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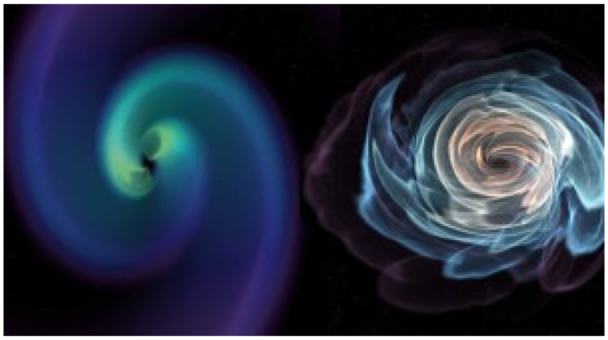
Gravitational Wave Observatories: Moving from detection to new astronomy

Written by Mantas Butkus, Volker Leonhardt, and Marco Arrigoni 20 February 2018



Gravitational waves were first detected in 2015 by the twin aLIGO observatories in the United States. One is in Hanford, Washington and the other in Livingston, Louisiana. (LIGO stands for Laser Interferometer Gravitational-Wave Observatory and aLIGO is Advanced LIGO, which includes many upgrades over first generation systems, including higher laser power and enhanced test mass isolation.) Three physicists have already received the Nobel Prize for this achievement (see Gravitational Waves Work Wins 2017 Nobel Prize).

The gravitational wave measurements were further improved recently when the Virgo observatory (Cascina, Italy) commenced operation in 2017. This enables more sophisticated analysis, namely accurate determination of gravitational wave source location and polarization orientation. Moreover, this is allowing gravitational wave detection to move beyond the proof-of-principle stage and to be used in multi-modal astronomical studies, where the data is combined with observations of electro-magnetic radiation at various wavelengths.

The Challenge of gravitational wave detection

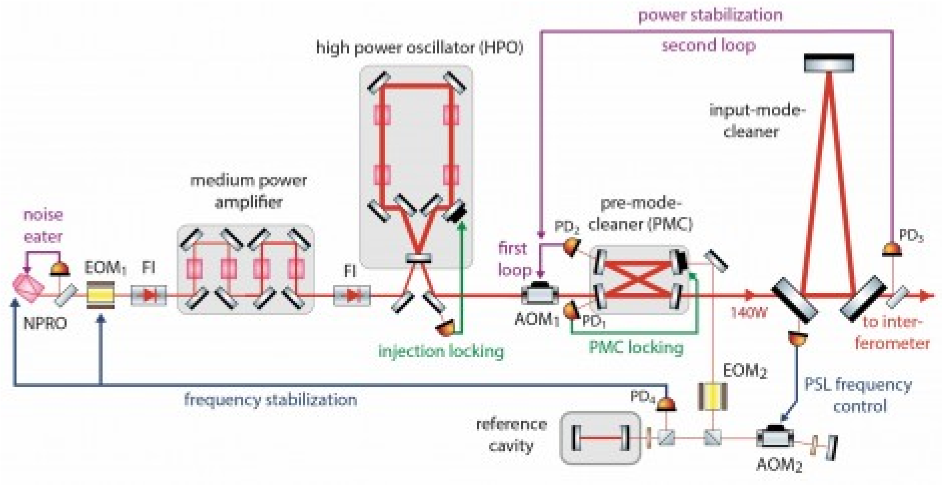
While Einstein predicted the existence of gravitational waves just over 100 years ago, their expected magnitude was so small that instrumentation sensitive enough to detect them could not be developed for some time (specifically, it requires the ability to observe modulations in spacetime as small as 1 part in 10^{22}).

In the 1960s, the availability of highly coherent and monochromatic laser light led scientists to converge on long path laser interferometry as the best hope for eventual successful detection. The Michelson “L” configuration was seen as the optimum geometry with two long arms (up to 4 km in length) arranged at 90°. Here a test mass incorporating a mirror surface is located at the end of both of the two arms. Gravitational waves are transverse in nature, which means the distortion in spacetime is orthogonal to the propagation direction. Consequently, the passing of one of these waves causes relative changes in the length of the two arms of the interferometer. Because the speed of light is constant, this results in a phase shift of coherent light transmitted through the two arms, which is converted to an amplitude (intensity) change when the beams are recombined at the detector.

Ultra-small signal demands ultra-low noise

While the theory of long–path interferometry is simple, the practical execution for gravitational wave detection represents a formidable signal-to-noise problem. With 4 km arms, the mirrors were expected to move by approximately $5\text{x}10^{-12}$ of the 1064 nm laser wavelength. Measuring a trillionth of a wavelength path difference required extreme measures and new levels of photonic performance.

Some of the key elements of the solution included a low noise, amplified laser, ultra-high (10^{-12} atmospheres) vacuum for the entire interferometer, multiple levels of both active and passive isolation of the mirror masses from any terrestrial sources of vibration, operation of the interferometer arms as Fabry-Perot cavities, and sophisticated software to process the data.



Schematic layout of the pre-stabilized laser (PSL) system developed for LIGO, showing the key components and feedback stabilization loops. Adapted from P. Kwee et al, Opt. Exp. Vol 20 (10) 10617 (2012)

In all current aLIGO observatories, the amplified laser systems are seeded by a non-planar ring oscillator (NPRO) – the Coherent Mephisto laser – which started as a custom design specifically for this application. This laser is available commercially with feedback inputs to allow external locking and stabilization. In aLIGO and Virgo, the laser is locked to a reference cavity and the naturally low noise of this NPRO is further lowered by several orders of magnitude.

The Fabry Perot arrangement, together with a power recirculation scheme, means that less than 100 watts of amplified laser input results in hundreds of kilowatts of power circulating within the Fabry Perot cavities in each of the interferometer's arms. This extreme power level is critically necessary to push the signals beyond the laser quantum noise limit. Additionally, multi-passing the arms in this way also increases the effective interferometer length by nearly three hundred times.

In spite of all these innovations, gravitational wave observations can only be confidently assigned by synchronizing two or more observatories, in order to distinguish real signals from spurious noise. Beyond this, the systems and their scientists are periodically blind tested by an independent team who purposefully inject false signals into the data stream.

VIRGO and the latest data

There are other advantages of having more than one observatory performing synchronized measurements, beyond just eliminating spurious noise signals. Specifically, this coordinated detection can provide details of the wave's polarization orientation and provide accurate celestial coordinates for the source. The latter can be used to alert worldwide observatories detecting electromagnetic radiation to rapidly align on these coordinates and perform observations in their particular wavelength bands. This is possible because, although the transient gravitational waves can be seen for seconds, afterglow effects in the electromagnetic spectrum persist long after that. Two recently confirmed events observed by both aLIGO and Virgo illustrates these advantages.

On August 14, 2017, gravitational waves were detected and analyzed to indicate they originated by the collision of a pair of black holes with 31 and 25 solar masses. They merged to produce a spinning black hole of 53 solar masses. In a joint aLIGO/Virgo press release, it was announced that combining the signals from Virgo and the two aLIGO observatories improved the sky localization of the source by over a factor of 10 compared to aLIGO alone.

Artistic conception of the first cosmic event detected in both gravitational waves and light. Image courtesy Georgia Tech Center for Relativistic Astrophysics, Image credit Chris Evans and Karan Jani.

Just four days later on August 17, 2017, aLIGO and Virgo jointly detected the first gravitational waves assigned to the collision of two neutron stars. Nearly 70 ground and space-based optical and radio frequency observatories then quickly aligned to the location and began accumulating data across the spectrum. This enabled detection gamma-ray (by the Fermi and INTEGRAL satellites) and optical (the Swope discovery image) signals from the transient event observed on August 17, 2017. The collective data immediately confirmed that gravitational waves travel at the speed of light. Additionally, the gamma radiation spectrum confirmed that these massive events produce over half of the elements heavier than iron.

Opening a new window

A number of breakthrough discoveries have already emerged from gravitational waves observatories in the last two years. This only became possible because of the relentless efforts of those involved in the work that spanned decades. Scientists now are employing state-of-the-art laser systems and related technologies in ingenious ways to deliver spacetime metrology data at a level of precision that seemed completely impossible until a short time ago. The fruits of this work are now opening a completely new observation window in astronomy.

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Labels: astronomy,gravitational waves,observatories,universe,Einstein