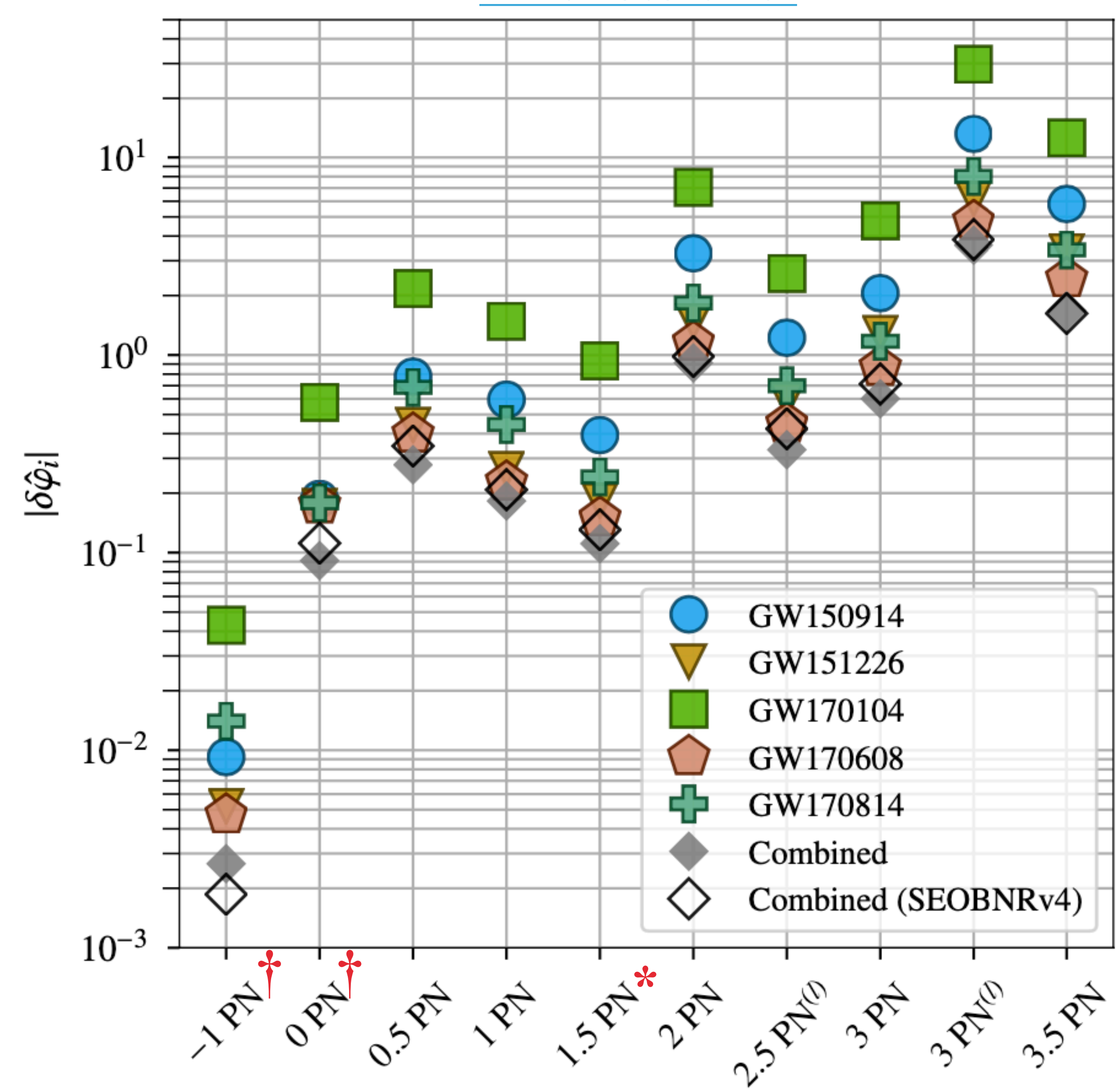


* **1.5 PN**: better bound from GW170608 (BNS)

† **-1 &0 PN**: better bound from double pulsars

all other PN: best bound from LIGO-Virgo BBHs

IMRPHENOMTP INSPIRAL: TAYLORT3 + PSEUDO-ORDERS

- **Amplitude ansatz:**

$$H_{22}^{\rm insp}(t) = H_{22}^{3.5\rm PN}(x) + 2\eta\sqrt{\frac{16}{5}}x\sum_{k=8}^{10}\hat{d}_k x^{k/2},$$

- pseudo-orders coefficients fitted to 3 collocation points:

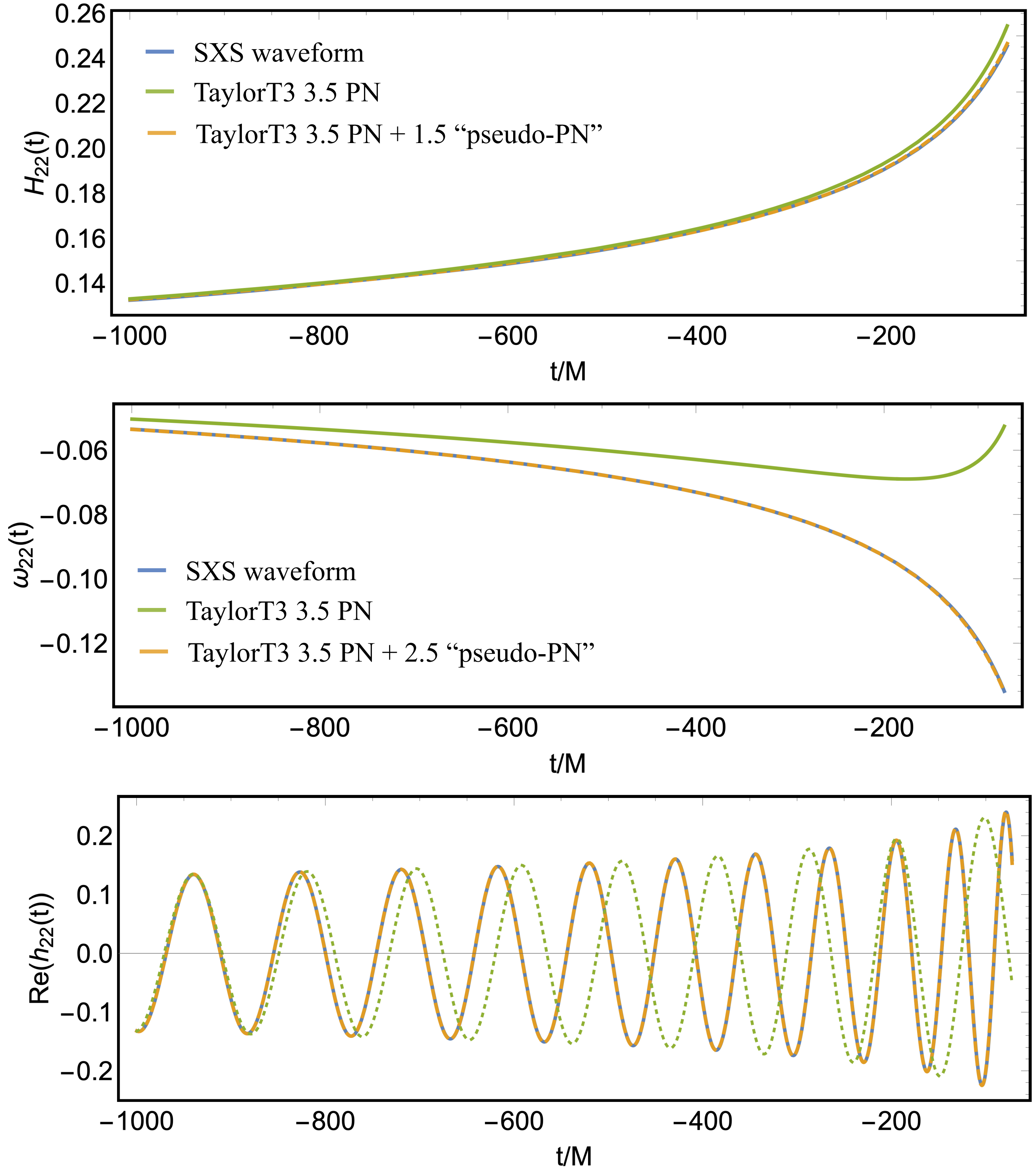
{t = -1000 ; t = 2 $t_{\rm MECO}$; t = $t_{\rm MECO}$ }

- **Frequency ansatz:**

$$\omega_{22}^{\rm insp}(t) = \omega_{3.5}^{(T3)}(t) + \omega_N^t\sum_{k=8}^{12}\hat{c}_k\theta^k,$$

- pseudo-orders coefficients fitted to 3 collocation points:

{t = -10^5 ; t = -2000 ; t = -1000 ; t = 2 $t_{\rm MECO}$; t = $t_{\rm MECO}$ }



IMRPHENOMTP MERGER

- **Amplitude ansatz**:

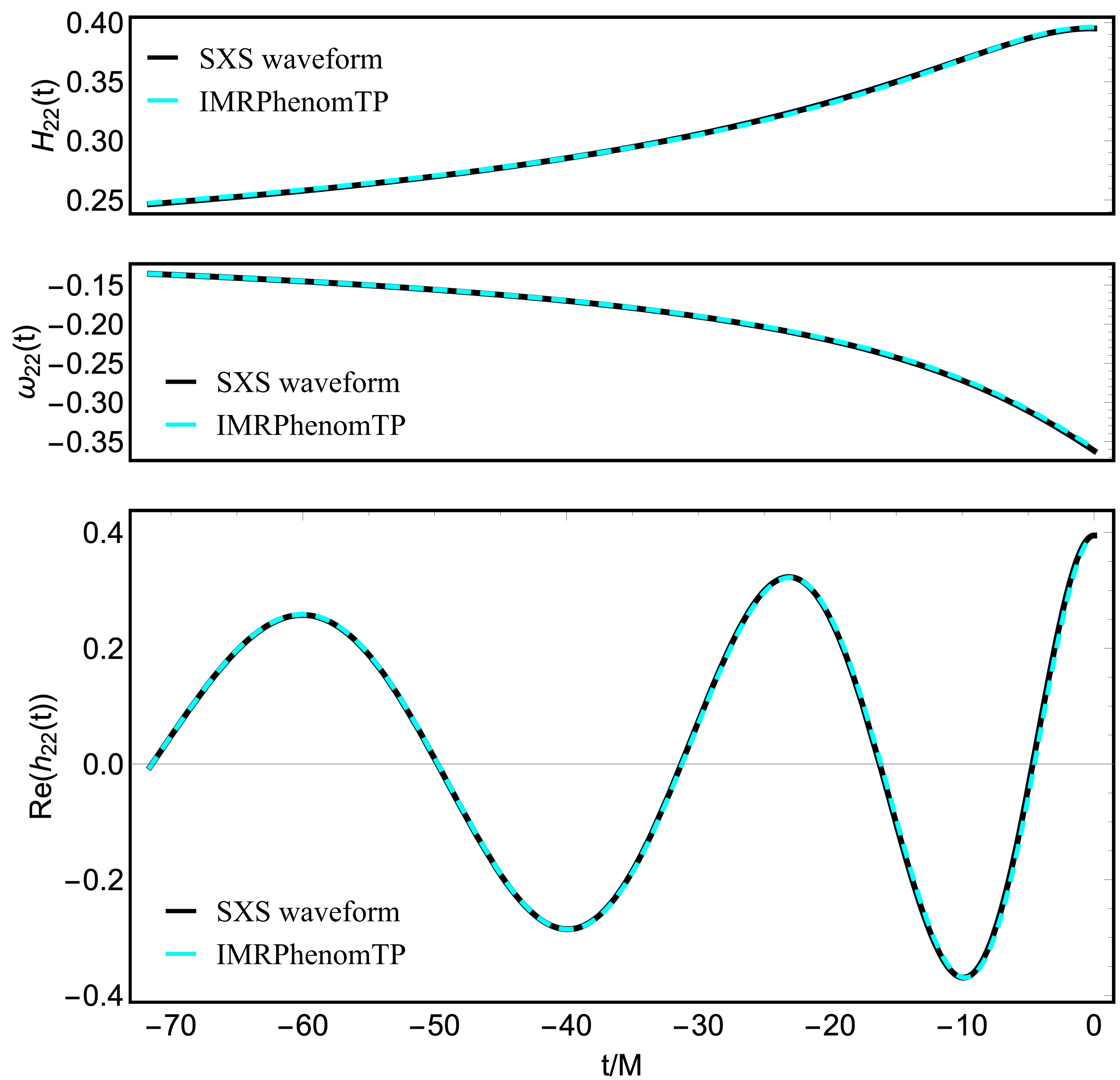
$$H_{22}^{\mathrm{merger}}(t) = b_0 + b_1 t^2 + b_2 \mathrm{sech}^{1/7}(\alpha t) + b_3 \mathrm{sech}(\alpha t),$$

- **Frequency ansatz**:

$$\omega_{22}^{\mathrm{merger}}(t) = \sum_{k=0}^{k=4} a_k \mathrm{arcsinh}^k(\alpha_1 t)$$

- pseudo-orders coefficients fitted to 3 collocation points:

$$\{t = 0.25\, t_{\mathrm{MECO}}\, ;\, t = t_{\mathrm{peak}}\, ;\, t = t_{\mathrm{MECO}}\}$$



IMRPHENOMTP RINGDOWN

- **Amplitude ansatz:**

$$H_{22}^{RD}(t) = e^{-\alpha_1(t-t_p)}|\bar{h}(t)|,$$

$$\downarrow$$

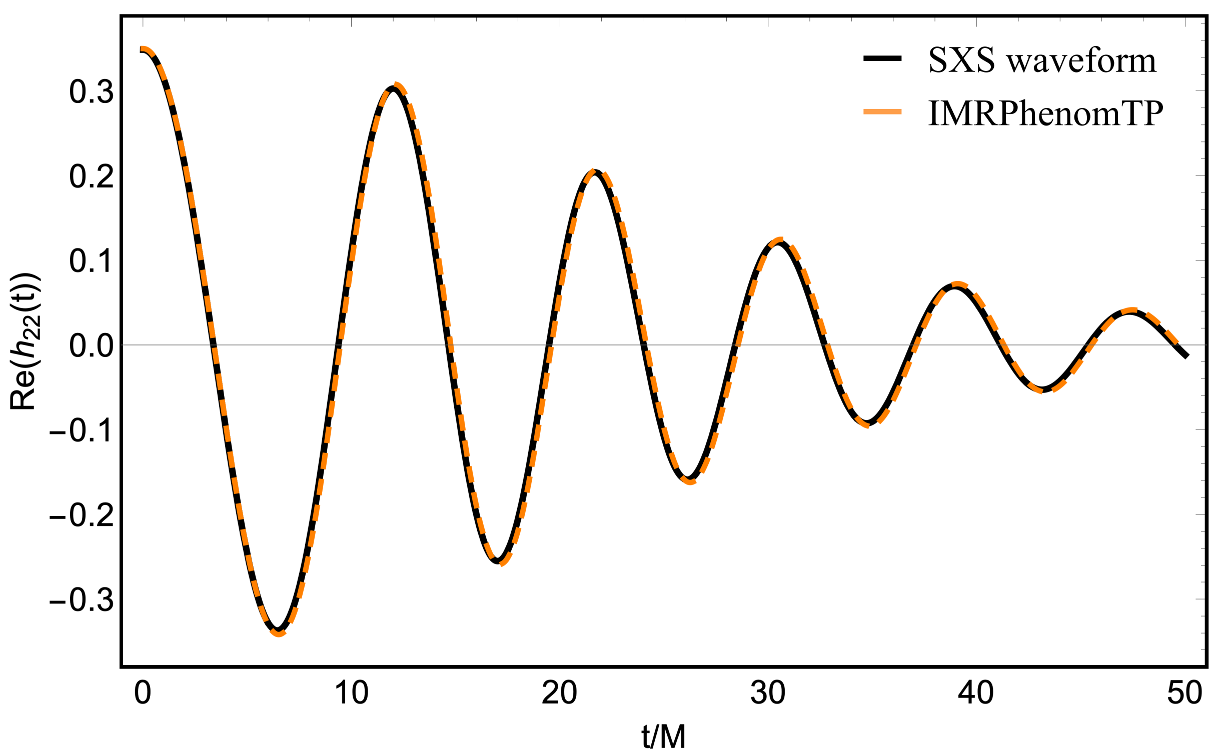
$$|\bar{h}(t-t_p)| = c_1 \tanh[(\alpha_2 - \alpha_1)(t-t_p) + c_3] + c_4,$$

- **Frequency ansatz:**

$$\omega_{22}^{RD}(t) = \bar{\omega}_{22}(t) - \omega_{22}^{RD}.$$

$$\downarrow$$

$$\bar{\omega}_{22}(t-t_0) = c_1 \frac{c_2(c_3 e^{-c_2(t-t_0)} + 2c_4 e^{-2c_2(t-t_0)})}{1 + c_3 e^{-c_2(t-t_0)} + c_4 e^{-2c_2\,(t-t_0)}},$$



IMRPHENOMTP VS OTHER MODELS