# *A BRIEF HISTORY OF GRAVITATIONAL WAVES*

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**Based on the Review Paper**

**Brief History of Gravitational Waves**

**Universe 2(3) 2016.**

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The ARIES WP6 Workshop: Storage Rings as Gravitational Wave Detectors
"SRGW2021" (February, 2021)

## Before General Relativity:

In 1864 Maxwell, 33 years old, predicted the existence of electromagnetic waves.

In 1867 Hertz, 30 years old, discovered the waves.

In 1870 William Kingdom Clifford: Gravitation is a manifestation of the geometry of space.

In 1905 H. Poincaré: “onde gravifique” .

In 1911 Max Abraham proposes tha gravitation can propagate with variable speed of light in space and time with a Poisson eq. in four dimensions (Minkowski).

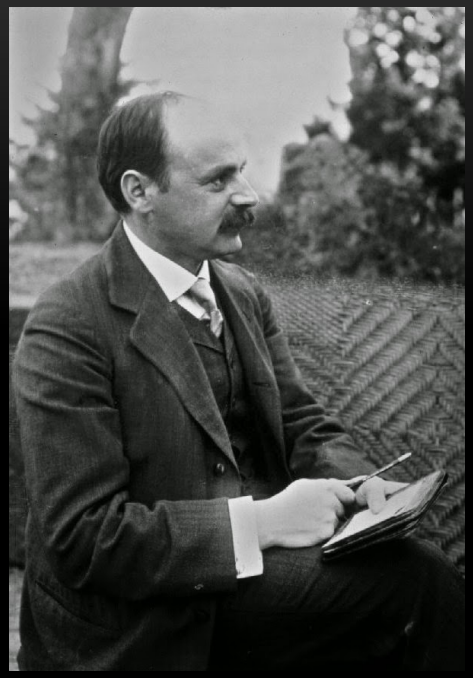
In 1912 Gunnar Nordström proposed the approximation that the mass a particle depends on the gravitational potential and the propagation happens at constant speed of light.

In 1913 Einstein and Grossmann published a document that contains an "Outline of a generalized relativity theory and a theory of gravitation ", commonly known as "Entwurf."

In 1915 Einstein published the General Relativity in its present form.
Gilbert deduced it from a variational principle.

Einstein to Schwarzschild:

**1916, February,** "Since then [November 14] I have handled Newton's case differently, of course, according to the final theory [the theory of General Relativity]. Also, there are no gravitational waves analogous to light waves. This probably is also related to the one-sidedness of the sign of the scalar T,
[nonexistence of a "gravitational dipole]".



Karl Schwarzschild

The analogy with electromagnetic waves is broken because there are no gravitational dipoles

# Näherungsweise Integration der Feldgleichungen der Gravitation.

Von A. Einstein.

Approximative integration of the field equations of gravitation

## § 3. Energieverlust körperlicher Systeme durch Emission von Gravitationswellen.

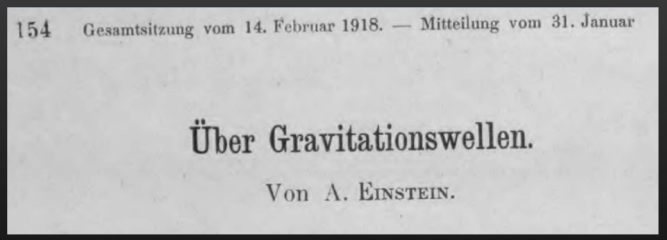
Energy loss in body systems due to the emission of gravitational waves

ein. Man erhält aus ihm also die Ausstrahlung $A$ des Systems pro Zeiteinheit durch Multiplikation mit $4\pi R^2$:

$$A = \frac{\varkappa}{2^4\pi} \sum_{\alpha\beta} \left( \frac{\partial^3 J_{\alpha\beta}}{\partial t^3} \right)^2. \qquad (21)$$

Würde man die Zeit in Sekunden, die Energie in Erg messen, so würde zu diesem Ausdruck der Zahlenfaktor $\frac{1}{c^4}$ hinzutreten. Berücksichtigt man außerdem, daß $\varkappa = 1.87 \cdot 10^{-27}$, so sieht man, daß $A$ in allen nur denkbaren Fällen einen praktisch verschwindenden Wert haben muß.

"... in all conceivable cases, ***A*** must have a practically vanishing value."



154 Gesamtsitzung vom 14. Februar 1918. — Mitteilung vom 31. Januar

Über Gravitationswellen.

Von A. Einstein.

Dabei ist zur Abkürzung

$$\mathfrak{J}_{\mu\nu} = \int x_\mu x_\nu \rho \, dV_0 \qquad (23)$$

gesetzt; $\mathfrak{J}_{\mu\nu}$ sind die Komponenten des (zeitlich variabeln) Trägheitsmomentes des materiellen Systems.

$$\gamma'_{23} = -\frac{\chi}{4\pi R}\ddot{\mathfrak{J}}_{23}.$$

Between 1917 and 1919 Einstein finds a wave equation with **three** solutions.

At the suggestion of a colleague, Einstein uses a coordinate system that makes it easy to find a wave equation with three solutions. These are baptized by Hermann Weyl as Longitudinal-longitudinal, transverse-longitudinal, and transverse-transverse (c. 1920).

Hermann Weyl

By 1922 Arthur Eddington publishes "The propagation of gravitational waves". It shows that 2 of the 3 wave types found by Einstein could travel at a speed that depended on the selected coordinate system. So they were spurious waves. Eddington did prove that the other wave type propagates at the speed of light in all coordinate systems, so he did not rule out its existence.


Two of them "…are merely sinuosities in the co-ordinate system, and the only speed of propagation relevant to them is *the speed of thought*."

In 1933 Einstein emigrated to the United States.

In 1936 Einstein writes to Max Born, “Together with a young collaborator [Rosen], I arrive at the interesting result that gravitational waves do not exist, although they have been assumed a certainty to the first approximation”. Publication sent to Phys Rev

Nathan Rosen

John T. Tate

Howard P. Robertson

The article showed that there are no wave solutions.

# July 27, 1936

Dear Sir.

“We (Mr. Rosen and I) had sent you our manuscript for publication and had not authorized you to show it to specialists before it is printed. I see no reason to address the—in any case erroneous—comments of your anonymous expert. On the basis of this incident I prefer to publish the paper elsewhere.”

Respectfully

Einstein

P.S. Mr. Rosen, who has left for the Soviet Union, has authorized me to represent him in this matter.

“I could not accept for publication in The Physical Review a paper which the author was unwilling I should show to our Editorial Board before publication”  John Tate

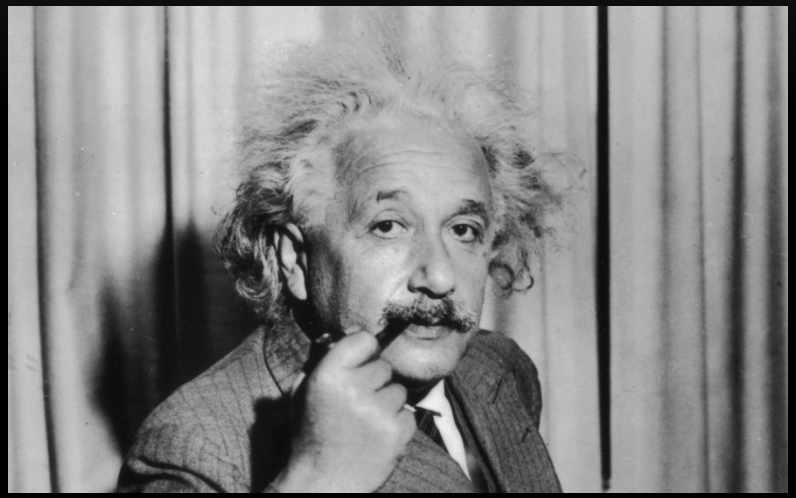
Einstein sends the article unchanged to J. Franklin Society

Robertson meets Infeld, who then convinces Einstein of his error.

Einstein and Leopold Infeld

Talk at PRINCETON

## “Nonexistence of gravitational waves”.



“If you ask me whether there are gravitational waves or not, I must answer that I don’t know. But it is a highly interesting problem”

# 1937 Text from the corrected abstract of the J. Franklin Institute

## ON GRAVITATIONAL WAVES.

BY

A. EINSTEIN and N. ROSEN.

ABSTRACT.

The rigorous solution for cylindrical gravitational waves is given. For the convenience of the reader the theory of gravitational waves and their production, already known in principle, is given in the first part of this paper. After encountering relationships which cast doubt on the existence of *rigorous* solutions for undulatory gravitational fields, we investigate rigorously the case of cylindrical gravitational waves. It turns out that rigorous solutions exist and that the problem reduces to the usual cylindrical waves in euclidean space.

### I. APPROXIMATE SOLUTION OF THE PROBLEM OF PLANE WAVES AND THE PRODUCTION OF GRAVITATIONAL WAVES.

It is well known that the approximate method of integration of the gravitational equations of the general relativity theory leads to the existence of gravitational waves. The method used is as follows: We start with the equations

$$R_{\mu\nu} - \tfrac{1}{2} g_{\mu\nu} R = -T_{\mu\nu}. \qquad (1)$$

We consider that the $g_{\mu\nu}$ are replaced by the expressions

$$g_{\mu\nu} = \delta_{\mu\nu} + \gamma_{\mu\nu}, \qquad (2)$$

At the end of the paper:

"Note—The second part of this article was considerably altered by me after the departure to Russia of Mr. Rosen as we had misinterpreted the results of our formula. I want to thank my colleague Professor Robertson for their friendly help in clarifying the original error. I also thank Mr. Hoffmann your kind assistance in translation."

# SECOND WORLD WAR

## 1939-1945

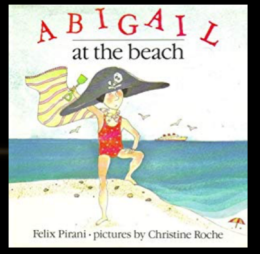
1945 the cold war starts, the scientific cooperation is blocked.

1950 Infeld travels to Poland (his parents' country) to help recover Polish physics. He is stripped of his Canadian citizenship.

1956 Felix A. E. Pirani (British) shows what the effects of the waves are on the matter: relative acceleration of particle pairs can be associated with the Riemann tensor. Publish these results in the *Acta Physica Polonica*.

Felix Pirani

1957, in February, published the *Invariant Formulation of Gravitational Radiation Theory*, in Phys. Rev.

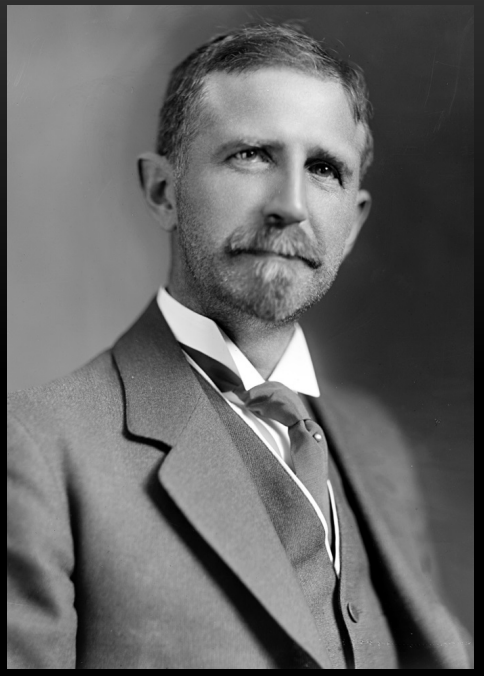



He is harassed by the British government. His children's book was censored.

1949 Roger Babson found the GRAVITY RESEARCH FOUNDATION

His sister dies drowned in a river.

He made a lot of money thanks to "Newton's laws".



Roger W Babson

Essay contest that dealt with "the chances of discovering a partial insulation, reflector, or absorber of gravity".
An annual award of $1000.

Bryce DeWitt

1953 wins a contest (critizing the theme of the contest)

1954 First director of the INSTITUTE OF FIELD PHYSICS

Agnew Bahnson also founded the new Institute with help of John Wheeler


# 1957 Meeting at CHAPEL HILL (GR1 meeting)

Topics:
Classic Gravitational Fields
Unification of gravitation - quantum mechanics
Cosmology
Radio astronomical measurements
Dynamics of the Universe
Gravitational waves

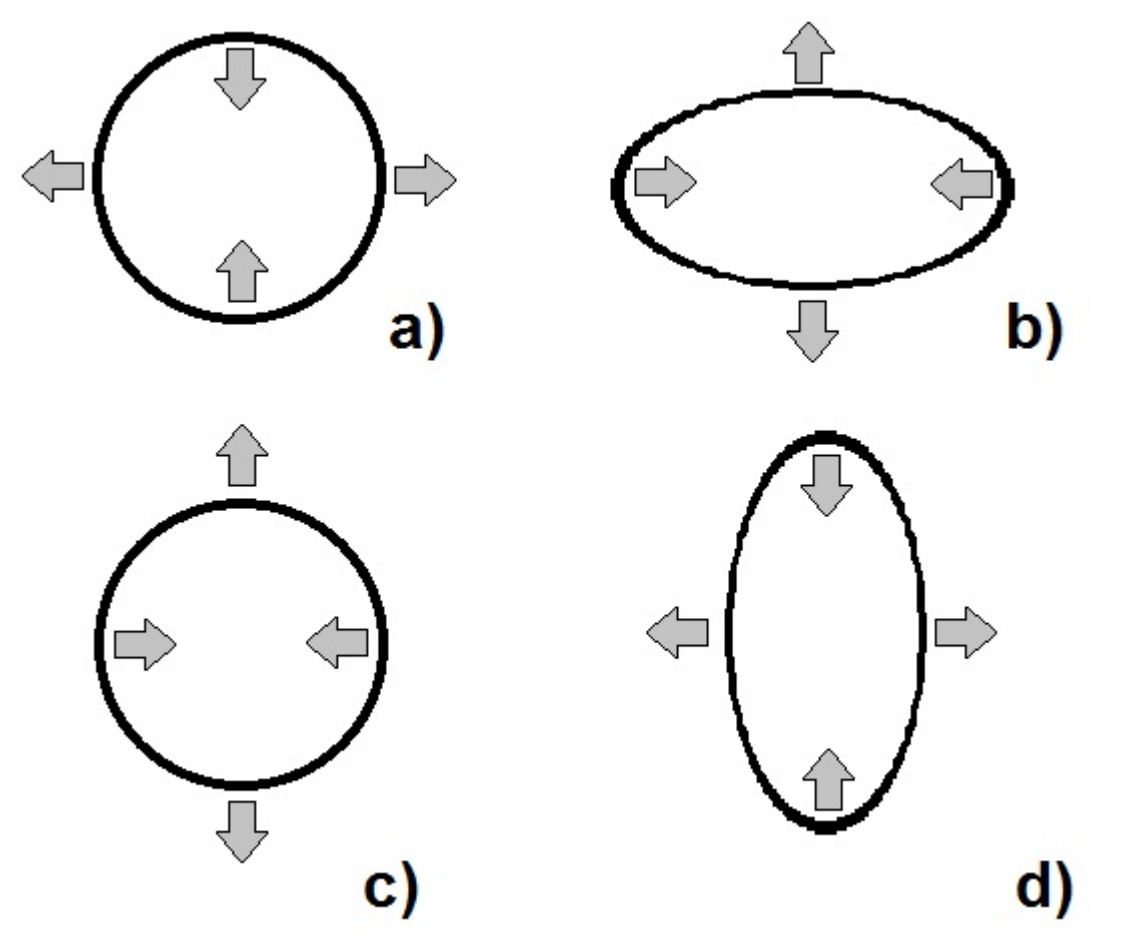
Hermann Bondi chaired the session of gravitational waves:

"...still do not know if a transmitter transmits energy radiation ..."

Among attendees:

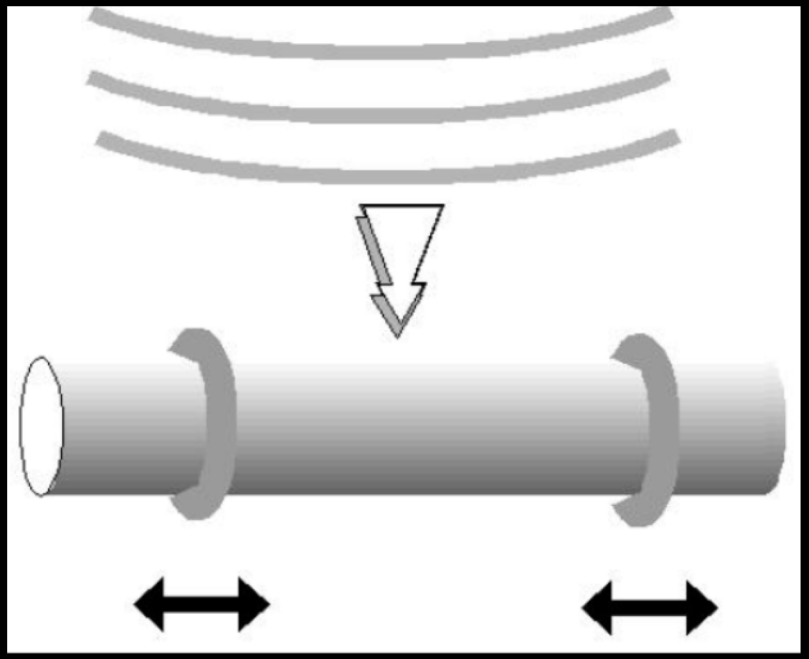
Feymann, Bondi, and Weber

After Pirani's 1956 paper:



"…still do not know if a transmitter transmits energy radiation ..."

" Sticky bead" argument  given by Feynman



It was convincing, the waves should transmit energy and therefore should be detectable.

# The search for the waves begins

Joseph Weber's antenna

aluminum cylinder 66 cm in diameter 153 cm in length, weighing 3 tons.

Two detectors: Maryland and Argonne

Help of sudents, Robert L. Forward

- Construction begins in 1958
- Weber, J *Detection and Generation of Gravitational Waves*. Phys. Rev. 1960,117, 306.
- Weber, J. *Observation of the Thermal Fluctuations of a Gravitational-Wave Detector*. Phys. Rev. Lett. 1966, 17,1228-1230.
- Weber, J. *Evidence for Discovery of Gravitational Radiation*. Phys. Rev. Lett. 1969, 22, 1320–1324.
- Weber, J. *Anisotropy and Polarization in the Gravitational-Radiation Experiments*. Phys. Rev. Lett. 1970, 25,180-184.
- but
- Sciama, D .; Field, G .; Rees, M. *Upper Limit to Radiation of Mass Energy Derived from Expansion of Galaxy*. Phys. Rev. Lett. 1969, 23, 1514–1515.
- Kafka, P. *Are Weber's Pulses Illegal?*Gravity Research Foundation: Babson Park, MA, USA, 1972.
- C. Misner vs R. Ruffini (Marcel Grossmann meetings) on Sinchroton radiation (1972).

# Other cylindrical antennas

In the mid 1970s other similar antennas were built. By the mid-seventies, several detectors were already operative and offered many improvements over Weber's original design; some cylinders were could down to very low temperatures to reduce noise:

Bell Labs Rochester-Holmdel, U. Glasgow, Italo-German joint project in Munich and Frascati, Moscow, Tokyo, and IBM labs in Yorktown Heights.

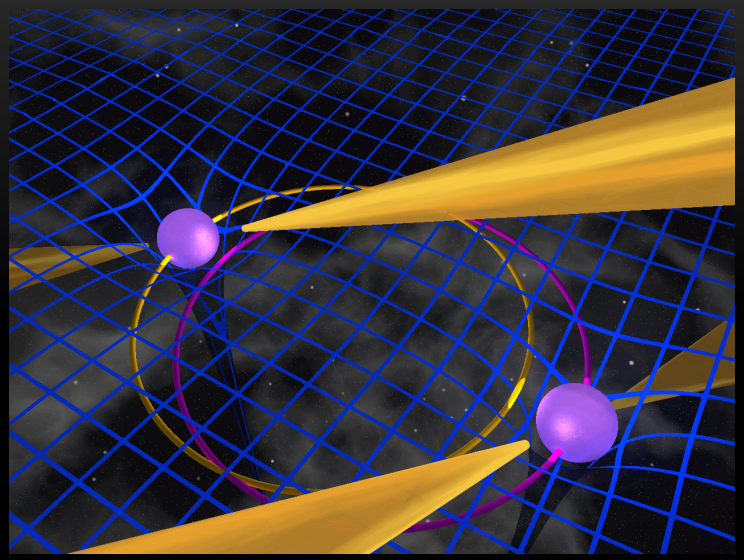
But all of them dismissed Weber's measurements

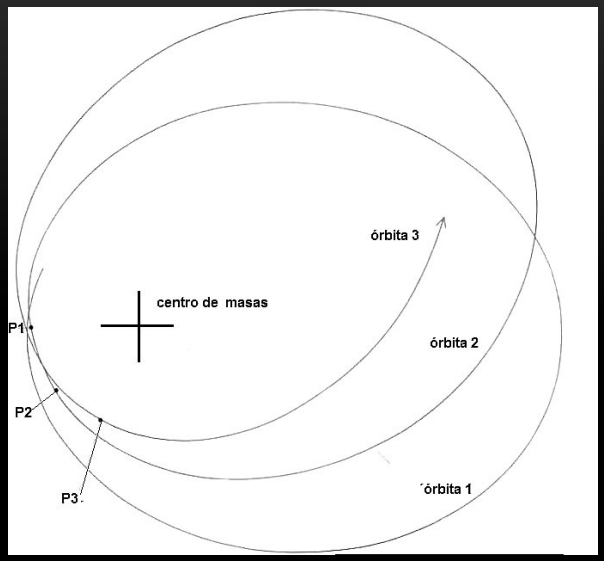
# EVIDENCE OF THE EXISTENCE OF THE WAVES

**1974-1979**

1967 Jocelyn Bell y Antony Hewish discovered the PULSAR (Nobel Prize 1974)

# 1974 Joseph Taylor y Russel Hulse discovered the binary pulsar (Nobel Prize 1993)

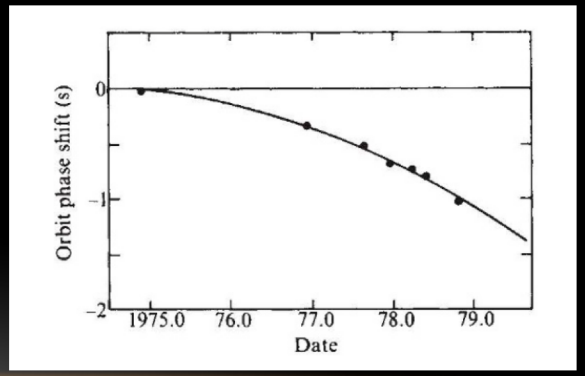





GW exist

Taylor, J.H.; Fowler, L.A.; McCulloch, P.M. *Overall measurements of relativistic effects in the binary* pulsar *PSR 1913 + 16.*

Nature **1979**, 277, 437–440.




"…quantitative confirmation of the existence of gravitational radiation at the level predicted by general relativity"

# INTERFEROMETERS FROM 1960´S TO TODAY

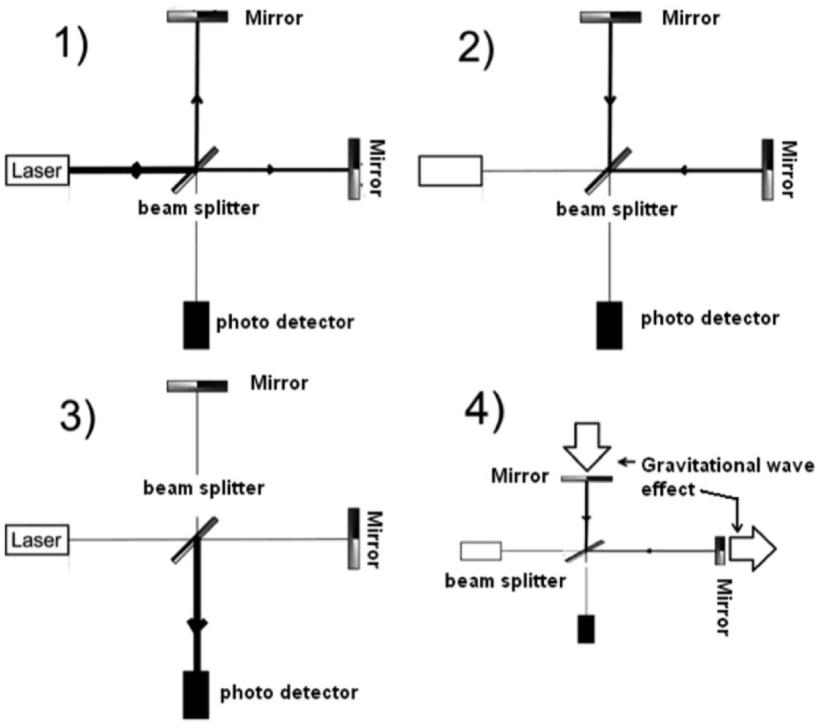



**Figure 8.** Schematic of an interferometer for detecting gravitational waves.

The first explicit suggestion of a laser interferometer detector was outlined in:

- Joe Weber wrote about using this technique in his laboratory notes.

- Gertsenshtein, M.E.; Pustovoit, V.I.
  *On the detection of low frequency gravitational waves*.
  Sov. J. Exp. Theor. Phys. **1962**, 16, 433-435.

- Braginski Vladimir, B.
  *Gravitational radiation and the prospect of its experimental discovery*.
  Sov. Phys. Usp. **1966**, 8, 513–521

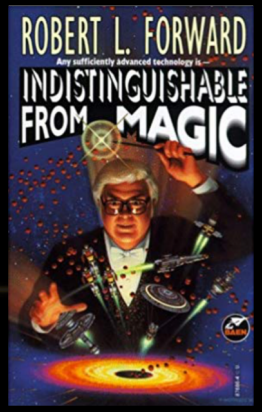
Moss, G.E.; Miller, R.L.; Forward, R.L. *Photon-noise-Limited Laser Transducer for Gravitational Antenna*. Appl. Opt. **1971**, 10, 2495–2498.

Forward, R. L.*Wide band Laser-Interferometer Gravitational-radiation experiment*. Phys. Rev. D **1978**, 17,379–390.

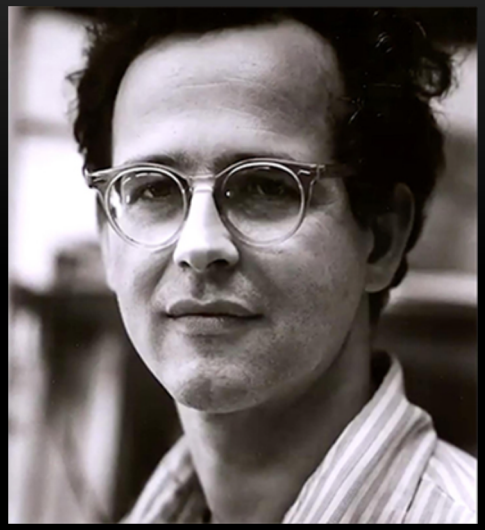
Forward, a Weber's former student, was the first scientist to build an interferometric GW detector of 8.5 meters arms (encouraged by Rainer Weiss) .

"The idea of detecting gravitational radiation by using a laser to measure the differential motion of two isolated masses has often been suggested in past[5]"
The footnote 5 reads, "To our knowledge, the first suggestion [of the interferometer device] was made by J. Weber in a telephone conversation with one of us (RLF) [Forward] on 14 September 1964"

The novels of the Cheela saga
"They are a physics textbook of neutron stars, disguised as a novel."



Rainer Weiss 1967

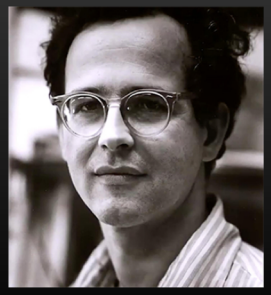


1967
He teaches a relativity seminar at MIT
Students ask about Weber antennas

1968
1.5-m long interferometer prototype, with military funds

1968
Mansfield Amendment

The idea also conceived by Philip Chapman (that became an astronaut)



**1974** Weiss (MIT) aks for funds to NSF

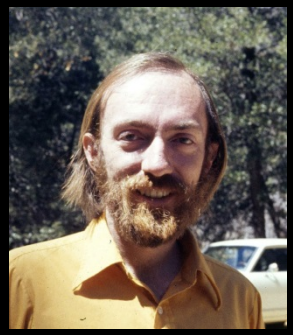
9-m arms

NSF referee is Kafka (Max Planck Inst. by Munich)

Peter Kafka

**1975** NSF provide funds, a small amount. Weiss makes a proposal of Interferometric Broad Band Gravitational Antenna

1975 Weiss meets Kip Thorne in Washington DC

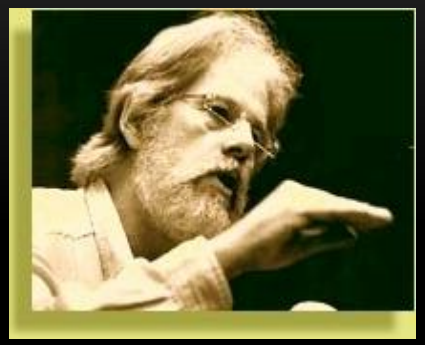


Kip Thorne

Weiss: "*We made a huge map on a piece of paper of all the different areas in gravity. Where was there a future? Or what was the future, or the thing to do?*"

Thorne decided that night to build in Caltech a GW interferometer. Braginski?

1975, Kafka delivered a talk in Erice, and ended it saying: "It seems obvious that only a combination of extremely high quality and extremely low temperature will bring resonance detectors [Weber bars] near the range where astronomical work is possible. Another way which seems worth exploring is *Laser interferometry with long free mass antennas*"
Ronald Drever (Glasgow) was in the audience. A few years later he built a 10-m arm interferometer, but then in 1979 he goes to Caltech.



Kafka

Garching group contacts Weiss

Weiss sends David Shoemaker

They build a 3 meter prototype (Heinz Billing et al)

Later, in 1983: 30 meter interferometer (MPQ)

In Weiss's words, "the Max Planck group actually did most of the very early interesting development. They came up with a lot of what I would call the practical ideas to make this thing [gravitational interferometers] better and better"

2005
LIGO
+
GEO

DREVER AT CALTECH
1979

1983: 40 m interferometer

No funds

1990


Jim Hough

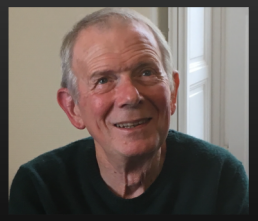
1986 plans for a Long Baseline Gravitational Wave Observatory

GEO
600
1995 construction began

1985

"Plans for a large Gravitational wave antenna in Germany" at the Marcel Grossmann Meeting in Rome. This document contains the first detailed proposal for a full-sized interferometer (3 km).

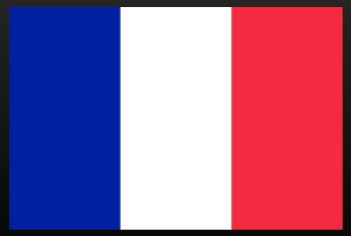
# VIRGO



**1980**
Allain Brillet postdoc in Colorado (Bender) and visits MIT

**1982**
Returns to Orsay

**1985**
M. Grossman Conference



1993 1994

VIRGO project

Adalberto Giazotto (Pisa)

development of suspension systems

The VIRGO Project

1994 Expropriate 50 lots in Casina near Pisa.

1996 Construction begins on an alluvial plain

1996-1999 Administrative problems due to having two directions: French and Italian.

2000 The EGO consortium is created to coordinate efforts

2003 VIRGO is completed

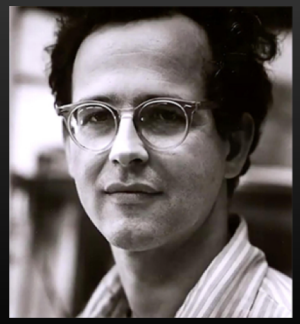
2007 Joint agreement VIRGO-LIGO

&

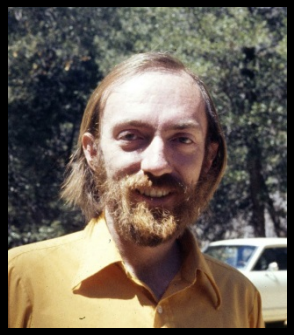
G 600 starts constuction in 1995

VIRGO starts constuction in 1996

The LIGO project



Weiss (MIT)



Thorne (Caltech)

Drever (Glasgow)

NSF

Initial LIGO

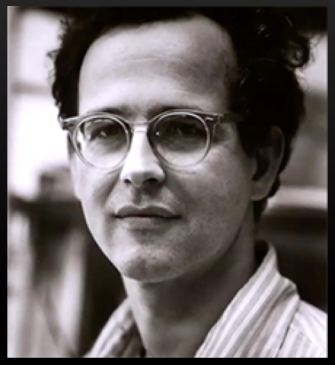
## BLUE BOOK

1983 By Peter Saulson and Paul Linsay

A study of a long Baseline Gravitational Wave

1983 a 40-m interferometer is built in Caltech

# What is better?



Weiss

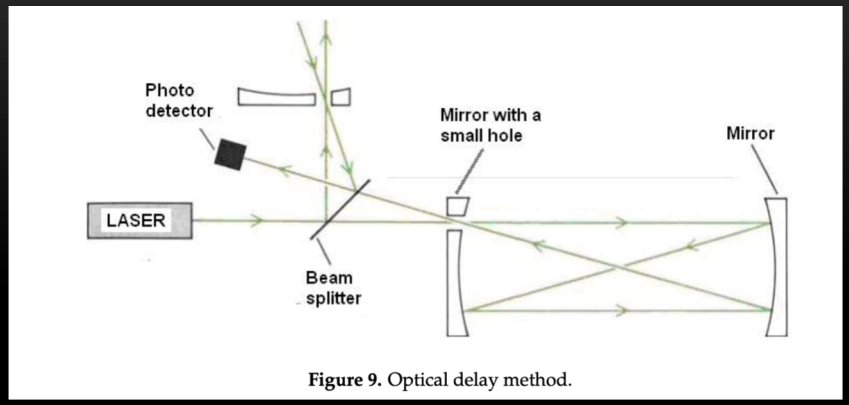



**Figure 9.** Optical delay method.

Drever

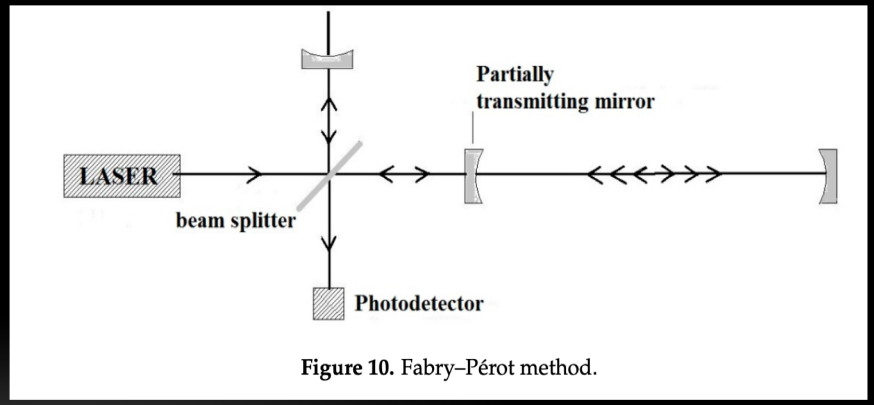



**Figure 10.** Fabry–Pérot method.

1986 Dissolution of the Triumvirate (Thorne, Drever, Weiss)

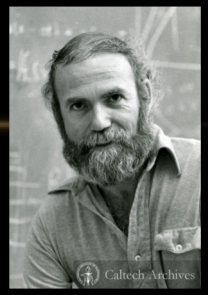
Rochus E. Vogt is named as project manager.

1988 LIGO got funds from the NSF.

1992 The LIGO project is resctructured. Drever leaves the project.

Thorne, Drever, Vogt 1990

1994 Barry Barish becomes the new director




1994, 1995 it began constructions in Hanford and Livingston

The initial LIGO operated between 2002 and 2010 and did not detect gravitational waves.

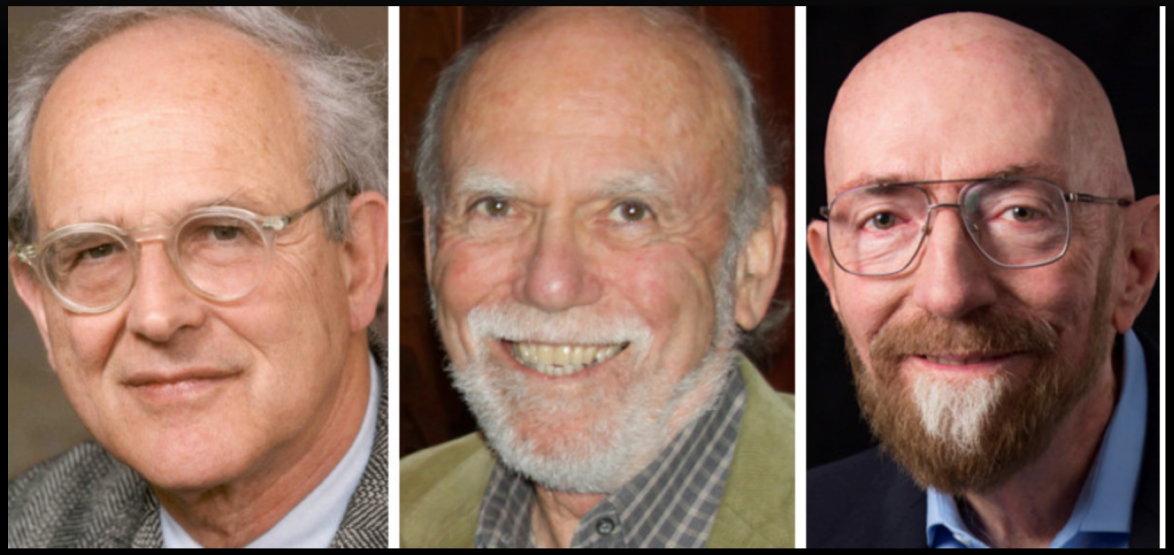

2010 Beginning of aLIGO.

2015 Start engineering tests.

2015 September 14th, 11:50:45 am CET,
Gravitational wave detection!

Physics Nobel Prize 2017

"*for decisive contributions to the LIGO detector and the observation of gravitational waves*"



Rainer Weiss (1/2) Barry C. Barish (1/4) Kip S. Thorne (1/4)

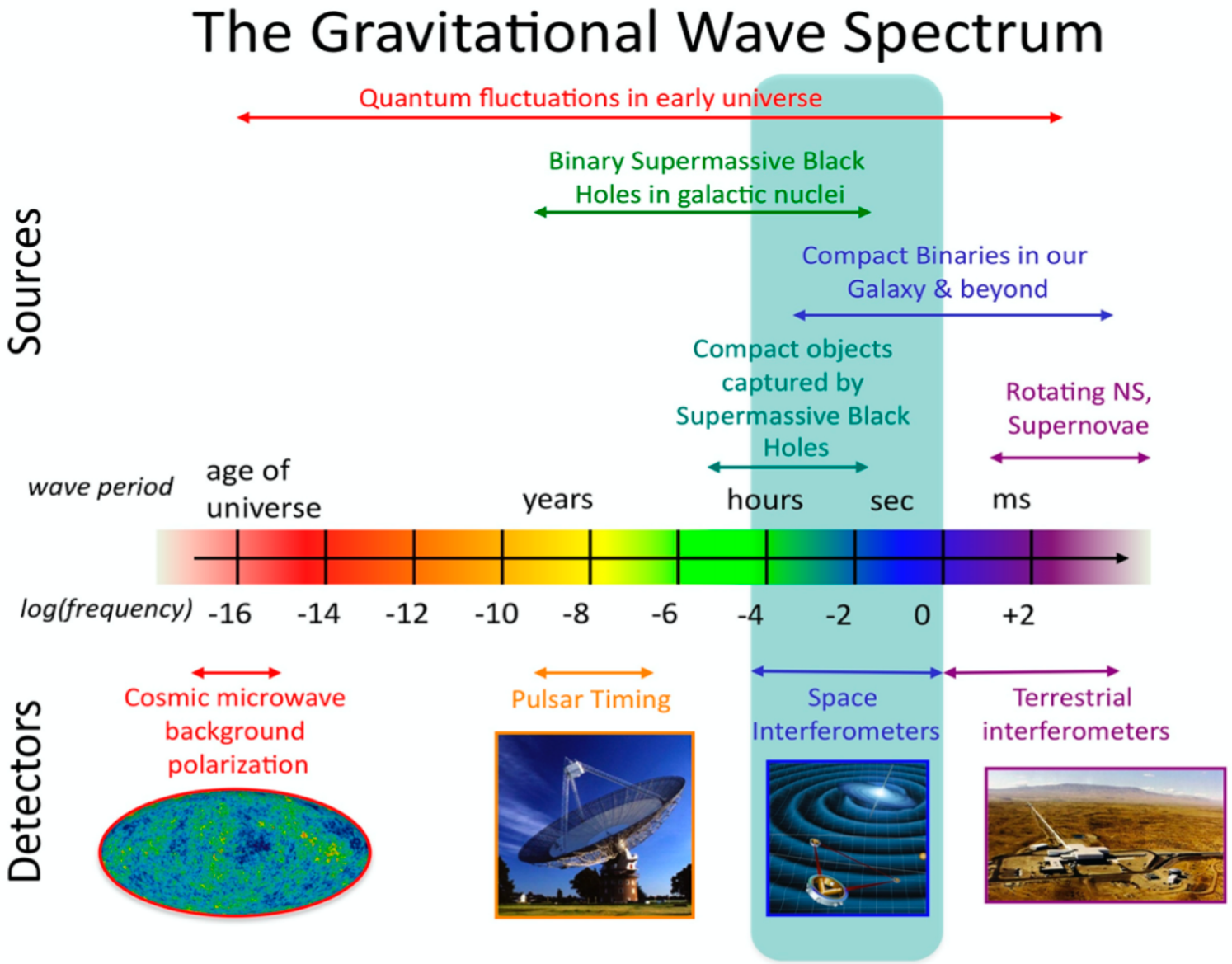



**Figure 7.** Gravitational wave spectrum showing wavelength and frequency along with some anticipated sources and the kind of detectors one might use. Figure credit: NASA Goddard Space Flight Center.

## Many aspects astrophysics/cosmology can be explored:

- Black hole astrophysics and galaxy formation.
- The merging of very massive black holes.
- The absorption of compact objects such as neutron stars by black holes.
- Study of GW propagation in different gravity theories, knowing the EW counterpart.
- Other sources including very old and still unknown remnants of the Big Bang.
- The frequency band of LISA observation corresponds to energies of the order of TeV in the very early universe, where new physics can be explored as extra dimensions, phase transitions, bubble formation that would efficiently produce gravitational waves.
- And many more…in gravitational astronomy!

The future is now!