Testing the strong-field dynamics of general relativity with binary black hole observations

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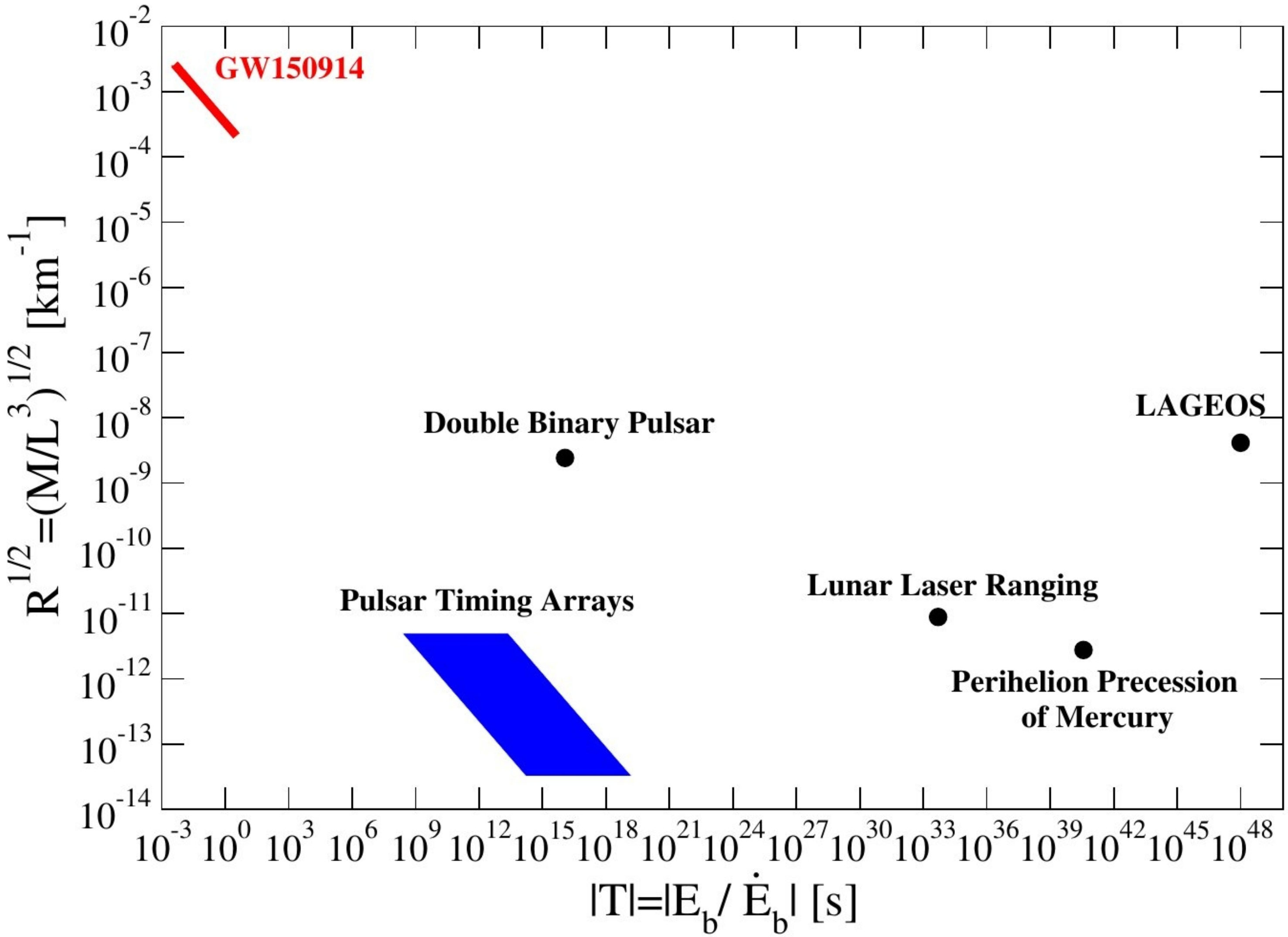
On behalf of the LIGO-Virgo Collaboration

Nikhef

July 11, GR21, New York City

LIGO VIRGO

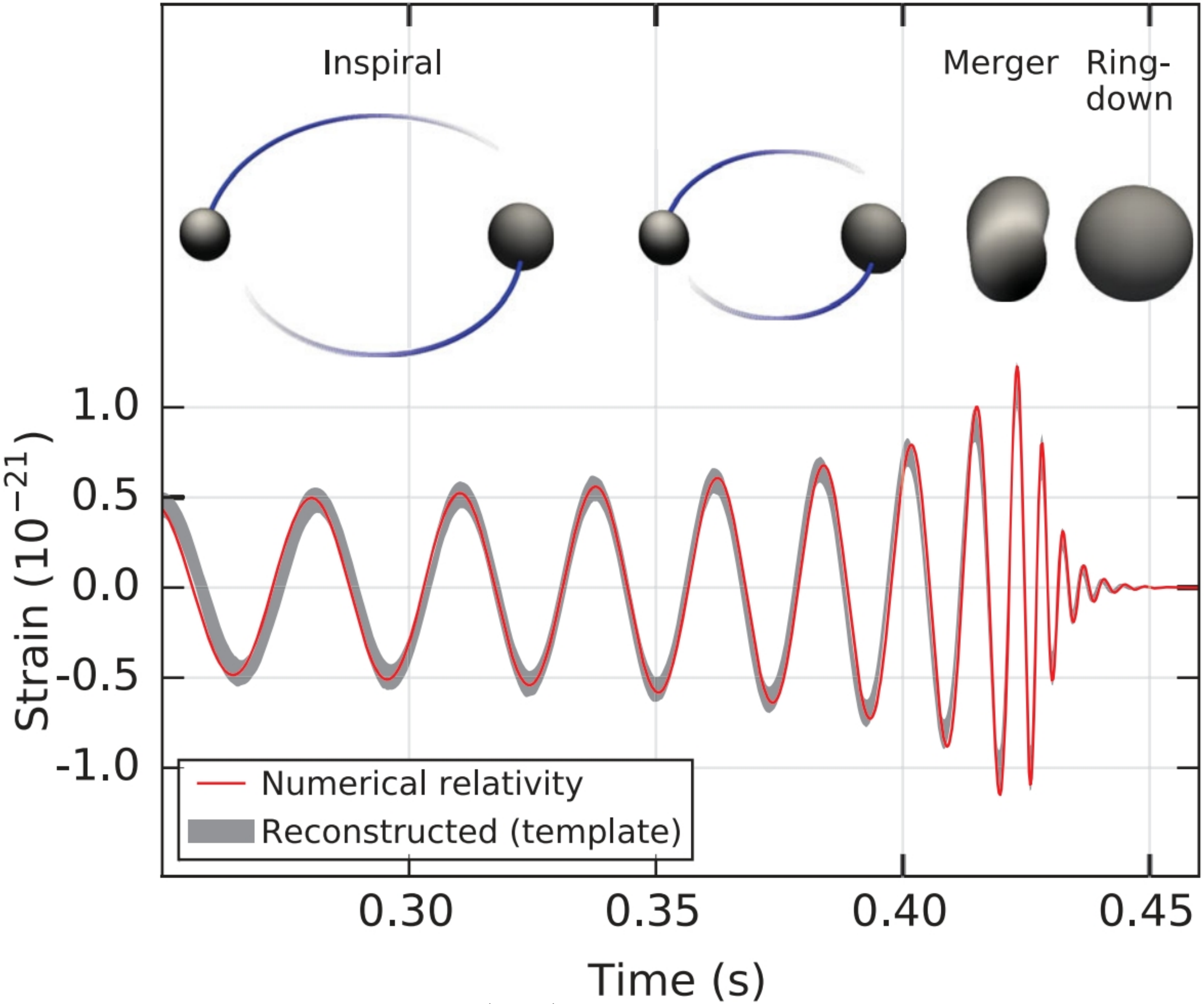
Access to new regime



Empirical access to genuinely strong-field dynamics of spacetime

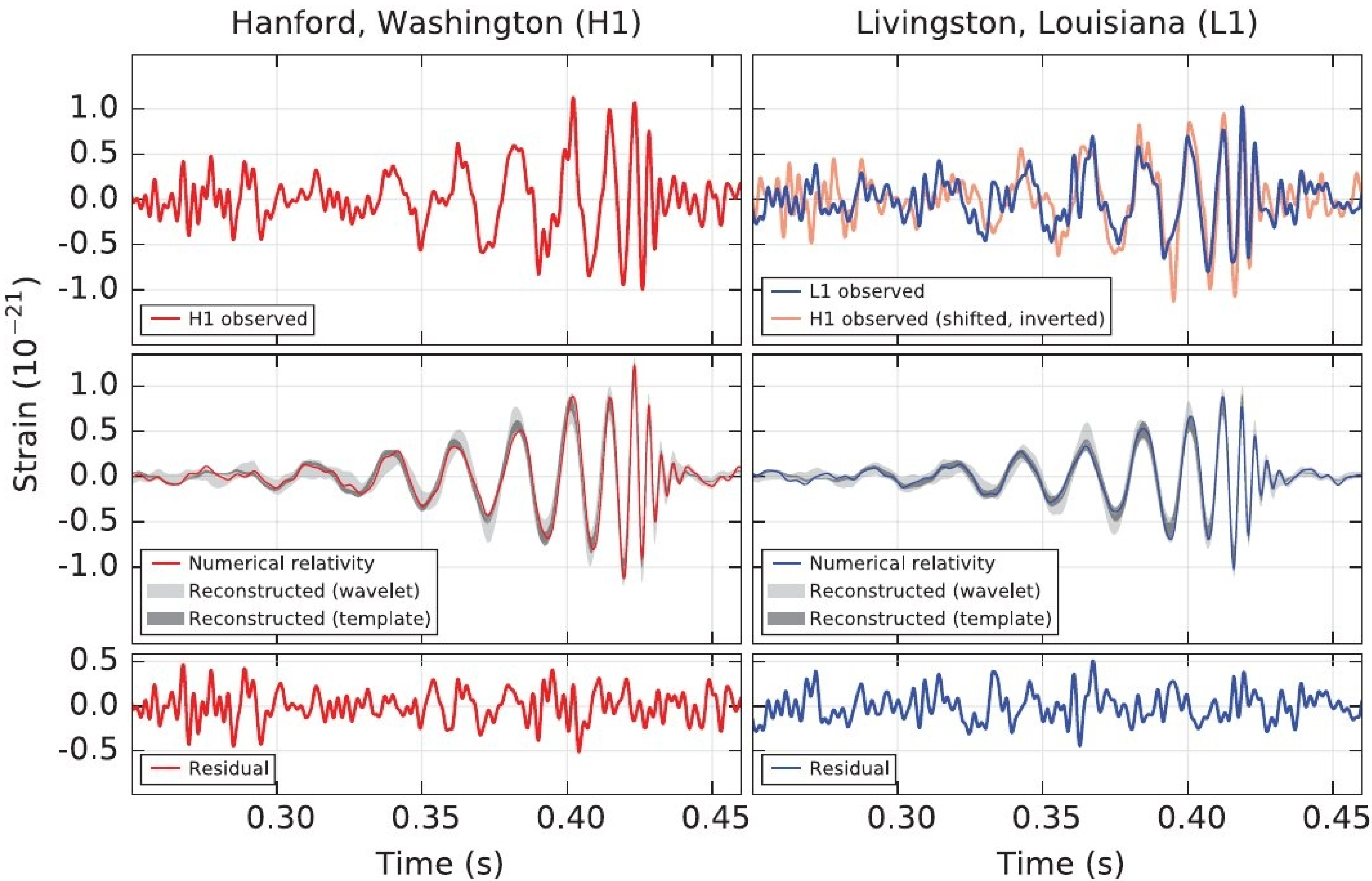
Yunes at al., arXiv:1603.08955 [gr-qc] (2016)

Coalescence of black holes



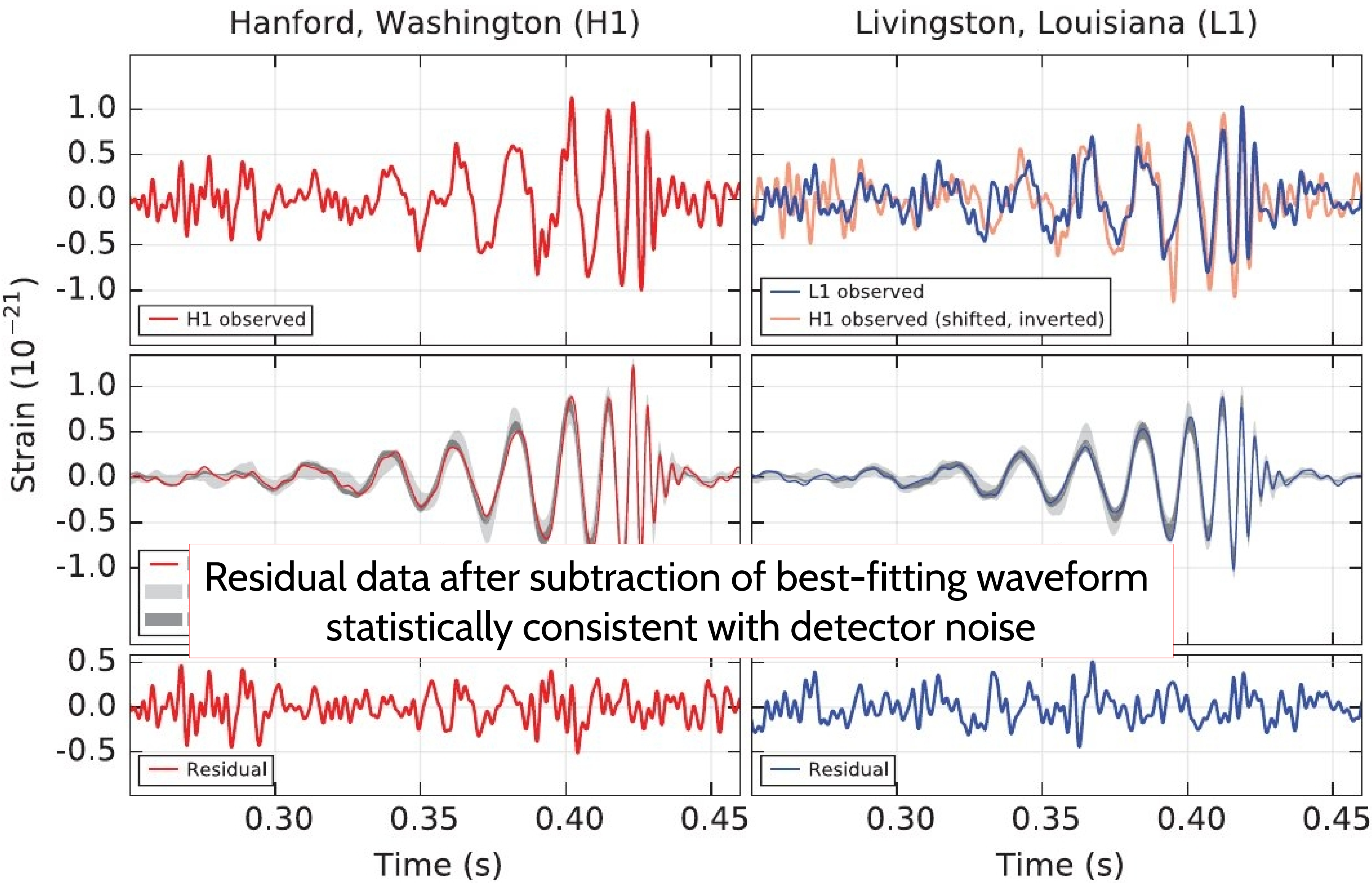
LIGO and Virgo Coll., Phys. Rev. Lett. **116**, 061102 (2016)

Detection of GW150914



LIGO and Virgo Coll., Phys. Rev. Lett. **116**, 061102 (2016)

Detection of GW150914

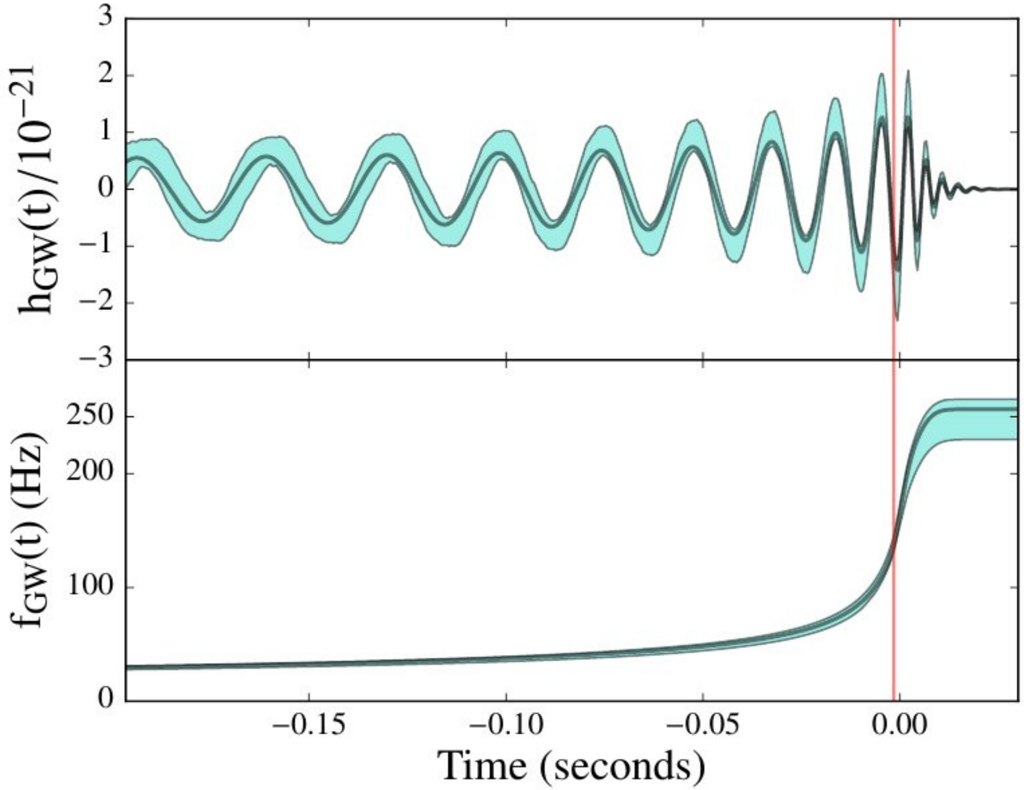


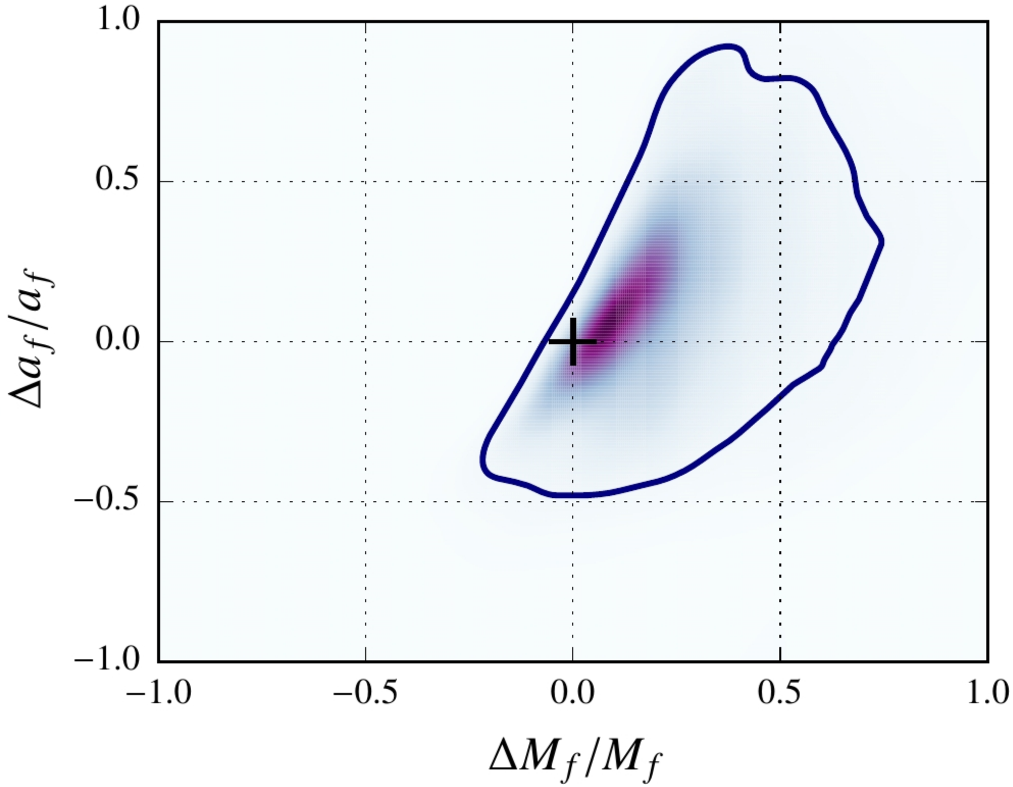
Residual data after subtraction of best-fitting waveform statistically consistent with detector noise

LIGO and Virgo Coll., Phys. Rev. Lett. **116**, 061102 (2016)

First tests of strong field dynamics

- Consistency between
  - Masses and spins of component objects
  - Mass and spin of final object

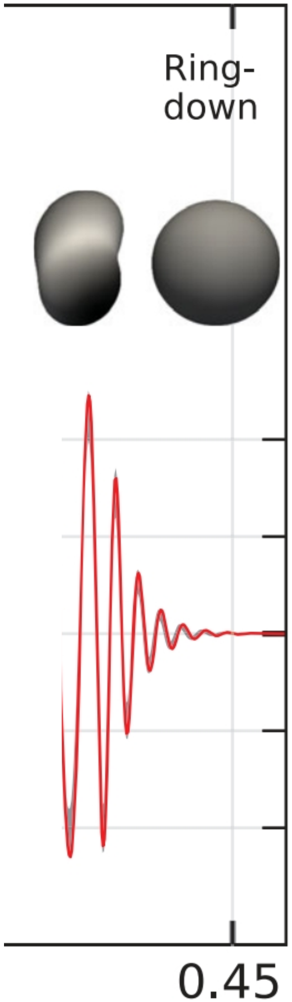


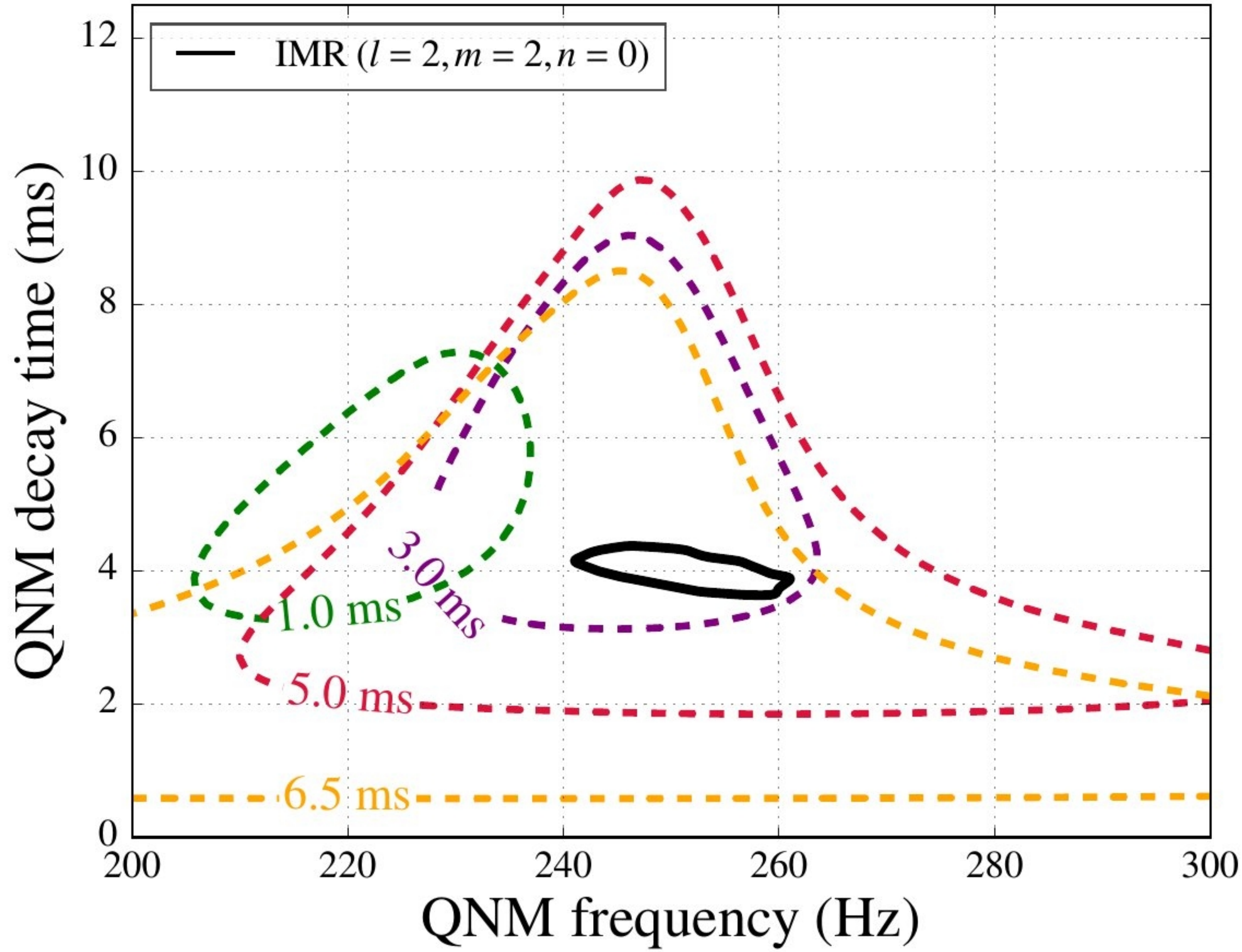


LIGO and Virgo Coll., Phys. Rev. Lett. **116**, 221101 (2016)

First tests of strong field dynamics

- Final part of signal consistent with there being a least-damped quasi-normal mode



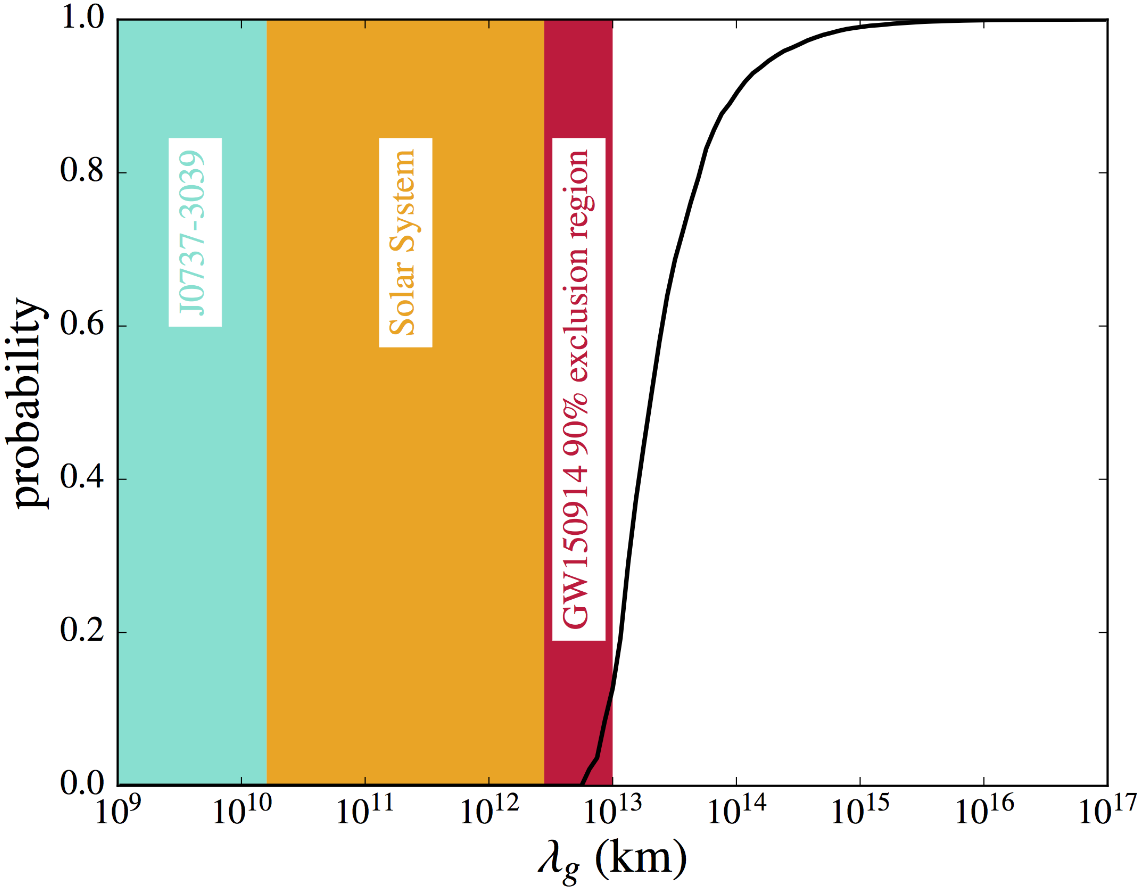


LIGO and Virgo Coll., Phys. Rev. Lett. **116**, 221101 (2016)

First tests of strong field dynamics

- Constraint on graviton Compton wavelength
  - For non-zero mass, high frequencies propagate faster than low frequencies

$$\frac{v_g}{c} \simeq 1 - \frac{1}{2}\left(\frac{c}{\lambda_g f}\right)^2$$



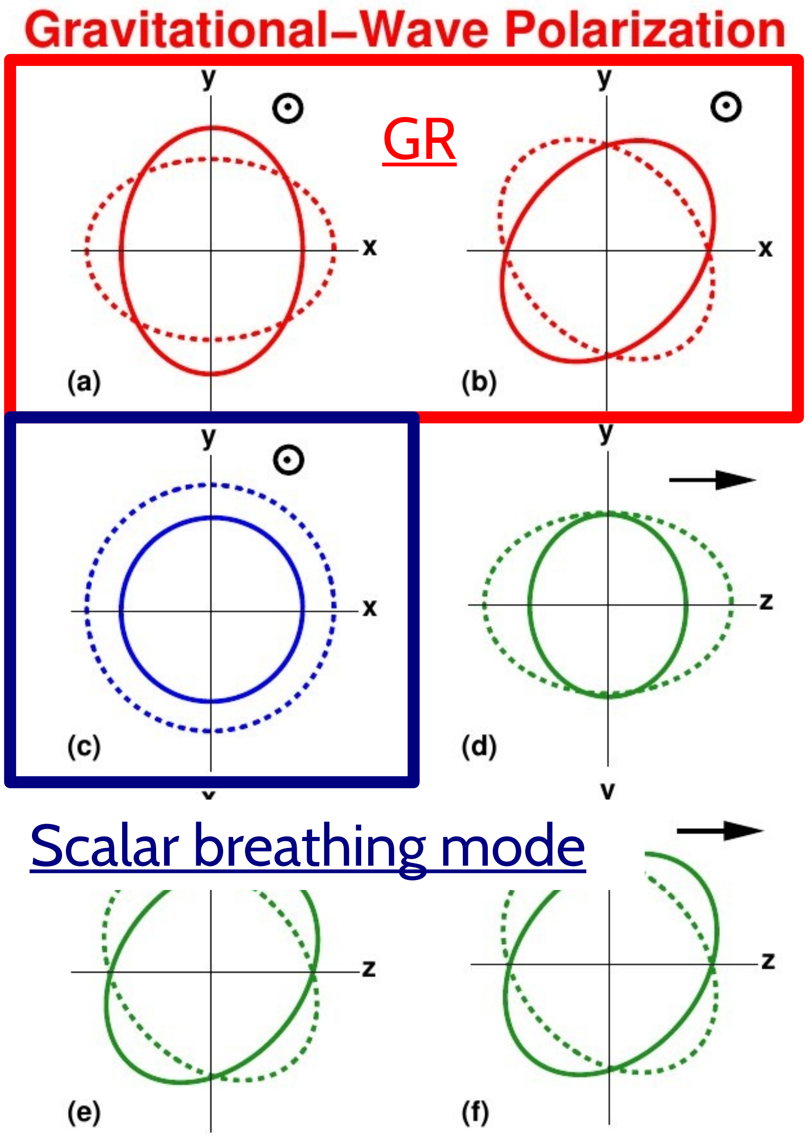
Dynamical lower bound:

$$\lambda_g > 10^{13}\,\mathrm{km}$$

$$m_g \leq 1.2 \times 10^{-22}\,\mathrm{eV}/c^2$$

LIGO and Virgo Coll., Phys. Rev. Lett. **116**, 221101 (2016)

First tests of strong field dynamics



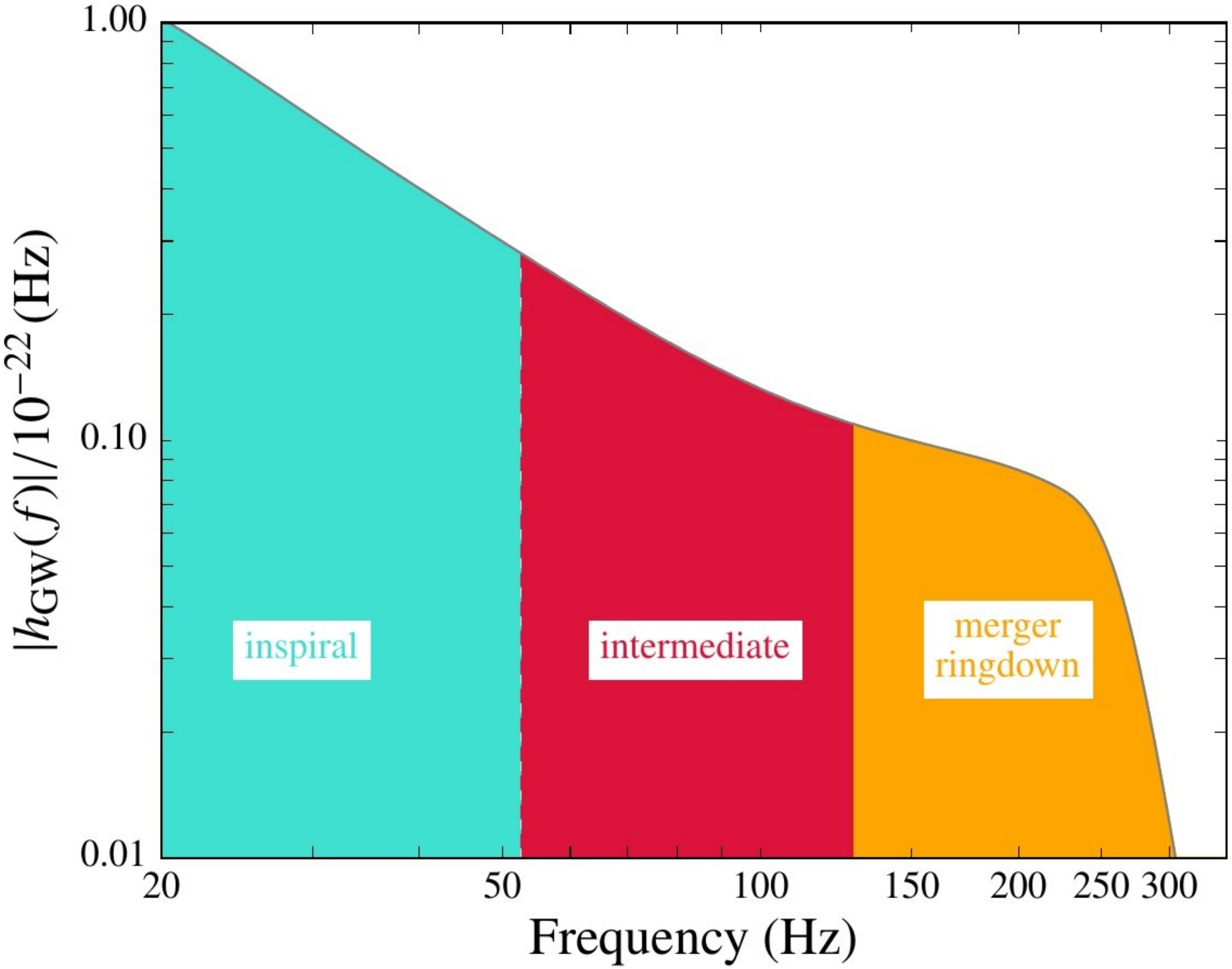
Clifford M. Will., Living Rev. Relativity. 17, 4 (2014)

- In metric theories of gravity up to 6 polarization modes
- Extreme example:
  GR versus only scalar breathing mode
- With only two detectors that have similar orientations:
  Can not distinguish between GR and non-GR polarizations
  - Need network with more detectors:
    Advanced Virgo, KAGRA, LIGO India

$$\log B^{\mathrm{GR}}_{\mathrm{scalar}} = -0.2 \pm 0.5$$

Concept of parameterized tests

- Phenomenological model realized through fitting to numerical waveforms



LIGO and Virgo Coll., Phys. Rev. Lett. **116**, 221101 (2016)

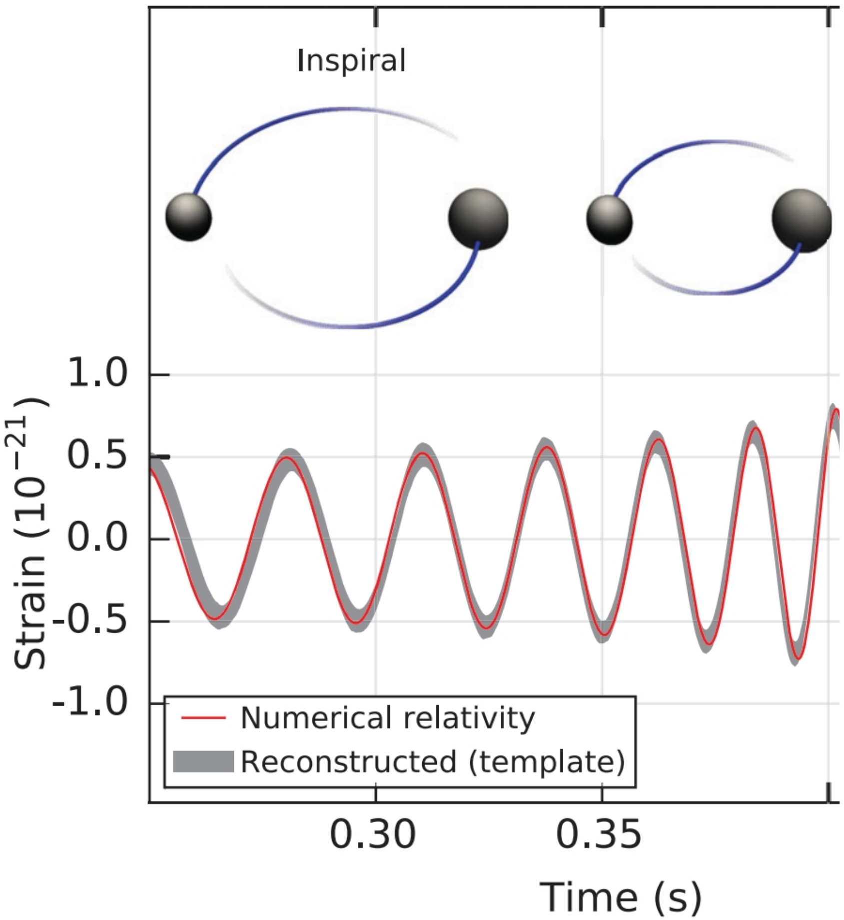
- Allow for fractional changes with respect to the GR value

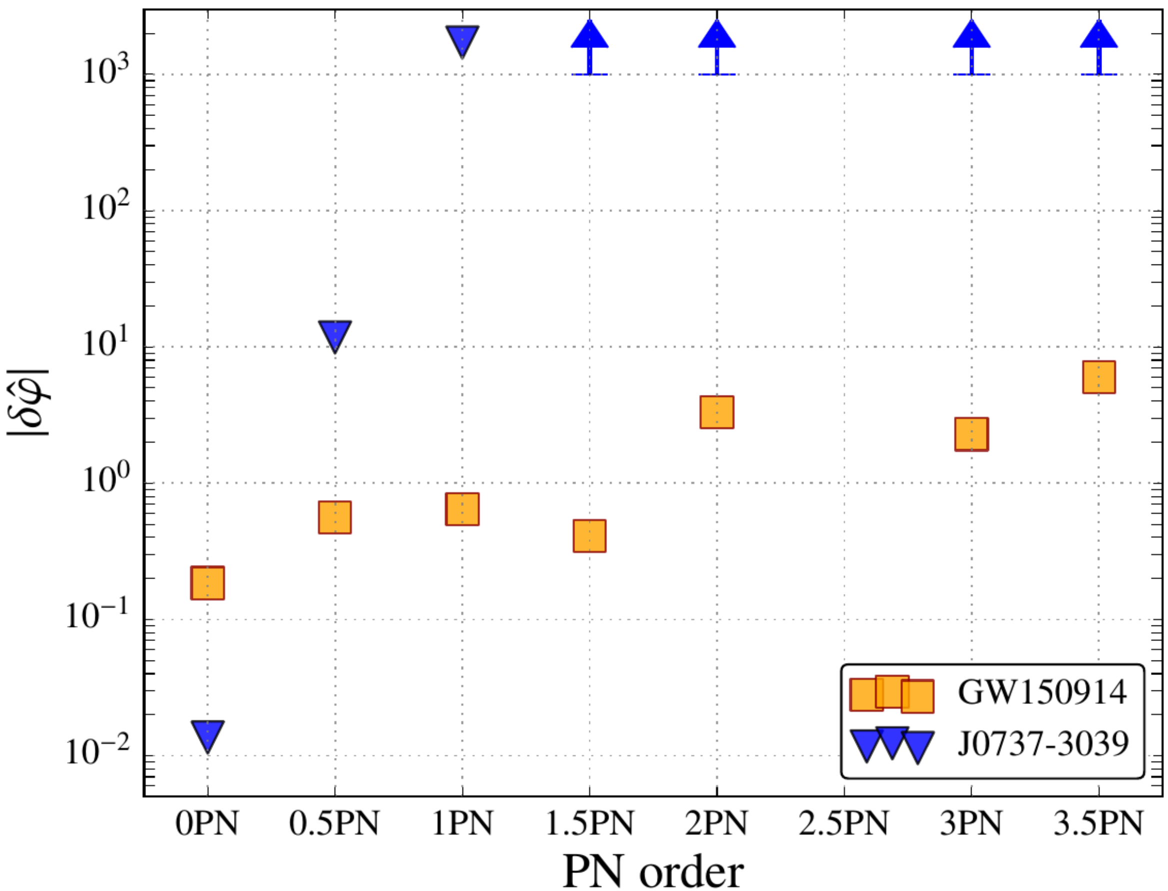
$$p_i \rightarrow (1 + \delta\hat{p}_i)p_i$$

- inspiral $\{\delta\hat{\varphi}_i\}$
- intermediate $\{\delta\hat{\beta}_i\}$
- merger-ringdown $\{\delta\hat{\alpha}_i\}$

First tests of strong field dynamics

- Bounds on deviations in post-Newtonian coefficients, which govern inspiral





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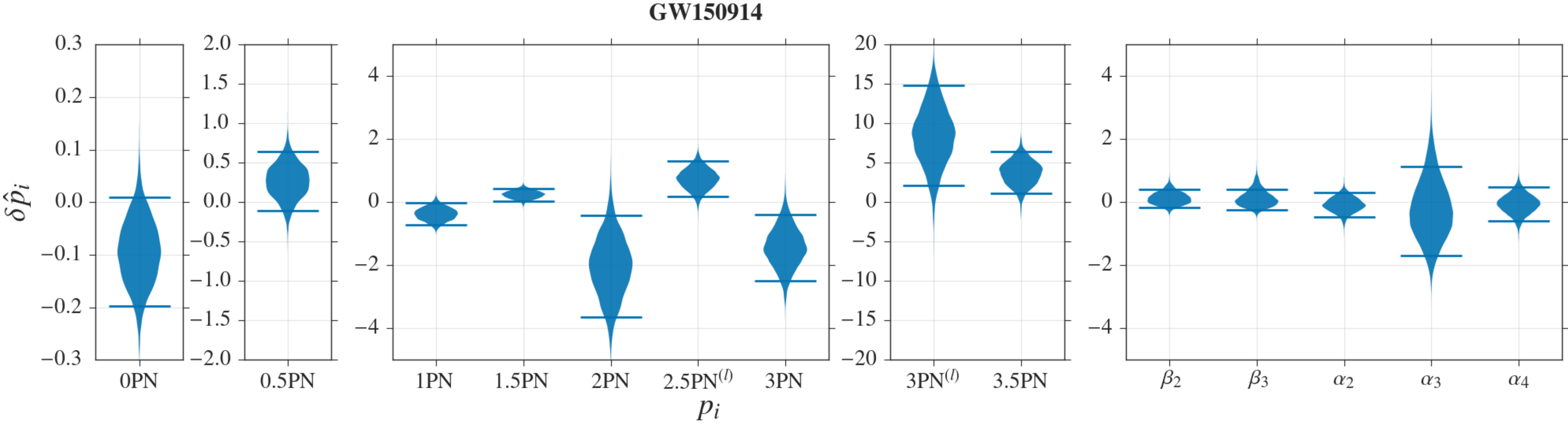
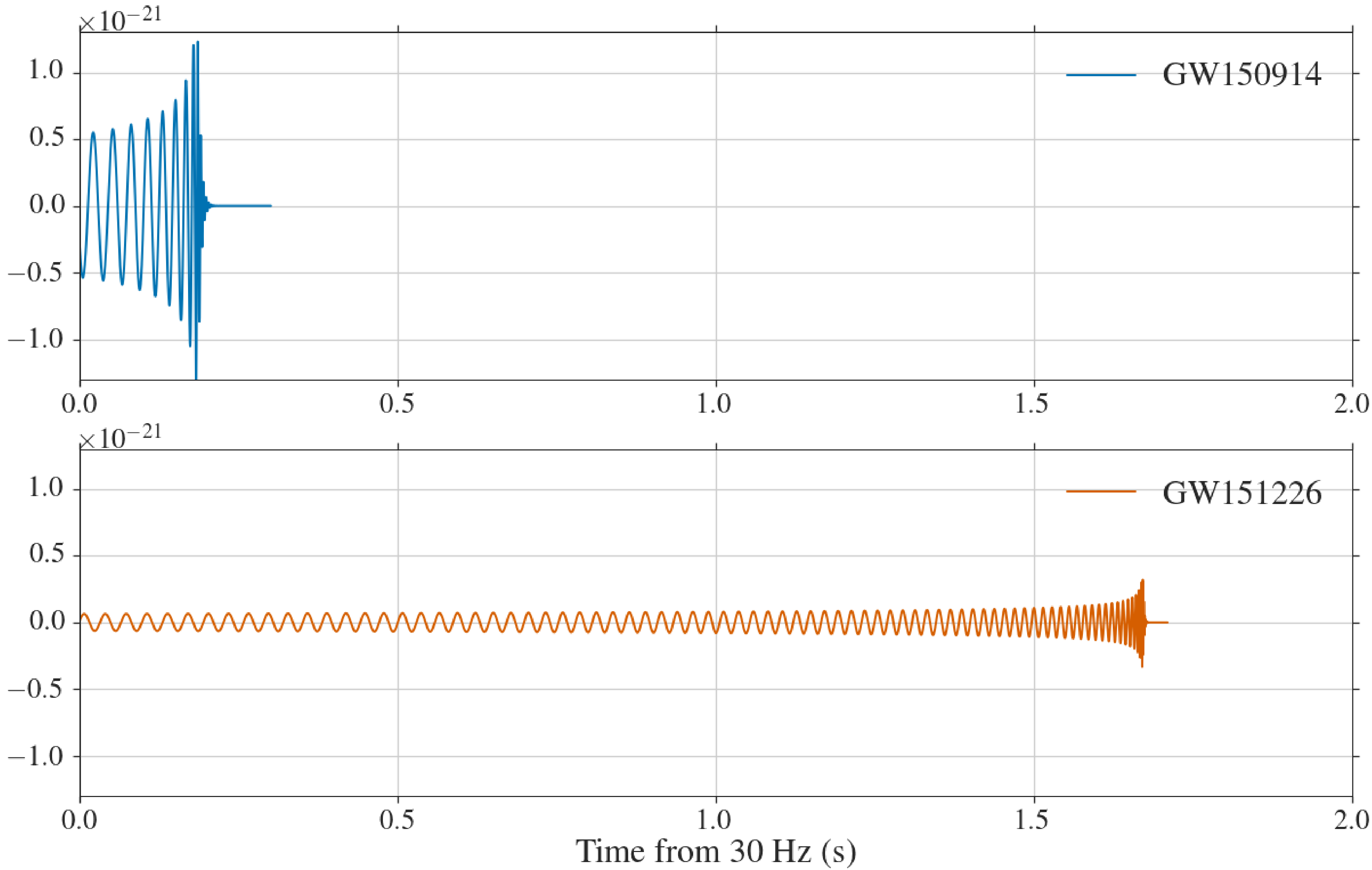
Posteriors on test parameters

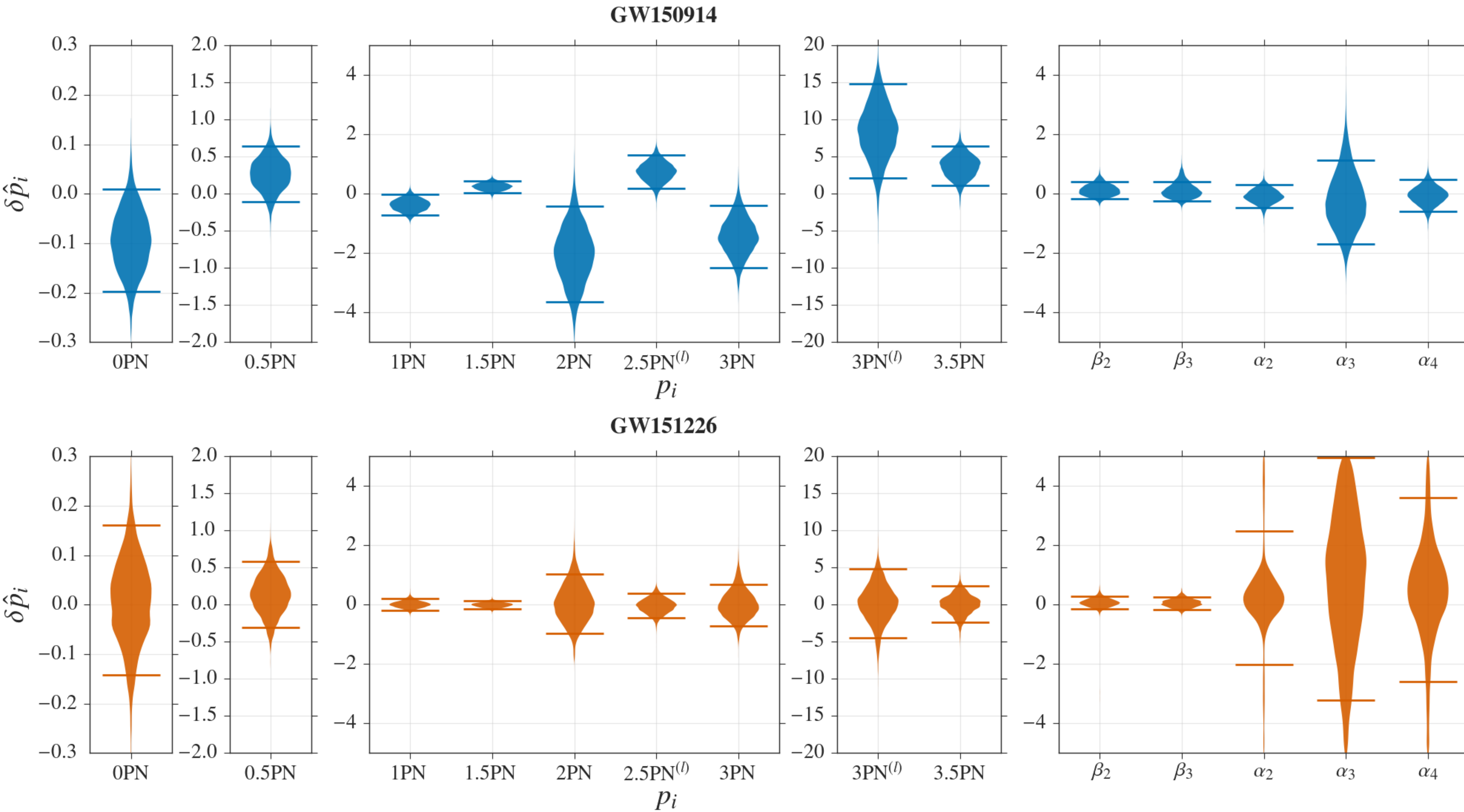


LIGO-Virgo Collaboration, LIGO Document Control Center P1600088 (2016), url:https://dcc.ligo.org/LIGO-P1600088/public.

Enter GW151226



Posteriors on test parameters



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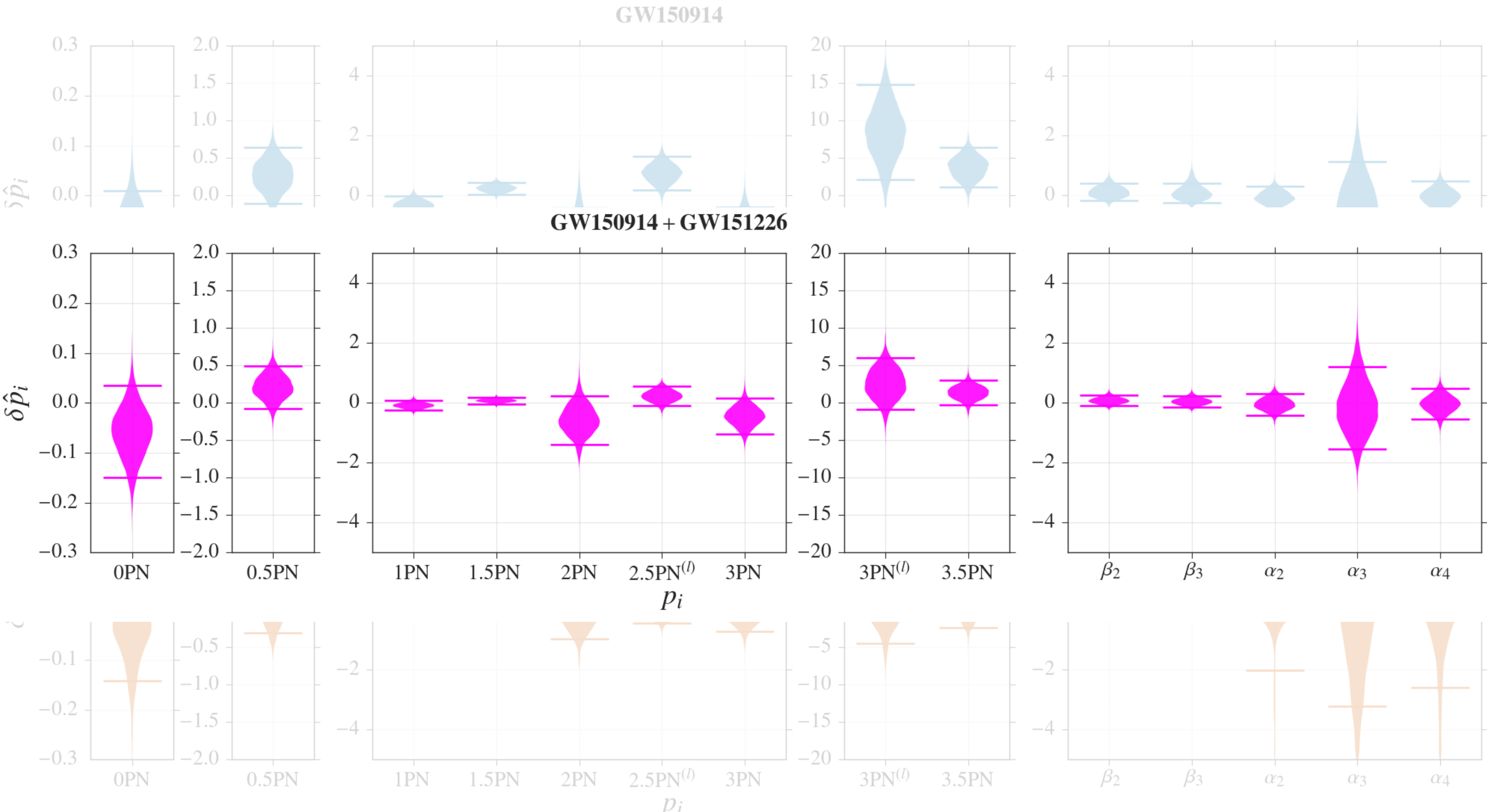
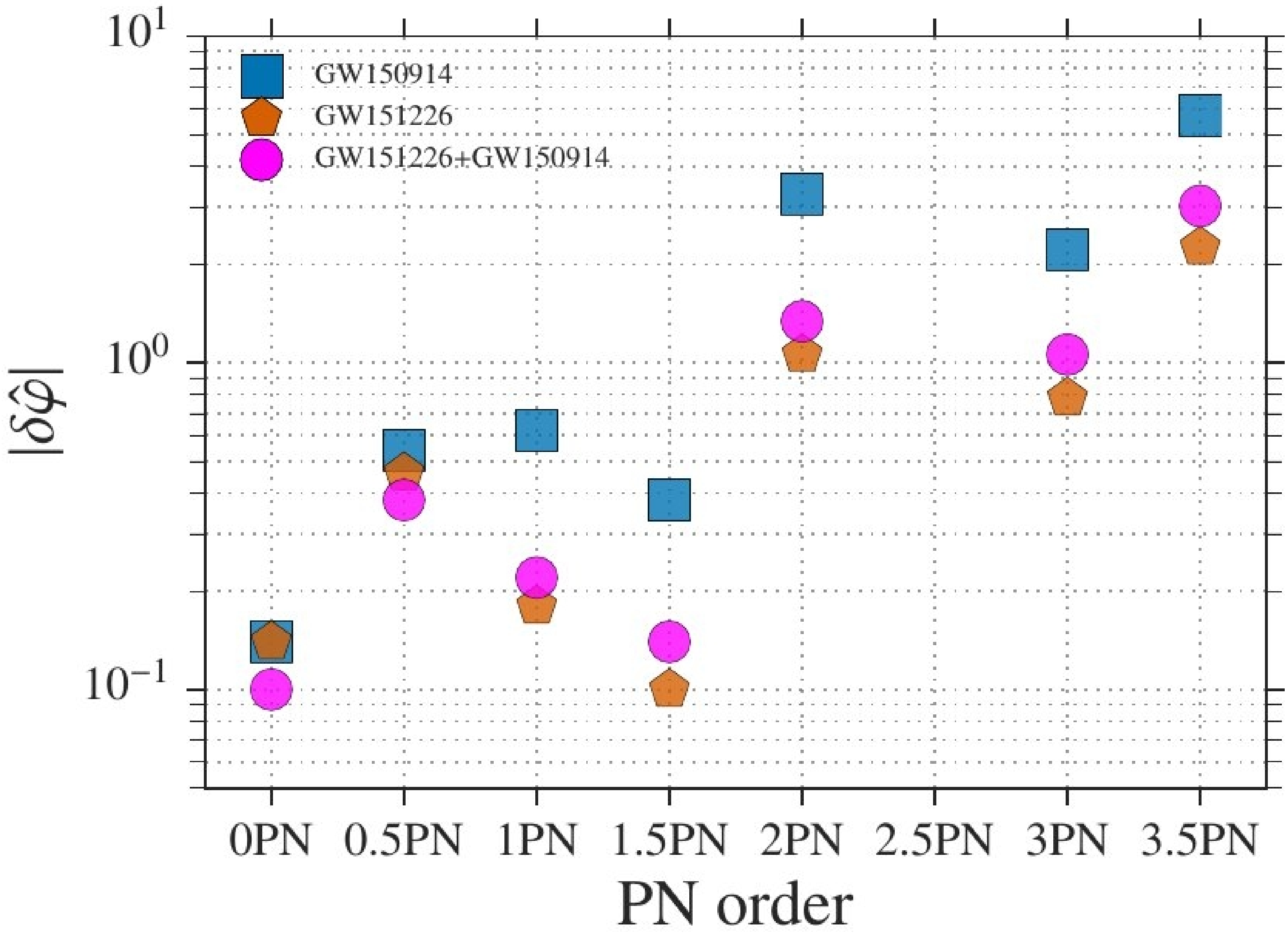


LIGO-Virgo Collaboration, LIGO Document Control Center P1600088 (2016), url:https://dcc.ligo.org/LIGO-P1600088/public.

Combined bounds on PN coefficients



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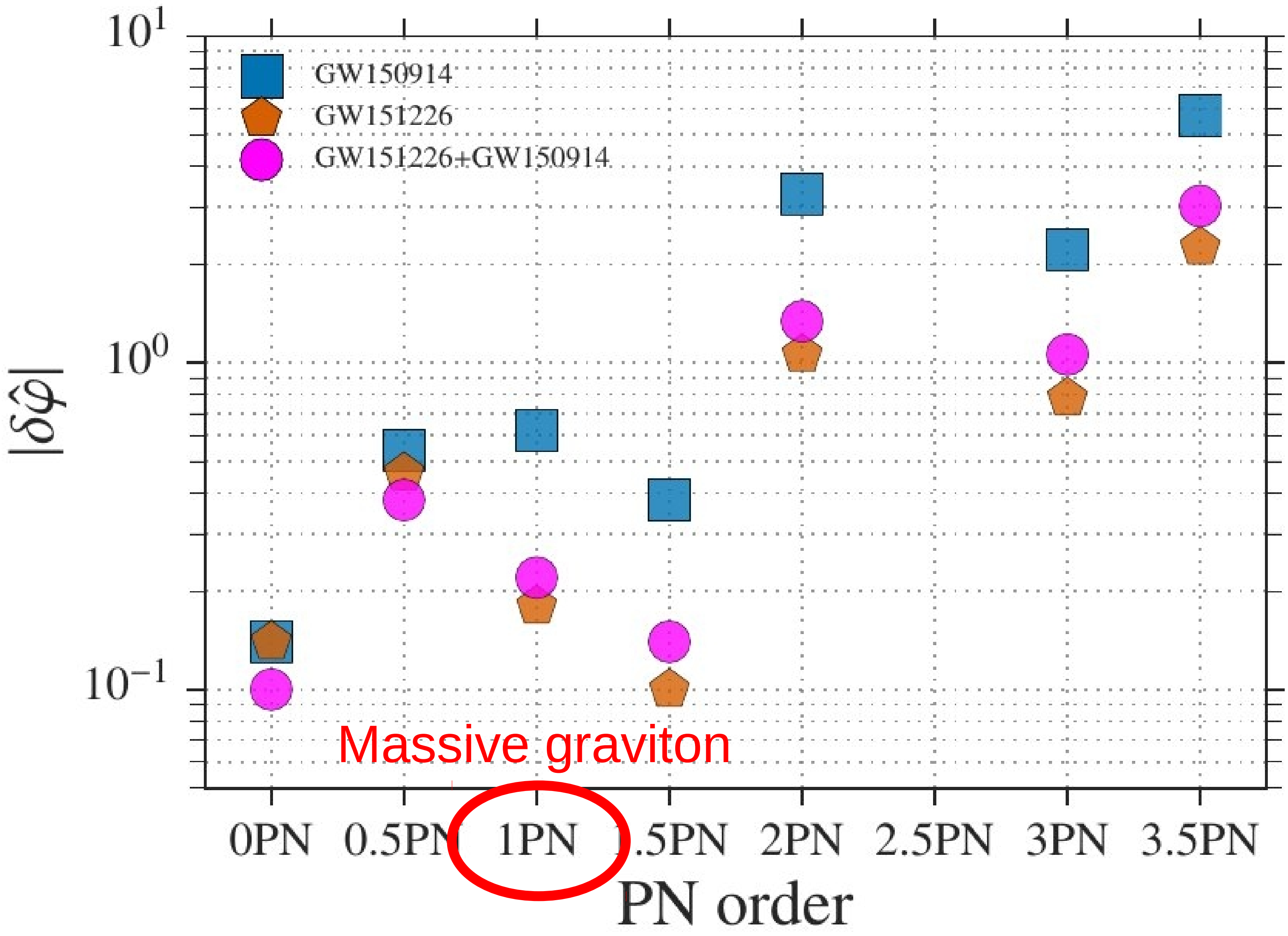

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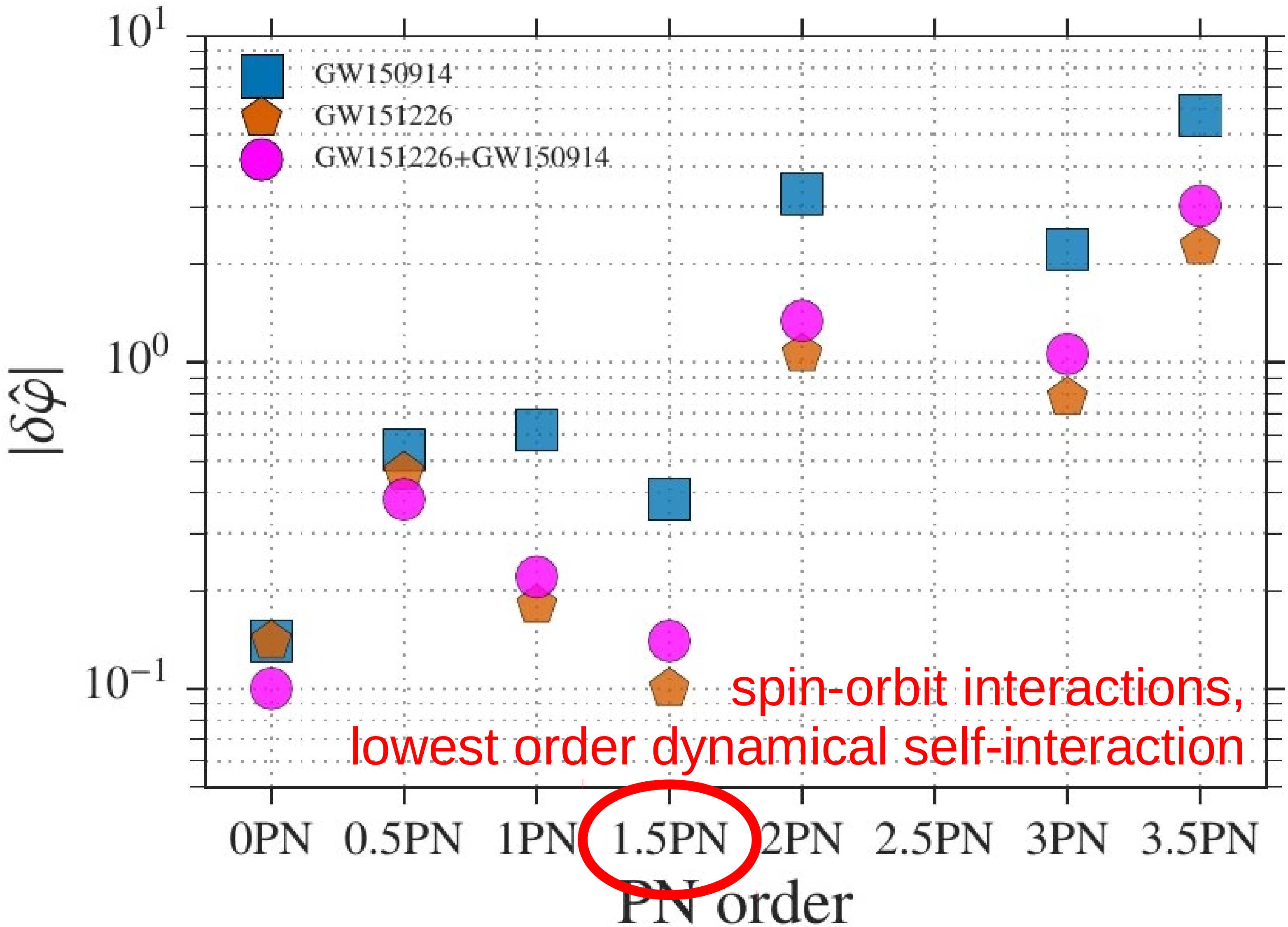

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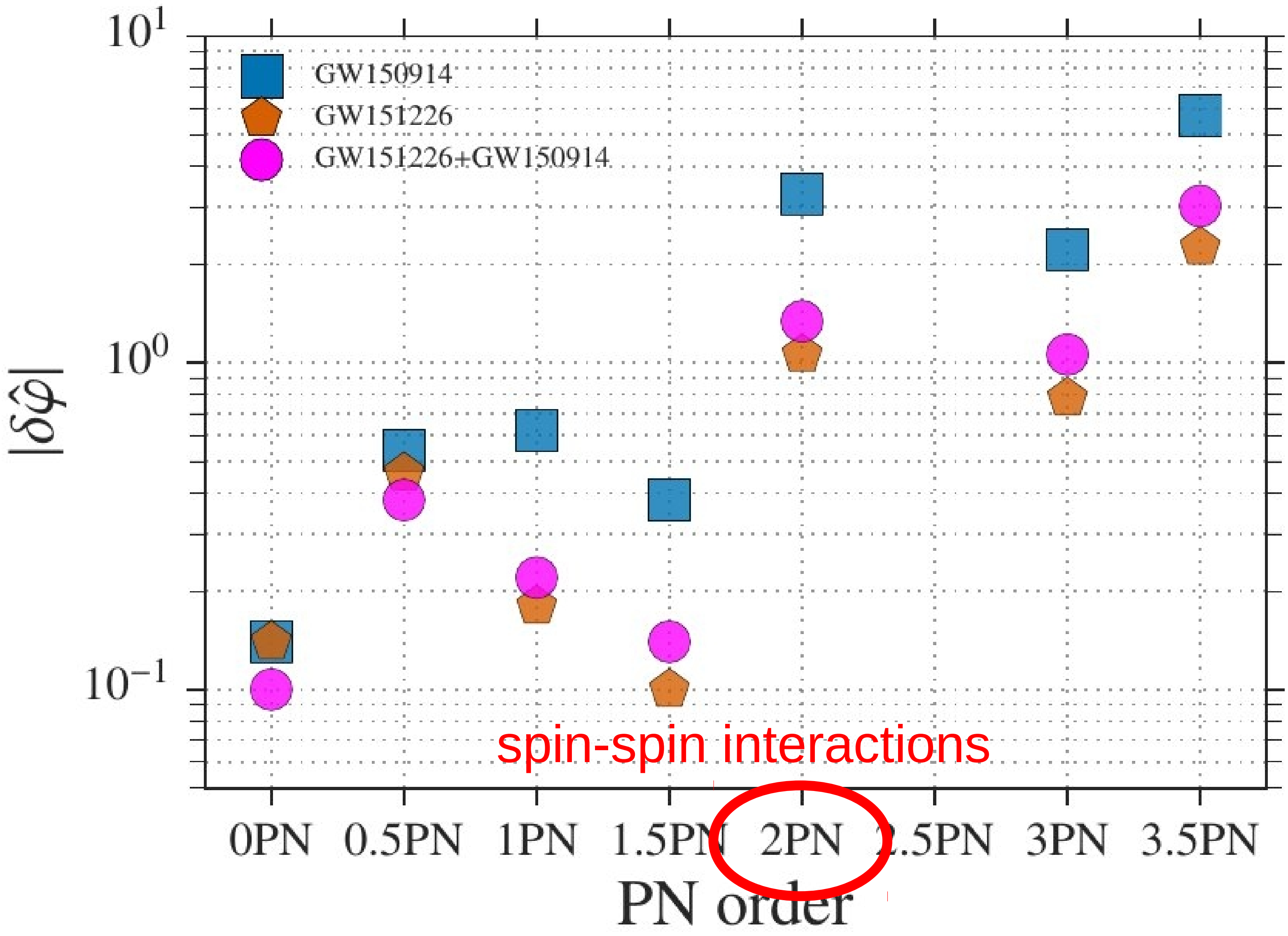

Summary

- Residual data after subtraction of best fitting waveform consistent with noise
- Masses, spins of component objects consistent with mass, spin of final black hole
- Final part of waveform consistent with there being least damped quasi-normal mode
- New dynamical bound on graviton Compton wavelength and mass

$$\lambda_g > 10^{13}\,\mathrm{km}$$

$$m_g \leq 1.2 \times 10^{-22}\,\mathrm{eV}/c^2$$

- As expected, can not distinguish between GR and non-GR polarizations using only two detectors with similar orientations
- Parameterized tests of inspiral-merger-ringdown dynamics
  - Constraints on deviations in post-Newtonian parameters up to high order
    - ~10% accuracy at 1.5PN
      (lowest order effects of dynamical self-interaction of spacetime geometry, spin-orbit interaction)
  - Constraints on deviations in merger-ringdown

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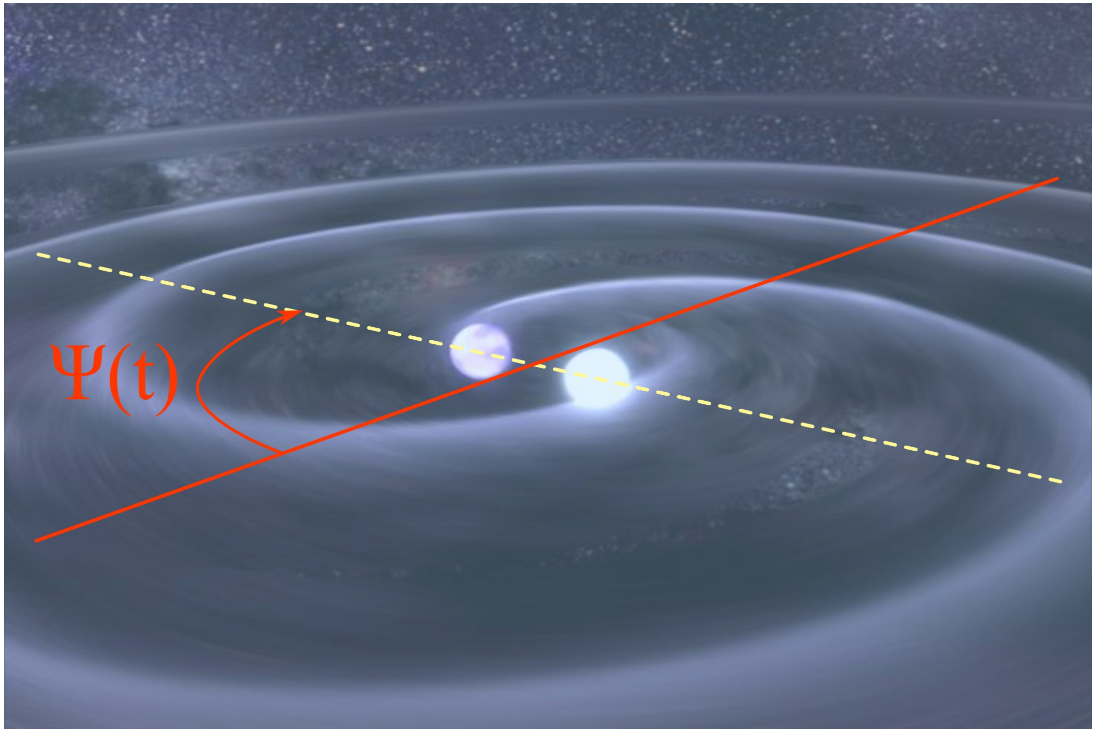
So far all results consistent with strong field dynamics of general relativity

Backups

The inspiral of compact binaries



- Orbital motion during inspiral in terms of

$$\Psi(v) = \left(\frac{v}{c}\right)^{-5} \sum_{n=0}^{7} \left[\psi_n + \psi_n^{(l)} \ln \frac{v}{c}\right] \left(\frac{v}{c}\right)^n$$

- Up to factor 2, also the phase of GW signal
- In general relativity: ψ_n and $\psi_n^{(l)}$ are specific functions of component masses and spins