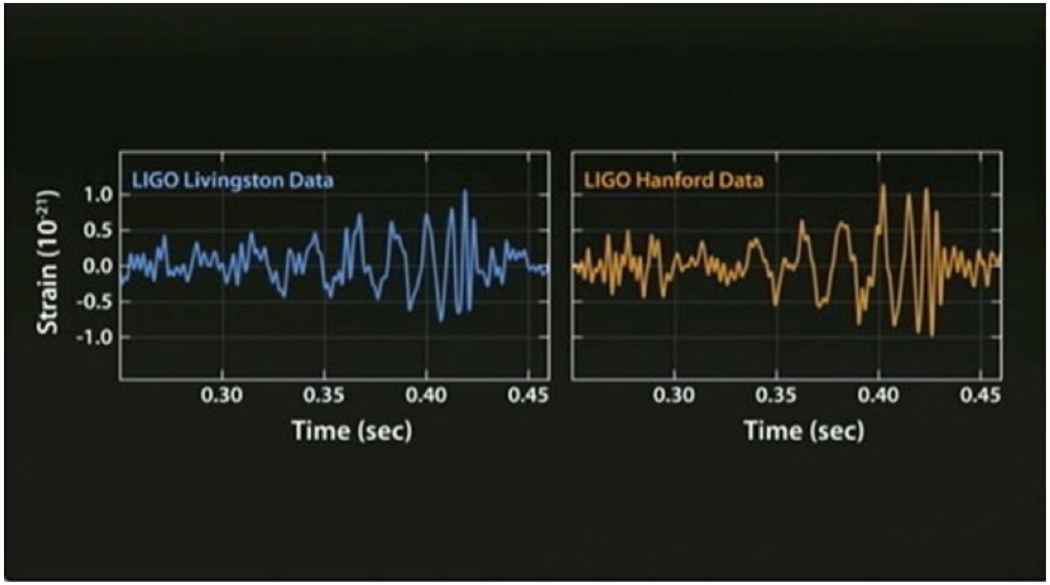
The direct detections of gravitational waves:

The first discoveries, and where we go from here



Direct detection of gravitational waves

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 1.0×10^{-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

What are gravitational waves?

- Einstein field equations:

$$G_{\mu\nu} = 8\pi \frac{G}{c^4} T_{\mu\nu}$$

- Far from the source: metric is flat with small perturbation

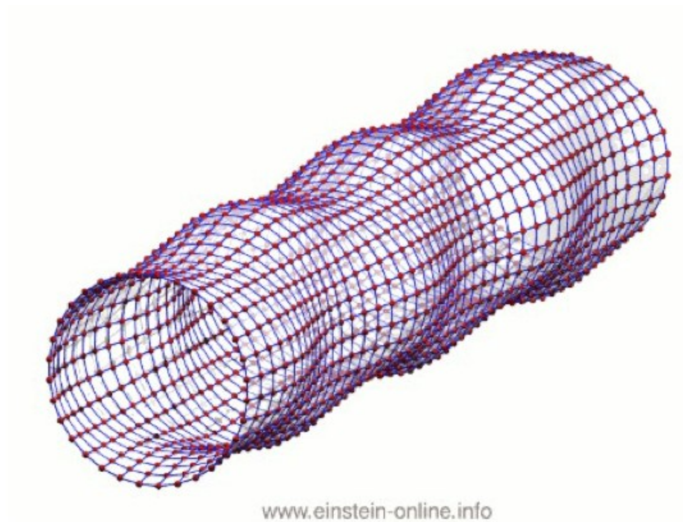
$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$

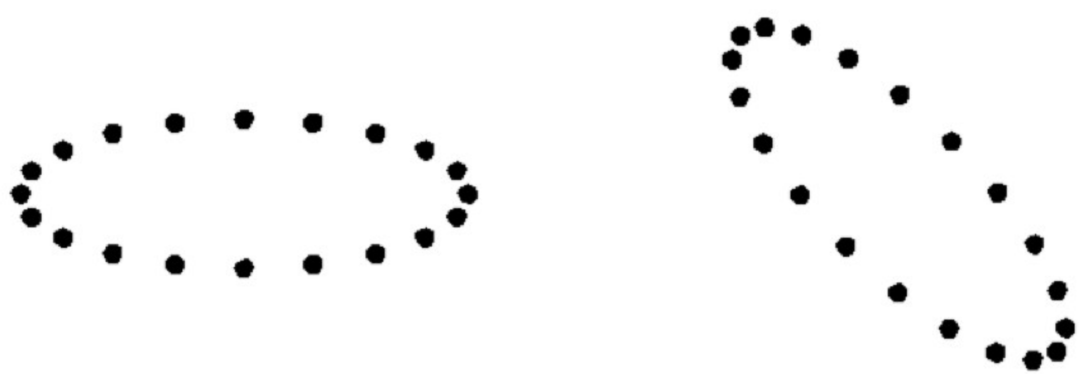
- Far from the source: Einstein equations reduce to wave equation for the perturbation:

$$\left(-\frac{\partial^2}{c^2\partial t^2} + \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2}\right) h_{\mu\nu}^{\mathrm{TT}} = 0$$

What are gravitational waves?

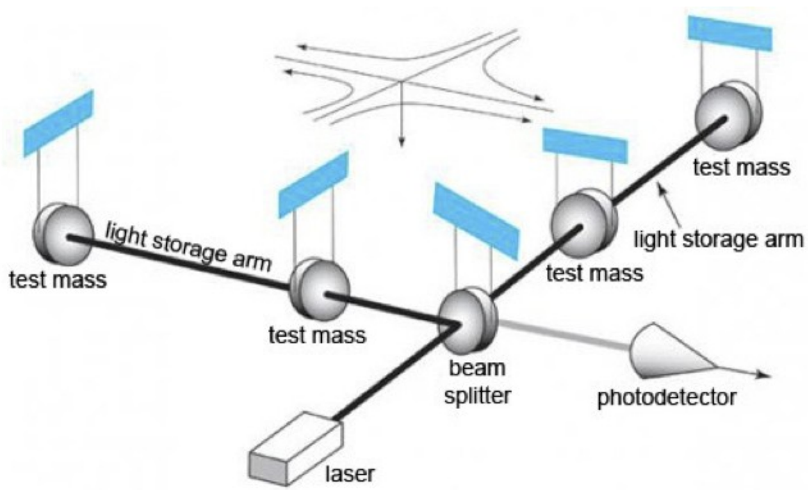
- Gravitational waves have the effect of traveling tidal waves



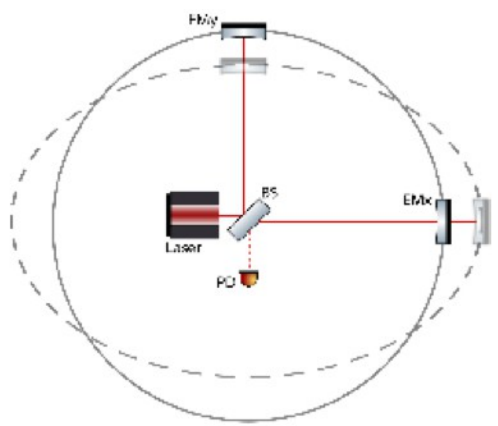


Detection of gravitational waves: laser interferometers

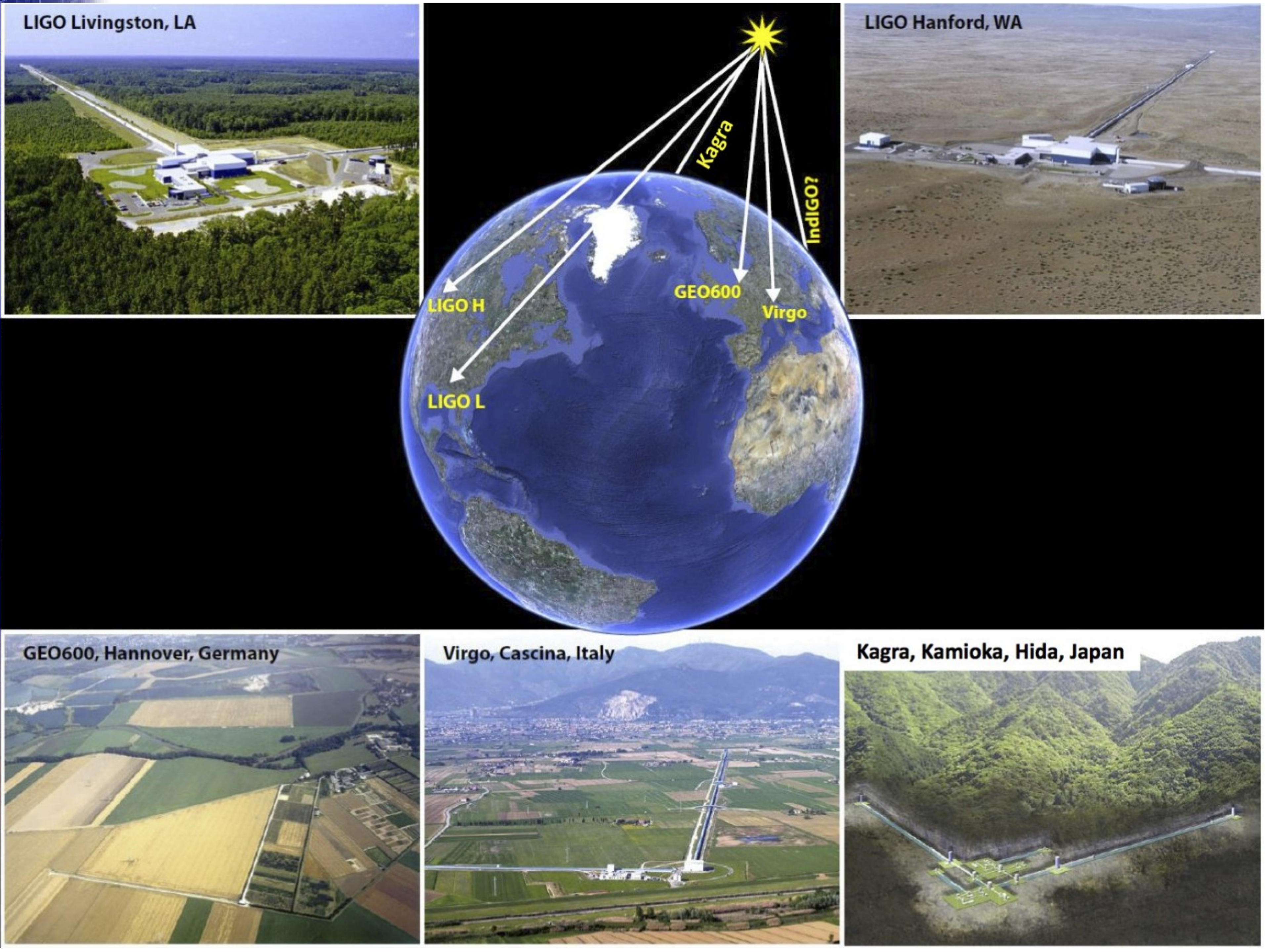
- Laser interferometer:



- Arms are periodically stretched and compressed by passing gravitational wave:



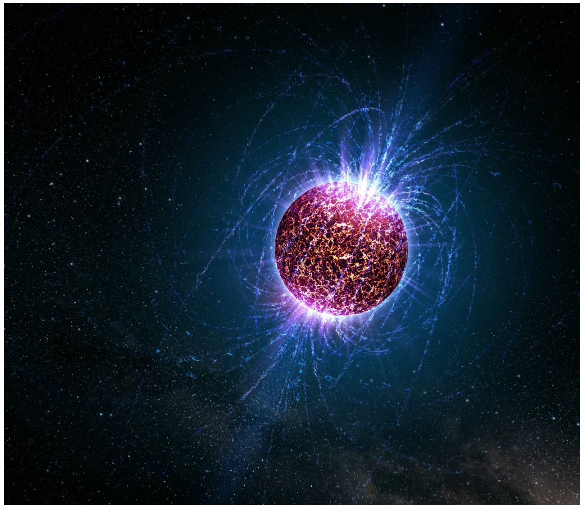
- Extreme sensitivities required: $\Delta L/L \sim 10^{-23}$


LIGO Livingston, LA
LIGO Hanford, WA
Kagra
IndIGO?
LIGO H
GEO600
Virgo
LIGO L
GEO600, Hannover, Germany
Virgo, Cascina, Italy
Kagra, Kamioka, Hida, Japan

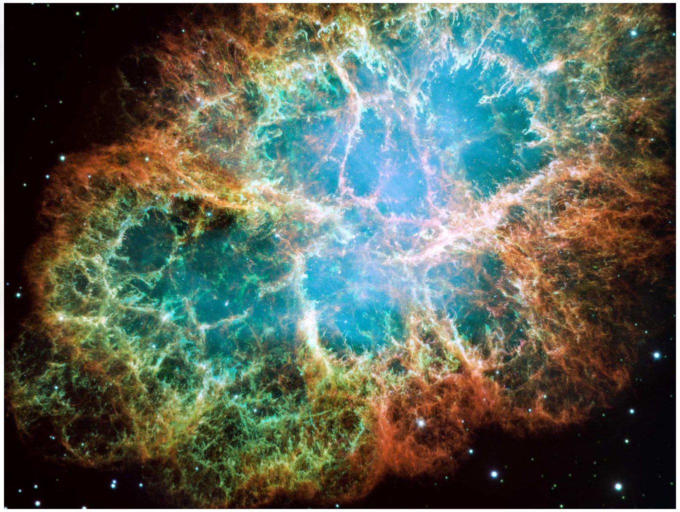
Sources of gravitational waves

Coalescing binary neutron stars and black holes

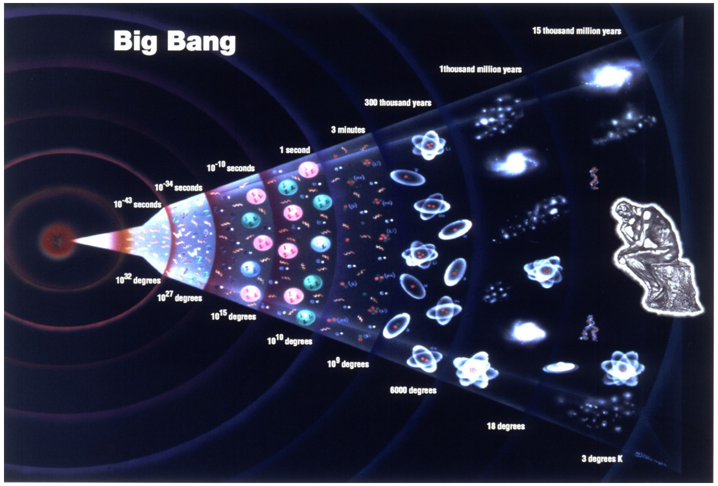
Fast-spinning neutron stars



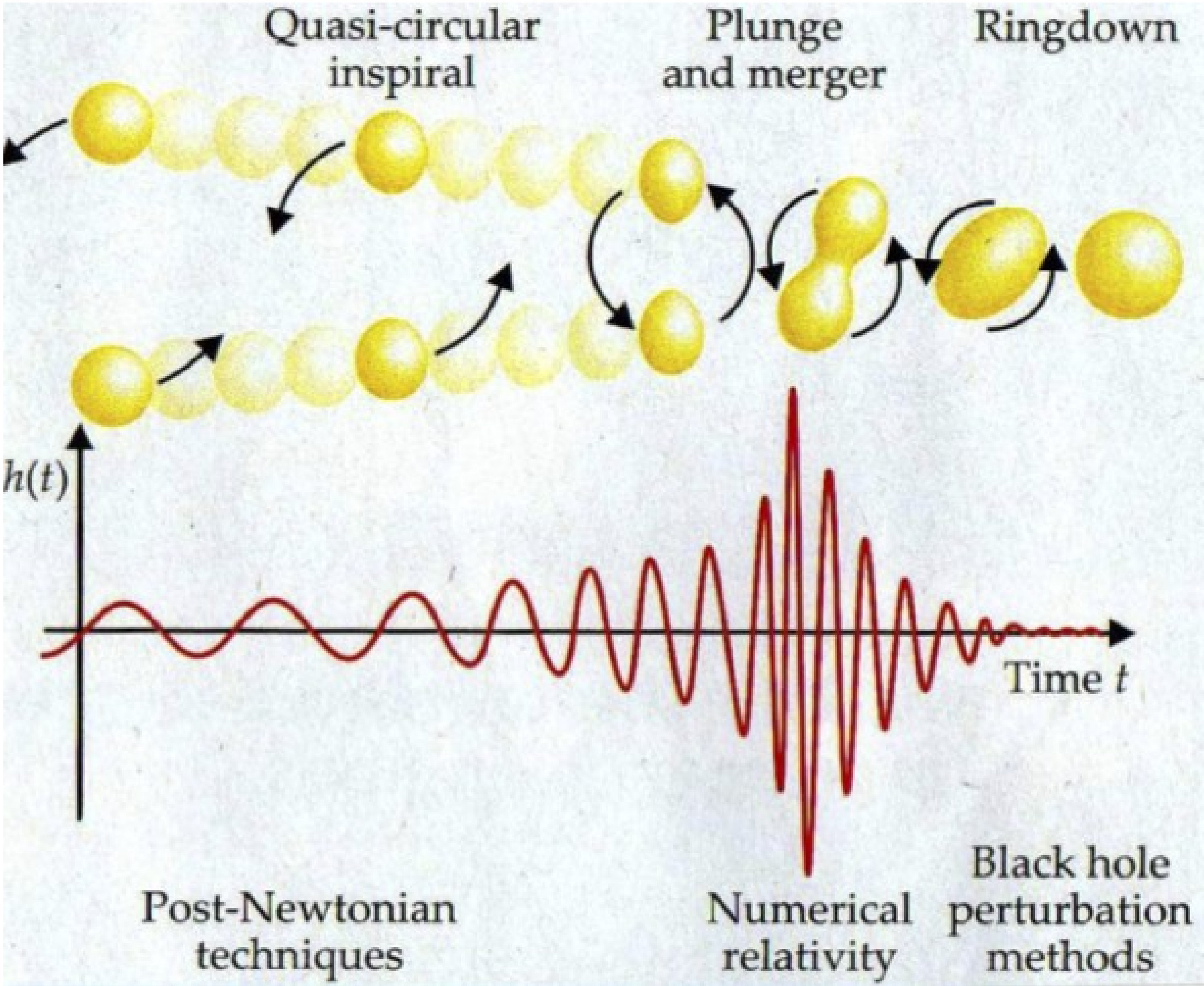
Bursts (e.g. supernovae)



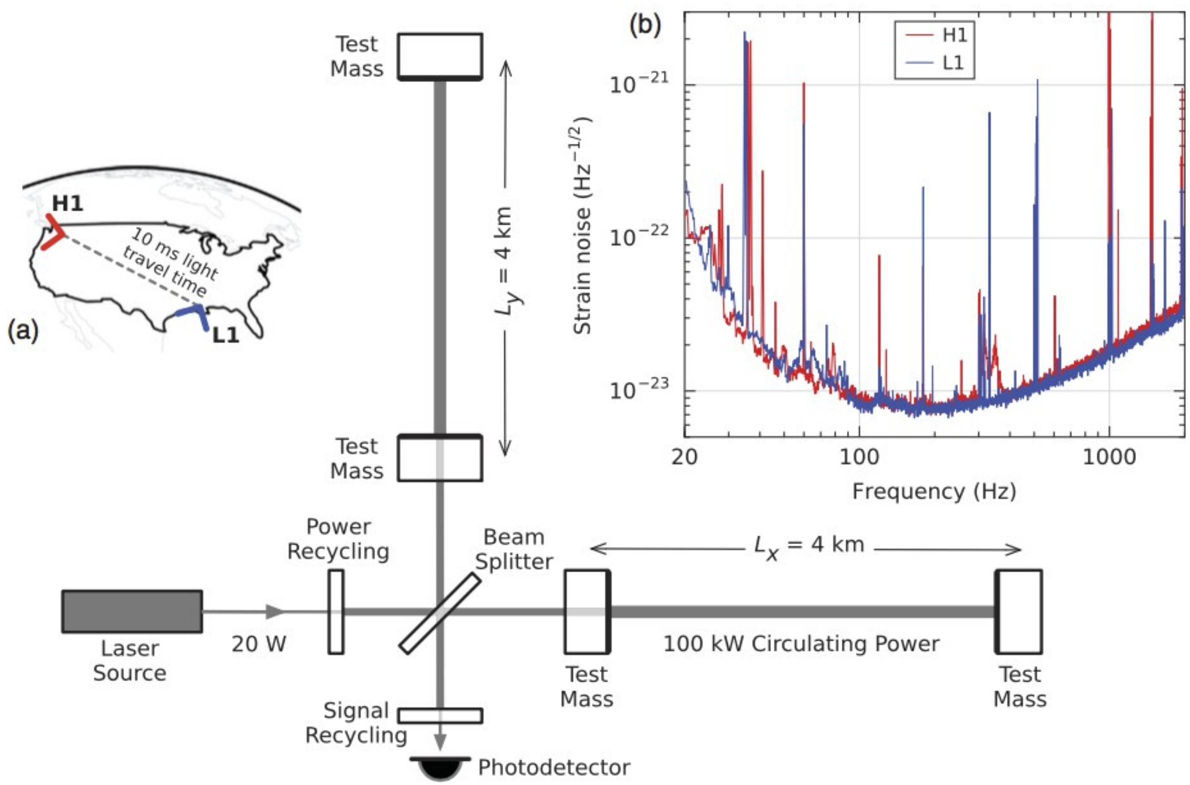
“Stochastic” gravitational waves



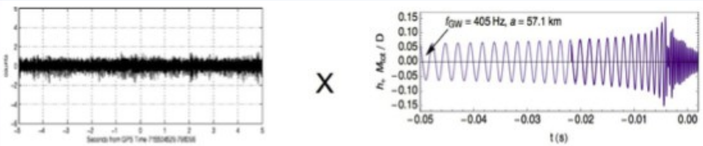
Coalescence of binary black holes

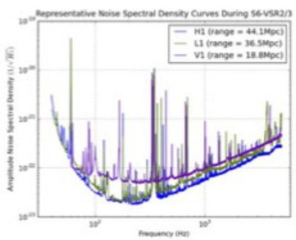


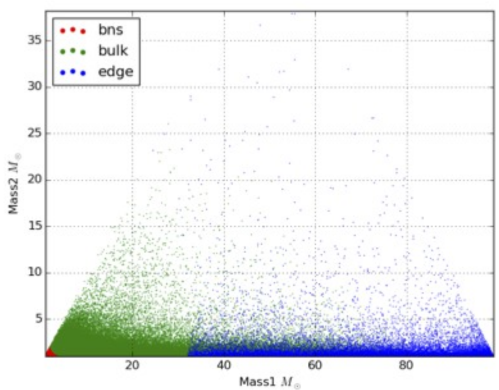
The Advanced LIGO detectors

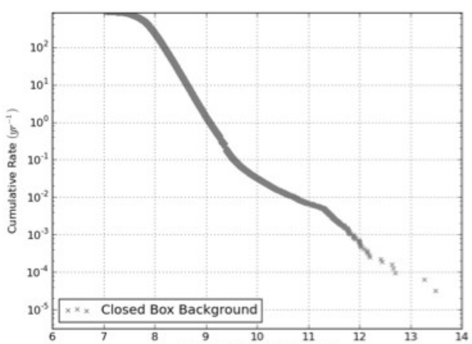


Searching for a signal







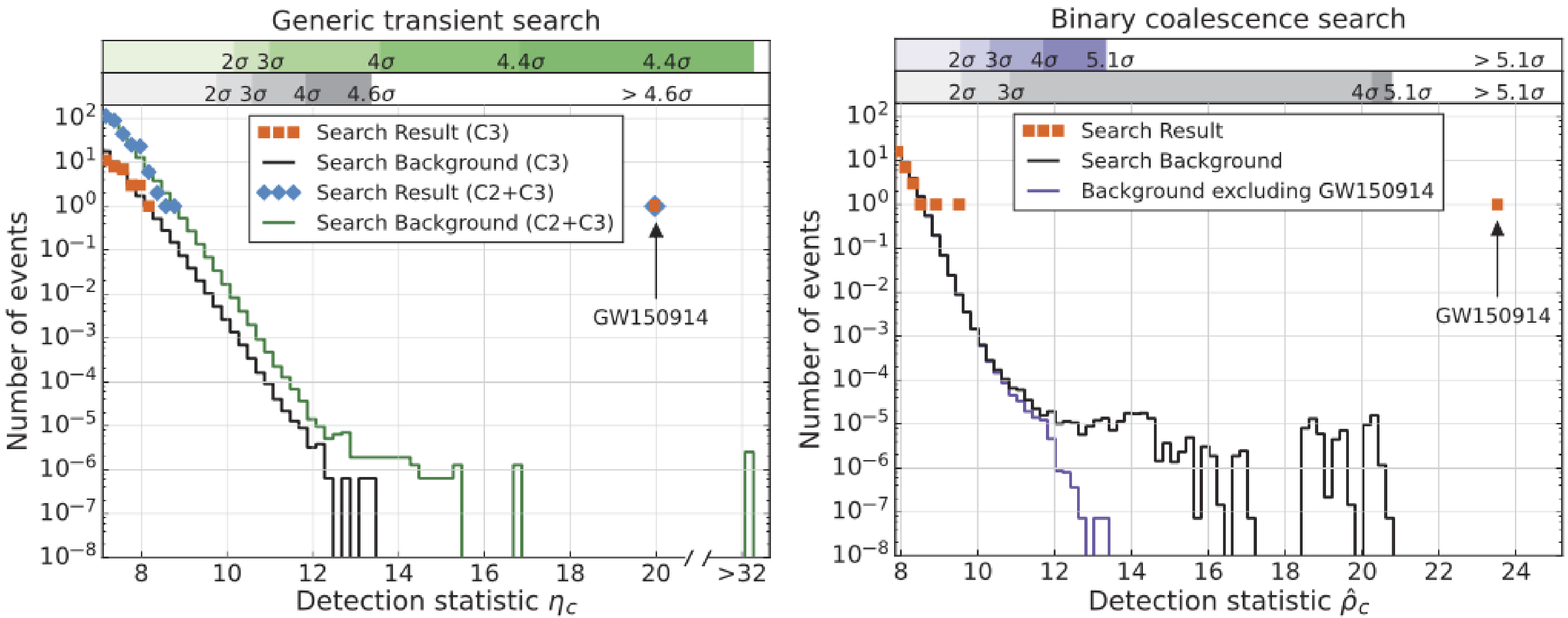


- Search by “matched filtering”
  - Integrate signal against data for fixed choice of masses and spins
  - Weigh the integrand with detector sensitivity as function of frequency

→ “Signal-to-noise ratio”

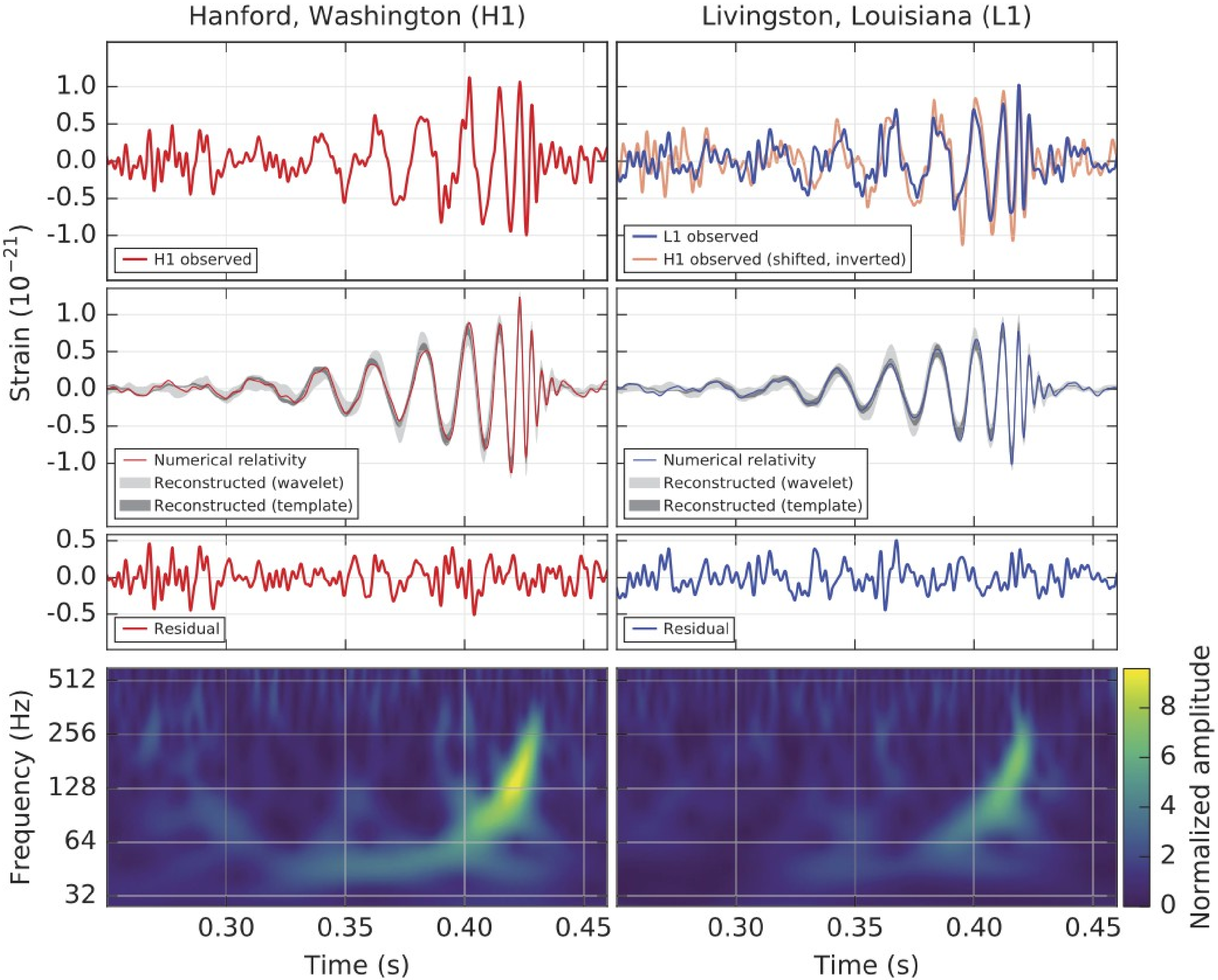
- Repeat for large number of parameter choices
  - “Template bank”
  - Density of templates determined by how different waveforms get as parameters are varied
- If high signal-to-noise ratio attained:
  - Waveform shape consistent with signal?
  - Coincident between detectors?
  - Consistent parameter between detectors?
- Time-slide data streams w.r.t. each other
  - Obtain distribution of false positives

The first detection



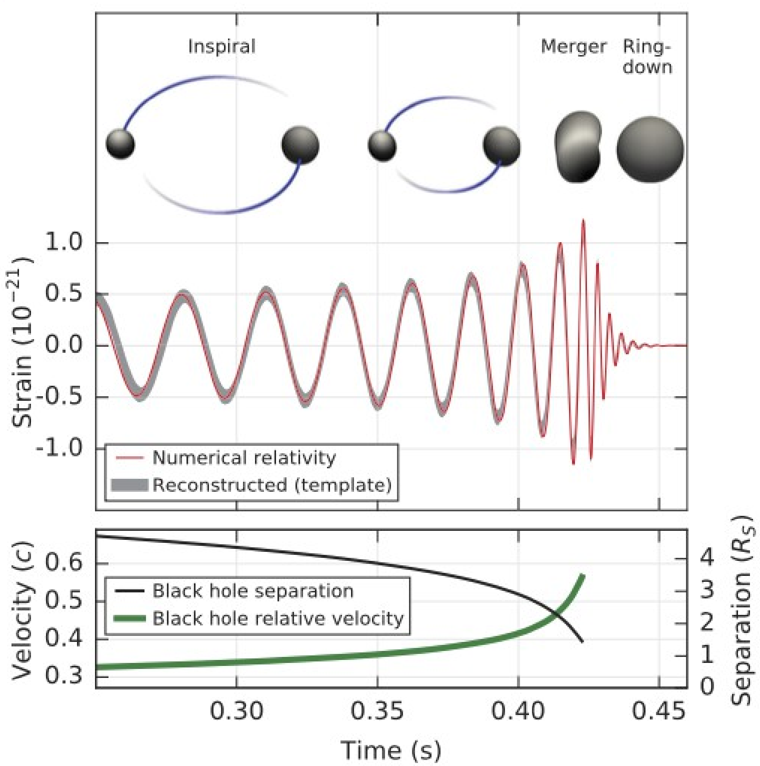
- Found in “unmodeled” and “modeled” searches
- “Modeled search” (which makes use of waveform predictions) using 16 days of coincident Livingston-Hanford data
- At time of first publication:
  - False alarm rate < 1 in 203000 years
  - **Significance > 5.1σ**

The first detection



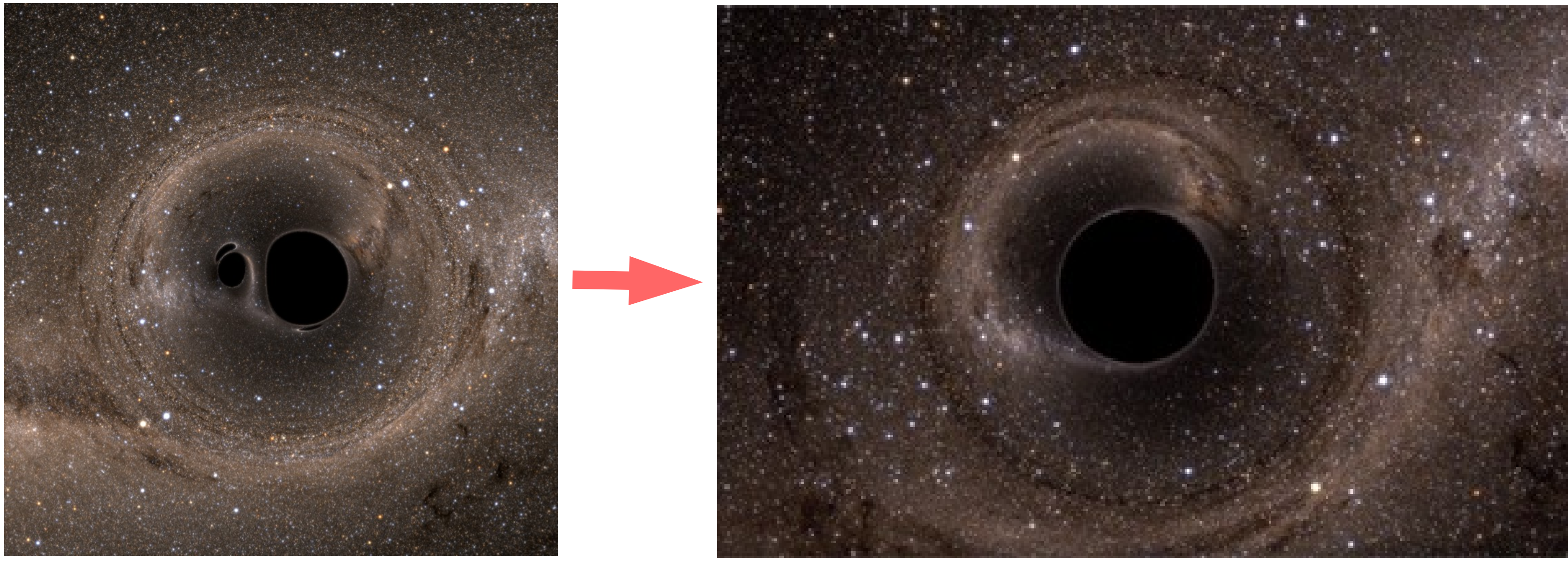
The first detection

- 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	$0.09^{+0.03}_{-0.04}$

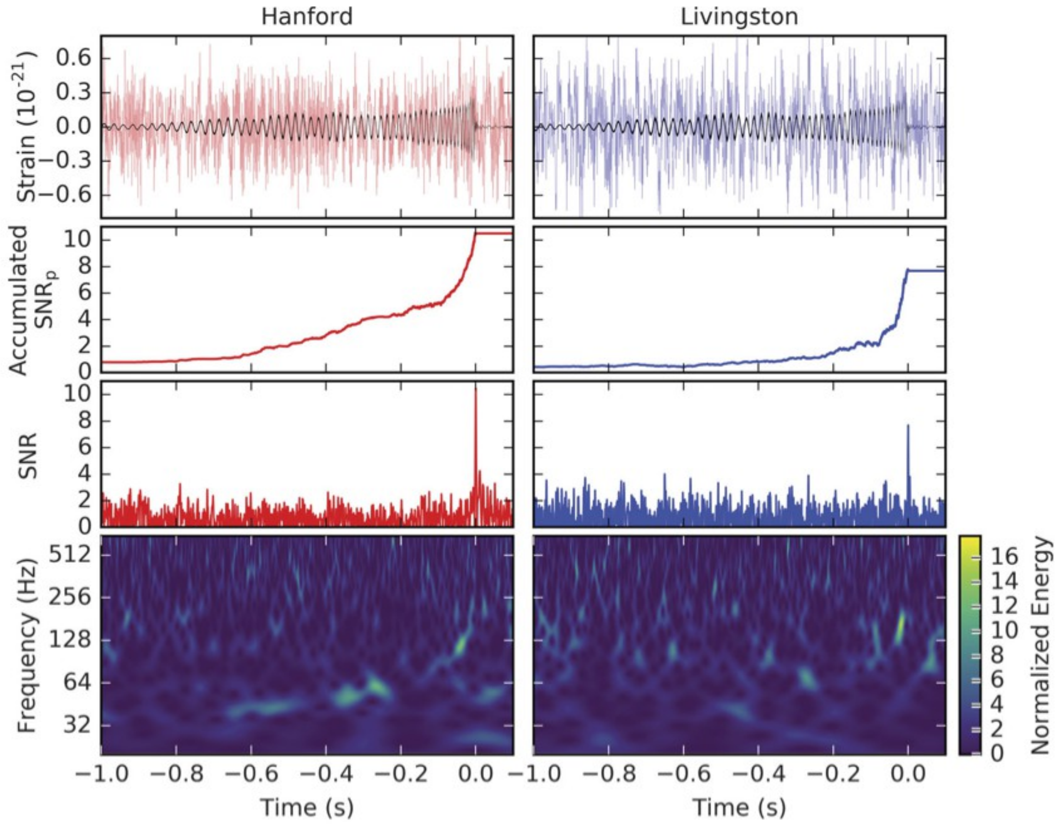
At least four breakthroughs in one



- 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

The second detection: GW151226

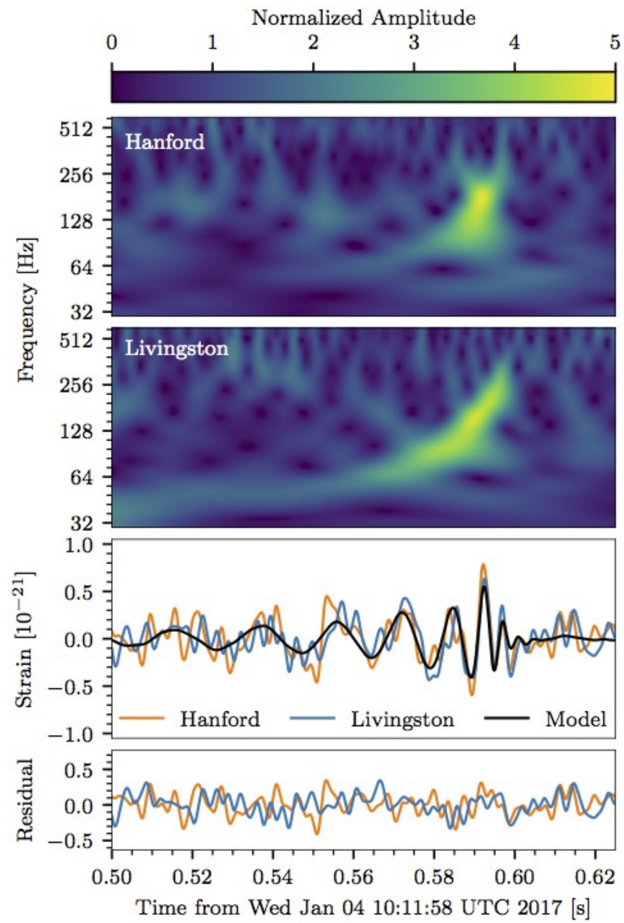
7.5 + 14 solar masses



https://arxiv.org/abs/1606.04856

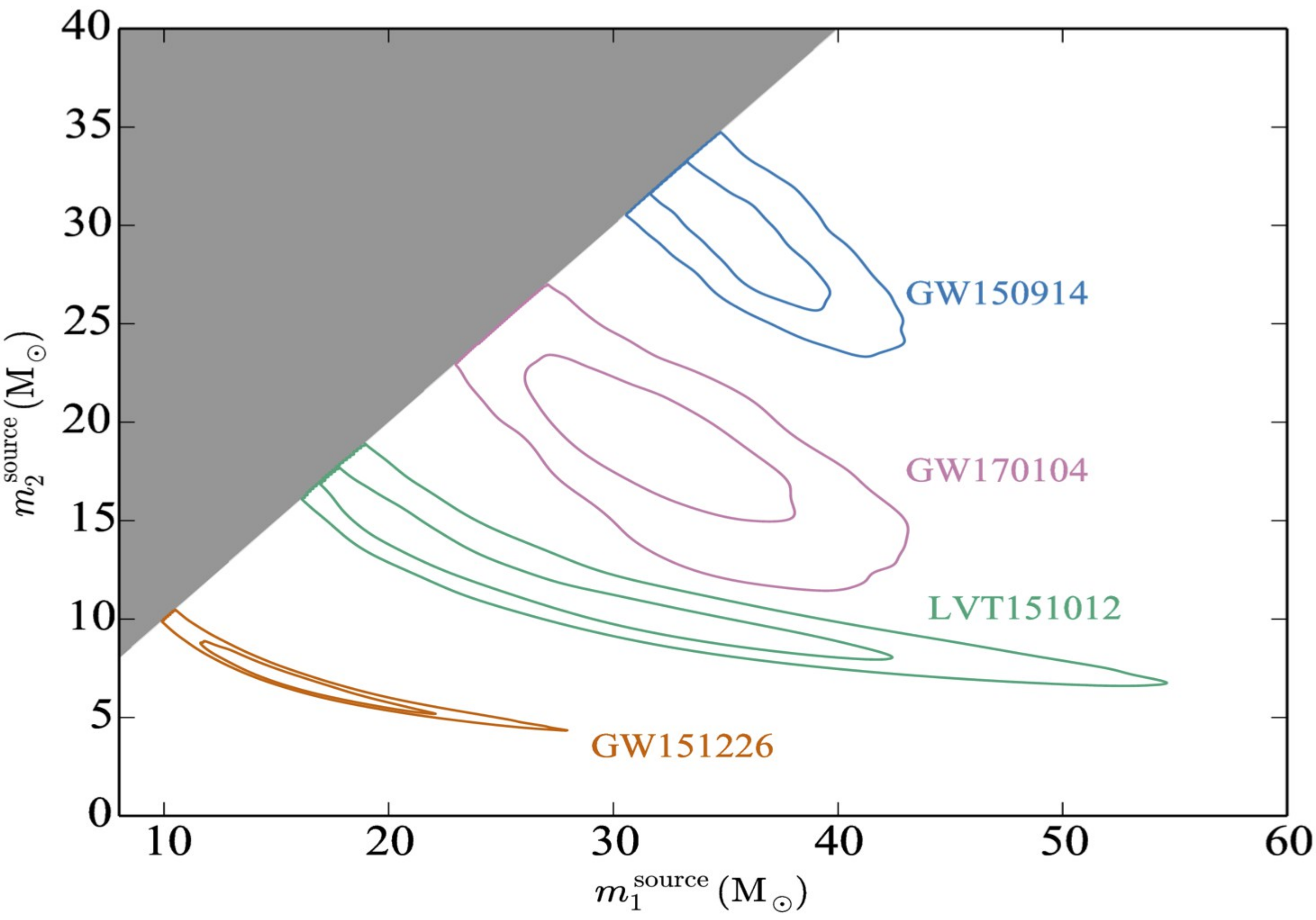
The third detection: GW170104

19.5 + 31 solar masses

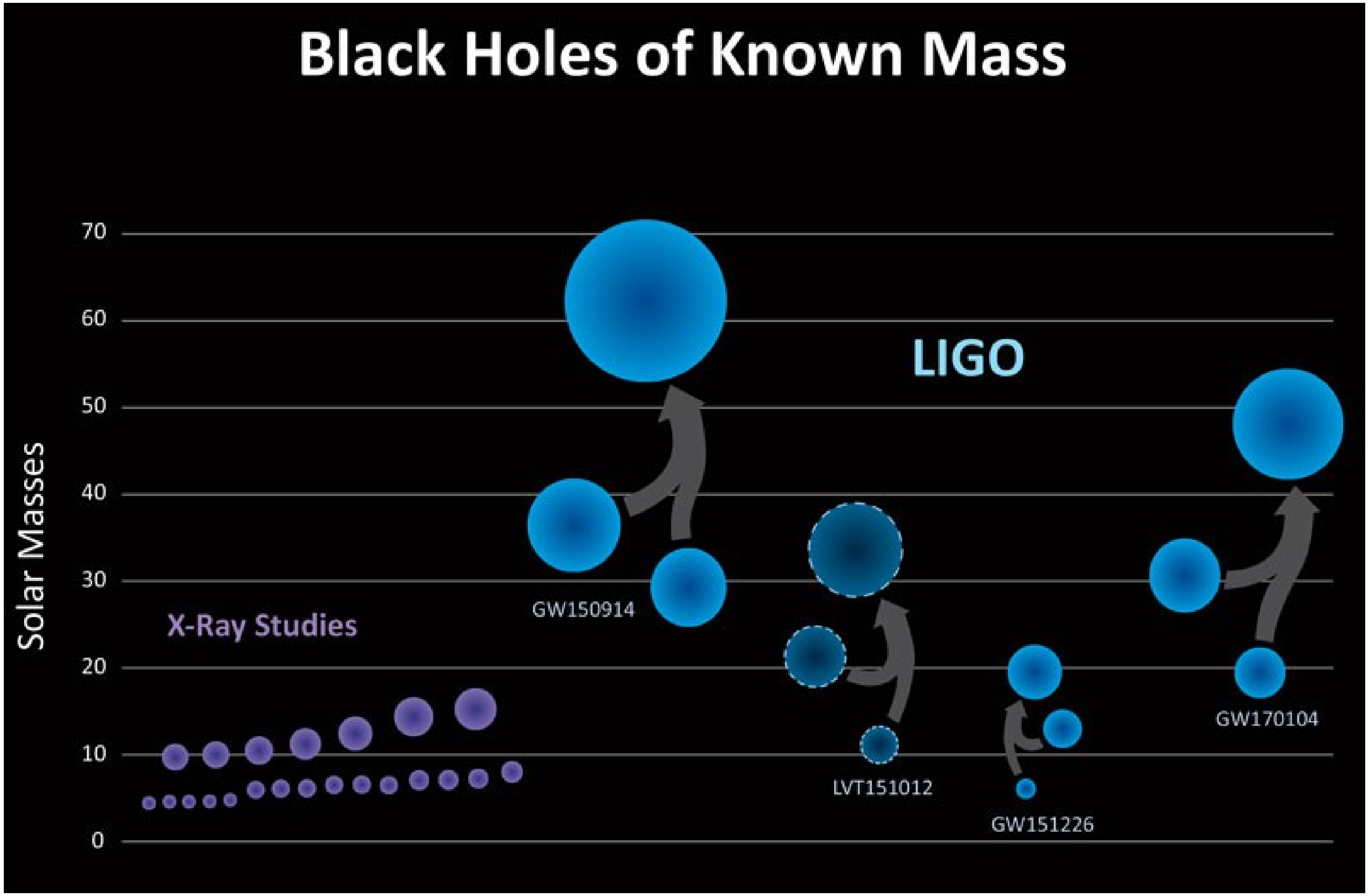


https://arxiv.org/abs/1706.01812

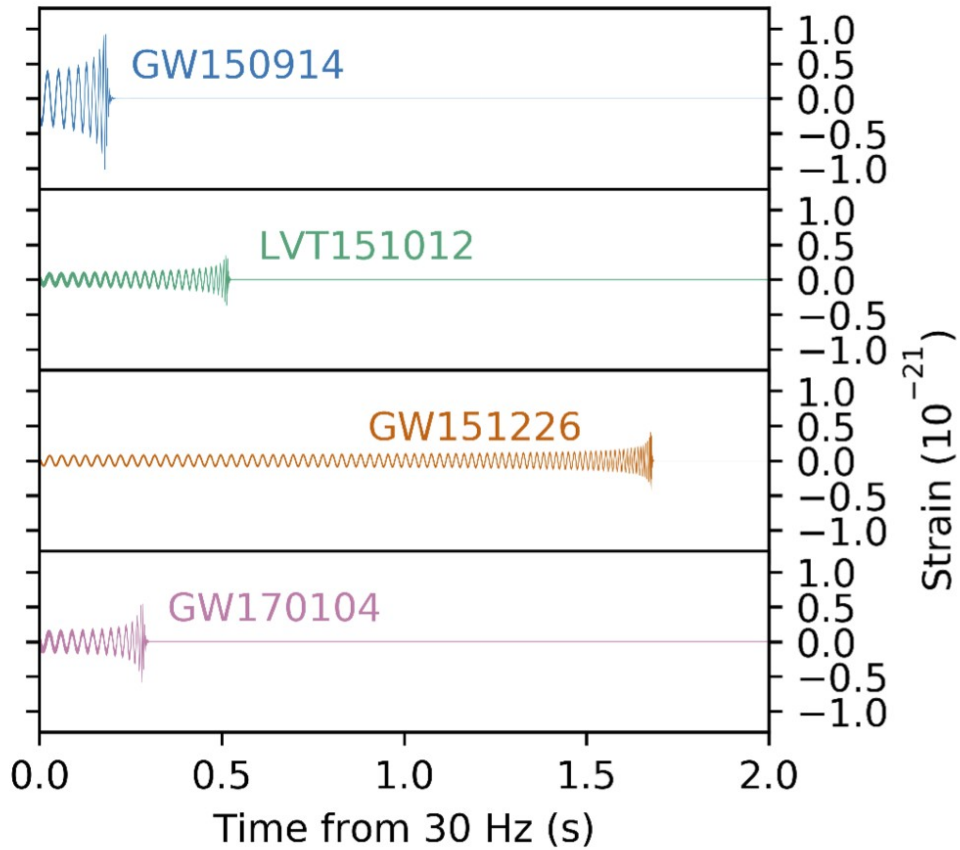
Unexpected variety of black holes!



Unexpected variety of black holes!



"3.9 detections"



> 5σ

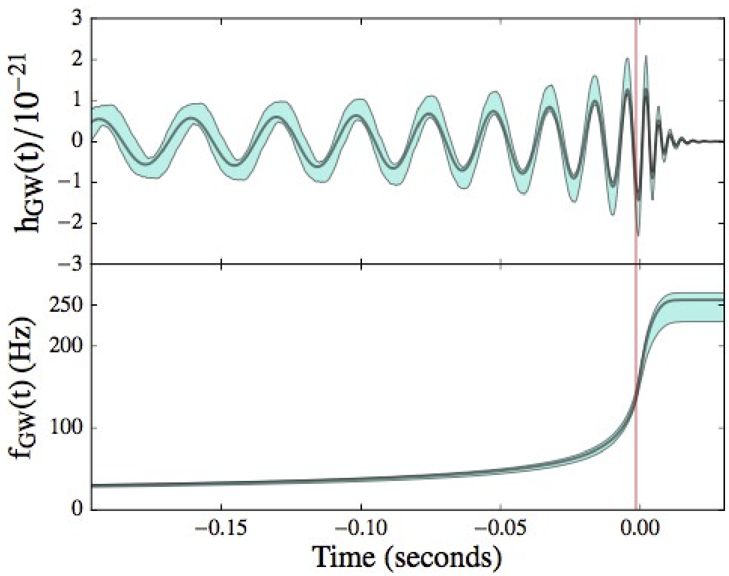
1.7σ

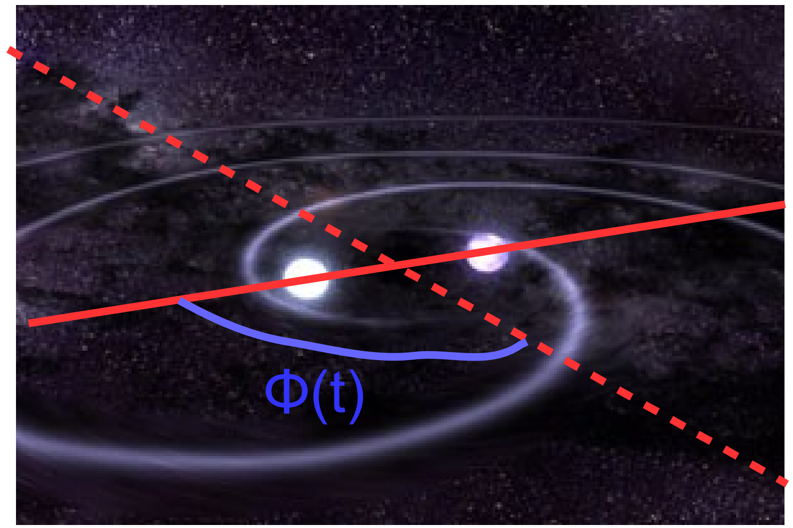
> 5σ

> 5σ

- Complementary information:
  - GW150914: merger at the most sensitive detector frequencies
  - GW151226: long inspiral in sensitive frequency band
  - GW170104: twice as far away → study propagation over large distances

Was the inspiral as predicted by general relativity?





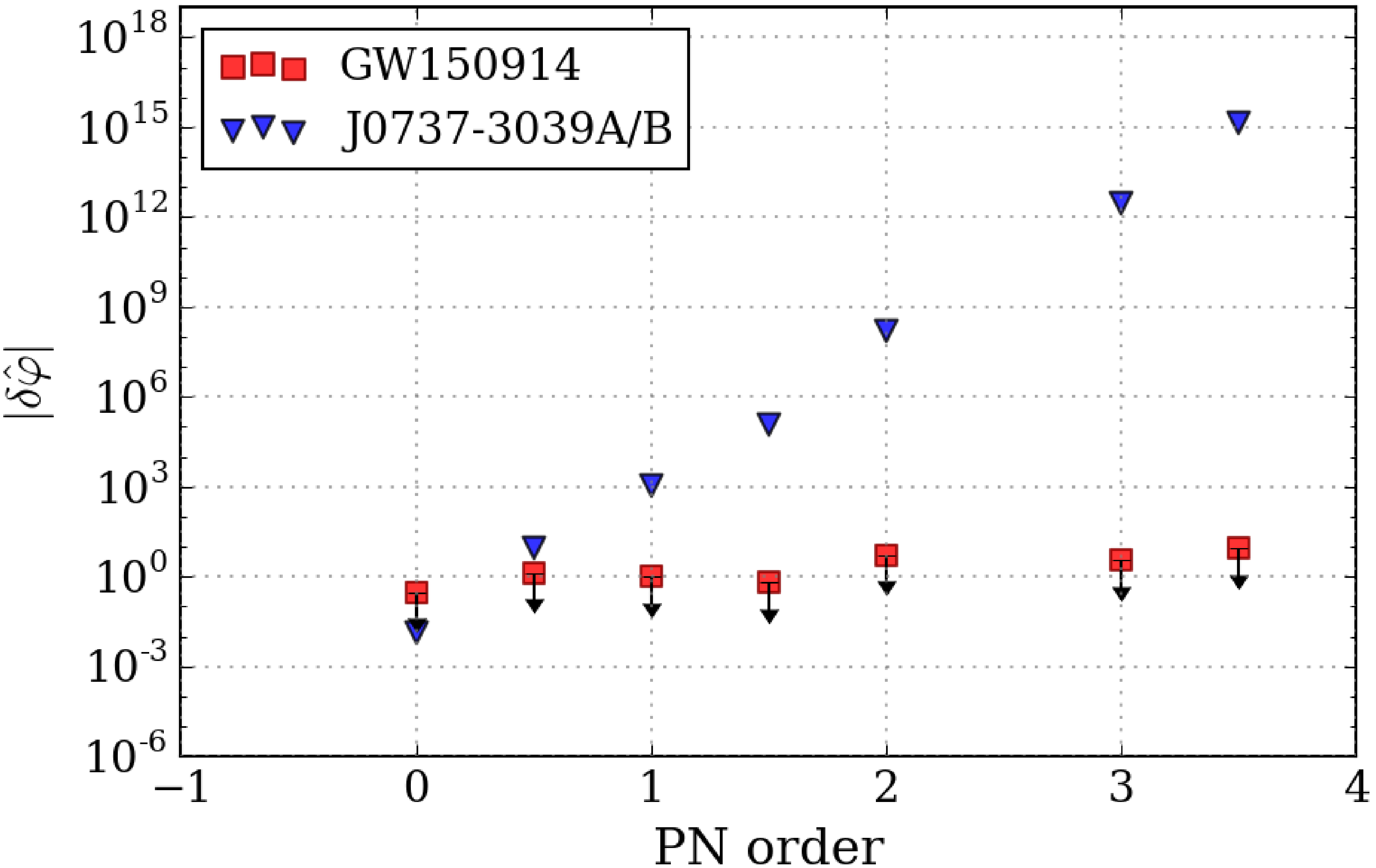
- Orbital phase during inspiral as a function of (ever increasing) orbital speed:

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

- 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?

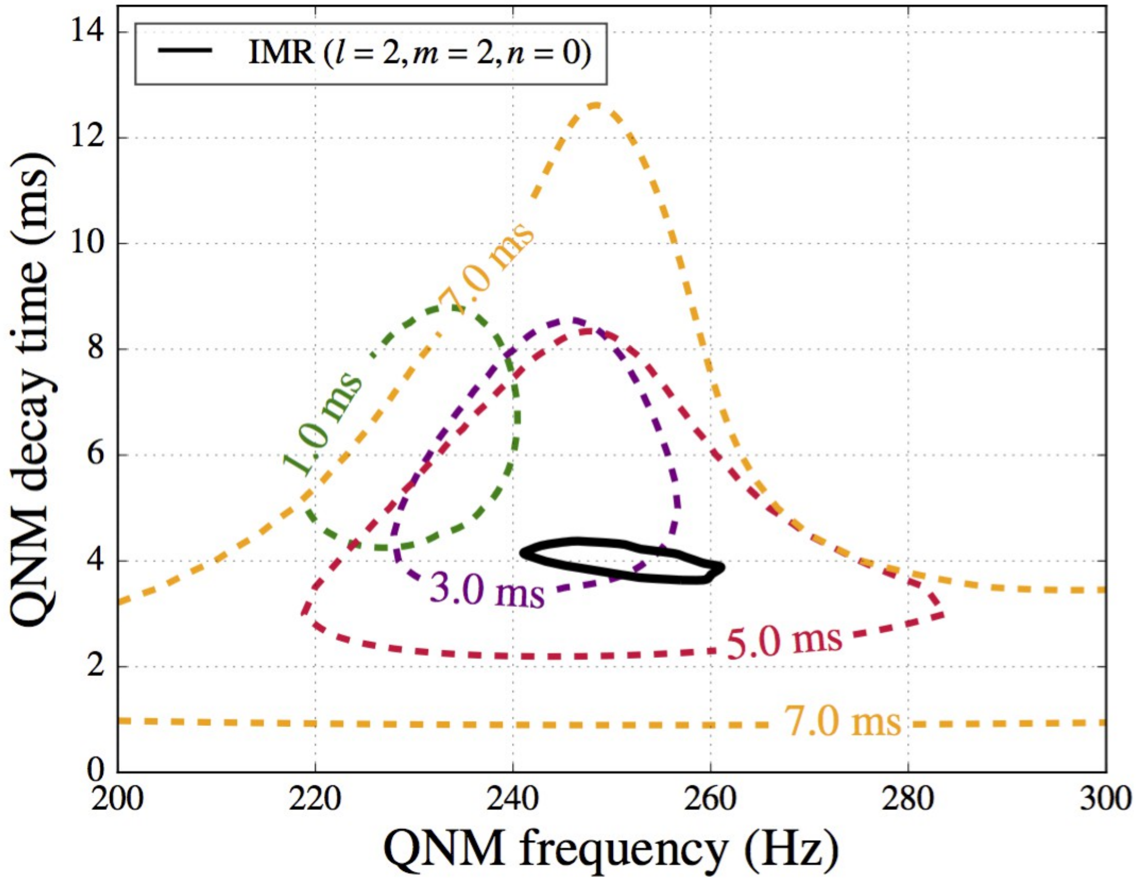
http://arxiv.org/abs/1602.03841

Was the inspiral as predicted by general relativity?



http://arxiv.org/abs/1602.03841

Was the frequency of the final black hole as predicted?

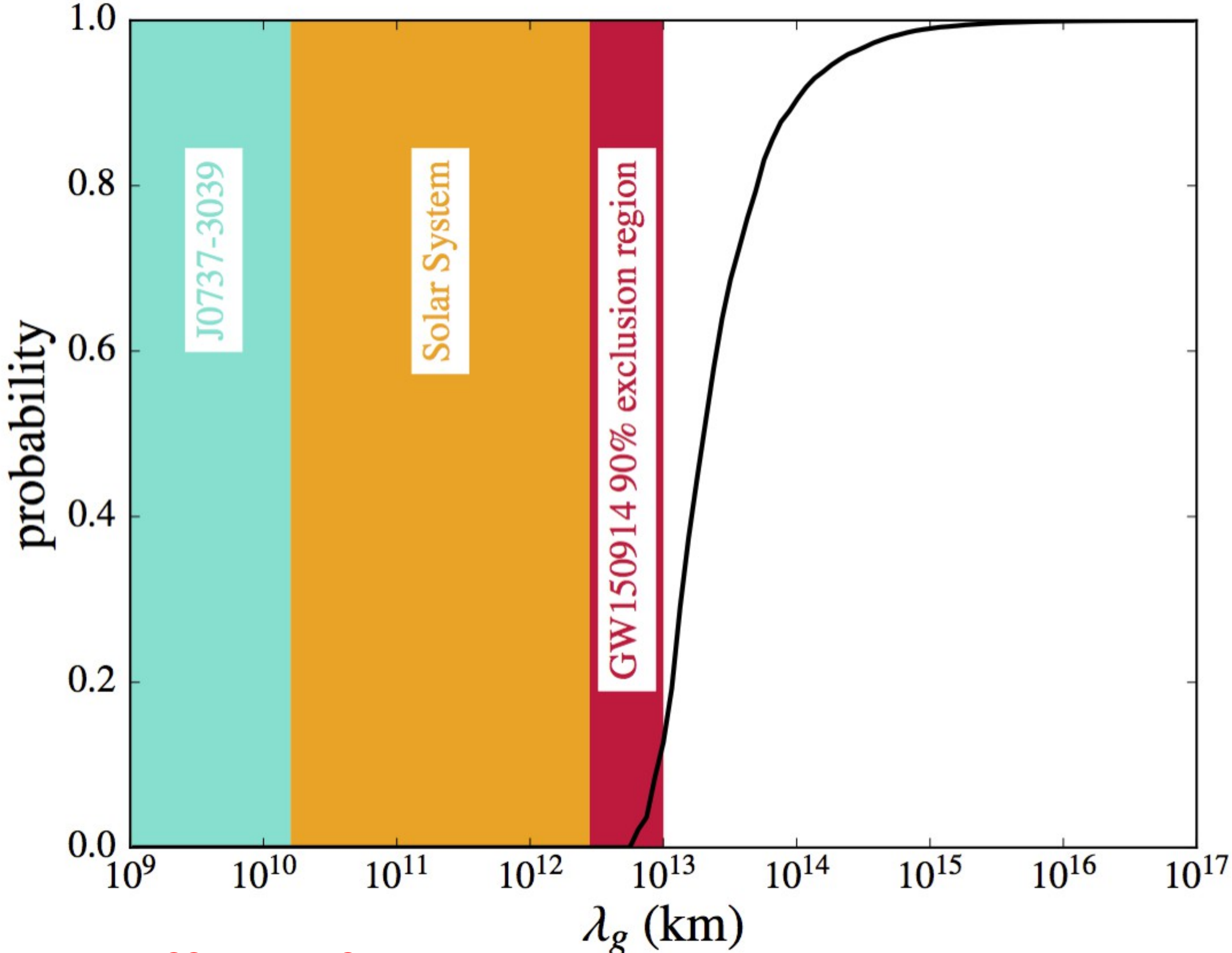


- From the inspiral, we can predict that ringdown frequency should be ~250 Hz

  ... and that's what we measure

http://arxiv.org/abs/1602.03841

Does the graviton have mass?

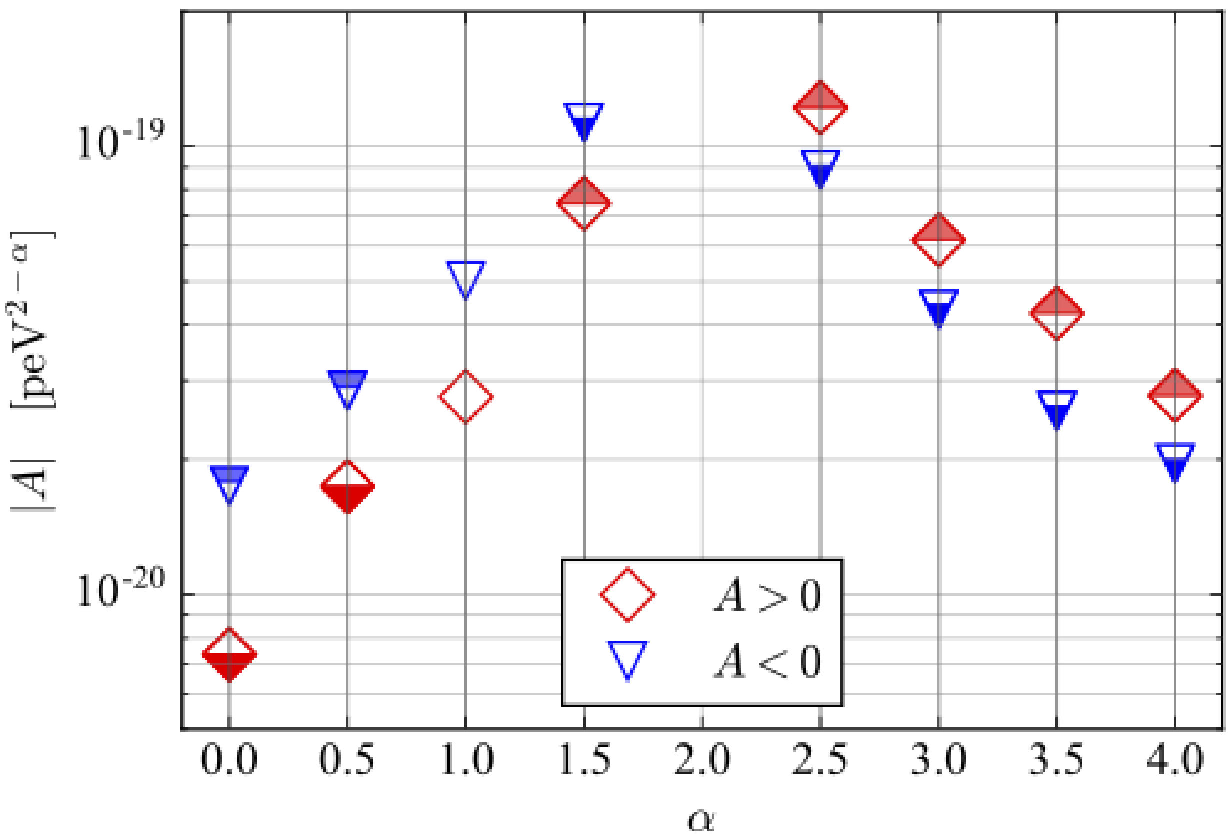


$m_g < 10^{-22}$ eV/c^2

http://arxiv.org/abs/1602.03841

Do gravitational waves propagate as predicted?

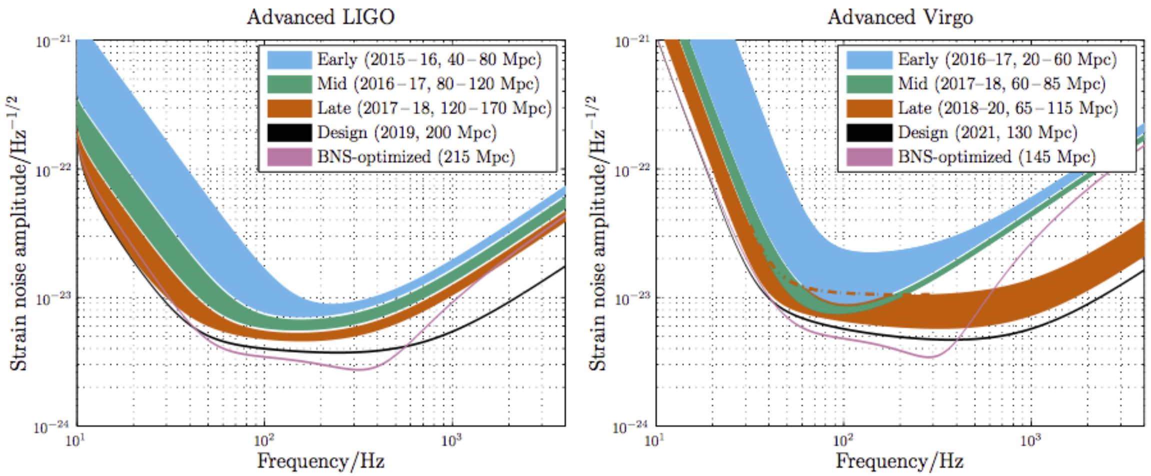
Anomalous dispersion of gravitational waves
(violating local Lorentz invariance): $E^2 = p^2c^2 + Ap^\alpha c^\alpha$



http://arxiv.org/abs/1706.01812

Where do we go from here?

Observing plans for the coming years



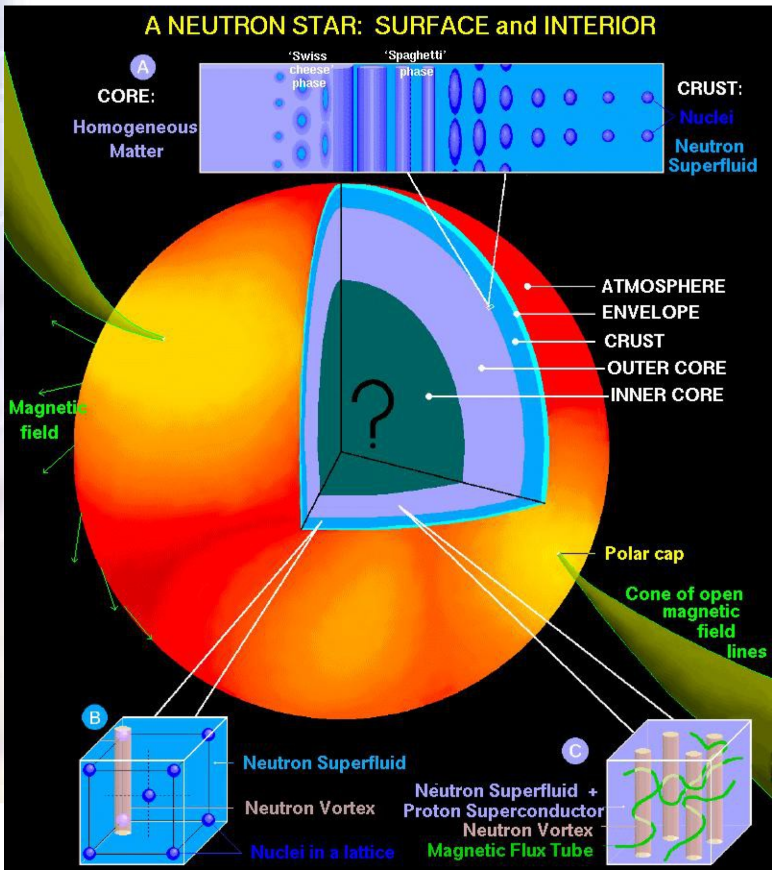
Progressive improvements in sensitivity:

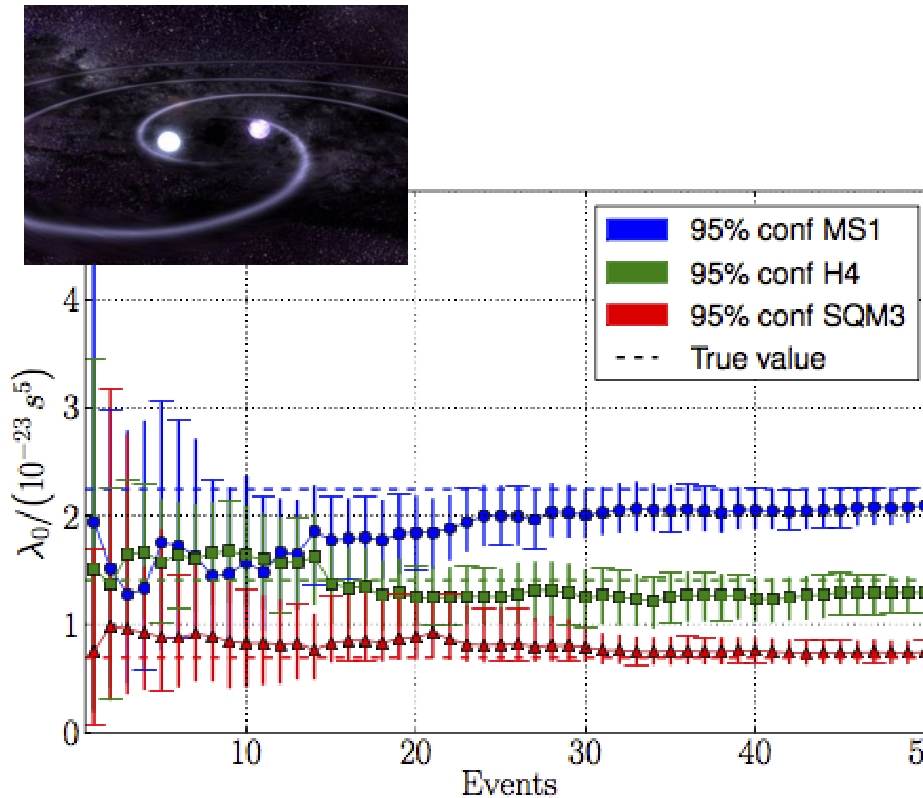
- 2015-2016 (**O1**): 4-month run with only Advanced LIGO
  - Detection of GW150914
  - Second half not yet analyzed – may contain further detection(s)!
- 2016-2017 (**O2**): longer run with **Advanced Virgo joining**
- 2018-2019 (**O3**): longer run: LIGO + Virgo + **KAGRA?**
- 2019+: LIGO + Virgo (towards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

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

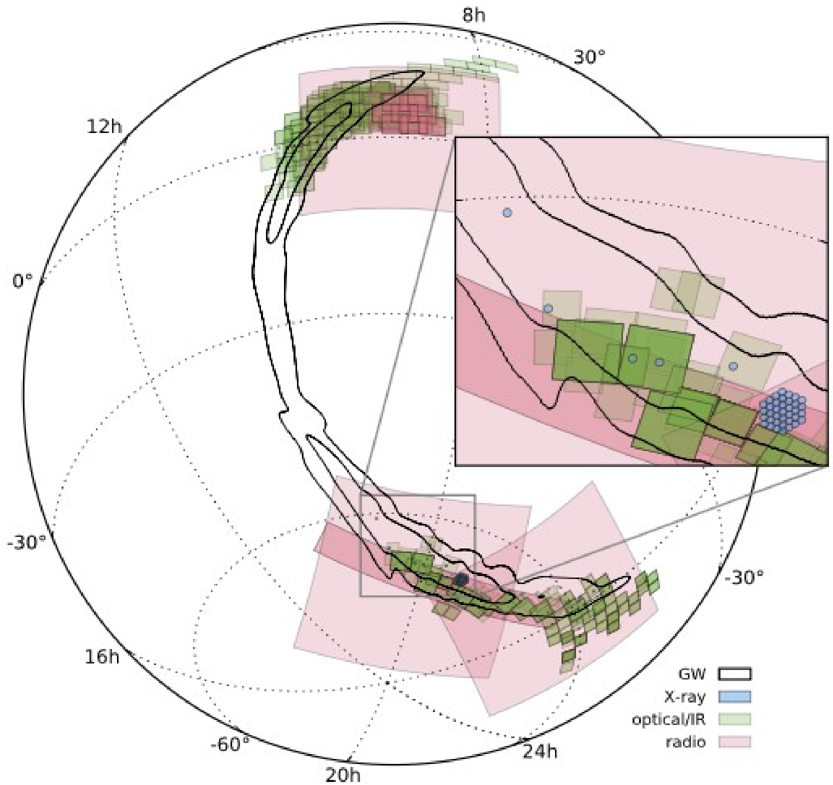




Del Pozzo, Li, Agathos, Van Den Broeck, Vitale,
Phys. Rev. Lett. **111**, 071101 (2013)

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!)

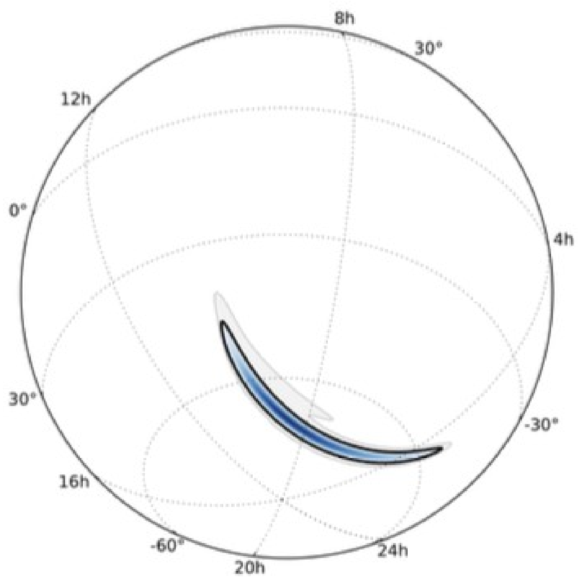


Footprints of Tiled Observations

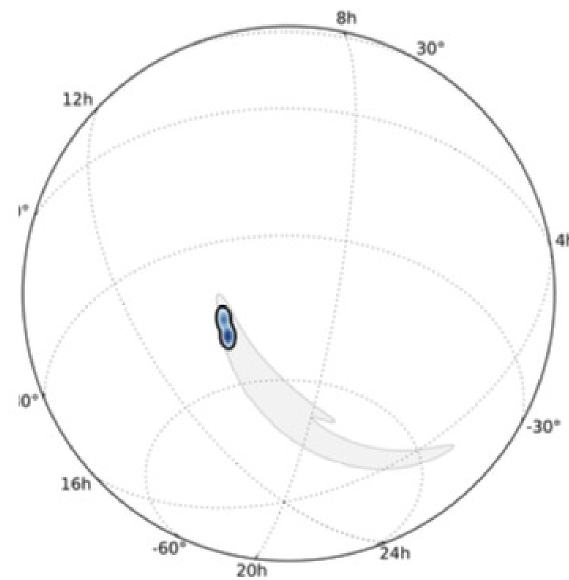
Group	Area (deg^2)	Contained probability (%)		
		cWB[a]	LIB[b]	LALInf[c]
Swift	2	0.6	0.8	0.1
DES	94	32.1	13.4	6.6
INAF	93	28.7	9.5	6.1
J-GEM	24	0.0	1.2	0.4
MASTER	167	9.3	3.3	6.0
Pan-STARRS	355	27.9	22.9	8.8
SkyMapper	34	9.1	7.9	1.7
TZAC	29	15.1	3.5	1.6
ZTF	140	3.1	2.9	0.9
(total optical)	759	76.5	46.8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

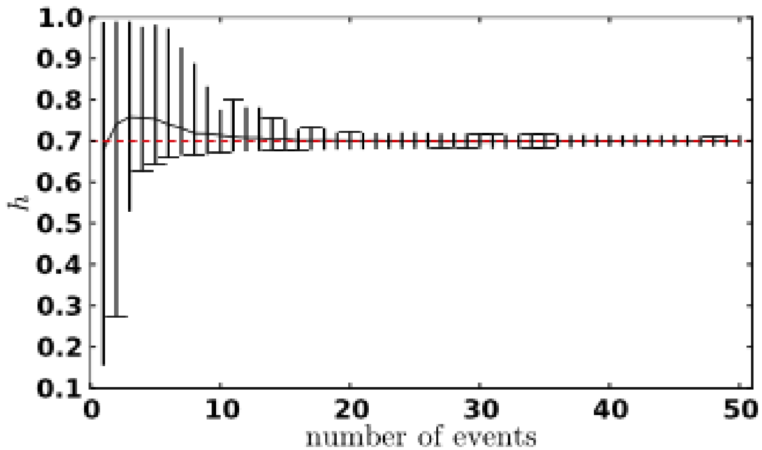
- Gravitational waves are cosmic distance markers:

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

  - 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!

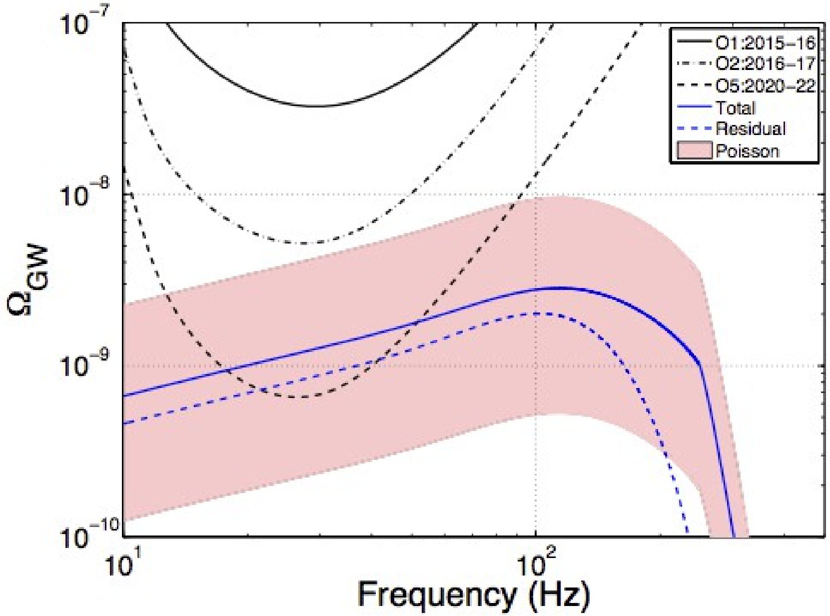
- If both distance D and redshift z are known, can perform independent measurement of the Hubble constant H_0
  - Use electromagnetic counterparts to find z
  - Or, infer it approximately from 3D position + galaxy catalogs

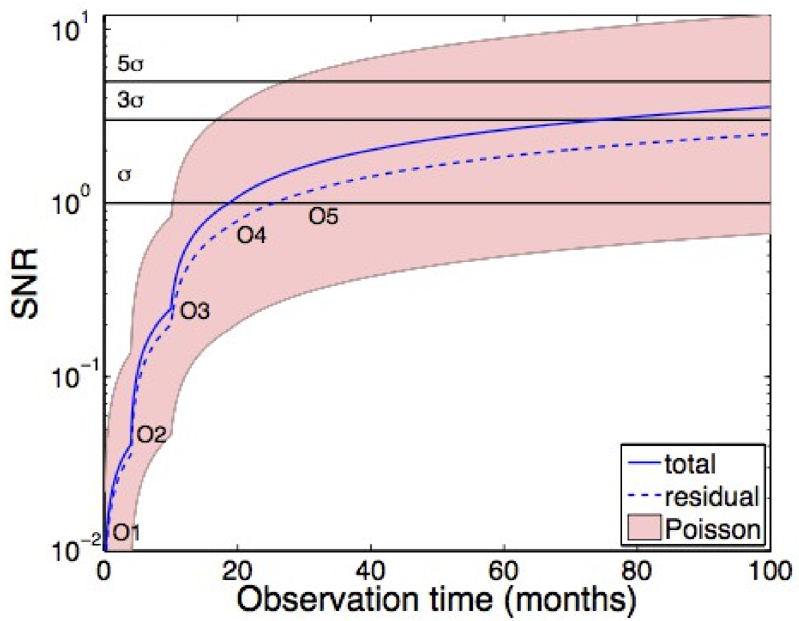


Del Pozzo, Phys. Rev. D **86**, 043011 (2012)

“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!

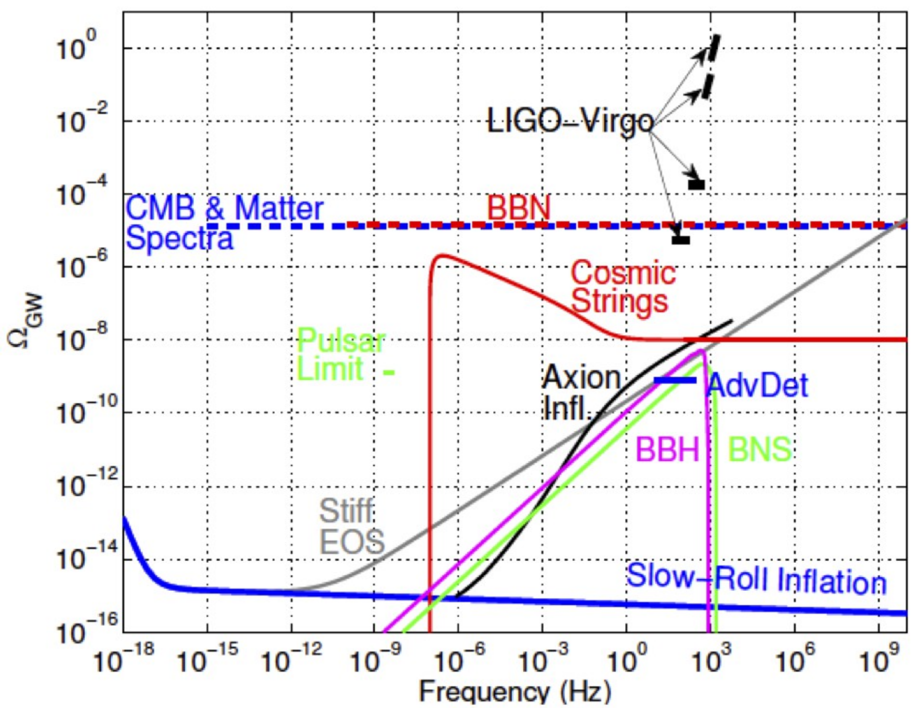




http://arxiv.org/abs/1602.03847

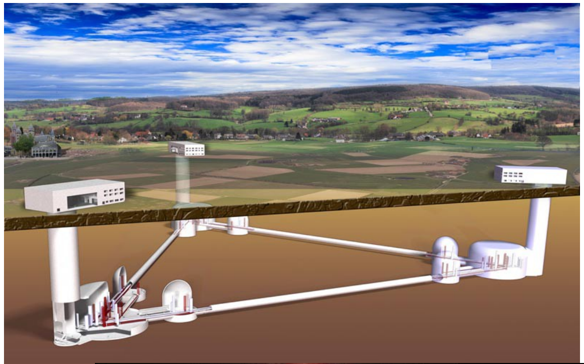
Primordial gravitational waves from early Universe

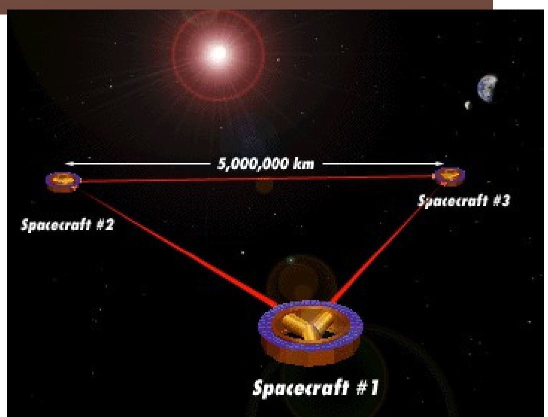
$$\Omega_{gw}(f) = \frac{d\rho_{gw}(f)}{\rho_c d(\ln f)}$$

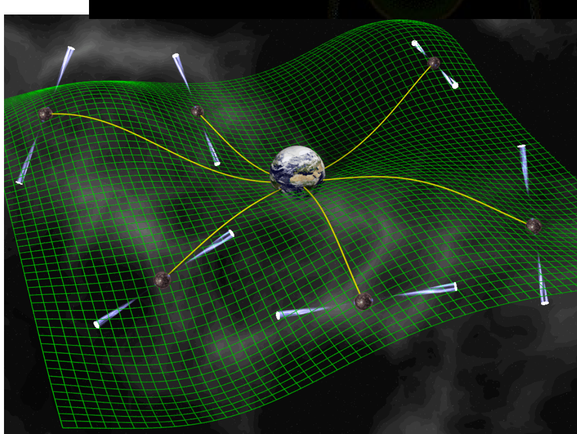


- Between initial and final advanced detectors: Factor 10^4 gain in Ω_{gw}
  - Better sensitivity overall
  - Wider frequency band
- Possible signals from a fraction of a second after Big Bang:
  - Termination of inflation (e.g. axion inflation)
  - Phase transitions: fundamental forces splitting off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

The next few decades







- Einstein Telescope (~2030?)
  - 3^{rd} generation observatory
  - 10^5 binary mergers per year
  - Evolution of the Universe (e.g. dark energy)
  - Build in The Netherlands?
- LISA (approved for 2034)
  - 3 probes in orbiting the Sun, 5 x 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!

The next few decades