Measurement variations of distances with high precision and accuracy

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Background information for teachers

This presentation introduces students to the major scientific achievement of the detection of gravitational waves, through the following steps:

1. they get familiarised with concepts such as space-time, interferometry and measurements of length
2. they are introduced to the basic concepts regarding variations of distances
3. the historical detection of gravitational waves is demonstrated to them and they are informed about its great significance to the scientific community, how long it took and how much effort was needed for its completion.

Background information for teachers

4. they get instructions and materials to construct a model of Michelson interferometer based on the Nikhef construction kit
5. working in groups, they build their own interferometer
6. upon completion of their task, they send (via email) photographs of their construction
7. students working cooperatively have to complete a working sheet based on the notions mentioned on the presentation and the youtube videos.

Overview of this lesson pack:

Name of the activity	Measurement variations of distances with high precision
Topics introduced	definition of the length of 1 meter….
Curriculum Connection	IRELAND: Waves and optics. Student should be able to: -Understand that something can only be classified as a wave if it exhibits all of the following phenomena: - Reflection - Refraction - Diffraction - Interference -Recognize the distinction between constructive and destructive interference; -Utilize the principle of superposition to predict the shape and amplitude of a wave form resulting from the interference of two waves -Outline the basis of Young's double slit experiment and discuss its implications -Demonstrate diffraction and interference in the lab using double slits and a monochromatic light source -Measure the wavelength of monochromatic light by laser method -Describe everyday examples of light interference patterns, e.g. petrc soap bubbles

Overview of this lesson pack:

Curriculum Connection	CROATIA: Waves and optics: Student: -Mathematically describes and explains Young's experiment. -Describes the phenomenon of polarization and interference of light and application in technology. -Analyses the influence of wavelength on the interference image by Young's experiment and on the optical grating -Conducts research on light interference from two sources (Young's experiment) and diffraction on an optical grating -Describes examples of polarization of light interference from nature (oil layer in water, bird feathers, soap bubble, polarizing glasses, birefringence). -Experimentally: determines the wavelength of light using an optical grating POLAND: IX. Waves and optics. Students: 3) apply the principle of wave superposition; give the conditions of amplification and blanking waves describes the phenomenon of wave interference and the spatial image of interference; 10) apply the principle of wave superposition; explain the phenomenon of wave interference; give conditions of amplification and extinction of waves; 11) analyze qualitatively the phenomenon of interference of light beams reflected from two the surface of a thin layer; 12) describe the dependence of the spatial interference image on the wavelength and distance between sources; 20) experimentally: c) observe the phenomenon of wave interference,

Overview of this lesson pack:

Curriculum Connection	PORTUGAL:Subdomain 2 - Electromagnetism and electromagnetic waves Understand the production of electromagnetic waves and characterize wave phenomena associated with them; base its use, namely in communications and knowledge of the evolution of the Universe. To establish an analogy between electromagnetic and gravitational waves.Understand how it is possible to detect gravitational waves using wave interference on a highly accurate scale . Investigate, experimentally, the phenomena of reflection, refraction, total reflection and light diffraction. • Apply, in problem solving, the Laws of Reflection and Refraction of light, explaining the resolution strategies and demonstrative reasoning that support a conclusion. • Interpret the role of knowledge about wave phenomena in the development of technological products. • To substantiate the use of electromagnetic waves in communications and knowledge of the Universe, integrating aspects that demonstrate the provisional nature of scientific knowledge and recognizing open problems. AL 3.2. - Wavelength and diffraction. Identify the phenomenon of diffraction by observing variations in the shape of the illuminated area of a target with the light of a laser, relating them to the size of the crack through which the light passes. Conclude that the observed light points result from diffraction and appear more spaced if the number of slits per unit length is increased. Determine the wavelength of the laser light. Justify the use of diffraction grids in spectroscopy, for example in the identification of chemical elements, based on the dispersion of polychromatic light that they originate.

Overview of this lesson pack:

Curriculum Connection	GREECE: In Physics it can be applied as a Project activity (no curriculum connection actually …) In Geometry lesson in Chapter 4 (Parallel Lines) we can talk about Non Euclidean Geometries. Then we can say that these geometries are used in the Theory of General Relativity. Introduce students to Gravitational Waves as aspect of this Theory

Overview of this lesson pack:

Reference Demonstrator	From the Michelson-Morley experiment to the gravitational-wave detection - Discovering and building a Michelson interferometer http://inspiringscience.rdea.gr/delivery/view/index.html?id=404b1c2b74af43b4960bbb75331921c9&t=p
Age of students	15 -19
Duration	6 hour classes (6x45min)

Overview of this lesson pack:

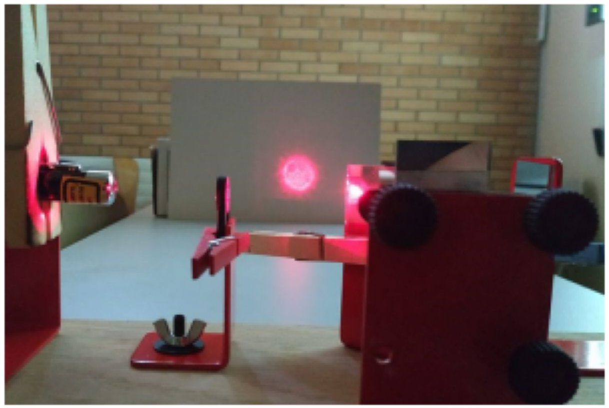
Type of activity	minds on, hands on, critical thinking, problem solving
Description of activity	**Teacher activities:** ● make a powerpoint presentation explaining scientific concepts, such as interference, waves and space-time ● present a youtube video showing how to build the interferometer ● explain the procedure on how to align beams in two arms ● supervise all student activities and help when necessary

Overview of this lesson pack:

Description of activity	**Student activities:** - Kahoot quiz to check their background on the waves and wave nature of the light - investigating wave interference and superposition of waves using Geogebra - building Michelson interferometer - investigating fringes' pattern - connect Michelson interferometer to the GW detection - solve the problems given at the end of the lessons

Equipment requirements	Michelson interferometer from Nikhef – The Netherlands, Construction kit from H.Hennes
Prior knowledge for students	Waves and wave properties,wave nature of light, electromagnetic waves

Background and overview of the demonstrator:



Discovering and building a Michelson interferometer

VIEW THE DEMONSTRATOR

From the Michelson-Morley experiment to the gravitational-wave detection - Discovering and building a Michelson interferometer

http://inspiringscience.rdea.gr/delivery/view/index.html?id=404b1c2b74af43b4960bbb75331921c9&t=p

Presentation for students

Teacher guidelines can be found in the notes attached to each slide

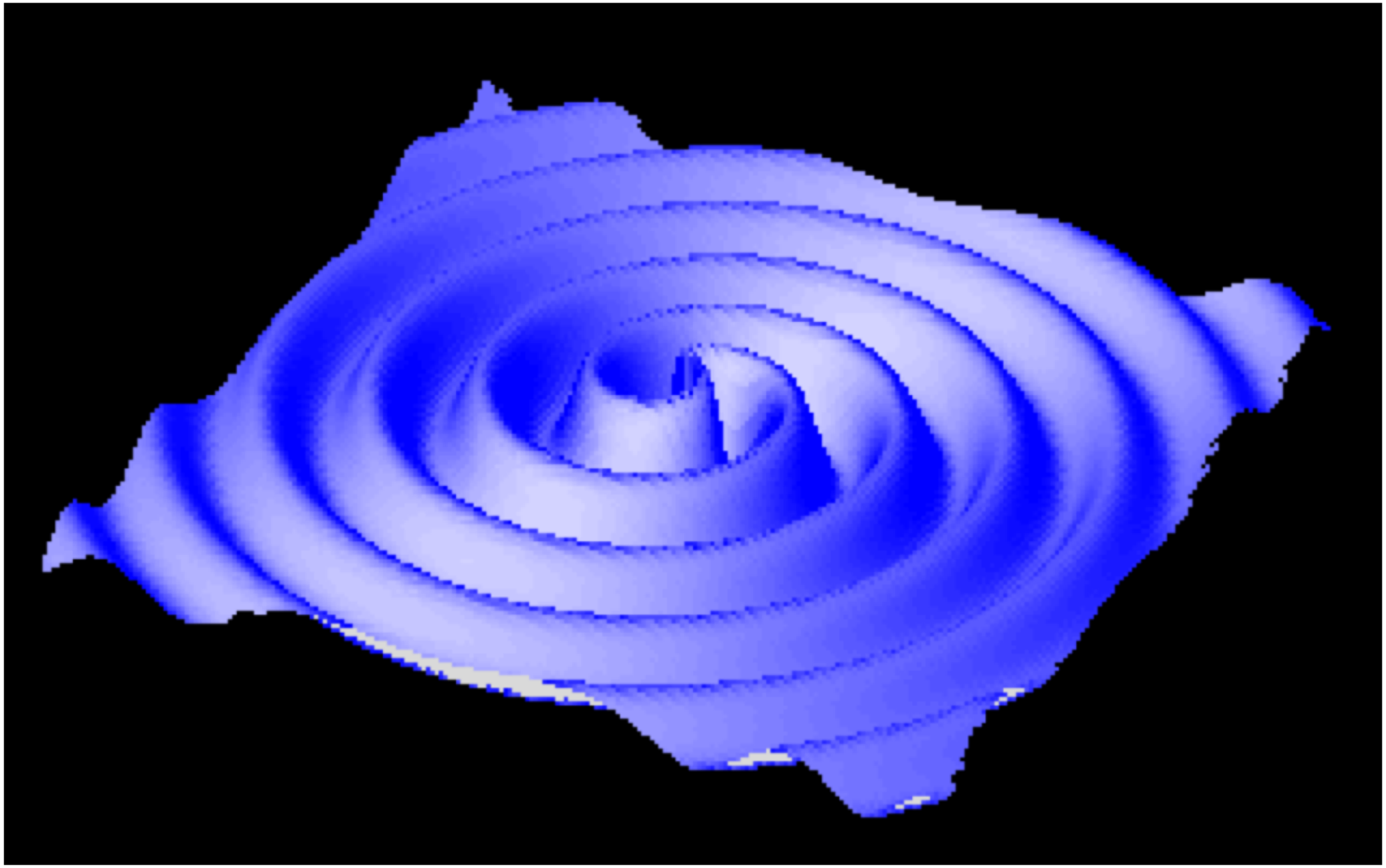
Lessons plan:

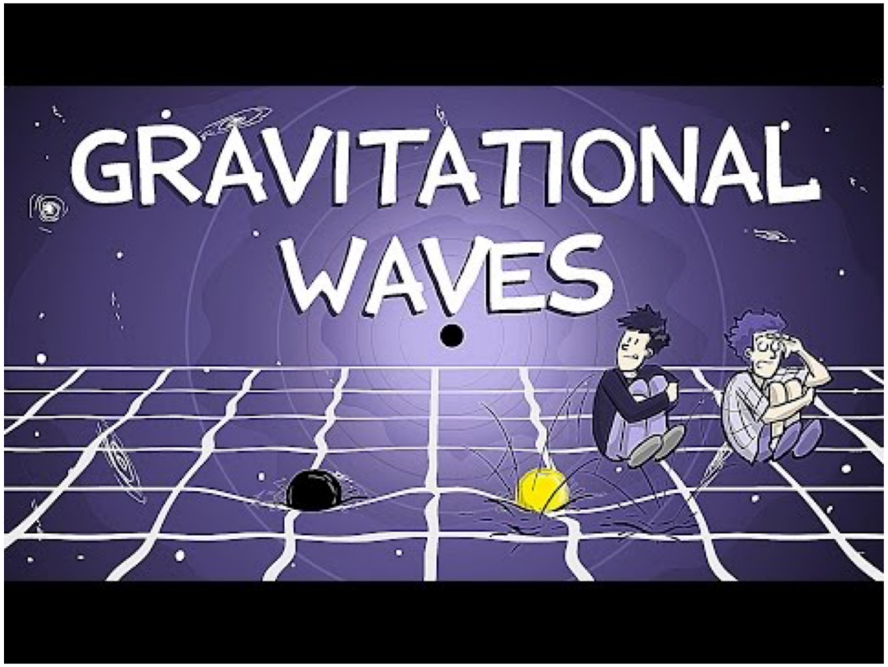
1-2 hours: Introduction
background information about the Michelson interferometer and the detection of gravitational waves

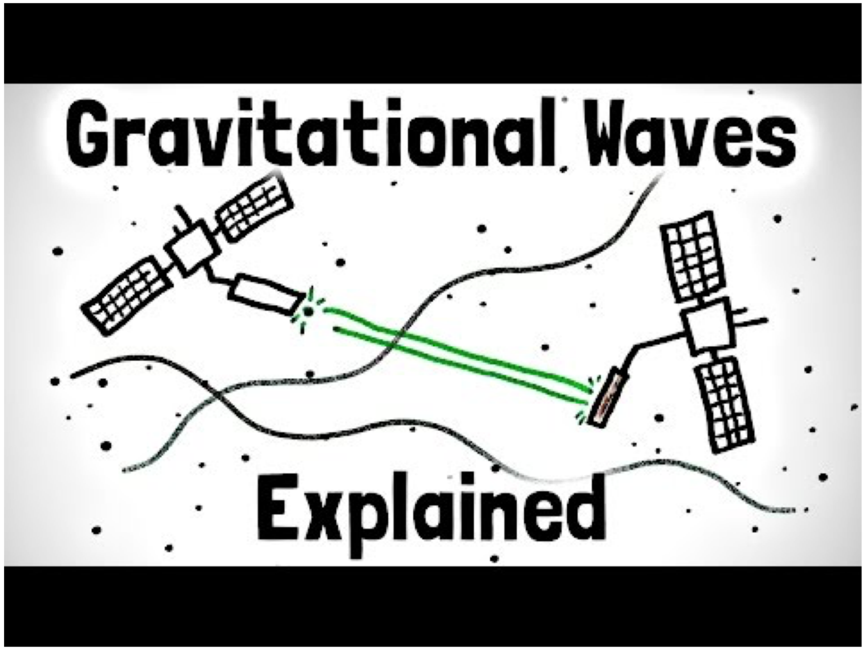
3-4 hours: Main part
Students get instructions and materials to construct a model of the Michelson interferometer based on the Nikhef construction kit. They work in groups, they build their own Michelson interferometer and investigate the fringes pattern.

5-6 hours: Evaluation
Present to other students and connect the Michelson interferometer to the GW detection
Problems to solve in pairs.

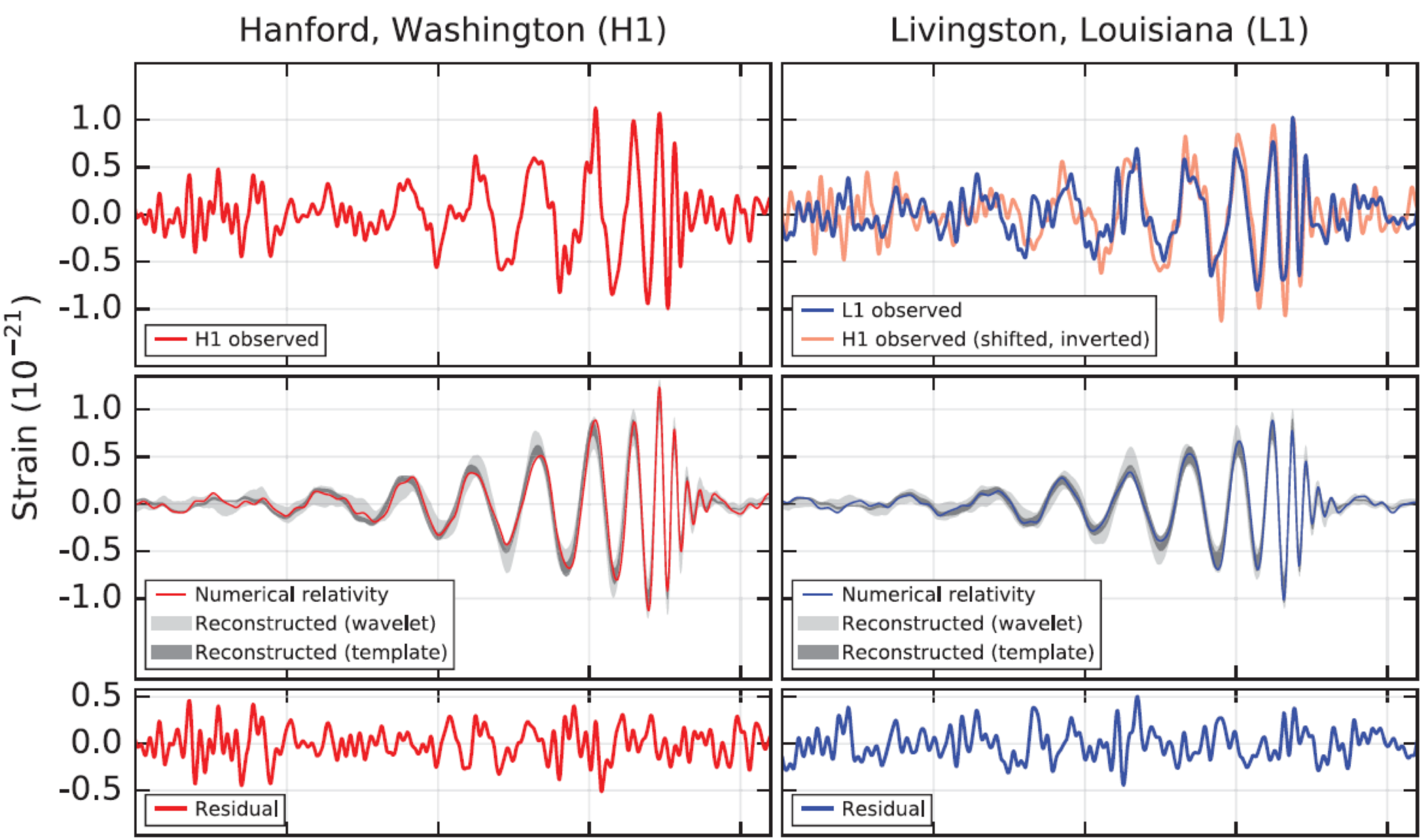
What are Gravitational Waves?




GRAVITATIONAL
WAVES


Gravitational Waves
Explained

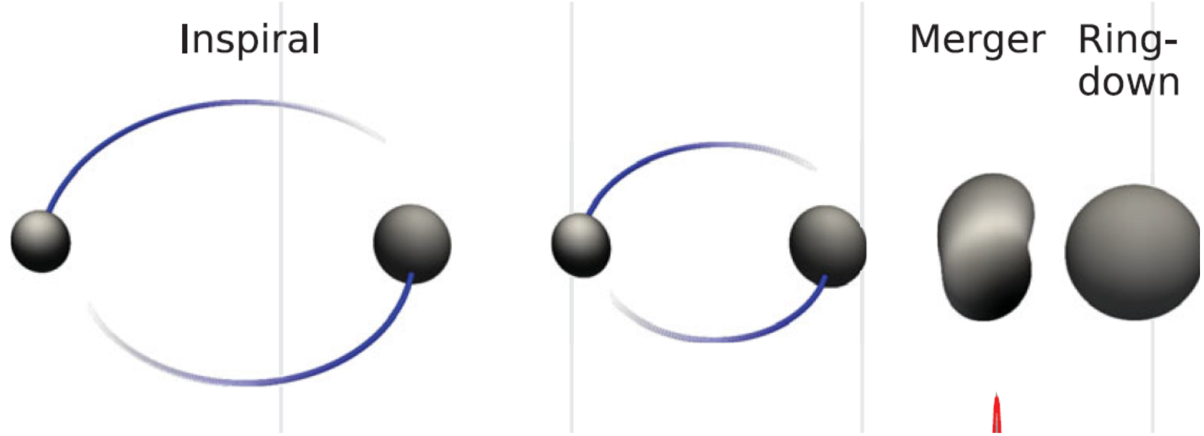
The gravitational-wave event GW150914 observed by the LIGO Hanford (H1, left column panels) and Livingston (L1, right column panels) detectors from Abott article.

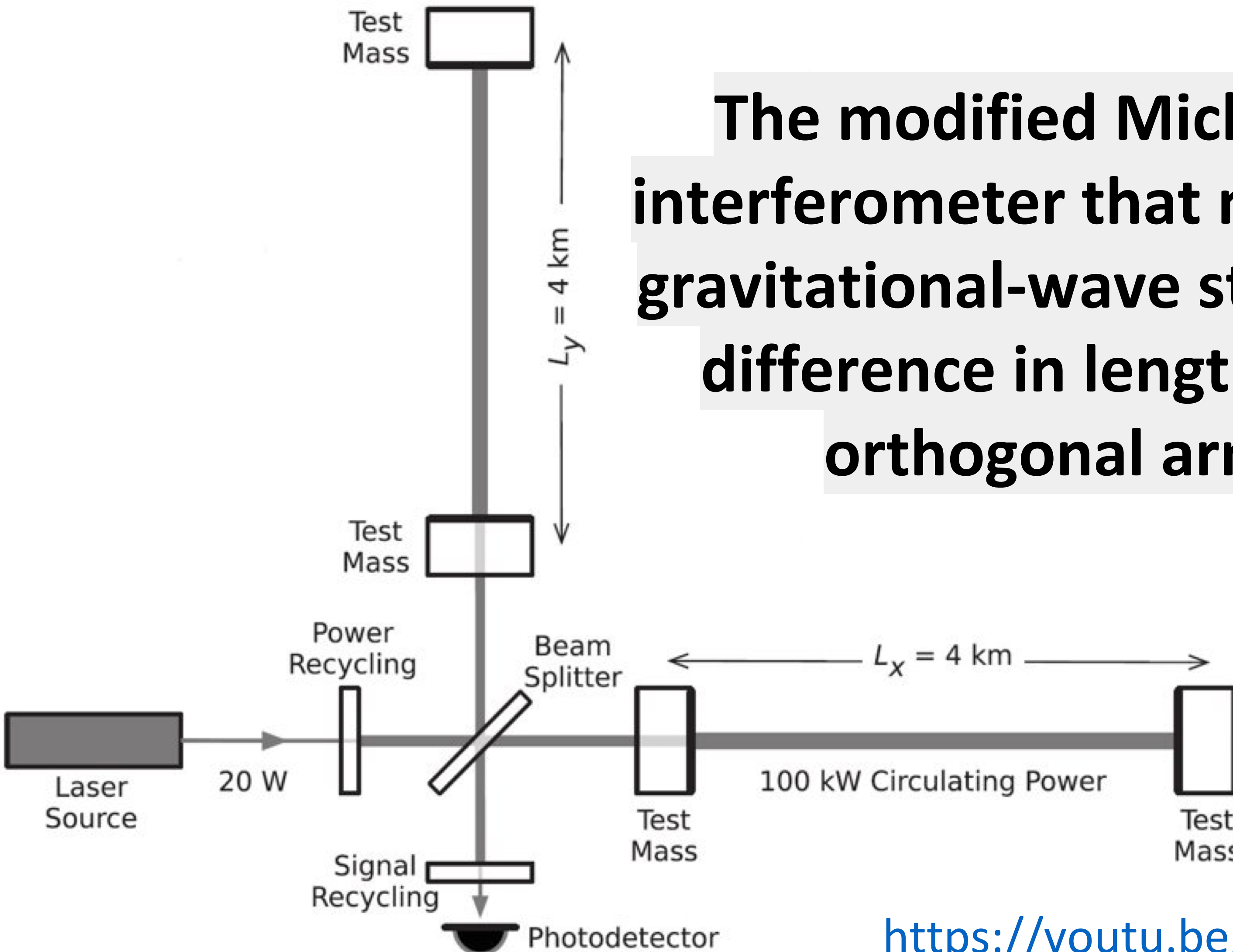


Gravitational wave detection

Almost 130 years after that crucial moment, the Michelson interferometer has been used again by LIGO and Virgo to detect the first ever gravitational waves and to illuminate the sky thanks to a new cosmic messenger, alternative to electromagnetic waves.

The first gravitational-wave detection was defined as “a discovery that shocked the world”, by the Nobel prize committee, who awarded three founding fathers of the LIGO detector with the 2017 prize in physics.





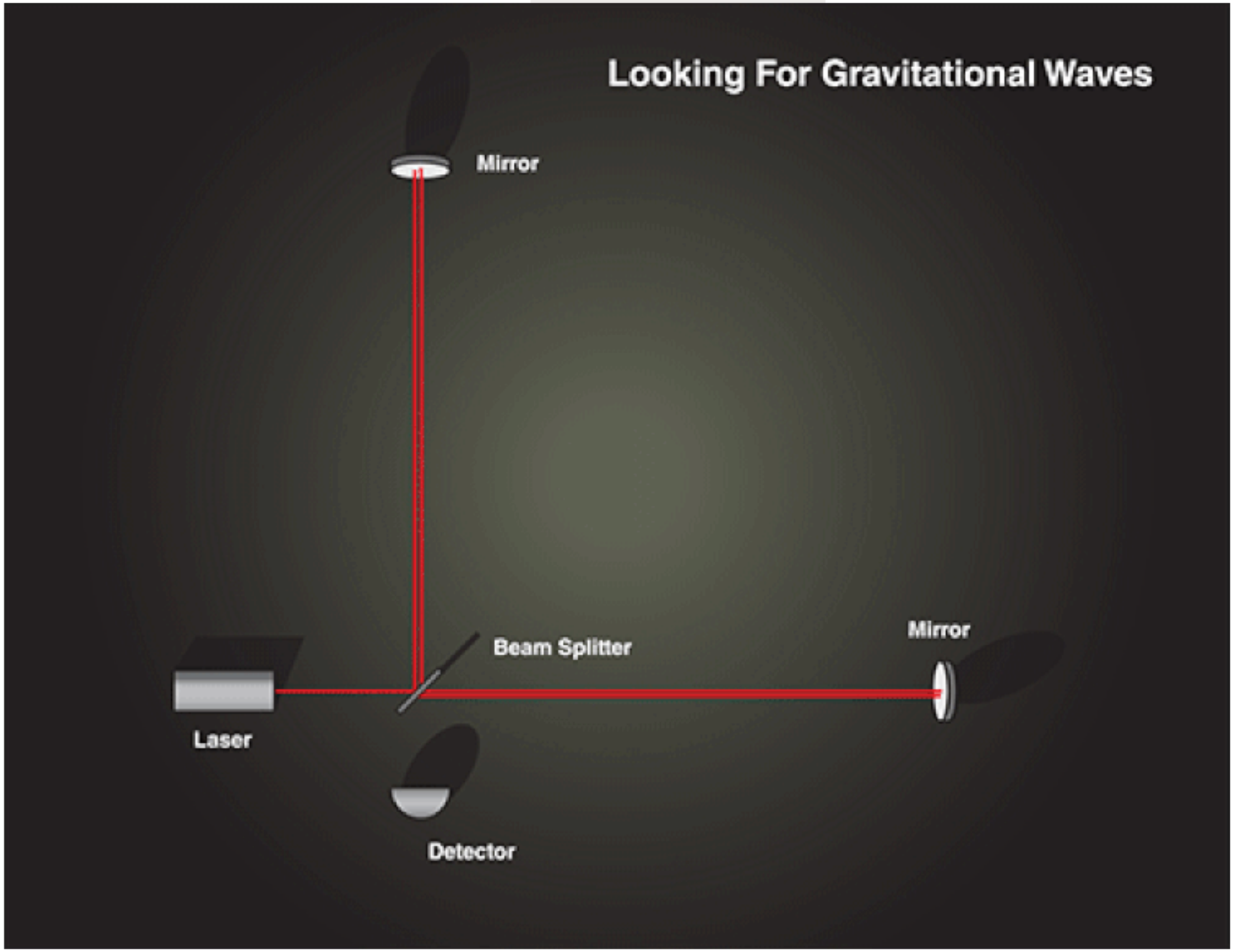
The modified Michelson interferometer that measures gravitational-wave strain as a difference in length of its orthogonal arms

https://youtu.be/6raomYII9P4

B. P. Abbott et al.*

Observation of Gravitational Waves from a Binary Black Hole Merger, Phys Rev Lett. 116.061102 (2016).

How to detect Gravitational

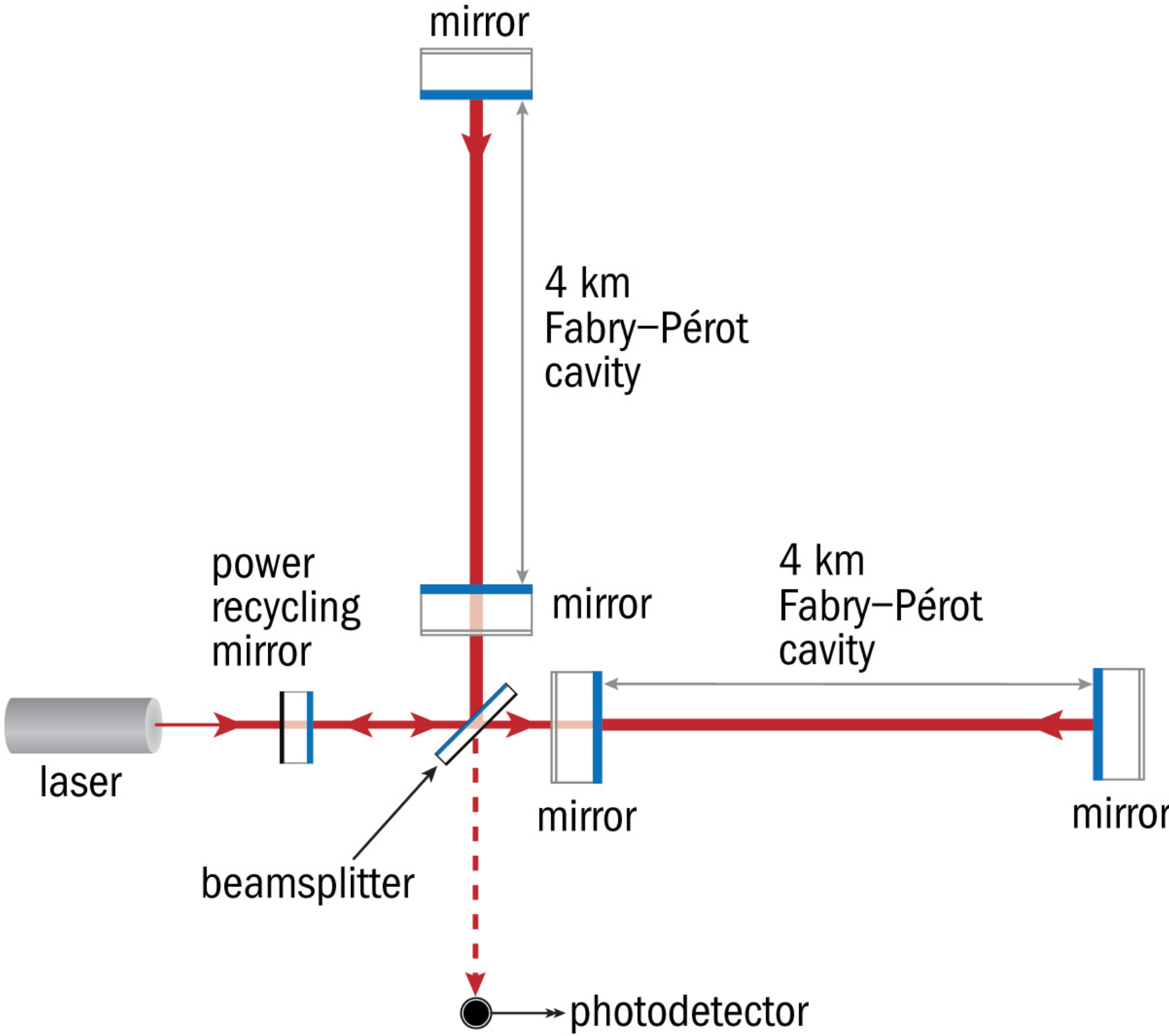


How to detect Gravitational wave?

Fabry Perot cavities

1. It builds up the laser light within the interferometer, which increases LIGO's sensitivity (more photons also makes LIGO more sensitive)

2. It increases the distance traveled by each laser from 4km to *1200km* thereby solving our length problem! (The light in Michelson's original interferometer only traveled 11 meters.)


mirror
4 km
Fabry–Pérot
cavity
power
recycling
mirror
mirror
4 km
Fabry–Pérot
cavity
laser
mirror
mirror
beamsplitter
photodetector

How to detect Gravitational waves?

Important findings:

The range of frequency of gravitational waves we can detect, depends on the length of the arm.

The longer the arm, the smaller frequency we can measure.

Albert Michelson

(December 19, 1852 – May 9, 1931)

Michelson was born in Strzelno, (Poland), the son of Samuel Michelson, and his wife, Rozalia Przyłubska, a daughter of a Polish merchant.

He moved to the US with his parents in 1855, at the age of two. He grew up in the mining towns of Murphy's Camp, California and Virginia City, Nevada, where his father was a merchant.

He spent his high school years in San Francisco in the home of his aunt, Henriette Levy (née Michelson), who was the mother of author Harriet Lane Levy.

President Ulysses S. Grant awarded Michelson a special appointment to the U.S. Naval Academy in 1869. During his four years as a midshipman at the Academy, Michelson excelled in optics, heat, climatology and technical drawing. After graduating in 1873 and two years at sea, he returned to the Naval Academy in 1875 to become an instructor in physics and chemistry until 1879.

Wavelength definition of metre

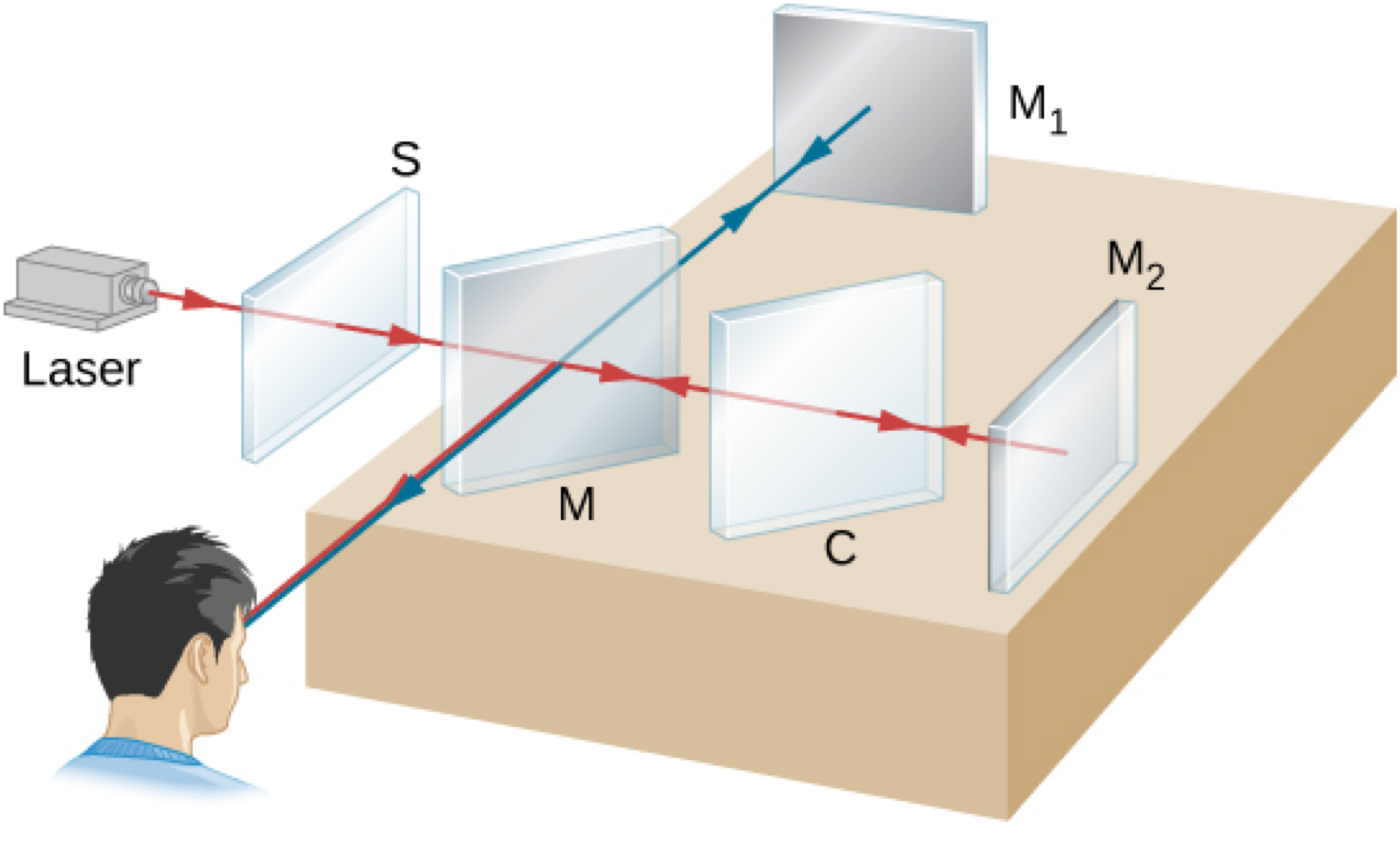
In 1893, the standard metre was first measured with an interferometer by Albert A. Michelson, the inventor of the device and an advocate of using some particular wavelength of light as a standard of length.

However, the International Prototype Metre remained the standard until 1960, when the 11th CGPM defined the metre in the new International System of Units (SI) as **equal to 1650763.73 wavelengths of the orange-red emission line in the electromagnetic spectrum of the krypton-86 atom in a vacuum**.

Nobel prize in physics 1907

"for his optical precision instruments and the spectroscopic and metrological investigations carried out with their aid."

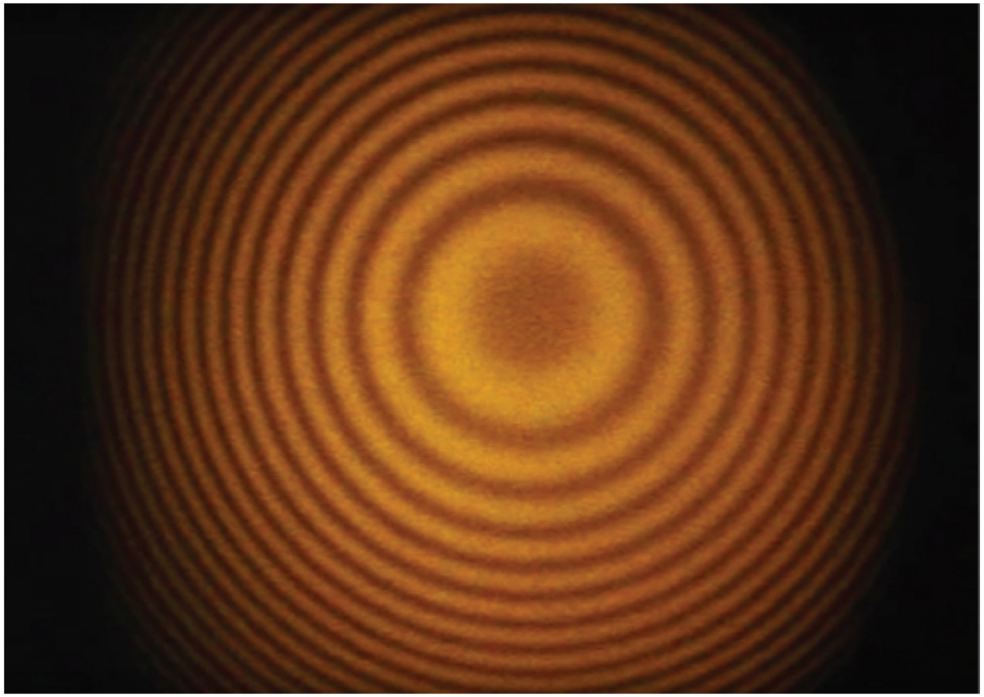
Michelson interferometer



Measurement of displacement with the Michelson Interferometer

Displacement measured by a Michelson interferometer

$$d = m\frac{\lambda_0}{2}$$



Accuracy of measurements

Precise Distance Measurements by Michelson Interferometer

A red laser light of wavelength 630 nm is used in a Michelson interferometer. While keeping mirror M1 fixed, mirror M2 is moved. The fringes are found to move past a fixed cross-hair in the viewer. Find the distance the mirror **is moved for a single fringe** to move past the reference line.

Solution For a 630-nm red laser light, and for each fringe crossing (m=1), the distance traveled by M2 if you keep M1 fixed is

$$d = m\frac{\lambda_0}{2} = 1\ \frac{630\ \text{nm}}{2} = 315\ \text{nm} = 0.315\ \mu\text{m}.$$

Student activity 1

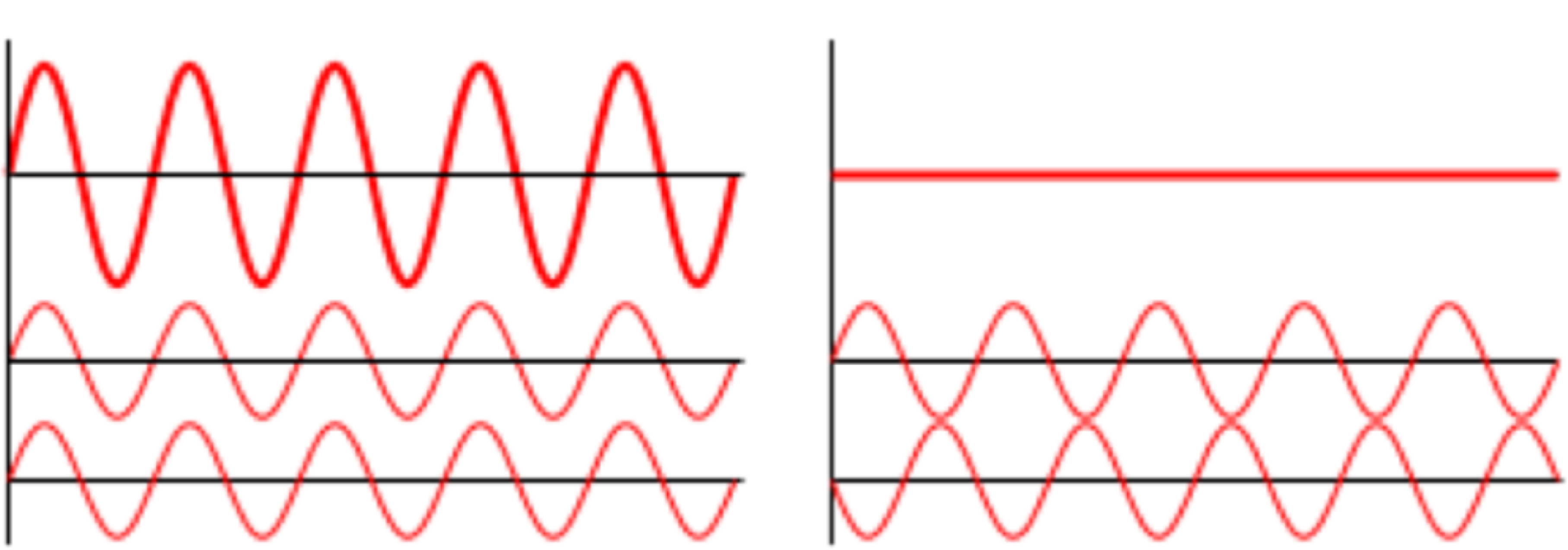
Watch the video:

https://www.ligo.caltech.edu/video/IFO-response

Answer the question:

How does the Michelson interferometer work in the context of gravitational-wave detection?

The wave nature of light



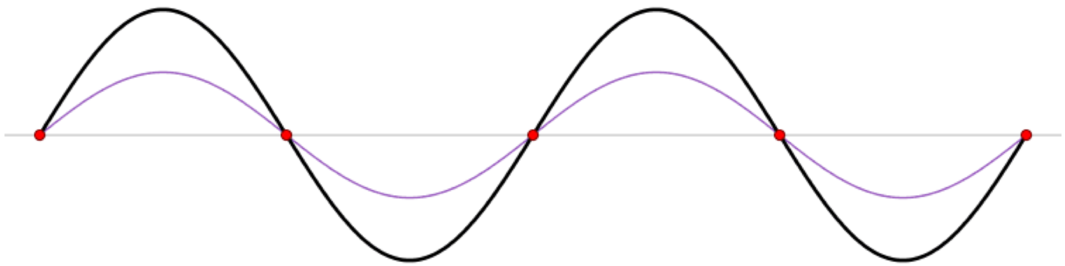
Light is a wave. Waves have a particular property which make them very different from particles: **interference.**

Student activity 2

Instructions for students:

- by varying the amplitude of both waves explore how this affects the amplitude of the resulting wave
- by varying the wavelength of waves explore how this affects the amplitude and the wavelength of the resulting wave

https://www.geogebra.org/m/mrFexEb9



Student activity 3

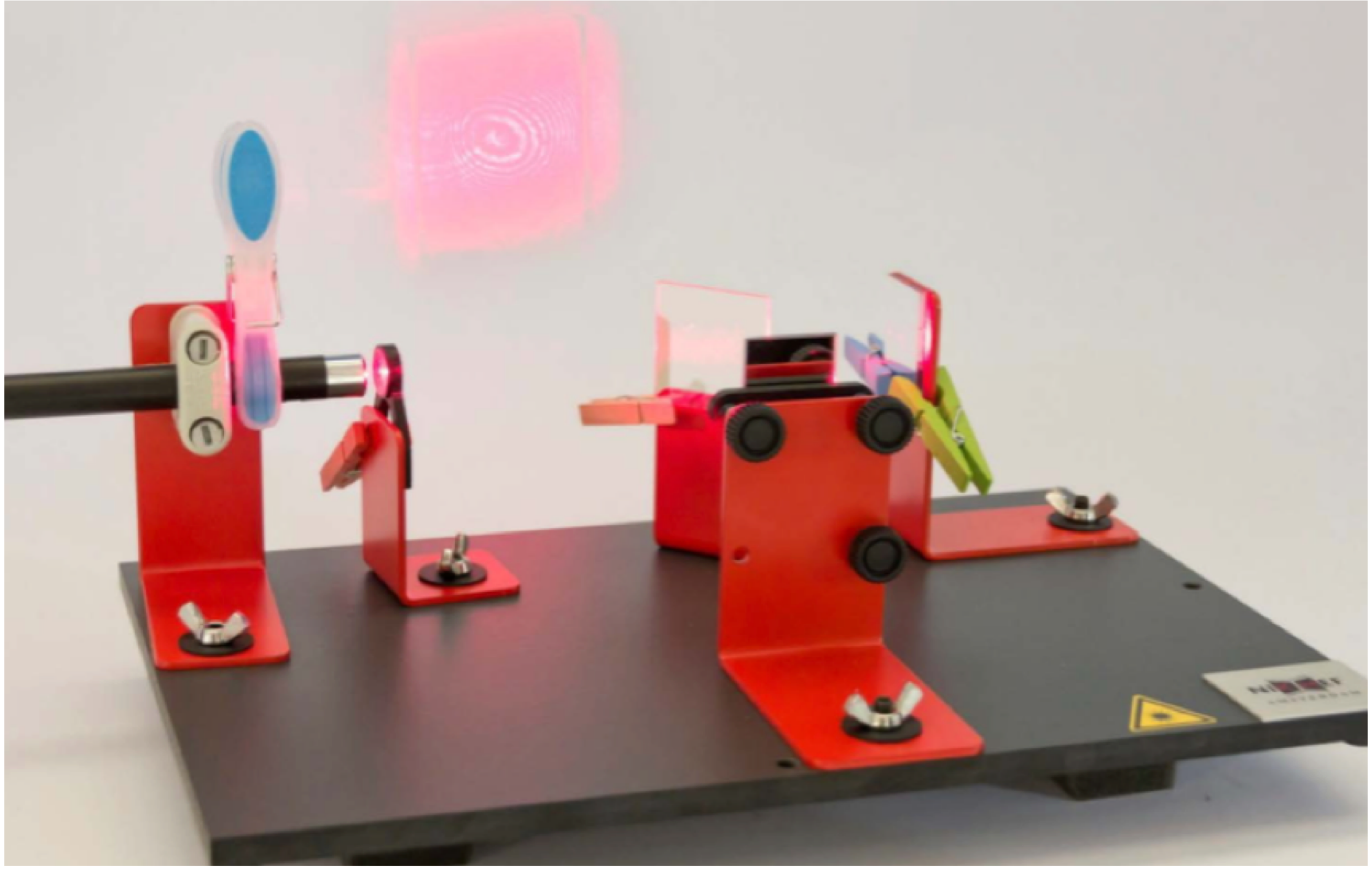
Watch the video again.

https://www.ligo.caltech.edu/video/IFO-response

Answer the question:

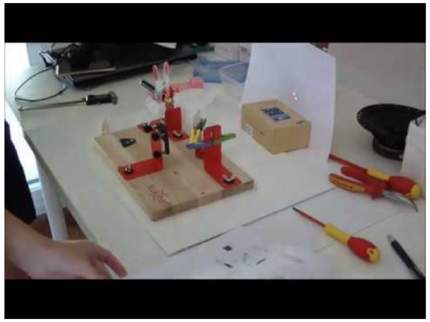
How the variation of distance is transformed in variation of luminosity on the screen of the interferometer by the interference?

Building Michelson interferometer



Michelson interferometer from Nikhef – The Netherlands
Construction kit from H.Hennes

Building Michelson interferometer



Watch the video.

Follow the various steps of the construction of the instrument as explained in the manual and in the video.

Once the interferometer is assembled, it should be aligned, until circular fringe patterns are observed.

Question: Why do we see these rings?

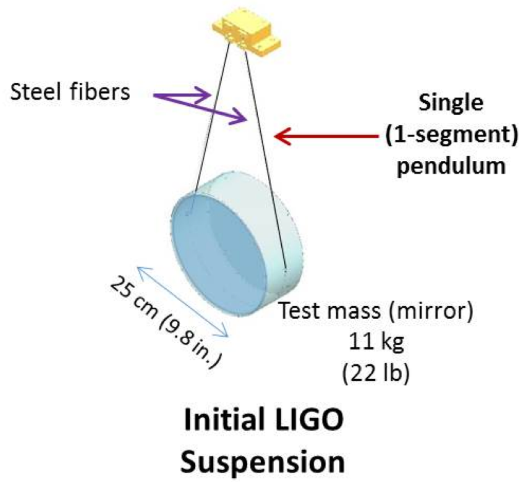
Observing the fringes

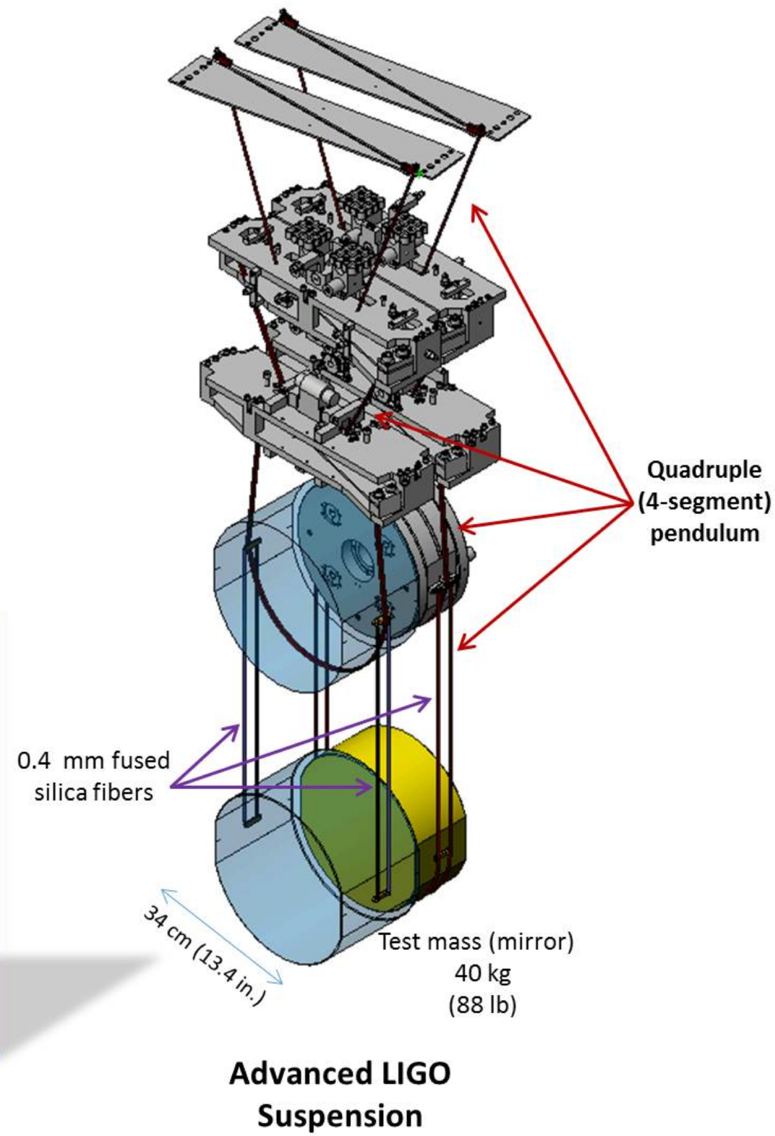
Observe how the fringes on the screen change.

Questions:

- Is the central part becoming alternatively dark and bright? If yes, why?
- What are the timescales of these changes?
- What do you think is the reason for the changes in brightness?

Seismic isolation





iLIGO vs aLIGO suspension systems

These engineering drawings illustrate the striking differences between Initial- and Advanced LIGO's suspensions. The suspensions are shown to scale.

Initial LIGO's suspension was a single pendulum design with an 11 kg (22 lb) 'test mass' (mirror) hung by steel fibers.

Advanced LIGO's suspension system is a **much** heftier quadruple ("quad") pendulum with a 40 kg (88 lb) 'test mass' (mirror) hung by fused silica fibers.

Students investigation

You can give a little push to one part of the instrument, or blow air in one of the two arms (be careful with your eyes!).

What effect do these actions produce on the interference pattern?

Analysis and interpretation

Answer the question:

Why is the instrument so sensitive?

Conclusions

We have seen that the optical interferometry is a very powerful way to measure small distance differences.

Evaluation

Group worksheet for the Michelson interferometer

FRONTIERS

Exercise 1:

Try to answer to the following questions (in a few lines)

- How does a Michelson interferometer work?
- Why have we used a laser in our experiment, instead of the light emitted by a lamp? Which is the difference between a laser and the light of a lamp?
- Is it possible to make interference with radio waves rather than visible light? Why is it so?
- Why is interferometry so powerful in measuring distances?
- Are there alternative methods to measure distances very precisely?
- Any ideas on how to remove the vibrations observed in the Nikhef interferometers?

Problem 1

A Michelson interferometer has two equal arms. A mercury light of wavelength 546 nm is used for the interferometer and stable fringes are found. One of the arms is moved by 1.5 μm. How many fringes will cross the observing field?

Problem 2

What is the distance the traveling mirror of a Michelson interferometer is moved by, that corresponds to 1500 fringes passing by a point of the observation screen? Assume that the interferometer is illuminated with a 606 nm spectral line of krypton-86.

Problem 3

In a Michelson interferometer, light of wavelength 632.8 nm from a He-Ne laser is used. When one of the mirrors is moved by a distance D, then 8 fringes move past the field of view. What is the value of the distance D?

Problem 4

When the traveling mirror of a Michelson interferometer is moved by 24 μm, then 90 fringes pass by a point on the observation screen. What is the wavelength of the light used?

Thank you!