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.

1916:

688 Sitzung der physikalisch-mathematischen Klasse vom 22. Juni 1916

Näherungsweise Integration der Feldgleichungen der Gravitation.

Von A. Einstein.

Bei der Behandlung der meisten speziellen (nicht prinzipiellen) Probleme auf dem Gebiete der Gravitationstheorie kann man sich damit begnügen, die $g_{\mu\nu}$ in erster Näherung zu berechnen. Dabei bedient man sich mit Vorteil der imaginären Zeitvariable $x_4 = it$ aus denselben Gründen wie in der speziellen Relativitätstheorie. Unter »erster Näherung« ist dabei verstanden, daß die durch die Gleichung

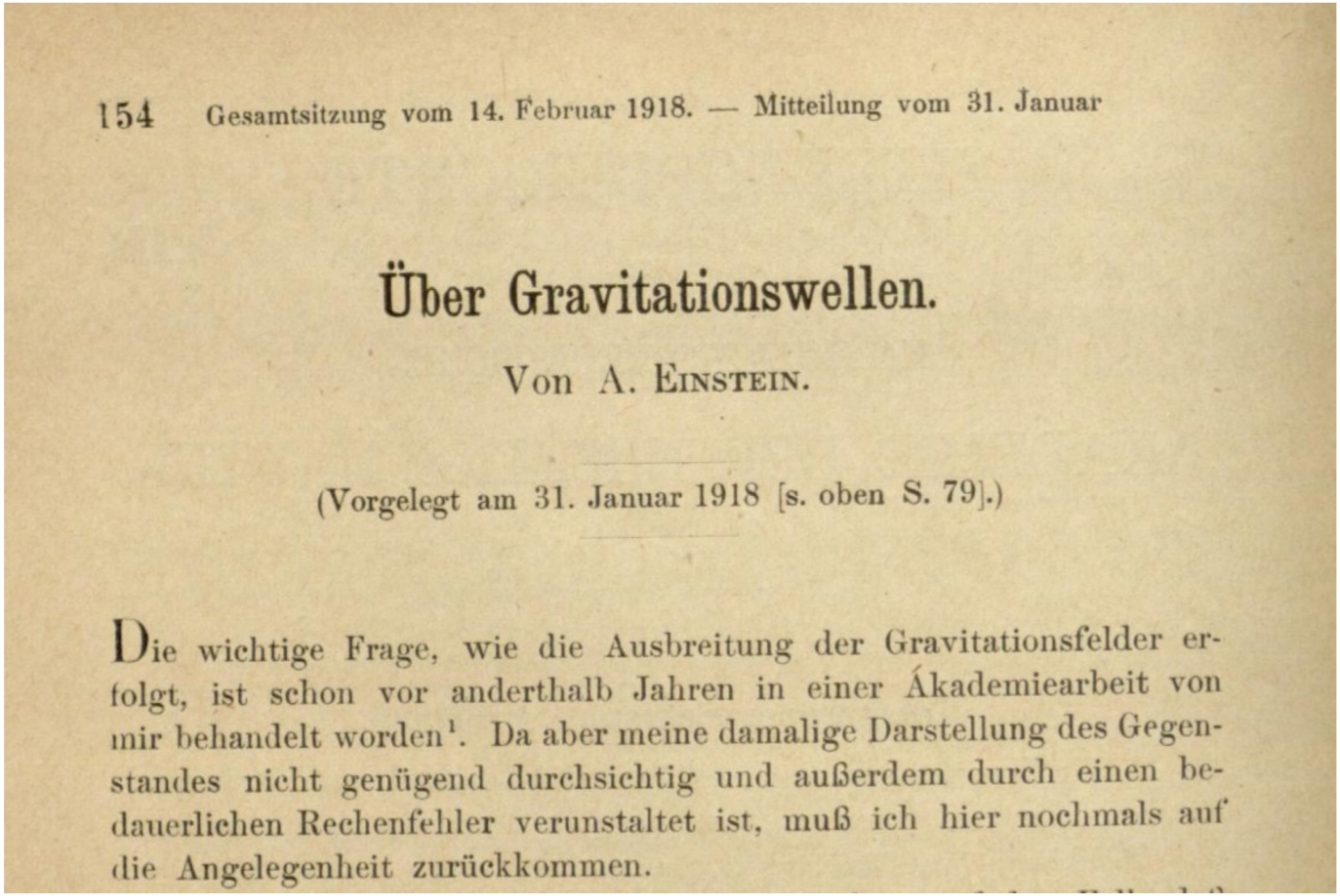
$$g_{\mu\nu} = -\delta_{\mu\nu} + \gamma_{\mu\nu} \qquad (1)$$

Approximate integration of Field equations of Gravity

Introduced gravitational waves.

Messed up calculation of sources.

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?

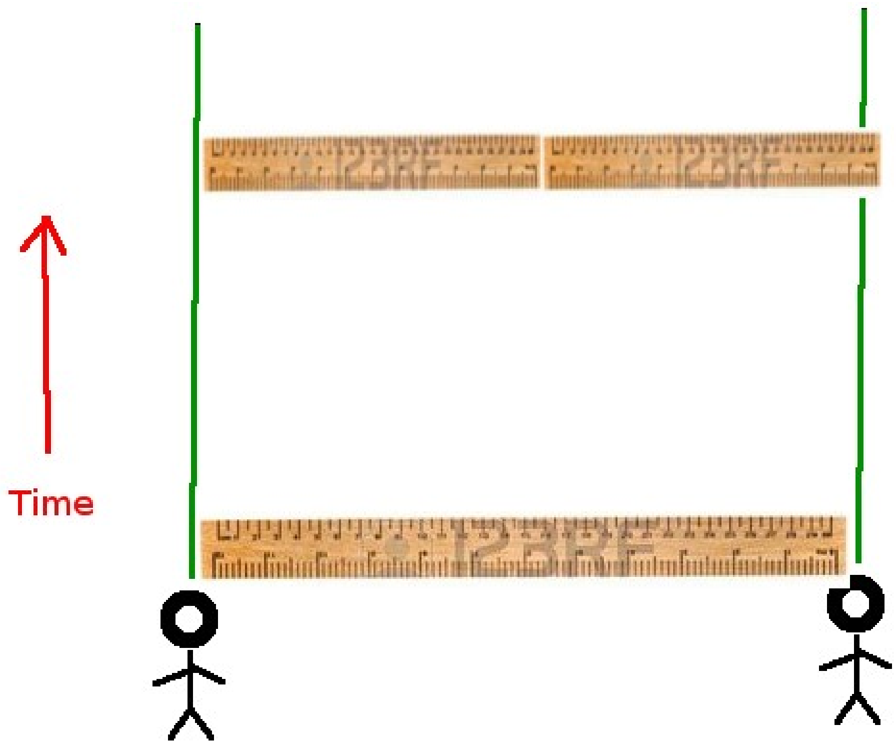
Gravity near earth is change in flow (amount) of time from place to place.

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.

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

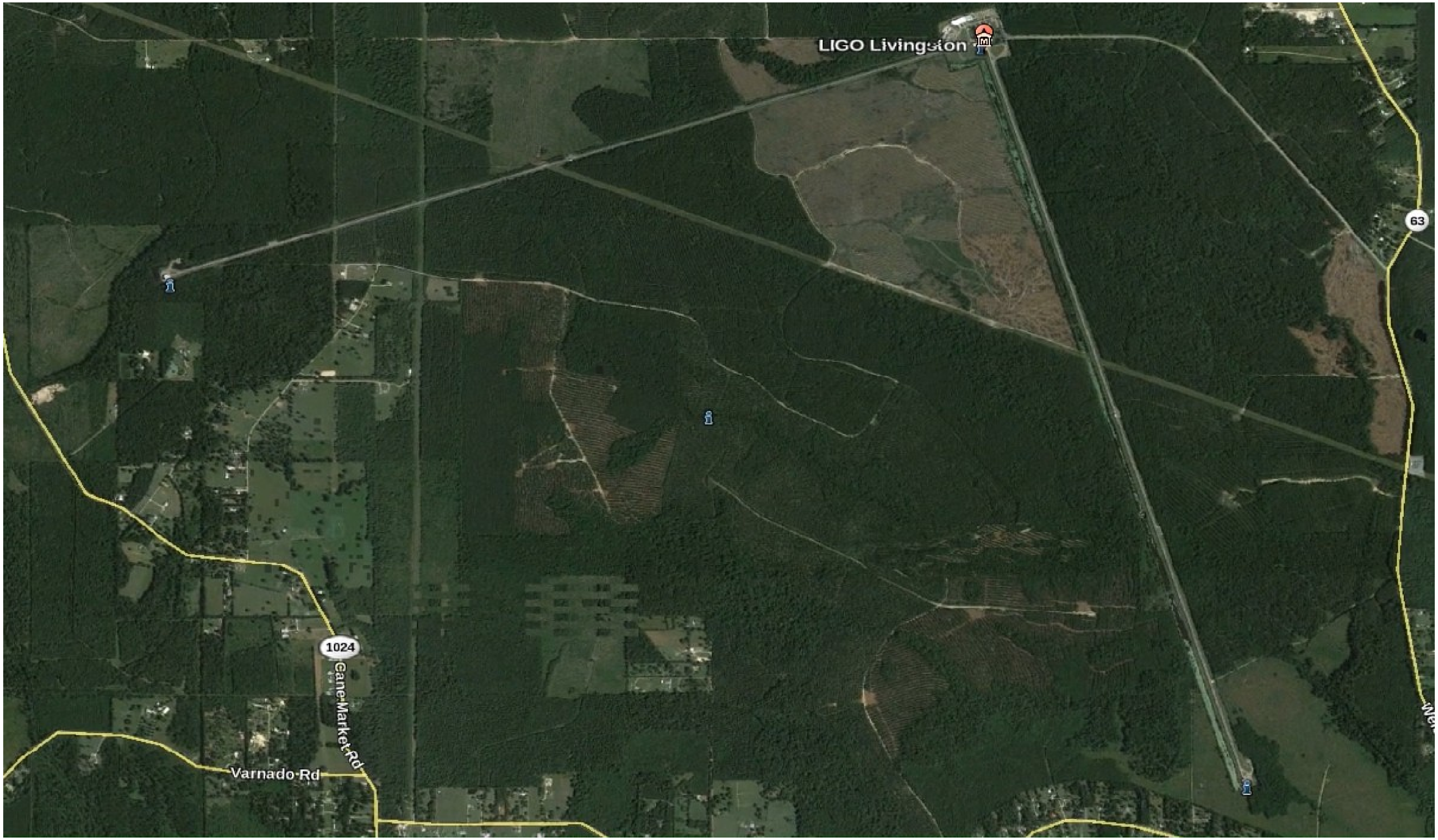


Changes in distance are perpendicular to the direction of travel of the wave.

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).

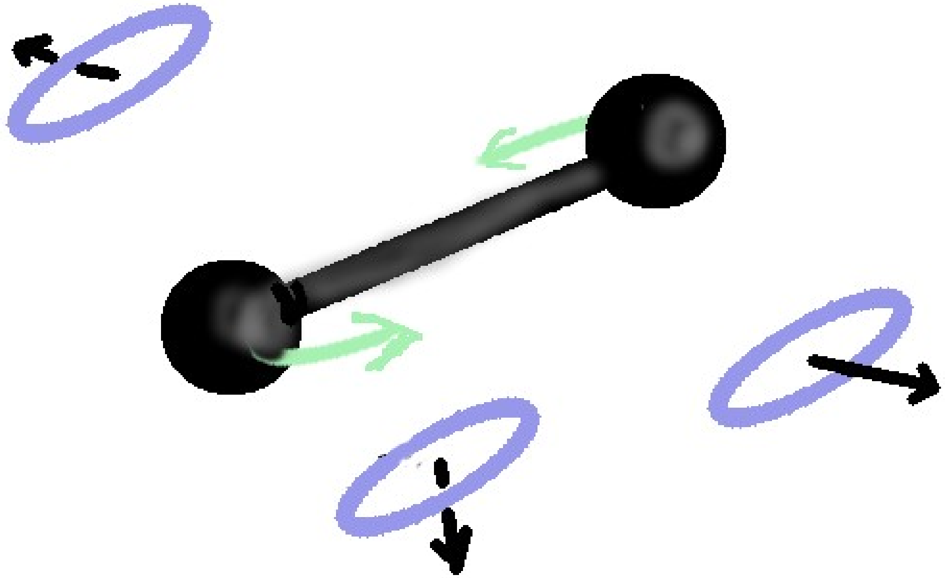
Effect of huge gravity wave on Louisiana detector h=0.05



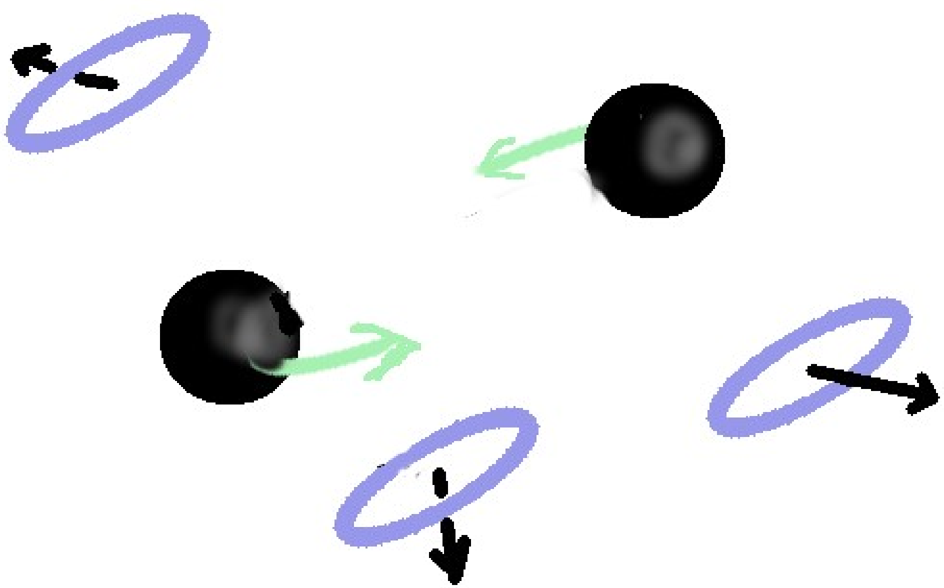
Arms are 4Km long.. Ends move about 200m as gravity wave comes by as seen by control room. But people at end see control room move.

Origin of gravitational waves.

Moving Masses



Orbiting Masses



Controversy for 50 years if orbits also emit waves.

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.

B) Directly measure distance changes.

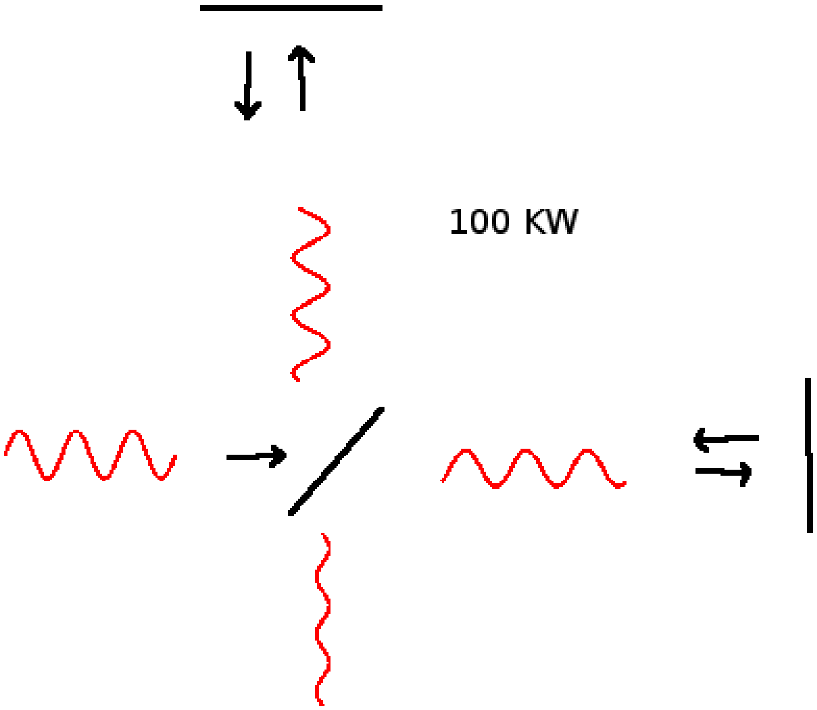
1980’s Ray Weiss (MIT), Kip Thorne(CalTech)
Ron Drever (Glasgow->Caltech)

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.

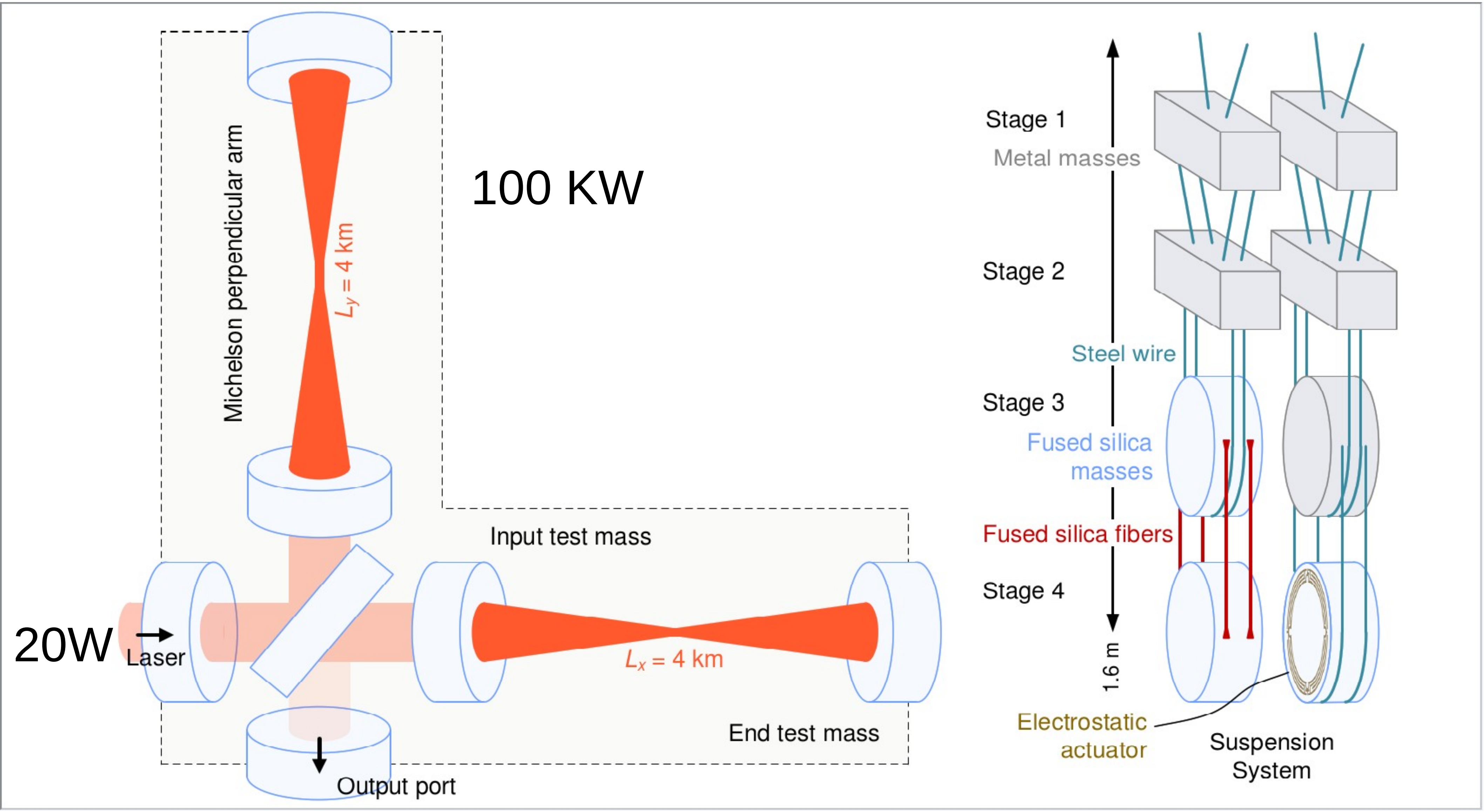
Measurement Noise

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.

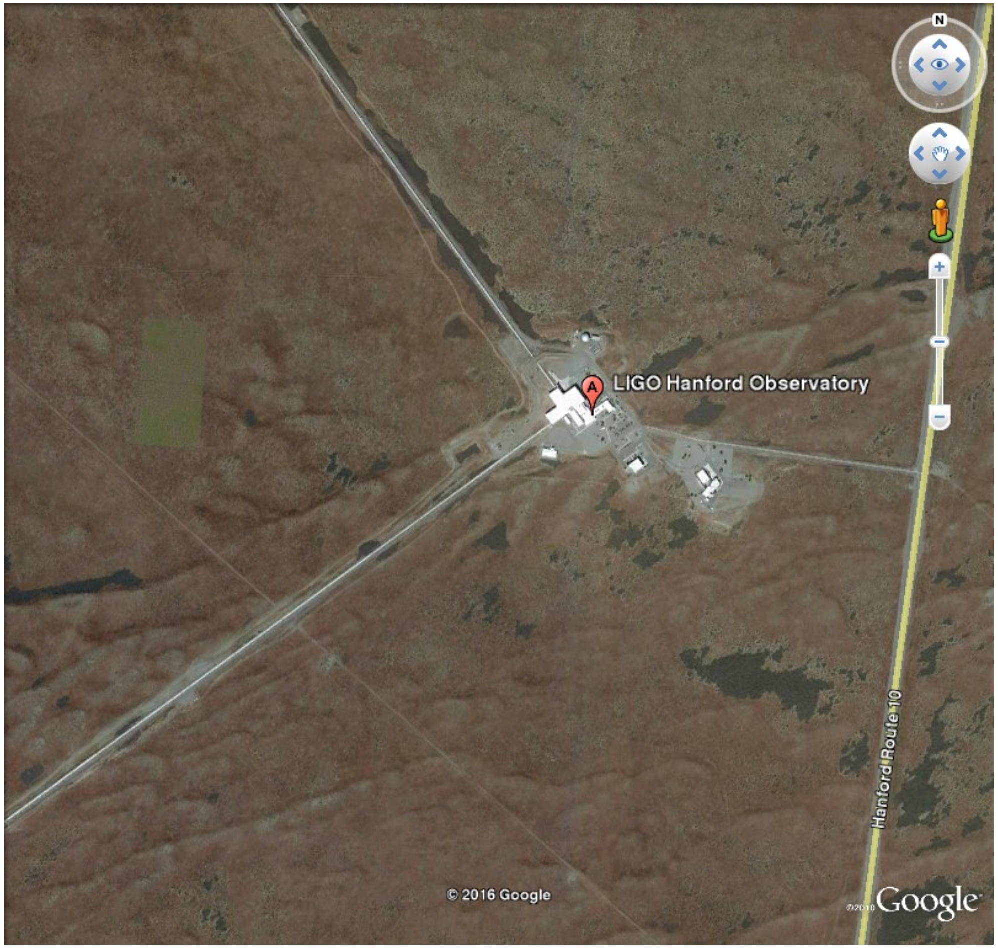
Light scattering

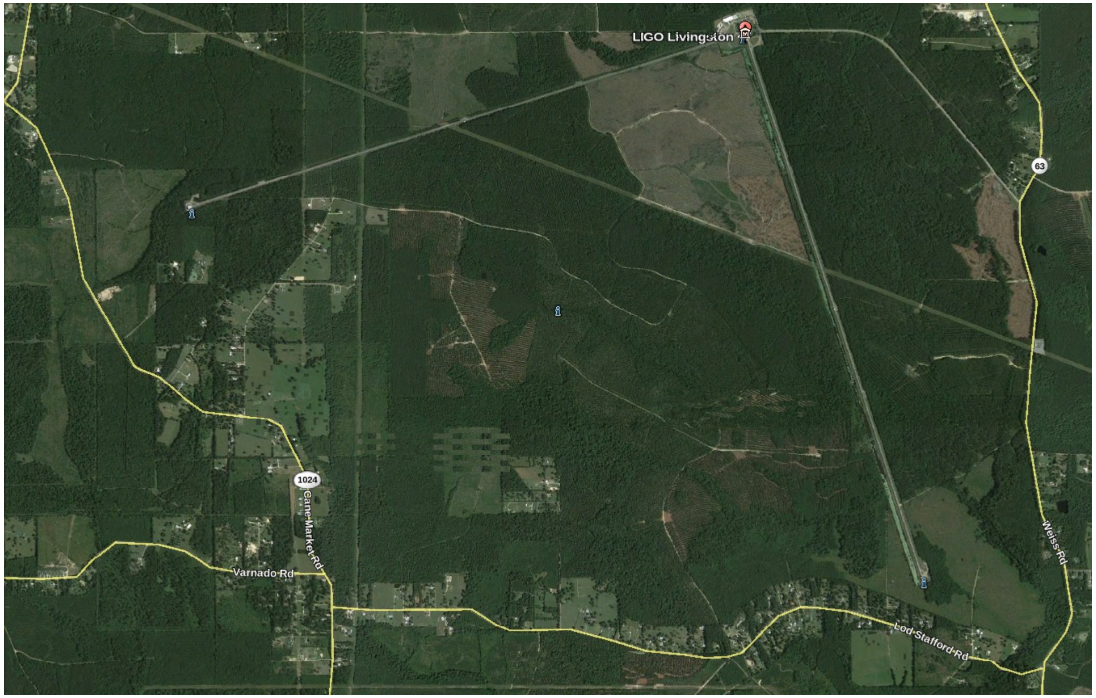
Vacuum-- less than a billionth of atmospheric.

Sketch of actual LIGO interferometer



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



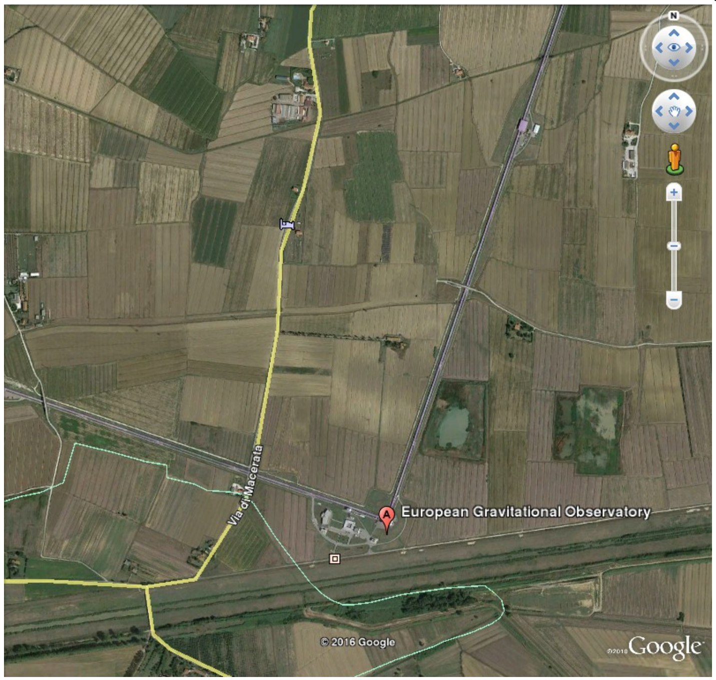


4km tubes. Vacuum 1 -10billionth of atm.
Concrete sheds (pot shots)

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 objcts

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.

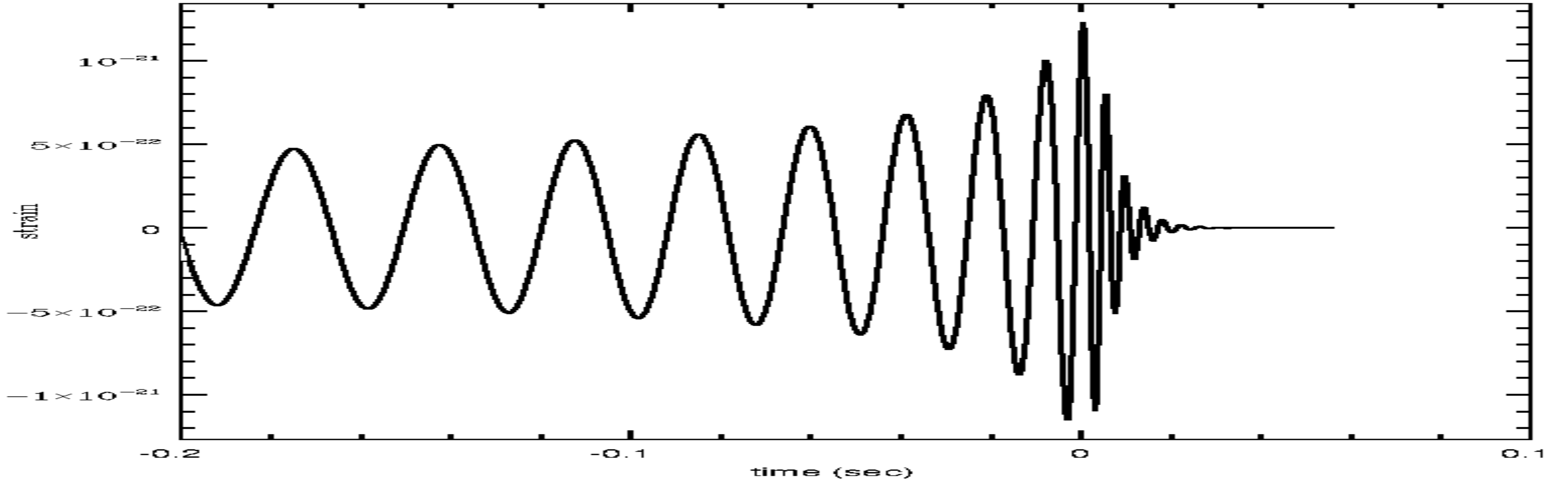
As detectors began to be planned, challenge of what to look for arose. Groups began to be formed and techniques developed.

Matt Choptuik, a student at UBC in 1980, and now faculty member, brought in key ideas into the field (eg Multigrid, Independent residual evaluation...).

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.

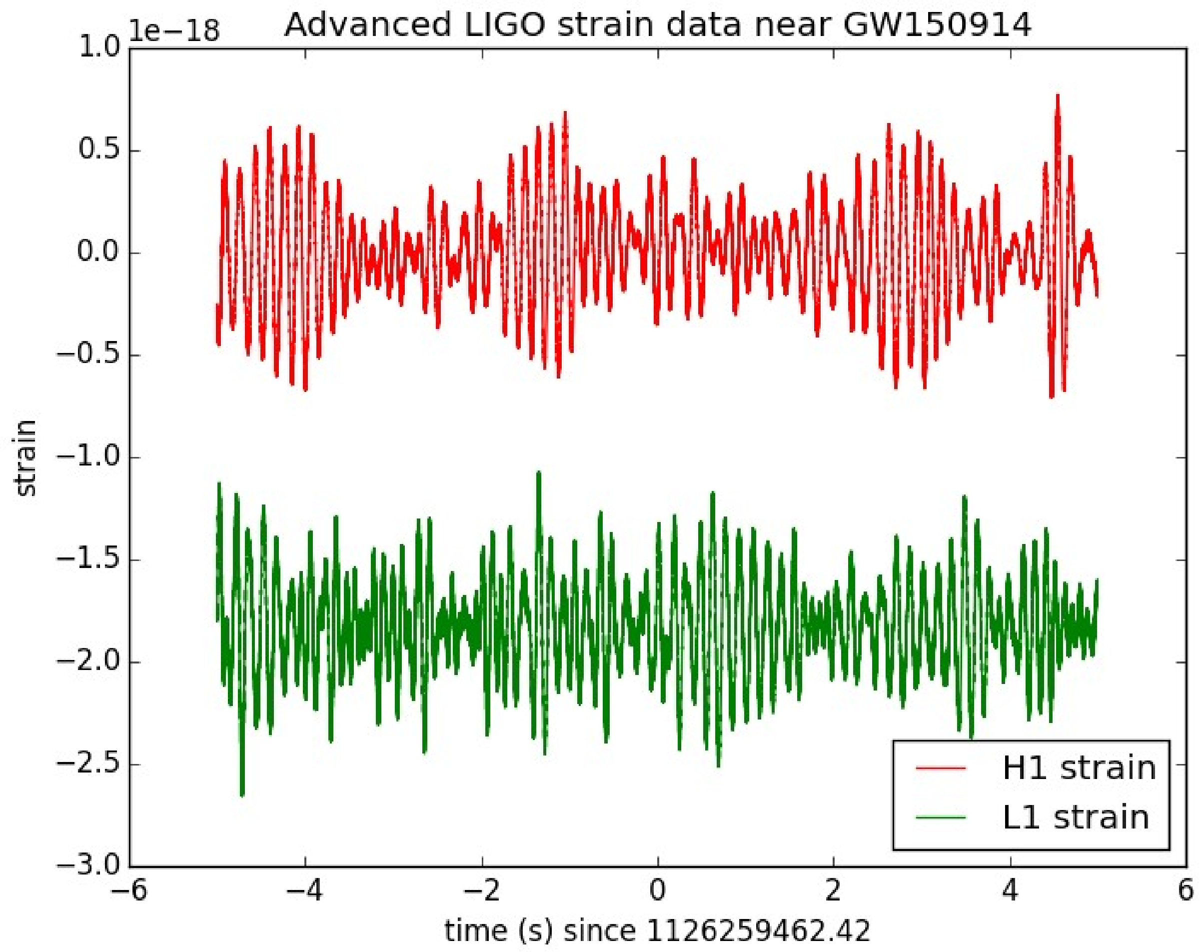


Sound

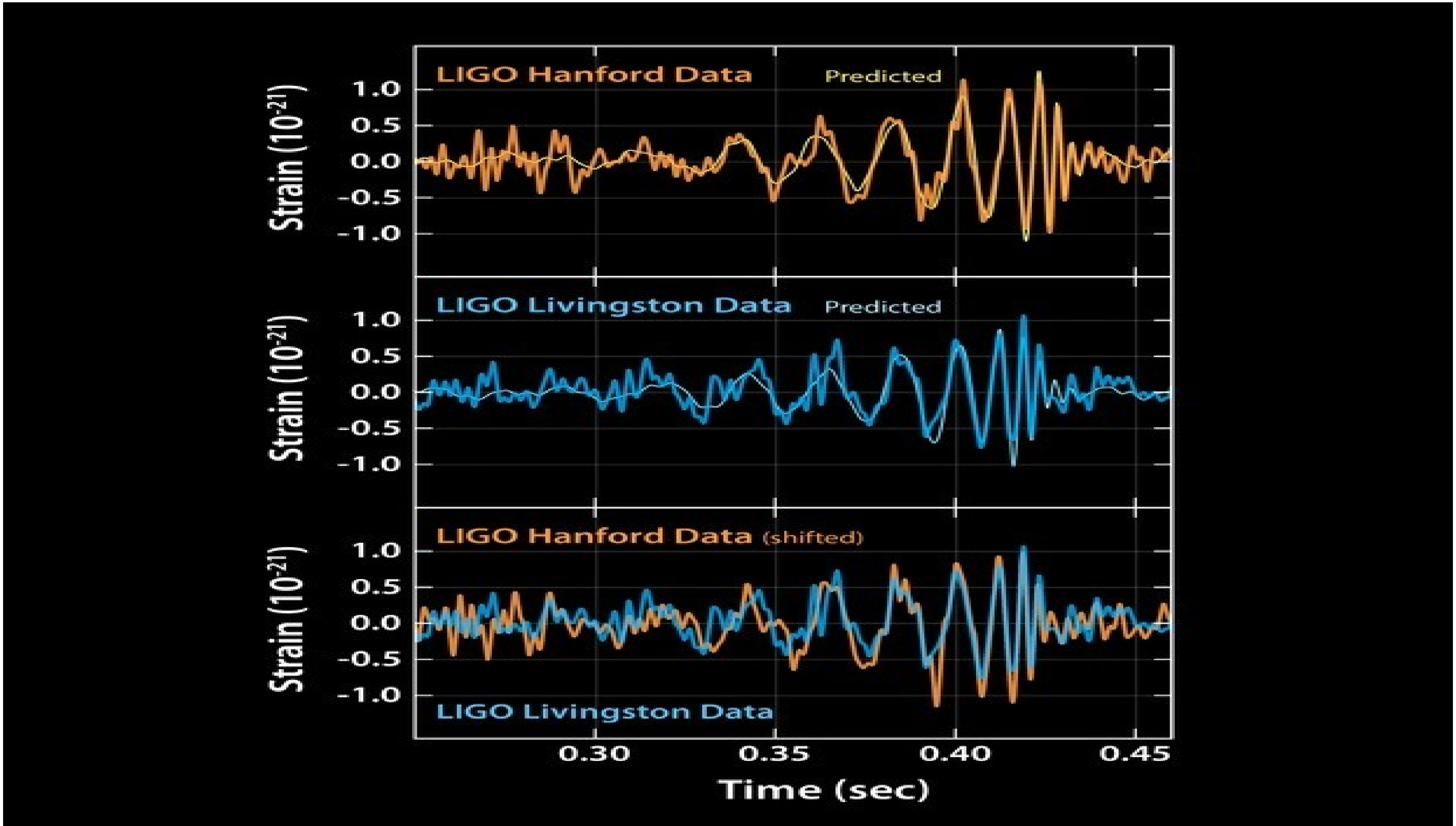
Sept. switched on Hanford and Louisiana detectors for engineering shakedown. Science run to start in Oct.

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.



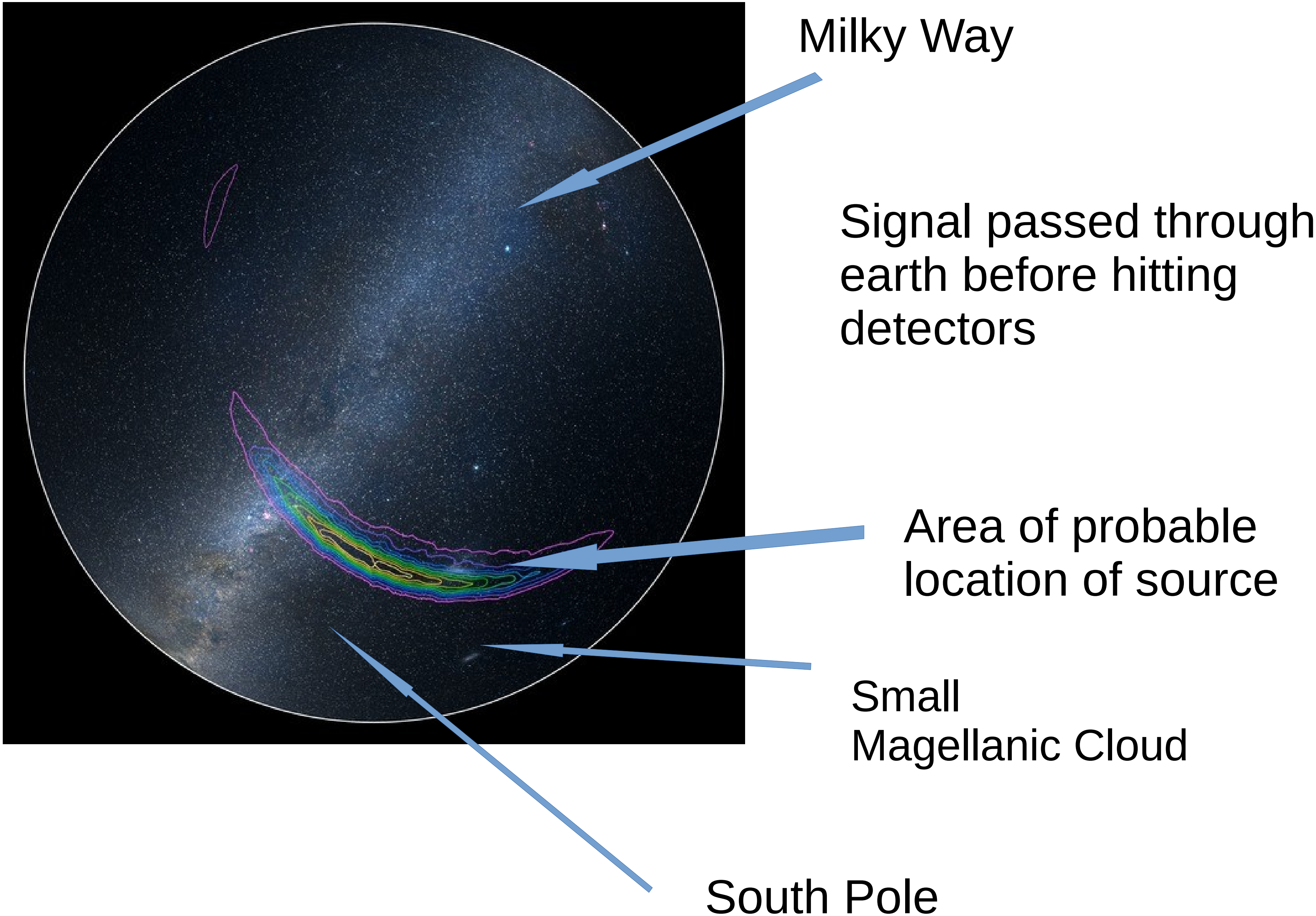
The timing of the data gives us the total mass. about 60sun
(The frequency is inversely proportional to the mass)
The detailed shape of the waveform gives relative masses
spins of the black holes (weakly) about 1.2

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)


Milky Way
Signal passed through earth before hitting detectors
Area of probable location of source
Small Magellanic Cloud
South Pole

In 1925 Heisenberg developed theory of quantum mechanics Uncertainty Principle. -- Cannot measure both position and momentum with arbitrary precision.

Momentum determines how body will move in the future.

Cannot measure a succession of positions of any object with arbitrary precision.

Heisenbeg Microscope: Shine light onto an atom-- scattering of light used to measure position, but that same scattering alters the momentum and velocity of the atom. Measurements always affect the object they are measuring.

from: slideplayer.info/slide/9084779/

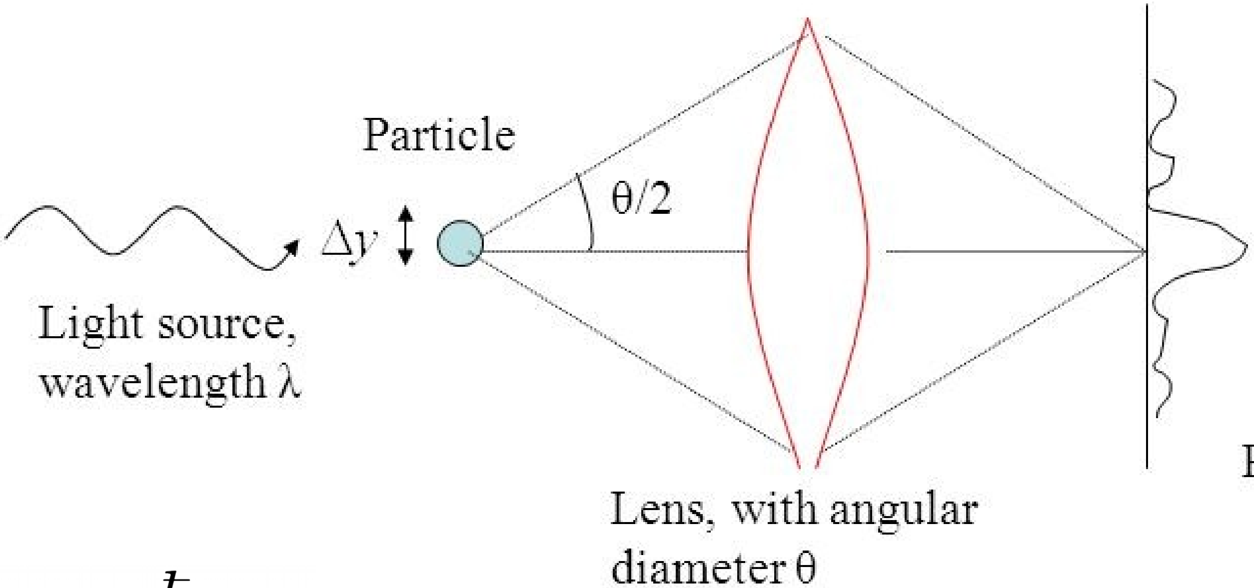
HEISENBERG MICROSCOPE AND THE UNCERTAINTY PRINCIPLE

(also called the Bohr microscope, but the thought experiment is mainly due to Heisenberg).

The microscope is an imaginary device to measure the position (y) and momentum (p) of a particle.

Heisenberg

Usually particle considered small (eg elecgtron)



Resolving power of lens:

$$\Delta y \geq \frac{\lambda}{\theta}$$

$$\Delta P = \frac{\hbar}{\lambda}\Delta\theta$$

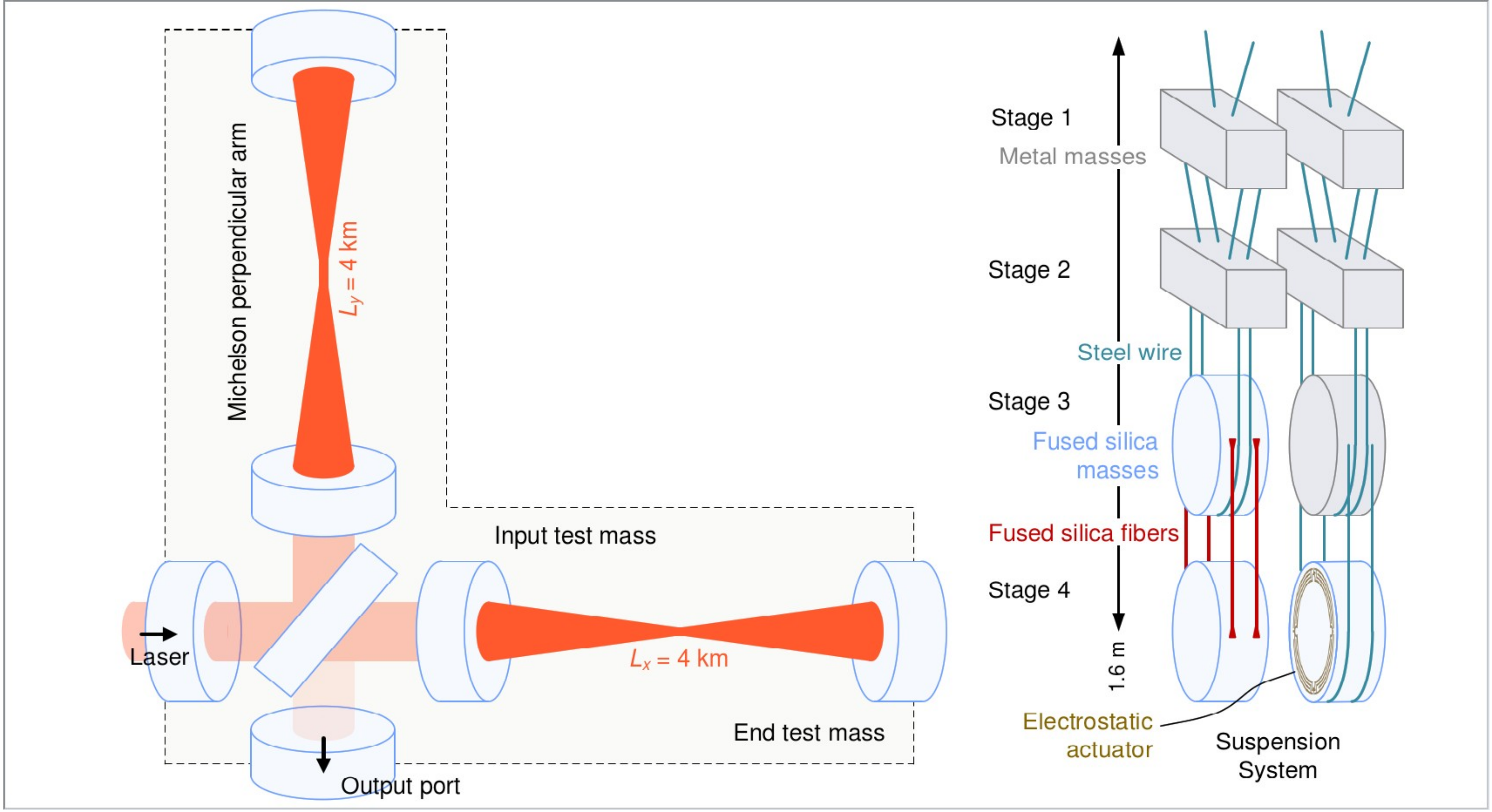
Ligo-- 40 kg mirrors, each almost 1m in diameter.

What does quantum mechanics have to do with these?

The quantum mechanics of these huge objects is a limit on ability to meaure.

Like Heisenberg microscope, using light to see where the mirrors are (or rather want the difference is in position of the two mirrors on the two arms.)

Accuracy of measurement of position of mirrors by light produces forces on the mirrors, which move them, making subsequent measurements of position uncertain.



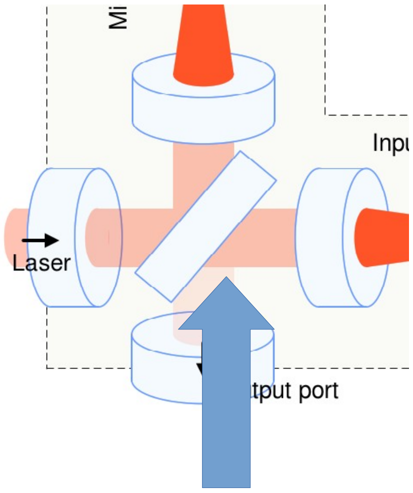
In operation, only tiny amount of light comes out to make sure both arms exactly the same length. Fluctuations in laser intensity do not come out the output but go back toward laser. (Common mode rejection).

Problem-- weak light detected as individual photons, giving noise

Shot noise-- Fundamentally a quantum phenomenon.

To reduce shot noise increase power in the interferometer (currently 100KW)

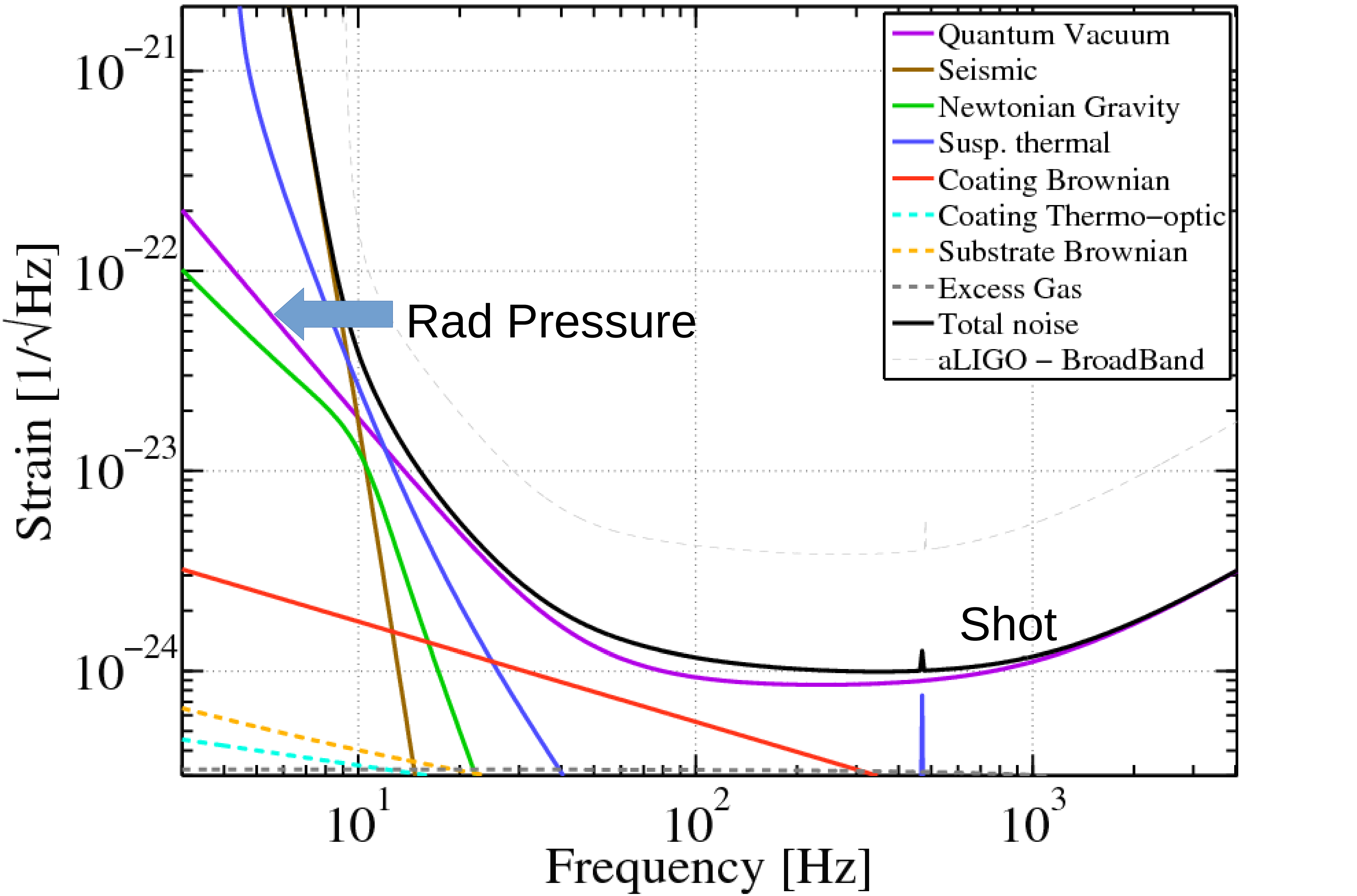
Problem-- quantum fluctuations in power (shot noise) exerts forces on the mirrors. -- From laser-- cancelled out.
But there is also light (or rather “no-light”-- vacuum) coming into the output port



Vacuum Fluctuations

Two effects:
Force on Mirrors in opposite directions (mimic grav wave)
Comes out output port and creates output shot noise.

Two effects are complimentary in Heisenberg sense.
(decrease one, increases other



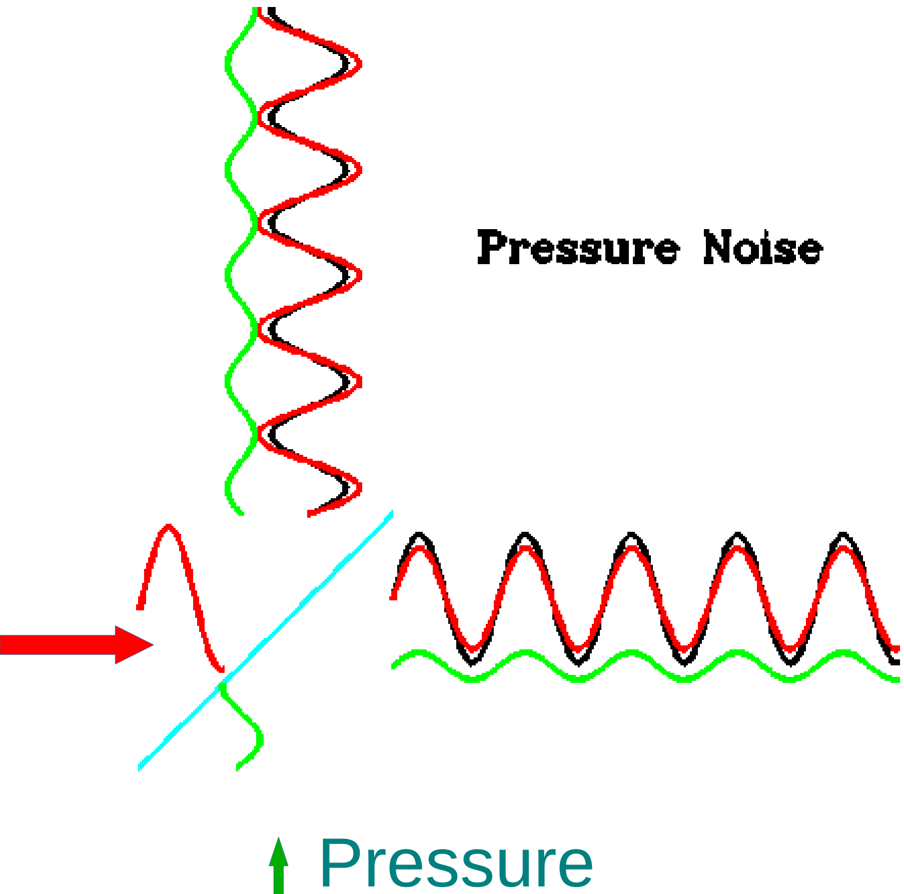
Quantum Noise dominates above the Seismic Threshold

Reduce quantum Noise?
a) Increase power (100KW-->MW?) -- problems with heating of mirrors.
b)Decreases shot noise, increases Radiation pressure noise

Vacuum Squeezing.

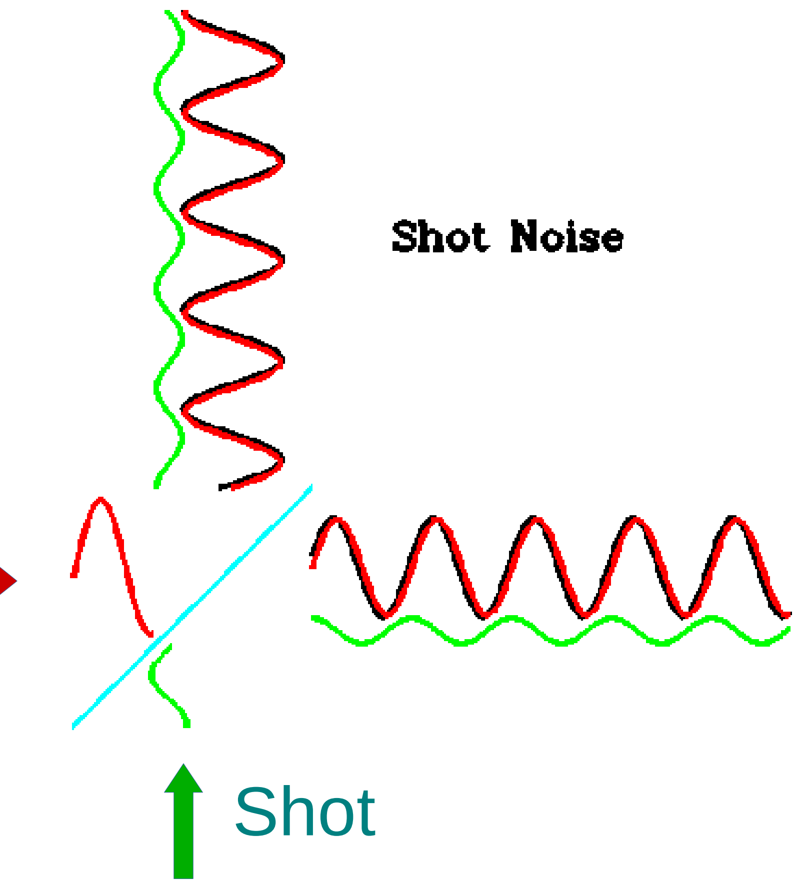
The noise comes from beating of vacuum fluctns with the laser power.(either at mirror or in output)

Decrease vacuum fluctuations!!
Cannot be the vacuum!



Pressure-- vacuum fluct “in phase” with signal. Gives greater/lesser pressure in two arms-- pushes mirrors by different amounts

Shot-- vac fluctn 90 degrees our of phase. Retards/advances main signal-- Looks as though one arm is longer than other



$$\Delta Shot \Delta Press = \hbar$$

Squeezing: Decrease fluctutations in one “phase” at expense of increasing in the other.

Vacuum state has fluctuations in both phases. One phase causes the radiation pressure fluctuations, the other phase causes the shot noise fluctuations.

If rad pressure noise is larger, make the vacuum fluctns smaller for the phase that is aligned with the phase of the light in the interferometer. This increases the shot noise. Do this until both are about equal noise sources.

If shot noise is larger, make vacuum fluctns smaller for the part that is 90 out of phase with the internal light. Makes radiatio pressure larger.

Standard quantum limit.

If two noise source are equal, because both come from the same vacuum fluctuations, one can choose a squeezing which decreases both in their effect on the measurement of the gravity wave signal.

Increases the noise in the total measurement of position of the masses, but decreases the noise's effect on the gravity wave signal.

Currently can “squeeze” by about a factor of 3. Ie, make ratio of noises change by about factor of 3. -- 3 times the sensitivity, increase distance we can see a given signal by 3, and the “volume” of space by 27.

Will be implimented in next upgrade of Ligo/Virgo (eg by time India detector will be online.)

Gravitational Radiation has been seen directly on earth

Source is from two orbiting black holes about 1000000 light years away (about 1/10 of the “radius”of observable universe away)-- Black holes exist! and of a mass unexpected.

Gravity waves come from strong region (fluctuations of distances at source about 10%)

Quantum Mechanics applies even to objects of mass 40Kg, and size of meters.

Heisenberg's Microscope has been shown to work even on such massive bodies.

Keep watching this space.
Exciting times ahead.