Testing GR with GW observations

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Wigner Theoretical Physics Seminar
Budapest, 30.6.17

(using the presentation of Chris Van Den Broeck)

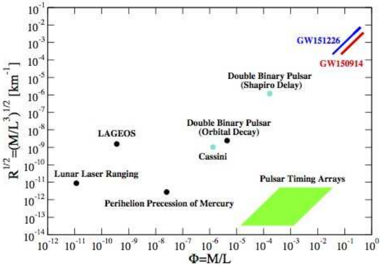
First access to the strong-field dynamics of spacetime

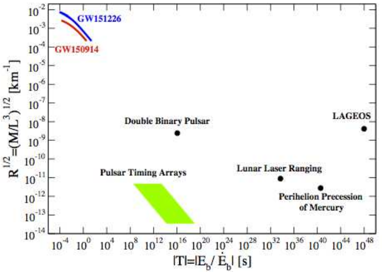
Before the direct detection of gravitational waves:

- 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:

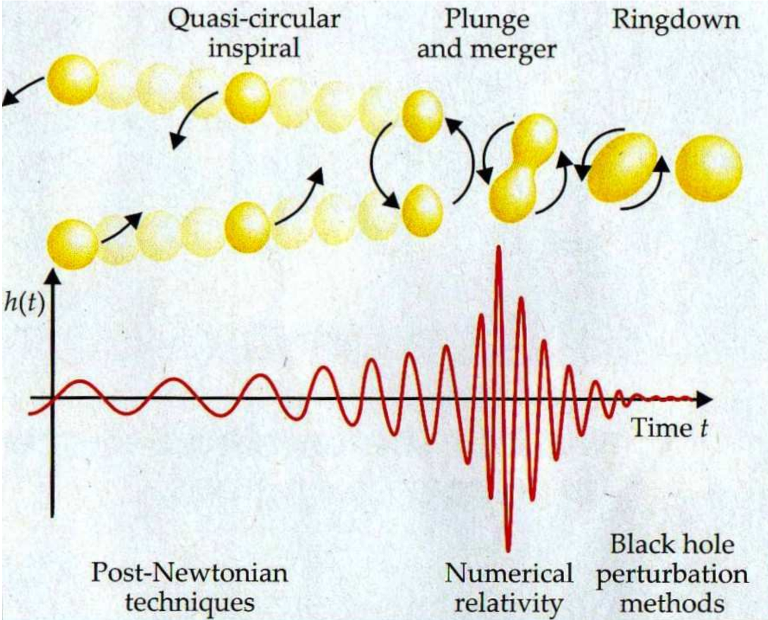
- Genuinely strong-field dynamics
- (Presumed) pure spacetime events



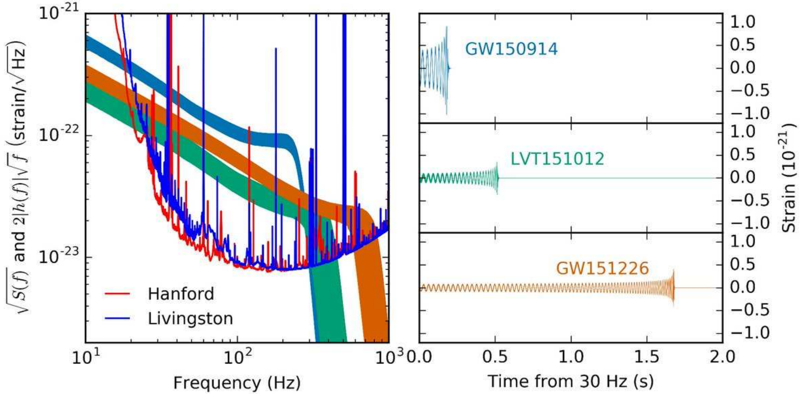


Yunes, Yagi, Pretorius, Phys. Rev. D **94**, 084002 (2016)

Coalescence of binary neutron stars and black holes



Complementary information from different events

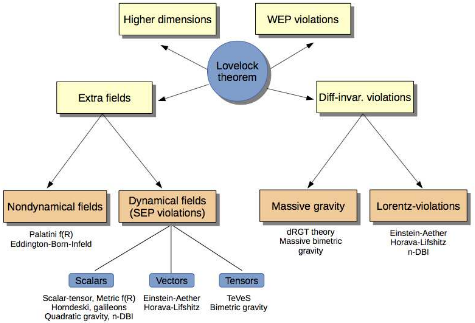


Signal-to-noise ρ : $$\rho^2 = \int_0^\infty \left(\frac{2|\tilde{h}(f)|\sqrt{f}}{\sqrt{S_n(f)}} \right)^2 d\ln(f)$$

- ⋆ GW150914 ($\rho \simeq 24$): merger at the most sensitive detector frequencies,
- ⋆ GW151226 ($\rho \simeq 13$): long inspiral in sensitive frequency band,
- ⋆ GW170104 ($\rho \simeq 13$): twice as far away $\to$ effects of distance on propagation

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
- 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

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:

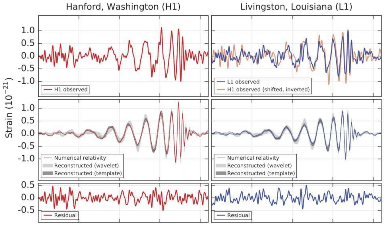
  $$\mathrm{SNR}_{\mathrm{res}}^2 = (1 - \mathrm{FF}^2)\,\mathrm{FF}^{-2}\,\mathrm{SNR}_{\mathrm{det}}^2$$

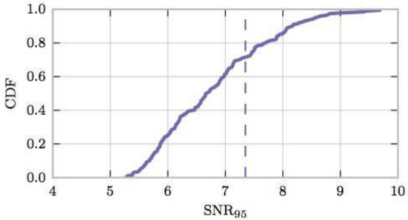
- $\mathrm{SNR}_{\mathrm{det}} = 25.3^{+0.1}_{-0.2}$

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

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

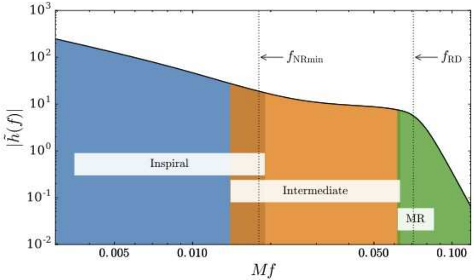
- GR violations limited to 4%, at least for effects that can not be absorbed into redefinition of physical parameters





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)

Parametrized phenomenological waveforms

A. Model waveform(s) and detector configuration

We start from the way TaylorF2 is implemented in the LIGO Algorithms Library [63]:

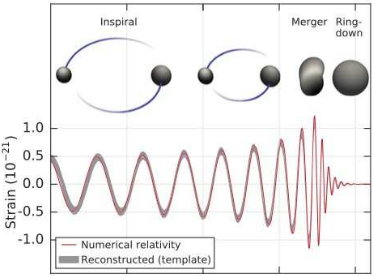
$$h(f) = \frac{1}{D} \frac{\mathcal{A}(\theta, \phi, \iota, \psi, \mathcal{M}, \eta)}{\sqrt{\dot{F}(\mathcal{M}, \eta; f)}} f^{2/3} e^{i\Psi(t_c, \phi_c, \mathcal{M}, \eta; f)}, \quad (1)$$

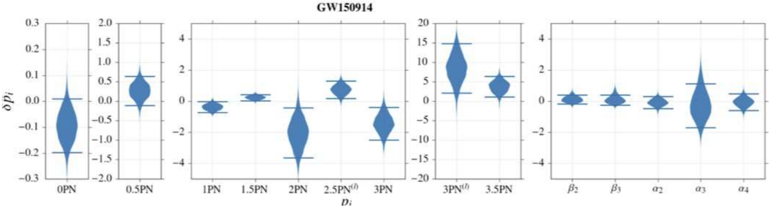
where D is the luminosity distance to the source, (θ, ϕ) specify the sky position, (ι, ψ) give the orientation of the inspiral plane with respect to the line of sight, $\mathcal{M}$ is the chirp mass, and η is the symmetric mass ratio.

In terms of the component masses (m_1, m_2), one has $\eta = m_1 m_2/(m_1 + m_2)^2$ and $\mathcal{M} = (m_1 + m_2)\eta^{3/5}$. t_c and ϕ_c are the time and phase at coalescence, respectively. The "frequency sweep" $\dot{F}(\mathcal{M}, \eta; f)$ is an expansion in powers of the frequency f with mass-dependent coefficients, and

$$\Psi(t_c, \phi_c, \mathcal{M}, \eta; f) = 2\pi f t_c - \phi_c - \pi/4 + \sum_{i=0}^{7}[\psi_i + \psi_i^{(l)} \ln f] f^{(i-5)/3}. \quad (2)$$

Parameterized tests of the coalescence process





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

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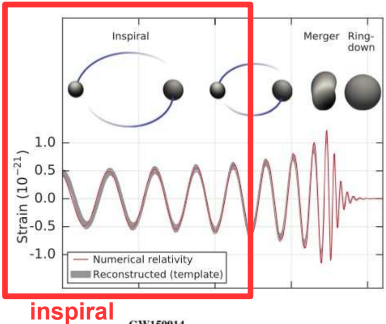

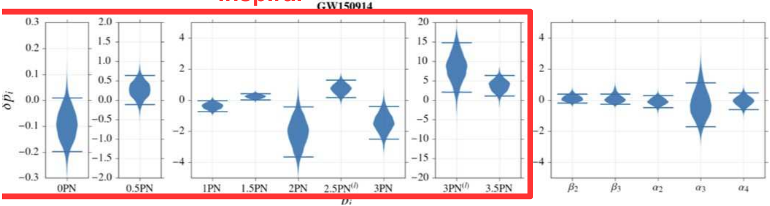

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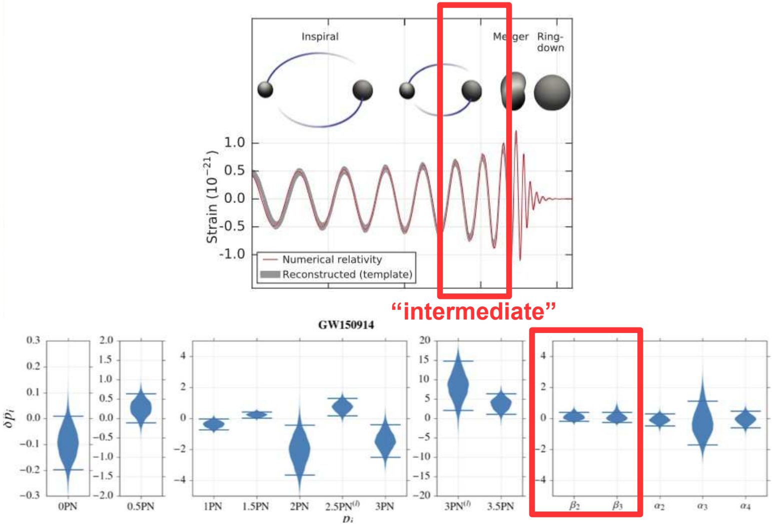

LSC+Virgo, Phys. Rev. X **6**, 041015 (2016)

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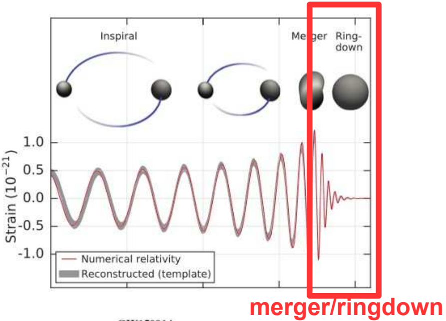
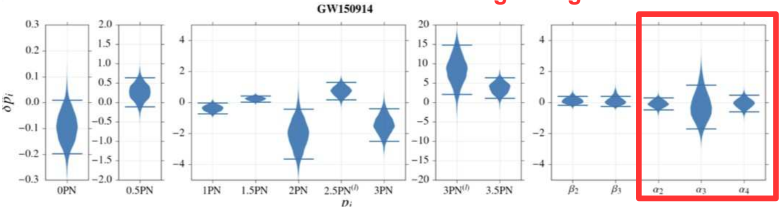
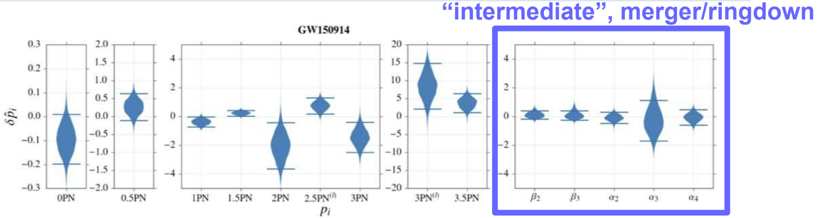




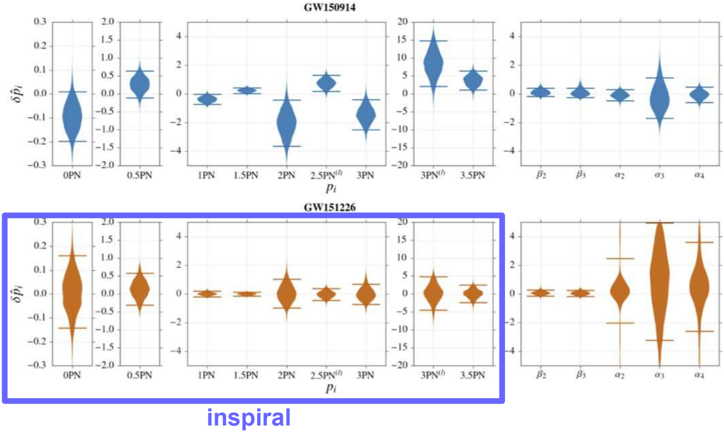
LSC+Virgo, Phys. Rev. X **6**, 041015 (2016)

GW150914: short inspiral, but merger well visible



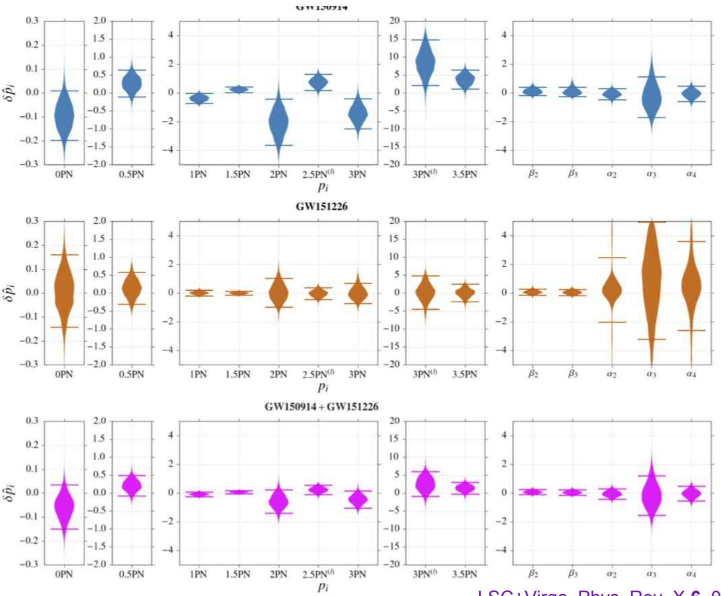
LSC+Virgo, Phys. Rev. X **6**, 041015 (2016)

GW151226: long inspiral, merger at higher frequency



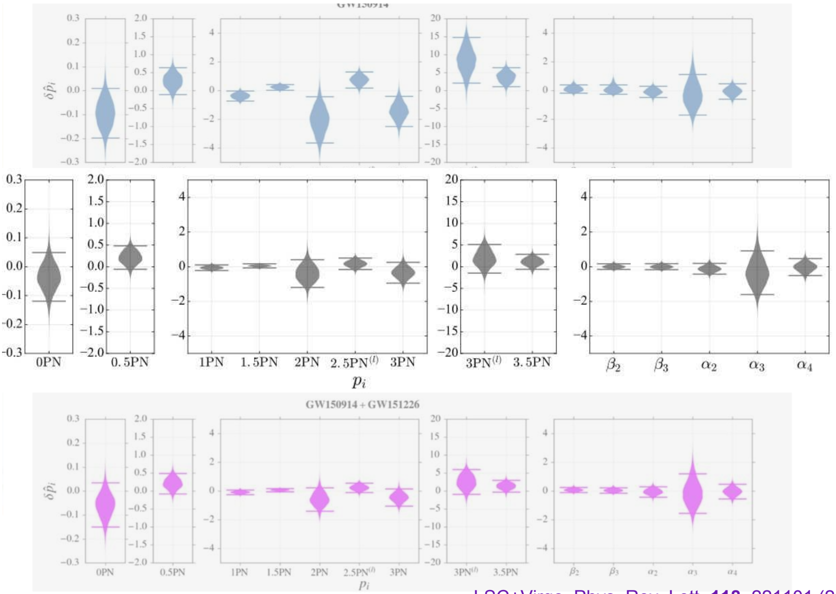
LSC+Virgo, Phys. Rev. X **6**, 041015 (2016)

Combine results from multiple sources



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

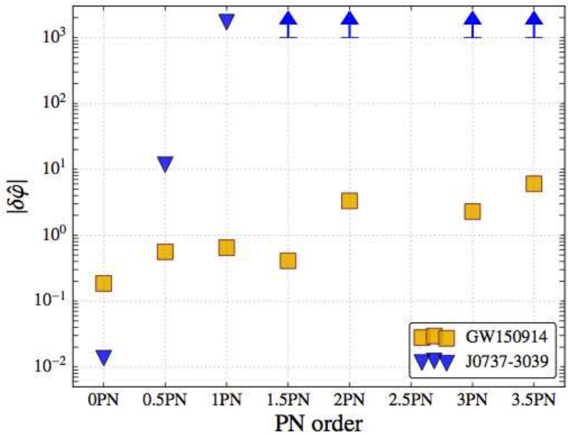
GW150914 + GW151226 + GW170104



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



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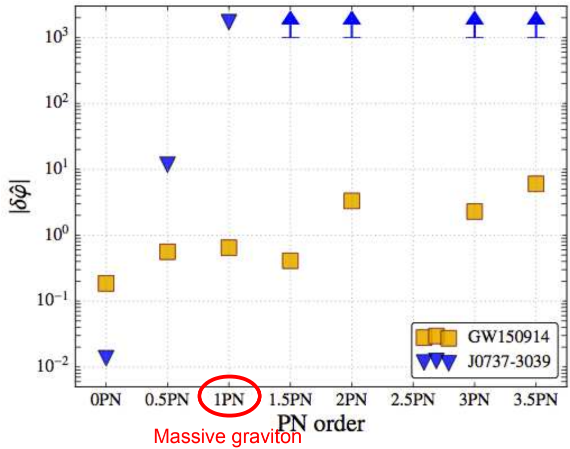

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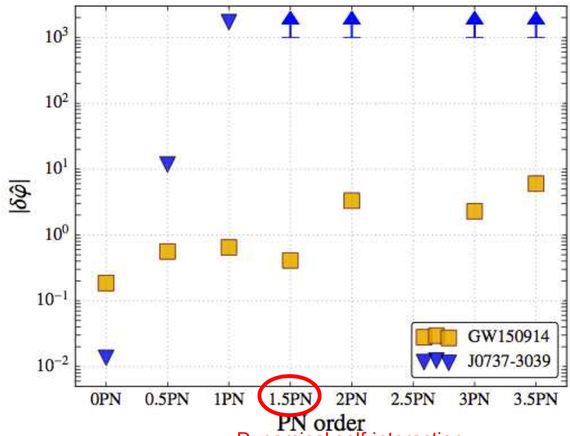

- Dynamical self-interaction
- Spin-orbit interactions

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

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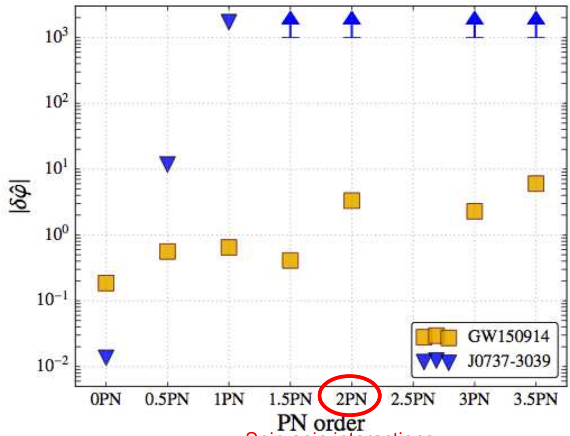
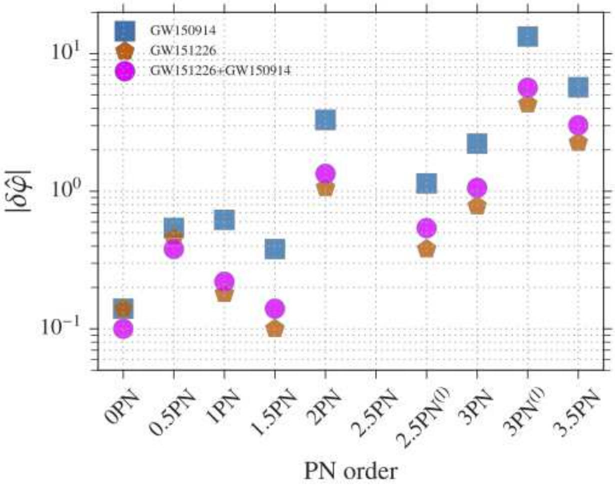


Spin-spin interactions

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?

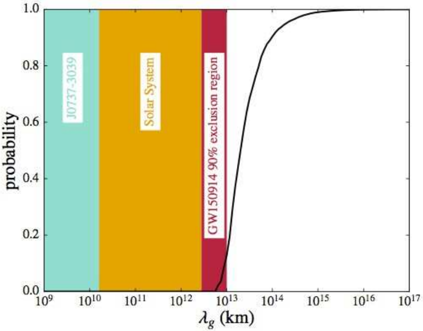
- Dispersion of gravitational waves?

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

- New bound on graviton Compton wavelength and mass:

  $\lambda_g > 10^{13}$ km $\qquad m_g < 10^{-22}$ 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:

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

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

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

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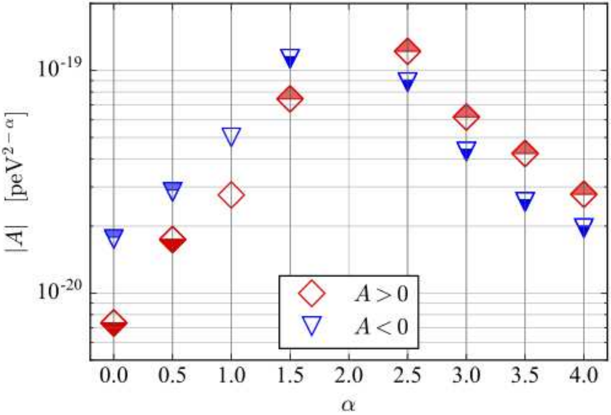
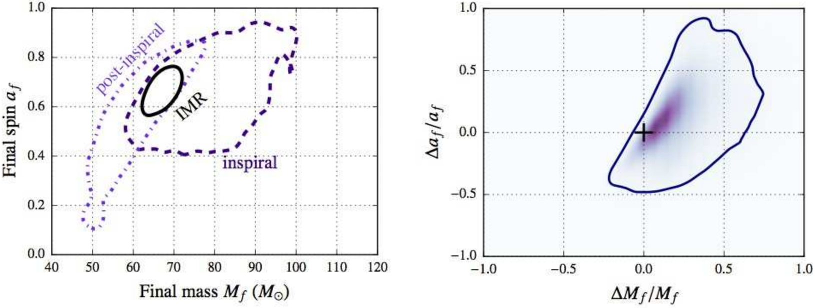


LSC+Virgo, Phys. Rev. Lett. **118**, 221101 (2017)

Consistency between inspiral and post-inspiral

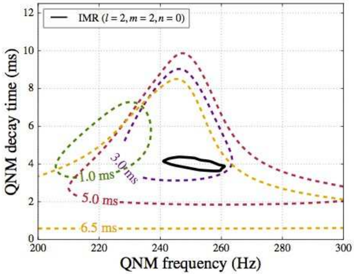
- General relativity predicts relationship between
  - Masses and spins of component objects
  - Mass and spin of final object
- Relationship can be extracted from numerical simulations
  - Accurate analytical fits (Healy et al. 2014)
- Compare inferred values from inspiral and post-inspiral



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)

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

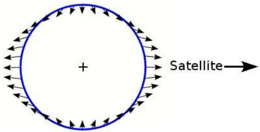
- Anomalous ringdown spectrum

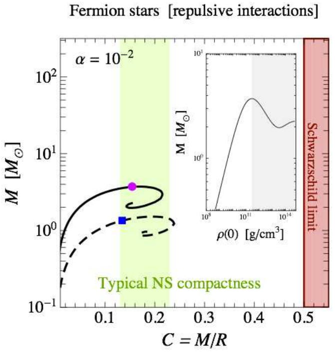
  Meidam et al., Phys. Rev. D **90**, 064009 (2014)

- Gravitational wave "echoes" after ringdown

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

Anomalous tidal effects during inspiral



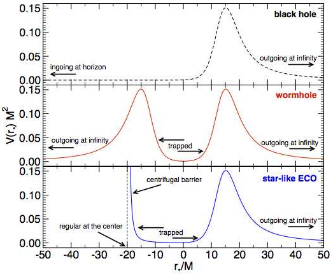


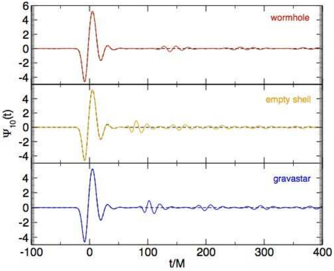
Giudice et al., JCAP **1610**, 001 (2016)

- 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
  - Can be still larger for
    - Dark matter stars
    - Boson stars
  - Detectable with Advanced LIGO/Virgo

Cardoso et al., arXiv:1701.01116

Gravitational wave echoes after ringdown





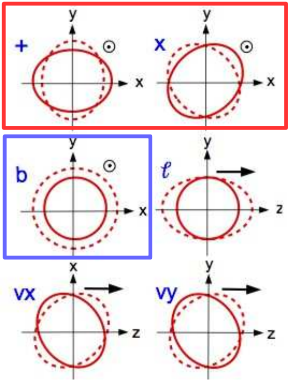
ardoso et al., Phys. Rev. D **94**, 084021 (2016)

- 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
    - $\Delta t = O(10)$ 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

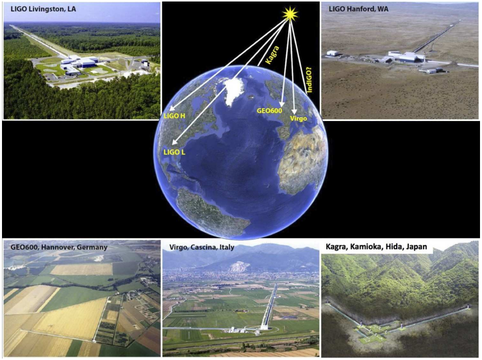


Will, Living Rev. Relativ. **17**, 4 (2014)

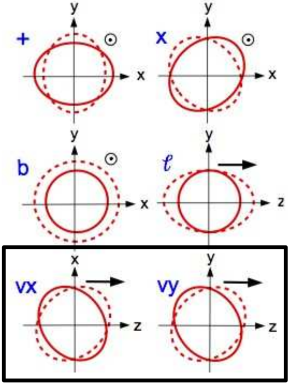
- Up to 6 different polarizations in metric theories of gravity
- For GW150914, compared polarizations for GR against pure breathing mode

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

- Need a larger network of detectors!

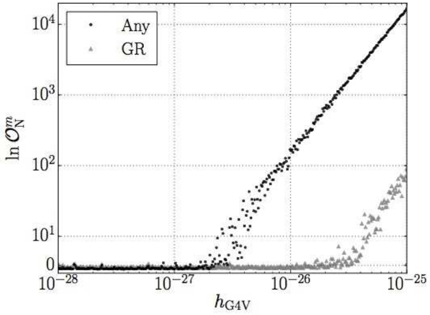


Alternative polarization states



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

- Can also probe polarization content using continuous wave signals from pulsars
  - Advanced LIGO-Virgo network
  - Simulated signals from Crab pulsar



Isi et al., arXiv:1703.07530

Summary

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