Virgo Virtual Visit

Visit Virgo from your class

Orientation Phase

Orienting and Asking Questions

Provide Contact with the content and/or provoke curiosity

Virgo Interferometer

The detection of Gravitational Waves (GW) and the discovery of their visible counterparts in 2016-17 has been one of the major scientific breakthroughs of the 21st century so far.

GWs has been predicted by the theory of general relativity. With that theory, Einstein has changed our view of the force that apparently, physicists thought to know better: gravity.

He showed us that the concept of gravity that Newton introduced, had to be changed. Gravity is only a consequence of the change of geometry of space-time produced by all objects that have mass.

GWs are ripples of space-time, produced by the collapse of extremely dense astrophysical objects, like black holes of neutron stars. Those signals induce on the matter small variation of length (less than 10^{-18} m at 100 Hz) that can be detected only by the world most precise rulers, the interferometers.

Imagine to drop a glass of water in the ocean. Due to that the global level of all the seas on the Earth will increase by an extremely small amount. A rough estimate would lead you to this amazingly tiny displacement: 10^{-18} m!! This length is equivalent to the sensitivity of current gravitational wave (GW) detectors.

There only a few instruments on Earth that can reach such amazing level of sensitivity: the two LIGO detectors in the USA and Virgo, in Cascina, Pisa, Italy.

These detectors are huge! They have the shape of an L with a length of several kms on each side. Virgo, viewed from above in figure 1, is 3 km long while LIGO has of 4 km length.

Figure 1 Aerial View of Advanced Virgo (EGO/Virgo collaboration)

Virgo and LIGO changed the history of science twice: first, when they measured for the first time the gravitational waves in 2015, discovery that was awarded with the 2017 Nobel prize in physics, then, when, on August 17th, 2017, they were able to detect the signals produced by a binary neutron star.

This kind of binary star, composed by two extremely dense objects made only by neutrons, collapsing becomes a single object that emits gamma rays and visible light. The radiation produced by these strange objects were never detected before. In August 2017 Virgo and LIGO were able to localize the position of the gravitational wave source with such a precision that all the telescopes of the world were able to point a very narrow region of the sky. They all found a new star as shown in figure 2.

This discovery marks the beginning of a new era in the history of astronomy. Thanks to the gravitational waves now we are not only able to study the astrophysical objects already present in the Universe, we can also predict their birth!

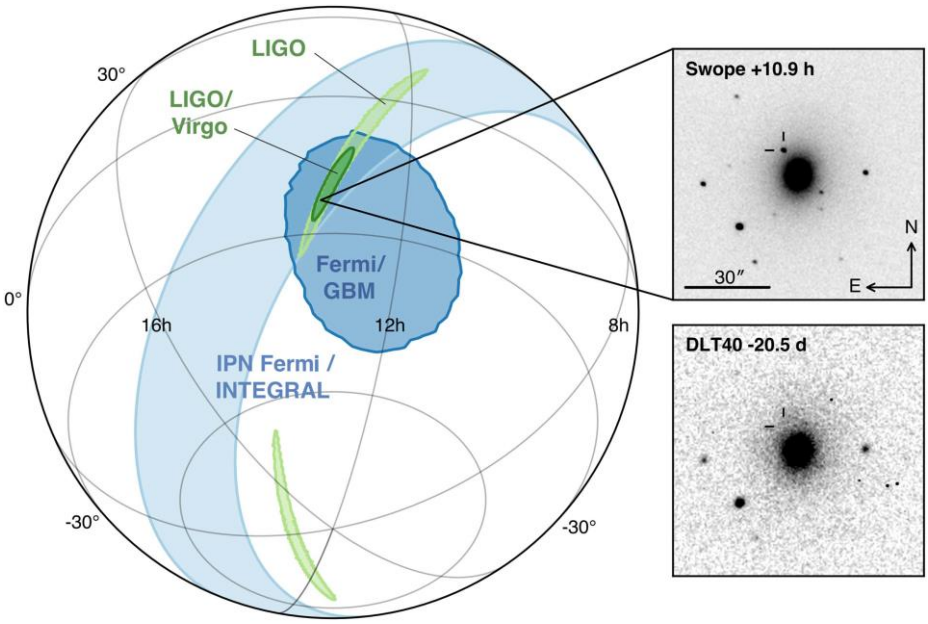

Figure 2 The impressive contribution of Virgo to the localization of the star, shown in top right plot, that was born after the GW signal of August 17th 2017.

Teacher Guidelines:

You may begin your lesson using the set of slides that will be provided. Trigger a small conversation with your class by asking your students the questions mentioned below and others like them.

- What is gravity? What Einstein understood about gravity?
- What are black holes? What are neutron stars?
- What are gravitational waves? Who won the 2017 Nobel prize for physics and why?
- What is Virgo?
- How does it work?
- Let's visit the interferometer!!

The answers will be given in the next sections and will constitute the introduction to the virtual visit.

Exploratory Phase

Question or Statement

Define Goals and/or questions from current knowledge

- What are gravitational waves?
- How does a gravitational wave detector work?
- What are the problems that we need to tackle in order to build it?

Generation of Hypotheses or Preliminary Explanations

Teacher Guidelines:

- Very nice explanation by B. Greene interviewed in a talk show: https://www.youtube.com/watch?v=ajZojAwfEbs
- R. Weiss talks about relativity and GWs: https://www.youtube.com/watch?v=x7rjlm4SH5U
- Simple Explanation with comics: https://www.youtube.com/watch?v=4GbWfNHtHRg
- Simple Explanation with sketches: https://www.youtube.com/watch?v=YHS9g72npqA

Step 1

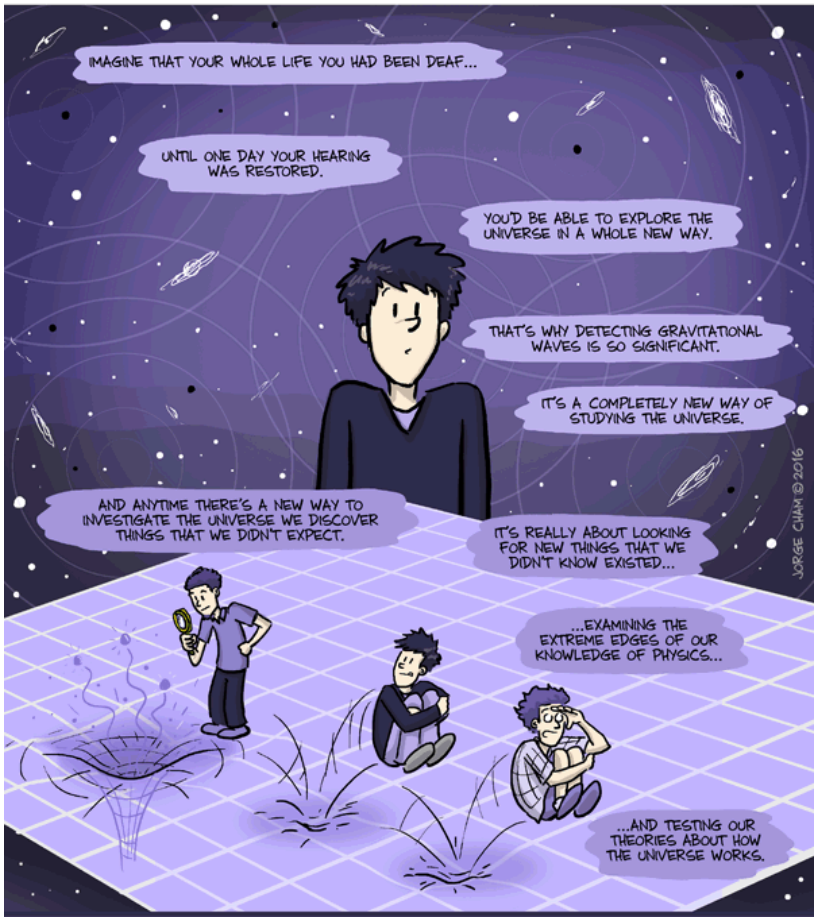

Figure 3 Astronomy status after gravitational wave detection.

What are gravitational waves?

Gravitational waves can be interpreted as the music of the universe. These signals have been predicted by general relativity, a scientific theory, widely confirmed experimentally, that Einstein finished conceiving almost exactly 100 years ago, in 1916.

Relativity provides the most accurate description available of the force that holds the whole Universe together, gravity. This force, studied since ancient times, reached its first mathematical formulation with Isaac Newton's Principia Mathematica of 1687. This description assumed that massive bodies were attracted by a force, inversely proportional to the square of the distance, which acted instantly on them. However, Einstein was the first to understand that no signal can propagate in nature at a speed higher than that of light. He also understood that time is not an absolute quantity but depends on the reference system in which we are. In particular, the faster we move, the slower the hands of our watch will be ticking. Putting these and other concepts

together, Einstein came to a purely geometric description of gravity. He understood that this force is simply the effect of the curvature of the intimate structure of the universe, the so-called space-time.

We can imagine space-time as an extremely rigid mattress, as big as the universe (figure 4). In the absence of massive bodies on it, the mattress is perfectly flat; but as soon as we put down a heavy object, like a bowling ball, it will curve near the object, forcing every lighter body, for example a ping-pong ball, to slide towards it or to spin around it. In other words, light bodies tend to move towards heavy bodies, not because they are attracted by a force, but because bodies of small mass move through space-time that is deformed by bodies of large mass.

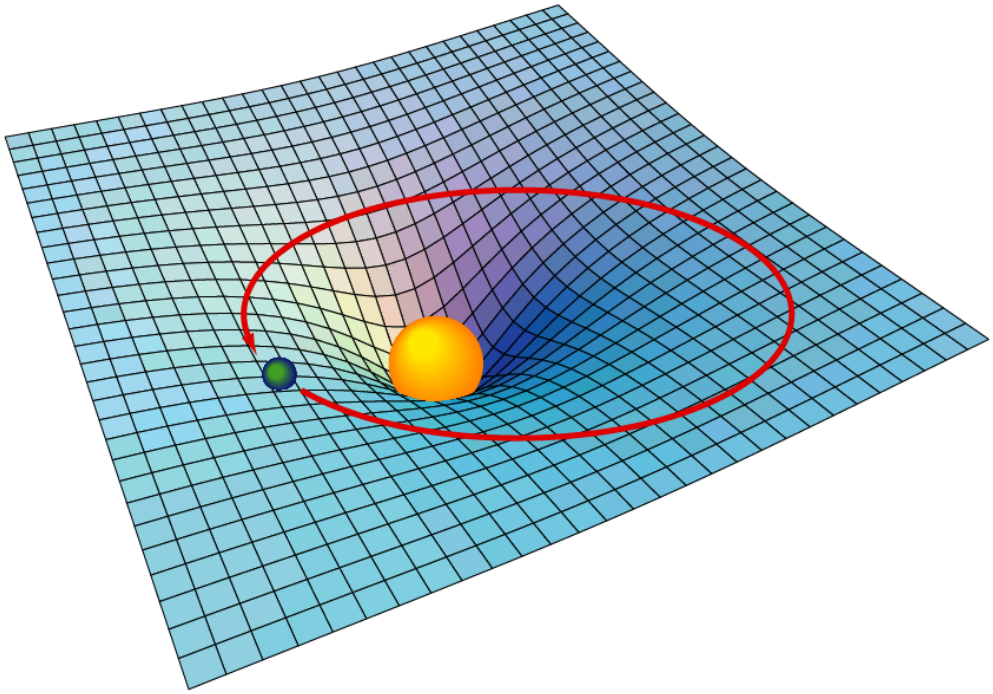

Figure 4 Space-time representation. A planet is orbiting around the Sun due to the geometrical deformation produced by the mass of the star.

If the mass of the objects and their speed are constant, the curvature produced does not change over time. However, if we imagine, for example, to instantly remove a massive body, the mattress, however rigid, will start to oscillate for a short time. These oscillations are called gravitational waves.

The astronomical events that produce gravitational waves of greater intensity are the explosion of supernovae or the fusion of the remains of dead stars like neutron stars or black holes. Near these latter objects the gravitational field is so intense that the light itself cannot escape them.

The effect of gravitational waves on matter is to dynamically distort space-time at the wave frequency, changing the size of the bodies the wave crosses. This deformation attenuates linearly with the distance and becomes very small when it reaches us. In fact, when Einstein foresaw the existence of gravitational waves, and calculated its

effect, he concluded that no detector would be ever built sensitive enough to reveal them.

Step 2

We can actually detect gravitational waves!

Fortunately, Einstein was wrong: today three powerful optical instruments, called interferometers, can observe these signals produced by the universe and to localize their origin.

Two of these instruments, both called LIGO, are in the United States, one in Louisiana, the other in the state of Washington, while the third, Virgo, is in Italy, in Cascina, in the province of Pisa. The three experiments work together as a single detector sharing data.

Virgo was inaugurated in 2003 and was born thanks to the collaboration between the Italian National Institute for Nuclear Physics (INFN) and the French equivalent of the CNR (CNRS). Today, 400 physicists, engineers and technicians from five countries work there in turn. The center is administered and managed by a consortium called European Gravitational Observatory (EGO).

Let's understand how an interferometer work!!

A laser interferometer is a very high-precision ruler!

The operating principle of all interferometers is quite simple (see figure 5). The light produced by a very powerful LASER (25 W for Virgo) passes through a semi-transparent mirror called beam splitter.

Why do we need a laser?

Using a LASER instead of a standard light source – like a LED for example - has several advantages. The main one is that the energy of the beam produced is concentrated almost entirely at one single frequency.

How does the interferometer work?

Half of the radiation emitted by the LASER crosses the beam splitter while the other half is reflected at 90 degrees. The two perpendicular beams run along the two arms of the L, 3 km long, at the end of which are reflected on two mirrors; they then go back, cross the beam splitter again and recombine on an optical bench equipped with a series of light sensors, called photodiodes.

The optical scheme is designed to have the two beams in phase opposition when they are recombined. The interferometer therefore works in an operating condition of destructive interference called dark fringe.

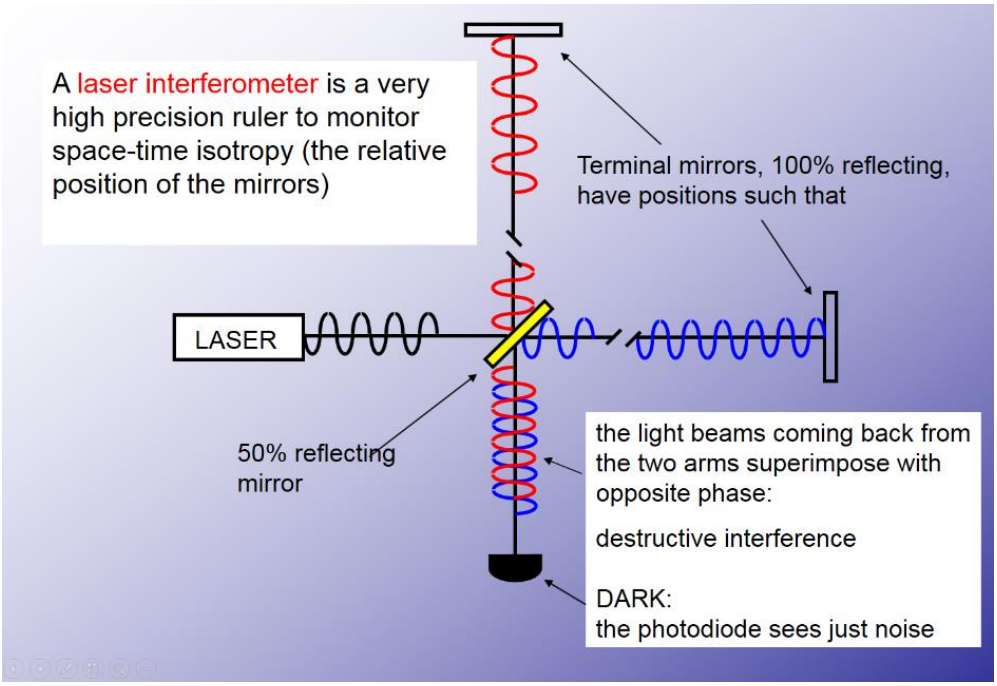

Figure 5 Sketch of a Michelson interferometer

Step 2

What happens when a gravitational wave arrives?

The incoming gravitational wave, deforming the space-time, produces a displacement of the end mirrors that misalign slightly the interferometer from the condition of dark fringe, producing a very weak light. This signal, that is measured by the photodiodes, contains all the information of the gravitational wave.

Each of the interferometer arms therefore works as a large 3 km ruler capable of measuring very small changes of its length. The length variations that Virgo and LIGO can measure are of the order of 10^{-18} m at 100 Hz, a quantity 1000 times smaller than the proton radius!

Teacher Guidelines:

- The sound of gravitational waves https://www.youtube.com/watch?v=QyDcTbR-kEA

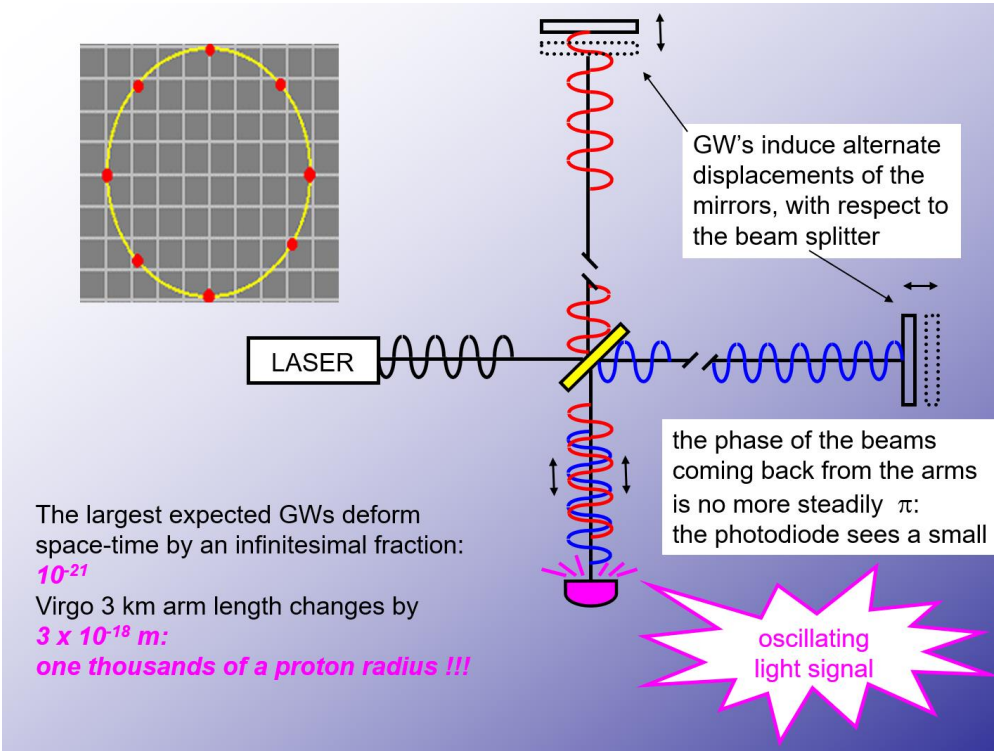

Figure 6 Effects of gravitational waves on an interferometer

Step 3

How small is 10^{-18} m?

Imagine to drop a glass of water in the ocean. Due to that the global level of all the seas on the Earth will increase by an extremely small amount.

Let's assume that the Earth is a sphere having 70 % of its surface covered by water:

$$S = 70\% \text{ of } 4 \times \pi \times r^2 = 0.7 \times 4 \times 3.14 \times (6.37e6 \text{ m})^2 \sim 3.6e14 \text{ m}^2$$

A volume of a glass can be assumed to be around

$$V = 25 \text{ cc} = 0.25e\text{-}3 \text{ m}^3$$

The ratio is therefore

$$V/S \sim 1e\text{-}18 \text{ m}$$

That is the same displacement sensitivity of modern GW detectors!!

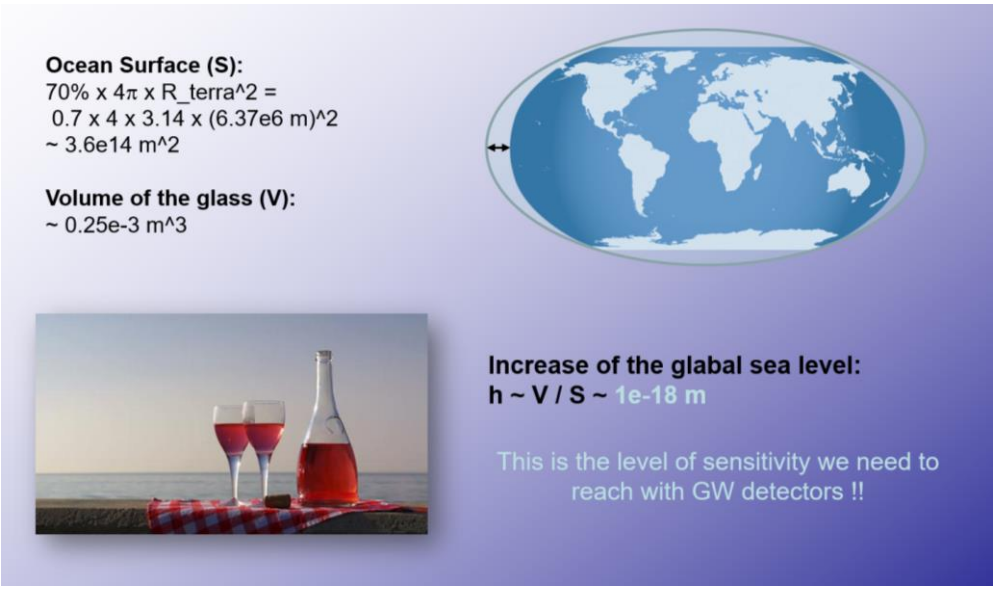

Figure 7 The impressive sensitivity of modern GW detectors

What are the noise sources of the GW detectors?

Many phenomena can mimic the effect of a gravitational wave by moving the interferometer mirrors or disturbing its beam.

Here you have a list of most important ones:

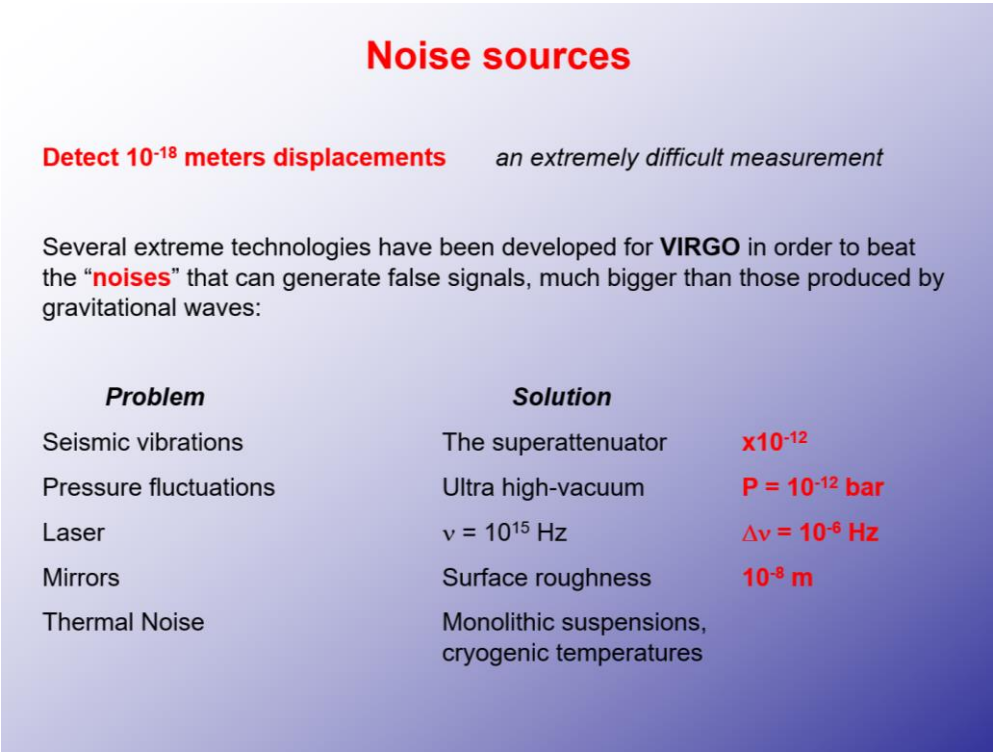

Figure 8 Noise sources of a GW detector

Step 4

The Seismic noise and the Superattenuators

Let's discuss about it

- What is seismic noise?
    - What happen during an earthquake?
    - Is the ground moving when there are no earthquakes? If yes, why?

The ground moves continuously even when no earthquake is occurring. While the high frequency part (above 1 Hz) is caused by human activity, the low frequency noise is due to excitation produced by the sea waves on the earth crust.

Seismic noise constitutes the main limitation at low frequency for the detection of gravitational waves on the Earth.

For this reason, all the main optical components of the interferometers must be suspended from ground. Virgo uses an 8m-long chain of pendula called Superattenutor. This mechanical device can reduce the motion of the ground by a factor 10^{12} that is a million of a million times!!

Teacher Guidelines:

- Wikipedia
  https://en.wikipedia.org/wiki/Microseism

- Simple and well done paper on Science magazine:
  https://science.sciencemag.org/content/307/5710/682

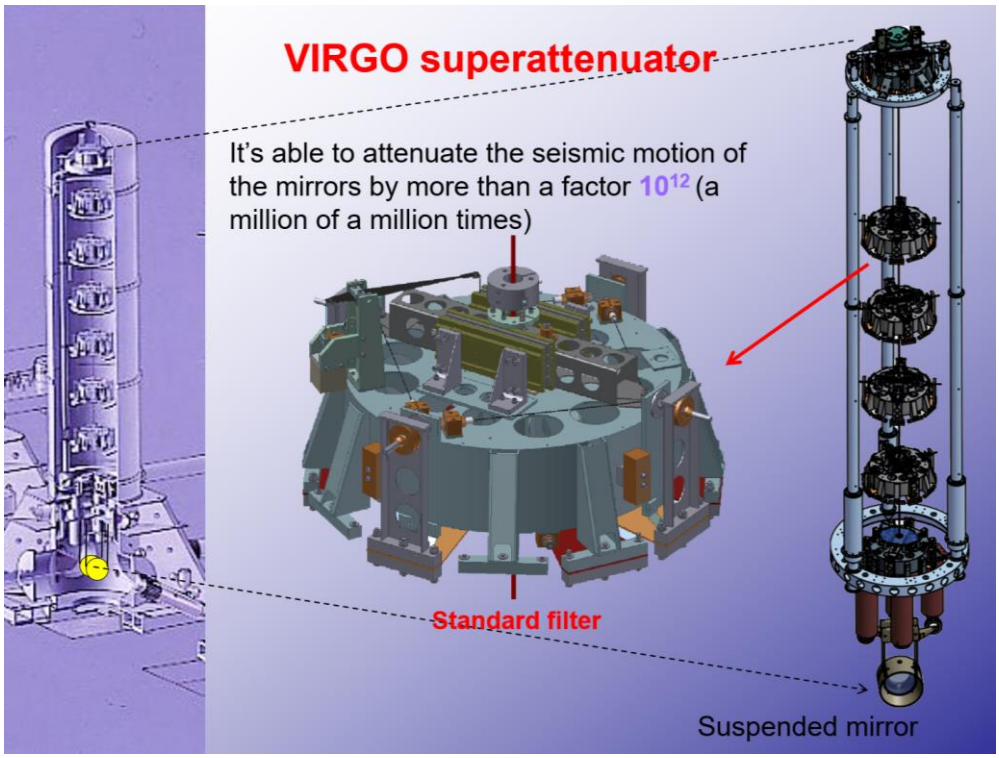

Figure 9 Virgo impressive seismic isolator: the superattenuator

Step 4

How a modern gravitational wave detector is made?

As shown in figure 10 a modern gravitational wave detector like Advanced Virgo is much more complex respect to a Michelson interferometer.

However, the basic parts are still there

- The LASER
- The Beam Splitter (BS)
- The end mirrors. They are called North End (NE) and West End (WE) since the arms are approximately aligned with North-South and East-West directions
- The photodiode

The input mirrors, called North Input (NI) and West Input (WI), constitute the most important difference: at the beginning of each arm, a mirror almost completely transparent is added. This trick allows to keep the light confined inside the arms, virtually increasing the effective optical length by a factor of about 400.

This means that Virgo interferometer is equivalent to a Michelson interferometer with 400 x 3 km = 1200 km long arms!!

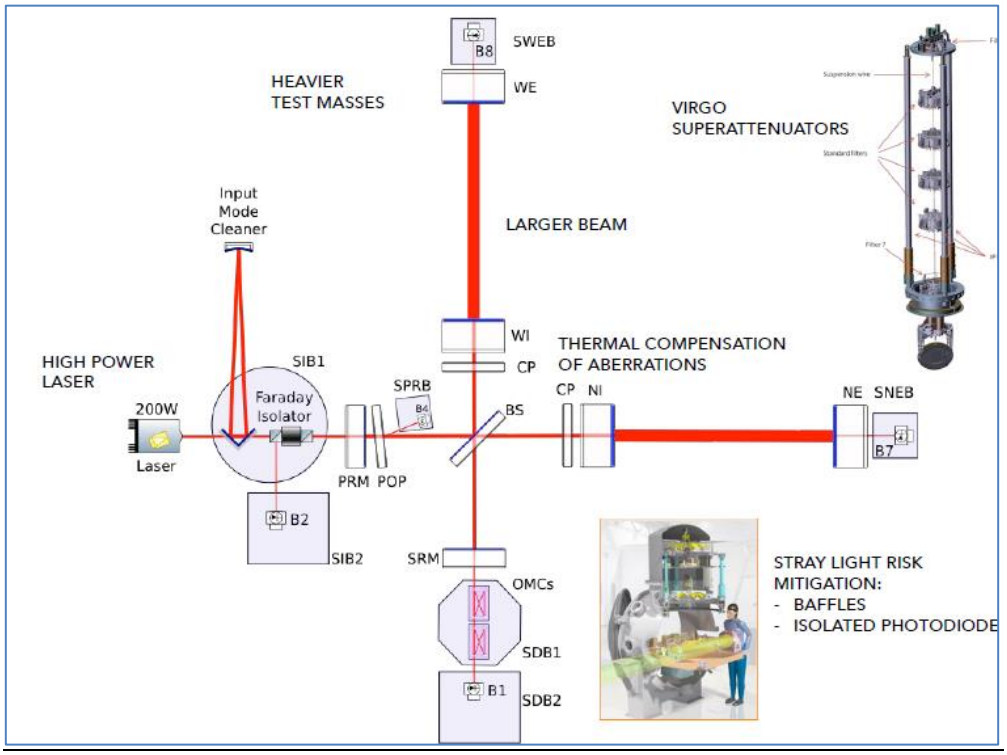

Figure 10 Optical scheme of Advanced Virgo, a modern GW detector

Teacher Guidelines:

- Very good video made by NIKHEF about Virgo: https://www.youtube.com/watch?v=h_FbHipV3No

Evidence

Perform Investigation

Option 1: Standard Virgo visit

Exactly like in a standard Virgo visit the teacher guides the students inside the main detector buildings asking questions

Option 2: The game

Let's visit the heart of Virgo, the only detector in Europe, able to see GWs!

Are you able to recognize Virgo components?

You can divide your students into groups of four students and start playing this game.

Where is the laser?

Where is the beam splitter mirror?

Where is North Input mirror?

Once you have identified the parts you can start playing. Virgo is like a big labyrinth. You need to crouch and jump in order to reach its components.

The team that reaches the target won points.

Analysis and Explanation

Analysis: Analyze evidence to discover a possible answer

Start exploring the interferometer using figure 10 as a treasure map.

Can you orientate in the central experimental building?

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

Start identifying a single optical component and align your map!

Consolidation Phase

Connect

Connect explanation with current scientific knowledge

Can you appreciate now how big the detector is?

Can you understand how difficult is to find a 30 cm mirror at the end of a 3 km tube?

You can now compare Virgo scheme to LIGO ones. Let's search on the web for pictures and data about the US-based detectors.

Communicate

Communicate and justify your explanation

Summarize what you learned in the entire lecture with a presentation.

The presentation can be about any of the many concepts you have learned.

Just choose one!! Confront your ideas with your classmates!

Reflect

Reflect on what you have learned from the learning process

Reflect on your virtual journey in the world of the gravitational wave.

What surprised you the most?

Do you understand now why it took 100 years to detect gravitational waves?

Do you now realize the importance of gravitational waves for the future of astronomy?

Implementation

To develop the application, we have been profiting of the already existing 3D CAD models developed in Virgo for different purposes. To allow users to experience those models as a dynamic and interactive virtual environment we used a 3D gaming software (the Unity Game engine) as the design software.

For creating a Virtual Tour of the Virgo Central Building (CEB) we started from an AutoCAD model of the building developed to support different civil and mechanical works (cable tray length assessment, feasibility study for the long towers scaffolding procurement, etc.).

Those models needed to be imported within the Unity Game engine and unfortunately, a direct import from civil/mechanical 3D CAD and Unity is not possible.

We have then resorted to import those models inside the Blender 3D creation suite (using one of the formats supported by it such as .obj, see Fig. 1) and then export from there a model that could be imported from Unity.

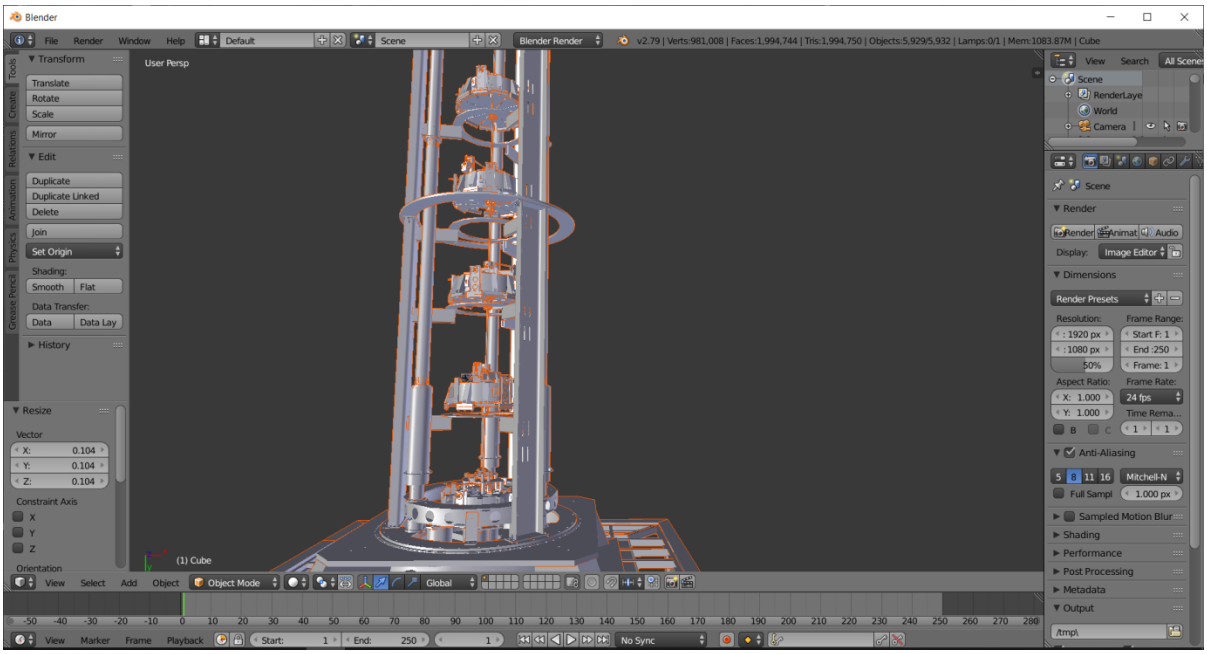

Figure 11: 3D CAD model importing in Blender

Once the model is available in Unity then all its powerful built-in functionalities are at disposal, such as rendering engines, navigations, and also interaction tools. Also the already available Virtual Reality extensions can also be exploited for providing a fully immersive experience. In particular Unity provide full support for high performances Virtual Reality headset such the Oculus (we have available few units, one of them a DK2 one) or low cost ones composed by a smartphone and a Google cardboard (https://vr.google.com/cardboard/).

As soon as we were able to finalize the needed Unity installation/customizations for the functionalities we mentioned, and imported the CEB model, by simply adding a First-Person Shooter (FPS) controller component (Fig.2) we could immediately make the model available for walkthrough.

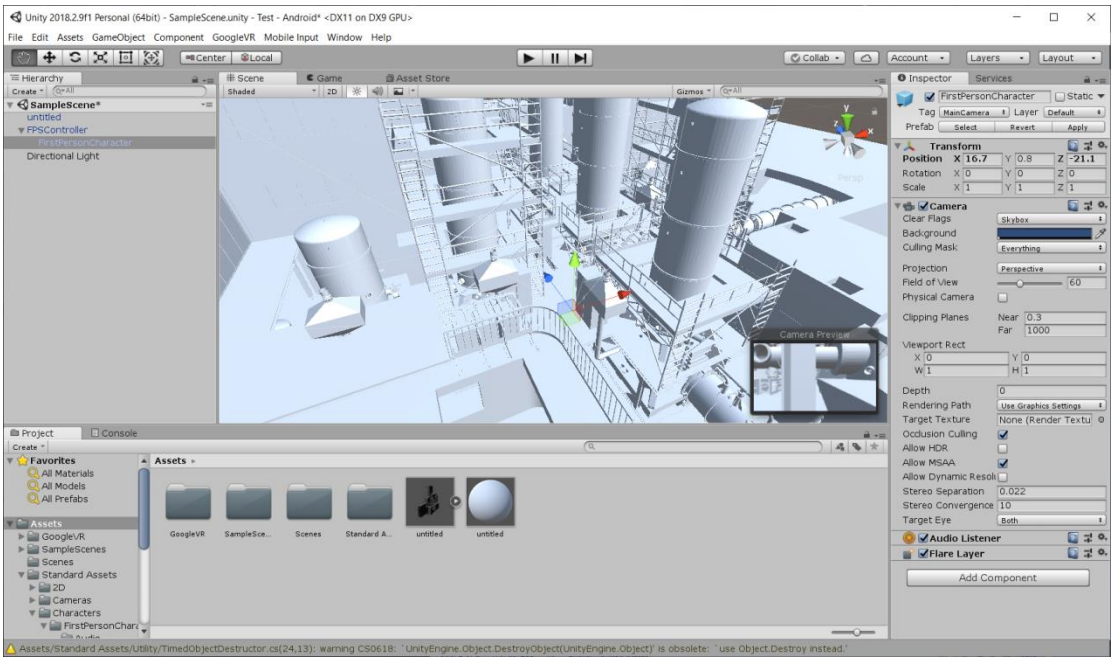

Figure 12: CEB model imported in Unity and FPS component added

At this point, the Unity ability to deploy to a wide variety of target platforms, using the same code and assets, can be exploited. As shown in Fig. 3 Unity currently support the exporting to Desktop (Windows, Mac, Linux), Android, iOS, WebGL and many gaming platform.

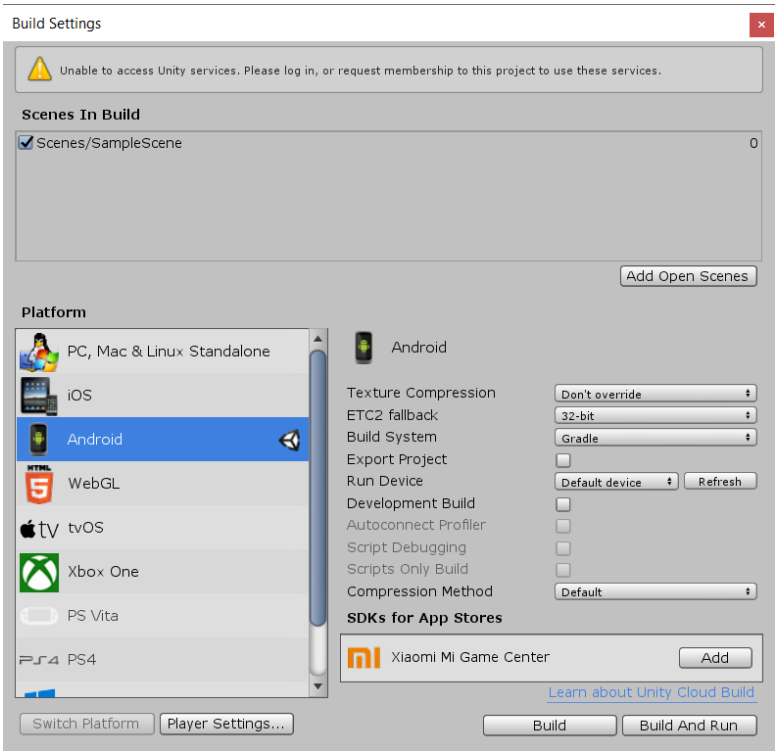

Figure 13: Unity supported target platforms

We have proceeded with a web based (WebGL) export and made it available on one of the Virgo site machine and verified a good level of responsiveness for smooth walkthrough (Fig. 4)

Figure 14: Walking around on the Virgo CEB

We are at the moment proceeding with iOS and Android exports (both plain and for Google VR Cardboard) in order to check for performances and make comparison with the WebGL/browser-based solution.

We believe that what currently achieved could be enough for a preliminary Frontier demonstrator and we are pursuing the following development path:

- Import further 3D CAD models, possibly including higher level of details on the mechanical/optical components
- Verify the possibility to import also components colors/textures from the original 3D models
- Define and check implementation effort of further functionalities such as:
    - improved and realistic textures
    - definition of a tour itinerary including interactive text and audio descriptions
    - addition of accompanying avatars
    - etc.