A retrospective on the first 25 years of LIGO

R. Weiss MIT

Advanced LIGO Dedication

LIGO Hanford Observatory

May 19, 2015

Outline

- How Caltech and MIT got together on LIGO
  - Basic ideas and some misconceptions
- The transition from table top to big science
- The advocacy and strategic thinking at the NSF
- The first committee recommendation
- The second committee recommendations
- Beginnings of a project
- A real project and two good things LIGO did
- Part of a legacy

Management and Operations Working Group for Shuttle Astronomy

Report of the sub-panel on Relativity and Gravitation

October 1975

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1. History of Sub-Panel

This report is a summary of the deliberations and the recommendations of a Sub-Panel of the Management and Operations Working Group in Shuttle Astronomy commissioned by Dr. Nancy G. Roman of NASA Headquarters to consider the role of the space program in the field of experimental relativity and gravitation.

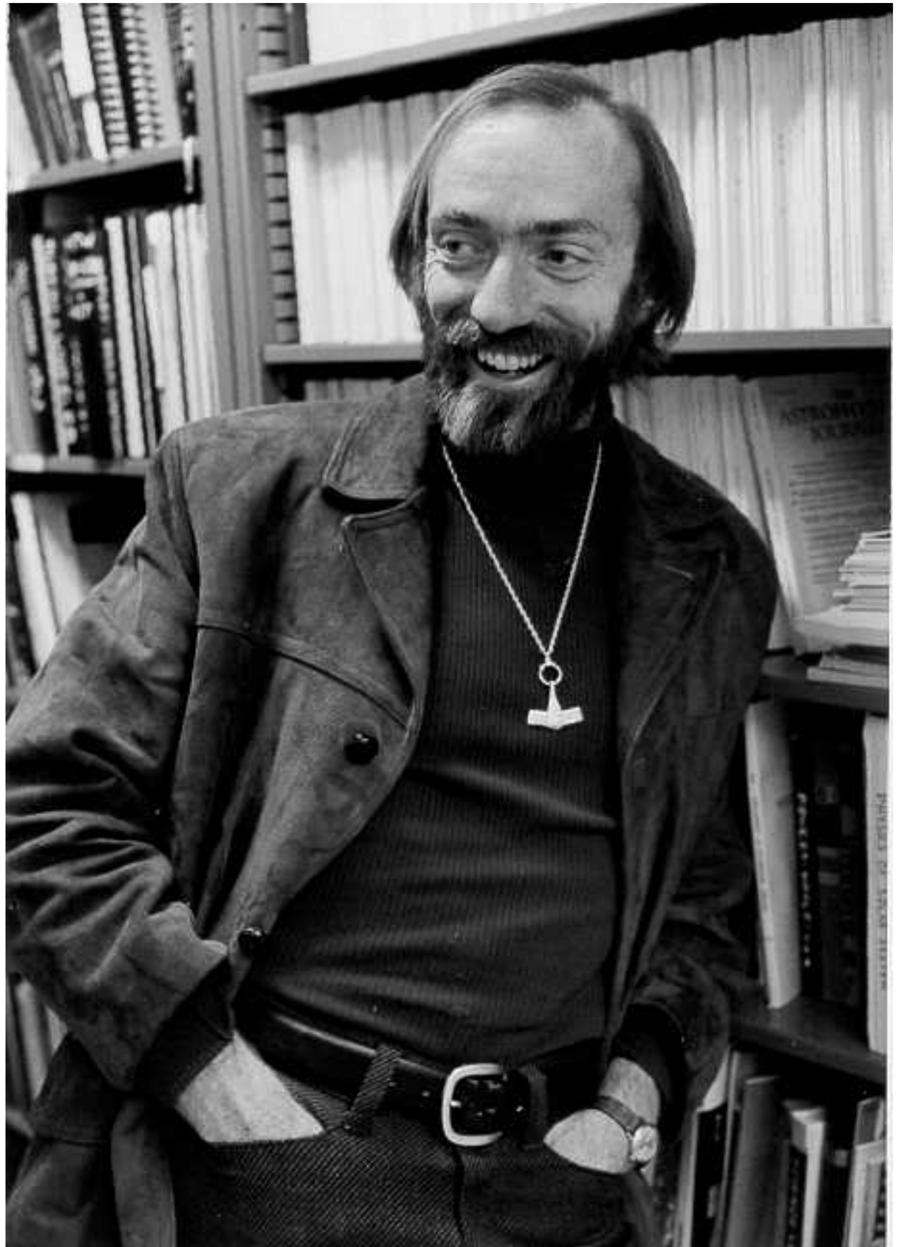
The panel members are Professors Peter Bender of the University of Colorado and the National Bureau of Standards, Charles Misner of the University of Maryland, Robert V. Pound of Harvard University and Rainer Weiss of M.I.T., chairman.

The panel met 4 times during 1975, and at several of the meetings it was joined by visitors interested in the field. The visitors were Dr. Rudolf Decher of NASA Huntsville, Dr. Nancy Roman, NASA Headquarters, Professors James Peebles of Princeton University, Irwin Shapiro of M.I.T. and Kip Thorne of Cal Tech.

The report introduces the reader to the fundamental problems in experimental relativity and gravitation and then follows with sections on various areas in the field. Each section reviews the present status of research and brings forward suggestions where the space program may have an impact.

2. Introduction

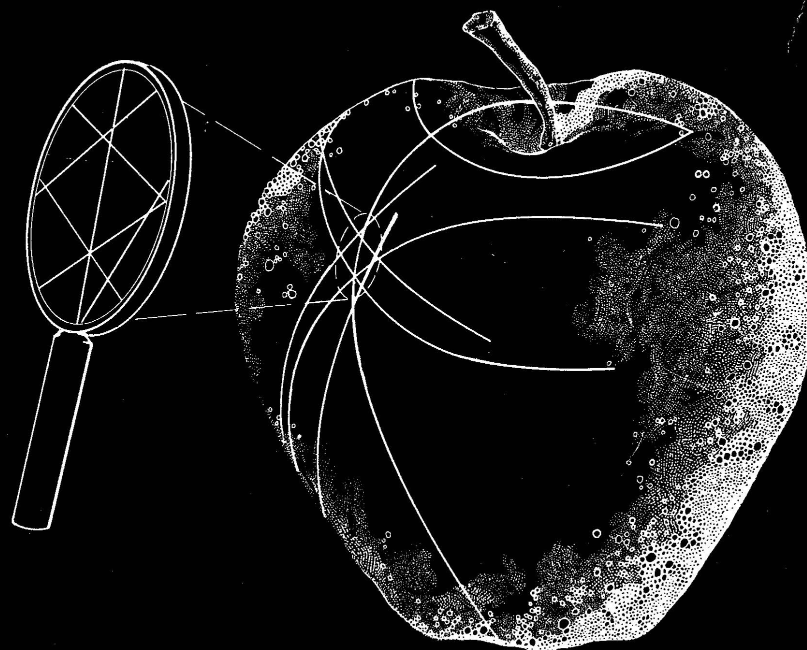
Gravitation is at the same time the dominant force in the universe for matter in the large as well as the weakest known fundamental interaction in nature. Gravitation opened the era



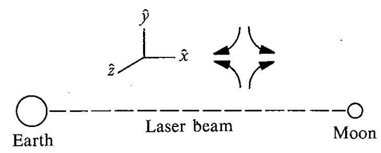
K. Thorne

GRAVITATION

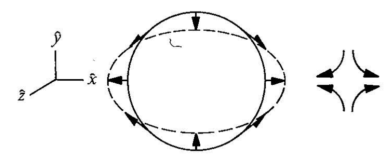
Charles W. MISNER   Kip S. THORNE   John Archibald WHEELER



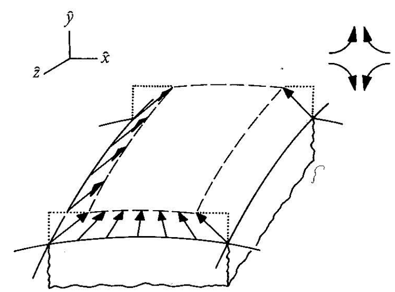
Types of GW detectors
MTW (1973)



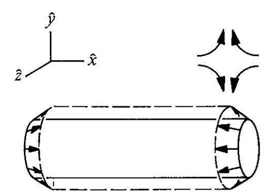
(a) Oscillations in Earth-moon separation (see exercise 37.7)



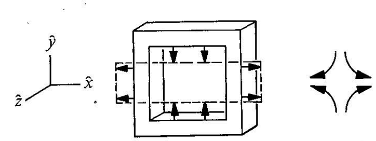
(b) Normal-mode vibrations of earth and moon [see Weber (1968)]



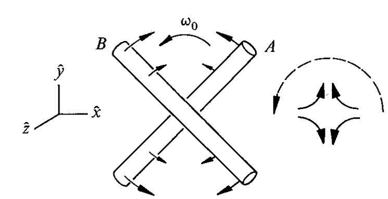
(c) Oscillations in Earth's crust [see Dyson (1969)]



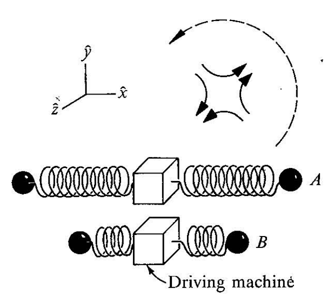
(d) Normal-mode vibrations of an elastic bar [see Weber (1969) and references cited therein]



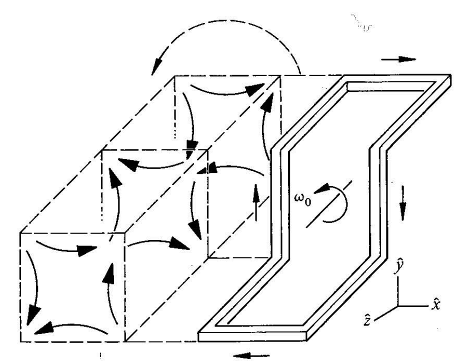
(e) Normal-mode vibrations of an elastic square, or hoop, or tuning fork [see Douglass (1971)]



(f) Angular accelerations of rotating bars ["Heterodyne detector"; see Braginsky, Zel'dovich, and Rudenko (1969)]



(g) Angular accelerations of driven oscillators [Sakharov (1969)]



(h) Pumping of fluid in a rotating loop of pipe [Press (1970)]. The pipe rotates with the same angular velocity as the waves; so the position of the pipe in the righthand polarized lines of force remains forever fixed

Figure 37.2.
Various types of gravitational-wave detectors.

1. The Relative Motions of Two Freely Falling Bodies

(1) freely falling bodies

As a gravitational wave passes two freely falling bodies, their proper separation oscillates (Figure 37.3). This produces corresponding oscillations in the redshift and round-trip travel times for electromagnetic signals propagating back and forth between the two bodies. Either effect, oscillating redshift or oscillating travel time, could be used in principle to detect the passage of the waves. Examples of such detectors are the Earth-Moon separation, as monitored by laser ranging [Fig. 37.2(a)]; Earth-spacecraft separations as monitored by radio ranging; and the separation between two test masses in an Earth-orbiting laboratory, as monitored by redshift measurements or by laser interferometry. Several features of such detectors are explored in exercises 37.6 and 37.7. As shown in exercise 37.7, such detectors have so low a sensitivity that they are of little experimental interest.

EXERCISES

Exercise 37.6. RELATIVE MOTION OF FREELY FALLING BODIES AS A DETECTOR OF GRAVITATIONAL WAVES [see Figures 37.2(a) and 37.3.]

Consider two test bodies initially at rest with respect to each other in flat, empty spacetime. (The case where other, gravitating bodies are nearby can be treated without too much more difficulty; but this exercise concerns only the simplest example!) A plane, nearly monochromatic gravitational wave, with angular frequency ω and polarization $\boldsymbol{e}_+$, impinges on the bodies, coming from the $-z$ direction. As shown in exercise 35.5, the bodies remain forever at rest in those TT coordinates that constituted the bodies' global inertial frame before the wave arrived. Calculate, for arbitrary separations $(\Delta x, \Delta y, \Delta z)$ of the test bodies, the redshift and the round-trip travel time of photons going back and forth between them. Compare the answer, for large $\Delta x, \Delta y, \Delta z$, with the answer one would have obtained by using (without justification!) the equation of geodesic deviation. Physically, why does the correct answer *oscillate* with increasing separation? Discuss the feasibility and the potential sensitivity of such a detector using current technology.

Exercise 37.7. EARTH-MOON SEPARATION AS A GRAVITATIONAL-WAVE DETECTOR

In the early 1970's one can monitor the Earth-moon separation using laser ranging to a precision of 10 cm, with successive observations separated by at least one round-trip travel time. Suppose that no oscillations in round-trip travel time are observed except those (of rather long periods) to be expected from the Earth-moon-sun-planets gravitational interaction. What limits can one then place on the energy flux of gravitational waves that pass the Earth? The mathematical formula for the answer should yield numerically

$$\text{Flux} \lesssim 10^{18}\ \text{erg/cm}^2\ \text{sec for } 0.3\ \text{cycle/sec} \lesssim \nu \lesssim 1\ \text{cycle/day}, \qquad (37.10a)$$

corresponding to a limit on the mass density in gravitational waves of

$$\text{Density} \lesssim 10^{-13}\ \text{g/cm}^3. \qquad (37.10b)$$

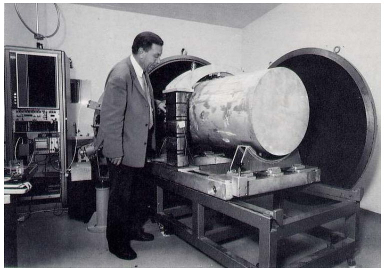
Why is this an uninteresting limit?

$h \sim \dfrac{\lambda}{L} = \dfrac{10^{-6}}{4\text{x}10^{3}} = 2\text{x}10^{-10}$ not good enough, not one photon, not one pass

really should have been

$$h \sim \frac{\lambda}{bL\sqrt{\dot{N}t_{int}}} = \frac{10^{-6}}{100 * 4\text{x}10^{3} * \sqrt{10^{23} * 10^{-2}}} = 8\text{x}10^{-23}$$

Initial interferometric GW detector groups late 1970's



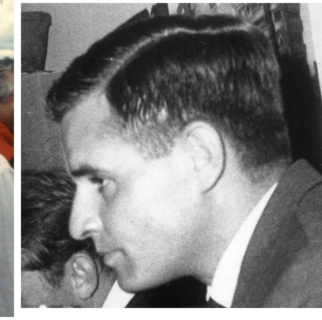
H. Billing

L. Schnupp

K. Maischberger

W.Winkler

R. Schilling



A. Rudiger

Max Planck Garching

Glasgow

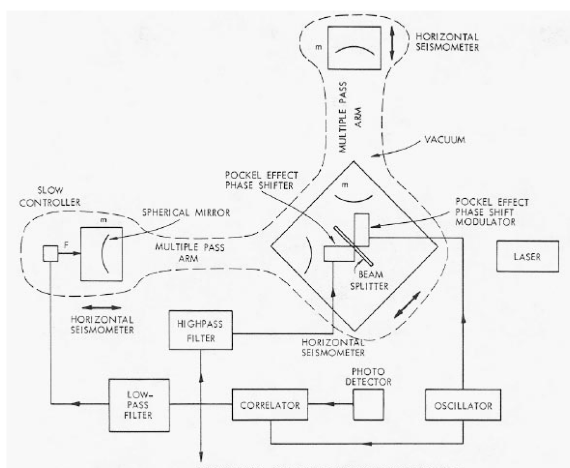
R. Drever

J. Hough

B. Meers

H. Ward

MIT



J. Livas , D.H. Shoemaker, D. Dewey

PHYSICAL REVIEW VOLUME 166, NUMBER 5 25 FEBRUARY 1968

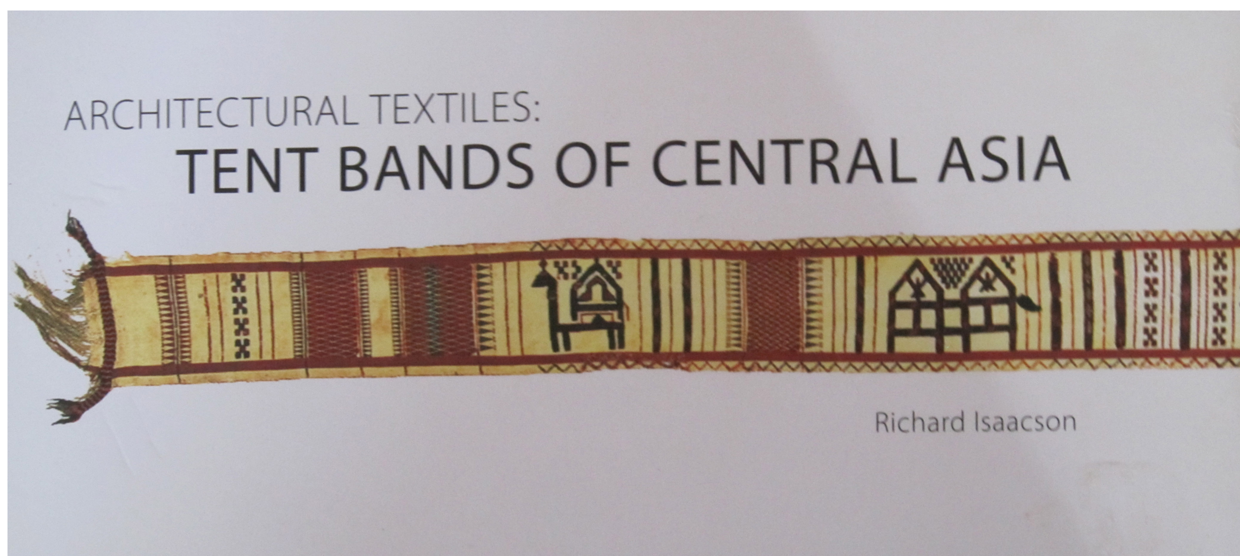
Gravitational Radiation in the Limit of High Frequency. II. Nonlinear Terms and the Effective Stress Tensor*

RICHARD A. ISAACSON†
Department of Physics and Astronomy, University of Maryland, College Park, Maryland
(Received 14 July 1967)

The high-frequency expansion of a vacuum gravitational field in powers of its small wavelength is continued. We go beyond the previously discussed linearization of the field equations to consider the lowest-order nonlinearities. These are shown to provide a natural, gauge-invariant, averaged stress tensor for the effective energy localized in the high-frequency gravitational waves. Under the assumption of the WKB form for the field, this stress tensor is found to have the same algebraic structure as that for an electromagnetic null field. A Poynting vector is used to investigate the flow of energy and momentum by gravitational waves, and it is seen that high-frequency waves propagate along null hypersurfaces and are not back-scattered by the lowest-order nonlinearities. Expressions for the total energy and momentum carried by the field to flat null infinity are given in terms of coordinate-independent hypersurface integrals valid within regions of high field strength. The formalism is applied to the case of spherical gravitational waves where a news function is obtained and where the source is found to lose exactly the energy and momentum contained in the radiation field. Second-order terms in the metric are found to be finite and free of divergences of the $(\ln r)/r$ variety.

R. Isaacson (Gravitation at NSF)

M. Bardon (Director of Physics NSF)



A STUDY OF A LONG BASELINE

GRAVITATIONAL WAVE ANTENNA SYSTEM

Prepared for the National Science Foundation
under NSF Grant PHY-8109581
to the Massachusetts Institute of Technology

Prepared By:

Paul Linsay	MIT
Peter Saulson	MIT
Rainer Weiss	MIT

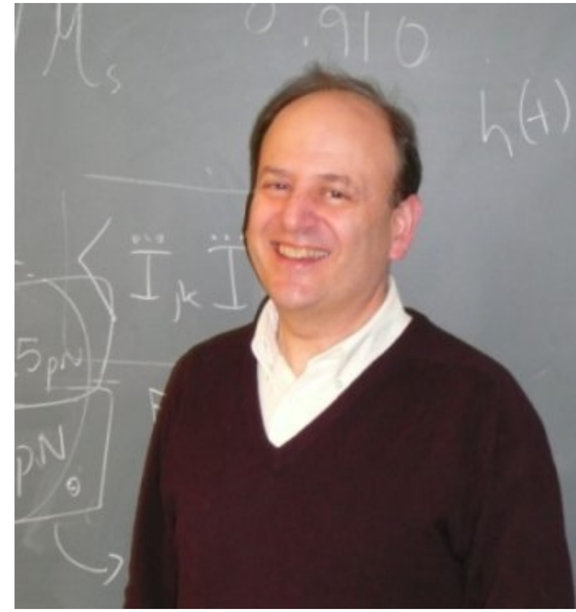
With Contributions By:

Stan Whitcomb	CalTech

Industrial Consultants:

Arthur D. Little Corporation	Cambridge, Massachusetts
Stone & Webster Engineering Corporation	Boston, Massachusetts

OCTOBER 1983



P. Saulson

S. Whitcomb

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NATIONAL SCIENCE FOUNDATION
ADVISORY COMMITTEE FOR PHYSICS

December 12-13, 1983
1800 G Street, N.W.
ROOM 540

Tentative Discussion Schedule

MONDAY, DECEMBER 12

9:00 a.m.	Introductions and Remarks - J. Armstrong, M. Bardon
9:30 a.m.	Oversight Review of the NSF Elementary Particle Physics Program
	NSF Role in Elementary Particle Physics - D. Berley
10:00 a.m.	DOE and Elementary Particle Physics - W. Wallenmeyer
10:30 a.m.	Report of Subcommittee for Review of NSF Elementary Particle Physics Program - R. Schwitters
11:00 a.m.	Discussion of Oversight Review
12:00 Noon	Lunch
1:30 p.m.	Cornell Upgrading - B. McDaniel
2:30 p.m.	Discussion of Elementary Particle Physics Program and Related Issues
6:00 p.m.	Adjourn

TUESDAY, DECEMBER 13

9:00 a.m.	Funding Pressures for FY 1984/1985 and Planning of Major Projects in Physics Division - M. Bardon
9:30 a.m.	University of Illinois Microtron - L. Cardman
10:30 a.m.	MIT/Caltech Laser Interferometer Project - R. Drever/R. Weiss
12:00 Noon	Lunch
1:30 p.m.	Report of Review Subcommittee - R. Schwitters
2:00 p.m.	Discussion of Long Range Plans
3:00 p.m.	Discussion with NSF Director, E. Knapp
3:30 p.m.	Continuation of Long Range Plan Discussion and Other Committee Business
6:00 p.m.	Adjourn

ADVISORY COMMITTEE FOR PHYSICS

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*TEMPORARY, 1982-83

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Laboratory Director
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GTE Products Corporation
Sylvania Lighting Center
Danvers, Massachusetts 01923
(617, 777-1900)

(November 1983)

Subcommittee:

G. Baym

S. Deser

R. Schwitters

(1) Final, unanimously appr. 12/1 [initials]

¶ The committee is impressed with the long-range scientific potential of gravitational wave detection. It will not only test our basic understanding of gravitation, but provide an entirely new window on the Universe. ¶ We have considered the major interferometric laser detection system now being developed by the Caltech and MIT groups. ¶ ~~As with~~

We note that not only is this an outstanding scientific opportunity, but the the Foundation is the only source of support for ground-based gravitational physics.

¶ As with any attempt at a qualitative advance, there are risks: ~~[illegible]~~ Here the uncertainties involve both the magnitude of the signals to be detected and the large extrapolation of known experimental technique inherent in the proposed scale.

(2)

~~The committee~~, We find, however, the fundamental scientific merits of such an investigation so important as to be worth a substantial investment.

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As with any attempt at a qualitative advance, there are risks: here the uncertainties involve both the magnitude of the signals to be detected and the large extrapolation of known experimental technique inherent in the proposed scale. We find, however, the fundamental scientific merits of such an investigation so important as to be worth a substantial investment.

Richard L. Garwin
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P.O. Box 218
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(914) 945-2555

February 4, 1986

Mr. Marcel Bardon
National Science Foundation
1800 G Street, NW
Washington, DC 20550

Dear Marcel,

I spoke last month at the General Electric Research Lab, and I had a chance to talk with Roland Schmitt about gravity-wave work. He mentioned to me the interest in the community to do "gravity-wave interferometer" work, and I am reasonably familiar with the various approaches.

I am firmly of the view that we do not need right now to spend $40 M or $100 M on such an effort.

If there is such an interest, then I think it would be useful to have a two-week summer study, where people who are not involved in the experiments have a chance to contribute, to reduce the cost, and to provide a wider community which is informed in the matter. I think that this was done reasonably well with the DUMAND effort.

Enclosed are some Star Wars items which you may not have seen.

Sincerely yours,

Dick Garwin

Richard L. Garwin

Encl:
- 11/17/85 "Reagan's Plan Caught Many Administration Insiders by Surprise," by Frank Greve San Jose Mercury News. (111785..FG)
- 09/25/85 "The Case Against Star Wars," by Philip W. Anderson, in Princeton Alumni Weekly. (092585.PWA)
- 09/13/85 "The Strategic Defense Initiative: 'Star Wars'," by John Bardeen. (091385..JB)
- 09/00/85 "SDI: The Grand Experiment," pages 33-64 of the September issue IEEE Spectrum including: Introduction 'The challenge of all time,' by Donald Christiansen;

Report to the NSF

Panel on interferometric observatories for Gravitational waves January 1987

5. SUMMARY

A) A strong case has been made for the scientific value of the goals of the project.

B) Though there are large uncertainties associated with the strengths of the many different kinds of astrophysical sources and the ultimate capability of interferometric detectors, there is a high probability that this facility will ultimately provide for a giant leap in our understanding of the gravitational force, one of the most fundamental forces of nature, as well as our knowledge of astrophysical phenomena.

C) It is anticipated that this facility would uniquely provide the most sensitive and certain prospect for detecting astrophysical events and identifying their nature. Essential to this capability is the twin nature of the two interferometers. Though companion efforts in other countries are highly desirable, a common management of the two LIGO detectors is important both for the coordination of the observational program and for the analysis and identification of observed events. This facility would provide for a continued and thriving development of the field.

D) It is important to proceed directly to the construction of a long baseline interferometer in a timely manner since many aspects of the detector development program cannot otherwise be tested.

E) The rate of detectable extragalactic events increases as the cube of the interferometer sensitivity, thus putting a high premium on the long baseline. Though a multistage, or phased authorization to the final configuration was carefully considered, the panel does *not* recommend this approach. We recommend full authorization with phased construction and appropriate milestones.

F) The plans as described in the presentations and in the various documents provided appear to be well conceived. The procedure which has been employed in drawing up the existing designs and in making the cost estimates appears reasonable and adequate for proceeding to the final design for submission. Effort should continue to examine design alternatives which may decrease costs, particularly in the area of the vacuum system and enclosure. We do not recommend that the project be delayed by this process of re-examination. It is important to make the choice between Fabry-Perot and Michelson interferometer type detectors before submission of the final design. However, it remains important to develop advanced detectors and therefore research should continue to this end.

G) Because of the magnitude and dual nature of the facility, with laboratory sites widely separated, it is especially important that the construction and operation be well managed. The panel feels that the project requires a single scientific project leader of high stature to direct the activities. Efforts should immediately be directed to providing such leadership.

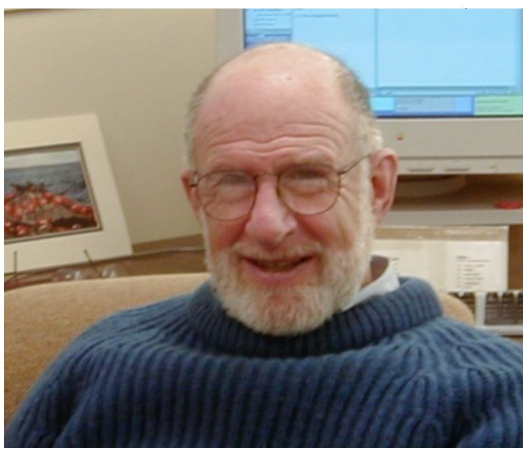
H) In looking forward to the utilization of the facilities it should be recognized that in addition to a budget for its operation, adequate funds will be required to support both the needs of experimental groups and further detector development.

I) In conclusion, the panel enthusiastically supports this development effort and urges that the plans for the project be refined along the lines indicated and that the design be completed. We recommend, then, that the construction project be brought to the National Science Foundation Board for consideration and (hopefully) for funding.

Panel Members:

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

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

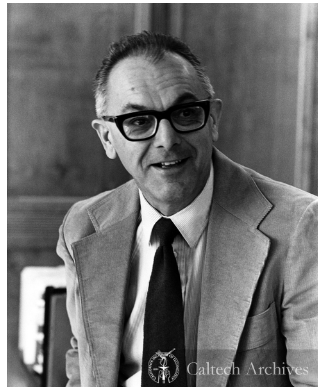


A. Sessler

B. McDaniel

R. Garwin

R.Drever



R. Vogt

W. Althouse

K. Thorne

F. Raab

Proposal to the National Science Foundation

THE CONSTRUCTION, OPERATION, AND SUPPORTING RESEARCH AND DEVELOPMENT OF A

LASER INTERFEROMETER GRAVITATIONAL-WAVE OBSERVATORY

Submitted by the
CALIFORNIA INSTITUTE OF TECHNOLOGY

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California Institute of Technology

Ronald W. P. Drever
Co-Investigator
California Institute of Technology

Kip S. Thorne
Co-Investigator
California Institute of Technology

Frederick J. Raab
Co-Investigator
California Institute of Technology

Rainer Weiss
Co-Investigator
Massachusetts Institute of Technology

F. Asiri

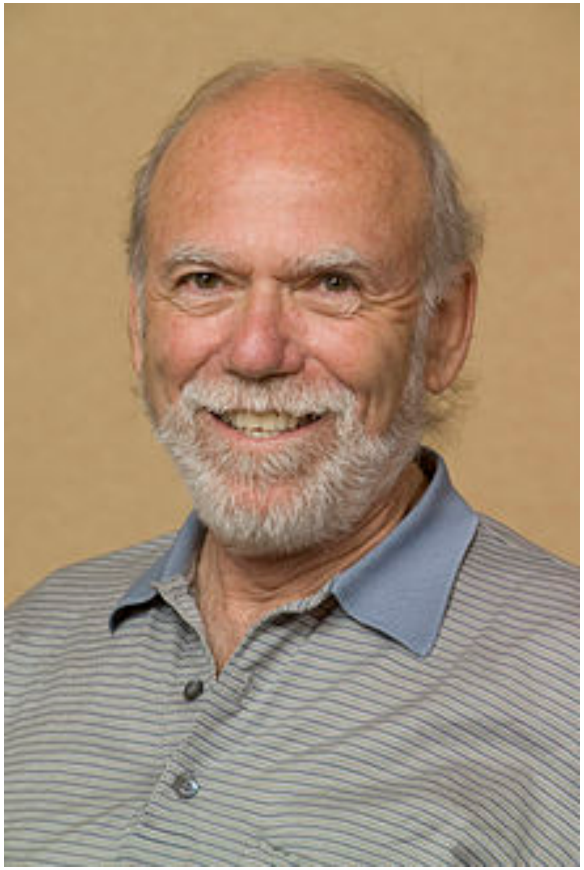
R. Savage

J. Worden

M. Zucker

L.Jones

The real start
1994



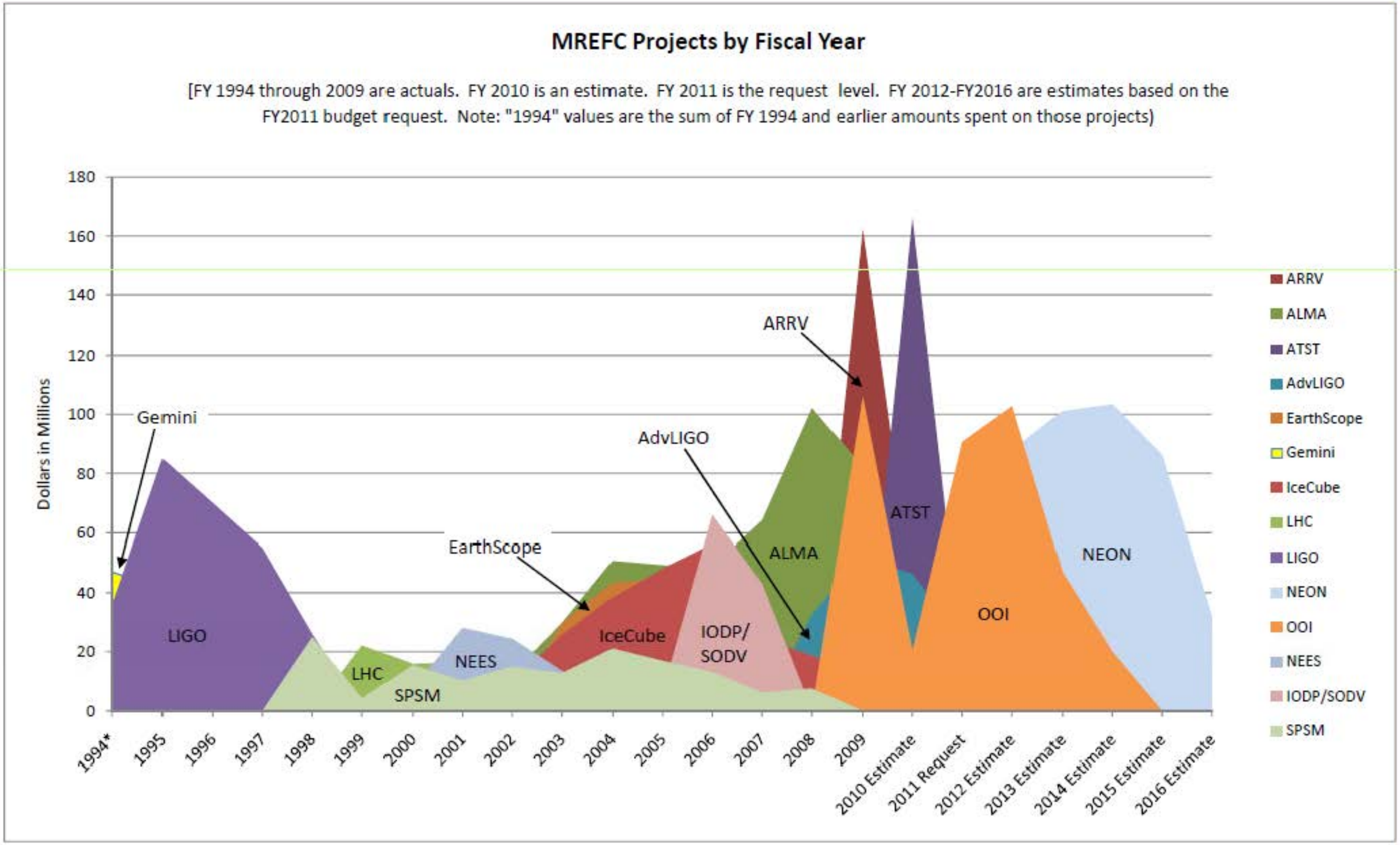
B. Barish

G. Sanders

A. Lazzarini

D. Coyne

NSF MREFC Program
history and future obligations



Barish: MREFC Program NSB Report

LIGO Scientific Collaboration

LIGO

LSC

Trinity University

University of Maryland

Andrews University

Washington State University

California State University Fullerton

indigo

The Australian National University (ANU)

Texas Tech University

R·I·T

ICTP SAIFR

Montana State University

Sonoma State University

University of the West of Scotland (UWS)

Montclair State University

Tsinghua University

American University, Washington, DC

University of Strathclyde

Michigan

CITA–ICAT

University of Glasgow

Whitman College

LSU

UTB TSC

University of Cambridge

Goddard Space Flight Center

Massachusetts Institute of Technology

Southern University and Agricultural & Mechanical College

The University of Western Australia

California Institute of Technology

University of Minnesota

The University of Mississippi

The University of Adelaide, Australia

The University of Melbourne

Embry-Riddle Aeronautical University

University of Washington

Universitat de les Illes Balears

Carleton College

Georgia Tech

Syracuse University

Cardiff University

Charles Sturt University

UF University of Florida

University of Wisconsin Milwaukee (UWM)

Universität Hamburg

ACIGA

University of Southampton

Korean Gravitational-Wave Group

University of Rochester

Leibniz Universität Hannover

Penn State

Hobart and William Smith Colleges

Science & Technology Facilities Council Rutherford Appleton Laboratory