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NOBEL PRIZE

Nobel Prizes, annual monetary awards granted to individuals or institutions for outstanding contributions in the fields of physics, chemistry, physiology or medicine, literature, international peace, and economic sciences. The Nobel prizes are internationally recognized as the most prestigious awards in each of these fields. The prizes were established by Swedish inventor and industrialist Alfred Bernhard Nobel, who set up a fund for them in his will. The first Nobel prizes were awarded on December 10, 1901, the fifth anniversary of Nobel’s death.

In his will, Nobel directed that most of his fortune be invested to form a fund, the interest of which was to be distributed annually "in the form of prizes to those who, during the preceding year, shall have conferred the greatest benefit on mankind." He stipulated that the interest be divided into five equal parts, each to be awarded to the person who made the most important contribution in one of five different fields. In addition to the three scientific awards and the literature award, a prize would go to the person who had done "the most or the best work for fraternity among nations, for the abolition or reduction of standing armies, and for the holding and promotion of peace congresses." Nobel also specified certain institutions that would select the prizewinners. The will indicated that “no consideration whatever shall be given to the nationality of the candidates, but that the most worthy shall receive the prize.”

In 1968 the Riksbank, the central bank of Sweden, created an economics prize to commemorate the bank's 300th anniversary. This prize, called the Nobel Memorial Prize in Economic Science, was first awarded in 1969. The bank provides a cash award equal to the other Nobel prizes.

In 1900 the Nobel Foundation was established to manage the fund and to administer the activities of the institutions charged with selecting winners. The fund is controlled by a board of directors, which serves for two-year periods and consists of six members: five elected by the trustees of the awarding bodies mentioned in the will, and the sixth appointed by the Swedish government. All six members are either Swedish or Norwegian citizens.

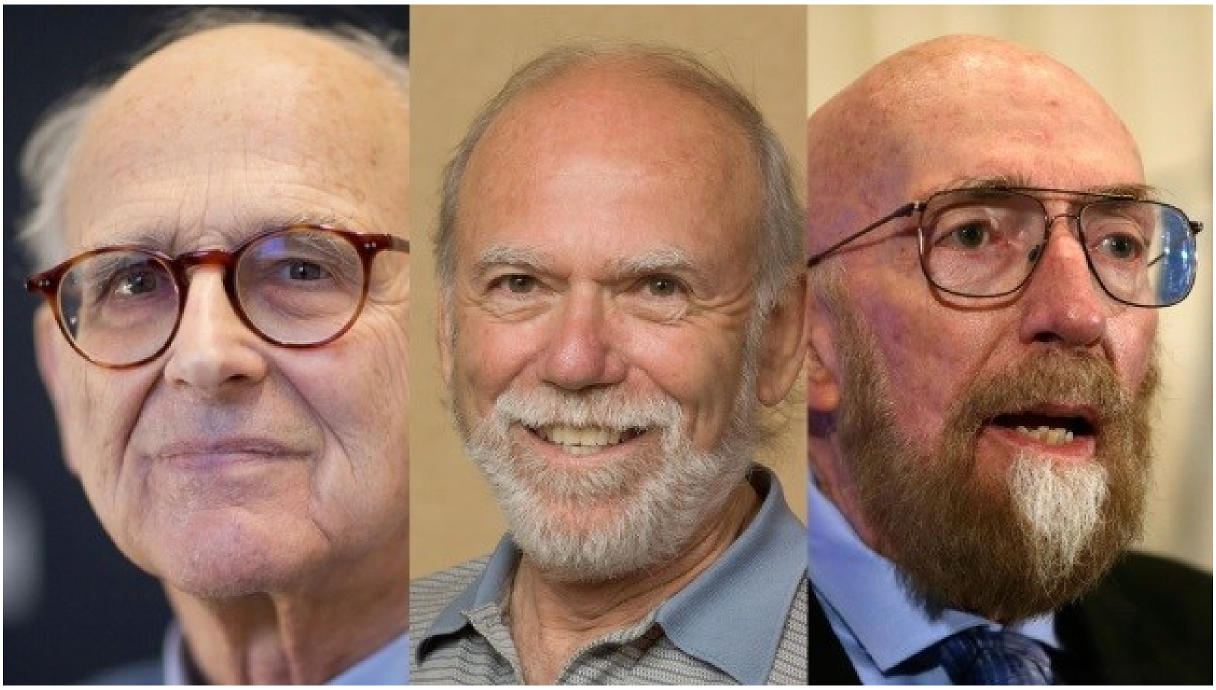
In his will, Nobel stated that the prizes for physics and chemistry would be awarded by the Swedish Academy of Sciences, the prize for physiology or medicine by the Karolinska

Institute in Stockholm, the literature prize by the Swedish Academy in Stockholm, and the peace prize by a five-person committee elected by the Norwegian Storting (Parliament). After the economics prize was created in 1968, the Swedish Academy of Sciences has held the responsibility of selecting the winners of that award.

All the prize-awarding bodies have set up Nobel committees consisting of three to five people who make recommendations in the selection process. Additional specialists with expertise in relevant fields assist the committees. The Nobel committees examine nominations and make recommendations to the prize-awarding institutions. After deliberating various opinions and recommendations, the prize-awarding bodies vote on the final selection, and then they announce the winner. The deliberations and voting are secret, and prize decisions cannot be appealed.

Winners of the Nobel Prize, one of six prizes were established by the estate of Swedish inventor and philanthropist Alfred Bernhard Nobel. One prize is offered in each of the fields of chemistry, economics, literature, physics, physiology or medicine, and one is offered for the promotion of world peace. The first prizes were given in 1901.

NOBEL PRIZE IN PHYSICS 2017



The Nobel Prize in Physics 2017 was divided, one half awarded to Rainer Weiss, the other half jointly to Barry C. Barish and Kip S. Thorne *"for decisive contributions to the LIGO detector and the observation of gravitational waves"*.

Rainer Weiss

Born: 1 June 1940, Logan, UT, USA
Affiliation at the time of the award: LIGO/VIRGO Collaboration, California Institute of Technology (Caltech), Pasadena, CA, USA
Prize motivation: "for decisive contributions to the LIGO detector and the observation of gravitational waves"

Rainer "Rai" Weiss; born September 29, 1932) is an American physicist, known for his contributions in gravitational physics and astrophysics. He is a professor of physics emeritus at MIT and an adjunct professor at LSU. He is best known for inventing the laser interferometric technique which is the basic operation of LIGO. He was Chair of the COBE Science Working Group.
He is a member of Fermilab Holometer experiment, which uses a 40m laser interferometerto measure properties of space and time at quantum scale and provide Planck-precision tests of quantum holographic fluctuation.
In 2017, Weiss was awarded the Nobel Prize in Physics, along with Kip Thorne and Barry Barish, "for decisive contributions to the LIGO detector and the observation of gravitational waves".
Rainer Weiss was born on September 29, 1932 in Berlin, Germany, the son of Gertrude Loesner and Frederick A. Weiss. His mother, a Christian, was an actress.[12] His father, a physician, neurologist, and psychoanalyst, was forced out of Germany by Nazis because he was Jewish and an active member of the Communist Party. The family fled first to Prague, but Germany's occupation of Czechoslovakia after the 1938 Munich Agreement caused them to flee; the philanthropic Stix family of St. Louis enabled them to obtain visas to enter the United States. Weiss spent his youth in New York City, where he attended Columbia Grammar School. He studied at MIT and after dropping out in his junior year returned to receive his S.B. degree in 1955 and Ph.D. degree in 1962 from Jerrold Zacharias. He taught at Tufts University in 1960–62, was a postdoctoral scholar at Princeton University from 1962 to 1964, then joined the faculty at MIT in 1964.

Achievements
Weiss brought two fields of fundamental physics research from birth to maturity: characterization of the cosmic background radiation, and interferometric gravitational wave observation.
He made pioneering measurements of the spectrum of the cosmic microwave background radiation, and then was co-founder and science advisor of the NASA COBE (microwave background) satellite. Weiss also invented the interferometric gravitational wave detector, and co-founded the NSF LIGO (gravitational-wave detection) project. Both of these efforts couple challenges in instrument science with physics important to the understanding of the Universe.
In February 2016, he was one of the four scientists of LIGO/Virgo collaboration presenting at the press conference for the announcement that the first direct gravitational wave observation had been made in September 2015.

Honors and Awards
Rainer Weiss has been recognized by numerous awards including:

- In 2006, with John C. Mather, he and the COBE team received the Gruber Prize in Cosmology.
- In 2007, with Ronald Drever, he was awarded the Einstein Prize for this work.
- For the achievement of gravitational waves detection, in 2016 and 2017 he received:
- The Special Breakthrough Prize in Fundamental Physics,
- Gruber Prize in Cosmology,
- Shaw Prize,
- Kavli Prize in Astrophysics
- The Harvey Prize together with Kip Thorne and Ronald Drever.
- The *Smithsonian* magazine's American Ingenuity Award in the Physical Science category, with Kip Thorne and Barry Barish.

- The Willis E. Lamb Award for Laser Science and Quantum Optics, 2017.
- Princess of Asturias Award (2017) (jointly with Kip Thorne and Barry Barish).
- The Nobel Prize in Physics (2017) (jointly with Kip Thorne and Barry Barish)

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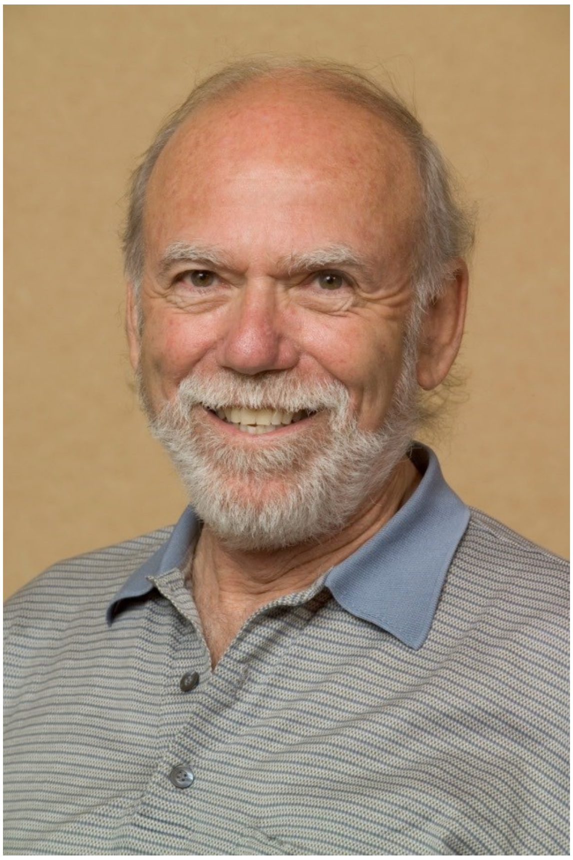
Barry Clark Barish



Barry Clark Barish (born January 27, 1936) is an American experimental physicist and Nobel Laureate. He is a Linde Professor of Physics, emeritus at California Institute of Technology. He is a leading expert on gravitational waves.

In 2017, Barish was awarded the Nobel Prize in Physics along with Rainer Weiss and Kip Thorne "for decisive contributions to the LIGO detector and the observation of gravitational waves".

Barish was born in Omaha, Nebraska, the son of Lee and Harold Barish. His parents' families were Jewish immigrants from a part of Poland that is now in Belarus. Just after World War II, the family moved to Los Feliz in Los Angeles. He attended John Marshall High School and other schools.

He earned a B.A. degree in physics (1957) and a Ph.D. degree in experimental high energy physics (1962) at the University of California, Berkeley. He joined Caltech in 1963 as part of a new experimental effort in particle physics using frontier particle accelerators at the national laboratories. In 1963-1966 he was a research fellow, in 1966-1991 an Assistant Professor, Associate Professor, and Professor of Physics. In 1991-2005 he became Linde Professor of Physics, and after that Linde Professor of Physics, Emeritus. In 1984-1996 he was the principal investigator of Caltech High Energy Physics Group.

Research

First Barish's experiments were performed at Fermilab using high-energy neutrino collisions to reveal the quark substructure of the nucleon. These experiments were among the first to observe the weak neutral current, a linchpin of the electroweak unification theories of Glashow, Salam, and Weinberg.

In the 1980s, he directed MACRO, an experiment in a cave in Gran Sasso, Italy, that searched for exotic particles called magnetic monopoles and also studied penetrating cosmic rays, including neutrino measurements that provided important confirmatory evidence that neutrinos have mass and oscillate.

In 1991, Barish was named the Maxine and Ronald Linde Professor of Physics at Caltech.

In the early 1990s, he spearheaded GEM (Gammas, Electrons, Muons), an experiment that would have run at the Superconducting Super Collider which was approved after the former project L* lead by Samuel Ting (and Barish as chairman of collaboration board) was rejected by SSC director Roy Schwitters. Barish was GEM spokesperson.

Barish became the principal investigator of the Laser Interferometer Gravitational-wave Observatory (LIGO) in 1994 and director in 1997. He led the effort through the approval of funding by the NSF National Science Board in 1994, the construction and commissioning of the LIGO interferometers in Livingston, LA and Hanford, WA in 1997. He created the LIGO Scientific Collaboration, which now numbers more than 1000 collaborators worldwide to carry out the science.

The initial LIGO detectors reached design sensitivity and set many limits on astrophysical sources. The Advanced LIGO proposal was developed while Barish was director, and he has continued to play a leading role in LIGO and Advanced LIGO. The first detection of the merger of two 30 solar mass black holes was made on September 14, 2015. This represented the first direct detection of gravitational waves since they were predicted by Einstein in 1916 and the first ever observation of the merger of a pair of black holes. Barish delivered the first presentation on this discovery to a scientific audience at CERN on Feb 11, 2016, simultaneously with the public announcement.

From 2001 to 2002, Barish served as co-chair of the High Energy Physics Advisory Panel subpanel that developed a long-range plan for U.S. high energy physics. He has chaired the Commission of Particles and Fields and the U.S. Liaison committee to the International Union of Pure and Applied Physics (IUPAP). In 2002 he chaired the NRC Board of Physics and Astronomy Neutrino Facilities Assessment Committee. Report "Neutrinos and Beyond".

In 2005-2013 Barry Barish was Director of the [Global Design Effort] for the International Linear Collider (ILC). The ILC is the highest priority future project for particle physics worldwide, as it promises to complement the Large Hadron Collider at CERN in exploring the TeV energy scale. This ambitious effort is being uniquely coordinated worldwide, representing a major step in international collaborations going from conception to design to implementation for large scale projects in physics.

Honors and Awards

In 2002, he received the Klopsteg Award of the American Association of Physics Teachers. Barish was honored by the University of Bologna (2006) and University of Florida (2007) where he received honorary doctorates. In 2007, delivered the Van Vleck lectures at the University of Minnesota. The University of Glasgow honored Barish with an honorary degree of science in 2013.

Barish was honored as a *Titan of Physics* in the On the Shoulders of Giants series at the 2016 World Science Festival.

In 2016, Barish received the Enrico Fermi Prize "for his fundamental contributions to the formation of the LIGO and LIGO-Virgo scientific collaborations and for his role in addressing challenging technological and scientific aspects whose solution led to the first detection of gravitational waves".

Barish was a recipient of the 2016 *Smithsonian* magazine's American Ingenuity Award in the Physical Science category.

Barish was awarded the 2017 Henry Draper Medal from the National Academy of Sciences "for his visionary and pivotal leadership role, scientific guidance, and novel instrument design during the development of LIGO that were crucial for LIGO's discovery of gravitational waves from colliding black holes, thus directly validating Einstein's 100-year-old prediction of gravitational waves and ushering a new field of gravitational wave astronomy."

Barish was a recipient of the 2017 Giuseppe and Vanna Cocconi Prize of the European Physical Society for his "pioneering and leading role in the LIGO observatory that led to the direct detection of gravitational waves, opening a new window to the Universe."

Barish was a recipient of the 2017 Princess of Asturias Award for his work on gravitational waves (jointly with Kip Thorne and Rainer Weiss).

Barish was a recipient of the 2017 Fudan-Zhongzhi Science Award "for his leadership in the construction and initial operations of LIGO, the creation of the international LIGO Scientific Collaboration, and for the successful conversion of LIGO from small science executed by a few research groups into big science that involved large collaborations and major infrastructures, which eventually enabled gravitational-wave detection." (jointly with Kip Thorne and Rainer Weiss).

In 2017, he won the Nobel Prize in Physics (jointly with Rainer Weiss and Kip Thorne) "for decisive contributions to the LIGO detector and the observation of gravitational waves".

Barish has been elected to and held fellowship at the following organizations:

- the American Academy of Arts and Sciences (AAAS)
- the National Academy of Sciences (NAS)
- the National Science Board (NSB)
- Fellow of American Physical Society (APS) (President 2011)
- Fellow of American Association for the Advancement of Science (AAAS)

Family

Barry Barish is married to Samoan Barish. Their children are Stephanie Barish and Kenneth Barish, professor and chair of Physics & Astronomy at University of California, Riverside.

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Kip Stephen Thorne

Kip Stephen Thorne (born June 1, 1940) is an American theoretical physicist and Nobel laureate, known for his contributions in gravitational physics and astrophysics. A longtime friend and colleague of Stephen Hawking and Carl Sagan, he was the Feynman Professor of Theoretical Physics at the California Institute of Technology (Caltech) until 2009[3] and is one of the world's leading experts on the astrophysical implications of Einstein's general theory of relativity. He continues to do scientific research and scientific consulting, most notably for the Christopher Nolan film *Interstellar*.

In 2017, Thorne was awarded the Nobel Prize in Physics along with Rainer Weiss and Barry C. Barish "for decisive contributions to the LIGO detector and the observation of gravitational waves".

Thorne was born in Logan, Utah on June 1, 1940. His father was an agronomist, his mother Alison (née Comish) Thorne, was an economist and the first woman to receive a Ph.D. in the Economics Department of Iowa State College. Raised in an academic environment, two of his four siblings also became professors. Thorne's parents were members of The Church of Jesus Christ of Latter-day Saints (Mormons) and raised Thorne in the LDS faith, though he now describes himself as atheist. Regarding his views on science and religion, Thorne has stated: "There are large numbers of my finest colleagues who are quite devout and believe in God. There is no fundamental incompatibility between science and religion. I happen to not believe in God."

Thorne rapidly excelled at academics early in life, becoming one of the youngest full professors in the history of the California Institute of Technology. He received his B.S. degree from Caltech in 1962, and Ph.D. degree from Princeton University in 1965. He wrote his doctoral thesis, *Geometrodynamics of Cylindrical Systems*, under the supervision of relativist John Wheeler. Thorne returned to Caltech as an associate professor in 1967 and became a professor of theoretical physics in 1970, the William R. Kenan, Jr. Professor in 1981, and the Feynman Professor of Theoretical Physics in 1991. He was an adjunct professor at the University of Utah from 1971 to 1998 and Andrew D. White Professor at Large at Cornell University from 1986 to 1992. In June 2009 he resigned his Feynman Professorship (he is now the Feynman Professor of Theoretical Physics, Emeritus) to pursue a career of writing and movie making. His first film project was *Interstellar*, working with Christopher Nolan.

Throughout the years, Thorne has served as a mentor and thesis advisor for many leading theorists who now work on observational, experimental, or astrophysical aspects of general relativity. Approximately 50 physicists have received Ph.D.s at Caltech under Thorne's personal mentorship.

Thorne is known for his ability to convey the excitement and significance of discoveries in gravitation and astrophysics to both professional and lay audiences. In 1999, Thorne made some speculations on what the 21st century will find as the answers to the following questions:

- Is there a "dark side of the universe" populated by objects such as black holes?
- Can we observe the birth of the universe and its dark side using radiation made from space-time warpage, or so-called "gravitational waves"?
- Will 21st century technology reveal quantum behavior in the realm of human-size objects?

His presentations on subjects such as black holes, gravitational radiation, relativity, time travel, and wormholes have been included in PBS shows in the U.S. and in the United Kingdom on the BBC.

Thorne and Linda Jean Peterson married in 1960. Their children are Kares Anne and Bret Carter, an architect. Thorne and Peterson divorced in 1977. Thorne and his second wife, Carolee Joyce Winstein, a professor of biokinesiology and physical therapy at USC, married in 1984.

Research

Thorne's research has principally focused on relativistic astrophysics and gravitation physics, with emphasis on relativistic stars, black holes and especially gravitational waves. He is perhaps best known to the public for his controversial theory that wormholes can conceivably be used for time travel. However, Thorne's scientific contributions, which center on the general nature of space, time,

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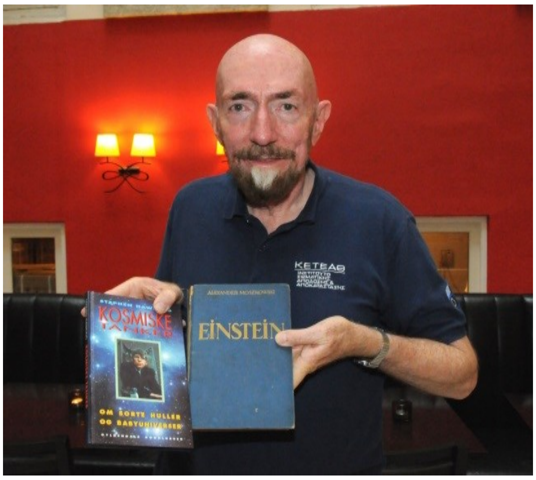
and gravity, span the full range of topics in general relativity.



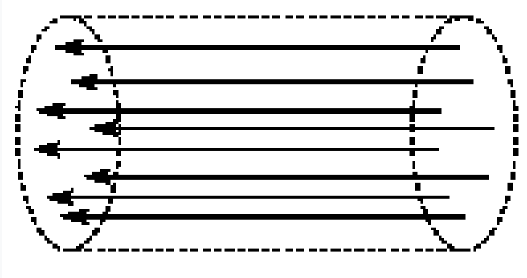
Gravitational waves and LIGO

Thorne's work has dealt with the prediction of gravitational wave strengths and their temporal signatures as observed on Earth. These "signatures" are of great relevance to LIGO (Laser Interferometer Gravitational Wave Observatory), a multi-institution gravitational wave experiment for which Thorne has been a leading proponent – in 1984, he cofounded the LIGO Project (the largest project ever funded by the NSF) to discern and measure any fluctuations between two or more 'static' points; such fluctuations would be evidence of gravitational waves, as calculations describe. A significant aspect of his research is developing the mathematics necessary to analyze these objects. Thorne also carries out engineering design analyses for features of the LIGO that cannot be developed on the basis of experiment and he gives advice on data analysis algorithms by which the waves will be sought. He has provided theoretical support for LIGO, including identifying gravitational wave sources that LIGO should target, designing the baffles to control scattered light in the LIGO beam tubes, and – in collaboration with Vladimir Braginsky's (Moscow, Russia) research group – inventing quantum nondemolition designs for advanced gravity-wave detectors and ways to reduce the most serious kind of noise in advanced detectors: thermoelastic noise. With Carlton M. Caves, Thorne invented the back-action-evasion approach to quantum nondemolition measurements of the harmonic oscillators – a technique applicable both in gravitational wave detection and quantum optics.

On February 11, 2016, a team of four physicists representing the LIGO Scientific Collaboration, announced that in September 2015, LIGO recorded the signature of two black holes colliding 1.3 billion light-years away. This recorded detection was the first direct observation of the fleeting chirp of a gravitational wave and confirmed an important prediction of Einstein's general theory of relativity.

Black hole cosmology

Main article: Hoop conjecture



A cylindrical bundle of magnetic field lines

While he was studying for Ph.D. in Princeton University, his mentor John Wheeler gave him an assignment problem for him to think over: find out whether or not a cylindrical bundle of repulsive magnetic field lines will implode under its own attractive gravitational force. After several months wrestling with the problem, he proved that it was impossible for cylindrical magnetic field lines to implode.

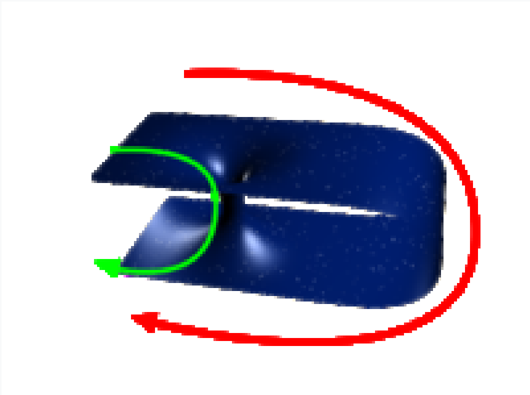
Why is it that a cylindrical bundle of magnetic field lines will not implode, while spherical stars will implode under their own gravitational force? Thorne tried to explore the theoretical ridge between the two phenomena. He found out eventually that the gravitational force can overcome all interior pressure only when an object has been compressed in all directions. To express this realization, Thorne proposed his hoop conjecture, which describes an imploding star turning into a black hole when the critical circumference of the designed hoop can be placed around it and set into rotation. That is, any object of mass M around which a hoop of circumference can be spun must be a black hole.

As a tool to be used in both enterprises, astrophysics and theoretical physics, Thorne and his students have developed an unusual approach, called the "membrane paradigm", to the theory of black holes and used it to clarify the "Blandford-Znajek" mechanism by which black holes may power some quasars and active galactic nuclei.

Thorne has investigated the quantum statistical mechanical origin of the entropy of a black hole. With his postdoc Wojciech Zurek, he showed that the entropy of a black hole is the logarithm of the number of ways that the hole could have been made.

With Igor Novikov and Don Page he developed the general relativistic theory of thin accretion disks around black holes, and using this theory he deduced that with a doubling of its mass by such accretion a black hole will be spun up to 0.998 of the maximum spin allowed by general relativity, but not any farther. This is probably the maximum black-hole spin allowed in nature.

Wormholes and time travel



A wormhole is a short cut connecting two separate regions in space. In the figure the green line shows the short way through wormhole, and the red line shows the long way through normal space.

Thorne and his co-workers at Caltech conducted scientific research on whether the laws of physics permit space and time to be multiply connected (can there exist classical, traversable wormholesand "time machines"?). With Sung-Won Kim, Thorne identified a universal physical mechanism (the explosive growth of vacuum polarization of quantum fields), that may always prevent spacetime from developing closed timelike curves (i.e., prevent backward time travel).

With Mike Morris and Ulvi Yurtsever he showed that traversable Lorentzian wormholes can exist in the structure of spacetime only if they are threaded by quantum fields in quantum states that violate the averaged null energy condition (i.e. have negative renormalized energy spread over a sufficiently large region). This has triggered research to explore the ability of quantum fields to possess such extended negative energy. Recent calculations by Thorne indicate that simple masses passing through traversable wormholes could never engender paradoxes – there are *no* initial conditions that lead to paradox once time travel is introduced. If his results can be generalized, they would suggest that none of the supposed paradoxes formulated in time travel stories can actually be formulated at a precise physical level: that is, that *any* situation in a time travel story turns out to permit *many* consistent solutions.

Relativistic stars, multipole moments and other endeavors

With Anna Żytkow, Thorne predicted the existence of red supergiant stars with neutron-star cores (Thorne–Żytkow objects). He laid the foundations for the theory of pulsations of relativistic stars and the gravitational radiation they emit. With James Hartle, Thorne derived from general relativity the laws of motion and precession of black holes and other relativistic bodies, including the influence of the coupling of their multipole moments to the spacetime curvature of nearby objects. Thorne has also theoretically predicted the existence of universally antigravitating "exotic matter" – the element needed to accelerate the expansion rate of the universe, keep traversable wormhole "Star Gates" open and keep timelike geodesic free float "warp drives" working. With Clifford Will and others of his students, he laid the foundations for the theoretical interpretation of experimental tests of relativistic theories of gravity – foundations on which Will and others then built. As of 2005, Thorne was interested in the origin of classical space and time from the quantum foam of quantum gravity theory.

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Publications

Thorne has written and edited books on topics in gravitational theory and high-energy astrophysics. In 1973, he co-authored the textbook *Gravitation* with Charles Misner and John Wheeler; that according John C. Baez and Chris Hillman, is one of the great scientific books of all time and has inspired two generations of students. In 1994, he published *Black Holes and Time Warps: Einstein's Outrageous Legacy*, a book for non-scientists for which he received numerous awards. This book has been published in six languages, and editions in Chinese, Italian, Czech, and Polish are in press. In 2014, Thorne published *The Science of Interstellar* in which he explains the science behind Christopher Nolan's film *Interstellar*; Nolan wrote the foreword to the book. In September, 2017, Thorne and Roger D. Blandford published *Modern Classical Physics: Optics, Fluids, Plasmas, Elasticity, Relativity, and Statistical Physics*, a

graduate-level textbook covering the six major areas of physics listed in the title.
Thorne's articles have appeared in publications such as:

- *Scientific American*,
- McGraw-Hill *Yearbook of Science and Technology*, and
- *Collier's Encyclopedia* among others.

Thorne has published more than 150 articles in scholarly journals.

Honors and Awards
Thorne has been elected to:

- the American Academy of Arts and Sciences (1972)
- the National Academy of Sciences,
- the Russian Academy of Sciences, and
- the American Philosophical Society.

He has been recognized by numerous awards including:

- the American Institute of Physics Science Writing Award in Physics and Astronomy,
- the Phi Beta Kappa Science Writing Award,
- the American Physical Society's Lilienfeld Prize,
- the German Astronomical Society's Karl Schwarzschild Medal (1996),
- the Robinson Prize in Cosmology from the University of Newcastle, England,
- the Sigma Xi: The Scientific Research Society's Common Wealth Awards for Science and Invention, and
- the California Science Center's California Scientist of the Year Award (2003).
- the Albert Einstein Medal in 2009 from the Albert Einstein Society, Bern, Switzerland
- the UNESCO Niels Bohr Medal from UNESCO (2010)
- the Special Breakthrough Prize in Fundamental Physics (2016)
- the Gruber Prize in Cosmology (2016)
- the Shaw Prize (2016) (together with Ronald Drever and Rainer Weiss).
- the Kavli Prize in Astrophysics (2016) (together with Ronald Drever and Rainer Weiss).
- the Tomalla Prize (2016) for extraordinary contributions to general relativity and gravity.
- the Georges Lemaître Prize (2016)
- the Harvey Prize (2016) (together with Ronald Drever and Rainer Weiss).
- the Princess of Asturias Award (2017) (jointly with Rainer Weiss and Barry Barish).
- the Nobel Prize in Physics (2017) (jointly with Rainer Weiss and Barry Barish)

He has been a Woodrow Wilson Fellow, Danforth Fellow, Guggenheim Fellow, and Fulbright Fellow. He has also received the honorary degree of doctor of humane letters from Claremont Graduate University.
He was elected to hold Lorentz chair for the year 2009 Leiden University, the Netherlands.

Thorne has served on:

- the International Committee on General Relativity and Gravitation,
- the Committee on US-USSR Cooperation in Physics, and
- the National Academy of Sciences' Space Science Board, which has advised NASA and Congress on space science policy.

Kip Thorne was selected by Time magazine in an annual list of the 100 most influential people in the American world in 2016.

Adaptation in Media

- Thorne contributed ideas on wormhole travel to Carl Sagan for use in his novel *Contact*.
- Thorne and his friend, producer Lynda Obst, also developed the concept for the Christopher Nolan film *Interstellar*. He also wrote a tie-in book, *The Science of Interstellar*.
- In Larry Niven's novel *Rainbow Mars*, the time travel technology used in the novel is based on the wormhole theories of Thorne, which in the context of the novel was when time travel first became possible, rather than just fantasy. As a result, any attempts to travel in time prior to Thorne's development of wormhole theory results in the time traveller entering a fantastic version of reality, rather than the actual past.
- In the film *The Theory of Everything*, Thorne was portrayed by actor Enzo Cilenti.

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The Science and Detection of Gravitational Waves

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One of the most important consequences of the Theory of General Relativity is the concept of gravitational waves. As we enter the new millennium, a new generation of detectors sensitive enough to directly detect such waves will become operational. Detectable events could originate from a variety of catastrophic events in the distant universe, such as the gravitational collapse of stars or the coalescence of compact binary systems. In these two lectures, I discuss both the astrophysical sources of gravitational waves and the detection technique and challenges using suspended mass interferometry. Finally, I summarize the status and plans for the Laser Interferometer Gravitational-wave Observatory (LIGO) and the other large new detectors.

Keywords: Gravitational waves; Detection; LIGO; Interferometry

1. Introduction

Gravitational waves are a necessary consequence of Special Relativity with its finite speed for information transfer. Einstein in 1916 and 1918[1,2,3] put forward the formulation of gravitational waves in General Relativity. He showed that time dependent gravitational fields come from the acceleration of masses and propagate away from their sources as a space-time warpage at the speed of light. This propagation is called gravitational waves.
The formulation of this concept in general relativity is described by the Minkowski metric, but where the information about space-time curvature is contained in the metric as an added term, $h_{\mu\nu}$. In the weak field limit, the equation can be described with linear equations. If the choice of gauge is the *transverse traceless gauge* the formulation becomes a familiar wave equation

$$(\nabla^2 - \frac{1}{c^2}\frac{\partial^2}{\partial t^2})h_{\mu\nu} = 0 \qquad (1)$$

The strain $h_{\mu\nu}$ takes the form of a plane wave propagating with the speed of light (c). The speed is the same for electromagnetic and gravitational radiation in Einstein's theory. Since the underlying theory of gravity is spin 2, the waves have two components, like electromagnetic waves, but rotated by 45^0 instead of 90^0 from each other. It is an interesting fact observation that if gravitational waves are observed and the two components are decomposed, this classical experiment will be capable of observing the underlying quantum spin 2 structure of gravity. The solutions for the propagation of gravitational waves can be written as

$$h_{\mu\nu} = h_+(t - z/c) + h_x(t - z/c), \qquad (2)$$

where z is the direction of the propagation and h_+ and h_x are the two polarizations.

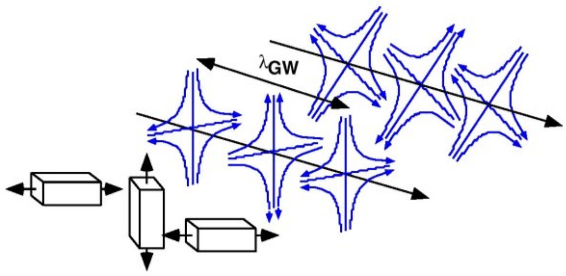

Fig. (1) The propagation of gravitational waves illustrating the two polarizations rotated 45^0 from each other.

Evidence of these waves resulted from the beautiful observations of Russell Hulse and Joseph Taylor in their studies of a neutron star binary system PSR1913+16[4,5,6]. They discovered this particular compact binary pulsar system in 1974. The pulsar frequency is about 17/sec. It was identified as being a binary system because they observed a variation of the frequency with just under an 8 hour period. Subsequent measurement accurately determined the characteristics of the overall binary system with remarkable precision. The most important parameters for our purpose are that the two neutron stars are separated by about 10^6 miles, have masses $m_1 = 1.4\ m_>$ and $m_2 = 1.36 m_>$, and the ellipticity of the orbit is $\varepsilon = 0.617$. They demonstrated that the motion of the pulsar around its companion could not be understood unless the dissipative reaction force associated with gravitational wave production were included. The system radiates away energy, presumably in the form of gravitational waves, and the two neutron stars spiral in toward one another speeding up the orbit. In detail the inspiral is only 3 mm /orbit so it will be more than 10^6 years before they actually coalesce.
Hulse and Taylor monitored these pulsar signals with 50µsec accuracy over many years. They demonstrated the orbital speedup experimentally

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with an accuracy of a fraction of a percent. The speedup is in complete agreement with the predictions from general relativity as illustrated in Figure 2. Hulse and Taylor received the Nobel Prize in Physics for this work in 1993. This impressive indirect evidence for gravitational waves gives us good reason to believe in their existence. But, as of this date, no direct detection of gravitational waves has been made using resonant bar detectors. A new generation of detectors using suspended mass interferometry promising improved sensitivity will soon be operational.

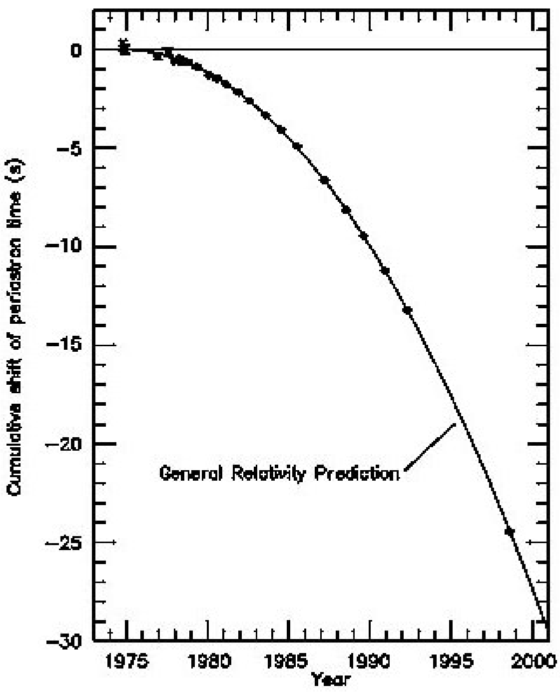

Fig. (2) The compact binary system PSR1916+13, containing two neutron stars, exhibits a speedup of the orbital period by monitoring the shift over time of the time of the pulsar's closest approach (periastron) to the companion star. Over 25 years the total shift recorded is about 25 sec. The plot shows the data points as dots, as well as the prediction (not a fit to the data) from general relativity from the parameters of the system. The agreement is impressive and this experiment provides strong evidence for the existence of gravitational waves.

The theoretical motivation for gravitational waves, coupled with the experimental results of Hulse and Taylor, make a very strong case for the existence of such waves. This situation is somewhat analogous to one in the 1930's that concerned the existence of the neutrino. The neutrino was well motivated theoretically and its existence was inferred from the observed apparent non conservation of energy and angular momentum in nuclear beta decay. Although there was little doubt that the neutrino existed, it took another 20 years before Reines and Cowan made a direct observation of a neutrino by detecting its interaction in matter. Following that observation, a whole new branch of elementary particle physics opened up that involved studies of the neutrino and its properties (the mass of the neutrino this remains one of the most important subjects in particle physics) on one hand and the direct use of the neutrino as a probe of other physics (eg. the quark structure of the nucleon by studying neutrino scattering) on the other hand. If we carry this analogy a step further, the next step for gravitational waves will likewise be direct observation. Following that important achievement, we can fully expect that we will open up a new way to study the basic structure of gravitation on one hand, and on the other hand we will be able to use gravitational waves themselves as a new probe of astrophysics and the Universe.

For fundamental physics, the direct observation of gravitational waves offers the possibility of studying gravitation in highly relativistic settings, offering tests of Relativistic Gravitation in the strong field limit, where the effects are not merely a correction to Newtonian Gravitation but produces fundamentally new physics through the strong curvature of the space-time geometry. Of course, the waves at Earth are not expected to be other than weak perturbations on the local flat space, however they provide information on the conditions at their strong field sources. The detection of the waves will also allow determination of the wave properties such as their propagation velocity and polarization states.

In terms of astrophysics, the observation of gravitational waves will provide a very different view of the Universe. These waves arise from motions of large aggregates of matter, rather than from particulate sources that are the source of electromagnetic waves. For example, the types of known sources from bulk motions that can lead to gravitational radiation include gravitational collapse of stars, radiation from binary systems, and periodic signals from rotating systems. The waves are not scattered in their propagation from the source and provide information of the dynamics in the innermost and densest regions of the astrophysical sources. So, gravitational waves will probe the Universe in a very different way, increasing the likelihood for exciting surprises and new astrophysics.

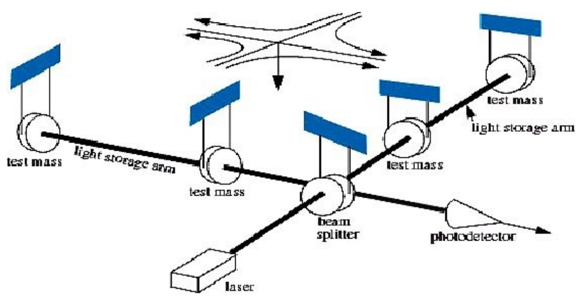

Fig. (3) A schematic view of a suspended mass interferometer used for the detection of gravitational waves. A gravitational wave causes one arm to stretch and the other to squash slightly, alternately at the gravitational wave frequency. This difference in length of the two arms is measured through precise interferometry.

A new generation of detectors (LIGO and VIRGO) based on suspended mass interferometry promise to attain the sensitivity to observe gravitational waves. The implementation of sensitive long baseline interferometers to detect gravitational waves is the result of over twenty-five years of technology development, design and construction.

The Laser Interferometer Gravitational-wave Observatory (LIGO) a joint Caltech-MIT project supported by the NSF has completed its construction phase and is now entering the commissioning of this complex instrument. Following a two year commissioning program, we expect the first sensitive broadband searches for astrophysical gravitational waves at an amplitude (strain) of $h \sim 10^{-21}$ to begin during 2002. The initial search with LIGO will be the first attempt to detect gravitational waves with a detector having sensitivity that intersects plausible estimates for known astrophysical source strengths. The initial detector constitutes a 100 to 1000 fold improvement in both sensitivity and bandwidth over previous searches.

The LIGO observations will be carried out with long baseline interferometers at Hanford, Washington and Livingston, Louisiana. To unambiguously make detections of these rare events a time coincidence between detectors separated by 3030 km will be sought.

Fig. (4) The two LIGO Observatories at Hanford, Washington and Livingston, Louisiana

The facilities developed to support the initial interferometers will allow the evolution of the detectors to probe the field of gravitational wave astrophysics for the next two decades. Sensitivity improvements and special purpose detectors will be needed either to enable detection if strong enough sources are not found with the initial interferometer, or following detection, in order to increase the rate to enable the detections to become a new tool for astrophysical research. It is important to note that LIGO is part of a world wide effort to develop such detectors[7,8,9,10,11], which includes the French/Italian VIRGO project, as well as the Japanese/TAMA and Scotch/German GEO projects. There are eventual plans to correlate signals from all operating detectors as they become operational.

2. Sources of Gravitational Waves

2.1 Character of Gravitational Waves and Signal Strength

The effect of the propagating gravitational wave is to deform space in a quadrupolar form. The characteristics of the deformation are indicated in Figure 5.

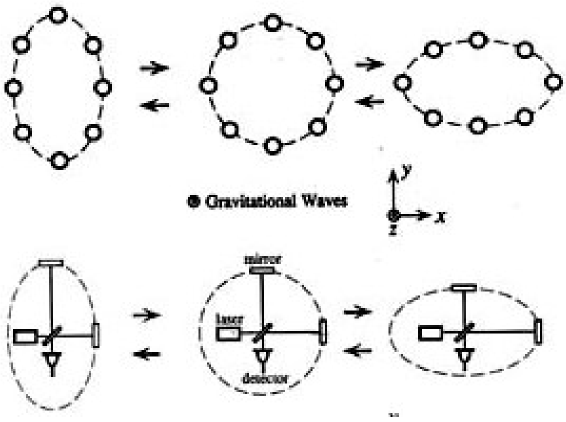

Fig. (5) The effect of gravitational waves for one polarization is shown at the top on a ring of free particles. The circle alternately elongates vertically while squashing horizontally and vice versa with the frequency of the gravitational wave. The detection technique of interferometry being employed in the new generation of detectors is indicated in the lower figure. The interferometer measures the difference in distance in two perpendicular directions, which if sensitive enough could detect the passage of a gravitational wave.

One can also estimate the frequency of the emitted gravitational wave. An upper limit on the gravitational wave source frequency can be estimated from the Schwarzshild radius $2GM/c^2$. We do not expect strong emission for periods shorter than the light travel time $4\pi GM/c^3$ around its circumference. From this we can estimate the maximum frequency as about 10^4 *Hz* for a solar mass object. Of course, the frequency can be very low as illustrated by the 8 hour period of PSR1916+13, which is emitting gravitational radiation. Frequencies in the higher frequency range $1Hz < f < 10^4\ Hz$ are potentially reachable using detectors on the earth's surface, while the lower frequencies require putting an instrument in space. In Figure 6, the sensitivity bands of the terrestrial LIGO interferometers and the proposed LISA space interferometers are shown. The physics goals of the two detectors are complementary, much like different frequency bands are used in observational astronomy for electromagnetic radiation.

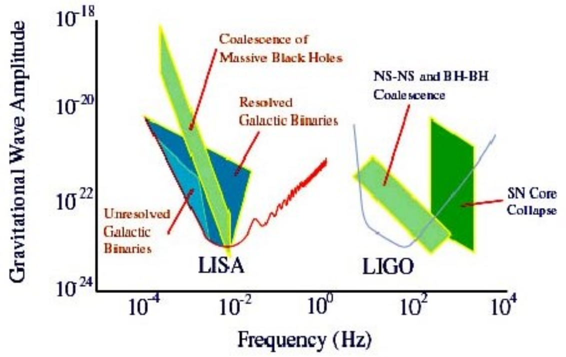

Fig. (6) The detection of gravitational waves on earth are in the audio band from ~ $10\text{-}10^4$ Hz. The accessible band in space of 10^{-4} - 10^{-1} Hz, which is the goal of the LISA instrument proposed to be a joint ESA/NASA project in space with a launch about 2010 complements the terrestrial experiments. Some of the sources of gravitational radiation in the LISA and LIGO frequency bands are indicated.

The strength of a gravitational wave signal depends crucially on the quadrupole moment. We can roughly estimate how large the effect could be from astrophysical sources. If we denote the quadrupole of the mass distribution of a source by Q, a dimensional argument, along with the assumption that gravitational radiation couples to the quadrupole moment yields:

$$h \sim \frac{G\ddot{Q}}{c^4 r} \sim \frac{G(E_{kin}^{non-symm.}/c^2)}{c^2 r} \qquad (3)$$

where G is the gravitational constant and $E_{kin}^{non-symm.}$ is the non-symmetrical part of the kinetic energy.
For the purpose of estimation, let us consider the case where one solar mass is in the form of non-symmetric kinetic energy. Then, at a distance of the Virgo cluster we estimate a strain of $h \sim 10^{-21}$. This is a good guide to the largest signals that might be observed. At larger distances or for sources with a smaller quadrupole component the signal will be weaker.

2.2 Astrophysical Sources of Gravitational Waves

There are a many known astrophysical processes in the Universe that produce gravitational waves[12]. Terrestrial interferometers, like LIGO, will search for signals from such sources in the 10Hz - 10KHz frequency band. Characteristic signals from astrophysical sources will be sought over background noise from recorded time-frequency series of the strain. Examples of such characteristic signals include the following:

2.2.1 Chirp Signals

The inspiral of compact objects such as a pair of neutron stars or black holes will give radiation that will characteristically increase in both amplitude and frequency as they move toward the final coalescence of the system.

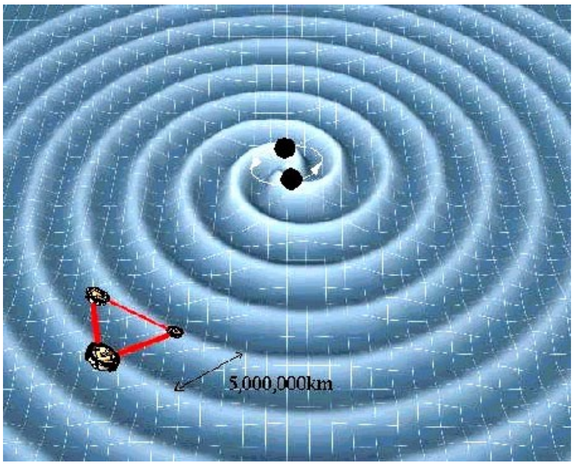

Fig. (7) An inspiral of compact binary objects (e.g. neutron star – neutron star; blackhole-blackhole and neutron star-blackhole) emits gravitational waves that increase with frequency as the inspiral evolves, first detectable in space (illustrated with the three satellite interferometer of LISA superposed) and in its final stages by terrestrial detectors at high frequencies.

This chirp signal can be characterized in detail, giving the dependence on the masses, separation, ellipticity of the orbits, etc. A variety of search techniques, including the direct comparison with an array of templates will be used for this type of search. The waveform for the inspiral phase is well understood and has been calculated in sufficient detail for neutron star-neutron star inspiral. To Newtonian order, the inspiral gravitational waveform is given by

$$h_+(t) = \frac{2G^{\frac{5}{3}}}{c^4}(1+\cos^2(i))\frac{\mu}{r}(\pi Mf)^{\frac{2}{3}}\cos(2\pi ft) \qquad (4)$$

$$h_-(t) = \pm\frac{4G^{\frac{5}{3}}}{c^4}\cos(i)\frac{\mu}{r}(\pi Mf)^{\frac{2}{3}}\sin(2\pi ft) \qquad (5)$$

where the + and – polarization axes are oriented along the major and minor axes of the projection of the orbital plane on the sky, i is the angle of inclination of the orbital plane, $M = m_1 + m_2$ is the total mass, $\mu = m_1 m_2/M$ is the reduced mass and the gravitational wave frequency f (twice the orbital frequency) evolves as

$$f(t) = \frac{1}{\pi}\left(\frac{c^3}{G}\right)^{\frac{5}{8}}\left(\frac{5}{256\mu M^{2/3}(t_0 - t)}\right)^{\frac{3}{8}} \qquad (6)$$

where t_0 is the coalescence time. This formula gives the characteristic 'chirp' signal – a periodic sinusoidal wave that increases in both amplitude and frequency as the binary system inspirals.

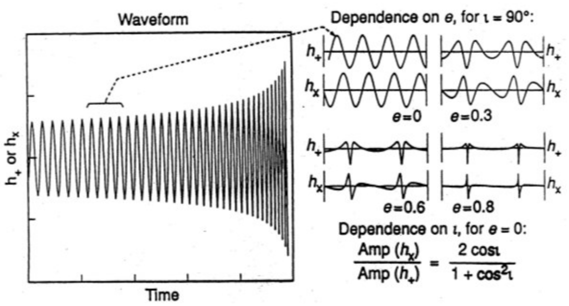

Fig. (8) An example is shown of the final chirp waveforms. The amplitude and frequency increase as the system approaches coalescence. The detailed waveforms can be quite complicated as shown at the right, but enable determination of the parameters (e.g. ellipticity) of the system

The Newtonian order waveforms do not provide the needed accuracy to track the phase evolution of the inspiral to a quarter of a cycle over the many thousands of cycles that a typical inspiral will experience while sweeping through the broad band LIGO interferometers. In order to better track the phase evolution of the inspiral, first and second order corrections to the Newtonian quadrupole radiation, known as the post-Newtonian formulation, must be applied and are used to generate templates of the evolution that are compared to the data in the actual search algorithms. If such a phase evolution is tracked, it is possible to extract parametric information about the binary system such as the masses, spins, distance, ellipticity and orbital inclination. An example of the chirp form and the detailed structure expected for different detailed parameters is shown in Figure 8.

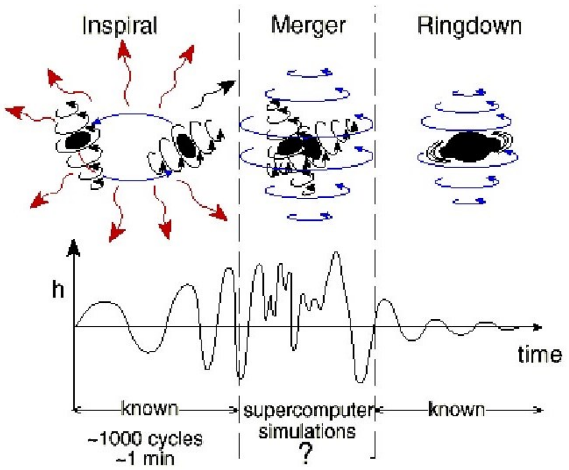

Fig. (9) The different stages of merger of compact binary systems are shown. First there is the characteristic chirp signal from the inspiral until they get to the final strong field case and coalescence; finally there is a ring down stage for the merged system

This inspiral phase is well matched to the LIGO sensitivity band for neutron star binary systems. For heavier systems, like a system of two black holes, the final coalescence and even the ring down phases are in the LIGO frequency band (see Figure 9). On one hand, the expected waveforms for such heavy sources in these regions are not so straightforward to parameterize, making the searches for such systems a larger challenge. Research is ongoing to better characterize such systems. On the other hand, these systems are more difficult to characterize because they probe the crucial strong field limit of general relativity, making such observations of great potential interest.
The expected rate of coalescing binary neutron star systems (with large uncertainties) is expected to be a few per year within about 200 Mpc. Coalescence of neutron star/black hole or black hole/black hole airs may provide stronger signals but their rate of occurrence (as well as the required detection algorithms) are more uncertain. Recently, enhanced mechanisms for ~10M> blackhole-blackhole mergers have been proposed, making these systems of particular interest.

2.2.2 Periodic Signals
Radiation from rotating non-axisymmetric neutron stars will produce periodic signals in the detectors. The emitted gravitational wave frequency is twice the rotation frequency. For many known pulsars, the frequency falls within the LIGO sensitivity band. Searches for signals from spinning neutron stars will involve tracking the system for many cycles, taking into account the doppler shift for the motion of the Earth around the Sun, and including the effects of spin-down of the pulsar. Both targeted searches for known pulsars and general sky searches are anticipated.

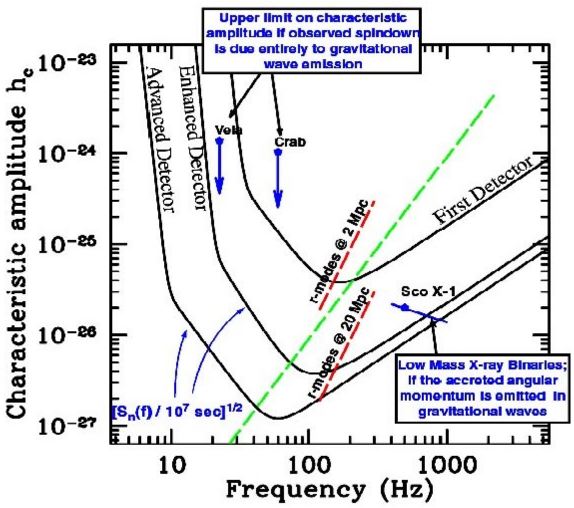

Fig. (10) Sensitivity of gravitational wave detectors to periodic soures is shown. The curves indicate the sensitivity in strain sensitivity of the initial LIGO detector and possible enhanced and advanced versions. The known Vela and Crab pulsars are shown at the appropriate frequencies and with the strain signal indicated if the spindown was dominantly into gravitational radiation. The signal from r-modes is also indicated.

2.2.3 Stochastic Signals

Signals from gravitational waves emitted in the first instants of the early universe, as far back as the Planck epoch at 10^{-43} sec, can be detected through correlation of the background signals from two or more detectors. Gravitational waves can probe earlier in the history of the Universe than any other radiation due to the very weak interaction.

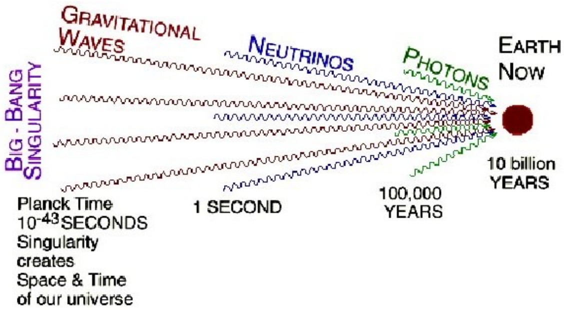

Fig. (11) Signals from the early universe are shown. The COBE studies of electromagnetic radiation have been extremely important in understanding the evolution of the early universe. That technique probes the early universe back to ~ 100,000 years after the big bang singularity. Neutrino background radiation, if that could be detected, would probe back to within one second of the big band, while gravitational radiation would actually allow probing the early universe to ~ 10^{-43} sec.

Some models of the early Universe can result in detectable signals. Observations of this early Universe gravitational radiation would provide an exciting new cosmological probe.

2.2.4 Burst Signals

The gravitational collapse of stars (e.g. supernovae) will lead to emission of gravitational radiation. Type I supernovae involve white dwarf stars and are not expected to yield substantial emission. However, Type II collapses can lead to strong radiation if the core collapse is sufficiently non-axisymmetric. The rate of Type II supernovae is roughly once every 30 years in our own Galaxy. This is actually a lower bound on the rate of stellar core collapses, since that rate estimate is determined from electromagnetic observations and some stellar core collapses could give only a small electromagnetic signal. The ejected mantle dominates the electromagnetic signal, while the gravitational wave signal is dominated by the dynamics of the collapsing core itself.

Numerical modeling of the dynamics of core collapse and bounce has been used to make estimates of the strength and characteristics. This is very complicated and model dependent, depending on both detailed hydrodynamic processes and the initial rotation rate of the degenerate stellar core before collapse. Estimating the event detection rate is consequently difficult and the rate may be as large as many per year with initial LIGO interferometers, or less than one per year with advanced LIGO interferometers. Probably a reasonable guess is that the initial detectors will not see far beyond our own galaxy, while an advanced detector should see out to the Virgo cluster.

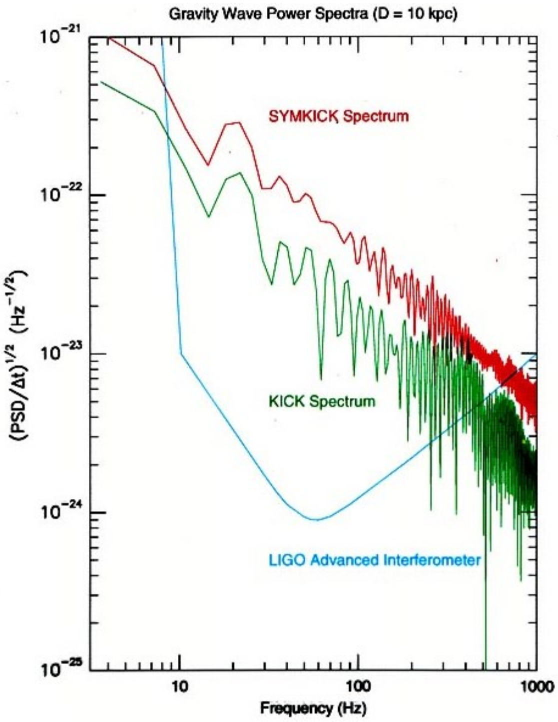

Fig. (12) Gravitational wave power spectra from Burrows et al compared to the LIGO advanced detector sensitivity. The LIGO detectors are expected to have sensitivity out to the Virgo cluster.

The detection will require identifying burst like signals in coincidence from multiple interferometers. The detailed nature of the signal is not well known, except that it is burst like and is emitted for a short time period (milliseconds) during the actual core collapse. Various mechanisms of hangup of this collapse have been considered and could give enhanced signatures of collapse. Burrows *et al* have calculated the gravitational wave signal, taking into account the detailed hydrodynamics of the collapse itself, the typical measured recoil neutron star velocities and the radiation into neutrinos. Figure 12 shows a model calculation of the emission power spectrum into gravitational waves compared with advanced LIGO sensitivities.

3. The Interferometry Technique

A Michelson interferometer operating between *freely suspended* masses is ideally suited to detect the antisymmetric (compression along one dimension and expansion along an orthogonal one) distortions of space induced by the gravitational waves (Fig. 13).

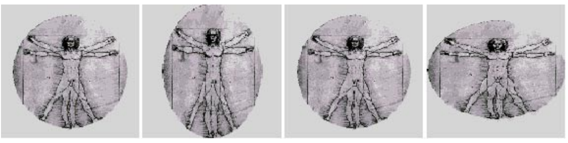

Fig. (13) The cartoon illustrates the effect of the passage of a gravitational wave through Leonardo da Vinci's "Vitruvian Man". The effect of the gravitational wave is to alternately stretch and squash space in two orthogonal directions at the frequency of the wave. The effect in this picture is greatly exaggerated. as the actual size of the effect is about 1000 times smaller than the nuclear size.

The simplest configuration, a white light (equal arm) Michelson interferometer is instructive in visualizing many of the concepts. In such a system the two interferometer arms are identical in length and in the light storage time. Light brought to the beam splitter is divided evenly between the two arms of the interferometer. The light is transmitted through the splitter to reach one arm and reflected by the splitter to reach the other arm. The light traverses the arms and is returned to the splitter by the distant arm mirrors. The roles of reflection and transmission are interchanged on this return and, furthermore, due to the Fresnel laws of E & M the return reflection is accompanied by a sign reversal of the optical electric field. When the optical electric fields that have come from the two arms are recombined at the beam splitter, the beams that were treated to a reflection (transmission) followed by a transmission (reflection) emerge at the antisymmetric port of the beam splitter while those that have been treated to successive reflections (transmissions) will emerge at the symmetric port.

In a simple Michelson configuration the detector is placed at the antisymmetric port and the light source at the symmetric port. If the beam geometry is such as to have a single phase over the propagating wavefront (an idealized uniphase plane wave has this property as does the Gaussian wavefront in the lowest order spatial mode of a laser), then, providing the arms are equal in length (or their difference in length is a multiple of 1/2 the light wavelength), the entire field at the antisymmetric port will be dark. The destructive interference over the entire beam wavefront is complete and all the light will constructively recombine at the symmetric port. The interferometer acts like a light valve sending light to the antisymmetric or symmetric port depending on the path length difference in the arms.

If the system is balanced so that no light appears at the antisymmetric port, the gravitational wave passing though the interferometer will disturb the balance and cause light to fall on the photodetector at the dark port. This is the basis of the detection of gravitational waves in a suspended mass interferometer. In order to obtain the required sensitivity, we have made the arms very long (4km) and included two additional refinements.

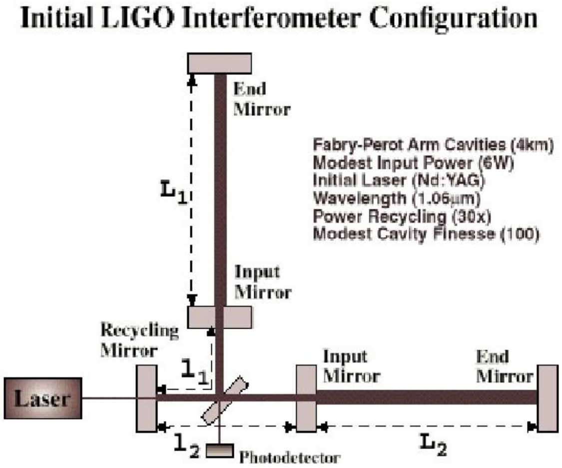

Fig. (14) The Optical layout of LIGO suspended mass Michelson interferometer with Fabry-Perot arm cavities.

The amount of motion of the arms to produce an intensity change at the photodetector depends on the optical length of the arm; the longer the arm the greater is the change in length up to a length that is equal to 1/2 the gravitational wave wave-length. Equivalently the longer the interaction of the light with the gravitational wave, up to 1/2 the period of the gravitational wave, the larger is the optical phase shift due to the gravitational wave and thereby the larger is the intensity change at the photodetector. The initial long baseline interferometers, besides having long arms also will fold the optical beams in the arms in optical cavities to gain further increase in the path length or equivalently in the interaction time of the light with the gravitational wave. The initial LIGO interferometers will store the light about 50 times longer than the beam transit time in an arm. (A light storage time of about 1 millisecond.)

A second refinement is to increase the change in intensity due to a phase change at the antisymmetric port by making the entire interferometer into a resonant optical storage cavity. The fact that the interferometer is operated with no light emerging at the antisymmetric port and all the light that is not lost in the mirrors or scattered out of the beam returns toward the light source via the symmetric port, makes it possible to gain a significant factor by placing another mirror between the laser and the symmetric port and 'reuse the light'. By choosing this mirror's position properly and by making the transmission of this mirror equal to the optical losses inside the interferometer, one can "match" the losses in the interferometer to the laser so that no light is reflected back to the laser. As a consequence, the light circulating in the interferometer is increased by the reciprocal of the losses in the interferometer. This is equivalent to increasing the laser power and does not effect the frequency response of the interferometer to a gravitational wave. The power gain achieved in the initial LIGO interferometer is designed to be about 30.

The system just described is called a power recycled Fabry-Perot Michelson interferometer and it is this type of configuration that will be used in the initial interferometers (Fig. 14). There are many other possible types of interferometer configurations, such as narrow band interferometers with the advantage of increased sensitivity in a narrow frequency range. Such interferometers may be used in subsequent detector upgrades.

The LIGO interferometer parameters have been chosen such that our initial sensitivity will be consistent both with the dimensional arguments given above and with estimates needed for possible detection of these known sources. Although the rate for these sources have large uncertainty, we should point out that improvements in sensitivity linearly improve the distance searched for detectable sources, which increases the rate by the cube of this improvement in sensitivity (Fig. 15). So, improvements will greatly enhance the physics reach and for that reason a vigorous program for implementing improved sensitivities is integral to the design and plan for LIGO.

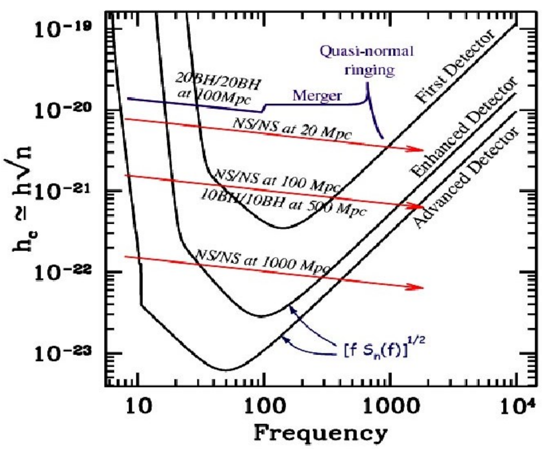

Fig. (15) The sensitivity curves of the initial and potential improved LIGO interferometers are shown and compared with the expected signal from the neutron star – neutron star binary inspiral benchmark events. Note that the sensitivity of the initial detector has been chosen as a balance of the arguments above making detection plausible and the use of demonstrated technologies. A program of improvements is envisioned, as indicated in the figure.

4. The Noise or Background: Limits to the Sensitivity

The success of the detector ultimately will depend on how well we are able to control the noise in the measurement of these small strains. Noise is broadly but also usefully categorized in terms of those phenomena which limit the ability to sense and register the small motions (sensing noise limits) and those that perturb the masses by causing small motions (random force noise). Eventually one reaches the ultimate limiting noise, the quantum limit, which combines the sensing noise with a random force limit. This orderly and intellectually satisfying categorization presumes that one is careful enough as experimenters in the execution of the experiment that one has not produced less fundamental, albeit, real noise sources that are caused by faulty design or poor implementation. We have dubbed these as technical noise sources and in real life these have often been the impediments to progress. The primary noise sources for the initial LIGO detector are shown in Figure 16.

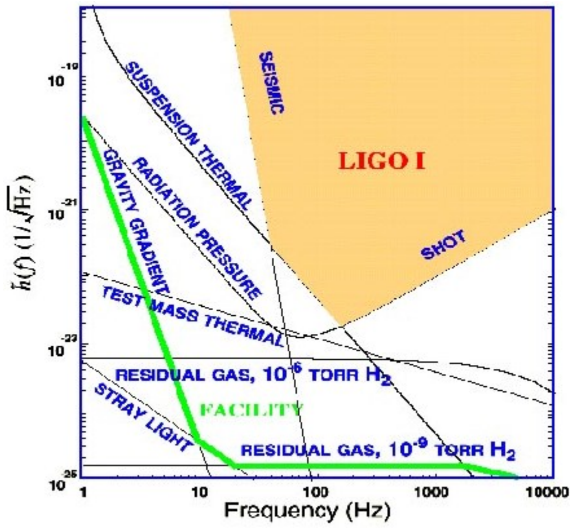

Fig. (16) Limiting noise sources for the initial LIGO detectors. Note that the interferometer is limited by different sources at low frequency (e.g. seismic), middle frequencies by suspension thermal noise, and at high frequencies by shot noise (or photo statistics). Lurking below are many other potential noise sources.

In order to control these technical noise sources, extensive use is made of two concepts. The first is the technique of modulating the signal to be detected at frequencies far above the 1/f noise due to the drift and gain instabilities experienced in all instruments. For example, the optical phase measurement to determine the motion of the fringe is carried out at radio frequency rather than near DC. Thereby, the low frequency amplitude noise in the laser light will not directly perturb the measurement of the fringe position. (The low frequency noise still will cause radiation pressure fluctuations on the mirrors through the asymmetries in the interferometer arms.)

A second concept is to apply feedback to physical variables in the experiment to control the large excursions at low frequencies and to provide damping. The variable is measured through the control signal required to hold it stationary. Here a good example is the position of the interferometer mirrors at low frequency. The interferometer fringe is maintained at a fixed phase by holding the mirrors at fixed positions at low frequencies. Feedback forces to the mirrors effectively hold the mirrors "rigidly". In the initial LIGO interferometers the forces are provided by permanent magnet/coil combinations. The mirror motion that would have occurred is then read in the control signal required to hold the mirror.

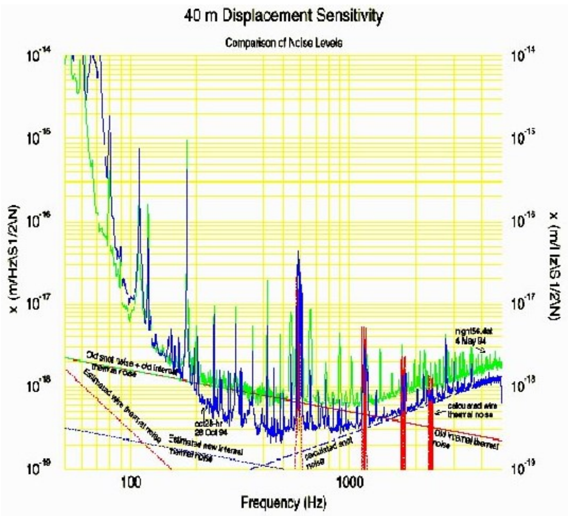

Fig. (17) The displacement noise measured in the 40m suspended mass interferometer LIGO prototype on the Caltech campus. The general shape and level are well simulated by our understanding of the limiting noise sources - seismic noise at the lowest frequencies, suspension thermal noise at the intermediate frequencies, and shot noise at the highest frequencies. Also, the primary line features are understood as various resonances in the suspension system.

We have taken great care in LIGO to control these technical noise sources. In order to test and understand our sensitivity and the noise limitations, we have performed extensive tests with a 40 meter LIGO prototype interferometer on the Caltech campus. This interferometer essentially has all the pieces and the optical configuration used in LIGO, so represents a good place to demonstrate our understanding before using in LIGO. The device has achieved a displacement sensitivity of $h \sim 10^{-19}$ *m*, which is essentially the displacement sensitivity required in the 4 km LIGO interferometers. Figure (17) shows the measured noise curve in this instrument and our understanding of the contributions from various noise sources.

In order to test our ability to split a fringe (or demonstrate we can reach the required shot noise limit) to 1 part in 10^{10}, we built a special phase noise interferometer. We have demonstrated that we can achieve the necessary level as shown in Fig. (18).

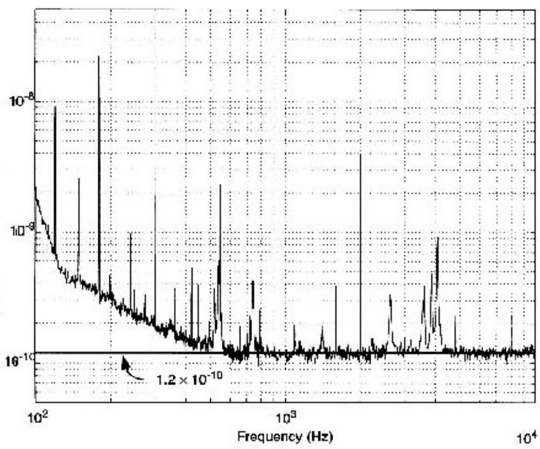

Fig. (18) The spectral sensitivity of the phase noise interferometer as measured at MIT. A demonstration interferometer has reached the required shot noise limit of LIGO above *500 Hz*. The additional features are from 60 Hz powerline harmonics, wire resonances (600 Hz), mount resonances, etc.

5. LIGO - Status and Prospects

Construction of LIGO infrastructure in both Hanford, Washington and in Livingston, Louisiana began in 1996 and was completed on schedule at the end of last year. The infrastructure consists of preparing both sites, civil construction of both laboratory buildings and enclosures for the vacuum pipes, as well as developing the large volume high vacuum system to house the interferometers.

The large vacuum system was the most challenging part of the project, involving 16 km or 1.2 m diameter high vacuum pipe. That system is in place and achieved 10^{-6} torr vacuum pumping only from the ends with vacuum and turbo pumps. The pipes were then 'baked' to accelerate the outgassing by insulating the pipes and running 2000 amps down the pipes raising the temperature to $\sim 160^0$ for about one week. Following cooldown, the pipes achieved a vacuum of better than 10^{-9} torr. All 16 km of beam pipe is now under high vacuum and the level of vacuum is such that noise from scattering off residual molecules should not be a problem for either initial LIGO or envisioned upgrades.

The long beam pipes are kept under high vacuum at all times and can be isolated from the large chambers containing the mirror-test masses and associated optics and detectors by the means of large gate valves that allow opening the chambers without disturbing the vacuum in the pipes. Figure 19 shows a photograph of several of the large chambers in the central area containing the lasers, beam splitters, input test masses, etc.

Fig. (19) A photograph of the large vacuum chambers containing the various LIGO detector components is shown. These chambers are isolated from the long vacuum pipes by gate valves to access the equipment.

The installation and commissioning of the detector subsystems has begun in earnest this year. The laser for LIGO is a 10W Nd:YAG laser at 1.064 μm in the TEM00 mode. The laser has been developed for production through Lightwave Electronics, using their 700 mW NPRO laser as the input to a diode pumped power amplifier. This commercialized laser is now sold by Lightwave as a catalog item. We have been running one laser continuously for about one year with good reliability. We are optimistic that this laser will make a reliable input light source for the LIGO interferometers.

For the LIGO application, the laser must be further stabilized in frequency, power and pointing. We have developed a laser prestabalization subsystem, which is performing near our design requirements. We require for 40 Hz < f < 10 KHz,

Frequency noise: $dn(f) < 10^{-2}$ Hz/Hz$^{1/2}$

Intensity noise: $dI(f)/I < 10^{-6}$/Hz$^{1/2}$

This low noise highly stabilized laser system has been tested and is performing near specifications. Figure 20 shows some performance measurements of the prestabilized laser system. Detailed characterization and improvement of noise sources continues.

The pre-stabilized laser beam is further conditioned by a 12 m mode cleaner, which is also operational. The beam has been transported through that system and then sent down the first 2 km arm. There is a half length and full length interferometer installed in the same vacuum chamber. The extra constraint of requiring a ½ size signal in the shorter interferometer will be used to eliminate common noise and lower the singles rate in the coincidence between the sites. The first long 2 km cavity has been locked for typical few hour times, at which point tidal effects need to be compensated for and those systems are not yet installed. Various monitoring signals for a 15 minute locked period are shown in Figure 21. Overall, the full vertex system consisting of a power recycled Michelson Interferometer has been made to operate, as well being done as in conjunction with each long arm of the Hanford 2km interferometer, individually. The next and final step doe the first interferometer, which we are using as a pathfinder, is to lock both arms at the same time, in order to create the full LIGO suspended mass Michelson Interferometer with Fabry-Perot arms.

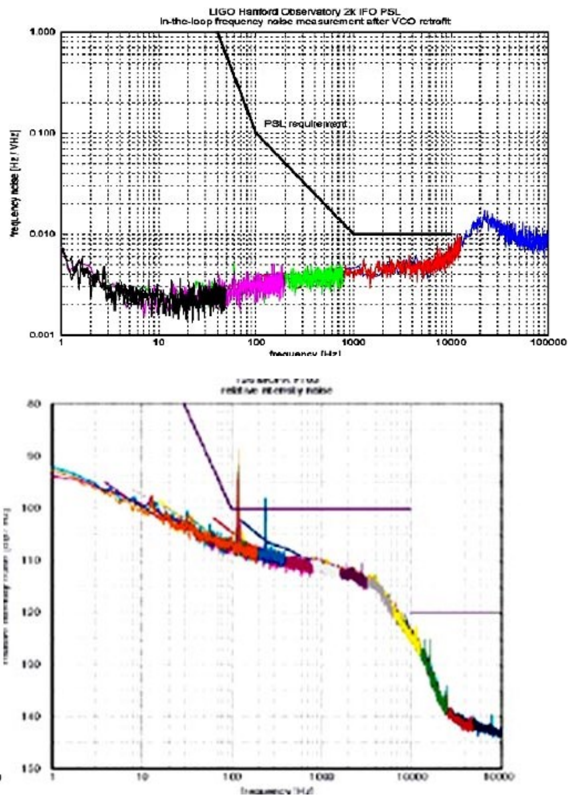

Fig. (20) Performance of the LIGO prestabilized laser in frequency (left) and power (right). The lines indicate the noise requirements for the interferometers.

We are now optimistic that we will achieve that major milestone this year and will then be able to concentrate on the noise issues, which we expect to interleaved with some engineering test runs for data taking. Our long-term plan is to begin a science data taking mode during 2002 with an eventual goal to collect at least 1 year of integrated coincidence data between the two sites with sensitivity near 10^{-21}. Depending on how well we do making LIGO robust and how quickly we solve the noise problems we estimate that goal should be reached by sometime in 2005, at which point we want to be prepared to

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undertake improvements that will give a significant improvement in sensitivity.

As described above, the initial LIGO detector is a compromise between performance and technical risk. The design incorporates some educated guesses concerning the directions to take to achieve a reasonable probability for detection. It is a broadband system with modest optical power in the interferometer arms and a low risk vibration isolation system. The suspensions and other systems have a direct heritage to the demonstration interferometer prototypes we have tested over the last decade. As ambitious as the initial LIGO detectors seem, there are clear technical improvements we expect to make, following the initial search. The initial detector performance and results will guide the specific directions and priorities to implement from early data runs.

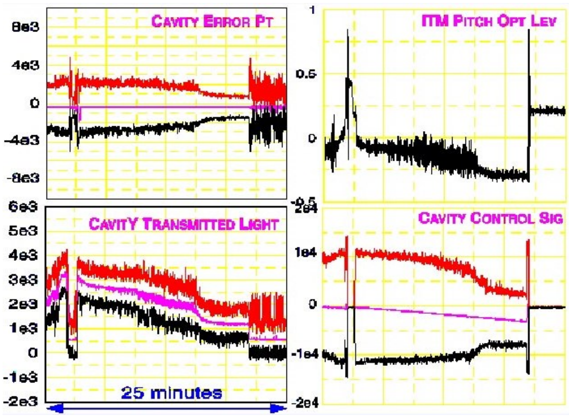

Fig. (21) A locked stretch of a 2km arm of LIGO showing the transmitted light and various control and error signals. This marks an important milestone in making LIGO operational.

We expect to be prepared to implement a series of incremental improvements to the LIGO interferometers following the first data run (2002 - 2005). We anticipate both reduction of noise from stochastic sources and in the sensing noise. These improvements will include improvements in the suspension system to improve the thermal noise, the seismic isolation and improvements to the sensing noise through the use of higher power lasers in conjunction with improved optical materials for the test masses/mirrors to handle this higher power. We believe it is quite realistic to improve the sensitivity at 100 Hz by at least a factor of 10, and to broaden the sensitive bandwidth by about a factor without any radically new technologies or very large changes. This will improve the rate (or volume of the universe searched) at a fixed sensitivity by a factor of 1000. If the physics arguments favor an even greater sensitivity in a narrower bandwidth, it will be possible to change the optical configuration and make a narrow band device. Longer term and move major changes in the detector might use new interferometer configurations and drive the system to its ultimate limits determined by the terrestrial gravity gradient fluctuations and the quantum limit.

We believe that prospects are good that gravitational wave detection will become a reality within the next decade and hopefully sooner.

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Rainer Weiss - Interview

Interview, October 2017
"Space is enormously stiff. You can't squish it"

Telephone interview with Rainer Weiss following the announcement of the 2017 Nobel Prize in Physics on 3 October 2017. The interviewer is Adam Smith, Chief Scientific Officer of Nobel Media. In this telephone interview, recorded immediately after his Nobel Prize was publicly announced, Rainer Weiss explains why measuring the effect of gravitational waves is so very hard to achieve, despite the extraordinarily high energies involved.

Transcript of the interview
[Rainer Weiss]: Hello
[Adam Smith]: Good morning, my name is Adam Smith calling from Nobelprize.org, the website of the Nobel Prize in Stockholm.
[Rainer Weiss]: Yeah, very good, I already talked to some of your ... with your colleagues this morning.
[Adam Smith]: First of all congratulations on the award of the Nobel Prize.
[Rainer Weiss]: Well thank you.
[Adam Smith]: It must be very special, in particular because you came up with the idea of this detector.
[Rainer Weiss]: Well be careful with that. Other people also had thought of detectors, so be careful with that. I mean, in fact there was a group in Russia in 1962 - Gertsenshtein and Pustovoit - I can't pronounce it for you well. They wrote a little paper in a Russian journal which none of us knew about that, not to do it by interferometry so much, but to use light as a way of doing this. And then it turns out, Joe Weber, unbeknownst to us, but also Joe Weber, who was sort of the first person to start thinking about this.
[Adam Smith]: With his Weber bars.
[Rainer Weiss]: Yeah the Weber bar, but at the end of the Weber bars he also has some notes about that maybe we should do this with interferometry. The whole world tried to reproduce the Weber experiments. I don't know, you're probably too young to know that, but the thing is that in '60 ... Weber made his big announcement in '69 and ... where he showed that he had, in three bars, he had seen gravitational waves and then that got, virtually everybody, well many, many groups, both in Europe and Asia and in the United States, tried to reproduce this and to everybody's disappointment nobody saw the same thing that Joe did, Joe Weber did. And, the way it happened in my life is I was teaching a course in general relativity, in the middle of that epic, sort of 1967, and I couldn't explain the way a Weber bar worked. Mostly because I just didn't know enough, ok, but it was that ... I thought that there must be an easier way to explain how a gravitational wave interacts with matter. If one just looked at the most primitive thing of all, 3D floating masses out in space and look at how the space between them changed because of the gravitational wave coming between them. And I gave that as a problem in the course, you know, and the kids in this course did it, because it's a fairly straightforward calculation. And that was sort of '67 and by about '72, '71 it turned out that many people were not seeing, I mean it was already quite clear that the bar technique and Weber's experiments were not being seen by others. And so I spent a summer thinking about, maybe this idea that I gave as an exercise in a course would be a nice way to try and do this because it was so easy to understand it. And that then turned into LIGO, but other people had thought of it. I didn't know that.
[Adam Smith]: Nevertheless a journey from the early seventies to now. The sense of achievement and excitement must be quite ...
[Rainer Weiss]: Oh no doubt. I mean look ... the thing ... it has nothing to do with pride. I did something that others didn't do. I actually did a calculation of what might be all the things that get in the way of being able to do it. Which actually turned out to be very useful. You know the different noises that would make it impossible to see it, or possible to see it, you had to solve a whole set of problems, and that was my contribution to it in the early days.
[Adam Smith]: Well that's it. It's quite mind-boggling to think of how precise this piece of equipment is.
[Rainer Weiss]: Yeah. [Laughs] That's true, and it's ... that's what took by the way. I think the easiest way to say it is that the concept is very straightforward. You measure the time it takes light to go between two orthogonal directions in the gravitational wave. And you measure that time very carefully, and that idea's sort of trivial. I mean most people who know a little bit of physics can make that calculation. On the other hand what happens to make it actually happen because the sizes of things is so small and I think the easiest way to say it ... Are you familiar with exponential notation, can I use that?
[Adam Smith]: You can yes.

[Rainer Weiss]: Well ok, I think the best way of saying it is this way. There are two factors of 1012 that had to be solved. One of them was that the light wavelength itself is 10-6 meters and so you had to devise a way to make light, which has this wavelength of 10-6 to go, to be good enough so you could measure 10-18 meters, and that is a factor of 1012. And that was not the hardest problem, but that was one of the major problems between, let's say 1972 to 2015. But the other one is another factor of 1012 which is just as serious and that's much harder to solve. And that took longer. And that took more effort. And that was that even though you may have this wonderful method of now breaking up a light fringe so you could do a part in 1012 of it, you still don't know that the thing that you're measuring is not being pushed around by forces that make it move much, much more, that are not gravitational, that are not gravitational waves. But other forces like thermal noise, like seismic motion, or god knows all the different things that happen in the world, that you were not being ... That, that same mirror that you're looking at is not being pushed around by, by things that make it move more than 10-18 meters. And that is another factor of 1012 about because it turns out that ground motion is about a few microns, 10-6 meters again. So you have to devise a wonderful way to get rid of the ground motion and then get rid of the thermal noise and now it's really at the point where we're worrying about the quantum noise. So ... But, it was all pretty well organised, I mean in the sense that people knew what the problems would be. It's just that it takes time to do a thing like that.

[Adam Smith]: The contrast between the minute precision to make the measurement and the size of the actual gravitational wave which is ...

[Rainer Weiss]: Yeah, yeah yeah. It's really ... What it tells you is something really interesting. It tells you that space is very, very stiff to distortion. You know the Einstein waves can be thought of as a distortion of space, and time. But the way we see it, we see it as a distortion of space. And space is enormously stiff. You can't squish it, you can't change its dimensions so easily. And it turns out that I think the easiest way to see that, or say it is that, it's ... I'll give you an example so that you can use it or think about it. If you put this whole thing that was detected, you know, back in the first detection, and put it not at a billion light years away , but rather put it at the sun, the distance of the sun. Suppose the sun had, somehow, put out those gravitational waves. You would have had a motion at the earth of, a motion of over a km, of about only 10-6 m. It's still tiny. In fact you could just about hear it in your ear, but the amount of power that went through you is something like 1024 watts per cm^2. It's huge. In other words, it's ... you know the sun puts out about 104 watts.

[Adam Smith]: So you can translate that into what, though?

[Rainer Weiss]: Yeah, yeah, in fact we did translate that in that initial paper into the amount of power was sort of brighter than anything in the universe, by 50 times brighter for the few moments in which that gravitational wave was actually, you know, travelling through you. It's an enormously stiff, the system just does not like to make, you cannot distort space very much but you do get a little bit and that's what we measure.

[Adam Smith]: That is a really beautiful concept to mention on this call, thank you so much. We will hopefully discuss all these things more when you come to Stockholm. You will be coming to Stockholm in December?

[Rainer Weiss]: Of course I will, and I intend, at least if you can manage it I would like to ... I prefer really often to talk to high school students, mostly because I think they're the future for us. And, I know I have to give lectures, I'm very happy to do that and so are my colleagues. But if you think that there's some high school students that would benefit from understanding this a little better I'd be very happy to do that.

[Adam Smith]: We will most certainly work to fill rooms with high school students for you. That's a great objective. We very, very much look forward to welcoming you to Stockholm. How do you feel about the coming day which will be completely taken over by this.

[Rainer Weiss]: What today? I don't know, I'm at home, still not completely dressed! Well I am now, a little but, yes I know that I have to confront all my colleagues and it's a charming thing to do, it's just a little awkward that's all.

[Adam Smith]: Good luck with finishing getting dressed and we look forward to meeting you in Stockholm in December.

[Rainer Weiss]: Yeah I'm very happy to come. I've been there once with - you gave a Nobel Prize to one of my colleagues named John Mather and George Smoot.

[Adam Smith]: Of course, because you also worked on the COBE project with them.

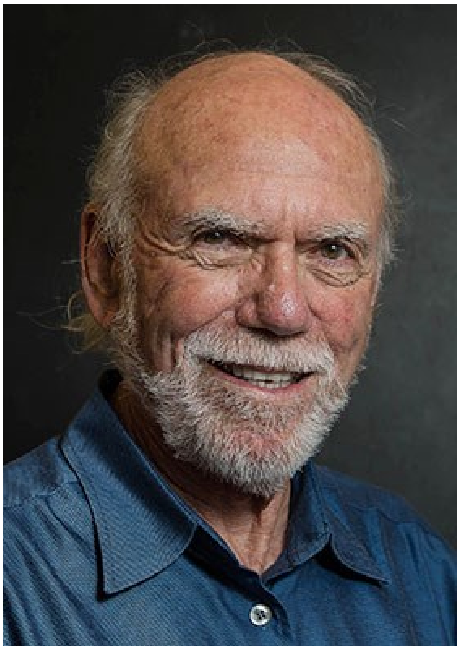
[Rainer Weiss]: Oh yeah I worked on that with them and I've been there and it's really quite a pleasure to come there.

[Adam Smith]: OK, well we greatly look forward to meeting you. Thank you so much.

[Rainer Weiss]: Bye bye.

Barry C. Barish - Interview

Interview, October 2017



"The actual size of the signal was about one thousandth the size of a proton!"

Telephone interview with Barry C. Barish following the announcement of the 2017 Nobel Prize in Physics on 3 October 2017. The interviewer is Adam Smith, Chief Scientific Officer of Nobel Media. In the interview, Barry C. Barish reflects on the incredible sensitivity of the instrument used to make the discoveries which led to this year's Nobel Prize in Physics.

Transcript of the interview
[Barry C. Barish]: Hello?
[Adam Smith]: This is Adam Smith calling from Nobelprize.org, the website of the Nobel Prize in Stockholm. Well first of all congratulations on the award of the Nobel Prize.
[Barry C. Barish]: Oh thank you. Of course I'm humbled and thrilled.
[Adam Smith]: How did the news come to you?
[Barry C. Barish]: I guess a telephone call about 10 minutes ago, just before they started the session I guess. So I learnt just before you learnt, I guess.
[Adam Smith]: It really couldn't have arrived any faster, the news, because the announcement of gravitational waves was only made last year.
[Barry C. Barish]: [Laughs] Yeah.
[Adam Smith]: Putting LIGO together and getting this result took many decades and an awful lot of work. Where did that dedication come from?
[Barry C. Barish]: I think that's a harsh question to answer. I think there's a personal part – you have to be someone who doesn't need instant gratification. But I think the scientific goals and the technical challenges were the two things that equally motivated me. The technical challenges were technical challenges that were not unbeatable; it was just that we had to learn how to do things, and how to build a sensitive enough device. That took us 20 years after we built the first version of the LIGO detector. And of course the science is unbelievable, so I think it is not hard to be motivated for 20 years to do the kind of science we're starting to be able to do.
[Adam Smith]: The precision of this instrument is quite unbelievable, isn't it.
[Barry C. Barish]: Yes it is, the size of the effect that we measured from the first event, the merging of two black holes, the actual size of the signal was about one thousandth the size of a proton, what it did to our apparatus. So we were able to measure a movement, or change of length of the apparatus, by the passage of the gravitational waves to that accuracy and then measure its form well enough to decide what that was. So that's pretty unbelievable.
[Adam Smith]: It's a testament to human ingenuity isn't it?
[Barry C. Barish]: And a testament to modern technology and science. I think this couldn't have been done 50 years ago, or 20 years ago, or 30 years ago. It's taken the best modern lasers and control and engineering to be able to do it.
[Adam Smith]: Will we be welcoming you to Stockholm in December?
[Barry C. Barish]: Yes of course.
[Adam Smith]: Lovely. It was great to talk to you. Congratulations again.
[Barry C. Barish]: OK, thank you. Bye bye.
[Adam Smith]: Bye bye.

Kip S. Thorne - Interview

Interview, October 2017

"Huge discoveries are really the result of giant collaborations"

Telephone interview with Kip S. Thorne following the announcement of the 2017 Nobel Prize in Physics, 3 October 2017. The interviewer is Adam Smith, Chief Scientific Officer of Nobel Media. In the interview, Kip S. Thorne reflects on how this year's Nobel Prize in Physics was a remarkable team effort.

Transcript of the interview
[Kip S. Thorne]: Hello
[Adam Smith]: Good morning, my name is Adam Smith calling from Nobelprize.org, the website of the Nobel Prize in Stockholm. First of all congratulations on the award of this year's Nobel Prize.
[Kip S. Thorne]: Thank you very much.
[Adam Smith]: It could hardly have come any quicker. The announcement was just last year.
[Kip S. Thorne]: Yes, that's right. It is amazingly quick.
[Adam Smith]: Einstein himself probably didn't think that gravitational waves could be recorded. But you have always been a believer I gather?
[Kip S. Thorne]: Well I have been a believer but I began ... I'm much younger than Einstein and by the time I came along there were lasers, there were massive computers, technology had changed, and our understanding of possible sources of gravitational waves had changed. Neutron stars and black holes which should be the strongest sources, Einstein had none of that to base his ideas on. So, yes, in his seminal paper on gravitational waves he indicated skepticism that gravitational waves would ever be detected.
[Adam Smith]: And they open a new window on the universe. What will we be able to see now that we can detect gravitational waves?
[Kip S. Thorne]: I think over the coming decades we will see enormous numbers of things. Just as electromagnetic astronomy was begun in essence, at least modern astronomy, by Galileo pointing his telescope in the sky and discovering Jupiter's moons. This is the same thing but for gravitational waves. This is ... Gravitational waves are the only other kind of wave, besides electromagnetic that propagate across the universe, bringing us information about the universe, so initially we will see not just binary black holes. We will see neutron stars collide, tear each other apart, we will see black holes tearing neutron stars apart, we will see spinning neutron stars, pulsars, when the space-based LISA mission is operating hopefully by about 2030, we'll be exploring basically the birth of the universe, the earliest moments of the universe. And there will ever so much more I'm sure, including huge surprises, as the years wear on.
[Adam Smith]: Talking of surprises, the one that you've just received, how did the news come to you?
[Kip S. Thorne]: Well I think it was not unexpected that this opening gravitational wave window onto the universe would get a Nobel Prize. I was hoping that the prize would go to the LIGO-Virgo collaboration, which made the discovery, or to the LIGO laboratory, the scientists of the LIGO laboratory, who designed and built and perfected the gravitational wave detectors and not to Barish, Weiss and me. We live in an era where some huge discoveries are really the result of giant collaborations, with major contributions coming from very large numbers of people. I hope that in the future the Nobel Prize committee finds a way to award the prize to the large collaborations that make this and not just to the people who may have been seminal to the beginning of the project, as we were.
[Adam Smith]: That I guess is a conversation and a debate that is going to run and run, yes.
[Kip S. Thorne]: I feel that I'm an icon for the LIGO-Virgo collaboration and the LIGO laboratory and I'm pleased to be that icon and represent what they have achieved.
[Adam Smith]: That's nicely said. So will we be welcoming you to Stockholm in December then?
[Kip S. Thorne]: Yes of course.
[Adam Smith]: [laughs] Good. Once again congratulations and we greatly look forward to meeting you in December.
[Kip S. Thorne]: Thank you
[Adam Smith]: Thank you. Bye bye.

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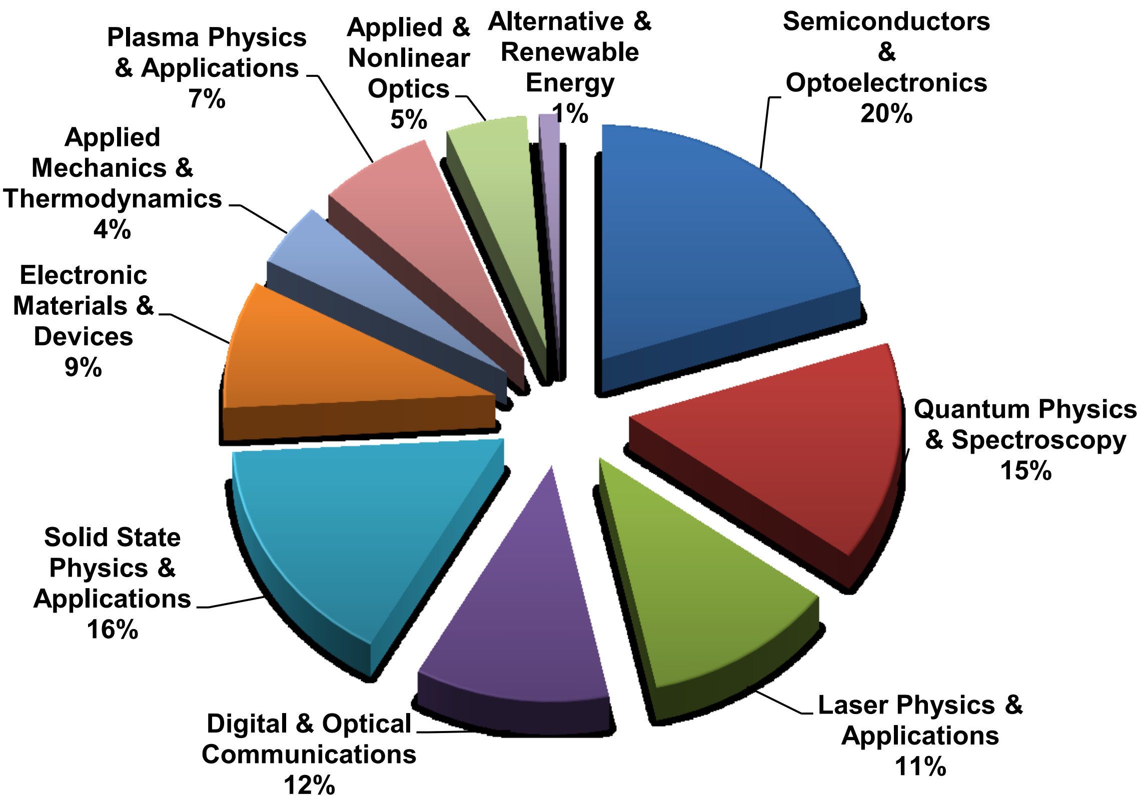

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Notes:
- 1(1), 3 refer to IJAP, Vol. 1, No. 1, page 3
- L1(1), 3 refer to IJAPLett, Vol. 1, No. 1, page 3

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