Tests of general relativity with gravitational waves

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Binary black hole mergers as laboratories to test GR

- Empirical access to genuinely strong-field dynamics of gravity
- Pure spacetime process
- Rich phenomenology

Yunes et al., arXiv:1603.08955
The events as seen in the detectors

- Test GR for different aspects of the coalescence process
  - GW150914: short inspiral; merger and ringdown visible
  - GW151226: mostly inspiral visible

1. Residual data after subtracting best-fitting waveform


- Subtract from data the best-fitting waveform model (GR prediction)
- Residual data statistically consistent with detector noise near GW150914
(2) 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*
(2) 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*
(3) Did the final object ring down as predicted?

- Evidence for a least-damped “quasi-normal” mode?
  - Fit damped sinusoid starting at different times after merger
  - Frequency, damping time consistent with expectation

Testing the black hole no-hair theorem?

- If multiple quasi-normal modes could be observed: test of no-hair theorem
  - Damping times $\tau_{nlm}$ and frequencies $f_{nlm}$ only depend on $M_f$ and $a_f$
  - Hence only two of them are independent $\rightarrow$ consistency test

- For multiple quasi-normal modes to be visible, need system with
  - Asymmetric component masses
  - More misalignment of orbital angular momentum with line of sight
(4) Constraining the graviton Compton wavelength

\[ E^2 = p^2 c^2 + m_g^2 c^4 \]
\[ \delta \Phi(f) = -\frac{\pi D c}{\lambda_g^2 (1+z)} f^{-1} \]
\[ \lambda_g = \frac{\hbar}{m_g c} \]


\[ m_g < 1.2 \times 10^{-22} \text{ eV/c}^2 \]

(5) 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:
  \[ \log B^{\text{GR}}_{\text{scalar}} = -0.2 \pm 0.5 \]
- Need larger network of detectors with different orientations
  - Advanced LIGO
  - Advanced Virgo
  - KAGRA
  - LIGO-India

(6) Parameterized tests of the coalescence process

- Allow for fractional changes in parameters with respect to GR values
  \[ p_i \rightarrow (1 + \delta \hat{p}_i) p_i \]

  - Inspiral: \( \{ \delta \hat{\varphi}_i \} \)
  - Intermediate: \( \{ \delta \hat{\beta}_i \} \)
  - Merger-ringdown: \( \{ \delta \hat{\alpha}_i \} \)
(6) Parameterized tests of the coalescence process

- **GW150914:**
  First-ever empirical bounds on high-order post-Newtonian inspiral parameters
(6) Parameterized tests of the coalescence process

GW150914

inspiral

intermediate

merger-ringdown

(6) Parameterized tests of the coalescence process
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Combined bounds on post-Newtonian inspiral parameters

Combined bounds on post-Newtonian inspiral parameters

![Graph showing combined bounds on post-Newtonian inspiral parameters. The graph plots the PN order against the mass ratio (\( \delta \)). Points are color-coded for different detections (GW150914, GW151226, GW151226+GW150914) and labeled by PN order (0PN, 0.5PN, 1PN, 1.5PN, 2PN, 2.5PN, 3PN, 3PN(0), 3.5PN). The green dot labeled "massive graviton" indicates a point of interest.](image)
Combined bounds on post-Newtonian inspiral parameters

- Lowest-order spin-orbit interaction
- Dynamical self-interaction of spacetime

- GNW150914
- GW151226
- GW151226+GW150914

PN order:
- 0PN
- 0.5PN
- 1PN
- 2PN
- 2.5PN
- 3PN

Labeled areas:
- 1.5PN

- Lowest-order spin-orbit interaction
- Dynamical self-interaction of spacetime
Combined bounds on post-Newtonian inspiral parameters

Spin-spin interaction
Outlook

- Genuinely strong-field dynamics of spacetime probed for the first time
  - Consistency of masses and spins between inspiral and post-inspiral
  - End of the signal consistent with least-damped quasi-normal mode
  - New dynamical bound on the graviton mass
  - First constraints on high-order post-Newtonian coefficients

- Future observations:
  - Seeing more than one quasi-normal mode would allow for test of no-hair theorem
  - Test of second law of black hole mechanics
  - Constraints on non-GR polarization states with network of detectors
  - Combining information from all future detections will set increasingly sharper bounds on PN coefficients

- For now: all tests performed show no disagreement with GR
Backup slides
What about specific alternative theories of gravity?

- With exception of $\lambda_g$ 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
  - 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 $\sim 3$ 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