Gravitational Wave Astronomy

A New Window on the Universe

UNIVERSITY OF
Southampton

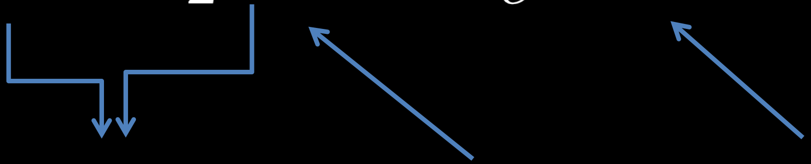
Prof Ian Jones

Image credit: National Science Foundation/LIGO/Sonoma State University/A. Simonnet.

In 1915, Einstein published his theory of General Relativity

Treats gravity not as a force, but as a *curvature in space-time*

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu} \ ,$$



Related to curvature; depend upon second derivatives of metric

Spacetime metric

Energy-momentum tensor

“Spacetime tells matter how to move; matter tells spacetime how to curve”

- John Wheeler

Gravitational waves

Consider small deviation away from flat spacetime:

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}, \quad h_{\mu\nu} \ll 1.$$

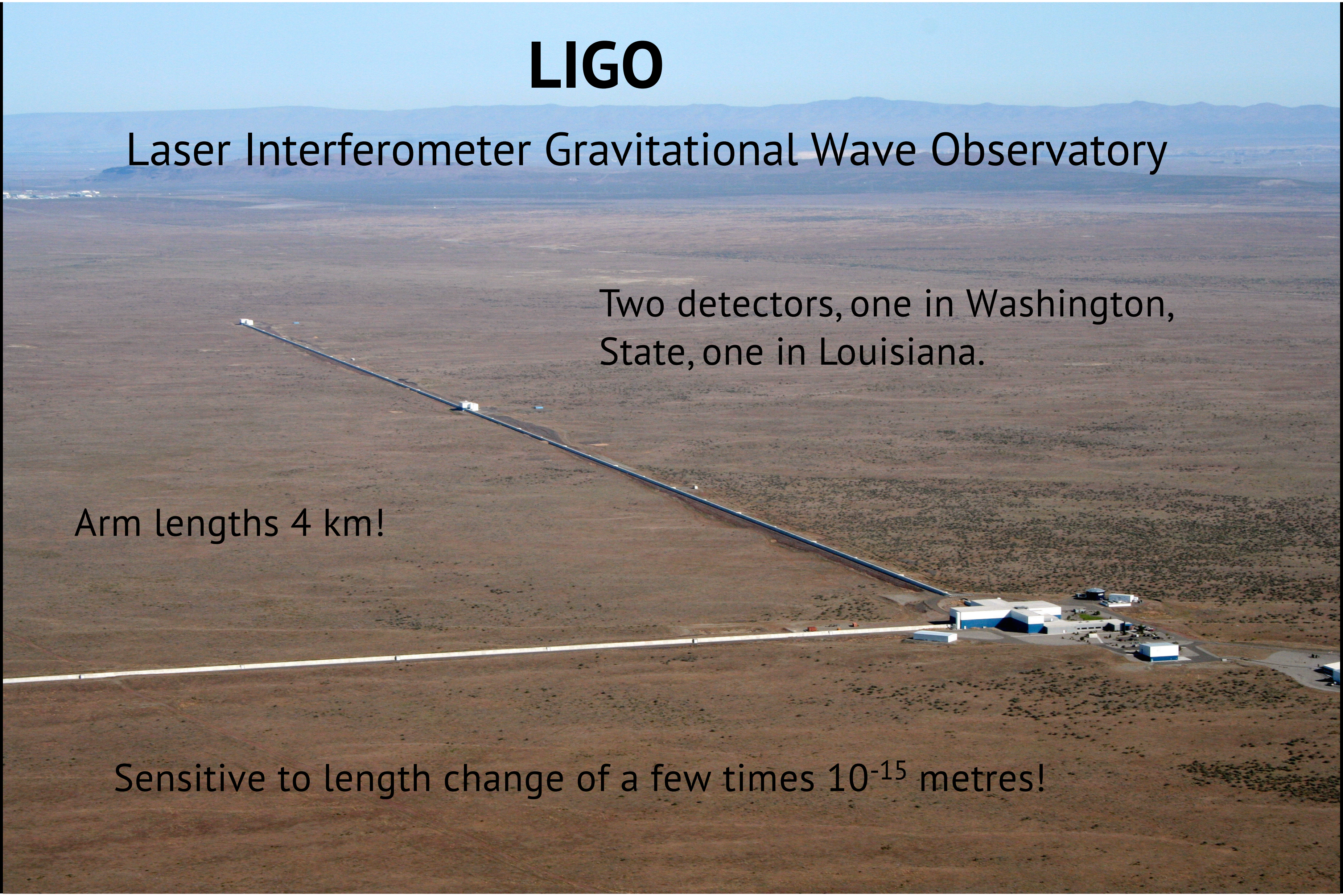
Can show that, for a suitable choice of coordinate system, the *linearised* Einstein field equations then lead to

$$\left(-\frac{\partial^2}{\partial t^2} + \nabla^2\right)\bar{h}_{\mu\nu} = -16\pi T_{\mu\nu}. \qquad \text{where} \qquad \bar{h}^{\alpha\beta} := h^{\alpha\beta} - \frac{1}{2}\eta^{\alpha\beta}h.$$

These ripples in spacetime are *gravitational waves*.

LIGO

Laser Interferometer Gravitational Wave Observatory

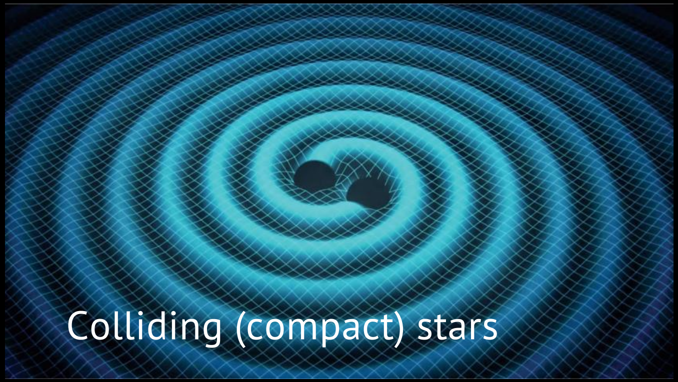


Two detectors, one in Washington, State, one in Louisiana.

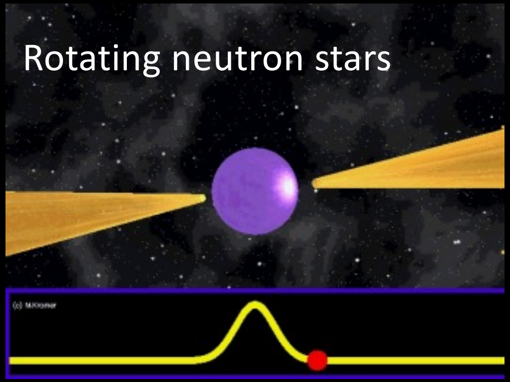
Arm lengths 4 km!

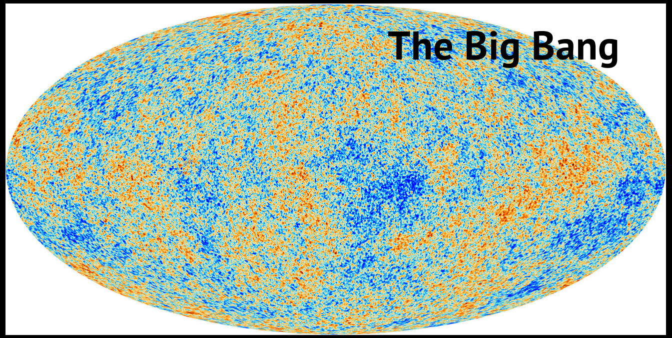
Sensitive to length change of a few times 10^{-15} metres!

What produces gravitational waves?

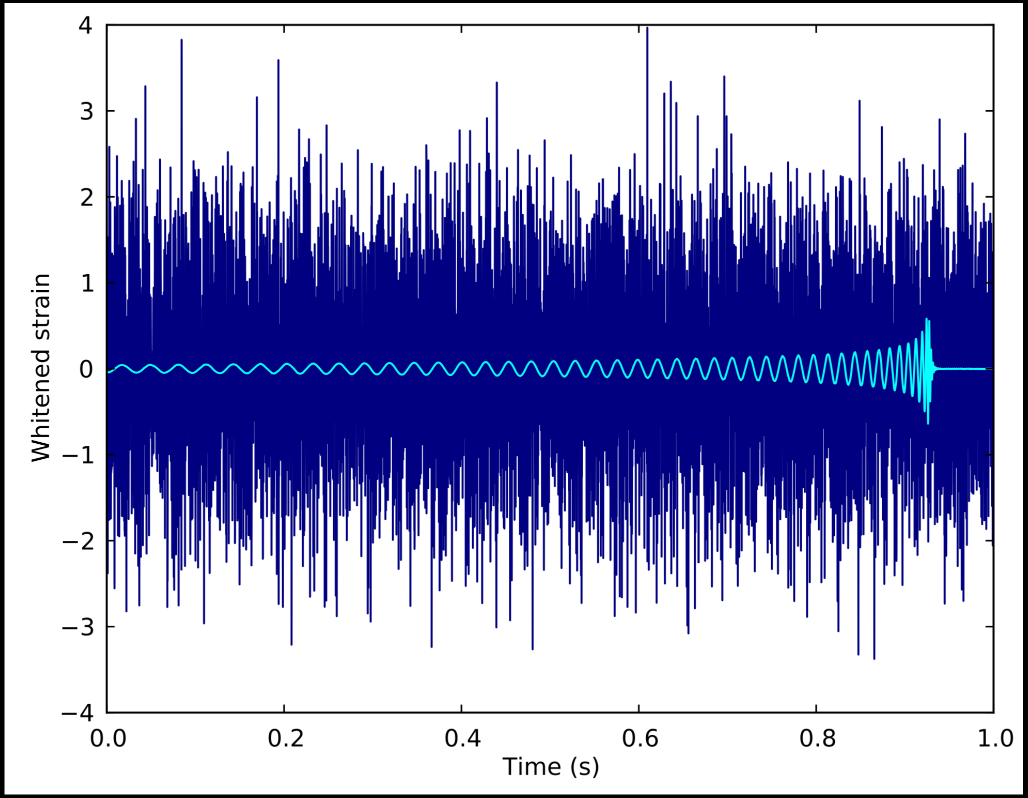

Colliding (compact) stars


Exploding stars


Rotating neutron stars


The Big Bang

Matched filtering



Actual signals are buried in detector noise

Use *matched-filtering* to identify weak signals

Look for the *correlation* $c(\vec{\lambda})$ between detector output $x(t)$ and a filter $q(t, \vec{\lambda})$:

$$c(\vec{\lambda}) = \int_{-\infty}^{\infty} x(t) q(t, \vec{\lambda}) \, dt$$

where $\vec{\lambda}$ is set of parameters describing waveform:

$\vec{\lambda}$ = {time of arrival, sky locations, masses, spins, ...}

Need to construct a large *template bank*.

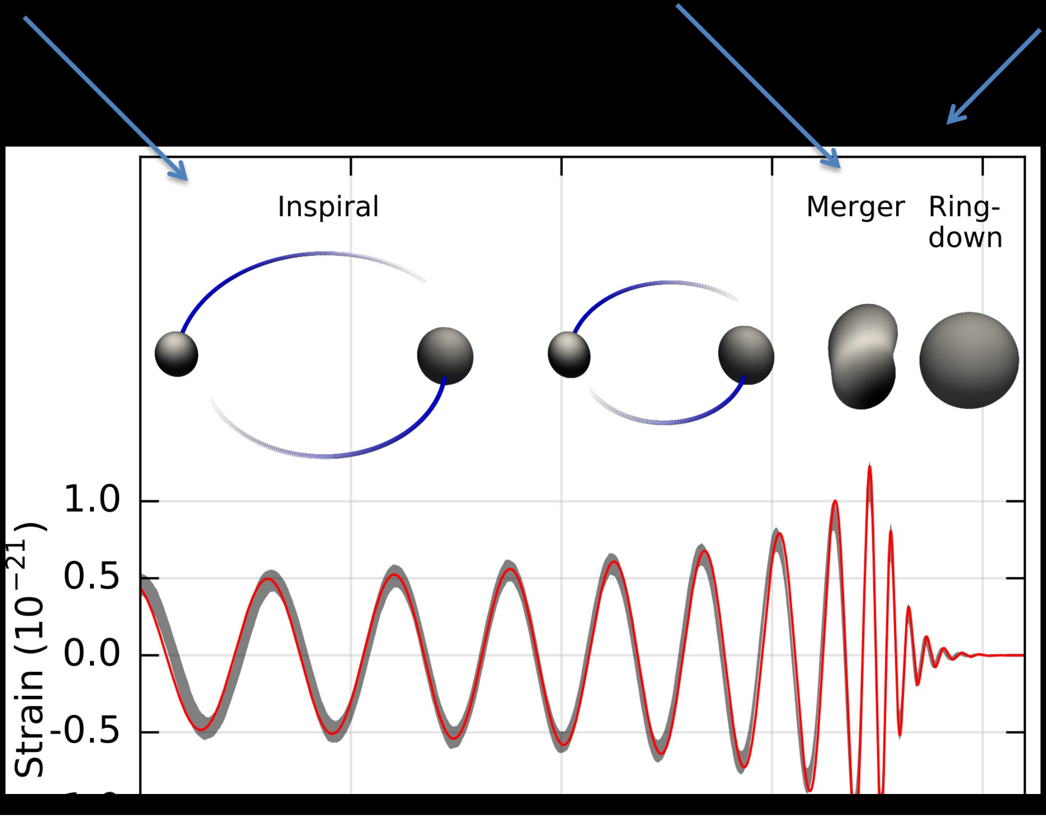
Figure credit: Gabbard et al. (2018)

Modelling binary inspiral

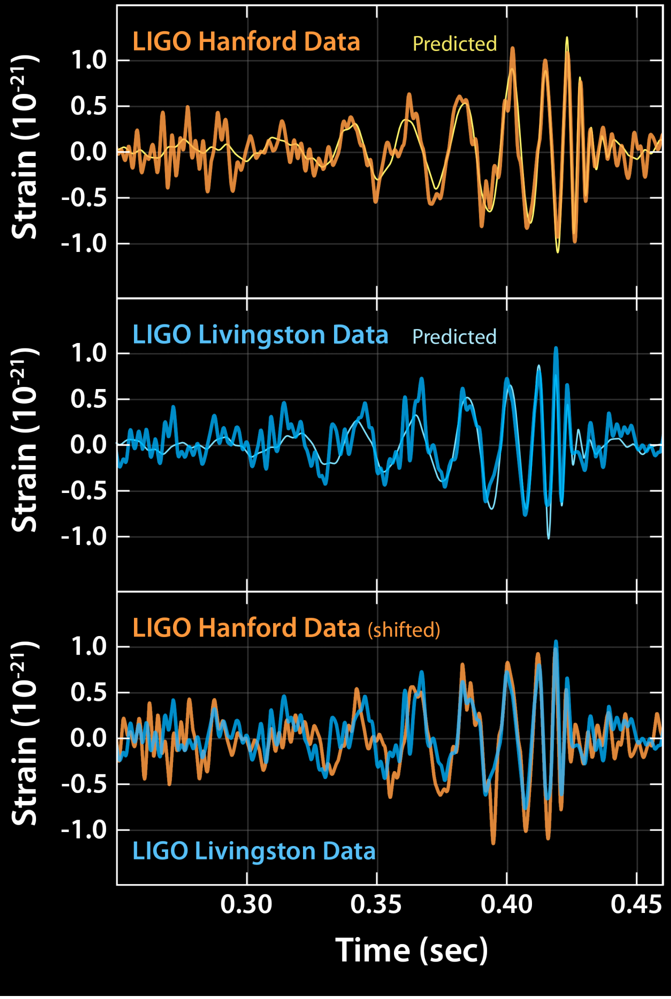
For v/c << 1, use *post-Newtonian theory*

For intermediate regime, use full-blown *numerical relativity*

For ring-down, use *quasi-normal mode perturbation theory*



GW150914: "The Event"

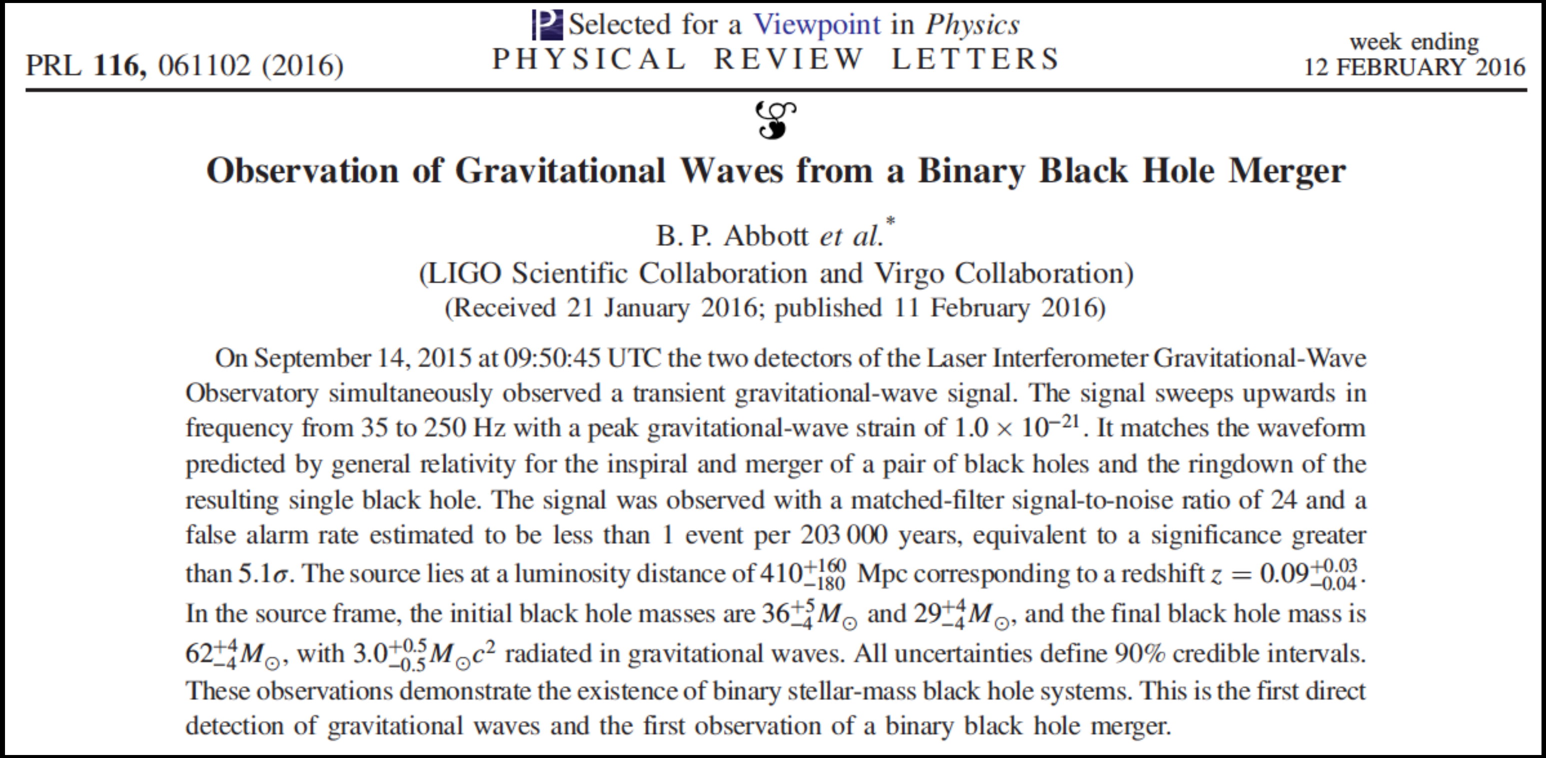


Advanced LIGO started taking data 12th September 2015

On September 14th 2015 strong signal seen in BOTH detectors

Automatic alarm sounded within 3 minutes!

Six months later…the Announcement!



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.

See for yourself at:
http://journals.aps.org/prl/abstract/10.1103/PhysRevLett.116.061102

Nobel Prize in Physics 2017

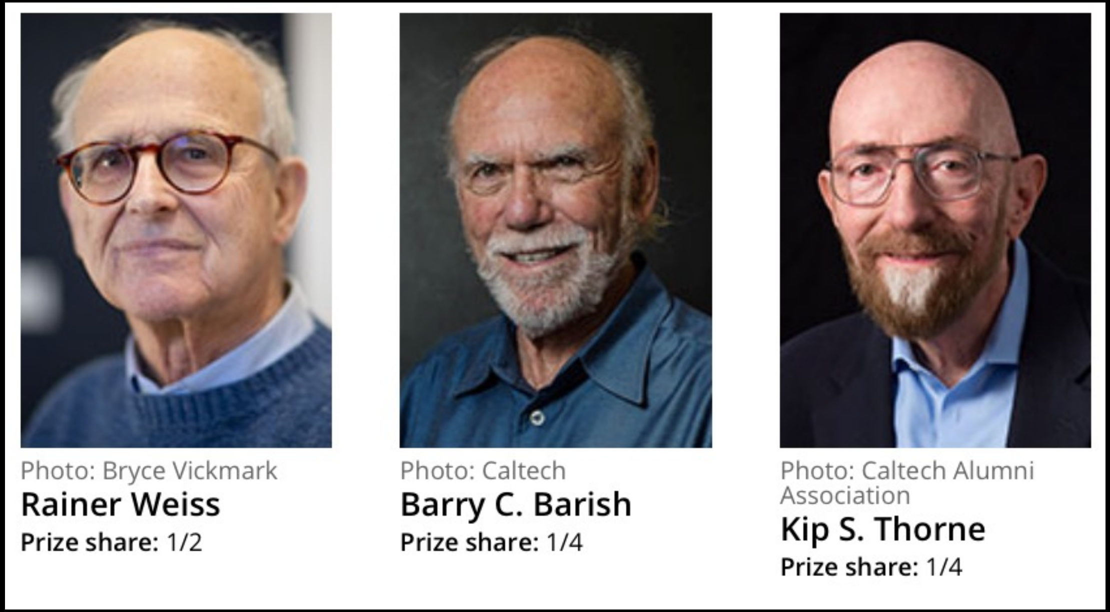


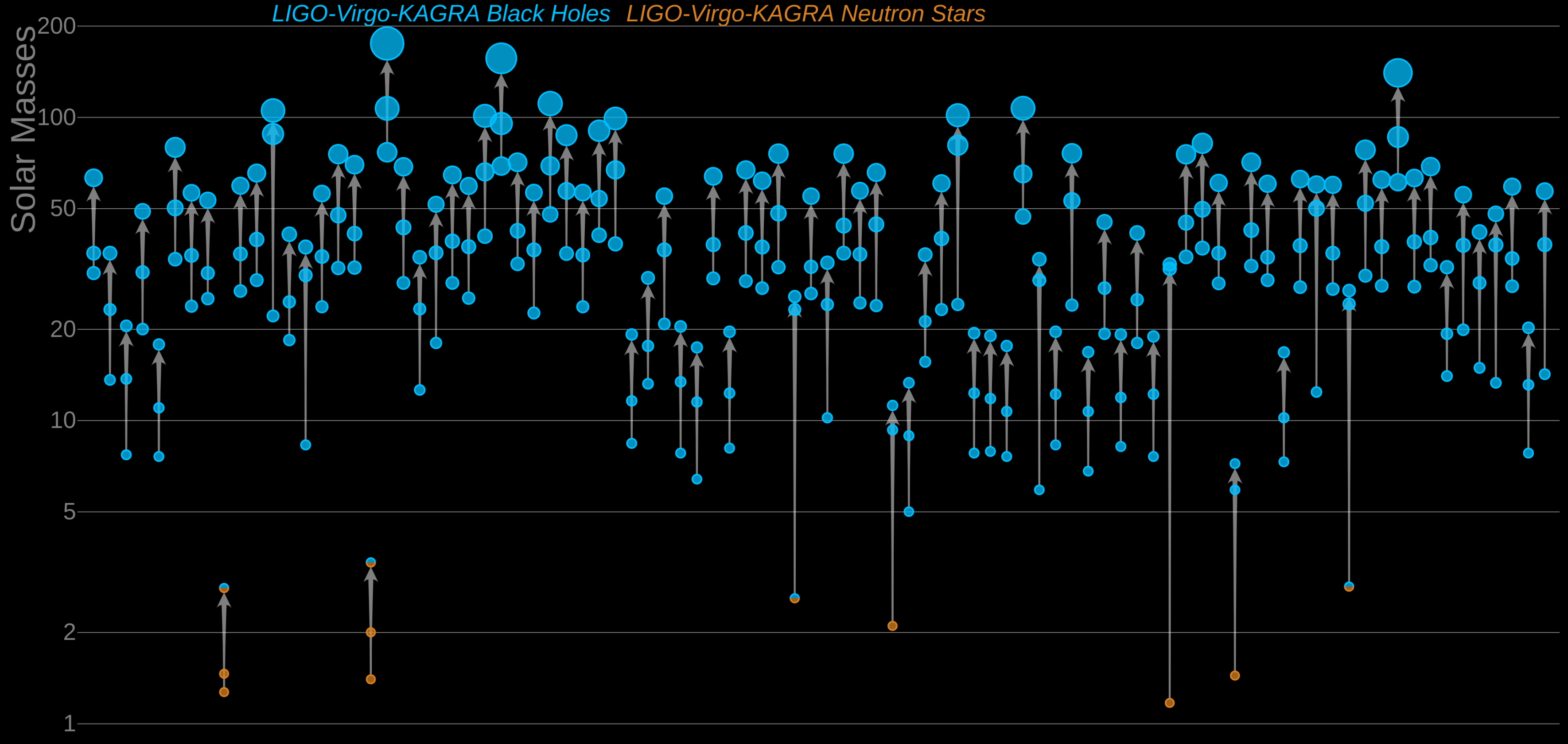
Photo: Bryce Vickmark
Rainer Weiss
Prize share: 1/2

Photo: Caltech
Barry C. Barish
Prize share: 1/4

Photo: Caltech Alumni Association
Kip S. Thorne
Prize share: 1/4

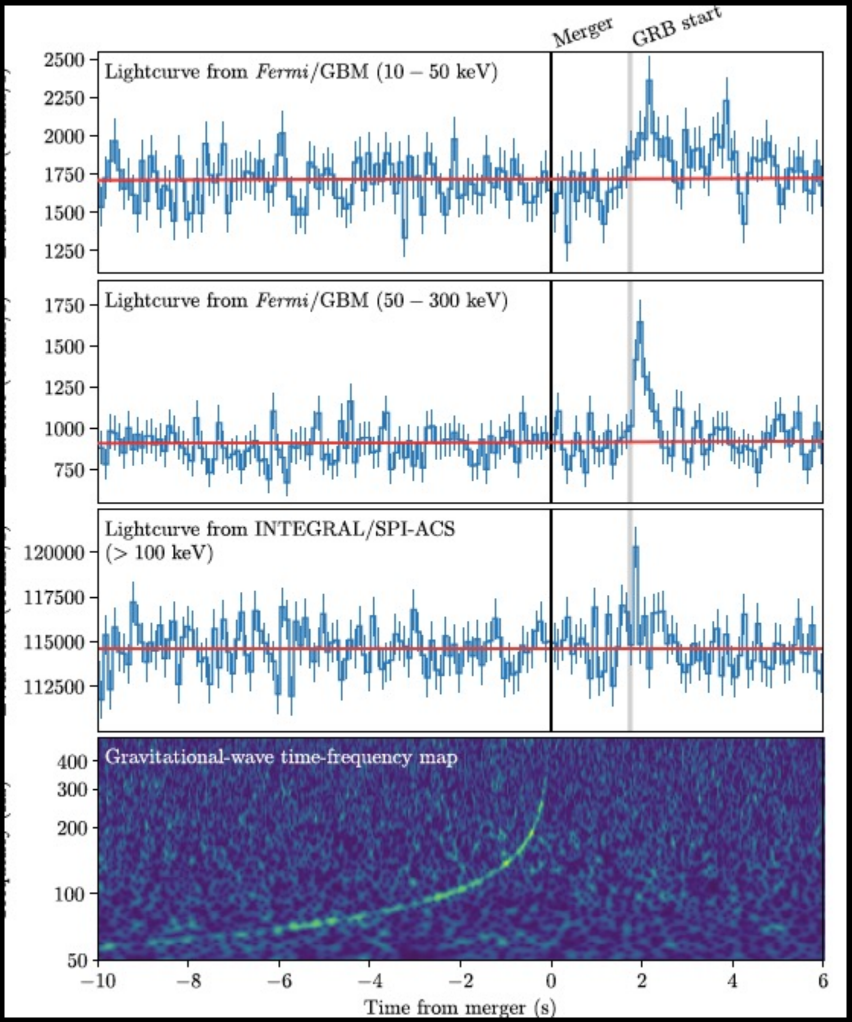
The Nobel Prize in Physics 2017 was divided, one half awarded to Rainer Weiss, the other half jointly to Barry C. Barish and Kip S. Thorne *"for decisive contributions to the LIGO detector and the observation of gravitational waves"*.

Masses in the Stellar Graveyard



LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

GW170817: The birth of multi-messenger astronomy



The GW detection GW170817 was Immediately followed by a short gamma-ray burst (sGRB).

Proved long-standing theory that short Gamma-ray bursts come from binary neutron star mergers.

The explosion was observed throughout the EM spectrum.

Did many interesting things with GW170817:

- Placed constraints on stiffness of neutron star matter
- Measured the Hubble constant
- Placed constraints on speed of gravity verses light
- Show where the heavy elements come from

The gravitational wave spectrum

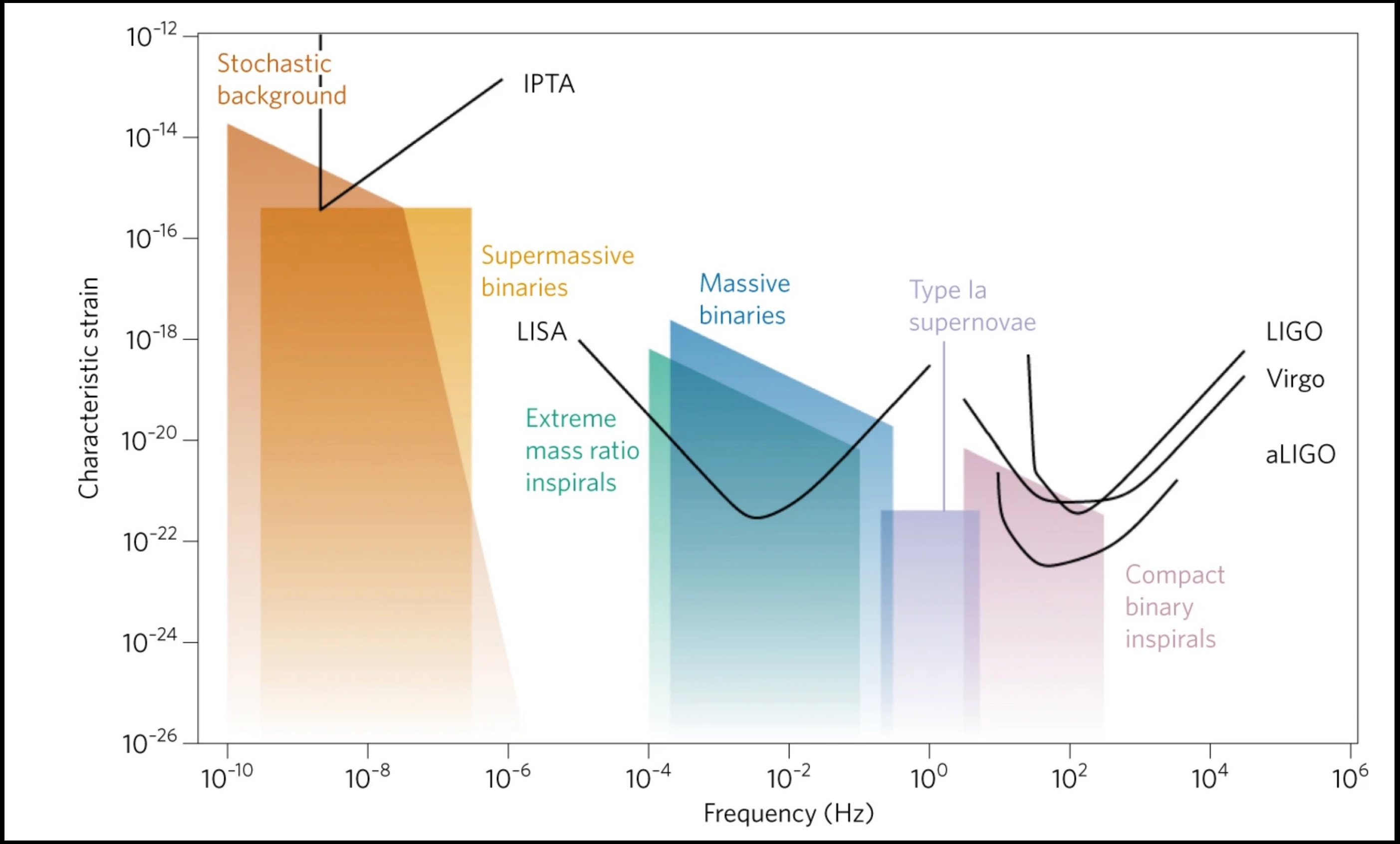
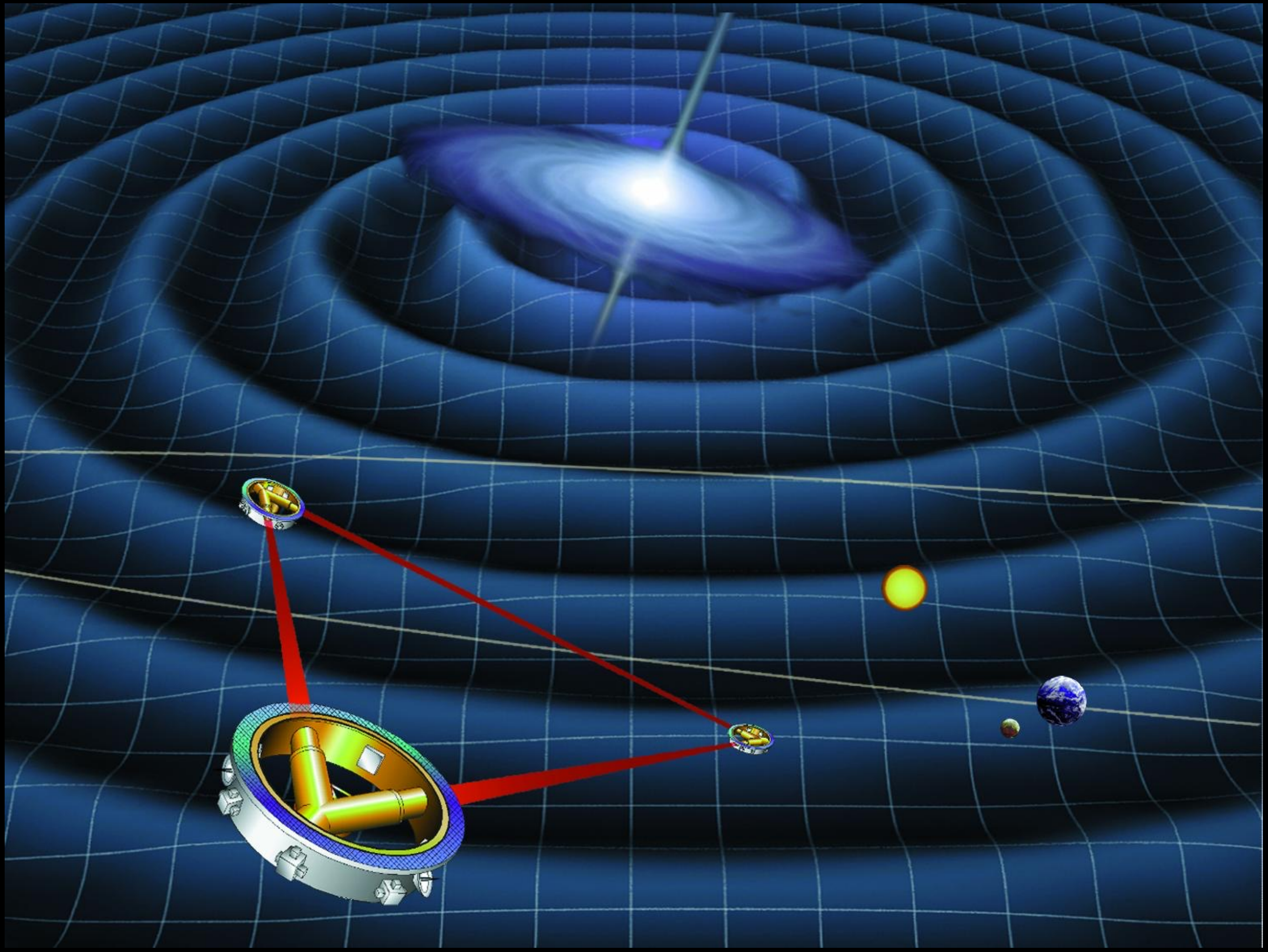


Figure credit: A. Lommen (2017)

A detector in space: LISA



Pulsar Timing Arrays (PTAs)

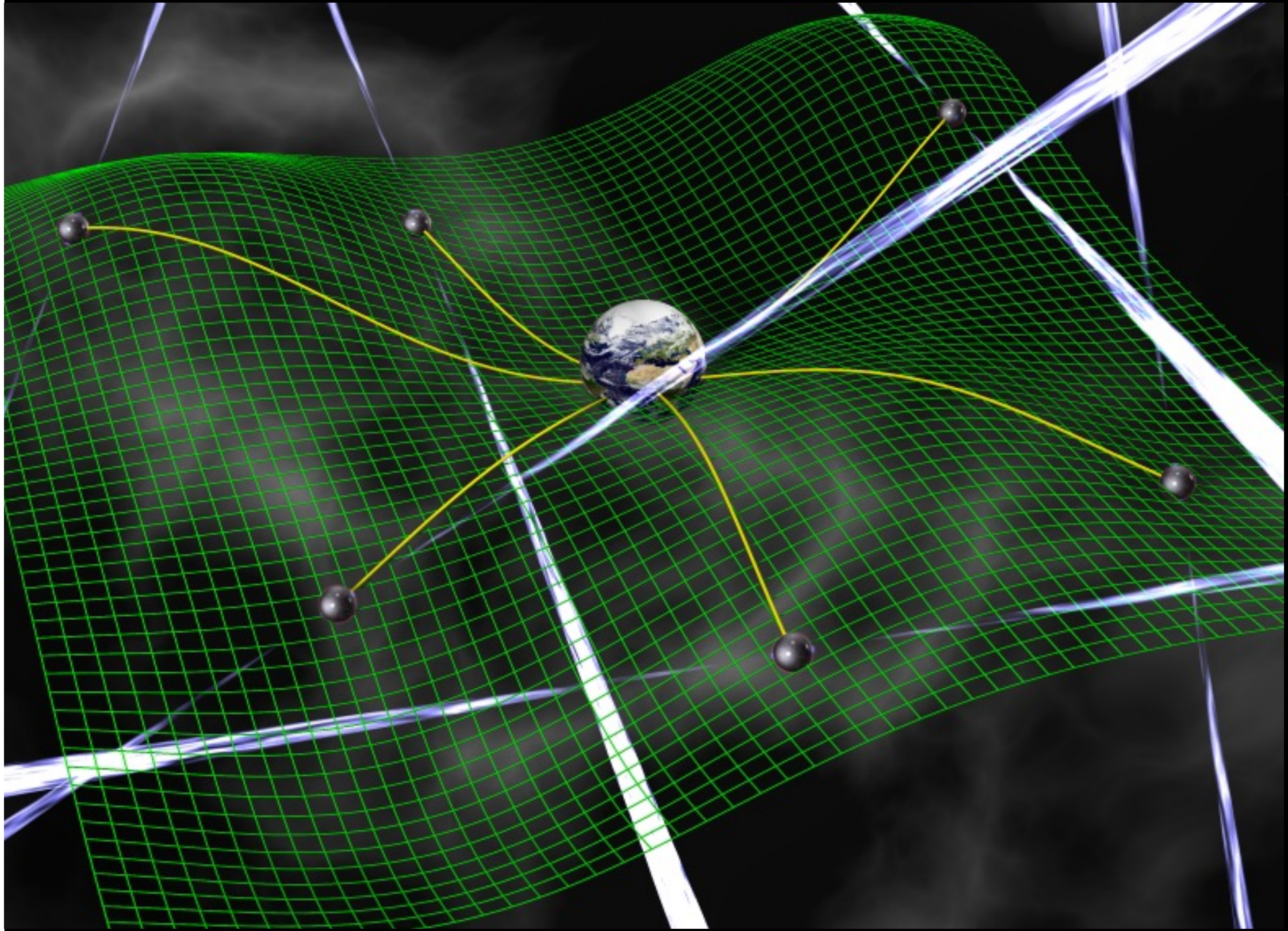


Figure credit: David Champion / MPIfR

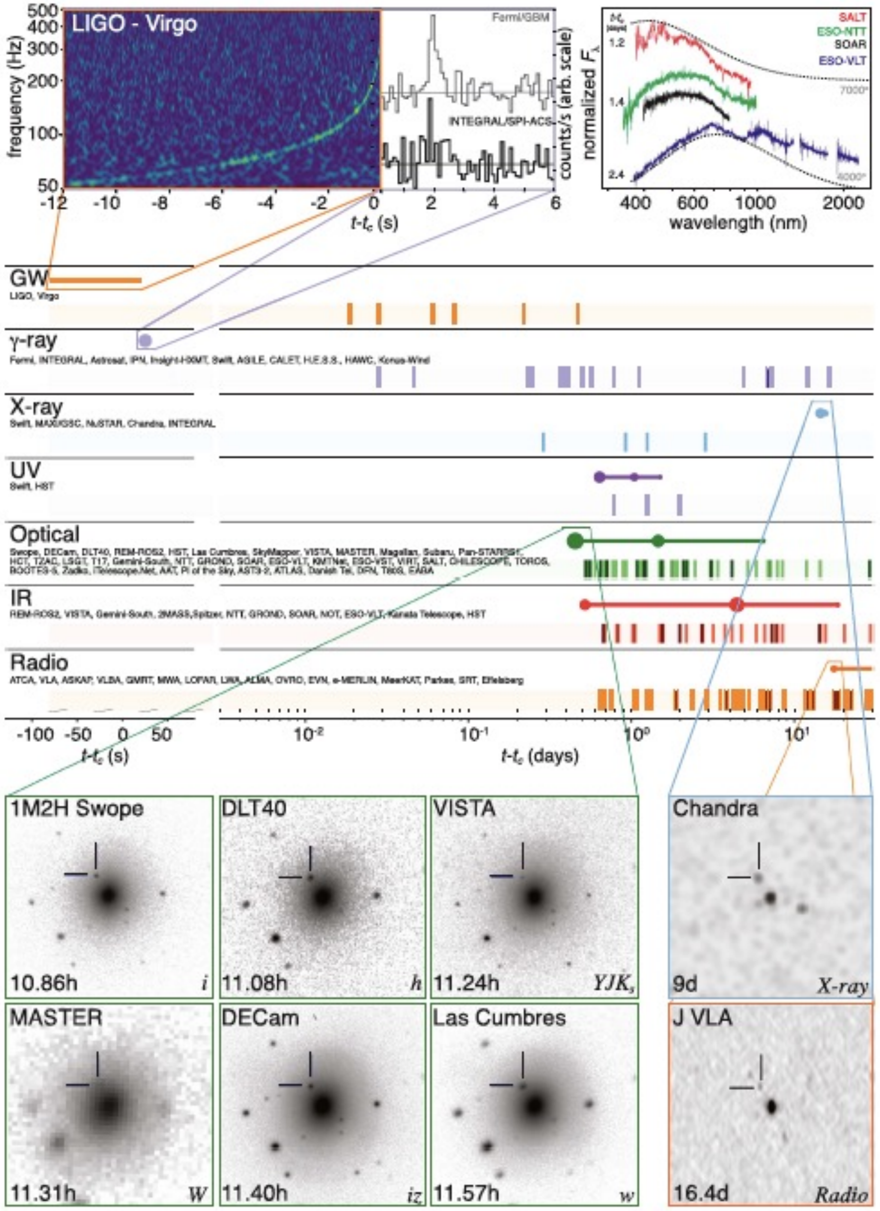
- Can detect low frequency (P ~ 1 year) using an *array of pulsars*.
- GWs show up as small timing variations in the observed pulsation rate.
- Radio astronomers recently detected a *stochastic GW background.*
- May be coming from a large population of supermassive black holes.

Summary

- Using ground-based detectors, have already seen ~90 signals from binary black holes (BBHs) with masses 5 - 200 $M_\odot$.
- The LISA space mission is capable of detecting supermassive BBHs out to cosmological distances; launch date ~2037.
- Using Pulsar Timing Arrays, have seen a stochastic gravitational wave background which may come from even more massive BBHs.

Back-up slides

The mulit-messenger timeline



Measuring the Hubble constant

Hubble constant: $v = H_0 d$, for nearby galaxies.

Can measure d using gravitational waves [Schutz (1986)]: compact binaries are self-calibrating:

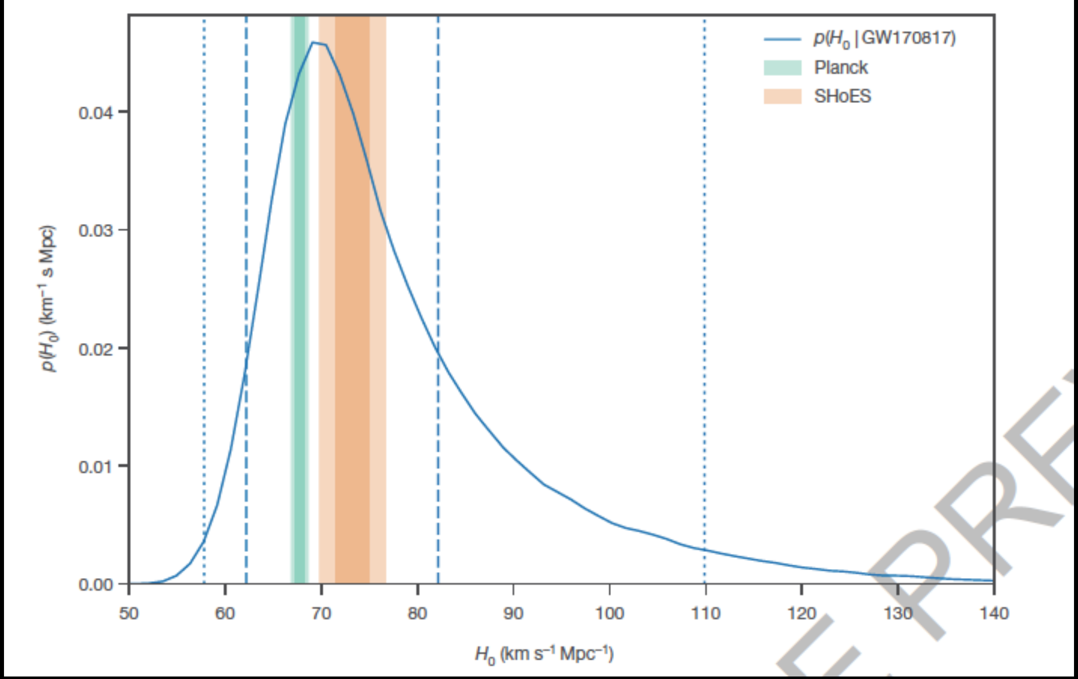
$$h \sim \frac{\Omega^{2/3} M_{chirp}^{5/3}}{d}, \qquad \dot{\Omega} \sim \Omega^{11/3} M_{chirp}^{5/3}, \qquad M_{chirp} = \left(\frac{m_1 m_2}{M^{1/3}}\right)^{3/5}$$

If you can measure recession speed v by other means (EM observation), get value for H_0.

Measuring the Hubble constant

Host galaxy NGC 4993 has recession velocity ≈ 3,300 km/s

Need to correct for local proper motion ≈ 300 km/s $\Longrightarrow v \approx$ 3,000 km/s



Abbott+2017

Result consistent with (discrepant) EM-only values.

More and better detectors