Tests of general relativity with gravitational waves

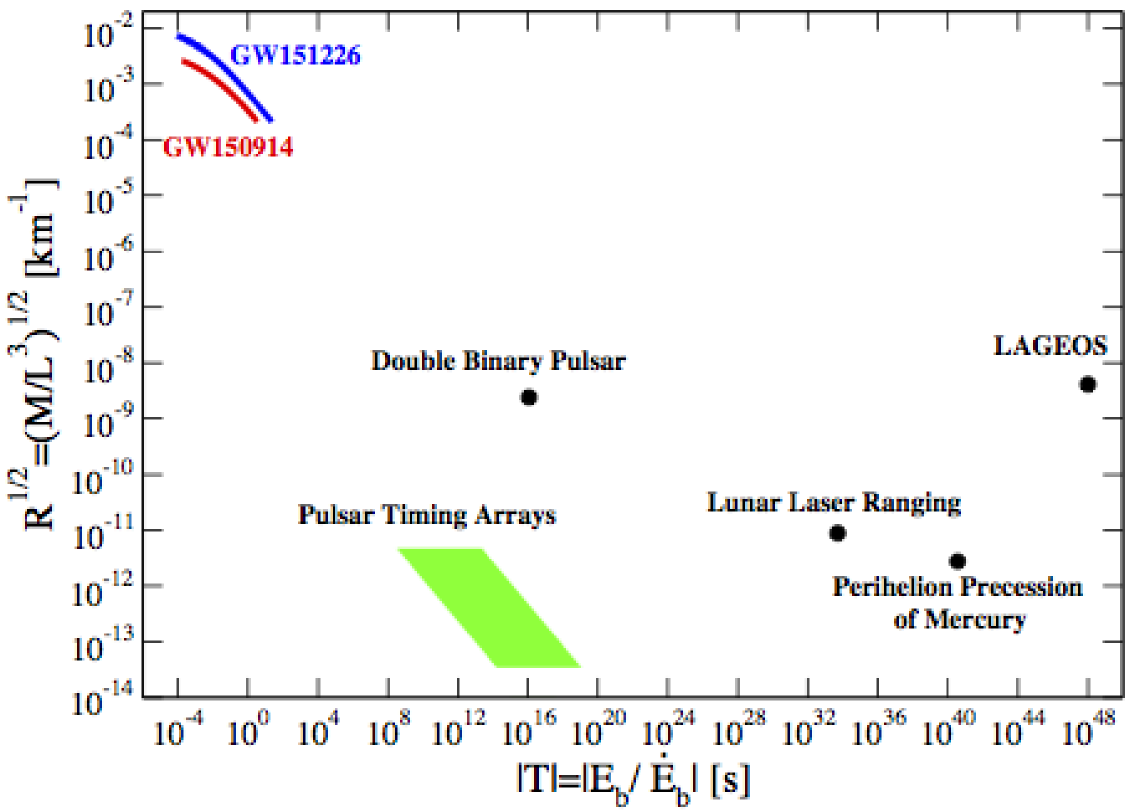
Chris Van Den Broeck

Nikhef

On behalf of the LIGO Scientific Collaboration and the Virgo Collaboration

TeVPA 2016, 12-16 September 2016, CERN

Binary black hole mergers as laboratories to test GR

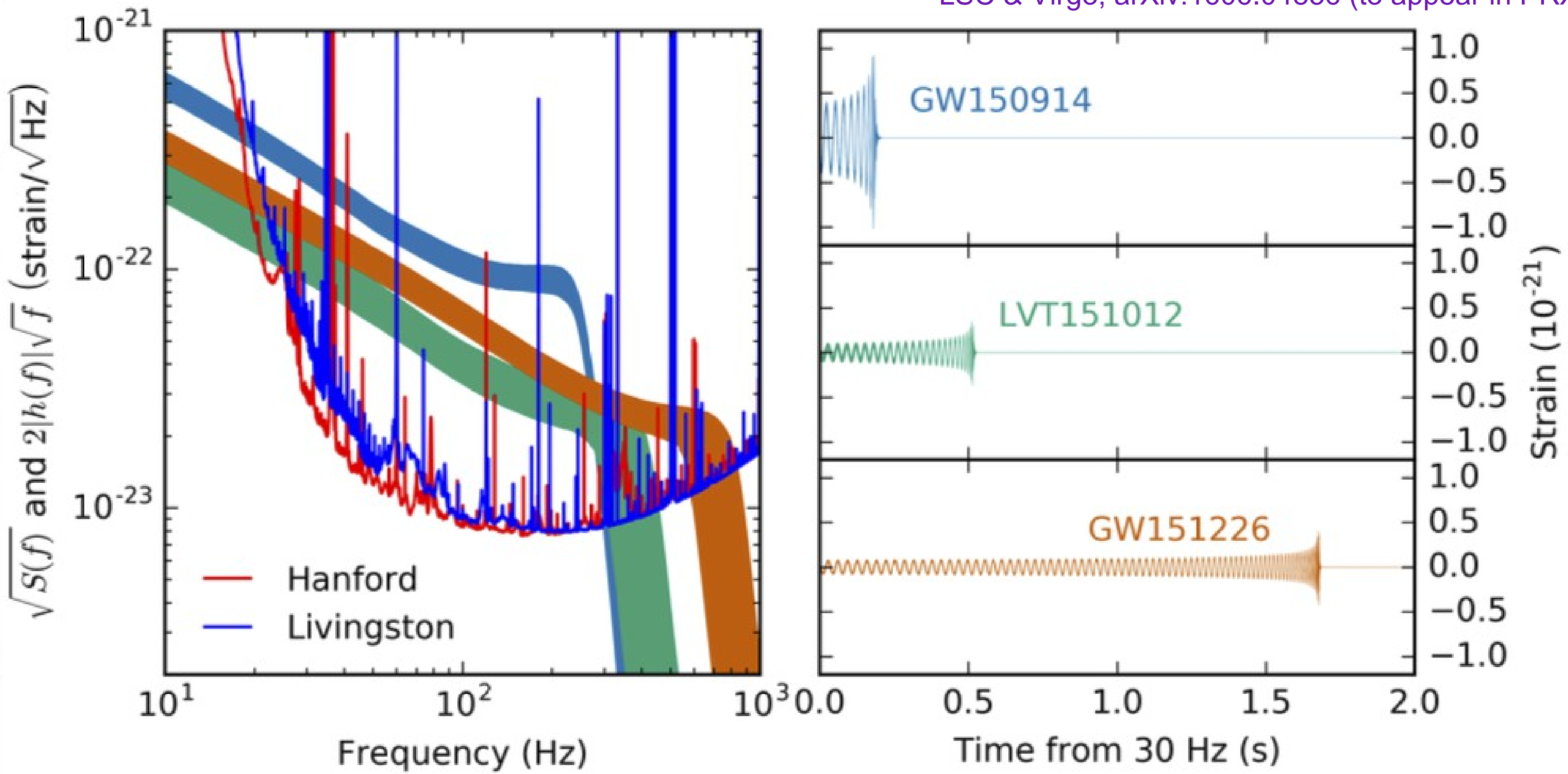


Yunes et al., arXiv:1603.08955

- ☐ Empirical access to genuinely strong-field dynamics of gravity
- ☐ Pure spacetime process
- ☐ Rich phenomenology

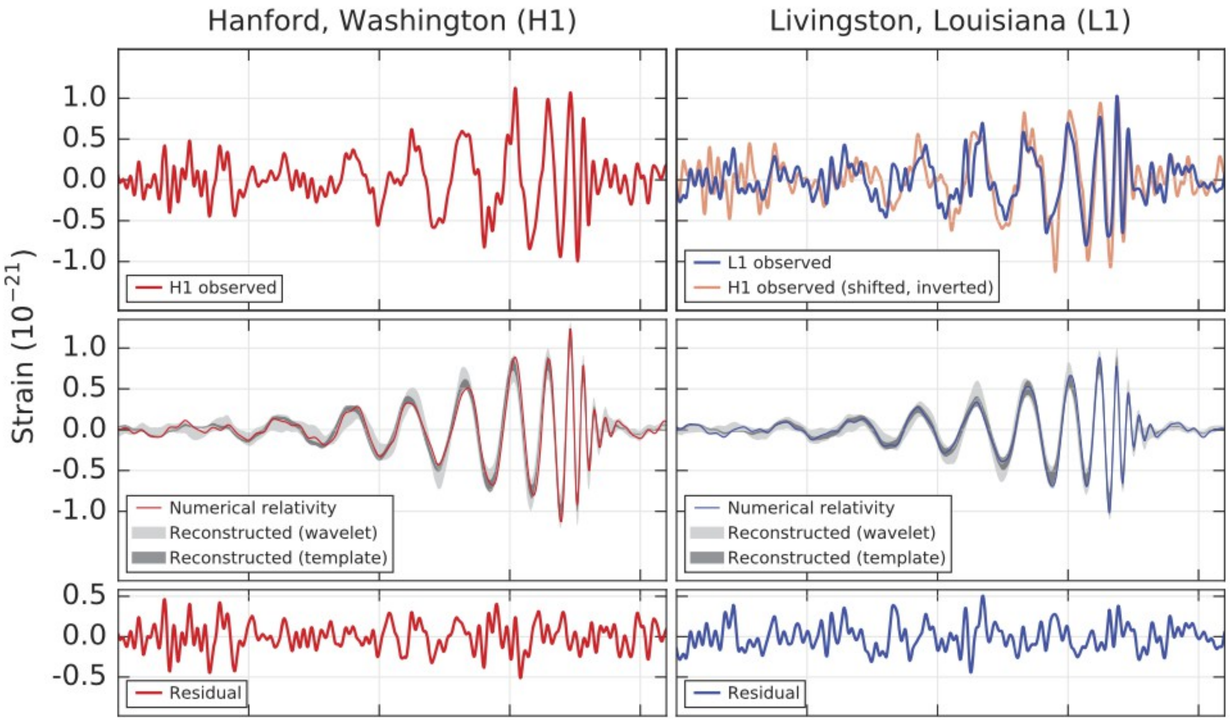
The events as seen in the detectors

LSC & Virgo, arXiv:1606.04856 (to appear in PRX)



- Test GR for different aspects of the coalescence process
  - GW150914: short inspiral; merger and ringdown visible
  - GW151226: mostly inspiral visible

(1) Residual data after subtracting best-fitting waveform

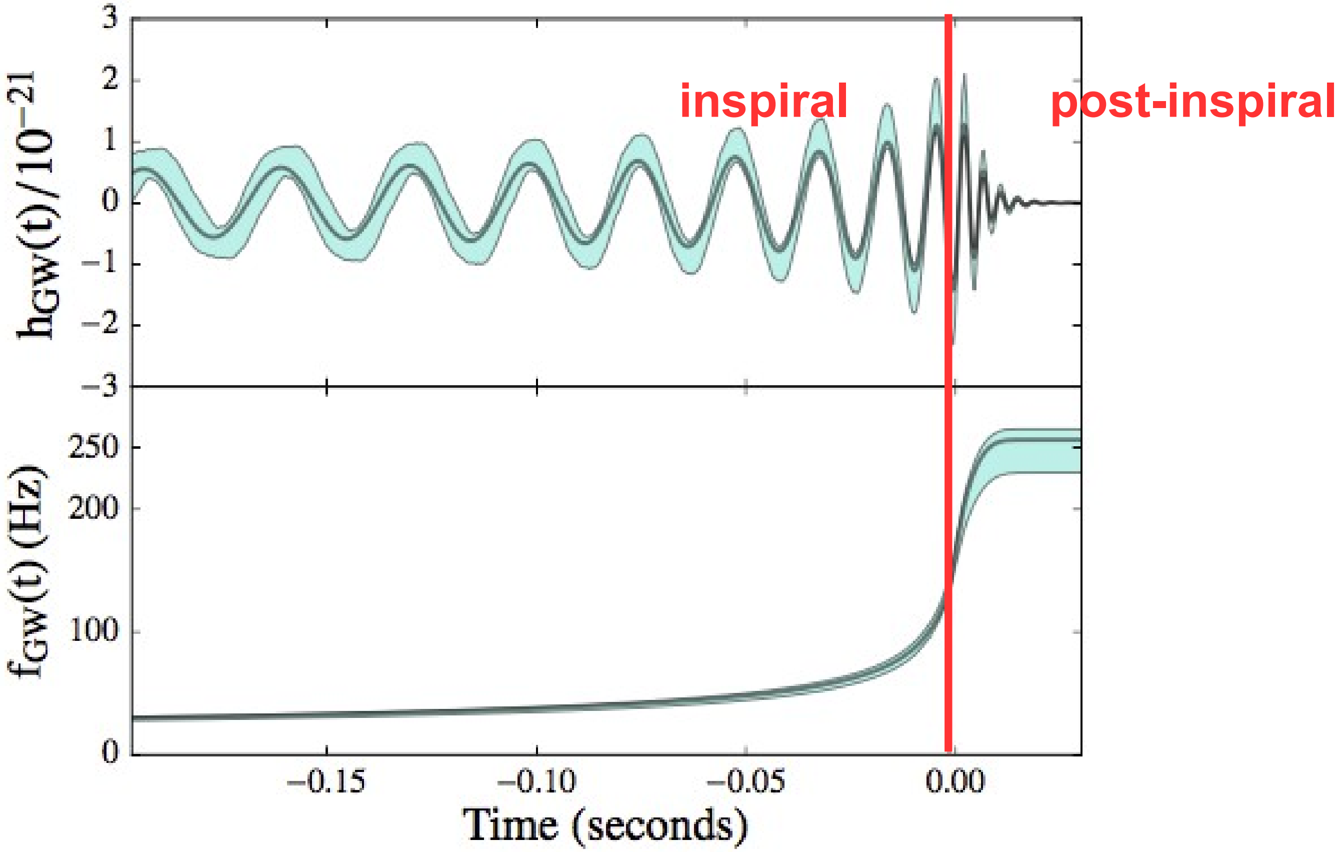


LSC & Virgo, Phys. Rev. Lett. **116**, 061102 (2016)

- Subtract from data the best-fitting waveform model (GR prediction)
- Residual data statistically consistent with detector noise near GW150914

(2) Consistency of masses and spins of initial and final objects

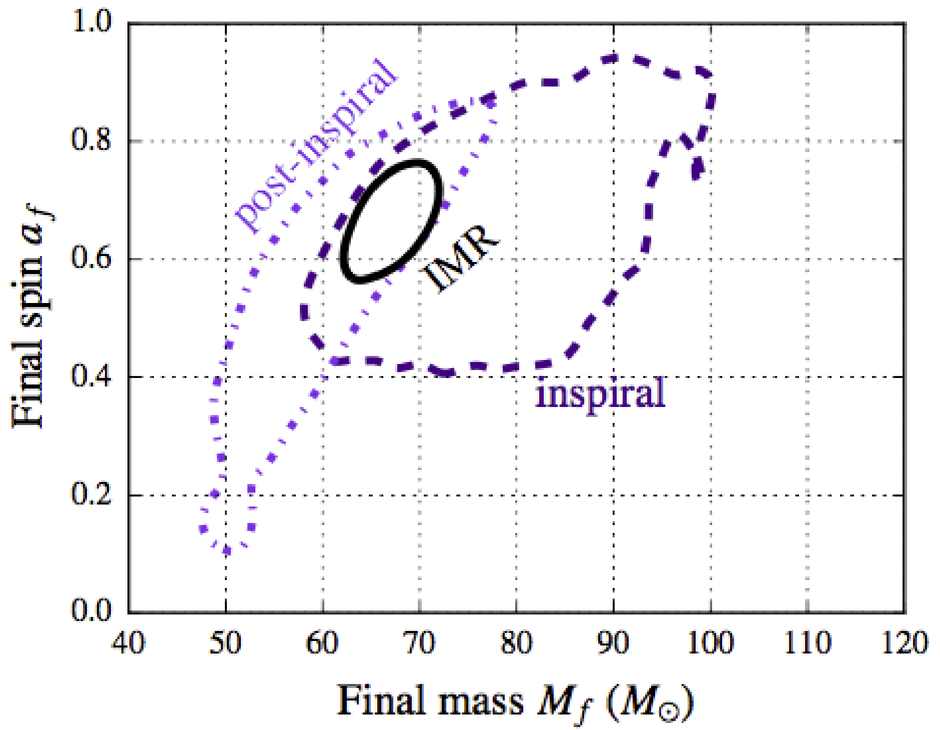
LSC & Virgo, Phys. Rev. Lett. **116**, 221101 (2016)



- Measure masses, spins of component black holes from *inspiral* signal
- General relativity allows to predict mass, spin of final black hole
- Compare with mass, spin of final black hole obtained from *post-inspiral*

(2) Consistency of masses and spins of initial and final objects

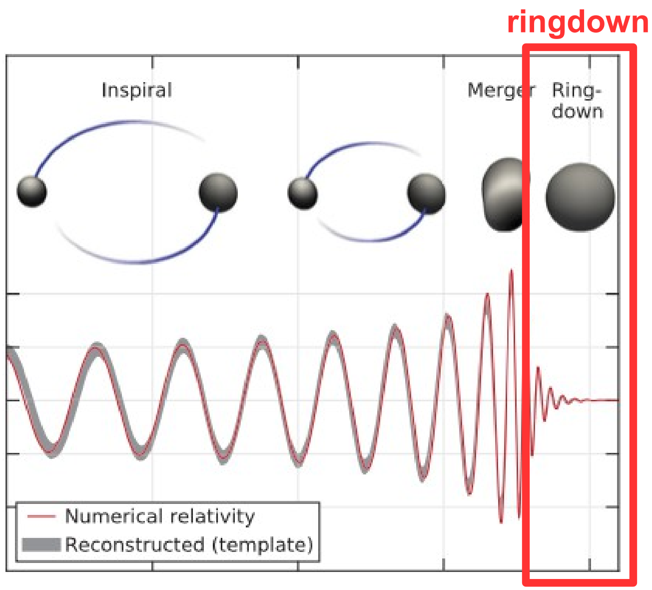
LSC & Virgo, Phys. Rev. Lett. **116**, 221101 (2016)

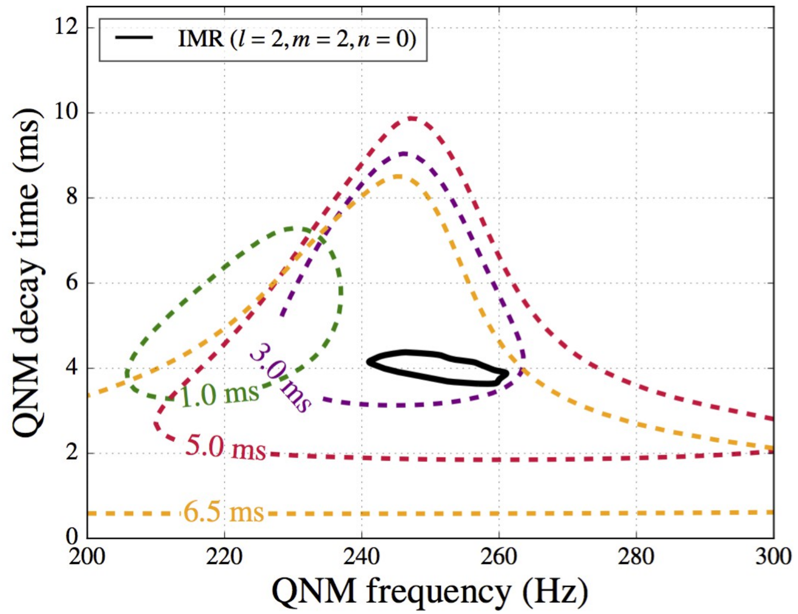


- Measure masses, spins of component black holes from *inspiral* signal
- General relativity allows to predict mass, spin of final black hole
- Compare with mass, spin of final black hole obtained from *post-inspiral*

(3) Did the final object ring down as predicted?

LSC & Virgo, Phys. Rev. Lett. **116**, 221101 (2016)

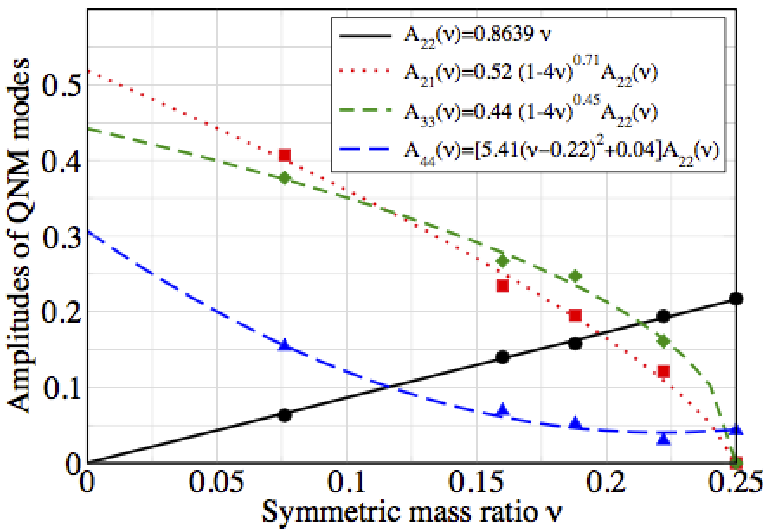




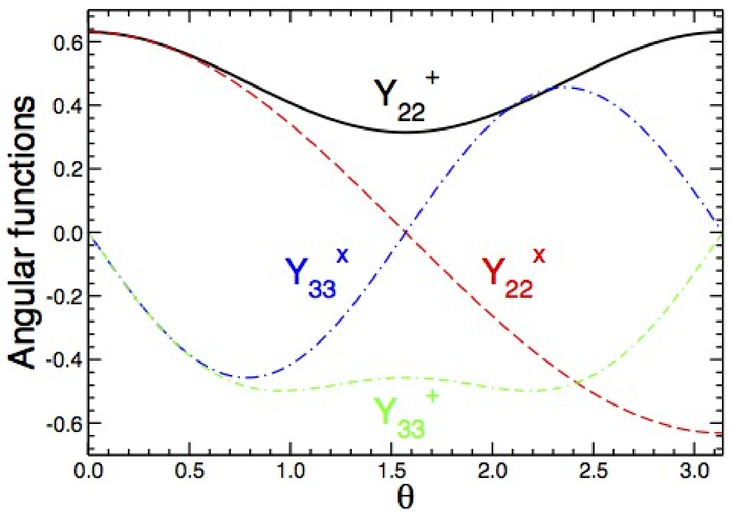
- ☐ Evidence for a least-damped "quasi-normal" mode?
  - Fit damped sinusoid starting at different times after merger
  - Frequency, damping time consistent with expectation

Testing the black hole no-hair theorem?

- If multiple quasi-normal modes could be observed: test of no-hair theorem
  - Damping times τ_{nlm} and frequencies f_{nlm} only depend on M_f and a_f
  - Hence only two of them are independent → consistency test
- For multiple quasi-normal modes to be visible, need system with
  - Asymmetric component masses
  - More misalignment of orbital angular momentum with line of sight



Gossan et al., Phys. Rev. D **85**, 124056 (2012)

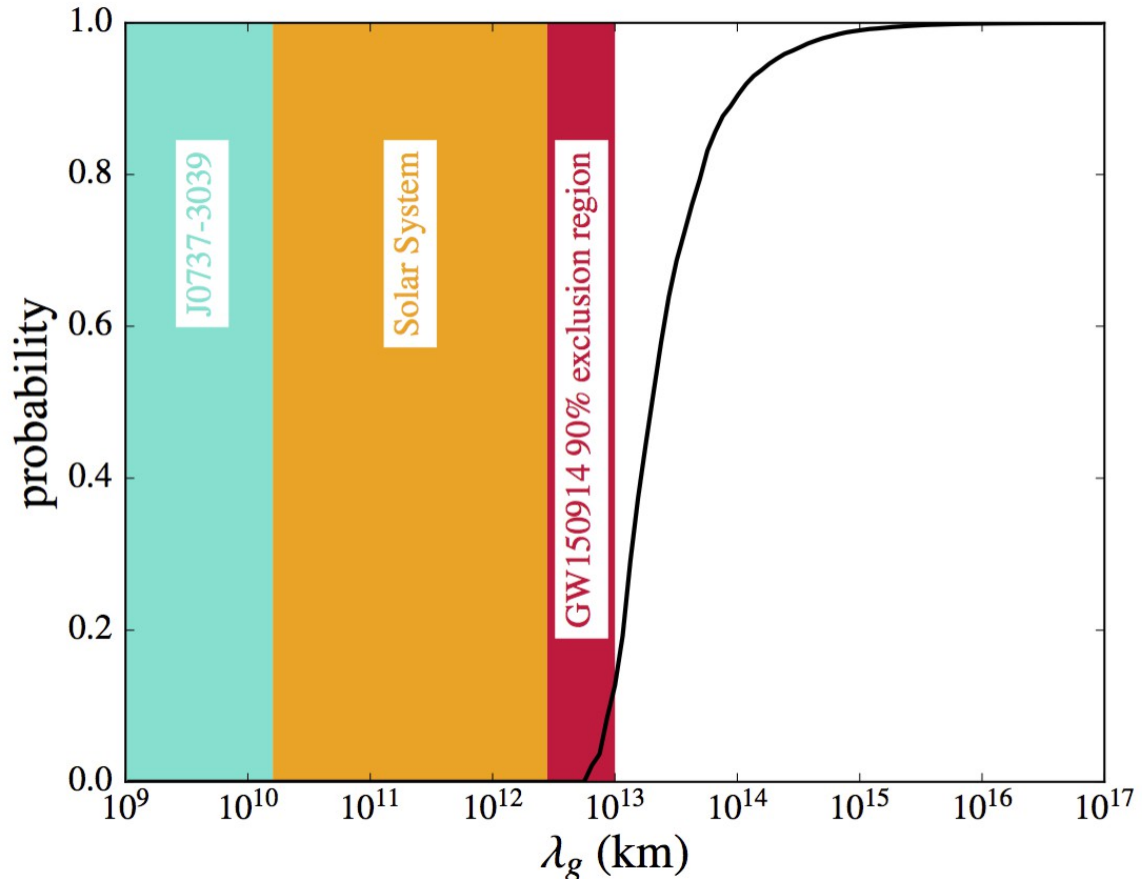


Berti et al., Phys. Rev. D **76**, 104044 (2007)

(4) Constraining the graviton Compton wavelength

$$E^2 = p^2c^2 + m_g^2c^4 \qquad \delta\Phi(f) = -\frac{\pi D c}{\lambda_g^2(1+z)} f^{-1} \qquad \lambda_g = \frac{h}{m_g c}$$

Will, Phys. Rev. D **57**, 2061 (1998)



$m_g < 1.2 \times 10^{-22}$ eV/c^2

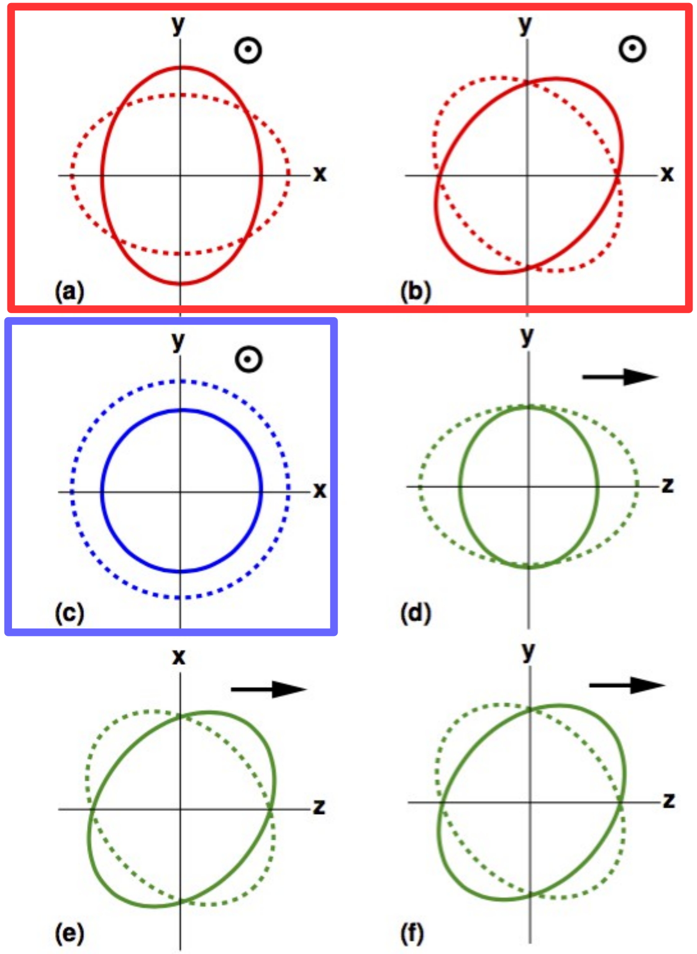
LSC & Virgo, Phys. Rev. Lett. **116**, 221101 (2016)

(5) No constraint on non-GR polarization states

- Metric theories of gravity allow for up to 6 polarization states
- Compare polarizations from GR with simple case of pure breathing mode
- Cannot distinguish between them:

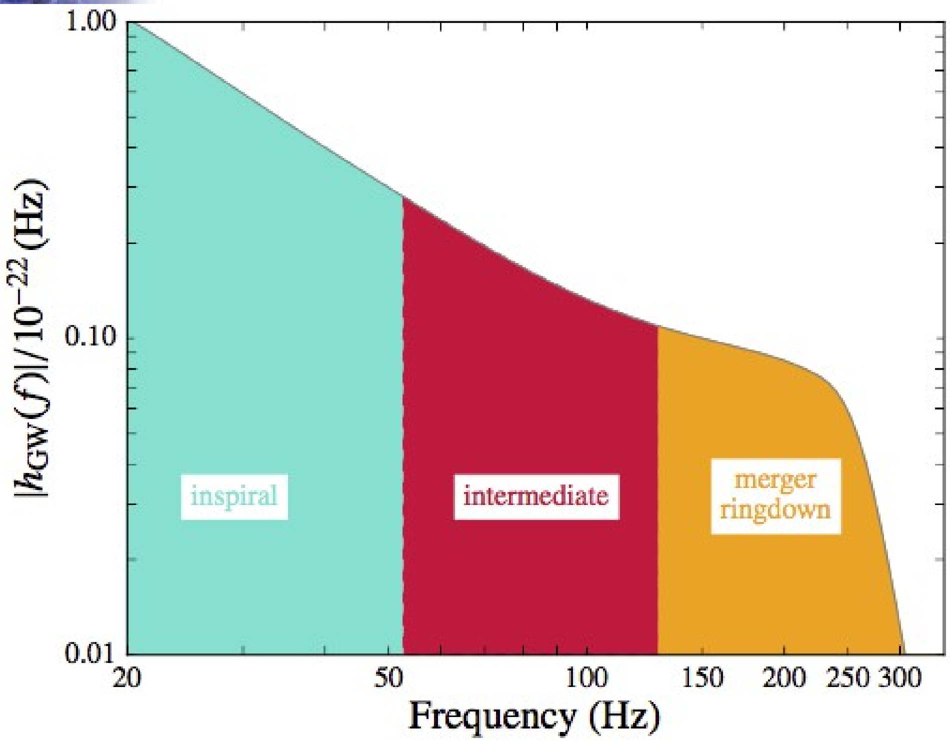
$$\log B^{\mathrm{GR}}_{\mathrm{scalar}} = -0.2 \pm 0.5$$

- Need larger network of detectors with different orientations
  - Advanced LIGO
  - Advanced Virgo
  - KAGRA
  - LIGO-India



Will, Liv. Rev. Rel. **17**, 4 (2014)

(6) Parameterized tests of the coalescence process

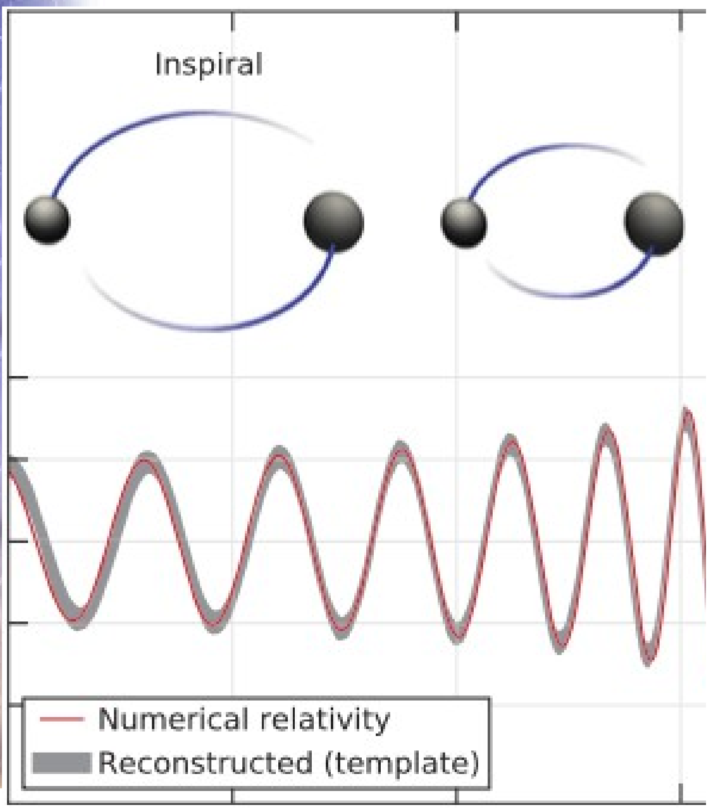


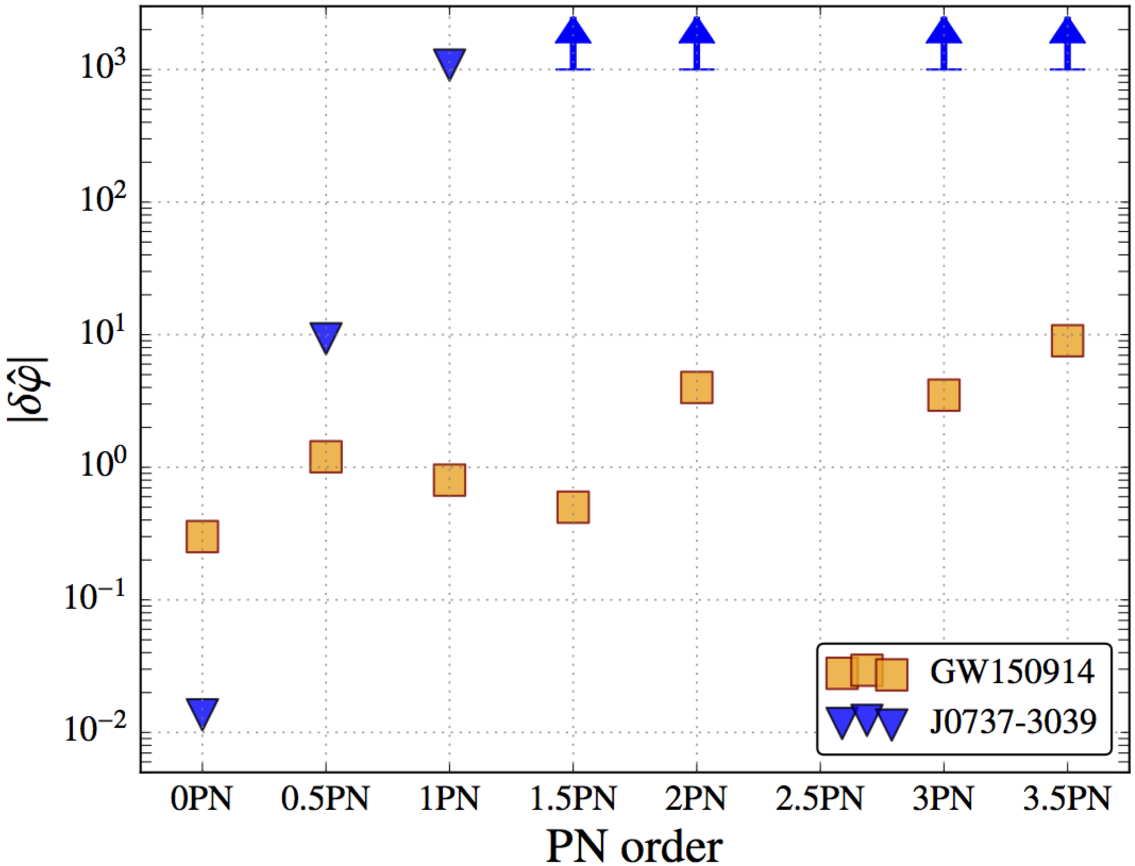
- Allow for fractional changes in parameters with respect to GR values $p_i \rightarrow (1 + \delta\hat{p}_i)\, p_i$
  - Inspiral: $\{\delta\hat{\varphi}_i\}$
  - Intermediate: $\{\delta\hat{\beta}_i\}$
  - Merger-ringdown: $\{\delta\hat{\alpha}_i\}$

LSC & Virgo, Phys. Rev. Lett. **116**, 221101 (2016)

(6) Parameterized tests of the coalescence process

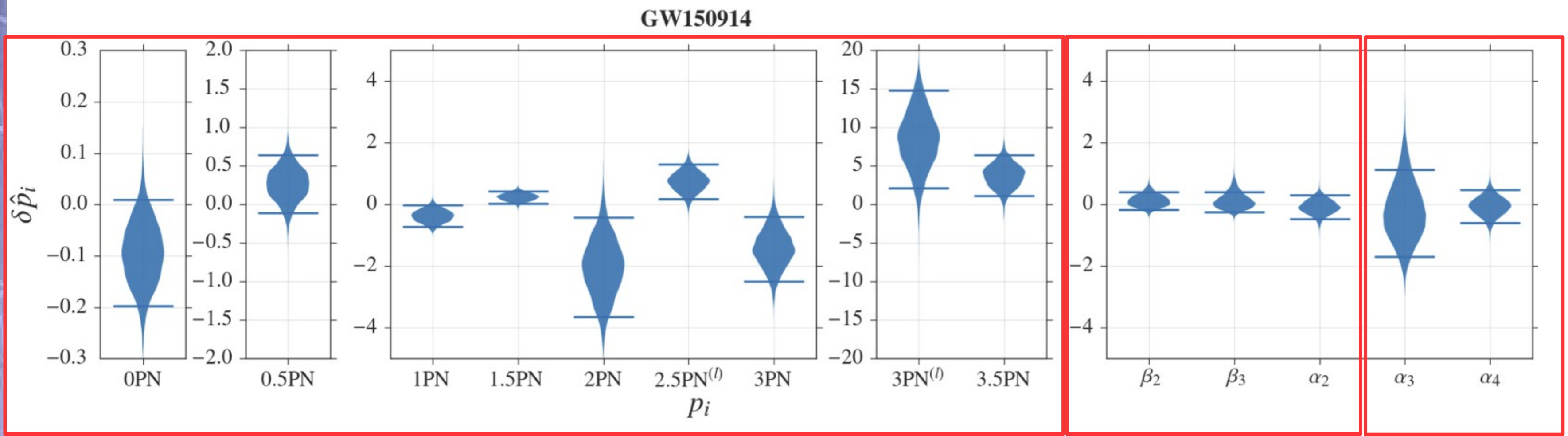
- GW150914:
  First-ever empirical bounds on high-order post-Newtonian inspiral parameters





LSC & Virgo, Phys. Rev. Lett. **116**, 221101 (2016)

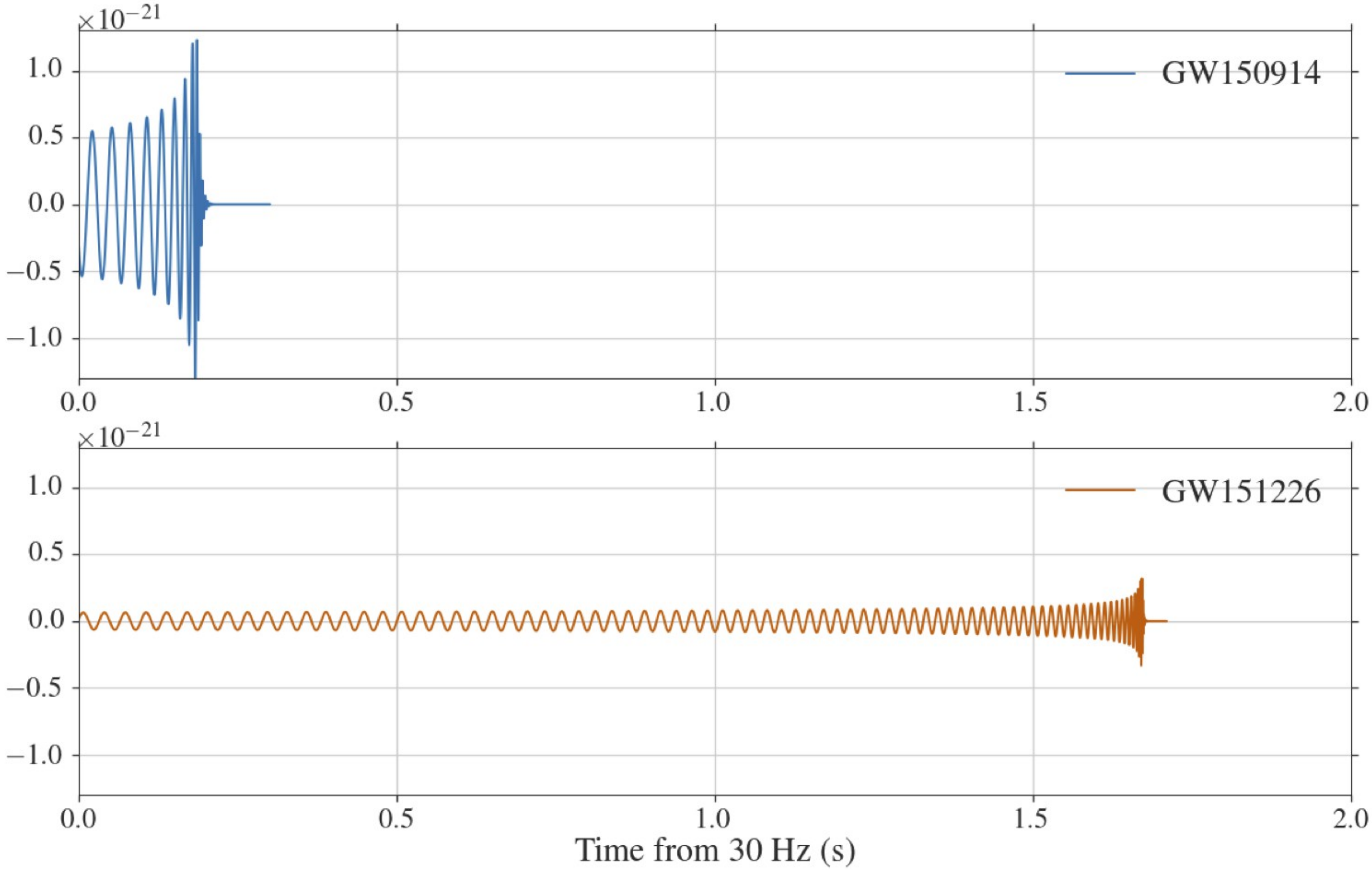
(6) Parameterized tests of the coalescence process



inspiral **intermediate** **merger-ringdown**

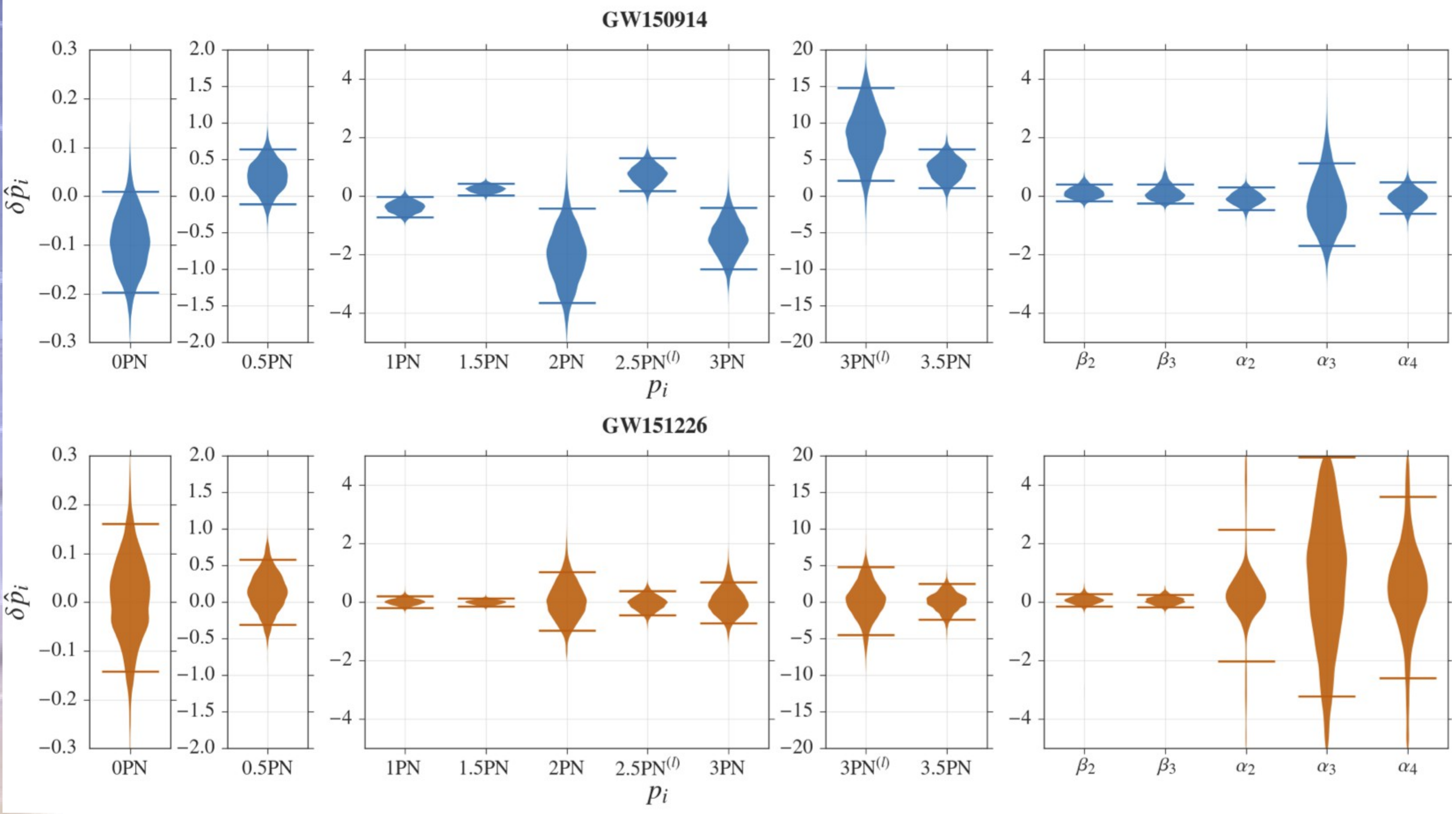
LSC & Virgo, arXiv:1606.04856 (to appear in PRX)

(6) Parameterized tests of the coalescence process



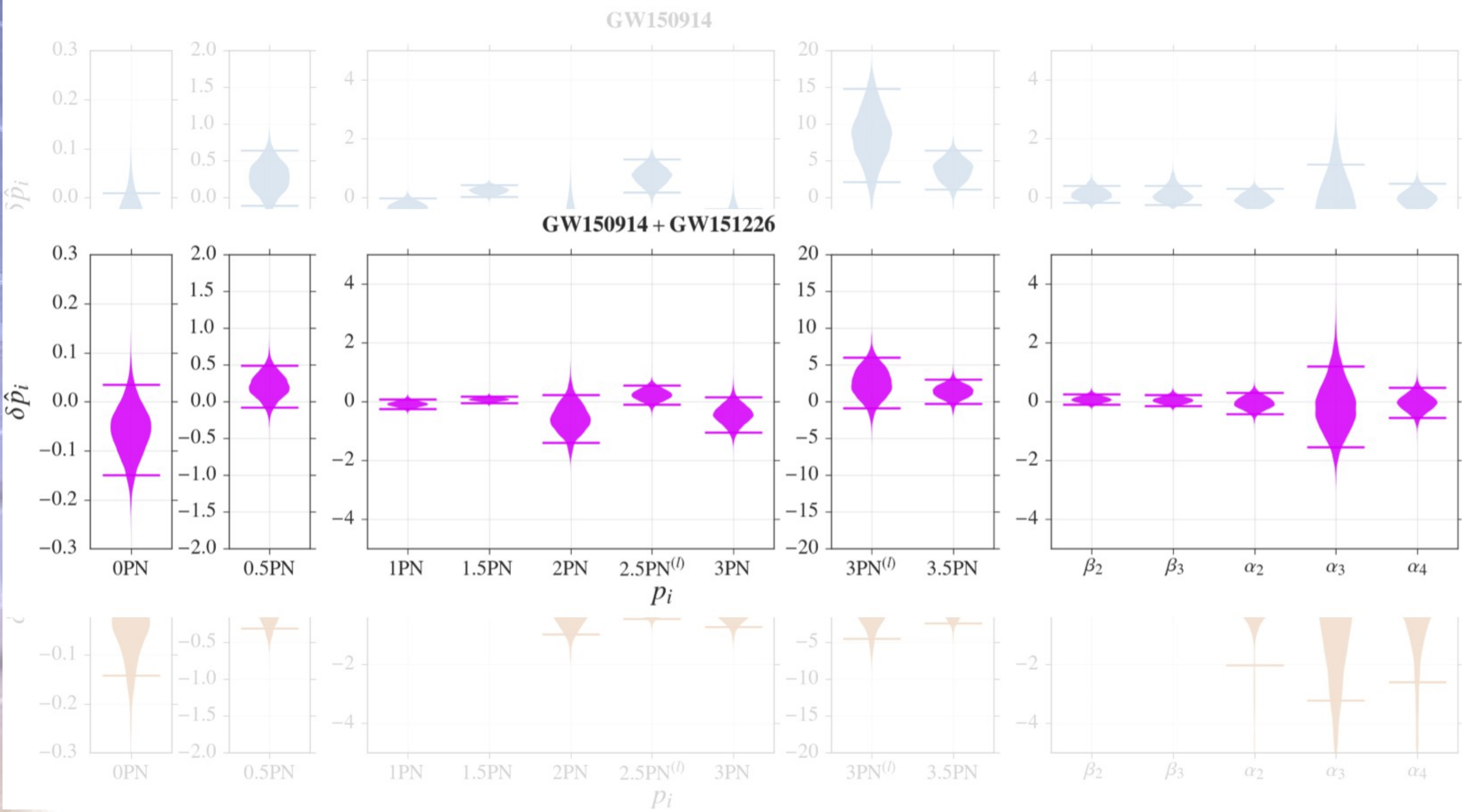
LSC & Virgo, arXiv:1606.04856 (to appear in PRX)

(6) Parameterized tests of the coalescence process



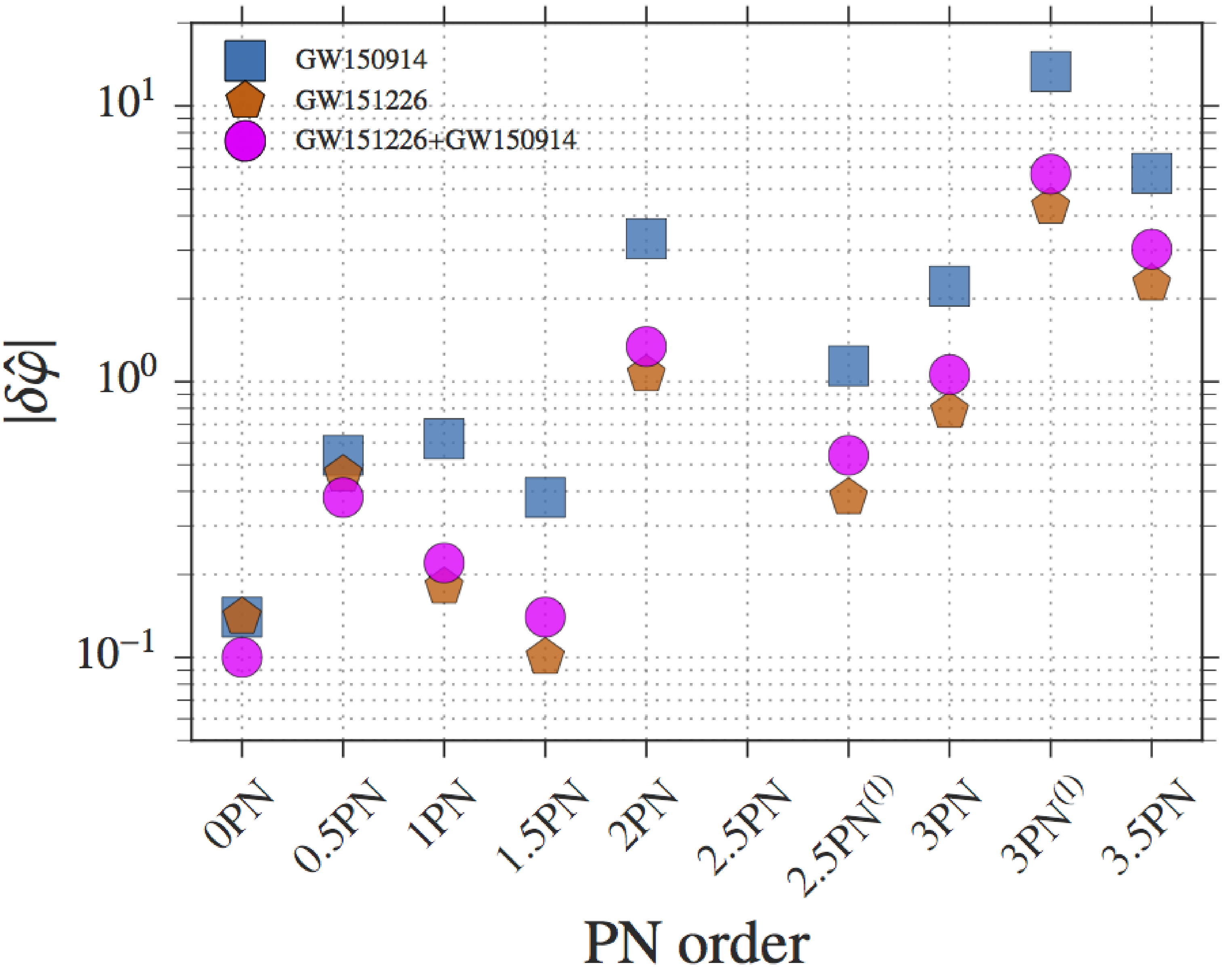
LSC & Virgo, arXiv:1606.04856 (to appear in PRX)

(6) Parameterized tests of the coalescence process



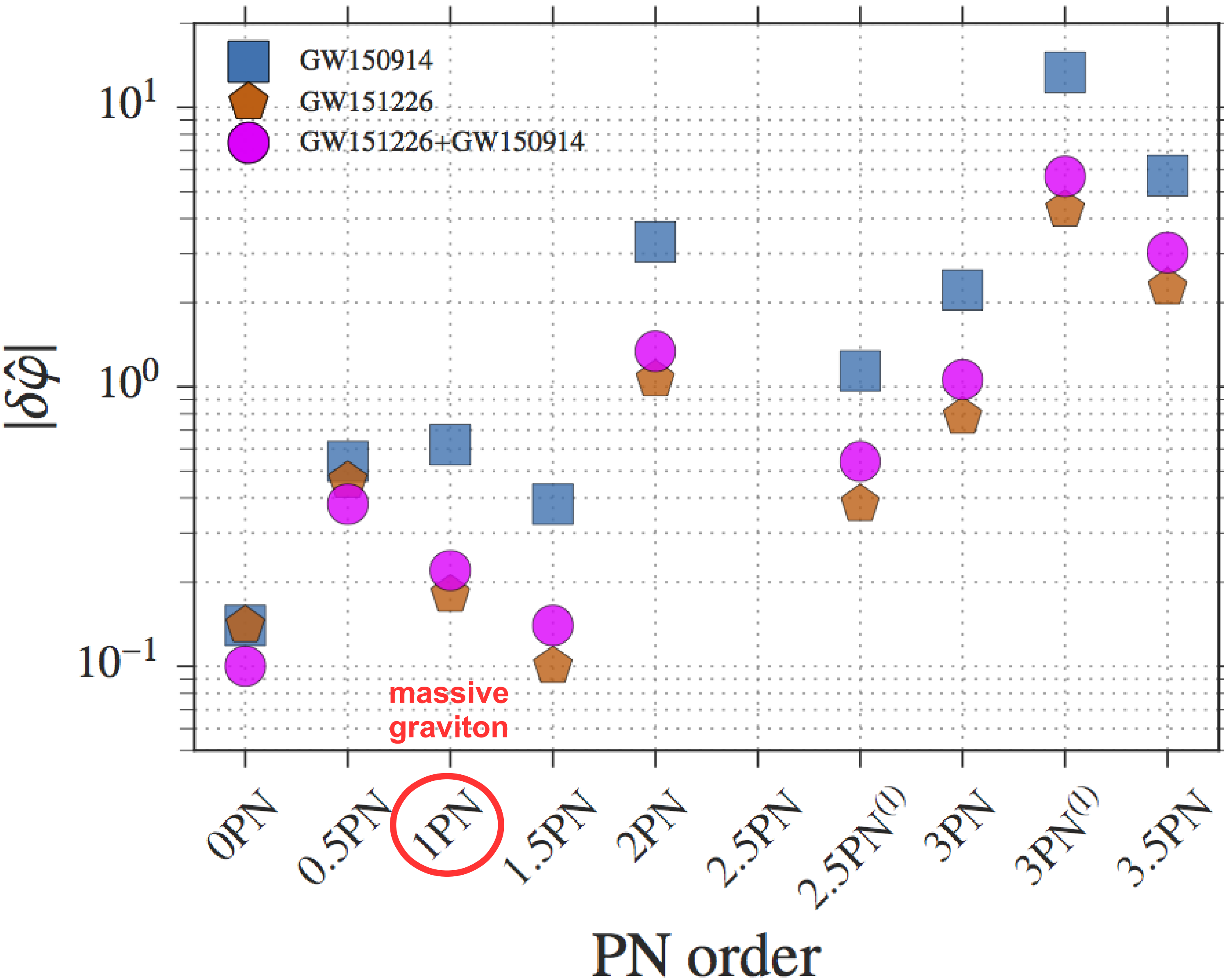
LSC & Virgo, arXiv:1606.04856 (to appear in PRX)

Combined bounds on post-Newtonian inspiral parameters



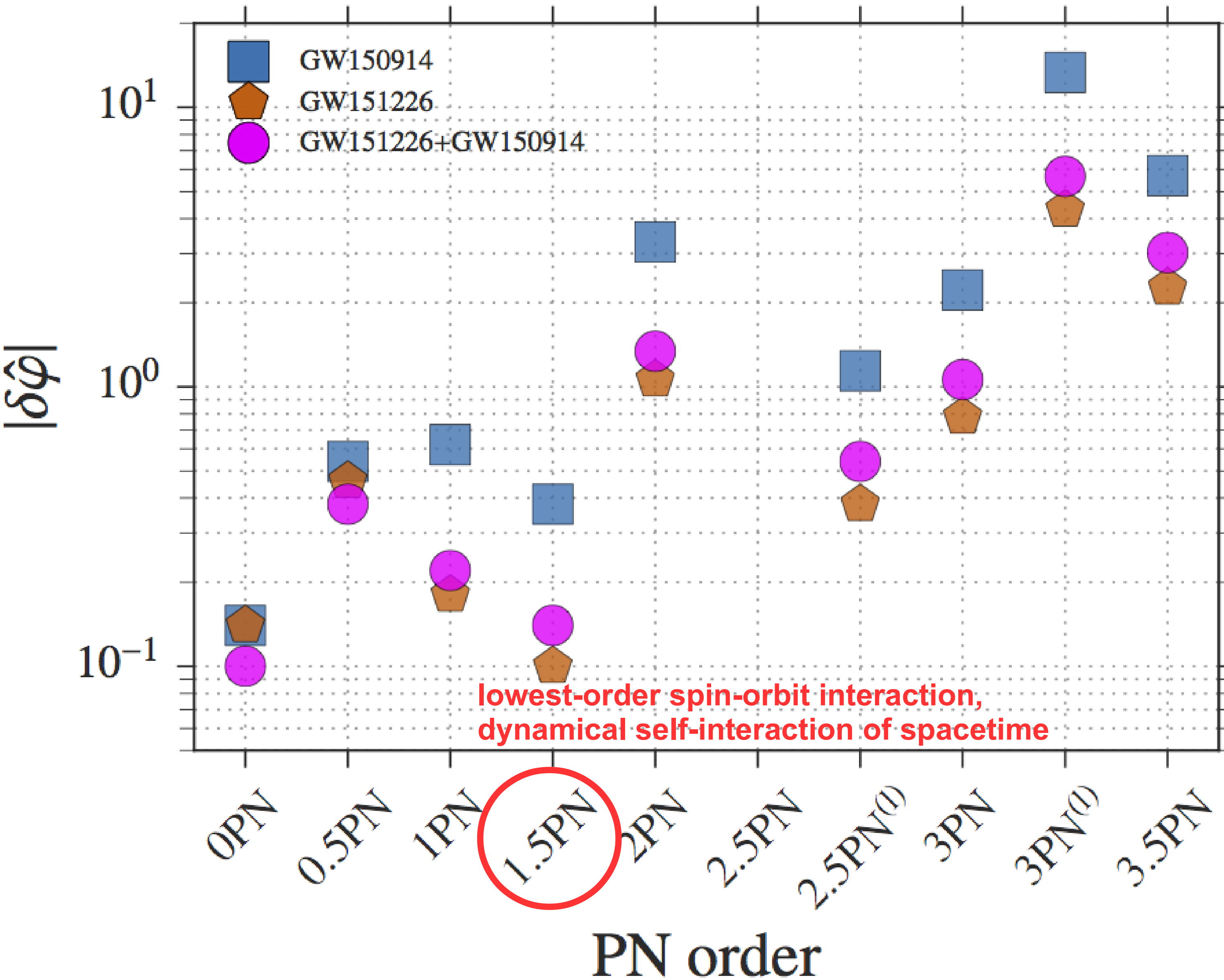
LSC & Virgo, arXiv:1606.04856 (to appear in PRX)

Combined bounds on post-Newtonian inspiral parameters



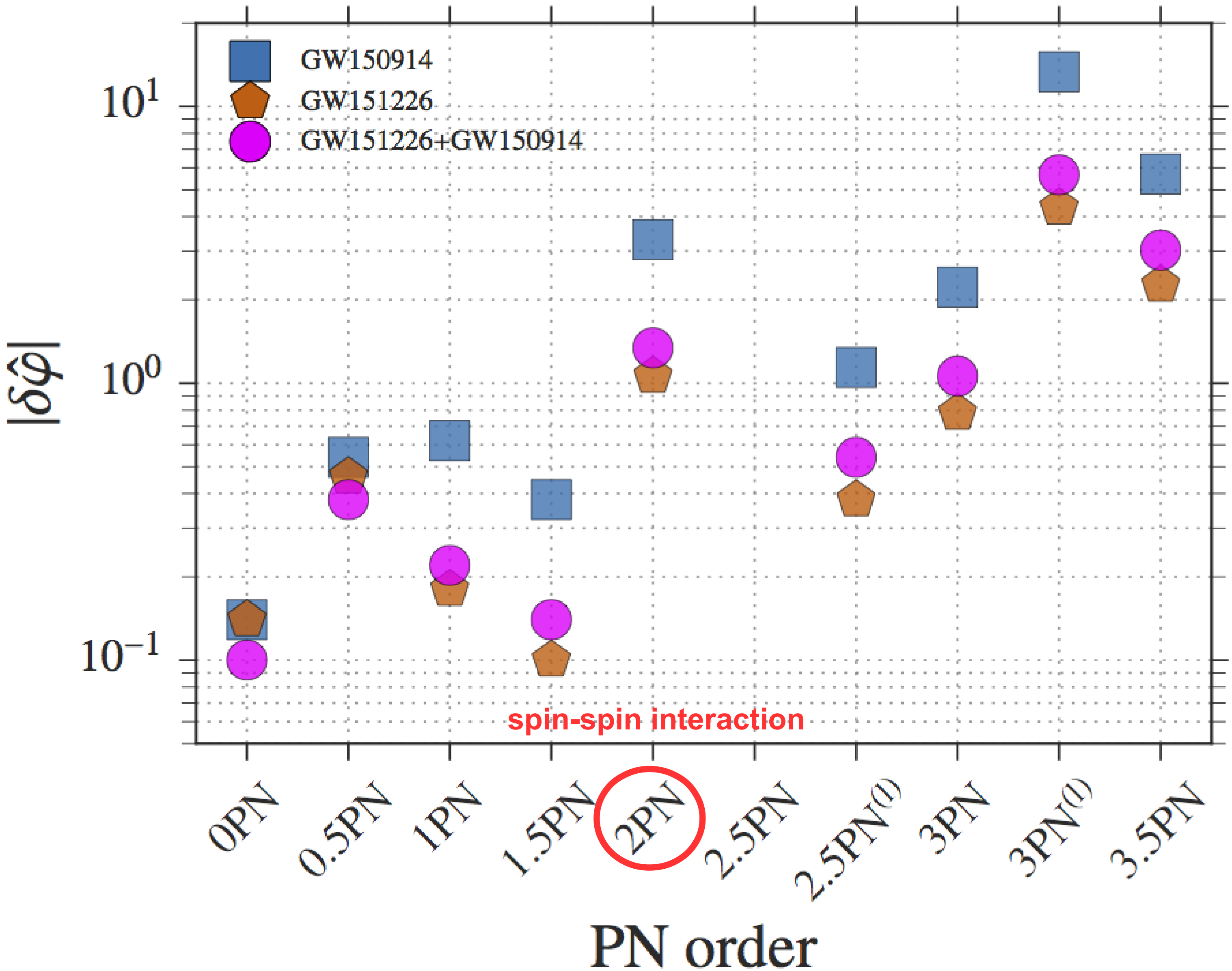
LSC & Virgo, arXiv:1606.04856 (to appear in PRX)

Combined bounds on post-Newtonian inspiral parameters



LSC & Virgo, arXiv:1606.04856 (to appear in PRX)

Combined bounds on post-Newtonian inspiral parameters



LSC & Virgo, arXiv:1606.04856 (to appear in PRX)

Outlook

- Genuinely strong-field dynamics of spacetime probed for the first time
  - Consistency of masses and spins between inspiral and post-inspiral
  - End of the signal consistent with least-damped quasi-normal mode
  - New dynamical bound on the graviton mass
  - First constraints on high-order post-Newtonian coefficients

- Future observations:
  - Seeing more than one quasi-normal mode would allow for test of no-hair theorem
  - Test of second law of black hole mechanics
  - Constraints on non-GR polarization states with network of detectors
  - Combining information from all future detections will set increasingly sharper bounds on PN coefficients

- For now: all tests performed show no disagreement with GR

Backup slides

What about specific alternative theories of gravity?

- With exception of λ_g bound and alternative polarizations study, did not look into implications for specific alternative theories of gravity:
  - Einstein-aether theory
  - Quadratic curvature corrections
  - Dynamical Chern-Simons theory
  - ...

  or the possibility of compact binaries composed of more exotic objects:
  - Boson stars
  - Gravastars
  - ...
- We lack accurate predictions for inspiral-merger-ringdown GW signals in specific alternative theories
  - Would be of interest if waveform models developed in near future

A wish list

- More asymmetric component masses
  - Sub-dominant harmonics of the signal become better visible (also inspiral)
  - If also high total mass, multiple QNMs in the ringdown can be seen
- Systems with lower total mass
  - More of the inspiral in sensitive band of detectors
  - Better bounds on PN parameters
- Significantly misaligned spins
  - Precession of spins and orbital plane
  - Spin-orbit and spin-spin interactions
- Higher SNRs
  - GW150914 would be factor ~3 louder in aLIGO at final design sensitivity
- Binary neutron star coalescences
  - Constrain new kinds of GR violations, e.g. dynamical scalarization
- Lots of detections!
  - Combine information from all detections to place stronger bounds on PN and other coefficients