Galactic Astrophysics

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About Me

- PhD in Astrophysics then astrophysics research and teaching
- Since 2023 teach on DAIM MSc
- DAIM – Centre for Data Science, Artificial Intelligence and Modelling
- MSc conversion course:
- https://www.hull.ac.uk/study/postgraduate/taught/artificial-intelligence-and-data-science-msc

Plan For Today

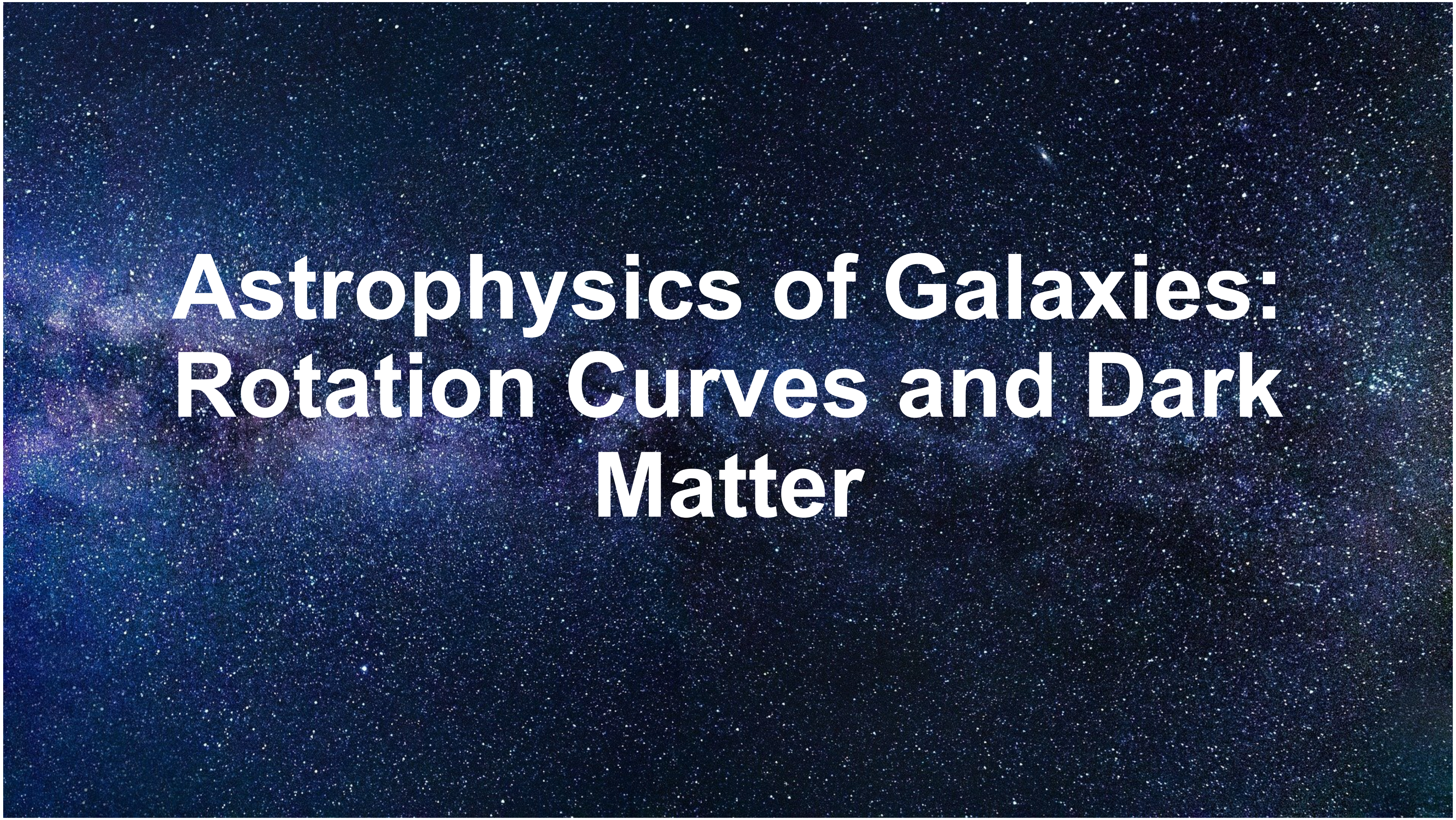
Morning:

Galaxy rotation curves and dark matter

Afternoon:

Galaxy clusters

Galaxy morphology


Astrophysics of Galaxies:
Rotation Curves and Dark
Matter

What is a galaxy?

Collections of

- Stars
- Gas
- Dust

All held together by gravity

Found in different shapes and sizes.

This is a spiral galaxy

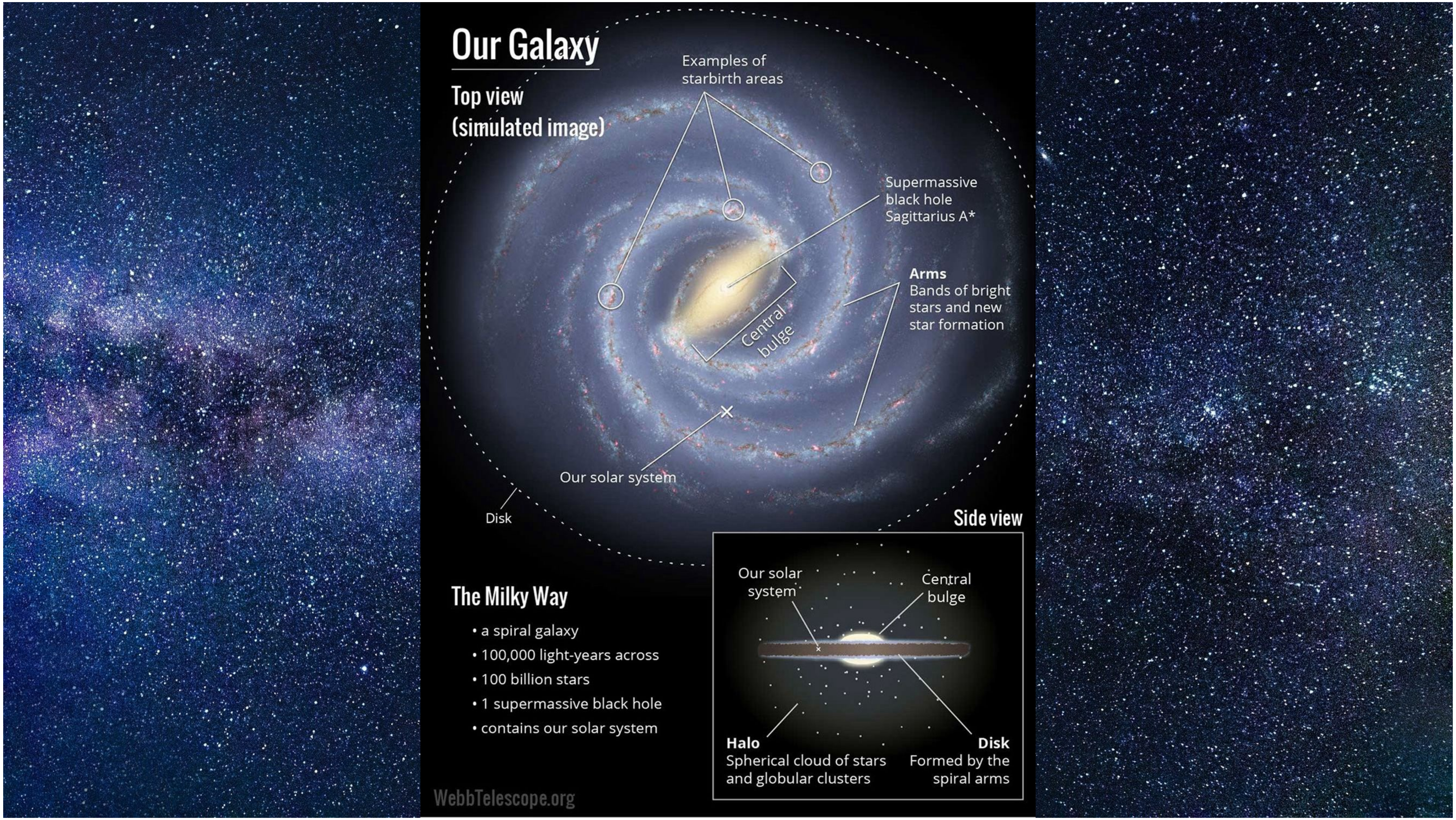
Pinwheel galaxy Credit: European Space agency & NASA

Barred Spiral Galaxies

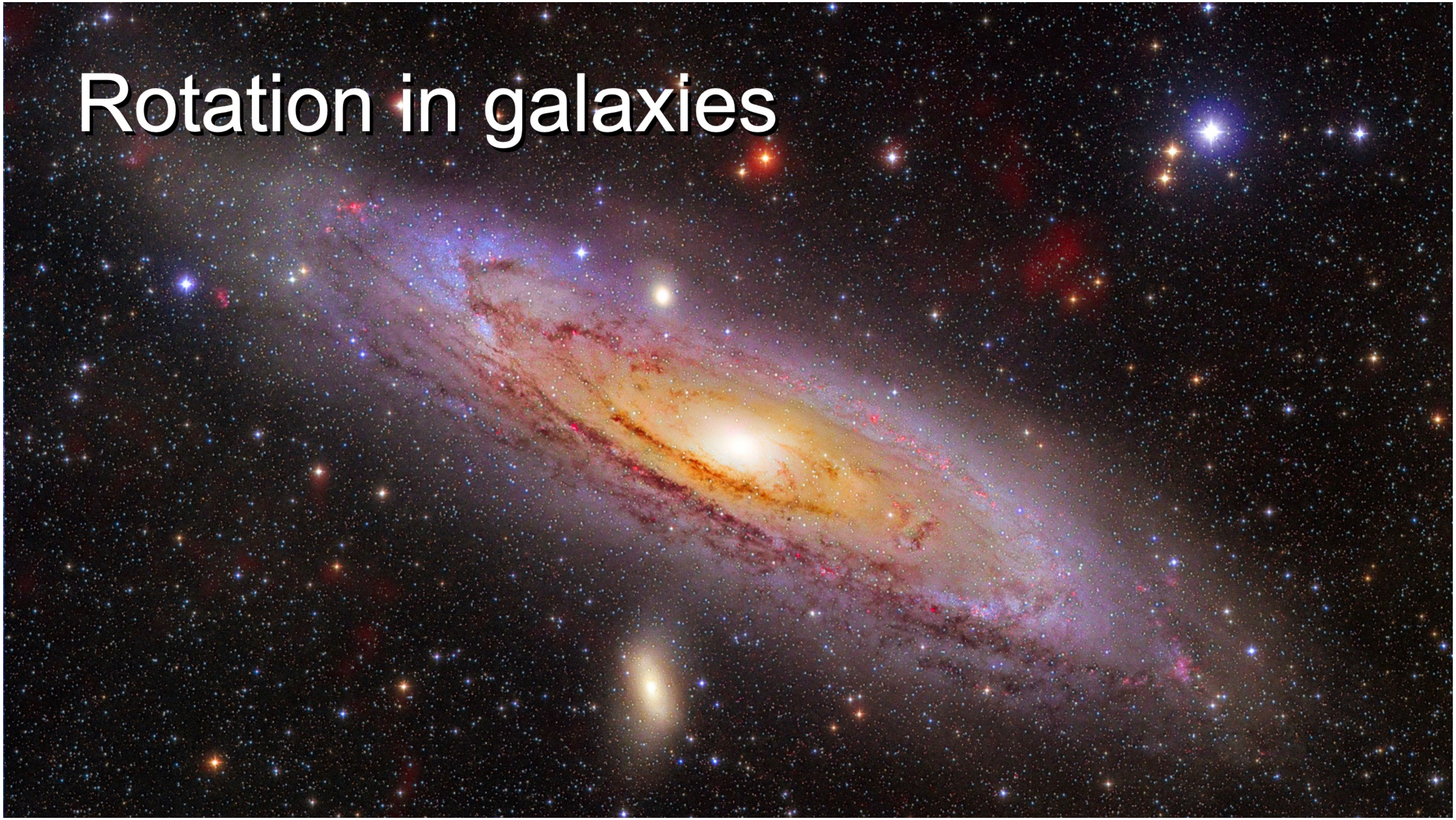
NGC 1300

NGC 1073

Credit: NASA, ESA and the Hubble Heritage Team

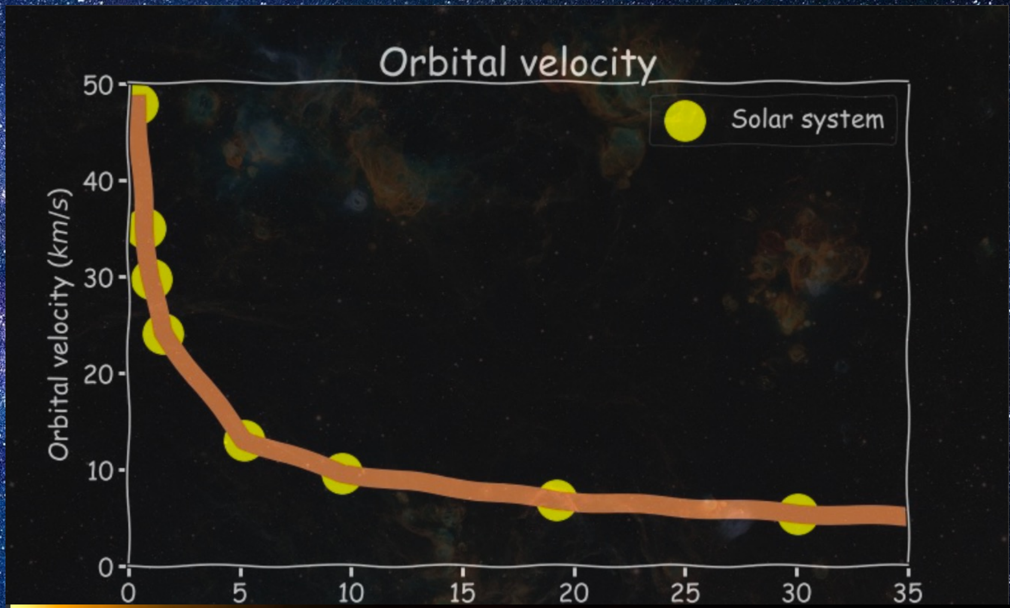

Our Galaxy
Top view
(simulated image)
Examples of
starbirth areas
Supermassive
black hole
Sagittarius A*
Arms
Bands of bright
stars and new
star formation
Central
bulge
Our solar system
Disk
Side view
Our solar
system
Central
bulge
Halo
Spherical cloud of stars
and globular clusters
Disk
Formed by the
spiral arms
The Milky Way
• a spiral galaxy
• 100,000 light-years across
• 100 billion stars
• 1 supermassive black hole
• contains our solar system
WebbTelescope.org

Rotation in galaxies



- Spiral galaxies spin like a plate or pizza, but different parts spin with different velocities.
- The bright areas are stars and gas which can be observed directly with telescopes
- Mass is spread out over a large area, very dense in the core, less dense further and further out.

Rotation curves – the solar system



Orbital velocity as a function of distance from centre.

Sun as central mass

What is a rotation curve?

Gravity is an attractive force which acts between all objects that have mass

The size of the force of gravity depends on

- The mass of each object
- The distance between the objects

The gravitational force keeps objects in orbit and determines how fast they move in their orbit.

What is a rotation curve?

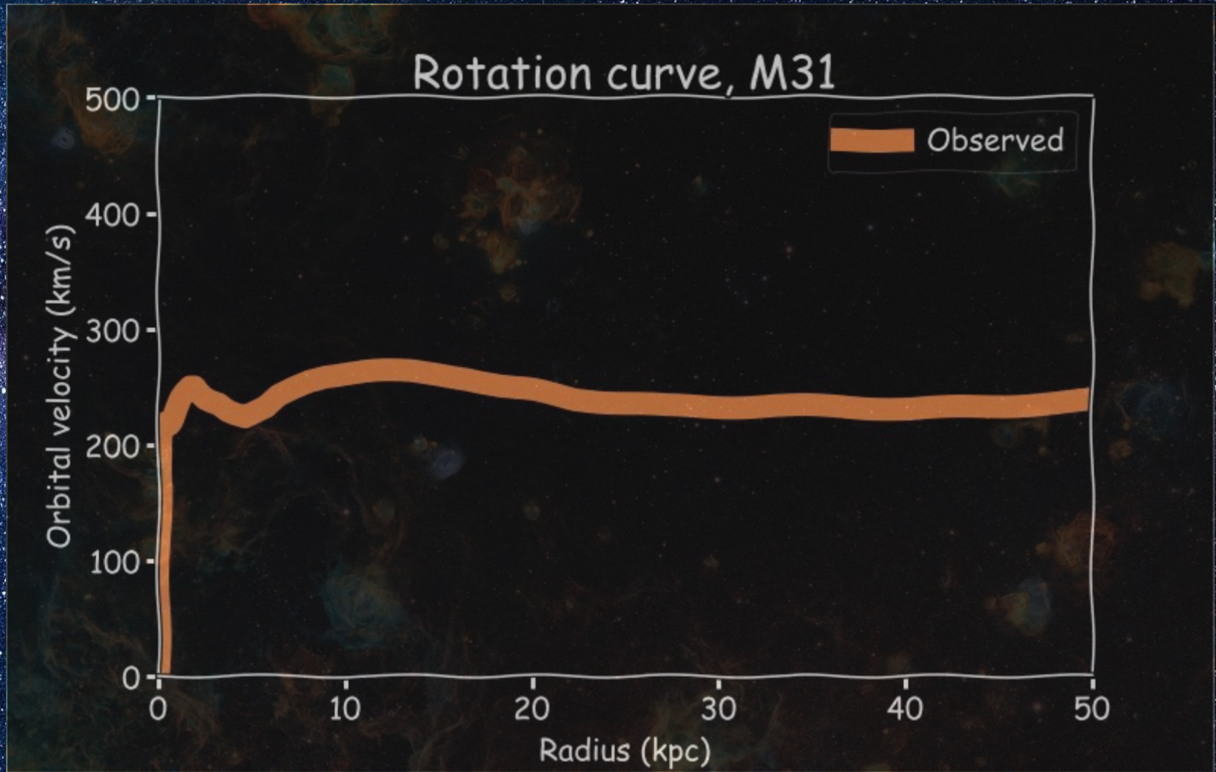
Orbital velocity as a function of distance from centre.

- M is the mass of the Sun
- R is the distance from the Sun
- G is the gravitational constant
- V is the speed of the planet

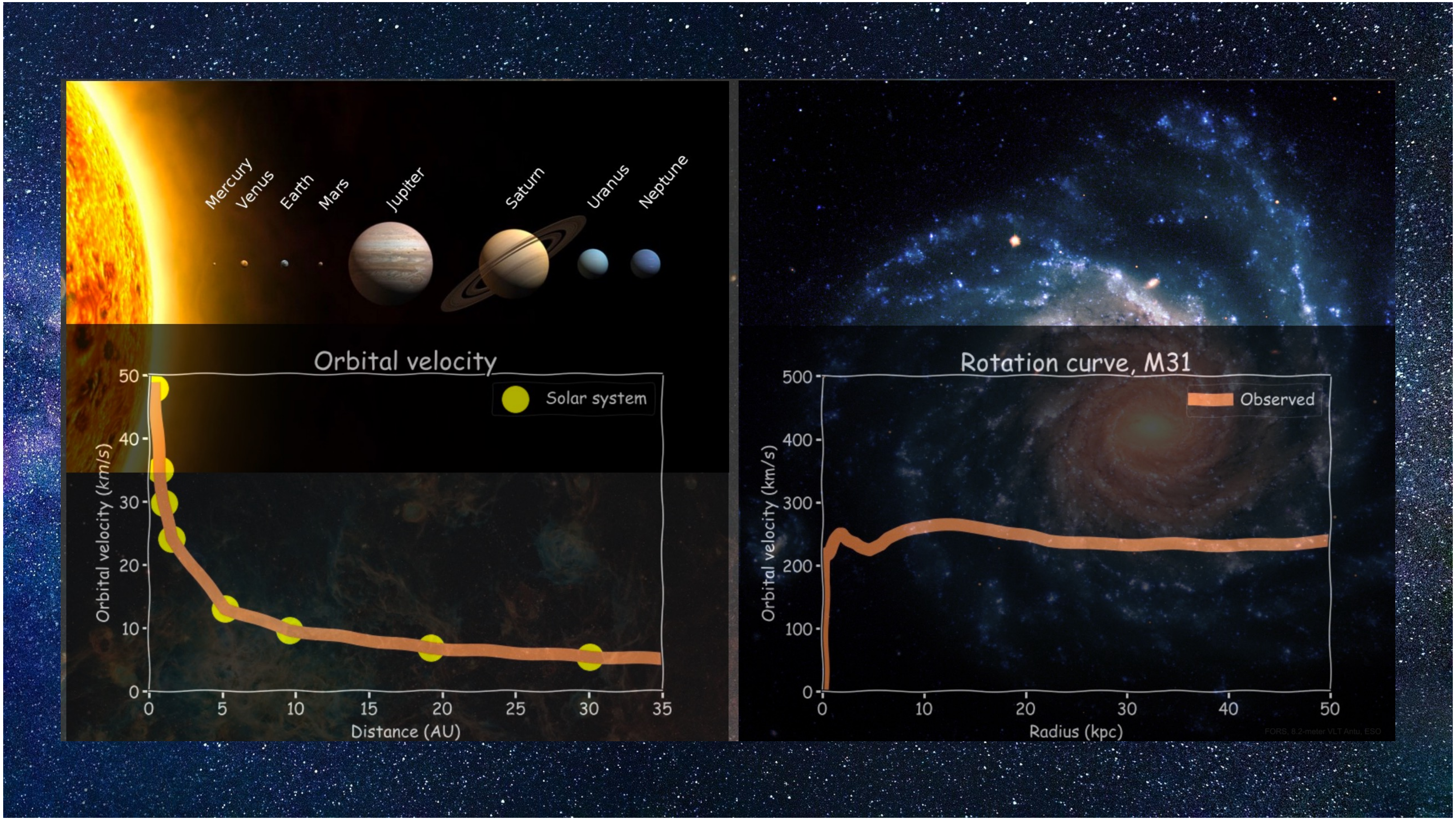
$$v^2 = \frac{GM}{r}$$

- Speed falls of with distance ($\sqrt{\frac{1}{r}}$)

Rotation curves of galaxies



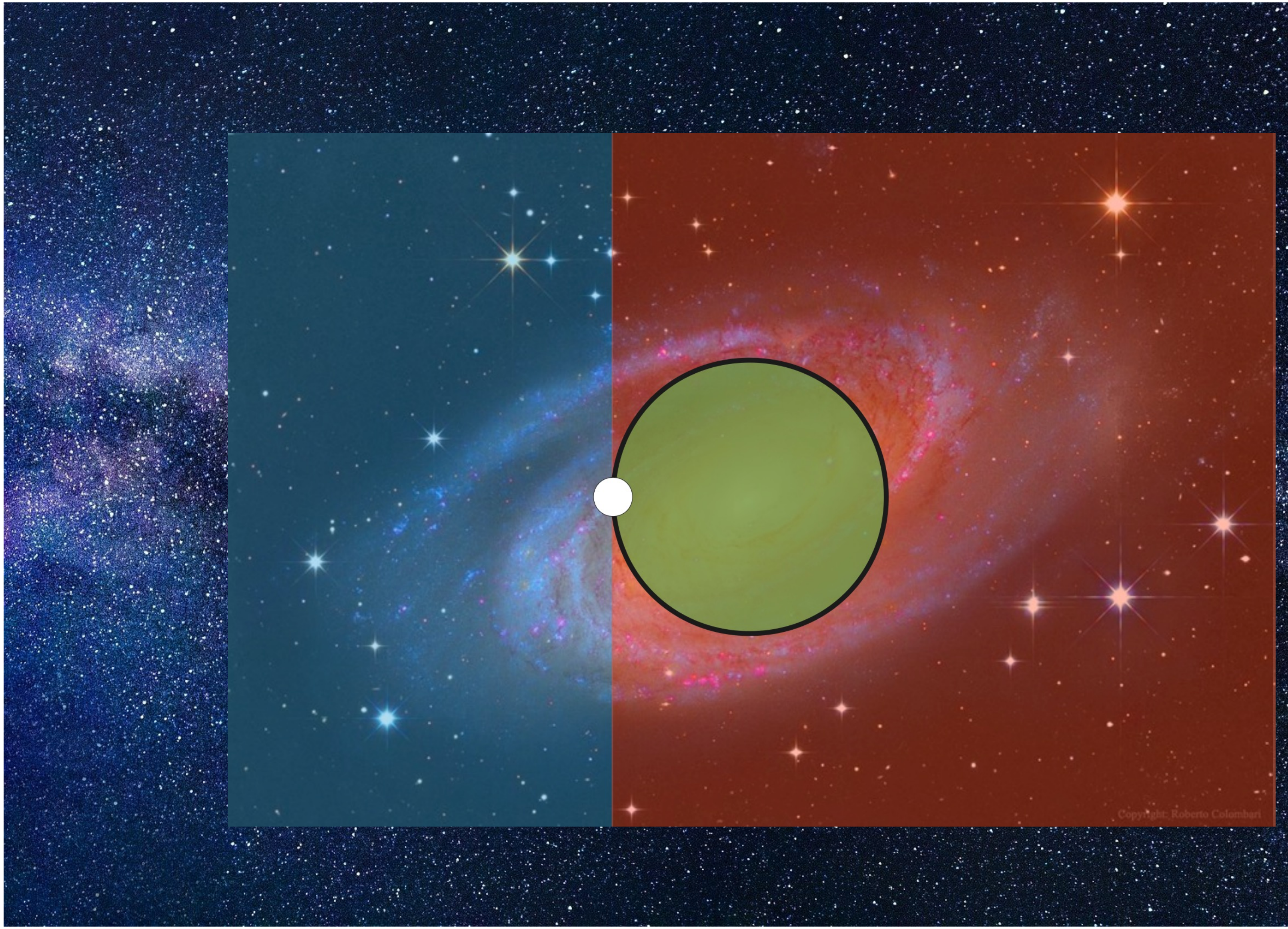
How is this different to a rotation curve for the solar system?


Mercury
Venus
Earth
Mars
Jupiter
Saturn
Uranus
Neptune
Orbital velocity
Solar system
Orbital velocity (km/s)
50
40
30
20
10
0
0
5
10
15
20
25
30
35
Distance (AU)
Rotation curve, M31
Observed
Orbital velocity (km/s)
500
400
300
200
100
0
0
10
20
30
40
50
Radius (kpc)
FORS, 8.2-meter VLT Antu, ESO

Rotation Curves of Galaxies

- The solar system had a single mass (the Sun or a star) at the centre.
- A galaxy is spread out over a large area. This raises questions:
    - The force that decides the orbit is the gravitational force. How does the extended mass distribution affect this?
    - What mass should we use in our equation? Can we even use the same equation?

The answer is surprisingly simple



$$V = \sqrt{\frac{GM(r)}{r}}$$

How to measure mass in galaxies

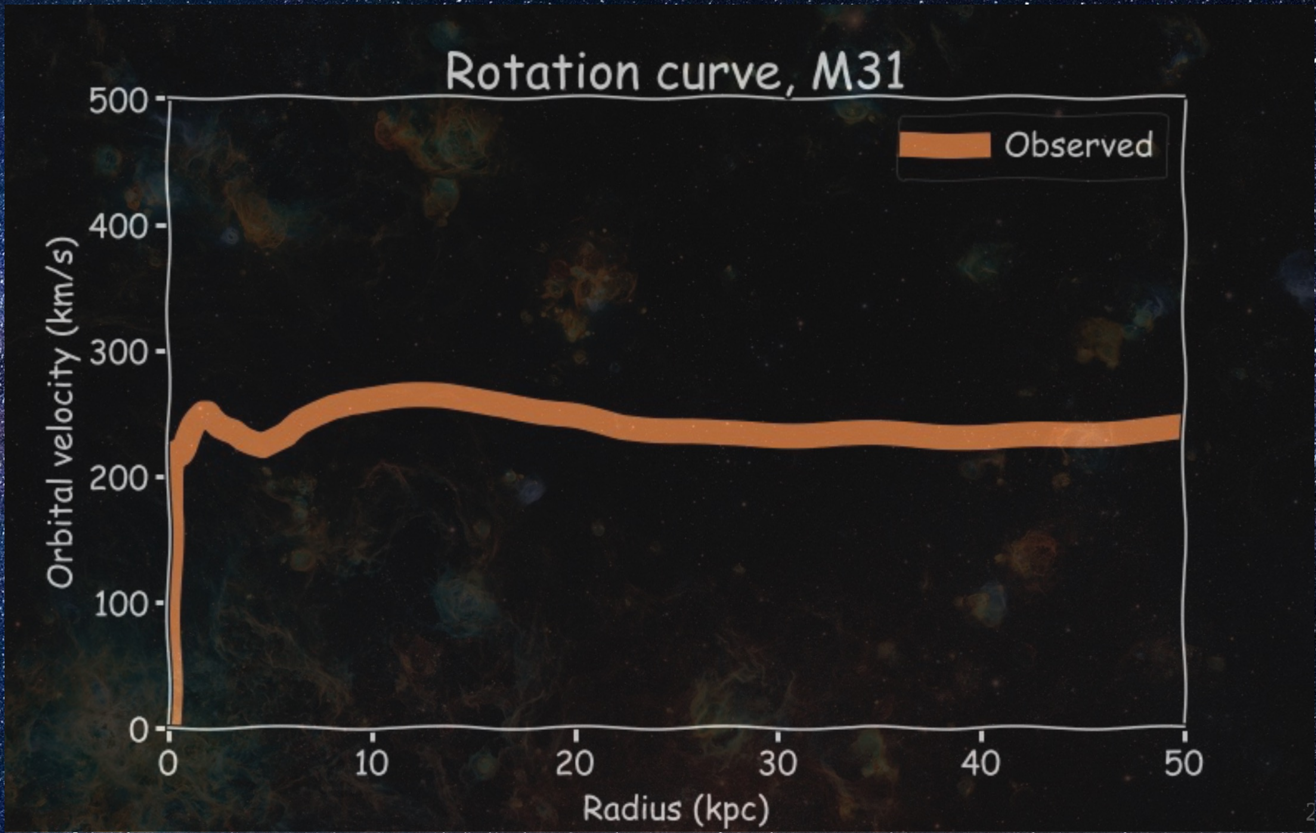
Astronomers can't measure mass directly... We have two methods:

1. Measuring the orbital velocity of stars and gas and use the orbital velocity equation to find the mass

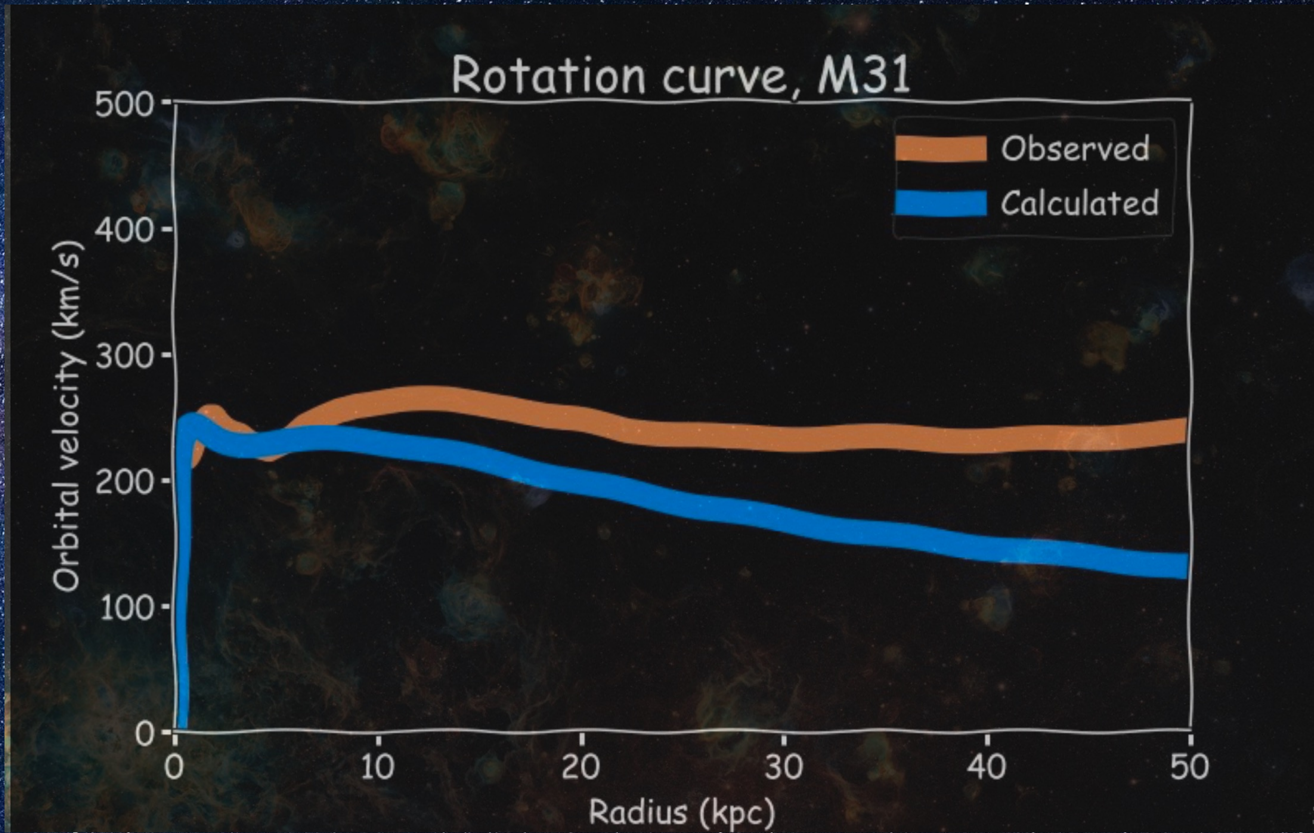
2. Measuring the light of the galaxy, which consists of only of light from stars and gas and since we know how bright one star is, we can infer the total mass (Mass-luminosity relation)

$$\boldsymbol{V} = \sqrt{\frac{\boldsymbol{GM(r)}}{\boldsymbol{r}}}$$

$$M \propto L^{\alpha}$$

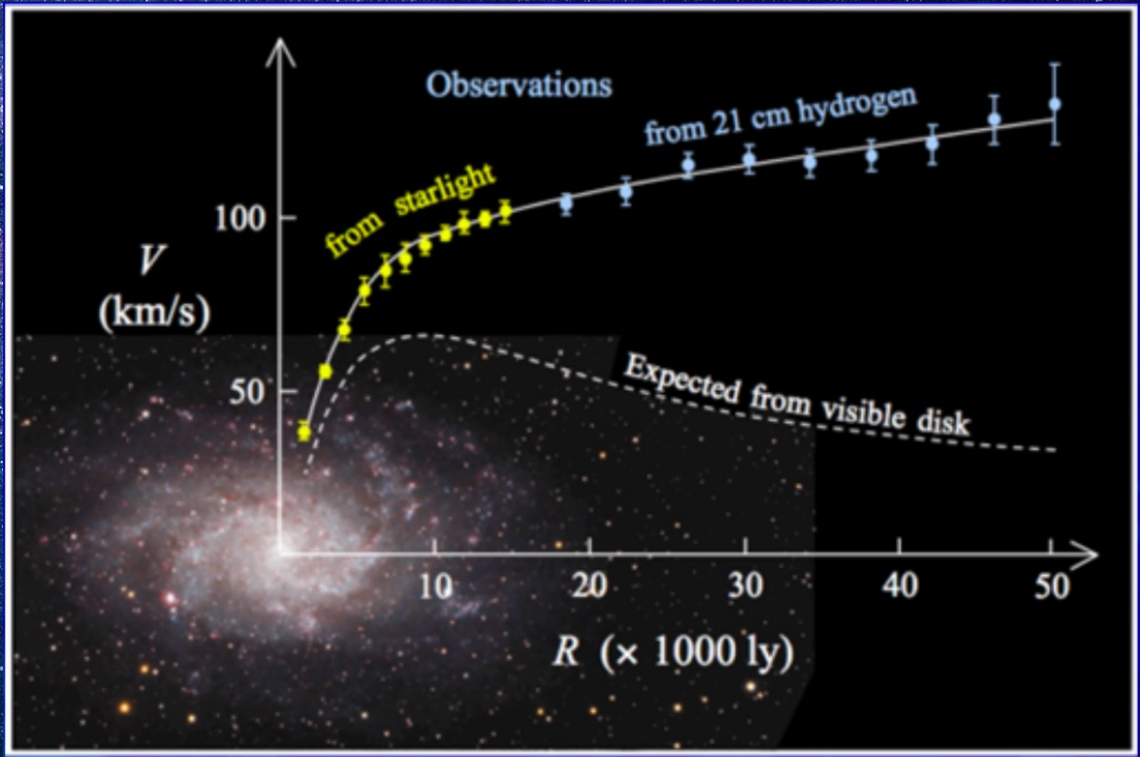


Rotation curve, M31
Observed
Orbital velocity (km/s)
500
400
300
200
100
0
0
10
20
30
40
50
Radius (kpc)



Rotation curve, M31
Observed
Calculated
Orbital velocity (km/s)
500
400
300
200
100
0
0
10
20
30
40
50
Radius (kpc)

Where is the missing mass?



Stars on the edge of the Andromeda galaxy are moving as fast as the galaxies at the centre!

Optical data from Rubin and Ford (1970) plus outer 21 cm data

What is dark matter

- We are made of ‘baryonic’ matter
- Refer to dark matter as ‘non-baryonic’ matter

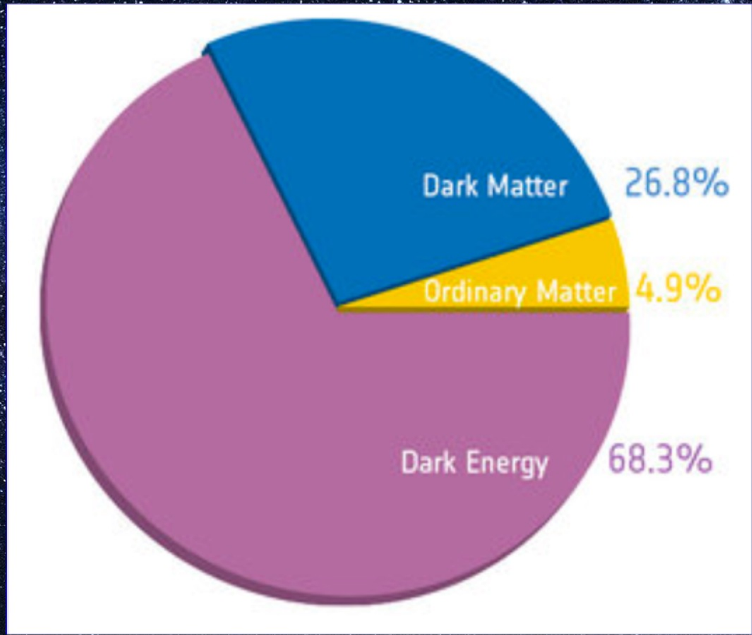
- Both take up space and hold mass

- Dark matter interacts with baryonic matter through gravity
- Dark matter does not interact with light

Lambda-CDM

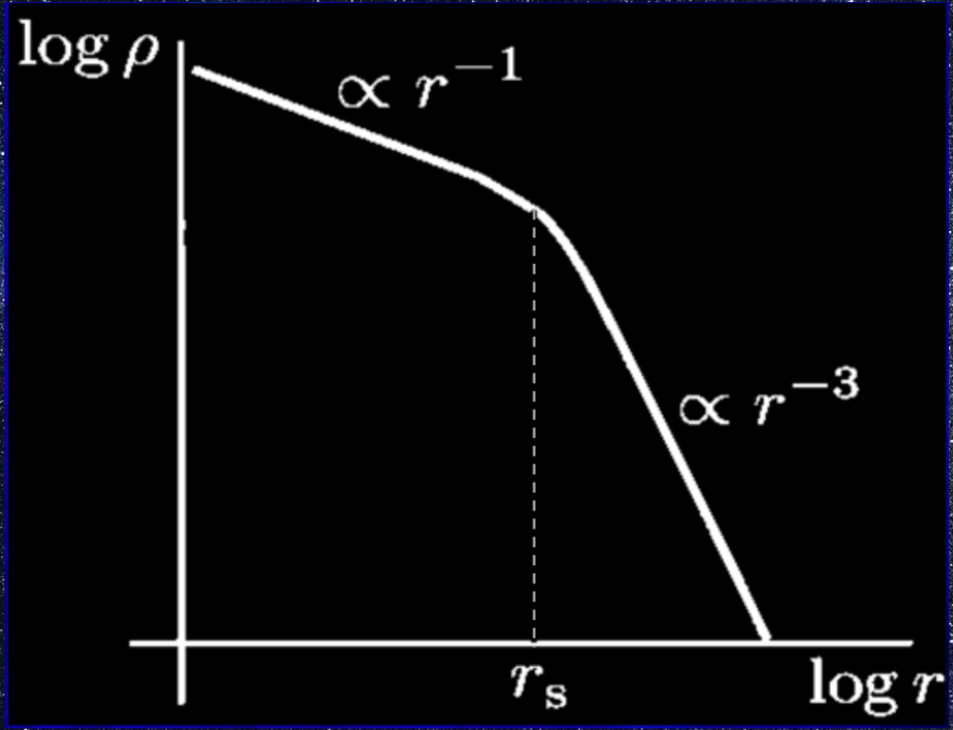
•Cold dark matter is now part of the *Standard Model of Cosmology* in addition to Dark Energy.

•Everything we can see around us and everything we can see in space makes up just 4.9% of the Universe!



Dark matter Mass

- N-body simulations study dark matter structure in CDM cosmology
- Distribution of dark matter follows the distribution of galaxies
- Find a universal density profile fits all DM structures (halos)



Navarro - Frenk - White Profile (1997)

We can describe this distribution with the following density and mass profiles:

$$\rho(r) = \frac{\rho_0}{\frac{r}{r_s}\left(1 + \frac{r}{r_s}\right)^2}$$

$$M = \int_0^{r_{max}} 4\pi r^2 \rho(r) dr$$

r is the radius
r_s is the scale radius

$\rho(r)$ is the density at a radius, r
ρ_0 *is the characteristic density*

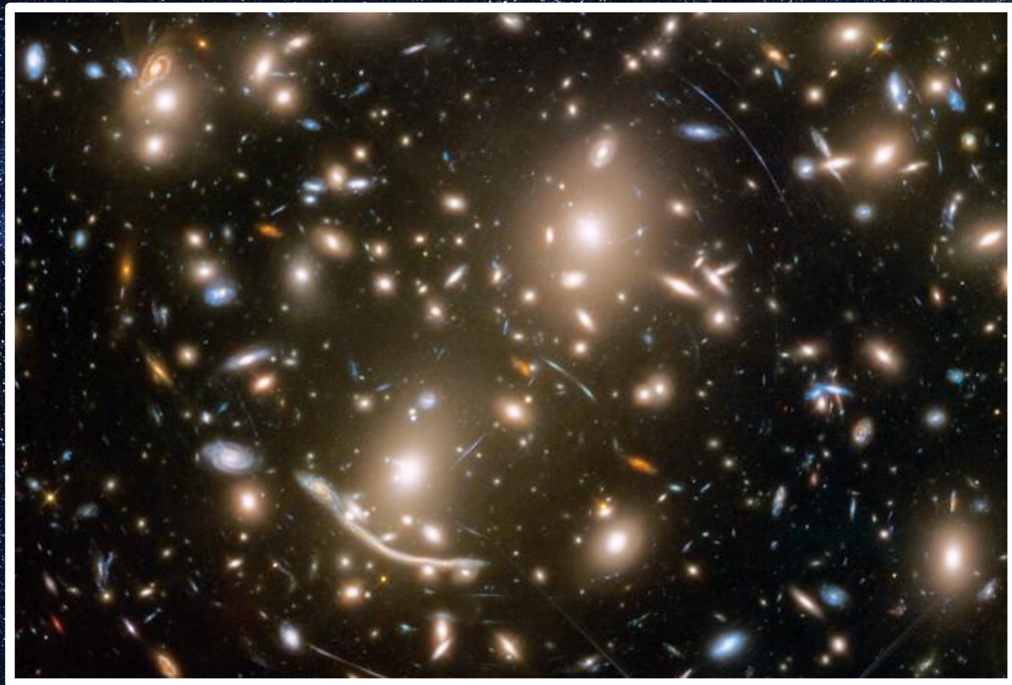
ρ_0 and r_s are parameters which vary from halo to halo

Other evidence for dark matter

Gravitational Lensing

- Stars and gas in galaxy clusters only make up about 5% of the total mass
- 80% of the mass in a cluster is in the form of dark matter,
- This mass provides enough gravity to bend the path of light passing by which magnifies galaxies that would ordinarily be too faint for us to see.
- Lensing lets astronomers map where the mass in a galaxy cluster is located.

We will talk about the remaining 15% later!



Credit: NASA, ESA, and J. Lotz and the HFF Team (STScI)

The Bullet Cluster

- Collision of two large clusters of galaxies
- Hot gas detected by Chandra in X-rays shows two pink clumps – normal matter
- Blue shows where most of the mass is (determined using gravitational lensing)
- Most of the matter in the clusters (blue) is separate from the normal matter (pink)


End of part 1!