

NOTE: Resources used in this module were revised by the Quantum for All Project from Perimeter Institute (PI), Institute for Quantum Computing (IQC) and LIGO. Links on final slide.

Interferometers

Split a beam of light into two paths, recombines them, and uses the resulting interference pattern to extract precise measurements of physical changes—displacement, surface shape, or material properties

Historical Perspective

The Michelson-Morley experiment (1887) used an interferometer which compared the path length for light moving in two perpendicular directions. The experiment was an attempt to detect the velocity of Earth with respect to luminiferous ether (the medium proposed to carry light waves).

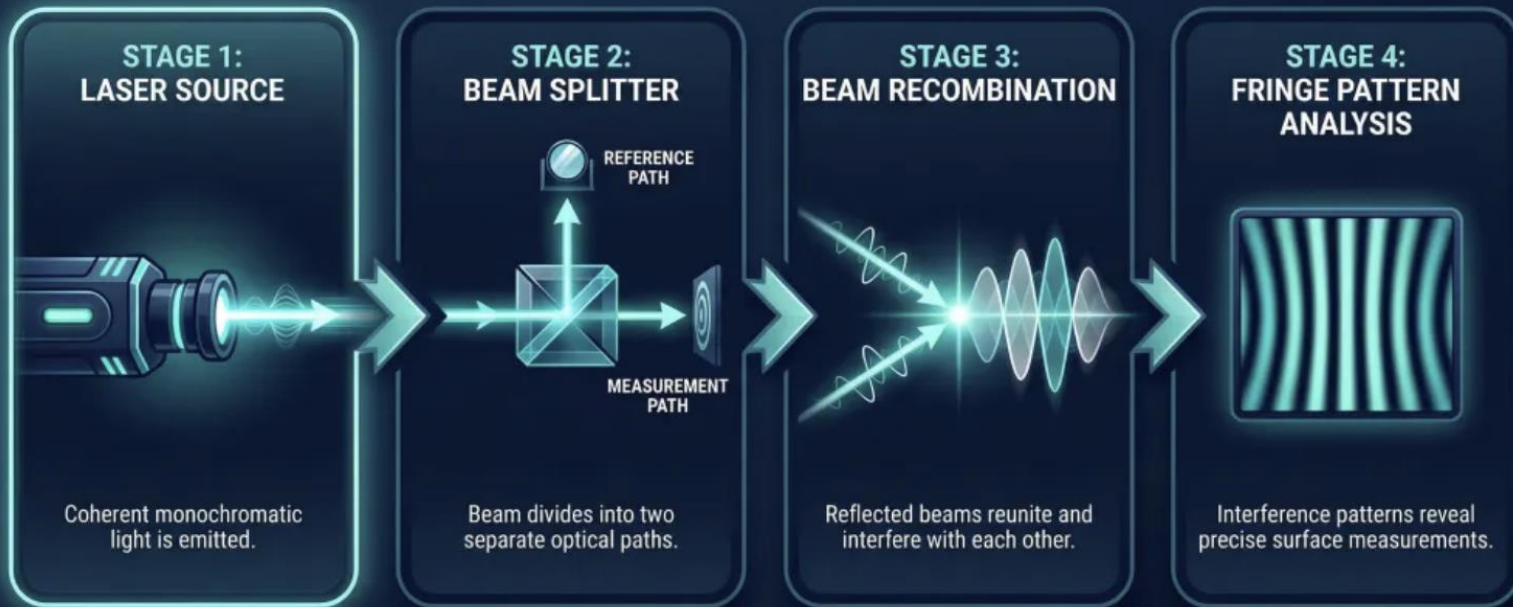
Michelson reasoned that if the speed of light were constant with respect to the ether through which the Earth was moving, the motion could be detected by comparing the speed of light in the direction of the Earth's motion and the speed of light at right angles to the Earth's motion.

No difference was found.

This ultimately led to the proposal by Einstein (1905) that the speed of light is a universal constant.

Relevance of Interferometers

- **Detect displacements and surface irregularities at sub-nanometer or picometer scales using light interference.
- **EXTREME accuracy, non-contact operation, real-time feedback, broad applications
 - Measure gravitational waves: detect space-time ripples from colliding black holes and neutron stars.
 - High resolution imaging: Event Horizon Telescope and European Observatory combine signals to resolve black hole event horizons and exoplanet atmospheres.
 - Atom Interferometry: manipulate matter-waves from ultra cold atoms to test quantum gravity, redefine precision gravity sensors
 - Quantum-Enhanced Sensing: uses entangled photon states to surpass classical noise limits which allows for imaging and testing without degradation.
 - Semiconductor Manufacturing: non-contact surface profiling, layer thickness measurements, and wafer alignment



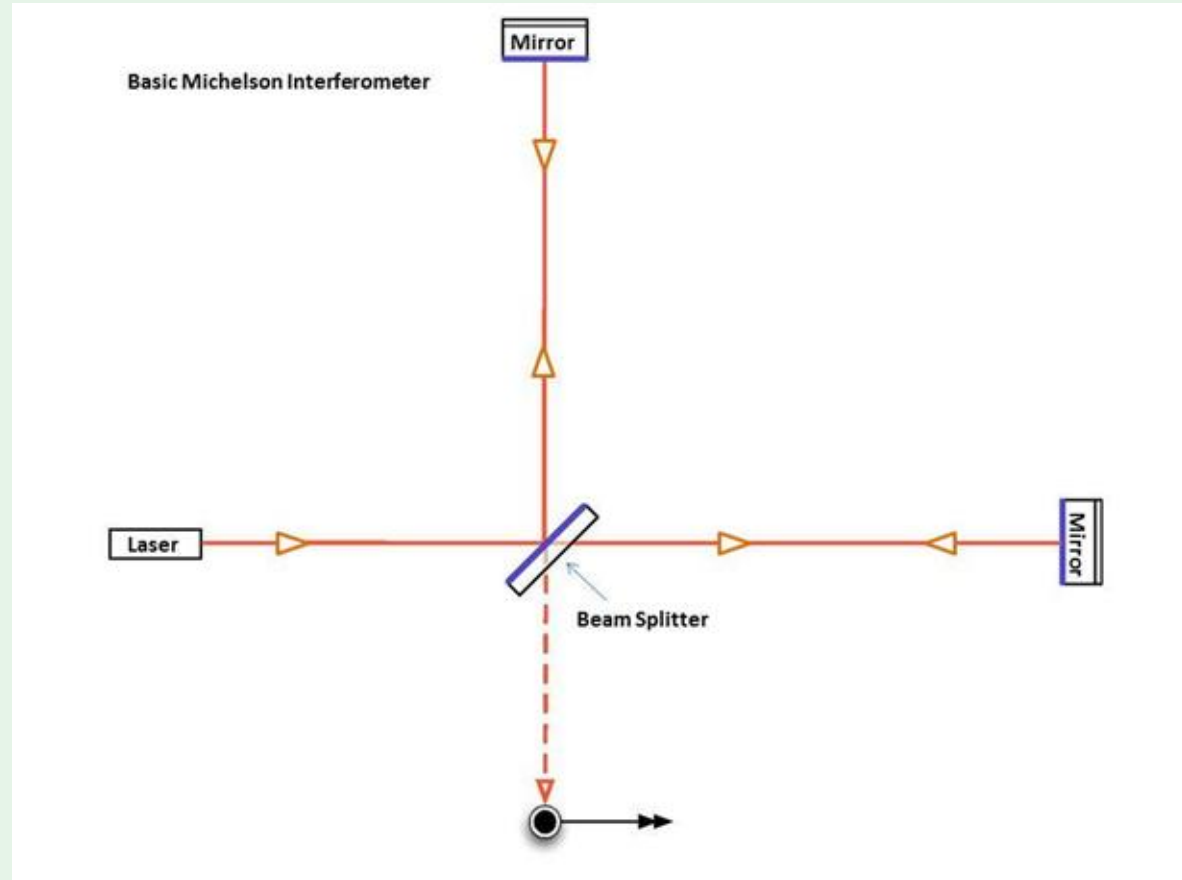
Interferometry Process Flow Diagram – Precision Measurement Technology.

Interfere-o-meter

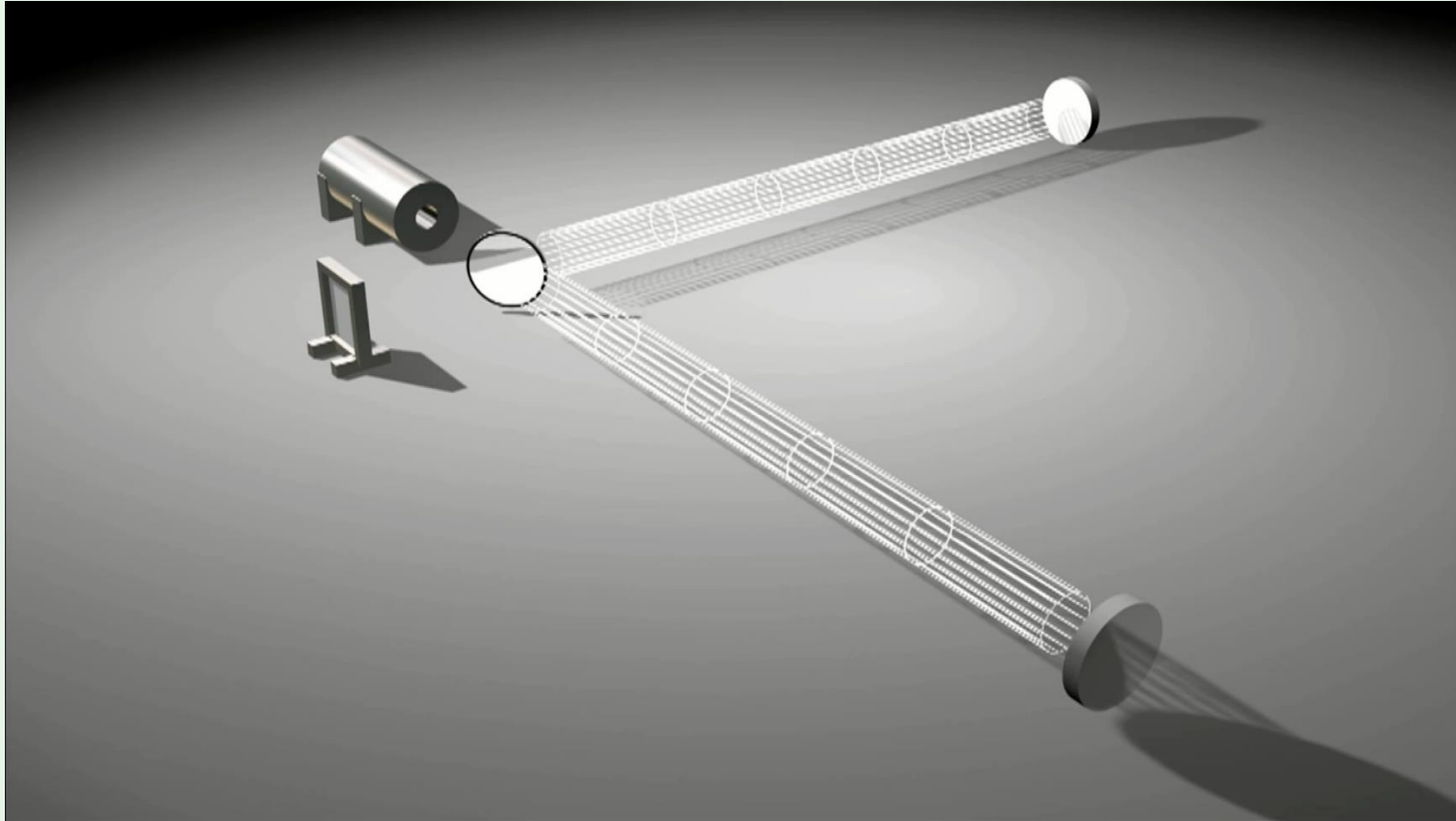
- Interferometers merge two or more sources of light to create an interference pattern that can be measured and analyzed.
- They are used to make very small measurements that cannot be measured any other way.
- LIGO's interferometers are designed to measure a distance of $1/10,000^{\text{th}}$ the width of a proton.
- In late 1960s, they were identified as a natural fit for detection of gravitational wave strain on space-time.
- Different types, but all superimpose beams of light to generate interference pattern.

Interferometer Basics

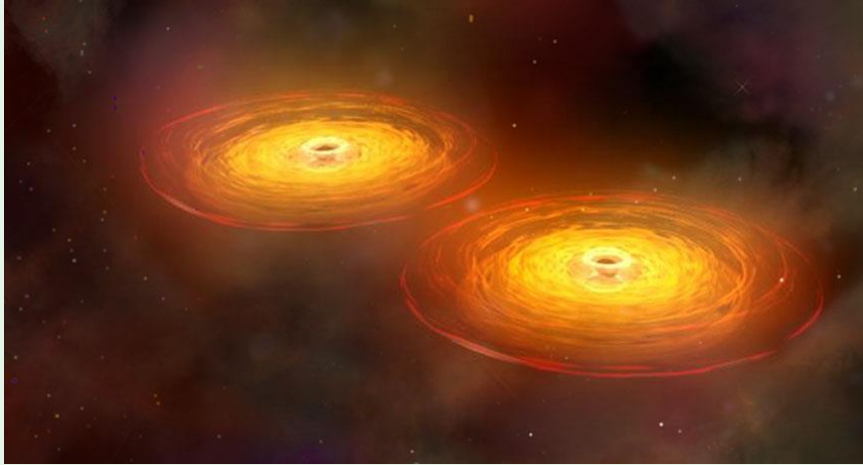
Waves travel different paths and then come back together. The two paths are different in some aspect and that difference is shown in the final addition of the waves



LIGO Video Narrated

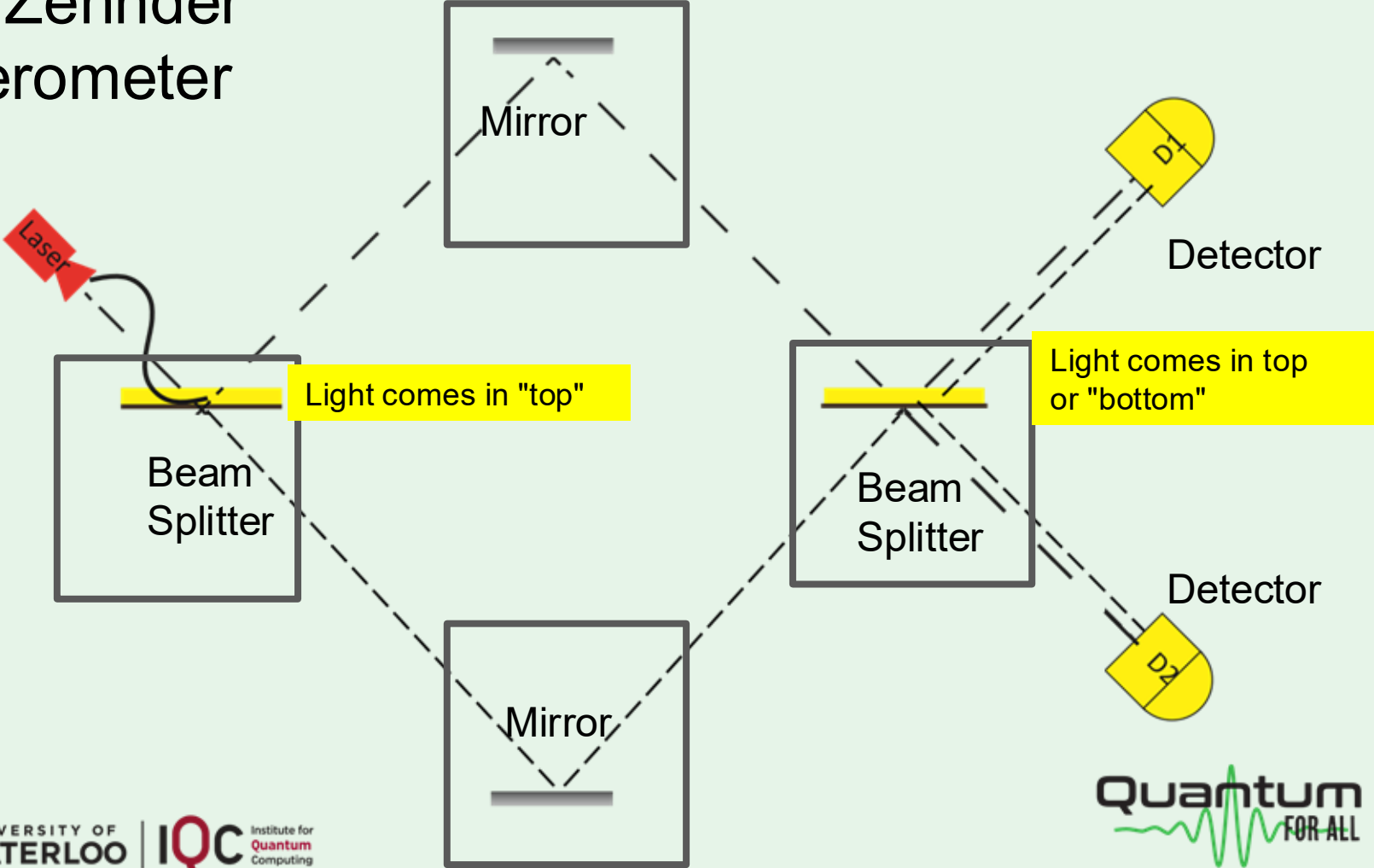


Is there a connection between black holes colliding and quantum?



An interferometer helps us investigate this dual nature of light at places like LIGO.

Mach Zehnder Interferometer



Michelson Interferometer

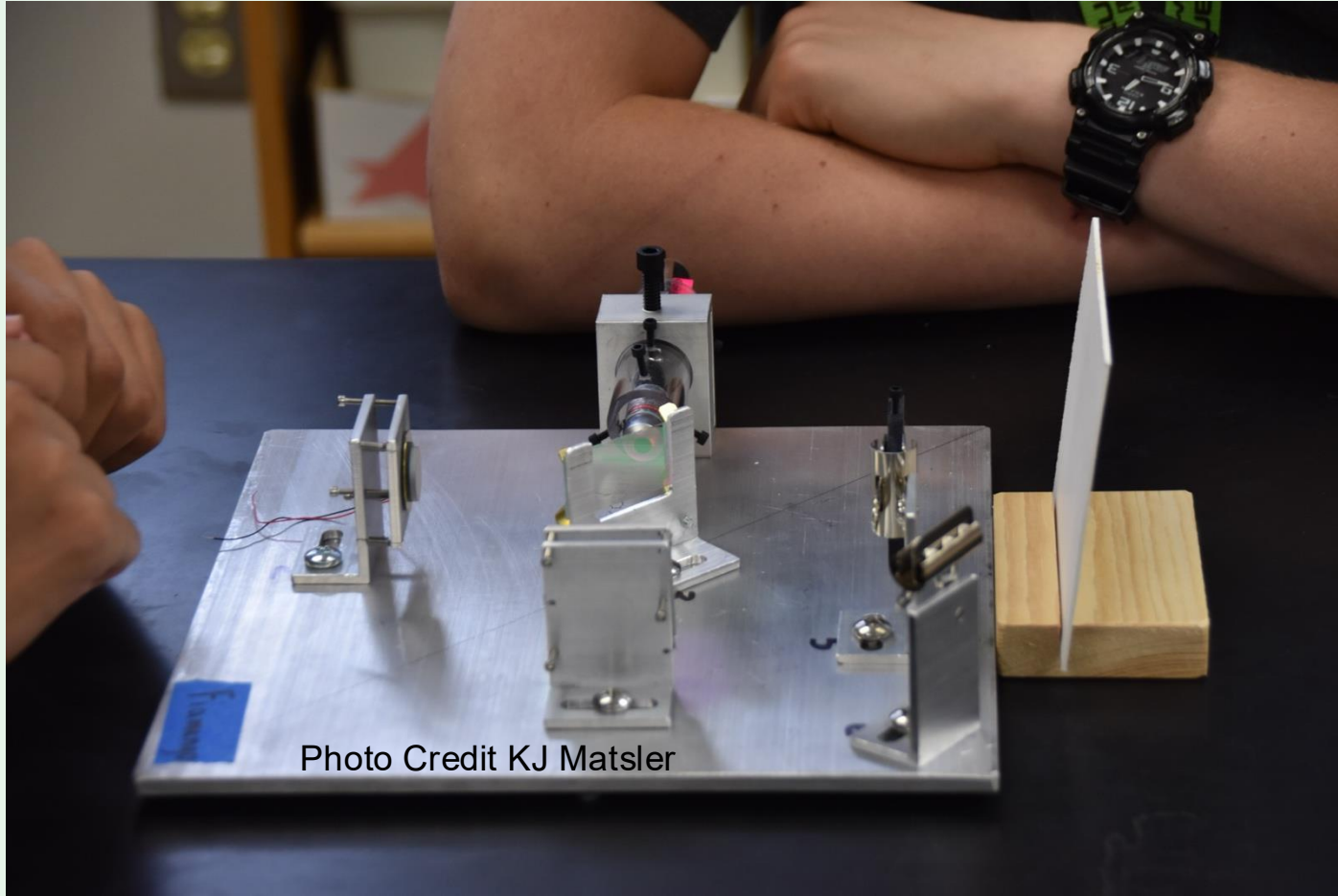


Photo Credit KJ Matsler

Michelson Interferometer

Assembly Instructions https://5e970ec1-6e6d-4ef8-a9aa-d2bd17a24495.usrfiles.com/ugd/5e970e_6c28e449ffeb40c68e67b012e5fd97bc.pdf

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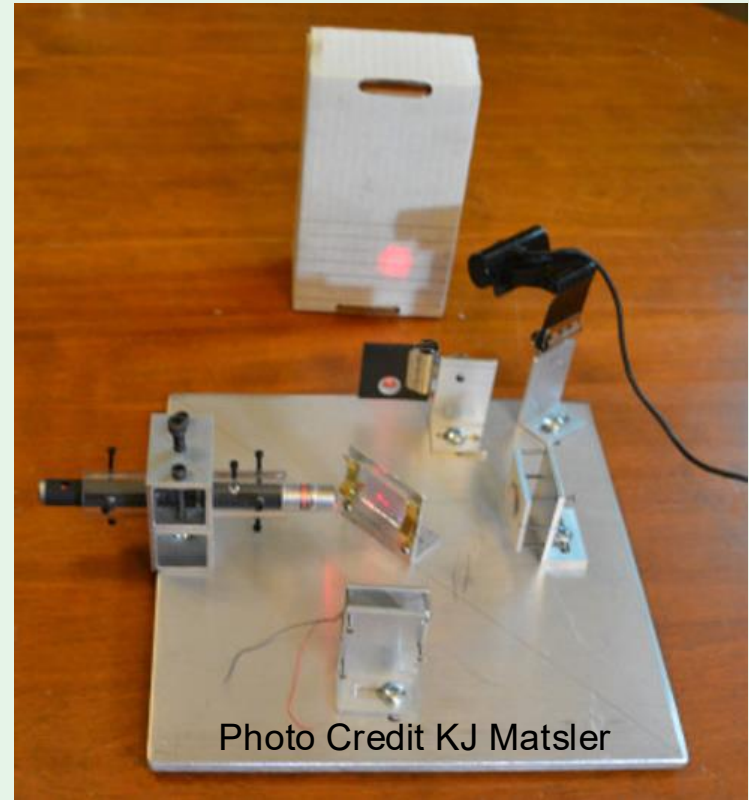


Photo Credit KJ Matsler

Mach-Zehnder

- Light travels path once
- Two outputs
- Two beam splitters
- Separation of arms large and accessible
- Two beam splitters (one split, one recombine)
- Alignment has wider view of field
- Path length change needs delay line or compensator
- Paths can be independently controlled
- Can place objects in 1 path without affecting the other
- Versatile

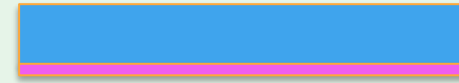
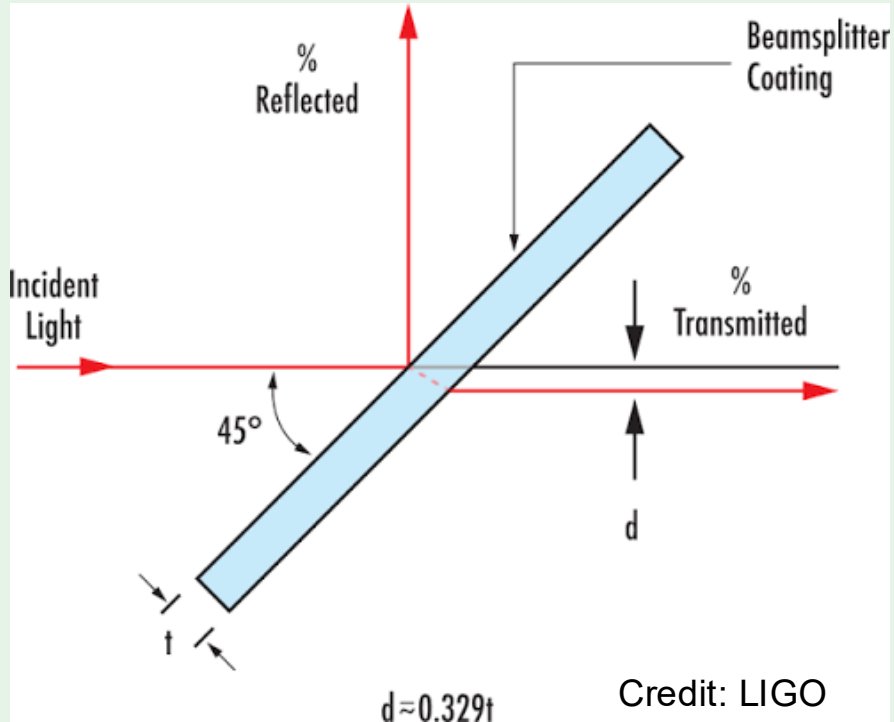
Michelson

- Light travels path more than once
- Single Output
- One beam splitter
- Separation of arms limited (arms share the beam splitter region)
- Classically 1 fixed and 1 movable mirror
- Alignment generally more critical and narrow field
- Easy to adjust path-length
- Simple and sensitive device

Applications

- Astronomy
- Fiber optics
- Engineering metrology
- Optical metrology
- Oceanography
- Seismology
- Quantum mechanics
- Nuclear and particle physics
- Refractive index
- Detecting surface irregularities
- Spectroscopy
- Plasma physics
- Remote sensing
- Optometry (nanometer precision)
- Mechanical stress/strain

Beamsplitter



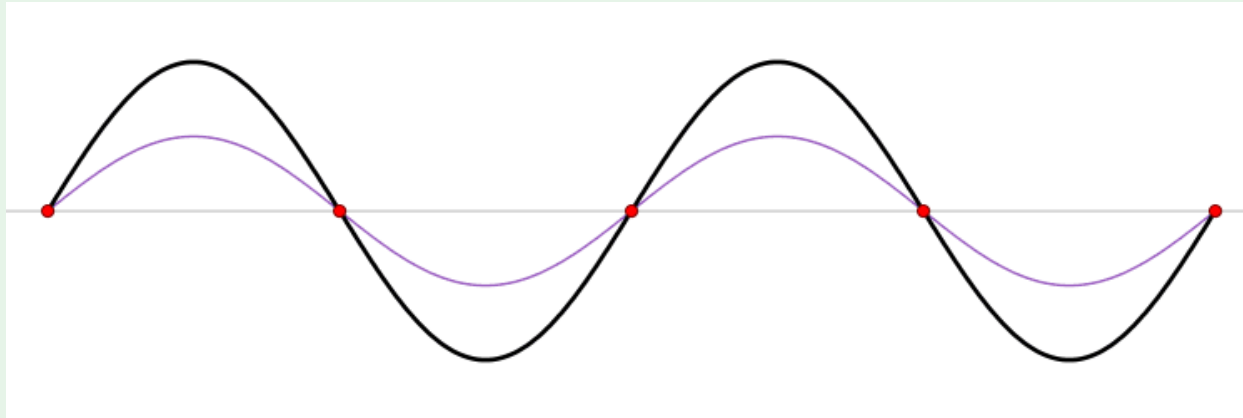
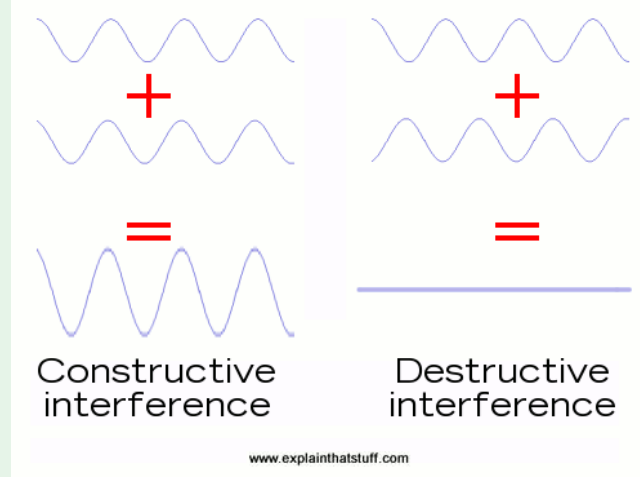
Glass

Coating

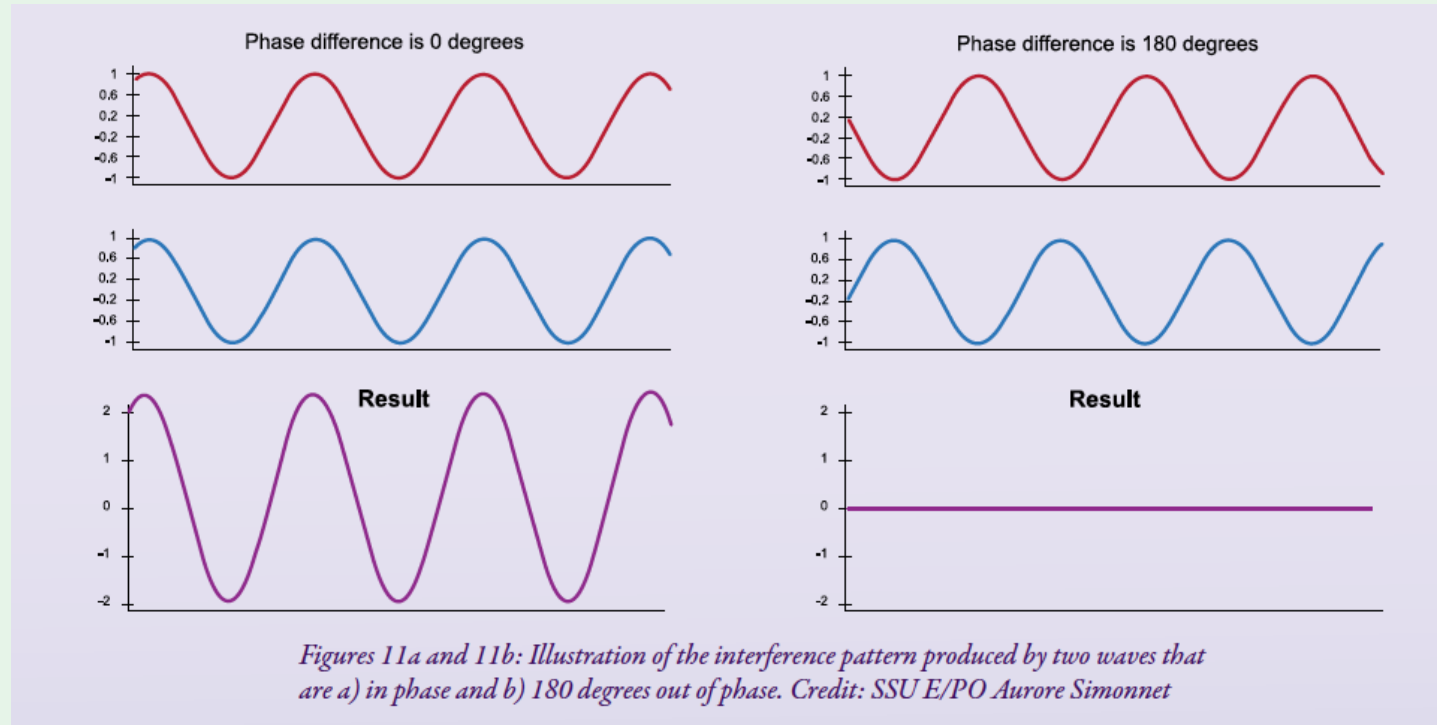
$$n_{air} < n_{coating} < n_{glass}$$

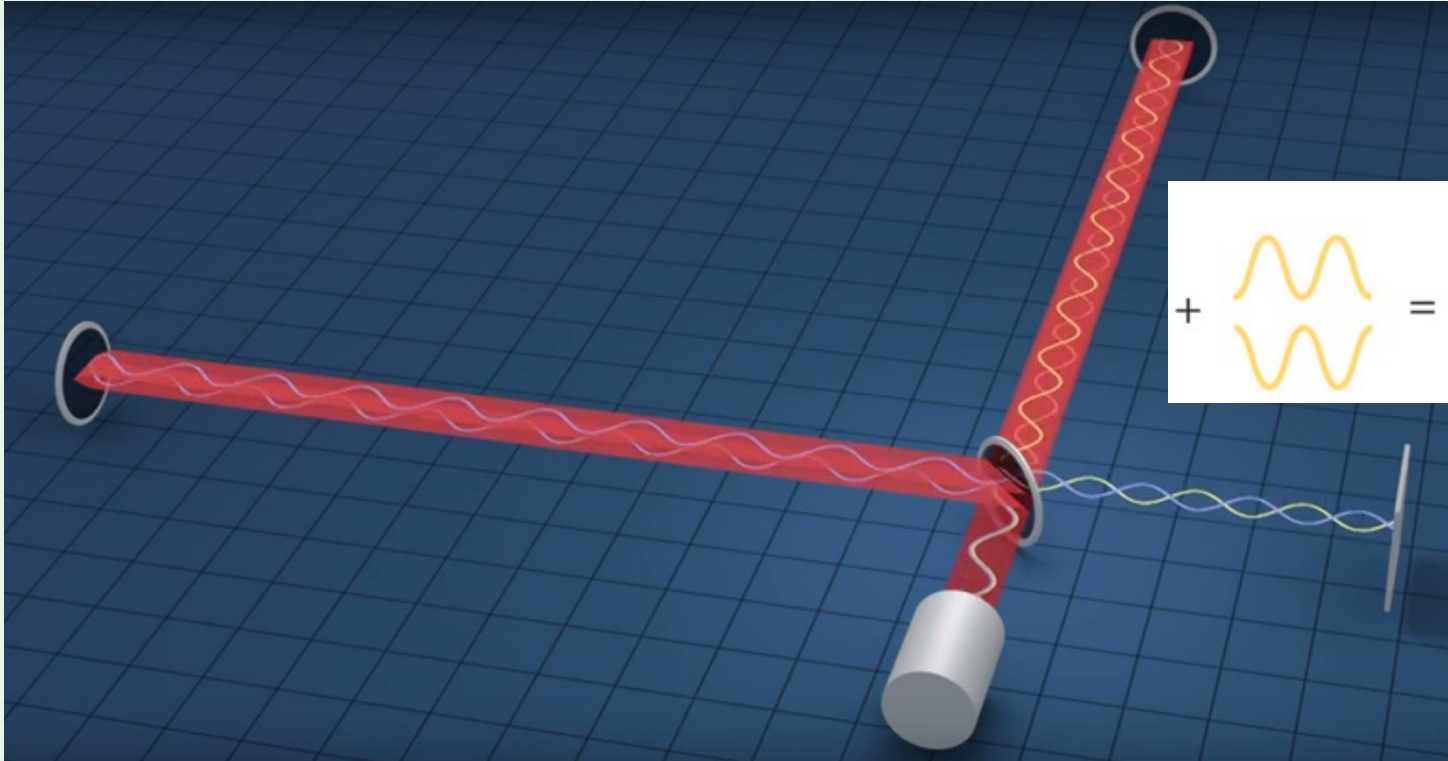
TN: What is interference?

- Constructive Interference
- Destructive Interference
- Standing waves
- Light vs no light
- White band vs colored band



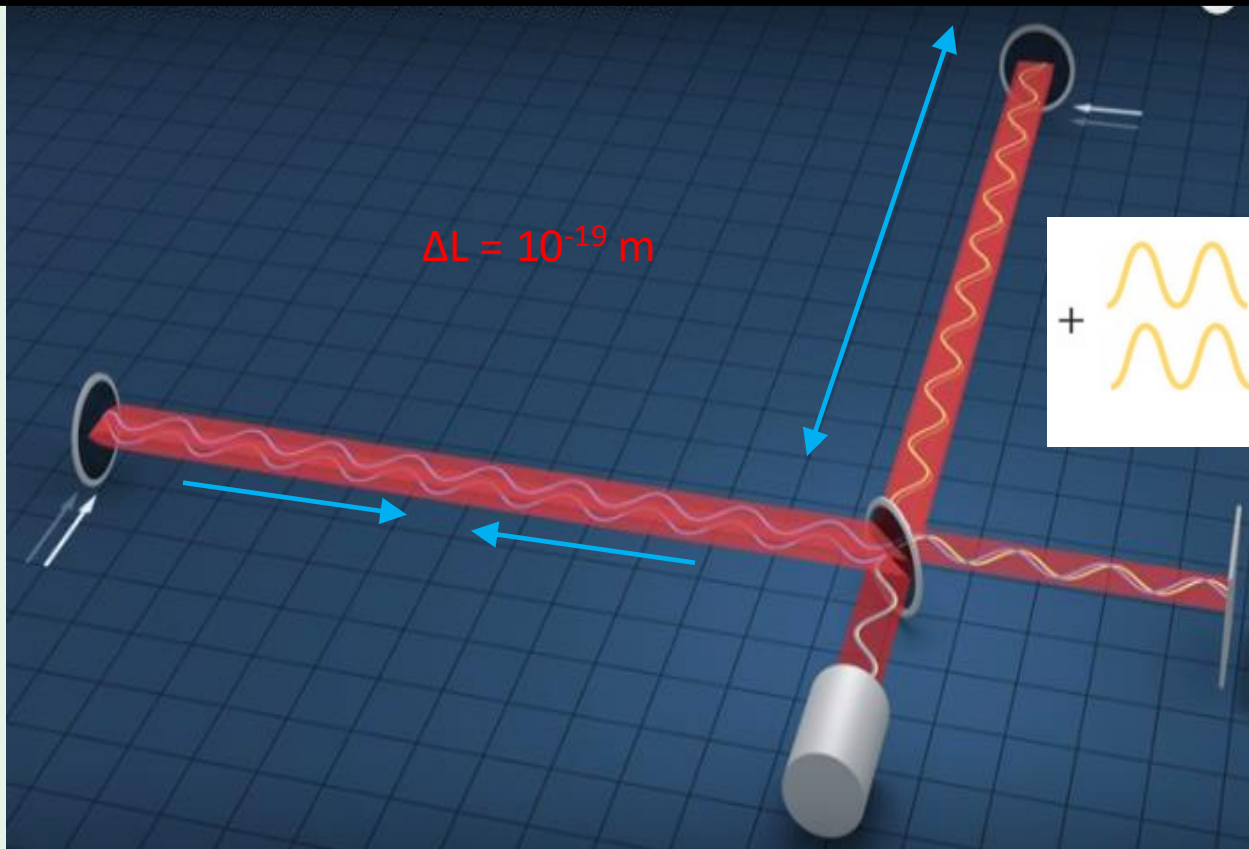
Constructive and destructive interference





$$+ \begin{array}{c} \text{~~~~~} \\ \text{~~~~~} \\ \text{~~~~~} \end{array} = \text{—————}$$

Credit: LIGO



Credit: LIGO

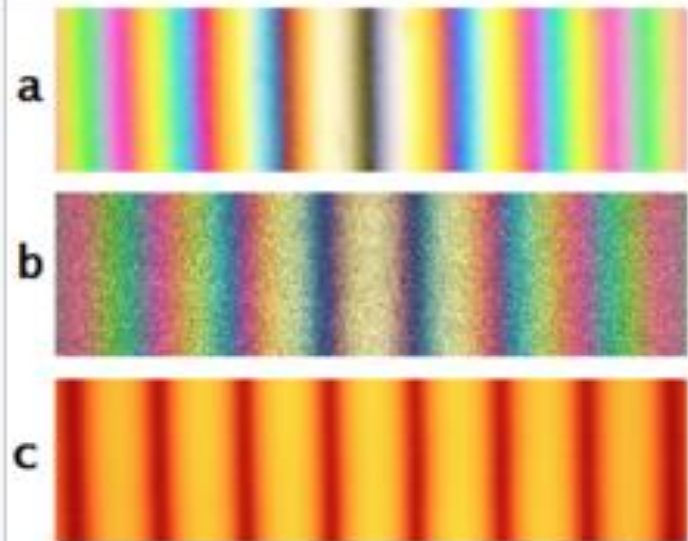


Figure 3. Colored and monochromatic fringes in a Michelson interferometer: (a) White light fringes where the two beams differ in the number of phase inversions; (b) White light fringes where the two beams have experienced the same number of phase inversions; (c) Fringe pattern using monochromatic light (sodium D lines)

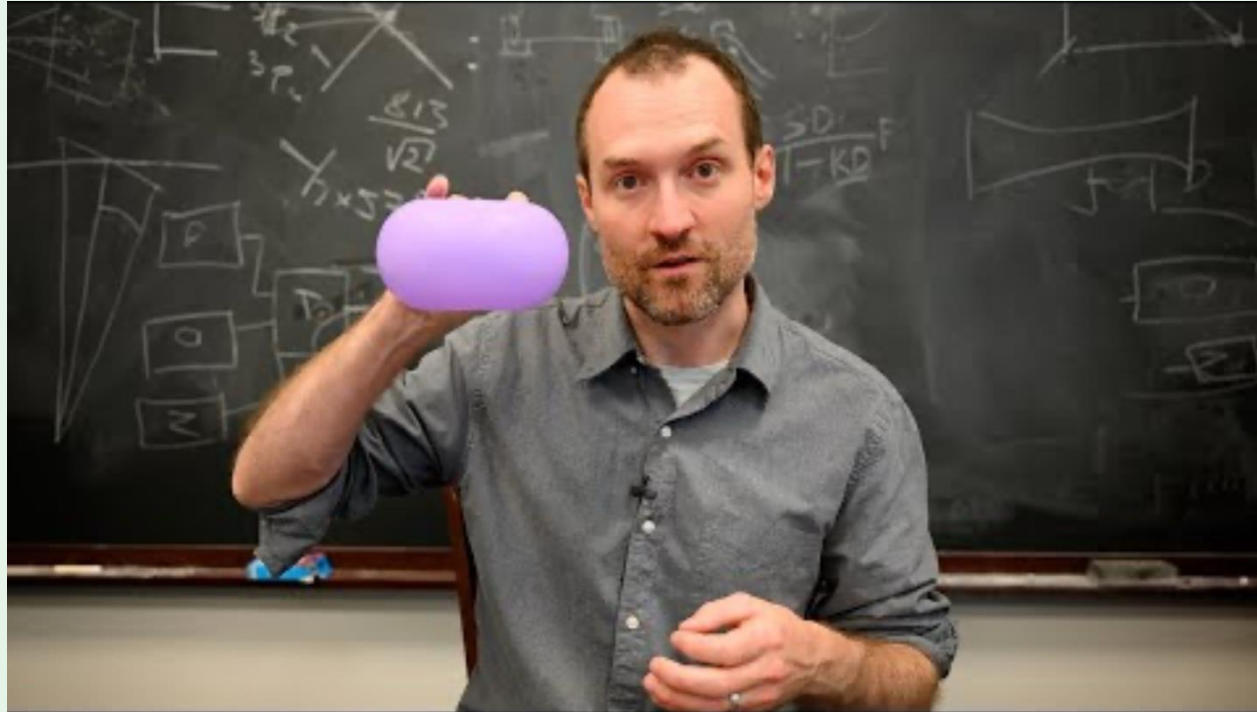


PI Guest Speaker: Detection via the Interferometer



Current Method of Detection: Quantum Squeezing

CalTech

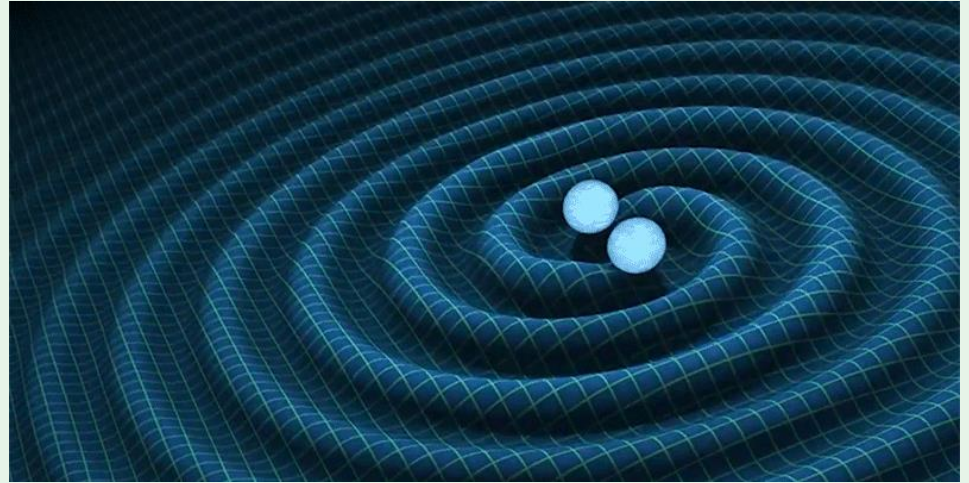


Black Holes and Gravitational Waves

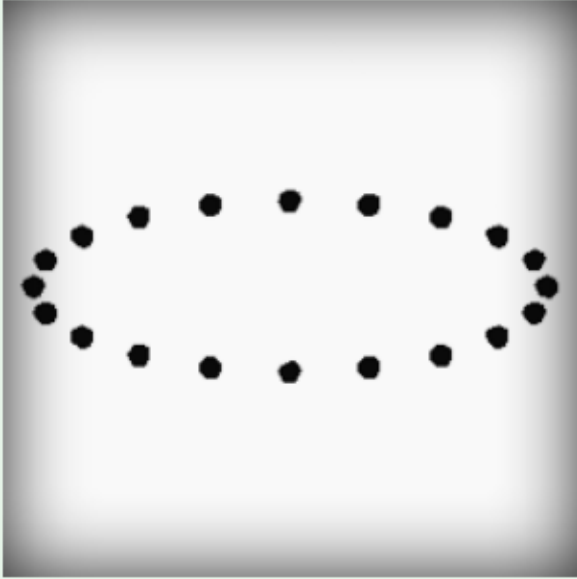
Accelerating Masses Produce Ripples



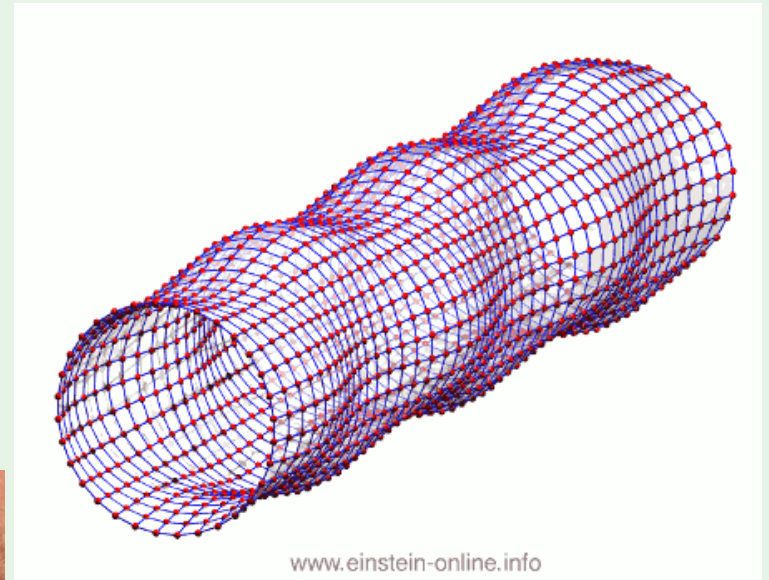
<https://perimeterinstitute.ca/>



Space is actually “waving”

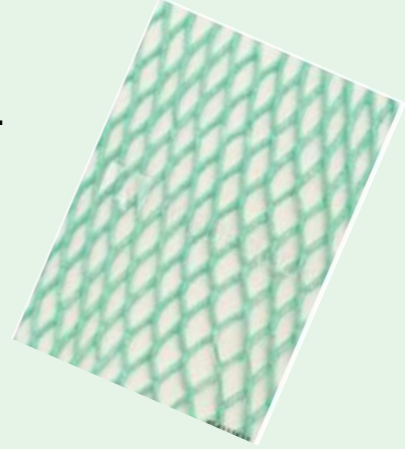


A wave produced in space can be the result of a gravity wave resulting from a star collision.



Gravitational Waves in Space

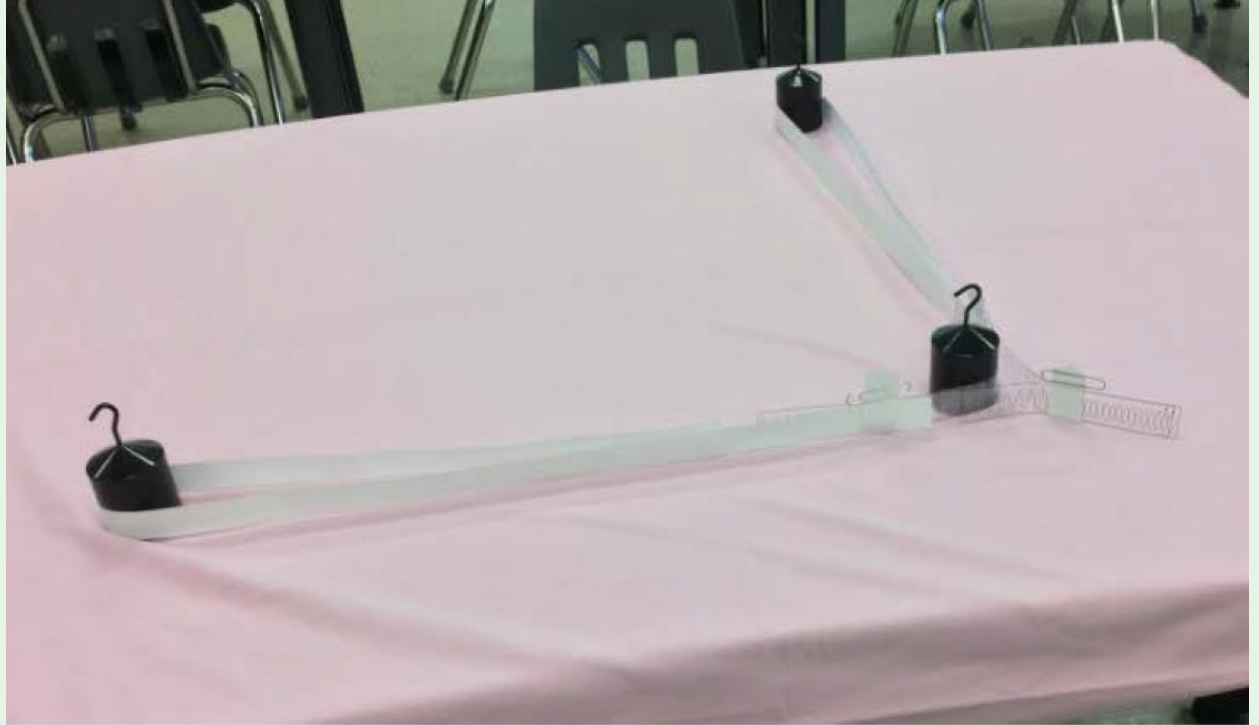
- Hold the mesh vertically with your left and right hands at the ends. Predict what will happen when the mesh is stretched by moving your hands farther apart. Discuss how this models a gravitational wave passing through space.
- Use the transparencies to simulate LIGO. Place ARM 1 over the top of ARM 2 aligning the right-hand edges. What type of interference is represented? Place ARM 1 Stretched over the top of the transparency Arm 2 Compressed aligning the right-hand edges. What type of interference is represented?
- Watch the LIGO animation of gravitational wave emitted by two orbiting neutron stars: <https://www.ligo.caltech.edu/video/BNS-merge>
- Stretch the lycra and place a ball in the center. Lift the ball quickly and record your observations.

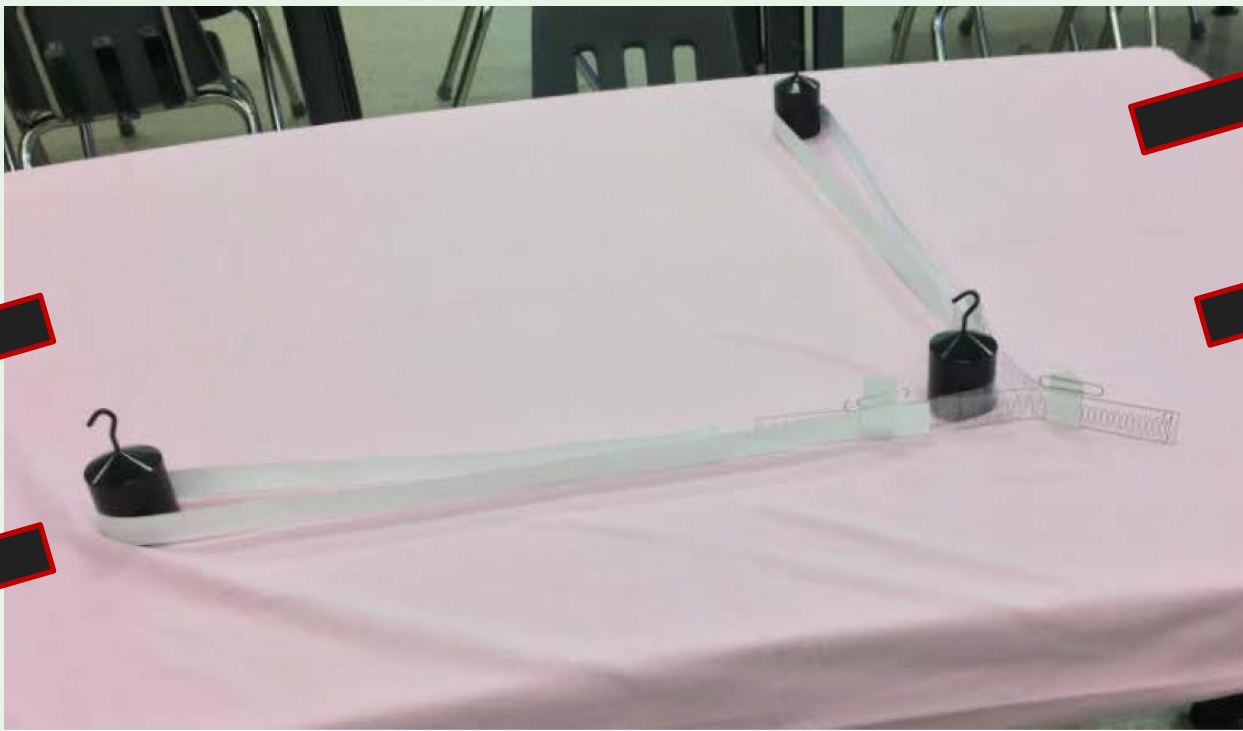


Hands-on

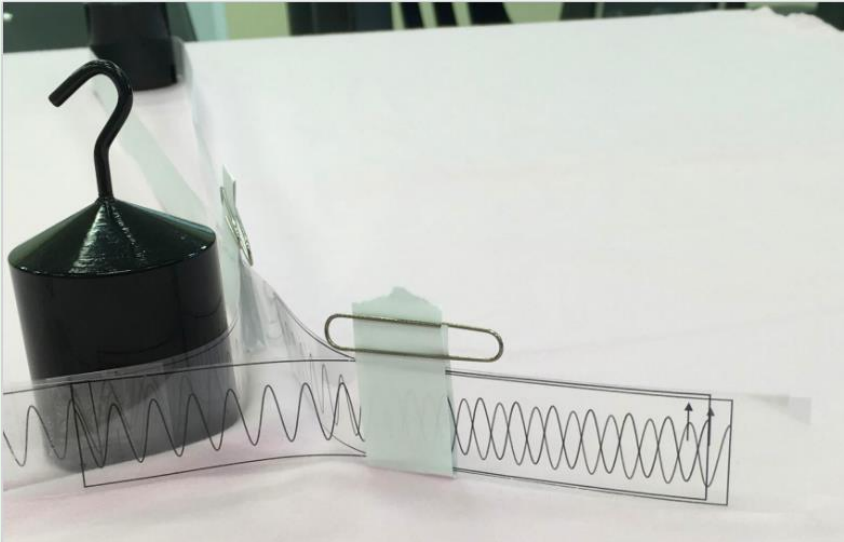
Determine the direction of the “gravitational” pulse (pull on opposite sides of the fabric).

Send the pulse through the apparatus and notice what happens to the overlapped transparent waves.





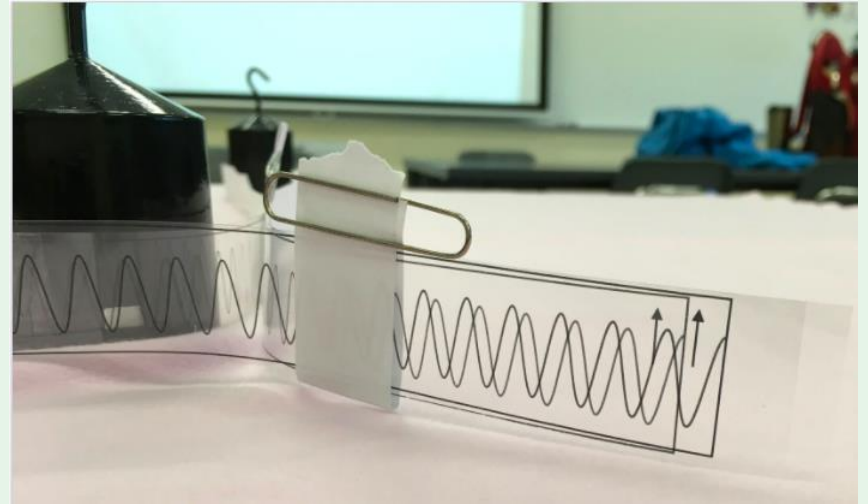
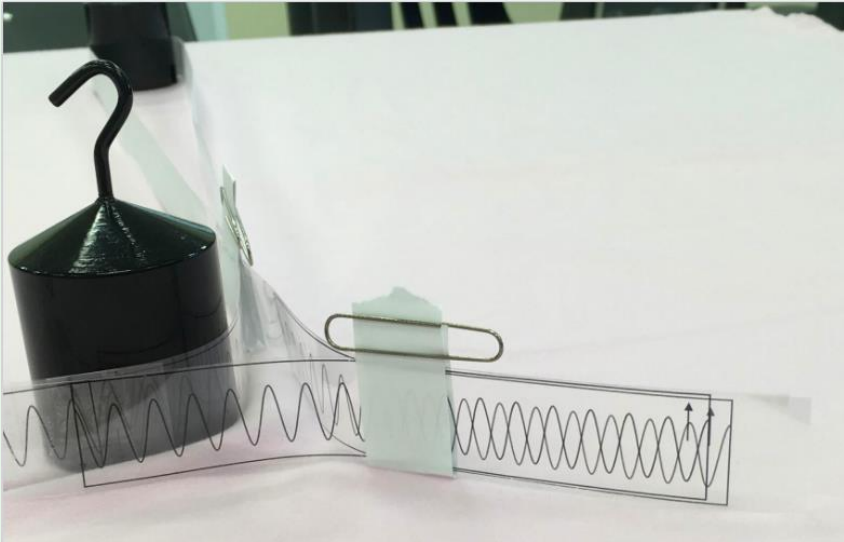
Tuned arms:



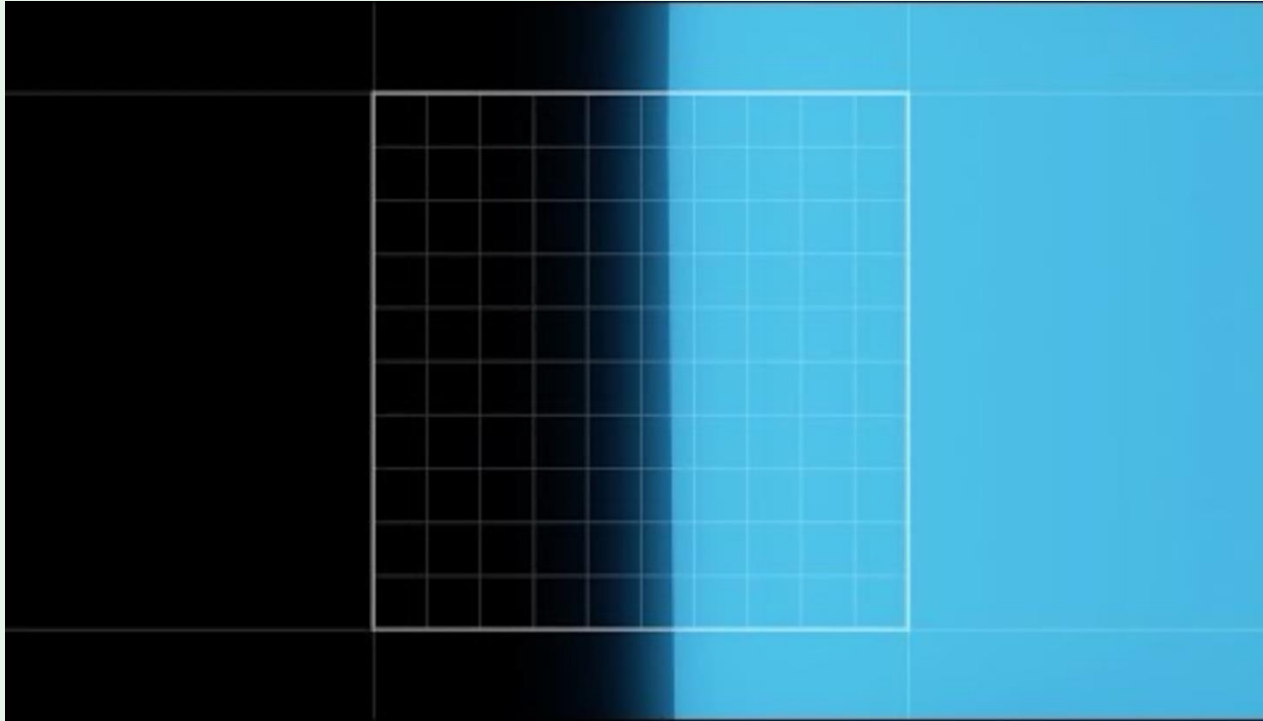
Before LIGO could make specific observations the length of the arms are adjusted by fine-tuning the location of the mirrors. Fine tune the length of **one** of arms of your model so that the overlapped waves produce **destructive interference**. (NOTE: you need to be very careful. Pick the mass up off the fabric to move it, do not slide it!)

Tuned arms:

After a “GW”



How large is the change in length?



<https://www.youtube.com/watch?v=s2qSAmYWvxc>

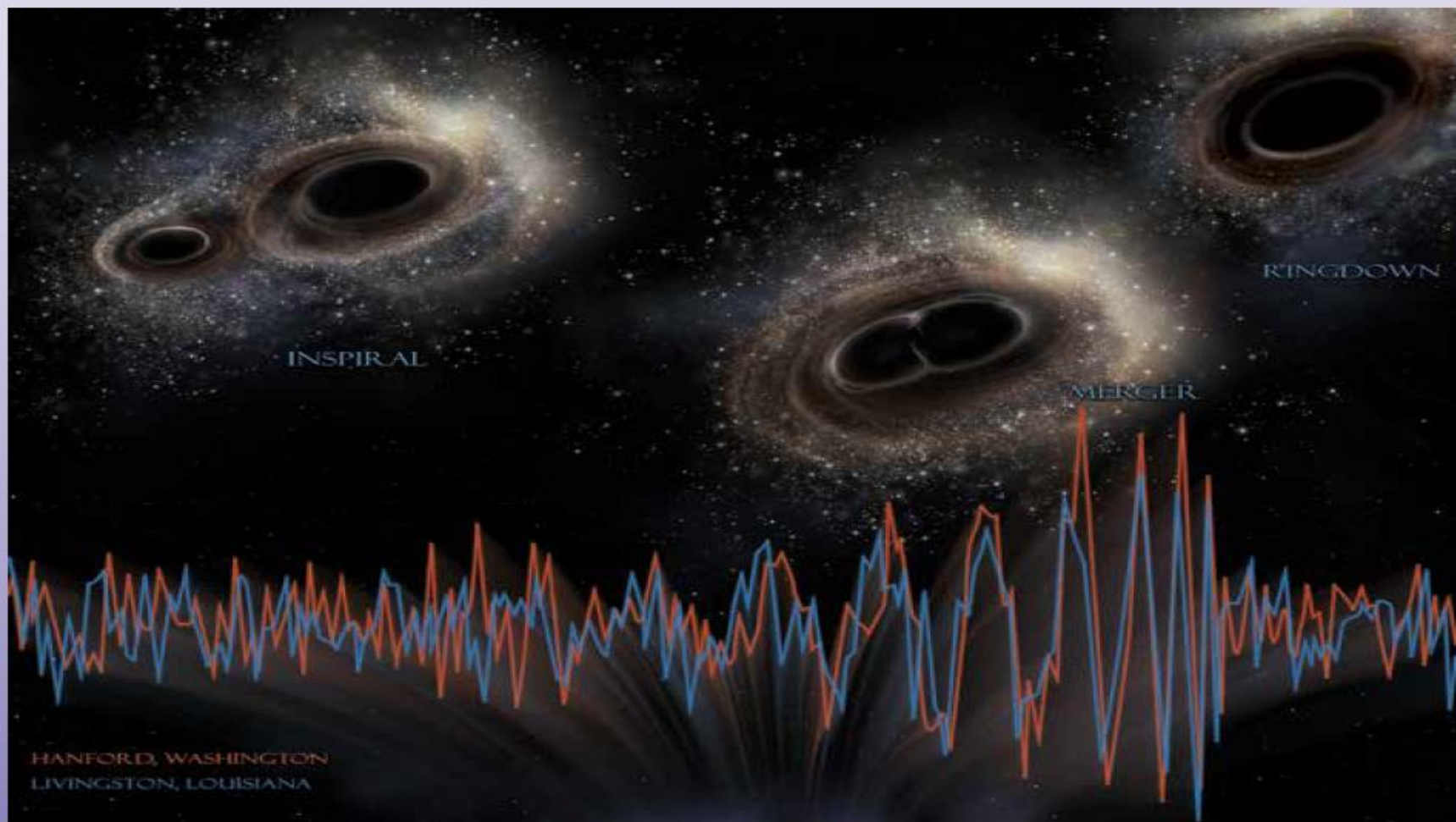
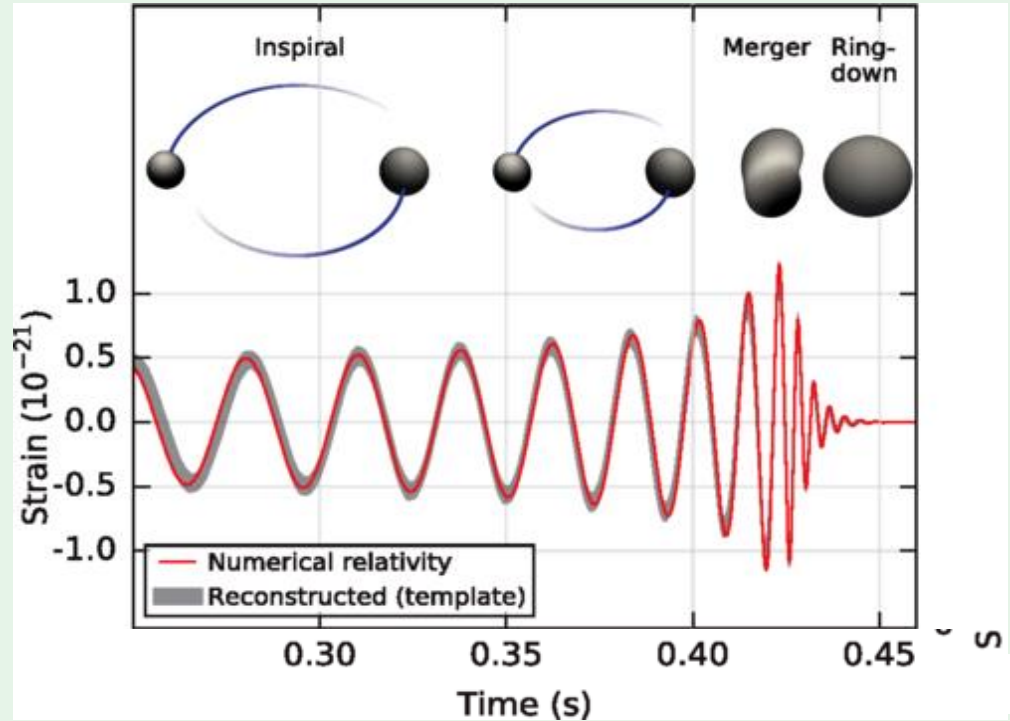


Figure 15: Artist's depiction of the merger process of two black holes, accompanied by the actual waveforms detected by LIGO Hanford and Livingston detectors. Credit: SSU E/PO Aurore Simonnet

The First Detection

- Collision between two black holes: 29 and 36 solar masses
- Final black hole mass: 62 solar masses
- 1.3 billion light years away



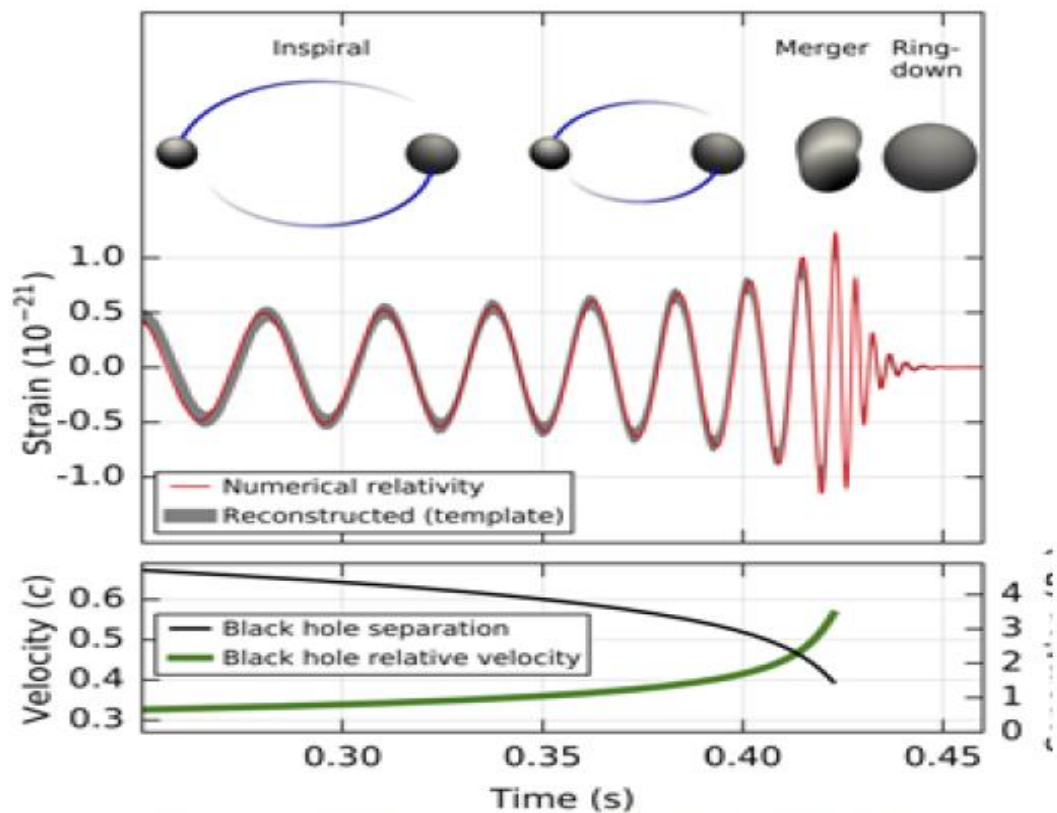


Figure 1: GW150914 models. Credit: LIGO

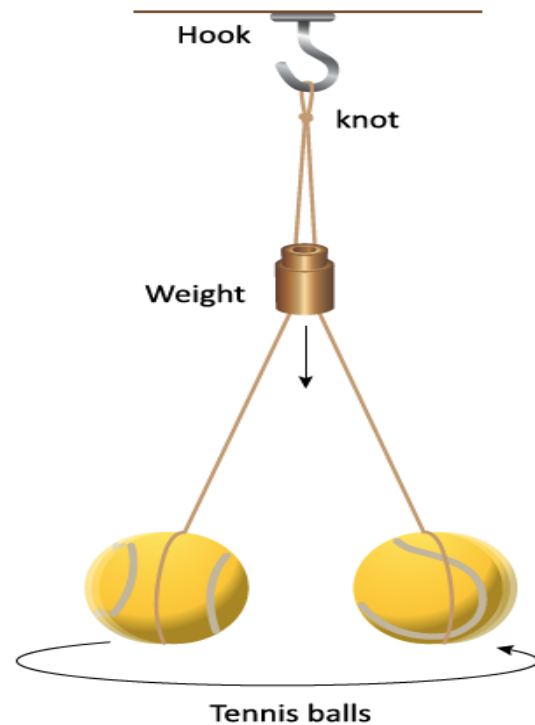


Figure 2: Demo set up.
Credit: SSU E/PO Aurore Simonnet



What does detection sound like?

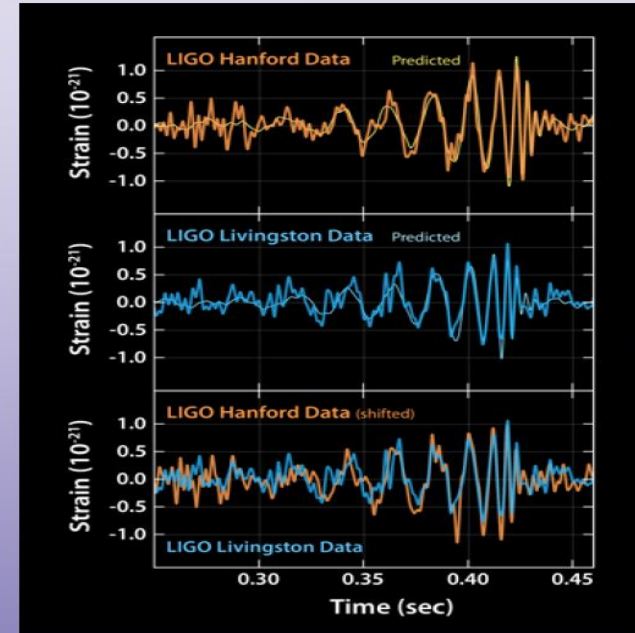
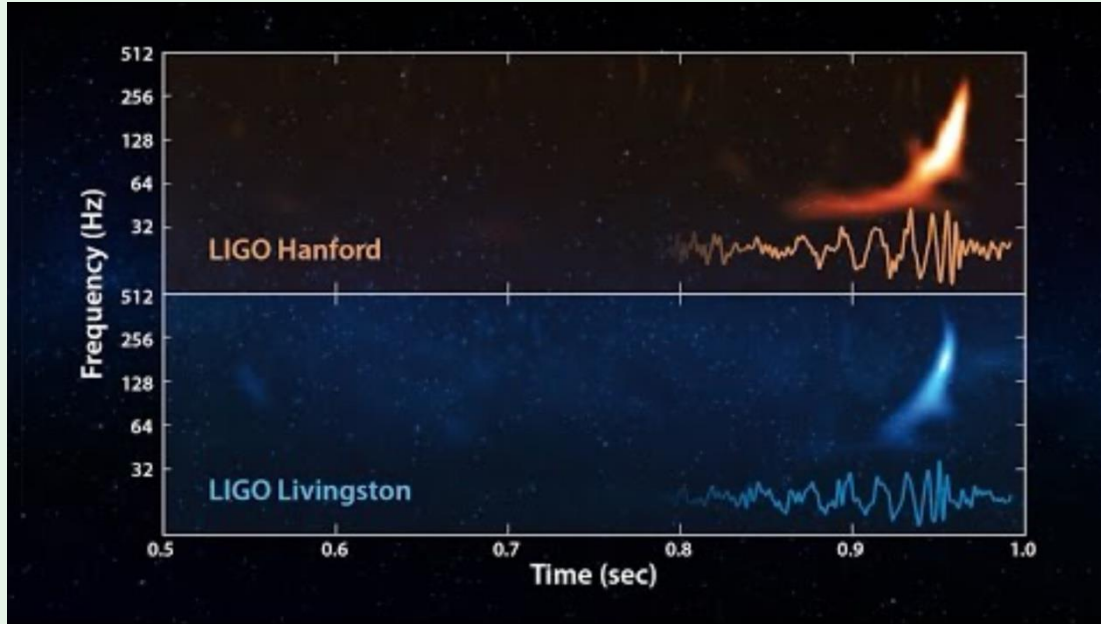
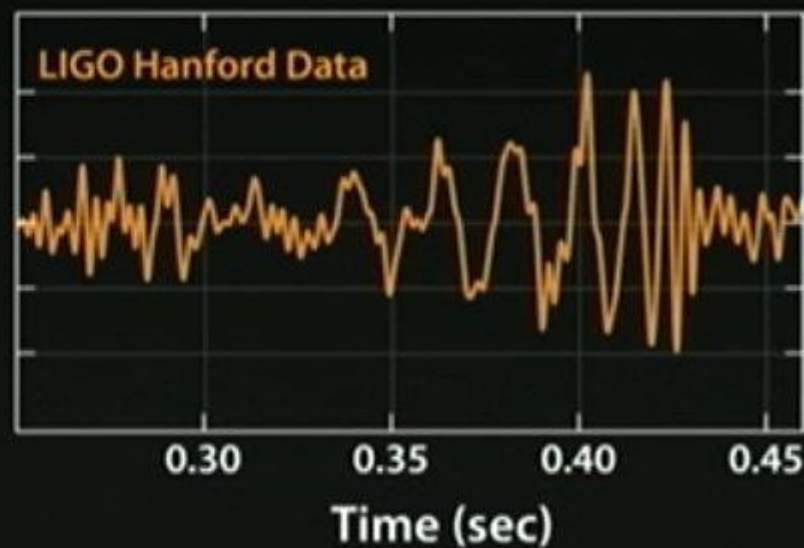
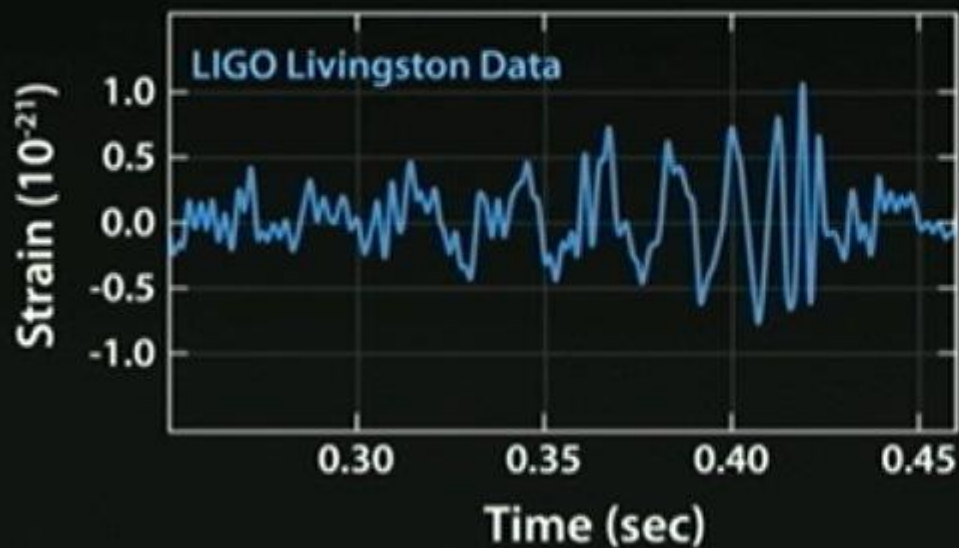


Figure 12: Data and Best-fit Models for LIGO's Direct Detection of Gravitational Waves. Credit: LIGO

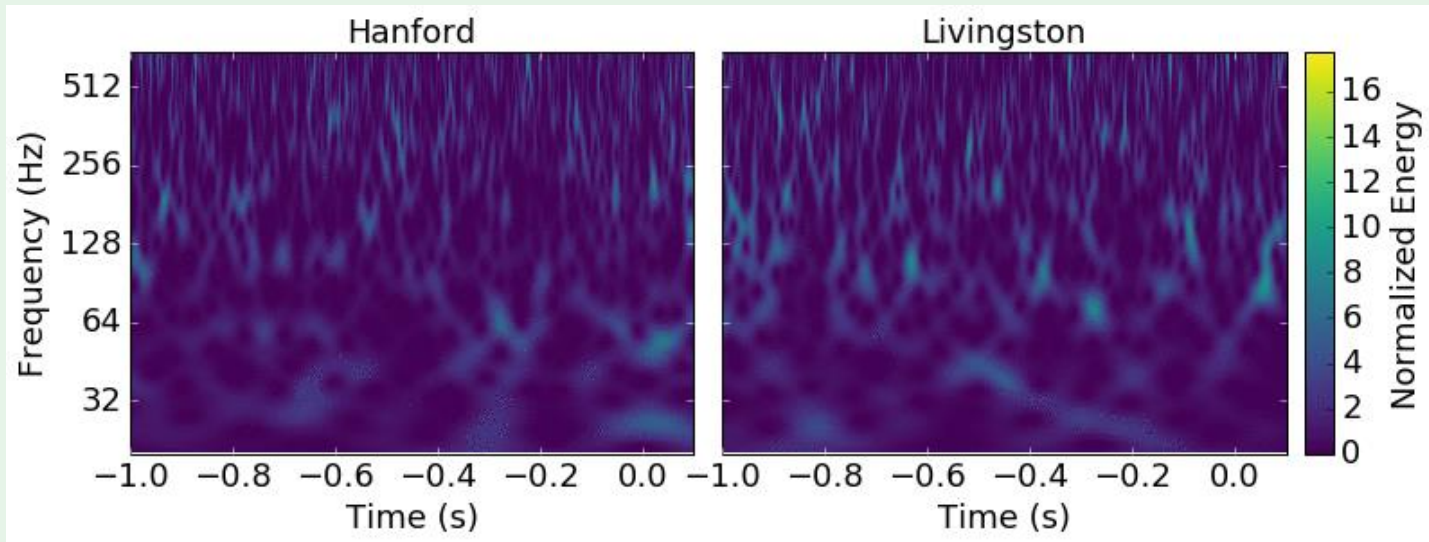
- <https://youtu.be/TWqhUANNFXw>

What did the detectors observe?



The Second Detection

- Collision between two black holes: 14 and 8 solar masses, final black hole mass: 21 solar masses
- Observed more orbits (27) than 1st event



Window to the Universe



What are Gravitational Waves? Neil Turok



Resource Credits

- Perimeter Institute for Theoretical Physics.
<https://resources.perimeterinstitute.ca/>
- Institute for Quantum Computing <https://uwaterloo.ca/institute-for-quantum-computing/outreach/quantum-educators>
- LIGO <https://www.ligo.caltech.edu/>