Gravitational Wave Detection: A Historical Perspective

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Einstein and relativity

In 1905, Einstein discovered an essential law of the universe:

No information can be transmitted faster than the speed of light, 186,000 mile/sec

Simple, but it revolutionized physics.

General Relativity: Einstein's account of gravity

In 1915, Einstein reformed our understanding of gravity for the first time since Isaac Newton (1686).

Gravity isn't a force that acts <u>in</u> space and time, but instead is <u>built into the actual structure</u> of space and time.

Space and time are *curved*; nothing can avoid feeling that curved structure. That makes gravity *universal*.

Gravitational waves

Gravity needs to obey the principle of relativity (no signals faster than light).

What about gravity from rapidly moving stars? Their gravitational effects at large distances can't change instantaneously. (If they did, that would violate relativity.)

Gravitational changes "ripple out" from a moving/changing object. Those ripples in the structure of space-time, moving at the speed of light, are *gravitational waves*.

Gravitational waves would be a new way to scan the skies

To make gravitational waves, you need something that dramatically changes the distribution of matter.

Binary stars are a good example. The more massive the stars, the better. The faster they move, the better.

Binaries made of neutron stars are very good.

Binaries made of black holes are best.

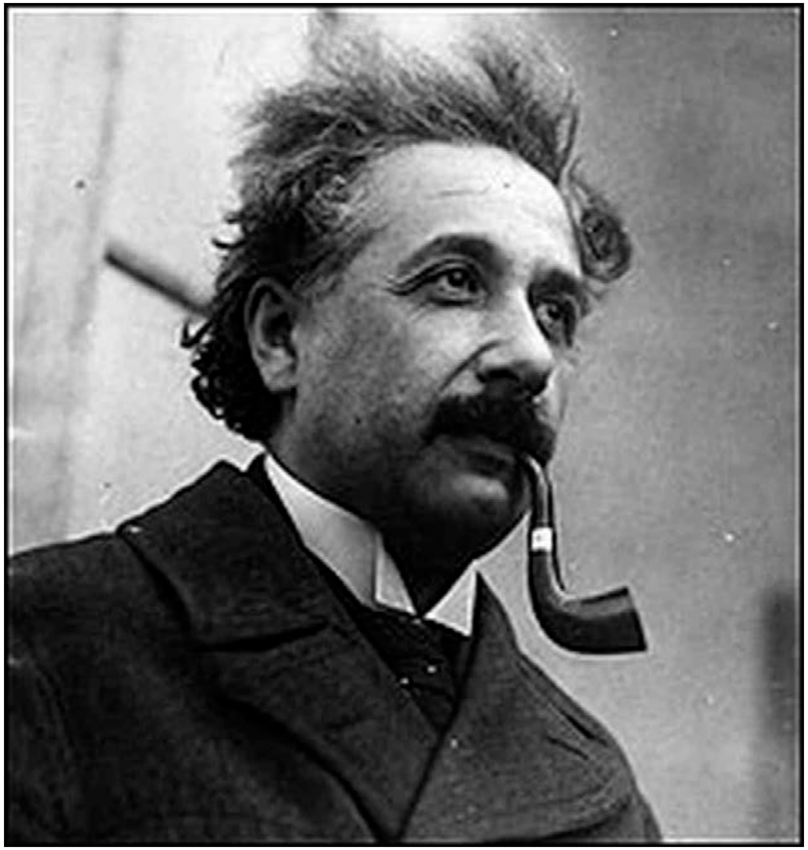
In gravitational wave signals, we'd see these things in ways no ordinary telescope can rival.

Einstein's prediction left many doubts …

… even for Einstein.

The theory was so subtle, Einstein was never sure that this prediction was correct.

The resolution of this question came in 1957, shortly after Einstein's death.



The Chapel Hill Conference

In January 1957, the U.S. Air Force (under program officer 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.

The "gravitational wave problem"

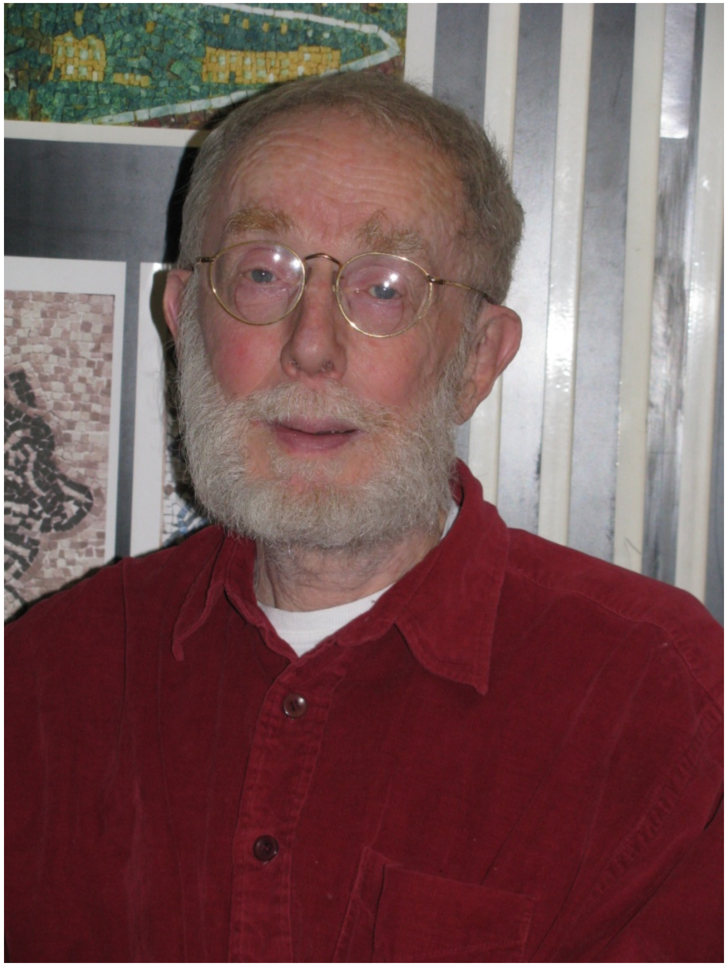
Were gravitational waves real, or were they "pure gauge"?

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 Goldberg had worked on this. It was hard. People were still 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

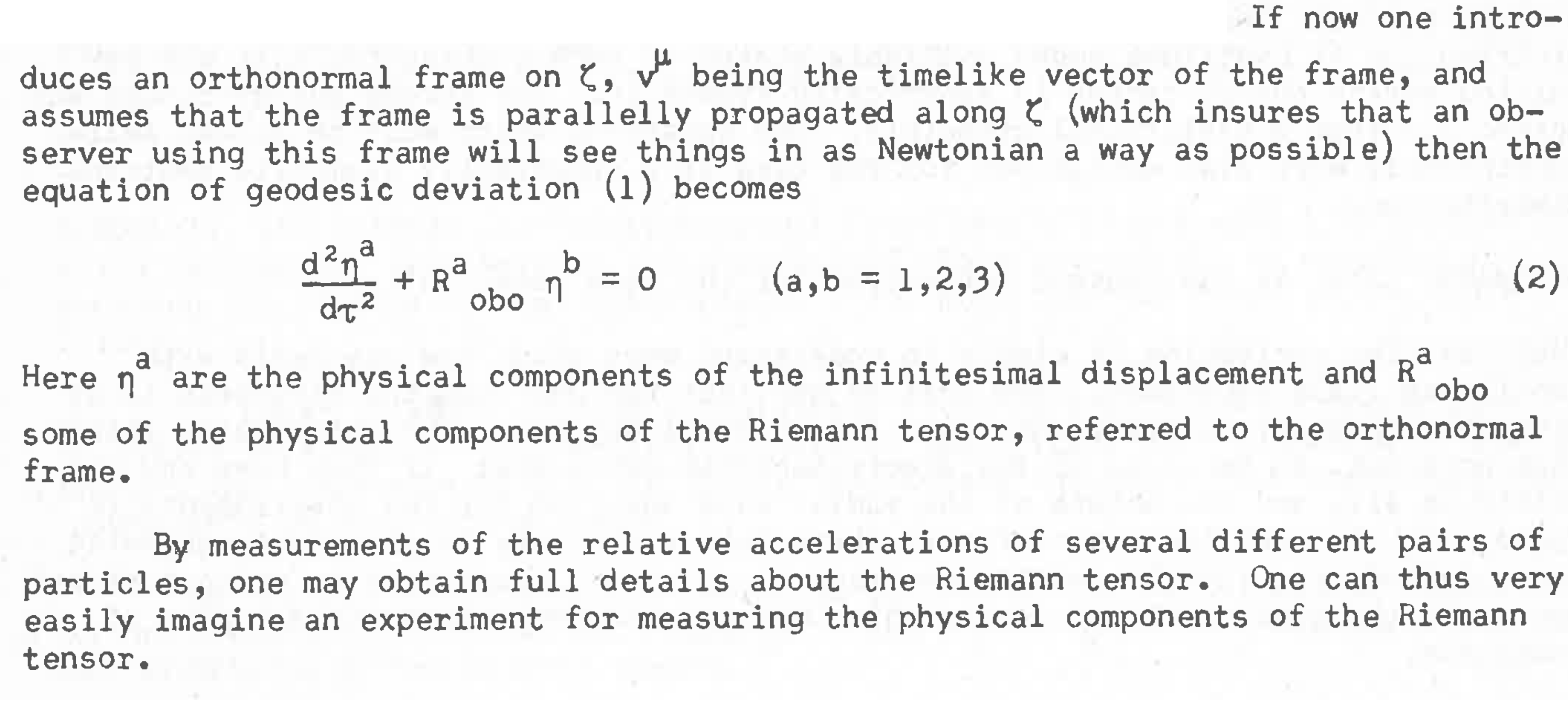
Pirani's 1957 papers

Pirani's insight 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



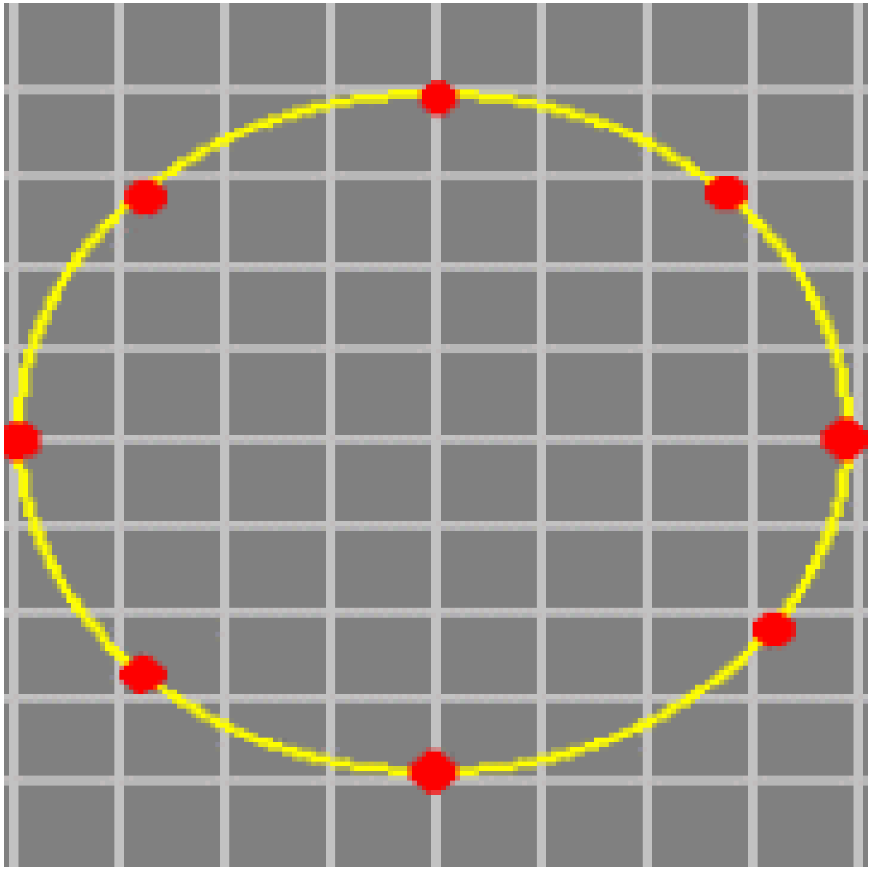
If now one introduces an orthonormal frame on ζ, v^μ being the timelike vector of the frame, and assumes that the frame is parallelly propagated along ζ (which insures that an observer using this frame will see things in as Newtonian a way as possible) then the equation of geodesic deviation (1) becomes

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

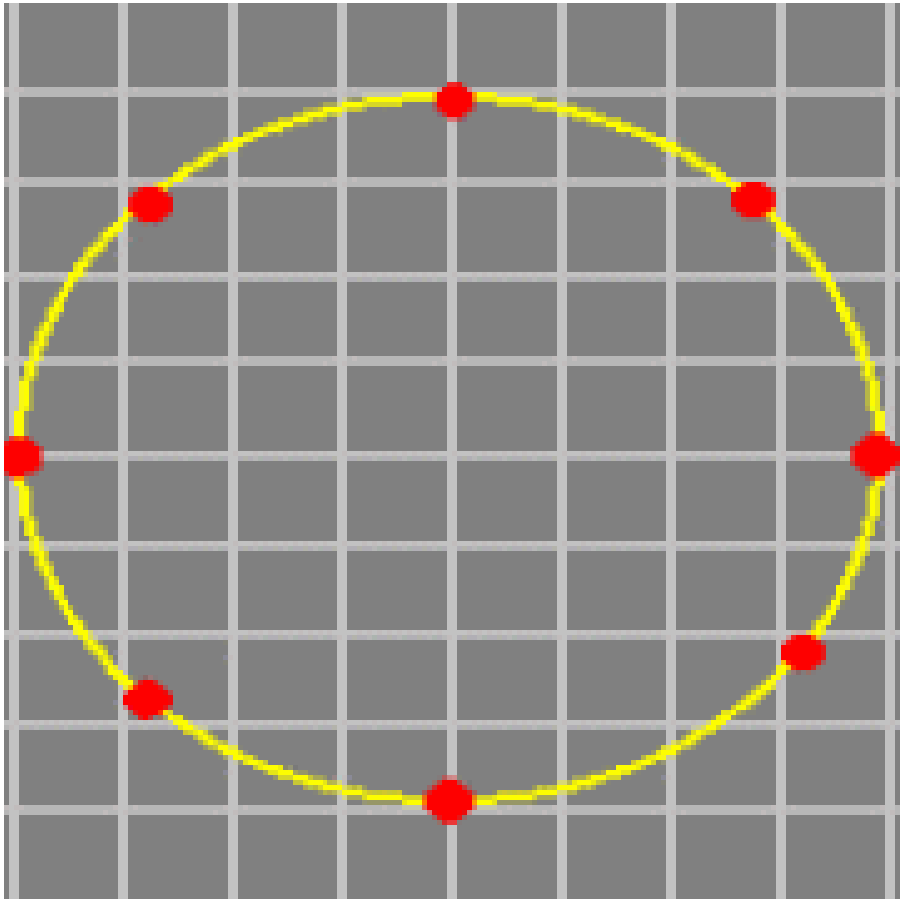
Here η^a are the physical components of the infinitesimal displacement and $R^a{}_{obo}$ some of the physical components of the Riemann tensor, referred to the orthonormal frame.

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



Pirani's mentor Hermann Bondi

Bondi arrived at Chapel Hill unsure about whether gravitational waves were real.

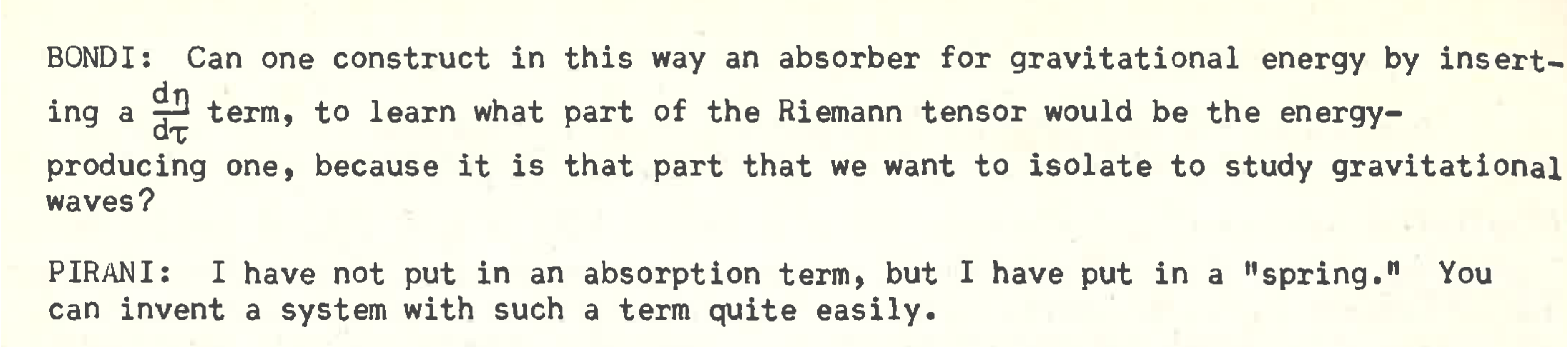
Bondi clarifies Pirani’s point

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

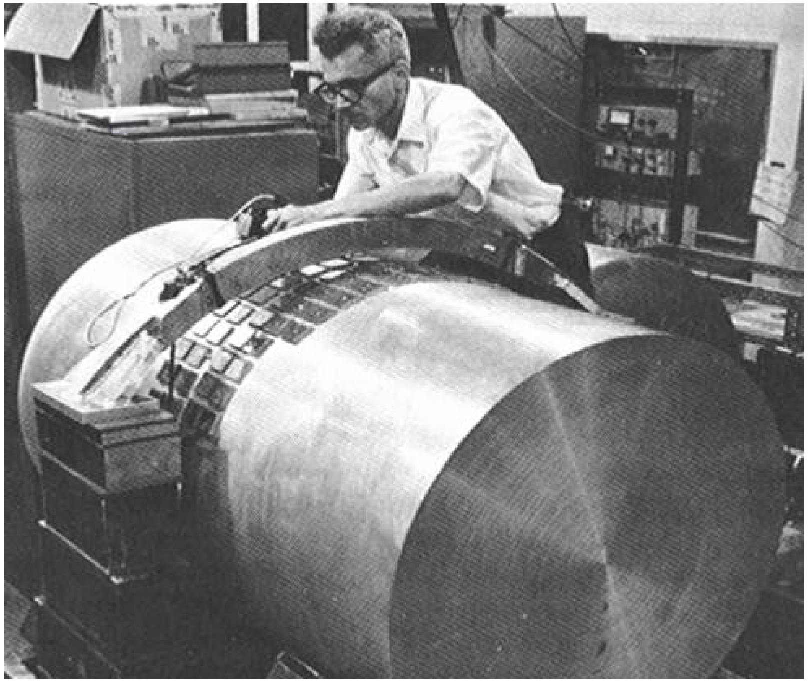
The two of them were at Chapel Hill, and listened well to Pirani’s talk.

Joe Weber starts GW detection

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

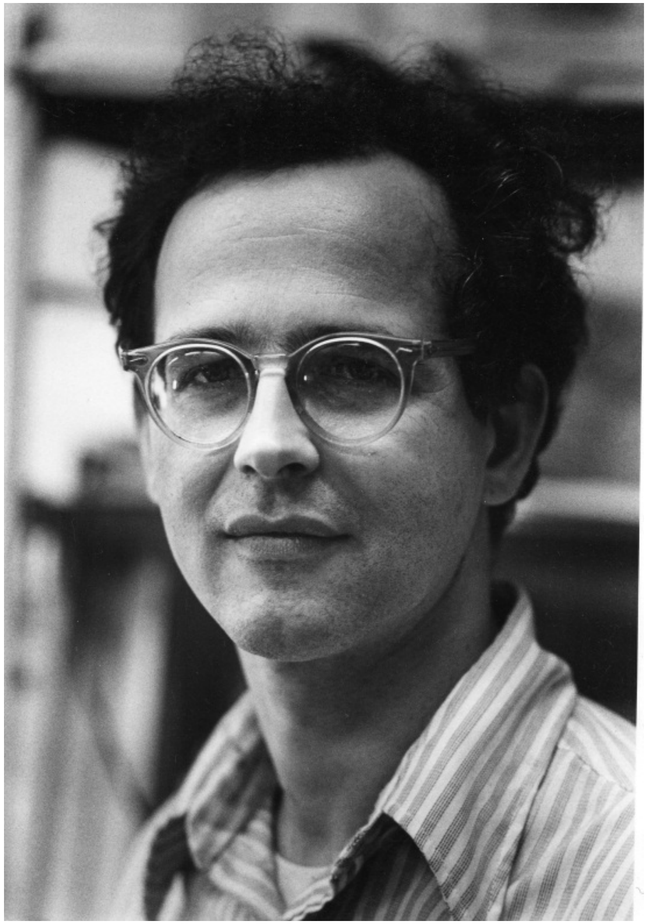
Joe expanded on the experimental ideas in two Gravity Research Foundation essays (3rd prize 1958, 1st prize 1959), leading to his 1960 Phys. Rev. paper laying out the bar program.

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.

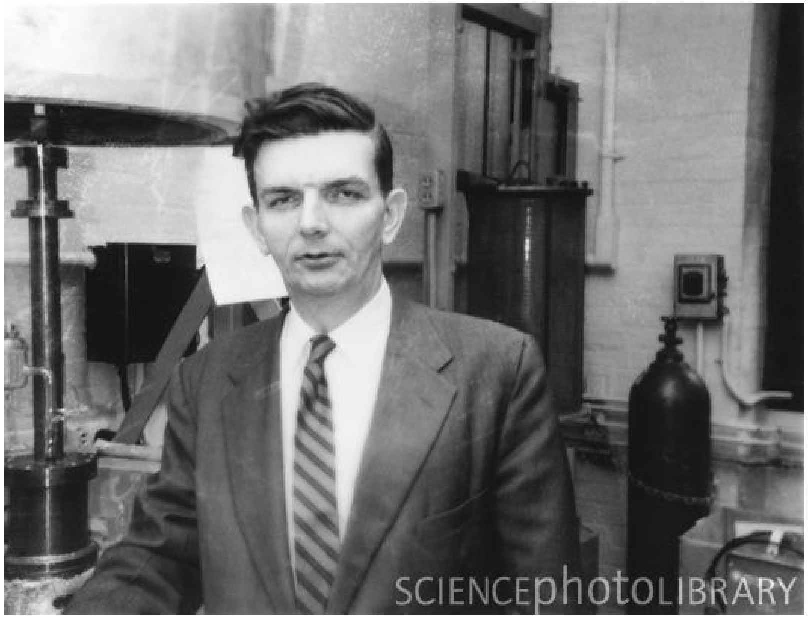
Rainer Weiss, not at Chapel Hill



In 1957, Rai Weiss was a grad student of Jerrold Zacharias at MIT, trying to make an atomic fountain clock.

In the early '60's, he worked 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."

By this time, Rai had been working on laser applications for gravity experiments, with Shaoul ("Ziggy") Ezekiel and Kingston Owens. Rai read Pirani, and knew that lasers could do the job of detecting a gravitational wave.

Weber announced the reception of signals

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.

Rai Weiss envisions LIGO in 1972

(V. GRAVITATION RESEARCH)

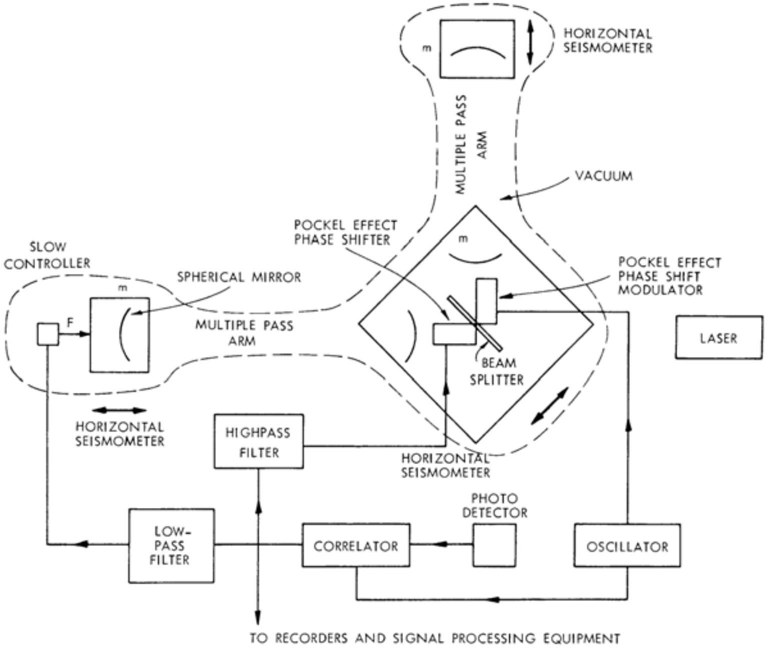


Fig. V-20. Proposed antenna.

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.

V.I. Pustovoit

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, no one else could see Weber's events …

… although lots of people tried.

By the time of GR7 at Tel Aviv in 1974, the consensus of the scientific community was that Weber's claims were not confirmed.

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 controversy.

Starting down the new road to interferometers

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

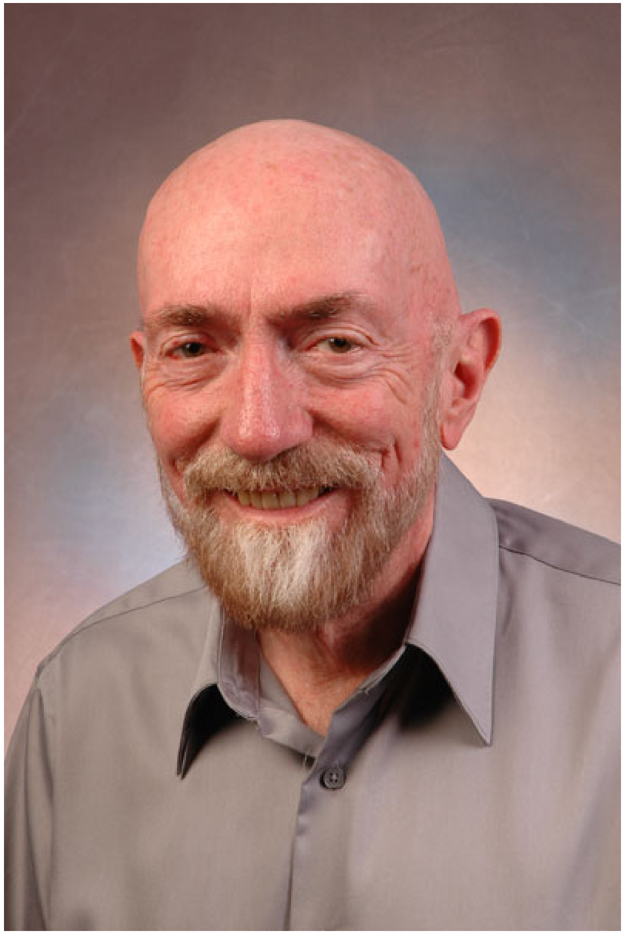
The Munich group decided that this was a better way forward.

Soon, so did Ron Drever and Jim Hough at Glasgow.

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.



NSF bets on gravitational waves

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

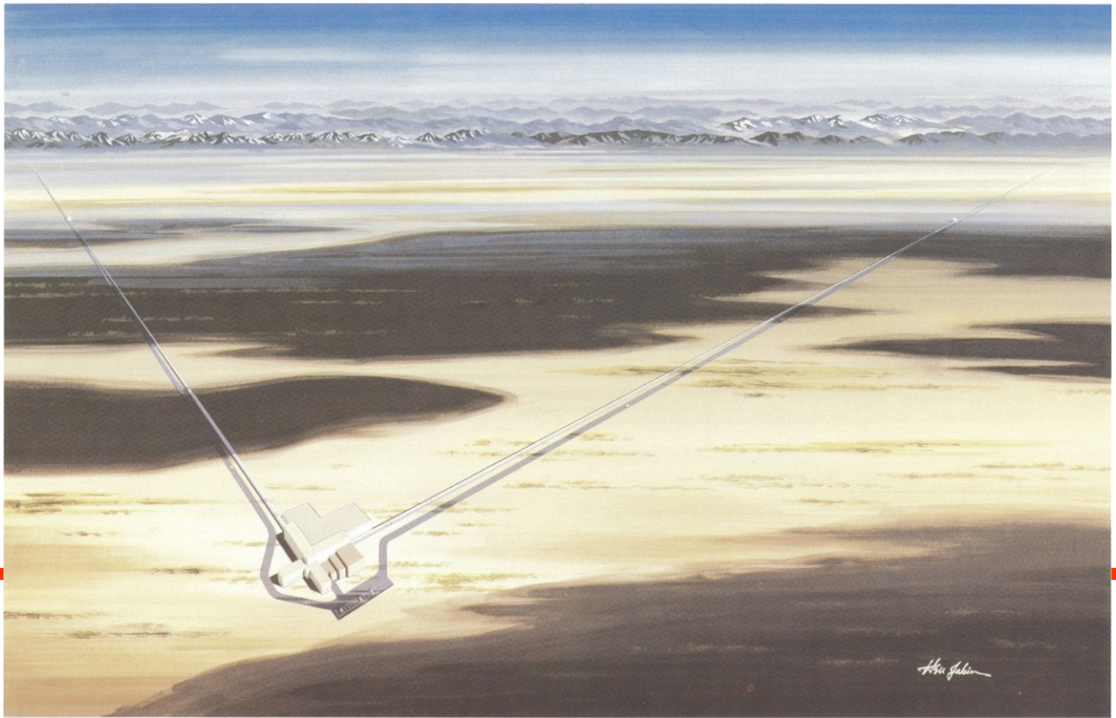
He funded the first engineering design studies of large interferometers, led by Weiss. The result:

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

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 (France) and Adalberto Giazotto (Italy) were the co-founders.

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

GEO (UK and Germany)

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

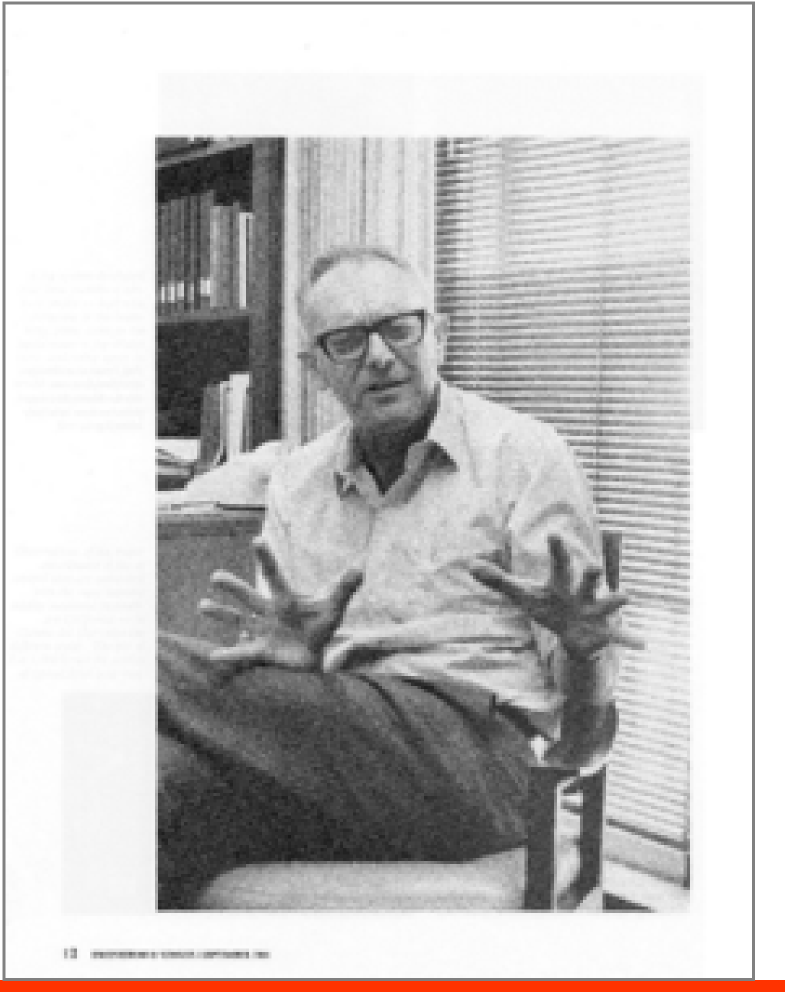
GEO built a 600-m interferometer with pioneering technology.

Bernard Schutz

LIGO

The strong leadership of Robbie Vogt 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.



Thought experiment becomes reality
Laser Interferometer Gravitational Wave Observatory (LIGO)

1972: Concept
2005: 4 km interferometers observe

LIGO Hanford Observatory, WA

LIGO Livingston Observatory, LA

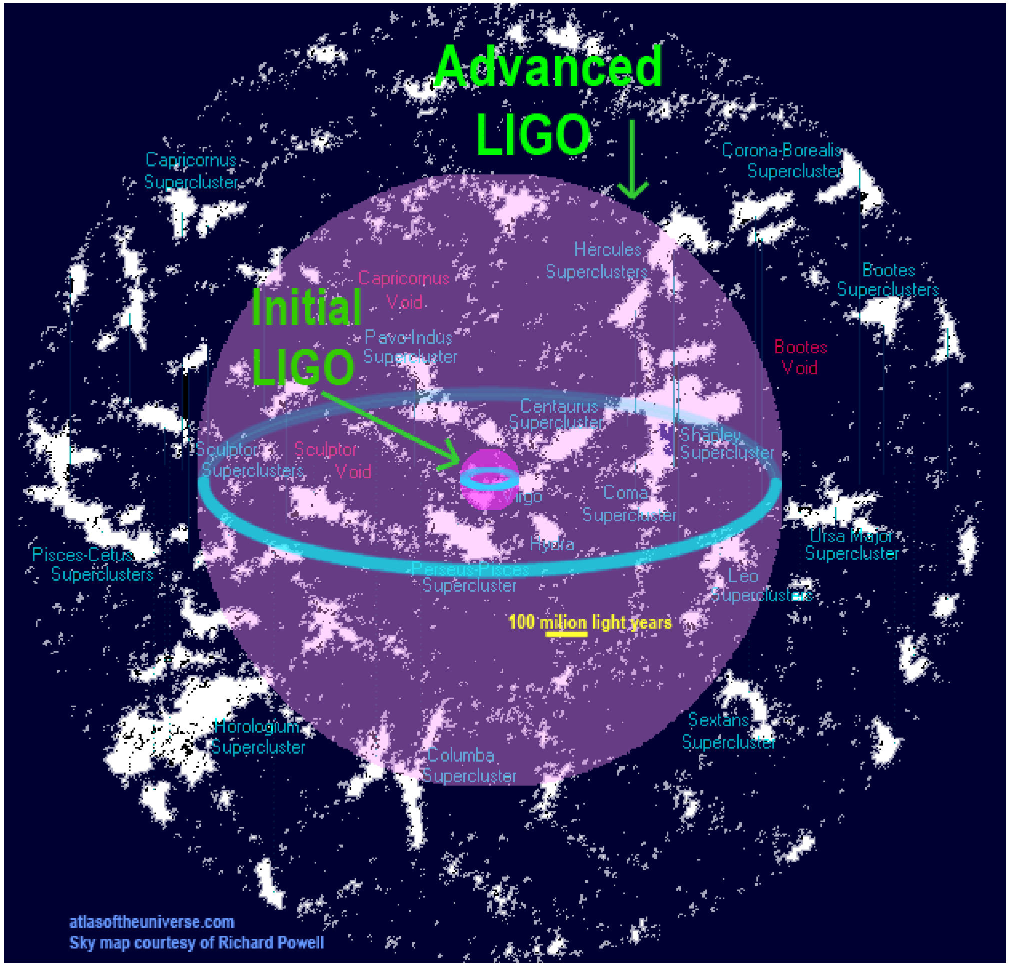
In Europe, Virgo and GEO600 observed with LIGO

Results of iLIGO

Over 90 papers setting upper limits on many different classes of signals, including:

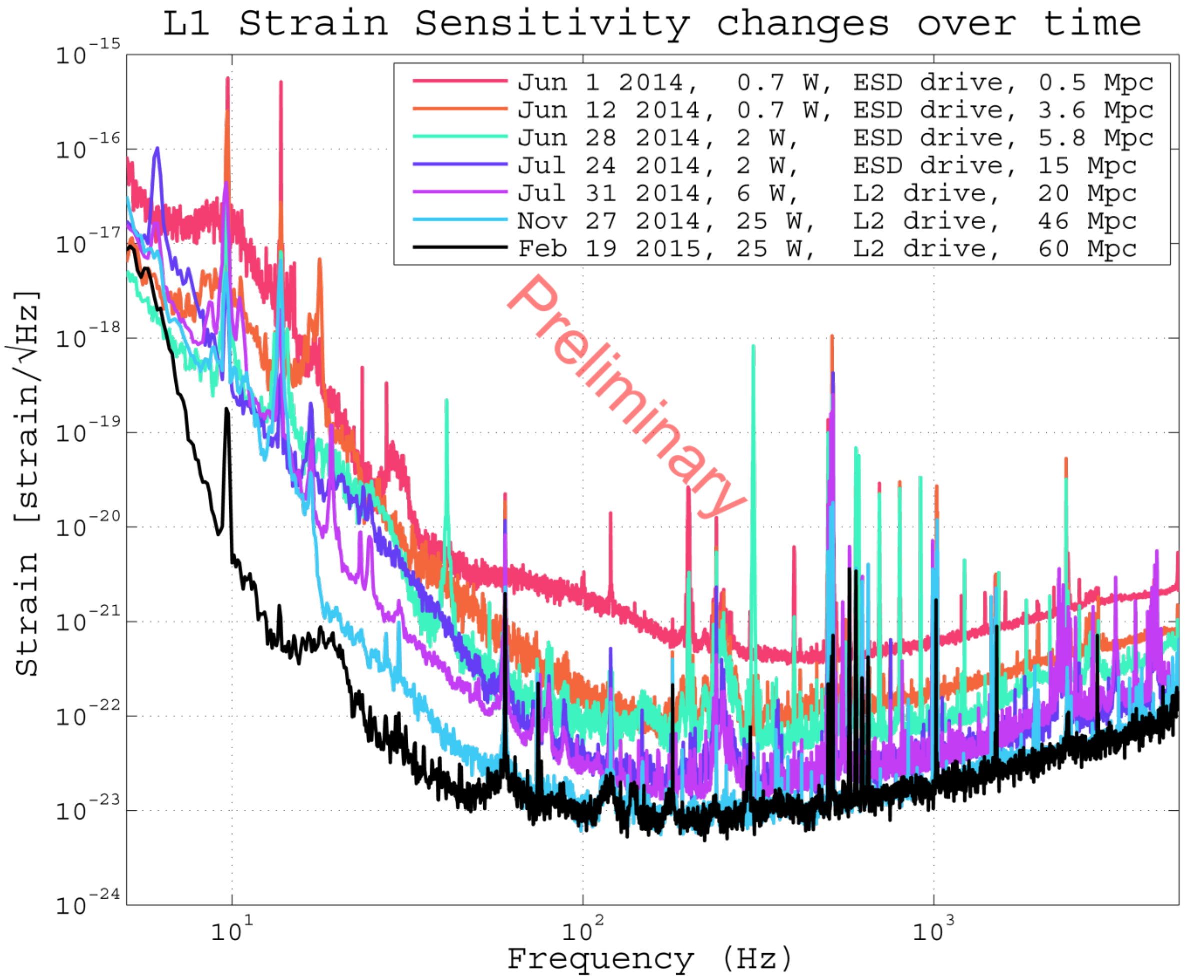
- Upper limits on a cosmological background of gravitational waves and on one from cosmic superstrings,
- Search for gravitational waves from the Crab pulsar, at sensitivity well below the “spindown limit”.
- Ruling out a purported short-hard GRB in M31.

aLIGO: design sensitivity should detect gravitational waves

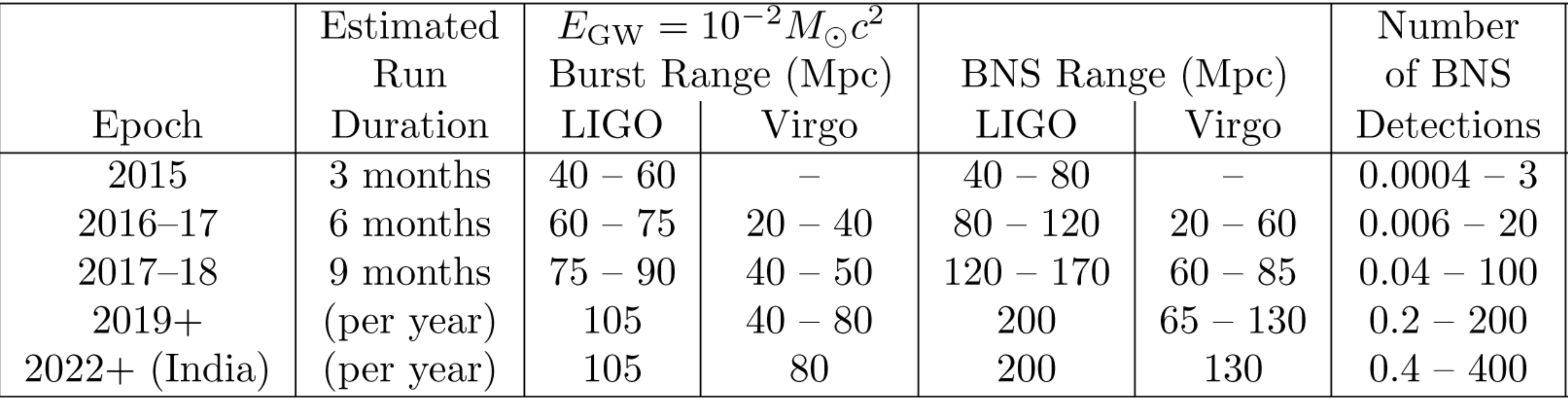


atlasoftheuniverse.com
Sky map courtesy of Richard Powell

aLIGO commissioning progress has been rapid



aLIGO is on schedule for its first observing run, Sept 2015



Epoch	Estimated Run Duration	$E_{\mathrm{GW}} = 10^{-2} M_\odot c^2$ Burst Range (Mpc)		BNS Range (Mpc)		Number of BNS Detections
		LIGO	Virgo	LIGO	Virgo	
2015	3 months	40 – 60	–	40 – 80	–	0.0004 – 3
2016–17	6 months	60 – 75	20 – 40	80 – 120	20 – 60	0.006 – 20
2017–18	9 months	75 – 90	40 – 50	120 – 170	60 – 85	0.04 – 100
2019+	(per year)	105	40 – 80	200	65 – 130	0.2 – 200
2022+ (India)	(per year)	105	80	200	130	0.4 – 400

We've come a long way since 1957. Here's hoping for a detection on the 60th anniversary of the Chapel Hill Conference!