ABSTRACT

The LIGO collaboration successfully detected gravitational waves on September 14, 2015 had its beginning in 1986 as a draft proposal by Prof Rai Weiss of MIT to the NSF. Stanford soon joined the LIGO effort and has contributed to the observatories and to next generation detectors. LIGO has now detected half dozen inspiral Black Hole binaries and recently the first neutron star binary inspiral (170817). The latter was detected in both the optical and gamma ray electromagnetic spectrum and opens the door to Multi-messenger astronomy in the future that encompasses all of the known forces in nature.

LIGO and Advanced LIGO nearly impossible requirements were met and enabled by advances in solid state lasers, isolation and control, and precision measurement techniques. This is a brief story of LIGO and the direct detection of gravitational waves: the most precise measurement ever conceived.
LIGO – suggested by Rai Weiss

Rai Weiss – 1972
NSF meeting – 1988
Funded! begin work 1992
Delivered 7 laser systems 1995
LIGO – suggested by Rai Weiss

Rai Weiss - 1972
NSF meeting - 1988
Funded! begin work 1992
Delivered 7 laser systems 1995
Detection Sept 2015 - 100 yrs!
First detection!
9:50:45 UTC, 14 September 2015

LIGO Hanford signal

LIGO Livingston signal
The Foundation of General Relativity

Byer Group

The Annotated Manuscript

The Road to Relativity

The History and Meaning of Einstein’s “The Foundation of General Relativity”

HANOTCH GUTFREUND & JÜRGEN RENN

FEATURING THE ORIGINAL MANUSCRIPT OF EINSTEIN’S MASTERPIECE
Einstein waffled - were gravitational waves even possible?

The reality of gravitational waves was debated through the first half of the twentieth century.

Then, in the mid-fifties Richard Feynman declared that gravitational waves were real - get on with the program of discovery.
John Wheeler Coined the term “Blackhole”

US theoretical physicist John Wheeler helped to bring general relativity into the mainstream.

**Einstein’s curve ball**

Graham Farmelo enjoys a ‘biography’ of the general theory of relativity.

The mathematical physicist Max Born remarked in 1955 that although his late friend Albert Einstein’s general theory of relativity was a peerless scientific achievement, “its connections with experience are slender.” The appeal of the theory for Born was similar to that of “a great work of art, to be enjoyed and admired at a distance.”

Today, Born’s comments seem quaint. In an age of precision astronomy, it is now possible to study consequences of the theory: the existence of gravitational waves, for instance, can be inferred from studying pulsars. With the theory’s centenary only a year away, this is an opportune time to look back on its inception and its achievements.

Ferreira describes, one of the most eminent of the physicists who brought the general theory back into the limelight was US theoretician John Wheeler. Wheeler was at first deeply uneasy about the theory’s mathematical singularities — the point at which the quantities used to measure the strength of gravitational fields become infinite — and even wanted to remove them. In December 1963, he was one of the speakers at the first Texas Symposium on Relativistic Astrophysics, where the audience excitedly discussed the recently identified “quasi stellar radio sources”, neatly dubbed quasars by one of the attendees. It seemed likely that general relativity might well be needed to understand this and other astronomical discoveries.
What is a Gravitational Wave?

Predicted by Einstein in 1916 as part of GR.

“Spacetime tells matter how to move, matter tells spacetime how to curve”

- J. A. Wheeler

Photograph by Orren Jack Turner, Library of Congress digital ID cph.3b46036.
Kip Thorne and Rai Weiss led "the neither paved nor well marked road" to LIGO
10.9 One of the two waveforms produced by the coalescence of two black holes. The wave is plotted upward in units of $10^{-21}$; time is plotted horizontally in units of seconds. The first graph shows only the last 0.1 second of the inspiral part of the waveform; the preceding minute of the waveform is similar, with gradually increasing amplitude and frequency. The second graph shows the last 0.01 second, on a stretched-out scale. The *Inspiral* and *Ringdown* segments of the waveform are well understood, in 1993, from solutions of the Einstein field equation. The coalescence segment is not at all understood (the curve shown is my own fantasy); future supercomputer simulations will attempt to compute it. In the text these simulations are presumed to have been successful in the early twenty-first century.

Diameter of one atom at the distance to the sun! 1/1000 diam proton at 4km
The challenge of LIGO data analysis
Numerical relativity solves BH Merger signal amplitude

This source:
Binary BH-BH system

Produces this waveform:
“Chirp” waveform

Embedded in this noise stream:

We use different methods (in this case optimal Weiner filtering using matched templates) to pull these signals from the noise:

The problem is that non-astrophysical sources also produces signals (false positives)
I) In conclusion, the panel enthusiastically supports this development effort and urges that the plans for the project be refined along the lines indicated and that the design be completed. We recommend, then, that the construction project be brought to the National Science Foundation Board for consideration and (hopefully) for funding.

Panel Members:

Daniel B. DeBra
Val L. Fitch
Richard L. Garwin
John L. Hall

Bryce D. McDaniel
Andrew M. Sessler
Saul A. Teukolsky
Alvin A. Tollestrup

Workshop Committee

D. Debra
V. F. Fitch
R. L. Garwin
J. L. Hall

Gravity Wave Research

A. Abramovici
A. C. C. Cole
Y. T. Chen
R. Drever
R. Fatto
K. T. Horne
S. Smith
M. Zucker
G. Leuchs
A. Liguori
R. Schilling
J. Hough
D. Meers
B. Schutz
H. Ward

Caltech
Coltech
Max Planck
Max Planck
Glasgow
Glasgow

P. Brillet
P. Tourrenc
N. Christiansen
J. Livio
J. Livio
J. Hough

Paris
Graz
MIT
MIT
MIT

P. Bender
Colorado

LARGE BASELINE PLANNING AND ENGINEERING

I. Corbett
R. Elder
J. Klein
V. Lobb
F. Schutz
Rutherford Appleton
JPL
JPL
Caltech/MIT

EXPERTS IN LASERS AND OPTICAL TECHNOLOGY

R. Byers
S. Volk
K. A. Lee
L. Hoessel
Stanford
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Perkin-Elmer
Livermore

Astronomy Lab
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Perkin-Elmer
Livermore

N. K. Wilson
NASA Langley

OBSERVERS

A. Komor
R. S. Moore
H. Miller
NSF
Illinois/NSF
NSF

*did not attend
Early Stanford LIGO participants

Tom Kane, R. L. Byer
“Monolithic, unidirectional Single-mode Nd:YAG ring laser”

NonPlanar Ring Oscillator
Single frequency: <10kHz
One thing leads to another…

Clockwise from top left: GP-B Principal Investigator, Francis Everitt and Co-PIs Bradford Parkinson, John Turneaure and Daniel DeBra
Scientific Applications of Lasers

Atmospheric Remote Sensing
- Quanta Ray 1J Unstable resonator Nd:YAG Laser
- 1.4 to 4.3 micron Tunable LiNbO3 OPO

Global Wind Sensing
- LD pumped Nd:YAG Laser
- Coherent Laser Radar

*LIGO and LISA & Gravitational Waves
- 10 W Nd:YAG slab MOPA for LIGO
- 200W fiber laser MOPA Adv LIGO
- 1W Iodine Stabilized Nd:YAG LISA
- Optical Clock for SMEX mission STAR

Global remote sensing 1980 - Needed a coherent laser oscillator.

Don’t undertake a project unless it is manifestly important and nearly impossible.” Edwin Land - 1982

“One thing leads to another…” (Brad Parkinson)
Scientific Applications of Lasers

....from Coherent Laser Radar to Gravitational Waves... 1988
LISA Concept - Led to LIGO meeting in Boston, Dec 1988

Schematic of LISA in 1988

Expected Launch date of 1998 (now 2035)
- Laser power 1W
- Laser stability extremely high
- Laser reliability > 5 years

Gravitational waves open a new window on universe

Detect amplitude and phase of gravitational waves with sensitivity to detect back the era of galaxy formation.
Coherent Laser Radar

**Local Oscillator**
Invention of the Nonplanar Ring Oscillator

**Power Amplifier**
Multipass 60 dB gain slab amplifier

**Heterodyne Receiver**
Fiber coupled heterodyne detection

**Goal:** wind sensing from the laboratory using a coherent Nd:YAG laser transmitter-receiver
Tom Kane, R. L. Byer
“Monolithic, unidirectional Single-mode Nd:YAG ring laser”

NonPlanar Ring Oscillator
Single frequency: <10kHz
LISA and LIGO Detection Bands

(LISA) Space–& (LIGO) Ground–Based Detectors

Gravitational Wave Amplitude

Frequency [Hz]

Unresolved Galactic Binaries
Resolved Galactic Binaries
Coalescence of Massive Black Holes
NS–NS and BH–BH Coalescence
Rotating Neutron Stars
SN Core Collapse

(LISA Science & Technology Study)
The LIGO concept
why it is nearly impossible

Gravitational waves are hard to measure because space doesn’t like to stretch.

Our signal strain, $h = 10^{-21}$, $dL = 4 \times 10^{-18}$ meters

(that’s why it’s taken so long, Einstein 1916, Weiss 1973)

1 atom between the earth and sun

1/1000 proton diameter in 4km
LIGO had a rough start – two groups not in sync!


Caltech group 1991 led by Robbie Vogt and Ron Drever

MIT group led by Rai Weiss
Jay Marx joined LIGO as Director - Jan 2006
David Reitze is current director
Laser Interferometer Gravitational-wave Observatory

- Managed and operated by Caltech & MIT with funding from NSF
- Ground breaking 1995
- 1st interferometer lock 2000
- Design sensitivity 2005
- LIGO Scientific collaboration: 45 institutions, world-wide
LIGO Interferometer
Michelson’s Interferometer!

1887 experiment to measure “luminiferous ether” with an interferometer

In the first experiment one of the principal difficulties encountered was that of revolving the apparatus without producing distortion; and another was its extreme sensitiveness to vibration. This was so great that it was impossible to see the interference fringes except at brief intervals when working in the city, even at two o’clock in the morning.

Michelson’s Interferometer!

1887 experiment to measure “luminiferous ether” with an interferometer

LIGO Interferometer Optical Layout

H1: 4km @ LHO
H2: 2km @ LHO
L1: 4km @ LLO

LIGO = Laser Interferometer Gravitational Wave Observatory
Quantum Fluctuations and Noise in Parametric Processes. I.

W. H. Louisell and A. Yariv
Bell Telephone Laboratories, Murray Hill, New Jersey

AND

A. E. Siegman
Stanford University, Stanford, California

(Received June 27, 1961; revised manuscript received August 31, 1961)

A quantum mechanical model for parametric interactions is used to evaluate the effect of the measuring (amplifying) process on the statistical properties of radiation. Parametric amplification is shown to be ideal in the sense that it allows a simultaneous determination of the phase and number of quanta of an electromagnetic wave with an accuracy which is limited only by the uncertainty principle. Frequency conversion via parametric processes is shown to be free of zero-point fluctuations.

I. INTRODUCTION

PARAMETRIC interactions, which were first studied by Faraday and Lord Rayleigh in the nineteenth century, are now receiving renewed attention which is their successful utilization as microwave parametron devices. It is becoming more clear that characterization of parametric processes or multiresonant systems in which an electromagnetic field is generated by a periodic energy exchange or a continuous transfer of energy between a modulating source and resonant systems or a continuous transfer of energy between a modulating source and a resonant amplifier is also an "ideal" phase sensitive amplifier. This is done by the use of a quantum mechanical model for parametric processes which in the classical limit yields all the known classical features of parametric amplifiers. This quantum mechanical model is in fact so simple, especially when compared to that of the negative-temperature (meser) type of amplification, that it makes the parametric amplifier an attractive model for the study of the statistical properties of phase-coherent amplification and the limiting uncertainties imposed on amplitude and phase measurements by quantum mechanical fluctuations.

The formalism of field quantization is used to obtain a solution for the time-dependent annihilation operator.
Quantum noise in a continuous-wave laser-diode-pumped Nd:YAG linear optical amplifier


Edward L. Ginzton Laboratory, Stanford University, Stanford, California 94305

S. Rowan and J. Hough

Department of Physics and Astronomy, University of Glasgow, Glasgow G12 8QQ, UK

Received September 24, 1998

We present measurements of the power noise that is due to optical amplification in a laser-diode-pumped Nd:YAG free-space traveling-wave linear amplifier in a master-oscillator–power-amplifier configuration. The quantum noise behavior of the optical amplifier was demonstrated by use of InGaAs photodetectors in a balanced detection configuration, at a total photocurrent of 100 mA and in a frequency band from 6.25 to 15.625 MHz. The experimental results are in good agreement with predictions. © 1998 Optical Society of America

OCIS codes: 140.4480, 270.2500, 140.3580, 270.5290, 140.3280.

High-power, low-noise lasers are required for laser interferometric gravitational-wave detection and free-space optical communication. The advanced detector in the Laser Interferometer Gravitational Wave Observatory (LIGO) program will require a low-noise, continuous-wave (cw), 100-W, single-frequency, diffraction-limited TEM$_{00}$ mode laser. High single-pass gains demonstrated in cw laser-diode-pumped zigzag slab lasers indicate that cw amplification in a Nd:YAG master-oscillator–power-amplifier (MOPA) guided-wave semiconductor and fiber laser amplifiers used in long-distance optical transmission systems. In studies of argon-laser amplifiers existing noise theories were applied to free-space amplifiers. However, the multiline operation of the argon-ion laser system required a detailed analysis of the spontaneous emission factor. The four-level nature of the Nd:YAG laser system simplifies this analysis because of the complete inversion of the gain medium. To our knowledge we present the first
10 Watt Nd:YAG Laser for LIGO
(7 lasers delivered in 1995 - all operated through 2005)

LIGO Prestabilized Laser
10 W TEM$_{00}$ mode
Nd:YAG NPRO Master Oscillator
Followed by Power Amplifier

LIGO Laser installed in Summer Of 1995. Diode pumped Nd:YAG has shown low noise, high reliability and capability for power scaling in the future.

NSF - what does 'discovery research' lead to in the real world?

Other applications of low noise laser sources
use in under water vessels
in space satellite communications
inspection of composite aircraft skins
Laser Interferometer Gravitational-wave Observatory

- Managed and operated by Caltech & MIT with funding from NSF
- Ground breaking 1995
- 1st interferometer lock 2000
- Design sensitivity 2005
- LIGO Scientific collaboration: 45 institutions, world-wide
LIGO Sensitivity Livingston 4km Interferometer

- May 2001
- Jan 2003
LIGO Sensitivity 2005

- L1, 5 June 2005, near best, 9.3 Mpc
- L1, S4 best, 7.3 Mpc
- SRD

Peter Fritschel, Commissioning Report, 15 Aug 2005, LIGO # G050371
NSF gave go-ahead to build Advanced LIGO!

Projected Advanced LIGO performance

- Newtonian background, estimate for LIGO sites
- Seismic 'cutoff' at 10 Hz
- Suspension thermal noise
- Test mass thermal noise
- Standard quantum noise dominates at most frequencies for full power, broadband tuning
**Advanced LIGO 180W Lasers - Benno Wilke, Hannover, Germany**

**Edge Pumped Nd:YAG slab - Stanford**

**Injection locked Nd:YAG oscillators - Hannover**

**Benno Willke**
Hannover

**In charge of 180W Laser program for Advanced LIGO**

**Unstable resonator -- Adelaide**
180W prototype - layout

- NPRO
- medium power stage
- high power stage
- pre-modecleaner
- to interferometer
Advanced LIGO

180 W

LRER -> MOD.

ACTIVE THERMAL CORRECTION

PRM T~6%

T=0.5%

30KG

BS

ITM

SRM T=5%

830 kW

PRM Power Recycling Mirror
BS Beam Splitter
ITM Input Test Mass
ETM End Test Mass
SRM Signal Recycling Mirror
PD Photodiode

Ribbons welded to silica ears bonded to mass
LIGO fused silica Test Mass
Coating absorption loss < 1ppm
LIGO Vacuum Equipment

- 1.2 m diameter
- Aligned to a mm
- Total of 16 km fabricated with no leaks
- 1 nTorr (!)
- Few, remote pumps
- Cover...

Vacuum pipes protected by concrete shell
Test of concrete Vacuum tube enclosures!
Gravitational Wave Sources

- **Bursts**
  - catastrophic stellar collapse to form black holes or neutron stars
  - final inspiral and coalescence of neutron star or **black hole binary systems** – possibly associated with gamma ray bursts

- **Continuous**
  - pulsars (e.g. Crab) (sign up for Einstein@home)
  - low mass X-ray binaries Sco-X1

- **Stochastic Background**
  - random background “noise” associated with cosmological processes, e.g. inflation, cosmic strings.....

A New Astronomy

SN1987a
Shoemaker led the Advanced LIGO Construction Project

David Shoemaker - MIT

- Started April 2008, completed in summer of 2015 with installation of the computing cluster
- The Project met all milestones in terms of ‘earned value’.
- Costs are good (a little under due to soft economy);
- No significant new noise sources or problems – should be able to get to that promised factor-of-10 in sensitivity

Engineering test run completed Summer 2015

1st Science run started September 2015 --to last 3 months

From Discovery to Astronomy!
David Shoemaker - MIT

- Started April 2008, completed in summer of 2015 with installation of the computing cluster
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Engineering test run completed Summer 2015

1st Science run started September 2015 --to last 3 months

Press Conference - Feb 11 2016

From Discovery to Astronomy!
LIGO Scientific Collaboration

- Australian Consortium for Interferometric Gravitational Astronomy
- The Univ. of Adelaide
- Andrews University
- The Australian National Univ.
- The University of Birmingham
- California Inst. of Technology
- Cardiff University
- Carleton College
- Charles Stuart Univ.
- Columbia University
- Embry Riddle Aeronautical Univ.
- Eötvös Loránd University
- University of Florida
- German/British Collaboration for the Detection of Gravitational Waves
- University of Glasgow
- Goddard Space Flight Center
- Leibniz Universität Hannover
- Hobart & William Smith Colleges
- Inst. of Applied Physics of the Russian Academy of Sciences
- Polish Academy of Sciences
- India Inter-University Centre for Astronomy and Astrophysics
- Louisiana State University
- Louisiana Tech University
- Loyola University New Orleans
- University of Maryland
- Max Planck Institute for Gravitational Physics
- University of Michigan
- Massachusetts Inst. of Technology
- Monash University
- Montana State University
- Moscow State University
- National Astronomical Observatory of Japan
- Northwestern University
- University of Oregon
- Pennsylvania State University
- Rochester Inst. of Technology
- Rutherford Appleton Lab
- University of Rochester
- San Jose State University
- Univ. of Sannio at Benevento, and Univ. of Salerno
- University of Sheffield
- University of Southampton
- Southeastern Louisiana Univ.
- Southern Univ. and A&M College
- Stanford University
- University of Strathclyde
- Syracuse University
- Univ. of Texas at Austin
- Univ. of Texas at Brownsville
- Trinity University
- Universitat de les Illes Balears
- Univ. of Massachusetts Amherst
- University of Western Australia
- Univ. of Wisconsin-Milwaukee
- Washington State University
- University of Washington
Gravitational-wave rumours in overdrive

Physicists say they've heard that the LIGO observatory may have spotted the signature of merging black holes.

Davide Castelvecchi

12 January 2016
LIGO Press Conference Feb 11, 2016

Join us for the live streaming of the LIGO Press Conference to discuss results from the first observation run of Advanced LIGO

Thursday, Feb 11th 2016 @ 7:30 am
Spilker 2nd Floor

All members of Ginzton Lab and HEPL are welcome to join
light breakfast will be provided

ligo.stanford.edu
February 11, 2016
LIGO announces
Gravitational waves

Ladies and Gentlemen, we have detected gravitational waves, we did it!
Gravitational Wave Signal Detected
Sept 14 2015 -- 150914

Signal to Noise ~23

Strong signal suggests merger of ~10 Solar Mass Black Holes
Merging binary BHs of 29 & 36 solar masses radiate 10,000x more power in 0.25sec than all the stars in the Universe

\[ E = M c^2 \quad M = 3 \text{ Solar Masses} \]

The LIGO suspension system developed at Stanford uses three stages with feedback control to isolate the LIGO optics from ground motion to <1pm/Hz^{1/2}

The LIGO suspension system allows detectors beyond Advanced LIGO
General Relativity Calculates space time distortion
Chirped Gravitational wave from 30Hz to 240Hz in 0.25sec
Celebration Cake for LIGO Success!

Congratulations Stanford and the LIGO Scientific Collaboration.

Stanford

LIGO VIRGO
Kip Thorne with LIGO students at Stanford
Feb 16 2016
LIGO Three detections - BH BH mergers
BH-BH Merger radiates 1 solar mass of energy
Location on the Southern Sky
Global network of interferometers
Build a Southern Observatory

- Detection confidence
- Source polarization
- Sky location
- Duty cycle
- Waveform extraction
GW170814: A three-detector observation of gravitational waves from a binary black hole coalescence

The LIGO Scientific Collaboration and The Virgo Collaboration

On August 14, 2017 at 10:30:43 UTC, the Advanced Virgo detector and the two Advanced LIGO detectors coherently observed a transient gravitational-wave signal produced by the coalescence of two stellar mass black holes, with a false-alarm-rate of \( \lesssim 1 \) in 27000 years. The signal was observed with a three-detector network matched-filter signal-to-noise ratio of 18. The inferred masses of the initial black holes are \( 30.5^{+1.3}_{-0.7} M_\odot \) and \( 25.8^{+2.5}_{-2.3} M_\odot \) (at the 90% credible level). The luminosity distance of the source is \( 840^{+130}_{-210} \) Mpc, corresponding to a redshift of \( z \approx 0.11_{-0.02}^{+0.03} \). A network of three detectors improves the sky localization of the source, reducing the area of the 90% credible region from 1160 deg\(^2\) using only the two LIGO detectors to 60 deg\(^2\) using all three detectors. For the first time, we can test the nature of gravitational wave polarizations from the antenna response of the LIGO-Virgo network, thus enabling a new class of phenomenological tests of gravity.

PACS numbers:

INTRODUCTION


On August 14, 2017, GWs from the coalescence of two black holes at a luminosity distance of \( 540^{+130}_{-210} \) Mpc, with masses of \( 30.5^{+1.3}_{-0.7} M_\odot \) and \( 25.8^{+2.5}_{-2.3} M_\odot \), were observed in all three detectors. The signal was first observed at the LIGO Livingston detector at 10:30:43 UTC, and at the LIGO Hanford and Virgo detectors with a delay of \( \sim 8 \) ms and \( \sim 14 \) ms, respectively.

The signal-to-noise ratio (SNR) time series, the time-frequency representation of the strain data and the time series data of the three detectors together with the inferred in Virgo and a BBH signal only in the LIGO detectors: the three detector BBH signal model is preferred with a Bayes factor of more than 1600. We note that our parameter estimation assumes that the noise in the detectors is Gaussian in the 4 s window around the event. An Anderson-Darling test on the whitened residuals, after subtraction of the best-fit waveform, is consistent with this assumption.

Until Advanced Virgo became operational, typical GW position estimates were highly uncertain compared to the fields of view of most telescopes. The baseline formed by the two LIGO detectors allowed us to localize most mergers to roughly annular regions spanning hundreds to about a thousand square degrees at the 90% credible level \( [7] \). Virgo adds additional independent baselines, which in cases such as GW170814 can reduce the positional uncertainty by an order of magnitude or more \( [8] \).
Rapid localization on the sky - ~ 5 x 5 degrees
Virgo turns on Aug 1 2017 - Detection almost immediately
Press release Sept 26, 2017

1st detection of merger with three interferometers

Gives localization of event on the sky to allow follow-up observations using other telescopes.

Scheduled LIGO Press Conference:

Oct 15, 2017
7:00 AM PDT - Spilker
Gravitational and Gamma Rays from Binary NS Merger

GRAVITATIONAL WAVES AND GAMMA RAYS FROM A BINARY NEUTRON STAR MERGER: GW170817 AND GRB170817A

LVC
GBM
INTEGRAL

(Dated: September 25, 2017)

ABSTRACT

The coalescence of two neutron stars was independently detected in gravitational waves by the Advanced Laser Interferometer Gravitational-Wave Observatory and Virgo instruments and in gamma-rays by the Fermi Gamma-ray Burst Monitor and the Anticoincidence Shield for the SPectrometer for INTErnational Gamma-Ray Astrophysics Laboratory. We discuss the association of the triggered short gamma-ray burst GRB170817A to the gravitational-wave trigger GW170817, confirm binary neutron star mergers as short gamma-ray burst progenitors, explore the fundamental physics and astrophysical implications made possible by the short time delay between these signals, and inform our understanding of short gamma-ray bursts based on the unique properties of GRB170817A. [FP: Add quantitative information when body of paper is finalized.]
Crashing neutron stars can make gamma-ray burst jets

- Simulation begins
- 7.4 milliseconds
- 13.8 milliseconds
- 15.3 milliseconds
- 21.2 milliseconds
- 26.5 milliseconds

Magnetic fields

Neutron stars:
- Masses: 1.3 suns
- Diameters: 17 miles (27 km)
- Separation: 11 miles (18 km)

Black hole forms:
- Mass: 2.9 suns
- Horizon diameter: 5.6 miles (9 km)

Jet-like magnetic field emerges
Dawn of an Era: Astronomers Hear and See Cosmic Collision

By Eric Betz | Published: Monday, October 16, 2017

Two neutron stars merge into a kilonova.
Illustration by Robin Dienel, courtesy of the Carnegie Institution for Science

For hundreds of millions of years, two city-sized stars in a galaxy not-so-far away circled each other in a fatal dance. Their dimensions were diminutive, but each outweighed our sun.

They were neutron stars — the collapsed cores left behind after giant stars exploded into supernovae. Charged dense, these stars had long been predicted to collide and explode in kilonovae. In 2017, the first such event was observed by astronomers around the globe.
**NGC 4883 Galaxy with NS NS Kilo Nova in visible light**

**GW170817**

**NGC 4993: The Galactic Home of an Historic Explosion**
Image Credit: NASA & ESA

**Explanation:** That reddish dot -- it wasn't there before. It's the dot to the upper left of galaxy NGC 4993's center, do you see it? When scanning the large field of possible locations of an optical counterpart to the unprecedented gravitational wave event GW170817 in August, the appearance of this fading dot quickly became of historic importance. It pinpointed GW170817's exact location, thereby enabling humanity's major telescopes to examine the first ever electromagnetic counterpart to a gravitational wave event, an event giving strong evidence of being a short gamma-ray burst kilonova, the element-forming explosion that occurs after two neutron stars merge. The featured image of lenticular galaxy NGC 4993 by Hubble shows the fading dot several days after it was discovered. Analyses, continuing, include the physics of the explosion, what heavy elements formed, the similarity of the speeds of gravitational radiation and light, and calibrating a new method for determining the distance scale of our universe.

More on GW170817: [Journal articles](#), [data](#), [graphics](#)

Tomorrow's picture: elements of you
In August 2017 the Gravitational Wave Detection Network, comprised of Advanced Virgo and the two Advanced LIGO observatories, was listening for GW events before it shut down again for refinements to improve sensitivity.

The operation in coincidence of the three detectors allowed, for the first time, triangulation in two directions and good directionality for the detected events.

During this brief window of time interesting events were detected, including at least one BH-BH and one NS-NS inspiral, and directionality was important!

The glimpse through this window showed us an exciting landscape and generated many new questions.

We are now in an active Q&A with the universe.

Figure 1: The detection of 5 BH and 1 NS inspiral. The last two August events, GW170814 and GW170817, have better directionality due to the triangulation allowed by the three-observatory detection mode. Surprisingly, all BHs are of a heavier mass than expected for stellar BHs. They
The GW signal from NS-NS Merger
More than 60 sec duration across LIGO frequency band

Figure 2: The first neutron star binary inspiral detected by the GW detection network (credit Dr. Alexander Nitz, Max Planck Institute for Gravitational Physics, Albert Einstein Institute).
BH and NS Signals to Date

GW150914 $M = 36+29 = 62$

LVT151012 $M = 15+23$

GW151226 $M = 14.2 + 7.5 = 20.8$

GW170104 $M = 31.2 + 17.04 = 48.7$

GW170814 $M = 30.5 + 25.3 = 53.2$

GW170817 $M = 1.36 + 1.17 = 2.74$
GW170814 and GW170817 were triangulated using LIGO and Virgo Detectors.
A wrinkle in space-time confirms Einstein's gravitation

“Ladies and gentlemen, we have detected gravitational waves. We did it!” The words from LIGO spokesperson David Reitze prompted cheers at the press conference on February 11, and with good reason. The tangibility of gravitational waves has taunted scientists since Albert Einstein first predicted them 100 years ago. In the intervening century, scientists have proved relativity a hundred times over. But no one had ever measured the delicate vibrations of the waves themselves. These ripples in space-time are currently detectable only when the universe’s densest objects — black holes or neutron stars — smash together. And on September 14, 2015, the ripples arrived from two black holes that merged some 1.3 billion light-years away. Despite the cosmos-shaking collision that produced the first recorded signal, LIGO (the Laser Interferometer Gravitational-wave Observatory) had to strain to hear it past the literal earthquakes and even nearby motor traffic that also jolts its detectors.

Merging black holes warp space around them in this artist’s illustration, gravitationally lensing background stars and causing the swirls visible around them.
Einstein: I told you so!
Kavli Prize to Drever, Thorne, Weiss, Sept 6, 2016

Newsletter

Dedicated to the advancement of science for the benefit of humanity, The Kavli Foundation supports scientific research, honors scientific achievement, and promotes public understanding of scientists and their work. For more information, visit: www.kavifoundation.org

Summer 2016

THE KAVLI PRIZE

CELEBRATING THE 2016 KAVLI PRIZE LAUREATES

On September 6, the Kavli Prizes in Astrophysics, Nanoscience and Neuroscience will be presented by Norway’s Royal Highness Crown Prince Haakon at an award ceremony in Oslo. KavliPrize.org will present a delayed webcast of the event.

Kavli Prize Week activities begin September 5 in Oslo - also on Facebook and Twitter.
Il Premio Fermi 2016 alle onde gravitazionali

Il prestigioso Premio Enrico Fermi della Società Italiana di Fisica è stato attribuito per il 2016 a Barry BARISH e Adalberto GIAZOTTO “per il loro fondamentale ruolo nella prima osservazione diretta delle onde gravitazionali e per la scoperta di buchi nebulosi in coalescenza”.

In particolare:
- a Barry Barish, California Institute of Technology, Pasadena, CA, USA, “per il suo fondamentale contributo alla rivelazione di onde gravitazionali attraverso la Maser Interferometrica in California”.
- a Adalberto Giazotto, Università di Torino, “per il suo contributo fondamentale alla rivelazione di onde gravitazionali attraverso la Maser Interferometrica in Italia”.

ULTIMI ARTICOLI
- Fisica nella tormenta
- Nuove e sfide: nuovi risultati da CLOUD
- A Padova il 102° Congresso SIF
- IONS Nazioni 2016, l'Italia ospita i giovani
Gravitational wave researchers win Nobel Prize
Three American physicists have won the 2017 Nobel Prize in Physics for their contribution to detecting gravitational waves.
LIGO Nobel Prize Cake - Nagoya Japan Oct 3, 2017