# The direct detection of gravitational waves:
# The first discovery, and what the future might bring

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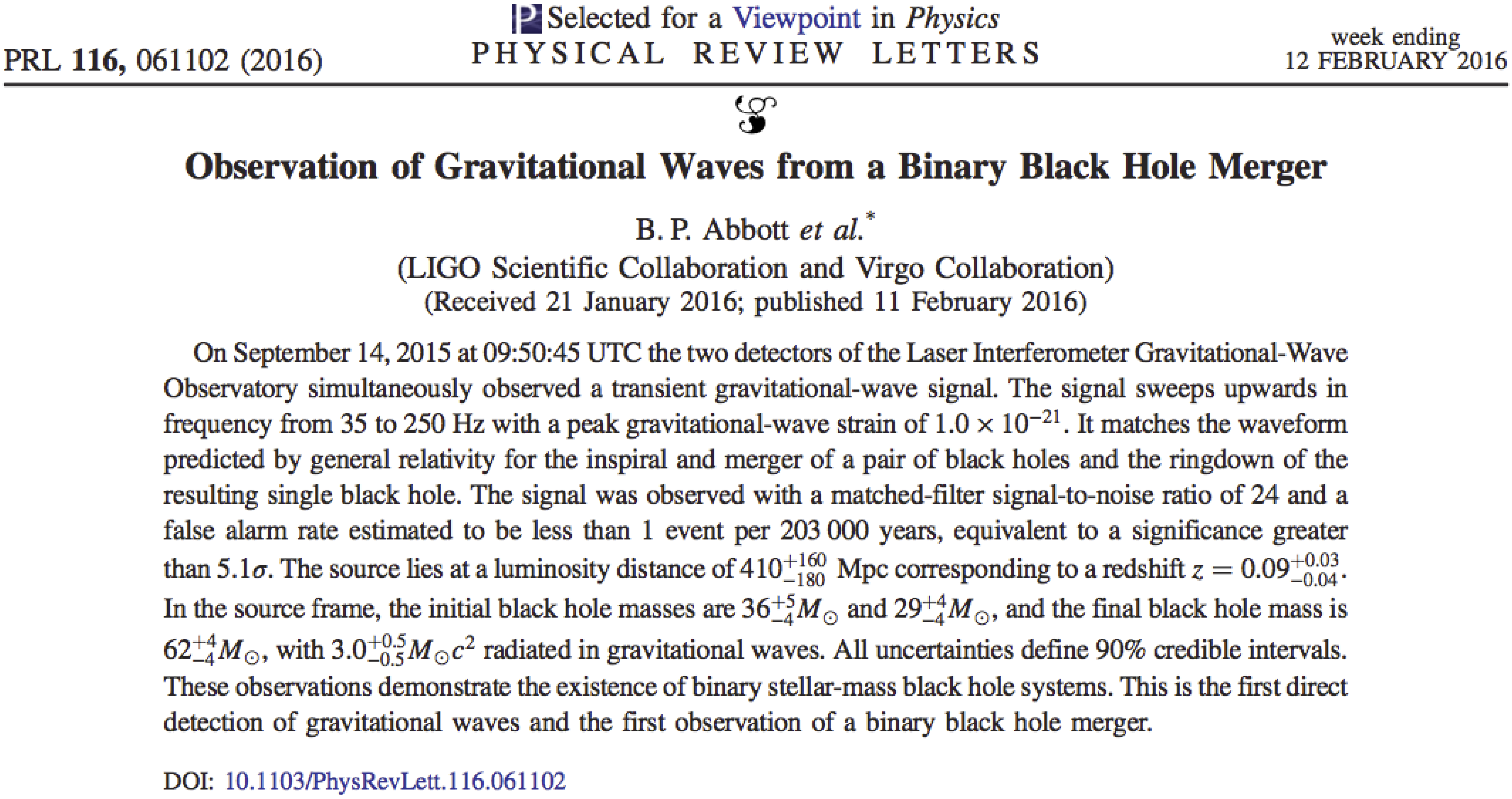
# GW150914



Selected for a Viewpoint in *Physics*

PRL **116,** 061102 (2016) PHYSICAL REVIEW LETTERS week ending 12 FEBRUARY 2016

## Observation of Gravitational Waves from a Binary Black Hole Merger

B. P. Abbott *et al.*[*]

(LIGO Scientific Collaboration and Virgo Collaboration)

(Received 21 January 2016; published 11 February 2016)

On September 14, 2015 at 09:50:45 UTC the two detectors of the Laser Interferometer Gravitational-Wave Observatory simultaneously observed a transient gravitational-wave signal. The signal sweeps upwards in frequency from 35 to 250 Hz with a peak gravitational-wave strain of $1.0 \times 10^{-21}$. It matches the waveform predicted by general relativity for the inspiral and merger of a pair of black holes and the ringdown of the resulting single black hole. The signal was observed with a matched-filter signal-to-noise ratio of 24 and a false alarm rate estimated to be less than 1 event per 203 000 years, equivalent to a significance greater than $5.1\sigma$. The source lies at a luminosity distance of $410^{+160}_{-180}$ Mpc corresponding to a redshift $z = 0.09^{+0.03}_{-0.04}$. In the source frame, the initial black hole masses are $36^{+5}_{-4} M_\odot$ and $29^{+4}_{-4} M_\odot$, and the final black hole mass is $62^{+4}_{-4} M_\odot$, with $3.0^{+0.5}_{-0.5} M_\odot c^2$ radiated in gravitational waves. All uncertainties define 90% credible intervals. These observations demonstrate the existence of binary stellar-mass black hole systems. This is the first direct detection of gravitational waves and the first observation of a binary black hole merger.

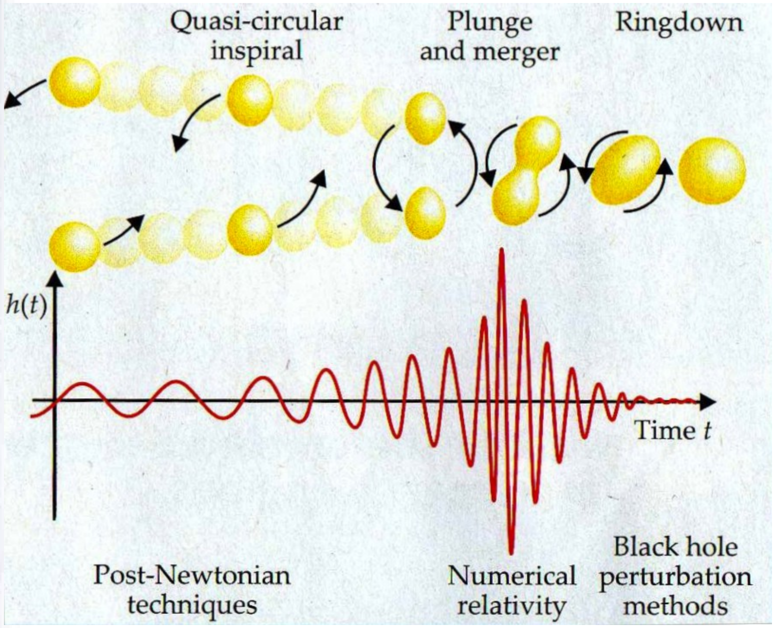
DOI: 10.1103/PhysRevLett.116.061102

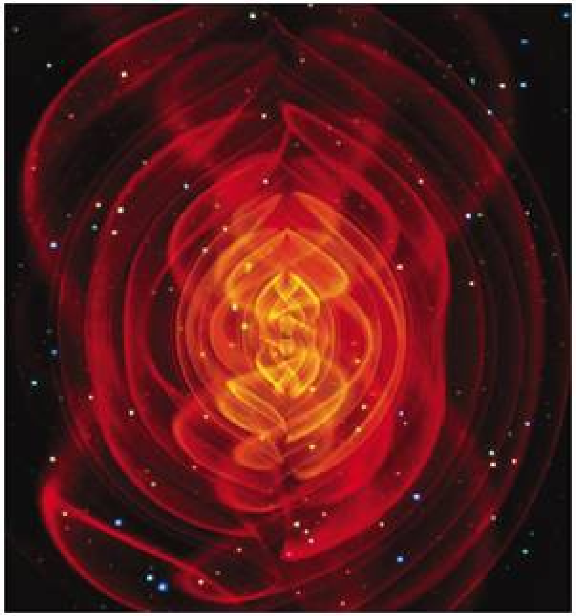
http://journals.aps.org/prl/abstract/10.1103/PhysRevLett.116.061102

# Companion papers

- GW150914: The Advanced LIGO detectors in the era of first discoveries
  http://arxiv.org/abs/1602.03838
- GW150914: First results from the search for binary black hole coalescences with Advanced LIGO
  http://arxiv.org/abs/1602.03839
- Properties of the binary black hole merger GW150914
  http://arxiv.org/abs/1602.03840
- Tests of general relativity with GW150914
  http://arxiv.org/abs/1602.03841
- The rate of binary black hole mergers inferred from Advanced LIGO observations surrounding GW150914
  http://arxiv.org/abs/1602.03842
- Observing gravitational-wave transient GW150914 with minimal assumptions
  http://arxiv.org/abs/1602.03843
- Characterization of transient noise in Advanced LIGO relevant to gravitational wave signal GW150914
  http://arxiv.org/abs/1602.03844
- Calibration of the Advanced LIGO detectors for the discovery of the binary-black hole merger GW150914
  http://arxiv.org/abs/1602.03845
- Astrophysical implications of the binary black-hole merger GW150914
  http://arxiv.org/abs/1602.03846
- GW150914: Implications for the stochastic gravitational wave background from binary black holes
  http://arxiv.org/abs/1602.03847
- High-energy neutrino follow-up search of gravitational wave event GW150914 with ANTARES and IceCube
  http://arxiv.org/abs/1602.05411
- Localization and broadband follow-up of the gravitational-wave transient GW150914
  http://arxiv.org/abs/1602.08492

# Coalescence of binary black holes





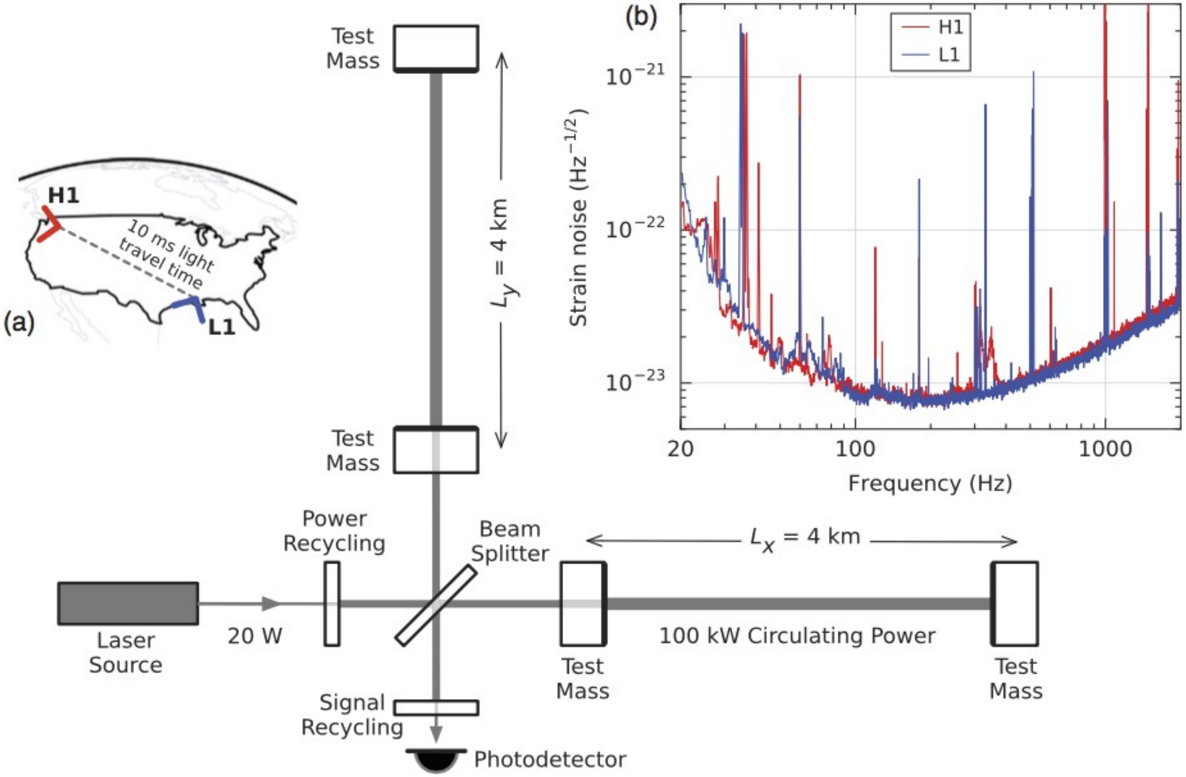
☐ Inspiral, merger, ringdown:

- Inspiral understood perturbatively
  - Post-Newtonian approximation
  - Effective One-Body
- Merger:
  Large-scale numerical simulations
- Ringdown:
  Black hole perturbation theory

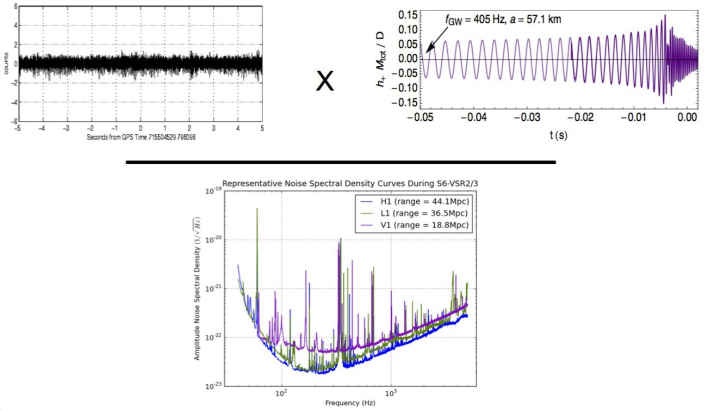
☐ Waveform approximants

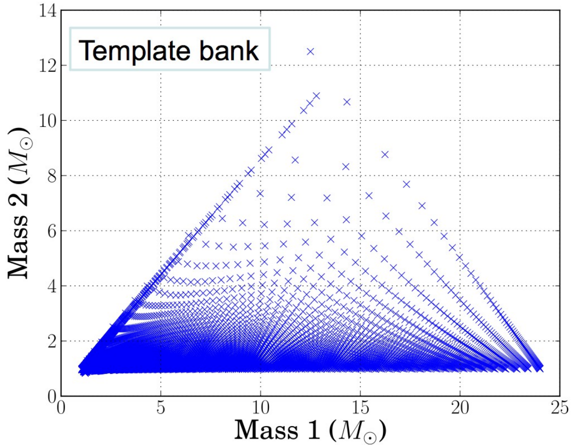
- Effective One-Body + ringdown
  - Regime around merger “calibrated” against numerical waveforms
- Phenomenological waveforms:
  - Post-Newtonian inspiral
  - Phenomenological merger, rindown

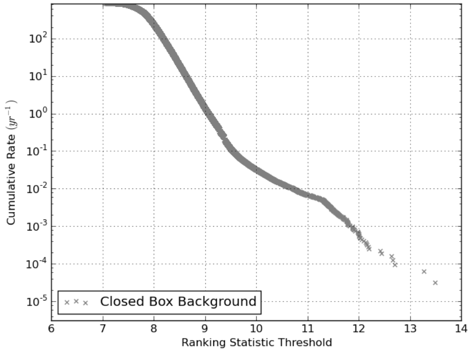
# The detectors



# Searching for a signal







☐ Search by “matched filtering”

- Integrate signal against data for fixed choice of masses and spins
- Integrand weighted by detector sensitivity as function of frequency

→ “Signal-to-noise ratio”

☐ Repeat for large number of parameter choices

- “Template bank”
- Density of templates determined by how different waveforms are when parameters varied

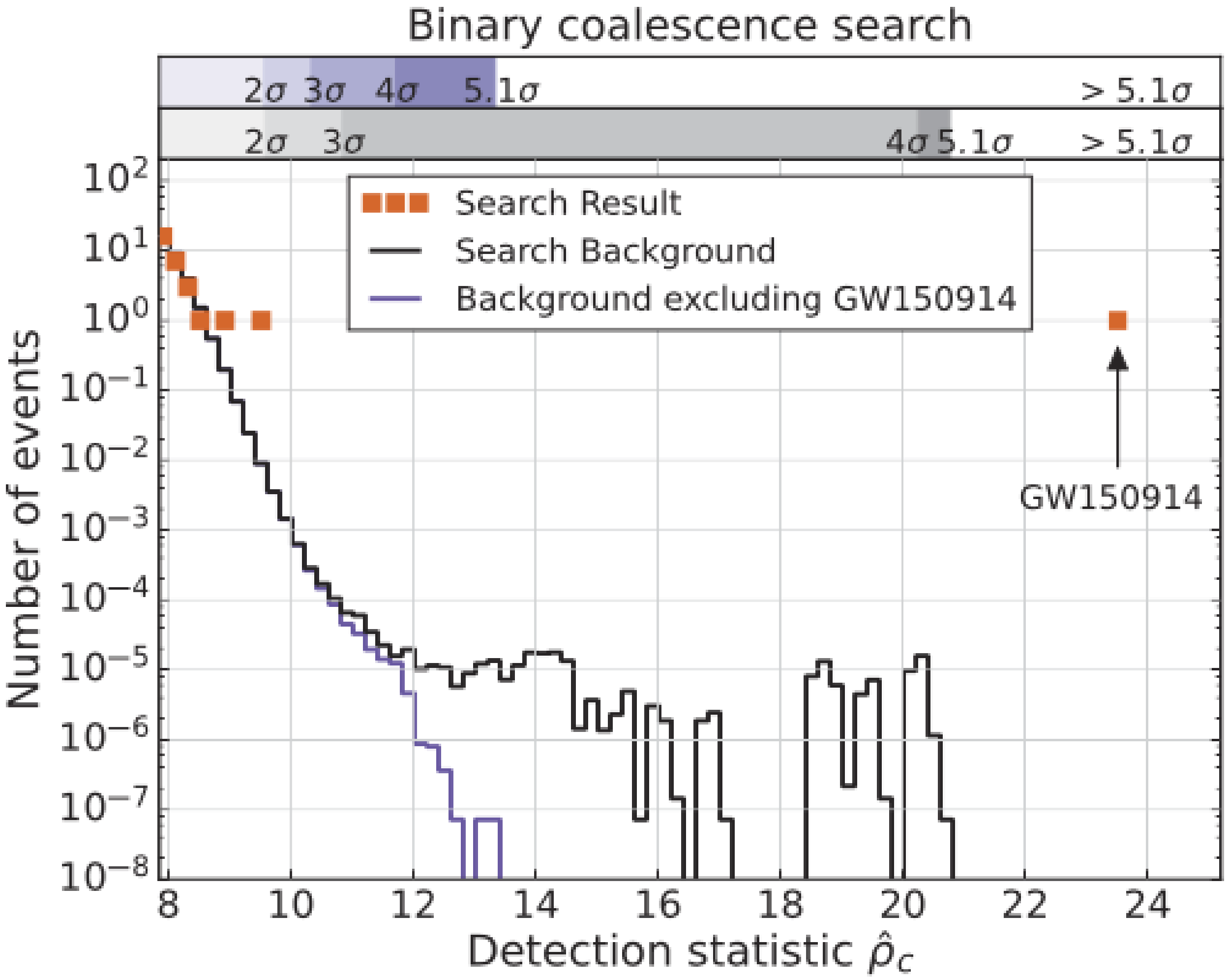
☐ If high signal-to-noise ratio obtained:

- Waveform shape consistent with signal?
- Coincident between detectors?
- Consistent parameters between detectors?

☐ Time-slide data streams w.r.t. each other

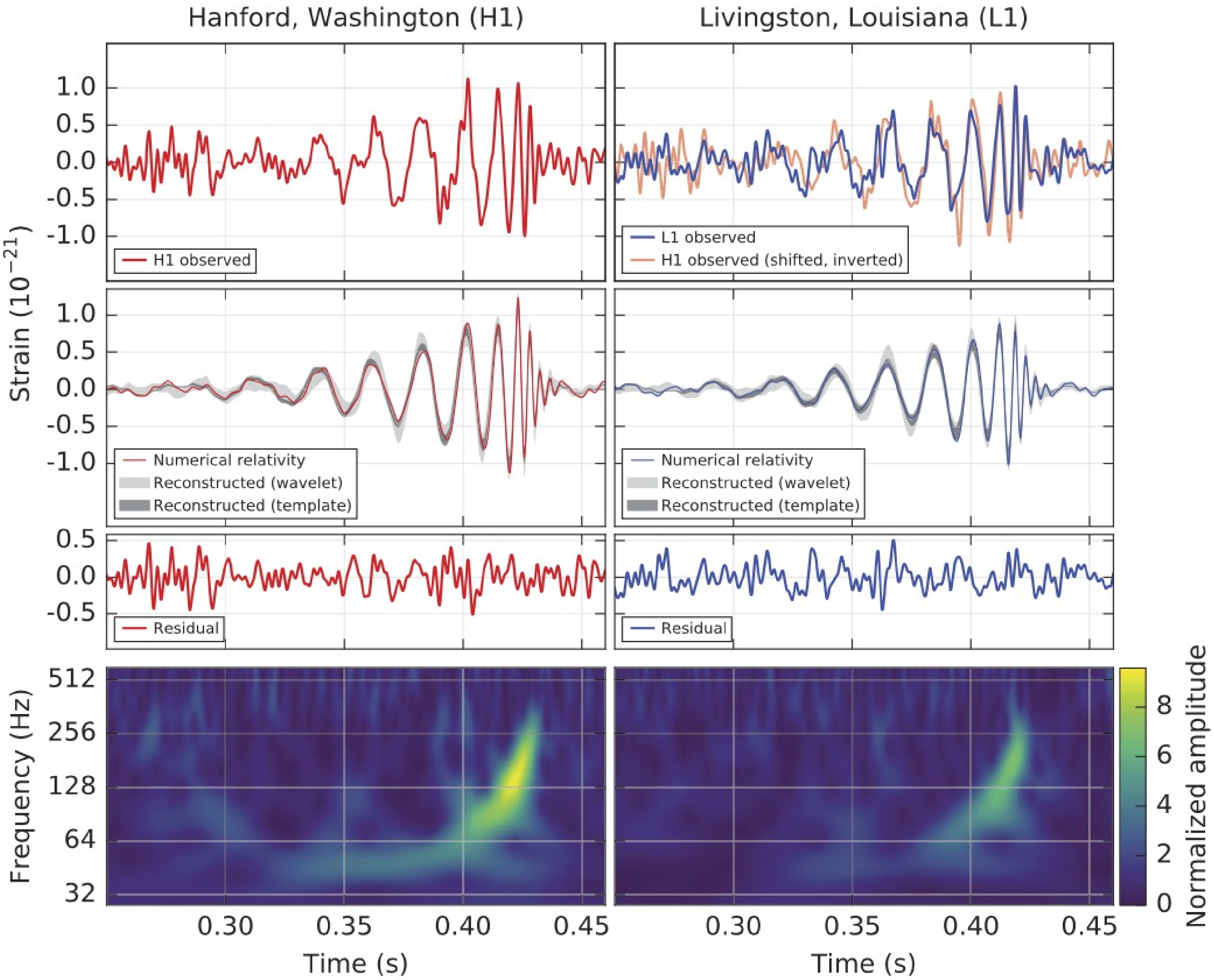
- Obtain distribution of false positives

# The detection



- ☐ False alarm rate < 1 in 203000 years
- ☐ **Significance > 5.1σ**

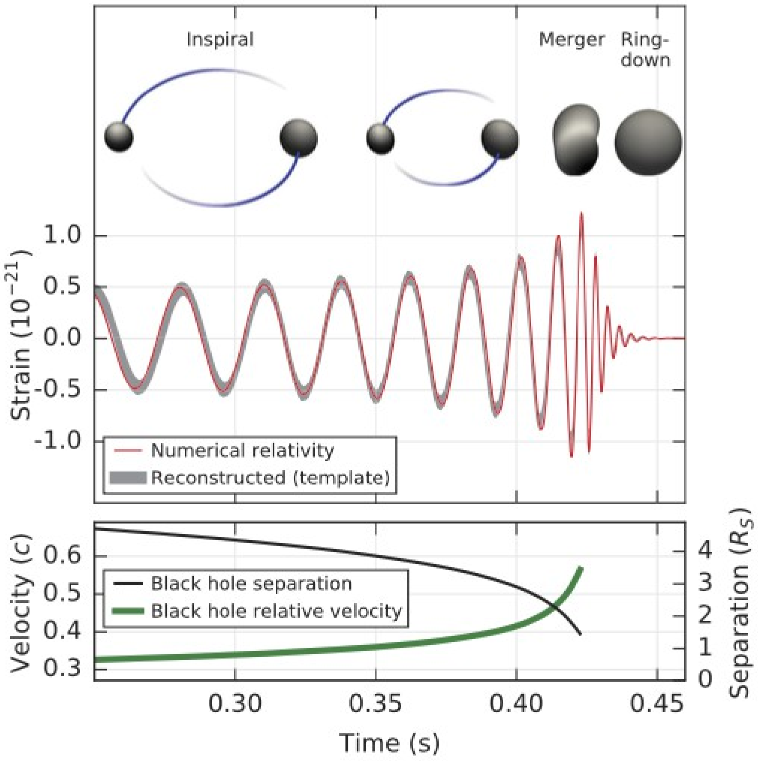
# The detection

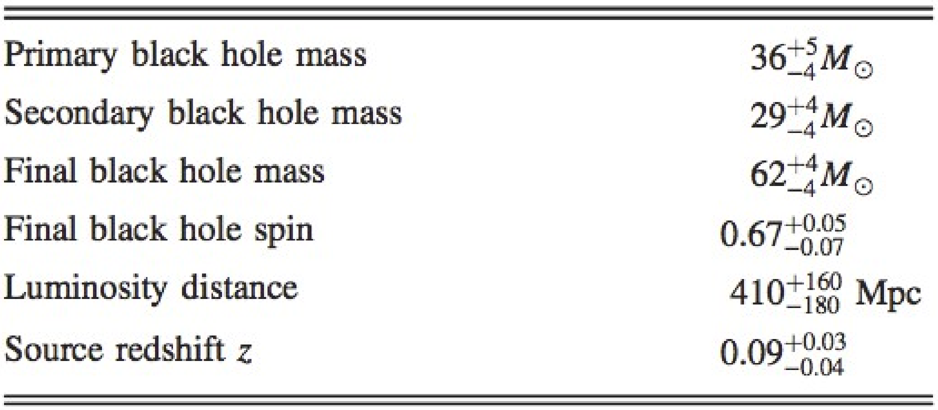


# The detection

☐ Signal consistent with binary black hole merger

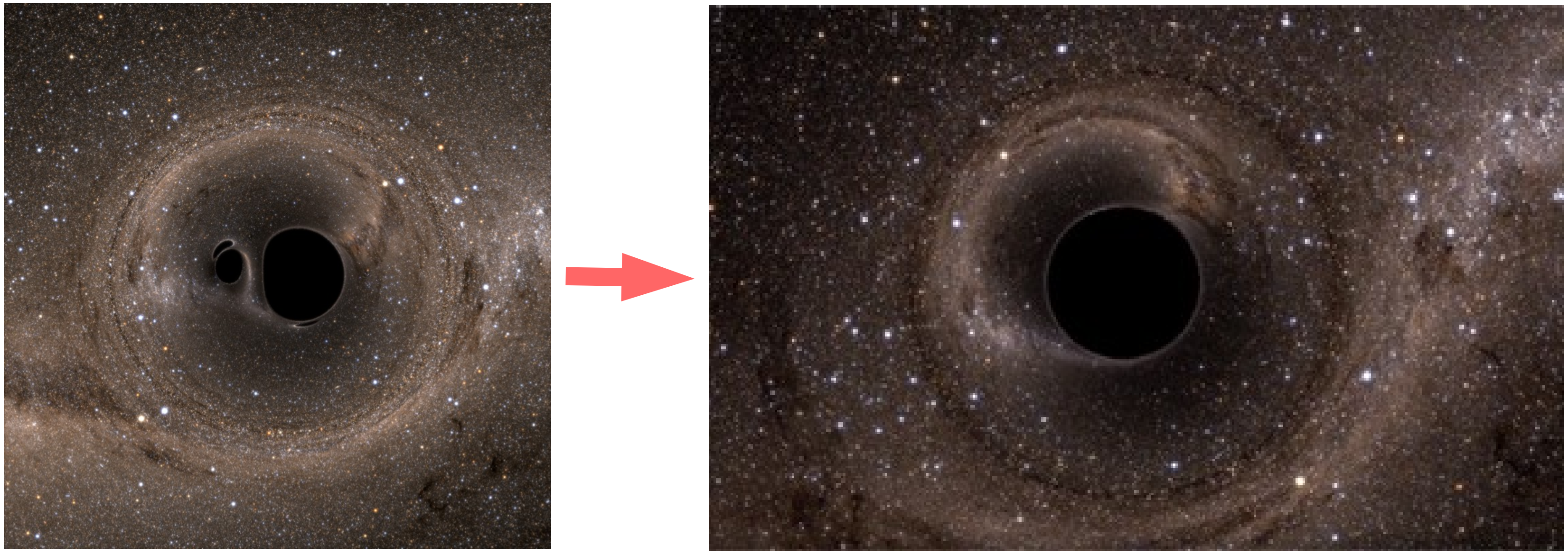
☐ Parameters measured by matching millions of trial waveforms in 15-dimensional parameter space





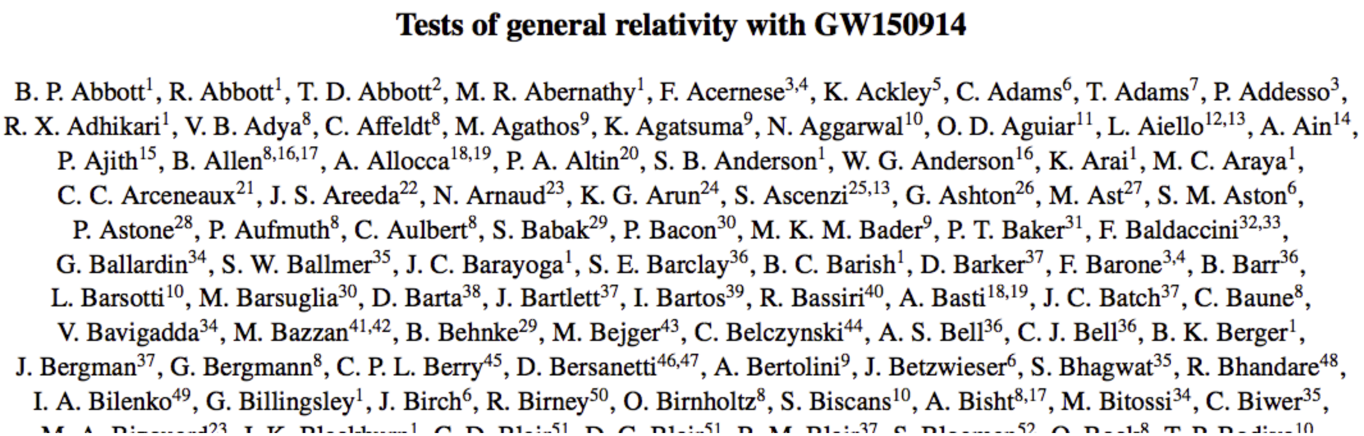
| | |
|---|---|
| Primary black hole mass | $36^{+5}_{-4} M_\odot$ |
| Secondary black hole mass | $29^{+4}_{-4} M_\odot$ |
| Final black hole mass | $62^{+4}_{-4} M_\odot$ |
| Final black hole spin | $0.67^{+0.05}_{-0.07}$ |
| Luminosity distance | $410^{+160}_{-180}$ Mpc |
| Source redshift $z$ | $0.09^{+0.03}_{-0.04}$ |

# At least four breakthroughs in one



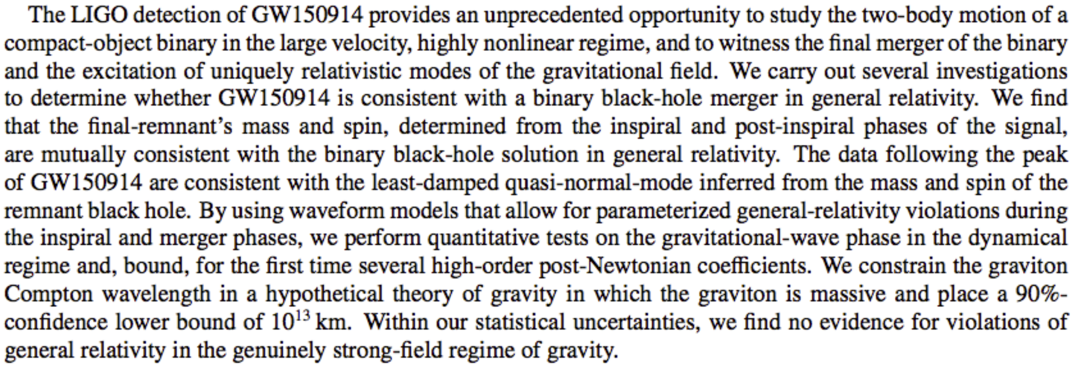
- First direct detection of gravitational waves
- First direct evidence for the existence of black holes
- First observation of a binary black hole merger
- First tests of genuinely strong-field dynamics of GR

# Tests of general relativity with GW150914



## Tests of general relativity with GW150914

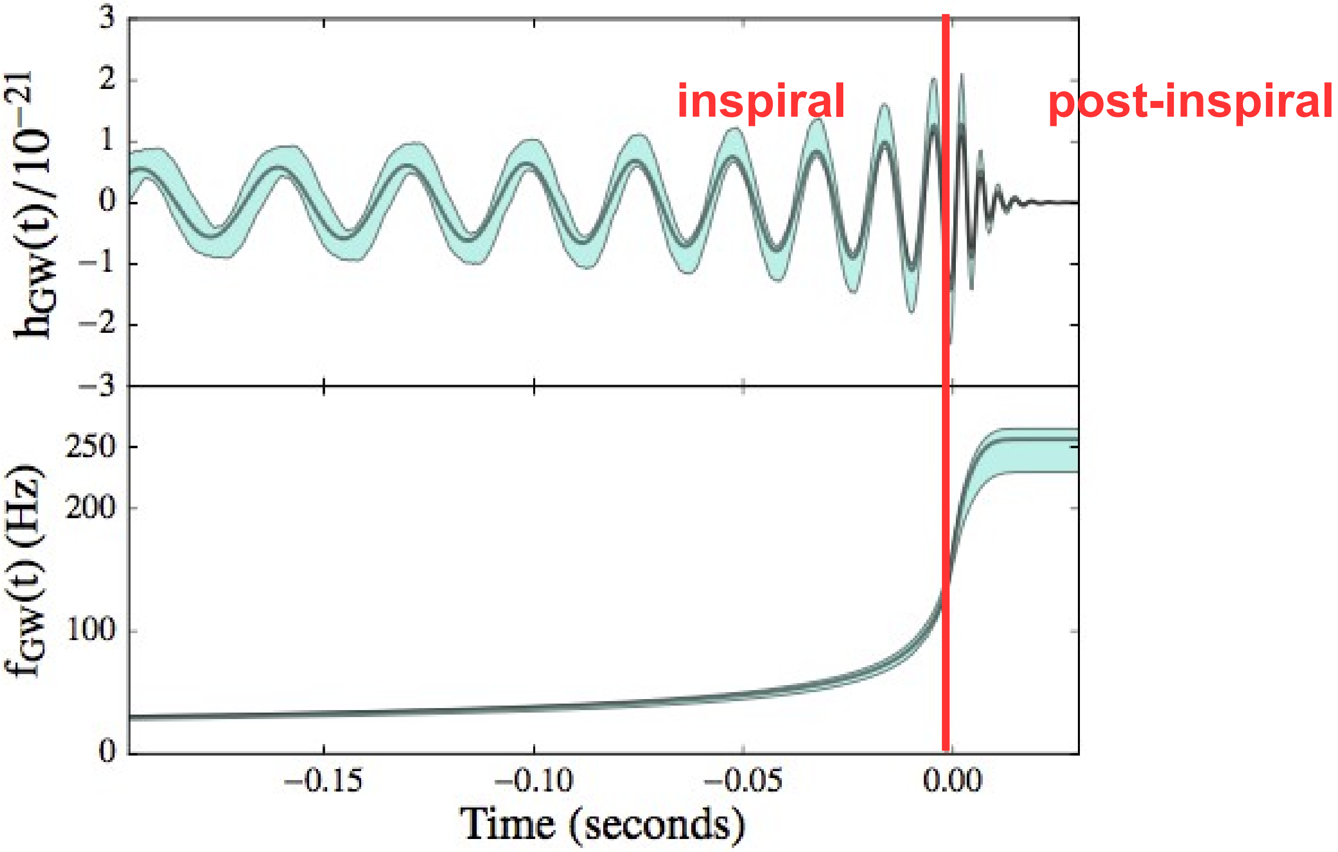
B. P. Abbott[1], R. Abbott[1], T. D. Abbott[2], M. R. Abernathy[1], F. Acernese[3,4], K. Ackley[5], C. Adams[6], T. Adams[7], P. Addesso[3], R. X. Adhikari[1], V. B. Adya[8], C. Affeldt[8], M. Agathos[9], K. Agatsuma[9], N. Aggarwal[10], O. D. Aguiar[11], L. Aiello[12,13], A. Ain[14], P. Ajith[15], B. Allen[8,16,17], A. Allocca[18,19], P. A. Altin[20], S. B. Anderson[1], W. G. Anderson[16], K. Arai[1], M. C. Araya[1], C. C. Arceneaux[21], J. S. Areeda[22], N. Arnaud[23], K. G. Arun[24], S. Ascenzi[25,13], G. Ashton[26], M. Ast[27], S. M. Aston[6], P. Astone[28], P. Aufmuth[8], C. Aulbert[8], S. Babak[29], P. Bacon[30], M. K. M. Bader[9], P. T. Baker[31], F. Baldaccini[32,33], G. Ballardin[34], S. W. Ballmer[35], J. C. Barayoga[1], S. E. Barclay[36], B. C. Barish[1], D. Barker[37], F. Barone[3,4], B. Barr[36], L. Barsotti[10], M. Barsuglia[30], D. Barta[38], J. Bartlett[37], I. Bartos[39], R. Bassiri[40], A. Basti[18,19], J. C. Batch[37], C. Baune[8], V. Bavigadda[34], M. Bazzan[41,42], B. Behnke[29], M. Bejger[43], C. Belczynski[44], A. S. Bell[36], C. J. Bell[36], B. K. Berger[1], J. Bergman[37], G. Bergmann[8], C. P. L. Berry[45], D. Bersanetti[46,47], A. Bertolini[9], J. Betzwieser[6], S. Bhagwat[35], R. Bhandare[48], I. A. Bilenko[49], G. Billingsley[1], J. Birch[6], R. Birney[50], O. Birnholtz[8], S. Biscans[10], A. Bisht[8,17], M. Bitossi[34], C. Biwer[35],



The LIGO detection of GW150914 provides an unprecedented opportunity to study the two-body motion of a compact-object binary in the large velocity, highly nonlinear regime, and to witness the final merger of the binary and the excitation of uniquely relativistic modes of the gravitational field. We carry out several investigations to determine whether GW150914 is consistent with a binary black-hole merger in general relativity. We find that the final-remnant's mass and spin, determined from the inspiral and post-inspiral phases of the signal, are mutually consistent with the binary black-hole solution in general relativity. The data following the peak of GW150914 are consistent with the least-damped quasi-normal-mode inferred from the mass and spin of the remnant black hole. By using waveform models that allow for parameterized general-relativity violations during the inspiral and merger phases, we perform quantitative tests on the gravitational-wave phase in the dynamical regime and, bound, for the first time several high-order post-Newtonian coefficients. We constrain the graviton Compton wavelength in a hypothetical theory of gravity in which the graviton is massive and place a 90%-confidence lower bound of $10^{13}$ km. Within our statistical uncertainties, we find no evidence for violations of general relativity in the genuinely strong-field regime of gravity.

http://arxiv.org/abs/1602.03841

# Are the masses and spins consistent with GR?



☐ Measure masses, spins of component black holes from *inspiral* signal

☐ General relativity allows to predict mass, spin of final black hole

☐ Measure these from *post-inspiral* signal and compare with prediction!

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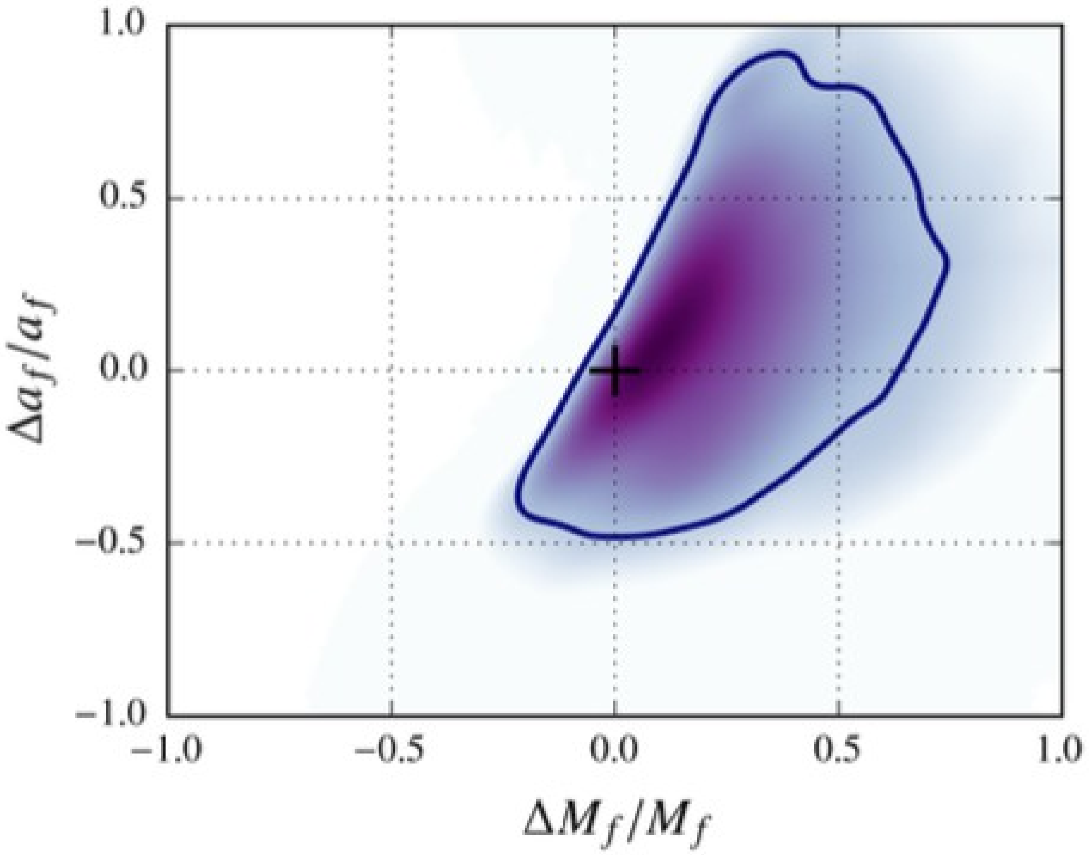

- ☐ Measure masses, spins of component black holes from *inspiral* signal
- ☐ General relativity allows to predict mass, spin of final black hole
- ☐ Measure these from *post-inspiral* signal and compare with prediction!

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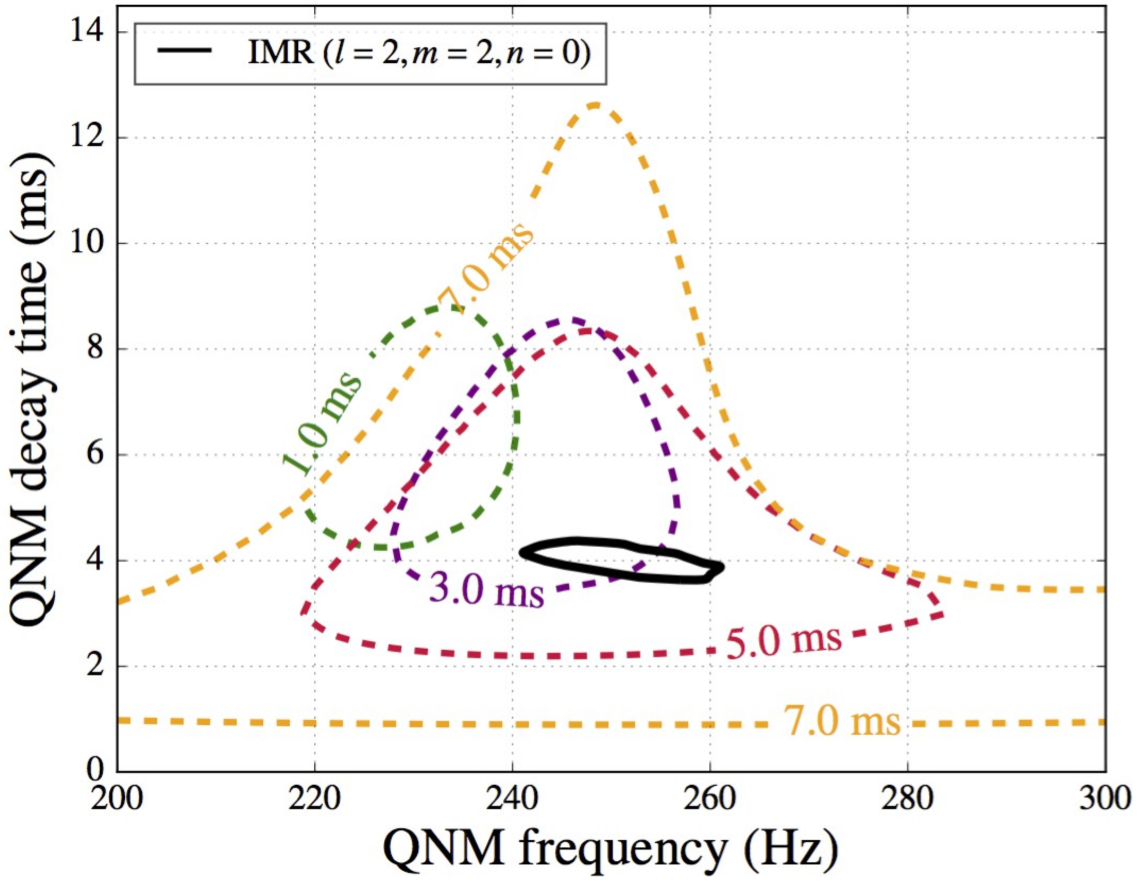
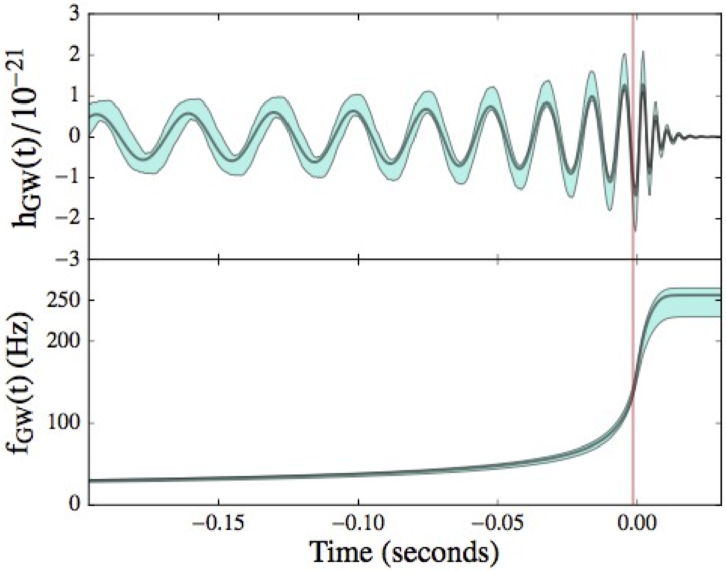
# Does the final black hole ring down as predicted?

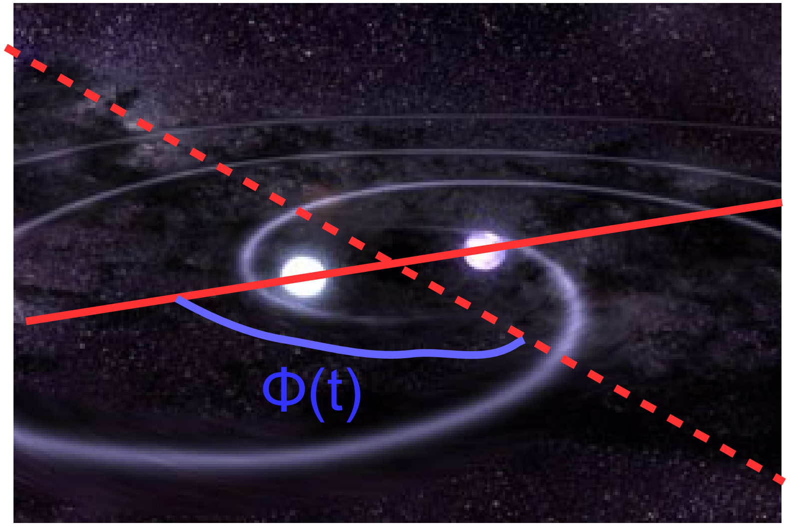


- ☐ Evidence for a dominant quasi-normal mode in the form of damped sinusoid?
- ☐ Frequency, damping time consistent with expectation

http://arxiv.org/abs/1602.03841

# Any deviations from GR in the shape of the wave?





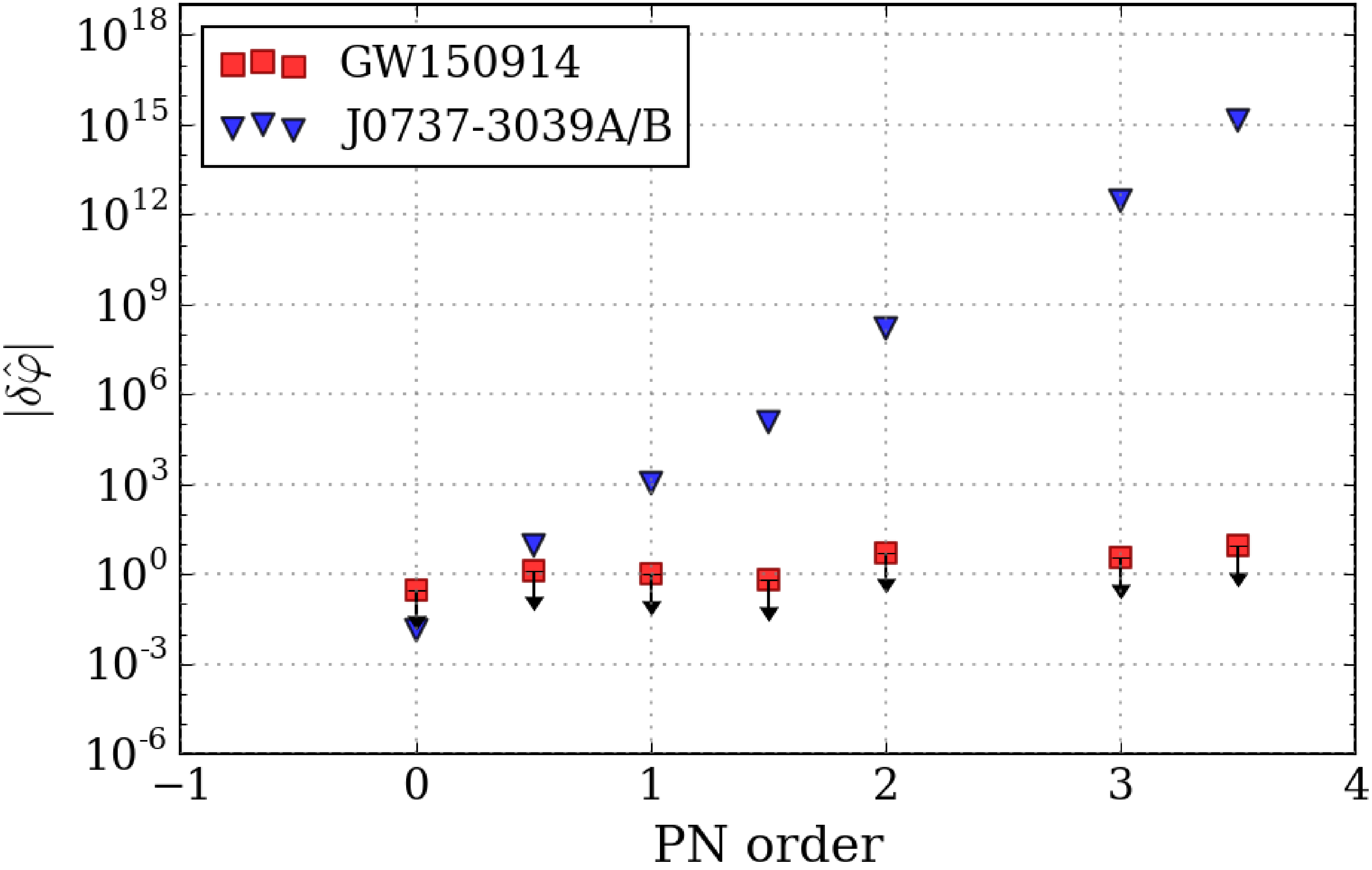
- Orbital phase during inspiral as a function of (ever increasing) orbital speed:

$$\Phi(v) = \left(\frac{v}{c}\right)^{-5} \sum_{n=0}^{\infty} \left[\varphi_n + \varphi_n^{(l)} \ln\left(\frac{v}{c}\right)\right] \left(\frac{v}{c}\right)^{n}$$

- Up to factor of 2, this is also the GW signal during inspiral
- In general relativity, the coefficients $\varphi_n$ and $\varphi_n^{(l)}$ are known functions of masses and spins
- Can we put bounds on possible deviations from the GR predictions?

http://arxiv.org/abs/1602.03841

# Any deviations from GR in the shape of the wave?



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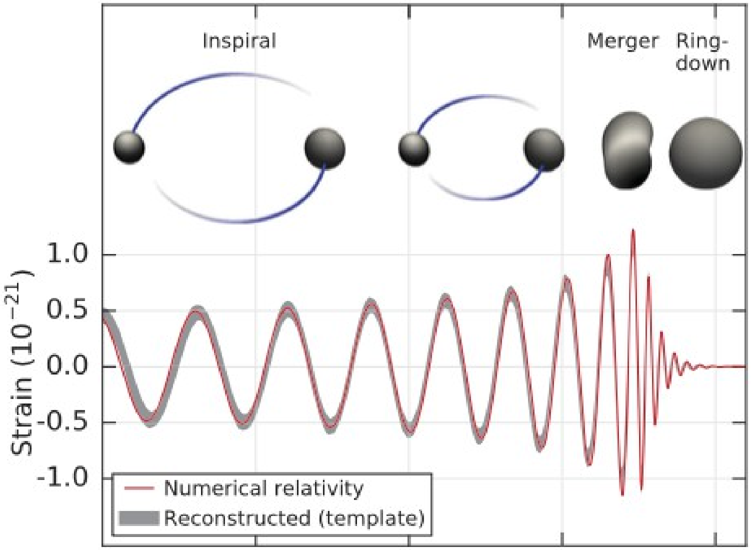

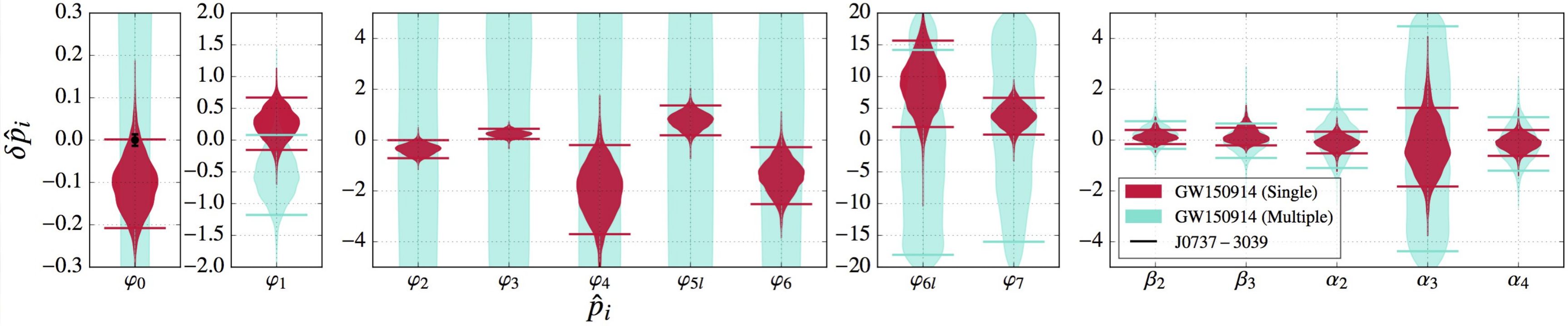

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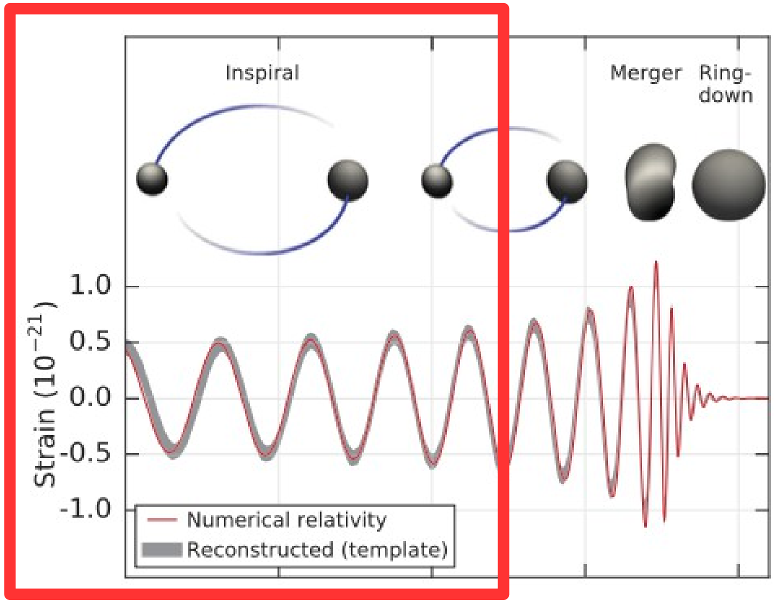
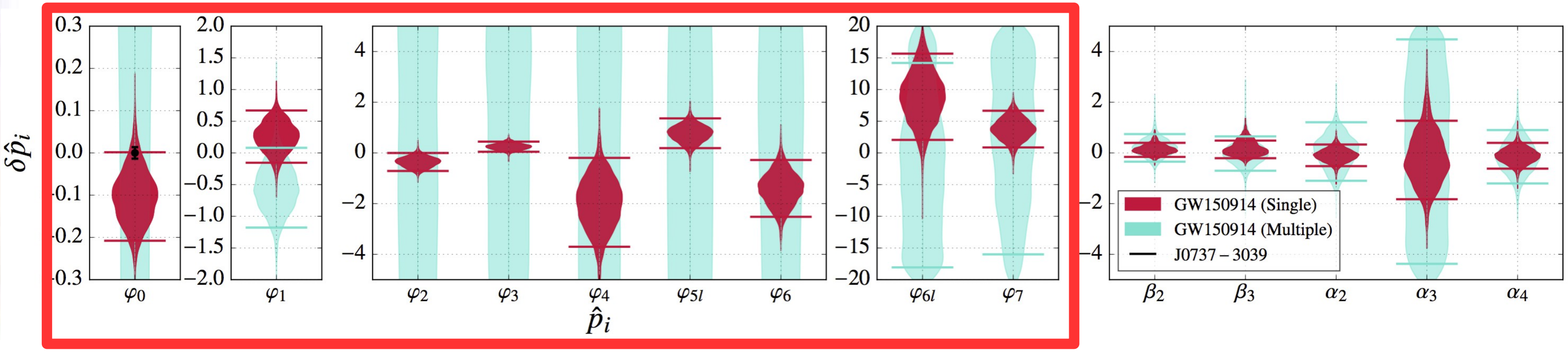


**inspiral**



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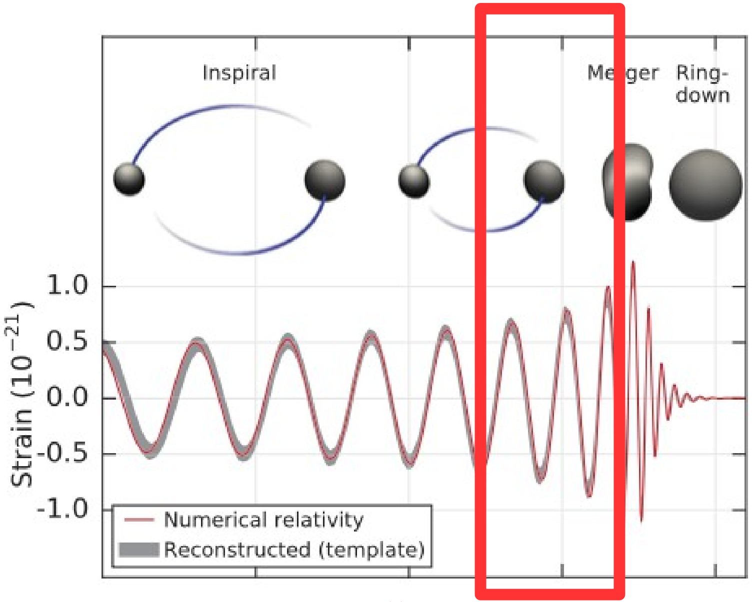
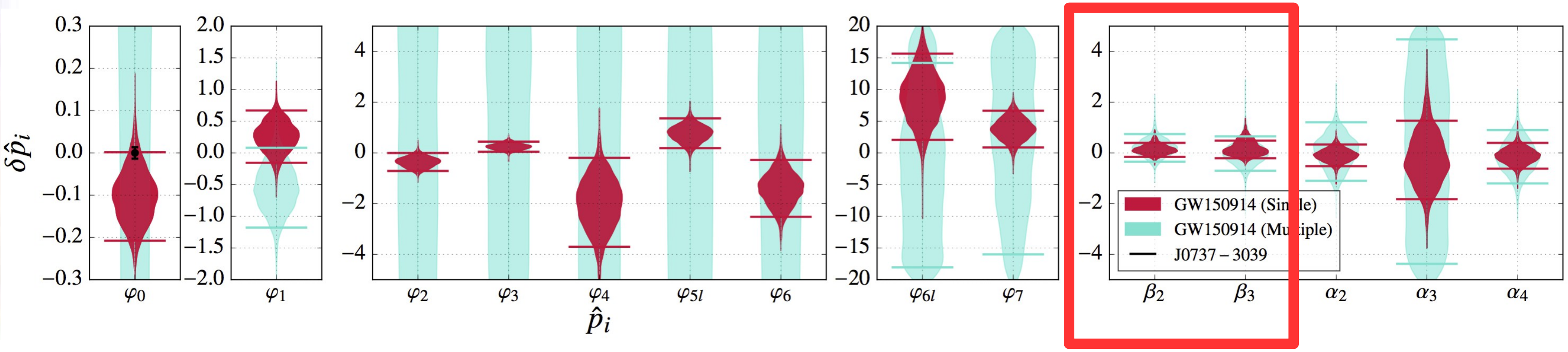


**“intermediate”**



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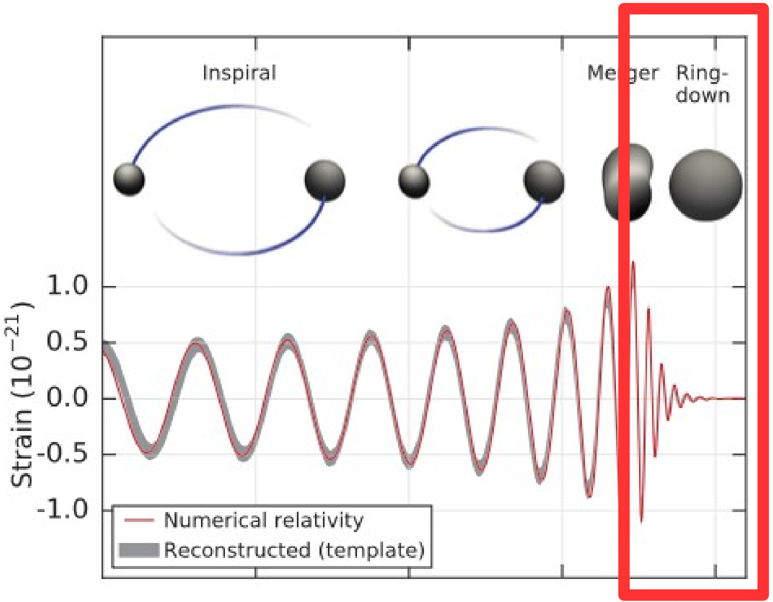
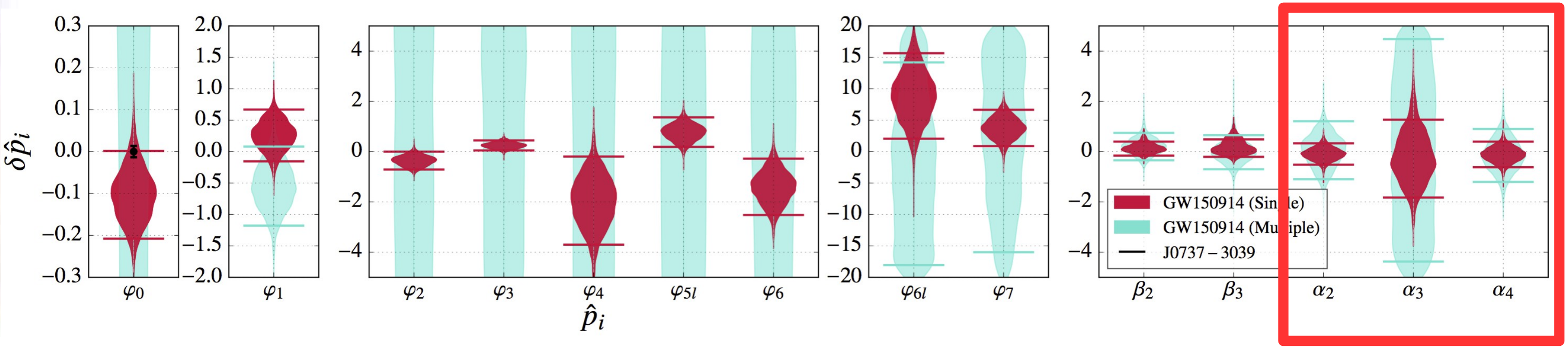


merger/ringdown



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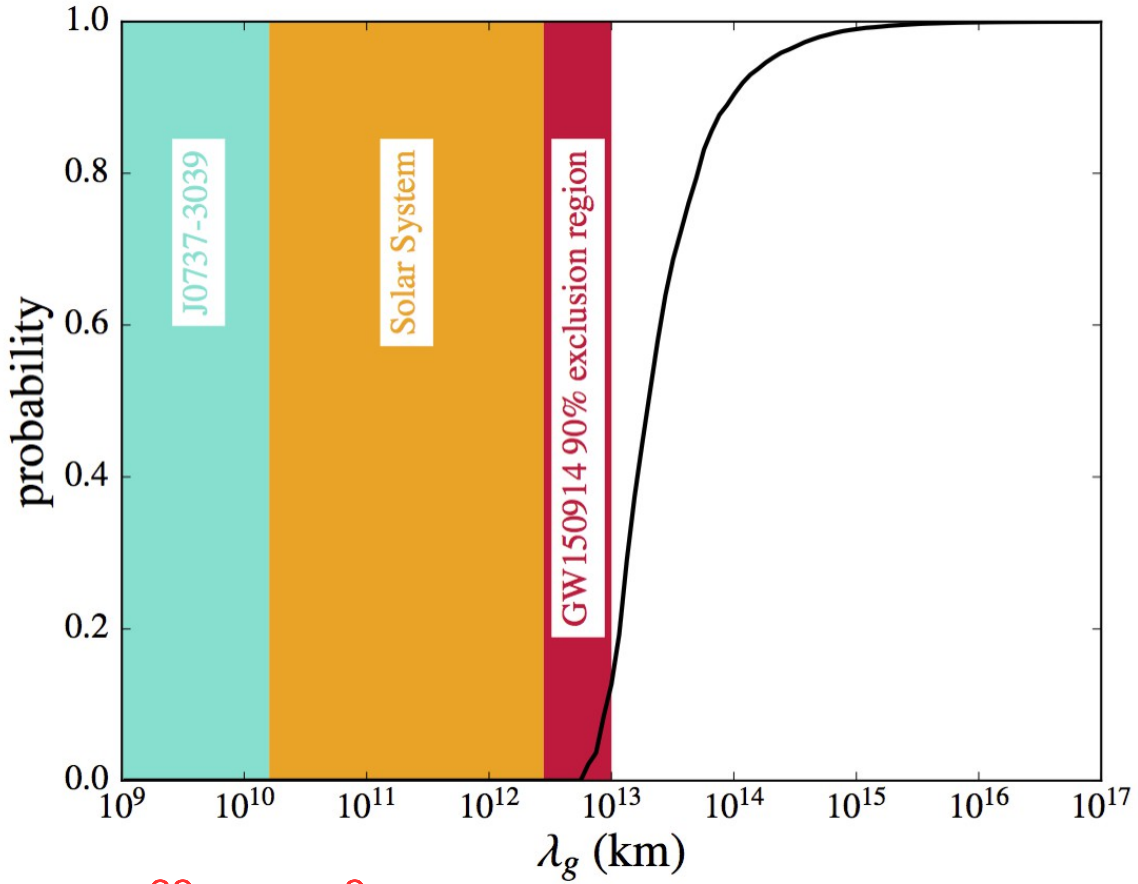
# Does the graviton have mass?

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

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

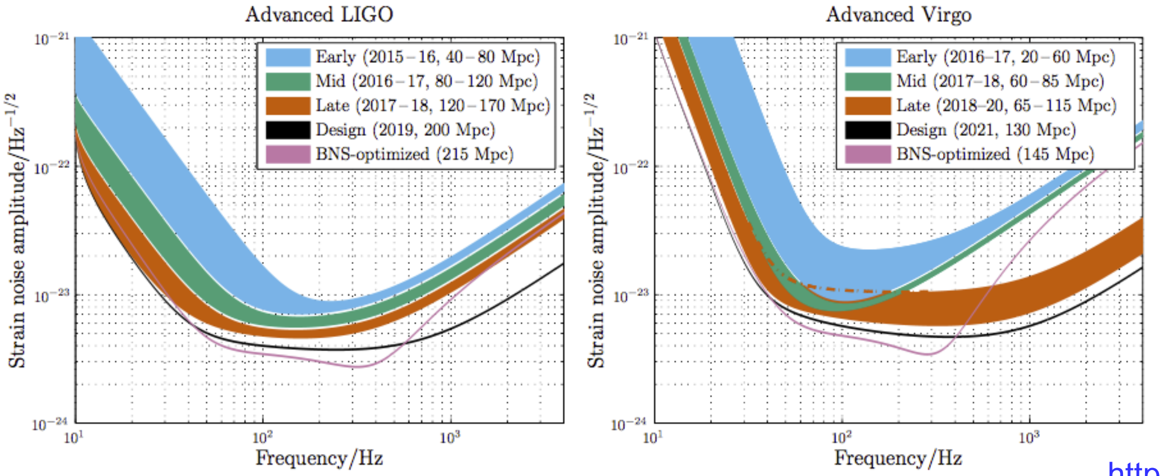


$m_g < 10^{-22}\ \mathrm{eV}/c^2$

http://arxiv.org/abs/1602.03841

# Where do we go from here?

# Observing plans for the coming years



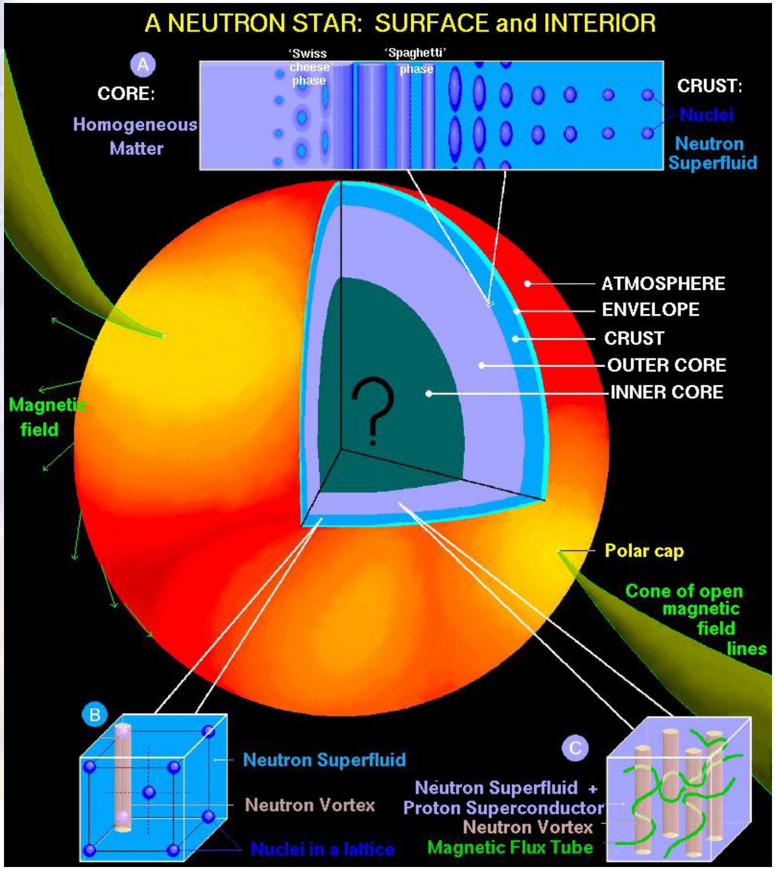
http://arxiv.org/abs/1304.0670

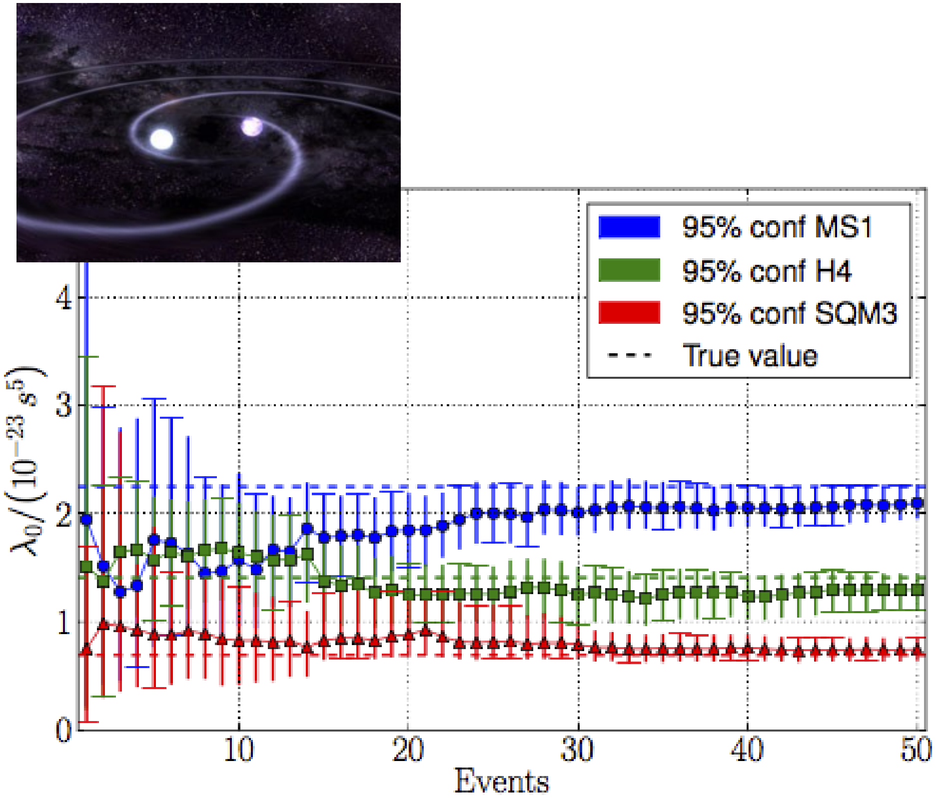
Progressive improvements in sensitivity:

- 2015-2016 (**O1**): 4-month run with only Advanced LIGO
    - Detection of GW150914
    - Second half of data set still under analysis
- 2016-2017 (**O2**): 6-month run with **Advanced Virgo joining**
- 2017-2018 (**O3**): 9-month run LIGO + Virgo + **KAGRA?**
- 2019+: LIGO + Virgo (towards full sensitivity) + KAGRA
- 2022+: **LIGO-India** joins the network
    - *17 February: LIGO-India project approved!*

# Detecting binary neutron stars

- Equation of state of neutron stars is currently unknown
- With multiple binary neutron star coalescences, from the GW signal alone one can distinguish between “soft”, “intermediate”, “hard” equation of state

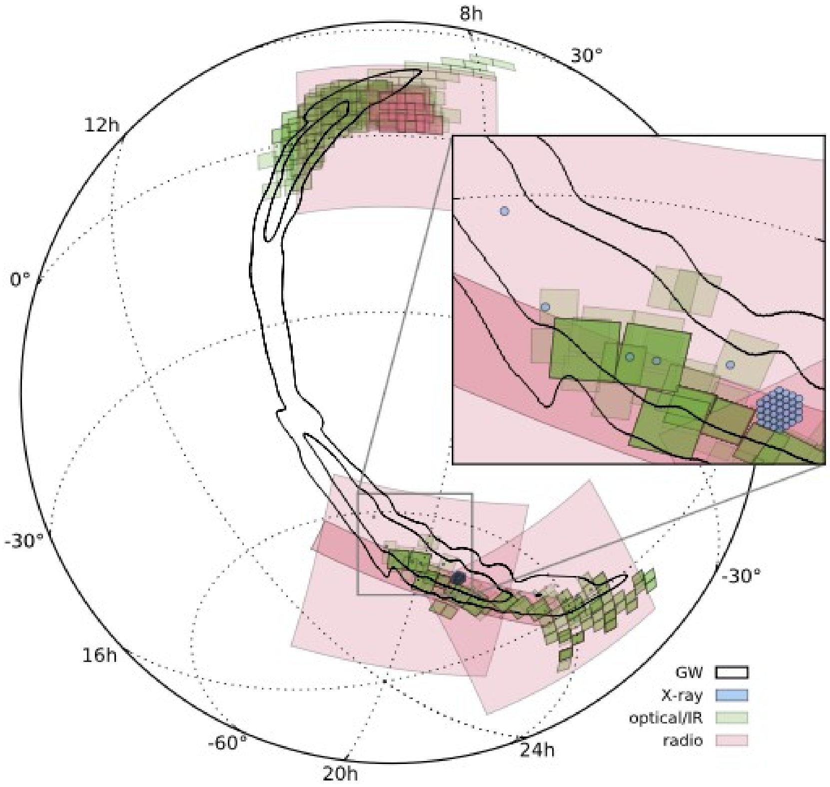




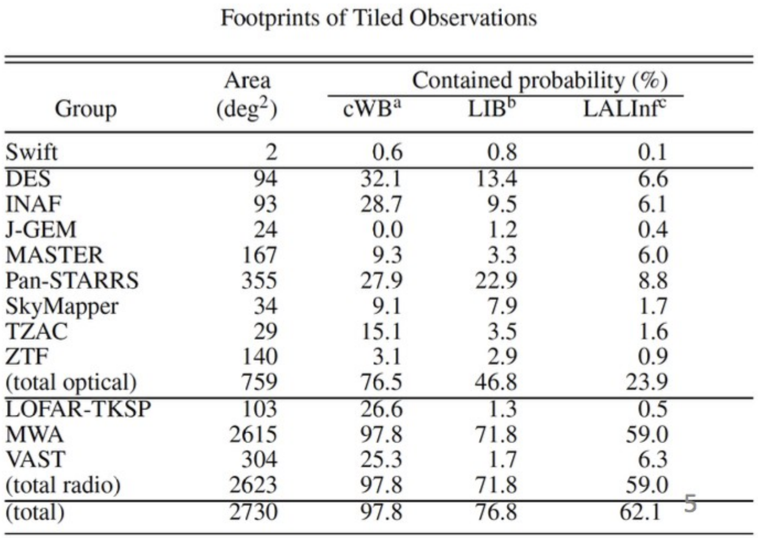
Del Pozzo, Li, Agathos, Van Den Broeck, Vitale, Phys. Rev. Lett. **111**, 071101 (2013)

# Detecting binary neutron stars

- Would be helpful to see electromagnetic counterpart
- Sky map for GW150914 was sent to astronomers, and they looked (though no EM emission expected from binary black holes!)



http://arxiv.org/abs/1602.08492

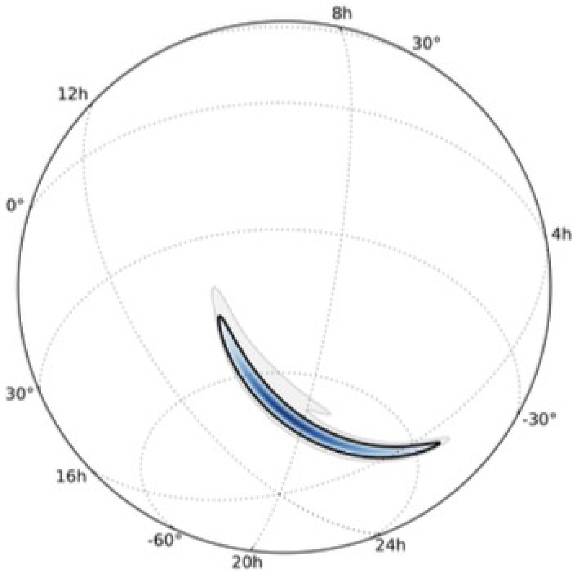


Footprints of Tiled Observations

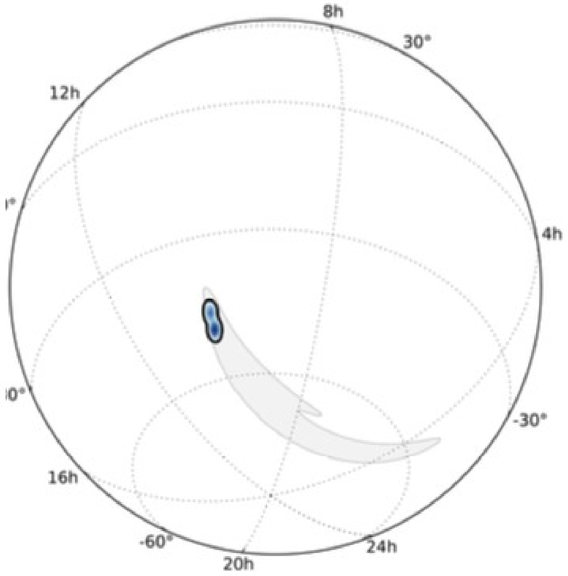
| Group | Area (deg$^2$) | Contained probability (%) cWB[a] | LIB[b] | LALInf[c] |
|---|---|---|---|---|
| Swift | 2 | 0.6 | 0.8 | 0.1 |
| DES | 94 | 32.1 | 13.4 | 6.6 |
| INAF | 93 | 28.7 | 9.5 | 6.1 |
| J-GEM | 24 | 0.0 | 1.2 | 0.4 |
| MASTER | 167 | 9.3 | 3.3 | 6.0 |
| Pan-STARRS | 355 | 27.9 | 22.9 | 8.8 |
| SkyMapper | 34 | 9.1 | 7.9 | 1.7 |
| TZAC | 29 | 15.1 | 3.5 | 1.6 |
| ZTF | 140 | 3.1 | 2.9 | 0.9 |
| (total optical) | 759 | 76.5 | 46.8 | 23.9 |
| LOFAR-TKSP | 103 | 26.6 | 1.3 | 0.5 |
| MWA | 2615 | 97.8 | 71.8 | 59.0 |
| VAST | 304 | 25.3 | 1.7 | 6.3 |
| (total radio) | 2623 | 97.8 | 71.8 | 59.0 |
| (total) | 2730 | 97.8 | 76.8 | 62.1 |

# Detecting binary neutron stars

- What if we had seen binary neutron star coalescence as loud as GW150914?
- With **Advanced Virgo** included, 90% confidence sky error box would be reduced from ~180 deg$^2$ to ~20 deg$^2$



LIGO Hanford + LIGO Livingston



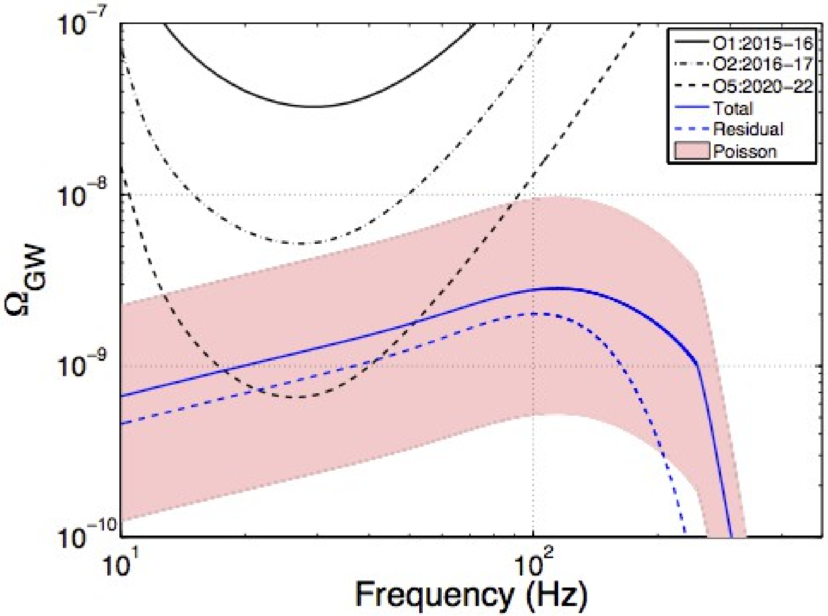
LIGO Hanford + LIGO Livingston

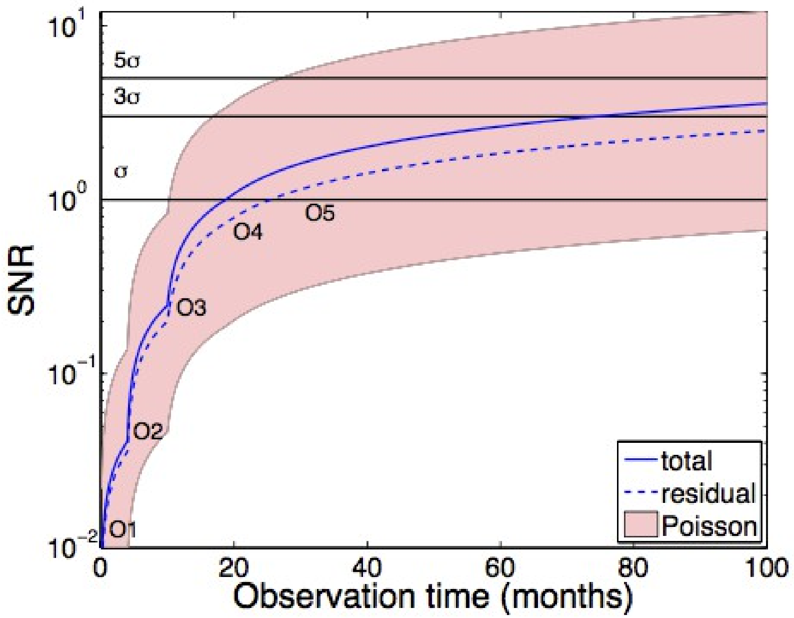
**+ Advanced Virgo**

Courtesy L. Singer

# “Background noise” from binary black hole mergers

- Binary black hole signals arriving regularly, but most will be too quiet to pick out individually
- However, they cause “noise” that is correlated between detectors
- Very characteristic spectrum: ~ $f^{2/3}$ up to ~100 Hz, then rapid fall-off
- Could be detected by the end of the decade!

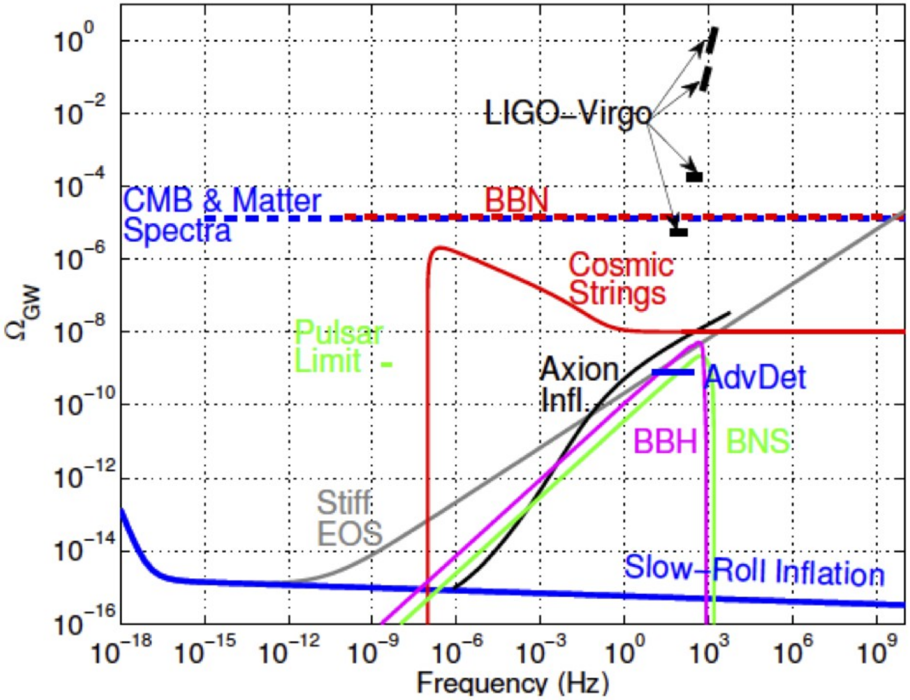




http://arxiv.org/abs/1602.03847

# Primordial gravitational waves from early Universe?

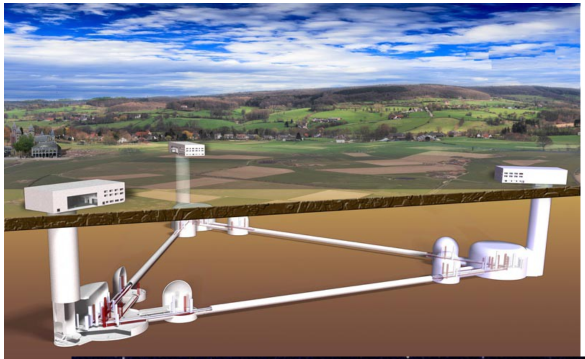
$$\Omega_{gw}(f) = \frac{d\rho_{gw}(f)}{\rho_c d(\ln f)}$$

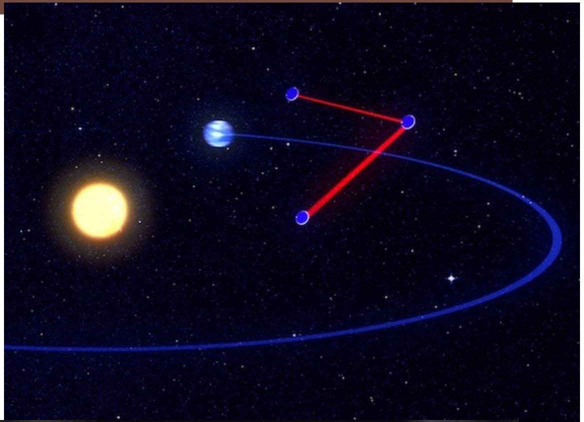


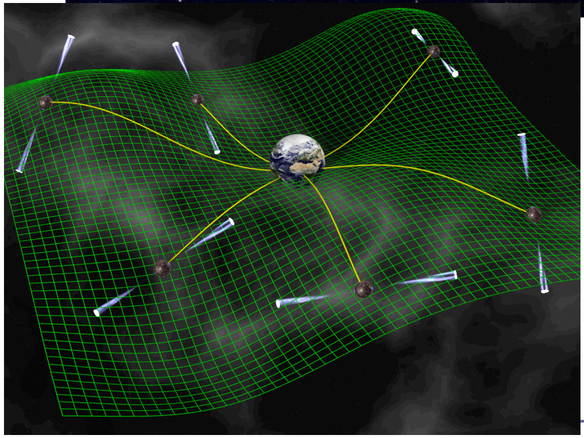
Courtesy T. Regimbau

- Between initial and final advanced detectors: Factor $10^4$ gain in $\Omega_{gw}$
  - Better sensitivity overall
  - Wider frequency band
- Possible signals from a fraction of a second after Big Bang:
  - Termination of inflation (e.g. axion inflation)
  - Phase transitions: fundamental forces splitting off
  - Cosmic strings
  - ...
  - The unknown?
- Different scenarios yield different spectra, which would allow us to distinguish

# The next few decades







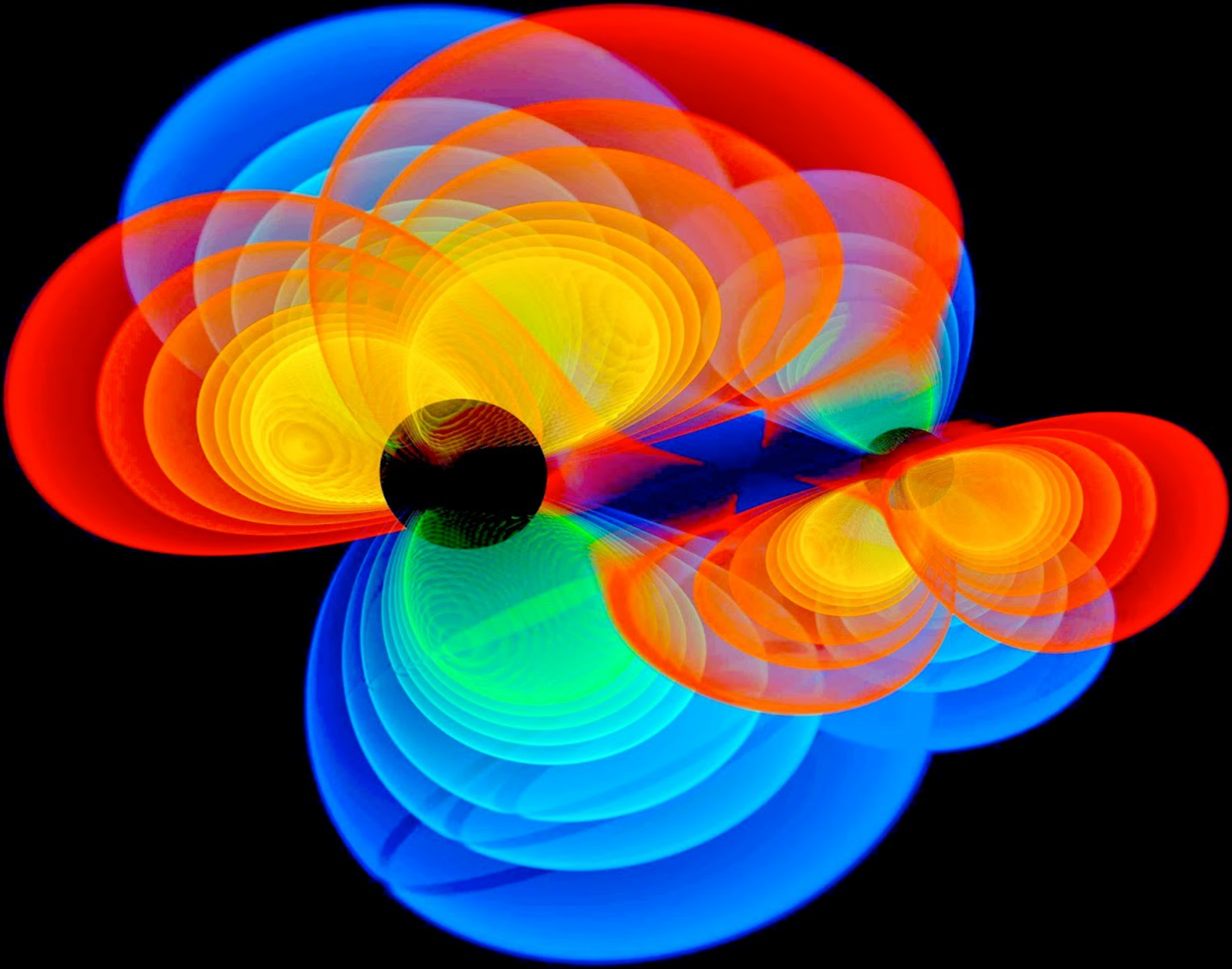
- Einstein Telescope (~2030?)
  - $3^{rd}$ generation observatory
  - $10^5$ binary mergers per year
  - Evolution of the Universe (e.g. dark energy)
  - Conceptual design study concluded in 2011
- (e)LISA (approved for 2034)
  - 3 probes in orbiting the Sun, $10^6$ km distance
  - Probe low frequencies: $10^{-5}$ – $10^{-1}$ Hz
  - Mergers of supermassive binary black holes throughout the Universe; study their growth
  - “Pathfinder” mission launched in 2015
- Pulsar timing arrays (in progress)
  - Correlate variations in pulse arrival times between widely spaced pulsars to see effect of GWs
  - Ultra-low frequencies: $10^{-9}$ – $10^{-6}$ Hz
  - Supermassive binaries long before they merge

*Together provide wide range of frequencies to search for primordial gravitational waves!*

# Overview

- Four breakthroughs in one:
  - First direct detection of gravitational waves
  - First direct evidence for existence of black holes
  - First observation of binary black hole merger
  - First tests of genuinely strong-field dynamics of general relativity
- Tests of general relativity
  - Consistency between inspiral and merger/ringdown
  - Ringdown frequency comes out as expected
  - Shape of the waveform as a whole is consistent with GR predictions
  - $m_g < 10^{-22}$ eV/$c^2$
- The future
  - Binary neutron stars and unraveling neutron star interior structure
  - Binary mergers as cosmic distance markers to study evolution of the Universe
  - Primordial gravitational waves from the early Universe
  - New observatories: Einstein Telescope, eLISA, pulsar timing arrays

# Stay tuned!



# Cosmography with gravitational waves

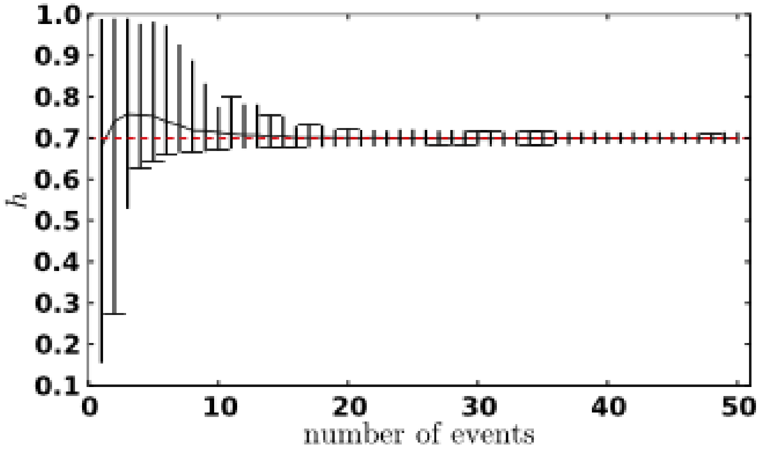
- Gravitational waves are cosmic distance markers:

$$A(t) = \frac{\mathcal{M}^{5/3}(m_1, m_2)\, g(\theta, \phi, \iota, \psi)\, F^{2/3}(t)}{D}$$

  - Masses $m_1$, $m_2$ can be obtained from the phase
  - Same with instantaneous frequency $F(t)$
  - With multiple detectors, information about sky position $(\theta,\phi)$ and orientation $(\iota,\psi)$

*Can extract distance D!*

- If both distance $D$ and redshift $z$ are known, can perform independent measurement of the Hubble constant $H_0$
  - Use electromagnetic counterparts to find $z$
  - Or, infer it approximately from 3D position + galaxy catalogs



Del Pozzo, Phys. Rev. D **86**, 043011 (2012)