Astronomers have finally found evidence of gravitational waves. Now things can get interesting.

(From *Discover* magazine)

After 100 years of theory and decades of experiments, astronomers have detected gravitational waves directly for the first time. The announcement, made Thursday by the Laser Interferometer Gravitational-Wave Observatory (LIGO) and accompanied by a paper in Physical Review Letters, describes a powerful signal that ultimately began with the merger of two black holes located 1.3 billion light-years away. The finding not only confirms yet another aspect of Albert Einstein's theory of gravity, known as general relativity, but it also opens another avenue for researchers to observe and study the universe.

"We have detected gravitational waves. We did it," said David Reitze, executive director of LIGO, at a conference Thursday at the National Press Club in Washington D.C. "I am so pleased to be able to tell you that."
Before crashing together, the black holes were 36 and 29 times the Sun's mass. Afterward, the new combined black hole has only 62 solar masses, with the colossal difference — 5,000 supernovas' worth of energy — radiated away as gravitational waves.

Gravitational waves are literally distortions in space-time, ripples in the fabric of the universe. Gravity is the weakest of the four fundamental forces, so only the most extreme events — black holes colliding, neutron stars twirling, a supernova erupting — would produce detectable waves. LIGO's twin detectors, in Louisiana and Washington state, use lasers to watch for these tiny stretches and squeezes of space-time.
These ripples open a new window on the universe, allowing astronomers to hear in the darkest regions of space where telescopes yield no information. Black holes, for instance, are infamously impossible to observe directly; they emit no light. But with gravitational waves, astronomers can probe the very heart of the singularities. They will discover black holes completely invisible to traditional observatories — and surely new surprises as well.

"Imagine the instrument as a giant ruler," says Marco Cavaglià, a University of Mississippi astronomer and assistant LIGO spokesman. "We measure distance along two perpendicular arms, and if these distances change, then we can see it with the laser light." Although the gravitational waves are incredibly weak — only enough to warp the distance between Earth and the Sun by the width of a hydrogen atom — LIGO's instruments are extremely sensitive.

Detection of gravitational waves, which were initially predicted in 1916, follows months of rumors. Just a week after the newly upgraded LIGO went online, popular (and unaffiliated) physicist Lawrence Krauss tweeted that he heard about a gravitational wave detection. About a month ago, another tweet from Krauss doubled down on the finding, sending rumors into overdrive. All official sources declined to comment until Thursday's announcement.

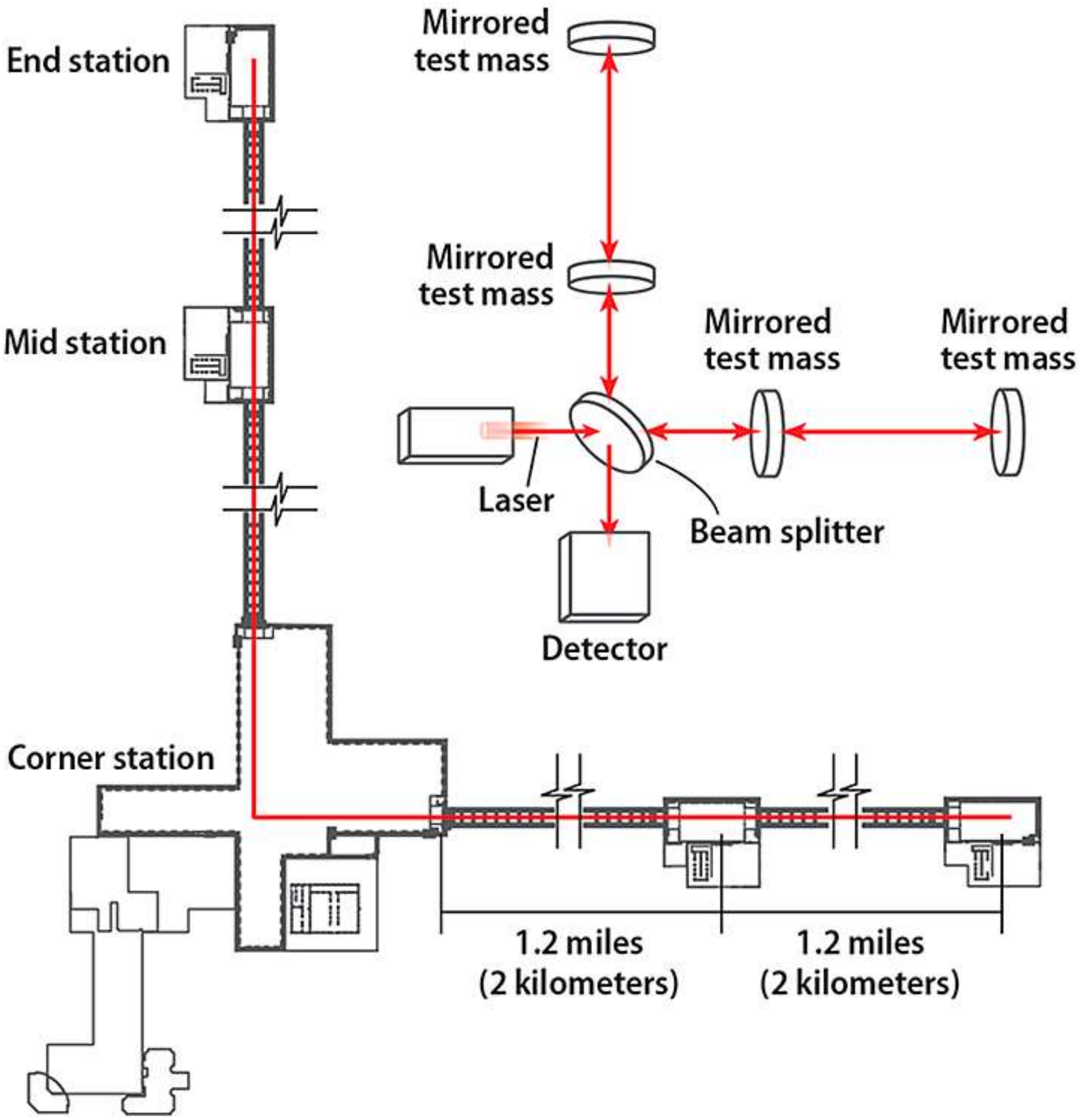
It's not hard to see why: This is one of the biggest scientific discoveries of the decade, if not the century. There's already talk of Nobel prizes for the discoverers. And with the stakes so high, the science must be accurate, especially given other recent ground-breaking announcements that later turned out not to be true.
Assuming these findings hold up, it's an exciting time in astronomy. Gravitational waves can now serve as another way to scour the cosmos, akin to being able to see a new colour. It's impossible to say what discoveries await in the coming gravitational wave era, but every time astronomers have found a new way to observe, breakthroughs have soon followed.

In 1865, James Clerk Maxwell predicted that light travels in waves, but humanity needed Heinrich Hertz's first radio transmitter to unleash modern technology and unveil new types of cosmic phenomena. In terms of historical significance and future potential, detecting gravitational waves had been one of the most anticipated discoveries in modern science. "It is, of course, the great hope of all the astrophysicists involved here that this new window will allow us to see things that one has not even thought of before," says Albert Einstein Institute senior scientist Albrecht Rüdiger, who spent his entire career developing detectors.

Astronomy: Roen Kelly; Portrait: Oren Jack Turner/Library of Congress, Prints & Photographs Division

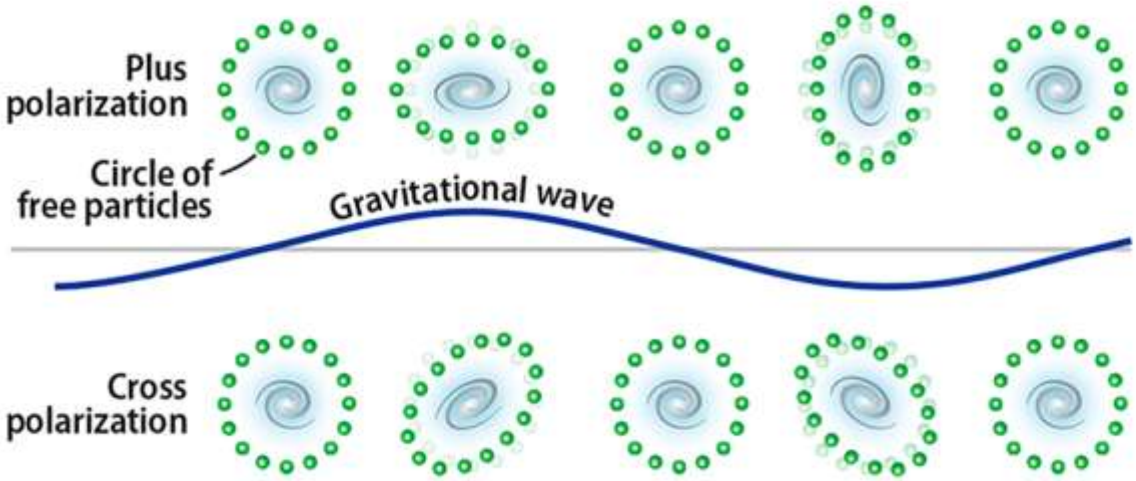
A most violent affair

The idea of gravitational waves began with Einstein's theory of general relativity, and his realization that gravity was simply the warping of the fabric of space-time by massive objects. He figured out that massive moving objects would create ripples in this fabric, like a child's bounce on a trampoline. What's more, these ripples would propagate at the speed of light throughout the universe.



This diagram shows the layout of the observatory in Hanford, Washington. By making laser light travel up and down the arms and interfere with itself, scientists can deduce minute changes in the light's path from a gravitational wave encounter. *Astronomy*: Roen Kelly

At the center of LIGO's equal-length, L-shaped arms sit a laser source and a device that splits the beam in two, sending the light racing toward mirrors at the end of each arm. Normally, light takes the same amount of time to travel back and forth along both arms, and scientists can study the laser's pattern of electromagnetic waves to test this. The peaks and troughs of the light's waves should line up when the two beams meet again at the crux of the L.



Astronomy: Roen Kelly

But when a gravitational wave passes, the bunching and squeezing of space-time stretches one arm while compressing the other, changing the distance the light has to travel. Now, when the laser beams rejoin, scientists see interference in the light's pattern, a jarring mismatch of peaks and valleys that spill the secrets of gravitational waves — if scientists can read through the static of local noise that can also jiggle the mirrors and mar the signal.

And just as stars, supernova explosions, and the Big Bang's fading glow all give off different frequencies of light, they also send out different frequencies of gravitational waves. "The most extreme events in the universe — colliding supermassive black holes — give off a hum 10,000 times deeper than whale song, too deep for LIGO to hear. Neutron stars are dense stellar corpses with masses "only" a little larger than the Sun crammed into a city-size sphere. Their crashes chirp at frequencies more or less within the range of a piano, and the stellar mass black hole collision announced Thursday falls into a similar range.

Joseph Taylor, who discovered gravitational radiation in 1978, won the Nobel Prize in physics 15 years later.
Nobel Prize

Q&A with Joseph Taylor

Learn about gravitational waves in this **interview** with the Nobel Prize winner.
LIGO was built specifically to search for compact binary objects. These include pairs of neutron stars, pairs of stellar mass black holes or one of each. But both involve dense objects locked in a death spiral toward one another. Astronomers can watch neutron stars orbit each other for many years using more traditional observatories, and all the while, energy leaks away from the system in the form of invisible gravitational waves. Joseph Taylor and Russell Hulse won the 1993 Nobel Prize in physics for showing such binary neutron stars radiate gravitational energy — an indirect proof of gravitational waves.

"LIGO senses those last few minutes or seconds of the waves generated just before the objects crash into one another," explains Patrick Brady, a professor at the University of Wisconsin-Madison and a member of the LIGO collaboration. LIGO begins to hear the impending collision once the orbits tighten to about five times per second. At that point, the gravitational waves reach a frequency of 10 hertz, or cycles per second, the low end of its range. And in the few minutes left in their lives, the tightening spiral causes both the frequency and strength of the gravitational waves to increase. “That means they sweep right through the most sensitive band of the LIGO instruments,” Brady says.

But the sensitivity of those instruments means astronomers hear plenty of local chatter as well. Nearby highway traffic, waves lapping at the shore of the Gulf of Mexico, or a tree falling in the forest near the Louisiana site can all swamp the gravitational waves. Major earthquakes anywhere in the world can knock LIGO offline completely.

Cavaglià likens the task to hunting through static with a car’s radio dial for a clear station. “At a certain point, you find a station because you know you hear a voice. Your brain has the template of the voice, and you are able to recognize that there is a signal there,” he says.

Researchers have expanded their theories from Einstein’s basic framework to detailed models of what the pattern of a gravitational wave should look like. By comparing the data streaming in to models of different potential sources, researchers can pick out the voice of cosmic gravity from the static of earthly mumblings. And the signal they heard was both clear and complete, encompassing not just the insprial and collision, but what’s called the “ringdown,” the aftershock as the black hole settles into its new shape.

With only two detectors currently online, pinpointing where this object or future findings are located on the sky is a rough measure at best — but backup is on the way."

A new kind of telescope

As is so often the case, a hard-fought breakthrough marks the beginning of an entirely new race, rather than the finish line — LIGO’s work is no different. Confirming the existence of gravitational waves is like finding the switch on a flashlight after fumbling inside a pitch-black cave. Now that we know gravitational waves exist, we can use them to reveal once-hidden features in the universe. Gravitational wave detectors of the future will refine our newly discovered “sense” by broadening the range of detectable gravitational waves and pinpointing their sources.

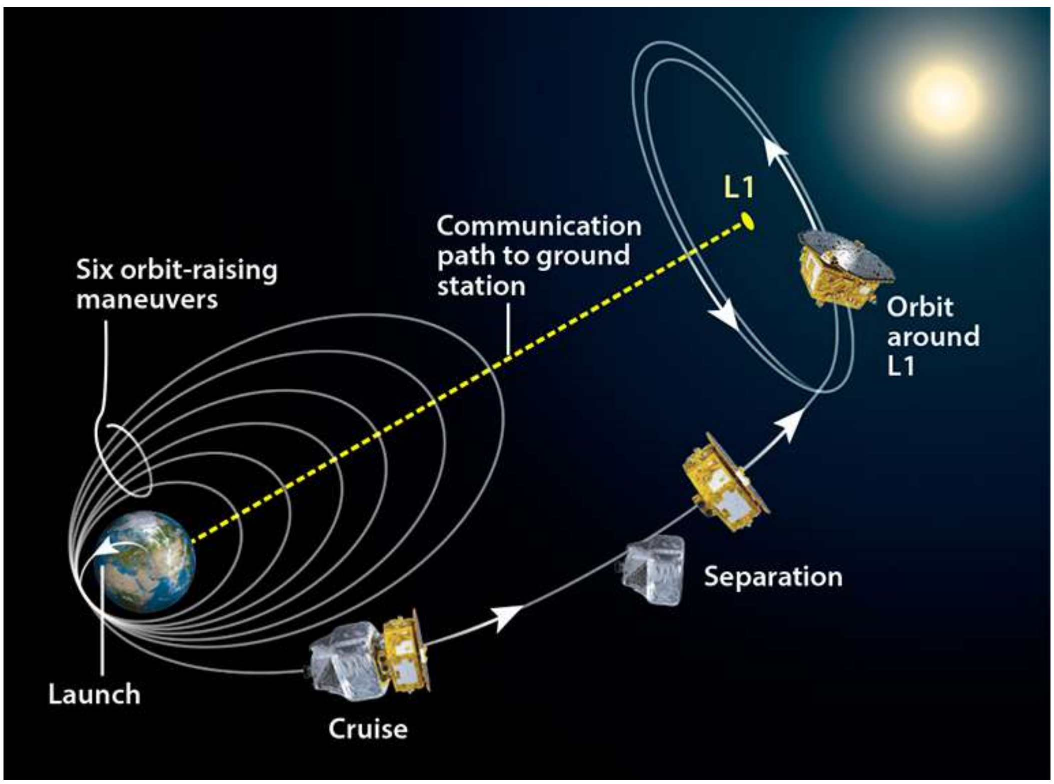
Italy’s Advanced Virgo instrument will come online this fall in conjunction with LIGO, allowing astronomers to pinpoint gravitational wave sources.

The Virgo Collaboration

Today’s ground-based instruments like LIGO and Virgo observe high frequencies, but to detect lower frequencies, we’ll need an extremely quiet place that’s sheltered from any disturbances — even gravitational forces as minuscule as those generated by a mosquito. In December, the European Space Agency launched the Laser Interferometer Space Antenna (LISA) Pathfinder into orbit 932,000 miles from

Earth. Pathfinder won’t look for gravitational waves, but it will prove that a hypersensitive, space-based wave detector is possible in the decades to come.

ESA



LISA Pathfinder launched on a proof-of-concept mission in December. The spacecraft is a flying physics lab that packs an optical laser bench with 22 mirrors and beam splitters. *Astronomy*: Roen Kelly

`"We want to make this the quietest place in the solar system," says Martin Hewitson, LISA Pathfinder scientist. "If we are able to do that, we can build a gravitational wave detector in the future."
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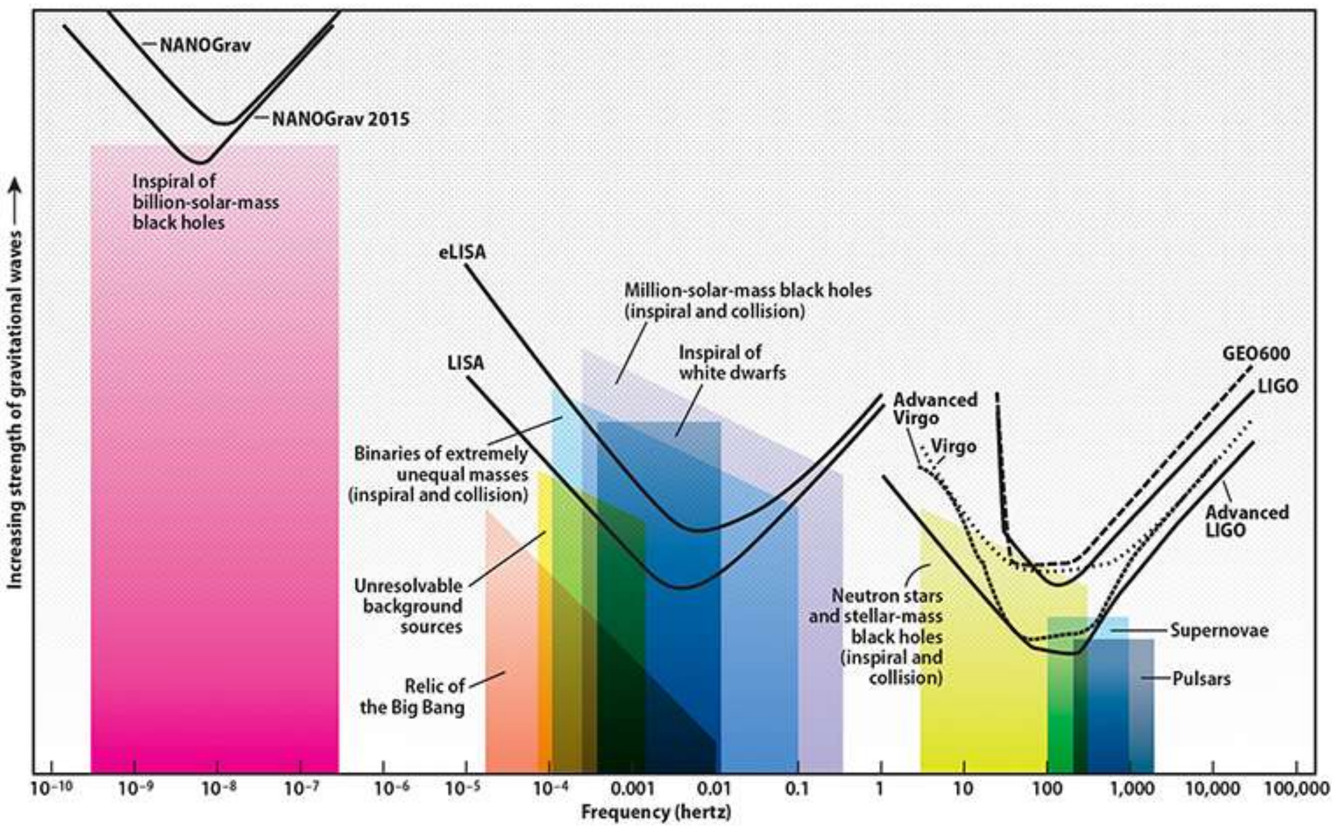
The 90-day experiment will begin March 1, and if it goes well, the findings will pave the way for eLISA, which will consist of a "mother" and two "daughter" spacecraft in an equilateral triangle connected by laser arms. The detector will pick up gravitational waves generated by binary supermassive black holes, ultra-compact binaries and small black holes falling into supermassive black holes.

The gravitational spectrum

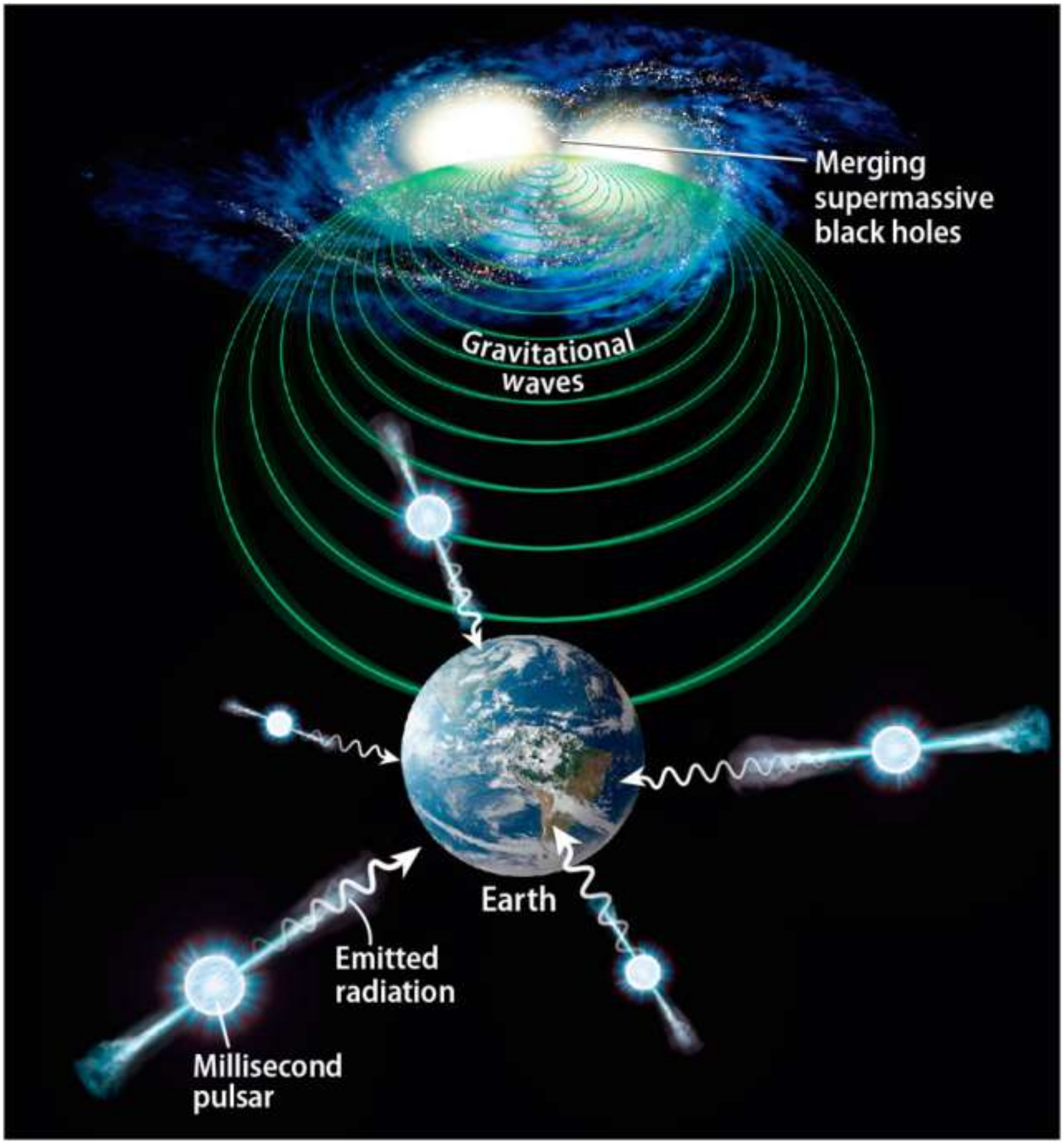


Different events produce gravitational waves of different frequencies.
This plot compares those sources against operating and future detectors.
Astronomy: Roen Kelly, after C. Moore, R. Cole, and C. Berry (Institute of Astronomy, Univ. of Cambridge

"eLISA will allow us to test fundamental concepts of black hole theory, since these signals can last very long and will allow us to sample the space-time around a black hole with unprecedented precision," says Benjamin Knispel, a physicist and spokesman for the Albert Einstein Institute in Hanover, Germany.

Astronomy: Roen Kelly

The gravity of the situation



Merging black holes, spiraling white dwarfs, and spinning neutron stars all emit gravitational radiation. For the first time, astronomers have seen one of these elusive signals.
Astronomy: Roen Kelly

Back on Earth, a number of ground-based gravitational wave detectors should turn on in the coming years. These new instruments will allow astrophysicists to triangulate the positions of waves and home in on their sources.

An upgraded version of Virgo, the European Gravitational Observatory's primary instrument in Italy, will begin observations in fall in conjunction with LIGO. Advanced Virgo's improvements will increase its sensitivity tenfold, and allow researchers to probe a volume of space 1,000 times larger than before. Virgo could pick up a gravitational wave signal once per month, or even per week, with its enhancements.

LIGO India is a proposed detector that would serve as the third in the LIGO family and could be operational by 2022. In Japan, crews have blasted and excavated tunnels in the abandoned Kamioka mine to make way for the Kamioka Gravitational Wave Detector (KAGRA). The instrument will feature two sets of 1.9-mile laser interferometric wave detectors. KAGRA is expected to detect signals from neutron star mergers every one or two months once it is fully operational in the 2020s.

The Einstein Telescope represents a third-generation detector that's still in the design phase. It would be 100 times more sensitive than current instruments. Based on the design concept, the Einstein Telescope would be buried underground to reduce noise and to form a full triangle like eLISA. The telescope would have three detectors: two for low-frequency signals and one to detect high frequencies.

With the fleet of current detectors, and detectors that are still to come, a new era in astronomy is set to begin. Equipped with an entirely new sense, we may solve age-old mysteries of the cosmos, and even cast light into its unknown unknowns.

"This is the birth of gravitational wave astronomy. We can now focus on routine observations in space," says Hewitson. "We've only been looking at the universe with our eyes, but we've never heard the universe before. It looks impressive, but imagine when you start listening."

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Even Einstein had his doubts

LIGO's detection presages the future, but it also caps off a century of speculation and hard work. Interestingly, Einstein himself was a prominent doubter. In 1936, 20 years after he introduced the concept, the great physicist took another look at his math and reached a surprising conclusion.

"Together with a young collaborator, I arrived at the interesting result that gravitational waves do not exist, though they had been assumed a certainty to the first approximation," he wrote in a letter to friend Max Born.

Einstein submitted his change of heart in a paper to the *Physical Review Letters* titled "Do gravitational waves exist?" The reviewer soon poked holes in the math, showing how Einstein's coordinate system lacked imagination when dealing with pesky singularities. Upset, Einstein took his paper to a lesser-known journal, and he was persuaded to change his mind just before publication.

Although Einstein came back around to accept the existence of gravitational waves, he still didn't expect they'd be strong enough to detect. Many physicists shared that view.

In 1959, Joseph Weber, who was also an early pioneer of the laser, became the first person to actually look for gravitational waves. The experimental physicist used an aluminum bar like a tuning fork and then waited for it to move, staring at the noise for much of a decade. By 1969, he was convinced he'd found gravitational waves. The community was skeptical.

Walter Winkler was just starting his career at the time. Together with his mentor, legendary computer scientist Heinz Billing, they flew from Germany to Pennsylvania to visit Weber. The physicist openly shared his instrument design drawings.

From 1972 to 1975, the team performed a gravitational wave search that improved on Weber's methods. Their work proved beyond any doubt that Weber was watching extraneous noise and reading patterns into it.

"I certainly do not think that he was cheating, but I think he was falling victim to his wishful thinking," says Albert Einstein Institute senior scientist Albrecht Rüdiger, who did computational work on the team.

"At that time, computers were not so common to everyone," adds Winkler. "He worked with a recorder, so he had the output of his detectors written down on long strips of paper, and he sat down watching the detectors. And if you stare into the noise, you can be sure you'll see something. He was a man, not a machine."