Gravitational Wave noise hunting

Orientation Phase

Orienting and Asking Questions

Provide Contact with the content and/or provoke curiosity

100 years after the conception of Einstein's theory of General Relativity which describes gravity in a new perspective, humankind comes to observe its greatest verifications.

1.3 billion years ago, 2 gigantic black holes with masses almost 30 times the mass of the sun each travelling at speed close to the speed of light collided creating a cataclysmic cosmic event! This collision created Gravitational Waves, "Ripples in Spacetime".

These ripples travelled throughout the cosmos, arrived at our very earth and were detected by the LIGO collaboration in USA.

Further detections of black hole mergers followed, and on August 2017, scientists directly detected gravitational waves in addition to light from the spectacular collision of two neutron stars . This marks the first time that a cosmic event has been viewed in both gravitational waves and light. The discovery was made on August 17, 2017 using the U.S.-based Laser Interferometer Gravitational-Wave Observatory (LIGO); the Europe-based Virgo detector; and some 70 ground- and space- based observatories.

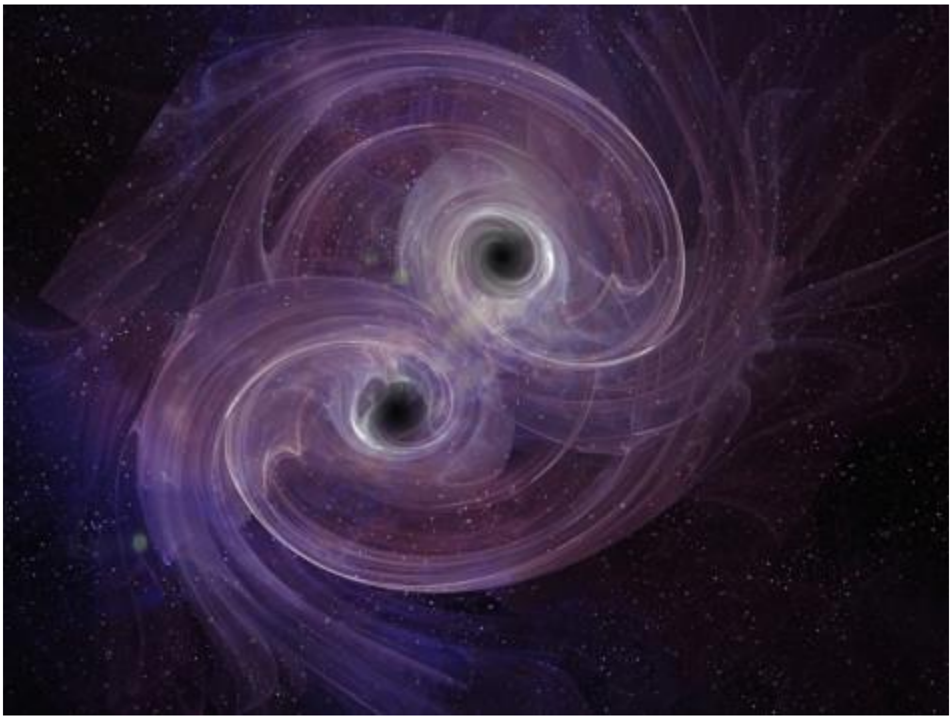


Fig. 1.1 : Artistic impression of a black hole merger.

These colossal discoveries open a new observational window in the Universe and

inaugurate the era of “Gravitational Wave Astronomy”.

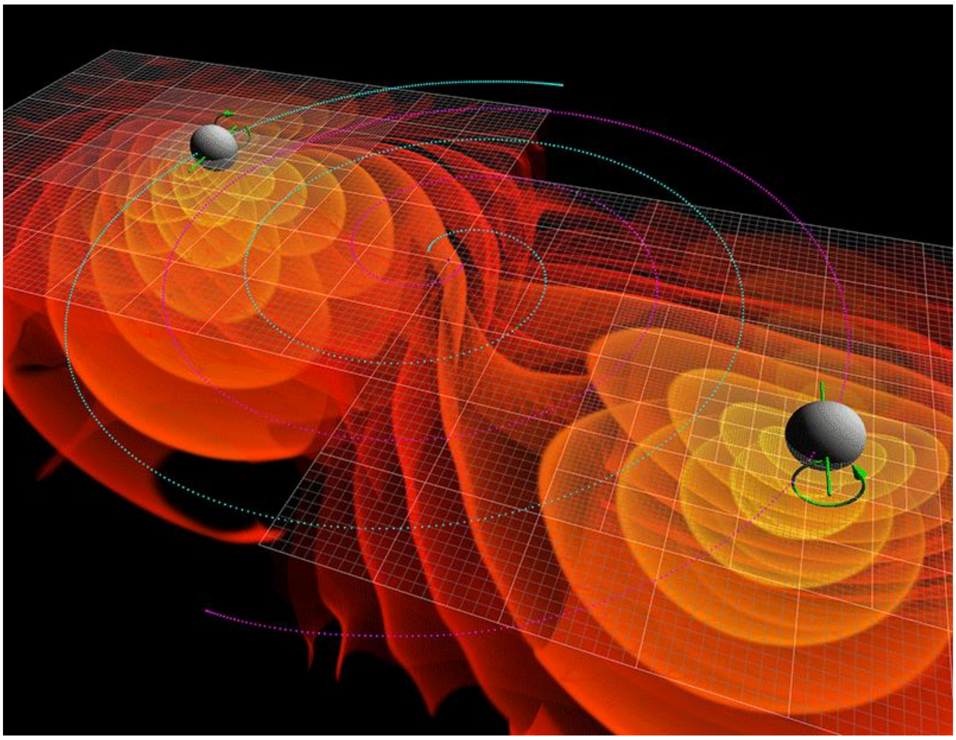


Fig.1.2 : Numerical simulation of the gravitational waves (orange) emitted by the merging of two black holes.

Fig.1.3.1: Fig. 1.3.1: The VIRGO Gravitational Wave Detector in Pisa, Italy

Fig.1.3.2 : The LIGO detector at Hanford, USA. Another similar detector is located at Livingston, USA.

Teacher Guideline:

The one black hole weighted 29 solar masses and the second black hole 36 solar masses.

After merging, a new black hole was created with a total mass of 62 solar masses. The energy corresponding to the 3 remaining solar masses was emitted in the form of gravitational waves.

Using Einstein's : E = mc², with m = 1.989* 10^30 kg: $m = 1.989 * 10^{30} kg$ we can find out that the total energy emitted was of the order 2*10^47 J: $2 * 10^{47} J$.

If we divide this number with the average world energy consumption which was 5.6*10^20 J $5.6 * 10^{20} J$ in 2012, we can conclude that the energy emitted by the black hole would be enough to power up the earth for 10^26 years $10^{26} years$, a number 10^17 10^{17} times larger than the Age of The Universe!!!!!

Another way to picture this is the famous quote of Kip Thorne: " The energy emitted in the form of Gravitational Waves is 50 times larger than the luminous energy emitted by the Universe altogether"!!

These comparisons may help students grasp the numbers, and comprehend the unprecedented violence of these cosmic events.

Watch the following introductory video and let's explore together this major discovery step by step:

https://www.youtube.com/watch?v=s06_jRK939I

Exploratory Phase

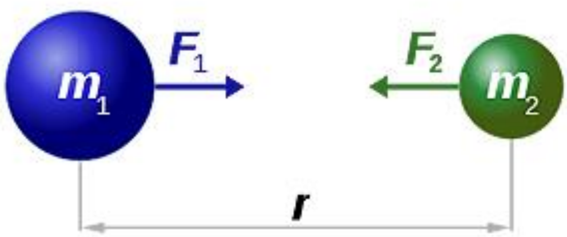
Hypothesis Generation and Design

Define Goals and/or questions from current knowledge

How would you describe the force of gravity? What causes objects to fall?
Discuss with your classmates

Gravity: From Newton to Einstein

According to Newton's classical theory of Gravitation, every massive object will attract every other massive object. The strength of this attraction will be proportional to the masses of the objects
(and that's why our weight on earth is 6 times larger than our weight at the moon! Earth's mass is bigger than the Moon's, therefore the force of gravity is stronger!!) ;
The interaction strength will also be inversely proportional to the square of the distance of the two masses: If we measure our weight on the surface of the earth and on Mt.Everest, the latter value will be smaller by a fraction due to our increased distance from the center of the earth.



$$F_1 = F_2 = G\frac{m_1 \times m_2}{r^2}$$

Fig.1.4 2 masses attracting each other.

This theory has been tremendously successful and even now applies in an enormous variety of cases, but has never answered a very fundamental question: What is the true nature of gravity?
Newton believed that gravity acts instantaneously. If the sun was to disappear, Earth, Venus, Mars and the other planets would "feel" its absence immediately and continue their paths in straight lines towards infinity.
However, Einstein opposed this belief. According to his Theory of Relativity, nothing could move faster than the speed of light in vacuum (c=3*108 m/s)

Teacher Guideline

For a simple introduction to General Relativity, visit:
http://ibphysicsstuff.wikidot.com/general-relativity
http://www.dummies.com/how-to/content/einsteins-general-relativity-theory-gravity-as-geo.html

If you have enough time, show your students the following video and have them observe the path from Newton to Einstein in the comprehension of the force of gravity!
https://www.youtube.com/watch?v=4yyb_RNJWUM

Spacetime

According to Einstein, the Universe has 4 dimensions. The 3 dimensions of space and the 4th dimension of time. Altogether, this "fabric" of the Universe is called: Spacetime!
Just like a trampoline curves when an object is placed on it, the same way a massive object will curve the spacetime around it, causing approaching objects to follow curved paths around it.
As the great physicist John Wheeler said: "Matter tells spacetime how to curve and spacetime tells matter how to move".

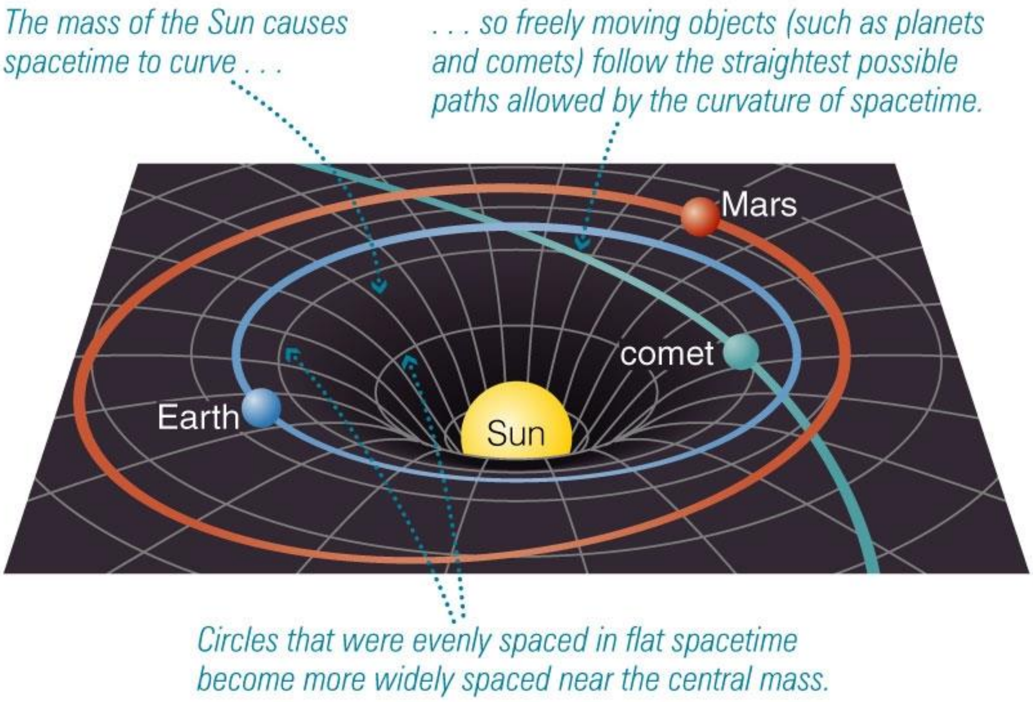


Fig. 1.5 Gravitational strength of the Sun on Earth, Mars and a comet. Spacetime view.

Even light follows curved paths when approaching a very massive object! Its trajectory is curved due to the curvature of the spacetime around the object!

Objects with increasing mass cause increase in the curvature of spacetime around them. If the object mass becomes higher than a value (about 3-4 times the mass of our sun) predicted by the General Theory of relativity, even incoming light will not be able to escape the gravity of the object.

The object has now become a "**black hole**", an object of extremely strong gravity which can suck everything in its vicinity.

Teacher Guidelines

Watch what happens when a black hole approaches a star:
https://www.youtube.com/watch?v=hu6hIhW00Fk

This documentary is an excellent review of the concept of spacetime.
https://www.youtube.com/watch?v=fUKN5oaP52s

Also, you are suggested to read 2 excellent popular science books on the field:
"SpaceTime Physics" by Taylor and Wheeler
"A Journey into Gravity and SpaceTime" by Wheeler.

An excellent activity which could be carried out to visualize gravity in 3 dimensions, you can show the students the following video:
https://www.youtube.com/watch?v=MTY1Kje0yLg
To carry out the activity by yourself and create your own "SpaceTime simulator", you can follow the guidelines provided in this link, at the "SpaceTime simulator" section:
http://prettygoodphysics.wikispaces.com/PGP-Modern+Physics.
A documentary about black holes can be found here
https://www.youtube.com/watch?v=JcD6la6o78I

Aaaand at Last! …Gravitational Waves

According to Einstein's General Relativity, an accelerating massive object will create ripples in the "fabric"of spacetime.

You can imagine this in a simple manner by considering the following:
Put your finger inside the water of a lake or the sea (or a bucket!) and start swirling it. The water around it will start “rippling” and these ripples will be emitted outwards in the form of water waves.

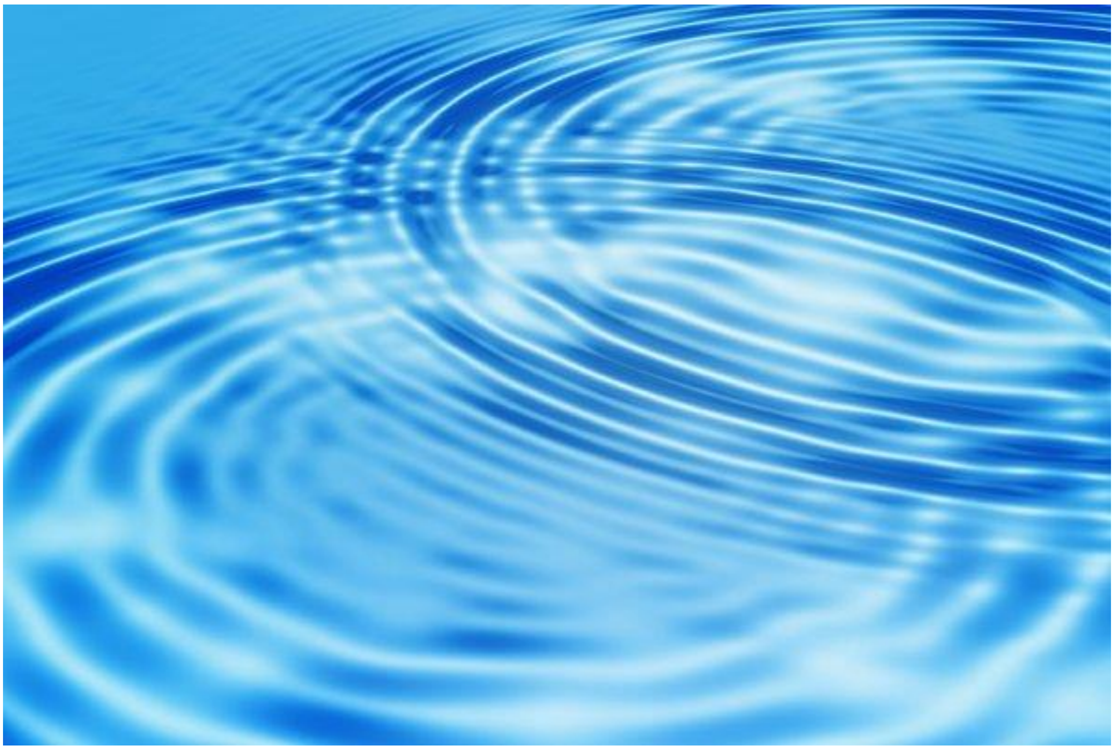


Fig. 1.6 Water waves created by two sources.

Likewise, accelerating masses will create ripples in spacetime which can travel throughout our universe with the speed of light.
These are the gravitational waves!
As every wave, they carry energy and momentum as well as a wealth of information about their source.
As these gravitational waves propagate they exert a periodic expansion and contraction of the spacetime they pass through in directions perpendicular to their direction of travel.

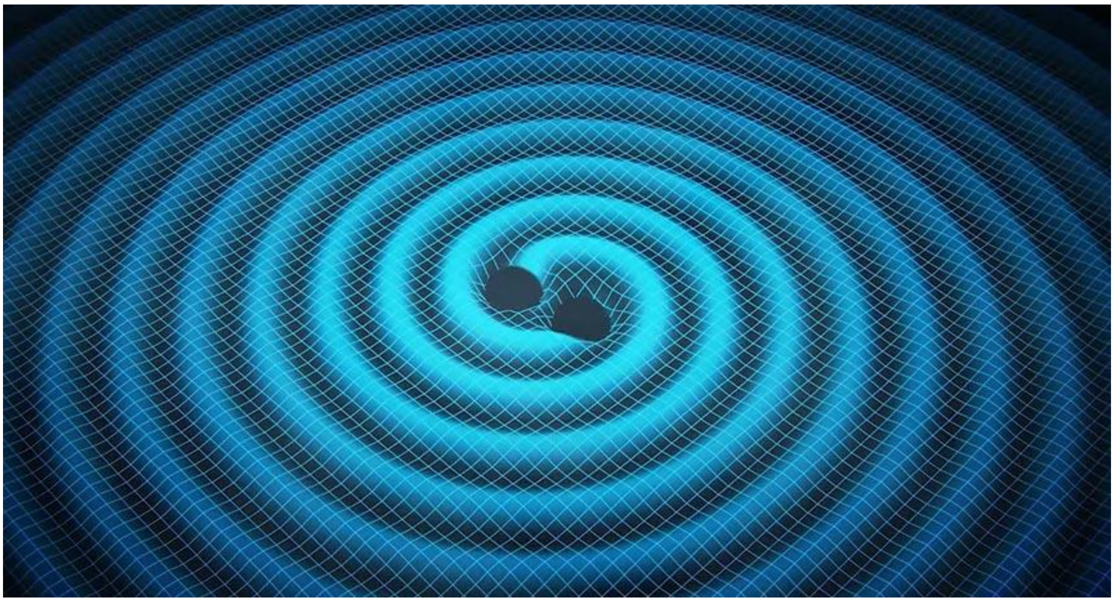


Fig. 1.7 Animation of two black holes merging and producing gravitational waves

Space is “stretched” in one perpendicular dimension and “squeezed” in the other.

This effect can be minuscule (actually, on earth we measured a distortion of which is a thousandth of the diameter of the proton!) and in order to detectit we need extremely sensitive detectors capable of measuring minuscule displacements.
Such detectors are LIGO and VIRGO.

Why is it important to detect gravitational waves?

Because they will open us a new window to the Universe! As Galileo turned his telescope to the sky in the 1600’s and revolutionized the science of Astronomy, by observing gravitational waves we might be able to observe the most violent phenomena in the Universe such as the merging of neutron stars, merging of black holes and even might get a glimpse of the gravitational waves which were produced immediately after the Big Bang!
What is more important though is not what we expect. But what we don’t expect! The Universe might turn out to be much different than we expected after all if we “listen” to it under the music of gravitational waves!

Teacher Guidelines

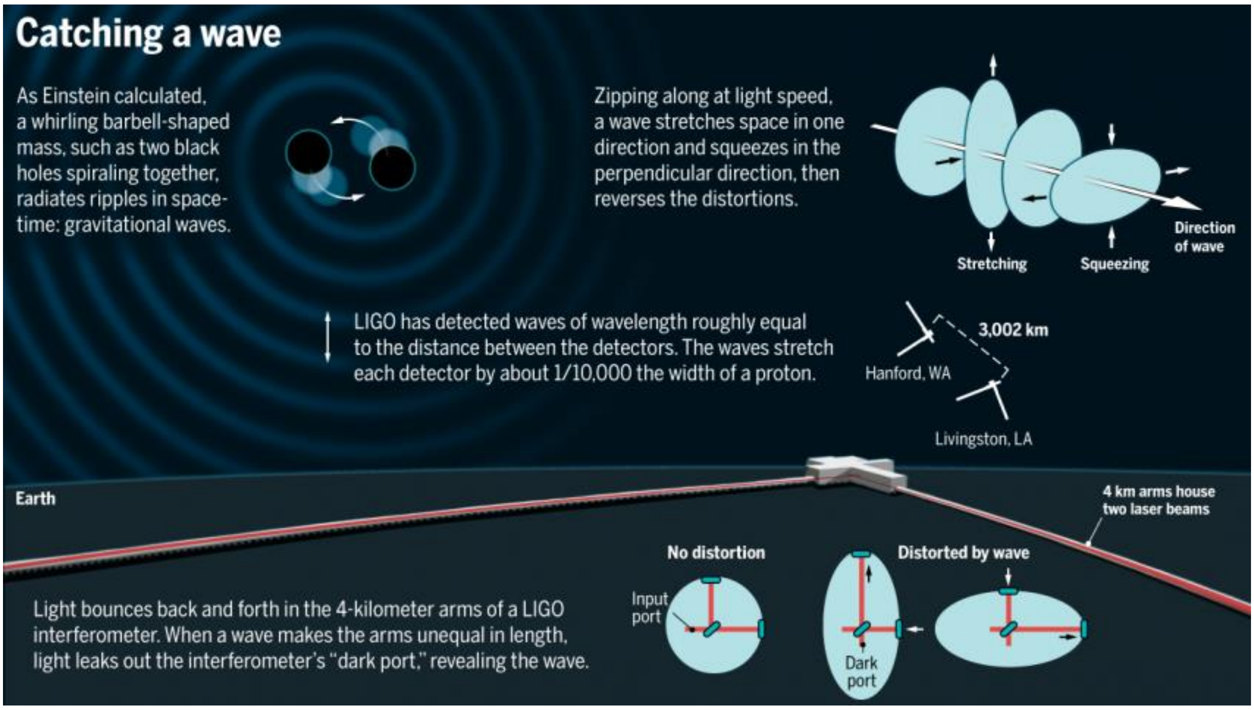
Even though the amount of energy emitted in the form of gravitational waves was so enormous, the energy that reached the earth caused distortions – think of displacements of a pendulum from its equilibrium- of the order of 10^-18 m !!
This can be understood by geometrical considerations: The amount of energy arriving on earth is only a fraction of the energy emitted in the form of gravitational wave energy at its source. If the distance between the Earth and the Gravitational Wave source is 1.3 billion light years, we might assume that the gravitational wave is emitted spherically (which is not the case).
The energy arriving at the detector can be roughly calculated as the ratio of the detector’s surface area to the total area of the sphere with the black holes as a center and the earth-

black hole distance as its radius.
This yields a result of 10^-5 J/m^2 for a gravitational wave with energy equal to 3 solar masses .
Imagine: 10^-5 J/m^2 cause a 10^-18m distortion on a 4 km long detector such as LIGO. This happens due to the "stiffness" of the vacuum →a large value of energy is needed in order to create minuscule distortions in spacetime.

Generation of Hypotheses or Preliminary Explanations

Now that we have gotten an idea of what gravitational waves really are, the next big question is: "How do we detect them?"

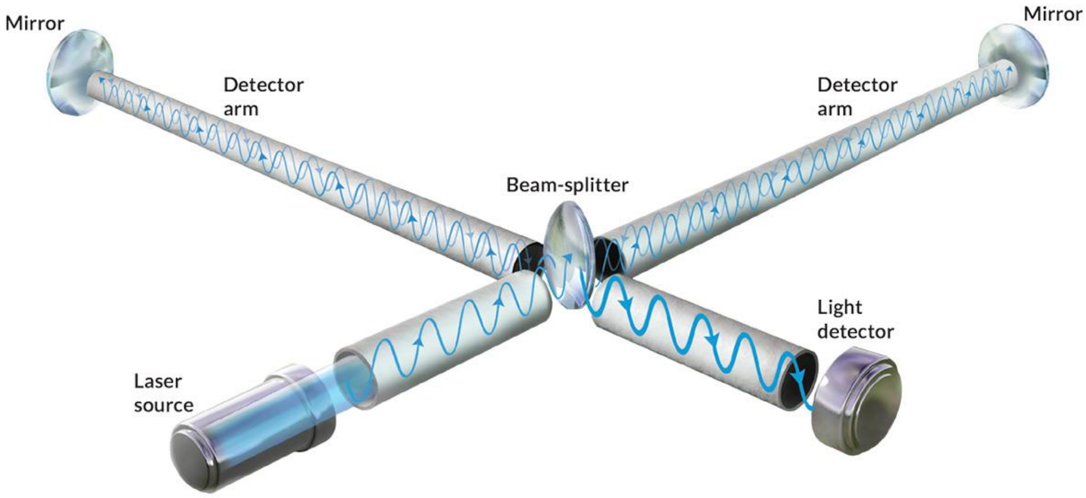
Below you can see the detection principle for a gravitational wave detector.



The LIGO and VIRGO setup is called an "interferometer", one of the most standard tools used in physics from the end of the 19th century.

It consists of 2, 4 (LIGO) and 3 (VIRGO) km long, arms vertical to each other. A laser source emits light which is splitted in two beams each one of which travels through each arm . The beams are reflected in mirrors which hang from sophisticated suspension mechanisms and are sent back to the splitter where they meet again and return to a photodetector.

Teacher Guideline
For more information on LIGO check this link: https://www.ligo.caltech.edu/page/ligo-gw-interferometer



What happens when the waves meet?
They interfere!

Below you can see the wave interference principle:

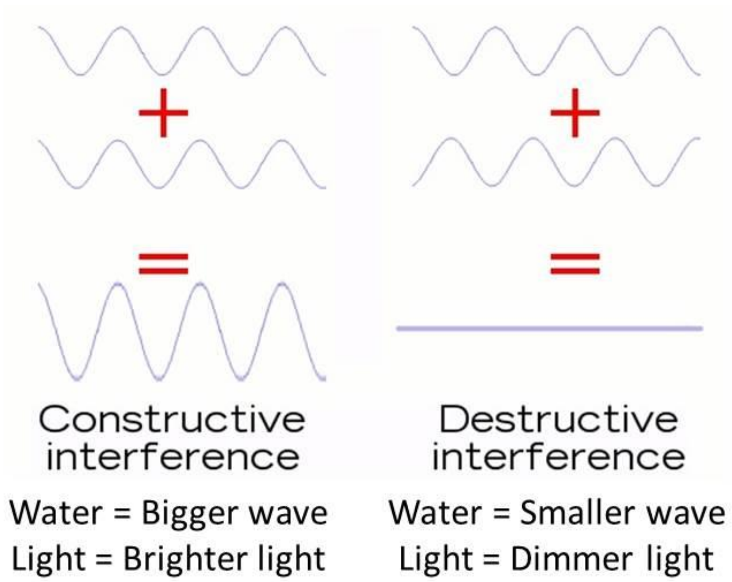


Fig. 2.1 Wave interference

When a wave crest arrives at our detector at the exact same moment with a similar wave trough, the two waves interfere "destructively". Our detector will observe nothing.

When a crest meets another crest at exactly the same instant in our detector, it will increase its amplitude. Therefore our detector will measure waves of twice the amplitude of each wave. This is called "constructive" interference.

As interference is a universal property of all waves, light which also behaves as a wave displays this property also.
When two similar light waves interfere constructively, our detector measures brighter light, whereas when they interfere destructively our detector measures fainter light.

The two laser beams interfere when they meet. If there is no distortion – thus the distances that the laser beams travel remain unchanged- then the laser beams are optimized to interfere destructively and the photodetector will measure nothing.
A tiny distortion will change their lengths of the arms of the interferometer, thus leading to a different signal in the photodetector!
This is how gravitational waves are being measured: By small changes in detected light!

Watch the following video in order to comprehend the detection principle behind the LIGO and VIRGO detectors.

https://www.youtube.com/watch?v=Uh1yBPLfcIs

Discuss the principle of interference and propose examples that you can use it in other physics experiments.

Teacher Guidelines

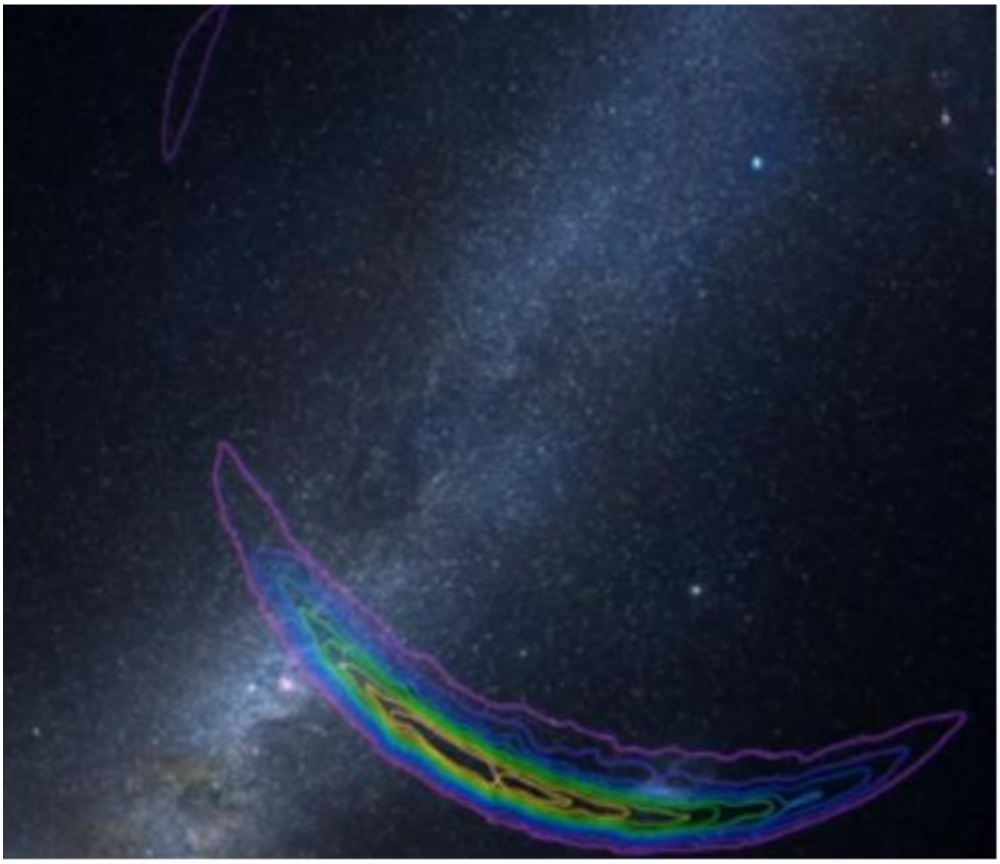
You can show this interactive http://www.gwoptics.org/processing/michelson01/ to your students in order to help them comprehend the physics of the interferometer.

A question that might come in mind is the following: Why does LIGO employ two detectors?
It is as simple as that:

Two detectors ensure that the effect observed is not due to some local disturbance in the area around one detector. If the two detectors observe the same signal at the same time then we have proof that the signal is more than just local noise.

Also remember: gravitational waves travel at the speed of light! This means that for a Hanford-Livingston distance which is of the order of 3000km the time it takes light to travel from the one to the other would be 7ms. This was actually observed proving that gravitational waves travel at the speed of light)

Furthermore, two detectors can show us roughly where our signal comes from as you can see in the following picture:



Three detectors may point us almost exactly to the source of the gravitational waves. (Thus helping scientists from other fields of astronomy such as X-Ray, Gamma or the newborn high energy neutrino astronomy search for followup signals from the same directions with their telescopes).

Another question that might pop in mind is: Why does LIGO have to be so big?

Every arm of LIGO's interferometers is as big as 4km.
This happens because the gravitational waves cause strains of the order of 10^-21.
(strain h= ΔL/L with ΔL being the distortion of an object and L the object's length).

The longer the object, the greater the distortion ΔL. Since this ΔL is what causes the phase difference of the laser beams which we will eventually detect, it has to be big enough to be within the limits of the detector's resolution.

LIGO's design resolution is of the order of 10^-19 m, therefore this is the minimum distortion one might observe for strains of 10^-21 m and arm length of 4km.

Model

Discuss: *What are the most important parameters that need to be taken into account to achieve sensitivities such as this of LIGO and VIRGO?*

LIGO operates two detectors. One placed in Livingston USA, and one in Hanford. The interferometer used by each LIGO setup is so sensitive that is capable of detecting distortions of the order of 10^{-18} m over 4000m of detector!

This equals to one thousandth of the radius of the proton! This sensitivity comes at a price though: If a scientist inside the lab claps his hands, the detector will measure a signal! Thus, the scientists trying to decipher the cosmic messages carried by gravitational waves have a very difficult and painstaking job to do: First, they have to exclude any possible sources of noise.

Any signal that might mimic the signal of gravitational waves by moving the gravitational wave detector's mirrors has to be removed from the data. Such signals might come from earthquakes, hurricanes, air conditioners or other sources. To achieve that, LIGO employs a series of seismometers on each of its two sites and has a dedicated seismology program.

Furthermore, many operational considerations are taken into account: The mirror materials, the suspension length of the pendulums that carry the mirrors, the laser power, the depth of the detector, its temperature and others.
All these parameters influence the sensitivity of the detector as well as the range up to which it can detect gravitational waves and it is these parameters that we are going to investigate in the following activity.

Planning and Experimenting

Plan Investigation

The following activity is divided in two parts:

In the first part, we will investigate how far can a gravitational wave detector "see" in the universe, by examining its operational parameters such as its temperature, the mirror material and others.

Teacher Guideline

In order to carry out the first part of this activity, the students will need access to PCs in order to play the "Space_Time Quest" game:

Download the game from this link: https://laserlabs.itch.io/spacetimequest

In order to run the game you must have a 32bit version of Java 1.5 (or higher) installed on an OpenGL capable computer.

From the Installation for Windows link you will be able to download a zip file with the .exe file.
Install the .exe file and choose the Language of your preference among the languages provided.

You can use this ebook as a reference: http://www.gwoptics.org/ebook/

In the second part, we will attempt find the noise of our setup for different gravitational wave frequencies.

This way, we will get a fundamental picture of some considerations under which such a supersensitive gravitational wave detector is constructed and of the difficulty in extracting a discovery signal from noisy data.

Perform Investigation

Part 1

- Divide in groups of 2-3 students per PC

- Download the “Space-Time Quest” application: https://laserlabs.itch.io/spacetimequest

- Go to your PC’s start menu → All Programs → gwoptics.org →
Space-Time Quest 1.2 and click on the version with the language of your preference.

- Enter your team’s name and your detector’s name.

- Follow the instructions provided until you reach your “Office”. From there you will be able to see that you have a starting budget of almost 100,000,000 pounds.

- You will be presented with three monitors: One about the Environment, one about the Vibration Isolation and one about the Optics.
Click on each monitor and browse through the options.

- You will observe that for each monitor you have to choose various components of your gravitational wave detector:

Fig. 3.1: The SpaceTime Quest interactive application

Each component, for example the laser, presents an option bar (for the laser it displays its power). As you optimize for each value, you will see that the cost scales accordingly and so does the complexity of the detector.

- Play with the parameters and with the help of your teacher, make sure that you comprehend the meaning of each of them.

- Every team should plan their own strategy on how to share their budget in each detector component. Make sure that you do not run out of money.

- When you are finished, go back to all the choices that you made and write their values at a dedicated blank page which you will need for the next parts of the activity.

- Go back to the Control Room and press the "Science Run" button:

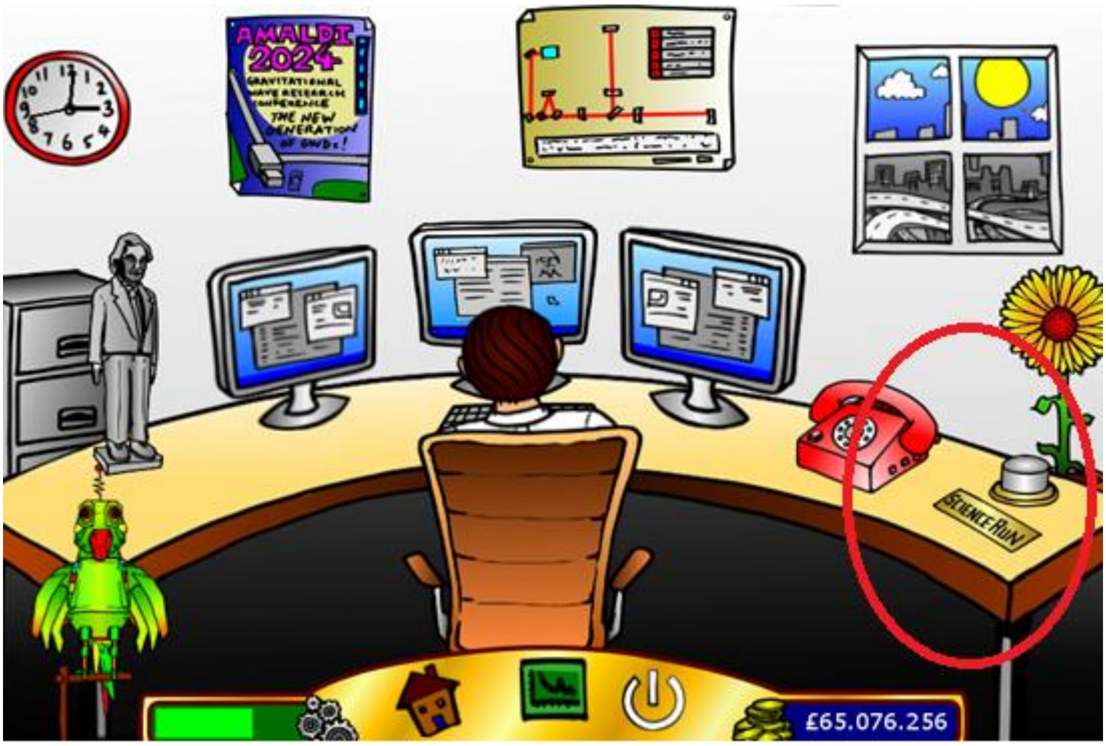


Fig. 3.2 The control room of the Space-Time Quest

- Note your score at your blank page.

- Discuss with your teacher.
  What is the optimal way to investigate the importance of each parameter you use?

Teacher Guideline

An idea would be to keep all the relevant variables at the 30% of their maximum value and observe the relevant reach.
Then, start varying one of them at a time keeping the rest constant.Observe how your reach changes with respect to each parameter in order to investigate the importance of it.
If you find the most important, then you can optimize it and with the rest of your money optimize the second most important variable.

- Repeat your measurement after discussing with your teacher and write down your new results.

- Write down the cost of your setup.

Part 2

Now, visit the SpaceTime Quest again and click on the middle image displaying your noise model:

Fig.3.3 The control room of the Space-Time Quest. Circled is the noise chart option.

Below you can see two sample graphs of the noise expected for different frequencies. (white) as well as its blow up in the factors that influence the noise results (different colors).

Fig. 3.4 The noise vs frequency for a set of parameter choices

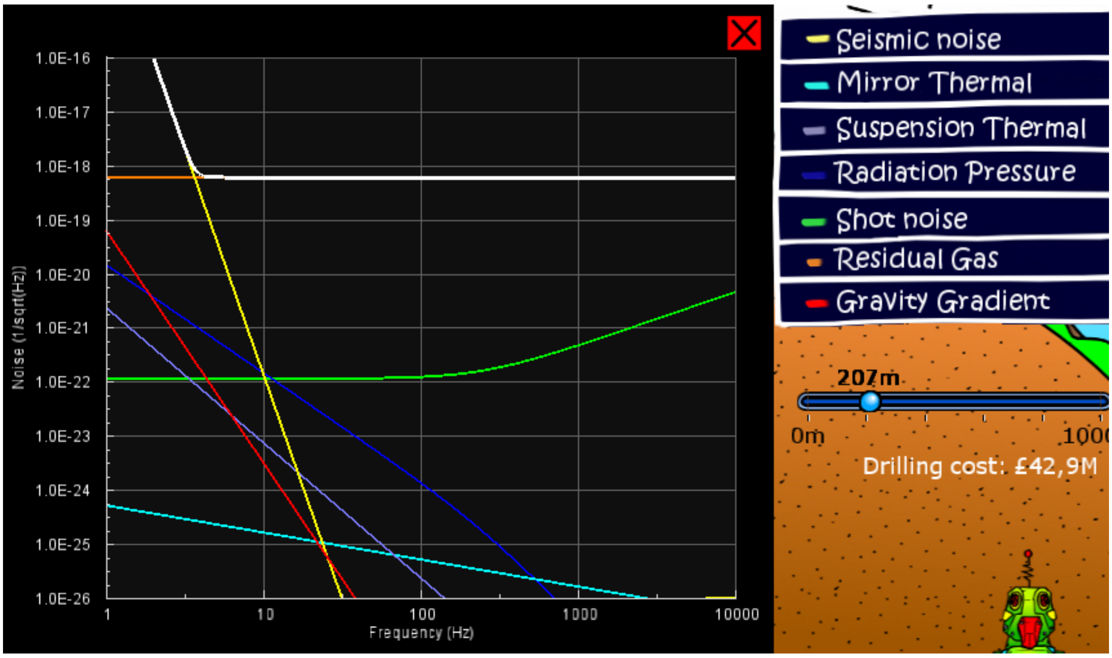


Fig. 3.5 Noise vs frequency for another set of parameter choices

Each team, take a snapshot of their respective plot and save it as a picture.

Teacher Guidelines

Make sure that you are familiar with the relevant parameters during the treatment of the noise:

For example:

- Seismic noise: Depth
- Shot noise: Temperature
- Residual Gas: Vacuum

Analysis and Explanation

Analysis: Analyze evidence to discover a possible answer

- Go back to your results sheet and copy your results to an excel file.

-Compare the reach results between each team and determine which parameters were the most crucial in obtaining a higher reach and thus seeing further in the Universe.

-Then, write at the dedicated excel column named noise the average value of total noise you measured.
The Gravitational Wave signal by LIGO was observed in the 35-250 Hz range.
Determine which one of your parameters is the most crucial in getting the lowest noise possible (and thus the greatest probability in detecting the LIGO gravitational waves).

- Now, all the teams combine your results in the Sheet 2 of the excel file.

- Find which team has the greatest reach, with the lowest possible noise and cost. This will be the winning team.

Explanation: Formulate an explanation based on the analysis of your evidence

Discuss the results of your research.

- Which parameter was the most crucial in reducing the noise of your detector in the 35-250 Hz interval we are interested in?

- Which parameter (or parameter combination) ensured the greatest reach of the detector in the Universe?
How far is this reach?
- How are the parameters defining the reach compared to the parameters that are needed to eliminate the noise? Is it correct that the lower the noise → the higher the reach?

- Transform your results in km using this formula:
1 kpc = $3.08567758 \times 10^{16}$ kilometers

and in light years, using this formula:
1 kpc = 3 261.63344 light years

- How does the reach you measured compare to the LIGO discovery of the black hole merger taking place 1.3 billion years away?

Consolidation Phase

Connect

Connect explanation with current scientific knowledge

Watch the following video which reviews the physics of gravitational waves:

https://www.youtube.com/watch?v=4GbWfNHtHRg

Teacher Guideline
You can have the students
watch this video of the historical press conference on the detection of gravitational waves (from 12:20 to 39:32) and express their views

https://www.youtube.com/watch?v=aEPIwEJmZyE

Reflect

Reflect on what you have learned from the learning process

Discuss : What do you believe we can learn from the detection of gravitational waves?

Use the Reflection tool to write your comments.

Communicate

Communicate and justify your explanation

The winning team will be the one to make a short presentation of gravitational waves in the rest of the classroom.
You will present what the gravitational waves are, how do we detect them and discuss why do you think they are important for science and astronomy.

Extra credit challenge!

Now that we have learned about sources of gravitational wave noise, we can go one step further and see how citizens can help scientists to identify noise patterns in a gravitational wave detector with the Gravity Spy Project.

https://www.zooniverse.org/projects/zooniverse/gravity-spy

Try it yourselves!
https://www.zooniverse.org/projects/zooniverse/gravity-spy/classify