Tests of general relativity in the nonlinear regime: a parametrized plunge-merger-ringdown waveform model

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Based on: EM, H. O. Silva, A. Buonanno, A. Ghosh, arXiv:2212.09655

Outline

How robust are the predictions of general relativity in the dynamical and nonlinear regime?

- Parametrized plunge-merger-ringdown test

- Waveform morphology

- Synthetic-signal injection studies

- Analysis of GW150914: first constraints on plunge-merger parameters

- Analysis of GW200129 [see H. O. Silva's talk]

The stages of compact binary coalescences

*Inspiral*   *Plunge*   *Merger*   *Ringdown*
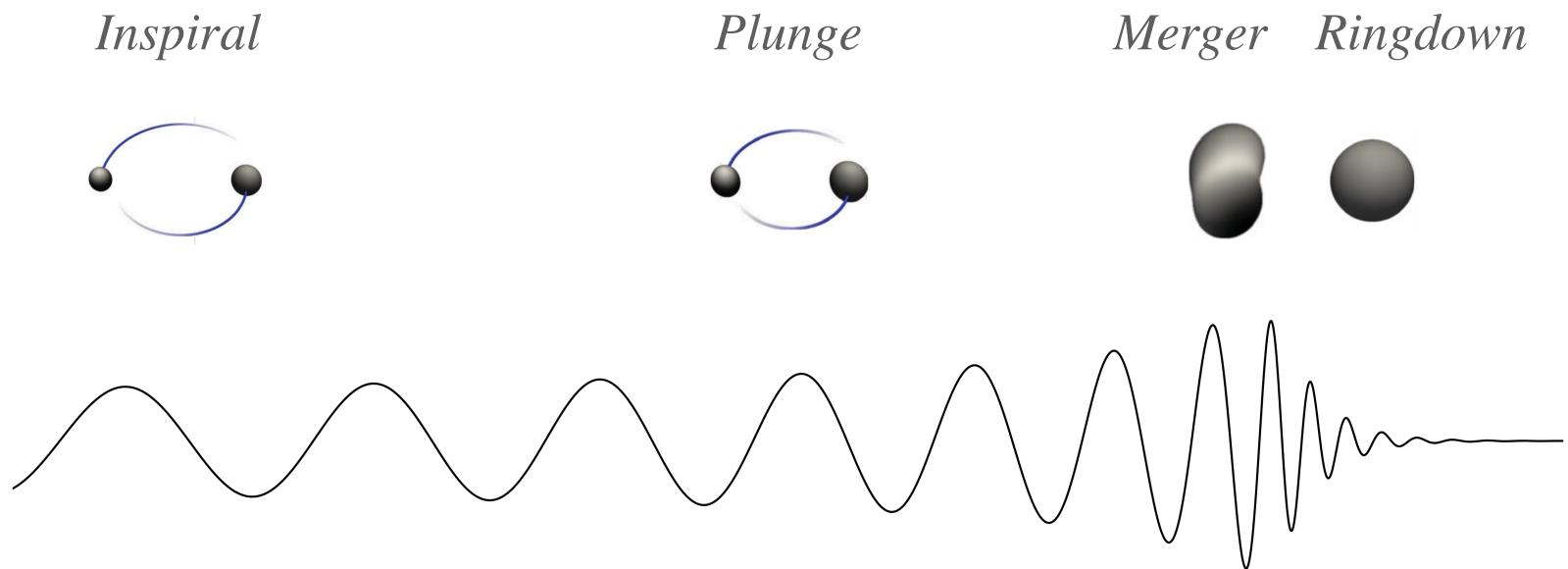
Adapted from Abbott+, PRL **116** n.6 (2016) 061102

Parametrized tests introduce generic deviations from the GR waveform to constrain the degree to which the data agree with GR predictions.

Waveform model in general relativity

Our baseline model is the waveform constructed in the effective-one-body formalism for quasicircular and spin-aligned binaries:

$$\boldsymbol{a}_1 \qquad m_1 \qquad \boldsymbol{a}_2 \qquad m_2$$

$$\boldsymbol{a} = \boldsymbol{a}_1 + \boldsymbol{a}_2 \qquad \mu = \frac{m_1 m_2}{M}$$

$$M = m_1 + m_2$$
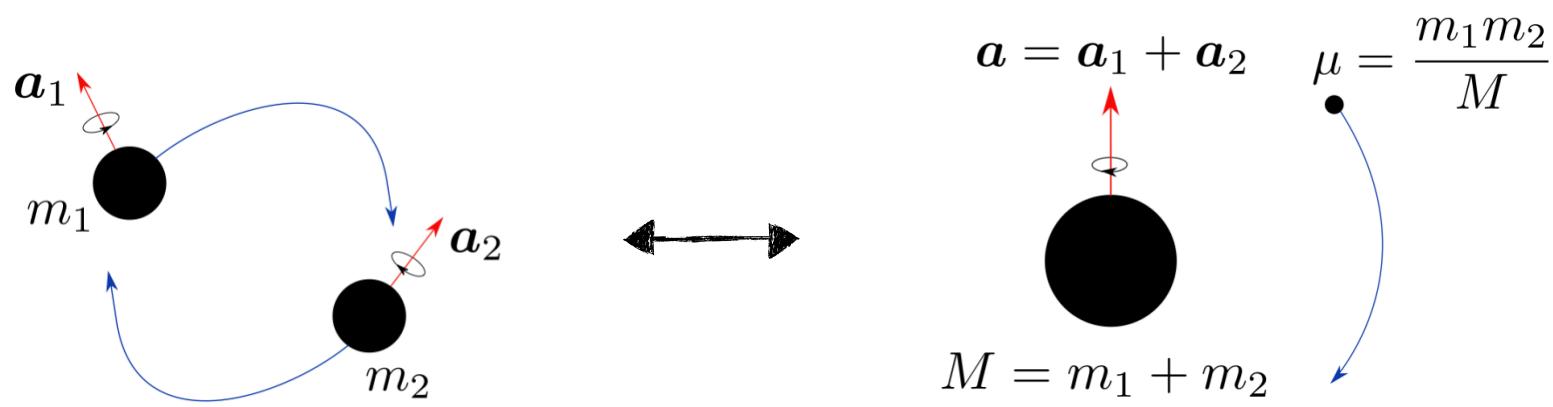
Credit: M. Khalil

$$h_{\ell m}(t) = h_{\ell m}^{\mathrm{insp-plunge}}\theta(t_{\mathrm{match}}^{\ell m} - t) + h_{\ell m}^{\mathrm{merger-RD}}\theta(t - t_{\mathrm{match}}^{\ell m})$$

Buonanno, Damour, PRD **59**, 084006 (1999); Buonanno, Damour, PRD **62**, 064015 (2000); Bohé+, PRD **95**, 044028 (2017); Cotesta+, PRD **98**, 084028 (2018); Mihaylov+, PRD **104**, 124087 (2021).

Parametrized plunge-merger-ringdown model

We introduce fractional deviations to the GR parameters in the plunge-merger-ringdown stage as:

$$\theta_{\mathrm{GR}} \rightarrow \theta_{\mathrm{GR}}(1 + \delta\theta)$$

We extend the **parametrized ringdown test** where the quasi-normal mode frequencies of the remnant are free parameters:

$$f_{\ell m 0} \rightarrow f_{\ell m 0}(1 + \delta f_{\ell m 0})$$
$$\tau_{\ell m 0} \rightarrow \tau_{\ell m 0}(1 + \delta\tau_{\ell m 0})$$

Brito+, PRD **98**, 084038 (2018); Ghosh+, PRD **103**, 124041 (2021)

Parametrized plunge-merger-ringdown model

We introduce fractional deviations in the:

- **Amplitude**: $\qquad |h_{\ell m}| \rightarrow |h_{\ell m}|(1 + \delta A_{\ell m})$

- **Frequency**: $\qquad \omega_{\ell m} \rightarrow \omega_{\ell m}(1 + \delta\omega_{\ell m})$

  at the matching time of the inspiral-plunge and merger-RD waveform;

- **Time shift** between the peak amplitude and the peak orbital frequency:

$$\Delta t_{\ell m} \rightarrow \Delta t_{\ell m}(1 + \delta\Delta t_{\ell m})$$

Waveform morphology

*How do the plunge-merger parameters affect the waveform?*
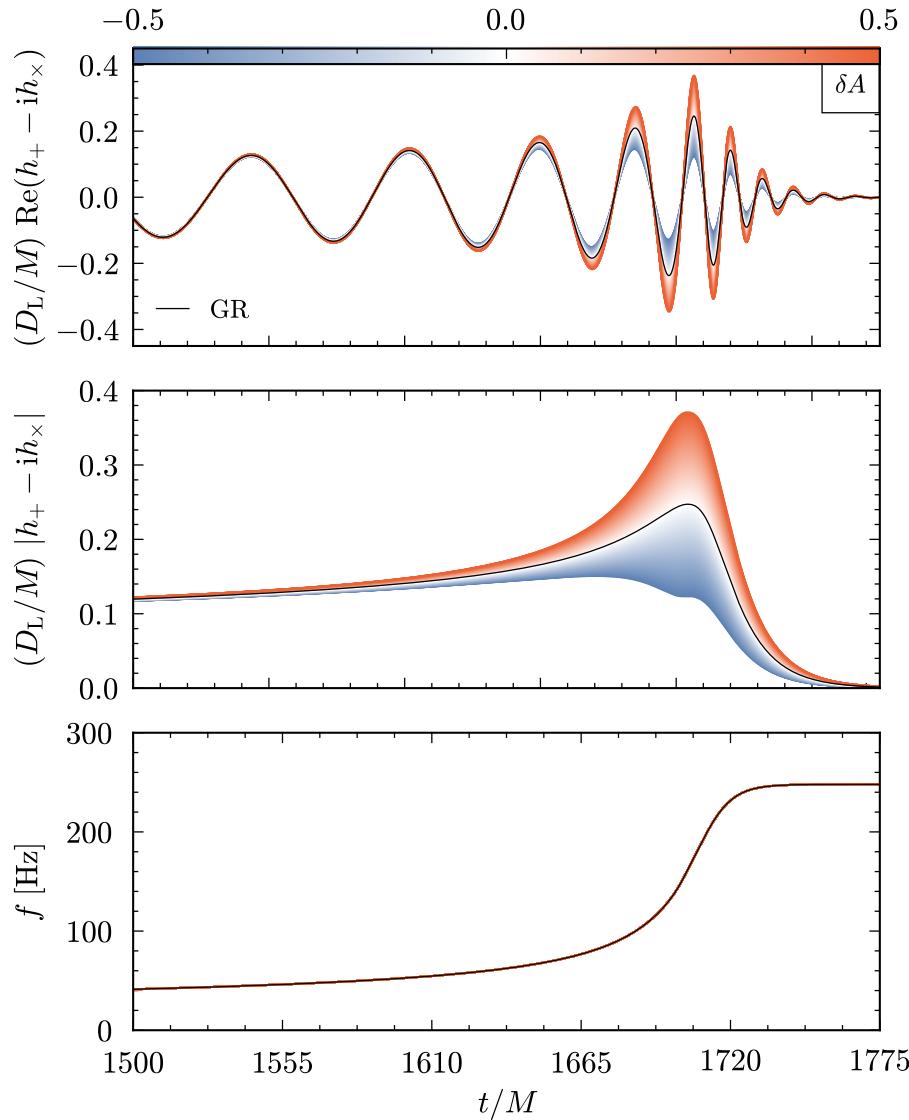
Amplitude:

$$|h_{\ell m}| \rightarrow |h_{\ell m}|(1 + \delta A_{\ell m})$$

Waveform morphology

*How do the plunge-merger parameters affect the waveform?*
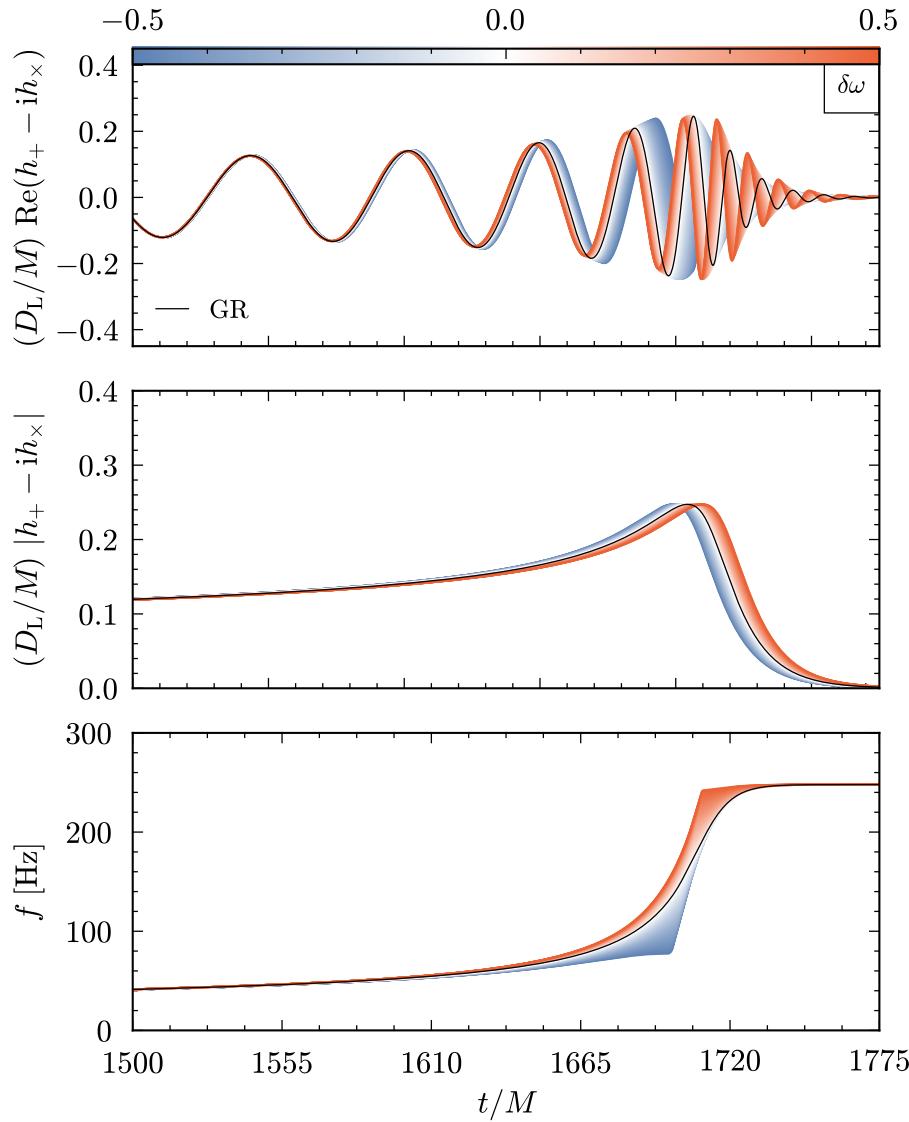
Frequency:

$$\omega_{\ell m} \rightarrow \omega_{\ell m}(1 + \delta\omega_{\ell m})$$

Waveform morphology

How do the plunge-merger parameters affect the waveform?
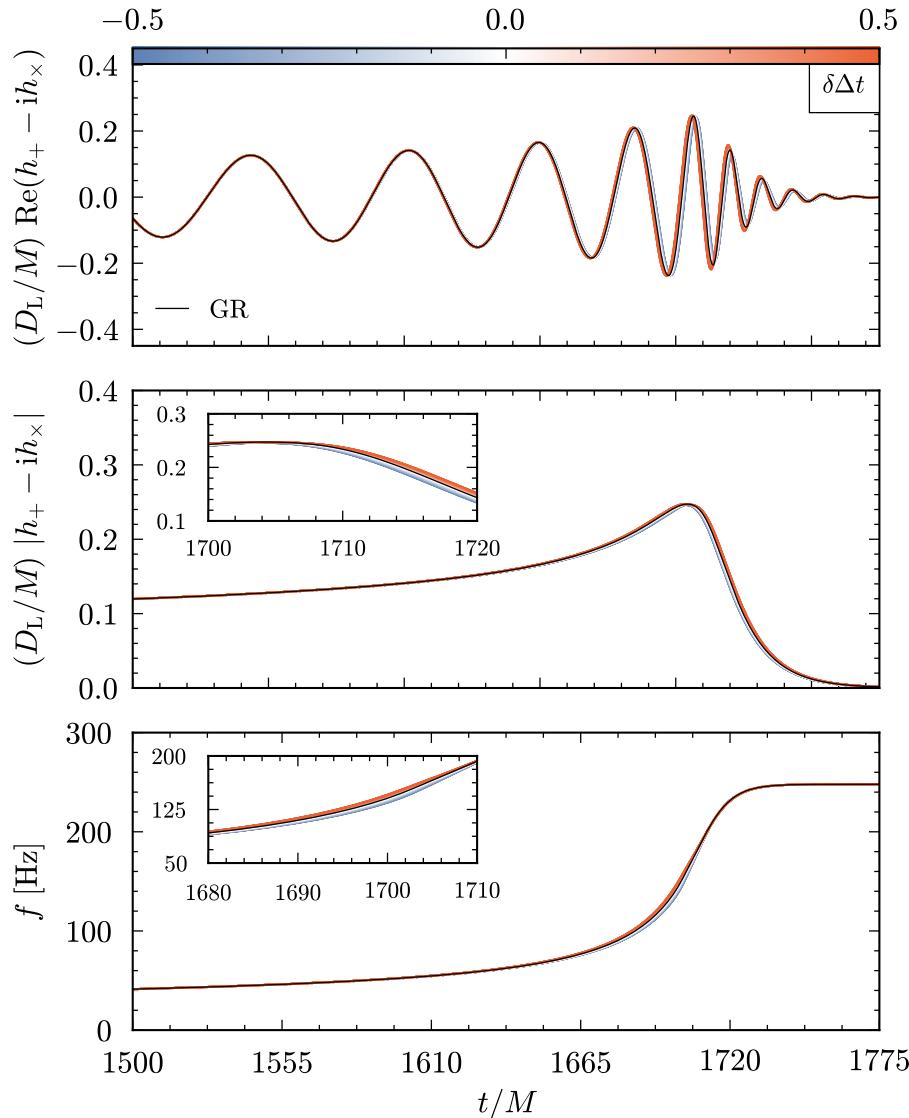
Time shift:

$$\Delta t_{\ell m} \to \Delta t_{\ell m}(1 + \delta\Delta t_{\ell m})$$

Synthetic-signal injection studies

A GW150914-like event with SNR=100 would constrain the non-GR parameters in the range between 5% (for δA and δf_{220}) and 20% (for $\delta \tau_{220}$).
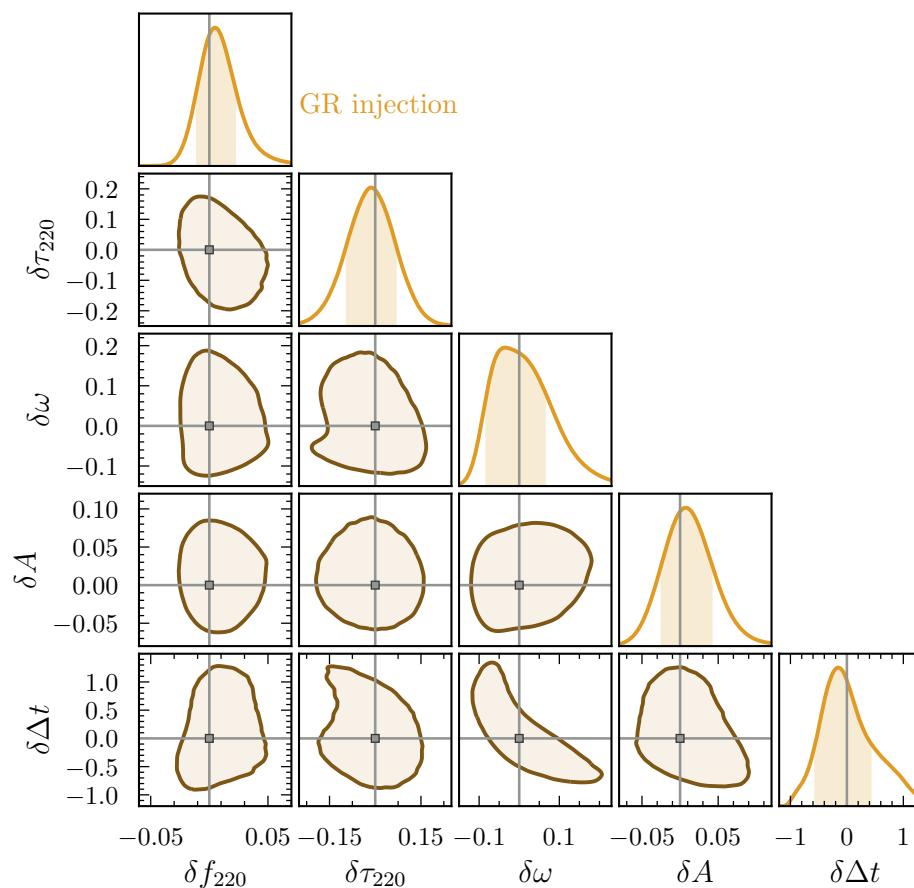
Merger test for GW150914

We can already constrain deviations from GR around the merger time to about 20% with current GW events.

$$\delta A = -0.03^{+0.21}_{-0.20}$$
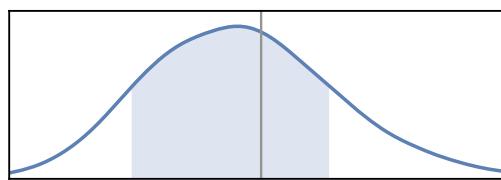
$$\delta \omega = 0.04^{+0.18}_{-0.13}$$
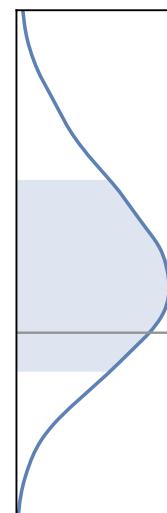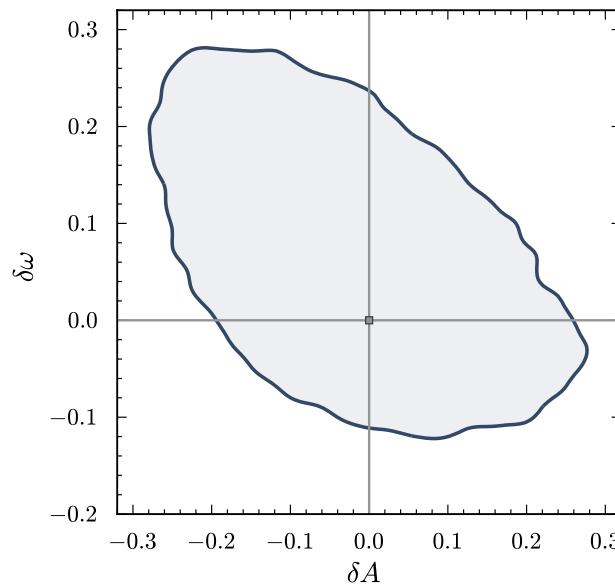
Conclusions and future prospects

- We developed a parametrized plunge-merger-ringdown waveform model that can capture signatures of beyond-GR physics in the nonlinear regime.

- We provided the first constraints on the plunge-merger parameters from the analysis of GW150914.

- A study of the implications of these bounds into the parameters of various modified gravity theories is left for future work.