Gen Relativ Gravit (2014) 46: 1782
DOI 10.1007/s10714-014-1782-3

REVIEW ARTICLE

Summary of session C6: Q&A—everything you wanted to know about gravitational waves but were afraid to ask

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Received: 20 December 2013 / Accepted: 28 July 2014

Abstract The paper summarizes the parallel session C6 *Q&A—everything you wanted to know about gravitational waves but were afraid to ask* of the joint 10th Amaldi Conference on Gravitational Waves and 20th International Conference on General Relativity and Gravitation.

Keywords Gravitational radiation · Theory · Detectors · Sources

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This article belongs to the Topical Collection: The First Century of General Relativity: GR20/Amaldi10.

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Published online: 25 September 2014

1 Introduction

The 10th edition of the Amaldi Conference hosted for the second time a session of questions and answers on gravitational wave (GW) related topics. This session is intended to answer questions about aspects of astrophysics, instruments, and searches in the field of GWs, and is aimed primarily at graduate students and other researchers new to the field. Seven topics were selected based on questions submitted by the GW/GR communities. Cornish discussed the observational evidence and the theoretical self consistency arguments supporting the existence of GWs. The detectability of GW radiation produced by a supernova explosion was the topic of Reisswig's talk. Stuver put the accent on the spin-offs of GW research, such as technology developed for LIGO/Virgo that is now being used elsewhere. Van Den Broeck presented an overview of the possible sources for the first direct detection of GWs. Sturani discussed the interaction of the gravitational radiation with a laser interferometric detector and if the detector itself absorbs some of the energy carried by the wave. Barsotti talked about the technique that makes it possible to achieve a higher signal-to-noise ratio by holding a GW interferometer's signal port at the dark fringe as opposed to halfway up a fringe. Finally, Sutton attempted to predict the date of the first detection by the next-generation ground-based GW detectors.

The reaction of the audience was very positive, and the informality and relaxed nature of the session encouraged lively debate between the speakers and the audience.

In the rest of this paper most of the talks contributed to the C6 session are sketched in more detail, in the order in which they were presented at the conference. For the others, the reader can refer to the GR/Amaldi website, http://www.fuw.edu.pl/~ktwig/c6.zip.

2 Invited talks

2.1 Why do we believe that GWs exist? (Presenter: N. Cornish)

The physical reality of GWs was a major topic at the last major international GR meeting held in Warsaw. At the time, Feynman wrote to his wife that he was "surprised to find a whole day at the conference devoted to this question" and that the discussions "were not good for my blood pressure". He asked her to to remind him to avoid future gravity conferences. Fifty-one years later, the questions of the existence of GWs is no longer in doubt thanks to the exquisite observational data showing overwhelming evidence for the orbital decay of compact binary systems in full accord with the predictions of General Relativity. The classic example of the Hulse–Taylor binary pulsar system PSR1913+16 [1] has now been augmented by the double pulsar system PSR J0737-3039A/B [2], the Pulsar—White Dwarf system PSR J0348+0432 [3] and the double White Dwarf system SDSS J0651+2844 [4].

But do we have any other astrophysical evidence for the existence of GWs? One possibility is the period distribution for binary systems. At long periods, the timescale for GW driven evolution is very long, and it is processes such as stellar scattering or gas dynamics that drive the systems towards merger. But as the binary hardens these processes become less effective, and GW emission takes over, leading to a number density as a function of period that scales as $N(P) \sim P^{11/3}$. If GWs did not exist, we would expect to see a pile-up of ultra-short-period binaries. Unfortunately the observational evidence is scant in the case of stellar remnants, and non-existent in the case of supermassive black holes. Nelemans [5] followed up on this possibility and compared the output of a white dwarf binary population synthesis code with and without GW emission included, and found small differences in the relative number of short to long period systems—factors of 2 or 3 between the models. Future wide field surveys may be able to distinguish between these possibilities, but for now the data is inconclusive. Less direct evidence for the existence of GWs comes from interacting white-dwarf binaries (so called AM CVn systems). GW driven inspiral is the most plausible explanation for the existence of these systems, and GW emission has long been held as the "sina qua non for stable mass transfer" [6], where the change in the radius of the donor star exactly matches the change in size of its Roche lobe. There is strong observational evidence [7] that the luminosity of AM CVn systems follow the mass transfer rate predicted by GW driven evolution. A similar mechanism has also been proposed to explain the tight clustering in the observed periods of low mass X-ray binaries [8]. While GWs provide the most natural explanation for the observed properties of interacting white dwarf binaries and low mass X-ray binaries, other possibilities exist, and for now these provide less compelling evidence for the existence of GWs than the binary pulsar systems.

On the theoretical front, there has been considerable progress on the questions that exasperated Feynman in Warsaw. The physical reality of GWs in GR has been put on sound footing by the work of Isaacson [9] and others (for a historical review see Ref. [10]), but what if GR is not the correct theory of gravity, would GWs still be a theoretical necessity? While it is difficult to produce a general proof that causal theories of gravity necessarily predict GWs, it is probably safe to conjecture that the vast majority of well posed theories of gravity predict GWs. Indeed, alternative metric theories of gravity generically have a *greater* number of GW degrees of freedom than the two polarization states of GR [11]. As noted by Laplace in 1805 [12], a causal theory of gravity where the force between two bodies is not aligned with the instantaneous separation vector necessarily implies non-conservation of angular momentum. In GR this aberration effect is partially cancelled by velocity dependent terms in the interaction [13]—the v/c through $(v/c)^4$ terms all cancel—but the $(v/c)^5$ term does not cancel, yielding the Burke-Thorne quadrupole formula for GWs [14]. Laplace's argument makes it hard to conceive of theories where GWs do not exist. Hopefully the physical reality of GWs will be confirmed decisively in the next few years with the first direct detections by ground based interferometers and Pulsar Timing Arrays.

2.2 What kinds of supernovae could produce a detectable GW signal? (Presenter: C. Reisswig)

2.2.1 Introduction

Gravitational waves offer a direct way of observing the inner dynamics of a supernova explosion. Much like neutrinos, they are largely unaffected by regions that are opaque to photons, and they carry first hand information about the dynamics of the explosion.

The strength of a GW signal generally depends at lowest order on time changes in the mass-energy quadrupole moment of the matter in the system. In a supernova explosion, matter is typically accelerated in an asymmetric manner that may trigger changes in the quadrupole moment. Therefore, one can generally expect a non-zero GW signal from an observed supernova explosion. The key question, however, is whether the emitted GW signal is actually strong enough to be detected by any of the upcoming next generation ground-based GW detectors. To address this question, we need to look at the various types of supernovae, what their progenitors are, and how an explosion is possibly triggered.

Supernovae are classified according to their observed light spectra into two main types: those which show presence of hydrogen (Type II) and those which do not (Type I). Each of these two main types can be further refined into several subtypes according to the presence of various elements. For instance, type Ia supernovae show presence of ionized silicon, while type Ib and Ic only show weak or no presence of it (see [15] for a review on observed supernova spectra). Despite the variety in their classification, however, there are only three distinct known kinds of explosions. Type Ia supernovae are caused by the thermonuclear disruption of a white dwarf (e.g. [16,17]; see [18] for an estimate of the expected GW signal from a type Ia supernova within the single-degenerate channel), while supernovae of types Ib/c, II (and all subtypes) are the result of the collapse of a massive star's core (e.g. [19,20]), or, alternatively, if the star had a mass between $\sim 130\ M_{\odot} \lesssim M \lesssim 260\ M_{\odot}$, could be the result of a pair-instability supernova (e.g. [21,22]). Here, we focus on the expected GW signals from core-collapse supernovae (see [23,24] for reviews).

2.2.2 Stellar core collapse

By the end of the life of a massive star ($8\ M_{\odot} \lesssim M \lesssim 130\ M_{\odot}$), its core is composed of an onion-skin structure of progressively heavier elements towards the center. At the center, the core is composed of iron-group nuclei which can no longer be converted into energy by means of nuclear fusion, and is supported against gravity by pressure from relativistically degenerate electrons. Iron is the end product of silicon burning, and as the star continues to burn silicon in the next surrounding shell, the iron core grows and is eventually pushed towards its effective Chandrasekhar mass. Radial instability sets in and the core starts to collapse, further accelerated by the loss of pressure support from the degenerate electrons which are captured by protons, which in turn leads to neutronization of the surrounding matter. The collapsing core separates into a subsonically infalling homologous ($v \propto r$) inner core and a supersonically infalling outer core. Once nuclear densities are reached, a new stable equilibrium emerges due to the sudden stiffening of the equation of state. The infalling inner core initially overshoots this new equilibrium and bounces back into the still infalling outer core. This leads to the formation of a very strong shock front which travels outwards into the infalling outer core. Shortly after its formation, however, the shock loses energy due to the dissociation of iron-group nuclei into free neutrons and protons and decelerates. Additionally, electron captures behind the shock result in neutrino losses, and thus lead to further loss of pressure behind the shock. Eventually, the shock succumbs to the ram pressure of the infalling outer material and turns into an accretion shock. To lead to a supernova explosion, the stalled shock must be re-energized by some mechanism within the first ∼0.5–3 s after core bounce. Otherwise, the accreting material from the infalling outer core will push the nascent protoneutron star at the center above its maximum mass, leading to black hole formation [25,26]. Detailed reviews of core-collapse physics are given in e.g. [19,20].

2.2.3 Explosion mechanisms

Currently, there are two favoured mechanisms for shock revival (see [20] for alternatives). The two mechanisms lead to distinct features in the emitted GW signal which we will very briefly discuss below.

The neutrino mechanism The neutrino mechanism [27–29] is the favoured mechanism for shock revival for the majority of core-collapse supernova explosions with energies $0.1 - 1$ B (1 Bethe $= 10^{51}$ergs). The collapse of the iron core leaves behind a hot protoneutron star. Over a timescale of a few seconds, the hot protoneutron star cools down due to the emission of copious amounts of neutrinos of all flavors [19]. This releases energy on the order of 100B which corresponds to about ∼99 % of the total gravitational energy released in the collapse. Some of that energy can be absorbed in a gain region behind the shock via charged-current neutrino captures, thus leading to net heating and potential shock revival [27]. Unfortunately, 1D simulations show that all but the lightest stars fail to explode, and those that do, result in rather low explosion energies (e.g. [30–32]). A number of studies suggest that hydrodynamic instabilities operating in multi-D are necessary to increase the dwell time of matter in the gain region, thus increasing the neutrino heating efficiency (see [33–40] for recent multi-D simulations). Two important hydrodynamic instabilities include convection and the standing accretion shock instability (SASI). The latter instability causes the shock front to strongly oscillate (e.g. [41,42]). Both hydrodynamic instabilities give rise to GW emission that can be seen by next generation ground-based GW interferometers, provided the explosion occurs within the Milky Way (e.g. [33]).

The magnetorotational mechanism A small fraction (∼1–2 %) of observed core-collapse supernova explosions are very energetic and reach explosion energies of $\sim$ 10 B [43]. It has been suggested that another mechanism, the magnetorotational mechanism, may be responsible for such powerful explosions (e.g. [44]). Due to the conservation of angular momentum, a rotating core may be spun up by a factor of ∼1,000 during the collapse [45]. A rapidly rotating core with period of ∼1 s may thus result in a ms-period rotating protoneutron star. Thus the available rotational energy is greater than the energy necessary for launching a powerful explosion. Magnetorotational processes can efficiently extract this spin energy and drive a powerful bipolar explosion along the axis of rotation (e.g. [44,46]). Since in this scenario, the collapsing core is required to be rapidly rotating, the GW signal will be dominated by a strong peak signal at core bounce (e.g. [47]). This is caused by the rotationally flattened collapsing core which, at bounce, generates a large accelerated quadrupole moment. Furthermore, this triggers strong fundamental mode excitations in the nascent protoneutron star that give rise to an oscillatory GW signal after bounce (e.g. [51]). In addition, non-axisymmetric instabilities can lead to powerful quasi-periodic GW emission tens of milliseconds after bounce, provided the protoneutron star is sufficiently rapidly rotating or further spun up during deleptonization (e.g. [48,49]).

The entire signal will be visible throughout the Milky Way (e.g. [47,49–52]).

2.2.4 Conclusions

Core-collapse supernovae (supernova types Ib/c, II) produce GWs that are detectable by the upcoming advanced GW detectors (aLIGO, aVirgo) within our own Milky Way. The morphology of the emitted GW signal of a core-collapse supernova greatly depends on the parameters of the progenitor and the explosion mechanism. If the progenitor star is rapidly rotating, the signal will be dominated by a pronounced peak at core bounce followed by an oscillatory signal generated by fundamental mode excitation in the nascent protoneutron star. Without rotation, the signal will be largely due to prompt convection, standing accretion shock instability (SASI) activity, and generally due to any aspherical motion in the region behind the shock. Interestingly, the types of explosion mechanisms lead to distinct features that can be isolated and detected based on Bayesian model selection and principle component analysis [53]. Thus, the GW signal from the next galactic supernova can inform us about the nature of the explosion mechanism.

2.3 Do laser interferometer gravitational wave detectors absorb energy from gravitational waves? (Presenter: R. Sturani)

The arrival of a GW onto a detector will in general alter the state of motion of an observer and the goal of this section is to study the energy exchange of a GW with the laser interferometer components: beam splitter, end mirrors and the laser itself. Let us place them in the $z = 0$ plane at coordinates respectively $(0, 0)$, $(L_x, 0)$ and $(0, L_y)$ and consider for simplicity a GW traveling along the z direction. In the Transverse–Traceless (TT) gauge the gravitational perturbation $h_{\mu\nu}$ has components $h_{0\mu} = 0$, $h_{xx} = -h_{yy} = h_+$, $h_{xy} = h_{yx} = h_\times$, and the the metric element restricted to the x–y plane can be written as

$$d\tau^2\Big|_{z=0} = dt^2 - (1 + h_+)dx^2 - (1 - h_+)dy^2 - 2(1 + h_\times)dxdy\,. \tag{1}$$

Interaction between the GW and matter Given two nearby geodesic parametrized by coordinates $x^i(\tau), x'^i(\tau)$, describing the motion of two test masses initially at rest ($dx^i/d\tau|_{\tau=0} = 0 = dx'^i/d\tau|_{\tau=0}$, $dt/d\tau|_{\tau=0} = 1 = dt'/d\tau|_{\tau=0}$), the (space) *coordinate* geodesic deviation $\xi^i \equiv x'^i - x^i$ at initial time satisfies (see sec. 1.3 of [59])

$$\frac{d^2\xi}{d\tau^2}\Big|_{\tau=0} = -\dot{h}_{ij}\frac{d\xi^i}{d\tau}\Big|_{\tau=0}\,, \tag{2}$$

as in the TT gauge at linear order $\partial_\mu \Gamma^i_{00} = 0$ and $\Gamma^i_{0j} = \partial_0 h_{ij}/2$, showing that the *coordinate* distance of two particle initially at rest remain constants in the TT gauge under the influence of a GW. However the *proper* distance s between the x-mirror and the beam splitter changes:

$$s = L_x(1+h_+)^{1/2} \simeq L_x\left(1+\frac{1}{2}h_+\right), \tag{3}$$

whose second derivative gives a Newtonian-like equation of motion

$$\ddot{s} \simeq \frac{1}{2}\ddot{h}_+ L_x \simeq \frac{1}{2}\ddot{h}_+ s \tag{4}$$

as to lowest order in h, $s \simeq L_x$. As the physical distance between two test masses (like the mirror and the beam splitter) is time dependent in the presence of a GW, it is expected that an energy transfer may take place between the GW and the interferometer, as first suggested in [60], by "putting in a spring" between objects in mutual motion.

The mirror and the beam splitter are hung to the ceiling of the laboratory, in a pendulum-like arrangement. The pendulum has a typical restoring period $T \sim \sqrt{l/g} \simeq$ few $\times 10^{-1}$ s (being l the length of the suspension and g the gravity acceleration), implying that the mirror is approximately in free fall for GW signals whose frequency $f_{GW} \gg Hz$. On longer time scales energy transfer, and eventually dissipation, between the mirror and its suspension will take place.

In a real laboratory, positions are marked by rigid rulers and not by freely falling particles. It is thus instructive to consider the mirror-GW interaction in the *proper detector frame* (PDF). A standard results within General Relativity is that it always possible to set to zero the Christoffel symbols $\Gamma^\rho_{\mu\nu}$ along an entire geodesic by using Fermi normal coordinates in the freely falling frame, see sec. 8.4 of [61]. Considering the relative coordinate distance x^i between an arbitrary space-time point and to the geodesic used to define Fermi normal coordinates, to linear order in x the metric is flat and at second order in x/λ (being λ the curvature scale of the space-time, $\lambda \sim |R_{0i0j}|^{-1/2}$) one has in the proper detector frame

$$\begin{aligned} d\tau^2_{PDF} \simeq\ & dt^2\left(1+R_{0i0j}x^i x^j\right) + 2dt\,dx^i\left(\frac{2}{3}R_{0jik}x^j x^k\right) \\ & -dx^i dx^j\left(\delta_{ij}-\frac{1}{3}R_{ikjl}x^k x^l\right). \end{aligned} \tag{5}$$

The laboratory may not be in free fall with respect to earth gravity field, but if we restrict to motion in the $z=0$ plane and to signals with $f_{GW} \gtrsim 10Hz$ all "environmental" effects can be safely neglected and the coordinate distance between neighboring geodesic results in

$$\ddot{\xi}^i_{PDF} = -R^i_{0j0}\xi^j_{PDF}\,. \tag{6}$$

Observing that at $O(x/\lambda)$ the metric is flat and that the Riemann tensor components are not only *covariant* (as common in General Relativity) but actually *invariant* in the linearized theory, so that $R^i_{0j0} = -\ddot{h}_{ij}/2$, being h the TT metric perturbation, we recover Eq. (4), which is frame-independent. Since in the proper detector frame coordinates track distances, from Eq. (4) we infer that a test particle of mass μ under the influence of a GW is experiencing a time-dependent, Newtonian force $F^i = -\frac{\mu}{2}\ddot{h}^{ij}L^j$, allowing to derive the energy-transfer rate dE/dt due to the force via $dE/dt = F^i dx^i/dt$.

In the presence of the GW only, $F^i dx^i/dt$ is a total derivative and for an oscillating h it averages to 0: after a short transient during which the massive object is set in motion by the GW there is no more energy transfer on average over an oscillation cycle. However the interferometer mirrors are not exactly freely-falling, because of the suspensions hanging them causes dissipation, leading to the actual equation (dropping the proper detector frame subscript)

$$\ddot{\xi}^i + \frac{\omega_0}{Q}\dot{\xi}^i + \omega_0^2\xi^i = -\frac{1}{2}\ddot{h}_{ij}\xi^j\,, \tag{7}$$

with $\omega_0 = 2\pi/T$ the pendulum proper angular frequency and the ω_0/Q term parametrizing the friction term, for which we assume $Q \gg 1$. Assuming for simplicity a GW of the type $h_+ = h_0\cos(\omega_{GW}t)$, $h_\times = 0$, we have the solution

$$\xi(t) - L = \left(2Lh_0\omega_{GW}^2/\pi^2\right)\frac{(\omega_{GW}^2 - \omega_0^2)\cos(\omega_{GW}t) - \omega_{GW}\omega_0/Q\sin(\omega_{GW}t)}{\left(\omega_{GW}^2 - \omega_0^2\right)^2 + \omega_{GW}^2\omega_0^2/Q^2}\,, \tag{8}$$

showing that the massive object motion is in phase with the GW, apart for a term proportional to the friction which is responsible for the dissipation

$$\left\langle\frac{dE}{dt}\right\rangle \simeq \left(\mu L^2 h_0^2\omega_{GW}^8/\pi^4\right)\frac{(\omega_{GW}^2 - \omega_0^2)\omega_0/Q}{\left[\left(\omega_{GW}^2 - \omega_0^2\right)^2 + \omega_{GW}^2\omega_0^2/Q^2\right]^2}\,. \tag{9}$$

In the limit $\omega_{GW} \gg \omega_0$ one obtains

$$\begin{aligned}\frac{dE}{dt} &\simeq \frac{\mu}{Q\pi^4}L^2h_0^2\omega_{GW}^2\omega_0 \simeq 2\times 10^{12}h_0^2\text{erg/sec}\\ &\times\left(\frac{Q}{10^8}\right)^{-1}\left(\frac{\omega_{GW}}{2\pi kHz}\right)^2\left(\frac{\omega_0}{2\pi Hz}\right)\left(\frac{\mu}{1kg}\right)\left(\frac{L}{3km}\right)^2,\end{aligned} \tag{10}$$

showing that the energy absorbed by the system from the GW is proportional to the friction term[1]. This is the energy absorbed by the massive object in order to keep its motion with a constant kinetic energy E_{kin} (averaged over a GW cycle)

[1] In principle one could consider the re-emission by the system made by the beam-splitter and the mirror, which has a time-varying quadrupole $Q_{xx}(t) \simeq \mu\xi^2(t)$. From the standard Einstein quadrupole formula

$$\langle E_{kin}\rangle \simeq \mu\omega_{GW}^2 L^2 h_0^2/\pi^2\,. \tag{11}$$

Interaction between the GW and and a Michelson-type interferometer. The laser in an interferometer monitors the distance between mirrors, and its electric field is also affected by the GW. The electric field in the two orthogonal beams in the interferometers "travel" from the beam splitter to the mirrors and back to recombine at the photo-detector at some time t. The phase of the electric field is conserved during free propagation, so at time t the electric fields recombine with the phase they inherit from the times $t_0^{(x)} \neq t_0^{(y)}$ when they left the beam splitter. Denoting by $E^{(x)}$ and $E^{(y)}$ the electric field coming respectively from the x and y arms, once they are recombining at the photo-detector after the beam splitter, we have

$$\begin{aligned} E^{(x)} &= -\frac{1}{2}E_0 e^{-i\omega_l t_0^{(x)}}\,,\\ E^{(y)} &= \frac{1}{2}E_0 e^{-i\omega_l t_0^{(y)}}\,, \end{aligned} \tag{12}$$

with ω_l being the laser angular frequency and the relative minus sign is due to the fact that reflection from opposite sides of the beam splitter brings a π shift in the phase [62]. Using the null geodesic in the metric given by Eq. (1) to relate the time t to $t_0^{(x,y)}$, we have (see sec. 9.1 of [59]) at $O(h)$

$$\begin{aligned} t_0^{(x)} &= t - 2L_x - h_+(t-L_x)\sin(\omega_{GW}L_x)/\omega_{GW}\,,\\ t_0^{(y)} &= t - 2L_y + h_+(t-L_y)\sin(\omega_{GW}L_y)/\omega_{GW}\,. \end{aligned} \tag{13}$$

Substituting the above expression for $t_0^{(x,y)}$ in Eq. (12) and expanding at linear order in the GW amplitude one obtains

$$\begin{aligned} E^{(x)}(t) = -\frac{1}{2}E_0 e^{i(2\omega_l L + phi_0)}\Bigg[& e^{-i\omega_l t} + \frac{i}{2}h_0\omega_l L\frac{\sin(\omega_{GW}L)}{\omega_{GW}L}\\ & \times\left(e^{-i(\omega_l-\omega_{GW})t}e^{-i\omega_{GW}L} + e^{-i(\omega_l+\omega_{GW})t}e^{i\omega_{GW}L}\right)\Bigg] \end{aligned} \tag{14}$$

where we have introduced $L \equiv (L_x+L_y)/2$ and $\phi_0 \equiv \omega_l\Delta L$, with $\Delta L \equiv L_x - L_y$, and where in $O(h_0)$ terms we have identified $L_x \simeq L_y \simeq L$. This shows that in each arm *sidebands* appear beside the career laser frequency at angular frequencies $\omega_l \pm \omega_{GW}$. The relative amplitude of the sidebands with respect to the career laser signal, for $\omega_{GW} \ll 1/L$, is given approximately by $h_0 L/\lambda_l \gg h_0$, being λ_l the laser wavelength.

Footnote 1 continued
$dE/dt|_{emitted} = G_N \dddot{Q}_{ij}^{\,2}/5 \sim G_N\mu^2L^4\omega_{GW}^6h_0^2$, which can be compared to the absorption given from Eq. (10) to obtain $dE/dt|_{emitted} \sim dE/dt|_{absorbed} \times 6 \times 10^{-22}\left(\frac{\omega_0}{2\pi Hz}\right)^{-1}\left(\frac{\omega_{GW}}{2\pi kHz}\right)^4\left(\frac{Q}{10^8}\right)\left(\frac{\mu}{1kg}\right)\left(\frac{L}{3km}\right)^2$, hence completely negligible.

Combining Eq. (14) with the analogous formula for the y-arm one can determine the total electric field at the photo-detector $E_{pd}(t) = E^{(x)} + E^{(y)}$

$$E_{pd} = -iE_0 e^{-i\omega_l(t-2L)} \sin\left[\phi_0 + h_0\omega_l L \frac{\sin(\omega_{GW}L)}{\omega_{GW}L} \cos(\omega_{GW}(t-L))\right]. \quad (15)$$

Detecting a GW from the laser light associated with this electric field is still impractical: in order for the output power be *linear* in h_0 one would be sensitive also to the fluctuations in the laser power at a frequency $\sim \omega_{GW}/(2\pi)$, that would completely hide the GW signal. The solution adopted in actual observatories is to inject sidebands into the laser light so that the input electric field is given by

$$\begin{aligned} E_{in} &= E_0 e^{-i(\omega_l t + \Gamma \sin(\Omega_{mod} t))} \\ &\simeq E_0 \left[e^{-i\omega_l t} + \frac{\Gamma}{2} e^{-i(\omega_l + \Omega_{mod})t} - \frac{\Gamma}{2} e^{-i(\omega_L - \Omega_{mod})t}\right], \end{aligned} \quad (16)$$

Working with $\phi_0 = 0$, so that $E_{pd} \propto h_0$ as per Eq. (15), and combining the effects of the GW with the injected modulating sidebands, one has the output electric field

$$\begin{aligned} E_{out} \simeq -iE_0 e^{-i(\omega_l t + 2L)} \Big[& \omega_l L \tfrac{\sin(\omega_{GW}L)}{\omega_{GW}L} h_0 \cos(\omega_{GW}t) \\ & + 2\Gamma \sin(\Omega_{mod}\Delta L) \cos(\Omega_{mod}(t-2L)) \Big], \end{aligned} \quad (17)$$

and the GW signal can be read in the output power from the interference term between the career field and the sidebands oscillating at $\pm\Omega_{mod}$, giving a light power at the photo-detector P_{pd} (for $\omega_{GW}L \ll 1$)

$$P_{pd} = |E_{out}|^2 \simeq 2E_0^2 \Gamma \omega_l L h_0 \cos(\omega_{GW}t) \sin(\Omega_{mod}\Delta L) \sin(\Omega_{mod}(t-2L)) + \ldots \quad (18)$$

where only the term oscillating at $\pm\Omega_{mod} \pm \omega_{GW}$ has been explicitly shown, as it is the only one linear in the GW amplitude.

The output is still sensitive to the power fluctuation (of the sidebands), but now the GW signal has to compete with laser power fluctuation not at $\omega_{GW} \lesssim 10$ kHz, but at $\Omega_{mod} \sim 10\,\mathrm{MHz} \gg \omega_{GW}$ and this is a great advantage as laser power fluctuations generally decrease with frequency [63].

The interferometers actually used as GW observatories contain Fabry-Perot cavities in which the laser beam goes back and forth several times in each arm before recombining. At an effective level, the Fabry-Perot cavity allow to "fold" the light path enhancing its length without changing the region of the laboratory space traveled by the laser. This results in a phase-shift enhanced, in the case $\omega_{GW}L \gg 1$, by a factor $N \equiv 4F/\pi$ (see e.g. sec. 9.2 of [59]) where F is the *finesse* of the cavity related to the *storage time* (i.e. the average time spent by a photon in the cavity) τ_s by $F \simeq \pi\tau_s/L$:

the effect of the Fabry-Perot cavity boils down to replace the term $h_0 L$ in the amplitude of the GW sidebands in Eq. (14) with

$$h_0 N L \frac{1}{\left[1+(NL\omega_{GW}/2)^2\right]^{1/2}}\,, \qquad \text{for } \omega_{GW} L \ll 1\,. \tag{19}$$

For initial LIGO (Virgo) $N \simeq 60(20)$.

The laser electric fields recombines at the beam splitter to form an output beam directed to the photo-detector and a beam heading back to the laser. We have described how the electric field at the photo-detector depend on the GW in Eq. (15). The electric field going back to the laser is $E_l = E^{(x)} - E^{(y)}$ (apart from an irrelevant overall phase), thus we can compute the total laser power

$$|E^{(x)} + E^{(y)}|^2 + |E^{(x)} - E^{(y)}|^2 = E_0^2\,, \tag{20}$$

which is unaffected by the GW, at least at $O(h)$. The appearance of the GW sidebands does not change the total power in the laser beam, but allows to identify a signal at a well-determined frequency and with amplitude highly enhanced with respect to h_0, see the $\omega_l L$ factor in Eq. (18).

In order to complete the energy balance of the interferometer interacting with a GW however we still need to consider the radiation pressure exerting a force F_{rp} on the masses set in motion by the GW [64]. The laser power in each arm is approximately $P_{arm} = P_{laser}/2 = E_0^2/2$ and the radiation-pressure induces a force on each end mirror $F_{rp} = 2P_{arm} = P_{laser}$. As the masses are set in motion by the GW with velocity v, the radiation pressure force change because of the Doppler effect to $F_{rp} \simeq 2P_{arm}(1-2v)$, where v can be obtained by deriving Eq. (8). The radiation pressure force has thus the effect of a friction term of the kind appearing in Eq. (7), with an effective "quality factor" Q_{rp} approximately given by

$$Q_{rp} = \frac{m\omega_0}{4P_{arm}} \simeq 3\times 10^{15} \left(\frac{P_{laser}}{100W}\right)^{-1} \left(\frac{m}{1kg}\right) \left(\frac{\omega_0}{1Hz}\right)\,. \tag{21}$$

Summing over the repeated bounces of each photon in the Fabry-Perot cavity, one can derive the dissipation due to radiation pressure [64]

$$\left.\frac{dE}{dt}\right|_{rp} \simeq 4P_{arm} \frac{N^2 L^2}{\pi^2} h_0^2 \omega_{GW}^2 \tag{22}$$

which can be obtained by substituting Q_{rp} in Eq. (10) and replacing L with NL.

2.4 How does searching for gravitational waves help us here on Earth? (Presenter: A.L. Stuver)

The value of gravitational-wave research is well established in the scientific community: to observe the Universe in a way humans have never before been able to do and to obtain new knowledge about our Universe that may have been forever out of our reach otherwise. This is indeed a noble cause. However, many people outside of academic circles value work differently, often favoring work that has more utilitarian ends. When engaging the public, through outreach or casually, it is useful to be able to answer the question, “What does looking for gravitational waves do for me?”

Gravitational waves will most likely never be able to be commercialized or weaponized. However, there are many byproducts of the search for GWs that can be applied in new ways. This is called spin-off technology, and many in the public will associate this term with developments from the space program. There have been several notable spin-off technologies from the interferometric search for GWs. The LIGO Scientific Collaboration has been cataloging these innovations (available on the web [54]) but it should also be noted that the potential of any new work is hard to predict soon after its development. Below are a selection of five examples.

2.4.1 Adaptive laser shaping: correcting the wavefront error caused by absorption

Whenever light is absorbed in optics, it heats the medium causing its shape and index of refraction to change. These perturbations in the optic cause wavefront errors to which interferometric gravitational-wave detectors are susceptible.

Corrections to this distortion can be made by using a second transparent element and placing heating elements along the edge to create a lensed shape in the heater material that counterbalances the wavefront errors caused by the mirrors absorption heating.

This technique of adaptive laser shaping has practical applications outside of the search for GWs as the development and use of other high-powered laser systems are challenged with controlling the beam wavefront.

2.4.2 Measuring optic absorption to higher precision

As described in Sect. 2.4.1, the absorption of optics in gravitational-wave interferometers needs to be minimized. As materials have improved, so has the need to be able to measure increasingly small absorptions, into the sub-ppm region. A new method to perform this task, called Photo-Thermal Common Path Interferometry (PTCPI), has been developed. Two laser beams are used: one high-power beam from which light will be absorbed and another low-power probe beam that will measure the thermal distortions in the optic caused by the high-power beam.

This technique has resulted in the creation of the Stanford Photo-Thermal Solutions (SPTS) and serves the optics and homeland security (US) communities.

2.4.3 High precision location sensing of optics

Once a suitable optic has been installed inside of a gravitational-wave interferometer, knowledge of its location and any motion it may be exhibiting is needed for basic instrument control. The standard way this has been done is with shadow detectors. A magnet is attached to the optic and separated from the optic in a cylinder containing within it a light source on one side and a photodiode on the opposite side. The cylinder is secured so that the magnet is within the cylinder without making contact. By detecting the shadow cast by the magnet, the location of the mirror can be sensed and then controlled by loops of current carrying wire wrapped around the outside of the cylinder. A series of these sensors placed strategically around the optic can then distinguish modes of motion and control it.

A potential replacement for this sensing method is the use of EUCLID (Easy to Use Compact Laser Interferometric Device), which would not require any mounting of parts onto the optic in order to sense its location. EUCLID uses homodyne interferometry to sense the location of the optic itself little interferometers measuring the location of the optics inside the larger interferometer. This new design is two-orders of magnitude better at detecting changes in location than the shadow sensing method. Due to this works possible applications, including anything where the very precise knowledge of where an object is needed, it has been awarded a patent (US2010/0238456 A1).

2.4.4 Development of oxide-bonding techniques

In first generation gravitational-wave interferometers, test mass mirrors were suspended by treated metal wires. These wires introduced thermal noise within the detectors sensitive bandwidth. In order to reduce this noise, the suspension was made to be quasi-monolithic, meaning that the fused silica mirrors are suspended from wires made of the same material. Similar work had been done for Gravity Probe B [55] and this work has been expanded upon by scientists at the University of Glasgow and Stanford University. Specifically, the bonding of the wires to the mirror needed to be thin, strong, and have low mechanical loss [56]. This method is being used for the Advanced LIGO detector, has been patented (US2007/0221326 A1), and is being used by multiple optics vendors for applications outside of gravitational waves.

2.4.5 A new blind search method for pulsars in gamma-ray and radio data

Besides physical technology, analytical techniques that have been developed for the search of GWs and are being used for other analyses. Of the many different analysis methods used to search for GWs, the search for continuous GWs (that is, long duration and consistent frequency signals like those produced by a spherically imperfect rotating neutron star) has found new application to the search for gamma-ray and radio pulsars. The LIGO Scientific Collaboration and the Virgo Collaboration have made use of the BOINC distributed computing platform [57] in order to harness household computers' unused CPU cycles to undertake Einstein@Home [58]: a very computationally expensive search for continuous GWs. Einstein@Home has also used archive data from the Arecibo radio telescope and the Parkes Multi-beam Pulsar Survey to search for radio pulsars and the Fermi gamma-ray satellite to search for gamma-ray pulsars to great effect. Since the beginning of 2012 to the time of this writing (late 2013), 48 new radio pulsars and 4 new gamma-ray pulsars have been discovered.

2.5 When do we finally get to make the first detection? (Presenter: P. J. Sutton)

It's hard to make predictions—especially about the future.
attributed to Robert Storm Petersen

The last question addressed in the Q&A session was the rather tongue-in-cheek *When do we finally get to make the first detection? Answers must be accurate to within the mass of the Galaxy (expressed in units of time), and supported by an excellent bottle of whiskey in case the respondent turns out to be in error.* We can attempt an answer in the same spirit[2], given three pieces of information:

The mass of the Galaxy (in units of time) A time-honoured amusement for lecturers of general relativity is to require students to convert physical quantities between time, length, and mass (preferably at a blackboard in front of the entire class). Rather than fumbling about with factors of G, we can recall that 1 $M_{\odot}$ is equivalent to 1.5 km, and divide by c to obtain a time. A Wikipedia search (the time-honoured student's revenge) quickly reveals that the virial mass of the Milky Way is $(1.26 \pm 0.24) \times 10^{12} M_{\odot}$ [66]. Using the respondent's prerogative, we may adopt the 1-σ upper limit, $1.5 \times 10^{12} M_{\odot}$ for our calculation. Applying our 1.5 km/c prescription, we get an equivalent time of 0.74×10^{7} s, which is pretty close to the convenient round number of 3 months[3].

The rate density of GW sources The gravitational-wave source generally considered to be the most likely to be detected first by interferometers such as advanced LIGO and advanced Virgo is the coalescence of a binary neutron star (BNS) system. The rate of these systems is thought to lie in the range 10^{-8} Mpc^{-3} y^{-1} to 10^{-5} Mpc^{-3} y^{-1}, with a "most likely" value of around 10^{-6} Mpc^{-3} y^{-1} [67].

The sensitivity of GW detectors Meanwhile, the LIGO and Virgo collaborations have released a projected schedule for the operation of their advanced detectors [68]. They foresee a series of few-month to year-long data-taking runs at progressively higher sensitivities starting in 2015, with final design sensitivity (up to 200 Mpc) reached c. 2019+.

So how kind is Nature? If the BNS rate density is as high as 10^{-5} Mpc^{-3} y^{-1} then a little algebra quickly reveals that an average sensitive range of order 50 Mpc is enough to expect to see one BNS event in a few months of observations. This sort of range is expected for the very first observing run. In that case we may get something special for Christmas 2015!

On the other hand, Nature may be a Grinch. For the lowest rate density, 10^{-8} Mpc^{-3} y^{-1}, even the final LIGO-Virgo design ranges only give one detection every few years. In that case Christmas is cancelled—at least until $\sim$2020.

We see that uncertainty in the actual BNS rate density stymies our effort to respond with the required 3-month accuracy. 2015? 2020? This will not do! Emboldened by the spirit of the occasion, we will wager that Nature follows the "realistic" rate. Assuming the 10^{-6} Mpc^{-3} y^{-1} value for the BNS rate density, we find that to detect one BNS

[2] Actually, we use the respondent's prerogative to answer in a different spirit: in honour of our host nation, the respondent offers in wager a bottle of his favourite vodka [65].

[3] Respondent's prerogative again: we round *up* to 3 months.

event in a few months of observations, the detectors must have an average sensitive range of order 100 Mpc. This range is foreseen for the 2016-17 run. This run is scheduled to last for 6 months—which is very convenient when the required accuracy is ±3 months! We therefore assert that the first detection will occur at the approximate mid-point of the run, 1 Jan 2017, satisfied that a detection at any point during the run (from Oct 2016 to Mar 2017) will satisfy our questioner – and our thirst for knowledge. *Na zdrowie*!

References

1. Weisberg, J.M., Nice, D.J., Taylor, J.H.: Timing measurements of the relativistic binary pulsar PSR B1913+16. Astrophys. J. **722**, 1030–1034 (2010). doi:10.1088/0004-637X/722/2/1030
2. Kramer, M., Stairs Ingrid, H., Manchester, R.N., McLaughlin, M.A., Lyne, A.G., et al.: Tests of general relativity from timing the double pulsar. Science **314**, 97–100 (2006). doi:10.1126/science.1132305
3. Antoniadis, John, Freire Paulocc, C.C., Wex, Norbert, Tauris Thomas, M., Lynch Ryan, S., et al.: A massive pulsar in a compact relativistic binary. Science **340**, 6131 (2013). doi:10.1126/science.1233232
4. Brown, W.R., Kilic, M., Hermes, J.J., Allende Prieto, C., Kenyon, S.J., Winget, D.E.: A 12 minute orbital period detached white dwarf eclipsing binary. Astrophys. J. Lett. **737**, L23 (2011). doi:10.1088/2041-8205/737/1/L23
5. Nelemans G.: Private communication (2013)
6. Vila, S.C.: Late evolution of close binaries. Astrophys. J. **168**, 217 (1971). doi:10.1086/151076
7. Ramsay, G., Groot, P.J., Marsh, T., Nelemans, G., Steeghs, D. et al.: XMM-Newton observations of AM CVn binaries: V396 Hya and SDSS J1240–01. Astron. Astrophys. **457**, 623–627 (2006)
8. Bildsten, L.: Gravitational radiation and rotation of accreting neutron stars. Astrophys. J. Lett. **501**, L89 (1998). doi:10.1086/311440
9. Isaacson, R.A.: Gravitational radiation in the limit of high frequency. II. Nonlinear terms and the effective stress tensor. Phys. Rev. **166**, 1272–1279 (1968). doi:10.1103/PhysRev.166.1272
10. Kennefic D.: Controversies in the history of the radiation reaction problem in general relativity. gr-qc/9704002 (1997)
11. Chatziioannou, K., Yunes, N., Cornish, N.: Model-independent test of general relativity: an extended post-einsteinian framework with complete polarization content. Phys. Rev. D **86**, 022004 (2012). doi:10.1103/PhysRevD.86.022004
12. Laplace, P.: A Treatise in Celestial Mechanics. Chelsea, New York (1966). originally published in 1805
13. Carlip, S.: Aberration and the speed of gravity. Phys. Lett. A **267**, 81–87 (2000). doi:10.1016/S0375-9601(00)00101-8
14. Burke, W.L.: Gravitational radiation damping of slowly moving systems calculated using matched asymptotic expansions. J. Math. Phys. **12**, 401–418 (1971). doi:10.1063/1.1665603
15. Filippenko, A.V.: Optical spectra of supernovae. Ann. Rev. Astron. Astrophys. **35**, 309 (1997)
16. Hillebrandt, W., Niemeyer, J.C.: Type IA supernova explosion models. Ann. Rev. Astron. Astrophys. **38**, 191–230 (2000)
17. Roepke FK.: Thermonuclear supernovae. arXiv:08042147 (2008)
18. Falta, D., Fisher, R., Khanna, G.: Gravitational wave emission from the single-degenerate channel of type Ia supernovae. Phys. Rev. Lett. **106**(20), 201103 (2011)
19. Bethe, H.A.: Supernova mechanisms. Rev. Mod. Phys. **62**, 801 (1990)
20. Janka, H.T., Langanke, K., Marek, A., Martínez-Pinedo, G., Müller, B.: Theory of core-collapse supernovae. Phys. Rep. **442**, 38 (2007)
21. Kasen, D., Woosley, S.E., Heger, A.: Pair instability supernovae: light curves, spectra, and shock breakout. Astrophys. J. **734**, 102 (2011)
22. Fryer, C.L., Woosley, S.E., Heger, A.: Pair-instability supernovae, gravity waves, and gamma-ray transients. Astrophys. J. **550**, 372–382 (2001). doi:10.1086/319719
23. Ott, C.D.: TOPICAL REVIEW: The gravitational-wave signature of core-collapse supernovae. Class Quantum Grav. **26**, 063001 (2009). doi:10.1088/0264-9381/26/6/063001

24. Kotake, K.: Multiple physical elements to determine the gravitational-wave signatures of core-collapse supernovae. Comptes Rendus Phys. **14**(4), 318–351 (2013)
25. O'Connor, E., Ott, C.D.: Black hole formation in failing core-collapse supernovae. Astrophys. J. **730**, 70 (2011)
26. Ugliano, M., Janka, H.T., Marek, A., Arcones, A.: Progenitor-explosion connection and remnant birth masses for neutrino-driven supernovae of iron-core progenitors. Astrophys. J. **69**, 757 (2012). doi:10.1088/0004-637X/757/1/69
27. Bethe, H.A., Wilson, J.R.: Revival of a stalled supernova shock by neutrino heating. Astrophys. J. **295**, 14 (1985). doi:10.1086/163343
28. Janka, H.T., Hanke, F., Hüdepohl, L., Marek, A., Müller, B., Obergaulinger, M.: Core-collapse supernovae: reflections and directions. Prog. Theor. Exp. Phys. **2012**(1), 01A309 (2012)
29. Burrows, A.: Colloquium: perspectives on core-collapse supernova theory. Rev. Mod. Phys. **85**, 245 (2013). doi:10.1103/RevModPhys.85.245
30. Liebendörfer, M., Rampp, M., Janka, H.T., Mezzacappa, A.: Supernova simulations with Boltzmann neutrino transport: a comparison of methods. Astrophys. J. **620**, 840 (2005)
31. Kitaura, F.S., Janka, H.T., Hillebrandt, W.: Explosions of O–Ne–Mg cores, the Crab supernova, and subluminous type II-P supernovae. Astron. Astrophys. **450**, 345 (2006)
32. Hüdepohl, L., Müller, B., Janka, H.T., Marek, A., Raffelt, G.G.: Neutrino signal of electron-capture supernovae from core collapse to cooling. Phys. Rev. Lett. **104**, 251101 (2010)
33. Ott, C.D., Abdikamalov, E., Mösta, P., Haas, R., Drasco, S., O'Connor, E.P., Reisswig, C., Meakin, C.A., Schnetter, E.: General-relativistic simulations of three-dimensional core-collapse supernovae. Astrophys. J. **768**, 115 (2013)
34. Hanke, F., Müller, B., Wongwathanarat, A., Marek, A., Janka, H.T.: SASI activity in three-dimensional neutrino-hydrodynamics simulations of supernova cores. Astrophys. J. **770**, 66 (2013)
35. Takiwaki, T., Kotake, K., Suwa, Y.: A comparison of two- and three-dimensional neutrino-hydrodynamics simulations of core-collapse supernovae. Astrophys. J. **786**(2), 83 (2014)
36. Bruenn, S.W., Mezzacappa, A., Hix, W.R., Lentz, E.J., Bronson Messer, O.E., Lingerfelt, E.J., Blondin, J.M., Endeve, E., Marronetti, P.: Axisymmetric Ab initio core-collapse supernova simulations of 12–25 $M_{\odot}$ stars. Astrophys. J. Lett. **767**, L6 (2013)
37. Couch, S.M.: Ott CD revival of the stalled core-collapse supernova shock triggered by precollapse asphericity in the progenitor star. Astrophys. J. Lett. **778**, L7 (2013)
38. Couch, S.M., O'Connor, E.P.: High-resolution three-dimensional simulations of core-collapse supernovae in multiple progenitors. Astrophys. J. **785**(2), 123 (2014)
39. Müller, B., Janka, H.T., Marek, A.: Ott CD revival of the stalled core-collapse supernova shock triggered by precollapse asphericity in the progenitor star. Astrophys. J. **756**, 84 (2012). doi:10.1088/0004-637X/756/1/84
40. Müller, B., Janka, H.T., Heger, A.: New two-dimensional models of supernova explosions by the neutrino-heating mechanism: evidence for different instability regimes in collapsing stellar cores. Astrophys. J. **761**, 72 (2012). doi:10.1088/0004-637X/761/1/72
41. Blondin, J.M., Mezzacappa, A., DeMarino, C.: Stability of standing accretion shocks, with an eye toward core-collapse supernovae. Astrophys. J. **584**, 971 (2003). doi:10.1086/345812
42. Guilet, J., Foglizzo, T.: On the linear growth mechanism driving the standing accretion shock instability. Mon. Not. R. Astron. Soc. **421**, 546 (2012). doi:10.1111/j.1365-2966.2012.20333.x
43. Smith, N., Li, W., Filippenko, A.V., Chornock, R.: Observed fractions of core-collapse supernova types and initial masses of their single and binary progenitor stars. Mon. Not. R. Astron. Soc. **412**, 1522 (2011)
44. Burrows, A., Dessart, L., Livne, E., Ott, C.D., Murphy, J.: Simulations of magnetically driven supernova and hypernova explosions in the context of rapid rotation. Astrophys. J. **664**, 416 (2007)
45. Ott, C.D., Burrows, A., Thompson, T.A., Livne, E., Walder, R.: The spin periods and rotational profiles of neutron stars at birth. Astrophys. J. Suppl. Ser. **164**, 130 (2006)
46. Takiwaki, T., Kotake, K.: Gravitational wave signatures of magnetohydrodynamically driven core-collapse supernova explosions. Astrophys. J. **743**, 30 (2011). doi:10.1088/0004-637X/743/1/30
47. Dimmelmeier, H., Ott, C.D., Marek, A., Janka, H.T.: Gravitational wave burst signal from core collapse of rotating stars. Phys. Rev. D **78**, 064056 (2008)
48. Ott, C.D., Dimmelmeier, H., Marek, A., Janka, H.T., Hawke, I., Zink, B., Schnetter, E.: 3D collapse of rotating stellar iron cores in general relativity including deleptonization and a nuclear equation of state. Phys. Rev. Lett. **98**, 261101 (2007)

49. Kuroda, T., Takiwaki, T., Kotake, K.: Gravitational wave signatures from low-mode spiral instabilities in rapidly rotating supernova cores. Phys. Rev. D **89**(4), 044011 (2014)
50. Abdikamalov, E., Gossan, S., DeMaio, A.M., Ott, C.D.: Measuring the angular momentum distribution in core-collapse supernova progenitors with gravitational waves. arXiv:13113678 (2013)
51. Ott, C.D., Abdikamalov, E., O'Connor, E., Reisswig, C., Haas, R., Kalmus, P., Drasco, S., Burrows, A., Schnetter, E.: Correlated gravitational wave and neutrino signals from general-relativistic rapidly rotating iron core collapse. Phys. Rev. D. **86**(2), 024026 (2012). doi:10.1103/PhysRevD.86.024026
52. Reisswig, C., Ott, C.D., Sperhake, U., Schnetter, E.: Gravitational wave extraction in simulations of rotating stellar core collapse. Phys. Rev. D **83**(6), 064008 (2011)
53. Logue, J., Ott, C.D., Heng, I.S., Kalmus, P., Scargill, J.: Inferring core-collapse supernova physics with gravitational waves. Phys. Rev. D. **86**(4), 044023 (2012). doi:10.1103/PhysRevD.86.044023
54. https://www.advancedligo.mit.edu/tech_overview.html
55. Gwo, D-H.: Ultra precision and reliable bonding method, United States Patent Number US6284085B1 (2001)
56. Rowan, S., et al.: Mechanical losses associated with the technique of hydroxide-catalysis bonding of fused silica. Phys. Lett. A **246**, 471–478 (1998)
57. http://boinc.berkeley.edu/
58. http://einstein.phys.uwm.edu/
59. Maggiore, M.: Gravitational Waves. Oxford University Press, Oxford (2008)
60. Pirani, F.: Measurements of classical gravitation fields. In: DeWitt, C.M., Rickles, D. (eds.) The Role of Gravitation in Physics. Proceedings of the 1957 Chapel Hill Conference, Max Planck Research Library for the History and Development of Knowledge (1957)
61. Hartle, J.B.: Gravity. An Introduction to Einstein's General Relativity. Addison Wesley, S. Franscisco (2003)
62. Freise A., Strain, K.A.: Interferometer techniques for gravitational-wave detection. Living Rev. Relativ. **13**(1) (2010) http://www.livingreviews.org/lrr-2010-1
63. Hough J.: In Perth 1988, Proceedings, Recent Developments in Theoretical and Experimental General Relativity, Gravitation and Relativistic Field Theories, pt. A, pp. 265–282 (1988)
64. Saulson, P.R.: How an interferometer extracts and amplifies power from a gravitational wave. Class. Quant. Grav. **14**, 2435 (1997)
65. http://www.zubrowka.com/
66. McMillan, P.: MNRAS **414**, 2446 (2011)
67. Abadie, J., et al.: Predictions for the rates of compact binary coalescences observable by ground-based gravitational-wave detectors. Class. Quant. Grav. **27**, 173001 (2010)
68. Aasi, J., et al.: Prospects for localization of gravitational wave transients by the advanced LIGO and advanced virgo observatories. arXiv:1304.0670 (2013)