Compact binary coalescence:

Testing general relativity with gravitational waves

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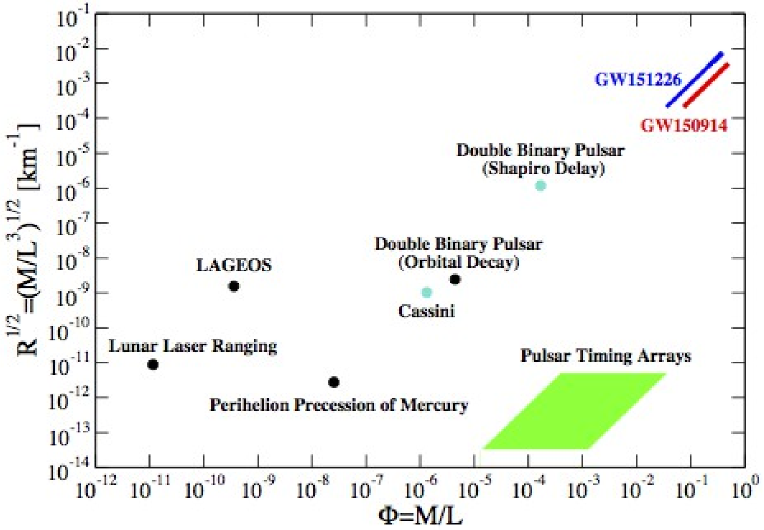
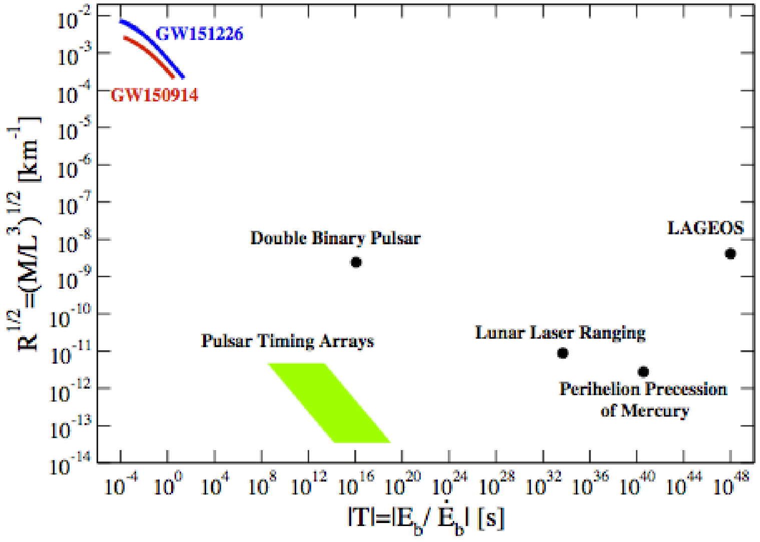
First access to the strong-field dynamics of spacetime

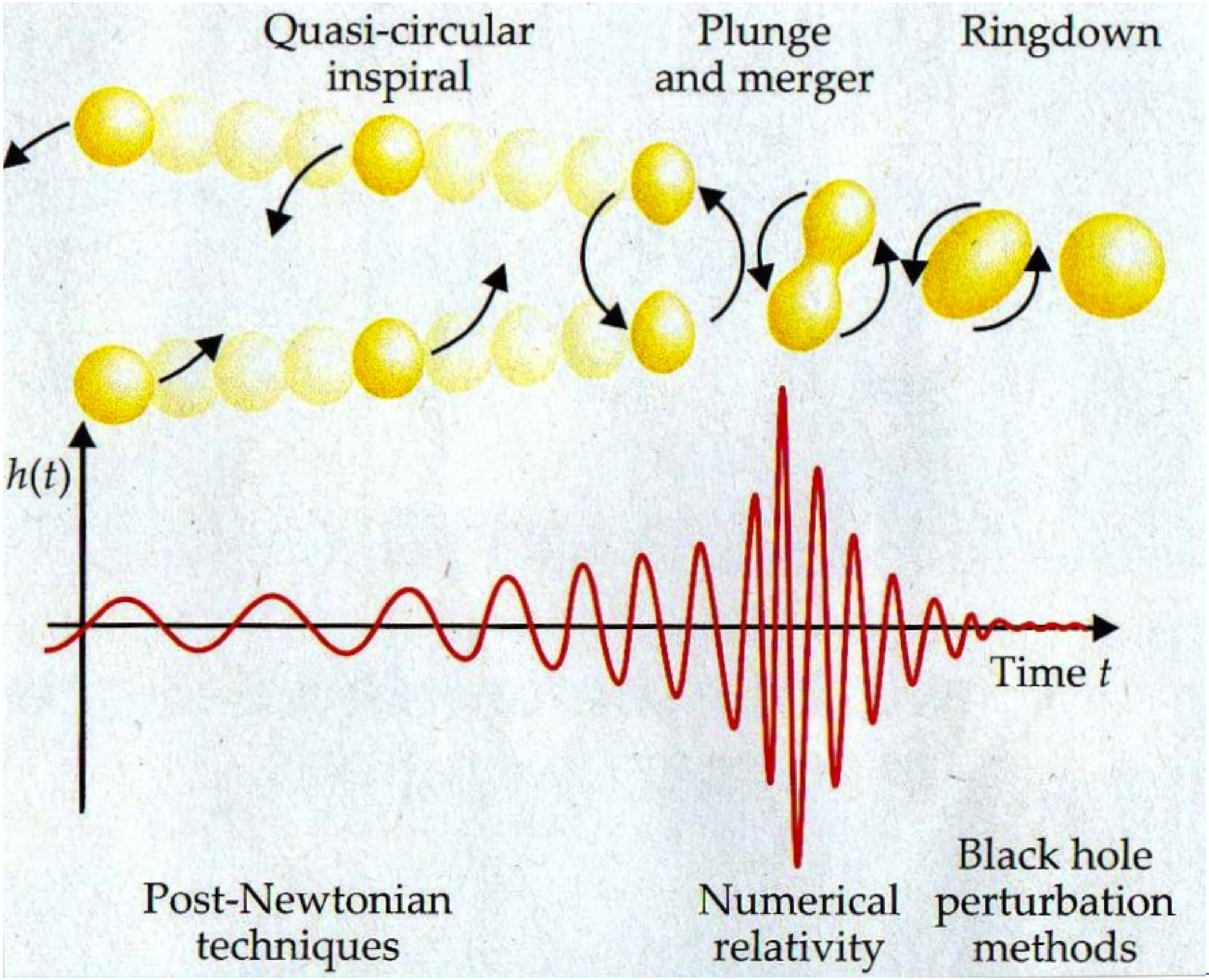
- ☐ Before the direct detection of gravitational waves:
  - Solar system tests:
    weak-field; dynamics of spacetime itself not being probed
  - Binary neutron stars:
    relatively weak-field test of spacetime dynamics
  - Cosmology:
    dark matter and dark energy may signal GR breakdown
- ☐ Direct detection of GW from binary black hole mergers:
  - Genuinely strong-field dynamics
  - (Presumed) pure spacetime events



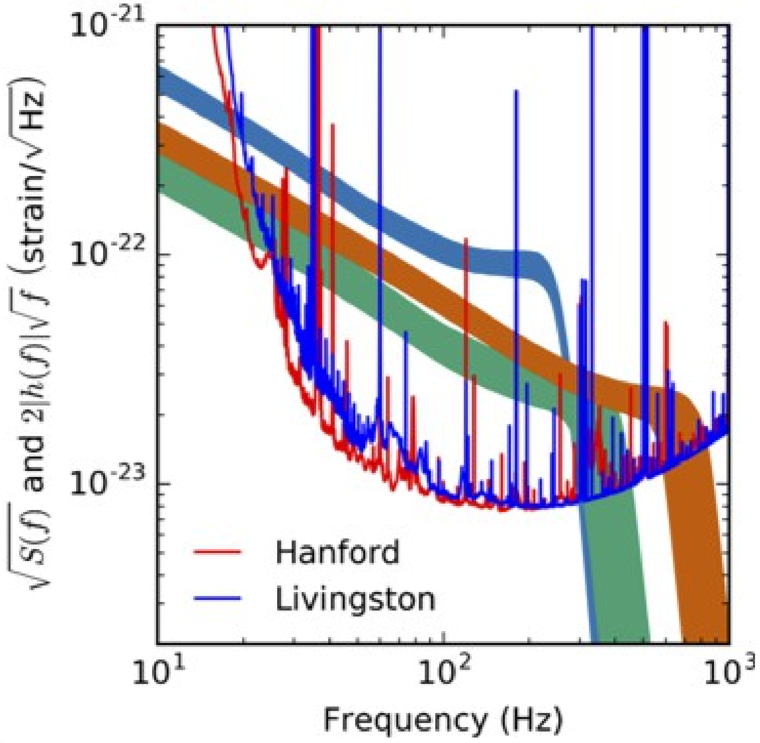


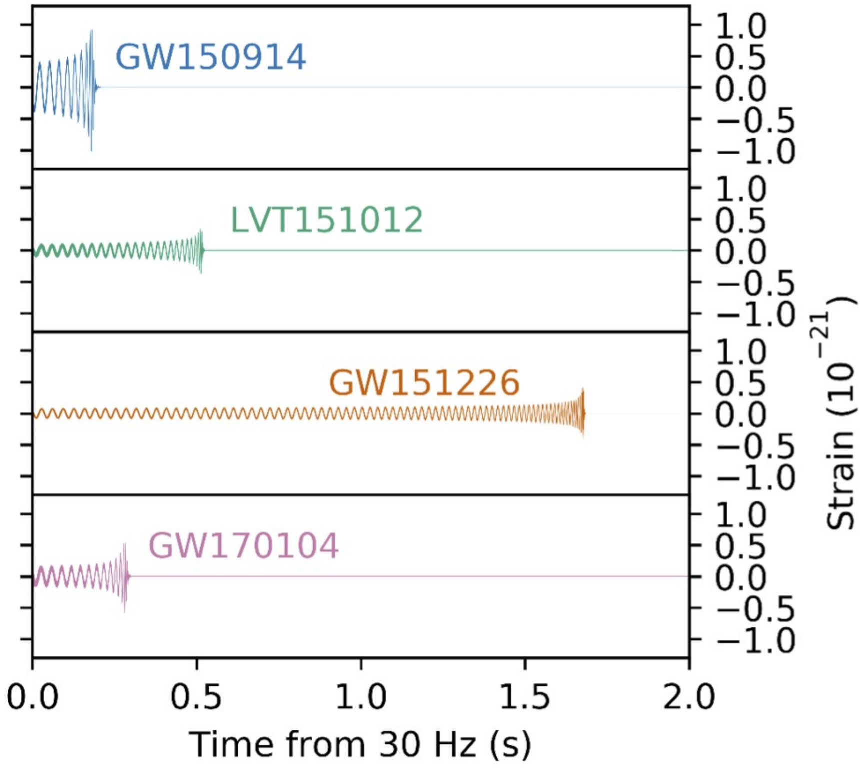
Yunes, Yagi, Pretorius, Phys. Rev. D **94**, 084002 (2016)

Coalescence of binary neutron stars and black holes



Complementary information from different events



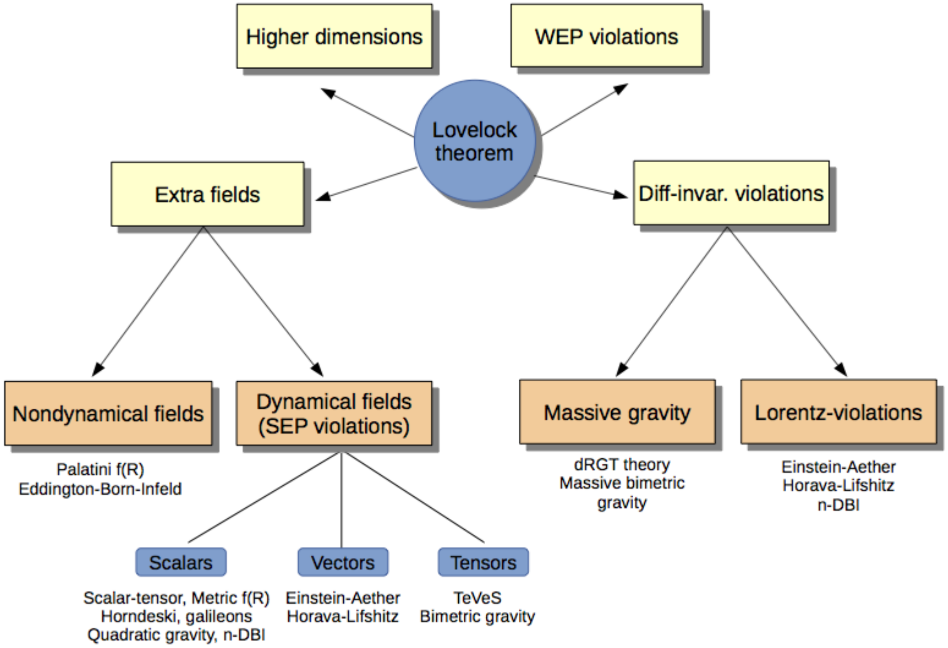


LSC+Virgo, Phys. Rev. X **6**, 041015 (2016)

- ☐ 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

A zoo of alternative theories of gravity

Lovelock's theorem:
"In four spacetime dimensions the only divergence-free symmetric rank-2 tensor constructed solely from the metric and its derivatives up to second order, and preserving diffeomorphism invariance, is the Einstein tensor plus a cosmological term"



Lovelock theorem

Higher dimensions

WEP violations

Extra fields

Diff-invar. violations

Nondynamical fields
Palatini f(R)
Eddington-Born-Infeld

Dynamical fields (SEP violations)

Scalars
Scalar-tensor, Metric f(R)
Horndeski, galileons
Quadratic gravity, n-DBI

Vectors
Einstein-Aether
Horava-Lifshitz

Tensors
TeVeS
Bimetric gravity

Massive gravity
dRGT theory
Massive bimetric gravity

Lorentz-violations
Einstein-Aether
Horava-Lifshitz
n-DBI

Berti et al., Class. Quantum Grav. **32**, 243001 (2015)

- ☐ Specific alternative theories can in principle be mapped to anomalies in the coalescence process and/or propagation of gravitational waves (Yunes+ 2009, 2016)
- ☐ In practice: no inspiral-merger-ringdown waveforms available of same quality as for GR
  - As much as possible, perform *model-independent* tests of GR itself
  - Phenomenological and effective one-body inspiral-merger-ringdown waveforms tuned to numerical simulations

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?

☐ Tidal effects during inspiral

- "Black hole mimickers": boson stars, dark matter stars, gravastars, ...
- If less compact than neutron stars, can have large tidal effects

☐ Plunge and merger

- Most dynamical regime

☐ Consistency between inspiral and post-inspiral regimes

☐ Ringdown

- From the quasi-normal mode spectrum: (indirect) test of no-hair theorem

☐ Gravitational wave echoes

- Quantum-modified black holes, exotic objects:
  repeated bursts of GWs after ringdown

☐ Anomalous propagation of gravitational waves over large distances

- Massive graviton, violations of local Lorentz invariance

Existing results

from

GW150914, GW151226, GW170104

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:

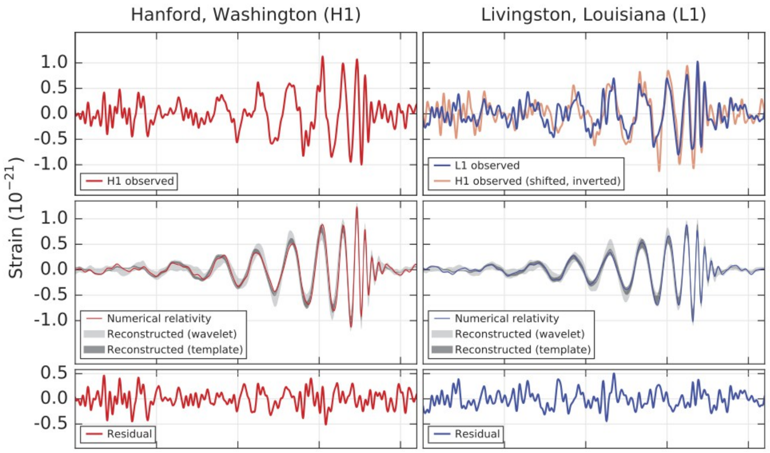
$$\mathrm{SNR}_{\mathrm{res}}^2 = (1-\mathrm{FF}^2)\,\mathrm{FF}^{-2}\,\mathrm{SNR}_{\mathrm{det}}^2$$

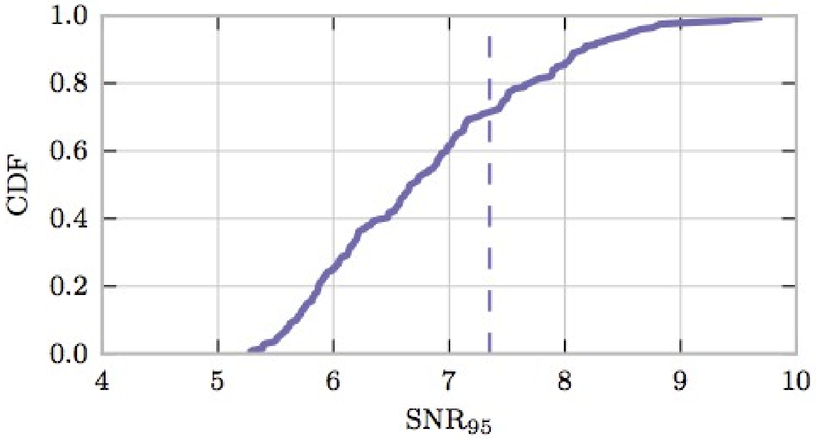
- $\mathrm{SNR}_{\mathrm{det}} = 25.3^{+0.1}_{-0.2}$

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

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

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

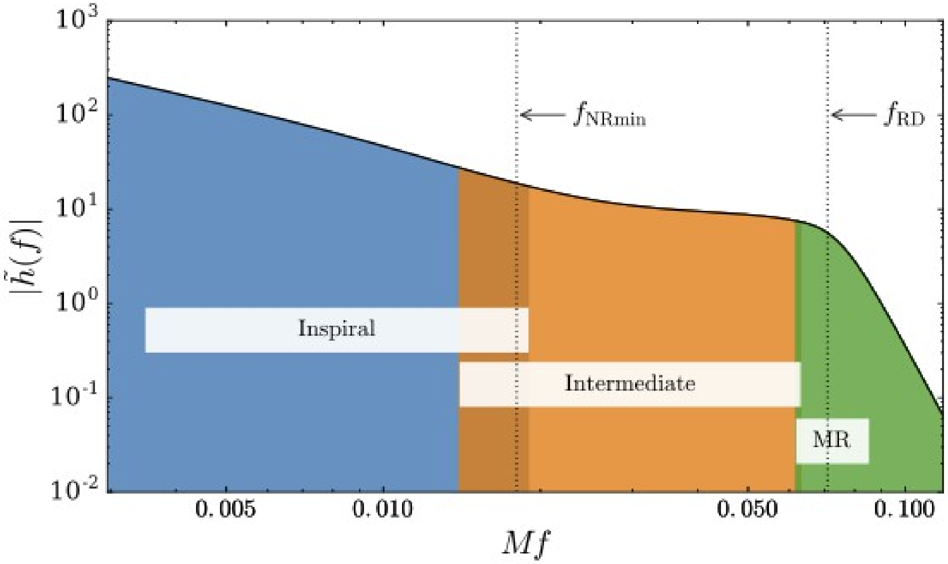


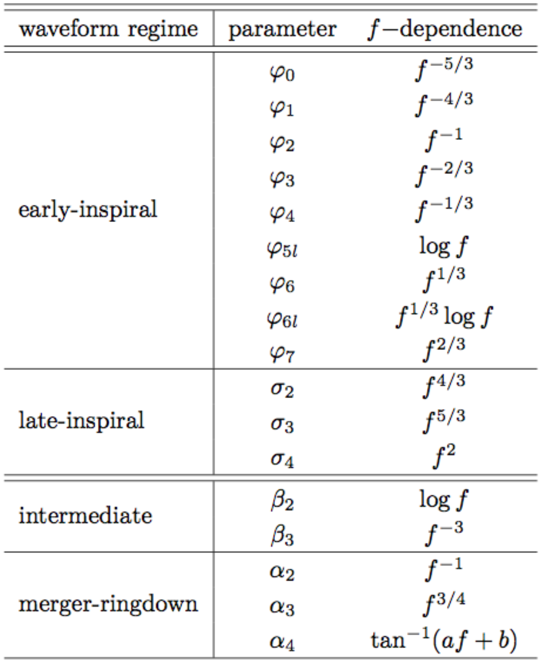


LSC+Virgo, Phys. Rev. Lett. **116**, 221101 (2016)

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	$\tan^{-1}(af+b)$

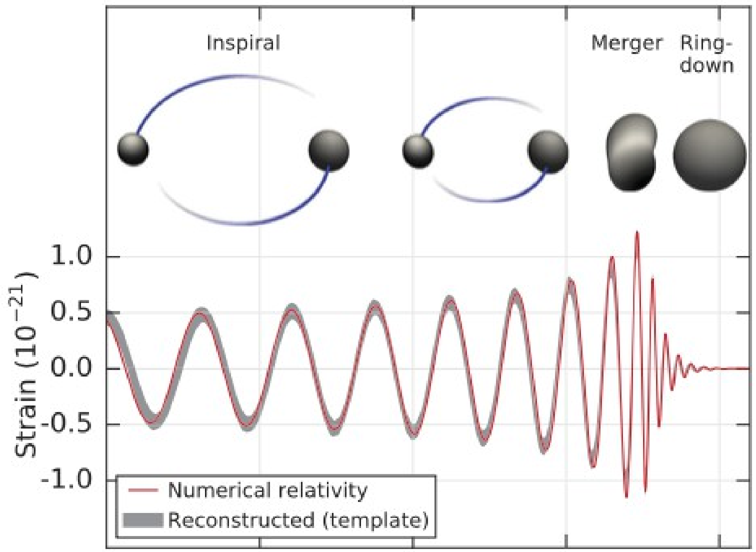
- Parameters p_i multiplying different functions of frequency in 3 regimes
- Introduce parameterized deformations of the waveform by replacing

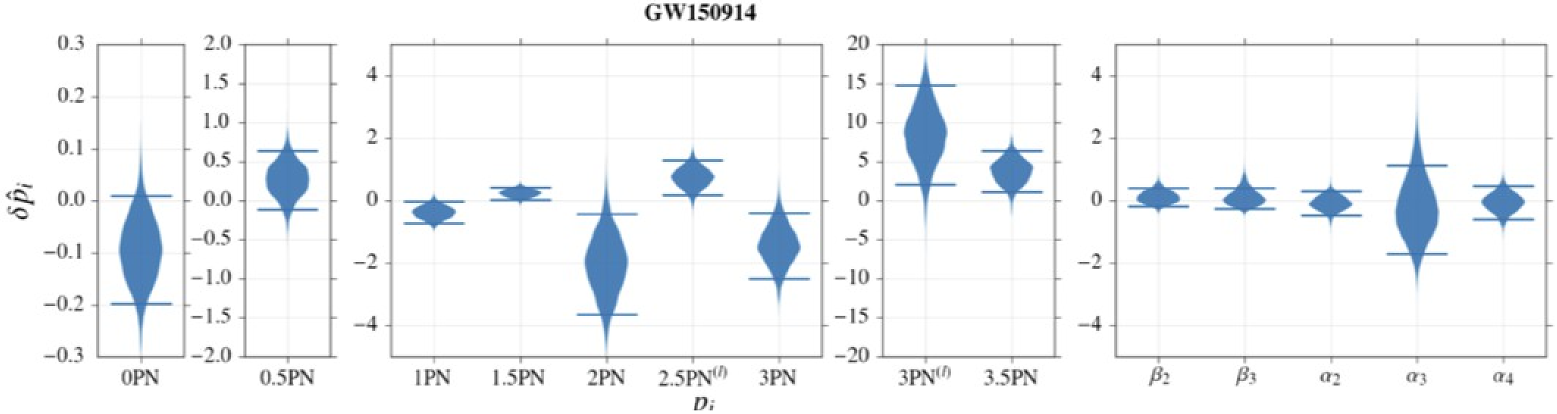
$$p_i \rightarrow (1+\delta\hat{p}_i)p_i$$

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)

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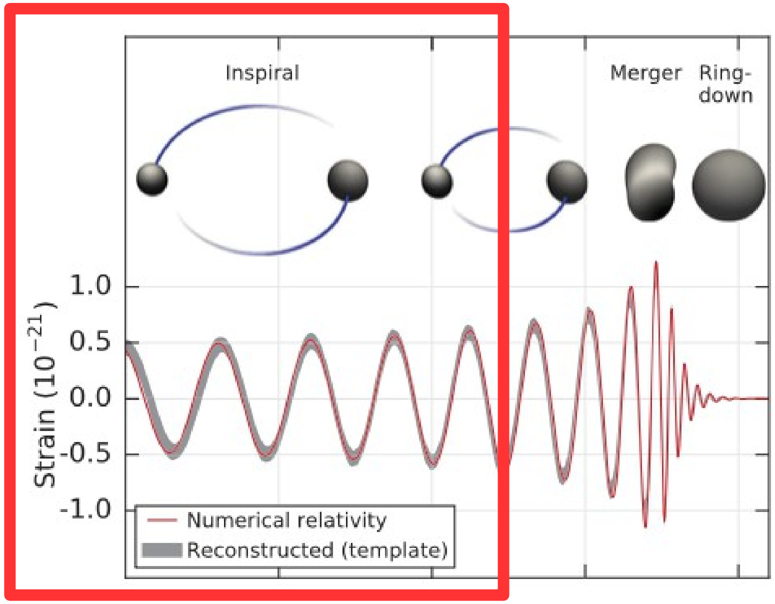
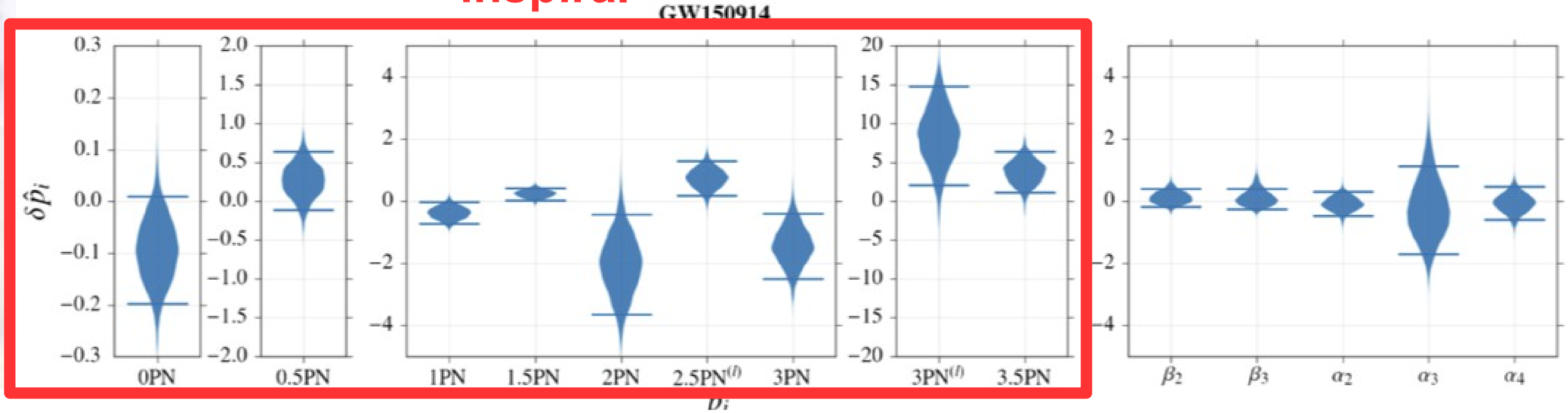
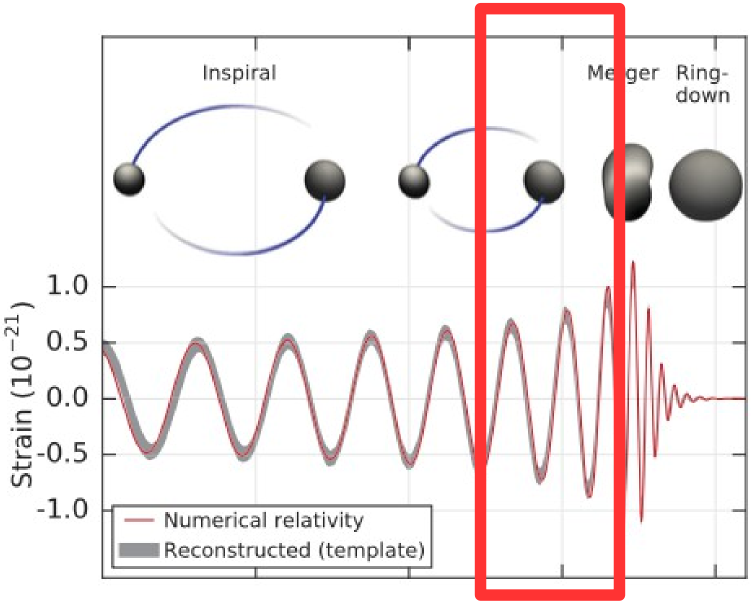


inspiral

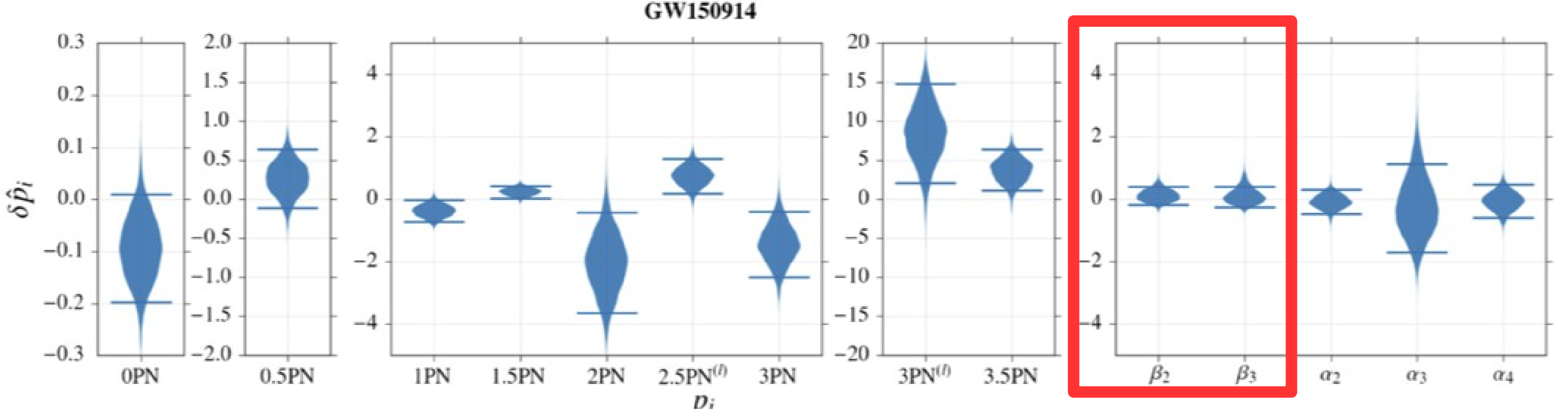


LSC+Virgo, Phys. Rev. X **6**, 041015 (2016)

Parameterized tests of the coalescence process

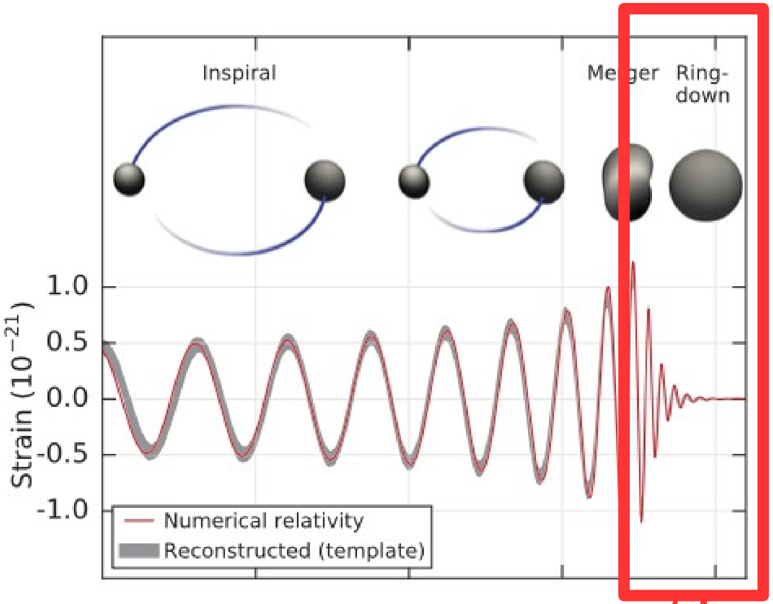


“intermediate”

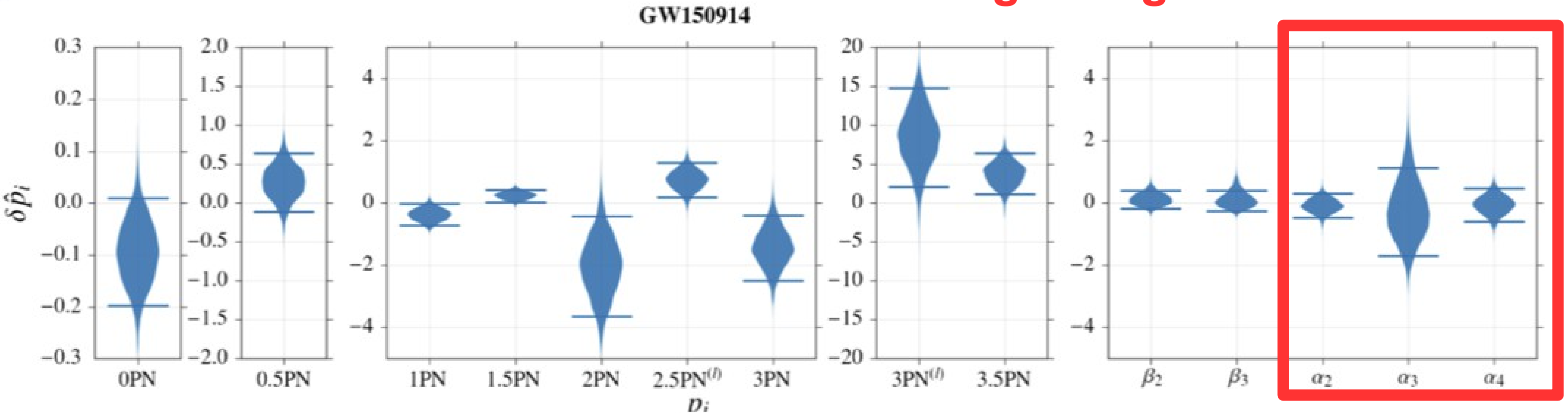


LSC+Virgo, Phys. Rev. X **6**, 041015 (2016)

Parameterized tests of the coalescence process

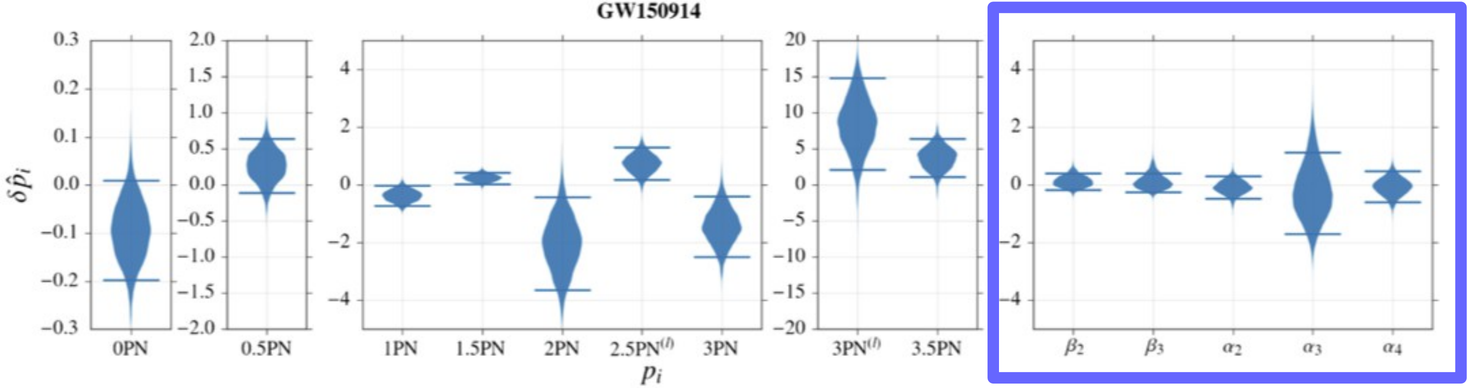


merger/ringdown



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

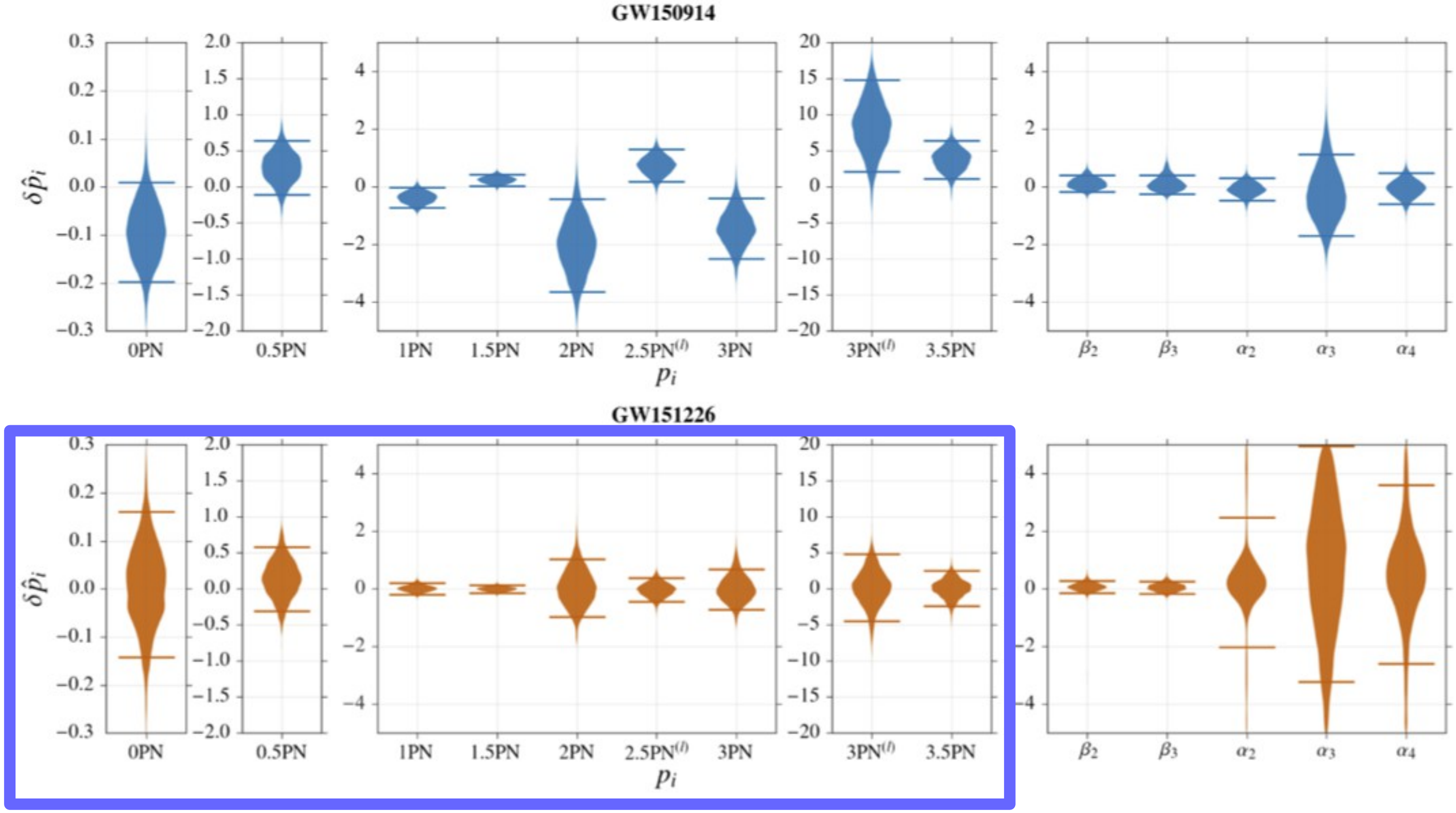
GW150914: short inspiral, but merger well visible



“intermediate”, merger/ringdown

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

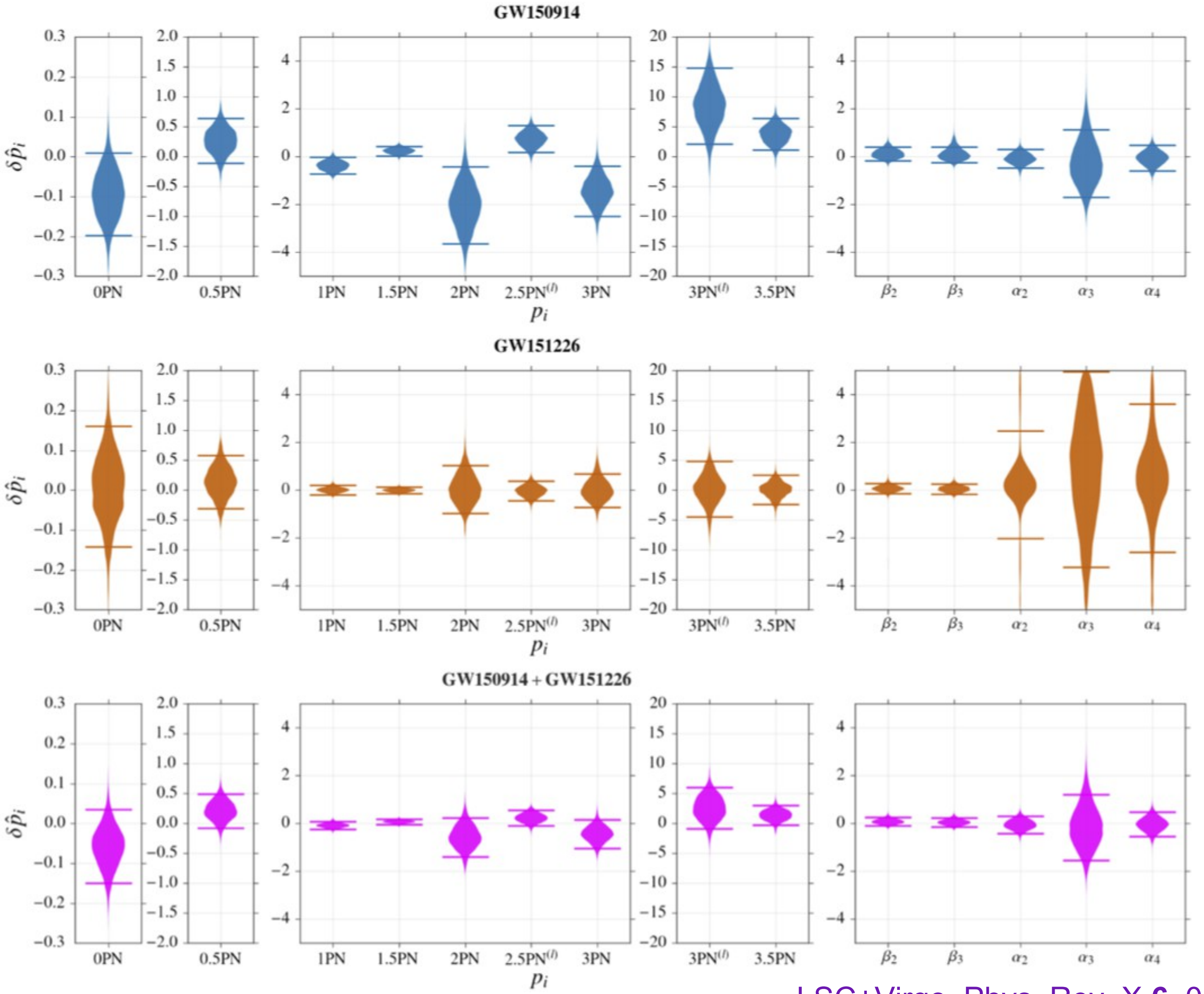
GW151226: long inspiral, merger at higher frequency



inspiral

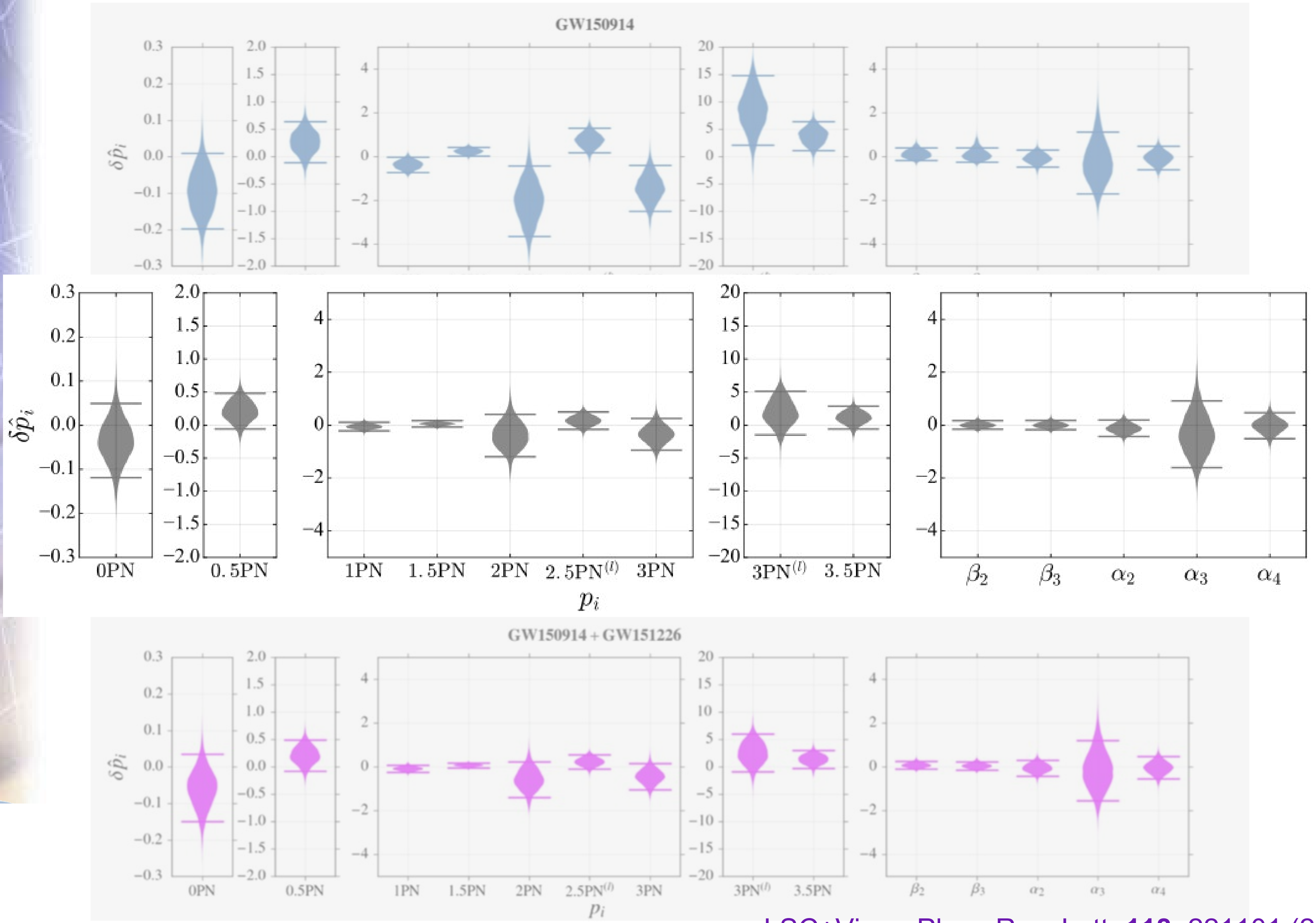
LSC+Virgo, Phys. Rev. X **6**, 04~~1015 (~~2016)

Combine results from multiple sources



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

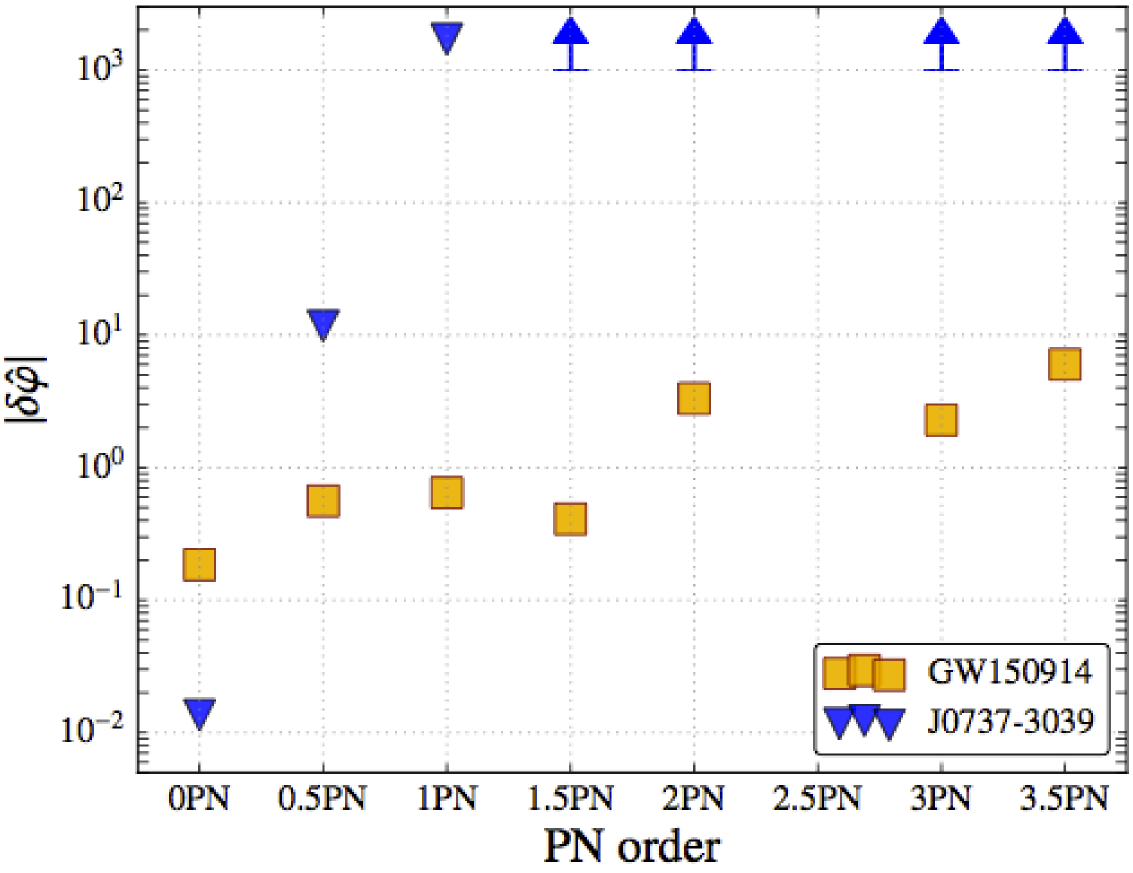
GW150914 + GW151226 + GW170104



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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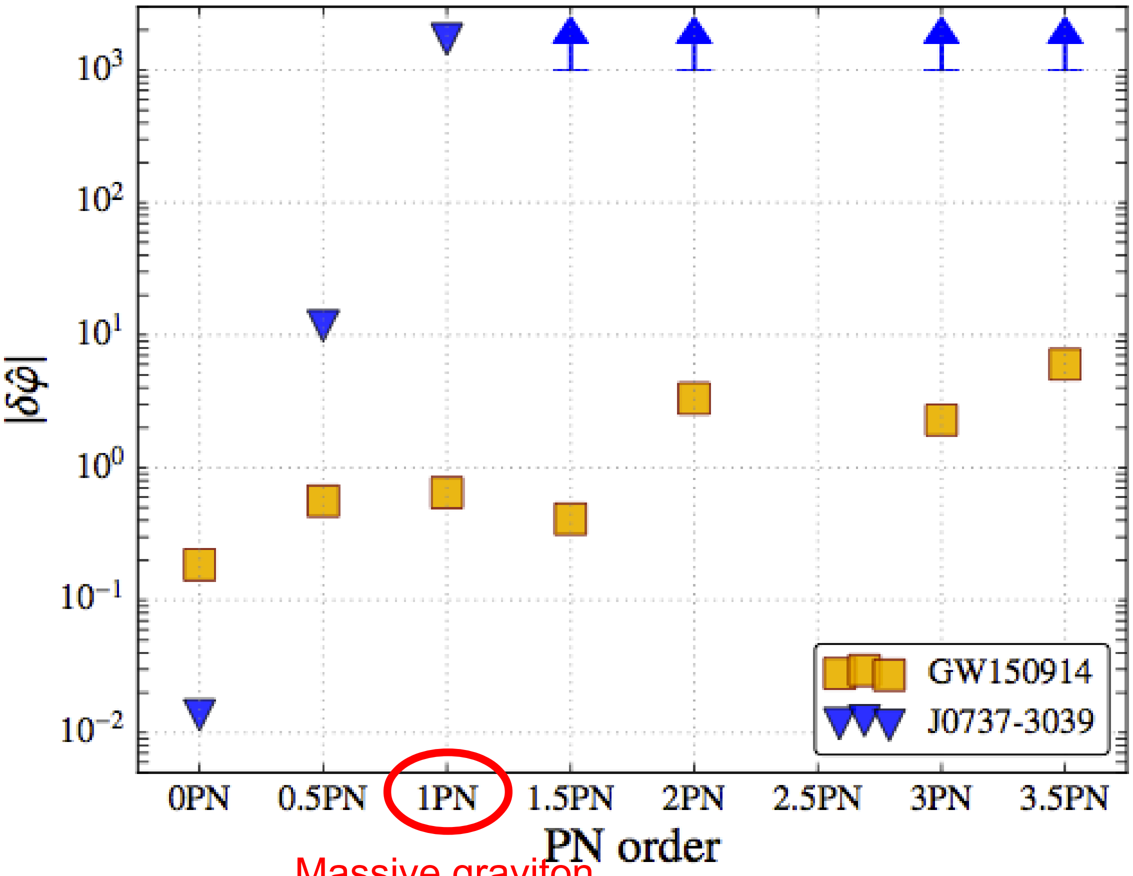

Massive graviton

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

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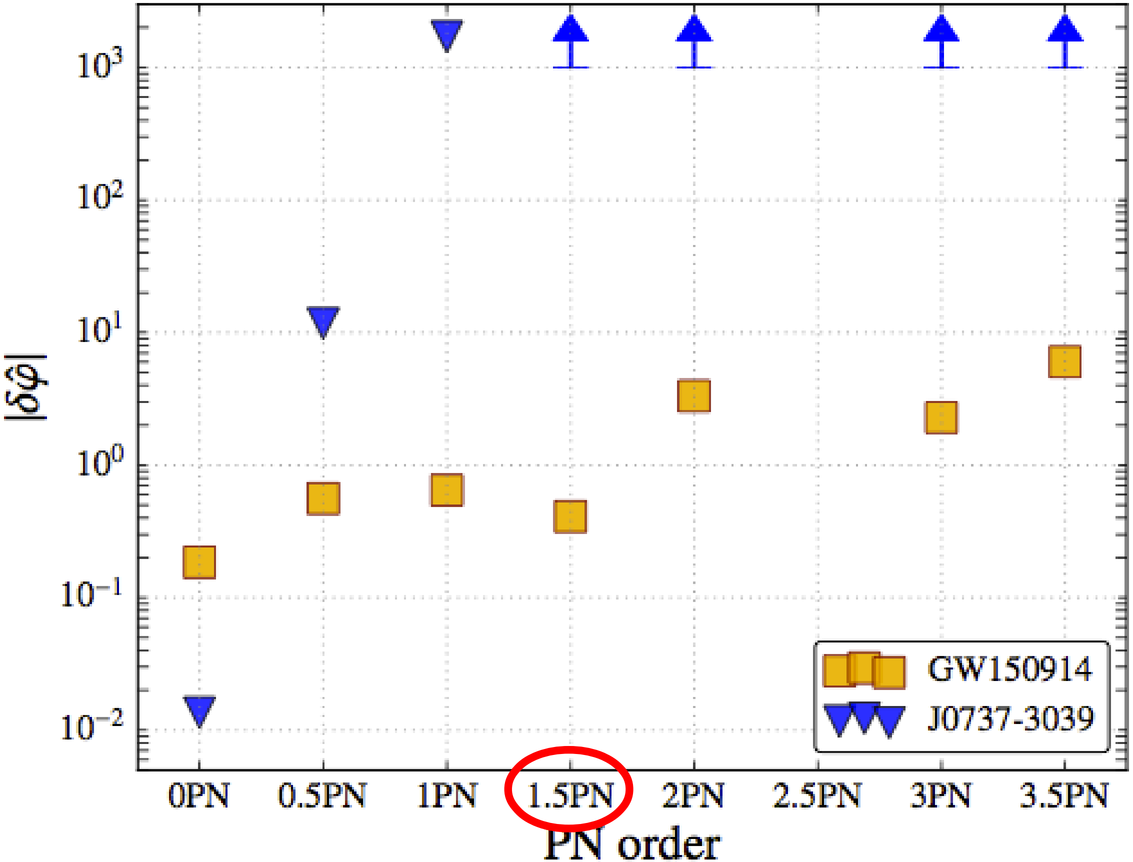

- Dynamical self-interaction
- Spin-orbit interactions

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

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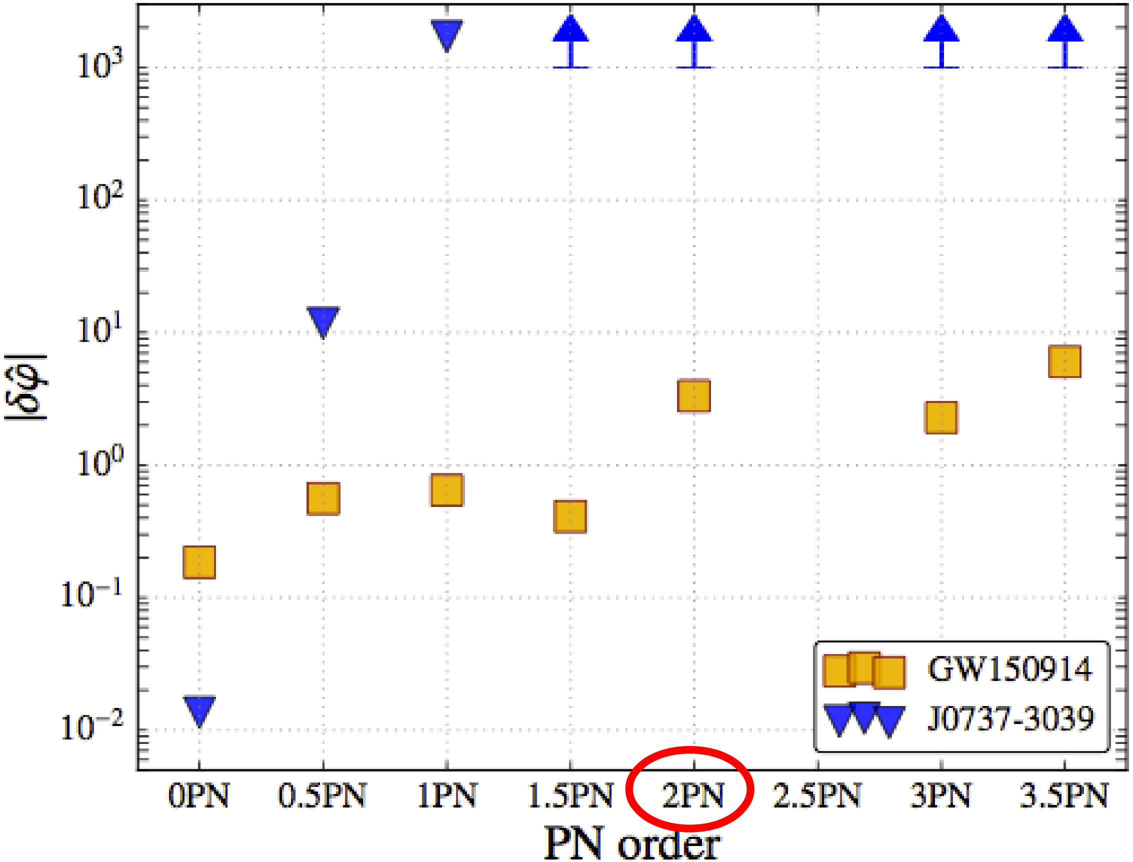
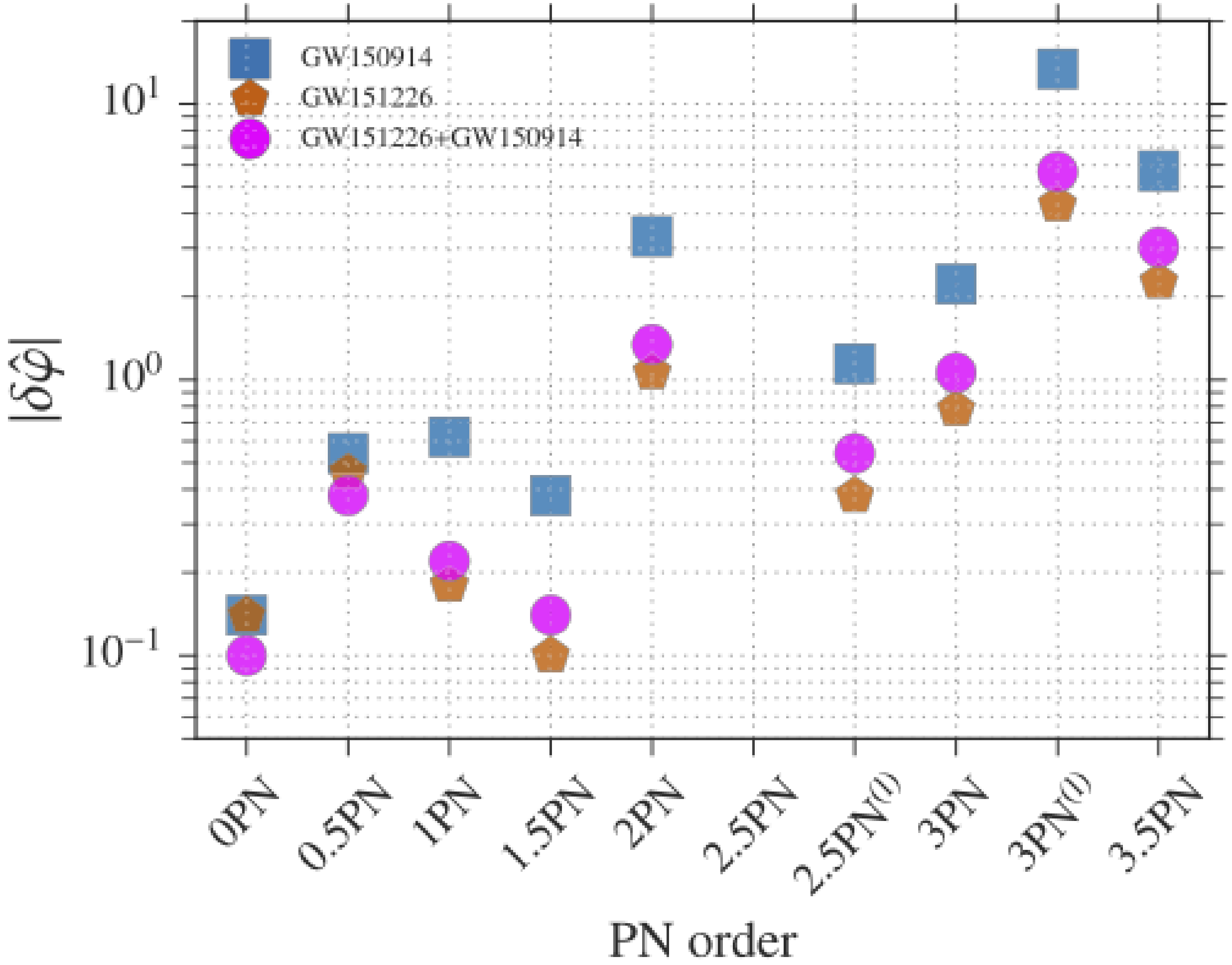


Spin-spin interactions

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

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?

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

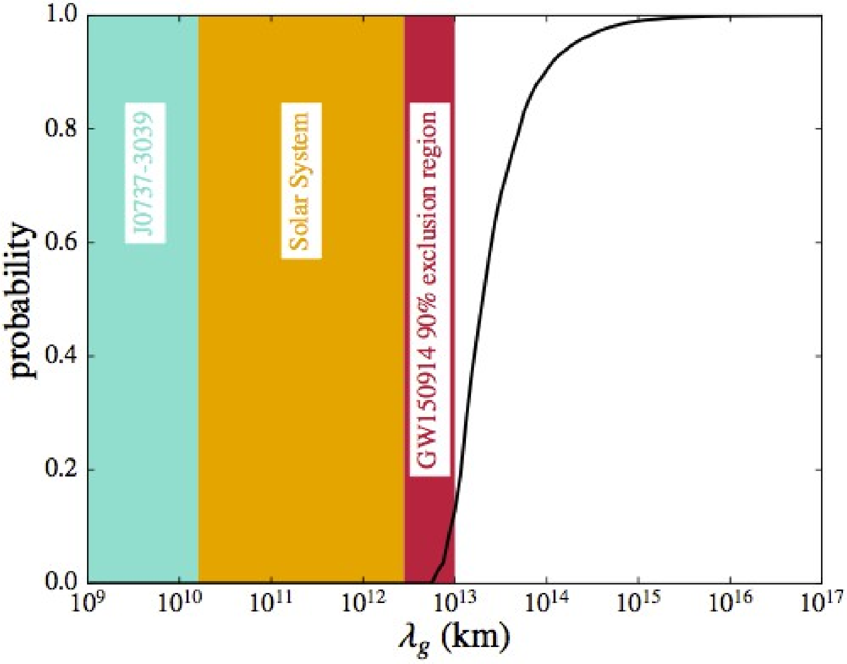
☐ Dispersion of gravitational waves?

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

- New bound on graviton Compton wavelength and mass:

  $\lambda_g > 10^{13}$ km $m_g < 10^{-22}$ eV/c^2

- 3 orders of magnitude better than only other existing dynamical bound
- Factor of a few better than (static) Solar system bound



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

Do gravitational waves propagate as predicted?

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

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

- Modified group velocity:

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

- Modification to the gravitational wave phase:

$$\delta\Psi = \begin{cases} \dfrac{\pi}{\alpha-1}\dfrac{AD_\alpha}{(hc)^{2-\alpha}}\left[\dfrac{(1+z)f}{c}\right]^{\alpha-1} & \alpha \neq 1 \\ \dfrac{\pi AD_\alpha}{hc}\ln\left(\dfrac{\pi G\mathcal{M}^{\mathrm{det}}f}{c^3}\right) & \alpha = 1 \end{cases}$$

$$D_\alpha = \frac{1+z}{H_0}\int_0^z \frac{(1+z')^{\alpha-2}}{\sqrt{\Omega_{\mathrm{m}}(1+z')^3+\Omega_\Lambda}}\mathrm{d}z'$$

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

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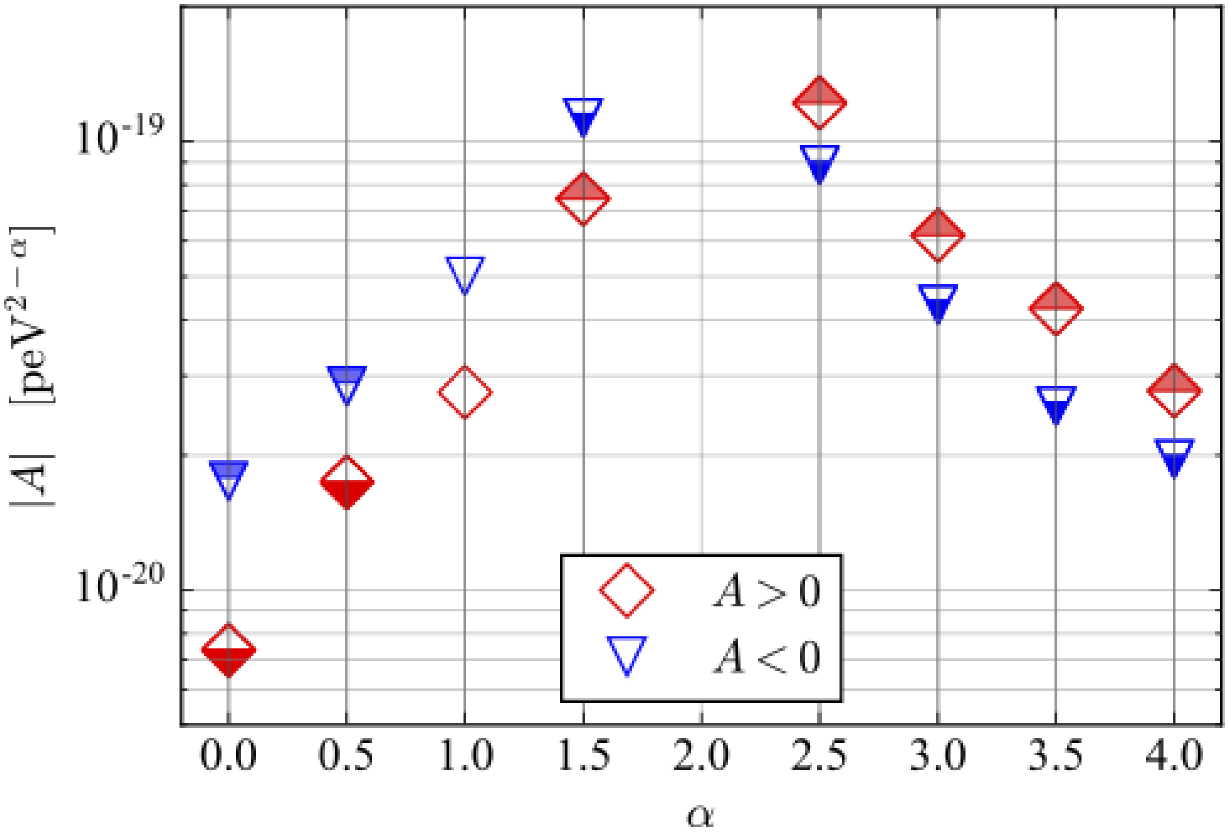

LSC+Virgo, Phys. Rev. Lett. **118**, 221101 (2017)

Do gravitational waves propagate as predicted?

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

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

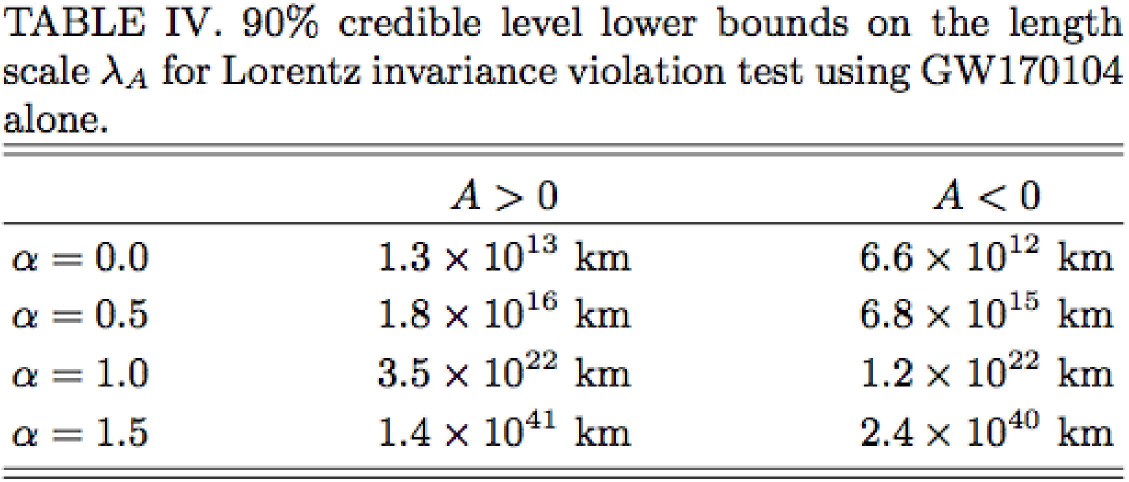


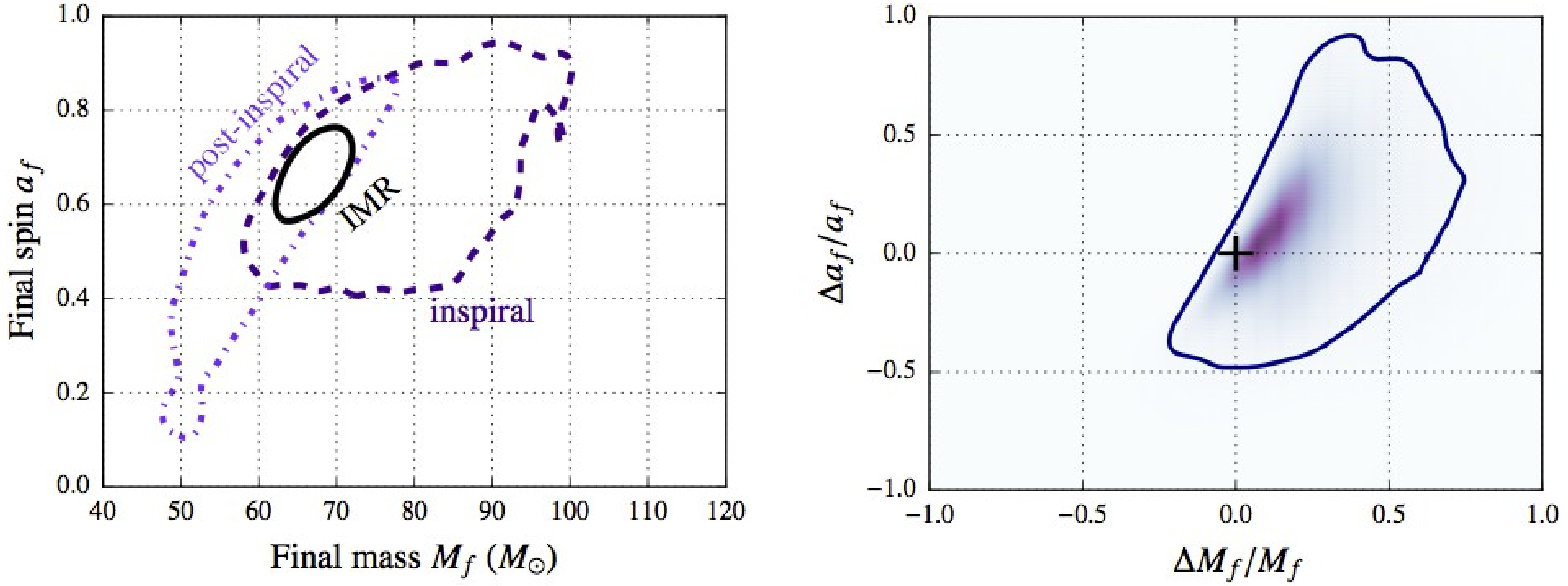
TABLE IV. 90% credible level lower bounds on the length scale λ_A for Lorentz invariance violation test using GW170104 alone.

	$A > 0$	$A < 0$
$\alpha = 0.0$	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)

Consistency between inspiral and post-inspiral

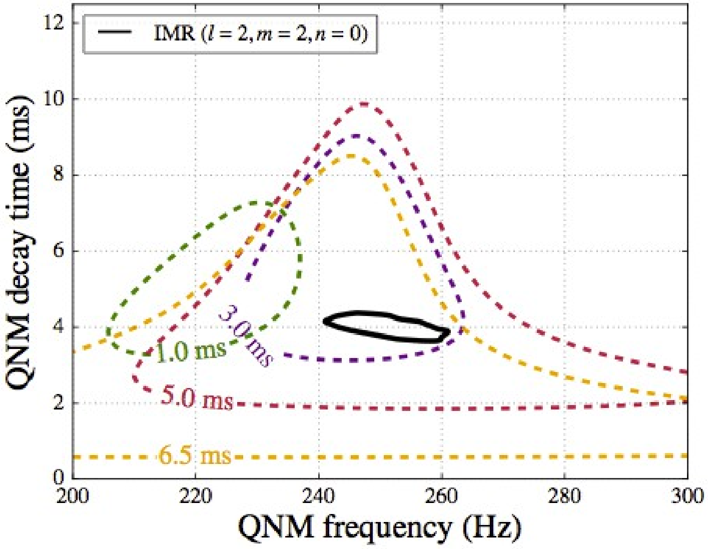
- General relativity predicts relationship between
  - Masses and spins of component objects
  - Mass and spin of final object
- Relationship can be extracted from numerical simulations
  - Accurate analytical fits (Healy et al. 2014)
- Compare inferred values from inspiral and post-inspiral



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)

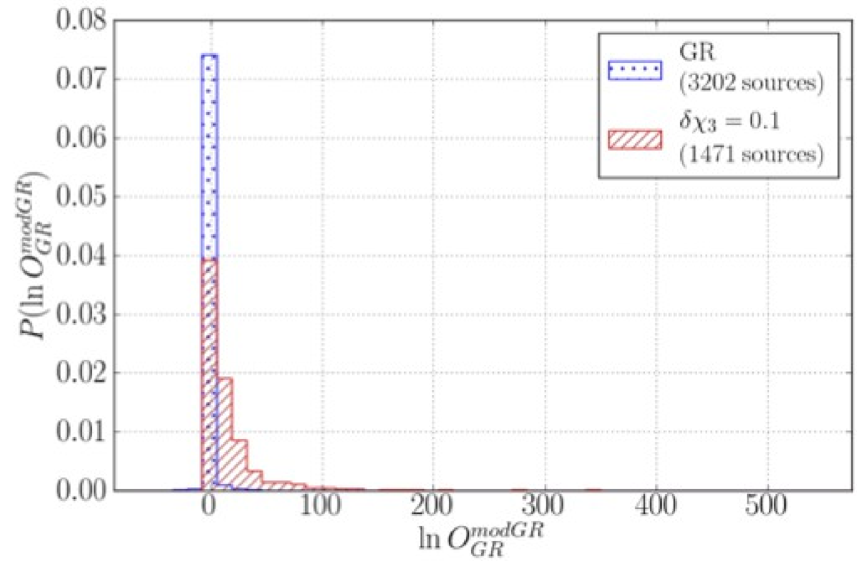
Into the future

Combining information from increasing number of detections

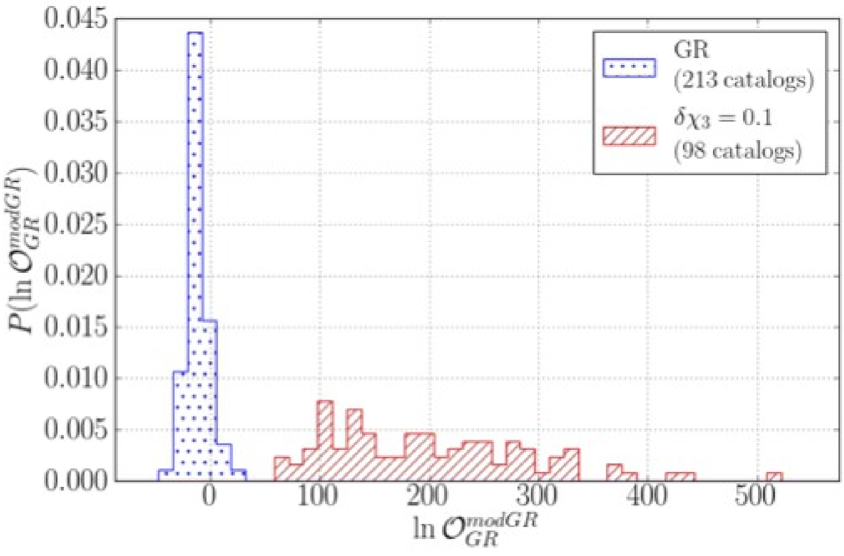
- Assuming GR is correct, bounds on violations will improve roughly with square root of number of sources
- Can also actively look for GR violations by Bayesian model selection:

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

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



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

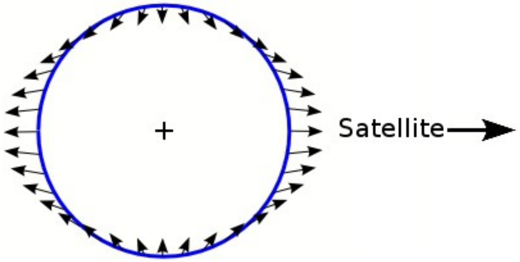
- Anomalous ringdown spectrum

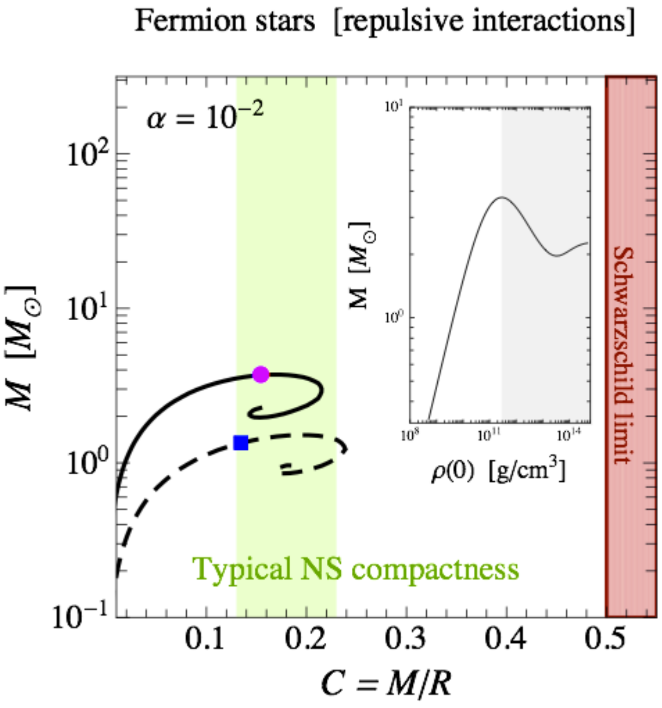
Meidam et al., Phys. Rev. D **90**, 064009 (2014)

- Gravitational wave "echoes" after ringdown

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

Anomalous tidal effects during inspiral





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

☐ Tidal field of one body causes quadrupole deformation in the other:

$$Q_{ij} = -\lambda(\mathrm{EOS}; m)\,\mathcal{E}_{ij}$$

where $\lambda(\mathrm{EOS}; m)$ depends on internal structure (equation of state)

- Black holes: $\lambda \equiv 0$
- Boson stars, dark matter stars: $\lambda > 0$
- Gravastars: $\lambda < 0$

☐ Enters inspiral phase at 5PN order, through $\lambda(m)/M^5 \propto (R/M)^5$

- $O(10^2 - 10^5)$ for neutron stars
- Also tidal signatures for
  - Dark matter stars
  - Boson stars

Cardoso et al., arXiv:1701.01116

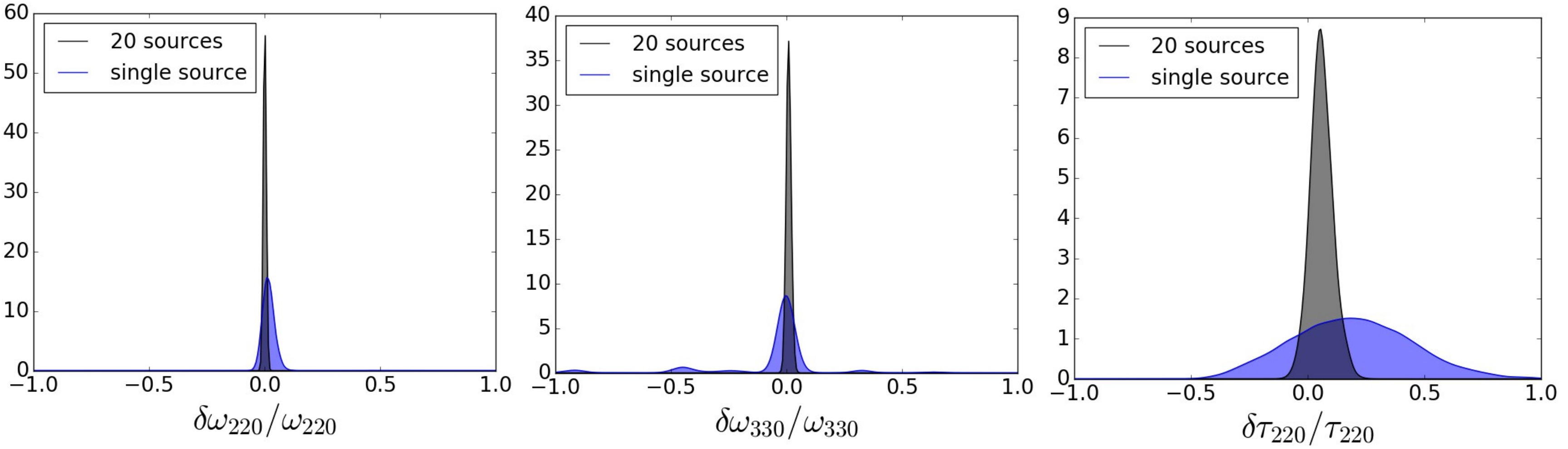
Testing the no-hair theorem

☐ GW150914: ringdown part had signal-to-noise ratio ~ 8

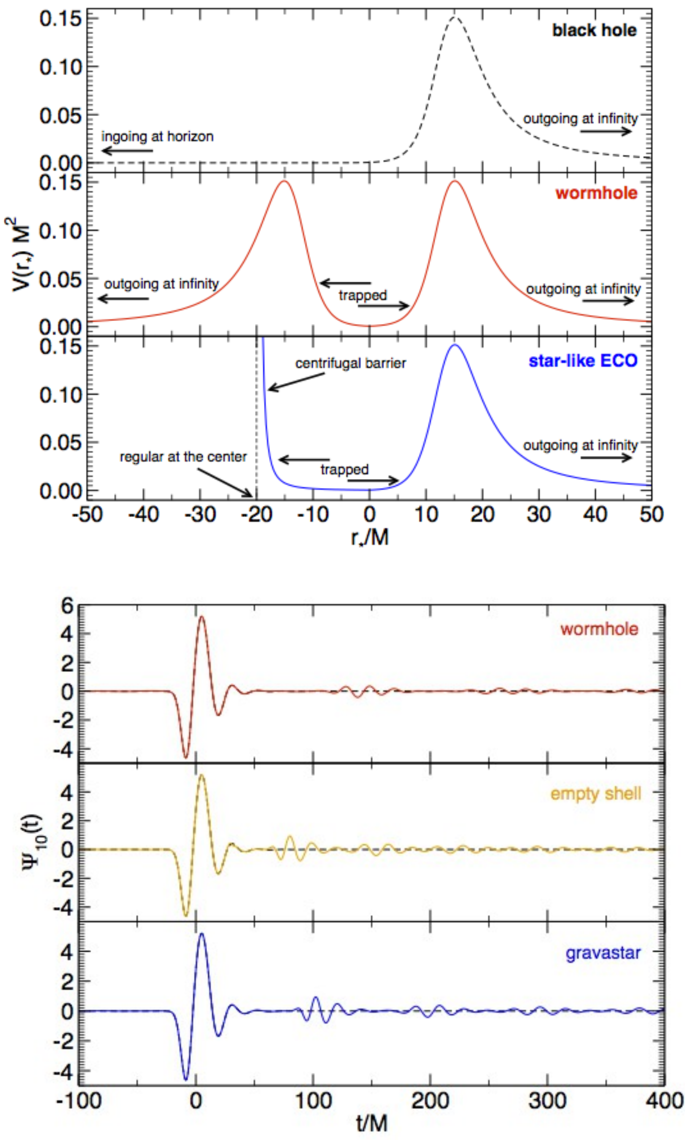
- **Would have been 3 times louder in aLIGO at design sensitivity**

☐ Future (indirect) tests of the no-hair theorem:

- No-hair theorem: stationary black hole characterized by mass M, spin J
- Linearized Einstein equations around Kerr background enforce specific dependences $\omega_{lmn}(M,J)$, $\tau_{lmn}(M,J)$
- Put bounds on deviations from these relationships:



Gravitational wave echoes after ringdown



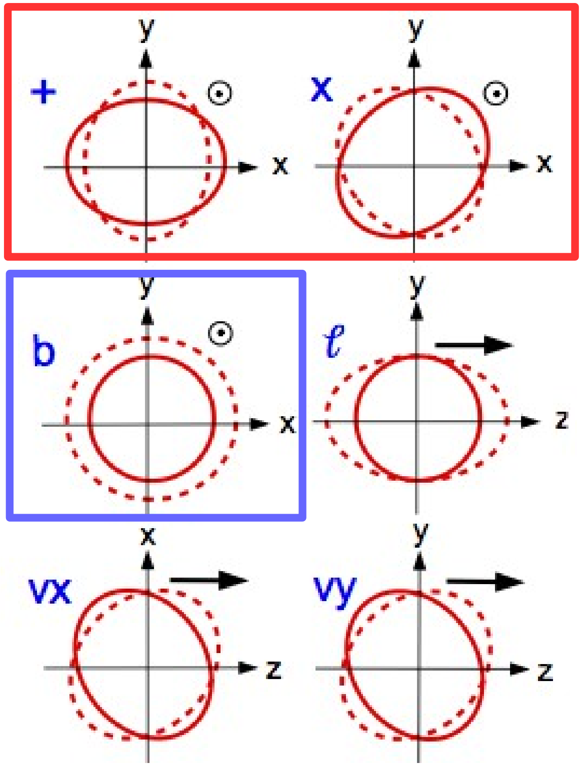
Cardoso et al., Phys. Rev. D **94**, 084021 (2016)

- ☐ If instead of black hole horizon, structure with characteristic size l_c, then *echoes* at time intervals

  $$\Delta t = n\ M \log(M/l_c)$$

  - n depends on nature of object (e.g. n = 8 for wormholes)
  - For mass M similar to GW150914, l_c the Planck length
    - Δt = O(100) ms
    - Amplitudes of first few echoes may be visible with aLIGO
- ☐ Already claimed to have been detected using publicly available data!
  - Abedi et al., arXiv:1612.00266
  - However, see also Ashton et al., arXiv:1612.05625

Alternative polarization states

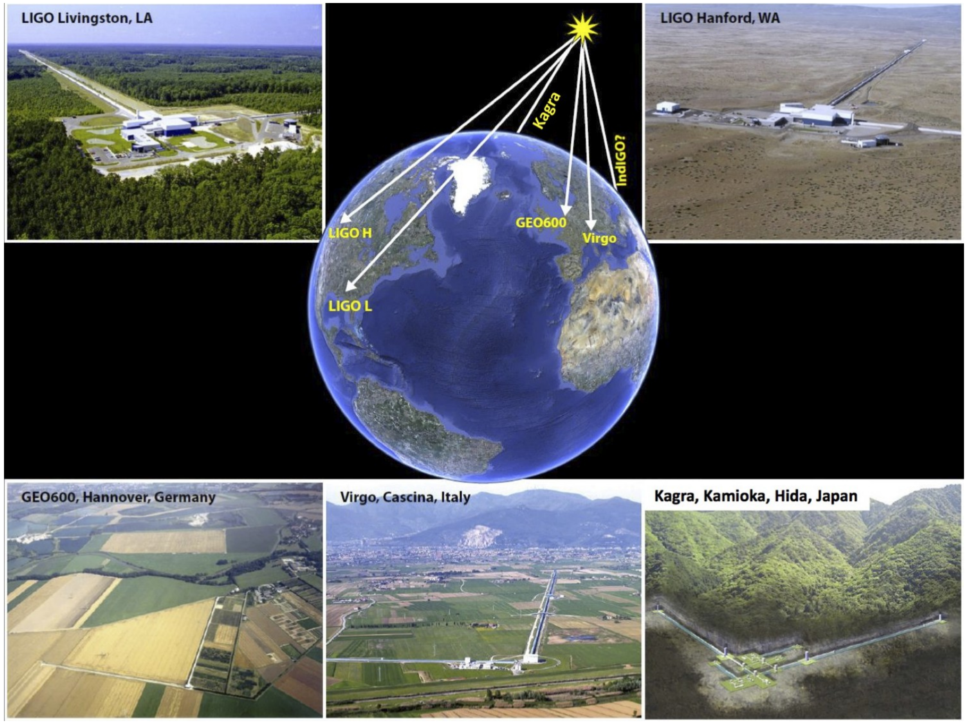


Will, Living Rev. Relativ. **17**, 4 (2014)

- Up to 6 different polarizations in metric theories of gravity
- For GW150914, compared polarizations for GR against pure breathing mode

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

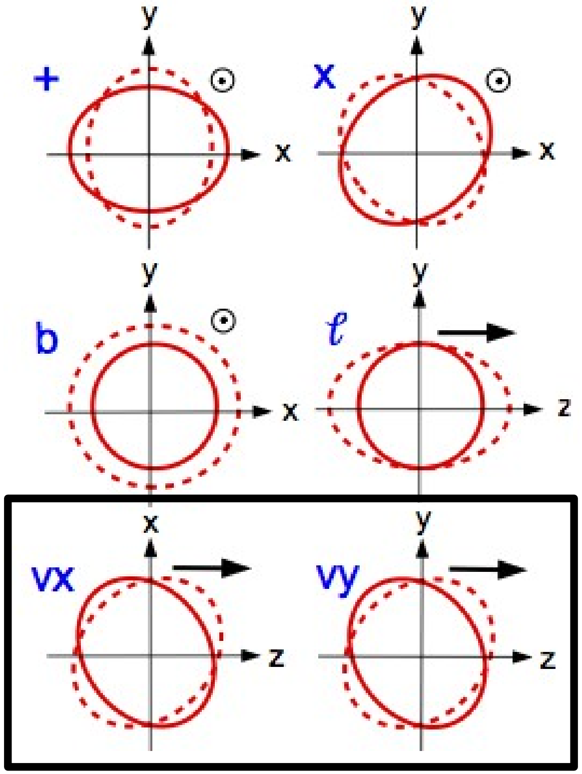
- Need a larger network of detectors!



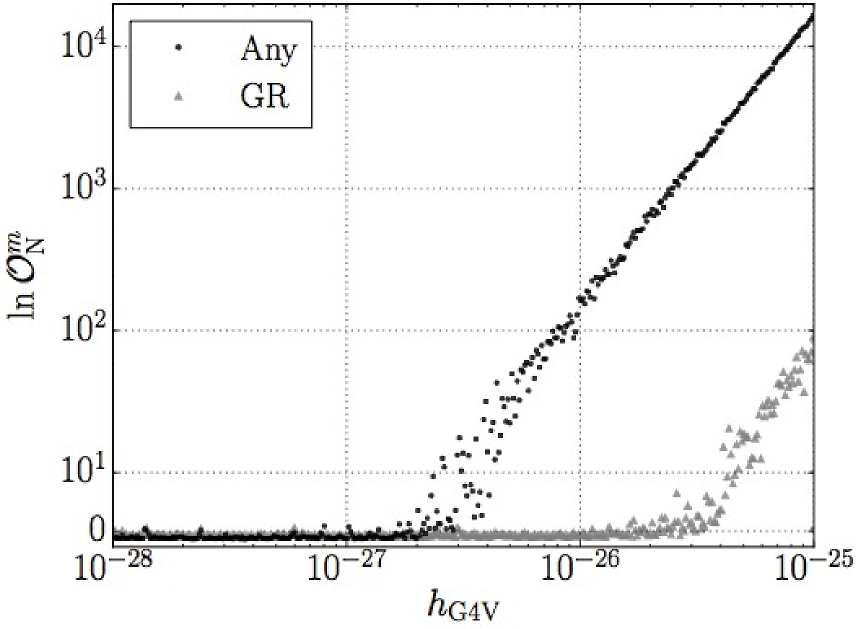
Alternative polarization states

☐ Can also probe polarization content using continuous wave signals from pulsars

- Advanced LIGO-Virgo network
- Simulated signals from Crab pulsar



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

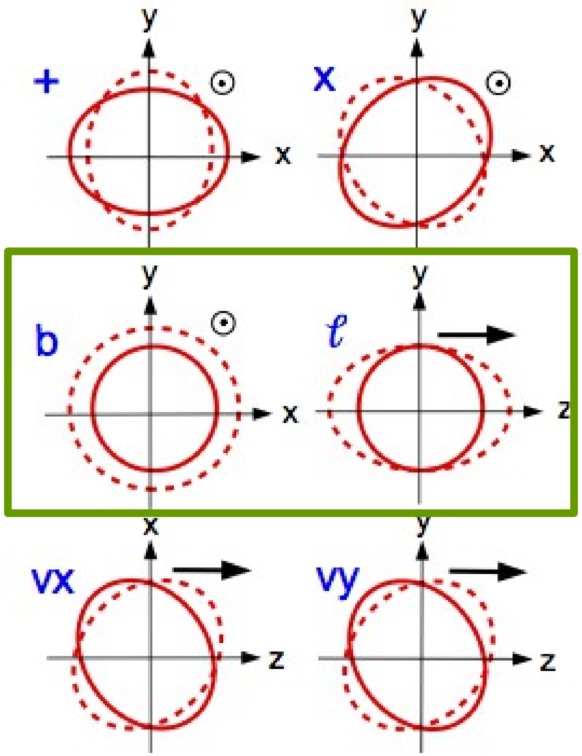


Isi et al., arXiv:1703.07530

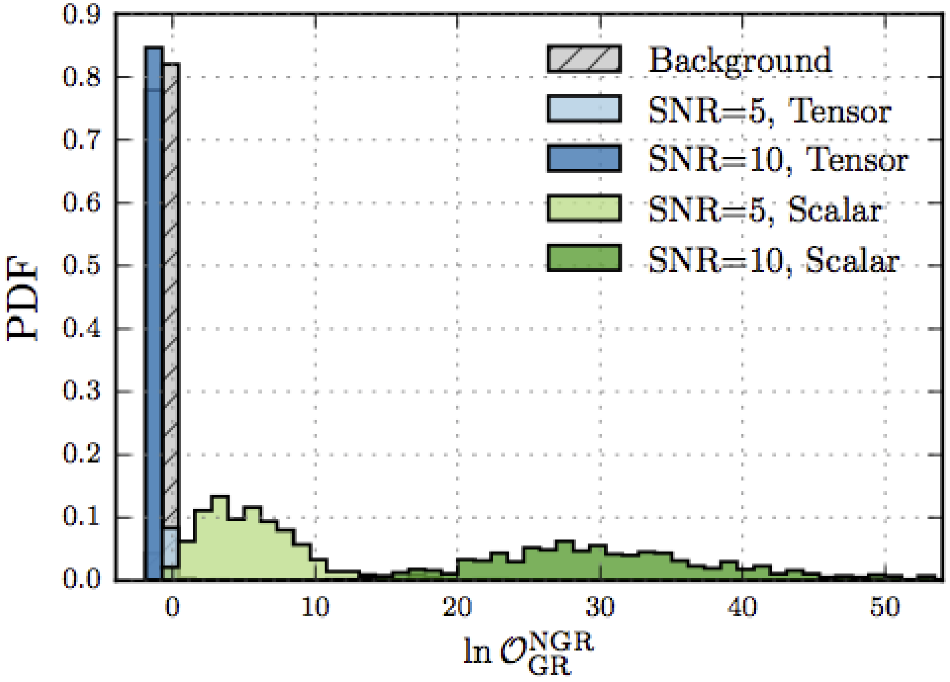
Alternative polarization states

☐ Similarly, can use stochastic backgrounds

- Advanced detectors, design sensitivity
- Accumulated signal from binary mergers, 3 years of observation



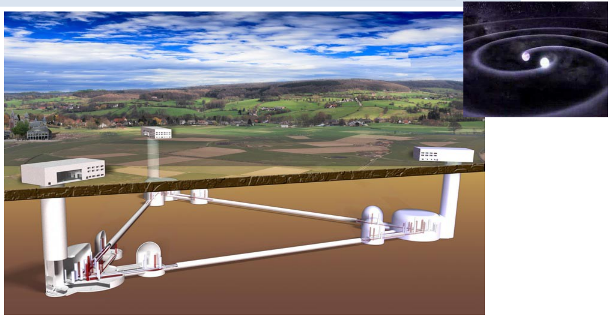
Will, Living Rev. Relativ. **17**, 4 (2014)

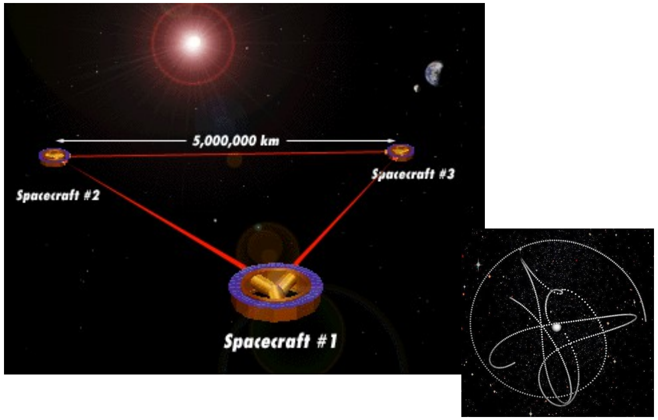


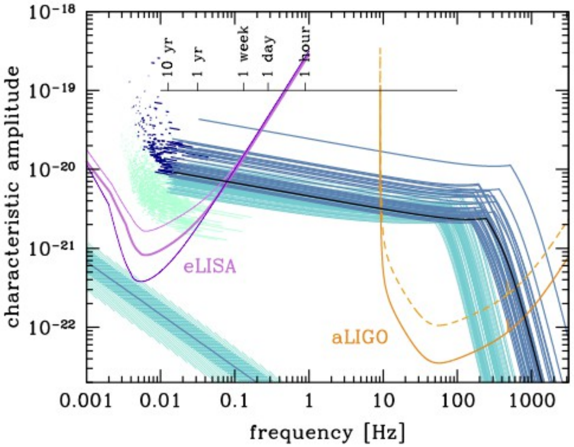
Callister et al., arXiv:1704.08373

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)

Overview

- First tests of the genuinely strong-field dynamics of pure spacetime with GW150914, GW151226, GW170104
  - 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
- To come:
  - Tests of the black hole nature of the component and remnant objects
    - Tidal effects in black hole mimickers
    - Ringdown and no-hair theorem tests
    - Gravitational wave echoes
  - Search for alternative polarizations
    - Requires larger detector network: Advanced Virgo, KAGRA, LIGO-India