Reports of the Detection of Gravitational Waves
2018 American Physical Society: Division of Gravitational Physics (APS DGRAV)
Lance Williams

The April 2018 APS Meeting was the first meeting after the Nobel prize for gravitational waves was awarded late last year, for a discovery made in 2015 and announced in 2016, and it was a historic moment. The prize winners recapitulated their Nobel speech for their friends and colleagues, and everyone was celebrating the victory of a 50-year battle. It seems this moment is as significant as when Hertz detected electromagnetic waves in the 1880s. I recorded this report from among all the presentations at the meeting, to show the single monumental story of the conception, search, and detection of gravitational waves. There are links to the various APS presentations referenced throughout.

The Great Discovery

The Nobel prize was awarded to Thorne, Weiss, and Barish in late 2017 for the detection of gravitational waves with the long-wave interferometric gravitational observatory (LIGO). Thorne was the theorist who conceived the feasibility, Weiss designed the detector, and Barish was the NSF observatory director.

On 14 Sept 2015, LIGO detected the final 200 milliseconds of the collision of 2 black holes, one around 40 solar masses, the other around 30 solar masses. The final black hole was around 62 solar masses, and 3 solar masses of energy were radiated away in gravitational waves! It was at a distance of over 400 Megaparsec, around a billion light-years – well outside our galaxy but still relatively close in the universe. The radiated energy peaked at 3×10^{49} watts – 50 times greater than the combined power of all the light radiated by all the stars in the universe.

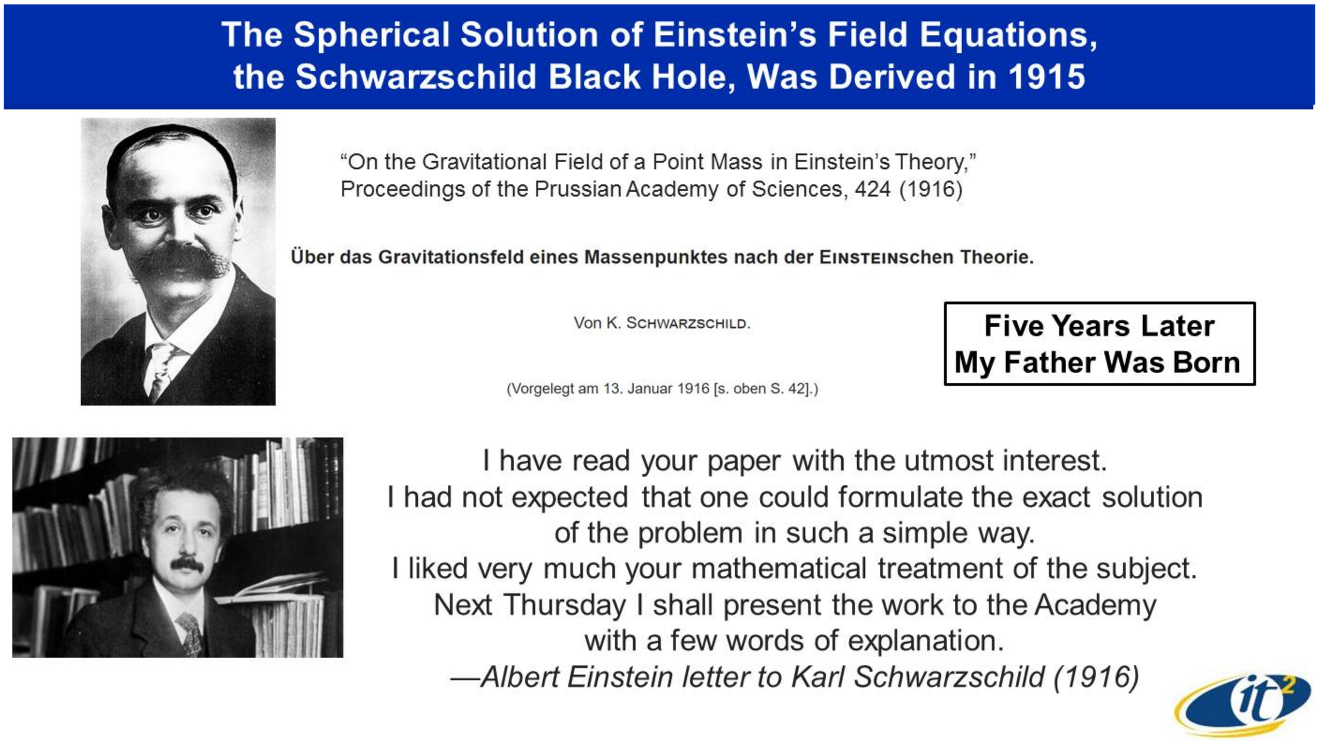
https://en.wikipedia.org/wiki/First_observation_of_gravitational_waves

The frequencies shifted from 35 Hz to 250 Hz, which is in the audible range, so you can hear it online:

https://www.youtube.com/watch?v=QyDcTbR-kEA

Although I expected a focus on gravitational waves at the meeting, that was an underestimate. The group of physicists was absolutely exultant, triumphant, about their accomplishment. Of 158 technical sessions (among all groups, not just DGRAV) -- and you could only do 2 or 3 a day -- 18 were on gravitational wave or LIGO physics. There were also several on the history of gravitational wave research and how they got here, that I found fascinating. I will weave the story for you from among the keynotes and history talks and Nobel lectures. I think it has lessons for any technical organization -- and it starts with the Air Force! The pictures are slides from various presentations. Links are provided to the presentations mentioned.

Einstein introduced general relativity in 1915, and predicted gravitational waves in 1916. But he doubted they could ever be observed. Also in 1916, Schwarzschild obtained the exact solution to Einstein's field equation for a massive object in space – including a black hole.



From Smarr's talk; an analytical solution for one black hole was obtained very soon after Einstein published his field equations. It would take Smarr decades to numerically simulate the two-black-hole solution

After the quantum revolution of the 1920s, research in GR stagnated during the 30s, 40s, and 50s while quantum field theory and quantum electrodynamics were invented (or discovered).

Bryce and Cecile DeWitt organized a conference in the late 50s to reinvigorate the field: the 1957 Chapel Hill conference on "the role of gravitation in physics". They invited a who's who of the best physicists from around the world.

Bryce & Cecile DeWitt

The Chapel Hill conference was funded by the USAF. They even flew around the world to pick up the physicists and bring them to Chapel Hill! The AF guy who was in charge, Joshua Goldberg, was actually at APS on Tuesday and spoke at a history session.

Air Force Support of Chapel Hill Conference

Goldberg was a good relativist in his own right, but when his old colleagues attempted to complement him, he seemed embarrassed. I suppose he had too much respect for those great physicists to want his own name mentioned with them. There were a few others who attended Chapel Hill but they are all quite aged. Anyone who was 30 in 1957 would be 91 now.

Goldberg said he could only speak from recollection because he didn't save any paper. But there were some historians and researchers there as well who did have lots of interesting research. I asked in the discussion why the AF funded it? There were some circumstantial answers, such as: It was very soon after the Bomb, which had appeared to the military to come out of nowhere, so the military was interested in finding out what else the physicists were capable of.

But the authoritative answer offered was that: It was a different time. Back then, the AF had a lot of budgetary discretion and was allowed to do things merely in the public good. At the time, whoever was Goldberg's boss had the authority and the budget, and he said yes. Period. When Congress got wind that the military was engaging in activity for the benefit of all mankind, they did what any responsible legislator would do -- they outlawed it -- with the 1968 Mansfield Amendment.

It struck me also that excellence was more widely distributed back then. The experts were not only university professors, but Air Force officers and corporate researchers. They also said NRL was important at that time. Some of the aged participants mentioned how their research was supported by military grants.

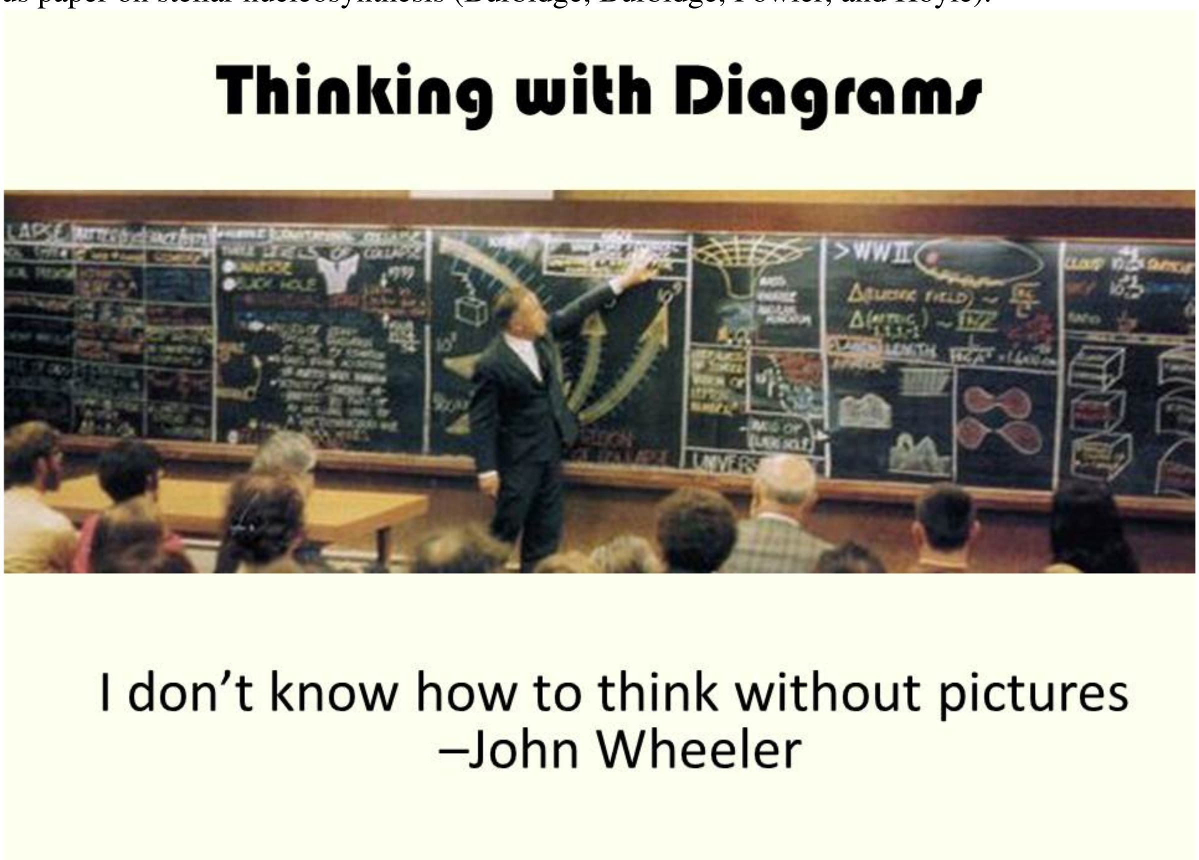
Chapel Hill focused on gravitational waves and quantum gravity. The latter problem is unsolved to this day, and that is where Bryce was expert. But at Chapel Hill they convinced themselves that gravitational waves would have measurable effects and began to think in experimental terms. Before then, it was debated whether they were only abstract concepts or were really something that could be measured. Although not widely known to history, they now credit the fundamental insight and suggestion at Chapel Hill to Felix Pirani, who passed away after the Nobel-winning detection was made, but only weeks before it was publicly announced.

How Felix Pirani launched the effort to detect gravitational waves

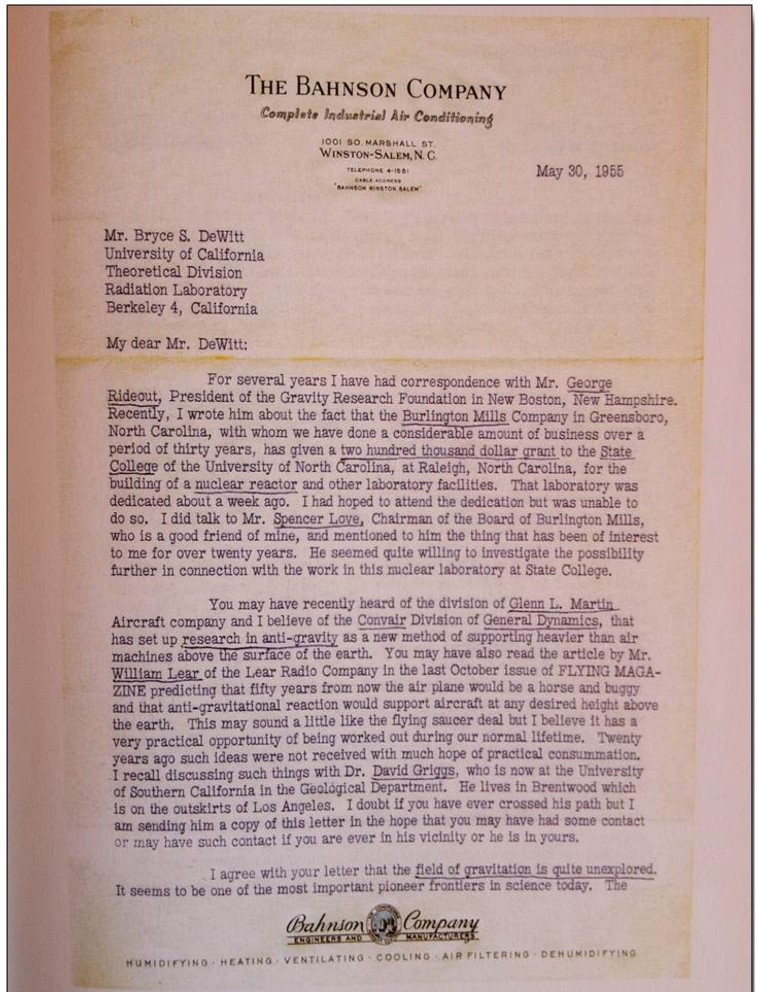
We now remember Chapel Hill for contributions by Wheeler (who wrote many of the proceedings papers) and Feynman.

Chapel Hill, Wheeler, and I

Check out this picture of Wheeler's blackboard; I am not surprised, having read his famous textbooks. But I had still never heard that he did his lectures with such beautiful pictures. One wise lady at the conference, Viriginia Trimble, said the man on the front row is Willie Fowler, who coauthored the famous paper on stellar nucleosynthesis (Burbidge, Burbidge, Fowler, and Hoyle).



But the reality was apparently more interesting. Someone gave a Chapel Hill backstory talk, about how the DeWitts were funded by an appliance tycoon named Bahnson who founded the Field Institute.



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May 30, 1955

Mr. Bryce S. DeWitt
University of California
Theoretical Division
Radiation Laboratory
Berkeley 4, California

My dear Mr. DeWitt:

For several years I have had correspondence with Mr. George Rideout, President of the Gravity Research Foundation in New Boston, New Hampshire. Recently, I wrote him about the fact that the Burlington Mills Company in Greensboro, North Carolina, with whom we have done a considerable amount of business over a period of thirty years, has given a two hundred thousand dollar grant to the State College of the University of North Carolina, at Raleigh, North Carolina, for the building of a nuclear reactor and other laboratory facilities. That laboratory was dedicated about a week ago. I had hoped to attend the dedication but was unable to do so. I did talk to Mr. Spencer Love, Chairman of the Board of Burlington Mills, who is a good friend of mine, and mentioned to him the thing that has been of interest to me for over twenty years. He seemed quite willing to investigate the possibility further in connection with the work in this nuclear laboratory at State College.

You may have recently heard of the division of Glenn L. Martin Aircraft company and I believe of the Convair Division of General Dynamics, that has set up research in anti-gravity as a new method of supporting heavier than air machines above the surface of the earth. You may have also read the article by Mr. William Lear of the Lear Radio Company in the last October issue of FLYING MAGAZINE predicting that fifty years from now the air plane would be a horse and buggy and that anti-gravitational reaction would support aircraft at any desired height above the earth. This may sound a little like the flying saucer deal but I believe it has a very practical opportunity of being worked out during our normal lifetime. Twenty years ago such ideas were not received with much hope of practical consummation. I recall discussing such things with Dr. David Griggs, who is now at the University of Southern California in the Geological Department. He lives in Brentwood which is on the outskirts of Los Angeles. I doubt if you have ever crossed his path but I am sending him a copy of this letter in the hope that you may have had some contact or may have such contact if you are ever in his vicinity or he is in yours.

I agree with your letter that the field of gravitation is quite unexplored. It seems to be one of the most important pioneer frontiers in science today. The

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Bahnson, who funded gravity research in the early 1950s because of an interest in anti-gravity

Bahnson was interested in searching for antigravity and flying cars. The DeWitts did not believe it was possible, and it was reported that DeWitt wrote an essay on it as a research application to the Institute.

New Directions for Research in the Theory of Gravitation

by Prof. Bryce S. DeWitt

Radiation Laboratory
University of California
Berkley 4, Cal.

1953

Before anyone can have the audacity to formulate even the most rudimentary plan of attack on the problem of harnessing the force of gravitation, he must understand the nature of his adversary. I take it as almost axiomatic that the phenomenon of gravitation is poorly understood even by the best of minds, and that the last word on it is very far indeed from having been spoken.

Nevertheless, the theoretical investigation of gravitation has received relatively little attention during the last three decades. There are several reasons for this. First, the subject is peculiarly difficult; the existing body of theory on it involves rather recondite mathematics, and the fundamental equations are almost hopeless of solution in all but a very few special cases. Although the accepted theory is motivated by two or three beautifully simple yet profound principles, these guiding principles have so far been of little help in predicting the general features of the solutions of the equations to which they give rise. And, as any researcher in the field knows, one can develop a serious case of "writer's cramp" in that manipulation of tensor indices which is usually necessary in order to prove only a single tediously trivial point.

Secondly, modern gravitational theory has few consequences which are even remotely susceptible of experimental verification. The old Newtonian theory, involving action-at-a-distance, has, for practical purposes, been far too adequate. Consequently, stimuli for the theoretical investigation of gravitation are virtually non-existent, and gravitational research is almost totally unrewarding. It is a field which had its brief brilliant hour, but which has since fallen into a state of near disrepute.

In spite of all this, it is very probable that the phenomenon of gravitation will eventually have to be reckoned with again in respectable circles, and it may well happen that this reckoning will present itself in a rather acute form. It is one of the purposes of this note to suggest that we may be already in the first phases of such a new development, and to point out some new directions into which we are likely to be led as a result.

I shall assume, virtually without question, the validity, in its appropriate domain, of the Einstein theory of gravitation - that is

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to say, of the original general theory of relativity, as distinct from later embellishments by many workers including Einstein himself. Einstein's theory is, to my mind, far too beautiful and satisfying to be cast aside. And it is so intimately connected with and firmly entrenched in those concepts of invariance and conservation which have come to be regarded as fundamental in physics, that in casting it aside, we should be casting aside much that has been enormously fruitful in the past as well as the present, to the experimenter no less than to the theorist. However, it should be borne in mind that the Einstein theory is a "classical" (that is, *non-quantum*) theory. It forms by itself a logical and self-contained system. Only the fact that the real world around us has taught us that the system may not be quite so self-contained after all, makes the following remarks of some interest.

For the sake of orientation let us reverse the usual order of things and first fix our sights on those grossly practical things, such as "gravity reflectors" or "insulators", or magic "alloys" which can change "gravity" into heat, which one might hope to find as the useful by-products of new discoveries in the theory of gravitation. The use of terms such as "reflector" or "insulator" clearly is based upon analogy with electromagnetism. Now, it is quite true that gravitation is similar to electromagnetism in many ways. Just as the latter can be split into an electric and a magnetic part, so can the former be split into two parts, one being that produced by static matter and the other that produced by moving matter. The *gauge group* of electrodynamics has its counterpart in the coordinate transformation group of gravidynamics. The electromagnetic and gravitational fields both propogate with the speed of light.

In other respects, however, the gravitational and electromagnetic fields differ profoundly. Of prime importance is the extreme weakness of gravitational coupling between material bodies, as compared with electromagnetic coupling (advice of professional weight-lifters notwithstanding!) The weakness of this coupling has the consequence that schemes for achieving gravitational insulation, via methods involving fanciful devices such as oscillation or conduction, would require masses of planetary magnitude. And even if the necessary masses could be manipulated, these schemes would be doomed to failure, for, since quantum forces would not be available for such macroscopic manipulation, non-gravitational force fields would have to be employed. But the existence of such external fields would defeat its own purpose, because every stress, every force-potential, and, indeed, every form of energy produces its own gravitational field. The gravitational field is all-pervading.

These features are built into the Einstein theory as consequences

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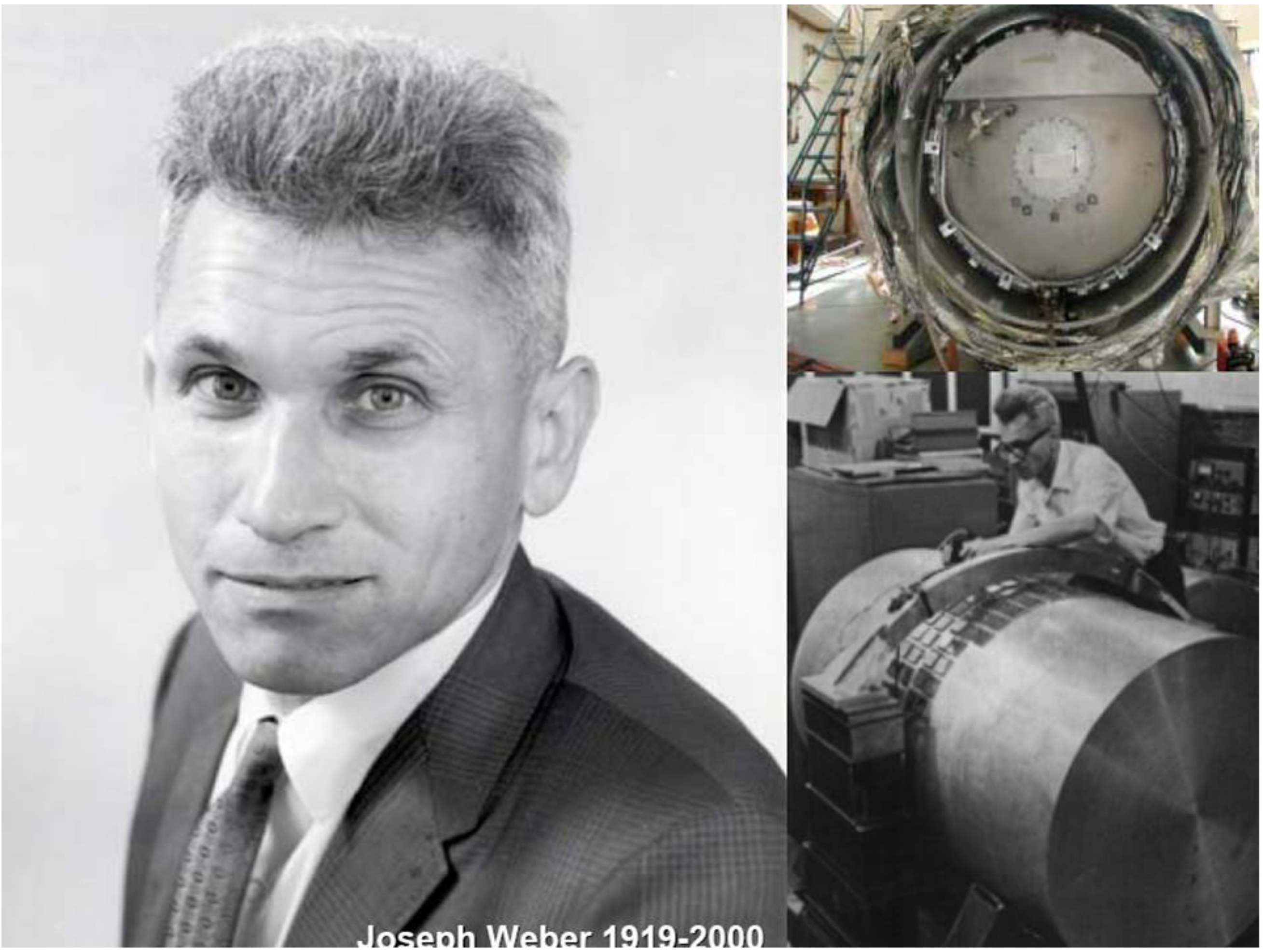
Bryce DeWitt's Prize-winning essay submitted to the Field Institute

<u>Behind the scenes at Chapel Hill</u>

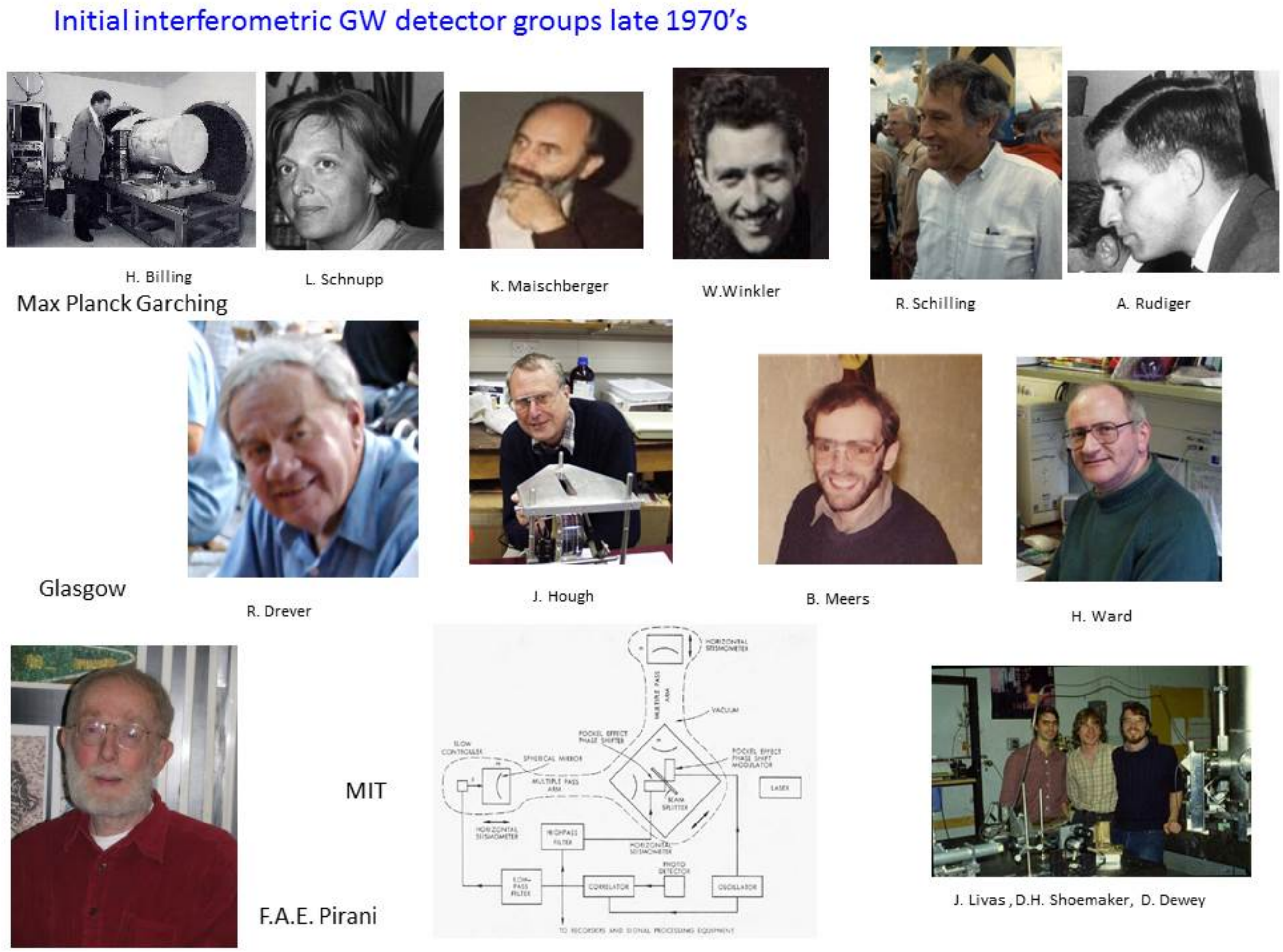
Imagine a wire cross with 1 bead sliding on each of the 4 arms. If a gravitational wave strikes the cross perpendicularly, the two bead pairs slide back and forth along the cross arms, so that the vertical pair will stretch out along the arms while the horizontal pair compresses inward along the arms, and then vice-versa, back and forth. An early concept for detecting gravitational waves suggested at Chapel Hill was to look for heat generated from friction of the beads sliding on the arms (in this example). That is not practical, but gives you the concept for measuring a gravitational wave. The movement of the bead along the arm of the cross is called the "strain".

Weber did the first real experiments to detect gravitational waves, with a giant aluminum bar, 4 feet wide and 8 feet long. They wrapped it in piezos to try and detect strain. Detection was in fact reported with this system in the 1960s, but the results were later called into question and now detection is doubted. It is now agreed that it was 2015 before the detection was made.



Joe Weber at work on his early gravitational wave detector, a giant aluminum bar. You can see him wrapping the piezos around it.

Rai Weiss designed the concept for the hanging interferometer that is used in LIGO. The interferometers are measuring motion of the mirrors of 10^{-18} meter -- 1/1000th the width of a proton! These guys are good… But it was the result of a long line of experimenters and contributors.

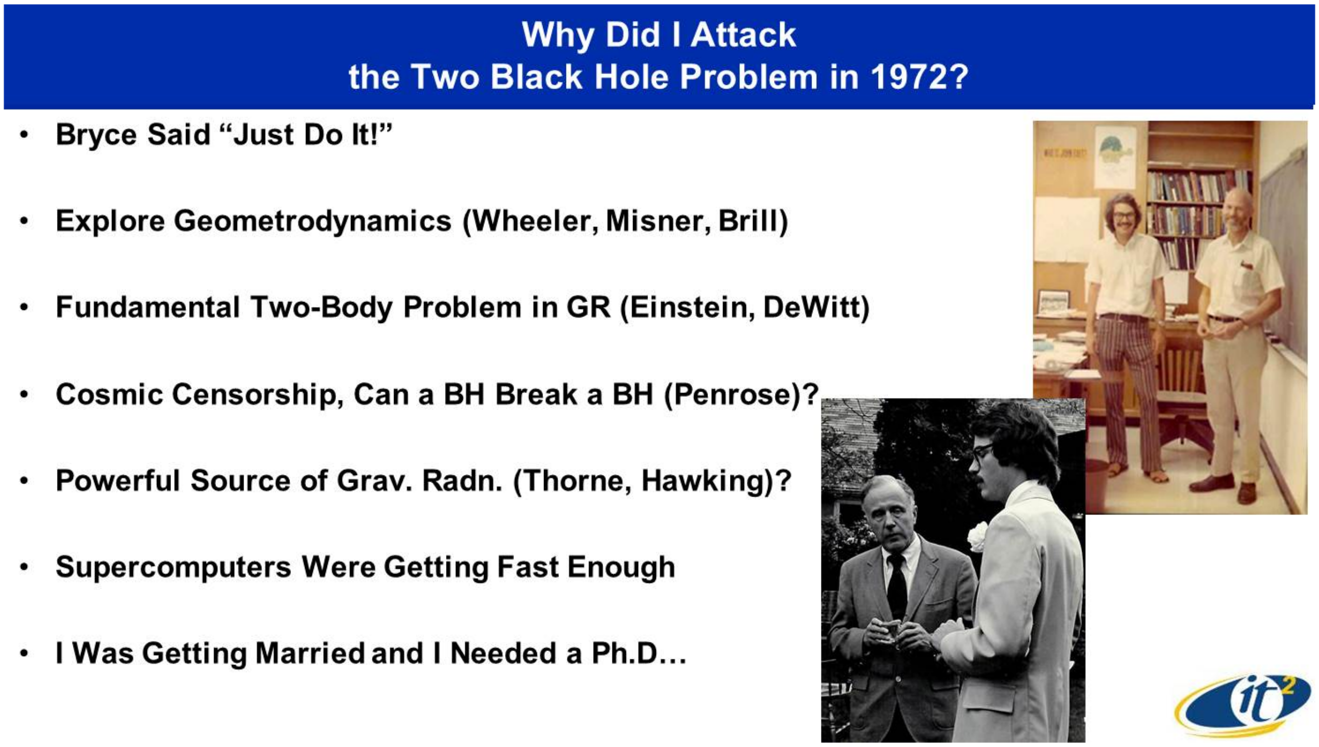


the diagram shows Weiss's design, but the slide doesn't mention him

The theory piece of the puzzle was done numerically. In the 1970s and 1980s, scruffy kid relativists in bell-bottoms were attempting to model the dynamics of colliding black holes on the new computers that were becoming available. It is "just" two Schwarzschild solutions attracting each other, and was said to be the fundamental two-body problem of general relativity. But it turned out to be very hard. The equations are non-linear, and so they were doing something new to computational physics. When they told people they were modeling black hole collisions, people would smirk "Like when will that ever happen?" Now we know -- about once a month.

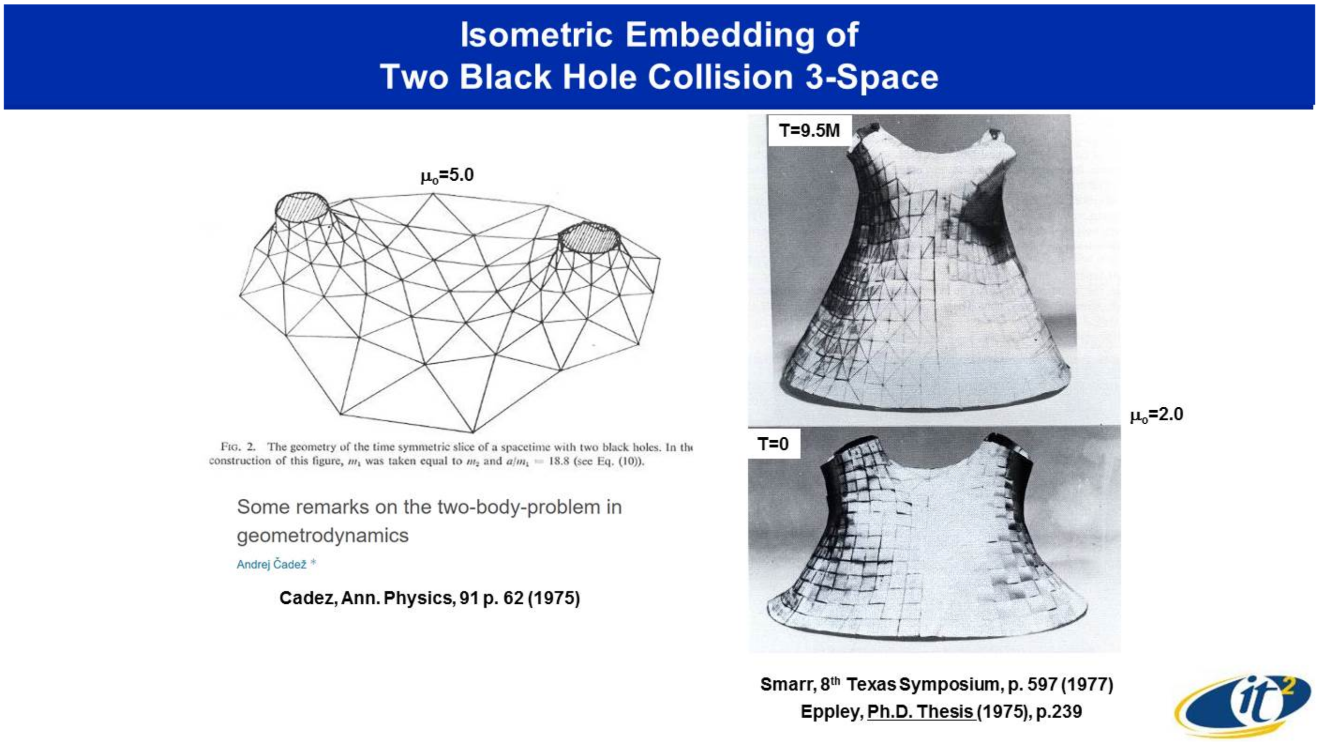
Evidently, it was a student of Bryce Dewitt, Larry Smarr that began to model black hole collisions. There was a lot of uncertainty as they sort of whistled in the dark, telling themselves "This should be simple. It's just differential equations, right?"

[Pre History of the Two-Black-Hole Collision Problem]



why Larry Smarr, a student of Bryce DeWitt, decided to investigate colliding black holes numerically

Not so simple. The early, naive computer simulations would crash in seconds. It was a feat just to get the codes to run and propagate the physics. They eventually understood they had to solve complicated elliptical differential equations just to get the boundary conditions, then run hyperbolic differential equations to get the time evolution. Smarr brought along this bizarre 3D plot made by hand of paper in the 1980s, since they didn't have graphing applications.



Larry Smarr's 3D visualization of his early computer code "still containing beer stains and bits of pretzel from the party we had putting them together"

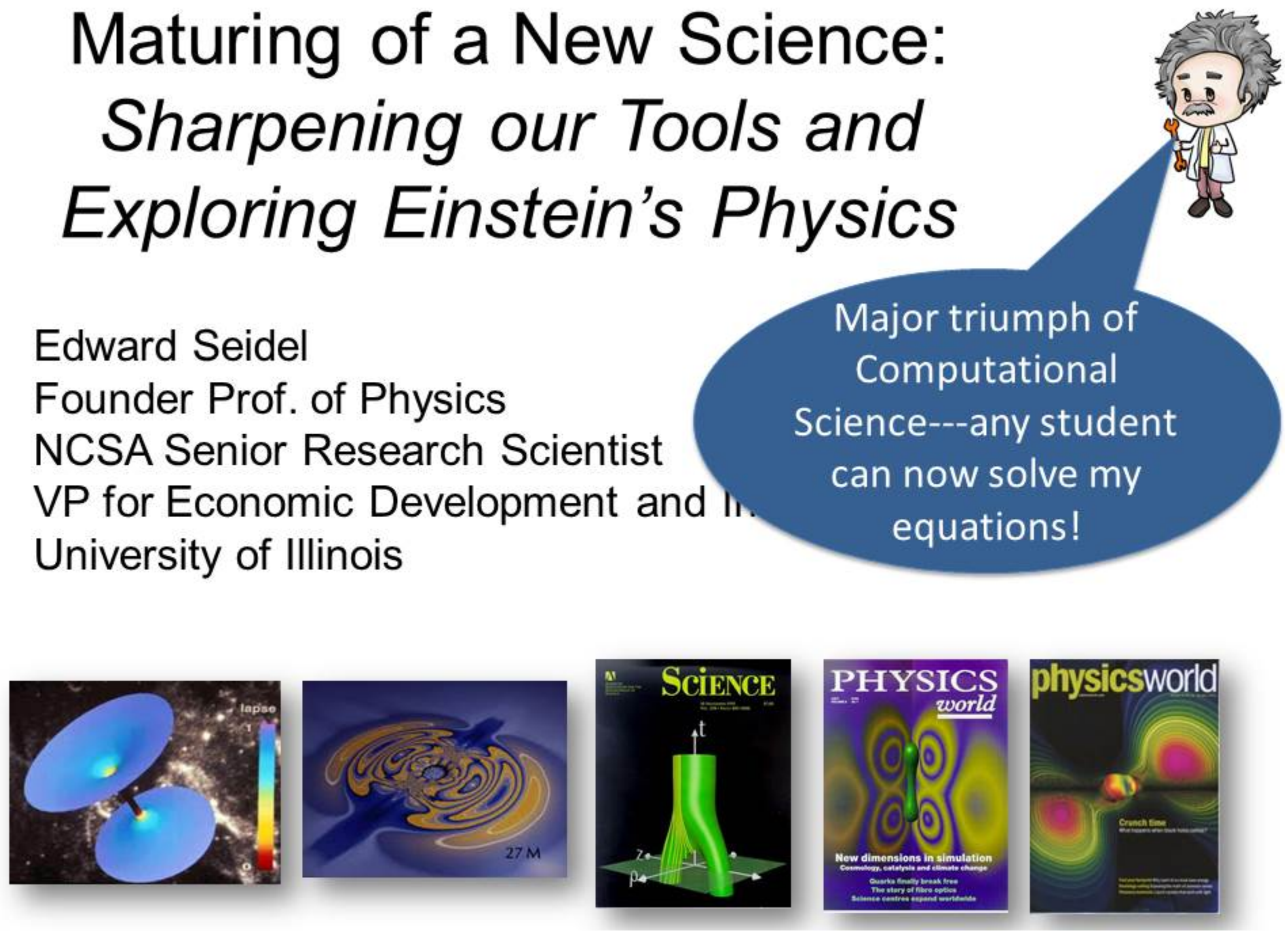
It was a milestone representing the output of a computer program they got to run all the way to black hole merger. One of the review talks described how they would "puncture" the codes to remove the singularities (the two black holes both have infinite values in the computer program and this must be managed somehow).

Recollections of 2005 breakthroughs in numerical relativity

Seidel described his epiphany at discovering numerical diffusion, because it allowed his codes to run stably.

Progress of numerical relativity in the 1980s and 1990s

They showed many pictures of all these people, and spoke to each of their key contributions in getting the codes to run. They said nowadays, a graduate student has access to well-developed general relativity computer codes and is now free to solve any problem in numerical relativity. The development of CACTUS relativistic software package was a milestone in the field.



Weiss and Barish recapped their Nobel lecture (Thorne was absent; Barish was the LIGO director), and the first thing they said was that they were only representatives of hundreds of people.

Nobel lecture 1. Weiss

Nobel lecture 2. Barish

They talked about the early concepts at Chapel Hill, and the interferometer design, and the numerical simulations. But they also called out program managers and directors of the NSF. It really seemed like a relay race, and everyone did their part to carry the baton. If anyone at the NSF had lost their nerve at any time, that would have been the end. They showed pictures of many people and talked about their contributions. It expressed the humanity of it all, and really seemed like the human race was at its best, here.

The CalTech LIGO proposal from 1989 and key team members

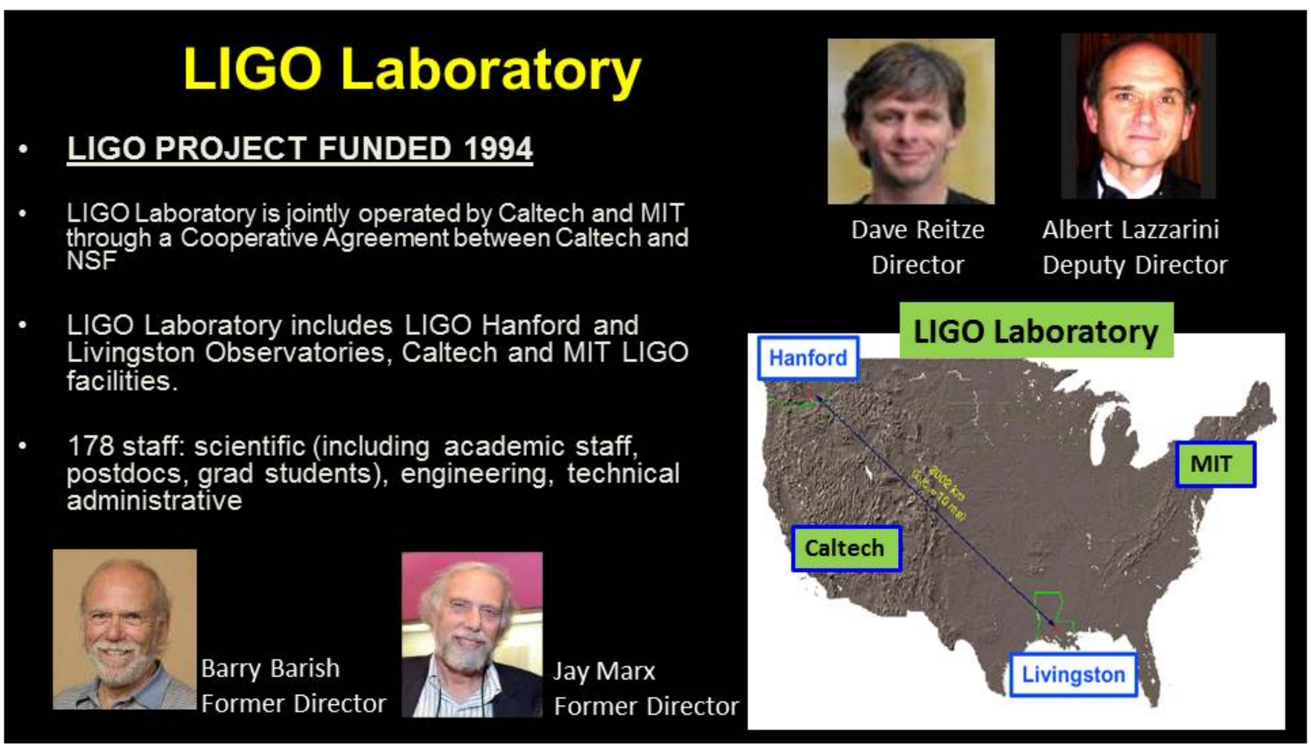
The NSF funded this over decades! Can you imagine such a commitment today? Many times the hounds were on their heels, but successive NSF directors believed in the enterprise and kept it going. There was hostility from the telescope community because LIGO was an "observatory", and therefore competed with telescope observatories. As they made improvements, they had to be careful not to call it "LIGO 2", in case someone thought another LIGO was being funded, which would provoke outrage.

NSF Directors critical for LIGO

Eric Block

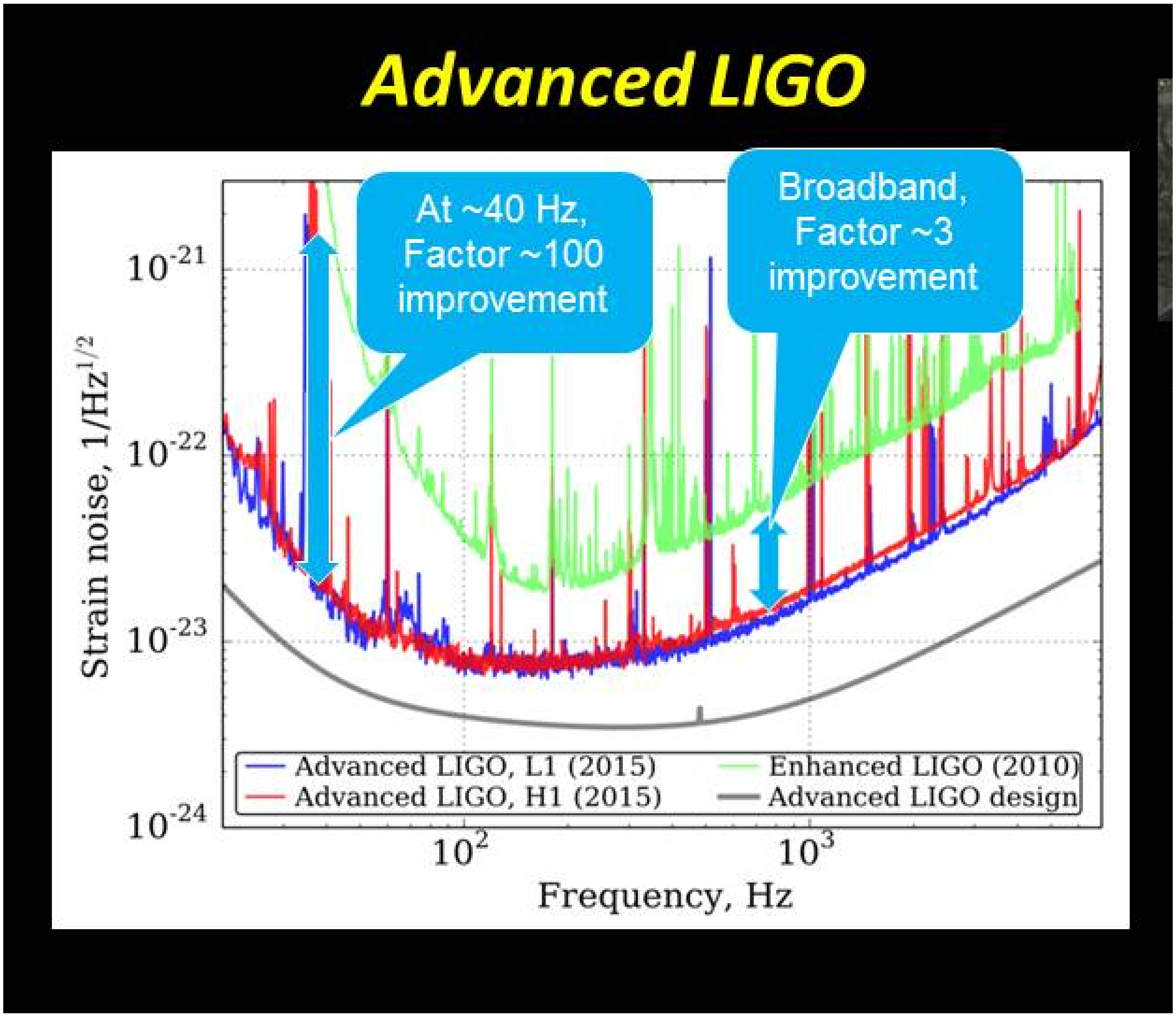
Walter Massey

Neal Lane



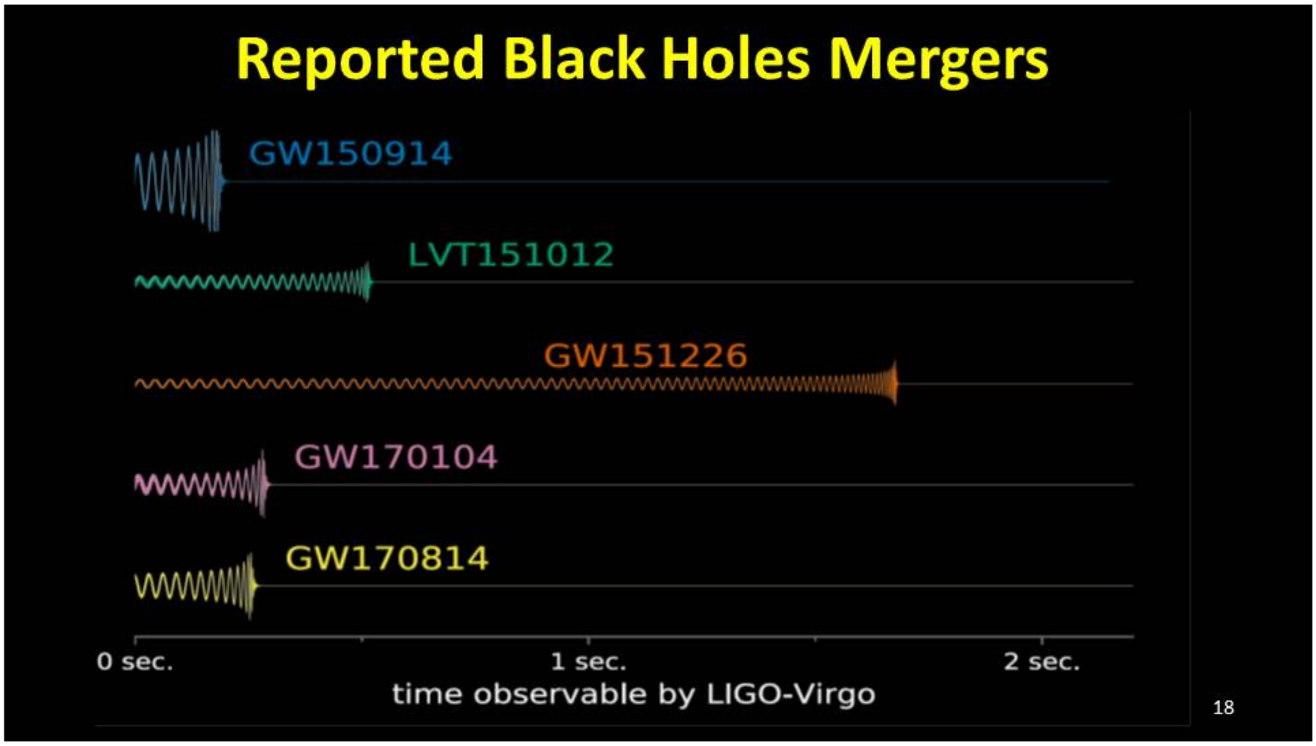
LIGO today. It's two observatories at Hanford and Louisiana

NSF funded LIGO for years without an observation. When they made their latest improvements, called Advanced LIGO, the increased sensitivity increased the volume of the universe detected and -- bang! -- they had an observation in weeks.

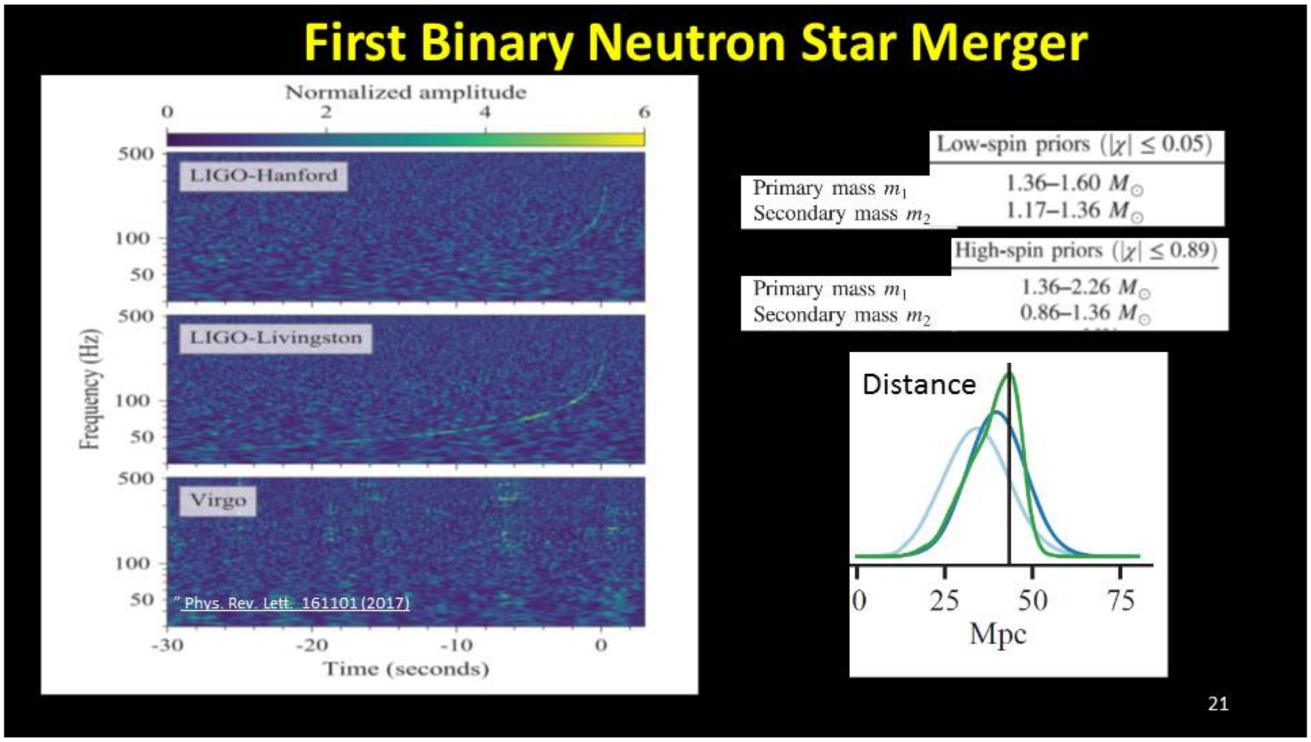


The improvement in sensitivity called Advanced LIGO that yielded the discovery in only weeks, after years of searching before

The rapidity made people skeptical, but as you see deeper into the universe, you pick up more events with the greater volume of space. Now they are already up to 5 or 6 black hole mergers.


Reported Black Holes Mergers
GW150914
LVT151012
GW151226
GW170104
GW170814
0 sec.
1 sec.
2 sec.
time observable by LIGO-Virgo
18

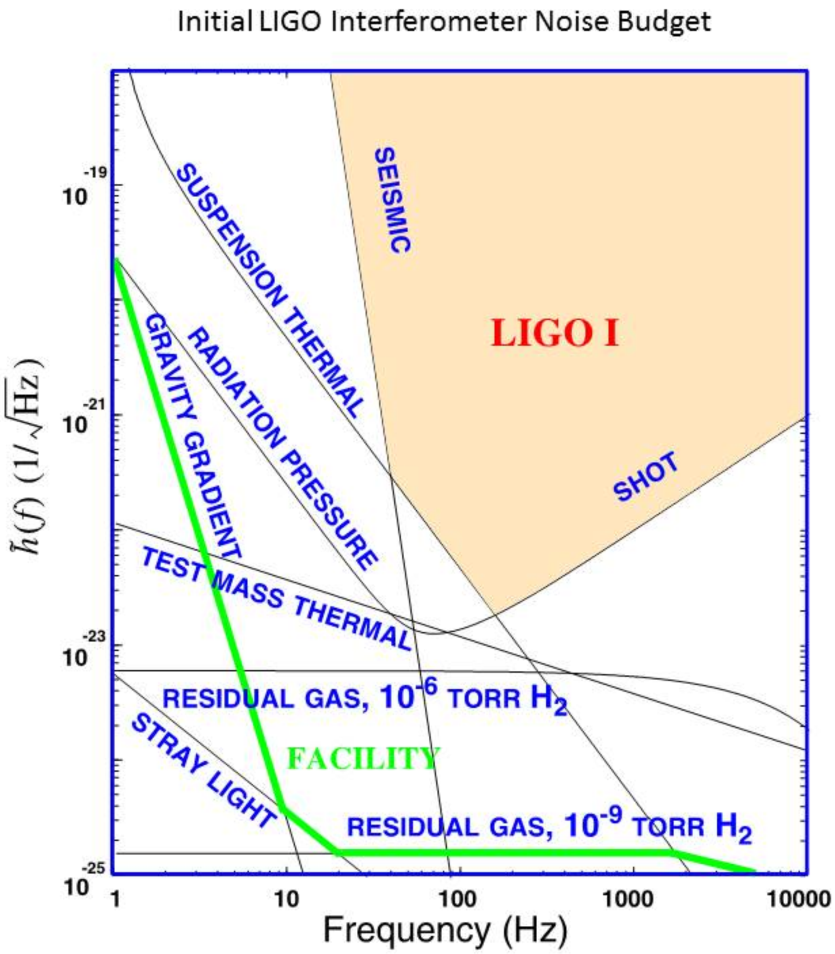
And now the first neutron star merger!



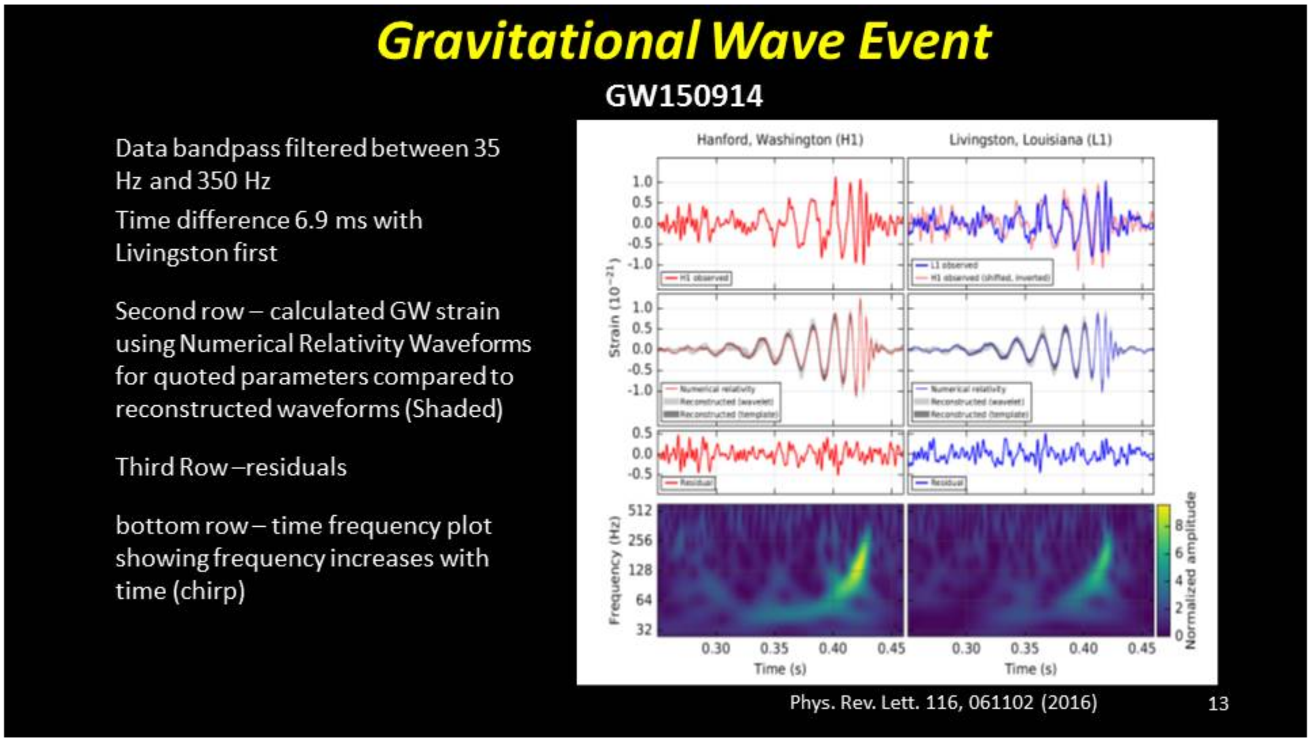
It reminds me of the exoplanets. Just a few years ago we got the first one, and now we are up to 4000 or so.

Other gravitational wave detectors are coming online, now, notably VIRGO, and so they are able to do better directional inferences with simultaneous detectors.

Here is a picture giving a sense of their exquisite noise budget:



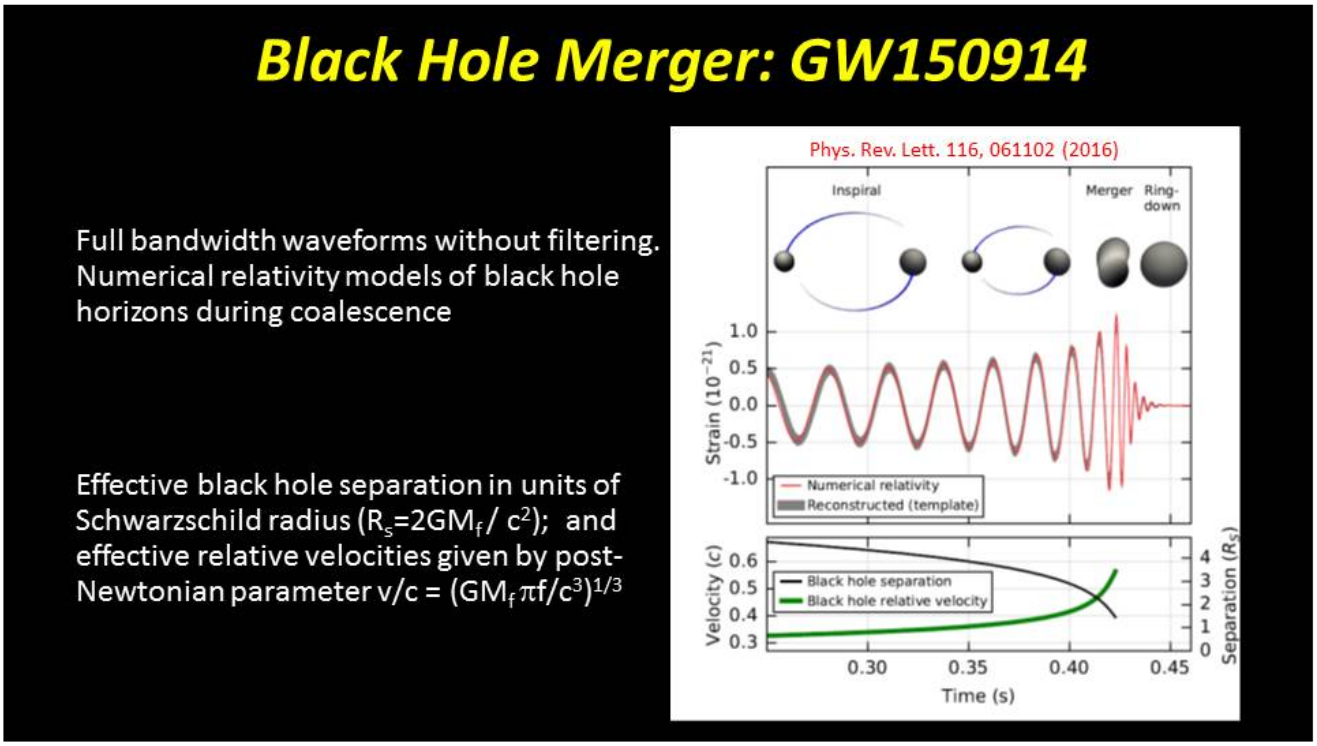
They speak about their measurements in terms of bandwidth, and they can only see a range of frequencies. The compact object mergers express themselves as a chirp, with the signal moving from low to high frequencies. Here is the first detection event that won the Nobel.



The observation that won the Nobel Prize. Chirp is in the lower 2D heat diagrams.

Their current "bandwidth" can see only when these black holes are 100 km apart and moving at 60% of the speed of light, for a total duration of 200 milliseconds. As they increase bandwidth, and see more low frequencies, they will begin to see earlier times in the mergers.

Here is another plot of the first event, showing what the measured signal looks like, compared with a diagram showing the merger.



Perfect match between theory and prediction. The waves represent "motion of the beads" vs time, overlaid with a picture of the black hole phases at that moment. You can see the chirp at the end

In the plot above, look closely: the theory and data are overplotted (although the data is smoothed). It seems we really do understand something about gravity.

I wish I had asked how they invert the data. To say that a particular signal is a 40-solar-mass black hole colliding with a 30-solar-mass black hole. The error bars are like +/- 5 solar masses. I imagine they have to run simulations with a range of parameters and then match to the data. With the complexity in the numerical simulations described above, it seems like data inversion is a monster.

They are also coordinating with electromagnetic astronomers so when they see a merger event, they can point the telescopes and look for optical signatures. Also, they are using gravitational waves to measure the Hubble constant. There is currently a "crisis" in cosmology because the Hubble constant values measured by the supernova groups and by the cosmic microwave background groups disagree by more than their error bars (but it seems like more of a toothache than a crisis to me). We are really in the golden age of observational astronomy these past 20 years. (The LIGO Hubble constant measurement has large error bars and agrees with both measurements).

All of astronomy so far since the ancient world has been through electromagnetic radiation: visible light, xray, gamma ray, radio, UV, IR, etc. This is the first time we have harnessed a wholly different force from electromagnetism: the force of gravity. There are only 4 forces known to science, and two are electromagnetism and gravity (the other two are microscopic forces inside the nucleus). I compare the gravitational wave detection with the detection by Heinrich Hertz of electromagnetic radiation in 1887, after Maxwell predicted it in 1865. It seems our species has achieved a real milestone of evolution, to be able to "see" gravity. We evolved electromagnetic eyes, but obviously we didn't evolve gravity eyes. Yet our minds were able to see it and conceive it ... words fail me.

Another thing that struck me was how aged these people are now. The generation that tutored under the giants of 20th century physics such as Dirac and Feynman, are the ones that conceived and executed LIGO over 50 years. Now they are aged, and their precious wisdom will be in some sense lost to humanity. I wonder who will take their place, and the question seems especially poignant since science itself is now under attack in swaths of the developed west. The World War II generation not only saved democracy and invested in rebuilding the world after, they also invested in scientific exploration. It came as natural to them as the idea that the Air Force could do things for the good of mankind. But now it seems unthinkable we would invest over decades for our children to make discoveries.

A final observation is that the group of gravitational physicists and astrophysicists looks like America. There is great cultural, ethnic, and gender diversity. This is very different from my experiences in a related research field in the 80s and 90s. There were always a few women, but then they trended older. Today it feels like women are well represented among the faculty and there are many young women students. Cecile would no doubt be at home.

This was the centennial of Richard Feynman's birth, and he is arguably the most brilliant, but definitely the most-loved, physicist of the late 20th century. So they had some memorial Feynman sessions.

Feynman after 40

In fact, no physics conference seems to be able to resist a Feynman tribute session. But one of the historians showed a picture of the audience at Feynman's famous Caltech undergraduate lectures from 1963:

Students respond to Richard Feynman (far right) during one of his lectures in 1963. (Photo from Realites/Courtesy of Caltech Archives.)

Women undergrads were not admitted to Caltech until 1970.

It seems like we have come a long way since 1957: scientifically, technologically, culturally, and now in our galactic reach as a species.

Postscript:
After returning home from APS, I noted the obituary of Cecile DeWitt-Morette in the February 2018 Physics Today. She died in May 2017, after the detection was announced. She was best known for establishing the Les Houches School of Physics in the French Alps, where a generation of gravitational physicists was cultivated.