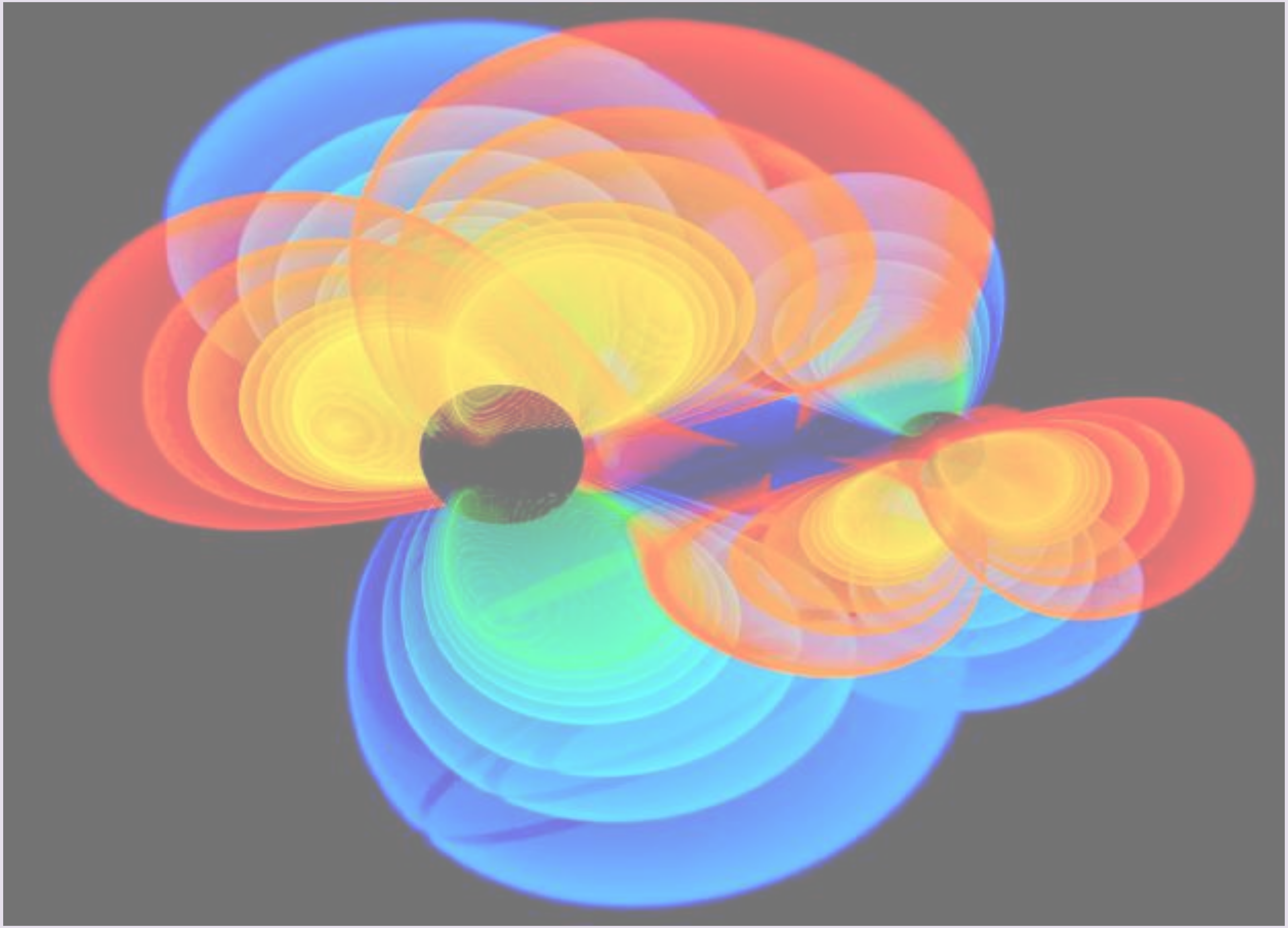
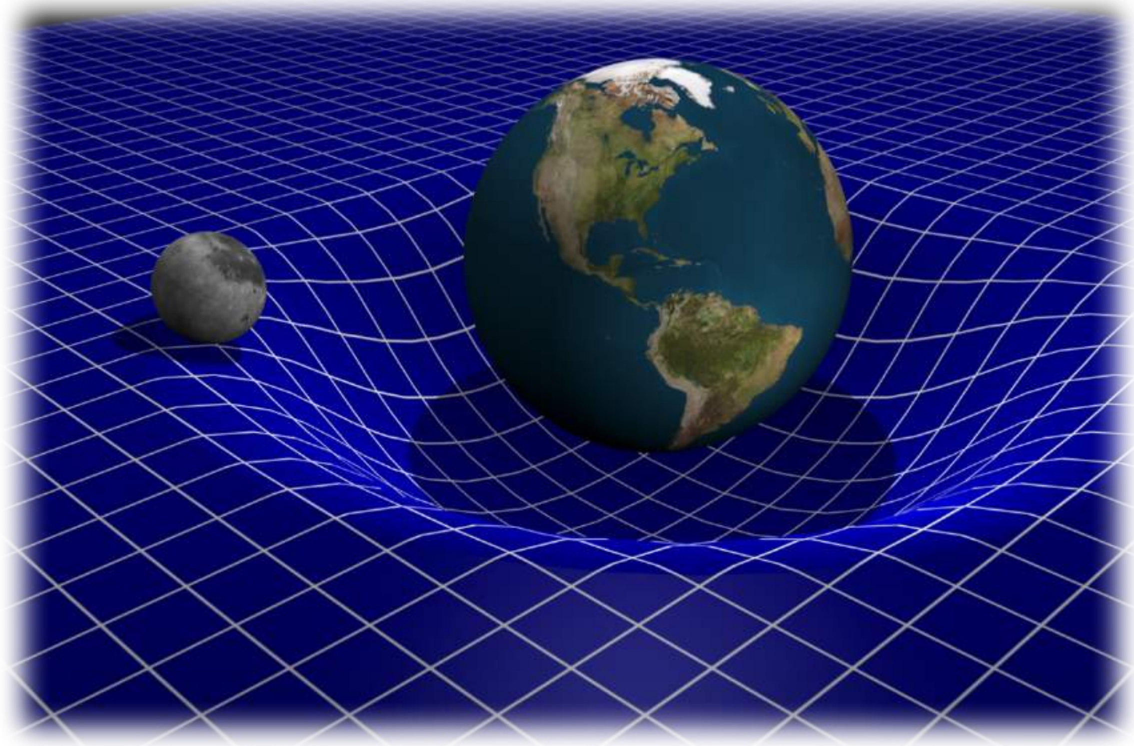
The discovery of gravitational waves



Subir sarkar

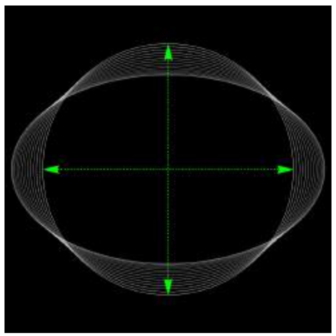
Saturday morning of theoretical Physics, Oxford, 6 May 2017

What are gravitational waves?

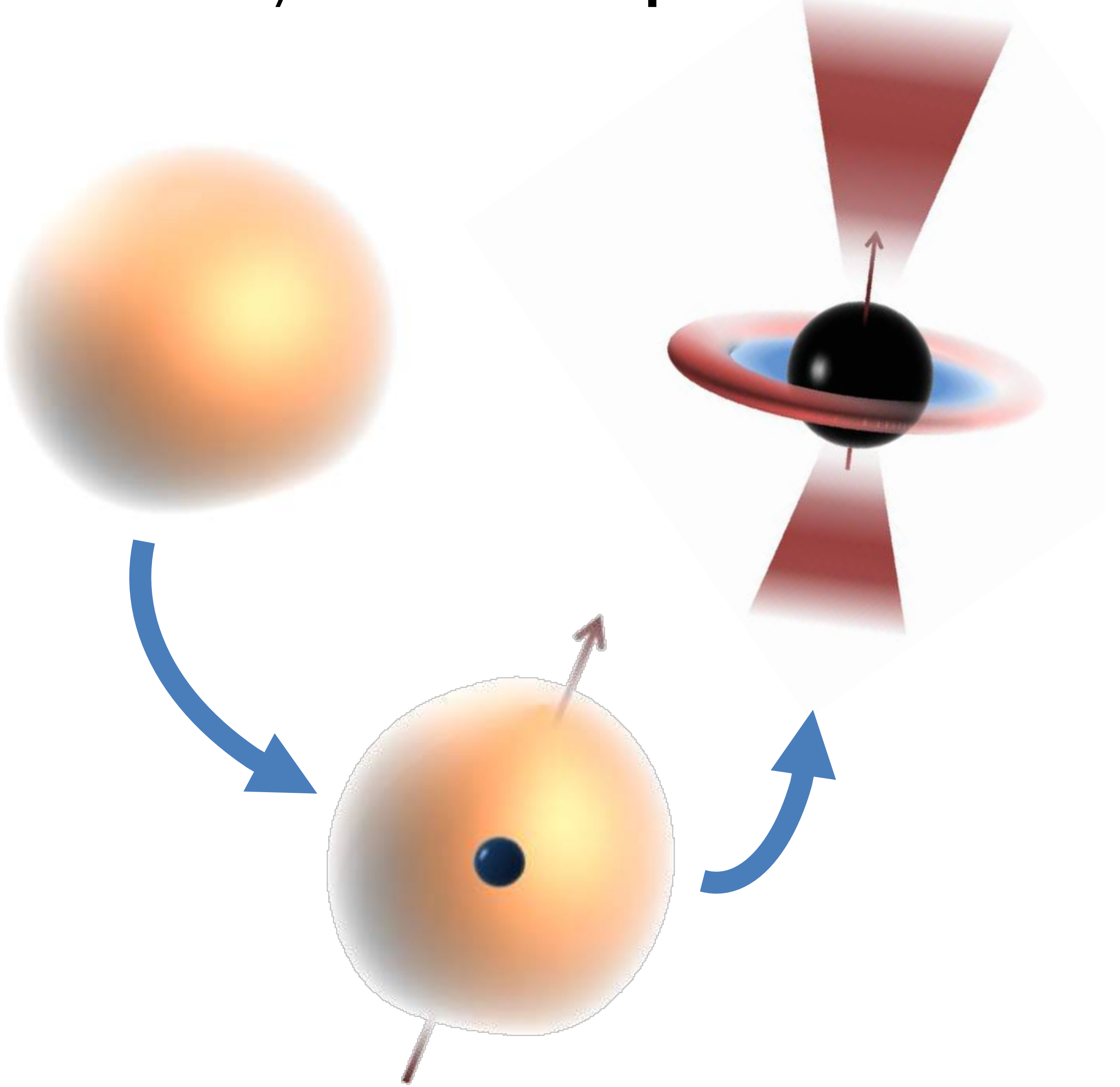


Spacetime tells matter how to move;
matter tells spacetime how to curve.

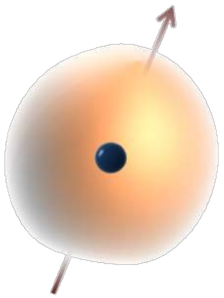
John Archibald Wheeler (2000)

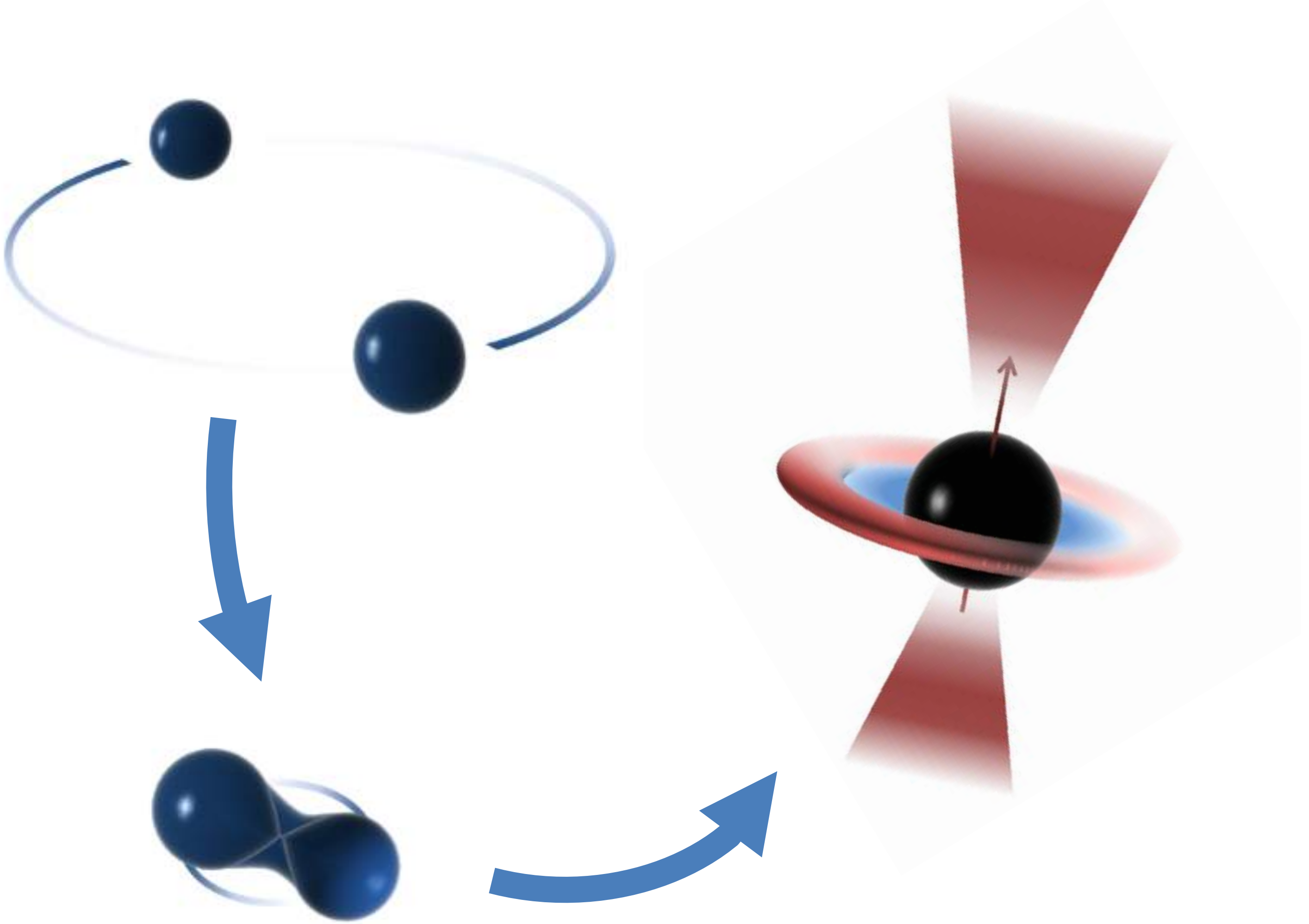


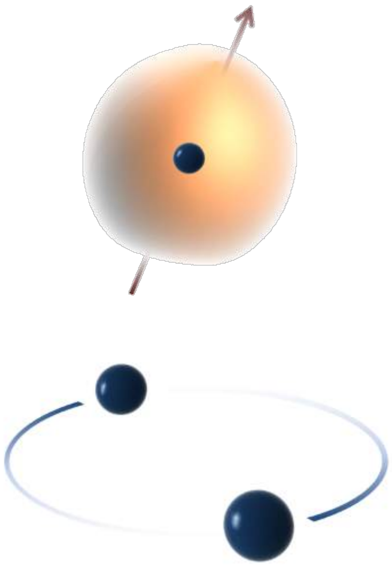
Likely sources: **Supernova**



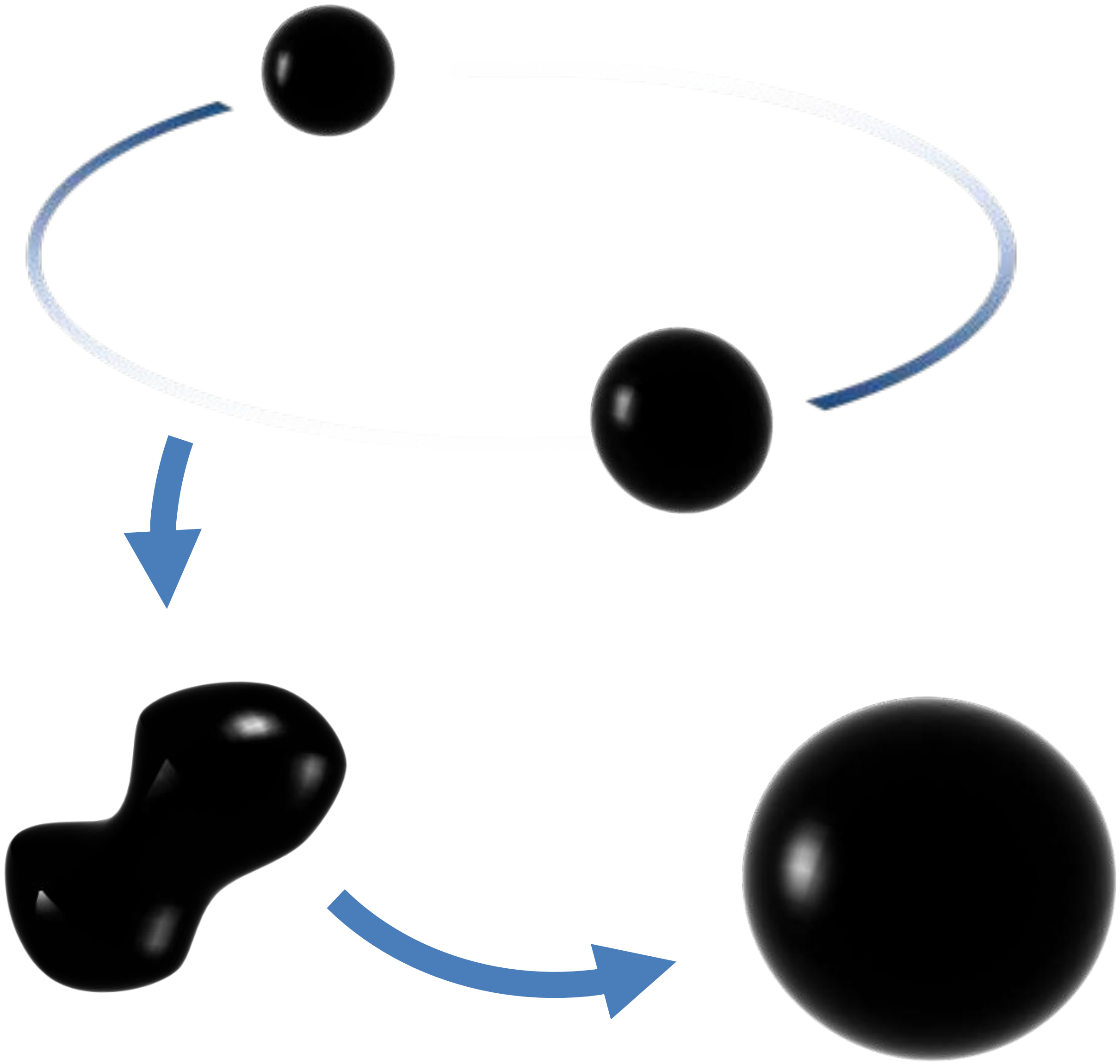
Likely sources: **Binary neutron star**

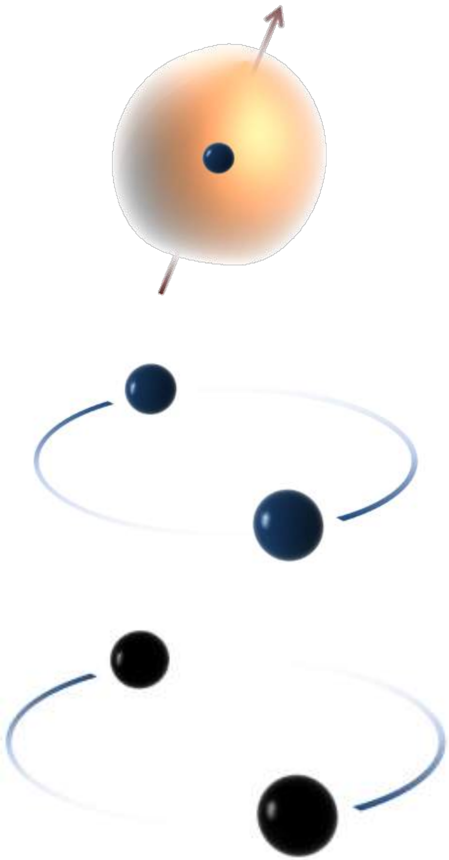




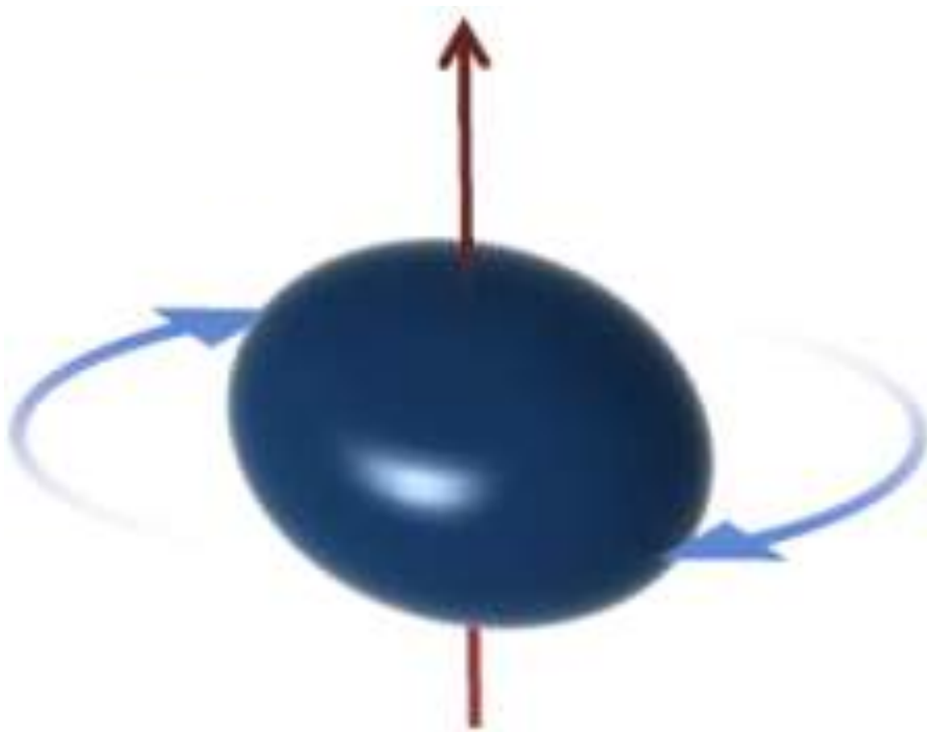


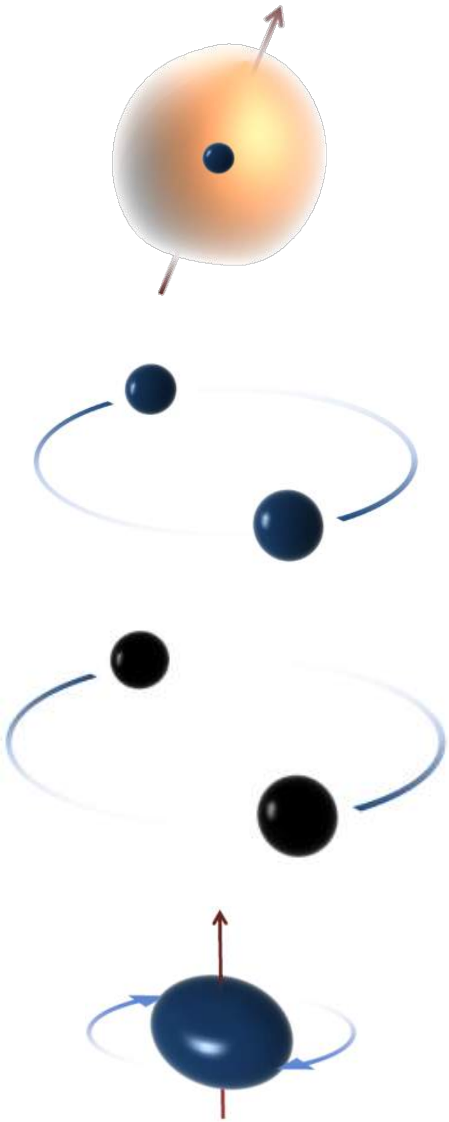
Likely sources: **Binary black hole**





Likely sources: **Rapidly rotating neutron star**





... are all out there

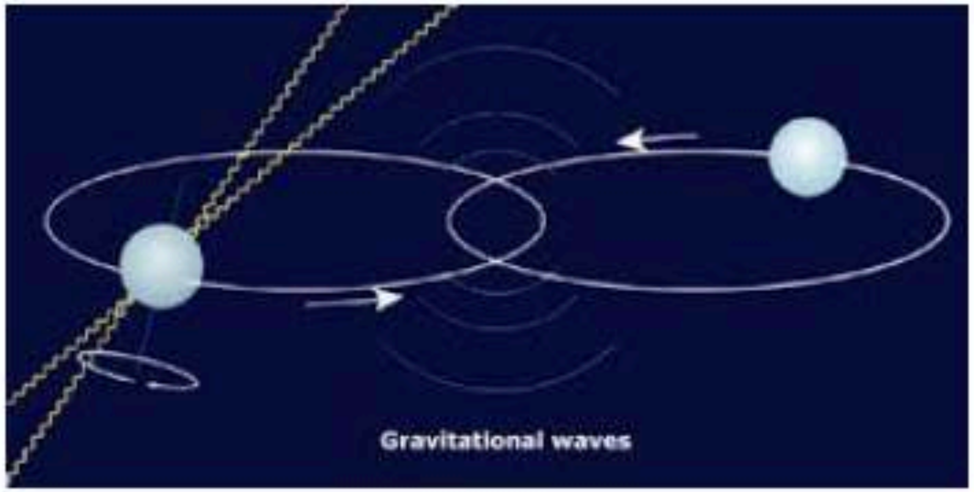
Indirect evidence for gravitational waves

Hulse-Taylor binary pulsar

NS-NS binary

a NS observed as pulsar ($P \simeq 59$ ms)

discovered 1974



Pulsars are clocks with exceptional intrinsic stability (comparable to atomic clocks)

Timing residuals affected by various effects due to GR (e.g. Roemer, Einstein and Shapiro time delays)

Orbital period = 7.75 hr, Minimum separation (periastron) ~ $1.1 R_\odot$

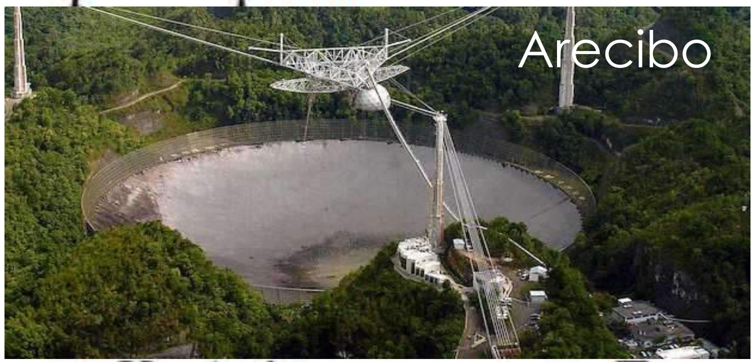
Indirect evidence for gravitational waves?

A 'click' every 59 ms and 27 yrs of data!

Fitting the timing formula, the parameters of the system are known very accurately

$(1/c)a_p \sin \iota$ (s)	2.3417725(8)
e	0.6171338(4)
T_0 (MJD)	52144.90097844(5)
P_b (days)	0.322997448930(4)
ω_0 (deg)	292.54487(8)
$\langle\dot{\omega}\rangle$ (deg/yr)	4.226595(5)
γ (s)	0.0042919(8)
$\dot{P}_b$	$-2.4184(9) \times 10^{-12}$

Keplerian parameters



post-Keplerian parameters. Two quantities fix m_p, m_c, the rest give

pure predictions

$$\rightarrow \quad m_p = 1.4414(2)M_\odot\,, \quad m_c = 1.3867(2)M_\odot$$

Indirect evidence for gravitational waves

Now everything is fixed and GR gives a prediction for $\dot{P}_b$ due to GW emission. Using Einstein quadrupole formula:

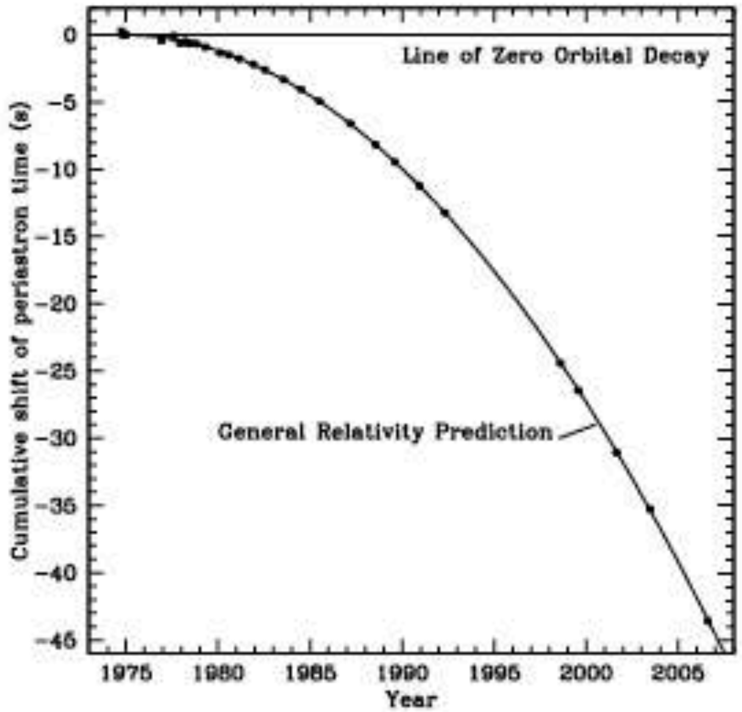
$$\dot{P}_b = -\frac{192\pi G^{5/3}}{5c^5} m_p m_c (m_p + m_c)^{-1/3} \left(\frac{P_b}{2\pi}\right)^{-5/3} \times \frac{1}{(1-e^2)^{7/2}} \left(1 + \frac{73}{24}e^2 + \frac{37}{96}e^4\right)$$

~ 7.35x10^{24} watt

Comparing to observation:

$$(\dot{P}_b)_{\mathrm{obs}}/(\dot{P}_b)_{\mathrm{th}} = 1.0013(21)$$

Nobel prize 1993

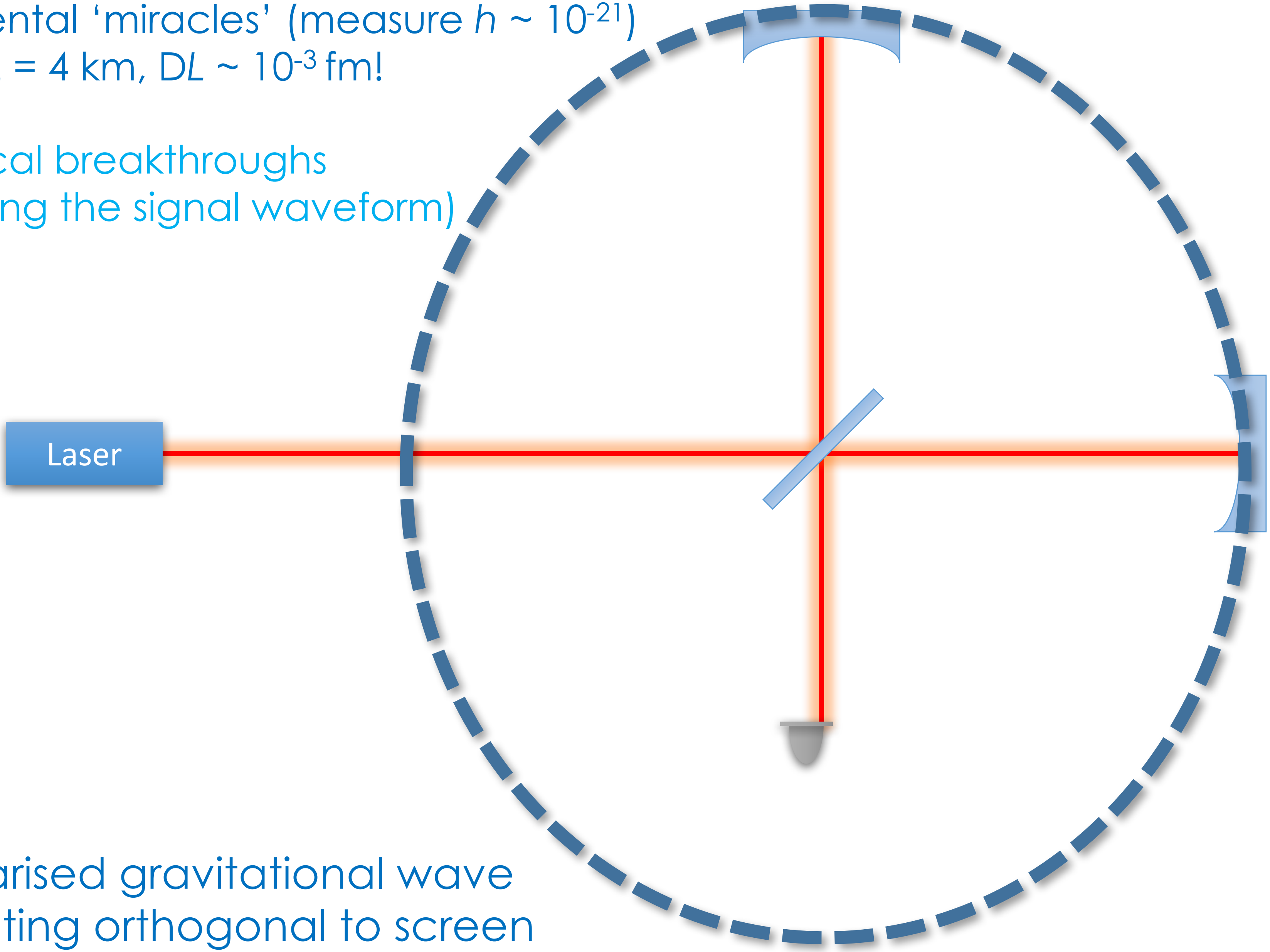


Direct detection of gravitational waves with a laser interferometer

Made possible by 40+ years of work, including:

- Experimental 'miracles' (measure h ~ 10^{-21})
  ⇒ over L = 4 km, DL ~ 10^{-3} fm!

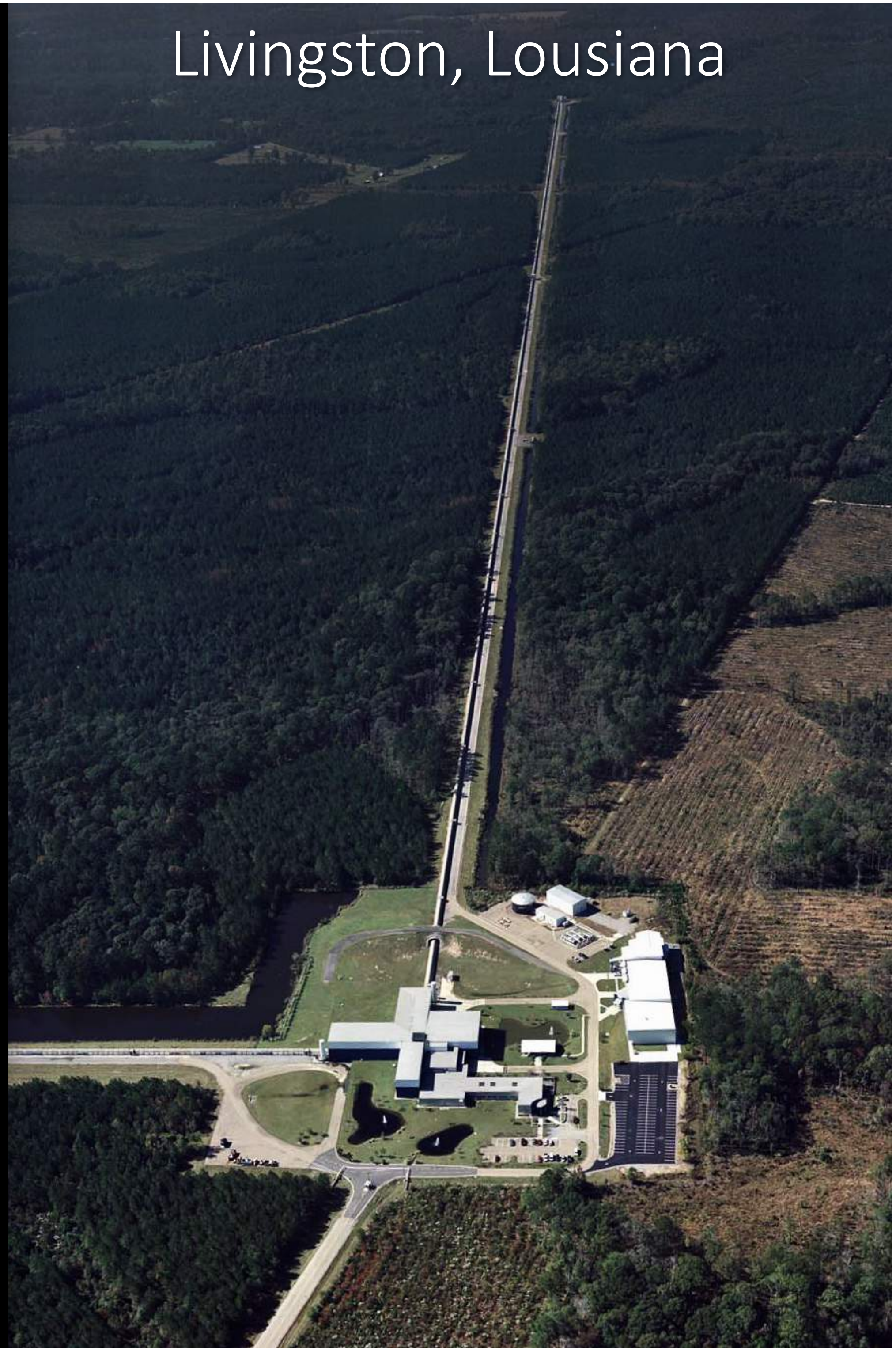
- Theoretical breakthroughs
  (predicting the signal waveform)



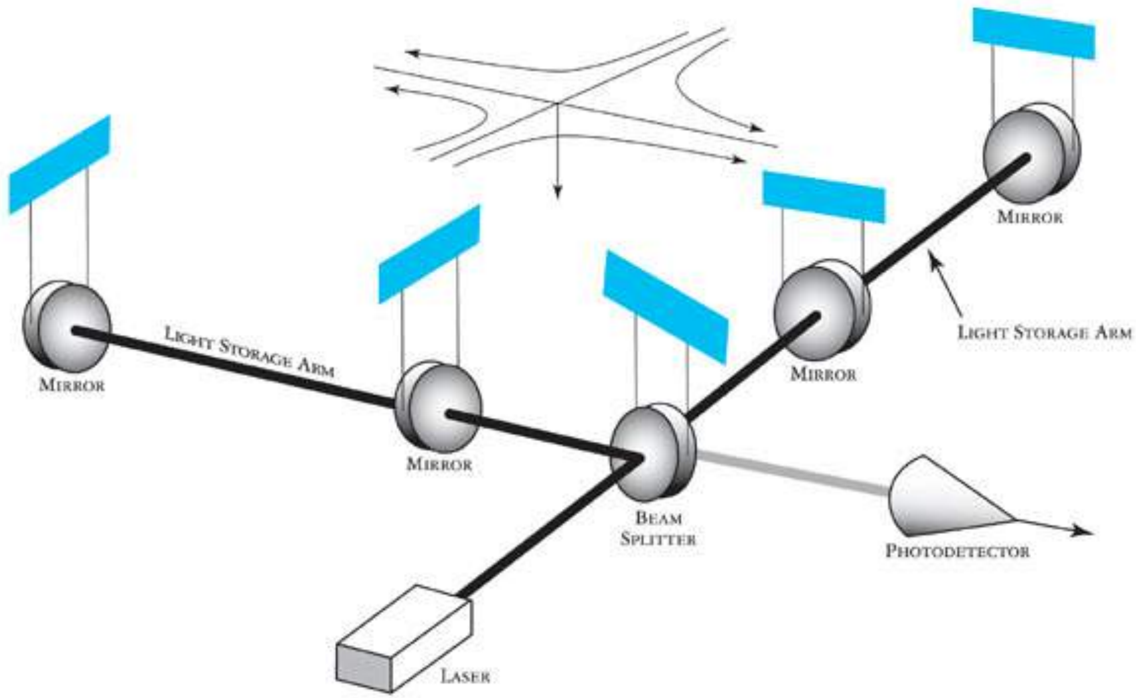
Courtesy: Giacomo Ciani (LIGO-G1101293)

"+" polarised gravitational wave
propagating orthogonal to screen


Hanford, Washington


Livingston, Lousiana

Direct detection of gravitational waves



- laser beam size $\sim$ 12 cm. Even if $\Delta L = 10^{-3}$ fm, we measure a coherent displacement of all atoms in the mirror! A better figure is given by the phase shift in the interferometer,

$$\Delta\phi = \frac{4\pi\mathcal{F}}{\lambda_L} h_0 L \sim 10^{-8} \text{ rad}$$

- does not detect a mirror motion $x(t)$ but $\tilde{x}(f)$ in a selected range of frequencies $\sim$ 10Hz – 3kHz. We are only sensitive to GW frequencies in this range

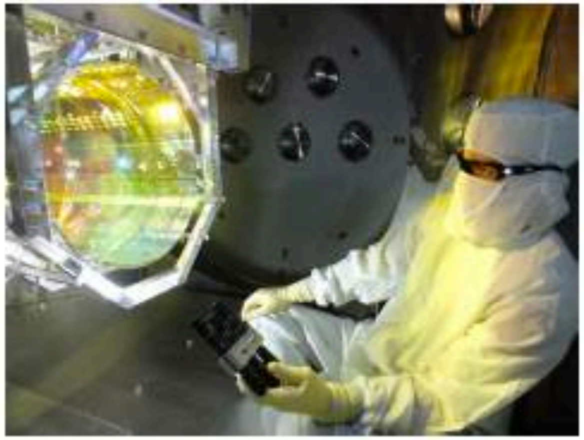
Direct detection of gravitational waves

- seismic attenuation: factor 10^{10} at 10 Hz
- $\Delta L = hL \quad \Rightarrow$ long arm-length + FP cavity ($L_{\rm eff} \sim 750$ km)
- power recycling: 750 kW of laser light circulating!
  (from a 200 W laser)
- mirrors: scatter less than 10 ppm of incident light

  micro-roughness < 0.16 nm

  shaped to control diffraction

  $M = 40$ kg to reduce radiation pressure
  and heating



- controls and locking: keep the FP cavities
  in resonance: $\delta L < (\lambda_L / 4\mathcal{F}) \sim 10^{-8}$ cm

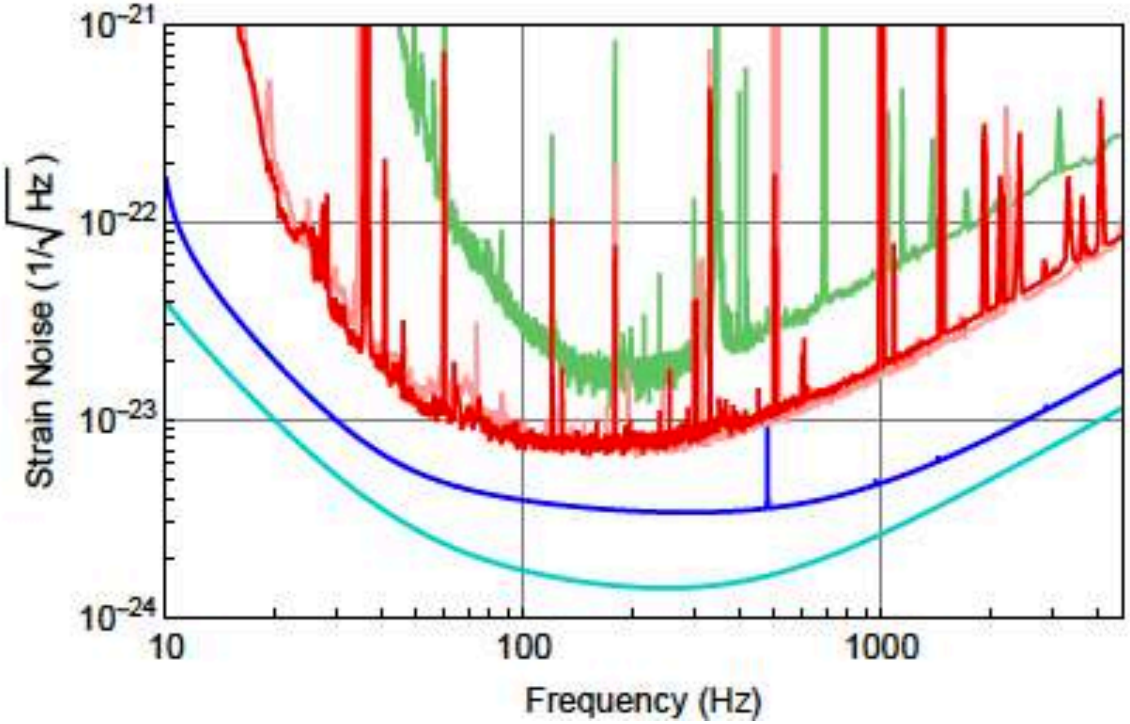
Detector sensitivity

Detector noise $n(t)$. In Fourier space $\tilde{n}(f)$

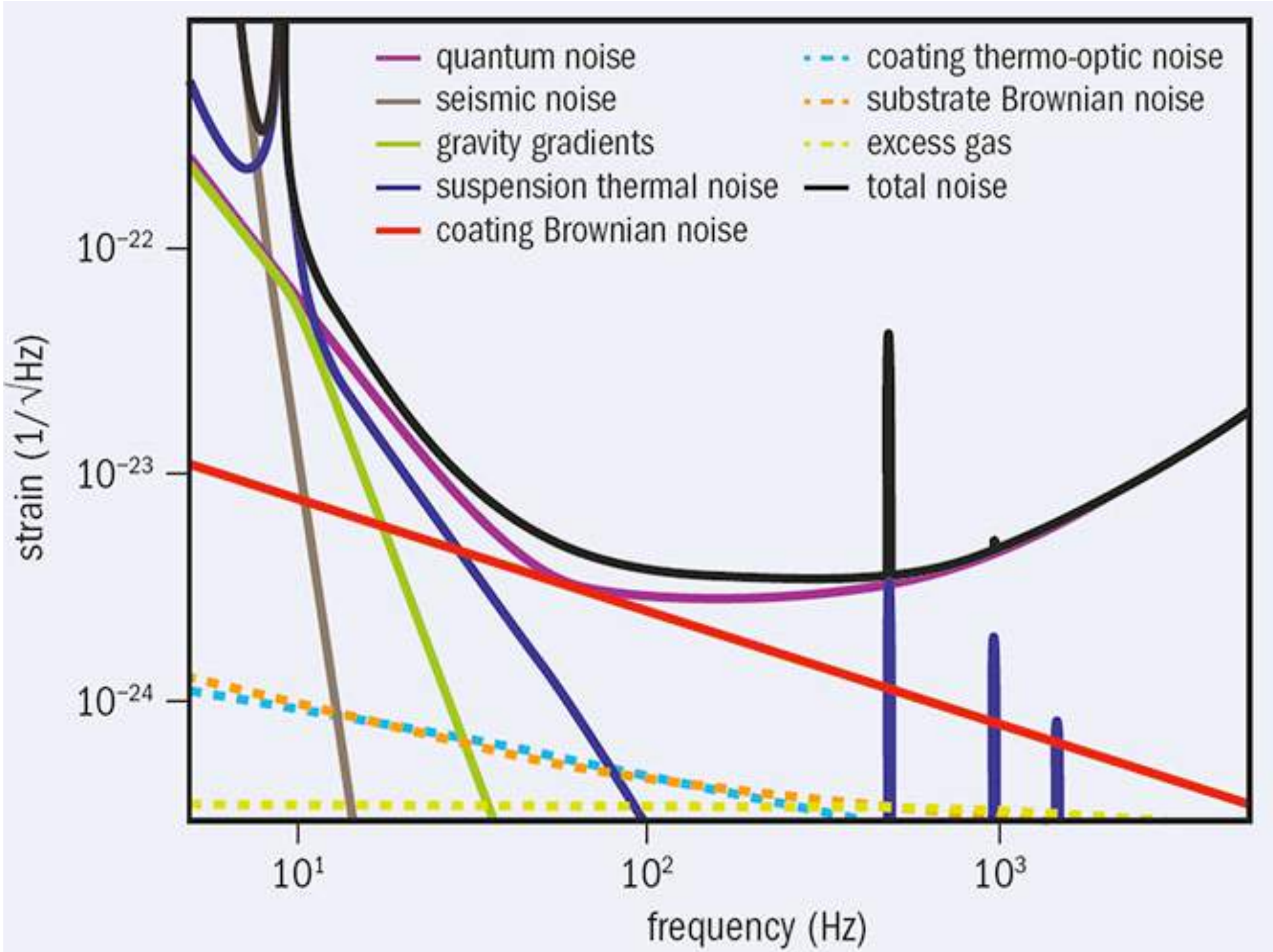
For stationary noise, $\langle \tilde{n}^*(f)\tilde{n}(f')\rangle = \delta(f-f')\frac{1}{2}S_n(f)$

$S_n(f) \propto \mathrm{Hz}^{-1}$ is the noise spectral density

$S_n^{1/2}(f) \propto \mathrm{Hz}^{-1/2}$ characterizes the detector sensitivity



Detector sensitivity



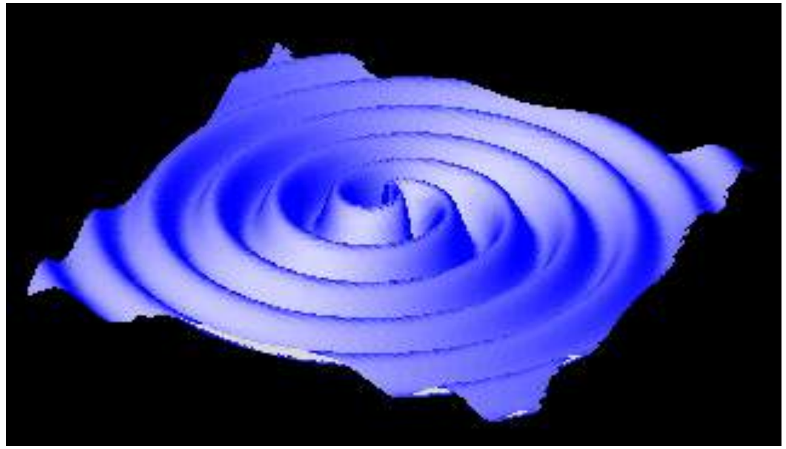
Martin, Killow & Hammond, CERN Courier, 13 Jan 2017

… helps to know what one is looking for!

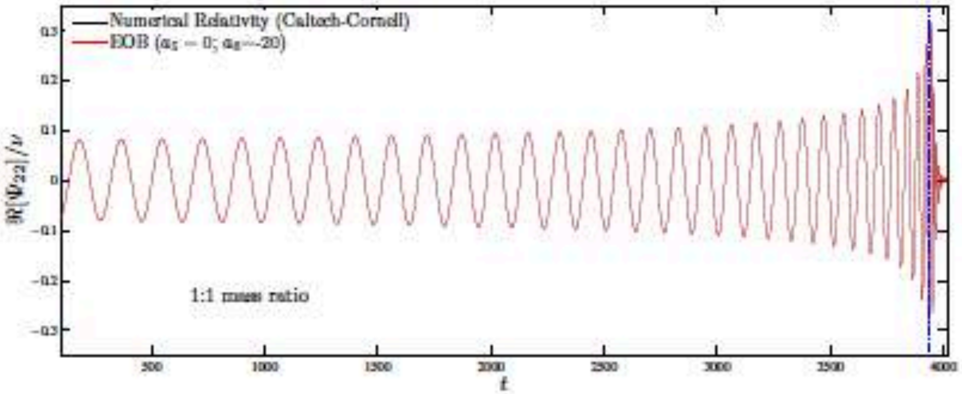
Accurate predictions of the waveform are crucial for

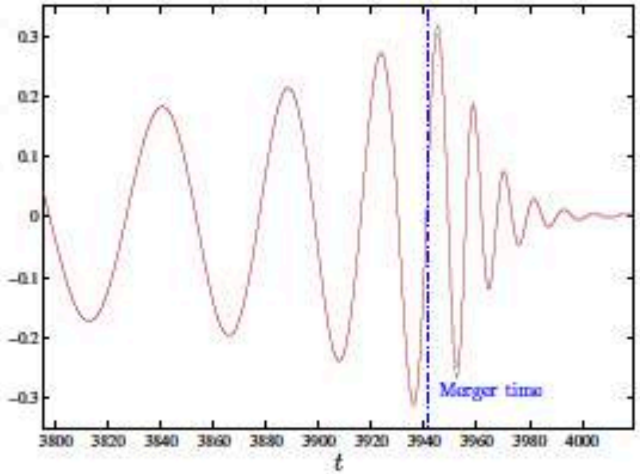
- extracting the signal from the noise
- extracting the physics from the event

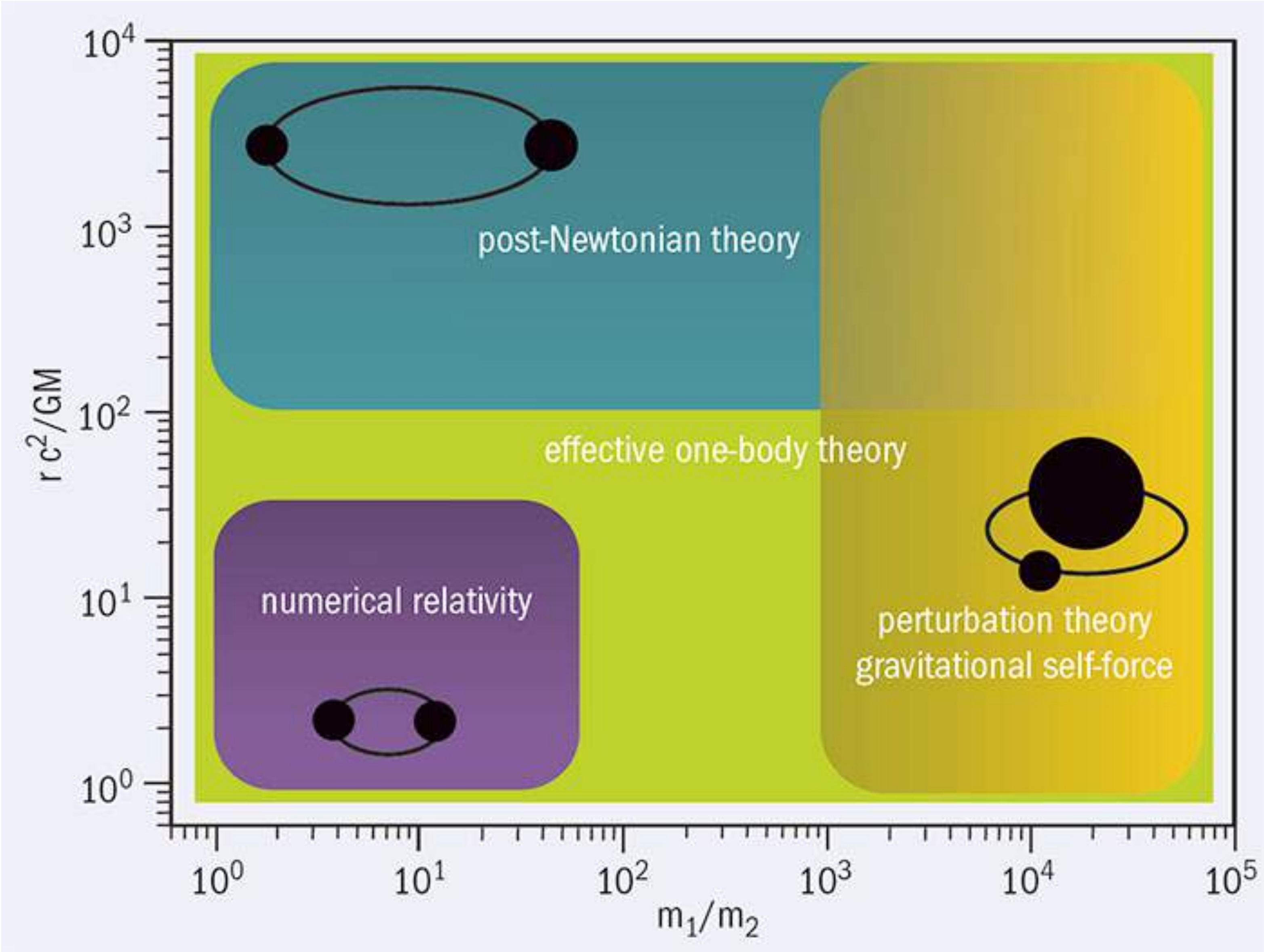
Three phases: inspiral-merger-ringdown



Thanks to decades of theoretical work, the waveform is fully under control







Courtesey: Alessandra Buonanno, CERN Courier, 13 Jan 2017

The long awaited discovery …

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)

1004 authors
90 institutions
15 countries

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

Awarded:

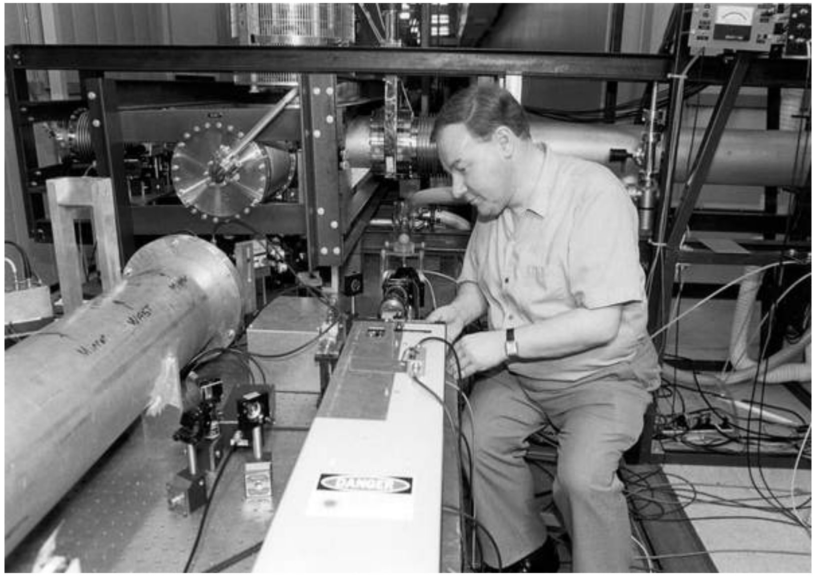
- The Gruber Cosmology Prize (2016)
- The Fundamental Physics Prize (2016)
- The Kavli Prize (2016)
- The Shaw Prize (2016)

http://arxiv.org/abs/1602.03841

Ronald Drever

(1931–2017)

Experimental physicist key to the detection of gravitational waves

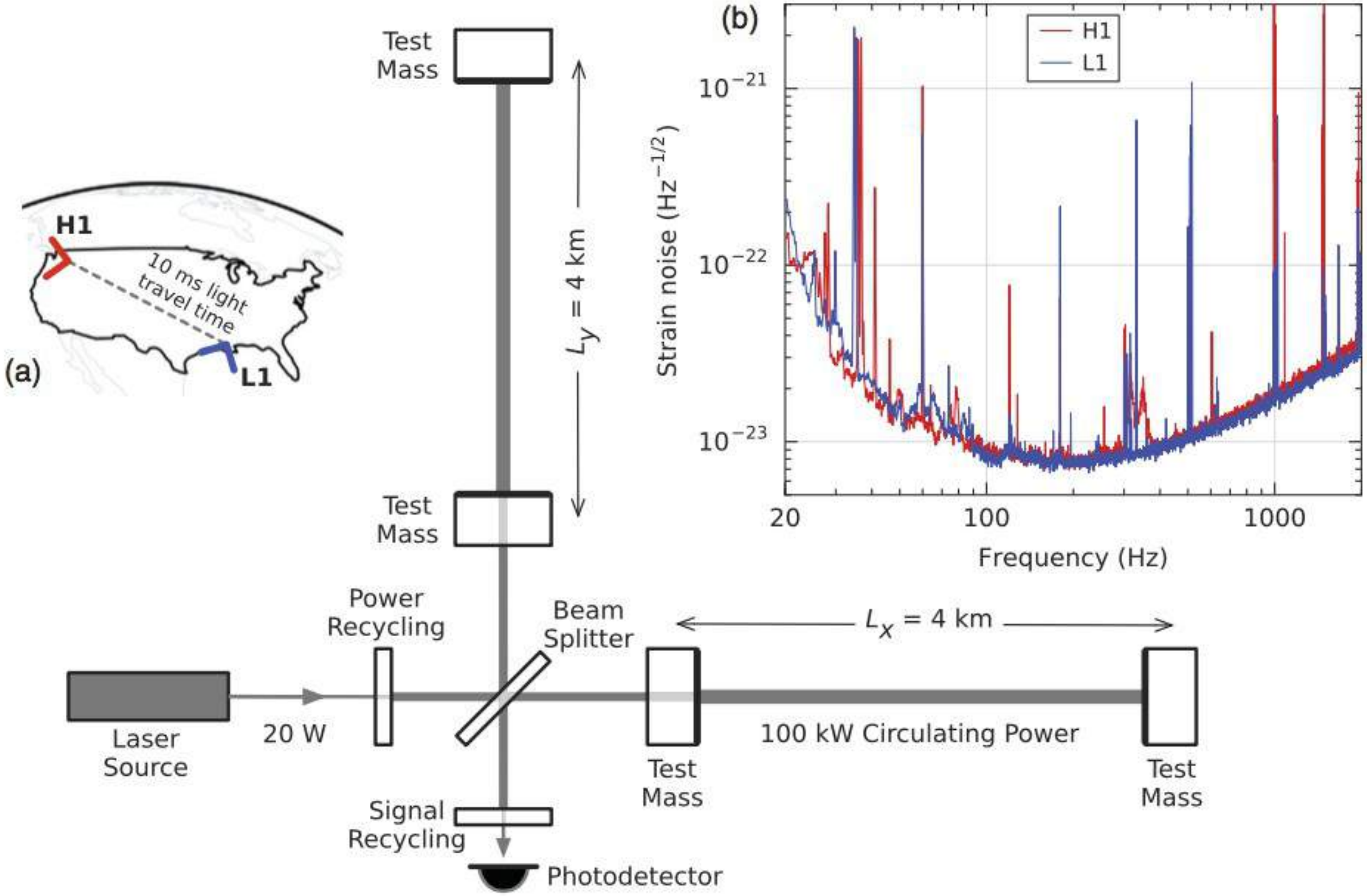


It is well known that Drever and I had different views about the direction for technical development for LIGO. I disagreed with him about the use of optical cavities; it turned out he was right. I held out for a solid-state laser while he insisted on a green argon one; Drever was wrong on that one. But we always respected each other's views, and as LIGO's construction progressed we became close colleagues and friends. ■ Rainer Weiss

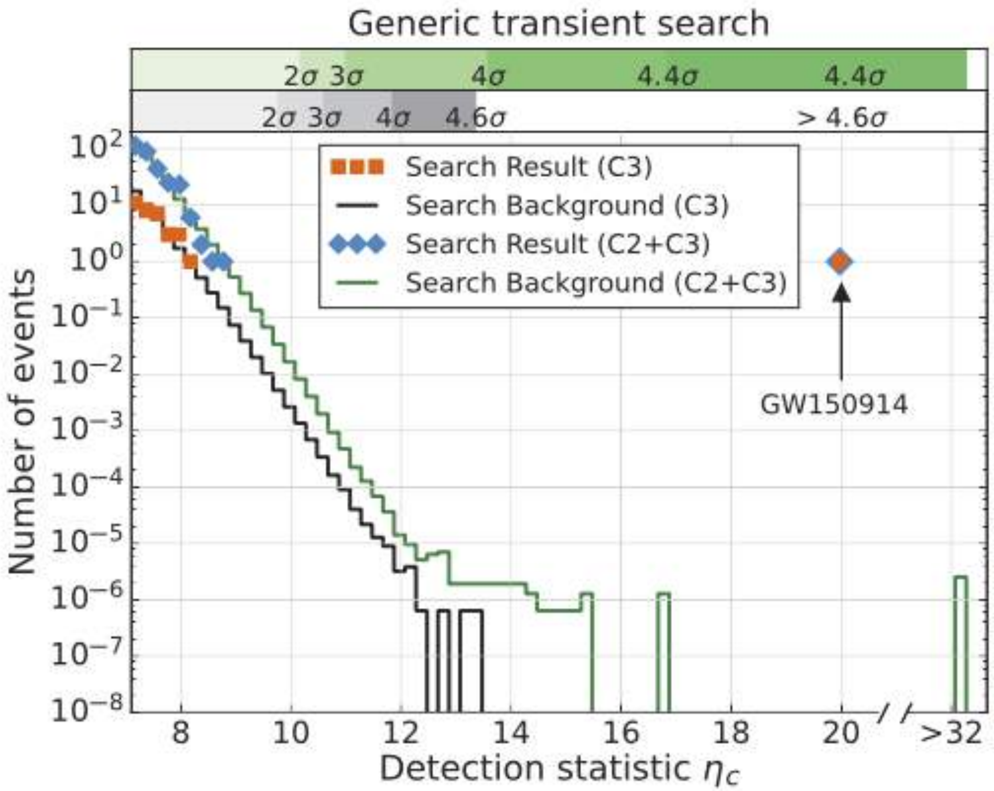
The detectors

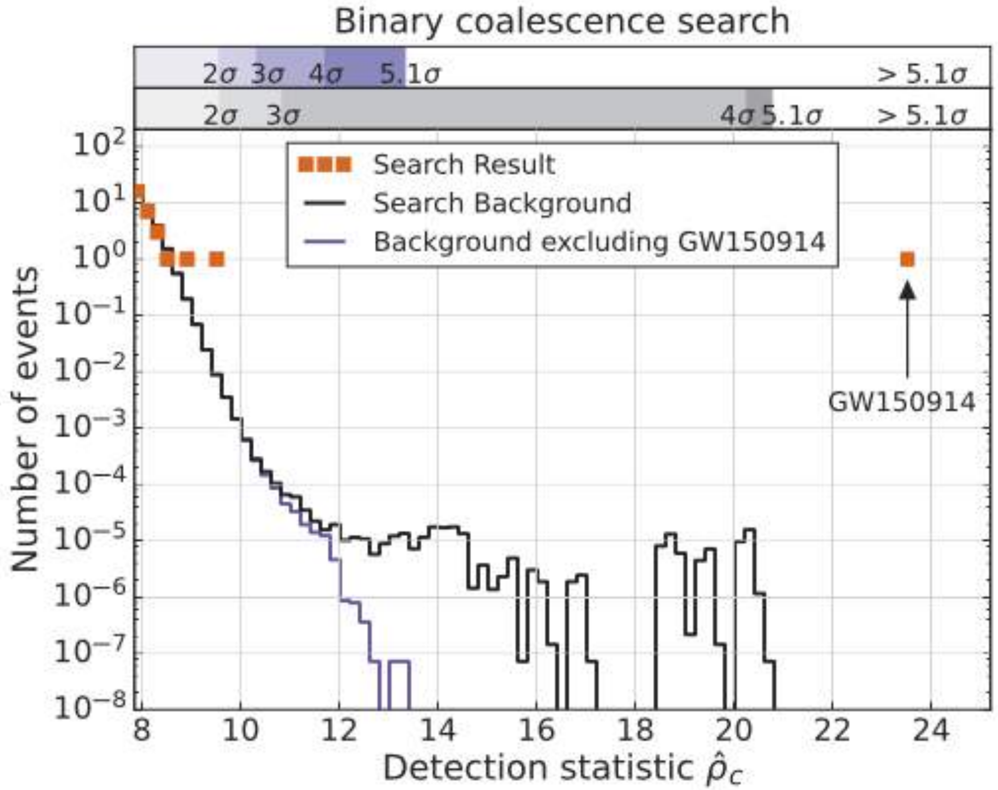
Livingston,
Louisiana

Hanford,
Washington



The detection



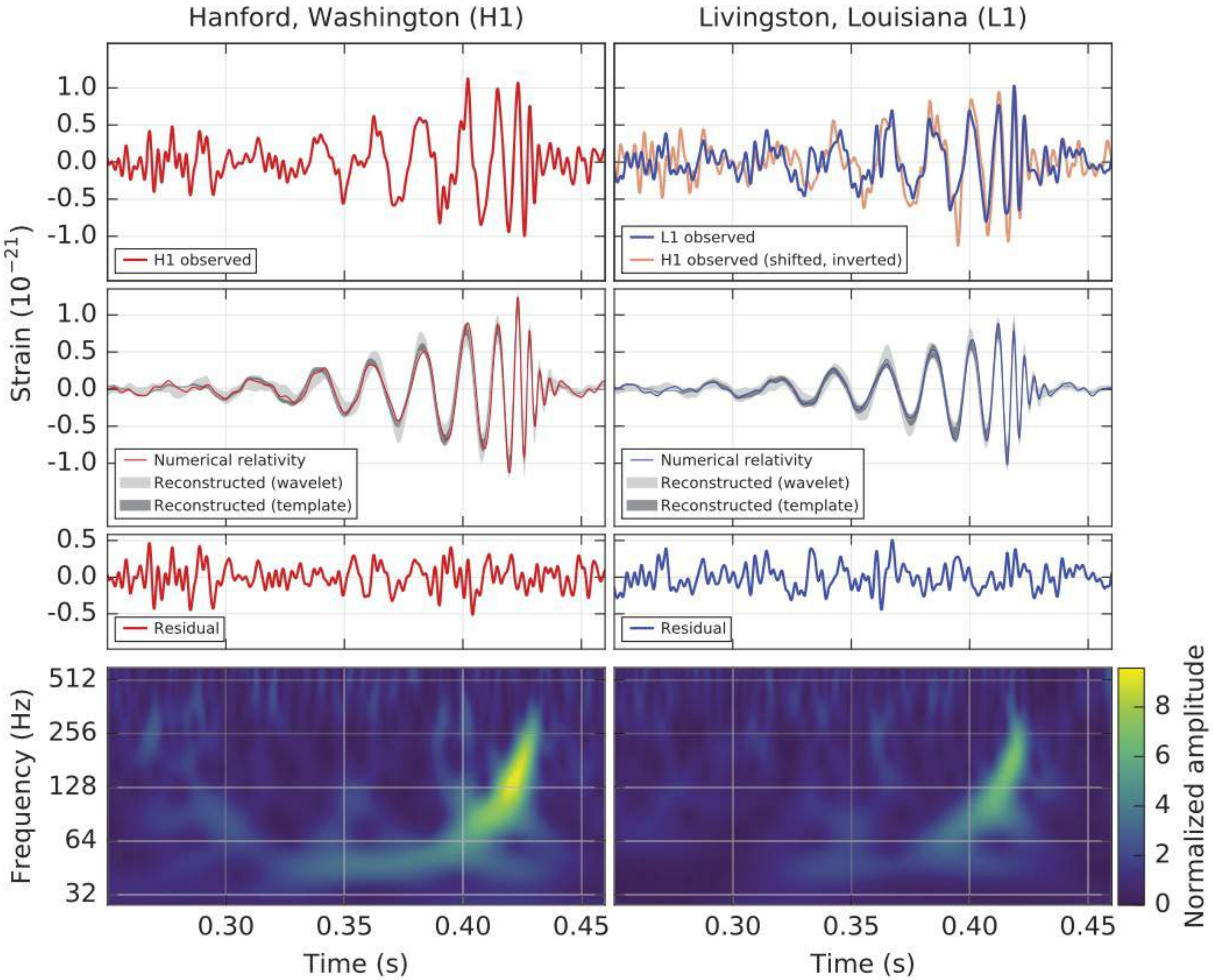


¤ Found in "unmodeled" and "modeled" searches

¤ "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

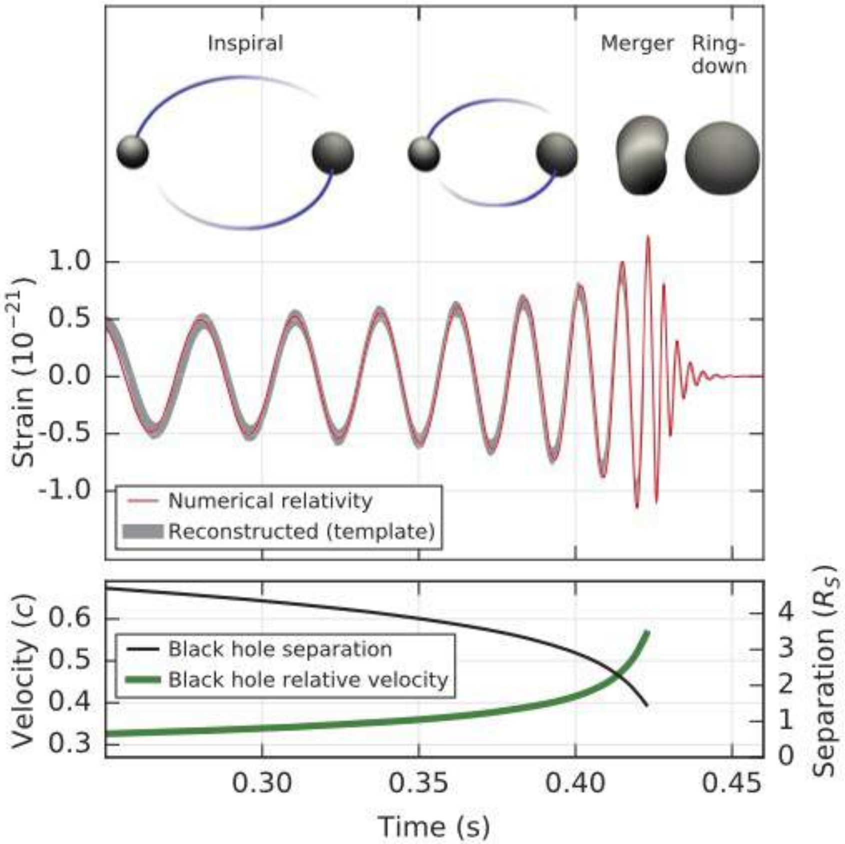


GW frequency rises from 35 to 150 Hz in 0.2 s, so orbital frequency (which is 1/2) *must* ⇒ 2 black holes of ~equal mass orbiting each other before merging

¤ 'Chirp mass' of binary black hole merger:

$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}} = \frac{c^3}{G}\left[\frac{5}{96}\pi^{-8/3} f^{-11/3} \dot{f}\right]^{3/5} \simeq 30 M_\odot$$

¤ Parameters measured by matching millions of trial waveforms in 15-dim. 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	$0.09^{+0.03}_{-0.04}$

Energy emission: ~3 M_{Sun} (⇒ 5×10^{54} erg)

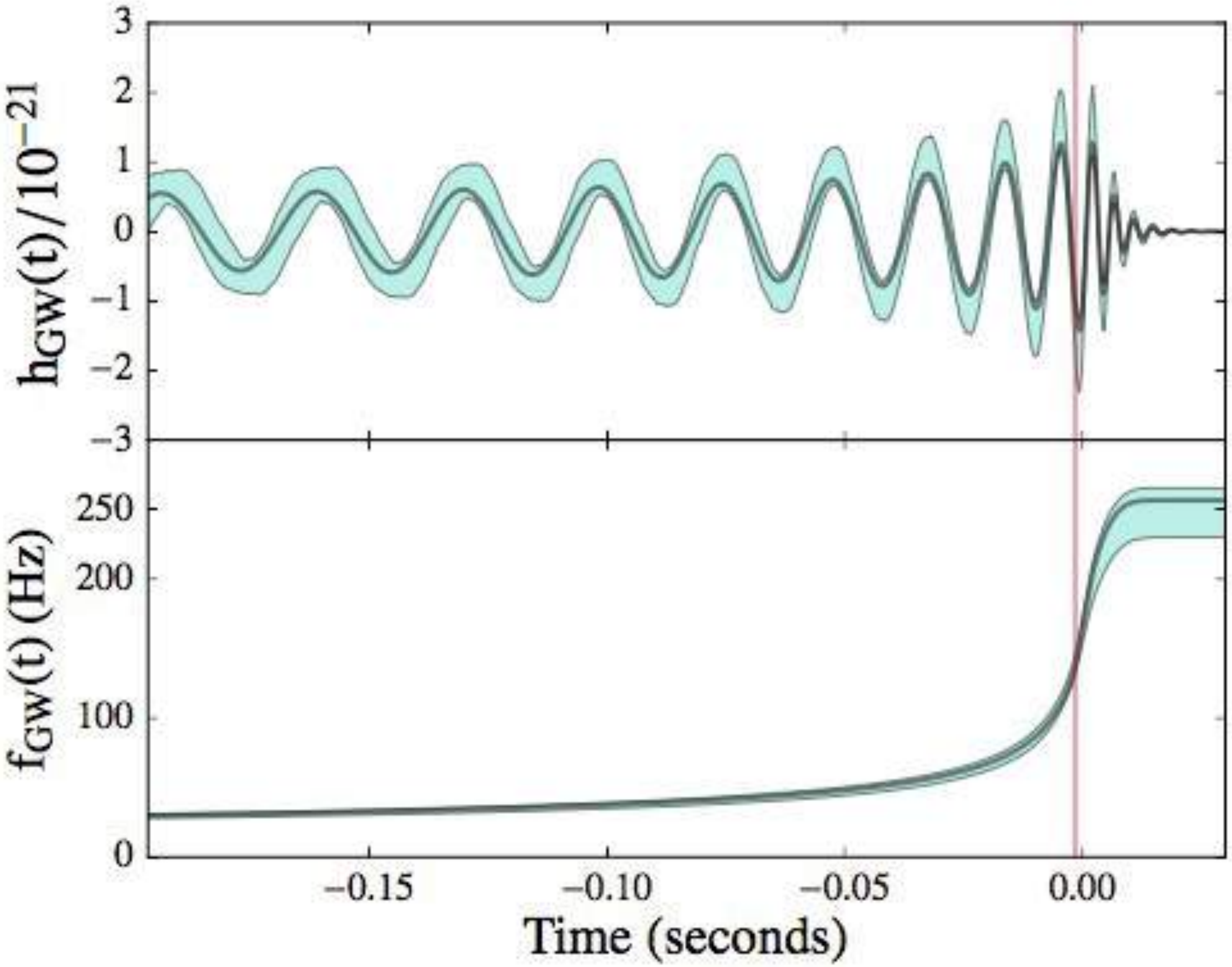
Peak Luminosity: ~200 M_{sun}/s (⇒ 4 $\times 10^{56}$ erg/s)

Biggest bang since the Big Bang!

Four Breakthroughs!

- 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



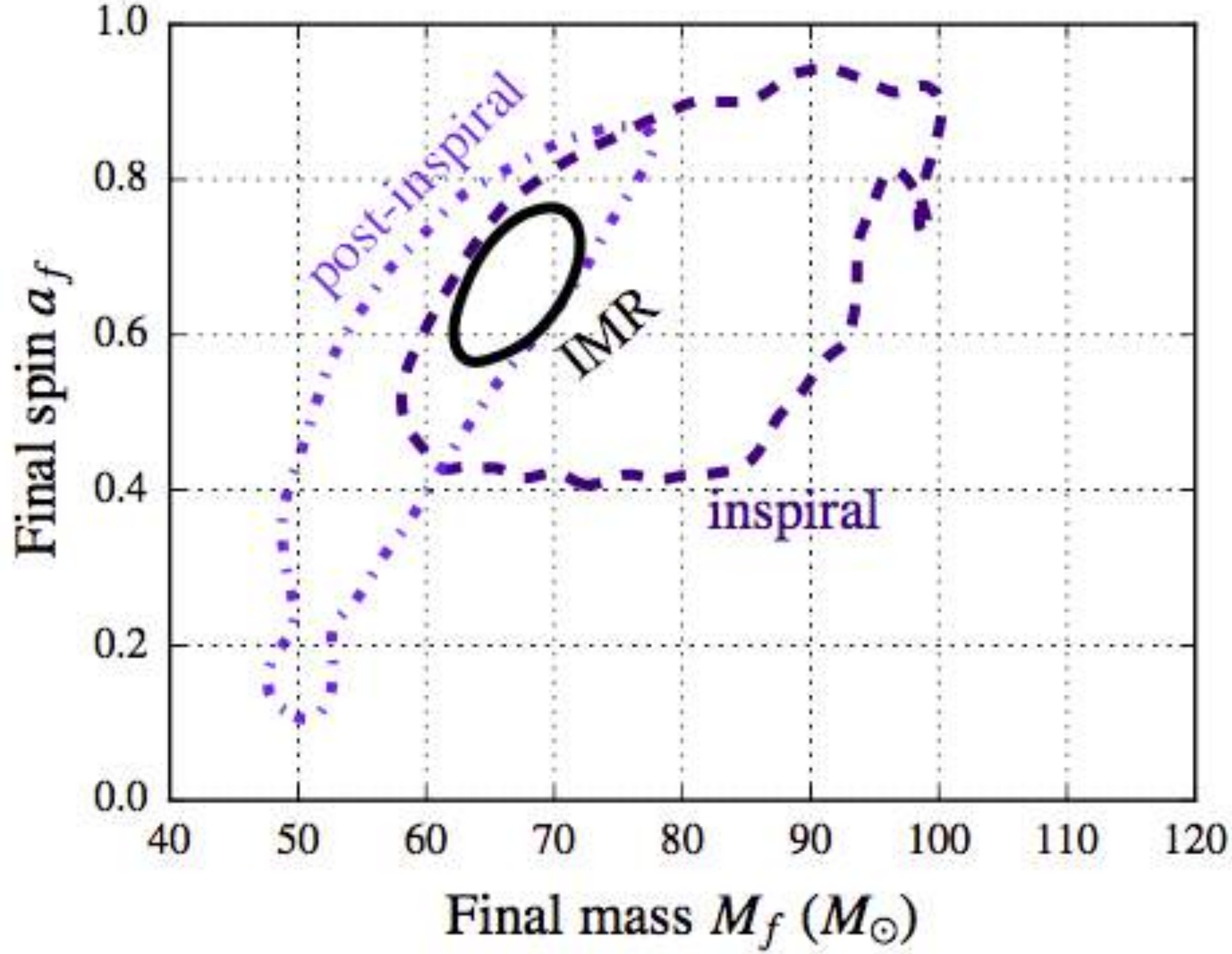
Phys. Rev. Lett. 116, 221101 (2016)

Measure masses, spins of component black holes from inspiral signal

¤ General relativity predicts mass, spin of final black hole

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

Tests of General Relativity



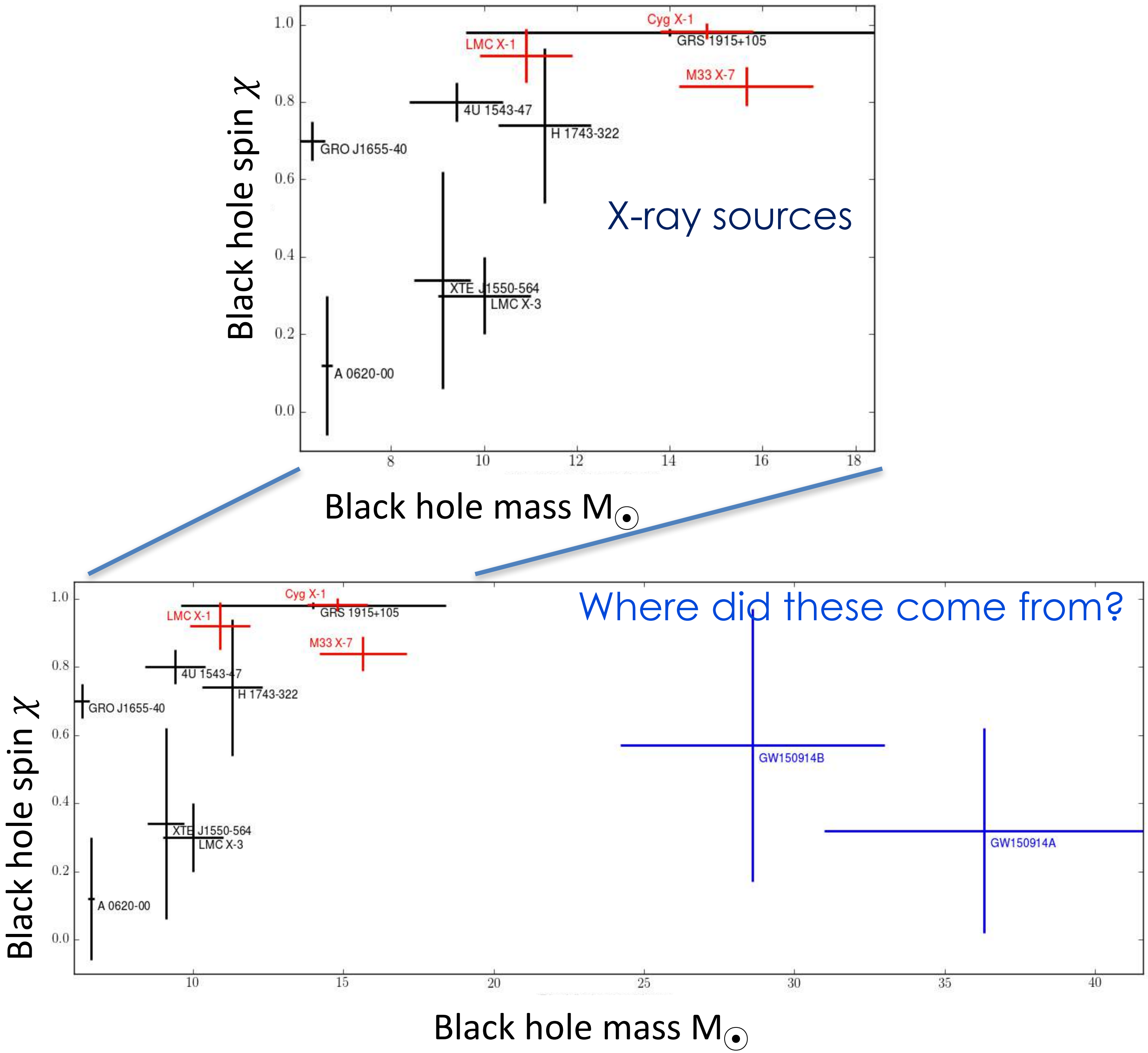
Phys. Rev. Lett. 116, 221101 (2016)

Measure masses, spins of component black holes from inspiral signal

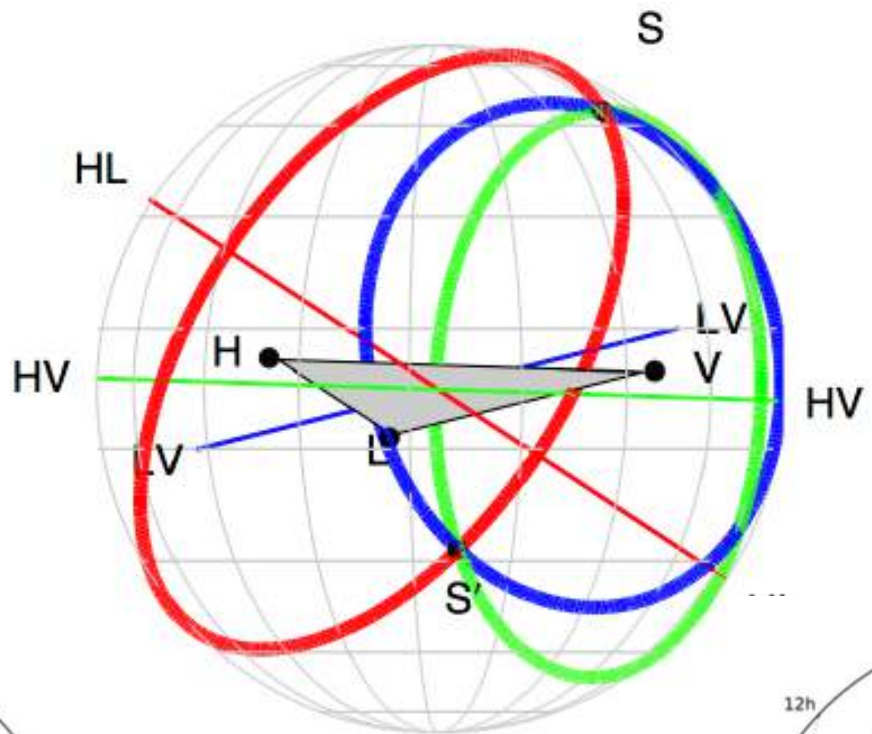
¤ General relativity predicts mass, spin of final black hole

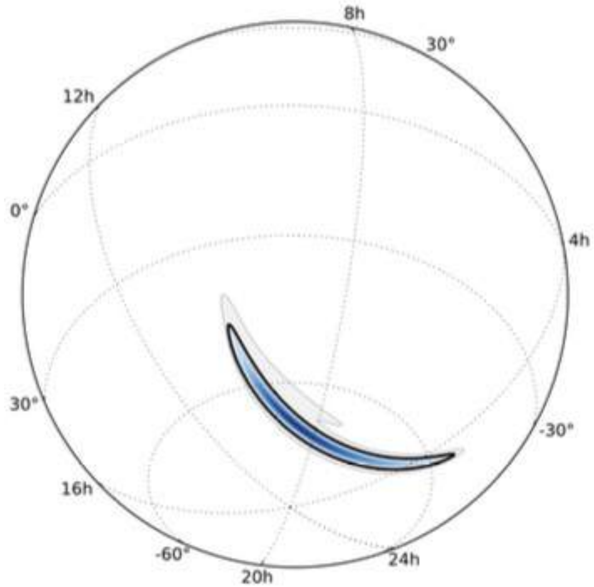
¤ Measure these from *post*-inspiral signal and compare with prediction!

Open question

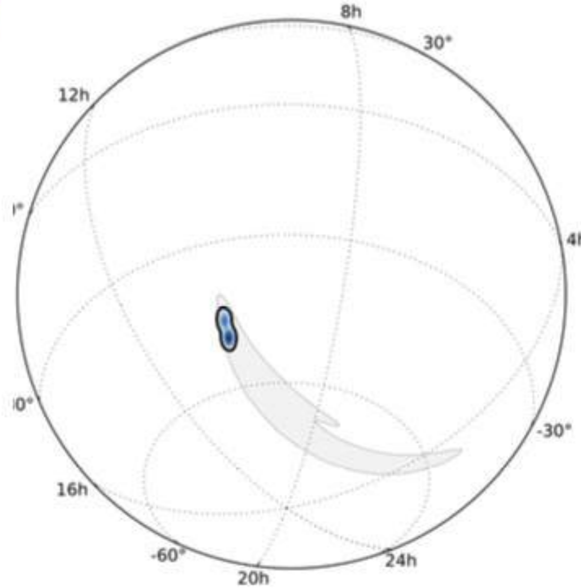


Three detectors will make astronomy possible





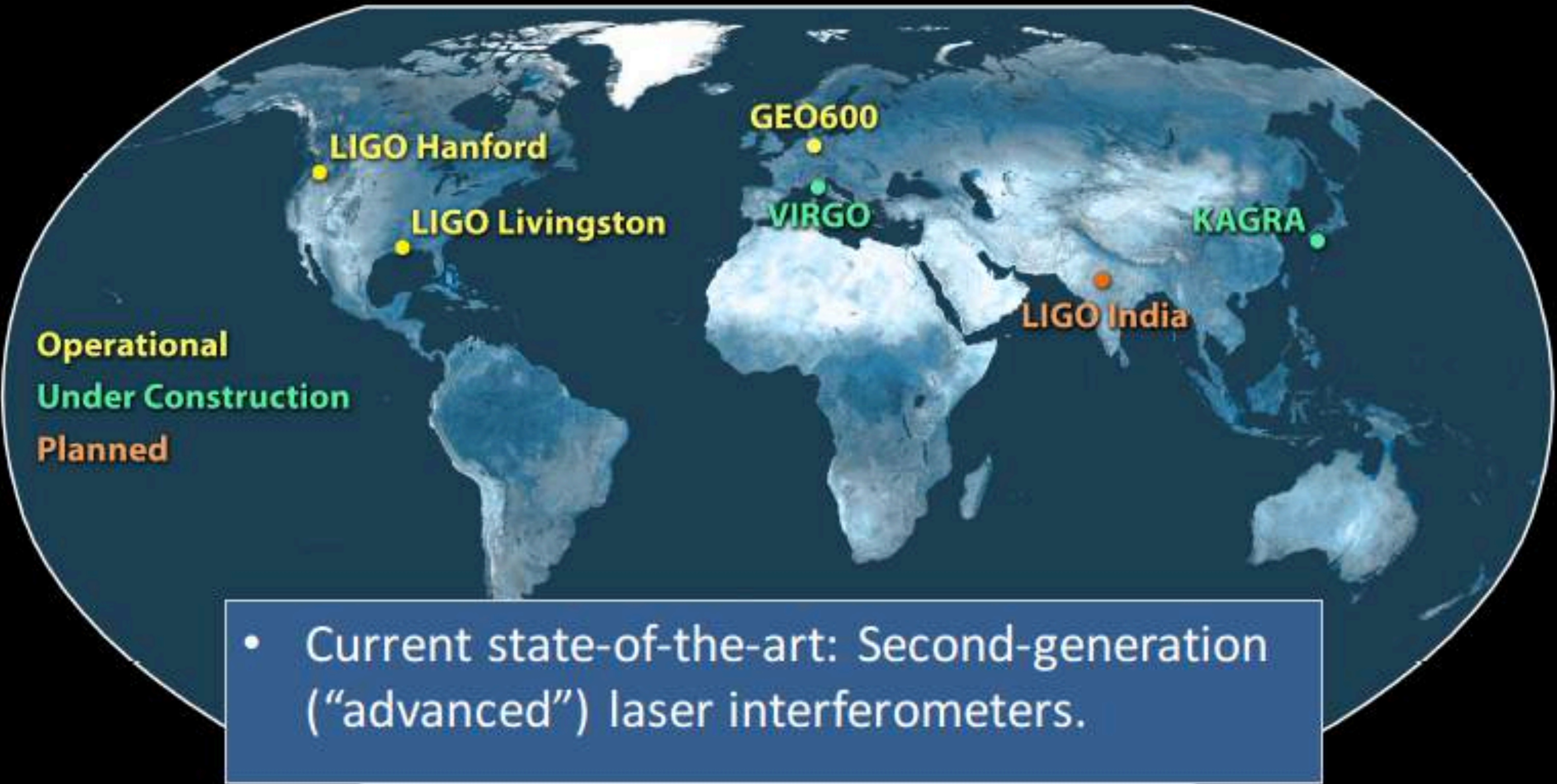
LIGO Hanford + LIGO Livingston



LIGO Hanford + LIGO Livingston + Advanced Virgo

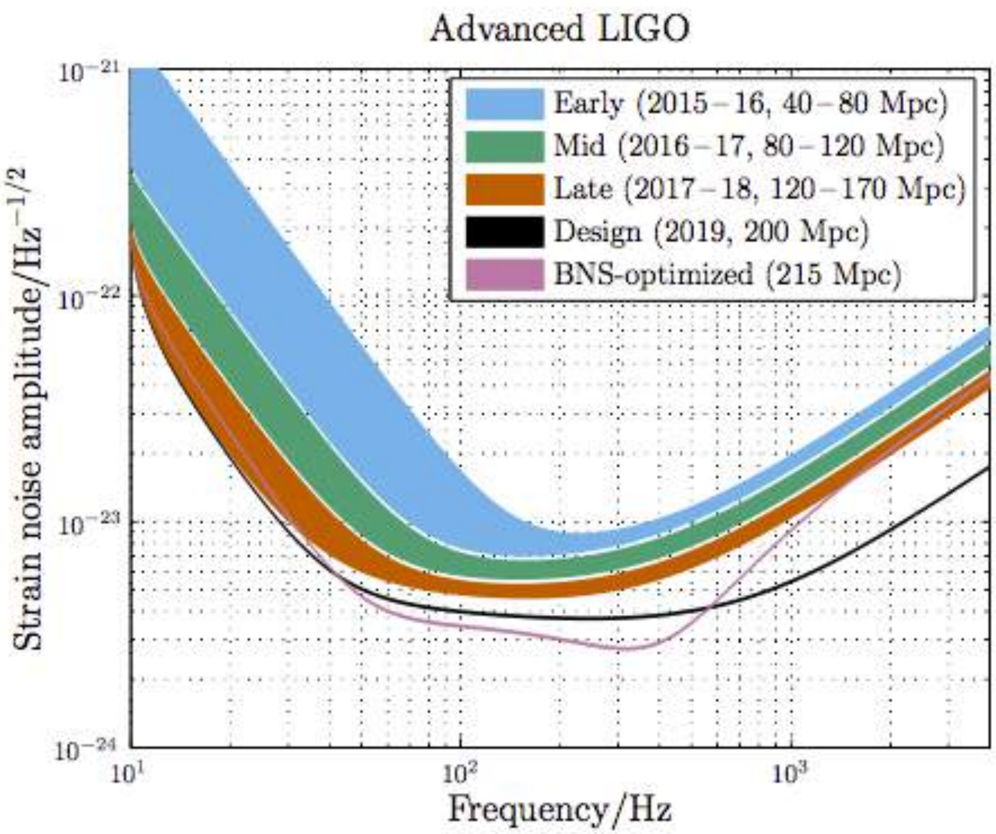
90% confidence error box can be reduced from ~180 deg^2 to 10 deg^2

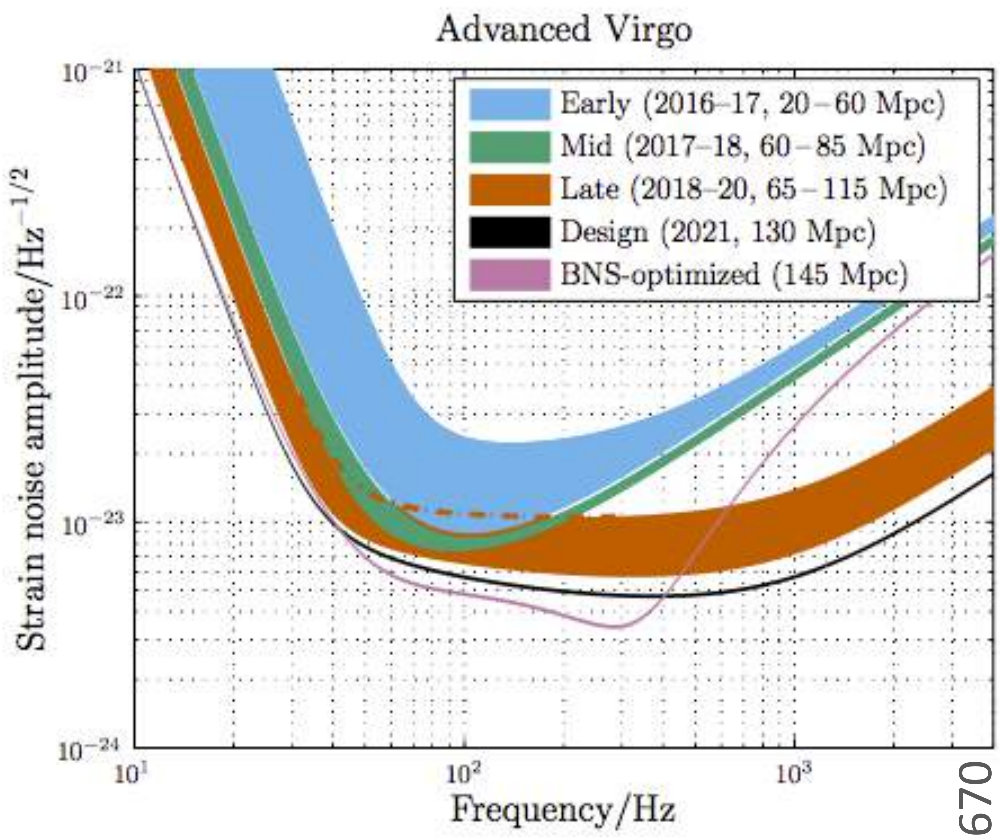
Global GW Detector Network



- Current state-of-the-art: Second-generation ("advanced") laser interferometers.

Observing plans





¤ 2015-16 (**O1**): 4-month run with only Advanced LIGO

- Detection of GW150914
- Second half of data analysed – detection of GW151226

¤ 2016-17 (**O2**): 6-month run with Advanced Virgo joining (… delayed)

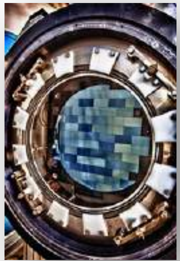
¤ 2017-18 (**O3**): 9-month run LIGO + Virgo + KAGRA?

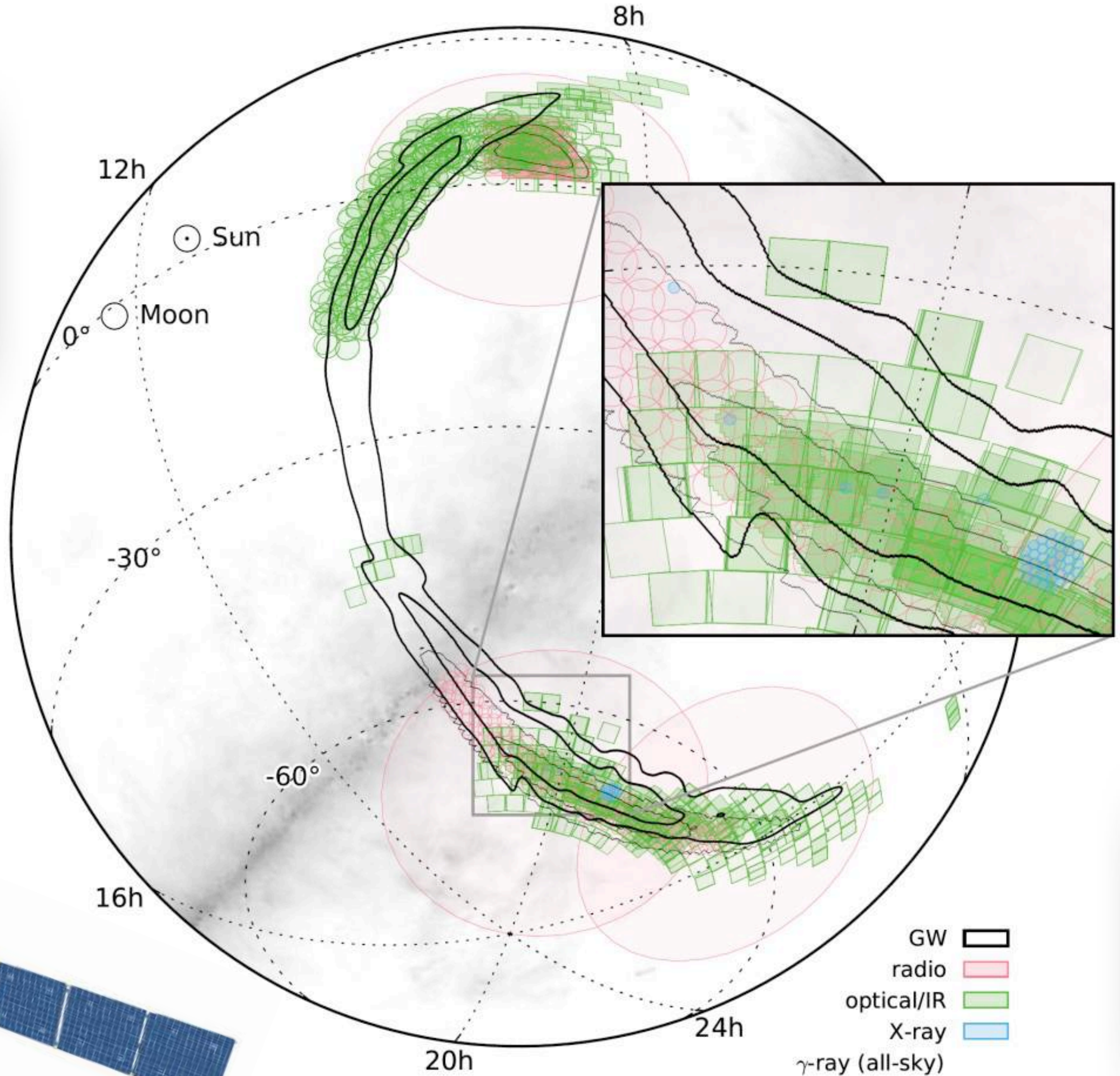
¤ 2019+: LIGO + Virgo (towards full sensitivity) + KAGRA

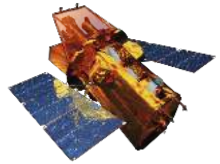
¤ 2022+: LIGO-India joins the network

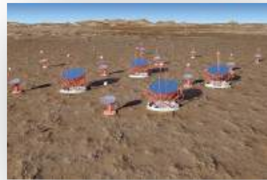
http://arxiv.org/abs/1304.0670

Multi-wavelength astronomy?





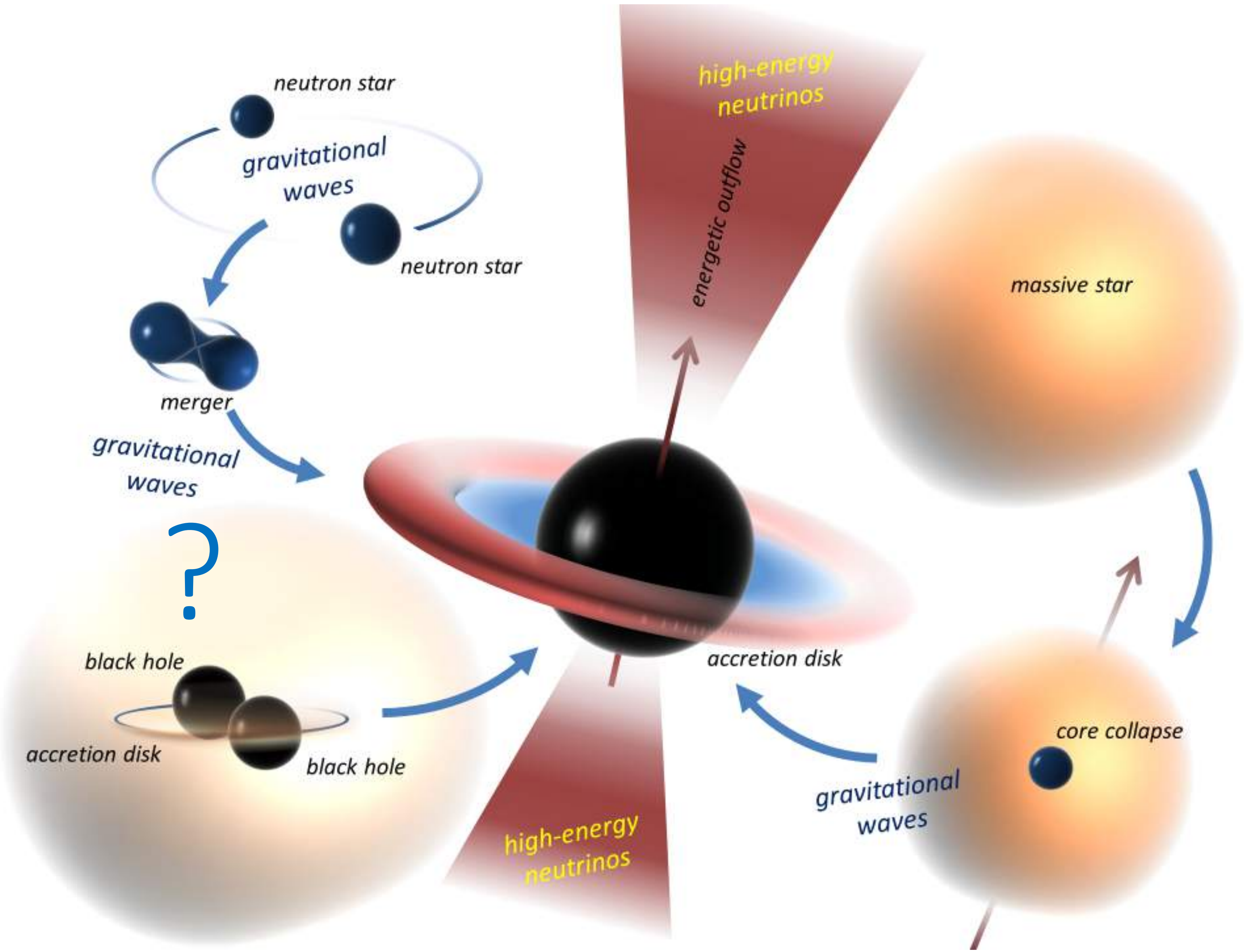




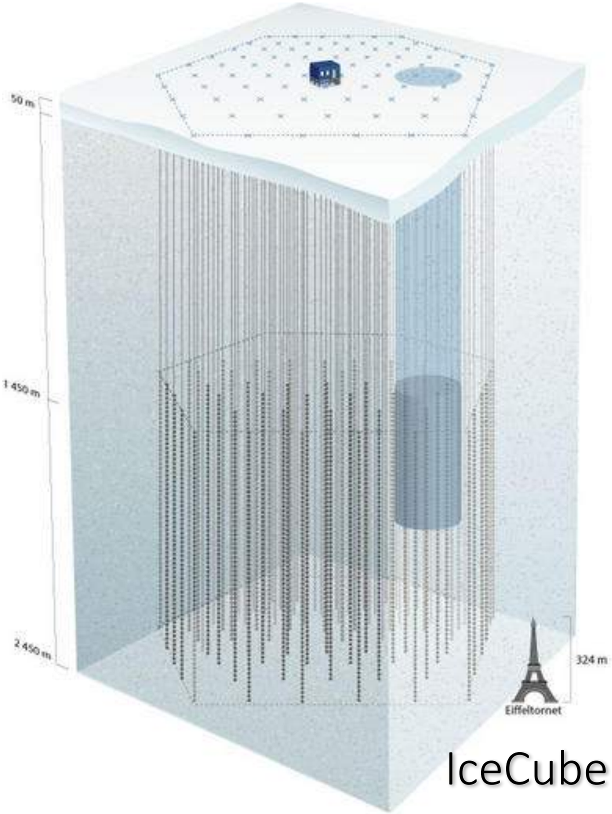
Astrophys. J..826, L13 (2016)

No coincident signals seen in photons … not unexpected however!

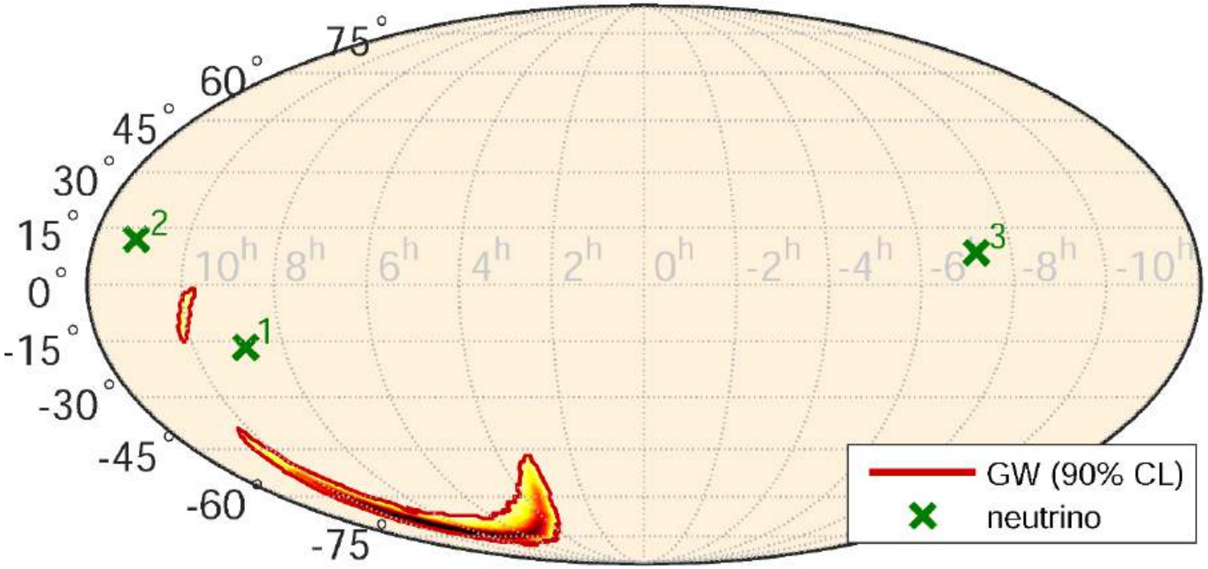
Could neutrinos be emitted?



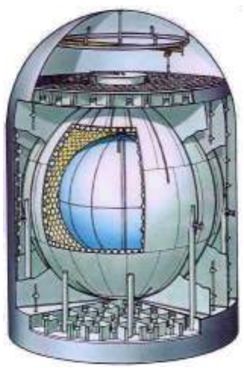
However no coincident neutrinos seen …



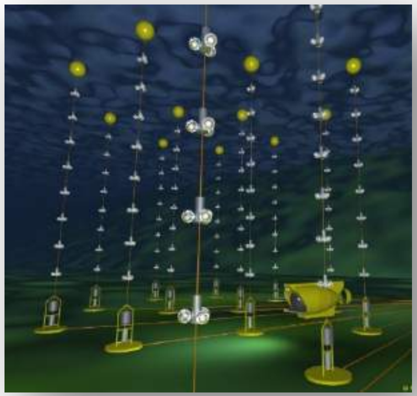
IceCube



KamLAND



ANTARES



#	ΔT [s]	RA [h]	Dec [°]	σ_μ^{rec} [°]	E_μ^{rec} [TeV]	fraction
1	+37.2	8.84	−16.6	0.35	175	12.5%
2	+163.2	11.13	12.0	1.95	1.22	26.5%
3	+311.4	−7.23	8.4	0.47	0.33	98.4%

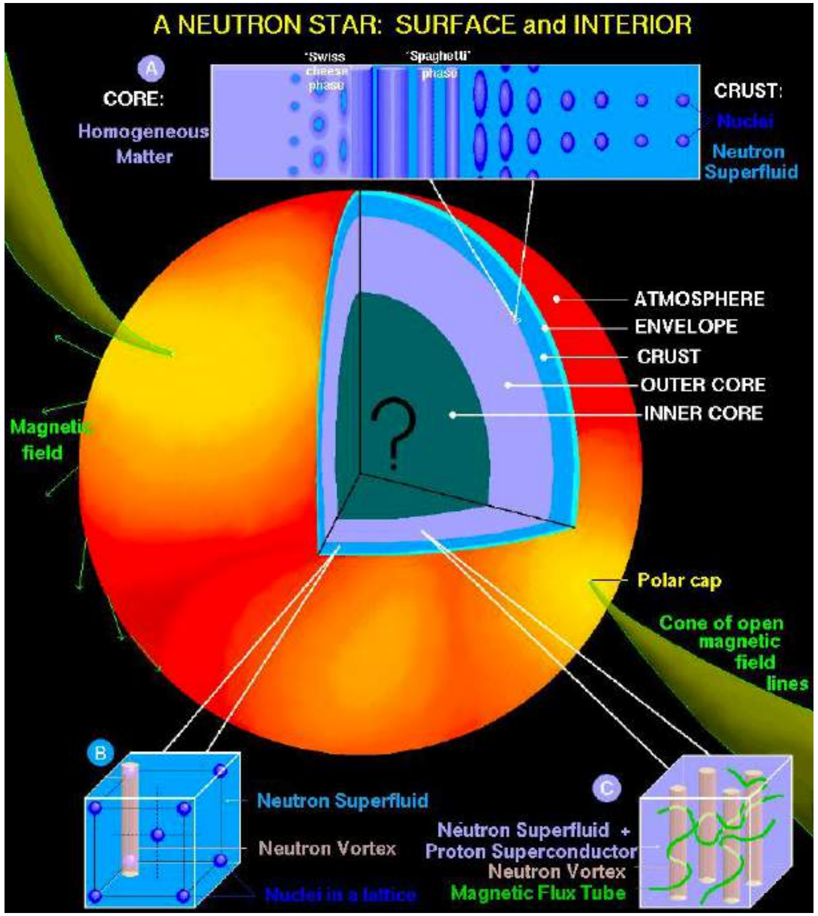
ANTARES+IceCube+LIGO+Virgo, Phys. Rev. D93, 122010 (2016)

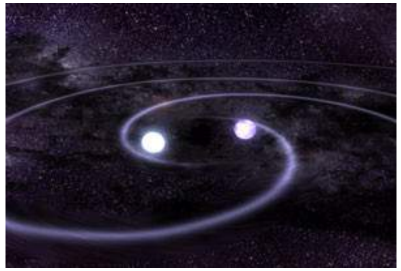
1606.07155

Detecting binary neutron star coalesence

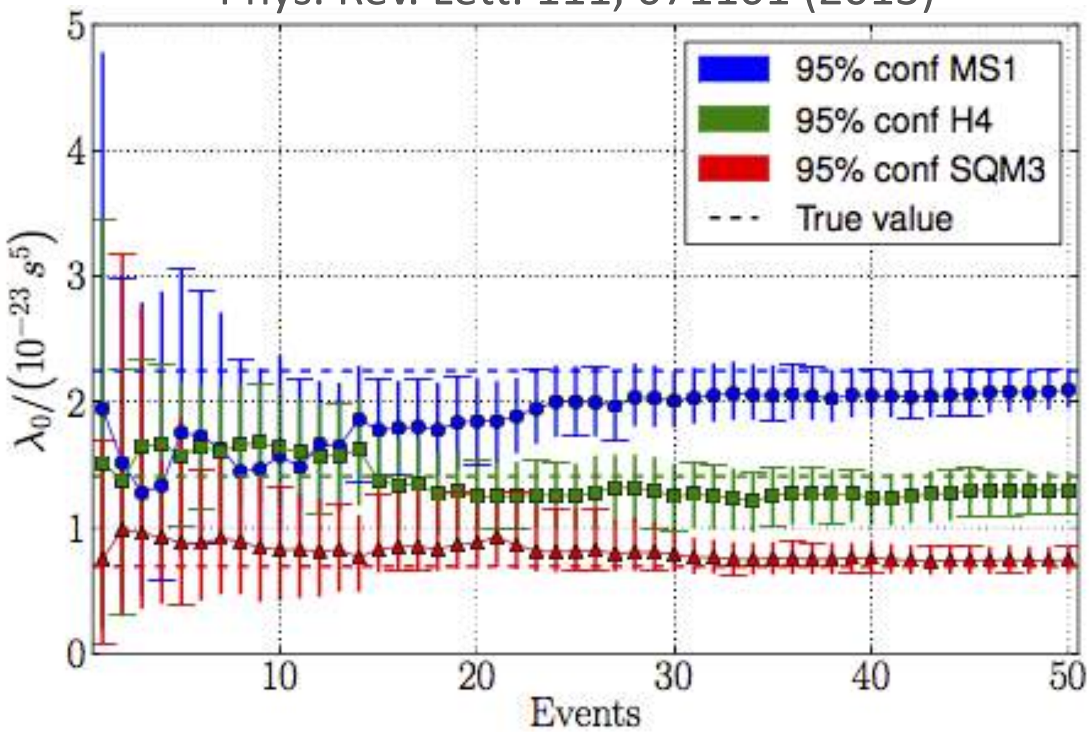
¤ Equation of state of neutron stars is currently unknown

¤ With multiple binary neutron star coalescences, from the GW signal alone one can distinguish between "soft", "intermediate", "hard" equation of state

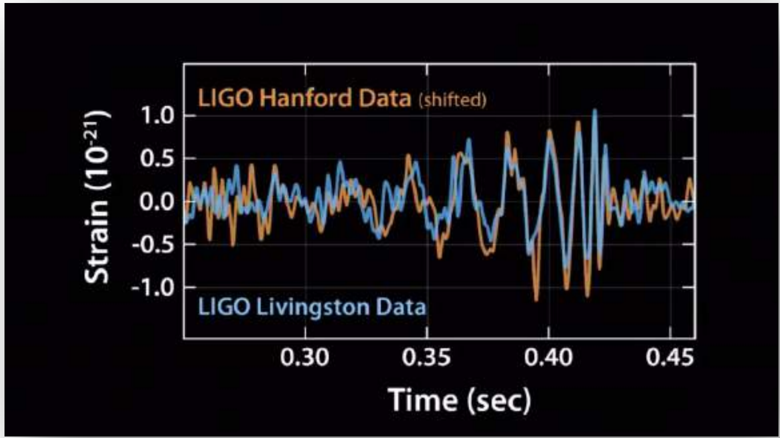




Phys. Rev. Lett. 111, 071101 (2013)

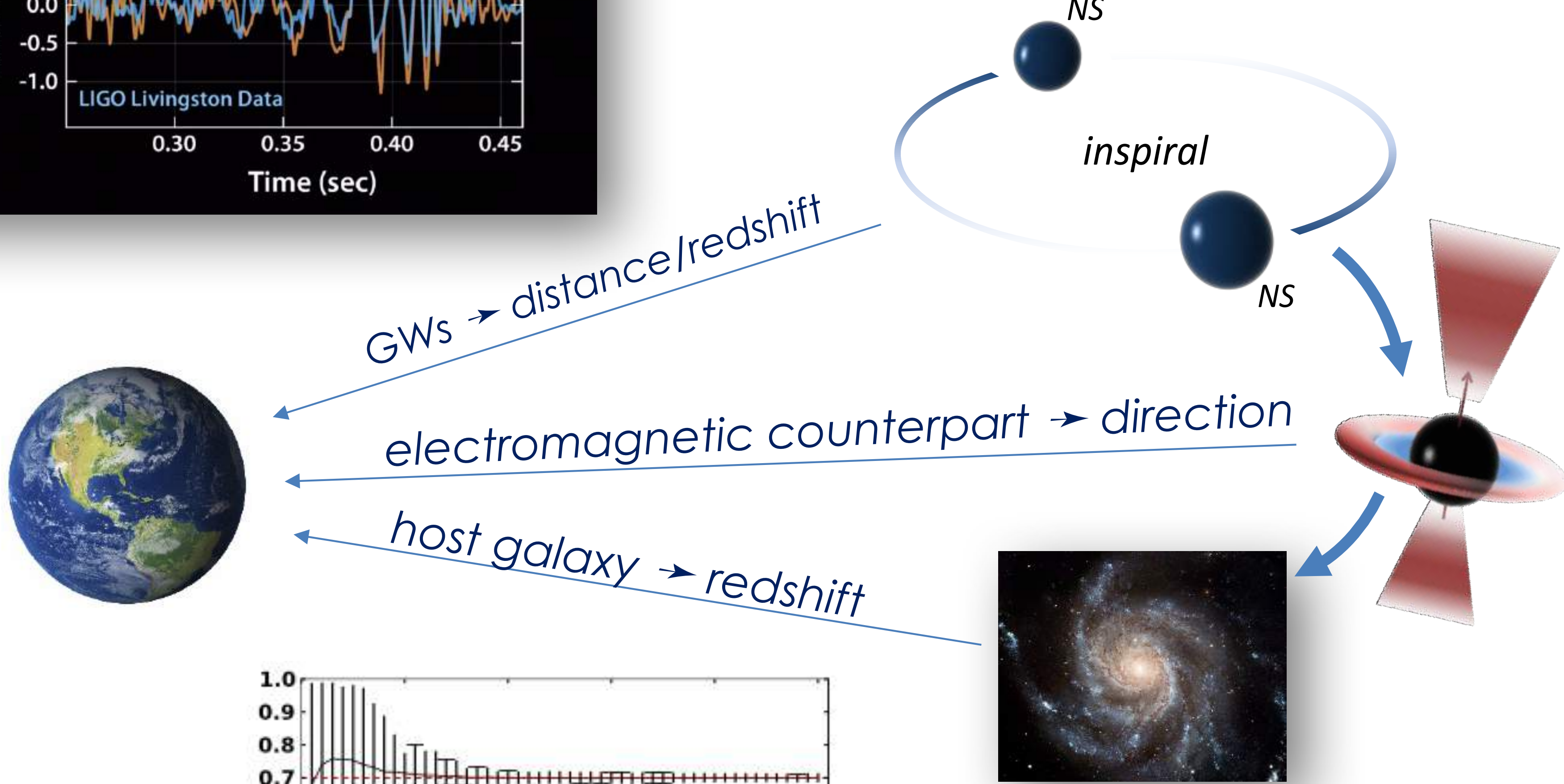


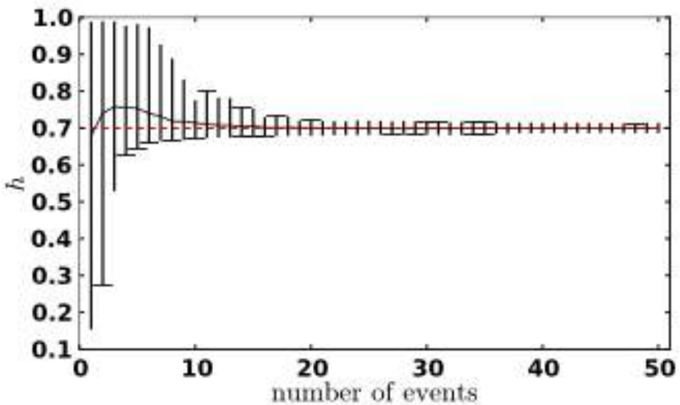
Cosmography with sources as ‘standard sirens’



Distance information in strain amplitude

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

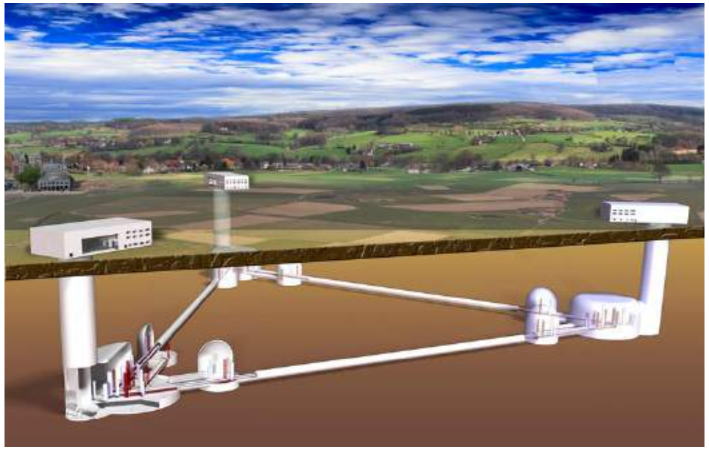




H_0 to ~5% with N_{det} = 15

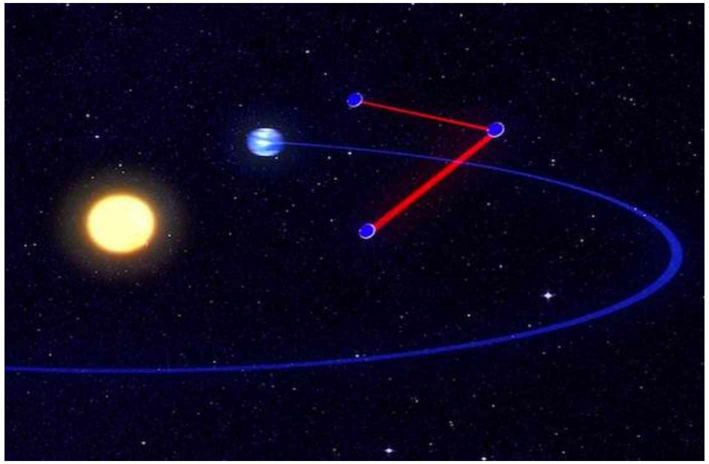
Phys. Rev. D 86, 043011 (2012)

The next few decades …



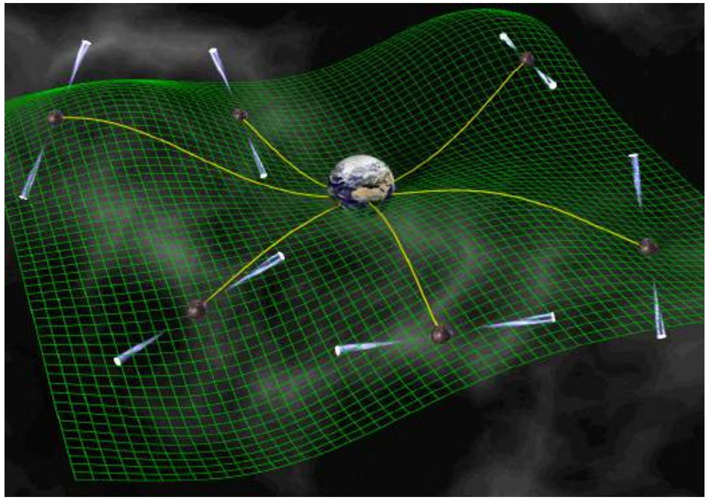
¤ Einstein Telescope (~2030?)

- 3^{rd} generation observatory
- 10^5 binary mergers per year
- Evolution of the Universe



¤ eLISA (approved for 2034)

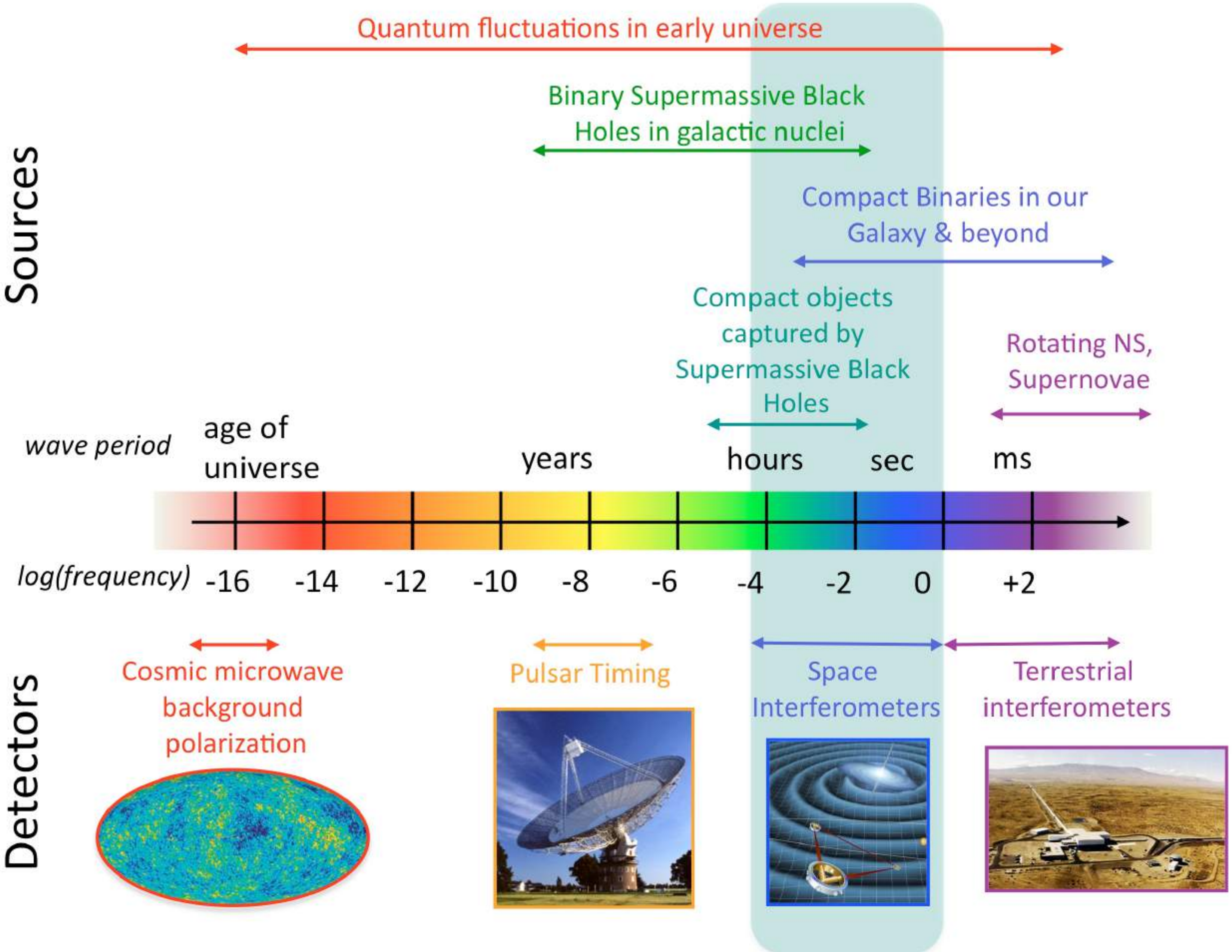
- 3 probes orbiting the Sun, 10^6 km apart
- Probe low frequencies: $10^{-5} – 10^{-1}$ Hz
- Mergers of supermassive binary black holes throughout the Universe
- Pathfinder mission launched in 2015



¤ Pulsar timing arrays (active now)

- Correlate variations in pulse arrival times between pulsars to see GW effects
- Ultra-low frequencies: $10^{-9} – 10^{-6}$ Hz
- Supermassive binaries *before* they merge

The Gravitational Wave Spectrum



'The real voyage of discovery consists not in seeking new lands … but in seeing with new eyes' Marcel Proust