LIGO: the Dawn of Gravitational Wave Astronomy

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Albert Einstein was a smart guy

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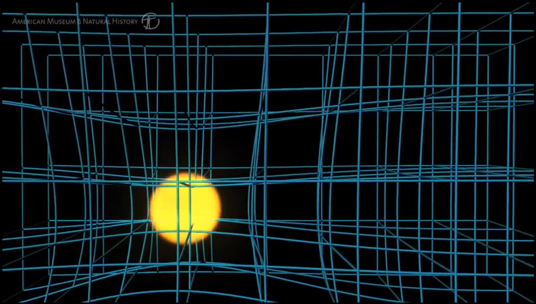
Why?
(partially) because of...

General Relativity: gravity is curved spacetime



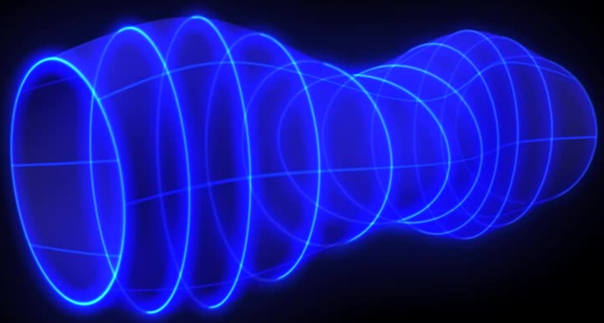
"Mass tells spacetime how to curve, spacetime tells mass how to move."

- J. Wheeler

$$G_{\mu\nu} = 8\pi \frac{G}{c^4} T_{\mu\nu}$$

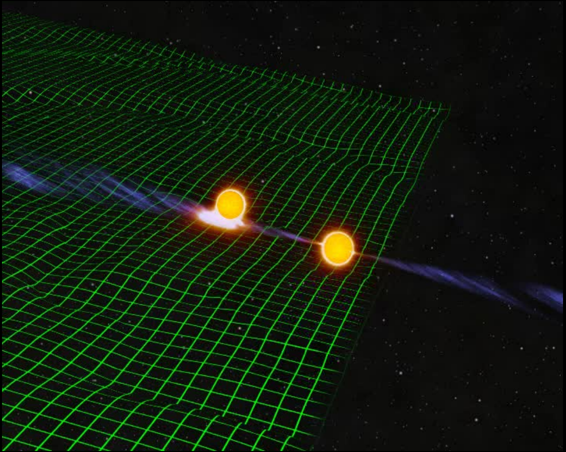
curvature of spacetime = $\sim 10^{-43}$ mass-energy content

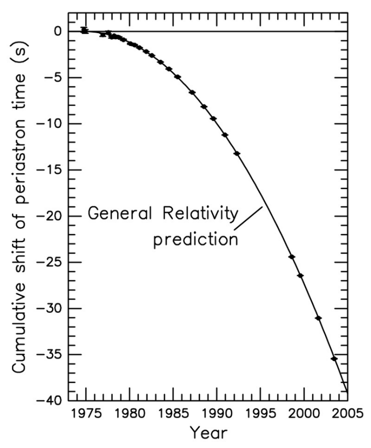
GR predicts *gravitational waves*: ripples in spacetime



GW produced by accelerating asymmetric mass distributions

1993 Nobel Prize in Physics: pulsar in binary system





Russell Hulse and Joseph Taylor
(decay measurement with J. Weisberg)

Joseph Weber: pioneer of GW experiment

Weber built the first ever gravitational wave detectors in the 1960s.

resonant mass detector

Designed to ring like a bell when struck by a gravitational wave.

He thought he detected something (but probably didn't).

In 1970s a new detection paradigm was conceived

Rainer Weiss
(MIT)

Kipp Thorne, Ronald Drever,
Rochus Voigt (Caltech)

Examine effect GW have on spacetime

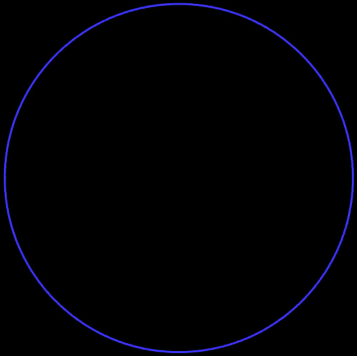
Gravitational waves cause a peculiar motion of spacetime as they pass:

differential strain

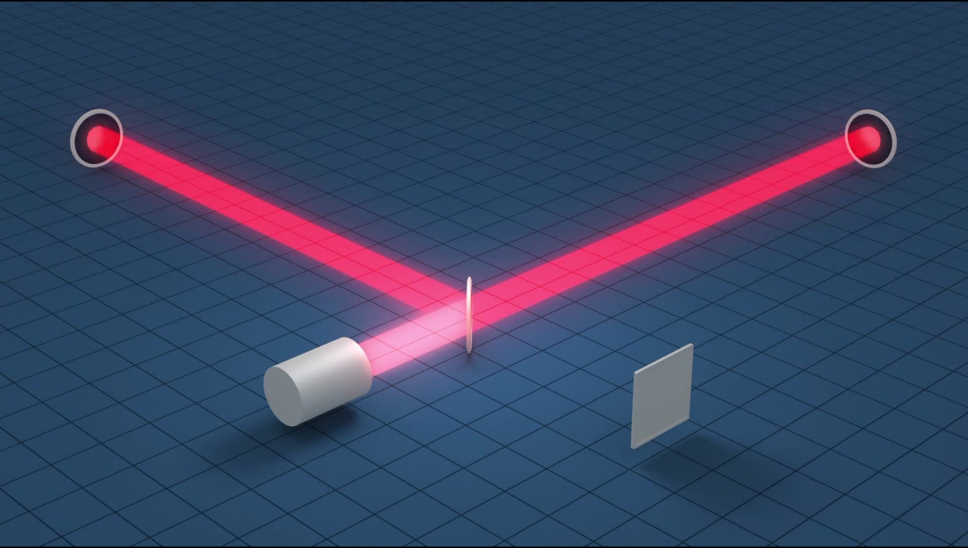
$$h = \frac{\Delta L}{L}$$

x stretches while y contracts, and vice versa.

Test masses placed on the ring will move with the spacetime.

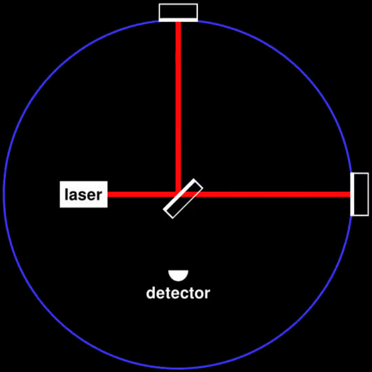


Use light to measure the strain: Michelson interferometer

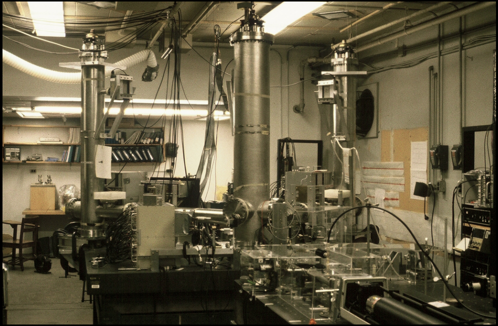


Michelson interferometer gives direct measure of strain

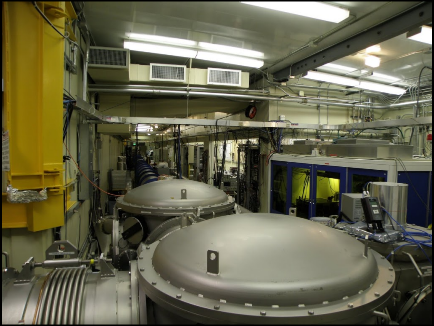
If the Michelson end mirrors rest on ring they *directly measure* the strain of the passing gravitational wave.



Prototype interferometric detectors where built

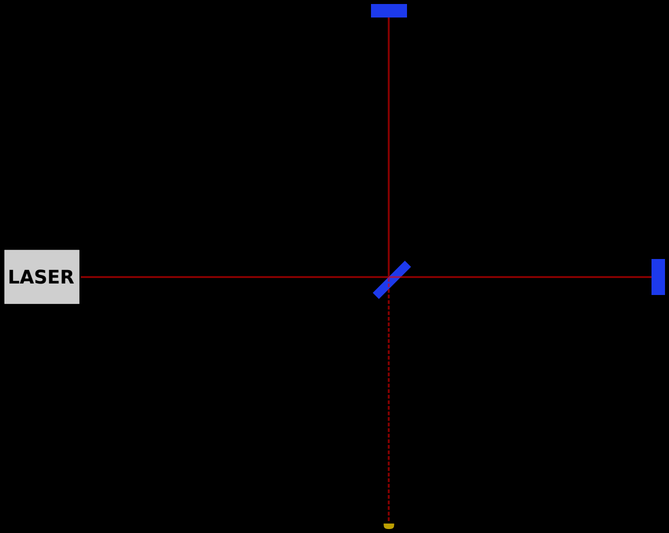


MIT 1.5m prototype

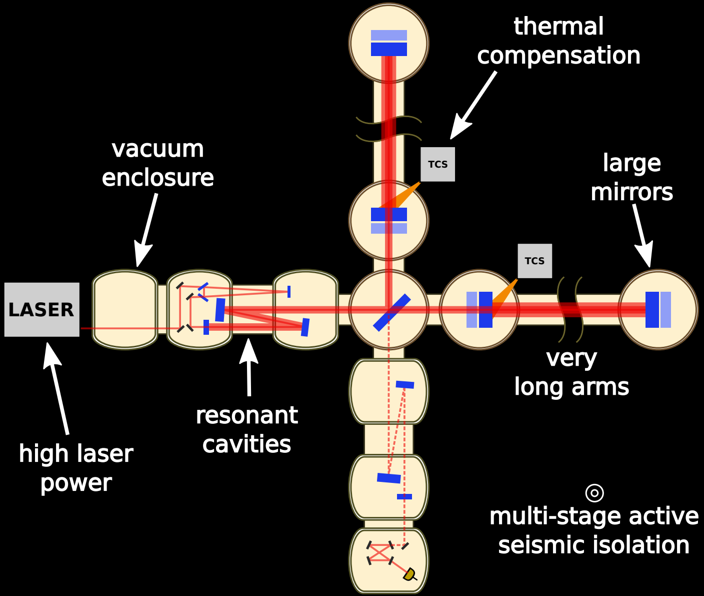


Caltech 40m prototype

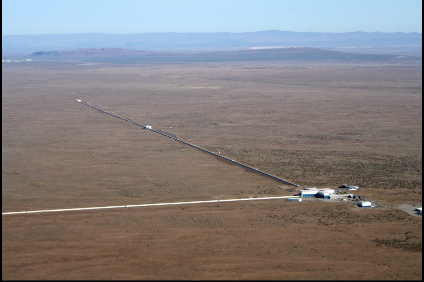
After much research, simple Michelson concept...



...evolved into something much more sensitive



Laser Interferometer Gravitational-wave Observatory



Hanford, WA (LHO)

Livingston, LA (LLO)

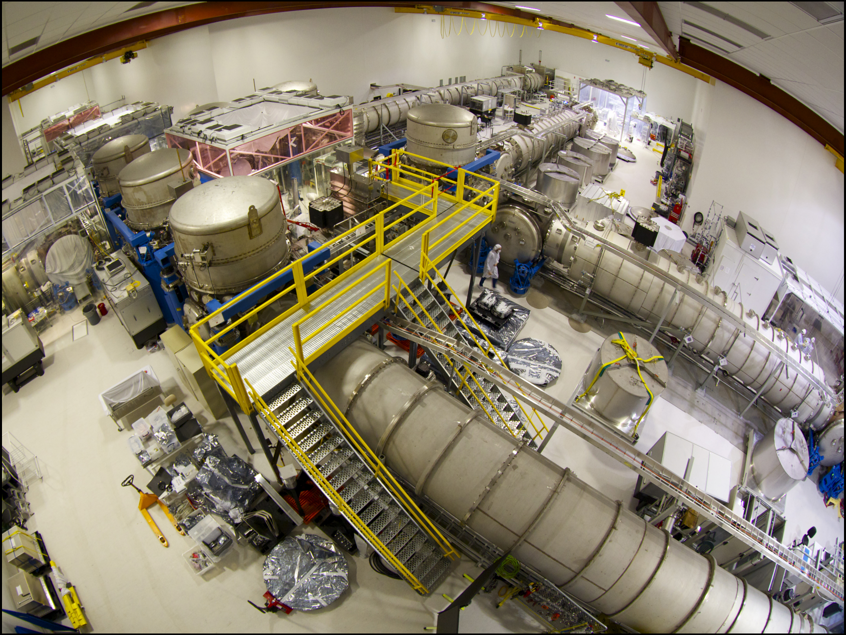
Laser Interferometer Gravitational-wave Observatory

NSF funded, jointly run by Caltech and MIT

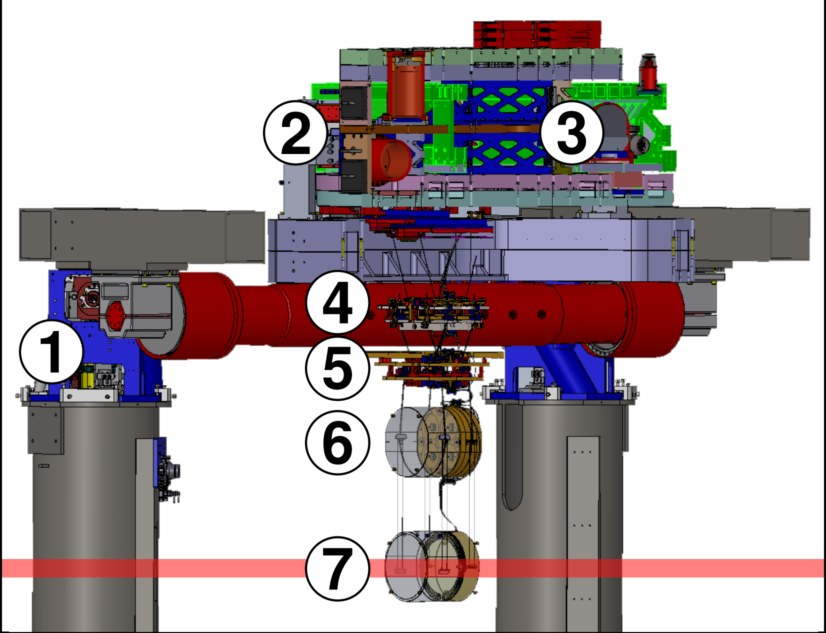
Two identical facilities operated as astrophysical observatories for gravitational waves.

International scientific collaboration
- 60 institutions
- 1000 individuals

Very large ultra-high vacuum enclosure

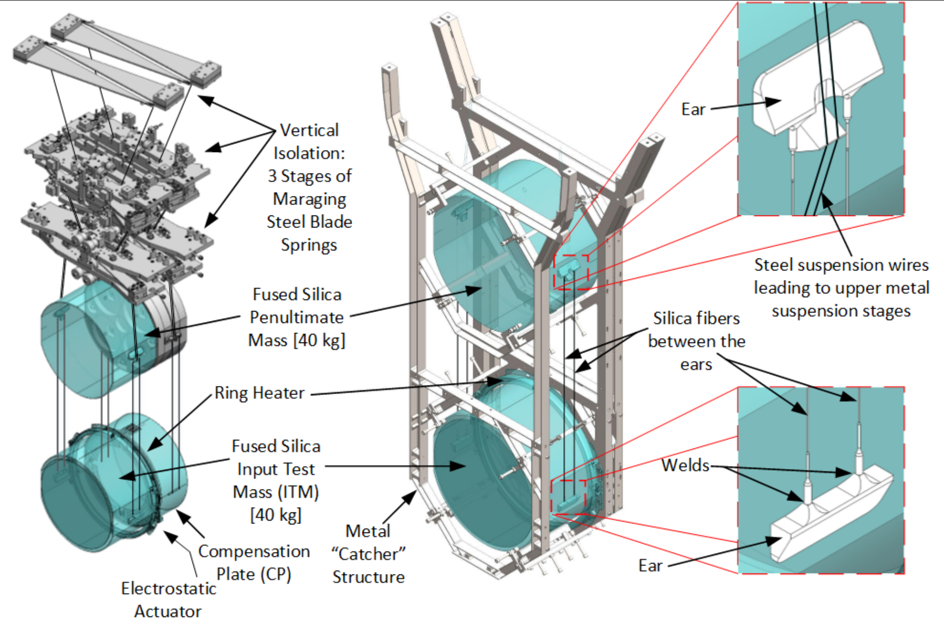


Seven stages of active seismic isolation

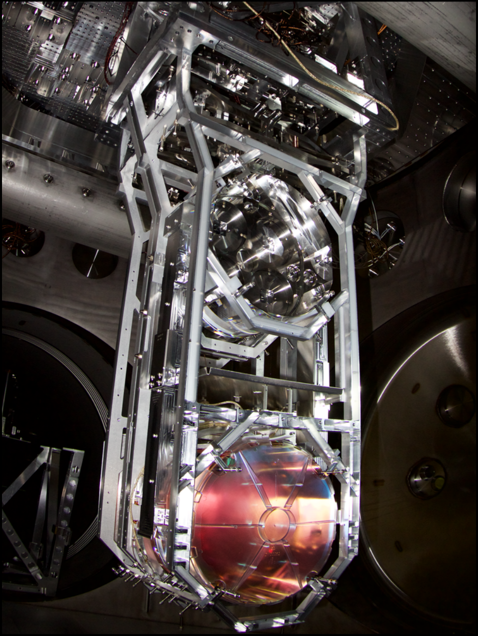


Seismic isolation platform

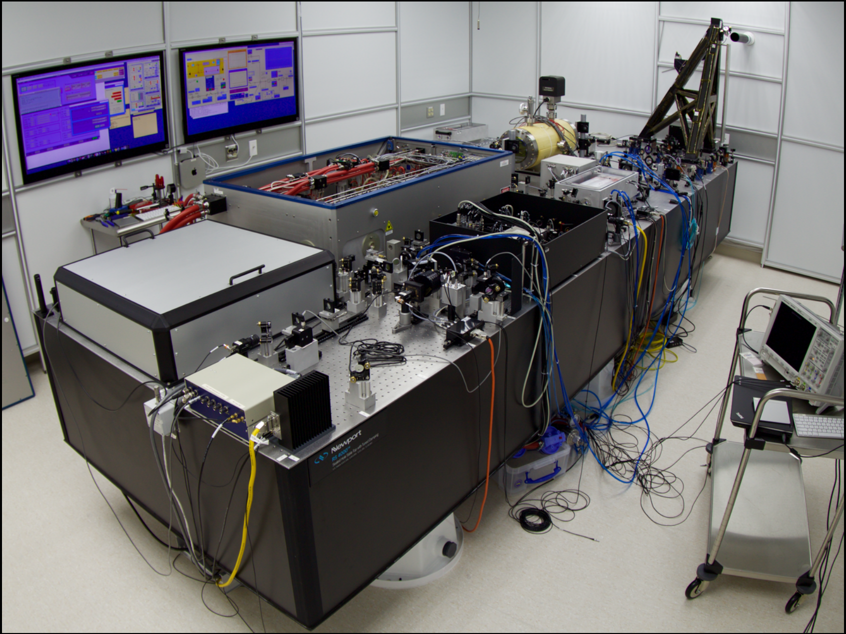
Large test masses and monolithic suspensions



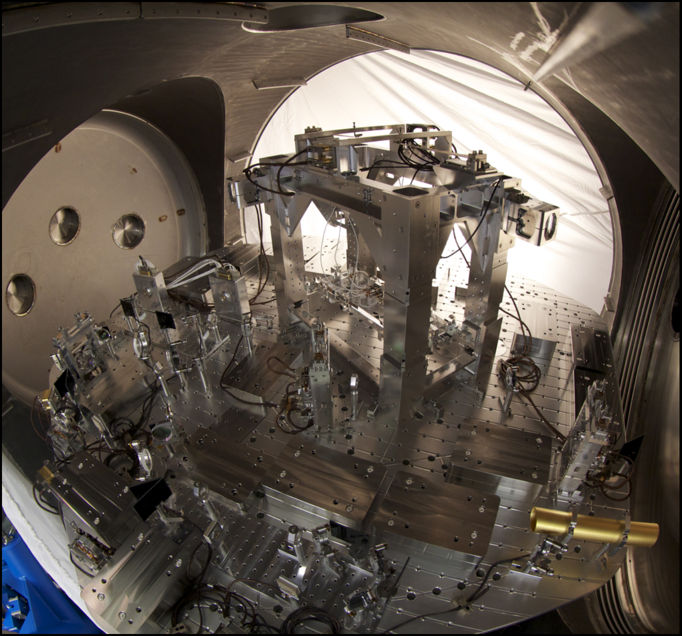
Large test masses and monolithic suspensions



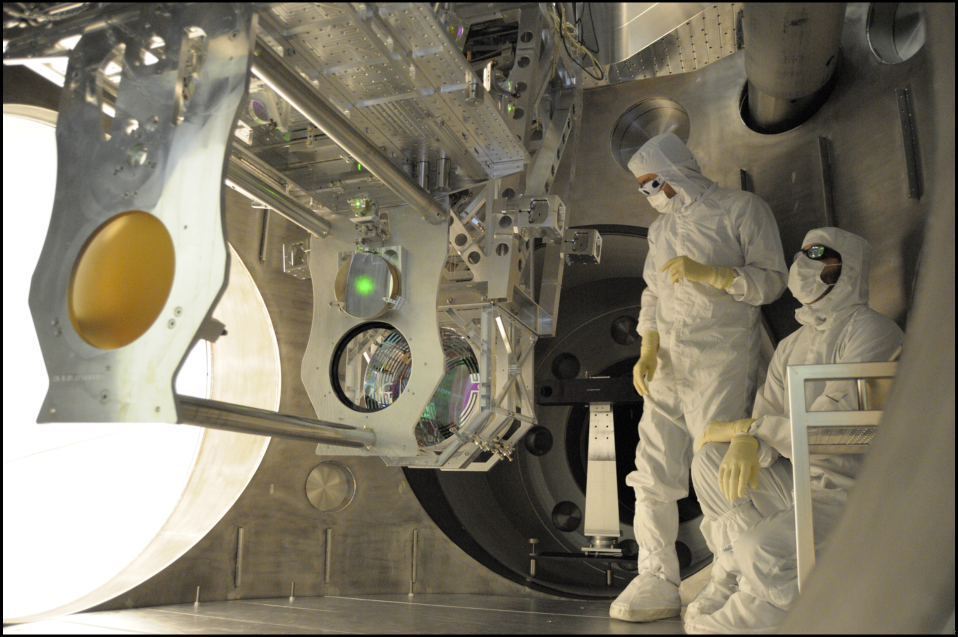
High power pre-stabilized laser source



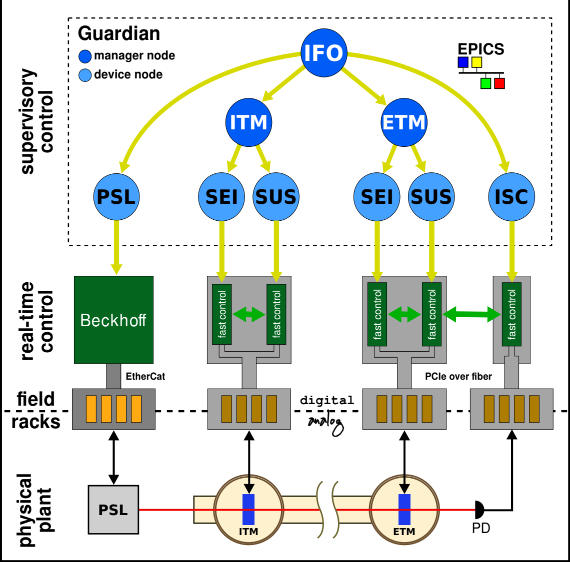
Readout optics and electronics



End test mass chamber assembly



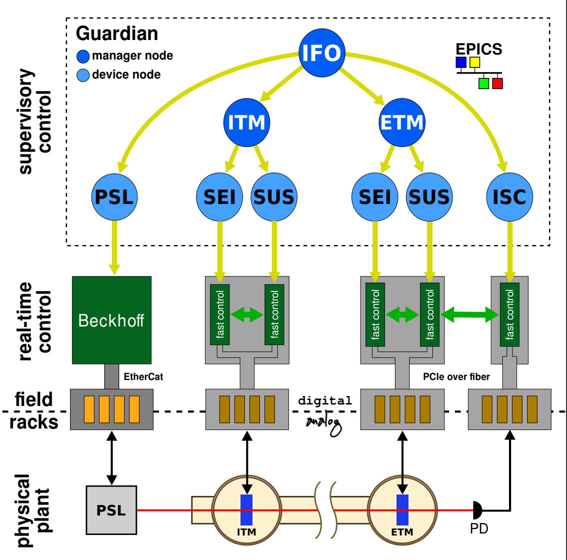
Fully digital controls



LIGO employs a hierarchical control structure for the full detector.

Feedback loops control all degrees of freedom (DOF) at the microscopic level with a custom built, modular, distributed, real-time digital control system (RTS) (using off the shelf PCs and a small linux kernel patch).

Fully digital controls



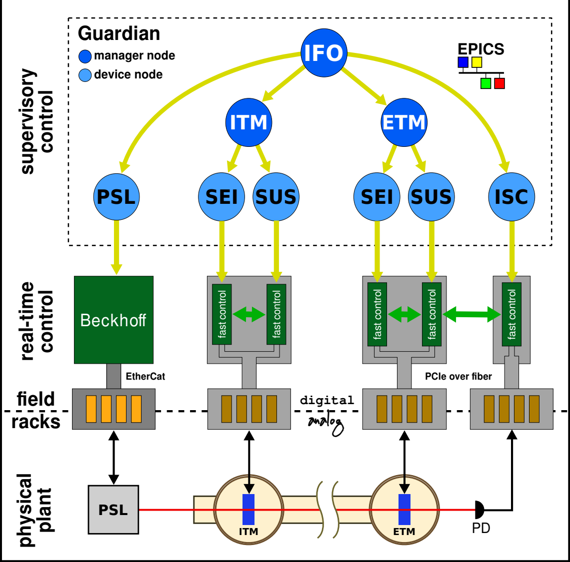
Hundreds of feedback loops:

suspensions active damping of 3-24 DOF per suspension (×18)

seismic isolation active damping and isolation of 18 DOF per seismic platform (×9)

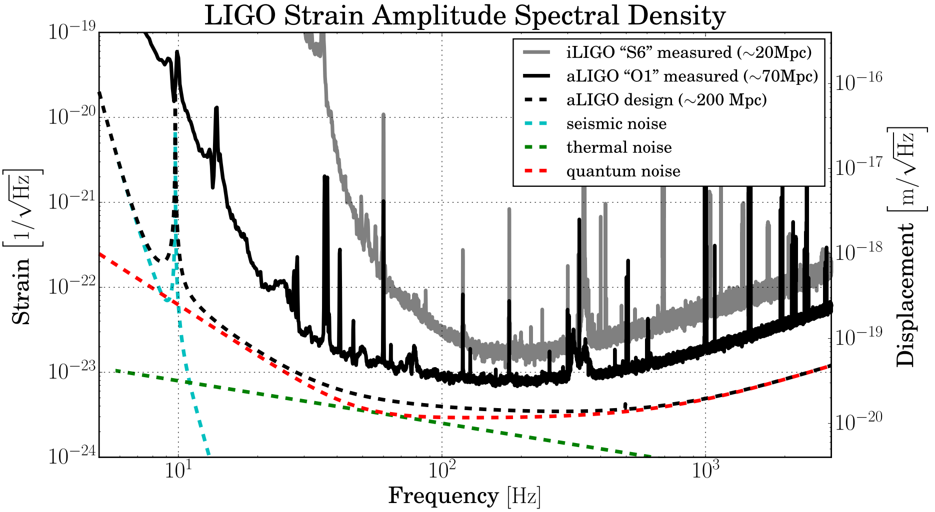
global control 5 length and 10 angular global DOF

Fully digital controls

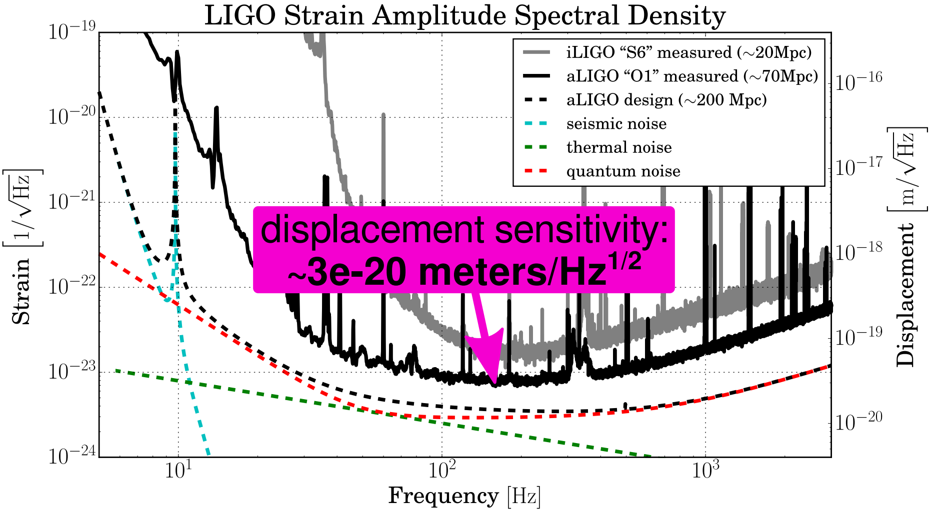


Supervisory control (automation) handled by a hierarchical, modular, distributed, state machine platform called Guardian.

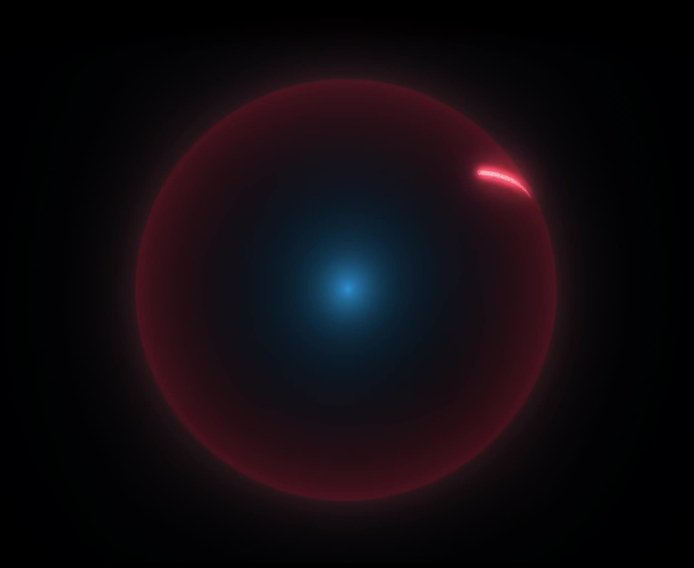
LIGO measurement as a function of frequency



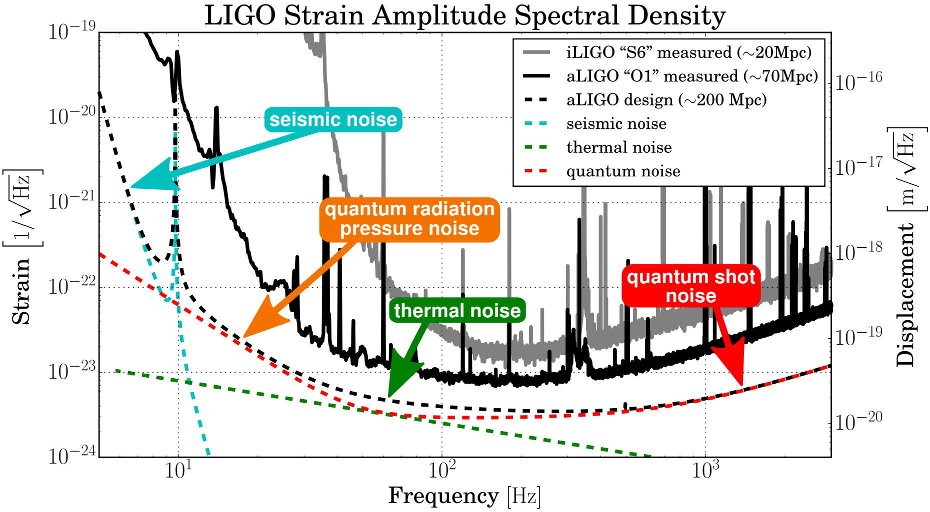
Performance: displacement sensitivity



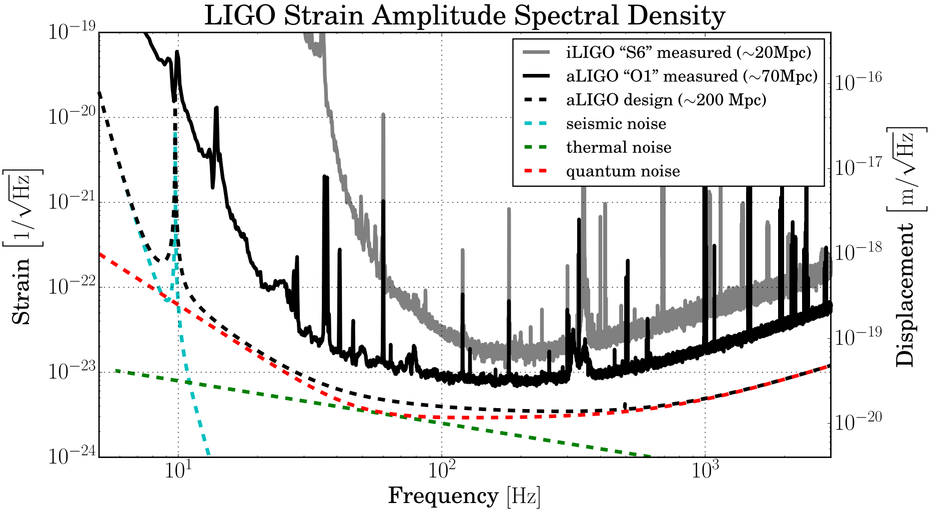
How small *is* that?!



Ultimately limited by fundamental noise sources



What does it sound like? Noise!

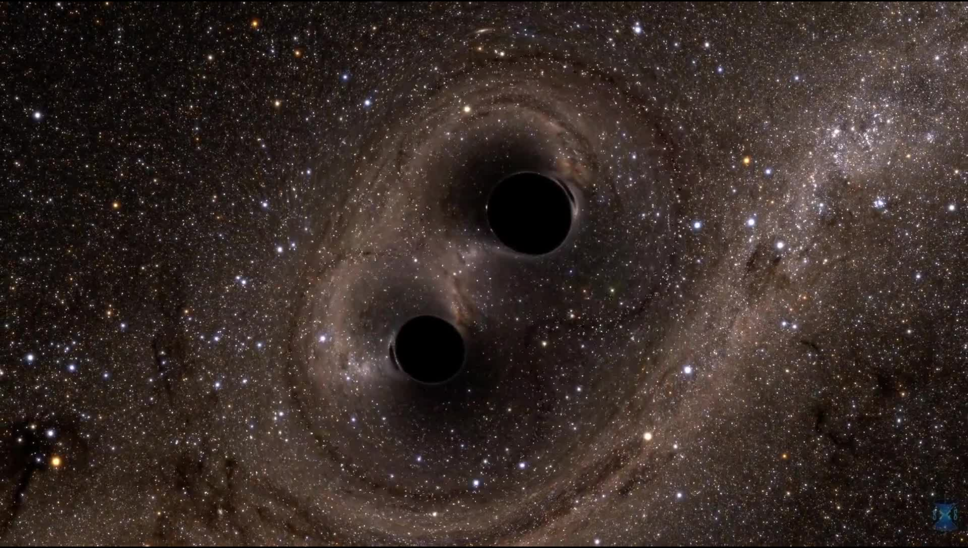


Meanwhile...

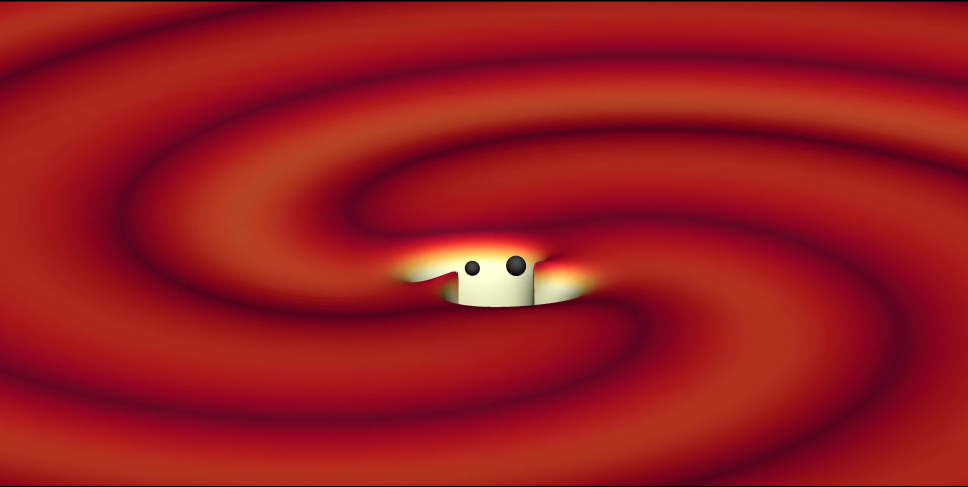
1.3 billion years ago,

in a galaxy far, far away...

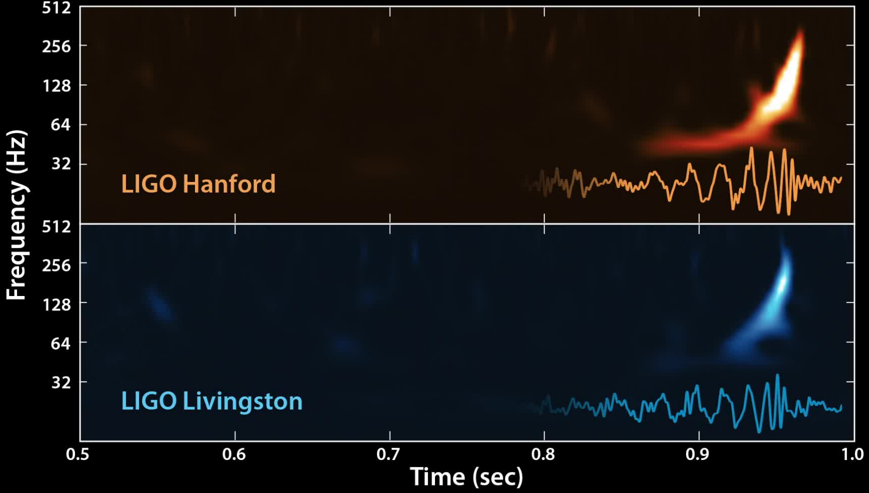
A pair of orbiting black holes inspiral and merge...



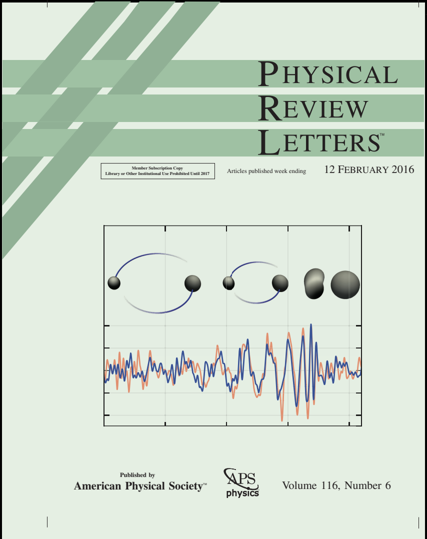
...and emit a *lot* of gravitational waves



Back on Earth, September 14, 2015...



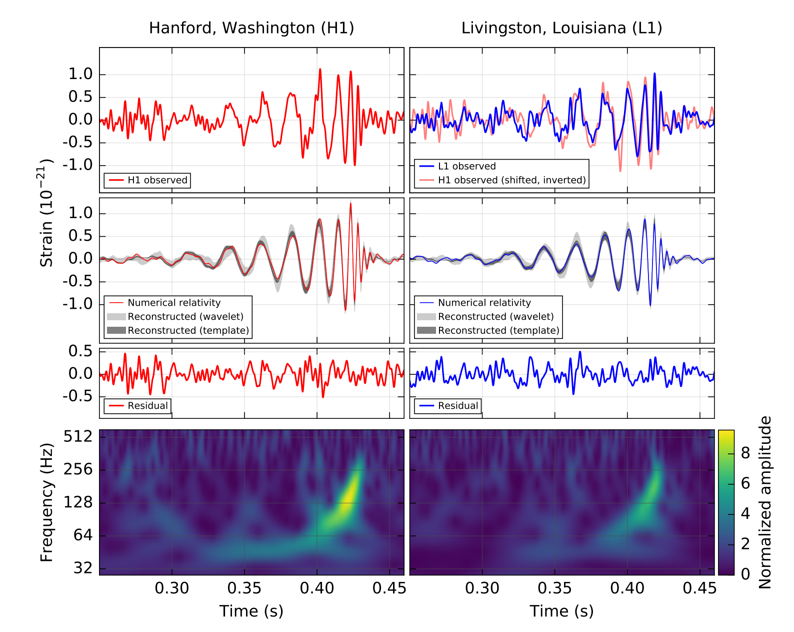
Observation of Gravitational Waves from a Binary Black Hole Merger



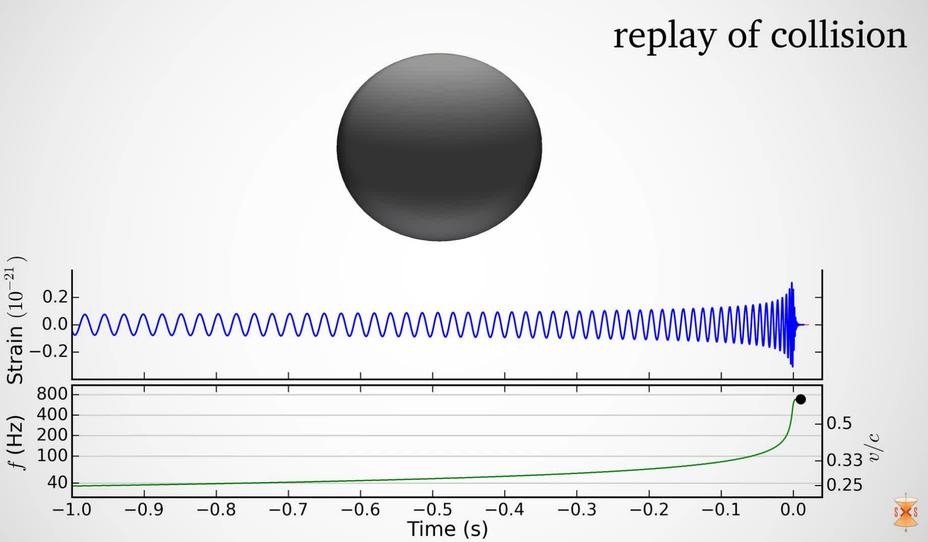
On September 14, 2015 at 09:50:45 UTC the two detectors of the Laser Interferometer Gravitational-Wave Observatory simultaneously observed a transient gravitational-wave signal. The signal sweeps upwards in frequency from 35 to 250 Hz with a peak gravitational-wave strain of 1.0×10^{-21}. It matches the waveform predicted by general relativity for the inspiral and merger of a pair of black holes and the ringdown of the resulting single black hole.

`https://papers.ligo.org/`

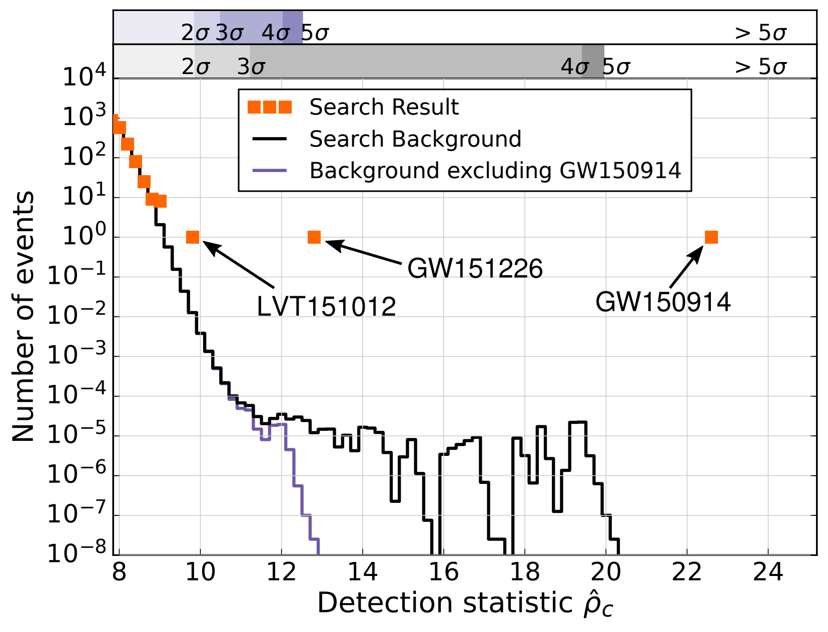
GW150914 - Observed strain



And then *again* on Christmas Day 2015



All events from the first observing run (O1)



GW150914 by the numbers

collision was 1.3 *billion* light years away

1/10th distance to edge of observable Universe

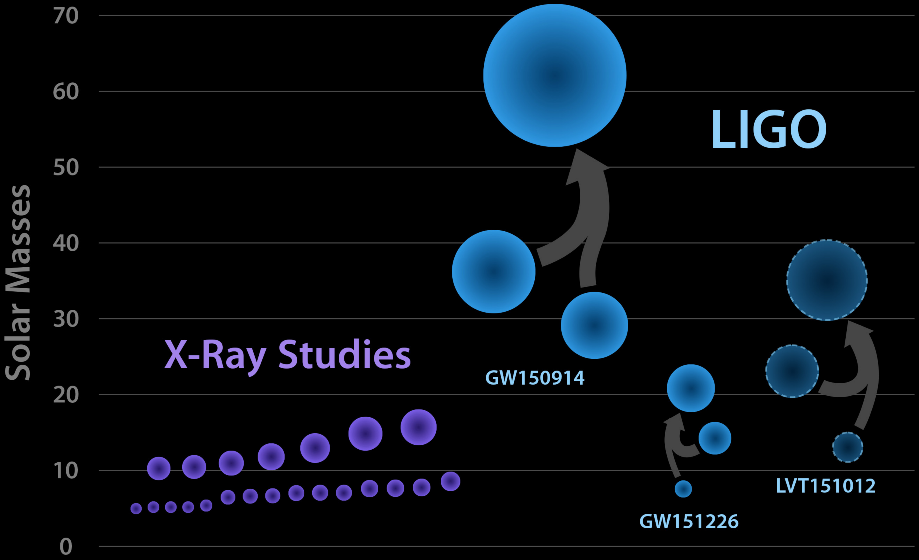
BH_1	$+$	BH_2	$\Rightarrow$	BH_f	
$36.2\ M_\odot$	$+$	$29.1\ M_\odot$	$\Rightarrow$	$62.3\ M_\odot$	**???**

3 suns worth of energy released as gravitational waves

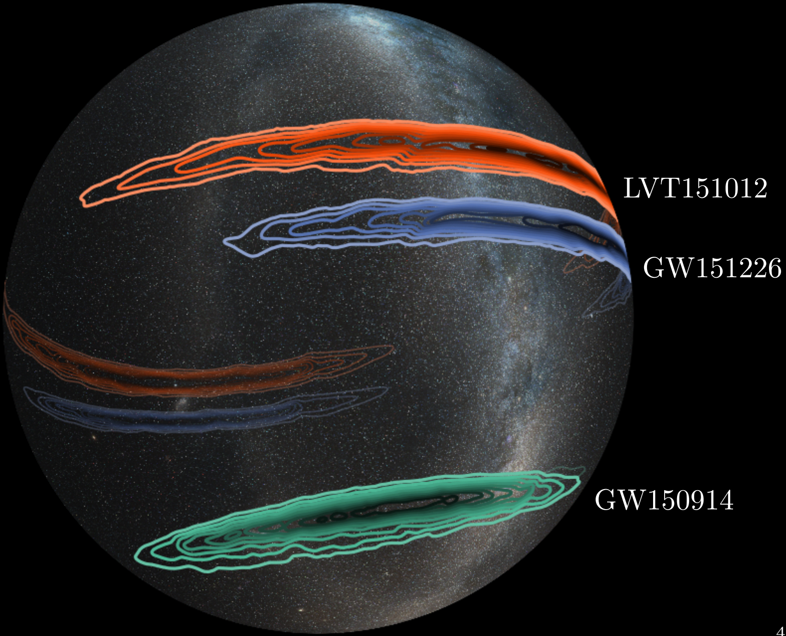
peak luminosity:	$\mathbf{3.6 \times 10^{56}}$	ergs/s
solar luminosity:	$\mathbf{3.8 \times 10^{33}}$	ergs/s
universe luminosity:	$\sim \mathbf{10^{55}}$	ergs/s

30× brighter than the entire Universe

All known black holes



Where in the sky did they come from it?



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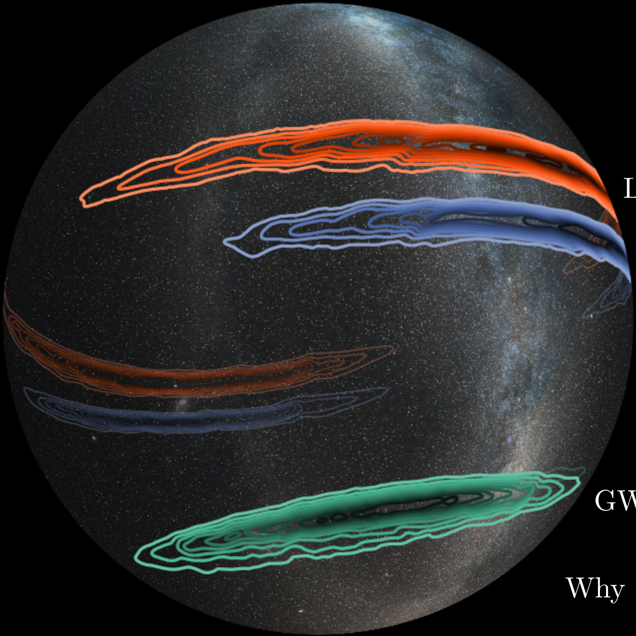


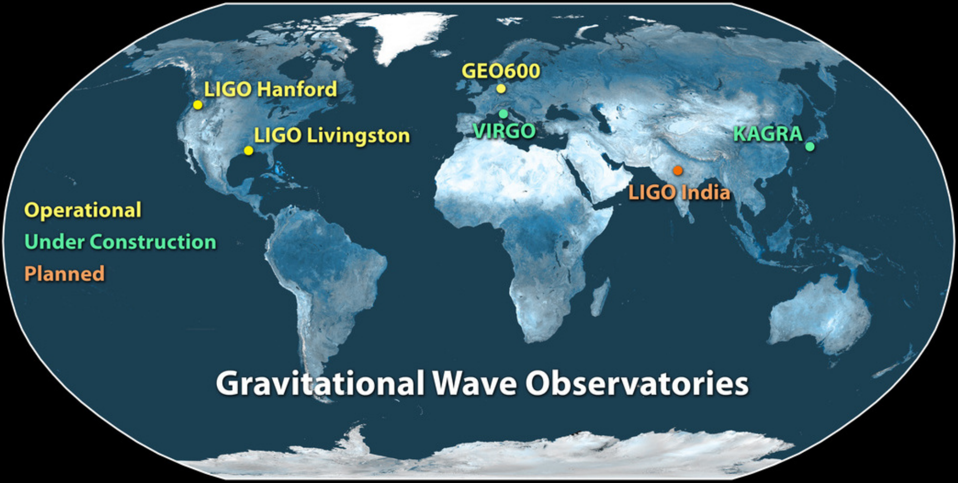
Why do we care?

This is what a binary black hole merger actually *looks* like

But a binary neutron star merger...

Or a core-collapse supernova...

World-wide network needed for better sky localization



The future of LIGO

LIGO currently down for improvements, prepping for late 2016 observing run start (hoping for $\sim 20\%$ sensitivity improvement).

At design sensitivity:

expect multiple events per week

More big discoveries soon?

- binary neutron star collisions?
- electromagnetic counterparts?
- ???

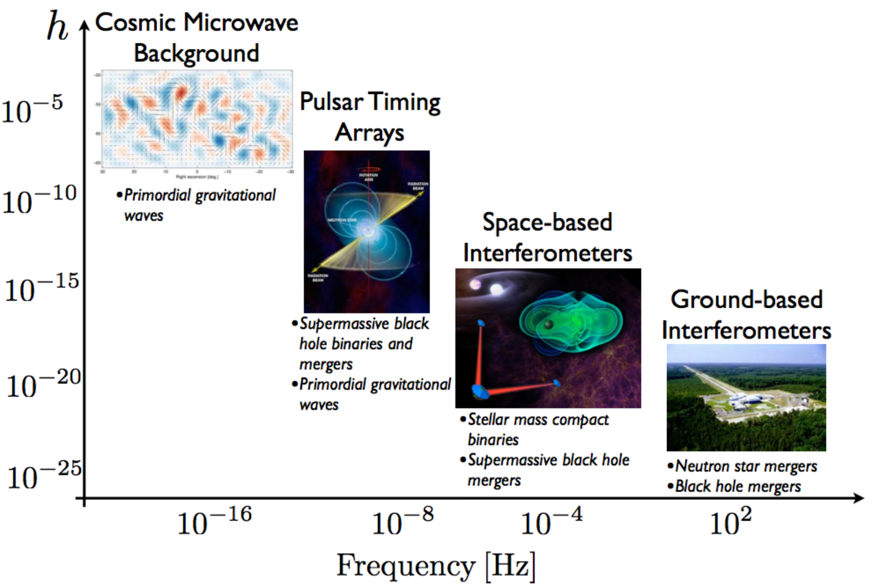
Future of gravitational wave detection

New and improved detectors needed

quantum noise	▪ more laser power ▪ *squeezed* vacuum
thermal noise	▪ better mirror coatings ▪ cryogenics
seismic noise	▪ longer suspensions, more stages ▪ seismic feed-forward cancellation
everything else	▪ longer arms

4th generation detectors can potentially have *cosmological* reach

GW should exist across a large spectrum



Thank you