

Testing general relativity with gravitational waves

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Amaldi, 9-14 July 2017, Pasadena, USA

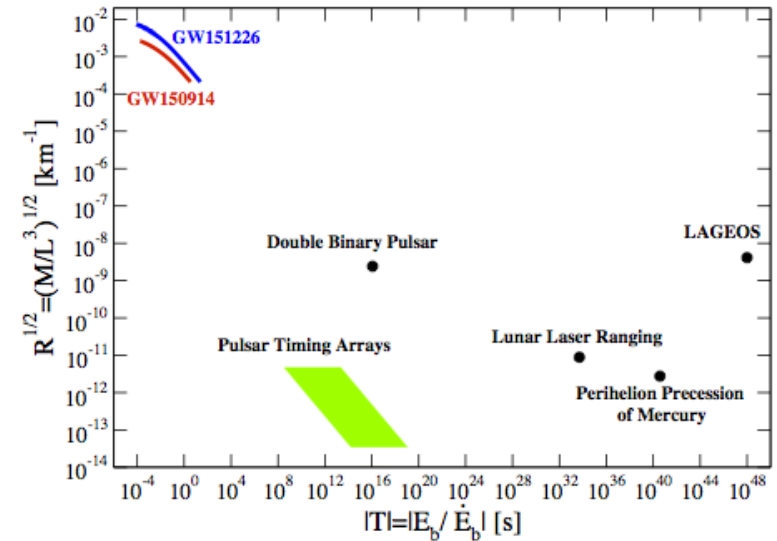
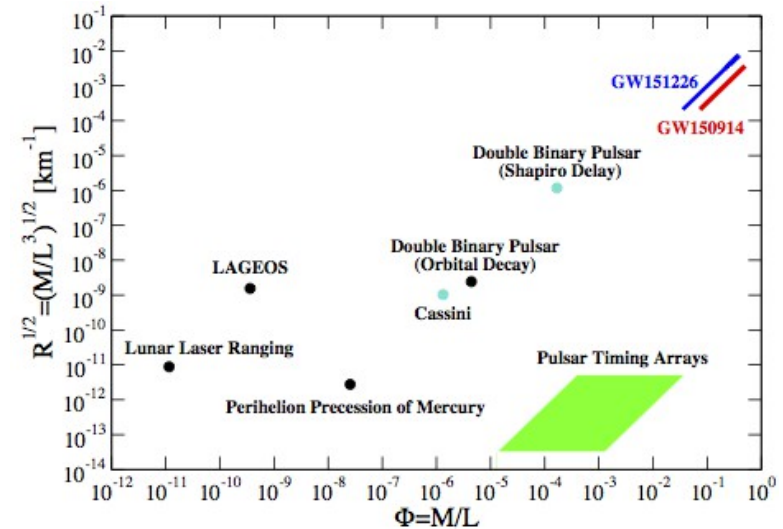
First access to the strong-field dynamics of spacetime

□ Before the direct detection of gravitational waves:

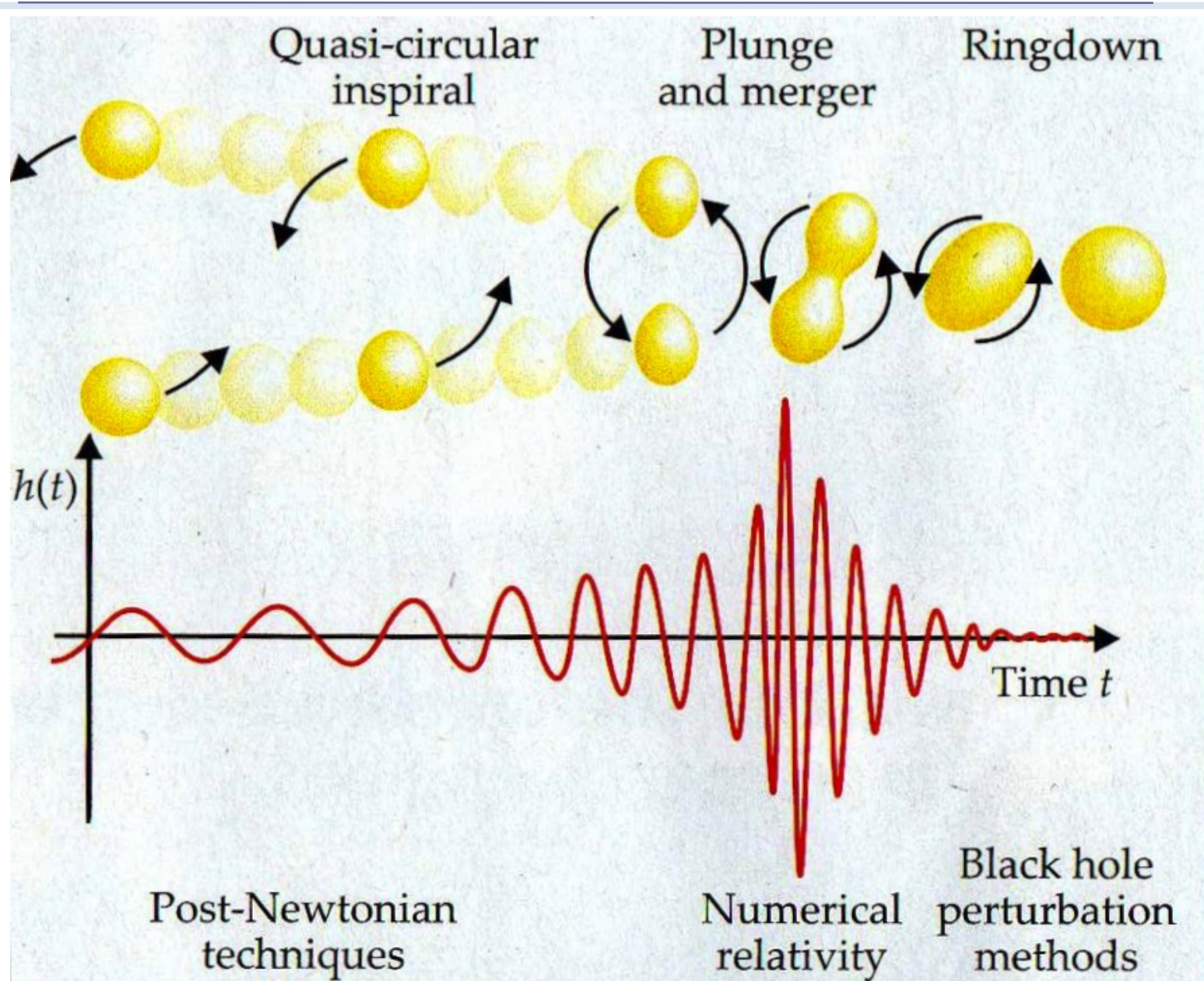
- Solar system tests: weak-field; dynamics of spacetime itself not being probed
- Binary neutron stars: relatively weak-field test of spacetime dynamics
- Cosmology: dark matter and dark energy may signal GR breakdown

□ Direct detection of GW from binary black hole mergers:

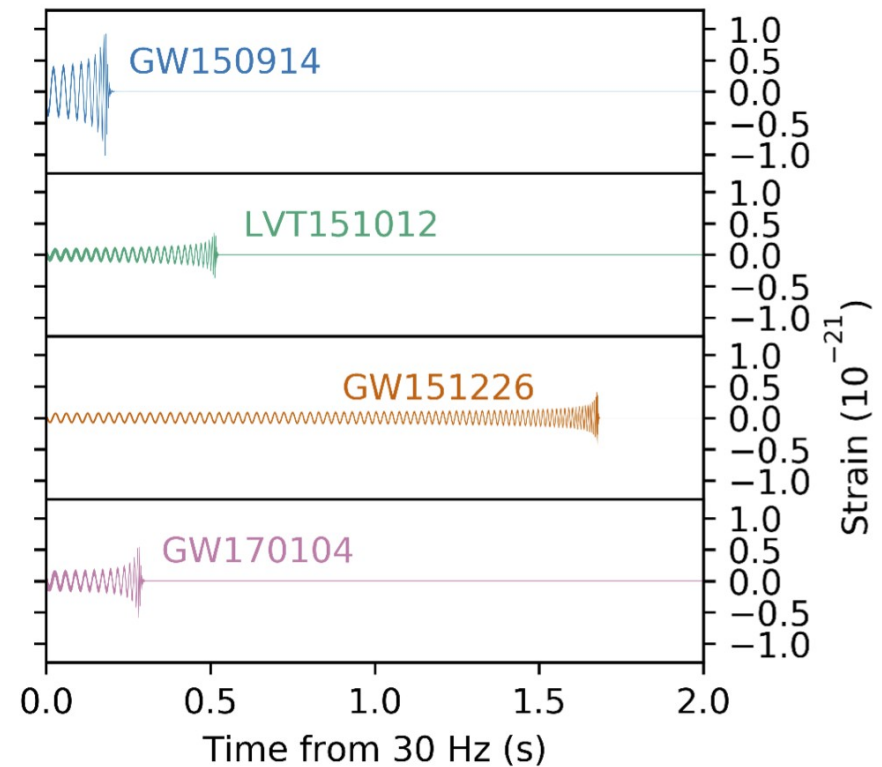
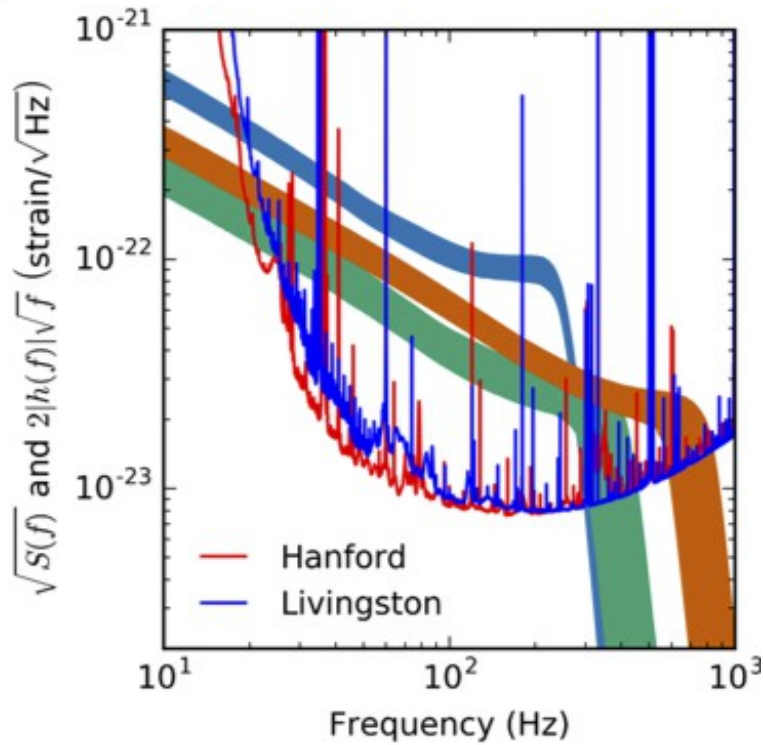
- Genuinely strong-field dynamics
- (Presumed) pure spacetime events



Coalescence of binary neutron stars and black holes



Complementary information from different events



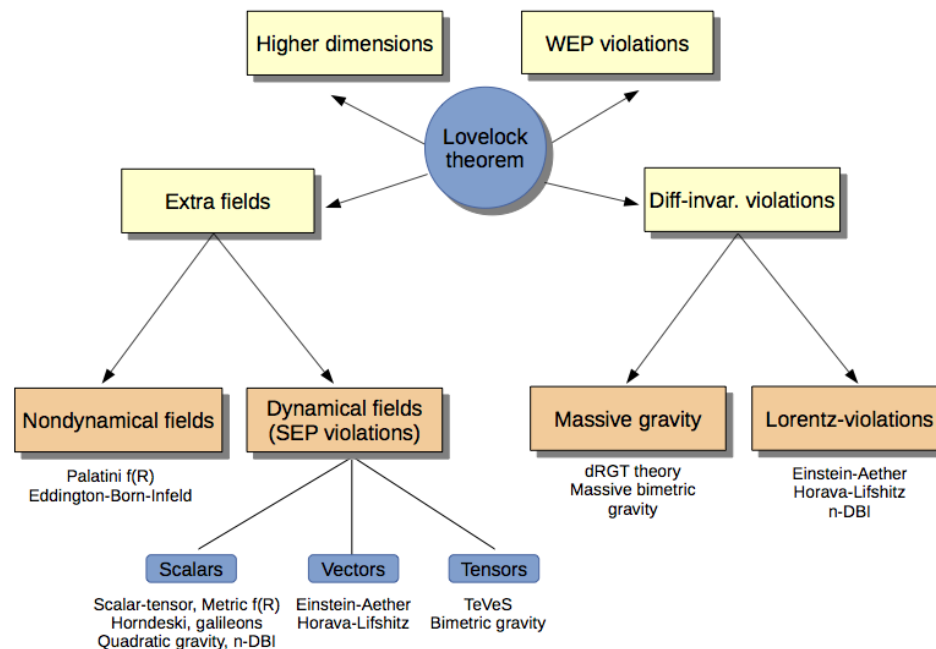
LSC+Virgo, Phys. Rev. X **6**, 041015 (2016)

- 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”



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:

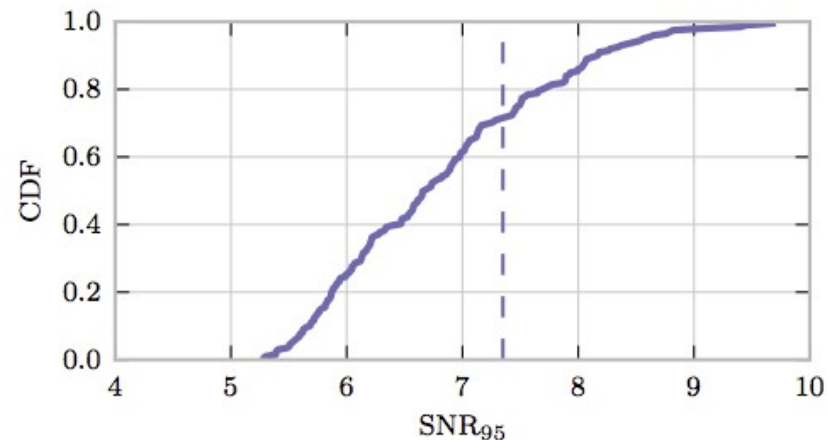
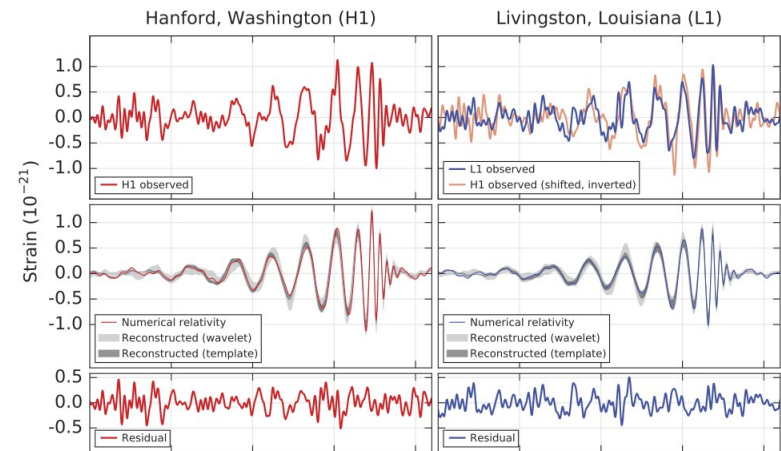
$$\text{SNR}_{\text{res}}^2 = (1 - \text{FF}^2) \text{FF}^{-2} \text{SNR}_{\text{det}}^2$$

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

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

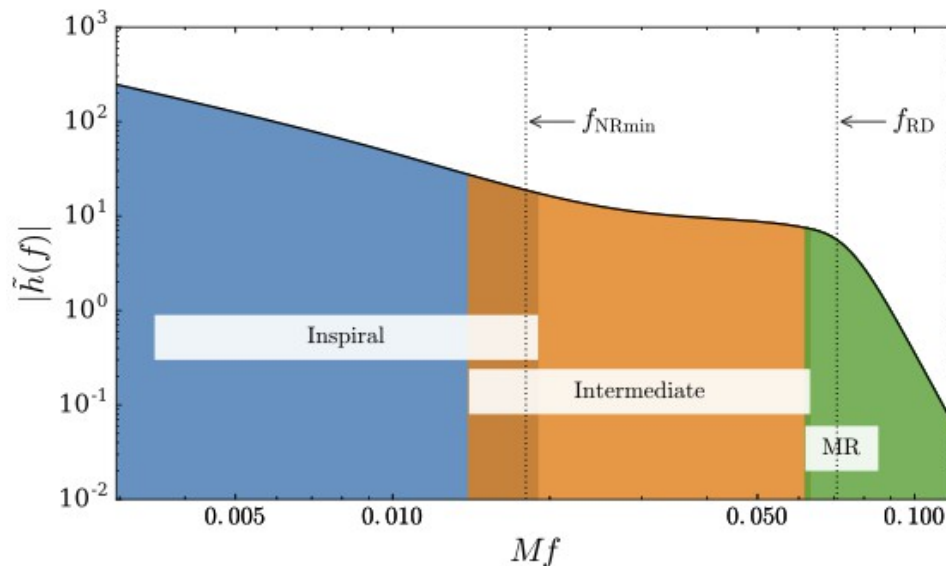
$$\rightarrow \text{FF} \geq 0.96$$

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



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}	$f^{1/3} \log f$
late-inspiral	φ_7	$f^{2/3}$
	σ_2	$f^{4/3}$
	σ_3	$f^{5/3}$
intermediate	σ_4	f^2
	β_2	$\log f$
merger-ringdown	β_3	f^{-3}
	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

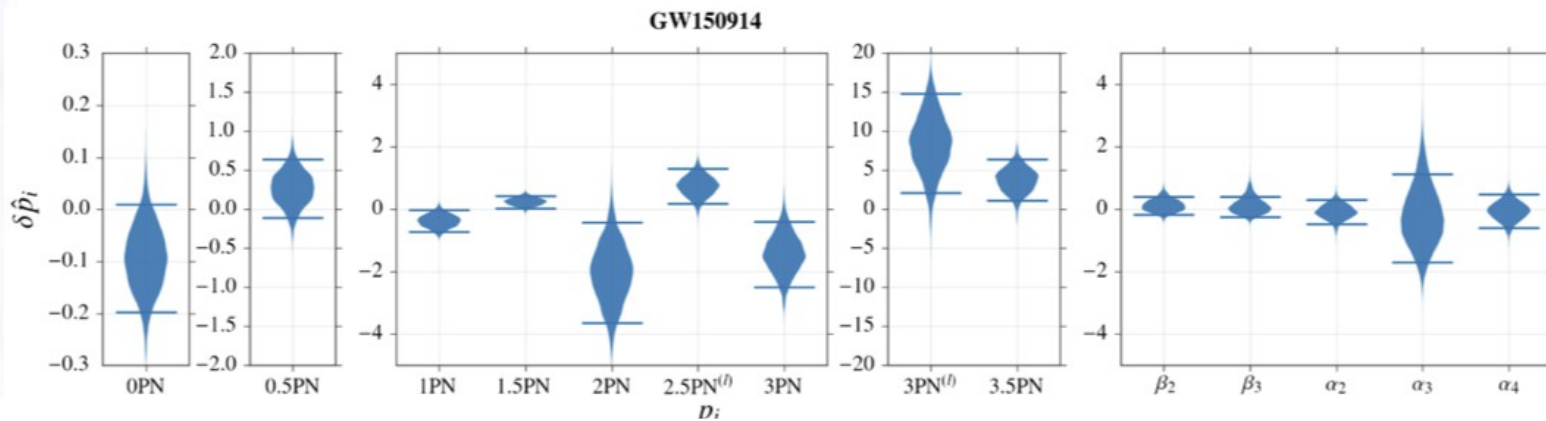
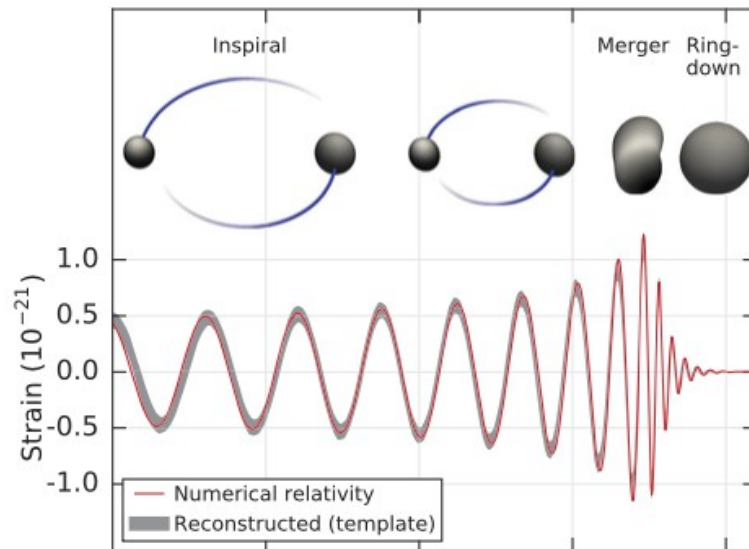
$$p_i \rightarrow (1 + \delta \hat{p}_i) p_i$$

and letting $\delta \hat{p}_i$ vary freely (along with masses, spins, extrinsic parameters)

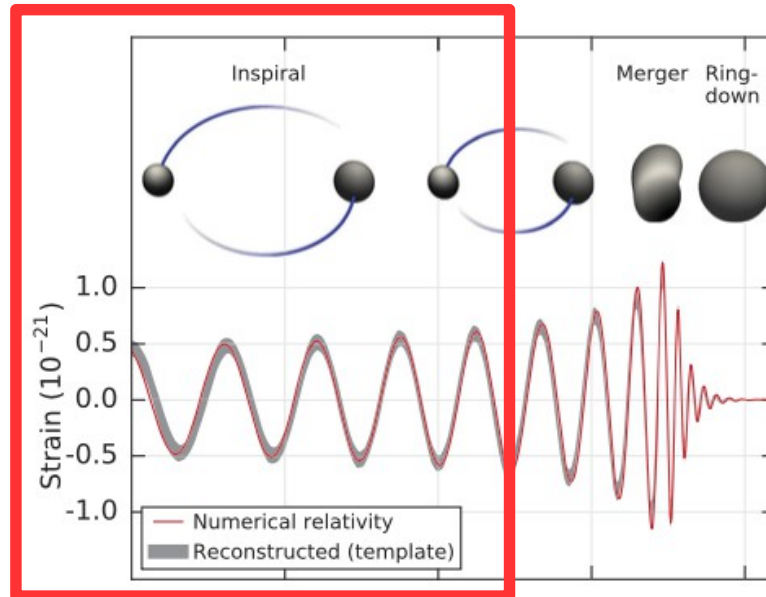
□ Do this for each of the p_i in turn

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

Parameterized tests of the coalescence process

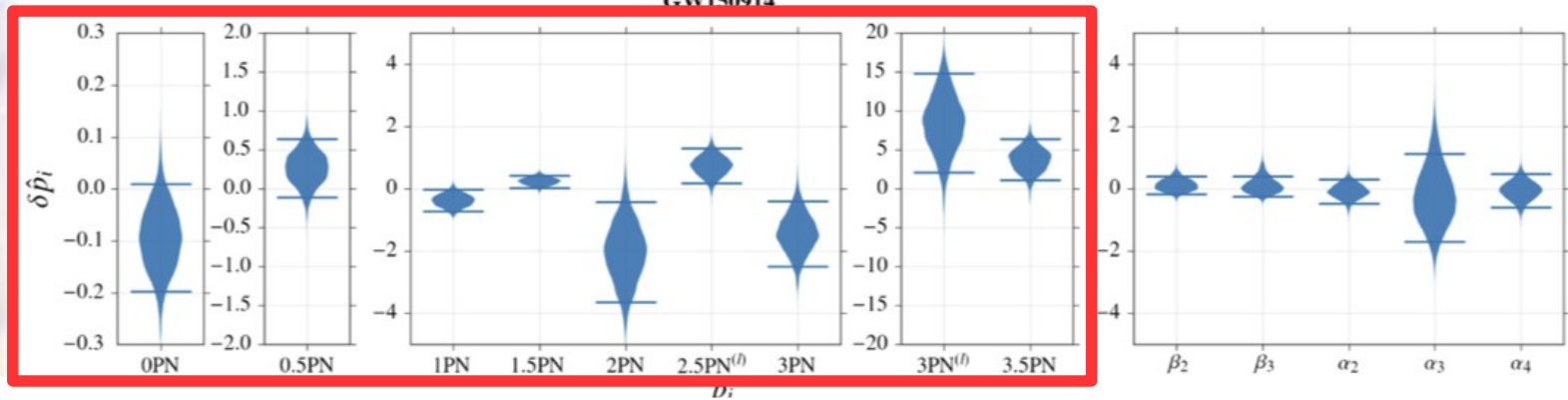


Parameterized tests of the coalescence process

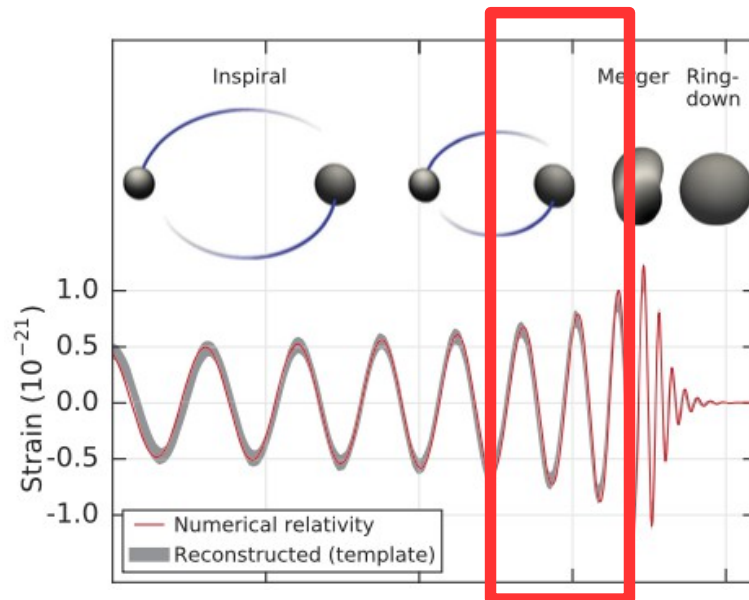


inspiral

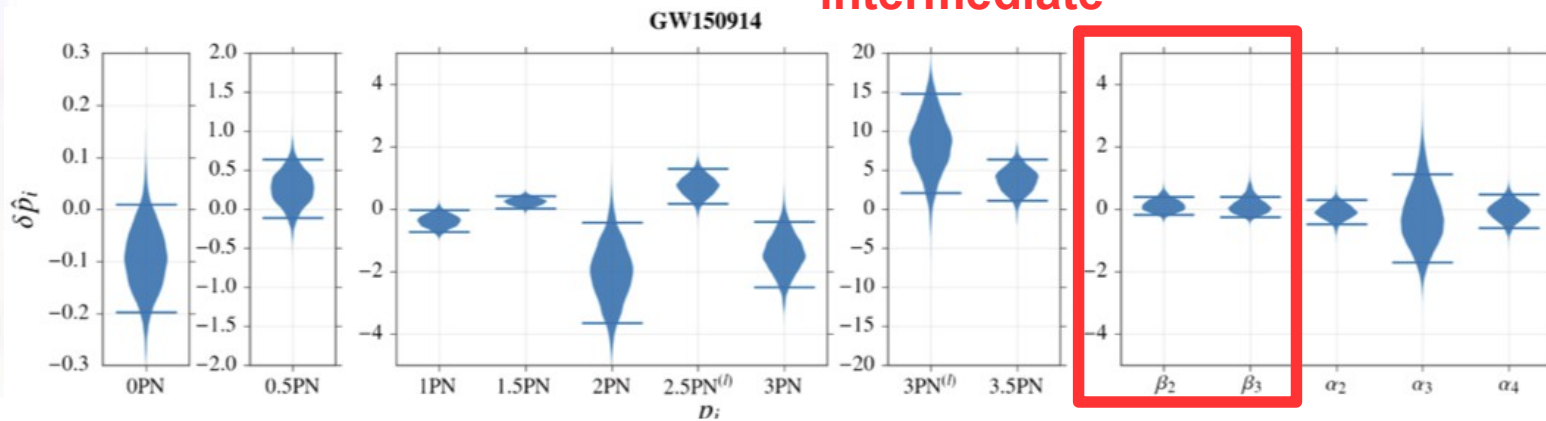
GW150914



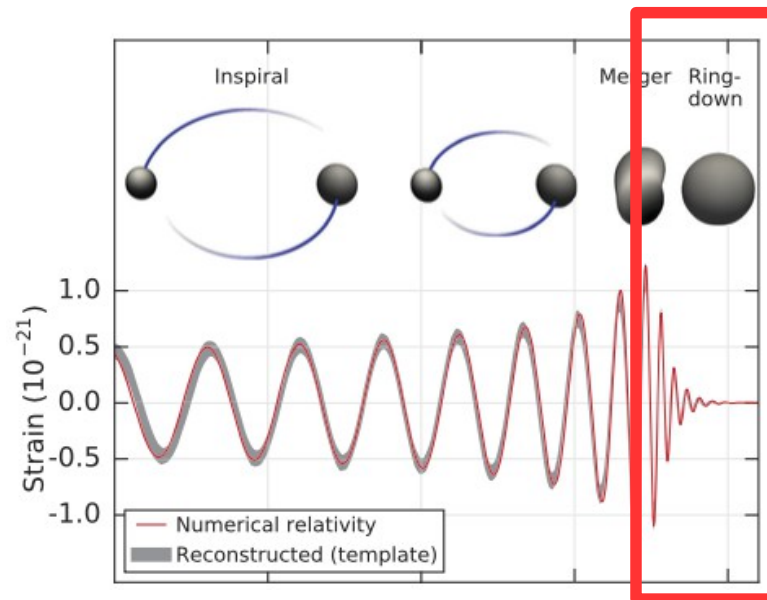
Parameterized tests of the coalescence process



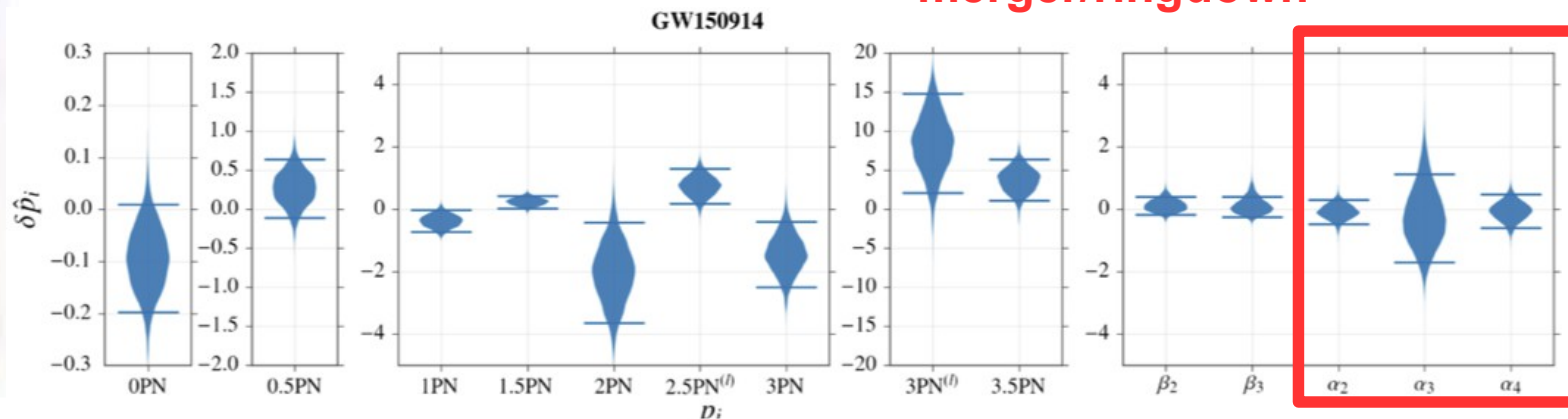
“intermediate”



Parameterized tests of the coalescence process

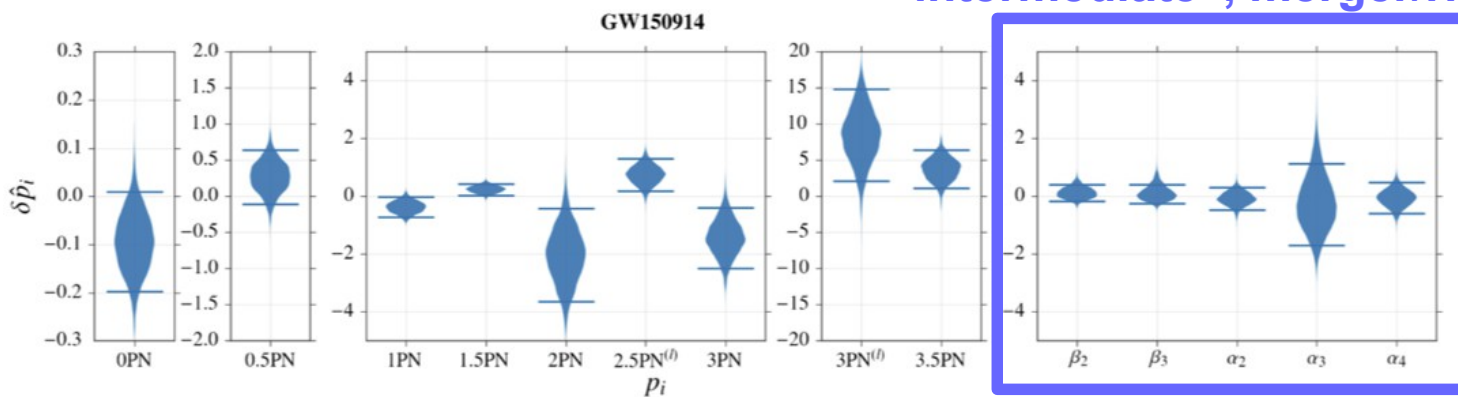


merger/ringdown

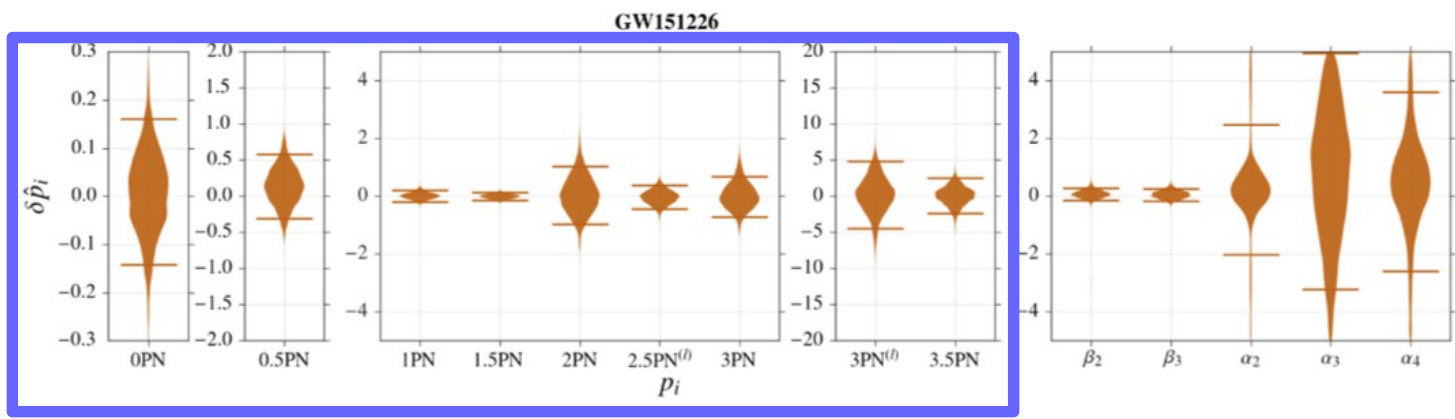
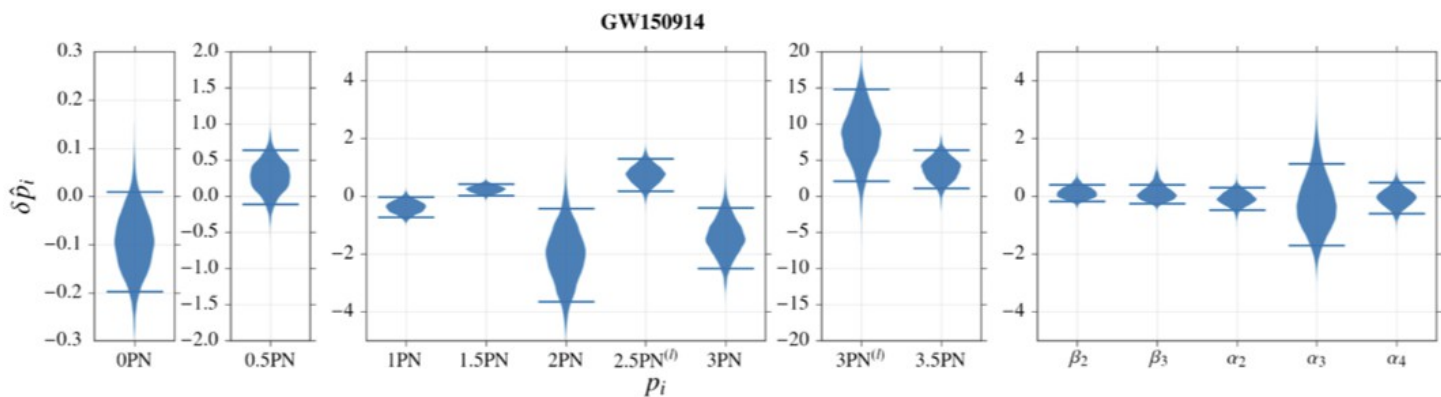


GW150914: short inspiral, but merger well visible

“intermediate”, merger/ringdown

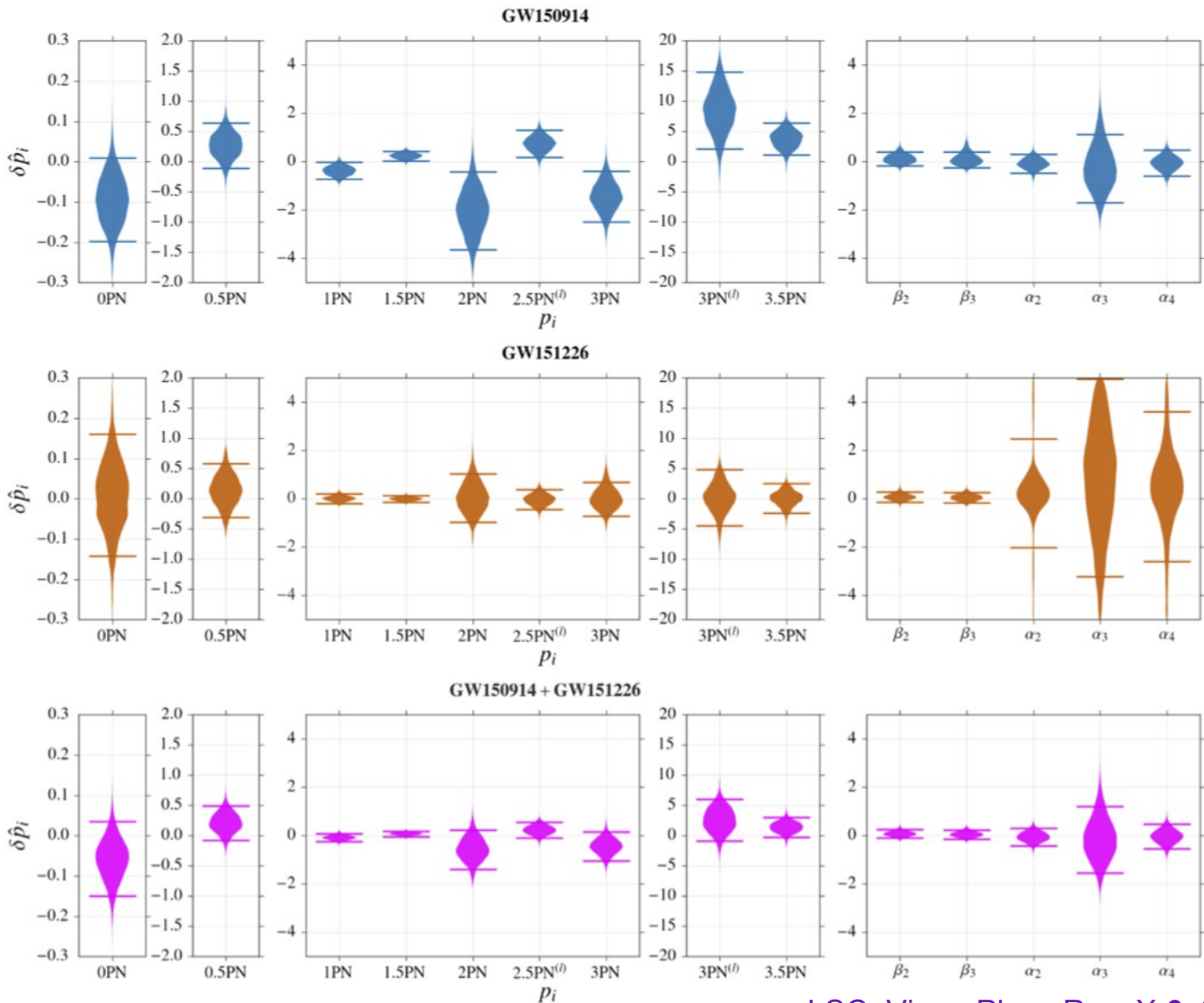


GW151226: long inspiral, merger at higher frequency

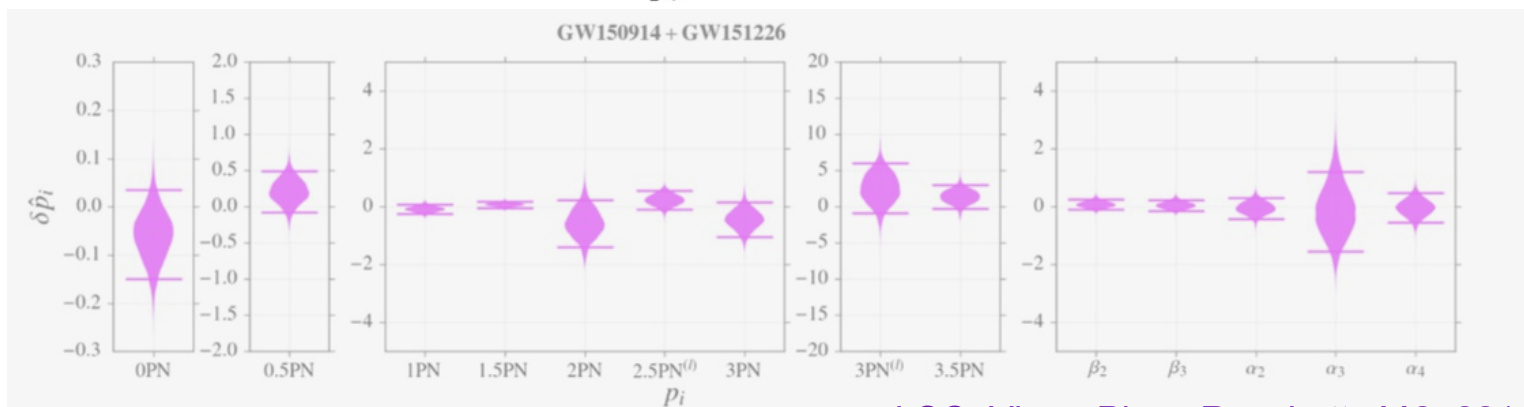
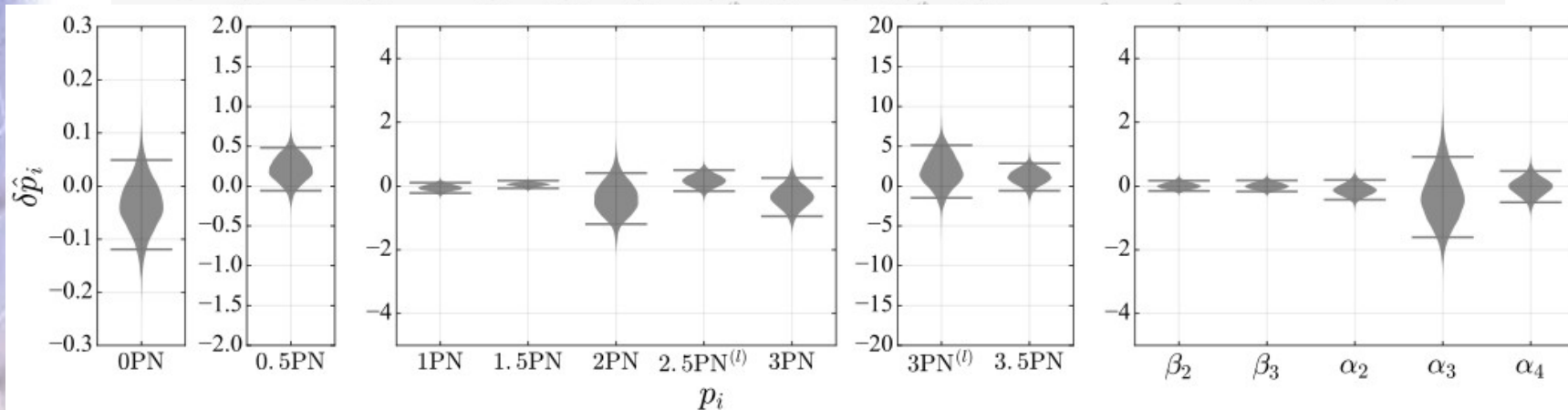
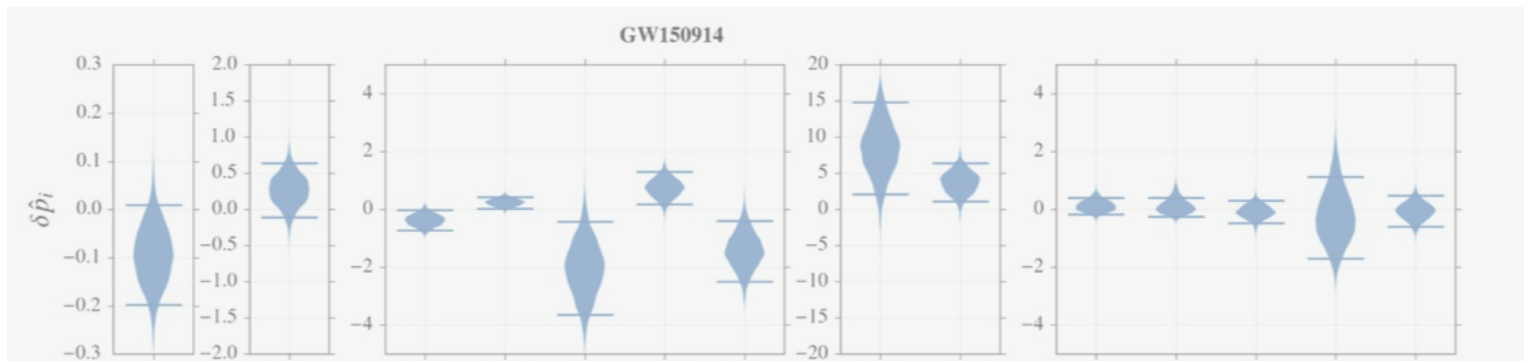


inspiral

Combine results from multiple sources

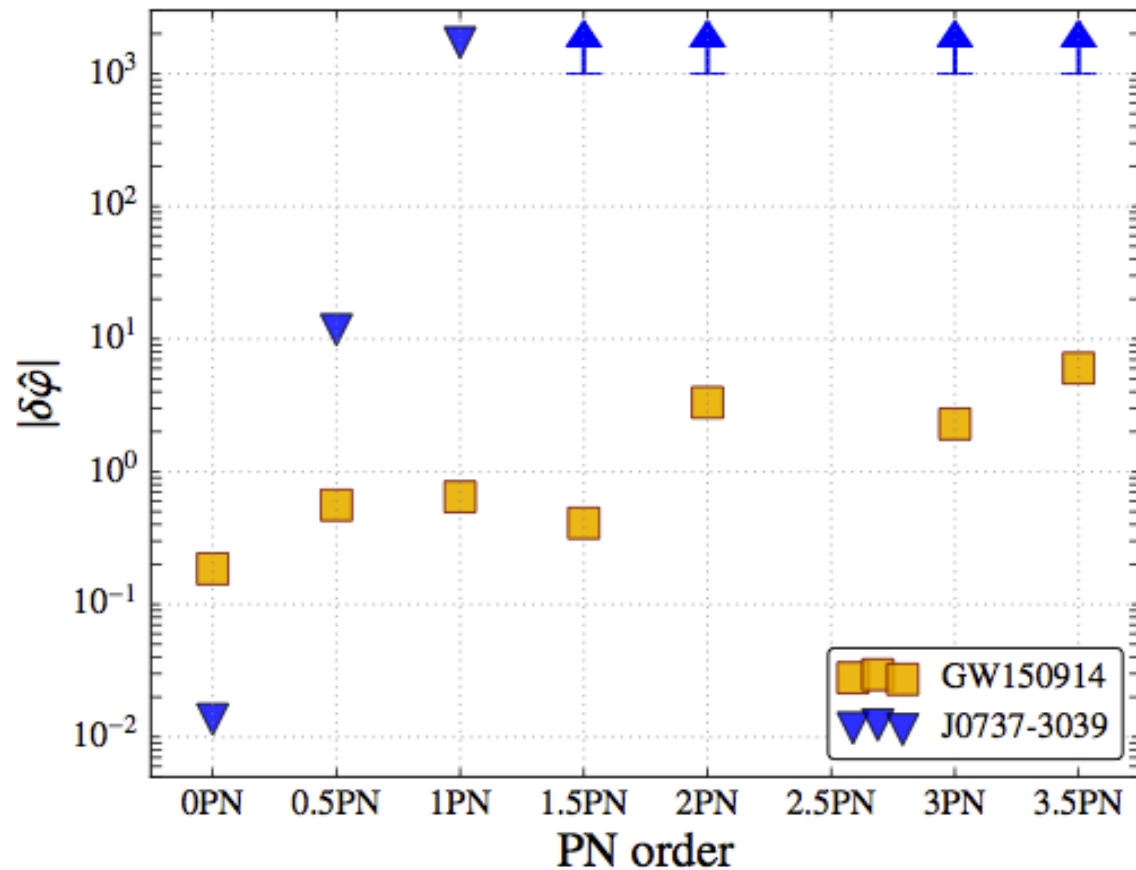


GW150914 + GW151226 + GW170104



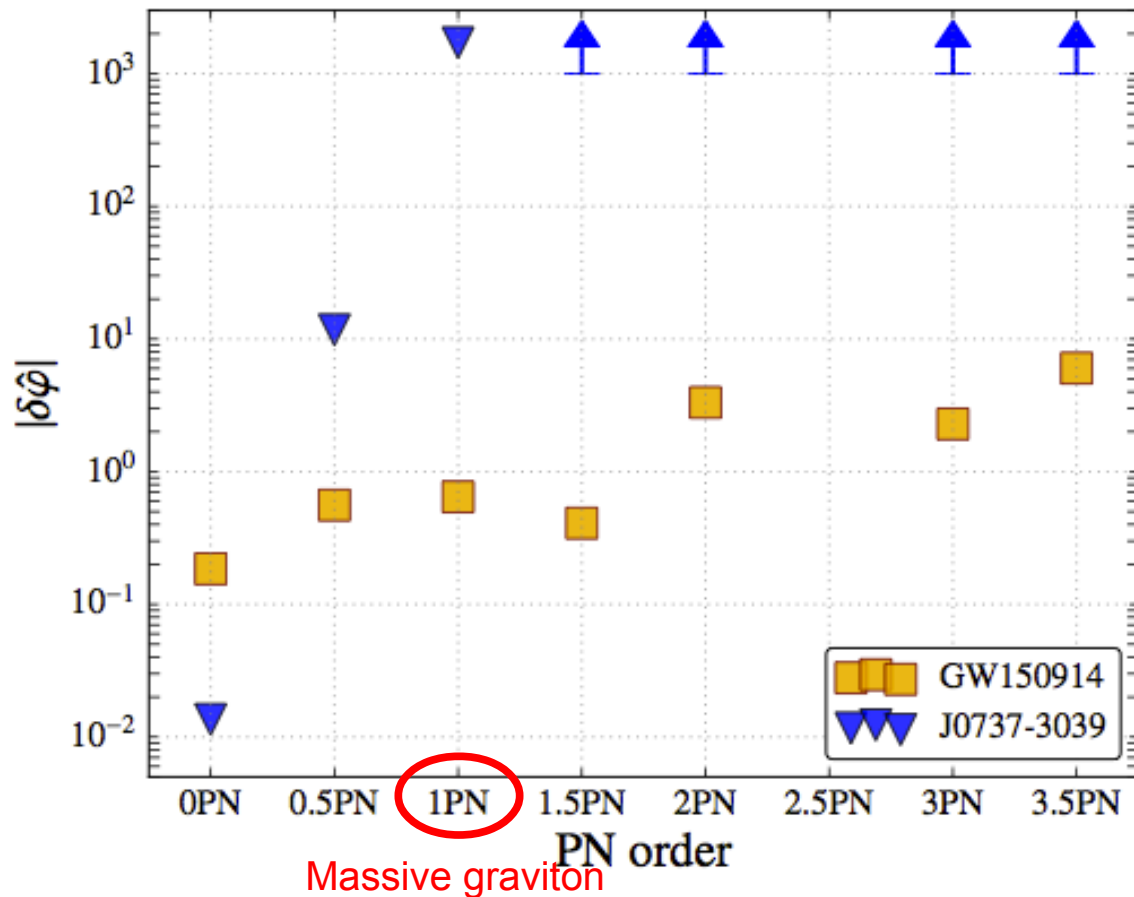
Testing the post-Newtonian description of inspiral

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



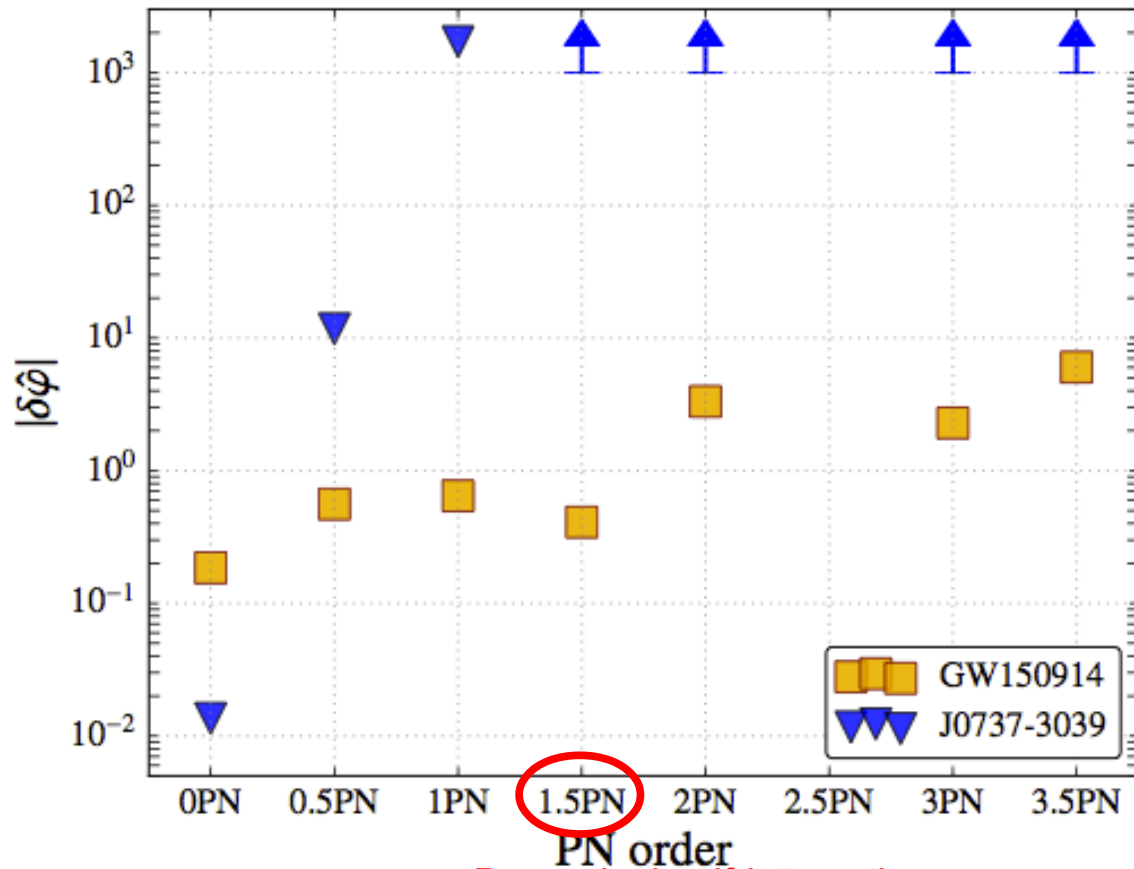
Testing the post-Newtonian description of inspiral

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



Testing the post-Newtonian description of inspiral

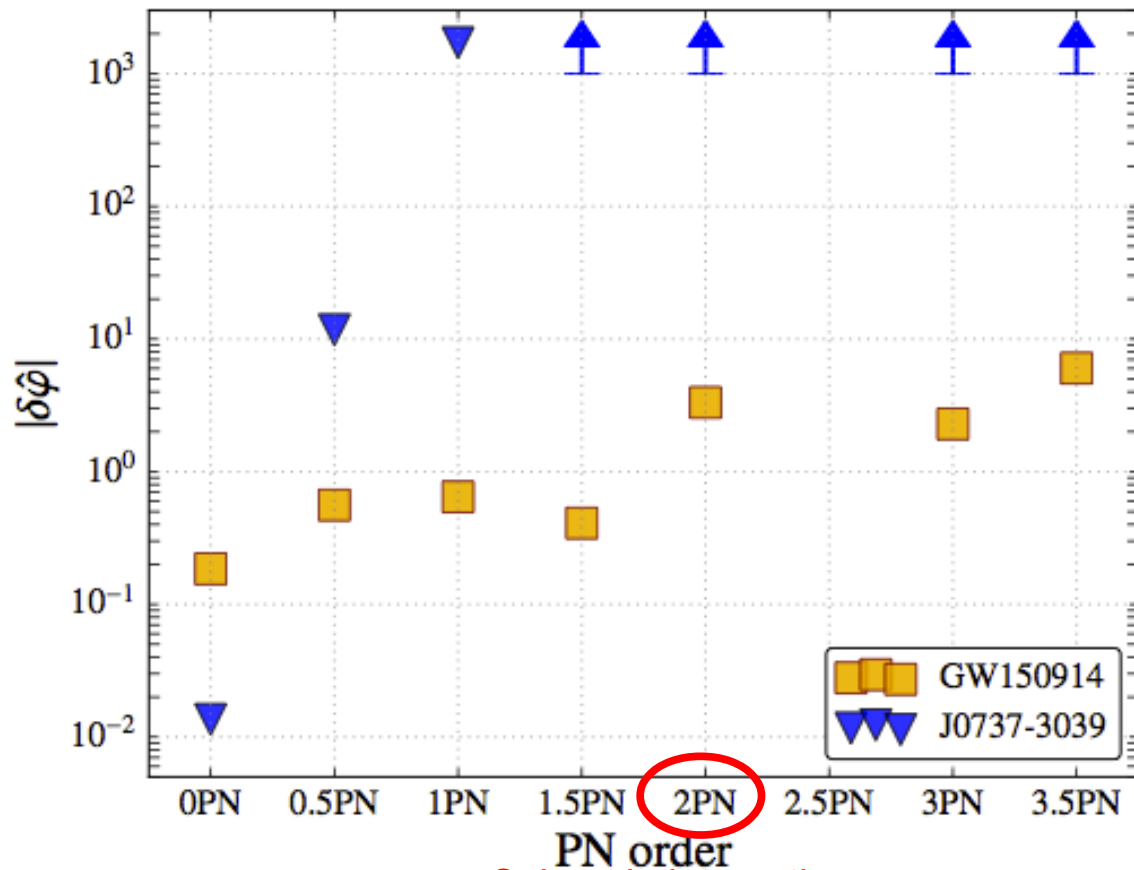
- First-ever bounds on post-Newtonian coefficients (inspiral dynamics) beyond leading order



- Dynamical self-interaction
- Spin-orbit interactions

Testing the post-Newtonian description of inspiral

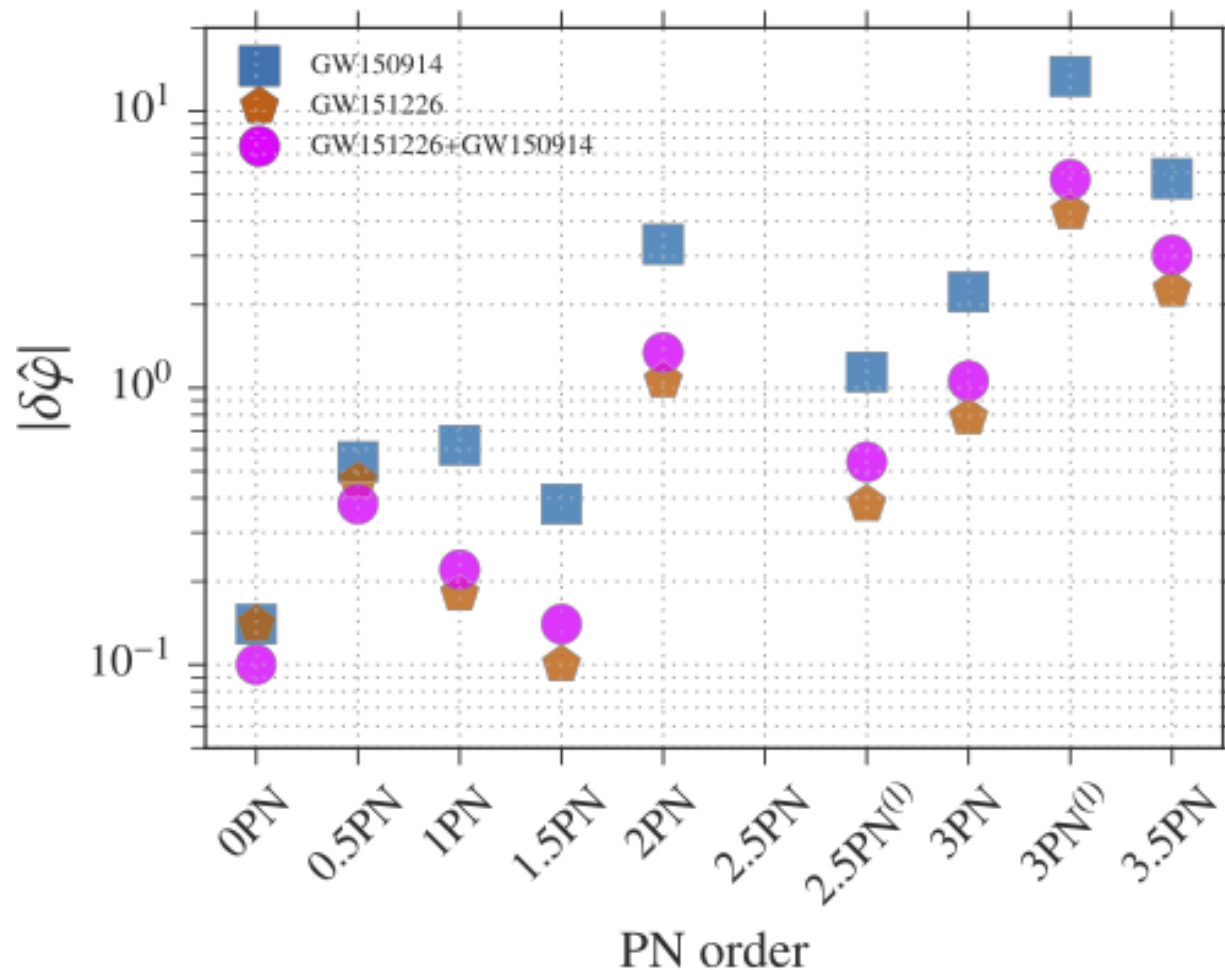
- First-ever bounds on post-Newtonian coefficients (inspiral dynamics) beyond leading order



Spin-spin interactions

Testing the post-Newtonian description of inspiral

- Combined bounds from GW150914 and GW151226:



Do gravitational waves propagate as predicted?

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

□ Dispersion of gravitational waves?

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

$$\lambda_g = h / (m_g c)$$

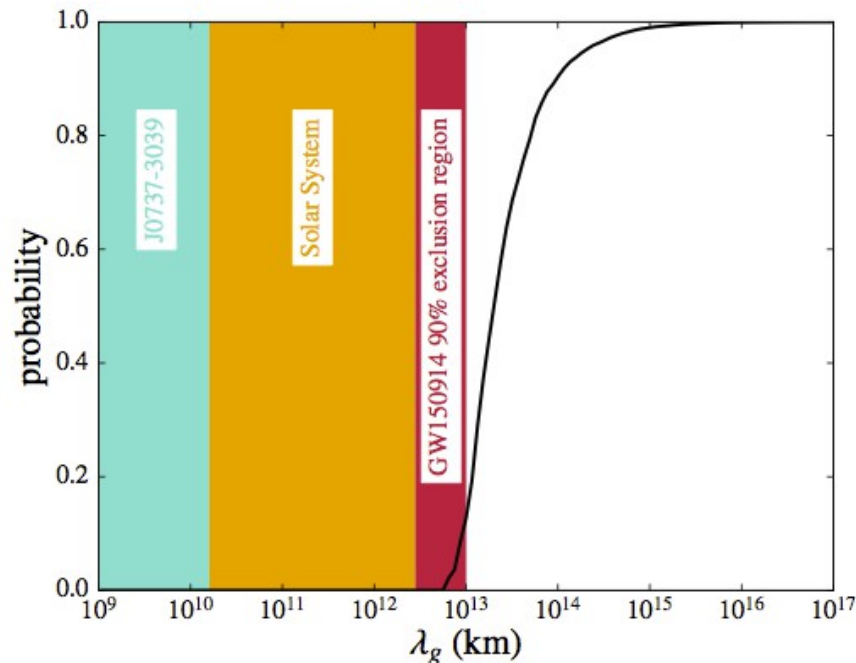
$$\Phi_{\text{MG}}(f) = -(\pi D c) / [\lambda_g^2 (1 + z) f]$$

- New bound on graviton Compton wavelength and mass:

$$\lambda_g > 10^{13} \text{ km}$$

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

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



Do gravitational waves propagate as predicted?

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

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

- Modified group velocity:

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

- Modification to the gravitational wave phase:

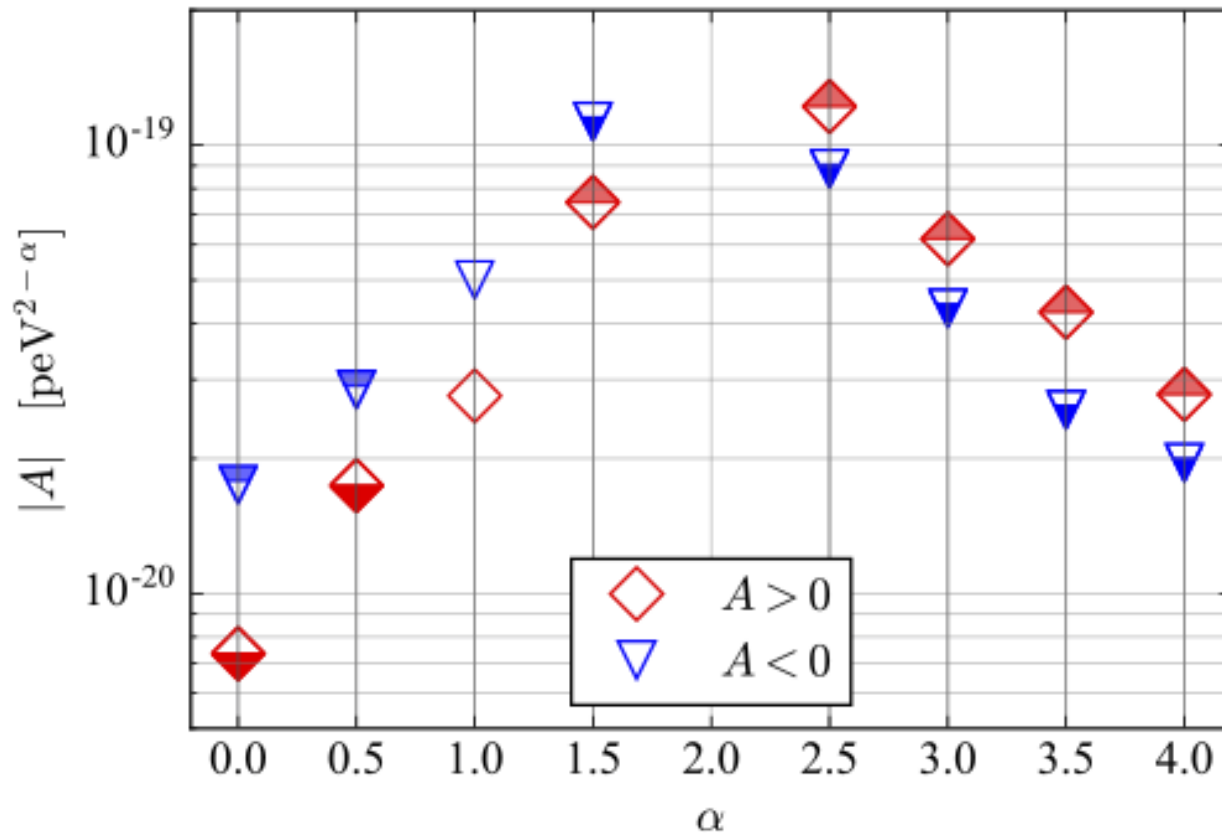
$$\delta\Psi = \begin{cases} \frac{\pi}{\alpha - 1} \frac{A D_\alpha}{(hc)^{2-\alpha}} \left[\frac{(1+z)f}{c} \right]^{\alpha-1} & \alpha \neq 1 \\ \frac{\pi A D_\alpha}{hc} \ln \left(\frac{\pi G M^{\det f}}{c^3} \right) & \alpha = 1 \end{cases}$$

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

Do gravitational waves propagate as predicted?

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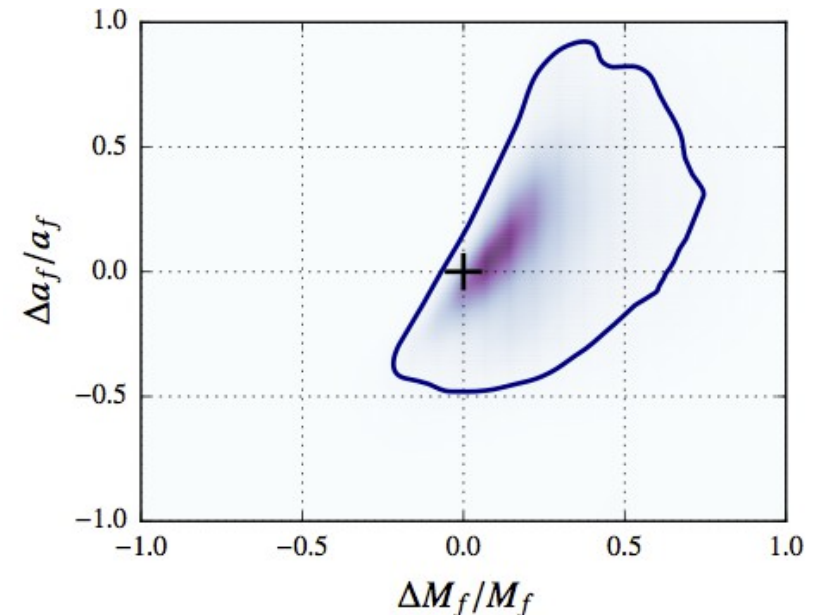
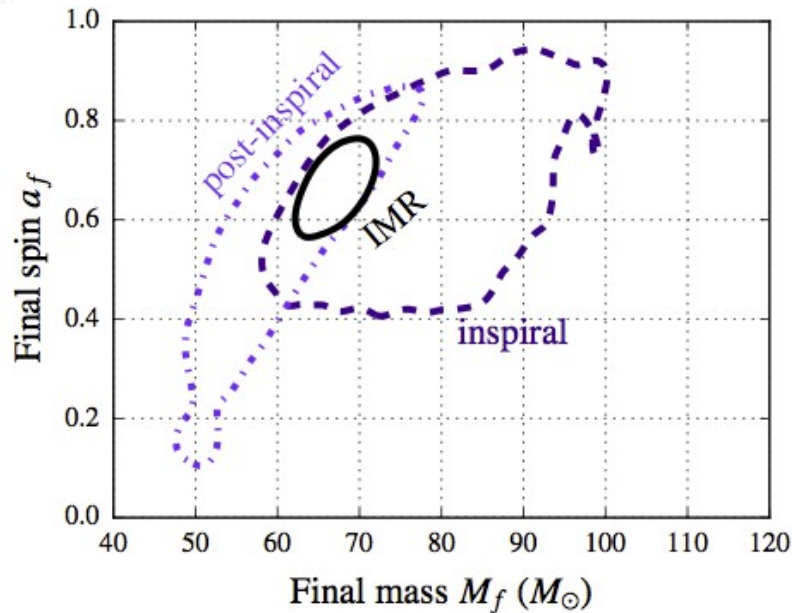
- In terms of characteristic length scales: $\lambda_A = hcA^{1/(\alpha-2)}$

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

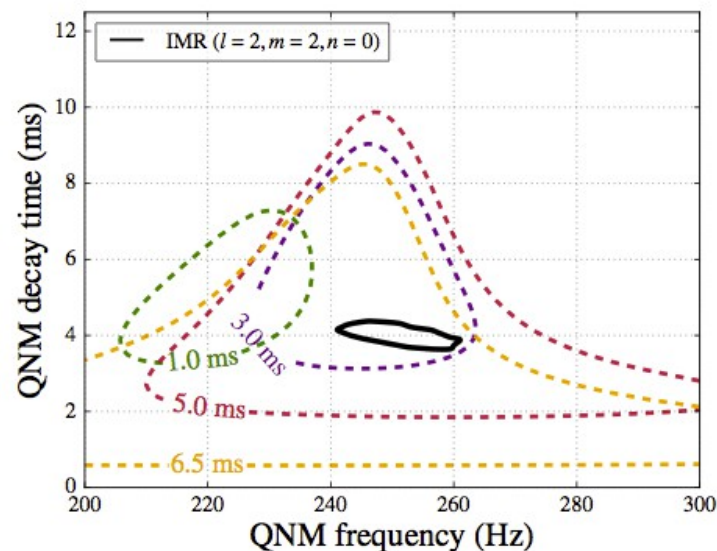
Consistency between inspiral and post-inspiral

- 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



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 $\sim 10 M$
 - For GW150914: $10 M \sim 3.5$ milliseconds
- Evidence for a least-damped quasi-normal mode from fitting damped sinusoid:





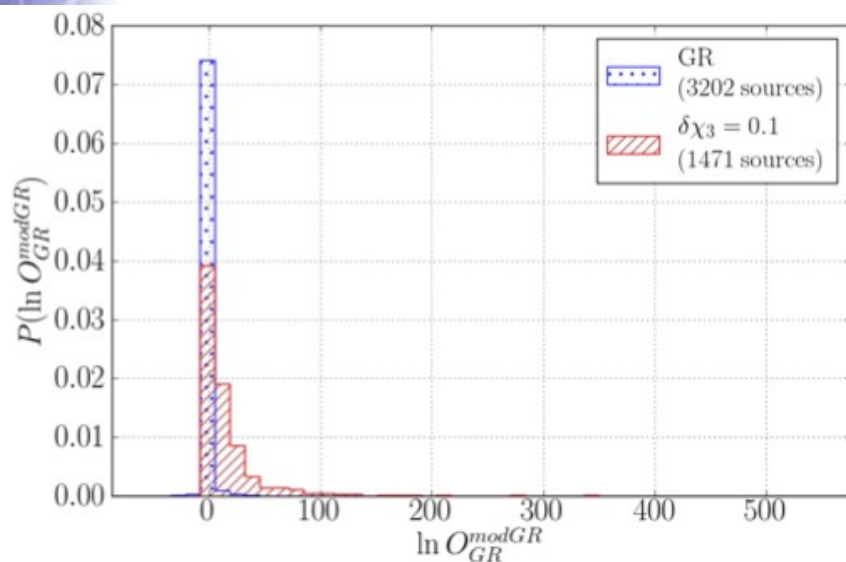
Into the future

Combining information from increasing number of detections

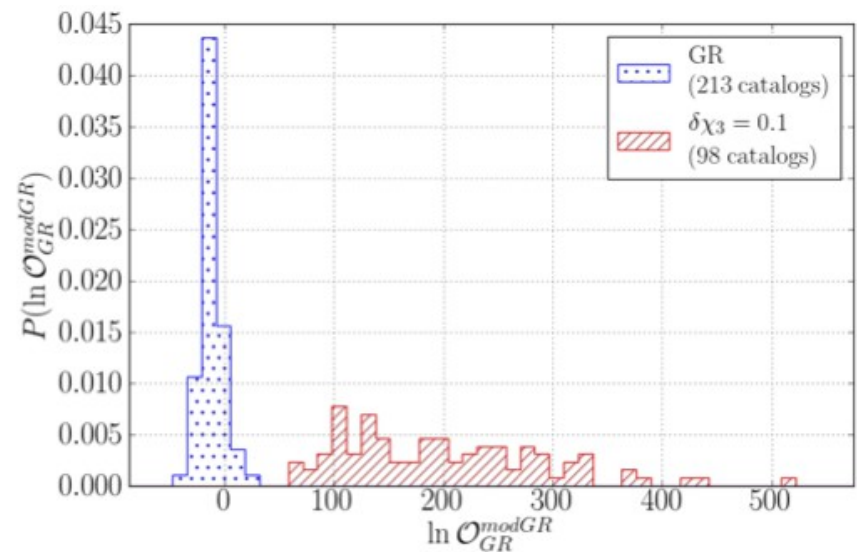
- Assuming GR is correct, bounds on violations will improve roughly with square root of number of sources
- Can also actively look for GR violations by Bayesian model selection:

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

$$\begin{aligned} & (N_T) O_{GR}^{\text{modGR}} \\ &= \frac{P(\mathcal{H}_{\text{modGR}}|d_1, \dots, d_N, \mathcal{I})}{P(\mathcal{H}_{GR}|d_1, \dots, d_N, \mathcal{I})} \end{aligned}$$



single sources



catalogs of 15 sources each

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

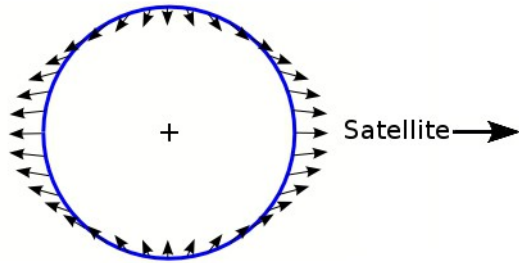
- Anomalous ringdown spectrum

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



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

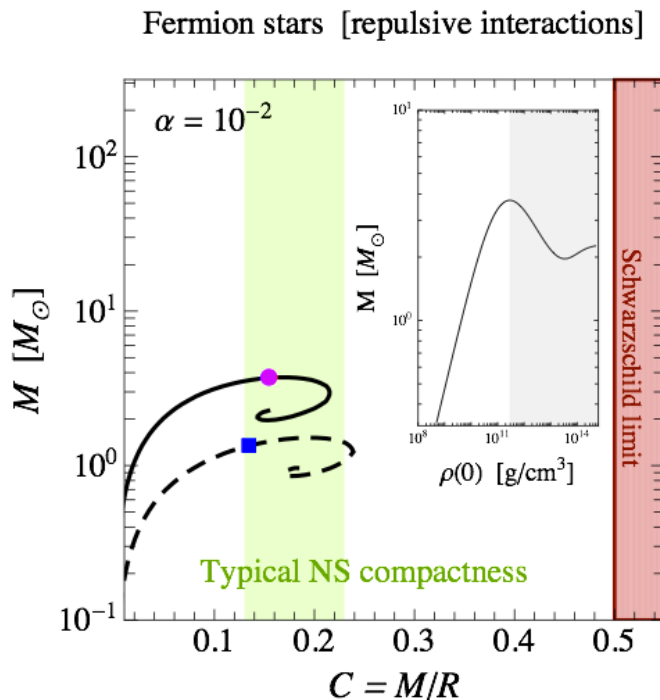
$$Q_{ij} = -\lambda(\text{EOS}; m) \mathcal{E}_{ij}$$

where $\lambda(\text{EOS}; m)$ 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 $\lambda(m)/M^5 \propto (R/M)^5$

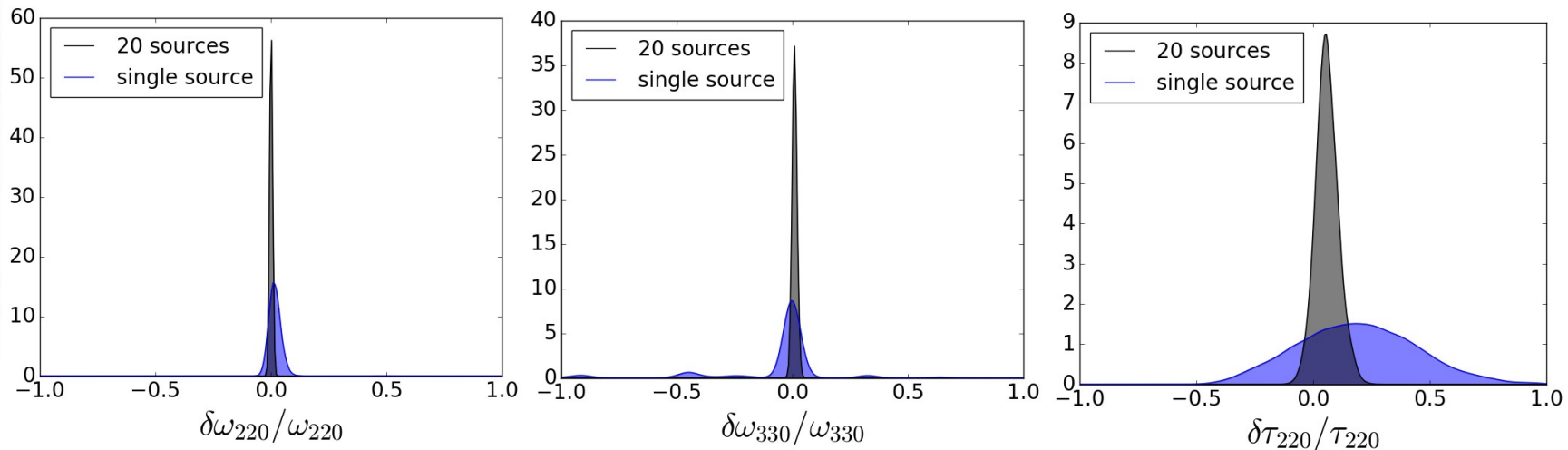
- $O(10^2 - 10^5)$ for neutron stars
- Can be still larger for
 - Dark matter stars
 - Boson stars
- Detectable with Advanced LIGO/Virgo



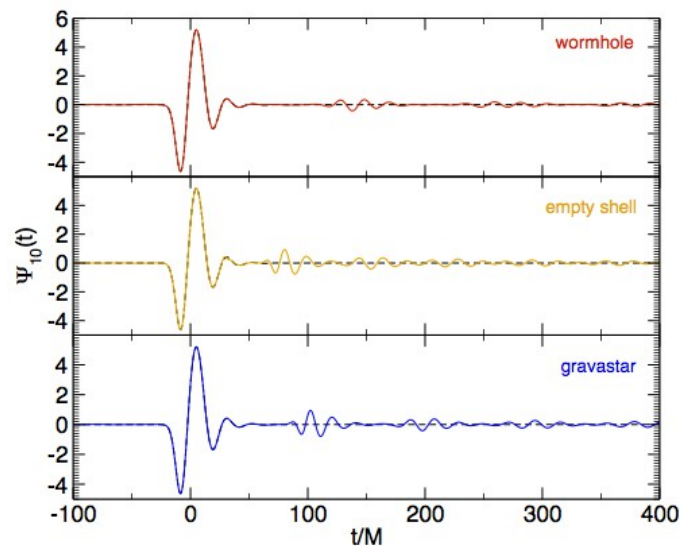
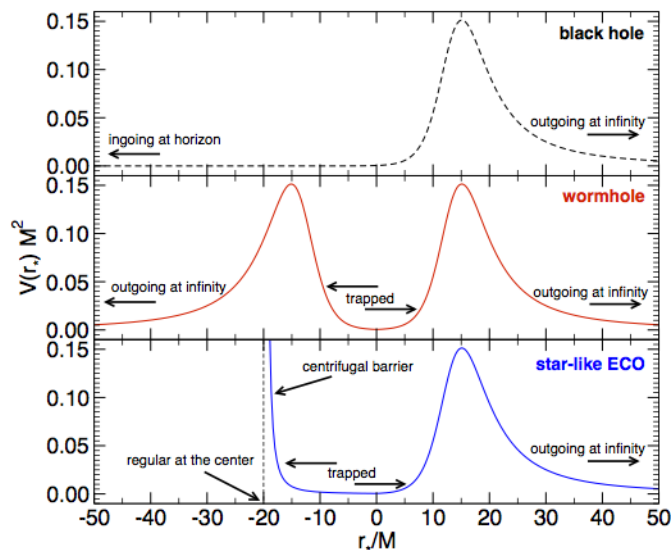
Testing the no-hair theorem

- 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

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



Gravitational wave echoes after ringdown



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

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

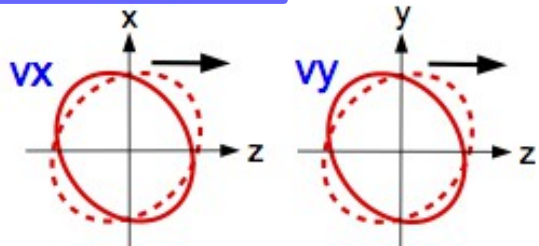
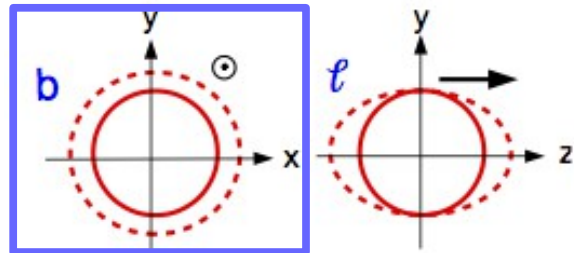
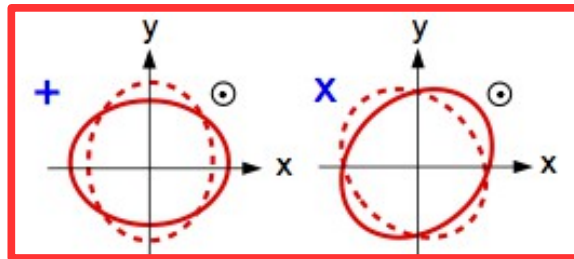
- n depends on nature of object (e.g. $n = 8$ for wormholes)
- For mass M similar to GW150914, l_c the Planck length

- $\Delta t = O(100)$ 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

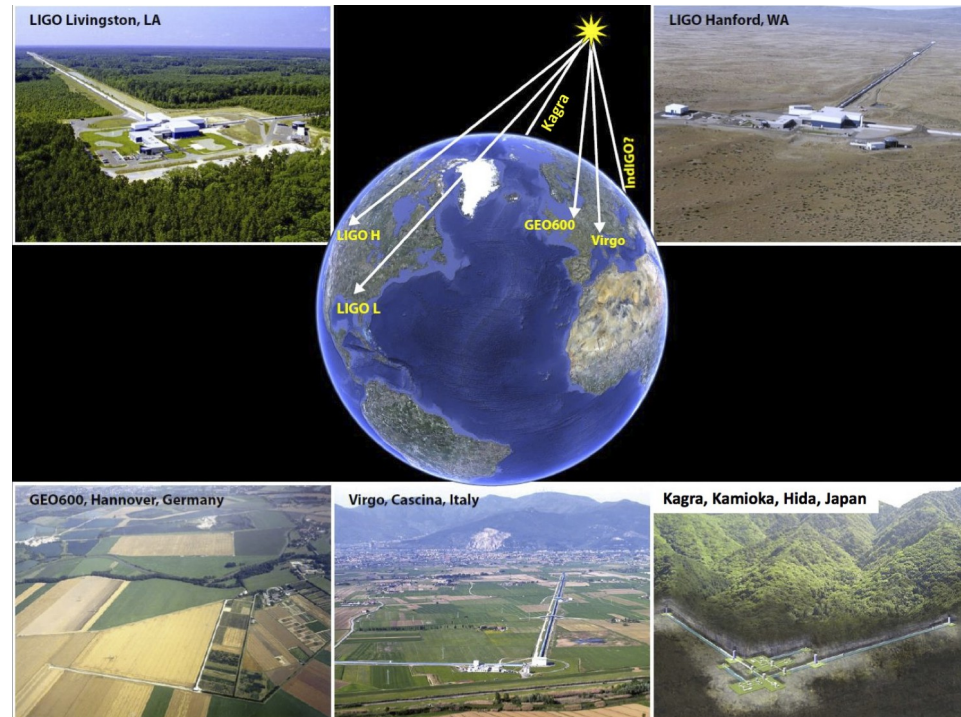


Will, Living Rev. Relativ. **17**, 4 (2014)

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

$$\log B_{\text{scalar}}^{\text{GR}} = -0.2 \pm 0.5$$

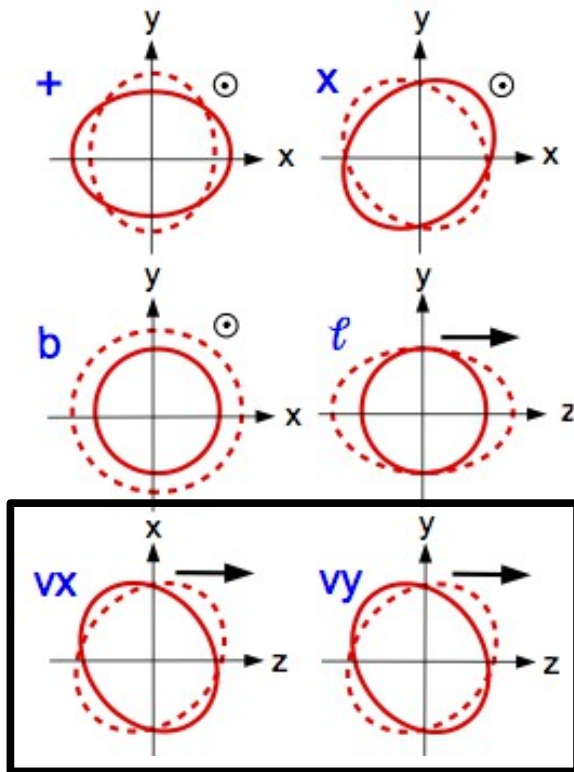
- Need a larger network of detectors!



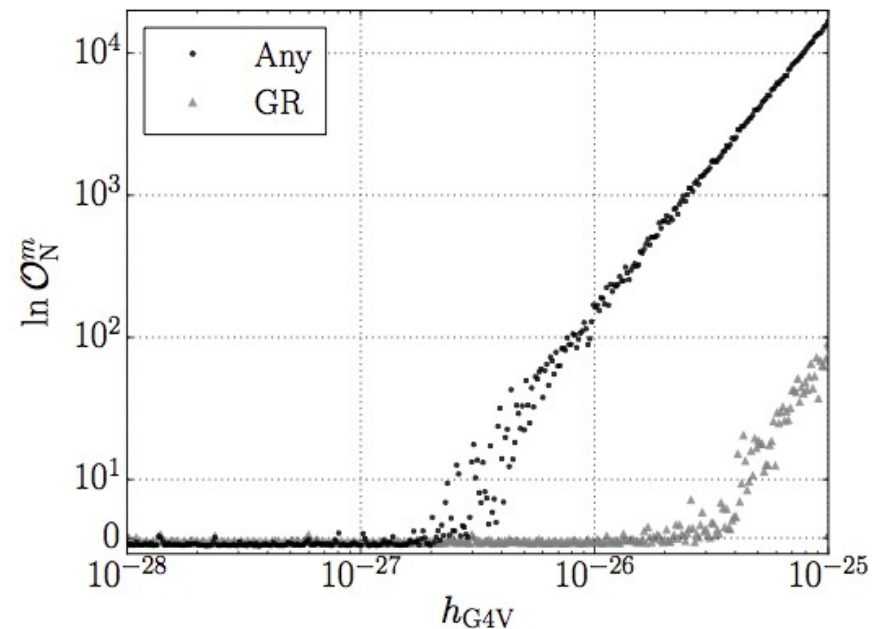
Alternative polarization states

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

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



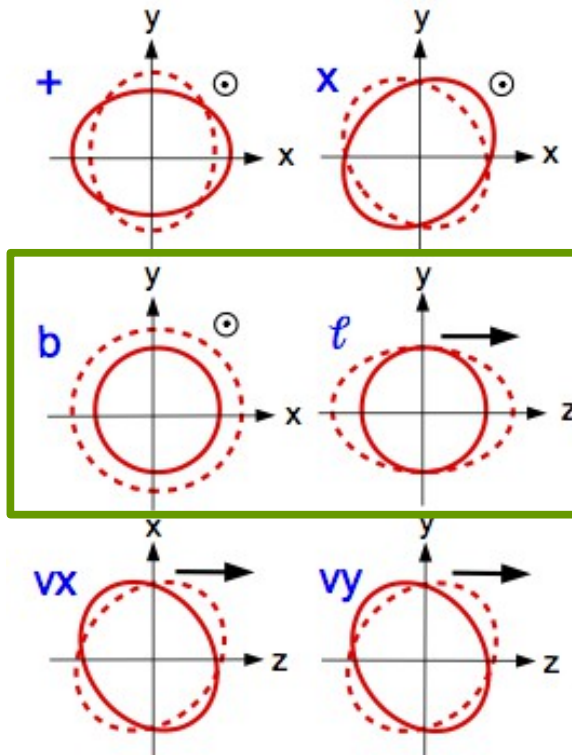
Will, Living Rev. Relativ. **17**, 4 (2014)



Isi et al., arXiv:1703.07530

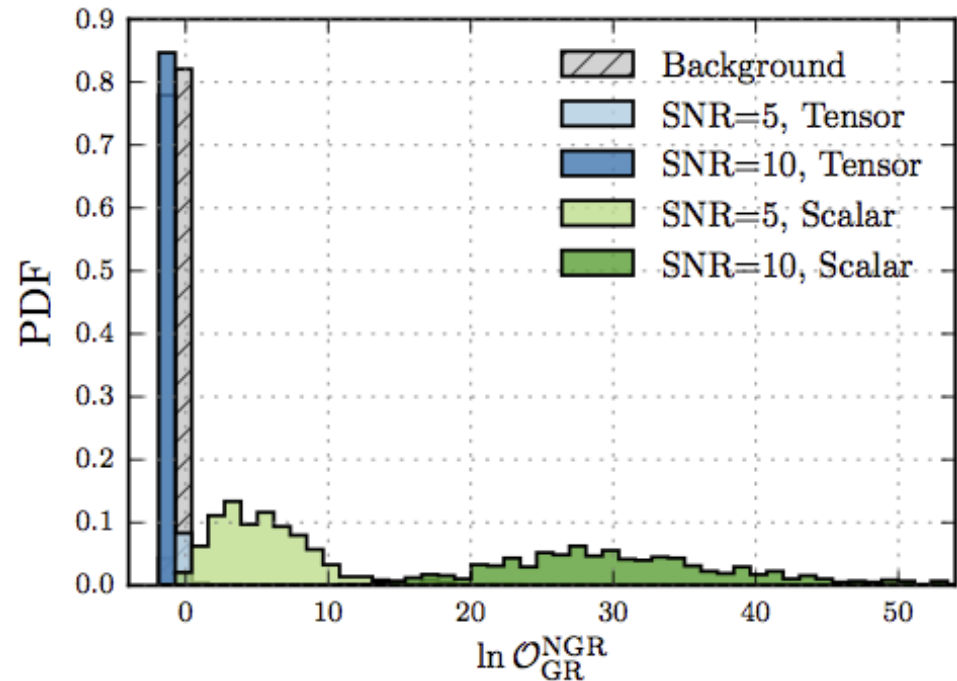
Alternative polarization states

□ Similarly, can use stochastic backgrounds



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

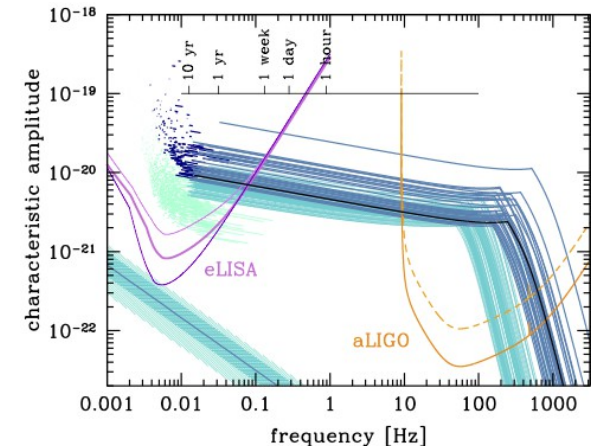
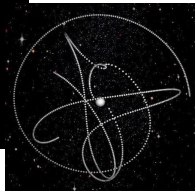
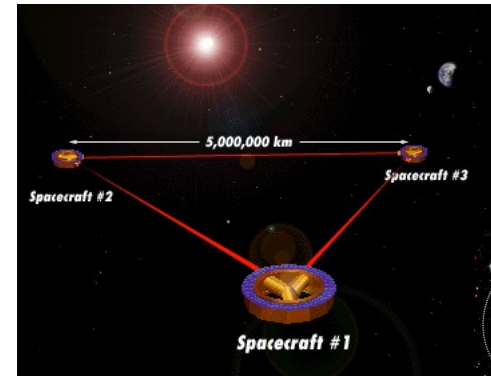
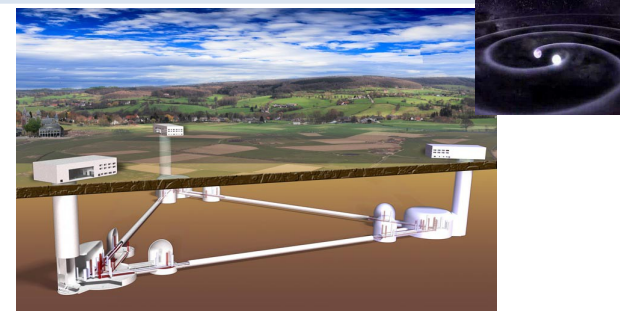
- Advanced detectors, design sensitivity
- Accumulated signal from binary mergers, 3 years of observation



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
- ...



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
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