Looking forward, looking back

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We're about to succeed!

We're about to discover gravitational waves.

It has been a long road.

In order to appreciate how exciting it is for all of us to be here at this moment together, let's look back on (part of) the path that brought us here.

Everything started in 1916

In 1916, Einstein saw that gravitational waves were a key prediction of General Relativity.

Rai Weiss discussed this last March.

Einstein’s prediction of grav waves didn’t settle the matter…

… even for Einstein. He doubted their physical reality until the end of his life.

Einstein proposed many experiments, including really hard ones, but never the search for gravitational waves.

The resolution of this question came in 1957.

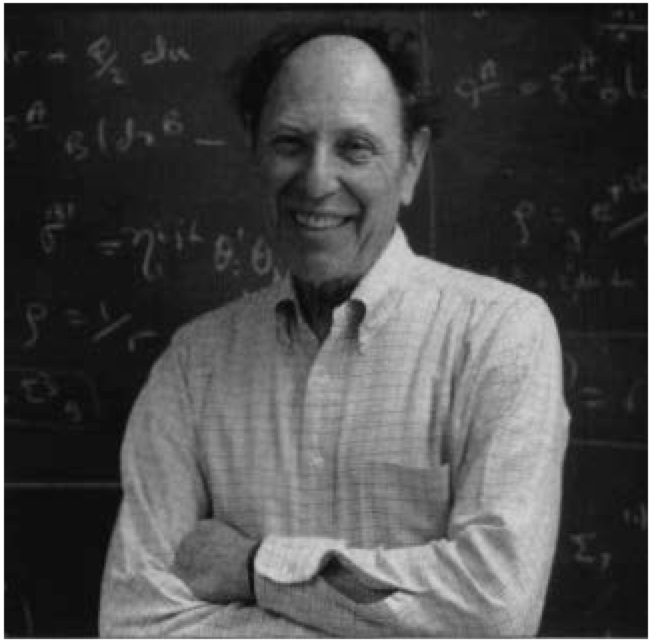
The Chapel Hill Conference

In January 1957, the U.S. Air Force (under program manager Josh Goldberg) sponsored the *Conference on the Role of Gravitation in Physics*, a.k.a. the Chapel Hill Conference, a.k.a. GR1. The organizers were Bryce and Cecile DeWitt. 44 of the world's leading relativists attended.

Much of the future of gravitational physics was launched then. (Numerical relativity was prefigured in a remark by Charles Misner.)

The "gravitational wave problem" was solved there, and the quest to detect gravitational waves was born.

Josh Goldberg



Josh earned his Ph.D. from Syracuse in 1952, with Peter Bergmann.

Among many other topics, he made important contributions to the question of whether a binary star emitted gravitational waves.

The "gravitational wave problem"

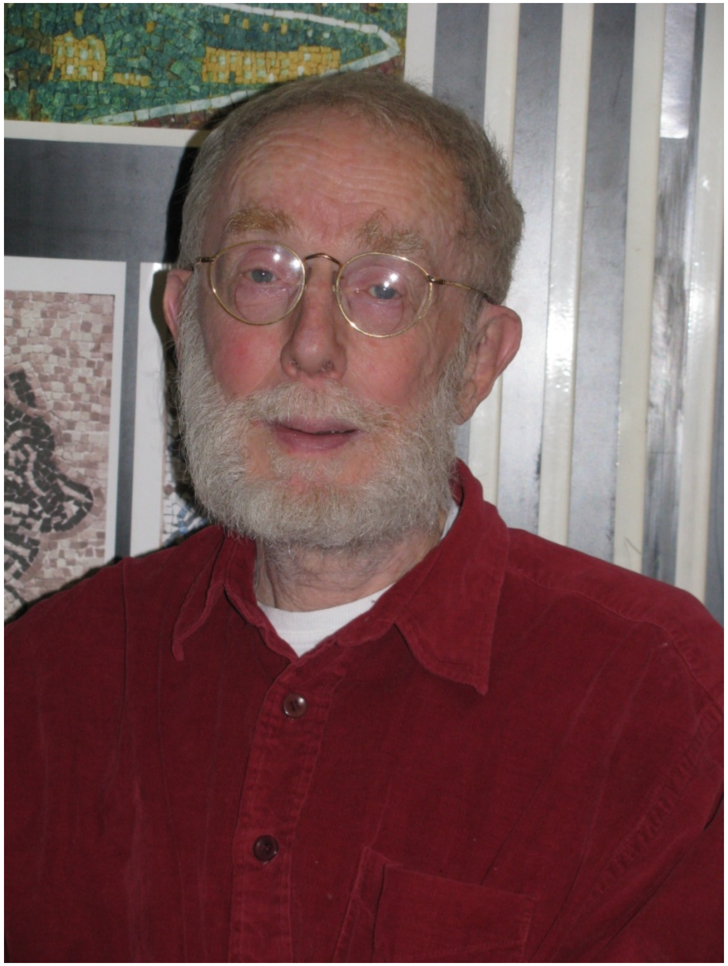
Were gravitational waves real, or were they "pure gauge"?

Before Chapel Hill, debate raged. Einstein wavered. Eddington suggested that gravitational waves "traveled at the speed of thought."

One main approach was to solve the equations of motion of a binary star, and show that they generated waves that couldn't be transformed away.

Josh worked on this. It was hard. People were still hard at work on it when Hulse and Taylor found the binary pulsar in 1974 …

Felix Pirani solved the problem of the reality of gravitational waves



Felix Pirani was a student of Alfred Schild's and then of Hermann Bondi's. In 1957 he was a junior colleague of Bondi at King's College, London.

At Chapel Hill, he gave the solution of the gravity wave problem, although Bondi (or Feynman) usually get the credit.

Photo by Josh Goldberg

Pirani’s mentors
Alfred Schild and Hermann Bondi

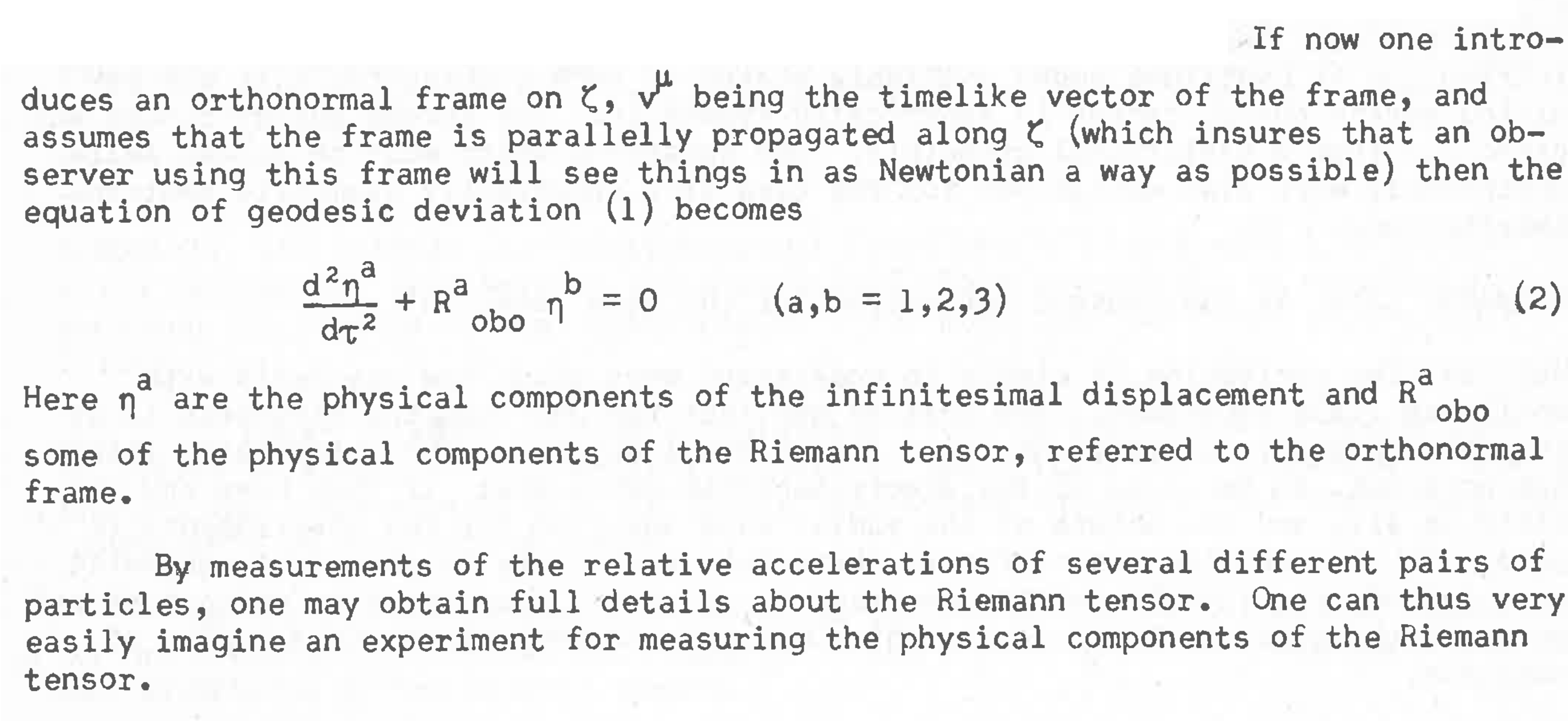
Pirani's 1957 papers

Pirani's breakthrough was to analyze the reception of gravitational waves, not their generation.

He showed that, in the presence of a gravitational wave, a set of freely-falling particles would experience genuine motions with respect to one another. Thus, gravitational waves must be real.

He made this case in two papers submitted before the Chapel Hill conference, and presented there.

Pirani’s talk



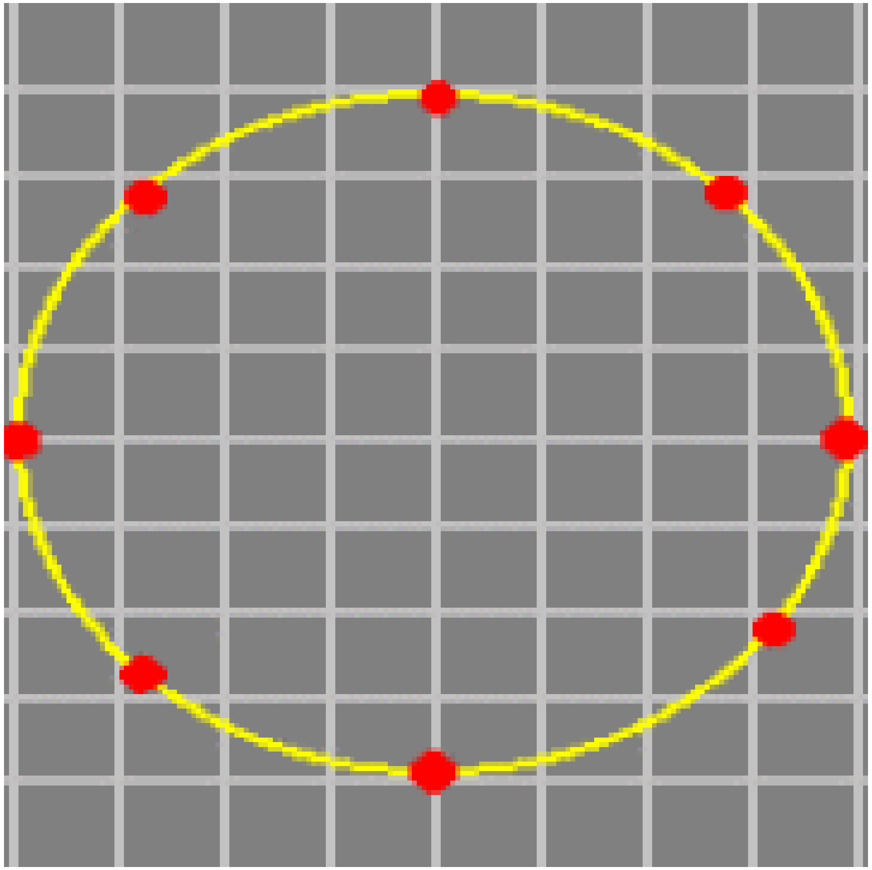
If now one introduces an orthonormal frame on ζ, v^μ being the timelike vector of the frame, and assumes that the frame is parallelly propagated along ζ (which insures that an observer using this frame will see things in as Newtonian a way as possible) then the equation of geodesic deviation (1) becomes

$$\frac{d^2\eta^a}{d\tau^2} + R^a{}_{obo}\,\eta^b = 0 \qquad (a,b = 1,2,3) \tag{2}$$

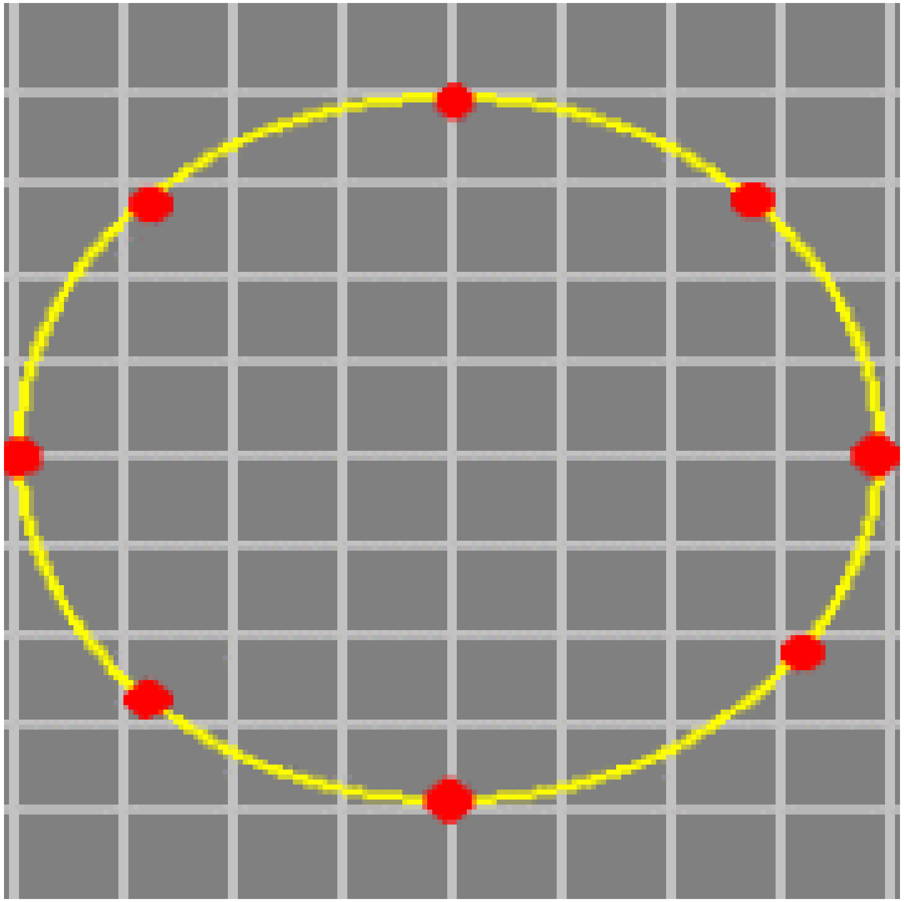
Here η^a are the physical components of the infinitesimal displacement and $R^a{}_{obo}$ some of the physical components of the Riemann tensor, referred to the orthonormal frame.

By measurements of the relative accelerations of several different pairs of particles, one may obtain full details about the Riemann tensor. One can thus very easily imagine an experiment for measuring the physical components of the Riemann tensor.

Pirani’s set of neighboring freely-falling test masses



They respond in a measurable way to a gravitational wave



Bondi clarifies Pirani's point

Pirani's mentor Bondi arrived at Chapel Hill unsure about gravitational waves.

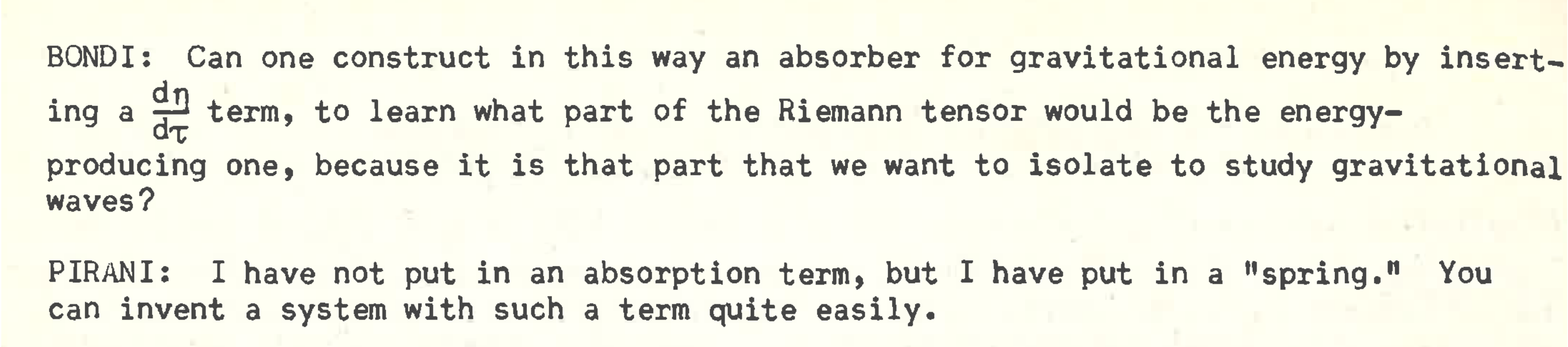
Listening to Pirani's talk, he asked whether you could connect two nearby masses with a dashpot, thus absorbing energy from the wave.

Energy absorption is the ultimate test of physical reality.

Pirani replied: "I have not put in an absorption term, but I have put in a 'spring'. You could invent a system with such a term quite easily."

Bondi is credited with the "sticky bead argument."

Proof by dialog that gravitational waves are real



BONDI: Can one construct in this way an absorber for gravitational energy by inserting a $\frac{d\eta}{d\tau}$ term, to learn what part of the Riemann tensor would be the energy-producing one, because it is that part that we want to isolate to study gravitational waves?

PIRANI: I have not put in an absorption term, but I have put in a "spring." You can invent a system with such a term quite easily.

Pirani got there first

The proceedings of the Chapel Hill meeting make it very clear that Felix Pirani’s insight was the key to the problem, and was considered to be one of the most important outcomes of the meeting.

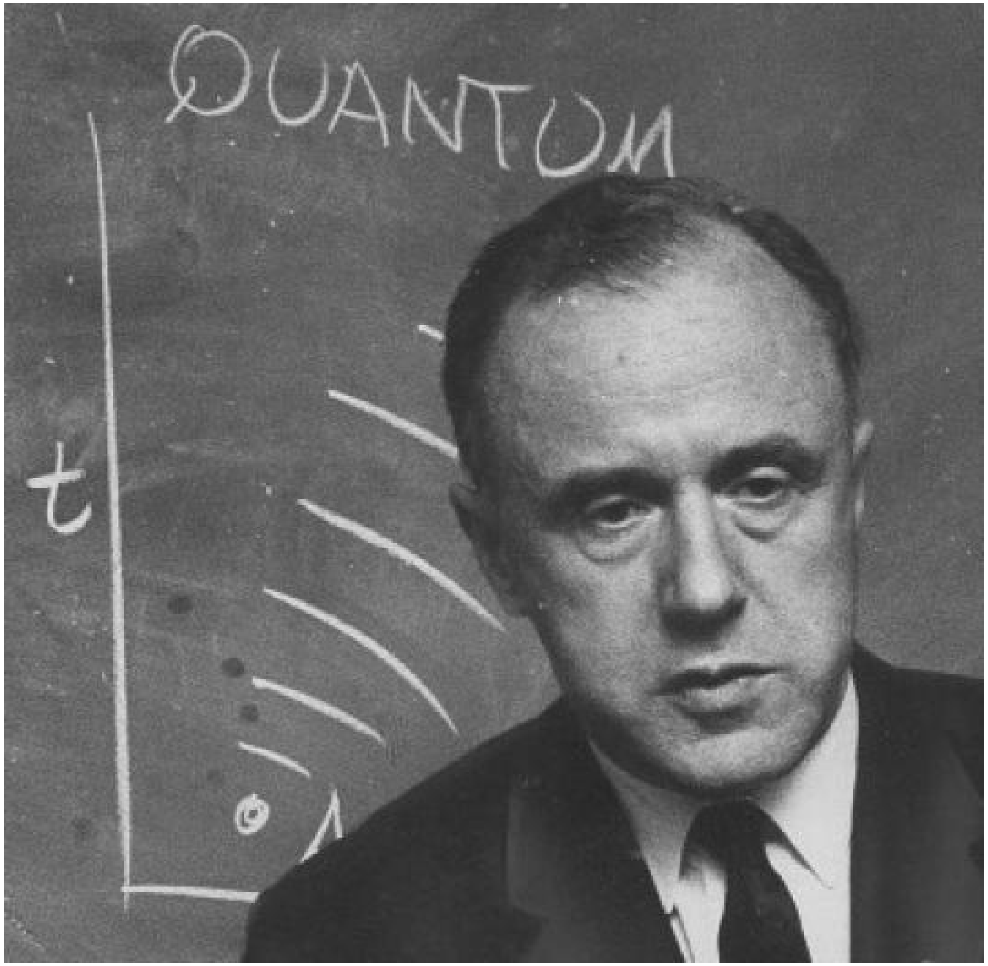
Feynman’s talk on the same subject came later in the meeting.

Joe Weber at Chapel Hill

Joe Weber, co-inventor of the maser, was working with John Wheeler at Princeton on gravitational waves.

The two of them were at Chapel Hill, and listened well to Pirani's talk.

Weber's mentor John Wheeler

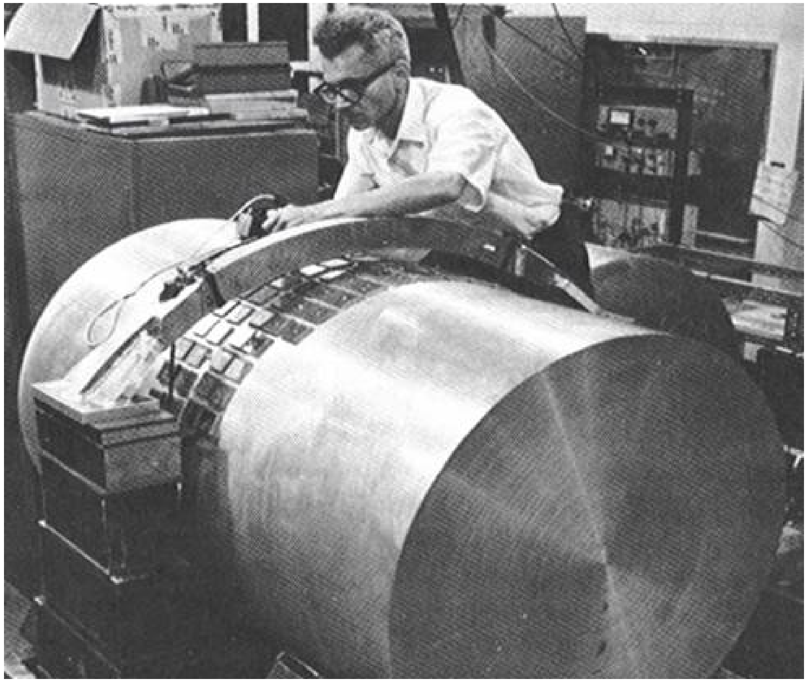


Joe Weber starts GW detection

Weber and Wheeler recapped Pirani's argument in a paper written within weeks of the Chapel Hill conference.

He expanded on the experimental ideas in two Gravity Research Foundation essays (3rd prize 1958, 1st prize 1959), leading to his 1960 Phys. Rev. paper laying out the bar program.

Weber's bar



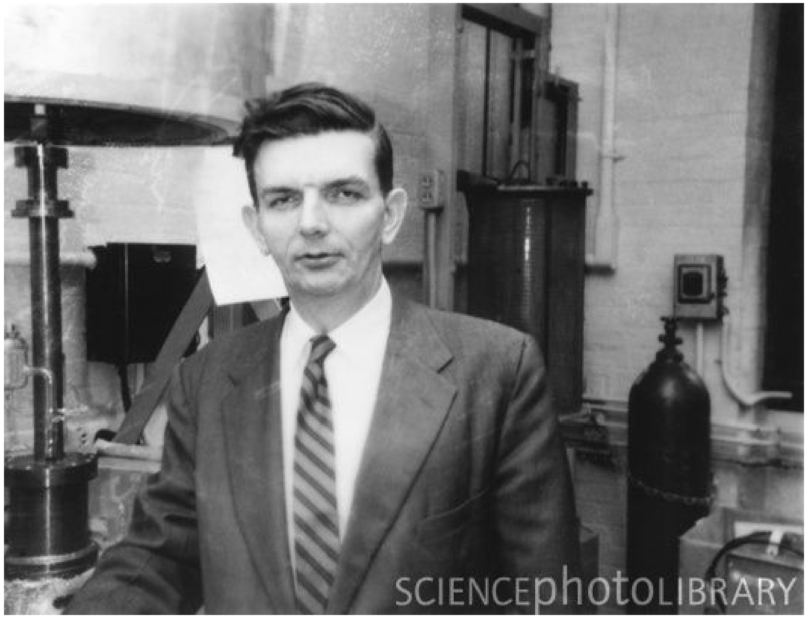
Weber's gravitational wave detector was a cylinder of aluminum. Each end is like a test mass, while the center is like a spring. PZT's around the midline are Bondi's dashpots, absorbing energy to send to an electrical amplifier.

Rainer Weiss, not at Chapel Hill

In 1957, Rai Weiss was a grad student of Jerrold Zacharias at MIT, working on atomic beams.

In the early ‘60’s, he spent two years working with Bob Dicke at Princeton on gravity experiments.

Rai Weiss's mentors, Jerrold Zacharias and BobDicke



Rainer Weiss and Joe Weber

In 1964, Rai was back at MIT as a professor. He was assigned to teach general relativity. He didn’t know it, so he had to learn it one day ahead of the students.

He asked, What’s really measurable in general relativity? He found the answer in Pirani’s papers presented at Chapel Hill in 1957.

What Pirani actually proposed

In Pirani’s papers, he didn’t “put in” either a spring or a dashpot between the test masses. Instead, he said:

“It is assumed that an observer, by the use of light signals or otherwise, determine the coordinates of a neighboring particle in his local Cartesian coordinate system.”

Zach’s lab at MIT was in the thick of the new field of lasers. Rai read Pirani, and knew that lasers could do the job.

Weber started seeing things

In 1969, Weber made his first of many announcements that he was seeing coincident excitations of two detectors.

That set the world on fire. If true, the signals would have been shockingly large.

Many other groups started building resonant bars, including: Glasgow, Rome, Frascati, Munich, Bell Labs, and IBM.

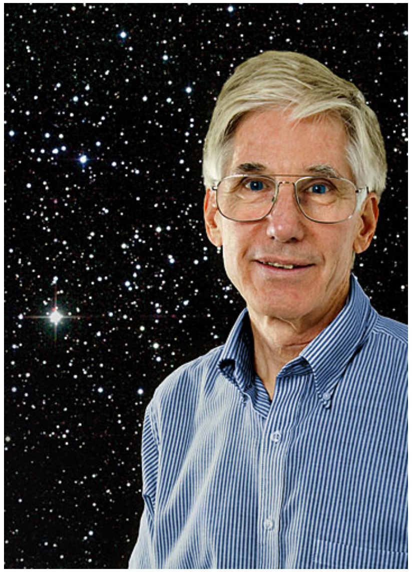
Joining the quest …

Ron Drever and Jim Hough, Glasgow

Edoardo Amaldi, Rome

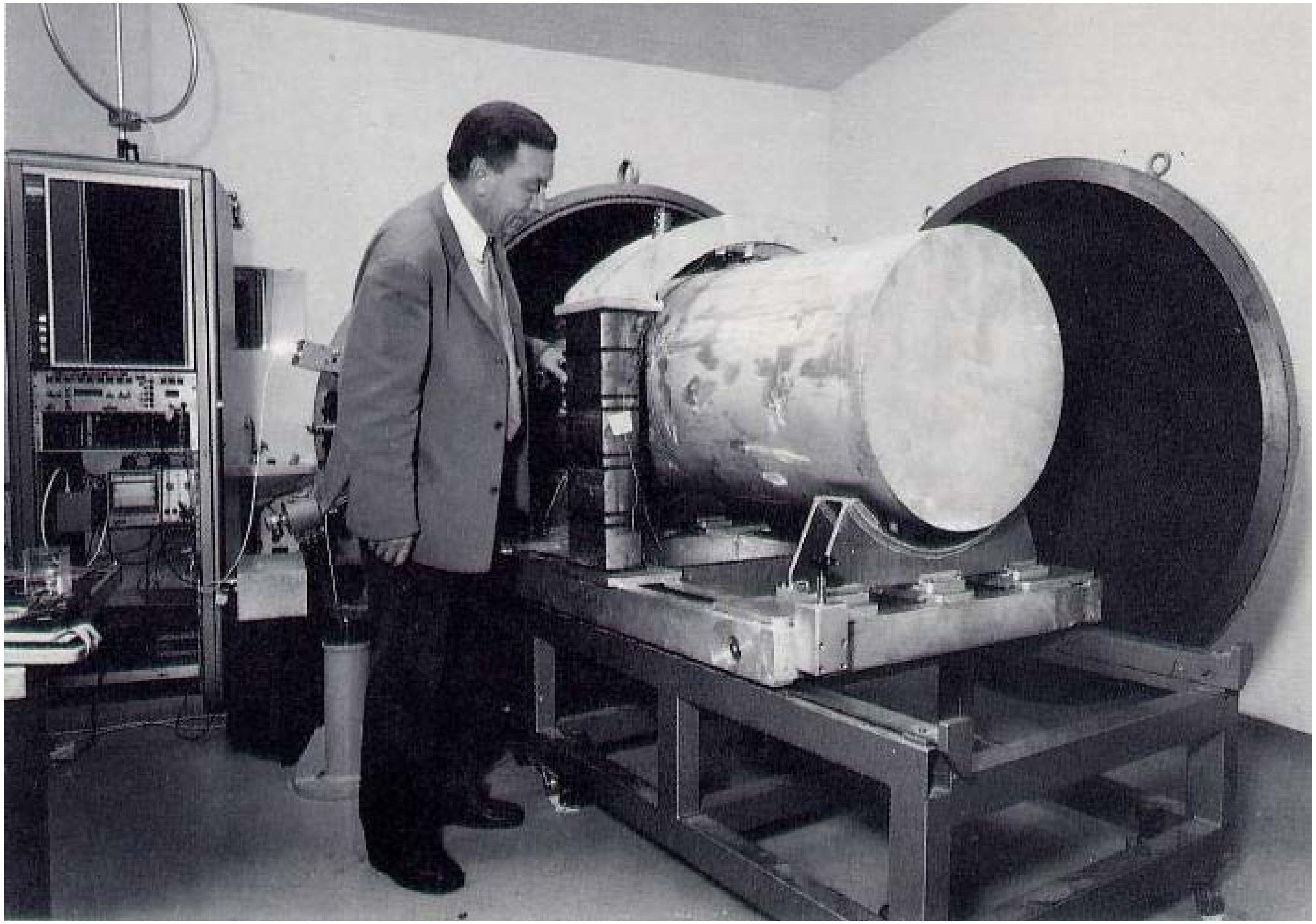
Scanned at the American Institute of Physics

Richard Garwin, IBM



Tony Tyson, Bell Labs

Billing and the bar at Munich



Rai Weiss envisions LIGO in 1972

(V. GRAVITATION RESEARCH)

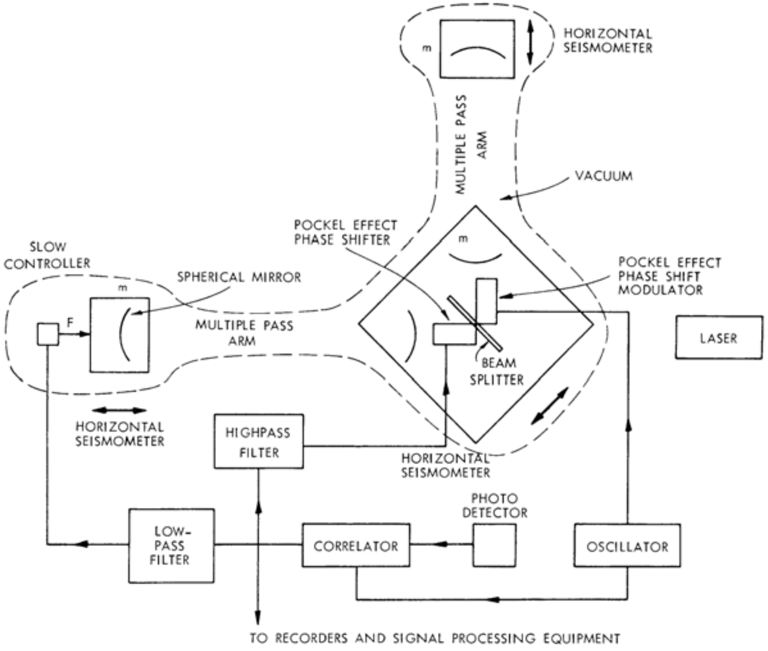


Fig. V-20. Proposed antenna.

Weiss knew of Weber's claimed detections. True or not, he saw how to do many orders of magnitude better, by implementing Pirani's free-test-masses-measured-by-lasers as a Michelson interferometer. Arms could be kilometers long. Lasers could measure sub-nuclear distances. $\Delta L/L \sim 10^{-21}$.

Weiss wasn't the first with this insight

Already in 1962, Gertsenshtein and Pustovoit, proposed that interferometers were a way to achieve much better sensitivity than Weber had.

Weiss wasn't the only one with this insight (2)

Weber's former student, Robert Forward, had thought about interferometers with Weber. At Hughes Research Lab, he started building a small interferometer and published the first gravity wave observations with it in 1978.

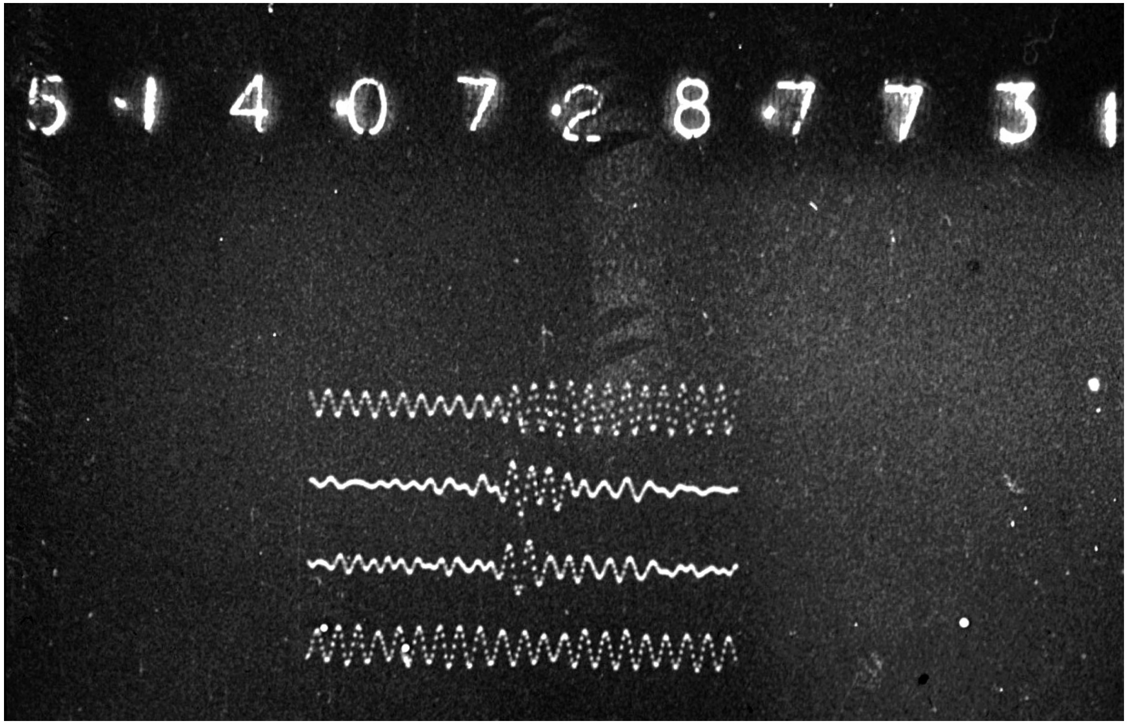
Sadly/inevitably, it became clear that Weber's signals weren't real

Lots of people tried, but no one else could see them.

By the time of GR7 at Tel Aviv in 1974, Weber's claims were dead. (Except to him.)

One possible exception: A coincidence seen between the two bars at Glasgow on 5 Sept 1972. A fluke? Incredible luck?

Ask Jim Hough about the strange coincidence on 5 September 1972



Bars could do much better! Many started working on that

Bill Fairbank (along with Amaldi's group in Rome) went to work on cryogenic Weber bars, and on the data analysis protocols necessary to ensure no repeat of the Weber fiasco.

Starting down the new road to interferometers

It wasn't just Weiss and Forward who started working on interferometers.

The Munich group decided that this was a better way forward.

Soon, so did Ron Drever and Jim Hough.

Building a strong team in Garching

Albrecht Ruediger joined Billing's group, along with Karl Maischberger, Roland Schilling, Lise Schnupp, and Walter Winkler.

Building a strong team in Glasgow

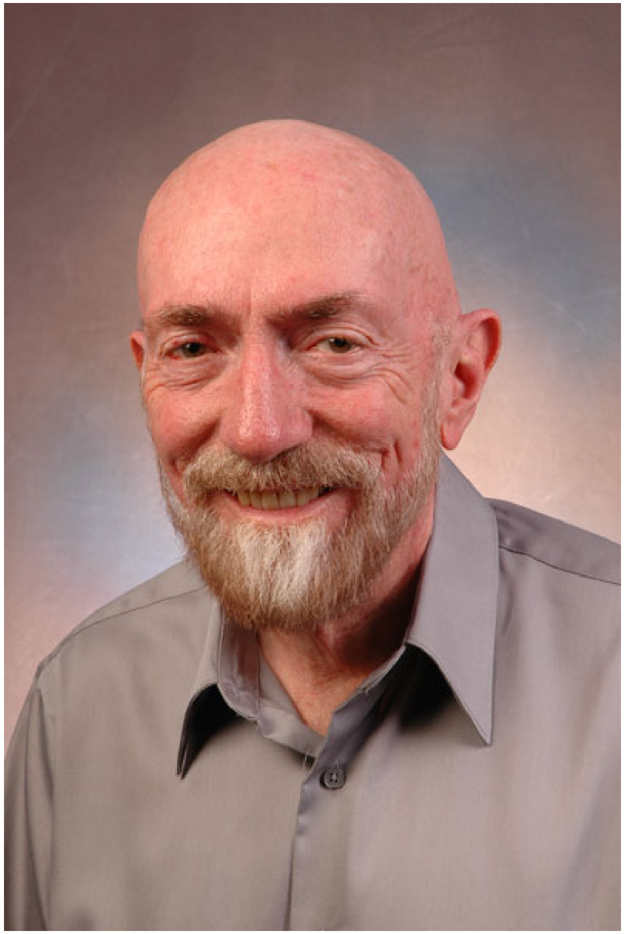
Drever and Hough attracted Norna Robertson, along with Harry Ward, Gavin Newton, and others.

They built a 10-meter interferometer.

Caltech bets on gravitational waves

Kip Thorne persuaded Caltech to build an experimental group.

Ron Drever was hired; at first Ron split his time between Glasgow and Caltech. Eventually, he stayed at Caltech full-time, and Jim Hough led the Glasgow group.



Clever ideas could make interferometers work better

Ron Drever brought Fabry-Perots, power and signal recycling, into our toolkit.

Famous sayings of Ron Drever:

“It is more economical!”

“How can it not work?”

How to lock a Fabry-Perot

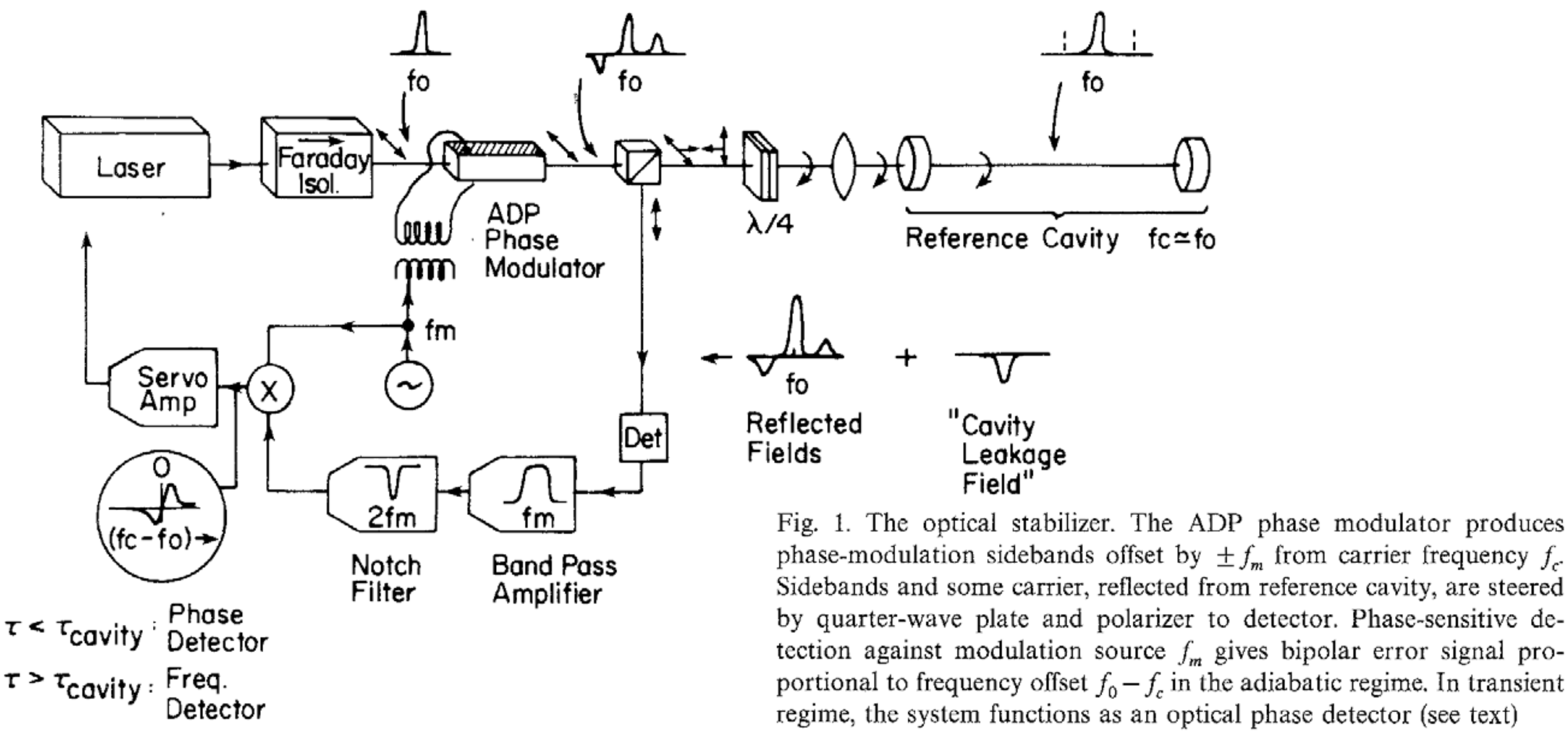


Fig. 1. The optical stabilizer. The ADP phase modulator produces phase-modulation sidebands offset by $\pm f_m$ from carrier frequency f_c. Sidebands and some carrier, reflected from reference cavity, are steered by quarter-wave plate and polarizer to detector. Phase-sensitive detection against modulation source f_m gives bipolar error signal proportional to frequency offset $f_0 - f_c$ in the adiabatic regime. In transient regime, the system functions as an optical phase detector (see text)

Stan Whitcomb made it work at Caltech

Stan Whitcomb, as junior faculty member, was Ron's deputy, making actual progress possible.

Caltech built a 40-meter interferometer that pioneered what became the design of LIGO.

Stan Whitcomb - 15 years

NSF bets on gravitational wave

At NSF, Gravity program head Richard Isaacson got the agency to take seriously that large interferometers ought to be pursued.

He funded the first engineering design studies of large interferometers, led by Weiss. The result:

A Study of a Long Baseline Gravitational Wave Antenna System (1983)

Garching 30-m showed that ifos can work at design sensitivity

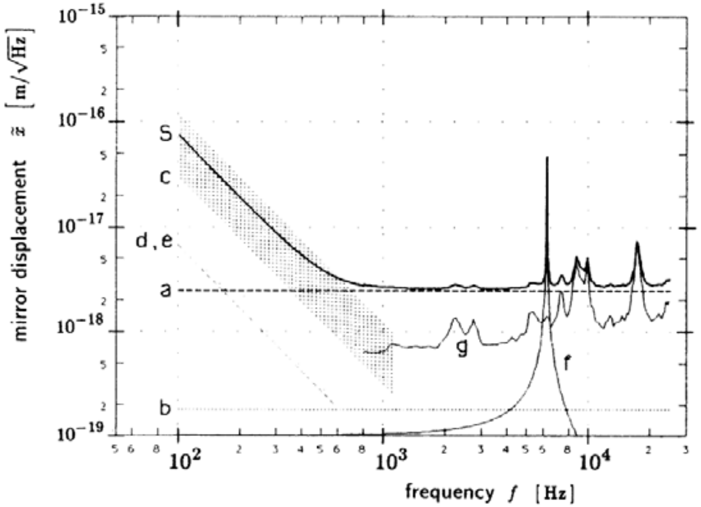


FIG. 2. Spectral densities of various noise sources, expressed as equivalent mirror motion $\tilde{x}$, in units of m/$\sqrt{\text{Hz}}$. *a*, photon shot noise; *b*, residual gas fluctuations; *c*, filtered ground motion; *d*, electronic damping system; *e*, pendulum thermal motion; *f*, mirror thermal motion; *g*, laser frequency fluctuations; *S*, quadratic sum of all of the noise sources above.

David Shoemaker was the first author of the 1988 paper with good (and understood!) noise.

By 1989, the time had come to build these things

1989 was the big year for proposals.

Virgo’s 3-km proposal in May, GEO’s 3-km proposal in September, and LIGO’s 2@4-km in December.

Virgo

Alain Brillet and Adalberto Giazotto were the co-founders.

Virgo led the way toward outstanding low-frequency sensitivity from the very start, and pioneered the use of YAG lasers.

GEO

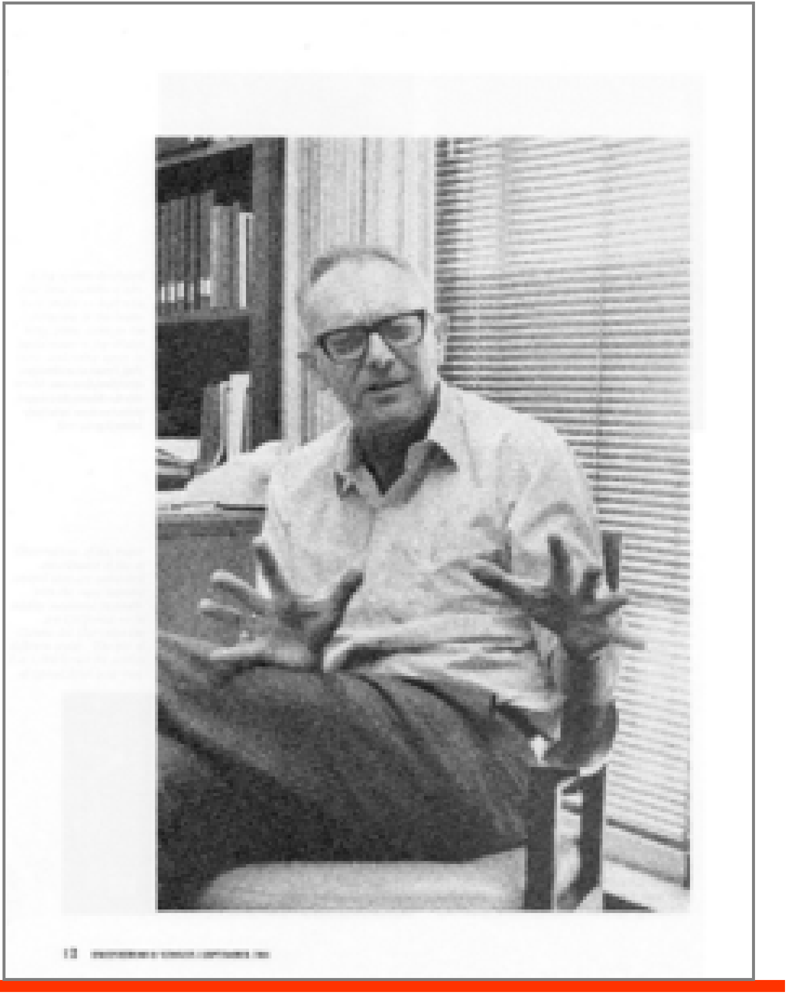
GEO’s U.K. leaders included Jim Hough and Bernard Schutz. German leaders were equally strong, but camera-shy.

The proposed 3-km interferometer would have been world-class; in 1990 Germany reunified, and gravitational waves took a back seat to history.

LIGO

Robbie Vogt’s “strong leadership style” forged LIGO into a real team.

He led the writing of the 1989 proposal and the did the lobbying that got LIGO funded in 1991.



We are making history

Look around this room.

We come from multiple projects and many countries. But in common, we are the inheritors of a great legacy, and we are about to make scientific history.

It is a great privilege to have reached this moment. We're doing great things together.

Let's finish the job as soon as we can!

For deeper understanding of our history

On the early history of gravitational waves:

Dan Kennefick, *Traveling at the speed of thought*

For the history of gravitational wave detection and detectors:

Harry Collins, *Gravity's Shadow* (and other works)

Marcia Bartusiak, *Einstein's Unfinished Symphony*