GRAVITATIONAL WAVES DETECTED 100 YEARS AFTER EINSTEIN'S PREDICTION

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For the first time, scientists have observed ripples in the fabric of spacetime called gravitational waves, arriving at the earth from a cataclysmic event in the distant universe. This confirms a major prediction of Albert Einstein's 1915 general theory of relativity and opens an unprecedented new window onto the cosmos.

Gravitational waves carry information about their dramatic origins and about the nature of gravity that cannot otherwise be obtained. Physicists have concluded that the detected gravitational waves were produced during the final fraction of a second of the merger of two black holes to produce a single, more massive spinning black hole. This collision of two black holes had been predicted but never observed.

The gravitational waves were detected on Sept. 14, 2015, at 5:51 a.m. Eastern Daylight Time (9:51 UTC) by both of the twin Laser Interferometer Gravitational-wave Observatory (LIGO) detectors, located in Livingston, La., and Hanford, Wash. The LIGO Observatories are funded by the National Science Foundation, and were conceived, built, and are operated by Caltech and Massachusetts Institute of Technology. The discovery, accepted for publication in the journal *Physical Review Letters*, was made by the LIGO Scientific Collaboration (which includes the GEO Collaboration and the Australian Consortium for Interferometric Gravitational Astronomy) and the Virgo Collaboration using data from the two LIGO detectors.

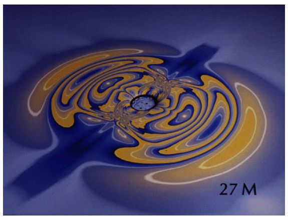
NCSA'S ROLE IN THIS DISCOVERY

Thirty years ago, the National Center for Supercomputing Applications (NCSA) was founded at the University of Illinois at Urbana-Champaign by Larry Smarr based on the premise that numerically modeling scientific problems, such as the colliding of black holes, required high-performance computing to make progress. Smarr's doctoral thesis had itself been on the modeling of the head-on collision of two black holes. In 2014, Smarr was honored with the Golden Goose award to highlight the impact that his black hole research had on creating NCSA and the NSF supercomputing centers program which led to the public Internet revolution via the creation of the NCSA Mosaic web browser, the first browser to have visual features like icons, bookmarks, and pictures, and was easy to use.

At NCSA, Smarr formed a numerical group, led by Edward Seidel—the current NCSA director. The group quickly became a leader in applying supercomputers to black hole and gravitational wave problems. For example, in 1994 the very first 3-dimension simulation of two colliding black holes providing computed gravitational waveforms was carried out at NCSA by this group in collaboration with colleagues at Washington University.

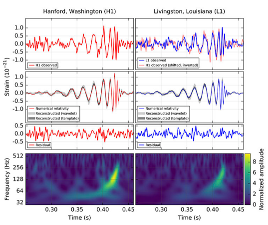
NCSA as a center has continued to support the most complex problems in numerical relativity and relativistic astrophysics, including working with several groups addressing models of gravitational waves sources seen by LIGO in this discovery. Even more complex simulations will be needed for anticipated future discoveries such as colliding neutron stars and black holes or supernovae explosions.

NCSA has also played a role in developing the tools needed for simulating relativistic systems. The work of Seidel's NCSA group led to the development of the Cactus Framework, a modular and collaborative framework for parallel computing which since 1997 has supported numerical relativists



Watch a video **of former NCSA Director Larry Smarr and current NCSA Director Ed Seidel discussing their work on colliding black holes.**

The LIGO detectors in Livingston, La., and Hanford, Wash, separated 1,865 miles. It took about 7 milliseconds for the gravitational wave to cover the distance between the two.



The panels show the gravitational wave (GW) event GW150914 (after its detection on September 14, 2015) as observed by the LIGO Hanford (H1) and Livingston (L1) detectors.

Top panel: **Time series filtered with a 35-350 Hz band-pass filter to suppress large fluctuations outside the detectors' most sensitive frequency band. The panels show the GW strain in H1 and L1. GW150914 arrived first at L1 and about 7 milliseconds later at H1.**

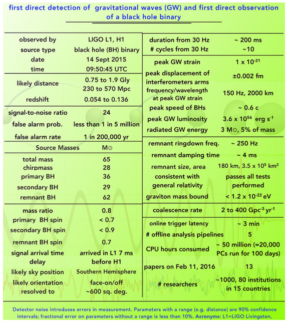
Second panel: **various reconstructions of the waveforms in the 35-350Hz band.**

Third panel: **residual noise after the filtered numerical relativity waveform is subtracted from the filtered detection time series.**

Bottom panel: **The plots show how the gravitational wave strain in**

each LIGO detector varies as a function of time and frequency. The time is measured in seconds and the frequency in Hertz, or number of waveform cycles per second. The plots show how the

gravitational wave event GW150914 sweeps from 35 Hz to 150 Hz over two tenths of a second.



first direct detection of gravitational waves (GW) and first direct observation of a black hole binary

observed by	LIGO L1, H1
source type	black hole (BH) binary
date	14 Sept 2015
time	09:50:45 UTC
likely distance	0.75 to 1.9 Gly 230 to 570 Mpc
redshift	0.054 to 0.136
signal-to-noise ratio	24
false alarm prob.	less than 1 in 5 million
false alarm rate	1 in 200,000 yr
Source Masses	M⊙
total mass	65
chirpmass	28
primary BH	36
secondary BH	29
remnant BH	62
mass ratio	0.8
primary BH spin	< 0.7
secondary BH spin	< 0.9
remnant BH spin	0.7
signal arrival time delay	arrived in L1 7 ms before H1
likely sky position	Southern Hemisphere
likely orientation	face-on/off
resolved to	~600 sq. deg.

duration from 30 Hz	~ 200 ms
# cycles from 30 Hz	~10
peak GW strain	1×10^{-21}
peak displacement of interferometers arms	±0.002 fm
frequency/wavelength at peak GW strain	150 Hz, 2000 km
peak speed of BHs	~ 0.6 c
peak GW luminosity	3.6×10^{56} erg s^{-1}
radiated GW energy	3 M⊙, 5% of mass
remnant ringdown freq.	~ 250 Hz
remnant damping time	~ 4 ms
remnant size, area	180 km, 3.5×10^5 km^2
consistent with general relativity	passes all tests performed
graviton mass bound	$< 1.2 \times 10^{-22}$ eV
coalescence rate	2 to 400 Gpc^{-3} yr^{-1}
online trigger latency	~ 3 min
# offline analysis pipelines	5
CPU hours consumed	~ 50 million (=20,000 PCs run for 100 days)
papers on Feb 11, 2016	13
# researchers	~1000, 80 institutions in 15 countries

Detector noise introduces errors in measurement. Parameters with a range (e.g. distance) are 90% confidence intervals; fractional error on parameters without a range is less than 10%. Acronyms: L1=LIGO Livingston,

Stats about the detected gravitational wave.

as well as other disciplines developing applications to run on supercomputers at NCSA and elsewhere. Built on the Cactus Framework, the NSF-supported Einstein Toolkit developed at Georgia Tech, RIT, LSU, AEI, Perimeter Institute and elsewhere now supports many numerical relativity groups modeling sources important for LIGO on the NCSA Blue Waters supercomputer.

"This historic announcement is very special for me. My career has centered on understanding the nature of black hole systems, from my research work in numerical relativity, to building collaborative teams and technologies for scientific research, and then also having the honor to be involved in LIGO during my role as NSF Assistant Director of Mathematics and Physical Sciences. I could not be more excited that the field is advancing to a new phase," said Seidel, who is also Founder Professor of Physics and professor of astronomy at Illinois.

Gabrielle Allen, professor of astronomy at Illinois and NCSA associate director, previously led the development of the Cactus Framework and the Einstein Toolkit. "NCSA was a critical part of inspiring and supporting the development of Cactus for astrophysics. We held our first Cactus workshop at NCSA and the staff’s involvement in our projects was fundamental to being able to demonstrate not just new science but new computing technologies and approaches," said Allen.

Eliu Huerta, member of the LIGO Scientific Collaboration since 2011 and current leader of the relativity group at NCSA, is a co-author of the paper to be published in *Physical Review Letters*. Huerta works at the interface of analytical and numerical relativity, specializing in the development of modeled waveforms for the detection and interpretation of gravitational wave signals. Huerta uses these models to infer the astrophysical properties of compact binary systems, and shed light on the environments in which they form and coalesce.

"The first direct observation of gravitational waves from a binary black hole system officially inaugurates the field of gravitational wave astronomy. There can be no better way to celebrate the first centenary of Einstein’s prediction of gravitational waves. We can gladly say that Einstein is right, and that the beautiful mathematical framework he developed to describe gravity is valid even in the most extreme environments. A new era has begun, and we will be glad to discover astrophysical objects we have never dreamt of," said Huerta.

Stuart Shapiro, a professor of physics and astronomy at Illinois, was appointed an NCSA research scientist by Smarr two decades ago. A leading expert in the theory that underpinned the search for gravitational waves, he has developed software tools that can simulate on NCSA supercomputers like Blue Waters the very binary black hole merger and gravitational waves now detected by LIGO. Shapiro said he is thrilled by the discovery.

"This presents the strongest confirmation yet of Einstein's theory of general relativity and the cleanest evidence to date of the existence of black holes. The gravitational waves that LIGO measures can only be generated by merging black holes—exotic relativistic objects from which nothing, including light, can escape from their interior," said Shapiro.

"Work at NCSA helps open windows into the universe," said Peter Schiffer, vice chancellor for research at the University of Illinois at Urbana-Champaign. "This is a wonderful fundamental discovery, and it’s exciting that the high performance computing capabilities that we developed to address challenges like this one are also being used to solve other significant societal problems."

Black holes are formed when massive stars undergo a catastrophic gravitational collapse. The gravitational field of these ultra compact objects is so strong that not even light can escape from them.

Gravitational waves are generated when ultra compact objects—black holes, neutron stars or white dwarfs—are accelerated to velocities that are a significant fraction of the speed of light. Gravitational waves couple weakly to matter, which means that they can travel unimpeded throughout the Universe and that only extremely sensitive detectors such as LIGO can detect them.

LIGO research is carried out by the LIGO Scientific Collaboration, a group of more than 1,000 scientists from universities around the United States and in 14 other countries. More than 90 universities and research institutes in the collaboration develop detector technology and analyze data; approximately 250 students are strong contributing members of the collaboration.

The LIGO Scientific Collaboration’s detector network includes the LIGO interferometers and the GEO600 detector. The GEO team includes scientists at the Max Planck Institute for Gravitational Physics (Albert Einstein Institute, AEI), Leibniz Universität Hannover, along with partners at the University of Glasgow, Cardiff University, the University of Birmingham, other universities in the United Kingdom, and the University of the Balearic Islands in Spain.

LIGO was originally proposed as a means of detecting these gravitational waves in the 1980s by Rainer Weiss, professor of physics, emeritus, from MIT; Kip Thorne, Caltech’s Richard P. Feynman Professor of Theoretical Physics, emeritus; and Ronald Drever, professor of physics, emeritus, also from Caltech.

Virgo research is carried out by the Virgo Collaboration, consisting of more than 250 physicists and engineers belonging to 19 different European research groups: six from Centre National de la Recherche Scientifique (CNRS) in France; eight from the Istituto Nazionale di Fisica Nucleare (INFN) in Italy; two in the Netherlands with Nikhef; the Wigner RCP in Hungary; the POLGRAW group in Poland and the European Gravitational Observatory (EGO), the laboratory hosting the Virgo detector near Pisa in Italy.

The discovery was made possible by the enhanced capabilities of Advanced LIGO, a major upgrade that increases the sensitivity of the instruments compared to the first generation LIGO detectors, enabling a large increase in the volume of the universe probed—and the discovery of gravitational waves during its first observation run.

The U.S. National Science Foundation leads in financial support for Advanced LIGO. Funding organizations in Germany (Max Planck Society), the U.K. (Science and Technology Facilities Council, STFC) and Australia (Australian Research Council) also have made significant commitments to the project. Several of the key technologies that made Advanced LIGO so much more sensitive have been developed and tested by the German UK GEO collaboration.

Significant computer resources have been contributed by the AEI Hannover Atlas Cluster, the LIGO Laboratory, Syracuse University, and the University of Wisconsin-Milwaukee. Several universities designed, built, and tested key components for Advanced LIGO: The Australian National University, the University of Adelaide, the University of Florida, Stanford University, Columbia University in the City of New York and Louisiana State University.