Exploring the Frontier of Astrophysical Relativity with Advanced LIGO

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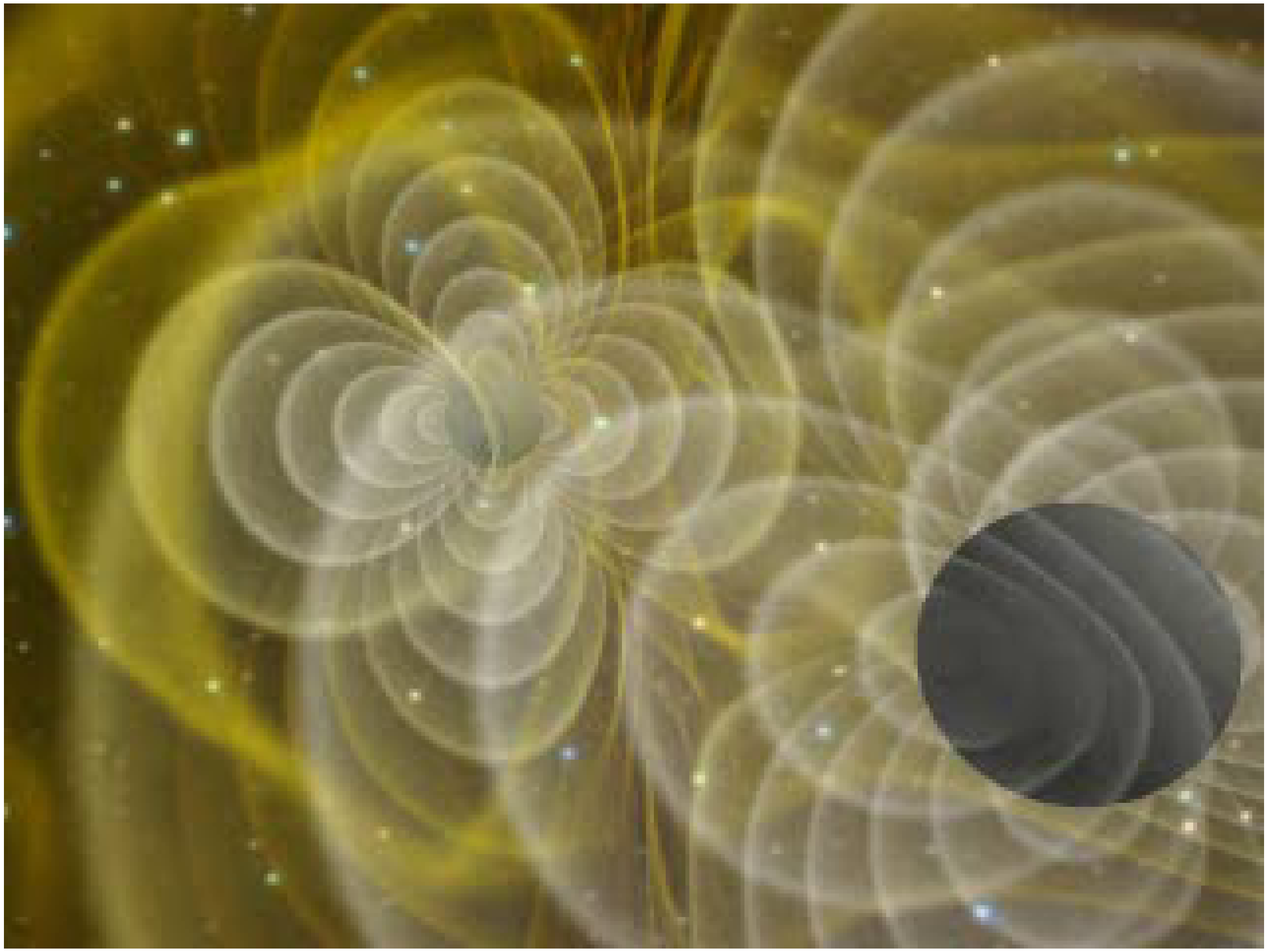
Topics

- What is a gravitational wave?
- What will we learn from detecting them?
- The challenge of detecting GWs
- How will we meet the challenge?
- What is Advanced LIGO about to see?
  - the special role for LIGO-India
- The coming decade of GW discovery

Binary inspiral is an essential process in the dynamics of the universe

Black holes in orbit around one another spiral into one another because they emit energy in *gravitational waves*.

Soon, we'll be able to observe this phenomenon in real time, and use it to learn more about black holes.



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.**

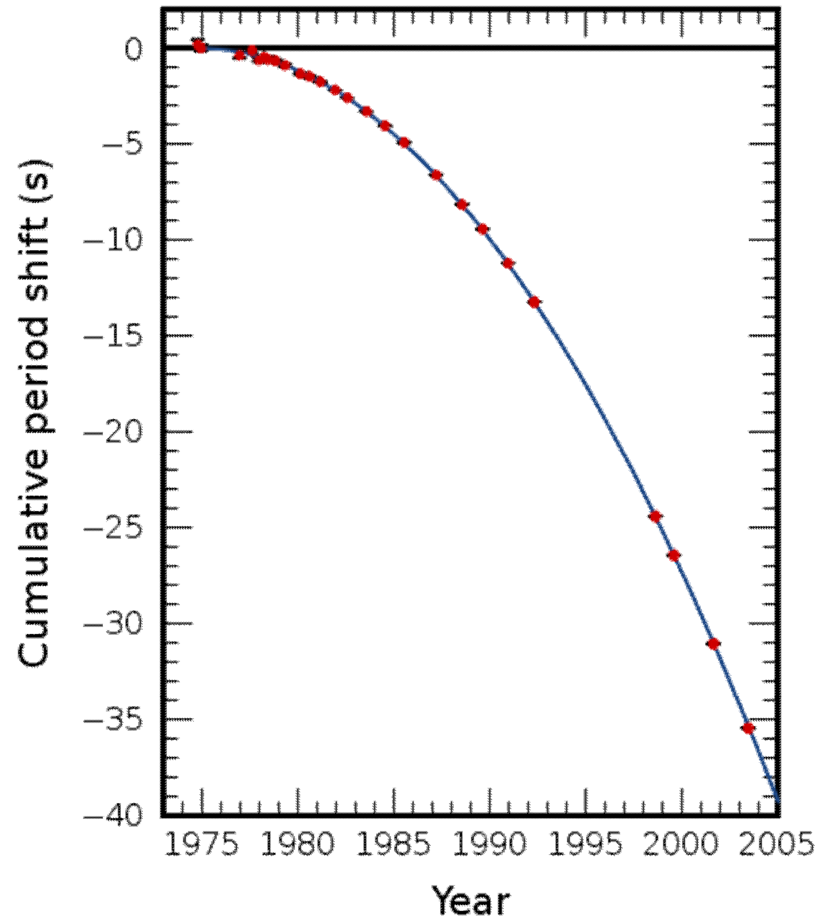
Gravitational wave detectors will also let us hear neutron star binaries, the stellar core collapse that ignites a supernova, and many other phenomena.

We've found neutron star binaries that inspiral, thus seen <u>that</u> gravitational waves <u>exist</u>

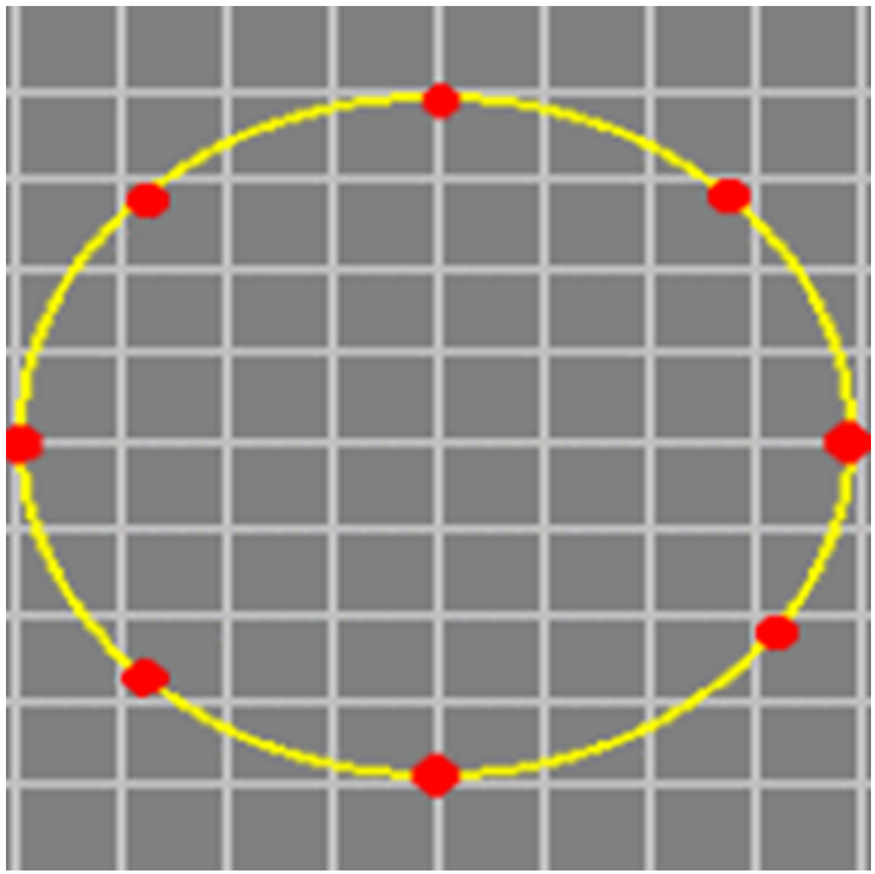
In 1974, Russell Hulse and Joe Taylor found PSR 1913+16, a pulsar in a binary orbit with another neutron star.

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.

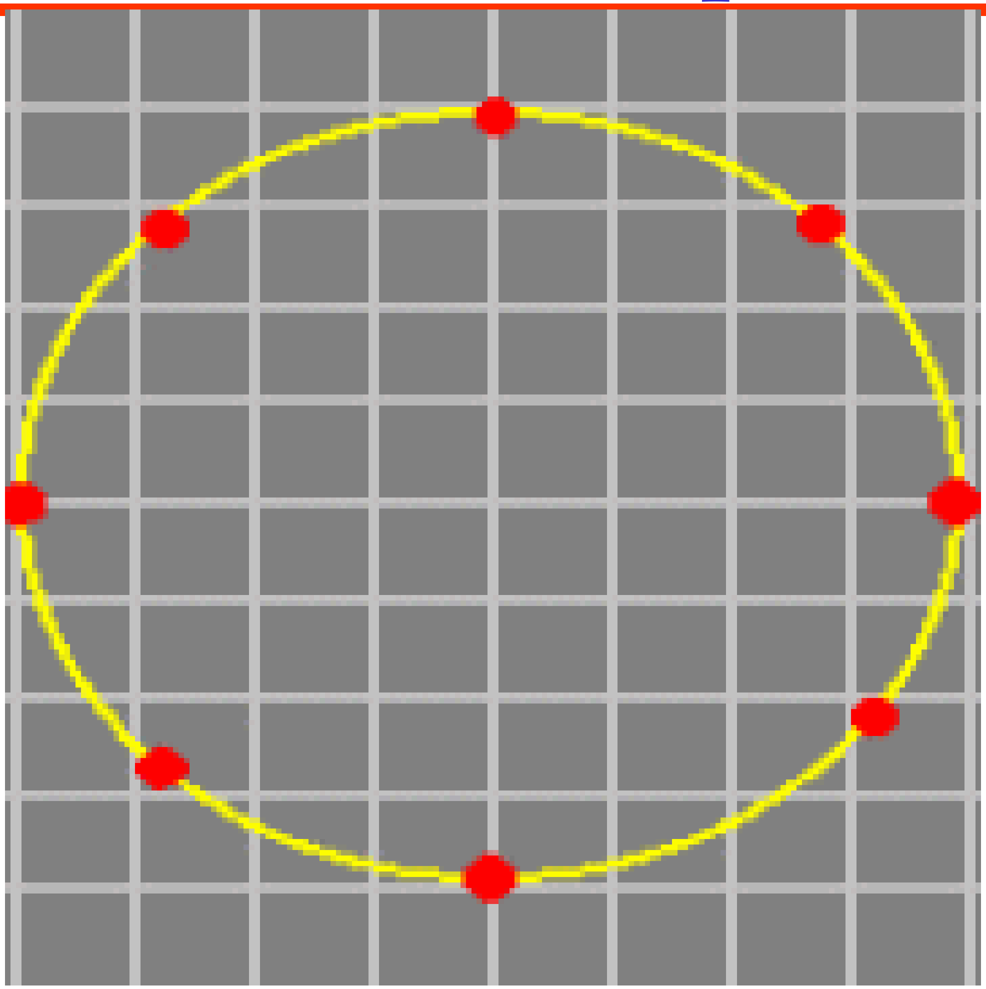
This was the discovery of gravitational radiation.



How to sense the vibrations of spacetime



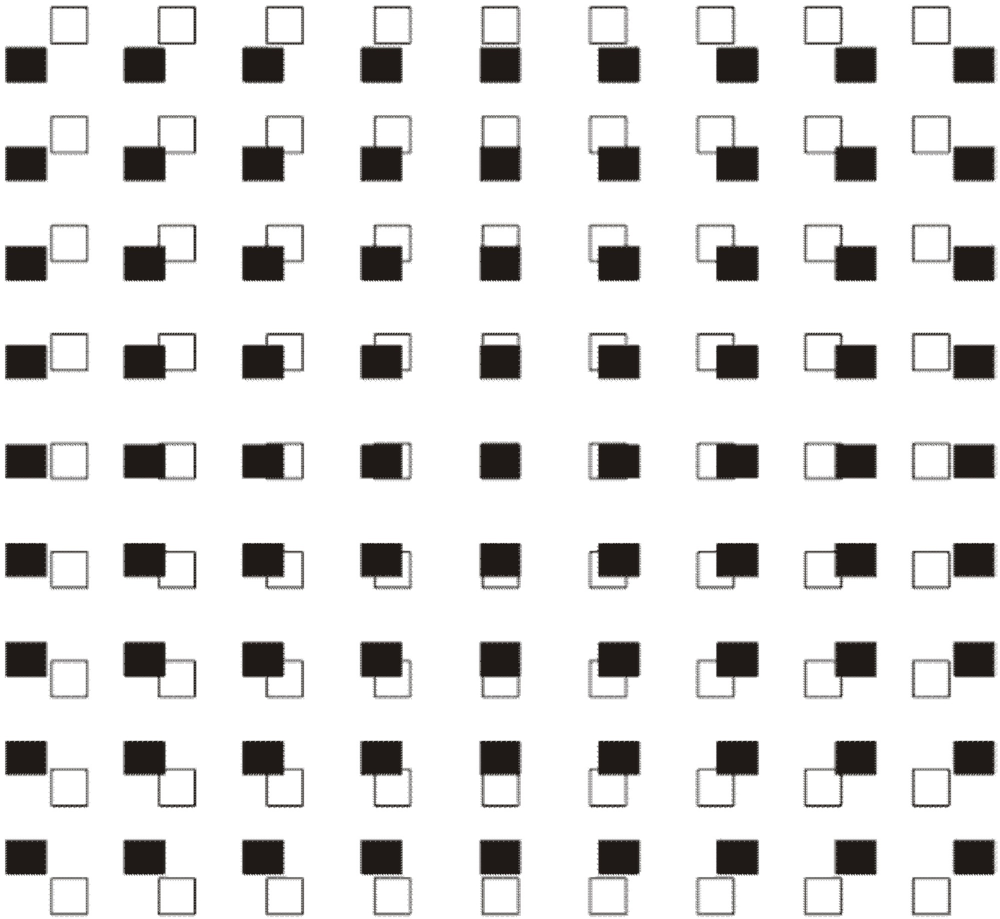
What happens when a gravitational wave passes by



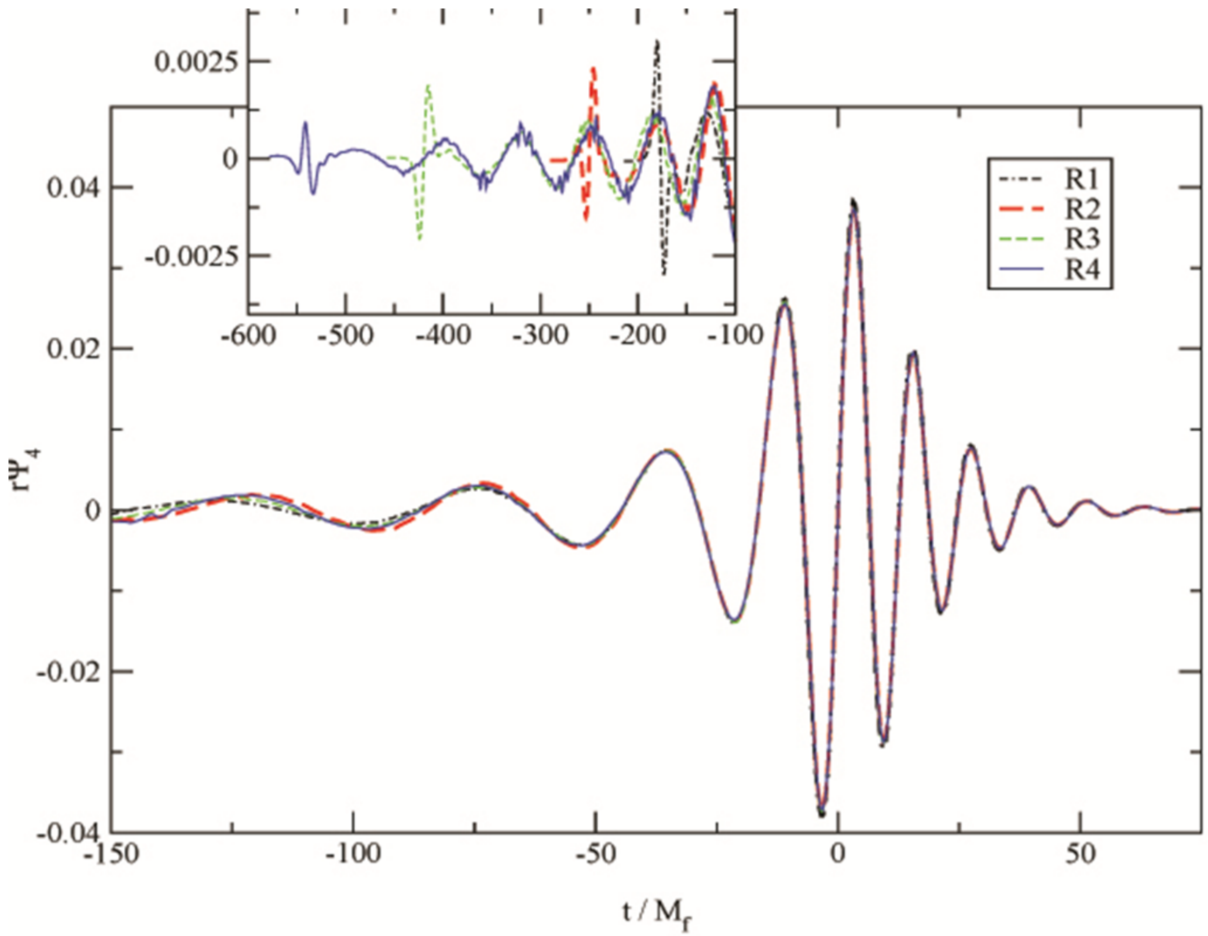
Gravitational wave strain pattern

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

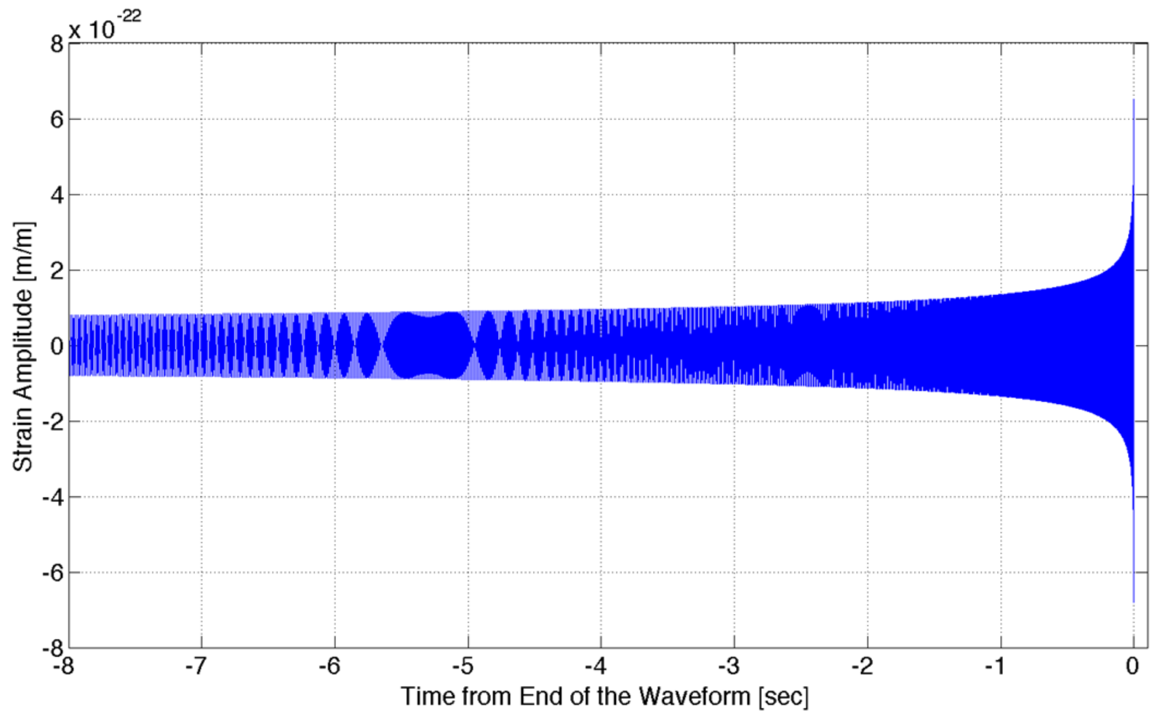
The effect is bigger over longer baselines.



Gravitational waveform = oscillation pattern of test masses



Since we understand general relativity, we can calculate waveforms



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

Gravitational waveforms let us read out source dynamics

To a very good approximation, the evolution of the mass distribution can be read out from the gravitational waveform:

$$h(t) = \frac{1}{R}\frac{2G}{c^4}\ddot{I}(t\text{-}R/c)$$

I is the mass quadrupole moment of the source.

Coherent relativistic motion of large masses can be directly observed.

Gravitational waves are built from our deepest relativistic insights

- Embody gravity's obedience to Einstein's key special relativistic insight: "No signal faster than light."
- Allow a view into the relativistic dynamics of orbits that inspiral.
- Will allow us to study the dynamics of astrophysical black holes, including:
  - gravitational collapse
  - the "no hair" theorem
  - quasi-normal modes

Detecting gravitational waves will allow us to:

- Show that gravitational waves travel at *c*, and that the graviton is massless and has spin 2
- Search for cosmic strings
- Determine the mechanism of gamma ray bursts
- Measure the equation of state of neutron stars
- Understand the cosmic abundances of heavy elements
- Explore the universe at Planckian timescales.

How to check that gravitational waves move at the speed of light

Short hard gamma-ray bursts probably come from the coalescence of neutron star binaries.

We should see some of these events in coincidence, within a few seconds. Then:

$$1 - \frac{v_{GW}}{c} = 5 \times 10^{-17} \left(\frac{200\ Mpc}{R} \right) \left(\frac{\Delta t}{1\ sec} \right)$$

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:

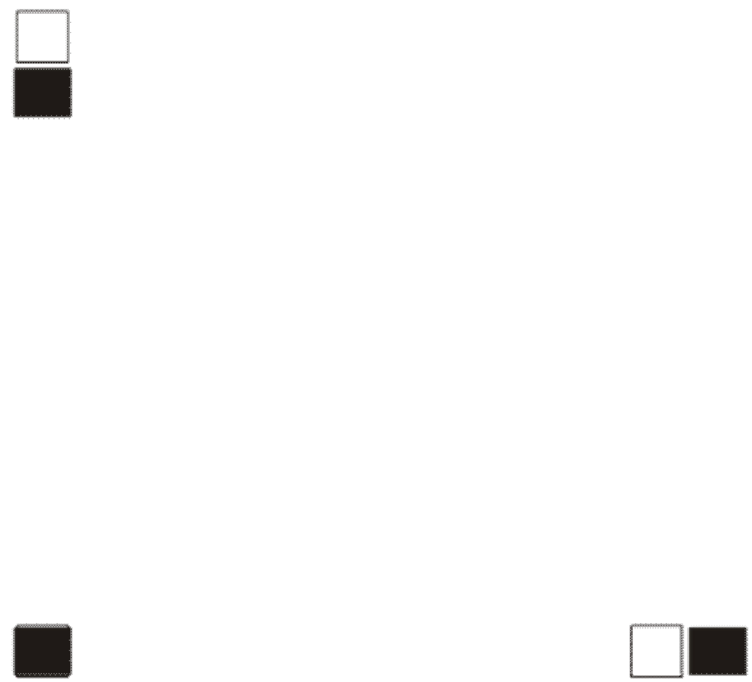
  Best astrophysical estimates predict fractional separation changes of only 1 part in 10^{22}, or less.

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

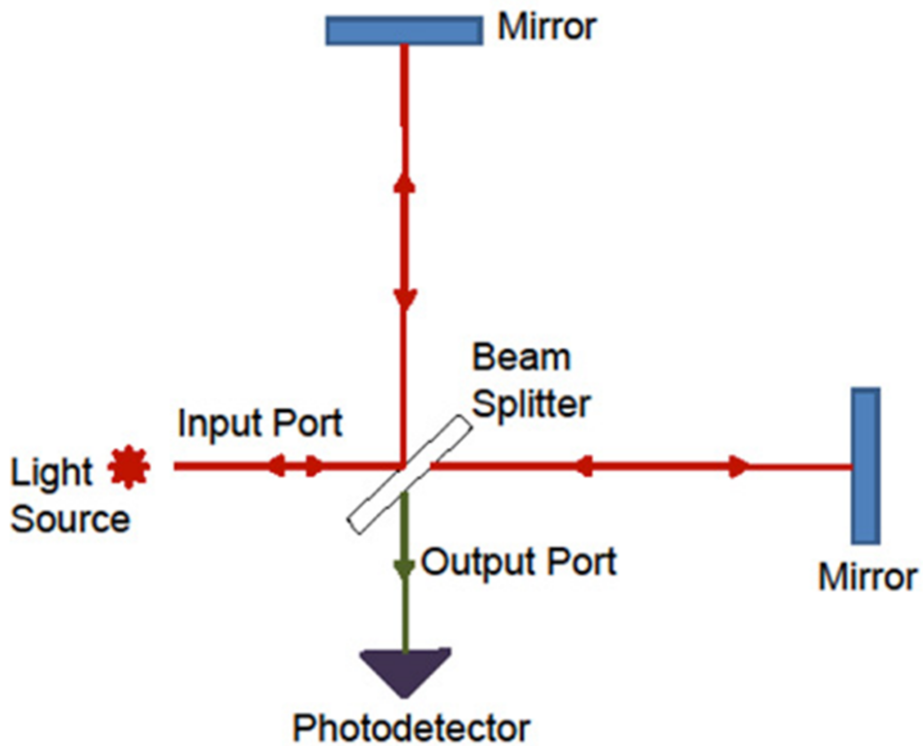
Let's invent a gravitational wave detector

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

In LIGO, we've put ours 4 km apart.



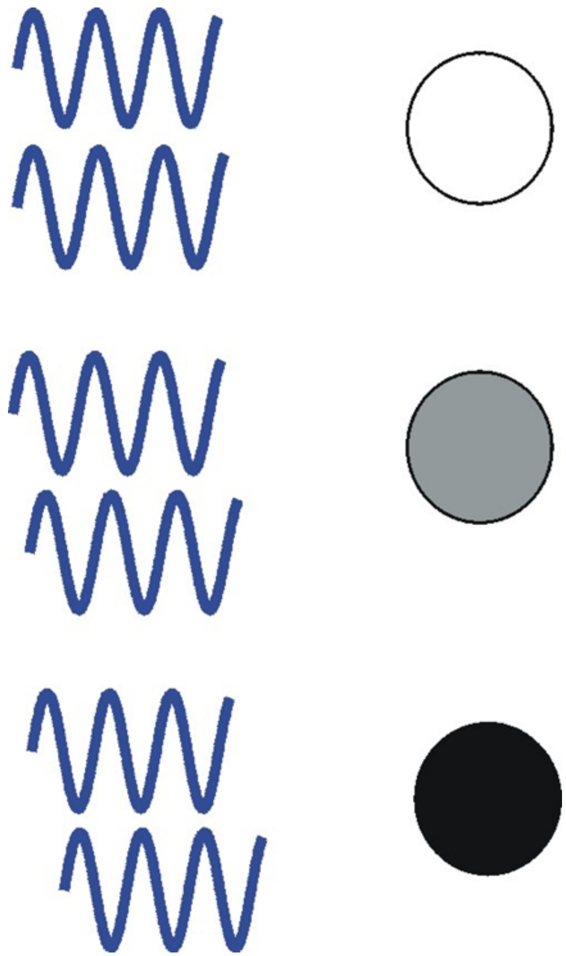
Use a Michelson interferometer to measure relative motion



Michelson interferometer =
transducer from length difference to brightness

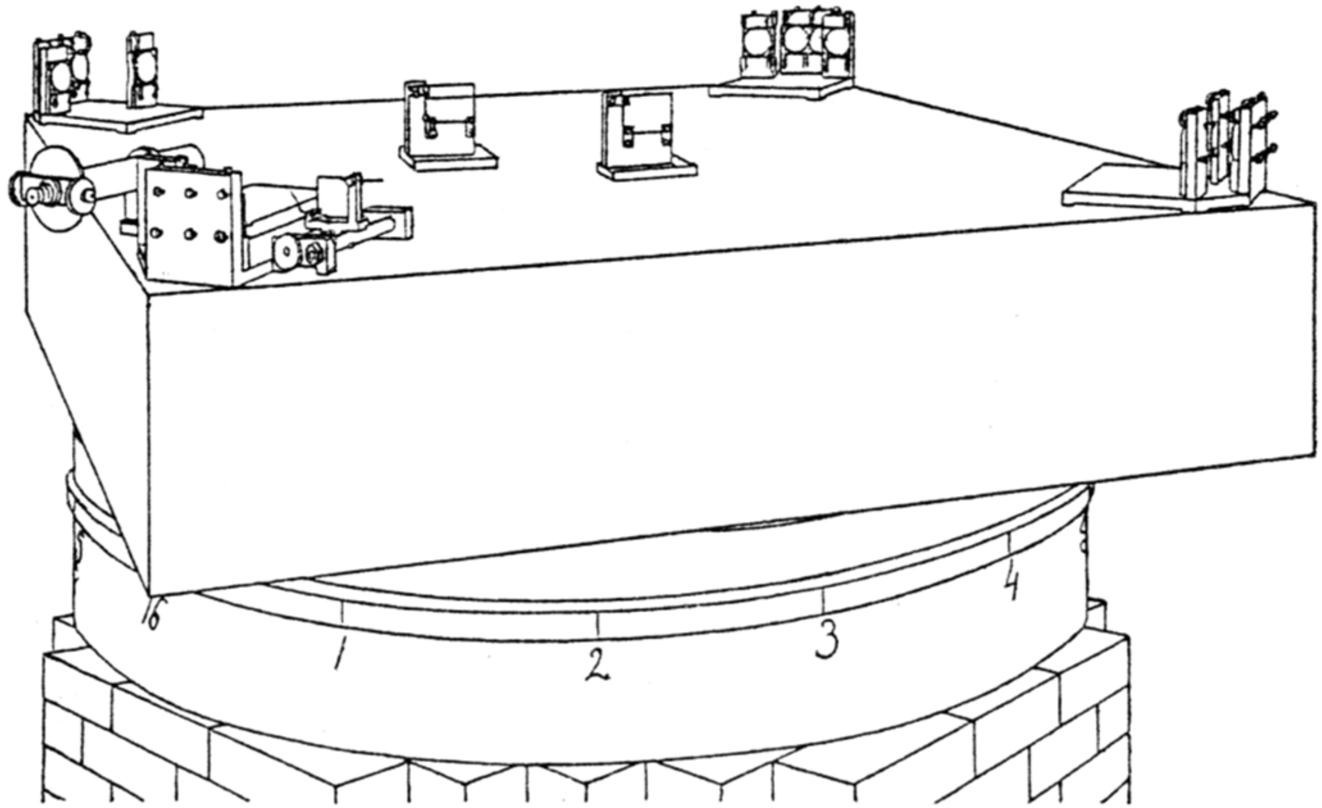
Light from x arm

Light from y arm



Brightness of superposed beams of light from the two arms.

Here's how A.A. Michelson showed that there's no "ether"



Here's how it looks as the Laser Interferometer Gravitational wave Observatory (LIGO)

LIGO Hanford Observatory, WA

LIGO Livingston Observatory, LA

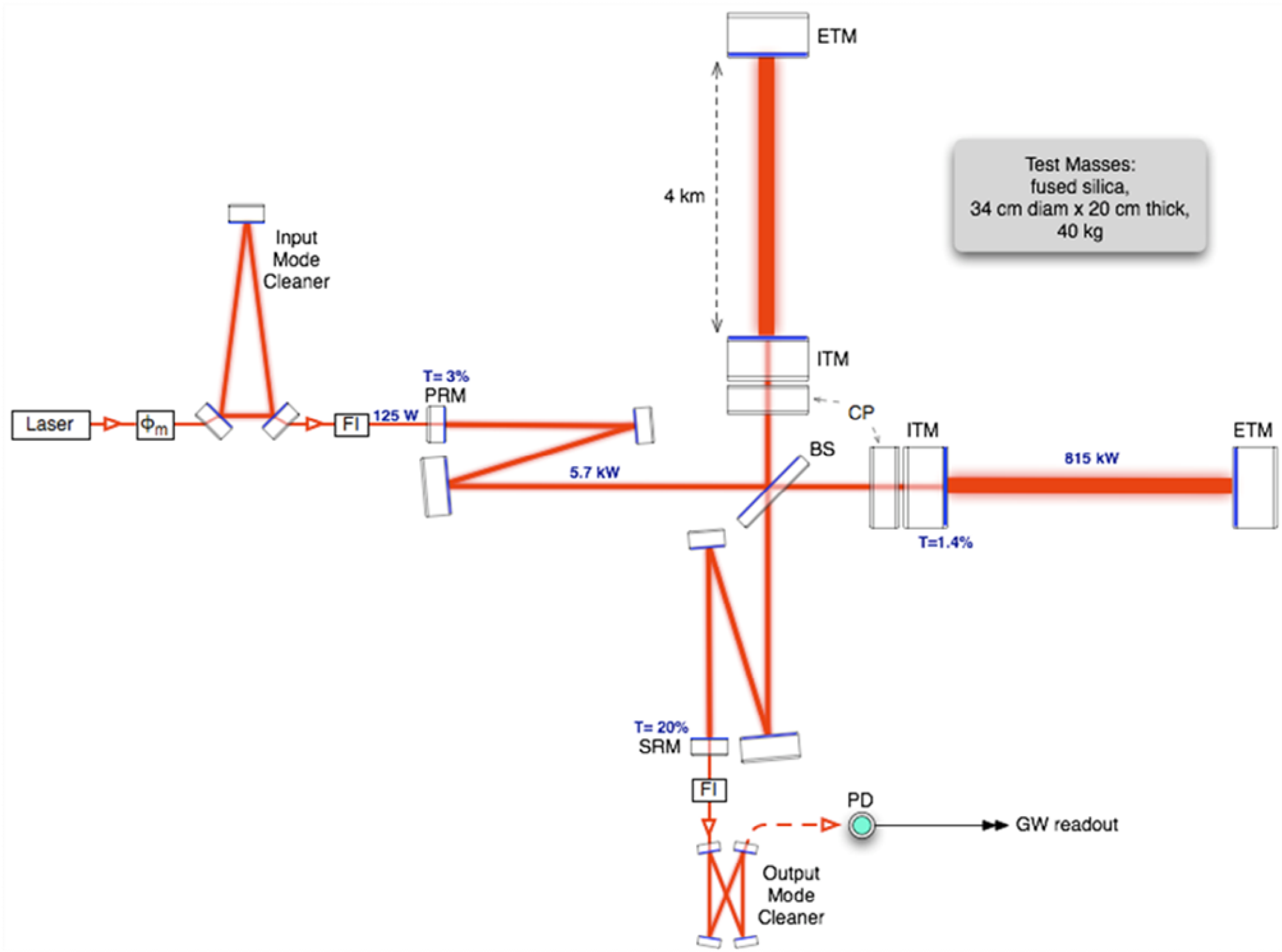
Two interferometers with 4 km arms, observed at a sensitivity of $h \sim 10^{-21}$ between 2005 and 2010.

GEO and Virgo observed and analyzed data with us

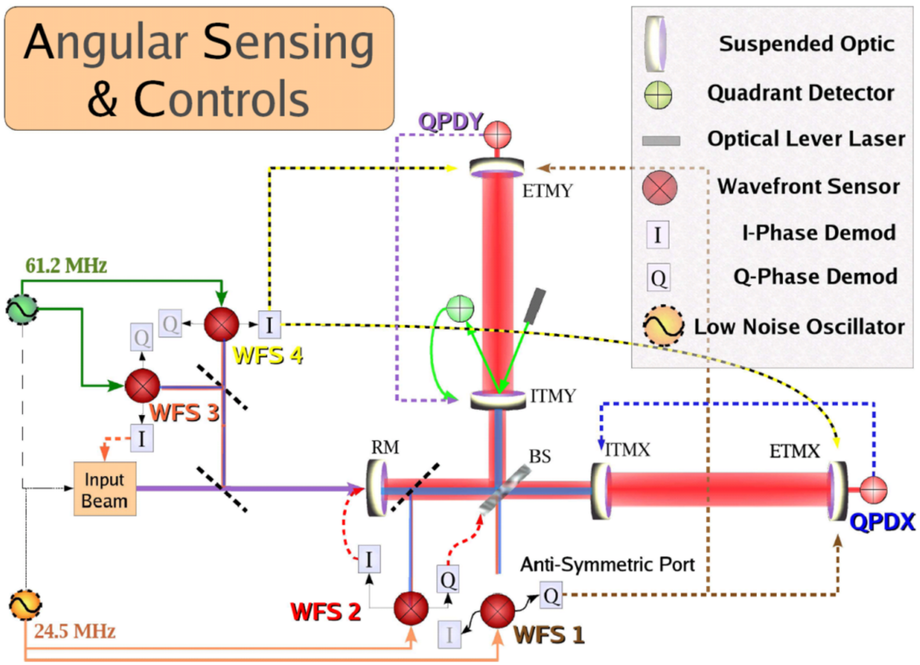
GEO, 600 m arms, near Hannover

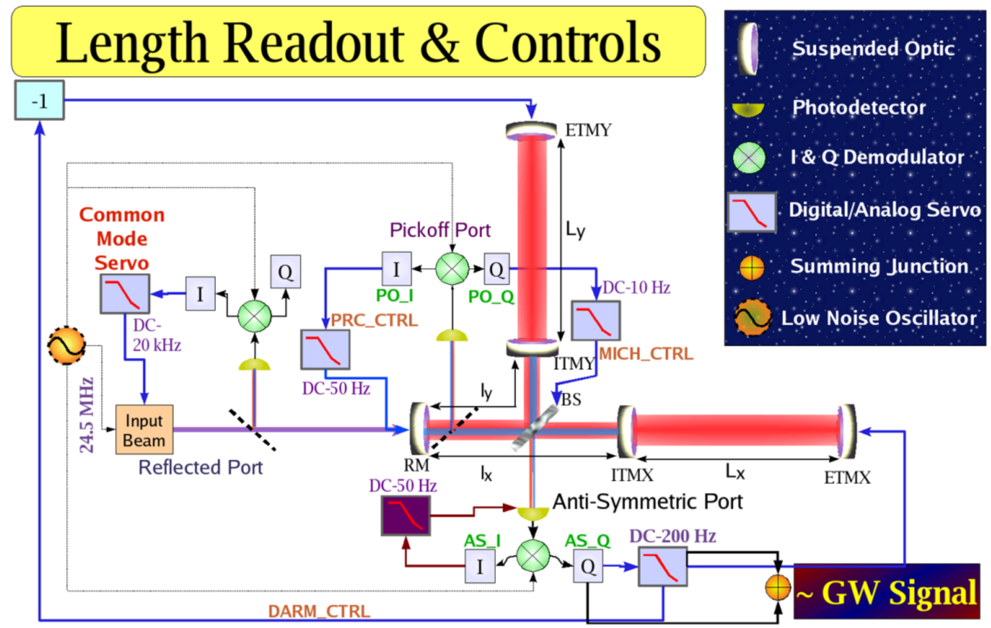
Virgo, 3 km arms, near Pisa

aLIGO optical layout (still simplified)



Free masses must also be precisely aligned and positioned



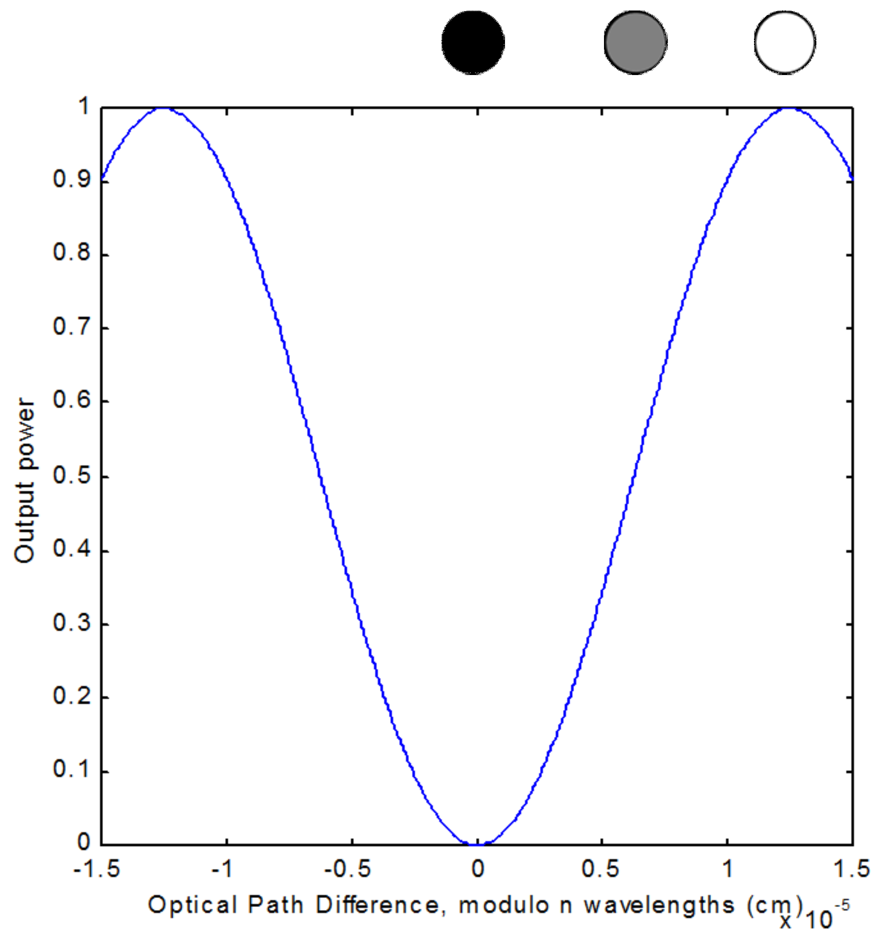


Mirror alignment and position controlled by a system of sensors and actuators. The system stays very close to a chosen operating point, while leaving the mirrors nearly free.

Can we measure $h \sim 10^{-22}$?

An interferometer is a transducer from length difference to brightness.

- Make the signal big by making the arms long.
- Make the transduction factor big by folding the arms.
- Allow fine measurement of output power by using lots of light.



aLIGO optical design

- Laser power: 125 W
- Folding of arms by factor of 450.

  Arms are resonant Fabry-Perot cavities.
- Re-use laser power by a factor of 500 by reflecting light back into the interferometer.

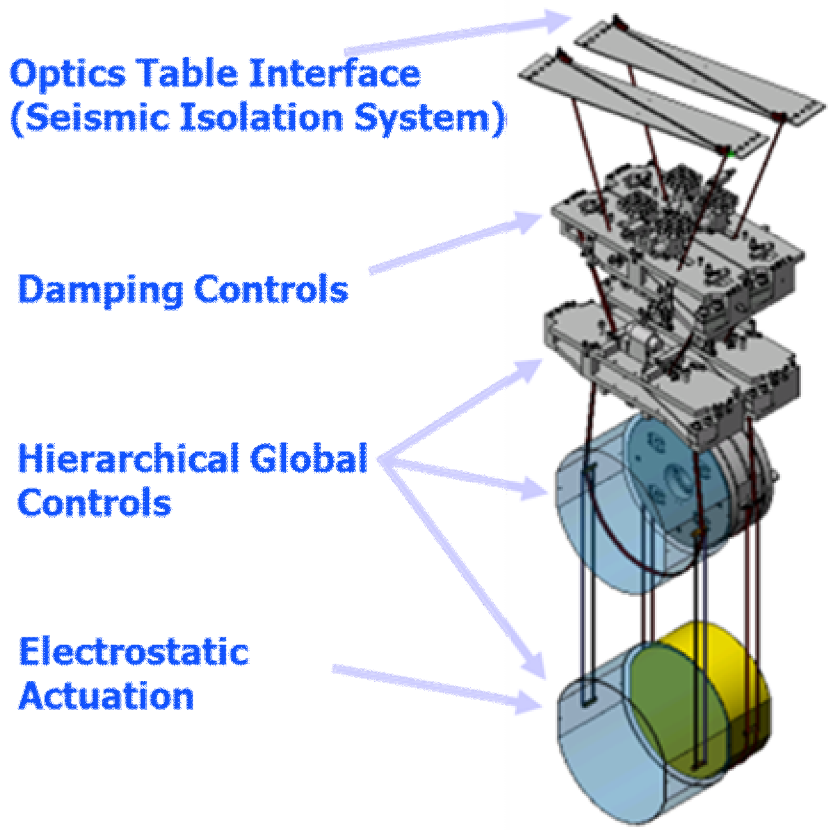
  "power recycling"
- Resonantly build up signal by reflecting "signal sidebands" back into interferometer.

  "signal recycling"

LIGO's 4 km arms, 10^{-8} torr

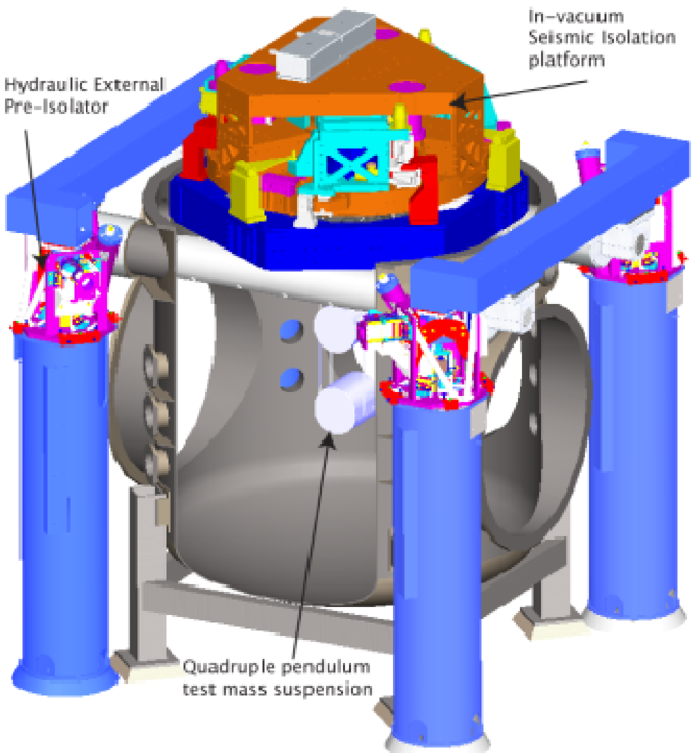
Vacuum chambers
here, beamsplitter and input test masses

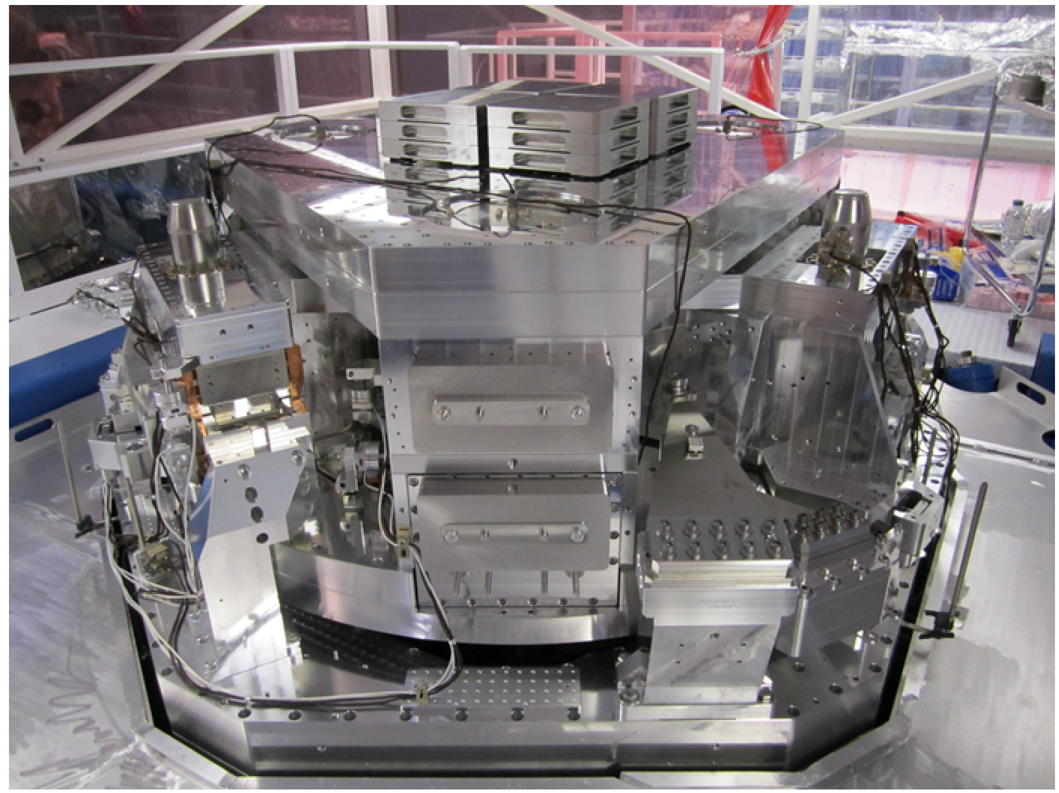
Quadruple pendulums suspend and isolate the test masses



Designed by the University of Glasgow

Two stages of active isolation supplement the pendulums



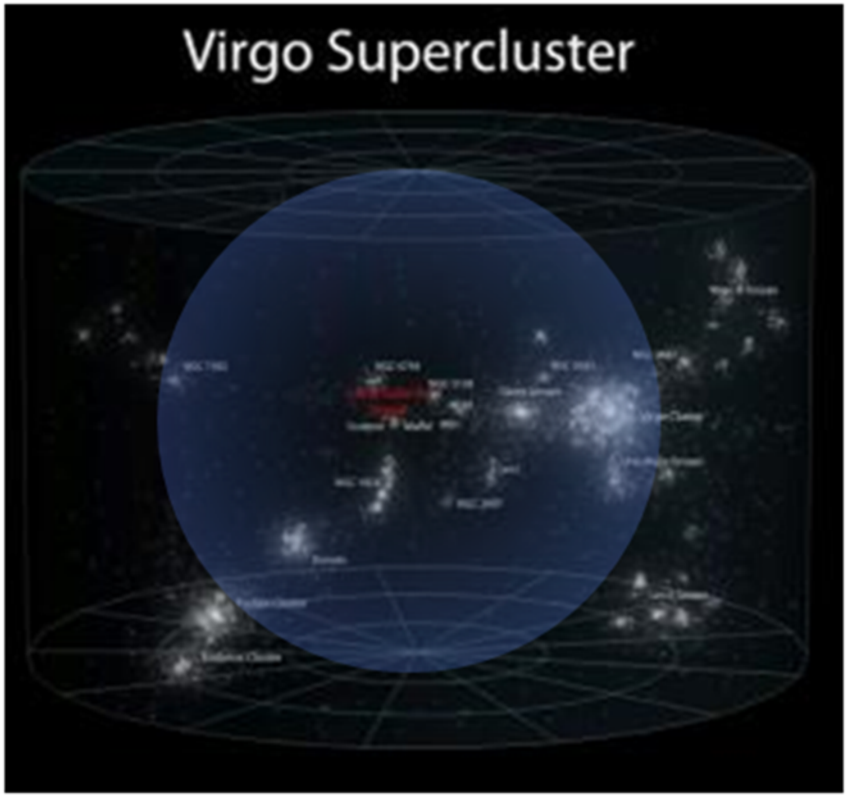


Initial LIGO didn't detect any gravitational wave signals

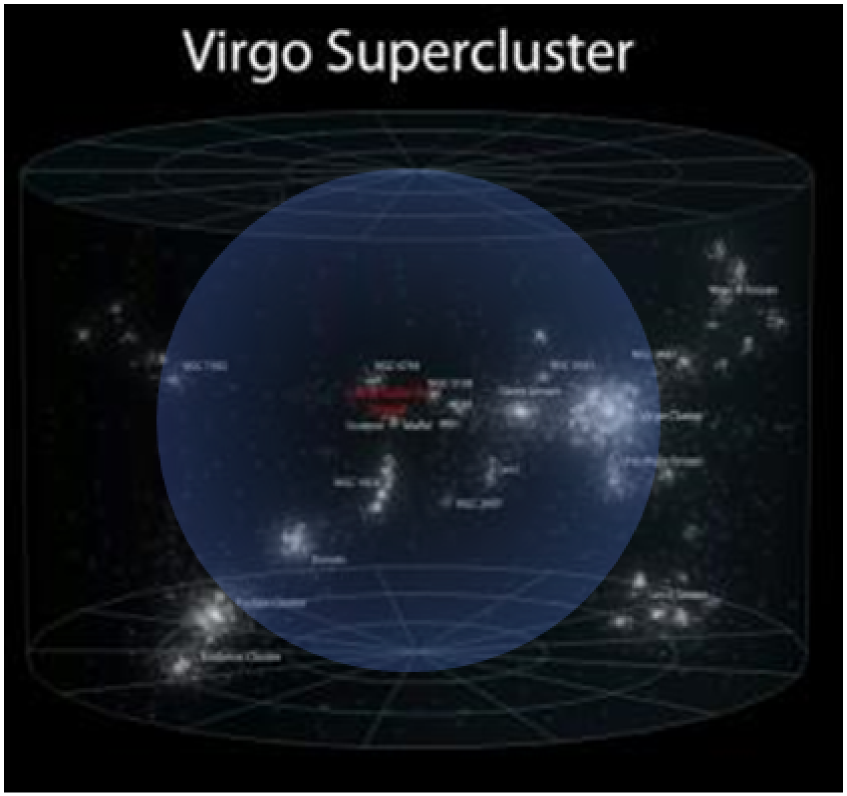
We were disappointed, but not surprised.

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.

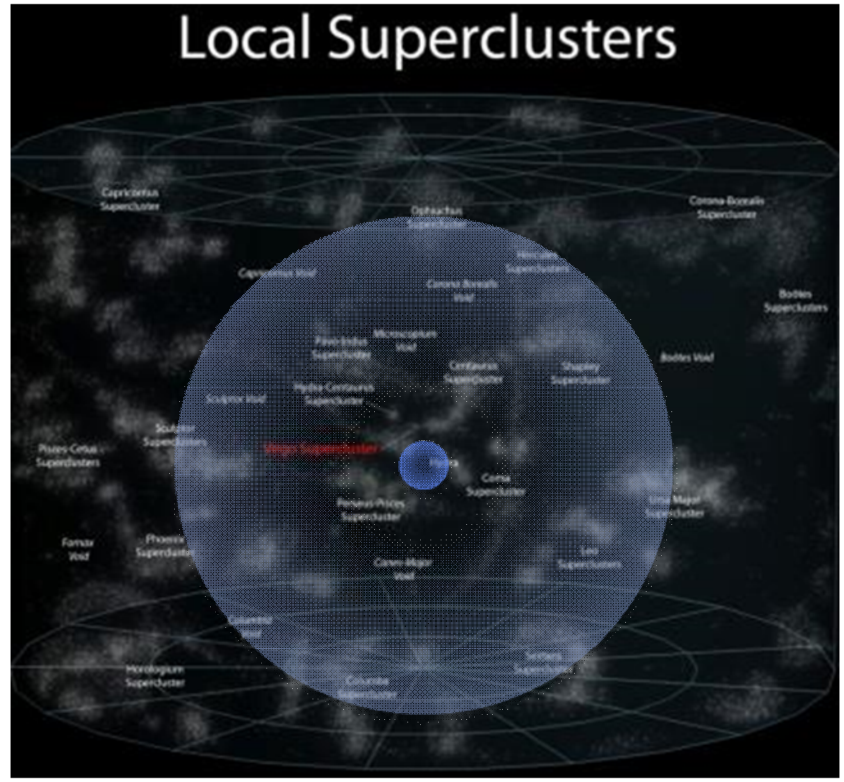
Advanced LIGO will see to 200 Mpc.



aLIGO will soon have the sensitivity that we need

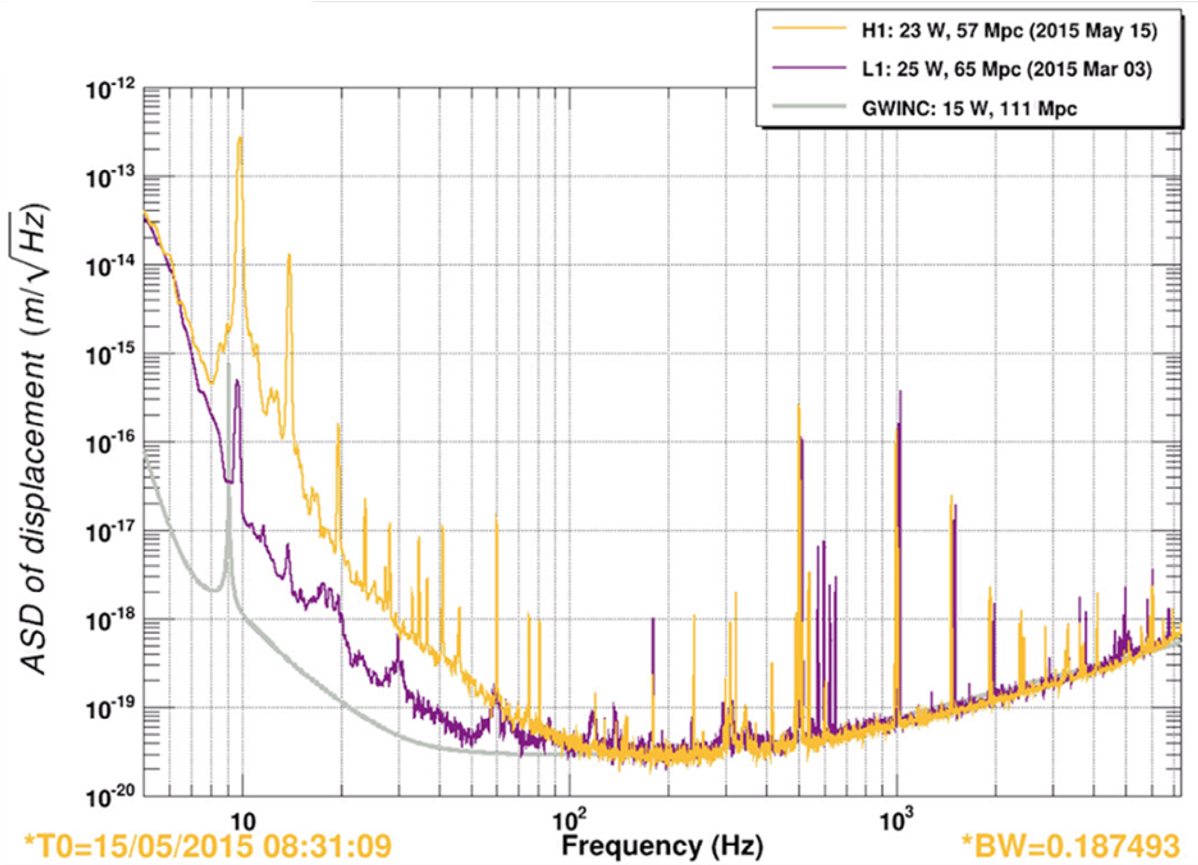


iLIGO could see the Virgo Cluster, 20 Mpc away.



aLIGO will survey to 200 Mpc, 1000x more volume.

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



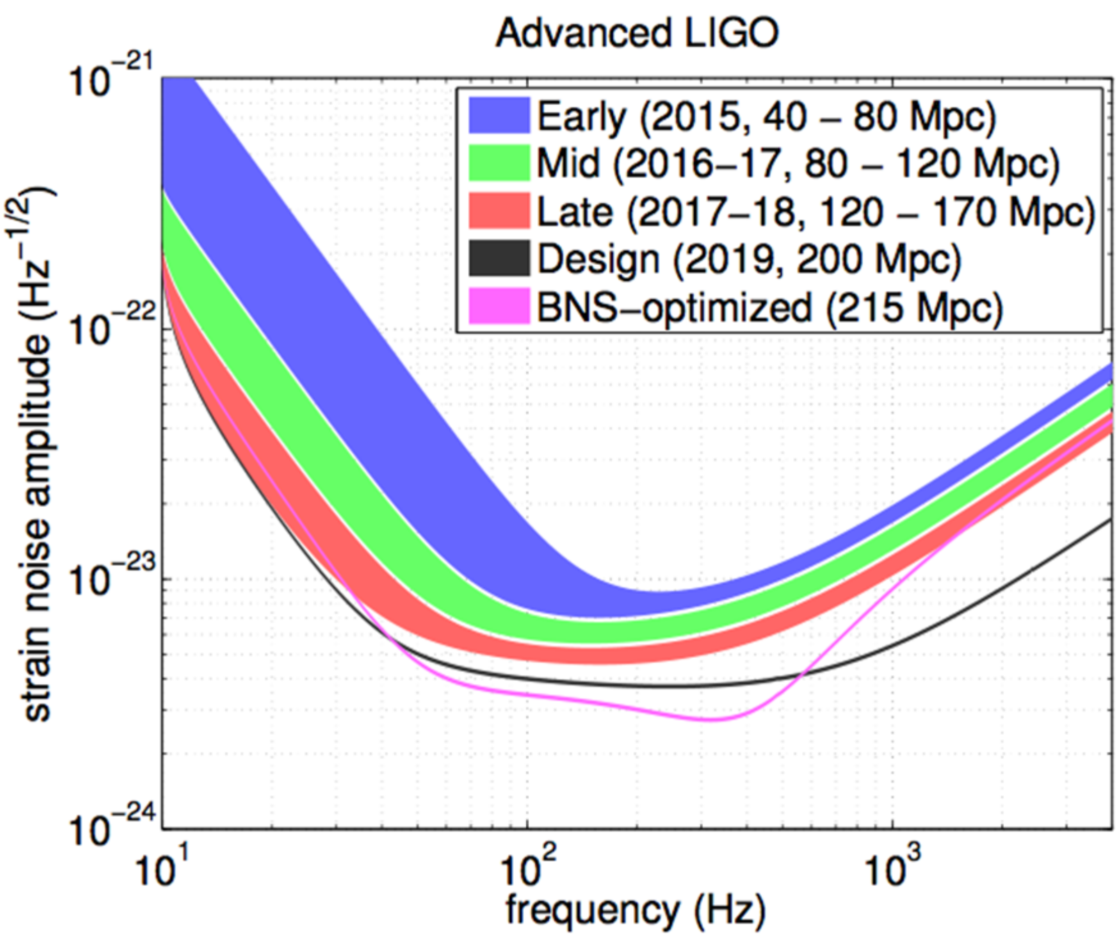
Our first observing run with Advanced LIGO starts Sept 2015.

Binary neutron star signals expected by 2017-19

aLIGO should 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.



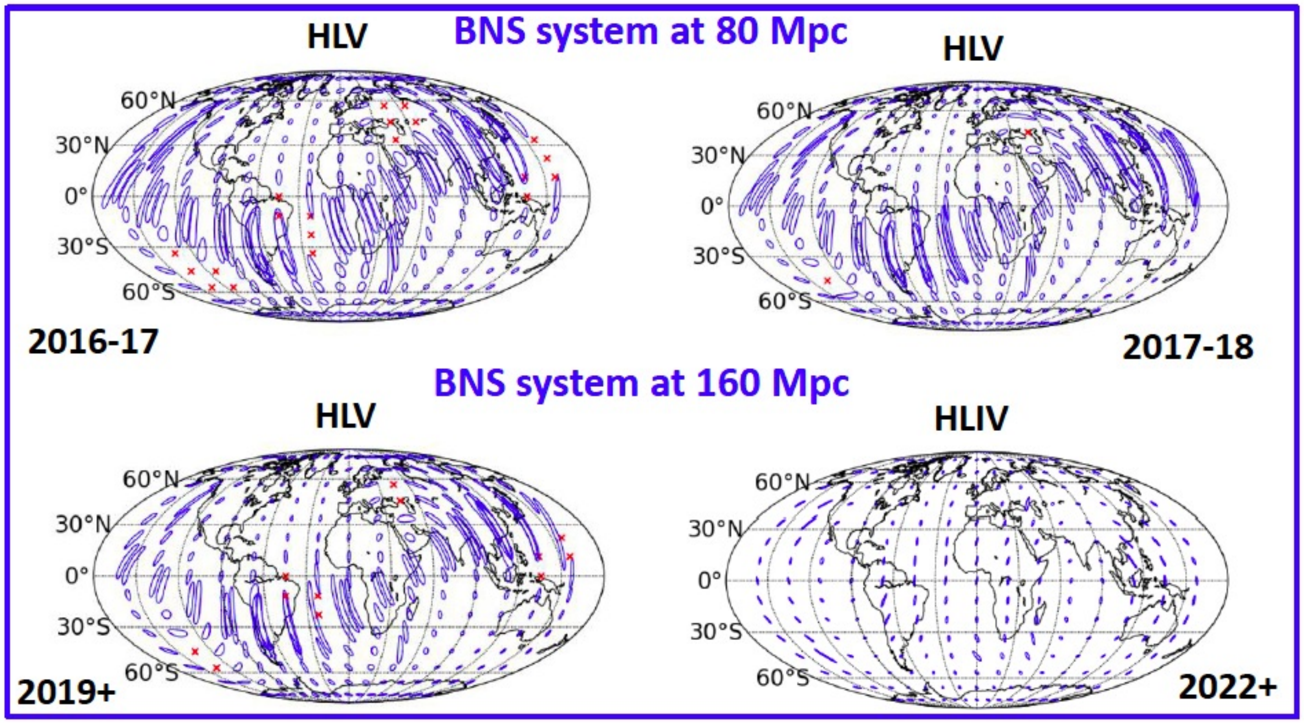
We need a global network to do gravitational wave astronomy

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

Advanced Virgo will join our network next year; an Advanced LIGO detector in India will turn on in 2022, we hope.

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

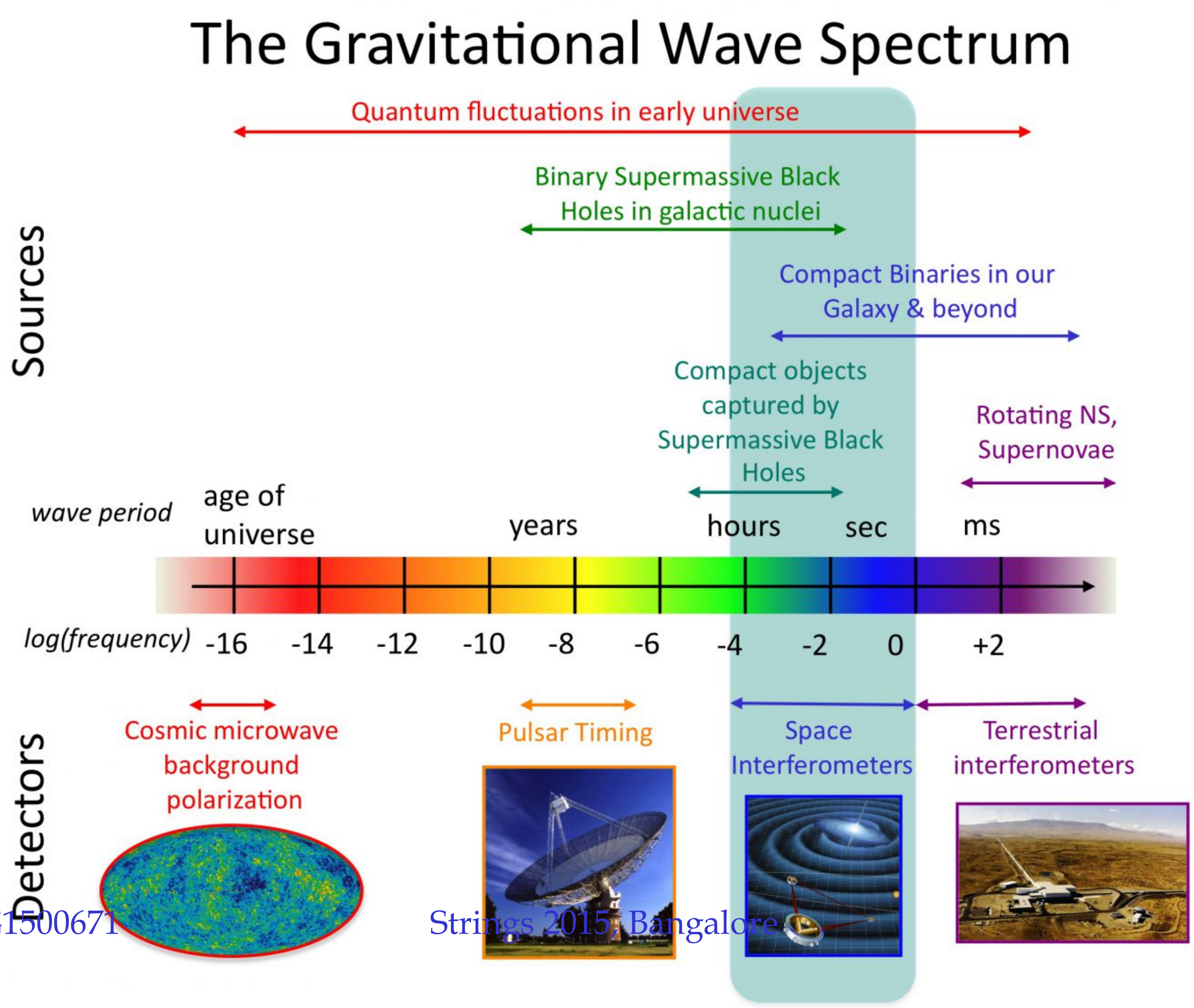
LIGO-India will play a crucial role in localizing sources



Position uncertainties with areas of **tens to hundreds of sq. degrees**

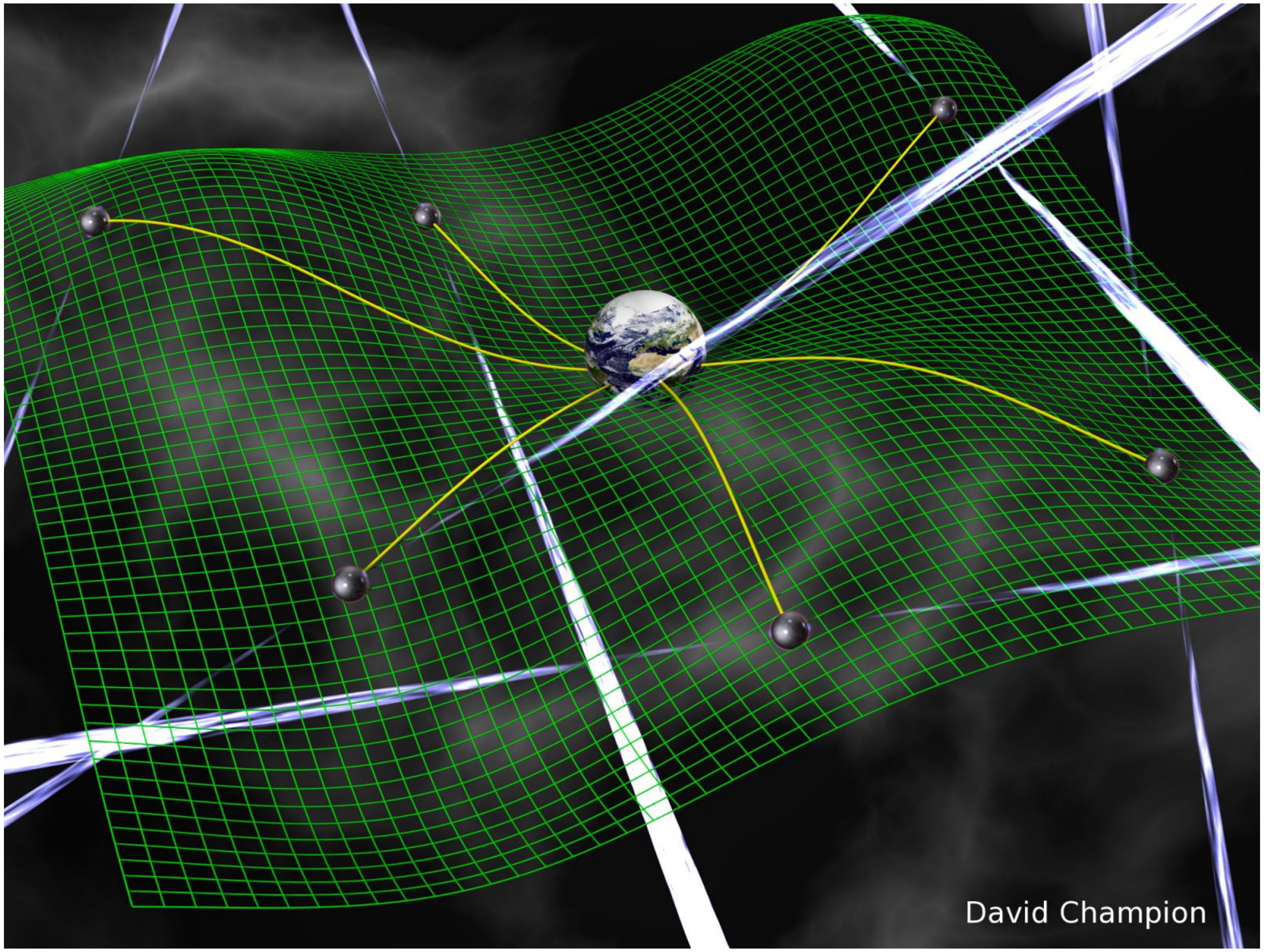
→ 90% confidence localization areas
X → signal not confidently detected

Many techniques to explore the gravitational wave spectrum



A Galaxy-scale "interferometer" by timing of pulsar signals

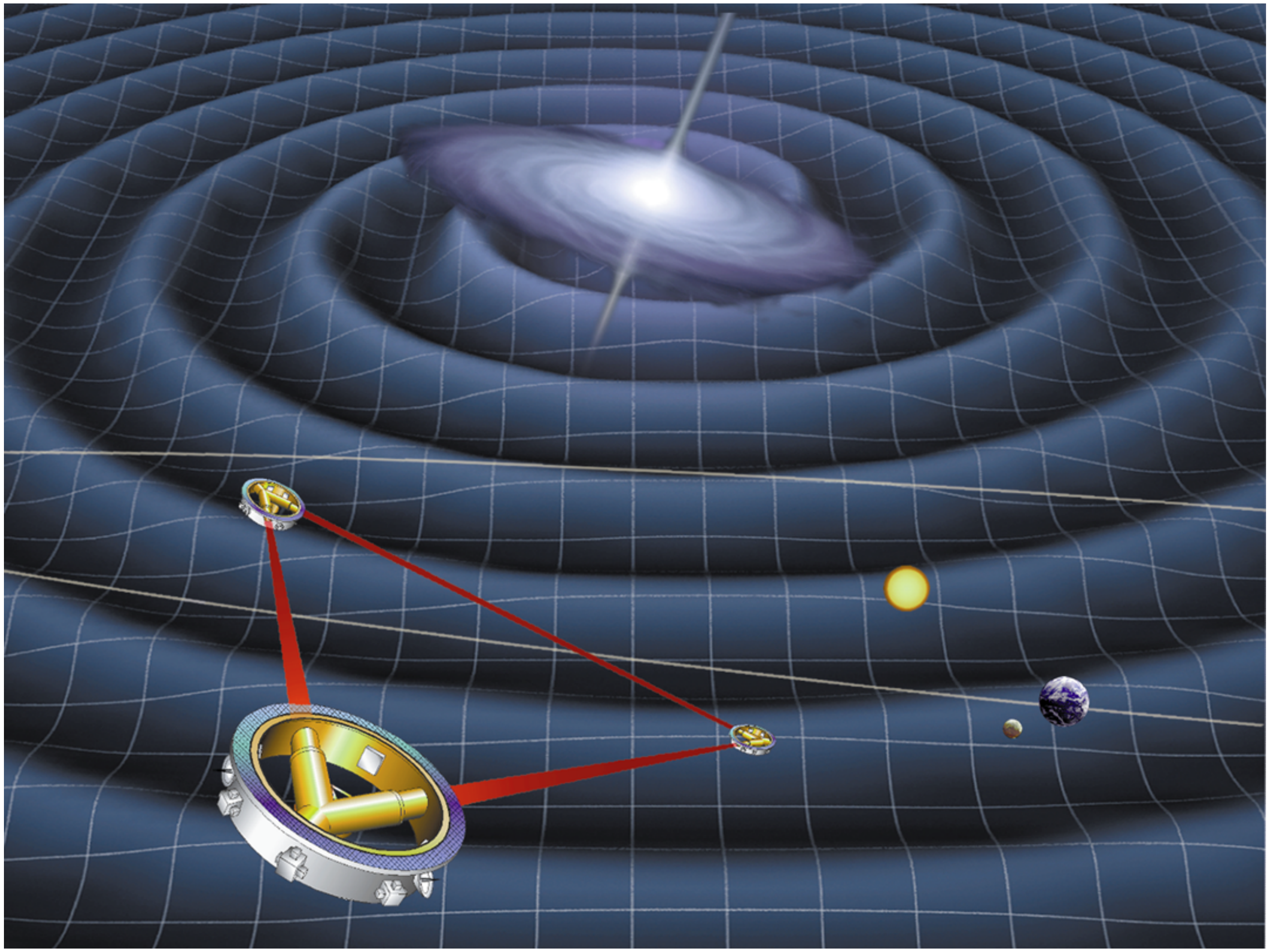
Arrival of precisely timed pulses will be delayed or advanced by gravitational waves from supermassive black hole binaries at the centers of distant galaxies.



Planck-scale quantum fluctuations may appear in cosmic background polarization

The Dark Sector Lab (DSL), located 3/4 of a mile from the Geographic South Pole, houses the BICEP2 telescope (left) and the South Pole Telescope (right). (*Steffen Richter, Harvard University*)

By 2034, we'll put GW detectors in space



This will be the decade of gravitational wave detection

- Gravitational wave interferometers should yield a detection of binary inspiral signals within the next few years.
- Pulsar timing arrays might make a detection around the same time.
- Cosmic background polarization studies might also reveal primordial GWs soon.

Gravitational wave observations will allow remarkable advances in astrophysical relativity.