Stochastic GW Backgrounds and Ground Based Detectors

Massimo Giovannini

Institute for Theoretical Physics, Lausanne University, CH-1015, Dorigny, Switzerland

Abstract. The interplay between different ground based detectors and stochastic backgrounds of relic GW is described. A simultaneous detection of GW in the kHz and in the MHz–GHz region can point towards a cosmological nature of the signal. The sensitivity of a pair of VIRGO detectors to string cosmological models is presented. The implications of microwave cavities for stochastic GW backgrounds are discussed.

MOTIVATIONS

The purpose of the present contribution is to summarise some general results whose implications can improve our understanding of cosmological models through the next decade. In this sense, the present session (devoted to GW) is complementary to the one on Cosmic Microwave Background (CMB) anisotropies. CMB experiments are the present of experimental cosmology, GW represent a foreseeable future.

Every departure of the background geometry from a radiation dominated evolution produces GW [1]. This simple fact can be easily understood because, during a radiation dominated phase, the evolution equation of the fields describing the two polarisation of a GW in a (spatially flat) Friedmann-Robertson-Walker (FRW) background are conformally invariant. The amplitude of the detectable signal depends not only upon the specific theoretical model but also upon the specific GW detector.

The GW spectrum ranges over thirty decades in frequency. GW with (present) frequencies around $f_0 \sim 10^{-18} \, h_0$ Hz correspond to a wave-length as large as the present Hubble radius [$h_0$ represents the indetermination of the (present) value of the Hubble parameter]. For these waves ideal detectors would be CMB experiments.

Frequencies of the order of $10^{-4}$ Hz correspond roughly to the operating region of the space-borne interferometer (LISA) which will be (hopefully) operating at some moment after 2017. Between few Hz and 10 kHz is located the operating window of ground based interferometers. The (narrow) band of resonant mass detectors is around the kHz. Finally between few MHz and few GHz microwave cavities can be used as GW detectors.

Between $10^{-18}$ Hz and 10 kHz there are, roughly, 22 decades in frequency. The very same frequency gap, if applied to the well known electromagnetic spectrum, would drive us from low-frequency radio waves up to x-rays or $\gamma$-rays. As the physics explored by radio waves is very different from the physics probed by $\gamma$ rays it can be argued that the informations carried by low and high frequency GW must derive from two different physical regimes of the theory.

In particular, low frequency GW are sensitive to the large scale features of the given cosmological model and of the underlying theory of gravity, whereas high frequency GW are sensitive to the small scale features of a given cosmological model and of the underlying theory of gravity. For instance string theory is expected to lead to a description of gravity which resembles very much Einstein-Hilbert gravity at large scales but which can deviate from Einstein-Hilbert gravity at smaller scales. That is only one of the many reasons why it is very important to have GW detectors operating over different frequency bands.

---

1) Contribution to CAPP-2000, Verbier (Switzerland) July 2000. To appear in the Proceedings (American Institute of Physics publication).
GROUND BASED GW DETECTORS

GW detectors can be divided in three broad classes: resonant mass detectors, interferometers and microwave cavities. There are five (cryogenic) resonant mass detectors which are now operating: NIOBE [2] (Perth, Australia), ALLEGRO [3] (Baton Rouge, Louisiana, USA), AURIGA [4] (Legnaro, Italy), EXPLORER [5] (Geneva, Switzerland) and NAUTILUS [6] (Frascati, Italy). They all have cylindrical shape (the are “bars”). They are all made in Aluminium (except NIOBE which is made of Niobium). Their approximate mass is of the order of 2200 kg (except NIOBE whose mass is of the order of 1500 kg). Their mode frequencies range from 694 Hz (in the case of NIOBE) to the 912 Hz of AURIGA. The shape of a resonant mass detector does not need to be cylindrical. In particular the nice idea of spherical GW detectors is being actively pursued [7,8].

There are, at the moment, four Michelson-Morley interferometers being built. They are GEO [10] (Hannover, Germany), TAMA [9] (Tokyo, Japan), VIRGO [11,12] (Cascina, Italy), and the two LIGO [13] (in Hanford [Washington], and Livingston [Louisiana], USA). The arms of the instruments range from the 400 m of TAMA up to the three km of VIRGO and to the 4 km of LIGO. The effective optical path of the photons in the interferometers is greatly enhanced by the use of Fabry-Pérot cavities. Microwave cavities have been originally proposed as GW detectors in the GHz–MHz region of the spectrum [14]. A first prototype has been built in MIT in 1978 showing that this idea could be actually implemented in order to detect small harmonic displacements [15]. It is not unreasonable to think that sensitive measurements could be performed in the near future. In particular improvements in the quality factors of the cavities (if compared with the prototypes of [14]) could be foreseen. Two experiments (in Italy [16] and in England [17]) are now trying to achieve this goal with slightly different technologies.

STOCHASTIC GW BACKGROUNDS

Define

\[ \Omega_{GW}(f, \eta_0) = \frac{1}{\rho_c} \frac{d\rho_{GW}}{d \ln f} \]  \hspace{1cm} (1)

as the fraction of critical energy density stored in relic GW at the present time. In ordinary inflationary models \( \Omega_{GW}(f) \) is minute. Consider an ordinary inflationary phase being replaced by a radiation dominated phase which evolves, in its turn, into a matter dominated epoch of expansion. Then, the GW spectrum has two branches: a soft branch (between \( 10^{-18} \) and \( 10^{-16} \) Hz) and a quasi-flat branch for \( f > 10^{-16} \). In the soft branch the logarithmic energy spectrum decreases as \( f^{-2} \). The gross features of inflationary models forbid \( h_0^2 \Omega_{GW} \) being larger that \( 10^{-15} \) in the flat branch of the spectrum. The reason is that at low frequencies (of the order of \( f_0 \)) the COBE bound imposes \( h_0^2 \Omega_{GW} < 7 \times 10^{-9} \). If we now assume (rather optimistically, indeed) that the inflationary GW spectrum is flat for \( f > 10^{-16} \) Hz we can compute quite easily the signal-to-noise ratio (SNR) for a pair, say, of correlated interferometers. Thus, even with a pair of advanced devices we can get (at most) down to \( \Omega_{GW}(0.1 \text{ kHz}) \sim 6.5 \times 10^{-11} \) [18–20]. Thus, ordinary inflationary models are invisible by ground based detectors.

In order to have a large detectable signal for frequencies larger than \( 10^{-16} \) Hz we have to invoke departures from scale invariance [21,22], i.e. scaling violation which can take place both in the case of quintessential inflationary models [23,24] and in the case of string cosmological models [25,26]. The scaling violations should go in the direction of logarithmic energy spectra which increase in frequency. Only in this case a large signal can be expected at high frequencies [27].

By recalling that interferometers will be operating between few Hz and 10 kHz and by recalling that microwave cavities will instead be operating for frequencies higher than the MHz we can envisage two different theoretical situations [19]. We can think of a model where the signal at the frequency of the interferometers is small. However, thanks to the frequency growth the same model could lead to a large signal at the frequency of the microwave cavities. We could also have the situation where the signal is large both at the interferometers scale and at the scale of the microwave cavities. The first case corresponds to quintessential inflationary models [22,24] the second case corresponds to string cosmological models [26,27].

In both cases a detection of a signal at the scale of the microwave cavities would be a probe of the cosmological nature of the process producing the GW background: no astrophysical sources are expected at such high frequencies. In both cases there are frequency regions where the signal exceeds (even by 8 decades in \( \Omega_{GW}(f) \)) the inflationary prediction. The idea of using electromagnetic detectors in order to probe stochastic GW backgrounds at high frequencies was also pointed out Grishchuk [28].
SENSITIVITY OF A VIRGO PAIR TO STRING COSMOLOGICAL GRAVITONS

Recently there have been concrete steps [29] towards the proposal of building in Europe an interferometer of dimensions comparable with VIRGO [11]. In view of this idea the sensitivity of the correlation between two VIRGO-like detectors to a generic stochastic GW background has been scrutinised in a number of papers [19,30].

Different locations for the site of the second detector have been examined in light of the possible stochastic sources. Given a theoretical model whose signal is, in principle, large enough to be detected by such a device there are two important aspects. In the first place, assuming a specific configuration of the VIRGO pair, we ought to know how the detectable signal changes by changing the parameters of the model. Secondly, we would like to know how much of the parameter space of the model can be probed assuming that the noises of the detectors are reduced by a given amount. These two questions have been discussed in [30]. In Fig. 1 the

![FIGURE 1. Under the assumption of selective thermal noise reduction we illustrate the behaviour of visibility region of the VIRGO pair in the case on growing logarithmic energy spectra of string cosmological type. At the left the overlap reduction is taken in the case where the two detectors are separated by 56 km. At the right the distance between the two sites is taken to be 958.2 km.](image)

visibility region of a VIRGO pair is illustrated in terms of the parameter space of string cosmological models. The shaded areas correspond to regions of the (two-dimensional) parameter space giving a signal-to-noise ratio larger than (or equal to) one. In both plots the normalisation the signal is compatible with all the physical bounds we can apply to stochastic GW backgrounds [24]. Fig. 1 refers to the case where the noises induced by the pendulum and by its internal modes are suppressed, respectively, by a factor of 10 and by a factor of 100 if compared with the initial VIRGO noise power spectrum. Different noise reductions give rise to different visibility regions. $\Omega$ is the minimal detectable $\Omega_{GW}(f)$ at a frequency of 0.1 kHz after one year of correlation of the two detectors. $\Omega^{th}$ is the theoretical normalisation of the spectrum. For all the points in the shaded regions $\Omega^{th}/\Omega > 1$.

CONCLUSIONS

It is very important to have detectors in different frequency regions. Interferometers and resonant mass detectors on one hand and microwave cavities on the other hand are complementary devices. Arrays of detectors
at intermediate and high frequencies (i.e. larger than the MHz) can provide informations on the spectrum. Large signals coming from string cosmology and quintessential inflation can be, in this context, inspiring for the experimental work.

REFERENCES

1. Grishchuk, L. P. Zh. Eksp. Teor. Fiz. 67, 825 (1974); Usp. Fiz. Nauk. 156, 297 (1988); Grishchuk, L. P. nad Solokhin, Phys. Rev. D 43, 2566 (1991).
2. Blair, D. G. et al., Phys. Rev. Lett. 74, 1908 (1995).
3. Manuceli, E. at al., Phys. Rev. D 54, 1264 (1996).
4. Cerdonio, M. et al., Class. Quantum Grav. 14, 1491 (1997).
5. Astone, P. et al., Phys. Rev. D 47, 362 (1993).
6. Astone, P. et al. Astroparticle Physics, 7, 231 (1997).
7. Lobo, J. A. Phys. Rev. D 52, 591; Coccia, E. et al., Phys. Rev. D 52, 3735 (1998); Coccia, E. et al. Phys. Rev. D 57, 2051 (1998).
8. Vitale, S., Cerdonio, M., Coccia, E., and Ortolan, A., Phys. Rev. D 55, 1741 (1997); Class. Quantum Grav. 14, 1487 (1997).
9. Tsubono, K. Gravitational Wave Experiments, Proceedings of the E. Amaldi Conference, edited by Coccia E., Pizzella G., and Ronga F., (World Scientific, Singapore, 1995), p. 112.
10. Danzmann, K. et al., Class. Quantum Grav. 14, 1471 (1997).
11. Caron, B. et al., Class. Quantum Grav. 14, 1461 (1997).
12. Vicere, A, these proceedings.
13. Abramovici, A. et al., Science 256, 325 (1992).
14. Pegoraro, F., Picasso, E., and Radicati, L. A. J. Phys. A 11, 1949 (1978); Pegoraro, F., Radicati, L. A. Bernard, Ph., and Picasso, E. Phys. Lett. A 68, 165 (1978); Iacopini, E., Picasso, E., Pegoraro, F., and Radicati, L. A., Phys. Lett. A 73, 140 (1979).
15. Caves, C.M., Phys. Lett. B 80, 323 (1979); Reece, C. E., Reiner, P. J., and Melissinos, A. C., Nucl. Inst. and Methods A 245, 299 (1986); Phys. Lett. A 104, 341 (1984).
16. Bernard, Ph., Gemme, G., Parodi, R., and Picasso, E. Coupled Microwave Cavities for the Detection of Small Harmonic Displacements, INFN/TC-98/17 (July 1998); The detection of GW by coupled Microwave Cavities: Theoretical Aspects, INFN/TC-99/21 (October 1999); The rf Control and Detection System for PACO (Parametric Converter detector), [physics/0004031].
17. Cruise, A. M. Class. Quantum Grav. 17, 2525 (2000); Mon. Not. R. Astron. Soc 204 485 (1983).
18. Allen, B., and Romano, J. D. Phys. Rev. D 59, 102001 (1999).
19. Babusci, D., and Giovannini, M., Phys. Rev. D 60, 083511 (1999).
20. Polarski, D., these proceedings.
21. Giovannini, M. plenary talk given at COSMO 99 (3rd International Conference on Particle Physics and the Early Universe, Trieste, Italy, 27 Sep - 3 Oct 1999), to appear in the proceedings, hep-ph/9912480.
22. Allen, B., and Romano, J. D. Phys. Rev. D 59, 083504 (1998).
23. Peebles, P. J. E., and Vilenkin, A., Phys. Rev. D 59, 063505 (1999).
24. Giovannini, M., Phys. Rev. D 58, 083504 (1998); Class. Quantum Grav. 16, 2905 (1999); Phys. Rev. D 60 123511 (1999).
25. Veneziano, G., Phys. Lett. B 265, 287 (1991).
26. Grishchuk, L. P., Pis'ma Zh. Eksp. Teor. Fiz. 23, 326 (1976).
27. Giazotto, A., Eur. Gravitational Wave Meeting (London, May 1999), private communication.
28. Babusci, D., and Giovannini, M., Class. Quantum Grav. 17, 2621 (2000); Updated VIRGO detector(s) and stochastic GW backgrounds, [gr-qc/9912035].