# Measuring the mass of galaxies

Luminous matter in a galaxy:

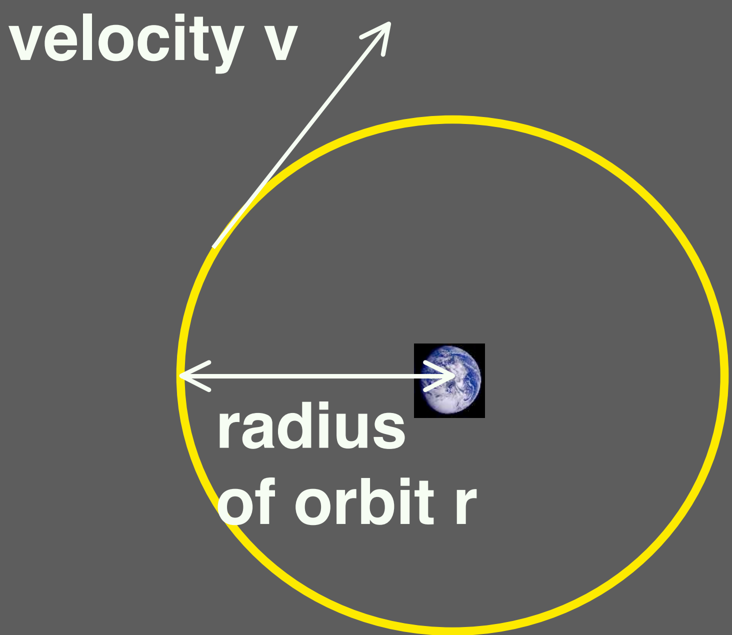
- stars (of different masses)
- gas (mostly hydrogen)

Can detect these directly using optical and radio telescopes - get an estimate of how much mass they contain

BUT… also non-luminous matter which we can't see directly. Example that we know exists - black holes that formed from stellar collapse.

# How can we measure mass we can't see?

**If we know the mass M of a body, can work out how fast we need to go to orbit at distance r:**




For a circular orbit:

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

…where G is called the gravitational constant. Numerically:

$$G = 6.67 \times 10^{-11}\ \mathrm{m}^3/(\mathrm{kg} \cdot \mathrm{s}^2)$$

**Recall: used this formula (lecture #13) to find mass of black hole at Galactic Center**

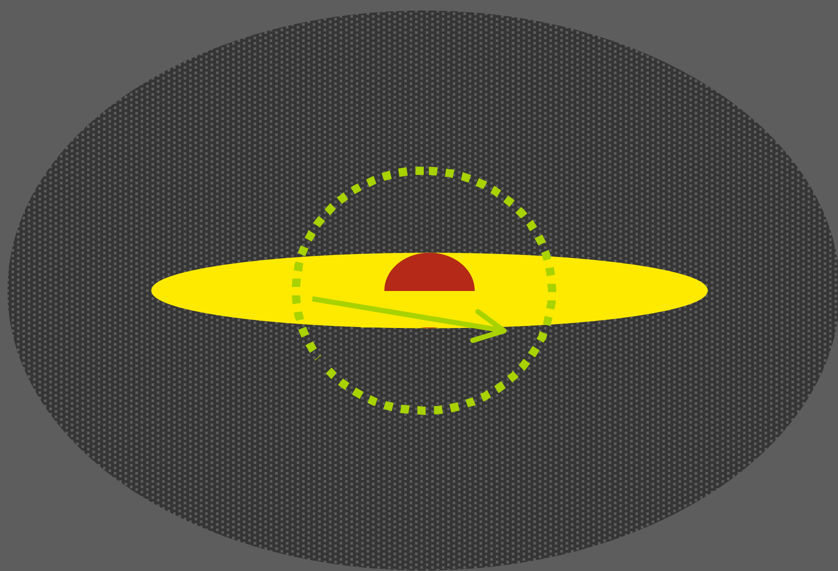
# Measuring the mass of the Milky Way

**Measure the velocity v of a star orbiting on a circular orbit at distance r from the center of the Milky Way. Same formula:**

$$M = \frac{rv^2}{G}$$

**…gives the mass M <u>interior</u> to the orbit of the star**

**Why only the interior mass? Gravitational forces from mass *outside* cancel out (exactly if the mass distribution is spherically symmetric).**



**e.g. the Sun orbits around the Galactic center at:**

**r = 2.6 x $10^{20}$ m**
**v = 220 km / s**

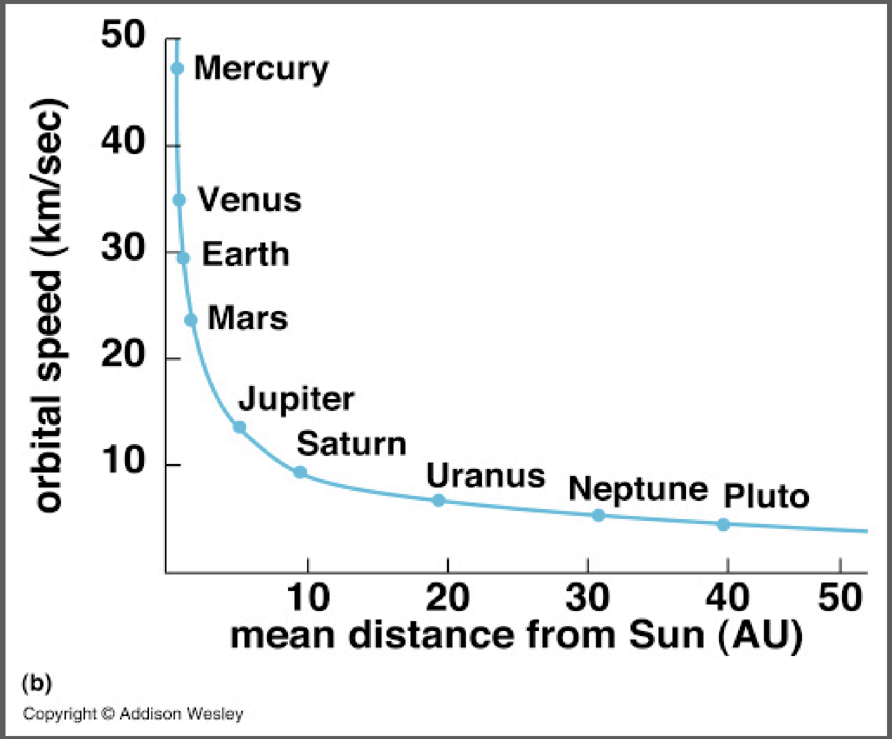
**Mass *inside* the orbit of the Sun is:**

$$M = \frac{2.6 \times 10^{20}\ \text{m} \times \left(2.2 \times 10^{5}\ \text{m/s}\right)^{2}}{6.67 \times 10^{-11}\ \text{m}^{3} / \left(\text{kg s}^{2}\right)} = 2 \times 10^{41}\ \text{kg}$$

**…which is about 100 billion Solar masses. This number is not unreasonable given the masses of known stars and gas in the inner regions of the Milky Way.**

# Rotation curve for gravity

- Example: Solar System
- Almost ALL the mass is in the center (Sun)
- Gravity is weaker farther out
- Rotation curve falls



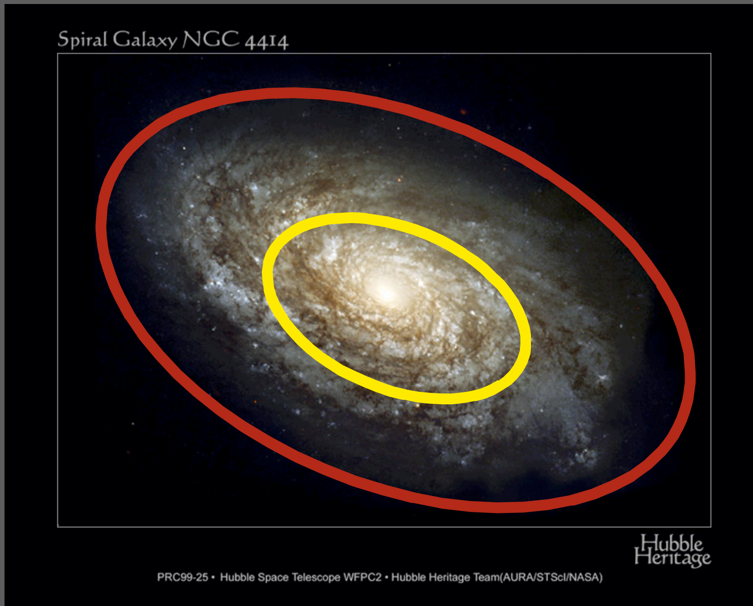
# A flat rotation curve

**Suppose we measure the velocities of stars at *different* radii from the center of the Galaxy**


**Each star allows us to calculate the mass *interior* to the orbit of that particular star**

**If we observe many stars (or gas clouds), can map out the <u>rotation curve</u> of the galaxy**

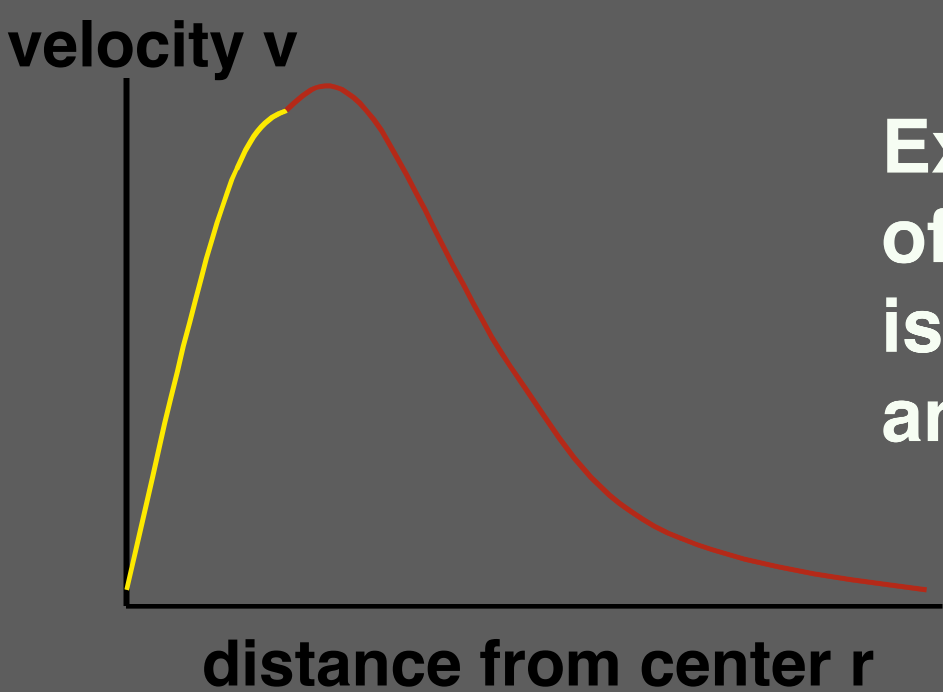
**Measures the mass distribution of the Milky Way**




## What do we expect?

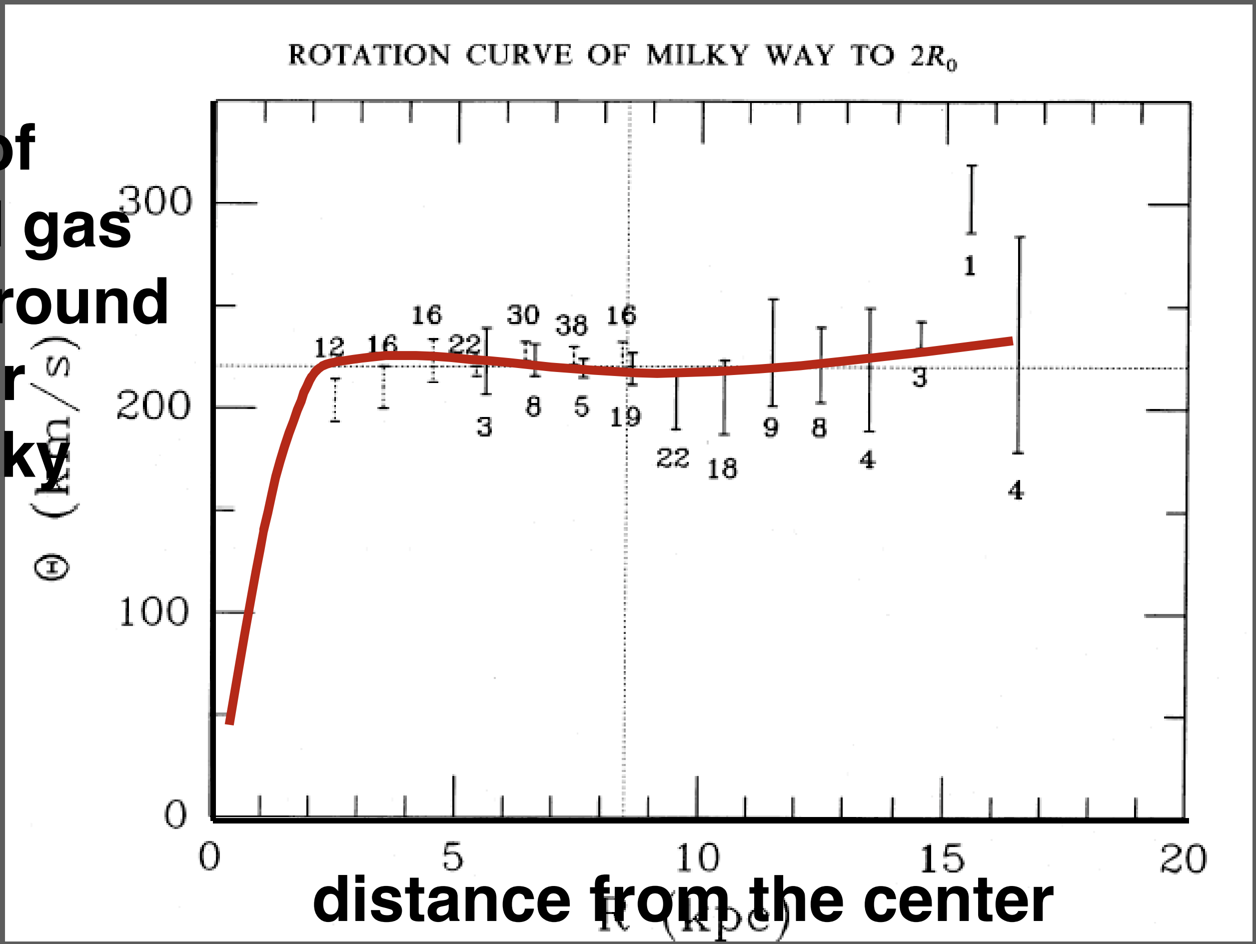
**Inner galaxy: enclosed mass rises, so does the velocity**

**Beyond the optical edge of the galaxy: no stars, so no more mass, velocity falls**




**Expected rotation curve of a galaxy if all the mass is due to observed stars and gas**

# Rotation curve of the Milky Way

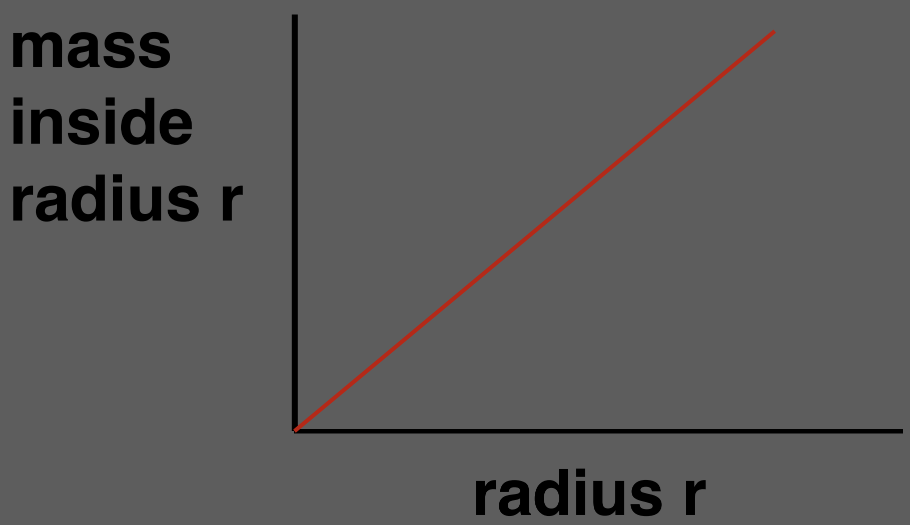



**Instead, observe a flat rotation curve - velocity stays the same as we move further away from the center!**

What does a flat rotation curve imply? Go back to the formula:

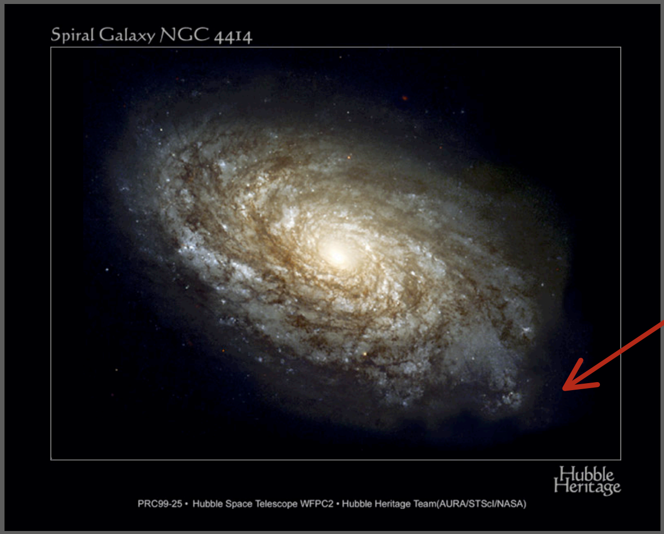
$$M = \frac{rv^2}{G}$$

If the velocity is constant with increasing radius, then the mass is proportional to radius:




More and more mass as we go to larger and larger distances from the center

# Dark matter




Flat rotation curve shows there is more matter out <u>beyond</u> the apparent edge of spiral galaxies

**For the Milky Way, the total mass exceeds the visible mass (stars + gas) by about a factor of 10**

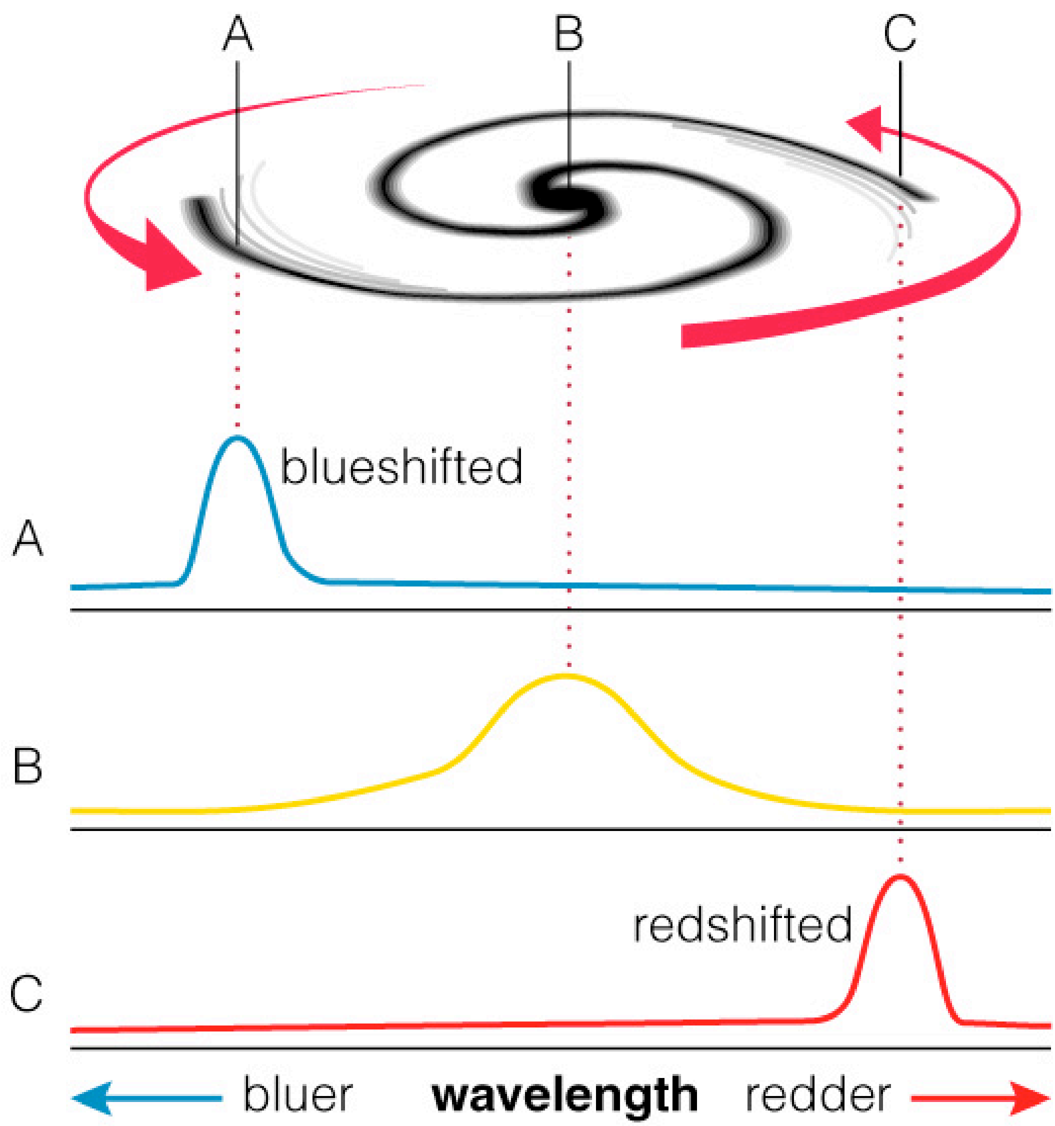
`Extra' mass is called **DARK MATTER**:

- infer existence from gravitational effect on ordinary stars and gas
- cannot be luminous or we would see it

# Rotation curves of other spiral galaxies

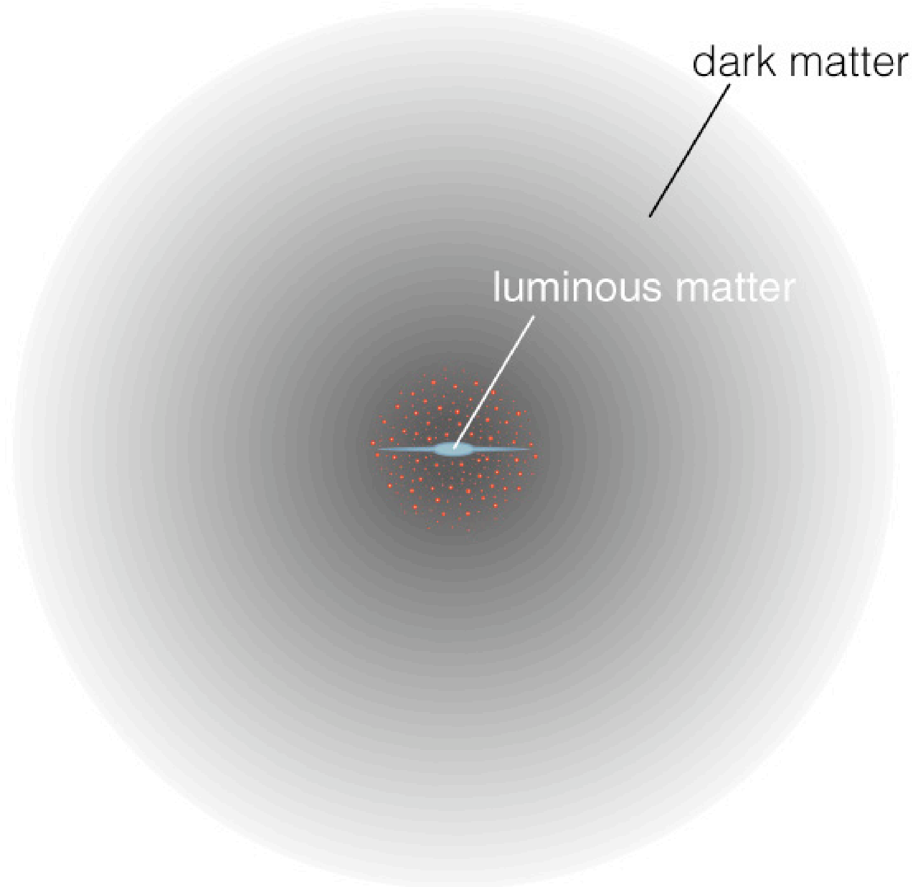
Can also measure the rotation curve of other spiral galaxies

Use the Doppler shift of spectral lines emitted by hydrogen gas to infer velocity of rotation - same idea as for measuring redshifts


A
B
C
blueshifted
A
B
redshifted
C
bluer
wavelength
redder

**Dark matter is more extended than the luminous matter**

**Picture of the Galaxy - very large massive halo of dark matter**






**Relatively insignificant sprinkling of ordinary stars and gas in the middle**

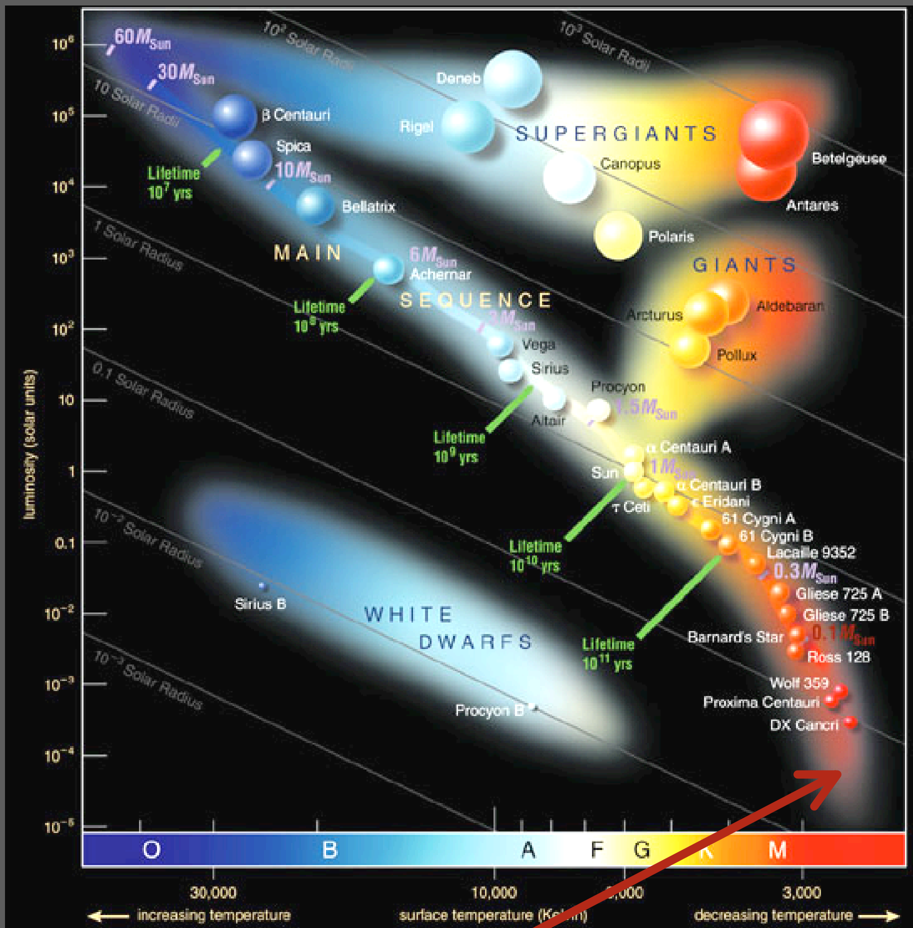
## Does dark matter really exist?

**Flat rotation curves could be explained by:**

- **existence of dark matter**
- **perhaps gravity does not behave in the same way as in the Solar System on very large scales?**

**Many independent ways to test how gravity behaves… so most astronomers confident dark matter exists even though we don't see it directly**

# Nature of dark matter is one of the most important mysteries in astronomy. Many candidates:




## 1) <u>Very low mass stars</u>

Very low mass stars or brown dwarfs emit very little light for their mass

Population of stars that *only* contained low mass stars would be hard to see

Dim, red stars and brown dwarfs (failed stars)

## 2) Very cold clouds of hydrogen gas

Cold clouds (~10K) of hydrogen molecules emit very little radiation - would be hard to detect unless they formed stars

## 3) White dwarfs or neutron stars

Perhaps the first stars in the Galaxy were all massive - they died long ago leaving only stellar remnants which are now cool and hard to see?

**All examples of BARYONIC DARK MATTER: dark matter made of the same stuff (neutrons and protons) as ordinary gas and stars**

There are also more exotic possibilities:

<u>4) Black holes</u> - either formed from the collapse of very massive stars, or primordial (formed in the early Universe)

<u>5) Unknown elementary particles</u> - stable particles which have not yet been discovered in lab experiments on Earth (e.g. because they are too massive)

**Called NON-BARYONIC DARK MATTER**

Most astronomers reckon unknown particles make up most of the dark matter

## Dark matter on Earth?

In the Solar System, the density of ordinary matter *vastly* exceeds that of dark matter.

BUT, dark matter particles should be present, pass freely through the Earth, Sun, us…

Very rarely, the dark matter might collide with ordinary nuclei - this might be detectable

# Dark matter on Earth?

Not seen, yet

Numerous experiments in deep mines underway, hoping to make the first direct detection of the dark matter