Getting to know gravitational waves

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Big Questions

- Do gravitational waves exist?
- Can we invent a feasible GW detector?
- Can a GW detector be sensitive enough?
- How can we know that we have detected a GW?
- What can we learn about the universe from the features of a gravitational wave signal?
Einstein and relativity

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

No information can be transmitted faster than the speed of light, 300,000 km/s.

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 in space and time, but instead is built into the actual structure of space and time.

Space and time are curved; nothing can avoid feeling that curved structure. That is what makes gravity universal.
Gravitational waves

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

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

Gravitational changes “ripple out” from an accelerating 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 accelerate, 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 1916 prediction left many doubts …

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

Could the waves be a coordinate effect only, with no physical reality? Einstein didn’t live long enough to learn the answer.
The Chapel Hill Conference

In January 1957, the U.S. Air Force 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.

The “gravitational wave problem” was solved there, and the quest to detect gravitational waves was born.
Where people were stuck

People were trying to understand the generation of gravitational waves.

For ex.: Solve the equations of motion of a binary star, and try to show that they generated waves that couldn’t be transformed away.

This was hard. People were still at work on it when Hulse and Taylor found the binary pulsar in 1974.

But, what about thinking instead about detecting gravitational waves?
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 set of neighboring freely-falling test masses
They respond in a measurable way to a gravitational wave

Neighboring test masses exhibit genuine relative motions.

“Just” need to find a way to implement the measurement, with sufficient sensitivity.
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.”
Joe Weber was at Chapel Hill

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

Joe gave a less-than-clear talk at Chapel Hill, and was critically questioned by Bondi.

The very next talk was Pirani’s. We can tell that Joe listened very well.
Joe Weber, 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.

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. PZTs 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 Bob Dicke
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

Weiss thought about 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. \( \Delta L/L \sim 10^{-21} \) could be achieved.
The greatest unpublished paper in 20th century experimental physics?

Rai never published this paper. It appeared in a Quarterly Progress Report for MIT’s Research Lab of Electronics:

https://dspace.mit.edu/handle/1721.1/56271

It lays out a plausible design for a kilometer-scale interferometric detector. Most importantly, it gives a tour de force analysis of almost every noise source that needs to be taken into account.

LIGO was born right here.
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.
The road toward GW150914

In the wake of the collapse of Weber’s claims, people didn’t give up.

Several groups continued to develop Weber bars, cooling them to reduce Brownian motion; a big improvement, but couldn’t see signals as small as $10^{-21}$.

Meanwhile, several other groups (at Garching, Glasgow, Caltech as well as in Weiss’s group at MIT) began serious development of interferometers.
The essential role of Caltech

Kip Thorne became convinced that gravitational wave detection was
- possible, and
- likely to provide tremendous new information for physics and astronomy.

He convinced Caltech to make a sustained commitment to developing gravitational wave interferometers. Ron Drever (from Glasgow) was hired to lead the experimental effort.

This was the essential foundation for LIGO.
Issues in 1981

Can instruments be made that are sensitive enough to detect gravitational waves?
If so, to detect them routinely with high SNR?
NSF 1981 grant for engineering study of big interferometers

NSF funded a design study of long-baseline interferometers, led by Weiss at MIT.

The study report concluded that:

- Good sensitivity could be achieved by building multi-km interferometers.
- Engineering demands were reasonable.
- Cost would be substantial but not unreasonable.

In other words, a good scientific opportunity.
Presentation of the Blue Book

At NSF’s urging, Caltech group joined with MIT to present this design study (the “Blue Book”) to NSF’s Advisory Committee for Physics in late 1983.

It got a respectful hearing as a white paper. But, along with its vision were weaknesses:

- Too conservative on interferometer technology
- Silent about social organization of project
- Budget was seriously underestimated.
The task of the 1980’s

Could a credible proposal for interferometric detectors be written?

Yes.

It became possible through:

- Serious alliance of groups at Caltech and MIT.
- All-in commitment of Caltech.
- Appointment of Robbie Vogt as Director.
1989 Proposal

A convincing proposal
Still, even after strong reviews, intense lobbying was required.
Successful!
  May 1990 -- NSB approval
  Fall 1991 -- Congress approves LIGO construction
Critique of the 1989 proposal

The instrument proposed was enormously ambitious. And yet, it wouldn’t be sensitive enough to guarantee that we could detect any known source. Either:

- We’d have to be lucky, and find an especially strong source of gravitational waves, or
- We’d have to learn how to design/build an instrument 10x more sensitive, and come back for a substantial new infusion of funds.

(The second option was the one that came true.)
LIGO was built, and worked!

LIGO facilities at Hanford, WA and Livingston, LA were successfully completed by the end of 1999. By 2005, the commissioning team had reached design sensitivity. LIGO searched the skies through 2010, collecting well over a year’s worth of coincident data.
LIGO Noise Spectrum

Best Strain Sensitivities for the LIGO Interferometers
Comparisons among S1 - S5 Runs
LIGO-G060009-03-Z

- LLO 4km - S1 (2002.09.07)
- LLO 4km - S2 (2003.03.01)
- LHO 4km - S3 (2004.01.04)
- LHO 4km - S4 (2005.02.26)
- LHO 4km - S5 (2007.03.18)
- LIGO I SRD Goal, 4km
Pattern of oscillations from black hole inspiral and merger

Credit: UMD/AEI/Milde Marketing/ESO/NASA
Finding a signal

Matched filtering lets you search for a weak signal buried in noise.

Cross-correlate the noisy with a template that has the shape of an expected signal.

Dual strategy: Hope for a “golden event”, but be ready for a small one.
Good news and bad news …

Good news: LIGO worked as designed.

Bad news: The gravitational wave sky was not a lot brighter than expected.

Good news: The LIGO team had learned how to design an instrument that could be more sensitive (by ~ x10), and thus would be able to see predicted signals.

The Advanced LIGO (aLIGO) proposal was submitted in Jan 2003, alongside the commissioning and running of Initial LIGO.
Then, in the final weeks of Initial LIGO’s observing run …

What??? Were these coincident signals really a gravitational wave detection?
Did the signal match what we expected from a real binary?
Yes! Subtract the best-fit template, and there’s nothing left.
It was almost a 5 sigma event.
We wrote a paper describing the discovery, and voted to publish

Evidence for the Direct Detection of Gravitational Waves from a Black Hole Binary Coalescence

The LIGO Scientific Collaboration\textsuperscript{1} and The Virgo Collaboration\textsuperscript{2}

\textsuperscript{1}LIGO \textsuperscript{2}Virgo

( RCS Id: detection.tex,v 1.81 2011/03/09 19:03:31 ajw Exp ; compiled 9 March 2011)

We report the observation of a gravitational-wave signal in data from a joint science run of the LIGO, Virgo and GEO 600 detectors. The signal exhibits the characteristic chirp waveform expected from a compact binary coalescence, and its form indicates a source with component masses 5.4 \(-\) 10.5 $M_\odot$ and 2.7 \(-\) 5.6 $M_\odot$ at a distance of less than 60 Mpc. There is strong evidence that the more massive component is a black hole with significant spin. The estimated false alarm rate for this event is 1 in 7000 y, and detailed checks show no evidence that it is an instrumental artifact.

LIGO-P1000146-v16 -- Circulation restricted to LSC and Virgo members

PACS numbers: 04.80.Nn, 04.25.dg, 95.85.Sz, 97.80.-d
But, was it a blind injection, inserted just to test us? The “envelop”, please …
The Blind injection team provided TWO triple coincident signals during S6---

One NS-BH inspiral (the big dog) and one short-lived pulsar signal.

In addition to the two coincident injections listed below, there were a few ultra-low SNR tests and a few single-detector transient injections when the other detectors were not in science mode.
Injected a blind inspiral around GPS 968654558 in L1, H1 and V1.

- Mass 1 = 24.8140793 Msun
- Mass 2 = 1.73517299 Msun
- Distance = 9.74132919 Mpc
- Right Ascension = 0.241240293 rads
- Declination = -1.28577304 rads
- $t_C$ at Geocentre = 968654558.0
- $t_C$ at Hanford = 968654558.011451630
- $t_C$ at Livingston = 968654558.005227478
- $t_C$ at Virgo = 968654558.014196834
- Network SNR = 18
Proof that we were ready to find gravitational waves

We’d passed the test of the blind injection program. But we hadn’t discovered an actual gravitational wave.

Sigh …

We spent 6 months of our lives practicing the whole scientific and social process of making a detection of gravitational waves.

Was it worth it? I think so.
Fast forward to 2015 Sept 14

Advanced LIGO commissioning had gone well. The instruments already had 3x better sensitivity than Initial LIGO.

We were ready to start observing run O1, but were finishing a few last tasks in engineering run ER8. Search pipelines were running on clean data.
This email arrived, and all hell broke loose.

From: Marco Drago <marco.drgo@aei.mpg.de>
Sent: Monday, September 14, 2015 6:56 AM
To: burst@sympa.ligo.org
Cc: cbc@ligo.org Binaries Group; The LIGO Data Analysis Software Working Group; Calibration; dac@sympa.ligo.org; <burst@ligo.org>; <detchar@sympa.ligo.org>; losc-devel@ligo.org; lsc-all@ligo.org
Subject: [CBC] Very interesting event on ER8

Hi all,
cWB has put on gracedb a very interesting event in the last hour.
https://gracedb.ligo.org/events/view/G184098

This is the CED:
https://ldas-jobs.ligo.caltech.edu/~waveburst/online/ER8_LH_ONLINE/JOBS/112625/1126259540-1126259600/OUTPUT_CED/ced_1126259420_180_1126259540-1126259600_slag0_lag0_1_job1/L1H1_1126259461.750_1126259461.750/

Qscan made by Andy:
https://ldas-jobs.ligo.caltech.edu/~lundgren/wdq/L1_1126259462.3910/
https://ldas-jobs.ligo.caltech.edu/~lundgren/wdq/H1_1126259462.3910/

It is not flag as an hardware injection, as we understand after some fast investigation. Someone can confirm that is not an hardware injection?
Everyone noticed

My Inbox had 50 messages with the subject line “Very interesting event on ER8” in just the first 24 hours.

This was just the beginning of 5 months of intense work.
This is what we saw

Hanford, Washington (H1)  Livingston, Louisiana (L1)

It was a genuine 5-sigma event
We were ready to find GW150914 because of the previous blind injection exercise.

BUT, the biggest obstacle to establishing belief in this genuine event was precisely that everyone thought it could be another blind injection exercise.

Establishing that GW150914 was not another test (or worse, a hack) occupied a great deal of attention.
On 18 Sept, a demand that the LIGO Directorate issue a “categorical statement”

Hi Dave, Gaby, Albert,

It is looking more and more like Monday’s event is real. Stefan and Josh have been performing investigations as to whether or not this could be a blind or malicious injection and their conclusion is that it is not (or that whoever did it is much better at injecting than everyone else who has tried to inject signals). I would like to see Christian, Michal, and Jeff confirm that they did not do this.

At this point, decisions are being made that affect people’s lives. Besides the personal strain on people working long hours (for good reason, if it is real!), there are other important things being dropped (students dropping classes to spend more time on analysis, faculty dropping the ball on departmental responsibilities, etc.)

I don’t think it is fair to carry on any longer if this is a blind injection. We have already learned several sociological lessons about the collaboration. To quote Peter: we shouldn’t destroy the village to save the village.

Is the LIGO Directorate prepared to make the categorical statement that this is NOT a blind injection and to the best of our knowledge this could be a real signal?

Cheers,
Duncan.
40 minutes later, the reply

Duncan,

This is *not* a blind, double blind, or supersecret triple blind injection. I am not yet convinced that we have completely ruled out a malicious injection; that will need to get more attention as we go forward. That caveat aside, so far so good.

Best,

Dave
It took five months to finish the checks and write the discovery papers
Getting “up close and personal” with black holes

Credit: B.P. Abbott et al., *PRL* 116, 061102 (2016)
Here’s what we learned

VIII. CONCLUSION

The LIGO detectors have observed gravitational waves from the merger of two stellar-mass black holes. The detected waveform matches the predictions of general relativity for the inspiral and merger of a pair of black holes and the ringdown of the resulting single black hole. These observations demonstrate the existence of binary stellar-mass black hole systems. This is the first direct detection of gravitational waves and the first observation of a binary black hole merger.
The sky is ablaze with gravitational waves

We found a second event during O1, another black hole binary called GW151226.

We’re about to start the O2 run. At LLO, we’ve reached 40% better sensitivity. (If it can operate at that level in a sustained way, it can survey 3x greater volume of space than in O1.)

At design sensitivity, aLIGO may see events like this daily (with some high SNR events), and perhaps other kinds of signals too.

Stay tuned!