Listening in on Black Holes: What Advanced LIGO is About to Hear

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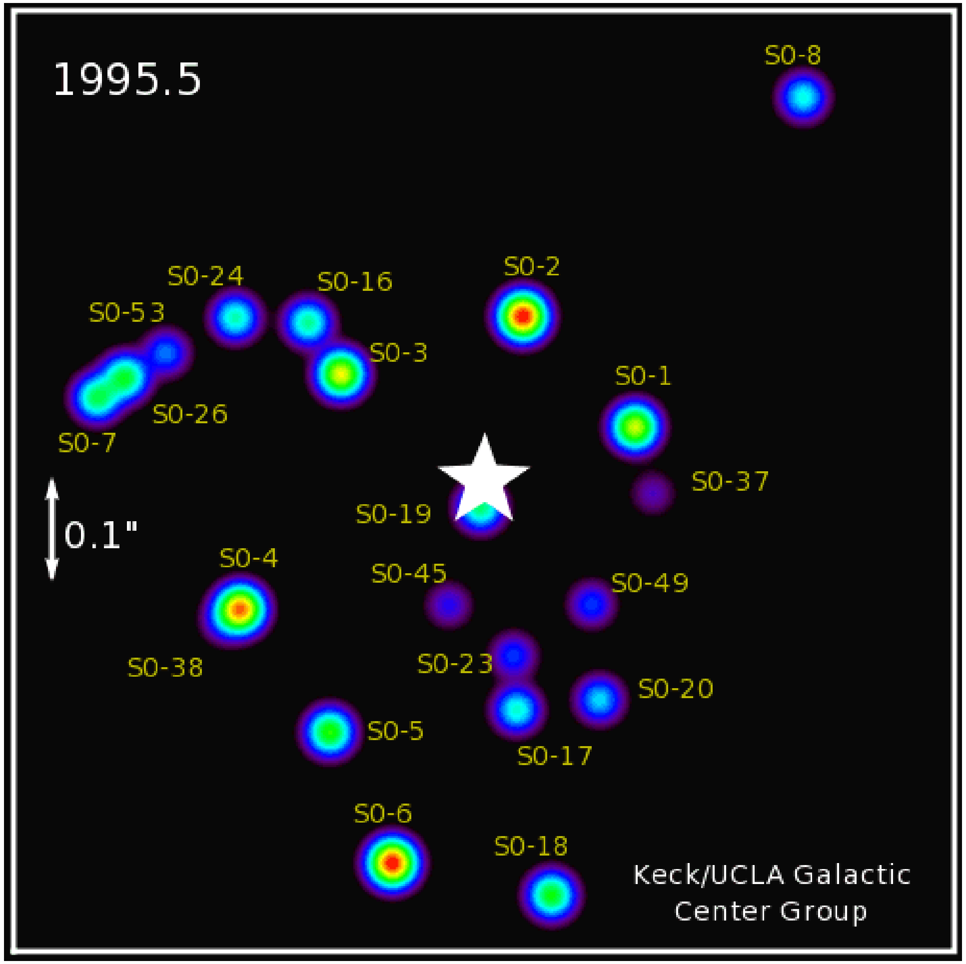
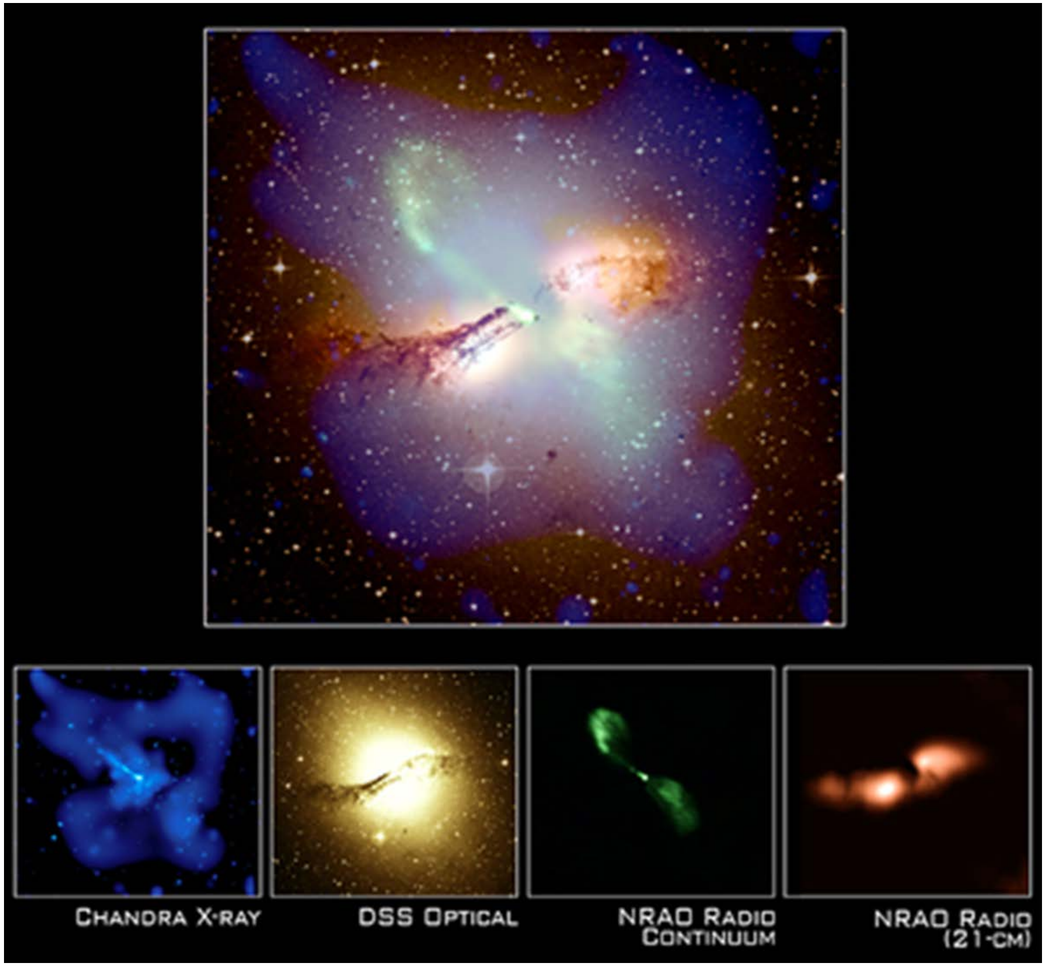
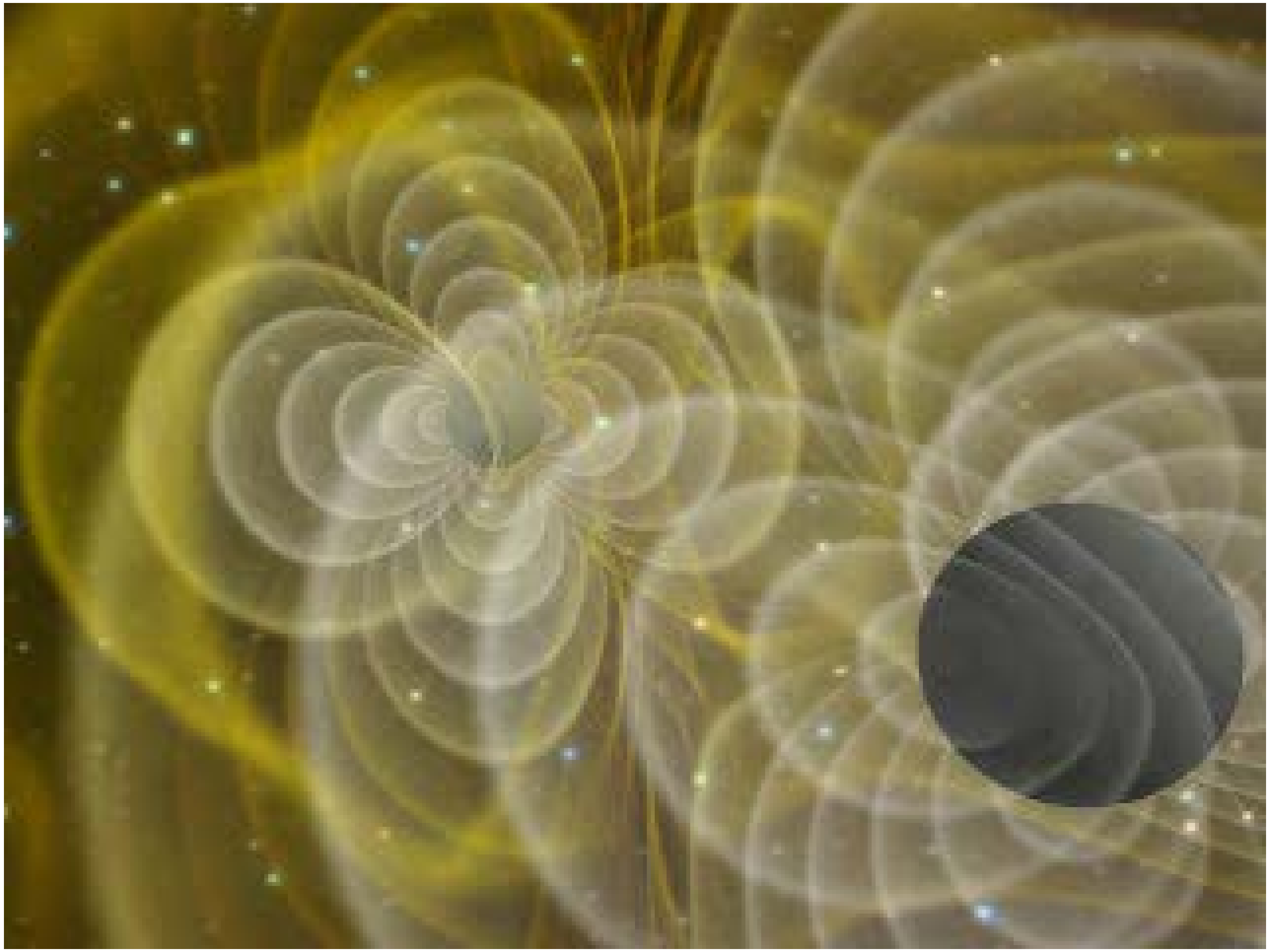
Black hole at the center of our Galaxy



The black hole in Centaurus A, via multi-messenger astronomy



A long time ago
in a galaxy far, far away …



Listening to the vibrations of spacetime?

We can find black hole binaries, and listen to them coalesce, if we build “audio telescopes” to sense the vibrations of spacetime that these events send out.

This is the project of **gravitational wave detection.**

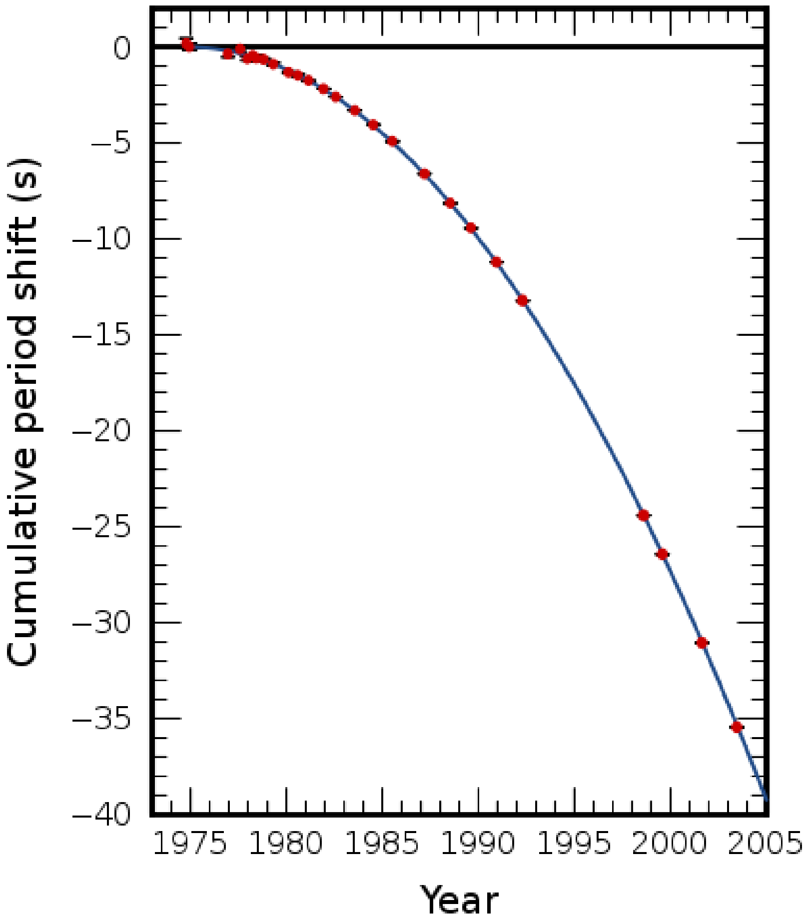
Gravitational wave detectors will also let us hear neutron star binaries, the stellar core collapse that ignites a supernova, and many other phenomena.

We've already seen that gravitational waves exist

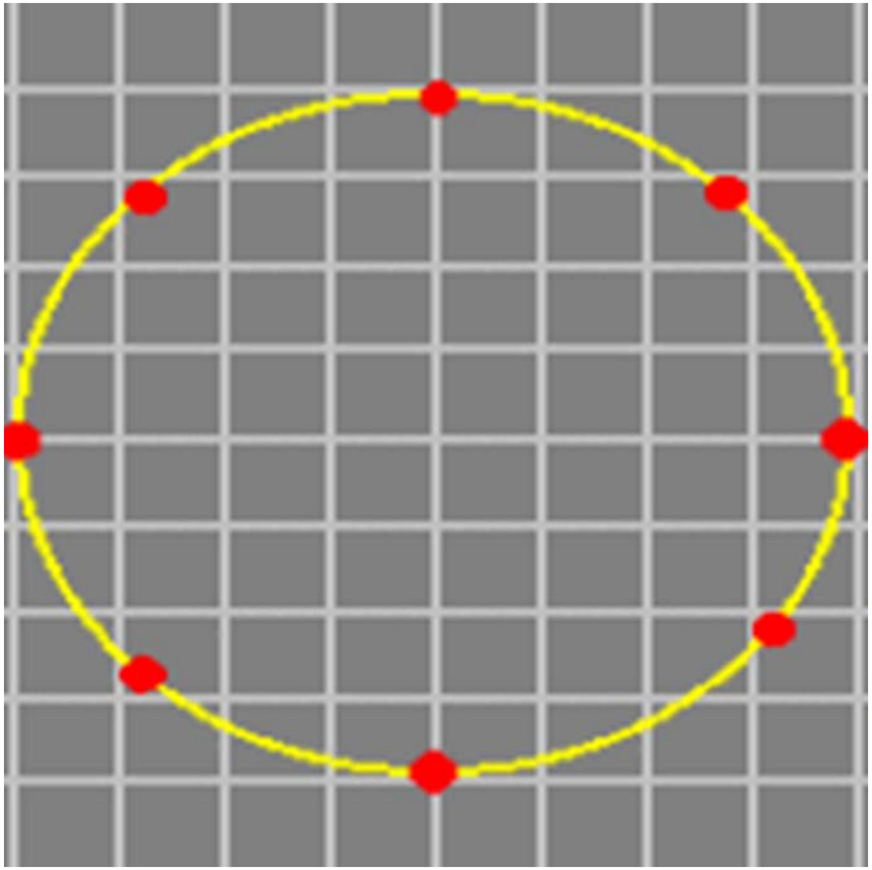
In 1974, Russell Hulse and Joe Taylor found PSR 1913+16, a pulsar in a binary orbit with another neutron star.

As Taylor followed the orbit over the years, he found it "getting ahead of itself." Energy loss caused the two neutron stars to fall closer together and orbit faster.

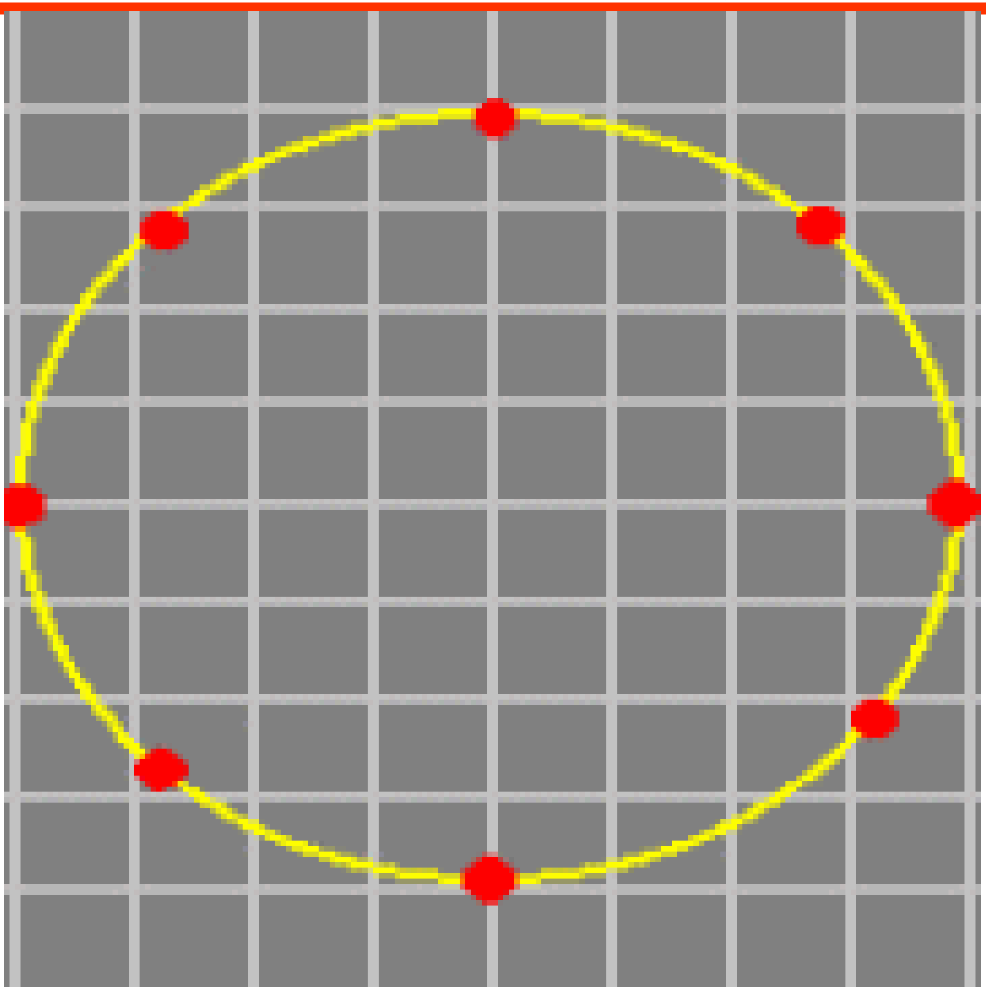
This was the discovery of gravitational radiation.



How to sense the vibrations of spacetime



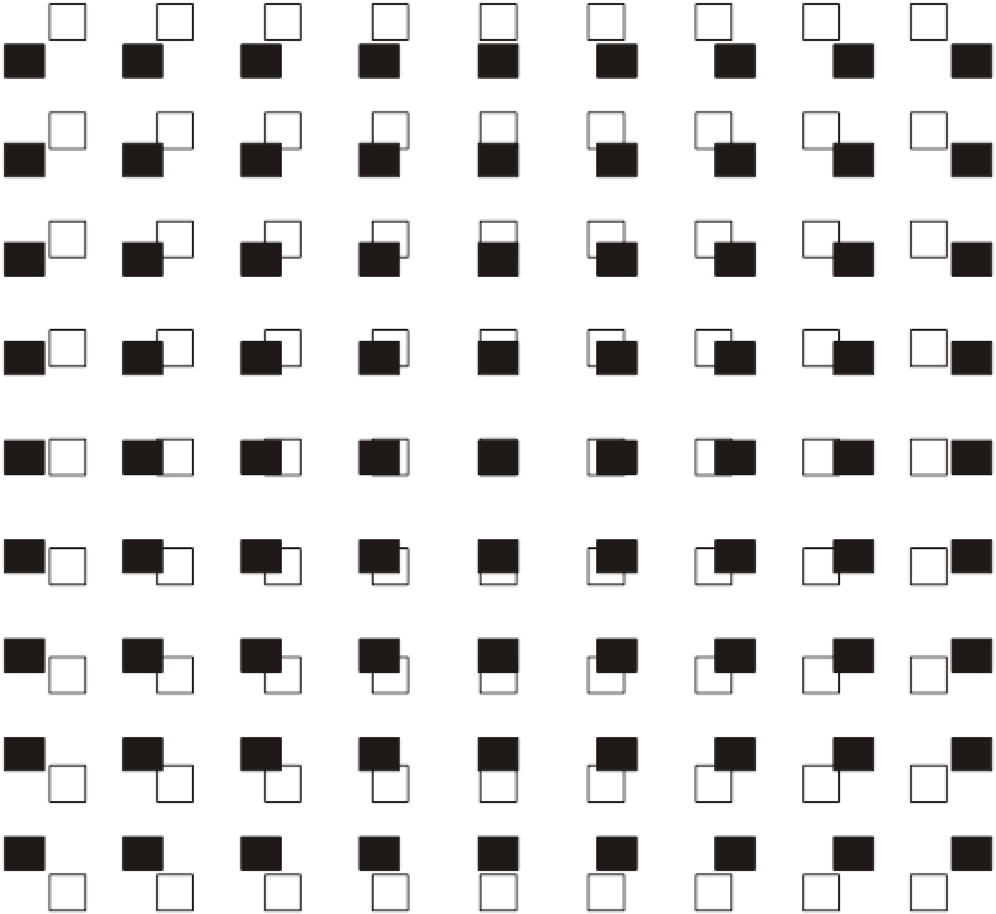
What happens when a gravitational wave passes by



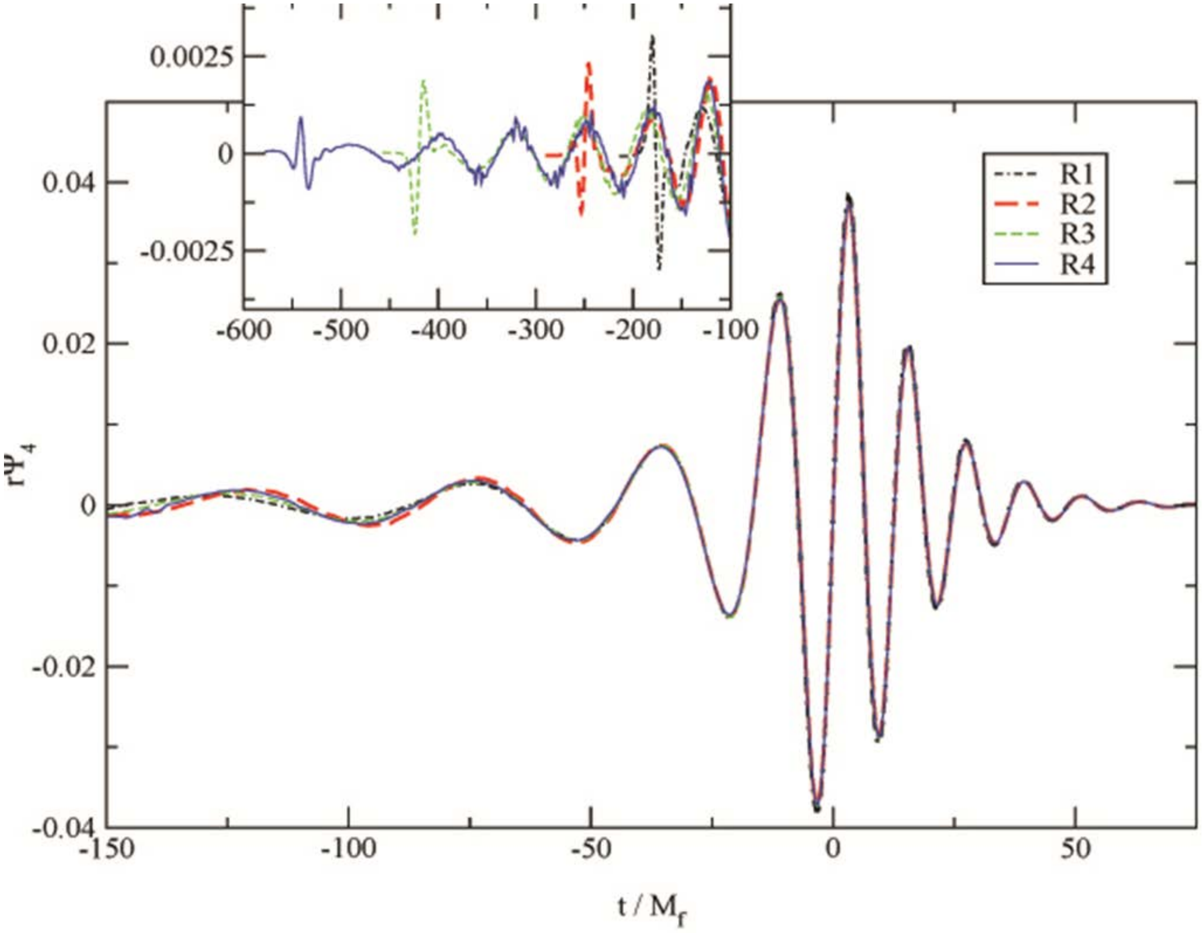
Gravitational wave “strain” pattern

strain amplitude:
$h = 2\,\Delta L/L$

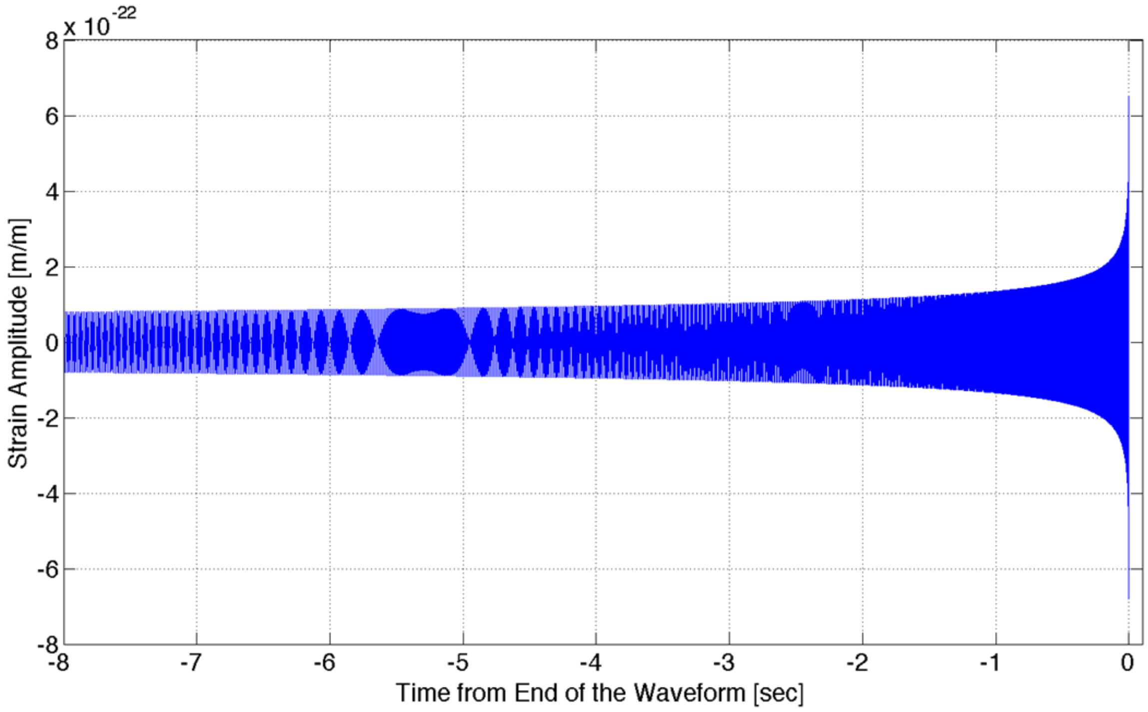
The effect is bigger over longer baselines.



Gravitational waveform = oscillation pattern of test masses



Since we understand gravity, we can calculate waveforms



Stellar-mass objects give signals in the audio band. (!)

Gravitational waves will give us a new "take" on the sky

- Embody gravity's obedience to the principle "no signal faster than light"
- Are made when large masses move at relativistic speeds
- Travel through otherwise opaque matter
- Can be generated by pure spacetime
  - Black holes
  - Early universe fluctuations

Gravitational waves are a new "messenger" for astronomy

- Binaries of neutron stars and black holes
  - Study black hole spacetime
  - Learn the internal forces in neutron stars
  - Determine the causes of gamma ray bursts
- Stellar core collapse
  - Dynamics that lead to supernova
- Rotating neutron stars
  - What mechanisms can make neutron stars lumpy?
- Early universe dynamics

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^{22}, or less.

  If test masses are separated by 4 km, that means a length change less than 10^{-19} m!

How small is 10^{-19} 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

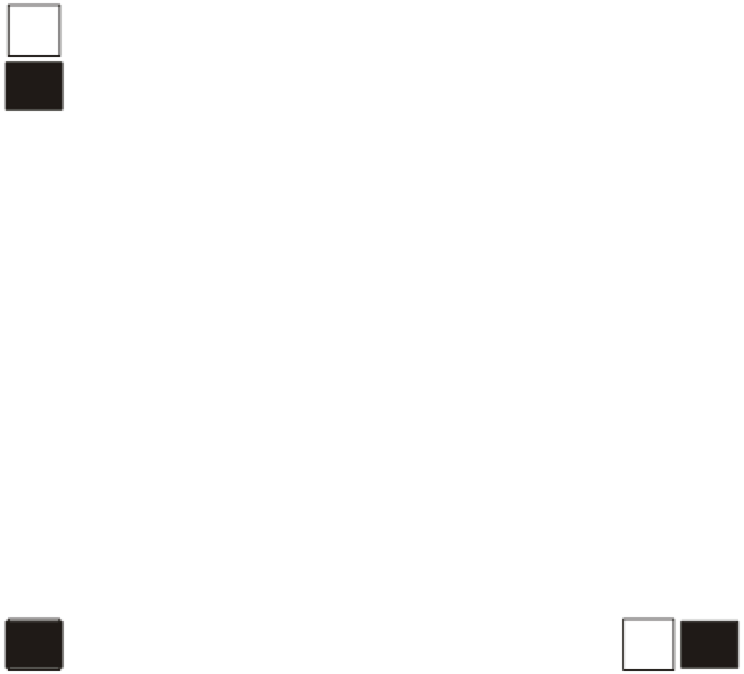
To succeed, we need to discern length changes 10,000 times smaller than a proton.

We can do it!

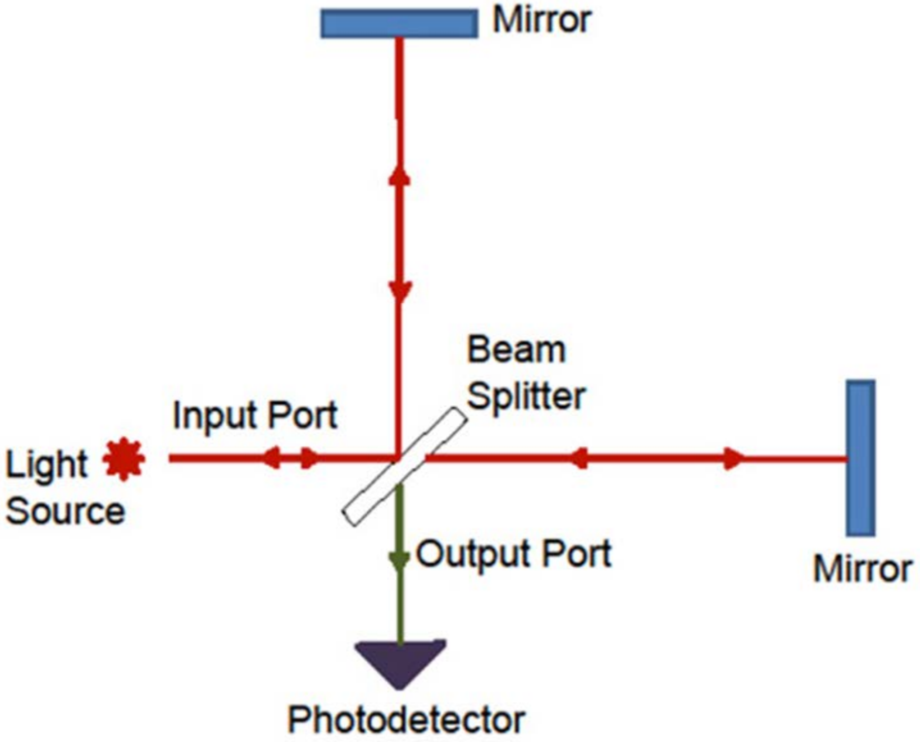
Let's invent a gravitational wave detector

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

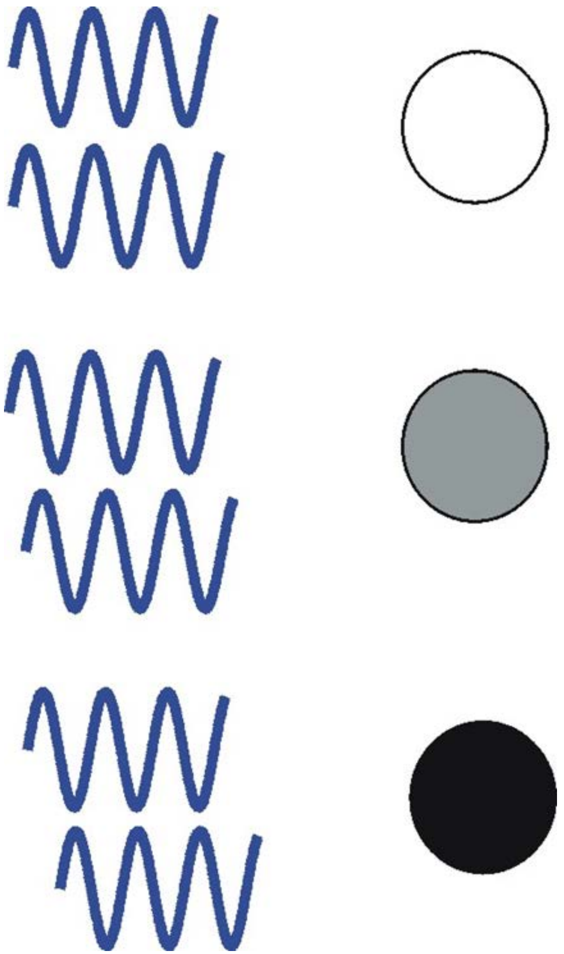
We've put ours 4 km apart.



Use a Michelson interferometer to measure relative motion

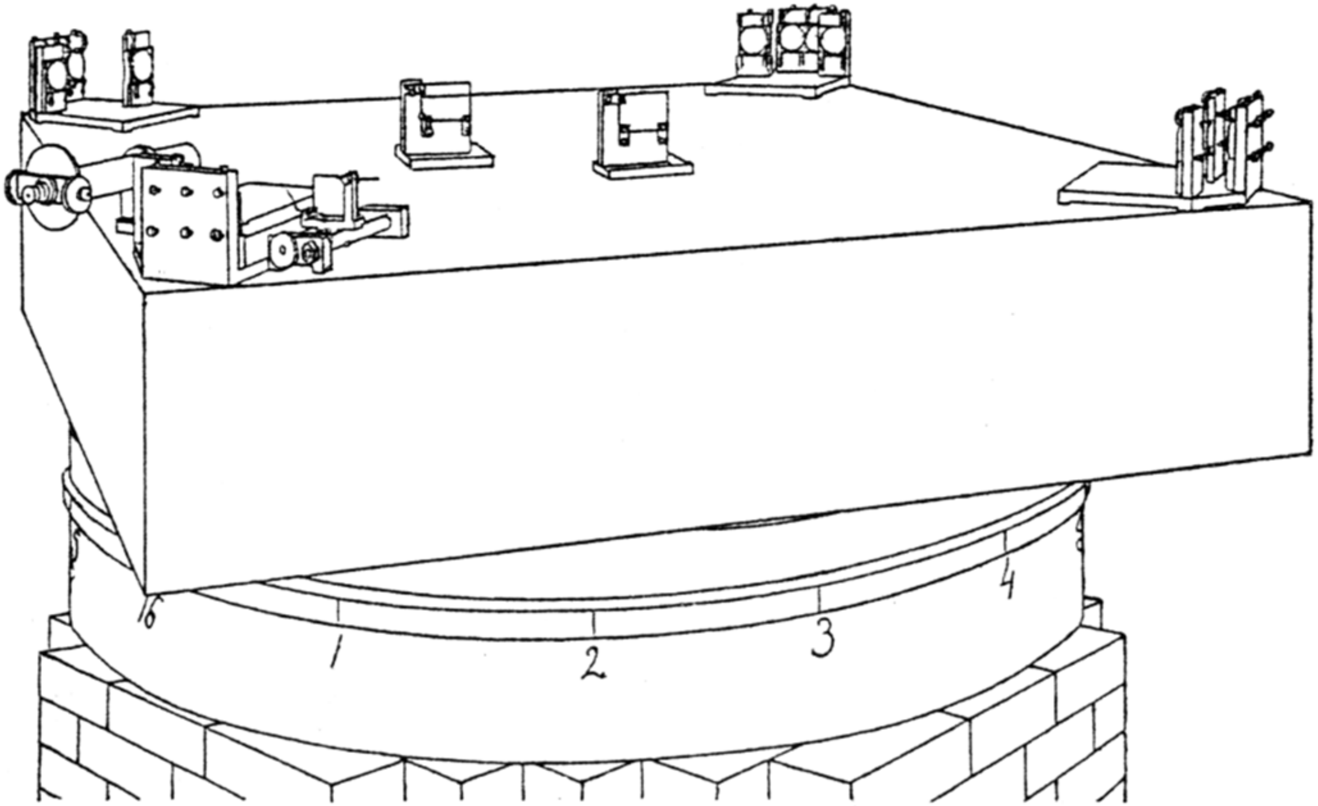


Michelson interferometer = transducer from length difference to brightness



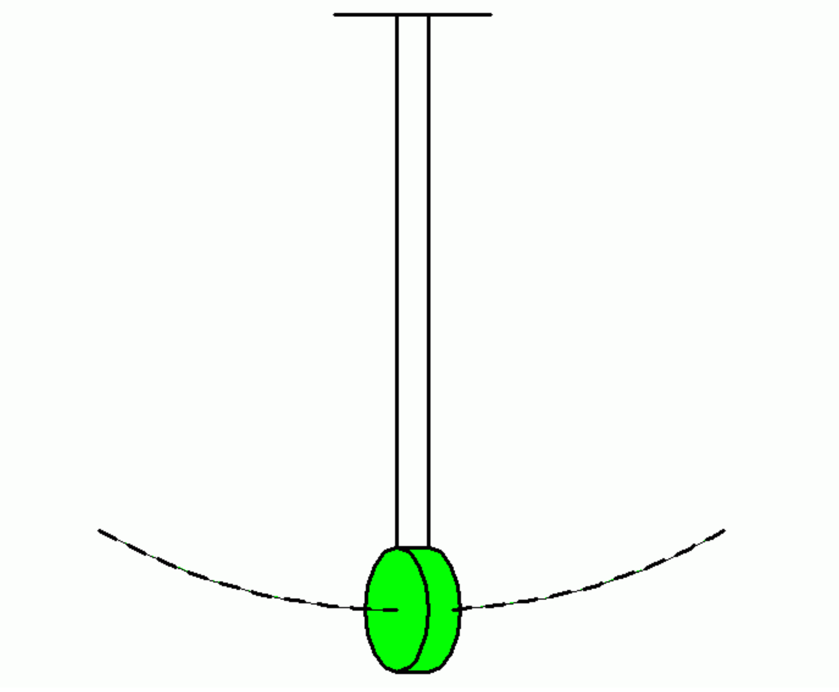
Brightness of superposed beams of light from the two arms.

Here’s how A.A. Michelson showed that there’s no “ether”



We suspend our mirrors instead of bolting them down, because …

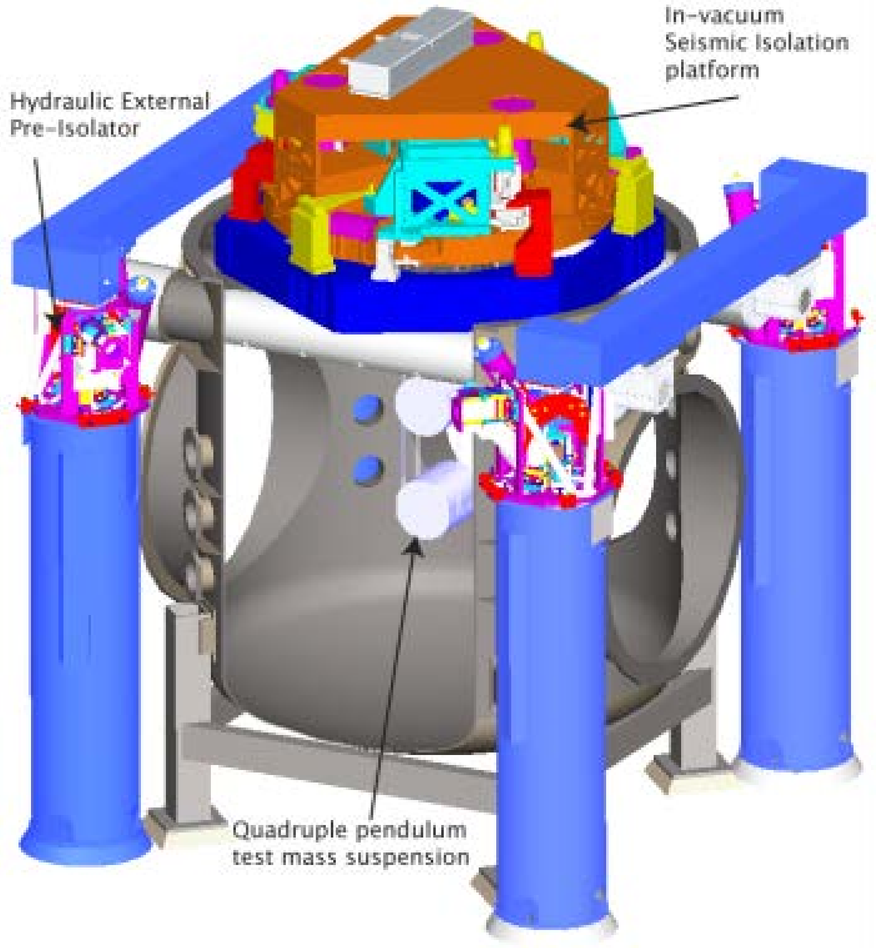
- A pendulum bob is dynamically free (above its resonant frequency).
  - "bob" = test mass = interferometer mirror
- A mass suspended as a pendulum is also isolated from external motions.



Isolate against seismic noise

Seismic motion of the ground is about 10 orders of magnitude larger than motion of mirrors from gravitational waves.

“Isolate, isolate, isolate.”



LIGO's two sites turned on in 2005, listened until 2010

LIGO Hanford Observatory, WA

LIGO Livingston Observatory, LA

Two years' worth of integrated coincident data, at or beyond design sensitivity, collected between 2005 and 2010.

GEO and Virgo observed and analyzed data with us

GEO, 600 m arms, near Hannover

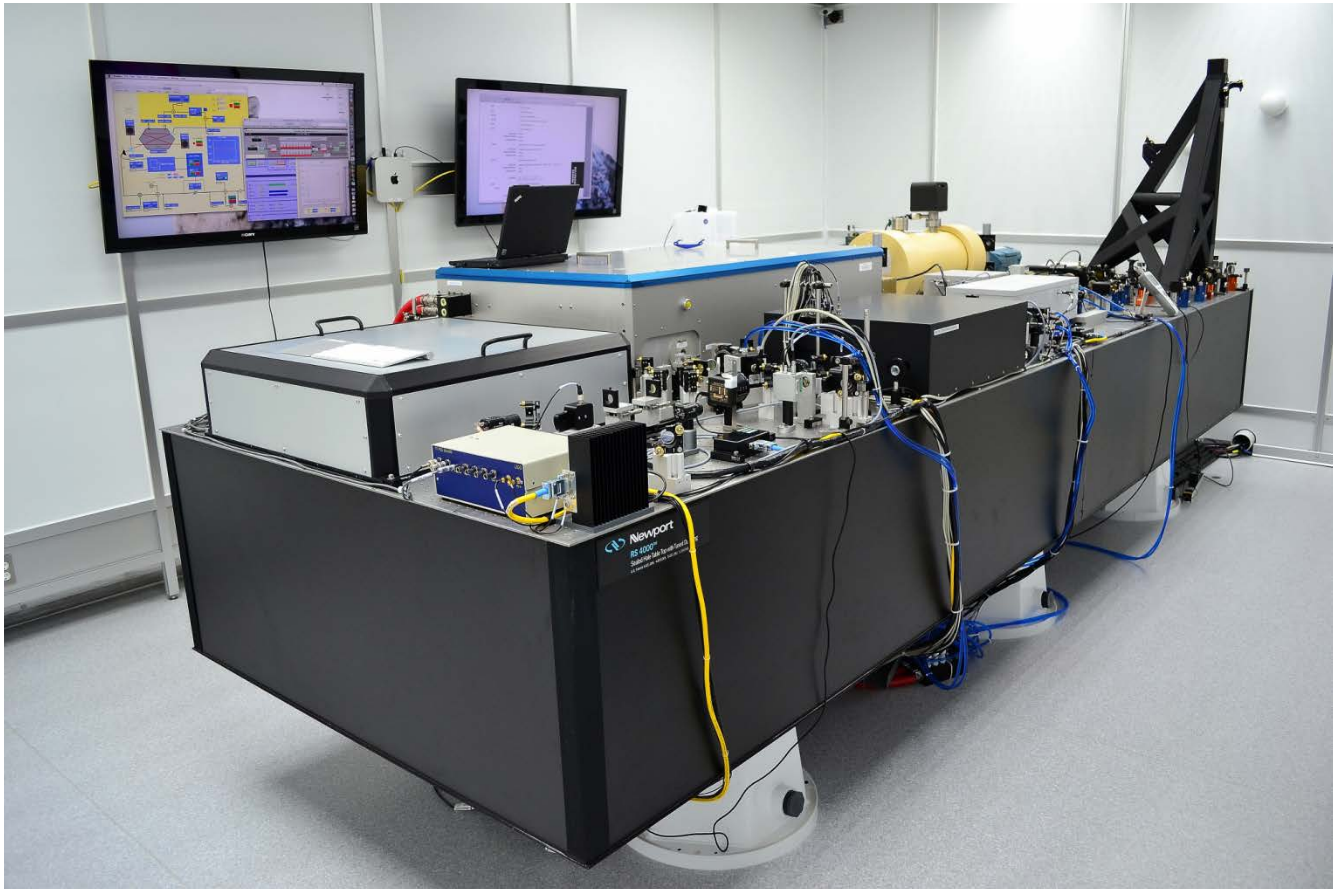
Virgo, 3 km arms, near Pisa

LIGO’s 4 km arms, 10^{-8} torr

Vacuum chambers

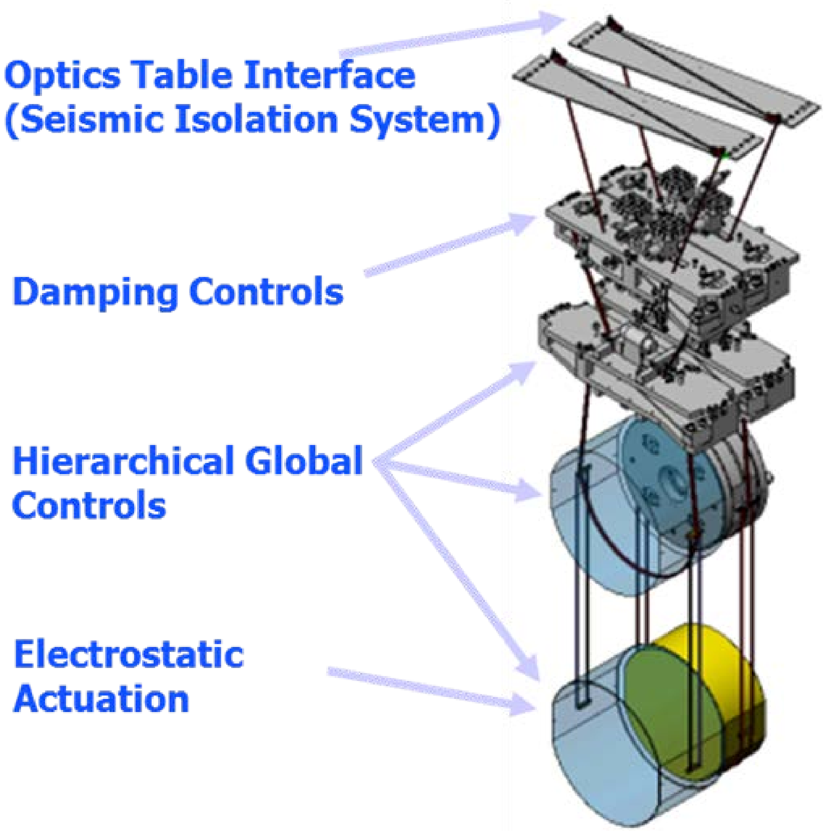
here, beamsplitter and input test masses

Advanced LIGO's 200 W Nd:YAG laser



Custom designed/built by Laser Zentrum Hannover

Quadruple pendulums suspend and isolate the test masses



Optics Table Interface
(Seismic Isolation System)

Damping Controls

Hierarchical Global
Controls

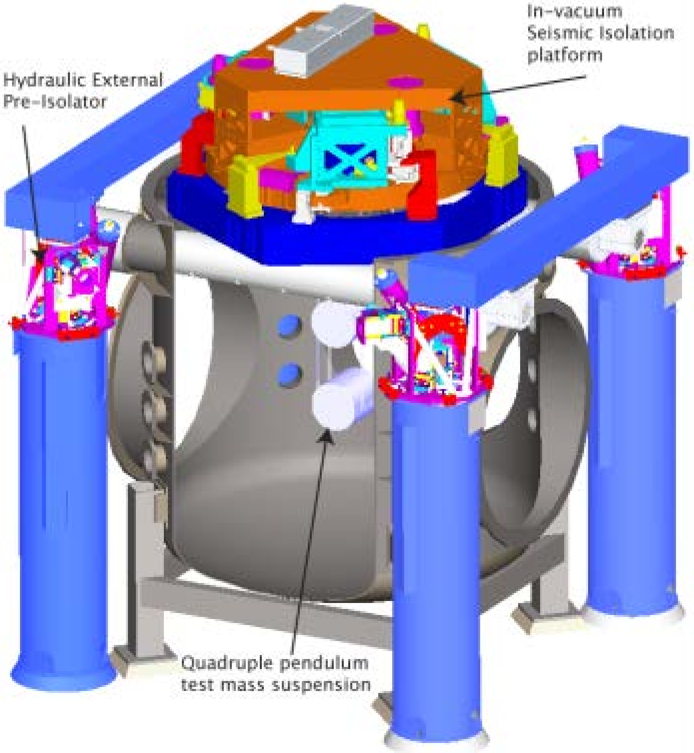
Electrostatic
Actuation

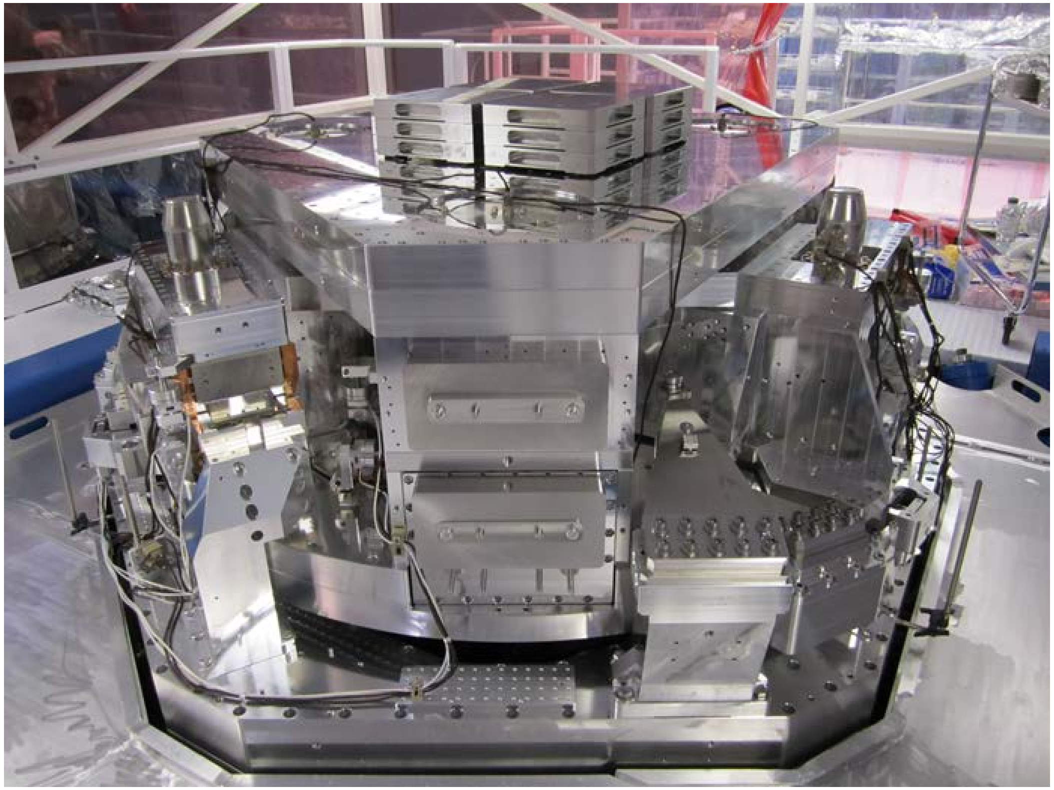
Designed by the University of Glasgow

Test masses suspended on fused silica fibers, welded in place

Note: Clean-room practice must be rigorously enforced.

Two stages of active isolation supplement the pendulums



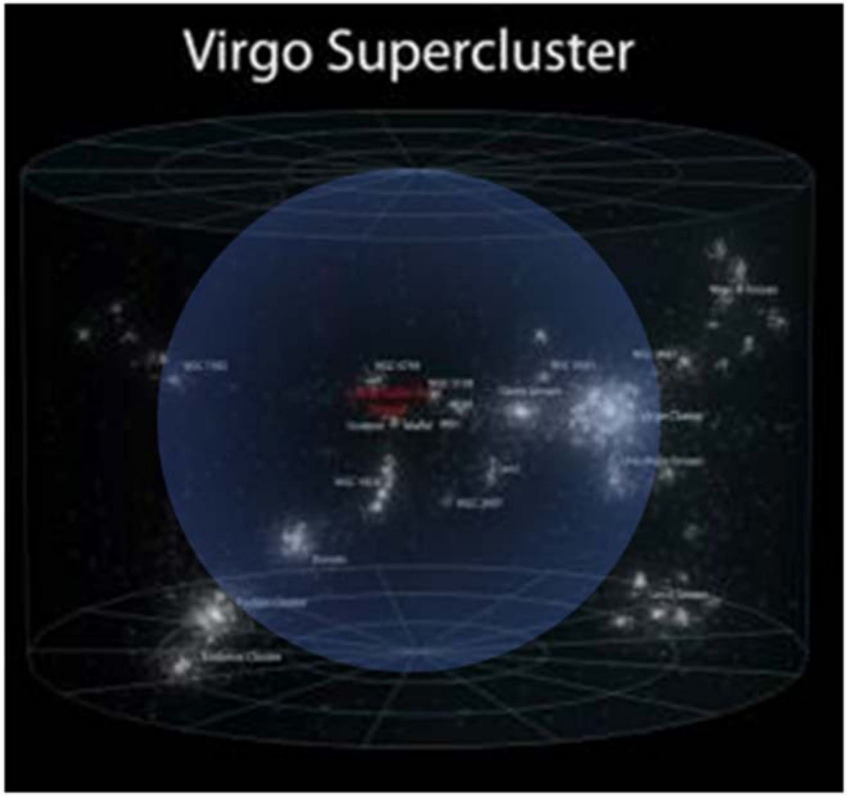


Initial LIGO didn't detect any gravitational wave signals

We were disappointed, but not surprised.

We could see neutron star binaries only out to 20 Mpc, while we needed to see to ~200 Mpc to expect a few per year.

Advanced LIGO will see to 200 Mpc.

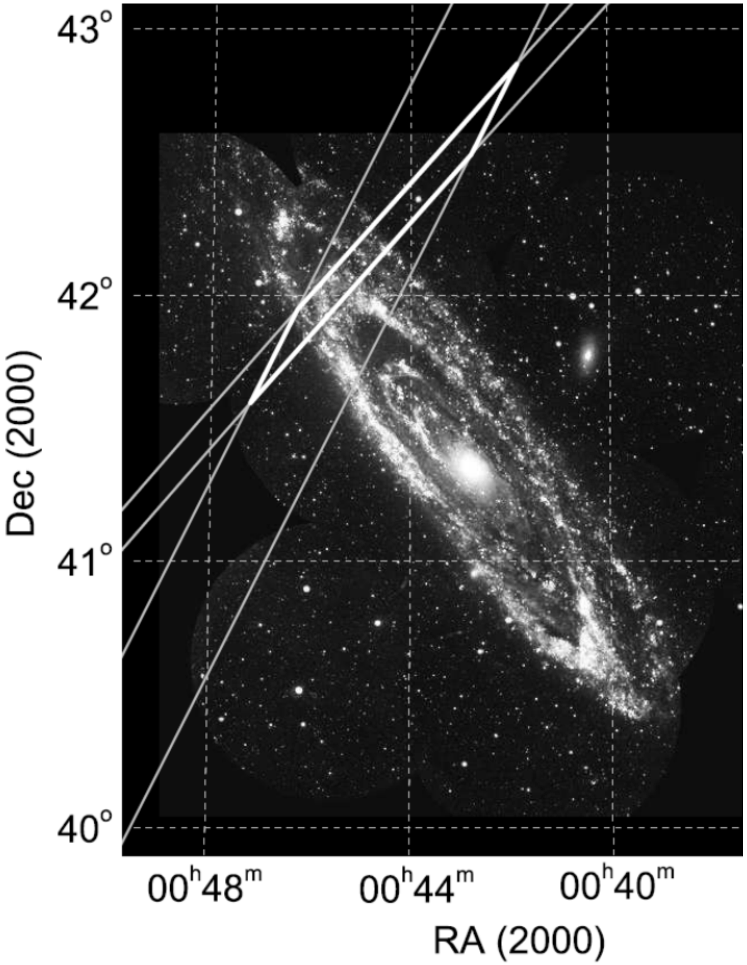


An interesting upper limit from initial LIGO observations

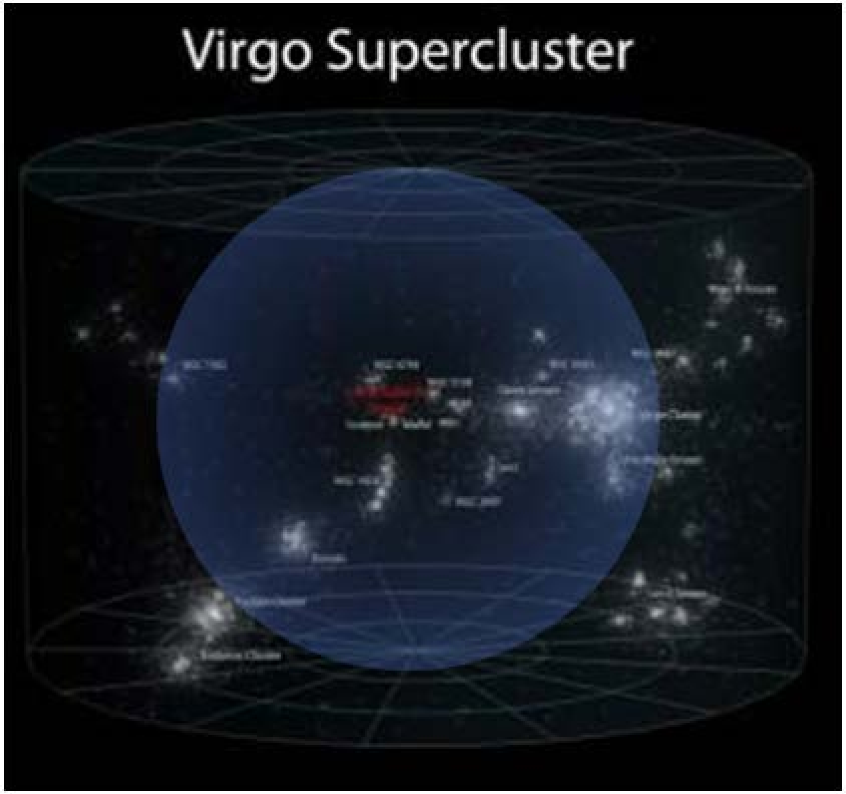
GRB 070201 was a short hard gamma ray burst, apparently in M31. (Distance = 0.8 Mpc, close!)

If it had been caused by a neutron star binary (or NS-BH binary), we would have seen it. We didn't.

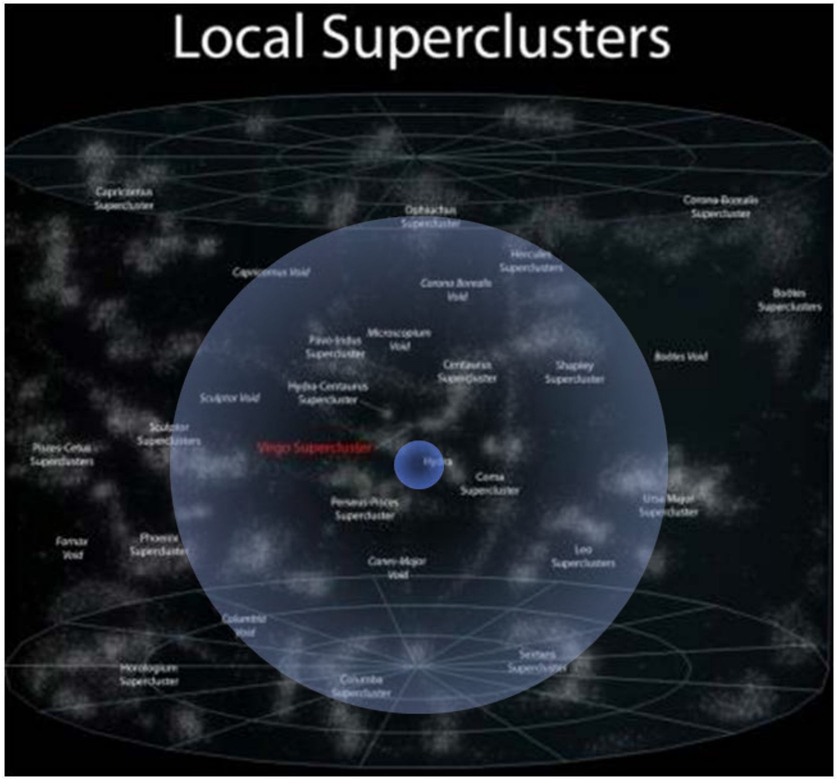
Most likely conclusion: It wasn't a classic short hard GRB, but was instead an SGR giant flare.



aLIGO will soon have the sensitivity that we need

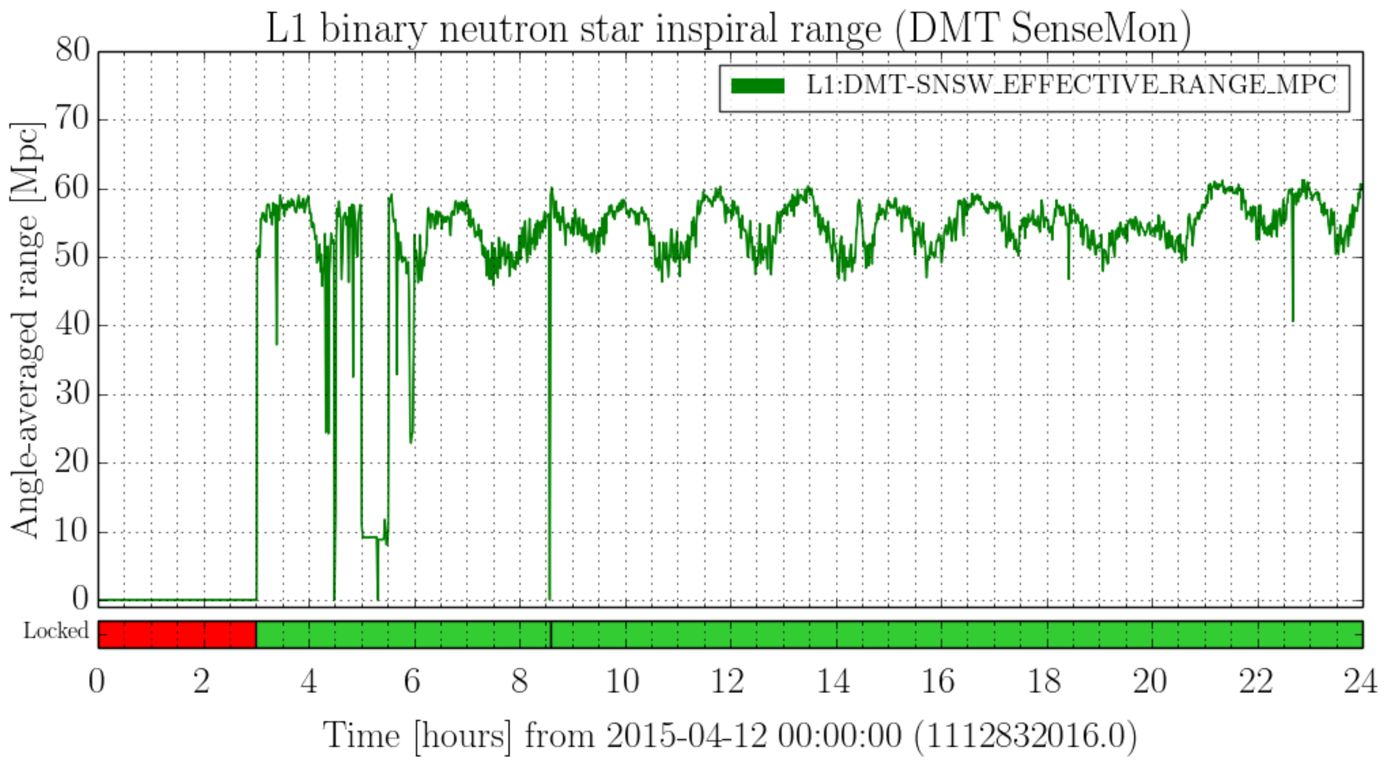


iLIGO could see the Virgo Cluster.



aLIGO will survey 1000x more volume.

Today, aLIGO can see three times as far as initial LIGO did.



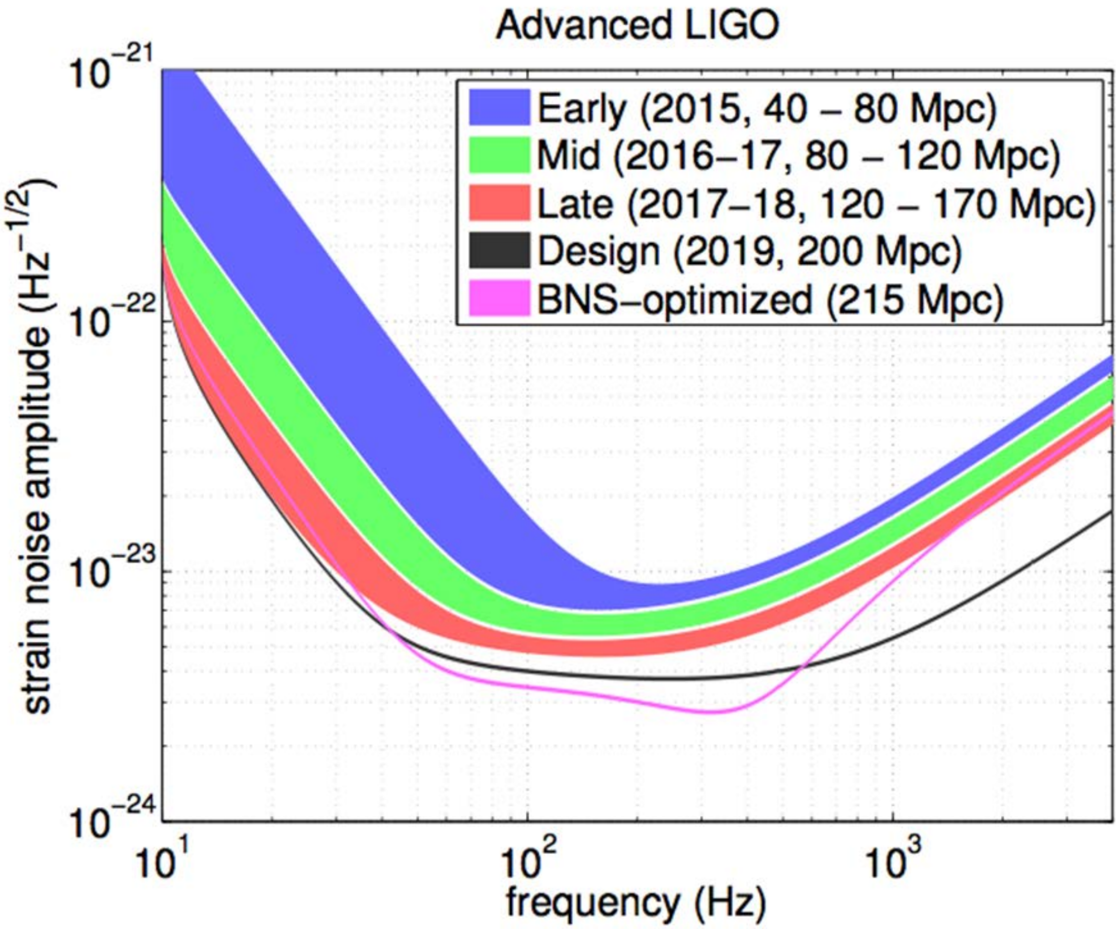
Our first observing run with Advanced LIGO starts Sept 2015.

Binary neutron star signals expected by 2017-19

aLIGO will reach design sensitivity by 2019.

Binaries with black holes will likely turn up as well.

There will be a lot of good physics and astrophysics to do.



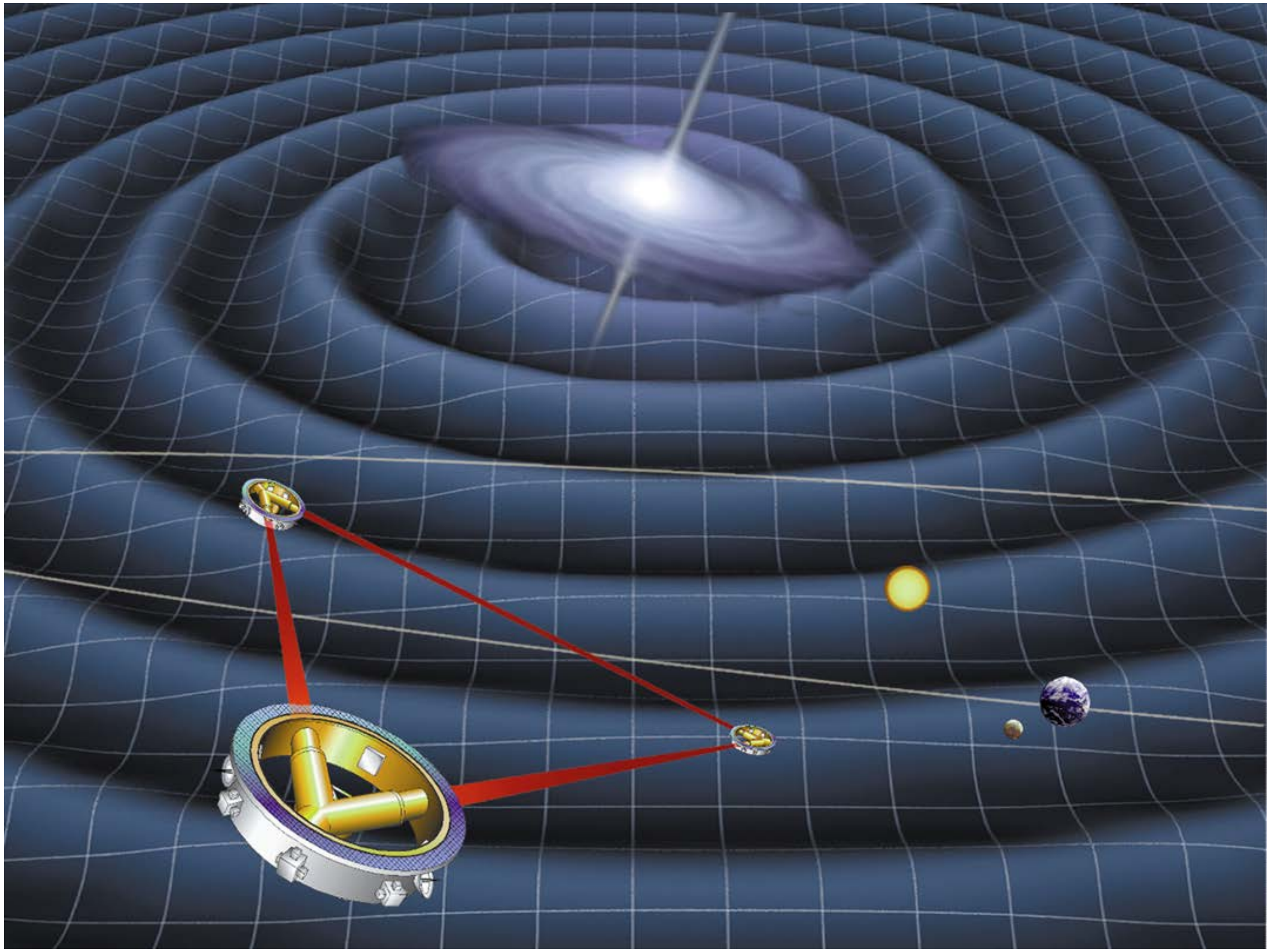
We need a global network to do gravitational wave astronomy

Like an ear, listening with a gravitational wave telescope is omni-directional. But with two (or more) ears, you can tell where a signal came from.

Advanced Virgo will join our network next year; a LIGO detector in India will turn on in 2022.

Soon, we'll be listening to the universe in high-fidelity quadraphonic audio.

Someday soon, we'll put GW detectors in space



There's a whole gravitational wave spectrum