What Advanced LIGO is about to see

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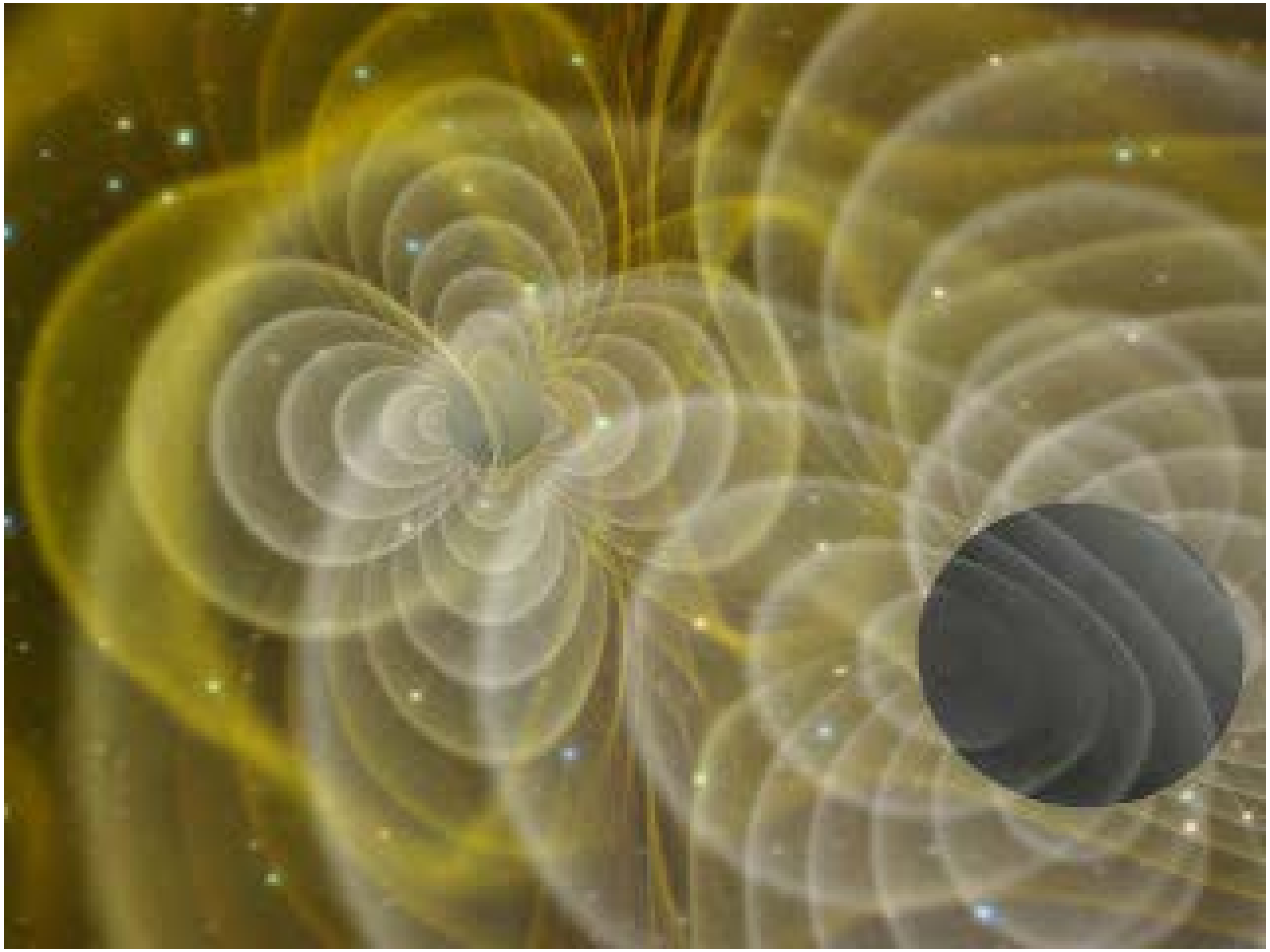
Outline

- What is a gravitational wave?
- What will we learn from detecting them?
- The challenge of detecting GWs
- How will we meet the challenge?
- What have we learned so far?
- What is Advanced LIGO about to see?

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

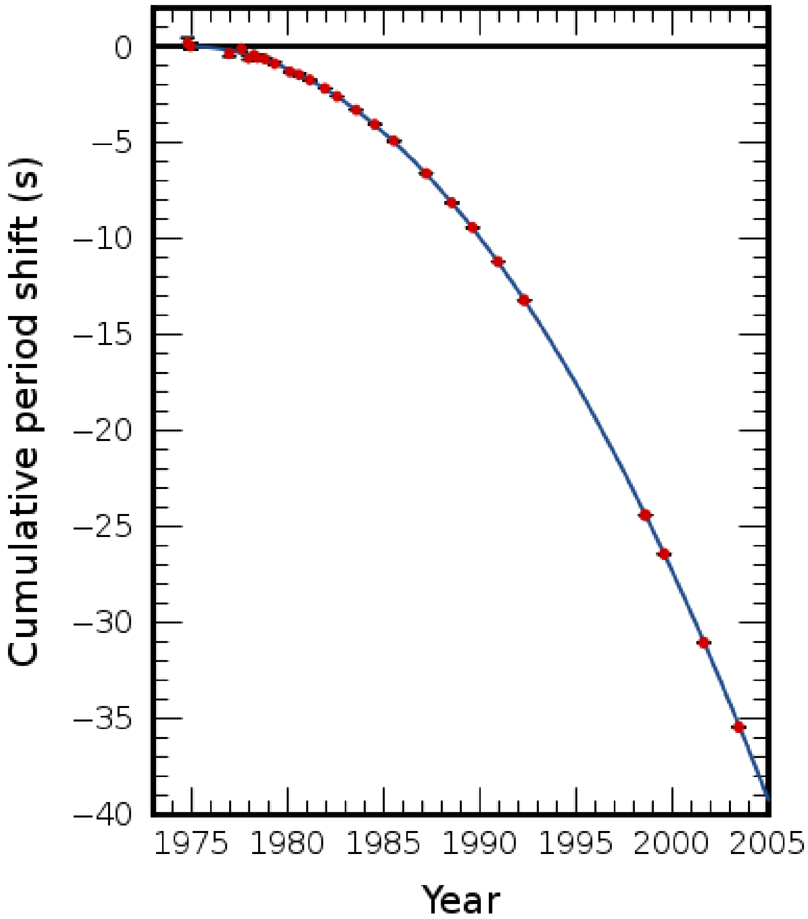


Much closer to home …

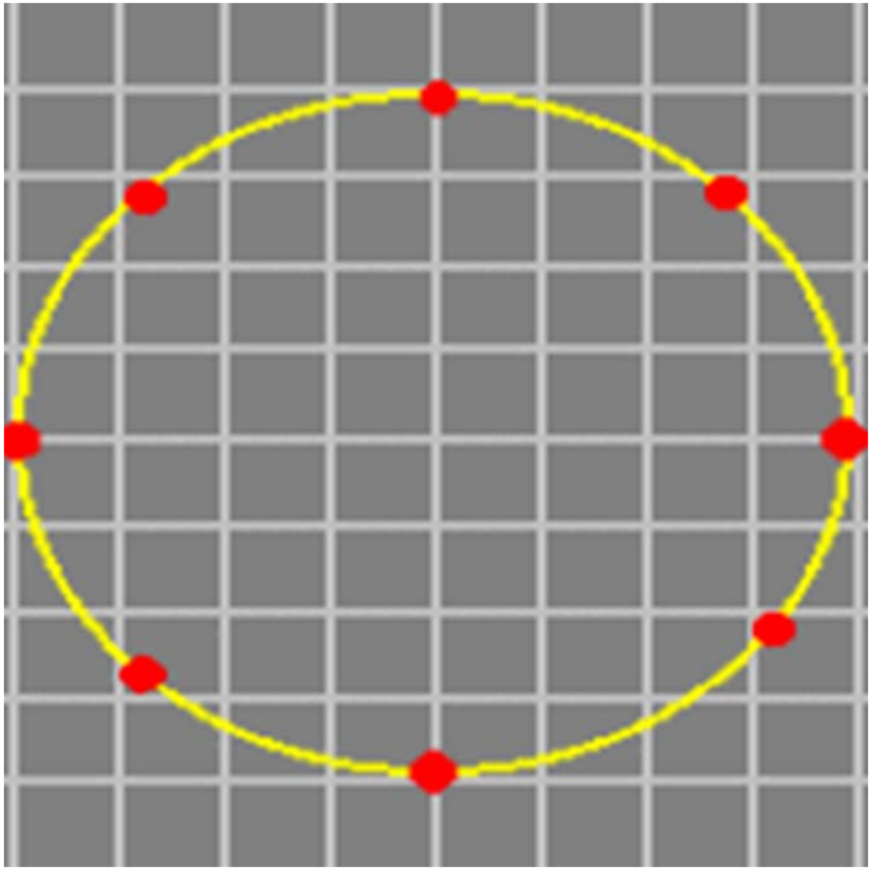
In 1974, Russell Hulse and Joe Taylor found PSR 1913+16, a pulsar in a binary orbit with another neutron star.

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.

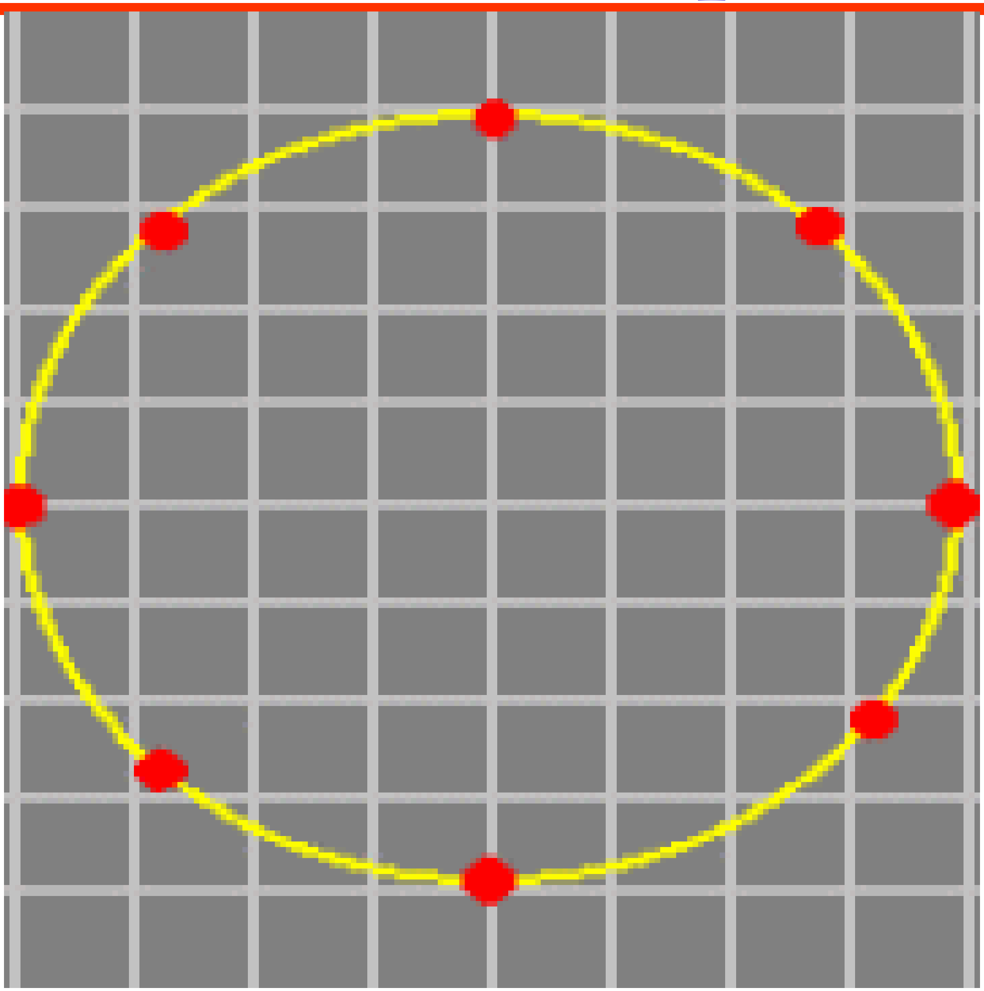
This was the discovery of gravitational radiation.



How to measure spacetime curvature

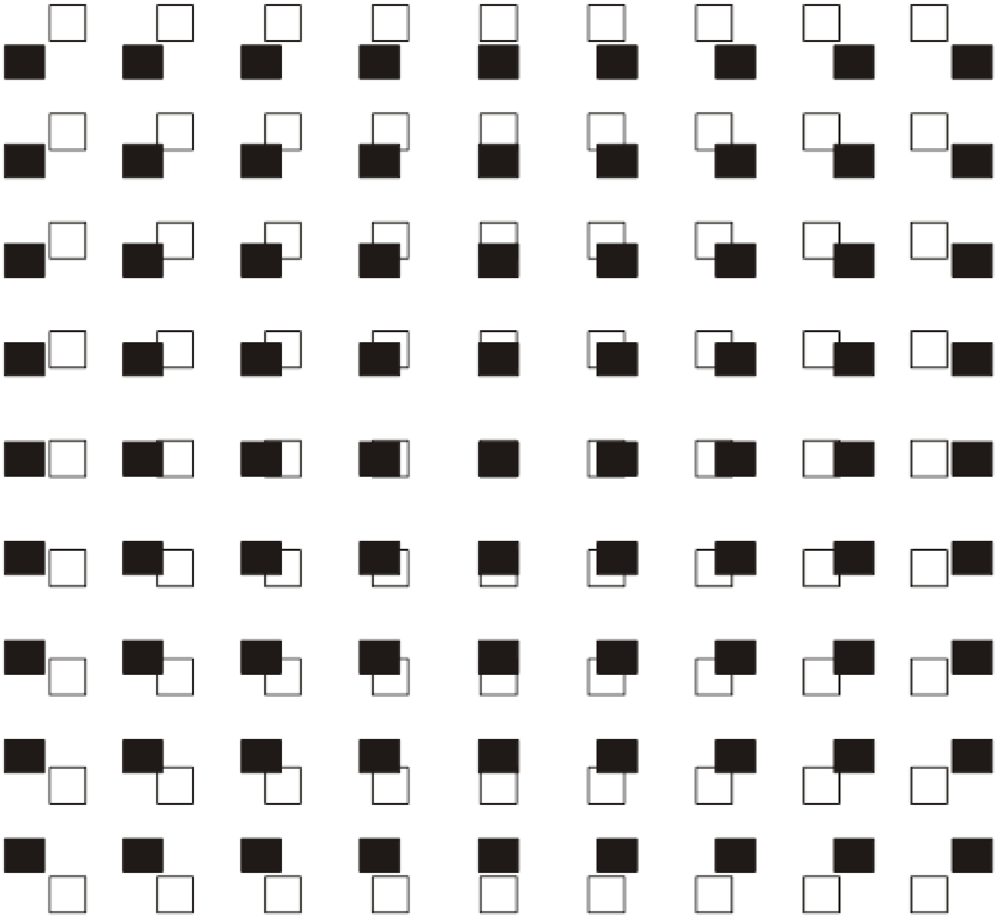


What happens when a gravitational wave passes by

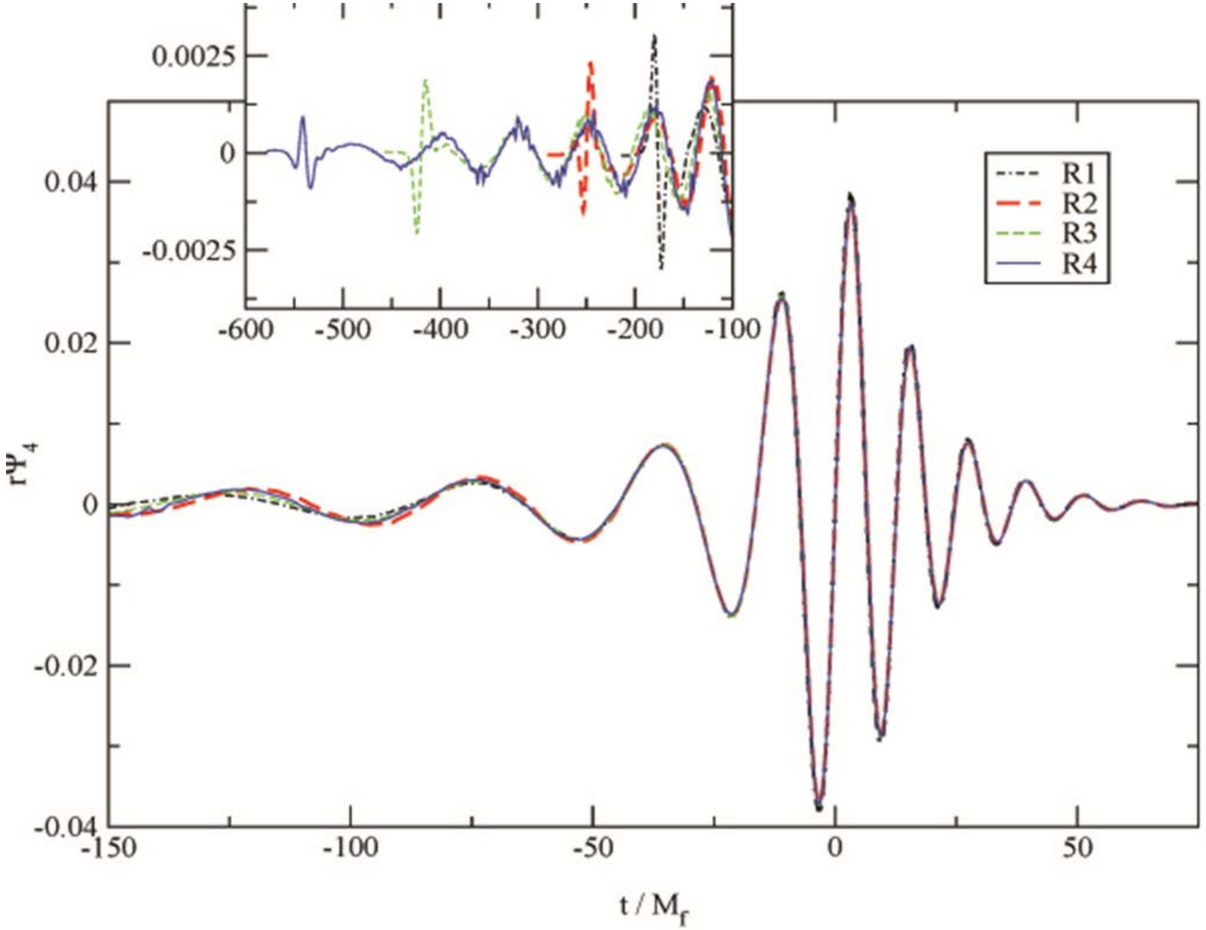


Gravitational wave:
a transverse wave of quadrupolar strain

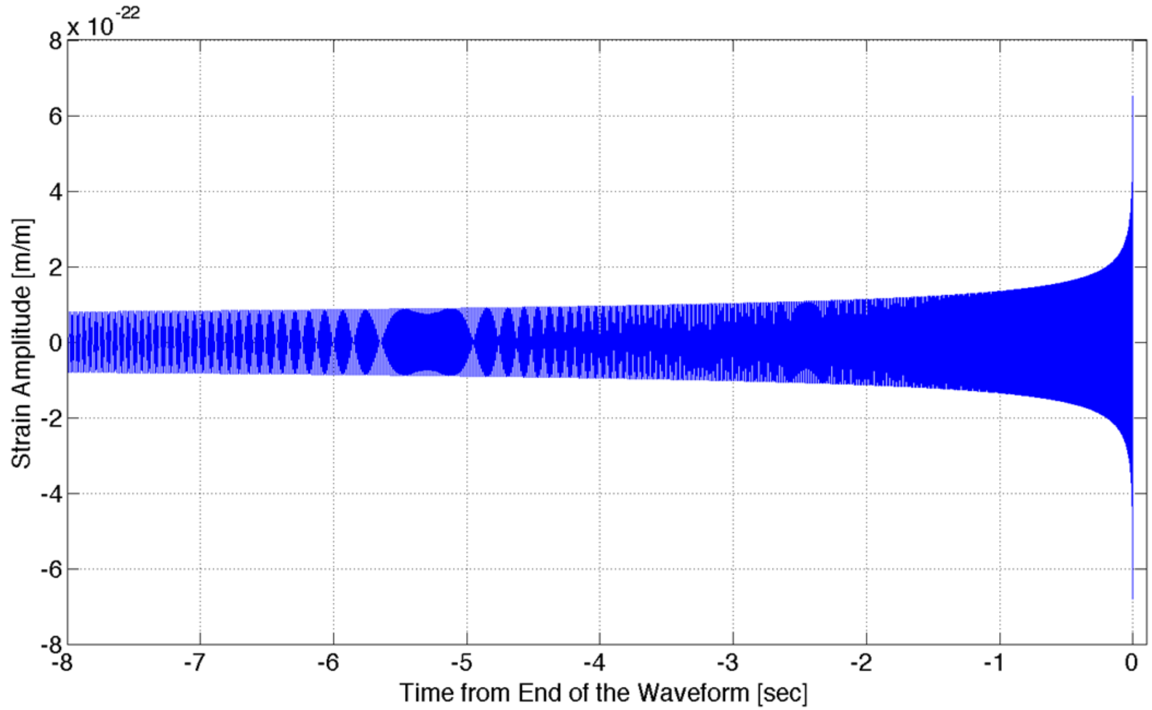
strain amplitude:
$h = 2\ \Delta L/L$



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 waveforms let us read out source dynamics

The evolution of the mass distribution can be read out from the gravitational waveform:

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

I is the mass quadrupole moment of the source.

Coherent relativistic motion of large masses can be directly observed.

What is interesting about gravitational waves?

- Embody gravity's obedience to the principle "no signal faster than light"
- Travel through otherwise opaque matter
- Can be generated by pure spacetime
  - Black holes
  - Early universe fluctuations

Thus, gravitational waves can reveal, like nothing else can, the dynamics of strongly-curved spacetime.

What kinds of things might we see? Might we learn?

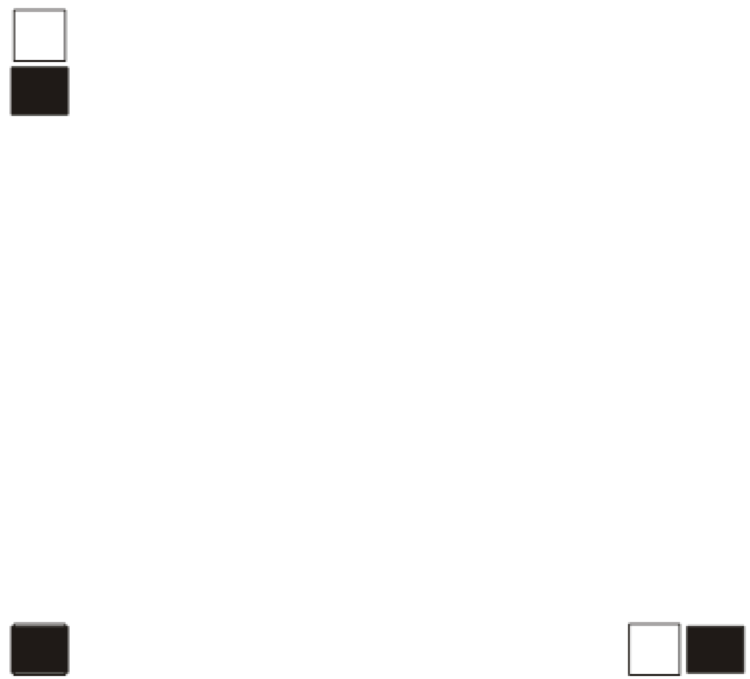
- Binaries of neutron stars and black holes
  - Study black hole spacetime
  - Learn neutron star equation of state
  - What is the engine of gamma ray bursts?
- Stellar core collapse
  - Dynamics that lead to supernova
- Rotating neutron stars
  - What mechanisms can make neutron stars lumpy?
- Early universe dynamics

What does it take to build a gravitational wave detector?

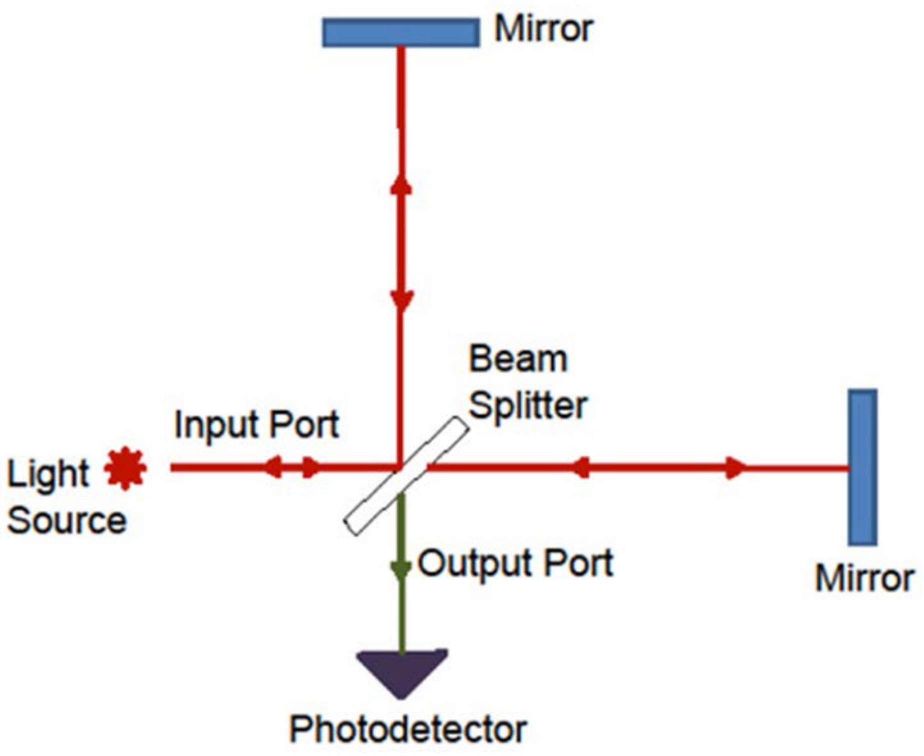
- We'll need:
  - A set of free test masses
  - A means to measure their relative motion
  - Isolation of the masses from other causes of motion.
- Here's the challenge:

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

Let's invent a gravitational wave detector



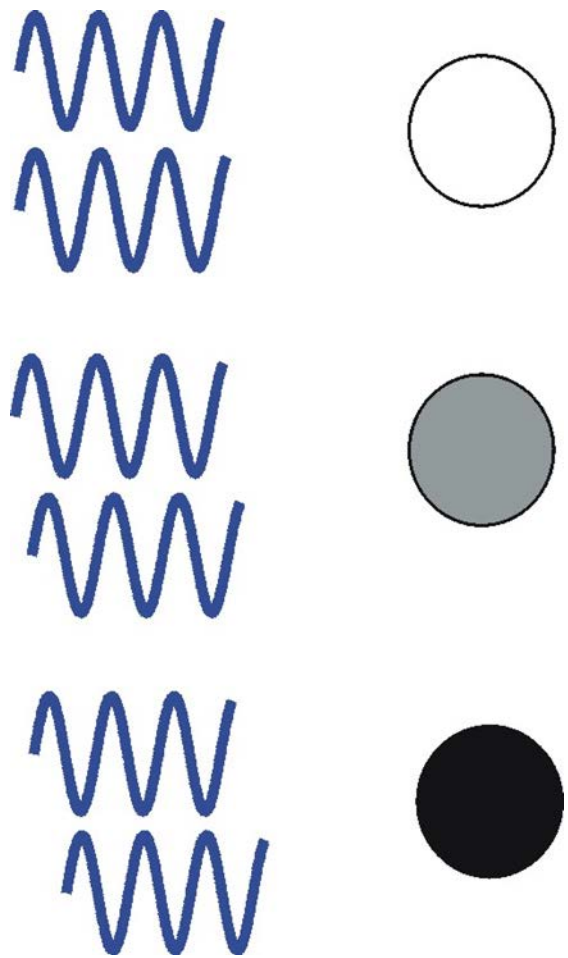
Use a Michelson interferometer to measure relative motion



Michelson interferometer = transducer from length difference to brightness

Light from x arm

Light from y arm



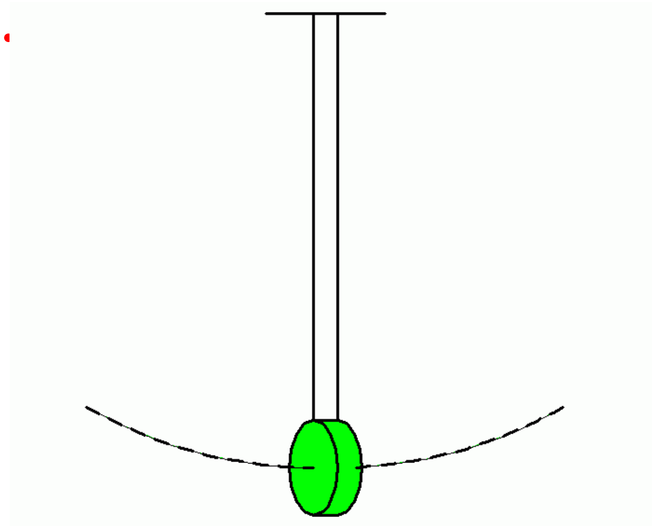
Brightness of superposed beams of light from the two arms.

Free test masses

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.



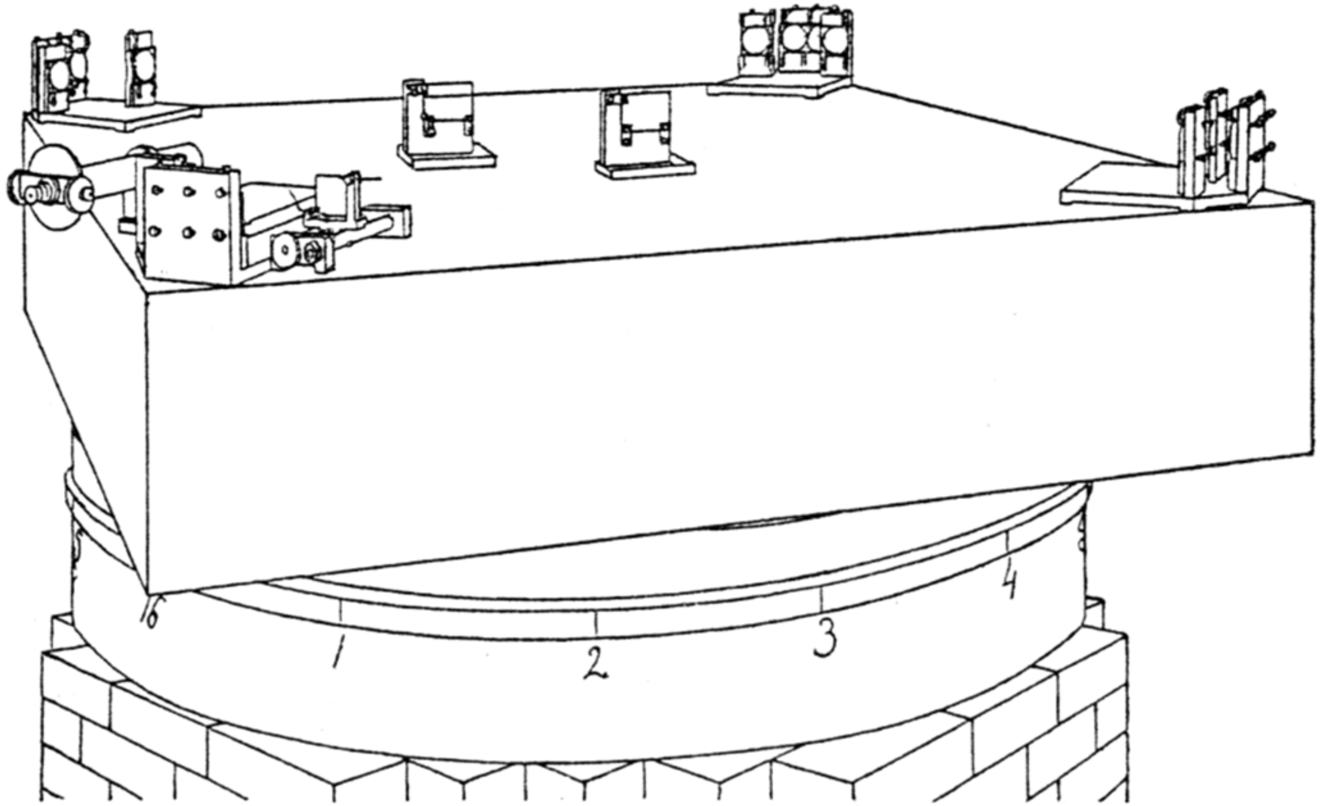
Can it work?

What is required for LIGO to succeed:

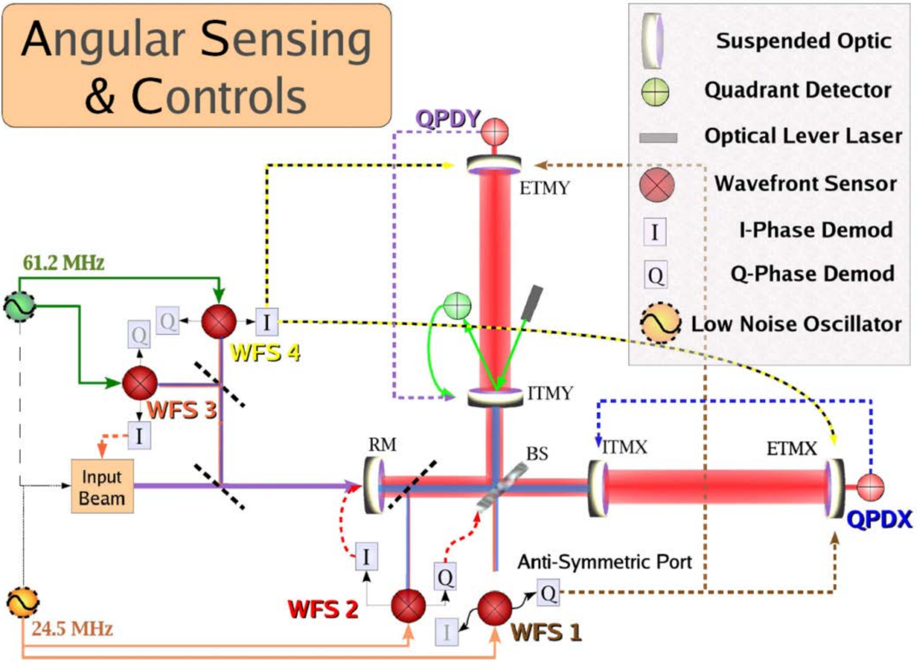
- interferometry with free masses,
- strain sensitivity of 10^{-22}
- in the presence of very large noise.

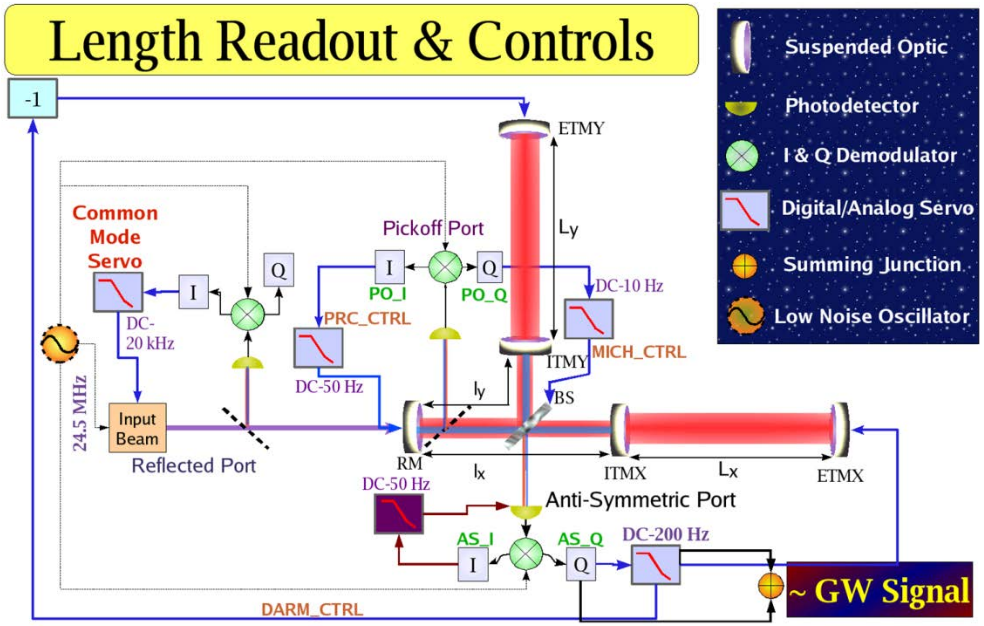
If you don't worry that this is impossible, you aren't taking it seriously.

Here's the sensible way to build an interferometer



Here’s how we do it: feedback everywhere



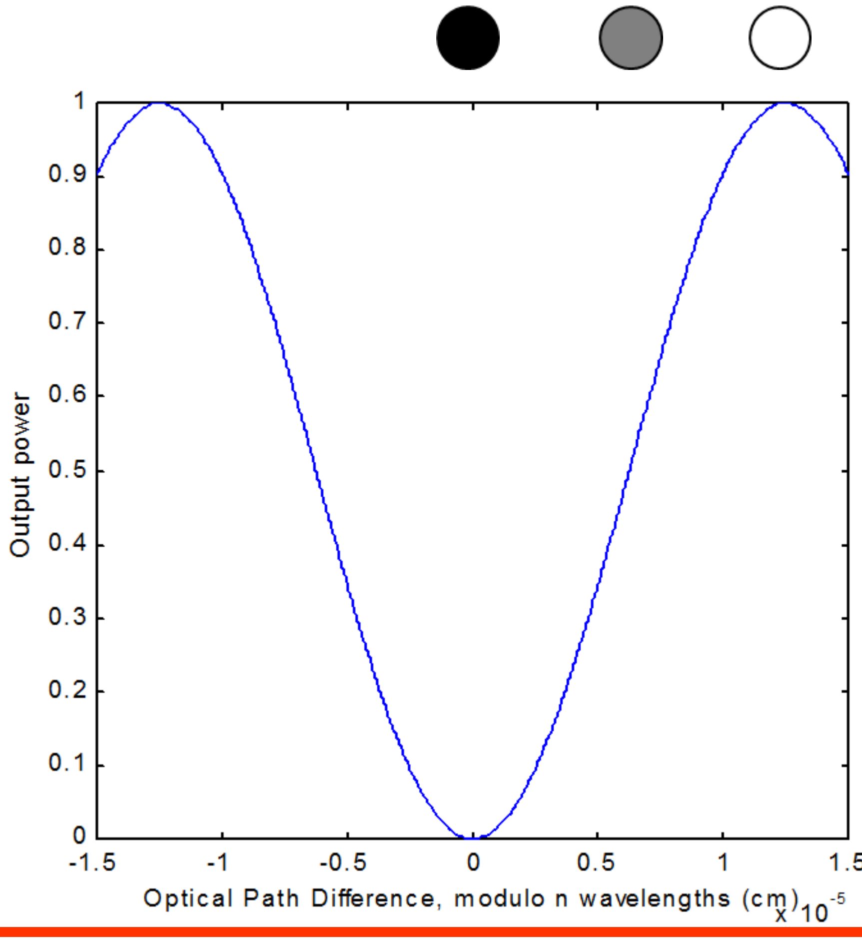


Mirror alignment and position controlled by a system of sensors and actuators. The system stays very close to a chosen operating point, while leaving the mirrors nearly free.

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

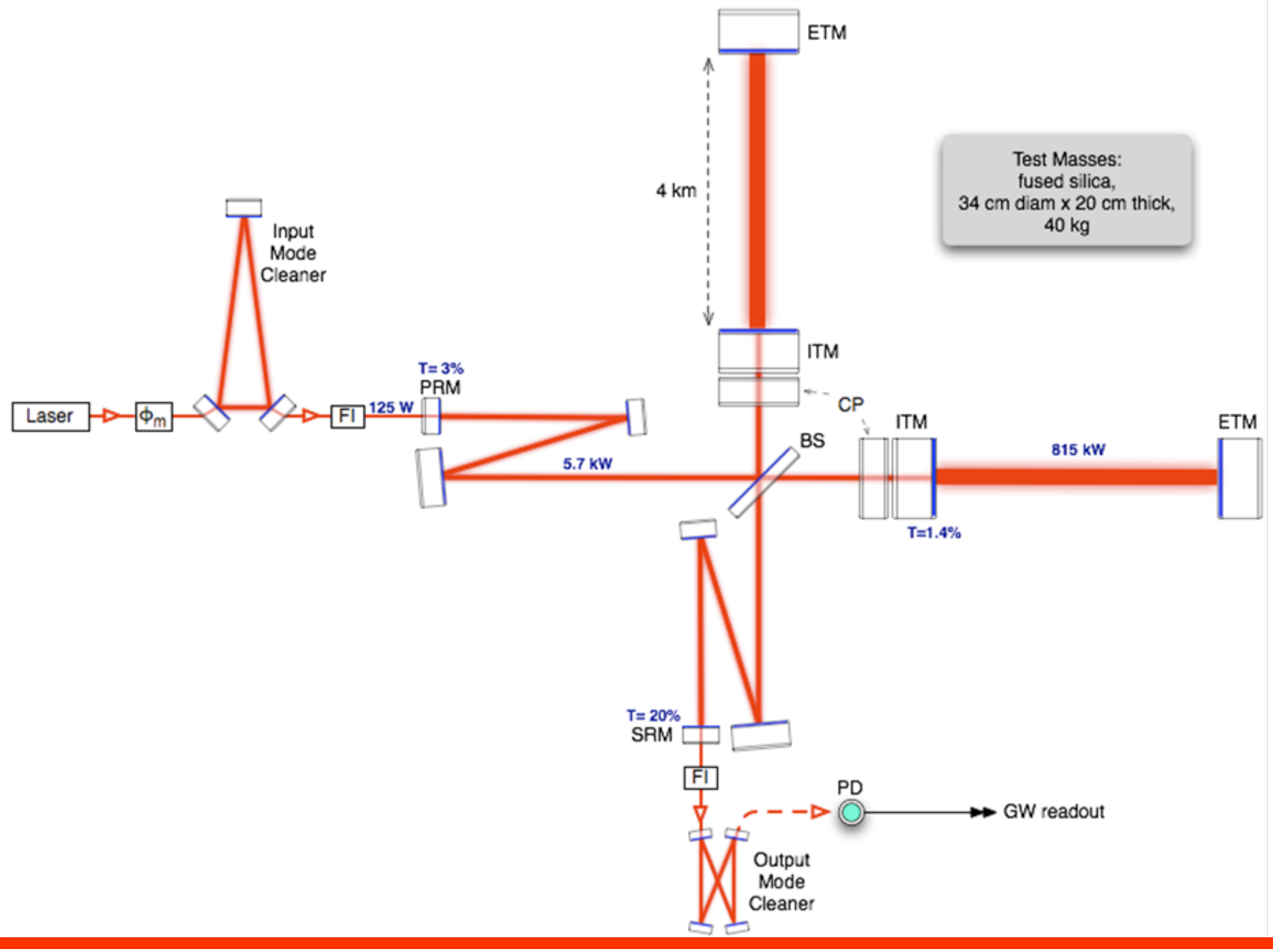
- Laser power: 125 W
- Folding of arms by factor of 450.

  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"

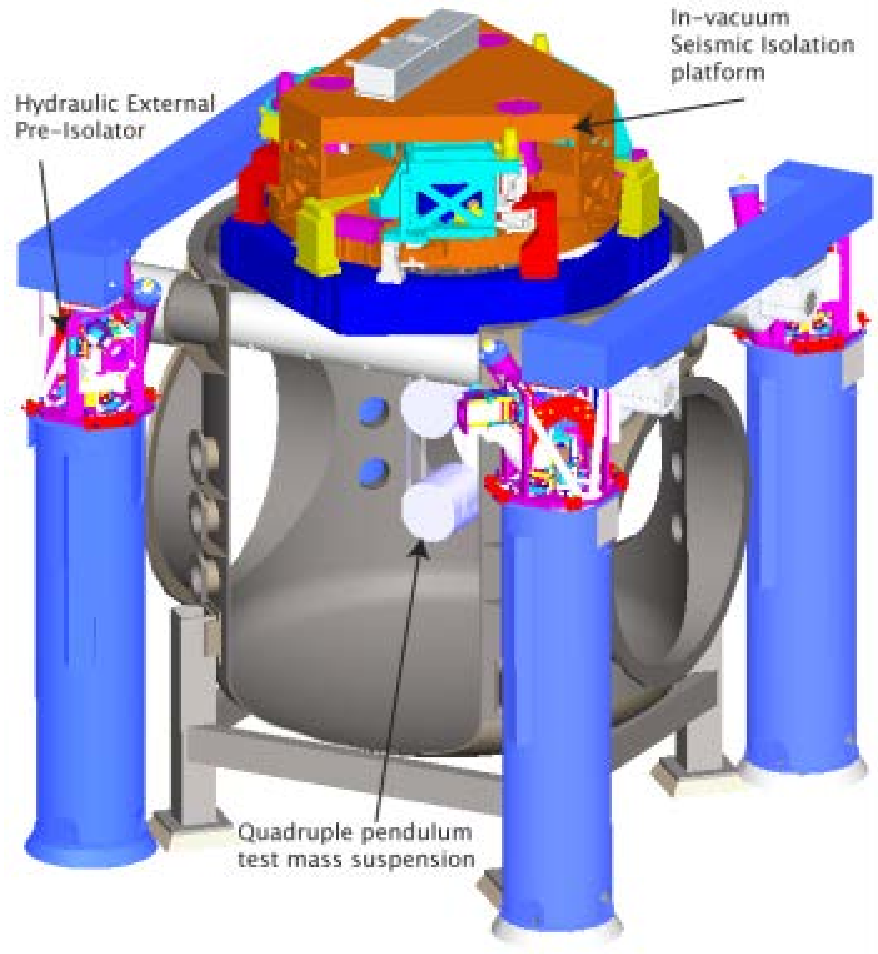
aLIGO optical layout (still simplified)



Isolate against seismic noise

Strain of 10^{-22} corresponds to mirror motions of a few x 10^{-19} m (!), with 4 km arms.
Seismic motion of the ground is about 10 orders of magnitude larger.

"Isolate, isolate, isolate."



Caveats re isolation

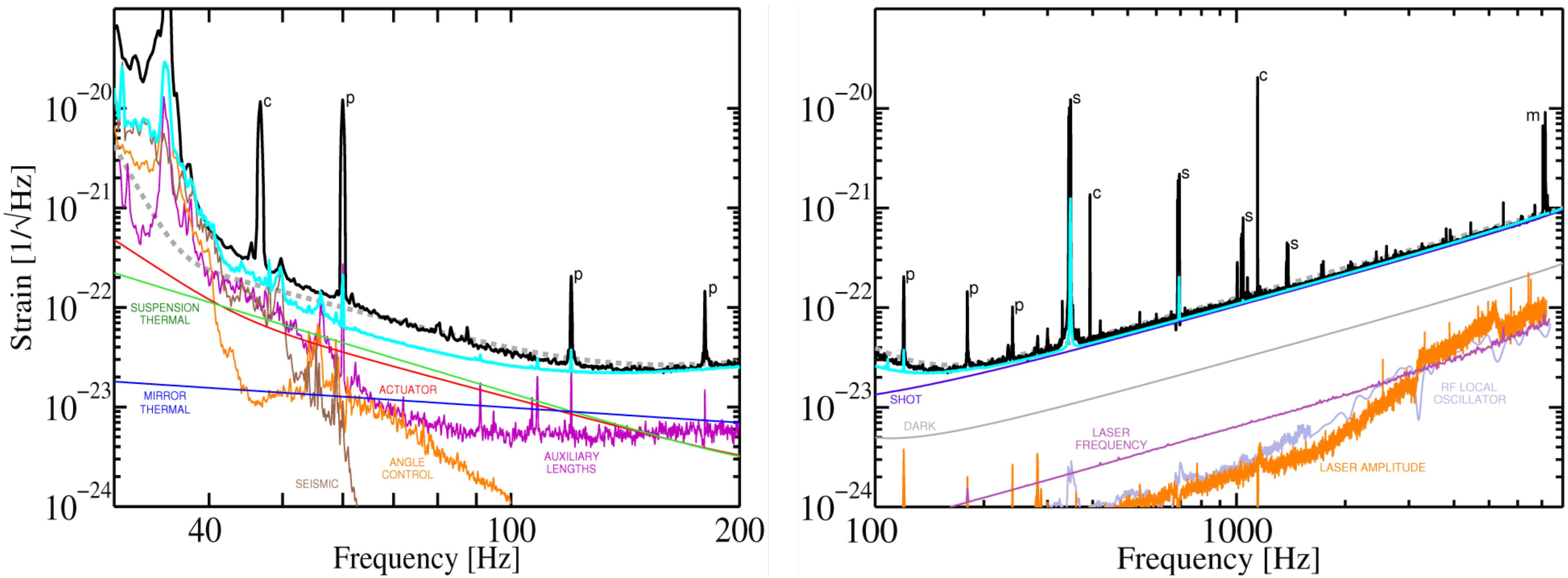
- Resonant vibration isolators don't work at low frequencies.
- Also, there's a gravitational "short-circuit" around a mechanical isolator.

  Ask Vuk for details.
- There's also a very large Brownian motion of the mirror, that needs to be tamed.

  Ask me in the question period, if you want.

Maybe, next time, we should go into space. (Or at least into a mine …)

Noise power spectrum of initial LIGO



Noise was well understood at almost all frequencies.
Photon shot noise dominated above 100 Hz.
Noise from servo loops was important below 50 Hz.

LIGO's two sites went into operation in 2005

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

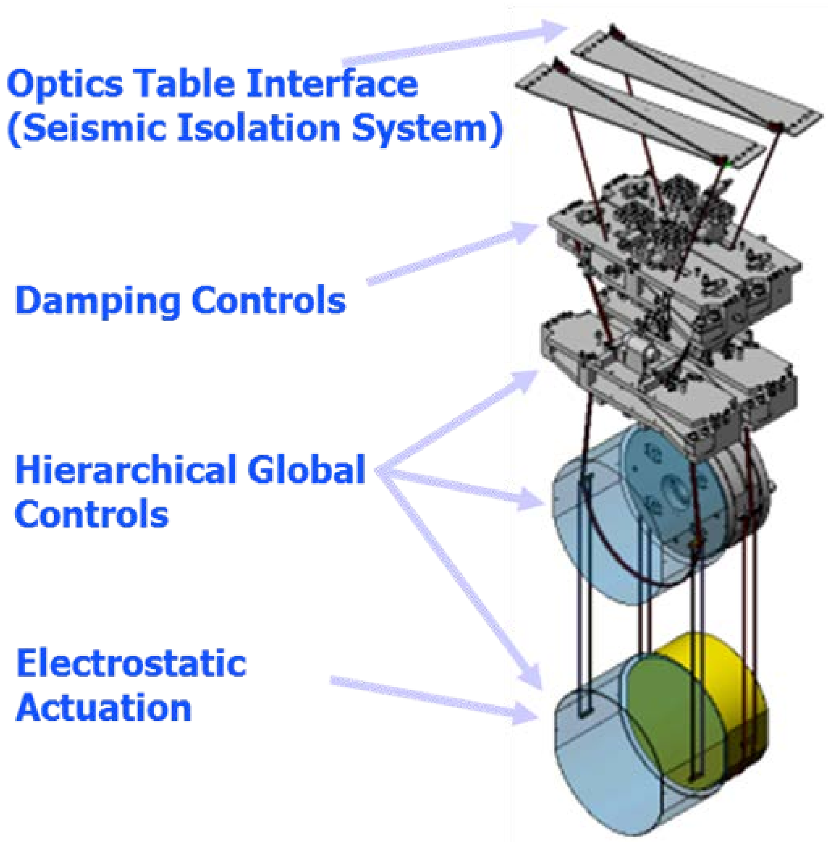
GEO, 600 m arms, near Hannover

Virgo, 3 km arms, near Pisa

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

Vacuum chambers
here, beamsplitter and input test masses

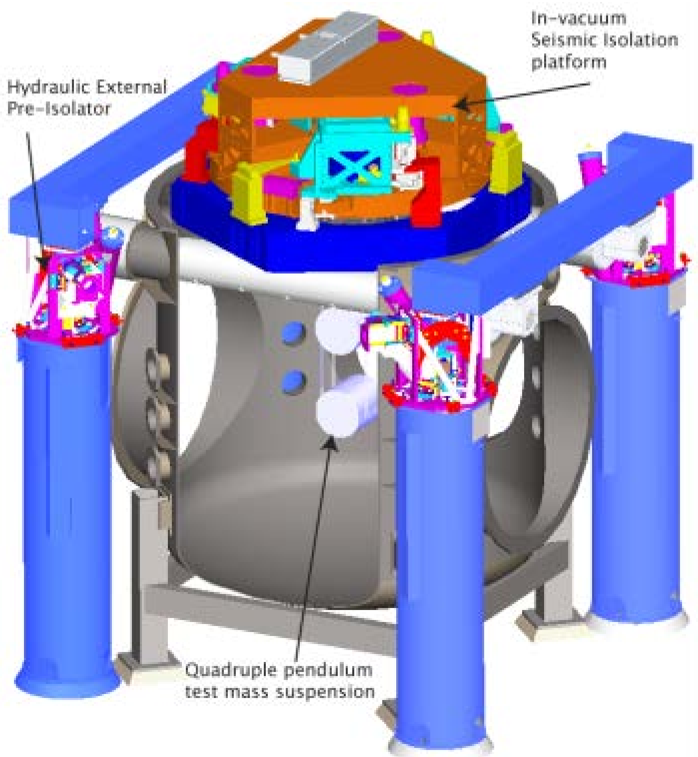
Quadruple pendulums suspend and isolate the test masses

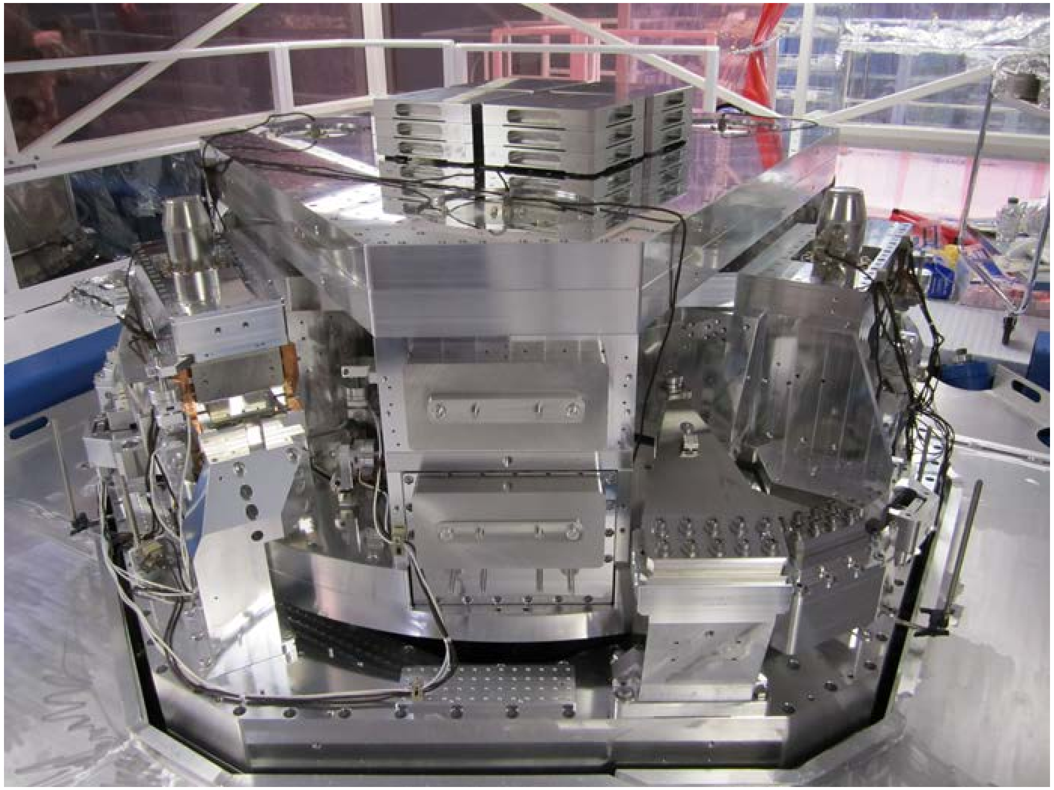


Test masses suspended on fused silica fibers, welded in place

Note: Clean-room practice must be rigorously enforced.

Two stages of active isolation supplement the pendulums



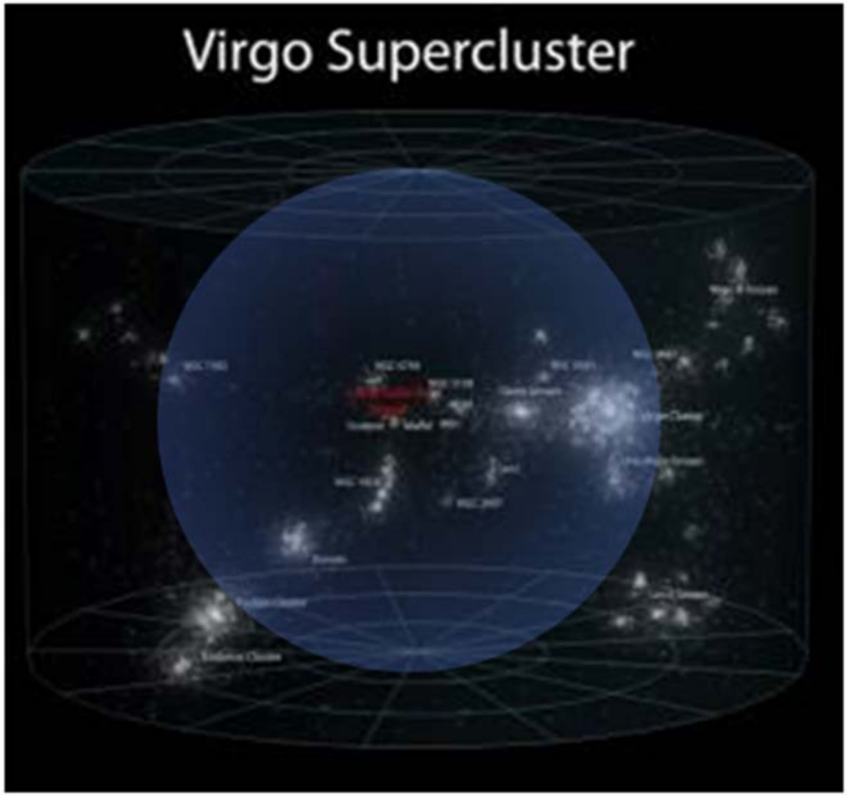


Initial LIGO didn’t detect any gravitational wave signals

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.

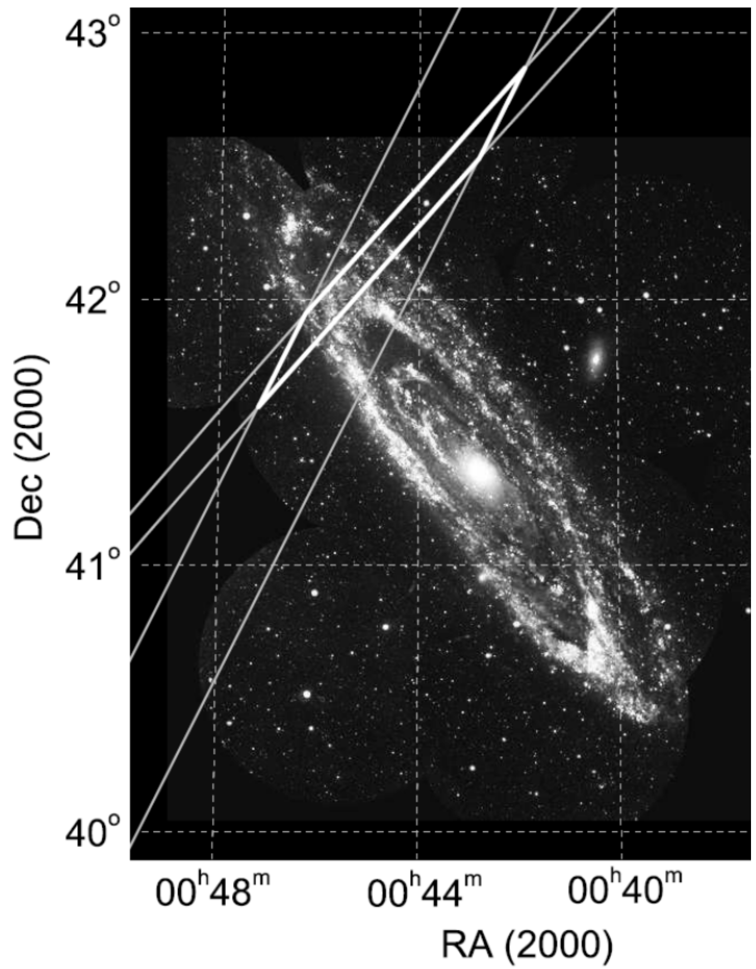


An interesting upper limit from initial LIGO observations

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.

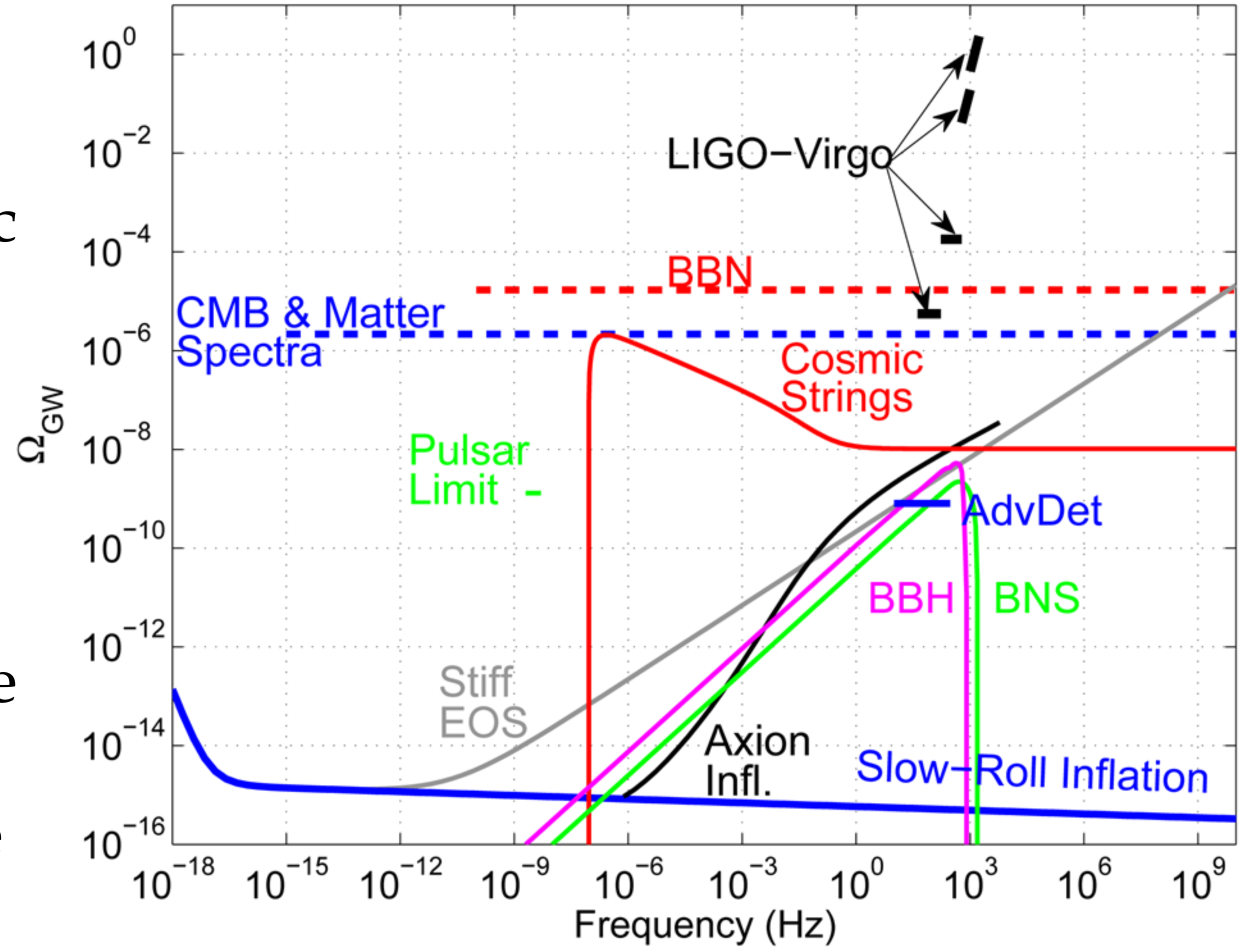
Most likely conclusion: It wasn't a classic short hard GRB, but was instead an SGR giant flare.



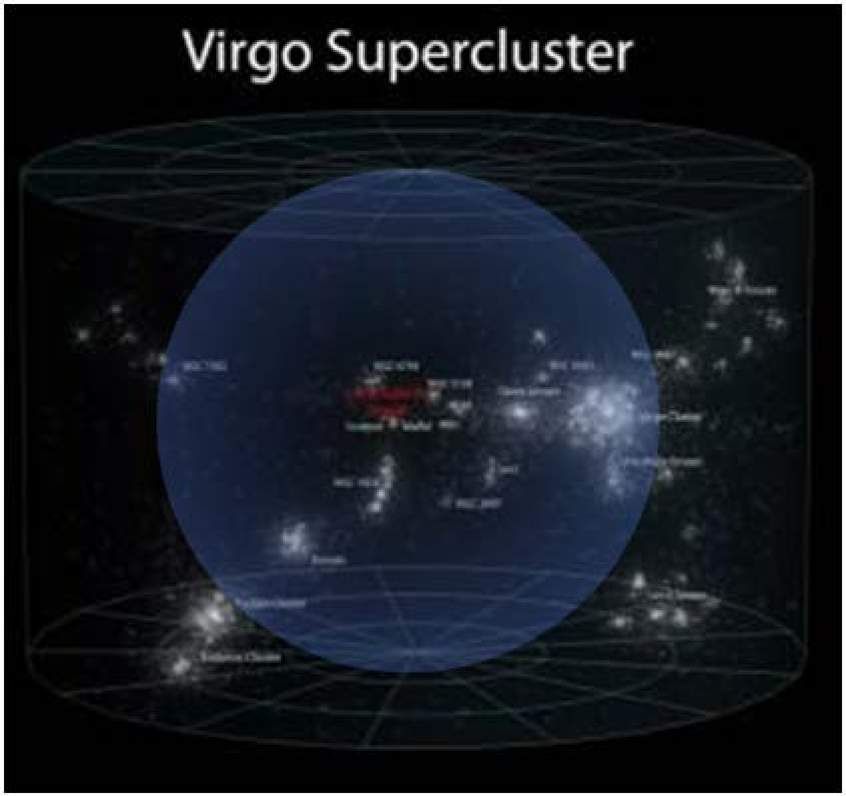
Another interesting upper limit from initial LIGO

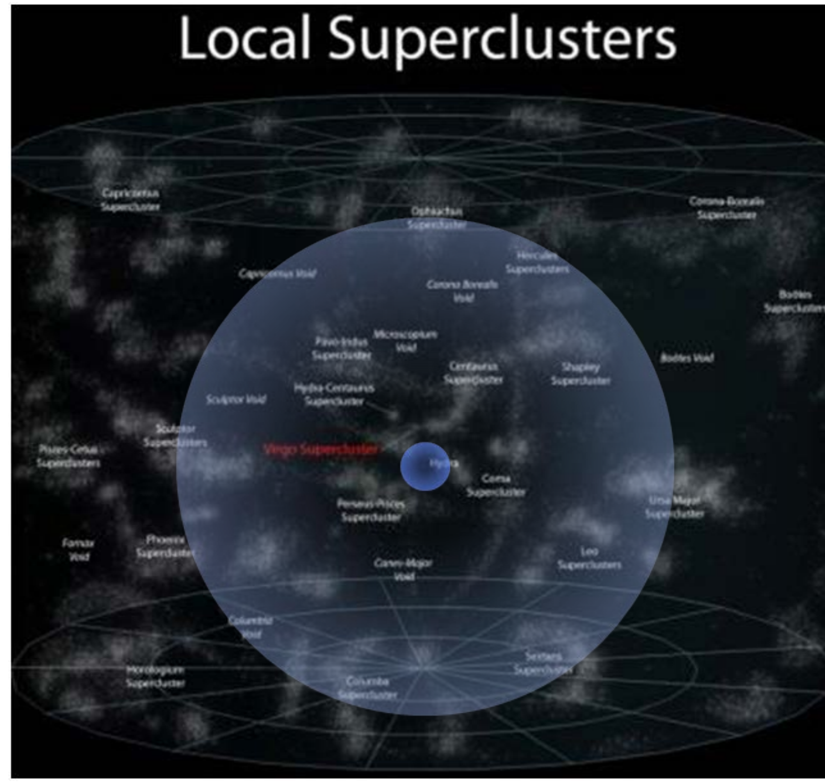
Initial LIGO set upper limits on the strength of a stochastic background of GWs that are competitive with most other techniques. (Stay tuned re BICEP 2 …)

aLIGO will test some interesting models. Ask Vuk and Gwynne for more details.



aLIGO will soon have the sensitivity that we need

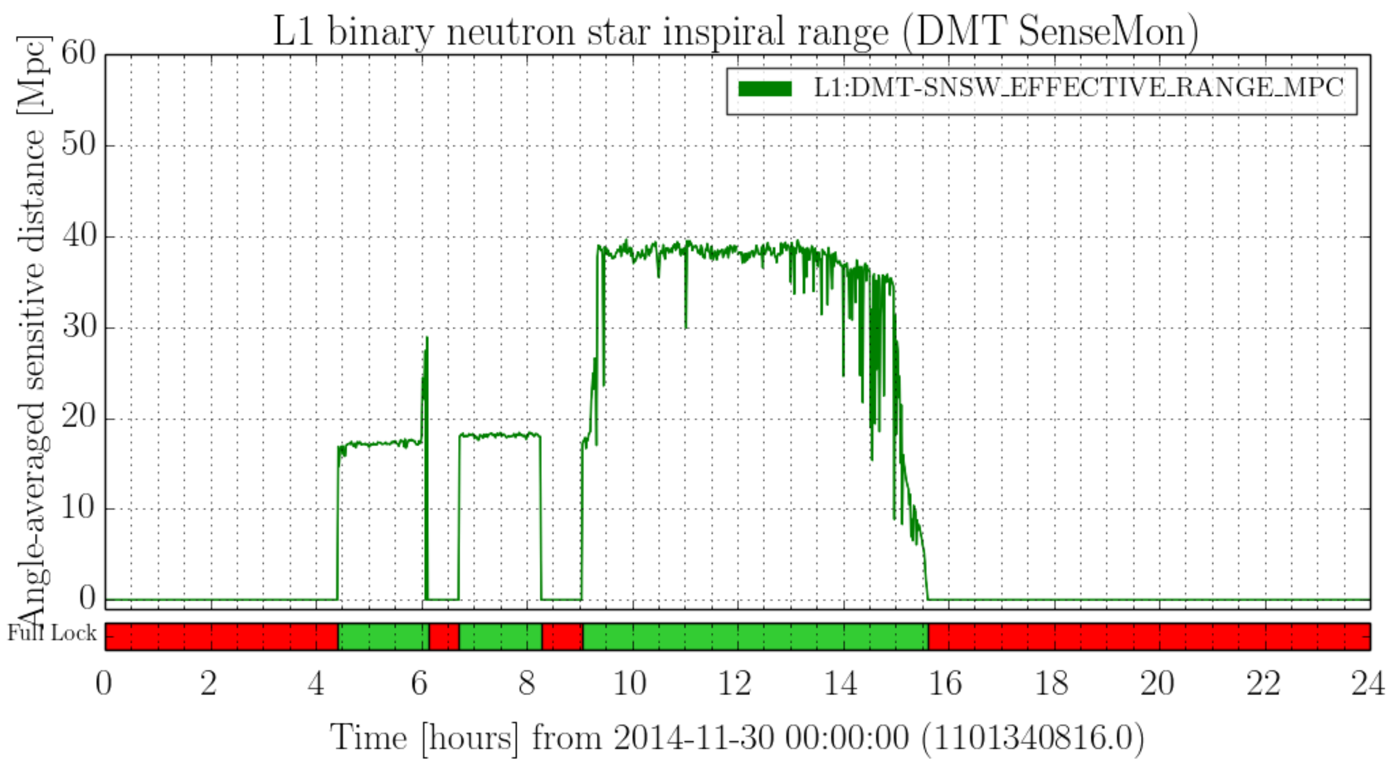




iLIGO could see the Virgo Cluster.

aLIGO will survey 1000x more volume.

Today, aLIGO can see twice as far as initial LIGO did.



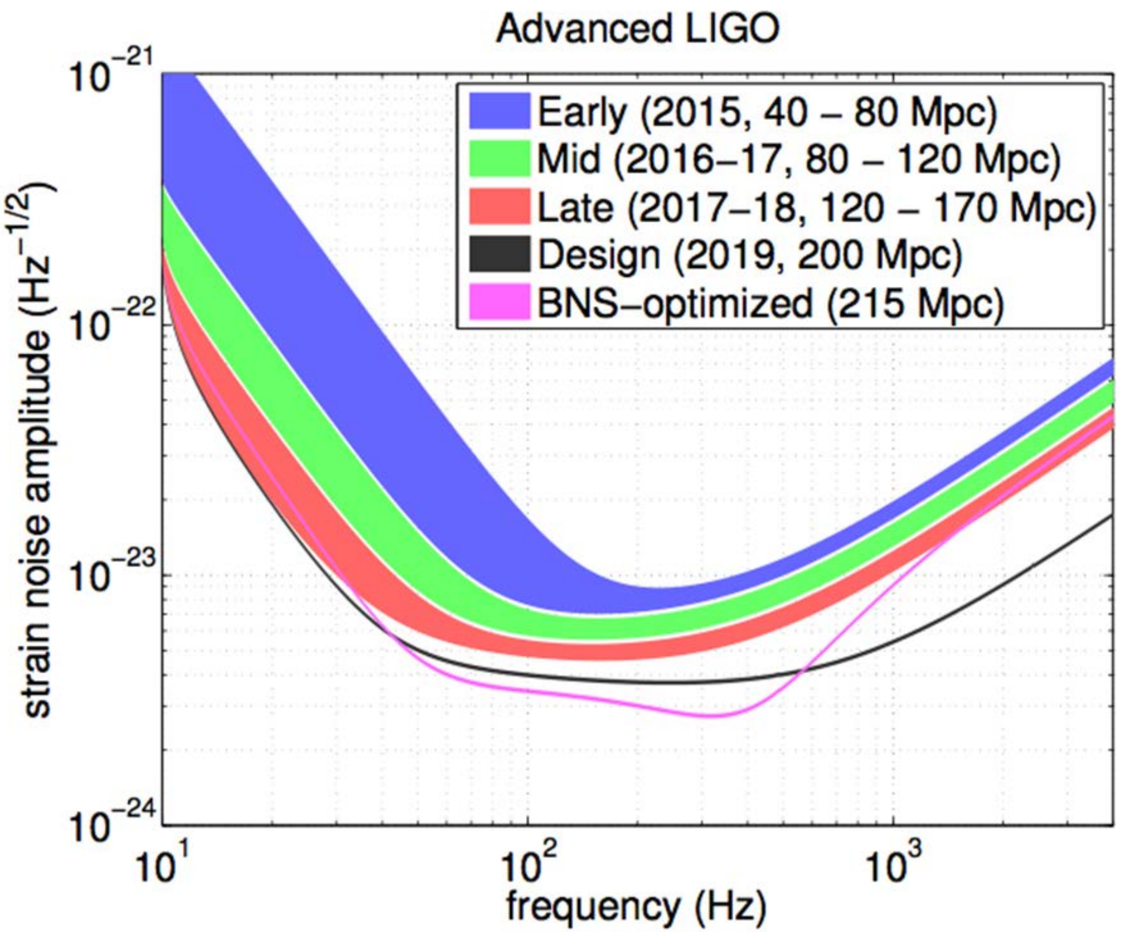
A week-long Engineering Run starts next week at Livingston.

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.



Prospects

Soon, Advanced Virgo will join the network. That will allow sky localization, opening the way to multi-messenger GW astronomy.

A few years later, LIGO India will give us much tighter error boxes.

The gravitational wave future looks very bright!