Testing General Relativity with GW150914

Based on the LIGO-VIRGO papers

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GW150914 with minimal assumptions

- September 14, 2015, 09:50:45 UT
- Transient signal
- $SNR \sim 20$

GW150914 assuming General Relativity

- Emitted by a black hole binary system
- Best fit parameterized template consistent with NR results
- Inspiral, merger, ringdown
- Pre-merger masses: $36^{+5}_{-4} M_{\odot}$, $29^{+4}_{-4} M_{\odot}$

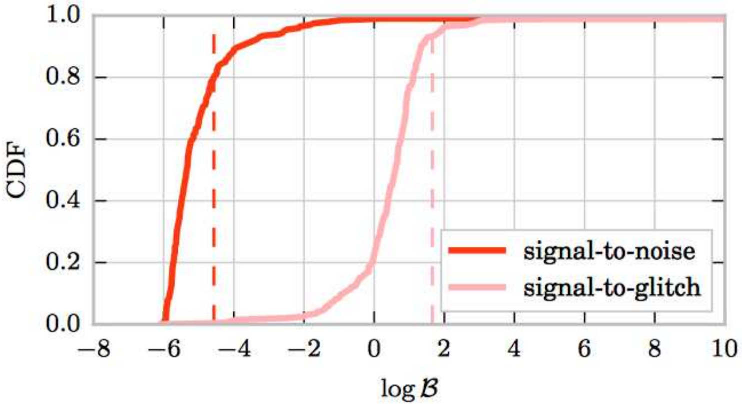
Previous tests of general relativity

- Time delay of light– radar ranging of planets
- Perihelion shift of Mercury
- Constancy of G:
  - Lunar laser ranging
  - Helioseismology
  - Big bang nucleosynthesis
- Binary pulsar– gravitational waves

Mining the residuals for a coherent signal

- Maximum *a postiori* (MAP) black-hole binary waveform
- Subtract from data to obtain residuals
- Second coherent Bayseian search on residuals
- Signal versus noise comparison
- Signal versus glitch comparison

Cumulative distribution of Bayes factors



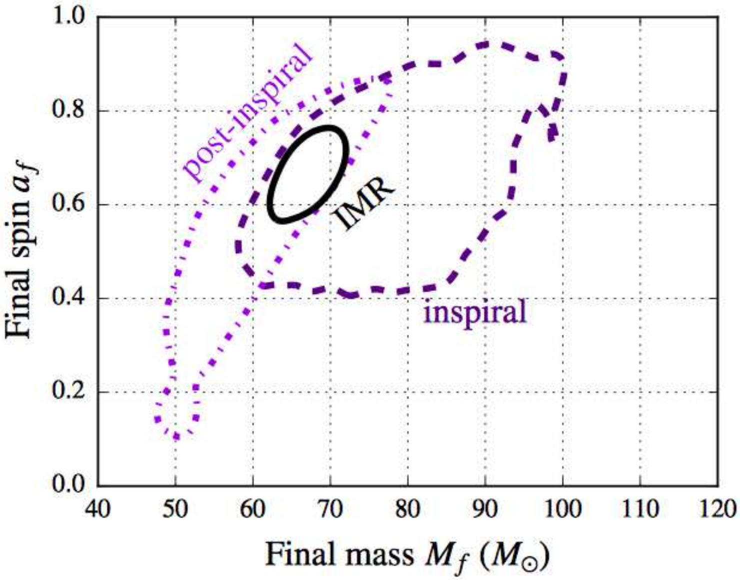
Fitting factor and level of verification

- $SNR_{res} \leq 7.3$ from residuals
- $SNR_{det} = 25.3^{+0.1}_{-0.2}$ is the network SNR
- $SNR^2_{res} = (1 - FF^2)FF^{-2}SNR^2_{det}$
- Fitting factor $FF \geq 0.96$
- **GR prediction verified to better than 4%!**

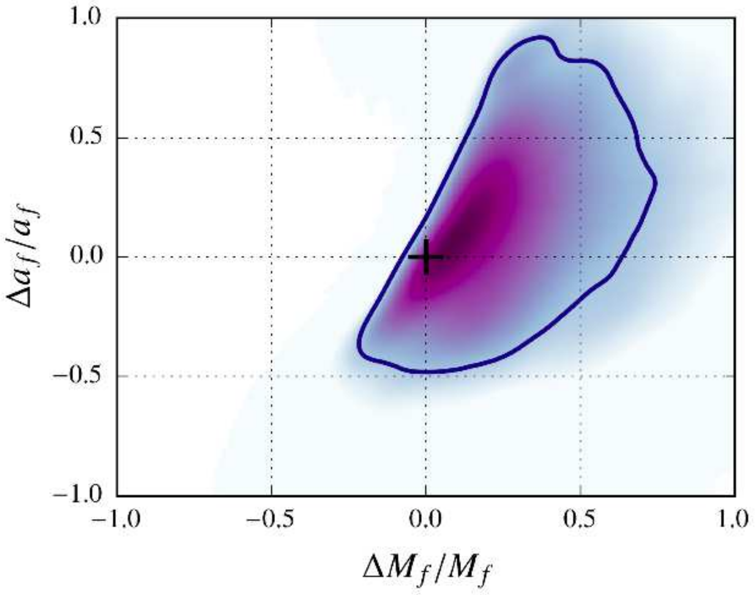
Consistency of inspiral with merger and ringdown

- Obtain (Bayesian) posterior distributions on final mass and spin two ways
- First, from search of pre-merger GW using parameterized form of inspiral.
- Then connect the initial masses to the final masses using formulas from Numerical Relativity (NR).
- Second, search of post-inspiral GW using formula from NR.

Consistency of inspiral with merger and ringdown



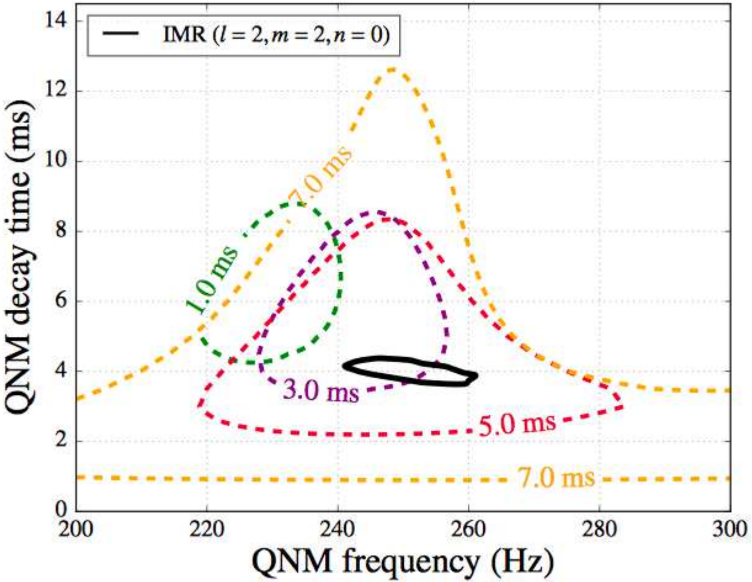
Consistency of inspiral with merger and ringdown



Quasinormal modes in the ringdown phase

- The fundamental QNM is an exponentially damped sinusoid.
- Use Bayesian search with 2D isotropic Gaussian prior on amplitude and phase in circular coordinates.
- Range of start times in intervals of 2 ns
- **Best correspondence to MAP waveform has a Bayes factor of** $\log_{10} B \sim 17$ **and an** $SNR \sim 7$**.**

Consistency of least damped quasi-normal mode during ringdown



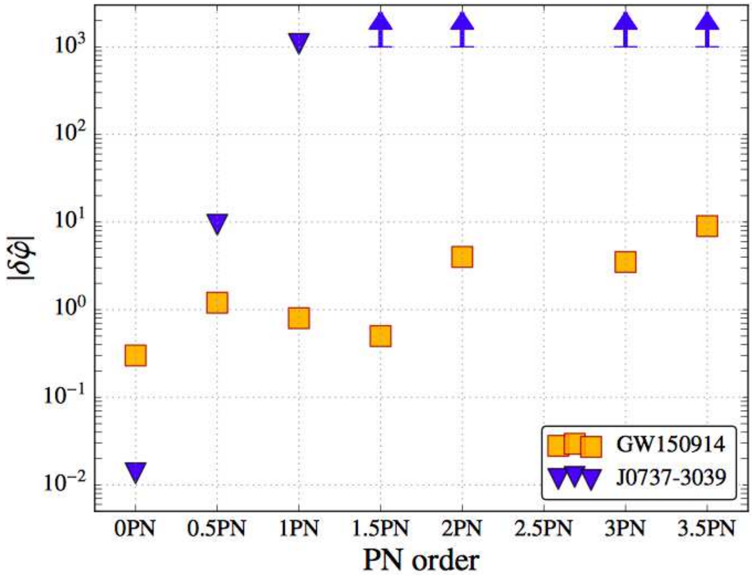
Constraining parameterized deviations from GR waveform

- Post-Newtonian expansion parameterizes inspiral
- Three additional parameters for merger and ringdown based on NR simulations.
- Constrain deviations from GR.
- Previous bounds have been set using highly relativistic pulsar binaries.

Post-Newtonian approximation

- Post-Newtonian: perturbative expansion of gravity in $\frac{v}{c}$ at integer and half integer orders, with some logarithmic terms.
- For first phase of inspiral, used PN coefficients to order 3.5.
- For later phase of inspiral, used PN coefficients to 4.5.
- PN coefficents can also be computed for other theories of gravity.

LIGO's constraints on Post-Newtonian parameters



Graviton compton wavelength

- In GR, gravitons are massless ($v = c$)
- $E = p^2c^2 + m_g^2c^4$
- $\lambda_g = \frac{h}{m_g c}$
- Newtonian potential altered by Yukawa correction: $\phi(r) = (GM/r)[1 - \exp(-r/\lambda_g)]$

Graviton compton wavelength

- Bayesian search using first order PN terms with dispersion
- Standard ΛCDM cosmology
- Uniform prior on graviton mass between 10^{-26} and 10^{-16}.

Graviton compton wavelength

Type	Source	Model-dependent?	Bound (km)
Dynamic	Binary pulsar	No	1.6×10^{10}
Static	Solar system	No	2.8×10^{12}
Dynamic	GW150914	No	1.0×10^{13}
Static	Globular clusters	Yes	6.2×10^{19}
Static	Weak lensing	Yes	1.8×10^{22}

No constraint on non-GR polarization states

- GR predicts two tensor polarization states, plus and cross
- In more general theories, could have scalar or vector states
- Livingston and Hanford are well-aligned, so not much can be said.
- To illustrate: use Bayesian search to reconstruct signal in scalar mode and in GR mode.
- Bayes factor between two hypotheses statistically insignificant.
- **Position on sky changes– need for VIRGO or EM counterparts to test these theories.**

Summary

- Residuals are consistent with GR to better than 4%.
- Inspiral and merger/ringdown waveforms recover consistent final masses and spins, and are also consistent with the full waveform parameters.
- Upper limits were set on the Post-Newtonian parameters that surpass the binary pulsar upper limits at all but 1PN order.
- GW150914 sets the strongest dynamic and strongest model independent bounds for the compton wavelength of the graviton.
- There are no constraints on the polarization of the gravitational wave– another interferometer or EM counterparts are needed to test these theories. ‘