# Weighing a Galaxy

## Introduction

How do Astronomers know how much matter is in a galaxy?

How do they know dark matter exists?

In this project, you will get access to some real galaxy data from the SAMI Galaxy Survey and learn to use the same tools that astronomers use to measure how fast the galaxy is rotating. From this you will calculate the amount of mass in your galaxy, and by comparing that with the expected values from other measurements we can make some assumptions about the existence of Dark Matter.

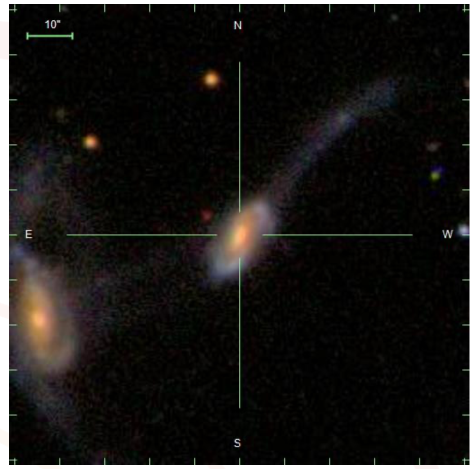


*Figure 1 - SAMI Galaxy 618992*

For this research project you will need:

- The use of a spreadsheet (our instructions will assume Excel)
- A pen and paper (we recommend printing this booklet out and writing in it)
- Access to the internet in order to download the data packages.

All the necessary data can be found at www.icrar.org/weighing-a-galaxy

## Research Plan

The goal is to measure the rotation curve and then derive the total mass (and dark matter components) for a nearby galaxy. You will:

1. Identify a suitable galaxy from an online dataset and download the necessary data.
2. Choose sample coordinates and measure their velocities from the galaxy rotation map and record these in a spreadsheet.
3. Once you've obtained sufficient measurements, plot the data to produce a rotation curve.
4. Using your rotation curve derive a total (dynamical) mass for the galaxy.
5. Comparing this result to the derived luminous (stellar) mass, infer the presence and effect of dark matter.

## Accessing the data

We will be making use of data from the SAMI Galaxy Survey which is hosted by the Australia Astronomical Observatory's DataCentral online database. The SAMI Galaxy Survey made 3D measurements of several thousand galaxies using the SAMI instrument on the Anglo-Australian Telescope at Siding Spring Observatory, NSW.

The database includes several hundred thousand spectra from several thousand galaxies, along with many measurements that were derived from these spectra, which is what we'll be working with today. The subset of galaxies that we have chosen all contain stars that are moving on regular, roughly circular, orbits.

> **NOTE:** All of this data and more is available in the Astronomy DataCentral Single Object Viewer (SOV)
>
> https://datacentral.org.au/services/sov/
>
> Galaxies in the database have simple numerical names between 1000 and 999999.

Choose a galaxy from the activity resource page and download the corresponding data file.

The data you are using comes from the *SAMI Data Release 2* and includes the *Ionised Gas Kinematics* results. This is a measurement of the emission spectrum lines of warm (ionised) hydrogen and helium (gas), telling us how fast that gas is moving (kinematics) with respect to us.

Using the data from the galaxy you have chosen we are going to follow the following steps as outlined in these next sections.

## Analysing the data

1. Open a new browser tab or window and load up the JS9 Online Astronomical Image Viewer. You can find the link on the activity resource page, or type it in manually: https://js9.si.edu/

2. From the File menu of this software, select the open... local file option to load your velocity map from where you saved it.

3. Zoom in so that the data fills the screen, either by using the Zoom menu or by pressing the "Best Fit" button.

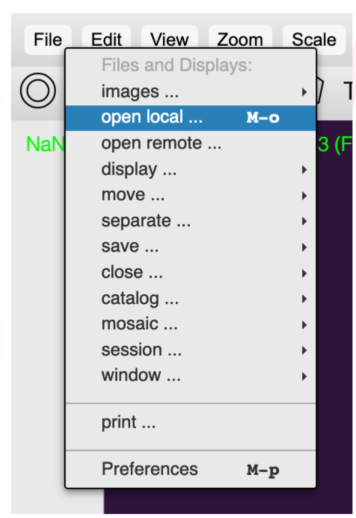



*Figure 2 - JS9 File -> Open menu.*

4. Adjust the colour selection using the Colour menu. We recommend *Turbo* as a good balance between visibility and legibility, but feel free to experiment and choose a scheme that works for you. It can always be changed at a later stage.

5. Under the Scale menu:
    a. Set the Scaling Algorithm to linear.
    b. Set the Data Limits to either "data min/max" or "zscale z1/z2".
    Pick the one that makes the image display the biggest range of colours in your dataset.

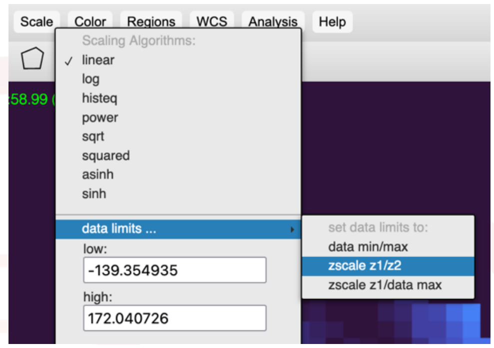



*Figure 3 - JS9 Scale menu.*

6. In the upper left corner of the viewer is a readout that shows all the data values at the point where your cursor is. From left to right they are:

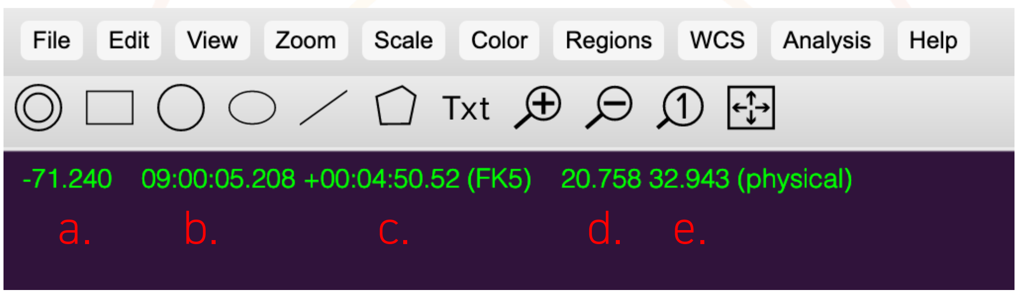



*Figure 4 - JS9 data readout.*

    a. The velocity of the gas (in km/s)
    b. Right Ascension (in Hours:Minutes:Seconds)
    c. Declination (in Degrees:Minutes:Seconds)
    d. X Coordinate (in arbitrary units)
    e. Y Coordinate (in arbitrary units)

We are going to be recording (a.) Velocity, (d.) X Coordinate, and (e.) Y Coordinate for our analysis.

7. Use the straight-line tool  to draw a line through the major axis of the galaxy. This line should pass through both the highest and lowest velocity values in the data, going through the greatest number of colours between the two.

a. Clicking on the straight-line tool will create a green diagonal line inside a box; click and drag the line until you see one corner of the box and click on that corner to resize the box until it only just contains the galaxy.
b. Click and drag on the rotation handle (the line with circles that sticks out of the side of the box) until the green straight-line is aligned with the major axis of the galaxy. You may also have to drag the box several times to position it correctly, but it doesn't need to be perfect.

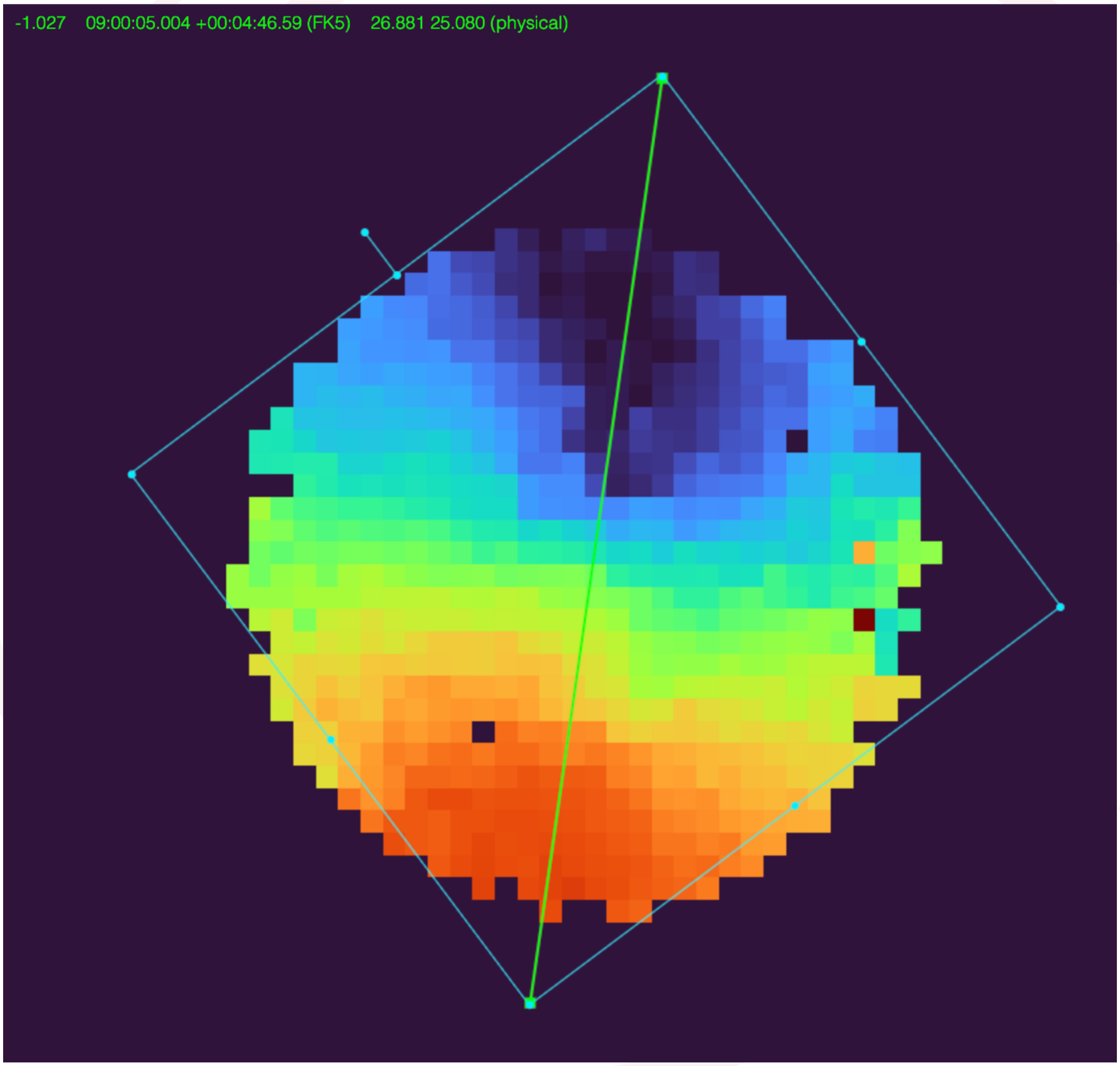



*Figure 5 - SAMI Galaxy with Major axis identified.*

8. Use your cursor to identify the minor-axis of the galaxy; this is the line where the velocities are all approximately zero and will be perpendicular to the major axis.
    a. Make a second straight-line by clicking the straight-line tool again and resize it like you did before so that it is the same size as the galaxy.
    b. Rotate the second straight-line so that it runs perpendicular to the major-axis line you made, then carefully move it so that it passes through as many of the "nearly zero" values as possible.

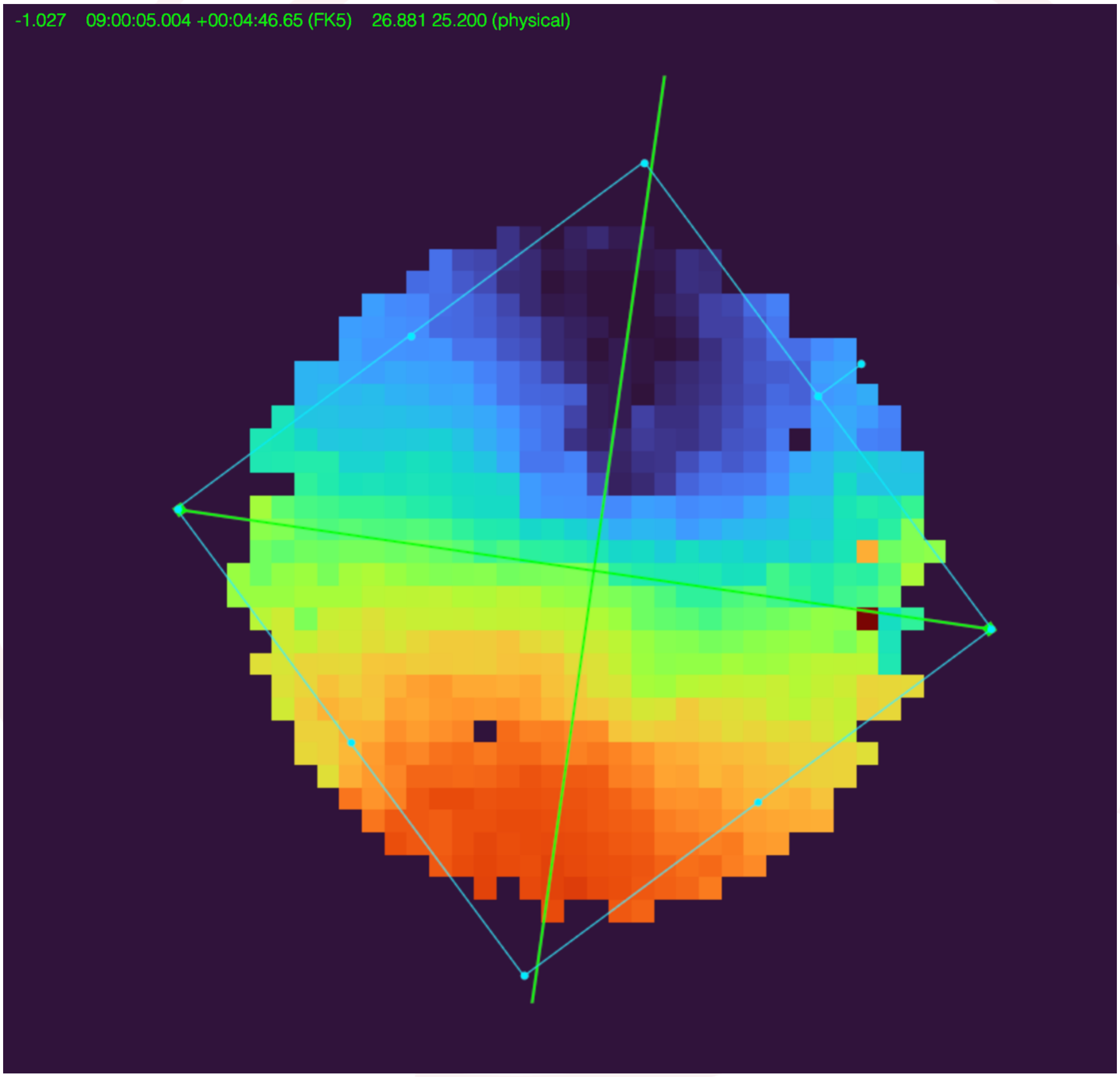



*Figure 6 - SAMI Galaxy image with both Major and Minor axis identified.*

9. Identify the coordinates of the point where the major- and minor-axis cross by hovering your cursor over the intersection of the two straight-lines. Record the Velocity, X Coordinate and Y Coordinate in the first row of the table below (labelled Galactic Centre).

**Tip:** Use a pen and paper to record these values. If you move your cursor away it will change the coordinates!

| | Velocity | X Coordinate | Y Coordinate |
|---|---|---|---|
| Galactic Centre | | | |
| Negative Velocity Points | | | |
| | | | |
| | | | |
| | | | |
| Positive Velocity Points | | | |
| | | | |
| | | | |
| | | | |

*Table 1 - Step 9: Record coordinates and velocity values*

10. Moving along the major-axis line that you have created, select four points on either side of the minor-axis line and record their values into the table as well. Start off with the most negative value and move towards the most positive value, otherwise plotting may be difficult later on.

    You should now have at least four points where the Velocity value is a negative number (i.e. moving towards us, shown in blue) and four values where it is a positive number (i.e. moving away from us, shown in red).

**Note:** You may like to take more than four samples on either side of the minor axis, as this will give you more accurate values for peak rotation velocity. However, doing so will more time and the extra accuracy does not really make a big difference to the final result.

## Processing the data

11. Create a new excel spreadsheet where you will process your data.

12. Add column headings in row 1:
    a. Distance (from galaxy centre)
    b. Velocity (km/s)
    c. X coordinate
    d. Y coordinate

13. Fill in the values that you have recorded in your table above. Leave the Distance column empty for now, as we are going to calculate that from the X-Y Coordinates

14. Row 2 will have the information for the galaxy centre in it, as you recorded this data point where the Major- and Minor-Axis intersected, and the Velocity was as close to zero as possible. We will define the distance at this point to be zero, so put a 0 into cell A2.

15. Row 3 onwards will have the velocity information that we want to use in our calculations, but we need to calculate the Distance values.

    In cell A3 we are going to enter a formula to calculate the distance from galaxy centre.

    You may recall from maths the formula for the distance between two coordinate points is:

$$d = \sqrt{(x_1 - x_0)^2 + (y_1 - y_0)^2}$$

    In excel we can write that as:

    =SQRT((A3-A2)^2+(B3-B2)^2)

    Where A3 and B3 are the cells that contain the X and Y Coordinates for this row, and A2 and B2 contain the X and Y Coordinates for the galactic centre.

16. Repeat this step for cell A4, changing the formula so that we are still comparing this fourth-row data point to the galactic centre in row two:

    =SQRT((A4-A2)^2+(B4-B2)^2)

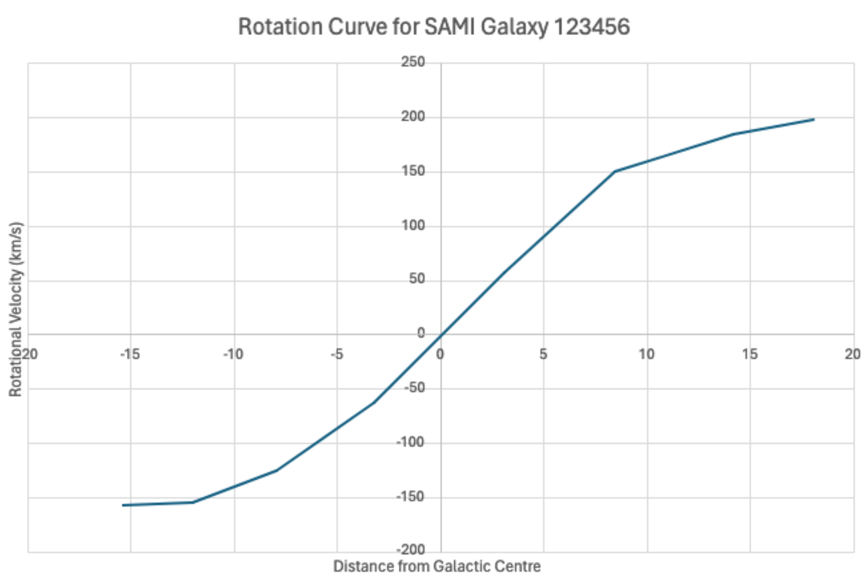
17. Continue this for cell A5, A6, and so on until you have calculated the Distance values for every one of your data points.

    **IMPORTANT:** You must make sure that in your formula you are keeping your $x_0$ as A2 and $y_0$ as B2 the same each time, and only changing the $x_1$ and $y_1$ values each time.

18. We now have the absolute value of the distance in each data point, but we need to make sure that the points on the far side of the galaxy have a negative value, just like their velocity values.
    a. Identify the rows where the distance value should be a negative.
    b. Modify the formula in that distance cell so that there is a "-" sign in front of the Square Root function, like this:

       =-SQRT((A4-A2)^2+(B4-B2)^2)

19. Next you will need to plot your Velocity values against their Distance values.
    a. Select the columns containing your velocity and distance measurements by clicking and dragging on cell A3 and dragging down to B10 (or whatever row is your last data point).
       Do not include the data points in Row 2.
    b. Under Insert, select Chart and then click on "X Y (Scatter with Straight Lines)". This will plot a rotation curve for your galaxy with Distance on the x-axis and Velocity on the y-axis.




**Tip:** You might want to edit the Chart Title to be something informative, such as: Rotation Curve for SAMI Galaxy #### (where the # is the number of your galaxy). It is a good idea to label your plot axis too.

20. Record the **absolute values** (ignoring the positive or negative signs) of the peak rotation velocity of your galaxy using your graph. To find this value, look for the two parts of your rotation curve that flatten out: one at the top and one at the bottom. If your curves aren't fully flat, estimate the value where you think they will become flat. These points are called the asymptotes.

21. The estimated peak rotation velocity is calculated by summing these two values together, and then dividing by two. As an example, in our plot above it would be:

(155+200)/2 = 177.5 km/s
= 177500 m/s

| Calculate the peak rotation velocity and record it here: |
|---|
| $v_{rot} =$ |

*Table 2 - Peak rotation velocity*

## Calculating the Stellar Mass

Now that we have our rotation curve and peak velocity, we can use it to calculate the total mass of the galaxy. To do this we need some extra data, all of which is available from a combination of the GAMA (Galaxy And Mass Assembly) Project and the SAMI Galaxy Survey database. We have collated the values you need on the activity resource page.

On the activity resource page, find your galaxy and record these values:

- CATID Your galaxy number
- $M_{star}$ Log stellar mass: the base-ten logarithm of how much mass we think is in the galaxy based on how bright the stars appear to be.
- $r_e$ Radius of the galaxy in arcseconds
- $z_{tonry}$ Observed redshift: a measure of how far away a galaxy is based on its recessional velocity (how fast it is moving away from us).



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Record all of these values for your galaxy in a table below:

| CATID | $M_{star}$ | $r_e$ | $z_{tonry}$ |
|---|---|---|---|
| | | | |

*Table 3 - Galaxy observational values*

These values are all based on observational astronomy and therefore don't use standard units. Before we can use them in our calculations, we need to convert some of them into physical quantities and, where possible, into SI units.

22. Redshift to velocity:

First convert the observed redshift value to a recession velocity using the Doppler approximation:

$$z \approx \frac{v}{c}$$

Where:

$z$ is redshift (or $\mathbf{z_{tonry}}$ in our case),

$v$ is recessional velocity, and

$c$ is the speed of light ($3 \times 10^5$ km/s)

We need velocity ($v$) so we need to rearrange the equation:

$$v = zc$$

| Calculate the velocity and record it here: |
|---|
| $v =$ |

*Table 4 - Recessional velocity*



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23. Velocity to distance:

We can then convert this velocity into a distance using Hubble's Law:

$$v = H_0 D$$

Where: $v$ is recessional velocity,

$D$ is the "proper distance" between us and the galaxy, and

$H_0$ is the Hubble Constant: 70 km/s/Mpc

We need proper distance so we must rearrange the equation:

$$D = \frac{v}{H_0}$$

| Calculate the distance and record it here: |
|---|
| $D =$ |

*Table 5 - Proper distance*

24. Convert to SI units:

Angular distance is measured using degrees, and in astronomy we divide the sky up into 360 degrees to make a circle. Each degree is then broken up into 60 "minutes of arc", which we call arcminutes (which is given the single quote symbol ′). Every arcminute is in turn broken up into 60 arcseconds (written as the double quote symbol ″).

To find the physical radius, we must first convert our units from arcseconds to degrees using the formula:

$$1° = \frac{1"}{(60)(60)}$$

Therefore, we can convert our $r_e$ value from arcseconds to radians by multiplying these values together.

$$r_e{}^{\circ} = \frac{r_e{}''}{3600}$$

| Convert the angular radius to degrees here: |
| --- |
| $r_e =$ |

*Table 6 - Angular radius in degrees*

Similarly, we must convert our distance values from megaparsecs (Mpc) to meters. While parsecs are great for describing big distances in space, it is always good practice to make sure the units we are using are consistent so that we can not only convert them easily but also perform unitary analysis to better understand our results.

If one parsec is defined as $3.086 \times 10^{16}$ m, and the mega- prefix denotes one million, then it follows that we can convert our distance such that:

$$D_m = D_{Mpc}(3.086e22)$$

| Convert the distance from Mpc to meters here: |
| --- |
| $D_m =$ |

*Table 7 - Proper distance in meters*

25. Angular radius to physical radius

An object that is a long way away from us appears smaller than the same object if it were much closer. As such we use angular measurements to describe an object's perceived size. If we also know how far away an object is, we can use these two things to calculate the true size of the object.

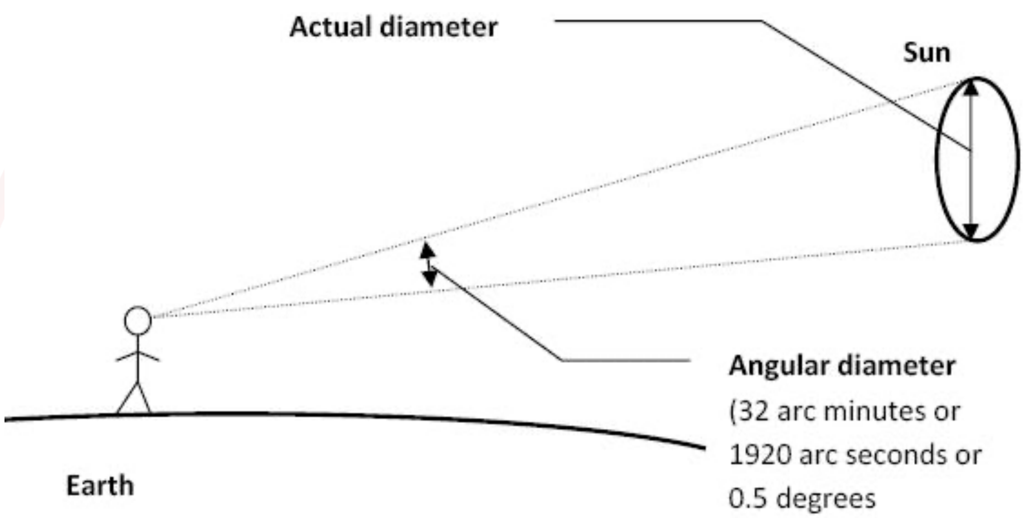


*Figure 7 - Angular diameter of the sun. Credit: Wikimedia commons*

When the angular diameter is very small, we can use the small angle approximation formula to find the physical radius (r) from the angular radius ($r_e$) and the distance (D) such that:

$$r = r_e D$$

| Calculate the physical radius here: |
| --- |
| $r =$ |

*Table 8 - Physical radius*

26. Log stellar mass to stellar mass:

Finally, we must convert the quoted value of the base-10 logarithm of the stellar mass to solar masses, simply by bringing it up to the exponent of 10 thus:

$$M_{stellar} = 10^{M_{star}}$$

| Calculate the stellar mass here: |
|---|
| $M_{stellar} =$ |

## Calculating the Gravitational Mass

27. You now have everything you need to calculate the total mass of your galaxy!

The matter inside galaxies (the stars, gas, dust, etc.) all orbit around the centres of the galaxy in much the same way as the Earth orbits around the Sun. The more mass a galaxy contains, the faster those orbits will be due to the increased force of gravity.

There are two equations that we need here:

- the force from gravity between two masses, $F = G\frac{Mm}{r^2}$
- the force from a mass undergoing centripetal motion, $F = \frac{mv^2}{r}$

Thus, we can equate them such that:

$$G\frac{Mm}{r^2} = \frac{mv^2}{r}$$

and by balancing and rearranging these equations we can find the relationship between the total mass of the galaxy (M), the radius (r), and the rotational velocity (v) such that:

$$M_{total} = \frac{rv^2}{G}$$

| Calculate the total mass of your galaxy: |
| --- |
| The physical radius calculated in **Step 25**<br>$r =$<br><br>The peak rotational velocity from **Step 21**<br>$v =$<br><br>The gravitational constant<br>$G = 6.67 \times 10^{-11}$<br><br>$M_{total} =$ |

*Table 9 - Total mass*

This total mass value is in kilograms, however in. order to compare with our stellar mass value we need to convert it back into Solar Masses. To do this we simply divide it by the mass of our Sun: $2 \times 10^{30}$ kg

**Note:** Solar masses are a very commonly used unit in astrophysics. The unit symbol for solar masses is $M_{\odot}$

| Convert the total mass to solar masses: |
| --- |
| $M_{total} =$ |

*Table 10 - Converting to solar masses*

## Calculating the Dark Matter Fraction

28. You have now calculated the total mass of the galaxy and have retrieved the stellar mass from the online database. Compare the two.

    The total mass calculated from the gravitational force far outstrips the amount of mass calculated from the brightness of the stars that we can see. Therefore, the missing mass must therefore be very dark. This **dark matter** mass is the difference between the stellar mass and the total mass.

$$M_{dark} = M_{total} - M_{stellar}$$

| Calculate the dark matter mass here: |
|---|
| The total mass calculated in **Step 27**<br>$M_{total} =$<br><br>The stellar mass calculated in **Step 26**<br>$M_{stellar} =$<br><br><br>$M_{dark} =$ |

*Table 11 - Dark matter mass*

29. You can now represent this as the Dark Matter Fraction:

$$f_{dark} = \frac{M_{dark}}{M_{total}}$$

| Calculate the dark matter fraction here: |
|---|
| $f_{dark} =$ |

*Table 12 - Dark matter fraction*

**Congratulations!**

You just calculated the actual amount of dark matter in a real galaxy.

Now pick another galaxy and do it all again…