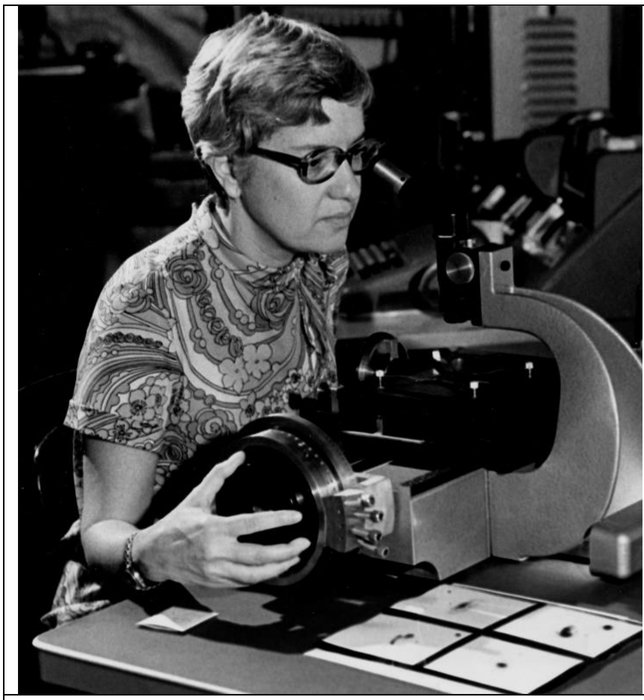
# Projection description

In this project we will focus on galaxies, the little island of the universe that hosts planets, stars, solar systems, and even black holes. In this project, you will use these seemingly ordinary objects to do “ground-breaking” science. The first two projects will introduce the difference between a spiral and an elliptical galaxy, how we measure the velocity, luminosity, and distance to a galaxy. The final project will be a role-playing game where you follow the path of famous astronomers in the history of physics and understand the ground-breaking science were made by them. You can either play as Vera Rubin (a brilliant female astronomer, one of the largest telescopes on Earth, the Rubin observatory was named after her) to discover that most of the matter in the universe is actually invisible. Alternatively, you can play as Edwin Hubble (a famous astronomer, the Hubble space telescope was named after him) to discover that the universe is expanding. Both discoveries by Vera Rubin and Edwin Hubble are of the most important findings in astronomy in the 20th century and lay the foundations for modern astrophysics and cosmology.



Vera Rubin

Edwin Hubble

# Projection plan

## Project 1.

Before we dive into the wonderful science done by Vera Rubin and Edwin Hubble, we will first introduce the galaxies to you.

Demonstration: Introducing the galaxies and the Hubble sequence of galaxies.

> *Comment: I will use the slides from PHYS3080. The objective here is to let the student know the difference between an elliptical and a spiral galaxy. I am not expecting them to tell the difference between Sb and Sc galaxies. This will take about 30-60 minutes.*

Activity: Classifying elliptical and spiral galaxies with galaxy zoo.

> *Comment: https://www.zooniverse.org/projects/zookeeper/galaxy-zoo/. This will take around 30-45 minutes.*

## Project 2.

Demonstration: Introducing the spectrum of galaxies.

- Part 1: The wave nature of light.
- Part 2: The spectrum of light.
- Part 3: The Doppler effect and the velocity of a galaxy.
- Part 4: The inverse square law and the apparent, absolute magnitude, and distance module.

*Comment: This will take around 2 hours. This session will introduce the basic knowledge they need to do the final project.*

## Project 3 (optional)

Demonstration: Introducing scientific notation, logarithmic and exponential calculation.

> *Comment: This is optional. They don't have to do it if they are familiar with the 3 concepts listed above. The first three projects are expected to finish in the first two days.*

# The final project (Choose one of them)

## Option 1 – Vera Rubin & Rotational Curves

### Playing as Vera Rubin (%ctional history) (In this project, you don t have to do any coding except the optional challenge)

It is 1980, you are working as a researcher at the Carnegie Institution of Washington in America. Your colleague just handed you some spectra of spiral galaxies and asked you to compute the rotational velocity of these galaxies. Knowing the rotational velocity is related to the "double-horn" structure in the spectrum, you quickly calculated the rotational velocity for these samples (this will be explained in project 2). You suddenly recalled the idea in the 1930s by Fritz Zwicky that there may be invisible matter in the universe. This idea was dismissed by mainstream scientists for the last 50 years, but you think there may be some truth in it. Therefore, you decide to use your data in hand to test this theory. You know if the theory is correct, then the mass of the galaxy will not be equal to the total mass of the stars in in the galaxies because galaxies are expected to only make up of stars. Here you encounter your first challenge: *how to get the mass of a galaxy*? Fortunately, you realize that for the spiral galaxy to not fall apart, its rotational force must be balanced out by the gravitational force. Therefore, you decide to use this method to calculate the mass of the spiral galaxies.

> Challenge 1: calculate the mass of galaxies using the fact that the rotational force of a spiral galaxy is equal to its gravitational force.

You finished calculating the mass of the galaxy. Now the next challenge you have is you don't know the total mass of stars inside the galaxy. To tackle this problem, you think you can first calculate how many sun-like stars it would need to generate the same luminosity as the galaxy. Since we know the mass of the sun and star with the same luminosity should have the same mass, so you can figure out the total mass of stars inside the galaxy.

> Challenge 2: Calculate the luminosity of the galaxy from its absolute magnitude.

> Challenge 3: Given luminosity of the sun, estimate how many sun-like stars are required to reach the same luminosity as the galaxy.

> Challenge 4: Given the mass of the sun, estimate the total mass of the star in the galaxy.

You found that the mass of the galaxy doesn't equal to the total mass of the star. You soon realized Zwicky's claim was correct: there are actually invisible matter in the universe. Otherwise, we cannot explain the missing mass.

#### *Optional (if you have time)*

You quickly write a paper and publish it, and the scientific community is shocked by your findings. However, a small group of scientists reject your claim because they say your sample size is too small and what you found is just a statistical fluke. You are determined to show your theory is correct but there aren't many spiral galaxies with both rotational velocity and luminosity measurements. You have a handful of spiral galaxies with rotational velocity but not their luminosity. You recalled your colleague Brent Tully and Richard Fisher has published a paper in 1977 that the luminosity and rotational velocity of the spiral galaxies follow a linear relation. You wonder whether you can use this linear relation to interpolate the luminosity for these galaxies.

> Challenge 5: Find the Tully-Fisher relation using the sample of your spiral galaxies that have both luminosity and rotational velocity measurements.

With the new luminosities, you can repeat the process and calculate the total mass and total mass of stars in these galaxies. Your new result silence the doubters and your claim is accepted by the main-stream scientist.

It is now 2015, it has been 35 years since you show there is invisible matter in the universe. However, this invisible matter or dark matter is still a mystery. A new telescope was built in Chile aims to study dark matter in more detail and they named this telescope after you.

## Option 2 – Edwin Hubble & Cosmological Expansion

### Playing as Edwin Hubble (fictional history) (In this project, you need to do some basic coding, but we will assume you have no coding background.)

It is 1929, you are working at the Mount Wilson Observatory. Just 5 years ago, you measure the distance to the Andromeda nebulae and show the distance is much larger than the size of the Milky Way. This finding shocked the whole scientific community because most scientists thought the Milky Way was the whole universe back then, so there is no galaxy other than the Milky Way. Due to this new finding, the Andromeda nebulae was renamed the Andromeda Galaxy.

Now you are focusing on a new challenge, your colleague Georges Lemaître sent you a letter on his theory that the universe is expanding. He is hoping you can help to prove his theory. You understand most of physicists believe the universe is static. For example, after learning Lemaître's expanding universe idea, the famous Albert Einstein replied,

> "*Your calculations are correct, but your physics is atrocious*".

However, you believe science should be based on observational data, not the statement of a famous scientist. You set out to collect data to test Lemaître's theory.

You decide to make a plot of the velocity of the galaxy against its distance from Earth. You know in a static universe; the velocity of galaxies should be random. You won't expect any relationship between the velocity and the distance of a galaxy. However, in an expanding universe like Lemaître's theory, the velocity of a galaxy is linearly proportional to the distance of the galaxy. The slope is given by the expansion rate of the universe. Over the last few weeks, you have collected the redshifts of several galaxies.

> Challenge 1: convert the redshift of these galaxies to the velocity.

You now have the velocity of these galaxies, so the only obstacle remain is the distance. You know both the apparent and absolute luminosity of the galaxy, you think you may be able to use the inverse square law to calculate the distance.

> Challenge 2: Using the absolute and apparent magnitude to calculate the distance to these stars and hence their host galaxies.

Aha, now you have both the velocity and distance. It is time to plot the diagram. You found the velocity of the galaxy is linearly proportional to its distance just as Lemaître predicted. Now you are interested in the expansion rate of the universe.

> Challenge 3: Find the slope and hence the expansion rate of the universe.

You write the paper and publish your result. Just like 5 years ago, your finding again shocked the whole scientific community. Even the mighty Albert Einstein later commented on his attempt to create a static universe with cosmological constant was his "his greatest blunder".

Now you prove the universe is expanding. However, you realize that your equation implies we may never observe the galaxies that are certain distance away from us because nothing can travel faster than the speed of light.

> Challenge 4: Calculate the minimum distance to a galaxy whose light will never be able to reach us.

*Optional (if you have time)*

Now you prove the universe is expanding now. However, you are wondering whether the expansion of the universe is accelerating or decelerating. Using the high redshift sample provided to you to draw the diagram of velocity against distance again.

> Challenge 5: From your new diagram, find out whether the expansion of the universe is accelerating, constant, or decelerating.

It is 1983, NASA planned to launch a new space telescope and they decided to name it after you for your discovery that the universe is expanding.

It is 1998, two independent teams of researchers discovered that the universe is not only expanding, but the expansion is also accelerating. The mysterious energy that causes the accelerating expansion is called dark energy. The leader of both teams received the Nobel prize in physics in 2011.

It is 2018, the International Astronomical Union recognized the contribution of Georges Lemaître in your work and renamed the linear relationship between velocity and distance of a galaxy from the Hubble law to the Hubble-Lemaître law.

It is 2022, the late and early universe measurements of the expansion of the universe (the slope of the linear relationship) are shown to be in disagreement. Some scientists think this is because our current model of the universe is incorrect and numerous alternative models have been proposed.