The Detection of Gravitational Waves with LIGO

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Gravitational wave emission is expected to arise from a variety of astrophysical phenomena. A new generation of detectors with sensitivity consistent with expectation from such sources is being developed. The Laser Interferometer Gravitational-Wave Observatory (LIGO), one of these ambitious undertakings, is being developed by a Caltech-MIT collaboration. It consists of two widely separated interferometers, which will be used in coincidence to search for sources from compact binary systems, spinning neutron stars, supernovae and other astrophysical or cosmological phenomena that emit gravitational waves. The construction of LIGO is well underway and preparations are being made for the commissioning phase. In this lecture, I review the underlying physics of gravitational waves, review possible astrophysical and cosmological sources and discuss the LIGO interferometer status and plans.

I. INTRODUCTION

Einstein first predicted gravitational waves in 1916 as a consequence of the general theory of relativity. In this theory, concentrations of mass (or energy) warp space-time, and changes in the shape or position of such objects cause a distortion that propagates through the Universe at the speed of light (*i.e.*, a gravitational wave).

It is tempting to draw the analogy between gravitational waves and electromagnetic waves. However, the nature of the waves is quite different in these two cases. Electromagnetic waves are oscillating electromagnetic fields propagating through space-time, while gravitational waves are the propagation of distortions of space-time, itself. The emission mechanisms are also quite different. Electromagnetic wave emission results from an incoherent superposition of waves from molecules, atoms and particles, while gravitational waves are coherent emission from bulk motions of energy. The characteristics of the waves are also quite different in that electromagnetic waves experience strong absorption and scattering in interaction with matter, while gravitational waves have essentially no absorption or scattering. Finally, the typical frequency of detection of electromagnetic waves is $f > 10^7$ Hz, while gravitational waves are expected to be detectable at much lower frequency, $f < 10^4$ Hz.

By making these comparisons it becomes clear that most sources of gravitational waves will not be seen as sources of electromagnetic waves and vice versa. This means there is great potential for surprises! However, it also means that (since most of what we know about the Universe comes from electromagnetic waves) there is much uncertainty in the types and characteristics of sources, as well as the strengths and rate.

The characteristics of gravitational radiation can be seen from the perturbation to flat space-time and in the weak field approximation is expressed by $g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$, where $h_{\mu\nu}$ is the perturbation from Minkowski space. The detailed information about the gravitational wave is carried in the form of the quantity $h_{\mu\nu}$. There is freedom of the choice of gauge, but in the transverse traceless gauge and weak field limit, the field equations become a wave equation

$$\left(\nabla^2 - \frac{1}{c^2}\frac{\partial^2}{\partial t^2}\right) h_{\mu\nu} = 0,$$

with the solution being plane waves having two polarizations for the gravitational wave,

$$h_{\mu\nu} = a\hat{h}_+\left(t - \frac{z}{c}\right) + b\hat{h}_\times\left(t - \frac{z}{c}\right),$$

with the two components at 45° from each other (Figure 1), rather than 90° as for electromagnetic waves.

Interestingly, this is a consequence of the spin 2 nature of gravity. The experiments discussed below, although classical experiments analogous to the Hertz experiment that demonstrated electromagnetic waves, are capable of decomposing the two components of the wave, thereby establishing empirically that gravity is spin 2. They also have capability to measure the speed of the gravitational wave, and can establish that they move with velocity c.

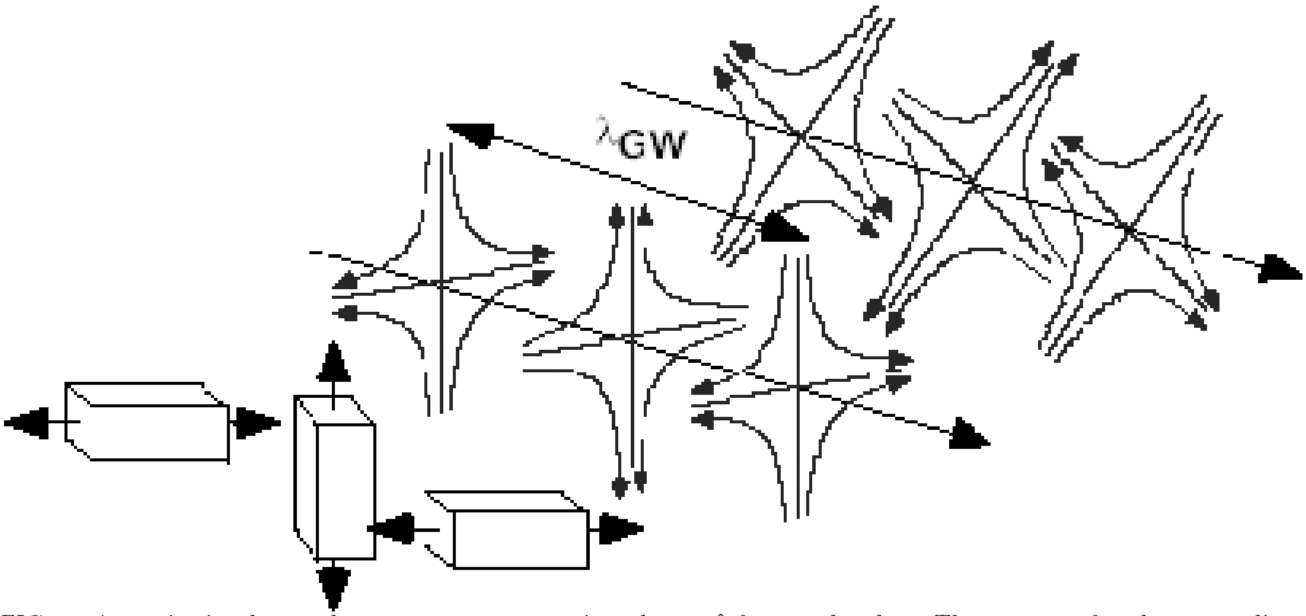

FIG. 1. A gravitational wave has two components oriented at 45° from each other. The passage of such a wave distorts space-time and produces change in length in two orthogonal directions which oscillate with gravitational wave frequency.

For gravitational radiation there is no monopole term or dipole term, so the first term is quadrupolar and the strength of the radiation depends on the magnitude of this non axisymmetric moment. The largest term for gravitational radiation is

$$h_{\mu\nu} = \frac{2G}{Rc^4}\ddot{I}_{\mu\nu},$$

where G is Newton's constant, R is the distance to the source, and $I_{\mu\nu}$ is the reduced quadrupole moment tensor. This yields a strain at the surface of the earth for the inspiral of a binary system of two neutron stars at a distance of the Virgo Cluster ($\sim$15 Mpc) of $h \simeq 10^{-21}$. The new generation of gravitational wave detectors promise to have resolution capable of measuring such small strain.

Until now, gravitational waves have not been observed directly, however, strong indirect evidence resulted from the beautiful experiment of Hulse and Taylor [1]. They studied the neutron star binary system PSR1913+16 and observed by using pulsar timing the gradual speed up of the $\sim$ 8 hour orbital period of this system. This speed up of about 10 seconds was tracked accurately over about 14 years and the result (Figure 2) is in very good quantitative agreement with the predictions of general relativity.

Of course, the motivation for direct detection of gravitational waves is based on the empirical desire to "'see these waves". However, such studies also have enormous potential both to study the nature of gravity in a new regime and to probe the Universe in a fundamentally new way. It is tempting to draw an analogy with the neutrino, where it was "indirectly observed" by Pauli and Fermi in the 1930's as the explanation for the apparent non-conservation of energy and angular momentum in nuclear beta decay. Decades of rich physics have followed, which were first focussed on the goal of direct detection. Since the direct detection by Reines and Cowan, neutrino physics has been a rich subject, both for studies of the properties of neutrinos themselves (*e.g.*, the question of neutrino mass remains an important topic) and as an important tool to probe the constituent nature of nucleons.

LIGO [2] is designed to directly detect gravitational ways using the technique of laser interferometry. The arms of the interferometer are arranged in an L-shaped pattern that will measure changes in distance between suspended test masses at the ends of each arm. The basic principle is illustrated in Figure 3. A gravitational wave produces a distortion of the local metric such that one axis of the interferometer is stretched while the orthogonal direction shrinks. This effect oscillates between the two arms with the frequency of the gravitational wave. Thus,

$$\Delta L = \Delta L_1 - \Delta L_2 = hL,$$

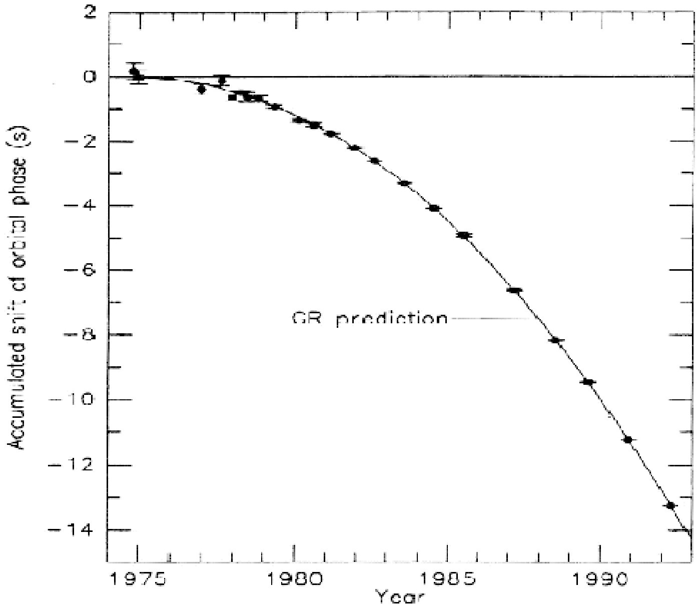

FIG. 2. Speed up of orbital period for PSR 1913+16 as measured by Hulse and Taylor and predictions from general relativity using measured parameters of this binary system.

where h is the gravitational strain or amplitude of the the gravitational wave. Since the effect is linearly proportional to L, the interferometer should have arm length as long as is practical and for LIGO that is 4 km, to yield the target strain sensitivity of $h \sim 10^{-21}$ for the initial interferometers now being installed.

II. SOURCES OF GRAVITATIONAL WAVES

Construction of LIGO is well underway at the two observatory sites: Hanford, Washington, and Livingston, Louisiana. The commissioning of the detectors will begin in 2000. The first data run is expected to begin in 2002 at a sensitivity of $h \sim 10^{-21}$. Incremental technical improvements that will lead to a better sensitivity of $h \sim 10^{-22}$ are expected to follow shortly, and the facility will allow further improved second generation interferometers when they are developed with sensitivity of $h \sim 10^{-23}$. It is also important to note that all the detectors in the world of comparable sensitivity will be used in a worldwide network to make the most sensitive and reliable detection. A comparably long baseline detector (VIRGO) is being built by a French-Italian collaboration near Pisa, and there are smaller interferometers being built in Japan (TAMA) and in Germany (Geo-600). Finally, an Australian group is working toward a detector in the Southern Hemisphere.

There are a large number of processes in the Universe that could emit detectable gravitational waves. Interferometers like LIGO will search for gravitational waves in the frequency range $f \sim 10$ Hz to 10 KHz. It is worth noting that there are proposals to put interferometers in space which would be complementary to the terrestrial experiments, as they are sensitive to much lower frequencies ($f < 0.1$ Hz), where there are known sources like neutron binaries or rotating black holes. For LIGO, characteristic signals from astrophysical sources will be sought by recording time-frequency data. Examples of such signals include the following:

Chirp Signals: The inspiral of compact objects such as a pair of neutron stars or black holes will give radiation that increases in amplitude and frequency as they move toward the final coalescence of the system. This characteristic chirp signal can be characterized in detail, depending on the masses, separation, ellipticity of the orbits, *etc.*. Figure 4 illustrates the "chirp" signal where the amplitude and frequency are determined by the masses of the neutron stars (the chirp mass), the distance to the sources and the orbital inclination. A variety of search techniques, including comparisons with an array of templates will be used for this type of search. The Newtonian (quadrupole) approximation is accurate at a level that allows a set of specific templates to be used.

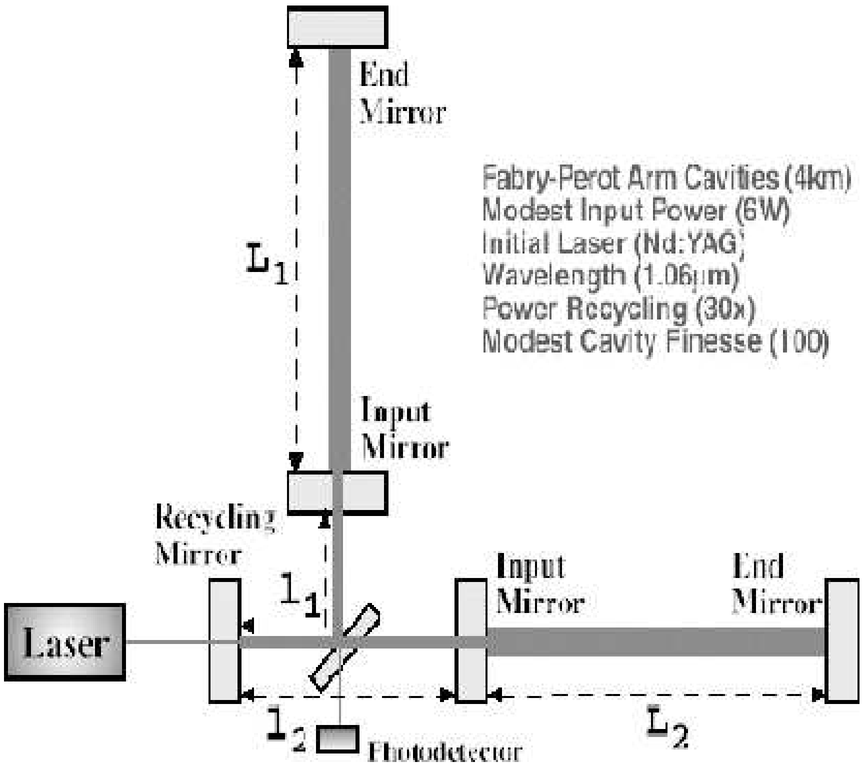

FIG. 3. The initial LIGO interferometer configuration.

Relativistic corrections to the time frequency behavior are typically <10% of the Newtonian contribution and can be extracted from the signal to high accuracy. A great deal of phenomenological work has been done to determine the number and range of templates required, the efficiency for extraction of signals in background noise, *etc.*. The results indicate that the range of anticipated neutron star parameters can be covered with a manageable number of templates. The final coalescence of NS/NS systems will yield information sensitive to the equation of state of nuclear matter, however this part of the spectrum is typically at frequencies 1 kHz or higher where the shot noise in the interferometers are a serious limitation. If such sources are observed, however, future configurations for the LIGO interferometer promise to yield the ability to have improved sensitivity in a narrower bandwidth which can be used for these studies.

The expected rate of such events is expected to be a few per year within about 200 Mpc from neutron star pairs. The rate is more uncertain for black hole pairs, but due to the heavier masses they make a large signal which will allow a deeper search into the Universe for a given LIGO sensitivity.

Burst Signals: The gravitational collapse of stars (e.g. supernovae) will lead to emission of gravitational radiation. Type I supernovae involve white dwarf stars and are not expected to yield substantial emission. However, Type II collapses can lead to strong radiation, if the core collapse is sufficiently non-axisymmetric. Estimates of the strengths indicate detection might be possible out to the Virgo Cluster, which would yield rates of one or more per year. However, the gravitational wave signal depends on the non axisymmetric component of the collapse and this is not well determined by calculation. Detection within or near or galaxy, however, seems assured even if the collapse is highly symmetrical. Calculations indicate that the signal from convectively unstable neutron starts during the first second or so of its life should be detectable in the frequency band of LIGO from sources throughout our galaxy.

The detection of signals from supernovae is a challenge because the waveforms are not well determined. The duration and general characteristics should allow identifying such burst signals with a generic search for bursts, and assurance of detection will require identifying burst like signals in coincidence from multiple interferometers. In addition, steps are underway to correlate signals from the large neutrino detectors and similarly, the gravitational wave signal can

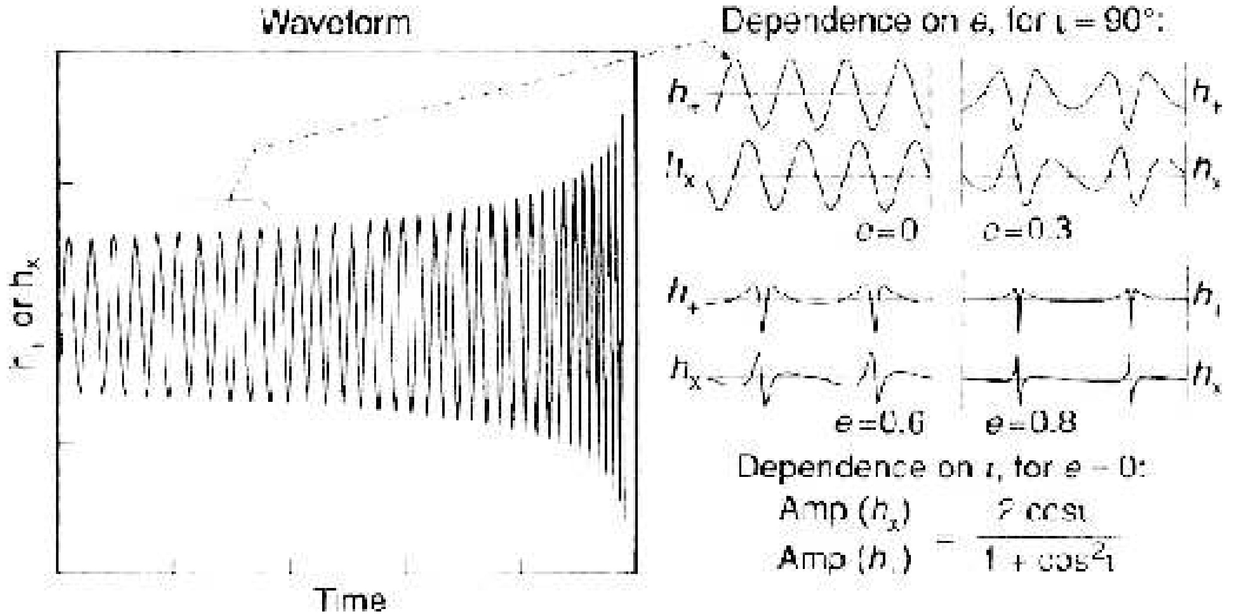

FIG. 4. The chirp waveform from a compact binary inspiral with increasing amplitude and frequency is shown. On the right are indicated detailed waveform dependence on parameters of the binary system: the ellipticity e. and orbital inclination i.

be coincidenced with these neutrino signals.

Periodic Signals: Radiation from rotating non-axisymmetric neutron stars will produce periodic signals in the detectors. The gravitational wave frequency is twice the rotation frequency, which is typically within the LIGO sensitivity band for known neutron stars. Neutron stars spin down partially due to emission of gravitation waves. Searches for signals from identified neutron stars will involve tracking the system for many cycles, taking into account the Doppler shift for the motion of the Earth around the Sun, and effects of spin-down of the pulsar. Both targeted searches for known pulsars and general sky searches are anticipated.

Stochastic Signals: Signals from gravitational waves emitted in the first instants of the early universe ($t \sim 10^{-43}$ sec) can be detected through correlation of the background signals from two or more detectors. Some models of the early Universe can result in detectable signals. Observations of this early Universe gravitational radiation would provide an exciting new cosmological probe.

III. THE LIGO FACILITIES

The LIGO facilities at Hanford, WA and Livingston, LA each have a 4 km "L" shaped vacuum enclosure, which is 1 meter in diameter. Vacuum is required to reduce scattering off residual molecules that bounce off the walls and are modulated by the small shaking of the vacuum walls modulating this background. In addition, we have installed baffles on the walls to reduce scattering. The large diameter of the tube is both to minimize scattering and to provide the ability to house multiple interferometers within the same facility. Each facility has a 4 km interferometer with test masses housed in vacuum chambers at the vertex and the ends of the L shaped arms. At Hanford, there will also be a 2 km interferometer implemented in the same vacuum system, allowing a triple coincidence requirement. The overall vacuum system is capable of achieving pressures of 10^{-9} torr. We presently have both arms at each site installed and they are vacuum tight. We are beginning to bake the tube to reach the desired high vacuum. We expect to have the entire vacuum system complete, all control systems operational and at high vacuum before the end of 1999.

The initial detector for LIGO is a Michelson interferometer with a couple of special features:

The arms are Fabry-Perot cavities to increase the sensitivity by containing multiple bounces and effectively lengthening the interferometer arms. The number of bounces is set to not exceed half the gravitational wave wavelength ($\sim$ 30 bounces). The interferometers are arranged such that the light from the two arms destructively interferes in the direction of the photodetector, thus producing a dark port. However, the light constructively interferes in the direction of the laser and this light is "re-used" by placing a recycling mirror between the laser and beam splitter. This mirror forms an additional resonant cavity by reflecting this light back into the interferometer, effectively increasing the laser power and thereby the sensitivity of the detector.

Much work has been done over the past decade to demonstrate this arrangement and the detailed techniques and required sensitivities in smaller scale laboratory prototypes. This includes experiments on a 40 m prototype interferometer at Caltech, which is a scale model of LIGO, which has provided an excellent test bed to study sensitivity, optics, controls and even some early work on data analysis, noise characterization, *etc.*. We also have built a special interferometer (PNI) at MIT, which has successfully demonstrated our required phase sensitivity, the limitation to the sensitivity at high frequencies.

LIGO is limited in practice by three noise sources, as illistrated in Figure 5:

At low frequencies ($\sim$ 10 Hz to 50 Hz), the limitation in sensitivity is set by the level of seismic noise in the system. We employ a seismic isolation system to control this noise that consists of a four-layer, passive vibration isolation stack having stainless steel plates separated by constrained-layer damped springs. This system is contained within large vacuum chambers. The stack supports an optical platform from which the test mass is suspended. The combination of the seismic isolation stack and the test mass suspension give an isolation from ground motion at the relevant frequencies of about 10 orders of magnitude. The possibility of a more elaborate isolation system and/or the addition of active isolation exists for the future, as well as improved suspension systems. Improvements in this area are planned early in the future improvement program of LIGO.

In the middle range of frequencies ($\sim$ 50 Hz to 200 Hz) the principle effect limiting the sensitivity is thermal noise. This noise comes partially from the suspension system, where there are violin wire resonances from the steel suspension fibers. However the principal noise source is from the vibrational modes of the test masses. This noise is reduced by the choice of test masses, presently fused silica, to have a very high Q thereby dissipating most of its noise out of our frequency band. The test masses will also improve in the future by using higher Q fused silica, better bonding techniques for the wires, and perhaps even new materials for the test masses, like sapphire.

At the higher frequencies (200 Hz to 5 kHz) the main limitation comes shot noise and the sensitivity is limited by the power of the laser (or the effective photostatistics). The initial laser (Nd:YAG) is designed and produced for LIGO, using a master oscillator/power amplifier configuration, which yield a 10 watt high quality output beam. We also have developed a system to pre-stabilize this laser in power and frequency. Again, we expect to incorporate higher power lasers in the future as they become available.

The expected sensitivity of the inital LIGO detectors and the advanced LIGO II detectors is shown in Figure 6, in comparison with signal strengths for various sources.

IV. CONCLUSIONS AND PROSPECTS

The LIGO interferometer parameters have been chosen such that our initial sensitivity will be consistent with estimates needed for possible detection of known sources. Although the rate for these sources have large uncertainty, improvements in sensitivity linearly improve the distance searched for detectable sources, which increases the rate by the cube of this improvement in sensitivity. So, anticipated future improvements will greatly enhance the physics reach of LIGO and for that reason a vigorous program for implementing improved sensitivities is integral to the design and plans for LIGO.

We are now entering into the final year of the construction of the LIGO facilities and initial detectors. We have formed the scientific collaboration that will organize the scientific research on LIGO. This collaboration already consists of more than 200 collaborators from 22 institutions. By early in the next millennium we will turn on and begin the commissioning of these detectors. We anticipate that we will reach a sensitivity of $h \sim 10^{-21}$ by the year 2002. At that point, we plan to enter into the first physics data run ($\sim$ 2 years) to search for sources. This will be the first search for gravitational waves with sensitivity where we might expect signals from known sources. Following this

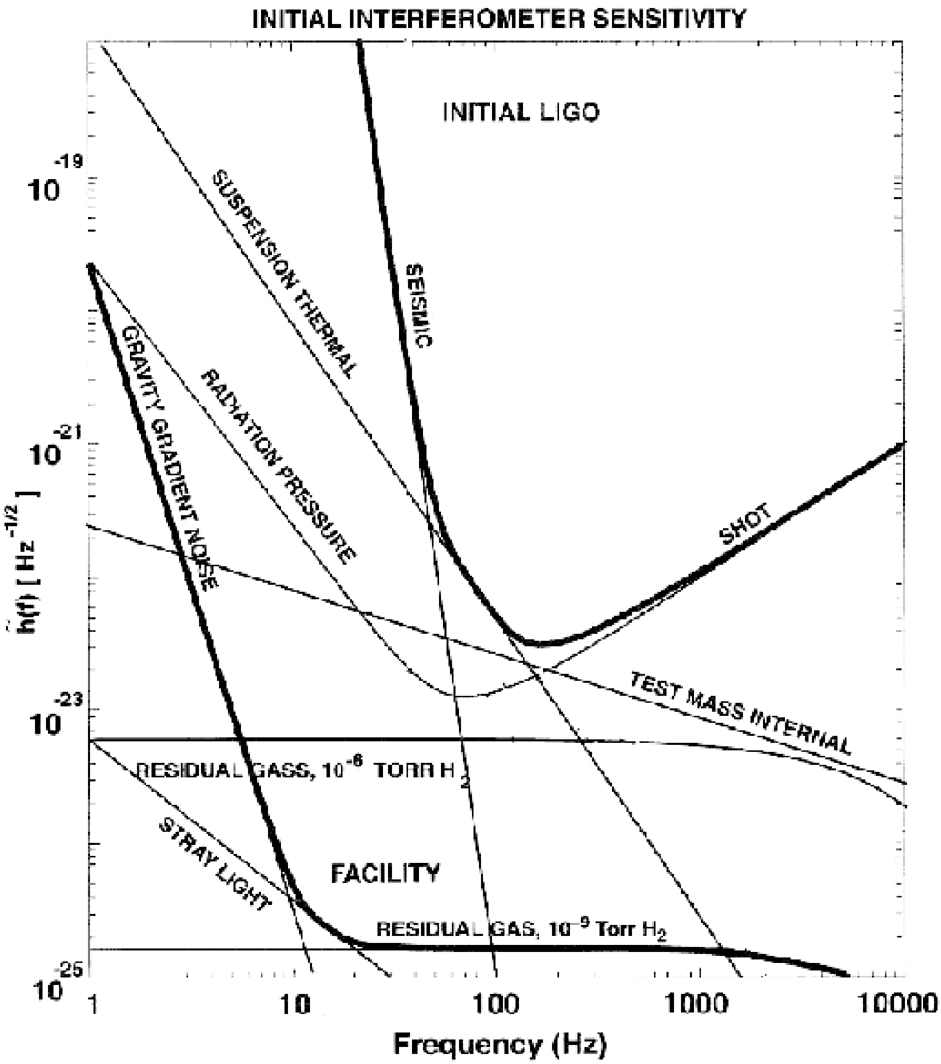

FIG. 5. The limiting noise curves are shown for the design of the initial LIGO interferometers. Note that at low frequency the limiting source is seismic, at middle frequencies it is suspension thermal and at the highest frequencies it is shot noise. Some of the other sources of noise that must be kept under control at a lower level are shown demonstrating the room for improvement from the limiting noise sources.

run in 2004, we will begin incremental improvements to the detector interleaved with further data runs. We expect to reach a sensitivity of $h \sim 10^{-22}$ within the next 10 years, making direct detection of gravitational waves within that time frame reasonably likely.

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[1] R.A. Hulse and J.H. Taylor. *Astrophys. J.*, 324 (1975); and J.H. Taylor, Rev Mod. Phys. 66 (1994).
[2] A. Abramovici *et al*, *Science*, 256, (1992).

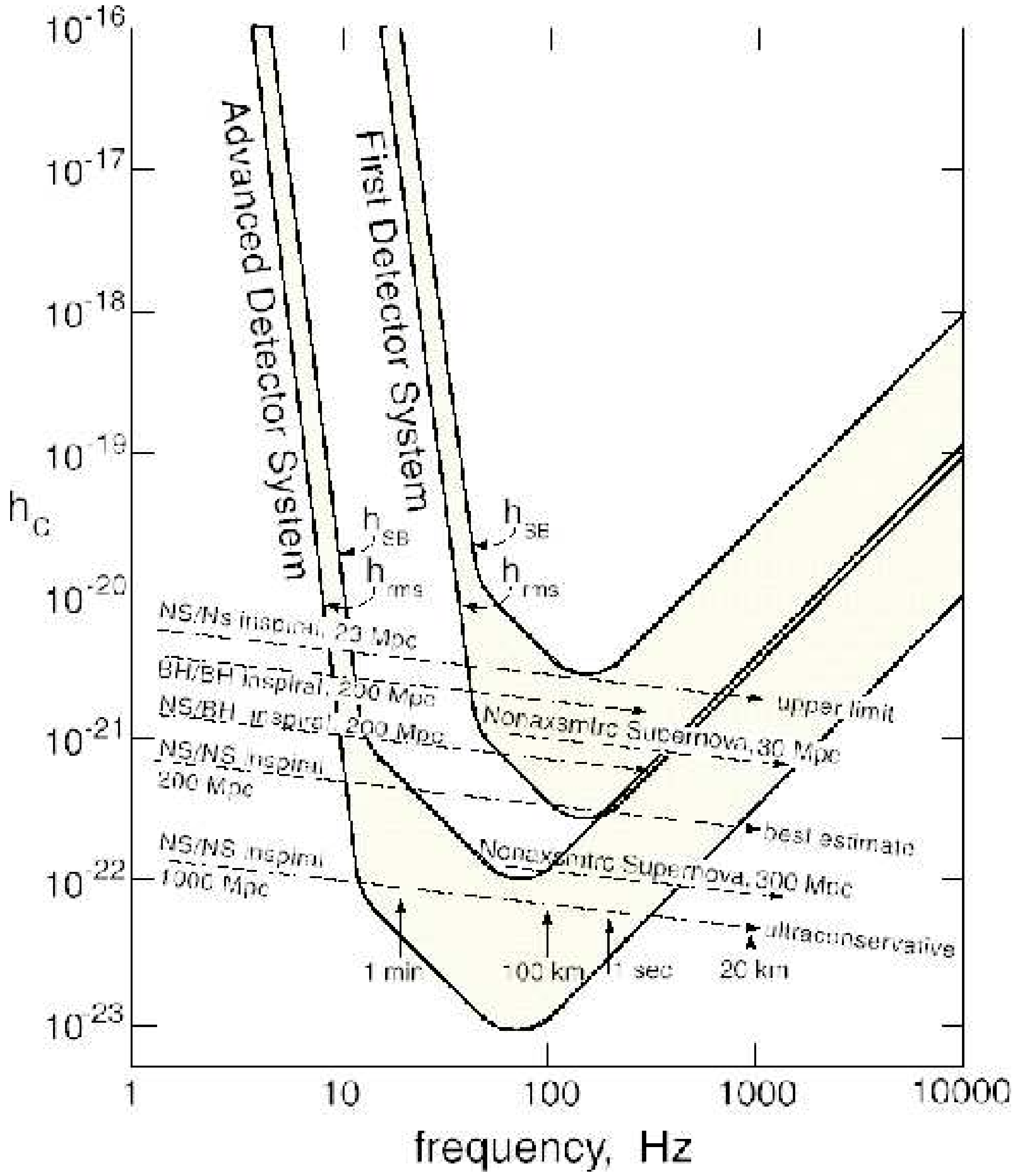

FIG. 6. Sensitivity of initial LIGO interferometers (∼2002-2004) and advanced LIGO interferometers (∼2007-2010) with signal strengths for various sources shown. The lower line h_{rms} is the noise expected noise level and h_{SB} represents approximate level for a signal/noise allowing reliable signal detection.