Tests of general relativity with gravitational wave observations

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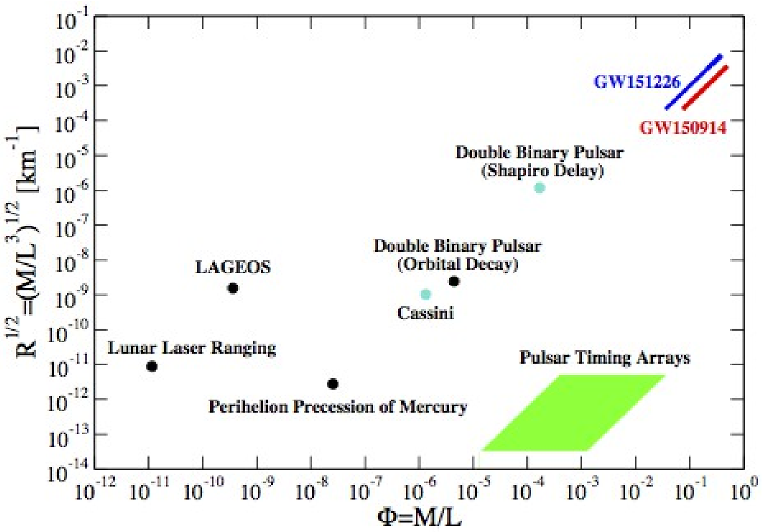
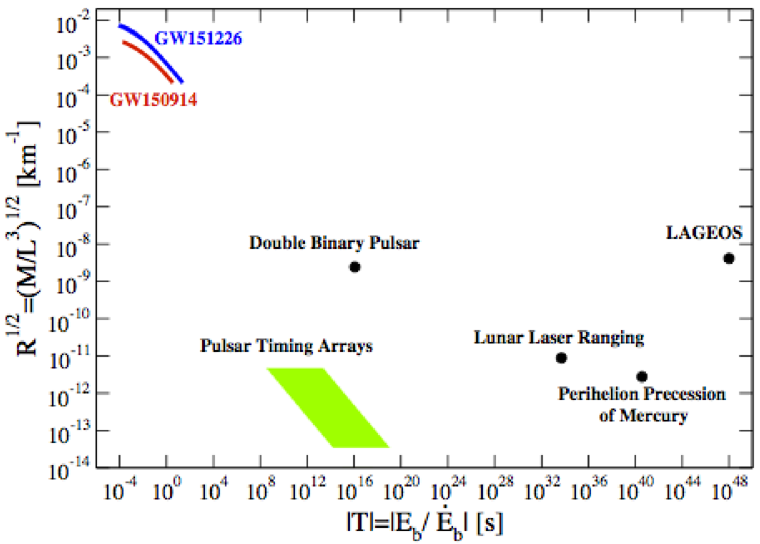
First access to the strong-field dynamics of spacetime

- Before the direct detection of gravitational waves:
  - Solar system tests: weak-field; dynamics of spacetime itself not being probed
  - Binary neutron stars: relatively weak-field test of spacetime dynamics

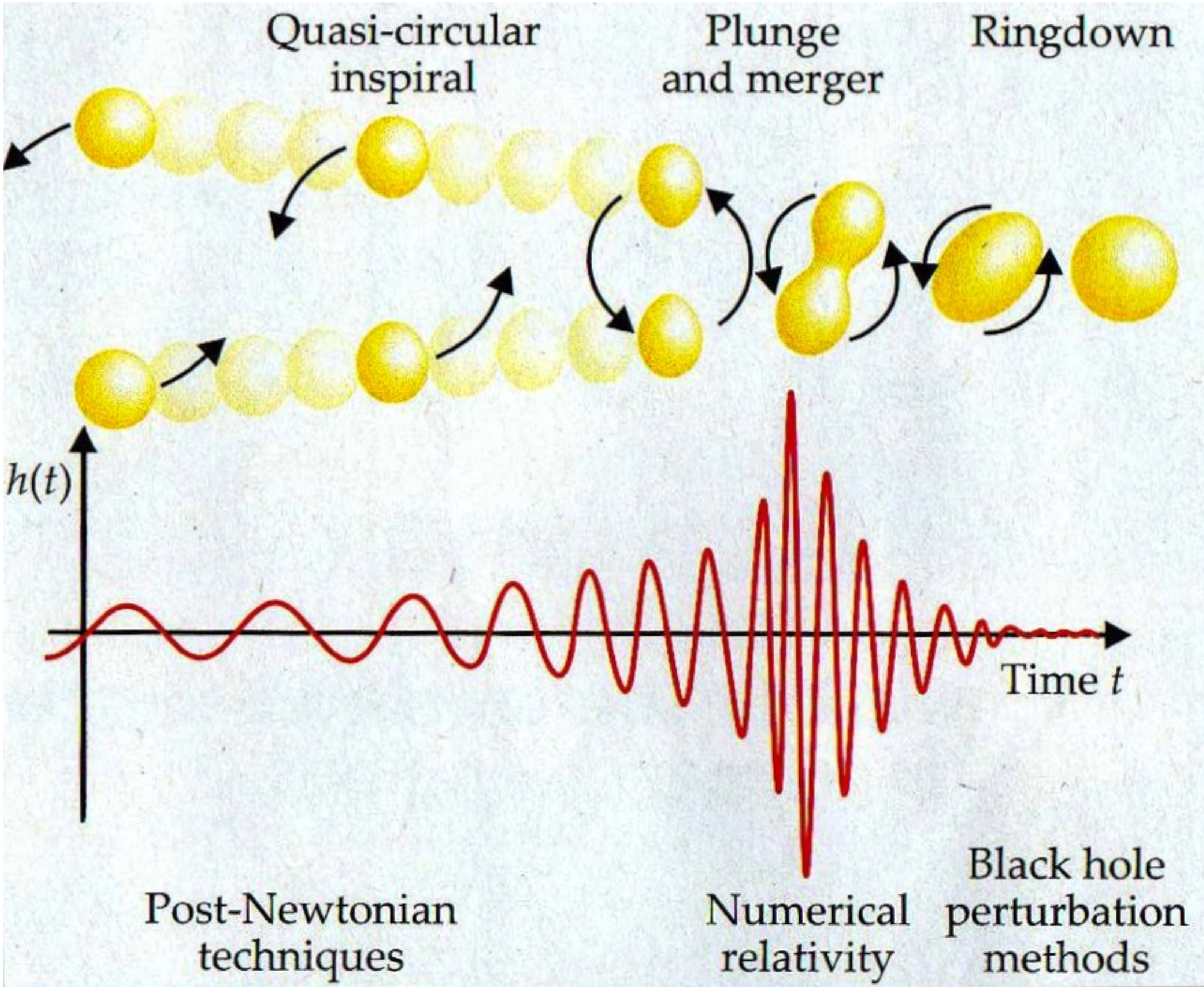


- Direct detection of GW from binary black hole mergers:
  - Genuinely strong-field dynamics
  - (Presumed) pure spacetime events

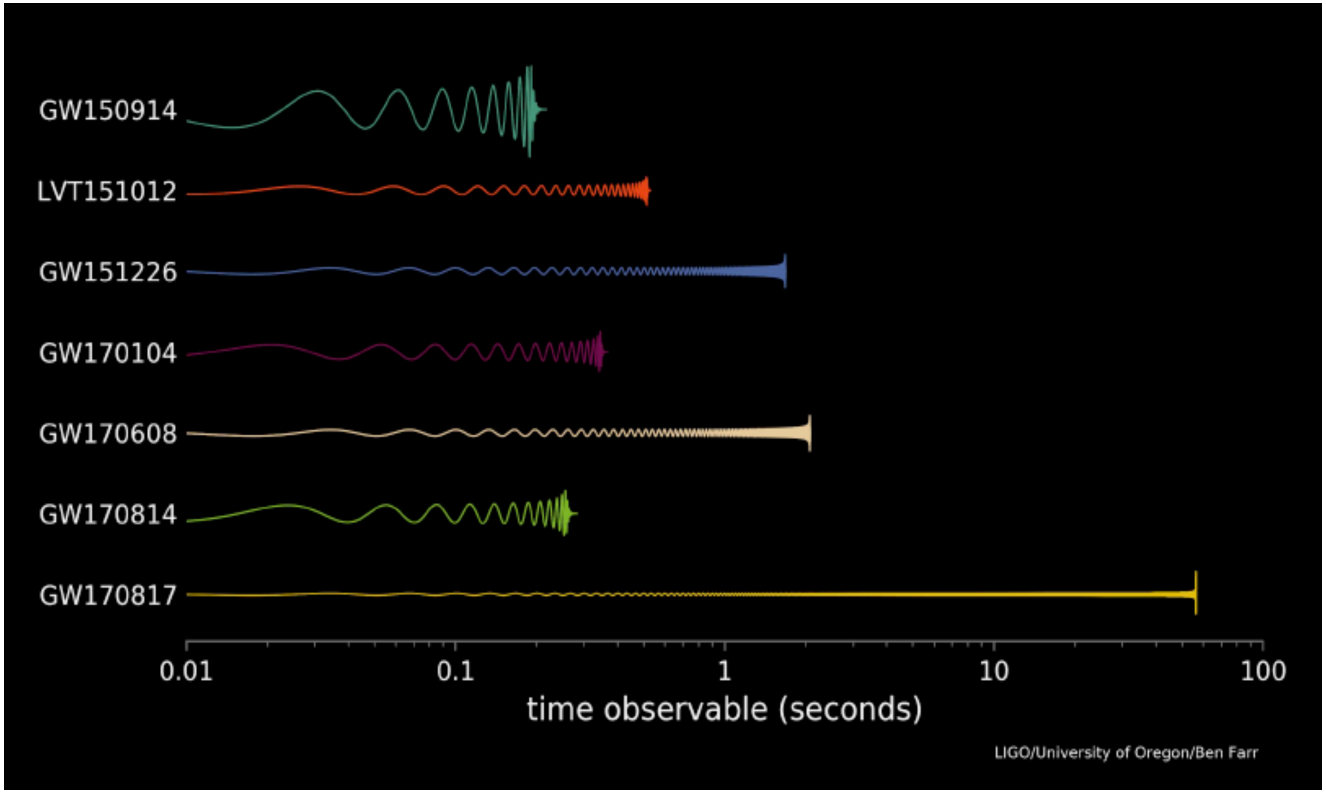


Yunes, Yagi, Pretorius, Phys. Rev. D **94**, 084002 (2016)

Coalescence of binary neutron stars and black holes



Complementary information from different events



- GW150914: merger at the most sensitive detector frequencies
- GW151226: long inspiral in sensitive frequency band
- GW170104: twice as far away → study GW propagation over large distances
- GW170814: triple detection → study GW polarization
- GW170817: GW speed, equivalence principle

Exploiting the phenomenology of inspiral, merger, ringdown

- Post-Newtonian description of inspiral
  - Expansion of e.g. gravitational wave phase in powers of (v/c)
  - Do the coefficients depend on masses, spins as predicted by GR?
- Plunge and merger
  - Most dynamical regime
- Consistency between inspiral and post-inspiral regimes
- Ringdown
  - quasi-normal mode spectrum
- Anomalous propagation of gravitational waves over large distances
  - Massive graviton, violations of local Lorentz invariance
- Tidal effects during inspiral
  - "Black hole mimickers": boson stars, dark matter stars, gravastars, ...
  - If less compact than neutron stars, can have large tidal effects

Residual data after subtraction of best-fitting waveform

- After subtraction of best-fitting semi-analytic waveform for GW150914, is residual data consistent with noise?
- Signal-to-noise ratio in residual data related to detection SNR through a fitting factor:

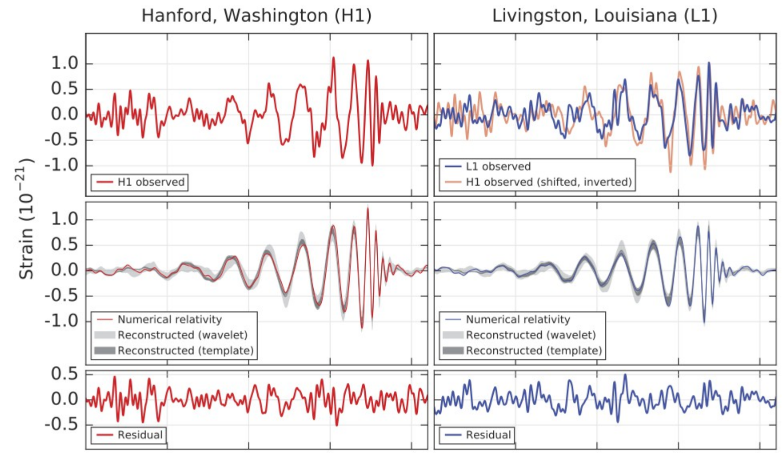
$$\mathrm{SNR}^2_{\mathrm{res}} = (1 - \mathrm{FF}^2)\,\mathrm{FF}^{-2}\,\mathrm{SNR}^2_{\mathrm{det}}$$

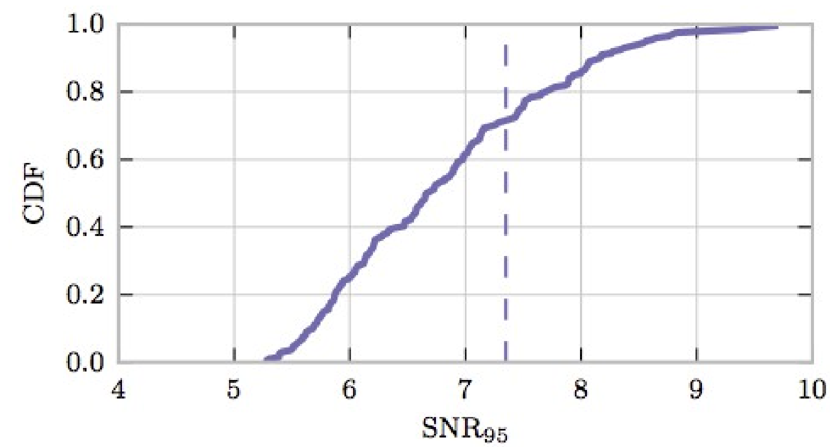
- $\mathrm{SNR}_{\mathrm{det}} = 25.3^{+0.1}_{-0.2}$

  $\mathrm{SNR}_{\mathrm{res}} \leq 7.3$

  $\rightarrow \quad \mathrm{FF} \geq 0.96$

- GR violations limited to 4%, at least for effects that can not be absorbed into redefinition of physical parameters

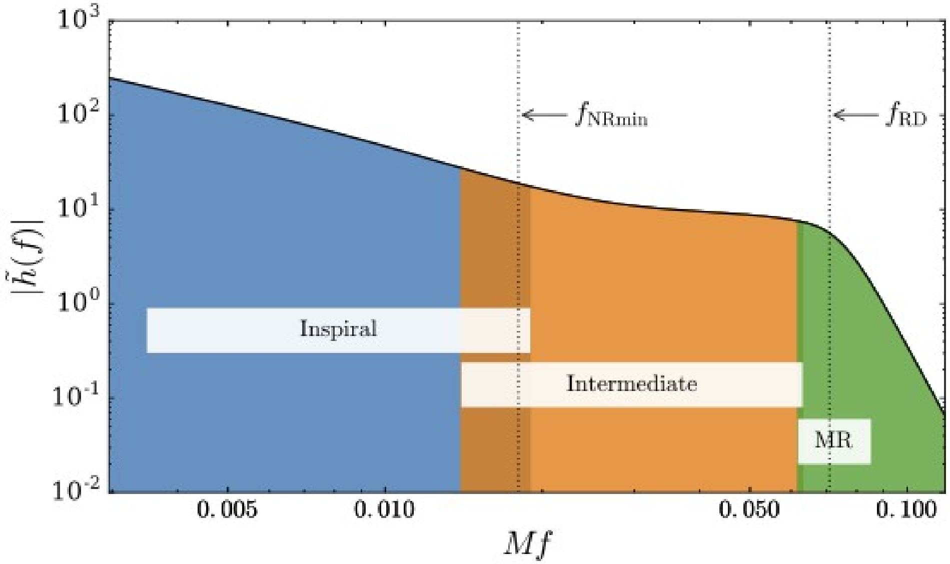




LSC+Virgo, Phys. Rev. Lett. **116**, 221101 (2016)

Parameterized tests of the coalescence process

- Phenomenological frequency domain waveforms



waveform regime	parameter	f−dependence
early-inspiral	φ_0	$f^{-5/3}$
	φ_1	$f^{-4/3}$
	φ_2	f^{-1}
	φ_3	$f^{-2/3}$
	φ_4	$f^{-1/3}$
	φ_{5l}	$\log f$
	φ_6	$f^{1/3}$
	φ_{6l}	$f^{1/3} \log f$
	φ_7	$f^{2/3}$
late-inspiral	σ_2	$f^{4/3}$
	σ_3	$f^{5/3}$
	σ_4	f^2
intermediate	β_2	$\log f$
	β_3	f^{-3}
merger-ringdown	α_2	f^{-1}
	α_3	$f^{3/4}$
	α_4	$\tan^{-1}(af+b)$

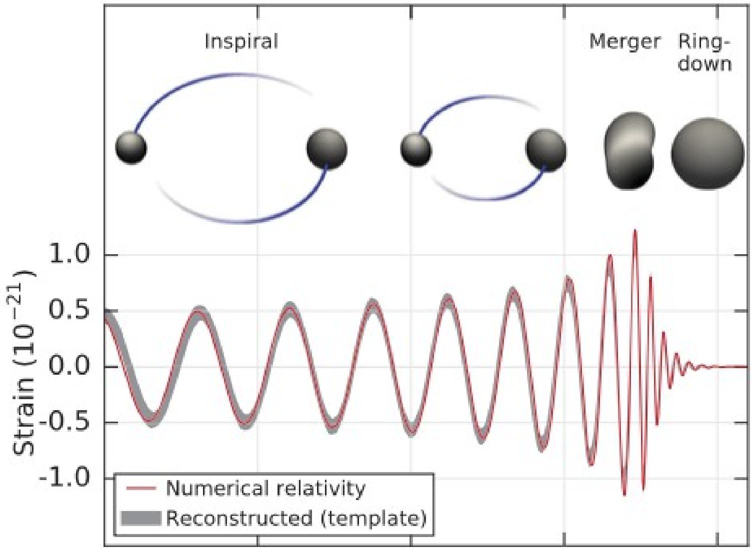
- Parameters p_i multiplying different functions of frequency in 3 regimes
- Introduce parameterized deformations of the waveform by replacing

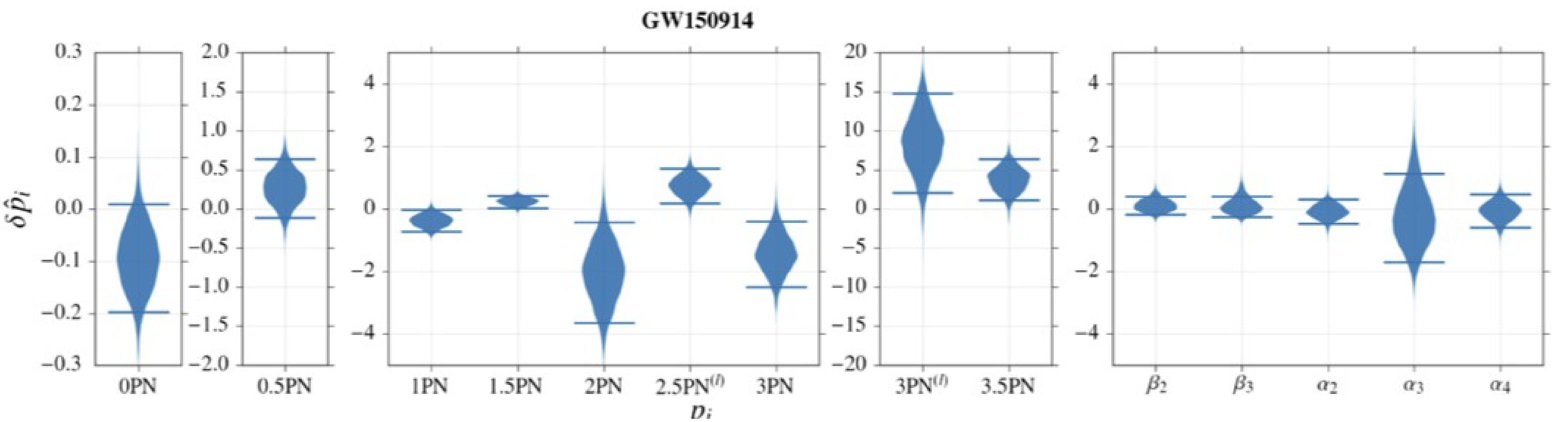
  $$p_i \rightarrow (1+\delta\hat{p}_i)p_i$$

  and letting $\delta\hat{p}_i$ vary freely (along with masses, spins, extrinsic parameters)
- Do this for each of the p_i in turn

  - Accurate model-independent tests
    Li et al., Phys. Rev. D **85**, 082003 (2012)

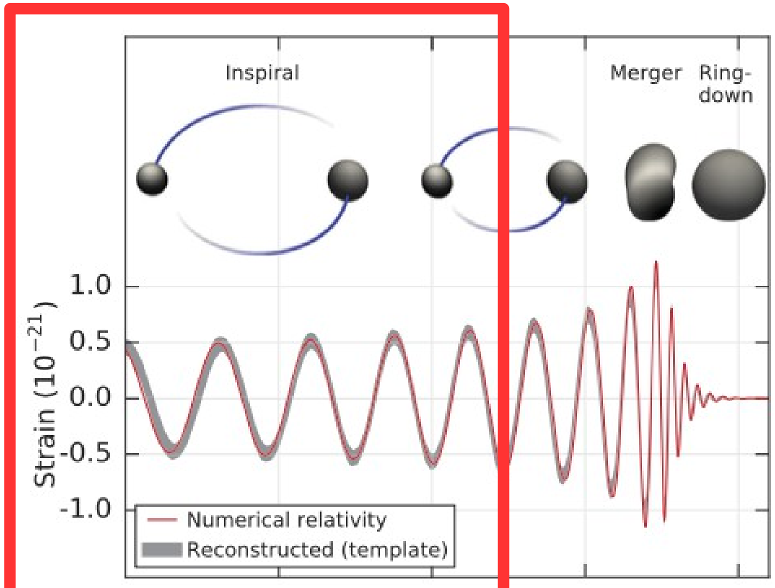
Parameterized tests of the coalescence process



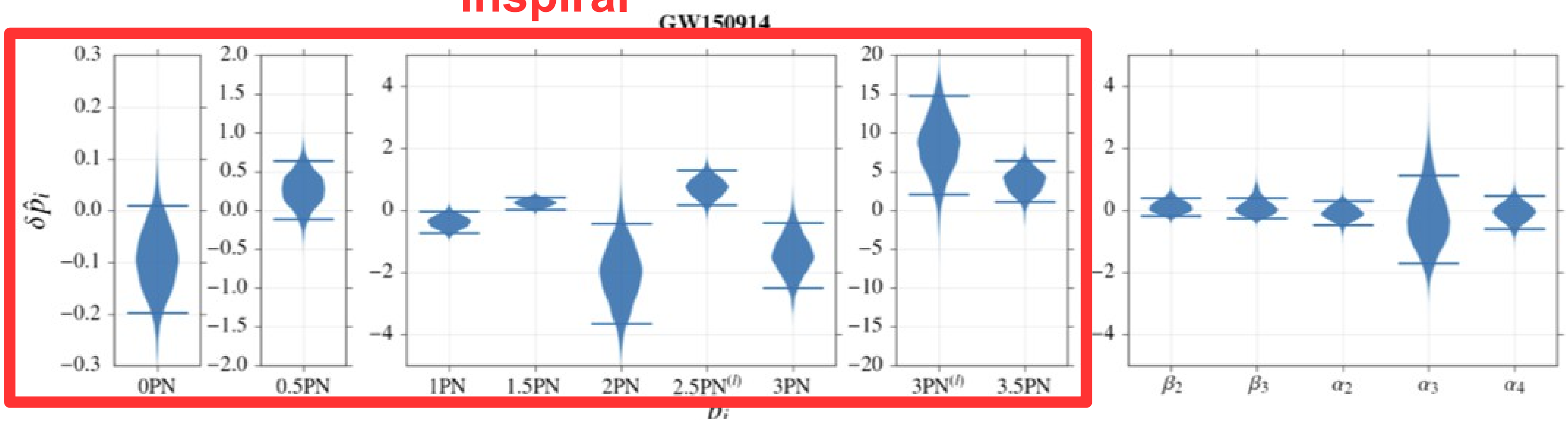


LSC+Virgo, Phys. Rev. X **6**, 041015 (2016)

Parameterized tests of the coalescence process

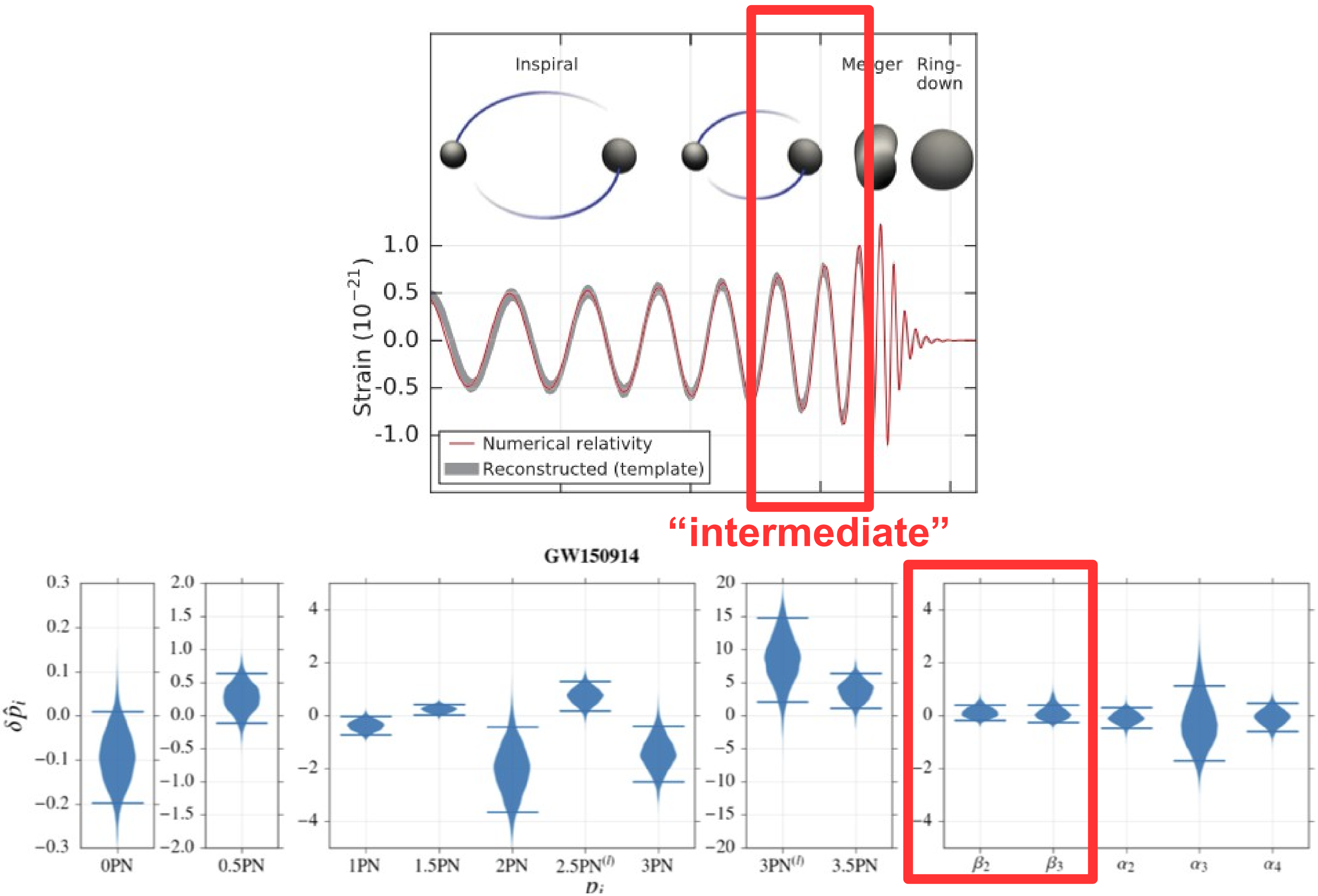


inspiral



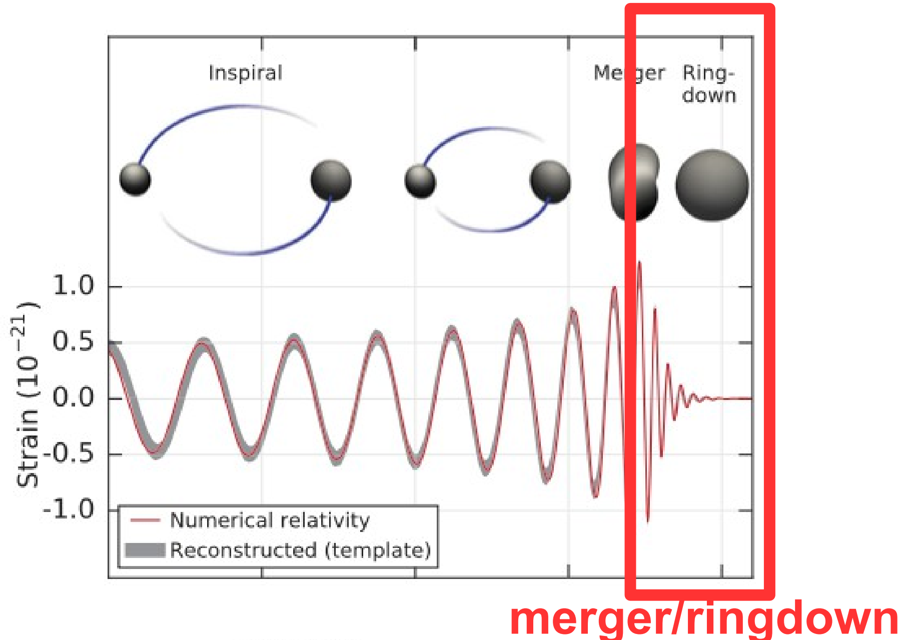
LSC+Virgo, Phys. Rev. X **6**, 041015 (2016)

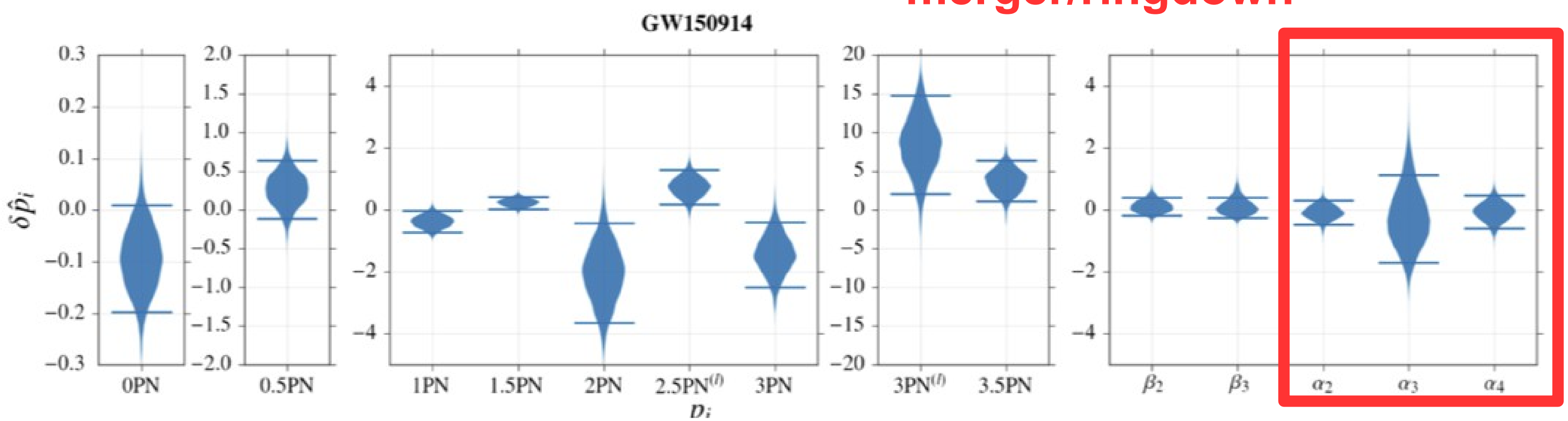
Parameterized tests of the coalescence process



LSC+Virgo, Phys. Rev. X **6**, 041015 (2016)

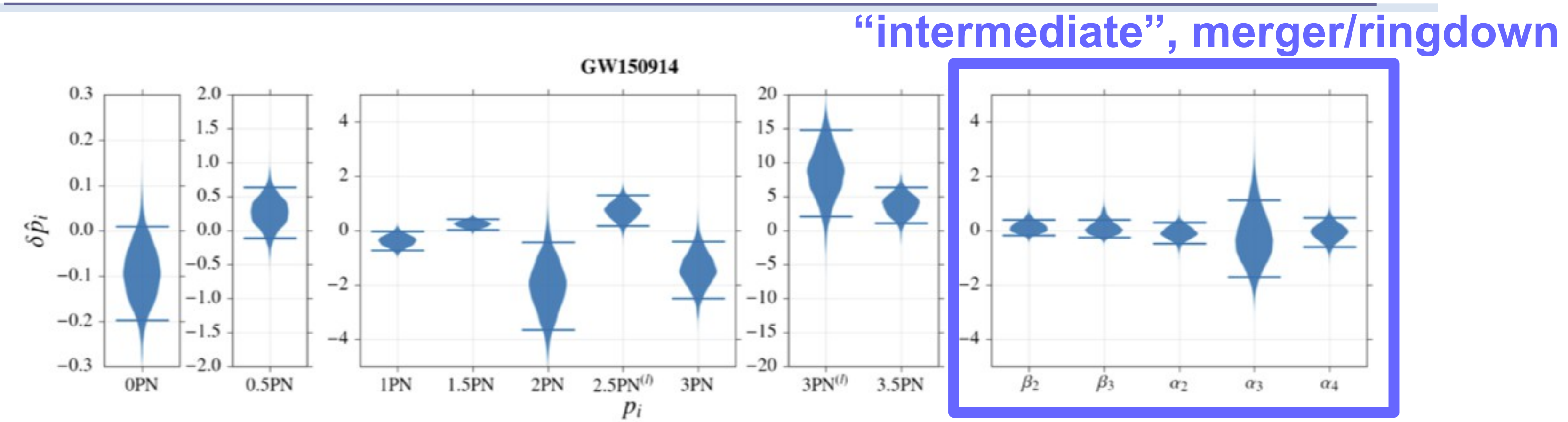
Parameterized tests of the coalescence process





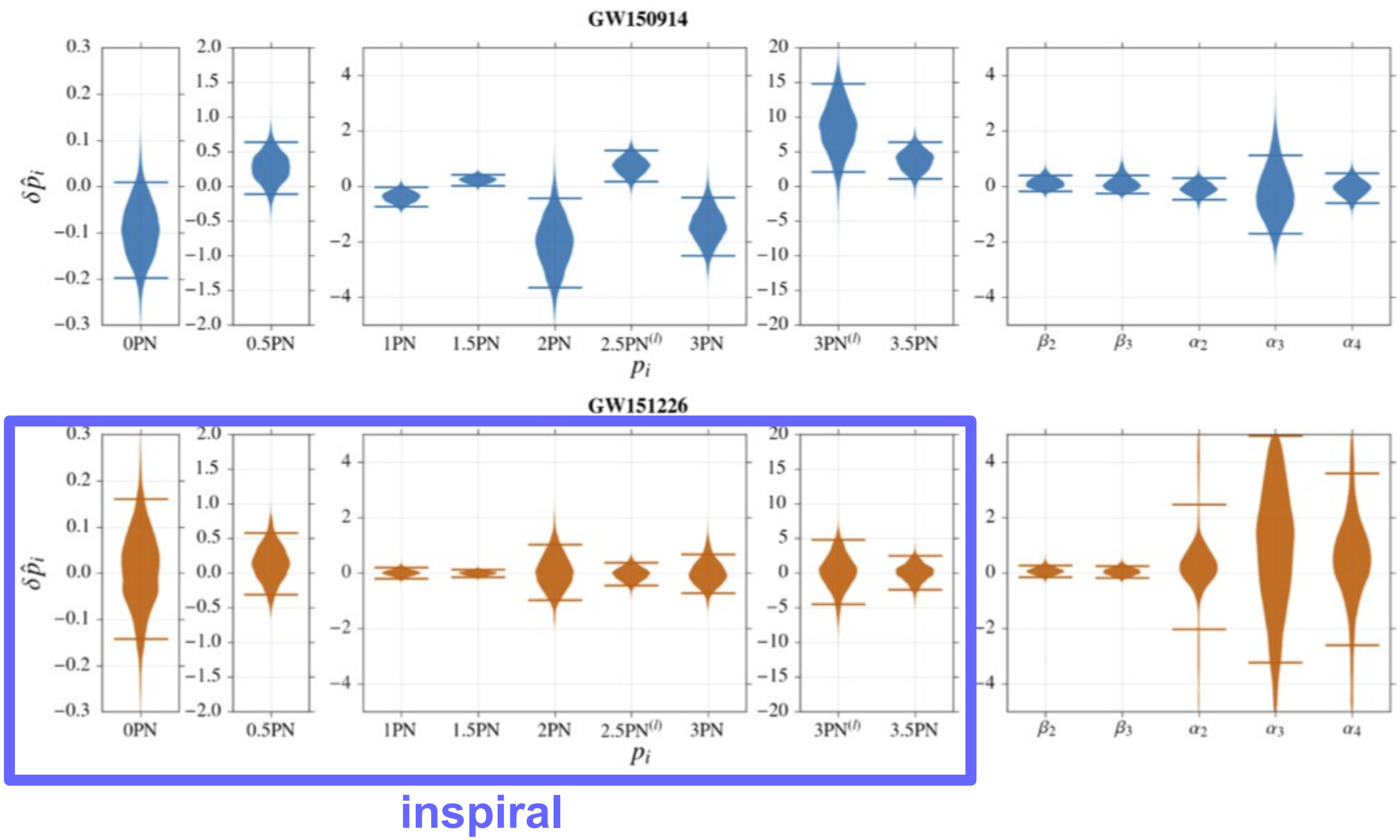
LSC+Virgo, Phys. Rev. X **6**, 041015 (2016)

GW150914: short inspiral, but merger well visible



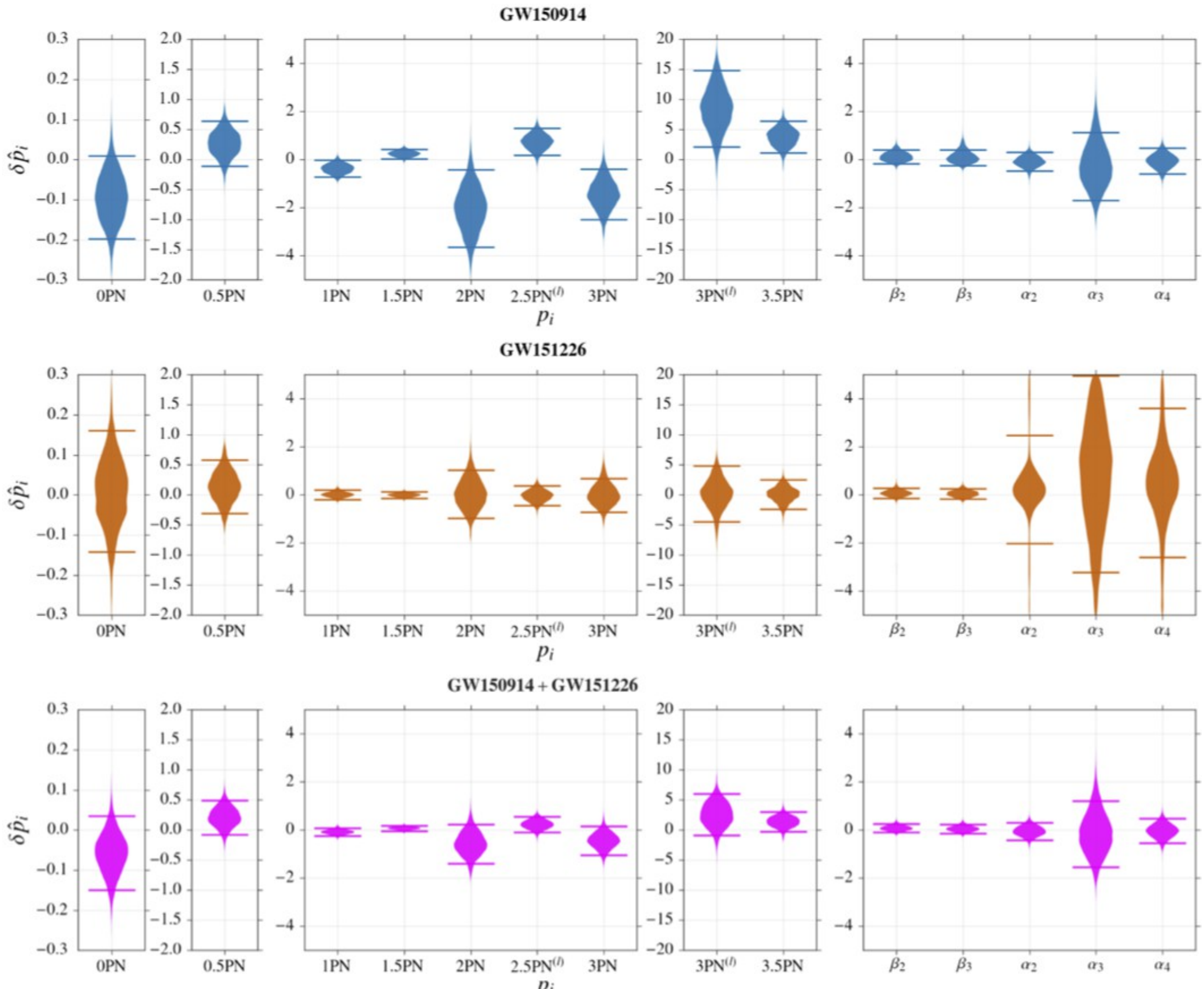
LSC+Virgo, Phys. Rev. X **6**, 041015 (2016)

GW151226: long inspiral, merger at higher frequency



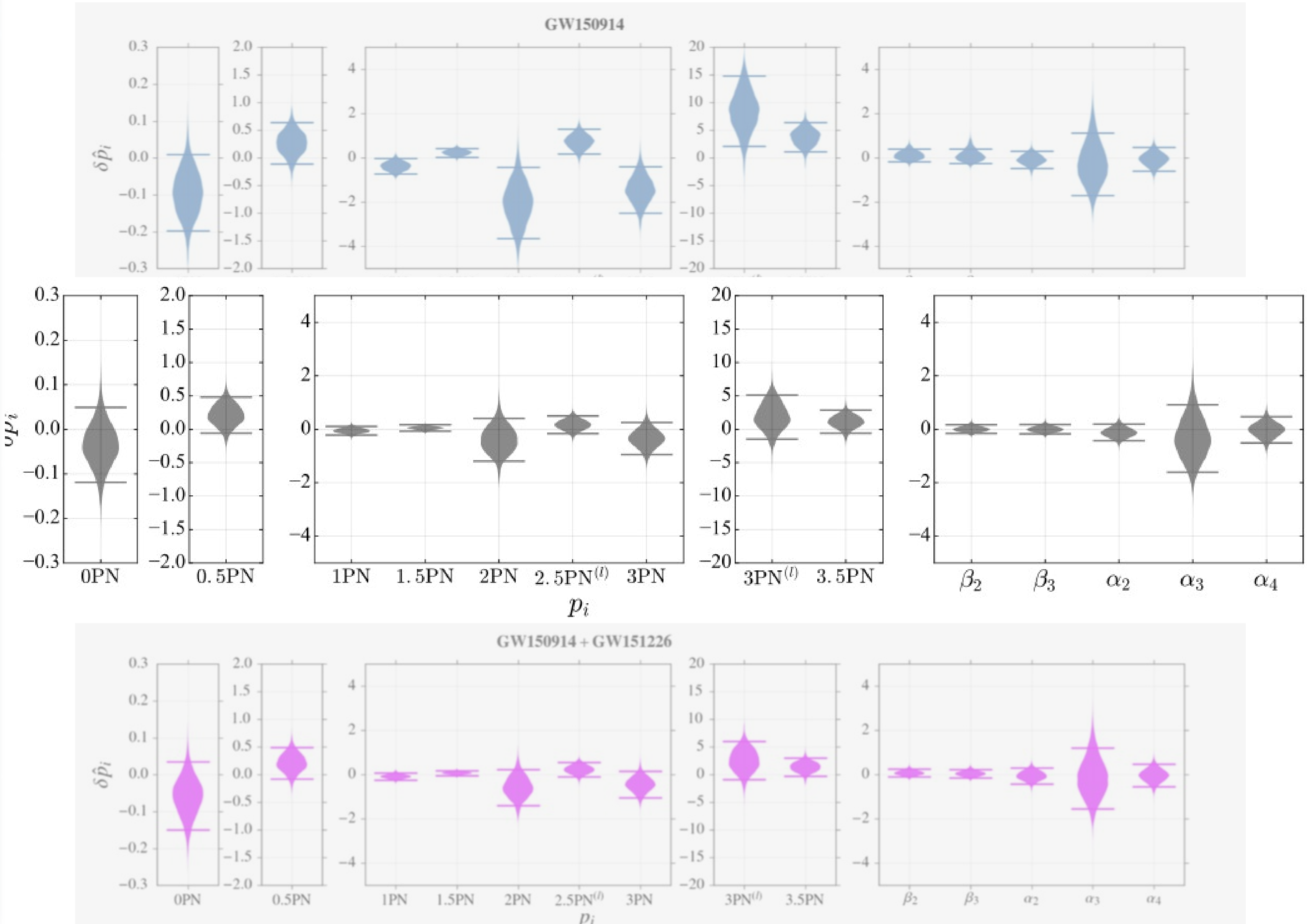
LSC+Virgo, Phys. Rev. X **6**, 04~~1015~~ (2016)

Combine results from multiple sources



LSC+Virgo, Phys. Rev. X **6**, 041015 (2016)

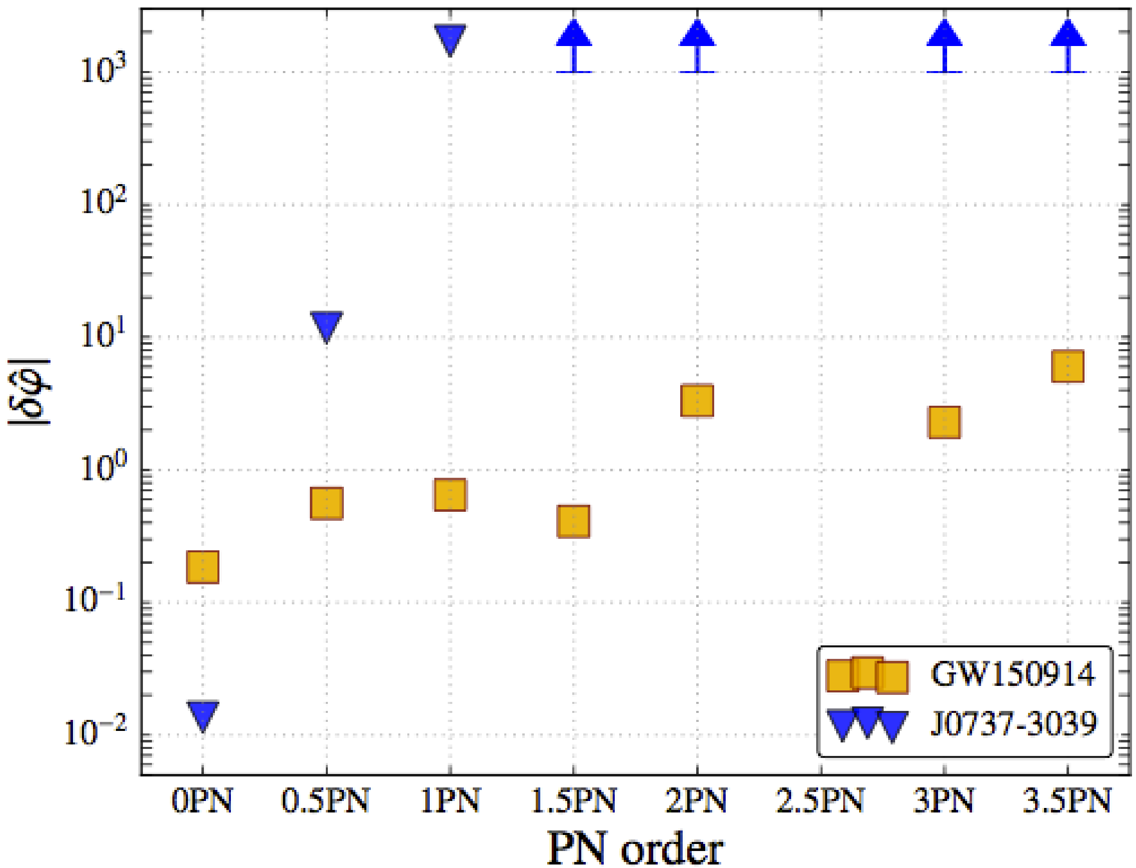
GW150914 + GW151226 + GW170104



LSC+Virgo, Phys. Rev. Lett. **118**, 221101 (2017)

Testing the post-Newtonian description of inspiral

- First-ever bounds on post-Newtonian coefficients (inspiral dynamics) beyond leading order



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

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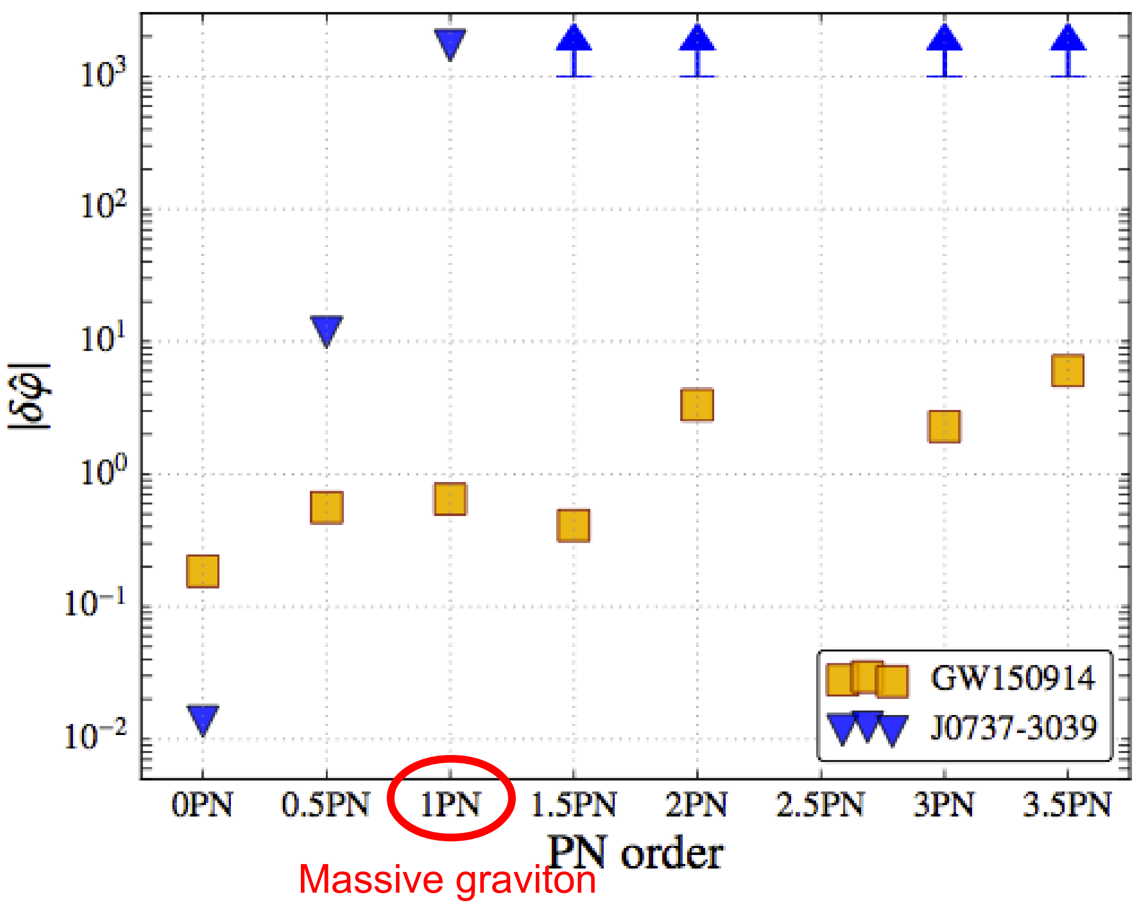

LSC+Virgo, Phys. Rev. Lett. **116**, 221101 (2016)

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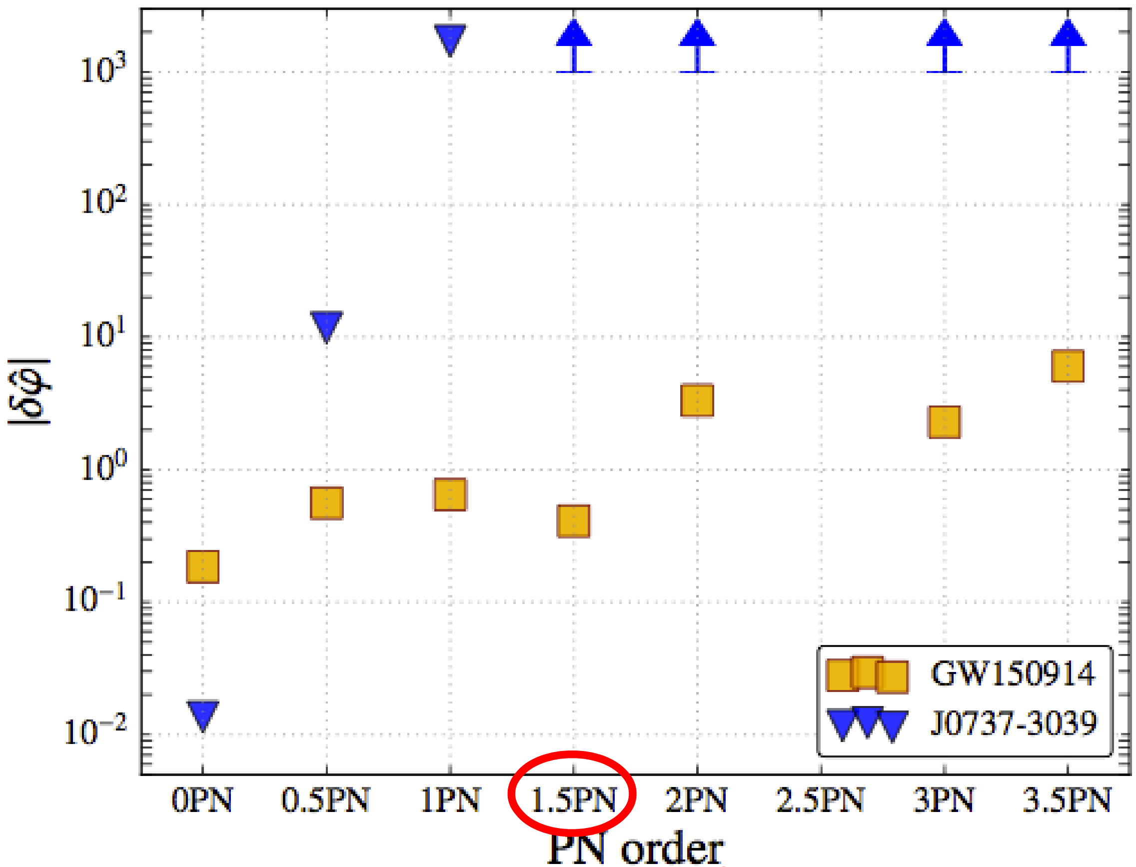

- Dynamical self-interaction
- Spin-orbit interactions

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

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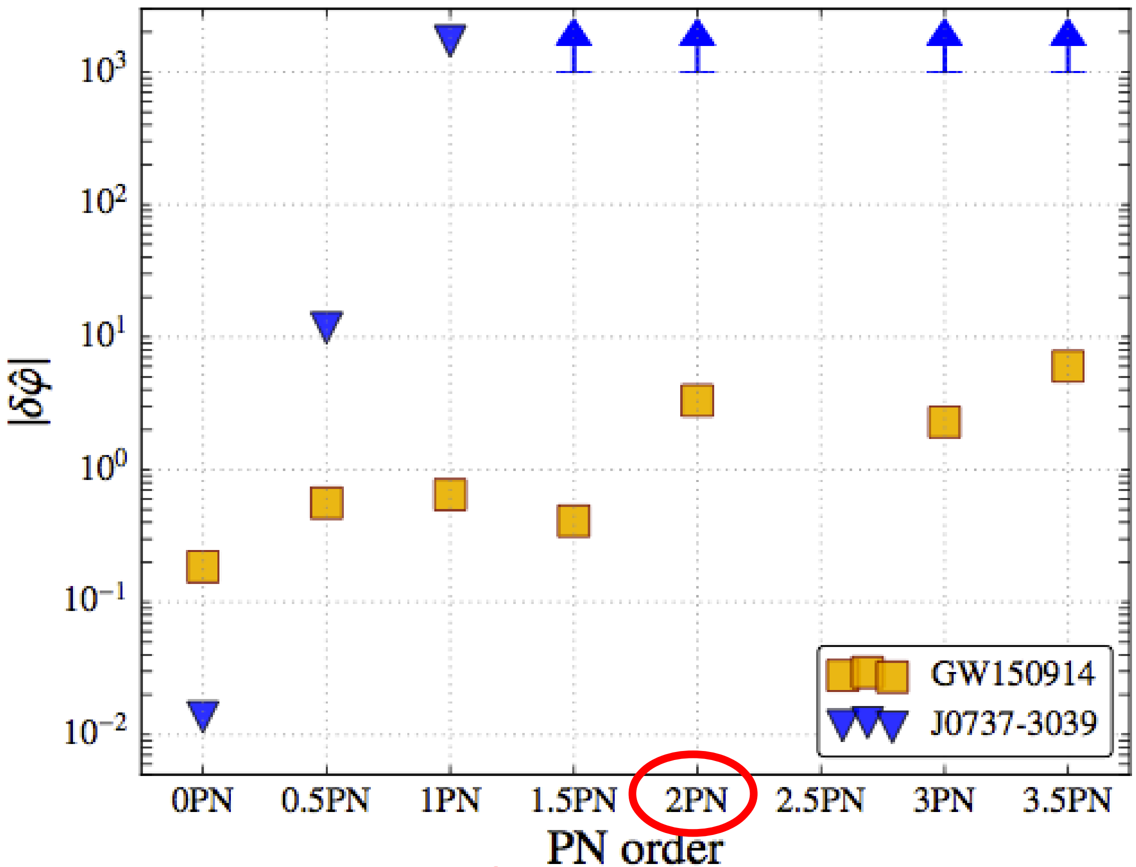


Spin-spin interactions

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

Do gravitational waves propagate as predicted?

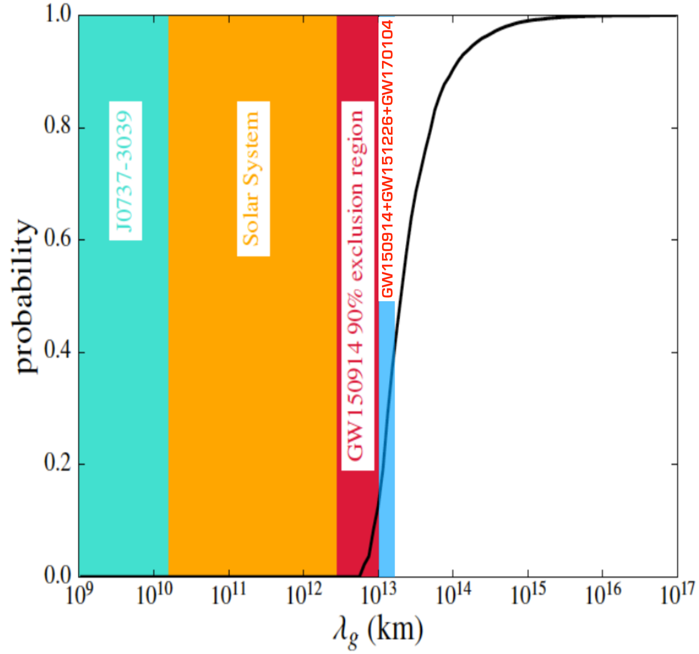
Will, Phys. Rev. D **57**, 2061 (1998)

- Dispersion of gravitational waves?

$$E^2 = p^2c^2 + m_g^2c^4 \qquad \lambda_g = h/(m_g c) \qquad \Phi_{MG}(f) = -(\pi D c)/[\lambda_g^2(1+z)f]$$

- New bound on graviton Compton wavelength and mass:

  $\lambda_g > 1.6 \times 10^{13}$ km $\qquad m_g < 7.7 \times 10^{-23}$ eV/c^2
- 3 orders of magnitude better than binary pulsar dynamical bound
- Factor of a few better than (static) Solar system bound



LSC+Virgo, Phys. Rev. Lett. **118**, 221101 (2017)

Do gravitational waves propagate as predicted?

- Anomalous dispersion of gravitational waves (Violating local Lorentz invariance):

$$E^2 = p^2c^2 + Ap^\alpha c^\alpha$$

- Modified group velocity:

$$v_g/c = 1 + (\alpha - 1)AE^{\alpha-2}/2$$

- Modification to the gravitational wave phase:

$$\tilde{h}_{\mathrm{GR}}(f) = \tilde{A}(f;\vec{\vartheta}_{\mathrm{GR}})e^{i\Psi(f;\vec{\vartheta}_{\mathrm{GR}})}$$

$$\downarrow$$

$$\tilde{h}(f) = \tilde{A}(f;\vec{\vartheta}_{\mathrm{GR}})e^{i\left[\Psi(f;\vec{\vartheta}_{\mathrm{GR}})+\delta\Psi(f;\vec{\vartheta}_{\mathrm{GR}},X_{\mathrm{modGR}})\right]}$$

Mirshekari et al., Phys. Rev. D 85, 024041 (2012)

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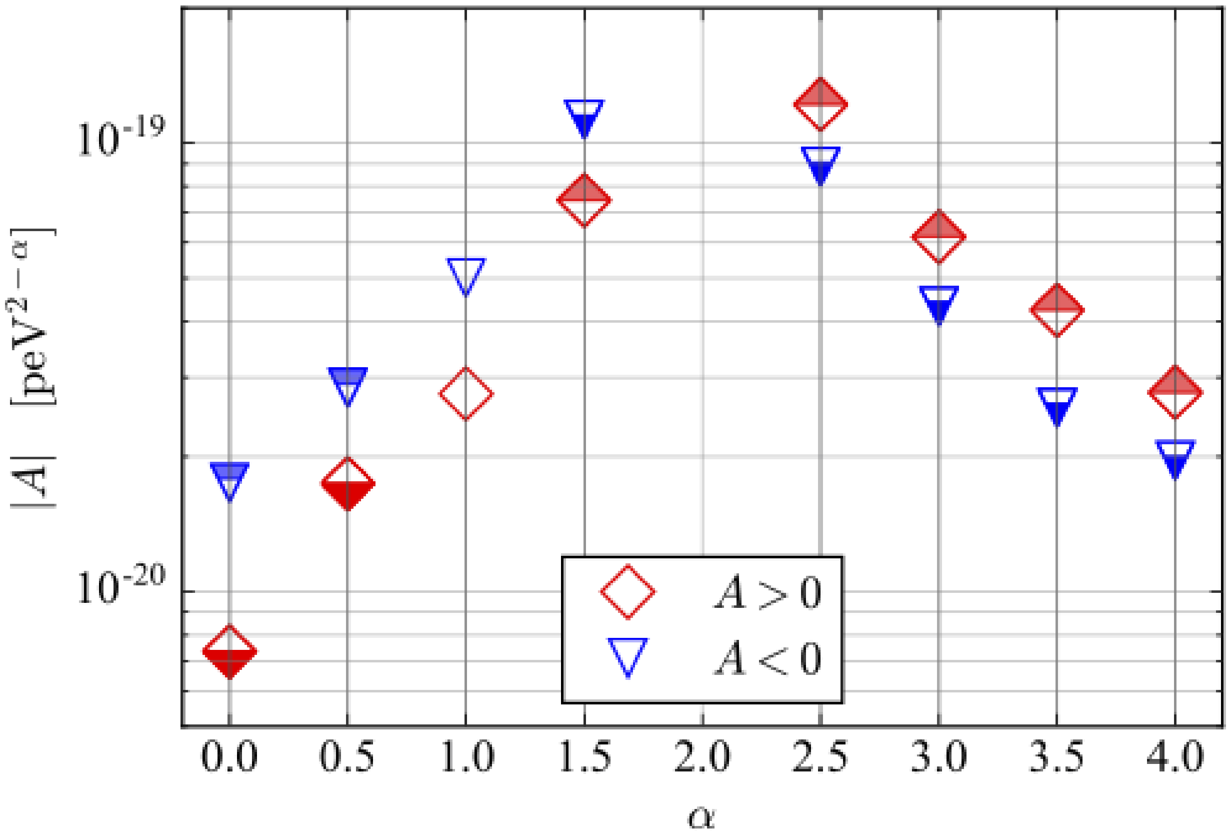
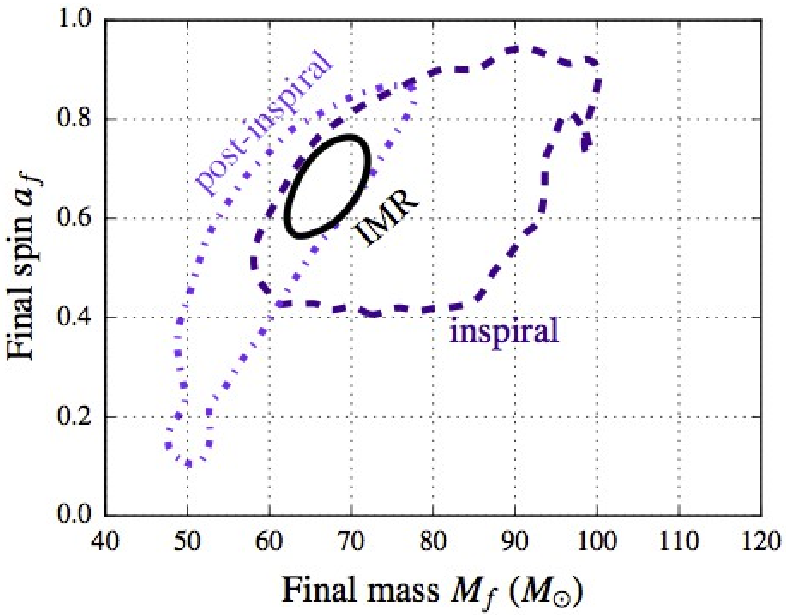
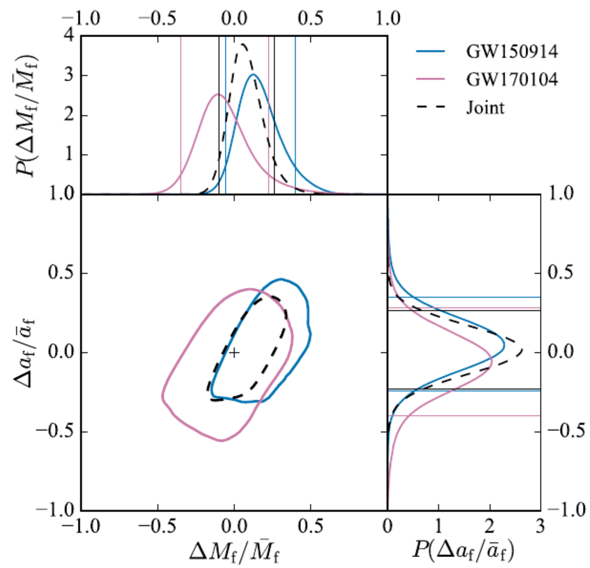


LSC+Virgo, Phys. Rev. Lett. **118**, 221101 (2017)

Consistency between inspiral and post-inspiral

- General relativity predicts relationship between
  - Masses and spins of component objects
  - Mass and spin of final object
- Relationship can be extracted from numerical simulations
  - Accurate analytical fits (Healy et al. 2014)
- Compare inferred values from inspiral and post-inspiral

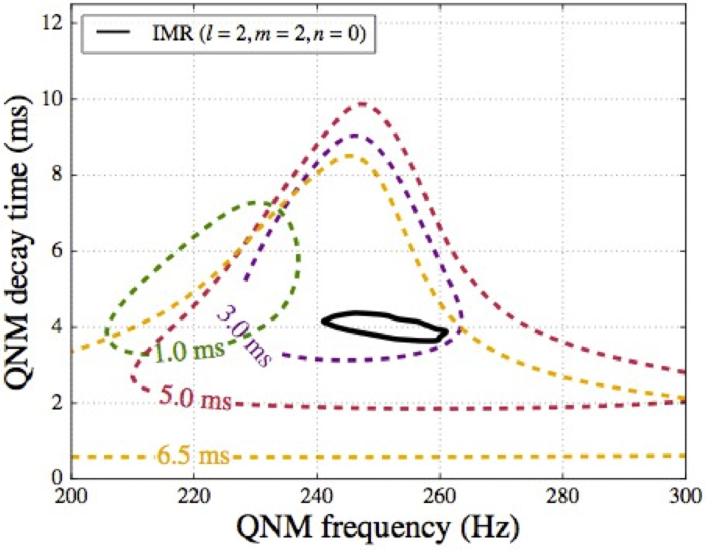




LSC+Virgo, Phys. Rev. Lett. **116**, 221101 (2016)

Ringdown

- Ringdown regime: Kerr metric + linear perturbations
- Ringdown signal is a superposition of quasi-normal modes with characteristic frequencies ω_{lmn} and damping times τ_{lmn}
- Numerical relativity: linearized regime valid from ~10 M
  - For GW150914: 10 M ~ 3.5 milliseconds
- Evidence for a least-damped quasi-normal mode from fitting damped sinusoid:



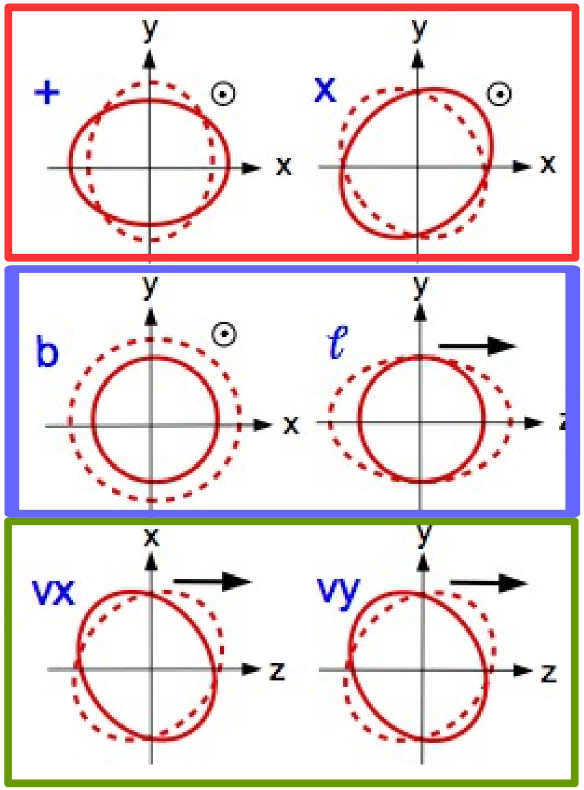
LSC+Virgo, Phys. Rev. Lett. **116**, 221101 (2016)

Alternative polarization states

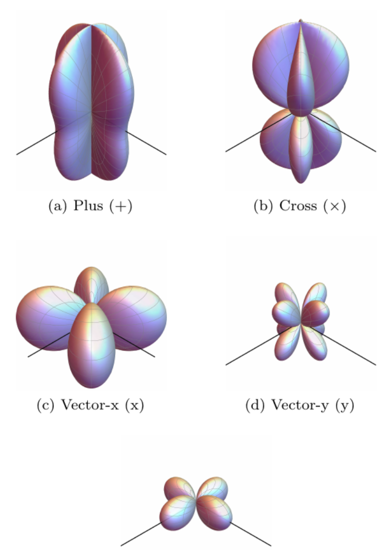
- Up to 6 different polarizations in metric theories of gravity
- In GR, GW have only tensor polarization
- Need a larger network of detectors!
- GW170814: with three detectors we tested

  Tensor vs pure scalar: 1000 / 1

  Tensor vs pure vector: 200 / 1



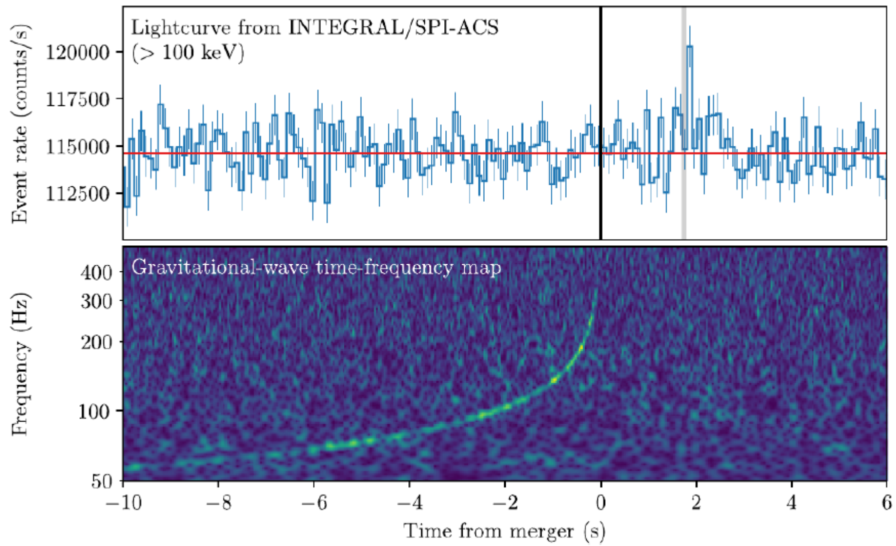
Will, Living Rev. Relativ. **17**, 4 (2014)



(a) Plus (+)
(b) Cross (×)
(c) Vector-x (x)
(d) Vector-y (y)
(e) Scalar (s)

Isi & Weinstein (2017)

Tests with GW170817 + GRB170817A



- Delay of a few second after a propagation over one hundred millions ly

$$t_{EM} - t_{GW} = 1.74 \pm 0.05\,\mathrm{s}$$

Constraint on speed of gravity

$$-3 \times 10^{-15} \leqslant \frac{v_{GW} - v_{EM}}{v_{EM}} \leqslant +7 \times 10^{-16}$$

Shapiro time delay of GW and EM in the MW gravitational potential

$$-2.6 \times 10^{-7} \leqslant \gamma_{GW} - \gamma_{EM} \leqslant 1.2 \times 10^{-6}$$

LSC+Virgo, Astrophys. J. Lett. 848, L13 (2017)

Overview

- First tests of the genuinely strong-field dynamics of pure spacetime
  - No evidence for violations of GR
- Tests of coalescence dynamics
  - Parameterized tests in inspiral, “intermediate”, and merger/ringdown regimes
  - Consistency of masses and spins between inspiral and post-inspiral
- Tests of gravitational wave propagation
  - Bound on graviton mass
  - Bounds on violation of local Lorentz invariance
  - Bound on the deviation of the speed of gravity from the speed of light
  - Violation of equivalence principle

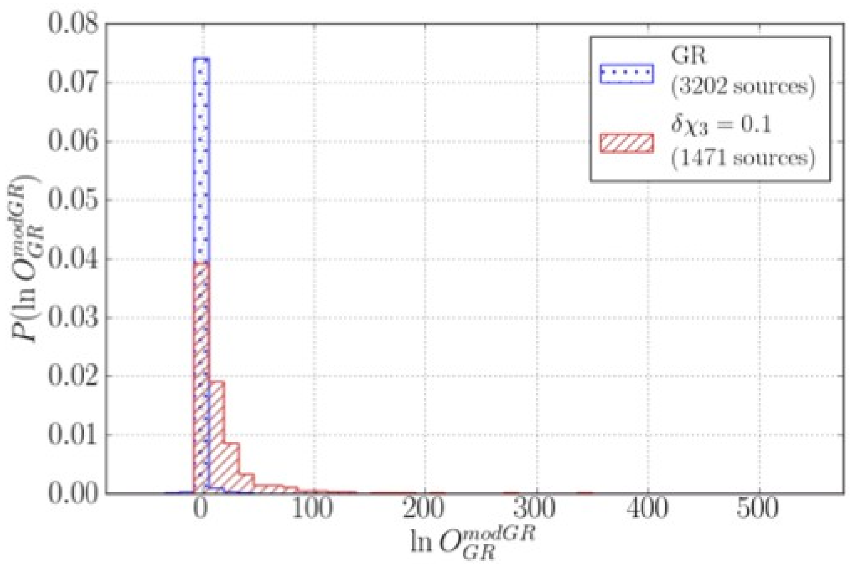
Into the future

Combining information from increasing number of detections

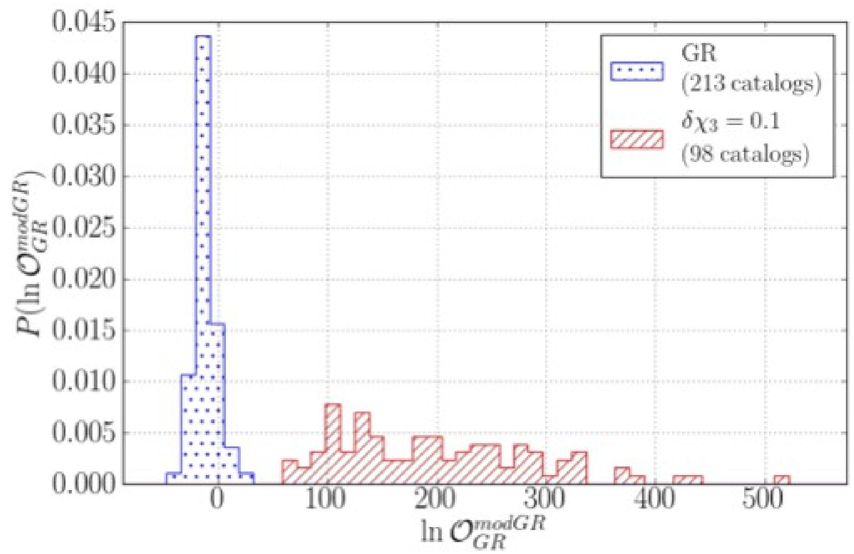
- Assuming GR is correct, bounds on violations will improve roughly with square root of number of sources
- Can also actively look for GR violations by Bayesian model selection:

$$O^{\rm modGR}_{\rm GR} \equiv \frac{P(\mathcal{H}_{\rm modGR}|d,\mathrm{I})}{P(\mathcal{H}_{\rm GR}|d,\mathrm{I})}$$

$$^{(N_T)}\mathcal{O}^{\rm modGR}_{\rm GR} = \frac{P(\mathcal{H}_{\rm modGR}|d_1,\ldots,d_{\mathcal{N}},\mathrm{I})}{P(\mathcal{H}_{\rm GR}|d_1,\ldots,d_{\mathcal{N}},\mathrm{I})}$$



single sources



catalogs of 15 sources each

Li et al., Phys. Rev. D **85**, 082003 (2012)
Agathos et al., Phys. Rev. D **89**, 082001 (2014)

Searching for exotic compact objects

- "Black hole mimickers":
  - Boson stars
  - Dark matter stars
  - Gravastars
  - Firewalls, fuzzballs
  - ...

Giudice et al., JCAP **1610**, 001 (2016)

- Find through:
  - Anomalous tidal effects during inspiral

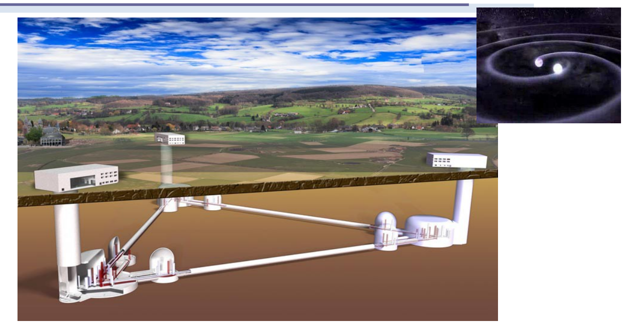
    Cardoso et al., arXiv:1701.01116
  - Anomalous ringdown spectrum

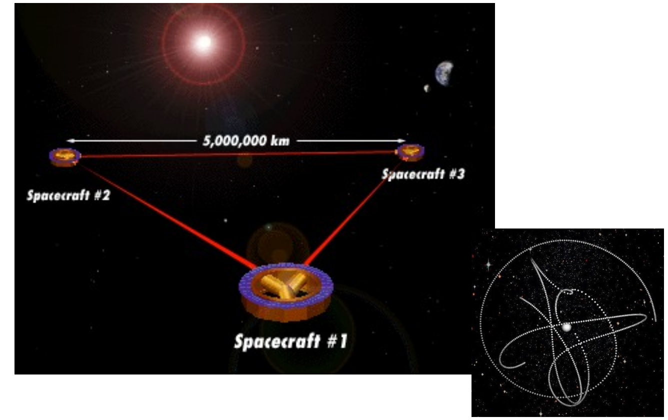
    Meidam et al., Phys. Rev. D **90**, 064009 (2014)
  - Gravitational wave "echoes" after ringdown

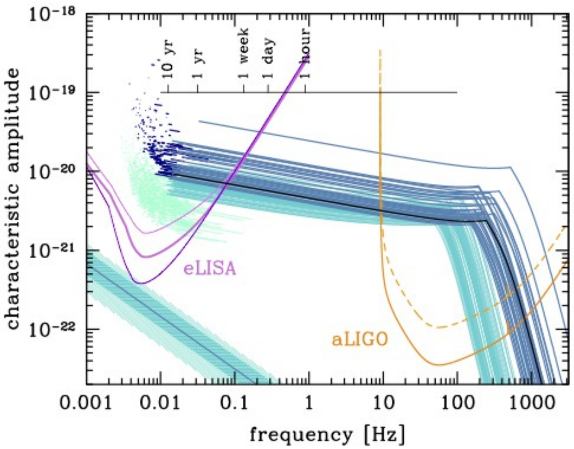
    Cardoso et al., Phys. Rev. D **94**, 084021 (2016)

The far future

- Einstein Telescope (ET) may observe $O(10^5)$ binary coalescences per year
  - Combine information from all sources
  - Ultra-high precision measurements of PN and other coefficients
- Equation of state of black hole mimickers?
- Precision observations of ringdown
- Intermediate and extreme mass ratio inspirals with ET and LISA
  - Test of the no-hair theorem
  - Dynamics of non-adiabatic inspiral
- Observing BBH in both the LISA and ET bands
  - Low and high frequency content of the same signal
- ...



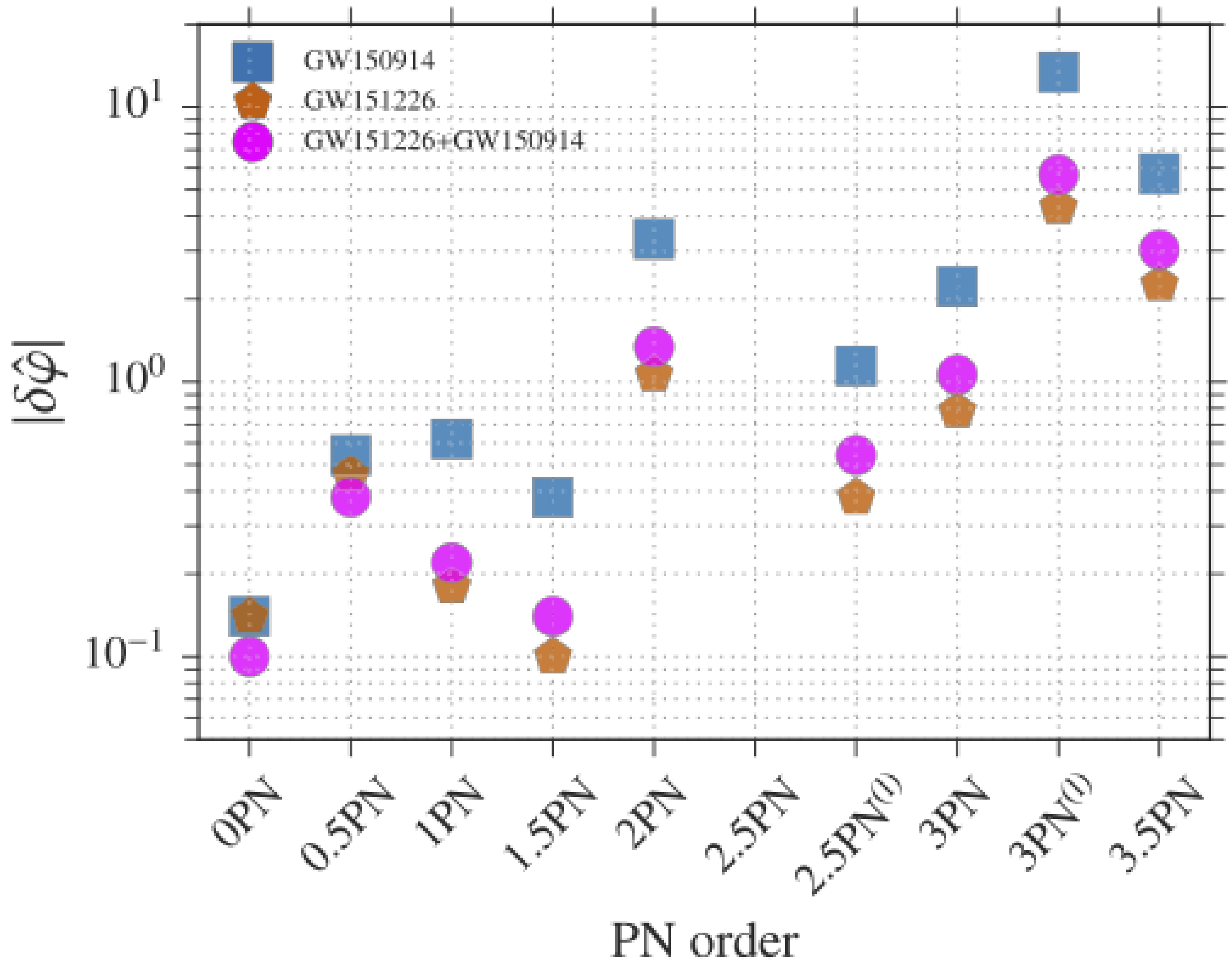




Sesana, Phys. Rev. Lett. **116**, 231102 (2016)

Testing the post-Newtonian description of inspiral

- ☐ Combined bounds from GW150914 and GW151226:



LSC+Virgo, Phys. Rev. X **6**, 041015 (2016)

Do gravitational waves propagate as predicted?

- Anomalous dispersion of gravitational waves (Violating local Lorentz invariance):

$$E^2 = p^2c^2 + Ap^\alpha c^\alpha$$

- In terms of characteristic length scales: $\lambda_A = hcA^{1/(\alpha-2)}$

TABLE IV. 90% credible level lower bounds on the length scale λ_A for Lorentz invariance violation test using GW170104 alone.

	$A > 0$	$A < 0$
$\alpha = 0.0$	1.3×10^{13} km	6.6×10^{12} km
$\alpha = 0.5$	1.8×10^{16} km	6.8×10^{15} km
$\alpha = 1.0$	3.5×10^{22} km	1.2×10^{22} km
$\alpha = 1.5$	1.4×10^{41} km	2.4×10^{40} km

LSC+Virgo, Phys. Rev. Lett. **118**, 221101 (2017)

Binary Pulsars vs GWs

- **EM observations of binary pulsars give** $dP_{orb}/dt \sim 10^{-14} - 10^{-12}$

  Confirm GW luminosity at leading order with excellent precision

- **Most relativistic (J0737-3039) has almost constant** dP_{orb}/dt $v_{orb}/c \sim 2 \times 10^{-3}$ **and** $t_c \sim 85$ Myrs

- **GW150419 had** $dP_{orb}/dt \sim -0.1$ (30Hz) to -1 (132 Hz)

  Just before merger the two BHs orbited each other 75 times/sec

- $v_{orb}/c \sim 0.5$ **just before merger**