CESAR Scientific Challenge

The Hidden Universe

Learning about gravitational lensing and dark matter in the Universe with the ESA/NASA scientific missions

Student's Guide

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Your Scientific Challenge

Finding the hidden Universe

Gravity is a phenomenon that we experience in our everyday life. From the moment we are born, we inevitably notice that things "fall" due to some kind of invisible "attraction". But gravity **is far more important than you might think**.
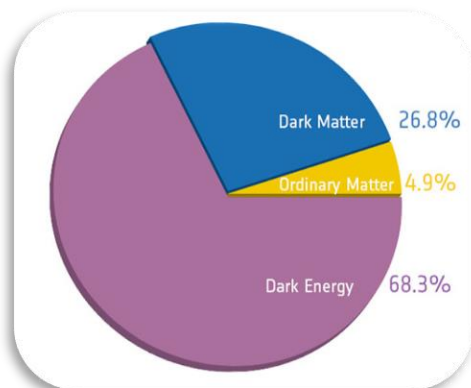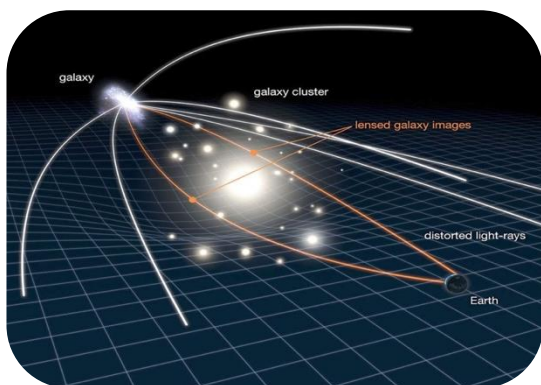
Figure 1: (Left) Schematic representation of astronomical gravitational lensing. (Credits: phys.org).
Figure 2: (Right) Energy and matter content of our universe. (Credit: public.nrao.edu).

In this Scientific Challenge you will study the **mysterious patterns of distortion** that appear around some massive galaxies. You will learn more about the elusive **Dark Matter** that scientist recently discovered could **make up 85% of the mass of our Universe!**

Follow the path of the famous scientist Vera Rubin (see Figure 3) and find out how gravity fits in this picture of galactic proportions.

Are you ready for this challenge?

Figure 3: Pictures of young Vera Rubin. First scientist to work on rotation curves of galaxies. (Credit: es.gizmodo.com)

Phase 0

Put things into context. We recommend students to watch these **videos:**

- [This is ESA](#) (10 min)
- [ESAC: ESA's A window on the Universe](#) (3 min)
- [Presentation to CESAR](#) (6 min)
- Here there is another complementary set of [videos](#).

We recommend to **work in teams** of 4-6 people with a clear role assigned in relation to some profession. **Students are required to fil in Table 0**.
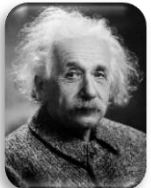
Challenge ID		Team (1-6):		
Names				
Profession	**Mathematician/ Software engineer**	**Astrophysics**	**Engineer**	**Physicist**
Roles	Lead the correctness of the calculations.	Lead the use of the virtual telescope ESASky and other platforms.	Find the optimum strategy agreed among the team members and its correct execution.	Search for energetic processes and the composition of celestial objects.
	[Katherine Johnson](#)	[Vera Rubin](#)	[Samantha Cristoforetti](#)	[Marie Curie](#)
	[Steve Wozniak](#)	[Matt Taylor](#)	[Pedro Duque](#)	[Albert Einstein](#)

Table 0: Role assignment and team identification. To be filled in by each group of students.

Note: The documentation makes use of [the International System of Units](#).

Phase 1

Activity 1. Refreshing concepts

Students should refresh concepts before starting with the Scientific Challenge. The teacher decides which is the best way for doing so with their class. We offer a set of links that may be fun to explore. **Enjoy them!**

Topic	References
Force	Newton's Laws: Crash Course Physics #5. ⇒ https://www.youtube.com/watch?v=kKKM8Y-u7ds
Mass and weight	Veritasium: The Difference Between Mass and Weight. ⇒ https://www.youtube.com/watch?v=_Z0X0yE8Ioc
Frames of reference and the speed of light	The speed of light is not about light | Space Time | PBS Digital Studios. ⇒ https://www.youtube.com/watch?v=msVuCEs8Ydo
Geodesics	Eva Smerekanych: Non-Euclidean Geodesics!! ⇒ https://www.youtube.com/watch?v=KsdIuVByfMc
Observation of galaxies (the electromagnetic spectrum)	Introduction to Astronomy: Crash Course Astronomy #1. ⇒ https://www.youtube.com/watch?v=0rHUDWjR5gg
Optical lenses	Geometric Optics: Crash Course Physics #38. ⇒ https://www.youtube.com/watch?v=Oh4m8Ees-3Q

Activity 2. Gravity and related theories

We all know what Gravity is, right? Let's see! In this activity, you have to think about **what gravity is** and the different theories that have been developed to understand its consequences. Try to answer these questions with your current knowledge.
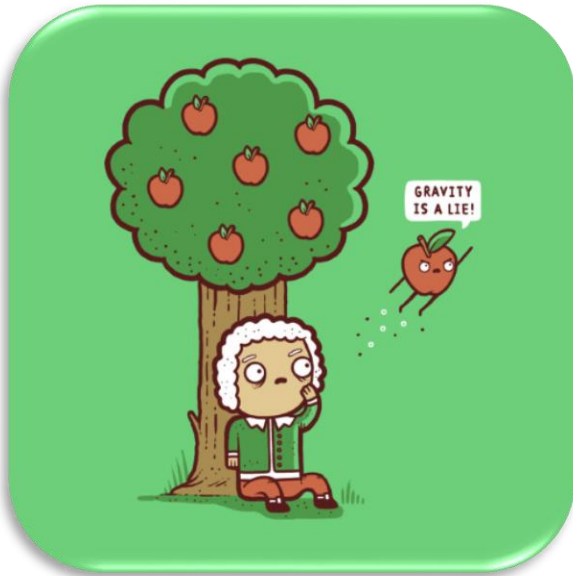
Figure 4: Humoristic depiction of Isaac Newton's famous anecdote of gravity. (Credit: teepublic)

Figure 5: Picture of ESA astronauts exploring 0G, similar to being in space without gravity. (Credit: ESA)

1.   How would you explain what gravity is?

2.   What theories of gravity do you know? What are their main differences?

3. Do you know of any measurements that have confirmed General Relativity?

4. Why do you think gravity is relevant and physicists put so much effort into understanding it?

In case you feel that the previous questions were too hard, watch the following video and try again!

5. Watch the following video (Minute Physics: What is Gravity?) about gravity and review your answers.

⇒ https://www.youtube.com/watch?v=p_o4aY7xkXg

Activity 2.1. Newton's theory

Method 1: Learn with visual resources

1. Crash Course Physics #5.

    ⇒ https://www.youtube.com/watch?v=kKKM8Y-u7ds

2. Minute Physics: Our Ignorance About Gravity.

    ⇒ https://www.youtube.com/watch?v=OTMELHUAzSM

3. Write down what you learned and comment on Figure 7
    in your own words.
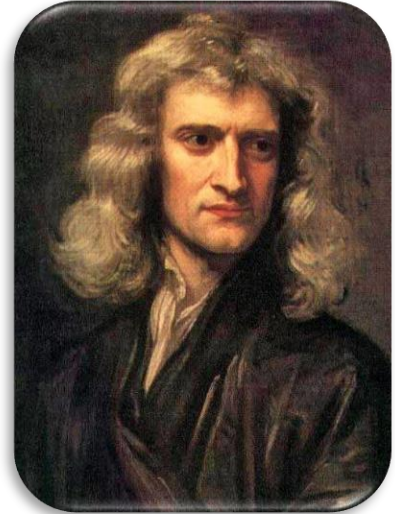
Figure 6: Isaac Newton. (Credit: commons.wikimedia)
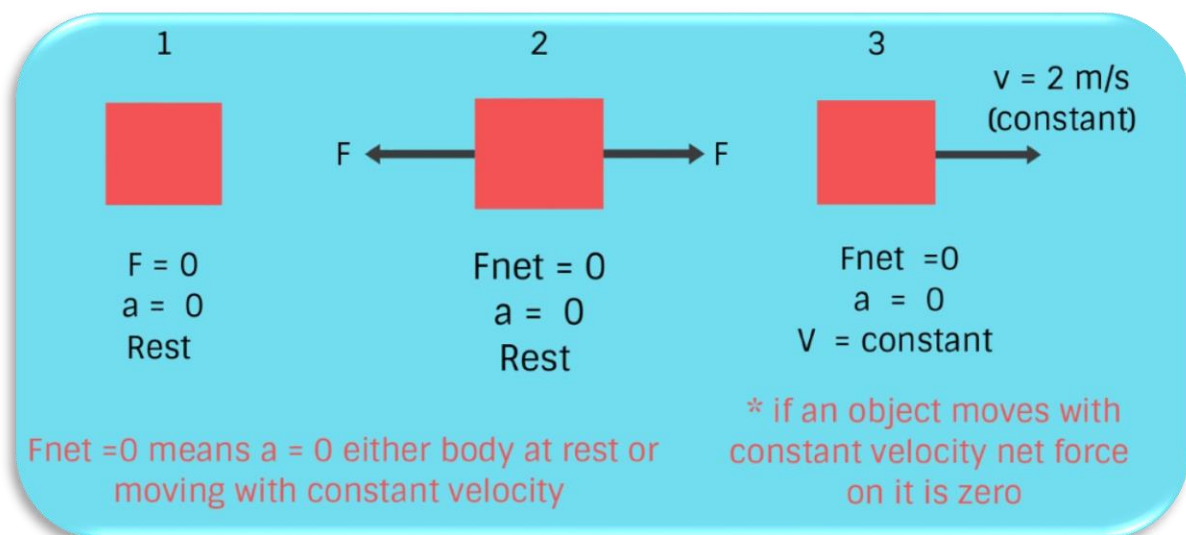
Figure 7: Schematic representation of Newton's Laws of Motion. (Credit: 1.bp.blogspot.com)

Method 2: Learn with theory

From the beginning of human history physicists, mathematicians, philosophers, monks, have tried to explain why we are bound to the Earth. But it was not until 1687 that Sir Isaac Newton published his famous Mathematical Principles of Natural Philosophy, commonly known as Principia, where he presented the Laws of Universal Gravitation, giving a valid explanation to the phenomenon of gravity.

> In today's language, this law states: Every mass attracts every other mass by a force acting along the line intersecting the two bodies. The force is proportional to the product of the two masses, and inversely proportional to the square of the distance between them.

$$F = G \frac{m_1 m_2}{r^2}$$

Equation 1: Newton's Universal Law of Gravity

Equation 1 is the mathematical representation of the Universal Law of Gravitation. *F* represents the force of gravity between two objects, *G* is the gravitational constant, m_1 and m_2 the masses of the two objects and r the distance between them. In Figure 8, F_1 represents the force that m_2 exerts on m_1 and F_2 represents the force that m_1 exerts on m_2. Notice that $F_1 = F_2$.
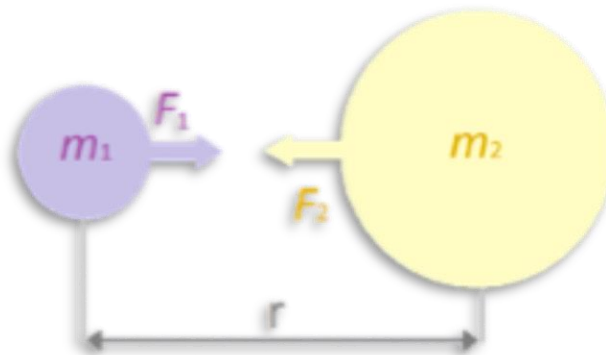
Figure 8: Visual representation of the gravitational force between two bodies as described by Newton. (Credit: thestargarden.co.uk)

Despite the overall success of Newton's contribution, it turned out to be only a good approximation for weak gravitational fields. Nevertheless, this model is still useful and applied today to describe the forces that we experience. Thanks to Newton's laws of motion, we know that some forces acting on an object can be described as the product of the mass of the object times its acceleration. ($F = m \cdot a$).

For example, the weight of objects on Earth can be calculated by substituting in Equation 1 the masses m_1 and m_2 for the mass of the object (m) and the mass of the Earth M_{Earth} ($5,9722 \cdot 10^{24}$ kg); additionally, the distance r must be substituted with R_{earth} (6371 km), the radius of the Earth. This provides the famous expression $F = mg$, where g is the acceleration sensed on the surface of Earth.

$$F_{weight} = mg = G\frac{m \cdot M_{Earth}}{R_{Earth}^2}$$

Equation 2: Newton's Law of Gravity applied to the weight calculation on planet Earth resulting in the well-known mass independent acceleration $g = 9,8 \, m/s^2$.

This evaluation allowed Newton's law of universal gravitation to explain the weight experienced on Earth but also the motion of stellar objects by reproducing the experimental relations detected by Kepler (in particular Kepler's Third Law).

$$\frac{T_1^2}{r_1^3} = \frac{T_2^2}{r_2^3}$$

Equation 3: Kepler's third law. The ratio of a planet's period (T) squared and its orbital radius cubed is constant for all planets in the system.

Kepler's third law states: **The ratio of one orbit's squared period and its cubed radius is constant and equal for any planet orbiting the Sun. This also holds for any similar system of orbits (e.g., planets and their moons).**

Activity 2.1.1. Connection between Newton's and Kepler's laws

Method 1: Learn with visual resources

1. Watch the following video (Newtonian Gravity: Crash Course Physics #8) and explain in your own words what you understood.

    ⇒   https://www.youtube.com/watch?v=7gf6YpdvtE0

    Prove that Newton's law of gravity is compatible with Kepler's in the case of circular orbits by equating the centripetal and gravitational forces (see

2. Figure 9).

$$F_{centripetal} = F_{gravitational}$$

$$m \cdot r \cdot \omega^2 = G \frac{m \cdot M}{r^2} \quad \Rightarrow$$

Method 2: Learn with theory

Let's consider a body orbiting around another one in constant motion (see Figure 9). One way to mathematically describe this scenario is by equating the centrifugal and gravitational (centripetal) forces[1].
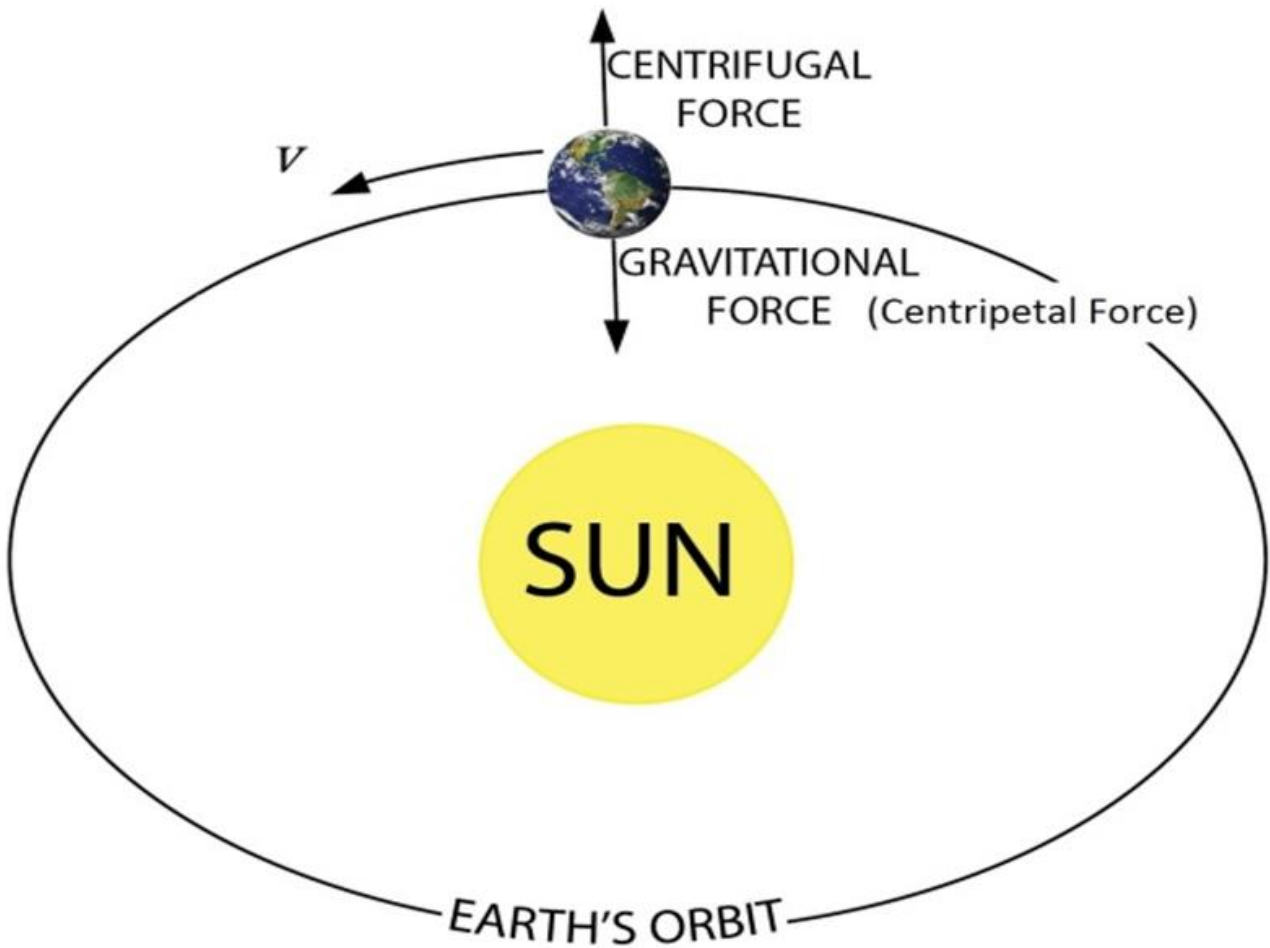
Figure 9: Forces acting on Earth causing its orbital motion. (Credit: www.rlassoc.org)

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[1] Notice that the only real force would be the gravitational (according to Newton's theory); the centrifugal appears as a consequence of choosing polar coordinates.

$$F_{centripetal} = F_{gravitational}$$

$$F_{centripetal} = m \cdot a_{centripetal} = m \cdot r \cdot \omega^2$$

$$F_{gravitational} = G \cdot \frac{m \cdot M}{r^2}$$

Where *m* is the mass of the orbiting object, *r* is the radius of the orbit, ω is the orbital velocity, *a* is the acceleration, *M* is the mass of the main object and *G* is the gravitational constant ($G = 6{,}674 \cdot 10^{-11} m^3 kg^{-1} s^{-2}$). Therefore:

$$m \cdot r \cdot \omega^2 = G \cdot \frac{m \cdot M}{r^2}.$$

For circular orbits, the angular velocity can be associated to the period (*T*) of the motion:

$$\omega = 2\pi/T$$

$$m \cdot r \cdot \left(\frac{2\pi}{T}\right)^2 = G \cdot \frac{m \cdot M}{r^2} \qquad \Longrightarrow \qquad \frac{r^3}{T^2} = const$$

Kepler's third law (see Equation 3) reveals as constant the ration between the squared period (*T*) and the cubed radius (*r*) of an orbit.

It's important to know that not only circular orbits are a solution to Newton's law, but also their generalised form: **ellipses**; which turns out, is the most precise type of orbit for planets. Kepler was able to derive his laws from astronomical observations.

3. Now that you learnt about the connection between the Third Kepler Law and the second Newton's Law, try to find the constant values of the third Kepler Law for Mars and Earth.

Planet	Mean distance to Sun (in AU)	Period (in days)	$\frac{r^3}{T^2}\left(\frac{AU^3}{days^2}\right)$

Earth	1	365.25	
Mars		689.95	

Table 1: Kepler's third law constant parameter for Earth and Mars.

Tip1: Since the outcome of Kepler's third law is a constant value for any planet in the system, you can use the units that you prefer.

Tip2: For planetary distances, it is convenient to use the Astronomical Unit AU (the mean distance from Earth to the Sun) and days.

1 AU = 149 597 900 km

Activity 2.2. Einstein's theory of relativity

Method 1: Learn with visual resources

1. Special Relativity: Crash Course Physics #42.
   ⇒ https://www.youtube.com/watch?v=AInCqm5nCzw

2. Physics Girl: Special Relativity and the Twin Paradox
   ⇒ https://www.youtube.com/watch?v=ERgwVm9qWKA

3. Write down your ideas on this topic and describe Figure 11.
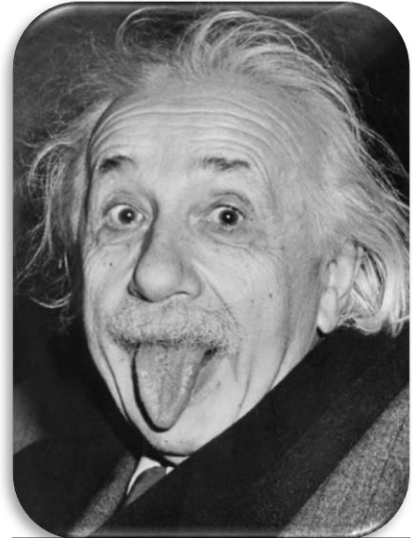
Figure 10: Albert Einstein. (Credit: commons.wikimedia)
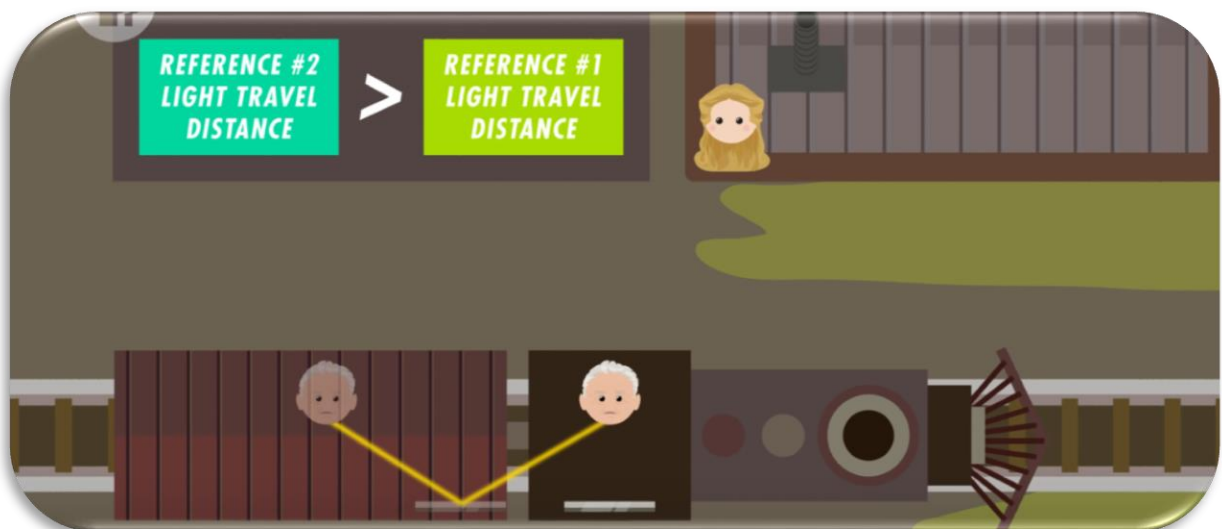
Figure 11: Picture showing light travelling different distances depending on the observer. (Credit: CrashCourse)

Method 2: Learn with theory

Albert Einstein was a very talented physicist who revolutionized the world with his discoveries. Einstein started from two hypothesis in order to develop his ideas:

Activity 2.2.1. Theory of Special Relativity

> **I. The laws of physics must be the same for any non-accelerating observer (inertial frame of reference).**
>
> **II. The speed of light in vacuum is measured to be the same by any observer.**

For this to be true (postulates I and II) **time and space could not be independent from each other** any longer. A new concept, called **space-time continuum, with four dimensions (x,y,z,t),** was defined to unify space and time as one.

Special Relativity explains the consequences of fast-moving objects on a flat space-time (approximation for small distances, masses and timescales)
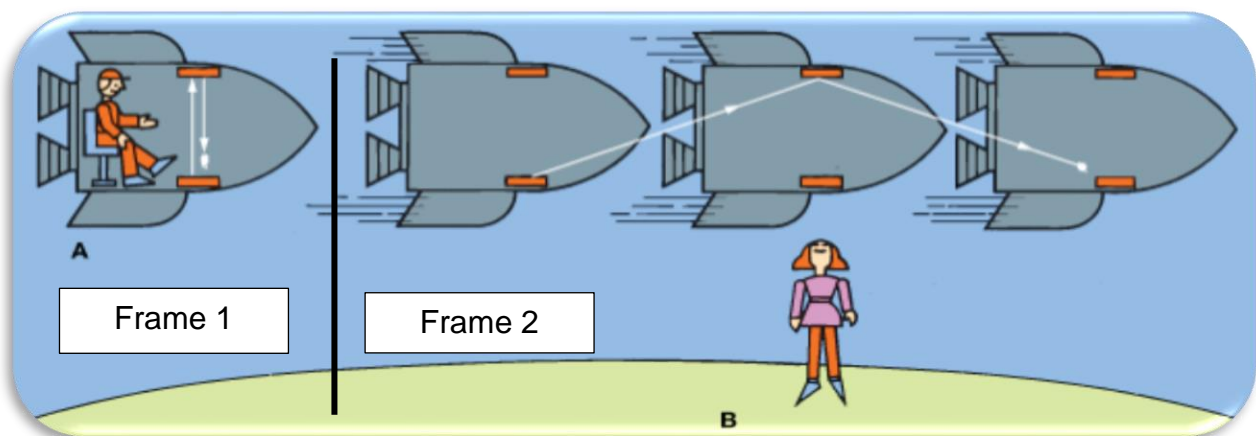
Figure 12: Thought experiment of a light beam moving inside a rocket to explain special relativity. (Credit: media.web.britannica.com)

To understand the implications of these postulates, look at Figure 12.

Frame 1 (left side of Figure 12):

Imagine a person sitting inside a rocket moving at a high constant speed. This person is watching a beam of light bounce from the floor to the roof.

1. If the height of the rocket is 1m how much distance (d) has the light beam travelled if it bounces from the floor to the roof and back to the floor?

2. Einstein postulated that the speed of light ($c \approx 3 \cdot 10^8 \ m/s$) must be the same for any observer. So, how much time does it take for the light beam to travel that distance ($t = d/c$)?

Frame 2 (right side of Figure 12):

Now imagine that the rocket has a big transparent window. You are watching the rocket passing by. For you the distance that the light travels seems longer because the beam has to meet the roof at a different position where the rocket was when the beam left the floor. But how is this possible if the speed of light has to be the same for both frames?

Einstein explained that the only possibility for light to be measured travelling at the same speed by these two observers is that time itself must be changing to compensate for the change in the distance travelled by the beam.

The speed of light does not change for any observer, so it must be space and time that change for each frame. This happens in processes known as **time dilation** and **length contraction**. These effects depend on a conversion factor called γ.

One observer (O') moves respect to another (O), that is static, at a constant speed *v*, away from the first frame in x' direction (x'=x direction). *C* is the maximum speed of information.

These transformations between frames of reference at high speeds (see Figure 13) can be described mathematically with what is called a Lorentz Transformation (see Equation 4).
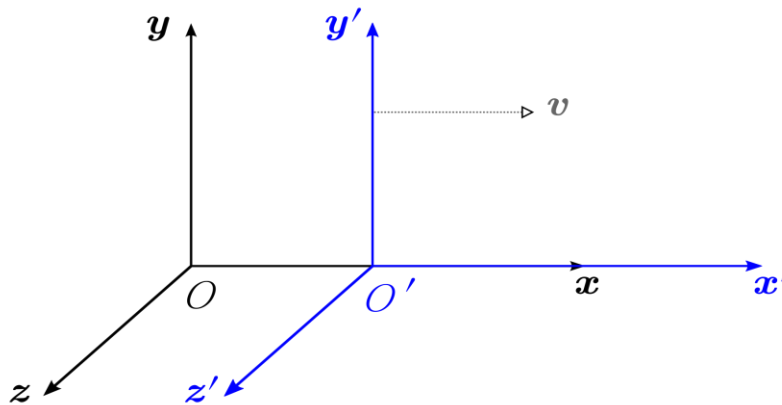
Figure 13: Two inertial (non-accelerating) frames of reference used to explain the Lorentz transformation. (Credit: en.wikipedia.org)

$$\begin{cases} t' = \gamma \left(t - \frac{vx}{c^2} \right) \\ x' = \gamma(x - vt) \\ y' = y \,; z' = z \end{cases} \text{ with } \quad \gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}}$$

Equation 4: Lorentz transformation between two frames with coordinates (t,x,y,z).

It's important to notice that there is nothing special about light or photons. The Lorentz transformation has nothing to do with the speed of light but instead it sets a limit for the speed of information.

As the particle of light is massless it can travel at the maximum speed that our Universe allows due to the change in the relativistic mass.

Extra activity: Light travelling horizontally inside a train
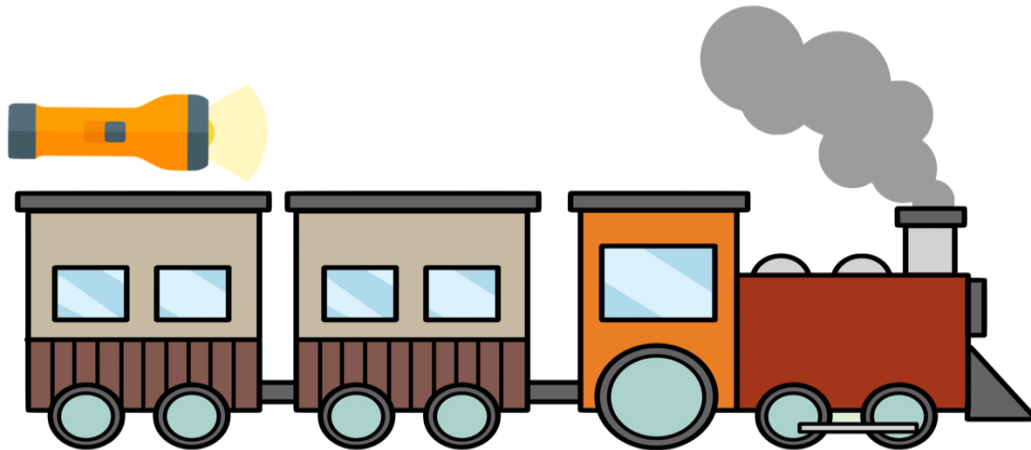
Figure 14: Image of a train. (Credits: www.wikihow.com)

1. Complete Table 2 taking into account the following situation.

    - Imagine a 75 m train driving towards you at half the speed of light (0,5c).

    - According to special relativity, the time period that a passenger experiences inside the train is dilated with respect to yours by a factor γ.

    - Additionally, the length of the train that you measure is contracted by $1/\gamma$. Both corrections are needed to preserve a constant speed of light from any reference frame (inside and outside the train).

    - Imagine that the train carries a flashlight that emits a beam in the direction of the train's propagation. **How much time does the light require to traverse the train's length for each observer?**

Frame of reference	Time period (s)	Train length (m)	Speed of light ($c = 3 \cdot 10^8\ m/_s$)
You (the moving observer at constant speed 0,5c, O')			
Passenger (a non-moving observer, O)		75	

Table 2: Complete the empty fields by calculating the time dilation and length contraction according to the Lorentz factor.

2. Use the box below to perform the required calculations.

<u>You (a moving observer with respect to the reference frame of the beam, O')</u>

Calculate the contracted length (x) of the train (length that you measure from outside the train)

Use Equation 4:

$$x' = 75m \implies 75m = \gamma(x - vt)$$

Imagine that you are able to measure the length instantaneously (t=0)

$$75m = \gamma x \implies x =$$

Knowing that the speed of light must be constant, you can calculate both time periods with t=x/c.

$$t = \frac{x}{c} =$$

<u>Passenger (a non-moving observer with respect to the reference frame of the beam, O)</u>

$$t' = \frac{x'}{c} =$$

Activity 2.2.2. General Theory of Relativity

Method 1: Learn with visual resources

1. Watch the following video.

    ScienceClick: What is General Relativity?

    ⇒   https://www.youtube.com/watch?v=DYq774z4dws

2. Explain with your own words what you have learnt so far.

Method 2: Learn with theory

General Relativity expands the concept of *time dilation* and *length contraction* and explains them in terms of *curved space-time* by comparing accelerating frames of reference with the acceleration caused by gravitational attraction. It predicts the "wrapping" of the fabric that spans the Universe.
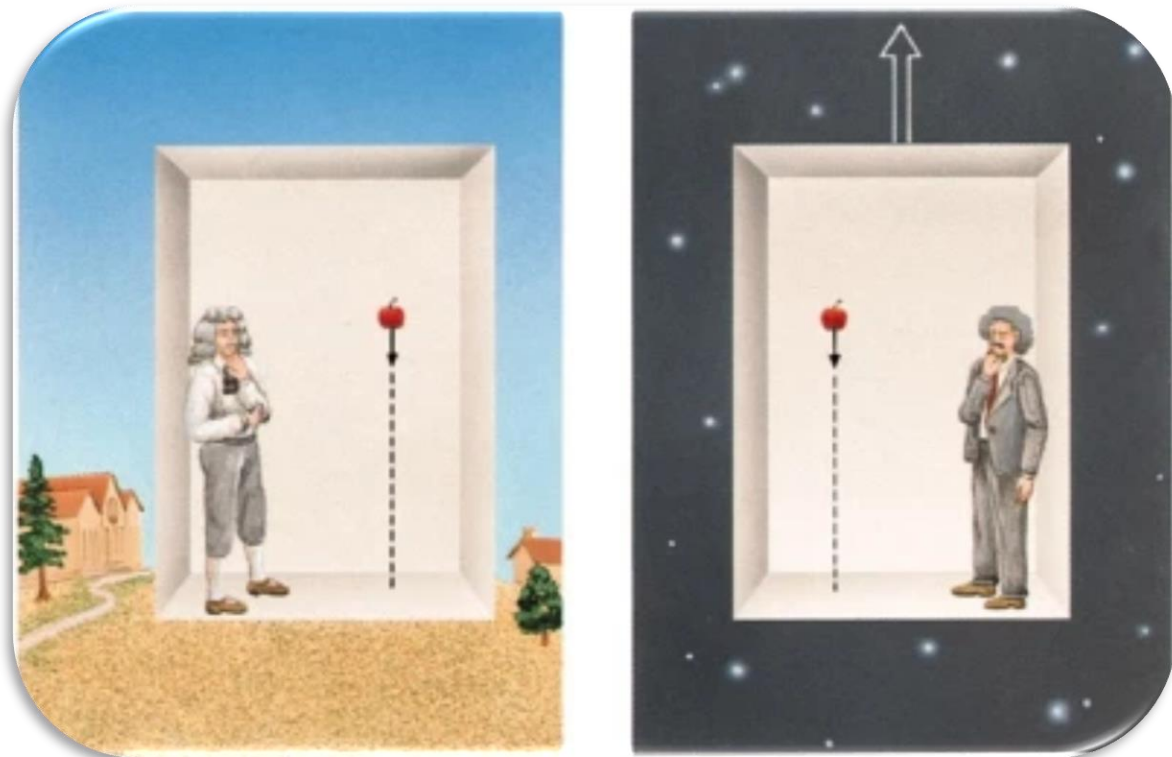
Figure 15: Depiction of Einstein's analogy for gravitational (left image) and inertial frames of reference (right image). (Credit: hackaday.com)

Making use of Einstein's analogy (see Figure 15), we can explain his ideas by imagining two scenarios that seem different at first glance.

> Einstein showed that there exists no physial experiment that allows us to distinguish a uniformly accelerated frame from a constant gravitational field.

The logical conclusion of these statements is that **space and time must be locally distorted around massive objects**

In the frame of General Relativity, gravity **is not a force but only a consequence of curved space-time**. Contrary to our everyday experience, space-time is not a flat nor a constant entity but a complicated 4-dimensional field that can be altered by the presence of massive objects such as planets, stars, galaxies... **The local shape of space-time** (its metric) **determines the motion of all particles** which move in geodesics but might look like curved trajectories from other frames of reference.
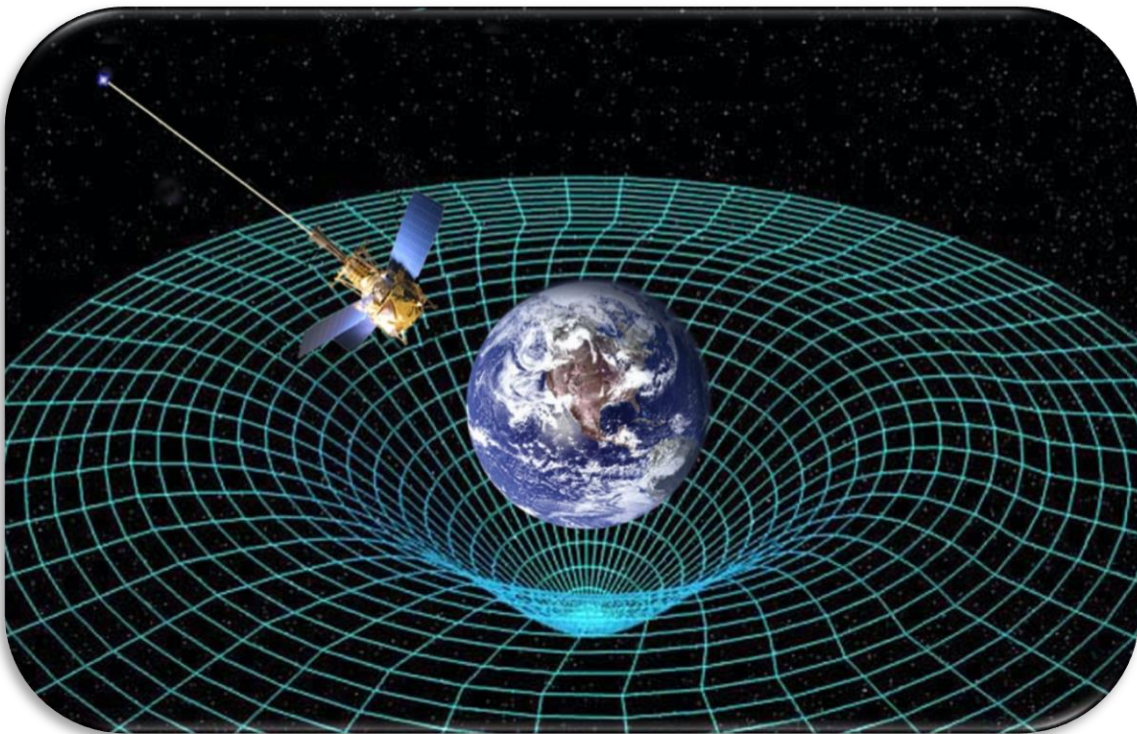
Figure 16: Visual representation of space-time distorted around a massive object. (Credit: space.com)

Summary

Space-time tells matter how to move	⟷	Matter tells space-time how to curve

We have learned from Special Relativity that **different frames of reference experience time with a relative dilation**. From General Relativity we know that **massive objects can distort space-time**, thus creating gradients of space and time.

Extra activity: A good example that combines both theories (Gravitational Redshift)

Now imagine how time passes for a photon escaping the surface of the sun and explain the consequences that we observe.
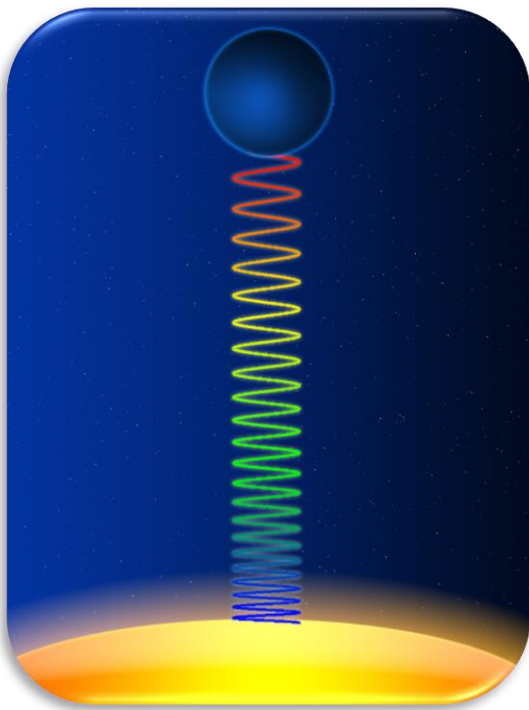
Figure 17: Visual representation of a photon escaping the gravitational field of the sun. (Credit: en.wikipedia.org)

Additional Resources

1. For more information, explore the following videos.

   ScienceClick: A new way to visualize General Relativity.

   ⇒ https://www.youtube.com/watch?v=wrwgIjBUYVc

   Dr. Becky: How does Mercury's orbit prove General Relativity?

   ⇒ https://www.youtube.com/watch?v=8Sm99OVG5A8

   Relgyro: Gravity Probe B in a Nutshell.

   ⇒ https://www.youtube.com/watch?v=noOkWegmVx4

2. Write down what you have learnt so far

Activity 2.3. Newton vs Einstein

Answer the following questions in the frame of Newton's and Einstein's theories independently.

1.   Is gravity a force? Give a complete explanation.

2. How can light be bent by gravity?

3. What would happen to an object orbiting another rotating object?

Activity 3. Geometric optics

Method 1: Learn with visual resources

1. How do lenses work? By Cognito.

    ⇒ https://www.youtube.com/watch?v=xpcX3B4xE7Q

2. Geometric Optics: Crash Course Physics #38.

    ⇒ https://www.youtube.com/watch?v=Oh4m8Ees-3Q

3. The sense of vision by Crash Course (A&P #18):

    ⇒ https://www.youtube.com/watch?v=o0DYP-u1rNM

4. What have you learned after watching these videos? Write down your own explanation and accompany it with some drawing.

Method 2: Learn with theory

Lenses are essential in our daily life; as a matter of fact, every time that we open our eyes, we are using a couple of them to perceive our surroundings (see Figure 18).
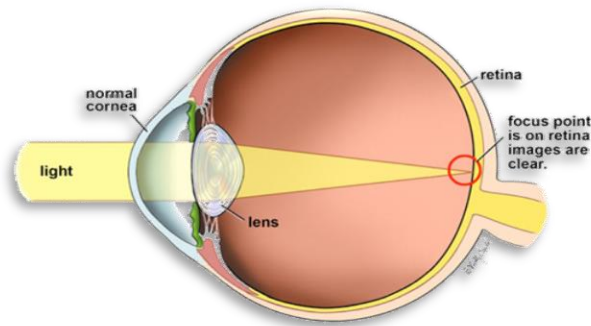
Figure 18: Representation of the path of light inside a human-eye. (Credit: 1.bp.blogspot.com)

Lenses are optical instruments that change the direction of light by refraction. This, combined with the fact that light goes through a curved optical medium, allows us to change the focal point of the rays as desired. We may differentiate between (see Figure 19):

- **Converging lenses:** they converge light rays and focus them at one point.
- **Diverging lenses:** they diverge light, so the light rays are dispersed.
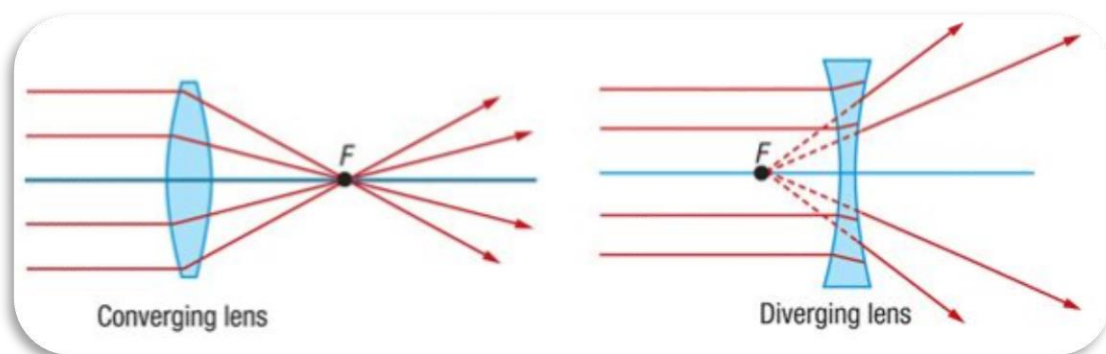
Figure 19: Light diagram of a converging (left) and diverging (right) lens. (Credit: sciencefacts.net)

Activity 4. Gravitational lensing (GL)

1. We have seen in Activity 3. how different lenses may change the direction of light. But what would happen if instead of a curved piece of glass we had a curved space?

2. Only from the name, what would you think a gravitational lens is? How do you think the gravitational lensing phenomenon may work?

Method 1: Learn with visual resources

Watch the following videos about gravitational lensing and explain with your own words:

1. What are gravitational lenses?
2. What effects may they cause?
3. What could we learn thanks to them?

4. HubbleESA: Gravitational Lensing - Space Sparks Episode 5.
   ⇒ https://www.youtube.com/watch?v=2ebFL0WcGS8&t=21s

5. SciShow Space: What Is Gravitational Lensing?
   ⇒ https://www.youtube.com/watch?v=VeAVmp9MLH4

Method 2: Learn with theory

Gravitational lensing is the effect of light-bending caused by the curvature of space-time. The most noticeable gravitational lenses are galaxies or clusters, but it's important to mention that all massive objects could create lensing effects (e.g., stars, planets). A gravitational lens, being in the line of sight between very distant objects and the observer, bends the emitted light. From the measurements of light displacement and intensity we can calculate the mass of the gravitational lens. Additionally, the focusing of light allows us to look further into deep space than we would be able to due to the limitations of our telescopes.
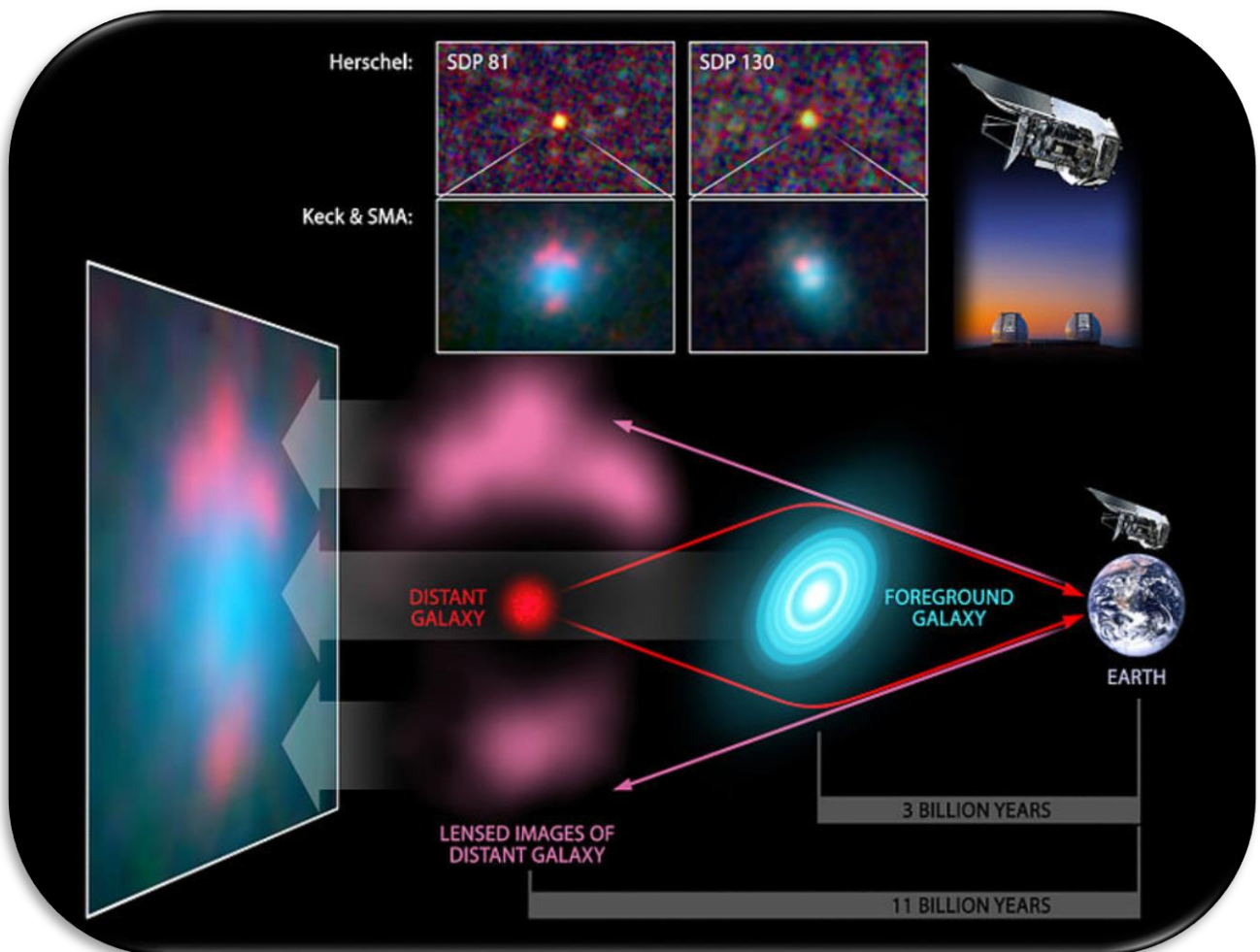
Figure 20: Light bending effect of gravitational influence as explained by General Relativity. (Credit: NASA)

Activity 4.1. Effects of gravitational lensing (GL)

1. Here are some effects of gravitational lensing. What do you think these effects might be? Fill in Table 3.

Effects	Name of the effect /Description of the effect
Figure 21: Magnifying lens. (Credit: https://www.educima.com)	Name: Description:
Figure 22: Effect of light bending with a wine glass. (Credit: kipac.stanford.edu)	Name: Description:
Figure 23: Kid using a periscope. (Credit: www.onlineplaygrounds.co.uk	Name: Description:

Table 3: Effects of gravitational lensing.

In the following table we explain the effects that gravitational lenses cause in the Universe.
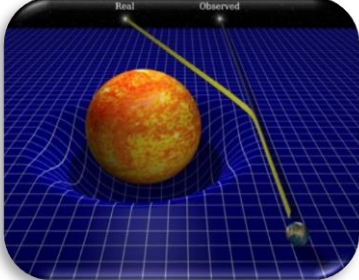
Effects	Gravitational lens effects in the Universe
Figure 24: Magnifying lens. (Credit: https://www.educima.com)	A gravitational lens magnifies the light that is able to reach us. Astronomers use this effect to detect faint objects that we wouldn't see without GL. Figure 25: Image of gravitational lensing. (Credit: www.businessinsider.com)
Figure 26: Light bending effect of a wineglass. (Credit: 4.bp.blogspot.com)	Some distant objects appear repeated in the sky due to the lensing effects of in-between galaxies. Figure 27: Example of an Einstein Cross. (Credit: www.constellation-guide.com)
Figure 28: Kid using a periscope. (Credit: www.onlineplaygrounds.co.uk)	Thanks to the gravitational pull of massive astrophysical objects, even light sources that would appear hidden by that object, are visible. Figure 29: Gravitational effect on a ray of light. (Credit: i.stack.imgur.com)

Table 4: Compilation of consequences of gravitational lensing and their everyday analogies.

Activity 4.2. Reproduce the effect of gravitational lensing with the bottom of a wine glass

1. Watch the following video and reproduce the experiment at home.

   ⇒   https://www.youtube.com/watch?v=PviYbX7cUUg

2. Add a picture of your experiment and describe your findings.

Activity 4.3. Observed patterns of gravitational lensing (GL)

Depending on the shape and alignment of the lens positioned between source and observer; we can see one or another pattern. We could classify them in any of these three types: Einstein Rings, Einstein Crosses or Arcs (see Figure 30).
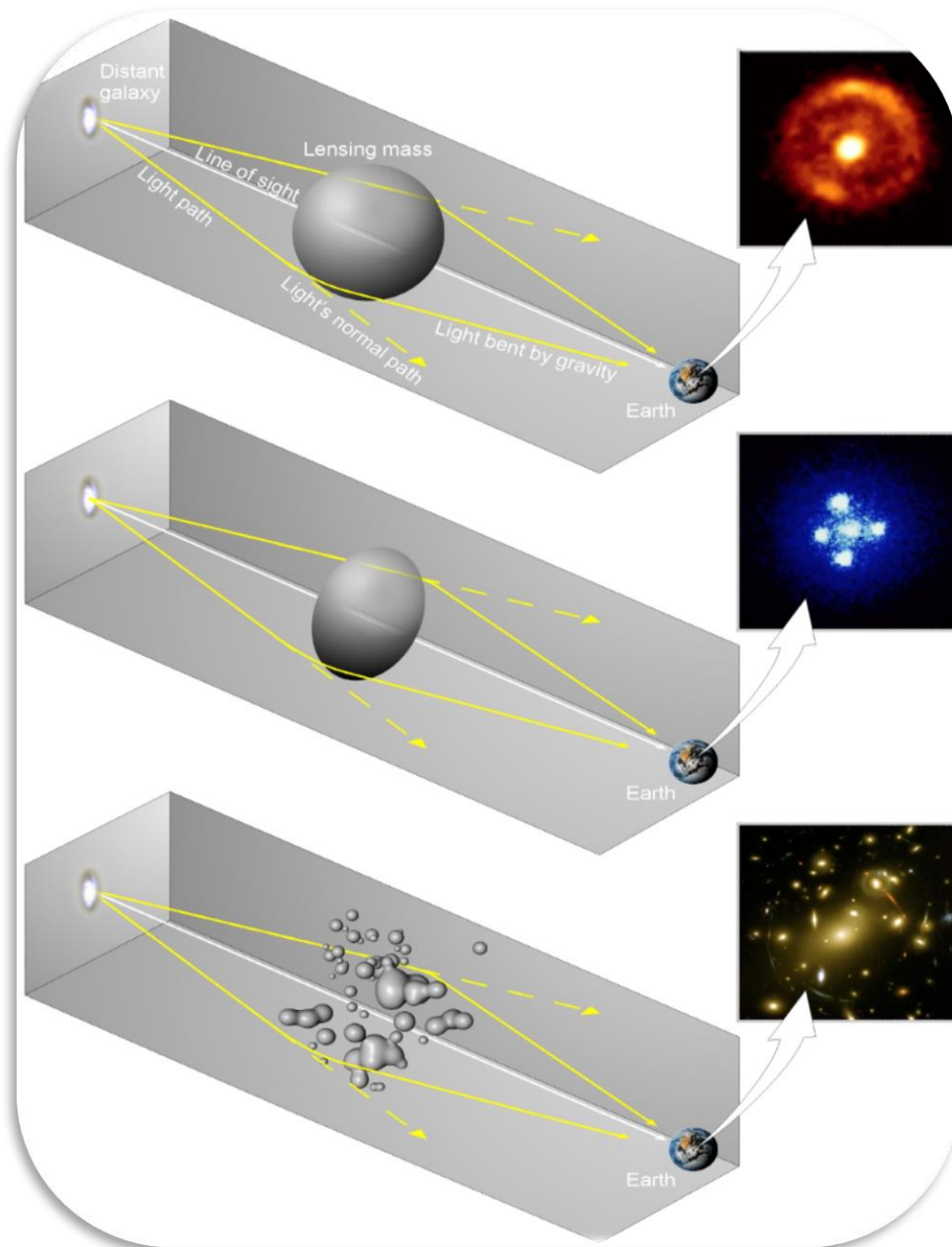
Figure 30: Bent light: Depending on the shape of the intervening object, gravitational lensing can produce rings, Einstein crosses or arcs. (Credit: ESA)

1. According to Figure 30, what alignment and shape of the lens could create the image patterns shown in Table 5?
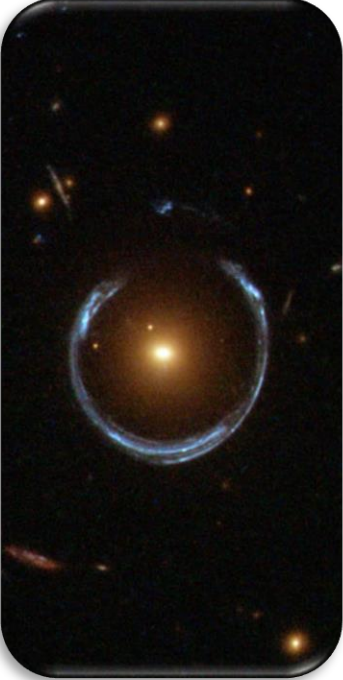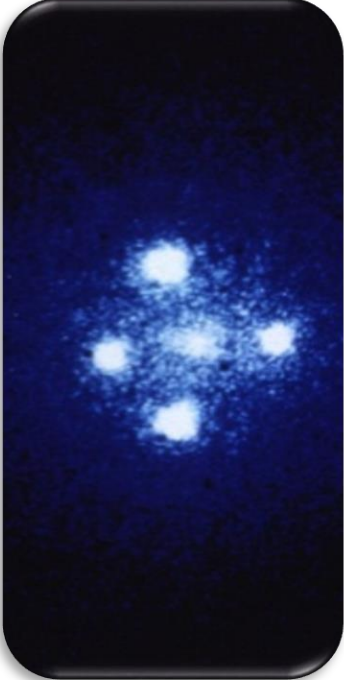
Figure 31: Einstein Ring. (Credit: apod.nasa.gov)	*Figure 32: Einstein Cross. (Credit: constellation-guide)*	*Figure 33: Multiple Arcs. (Credit: wordlesstech.com)*

Table 5: Different transmission patterns produced by GL depending on the alignment.

2. Match the real data images of Table 6 collected by the Hubble Space Telescope with the theoretical alignments of gravitational lenses of Table 7. Fill in Table 7 with the number of the image which effect is caused by the gravitational lensing system (from 1-4).

Gravitational Lens 1

Gravitational Lens 2

Gravitational Lens 3

Gravitational Lens 4
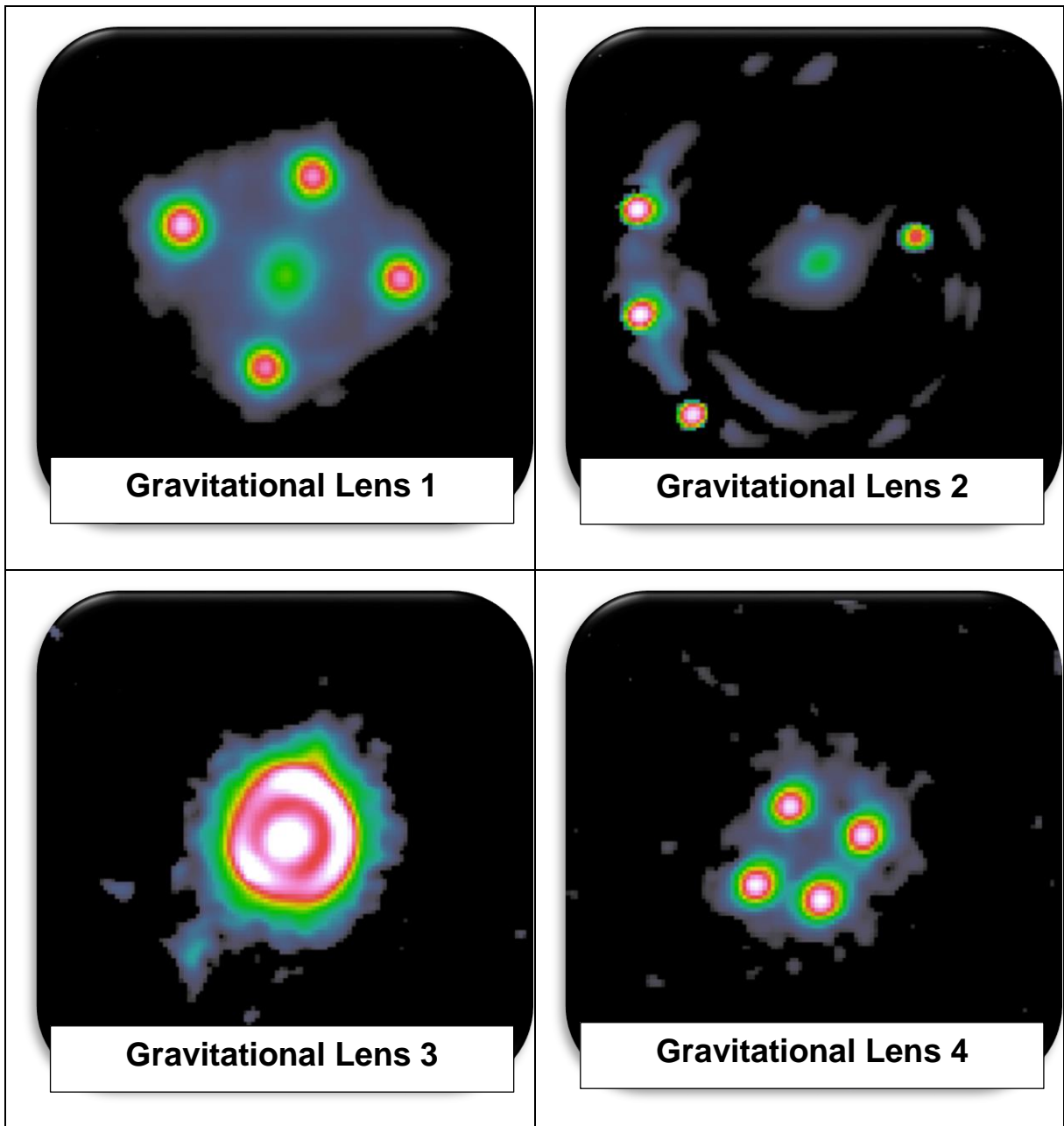
Table 6: Real images of different Gravitational Lensing effects.
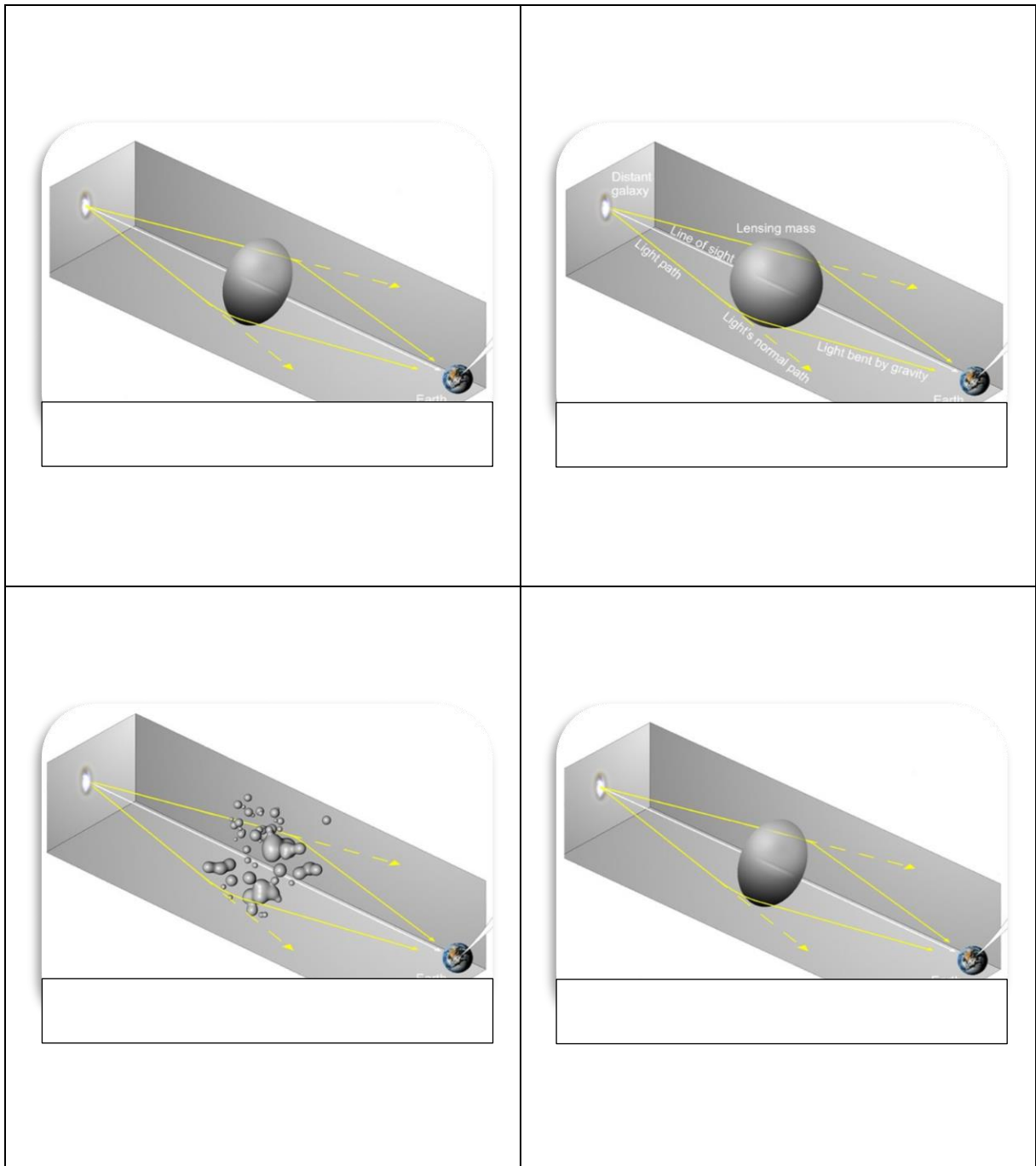
Table 7: Theoretical alignment for different Gravitational Lensing effects.

The gravitational lensing effects include not only the visible but also the non-visible components of the lens (galaxy/galaxy cluster). It is possible to infer the total mass of the galaxy/cluster that acts as a gravitational lens, revealing the so-called "Dark Matter".

Activity 4.4. Calculate the mass of a gravitational lens creating an Einstein ring pattern

From Einstein's field equations, one can derive the mass of a lens causing an Einstein ring of a given size.

$$\theta_1 = \sqrt{\frac{4GM}{c^2}\frac{D_{LS}}{D_S D_L}}$$

Equation 5: Formula derived from the Theory of General Relativity to calculate the mass of a gravitational lens depending on the radius of the Einstein Ring it creates. (Credit: en.wikipedia.org)

Here θ is the radius of the Einstein ring in radians, G is the gravitational constant, M is the mass of the lens, c is the speed of light, D_{LS} the distance from the source to the lens, D_S the distance from the object to the observer and D_L the distance from the lens to the observer. Have a look at Figure 34 to better understand the optical system.
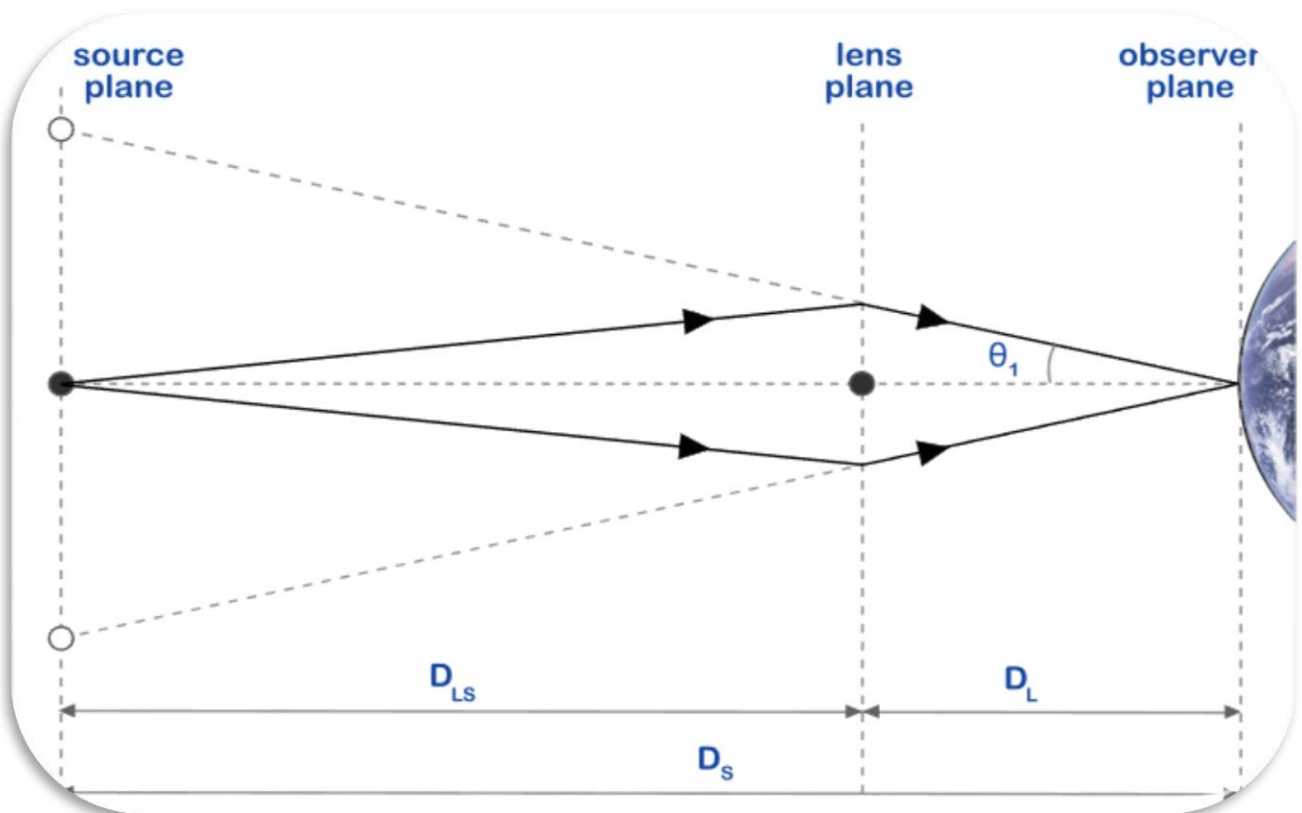
Figure 34: Graphical representation of the required alignment for gravitational lensing with labelled distances. (Credit: en.wikipedia.org)

Due to the expansion of the Universe (discovery made by astronomer Edwin Hubble), it is possible to infer the approximate distance (d) of distant objects on the celestial sphere by measuring their redshift value (z). In Activity 7.2. this type of measurement is discussed in more detail. The following equation, that includes the Hubble constant (H_0) and the speed of light (c), can be used to approximately relate the redshift to a distance in units of length.

$$d = z \cdot c / H_0$$

Equation 6: Hubble's equation relating redshift and distance for far objects on the celestial sphere.

Once the distances to both objects (gravitational lens and ring) have been obtained, Equation 5 can be rewritten to calculate the mass of the gravitational lens. Looking at Figure 34 it can be seen that the distance between source and lens (D_{LS}) can be obtained simply by subtracting the total distance to the source minus the distance to the lens ($D_{LS} = D_S - D_L$).

$$\theta = \sqrt{\frac{4GM}{c^2}\frac{D_{LS}}{D_S D_L}} \implies M = \frac{\theta^2 c^2 D_L D_S}{4G(D_S - D_L)}$$

Equation 7: Mass calculation for an Einstein Ring. We have used $D_{LS} = D_S - D_L$.

Activity 5. Dark Matter and its discovery

1. Watch the following video about Vera Rubin and Dark Matter. Explain what was the discovery made by Vera Rubin.

   ⇒   https://www.youtube.com/watch?v=pkrljGUJOPA

   _____
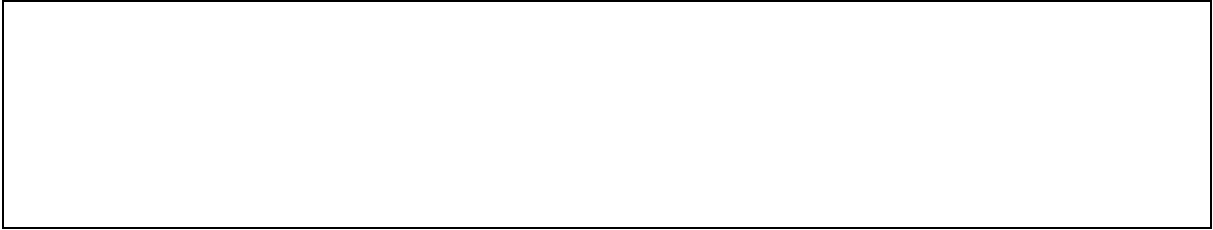
2. What do you think astronomers call Dark Matter?
   a. Matter located at dark regions of the sky (i.e., Horsehead Nebula).
   b. Matter that appears in empty regions of the sky.
   c. Matter that hasn't been detected, but can be inferred (for example, from gravitational observations).

Dark Matter is a hypothesised solution to the apparent missing matter at galactic scales. **It is important to mention that, so far, Dark Matter hasn't been found and that it only represents one of the possible solutions to the problem.** Other alternatives might be that gravity does not behave as expected at galactic scales. Nevertheless, for the sake of simplicity, we will proceed under the hypothesis of Dark Matter being some kind of non-luminous undiscovered particle.

As we mentioned in Activity 4., how much the light is distorted cannot be explained with the visible parts of the galaxy (or cluster of galaxies) causing the gravitational lensing effect. But even taking into account the ordinary non-visible matter, the results do not match. The total mass of a galaxy (or cluster of galaxies) involves the so-called "Dark Matter" as well.

> **Dark matter** is called dark, but it **should actually be called invisible** because it does not appear to interact with the electromagnetic field. Dark Matter does not absorb, reflect or emit electromagnetic radiation, being undetectable by telescopes.

Baryonic matter or ordinary matter is the matter that we know and can be detected by astronomers with direct measurements. The ordinary matter corresponds only to ~5% of the mass-energy content in the Universe. The rest is thought to be divided between the so call **dark matter** and **dark energy**, in the proportion indicated by Figure 35.
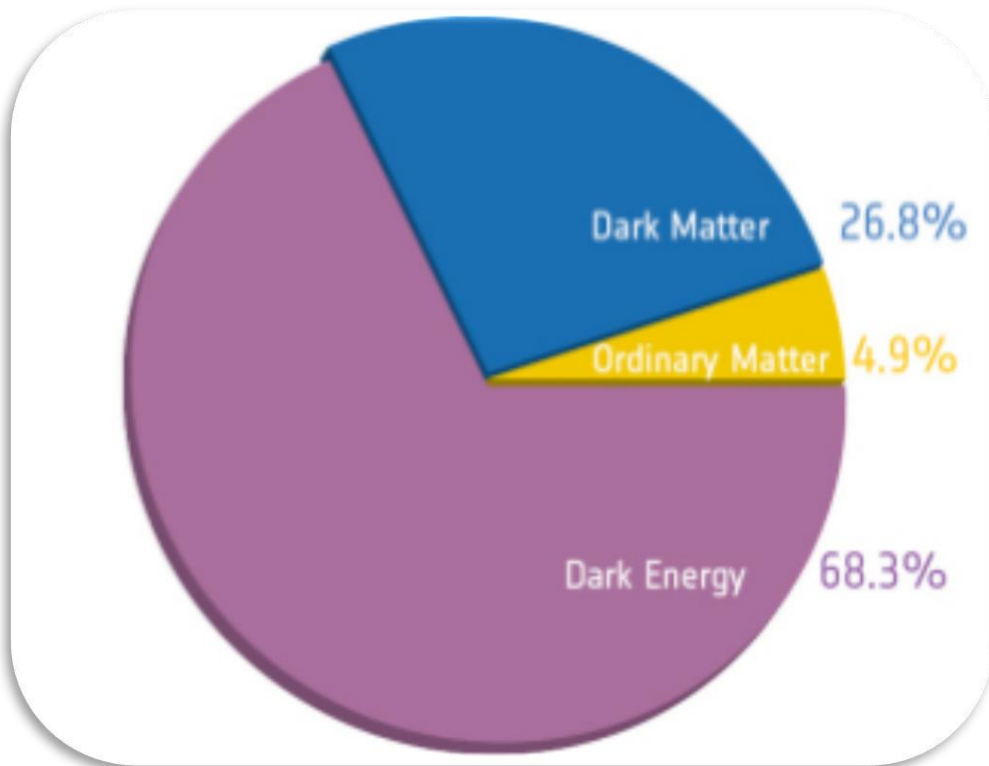
Figure 35: Energy content of our Universe as measured by the ESA/Planck. (Credit: ESA)

One useful example to understand the nature of dark matter is the Bullet Cluster (see Figure 36). It is important to mention that the colours in Figure 36 do not correspond to "real colours" (optical wavelengths) but have been added to show the different components of the galaxies acting as gravitational lens. The ordinary matter has been coloured in red and the strength of the gravitational lensing in purple.

Figure 36: Optical image of the Bullet Cluster. In red regular matter is revealed according to x-ray measurements. In purple the mass distribution from gravitational lensing is shown. (Credit: apod.nasa.gov)

Figure 36 shows in purple the total mass distribution of the two galaxies (from gravitational lensing measurements), which suggests that the galaxies have passed by without friction. However, when analysing the x-ray images (red region), it shows a clear collision with a higher concentration of mass next to the centre of gravity. The discrepancy between these two measurements suggest that galaxies are indeed formed by two different kinds of matter:

1. **Regular baryonic matter – which has a high electromagnetic interaction.** It emits light in some region of the electromagnetic spectrum and can be detected.

2. **Dark Matter – which does not seem to interact with the electromagnetic force.** In fact, we haven't seen it interact with any other force than the gravitational.

As revealed from the gravitational lensing, **most of the mass of a galaxy is Dark Matter.** Although the existence of dark matter is generally accepted by the scientific community, some astrophysicists argue for various modifications of the standard laws of general relativity, such as modified Newtonian dynamics. These models attempt to account for all observations without invoking supplemental dark matter.

Activity 5.1. Mass content inferred from Gravitational Lensing
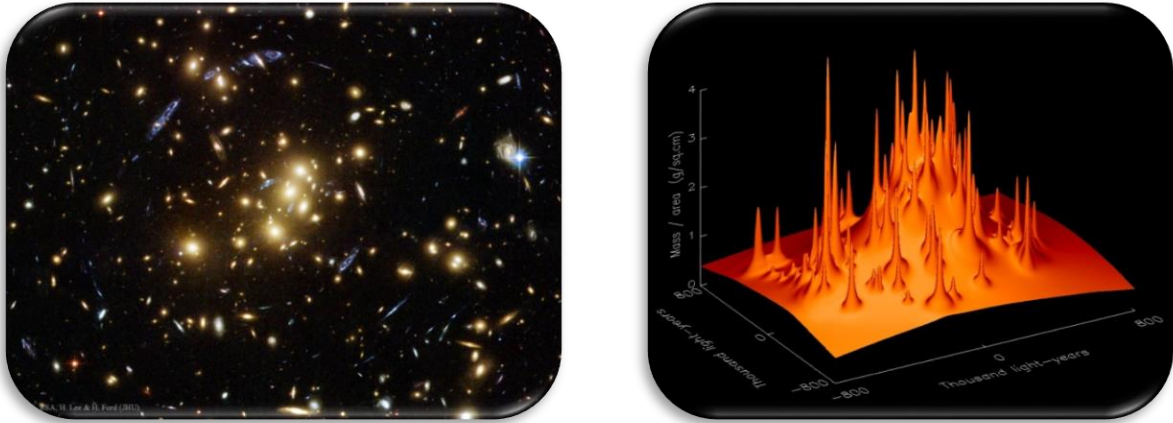
Figure 37: (Left image) Optical picture of the cluster CL0024+1654. (Credit: apod.nasa.gov). (Right image) Mass distribution of the cluster CL0024+1654 obtained from measurements on GL. Credit: (Evrard, 1998)

Apart from revealing new parts of the Universe and helping us understand gravity, one of the most useful applications from gravitational lensing is **Weighting Galaxies**.

Depending on how strong the bending of light passing close to a galaxy or cluster of galaxies (acting as gravitational lens) is, we can infer the mass and mass distribution of it. Computer simulations, as seen in Figure 37, have shown to be very powerful tools to better understand the mass distribution from the real data collected.

> **Gravitational lensing measurements** and **rotation curves are two independent methods to determine** the amount of matter in a region. Both measurements have shown a discrepancy between the seen and measured mass (from gravitational effects). So, scientists are certain that our knowledge in particle physics or gravity (or even both) is incomplete.

Activity 6. Galaxies and types

Method 1: Learn with visual resources

1. Watch the following video (Galaxies part 1: Crash Course Astronomy # 38) and tell us what you have learnt about galaxies.

    ⇒   https://www.youtube.com/watch?v=I82ADyJC7wE

Method 2: Learn with theory

One century ago, astronomers believed that the whole Universe was compressed within the Milky Way (the galaxy where we live). In the early years of 1900 there was a big discussion on whether the milky patches of light, with a spiral shape, that were seen scattered among the stars were outside the Milky Way or were part of it.
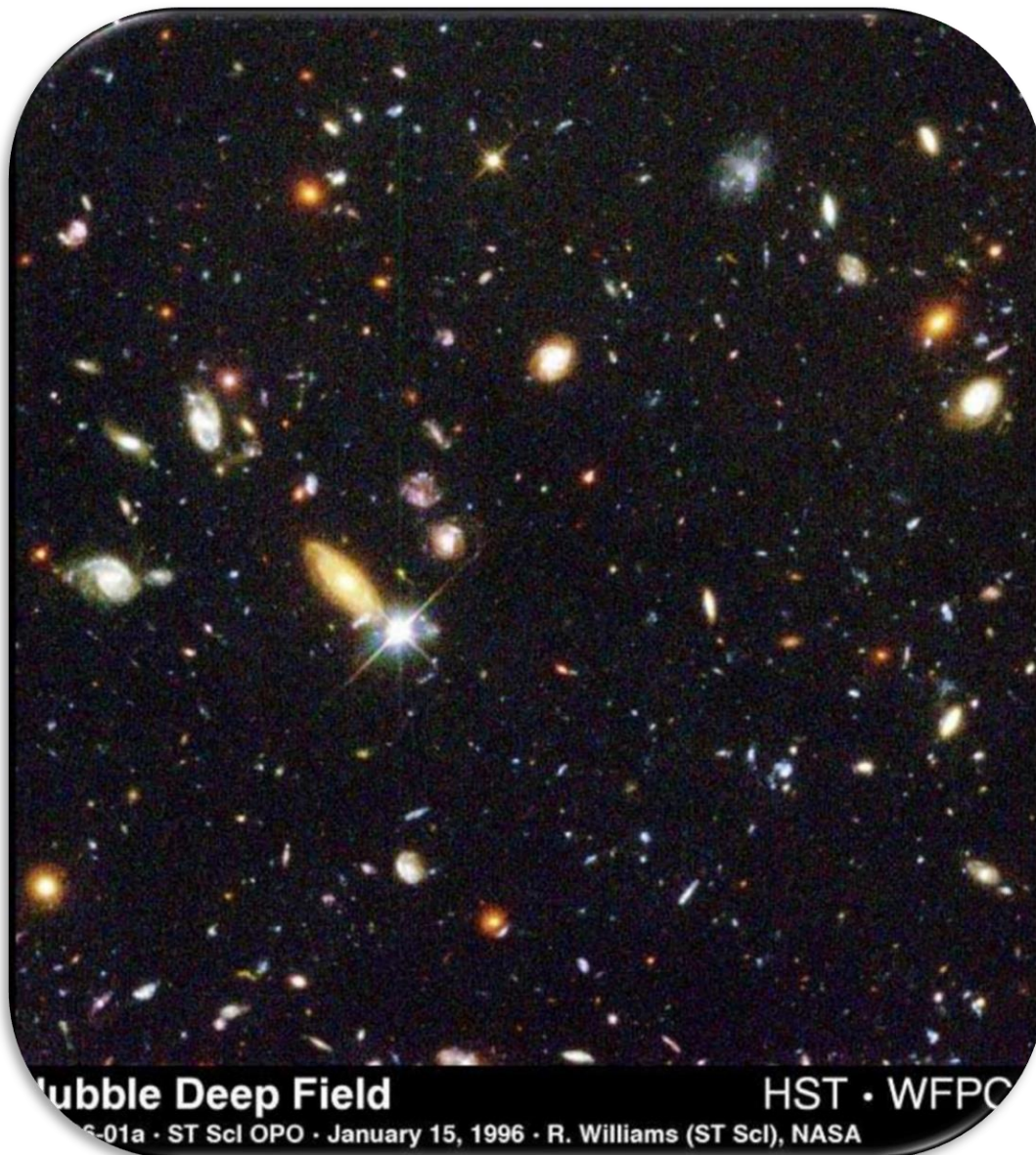
Figure 38: Hubble Deep Field of Galaxies. (Credit: ESA/NASA Hubble Space Telescope).

It was not until work by Edwin Hubble in the 1920s when it was established that each of the spiral nebulae was a huge star system, called a galaxy. They were able to measure the distance to some of these galaxies, proving that the Universe was much vast than previously thought, and that our Galaxy is just one of billions of galaxies in the Universe.

Since then, astronomers have learned a lot about galaxies: how many they are, what types of galaxies exist, and the stars that they contain. They have also started to figure out how galaxies formed and how they evolve. And all this thanks to the light coming from those galaxies, emitted by the thousands to trillions of stars within them

1.   How would you define what a galaxy is and what is it made of? Make a drawing of what you imagine to be a galaxy and its components.

Most galaxies have a diameter size of 1000 to 100 000 parsecs (pc)[2] or approximately 3000 – 300 000 light years and are separated by distances of millions (~ 1 000 000) parsecs apart. **This means that a photon (a light ray) would need ~3000 years to cross the smallest galaxies and ~3 000 000 years to arrive from the edge of a galaxy to another one.**

Tip: For comparison, a photon would "only" require 250 min to cross our solar system. **Yes, the Universe is huge!**

The matter content of galaxies can be broadly classified into luminous and non-luminous matter. Luminous matter is that which emits radiation in some strip of the electromagnetic spectrum (stars, planets, gas, etc.) and non-luminous matter is that which does not interact with the electromagnetic force (neutrinos or dark matter). Dark matter has not been directly detected, but if it exists and is formed of a new type of particle, it would be part of the non-luminous matter that seems to be missing in galaxies; as Vera Rubin discovered.

Activity 6.1. Classifying galaxies

Your following task is to classify a sample of galaxies by their visual morphology and study some of their properties, as Edwin Hubble did in 1920.

For this exercise you will access to a list of images galaxies through the ESASky web portal, which play the role of a virtual telescope.

All ESASky help tutorials are available on this link.

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[2] 1pc = 3,26 light years or in other words, the distance light travels through vacuum in 3,26 years.
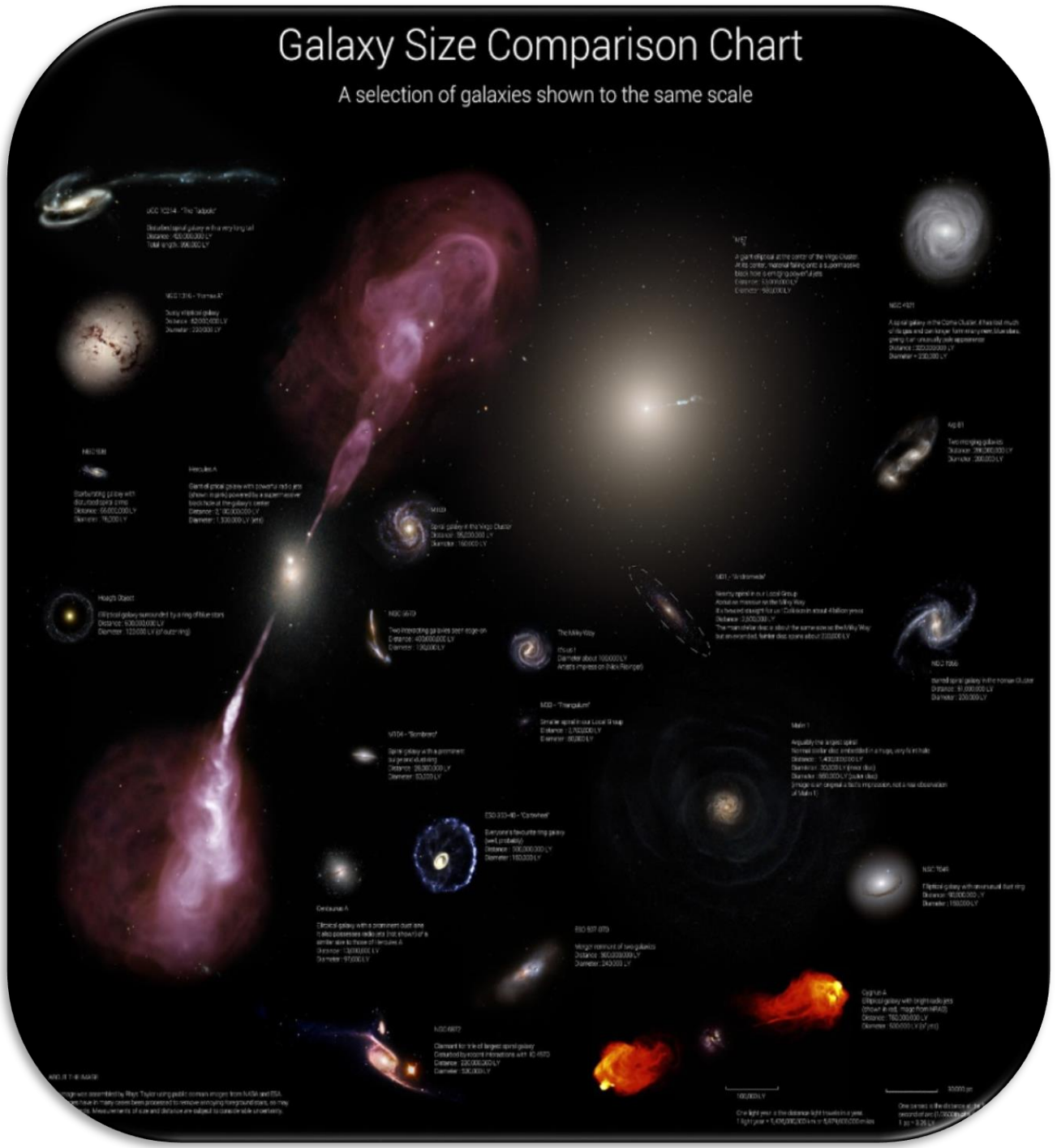
Figure 39: Galaxy size comparison. (Credit: universetoday.com).

You may follow any of the two procedures available for this task: in instructions and/or in images.

Classification name	Common characteristics of this classification of galaxies	Sketch
Type 1:		
Type 2:		

Type 3:		
Type: 4		

Table 8: Galaxy classification scheme depending on morphology.

PROCEDURE IN INSTRUCTIONS:

1. Click on this link to go into *ESASky* in your browser
2. Choose the option "Explorer" (see Figure 40), that is the simplest way to get familiar with ESASky.
3. Click on the upper left button (see Figure 41) to select one of the existing target lists on ESASky[3].
4. Group the galaxies that, from your point of view, have something in common and give a name to each type of galaxy in your classification, explain their characteristics, and sketch them. (Fill as many types as needed for your classification).

PROCEDURE IN IMAGES:
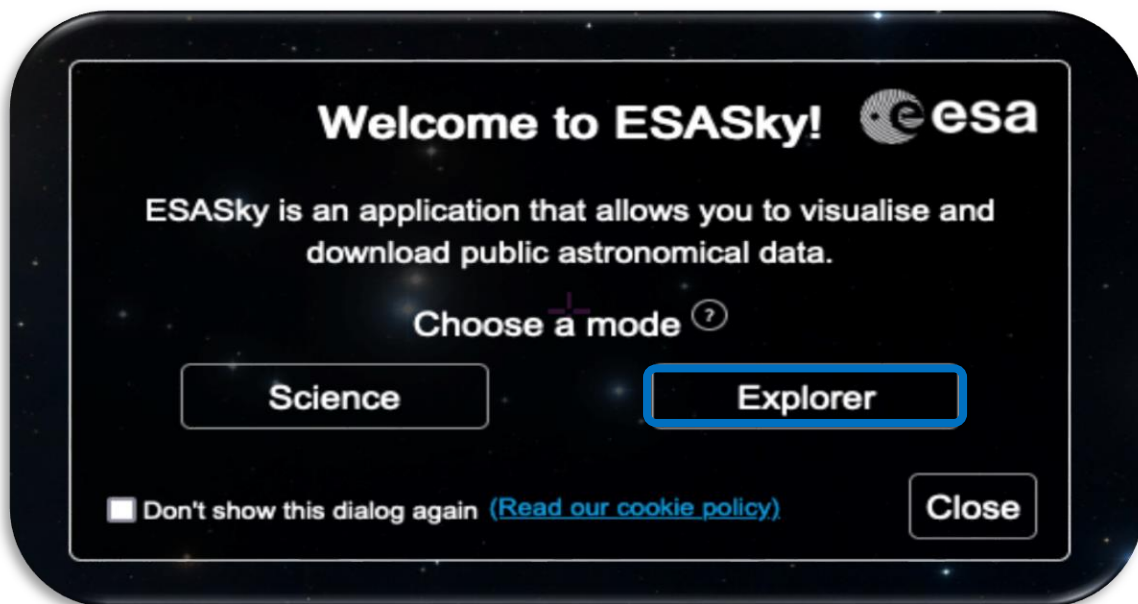
Figure 40: ESASky portal selecting Explorer Mode. (Credit: http://sky.esa.int/)

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[3] ESASky target lists: lists compiled by the ESASky team with the same type of objects.

Figure 41: ESASky select target list. (Credit: http://sky.esa.int/)
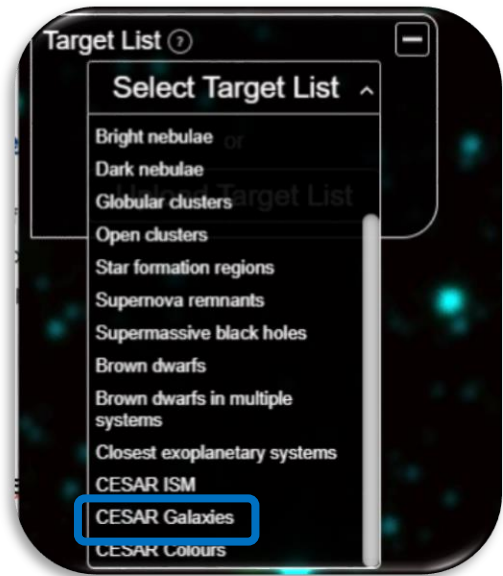
Figure 42: ESASky choose CESAR Galaxies. (Credit: http://sky.esa.int/)

Figure 43: Each one of the galaxies in the list of ESASky select sky tool to choose under the name of CESAR Galaxies. (Credit: http://sky.esa.int/)
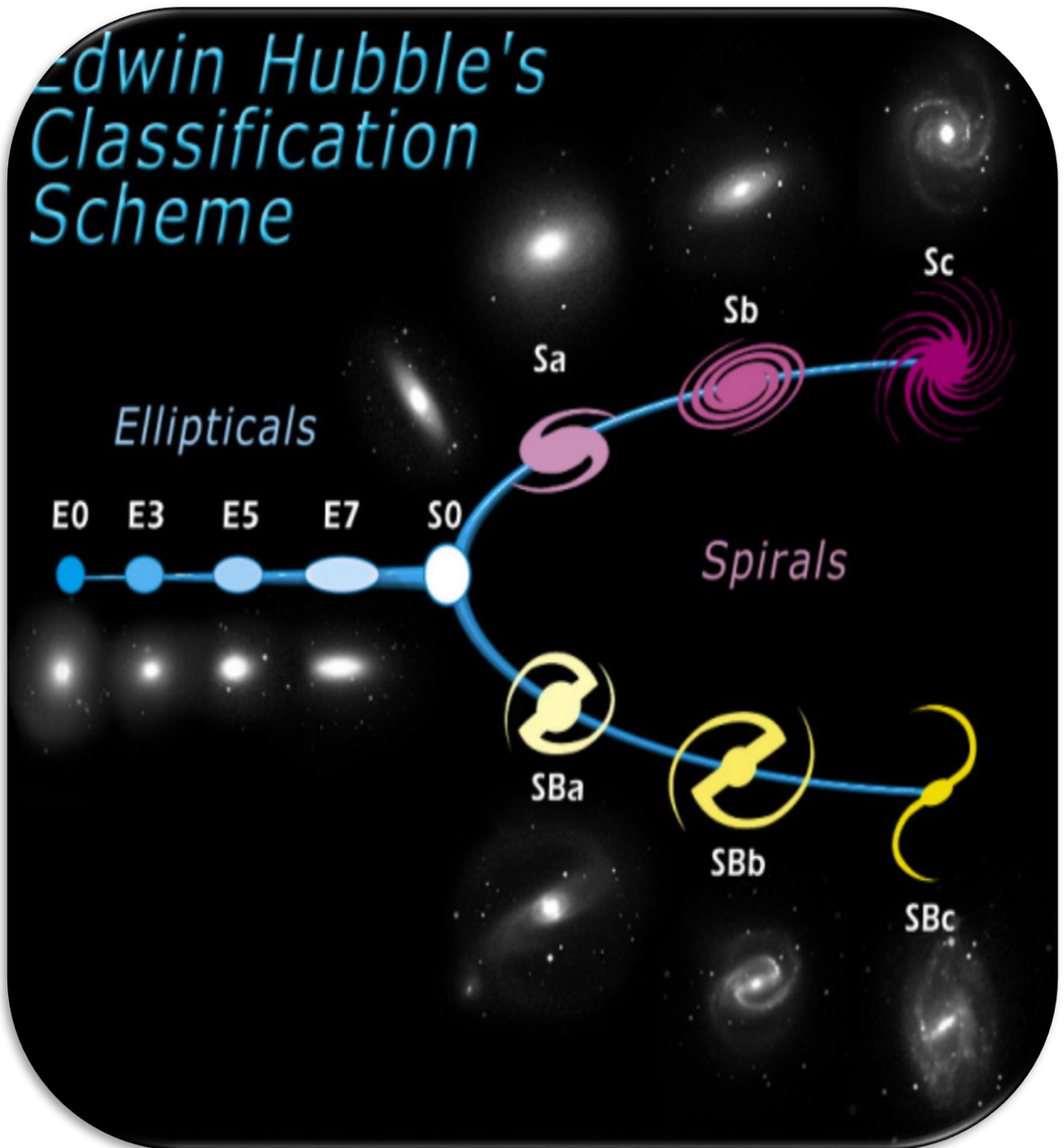
Figure 44: Hubble classification of galaxies. (Credit: en.wikipedia.org)

These are the main two groups of galaxies identified by Hubble, based on their morphological classifications as shown in Figure 44.

- **Ellipticals:** Shapes E0 to E7 are considered elliptic (see Figure 44). Their appearance shows little structure and they typically have relatively little interstellar matter (such as gas or dust). Consequently, these galaxies also have a low rate of new star formation. Instead, they are dominated by generally older, more evolved stars that are orbiting the common centre of gravity in random directions.

- **Spirals:** Most of the luminous matter is located on the same plane of rotation. Extending outward from the bulge are relatively bright arms. Hubble differentiated between spiral and bar-shaped spiral galaxies.

  - **Type S:** In the Hubble classification scheme, spiral galaxies are listed as type S, followed by a letter (a, b, or c) which indicates the degree of tightness of the spiral arms and the size of the central bulge. An Sa galaxy has tightly wound, poorly defined arms and possesses a relatively large core region. At the other extreme, an Sc galaxy has open, well-defined arms and a small core region.

  - **Type SB:** A majority of spiral galaxies, including our own Milky Way galaxy, have a linear, bar-shaped band of stars that extends outward to either side of the core, then merges into the spiral arm structure. In the Hubble classification scheme, these are designated by an SB, followed by a lower-case letter (a, b or c) which indicates the form of the spiral arms (in the same manner as the categorization of normal spiral galaxies). Bars are thought to be temporary structures that can occur as a result of a density wave radiating outward from the core, or else due to a tidal interaction with another galaxy.

Activity 6.2. Components of a galaxy

Figure 45 shows most astronomical objects that exist.
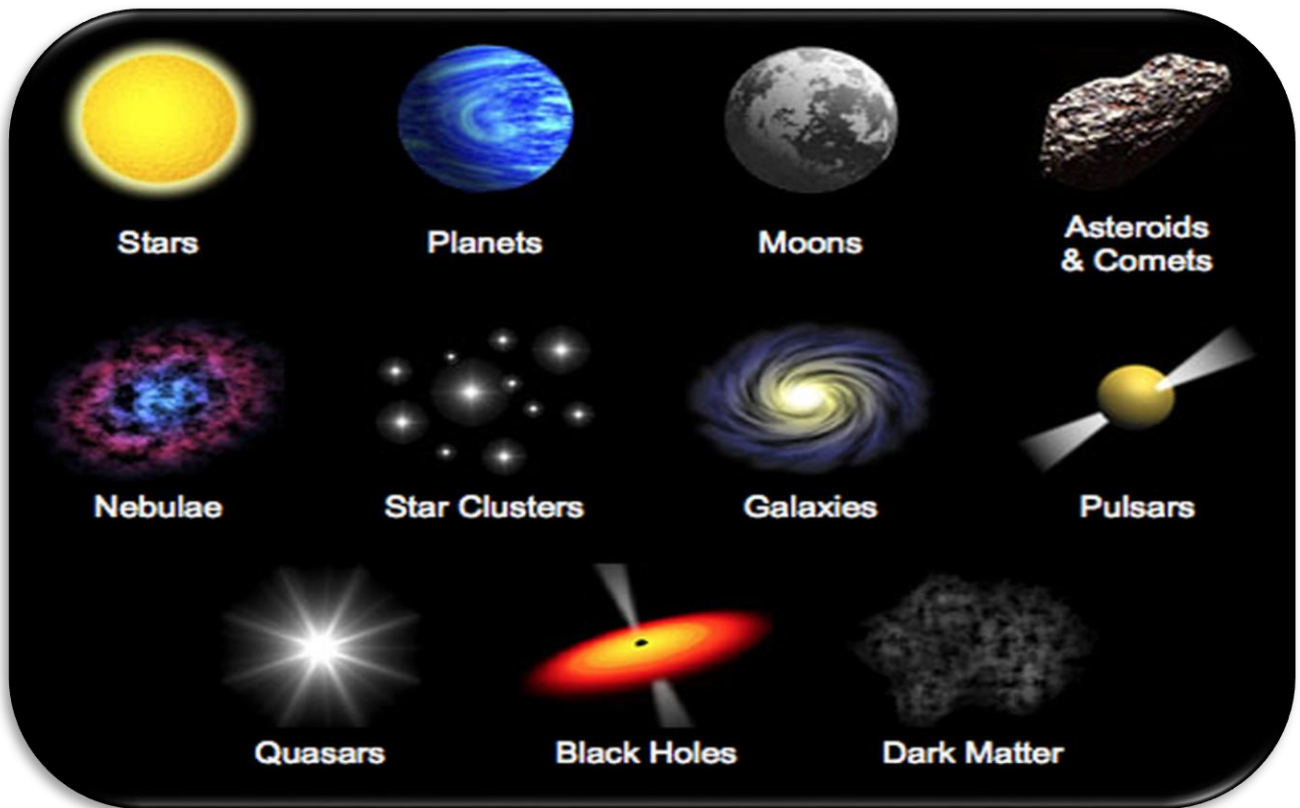
Figure 45: Main objects constituting a galaxy. (Credit: https://clarkscience8.weebly.com)

In a generic and simplified way, we can represent a spiral galaxy (see Figure 46) consisting of three structures that differ in content (type of matter and objects that constitute it) and orbital properties. They can generally be distinguished by observing the galaxy in different images of the electromagnetic spectrum, as each astronomical object emits radiation in different regions of it (except for dark matter that has not been seen to interact by the electromagnetic force).

- **Bulge**, it corresponds to the centre of the galaxy and has a spherical distribution. It normally consists of a super-massive black hole, surrounded by stars orbiting in random directions. Its total mass can be inferred from the analysis of the light spectrum since there is a clear correlation between the spectrum of a star and its mass.

- **Disk**, its shape is flat and all the objects that constitute it tend to orbit in the same direction. Their exact mass is more difficult to infer, due to the existence of interstellar matter (gas, dust, etc.). It usually extends to distances of 4 or 5 times the radius of the Bulge.
- **Halo**, a sphere of matter that orbits randomly around the centre of the galaxy. Unlike the bulge, its components extend to distances much farther than the boundaries of the galactic disk (100-1000 kpc). Before the discovery of dark matter, its contribution to the total mass of the galaxy was thought to be much lower than that of the bulge or disk. Its regular matter density is lower and consequently has a lower density of stars.
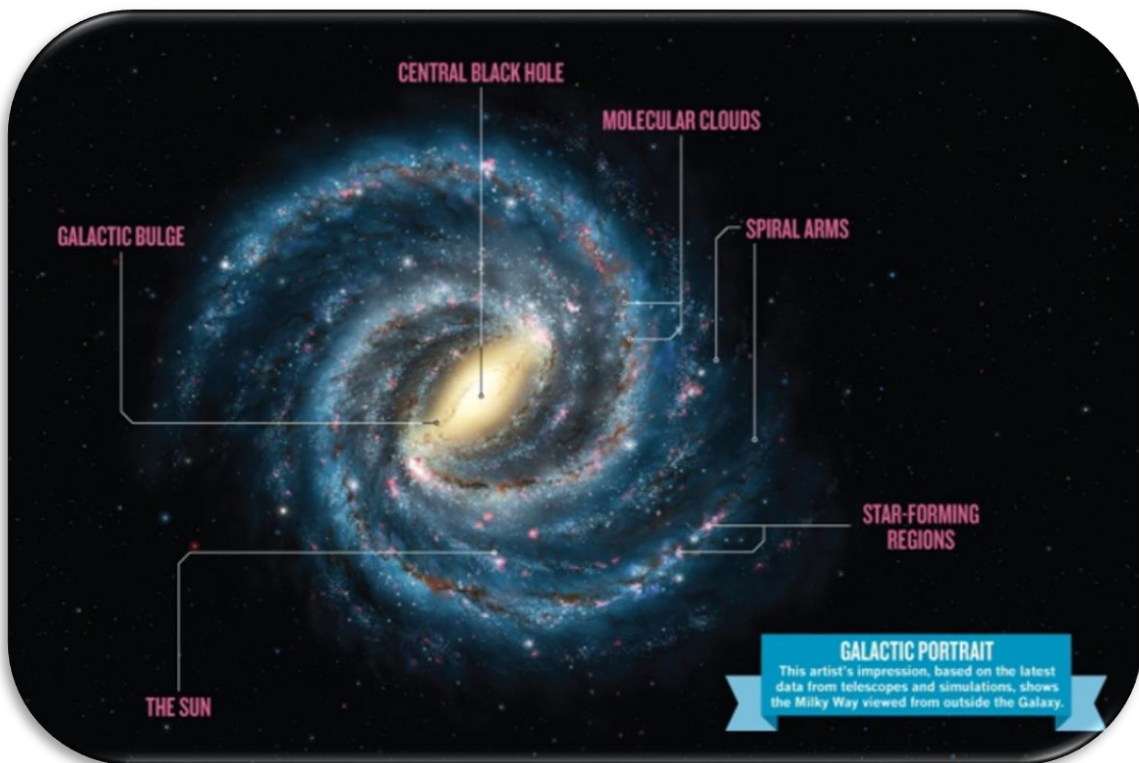
Figure 46: Typical shape and components of a spiral Galaxy. (Credit: Lynette Cook, Nature)

1. Access to ESASky and study the M31 galaxy at different wavelengths. Table 9 shows the andromeda galaxy in different wavelengths. Depending on the image, the bulge and disk appear clearly distinguishable. On the contrary, the halo cannot be detected so easily.

Soft X-ray	Ultraviolet	Optical
Figure 47: X-ray pic. of M31.	*Figure 48: UV pic. of M31.*	 *Figure 49: Optical pic. of M31.*
Near Infrared	**Far Infrared**	**Submillimeter**
Figure 50: Near IR pic. of M31.	*Figure 51: Far IR pic. of M31.*	*Figure 52: Submillimetre pic. of M31.*

Table 9: Compilation of M31 pictures in different wavelengths ranging from UV to Submillimetre. Galactic Bulge and Disk should be distinguishable when comparing all different pictures.

PROCEDURE IN INSTRUCTIONS:

1. Access to ESASky: https://sky.esa.int.
2. Write in the search box the target you want to look for (M31).
3. Go to skies and create a stack of filters as requested in Table 9.
   - Soft X-ray, ultraviolet, optical, near-infrared, far-infrared and submillimetre
4. Create a snapshot of each of the images of M31 at those wavelengths, with a similar field-of-view (size) than the optical one provided (Tip: click on the "-" button as many times as needed).

PROCEDURE IN IMAGES:

Figure 53: ESASky portal selecting Explorer Mode. (Credit: http://sky.esa.int/)

Figure 54: Insert the name of the target M31 in the search box. (Credit: http://sky.esa.int/)

Figure 55: *Add this list of skies.* (Credit: http://sky.esa.int/)
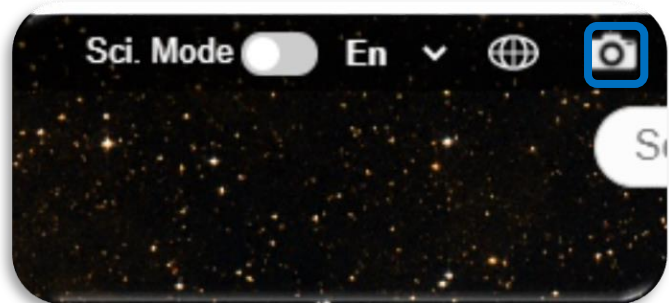
Figure 56: *Make snapshots of M31 with the camera icon for the various skies and fill in* Table 9. (Credit: http://sky.esa.int/)

Activity 6.3. Quasars

Quasars are a type of active galaxies. This means that they are really powerful and bright galaxies with an active black hole in its core. Quasars are mostly really old (although some of them are relatively close and still live today) and formed at the youngest ages of our Universe (billions of years ago).

We can mostly see them at large distances. Its name is derived from the word quasi-stellar objects, because they were initially thought to be stars due to its high brightness. Nevertheless, a closer inspection of its spectrum and redshift revealed them as distant galaxies.

1. Check out the following link for more information:

   ⇒   https://esahubble.org/wordbank/quasar/
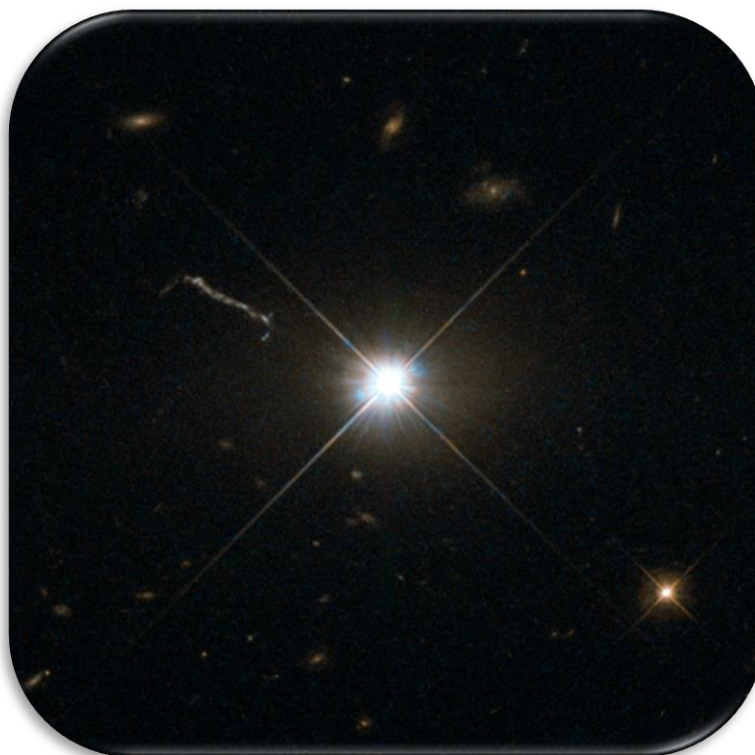
Figure 57: Image of a quasar. (Credit: esahubble.org)

Activity 7. The Doppler effect

Method 1: Learn with visual resources

1. Watch the following video about the Doppler Effect.

   ⇒ https://www.youtube.com/watch?v=SqGtp6RQy_8

2. Watch the following video of Astronomic about redshift.

   ⇒ https://www.youtube.com/watch?v=ikgRZt1BSyk

3. Write down what you have learned so far.

Method 2: Learn with theory

Light is an electromagnetic wave that can propagate through the vacuum of space. There are different energies of light that can be defined by their frequency or wavelength.

- **Frequency (f):** Number of waves that pass a fixed point in a unit of time (for example, per second).

- **Wavelength (λ):** One cycle of a wave, measured as the distance between two consecutive points in the same phase, for example, the distance between two consecutive wave peaks.
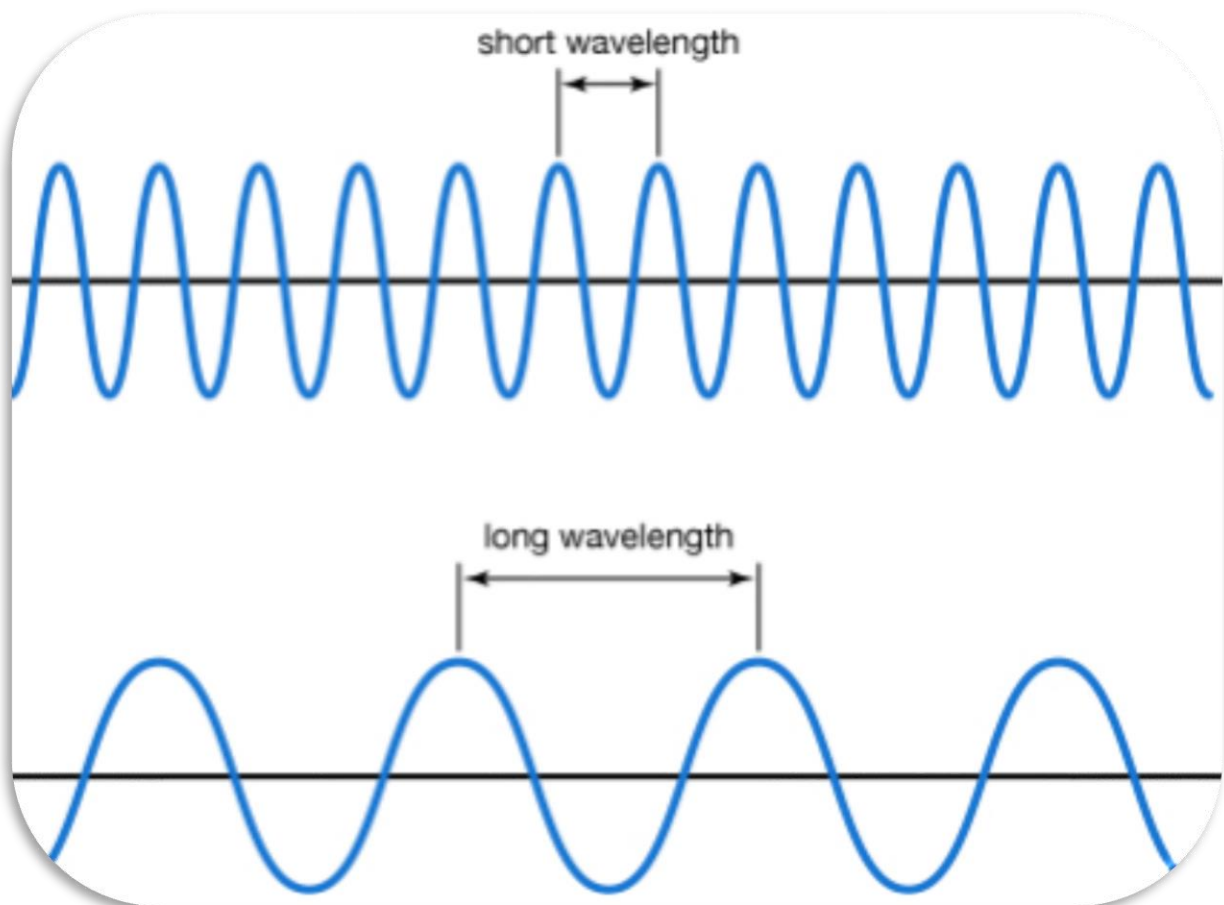
Figure 58: Picture of how wavelength changes with frequency. Credit: kids.britannica.com

As you already know, light can be considered as a wave or as a particle. The particles that compose light are called photons. An easy way to understand how energy and electromagnetic waves work is by looking at the energy of a photon. The energy of a photon (of light) depends on its wavelength or frequency, as the next equation shows.

$$E = h \cdot \frac{c}{\lambda} = h \cdot f$$

Equation 8: Energy of an electromagnetic wave.

For this equation, h being the Planck constant, c the speed of light, λ the wavelength and f the frequency.

As you can see, high frequency light (blue or ultraviolet light for example) will have more energy than low frequency light (red light). You can also say that the higher the frequency, the shorter the wavelength and the other way around.

Note: This is why people are urged to avoid overexposure to ultraviolet light coming from the Sun.

Activity 7.1. The Doppler Effect (acoustic)

Let's take a look at the Doppler effect. Consider a source emitting waves (acoustic or electromagnetic) and an observer receiving them. Imagine that you are the observer and the siren of an ambulance is the emitting source (acoustic waves).

If you (the observer) are sitting on a bench and the ambulance, with its siren turned on (the emitting source), is parked, you will receive acoustic waves of constant frequency (and a constant wavelength). However, if the ambulance starts moving towards you, you will perceive the sound waves at a higher frequency (and shorter wavelength).

The peak of the intensity is reached once the ambulance is at its closest point to you, and it diminishes as it moves away. This phenomenon is known as the "Doppler shift" and it

happens every time a source of waves (both sound and light) is moving away or towards an observer.
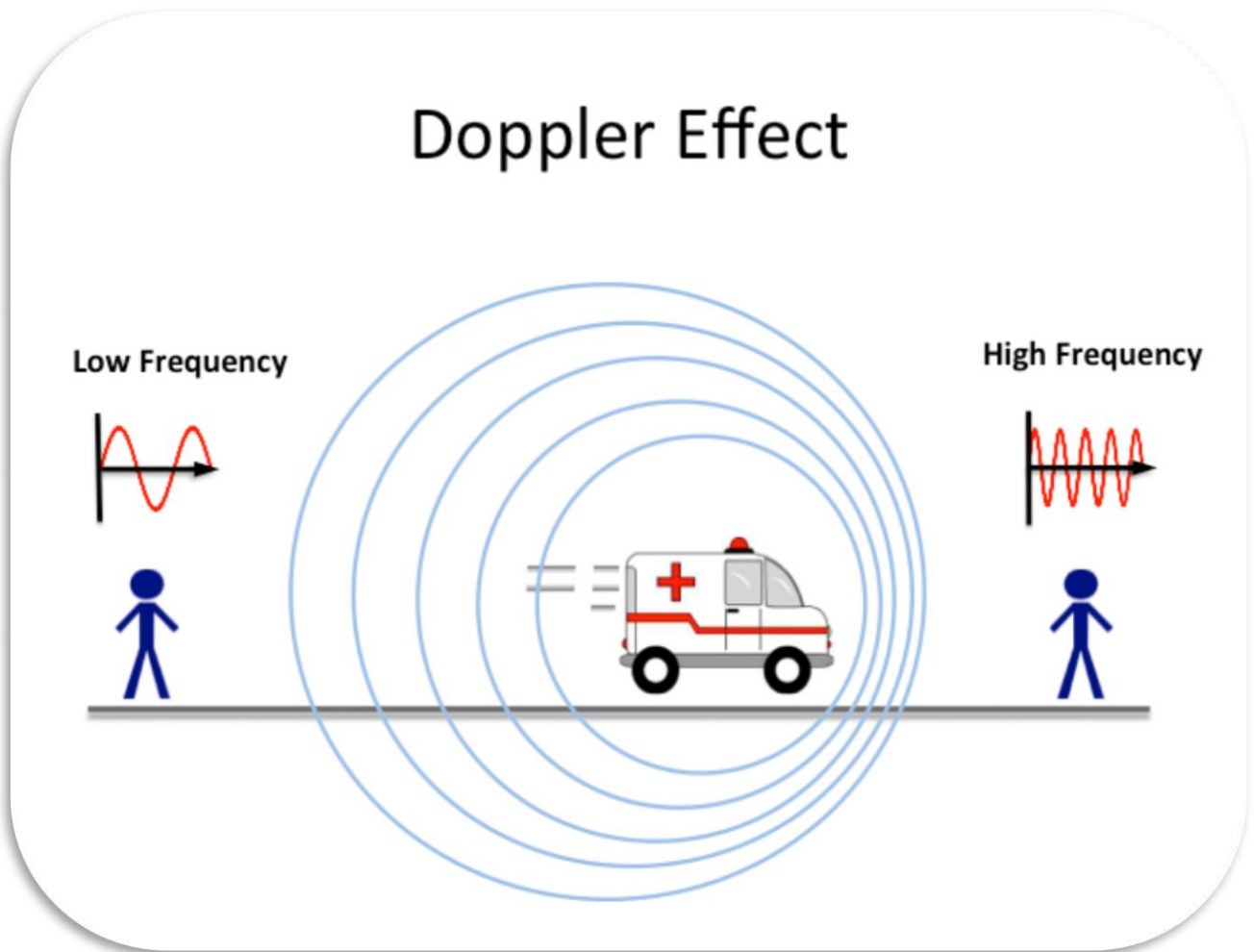
Figure 59: Graphic representation of the Doppler Effect for two different observers. (Credit: 3.bp.blogspot.com)

Activity 7.2. Red- and blueshift of galaxies

When the waves are not acoustic but electromagnetic, the increase in frequency is called blueshift and the decrease **red-shift**.

The term **blue-shift** means that the light shifts to higher frequency colours (it does not necessarily mean that it turns blue). It is similar for redshifted light which shifts towards lower frequency colours (not necessarily turning to red).

The rotational motion of stars in the galaxy can be calculated by measuring the red- or blue-shift of the stars that orbit in circular motion. **Error! Reference source not found.** represents a galaxy as observed from Earth. In red are the regions where the stars are moving further from Earth (red-shifted) and in blue, those that are moving towards the Earth (blue-shifted). This method works best on Spiral Edge-On galaxies.
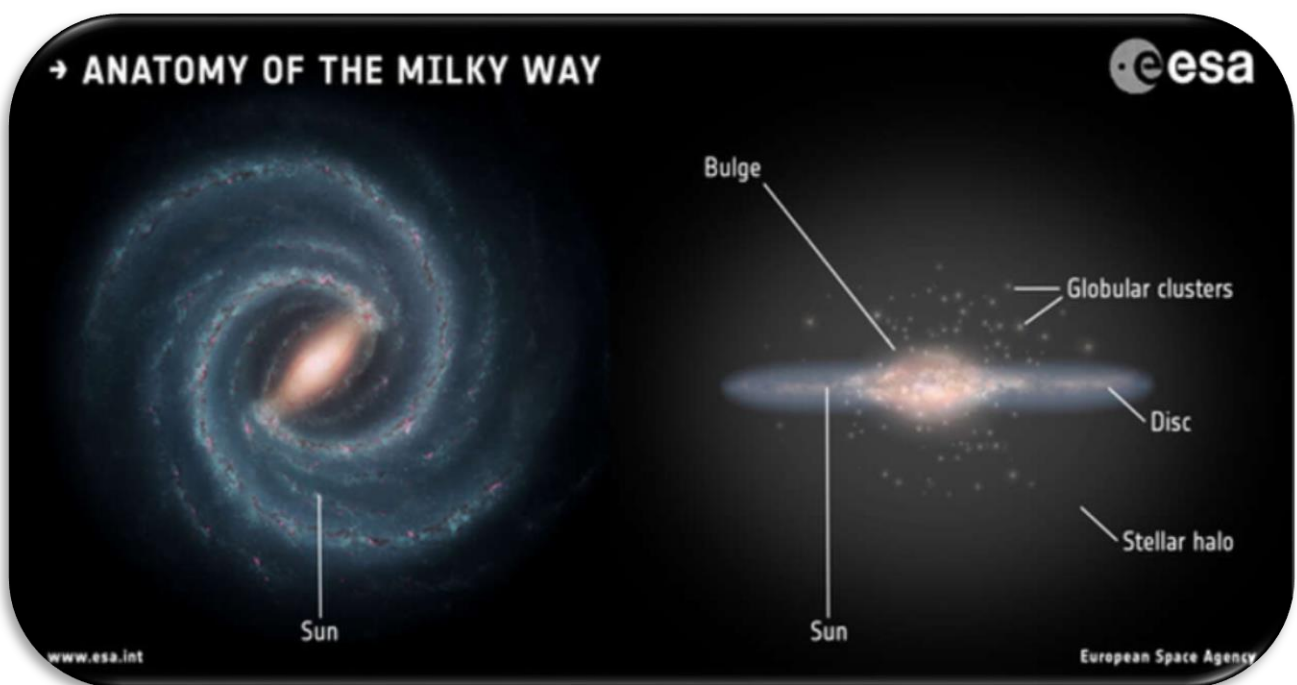
Figure 60: *View of a spiral galaxy, the left image with edge off and the right image with edge-on view. (Credit: ESA)*
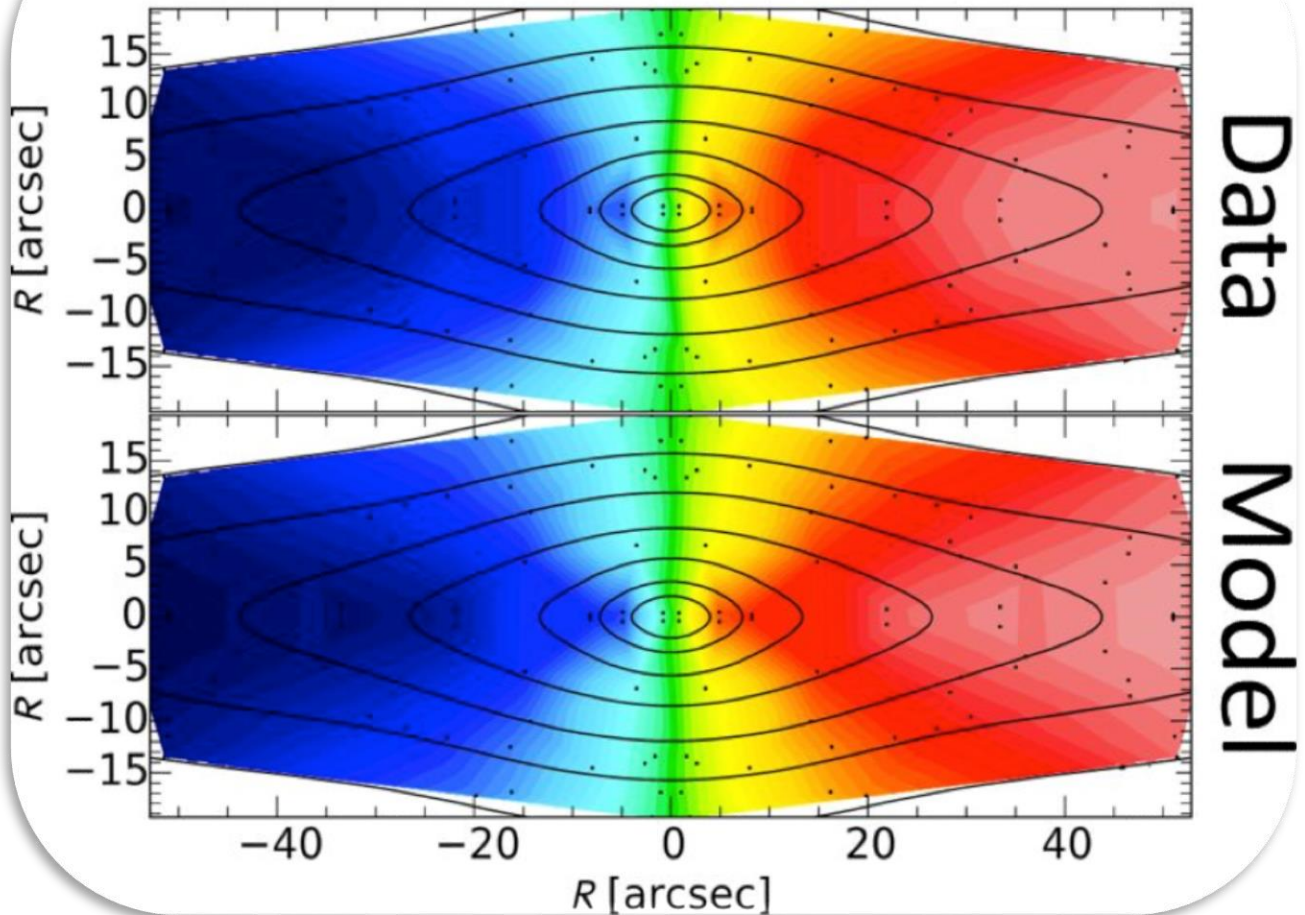
Figure 61: *Example of mapping out and analysing the speeds of stars in an elliptical galaxy. Blue colours show regions where the stars are hurtling toward the observer on Earth, and red colours show regions that are moving away. The top panel shows the original data and the bottom panel shows a numerical model. (Credit: W. M. Keck Observatory)*)

Note: By subtracting the total redshift due to the expansion of the Universe[4], physicists can determine the rotation of the disk along the perpendicular axis from our point of view.

---

[4] Universe Expansion: Watch this video to know more about it (https://www.esa.int)

Activity 8. Rotational Motion

Method 1: Learn with visual resources

1. Watch the following video (Rotational Motion: Crash Course Physics #11) about Rotational Motion to and try to extrapolate the information to galactic structures.

   ⇒ https://www.youtube.com/watch?v=fmXFWi-WfyU

2. Write down what you have learned so far.

Method 2: Learn with theory

> A rotational motion is the **movement of an object that maintains a constant distance to some fixed point in space.** In the case of circular orbits, it can be interpreted as a change in the velocity's direction but not its value.

In general, most objects experience a combination of linear and rotational motion that influences both the direction and value of their velocity. Nevertheless, for some systems like planets orbiting a star or stars orbiting a galactic centre, the motion can be approximated as a pure rotational motion.

This motion can be predicted by the laws of Newton. We have learned that every force corresponds to some acceleration which means a change in velocity. But this change can be purely directional as in the case of circular orbits. Thus, the effects of gravity can be used to predict the circular rotation expected at any distance from the system's centre (where the mass is located).
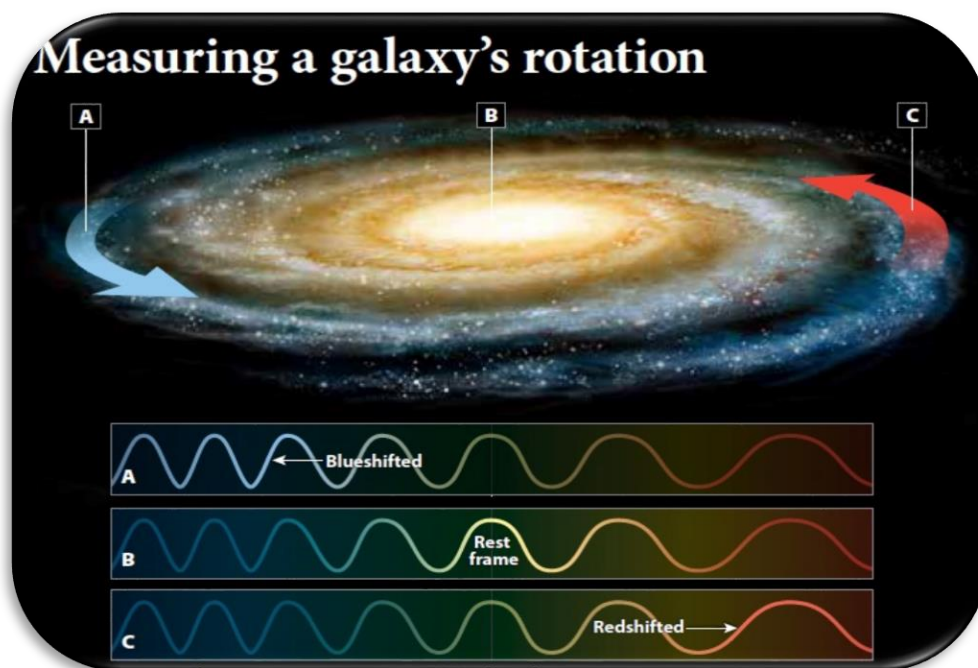
Figure 62: Graphical description of galaxies' rotational motion. (Credit: https://astronomy.com)

Activity 8.1. Rotation curves of galaxies

Method 1: Learn with visual resources

1. Watch the following video of Vera Rubin and Dark Matter

    ⇒   https://youtu.be/pkrIjGUJOPA

2. Describe with your own words what you understood from this video.

3. What did Vera Rubin discover?

Method 2: Learn with theory

A galaxy's **rotation curve** is a visual representation of the orbiting speed that objects have inside a galaxy with respect to their distance to the galactic centre, as shown in Figure 63.

From what we learnt in Activity 6.2., the matter content of any galaxy could be composed by the matter of the bulge, disk and halo. Ideally, physicist would like to develop methods to individually calculate each of these components.

$$M_{galaxy} = M_{bulge} + M_{disk} + M_{halo}$$

Equation 9: Mass content of a galaxy for the different components.
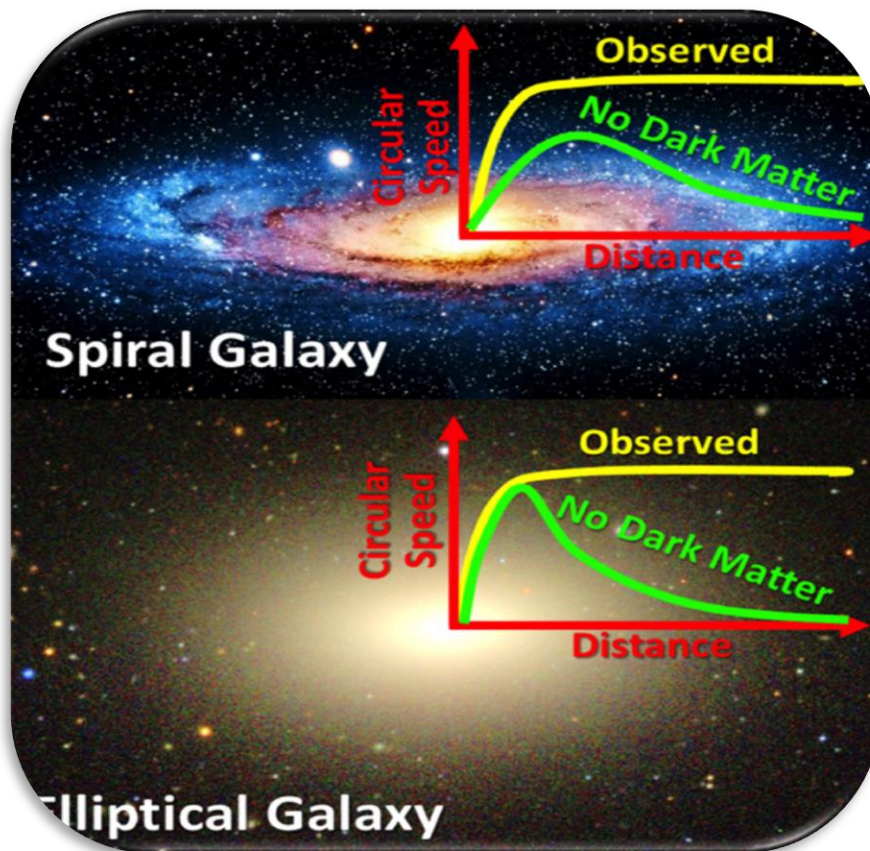
Figure 63: The speeds of stars on circular orbits have been measured around both spiral and elliptical galaxies. Without dark matter, the speeds should decrease with distance from the galaxy, at different rates for the two galaxy types. Instead, the dark matter appears to conspire to keep the speeds steady. (Credit: M. Cappellari and the Sloan Digital Sky Survey)

Under the hypothesis of the existence of Dark Matter, the total **mass of a galaxy** can be thought as the sum of luminous and non-luminous matter (Dark Matter, neutrinos). The halo content of a galaxy could be inferred from its total mass (calculated from rotation curves or gravitational lensing) by subtracting the mass contribution of the bulge and disk (calculated from astronomical observations of the full electromagnetic spectrum).

Activity 8.2. Classical prediction of rotation curves in galaxies

Method 1: Learn with visual resources

1.   Watch the following video of Gideon Bulton: Rotation Curves.

⇒   https://www.youtube.com/watch?v=wAtFniEKP3I

2.   Write down what you understood of this video.

3.   Draw the expected (predicted) vs. the measured rotation curves of galaxies. What does this mean?

Method 2: Learn with theory

In this activity we are going to predict the rotation curve of a spiral galaxy by assuming a constant density sphere with the size of the galactic Bulge. Notice that in this model we are neglecting the influence of the matter distributed in the disk and the halo.

We are going to make use of these equations to derive the expected rotation speed of objects inside a galaxy with respect to their distance to the galactic centre.

1. Newton's 2nd law $F = ma$
2. The definition of radial acceleration $a = v_{rot}^2/r$, where v_{rot} is the rotation speed and r the radius of orbit
3. The formulas for volume (V) and density (ρ) of a sphere.

$$\rho = \frac{M}{V} \quad and \quad V = \frac{4}{3}\pi r^3$$

Consequently, we could consider two main distributions for assessing the expected rotation velocity distribution:

1) Objects rotating outside the bulge – considered as punctual points
2) Objects rotating inside of the bulge – considered with a single density distribution

1. **Expected rotation velocity distribution for the rotating objects outside the bulge:**
   For each of the objects, with mass *m* and acceleration *a*, rotating outside of the bulge at a distance *r*, being the mass of the bulge *M*, the Equation 15 applies to their rotation velocity distribution (v_{rot}^{out}).

$$F = ma = G\frac{Mm}{r^2} \implies m\frac{v_{rot}^2}{r} = G\frac{Mm}{r^2} \implies v_{rot}^{out} = \sqrt{\frac{GM}{r}}$$

$$v_{rot}^{out} \propto \sqrt{1/r}$$

Equation 10: Rotation velocity expected for bodies outside the galactic bulge.

2. **Expected rotation velocity distribution for the rotating objects inside the bulge:**
   For each of the object orbiting inside of the bulge at a distance to the centre or the

bulge (r), assuming a constant density of the bulge (ρ), the Equation 16 is the one that applies to the expected rotation velocity distribution (v_{rot}^{in}).

$$\rho = \frac{M}{V} \quad and \quad V = \frac{4}{3}\pi r^3 \quad \Rightarrow \quad v_{rot}^{in} = \sqrt{GM/r} = \sqrt{G\rho\frac{4}{3}\pi r^3/r}$$

$$v_{rot}^{in} \propto r$$

Equation 11: Rotation velocity expected for bodies inside the galactic bulge.
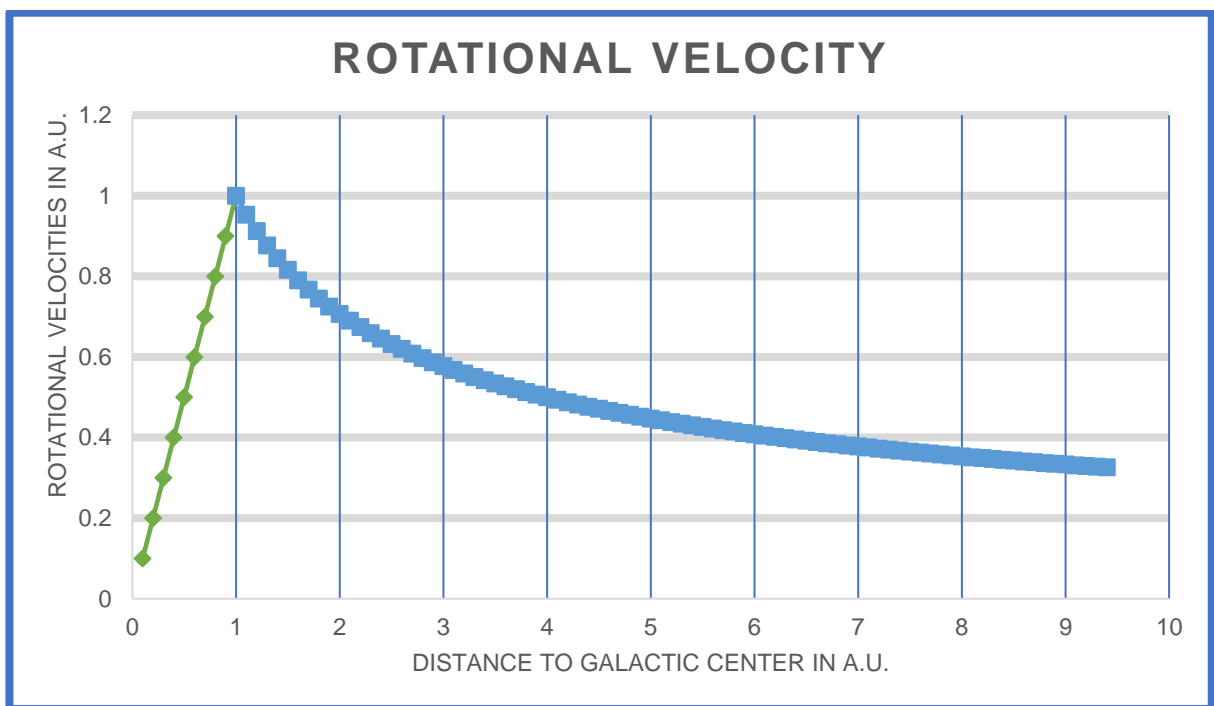
Figure 64: Graphical representation of the expected velocity distribution of objects gravitationally bound to a spiral galaxy. (Credit: Sergio.manthey@gmail.com)

Assuming that the highest gravitational potential arises from the galactic bulge and neglecting the effects of the disk and halo, rotation curves are expected to rise linearly inside the bulge and then decrease with $1/\sqrt{r}$ inside the Disk.

1.   Can you think of some way to measure the rotation curves of galaxies?

Activity 8.3. Calculate the mass of a Galaxy

The total mass of a galaxy can be approximated from the rotation curves of objects orbiting at the edge of galactic structures. Using rotations curves and the following equation the total galactic mass can be estimated. This equation can be easily obtained by inverting the final expression in Equation 10:

$$M_{galaxy} = \frac{v_{edge}^2 \cdot r_{edge}}{G}$$

Equation 12: Approximation of the total galactic mass.

M_{galaxy} is the total mass of the galaxy, v_{edge} is the rotation speed of objects orbiting at the edge of the galaxy, r_{edge} is the distance to the far orbiting objects that still sense the gravitational effects of the galaxy and G is the gravitational constant.

Notice that this measurement is highly dependent on the distance of objects that you consider "inside the galaxy". To have a correct estimate of this method you have to consider objects that orbit much further away than the apparent width of the galactic disk.

1. Why do you think that observed and expected rotation velocities are so different?

$$M_{galaxy} = M_{detectable} + M_{undetectable} = M_{bulge} + M_{disk} + M_{halo} + M_{undetectable\ halo}$$

Equation 13: Mass content of a galaxy for the different components.

Activity 9. Celestial coordinates: Equatorial vs. Galactic

Method 1: Learn with visual resources

1. Watch the following video about the Equatorial coordinate system by Launch Pad Astronomy.

    ⇒   https://www.youtube.com/watch?v=WvXTUcYVXzI

2. Watch the following video about the Galactic coordinate system by Loren Anderson

    ⇒   https://www.youtube.com/watch?v=FaBYbh2KJlQ

3. Draw a sketch of both coordinate systems and write down any comments.

Method 2: Learn with theory

Activity 9.1. Equatorial Coordinate System (J2000)

If we observe the night sky, we will notice how stars appear to move in circular orbits with increasing radius the further away they are from the North point (see Figure 65). This is no coincidence and today we know that this apparent trajectory is just a consequence of Earth's own rotation.

Figure 65: Trajectory of stars in the night sky. (Credit: ak8.picdn.net)

Nevertheless, this observation led Greek astronomers to the creation of a model where the Earth was in the centre of the Universe, and the planets and Sun would orbit around it. The stars would be holes on a dark sphere that surrounded the solar system and turned around Earth as well (see Figure 66).

Due to the distance of the stars to Earth, they all appear to be fixed points in what we nowadays call the Celestial Sphere. A 2D map of the sky that contains all astronomical objects. The way in which we refer to points on this map is called a coordinate system.
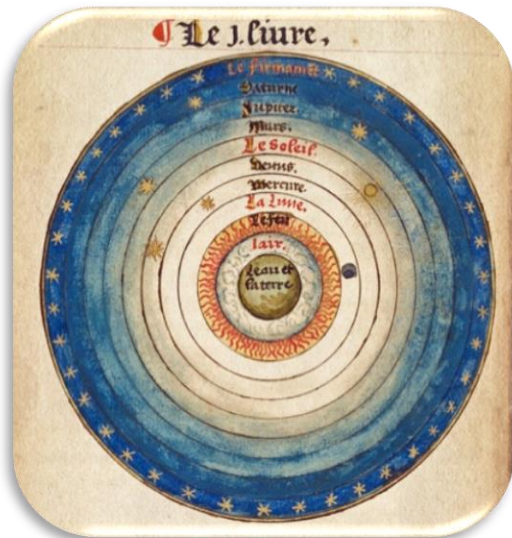
Figure 66: Ancient representation of cosmology. (Credit: ak8.picdn.net)

Figure 67: Model of Earth inside the Celestial Sphere. (Credit: lh3.googleusercontent)

Nowadays, we know this ancient model to be wrong. The Earth is not the centre of the Universe. It's just another planet inside a random solar system inside a random galaxy. Nevertheless, due to the extreme distances between stars, we do not observe the effects of Earth motion around our Sun, in fact (neglecting the rotation of the Celestial Sphere) most objects appear to be fixed points on the night sky with respect to human timescales. The requirement of more precise observations led to the first and broader used system of coordinates in astronomy: **The Equatorial system**.

The equatorial coordinate system is usually implemented in spherical coordinates. Its fundamental plane is formed by the projection of the Equator line onto the Celestial Sphere. This plane provides the reference for the two coordinates necessary to identify any point in the surface of the celestial sphere:

- **Declination (DEC)** is the angular distance perpendicular to the equatorial plane. It is measured in degrees and conventionally it is positive to the north and negative to the south.

- **Right Ascension (RA)** is the angular distance inside the equatorial plane. For this measurement, the Vernal Equinox (the intersection of the equatorial plane and the

ecliptic[5]) serves a reference point. For historical reasons, the RA is commonly expressed in sideral hours, minutes and seconds (instead of degrees).

Due to the precession of the Earth's rotation axis, this coordinate system turns westwards around the poles over time. This is an effect that is only noticeable over longer time scales. Nevertheless, for accurate measurements all equatorial coordinates need to be accompanied by an exact date of the equinox, known as an epoch. One of the most common is J2000, which corresponds to the year 2000 of the Julian calendar.
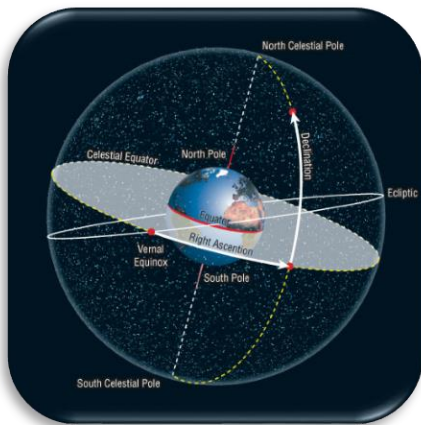
Figure 68: Equatorial coordinate system. (Credit: davemckay.ca)
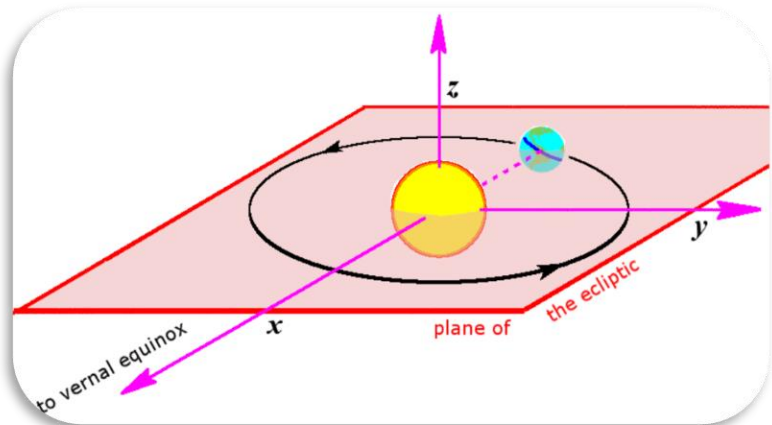
Figure 69: Graphical representation of the yearly Vernal Equinox. (Credit: vernal.equinox)

Despite the success of the Equatorial System, there are cases in which others might be more convenient. For example, when studying our galaxy, the Milky Way, it would be clearer to define a spherical system with its main plane corresponding to the galactic disk, where most of the motion occurs and most of the matter is contained.

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[5] The ecliptic is the line that runs along the Sun's trajectory on the celestial sphere.

Activity 9.2. Galactic Coordinate System (GAL)

The Galactic Coordinate System is a spherical system of reference that uses as its main plane, the galactic disk of the Milky Way. On this plane, it chooses its origin in the centre of our Sun and the reference line connects this with the galactic centre. It is built from two coordinates:

- **Galactic Latitude (b)** is the angular distance perpendicular to the galactic plane. It is measured in degrees and conventionally it is positive to the north and negative to the south.

- **Galactic Longitude (l)** is the angular distance inside the galactic plane and eastwards with respect to the centre. It is measured in degrees.

The relatively small motion of the Sun with respect to the galactic centre, means that this system does not noticeably change with time, but our lack of precision when measuring the galactic centre requires this system to be defined from the Equatorial.

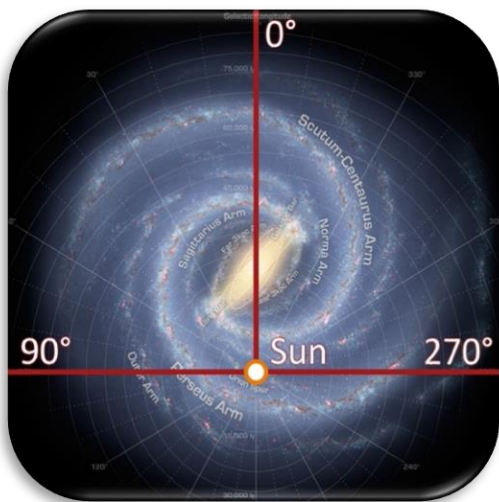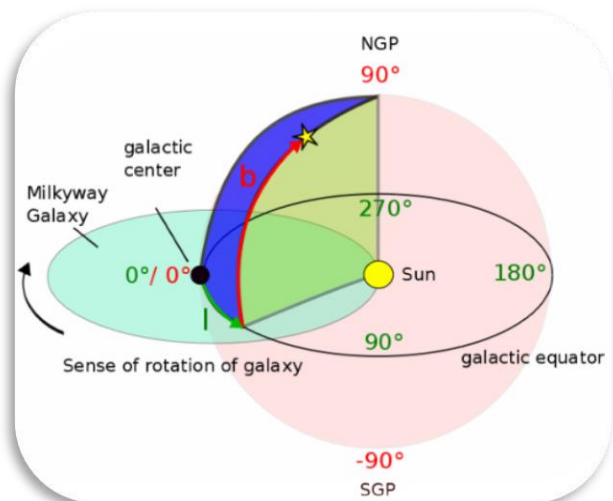*Figure 70: Longitudinal coordinate of the galactic system. (Credit: en.academic)*

Figure 71: Graphical representation of the Galactic Coordinate System. (Credit: auger.org)

You can use the following link to observe this particular system dynamically with WOLFRAM.

⇒ https://demonstrations.wolfram.com/GalacticCoordinateSystem/

Activity 9.3. Equatorial vs. Galactic
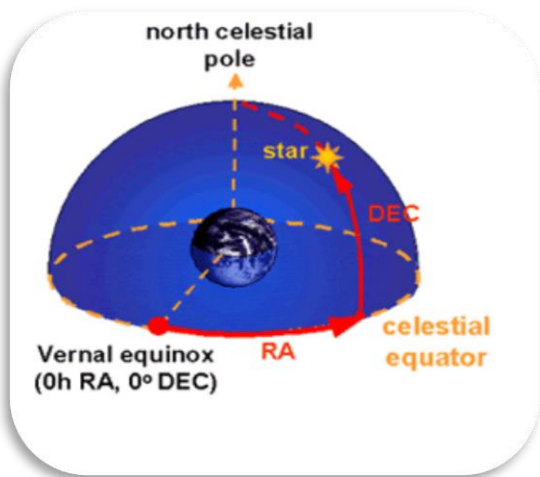
Figure 72: Equatorial coordinate system. (Credit: astronomy.swin.edu.au)	Figure 73: Galactic coordinate system. (Credit: 4.bp.blogspot.com)
Figure 74: Superposition of common astronomical systems with marked equatorial reference. (Credit: upload.wikimedia.org)	Figure 75: Superposition of common astronomical systems with marked galactic reference. (Credit: upload.wikimedia.org)
The J2000 coordinate system is the equatorial coordinates system more standardly used.	The Galactic coordinate system is mostly used when studying the Milky Way.
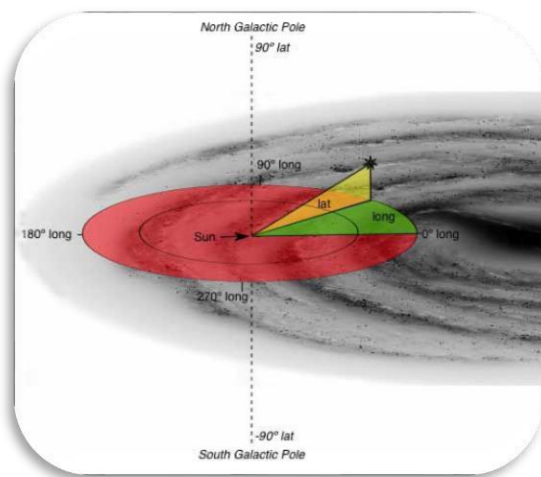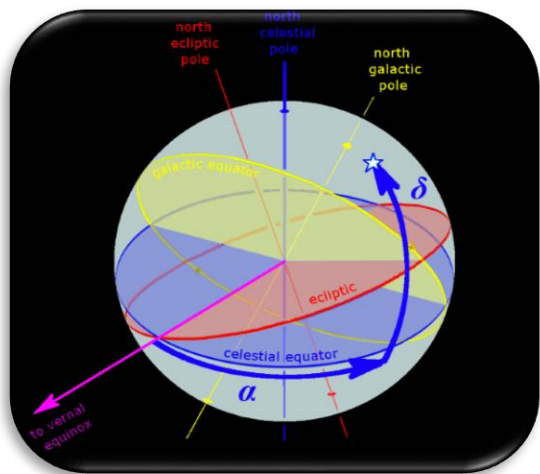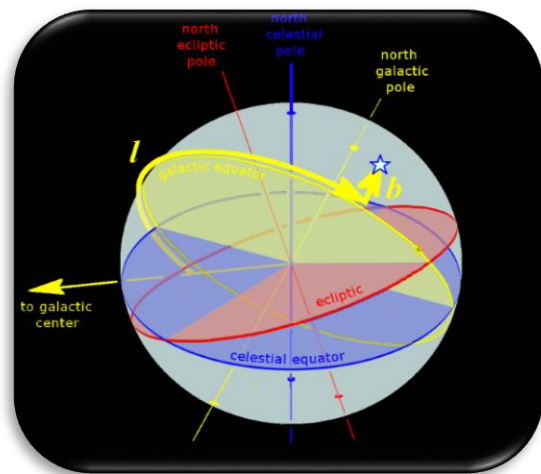
Table 10: Comparison of equatorial and galactic coordinate systems.

The conversion between systems is rather complicated and out of the scope of these activities, but you can observe the relative position of stars in both systems in Figure 74 and

Figure 75. Notice how the main planes of the Equatorial system is tilted with respect to the Galactic one. This has as a consequence a rotation that can be observed, for example, when changing between coordinate systems in ESASky.

Apart from changing between coordinate systems you might want to represent each coordinate in degrees (º) or degrees (º), arcminutes (') and arcseconds (''). For this you need to know that 1 arcminute is defined as 1/60 of a degree (º) and that 1 arcsecond is defined as 1/60 of an arcminute.

For a point P in degrees (º), arcminutes ('), and arcseconds ('') to degrees (º):

- $P = (x^º, y', z'') = x^º + (y/60)^º + (z/3600)^º$

For a point P in degrees (º) to degrees (º), arcminutes ('), and arcseconds ('').

- $P = x^º = d(^º), dd('), ddd('')$
- $d(^º) = integer(P)$
- $dd(') = integer((P-d) \times 60)$
- $ddd('') = integer((P-d-dd/60) \times 3600)$

For example, $P = 30,263\hat{8} = 30^º, 15', 50''$

$d(^º) = integer(P) = 30^º$

$dd(') = integer((P-d) \times 60) = integer(0,263\hat{8} \times 60) = 15'$
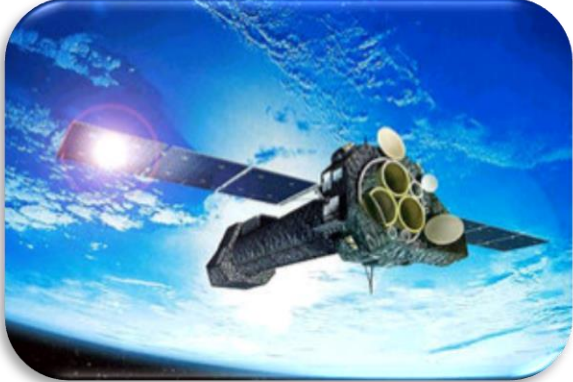
$ddd('') = integer((P-d-dd/60) \times 3600) = integer((0,263\hat{8} - 15/60) \times 3600) = 50''$

Additionally, one might want to change between hours, minutes and seconds and degrees for measurements of Right Ascension (RA). This can be simply done with (360º/24h=15º):

- $P(^º) = (hh, mm, ss) = 15 \times (hh, mm/60, ss/3600)$.

Activity 10. Gravitational lensing and Dark Matter exploration by the European Space Agency

The many existing questions about gravitational lensing and Dark Matter are one step closer to being answered thanks to scientific exploration conducted by, for example, the European Space Agency (ESA). ESA missions are constantly pushing the boundaries of our knowledge and helping astronomers understand the evolution of our Universe. Such missions include:

Instrument Description	Image
The **Hubble Space Telescope**, a collaboration between ESA and NASA, was launched in 1990 and is still in operation. One of the main mission objectives included the study of the history and evolution of the Universe. Hubble has produced a 3D map of the dark matter in concrete regions of our Universe. This milestone is a fundamental step in understanding how galaxies formed and grow over the timescales of a billion years.	*Figure 76: Hubble Space Telescope. (Credit: www.sun.org)*
XMM-Newton stands for X-ray Multi-Mirror and is an ESA X-ray observatory honouring Sir Isaac Newton. It was launched in 1999 and is the most powerful X-ray telescope built. It is still detecting X-ray sources and helping solve cosmic mysteries. The observations of distant galaxies conducted by XMM-Newton have allowed astronomers to study the evolution of dark matter and produce breakthrough results.	*Figure 77: XMM-Newton. (Credit: www.esa.int)*

Planck is an ESA satellite launched in 2009 and the first European mission with the aim of analyzing the remaining radiation originating from the Big Bang whilst also providing answers to questions on what dark matter is and how it dominates in the Universe.

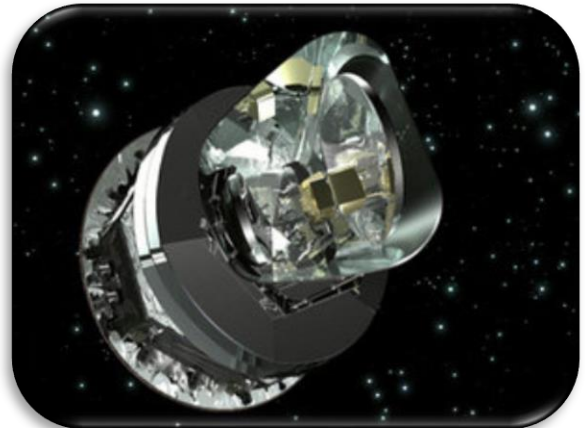*Figure 78: Planck Telescope. (Credit: www.21stcentech.com)*

Herschel is the largest ESA infrared space observatory ever launched, in 2009. The first data released by Herschel contained five gravitational lens systems, which provided significant game-changing information on gravitational lenses. Herschel was shut off in 2013.
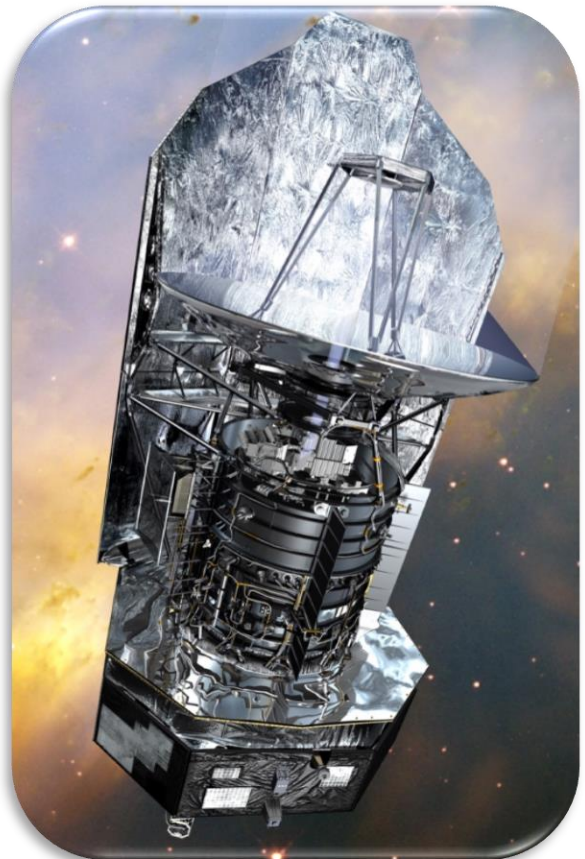

Figure 79: Herschel Telescope. (Credit: mappingignorance.org)

Gaia is an ESA space observatory launched in 2013 with the goal of producing the largest 3D map on the Milky Way, in order to reveal its history. Gaia's state-of-the-art precision when measuring objects' position will put Einstein's theory of General Relativity to the test since it will be able to capture gravitational effects which have been neglected up to now. Such an effect is the gravitational microlensing detected in the Gaia16aye star. Its brightness was seen to vary strangely due to the presence of a massive object across its line of sight which was acting as a lens on the star. Scientists expect Gaia to detect many of such micro-lensing events.
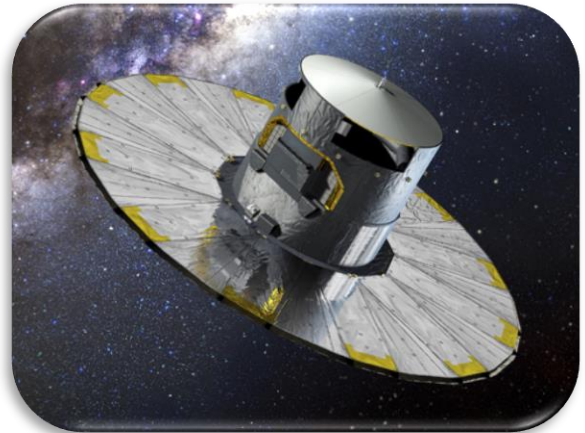
Figure 80: Gaia Telescope. (Credit: img.rt.com)

The **James Webb Telescope** (JWST) is the next space science observatory scheduled to be launched in 2021. It is a collaboration between NASA, ESA, and the Canadian Space Agency and aims to explore the very first galaxies and make breakthrough discoveries. It is the most powerful space telescope ever built and will be Hubble's successor. The idea is to map the dark matter around galaxies. This infrared observatory will be able to observe objects which are more than 13 billion light-years away! It will do this by detecting light gravitationally lensed by galaxy clusters.

Figure 81: James Webb Telescope. (Credit: mediadc.brightspotcdn.com)

Euclid is an ESA space telescope that aims to image billions of galaxies in the sky and help measure the expansion of the Universe, as well as the rate at which galactic structures grow. This in turn will help astronomers understand dark matter further and test Einstein's General Relativity theory. Euclid will be launched in 2022. It is also prepared to probe gravitational lensing measuring the distortion of galaxy images and thereby map the distribution of dark matter.
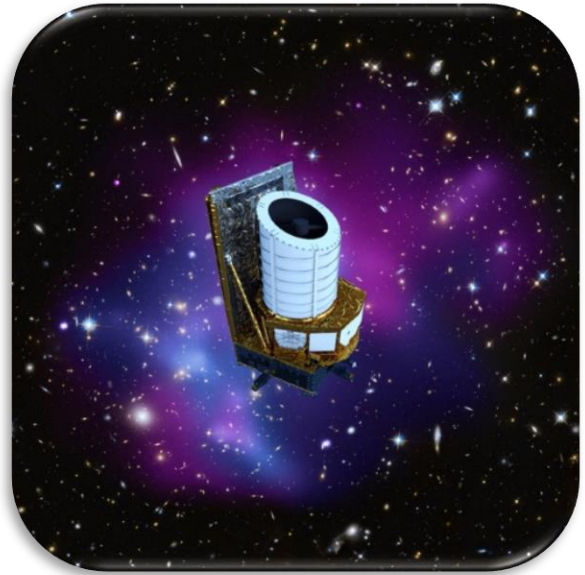
Figure 82: Euclid Telescope. (Credit: www.spacenewsfeed.com)

Table 11: List and description of some of the most important ESA missions.

Phase 2

Activity 11. What have you learned so far?

Complete [this quiz](#) to evaluate your learning.

Activity 12. Request a video call with the CESAR team

The CESAR team is always there to answer your needs and questions. We are happy to help in any issue regarding the well-functioning of our guides and activities. Don't hesitate to contact us in case that you need support.
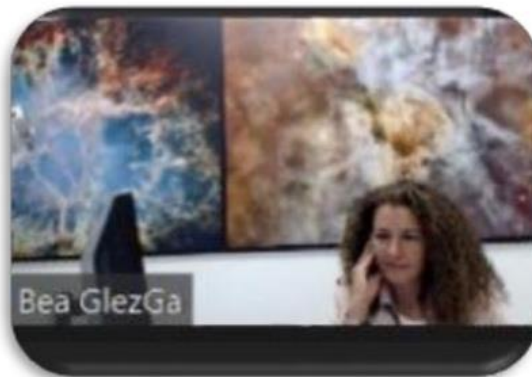
Figure 83: Image of the CESAR Team making a video call.

Phase 3

Activity 13. Introduction to scientific working

During the following challenges you will follow the scientific method. This method ensures that scientific knowledge leads to the correct and always better understanding of our Universe (see Figure 84 for a graphic summary).

1) **Question:** Ask yourself about the reality of nature (e.g., what Dark Matter and Gravitational Lensing might be)
2) **Research:** As done during Phase 1, research your topic of study and develop a good understanding of all involved phenomena.
3) **Hypothesis:** create a model of the system that you want to study and try to predict theoretically the outcome of your experiment.
4) **Test:** Perform your own experiment (if possible) or evaluate the data provided by other scientists while remembering to cross-check all information.
5) **Analyse:** Compare your predictions against real data and check for similarities and deviations.
6) **Results:** Try to give an explanation about the success or failure of your model and refine it (if possible) by adding new components that better fit the data.
7) **Repeat!**
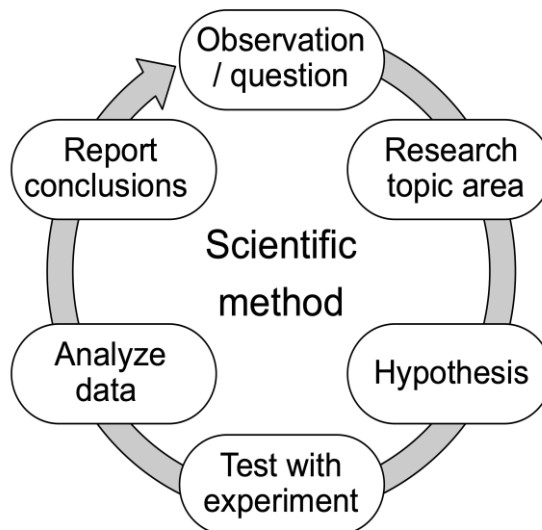
Figure 84: The scientific method. Credit: en.wikipedia.org

Activity 14. Scientific challenge 1: The Einstein rings

In this scientific challenge you will explore the Universe using ESASky. Your goals are the following:

1. Search for different Einstein Rings caused by Gravitational Lensing.
2. User ESASky's incorporated tools to select between different telescopes.
3. Recognise the two different coordinate systems for each object.
4. Export an image of each object.

You will be asked to fill in Table 12 with the outcome of your exploration and answer the questions that follow.

Activity 14.1. Let's get started!

Most probably you have seen on the internet some news about Einstein rings:

Figure 85: Tweet from Mario Picazo about real images of Einstein Rings. (Credit: twitter.com)

Do you remember what they are and how they are formed? Check our Activity 4 on gravitational lensing if this is not the case.

In the Hubble website you can see different types of Einstein's rings (see Figure 86). Click the following link to obtain a good impression of what we are going to be looking at.
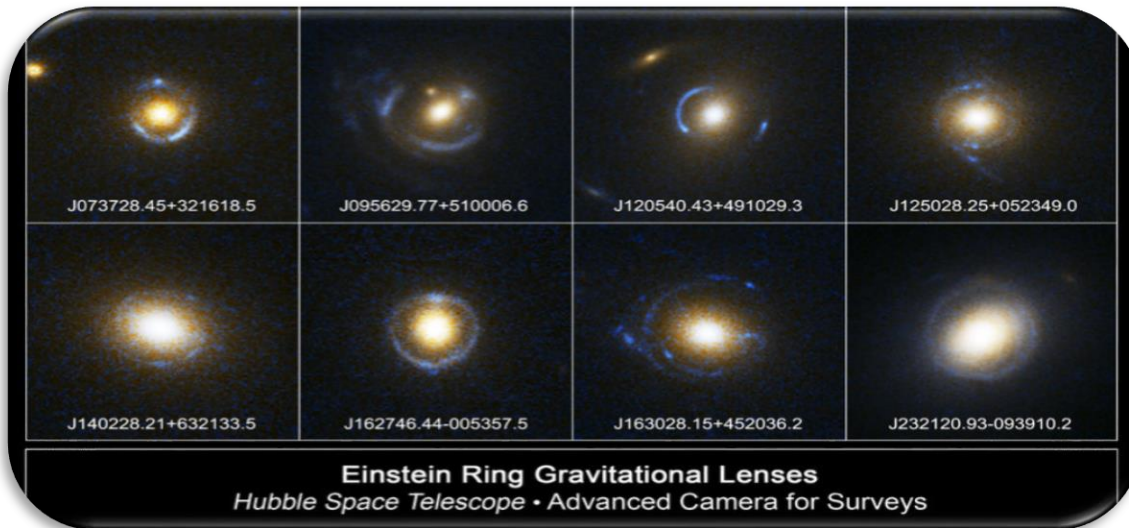
Figure 86: Gallery of Einstein Rings. (Credit: hubblesite.org)

Activity 14.2. Getting familiar with ESASky

ESASky is a scientific discovery portal that allows easy access to the entire sky observed by the European Space Agency's scientific missions.

All ESASky help tutorials are available on this link.

1. Click on this link to go into ESASky in your browser (see Figure 87). Choose the option "Explorer" (that is the simplest way to get familiar with ESASky).
2. If you want to search for a specific object (i.e., Crab Nebula) type its name at the search box that is located at the top-right area of the portal (see Figure 88). Note that it is necessary to write the name of the object in English and/or in a particular format, to be recognized by astronomical databases.

Figure 87: ESASky portal selecting Explorer Mode. (Credit: sky.esa.int)

Figure 88: Search box of ESASky. (Credit: sky.esa.int)

3.   Click on the upper left button (see Figure 89) to activate the "Select Sky" tool. From there you will be able to choose between the different wavelengths and telescopes available. Select the wavelength and facility indicated in the first column of Table 12.

Figure 89: ESASky select sky tool to choose instrument. (Credit: sky.esa.int)

Note: not for all of them there will be data of your selected object as this is real data collected by scientific missions and not a simulation. Notice that on top of the upper left buttons there is a coordinate indicator (see Figure 90).
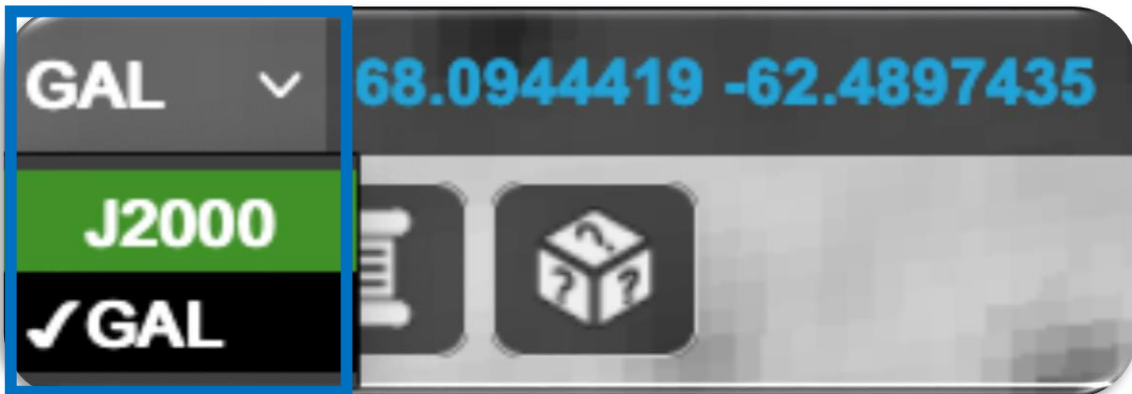
Figure 90: Top left corner with coordinate system selection. (Credit: sky.esa.int)

4. By clicking the name of the coordinate system (J2000 or GAL) you will be able to switch between the two. The exact details of both systems can be found in Activity 9. If you need more information, consult the following pages.

- J2000 Equatorial Coordinate System:
   ⇒ https://en.wikipedia.org/wiki/Equatorial_coordinate_system
- GAL Galactic Coordinate System:
   ⇒ https://en.wikipedia.org/wiki/Galactic_coordinate_system

The main differences that you have to remember are that J2000 is an equatorial coordinate system, while GAL is based on the galactic plane.

5. You can take a snapshot on ESASky of the object in your field of view. To do this, press the camera button in the top of your screen as indicated in Figure 91.

Figure 91: Top left corner with snapshot button. (Credit: sky.esa.int)

Activity 14.3. Take a picture of some Einstein Ring

Fill in Table 12 with the data collected of Einstein Rings from ESASky.

The information given as input is:

- Object name.

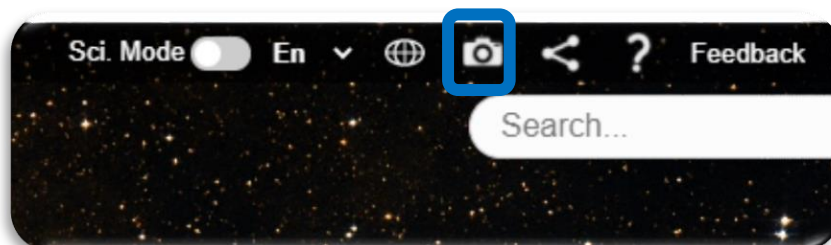- Filter (always optical).

- Facility (telescope and/or space satellite) and instrument.

The information required to fill in the table is:

- Coordinates of the centre of the object in Equatorial Coordinates (J2000 epoch).

- Coordinates of the centre of the object in Galactic Coordinates.

- Snapshot of the Einstein Ring.

To do this, follow the next steps:

1. Select the option "*Select Sky*" and try to find the correct filter/facility/instrument for each object name of Table 12 (check out Activity 13.2. for more information on this).

2. Complete the column **Coordinates** with both Equatorial (J2000) and Galactic (GAL) systems. Check Activity 13.2. for more information on this.

3. Take a snapshot of each of the Einstein ring patterns from ESASky and fill in the column **Image** of Table 12 (see Figure 91 for more information on this).

Object name, Filter/Facility/ Instrument	Coordinates	Image
J073728.45+321618.5 Optical/HST/WFC3	Equatorial J2000:	
	GAL:	

J095629.77+510006.6 Optical/HST/WFC3	Equatorial J2000:	
	GAL:	
J120540.43+491029.3 Optical/HST/ACS	Equatorial J2000:	
	GAL:	
J125028.25+052349.0 Optical/HST/ACS	Equatorial J2000:	
	GAL:	
J140228.21+632133.5 Optical/HST/ACS	Equatorial J2000:	
	GAL:	
J162746.44-005357.5 Optical/HST/ACS	Equatorial J2000:	
	GAL:	

J163028.15+452036.2 Optical/HST/WFC3	Equatorial J2000:	
	GAL:	
J232120.93-093910.2 Optical/HST/ACS	Equatorial J2000:	
	GAL:	

Table 12: Name of Einstein Rings with corresponding coordinates and images.

4. Have you noticed some correlation between the name of the Einstein Rings and their coordinates?

5. What happens when you change between the two different coordinate systems? Can you explain why? Draw a sketch with your explanation.

Activity 14.4. Calculate the mass of a gravitational lens

As we saw in Activity 4.3., an Einstein Ring is a special pattern of gravitational lensing, where the observer, lens and galaxy are nearly perfectly aligned; and the mass projection is approximately radially symmetric. This symmetry causes a ring-like distortion.

Let's calculate the mass of certain Einstein Rings provided in Table 12. Follow the example of this calculation for the Einstein ring J073728.45+321618.5 and replicate these steps for other two objects of Table 12.

1. **Find the coordinates of centre and edge of the Einstein Ring:**

   Search for the coordinates of the centre and edge of the Einstein Ring on ESASky in order to calculate the radial distance in radians (rad). **Tip: use the GAL coordinates which are expressed in degrees and can be easily transformed to rad.**

   See the Figure 92 to read out the coordinates of any selected point in ESASky.
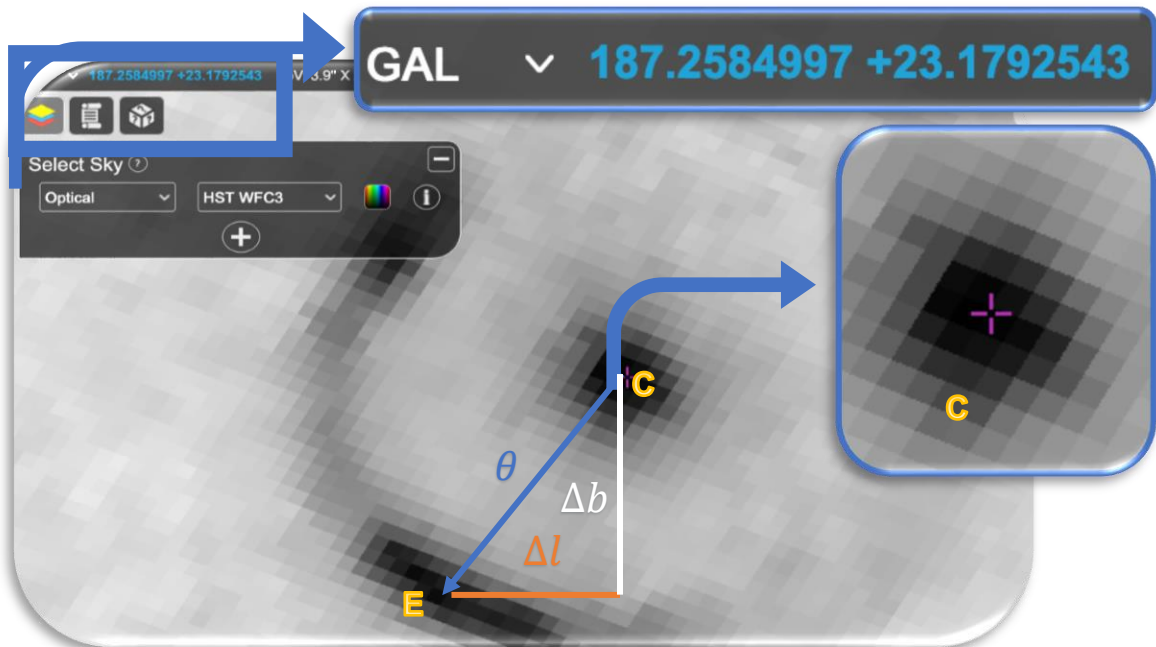

Figure 92: Visual guide to read coordinates in ESASky.

You can read the coordinates of your cursor at the top left corner on ESASky. Make sure that you have selected the correct coordinate system, that the letters appear blue and that the purple cursor corresponds to the point that you are interested in.

2. **Calculate radius of the Ring following this procedure**:

Given two coordinate points $C = (l_1, b_1)$ and $E = (l_2, b_2)$ one can calculate the difference of their individual coordinates with the following set of equations:

$$\Delta l = l_1 \cos(b_1) - l_2 \cos(b_2) \text{ or (for small distances) } \Delta l = (l_1 - l_2)\cos(b_1)$$

$$\Delta b = b_1 - b_2$$

Equation 14: Vector calculation between two points on a spherical plane.

In a simplified manner, for nearby points, the distance θ of the ring's radius can be calculated using the Pythagorean theorem.

$$\Delta l^2 + \Delta b^2 = \theta^2$$

Equation 15: Pythagorean Theorem. The sum of the squares of the sides of a regular triangle equals the square of its hypotenuse.

Use the following box to perform the same calculations for different Rings. Look for the coordinates of edge and centre of the Einstein Rings in ESASky (see Figure 92).

Remember that in order to convert Degrees in Radians you have to multiply a factor of $\pi/180$.

3. Complete the following table with the selected points and the calculated values for the radial distance.

Object name	Einstein Ring centre in GAL coordinates (in º)	Einstein Ring edge GAL Coordinates (in º)	Radius θ (in rad)
J073728.45+321618.5			

Table 13: Calculation of the radius for different Einstein Rings.

Use the following box to calculate the Einstein Ring radius for your selected objects.

4. Use equation Equation 6 to calculate the relative distances to the lens and ring and complete Table 14. The redshift value necessary for this calculation can be obtained for our object J073728.45+321618.5 from the following link:

⇒ https://hubblesite.org/contents/media/images/2005/32/1794-Image.html

Tip: A quick query of the name in any internet search engine will take you to the corresponding Hubble.org page for all the objects listed above.

Name of the object and redshift values	D_L Distance to the lens (in m)	D_S Distance to the ring (en m)	D_{LS} Distance between ring and lens (en m)
J073728.45+321618.5 $z_{Lens} = 0{,}3223$ $z_{Ring} = 0{,}5812$			
   $z_{Lens} =$ $z_{Ring} =$			
   $z_{Lens} =$ $z_{Ring} =$			

Table 14: Distance calculation from the redshift of the components involved of the objects in Table 12.

Use the following box to perform the appropriate calculations:

Use Equation 6 with the Hubble constant $H_0 = 70 \cdot 10^3 (m/s)/Mpc$

Remember that $1 Mpc = 3,0857 \cdot 10^{22} m$

5. Use Equation 7 to recover the mass of the lens. Give your result in kg and in terms of solar masses ($1\ M_\odot = 2 \cdot^{30}\ kg$).

$c = 3 \cdot 10^5\ km/s.$

$G = 6{,}67 \cdot 10^{-11}\ ^{m^3}/_{kg\ s^2}$

6. Fill in the next table with the values according to Equation 7 for the Rings that you have evaluated in the previous activity.

Name	Ring's Radius (in rad)	Mass of the lens (in kg)	Mass of the lens (in Solar Masses $M_\odot$)
J073728.45+321618.5			

Table 15: Mass calculation of the lenses for different Einstein Rings.

Use the following box to calculate the masses of the other lenses.

7. Well done! Now it is time to stop and think about your answers to these questions. Accounting for the individual components of a galaxy that we learned in Activity 6., to which part of the galactic lens does the mass that we have calculated in this exercise correspond to?

Activity 15. Scientific challenge 2: A real case study of a gravitational lensed quasar with quadrupole images SDSS J1004+4112

In this challenge, you are going to reproduce the work of Naohisa Inada and his collaborators published in Nature year 2003 (Inada, 2003) about the gravitational lens SDSS J1004+4112.
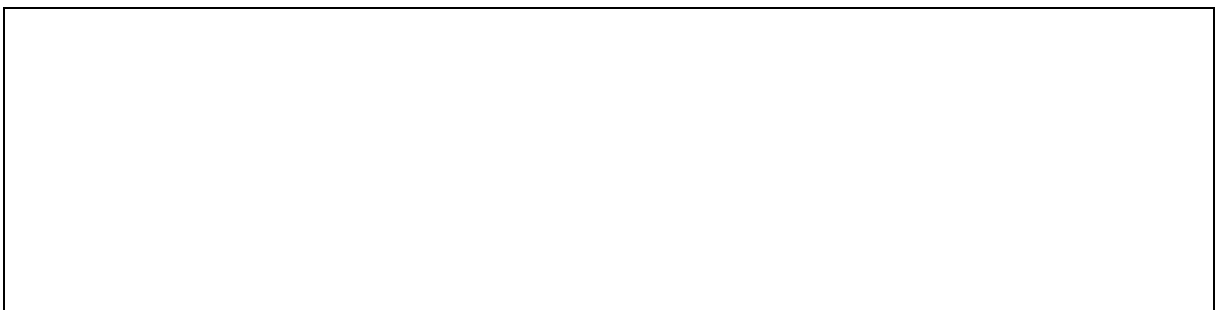
Full paper here *([Inada n. et al., 2003, nature, 426, 810](#))*

Activity 15.1. Analyse the object SDSS J1004+4112

To do so, follow these steps:

1. Look into the ESA portal for the central coordinates of the gravitational lens (SDSS J1004+4112).

    ⇒   https://spacetelescope.org/images/heic0606b/

2. Access to the Sloan Digital Sky Survey and database to display the available data for this region from the Sloan Digital Sky Survey (SDSS)

    ⇒   http://skyserver.sdss.org/dr15/en/tools/chart/navi.aspx

    As you can see, the coordinates are asked to be introduced in degrees and this is all the information displayed (see Figure 93).
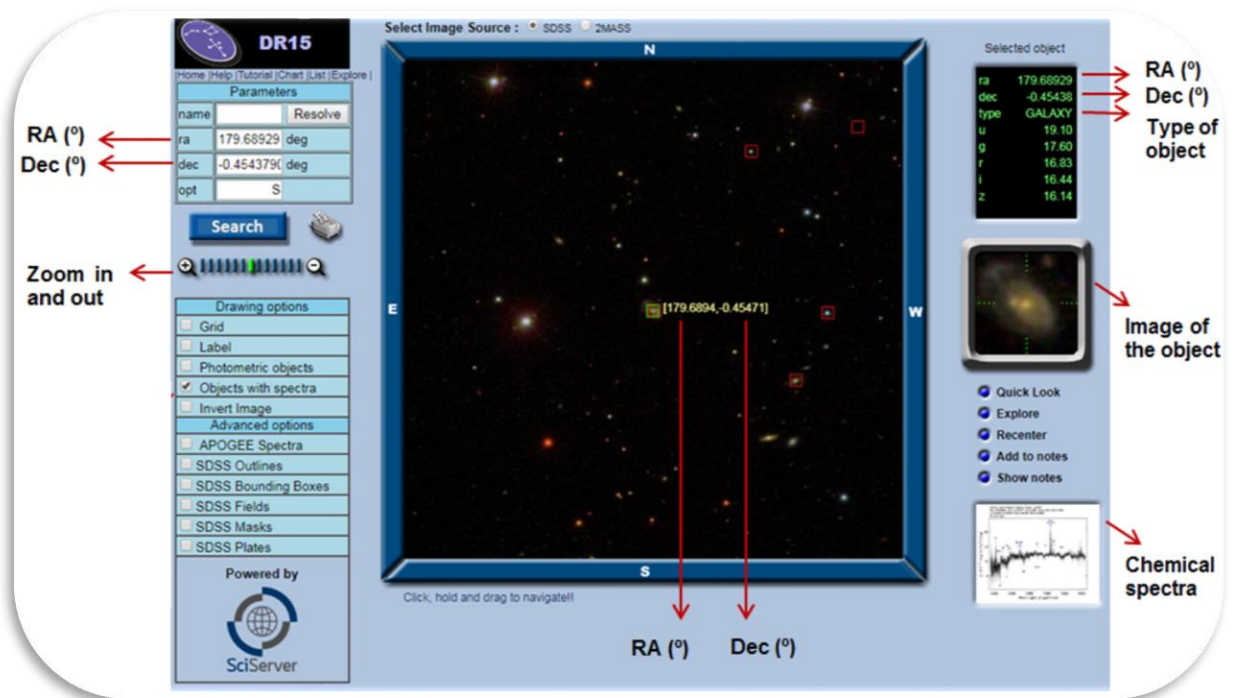
Figure 93: Screenshot of the Sloan Survey with added information about the layout. (Credit: SDSS)

3. Convert the equatorial coordinates (hh mm ss, degrees arcmin arcsec) to degrees (check Activity 9.3. in Phase 1 to know more about this procedure) in order to search our object in the Sloan Digital catalogue. We propose you to do this in 2 steps:

- The Right Ascension (RA) is usually given in hours, minutes and seconds (hh,mm,ss). Convert *hours, minutes, seconds* into *degrees.*

$$RA = 15 * \left(h + \frac{m}{60} + \frac{s}{3600} \right) \rightarrow$$

- The declination (DEC) is usually given in degrees, minutes and seconds (º ' "). Convert *degrees, minutes, seconds* into *degrees* (XX.YYY °).

$$DEC = \left(º + \frac{'}{60} + \frac{''}{3600} \right) \rightarrow$$

4. Insert the proper coordinates of SDSS J1004+4112 into the Sloan Sky server and inspect each of the five components of this gravitational lens. For this click on each of the sources identified in Figure 95 as (A, B, C, D and E) in the Sloan Digital Sky Survey (http://skyserver.sdss.org/dr15/en/tools/chart/navi.aspx)
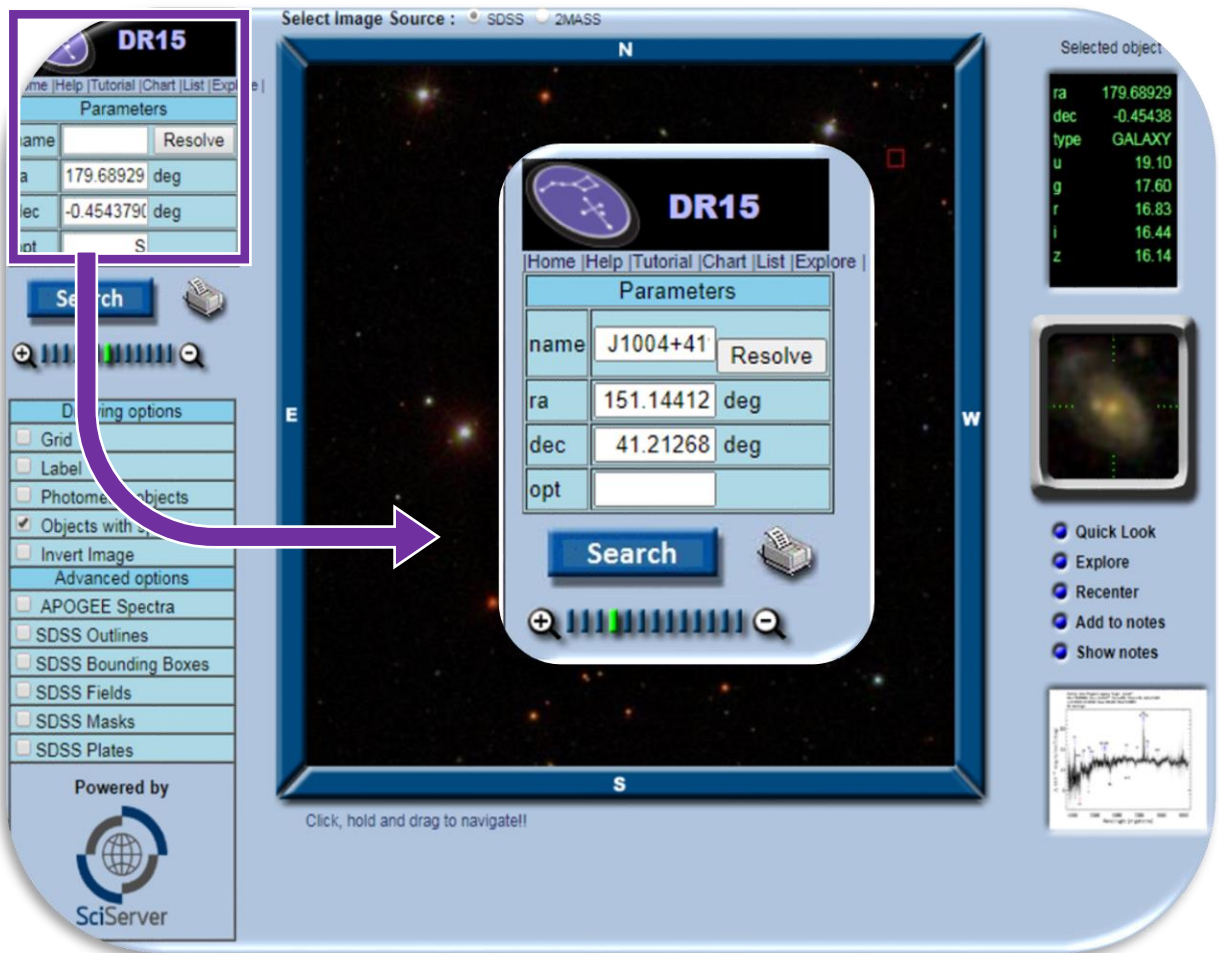

Figure 94: Screenshot of the webpage corresponding to the Sloan Digital Sky Survey. (Credit: skyserver.sdss.org)

If you magnify your image, you should be seeing a similar image as the left one in Figure 95. Try to identify the components A, B, C, D and E from the right image of Figure 95. Then, fill in Table 16 with the exact coordinates for each component.
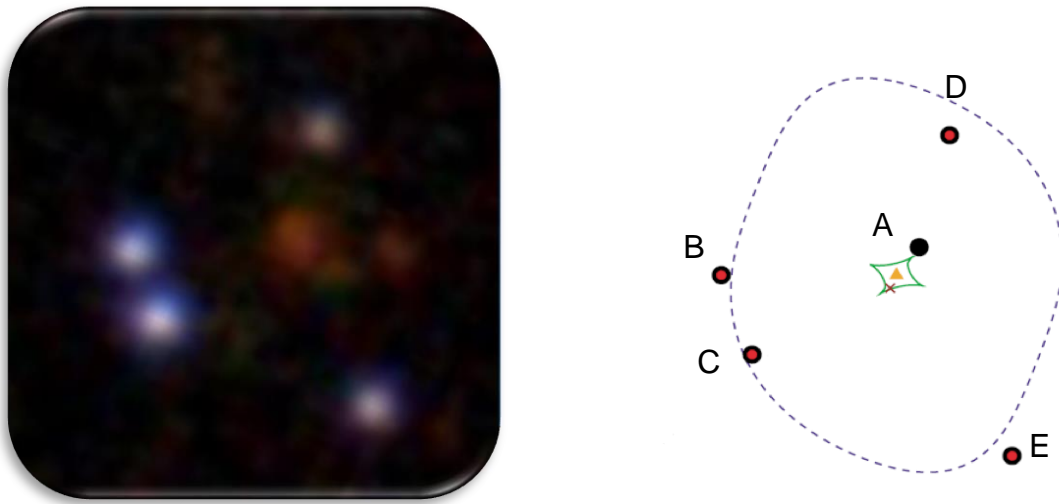
Figure 95: (Left) Image of J1004+4112 with (right) labels for each object that we observe. (Credit: skyserver.sdss.org)

5. Try to identify to which type of object corresponds each of the 5 components of the gravitational lens (A, B, C, D, E). This information can be obtained from the top right box window once you select an object (see Figure 96).
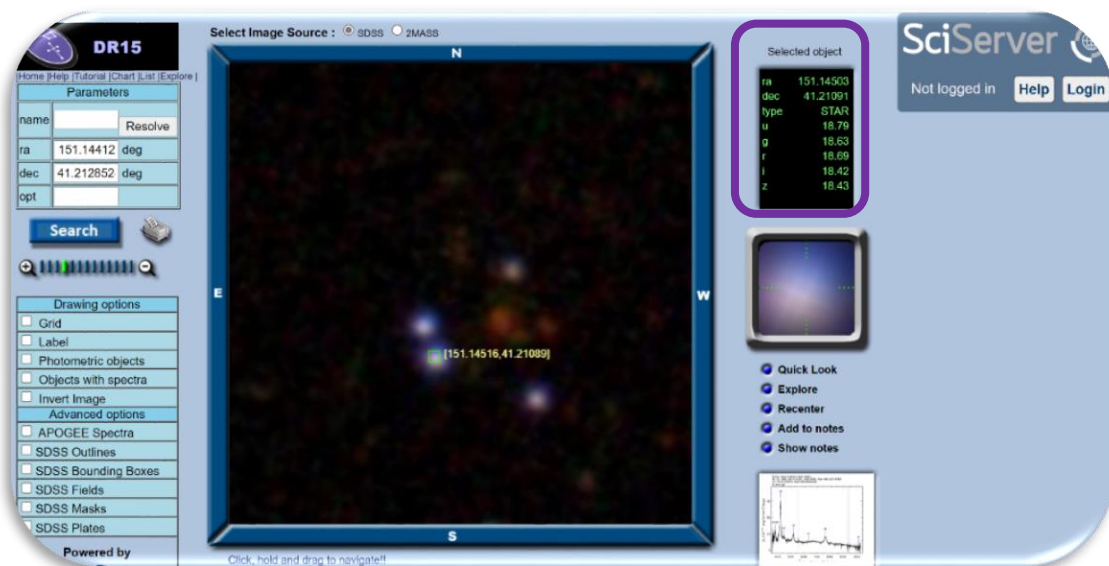

Figure 96: Screenshot of the webpage corresponding to the Sloan Digital Sky Survey. (Credit: skyserver.sdss.org)

The main options are GALAXY type and STAR type, depending on their extension.

6. Analyse your findings. Looking at the spectra available of the different components in J1004+4112, pay attention to their shape (intensity distribution) and chemical elements and fill in Table 16 with the information found in the Sloan Digital Sky viewer following this procedure.

    Procedure:

    - Click in the box "Objects with spectra", at the left panel of the sky server viewer (see Figure 97)
    - Select an object (a box will indicate which object you have selected).
    - You will see at the bottom right panel a small image of the spectra available per target. Clicking on these images you will have access to their spectra at the right of the screen. Tip: It may be possible that there is not available spectrum for all sources.
    - Write the elements shown in the spectra of A, B, C, D and E in the elements slot in Table 16.
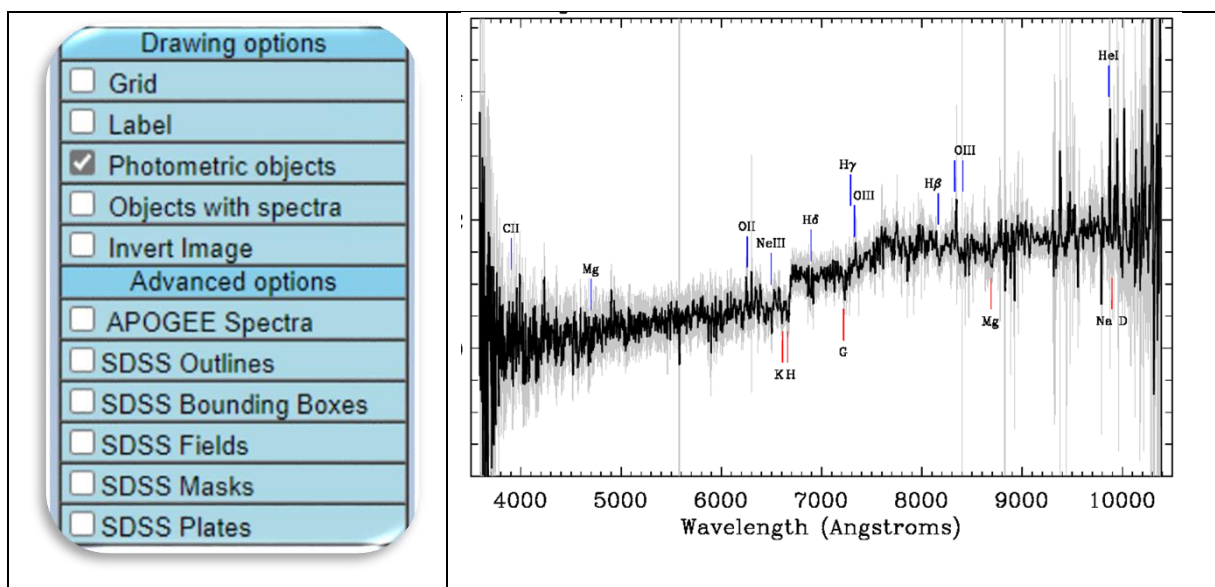

Figure 97: Screenshot of the webpage corresponding to the Sloan Digital Sky Survey. (Credit: skyserver.sdss.org)
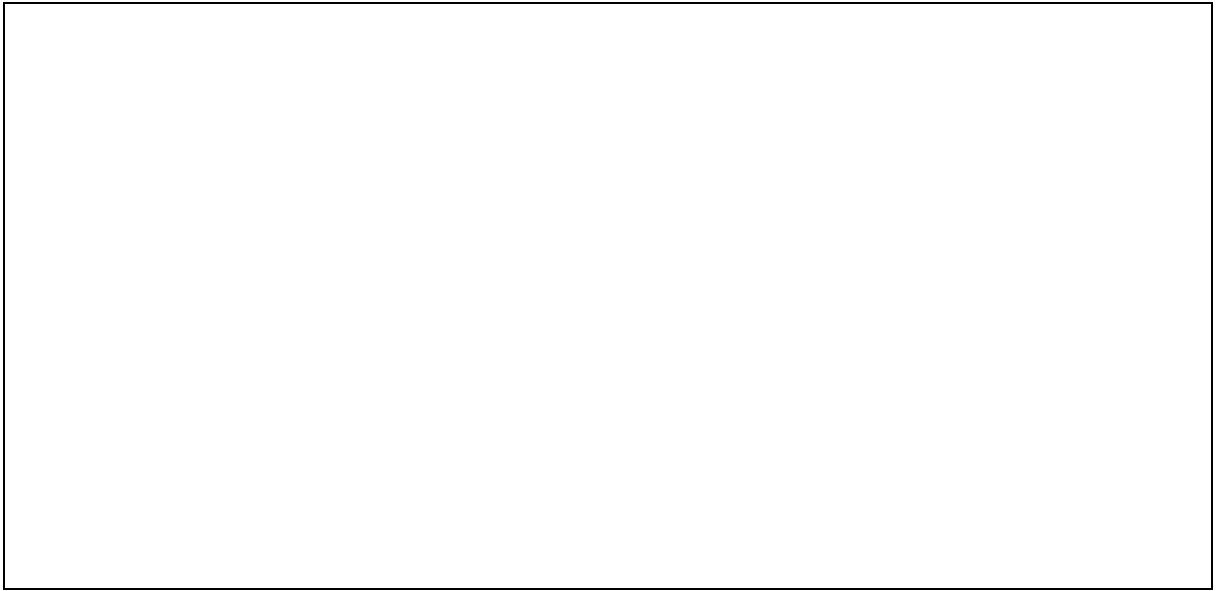
7. Now answer the following questions

Do you see any similarity between any of these spectra?

Based on their similarities and differences in the elements and intensities, could you conclude that any of them are the same object?

Can you relate your previous answer to the theory that we have studied?

If you have arrived to the conclusion that this is a gravitational lens system, which of the objects of the system is acting as a gravitational lens? Make a sketch of it.
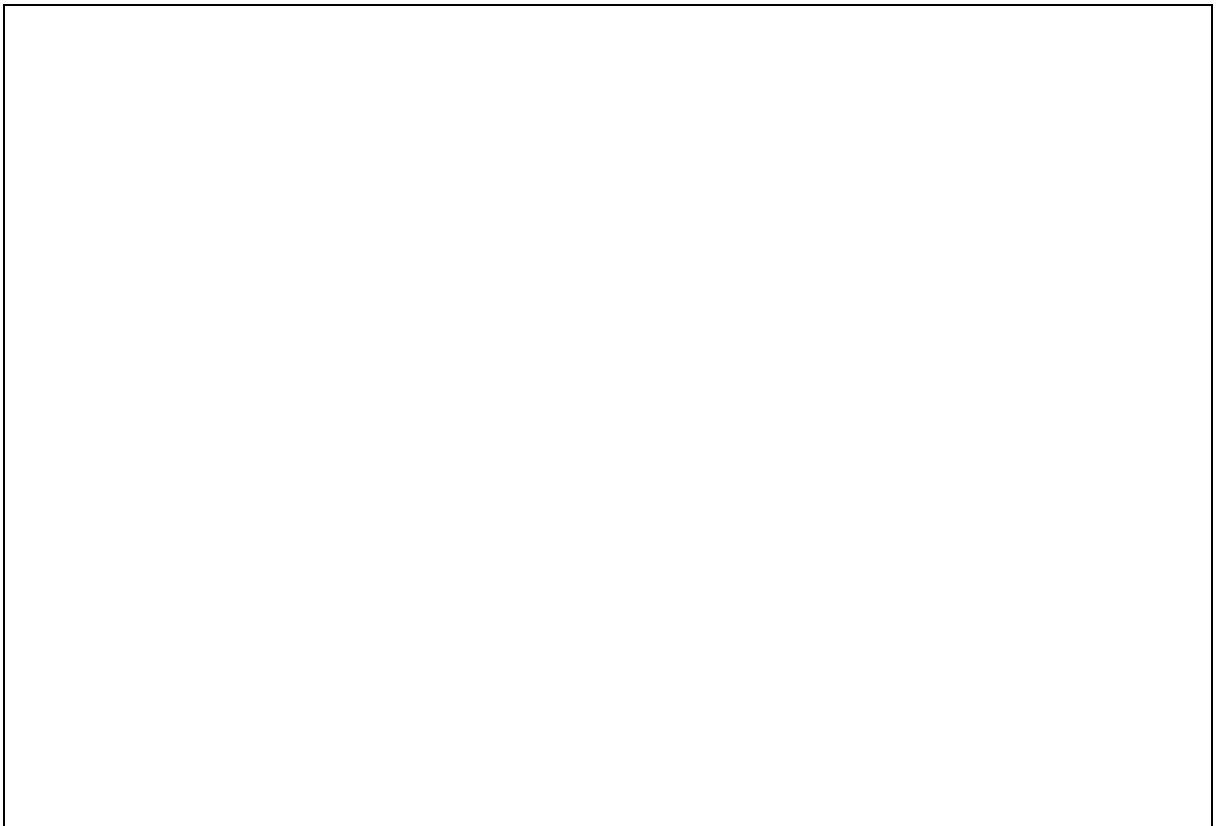
Activity 15.2. Create a scientific paper with your research

CREATE YOUR OWN SCIENTIFIC PAPER: Look at the instructions given in this Activity to fill in the appropriate areas with your previous research to write a paper as Inada did.

Title

Team Members

Abstract

Introduction	Analysis
Gravitational lensing is a powerful way to investigate distant and faint objects. This effect has several patterns. It may create a pattern of arcs or multiple images of the same object. This later case is what we have found for the object J1004+4112, where a quasar is lensed by a galaxy cluster creating four images of it.	

Observations

Object identificator	Object type	Ra	Dec	Chemical elements
A				
B				
C				
D				
E				

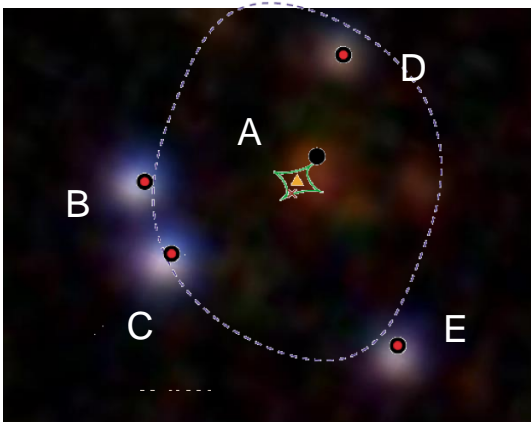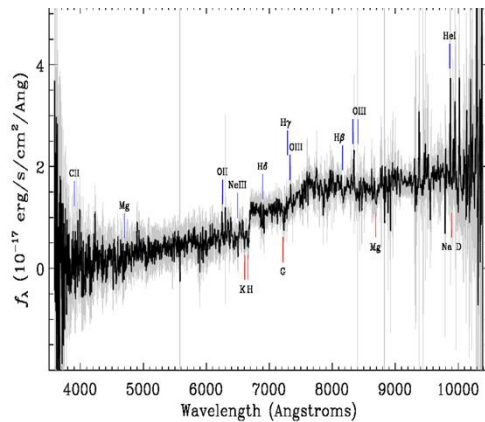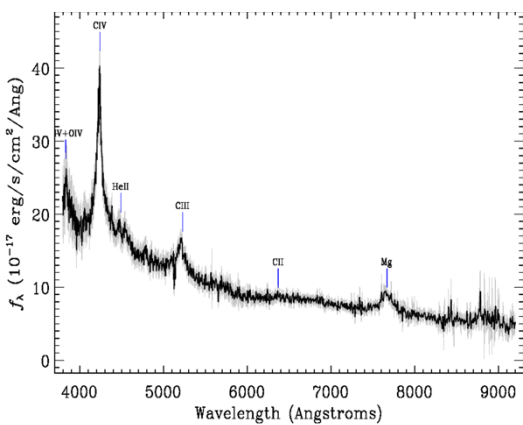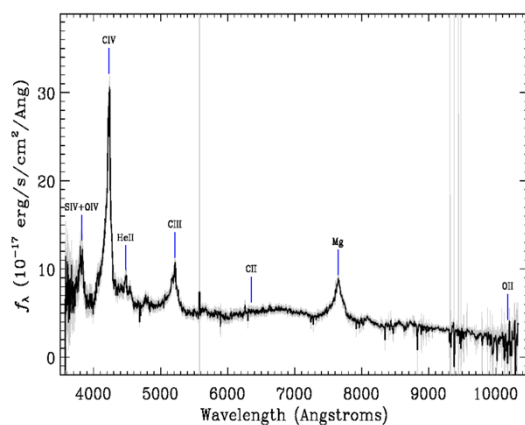*Table 16: Characterisation of all objects found in the cluster J1004+4112.*

Image of to the object of interest.

Spectrum of object:

Spectrum of object:

Spectrum of object:

Instructions on how to write a scientific paper

TITLE:
The title should contain a brief description about the results of your investigation (your findings, the object). At the same time, the title should be catchy and innovative (no more than 5-10 words)

TEAM MEMBERS:
Here you should write the names of the team members involved in the research. The names are usually shown in the following format:
Last Name, X (being X the first letter of your name).

Example: if your name is *Maria Arriba*, you would write *Arriba, M*. If your last name is widely used (e.g., *Smith*) you may use a second or middle names (i.e, *Smith Arriba, M.*).

ABSTRACT:
Briefly explain what is your work is about including your findings (1 paragraph)

INTRODUCTION:
Here you should introduce some basic information about your study. In this case, there are at least two points to talk about:
1)   Some background about the type of object studied (gravitational lenses).
2)   Some background about what is known from the studied region J1004+4112.
Tip: check the link https://spacetelescope.org/images/heic0606b/.

OBSERVATIONS:
In this section you should collect the relevant data used for this research (images and/or spectra collected and referenced to telescopes, data servers…), tables and a sketch of the area. With this information anyone should be able to reproduce your work. Take into account that in this exercise you will find the figures and a table that should help you accomplish the task. Example:

- Table 16: Summary of some properties of the objects in the studied region (coordinates, characteristics of the objects like: type, shape, brightness, chemical composition, etc).
- Images and spectra related to the identified objects.

If you have arrived to this point filling the paper above, congratulations!

Your first scientific paper and work as scientist is complete!

We hope you have enjoyed this activity and discovered many interesting things. We also hope to see you here in a few years as an astronomer, cosmologist or as computer engineer!

Activity 16. Scientific challenge 3: A real case study of the rotation curves of spiral galaxies (The Milky Way and M31)

In this scientific challenge you are going to reproduce, in a more simplified wat, the research work of (Sofue, Dark halos of M 31 and the Milky Way, 2015)

Full paper here [Dark halos of M 31 and the Milky Way | Publications of the Astronomical Society of Japan | Oxford Academic (oup.com)](#)
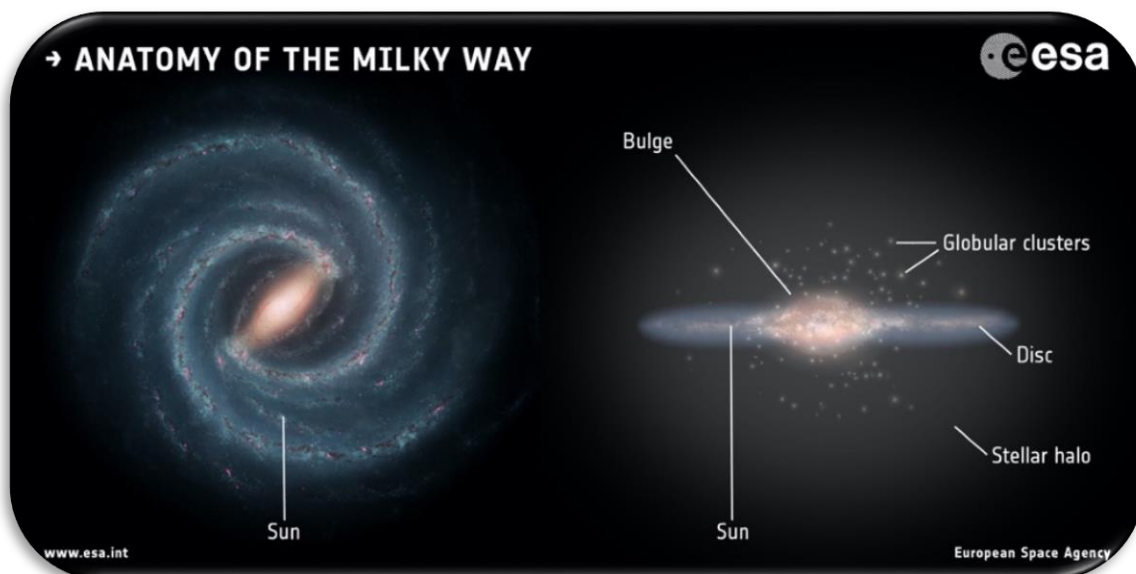

Figure 98: Topography of a Galaxy. (Credit: [www.esa.int](#))

You will compare the expected rotation curve of spiralling galaxies with real data of the Milky Way and M31. Additionally, you will derive the total mass of these galaxies. In order to do so, you are going to follow these steps:

How to perform these steps is explained in the following Activities.

Activity 16.1. Theoretical prediction of rotation curves

In this exercise we are going to discover the expected rotation curve of a galaxy. For this we will make the assumptions that a galaxy is a bulge-sized sphere with all the galactic matter inside. Notice that in this model we are neglecting the influence of the matter distributed in the disk and the halo.

Consequently, we could consider two main distributions for assessing the expected rotation velocity distribution:

1) Objects rotating outside the bulge – considered as punctual points
2) Objects rotating inside of the bulge – considered with a single density distribution

1. **Expected rotation velocity distribution for the rotating objects outside the bulge:**
   For each of the objects, with mass m and acceleration a, rotating outside of the bulge at a distance r, being the mass of the bulge M, the Equation 16 applies to their rotation velocity distribution (v_{rot}^{out}).

$$F = ma = G\frac{Mm}{r^2} \implies m\frac{(v_{rot}^{out})^2}{r} = G\frac{Mm}{r^2} \implies v_{rot}^{out} = \sqrt{\frac{GM}{r}}$$

$$v_{rot}^{out} \propto \sqrt{1/r}$$

Equation 16: Simple relation between rotation speed (v_{rot}) and dintance (r) outside a massive sphere.

2. **Expected rotation velocity distribution for the rotating objects inside the bulge:**
   For each of the object orbiting inside of the bulge at a distance r to the centre, assuming a constant density of the bulge (ρ), the Equation 17 applies to calculate the expected rotation velocity distribution (v_{rot}^{in})

$$\rho = \frac{M}{V} \quad and \quad V = \frac{4}{3}\pi r^3 \implies v_{rot}^{in} = \sqrt{GM/r} = \sqrt{G\rho\frac{4}{3}\pi r^3/r}$$

$$v_{rot}^{in} \propto r$$

Equation 17: Relation between rotation speed (v_{rot}) and distance (r) inside a massive sphere.

Fill in Table 17 with the velocity values associate with the given radial distance values. **Tip:** Depending on whether the object are inside the bulge (r < 1 a.u.)[6] or outside the bulge (r > 1 a.u.) you may use Equation 16 or Equation 17 for these calculations.

Radial distance inside the galactic bulge in a.u.									
0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
Rotation velocity in a.u.									
Radial distance outside the galactic bulge in a.u.									
1	2	3	4	5	6	7	8	9	10
Rotation velocity in a.u.									

Table 17: Data points for a predicted rotation curve of any Galaxy in a.u.

3. **Draw the values show in** Table 17 in the following grid to obtain the predicted rotation curve of a spiral galaxy. Tip: you can use an Excel file with the information of Table 17 to automatically do this drawing)

---

[6] a.u. stands for arbitrary units. We are not interested in specific sizes but only in the general shape of the curve.
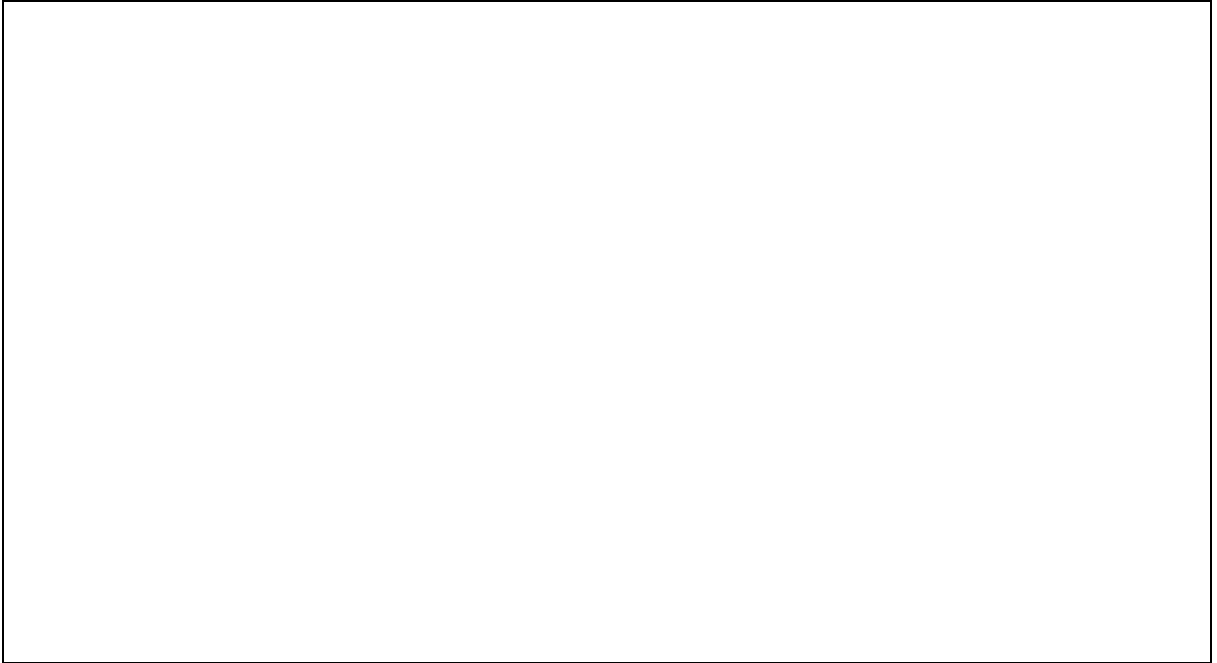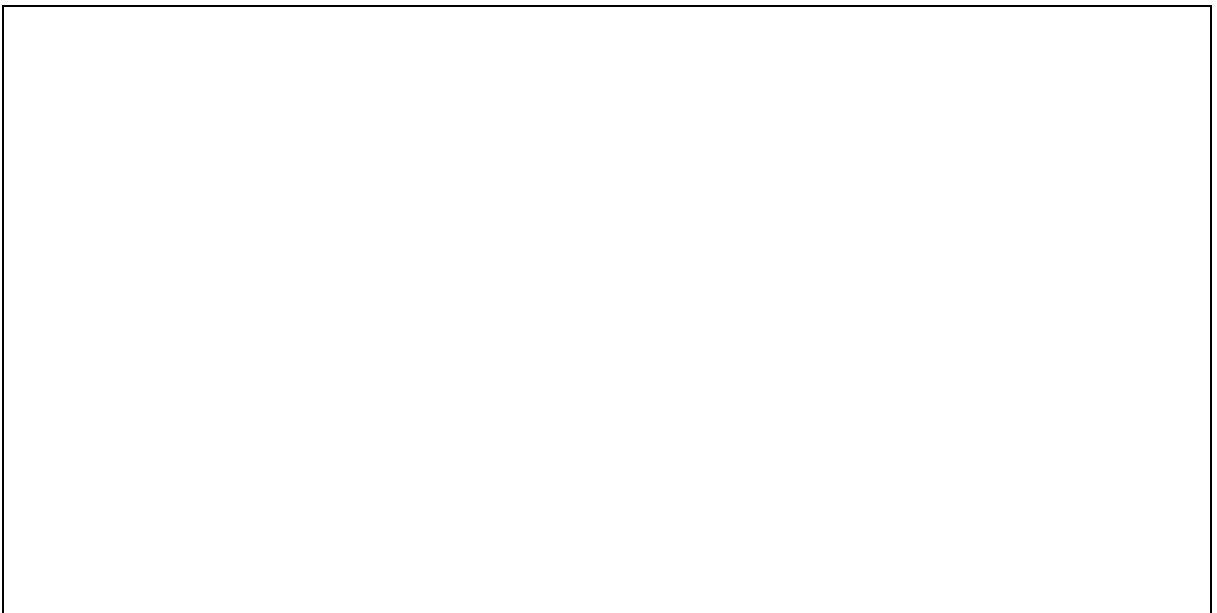
Figure 99: Graphical representation of the expected velocity distribution of objects gravitationally bound to a spiral galaxy. (Credit: You)

4.   How would you describe these two distributions?

This calculation corresponds to the expectation of the first scientists, such as Vera Rubin, who studied the gravitational effects on spiralling bodies.

Activity 16.2. Compare the predicted/expected and observed rotation curve of a galaxy

Figure 100 shows the comparison of the expected rotation curve of the Milky Way (in blue) compared to its observed rotation curve (in green). The plot is showing the dashed lines which represents the 3 main components of a spiral galaxy, like the Milky Way.
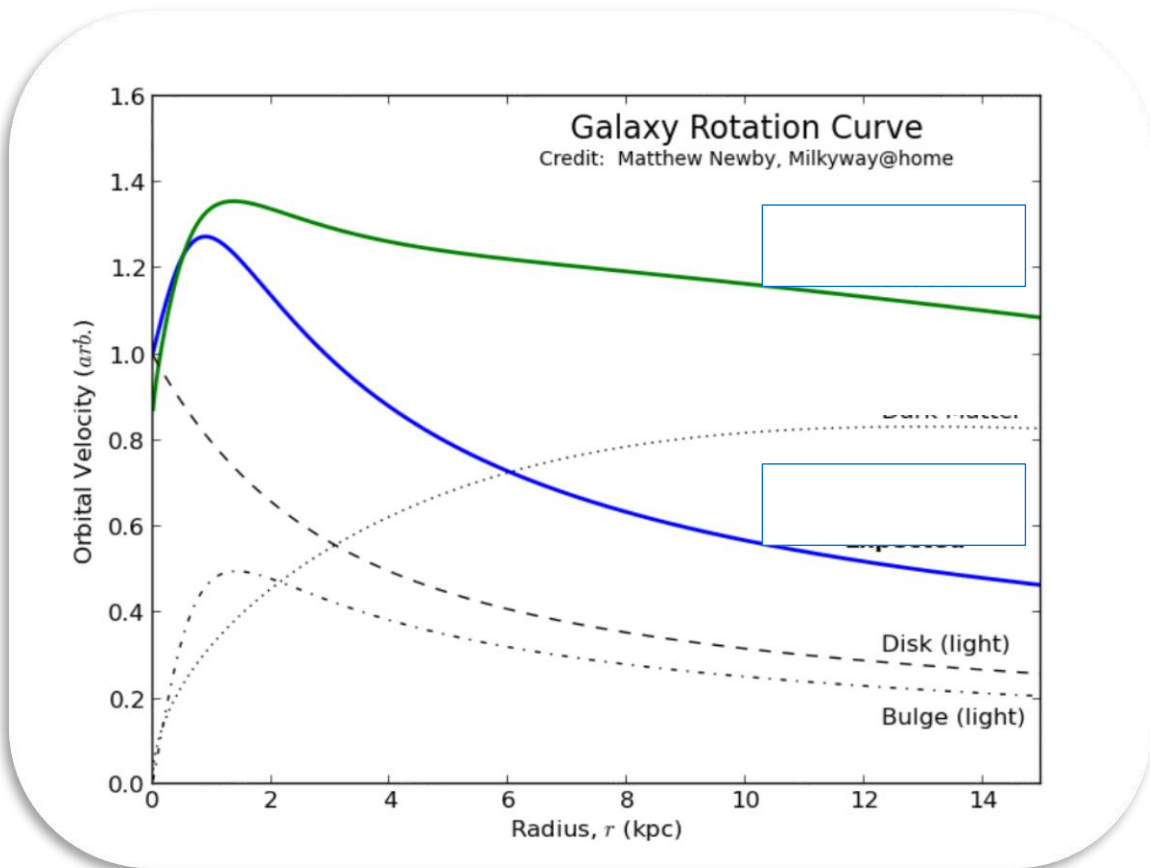

Figure 100: Graphic representation of the individual mass contributions of the components of a galaxy. (Credit: Milkyway@home)

1. Why do you think the expected and the observe rotation velocity curves do not match?

2. What is the component that seems to match with the expected distribution of the rotation velocity curve?

3. What could be the other component that is creating the main difference between the expected and the observed rotation velocity?

4. What could you conclude, as Vera Rubin did, as part of her research?

5. Watch this video about Vera Rubin's discoveries and see whether you find some similarities with your current discovery.

⇒ https://www.youtube.com/watch?v=pkrljGUJOPA

Activity 16.3. How to do an approximate calculation to the total mass of a galaxy

We are going to analyse the mass of the halo of some spiral galaxies from the research done by Sofue in 2015.

Activity 16.3.1 The Milky Way

Here you have the observed rotation velocity curve of the Milky Way and the Table of calculations done by Sofue, of the different contributions of the galaxy

Milky Way	Bulge	Disk	Halo	Total Galaxy
Radius (kpc)	$0,87 \pm 0,07$	$5,73 \pm 1,23$	$10,7 \pm 2,9$	~ 500
Orbital Velocity (km/s)				
Mass ($M_\odot \cdot 10^{11}$)	$0,25 \pm 0,02$	$1,12 \pm 0,4$		

Table 18: Matter content of the Milky Way galaxy based on a simple edge of rotation curve calculation.
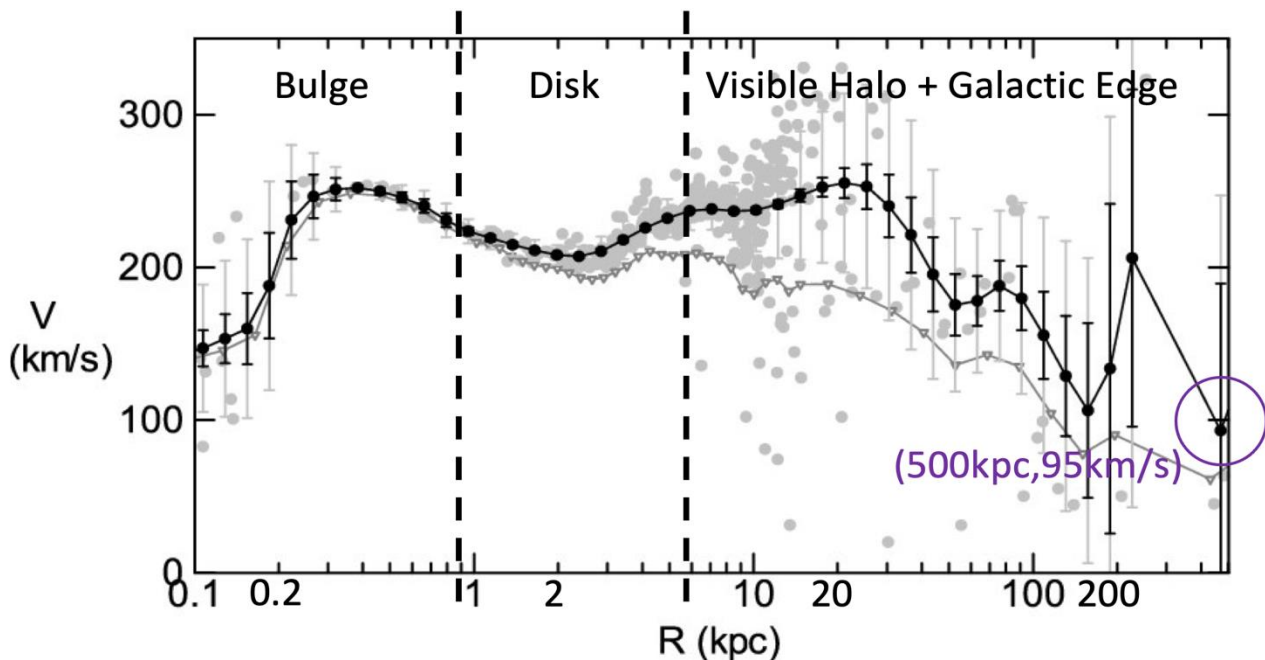

Figure 101: Grand Rotation Curve for the Milky Way Galaxy. (Credit: arxiv.org/abs/1504.05368)

1. Obtain the orbital velocities by checking Figure 101
2. Obtain the total mass of the galaxy with Equation 12.

Use the expression that we learned to calculate the total mass (M_{galaxy}) of a Galaxy by using the rotation velocity (v_{edge}) of the objects at the edge of its halo (r_{edge}). The data required to perform these calculations can be found in Table 18. Remember that:

$$1\ kpc = 3{,}0857 * 10^{16}\ km$$
$$G = 6{,}674 * 10^{-20} km^3/kg\ s^2$$
$$M_{galaxy} = \frac{v_{edge}^2 \cdot r_{edge}}{G}$$

3. Calculate the mass in terms of solar masses.

Remember that:
$$1\ M_{\odot} = 2 \cdot 10^{30} kg$$

4. Calculate the matter content of the Halo by subtracting to the total the contributions of Bulge and Disk like described in Equation 9.

5. Use the following box to calculate what percentage of the total galactic mass corresponds to the Halo.

Activity 16.3.2. Andromeda

1. Repeat the previous procedure for the Andromeda galaxy. See Figure 102 to complete Table 19 with approximated values for orbital speeds.

Andromeda	Bulge	Disk	Halo	Total Galaxy
Radius (kpc)	$1{,}35 \pm 0{,}02$	$5{,}28 \pm 0{,}25$	$34{,}6 \pm 2{,}1$	~400
Orbital Velocity (km/s)				
Mass ($M_\odot \cdot 10^{11}$)	$0{,}35 \pm 0{,}004$	$1{,}26 \pm 0{,}08$		

Table 19: Matter content of the Andromeda galaxy based on a simple edge of rotation curve calculation. The masses are given in units of Solar Masses ($M_\odot = 2 \cdot 10^{30}\ kg$).
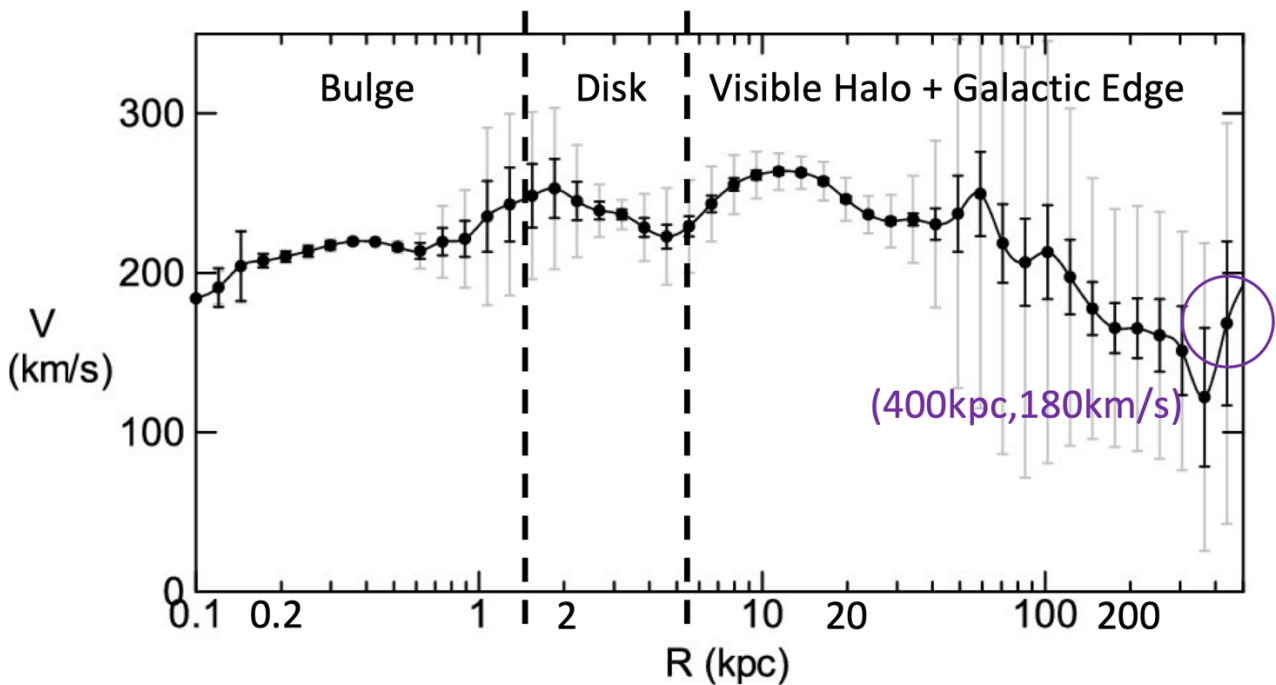
Figure 102: Grand Rotation Curve for the Andromeda Galaxy (M31, NGC224). (Credit: arxiv.org/abs/1504.05368)

2. Use the box below to calculate the total mass of the galaxy:

3. Use the following box to represent the total mass in terms of solar masses:

4. Use the following box to calculate the matter content of the Halo:

5. Use the following box to calculate what percentage of the total galactic mass corresponds to the Halo.

Activity 16.4. Evaluate your results and draw your own conclusions

1. If you have performed the calculations correctly, you should have seen that the Halo makes up around 90% of the galaxies' matter content. **What does this mean?**

2. Compare your results for the Milky Way and Andromeda. From your results, what similarities and differences do you see between these two galaxies?

3. How does the shape of the observed galactic rotation curve compare to the expected calculation? Do they look the same or different?

4. What does the shape of the rotation curve tell you about how the mass is distributed? Is most of the mass in the galactic Bulge or is there a significant amount of mass in the Halo or non-luminous part?

5. How does the visible mass of the galaxy compare to the dynamical mass of the galaxy? How much matter is in the Halo compared to the galactic bulge and disk?

6. Do you know other methods to calculate the galactic mass content?

Activity 16.5. Present your studies

Implement the answer of this questions and your predictions, calculations and discussions in a complete scientific report/poster. You can follow a structure similar to the following (see as an example the implementation of a poster in Figure 103):

- **Abstract.** State the current state of knowledge about gravity, spiral galaxies, rotation curves and dark matter.

- **Methods.** Explain the calculations that you are about to perform and the goal that you pursue.

- **Results.** Present the calculations, graphs and pictures showing your work and studies.

- **Conclusion.** Elaborate on the explanation of your results towards what you wanted to predict in the first place and the repercussions that you have considered.

- **References**. Include a list of the scientific books, papers or sources that you have used to create your work.

Figure 103: Example of a simple scientific poster. (Credit: i.pinimg.com/)

Phase 4

Activity 17. Auto- and co-evaluation

Congratulations!
You have completed your Science Challenge! Tell us your story!

Take a moment to think about the Experience with your Team and teacher and complete these Activities.

- **Teams:** Fill in this questionnaire so that you can check what you have learned in the Challenge.

- **With your teacher:** Give us your feedback

Activity 17.1. Tell us your adventure

If you have executed Activity 14. or Activity 15., you already have been advised on how to create a scientific paper. If you wish, you can use the same structure for your poster.

Otherwise, you can find some examples at:

$\Rightarrow$ https://cesar.esa.int/index.php?Section=CESAR_on-line_Space_Science_Experiences_Contest

Students will have to create a final product (an A0 poster in pdf format, using power point, for example) showing what they have learned in the different phases of the Scientific Challenge.

This poster is the ticket to participate in the CESAR international adventure competition.

Congratulation teacher!

Thanks to your dedication, your class will receive a CESAR Team Super Diploma!

Links

ESASky

General documents.

⇒ https://www.cosmos.esa.int/web/esdc/esasky-how-to

How to upload a target list (video).

⇒ https://www.youtube.com/watch?v=M-aJn5TTd50

How to explore multi-wavelength skies (video):.

⇒ https://www.youtube.com/watch?v=zkJkhSDr0nQ

Material prepared to be executed on-line, based on previous activities developed by the ESASky

INITIAL VERSIONS:

http://cesar.esa.int/index.php?Section=SSE_The_Secrets_of_the_galaxies

http://cesar.esa.int/index.php?Section=The_Secrets_of_Galaxies

Credits

The CESAR Team counted with the support of the <u>Young Graduate Trainee (YGT) Programme.</u>