LIGO and Gravitational Waves
Einstein, Lasers, Black Holes and Neutron Stars!

Robert L. Byer
Department of Applied Physics
Stanford University
rlbyer@stanford.edu

ABSTRACT

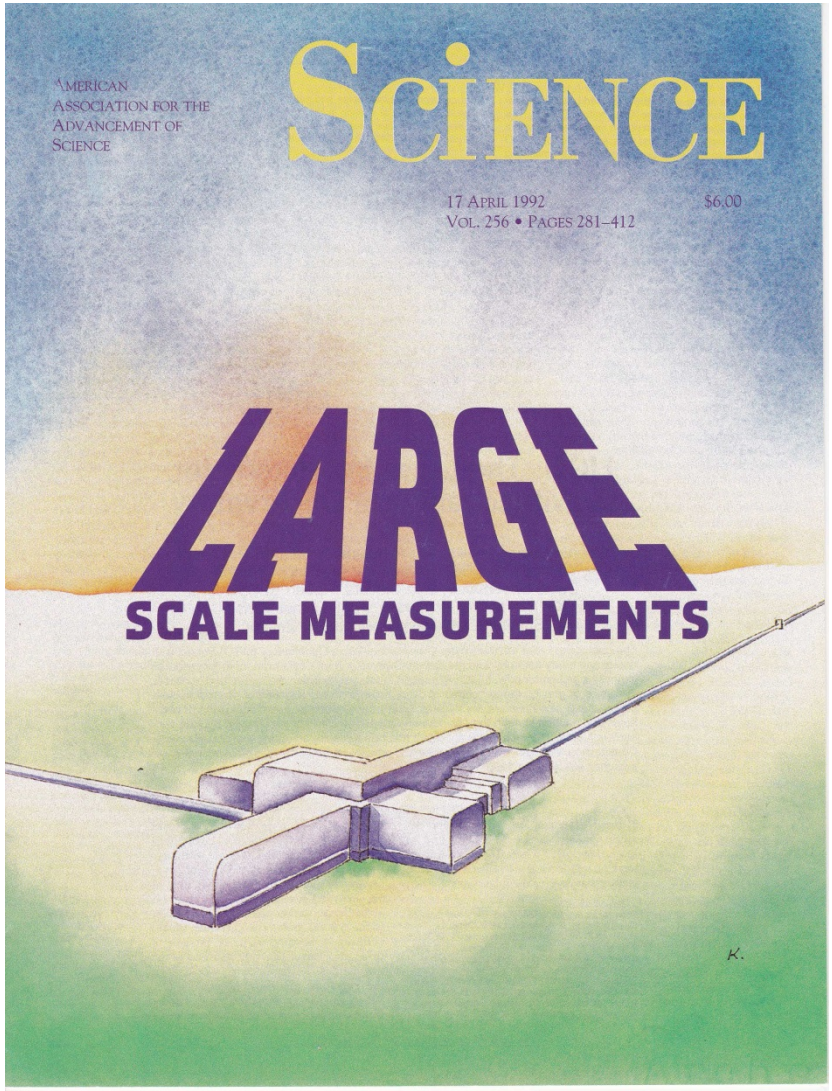
The LIGO collaboration successfully detected gravitational waves on September 14, 2015 had its beginning in 1986 as a draft proposal by Prof Rai Weiss of MIT to the NSF. Stanford soon joined the LIGO effort and has contributed to the observatories and to next generation detectors. LIGO has now detected 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.

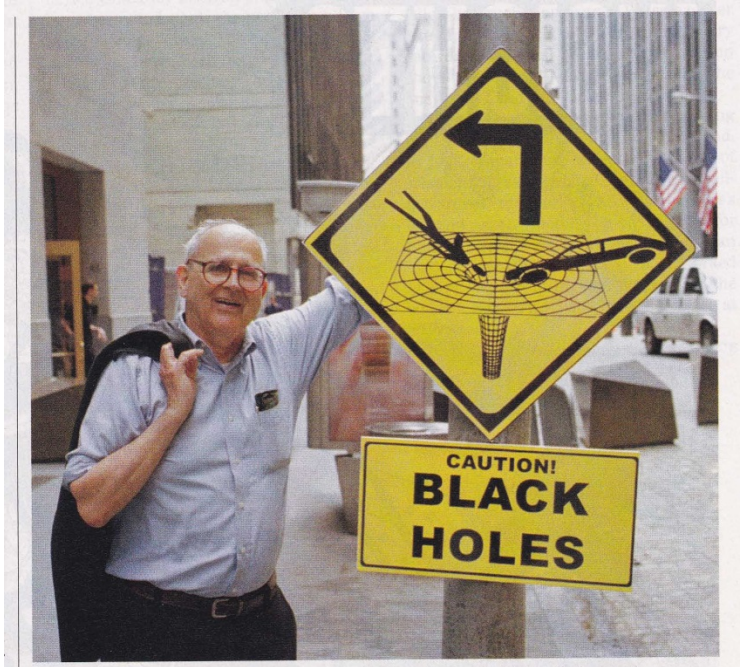
LIGO and Advanced LIGO nearly impossible requirements were met and enabled by advances in solid state lasers, isolation and control, and precision measurement techniques. This is a brief story of LIGO and the direct detection of gravitational waves: the most precise measurement ever conceived.

Stanford Center Position Navigation and Time
Stanford Faculty Club
November 8, 2017

LIGO – suggested by Rai Weiss

Byer Group



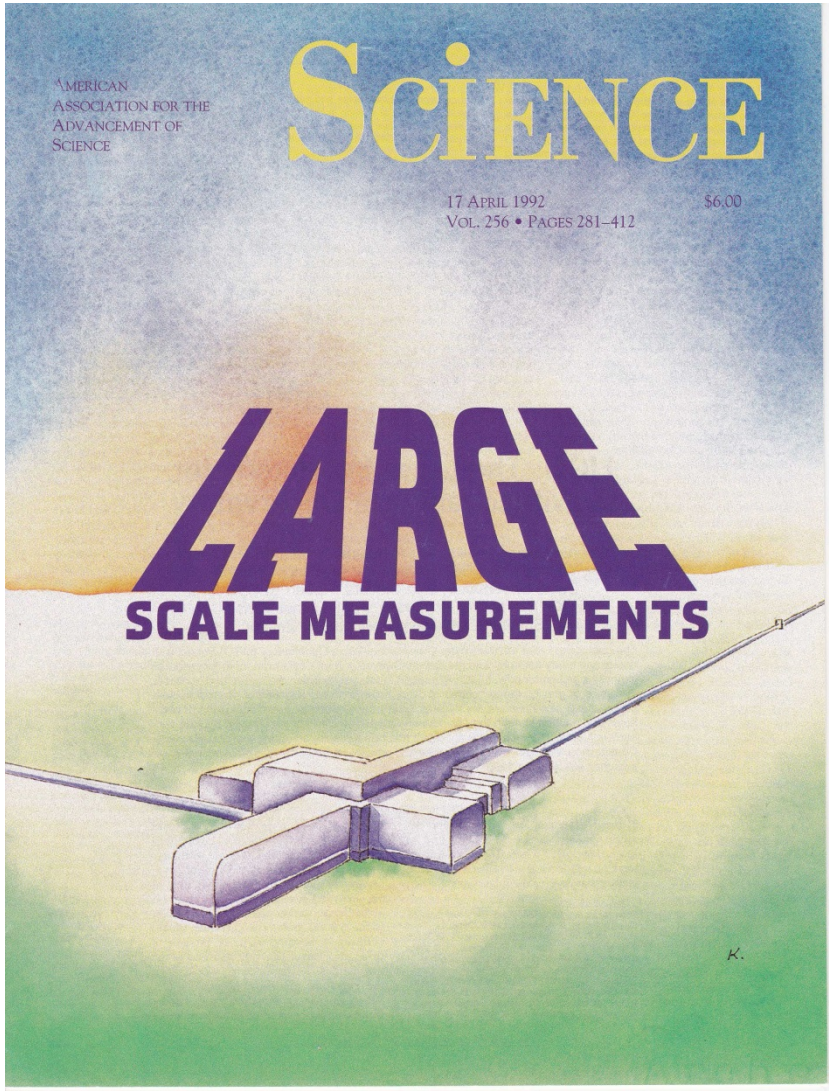


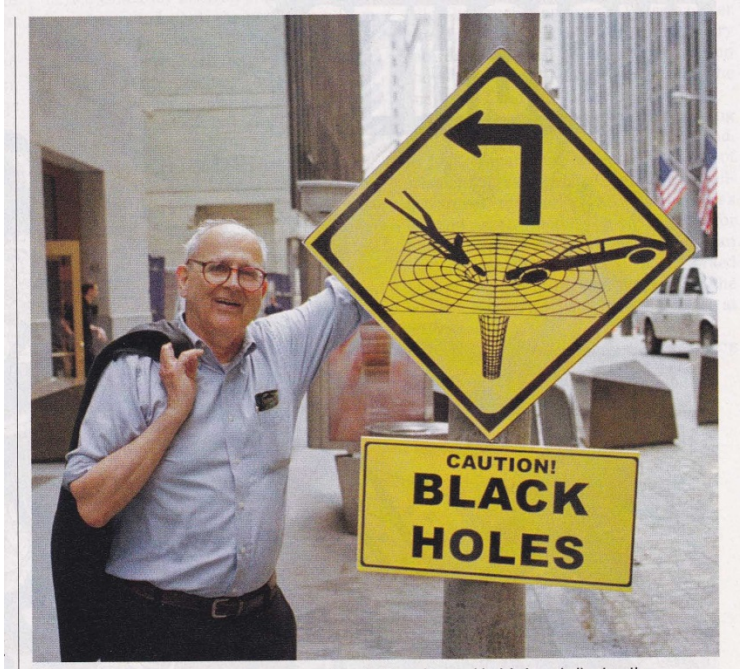
LIGO has spotted just the type of source Rainer Weiss had hoped to see: black holes spiraling together.

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

LIGO – suggested by Rai Weiss

Byer Group





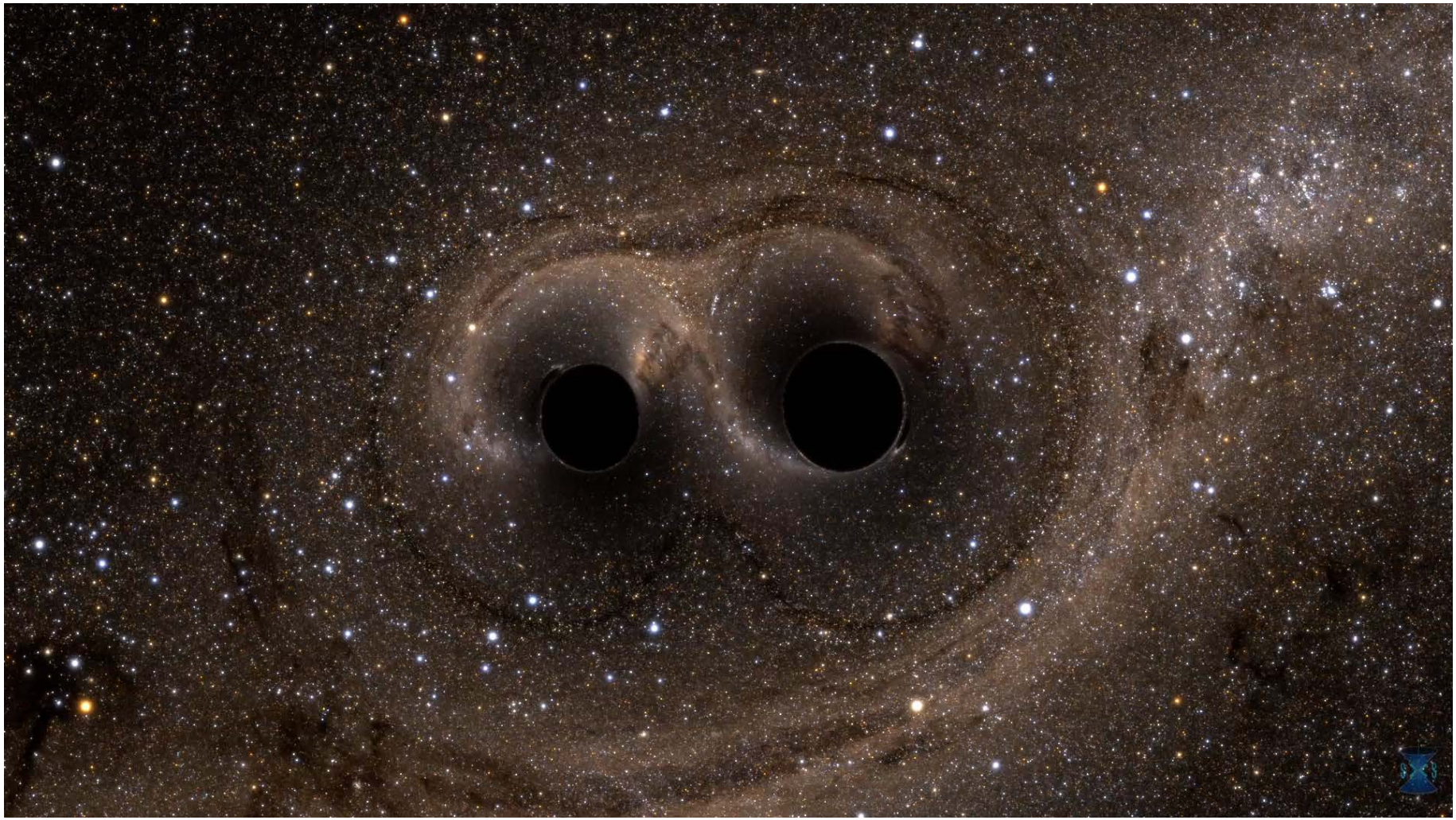
LIGO has spotted just the type of source Rainer Weiss had hoped to see: black holes spiraling together.

Rai Weiss – 1972
NSF meeting – 1988
Funded! begin work 1992
Delivered 7 laser systems 1995
Detection Sept 2015 - 100 yrs!


LIGO MAGAZINE
issue 8 3/2016
First detection!
9:50:45 UTC, 14 September 2015
LIGO Hanford signal
LIGO Livingston signal

Merger of Two Black Holes

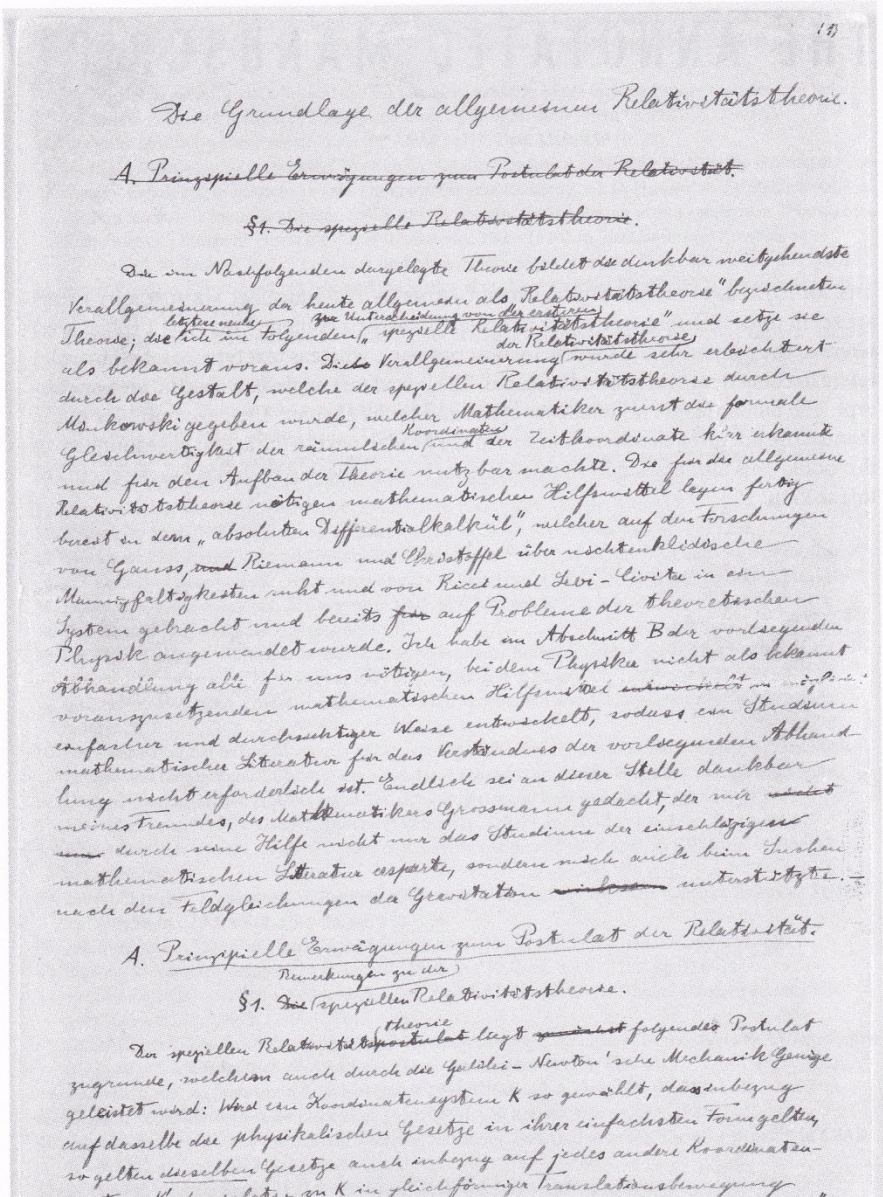
Byer Group



The Foundation of General Relativity

Byer Group

THE ANNOTATED MANUSCRIPT



(1)

Die Grundlage der allgemeinen Relativitätstheorie.

~~A. Prinzipielle Erwägungen zum Postulat der Relativität.~~

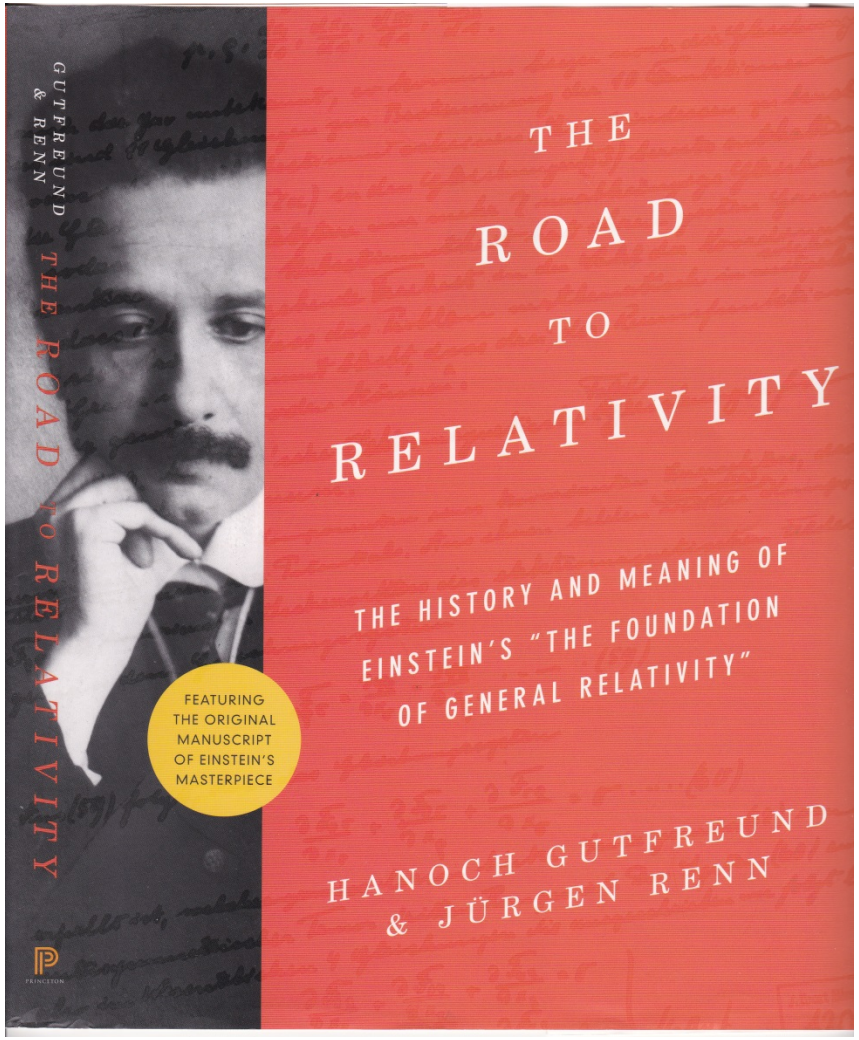
~~§1. Die spezielle Relativitätstheorie.~~

Die im Nachfolgenden dargelegte Theorie bildet die denkbar weitgehendste Verallgemeinerung der heute allgemeinen als „Relativitätstheorie" bezeichneten Theorie; die letztere nenne ich im Folgenden „spezielle Relativitätstheorie" und setze sie als bekannt voraus. Die Verallgemeinerung der Relativitätstheorie wurde durch die Gestalt, welche der speziellen Relativitätstheorie durch Minkowski gegeben wurde, welcher Mathematiker zuerst die formale Gleichwertigkeit der räumlichen Koordinaten und der Zeitkoordinate klar erkannte und für den Aufbau der Theorie nutzbar machte. Die für die allgemeine Relativitätstheorie nötigen mathematischen Hilfsmittel lagen fertig bereit in dem „absoluten Differentialkalkül", welcher auf den Forschungen von Gauss, Riemann und Christoffel über nichteuklidische Mannigfaltigkeiten ruht und von Ricci und Levi-Civita in ein System gebracht und bereits auf Probleme der theoretischen Physik angewendet wurde. Ich habe im Abschnitt B der vorliegenden Abhandlung alle für uns nötigen, bei der Physik nicht als bekannt voraussetzbaren mathematischen Hilfsmittel in einfacher und durchsichtiger Weise entwickelt, sodass ein Studium mathematischer Literatur für das Verständnis der vorliegenden Abhandlung nicht erforderlich ist. Endlich sei an dieser Stelle dankbar meines Freundes, des Mathematikers Grossmann gedacht, der mir durch seine Hilfe nicht nur das Studium der einschlägigen mathematischen Literatur ersparte, sondern mich auch beim Suchen nach den Feldgleichungen der Gravitation unterstützte.

A. Prinzipielle Erwägungen zum Postulat der Relativität.

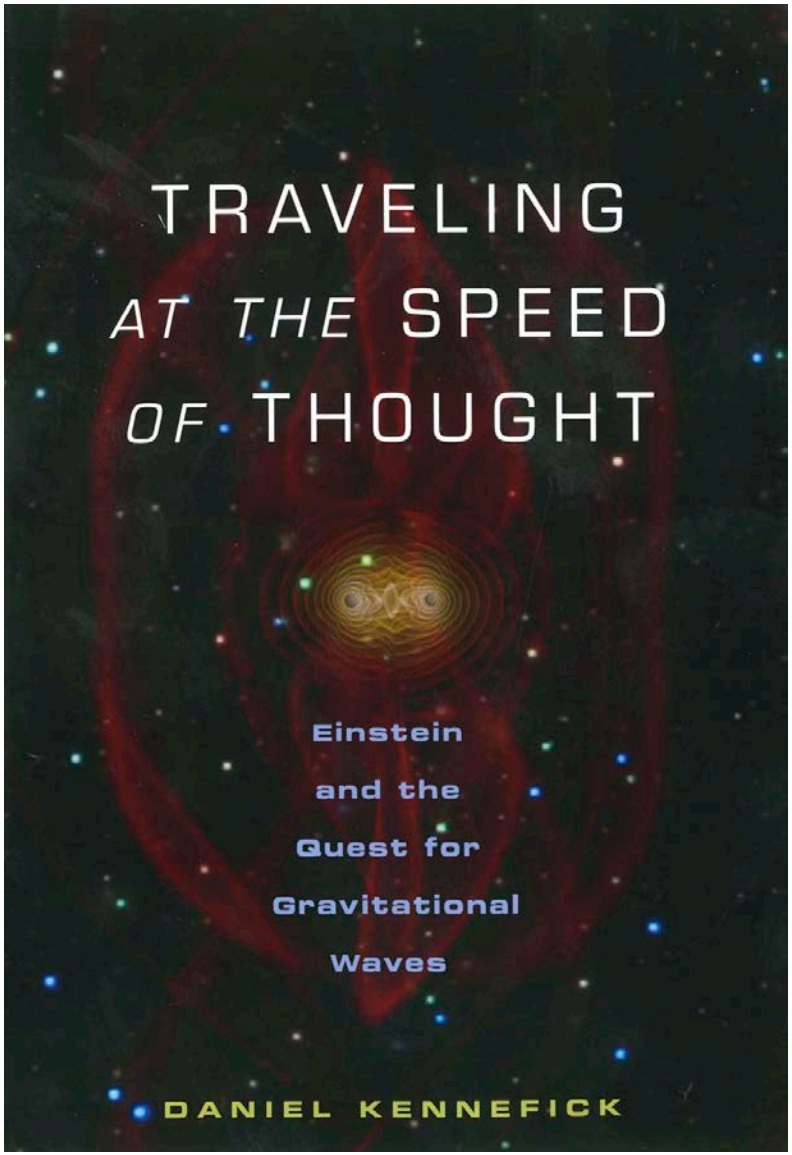
§1. Bemerkungen zur speziellen Relativitätstheorie.

Der speziellen Relativitätstheorie ~~Postulat~~ liegt folgendes Postulat zugrunde, welches auch durch die Galilei-Newton'sche Mechanik Geltung geleistet wird: Wird ein Koordinatensystem K so gewählt, dass bezüglich auf dasselbe die physikalischen Gesetze in ihrer einfachsten Form gelten, so gelten dieselben Gesetze auch bezüglich auf jedes andere Koordinatensystem, welches relativ zu K in gleichförmiger Translationsbewegung



Einstein waffled – were gravitational waves even possible?

Byer Group



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"

COMMENT BOOKS & ARTS

EMILIO SEGRE VISUAL ARCHIVES/AIP/SPL

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

PHYSICS

Einstein's curve ball

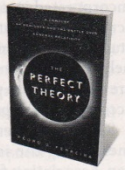
Graham Farmelo enjoys a 'biography' of the general theory of relativity.

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,

penetration, physical intuition and mathematical skill', Einstein developed his general theory of relativity — a new theory of gravity — and published it eight years later. In the final straight, the German mathematician David Hilbert was hot on his heels.

Ferreira outlines the theory, but I wish that he had tried a little harder to con-



The Perfect Theory: A Century of Geniuses and the Battle over General Relativity
PEDRO G. FERREIRA
Houghton Mifflin Harcourt: 2014.

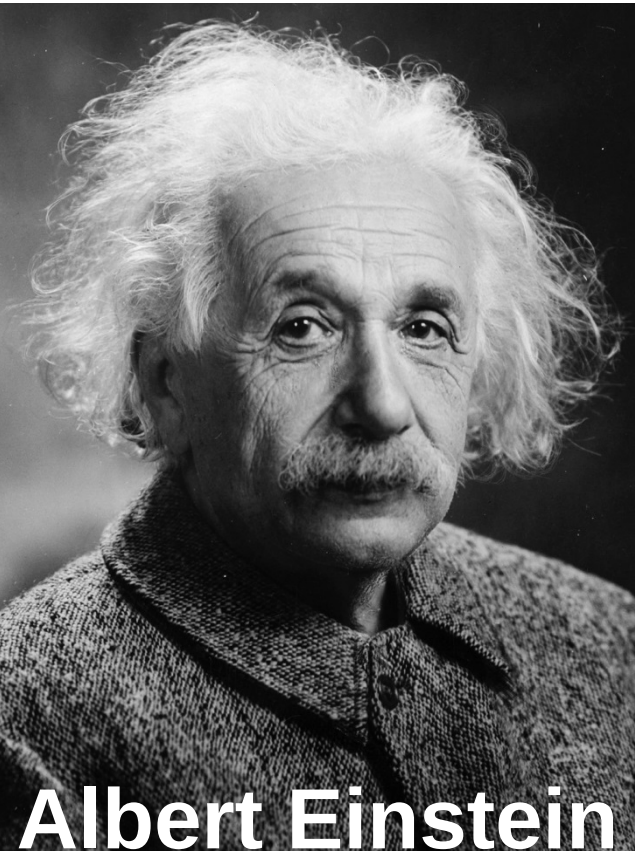
Ferreira describes, one of the most eminent of the physicists who brought the general theory back into the limelight was US theoretician John Wheeler. Wheeler was at first deeply uneasy about the theory's mathematical singularities — the point at which the quantities used to measure the strength of gravitational 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 discover-

What is a Gravitational Wave?

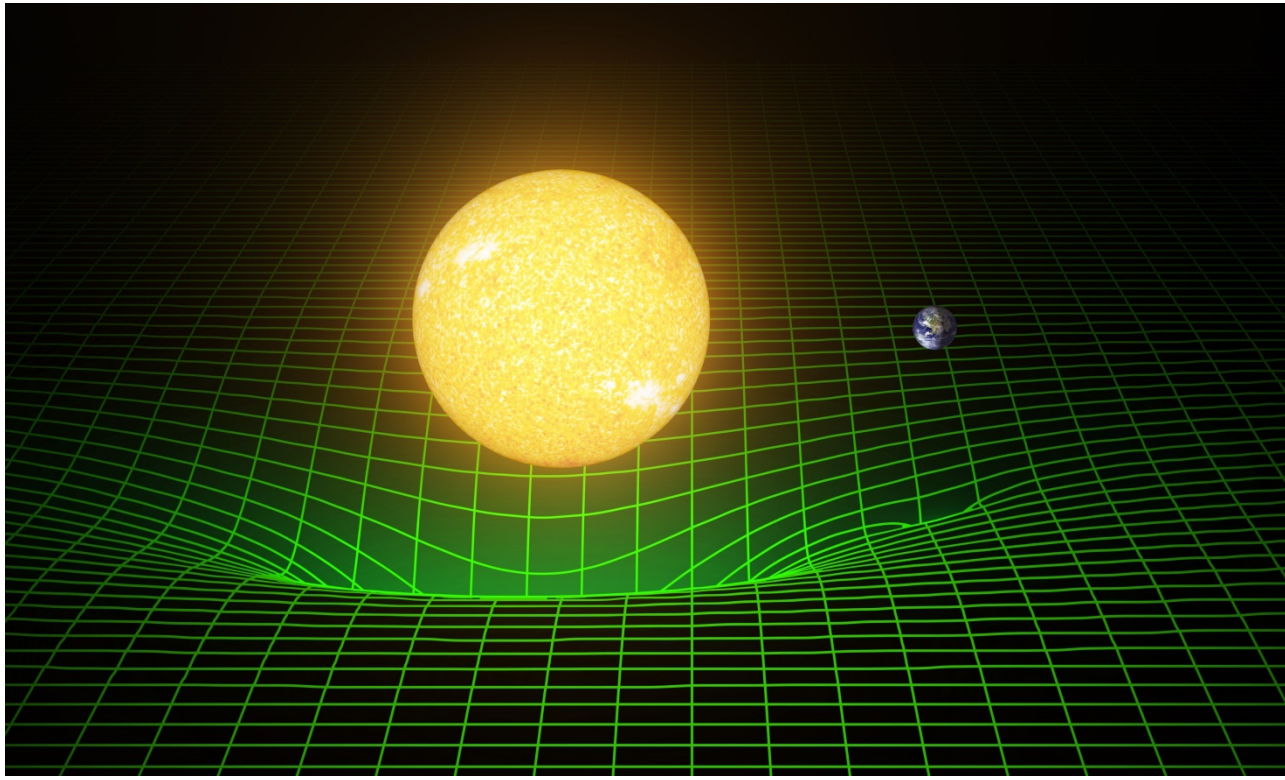
Predicted by Einstein in 1916 as part of GR.

"Spacetime tells matter how to move,
matter tells spacetime how to curve"

- J. A. Wheeler

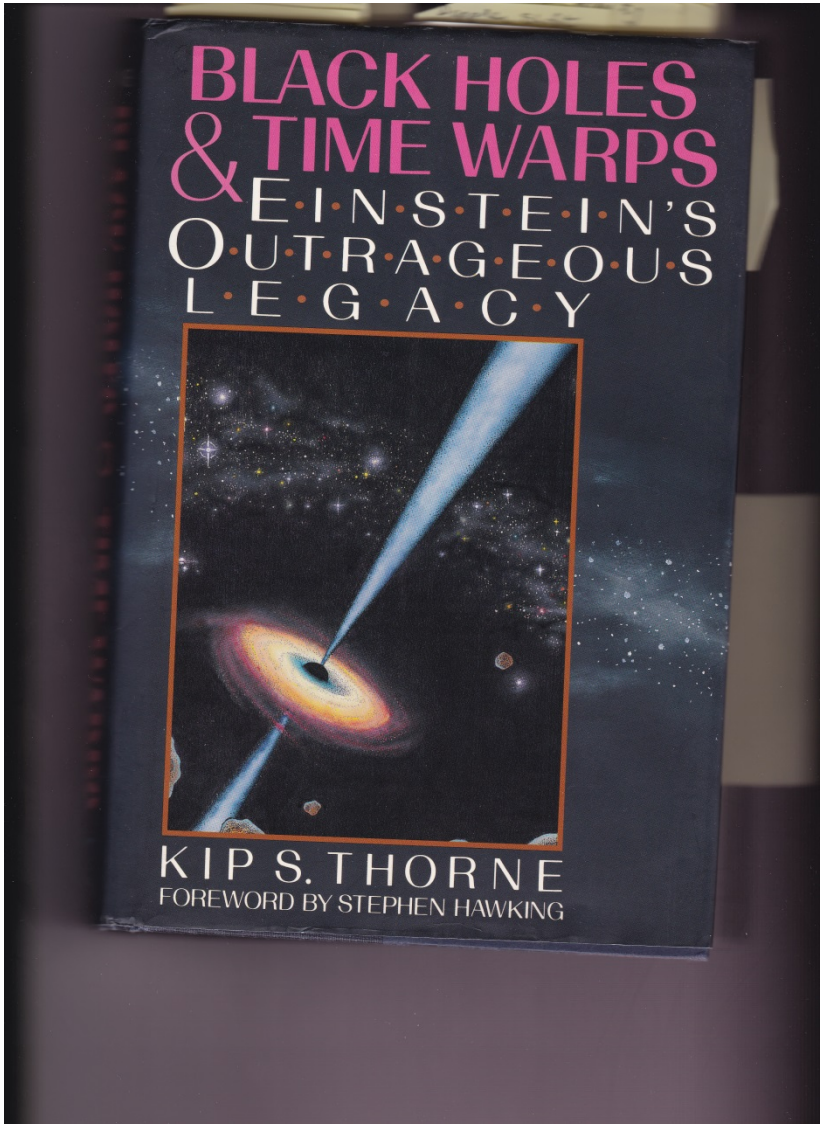


Photograph by Orren Jack Turner, Library of Congress digital ID cph.3b46036.



Kip Thorne and Rai Weiss led
" the neither paved nor well marked road " to LIGO

Byer Group



ISBN 0-393-03505-0 $30.00 USA
$35.00 CAN.

BLACK HOLES & TIME WARPS
EINSTEIN'S OUTRAGEOUS LEGACY

KIP S. THORNE
FOREWORD BY STEPHEN HAWKING

Ever since Albert Einstein's general theory of relativity burst upon the world in 1915 some of the most brilliant minds of our century have sought to decipher the mysteries bequeathed by that theory, a legacy so unthinkable in some respects that even Einstein himself rejected them.

Which of these bizarre phenomena, if any, can really exist in our universe?

- **Black holes**, down which anything can fall but from which nothing can return.
- **Wormholes**, short spacewarps connecting regions of the cosmos.
- **Singularities**, where space and time are so violently warped that time ceases to exist and space becomes a kind of foam.
- **Gravitational waves**, which carry symphonic accounts of collisions of black holes billions of years ago.
- **Time machines**, for traveling backward and forward in time.

Kip Thorne, along with fellow theorists Stephen Hawking and Roger Penrose, a cadre of Russians, and earlier scientists such as Oppenheimer, Wheeler and Chandrasekhar, has been in the thick of the quest to secure answers. In this masterfully written and brilliantly informed work of scientific history and explanation, Dr. Thorne, the Feynman Professor of Theoretical Physics at Caltech, leads his readers through an elegant, always human, tapestry of interlocking themes, coming finally to a uniquely informed answer to the great question: what principles control our

(continued on back flap)

Jacket design by Tim Gaydos
Jacket illustration by Matt Zimet

2–94

(continued from front flap)

universe and why do physicists think they know the things they think they know?

Stephen Hawking's *A Brief History of Time* has been one of the greatest best-sellers in publishing history. Anyone who struggled with that book will find here a more slowly paced but equally mind-stretching experience, with the added fascination of a rich historical and human component.

Credit: Bob Paz/Cal Tech

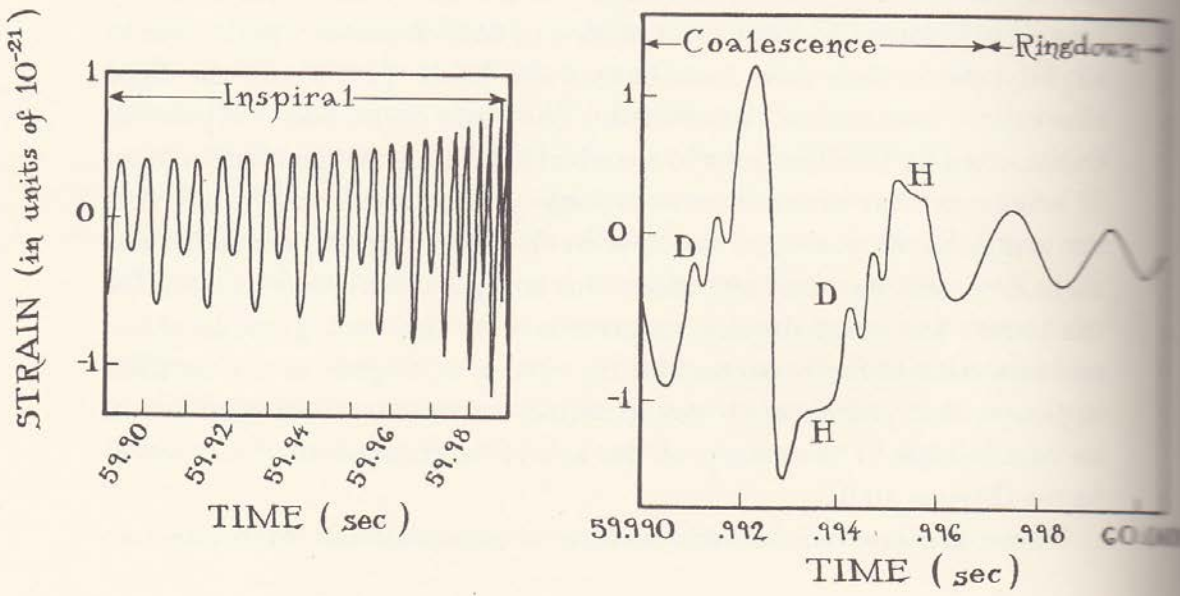
Born in Logan, Utah, in 1940, KIP S. THORNE holds a Ph.D. from Princeton and is currently the Feynman Professor of Theoretical Physics at the California Institute of Technology. A member of the American Academy of Arts and Sciences and the National Academy of Sciences, Dr. Thorne received an honorary degree from Moscow State University in 1981 and was the first recipient of the American Institute of Physics-U.S. Steel Foundation Science Writing Award in Physics and Astronomy. He has held Guggenheim, Danforth, Woodrow Wilson, and Fulbright fellowships and is the author of three other books, including (with John Wheeler and Charles Misner) *Gravitation*, the text from which, for the past twenty years, most physicists have learned Einstein's general theory of relativity.

Printed in the United States of America

Kip Thorne's BH Merger approximate signal amplitude ~10^{-21}

Byer Group

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.



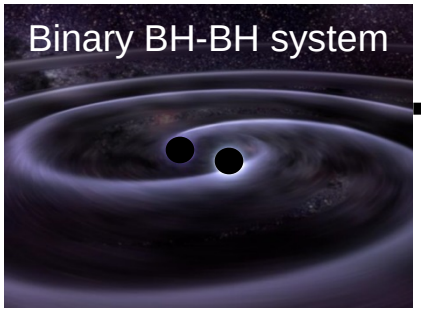
Diameter of one atom at the distance to the sun! 1/1000 diam proton at 4km

The challenge of LIGO data analysis

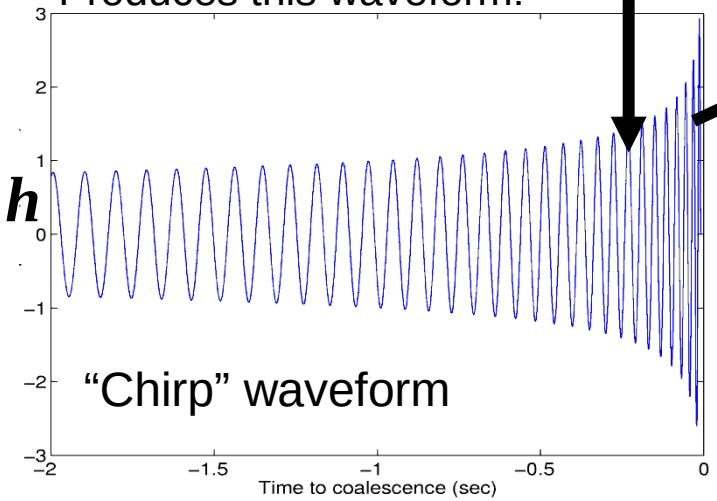
Numerical relativity solves BH Merger signal amplitude

Byer Group

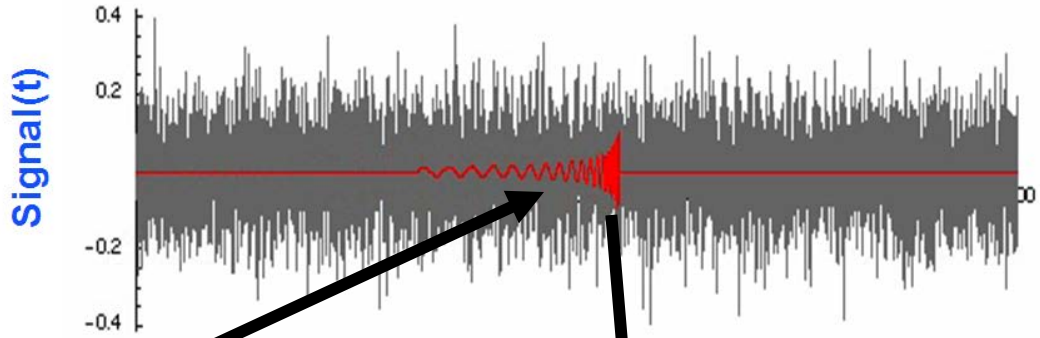
This source:



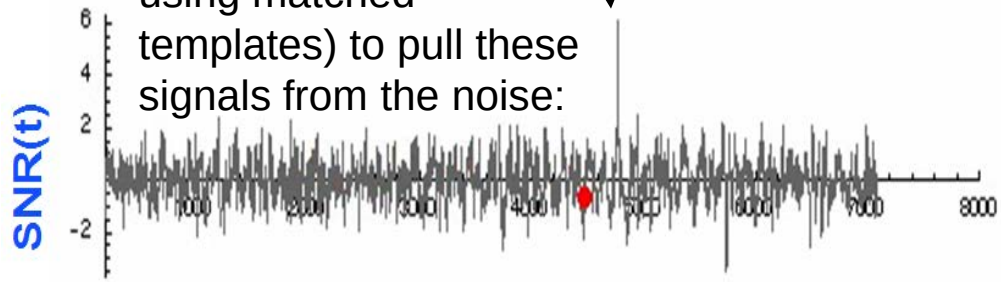
Produces this waveform:



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)

Pre LIGO Panel

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

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

(amended Nov 15,1986)

LI

WORKSHOP COMMITTEE

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

GRAVITY WAVE RESEARCH

A.Abramovici			
A.Cadez			
Y.T.Chen			
R.Drever			
R.Spero	Caltech	A.Brillet	Orsay
K.Thorne	Caltech	P.Tourrenc	Paris
S.Smith	Caltech		
M.Zucker	Caltech	P.Bender	Colorado
G.Leuchs	Max Planck	N.Christiansen	MIT
A.Rudiger	Max Planck	J.Livas	MIT
R.Schilling	Max Planck	M.Burka	MIT
		A.Jeffries	MIT
J.Hough	Glasgow	P.Linsay	MIT
B.Meers	Glasgow	P.Saulson	MIT
B.Schutz	Cardiff	R.Weiss	MIT
H.Ward	Glasgow		

LARGE BASELINE PLANNING AND ENGINEERING

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

EXPERTS IN LASERS AND OPTICAL TECHNOLOGY

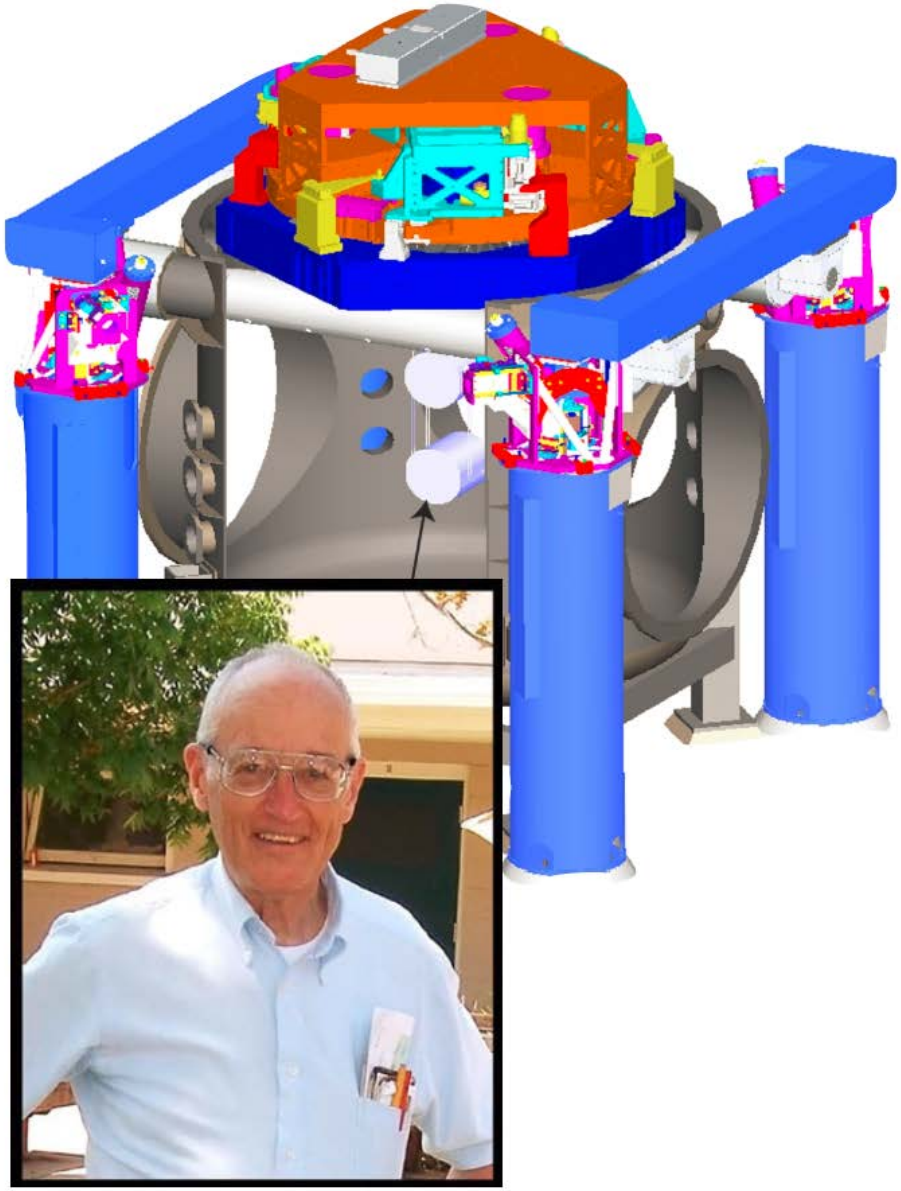
H.Bennett	Michelson Lab	T.Johnston	Coherent Inc
R.Byer	Stanford	H.Kogelnik	Bell Labs
S.Ezekiel	MIT	P.Silverglate	Perkin Elmer
C.Volk	Litton	J.Hannon	Kodak
Kotik Lee	Perkin Elmer	*A.Szoke	Livermore
L.Hackel	Livermore	A.Slomba	Perkin Elmer

OBSERVERS

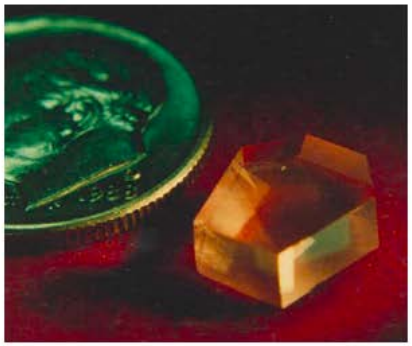
A.Komar	NSF	*F.Allario	NASA Langley
R.Isaacson	Illinois/NSF	M.K.Wilson	NSF
H.Willard	NSF		

*did not attend

Early Stanford LIGO participants

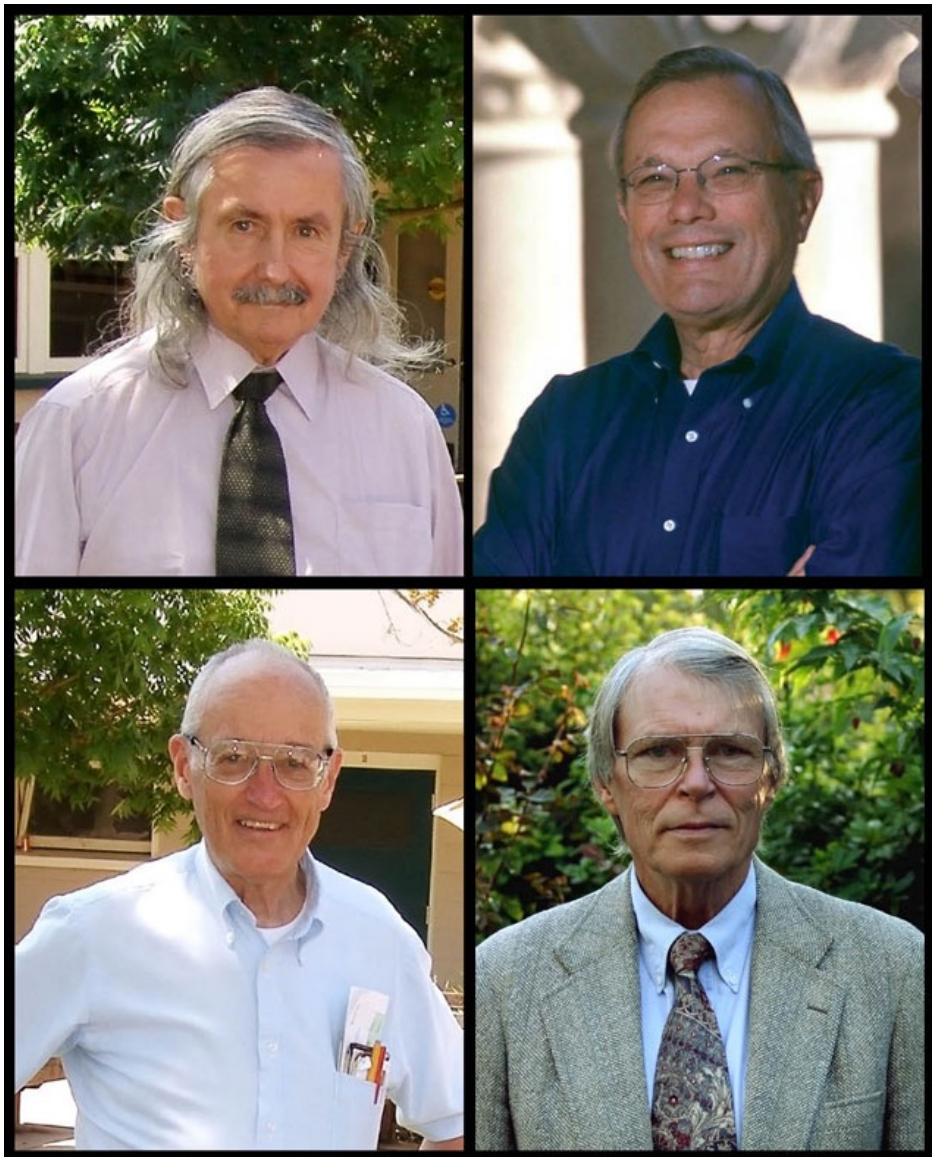


Tom Kane, R. L. Byer
"Monolithic, unidirectional
Single-mode Nd:YAG ring laser"
Opt. Lett. 10,65,1985



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

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

Scientific Applications of Lasers

Atmospheric Remote Sensing

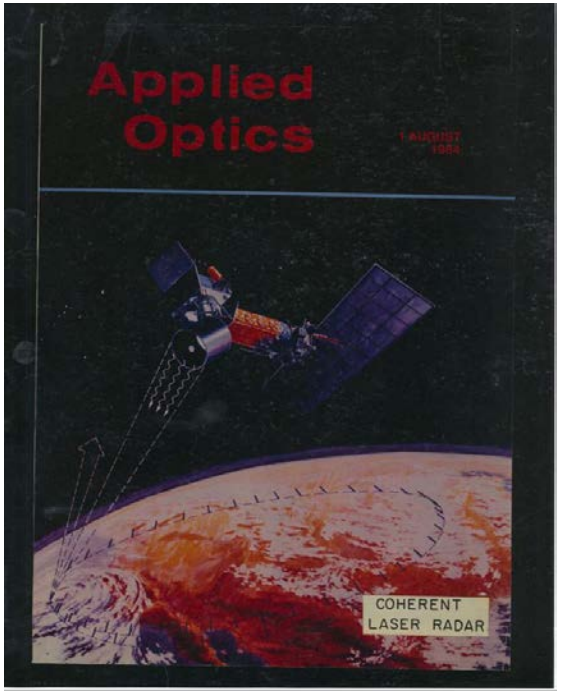
Quanta Ray 1J Unstable resonator
Nd:YAG Laser
1.4 to 4.3 micron Tunable LiNbO3 OPO

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

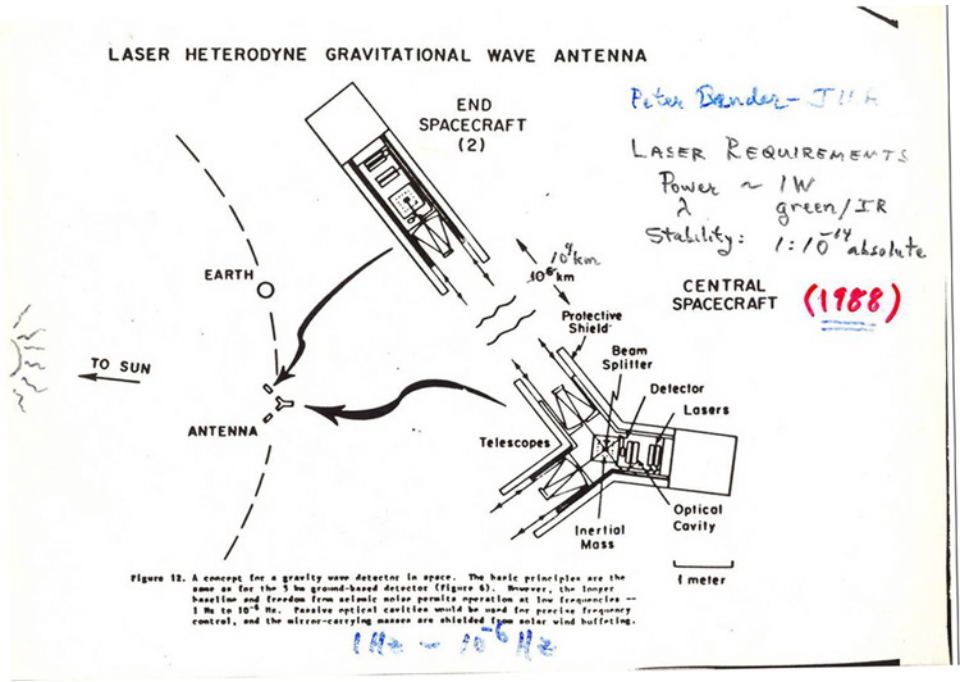


Global remote sensing 1980 – Needed a coherent laser oscillator.

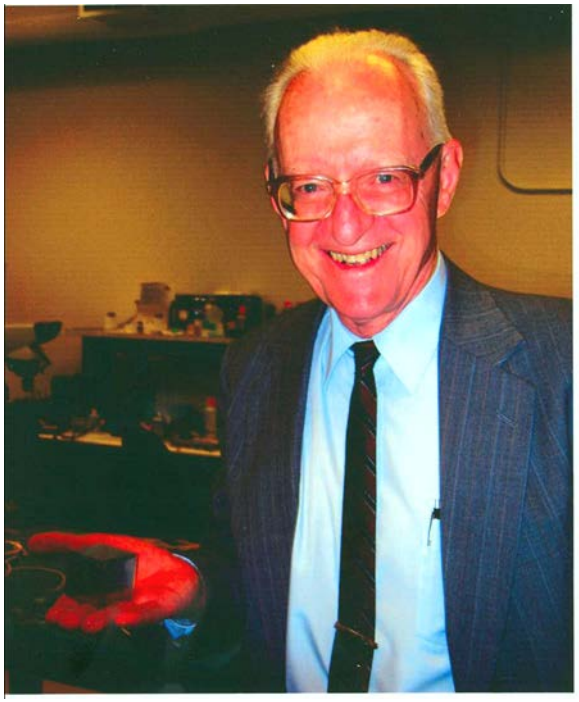
….from Coherent Laser Radar to Gravitational Waves… 1988

LISA Concept – Led to LIGO meeting in Boston, Dec 1988

Byer Group

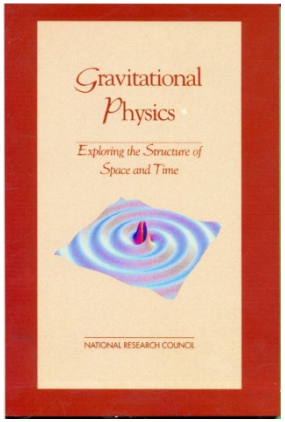


Schematic of LISA in 1988



Peter Bender holding 4x4cm Au/Pt cube

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

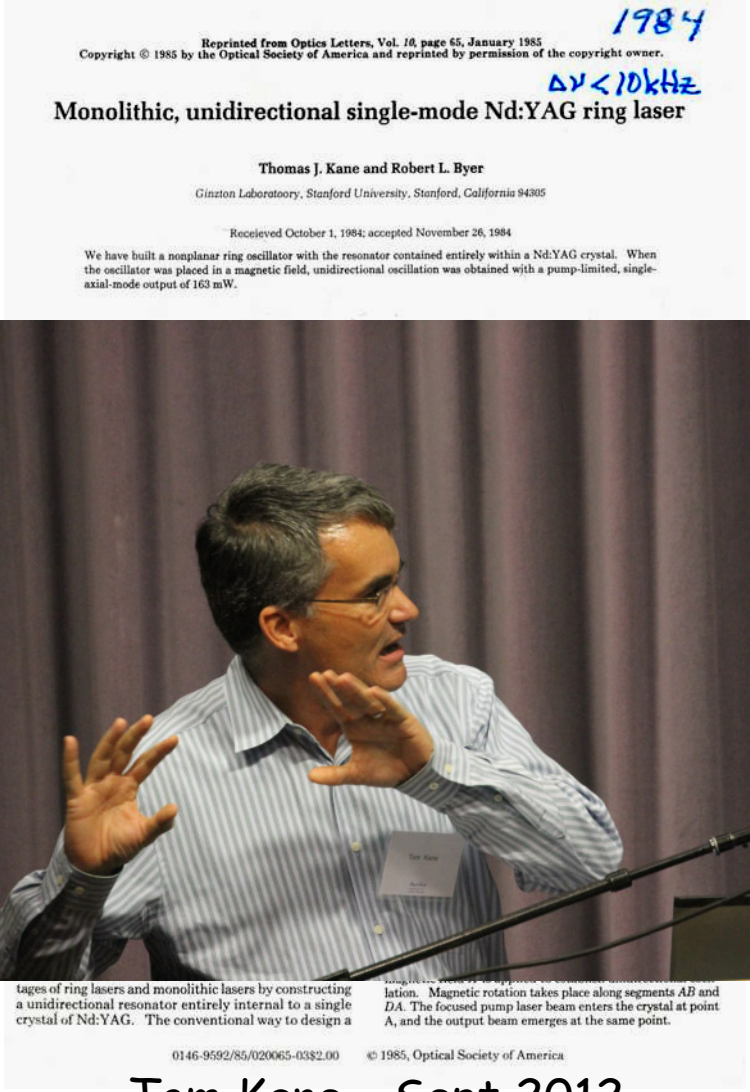
Multipass 60 dB gain slab amplifier

Heterodyne Receiver

Fiber coupled heterodyne detection

Goal: wind sensing from the laboratory using a coherent Nd:YAG laser transmitter-receiver

The Non-Planar Ring Oscillator - 1984



1984

Reprinted from Optics Letters, Vol. 10, page 65, January 1985

$\Delta\nu < 10$kHz

Monolithic, unidirectional single-mode Nd:YAG ring laser

Thomas J. Kane and Robert L. Byer

Ginzton Laboratoory, Stanford University, Stanford, California 94305

Received October 1, 1984; accepted November 26, 1984

We have built a nonplanar ring oscillator with the resonator contained entirely within a Nd:YAG crystal. When the oscillator was placed in a magnetic field, unidirectional oscillation was obtained with a pump-limited, single-axial-mode output of 163 mW.

tages of ring lasers and monolithic lasers by constructing a unidirectional resonator entirely internal to a single crystal of Nd:YAG. The conventional way to design a

lation. Magnetic rotation takes place along segments *AB* and *DA*. The focused pump laser beam enters the crystal at point A, and the output beam emerges at the same point.

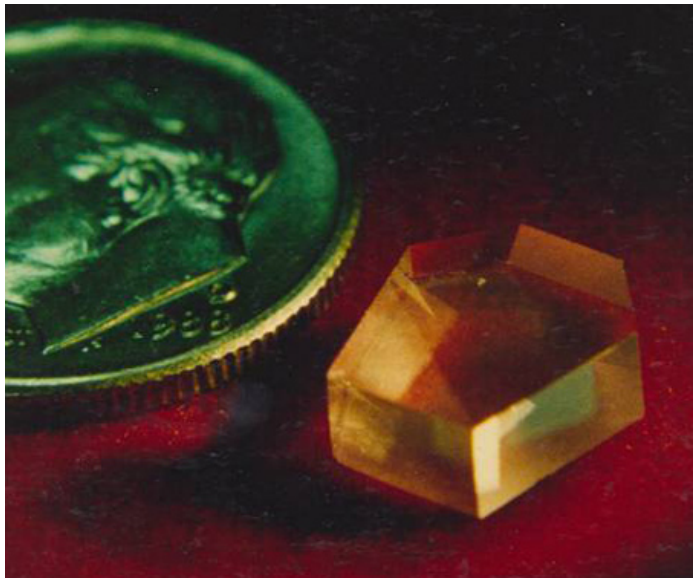
0146-9592/85/020065-03$2.00

Tom Kane – Sept 2012

Tom Kane, R. L. Byer

"Monolithic, unidirectional Single-mode Nd:YAG ring laser"

Opt. Lett. 10,65,1985

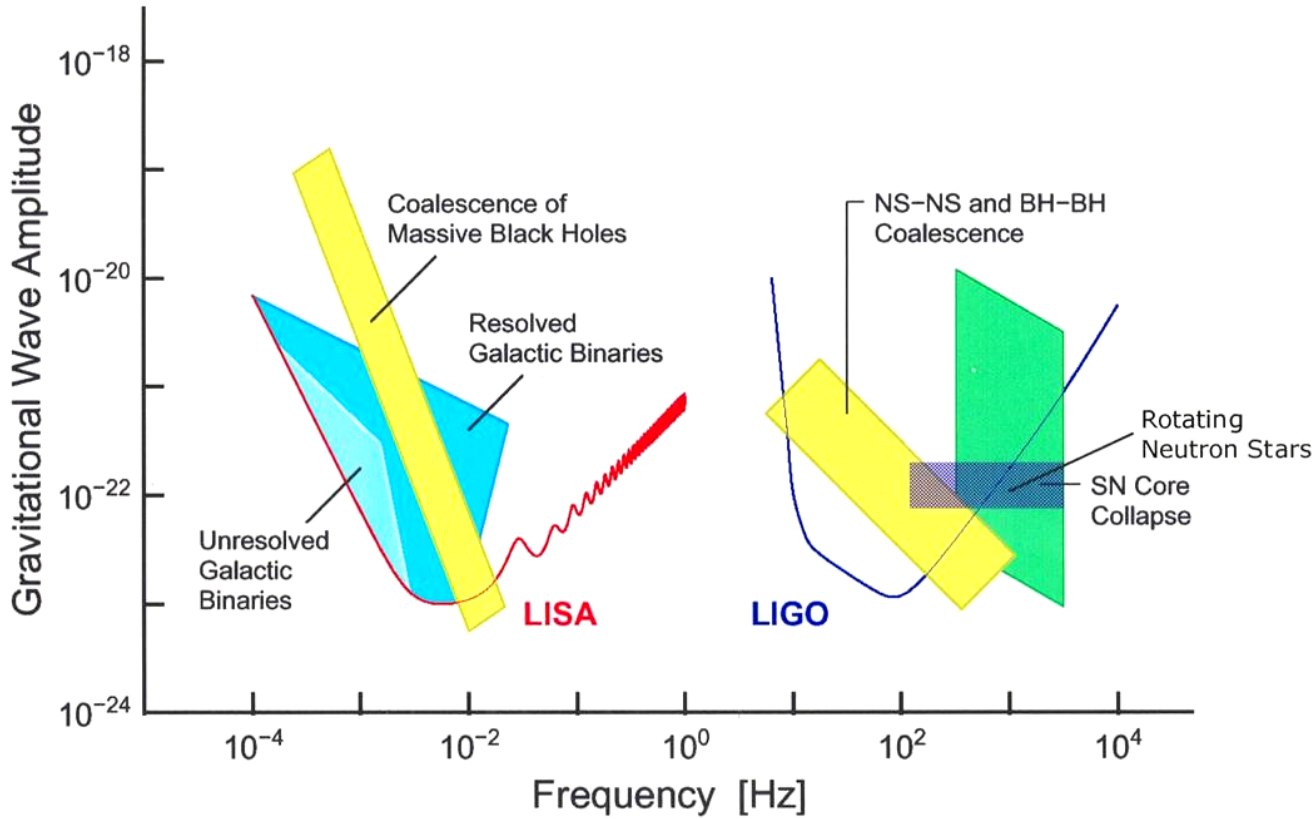


NonPlanar **R**ing **O**scillator

Single frequency: <10kHz

LISA and LIGO Detection Bands

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



(LISA Science & Technology Study)

Kip Thorne,
CalTech

Rai Weiss
MIT

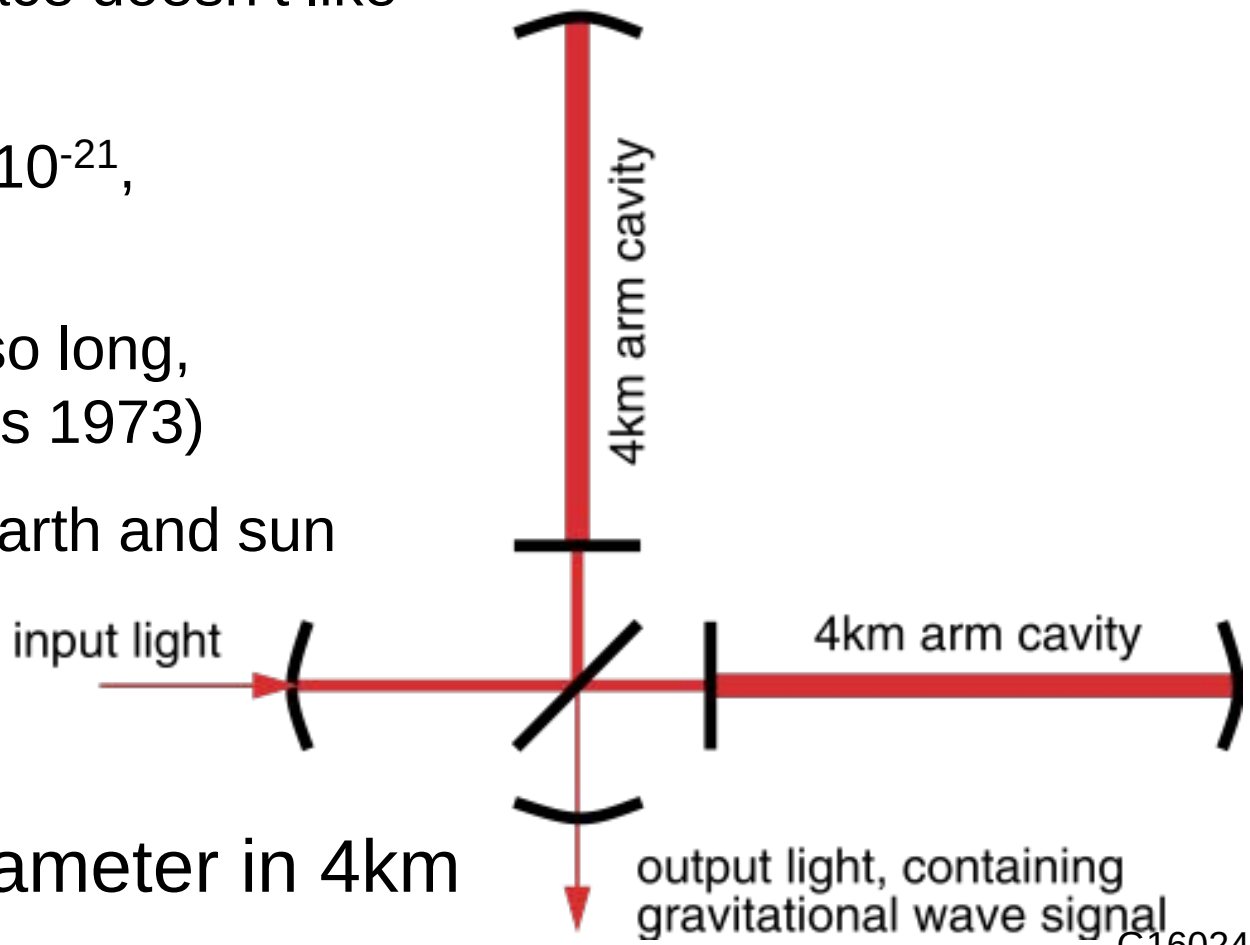
The LIGO concept
why it is nearly impossible

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

Our signal strain, $h = 10^{-21}$,
$dL = 4*10^{-18}$ 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!

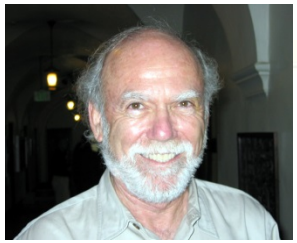
Byer Group

A portion of the Caltech/MIT team of LIGO scientists in late 1991. *Left:* Some Caltech members of the team, counterclockwise from upper left: Aaron Gillespie, Fred Raab, Maggie Taylor, Seiji Kawamura, Robbie Vogt, Ronald Drever, Lisa Sievers, Alex Abramovici, Bob Spero, Mike Zucker. *Right:* Some MIT members of the team, counterclockwise from upper left: Joe Kovalik, Yaron Hefetz, Nergis Mavalvala, Rainer Weiss, David Schumaker, Joe Giaime. [Left: courtesy Ken Rogers/Black Star; right: courtesy Erik L. Simmons.]

Caltech group 1991 led by Robbie Vogt and Ron Drever

MIT group led by Rai Weiss

LIGO Observatory Sites



Barry Barish*

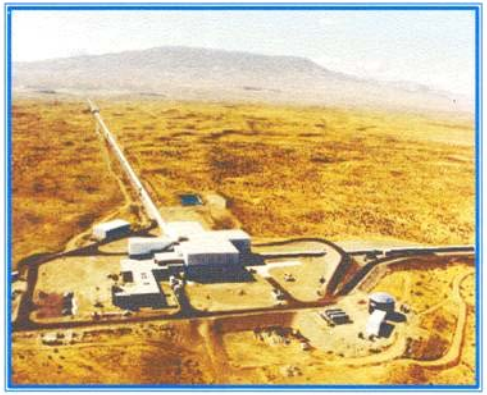
Rai Weiss
MIT

LIGO Sites

- Jay Marx joined LIGO as Director – Jan 2006
- David Reitze is current director

LIGO-G9900XX-00-M NSF LIGO II Review 5

LIGO sites



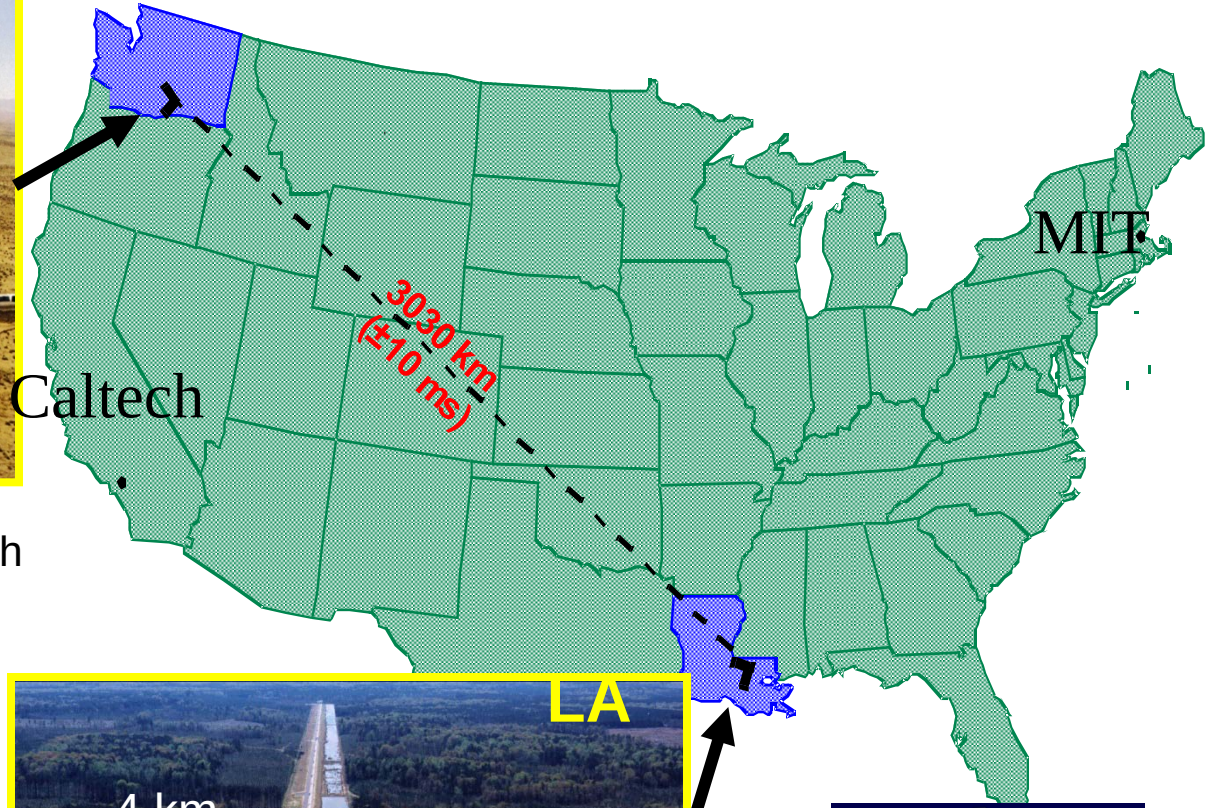
- Hanford Obseratory

- Livingston Observatory

LIGO-G9900XX-00-M NSF LIGO II Review 12

Laser Interferometer Gravitational-wave Observatory

Byer Group



- 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

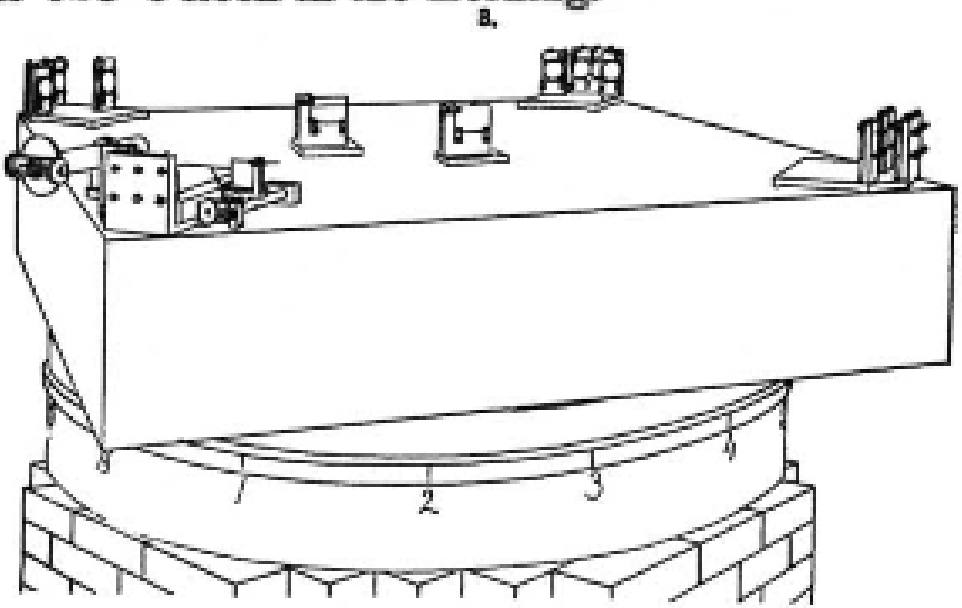

LIGO
Interferometer

Michelson's Interferometer!

Edward Morley

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.



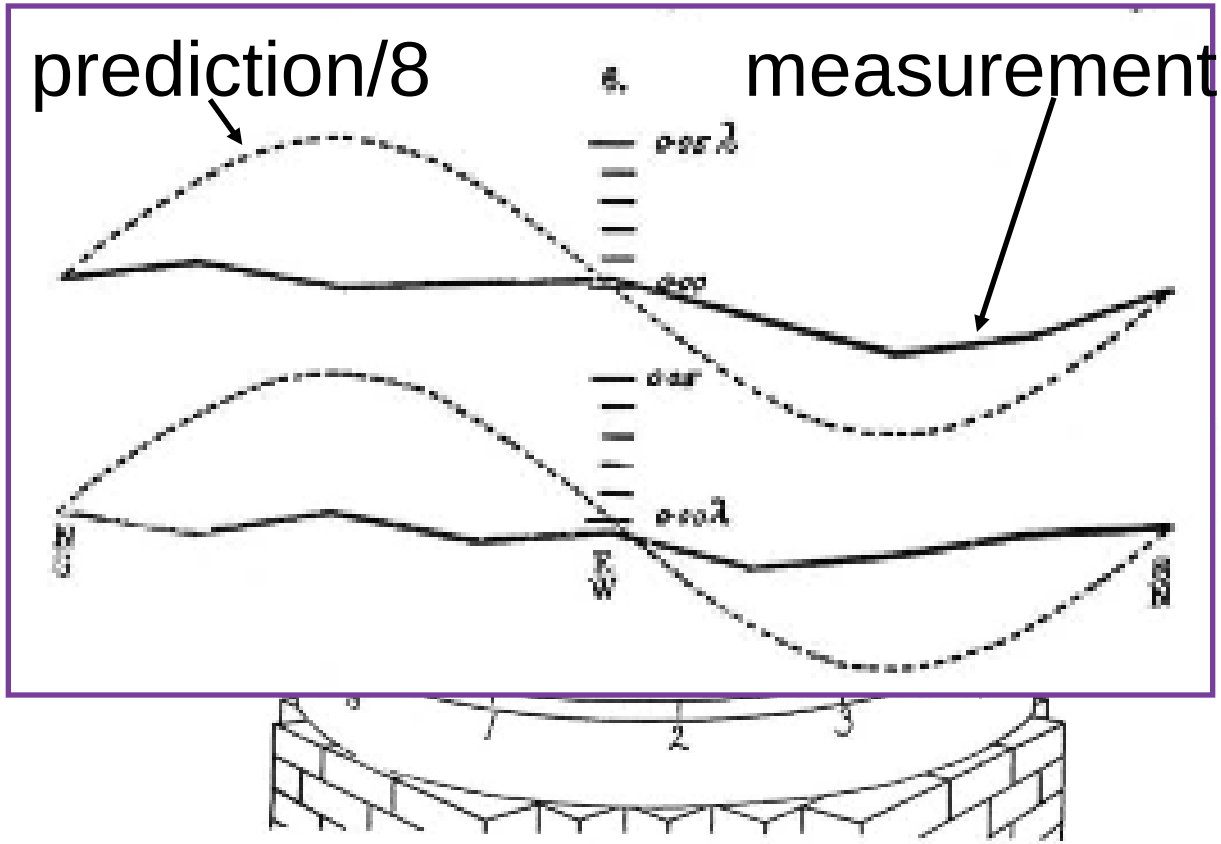
Am. Jour. Sci. - Third Series, Vol. 34, No. 203, Nov. 1887. pg 333-345

Michelson's Interferometer!

Edward Morley

Albert Michelson

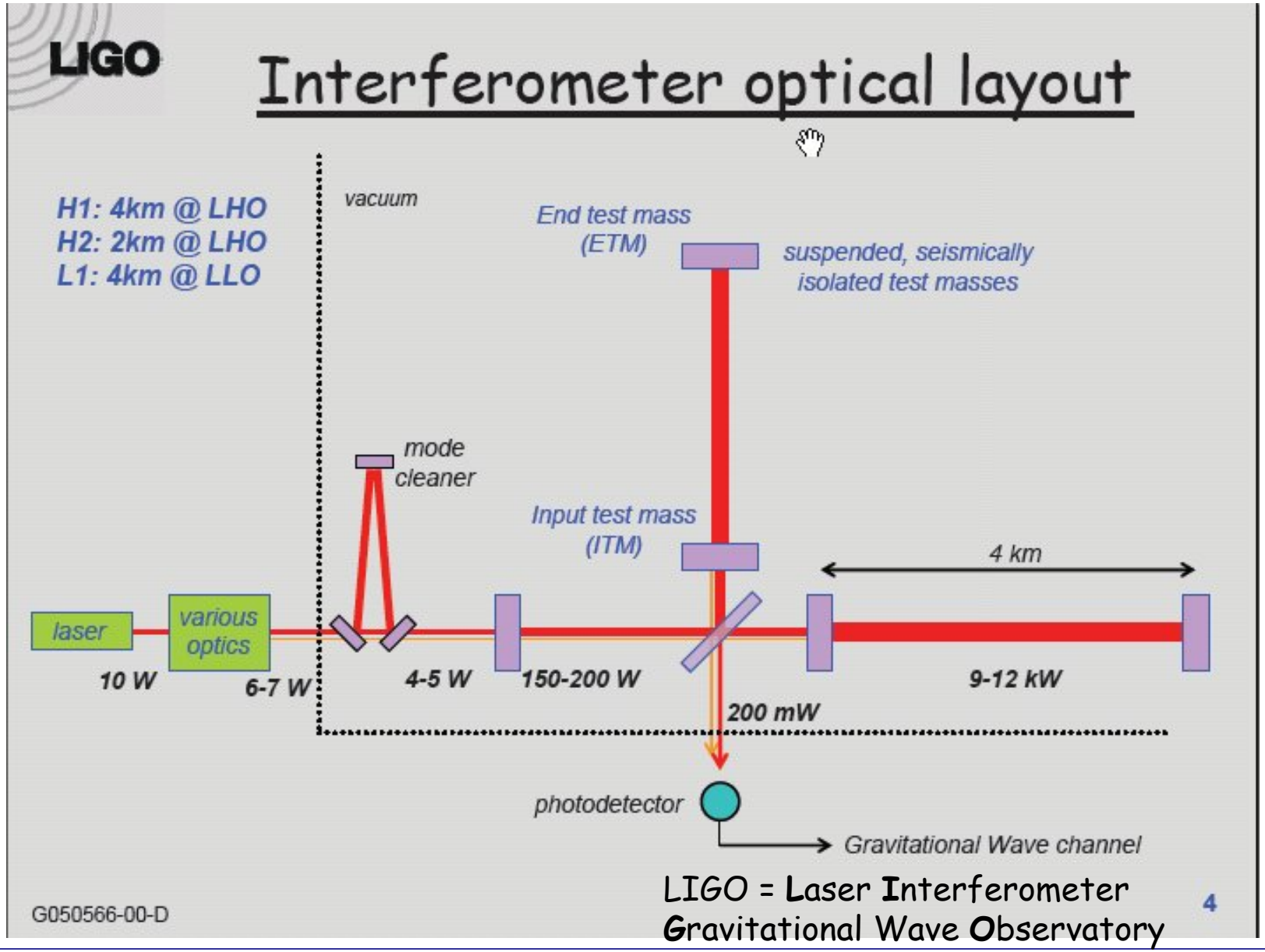
1887 experiment to measure
"luminiferous ether" with an interferometer



Am. Jour. Sci. - Third Series, Vol. 34, No. 203, Nov. 1887. pg 333-345

LIGO Interferometer Optical Layout

Byer Group



LIGO = **L**aser **I**nterferometer **G**ravitational Wave **O**bservatory

Quantum Noise in Amplifiers

Byer Group

PHYSICAL REVIEW VOLUME 124, NUMBER 6 DECEMBER 15, 1961

Quantum Fluctuations and Noise in Parametric Processes. I.

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

and

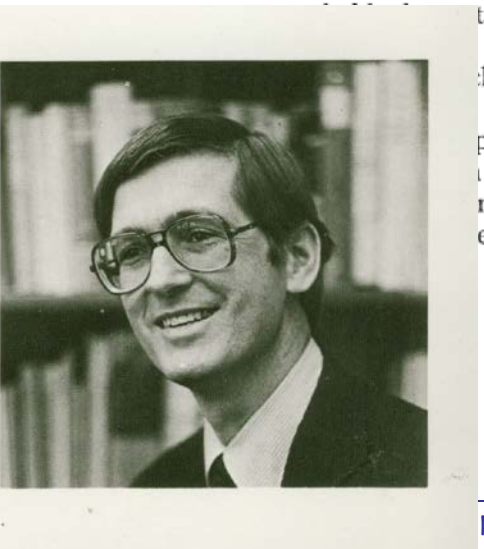
A. E. Siegman
Stanford University, Stanford, California

(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



characterization of parametric processes
or multiresonant systems in which an
parameter is harmonically modulated.
can cause a periodic energy exchange
nant systems or a continuous transfer of
e modulation source to the 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 (maser) 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

LIGO team measured shot noise of laser amplifier

Byer Group

1852 OPTICS LETTERS / Vol. 23, No. 23 / December 1, 1998

Quantum noise in a continuous-wave laser-diode-pumped Nd:YAG linear optical amplifier

W. M. Tulloch, T. S. Rutherford, E. H. Huntington,* R. Ewart,† C. C. Harb, B. Willke, E. K. Gustafson, M. M. Fejer, and R. L. Byer

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.

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

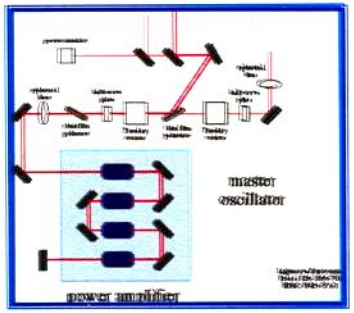
High-power, low-noise lasers are required for laser interferometric gravitational-wave detection[1,2] and free-space optical communication.[3] The advanced detector in the Laser Interferometer Gravitational Wave Observatory (LIGO) program will require a low-noise, continuous-wave (cw), 100-W, single-frequency, diffraction-limited TEM_{00} mode laser.[4] High single-pass gains demonstrated in cw laser-diode-pumped zigzag slab lasers[5] indicate that cw amplification in a Nd:YAG master-oscillator–power-amplifier (MOPA) guided-wave semiconductor[11] and fiber laser amplifiers[12] used in long-distance optical transmission systems. In studies of argon-laser amplifiers existing noise theories were applied to free-space amplifiers.[13] 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)

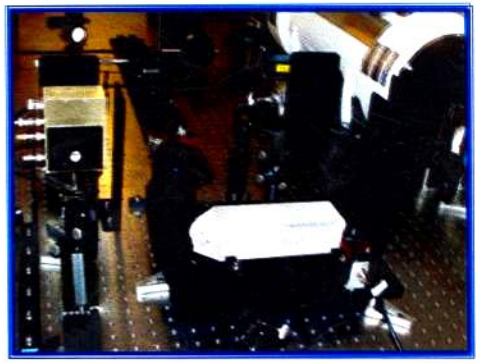
Byer Group

LIGO

LIGO
Laser



- Nd:YAG
- 1.064 μm
- Output power > 8W in TEM00 mode



LIGO-G9900XX-00-M NSF LIGO II Review 26

LIGO Prestabilized Laser

10 W TEMoo 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.

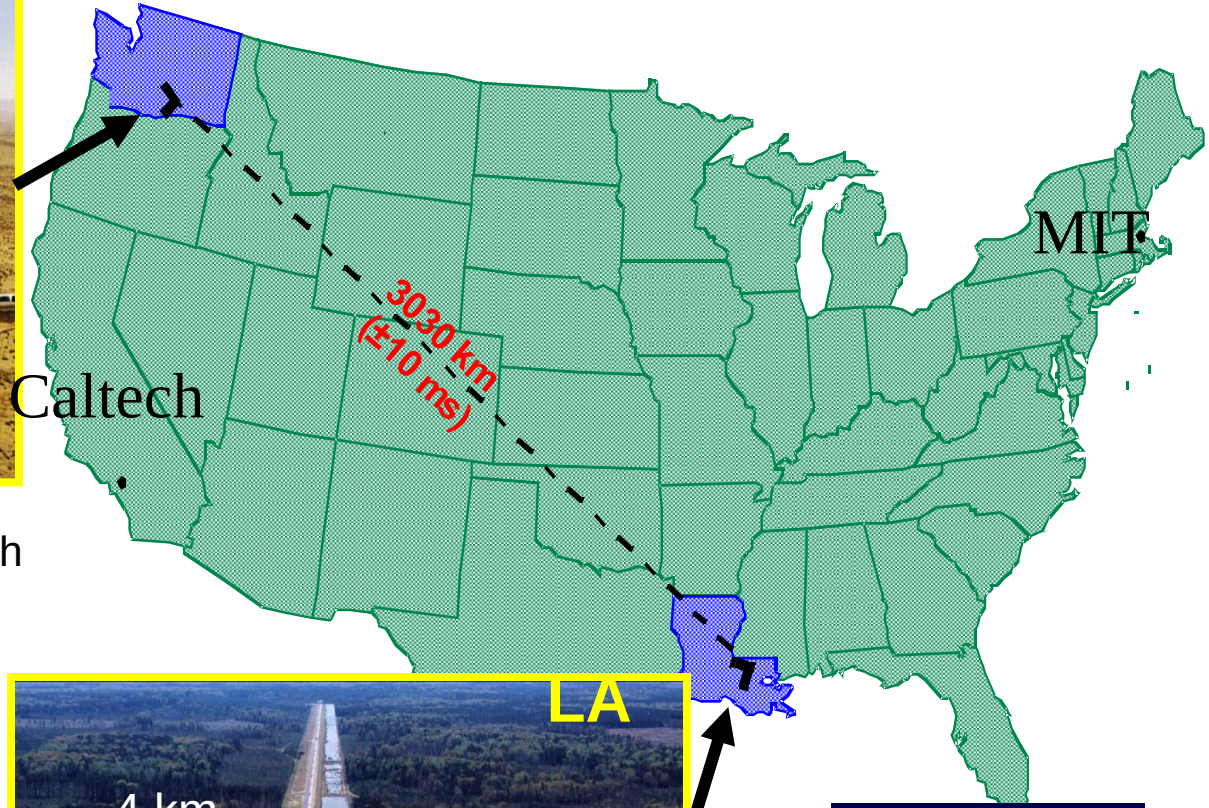
NSF – what does 'discovery research' lead to in the real world?

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

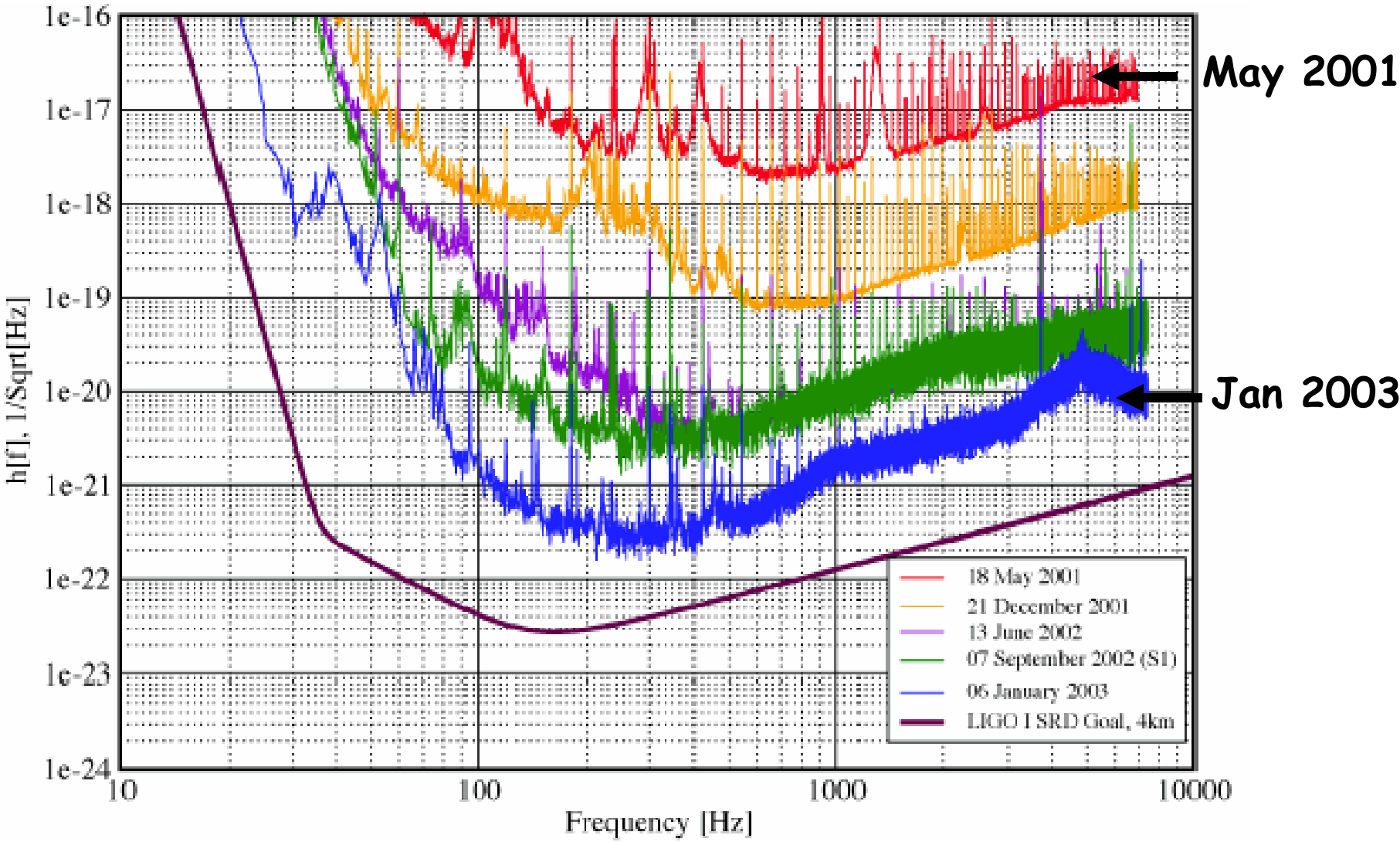
Byer Group



- 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

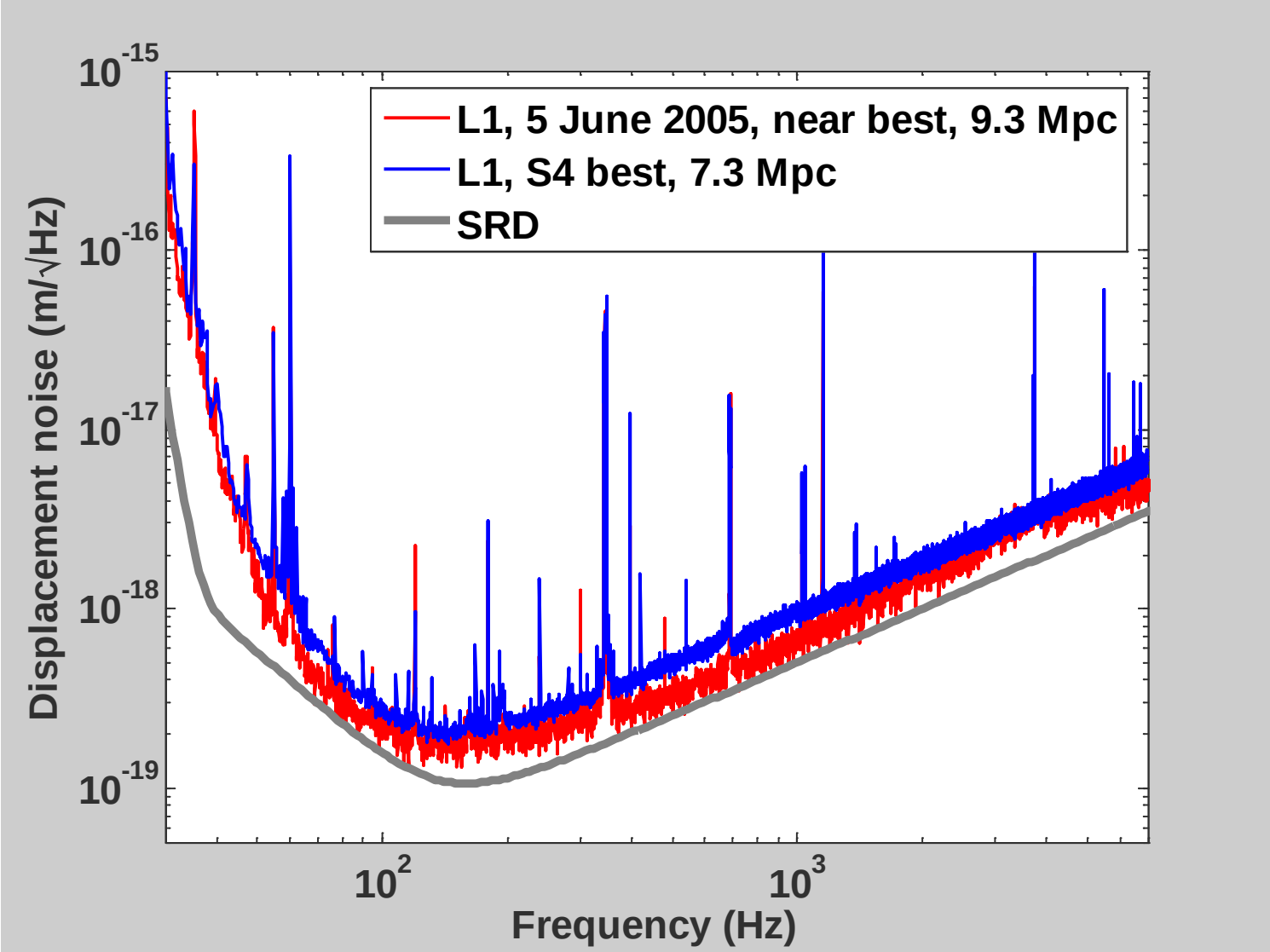
LIGO Sensitivity Livingston 4km Interferometer

Byer Group



LIGO Sensitivity 2005

Byer Group



Peter Fritschel, Commissioning Report,15 Aug 2005, LIGO # G050371

S5 Science Run: LIGO I at Design Sensitivity

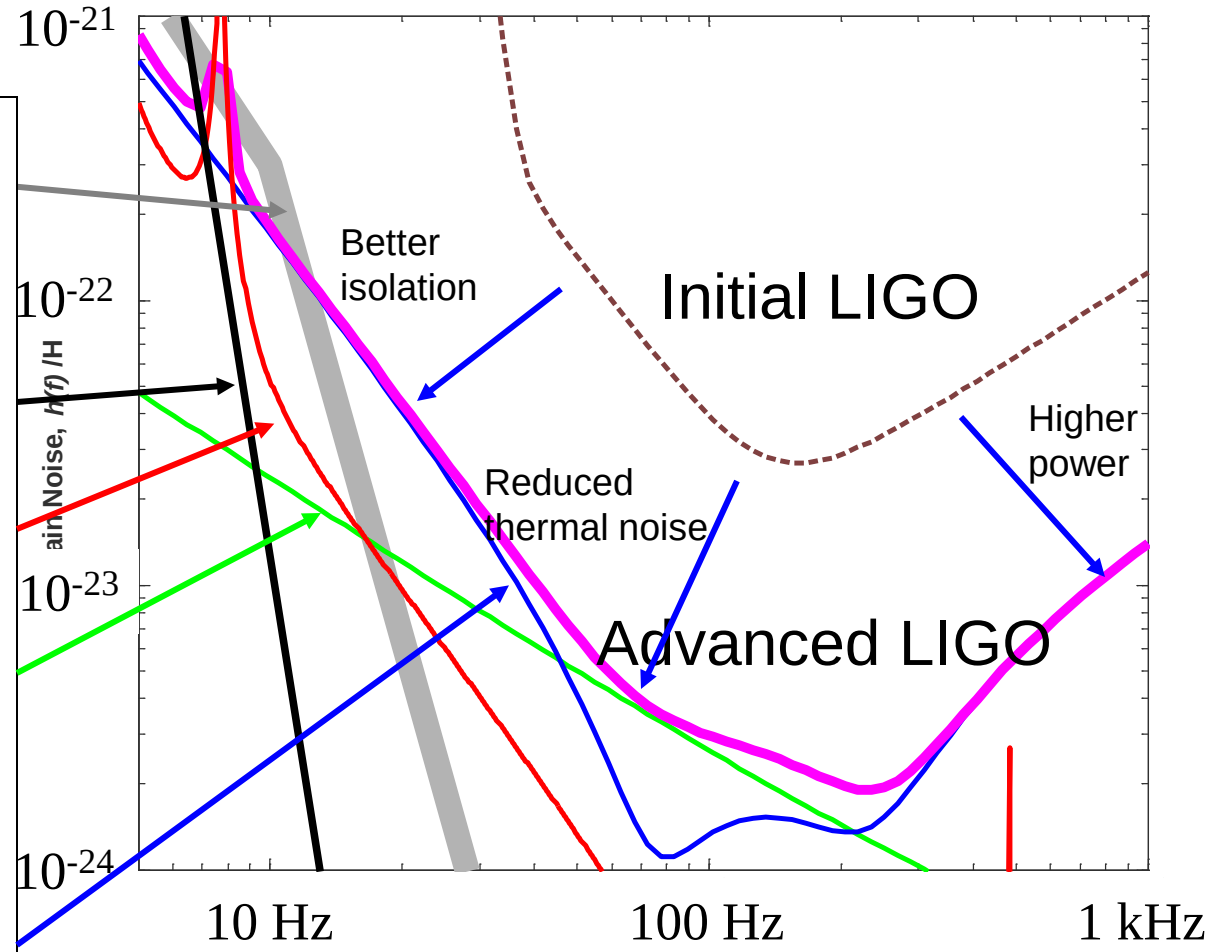
Byer Group

Met NSF major milestone in 2007. Next move to Adv LIGO by 2016

NSF gave go-ahead to build Advanced LIGO !
Projected Advanced LIGO performance

Byer Group

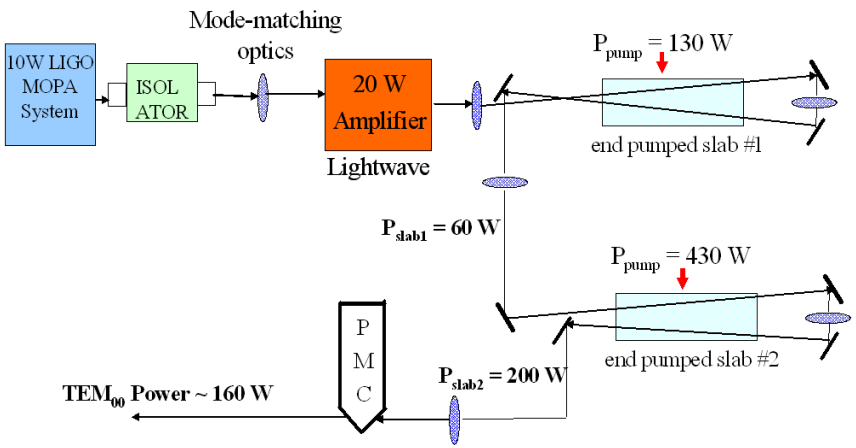
- Newtonian background, estimate for LIGO sites
- Seismic 'cutoff' at 10 Hz
- Suspension thermal noise
- Test mass thermal noise
- Standard quantum noise dominates at most frequencies for full power, broadband tuning



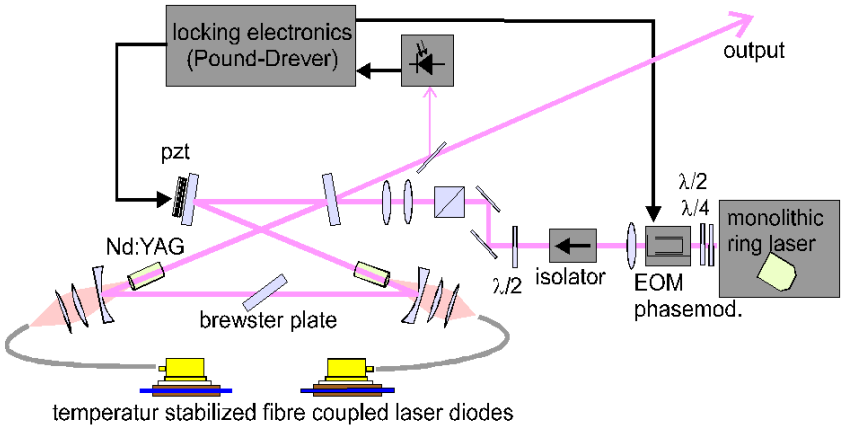
David Shoemaker/adapted

Advanced LIGO 180W Lasers – Benno Wilke, Hannover, Germany

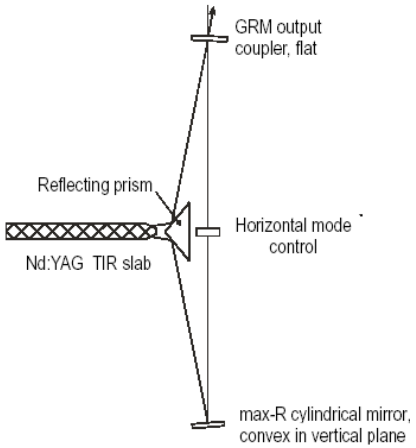
Byer Group



Edge Pumped Nd:YAG slab - Stanford



Injection locked Nd:YAG oscillators Hannover



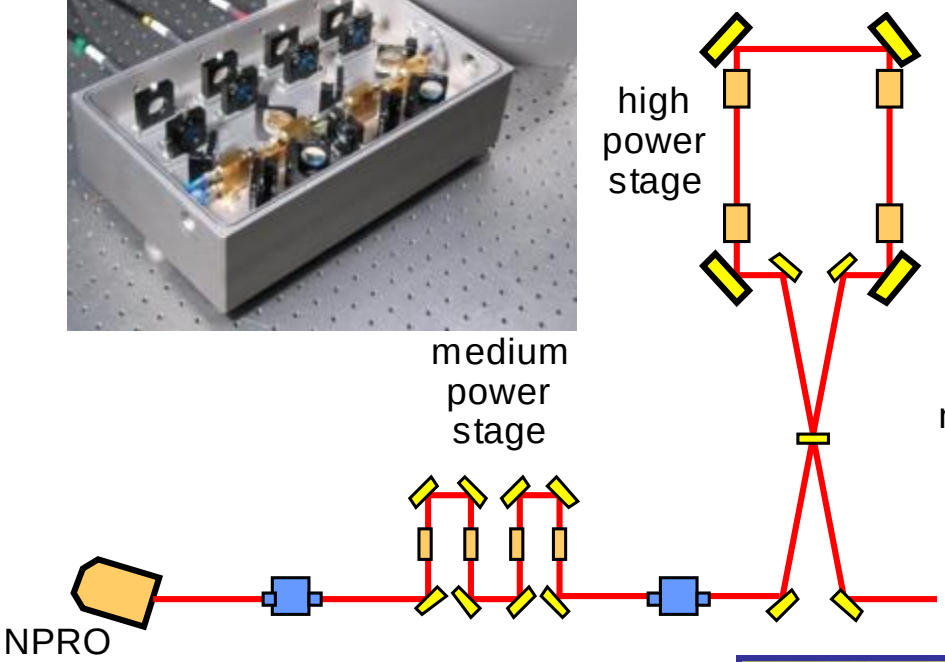
Unstable resonator -- Adelaide

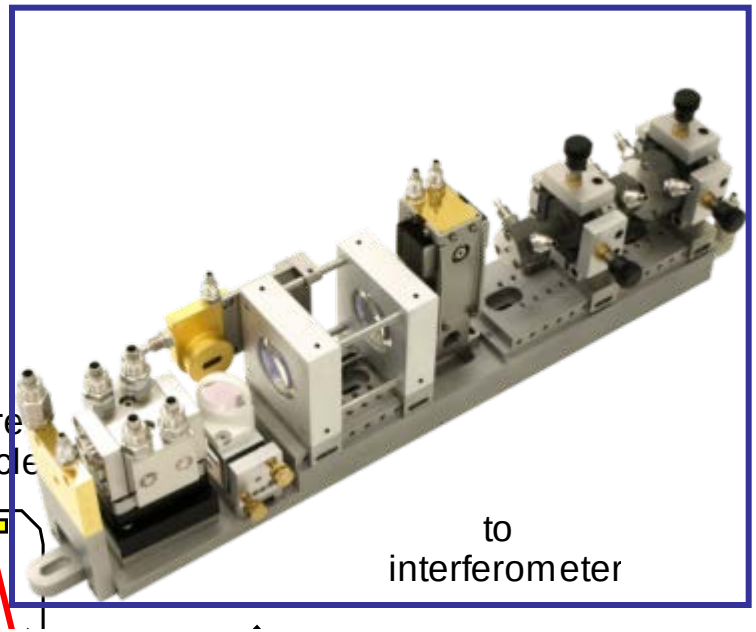
Benno Willke
Hannover

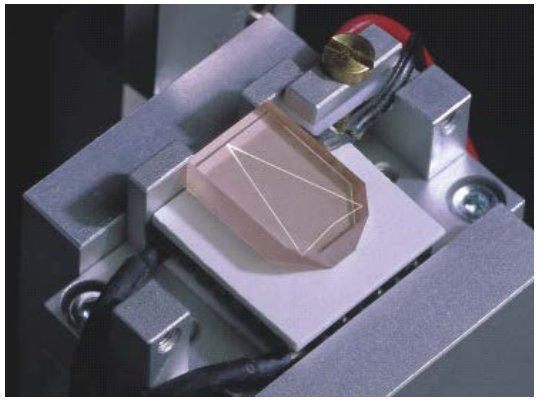
In charge of 180W Laser program for Advanced LIGO

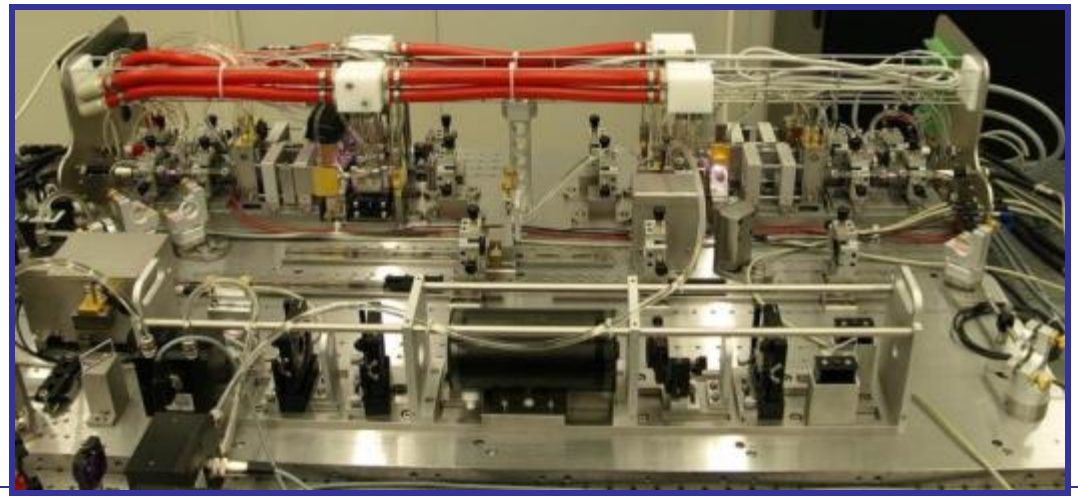
180W prototype - layout

Byer Group

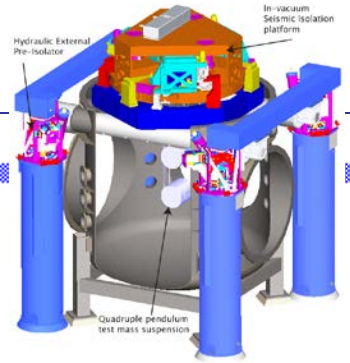


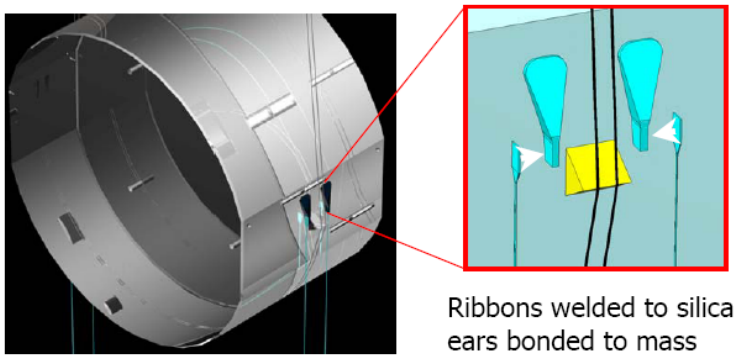






Advanced LIGO





30KG

INPUT MODE CLEANER

ACTIVE THERMAL CORRECTION

T=0.5%

180 W

830 kW

LASER

MOD.

125W

PRM
T~6%

BS

ITM

ETM

SRM

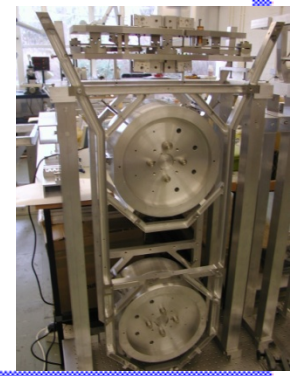
T=5%

OUTPUT MODE CLEANER

PD

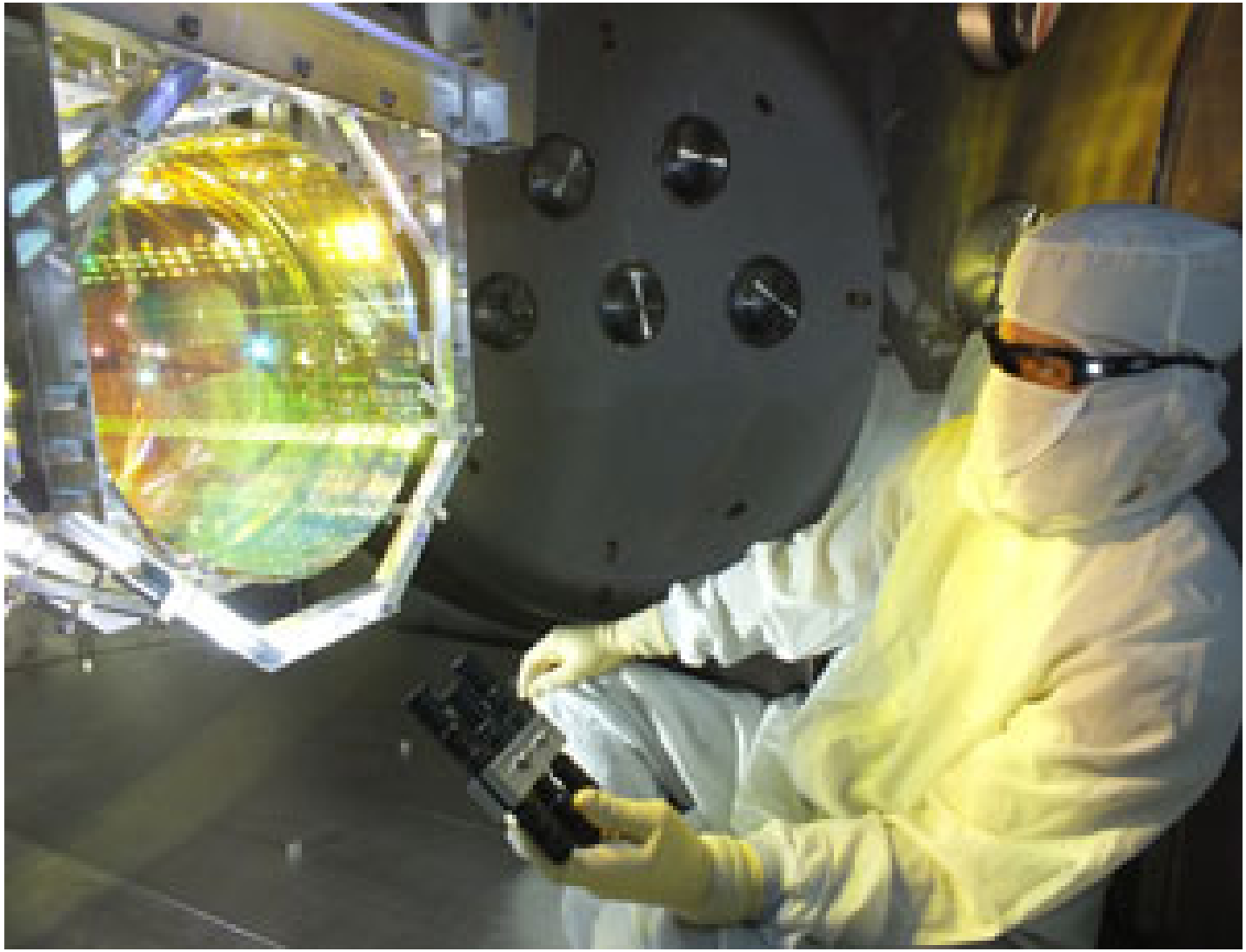
GW READOUT

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



LIGO fused silica Test Mass
Coating absorption loss < 1ppm

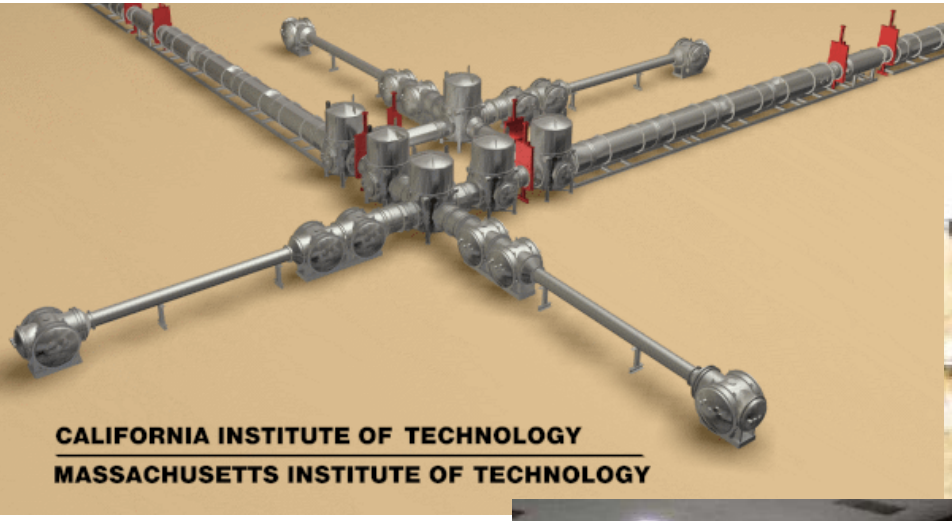
Byer Group

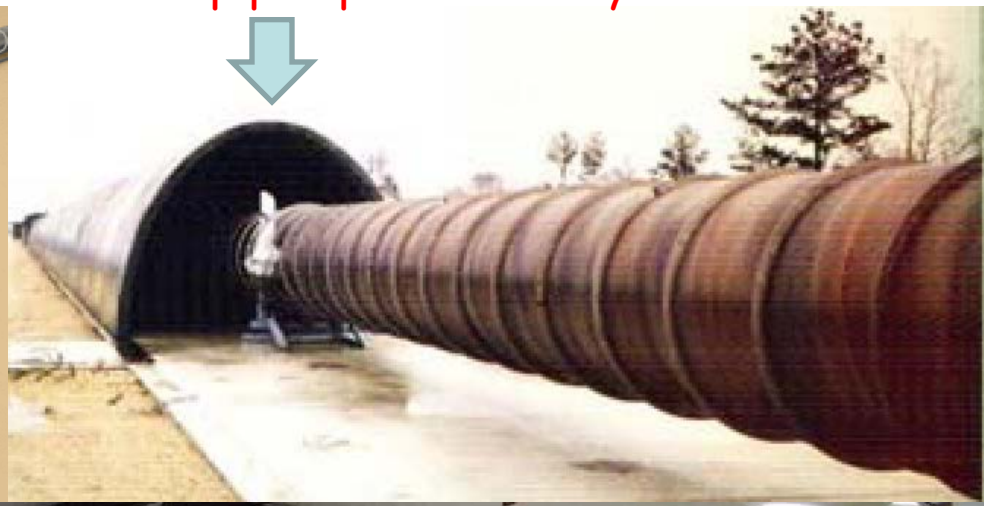


LIGO Vacuum Equipment

Byer Group

Vacuum pipes protected by concrete shell





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

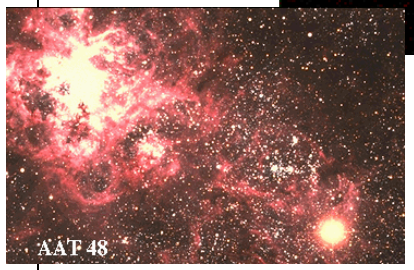
Test of concrete Vacuum tube enclosures!

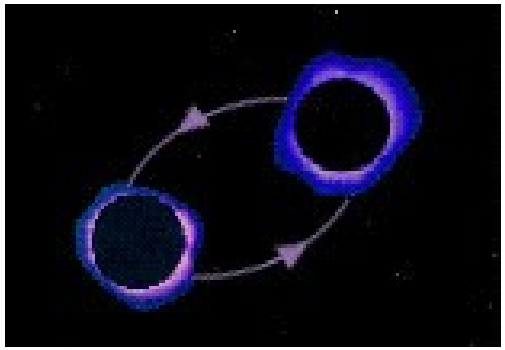
Byer Group

Gravitational Wave Sources

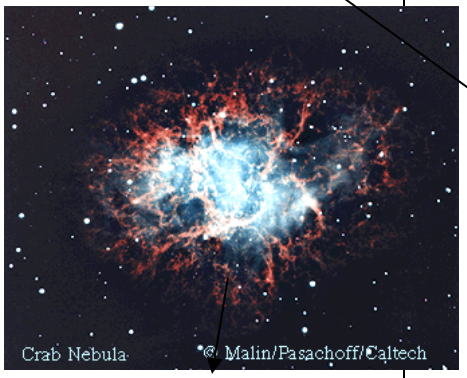
- ***Bursts***
  - catastrophic stellar collapse to form black holes or neutron stars
  - final inspiral and coalescence of neutron star or **black hole binary systems – possibly** associated with gamma ray bursts

SN1987a





- ***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

Shoemaker led the Advanced LIGO Construction Project

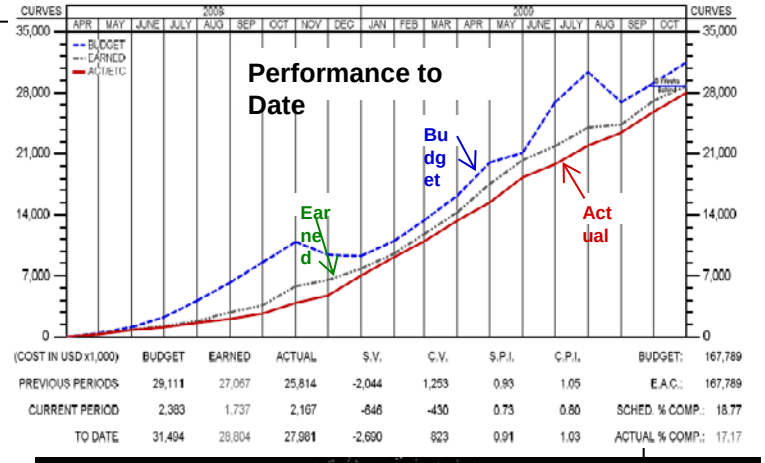
Byer Group

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



(COST IN USD x1,000)	BUDGET	EARNED	ACTUAL	S.V.	C.V.	S.P.I.	C.P.I.		
PREVIOUS PERIODS	29,111	27,067	25,814	-2,044	1,253	0.93	1.05	BUDGET:	167,789
CURRENT PERIOD	2,383	1,737	2,167	-646	-430	0.73	0.80	E.A.C.:	167,789
TO DATE	31,494	28,804	27,981	-2,690	823	0.91	1.03	SCHED. % COMP.:	18.77
								ACTUAL % COMP.:	17.17

From Discovery to Astronomy!

Advanced LIGO Detects Gravitational Waves – Sept 2015 !

Byer Group

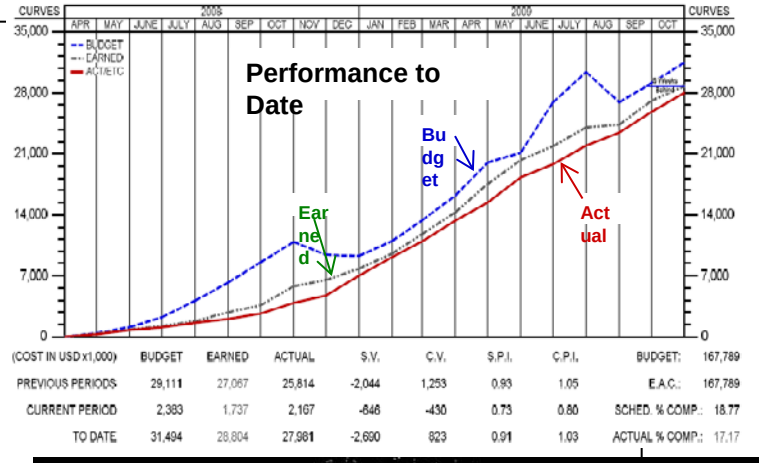
David Shoemaker - MIT

- **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

Press Conference - Feb 11 2016

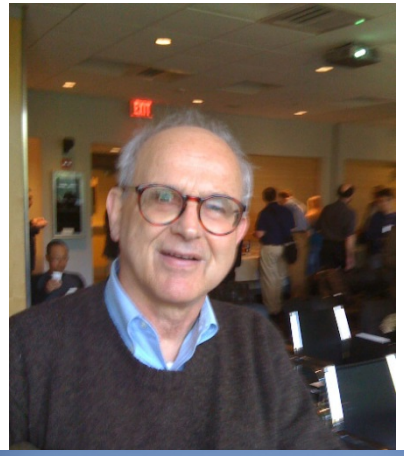


(COST IN USD x1,000)	BUDGET	EARNED	ACTUAL	S.V.	C.V.	S.P.I.	C.P.I.		
PREVIOUS PERIODS	29,111	27,067	25,814	-2,044	1,253	0.93	1.05	BUDGET:	167,789
CURRENT PERIOD	2,383	1,737	2,167	-646	-430	0.73	0.80	E.A.C.:	167,789
TO DATE	31,494	28,804	27,981	-2,690	823	0.91	1.03	SCHED. % COMP.:	18.77
								ACTUAL % COMP.:	17.17

From Discovery to Astronomy!

LIGO faces

Byer Group



LIGO Scientific Collaboration

LIGO

LSC Group

- 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

NATURE | NEWS: EXPLAINER

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

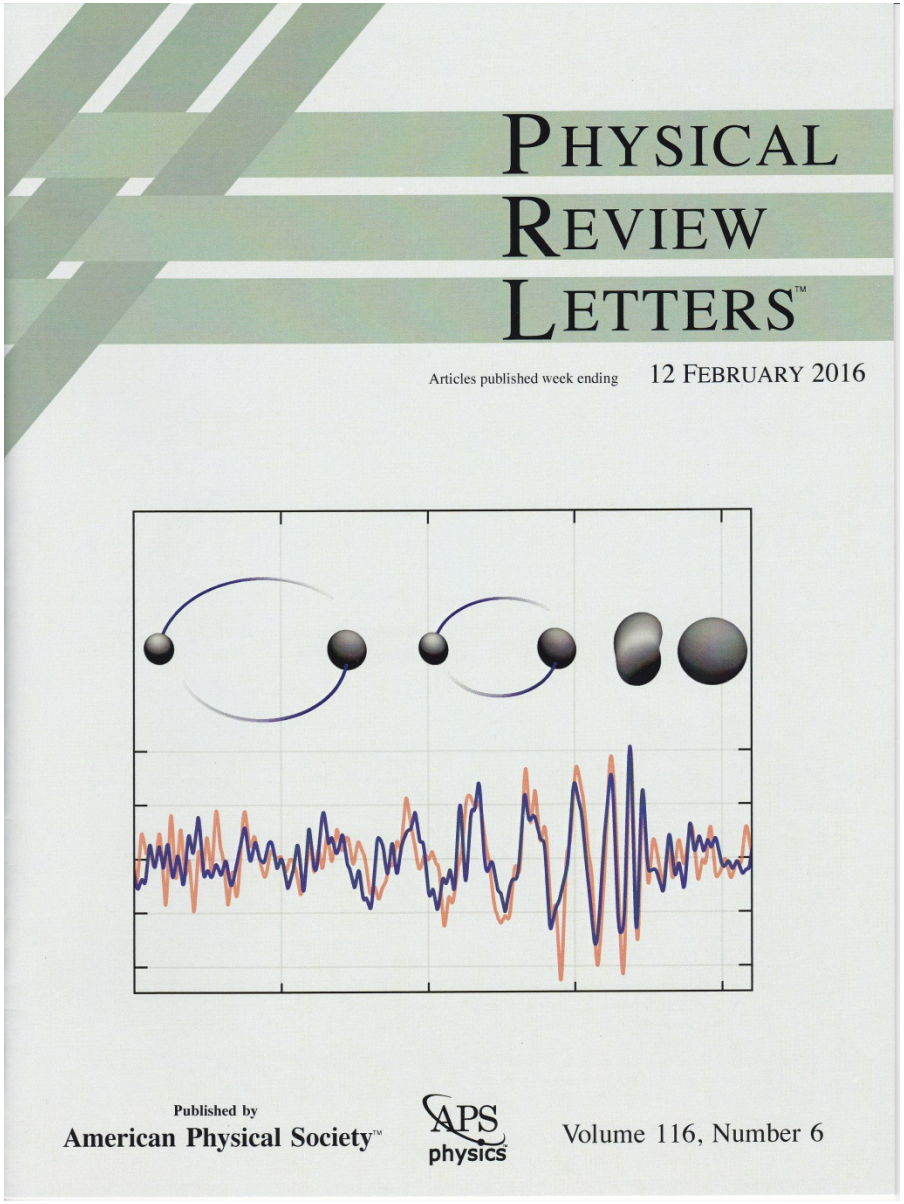
February 11, 2016
LIGO announces Gravitational waves

Ladies and Gentlemen, we have detected gravitational waves, we did it!

Discovery Paper ~1000 authors

Phys Rev Letters Feb 11, 2016

Byer Group

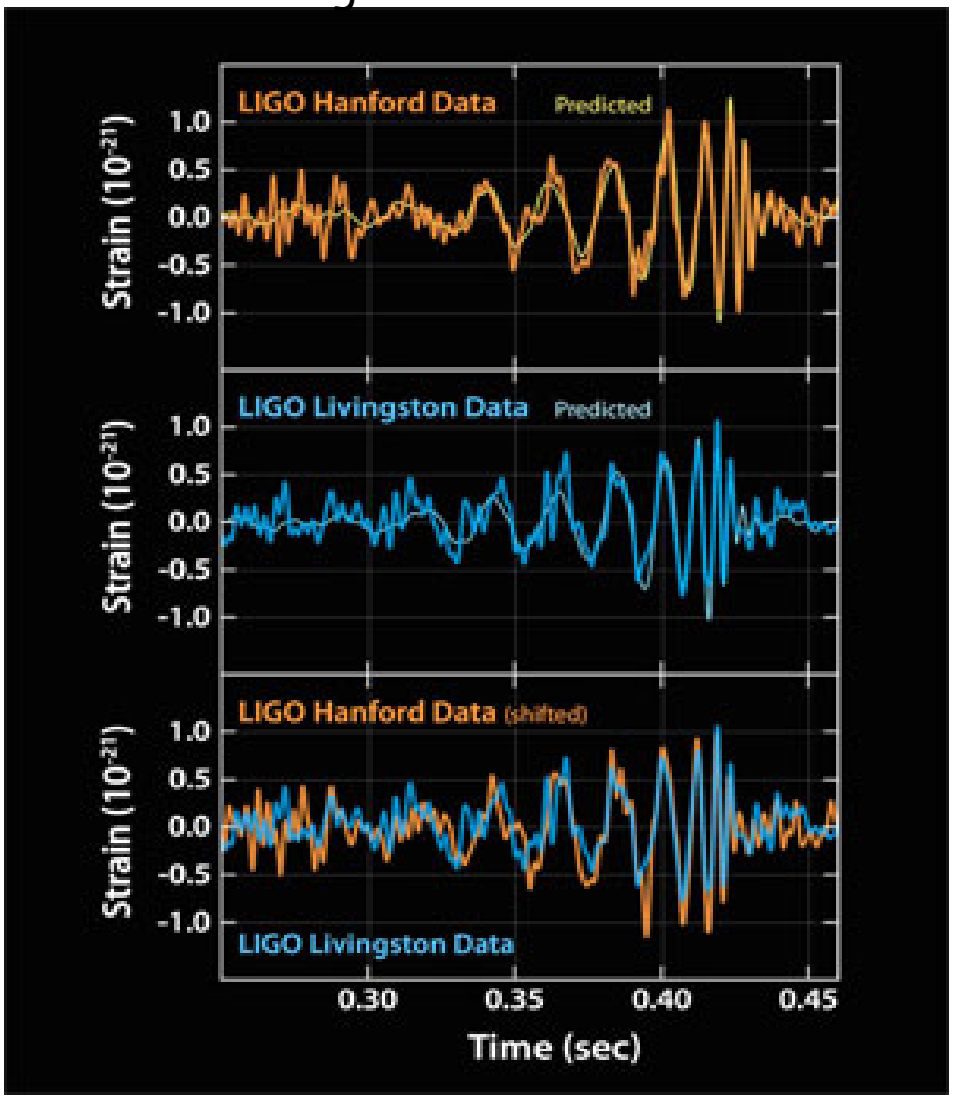


Gravitational Wave Signal Detected

Sept 14 2015 -- 150914

Byer Group

Signal to Noise ~23



Strong signal suggests merger of ~10 Solar Mass Black Holes

LIGO press conference – Feb 11, 2016
S/N ratio 23:1

Byer Group

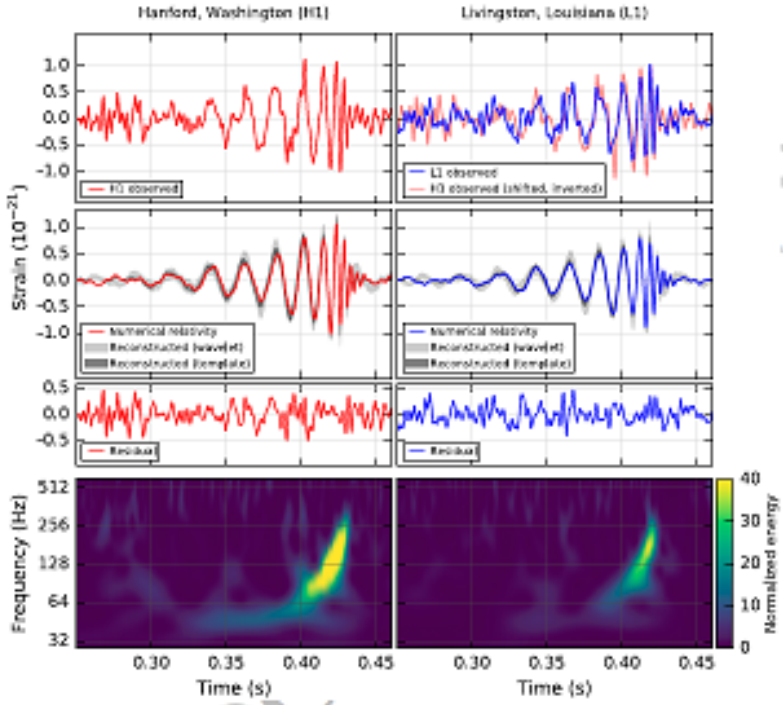


FIG. 1. The gravitational-wave event GW150914 observed by the LIGO Hanford (H1, left column) and Livingston (L1, right column) detectors shown relative to September 14, 2015 at 09:50:45 UTC. Time series are filtered with a i) a 35–350 Hz band-pass filter to suppress large fluctuations outside the detector's most sensitive frequency band, and ii) band-reject filters to remove the strong instrumental spectral lines seen in the Fig. 3 spectra. *Top row, left*: H1 strain. *Top row, right*: L1 strain. GW150914 arrived first at L1 and ~ 7 ms later at H1; for a visual comparison the H1 data are also shown, shifted in time by this amount and inverted (to account for the detectors' relative orientations). *Second row*: Gravitational-wave strain incident on each detector (solid lines) in the 35–350 Hz band, calculated with numerical relativity [31], and 95% credible regions (shaded areas) for two waveform reconstructions: one that models the signal as a set of sine-Gaussian wavelets [32, 33] and one that models the signal using binary-black-hole template waveforms [34]. *Third row*: Residuals after subtracting the filtered numerical relativity waveform from the filtered detector time series. *Bottom row*: A time-frequency decomposition [35] of the signal power associated with GW150914. Both plots show a significant signal with frequency increasing over time.

quent final black hole ringdown. Over 0.2 s, the signal increases in frequency and amplitude in about 8 cycles from 30 to 150 Hz. The most plausible explanation for this evolution is the inspiral of two orbiting masses m_1 and m_2 due to gravitational-wave emission. At the lower frequencies, such evolution is characterized by the chirp mass [39]

$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}} = \frac{c^3}{G}\left[\frac{5}{96}\pi^{-8/3} f^{-11/3} \dot{f}\right]^{3/5},$$

where f and $\dot{f}$ are the observed frequency and its time derivative and G and c are the gravitational constant and speed of light. Estimating f and $\dot{f}$ from the data one obtains a chirp mass of $\mathcal{M} \approx 30\,M_\odot$, implying that the total mass M must be at least $70\,M_\odot$. This bounds the sum of the Schwarzschild radii of the binary components to $2GM/c^2 \gtrsim 210$ km. But to reach the high orbital frequency of 75 Hz (half the gravitational-wave frequency) the objects must have been very close, and hence very

High Energy Physics

Merging binary BHs of 29 & 36 solar masses radiate 10,000x more power in 0.25sec than all the stars in the Universe

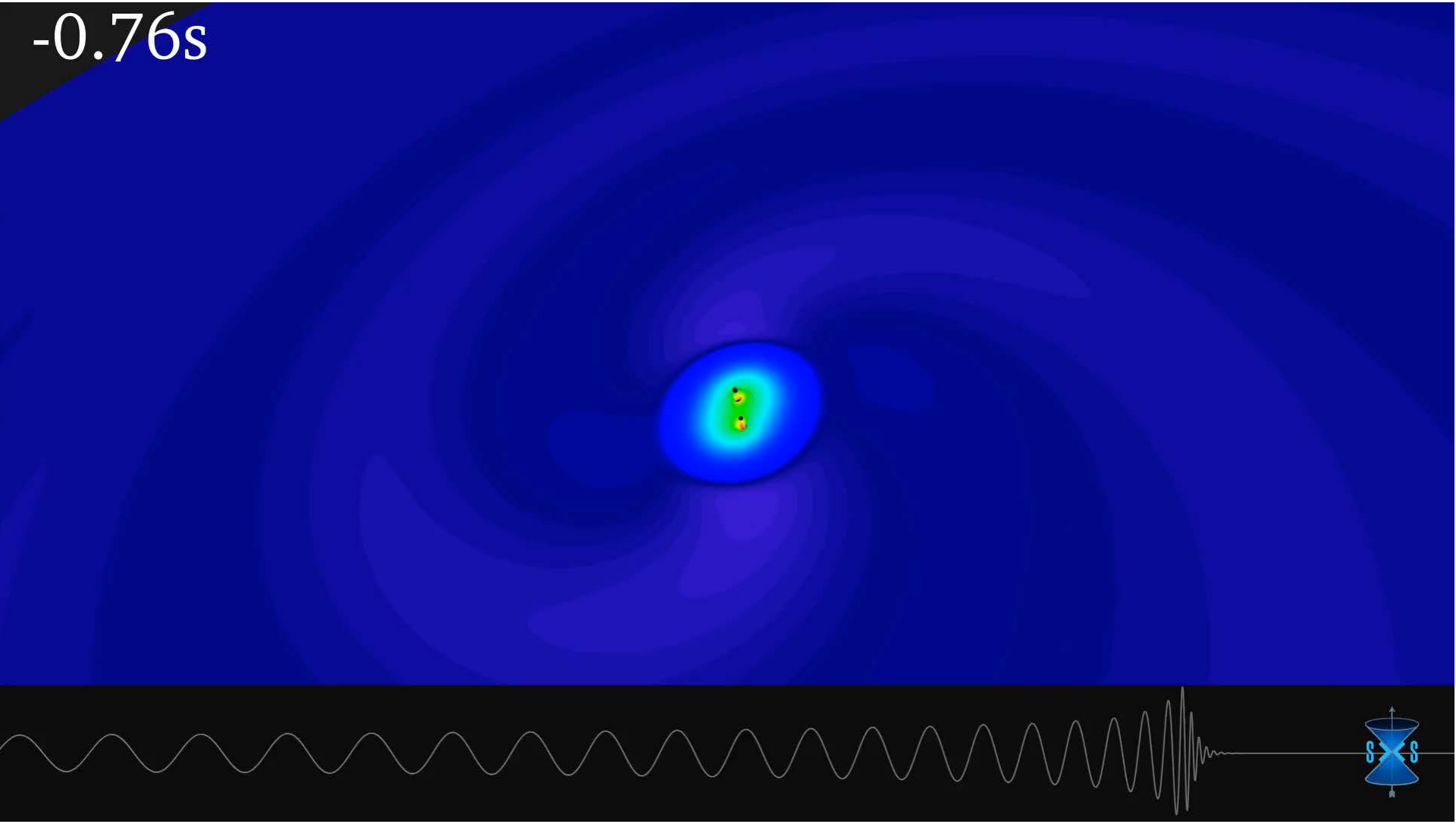
($E = Mc^2$ $M = 3$ Solar Masses)

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

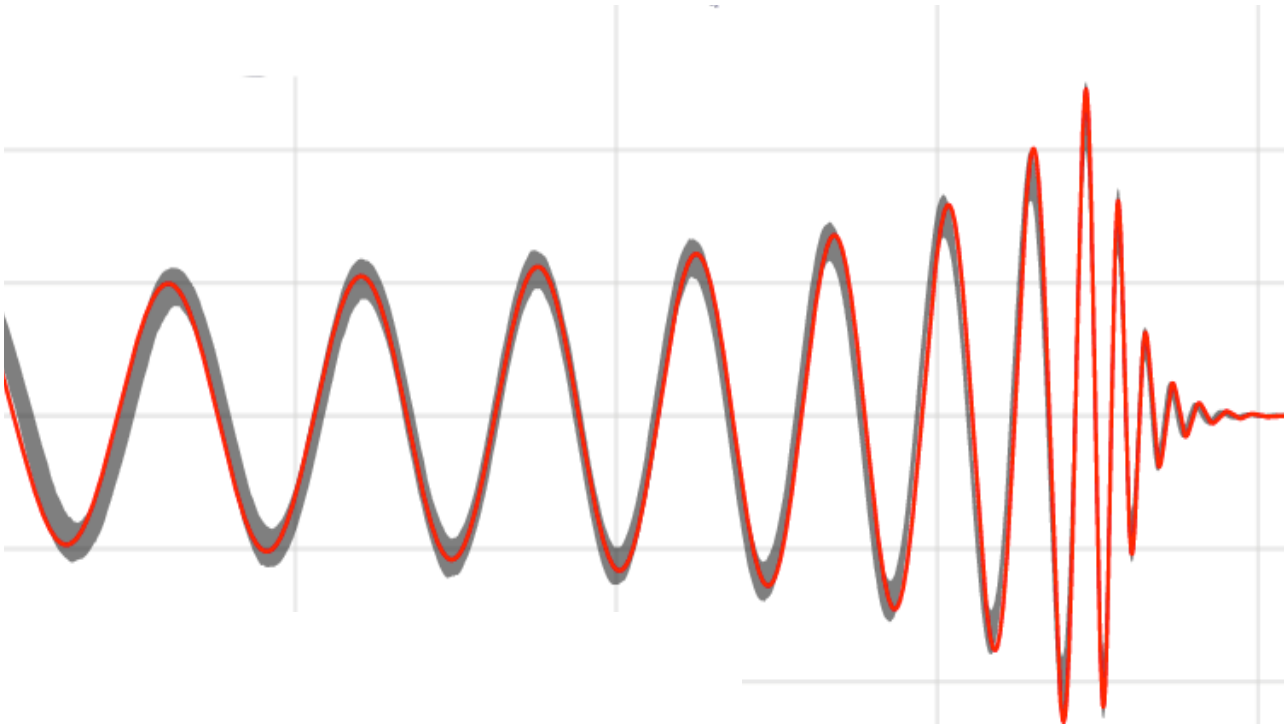
General Relativity Calculates space time distortion

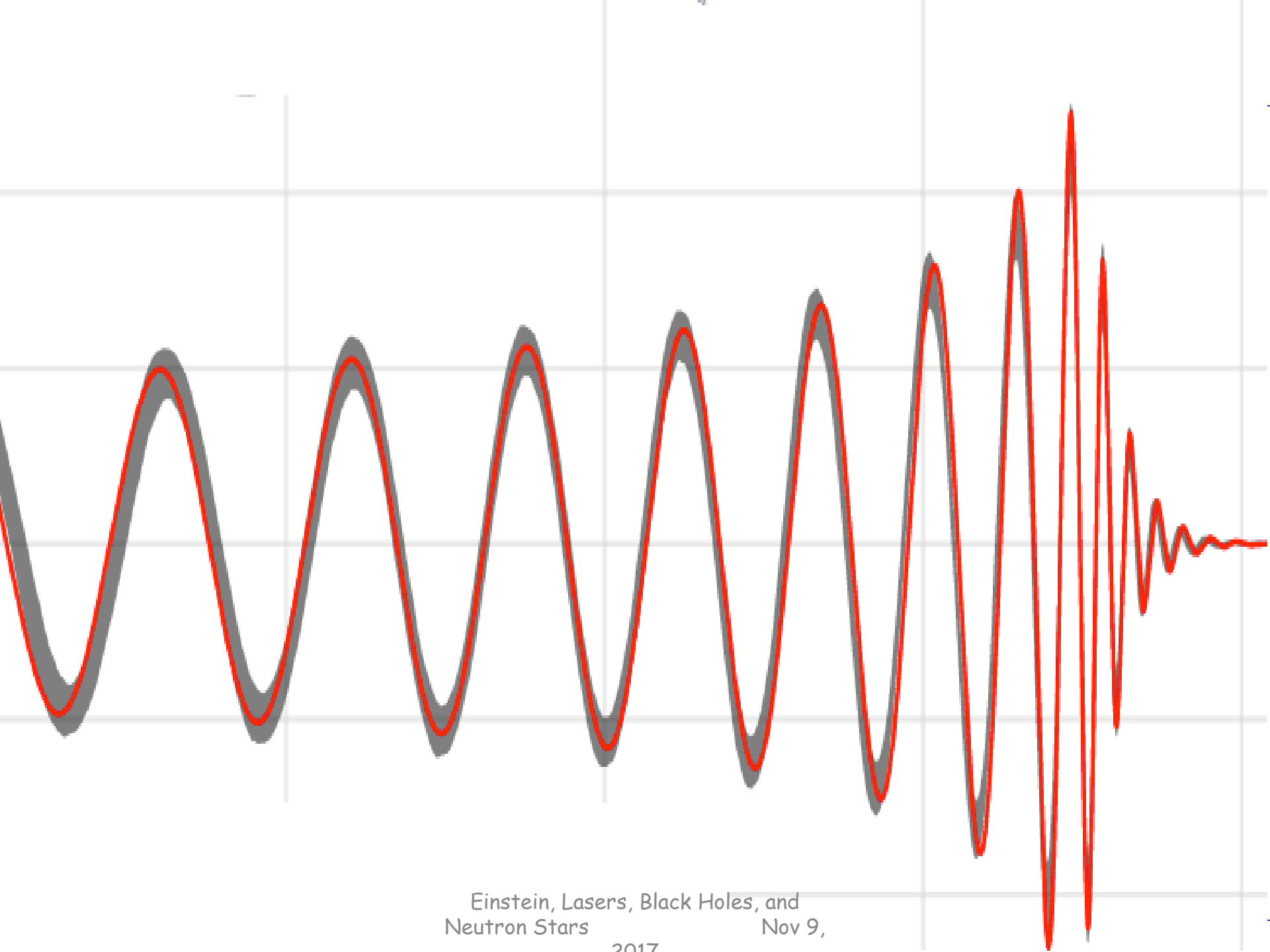
Byer Group



Chirped Gravitational wave from 30Hz to 240Hz in 0.25sec

Byer Group





Celebration Cake for LIGO Success!

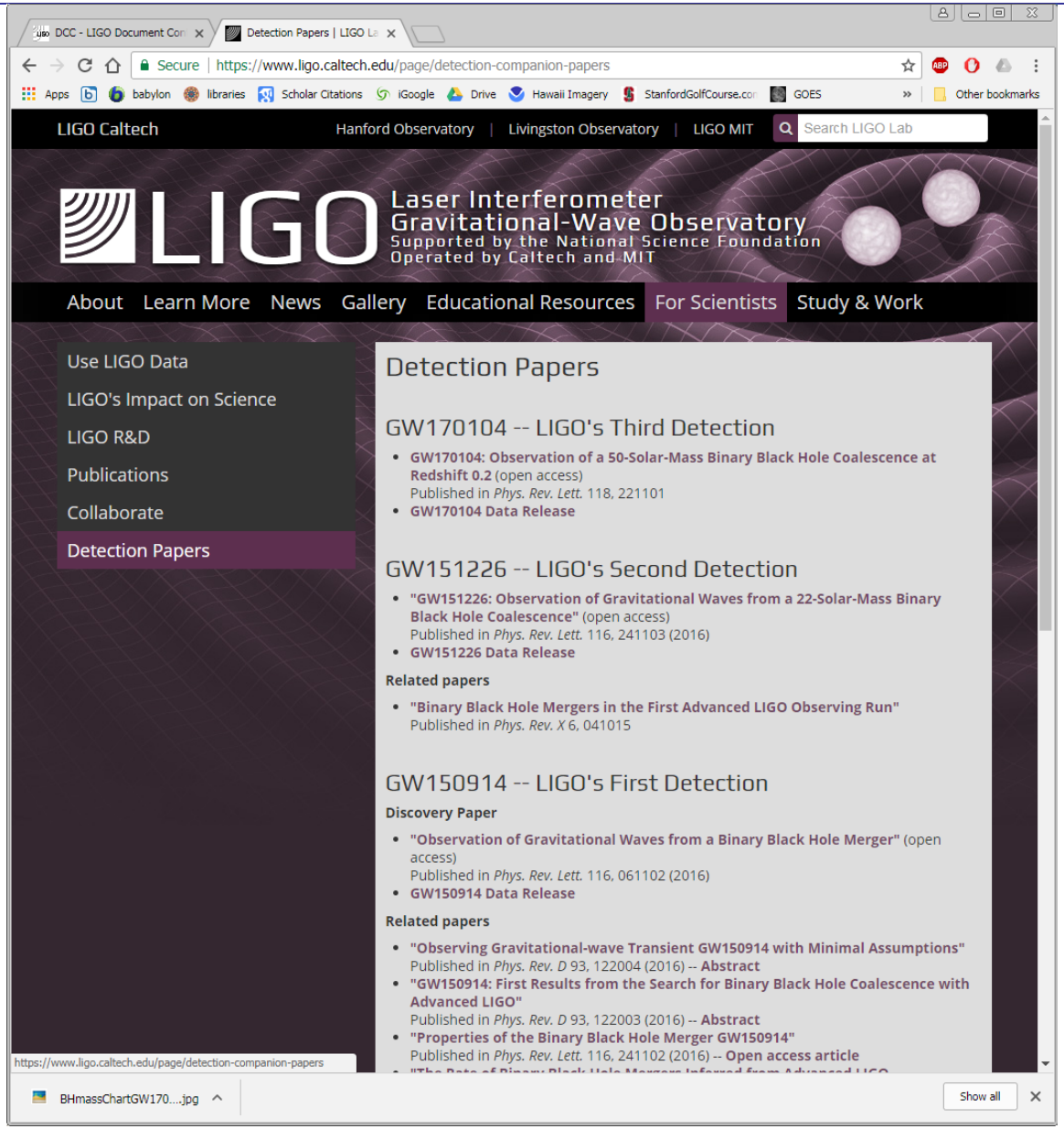
Byer Group

Kip Thorne with LIGO students at Stanford
Feb 16 2016

Byer Group

LIGO Three detections - BH BH mergers

Byer Group



Boxing Day Event – Dec 26, 2015

Merger of 14.3 + 7.5 to yield 20.8 solar Mass BH

Byer Group

GW151226: Second Observation of Gravitational Waves from a Binary Black Hole Coalescence

The LIGO Scientific Collaboration and The Virgo Collaboration

We report the observation of a gravitational-wave signal produced by the coalescence of two stellar-mass black holes. The signal, GW151226, was observed by the twin detectors of the Laser Interferometer Gravitational-wave Observatory (LIGO) on December 26, 2015 at 03:38:53 UTC. The detection was initially made within seventy seconds by an online matched-filter search targeting binary coalescences. Subsequent offline analyses recovered GW151226 with a network signal-to-noise ratio of 13 and a significance greater than 5σ. The signal persists in the LIGO frequency band for approximately 5 seconds, increasing in frequency and amplitude over 150 cycles from 20 to 600 Hz and reaches a peak gravitational strain of 3.3×10^{-22}. The source-frame progenitor masses are found to be $14.3^{+8.3}_{-3.7}\,M_\odot$ and $7.5^{+2.3}_{-2.3}\,M_\odot$, and the final black hole mass to be $20.8^{+6.1}_{-1.7}\,M_\odot$. Based on current waveform modeling, we find that at least one of the component black holes has significant positive spin. This source is located at a luminosity distance of 440^{+180}_{-190} Mpc corresponding to a redshift of $0.09^{+0.03}_{-0.04}$. All uncertainties define a 90% credible interval. This second gravitational wave observation provides improved constraints on stellar populations and on deviations from general relativity.

PACS numbers: 04.80.Nn, 04.25.dg, 95.85.Sz, 97.80.-d

Introduction. A century after Einstein predicted the existence of gravitational waves [1], the Laser Interferometer Gravitational-wave Observatory (LIGO) [2, 3] observed the first gravitational-wave signal GW150914 from a binary black hole merger [4]. In this letter we report the observation of a second coincident signal GW151226, also from the coalescence of two black holes. Full details of all binary black hole observations during Advanced LIGO's first observing period, September 12, 2015 to January 19, 2016, are given in [5].

Over 5 seconds, GW151226 passes through LIGO's sensitive band, increasing in frequency and amplitude over approximately 150 cycles from 20 to 600 Hz. A significantly large fraction of the signal's detectable power or signal-to-noise ratio (SNR) is due to the early inspiral phase (~140 cycles from 20 Hz to ~100 Hz). This is very different from the more massive GW150914 binary, whose last ten cycles, comprising inspiral and merger, dominated the SNR. Consequently, the use of accurate waveform models for com-

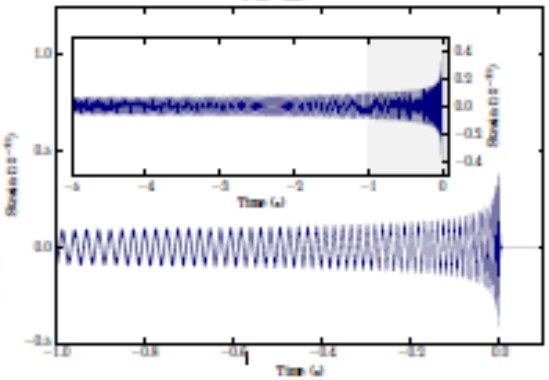
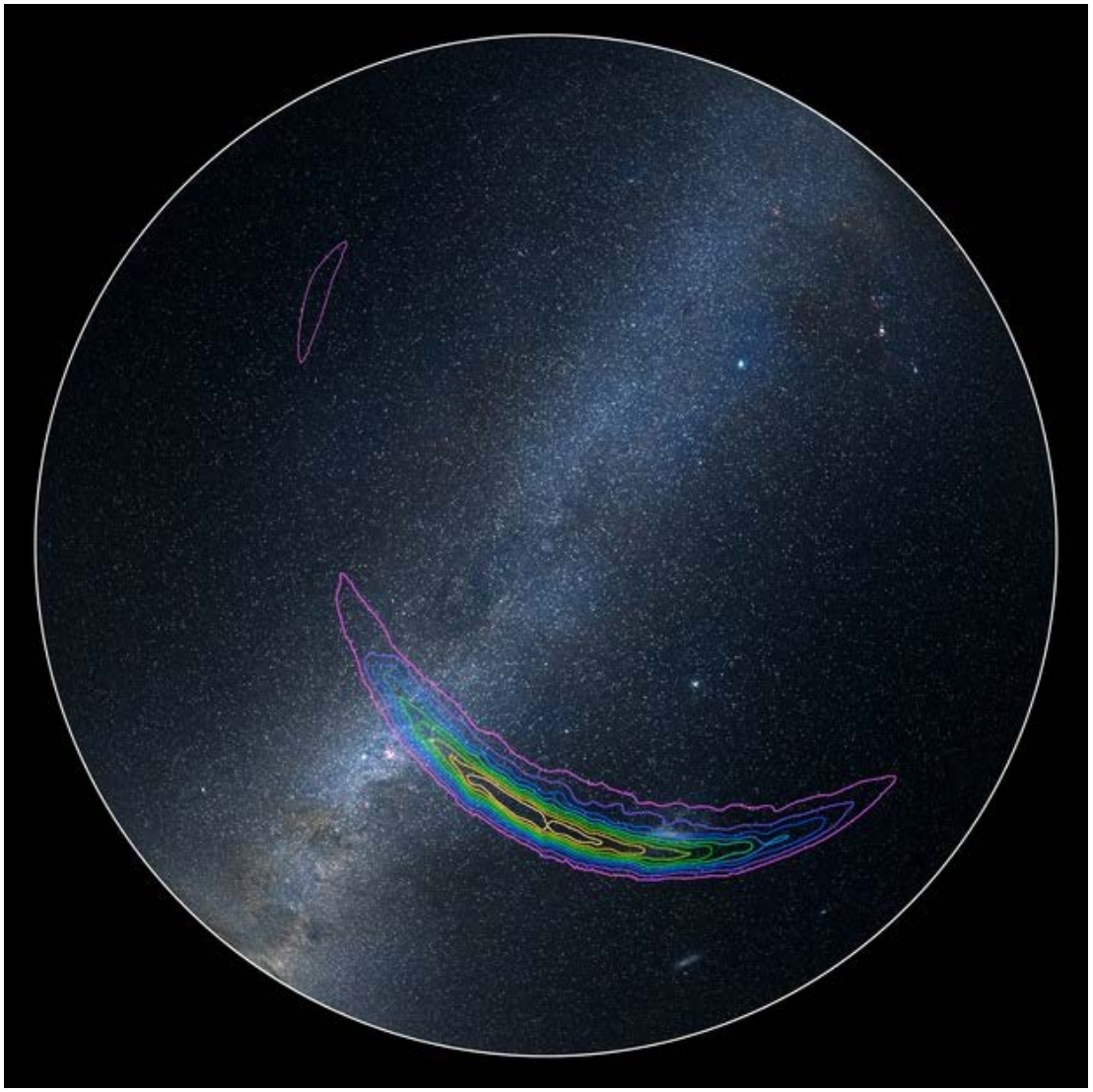


FIG. 1. Reconstruction of the best-match binary black hole template waveform in the Livingston detector. The waveform model does not include spin-precession effects. All times are relative to December 26, 2015 at 03:38:53.648 UTC.

BH-BH Merger radiates 1 solar mass of energy

Location on the Southern Sky

Byer Group



Global network of interferometers
Build a Southern Observatory

Byer Group

LSC:
LIGO+GEO

- 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 $30.5^{+5.7}_{-3.0}\,M_\odot$ and $25.3^{+2.8}_{-4.2}\,M_\odot$ (at the 90% credible level). The luminosity distance of the source is 540^{+130}_{-210} Mpc, corresponding to a redshift of $z = 0.11^{+0.03}_{-0.04}$. 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

The era of gravitational wave (GW) astronomy began with the detection of binary black hole (BBH) mergers, by the Advanced Laser Interferometer Gravitational Wave Observatory (LIGO) detectors [1], during the first of the Advanced Detector Observation Runs. Three detections, GW150914 [2], GW151226 [3], and GW170104 [4], and a lower significance candidate, LVT151012 [5], have been announced so far. The Advanced Virgo detector [6] joined the second observation run on August 1, 2017.

On August 14, 2017, GWs from the coalescence of two black holes at a luminosity distance of 540^{+130}_{-210} Mpc, with masses of $30.5^{+5.7}_{-3.0}\,M_\odot$ and $25.3^{+2.8}_{-4.2}\,M_\odot$, 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 ~8 ms and ~14 ms, respectively

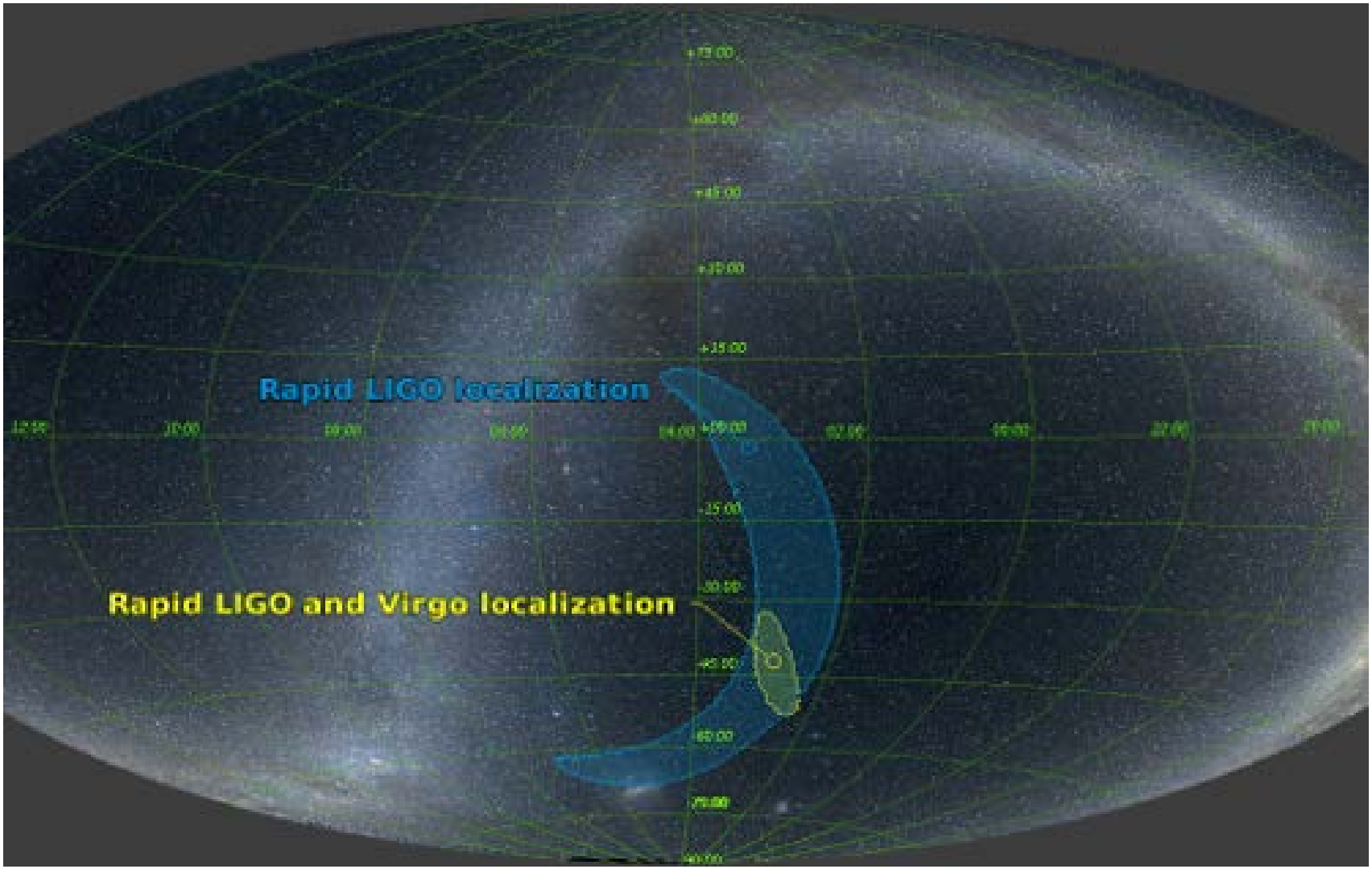
The signal-to-noise ratio (SNR) time series, the time-frequency representation of the strain data and the time series data of the three detectors together with the inferred

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 [7–9]. Virgo adds additional independent baselines, which in cases such as GW170814 can reduce the positional uncertainty by an order of magnitude or more [8].

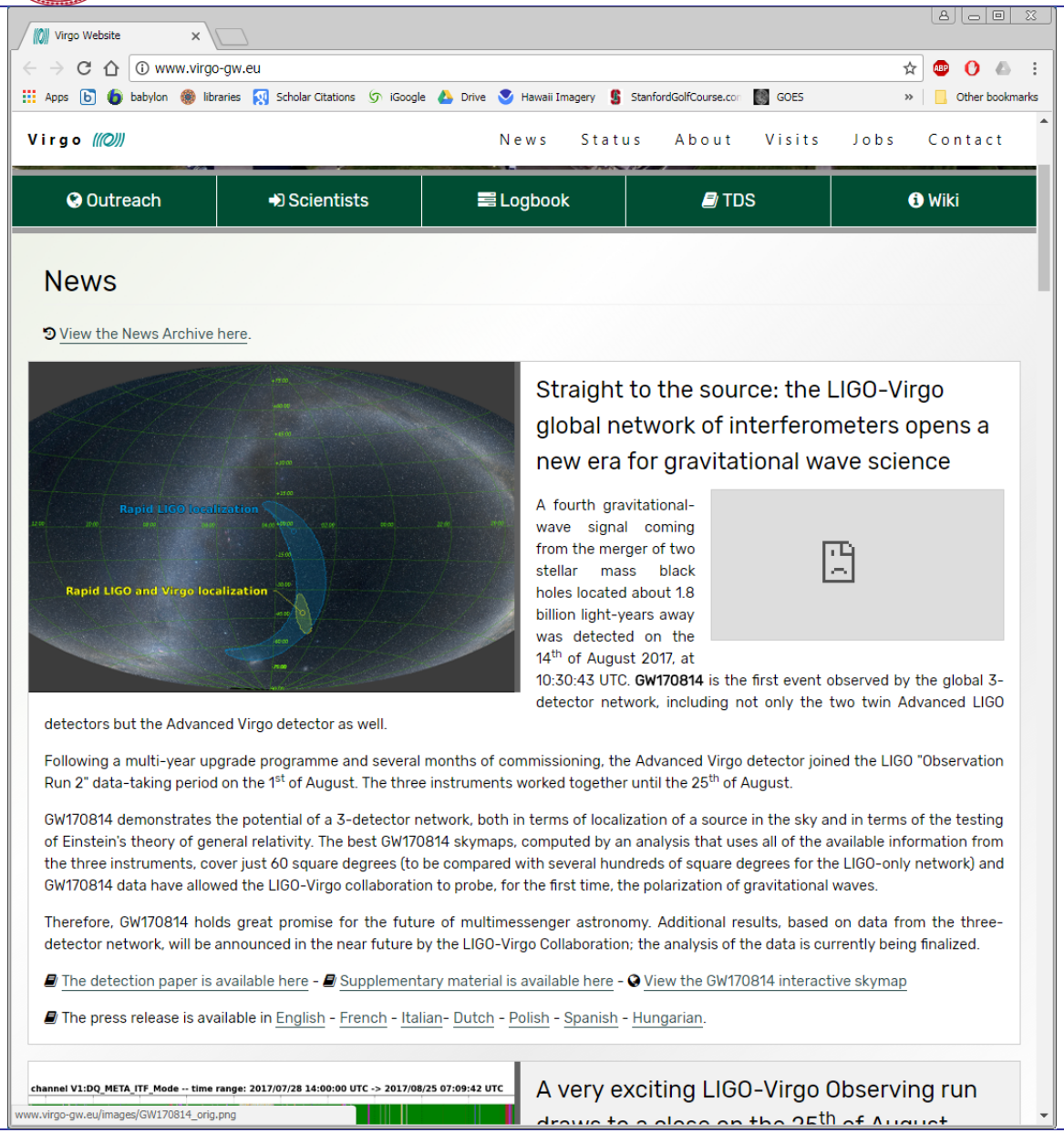
Rapid localization on the sky - ~ 5 x 5 degrees
Virgo turns on Aug 1 2017 – Detection almost immediately

Byer Group



LIGO Livingston & Hanford + VIRGO = Localization in the Sky (Press release Sept 26, 2017)

Byer Group



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

LVC

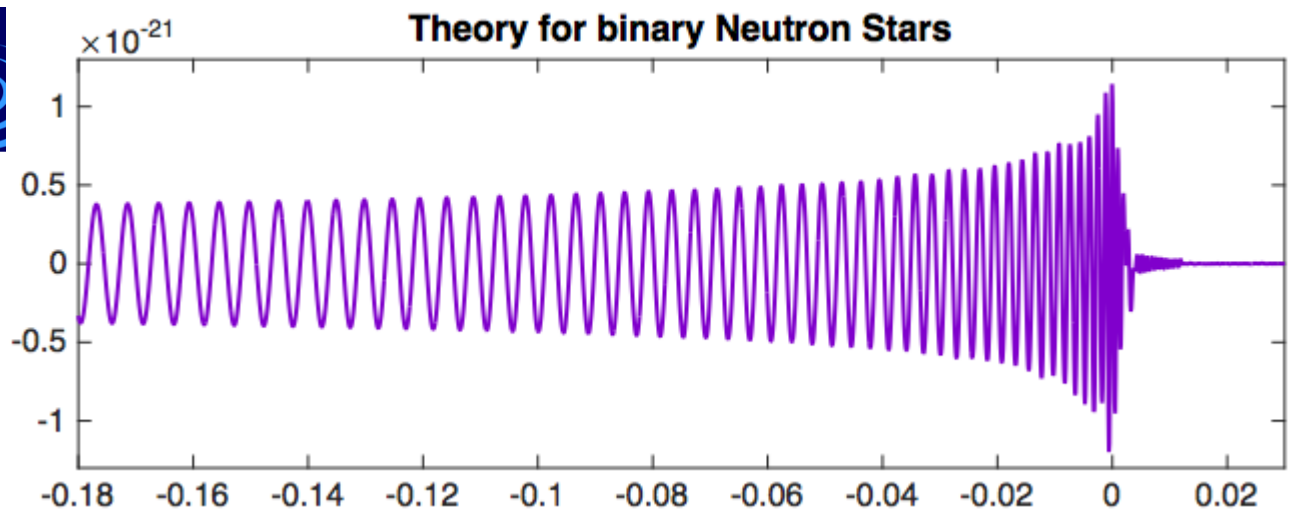
GBM

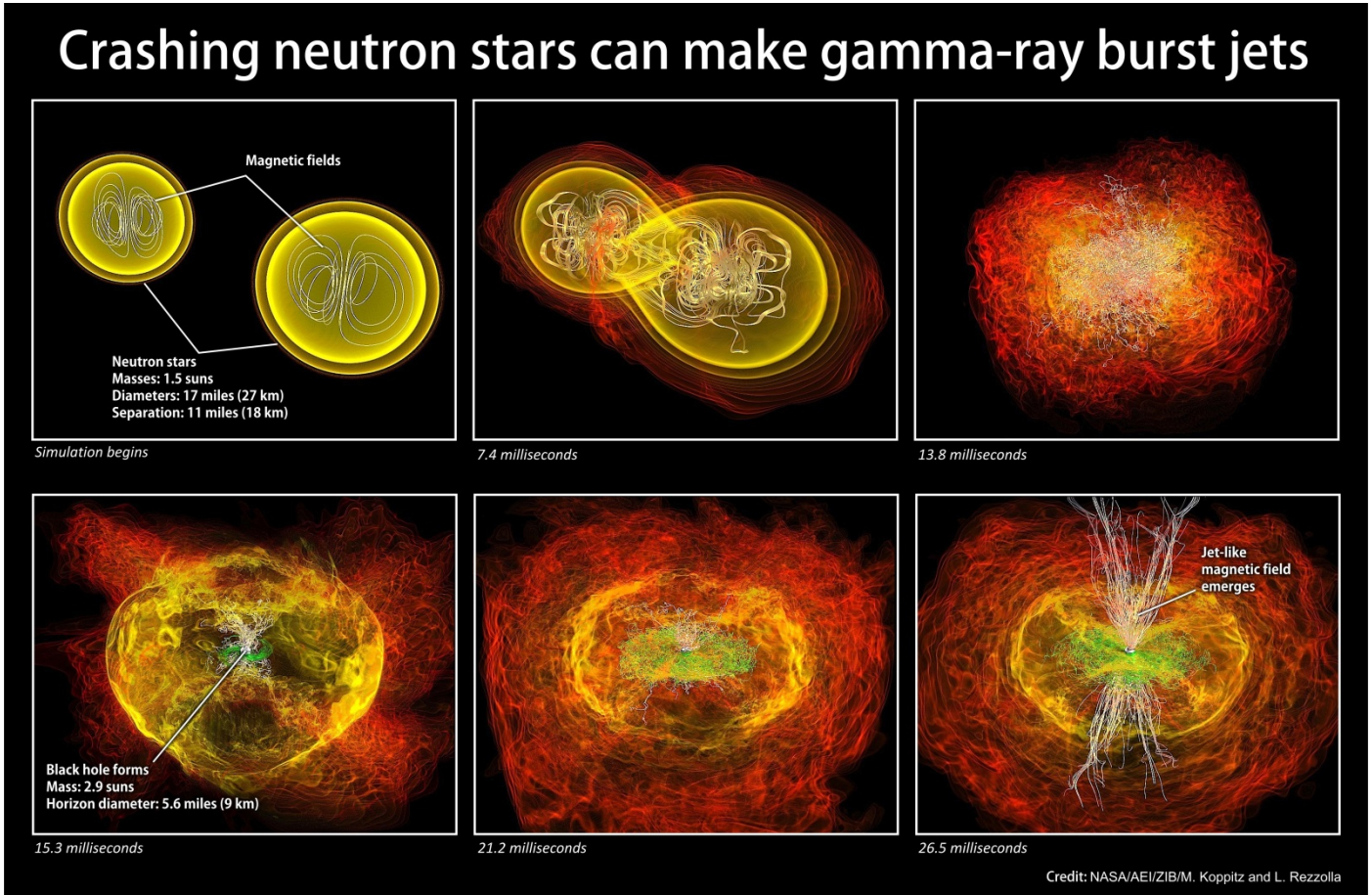
INTEGRAL

(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 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.]


Theory for binary Neutron Stars
×10^-21
1
0.5
0
-0.5
-1
-0.18
-0.16
-0.14
-0.12
-0.1
-0.08
-0.06
-0.04
-0.02
0
0.02


Crashing neutron stars can make gamma-ray burst jets
Magnetic fields
Neutron stars
Masses: 1.5 suns
Diameters: 17 miles (27 km)
Separation: 11 miles (18 km)
Simulation begins
7.4 milliseconds
13.8 milliseconds
Black hole forms
Mass: 2.9 suns
Horizon diameter: 5.6 miles (9 km)
15.3 milliseconds
21.2 milliseconds
Jet-like magnetic field emerges
26.5 milliseconds
Credit: NASA/AEI/ZIB/M. Koppitz and L. Rezzolla

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.

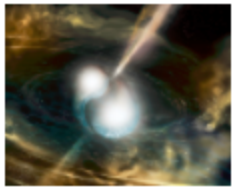
Illustration by Robin Dienel, courtesy of the Carnegie Institution for Science

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.

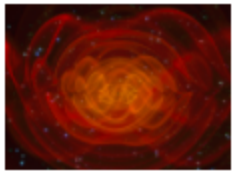
They were neutron stars — the collapsed cores left behind after

LATEST NEWS

Dawn of an Era: Astronomers Hear and See Cosmic Collision



LIGO Detects a Neutron Star Merger



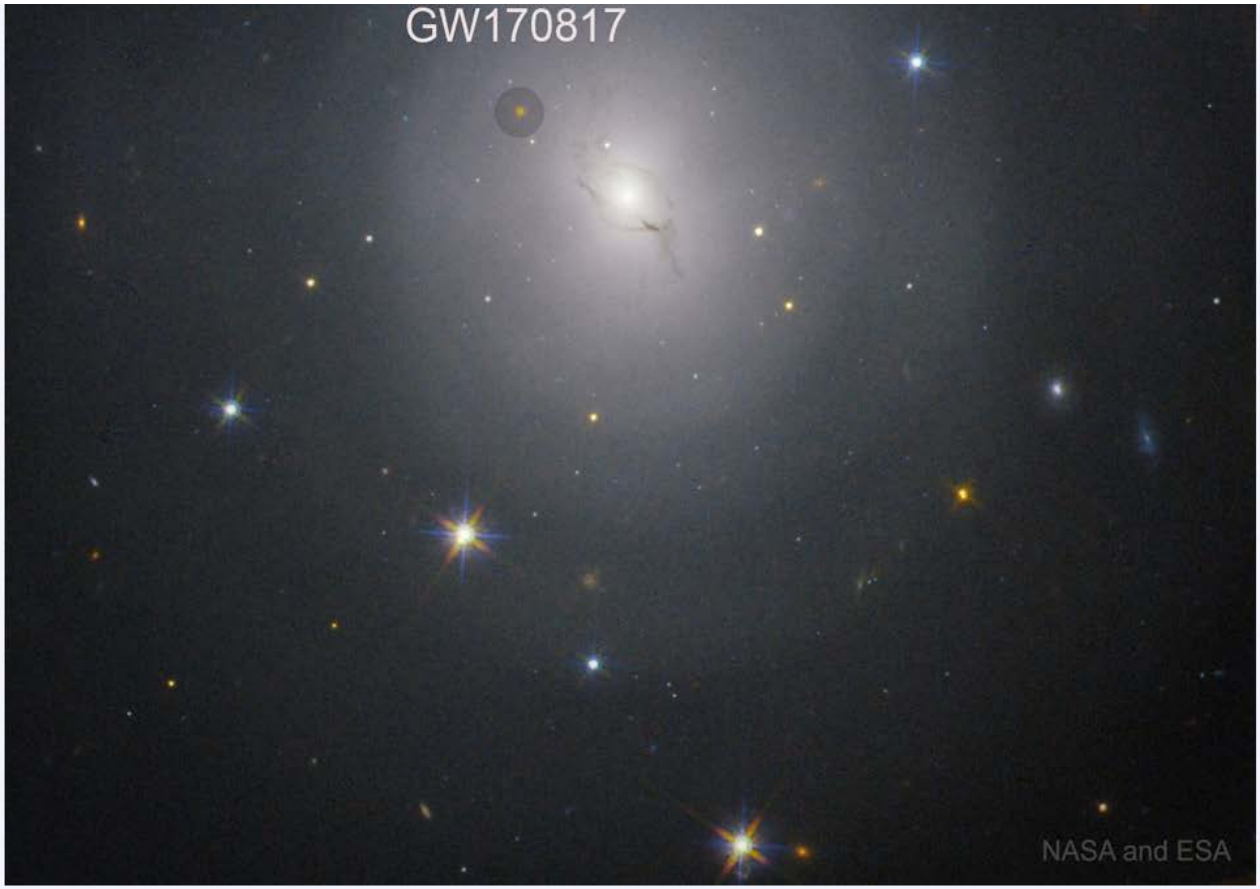
Astronomy without light

POPULAR

Soupy mix of minerals a 'jackpot' on Mars

NGC 4883 Galaxy with NS NS Kilo Nova in visible light

Byer Group



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 wave 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

NS-NS Binary Merger 170717

A Galactic Gold Factory

Riccardo DeSalvo

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.

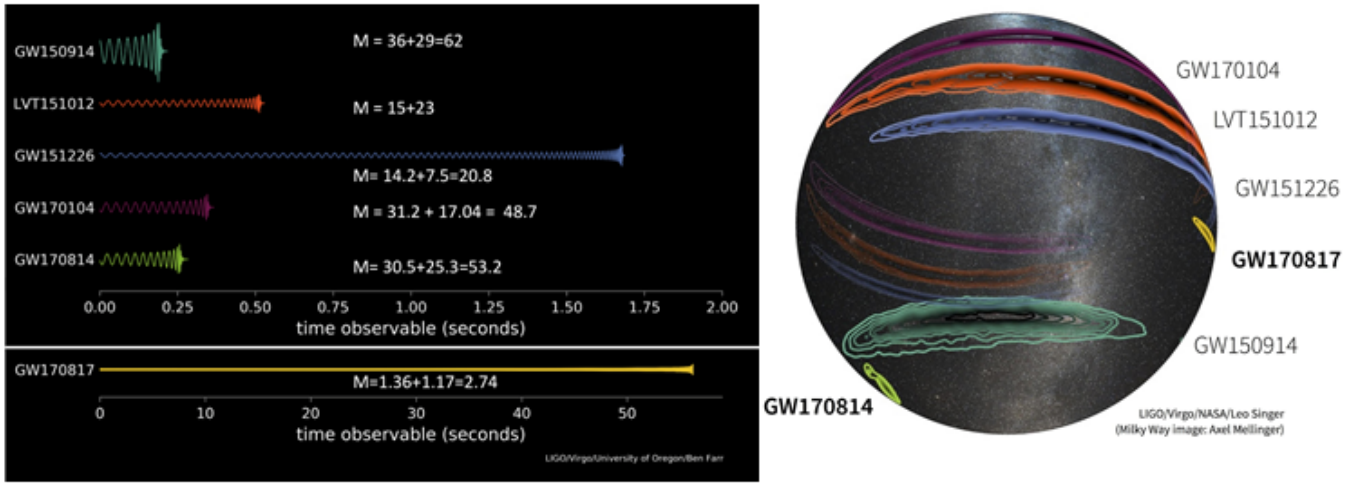
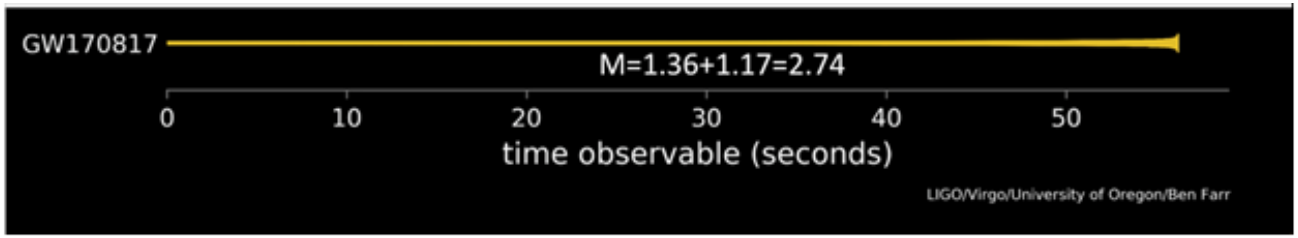


Figure 1: The detection of 5 BH and 1 NS inspiral. The last two August events, GW170814 and GW170817, have better directionality due to the triangulation allowed by the three-observatory detection mode. Surprisingly, all BHs are of a heavier mass than expected for stellar BHs. They

The GW signal from NS-NS Merger
More than 60 sec duration across LIGO frequency band

Byer Group



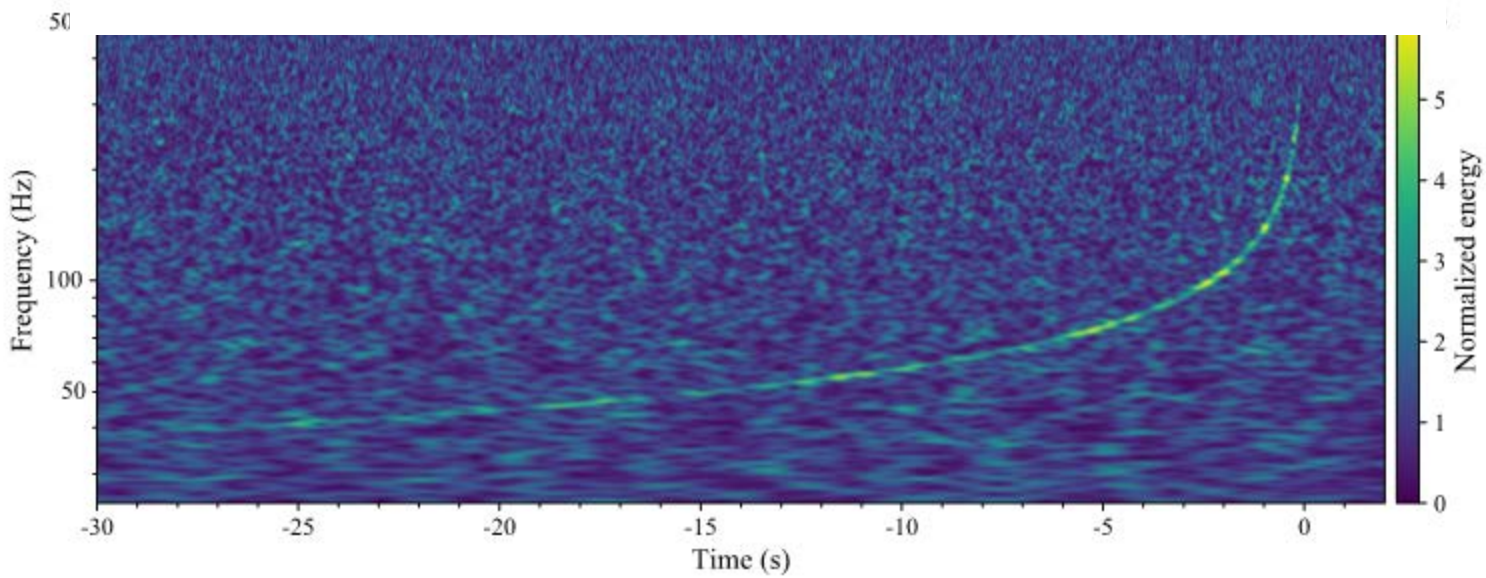
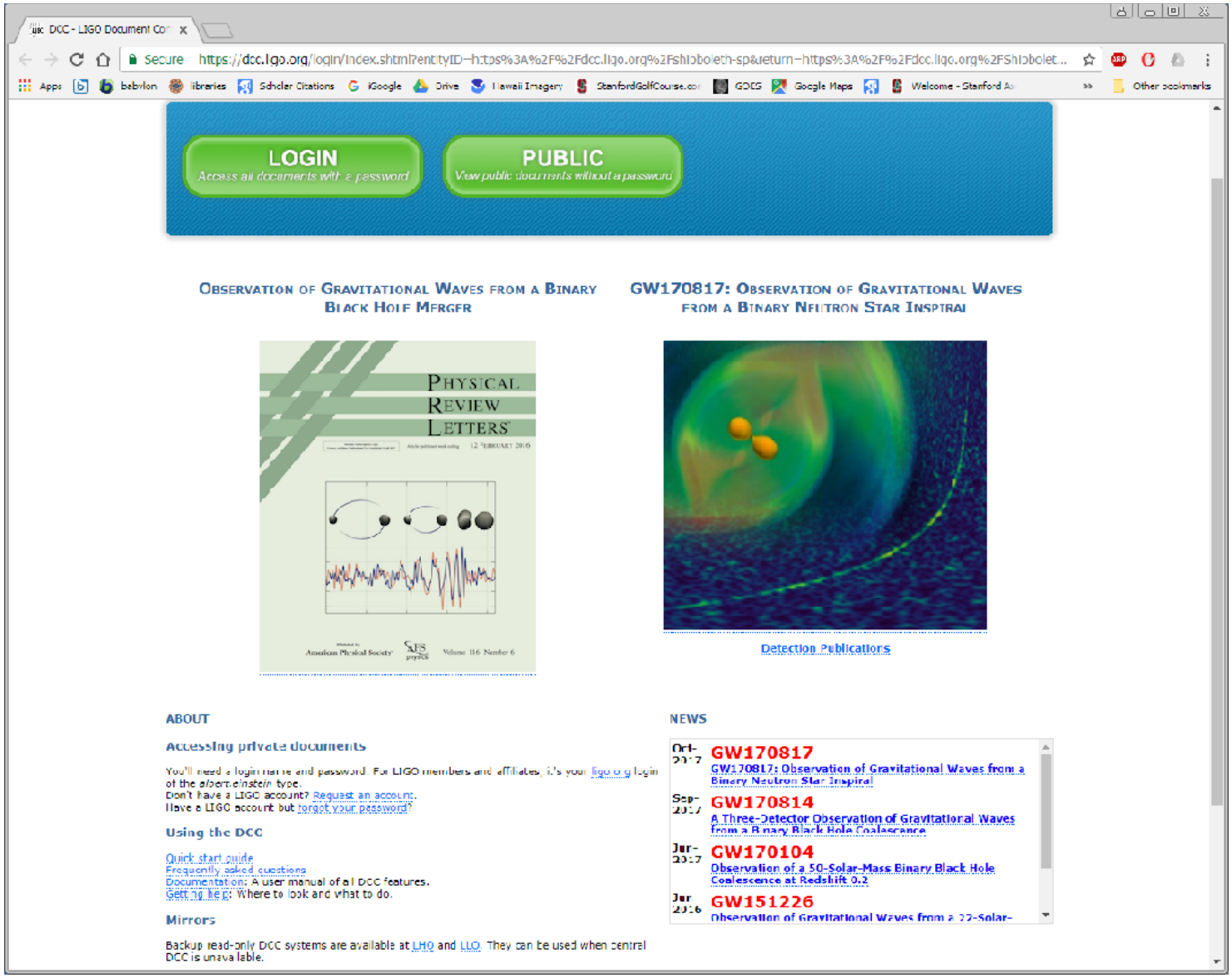


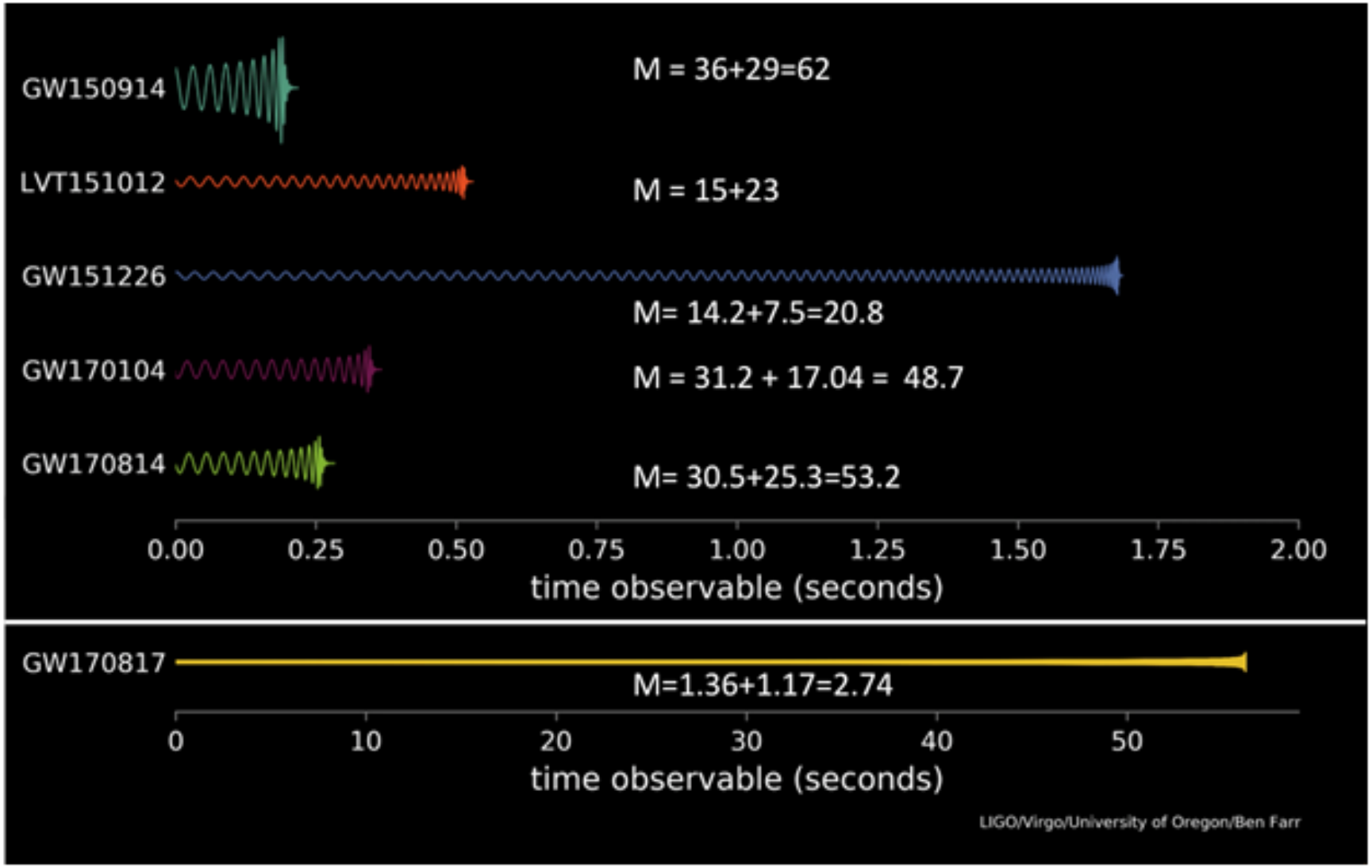
Figure 2: The first neutron star binary inspiral detected by the GW detection network (credit Dr. Alexander Nitz, Max Planck Institute for Gravitational Physics, Albert Einstein Institute).

BH-BH to NS-NS mergers 170817

Byer Group

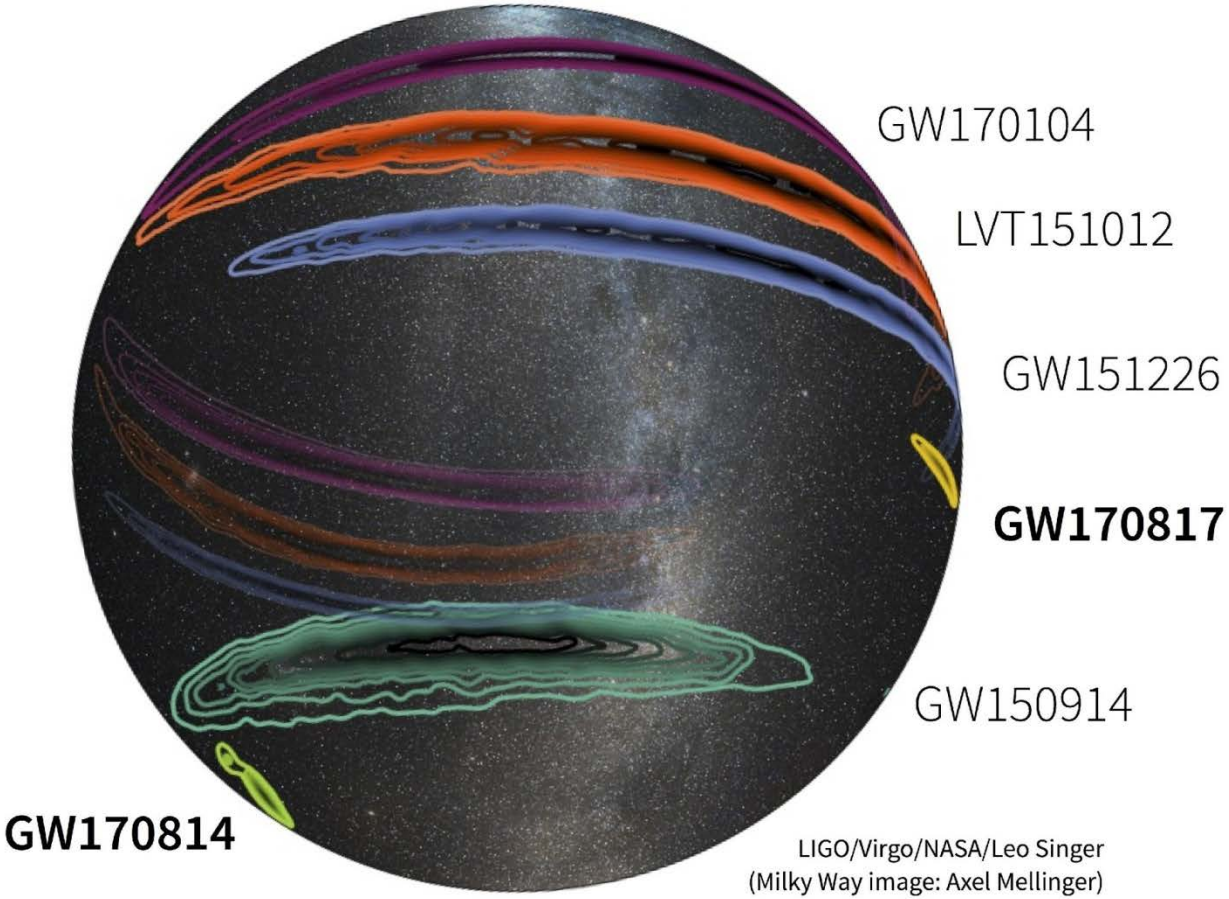


BH and NS Signals to Date



Location of BH BH and NS NS events on the sky

Byer Group



GW170814 and GW170817 were triangulated using LIGO and Virgo Detectors

Gravitational waves

Astronomers have finally found gravitational waves. Now things can get interesting. by Korey Haynes and Eric Betz

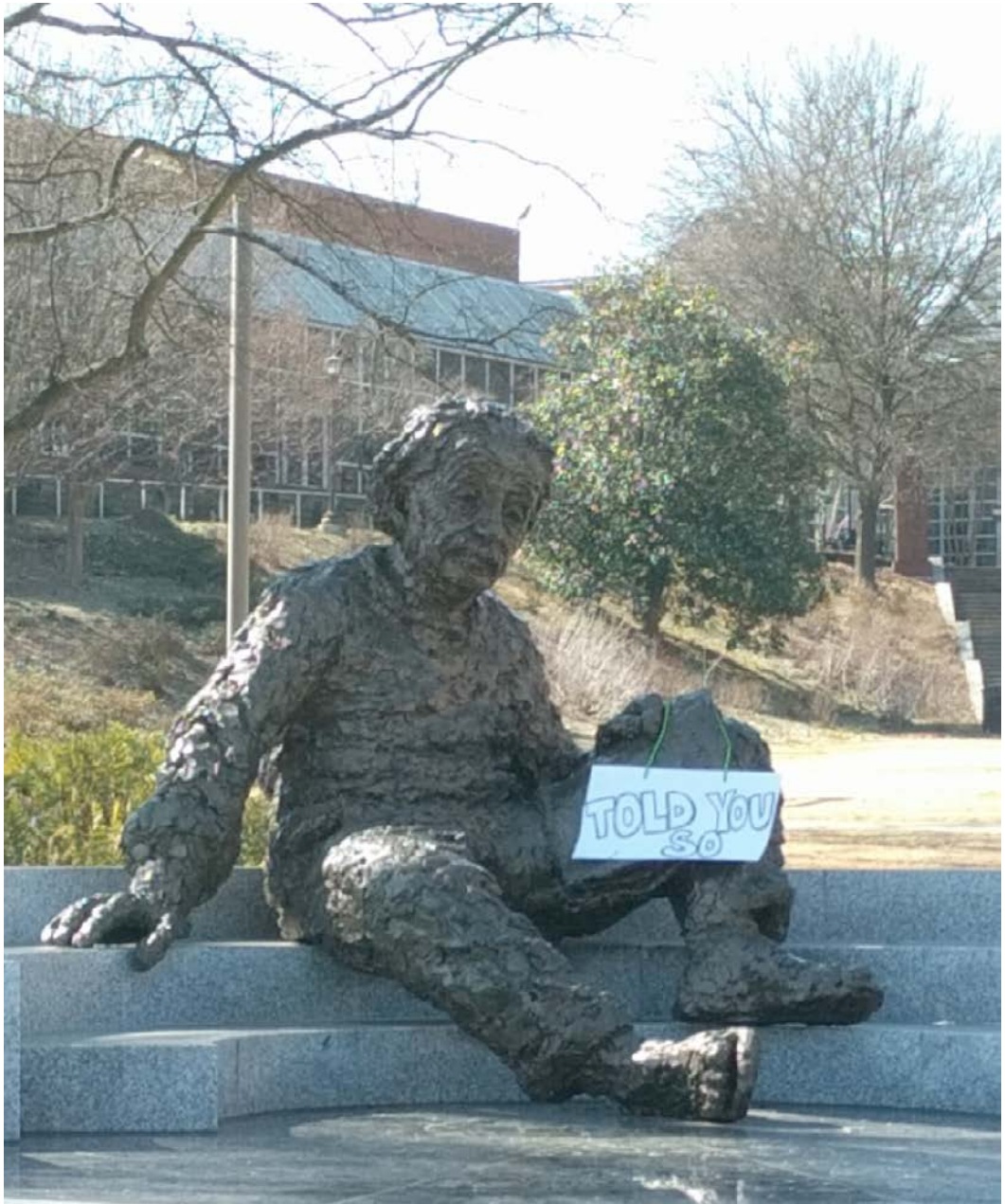
A wrinkle in space-time confirms Einstein's gravitation

"Ladies and gentlemen, we have detected gravitational waves. We did it!" The words from LIGO spokesman 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 jounces 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. SXS

Einstein: *I told you so!*



Kavli Prize to Drever, Thorne, Weiss, Sept 6, 2016

Newsletter **Summer 2016**

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.kavlifoundation.org.

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.

Fermi Prize to Barry Barish and Adalberto Giazotto - 2016

Byer Group

SIF prima pagina

Società Italiana di Fisica — 115 anni e oltre

Topics | CHI SIAMO / About us | ARCHIVIO / Archive | Newsletter | Facebook | CERCA / Search

N. 31 - Luglio 2016 > Il Premio Fermi 2016 alle onde gravitazionali

PREMI Prizes

Il Premio Fermi 2016 alle onde gravitazionali

A. BETTINI, L. CIFARELLI — 28-07-2016 — LEGGI IN PDF

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 neri binari in coalescenza"*.

In particolare:
– a Barry Barish, California Institute of Technology, Pasadena, CA, USA, *"per il suo fondamentale*

Galileo Galilei e la Cina

Intervista ad Antonino Zichichi di L. Cifarelli

Il Premio Fermi 2014 alla microelettronica

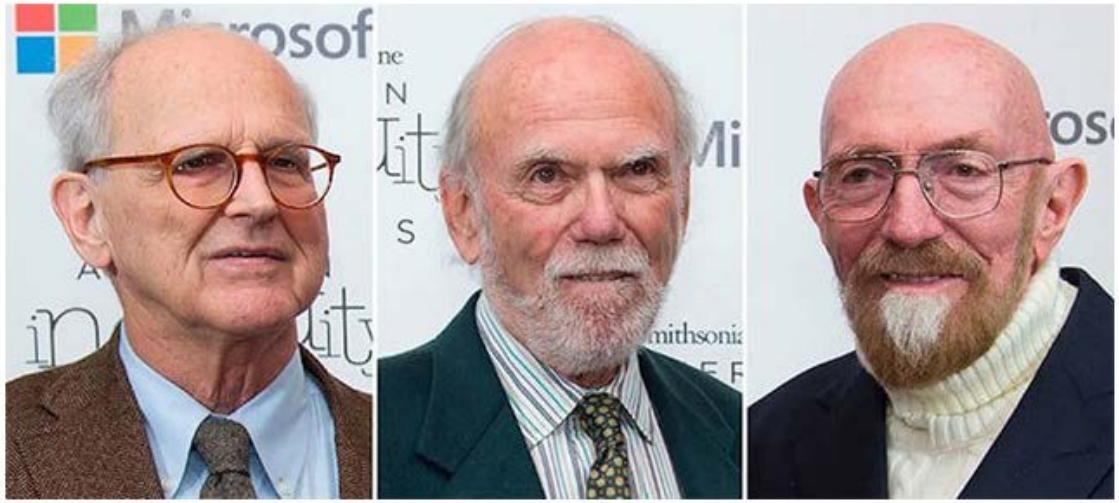
Il Premio "Enrico Fermi" 2014 della Società Italiana di Fisica è stato attribuito a Federico Faggin

ULTIMI ARTICOLI

- Fisica nella tormenta
- Nuvole e clima: nuovi risultati da CLOUD
- A Padova il 102° Congresso SIF
- IONS Naples 2016, l'Italia ospita i giovani

Rai Weiss, Barry Barish, Kip Thorne
Nobel Prize to LIGO – October 3 2017

Byer Group



MOLLY RILEY/AGENCE FRANCE-PRESSE □ GETTY IMAGES

Gravitational wave researchers win Nobel Prize

Three American physicists have won the 2017 Nobel Prize in Physics for their contribution to detecting gravitational waves.

READ »

LIGO Nobel Prize Cake – Nagoya Japan Oct 3, 2017

Byer Group