What can LIGO detect?

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Abstract

This briefly reviews the literature on gravitational wave astronomy, including theoretical basis, experimental design of LIGO, the Laser Interferometer Gravitational Wave Observatory, current searches using LIGO, and the prospects for finding unequivocal gravitational wave detection.

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Thanks to my family, who believed in me even when I didn't.

I. INTRODUCTION

Gravitational waves, or oscillations in spacetime, are predicted by general relativity. They arise from the acceleration of mass in an analogous way that electromagnetic radiation arises from an acceleration of charges.

Gravitational-wave astronomy provides information of a qualitatively different nature than electromagnetic astronomy. In particular:

- Gravitational waves are "coherent superpositions of radiation that arise from the bulk dynamics of a dense source of mass-energy ... [t]hey provide direct information about the system's dynamics." [1]
- The wavelength of gravitational radiation is usually larger than the radiating source. Although this cannot be used for imaging, the two wave polarizations carry stereophonic information about the source's dynamics in a manner similar to sound.
- Gravitational-wave astronomy is typically 4π-steradian sensitive. Although angular resolution is poor, overall information content is good, again analagous to hearing (gravitational-wave astronomy) vs. sight (electromagnetic astronomy).

The linearized gravitational quadrupole moment formula yields:

$$h \approx \left(\frac{2GM}{c^2}\right)\left(\frac{v}{c}\right)^2 \frac{1}{r} \tag{1}$$

Where G is Newton's constant, M is the mass of the wave-generating object, c is the speed of light, v is the velocity of the wave-generating object, and r is the detection range. Some convenient numbers are:

$$G = 6.673 \times 10^{-11} \left[\frac{m^3}{kg \cdot s^2}\right]$$

$$c = 2.997 \times 10^{8} \left[\frac{m}{s}\right]$$

$$1 light\, year = 9.46 \times 10^{15}\, [m]$$

This is a formula for strain, that is, meters per meter. LIGO's sensitivity is 10^{-18} meters over a 4 km length, or a strain of about 10^{-22}. A large cosmic event produces strains of up to 10^{-17}, giving a detection distance on the order of ~10^9ly. How such exquisite sensitivity is possible will be revisited in Section II.

There are several types of phenomena that are open for inspection by gravitional-wave astronomy. They include: [2]

- Strong-field gravity around black holes and in the early universe
- Compact binary inspirals (in units of $10^{-6}yr^{-1}L_{10}^{-1}$ where $L_{10}$is equal to a volume of 10^{10} solar blue-light luminosities)
  - Neutron star - Neutron star ~ 10 - 170
  - Black hole - Neutron star ~ 0.15 - 10
  - Black hole - Black hole ~ 0.1 - 15
- Unmodelled bursts
  - Core-collapse supernovae, gamma-ray burst engines
- Continueous quasi-monochromatic emissions
  - Non-axisymmetric spinning neutron stars
- Stochastic background
  - Gravitational wave background from the Big Bang
  - Cosmic string networks
  - Black hole mergers

Some of these phenomena, for example, the slowing of non-axisymmetric neutron star spin rate due to gravitational wave emission can be detected indirectly. But the direct detection of gravitational waves offers many more benefits.

From equation 1 we see that gravitational radiation drops off as $\frac{1}{r}$, which means that doubling detector sensitivity increases the volume of sky scanned by nearly an order of magnitude. Furthermore, since gravitational waves interact weakly with matter, direct detection offers penetrating insights into otherwise hidden phenomena (core collapse of stars, early universe dynamics).

II. METHODS

LIGO is composed of two separate locations and three Michelson interferometers with Fabry-Perot arm cavities:

- L1, a 4 km interferometer in Livingston, LA, USA
- H1, a 4 km interferometer in Hanford, WA, USA
- H2, a 2 km interferometer in Hanford, WA, USA

A Fabry-Perot Michelson Interferometer uses tests masses of highly transparent material at the end of arms with mirrors of relectivity approaching unity. For a cavity finesse of $\mathcal{F}$ and a corner reflectivity of r_{corner} (~3%) then each photon can make $\frac{\mathcal{F}}{\pi} \backsimeq \sqrt{r_{corner}}/_{1-r_{corner}} \sim 65$ bounces. The mirrors are positioned so that, in absence of a signal, all light goes back towards laser and the photodiodes read no signal. An incoming gravitational wave perturbs the arms, causing a change in the interference pattern. This change is automatically compensated for by servomotors, and the signal is read from the changes the servomotors made to rebalance the interferometer back to zero.

As mentioned before, for a laser of $\lambda = 1\mu$-m the total strain in the FPMI is on the order of 10^{-18} meters. However, as the light bounces roughly 100 times before leaving the arm cavity, the total acquired phase shift is given by:

$$\Delta\Phi_{GW} \sim 100 \times 2 \times \Delta L \times {}^{2\pi}/_{\lambda} \sim 10^{-9} \tag{2}$$

This signal can be measured if the photon shot noise at the photodiode obeys:

$$\Delta\Phi_{shot} \sim {}^{1}/_{\sqrt{N}} < \Delta\Phi_{GW} \tag{3}$$

For a gravitational wave of frequency 100Hz (inversely related to the mass of the object, but in the range of .1 to 1000 Hz for astronomical phenomena), we must therefore collect 10^{18} photons in 10^{-2} seconds, or ~ 100 W of laser power. However, because the losses from the cavity corner mirrors are small (~3% given above), in practice we can get away with lasers of power ~ 10W.

Finally, thermal excitations in the surfaces can be given by:

$$\delta l_{atom} = \sqrt{\frac{kT}{m\omega^2}} \sim 10^{-12}m \tag{4}$$

For room temperature T, atomic mass m, and vibrational frequency $\omega \sim 10^{14}s^{-1}$. This effect appears to be much larger than what we wish to measure! However, it is random, whereas our signal is coherent. There remains active and ongoing research in how best to compensate for these sources, however, the following figure is illustrative.

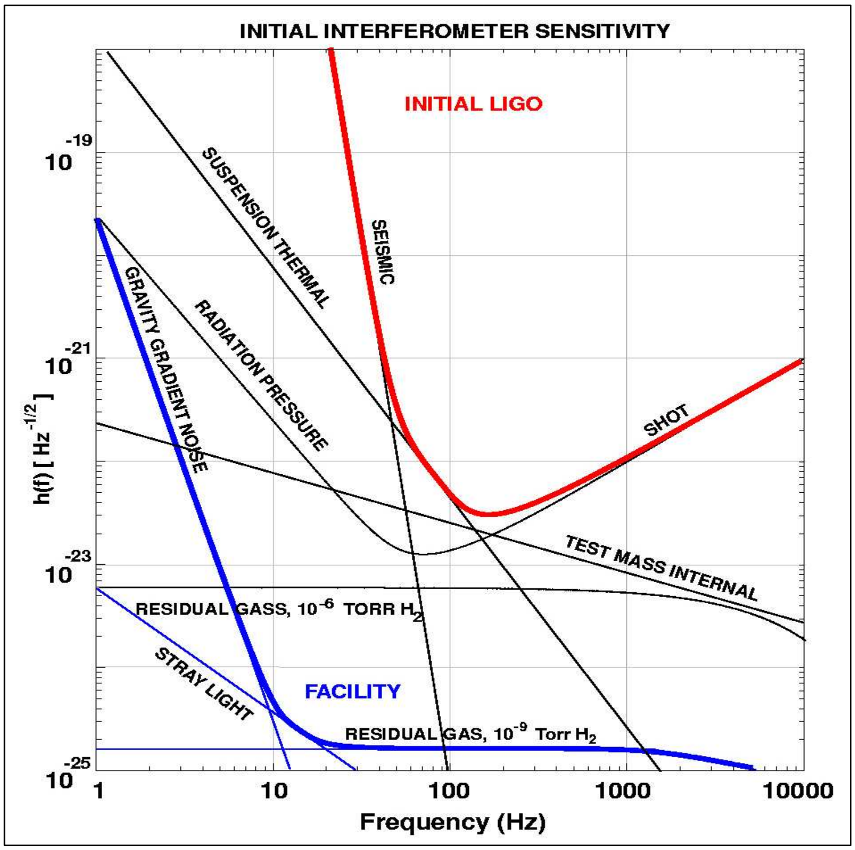

Figure 1: Illustration of LIGO sensitivity, showing the amplitude strain noise spectrum for various noise sources. The heavy line labeled "Initial LIGO" is the design goal for initial LIGO interferometers; that labeled "Facility" shows the facility limitations that cannot be avoided even if other noise sources are perfectly controlled. From Hughs, et. al.

LIGO has conducted 5 science runs, starting with S1 in 2002 and culminating in S5 from November of 2005 - October of 2007. Data from S3 is currently being analyzed, and L1 and H1 were sensitive to NS-NS mergers of 2.8 solar masses to a distance of 15 megaparsecs. In 2009, Enhanced LIGO is expected to push noise levels down by ~10, making it 2-4 times more sensitive, and in 2014 Advanced LIGO is expected to make LIGO 10-15 times more sensitive. The following figure shows the detection space for the various versions of LIGO. [5]

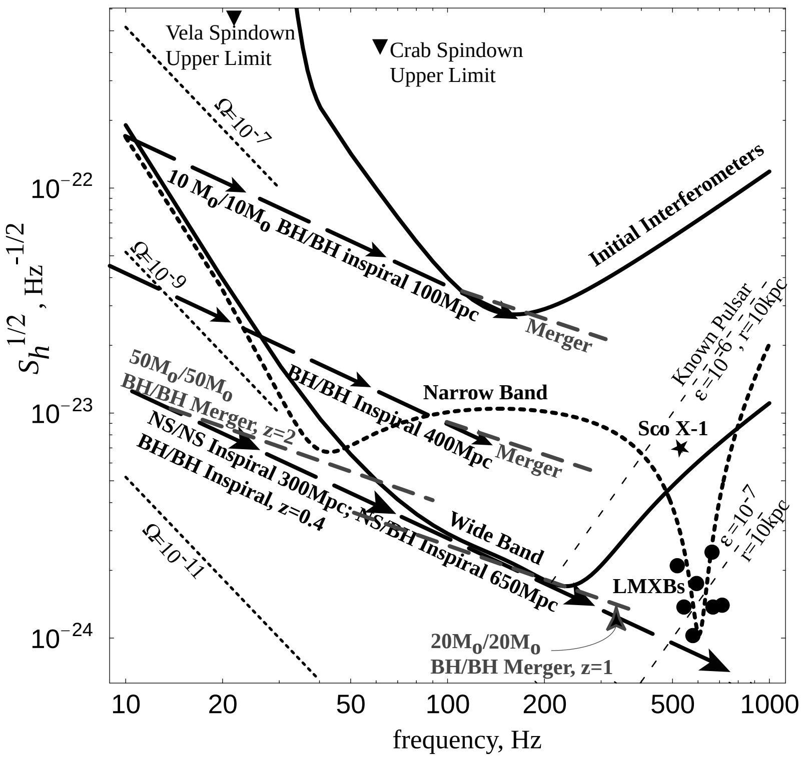

Figure 2: Comparison of source strength to noise magnitude for several astrophysical gravitational-wave sources. The heavy black bands are the various incarnations of LIGO interferometers: initial (top, solid), advanced in wide band configuration (bottom, solid), advanced in narrow band configuration (bottom, dotted).

At current instrument sensitivity, LIGO is expected to detect $< 0.01 yr^{-1}$ (NS-NS) inspirals and $< 0.1 yr^{-1}$(BH-BH). Enhanced LIGO is expected to detect (NS-NS) inspirals at the rate of $< 0.3 yr^{-1}$ while for Advanced LIGO it is expected to be$\simeq 7 - 400 yr^{-1}$.

In addition, the LIGO Scientific Collaboration [4] shares data and combines results with:

- GEO-600, a 600 m Fabry-Perot Michelson Interferometer in Hannover, Germany [6]
- Virgo, a 3 km FPMI in Cascina, Italy [7]
- TAMA 300, a 300 m FPMI in Mitaka, Japan [8]
- AIGO at AIGRC in Gingin, Australia [9]

Overall, there are more than 1,000 scientists in the LIGO Scientific Collaboration. The penetrating nature of gravitational waves means that detections can be cross-correlated with all of the FPMI's within the LSC.

Finally, the Einstein@Home project is used to do computationally intensives searches on data gathered by LIGO/LSC. [10]

Acknowledgments

Thanks to Prof. John Conway and the class of PHY 245C for and interesting look at a great many topics!

[1] Scott A. Hughes et al., "New physics and astronomy with the new gravitational-wave observatories," http://arxiv.org/abs/astro-ph/0110349

[2] P.J. Sutton, "Searching for gravitational waves with LIGO," in Journal of Physics: Conference Series, vol. 110 (presented at the The 2007 Europhysics Conference on High Energy Physics, IOP Publishing, 2008), http://www.iop.org/EJ/abstract/1742-6596/110/6/062024

[3] Romain Gouaty, "Detection confidence tests for burst and inspiral candidate events," Class. Quantum Grav. 25, no. 18 (September 21, 2008): 12

[4] "LIGO Scientific Collaboration :: Science," http://www.ligo.org/science/

[5] K. S. Thorne, "The Scientific Case for Mature LIGO interferometers," LIGO Technical Report LIGO-P000024-00- R, Caltech/MIT, November 2000.

[6] "Welcome — GEO600," http://geo600.aei.mpg.de/

[7] "Virgo interferometer - Wikipedia, the free encyclopedia," http://en.wikipedia.org/wiki/VIRGO

[8] "TAMA Project Office," http://tamago.mtk.nao.ac.jp/

[9] "Welcome to AIGRC," http://www.gravity.uwa.edu.au/

[10] 1"Einstein@Home," http://einstein.phys.uwm.edu/