Gravitational Waves have been detected on Earth

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UBC Feb 24 2016

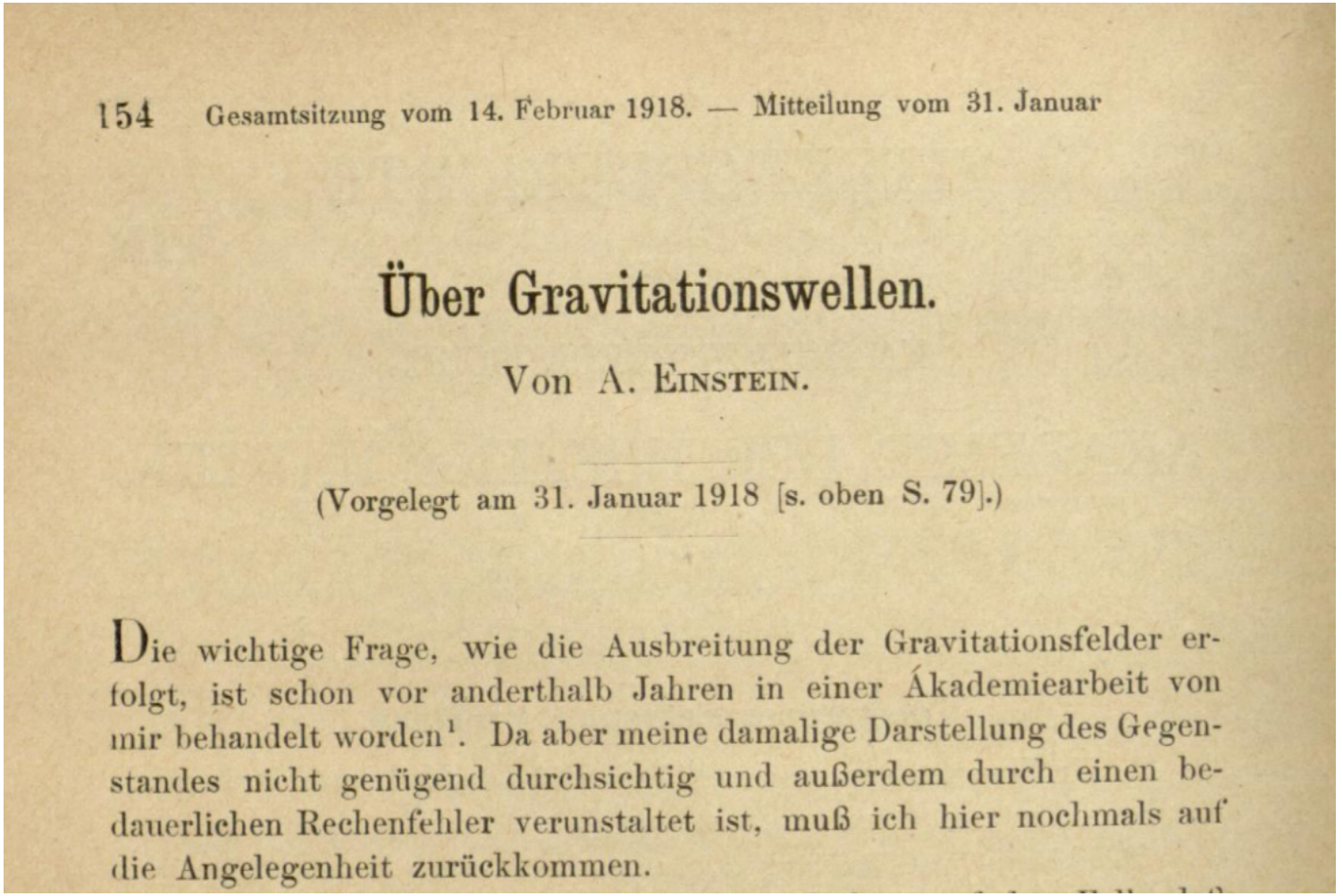
In 1915 Einstein found and published his theory of gravity

Gravity on earth: Is the inequable
flow of time from place to place.

[Not gravity causes time to flow inequably
but gravity IS that inequable flow.]

Gravity is not a force.
Particles under gravity along travel along straight lines.

1918:



154 Gesamtsitzung vom 14. Februar 1918. — Mitteilung vom 31. Januar

Über Gravitationswellen.

Von A. Einstein.

(Vorgelegt am 31. Januar 1918 [s. oben S. 79].)

Die wichtige Frage, wie die Ausbreitung der Gravitationsfelder erfolgt, ist schon vor anderthalb Jahren in einer Akademiearbeit von mir behandelt worden[1]. Da aber meine damalige Darstellung des Gegenstandes nicht genügend durchsichtig und außerdem durch einen bedauerlichen Rechenfehler verunstaltet ist, muß ich hier nochmals auf die Angelegenheit zurückkommen.

On Gravitational waves

Fixed calculation of sources-- “Quadripole formula”
Moving masses create gravity waves.

What are gravitational waves?

Often called “ripples in the fabric of spacetime”. I have no idea what that means.

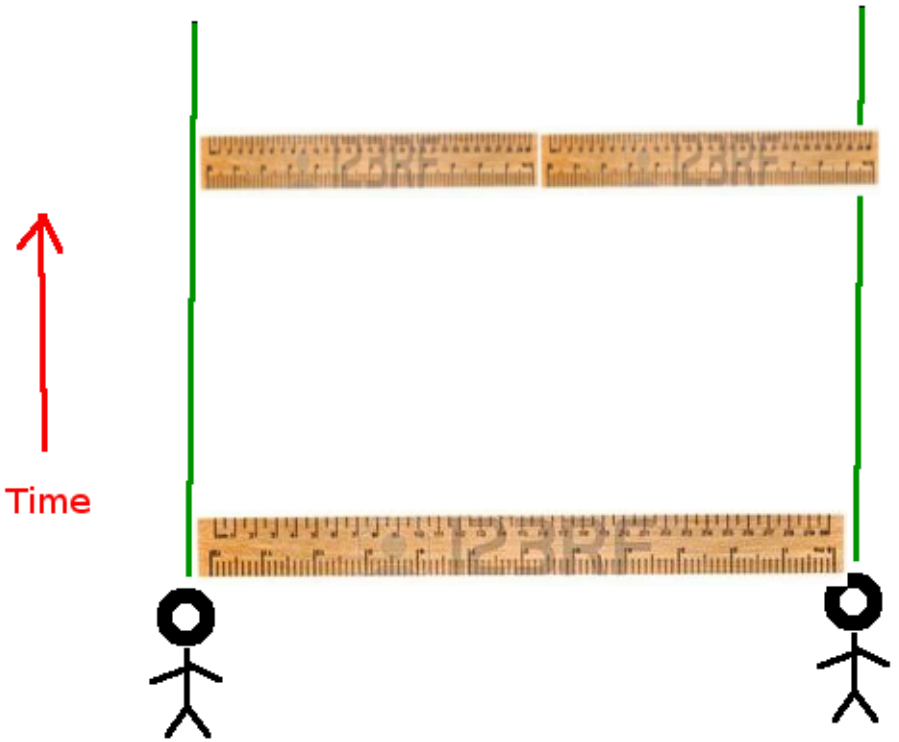
Gravity near earth is change in flow (amount) of time from place to place.

Time and space unified.

Grav waves are the changes in amount of distance from time to time.

Distances between objects can change without motion of objects. (Ie, objects feel no accelerations.)

Two objects sitting still.
Suddenly distance increases, but neither feels a force moving them.

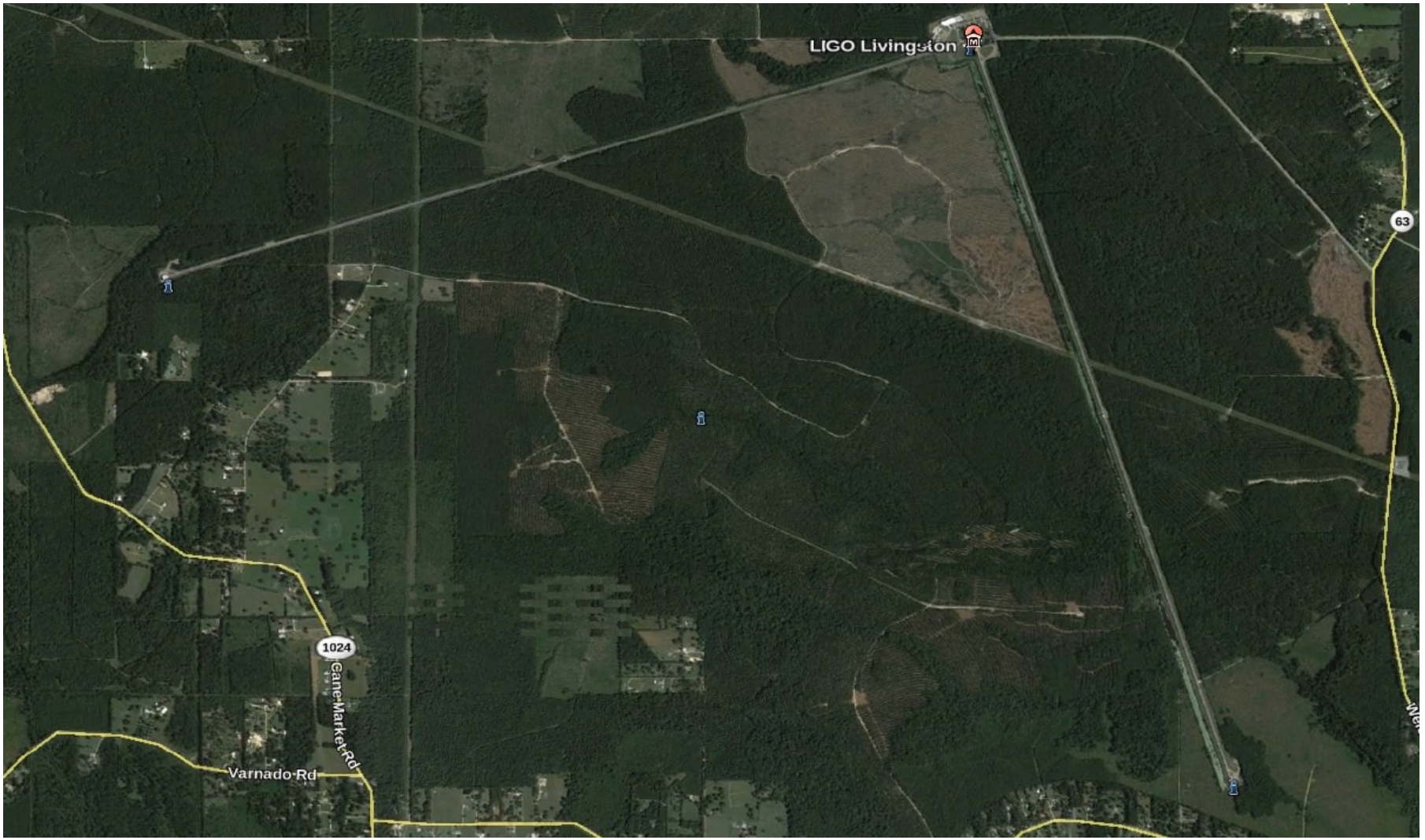


Changes in distance are perpendicular to the direction of travel of the wave.

Changes are balanced-- areas remain same.
Change in one direction is balanced by opposite change in other direction.

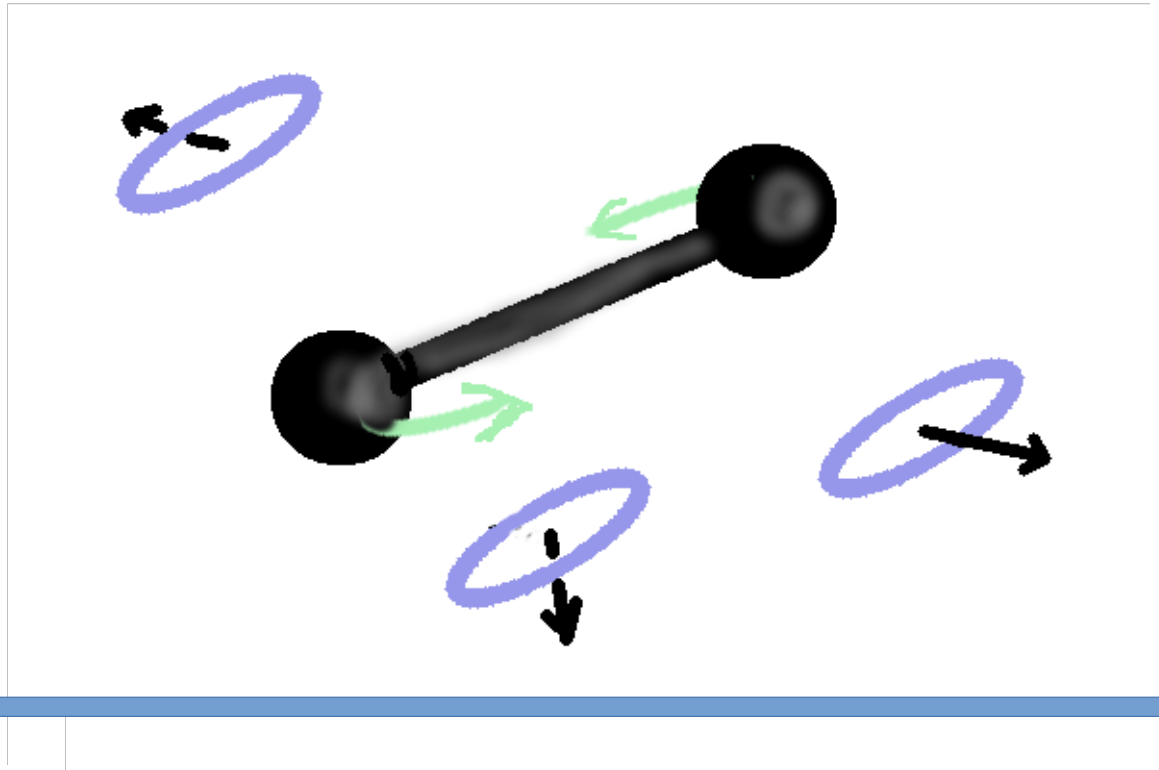
Livingston detector as very intense gravity wave goes by, as “seen” from the central control room.
Picture is of distances as measured from that center.
(Amplitude is 10,000,000,000,000,000,000 greater than actually seen, and about 50 times slower than the actual signal).

Effect of huge gravity wave on Louisiana detector h=0.05

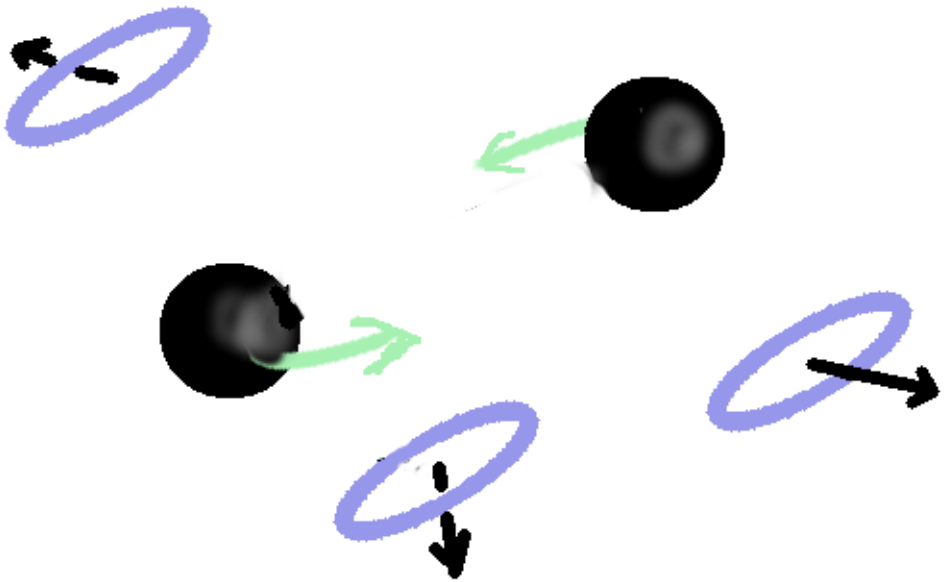


Arms are 4Km long.. Ends move about 200m as gravity wave comes by as seen by control room. But people at end see control room move.

Origin of gravitational waves.



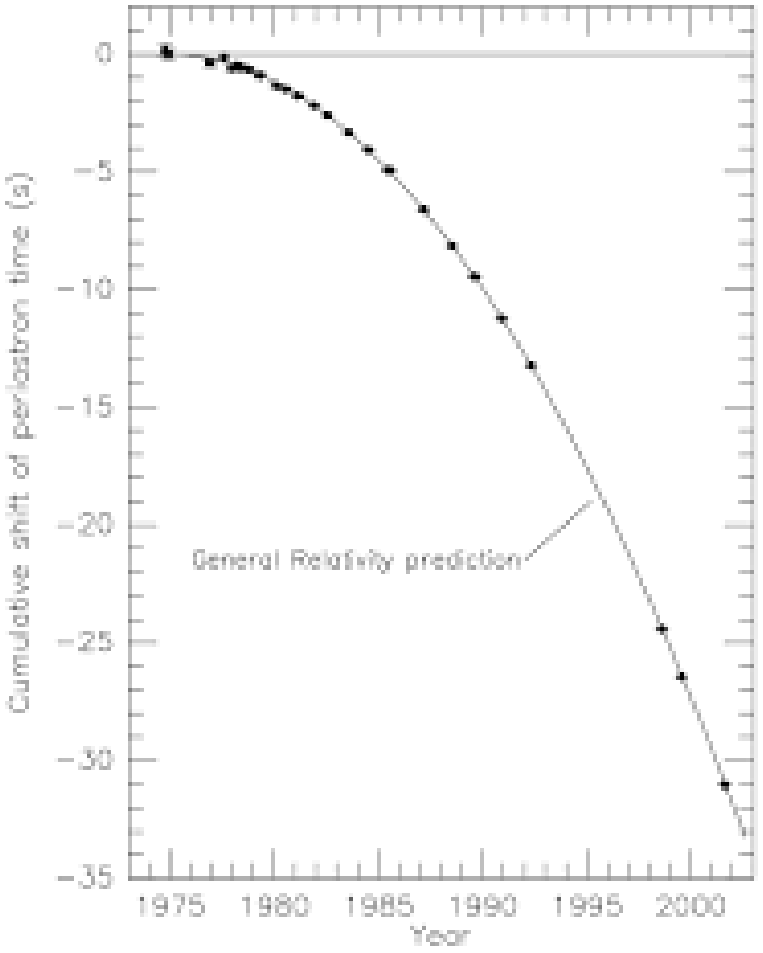
Moving Masses

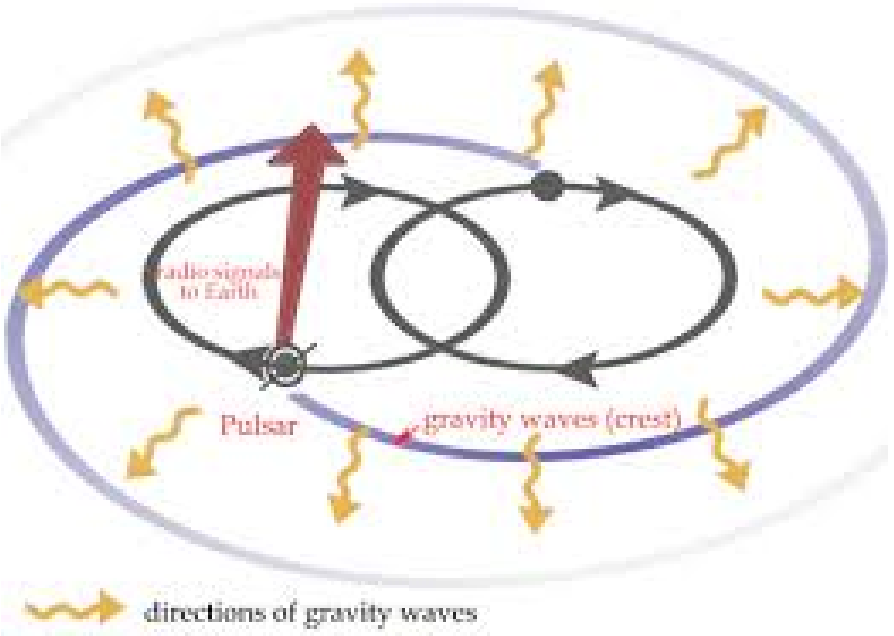


Orbiting Masses

Controversy for 50 years if orbits also emit waves.

1973--> Hulse and Taylor : Binary pulsar (1993 Nobel)





Very weak grav waves even at origin. (Einstein 1918 could explain).

(<1/100,000)

Detect waves which are strong at origin?

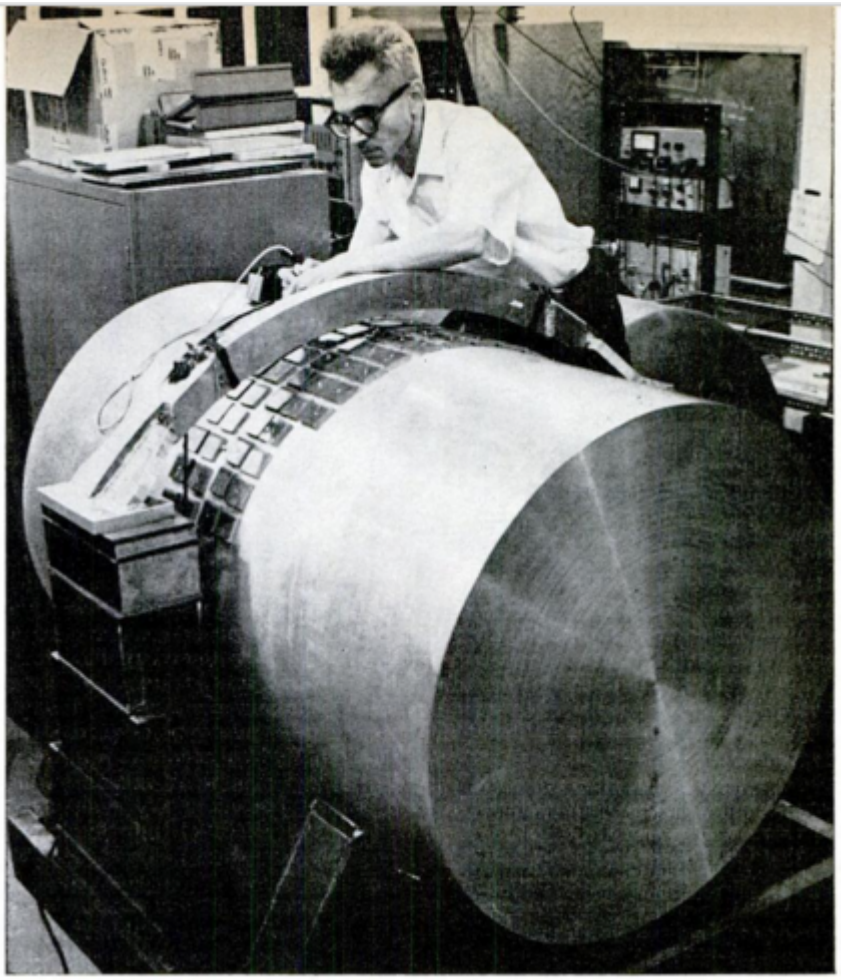
Cannot “see” them-- either a huge mess of matter hides everything as core of collapsing star tears itself apart, or black holes which emit no light/radio waves etc.

How to detect gravity waves on earth?

A) Matter reacts to its length changing, and moves.

B) Directly measure distances between “free” objects.

A)-- Done first by Weber – began in 1959, announced detection in 1969.



Over 1 ton aluminium bar vibration much less than an atom.

If he was right, energy of hundreds of solar masses needed to beconverted to gravity waves in our galaxy!

Results not duplicated. But got the ball rolling (people invested lives in building detectors-- how good ?)

B) Directly measure distance changes.

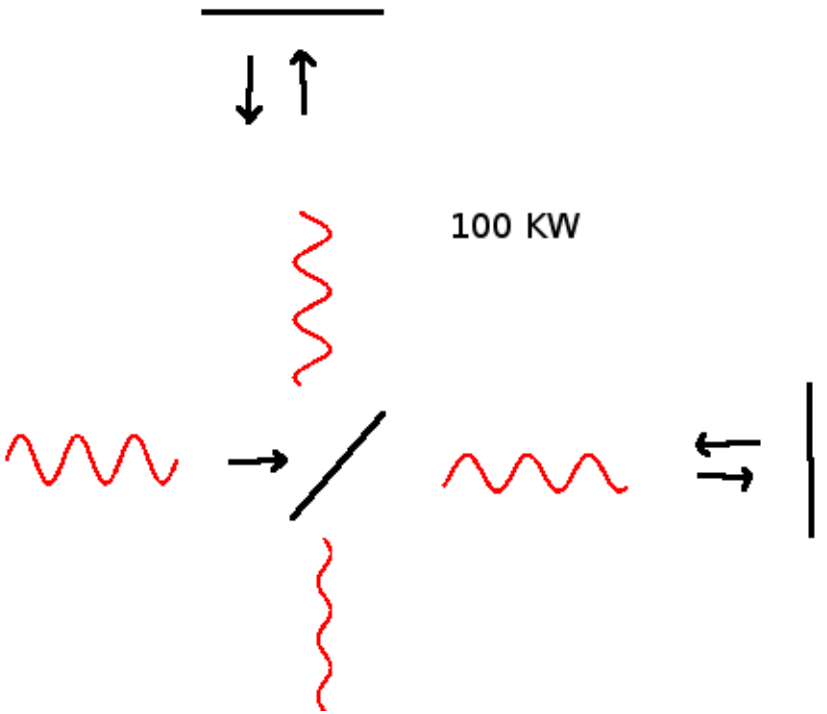
1980’s Ray Weiss (MIT), Kip Thorne(CalTech)
Ron Drever (Glasgow->Caltech)

Laser Interferometer to measure change in distance.

Time light going along path to measure distance.

No clocks accurate enough.

Light wave naturally stronger and weaker-- contains its own clocks.



Crests and troughs line up in two beams.
Cancellation at half mirror depends crucially on lengths of arms.

Millions of Problems:

Ground jiggling.

Louisiana-- Careful site selection for low noise.
Interferometer built, and logging company moved in and logged the trees around the interferometer (they owned the land).

Trucks on highways, wind storms, hail,....

Waves on ocean breaking on land 300km away causes enough jiggling to destroy sensitivity.

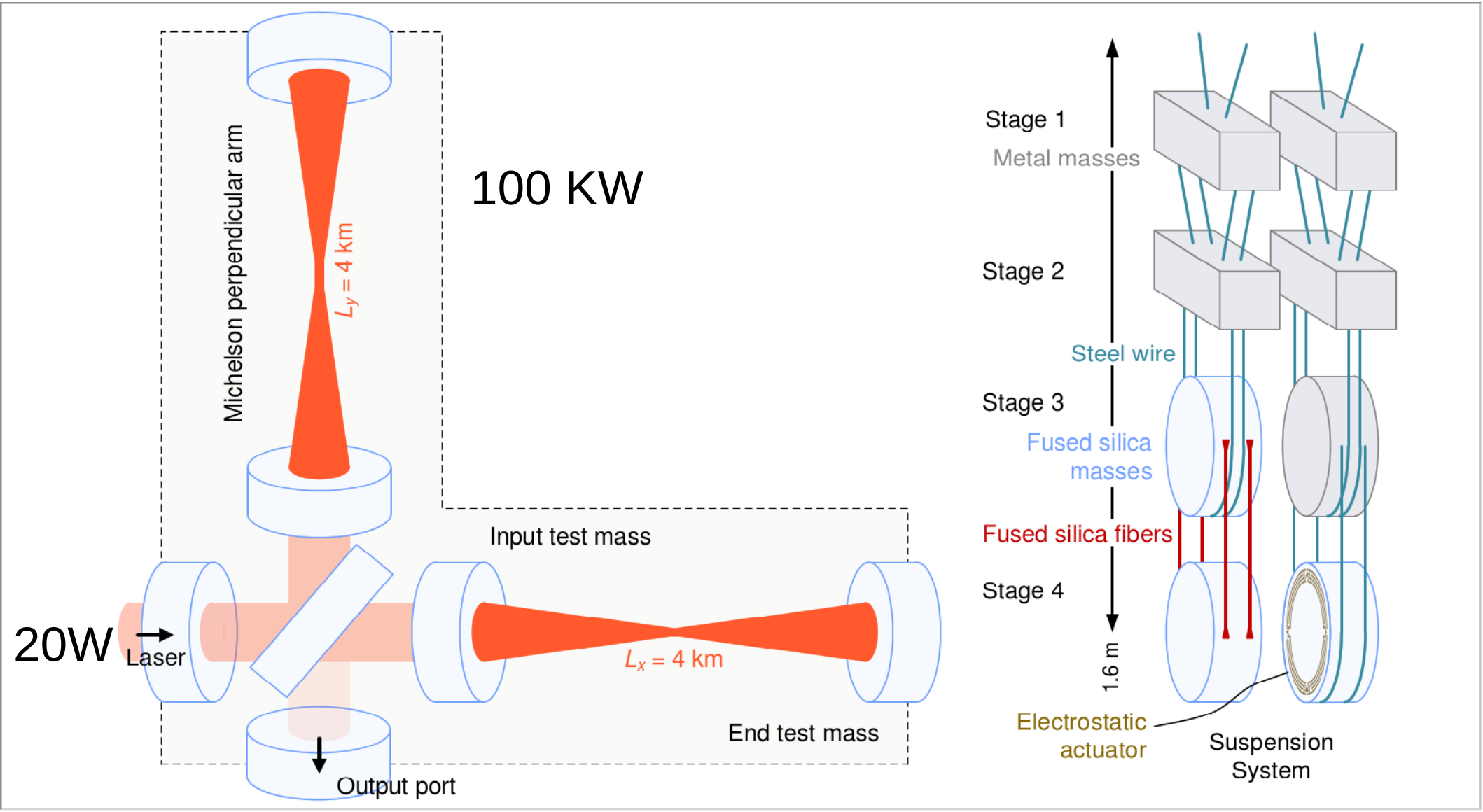
Measurement Noise

Light interacts as photons.-- shot noise in detection and in pressure on mirrors—tradeoff. (Increase power to decrease detection shot noise increases shot noise on mirrors. -- ultimate limit.)
Increase power to reduce shot noise. (Heating of mirros?)
Make mirrors heavier to reduce pressure noise.

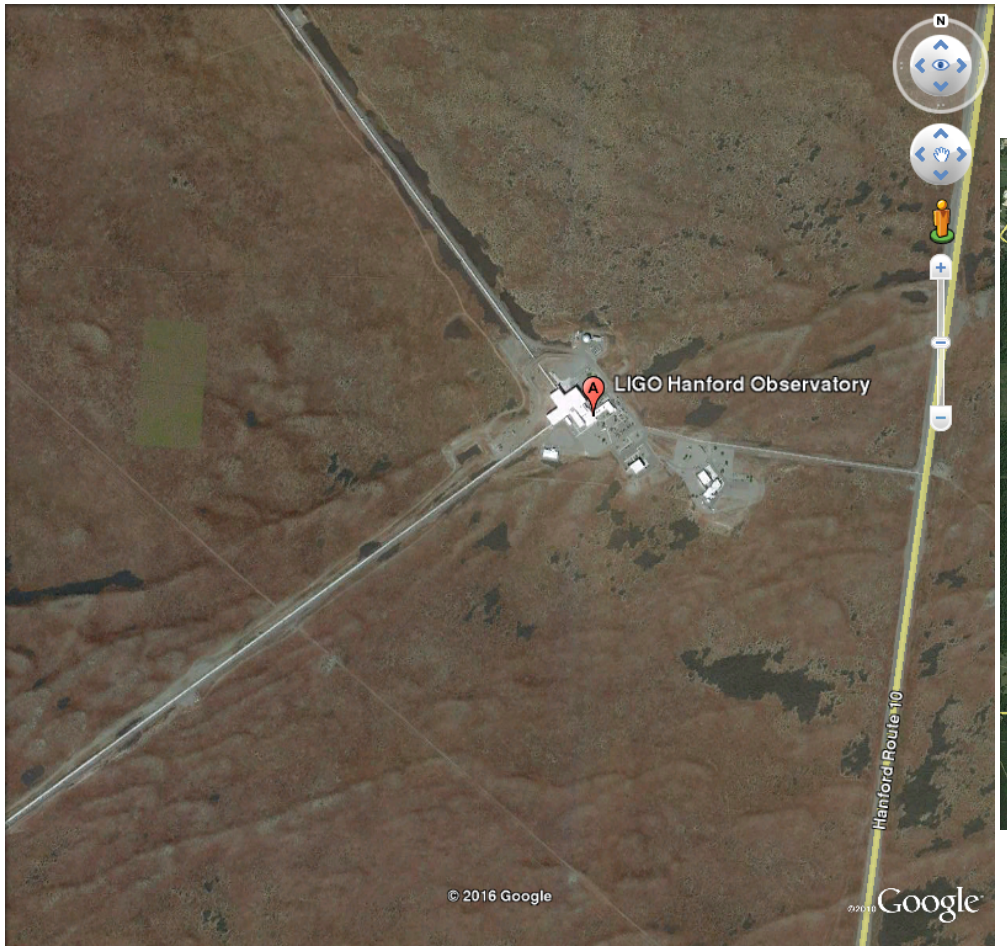
Light scattering

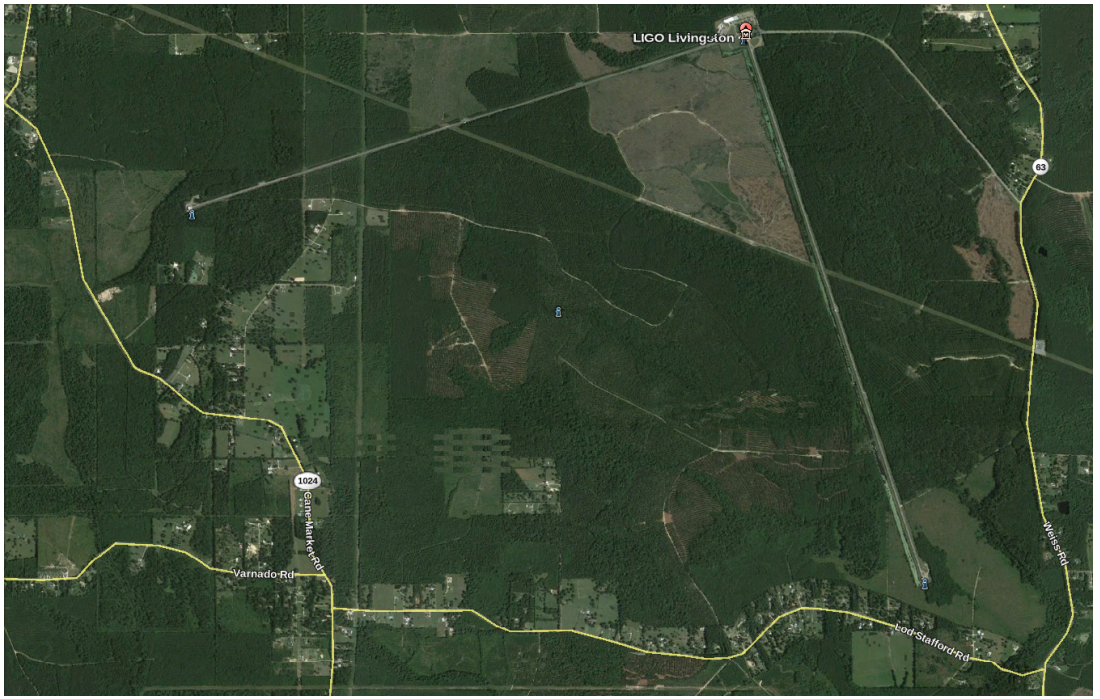
Vacuum-- less than a billionth of atmospheric.

Sketch of actual LIGO interferometer



LIGO-- Two sites-- Hanford, Washington
Livingston, Louisiana



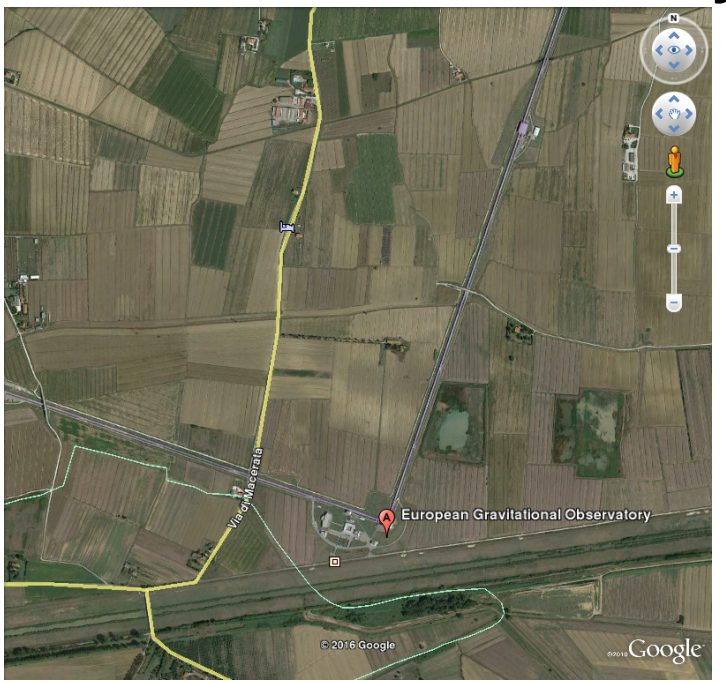


4km tubes. Vacuum 1 -10billionth of atm.
Concrete sheds (pot shots)

Others: (None operating at the time)

GEO600 ,Hanover, Germany (Test Bed)

aVIRGO, Pisa Italy



KAGRA, west Japan (Kamioka mine)
Cryogenic, 3Km arms

Maybe India-- (LIGO offered their other Hanford detector to India- awaiting final decision)
Modi agreed 2 days after detection.

LIGO, VIRGO operated for about 10 years. Saw nothing

Advanced LIGO, VIRGO.-- Heavier mirrors, better isolation increased laser power, better mirror coatings,....
3-10 times more sensitive.

Looking for What?

If you are looking for something in a cluttered environment, it helps to know what you are looking for.

In a flat desert, it does not matter so much since anything that sticks out is probably interesting.

Solve Einstein Equations for Orbiting objects

Einstein's equations are horribly complicated.
10 equations, each with hundreds of terms.
Impossible by paper and pencil to solve except in simple situations.

If objects far apart (weak waves)-- use techniques Einstein started
Post Newtonian Formalism (PPN)

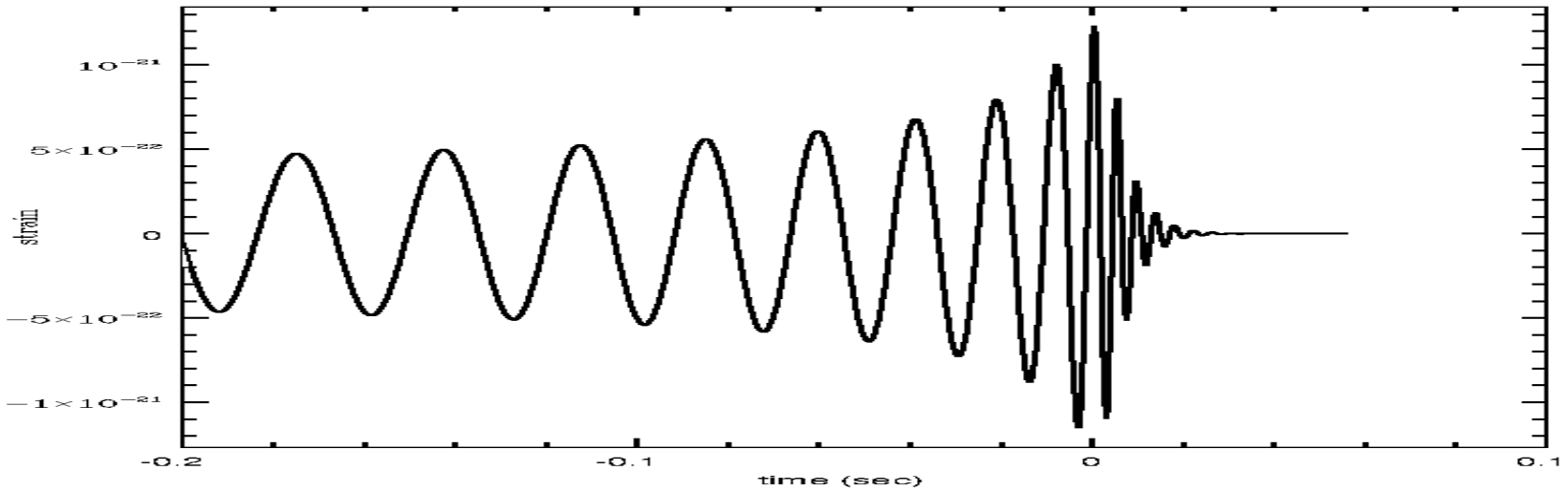
Numerical Relativity.

Early 1970's – DeWitt in Texas had students look into solving Einstein's equations with computer.
Larry Smarr was one of first.

2005-- Frans Pretorius—former student of Choptuik-- first "long term" (many orbits) evolution of black holes orbiting each other.

Broke open the field and people (eg, H Pfeiffer, McMaster, UofT) generated thousands of solutions
Creation of “Template” bank. --
Timing-> Mass ->Size Amplitude->distance (1/r)
Relative masses of black holes. Spins values and spin orientation of black holes and orbits., polarization, detector geometry

Amplitude of waves fall off as 1 over distance.

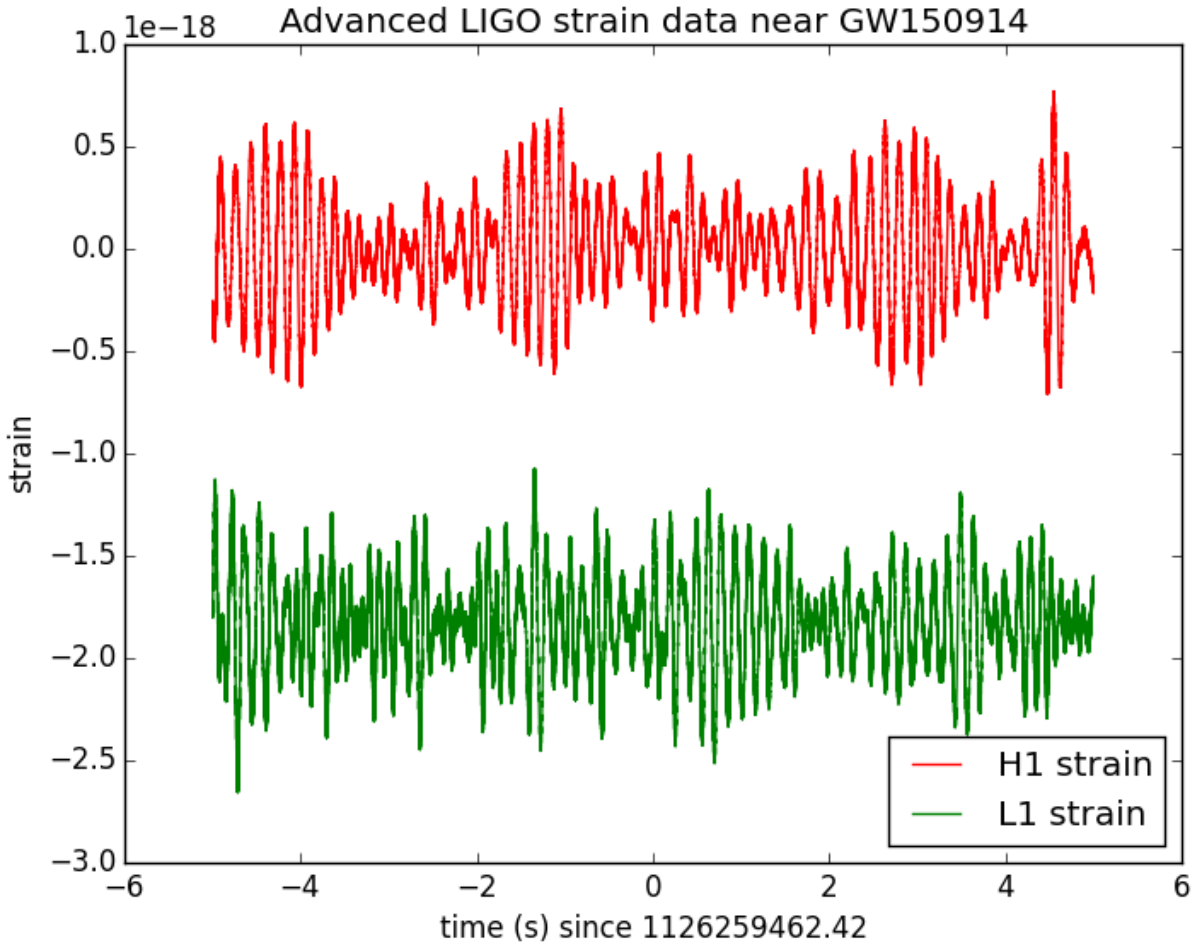


Sound

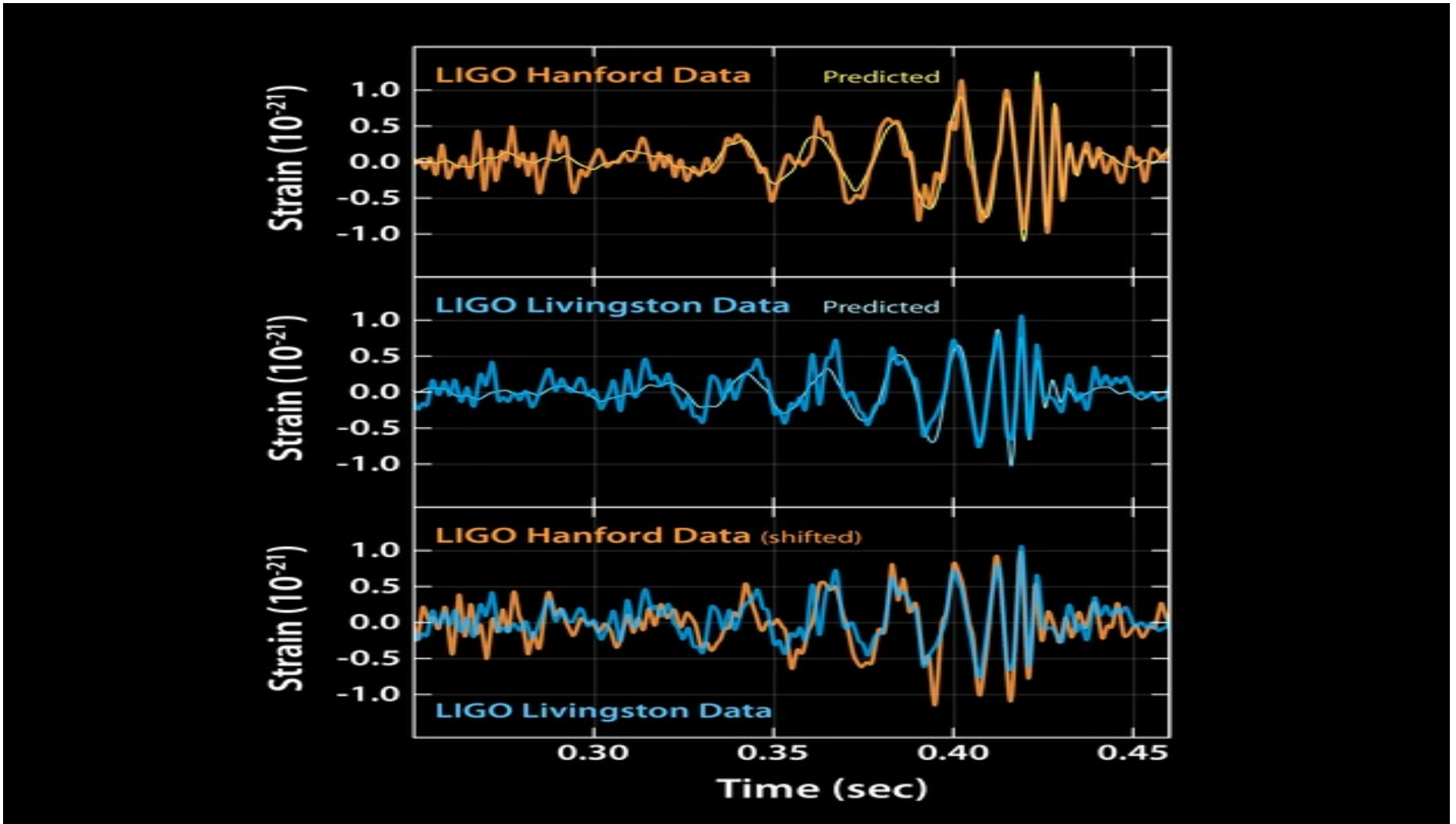
Sept. switched on Hanford and Louisiana detectors for engineering shakedown. Science run to start in Oct.

On Sep 14 2015. This was the output of the detector.

All Noise
Low freq.



Filter out low frequencies (eg, oscillations of mirrors as pendula, laser pressure fluctn., shot noise, seismic,...)
Filter out narrow line noise (eg 60Hz, 120Hz, 180Hz from powerlines,Filter out 500Hz string frequency of support wires, 10 calibration lines.



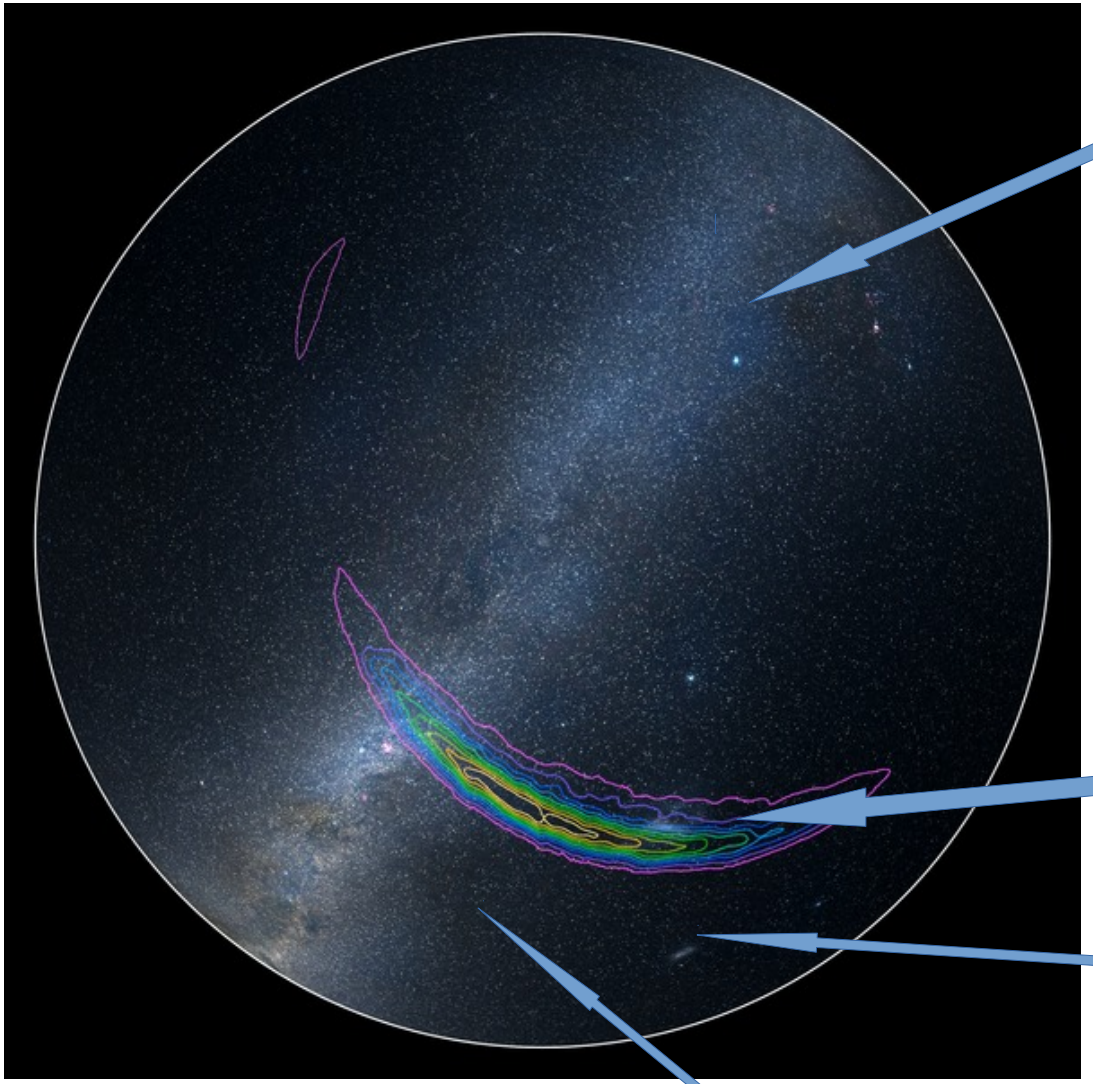
The timing of the data gives us the total mass. about 60sun
(The frequency is inversely proportional to the mass)
The detailed shape of the waveform gives relative masses
spins of the black holes (weakly) about 1.2

The amplitude gives us the distance to the system.
(h=.1 at about 10 times the Schwartzschild radius)

About 1billion light years away.

The time delay (.007 sec) give part of direction in sky.

The difference in shape and amplitude of the curves give refined direction and orbital parameters
(No difference between the curves at the two detectors)



Milky Way

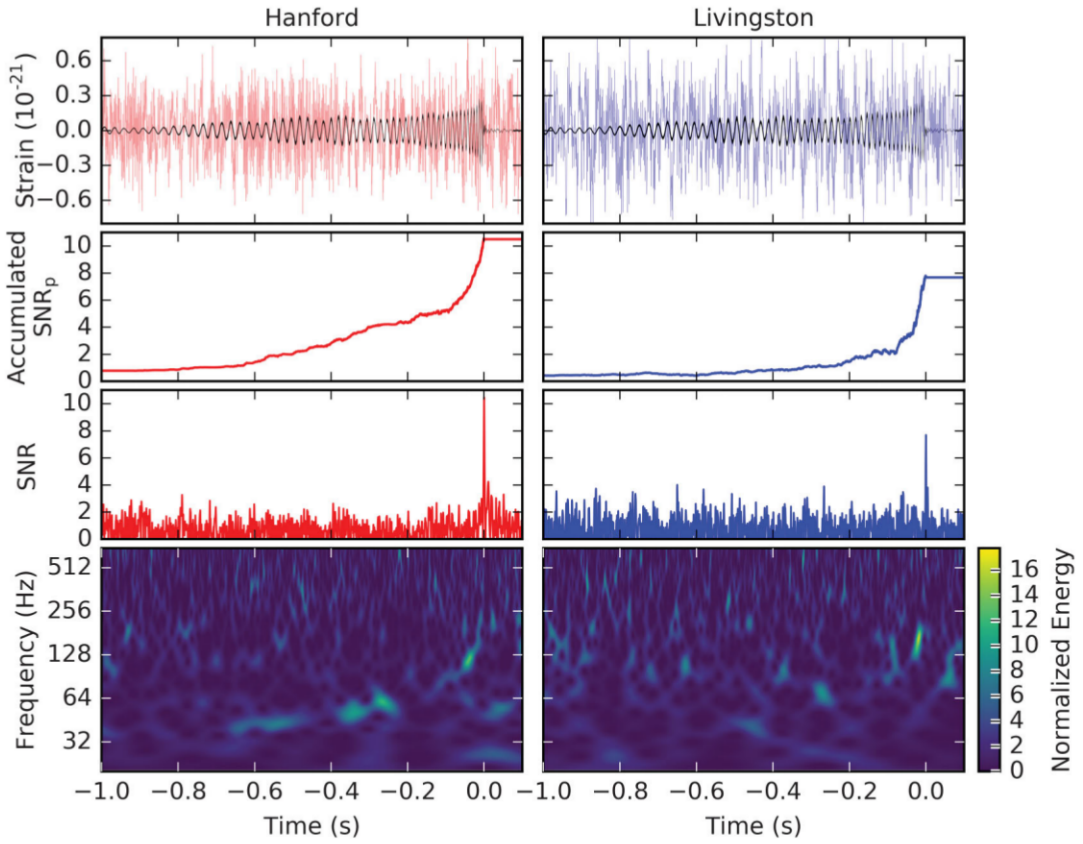
Signal passed through earth before hitting detectors

Area of probable location of source

Small Magellanic Cloud

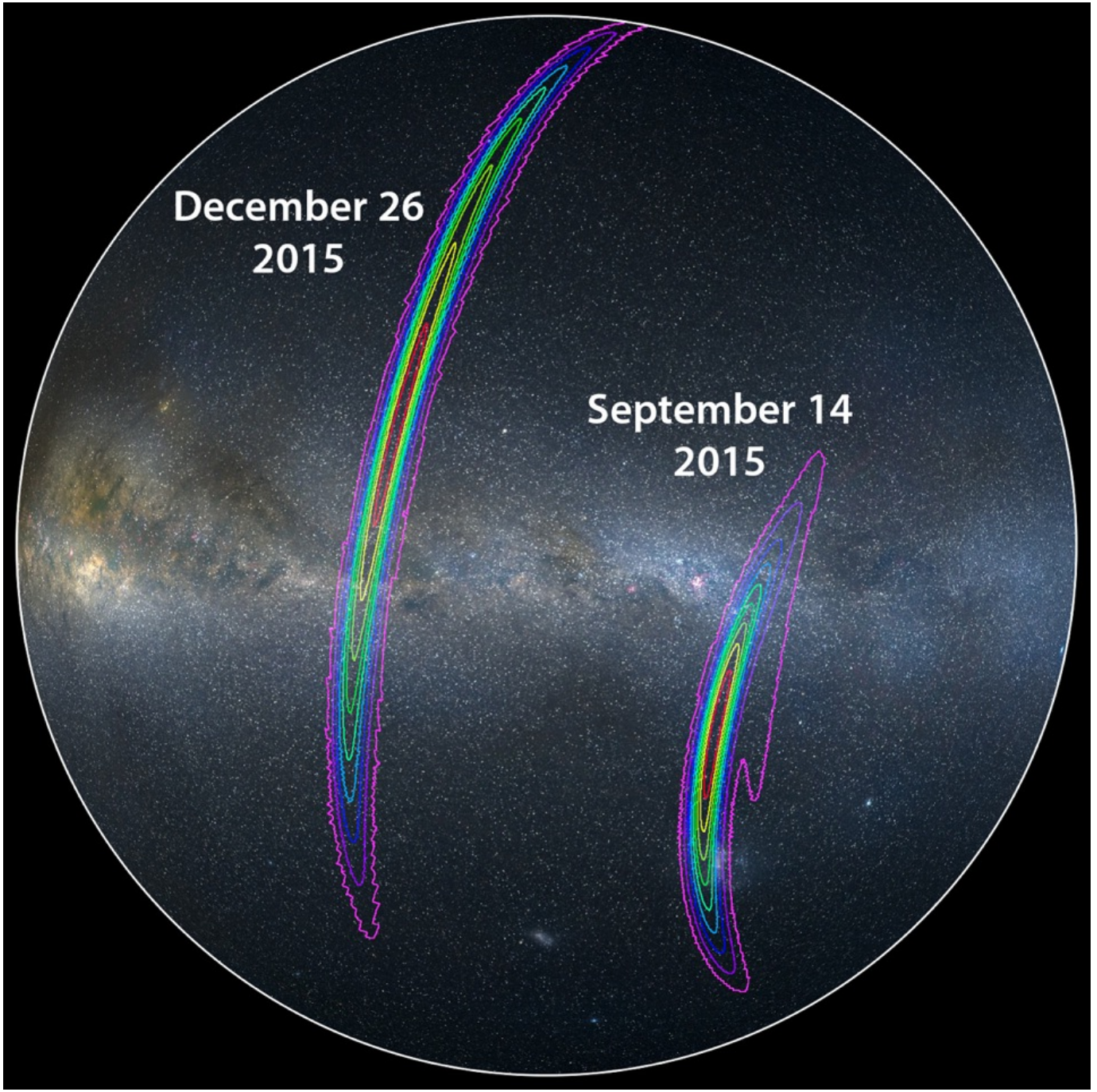
South Pole

“Boxing Day” 2015



14.2 and 7.5 Msun 1.4Glt-yr (10% back to Big Bang.)

Direction in sky to source
Of GW.



What next?

There are more candidates from the three months of running.

Tuned Advanced Ligo-- improvement of about another factor of 3-10.
Advanced Virgo online in a year, Kagra in about 2.
Timing gives much better location in sky. Different orientations give other polarization data. India?

eLISA-- (European Space interferometer 1 million km arms)
Sensitive to much lower frequencies (periods of 1s-1000s --no ground shaking in space)
Pathfinder mission lauched in Dec 2015

Pulsar timing array

Pulsars are very good clocks. If distance between us and pulsar changes due to grav. wave, can detect it by looking timing of pulses from pulsar (to about a microsecond-- a millionth of a sec.)

Gravity waves of period months to years. (from birth of universe or from massive black holes inside galaxies billions of solar masses).

In progress.

Stay tuned for further results.