The direct detection of gravitational waves:

The first discovery, and where we go from here

Chris Van Den Broeck

Nikhef

Nikhef colloquium, 19 February 2016

Direct detection of gravitational waves

PRL 116, 061102 (2016)

Selected for a Viewpoint in *Physics*
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 1.0×10^{-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 5.1σ. 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

- Tests of general relativity with GW150914

  http://arxiv.org/abs/1602.03841

- Properties of the binary black hole merger GW150914

  http://arxiv.org/abs/1602.03840

- Astrophysical implications of the binary black-hole merger GW150914

  http://arxiv.org/abs/1602.03846

- The rate of binary black hole mergers inferred from Advanced LIGO observations surrounding GW150914

  http://arxiv.org/abs/1602.03842

- GW150914: Implications for the stochastic gravitational wave background from binary black holes

  http://arxiv.org/abs/1602.03847

- GW150914: First results from the search for binary black hole coalescences with Advanced LIGO

  http://arxiv.org/abs/1602.03839

- Observing gravitational-wave transient GW150914 with minimal assumptions

  http://arxiv.org/abs/1602.03843

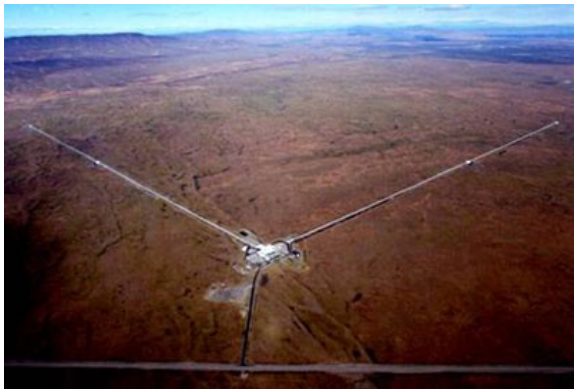
- Characterization of transient noise in Advanced LIGO relevant to gravitational wave signal GW150914

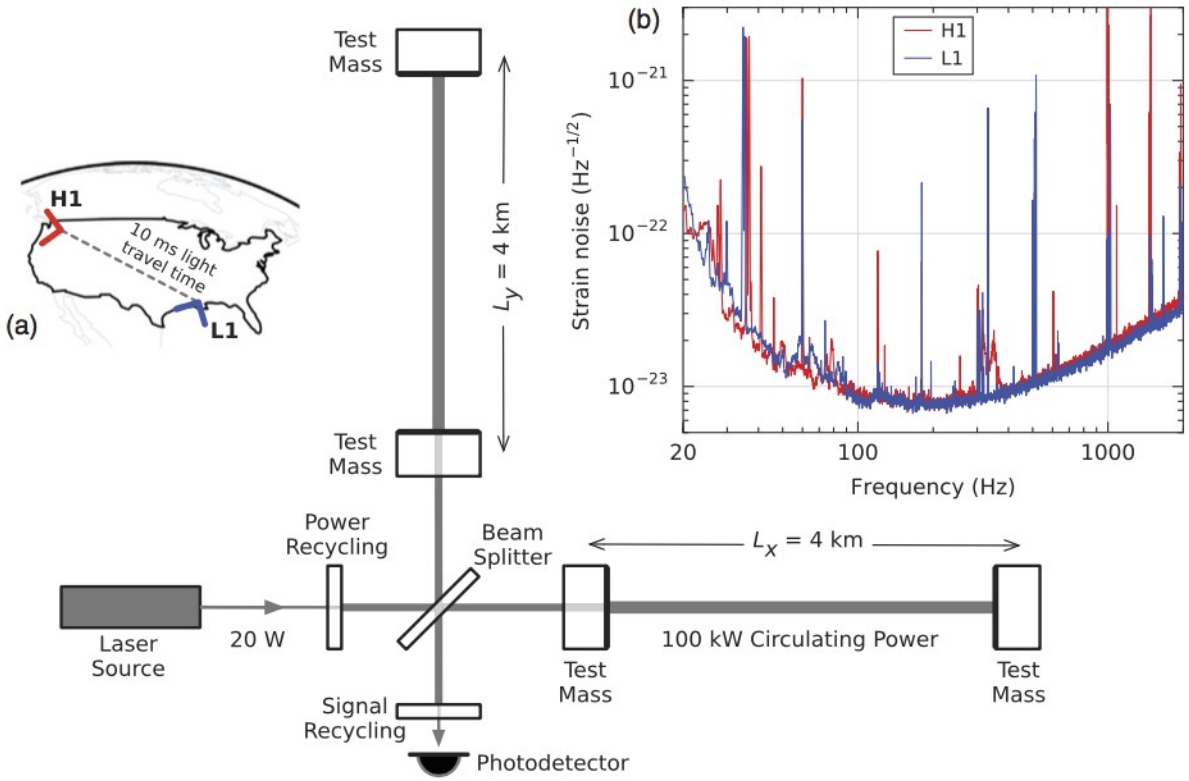
  http://arxiv.org/abs/1602.03844

- Calibration of the Advanced LIGO detectors for the discovery of the binary-black hole merger GW150914

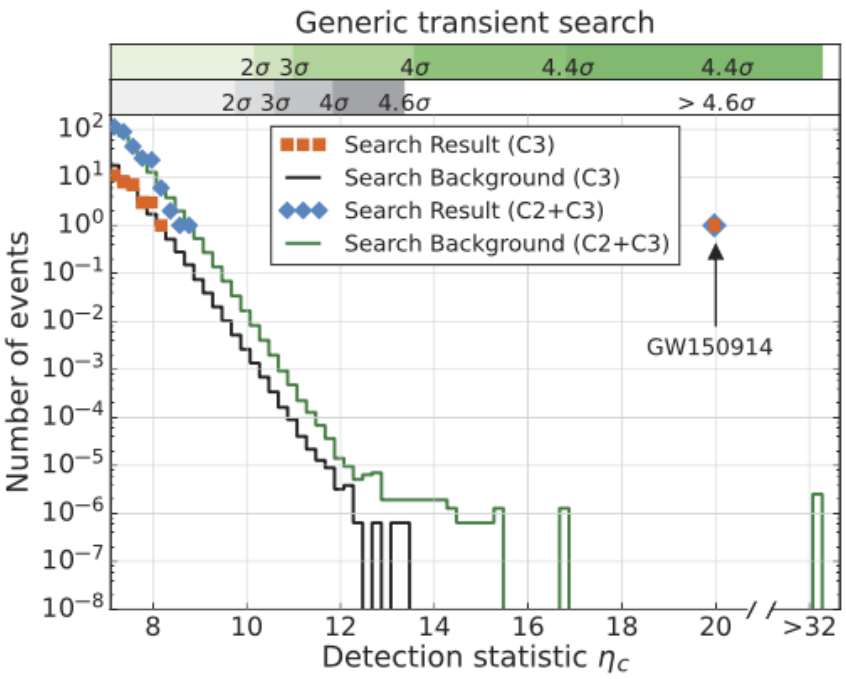
  http://arxiv.org/abs/1602.03845

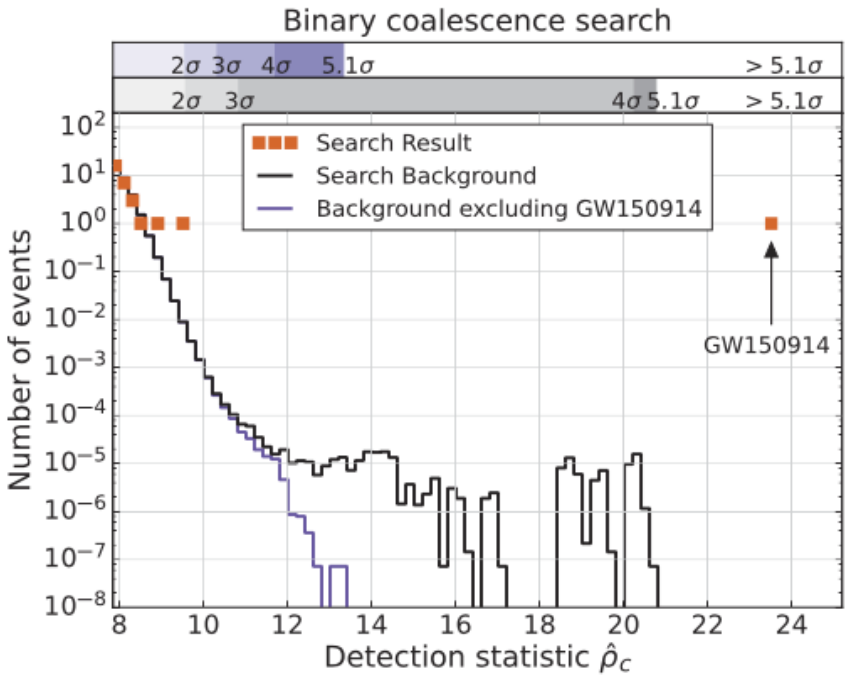
The detectors





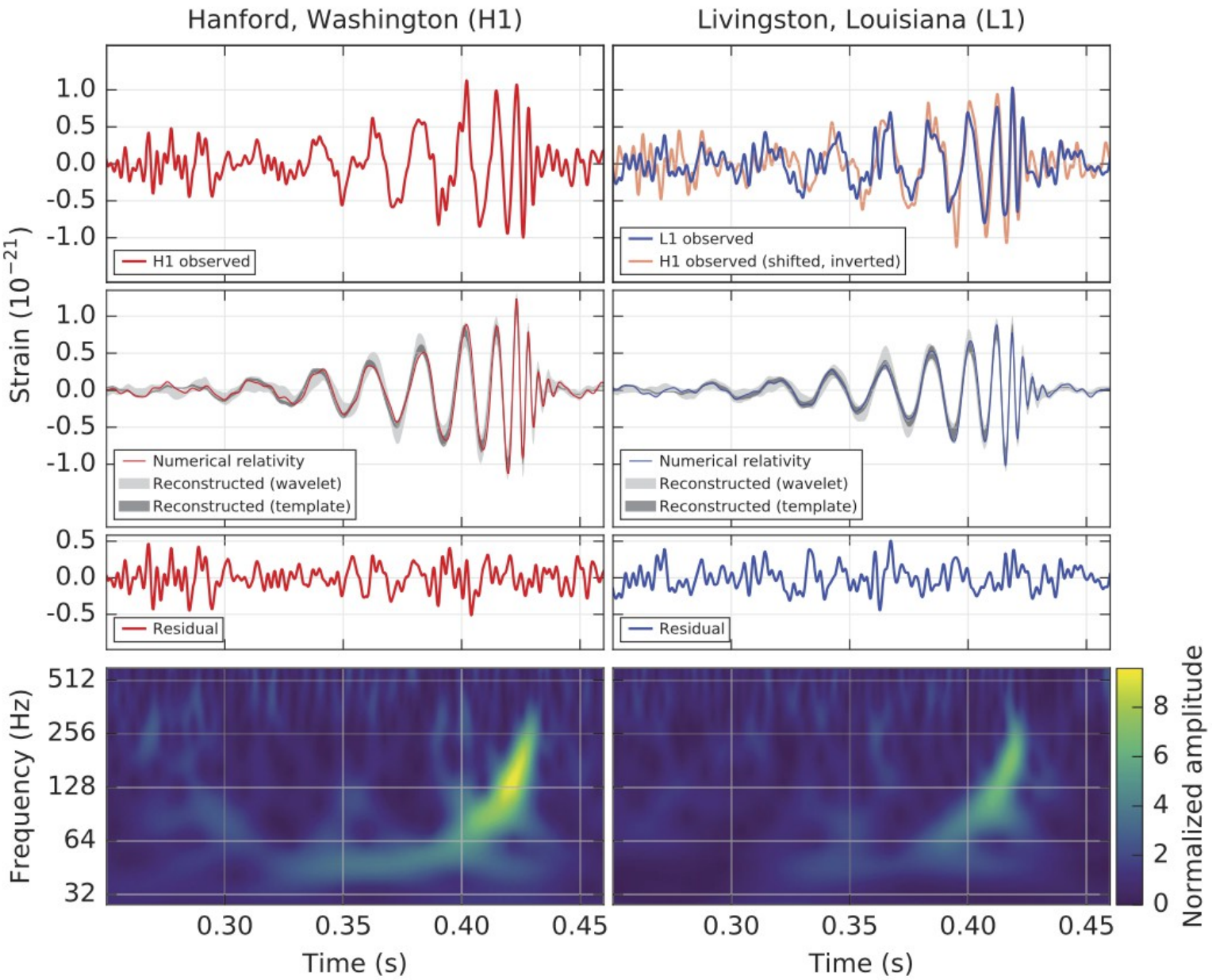
The detection





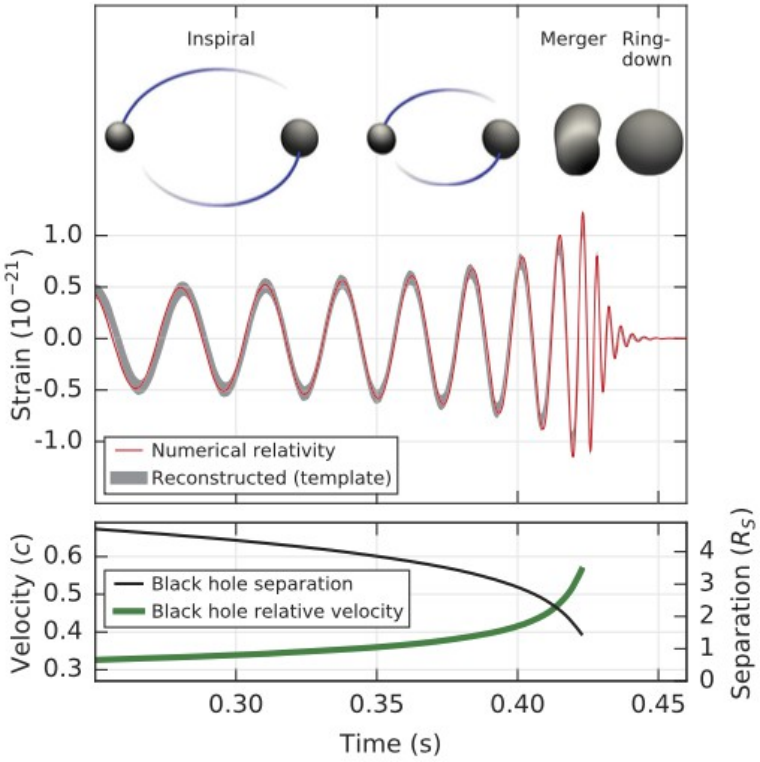
- Found in "unmodeled" and "modeled" searches
- "Modeled search" (which makes use of waveform predictions) uses 16 days of coincident Livingston-Hanford data
  - False alarm rate < 1 in 203000 years
  - **Significance > 5.1σ**

The detection



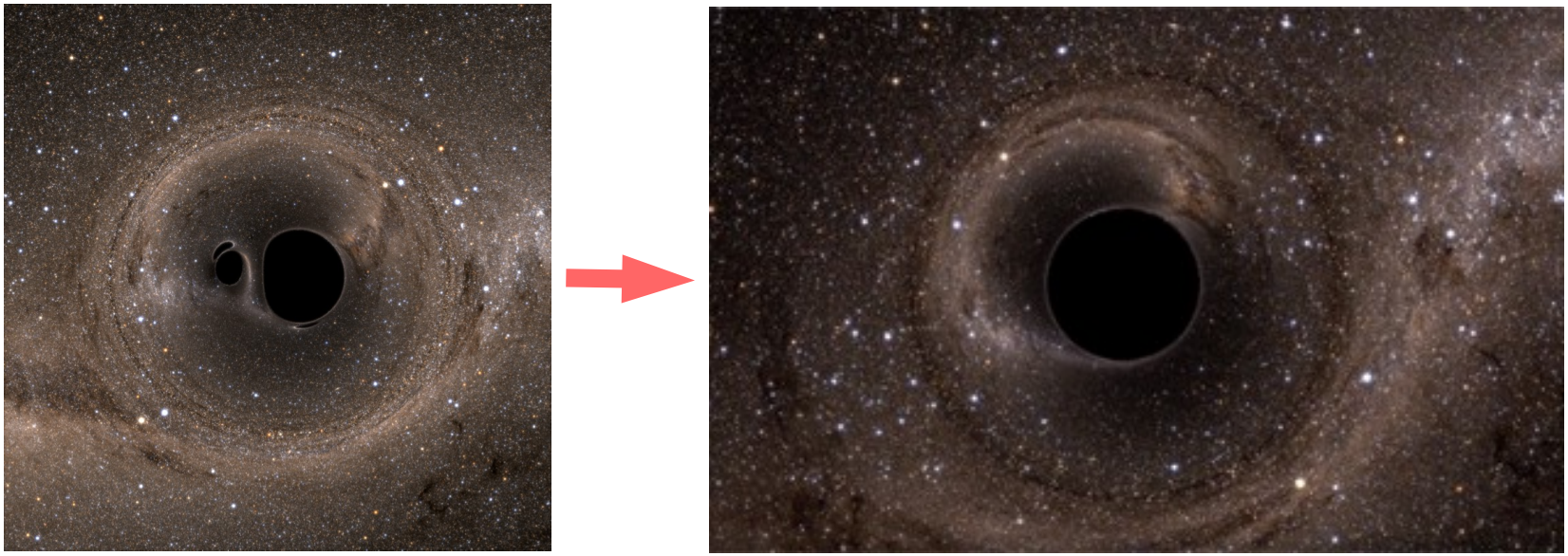
The detection

- 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

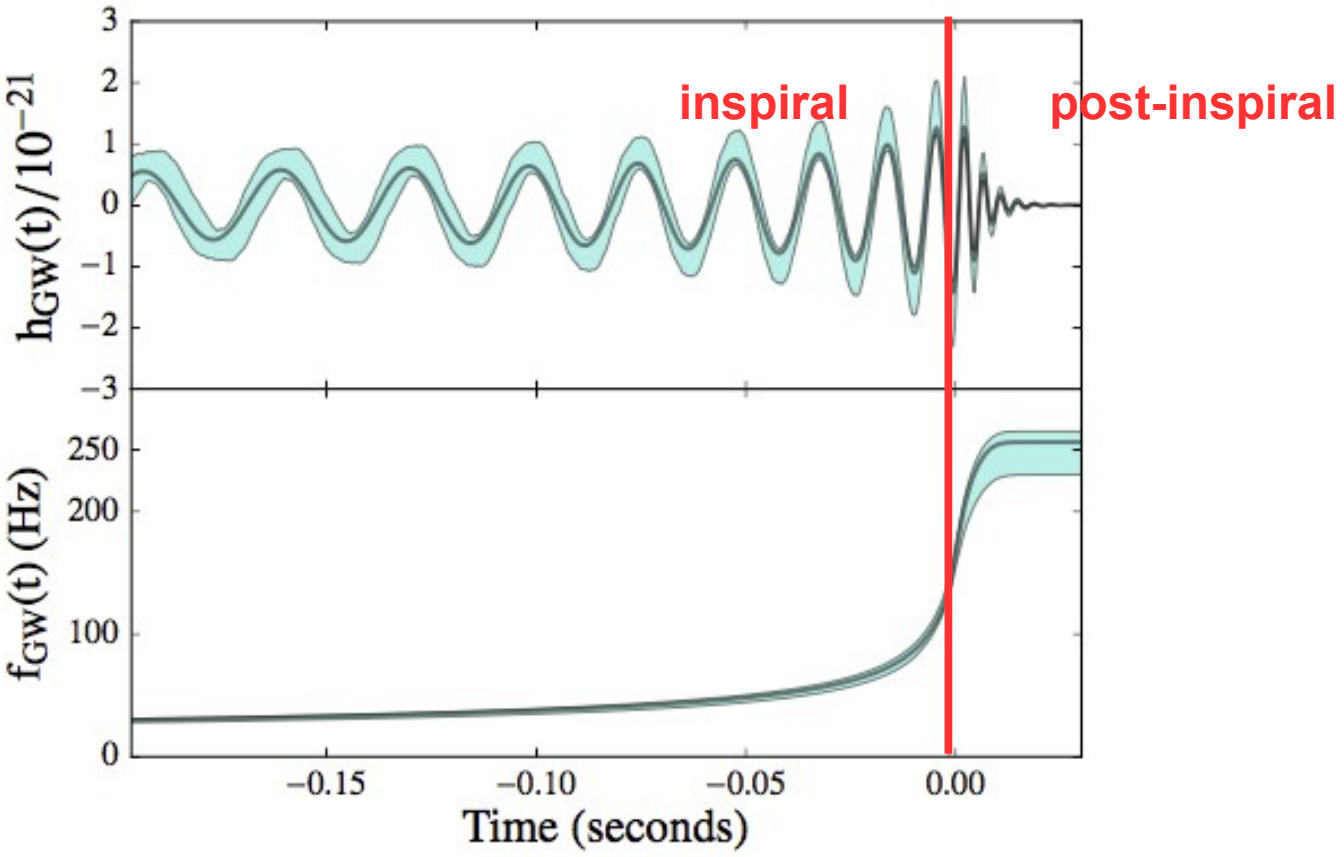
Tests of general relativity with GW150914

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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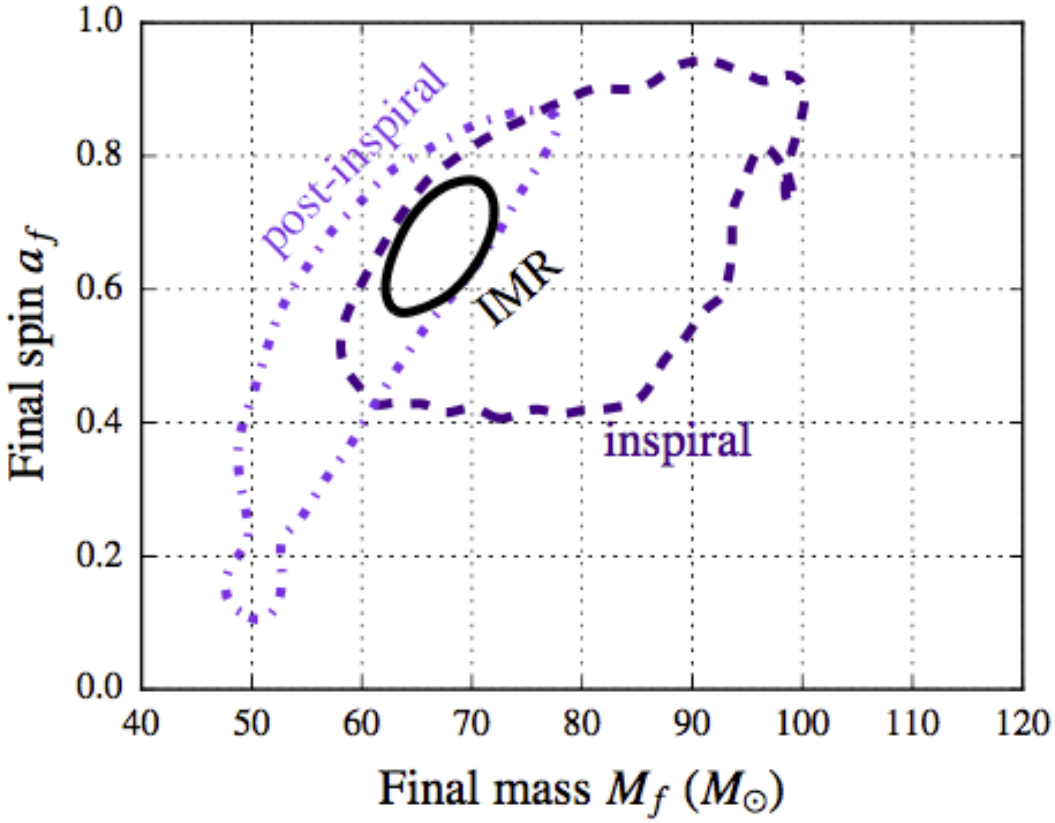

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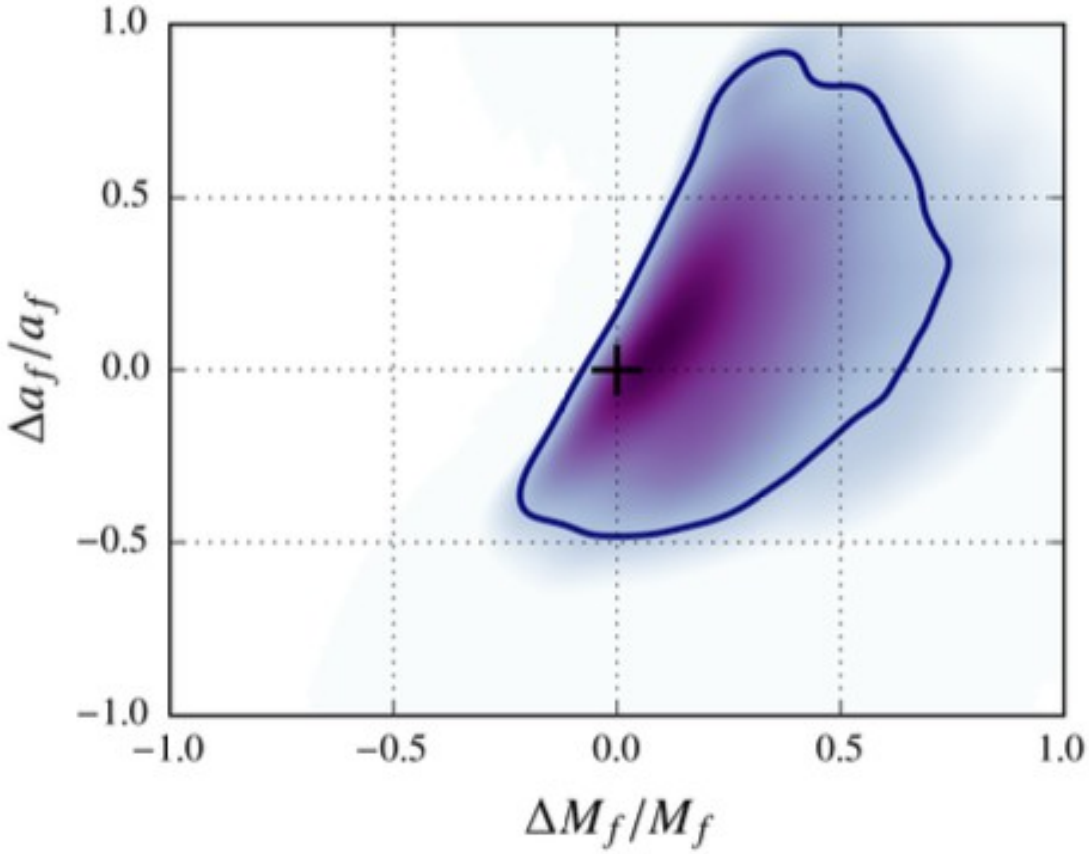

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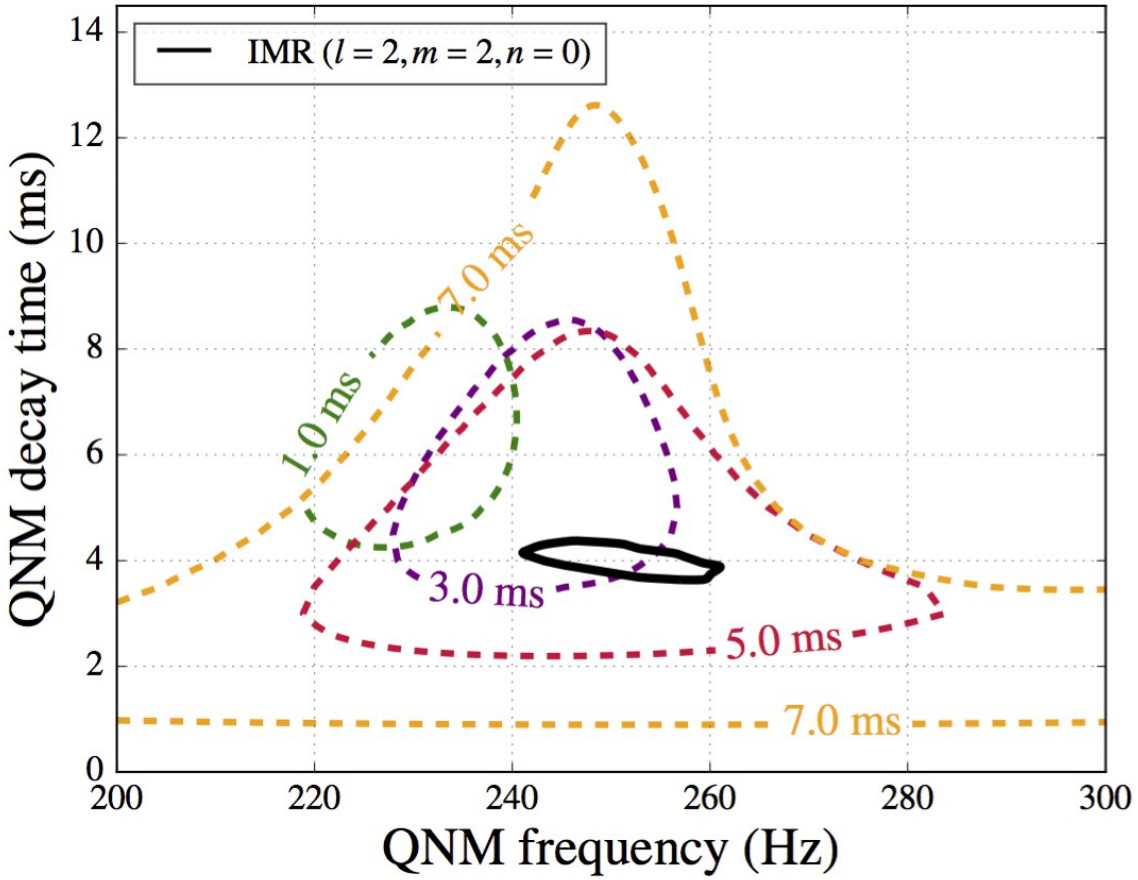
Is the frequency of the final black hole as predicted?

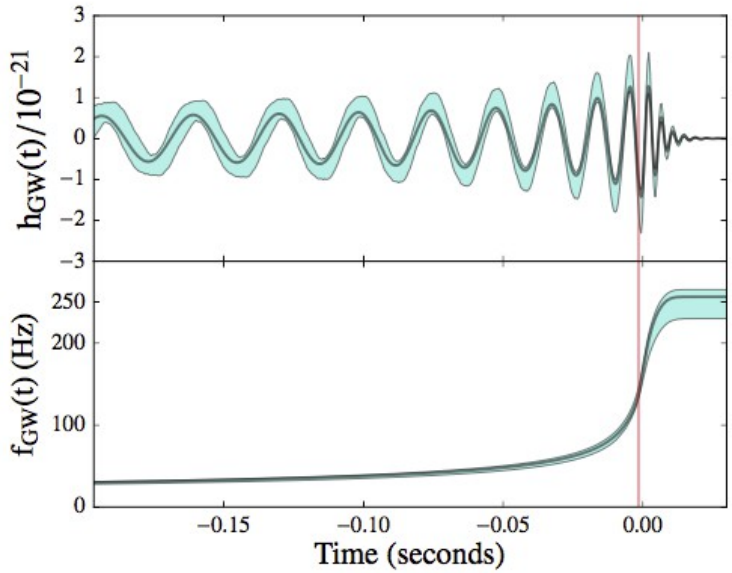


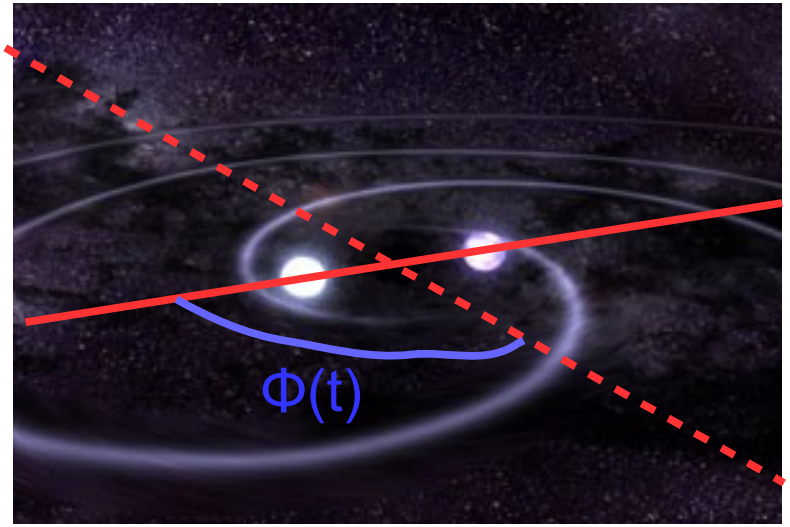
- From the inspiral, we can predict that ringdown frequency should be ~250 Hz

  ... and that's what we measure

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 φ_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

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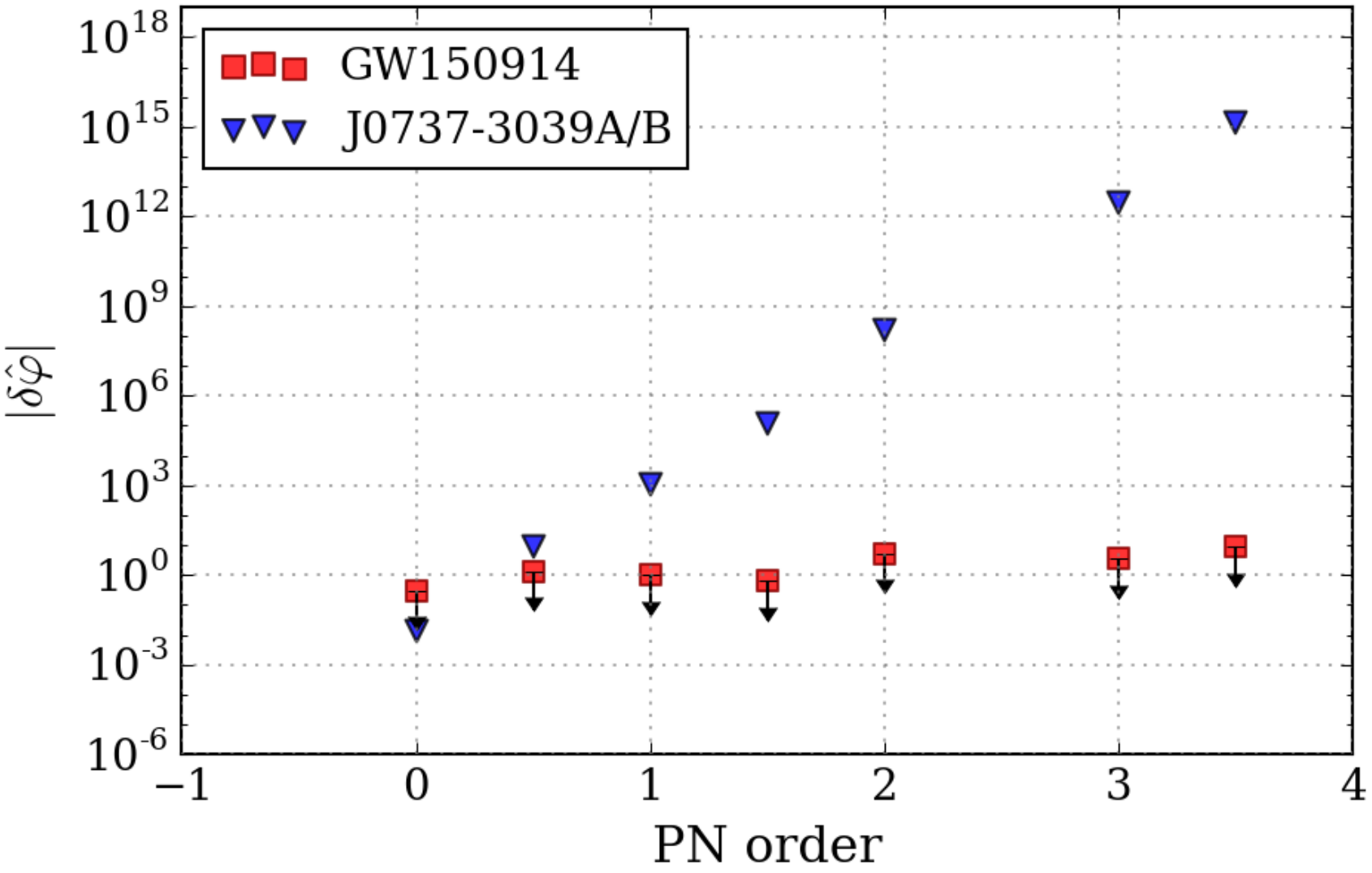

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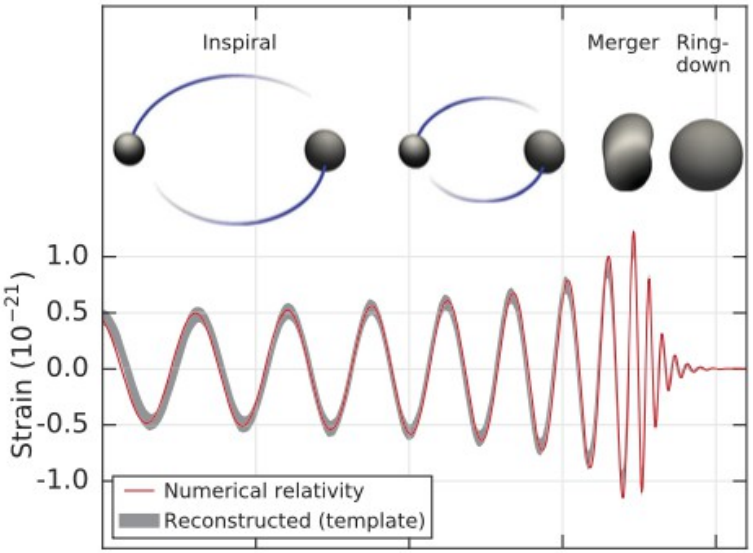

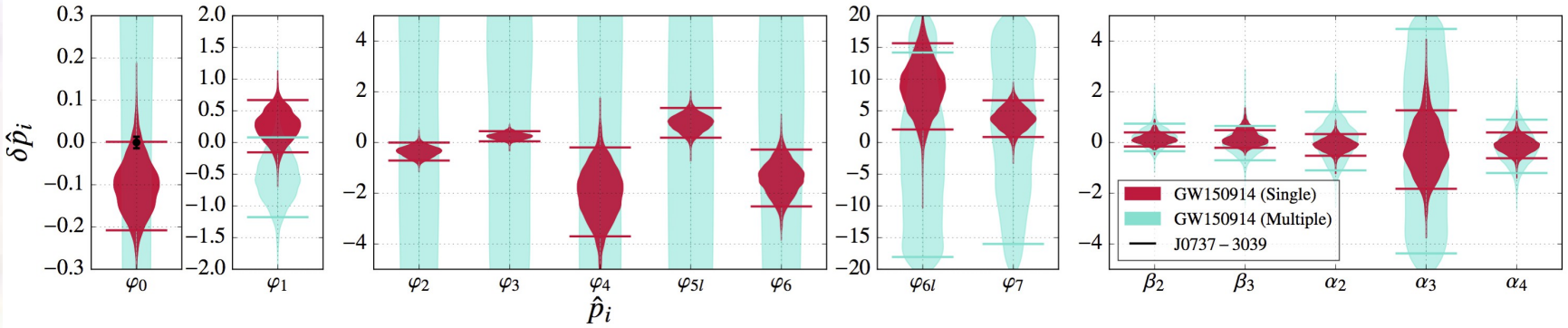

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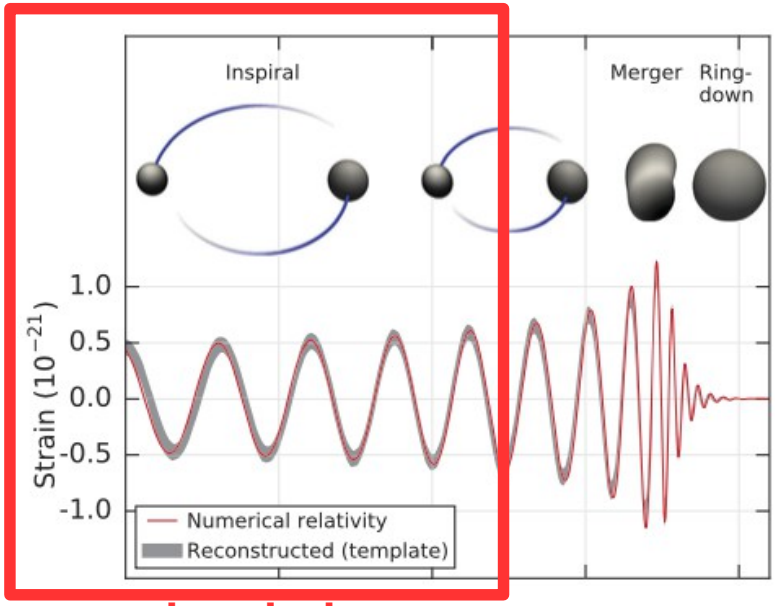
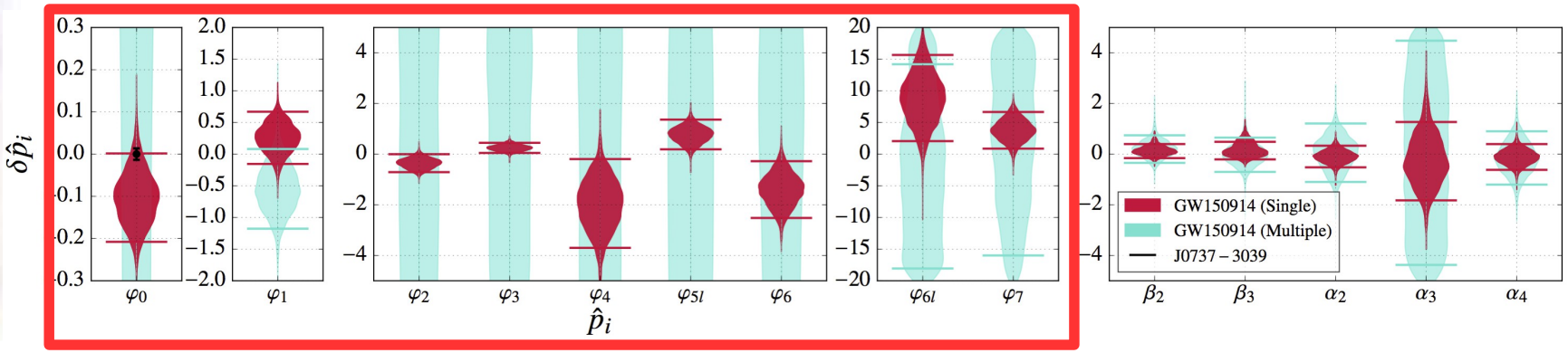


inspiral



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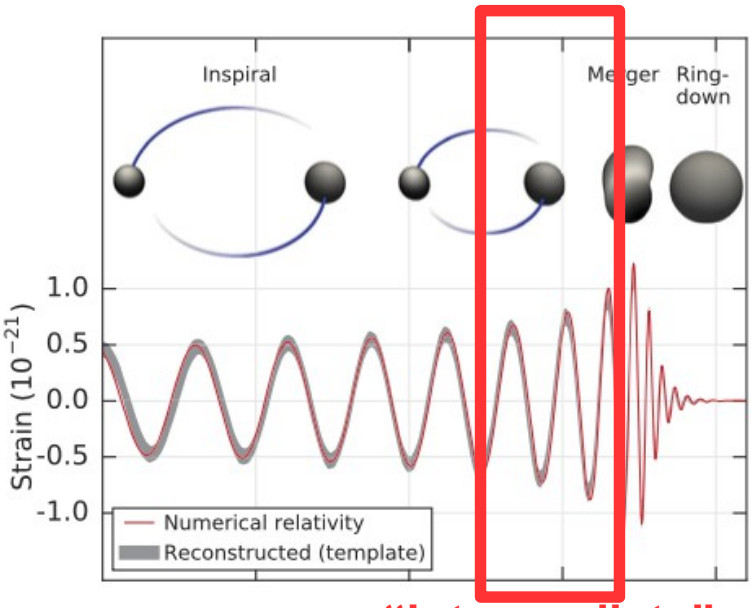
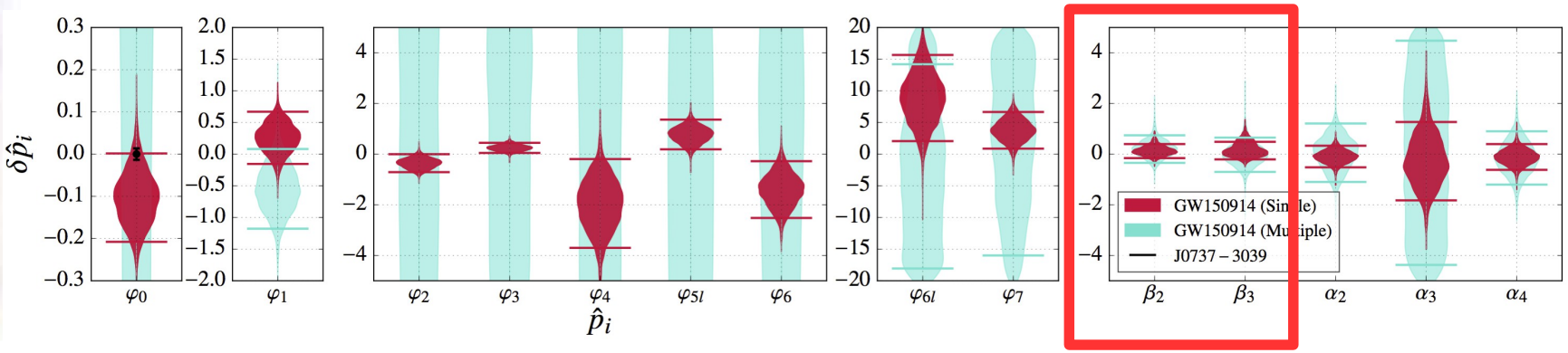


“intermediate”



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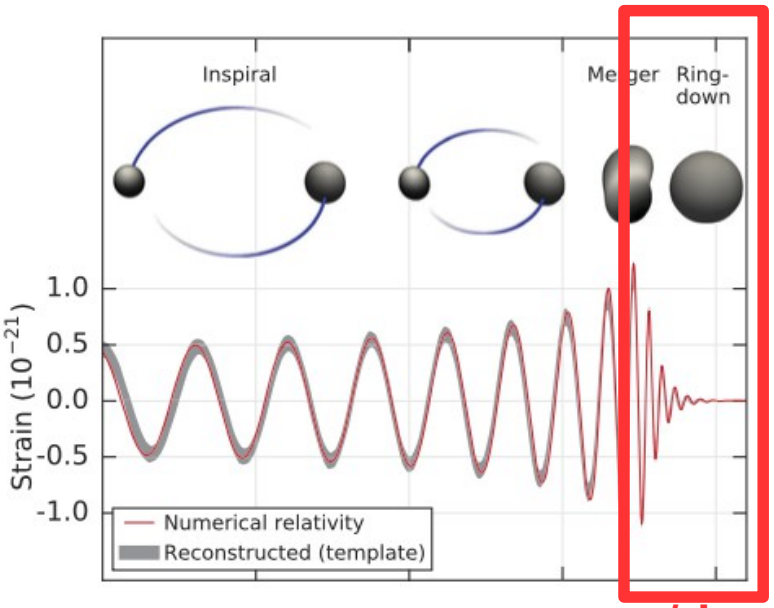
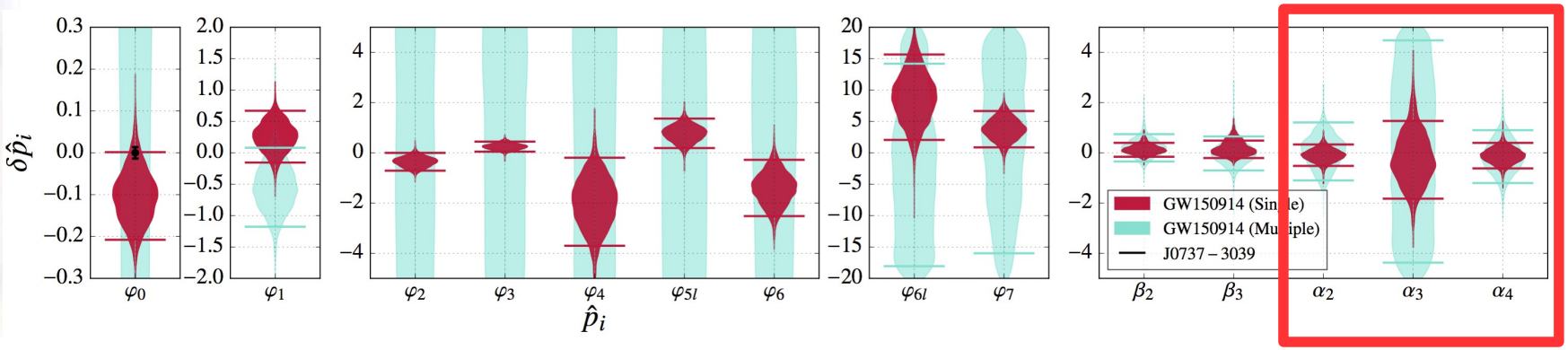


merger/ringdown



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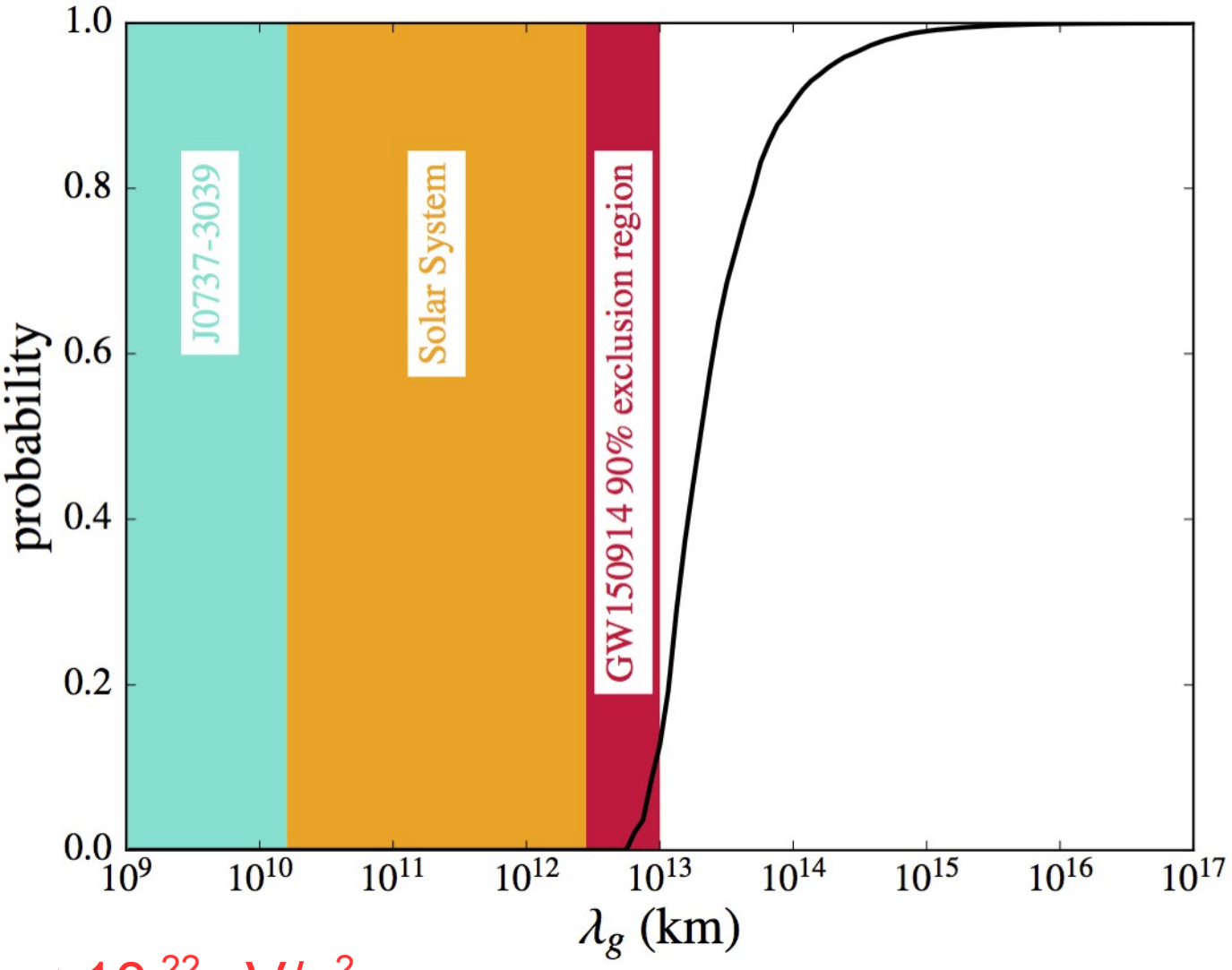
Does the graviton have mass?

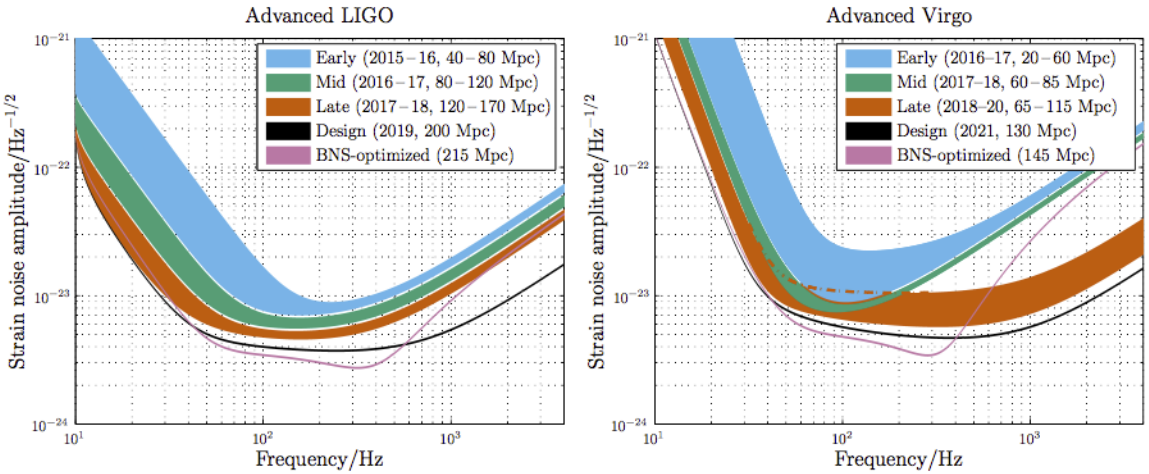


$m_g < 10^{-22}\ eV/c^2$

http://arxiv.org/abs/1602.03841

Where do we go from here?

Observing plans for the coming years



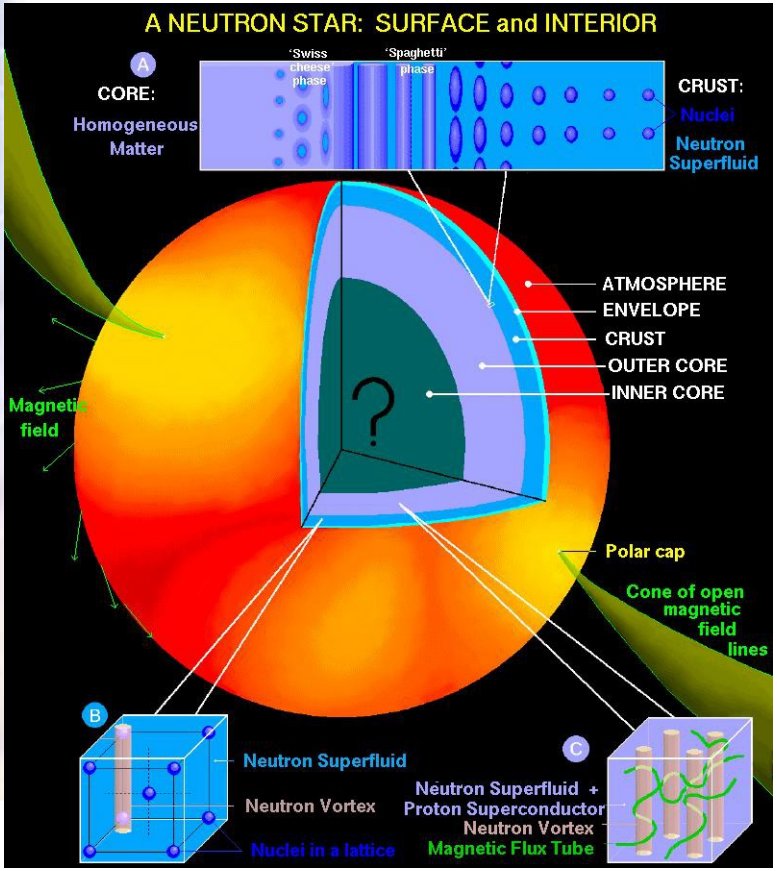
Progressive improvements in sensitivity:

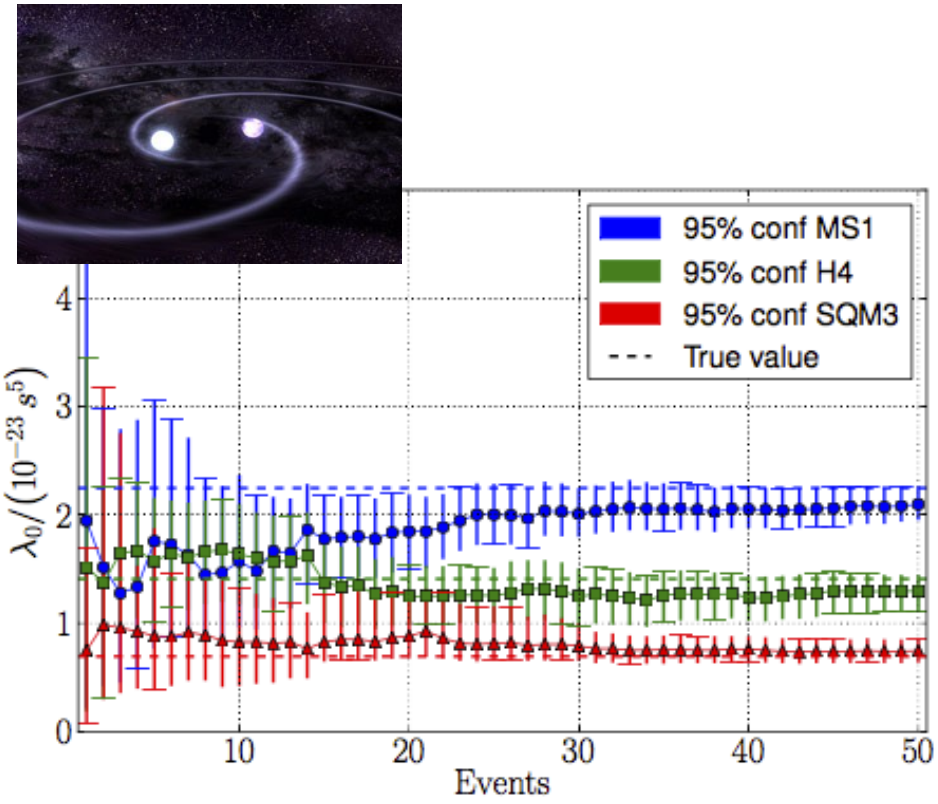
- 2015-2016 (**O1**): 4-month run with only Advanced LIGO
  - Detection of GW150914
  - Second half not yet analyzed – may contain further detection(s)!
- 2016-2017 (**O2**): 6-month run with **Advanced Virgo joining**
- 2017-2018 (**O3**): 9-month run LIGO + Virgo + **KAGRA?**
- 2019+: LIGO + Virgo (towards full sensitivity) + KAGRA
- 2022+: **LIGO-India** joins the network
  - *LIGO-India project approved this week!*

http://arxiv.org/abs/1304.0670

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

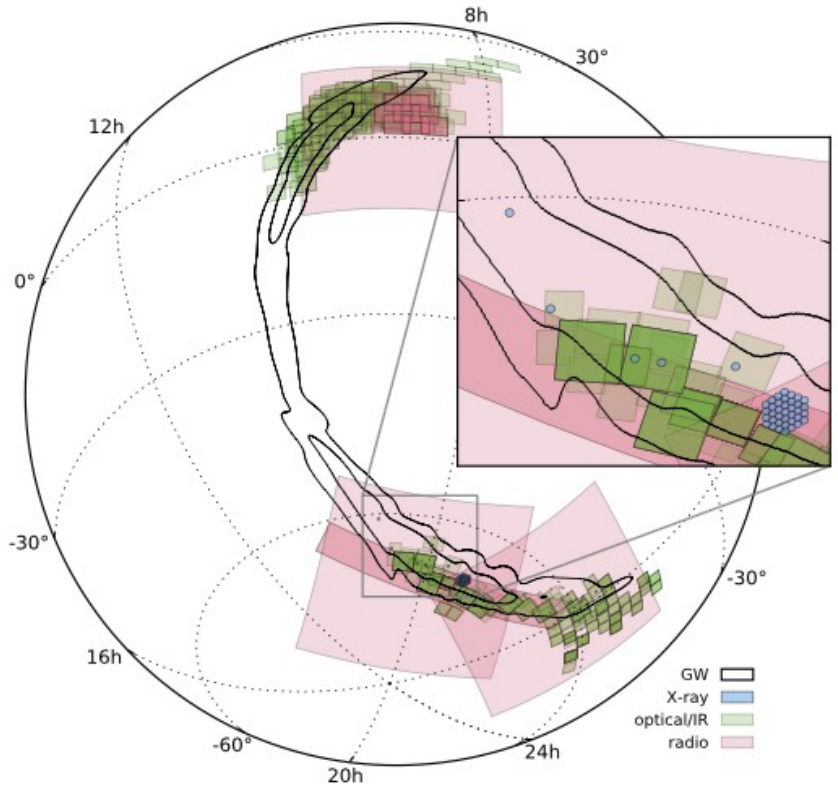




Del Pozzo, Li, Agathos, Van Den Broeck, Vitale, Phys. Rev. Lett. **111**, 071101 (2013)

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!)

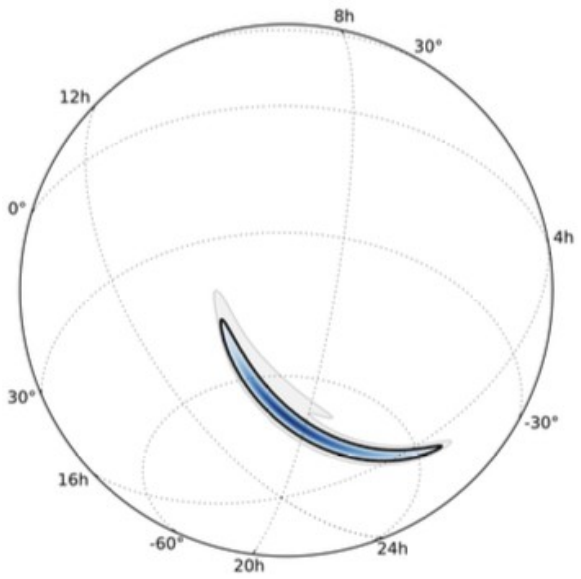


Footprints of Tiled Observations

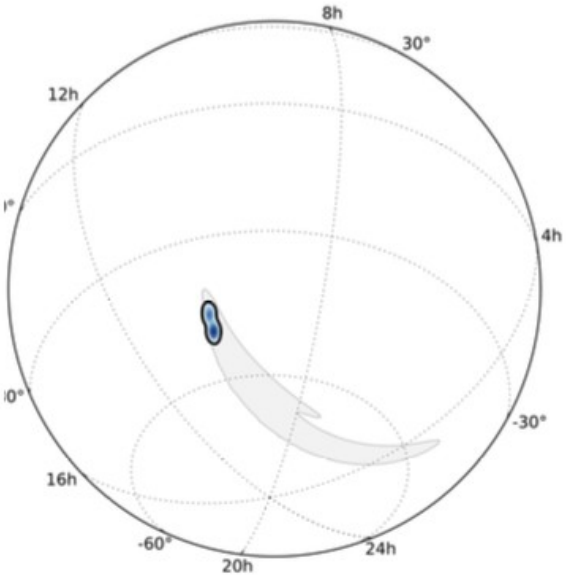
Group	Area (deg^2)	Contained probability (%) cWB[a]	LIB[b]	LALInf[c]
Swift	2	0.6	0.8	0.1
DES	94	32.1	13.4	6.6
INAF	93	28.7	9.5	6.1
J-GEM	24	0.0	1.2	0.4
MASTER	167	9.3	3.3	6.0
Pan-STARRS	355	27.9	22.9	8.8
SkyMapper	34	9.1	7.9	1.7
TZAC	29	15.1	3.5	1.6
ZTF	140	3.1	2.9	0.9
(total optical)	759	76.5	46.8	23.9
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 ~10 deg^2



LIGO Hanford + LIGO Livingston



LIGO Hanford + LIGO Livingston

+ Advanced Virgo

Cosmography with gravitational waves

- Gravitational waves are cosmic distance markers:

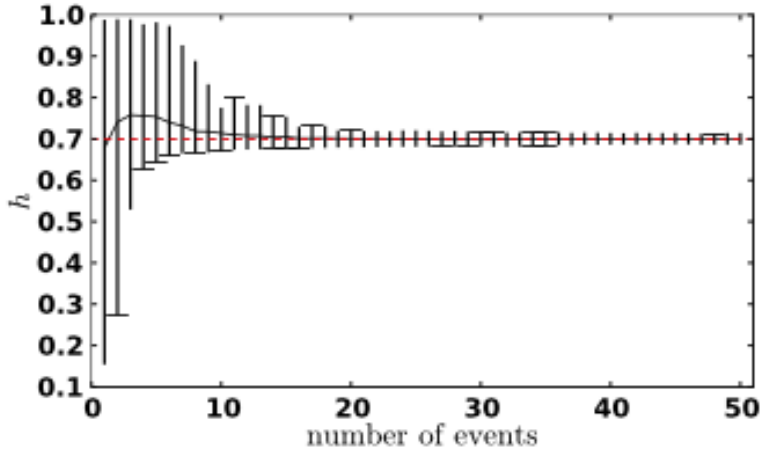
$$A(t) = \frac{\mathcal{M}^{5/3}(m_1, m_2) g(\theta, \phi, \iota, \psi) F^{2/3}(t)}{D}$$

  - Masses m_1, m_2 can be obtained from the phase
  - Same with instantaneous frequency $F(t)$
  - With multiple detectors, information about sky position (θ,ϕ) and orientation (ι,ψ)

Can extract distance D!

- If both distance *D* and redshift *z* are known, can perform independent measurement of the Hubble constant H_0

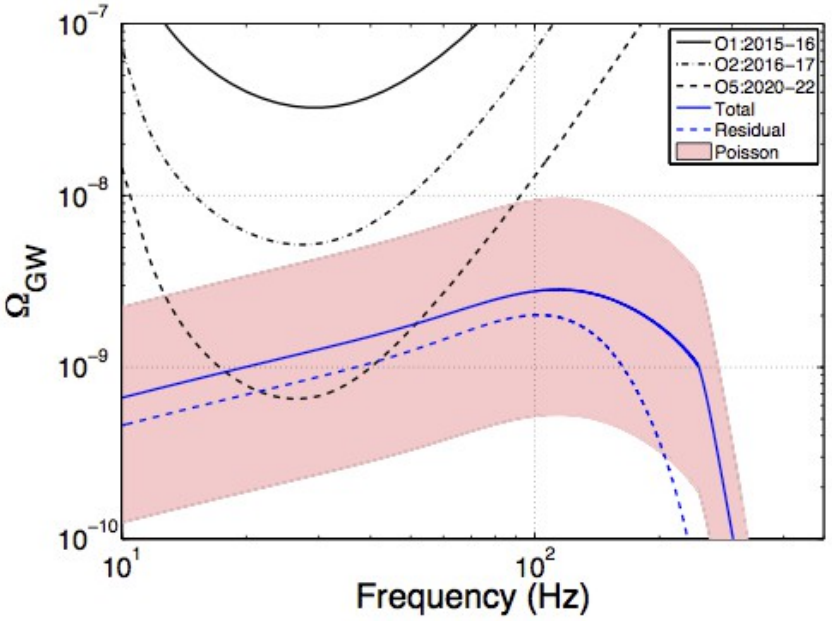
  - Use electromagnetic counterparts to find *z*
  - Or, infer it approximately from 3D position + galaxy catalogs

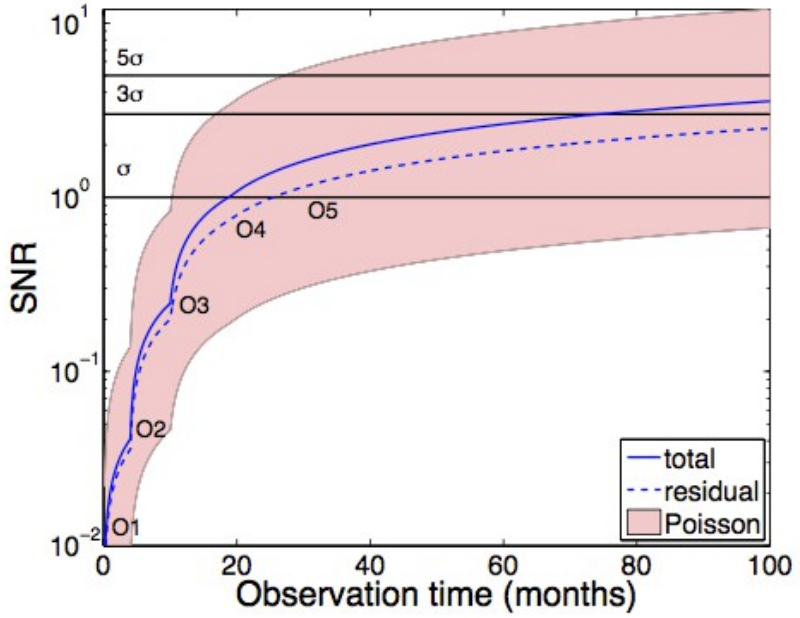


Del Pozzo, Phys. Rev. D **86**, 043011 (2012)

“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!

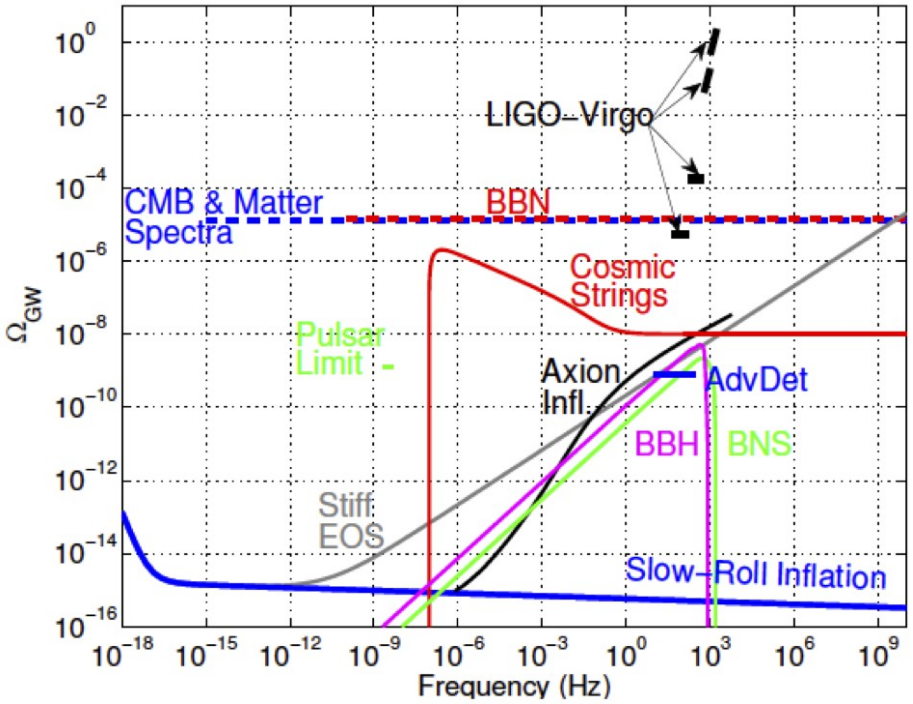




http://arxiv.org/abs/1602.03847

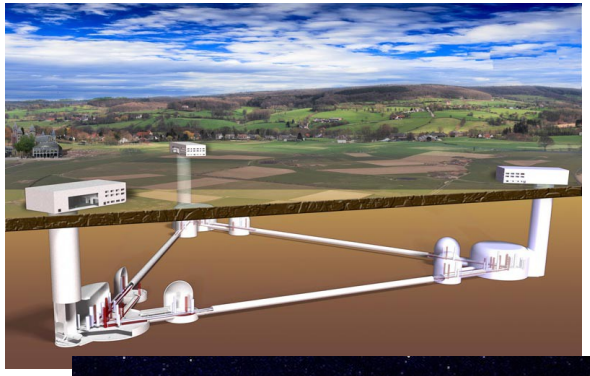
Primordial gravitational waves from early Universe

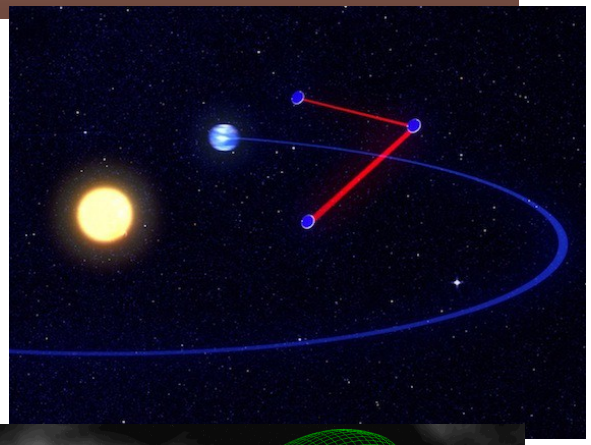
$$\Omega_{gw}(f) = \frac{d\rho_{gw}(f)}{\rho_c d(\ln f)}$$

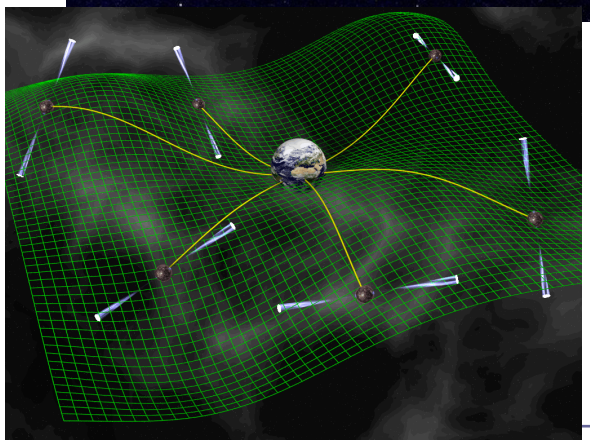


- Between initial and final advanced detectors: Factor 10^4 gain in Ω_{gw}
  - Better sensitivity overall
  - Wider frequency band
- Possible signals from a fraction of a second after Big Bang:
  - Termination of inflation (e.g. axion inflation)
  - Phase transitions: fundamental forces splitting off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

The next few decades



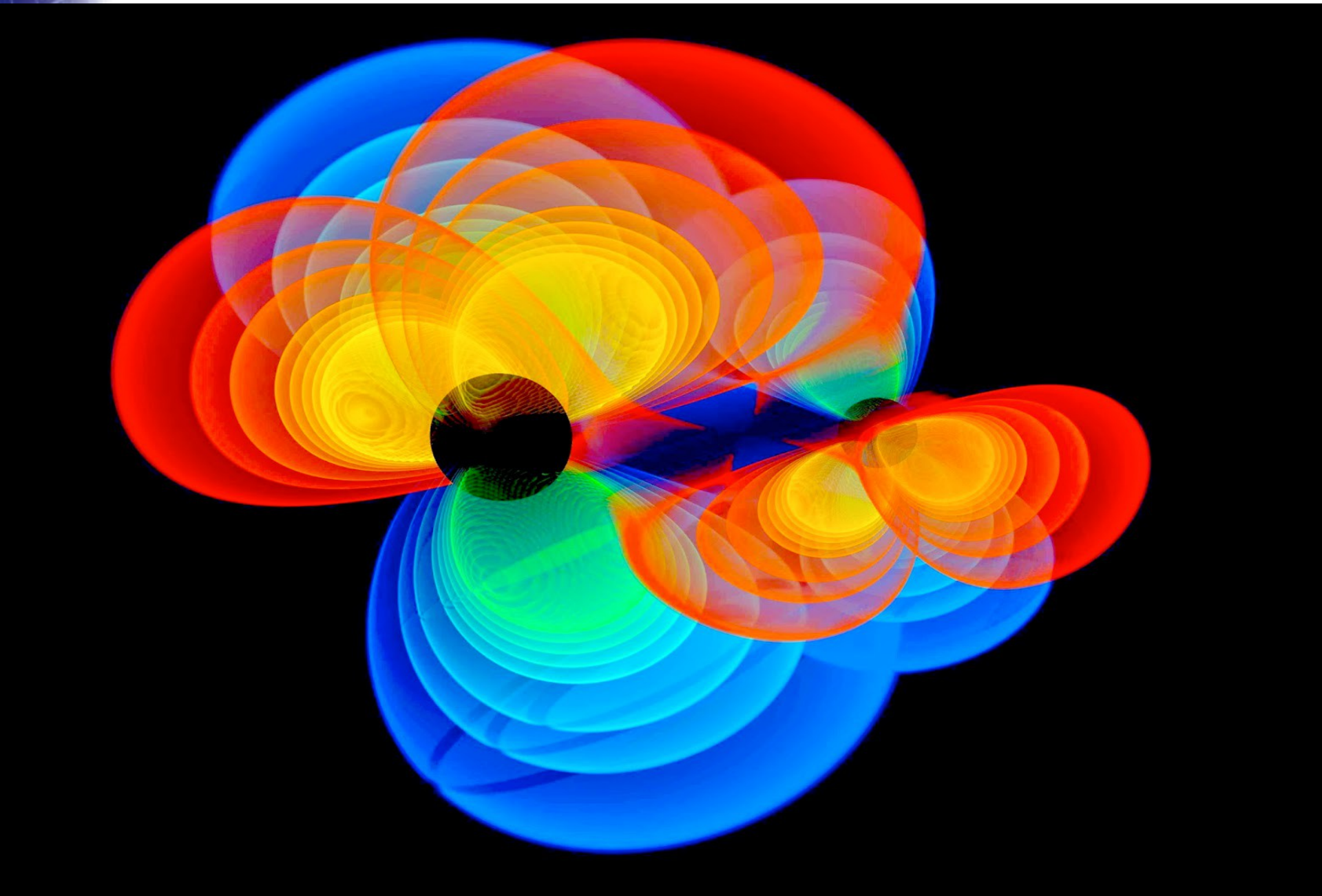




- Einstein Telescope (~2030?)
  - 3rd generation observatory
  - 10^5 binary mergers per year
  - Evolution of the Universe (e.g. dark energy)
  - Build in The Netherlands?
- eLISA (approved for 2034)
  - 3 probes in orbiting the Sun, 10^6 km distance
  - Probe low frequencies: 10^{-5} – 10^{-1} Hz
  - Mergers of supermassive binary black holes throughout the Universe; study their growth
  - Pathfinder mission launched in 2015
- Pulsar timing arrays (active now)
  - 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!