IOP Conf. Series: Journal of Physics: Conf. Series **873** (2017) 012013 doi:10.1088/1742-6596/873/1/012013

First detections of gravitational waves from binary black holes

Michał Bejger

Nicolaus Copernicus Astronomical Center, Polish Academy of Sciences, ul. Bartycka 18, 00-716 Warsaw, Poland

E-mail: bejger@camk.edu.pl

Abstract. Recent direct detections of gravitational waves from coalescing binary black holes systems herald a new era in the observational astronomy, as well as in experimental verifications of the theories of gravity. I will present the principles of detection of gravitational waves, current state-of-art laser interferometric detectors (Advanced LIGO and Advanced Virgo), and the most promising astrophysical sources of gravitational waves.

1. Introduction

Before I begin, I would like to express my pleasure to be here and to present these exciting new results on the special session of the DISCRETE 2016 Symposium and the Leopold Infeld Colloquium. As a collaborator of Albert Einstein himself, prof. Infeld was, as you know, intimately involved in the early gravitational-wave research.

According to Einstein's general theory of relativity, published in 1915, the force of gravity is an illusion. Massive bodies seem to attract each other because they move in a curved spacetime on the "most straight" trajectories, geodesics. As phrased by John Archibald Wheeler, there is a reciprocal relation between massive objects and the geometry of spacetime: "mass tells spacetime how to curve, and spacetime tells mass how to move". This has to be contrasted with the usual Newtonian viewpoint on the mechanics of moving bodies - any observer can always tell the time and space coordinate of any given event, because objects move in absolute time and within absolute space. Because of the relation between the geometry and objects acting in it, phenomena thought to be stable (everlasting, not changing in time) are no longer such. For example, the classic example and success of the Newtonian theory - the binary system - is doomed to change its parameters and finally seize to exist. In the story of general relativity, in addition to two bodies comprising the binary there is a third actor, taking the energy from the system - the spacetime.

Very shortly after announcing the general theory of relativity, Albert Einstein realized that a linearised version of his equations resembles the wave equation [1]. The solution is interpreted as a short-wavelength, time-varying curvature deformation propagating with the speed of light on an otherwise slowly-varying, large-scale curvature background (a gravitational-wave "ripple" propagating through the four-dimensional spacetime); from the point of view of a metric tensor, it represents a small perturbation of a stationary background metric. Linear approximation corresponds to the waves propagating in the far-field limit. An intuitive picture was provided by Kip Thorne in [2]. Far-field limit for gravitational waves is there illustrated with an orange:

the background (slow-varying) curvature radius is the radius of the orange, and the small-scale dimples on the surface of the orange are the gravitational waves. By exploiting the gauge freedom of the theory one may show that the solution has features similar to electromagnetic waves: it is a transverse wave which may be polarized (has two independent polarizations).

Over the next 40 years, during which Einstein changed his mind to argue against their genuineness, a controversy persisted over the true nature of gravitational waves. One of the fundamental concepts of general relativity is that the results should be coordinate independent: one should be able to choose a system of coordinates and recover the same results. Einstein became convinced that gravitational waves are an artifact of a poor choice of coordinate system (Leopold Infeld was involved in these works as Einstein's assistant while working with him on the problem of relativistic binary system motion in the Institute for Advanced Study in Princeton).

Only in the late 50s and early 60s the works of Felix Pirani, [3], Herman Bondi [4], Ivor Robertson and Andrzej Trautman [5] convincingly showed that gravitational waves are indeed physical phenomena that carry and deposit energy. Anecdotally, a simple argument called "the sticky bead argument" was supplied anonymously by Richard Feynman under a pseudonym Mr. Smith at a conference at Chapel Hill, North Carolina in 1957. Feynman's gravitational-wave detector would consists of "two beads sliding freely (but with a small amount of friction) on a rigid rod. As the wave passes over the rod, atomic forces hold the length of the rod fixed, but the proper distance between the two beads oscillates. Thus, the beads rub against the rod, dissipating heat" (from the foreword of Kip Thorne and John Preskill in [6]). Leopold Infeld was also finally convinced of the reality of gravitational waves by one of his student collaborators, Róża Michalska-Trautman [7, 8].

The idea to use the light (beam detectors) for the gravitational-wave detection was first suggested in 1956 by Felix Pirani. Critical insight of the late 1950s convinced the experimentalists that it is worth investing some effort into building a device able to detect gravitational waves. In 1962 M. E. Gertsenshtein and V. I. Pustovit were the first to suggest an optical interferometer as a detecting device [9]. From the mid-1960s Joseph Weber pursued the idea of a *resonant bar* detector - a gravitational wave passing through an isolated mass of known characteristic frequency would induce tiny vibrations that may in principle be detected. The concept of laser interferometry was independently re-discovered by Rainer Weiss in the 1970s, which ultimately led to the LIGO project.

Before going to describe the current state of detectors and the first detections, I would also like to mention an early deep insight of Bohdan Paczyński, who already in 1967 understood the impact of gravitational wave emission on the fate of tight binary systems of stars [10]: the WZ Sge and AM CVn couldn't exist in their present state if not for the gravitational-wave emission. In the 1974 the first relativistic binary neutron-star system was discovered by Russell Hulse and Joseph Taylor [11]; it was shown without doubt that it is losing orbital energy in concordance with the emission of gravitational waves in the general relativity [12, 13]. These early observations provided much needed, *indirect* support for the existence of gravitational waves.

2. The era of detections

Recent first direct detections of gravitational waves with the two LIGO detectors [14, 15] create an unprecedented opportunity for studying the Universe through a novel, never before explored channel of spacetime fluctuations. Gravitational wave astronomy is often compared to 'listening to' rather than 'looking at' the skies. By design which is motivated by the choice of potential sources, the ground-based gravitational wave detectors of Advanced LIGO [16] and Advanced Virgo [17] are sensitive in the range of frequencies similar to the audible range of human ears - between 10 Hz and a few kHz. As in the case of an ear, a solitary laser interferometric detector is practically omnidirectional (has a poor angular resolution), and has no imaging capabilities.

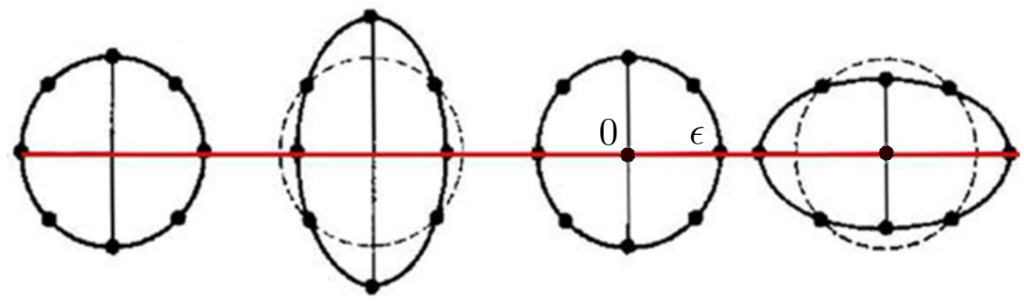

Figure 1. Proper distance change in the ring of test particles.

It registers a coherent signal emitted by a bulk movement of large, rapidly-moving masses. Once emitted, gravitational waves are weakly coupled to the surrounding matter and propagate freely without scattering. This has to be contrasted with the electromagnetic emission which originates at the microscopic level, is strongly coupled to the surroundings and often reprocessed; it carries a reliable information from the last scattering surface only. It seems therefore that gravitational wave detectors are the perfect counterpart to the electromagnetic observatories as they may provide us with information impossible to obtain by other means.

A realistic wave phenomenon (and not, say, a coordinate artifact) must be capable of transmitting energy from the source to infinity. If the amplitude of an exemplary isotropic field at a radial distance r from the source is $h(r)$, then the flux of energy over a spherical surface at r is $\mathcal{F}(r) \propto h^2(r)$, and the total emitted power (the luminosity) is $\mathcal{L}(r) \propto 4\pi r^2 h^2(r)$. Since the energy has to be conserved, the amplitude $h(r)$ falls like $1/r$, irrespectively of the multipole character of the source (the lowest radiating multipole in the gravity theory is the quadrupole distribution, because for an isolated system a time-changing monopole would correspond to the violation of the mass-energy conservation, and a time-changing dipole would violate the momentum conservation law).

Gravitational waves are related to the changes in the spacetime distance (the proper time interval), therefore they cannot be detected by a local measurement - one has to compare the spacetime positions of remote events [3]. The difficulty of the experiment is then described by a question: how to measure space-time distances, if the ruler also changes length? Fortunately, there is one aspect of the world that is constant at all times: the speed of light.

Consider the proper distance between free-falling particles initially forming a ring (see Fig. 1). Assuming a metric tensor composed of two parts, $g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$, where the $h_{\mu\nu}$ is denoting the gravitational-wave distortion, and taking a coordinate system in which for two test particles, both initially at rest, one at $x = 0$ and the other at $x = \epsilon$ the proper distance between them is

$$\Delta s = \int |g_{\mu\nu} dx^\mu dx^\nu|^{1/2} \rightarrow \int_0^\epsilon |g_{xx}|^{1/2} \approx \epsilon \sqrt{g_{xx}\,(x=0)}. \tag{1}$$

By taking $g_{xx}\,(x=0) = \eta_{xx} + h_{xx}\,(x=0)$ and keeping only the linear terms one gets

$$\Delta s \approx \epsilon \left(1 + \frac{1}{2} h_{xx}(x=0)\right), \tag{2}$$

which is, in general, time-varying. This simple argument can be made robust by solving the geodesic deviation equation.

This detection principle in the case of the laser interferometric detector is to measure the difference of the relative change in its perpendicular arms' lengths L_x and L_y, $\delta L_x - \delta L_y = \Delta L/L$, by measuring the interference pattern in the output port located at the apex of the device (or, equivalently, to measure the difference of round-trip times of a laser light circulating in the arms of the detector). Due to the quadrupolar nature of a gravitational wave, shortening of one arm corresponds to elongation of the other. This change of lengths is reflected in varying paths that the laser light has to cross before the interference. The dimensionless gravitational-wave amplitude $h = \Delta L/L$ (the "strain") is proportional to the amount of outgoing laser light. The fact that the directly-measurable quantity is the amplitude $h \propto 1/r$, not the energy of the wave as in the electromagnetic antennæ, has a direct consequence for the reach of the observing device: one-order-of-magnitude sensitivity improvement corresponds to one-order-of-magnitude growth of distance reach r, as opposed to the factor of $\sqrt{10}$ in the electromagnetic observations (consequently, the volume of space grows like r^3 in case of gravitational-wave observations, encompassing hundreds of thousands of galaxies for a distance reach of the order of hundreds of Mpc, see [18]).

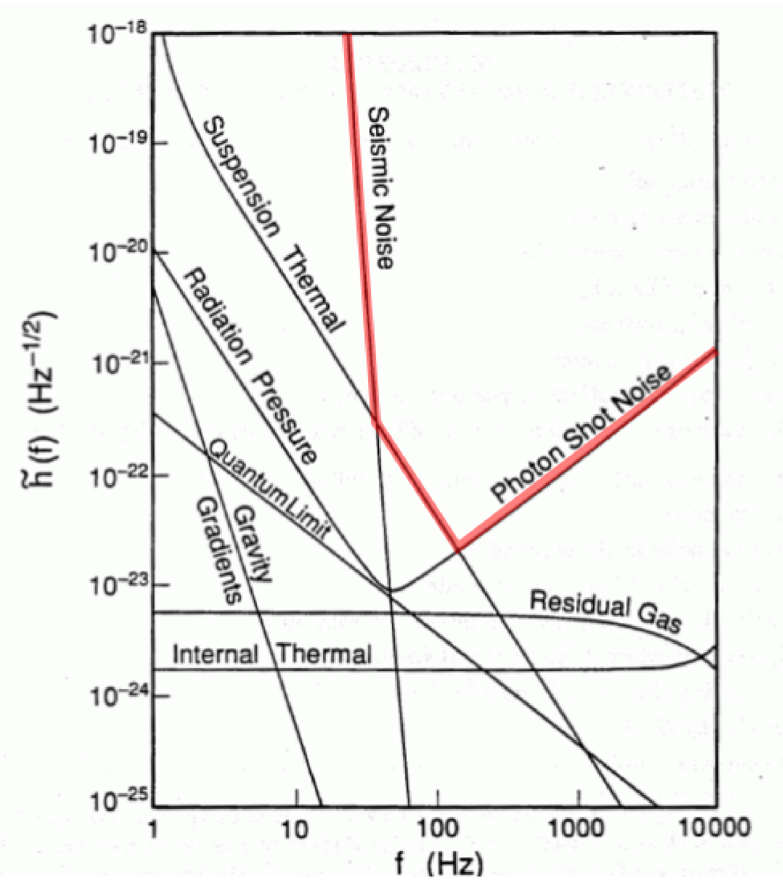

Figure 2. The sensitivity curve of the Initial LIGO detector (from the 1989 LIGO proposal to NSF[2]). The main sources of noise is the ground movement (seismic noise) for low frequencies, thermal movement of mirrors and their suspensions for frequencies about 100 Hz, and photon-shot noise related to the quantum nature of the laser light for high frequencies. For comparison see inset (b) in Fig. 5 for the LIGO O1 observational campaign sensitivity curve.

Among promising sources of gravitational radiation are all asymmetric collapses and explosions (supernovæ), rotating deformed stars (gravitational-wave 'pulsars' of continuous and transient nature), and tight binary systems of e.g., neutron stars and black holes. In the following we will focus on the binary systems, since their properties make them the analogues to standard candles of traditional astronomy. The fittingly descriptive term "standard siren" was first used in [19] in the context of gravitational waves from super-massive binary black holes as a target for the planned spaceborne LISA detector [20]. The idea of using well-understood signals to infer the

[2] `https://dcc.ligo.org/LIGO-M890001/public`

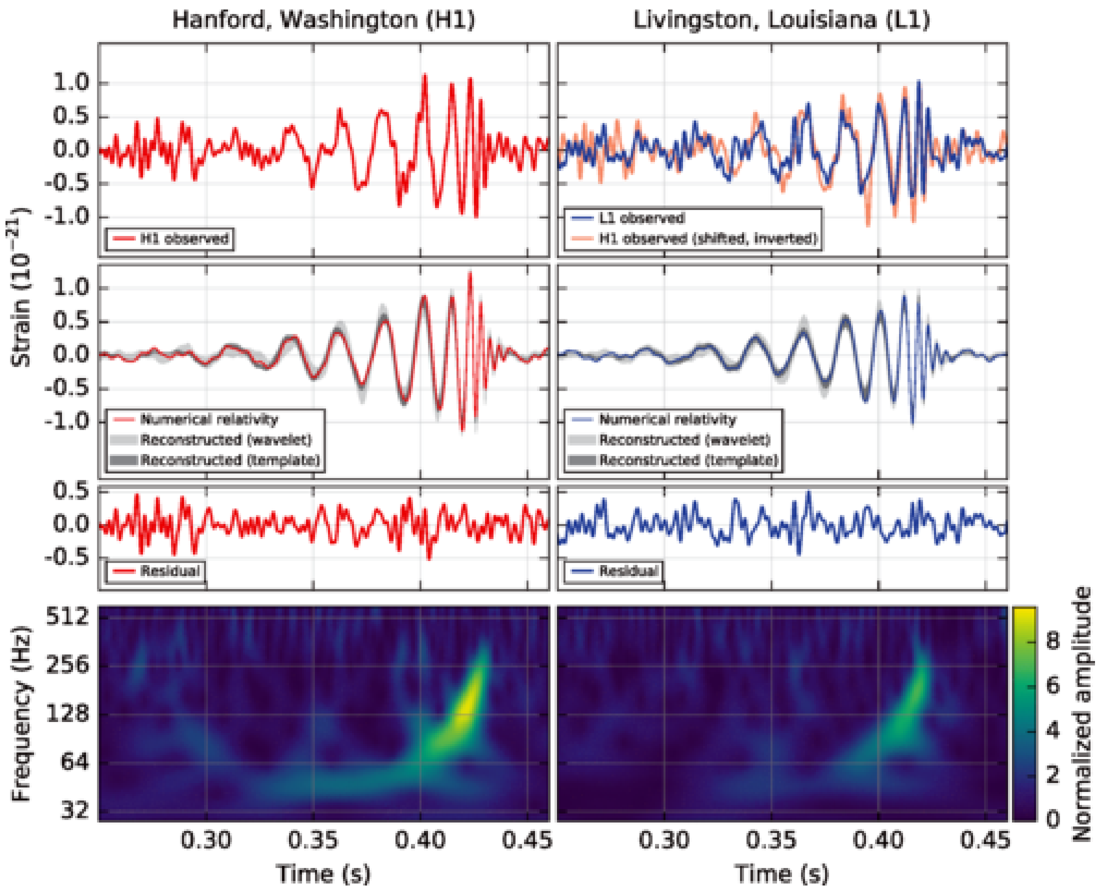

Figure 3. The gravitational-wave event GW150914 observed by the LIGO Hanford (H1, left column panels) and Livingston (L1, right column panels) detectors. Times are shown relative to September 14, 2015 at 09:50:45 UTC. For visualization, all time series are filtered with a 35-350 Hz bandpass filter to suppress large fluctuations outside the detectors' most sensitive frequency band, and band-reject filters to remove the strong instrumental spectral lines seen in the Fig. 3 spectra. *Top row, left:* H1 strain. *Top row, right:* L1 strain. GW150914 arrived first at L1 and $6.9^{+0.5}_{-0.4}$ ms later at H1; for a visual comparison, the H1 data are also shown, shifted in time by this amount and inverted (to account for the detectors' relative orientations). *Second row:* Gravitational-wave strain projected onto each detector in the 35-350 Hz band. Solid lines show a numerical relativity waveform for a system with parameters consistent with those recovered from GW150914. Shaded areas show 90% credible regions for two independent waveform reconstructions. *Third row:* Residuals after subtracting the filtered numerical relativity waveform from the filtered detector time series. Bottom row:A time-frequency representation of the strain data, showing the signal frequency increasing over time (the characteristic chirp). Reprinted from [14] under the terms of the Creative Commons Attribution 3.0 License.

distance and constrain the cosmological parameters was however proposed much earlier [21, 22]. Here we will focus on the inspiraling and merging binary systems.

Magnitudes of the gravitational-wave strain h and the luminosity $\mathcal{L}$ may be estimated using dimensional analysis and Newtonian physics. As the waves are generated by the accelerated movement of masses and the mass distribution should be quadrupolar, one may assume that h

is proportional to a second time derivative of the quadrupole moment $I_{ij} = \int \rho(\mathbf{x}) x_i x_j d^3x$ for some matter distribution $\rho(\mathbf{x})$. For a binary composed of masses m_1 and m_2, orbiting the center of mass at a separation a with the orbital angular velocity ω, h is proportional to the system's moment of inertia μa^2 and to ω^2, as well as inversely proportional to the distance, $h \propto \mu a^2\omega^2/r$, where $\mu = m_1 m_2/M$ is the reduced mass, and $M = m_1 + m_2$ the total mass. In order to recover the dimensionless h, the characteristic constants of the problem, G and c, are used to obtain

$$h \simeq \frac{G}{c^4}\frac{1}{r}\mu a^2\omega^2 = \frac{G^{5/3}}{c^4}\frac{1}{r}\mu M^{2/3}\omega^{2/3} \qquad \left(h_{ij} = \frac{2G}{c^4 r}\ddot{I}_{ij}\right), \tag{3}$$

with the use of Kepler's third law ($GM = a^3\omega^2$) in the second equation. The expression in brackets represents the strain tensor h_{ij} in the non-relativistic *quadrupole approximation* [23]. Similarly, the luminosity $\mathcal{L}$ (the rate of energy loss in gravitational waves, integrated over a sphere at a distance r) should be proportional to $h^2 r^2$ and some power of ω. From dimensional analysis one has

$$\mathcal{L} = \frac{dE_{GW}}{dt} \propto \frac{G}{c^5}h^2\omega^2 \propto \frac{G}{c^5}\mu^2 a^4\omega^6 \qquad \left(\mathcal{L} = \frac{c^3}{16G\pi}\iint \langle \dot{h}_{ij}\dot{h}^{ij}\rangle\, dS = \frac{G}{5c^5}\langle \dddot{I}_{ij}\dddot{I}^{ij}\rangle\right), \tag{4}$$

with the proportionality factor of $32/5$. Again, the expression in brackets refers to the quadrupole approximation; the angle brackets denote averaging over the orbital period. Waves leave the system at the expense of its orbital energy $E_{orb} = -Gm_1m_2/(2a)$. Using the time derivative of the third Kepler's third law, $\dot{a} = -2a\dot{\omega}/(3\omega)$, one gets the evolution of the orbital frequency driven by the gravitational-wave emission:

$$\frac{dE_{orb}}{dt} \equiv \frac{Gm_1m_2}{2a^2}\dot{a} = -\frac{dE_{GW}}{dt} \quad \Longrightarrow \quad \dot{\omega} = \frac{96}{5}\frac{\omega^{11/3}}{c^5}G^{5/3}\mathcal{M}^{5/3}. \tag{5}$$

The system changes by increasing its orbital frequency; at the same time the strain amplitude h of emitted waves also grows. Orbital frequency is related in a straightforward manner to the gravitational-wave frequency f_{GW}: from the geometry of the problem it is evident that the frequency of radiation is predominantly at twice the orbital frequency, $f_{GW} = \omega/\pi$. This characteristic frequency-amplitude evolution is called the *chirp*, by the similarity to birds' sounds, and the characteristic function of component masses,

$$\mathcal{M} = \left(\mu^3 M^2\right)^{1/5} = \frac{c^3}{G}\left(\frac{5}{96}\pi^{-8/3}f_{GW}^{-11/3}\dot{f}_{GW}\right)^{3/5} \tag{6}$$

is called the *chirp mass*. It is a quantity measured *directly* from the recorded values of f_{GW} and $\dot{f}_{GW}$. By combining the equations for $\dot{f}_{GW}$ and h, one recovers the distance to the source r. The distance, as a function of the frequency and amplitude parameters is, similarly to $\mathcal{M}$, *directly* measured by the detector:

$$r = \frac{5}{96\pi^2}\frac{c}{h}\frac{\dot{f}_{GW}}{f_{GW}^3} = 512\frac{1}{h_{21}}\left(\frac{0.01\text{ s}}{\tau}\right)\left(\frac{100\text{ Hz}}{f_{GW}}\right)^2 \text{ Mpc}, \tag{7}$$

where h_{21} denotes the strain in the units of 10^{-21} and $\tau = f_{GW}/\dot{f}_{GW}$ denotes the rate of change of the gravitational-wave chirp frequency. Note that within the simple Newtonian approximation presented here (at the leading order of the post-Newtonian expansion) the product $h\tau$ is independent of the components' masses [24]. The simplified analysis presented above does not take into account the full post-Newtonian waveform, polarization information, network of detectors analysis etc., but is intended to demonstrate that binary systems are indeed truly extraordinary "standard sirens". Their observations provide absolute, physical distances directly, without the need for a calibration or a 'distance ladder'. Among them, binary black hole systems occupy a special position. In the framework of general relativity, binary black holes waveforms are independent from astrophysical assumptions about the systems' intrinsic parameters and their environment. At cosmological scales the distance r has a true meaning of the *luminosity distance*. However, since the vacuum (black-hole) solutions in general relativity are scale-free, the measurements of their waveforms alone cannot determine the source's redshift. The parameters measured by the detector are related to the rest-frame parameters by the redshift z: $f_{GW} = f^{rf}_{GW}/(1+z)$, $\tau = \tau^{rf}(1+z)$, $\mathcal{M} = \mathcal{M}^{rf}(1+z)$. Independent measurements of the redshift which would facilitate the cosmographic studies of the large-scale Universe requires the collaboration with the electromagnetic observers i.e., the *multi-messenger astronomy*. This may be obtained by assessing the redshift of the galaxy hosting the binary by detecting the electromagnetic counterpart of the event [25, 26] or by performing statistical study for galaxies' redshifts correlated with the position of the signal's host galaxy [27]. The omnidirectional nature of a solitary detector is mitigated by simultaneous data analysis from at least three ground-based detectors in order to perform the triangulation of the source position, hence the crucial need for the LIGO-Virgo collaboration, which will be in the future enhanced by the LIGO-India detector, and the KAGRA detector in Japan [28].

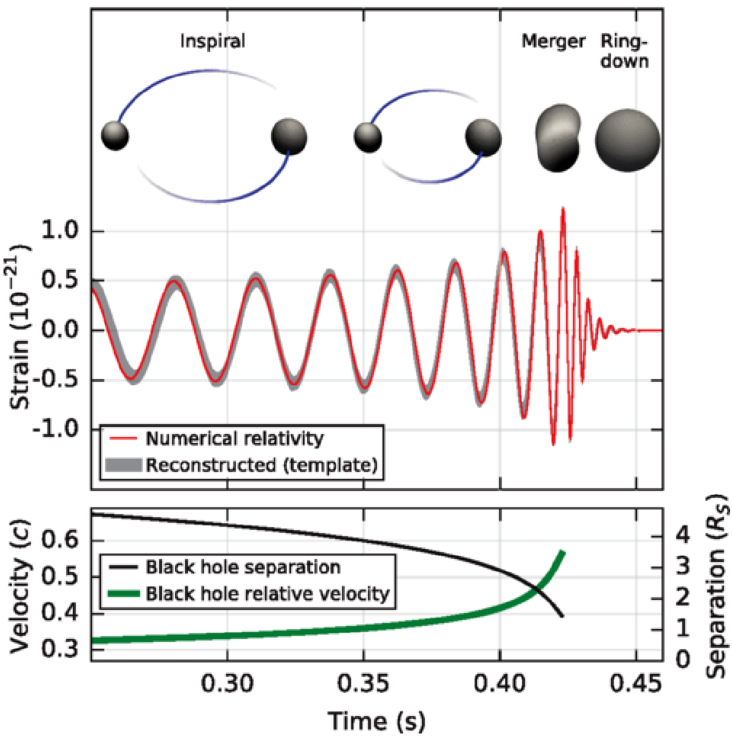

Figure 4. *Top:* Estimated gravitational-wave strain amplitude from GW150914 projected onto the H1 detector. This shows the full bandwidth of the waveforms, without the filtering used for Fig. 3. The inset images show numerical relativity models of the black hole horizons as the black holes coalesce. *Bottom:* The Keplerian effective black hole separation in units of Schwarzschild radii $R_s = 2GM/c^2$, and the effective relative velocity given by the post-Newtonian parameter $v/c = (GM\pi f_{GW})^{1/3}/c$, where f_{GW} is the gravitational-wave frequency obtained from numerical relativity calculations and M is the total mass of the system. Reprinted from [14] under the terms of the Creative Commons Attribution 3.0 License.

3. GW150914

On the 14th of September 2015, both LIGO detectors (first Livingston, Hanford 7 ms later) registered a signal featured in Fig. 3. The false alarm probability (probability of this signal to be spurious and occurring in pure noise data) was estimated to be less than 1 in 5 million, which

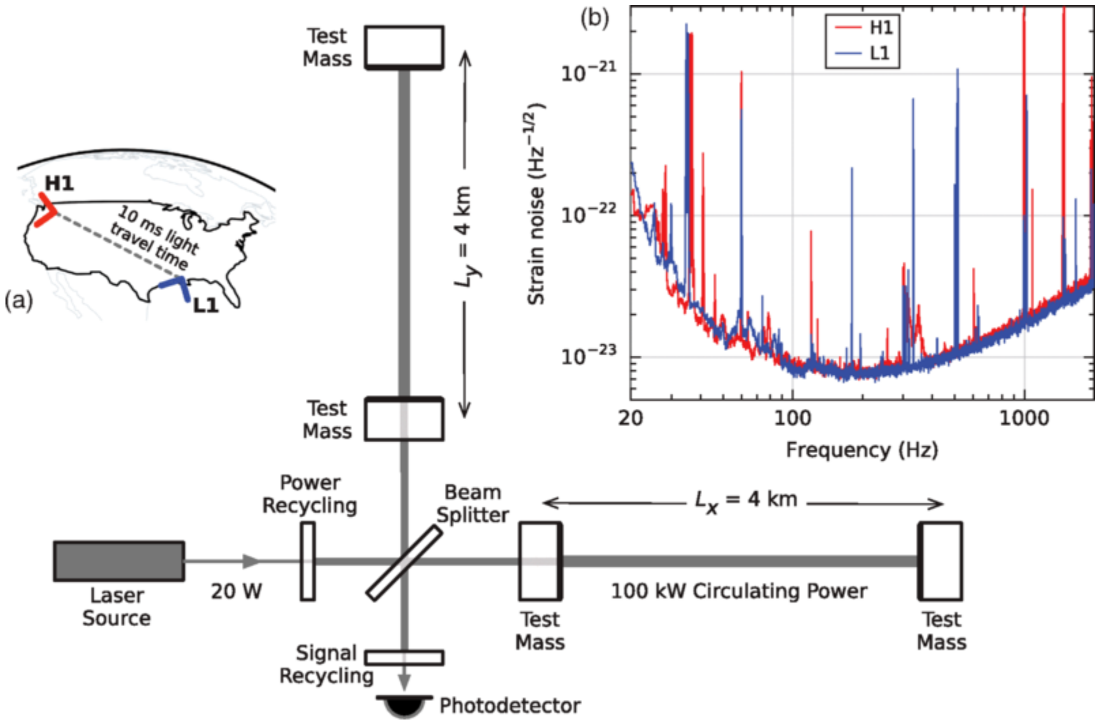

Figure 5. Simplified diagram of an Advanced LIGO detector (not to scale). A gravitational wave propagating orthogonally to the detector plane and linearly polarized parallel to the 4-km optical cavities will have the effect of lengthening one 4-km arm and shortening the other during one half-cycle of the wave; these length changes are reversed during the other half-cycle. The output photo-detector records these differential cavity length variations. While a detector's directional response is maximal for this case, it is still significant for most other angles of incidence or polarizations (gravitational waves propagate freely through the Earth). Inset (a): Location and orientation of the LIGO detectors at Hanford, WA (H1) and Livingston, LA (L1). Inset (b): The instrument noise for each detector near the time of the signal detection; this is an amplitude spectral density, expressed in terms of equivalent gravitational-wave strain amplitude. The sensitivity is limited by photon shot noise at frequencies above 150 Hz, and by a superposition of other noise sources at lower frequencies. Narrow-band features include calibration lines (33-38, 330, and 1080 Hz), vibrational modes of suspension fibers (500 Hz and harmonics), and 60 Hz electric power grid harmonics. Reprinted from [14] under the terms of the Creative Commons Attribution 3.0 License.

corresponds to a false alarm rate of less than 1 in 200000 years. The source frame component black-hole masses were estimated, by selecting a best-fit model in an offline comparison with detailed numerical relativity simulations, to $m_1 = 36^{+5}_{-4}\,M_\odot$ and $m_2 = 29^{+4}_{-4}\,M_\odot$. The final black hole mass is $M_f = 62^{+4}_{-4}\,M_\odot$, and its spin was estimated to be $a = 0.67^{+0.05}_{-0.07}$. The event happened at a distance of 410^{+160}_{-180} Mpc (the central value corresponds to 1 billion 300 million light years), and a redshift of $z = 0.09^{+0.03}_{-0.04}$, assuming standard cosmology. The uncertainties define the 90% credible intervals. This first ever direction of gravitational waves shows its potential for making truly long-range cosmological observations.

The whole event took less than 0.2 s in the sensitivity band of the detector, that is for frequencies higher than about 30 Hz. Final orbital velocity of the system components was larger than 0.5 c (see Fig. 4). Total energy emitted in gravitational waves during the lifetime

IOP Conf. Series: Journal of Physics: Conf. Series **873** (2017) 012013 doi:10.1088/1742-6596/873/1/012013

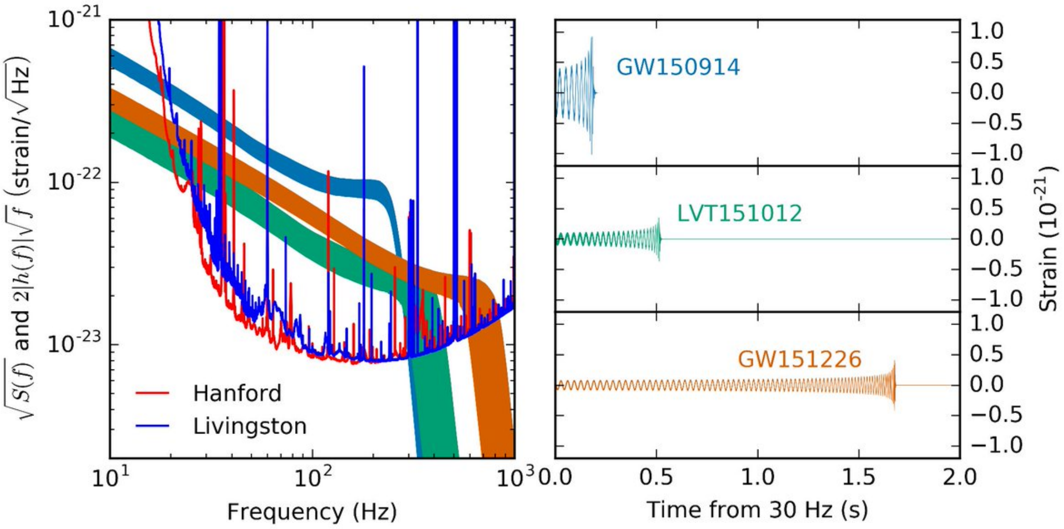

Figure 6. *Left panel:* Amplitude spectral density of the total strain noise of the H1 and L1 detectors, $\sqrt{S(f)}$, in units of strain per $\sqrt{\text{Hz}}$, and the recovered signals of GW150914, GW151226, and LVT151012 plotted so that the relative amplitudes can be related to the signal-to-noise of the signal (see Eq. 9). *Right panel:* Time evolution of the recovered signals from when they enter the detectors' sensitive band at 30 Hz. Both figures show the 90% credible regions of the LIGO Hanford signal reconstructions from a coherent Bayesian analysis using a non-precessing spin waveform model. Reprinted from [30] under the terms of the Creative Commons Attribution 3.0 License.

of the system was estimated to be equal to $3^{+0.5}_{-0.5}\ M_{\odot}c^2$. Peak "brightness" of the event, which happened while the two black holes were already merging was estimated to be $3.6^{+0.5}_{-0.4} \times 10^{49}$ Joule/s. This amazing efficiency of transmitting the energy into spacetime means that this event was the most energetic phenomenon observed by humanity to date; the brightness exceeded the electromagnetic brightness of all the 10^{22} stars in the observed Universe. From the point of view of energy production, it equals $200^{+30}_{-30}\ \mathrm{M}_{\odot}\mathrm{c}^2/\mathrm{s}$.

Why do we think it was a binary black hole system? From the gravitational-wave amplitude dependence for a binary system,

$$h \propto \mathcal{M}^{5/3} \times f_{GW}^{2/3} \times r^{-1}, \tag{8}$$

the function of masses, the chirp mass $\mathcal{M}$, is known function of the observed frequency f_{GW} (see Eq. 6). From higher order post-Newtonian corrections one gets the mass ratio m_2/m_1 and the components of the black-hole spins. Measured $\mathcal{M}$ is about 30 $M_{\odot}$, which means that the sum of masses is about $M = 70\ M_{\odot}$ (one can obtain this quick estimate assuming $m_1 = m_2$, then $M = 2^{6/5}\mathcal{M}$). In the sensitivity band of the detector 8 last orbits of the system were recorded until a limiting frequency of about 150 Hz (corresponding to the orbital frequency of 75 Hz).

In order to explain these observations one could argue that the observations were linked to a binary neutron star system. Double neutron star system is compact enough to exist at the observed orbital frequencies, but it's too light to be reconciled with the measured $\mathcal{M}$ and the total mass. Another possibility would be a mixed black hole-neutron star binary - here one could obtain the correct total mass, but the final orbital frequency at which the neutron star plunges into the black hole is much lower than the observed one. The basic physics of the binary black hole merger GW150914 is described in [29].

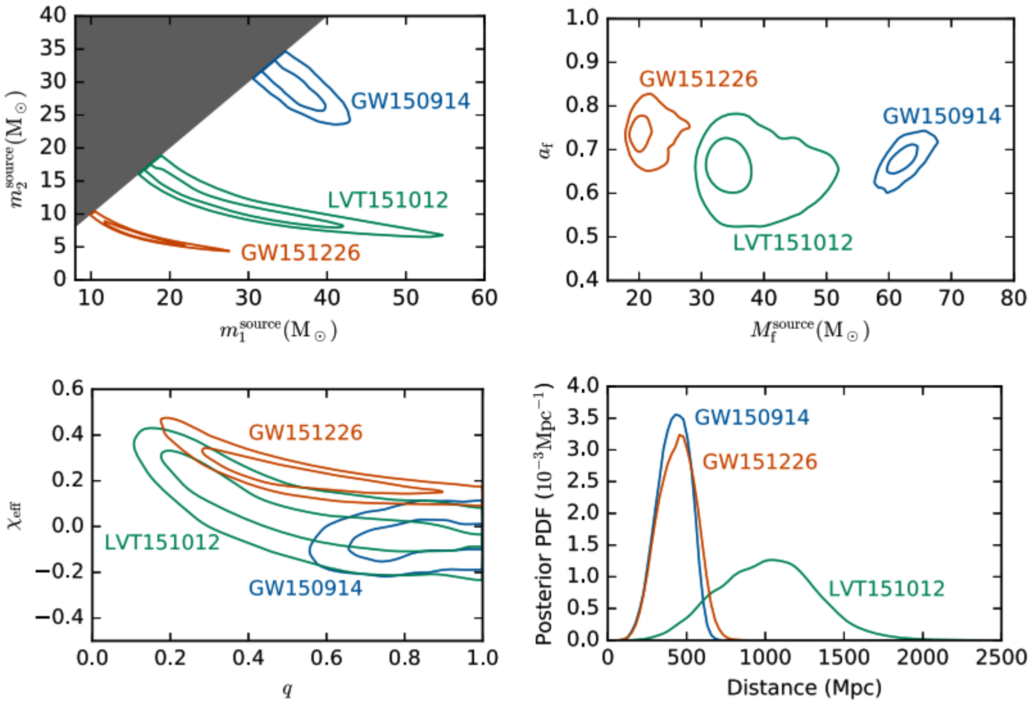

Figure 7. Posterior probability densities of the masses, spins, and distance to the three events GW150914, LVT151012, and GW151226. For the two-dimensional distributions, the contours show 50% and 90% credible regions. *Top left panel:* Component masses m_1 and m_2 in the source frame. *Top right panel:* The mass and dimensionless spin magnitude of the final black holes. *Bottom left panel:* The effective spin and mass ratios of the binary components. *Bottom right panel:* The luminosity distance to the three events. Reprinted from [30] under the terms of the Creative Commons Attribution 3.0 License.

4. O1 detections

During the Advanced LIGO O1 observational campaign two other binary black hole mergers were recorded. GW151226, with a significance of greater than 5σ over the observing period. A third possible signal, LVT151012, was also identified, with substantially lower significance and with an 87% probability of being of astrophysical origin [30], hence the number of detections is sometimes described as "two and a half". Figure 6 shows the detected signal wave trains in comparison with the sensitivity curve of detectors. The signal to noise ratio ρ is defined as

$$\rho^2 = \int_0^\infty \left(\frac{2|\tilde{h}(f)|\sqrt{f}}{\sqrt{S(f)}} \right)^2 d\ln(f), \tag{9}$$

where the $\tilde{h}(f)$ is the best match template signal waveform and $S(f)$ is the amplitude spectral density of the data stream. From this form it is evident that the signal-to-noise ratio is the area between the template waveform $\tilde{h}(f)$ and the sensitivity curve; for GW150914 $\rho \simeq 24$, whereas for GW151226 $\rho \simeq 13$, and in case of LVT151012 $\rho \simeq 10$.

The estimated parameters of the two ("and a half") O1 detections are presented in Fig. 7. The spins a_i, the component of spin angular momentum S_i aligned with the direction of the orbital angular momentum $\hat{L}$, and the effective spin parameters $\chi_{\rm eff}$ are defined as follows:

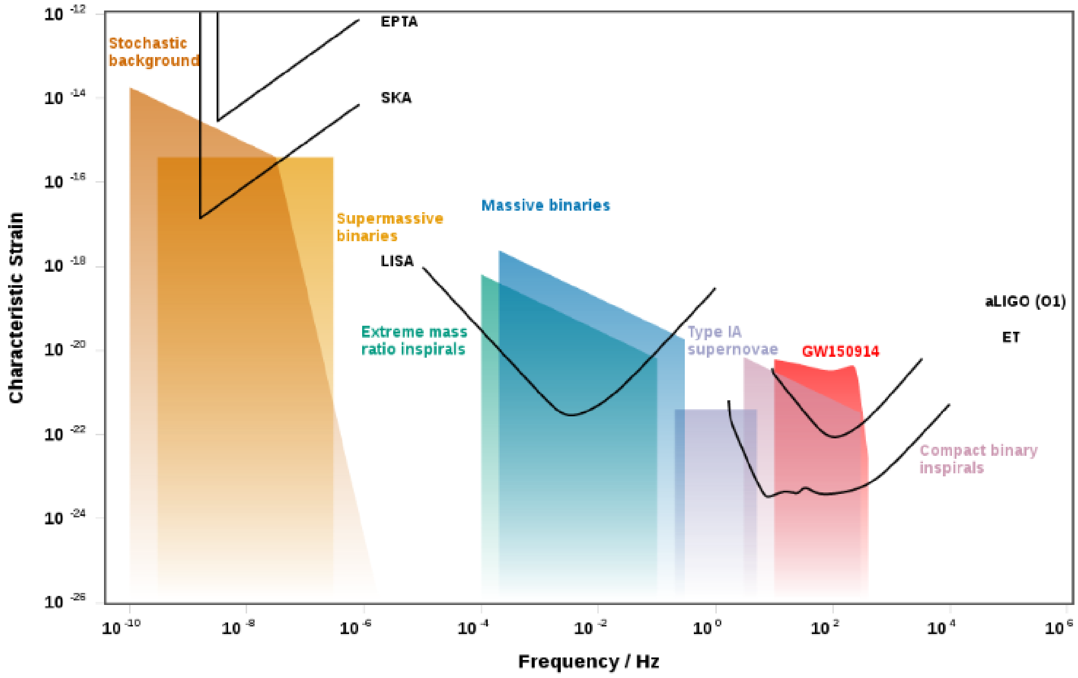

Figure 8. A comparison of Earth-based detectors' frequency sensitivity range with the proposed space-borne detector LISA [31] and pulsar timing array projects (here EPTA, `http://www.epta.eu.org`). ET denotes the planned third generation underground 10 km arm interferometer (`http://www.et-gw.eu`), and SKA is the Square Kilometer Array (`skatelescope.org`).

$$a_i = \frac{c}{Gm_i^2} S_i, \quad \chi_i = \frac{c}{Gm_i^2} S_i \cdot \hat{L}, \quad \chi_{\text{eff}} = \frac{\chi_1 m_1 + \chi_2 m_2}{m_1 + m_2}. \tag{10}$$

Measured masses draw the mass function of stellar-mass black holes much different than the one inferred from the observations within our Galaxy. Especially, the high masses of GW150914 suggest low-metallicity environment in which high mass progenitors of supernovæ lose less mass during their evolution and are able to produce high black-hole remnants.

5. Summary

We have recently witnessed first direct detections of gravitational waves, first observations of near-horizon dynamics, new method for measuring BH masses and spins, first observations of a BH binary system, "brightest" phenomenons ever recorded in history and new ways to test gravity theories in the strong-field regime. Up to date the three O1 detections are in concordance with general relativity. The inferred merger rate for stellar mass binary black hole systems was estimated to be in the range of $9 - 240$ Gpc^{-3} yr^{-1}.

Astrophysics of gravitational waves is qualitatively different from anything we were studying so far. Observations of objects dark in electromagnetic waves, and joint observations of gravitational and electromagnetic waves (the multi-messenger astronomy) will allow to probe the details of previously unaccessible phenomena. For example, stellar-mass black hole binary inspirals similar to GW150914 and GW151226 would be visible at lower frequencies [32] by a proposed space-borne detector LISA [31] (see also Fig. 8). The onset of the gravitational-wave astronomy heralds a completely new way to study the Universe.

6. Acknowledgements

This work was partially supported by the Polish National Science Centre grant no. UMO-2014/14/M/ST9/00707.

References

[1] Einstein A 1916 *Sitzungsberichte der Königlich Preußischen Akademie der Wissenschaften (Berlin), Seite 688-696.*

[2] Thorne K S 1987 *Gravitational radiation.* pp 330–458

[3] Pirani F A E 1956 *Acta Physica Polonica* **15** 389–405

[4] Bondi H 1957 Nature **179** 1072–3

[5] Robinson I and Trautman A 1960 *Physical Review Letters* **4** 431–2

[6] Feynman R P, Morinigo F B and Wagner W G 1995 *Feynman lectures on gravitation* (Reading, Addison-Wesley)

[7] Infeld L and Michalska-Trautman R 1969 *Annals of Physics* **55** 561–75

[8] Infeld L and Michalska-Trautman R 1969 *Annals of Physics* **55** 576–86

[9] Gertsenshtein M E and Pustovoit V I 1962 *Soviet Journal of Experimental and Theoretical Physics* **43** 605–7

[10] Paczyński B 1967 Acta Astron. **17** 287

[11] Hulse R A and Taylor J H 1975 ApJ **195** L51–3

[12] Weisberg J M, Taylor J H and Fowler L A 1981 *Scientific American* **245** 74–82

[13] Taylor J H and Weisberg J M 1982 ApJ **253** 908–20

[14] Abbott B P, Abbott R, Abbott T D, Abernathy M R *et al.* 2016 Phys. Rev. Lett. **116** 061102 (*Preprint* `1602.03837`)

[15] Abbott B P, Abbott R, Abbott T D, Abernathy M R *et al.* 2016 Phys. Rev. Lett. **116** 241103 (*Preprint* `1606.04855`)

[16] Aasi J, Abbott B P, Abbott R, Abbott T *et al.* 2015 Class. Quant. Grav. **32** 074001 (*Preprint* `1411.4547`)

[17] Acernese F, Agathos M, Agatsuma K, Aisa D *et al.* 2015 Class. Quant. Grav. **32** 024001 (*Preprint* `1408.3978`)

[18] Abbott B P, Abbott R, Abbott T D, Abernathy M R *et al.* 2016 *Living Reviews in Relativity* **19** (*Preprint* `1304.0670`)

[19] Holz D E and Hughes S A 2005 ApJ **629** 15–22 (*Preprint* `astro-ph/0504616`)

[20] Danzmann K *et al.* (LISA Study Team) 1996 *Class. Quantum Grav.* **13** A247–50

[21] Schutz B F 1986 Nature **323** 310

[22] Schutz B F 2002 Lighthouses of Gravitational Wave Astronomy *Lighthouses of the Universe: The Most Luminous Celestial Objects and Their Use for Cosmology* ed Gilfanov M, Sunyeav R and Churazov E p 207 (*Preprint* `gr-qc/0111095`)

[23] Einstein A 1918 *Sitzungsberichte der Königlich Preußischen Akademie der Wissenschaften (Berlin), Seite 154-167.*

[24] Królak A and Schutz B F 1987 *Gen. Relativ. Gravit.* **19** 1163–71

[25] Bloom J S, Holz D E, Hughes S A, Menou K *et al.* 2009 (*Preprint* `0902.1527`)

[26] Singer L P, Chen H Y, Holz D E, Farr W M *et al.* 2016 ApJ **829** L15 (*Preprint* `1603.07333`)

[27] MacLeod C L and Hogan C J 2008 Phys. Rev. D **77** 043512 (*Preprint* `0712.0618`)

[28] Aso Y, Michimura Y, Somiya K, Ando M *et al.* 2013 Phys. Rev. D **88** 043007 (*Preprint* `1306.6747`)

[29] Abbott B P, Abbott R, Abbott T D Abernathy M R *et al.* 2016 (*Preprint* `1608.01940`)

[30] Abbott B P, Abbott R, Abbott T D, Abernathy M R *et al.* 2016 *Physical Review X* **6** 041015 (*Preprint* 1606.04856)

[31] Amaro-Seoane P, Audley H, Babak S, Baker J *et al.* 2017 (*Preprint* 1702.00786)

[32] Sesana A 2016 *Physical Review Letters* **116** 231102 (*Preprint* 1602.06951)