Tests of general relativity with GW150914

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Companion papers

- GW150914: The Advanced LIGO detectors in the era of first discoveries
  http://arxiv.org/abs/1602.03838
- GW150914: First results from the search for binary black hole coalescences with Advanced LIGO
  http://arxiv.org/abs/1602.03839
- Properties of the binary black hole merger GW150914
  http://arxiv.org/abs/1602.03840
- Tests of general relativity with GW150914
  http://arxiv.org/abs/1602.03841
- The rate of binary black hole mergers inferred from Advanced LIGO observations surrounding GW150914
  http://arxiv.org/abs/1602.03842
- Observing gravitational-wave transient GW150914 with minimal assumptions
  http://arxiv.org/abs/1602.03843
- Characterization of transient noise in Advanced LIGO relevant to gravitational wave signal GW150914
  http://arxiv.org/abs/1602.03844
- Calibration of the Advanced LIGO detectors for the discovery of the binary-black hole merger GW150914
  http://arxiv.org/abs/1602.03845
- Astrophysical implications of the binary black-hole merger GW150914
  http://arxiv.org/abs/1602.03846
- GW150914: Implications for the stochastic gravitational wave background from binary black holes
  http://arxiv.org/abs/1602.03847
- High-energy neutrino follow-up search of gravitational wave event GW150914 with ANTARES and IceCube
  http://arxiv.org/abs/1602.05411
- Localization and broadband follow-up of the gravitational-wave transient GW150914
  http://arxiv.org/abs/1602.08492

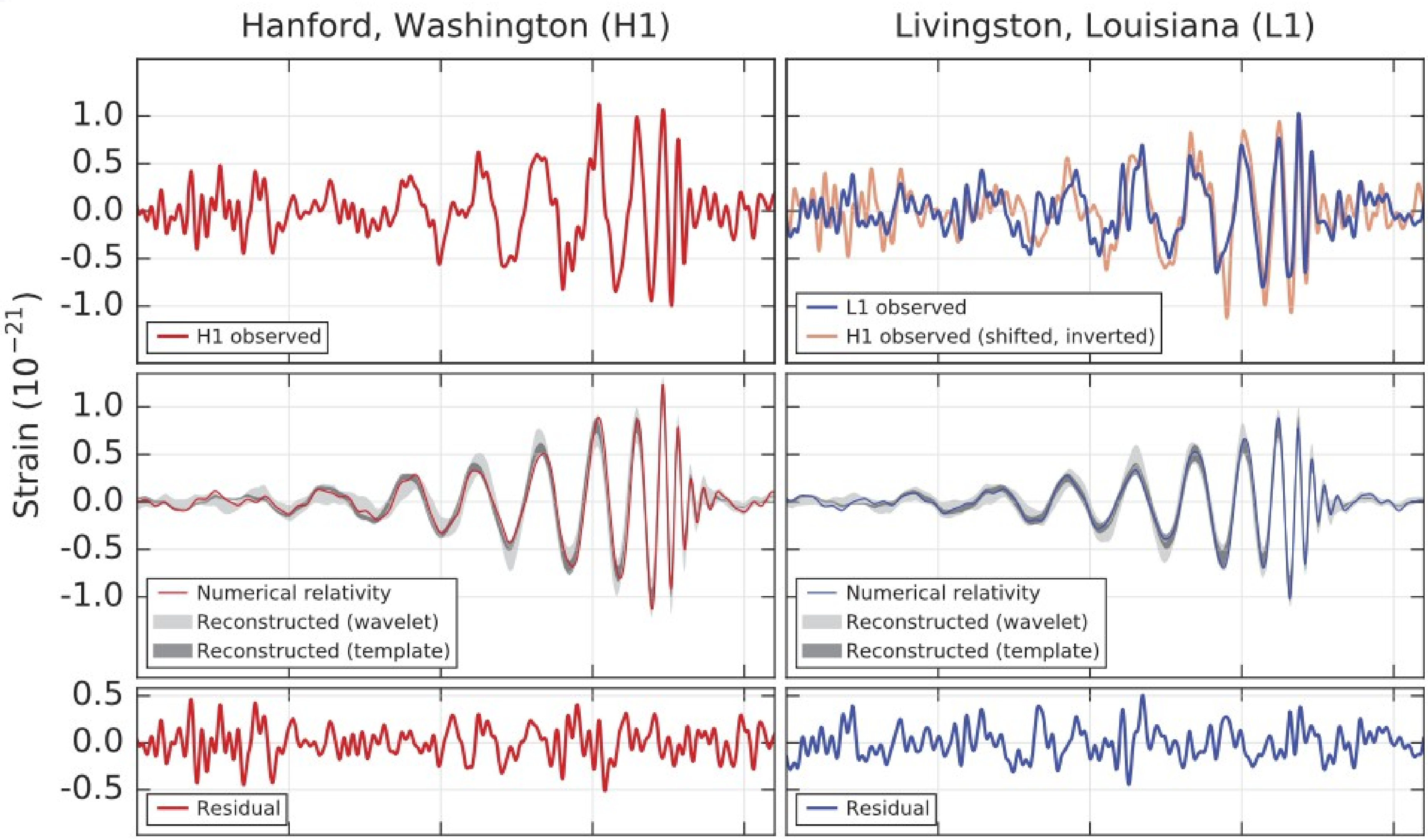
Tests of GR with GW150914

- Some of the most stringent tests: Binary neutron star observations
  - Change in orbital period $\dot{P}_{\rm orb} \sim -10^{-14}$–$10^{-12}$ $\rightarrow$ test of quadrupole formula
  - Orbital compactness GM/c^2R ~ (few) x 10^{-6}, typical speed v/c ~ (few) x 10^{-3}
  - Mostly tests in low-velocity, weak-field regime
    - Also some strong-field tests, but not of the spacetime dynamics
- GW150914:
  - Orbital period from $\dot{P}_{\rm orb} \sim -0.1$ at f_{GW} = 30 Hz to $\dot{P}_{\rm orb} \sim -1$ at f = 132 Hz
  - Just before merger: compactness GM/c^2R ~ 0.2, speed v/c ~ 0.5
  - Pure spacetime process
  - Opportunity to probe new regimes of gravity:
    - Signal consistent with merger of two black holes to form single, Kerr BH?
    - Dynamics of the process in agreement with vacuum Einstein equations?
    - Can we place bounds on deviations in e.g. post-Newtonian coefficients?
    - Was the propagation of the signal as predicted by GR?
    - Can we constrain non-GR polarization states?

Waveform models

- Inspiral-merger-ringdown effective one-body model (SEOBNRv2):
  - Post-Newtonian theory for the inspiral
  - Perturbation theory for the final black hole
  - Calibrated against numerical relativity waveforms
  - Double aligned spins
- Phenomenological models (IMRPhenomPv2):
  - Post-Newtonian theory for early inspiral
  - Phenomenological description of late inspiral, merger, ringdown
  - Calibrated against numerical relativity waveforms
  - Effective description of precessing spins
- Further validation for analyses of GW150914:
  - Comparison with existing NR waveforms as well as new, targeted simulations
  - Systematic waveform uncertainties $<$ statistical measurement uncertainties

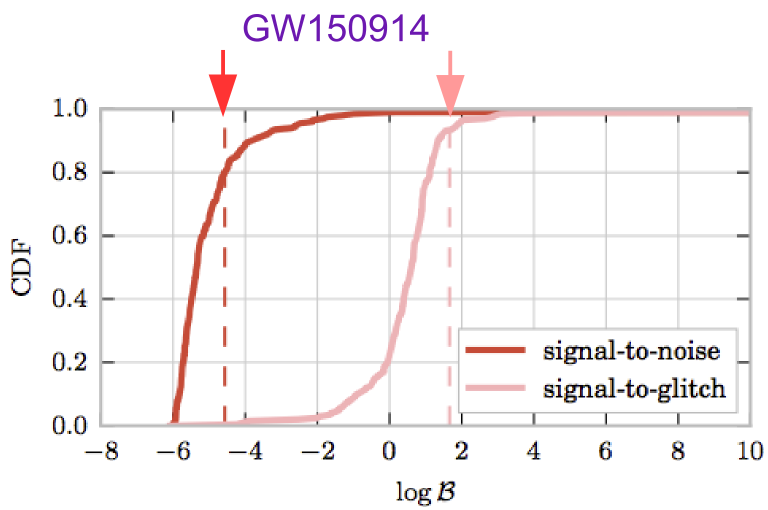
Subtraction of most probable waveform from the data

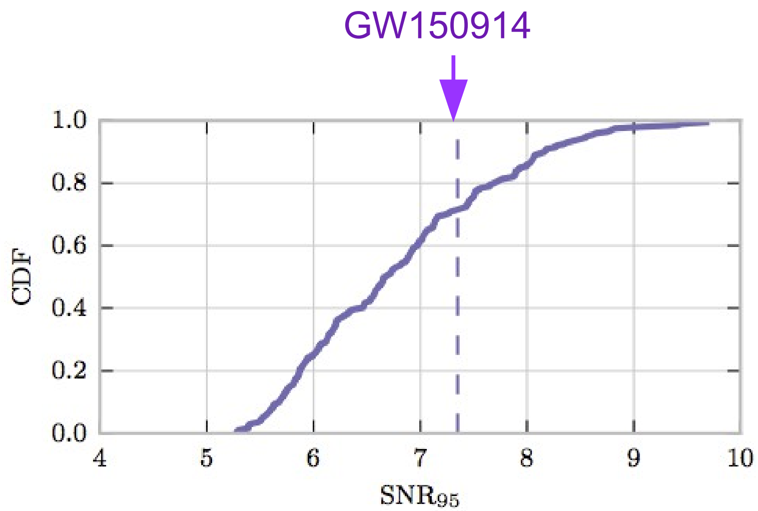


Subtraction of most probable waveform from the data

- Compute log Bayes factor (logarithm of ratio of evidences) for:
  - Signal against noise
  - Signal against glitch

  Noise-only hypothesis preferred over both glitch and signal hypotheses
  - Indication of the stability of the detectors at time of GW150914
- Coherent SNR of residual consistent with detector noise

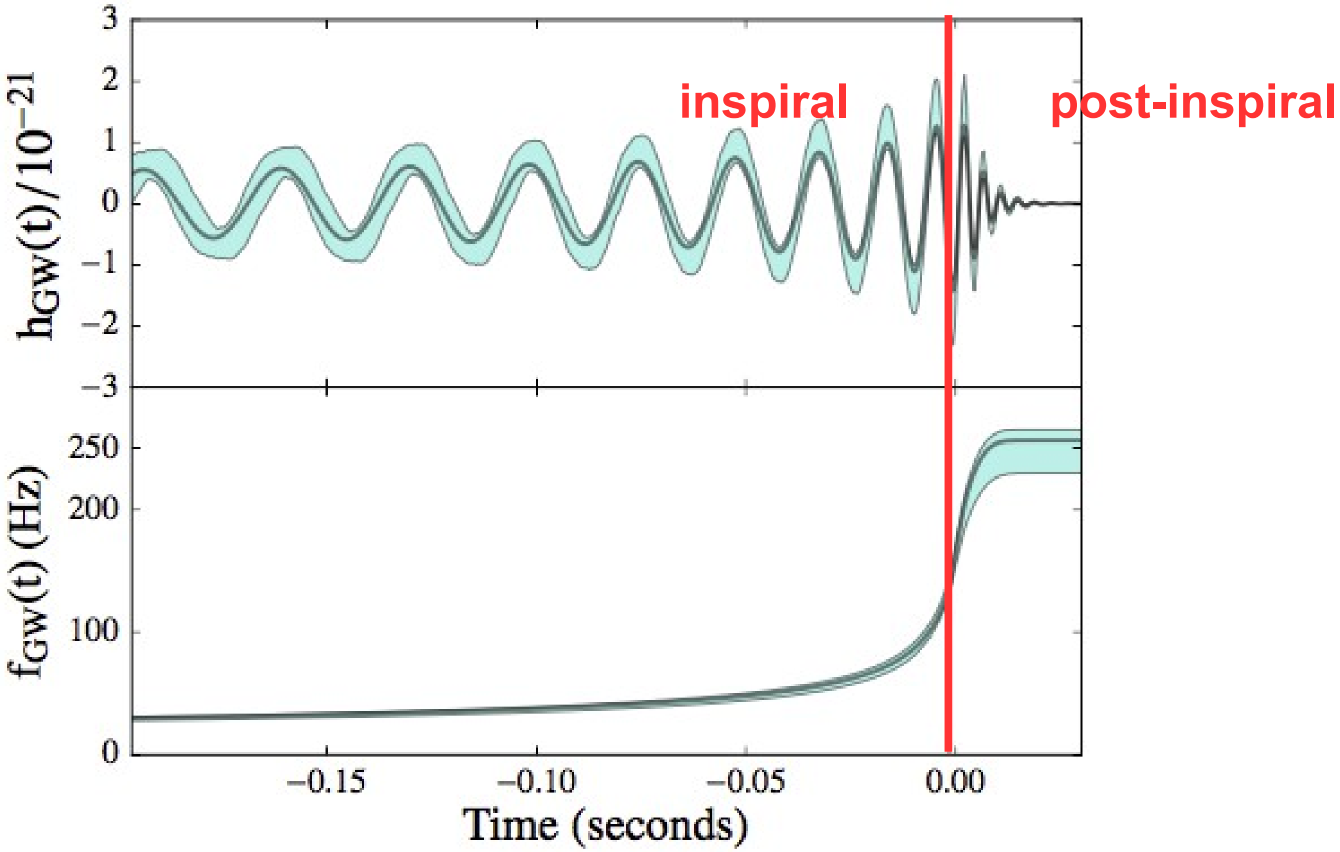




- Residual SNR leads to fitting factor of most probable waveform and GW150914:

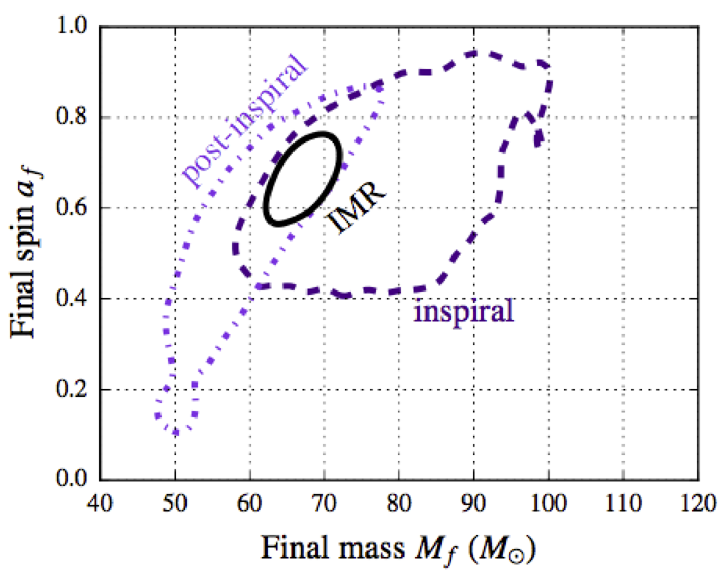
$$\mathrm{SNR}_{\mathrm{res}}^2 = (1 - \mathrm{FF}^2)\,\mathrm{FF}^{-2}\,\mathrm{SNR}_{\mathrm{det}}^2 \quad \rightarrow \quad \mathrm{FF} \geq 0.96$$

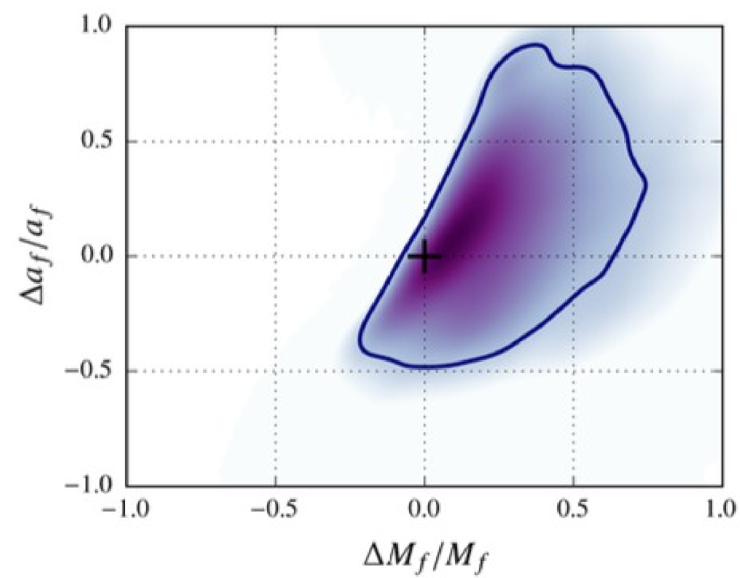
Consistency of masses and spins of initial and final objects



- 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*

Consistency of masses and spins of initial and final objects





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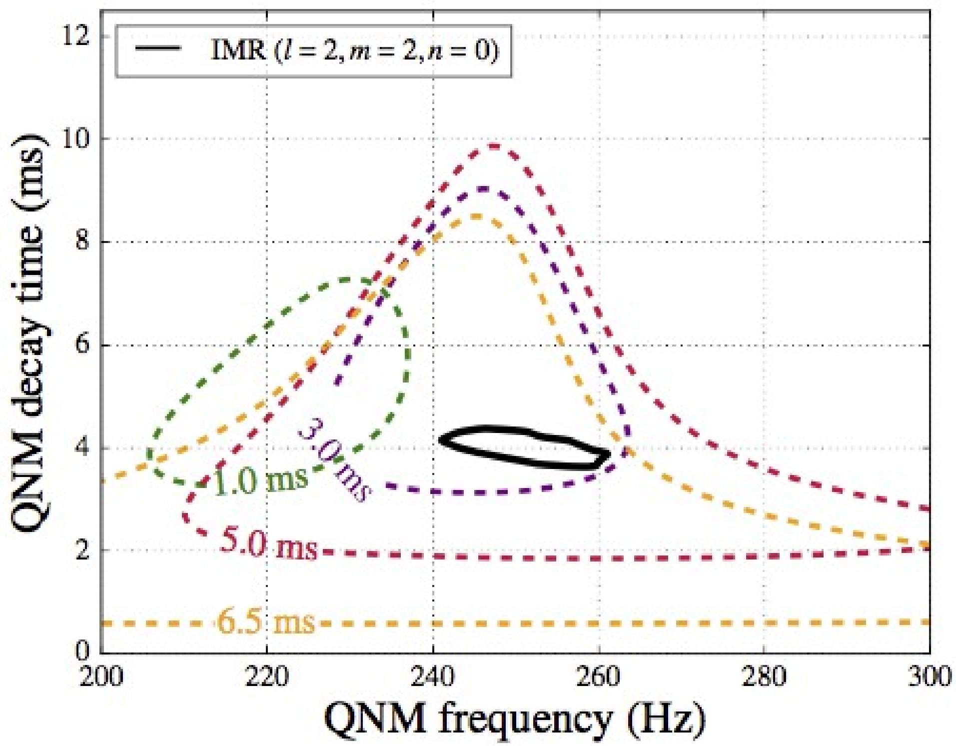
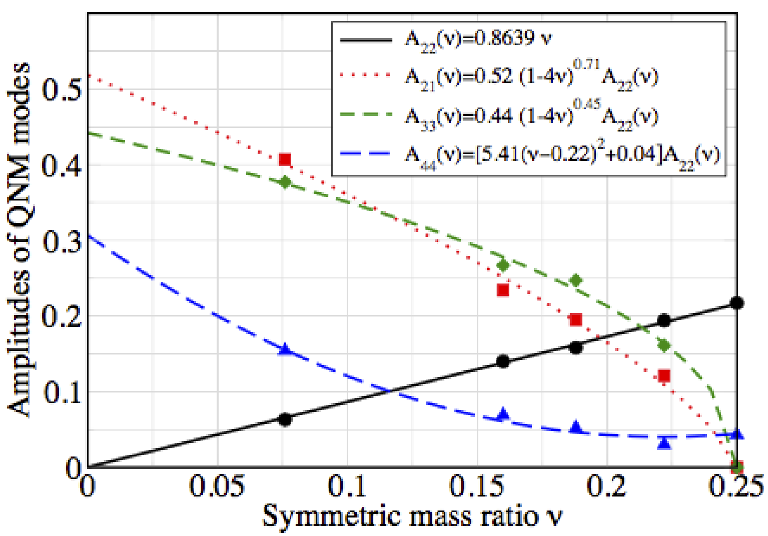
Searching for a least-damped quasi-normal mode

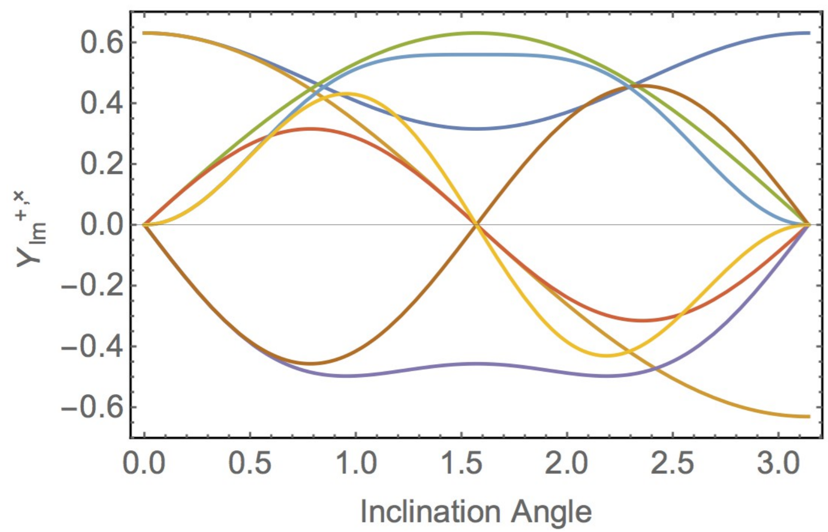
- Fit single damped sinusoid to find damping frequency and damping time
  - Assumption that other modes hard to extract
- NR simulations suggest that QNM regime starts at 10 to 20 M after merger
  - For M ~ 68 M_{sun} this means 3 to 7 ms after merger
  - Match damped sinusoids with different starting times after merger (dashed curves)
  - Compare with predictions from mass and spin measured with full IMR waveforms



Testing the black hole no-hair theorem?

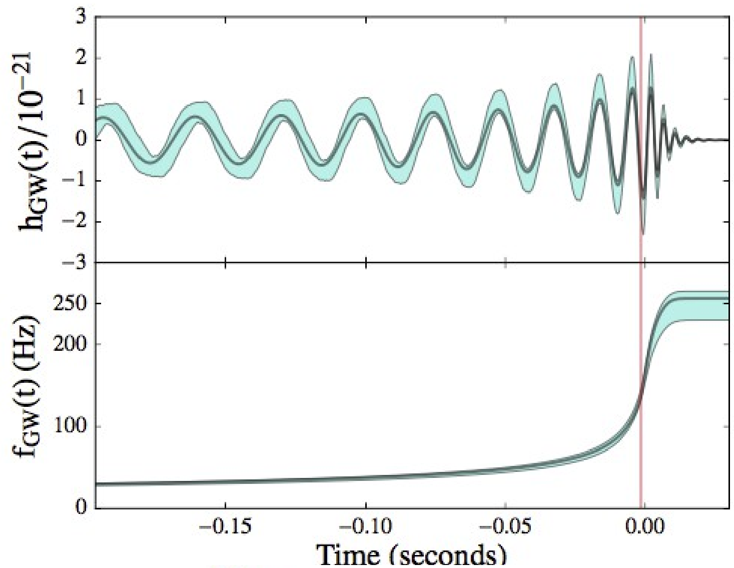
- If multiple QNMs could be observed: test of no-hair theorem
  - Damping times τ_{nlm} and frequencies f_{nlm} only depend on M_f and a_f
  - Hence only two of them are independent → consistency test
- For multiple QNMs to be visible, need system with
  - Asymmetric component masses
  - More misalignment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

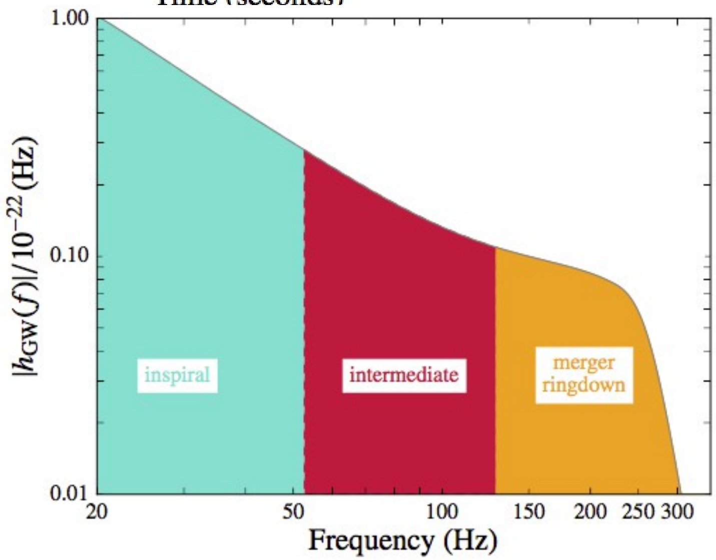




Gossan et al., PRD **85**, 124056 (2012)

Constraining parameterized deviations from GR





- IMRPhenom waveform:
  - Inspiral regime
    - Post-Newtonian parameters $\{\varphi_0, \varphi_1, \ldots, \varphi_7\}, \ \{\varphi_{5l}, \varphi_{6l}\}$
    - Late-inspiral parameters: $\{\sigma_1, \sigma_2, \sigma_3, \sigma_4\}$
  - Intermediate regime $\{\beta_1, \beta_2, \beta_3\}$
  - Merger-ringdown regime $\{\alpha_1, \alpha_2, \alpha_3, \alpha_4\}$
- Phenomenological parameters capture frequency dependences in different regimes

Constraining parameterized deviations from GR

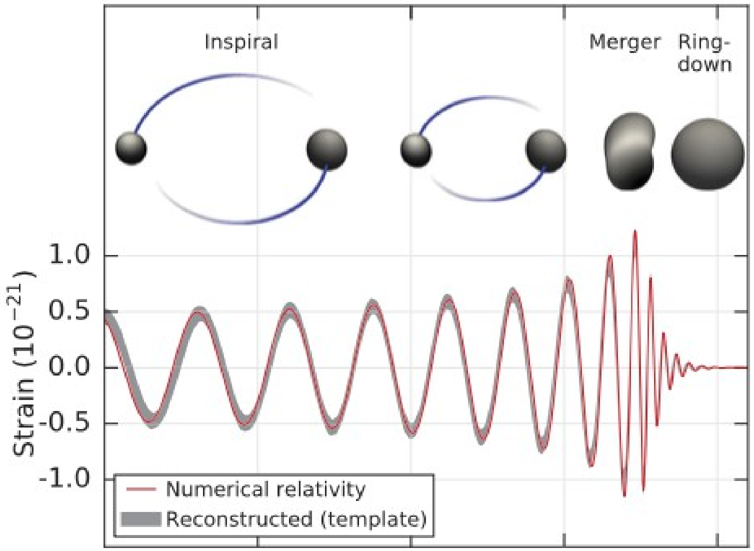
- Allow for *fractional deviations* in parameters characterizing waveform:

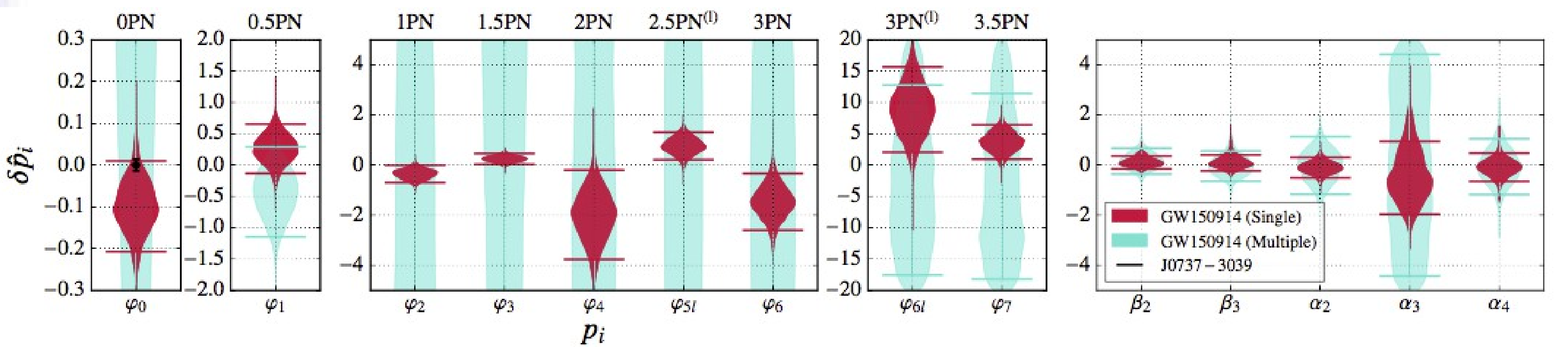
  $$p_i \rightarrow (1 + \delta\hat{p}_i)\, p_i$$

  - Let $\delta\hat{p}_i$ vary freel in addition to other system parameters (masses, spins, ...)
  - General relativity: $\delta\hat{p}_j = 0$

- Single-parameter analyses:
  - Only one of the $\delta\hat{p}_i$ left free at a time, all others set to zero
  - Probes deviations that occur predominantly at e.g. a particular PN order
  - If measurable deviation at multiple PN orders, should also be picked up
- Multiple-parameter analyses:
  - Multiple $\delta\hat{p}_i$ left free in batches:
    - All the PN parameters together
    - All the intermediate-regime parameters together
    - All the merger-ringdown parameters together

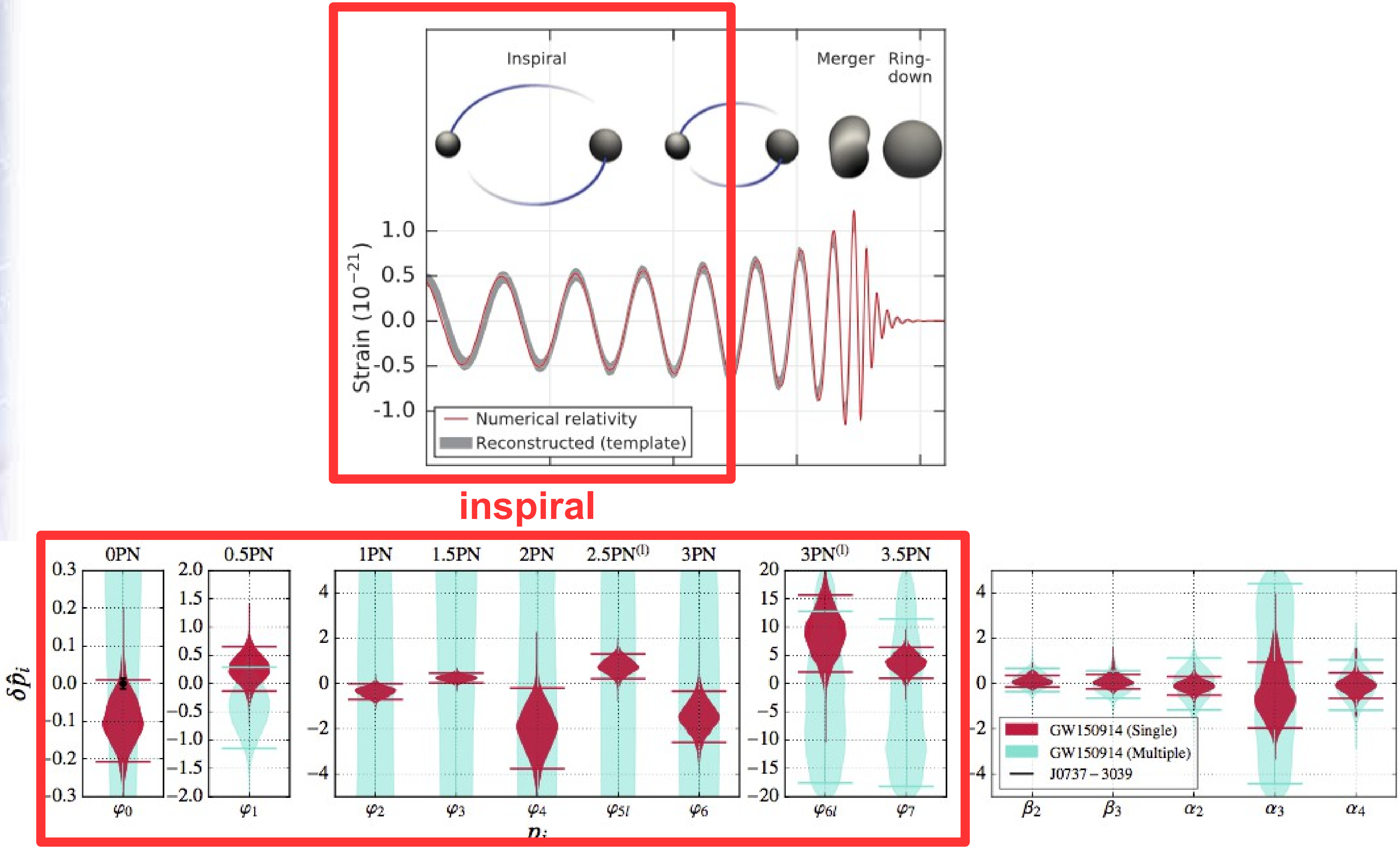
Constraining parameterized deviations from GR





- Red: single-parameter analyses
- Cyan: multiple-parameter analyses

Constraining parameterized deviations from GR



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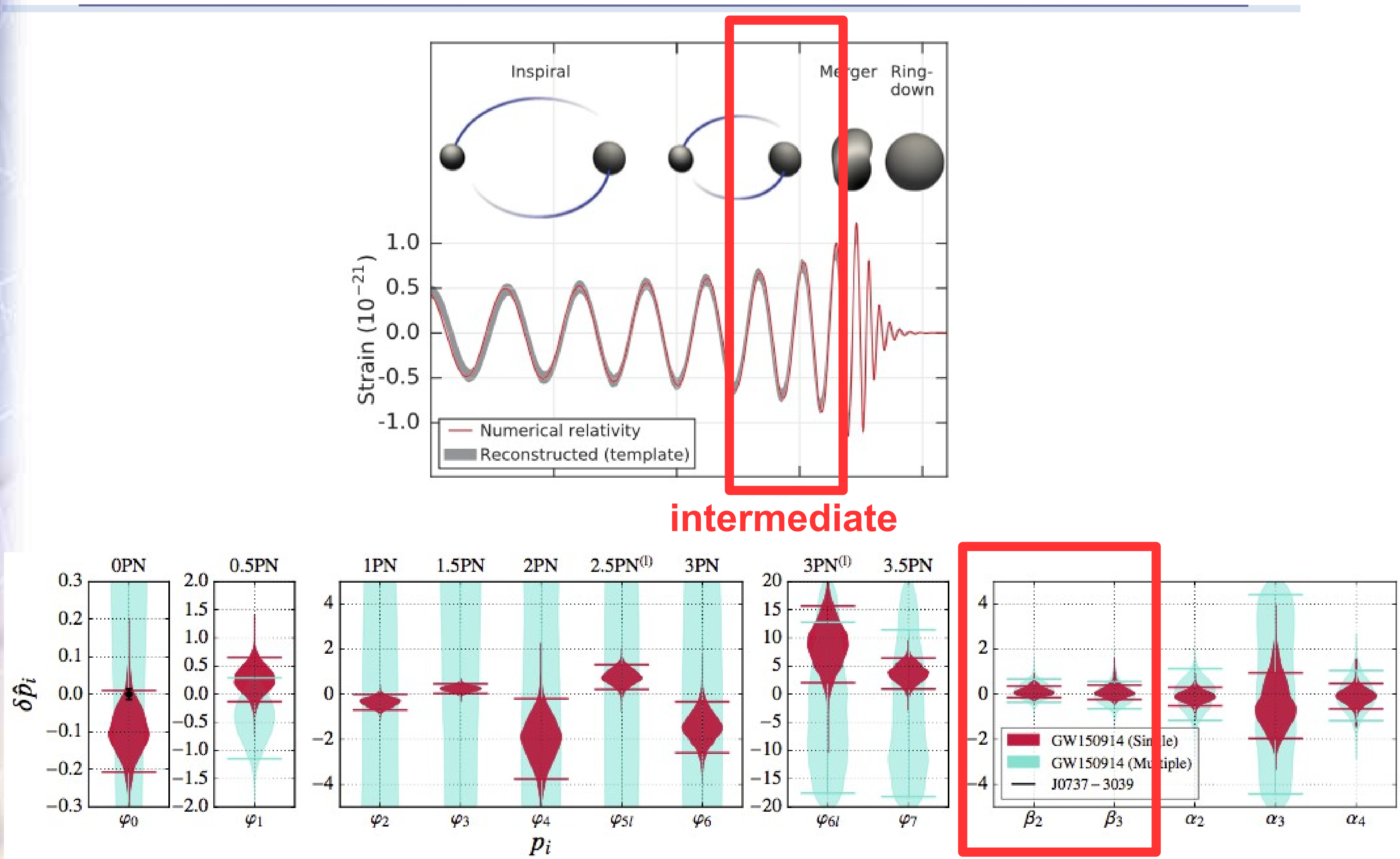

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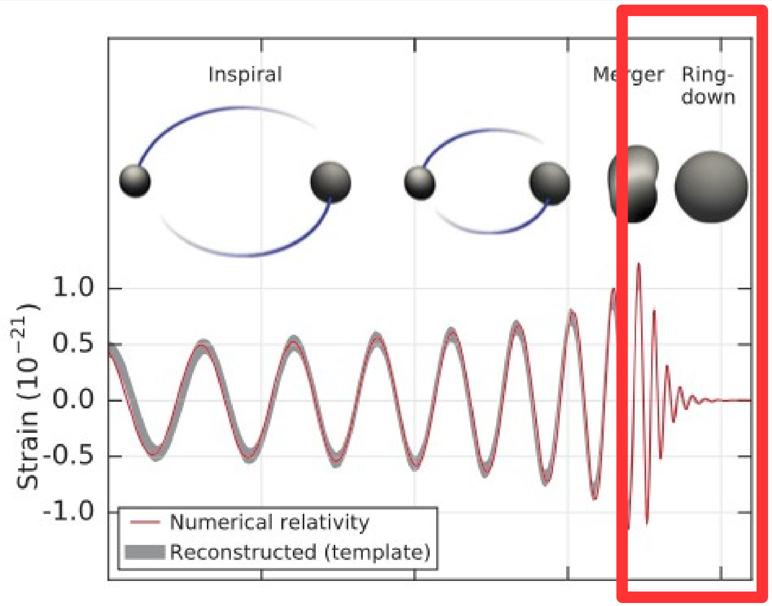
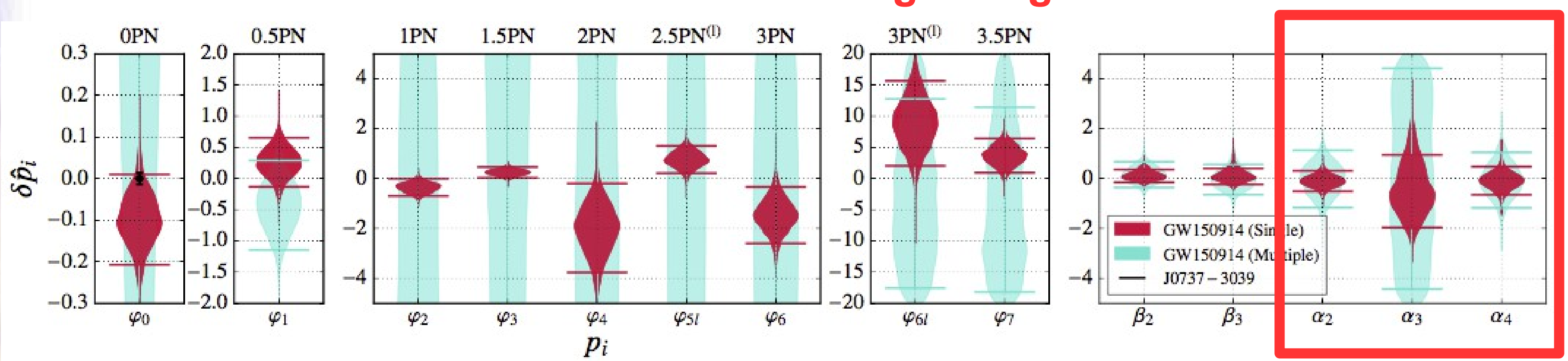


merger-ringdown



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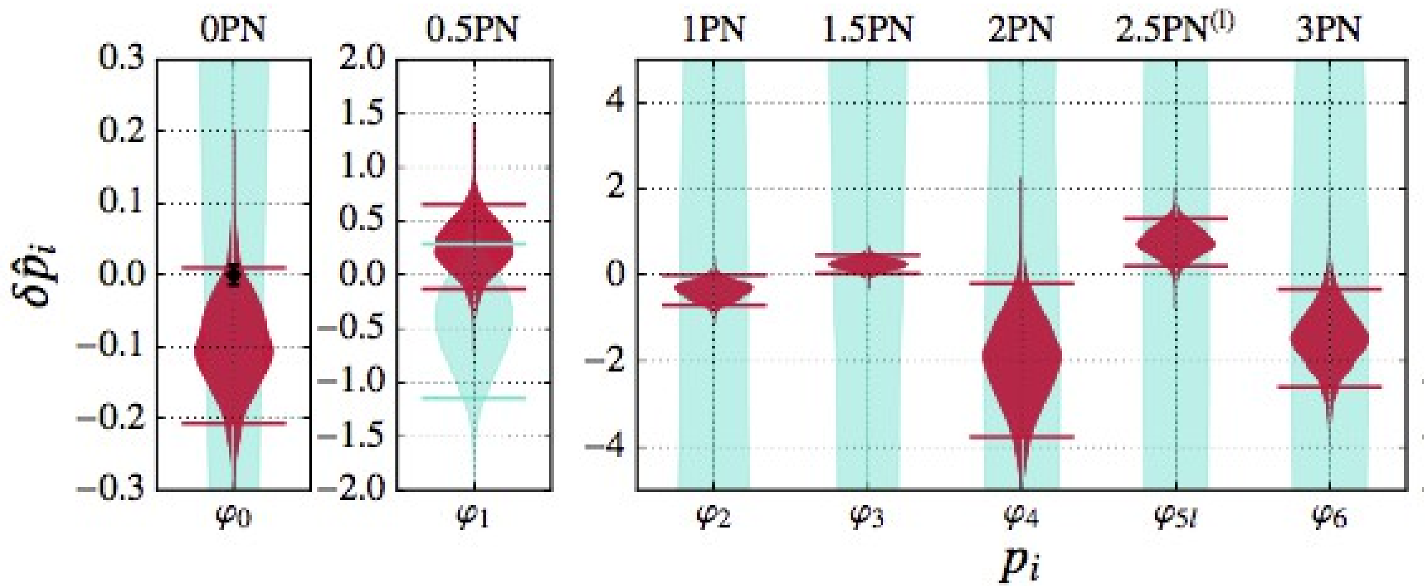


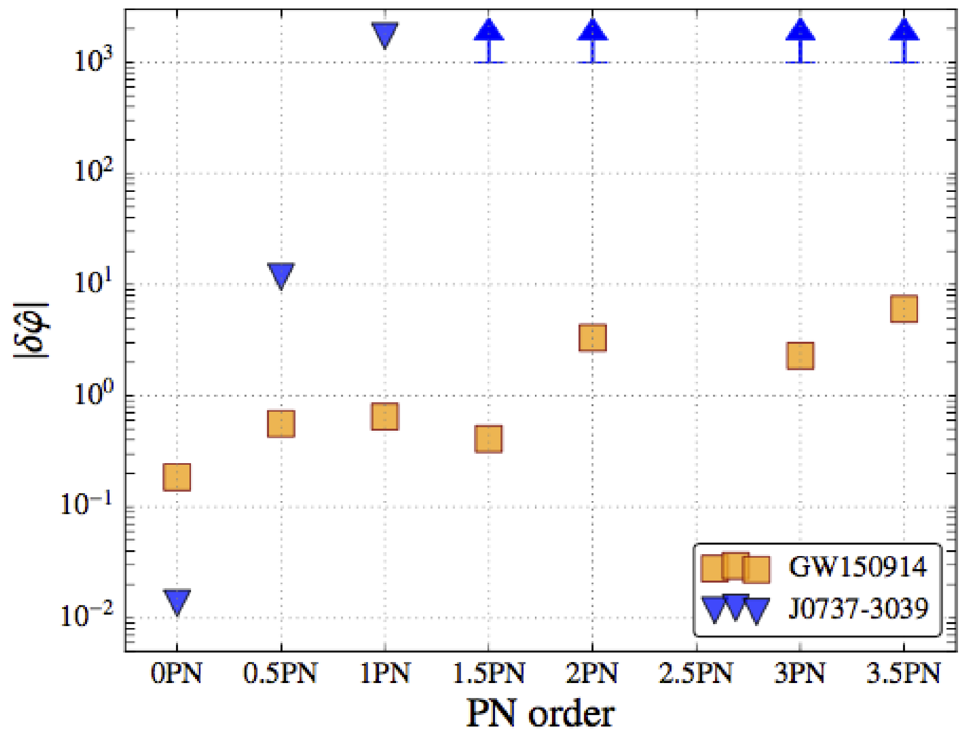
- For the post-Newtonian parameters: Offsets at the 2 – 2.5 σ level
  - Could be due to noise realization
    - Took NR waveform with parameters consistent with GW150914
    - Put this in 20 stretches of noise close to time of GW150914
    - Found results very similar to the above in 1 case
  - But: cannot exclude missing physics – more detections needed

Constraining parameterized deviations from GR

- Log Bayes factors (ratio of evidences) for GR versus the extended models

waveform regime	parameter	f–dependence	median single	median multiple	GR quantile single	GR quantile multiple	$\log_{10} B^{GR}_{model}$ single	$\log_{10} B^{GR}_{model}$ multiple
	$\delta\hat{\varphi}_0$	$f^{-5/3}$	$-0.1^{+0.1}_{-0.1}$	$1.4^{+3.3}_{-3.0}$	0.94	0.21	1.9 ± 0.1	
	$\delta\hat{\varphi}_1$	$f^{-4/3}$	$0.3^{+0.4}_{-0.4}$	$-0.4^{+0.7}_{-0.7}$	0.14	0.87	1.6 ± 0.1	
	$\delta\hat{\varphi}_2$	f^{-1}	$-0.35^{+0.3}_{-0.35}$	$-3.2^{+19.3}_{-15.2}$	0.97	0.60	1.2 ± 0.2	
	$\delta\hat{\varphi}_3$	$f^{-2/3}$	$0.2^{+0.2}_{-0.2}$	$2.6^{+13.8}_{-15.7}$	0.04	0.41	1.2 ± 0.1	
early-inspiral regime	$\delta\hat{\varphi}_4$	$f^{-1/3}$	$-2.0^{+1.6}_{-1.8}$	$0.5^{+17.3}_{-18.2}$	0.98	0.49	0.3 ± 0.1	3.9 ± 0.1
	$\delta\hat{\varphi}_{5l}$	$\log(f)$	$0.8^{+0.6}_{-0.55}$	$-1.5^{+19.1}_{-16.3}$	0.02	0.55	0.7 ± 0.1	
	$\delta\hat{\varphi}_6$	$f^{1/3}$	$-1.5^{+1.1}_{-1.1}$	$-0.6^{+18.2}_{-17.2}$	0.99	0.53	0.4 ± 0.1	
	$\delta\hat{\varphi}_{6l}$	$f^{1/3}\log(f)$	$8.9^{+6.8}_{-6.8}$	$-2.4^{+18.7}_{-15.2}$	0.02	0.57	-0.2 ± 0.1	
	$\delta\hat{\varphi}_7$	$f^{2/3}$	$3.7^{+2.6}_{-2.75}$	$-3.4^{+19.3}_{-14.8}$	0.02	0.59	-0.0 ± 0.2	
intermediate regime	$\delta\hat{\beta}_2$	$\log f$	$0.1^{+0.4}_{-0.3}$	$0.15^{+0.6}_{-0.5}$	0.29	0.35	1.2 ± 0.1	2.2 ± 0.1
	$\delta\hat{\beta}_3$	f^{-3}	$0.1^{+0.5}_{-0.3}$	$-0.0^{+0.8}_{-0.6}$	0.38	0.56	0.6 ± 0.1	
	$\delta\hat{\alpha}_2$	f^{-1}	$-0.1^{+0.4}_{-0.4}$	$-0.0^{+1.0}_{-1.15}$	0.68	0.51	1.1 ± 0.1	
merger–ringdown regime	$\delta\hat{\alpha}_3$	$f^{3/4}$	$-0.5^{+2.0}_{-1.5}$	$-0.0^{+4.4}_{-4.4}$	0.67	0.50	1.3 ± 0.1	2.1 ± 0.1
	$\delta\hat{\alpha}_4$	$\tan^{-1}(af+b)$	$-0.1^{+0.5}_{-0.6}$	$-0.0^{+1.2}_{-1.1}$	0.61	0.55	1.2 ± 0.1	

Constraints on deviations in post-Newtonian parameters



- *First empirical bounds on high-order PN phase parameters*
- Bounds not yet very tight, but:
  - May see sources with more inspiral cycles in detector's sensitive band
    - Light binary black holes, or binary neutron star coalescences
  - Same source at final aLIGO design sensitivity would have been ~3 times louder
  - Will be able to combine results from all future detections!

Constraining the mass of the graviton

- Assume only effect on propagation, not on binary dynamics
- Modified dispersion relation for the graviton:

$$E^2 = p^2c^2 + m_g^2c^4$$

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

$$\lambda_g = \frac{h}{m_g c}$$ Compton wavelength

- Arrival times altered: frequency-dependent effect

$$t_a = (1+z)\left[t_e + \frac{D}{2(\lambda_g f)^2}\right]$$

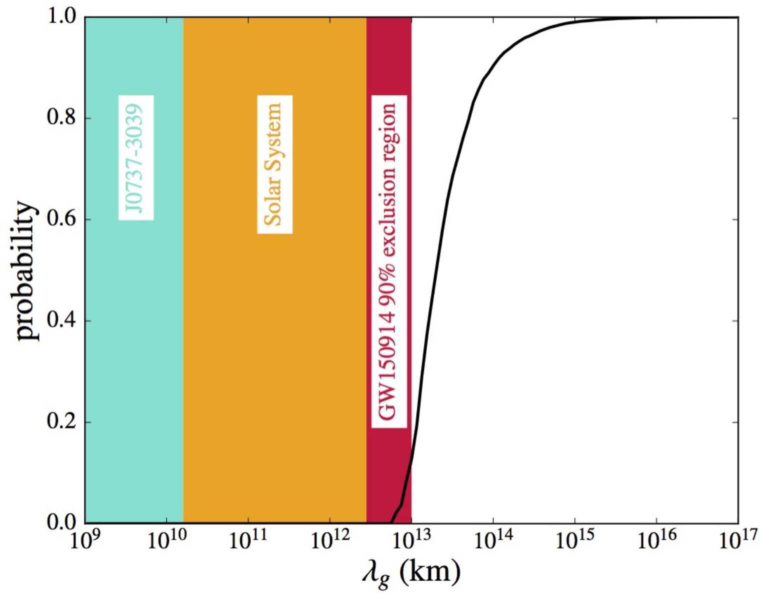
- Effect on the GW phase:

$$\delta\Phi(f) = -\frac{\pi D c}{\lambda_g^2(1+z)} f^{-1}$$

- Will compare results with "static" bounds (e.g. Solar system)
  - Newtonian potential gets Yukawa-like correction (gravity now has finite range):

$$\varphi(r) = -GM/r \quad \longrightarrow \quad -(GM/r)\exp(-r/\lambda_g)$$

Constraining the mass of the graviton



$\lambda_g > 1.0 \times 10^{13}$ km

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

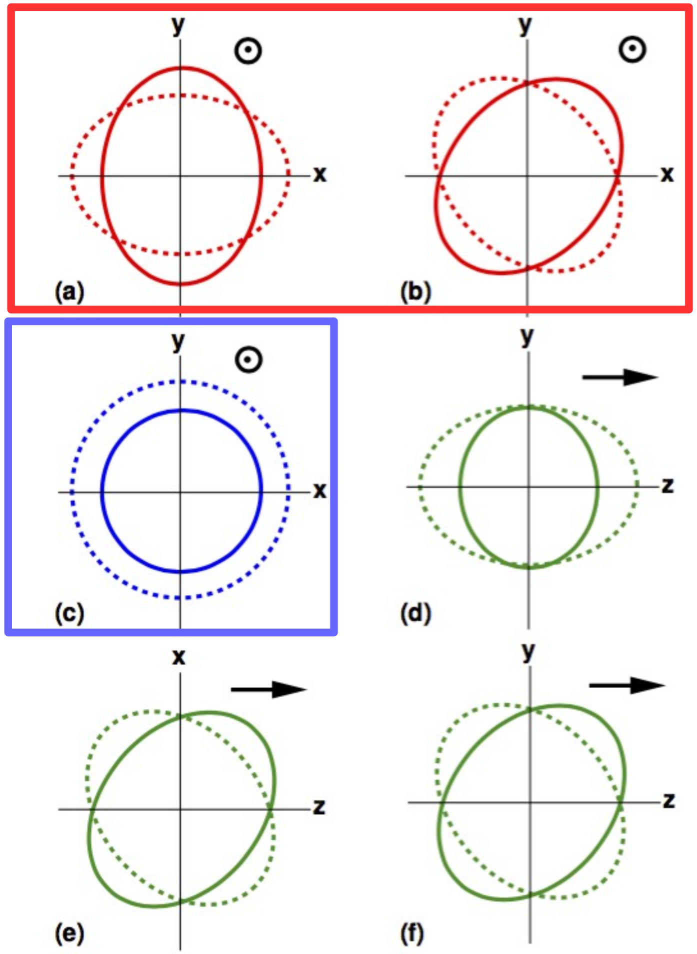
- GW150914 improves on binary pulsar bound (only other dynamical bound) by 3 orders of magnitude
- GW150914 improves on Solar system static bound by factor of few
- Other bounds available:
  - Dynamics of galaxy clusters ($\lambda_g > 6.2 \times 10^{19}$ km), weak lensing ($\lambda_g > 1.8 \times 10^{22}$ km)
    - But: uncertainty in amount of dark matter and its distribution
  - Non-observation of superradiant instabilities in supermassive black holes ($\lambda_g > 2.5 \times 10^{13}$ km)

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:

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

- Meant to illustrate difficulty in distinguishing between GR and non-GR polarization states with GW150914
- Need larger network of detectors with different orientations
    - Advanced LIGO
    - Advanced Virgo
    - KAGRA
    - LIGO-India



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

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
  - Much 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

Conclusions for now

GW150914 allowed us to probe of the genuinely strong-field dynamics of spacetime

- Residual data after subtraction of most probable waveform were consistent with noise
- Component masses and spins during inspiral were consistent with mass and spins of the final black hole
- End of the signal consistent with least-damped quasi-normal mode
- First constraints on high-order post-Newtonian coefficients as well as parameterized deviations in merger/ringdown
- Best dynamical bound on the graviton mass so far: $m_g < 1.2 \times 10^{-22}$ eV/c^2
- However, no constraint on non-GR polarization states

The results from all tests performed on GW150914 are consistent with GR