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Ripples in Space-Time: Demystifying Gravitational Waves

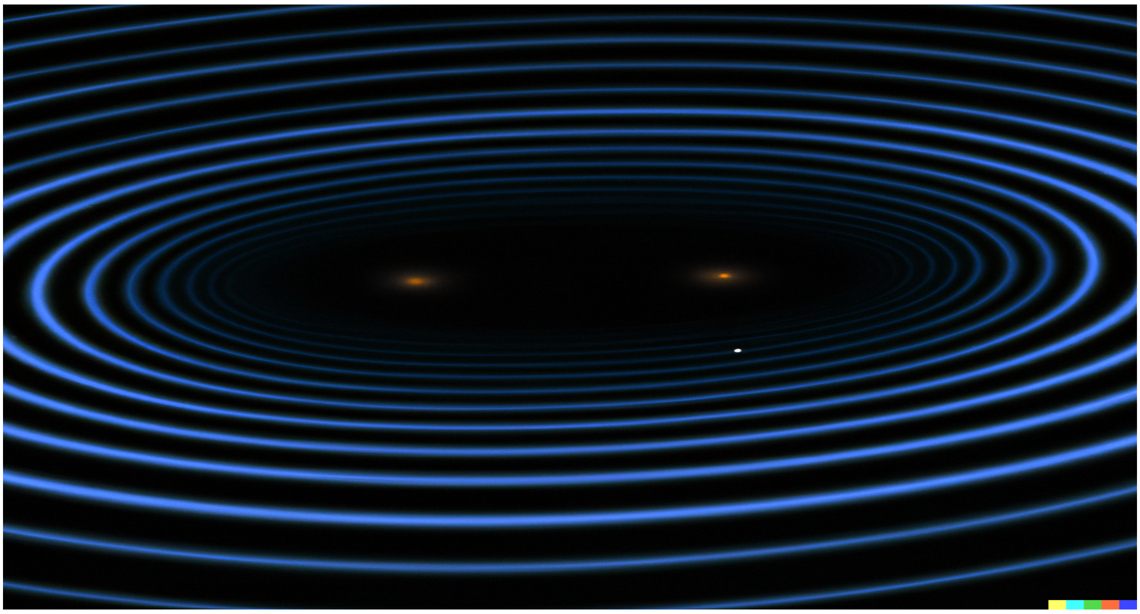

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Table of Contents

List of Figures

List of Tables

Ripples in Space-Time: Demystifying Gravitational Waves

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Abstract

This paper presents the development of an educational exhibit for the visitor gallery of the ETPathfinder, a crucial precursor project to the future Einstein Telescope (ET). The exhibits aim to demystify gravitational waves and engage non-scientific audiences, including children and dignitaries, by providing an accessible and immersive experience. The exhibits address the importance of public support and communication in scientific projects, drawing lessons from the cancellation of the Superconducting Super Collider. Furthermore, the strategic positioning of the region through the ETPathfinder is discussed, highlighting the short-term benefits of accelerated research, network expansion, and innovation. The exhibits also play a pivotal role in strengthening cooperation among various stakeholders in the region, showcasing the availability of expertise and the willingness to collaborate for the ET. Overall, this project underscores the significance of effective public engagement and collaboration in fostering scientific literacy, securing support for major scientific endeavors, and maximizing the potential of the ET for scientific, economic, and societal advancements.

Keywords— *Andragogy, Education and Outreach, ETPathfinder, Einstein Telescope (ET), Gravitational Waves, Non-scientific audiences, Public engagement*

1 Introduction

The Einstein Telescope, henceforth referred to as the ET, will be the first third generation gravitational wave detector. A new generation of gravitational wave detectors is required to further advance science, since it is expected to allow measurement of stochastic background waves. The location of this detector is currently to be decided between the Netherlands (in the South of Limburg) and Italy (Sardinia), both of which have invested a significant amount of money into the project [1, 2].

The Netherlands has strengthened itself as a candidate by building the ETpathfinder, a research and development facility that develops the technologies needed for the ET. The ETpathfinder consistently attracts international scientists and facilitates collaboration between countries, even before the ET's final destination is decided [1].

A key role of the ETpathfinder is to coordinate stakeholders across the region, creating a conducive environment to collaboration and cooperation. Having a cooperative effort between countries and knowledge domains strengthens the regional consortium for the ET, particularly when companies show strong interest and there is a well-established working relationship between countries [1].

However, whilst science as a whole is often regarded as purely an objective pursuit of knowledge and inquiry, more often than not the advancements of scientific projects and especially large scale projects inherently have political aspects [3]. The construction of scientific facilities requires a significant commitment of resources including funding, technical knowledge, and public backing. As a result, political dynamics, governmental policies, public opinion, and stakeholder interests inevitably influence decision-making and the execution of major projects. The future of pioneering scientific undertakings is frequently decided within this intersection of scientific ambition and political realities.

One notable example and cautionary tale is the Superconducting Super Collider's (SSC) cancellation in the 1990s. Insufficient communication and outreach efforts led to significant opposition and public skepticism about the SSC, a particle accelerator of unprecedented magnitude. Eventually, in the absence of support, the project ultimately failed, resulting in missed opportunities for groundbreaking discoveries in particle physics [4]. This example highlights the importance of public perception and political will in shaping scientific endeavors. The successful communication of science can ensure the realization and development of ambitious projects such as the ET [1].

Hence, in order to bridge the gap between the scientific research and the public support necessary to actualize the ET, it becomes imperative to examine science communication in the context of gravitational waves. Especially aimed at students and politicians. Since students represent the future generation of scientists and policymakers, it is crucial to communicate the significance and potential impact of gravitational wave research. Moreover, engaging politicians in science communication initiatives is essential to ensuring the ET receives continued funding and support [1].

To that extent, the paper aims to employ the scientific communication of gravitational waves to engage and educate students and politicians, fostering their understanding, support, and enthusiasm for projects like the ET.

2 Background

In this section, an overview of the most important background information pertaining to gravitational waves (GWs) is presented. In subsection 2.1, the significance of GWs is discussed. After this, their creation (subsection 2.2) and propagation (subsection 2.3) are covered. Lastly, subsection 2.4 discusses the detection of GWs.

2.1 Significance of Gravitational Waves

Firstly, it is relevant to discuss further why the detection of GWs is important to our understanding of the universe. Simply put, gravitational waves allow us to identify the location and types of relatively rare cosmological objects and may provide a more nuanced insight into the physics of the early universe [5]. Einstein's theory of general relativity was used to predict gravitational waves and their properties. Therefore studying GWs helps us further confirm or disprove different predictions made by Einsteins General theory of relativity or explore its limitations.

For approximately 380,000 years after the Big Bang, the universe consisted of a dense, hot, primordial plasma comprised of free photons and ionized gas [6]. The free electrons in this plasma scatter photons in a process known as Thompson Scattering, stopping them from freely traveling and effectively making the plasma opaque to electromagnetic radiation [6, 7]. As the universe expanded and cooled down, eventually the electrons lost enough energy to combine with free protons and form neutral hydrogen, in a process referred to as recombination [5, 7]. It was not until this point in time that the photons could travel freely without being scattered. The photons which were released at this point in time now make up the Cosmic Microwave Background, the furthest and oldest light detectable by any telescope [6, 8].

As a direct result, we should not expect to directly observe any events preceding recombination using light. However, in contrast to Electromagnetic waves, which rely on the coupling of electric and magnetic fields, GWs rely on masses. Because of this, they are not affected by Thompson scattering, and could freely travel even before recombination [8]. As such, GWs can be used to look back further in time than with light [9].

Such early universe GWs, known as primordial GWs, are hypothesized to have been produced as a direct result of the rapid expansion of the universe during inflation, which happened seconds after the Big Bang. These GWs are incredibly difficult to detect, as they are buried under numerous sources of noise, which are discussed in the following section [5, 8].

2.2 Sources and Creation of Gravitational Waves

Whilst in some way GWs have properties comparable to other waves such as electromagnetic waves like wavelength, frequency, or the concept of polarization, in many other ways they differ. One notable example is the conditions required for the production of any significant amount of radiation. Electromagnetic waves are produced by the disjointed excitations of individual particles, unlike GWs which are produced by the bulk movement of massive bodies, where each particle contributes equally to the wave produced. This means that a source of GWs needs not only be massive enough, but should also have significant bulk motions [1]. [8]. Currently, a number of sources fulfilling these conditions are known.

The most dominant sources of GWs are binary systems. When both objects are sufficiently massive, gravitational radiation results in a decay in orbit. Common constituents of such binaries are, for example, white dwarfs, neutron stars or binary black holes. These objects have enough energy to curve spacetime to a degree that emits substantial GWs, increasing in amplitude the closer the objects are to each other, producing the signal seen in Figure 1 [10].

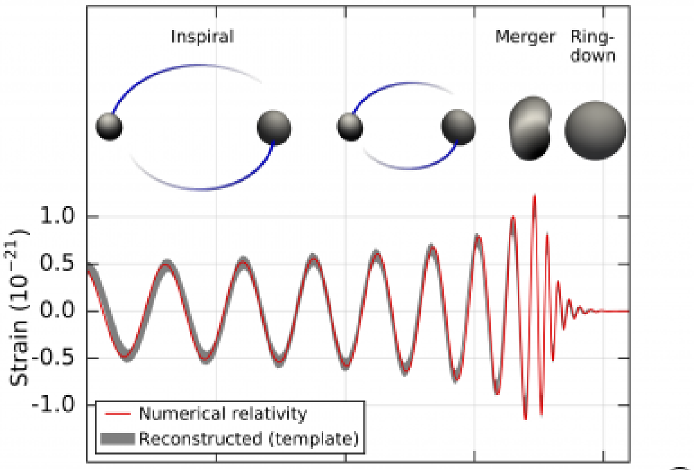


Figure 1: This plot shows the three phases of the binary black hole system's evolution following the first gravitational wave detection, GW150914 Bambi [10]

Another source of GWs would be core collapse in massive stars. Such events give rise to supernovae which are expected to generate GWs if the collapse is not perfectly symmetric. Only in such a case, the moment of inertia varies about different axes, changing as the star rotates and deforms. In other words, for asymmetric core collapses the mass distribution of the star has a time-varying quadruple moment. Such time-varying quadruple moments are sources of gravitational radiation. However, as even a small perturbation breaks the symmetry, most of the core collapses are in fact expected to be asymmetric in nature [8, 11]. At the time of writing, GWs from such sources are still waiting to be detected [12].

2.3 Propagation Through Space

Once emitted, the theory of general relativity[2] posits that GWs travel at the speed of light, manifesting by stretching and compressing the distances between points in space. However, as with other waves, they lose their amplitude as they travel due to dispersion. The magnitude of this effect is proportional to the inverse of the distance travelled. This implies that a detector with twice the sensitivity will have twice the range, and 8 times the number of detectable sources [10]. The aim is for the ET to be 10 times more sensitive than other detectors having a similar wide-band sensitivity of $1Hz - 10KHz$ [13].

Furthermore, as the universe expands, the wavelength of such gravitational waves is stretched and their amplitude decreased. This phenomenon is referred to as redshift, the effect in which the wavelength of a wave is stretched as a result of the expansion of space between the source and the observer.

Then from the accumulation of these effects, it follows that the GWs emitted before recombination (Primordial GWs), or at any point in the early universe and only reaching us now will be amongst the hardest to detect [10].

2.4 Detection of Gravitational Waves

In general, GWs can have a wide range of amplitudes, which can also be described by a measure called strain. Strain is the ratio

[1] In addition to fullfilling other, stronger requirements.

[2] Other theories of gravity propose that GWs could have different group and phase velocities which depend on their source.

of variation in length ΔL between two test bodies due to a GW and the proper distance between them L.

$$h = \frac{\Delta L}{L} \tag{1}$$

GWs are extremely faint and cause tiny distortions in the space-time fabric as they pass through. A typical strain of GWs passing through the Earth is of the order 10^{-20}. This means that the radius of the Earth ($R \approx 6,000m$) undergoes a change of only $\Delta R = 60fm$ as a GW of h=10^{-20} passes through. For comparison, the radius of an atom is $\sim 10^5 fm$. Such minute changes are beyond the resolution of conventional distance measurements [10]. Hence, a different measurement standard was proposed based on wave properties. The aim of GW detectors is to measure tiny changes in the arm lengths due to GWs with interferometers, which detect interference patterns in light waves.

GW Detectors can be subdivided into 3 categories:

1. Resonant Detectors
2. Interferometers
3. Pulsar Timing Arrays

2.4.1 Resonant Detectors

An oscillating test mass is used to measure the effect of gravitational waves on resonant detectors. This device consists of a large, solid metal body, which is immune to outside vibrations. The metal body vibrates at its natural frequency when a gravitational wave passes through it. Sensors attached to the metal body can detect this vibration [8].

2.4.2 Interferometers

Using an interferometer such as the one seen in Figure 2[8], changes in phase of two separate laser beams can be measured, using constructive or destructive interference. In particular, a laser beam is split into two by a beam splitter (a semi-reflective mirror). Each one of the two beams is then reflected by a mirror. The two beams recombine at the center resulting in interference, which depends solely on the distances between the two mirrors and the beam-splitter [8]. The two mirrors are originally placed at a distance such that the two beams interfere destructively. The passage of a GW induces minute fluctuations in spacetime that cause the arms of the detector to alternately stretch and squeeze. Due to this, the distance between the mirrors and the beam-splitter changes, causing the two beams to interfere constructively and, therefore, producing a signal that is detected [8].
This process can be made sensitive enough to detect the small change in the length a GW introduces [10].

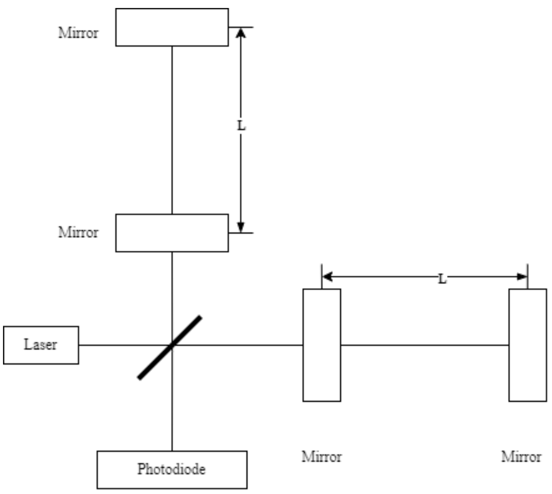


Figure 2: A representation of an interferometer, reproduced from Carroll [8]

Possessing the lowest amplitude or strain of all sources, primordial GWs will be the hardest to detect and therefore, will require equipment of the highest sensitivity. However, it is expected that if primordial GWs can indeed be measured, that the ET will likely possess the technological capabilities to detect them [5].

2.4.3 Pulsar Timing Arrays

Neutron stars that rotate at high speeds and emit electromagnetic radiation from their magnetic poles are called pulsars. When the beams sweep across the Earth's line of sight, they appear to pulse, like cosmic lighthouses. Millisecond pulsars can be used as very precise clocks. In the same manner as discussed in subsubsection 2.4.2, the passage of a GW changes the distance between two test bodies, resulting in a variation of the arrival time of the signal from a pulsar. With distances between pulsars of the order $1 - 10Kpc$ they provide a tool to measure low frequency gravitational waves [10].

3 Research

The exhibit must be designed based on the backgrounds, interests, and knowledge levels of children and politicians, in order to be engaging and informative. To ensure that the exhibit would be suitable for both demographics, thorough research was conducted which will be presented in this section.

Younger kids benefit from analogies by developing their creative potential and relating abstract concepts to familiar situations. Adults can also benefit from the use of analogies when connecting new information with old knowledge they have already accumulated, especially if an analogy can be related to concepts they have an inherent interest in.
Table 1 is a comparison of Andragogy and Pedagogy

3.1 Pedagogy

In these environments, the process of "learning" extends beyond acquiring content knowledge. Among other things, it involves developing interest, fostering perceptions of a field or topic, as well as providing memorable and awe-inspiring experiences. Exhibits and museums provide unique potential to learn through informal and non-traditional approaches [14]. Utilizing various mediums to display information allows visitors to engage in active learning environments by employing multiple senses [15]. Especially for children, adding this level of interaction and playfulness leads to higher focus and understanding [16, 17]. Interacting with complex science in a way that is fun, for example with the use of simple children's toys in the ETpathfinder exhibit, aims to decrease the levels of intimidation surrounding physics. In addition to this, exhibits have the ability to creatively display scientific content, for example by adding an emotional aspect through a storyline. Emotional interest is important to consider for younger students, as it can draw out their personal motivation and curiosity [16].

Implementing the use of demonstrations creates interactive environments which can spark discussion surrounding the topic, for example when working in groups [14]. Furthermore, hands-on learning has been found to enhance engagement, independence, and self-motivation [16]. When presented with demonstrations or hands-on experiments, it forces the learner to analyse the situation, come up with predictions, and critically reach conclusions. [15, 16]. However, there are issues with demonstrations that can prevent students from fully benefiting from them. To understand demonstrations, students must already possess the intuition to separate important information from unimportant information, as well as having sufficient theoretical background to draw their own conclusions. Some students might be distracted by aspects of the demonstration or simply need more time than their peers to piece information together [15, 18]

3.2 Andragogy

The Adult Learning Theory, otherwise known as the Andragogy Learning theory, states that as learners, adults differ from children on a large scale, ranging from their motivation, to the relevancy of education with respect to their lives, and how they apply that education [19].

Derived from Greek, the word "Andragogy" is a combination of two words: The word "Ανδρας" (Andras), meaning "Man", and the word "Αγωγός" (Agogos), meaning "Leader of/ Mentor/ Guider of ". Through this synthesis, the word literally means "Leading men" " Teaching men"; the exact opposite of the word "Pedagogy", meaning "Teaching children" [20].

When discussing the differences children and adults have in the classroom, it is important to outline the six main domains related to learning:

1. ***The idea of self*** Self-concept is the idea of the self constructed from the beliefs one holds about oneself [21], which largely affects the level of independence exhibited. Children tend to have a higher dependency on the teacher, whilst adults have the tendency to be more self-directed [20].
2. ***Experiences*** As one accumulates more and more life experience throughout the years, they tend to dependent on that as a resource during the learning process. Something that brings up [20].
3. ***Readiness*** The ability to be open and ready to learning something new can often be tarnished by past experiences. Having a fresh mind, with no previous experiences acting as a buffer or barrier, can function as an advantage when teaching children, as they tend to wait for instructions to be given. Adult learning, on the other hand, is often driven by their social or professional environment [20].
4. ***Motivation*** Motives behind learning, can be influenced by both intrinsic and extrinsic factors, such as salary, job satisfaction, etc. But, thoughts revolving the aforementioned only live in an adult's brain. Young learners are usually driven by their role models; their parents, friends, or teachers. All people that they admire and aspire to be like [20].
5. ***Need to Know*** "Why?" often echoes in classrooms, but why a student needs to learn a particular subject is something adults need to know before learning. Something that is reflected in Andragogy and adult teaching methods [20].
6. ***Problem-Centered Learning*** To address the "Why?" of it all, when teaching adults, problem-based and student-centered learning is mostly implemented. The exact opposite applies for children, where teacher-centered and curriculum-based learning is used [20].

It is anticipated that politicians would demonstrate a heightened concern for the societal impact of both the ETPathfinder and the ET, given the inherent nature of their professional responsibilities.

Table 1: Outline of the differences between Andragogy and Pedagogy. Taken from Purwati et al. [20].

Characteristic	Pedagogy	Andragogy
Self-Concept	Children are more dependent on the teachers in the teaching and learning process. The teachers tend to be 'the decision makers' in terms of deciding what and why children are learning the lesson.	Adults are more self-directed and responsible in their learning as they are independent learners.
Experiences	Children are less experienced than adults. Therefore, as the resource of learning, they rely on the experience from teachers. Teachers might not be able to employ independent learning techniques in this stage since children use teachers' experiences during the process of learning.	Adults have more experiences and they rely on their experiences as the resource during the process of learning. To explore adults' experiences, teachers/lecturers may employ independent learning methods.
Readiness to learn	Children need to wait for the instruction of teachers related to what, why, and how to learn.	The readiness of adult learners in learning is also dependent on the social and professional environment.
Motivation	Young learners are driven by external factors in learning, such as parents, friends, or their teachers.	Adults are motivated by both intrinsic and extrinsic motivations, such as salary, job satisfaction, and etc.
Need To Know	Young learners do not need to know the reasons why they learn particular lessons as they more highly rely on their teachers in guiding them.	Before learning, adult learners need to know why they have to learn particular subjects.
Problem/Center Learning	Teachers can use teacher-centered learning, curriculum-based learning and other types of teachers learning center.	In teaching adult learners, teachers/lecturers can employ student-centered learning, problem-centered learning, performance-based learning

4 Materials and Methods

4.1 Demonstration 1: Light in the Early universe

In order to foster an intuition for the phenomenon of light not being able to freely travel under early universe conditions, an analogous situation was used and illustrated by a sand art toy (Figure 3). Such a toy consists of a transparent container filled with water and coloured sand, representing the primordial plasma. By perturbing the container, the sand can be made to simulate the state of the early universe, creating a dense and opaque medium such that when a light source is placed behind the container it could be demonstrated that the light propagation would be impeded.

Figure 3: Sand art toy used to demonstrate opacity and density of the universe

4.2 Demonstration 2: Gravitational Wave Sources

The 3-dimensional graphics computer software tool Blender [22] was used to design and render four animations of which two showcase unique sources of GWs, another showcases (in an exaggerated way) their physical affects on matter, and the last is an animation of a potential GW detection source that is currently only hypothesized. In addition, Holapex Hologram Video Maker [23] converted these animations into a specific video format adapted for hologram projectors. Finally, a mirror prism, or hologram projector was purchased, in order to use the Holapex Hologram Video Maker and display the four animations as 3-dimensional holograms. A black box with the option to leave one of its faces open was also purchased in order to place the hologram projector within, providing a darker setting and therefore a more visible image.

4.3 Demonstration 3: Propagation of Gravitational waves

In order to demonstrate the ways in which gravitational waves travel and interact with physical matter, a classical gravity well type demonstration was used. A small plastic loop with hollow support legs, able to be filled with sand, water, or some other dense material was purchased. The fiber mesh initially stretched over the loop was removed and replaced by spandex. Dense iron spheres represented relatively massive cosmological objects, and some smaller marbles and lightweight spheres represented smaller massive objects.

In order to start the demonstration, either one or two of the heavier spheres were placed in the middle of the spandex, curving it towards themselves. This can give a good insight on how mass in general can curve and influence spacetime. To push the demonstration further, when single spheres were disturbed vertically, or when binary systems inspiraled, the spandex rippled in a way analogous to GWs. A less massive object placed relatively far from the source of the waves would feel significantly less disturbance compared to an object placed closer to the source. This illustrates the method by which GWs lose their energy as they travel. In addition, as long as the object is much less massive than the source of the waves, it can be demonstrated that matter leaves GWs largely unaffected as the ripples in the spandex will pass through the object.

4.4 Demonstration 4: Detection of Gravitational waves

A model interferometer was created based on the proposed mechanism of the ET. The set-up for this demonstration followed closely the one presented in Kraus and Zahn [24].

The model interferometer (Figure 4) was built by replacing the typical laser source with a source of ultrasonic waves of 25 kHz frequency. The reflective mirrors were then replaced by wooden plates. The typical half mirror (beam splitter) was adjusted for ultrasonic waves by using plastic wrap in an embroidery loop. In this manner, the tightness of the plastic wrap could be changed at will to maximize the quality of the reflection and passing of the ultrasound waves. In addition, the plastic wrap could be easily replaced when worn out or damaged.

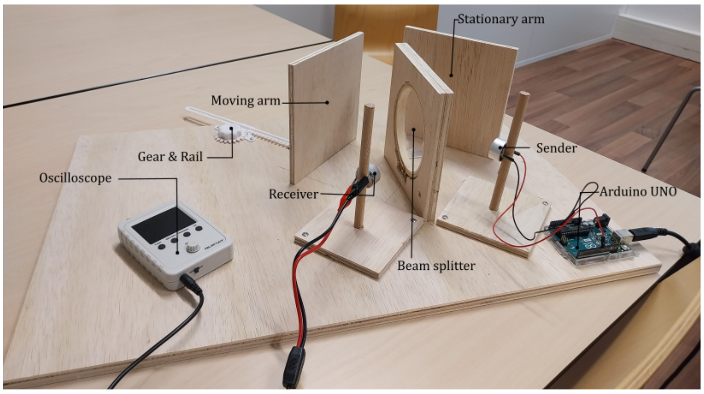


Figure 4: The model interferometer

The ultrasound was emitted by a transducer (transceiver SE04B25T, acquired from Gotron) which was connected to an Arduino UNO micro-controller. In order to receive the ultrasound signal resulting from the interference, another identical transducer was used.

The second transceiver converted the ultrasonic signal into an electrical one, and it was connected to a digital oscilloscope (QUIMAT TFT 2,4) which plotted the amplitude of the wave in real-time. One 3D printed cog and a straight bar of corresponding cog teeth were utilized to allow for the movement of one of the mirrors by very small increments.

By emitting the ultrasound and slowly moving one mirror, the two waves of sound were moved out of phase as their distance of propagation changed. The received signal, visible on the oscilloscope, varied from largest amplitude during constructive interference to the smallest amplitude during destructive interference. This effect replicated the stretching that a gravitational wave would produce in space-time and hence the signal that a gravitational wave detector such as the Einstein Telescope(ET) could pick up.

The Arduino's sketch can be found in Appendix B. A more detailed instruction manual containing specific information on the functioning of the apparatus, the different components, how to connect them and how to replace them has also been produced. It can be found in subsection C.4.

5 Results and Discussion

As a final product, the exhibit includes four standalone demonstrations, each accompanied by sufficient additional information to promote understanding. The exhibits are arranged in chronological order, but each demonstration is designed to be comprehensible independently, allowing visitors to engage with any exhibit of their choice.

5.1 Demonstration 1: Light in the Early universe

An unexpected benefit was that the voids or bubbles created by tilting the container, could serve as an analogy of the ionization of neutral hydrogen atoms by the first stars and galaxies, creating the first regions of transparency in the early universe. Caution should be used however, to avoid the nurturing of an invalid understanding. This demonstration is an analogy and should not carelessly be taken as truth.

The reason why the toy becomes transparent is that gravity causes the sand particles to settle down. Whereas the universe eventually becomes transparent because of its expansion and resultant cooling down.

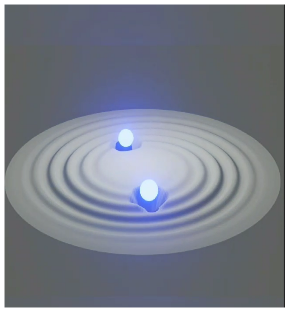
Furthermore, the demonstration uses visible light, this is not at all representative of the much more energetic photons which would be found at the moment of recombination.

5.2 Demonstration 2: Gravitational Wave Sources

Two out of the four animations created are similar and used to display well understood GW sources. The first being a binary system of two black holes spiraling in a collision course towards each other (Figure 5a), and the second being a binary system of neutron stars forming a black hole after their collision (Figure 5b). These two animations show how low amplitude GWs require significant mass to bend the fabric of spacetime. Hence, this indicates how intricate and sensitive GW detectors have to be in order to detect GWs which have dissipated over distance.

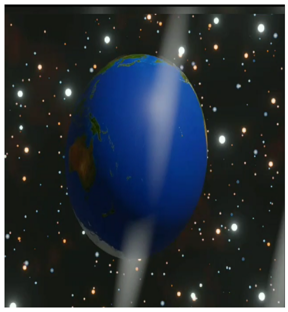
The third animation (Figure 5c) shows an asymmetric supernova explosion. As section 2 explains, gravitational waves from supernovae are only hypothetical and have not been confirmed yet. Instead of presenting a speculative scenario as a fact, visitors are actively invited to imagine how such GWs might look like. Despite there not being any solid evidence for supernovae to be GW sources, it is still important to include them as part of the exhibition, as the ET is predicted to be sensitive enough that it could potentially discover signals coming from supernovae and expand our current understanding of GW sources.

(a) Animation of the gravitational wave production of a binary black hole system



(b) Animation of the gravitational wave production of a binary neutron star system

(c) Animation of the gravitational wave production of an asymmetric core collapse in a neutron star resulting in a supernova.



(d) Exaggerated visualization of gravitational waves passing through the earth.

Figure 5: Stills of the different animations discussed in this section.

The fourth animation (Figure 5d) visualizes the effect of GWs as they pass through cosmic objects, in this case the Earth. In the animation the Earth is being stretched and contracted as GWs pass through it. Although the stretching and contracting of the Earth are highly exaggerated, they help understand how GWs affect massive objects and GW detectors can detect signals. Such an exaggerated effect could, however, lead to misconceptions or may in rare cases elicit fear or anxiety in some viewers who lack sufficient background knowledge on gravitational waves and their actual impact. It therefore is imperative to emphasize that the animation is greatly exaggerated.

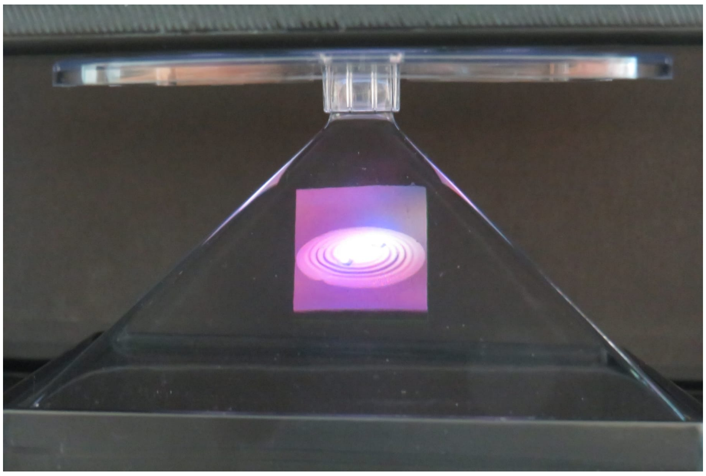


Figure 6: Projected hologram using the projection pyramid

The choice of using a hologram projector (see Figure 6) instead of a screen is made in order to allow visitors to have a unique and engaging experience. The option of choosing which video to watch, and subsequently project, makes it so that the viewer creates a private environment and is much more attentive, which provides a better understanding of the scenario. This can prove itself as an ideal solution to capture maximum attention from a younger audience, and still be effective and stimulating for any age group.

Blender is a free and accessible software for creating animations and simulations of cosmic events. However, it also has some drawbacks, such as its steep learning curve, its high demand on computer performance, and its long rendering time. These factors can limit the visual accuracy and complexity of the animations, especially for advanced and complicated scenarios.

It may be possible to achieve improved animations in the future by carefully planning and creating animations over a long period of time, making use of Blender's potential to simulate cosmic events as accurately as possible. Additionally, a powerful computer is crucial for a smooth user experience and the creation of complex and realistic animations that grab the audience's attention.

5.3 Demonstration 3: Propagation of Gravitational waves

The gravity well is a classical method of representing spacetime in lower dimensions. It demonstrates the properties of the propagation of GWs by good analogy. Those properties being the energy loss of GWs over distance, as well as their resistance to interference from massive objects. However, a limitation is the motion of the spandex occurs rapidly and it can be challenging to observe the wave-like action with the naked eye. One possible solution is to have the gravity well accompanied by a video recorded in slow motion of the spandex, making the wave much easier to observe.

Such a gravity well is quite versatile and can be used to illustrate numerous other concepts relating to the deformation of spacetime. It may therefore also be used to help interested visitors gain a deeper understanding of and intuition for gravity as the curvature of spacetime in general. This concept may still be unfamiliar to guests prior to visiting ETpathfinder. It is beneficial for guests to first understand the way gravity acts upon objects, to gain a deeper understanding of the way GWs work. Therefore the gravity well still fulfills its classical purpose in addition to the original intended use.

However, whilst a gravity well serves as a good analogy for spacetime on certain fronts, it also introduces potential for fallacy. The gravity well demonstration relies on an embedding of a two-dimensional surface in a three-dimensional space, which fails to capture the full complexity of spacetime, which is a four-dimensional construct. As a result of embedding, it is possible for objects to be construed to fall into a well-like depression in spacetime, creating the misconception that gravity is caused by objects falling. This visualization is helpful in understanding objects in motion under gravity's influence, but it does not cover the mechanics of gravity as described by general relativity. It is more accurate to describe gravity as the curvature of spacetime caused by mass and energy, instead of a simple falling motion along a two-dimensional plane.

It should be noted that trying to correct the gravity well analogy misconception may result in overwhelming non-scientists with complex scientific explanations. As a result, they may lose interest in the concept and find it difficult to grasp. In the end, it is important to consider the audience's background and prior knowledge in order to present information in an appealing, relatable, and interesting manner. Achieving this balance, especially in this demonstration, makes it more likely to foster understanding and maintain nonscientific interest.

5.4 Demonstration 4: Detection of Gravitational waves

The model interferometer can show the working principles of a gravitational wave detector despite having a significant difference, ultrasound is used instead of lasers due to safety reasons. The ultrasound transceivers are only able to produce and detect ultrasounds, which are normally absent or very weak in the environment and almost completely eliminates the problem of background noise interfering with the system. This effect is both an advantage and a drawback. On one hand the effect of constructive and destructive interference is very clear because of the lack of noise from the environment. However, as a result the demonstration provides a less realistic representation of the issue of background noise that full-scale GW detectors face. As mentioned above, the main and most important advantage of the ultrasonic interferometer is that it does not involve lasers, making it safe to be used by visitors of all ages (including children). In addition, it is built with cheap materials and therefore can be easily repaired in case of damage.

Although the demonstration shows quite well the working principle of gravitational wave detectors, it is not an accurate representation of the structure of the Einstein telescope: here, only one interferometer is present, whereas the ET will be formed by 3 Michelson interferometer "folded" in a triangular shape. Moreover, as already mentioned, in the model, background noise does not interfere with the signal, although it is one of the main problems when detecting gravitational waves. Initially, it was thought to use sound waves instead of ultrasounds to give an idea of this challenge, although the plan has been discarded for several reasons:

1. When tested using the equipment and the materials of the lab, it was noticed that the signal was barely visible, and therefore the demonstration would have been unsuitable for the location and conditions we would expect there.
2. The demonstration would have required the use of a high-pitch sound, which was deemed unpleasant.
3. The use of sounds would have required a much more complex circuit, with an amplification stage and a band-pass filter which would have occupied much more space. Additionally, it would have been more expensive due to the presence of operational amplifiers, which requires a positive and negative power supply. This would have required buying a dual-voltage power supply (since it was unrealistic to build one in the time frame of the project), which would have not fit in the budget.

Moreover, the use of ultrasounds is beneficial since it draws an indirect parallel to the idea of "listening" to gravitational waves (rather than "seeing them"), highlighting that what is measured is something that cannot be looked at. This fact would have been less clear if a laser was used since, by nature, it gives the idea of measuring something that can be seen.

Furthermore, due to the limited budget, it was not possible to acquire a very precise oscilloscope, which limits the stability of the signal on the screen because the voltage is very small. Possible solutions could be either amplifying the electric signal coming from the receiver (which would require an OpAmp, see what was discussed above) or buying a more precise oscilloscope (such as the one produced by Rigol). For the same reason, it was decided to use an Arduino instead of a waveform generator to produce the ultrasonic signal. This however does not seem to have significantly impacted the quality of the demonstration.

In addition, this demonstration could be suitable to create a playful learning moment, particularly suitable for children. For example, a competition could be made between the children to see who can find the constructive interference fastest. Stimulating this kind of engagement would allow the children to gain a deeper understanding of how the instrumentation works, as well as spark interesting discussions between themselves. By combining this playful aspect with learning, the aim is to remove any intimidation from complex physics concepts [14, 17].

Another improvement could be connecting a potentiometer to the Arduino to change the wavelength produced and, therefore, change the distance at which destructive interference will occur. In this way, it would be possible to let the public "discover" which wavelength is used in the production of the signal, to enhance the emotional response in the public and make them feel like "real scientists".

5.5 Overall exhibit

In addition to examining each demonstration individually, the effects of the overall exhibit on the target audience should be discussed.

The majority of the demonstrations consist of what are effectively repurposed children toys, with the exception being the interferometer. The hope here is that this might demonstrate their accessibility whilst simultaneously prompting the younger audience to explore further at home. Fostering a healthy curiosity and sense of exploration play a large role in raising the next generation of scientists. Whilst certain levels of prior theory and intuition are required to properly engage with demonstrations [15], the ones created for this exhibit have been designed in a way that provide direct analogy and simplistic visual representations of difficult concepts withing general relativity. For example, the early universe demonstration almost directly replicates the concept of light not being able to pass through plasma in the universe, however, in a visually appealing way using common things that children already play with such as water and sand. Accompanying instructional manuals can aid guides in the explanation of the demonstrations, or can be read directly by older students to fill in any gaps in their knowledge. It felt important to create active learning environments in which children can utilize hands-on learning to better grasp the science behind the ETpathfinder whilst keeping the exhibit fun and playful.

Moreover, the demonstrations have been thought with a specific order, but can also be visited as stand-alone pieces. The first option is more suited for children or high school students, who usually need more guidance, and the latter more suited for adults, who usually prefer a more self-directed and independent learning style [20].

Furthermore, what the ETPathfinder is doing with regards to public outreach will certainly be beneficial for its standing in the decision of the final location of the ET. Assuming that politicians visiting the ETPathfinder recognize this they should also recognize that increased effort towards public outreach at this point in time will lead to a larger and better educated group of scientists in the future. The goal is that this will improve the trust in the plans for the ET. The drawback is that increased attention must be paid to ensure that such an older audience does not feel talked down to. For example, one should not use the same tone with an audience of children as they would an audience of adults.

To support the exhibit, a website was created at `https://snrts.github.io/Ripples_in_SpaceTime/`. This website has multiple functions. Currently, accompanying each demonstration is a poster, (see Appendix D for the different posters), which are in English by default. This decision was made based on the expected linguistic profile of the Pathfinder visitors. However to enhance accessibility the same posters will soon be offered on the website in Dutch, German and French. These languages correspond to the countries that are most involved in the research for the ET in the Meuse-Rhine region.

Table 2: Chronology of the different topics woven into the exhibit

Topic	Problem	Solution	Demonstration	Next Problem
Light in the early Universe	We want to study the early universe but we can only detect emitted light emitted from 380,000 years after the big bang.	Unlike Electromagnetic waves, GW remain largely unaffected by physical matter and will travel relatively unobstructed.	subsection 5.1	But we haven't (yet) measured primordial GW but where do the GW that we **have** measured come from?
Sources of GW	Where do GW come from? How are they created? What are their sources?	Compact binaries (BNS, BBH, NSBH), asymmetric Supernovae.	subsection 5.2	Once these GW reach us how can we detect them? especially since they lose so much energy before reaching us?
GW Propagation	How do Gravitational waves propagate	Properties of GW such as low interaction, energy loss, the speed at which they travel.	subsection 5.3	Since the waves that arrive on Earth carry such little energy, how do we measure them??
Detection	How do the GW detectors allow us to measure low amplitude GW?	Explain how detectors work	subsection 5.4	Why do we need bigger detectors?

6 Conclusion

To summarize, the main goal of the project was to present a way of using scientific communication to engage the non-scientific public (children, high school students, and politicians) and increase its interest in the topic of GWs and, more specifically, the ET. The importance of involving this group (the non-scientific public) to learn about the ET was discussed and determined to be essential for the longevity of such scientific endeavours. The project aimed to explain four main topics regarding GWs, the significance of gravitational waves, how they are created, how they propagate through space and how they are detected here on earth. This was achieved by proposing an exhibition consisting of four different demonstrations, each exploring a corresponding topic through an accessible analogy. Although they can be visited in any order, these demonstrations were designed with a specific chronology in mind, and each topic is presented through a problem-solution approach (Table 2) to keep the public's attention vivid. For the same reason, the demonstrations were made as interactive as possible. Moreover, they were constructed using accessible materials (mainly children's toys) to ensure the durability of the exhibition and ease of replacement in case of damage. This has also the additional benefit to show that physics, even if complicated, can be accessible to everyone. All the demonstrations were also correlated with posters providing the necessary explanations.

Due to the limited time of the project, it was unfortunately not possible to test the effectiveness of the exhibit in conveying knowledge and catching the interest of the public. This could be a subject for a follow-up project, for example, by showing the exhibition to different age groups and collecting their answers through a survey. Finally, although some ideas on how to improve the demonstrations have already been provided, it may also be interesting for future projects to collect visitors' opinions on the demonstrations, to have a better understanding of what the general public would like to see and, therefore, better engaging with it.

Acknowlegements

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A Contributions

Name	Contributions to the paper/presentation	Contributions to the exhibit
Alexander Verheyden	• Presentation (design)	• Design Posters
David Tóth	• Materials and methods (Demonstration 2) • Discussion (Demonstration 2)	• Animations • Hologram Demonstration
Eli Showalter-Loch	• Background section (section 2) • Discussion (Demonstration 3) • Materials (Demonstration 2 and 3)	• Light in the Early universe demonstration. • Instructions Demonstrations.
Evangelia Eleni Taliadorou	• Research section, Andragogy subsection. • Presentation design, text and presenting.	• Poster design and text for "What are the Sources of Gravitational Waves?".
Finn Stapley	• Review of grammar and spelling • Materials and methods (demonstration 4)	• Interferometer demonstration
Jens Hieronymus	• Andragogy section • Review	• Student Leader • Interferometer demonstration
Nathalie Sowden	• Research and Discussion section: pedagogy	• Design posters • Website design
Sanne Aarts	• Introduction section (section 1). • Background section. • Discussion overall exhibit. • Formatting paper.	• Student Leader • Gravity well demonstration. • Procuring Resources • Development of website (front & back-end) • Photography
Tom Chalabi Prat	• Materials and methods (demonstration 4) • Review	• Interferometer demonstration
Tommaso Siligardi	• Materials and methods (demonstration 4) • Discussion (demonstration 4, overall exhibit) • Conclusion • Presentation (design & presenting)	• Interferometer demonstration
Zilan Mamuk	•	•

Table 3: Contribution of individuals to the final product

B Arduino code

```
int sender=10;
void setup() {
  pinMode(sender,[2]OUTPUT);

}

void loop() {
  tone(sender,25000);

}
```

C Instructions for the demonstrations

C.1 Instructions Early Universe Demonstration

C.1.1 Preface

In the first 300,000 years of the universe, all the particles were freely moving around, analogous to a dense, hot soup. After this, they settled down and got farther apart, Eventually resulting in the universe we know and love today. In that early time though, if a particle of light was emitted, it quickly hit something else and was absorbed. Therefore, light can't tell us anything about the universe during that early time.

C.1.2 Activity

Flip the disc with the sand upside down, or shake gently, and hold it in front of the light. The sand falling through the liquid demonstrates the early universe, the light is blocked and clouded by the sand. As time passes and the universe gets older, the sand settles and the light can get through.

C.1.3 Lesson

Although light can't travel in the early universe, waves can still go through the liquid. This is similar to how gravitational waves can still move through the early universe, they move through the liquid and therefore aren't impeded by the sand. Therefore they may be our best chance at looking into that time of our universe.

C.2 Instructions hologram demonstration

C.2.1 Preface:

There are many different sources that can create gravitational waves. The ones that are significant enough for us to detect usually are very large and heavy cosmological objects. This is because gravitational waves aren't exactly like the waves you know. They stretch and compress spacetime itself, and this takes a very large amount of energy, or mass.

C.2.2 Activity:

Visit https://snrts.github.io/Ripples_in_SpaceTime/videos, use the sliders to switch between the normal videos or the hologram variants needed for this demonstration.

qrcode[height=0.75in]https://snrts.github.io/Ripples_in_SpaceTime/videos.html

Play the hologram videos. Three different types of sources, binary black holes, neutron stars, supernovae. Shows the different mechanisms for how these sources create their respective gravitational waves, and an interpretation of what they might look like when initially emitted. Another video illustrates how Gravitational Waves interact with the Earth.

C.2.3 Lesson:

These sources are littered throughout the universe, creating gravitational waves for us to detect, we simply have to wait for one to pass through us. But since there are so many of these sources throughout the universe, it disturbs the primordial gravitational waves and makes it harder for us to measure.

C.3 Instruction gravity well demonstration

C.3.1 Preface

Gravitational waves travel at the speed of light, but they don't necessarily move through spacetime, they are the movement of spacetime itself. What does that mean physically though? If a gravitational wave passes by, it changes the distance between any two points, you would be stretched momentarily, but so is everything else around you, and therefore you wouldn't know. Just like any other waves, gravitational waves get weaker over distance, simply because they spread out. That means when they reach humans and earth they are much weaker compared to when they were created, and it's extremely difficult to detect them. However, since they are hard to create and detect, they also are extremely hard to disturb, and will pass through almost anything unaffected. Whatever they looked like when they were created is extremely similar to what they look like once measured by humans.

C.3.2 Activities

Activity 1: Hologram of earth stretching, an over exaggeration but the concept is the same. The entire earth would be stretched along a specific direction.
Activity 2: Drop a heavy mass in the center, noticing the curvature of the spandex. Then either push the mass to make it bounce vertically, or add a second heavy mass and make them orbit each other. Notice the ripples in the spandex, but more importantly, that they get weaker the further out from the source they are. For visualization, may be best to put a smaller mass at the edge of the fabric. This smaller mass doesn't affect the ripples much if at all. This is similar to the resistance of Gravitational Waves to being disturbed by mass. Activity 3: Drop a heavy mass in the center, notice the curvature, analogous to gravity, when small mass is placed, it falls into the large mass, accelerating as it gets closer. If the small mass is rolled tangentially to the large mass, it settles into an orbit.

C.3.3 Lesson

Even though they are very weak and hard to detect, the fact that gravitational waves are largely unaffected by anything means they carry clear information of the past. This is the significance in their detection.

C.4 Interferometer Instruction manual

C.4.1 List of materials

1. Two ultrasonic transceivers 28KHz (such as the one from Gotron);
2. Arduino Microcontroller;
3. Plastic wrap for the beam-splitter;
4. Wooden supports for the transceivers;
5. Wooden plates;
6. Central support for the beam-splitter;
7. Appropriate cables;
8. Oscilloscope.

C.4.2 Set-Up

The final Setup is shown below

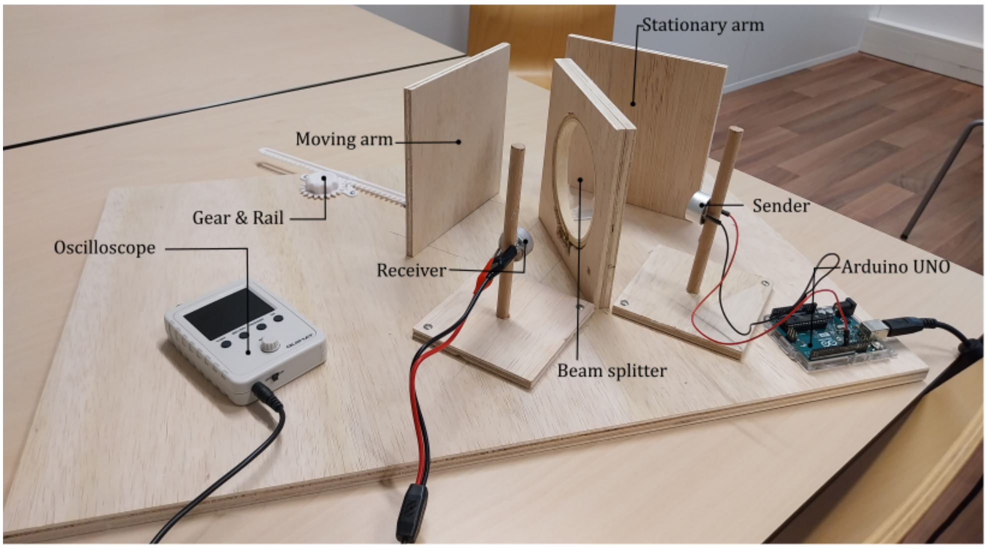

Figure 7: Final set-up

- Connect an ultrasonic transceiver (alternatively an ultrasonic sender) to the Arduino: the positive pole needs to be connected to the output pin (10 in this case) and the negative pole to the ground. This will be the sender. The polarities of the acquired transceiver are shown in the figure below.

Figure 8: Polarities of the ultrasonic transceivers

A waveform generator can be used instead of the Arduino.

- If not already uploaded, connect the Arduino to a laptop and upload the sketch, otherwise, it can be connected directly to the power socket,
- Connect a second ultrasonic transceiver (alternatively an ultrasonic receiver) to the oscilloscope paying attention to the polarities. This will be the receiver. If using a waveform generator it might be necessary to connect the oscilloscope ground to the generator.
- It might be necessary to stabilize the signal on the oscilloscope, by regulating the amplitude and the trigger value. The procedure depends on the oscilloscope used.

C.4.3 Experiment

One of the two wooden plates (mirrors) can be moved. When moving it, the amplitude of the signal displayed on the oscilloscope varies. This simulates what happens when gravitational waves passe through earth: due to small stretching and squeezing of the space, the relative distance between the two mirrors changes and, therefore, the type of interference changes from destructive to constructive.

C.4.4 Lesson

GWs can be detected using an interferometer, because they change the length of the interferometer arms and, therefore, the interference.

D Posters

All posters are on the next pages:

GRAVITATIONAL WAVE SOURCES

Where do gravitational waves come from?

In technical terms, every physical object that is accelerating through spacetime can produce gravitational waves. This can include things like cars, humans, aeroplanes, animals, etc. But masses and accelerations of objects found here, on planet Earth, generate gravitational waves of far too small magnitudes, for their detection to be possible. To find large enough gravitational waves, we must look beyond the limits of our own solar system [1].

Generally, gravitational waves are the expression of all the different fluctuations happening in the curvature of spacetime, and the strongest ones are produced by the most violent and energetic processes in the Universe. Cataclysmic events, such as supernovae explosions, collapsing black holes, or neutron star fusions, are all instances of incredibly massive objects undergoing rapid accelerations that then allow for the generation of detectable gravitational waves, which then propagate at the speed of light [3].

Figure 1-Binary Black Holes. [2]

How are they actually generated?

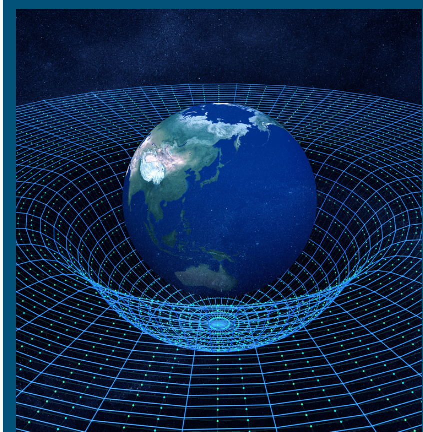

Figure 2-An artist's illustration of the Earth's curvature on the fabric of spacetime [4]

The mechanisms involved in the generation of gravitational waves are analogous to the ones involved in electromagnetic wave generation. As electric or magnetic fields change/ fluctuate, they produce electromagnetic waves. Very much in the same way, gravitational waves are expected to be generated by "changing/ fluctuating gravitational fields", something that emerges from the curvature of spacetime [5].

According to Einstein's theory of General Relativity, curvature is determined by the distribution of masses in spacetime, and the motion of said masses is then in turn determined by the curvature. As a result, any variations within the gravitational field (curvature of spacetime) are expected to be transmitted from place to place as waves, just like any variations within an electromagnetic field travel as waves [6]. To further elaborate on their analogous nature, when disturbances appear in an electromagnetic field, electromagnetic radiation is emitted, which then travels in the form of waves that carry the generated energy. Likewise, the gravitational radiation, caused by variations in the curvature of spacetime, is transmitted as gravitational waves.

Electromagnetic Vs Gravitational Radiation

Electromagnetic and gravitational radiation are both types of waves that are emitted by objects in space. However, they have a different way of sending out the waves. Electromagnetic radiation is emitted by single particles that speed up or slow down. For example, when an electron moves around an atom, it emits light waves. Gravitational radiation is emitted by large masses that speed up or slow down. For example, when two black holes collide, they emit gravitational waves. These masses are made of many particles, but they all work together to create the same wave. Gravitational radiation is much harder to produce than electromagnetic radiation, because it requires more energy and more rare events [6, 7, 8].

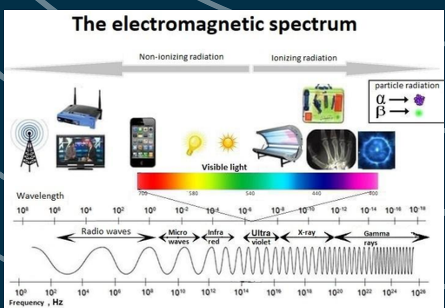

Figure 3-Electromagnetic spectrum giving an overview of electromagnetic radiation [9].

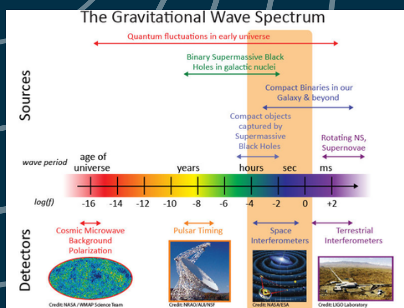

Figure 4-The spectrum of gravitational waves with possible sources and detectors. The gravitational wave spectrum from first-order phase transitions in the early universe are expected to peak in the sensitivity range of LISA. [10].

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CLASSIFYING THE SOURCES

What are their sources? - 1st classification

Depending on what object or system is generating the waves, the type of the gravitational wave is determined. In total, there are four categories, with each one having its signature set of gravitational wave signals. The first classification is the Continuous gravitational waves, which includes gravitational waves produced by a single massive spinning object, like a neutron star. A neutron star is the imploded core of a massive star produced by a supernova explosion [1]. Any bumps or imperfections found on the surface of the spinning star generate gravitational waves, and if said star remains at a constant spin-rate, then the waves will remain constant as well. The waves will continuously hold the same frequency and amplitude, much like an opera singer holding the same note continuously [4].

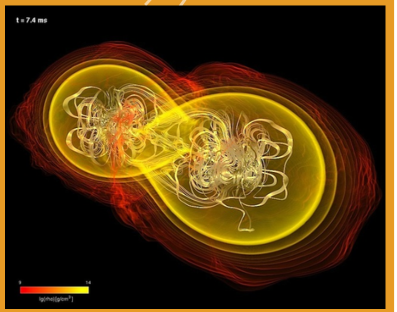

Figure 1-Binary Neutron Star inspiral. [2]

2nd classification: Compact Binary Inspiral

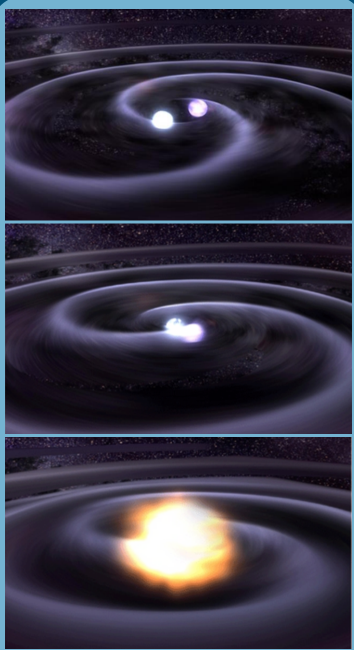

Figure 2-An artist's impression of two stars orbiting each other and progressing (from left to right) to merger, with resulting gravitational waves. [3]

The second classification is the Compact Binary Inspiral gravitational waves. This type consists of the most commonly detected gravitational waves, and includes waves produced by binary star systems; Systems where two stars are gravitationally bound to and in orbit around each other [5]. Any type of star and star combination can be involved in such a system, such as white dwarf stars, black holes, or neutron stars. The general wave-generation mechanism behind these systems, though, is called inspiral. Inspiral is a process that occurs over the span of millions of years, as these two paired masses are orbiting each other. As they revolve around each other over the years, they radiate gravitational waves that carry away, each time, a percentage of the system's orbital energy. The closer they get to each other, the faster they orbit each other, which then in turn generates even stronger gravitational waves and causes the system to lose even more orbital energy. The less orbital energy the system has, then the closer to each other, the two stars are pulled. This accelerating spiralling state is what will eventually cause for the two objects to collide and merge.

3rd classification: Stochastic

The third classification is the Stochastic gravitational waves, which consists of the background "static", caused by a meshwork of all the many, small, and random gravitational waves passing by Earth from all over the Universe. This murmur and rustling from all the background noise make up something called a "Stochastic Signal"; Gravitational waves with random patterns that can be statistically analysed, but not with precision. Part of this stochastic signal is presumed to be gravitational waves originating from the Big Bang. Detecting these primordial waves, could possibly unlock a whole new chapter within the scientific world in regard to understanding the creation and history of our Universe.

4rth classification: Burst

Lastly, the fourth classification is the Burst gravitational waves, comprised of gravitational waves coming from short duration unknown or unanticipated sources [6], that have yet to be directly observed or interacted with by us. These types of waves are unpredictable in the sense that we cannot presume any of their properties, unlike continuous gravitational waves, for example, that have a well-defined set of characteristics. This means that any research involved cannot be restricted only to the signature look other classifications of gravitational waves have.

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[5] scheme=AGLSTERMS.AglsAgent; corporateName=CSIRO Australia Telescope National Facility; address=PO Box 76 Epping NSW 1710 Australia; contact=+61 2 9372 4100 (phone),+61 2 9372 4310 (fax); jurisdiction=Commonwealth. (n.d.). Introduction to Binary Stars. https://www.atnf.csiro.au/outreach/education/senior/astrophysics/binary_intro.html#:~:text=A%20binary%20system%20is%20simply,stars%20are%20in%20binary%20systems.
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GRAVITATIONAL WAVE PROPAGATION

Speed

Gravitational waves travel at the speed of light, which means that they can propagate throughout the entire observable universe [7].

Strength

Gravitational waves are very weak and interact weakly with all matter. The range of frequencies for gravitational waves is very large, ranging from 10^-17m to 10^4m. However, the displacement of spacetime that gravitational waves generate is on the order of 10^-19m [8]. This is an incredibly small change and is what makes gravitational waves so hard to detect.

Interference

Gravitational waves can interfere constructively and destructively with each other, however, as the events which produce gravitational waves are rare, modern detectors have not yet measured interference effects [5].

Interactions

Gravitational waves interact incredibly weakly with matter, meaning they can travel through matter without being distorted. Gravitational waves are essentially invisible to the rest of the universe as regular behaviors of waves such as absorption, reflection, and scattering have negligible effects [3][4].

Gravitational waves get redshifted as they travel through spacetime. As waves travel, they lose energy and their frequency decreases, leading to an increased wavelength. For visible light, a longer wavelength corresponds to a redder color (red-shift!) [6].

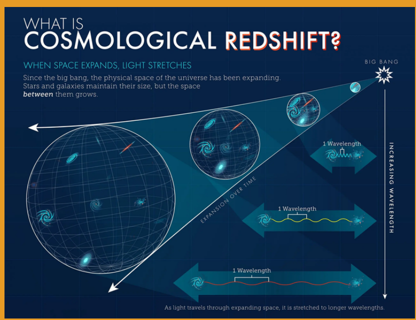

Figure 1: Cosmological redshift [1]

Polarization

Gravitational waves are transverse waves, meaning they oscillate perpendicularly to their direction of travel. There are two possible polarizations for gravitational waves. Polarization refers to the geometrical orientation of the wave oscillations. One polarization is the plus (+) polarization, and the other is the cross (X) polarization, both in the x and y plane [2].

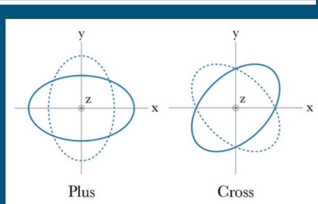

Figure 2: Graphical representation of the plus and cross polarization [2]

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STUDYING THE EARLY UNIVERSE

What are Gravitational Waves?

Over 100 years ago, Einstein predicted the existence of gravitational waves in his theory of General Relativity. These waves are disturbances of spacetime and can be thought of as "ripples" which travel through spacetime, just like waves travel through water [6]. Spacetime refers to a special construction which relates distances to time, building the fabric of the universe and suspending all matter within it. The presence of matter and energy bends or stretches spacetime; the heavier the matter, the more spacetime is curved around it. Primordial gravitational waves were produced at the very beginning of the universe after the big bang. But, they are also produced much later, during cataclysmic cosmological events, like the merging of two black holes or neutron stars. When gravitational waves propagate, they stretch and compress spacetime itself. This means that physical distances will be contracted and stretched by the passing of a gravitational wave. Generally, gravitational waves are an incredibly useful tool in studying the early universe and celestial bodies.

Why Do We Want to Study Gravitational Waves?

Gravitational waves can provide scientists with entirely new ways of observing and studying the universe. Unlike other forms of radiation, such as light or radio waves, gravitational waves do not interact strongly with matter, allowing them to penetrate through cosmic dust, gas, and even black holes. This allows for observations of regions of the universe that were previously hidden from traditional telescopes .Studying gravitational waves which are produced in astrophysical events leads to deeper understanding of the dynamics and properties of the sources (black holes, neutron stars, or supernovae) [4].

Furthermore, primordial gravitational waves offer a window into the very early universe. Most astronomical and cosmological research is done using optical telescopes which can observe electromagnetic radiation. However, there is a limit to how far back in time this electromagnetic radiation let us see. Photons, which are the force carriers of the electromagnetic field, existed immediately after the big bang in a plasma of extremely hot particles, including protons, neutrons, and electrons. This hot plasma made the universe opaque as the photons were constantly being scattered and could not travel very far. 380,000 years after the big bang, the universe had cooled down enough for these protons, neutrons, and electrons to combine into neutral hydrogen atoms. Once this occurred, the photons were able to travel freely. This event, named recombination, corresponds to the point in time when the universe became 'transparent' as photons were finally able to spread out and travel normally [7]. Currently, we cannot observe the universe past this opaque plasma using technologies that are based on electromagnetic wave detection. However, primordial gravitational waves which were produced prior to recombination and do not propagate through the electromagnetic field but rather through spacetime, are expected to still be traveling through the universe today. Their detection can function as an unprecedented way for scientists to investigate the very first stages of the universe [5].

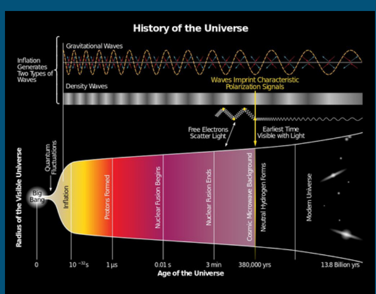

Figure 2: History of the universe and accompanying gravitational waves [2]

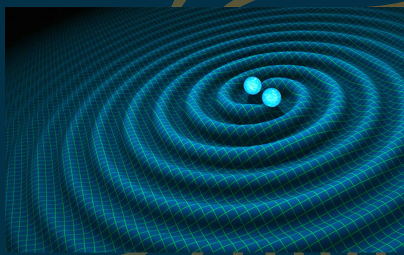

Figure 1: Visualization of gravitational waves [1]

Detecting Primordial Gravitational Waves

The detection of primordial gravitational waves is extremely difficult due to the stretching of these waves as the universe expands. As waves travel, they lose energy and their frequency decreases, leading to an increased wavelength. For visible light, a longer wavelength corresponds to a redder color (red-shift!). Gravitational waves can be redshifted just like electromagnetic radiation [7]. Primordial gravitational waves have been traveling for nearly 13.8 billion years! This means they would have had a lot more time to be stretched and very redshifted, which makes the signals weak and hard to detect. Future gravitational wave detectors, such as the Einstein Telescope, are expected to be accurate enough to measure primordial gravitational waves [8].

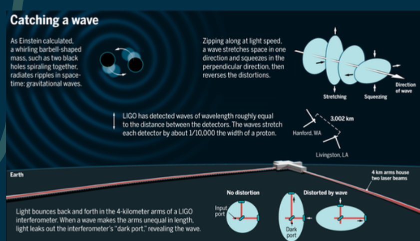

Figure 3: Gravitational wave graphical summary [3]

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GRAVITATIONAL WAVE DETECTION

Why are gravitational waves so difficult to detect?

As previously described, gravitational waves propagate through the fabric of spacetime. This means that compared to other "typical" waves like light or sound, which can be detected simply by observing the system they are going through, the task of detecting gravitational waves becomes increasingly harder as we are ourselves also bound by spacetime. In other words, gravitational waves cause the grid of the universe to warp and so everything in it equally, making them essentially invisible to common detection techniques, as the instruments used get gravitationally distorted as well.

Another hurdle in gravitational wave detection lies in their size. Indeed, not only are gravitational waves small by nature, in conjunction with that, the further they travel from their source, the weaker they become. As the volume they cover gets increasingly big, the more they get stretched and thus, the weaker they get, much like ripples in a pond. Overall, we are looking at changes the size of 1/200 of a proton radius, using lasers and instruments that are on a much larger scale in size [1]. This extreme smallness, causes the detected signal to be easily corrupted by surrounding noises, ranging from nearby cities to vibrating atoms [2]. Detecting such signals is like trying to decipher the words of someone whispering in a crowd of people shouting. Our best hopes rely mostly on big gravitational wave-causing events, such as binary neutron star or black hole fusions, but these events are very rare and represent only a fraction of the potential doors gravitational waves could open, not only for the scientific community, but for everyone [1].

So how do we detect them?

To overcome these challenges the best solution found was the Michelson interferometer. This extremely high precision instrument upon which all gravitational detectors are nowadays based on uses the destructive/constructive property of wave interferences to detect the passage of a gravitational wave. Using several detectors around the world and triangulation then allows us to tell where from in the sky does the signal comes from [3].

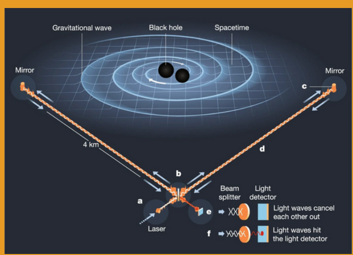


Figure 1. Diagram illustrating the mechanism of a Michelson interferometer [1]

The design of the instrument is simple, a laser beam is split into two perfectly identical beams which travel several equal kilometres away from each over, to mirrors which reflect them back to the beam splitter where they reunite and cancel out due to destructive wave interference. Indeed, two waves the same wavelength and perfectly complementary (dip to peak and peak to dip) will cancel out perfectly. However, in the event of a gravitational wave passing through, one "arm" of the interferometer will get slightly contracted before the second arm, this causes for a brief moment both arm distances to not be equal anymore and so the resulting combined laser beam to not cancel out which can be detected by a photodetector. Making the arms as long as possible and the mirrors and other apparats as stable as our current technologies allows us to makes it possible to reduce unwanted noises and vibrations to a certain extent and so detect gravitational wave patterns. We also know how these should resemble from theory, thus allowing us to extract as much as possible of the desired signal from the background noise. Extra mirrors can also be placed in both arms to make the beam bounce back and forth and thus artificially elongate the distance it travels. Often a power recycling mirror is also added between the laser source and the beam splitter to use the maximum amount of light possible.

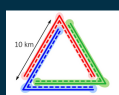
Figure 2. Laser Interferometer Gravitational-Wave Observatory (LIGO) in Livingston, US. [4]

Yet, even with all of these modifications and improvements, it is still not possible to achieve the desired "clearness" and precision to detect primordial gravitational waves and precursor indices of black hole or neutron star fusions [4].

Newer generation gravitational detectors

Newer gravitational wave detectors such as the Laser Interferometer Space Antenna (LISA), the Einstein telescope (ET) or its R&D prototype ETpathfinder all will use newer technologies and modifications which should allow them to reach these coveted unprecedented precision capacities able of looking even closer to the Big Bang and the core of neutron star and black hole fusions.

Such innovations include the use of 3 arms instead of 2, arranged in a triangle shape for both LISA and ET. There will thus be one detector at each vertex of the triangle, each calibrated to detect different frequencies and altogether even be able to study more complex aspects such as gravitational wave polarization [5] Another great promising change is that LISA will be in space using three heliocentrically orbiting satellites [6]. This will not only drastically reduce noises due to the emptiness of space but also easily increase the size of the interferometer arms to 2.5 million kilometers [6]. For the Einstein Telescope, components will be made of newer materials and cooled to temperatures close to absolute zero in the best the vacuum possible. Furthermore, it will also be built underground to reduce seismic noise and have arms more than twice as long as previously existing detectors [7]. All these improvements will make of these two detectors among the most precise instruments ever created and the best gravitational detectors there is, allowing incredible and hopefully century defining breakthroughs in physics. Potentially answering questions such as what is inside black holes, neutron stars or even at the beginning of the Universe.



Description

Figure 3. Einstein Telescope's optical layout of three interferometers folded in a triangle [5]

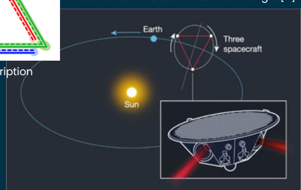


Figure 4. Diagram of the Laser Interferometer Space Antenna (LISA) [1]

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