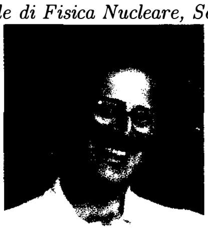
Observational perspectives with advanced gravitational wave detectors

Andrea Viceré
on behalf of the LIGO Scientific Collaboration and of the Virgo Collaboration
Dipartimento di Scienze di Base e Fondamenti, Università di Urbino "Carlo Bo",
Via S.Chiara 27, I-61029 Urbino (PU), Italy
Istituto Nazionale di Fisica Nucleare, Sezione di Firenze



The installation and commissioning of 2nd generation, advanced gravitational wave detectors is progressing on schedule, and observations will start in the second half of 2015, beginning with the two LIGO detectors, whereas Virgo will join in 2016. The instruments will gradually lower their noise floor, eventually achieving a tenfold increase in amplitude sensitivity, which translates for some impulsive sources in a thousandfold increase in event rate. In this talk we will review the main science objectives and expected observational perspectives of the advanced detectors network.

1 Introduction

A second generation of interferometric, large gravitational wave detectors is about to start its observations: in the second half of 2015 the two Advanced LIGO (aLIGO) detectors[1] will carry out their first observational run O1, at a sensitivity that promises to be already significantly better than iLIGO. Then in the second half of 2016, after several further improvements, a O2 run will be carried out with the participation also of Advanced Virgo (AdV)[2].

The evolution of advanced detectors' sensitivity is anticipated in the official LIGO and Virgo plans[3]; a useful benchmark is the BNS range of the instrument, which is the distance at which a pair of neutron stars with $m_{1,2} = 1.4 M_{\odot}$ will yield an SNR of 8, after averaging over source direction and polarization[a].

In the Early phase (2nd half of 2015) aLIGO will have a range in the $40 - 80$ Mpc range; in the Mid phase (2016-17) the range will ramp up to $80 - 120$ Mpc, and in the Late phase (2017-18) to $120 - 170$Mpc. Similarly, AdV in the Early phase (2016-17) will have a range in $20 - 60$ Mpc, in the Mid phase (2017-18) the range will increase to $60 - 85$ Mpc and in the Late phase (2018-20) the range will lie in $85 - 115$ Mpc. It is notable that AdV lags aLIGO by about 2 years; this is just the result of a later start of the Advanced Virgo project.

[a] At the same distance, an optimally located and polarized source would yield an SNR exceeding 18; this is why the "horizon distance", namely the distance at which an optimal source yields an SNR 8, is significantly larger than the range.

Eventually, the advanced detectors are expected to achieve their design sensitivity: for aLIGO, in 2019, with a range of 200 Mpc, for AdV in 2021, with a range of 130 Mpc. These figures or merit are about 10 times better than first generation instruments, thanks to the sensitivity improvements shown in Fig. 1; note that also the bandwidth will be widened, particularly at low frequencies for aLIGO.

In addition to LIGO and Virgo instruments, in 2016 it is expected to start its operation the KAGRA detector [6], which may join the network around 2018 with comparable sensitivity.

Which science will the advanced detectors harvest thanks to these improvements? It is the purpose of this short note to summarize the expected scientific outcomes, focusing on topics which are best known, with no attempt at any generality.

2 Binary coalescences

The one source of gravitational waves (GW) we have several certainties about is the coalescence of binary neutron stars (BNS); thanks to the observation of binary pulsars, we know that these sources do exist [7]. Furthermore, their dynamics is computable and allows predicting the resulting GW signal with accuracies good enough to grant applying matched filtering techniques, which potentially yield optimal sensitivity in the analysis [8]. And finally, a number of studies based both on the observed binary systems and on the simulation of stellar evolution allow to predict the abundance of these sources, as summarized in [9]. Similar studies allow to predict the abundance of pairs of black holes (BH) or of BH and NS, although with lesser certainty for lack of observed systems.

The advanced detectors at design sensitivity will be able to monitor about 10^5 galaxies for the occurrence of BNS coalescences, in a volume of space 1000 times larger than the one monitored by first generation instruments. In such a volume, the number of detectable BNS events is still pretty uncertain: realistic values of 40 events/year are reported, but these could be significantly higher or smaller, down to less than 1 event/year in the pessimistic case, or up to 400 events/year in a more optimistic scenario. The volume accessible when looking for BH-NS or BH-BH events is potentially much larger, but the abundance in a given galaxy is expected to be much smaller, so that the predicted event rates are similar to those for BNS.

Assuming that nature provides us with a significant number of observations, what will we learn from them?

2.1 Constraining the evolution of massive stars

Advanced detectors will *measure* the rate of binary coalescences, and this will help constraining the formation and evolution of massive stars, and shed light on the mechanisms that lead to binary systems sufficiently tight to coalesce in less than a Hubble time.

This is particularly interesting for pairs of massive black holes, say of O(100) $M_{\odot}$, whose coalescence would yield GW events detectable out to $z \sim 2$, and for which the models are highly uncertain [10], to the point that some mechanisms predict no binaries at all.

For binary black holes, the shape of the signal received can provide information about the relative configuration of the BH spins and of the orbital angular momentum of the system; actually, two configurations characterized by different spin-orbit resonances exist, and they carry an imprint of the formation scenario of the binary, which might therefore be accessible by measuring with advanced detectors the fraction of systems in each configuration [11].

2.2 BNS as standard sirens

It is well known that binary neutron stars can provide information about the Hubble constant [12]; the basic idea is that the *shape* of the BNS signal gives access to the mass of the stars involved,

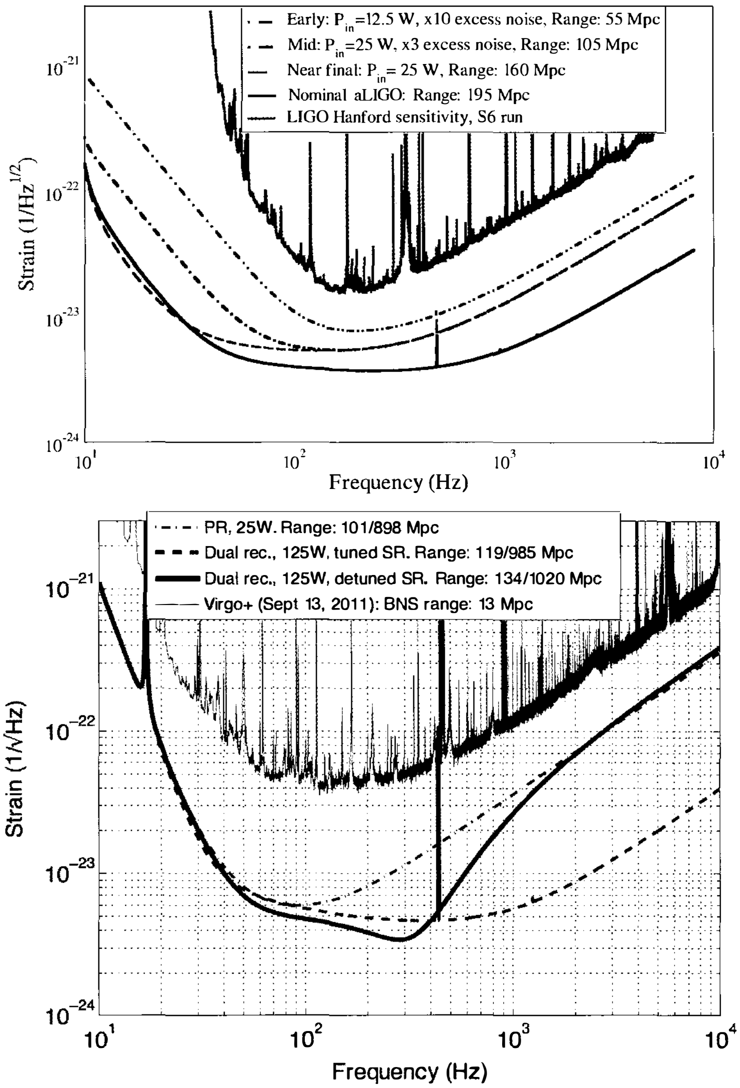


Figure 1 – Up: expected sensitivity of Advanced LIGO (aLIGO) in different configurations [4], compared with the best sensitivity achieved during run S6 [5]. Down: expected sensitivity of Advanced Virgo (AdV) in different configurations [2], compared with the sensitivity achieved in September 2011; where the "Range" reports two figures, the first one is the range for BNS sources, the second one for BBH sources of $10{+}10M_{\odot}$.

and therefore allows predicting the expected amplitude of the GW signal. The measured amplitude depends on the distance of the system, but also on the relative orientation of the detector and of the source system; a network of instruments allows to deconvolve the effect of the antenna patterns and therefore to extract the distance information.

At this point, if one has access to an electromagnetic counterpart, and is therefore able to identify the host galaxy, its recession speed can be correlated with its measured distance, thus providing a sample measurement of the Hubble constant H_0; already 10 sample measurements within 100 Mpc would yield a 3% accuracy.

Recently it has been shown that it is not mandatory to identify the host galaxy by detecting an electromagnetic counterpart: combining the sky localization information made possible by the network of interferometric detectors with a catalogue of potential host galaxies, it is still possible to perform a reasonable association [13], using a larger number of events, say 30, in order to achieve a comparable accuracy. It is worth underlining that the electromagnetic signal may not be accessible for a large part of GW events because of short GRB beaming effects, hence this method is expected to be competitive. The drawback is that a fairly complete catalogue of galaxies is required, whereas out to $z \sim 0.1$ such catalogues are known to be still incomplete, though surveys have been proposed [14] which could raise their completeness above 50%.

2.3 Equation of state of neutron stars

The two-body dynamics, albeit complex to calculate, is relatively straightforward even in General Relativity, as far as the masses can be considered points; things get much more complicated, but also more interesting, when the NS starts to be deformed by the tidal forces. The equation of state (EOS) of the nuclear matter that is supposed to constitute these objects becomes relevant, and this affects the last stages of the coalescence before the merger, which reflects in the shape of the signal. Basically, if the EOS is "soft", namely if a change of density yields a smaller pressure increase, the star is easier to compress and the collapse to a black hole is prompt, yielding a waveform which terminates more abruptly. Conversely, if the EOS is "stiff", even a small density change yields a large pressure change, and the star resists to compression; hence during the merger a structure may form, like a bar mode, which lasts for some orbits before the collapse. As a result, the merger waveform is more complicated, with oscillations relating with the rotation of the bar.

It has been shown that these effects can be visible already in second generation detectors [15,16,17], and the observation of a realistic number of events would allow measuring parameters like the NS radius or its tidal deformability with interesting accuracies.

2.4 The BNS - GRB connection

A BNS coalescence is long proposed to be the origin of the short GRBs [18], but this association will not be confirmed until we are able to observe a temporal and spatial coincidence between the e.m. energy emitted by the GRB and a GW signals consistent with a coalescence.

Even though first generation detectors have searched for such associations [19], the chances to find any were dim, since less than 7% of the observed GRB have redshift smaller than 10^{-1}, whereas LIGO and Virgo could exclude events only up to a redshift about 10 times smaller. The situation, as shown in the same paper, changes with advanced detectors: referring particularly to Fig. 8 in [19], the population of observed GRB becomes comparable with the projected exclusion curves in the advanced detectors era, which means that an observed association is possible or an exclusion will be highly significant.

2.5 Tests of General Relativity

The good theoretical knowledge of the GW signal emitted by a BNS coalescence, along with the possibility of detecting a fair number of events, will allow performing also tests of General

Relativity, for instance to probe the 1.5 Post-Newtonian contribution to the phase of the signal at the 10% level [20], an accomplishment which is not possible for instance using data from binary pulsars or electromagnetic observations. Analysis methodologies exist to this end which have been shown to be robust against poorly modeled effects of an instrumental, astrophysical, and fundamental nature [21].

3 Supernovae

Supernovae events are a potential source of short GW signals. Their rate is known with reasonable accuracy, particularly thanks to the observation by the INTEGRAL satellite [22] of the γ-rays emitted by the isotope ^{26}Al, copiously produced by supernovae; we expect about 1 event/century in our own Milky Way, whereas we observe several events/year in the Virgo Cluster.

Of the different kinds of supernovae, we expect an emission of GW from the so-called *core-collapse* ones, in which the nucleous undergoes a rapid implosion. However, the waveform emitted depends on how asymmetric the implosion is, which remains a matter of modeling. As of today, the energy emitted in GWs by supernovae is highly uncertain, with different models predicting values in the $10^{-11} - 10^{-7} M_{\odot} c^2$ range [23].

In addition to the uncertainty in the emitted energy, also the details of the waveforms are not fully known, even though the simulations allow to predict some general characteristics about their duration. For such signals, a convenient figure of merit is the root square mean signal

$$h_{rss} \equiv \sqrt{\int \left[|h_+(t)|^2 + |h_\times(t)|^2 \right] dt} \ . \qquad (1)$$

Advanced detectors will be able to probe values of $h_{rss} \leq 10^{-23} \mathrm{Hz}^{-1/2}$, however the translation into an energy is distance and model dependent. For signals close to the frequency range where the detectors have their best sensitivity, such h_{rss} value translates into $E_{GW} \leq 10^{-9} M_{\odot} c^2$, for a source at 10 kpc [24].

It is clear from these considerations that the detection of the next galactic supernova is possible, but not certain: apart from the possibility that the signal is emitted according to pessimistic models, and therefore falls below the analysis threshold, the duty cycle of the detector network, particularly in double coincident mode [b], will certainly not be 100%.

The detection of non-galactic supernovae will be limited, assuming optimistic emission models, to a range of few Mpc, therefore to the galaxies of the Local Group.

Despite the uncertain prospects, even the detection of a single supernova could yield very important scientific results. For instance there are good reasons to believe that the neutrino flash and the gravitational signal are emitted almost simultaneously, therefore any delay among the two signals received should be due to the propagation itself. Assuming that GW propagate at the speed of light, the delay could be due to the neutrino mass [25]:

$$\delta t_{prop} = 5\,\mathrm{ms} \frac{d}{10\,\mathrm{kpc}} \left(\frac{m_\nu}{1\,\mathrm{eV}} \right)^2 \left(\frac{10\,\mathrm{MeV}}{E_\nu} \right)^2 \qquad (2)$$

on which stringent limits could be placed.

The collapse of very large stars has been proposed as a mechanism to explain the class of long γ-ray bursts. Again signal models are quite uncertain; under optimistic assumptions the advanced instruments could detect transient GW in coincidence with long GRBs as far away as 300 Mpc, a distance at which such events are not infrequent (a few/year) [26,27].

[b] A double or triple coincidence will be probably needed in order to reject false alarms, which in absence of a signal model could be unacceptably frequent.

4 Periodic signals

The detection of continuous signals emitted by rotating NS has long been one of the main objectives of interferometric detectors, and the sensitivity improvement granted by advanced detectors will translate directly in improved upper limits on the signal amplitude, constraining the parameters of the emitter. The signal has the characteristic amplitude

$$h \simeq 3 \times 10^{-27} \left(\frac{10\,\mathrm{kpc}}{r}\right) \left(\frac{I}{10^{45}\mathrm{g\,cm}^2}\right) \left(\frac{f}{100\,\mathrm{Hz}}\right)^2 \left(\frac{\epsilon}{10^{-6}}\right) \tag{3}$$

which tells that the detection is necessarily limited to galactic NS. Nevertheless, even focusing just on the known pulsars, for several tens of objects it will be possible to place relevant upper limits on the amplitude [28], which will translate linearly into better limits on the oblateness parameter ϵ, thus providing information about the deformability of the star and its EOS.

5 Stochastic background

The first generation detectors have been able to place upper limits on the logarithmic energy spectrum in gravitational waves, defined as

$$\Omega(f) = \frac{f}{\rho_c}\frac{d\rho_{GW}(f)}{df} \; ; \tag{4}$$

for instance, assuming a flat spectrum $\Omega(f) = \Omega_0$, a limit $\Omega_0 < 6.9 \times 10^{-6}$ has been placed [29].

The advanced detectors will improve significantly over this limit, achieving $\Omega_0 < 10^{-9} - 10^{-10}$. This is at first sight not obvious, since as commonly stated the advanced detectors will achieve a tenfold improvement in *amplitude* sensitivity, hence a limit on *energy* should be "just" 100 times better. Actually, as shown in Fig. 1, the bandwidth is going to be significantly widened towards low frequencies, and this results in a further factor $10 - 100$ in sensitivity to Ω, depending on the configuration.

Will these sensitivities grant a significant breakthrough in the search for a cosmological stochastic background? Not for the cosmological background due (for instance) to slow-roll inflation, which is predicted [30] to scale as

$$\Omega(f) \sim 10^{-16} \left(\frac{\mathcal{V}}{10^{16}\,\mathrm{GeV}}\right)^2 \tag{5}$$

as a function of the unknown energy scale of inflation $\mathcal{V}$, and is expected to be several orders of magnitude weaker then the range accessible to advanced detectors.

But other sources of stochastic background will be constrained, for instance most of the parameter space for cosmic (super) string models will become accessible [31].

6 Conclusions

Advanced detectors are about to start their operation, and we have good reasons to expect that several sources will become accessible, thanks to the improved detectors' sensitivity.

Are we going to witness the birth of observational gravitational astronomy? Time will, soon, tell!

Acknowledgments

The authors gratefully acknowledge the support of the United States National Science Foundation (NSF) for the construction and operation of the LIGO Laboratory, the Science and Technology Facilities Council (STFC) of the United Kingdom, the Max-Planck-Society (MPS), and the State of Niedersachsen/Germany for support of the construction and operation of the GEO600 detector, the Italian Istituto Nazionale di Fisica Nucleare (INFN) and the French Centre National de la Recherche Scientifique (CNRS) for the construction and operation of the Virgo detector and the creation and support of the EGO consortium. The authors also gratefully acknowledge research support from these agencies as well as by the Australian Research Council, the International Science Linkages program of the Commonwealth of Australia, the Council of Scientific and Industrial Research of India, Department of Science and Technology, India, Science & Engineering Research Board (SERB), India, Ministry of Human Resource Development, India, the Spanish Ministerio de Economía y Competitividad, the Conselleria d'Economia i Competitivitat and Conselleria d'Educació, Cultura i Universitats of the Govern de les Illes Balears, the Foundation for Fundamental Research on Matter supported by the Netherlands Organisation for Scientific Research, the Polish Ministry of Science and Higher Education, the FOCUS Programme of Foundation for Polish Science, the European Union, the Royal Society, the Scottish Funding Council, the Scottish Universities Physics Alliance, the National Aeronautics and Space Administration, the Hungarian Scientific Research Fund (OTKA), the Lyon Institute of Origins (LIO), the National Research Foundation of Korea, Industry Canada and the Province of Ontario through the Ministry of Economic Development and Innovation, the National Science and Engineering Research Council Canada, the Brazilian Ministry of Science, Technology, and Innovation, the Carnegie Trust, the Leverhulme Trust, the David and Lucile Packard Foundation, the Research Corporation, and the Alfred P. Sloan Foundation. The authors gratefully acknowledge the support of the NSF, STFC, MPS, INFN, CNRS and the State of Niedersachsen/Germany for provision of computational resources.

This document has been assigned LIGO Laboratory document number LIGO-P1500092.

References

1. J. Abadie *et al.*, *Class. Quantum Grav.* **32**, 074001 (2015)
2. F. Acernese *et al.*, *Class. Quantum Grav.* **32**, 024001 (2015)
3. J. Aasi *et al.*, arXiv:1304.0670 [gr-qc]
4. L. Barsotti and P. Fritschel, *Early aLIGO Configurations: example scenarios toward design sensitivity*, LIGO-T1200307-v4, `https://dcc.ligo.org/LIGO-T1200307/public`
5. LSC and Virgo Collaborations, *Sensitivity Achieved by the LIGO and Virgo Gravitational Wave Detectors during LIGOs Sixth and Virgos Second and Third Science Runs*, LIGO-T1100338-v13, `https://dcc.ligo.org/LIGO-T1100338/public`
6. T. Akutsu (for the KAGRA collaboration), *J. Phys.: Conf. Ser.* **610**, 012016 (2015)
7. D. Lorimer, *Living Rev. Rel.* **11**, 8 (2008)
8. L. Blanchet, *Living Rev. Rel.* **17**, 2 (2014)
9. J Abadie *et al.*, *Class. Quantum Grav.* **27**, 173001 (2010)
10. K. Belczynski *et al.*, *ApJ* **789**, 2014 (120)
11. D. Gerosa *et al.*, *Phys. Rev.* D **89**, 2014 (124025)
12. B.F. Schutz, *Nature* **323**, 310 (1986)
13. W. Del Pozzo, *Phys. Rev.* D **86**, 043011 (2012)
14. B.D. Metzger *et al. ApJ* **764**, 2013 (149)
15. W. Del Pozzo *et al.*, *Phys. Rev. Lett.* **111**, 071101 (2013)
16. B.D. Lackey and L. Wade, *Phys. Rev.* D **91**, 043002 (2015)
17. M. Agathos *et al.*, arXiv:1503.05405 (Phys. Rev. D, to appear)
18. D. Eichler *et al.*, *Nature* **340**, 126 (1989)
19. J.Abadie *et al.*, *ApJ* **760**, 12 (2012)
20. T.G.F. Li *et al.*, *Phys. Rev.* D **85**, 082003 (2012)
21. M. Agathos *et al.*, *Phys. Rev.* D **89**, 082001 (2014)
22. R. Diehl *et al.* (INTEGRAL), *Nature* **439**, 45 (2006)

23. C. L. Fryer and K. C. B. New, *Living Rev. Rel.* **14**, 1 (2011)
24. J. Abadie *et al.*, *Phys. Rev.* D **85**, 122007 (2012)
25. N. Arnaud *et al.*, *Phys. Rev.* D **65**, 033010 (2002)
26. J. Aasi *et al. Phys. Rev.* D **88**, 122004 (2013)
27. J. Aasi *et al. Phys. Rev. Lett.* **113**, 011102 (2014)
28. J. Aasi *et al.*, *ApJ* **785**, 119 (2014)
29. J.Aasi *et al. Phys. Rev. Lett.* **113**, 231101 (2014)
30. A. Cooray, *Mod. Phys. Lett.* A **20**, 2005 (2503)
31. X. Siemens *et al.*, *Phys. Rev. Lett.* **98**, 111101 (2007)