1) The discovery
Taylor and Hulse's discovery of Gravitational Wave (GW) emission by the compact binary system composed by two Neutron Stars PSR1913+16 has been, for the experimental physicists working in this field, the definitive thrust allowing to reach the extremely sophisticated technology needed for investigating in this field of research.

In Fig.1.1 the famous histogram showing the decreasing of periaster passage time produced by the associated emission of GW together with the prediction evaluated through General Relativity (GR), is shown. Today at least other 6 similar systems are investigated and energy loss remarkably agrees with the prediction of GR.

2) The generation and detection of gravitational waves
Gravitational Waves are a consequence of Einstein’s GR; they are shown to be ripples in the space-time curvature traveling at light speed. It is easy to show that GW amplitude has two polarizations $h^+$ and $h^x$:

$$h^{TT}_{\mu\nu} = h^{TT}_{11} \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} + h^{TT}_{12} \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \end{pmatrix} = h^{+}_{ik} + h^{x}_{ik}$$  \text{Eq. 1}

The wave amplitude in the Transverse Traceless (TT) system satisfy the following equation:

$$\ddot{h}^{TT}_{\alpha\beta} = -\frac{2G}{c^4R_0} \frac{d^2}{dt^2} \int \rho(x_\alpha x_\beta)^{TT} dV$$  \text{Eq. 2}

Where $R_0$ is the source distance, $G$ is Newton constant, and the integral is extended to source volume. Eq. 2 shows that only asymmetric sources can emit GW; most efficient are coalescing.
binaries sources, while pulsar can rely only on ellipticities, usually very small. Supernovae could have relevant asymmetries but this is very unlikely.

In his fundamental papers on Gravitational Waves, A.Einstein shows how a mechanical system is creating GW. For the detection of GW he shows that GW couple to matter and increase the energy of a suited mechanical system but it was F.A.E.Pirani \(^4\) in 1956 who proposed the geodesic deviation equation as a tool for designing a practical GW receiver. The result is that the relative acceleration of two freely falling bodies, due to GW action is:

\[
\frac{d^2 \xi_\alpha}{d\tau^2} = \frac{1}{2} h^{\gamma\tau}_{\alpha\beta} \xi_\beta
\]

3) Early detectors

It is relevant to start this paragraph by quoting very briefly some highlights of Weber life, the part more connected with GW detection, because I believe that not enough appreciation from the scientific community has been given to this great scientist. As it can be read he was also dealing with interferometric detectors too.

Joseph Weber
-Born on 17 May 1919 in Paterson, New Jersey,
- In the early 1960s, J.Weber \(^5\) turned his attention to testing the general relativistic prediction of gravitational waves from strong gravity collisions.
- Then, in 1959, he studied a detector that might be able to measure displacements smaller than the size of the nucleus.
- He was alone in charting these unknown waters: His first paper on how to build a gravity wave detector was published in 1959.
- Weber developed an experiment using a large suspended bar of aluminum, with a high resonant \(Q\) at a frequency of about 1 kHz.
- In 1969 he was claiming evidence for observation of gravitational waves (Physical Review Letters (1969)) based on coincident signals from two bars separated by 1000 km. Those events, later, have been demonstrated to be consistent with cosmic rays.
- Weber also proposed the idea of doing an experiment to detect gravitational waves using laser interferometric techniques.
- Robert Forward, Weber's student and postdoctoral associate, started in 1970 the first laser interferometric gravitational wave experiments at Hughes Research Labs.
- Joseph Weber, professor emeritus of physics at the University of Maryland, College Park, died on 30 September 2000 in Pittsburgh, Pennsylvania.

Fig.3.1- A schematic diagram showing a bar detector with the transducer. The GW Riemann forces excite longitudinal modes of the Bar. Bar elongation is detected by the transducer and transformed to an electrical signal. The length L is typically 2-3 m.

Picture courtesy M. Cerdonio
4) Modern Bar Detectors: Cryogenic Bars.

All these modern detectors were originate from early Weber’s detectors. In the world 5 cryogenic bar detectors have been built for working at temperatures <4K: Explorer at CERN (see Fig. 4.1), Nautilus at Frascati INFN National Laboratory (see Fig. 4.2), Auriga at Legnaro INFN National Laboratory (see Fig. 4.3), Allegro at Louisiana State University (see Fig. 4.4) and Niobe in Perth. Instrumental details can be found in an extensive literature. I report the sensitivity and stability of performances of only four of them since Niobe stopped operation in 1997.

IGEC (Resonant Bar Detectors International Gravitational Event Collaboration) was established in 1997 in Perth. IGEC has been the first GW Detector network. During IGEC-1 (1997-2000) the following coincidences where registered:
29 days of four-fold coinc.
178 days of three-fold coinc.
713 days of two-fold coinc.
Sensitivity and bandwidth are shown in Fig. 4.5.
Followed by a series of upgrades, resumed operations EXPLORER in 2000, AURIGA and NAUTILUS in 2003, ALLEGRO in 2004 the Collaboration started to take data. With IGEC-2 (2005--) first data analyzed covered May-November 2005 when no other observatory was operating. Sensitivity and operation stability are shown in Fig. 4.6 and 4.7 respectively Bar Detectors situation at present (oct. 2007) is the following: NIOBE (Perth) stopped operation and did not join IGEC-2, ALLEGRO (LSU) stopped operation in 2007. In 2006 INFN acted as follows: a) stopped R&D on Spherical Detectors b) left on the R&D on DUAL. c) left Auring, Nautilus and Explorer running on an annual evaluation. These three detectors are currently running with very good sensitivity and duty cycle. Their role is particularly relevant when Virgo and LIGO will be shut down for upgradings to Virgo Plus and Henanced LIGO; their running is aimed to a coincidence with GEO 600 and Tama 300 interferometers for a kind of observation which has been named “Astro watch”.

5) Spherical detectors
A spherical antenna will be able to determine the wave polarization and localize its astrophysical source on the sky. Another very important advantage of this kind of detector comes exactly from the fact that it has many transducers monitoring many quadrupolar modes. Mario Schenberg: this detector (see Fig.5.1) is built in San Paolo (Brazil) and has a 65cm-diameter CuAl6% sphere weighing about 1.15 ton; sensitivity is shown in Fig. 5.2. In this detector each one of the five quadrupole modes of the sphere has an effective mass for oscillation of 287 kg.
The MiniGRAIL detector is a cryogenic 68 cm diameter spherical gravitational wave antenna (see Fig.5.3) built at Kamerlingh Onnes Laboratory of Leiden University, made of CuAl(6%) alloy with a mass of 1400 Kg, a resonance frequency of 2.9 kHz and a bandwidth around 230 Hz, possibly higher. The quantum-limited strain sensitivity dL/L would be \(\sim 4 \times 10^{-21}\) (see Fig. 5.4). The antenna will operate at a temperature of 20 mK.

6) Interferometric detectors

In this case free falling masses are interferometer mirrors which can be separated km far apart (3km for Virgo, 4km for LIGO), consequently GW Riemann force can be several order of magnitude larger than in bar detectors. Accompanying large sensitivity is the very large Bandwidth (10-10000 Hz) due to the fact that mirrors are suspended to pendula having resonance in the Hz region; above resonance frequency mirrors are freely falling masses in the horizontal plane.

Fig.6.1-GW deform a test masses circular ring (red) in an elliptical one (green) and the red masses displace in the blue position. If two mirrors are attached to the test masses the arm unbalance \(\Delta L = L_A - L_B\) can be measured interferometrically. Interferometer’s displacement sensitivity can reach \(\sim 10^{-19}-10^{-20}\) m, then, for measuring \(h=\Delta L/L_{\sim 10^{-22}}\) \(L_A\) and \(L_B\) should be km long.
Due to quadrupolar nature of GW a circle of test masses, in red in Fig. 6.1, is deformed in the green ellipse. Always with reference to Fig. 6.1, by connecting mirrors to the freely falling test masses, we can interferometrically measure GW intensity by the relative unbalance $\Delta(L_A-L_B)/L$ of the two ellipse radii; this relative length unbalance is equal to GW amplitude $h$.

Interferometer’s displacement sensitivity can reach $\sim 10^{-19}-10^{-20}$ m, then, for measuring $h=\Delta(L_A-L_B)/L \sim 10^{-22}$, $L_A$ and $L_B$ should be km long.

With reference to Fig. 6.3 the two polarizations $h_x$ and $h_+$ gives contribution to total mirror displacement according to Eq. 3.

$$\frac{\Delta L_1 + \Delta L_2}{L} = \frac{1 + (n,\zeta)^2}{2} \frac{(n,\xi)^2 - (n,\eta)^2}{1 - (n,\zeta)^2} h + 2 \frac{(n,\xi)(n,\eta)(n,\zeta)}{1 - (n,\zeta)^2} h$$

Eq. 3

In Fig. 6.2 the Coordinate system having $\xi$ and $\eta$ axis coinciding with interferometer arms is shown; $n$ is GW versor and $\theta$ and $\varphi$ are his polar and azimuthal angles. From Eq. 3 it is easy to evaluate the sensitivity pattern summed on GW polarizations for an interferometer having arms at $90^0$; the antenna pattern is shown in Fig. 6.3. The effect of the two GW polarizations on a circular ring (red) of masses for a wave travelling normally to the circle plane, is shown in Fig. 6.4.

7) Interferometer noises

It is easy to imagine that a plethora of noises is affecting interferometers for GW detection; infact this kind of interferometers has mirrors supended and free to move in the horizontal plane. We should imagine how small is the displacement to be measured by these machines i.e. $<10^{19}$ m/sqrt(Hz) in the frequency band 4-10000 Hz. Just for making a mere list we have (see Fig. 7.1, 7.2):

**Optical Noises**: Shot Noise, Laser frequency fluctuations, Laser power fluctuations, Diffused and Scattered light hitting vacuum vessels, where collects vibrations, and partially reflected back in the main optical path. Acoustic noise……

**Force Noises**: Radiation pressure fluctuations, Thermal noise in the mirrors and in the mirror suspensions, Electromagnetic noises producing forces on the mirrors…..

A pictorial view of noises affecting a suspended mirror interferometer is shown in Fig.7.1. In Fig. 7.2 the accent is given on two kinds of fundamental noises: Thermal noise and Optical Noises i.e. Shot noise, Radiation pressure fluctuation noise and Standard Quantum Limit. Optical noises can be reduced by Quantum Non-Demolition (QND) techniques Thermal noise is likely to be reduced by keeping the Interferometer mirrors close to 4 K.
If we define $W$ the laser power, $F$ and $L$ the cavity finesse and length respectively, $v_0$ the laser frequency, $\Omega$ the observation frequency and $M$ the mirror mass, the optical noises will give the following limit to $h$: In Eq. 4 the first term on the right hand side is due to to radiation pressure fluctuation while the second is due to shot noise. By minimizing $\bar{h}$ with respect $WF^2$ we obtain the Standard Quantum Limit (SQL) Eq. 5. Today ways¹ exist, by using squeezed light techniques, able to cancel Radiation pressure fluctuations in interferometers and then overcoming SQL.

\[ h^2 > \left( \frac{2}{LM\Omega c} \right)^2 h v_0 WF^2 + \left( \frac{\hbar}{4\pi} \right)^2 \frac{h v_0}{WF^2} \left( \frac{\Omega FL}{c} \right)^2 + \frac{1}{L\Omega} \sqrt{\frac{h v_0}{M}} \]

8) The Network of interferometric GW detectors

Some relevant reasons for starting network coherent analysis are:
- Sensitivity increase.
- Source direction determination from time of flight differences.
- Sources polarizations measurement.
- Test of GW Theory and GW physical properties.

Some relevant astrophysical targets are:
- Far Universe expansion rate measurement.
- GW energy density in the Universe.
- Knowledge of Universe at times close to Planck’s time.
In Fig 8.1 the optical diagram of Virgo, a typical large base GW detector, is shown. With reference to Fig. 11.1, the laser beam is prestabilized up to 2 Hz, at a frequency stability $\Delta \nu = 10^{-4} \text{Hz}^{1/2}$ by means of a Ultra Low Expansion cavity and then, by using the 3+3 km cavities operated in common mode, for frequencies in the range 2-10000 Hz, to a frequency stability level of $\Delta \nu = 10^{-6} \text{Hz}^{1/2}$. The power recycling mirror PR allows to increase by a factor 20 the power on the beam splitter mirror BS; the two 3 km Fabry-Perot cavities have a Finesse of 30 and, in Virgo, cavities mirrors are aligned by using Anderson’s technique.

In the following a brief description of GW interferometers performances is presented.

LIGO
LIGO project, run by Caltech and MIT, is the largest existing GW detector, composed by 3 interferometers: a 4 km+ 2 km interferometers inside the same vacuum pipe in Hanford (Washington state) (see Fig 8.2) and a 4 km detector in Livingston (Louisiana state) (see Fig. 8.3).

The distance between Hanford and Livingston is about 3000 km.

The sensitivity of Hanford machine, really outstanding, is shown in Fig. 8.4; the graph shows only the sensitivity of Hanford machine, but a graph showing sensitivities of all three LIGO machines will be shown later; the sensitivity progress of Hanford machine is shown in Fig.8.5 while operation stability is shown in Fig.8.6. The science run time progression is shown in Fig.8.7. Fig. 8.6 shows LIGO operation stability; in the ordinate axis of this plot is the distance in Mpc at which a 1.4-1.4 Mo NS-NS coalescing binary system, averaged on orbital plane directions, is detectable. Sensitivity uniformity and operation stability are remarkable.
Virgo\textsuperscript{11} is a collaboration, initially between INFN (Italy), CNRS (France) at which later added NIKHEF (Holland), has built a 3 km interferometer (see Fig. 11.8) located in Cascina, about 20 km from Pisa.

\[ 4K \text{ strain noise at 150 Hz} \]

**Fig. 8.8** - The Virgo 3 km interferometer.
Virgo has a very sophisticated antiseismic system whose basic elements are called Superattenuators (SA) (see Fig. 8.9). These devices, thoroughly described elsewhere, are capable of attenuating seismic noise below expected thermal noise down to 4 Hz. In Fig. 8.10 the measured SA attenuation transfer function, measured stage by stage, while the upper limit point at 4 Hz has been obtained by shaking the SA suspension point.

Fig. 8.10 - The seismic noise remnant amplitude having assumed a seismic spectral displacement $10^{-7}/s^{2}$ m/sqrt(Hz). The Superattenuator transfer function measured stage by stage (red curve) and directly by shaking the SA suspension point (black point).
GEO600, a collaboration between Great Britain and Germany, is a 600 m long arms signal and power recycled interferometer located near Hannover (see Fig. 8.14).

In Fig. 8.11 Virgo sensitivity progress is shown; it is noticeable the impressive low frequency sensitivity improvements spanning about 8 orders of magnitude. At high frequency design sensitivity has not yet been reached since Virgo is running at low power due to mirror lensing effects. Lensing corrective devices are being tested.

Virgo operation stability over 8 hours of running is shown in Fig. 8.12; in the ordinate axis of this plot is the distance in Mpc at which a 1.4–1.4 M_0 NS-NS coalescing binary system, averaged on orbital plane directions, is detectable. In Fig. 8.13 Virgo operation duty cycle over 1 month of running is shown.

GEO600\textsuperscript{13} GEO600, a collaboration between Great Britain and Germany, is a 600 m long arms signal and power recycled interferometer located near Hannover (see Fig. 8.14).
The optical diagram is shown in Fig. 8.15; the interferometer has two single pass arms and is equipped with both signal and power recycling mirrors. Mirrors are suspended by means of Silica fibers for reducing thermal noise.

Signal recycling is an important addition since may create radiation pressure fluctuation noise reduction in some frequency range. In Fig. 8.16 sensitivity progression is shown, while in Fig. 8.17 the effect of quadrature rotation, produced by signal recycling mirror is shown.

TAMA 300

TAMA 300 m interferometer (see Fig. 8.18), located at National Astronomical Observatory of Japan (Tokyo) has been the first interferometric detector reaching sensitivity good enough for starting a realistic gravitational event search. TAMA construction started in 1995, and, even if the project was run by a relatively small number of scientists, it was immediately supplying the world best performances; during the period 2000-2002 attained the world best sensitivity.
In Table 1 TAMA milestone progress is presented:

With DT1 In 1999 TAMA started to make observations, in DT4 attained the world best sensitivity, in DT6 performed 1000 hours of data taking and with DT7 started operating with power recycling. Joint observation with LIGO was performed during DT7 to DT9. In Fig. 8.19 the sensitivity progress is presented; best strain sensitivity attained was $1.7 \times 10^{-21} \text{Hz}^{-1/2}$ with a recycling factor of 4.5

| Run | Term | Year | Live Time (Hour) |
|-----|------|------|------------------|
| DT1 | 6-Aug → 7-Aug | 1999 | 7 |
| DT2 | 17-Sept → 20-Sept | 1999 | 31 |
| DT3 | 20-Apr → 23-Apr | 2000 | 13 |
| DT4 | 21-Aug → 4-Sept | 2000 | 161 |
| DT5 | 2-Mar → 8-Mar | 2001 | 111 |
| DT6 | 15-Aug → 20-Sept | 2001 | 1038 |
| DT7 | 31-Aug → 2-Sept | 2002 | 25 |
| DT8 | 14-Feb → 14-Apr | 2003 | 1158 |
| DT9 | 28-Nov → 10-Jan | 2004 | 558 |

Table 1 - TAMA data taking runs progress and running times. Courtesy Kazuaki Kuroda for the TAMA/CLIO/LCGT Collaboration

In Fig. 8.20 sensitivities of all kinds of operating GW detectors are displayed; original sensitivity graphs for bar detectors can be seen in Fig. 4.6 and for TAMA in Fig. 8.19.

GW Network Detector Sensitivities
9) Resumé of status of GW detection.

IGEC: Bar Detector Network (Auriga, Explorer, Nautilus, Allegro) started 1997 for detecting impulsive GW\textsuperscript{15}.

**No evidence of any significant signal**

---

**Periodic\textsuperscript{16} Sources:**
LIGO-GEO600: OG da Pulsar (28 known):
$\varepsilon < 10^{-5} - 10^{-6}$
(no mountains > 10 cm)-
Upper Limits h :
$2.10^{-24}@200Hz$,
$5.10^{-24}@400Hz$,
$10^{-23}@1KHz$. See Fig. 9.1 and 9.2.

Fig. 9.1-Periodic sources upper limits: this is the all sky upper limit for periodic sources strain (95% confidence level), obtained for the Hanford observatory. The plot compares several search method, documented in the S4 paper LIGO-P060010-05-Z.

Fig. 9.2-Periodic sources upper limits: the same of the previous figure, for the Livingston observatory.

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**Coalescence\textsuperscript{17}**
LIGO-GEO600,TAMA (see LIGO paper arXiv:0704.3368) upper limits (see Fig.9.3, 9.4, 9.5): - Fig.9.3-Upper limits on the binary inspiral coalescence rate per year and per L10 as a function of total mass of the binary, for Primordial Black Hole binaries. The darker area shows the excluded region after accounting for marginalization over estimated systematic errors. The lighter area shows the additional excluded region if systematic errors are ignored.
Coalescence\textsuperscript{17} cont.:

Fig. 9.4-Upper limits inspirals: Same as the previous figure for Binary Black Holes.
Fig. 9.5-Upper limits inspirals: Same as the previous figure for Binary Neutron Stars
Upp. Lim. Coalescing
NS-NS <1 event/(galaxy.year) \(2 < M_0 < 6\),
Coalescing BH-BH <1 event/(galaxy.year) \(10 < M_0 < 80\)

Impulsive\textsuperscript{18}:
LIGO and LIGO-Tama upper limits for S1, S2, S4 scientific runs are shown in Fig. 9.6 and 9.7.
Figure 9.6 and 9.7. Exclusion diagrams (rate limit at 90% confidence level, as a function of signal amplitude) for (a) sine-Gaussian and (b) Gaussian simulated waveforms for this S4 analysis compared to the S1 and S2 analyses (the S3 analysis did not state a rate limit). These curves incorporate conservative systematic uncertainties from the fits to the efficiency curves and from the interferometer response calibration. The 849 Hz curve labeled “LIGO-TAMA” is from the joint burst search using LIGO S2 with TAMA DT8 data [18], which included data subsets with different combinations of operating detectors with a total observation time of 19.7 days and thereby achieved a lower rate limit. The hrss sensitivity of the LIGO-TAMA search was nearly constant for sine-Gaussians over the frequency range 700–1600 Hz.
Upper bounds on Stochastic Background\(^{19}\): 90% Upper Limit on GW spectrum at 100 Hz (see the model on the right) as a function of \(\alpha\) for S3 H1L1 and S4 H1L1+H2L1 combined, and expected final sensitivities of LIGO H1L1 and H1H2 pairs, assuming LIGO design sensitivity and one year of exposure, are shown in Fig. 9.8.

Virgo, LIGO, GEO 600 on May 18, 2007 started common and coherent data taking analysis; main target impulsive events.

10) The Future

In Table 2 the totality of future GW experiments is presented, grouped by status of approval level with a brief explanation of forecast upgradings.

Table 2: The Future

| year | 06 | 07 | 08 | 09 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 |
|------|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|
| TAMA300 | Running | | | | | | | | | | | | | | | |
| GEO600 | In Approval | | | | | | | | | | | | | | | |
| Virgo | | | | | | | | | | | | | | | | |
| LIGO Hanford | | | | | | | | | | | | | | | | |
| LIGO Livingston | | | | | | | | | | | | | | | | |
| LCGT ? | | | | | | | | | | | | | | | | |
| AIKO ? | | | | | | | | | | | | | | | | |
| LISA ?? | | | | | | | | | | | | | | | | |
| Einstein ?? Telescope | | | | | | | | | | | | | | | | |

Fig. 9.8

\[ \Omega_{GW}(f) = \int \frac{d\Omega_{GW}}{f} = \Omega_{\alpha}(f) = \Omega_{\left(\frac{f}{100Hz}\right)^{\alpha}} \]
Running Interferometers

**TAMA** intend to operate with new Superattenuators mounted for better control and seismic isolation; timing is outlined in Table 2.

**GEO600** intend to push high frequency sensitivity (new name GEO HF) to much higher level as shown in Fig. 10.1. Fig. 13.2-GEO HF high frequency sensitivity is strongly improved by increasing Intra Cavity Power and by optimizing squeezing. Purpose of GEO HF is also the study of advanced techniques to be applied in future large interferometers with particular reference to signal recycling and squeezing. Timing is outlined in Table 2.

**Virgo**

The expected sensitivity of the upgrading to Virgo Plus is presented in Fig. 10.2; the main items are the power increase to 50 w, implementation of fused silica suspensions (very much depending on how Virgo removes low frequency noise) and increase of Fabry-Perot cavities finesse to about 150 in such a way to produce firm sensitivity increase in the 100-400 Hz region.

The sensitivity increase in this frequency interval will improve a lot coalescing binary system detection sensitivity range up to 28 Mpc. Expected to start running in june 2009.
**Virgo Advanced:**

Optical configuration will be changed in such a way to have the optical waist displaced to 1500m, in this way thermal noise of the cavity entrance mirrors will be reduced. Advanced Virgo expected sensitivity is shown in Fig. 10.3.

A further reduction of thermal noise will, hopefully, come from coatings losses reduction by using other less lossy metals than Titanium in the coating recepies. Laser power will also be increased and optical read out changed from heterodyne to DC.

Virgo Advanced will also be equipped with signal recycling mirror for implementing radiation pressure fluctuations noise reduction.

**LIGO^{21} Henanced.**

The first set of improvements will be set in the LIGO Henanced configuration for starting scientific runs together with Virgo Plus in june 2009. They are Higher laser power, DC readout and insertion of an Output modecleaner; LIGO H will also serv as test bench of Advanced LIGO hardware and techniques. Target is a factor of 2 improvement in sensitivity (factor of 8 in event rate).

**LIGO Advanced:**

will implement active anti-seismic system operating to lower frequencies, lower thermal noise suspensions and optics, higher laser power and more sensitive and more flexible optical configuration; expected sensitivity is shown in Fig. 10.4. In table 3 main technical improvements with respect to initial LIGO, are presented.
Interferometers in approval phase

LCGT
Large-scale Cryogenic Gravitational wave Telescope (LCGT)\textsuperscript{22} This detector has a very relevant impact in the technology of next generation interferometers for GW detection, infact it is the first one to be designed with Fabry Perot cavity mirrors brought to 20 K. Cold mirror technology seems to be the only one able to win, at lest in part, thermal noise limits. As it was shown by Numata\textsuperscript{22} coating losses seems to be quite insensitive to temperature, infact a loss angle of about $4 \times 10^{-7}$ was measured to remain constant at various temperature and down to 4K. This mirror coating anomalous and unfortunate behavior is creating a problem for next generation machines where thermal noise limits will be met. As far as we know, at present, the only known possibilities for reducing mirror thermal noise are coating loss angle reduction by using new coating materials and cooling mirrors. The latter benefits from the fact that thermal stochastic force is decreasing with $T^{1/2}$ ($T$ is the temperature), hence bringing mirrors to 4K there is a factor about 10 expected reduction of mirror thermal noise.

LCGT, expected to work at 20 K, is a 3 km interferometer with cryogenic mirror. Constructed underground in the depth of the Kamioka mine, has two beams (see Fig. 10.5) in the same pipe and the upper beam is used for a suspension point interferometer; the optical diagram is shown in Fig 10.6 and the expected sensitivity in Fig. 10.7.

\textit{Courtesy Kazuaki Kuroda for the TAMA/CLIO/LCGT Collaboration}
AIGO is a project for the construction of a 5+5 km interferometer in Gin Gin, 80 km east of Perth (see Fig 10.8); it a very long time since Australian Consortium for Interferometric Gravitational Astronomy (ACIGA) is trying to get approval from Minister for the construction of AIGO. The importance of AIGO, beyond the very relevant fact that a large GW detector is adding to the existing ones, is its geographical position on Earth; in fact a very sensitive GW detector in the southern hemisphere will allow to measure GW sources angular positions with greater accuracy than the one obtained by Earth northern hemisphere detectors, as shown in Fig.s 10.9. The detector, designed for being sensitive to very low frequency GW sources, is equipped with superattenuators, in some way similar to the Virgo ones. **GW detector community is really looking forward for AIGO approval.**

Plots courtesy David Coward and David Blair

GW detectors whose final approval phase is still far

LISA consists of three spacecraft mutually separated by 510^6 km. It is aimed to detect GW in the range 10^{-4}-10^{-3} Hz, as shown in Fig. 10.10. One of the of LISA keypoints is the possibility to measure GW emitted by galactic “Standard Candles”, such as cataclysmic variables, per ex. AmCvn at 2 mHz and by other binary systems whose GW amplitude is evaluated by the system physical parameters. If GW will not be detected before LISA being in air, then LISA can give an inconfutable check of General Relativity validity. Let us hope this will not be the case. Lisa description is so complex that we leave it to more specialized literature.

Fig. 10.10
Einstein Telescope\textsuperscript{26} (ET)

ET will be the future challenge for GW detection since it should attain a factor 100 more in sensitivity with respect to Virgo and LIGO (see Fig. 13.15). One day of data taking of ET is equivalent to $10^6$ days of data taking of Virgo and LIGO machines.

It is at least a 10+10 km machine underground mainly for reducing seismic noise and Newtonian noise, but also for avoiding strong surface environmental impact. It is possible that the lower frequency should be less than 10 Hz; this is a real challenge since noises at very low frequency are very rugged and hard to eliminate.

Optical noises will be reduced either by using signal recycling or by injecting squeezed vacuum in beam splitter black port; still to understand how to get rid of vacuums introduced by photodiode inefficiencies. ET will be a cryogenic detector with mirrors kept at 4 K; it is not obvious if it is necessary to cool also power recycling, signal recycling and beam splitter mirrors.

ET will be formed by at least 4 detectors separated by some thousand km for solving the inverse problem i.e. determination of source 2 polarizations and 2 angles.

Final Considerations

Cryogenic Bar Detectors have reached high sensitivity ($h>10^{-21}$) and a duty cycle so high that the first network of GW detectors has been created i.e. IGEC.

A big step forward in the last 10 years has been in the Interferometer technology. Design sensitivity, above 100 Hz, has been reached ($h>5 \times 10^{-23}$) and stability is so good that a very efficient detector network has been set up. The big challenge will be in the operation of Advanced Interferometers for which sensitivity should reach $h>4 \times 10^{-24}$.

I believe, after what we have learned from Virgo, LIGO, GEO600 and TAMA construction and operation, that class Einstein detectors (third generation) having sensitivity $h>10^{-25}$, seems feasible with very high probability of success. This seems to be the right way for starting GW astrophysics.

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