Opening the Gravitational Wave Window on the Universe

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Facts about the new LIGO gravitational wave observatory

- On 14 September 2015, LIGO heard the collision of two black holes by receiving their gravitational waves.
- The two black holes were each about 30 times more massive than our Sun.
- They spun around each other several times in the last few tenths of a second before they collided.
- This happened 1.3 billion light years away, 1.3 billion years ago.

Questions that you might have

- What is a black hole?
- What is a gravitational wave?
- What is LIGO? How does it work to detect gravitational waves?
- What did LIGO find?
- What kind of imaging can we do?

What is a black hole?

If enough matter is placed into a small enough place, its gravity is so strong that nothing can escape from it, not even light. It then becomes invisible – a **black hole.**

If all of the matter of the Earth were squeezed into a ball 2.5 cm in diameter, it would be a black hole.

To make the Sun a black hole, squeeze it into 6.5 km in diameter. (Its actual diameter is 1.4 million km.)

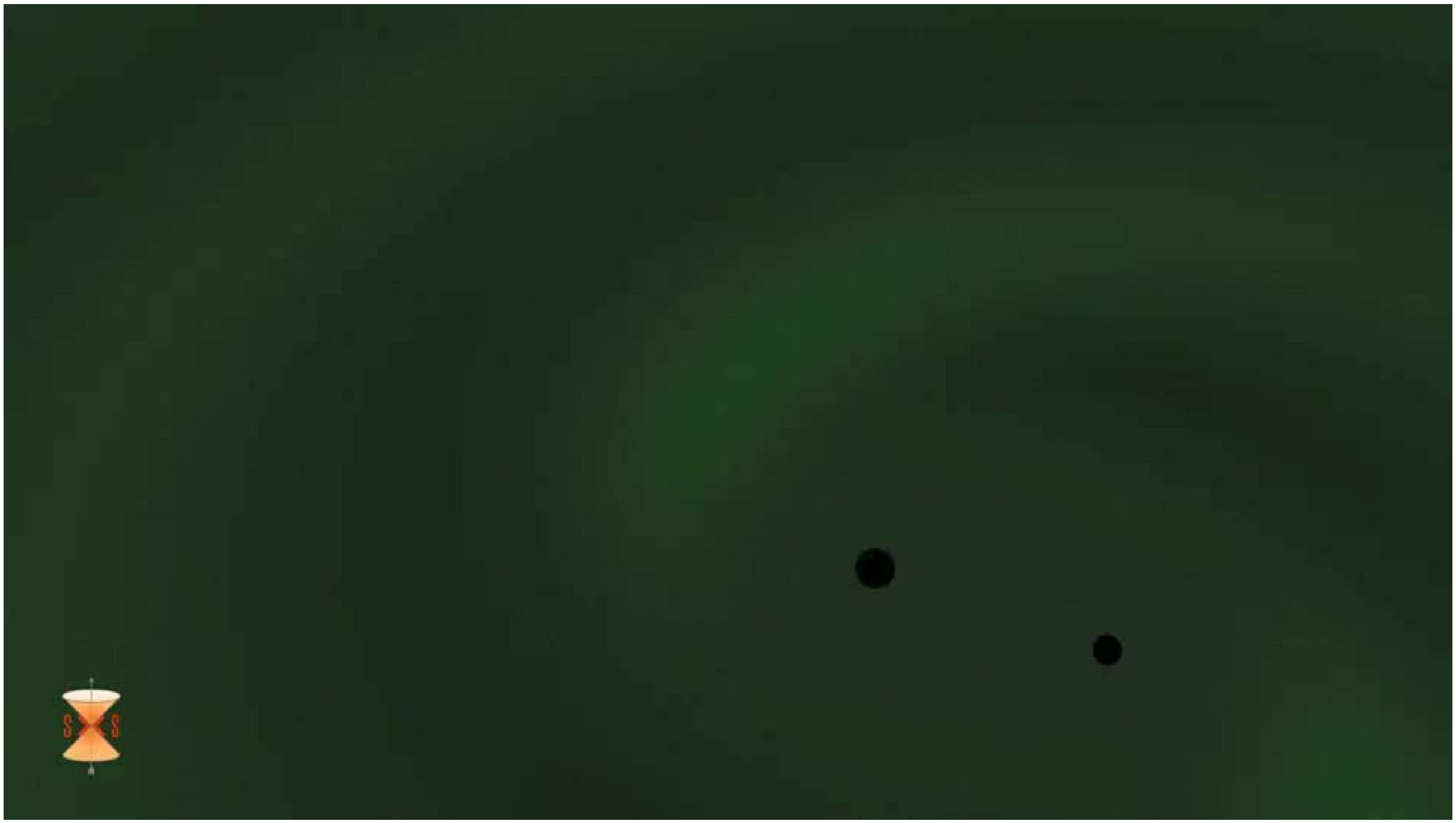
What is a gravitational wave?

A **gravitational wave** is a ripple in space itself.

Gravitational waves travel at the speed of light.

They are made when large masses (like large stars that have turned into black holes) move at close to the speed of light.

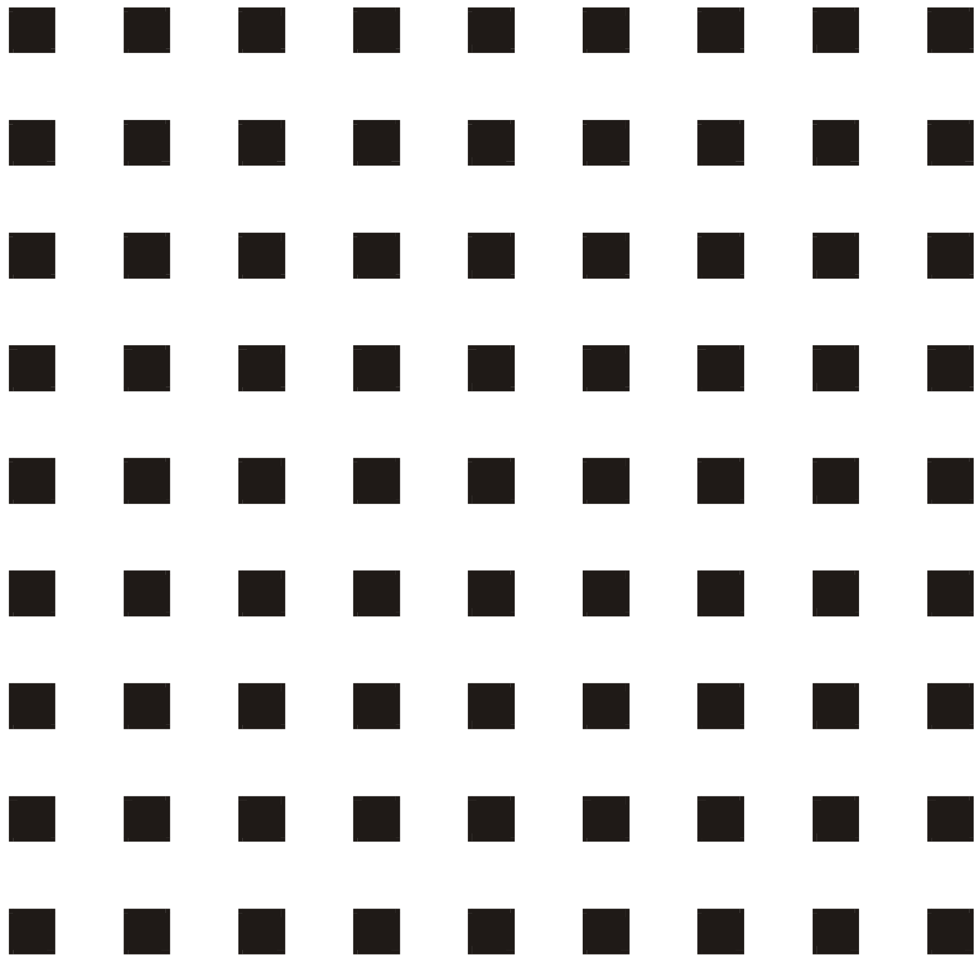
Here's how two black holes generate gravitational waves



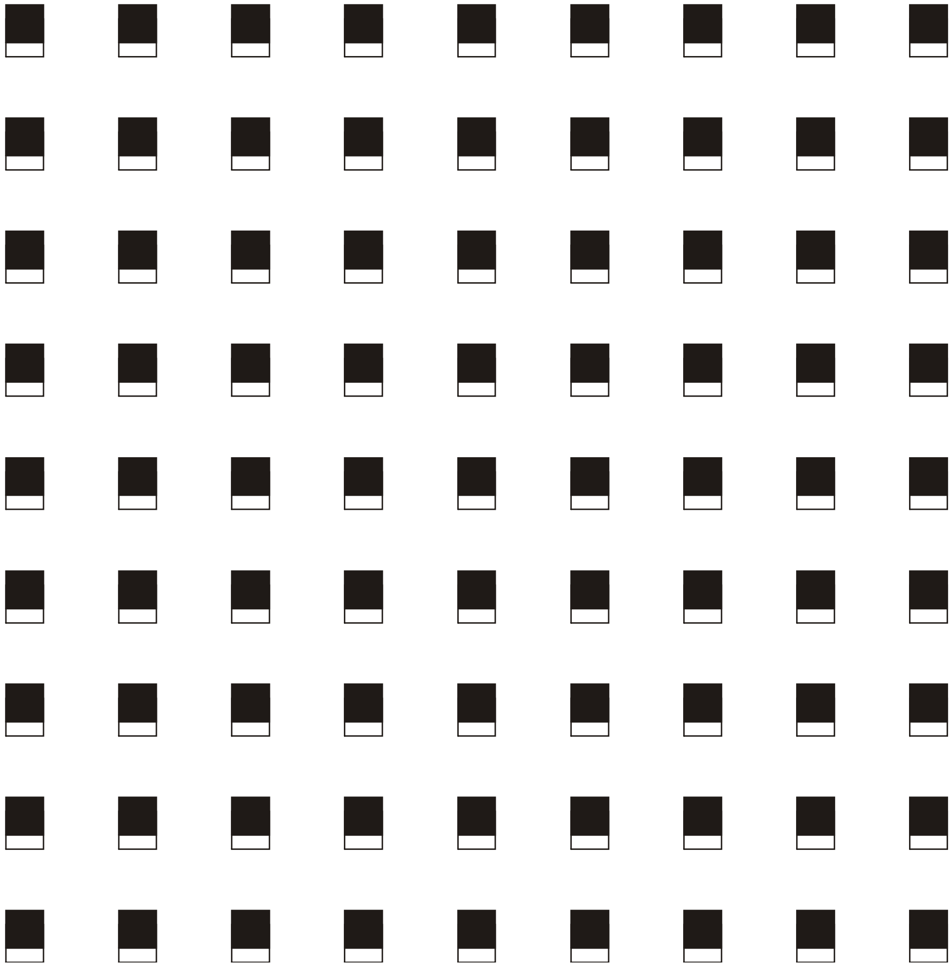
What is a gravitational wave, anyway?

And, can that understanding suggest a way to detect them?

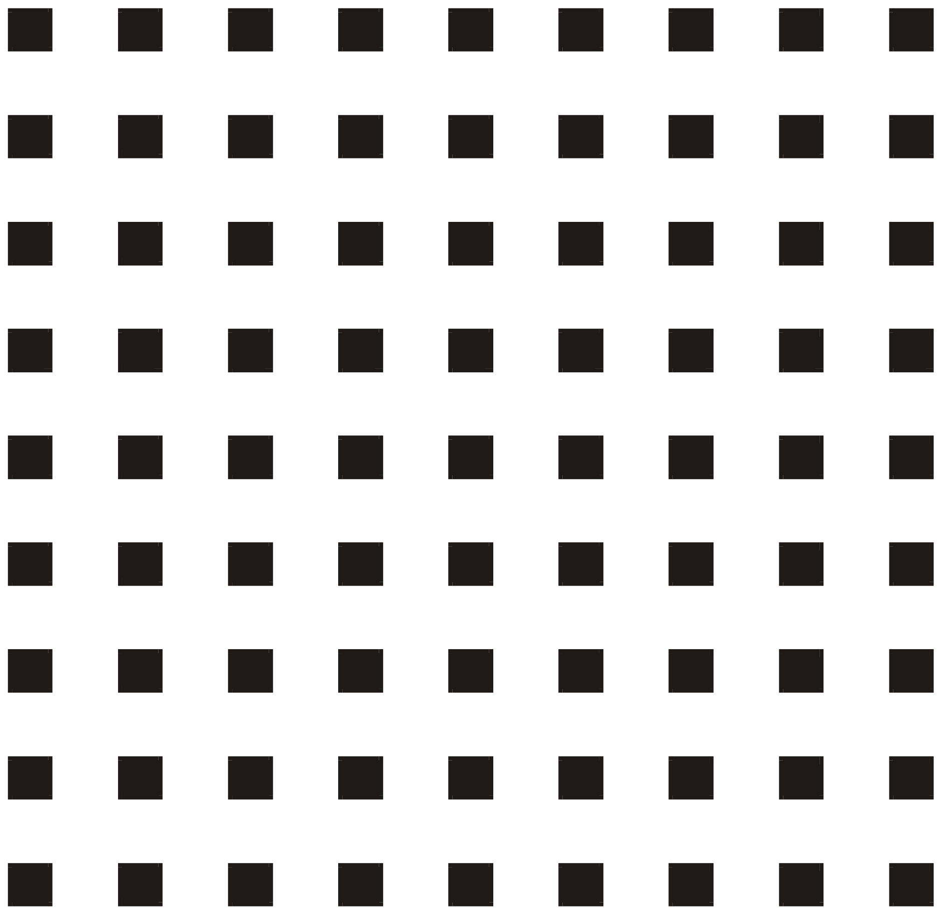
A set of free test charges



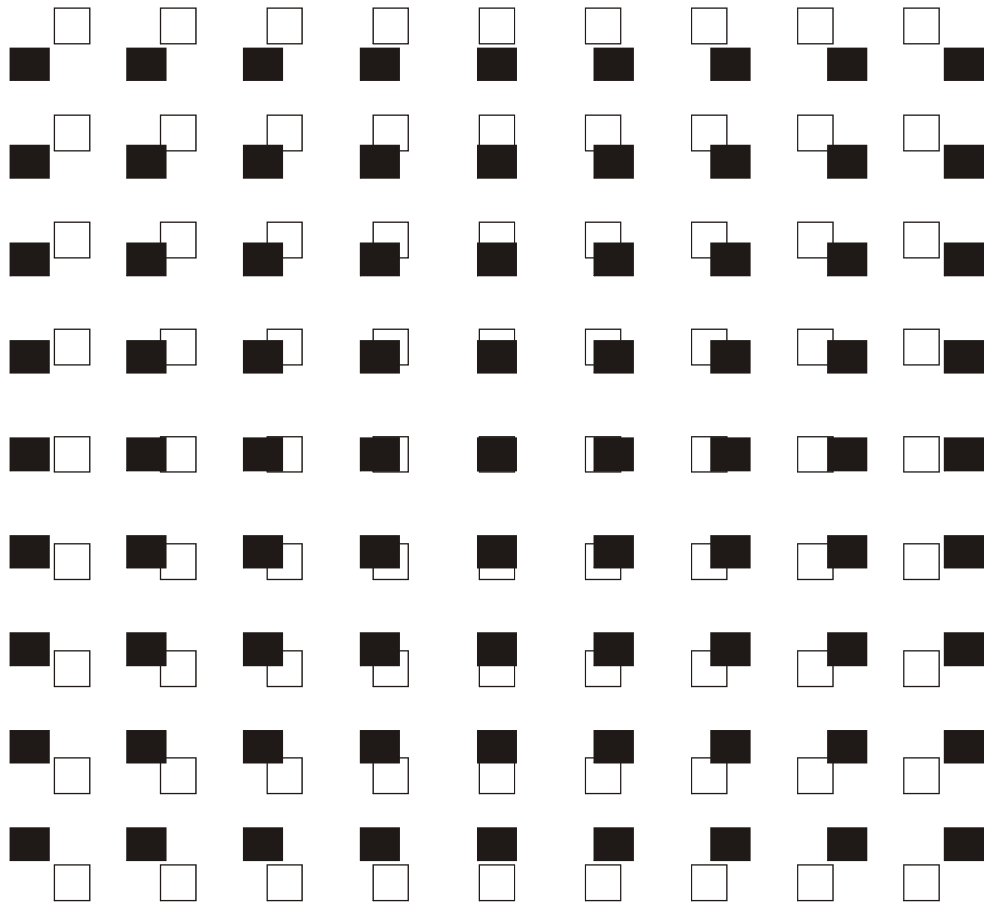
Electromagnetic wave moves charged test bodies



A set of freely-falling test masses



A grav wave distorts set of test masses in a quadrupolar pattern

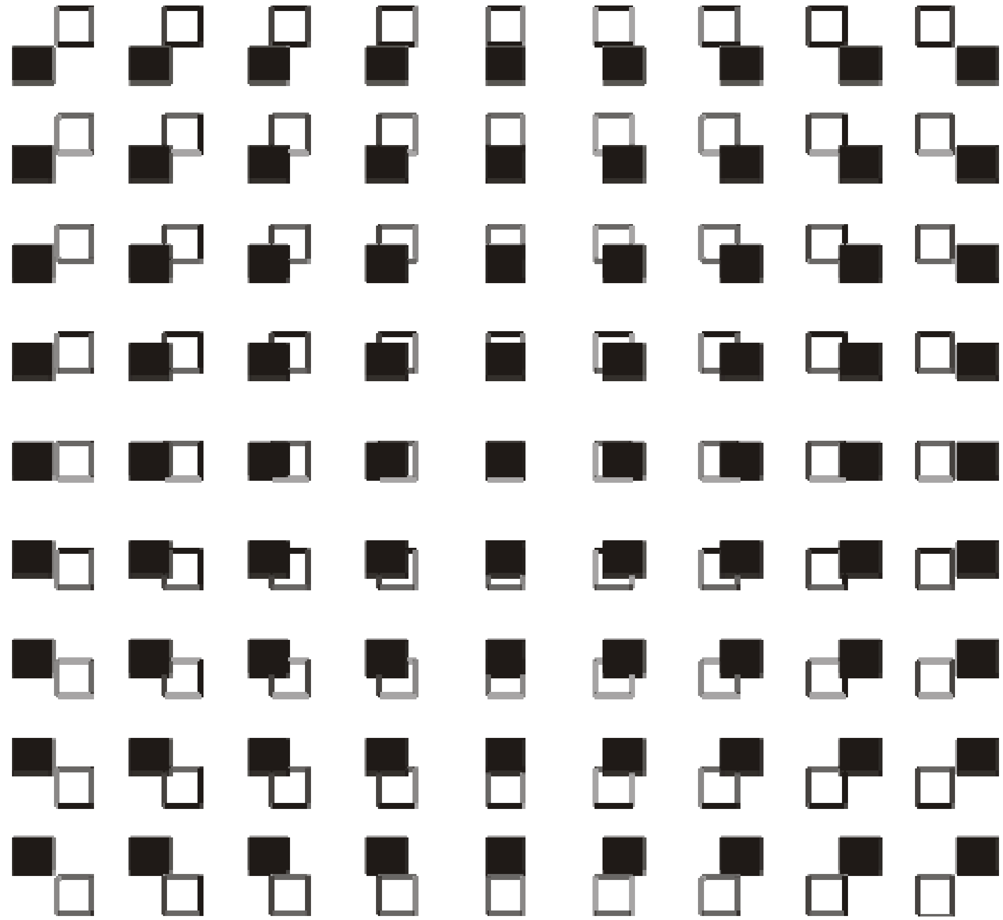


Gravitational wave "strain" pattern

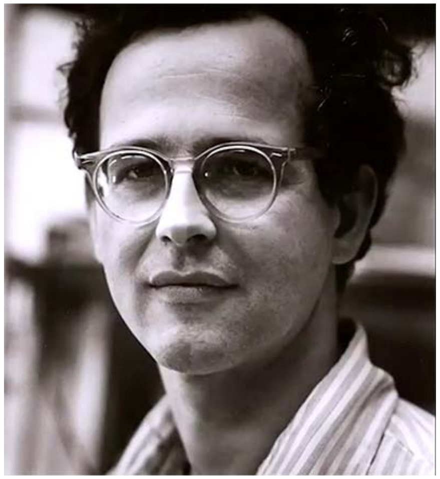
Effect is transverse to the direction of propagation.

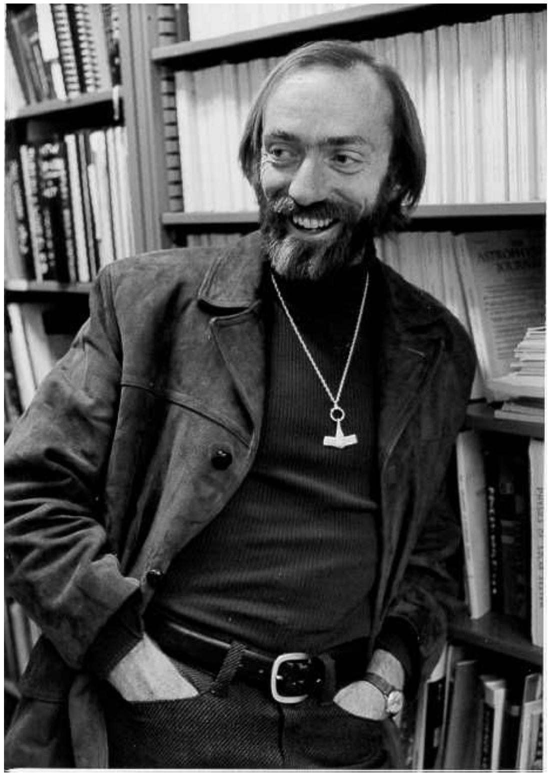
Strain amplitude:
$h = 2\ \Delta L/L$

The effect is bigger over longer baselines.



Founders of LIGO ca. 1972



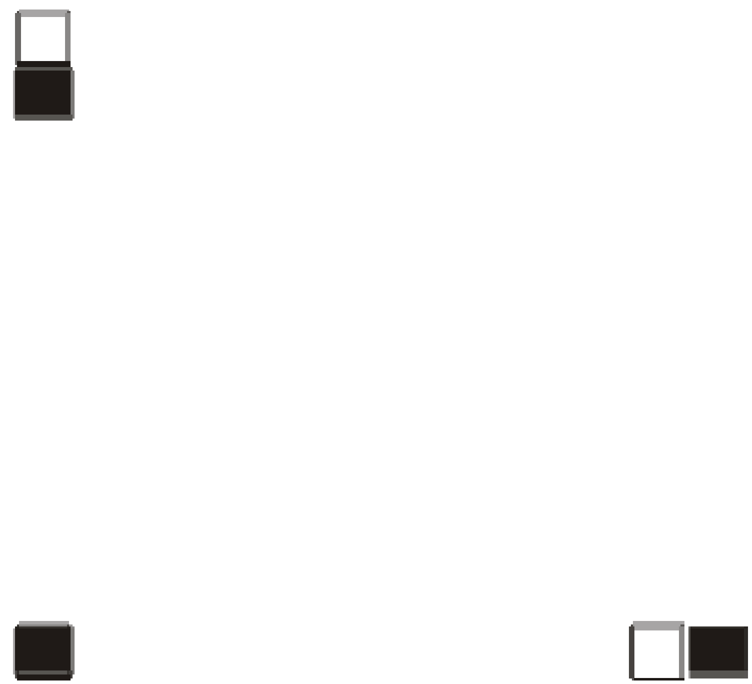


LIGO's co-inventors in the 1970s:
Experimenters Rainer Weiss (MIT) and Ronald Drever (Glasgow, then Caltech), and theorist Kip Thorne (Caltech).

Let's invent a gravitational wave detector

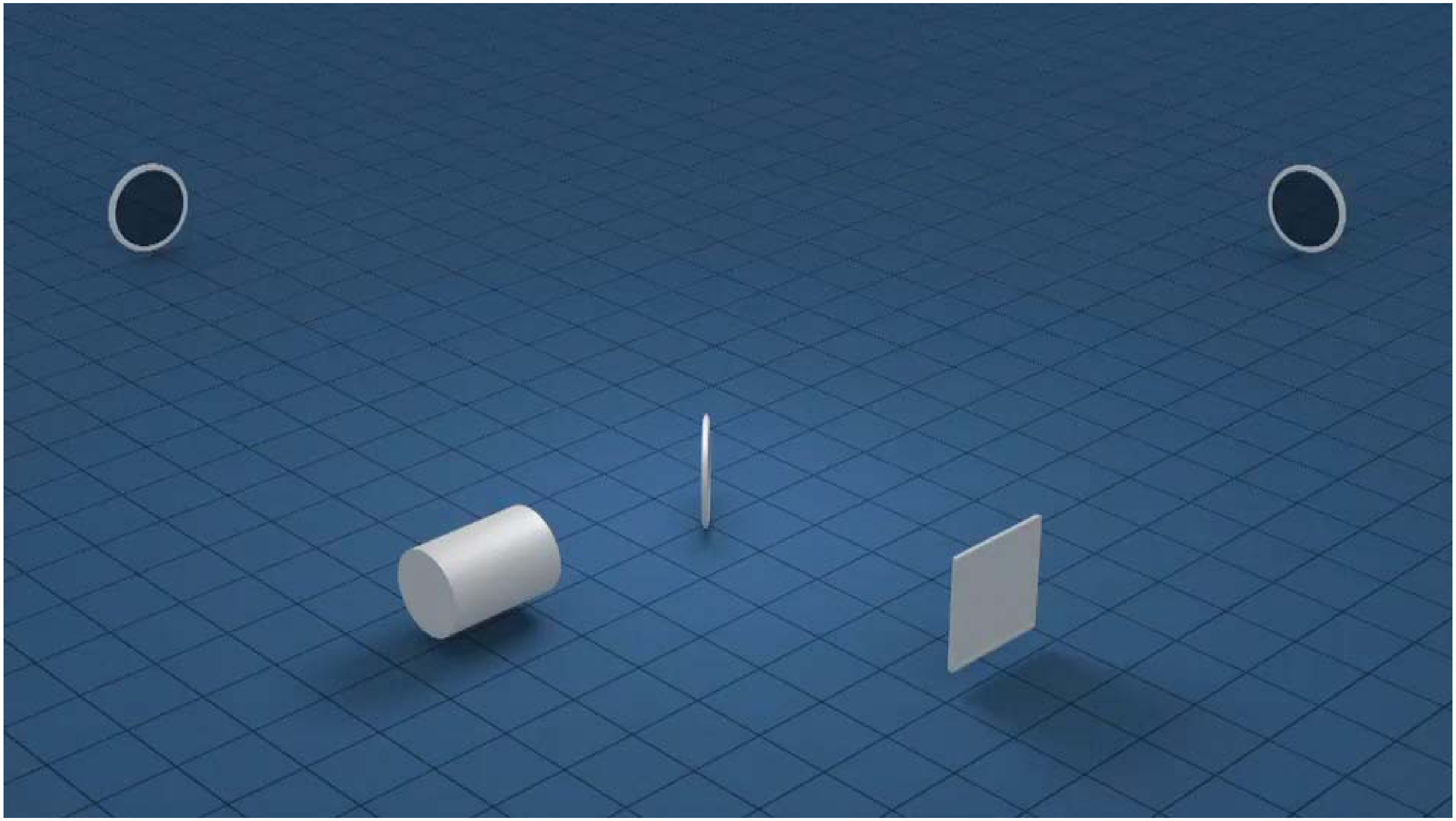
In principle, there's no limit to how far apart we can put our test masses.

We've put ours 4 km apart.

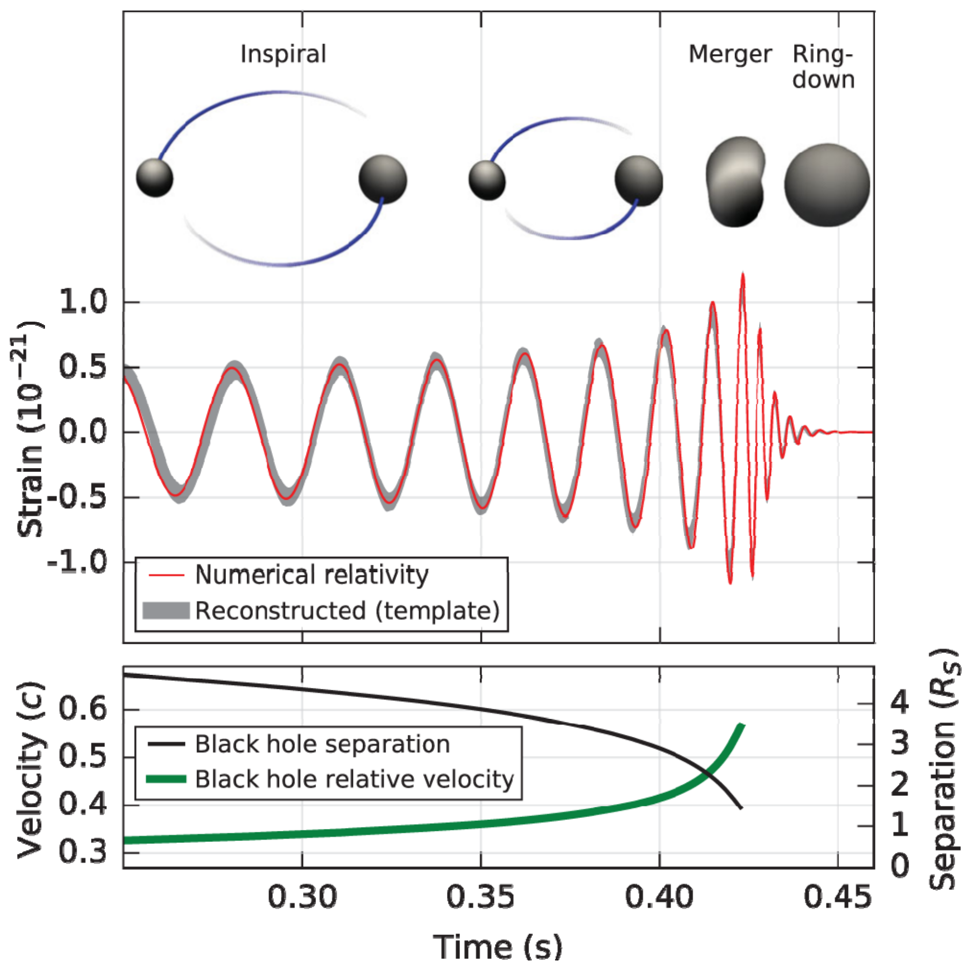


How LIGO Works

Credit: LIGO/T. Pile

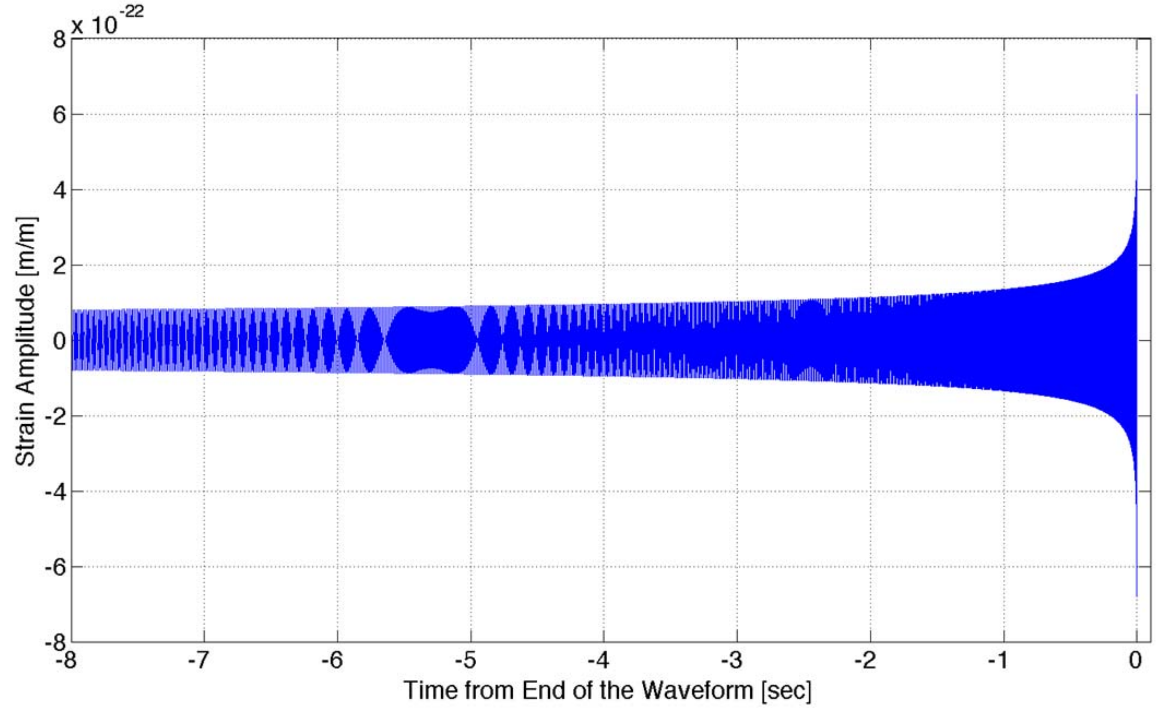


Strain vs. time records the history of system that made the wave

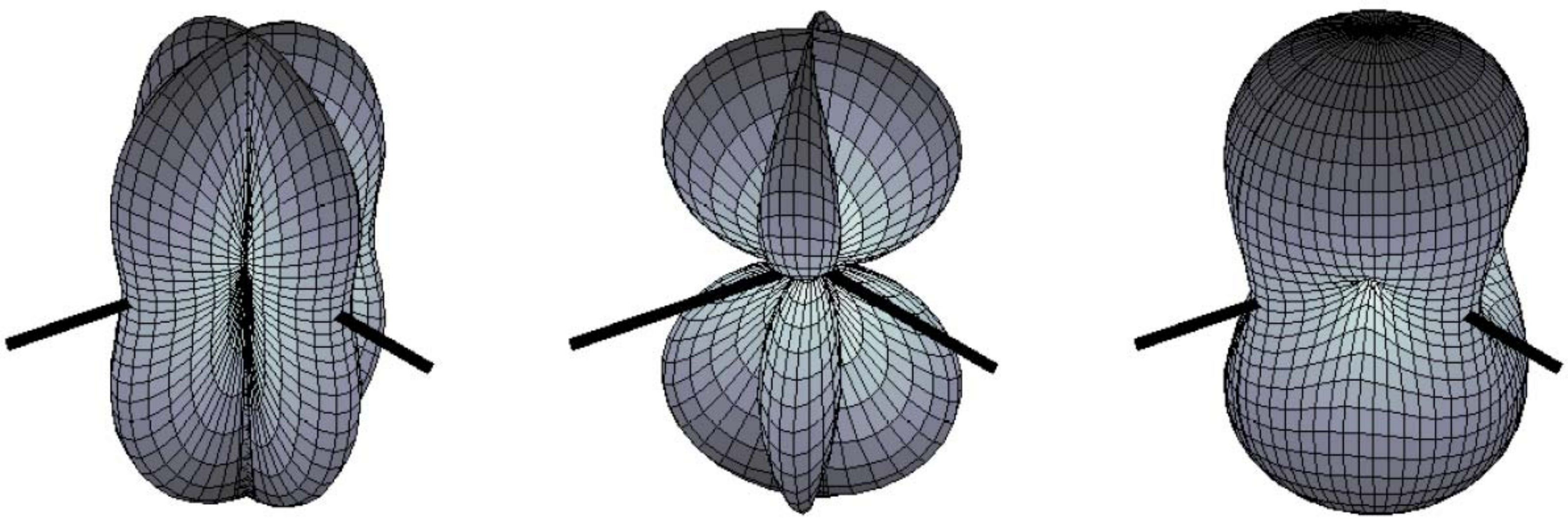


B. P. Abbott et al. (LIGO Scientific Collaboration and Virgo Collaboration)
Phys. Rev. Lett. 116, 061102

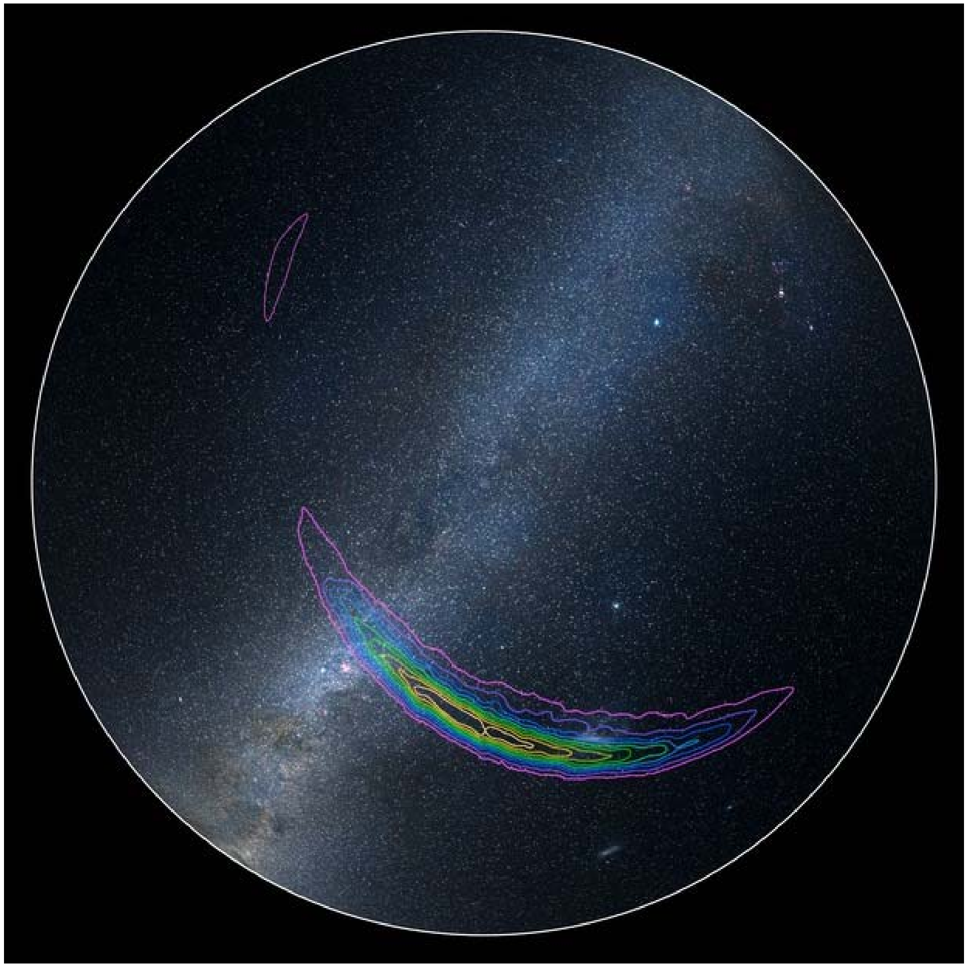
Orbital periods of stellar-mass binaries are in the audio band!



Antenna pattern



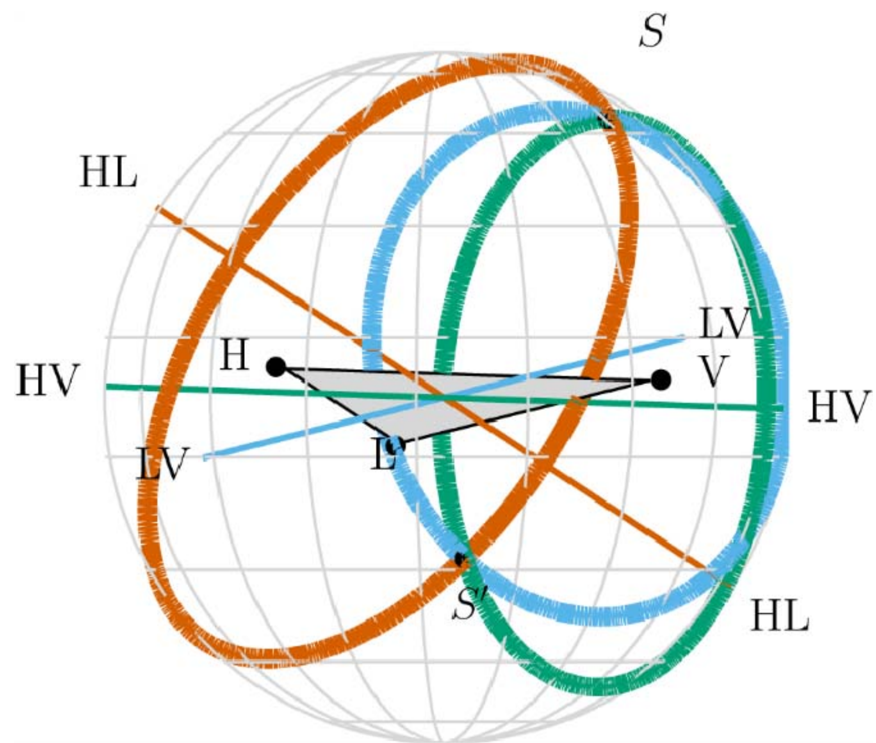
LIGO as an imaging device



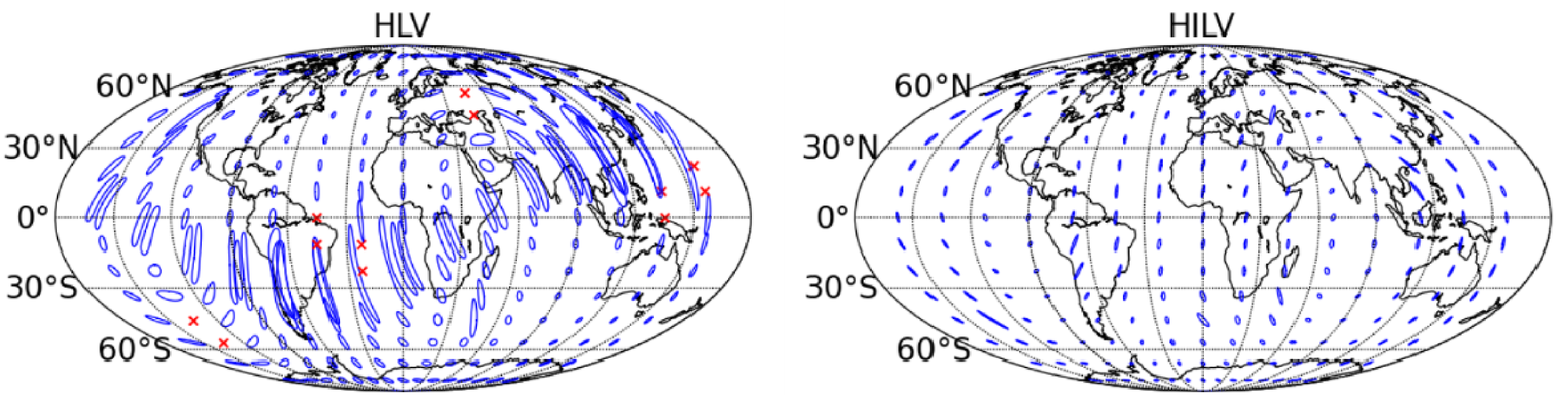
Credit: LIGO/
Axel Mellinger

Localization by triangulation

Benjamin P. Abbott et al. (LIGO Scientific Collaboration and Virgo Collaboration), "Prospects for Observing and Localizing Gravitational-Wave Transients with Advanced LIGO and Advanced Virgo", Living Rev. Relativity 19, (2016)



Improved localization via: signal ratios, more detectors



Benjamin P. Abbott et al. (LIGO Scientific Collaboration and Virgo Collaboration), "Prospects for Observing and Localizing Gravitational-Wave Transients with Advanced LIGO and Advanced Virgo", Living Rev. Relativity 19, (2016)

Gravitational waves: new physics, new astronomy

- Embody gravity's obedience to the principle "no signal faster than light"
- Are made when large masses orbit at relativistic speeds
- Travel through otherwise opaque matter
- Can be generated by pure spacetime
  - Black holes
  - Early universe fluctuations
- Can't be made by any conceivable artificial source, but are a great new tool for astronomy

What does it take to build a gravitational wave detector?

- We'll need:
  - A set of free test masses, far apart,
  - A means to measure their relative motion, and
  - Isolation of the masses from other causes of motion.
- Here's the challenge:

  Best astrophysical estimates predict fractional separation changes of only 1 part in 10^{21}, or less.

  If test masses are separated by 4 km, that means a length change less than 10^{-18} m!

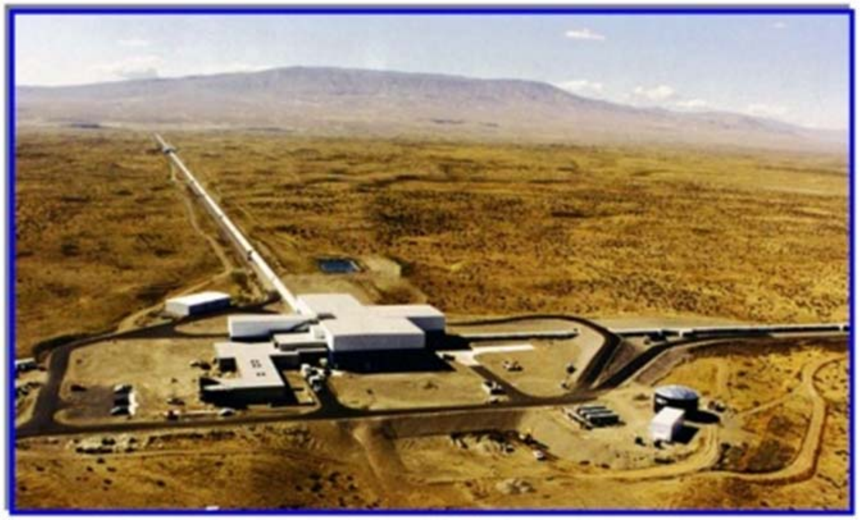
How small is 10^{-18} m?

- Diameter of human hair: 10^{-5} m
- Diameter of atom: 10^{-10} m
- Diameter of atomic nucleus: 10^{-14} m
- Diameter of proton: 10^{-15} m

To succeed, we need to discern length changes 1,000 times smaller than a proton.

We can do it!

LIGO's two sites observed from 2005 to 2010, then upgraded.



LIGO Hanford Observatory, WA

LIGO Livingston Observatory, LA

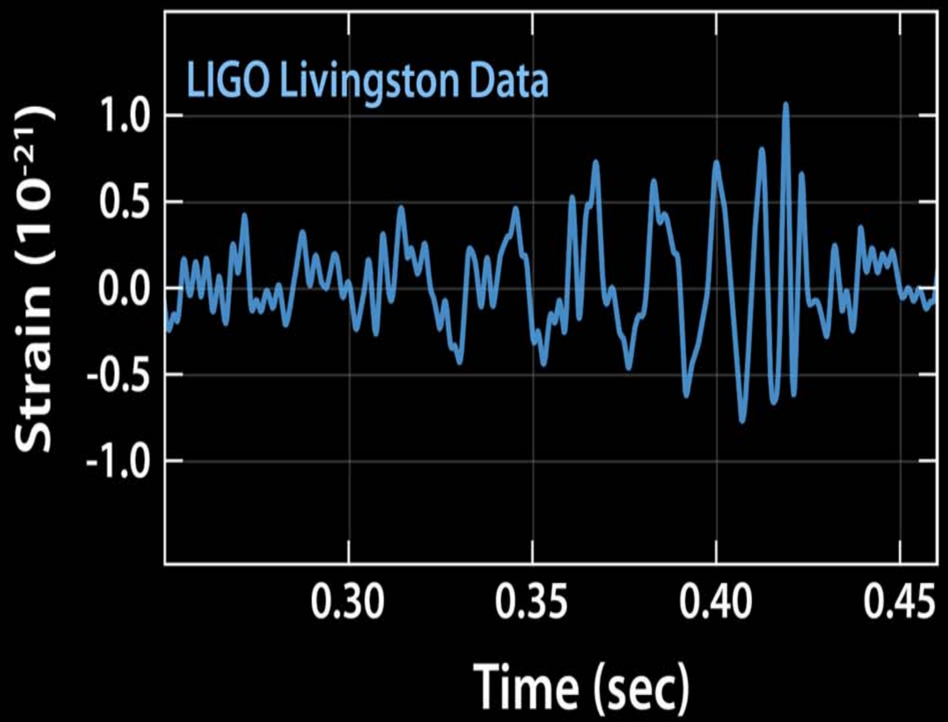
Advanced LIGO will eventually have 10 times the sensitivity of initial LIGO. Last fall, when we were "halfway there", we made our first observing run.

Our partners, GEO and Virgo

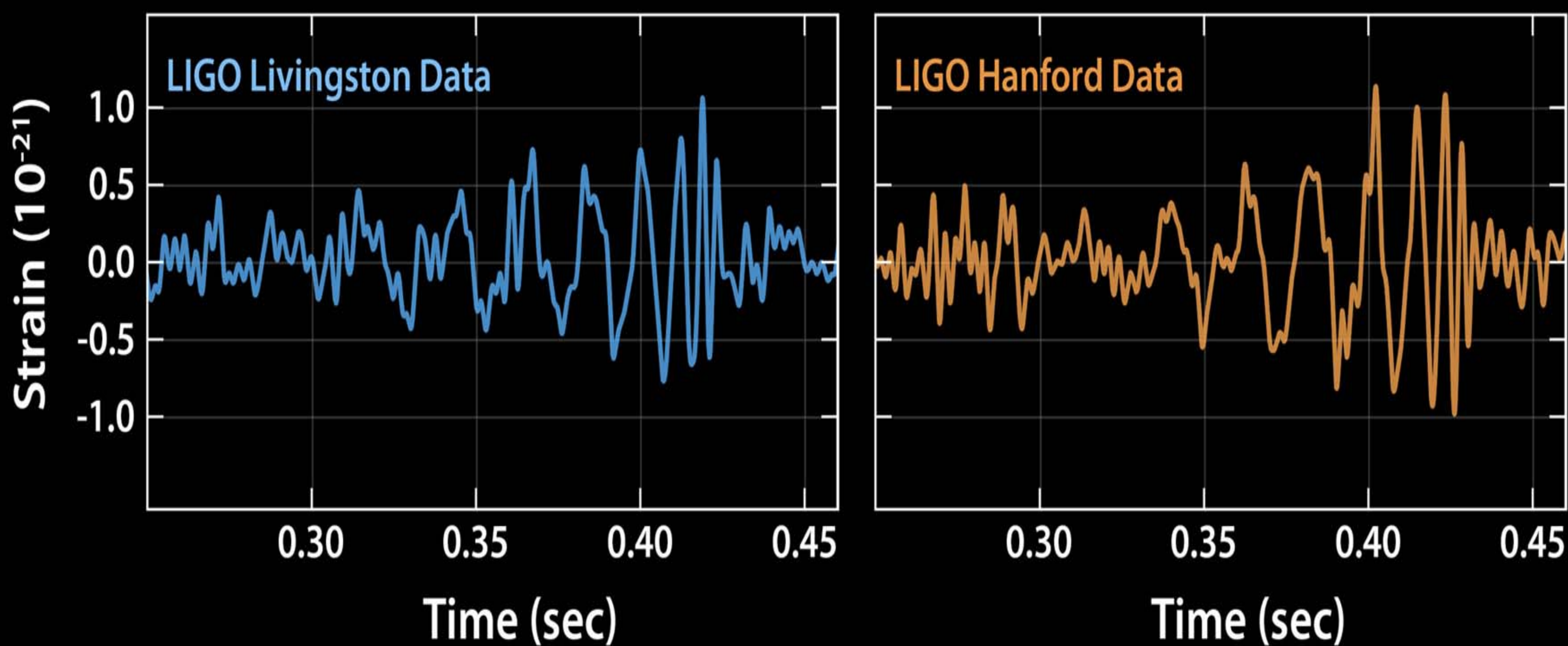
GEO, 600 m arms, near Hannover

Virgo, 3 km arms, near Pisa

2015 Sept 14 09:50:45 UTC



2015 Sept 14 09:50:45 UTC



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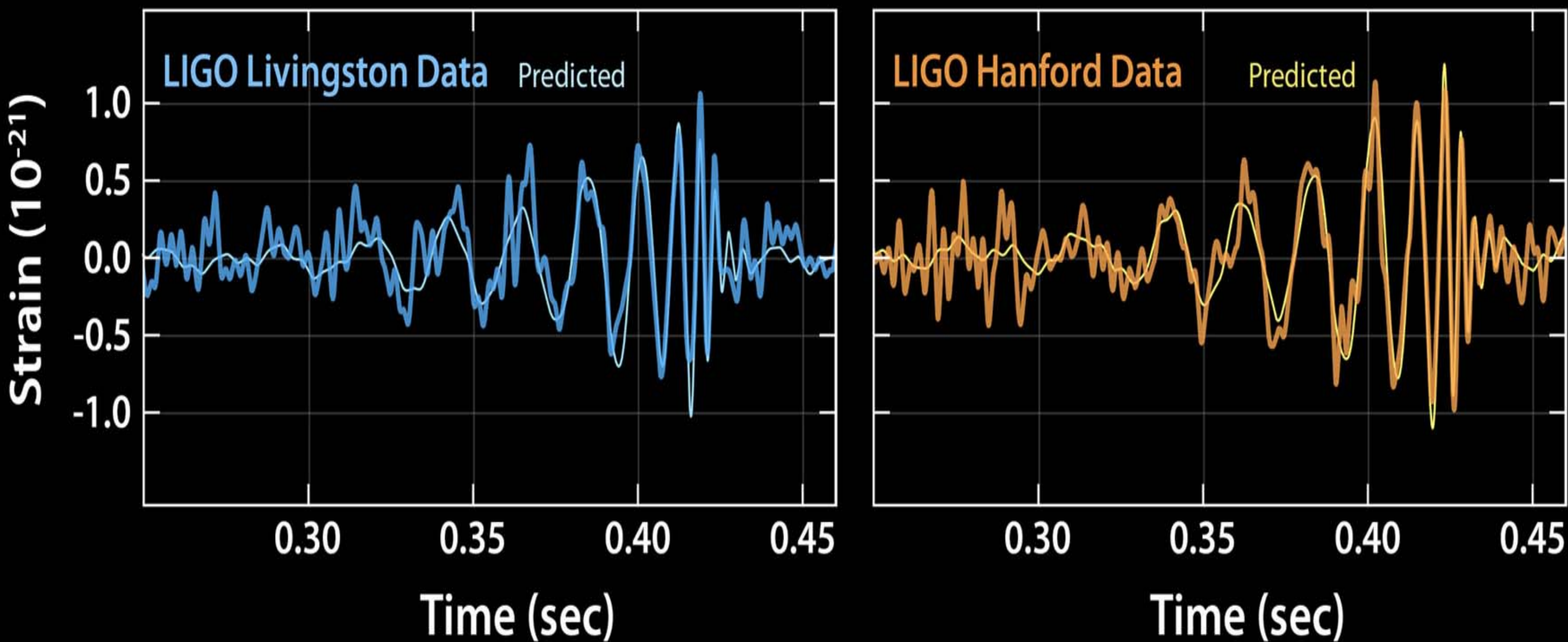
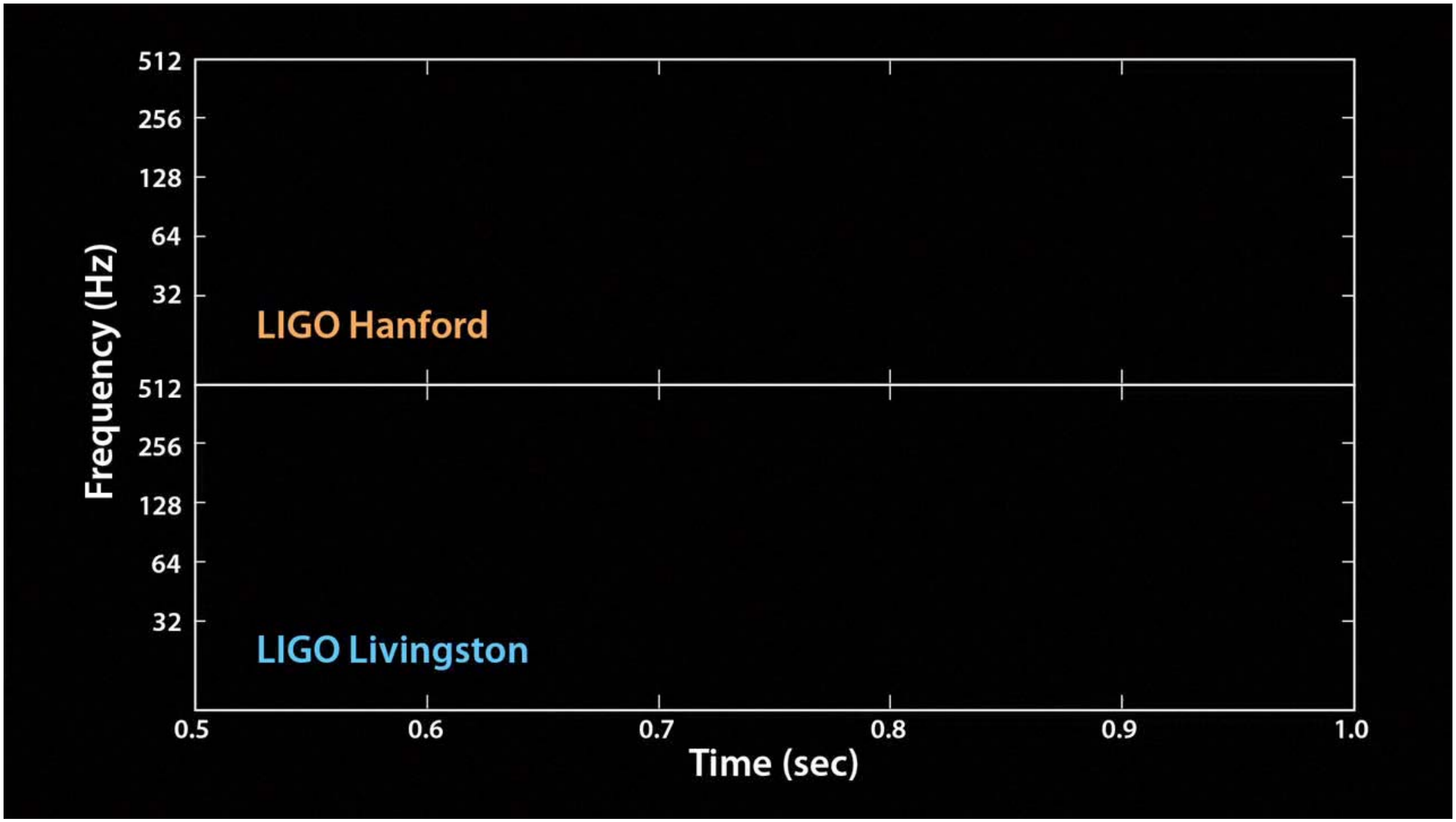


Listen to the signal



The gravitational wave future is bright!

LIGO plans to start its next observing run within a few months. During that period, we hope to be joined by Virgo.

We ought to find more binary black holes.

Someday soon, perhaps also binary neutron stars, or even more exotic objects.

Stay tuned!