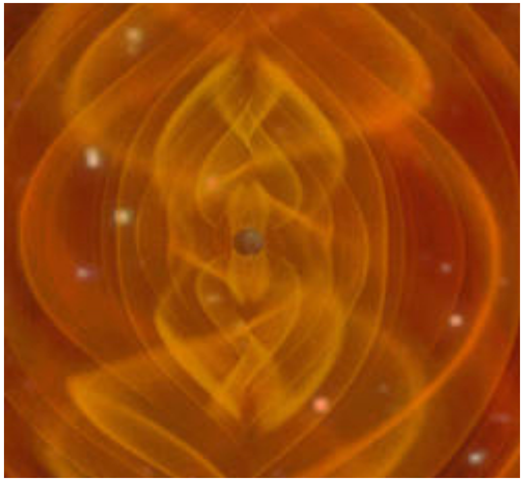

Tests of general relativity through the direct detection of gravitational waves

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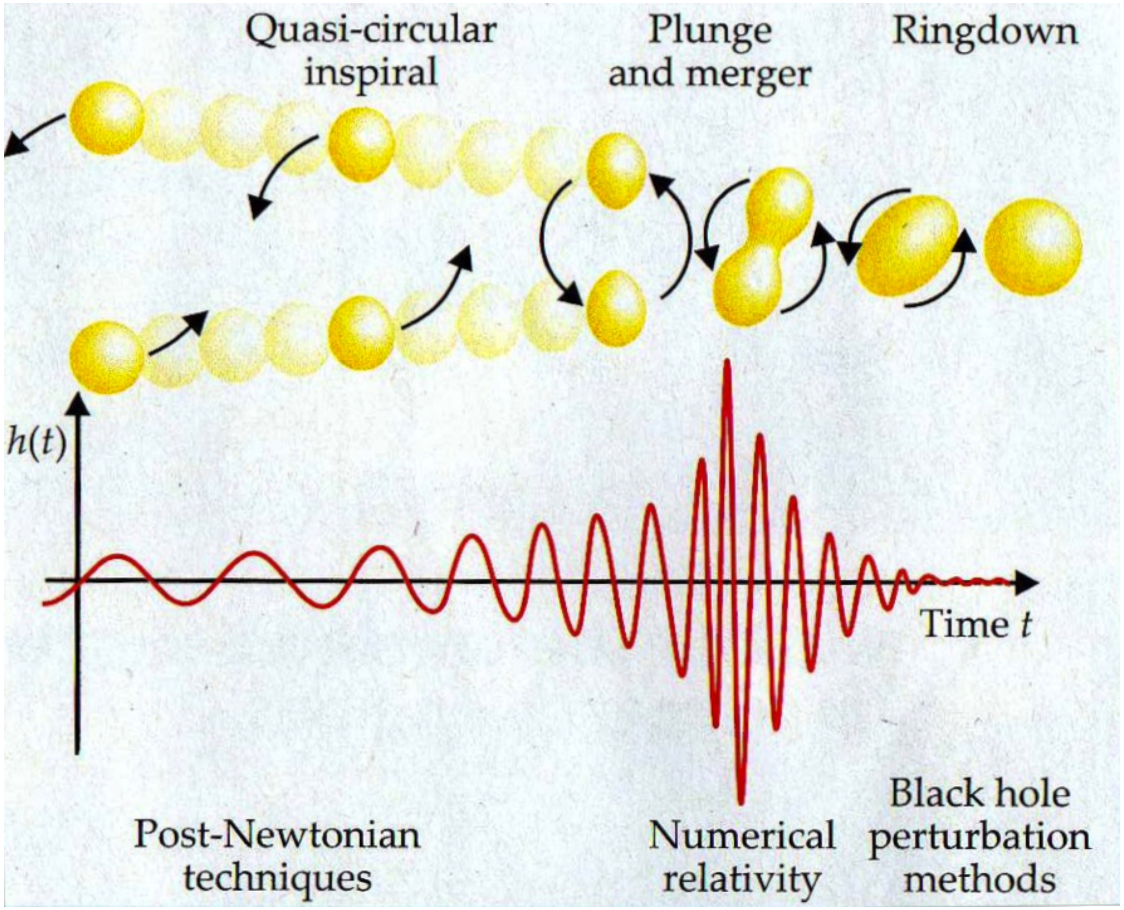
Virtual Conference of the Polish Society on Relativity 2020
24-25 September 2020

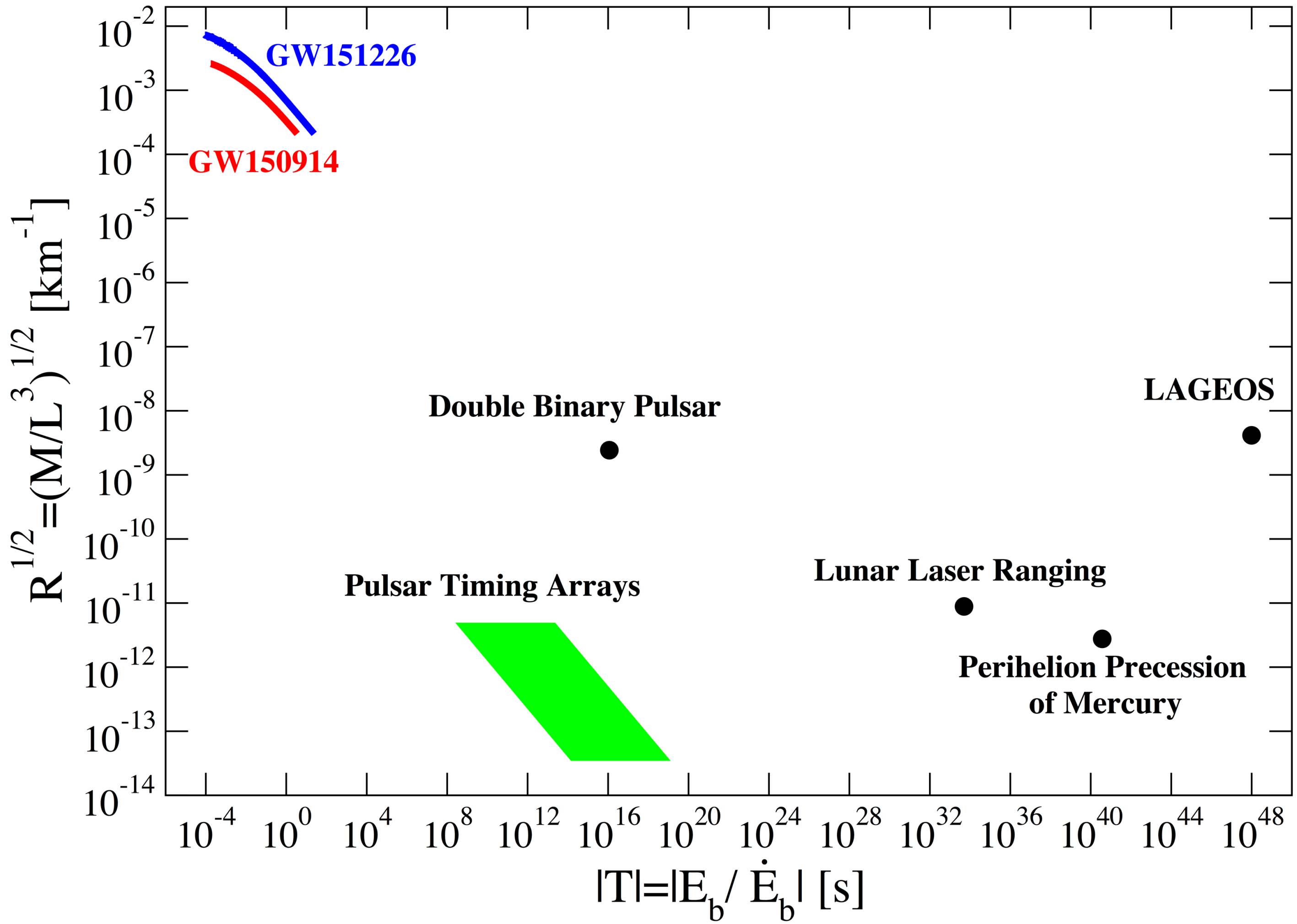
Coalescing binary neutron stars and black holes: inspiral-merger-ringdown



- 13 published binary black hole detections so far:
  GW150914, GW151012, GW151226, GW170104, GW170608, GW170729, GW170809, GW170814, GW170818, GW170823, GW190412, GW190814, GW190521
- Binary neutron star GW170817; possible binary neutron star GW190425

Access to strongly curved, dynamical spacetime

Curvature of spacetime



Characteristic timescale

Yunes et al., PRD **94**, 084002 (2016)

Fundamental physics with gravitational waves (from coalescing binaries)

1. The strong-field dynamics of spacetime

2. The propagation of gravitational waves

3. The nature of compact objects

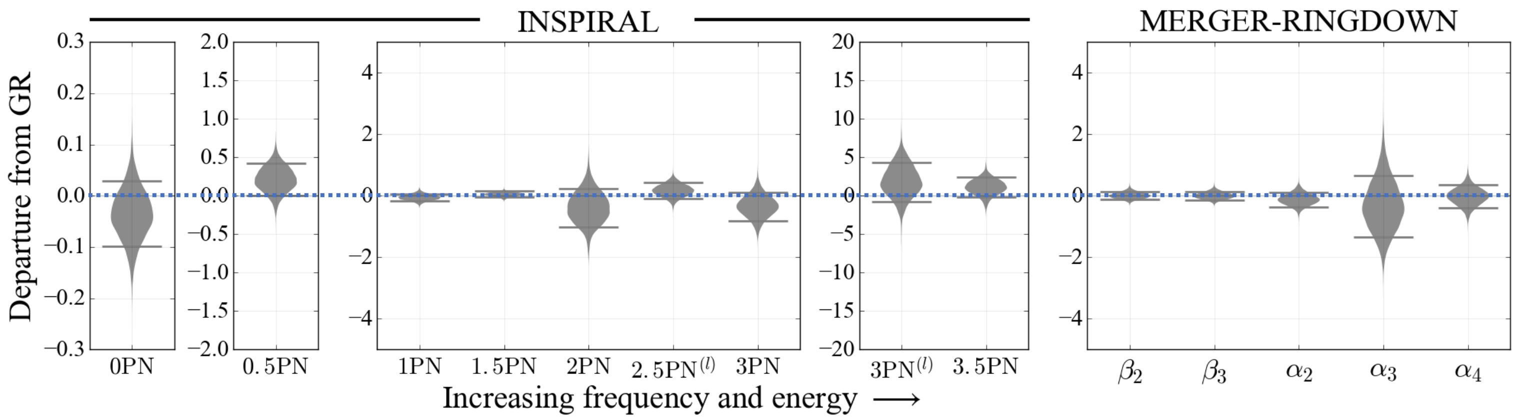
1. The strong-field dynamics of spacetime

- Inspiral-merger-ringdown process
  - Post-Newtonian description of inspiral phase

$$\Phi(v) = \left(\frac{v}{c}\right)^{-5} \left[\varphi_{0\mathrm{PN}} + \varphi_{0.5\mathrm{PN}} \left(\frac{v}{c}\right) + \varphi_{1\mathrm{PN}} \left(\frac{v}{c}\right)^2 + \ldots + \varphi_{2.5\mathrm{PN}^{(l)}} \log\left(\frac{v}{c}\right) \left(\frac{v}{c}\right)^5 + \ldots + \varphi_{3.5\mathrm{PN}} \left(\frac{v}{c}\right)^7 \right]$$

  - Merger-ringdown governed by additional parameters β_n, α_n

- Look for possible deviations in these parameters:



LIGO + Virgo, PRL **118**, 221101 (2017)

- Rich physics:
  Dynamical self-interaction of spacetime, spin-orbit and spin-spin interactions, …

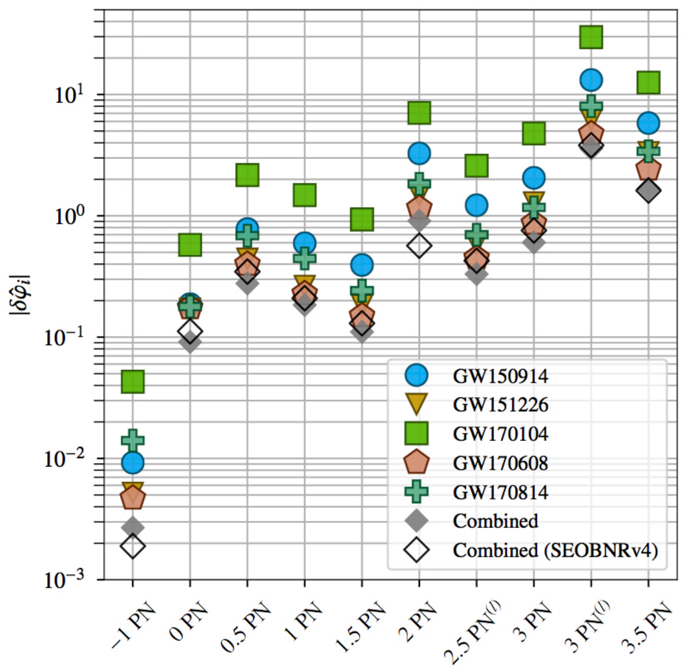
1. The strong-field dynamics of spacetime

- Inspiral-merger-ringdown process
  - Post-Newtonian description of inspiral phase

$$\Phi(v) = \left(\frac{v}{c}\right)^{-5}\left[\varphi_{0\mathrm{PN}} + \varphi_{0.5\mathrm{PN}}\left(\frac{v}{c}\right) + \varphi_{1\mathrm{PN}}\left(\frac{v}{c}\right)^2 + \ldots + \varphi_{2.5\mathrm{PN}^{(l)}} \log\left(\frac{v}{c}\right)\left(\frac{v}{c}\right)^5 + \ldots + \varphi_{3.5\mathrm{PN}}\left(\frac{v}{c}\right)^7\right]$$

  - Merger-ringdown governed by additional parameters $\beta_{n,}$ α_n

- Combine information from multiple sources:

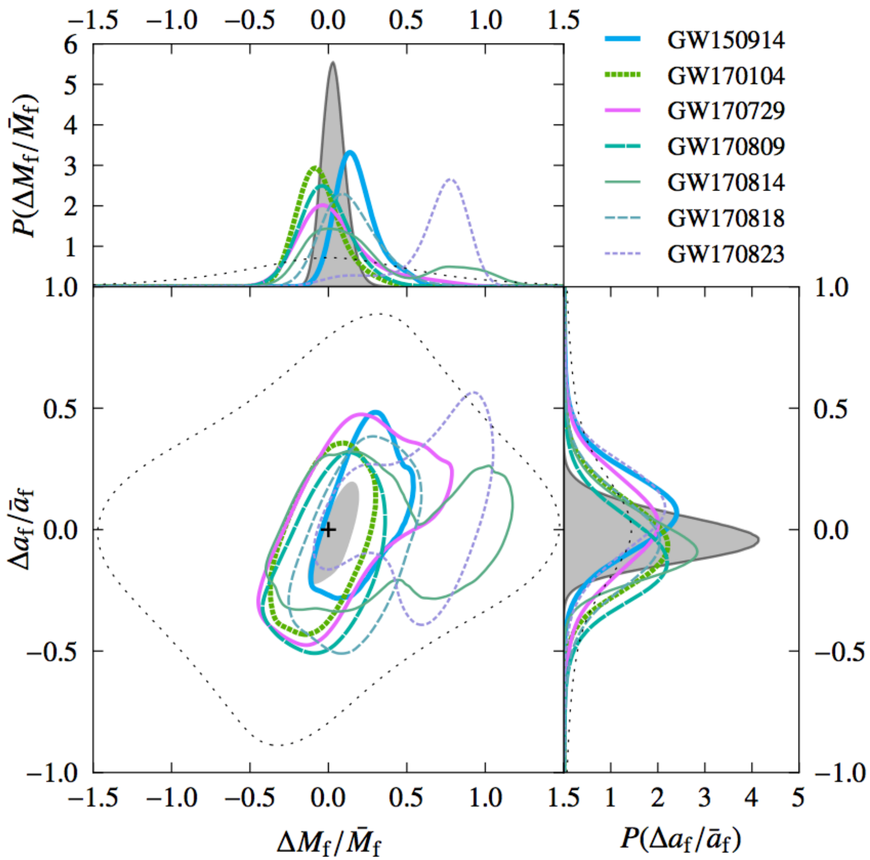


LIGO + Virgo, PRD **100**, 104036 (2019)

1. The strong-field dynamics of spacetime

- Consistency between inspiral and merger-ringdown?
  - Masses and spins during inspiral can be used to predict mass and spin of the final object
  - Compare prediction from inspiral with what follows from merger-ringdown

- Here too, combine information from multiple sources



LIGO + Virgo, PRD **100**, 104036 (2019)

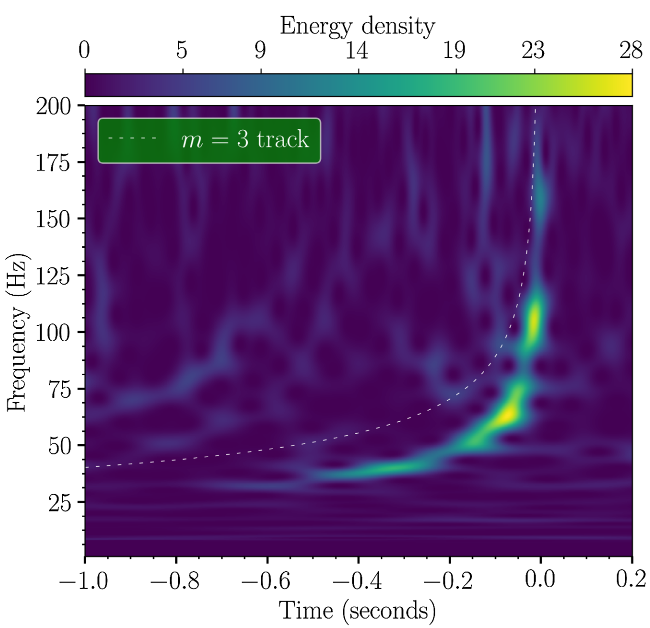
1. The strong-field dynamics of spacetime

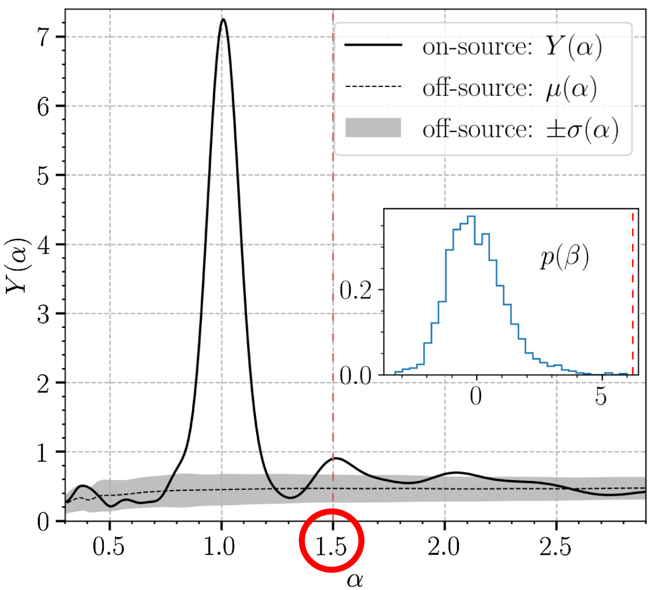
- Full structure of a gravitational wave signal:

$$h_+ - ih_\times = \sum_{\ell \geq 2} \sum_{-\ell \leq m \leq \ell} h_{\ell m}(t)\ {}_{-2}Y_{\ell m}(\theta, \phi)$$

  - Dominant harmonic: $\ell = m = 2$
  - Frequency as function of time of higher-order modes: $f_{\ell m}(t) = (|m|/2)\, f_{22}(t)$
  - **Search for sub-dominant modes with frequency $\alpha f_{22}(t)$, where α is left free**

- Sub-dominant modes more prominent when strongly unequal component masses
  - GW190412: $m_2/m_1 \sim 0.3$; GW190814: $m_2/m_1 \sim 0.1$





- In both cases strong evidence for modes at $\alpha = 1.5$ i.e. $m = 3$

LIGO + Virgo, PRD **102**, 043015 (2020)
LIGO + Virgo, ApJ Lett. **896**, L44 (2020)

2. The propagation of gravitational waves

- Dispersion of gravitational waves?
  E.g. as a result of **non-zero graviton mass**:
  - Dispersion relation:

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

  - Group velocity:

    $$v_g/c = 1 - m_g^2c^4/2E^2$$

  - Modification to gravitational wave phase:

    $$\delta\Psi = -\pi Dc/[\lambda_g^2(1+z)\,f] \qquad \lambda_g = h/(m_g c)$$

- Bound on graviton mass:

  $$\boxed{m_g \leq 4.7 \times 10^{-23}\,\mathrm{eV}/c^2}$$

LIGO + Virgo, PRD **100**, 104036 (2019)

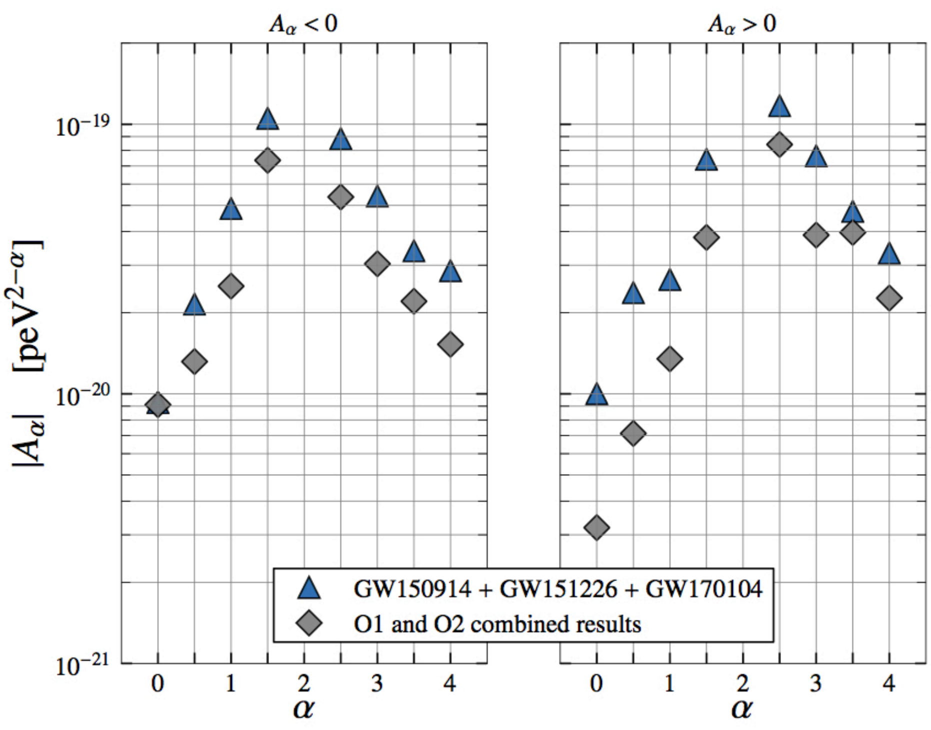
2. The propagation of gravitational waves

- More general forms of dispersion:

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

$\alpha \neq 0$ corresponds to violation of local Lorentz invariance

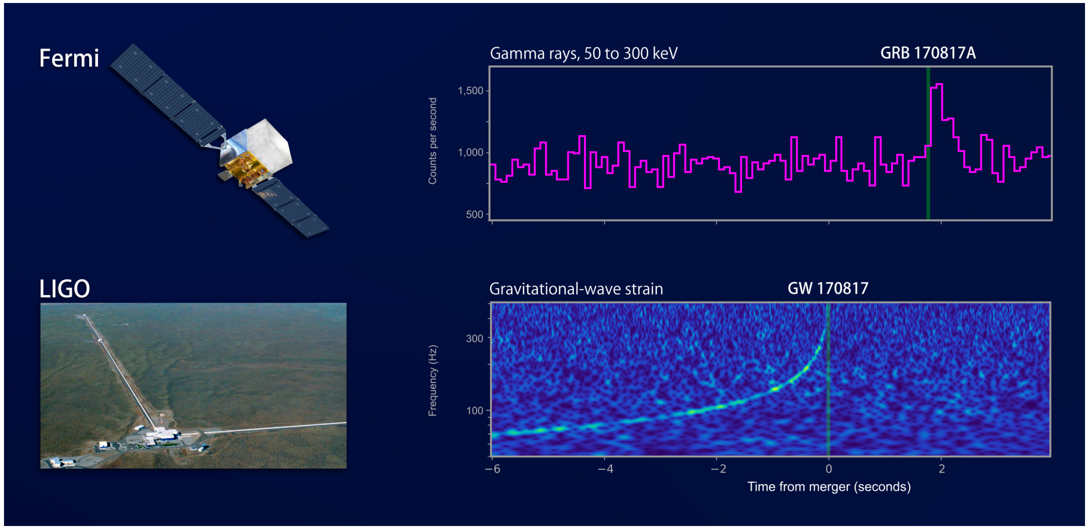
- $\alpha = 2.5$ multi-fractal spacetime
- $\alpha = 3$ doubly special relativity
- $\alpha = 4$ higher-dimensional theories



LIGO + Virgo, PRD **100**, 104036 (2019)

2. The propagation of gravitational waves

- Does the speed of gravity equal the speed of light?
- The binary neutron star coalescence GW170817 came with gamma ray burst, **1.74 seconds afterwards**



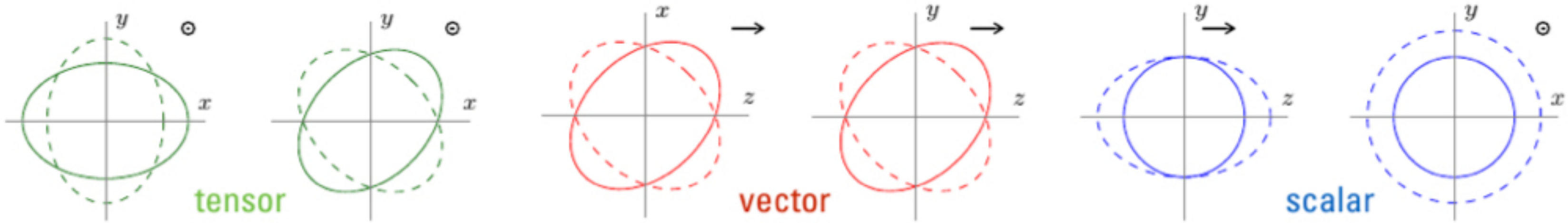
- With a conservative lower bound on the distance to the source:

$$\boxed{-3 \times 10^{-15} < \Delta v / v_{EM} < +7 \times 10^{-16}}$$

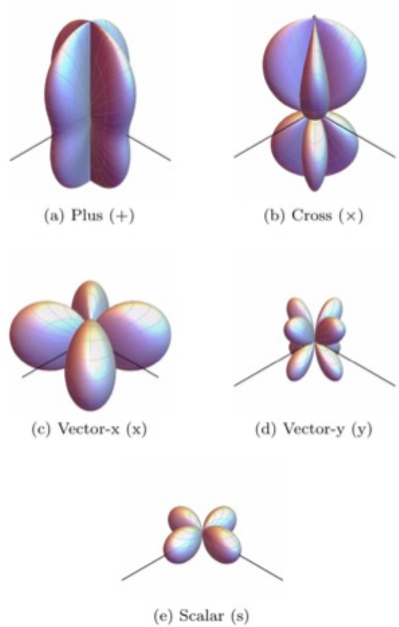
- Excluded certain alternative theories of gravity designed to explain dark matter or dark energy in a dynamical way

LIGO + Virgo + Fermi-GBM + INTEGRAL, ApJ. **848**, L13 (2017)

2. The propagation of gravitational waves



- Metric theories of gravity allow up to 6 polarizations
- Distinct antenna patterns:



$$|F_{\mathrm{t}}^{I}(\alpha,\delta)| \equiv \sqrt{F_{+}^{I}(\alpha,\delta)^2 + F_{\times}^{I}(\alpha,\delta)^2}\,,$$

$$|F_{\mathrm{v}}^{I}(\alpha,\delta)| \equiv \sqrt{F_{\mathrm{x}}^{I}(\alpha,\delta)^2 + F_{\mathrm{y}}^{I}(\alpha,\delta)^2}\,,$$

$$|F_{\mathrm{s}}^{I}(\alpha,\delta)| \equiv \sqrt{F_{\mathrm{b}}^{I}(\alpha,\delta)^2 + F_{\mathrm{l}}^{I}(\alpha,\delta)^2}$$

Isi & Weinstein, PRD **96**, 042001 (2017)

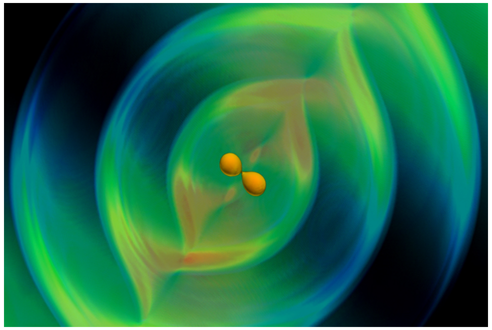
- In the case of GW170817, sky position was known from EM counterpart
  - Pure tensor / pure vector = 10^{21} / 1
  - Pure tensor / pure scalar = 10^{23} / 1

LIGO + Virgo, PRL **123**, 011102 (2019)

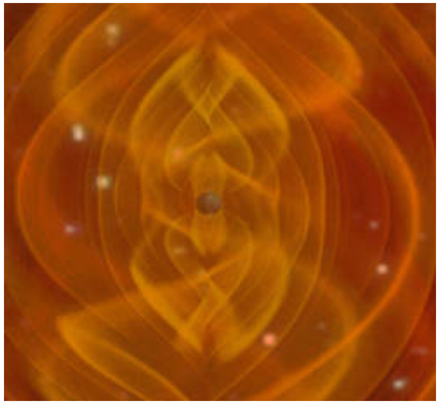
3. What is the nature of compact objects?

- Black holes, or still more exotic objects?
  - Boson stars
  - Dark matter stars
  - Gravastars
  - Wormholes
  - Firewalls, fuzzballs
  - *The unknown*

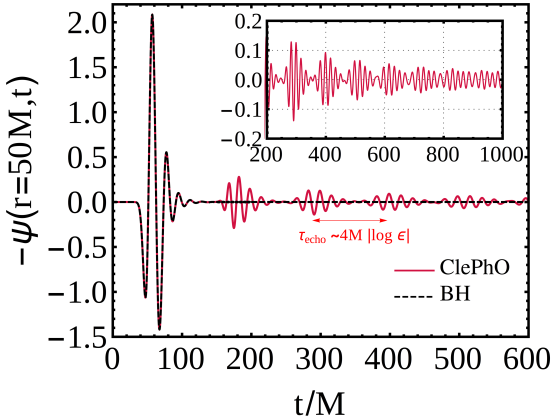
3. What is the nature of compact objects?



Anomalous effects during inspiral

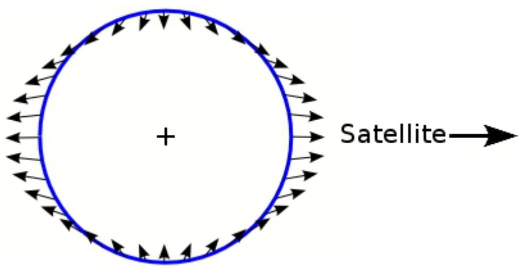


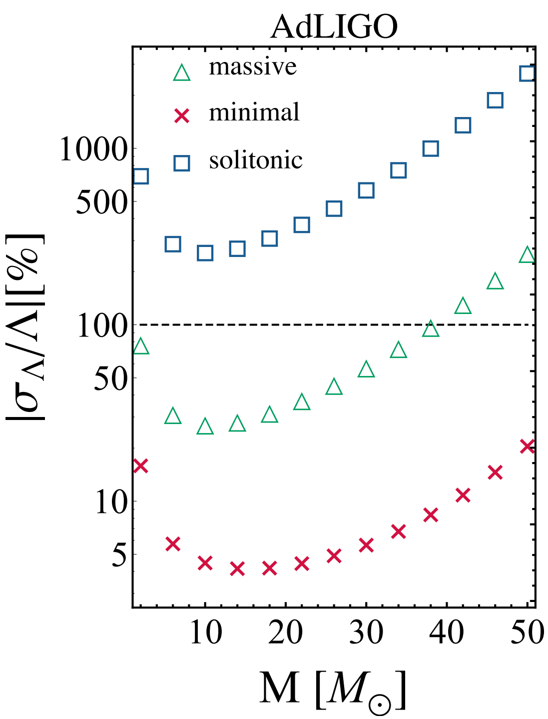
Ringdown of newly formed object



Gravitational wave echoes

Anomalous tidal effects during inspiral





- 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 also be measurable for black hole mimickers, e.g. boson stars

Cardoso et al., PRD **95**, 084014 (2017)
Johnson-McDaniel et al., arXiv:1804.0826

Ringdown of newly formed black hole

- Ringdown regime: Kerr metric + linear perturbations
  - Ringdown signal is a superposition of quasi-normal modes

$$h(t) = \sum_{nlm} \mathcal{A}_{nlm} e^{-t/\tau_{nlm}} \cos(\omega_{nlm} t + \phi_{nlm})$$

  - Characteristic frequencies ω_{nlm} and damping times τ_{nlm}

- No-hair conjecture: stationary, electrically neutral black hole completely characterized by mass M_f, spin a_f
  - Linearized Einstein equations around Kerr background enforce specific dependences:

$$\omega_{nlm} = \omega_{nlm}(M_f, a_f)$$
$$\tau_{nlm} = \tau_{nlm}(M_f, a_f)$$

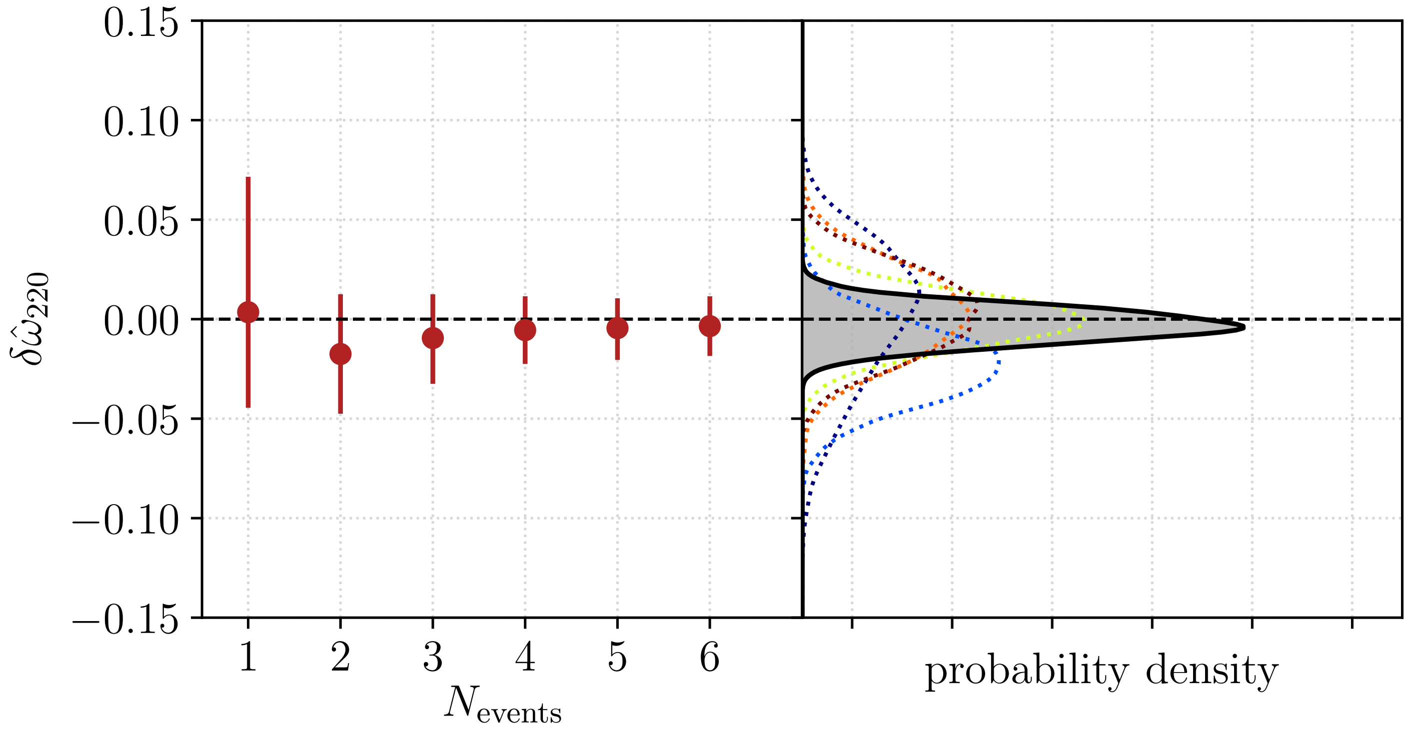
  - Look for deviations from the expressions for frequencies, damping times:

$$\omega_{lmn}(M_f, a_f) \;\rightarrow\; (1 + \delta\hat{\omega}_{lmn})\, \omega_{lmn}(M_f, a_f)$$
$$\tau_{lmn}(M_f, a_f) \;\rightarrow\; (1 + \delta\hat{\tau}_{lmn})\, \tau_{lmn}(M_f, a_f)$$

Carulllo et al., PRD **98**, 104020 (2018)
Brito et al., PRD **98**, 084038 (2018)

Ringdown of newly formed black hole

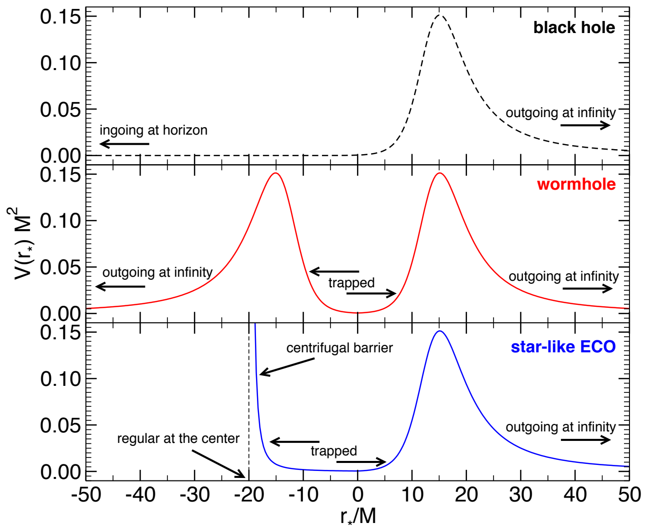
- Assume Advanced LIGO/Virgo at design sensitivity
- 6 sources similar to GW150914
  - $\delta\hat{\omega}_{220}$ **measurable to O(2%)**
  - $\delta\hat{\tau}_{220}$ **measurable to O(10%)**

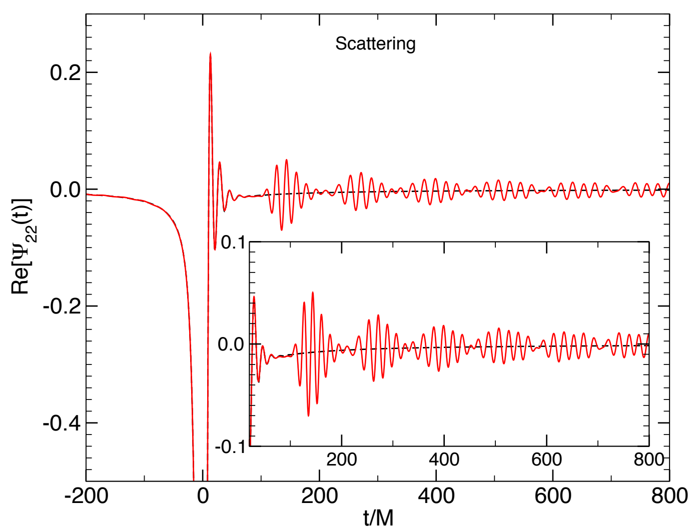


Simulation

Carulllo et al., PRD **98**, 104020 (2018)

Gravitational wave echoes





- Exotic objects with corrections near horizon: inner potential barrier for radial motion
- After formation/ringdown: continuing bursts of radiation called *echoes*
- If microscopic horizon modification $\ell \ll M$ then time between successive echoes

$$\Delta t \sim -nM \log\left(\frac{\ell}{M}\right)$$

where *n* set by nature of object:

  - *n* = 8 for wormholes
  - *n* = 6 for thin-shell gravastars
  - *n* = 4 for empty shell

- For GW150914 (M = 65 M_{sun}), taking $\ell = \ell_{Planck}$, and *n* = 4: **Δ**t = 117 ms

Cardoso et al., PRL **116**, 171101 (2016)
Cardoso et al., PRD **94**, 084031 (2016)

Tsang et al., PRD **98**, 024023 (2018)

Gravitational wave echoes

- Detection claims and counter-claims:

  - Abedi et al. 2016: tentative evidence (2.5σ) for Planck scale structure near horizon from GW150914, GW151012, GW151226

    Abedi et al., PRD **96**, 082004 (2017)

  - Abedi et al. 2018: claimed significance 4.2σ for GW170817

    Abedi et al., arXiv:1803.10454 (2018)

  - Westerweck et al. 2018
    - More extensive background calculation for the BBHs, reduced significance
    - Re-evaluation of prior boundaries and density distributions of waveform templates

    Westerweck et al., PRD **97**, 124037 (2018)

  - Other non-detection statements

    Lo et al., PRD **99**, 084052
    Nielsen et al., PRD **99**, 104012 (2019)
    Uchikata et al., PRD **100**, 062006 (2019)

  - *Most of the above relied on template waveforms*
    - Theoretical predictions still in early stages, and there may be exotic objects that have yet to be envisaged!
    - Need for morphology-independent search methods

    Conklin et al., PRD **98**, 044021 (2018)
    Tsang et al., PRD **98**, 024023 (2018)
    Tsang et al., PRD **101**, 064012 (2019)

Summary

- The first direct detection of gravitational waves has enabled unprecedented tests of general relativity:
  - First access to genuinely strong-field dynamics of vacuum spacetime
  - Propagation of gravitational waves over large distances
  - Polarizations of gravitational waves

- How sure can we be that the massive compact objects we see are the standard black holes from GR?
  - Look for anomalous tidal effects during *inspiral*
  - Probing *ringdown* will enable indirect tests of no-hair conjecture
  - Searching for *echoes*

- Ultra-high precision tests with next-generation observatories: LISA, Einstein Telescope, Cosmic Explorer
  - Higher accuracy
  - Larger number of sources
  - Propagation of gravitational waves over cosmological distances