Searches for Gravitational Waves with the Laser Interferometer Gravitational-Wave Observatory (LIGO)

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Gravitational waves are one of the newest and most exciting frontiers in physics and astronomy. The Laser Interferometer Gravitational-wave Observatory (LIGO) is the world's leading facility with the goal of detecting gravitational waves from astrophysical sources. LIGO aims to test the General Theory of Relativity in the domain of highly nonlinear dynamic gravity and open a completely new observational window on the universe that *fundamentally* differs from that provided by electromagnetic or particle astronomy.

Although gravitational waves have yet to be directly detected, their observations will provide answers to some of the outstanding questions about the fundamental nature of gravity and the high energy universe, including: (i) Do short hard gamma-ray bursts come from the merger of two neutron stars or the merger of a neutron star and a black hole? (ii) What causes the shock revival in the core-collapse of massive stars? (iii) What is the equation of state of matter at nuclear pressures and densities? (iv) What is the mass distribution of black holes and do they conform to the no-hair theorem? and (v) Are observed gravitational waves consistent with those predicted by General Relativity? Gravitational-wave observations are uniquely suited to explore these and many other outstanding questions in strong field gravity and high energy astrophysics.

LIGO relies on ultra-precise laser interferometry to measure the extremely minute distortions of space-time induced by passing gravitational waves. Advanced LIGO, a second generation detector designed to increase the sensitivity and observational range of Initial LIGO by a factor of 10 (thus the volume of space probed by 1000 times; Fig 1 and Fig 2), is currently nearing the end of a seven year construction phase and is scheduled to commence science operations later this year. The Advanced LIGO detector consists of two interferometers with equal 4 km arm lengths housed in separate observatories located in Hanford, WA and Livingston, LA. Once operating at their design sensitivities, they will be capable of sensing binary neutron star coalescences out to 200 Mpc and binary black hole coalescences beyond 2 Gpc.

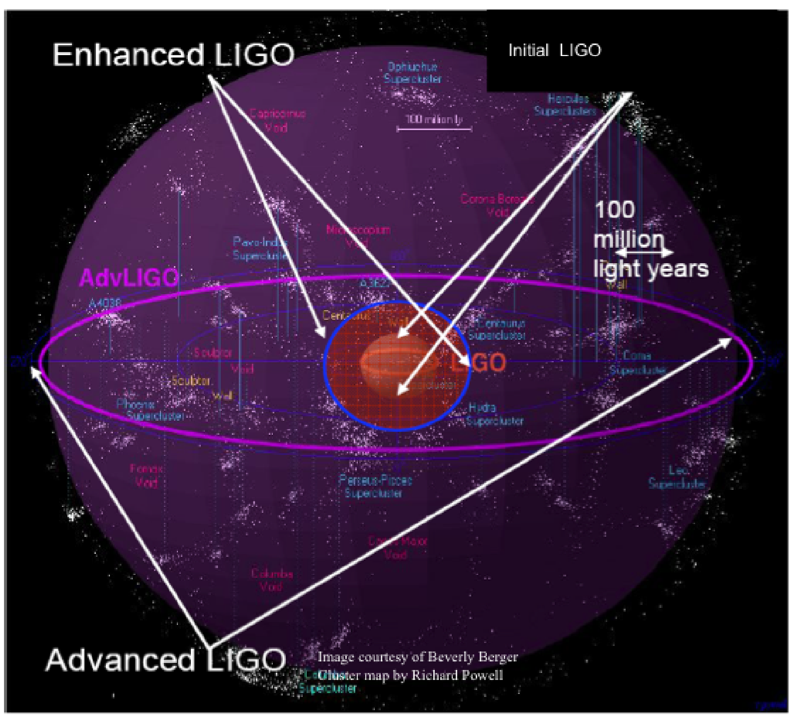

Figure 1: Relative reach of Initial and Advanced LIGO

During Initial LIGO the majority of astrophysical analyses operated on the LIGO Data Grid and Einstein@Home. The LIGO Data Grid is a federated resource of high-throughput computing clusters that provides a uniform computing environment to minimize code portability and data access problems for scientists. It is operated by the LIGO Laboratory as well as both US and international LIGO Scientific Collaboration institutions at a current scale of $\sim$ 25k CPU-cores. Einstein@Home is a distributed computing effort that utilizes BOINC and is currently running at a scale of $\sim$ 1PFlop. In addition, LIGO currently curates $\sim$ 5PB of Initial LIGO data stored in $>$ 1B files and has begun the process of making key science data open to the public.

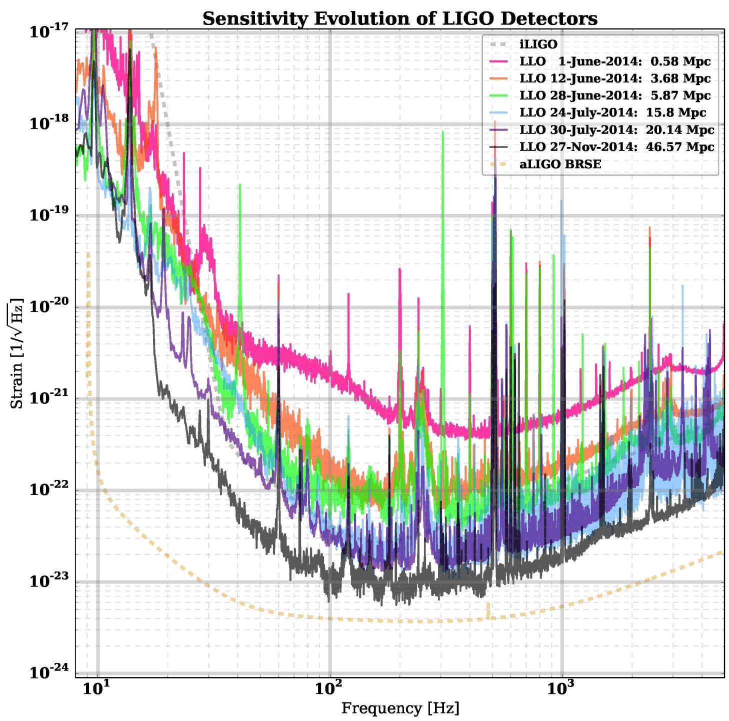

Figure 2: Progression of sensitivity of Advanced LIGO. The best Initial LIGO sensitivity is shown by the upper dotted line (largely obscured by early sensitivity curves). The bottom dotted line corresponds to the sensitivity goal for Advanced LIGO.

In preparation for the larger computational needs of Advanced LIGO three classes of computing are being pursued: i) dedicated LIGO Laboratory resources for detector characterization and production low-latency searches that need low-latency results, ii) dedicated LIGO Scientific Collaboration and shared resources (e.g., XSEDE) for production offline searches and search development, and iii) Einstein@Home, for offline searches with low data-to-processing ratios that might otherwise be prohibitively expensive and for which very high latency of results is acceptable. Analysis methods and search algorithms are specifically tailored and tuned to each source class, however, they all have in common that they are efficiently decomposed into “embarrassingly parallel” tasks amenable to high-throughput computing systems.

The challenge for LIGO computing going forward is primarily: i) to maintain sufficient flexibility given that gravitational-wave physics is still in a discovery phase and the first gravitational-wave signals detected may be different than expected; ii) to continue to develop and optimize robust algorithms that are as sensitive as possible for the expected low signal-to-noise ratio signals given the statistical properties of the data generated by new Advanced LIGO detectors are not yet fully characterized; iii) to increase the portability of existing data analysis pipelines so that they can take advantage of additional shared resources; and iv) to keep a healthy research and development program going to investigate potentially important, and possibly even larger computational cost searches, that may be needed in the future, e.g., research, if the need is indicated, into developing a search for precessing binary coalescence systems.