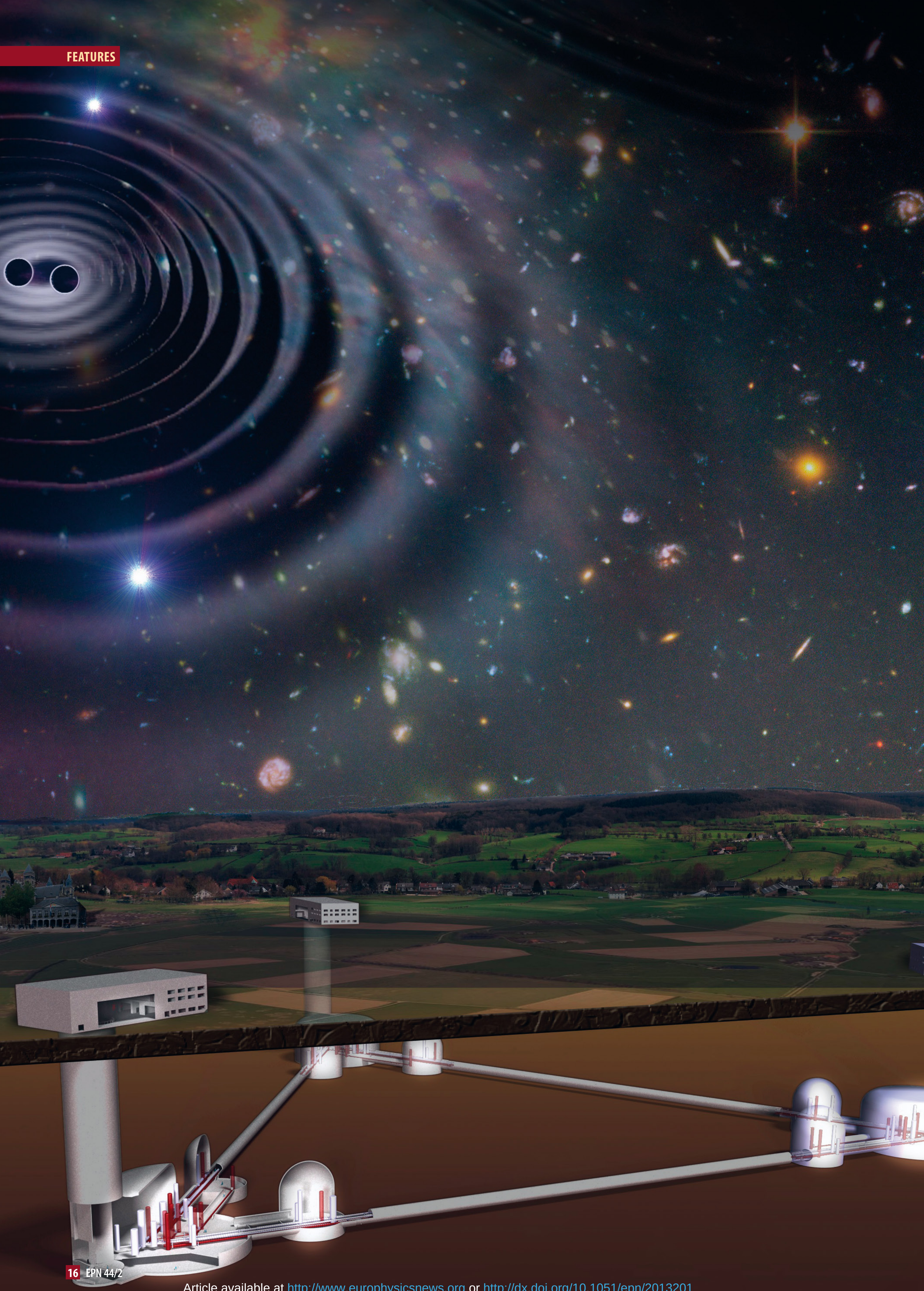
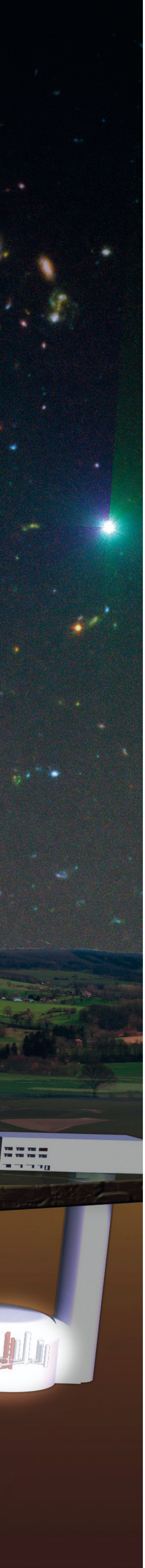


Article available at http://www.europhysicsnews.org or http://dx.doi.org/10.1051/epn/2013201



OPENING A NEW WINDOW ON THE UNIVERSE:

THE FUTURE GRAVITATIONAL WAVE DETECTORS

Michele Punturo – Istituto Nazionale di Fisica Nucleare – Sezione di Perugia (Italy) – DOI: 10.1051/epn/2013201

Thanks to a worldwide scientific and technical effort, the second generation of gravitational wave interferometers will be soon operative. These new detectors will open a new era for the observation of the Universe. Will the gravitational messenger unravel the enigmas still unsolved in astrophysics and cosmology?

The current model of the Universe is like a puzzle with many cards missing. Photons are the messengers that described almost all we know about the Universe. We are investigating the sky at all accessible wavelengths of the electromagnetic radiation, with the intrinsic contradiction that, as far we understand, only a small fraction of the Universe - less than 5% - can be defined composed by "ordinary" matter (see Figure 1). A relevant fraction (~30%) of the Universe should be composed of matter that is not emitting photons and the predominant part should be composed of invisible energy, affecting the expansion acceleration of the universe.

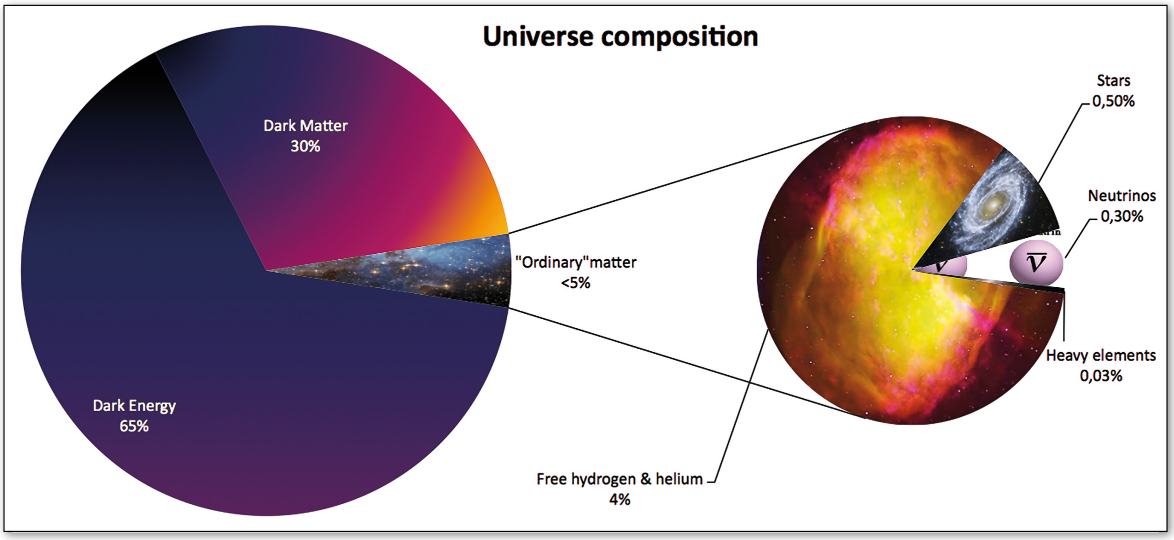
It is quite obvious that we need another investigation window of the Universe, a window not relying on electromagnetic emission. The dark matter hypothesis is mainly based on the observation of its gravitational effects and, hence, **the gravitational window seems to be the most promising discovery tool for future investigation of the Universe.**

The opening of the gravitational window for scrutinizing the Universe is promised by a new generation of instruments, currently under construction in many countries: the Advanced Gravitational Wave detectors.

Gravitational Waves

Already in 1916, Albert Einstein predicted the existence of Gravitational Waves (GWs) as a direct consequence of his theory of General Relativity. GWs are faint deformations of the space-time geometry, propagating at the speed of light and generated by catastrophic events in the Universe, in which strong gravitational fields and sudden acceleration of asymmetric distribution of large masses are involved. GWs have a quadrupolar nature and have two polarizations, h_+ and $h_\times$, where h is the so-called space-time strain $h=\delta L/L_0$, the relative dimensional

◂ An artistic view of the Einstein Telescope, a third generation gravitational wave observatory currently under design



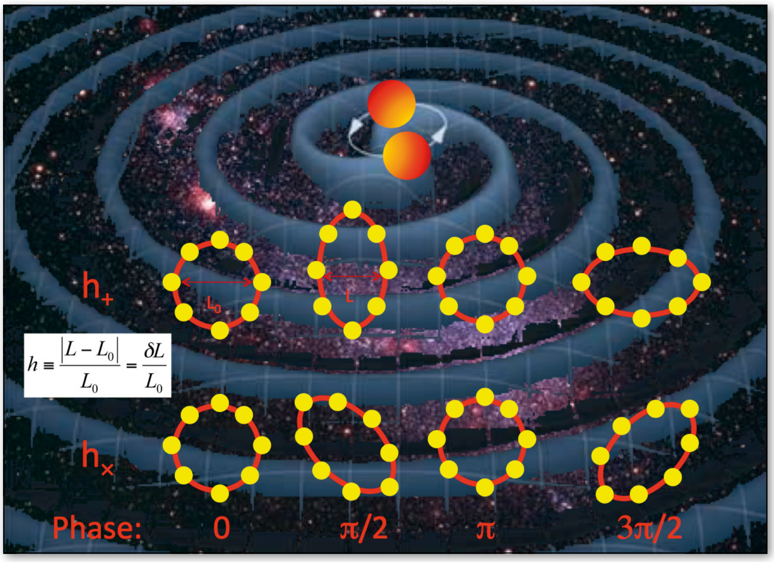
▾ **FIG. 1:** Composition of the Universe distortion of an extended mass distribution. The effect of these two polarizations on a circular mass distribution is shown in Figure 2.

Whereas electromagnetic waves are created by moving charges, GWs are created by accelerating masses. But because gravity is the weakest of the four fundamental forces, GWs are extremely small. For this reason, only extremely massive and compact objects having intense and asymmetric gravitational fields, like neutron star and black hole binary systems, are expected to be able to generate detectable GW emission.

“We need an investigation window of the Universe not relying on electromagnetic emission”

The first indirect confirmation of the existence of GWs has been reported. The discovery and precise timing measurements of the binary pulsar system PSR 1913+16 by Russell Hulse and Joseph Taylor [1] in 1975 showed that the decay of the orbit of this system over 10 years could be accurately accounted for (within 0.2% of error) by the emission of GWs [2], as predicted by Einstein's theory. A Nobel Prize was awarded in 1993 to Hulse and Taylor for the discovery of this binary system and for the long lasting stringent measurement they made.

But the direct detection of GWs is still missing and it is quite easy to understand why. For example, the expected amplitude on Earth of the GW emitted by a coalescing binary system of neutron star located in the Virgo cluster is of the order of $h \sim 10^{-22}$. This means that a detector having a dimension of a meter experiences an oscillating deformation of 10^{-22} m, an astonishingly small quantity.



▾ **FIG. 2:** The effect of the two polarizations of a GW, for example emitted by a coalescing binary system of neutron stars, on a circular mass distribution (red ring with yellow spots).

The gravitational wave detectors

Because of the faintness of the space-time deformation caused by a GW, even Albert Einstein believed it impossible to achieve its direct detection. But in the 1960s, a few pioneers started to realize the first GW detectors, based on a (multi)-ton resonant bar, that should resonate when excited by the passage of a GW. These detectors evolved, operating at cryogenic temperature to minimize the disturbance of the thermal Brownian vibration and being read by very low noise transducers. They reached their apotheosis in the 1990s thanks to the AURIGA [3], Explorer and Nautilus [4] cryogenic resonant bars, developed by INFN. These detectors reached a sensitivity of the order of a few $\times 10^{-21}$ around the main resonant mode frequency, which is of the order of one kHz. Although two of these detectors are still operating, it is worth stating that their era has ended due to the realization of a new kind of GW detector: giant interferometers, operating since the first years of the 2000 decade.

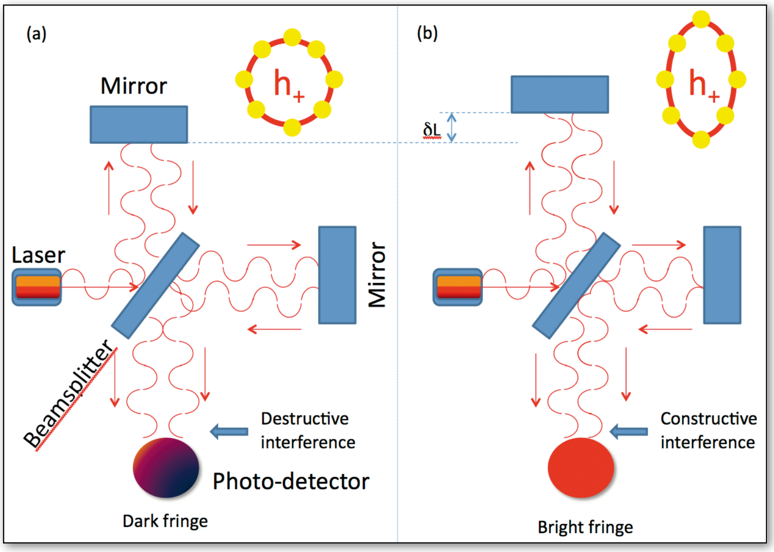
Why giant interferometers? These instruments profit from two key elements of the GW; (i) the tidal nature of a GW: the expected metric deformation δL of a body traversed by a GW is proportional to its size $\delta L \sim h \times L_0$. Hence, if the expected space-time deformation h is of the order of 10^{-22}, the effect on a multi-km detector will be a deformation $\delta L \sim 10^{-19}$-10^{-18} m. (ii) the quadrupolar nature of the GW. A Michelson interferometer is sensitive to the difference in optical path length between its two arms, as shown in Figure 3, and it can match the metric deformation imposed by the GW.

The first operative GW interferometric detector has been the Japanese TAMA, a 300m Michelson interferometer that opened the path to this new family of instruments, but had a sensitivity limited by its reduced length and by its location, in the center of Tokyo, affected by too high environmental disturbance. In Europe two interferometric GW detectors have been realized; GEO600, a 600 m Michelson interferometer, built close to Hannover by a British-German collaboration, and Virgo [5], a Michelson interferometer having Fabry-Perot resonating cavities inserted in the 3 km long arms, built close to Pisa (see Figure 4). The longest interferometric GW detectors in the World are the two 'Laser Interferometer Gravitational wave Observatory' (LIGO) detectors, having 4 km long arms, realized in Louisiana and Washington State (USA) with a topology similar to Virgo. The Virgo detector has been realized by a French (CNRS) – Italian (INFN) collaboration and now the Virgo collaboration includes also Dutch, Polish and Hungarian research teams. INFN and CNRS founded and are funding the European Gravitational Observatory (EGO), the consortium having the duty to manage the Virgo infrastructures and to promote the GW research in Europe. Thanks to the long Fabry-Perot cavities in the arms of the Virgo and LIGO detectors, the photons are forced to bounce back-and-forth between the suspended mirrors, thus squeezing a hundreds km long optical path in the few km long detector infrastructure, increasing the sensitivity to the space-time deformation. The length limitation, dictated by technical constrains and affecting the terrestrial GW detector infrastructures, will obviously disappear in the space-based observatories, like the eLISA/NGO detector [6]. This project of a multi-million km GW interferometer is to be launched at the end of the 2020 decade, in a heliocentric orbit, and is devoted to the observation of ultra-low-frequency sources (10^{-5}-10^{-3} Hz), like hyper-massive black holes.

Virgo, GEO600 and LIGO detectors operated in a network during the second half of the 2000 decade, 'listening' to the sky in the 10-10000 Hz frequency range. It is mandatory for this kind of research to operate the detectors in a distributed network of distant observatories that are simultaneously recording data. In fact, the localization of the GW source requires signals by at least three detectors, and the suppression of the false alarm rate benefits of any redundancy in the network. Because of the actual sensitivity of the GW initial detector network, the detection distance is limited to a few tens of Megaparsec (1 Mpc = 3.26×10^6 light-years). Taking into account the expected density of potential GW sources, the probability for a detection occurring in the few past years of observation was very low. In fact, no detection of GW signal has been obtained so far but, nevertheless, relevant scientific targets have been reached, putting constraints on potential GW emission by some astrophysical source. For example, thanks to the joint LIGO and Virgo data, an upper limit has been set to the possible GW emission of the Vela [7] and Crab [8] pulsars. These pulsars, remnants of supernovae explosions, are compact neutron stars rotating about 11 and 30 times per second, respectively, illuminating the Universe with their radio emission like a lighthouse in front of the ocean. The pulsars are expected to emit GWs at a frequency double their rotation rate, and at an amplitude depending on many (unknown) parameters characterizing these stars. Through the radio signal, it is well known that these pulsars are slowing down because of emission of energy, due to several possible mechanisms. LIGO and Virgo have been able to set an upper limit to the fraction of that energy emission due to GWs, stating that no more than few per cent of the energy loss can be due to GW radiation.

The future: Advanced detectors and 3rd generation observatories

The Virgo and LIGO detectors are currently offline, being upgraded toward the 2nd generation or "advanced" level [9]. In fact, in the period 2011-2015 several parts of the detectors will be replaced to improve the sensitivity by a factor of ten. New lasers with larger power, new mirrors (heavier, more reflective and with a lower level of imperfection), new optical and mechanical components will be installed to achieve this difficult target. An improvement by a factor of ten in sensitivity corresponds to an increase by a factor of a thousand in detection rate: in one year of operation of the advanced detectors at the nominal sensitivity, about 40 coalescences of neutron star binary systems are expected to be detected. The advanced detectors' capability to detect a coalescence of a binary neutron star system at a distance of about 140 Mpc, and a coalescence of a binary systems of black holes at a distance of about 1 Gpc, will open up a **gravitational-wave astrophysics era.** It will be possible, for example, to compare the signal detected from the coalescence of a binary system of neutron stars with the general relativity prediction. Or it will be possible to investigate the nature of an isolated neutron star by looking at its GW emission. Few years later the completion of the Advanced Virgo detector in Europe and of the Advanced LIGO detectors in USA, new nodes will enter the network of GW observatories: a very innovative 3km interferometer (KAGRA), underground and cryogenic, is under construction in Japan. Furthermore, a 3rd Advanced LIGO site is under evaluation in India. Obviously, the first detection of a GW signal will give an exceptional additional boost to the research in this field. A large community of European



▲ FIG. 3: Principle of a Michelson interferometer as GW detector. The operative point of the detector is close to the dark fringe pattern (panel (a)); the passage of a GW causes a tiny displacement from the dark fringe, raising the intensity on the detector. This effect is heavily exaggerated in panel (b).

▼ FIG. 4: Aerial view of the Virgo detector, Cascina (Pisa). The 3km long arms are well visible.

scientists is attempting to anticipate and to drive the evolution of this research field. Thanks to the support of the European Commission, through the design study tool in the Seventh Framework Programme (FP7), the conceptual design of a 3rd generation GW observatory has been realized, able to compete and collaborate with the most sensitive optical telescopes: the Einstein GW Telescope (ET) [10][11]. This new infrastructure (see Figure 5), aimed to be operative in the 2020 decade, will test the cosmological model of the universe using GW signals, thanks to its capability to see many sources at large red-shift [12]; **ET will be a wonderful proofing tool of the general relativity predictions in all radiative processes involving intense gravitational fields,** like in the presence of intermediate-mass black holes ($M \sim 10\text{-}1000\ M_{sun}$). It will allow detailed investigations of the nature of isolated neutron stars looking both to the continuous emission of the pulsars and to the explosion of supernovae. ■

About the Author

Michele Punturo is senior researcher at the Italian Institute for Nuclear Physics (INFN-Perugia). He started his career in high energy particle physics, at CERN. He is working in the Virgo experiment, having served as detector coordinator from 2004 to 2008. PI of an ESF exploratory workshop (2005) on 3rd generation GW detectors and scientific coordinator of the ET FP7 design study (2008-2011). He is now the coordinator of the FP7 project ELiTES, an exchange programme between Japan and Europe focused on GW detectors technologies.

References

[1] R.A. Hulse et J.H. Taylor, *Astrophysical Journal* **195**, L51 (1975).

[2] J.M. Weisberg, D.J. Nice and J.H. Taylor, *Astrophysical Journal* **722**, 1030 (2010). arXiv:1011.0718v1

[3] A. Vinante (The AURIGA coll.), *Classical and Quantum Gravity* **23**, S103 (2006).

[4] P. Astone (The ROG coll.), *Classical and Quantum Gravity* **21**, S1585 (2004).

[5] T. Accadia *et al.* (Virgo Coll.), *Journal of Instrumentation* **7**, 103 (2012).

[6] « *LISA: Laser Interferometer Space Antenna* » [online]. Available: www.elisa-ngo.org.

[7] J. Abadie *et al.*, *Astrophysical Journal* **737**, 93 (2011).

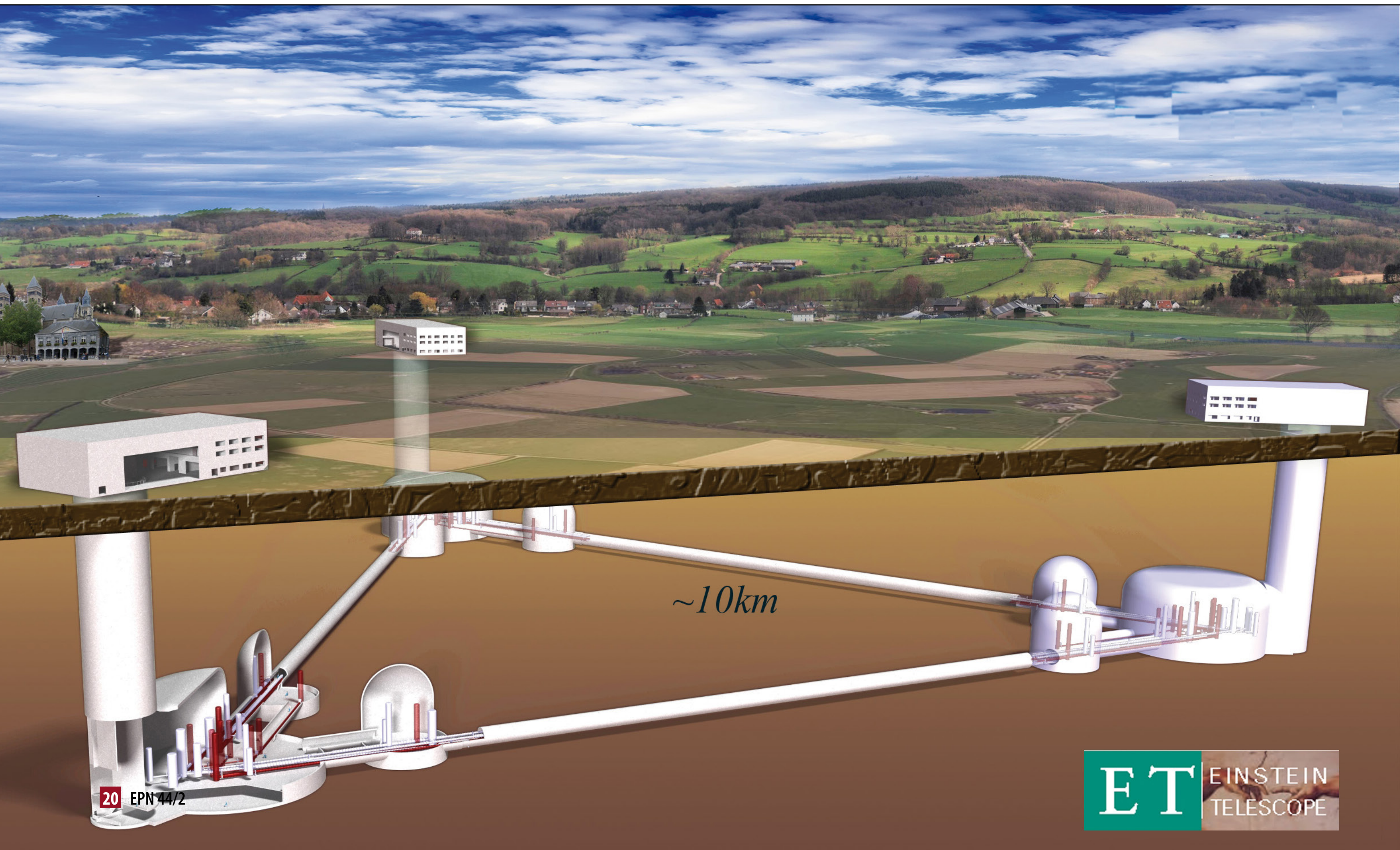
[8] B.P. Abbott *et al.*, *The Astrophysical Journal* **713**, 671 (2010).

[9] D.G. Blair, *Advanced gravitational wave detectors*, Cambridge: Cambridge University Press (2012).

[10] The ET science Team, « *The Einstein Telescope Design Study Document* » 2011. [online]. Available: https://tds.ego-gw.it/ql/?c=7954.

[11] M. Punturo *et al.*, *Classical and Quantum Gravity* **27**, 194002 (2010).

[12] B. Sathyaprakash *et al.*, *Classical and Quantum Gravity* **29**, 124013 (2012).



▼ **FIG. 5:** Artist's view of the Einstein Telescope infrastructure (courtesy of the ET-Nikhef group). It will be realized underground to minimize the environmental and seismic disturbance. The arms of the interferometers are expected to be about 10km long.