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- **Stellar component of the Milky way**
  - Disk, Bulge, stellar halo
  - Star motion in the galaxy
  - Stellar population
- **Milky Way formation**
  - Halo Stars first
  - Disk Stars

Galaxies and Modern Cosmology

Chapter 20

Questions of the day

- What patterns do we find among the properties of the galaxies?
- Which are the different types of galaxies?

Types of galaxies

- Three major types
  - Spiral/disk galaxies
  - Elliptical galaxies
    - and “Lenticular” galaxies: transition between disk and elliptical types
  - Irregular galaxies

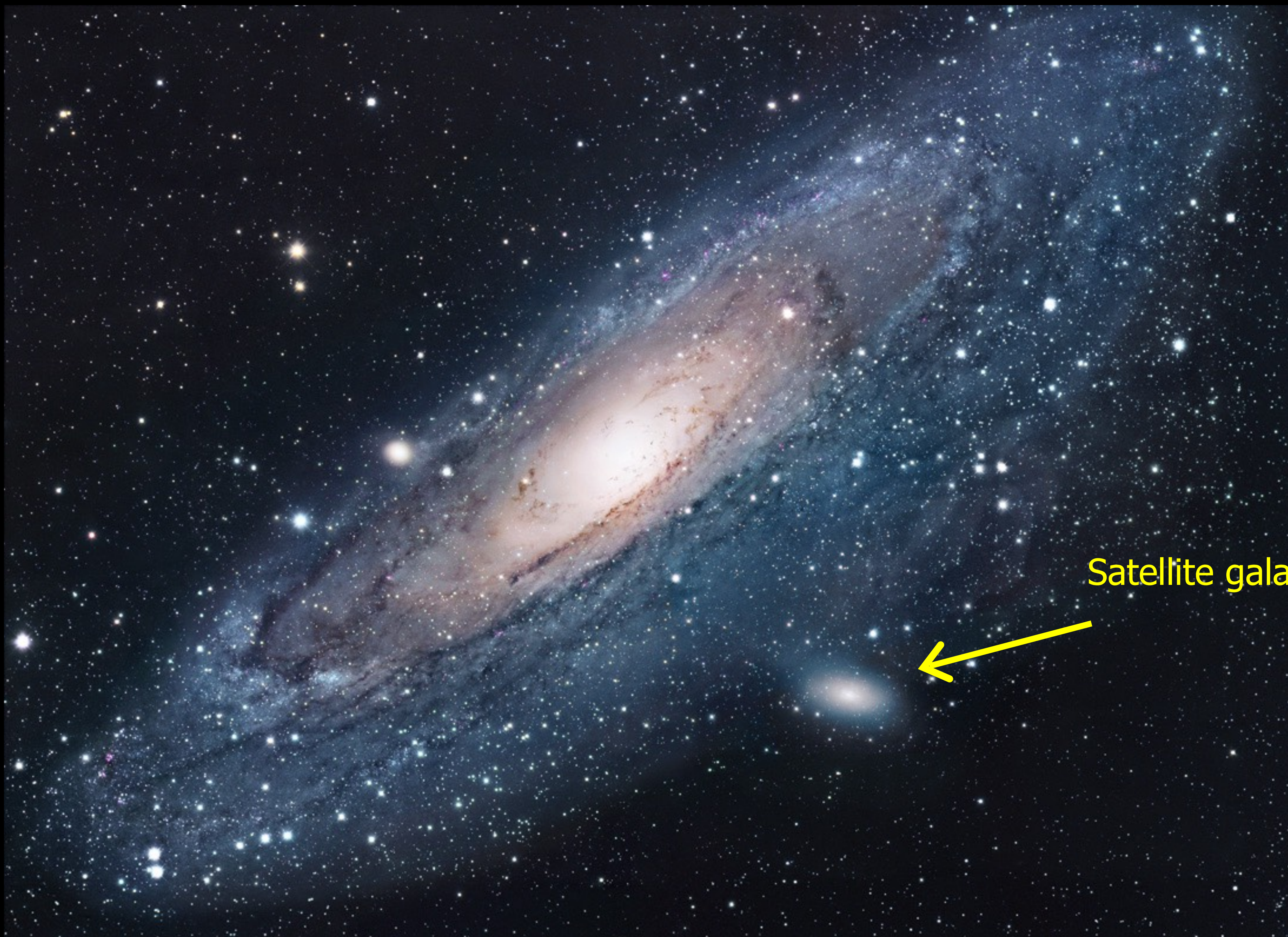
Spiral/disk Galaxies

- Flat disk (often with a bulge at center), like the Milky Way
- Size of bulge and prominence of spiral pattern varies
- Disk contains **interstellar medium** (ISM) of cool gas and dust

Shape depends on orientation

Shape depends on orientation

Andromeda (M31) is also a spiral galaxy



Classification of spirals

1. Lumpiness of the spiral arms (i.e. degree of resolution in knots, HII regions, etc)
2. “Bulge-to-Disk Ratio”
3. How tightly the spiral arms are wound

Sa Sb Sc

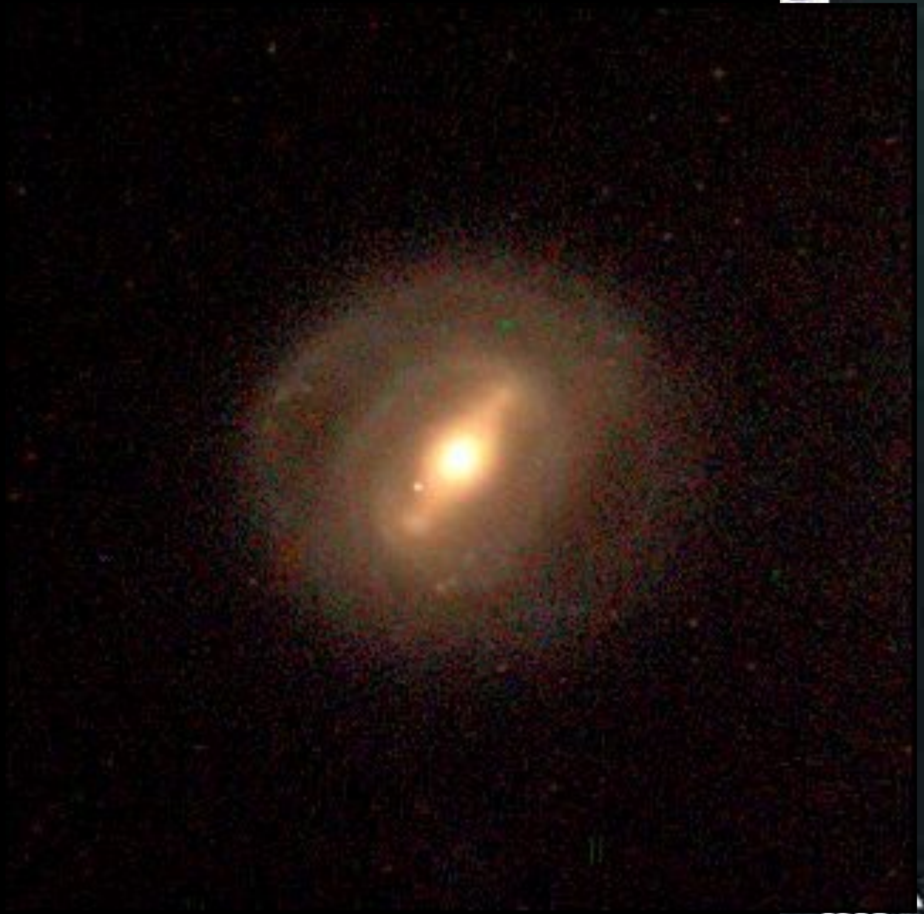
Note: These are not exact trends. Galaxies are much more complex than stars. Features are often contradictory.

Classification of normal spirals: S_

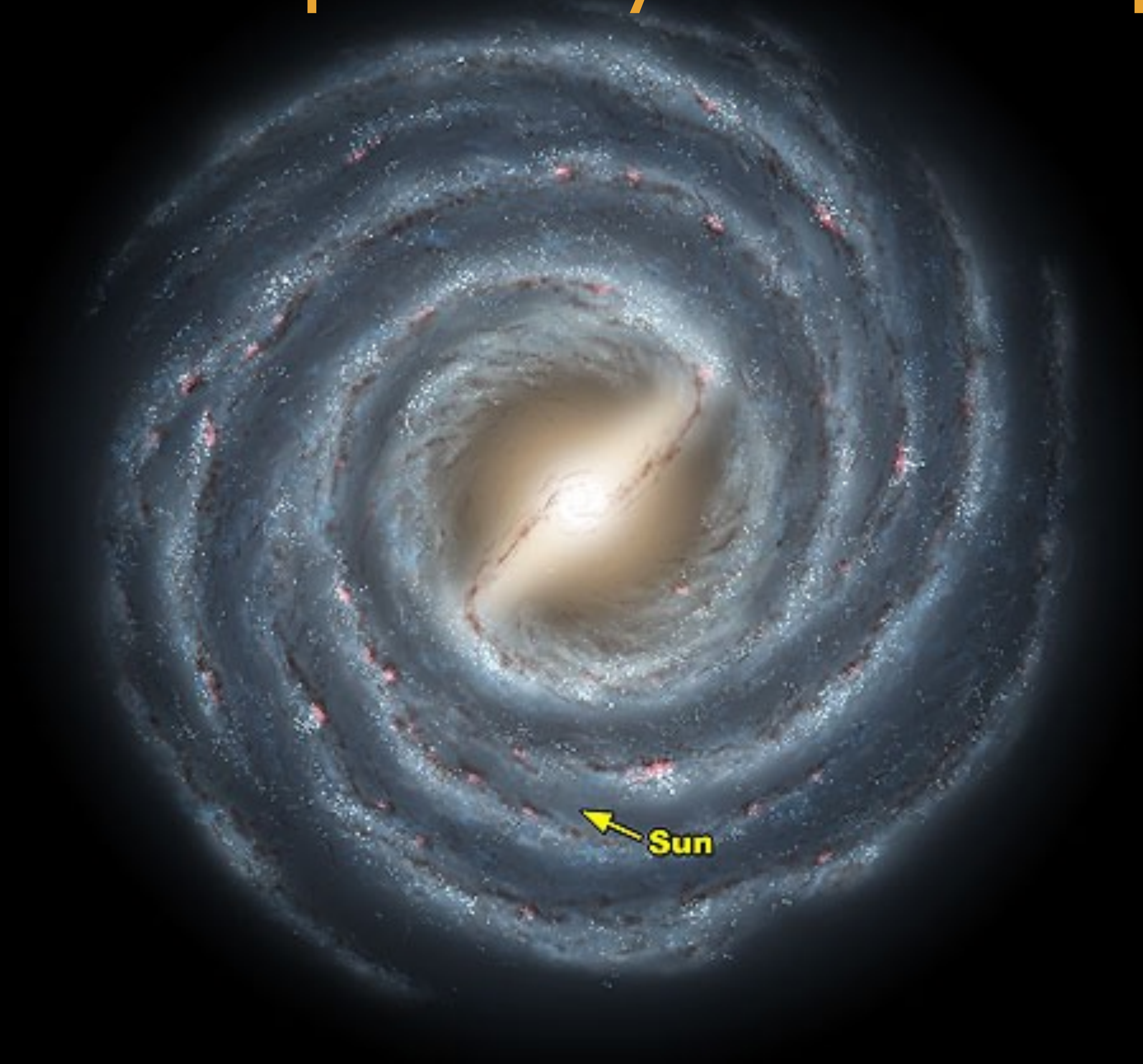
- **Sa**: Tightly wound spiral arms, small lumps, big bulge
- **Sb**: Smaller bulge, looser and lumpier arms (like M31)
- **Sc**: Lumpy arms, open arms, small bulge
- **Sd**: Lumpy spiral arms, but no (or miniscule) bulge

Many spiral galaxies have “bars” – linear arrangements of stars

We classify these as SB_



The MW is probably a barred spiral



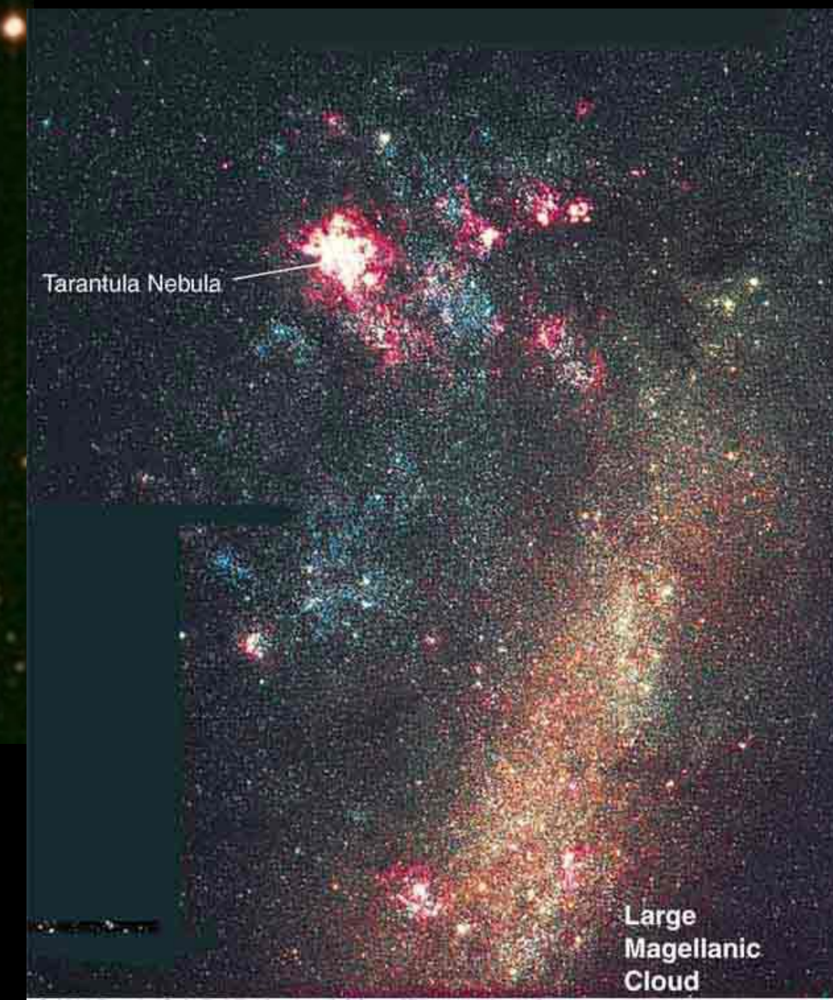
Elliptical galaxies

- All bulge (spheroid); no disk or spiral arms
- Little gas
- Probably old!

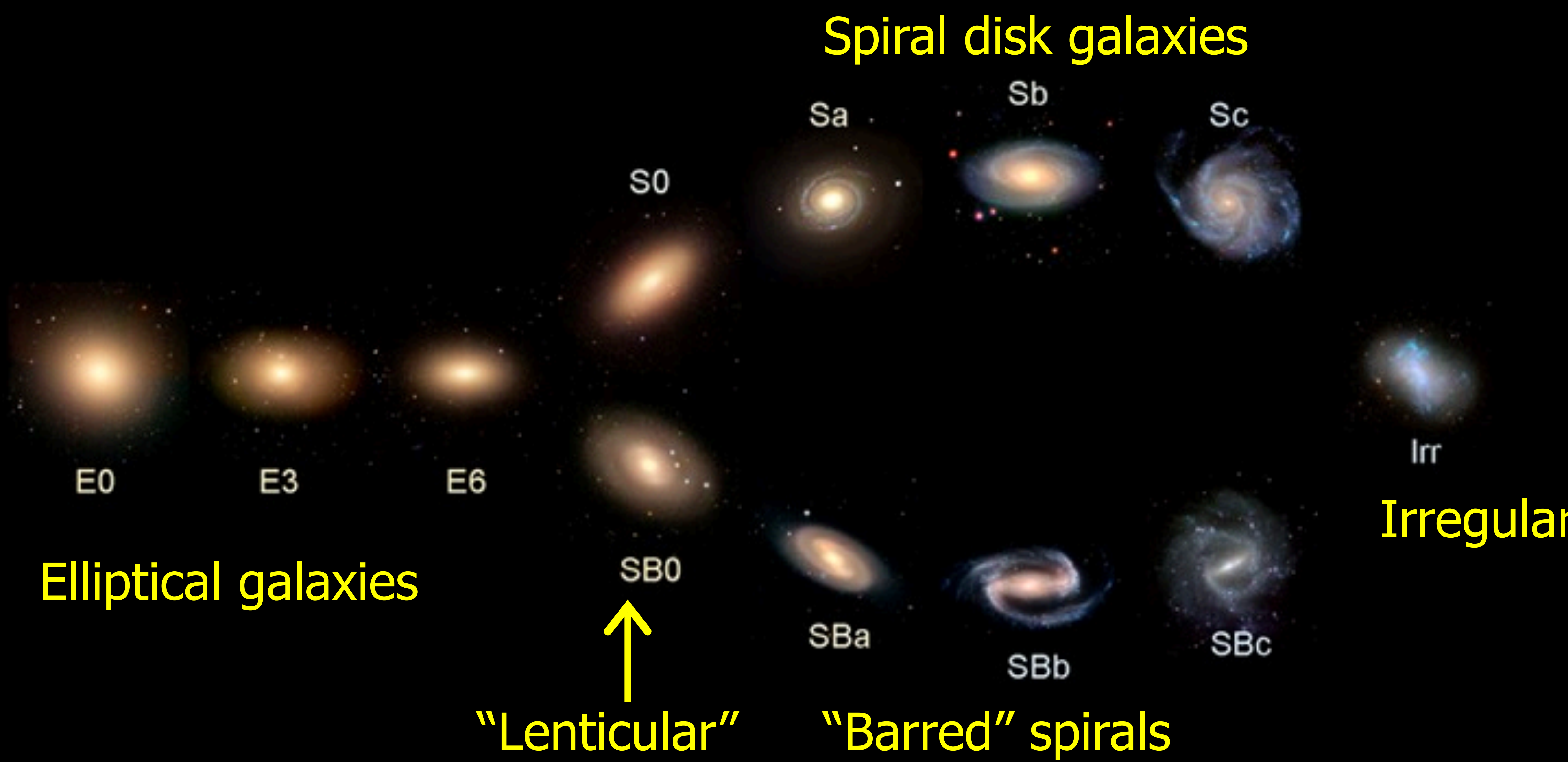
Evolved to the point where no gas is left for making new stars!

Irregular galaxies



- Low mass
- No clear disk, spiral pattern, or nucleus
- Chaotic appearance
- Often have lots of star formation
- Often rich in gas
- Most common type of galaxy

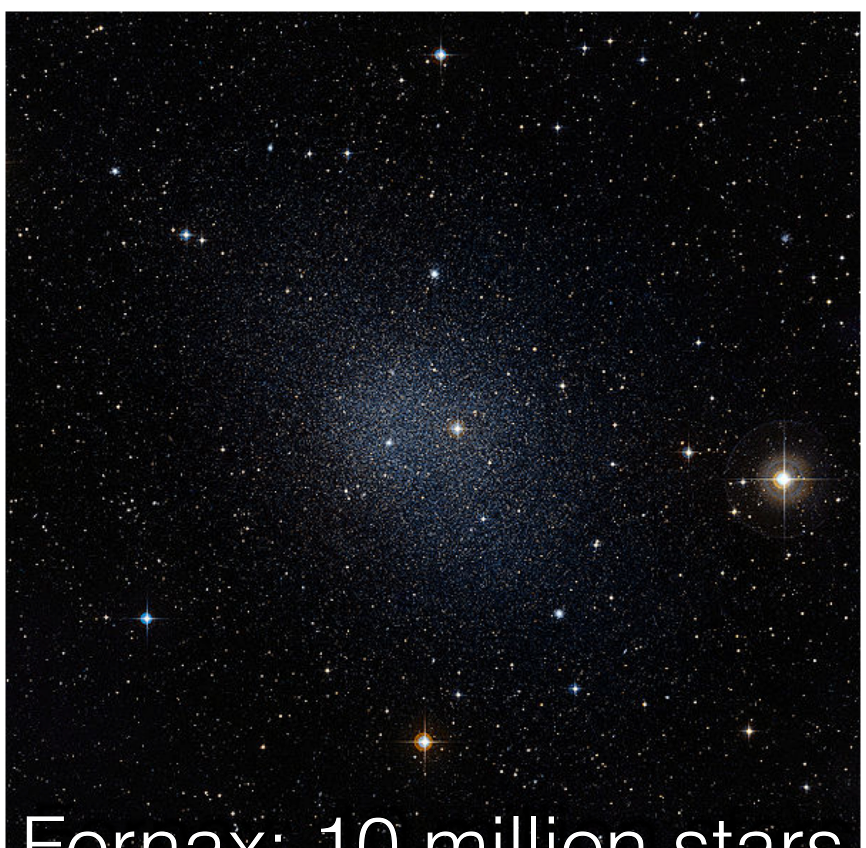
Galaxy Classes



Dwarf galaxies — small, very common, and hard to find

MW-like galaxy: 100 billion stars

Magellanic Clouds: 1 billion



Fornax: 10 million stars

Recap: what have we learned?

- **What patterns do we find among galaxies?**
  - There are three main types of galaxies:
    - Spiral (disk)
    - Elliptical
    - Irregular
  - Gas, dust, and young stars are much more abundant in spiral and irregular galaxies

Dark Matter
(in the Milky Way and other galaxies)

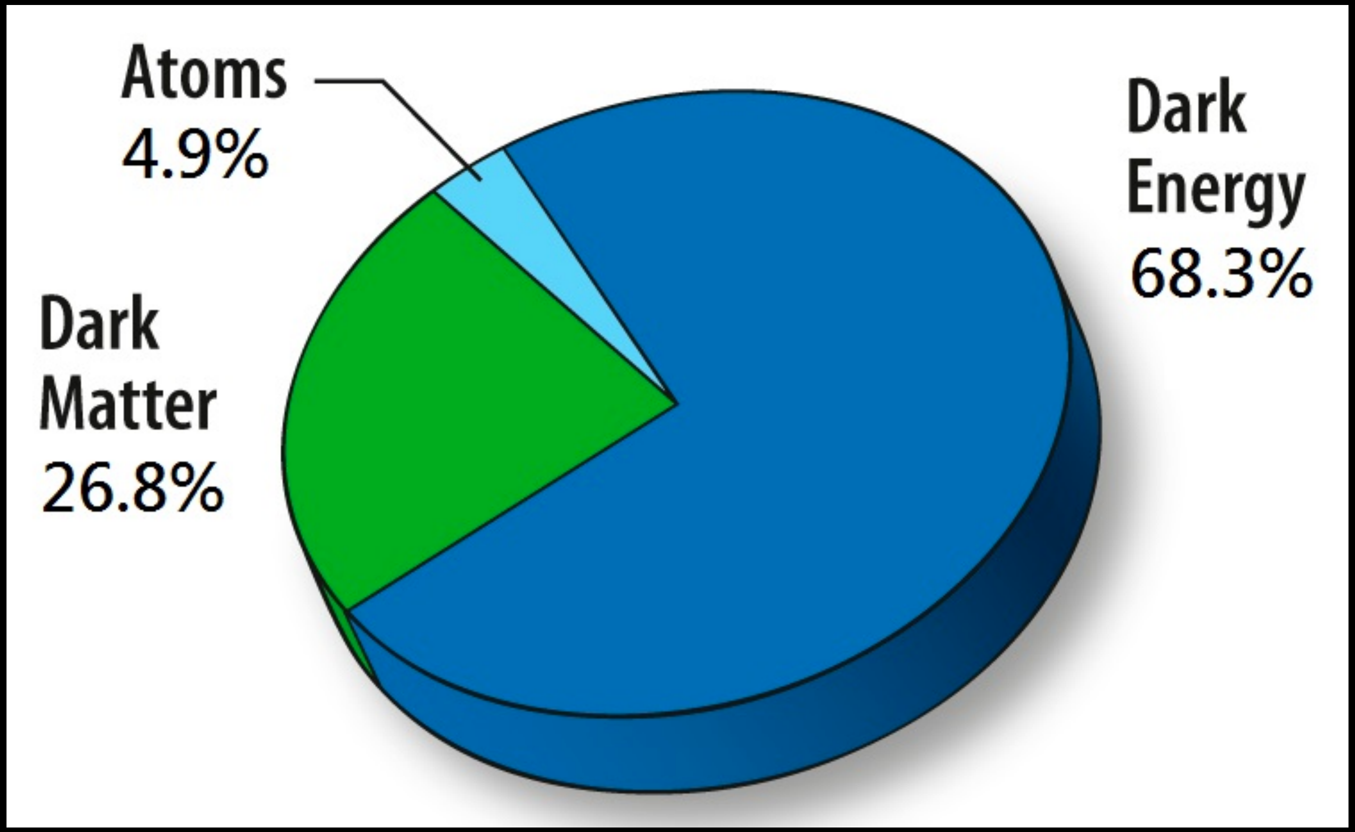
Chapter 23

Further questions of the day

- What do we mean by "Dark Matter"?
- What is the evidence for dark matter in the Milky Way, and in other galaxies?
- What is the evidence for dark matter in clusters of galaxies?

What is "Dark Matter"?

- **Dark Matter** is the name given to a form of **mass** that does not interact with light, but can be detected by its gravitational effects
- We think that ~80% of the total mass in the universe is some form of dark matter
  - The other ~20% is "normal" matter (mostly atoms)
- We know **where** the dark matter is, based on its gravity… but we do not know **what** it is!



Atoms: chapter 5
Dark matter: chapter 23
Dark energy: later! (also in chapter 23)

How we measure the mass of a galaxy?

How we measure the mass of a galaxy?

$$P^2 = \frac{4\pi^2}{G\left(M_1 + M_2\right)} a^3$$

Newton version of Kepler law

$$P^2 \approx \frac{4\pi^2}{GM_1} a^3$$

if M_1 is much bigger than M_2

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If you measure the radial velocity of a star in a galaxy and you know the orbit of the star ……

you can measure the mass of the galaxy within the star orbit!!

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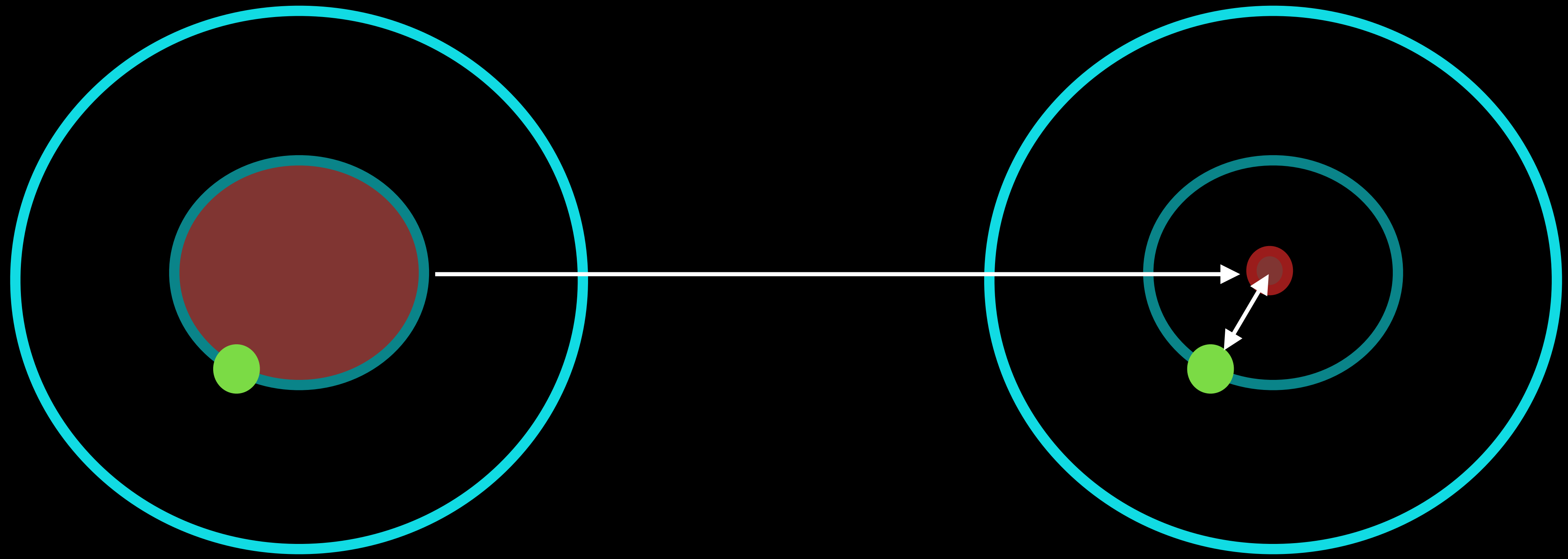

if you have a mass distribution on a sphere, you can consider all the **mass concentrated in its center of mass**

.... but why only within the star orbit?

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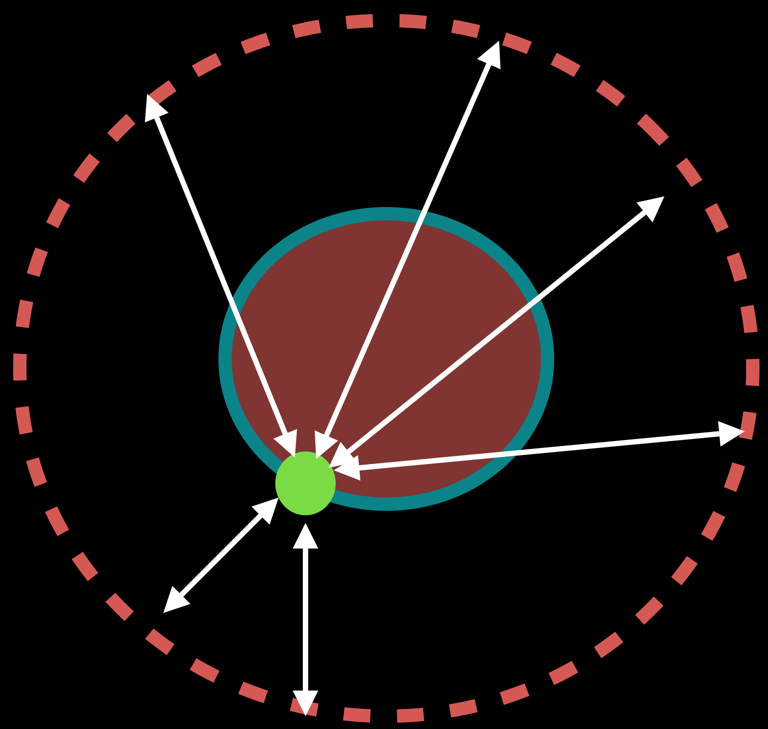
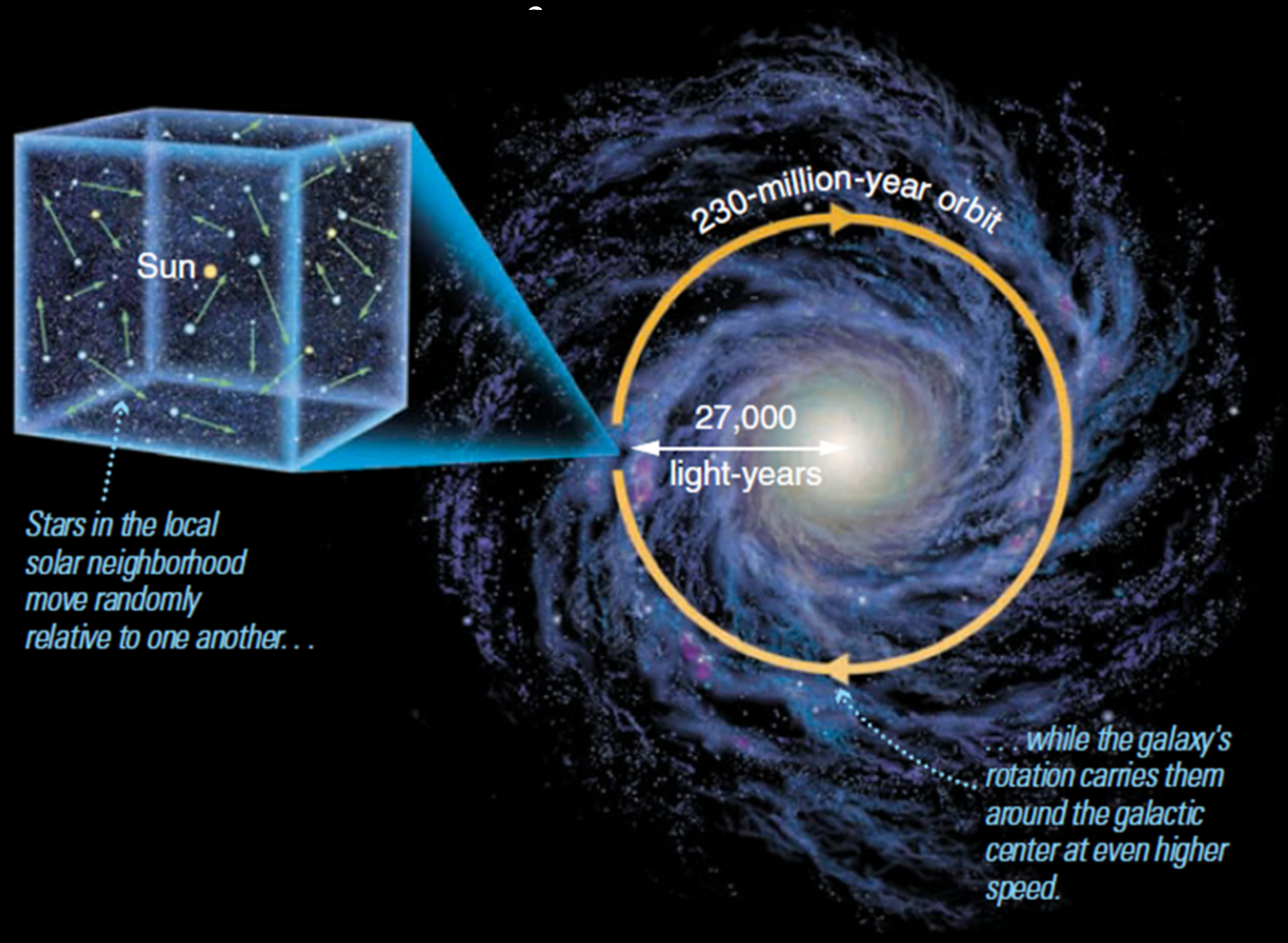


mass outside the orbit will **cancel out**

.... but why only within the star orbit?

How we measure the mass of a galaxy?



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For circular orbits:

$$P = \frac{2\pi a}{v}$$

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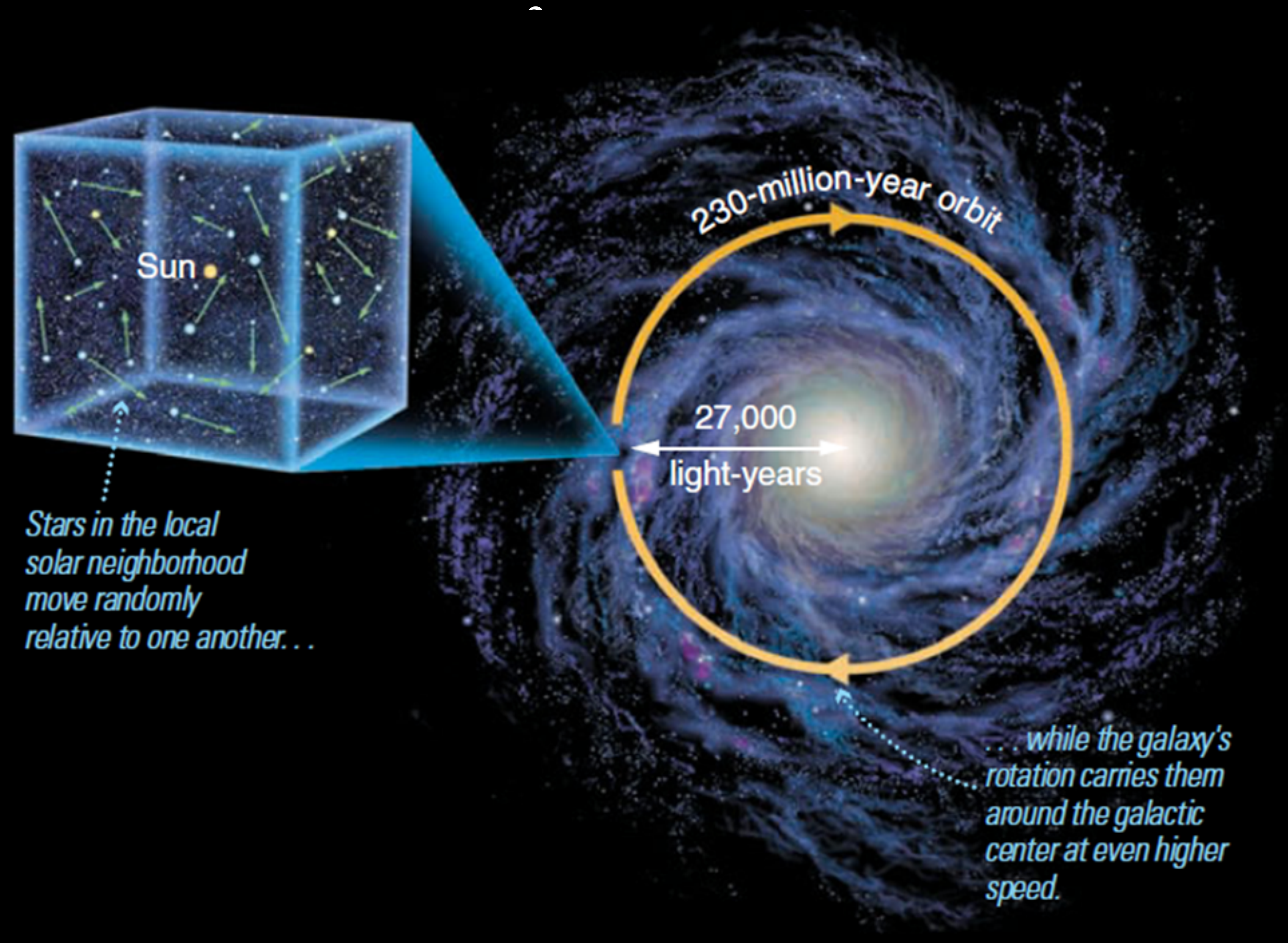

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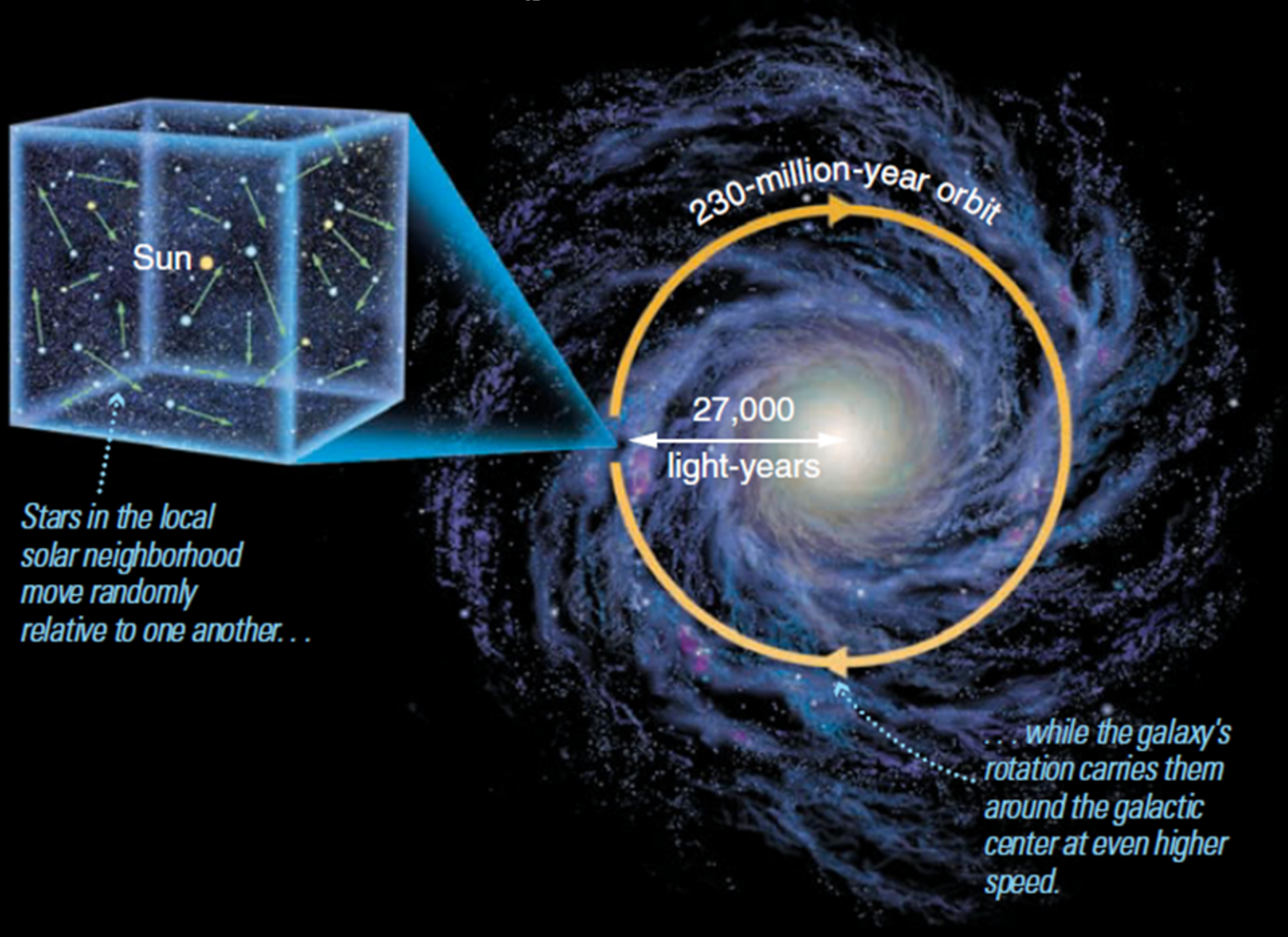
Putting this together:

$$M_R = \frac{A \times v^2}{G}$$

How we measure the mass of a galaxy?

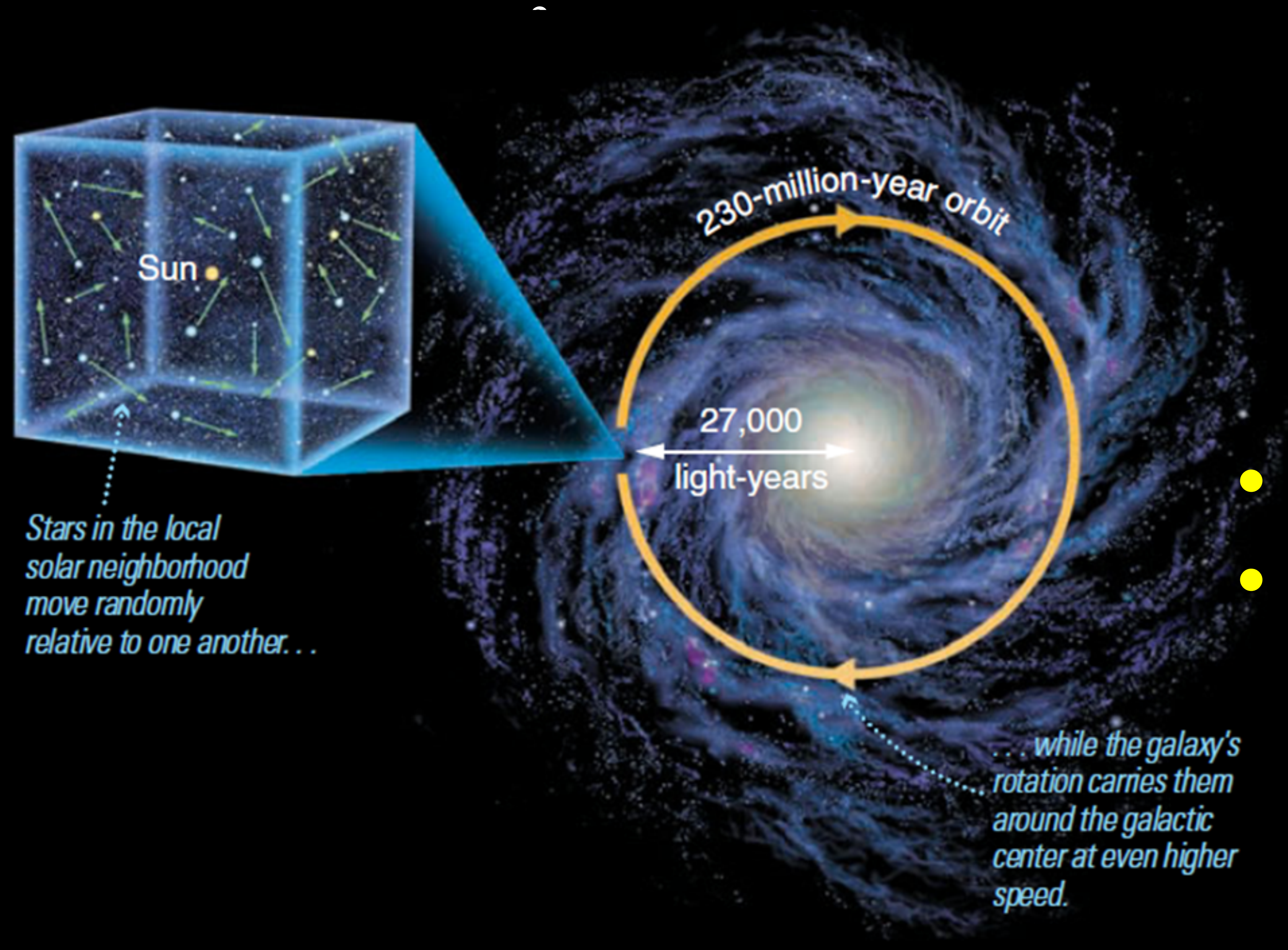


$$M_R = \frac{A \times v^2}{G}$$

"Orbital velocity law": A = radius, v = velocity, M = mass

G is a constant (Newton's constant)

How we measure the mass of a galaxy?



$$M_R = \frac{A \times v^2}{G}$$

For our galaxy

- Radius **R = 8 kpc**
- Velocity **v = 220 km/s**

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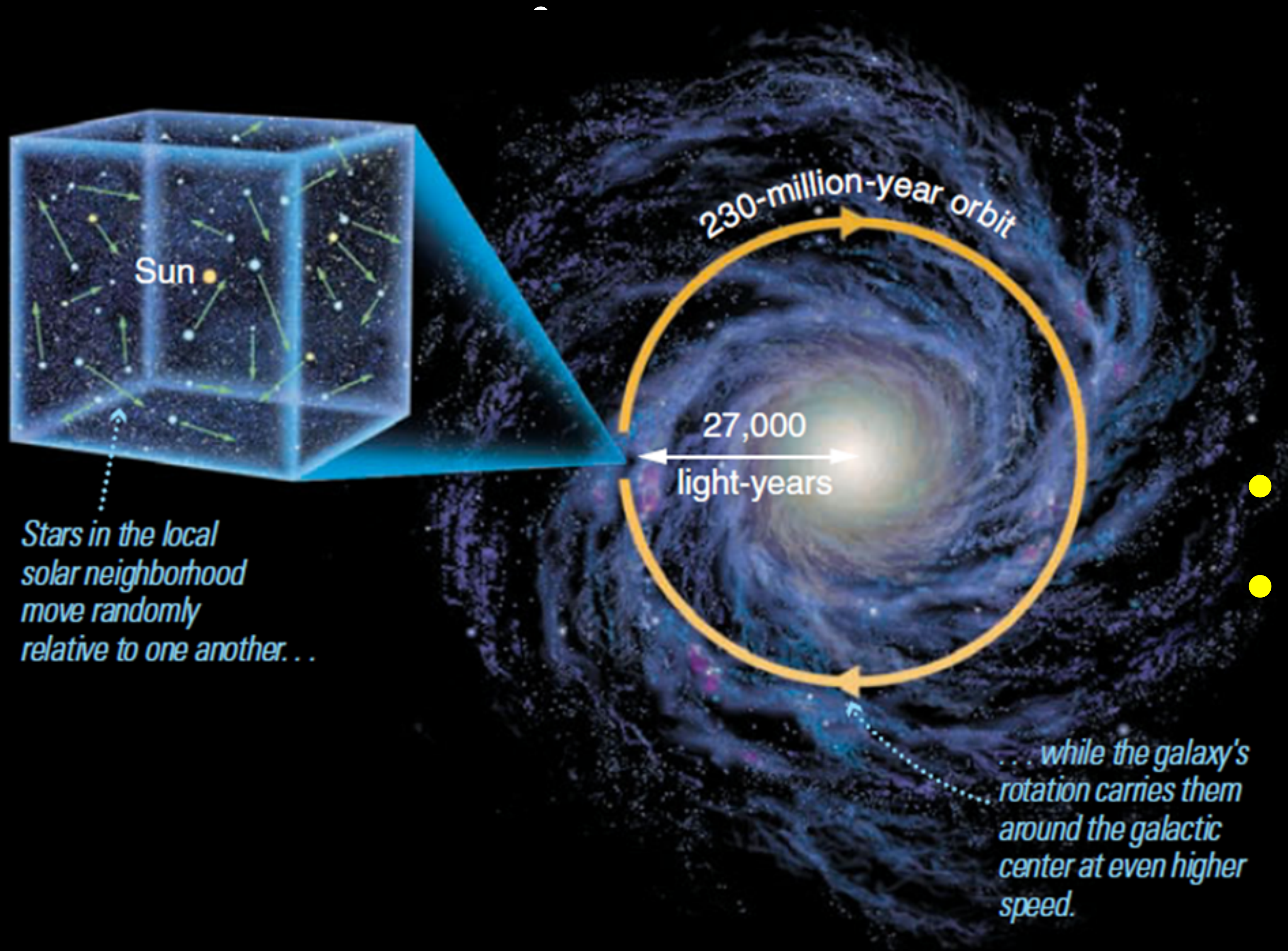
How we measure the mass of a galaxy?



$$M_R = \frac{A \times v^2}{G}$$

For our galaxy

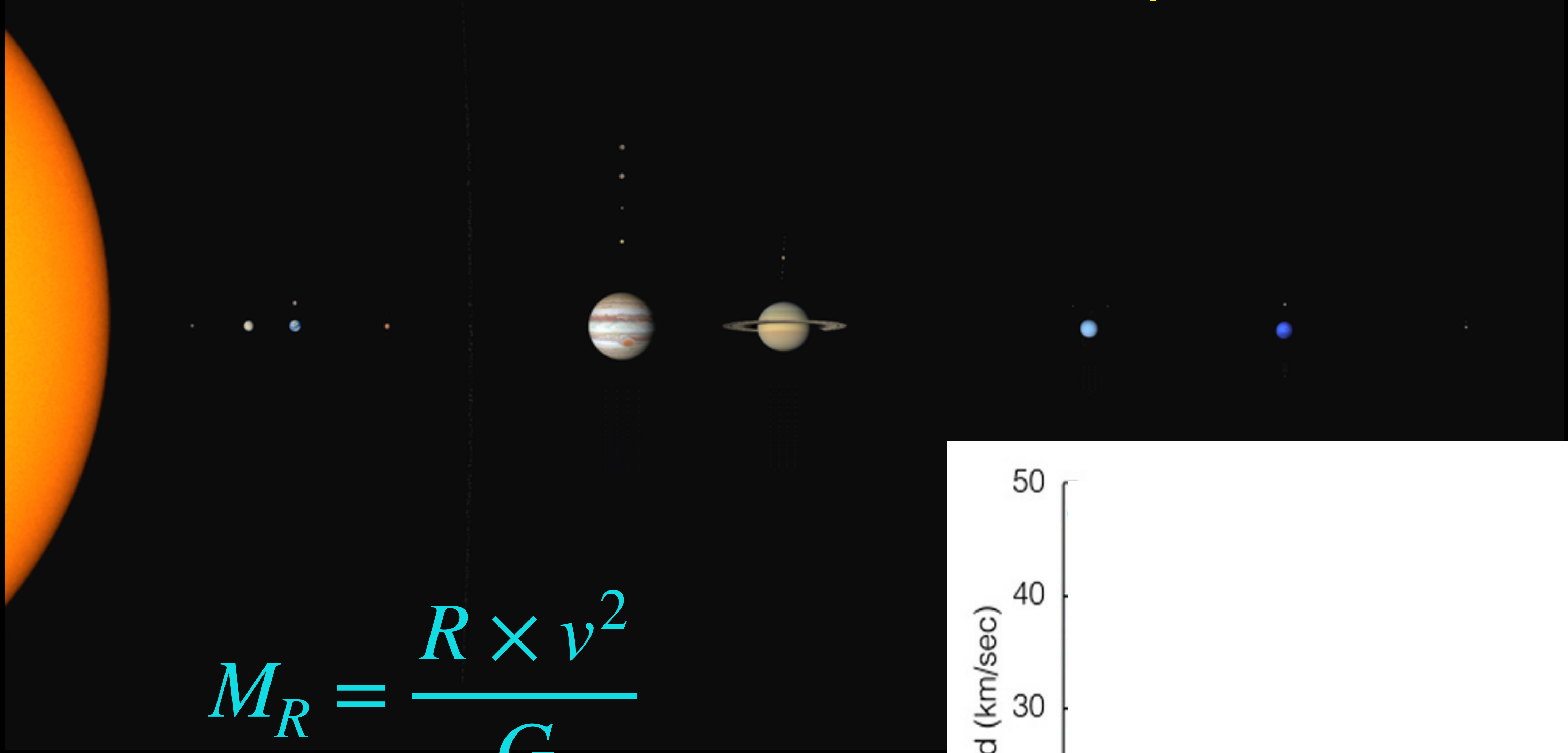
- Radius **R = 8 kpc**
- Velocity **v = 220 km/s**

Result: Mass = **10^{11} $M_\odot$** within the Sun's orbit

- 100 billion times the mass of the Sun!

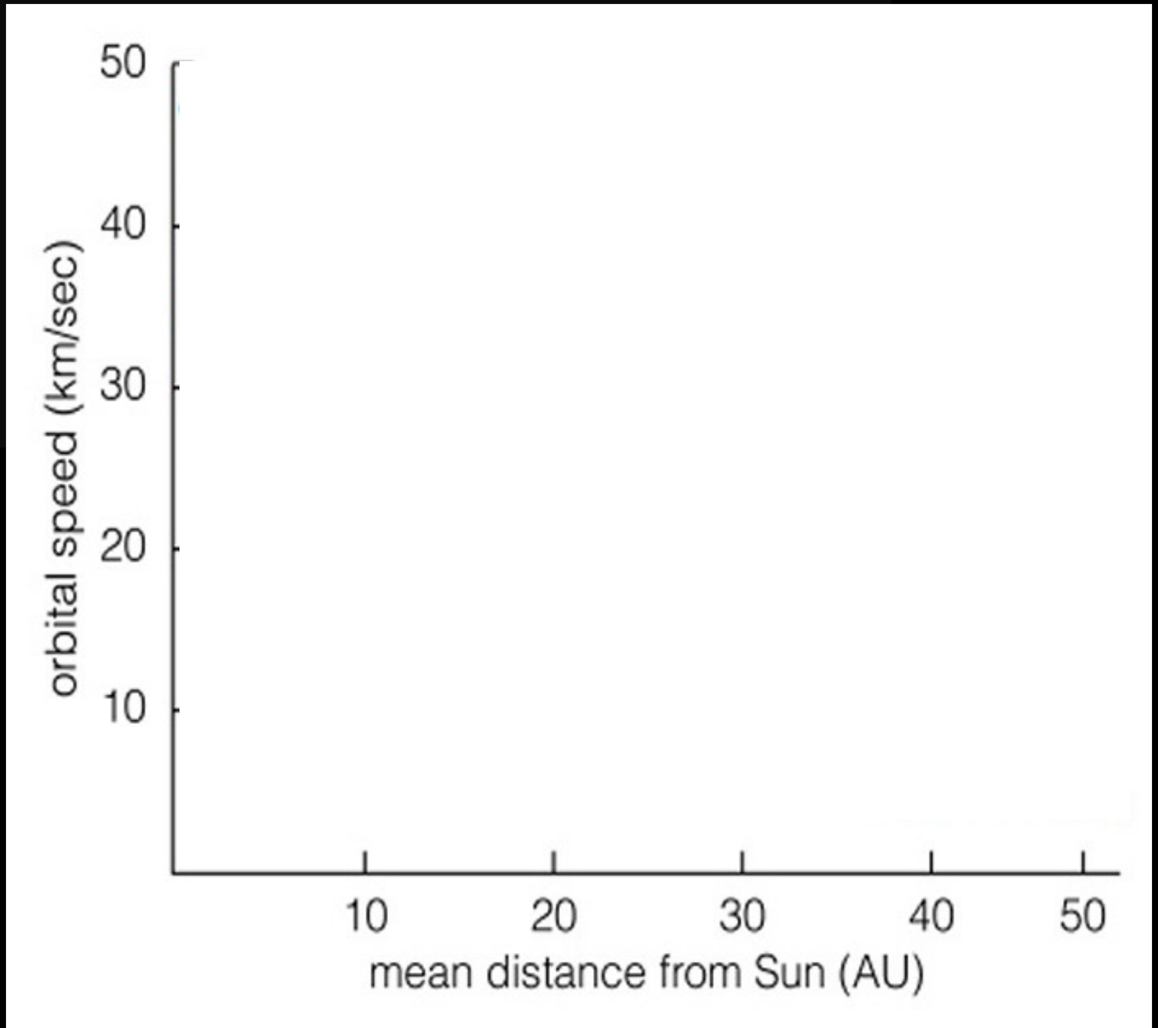
Example: mass in our Solar System

The Sun is 99.8% of the Solar system Mass



$$M_R = \frac{R \times v^2}{G}$$

$$\frac{1}{v^2} = \frac{1}{M_R G} \times R$$



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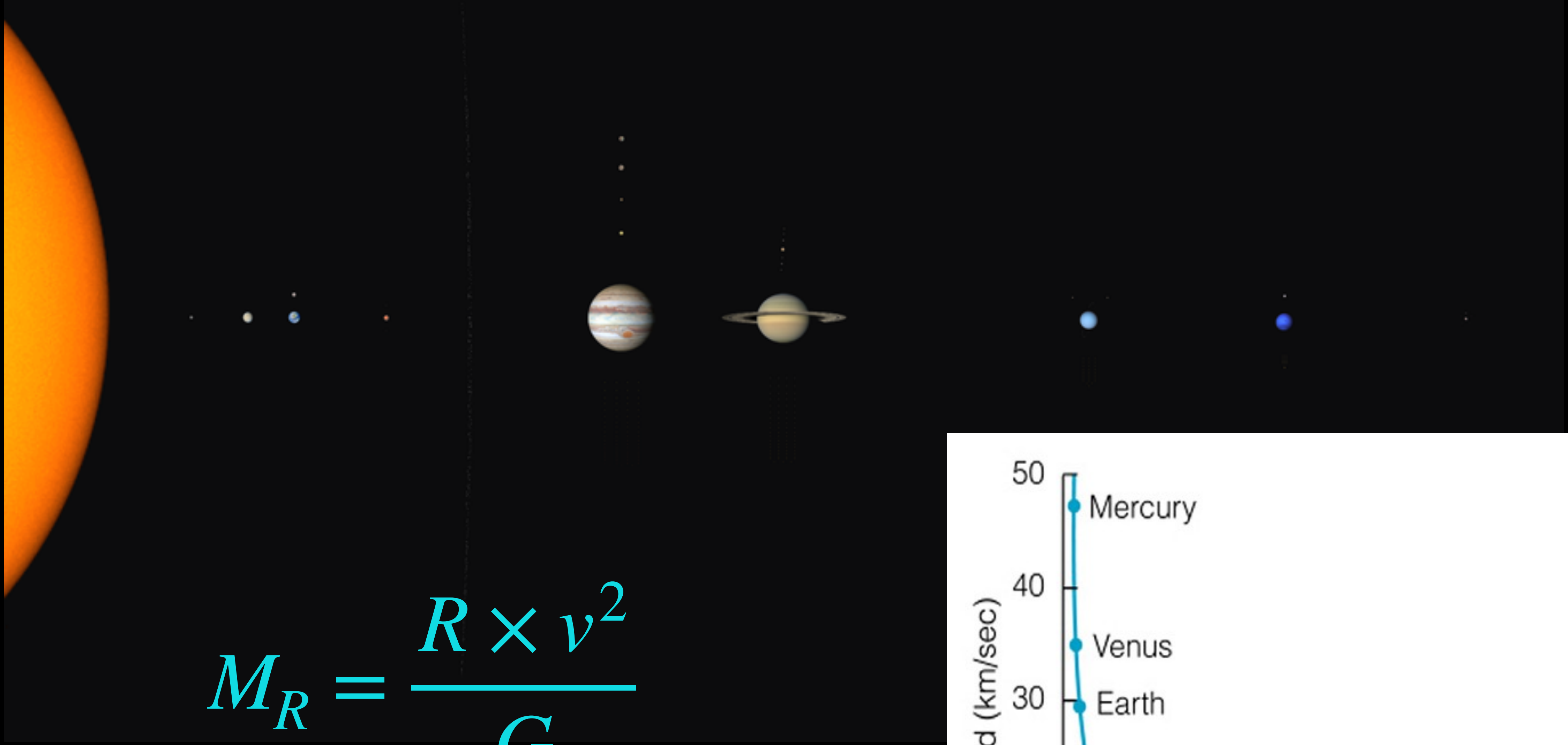
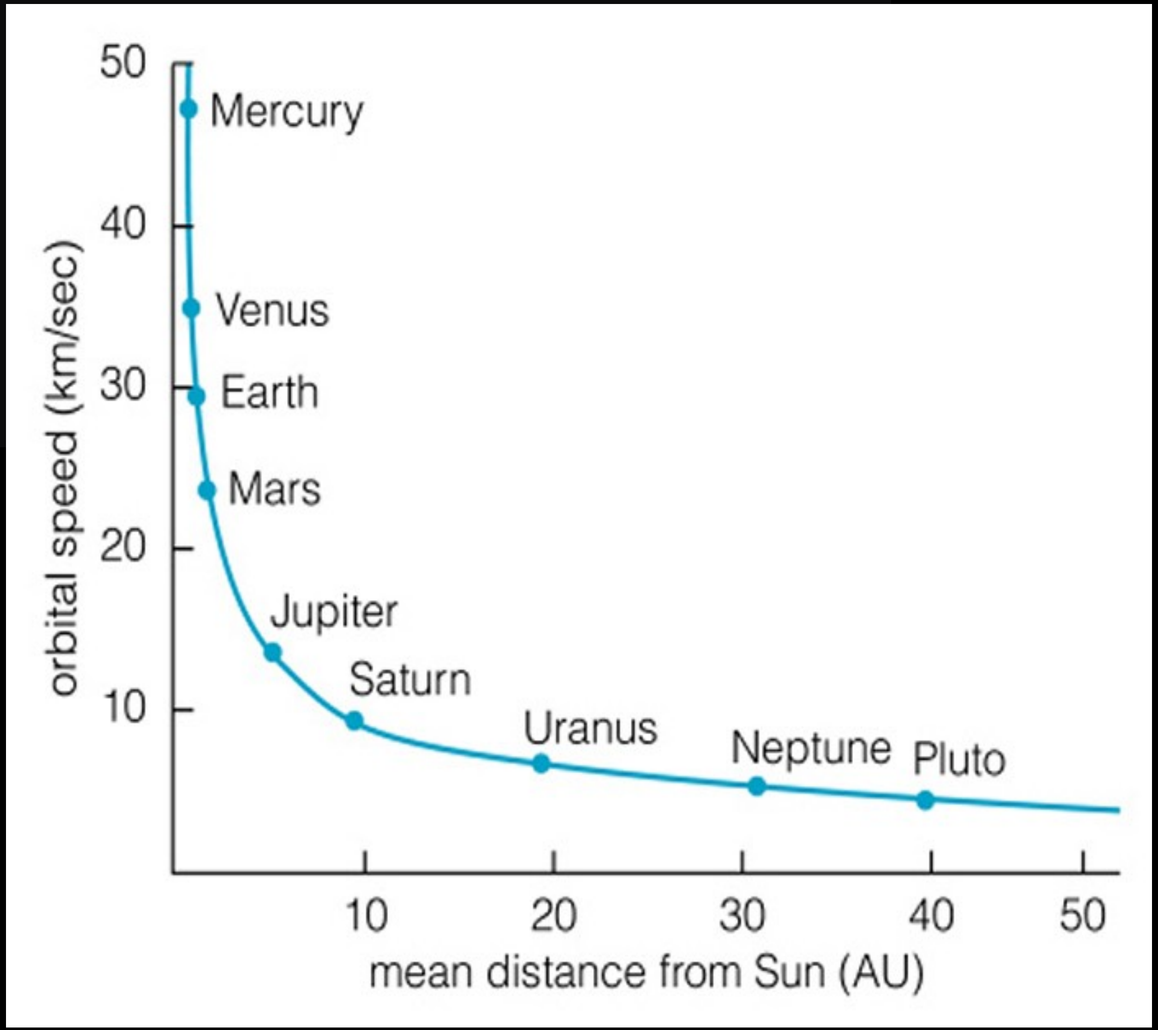


$$M_R = \frac{R \times v^2}{G}$$

$$\frac{M_R}{v^2} = \frac{1}{G} \times R$$



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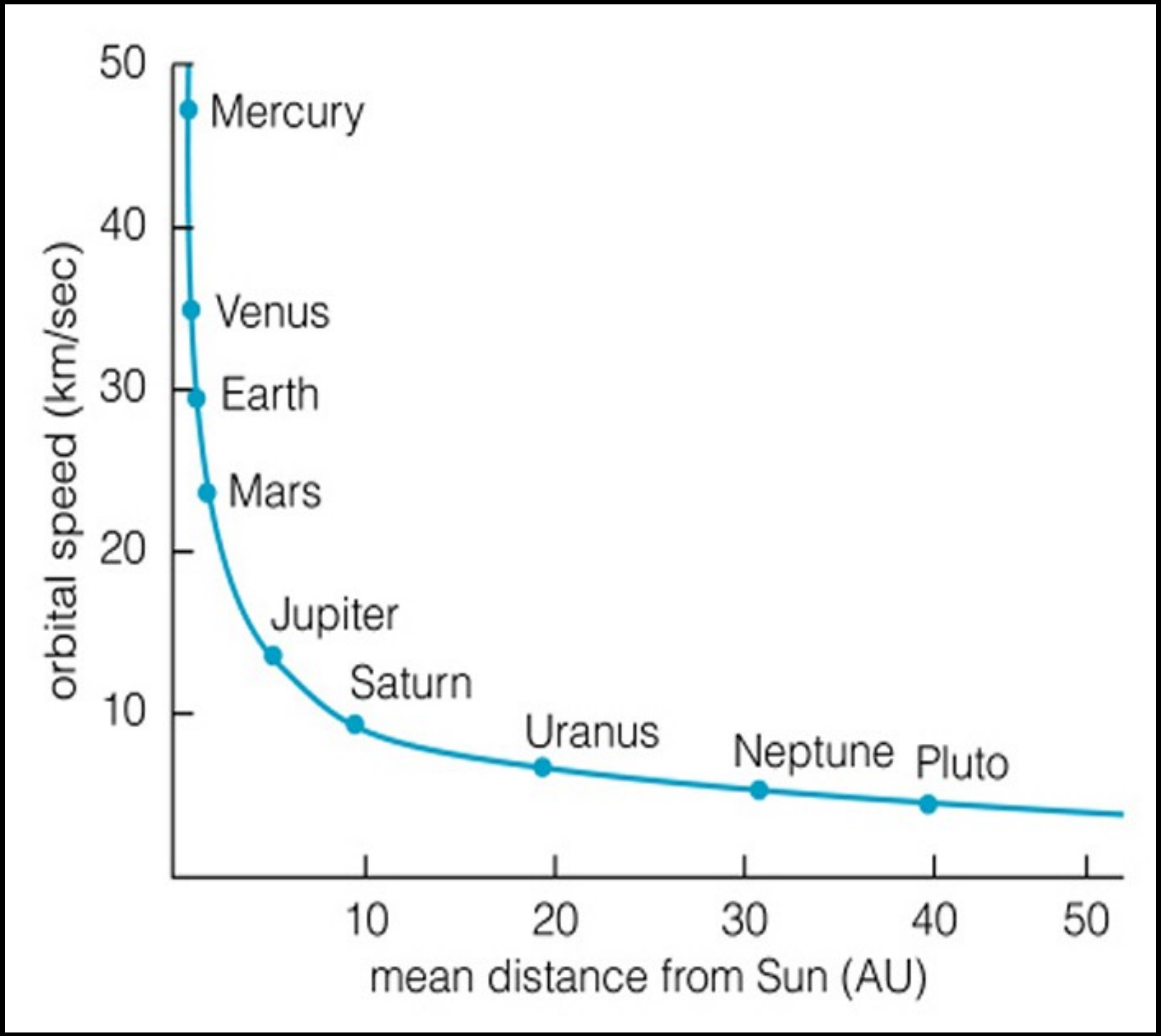
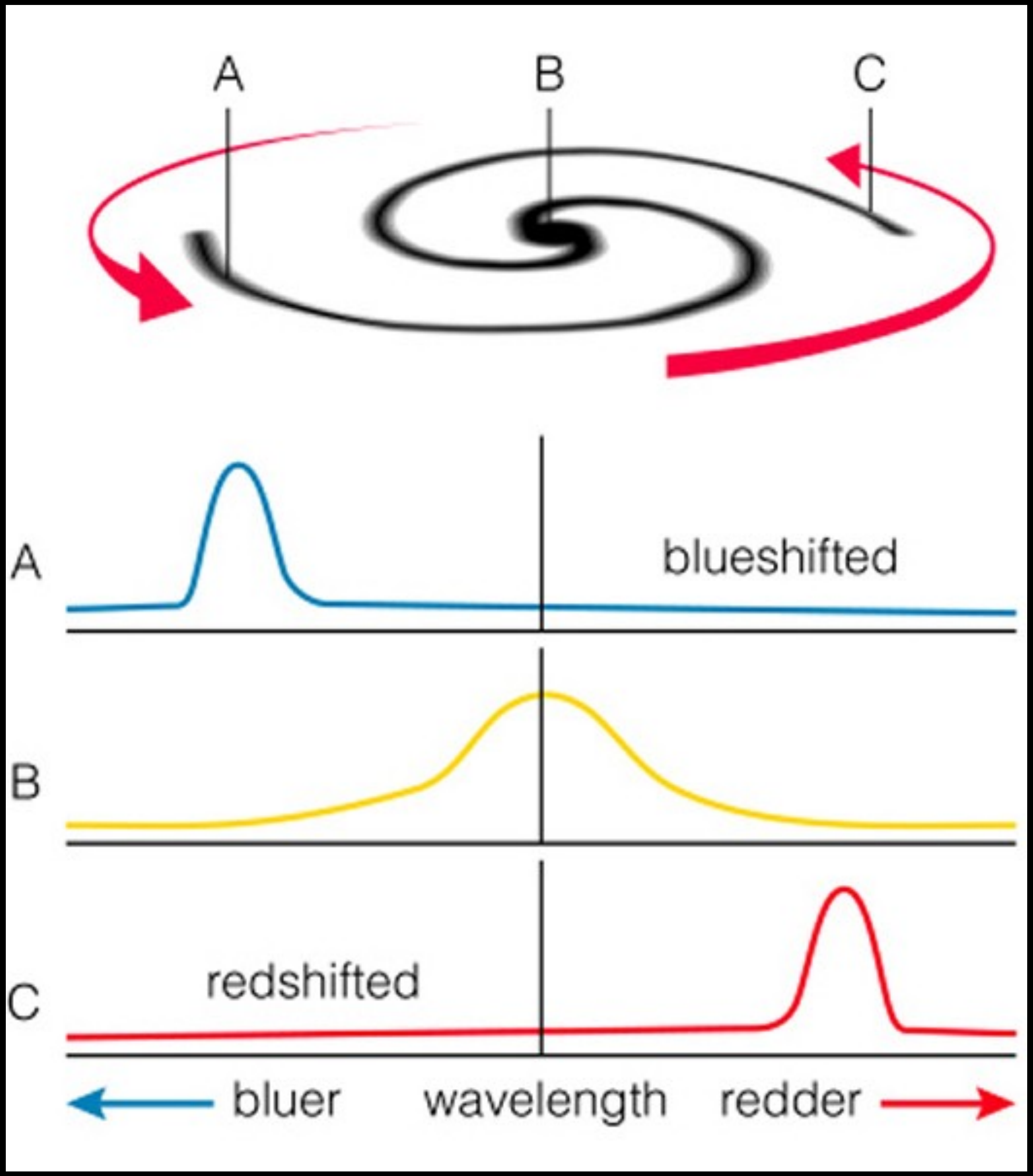


- The planets are on nearly circular orbits around the Sun
  - Radius and velocity vary
  - In all cases, the total mass within each orbit is nearly the same: ~ mass of Sun

$$M_R = \frac{R \times v^2}{G}$$

Result: Mass ≈ **1 $M_\odot$** within each planet's orbit

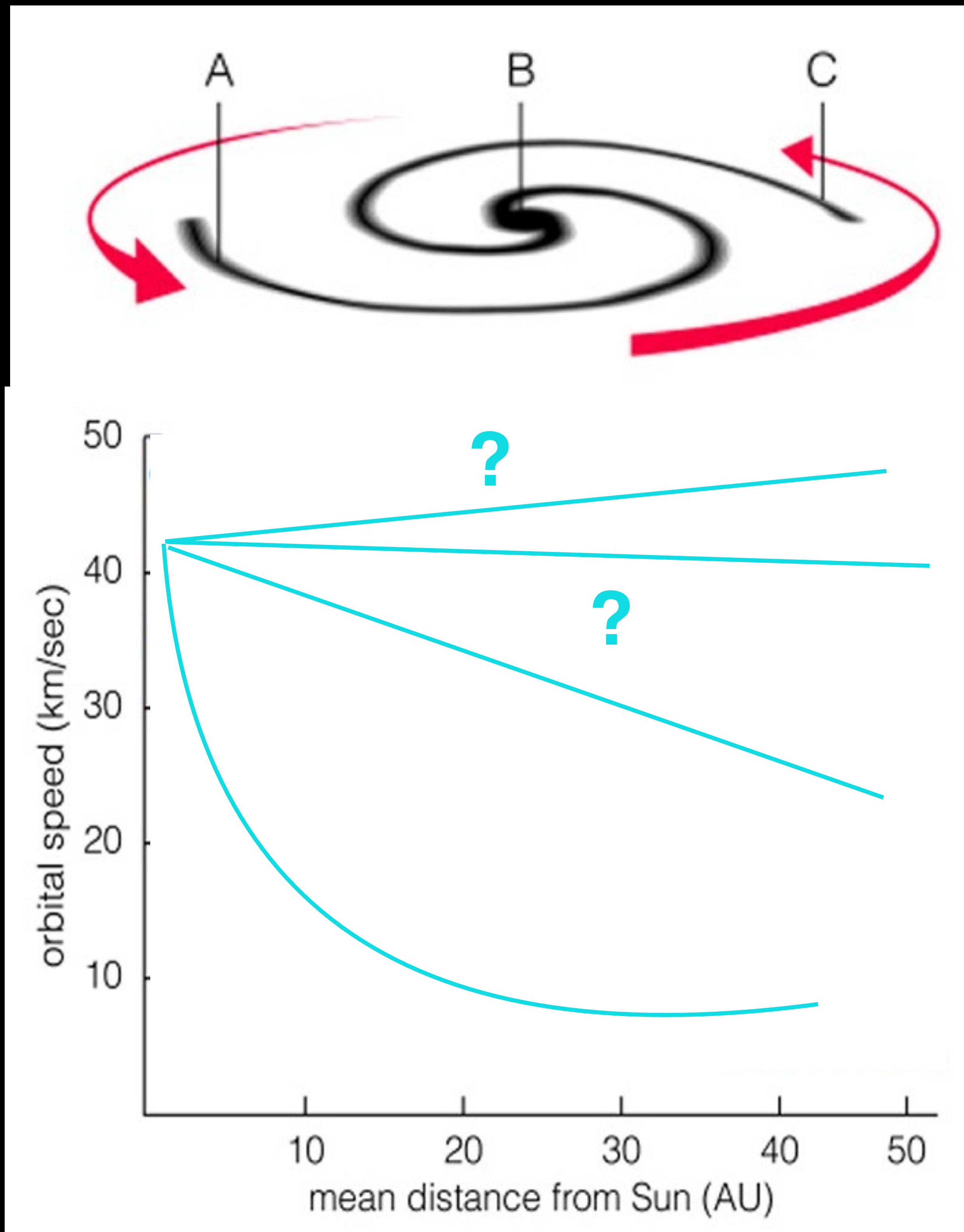
Mass versus radius: Rotation Curves



- We can measure velocities using the Doppler shift
  - $v = c \times \frac{\Delta\lambda}{\lambda}$
- We can measure velocity in a disk, at different radii R
  - Use orbital velocity equation to calculate mass as a function of radius
  - Determine **where** the mass is!

$$\frac{M_R}{v^2} = \frac{1}{G} \times R$$

Mass versus radius: Rotation Curves

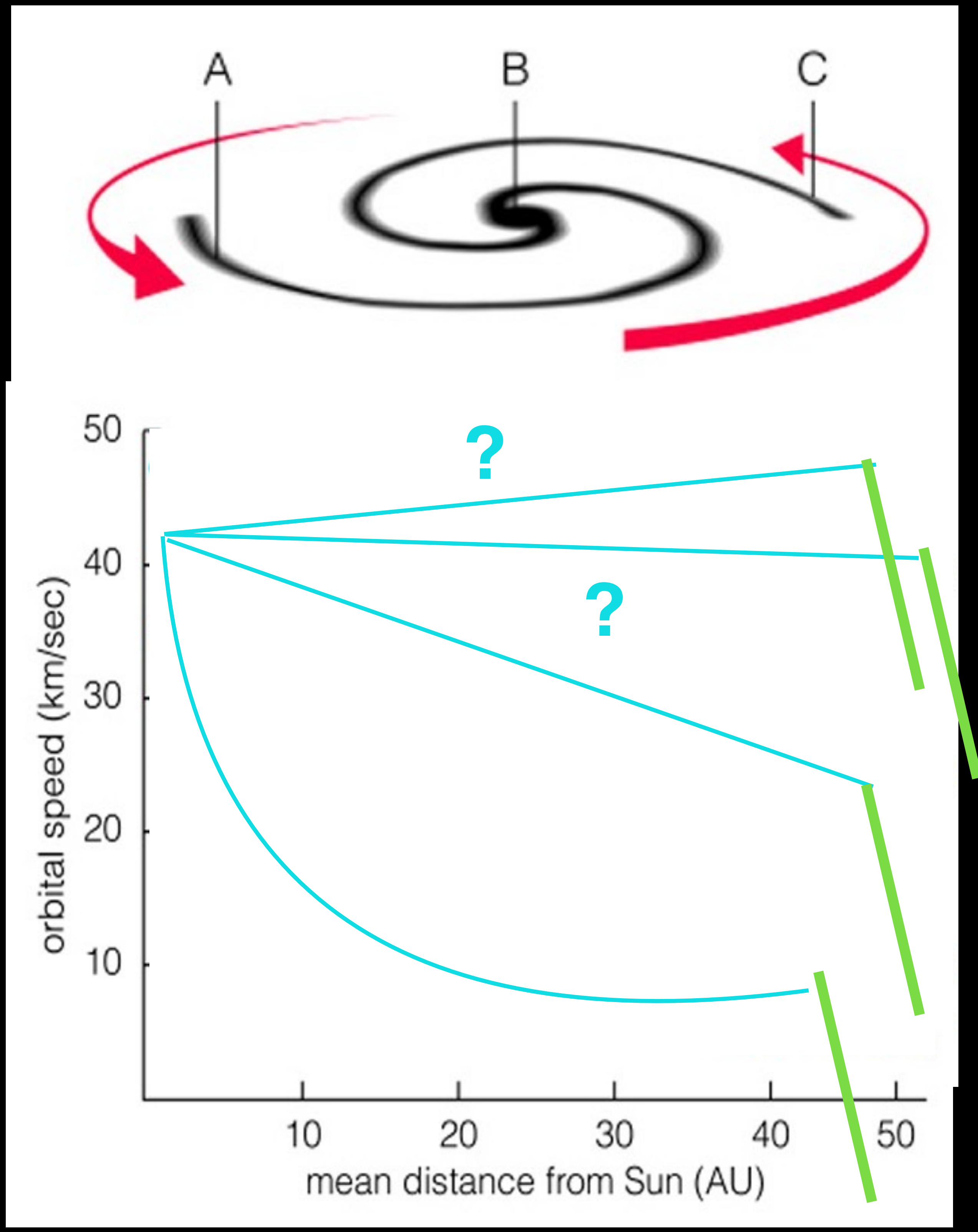


- For galaxies, the mass increase with the radius

$$\frac{M_R}{v^2} = \frac{1}{G} \times R$$

- The orbital velocity will change with radius depending on the mass distribution

Mass versus radius: Rotation Curves



- For galaxies, the mass increase with the radius

$$\frac{M_R}{v^2} = \frac{1}{G} \times R$$

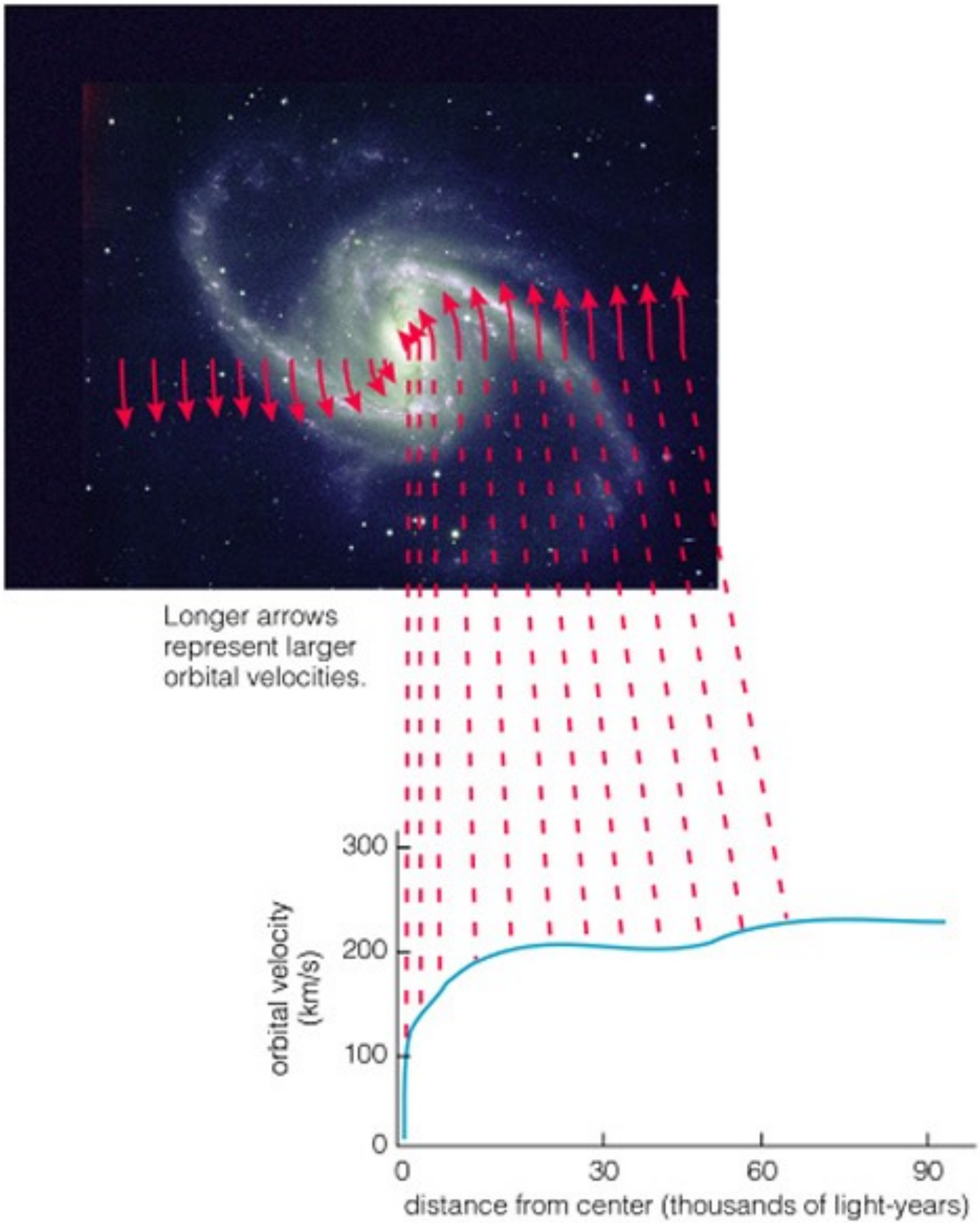
- The orbital velocity will change with radius depending on the mass distribution

Rotation Curves

Most spiral galaxies have nearly constant rotational velocities, outside of the center

If **v** is the same, then total mass increases with radius:

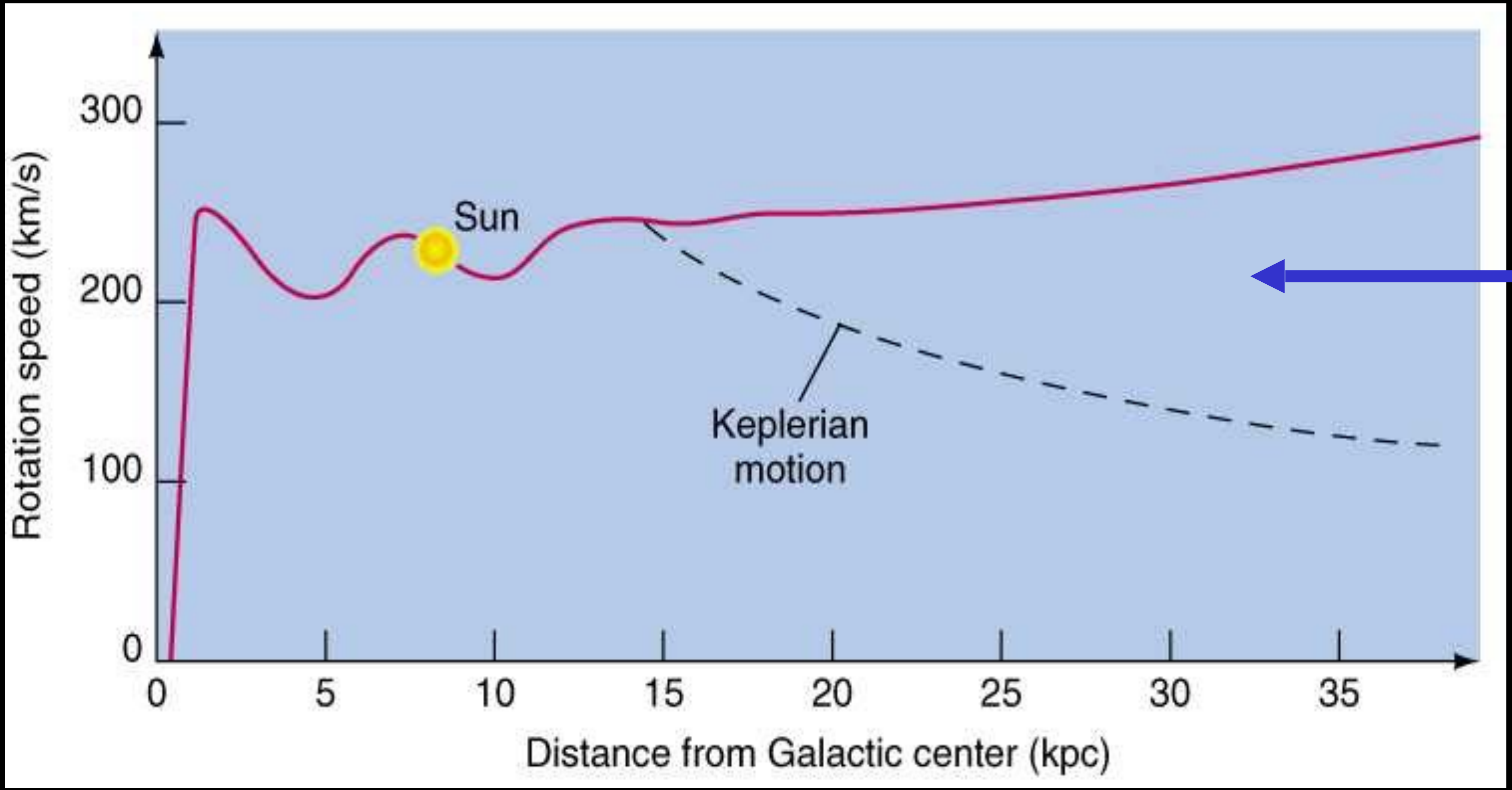
$$M_R = \frac{R \times v^2}{G}$$



This may not bother you at first…

- Stars and gas in galaxies are extended, so of course there is mass far outside of the center
- However, there is less and less normal matter (stars & gas) at large radii

Problem: the Milky Way's rotation does not slow down where it should!

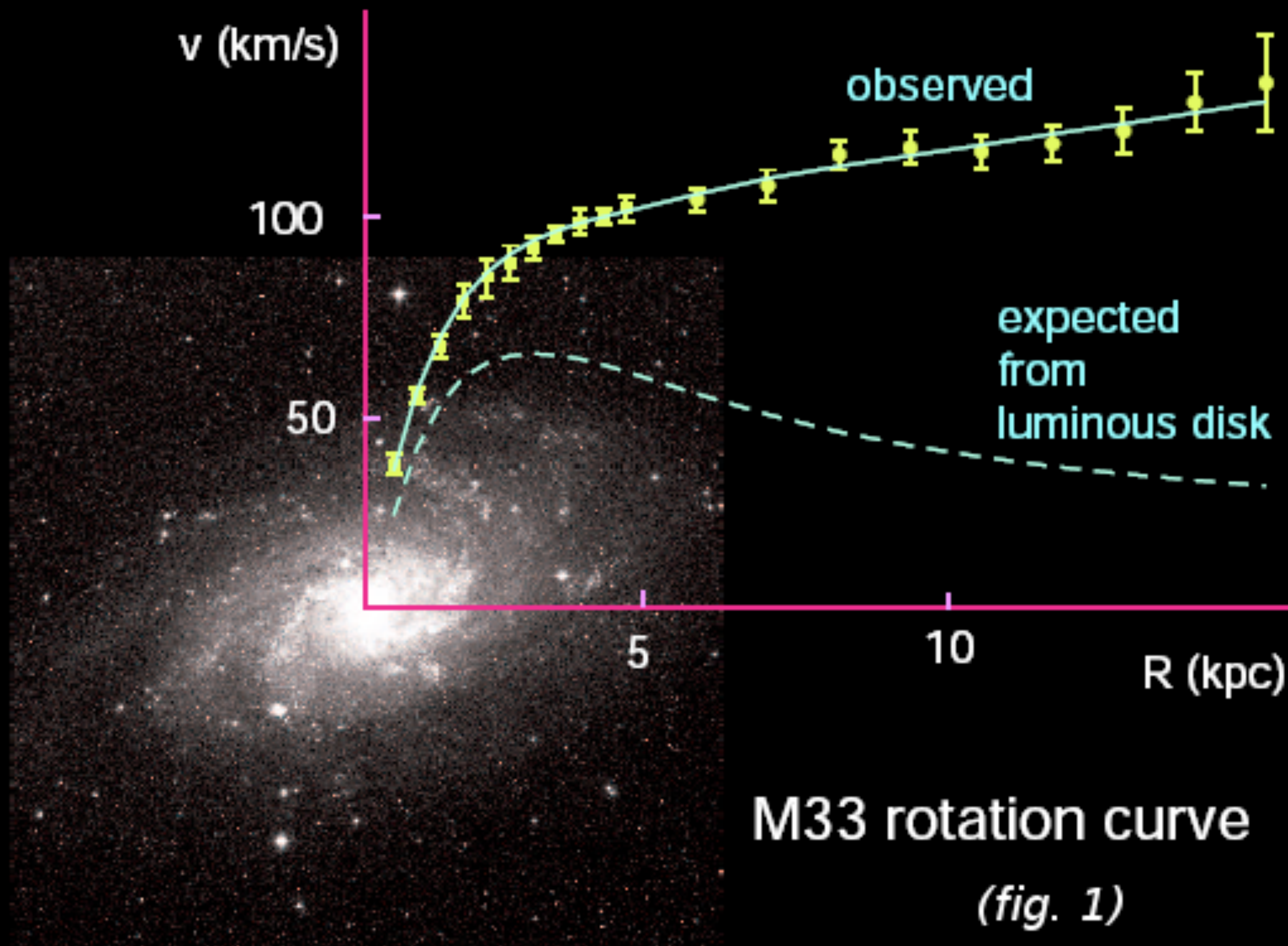


There must be **invisible** mass out here!

There is little **visible** matter in the Milky Way beyond 15 kpc (only trace amounts of Hydrogen gas).

We would expect the rotation velocity to decrease beyond this point, but it actually increases!

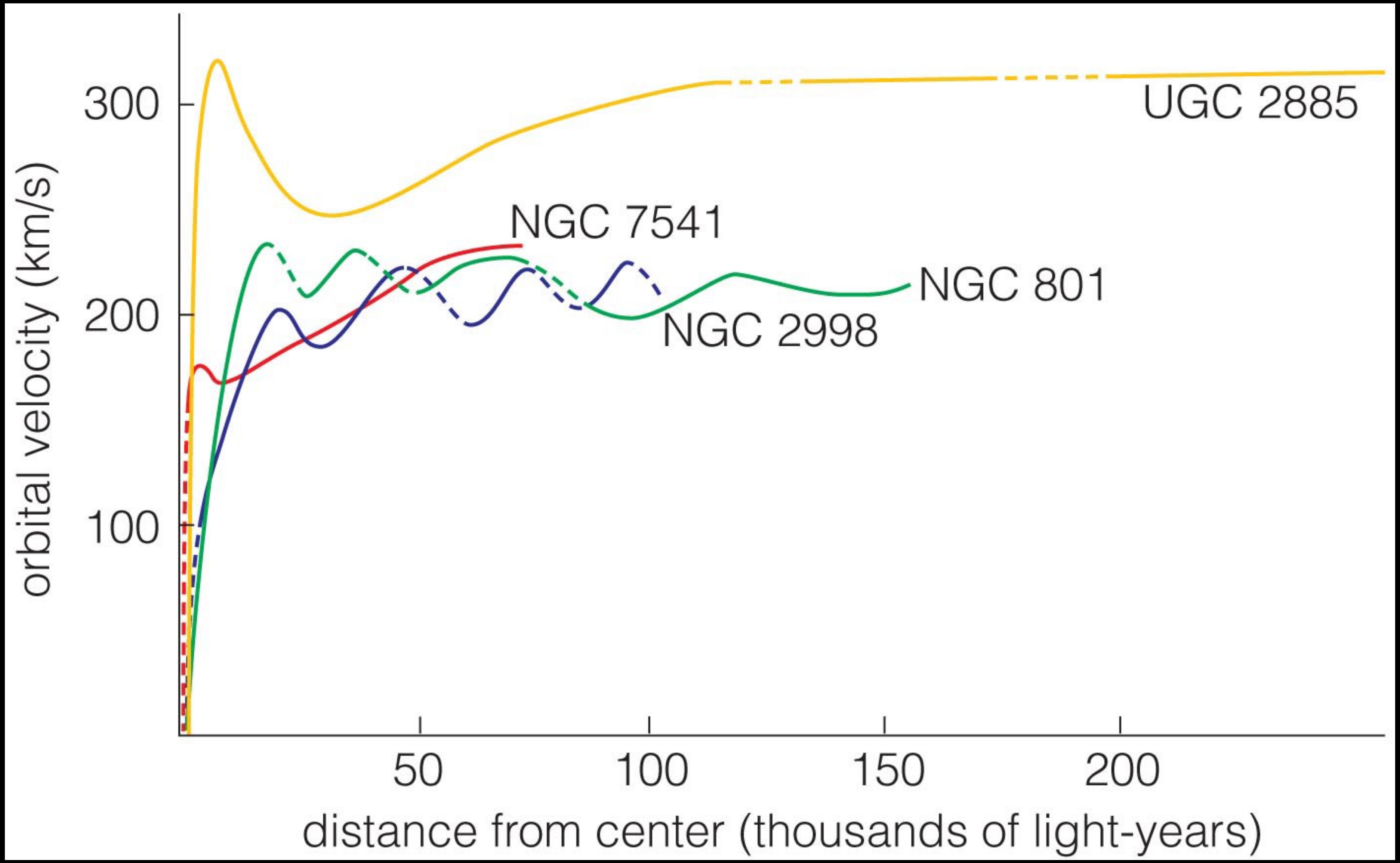
This is true of other galaxies as well!



M33 rotation curve

(fig. 1)

This is true of other galaxies as well!

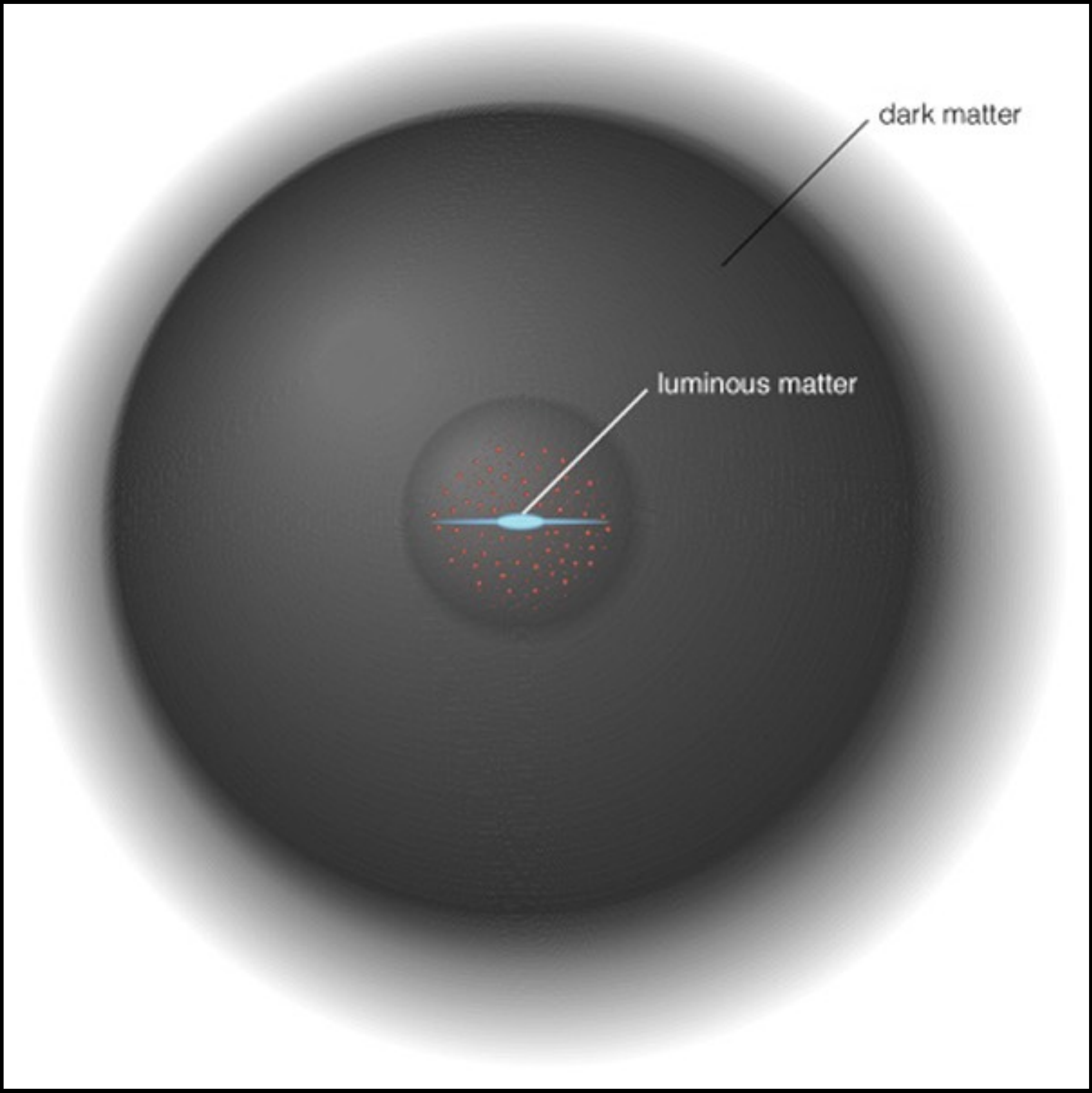


Rotation curves are usually “flat”.

All galaxies appear to have large amounts of mass well beyond the visible extent of the stars and gas!

ALL galaxies are embedded within a "halo" of Dark Matter!

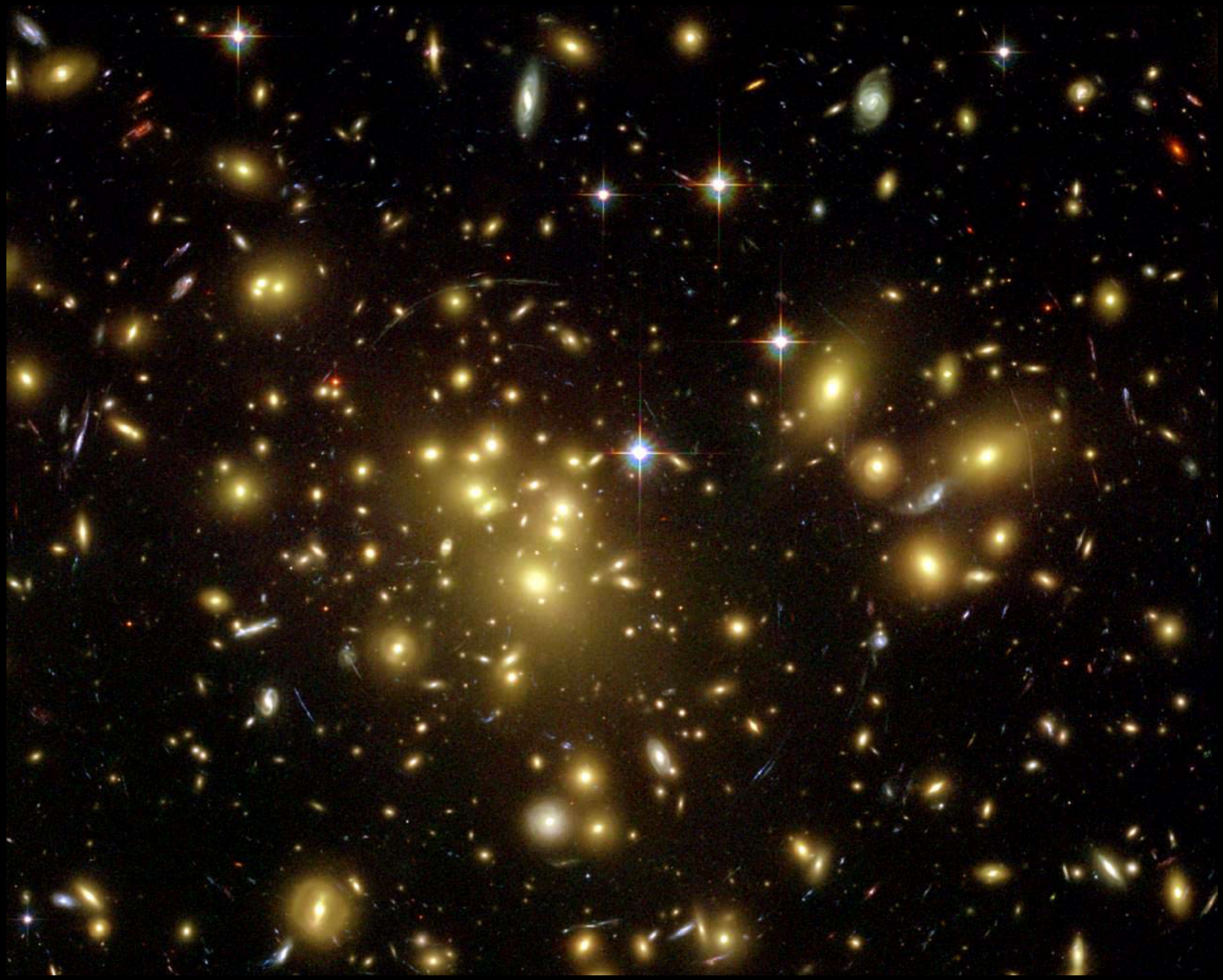
- We cannot see it!
- Much larger than the luminous galaxy
- Has most of the total mass of the galaxy (~90%)!
- We do not know what it is made of



Recap: what have we learned?

- **What is “Dark Matter”?**
  - Dark matter is what we call a form of matter which does not interact with light, but which has mass
  - We detect dark matter by its gravitational influence, but we do not know what it is
- **What is the evidence for Dark Matter in the Milky Way and other galaxies?**
  - Rotation velocities of galaxies are approximately constant, indicating that most of their total mass lies beyond the visible regions

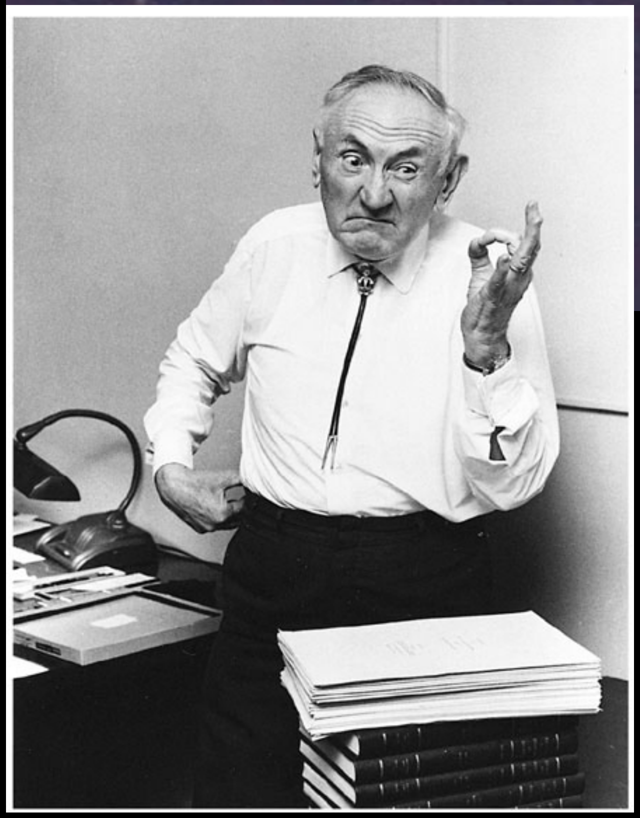
What about clusters of galaxies?



$$M_R = \frac{R \times v^2}{G}$$

You can measure the mass of clusters of galaxies measuring the velocity dispersion of galaxies within the cluster!

Galaxies in clusters move very fast…

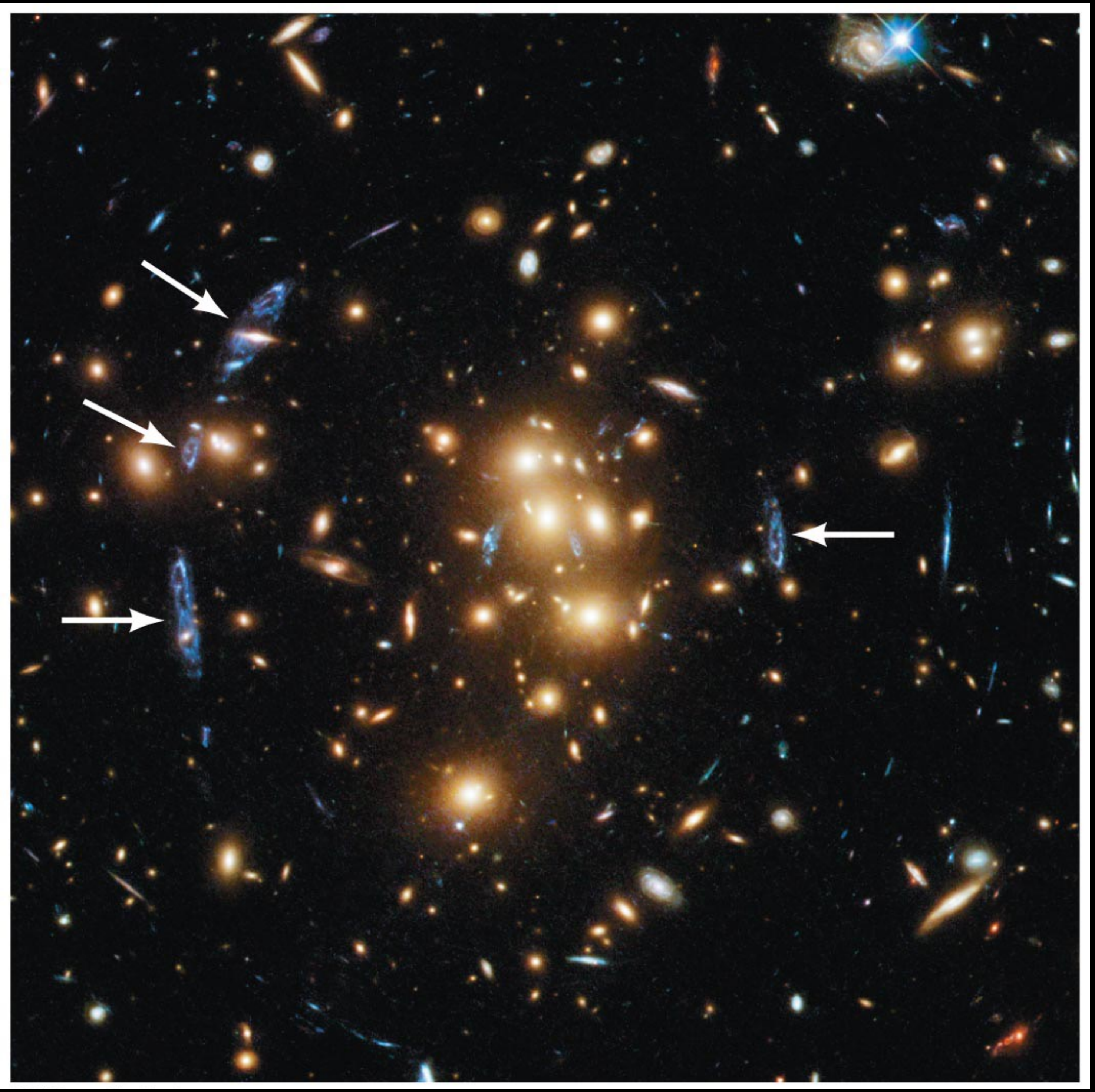


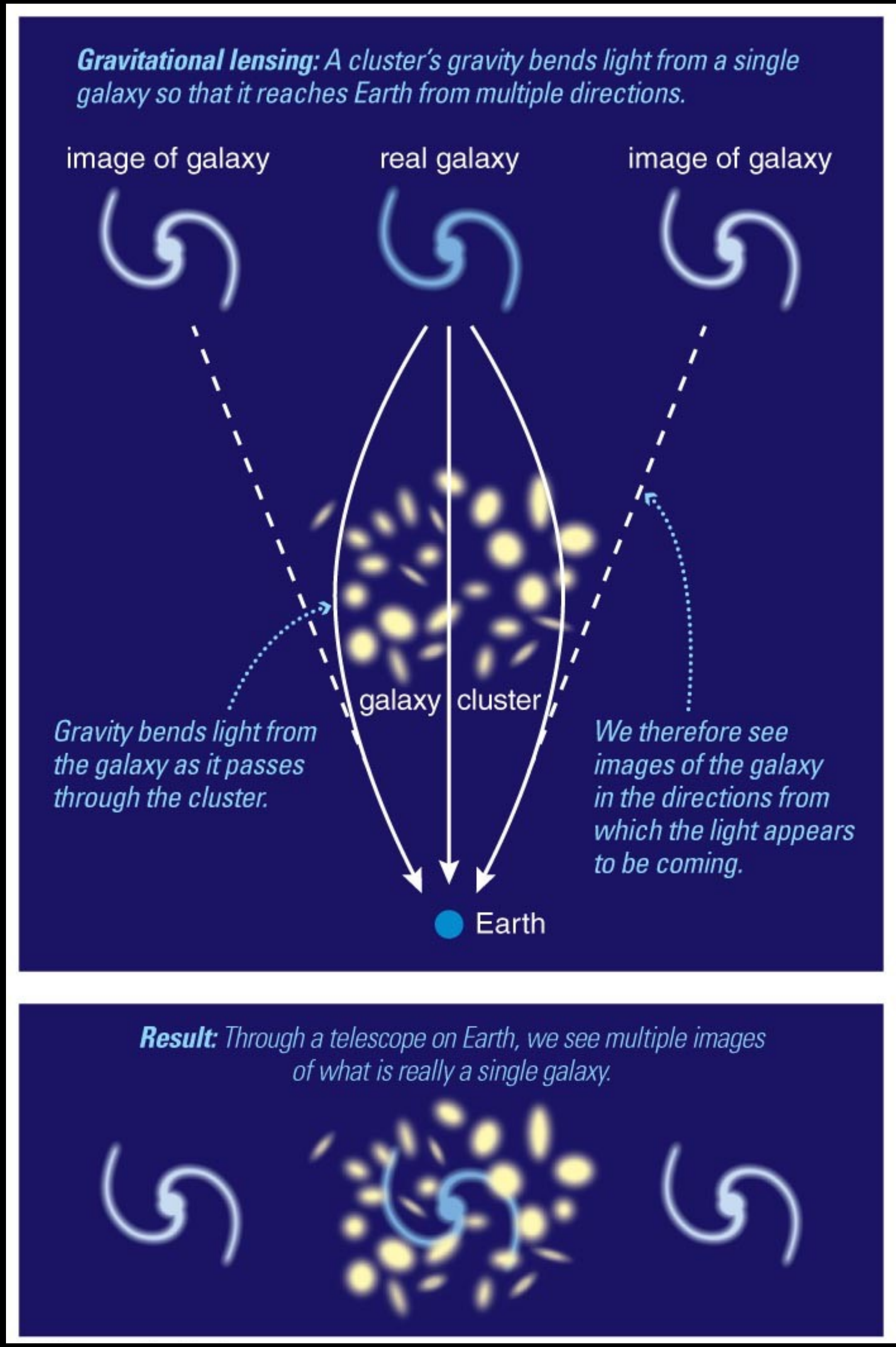
- Galaxies in clusters move at velocities of ~1000 km/s
- Based on the mass of the visible stars and gas, they should move at ~100 km/s
- There must be "extra" mass between them to accelerate them gravitationally
  - **Dark matter**!

Galaxy clusters masses

- The Coma cluster: nearest example of a galaxy cluster
- 1000's of galaxies!
- Typical galaxy velocities of ~1000 km/s
- Massive! ($>10^{14}\,M_{\odot}$!)

Galaxy clusters also act as gravitational lenses!





Recall from general relativity: mass causes a deflection of light.

The amount of deflection tells us the mass!

Masses of galaxy clusters

- We have 3 different ways to measure the masses of galaxy clusters
  - The velocities of galaxies in the cluster
    - $M = v^2 r / G$
  - The temperature of the gas (thermal radiation)
    - Kinetic energy (temperature) is directly related to gravitational potential energy (mass)
  - Gravitational lensing
    - Independent method; does not rely on motion!
- All 3 methods say that galaxy clusters are dominated by dark matter
  - Dark matter in galaxy clusters has **50 times more mass** than the stars within the galaxies

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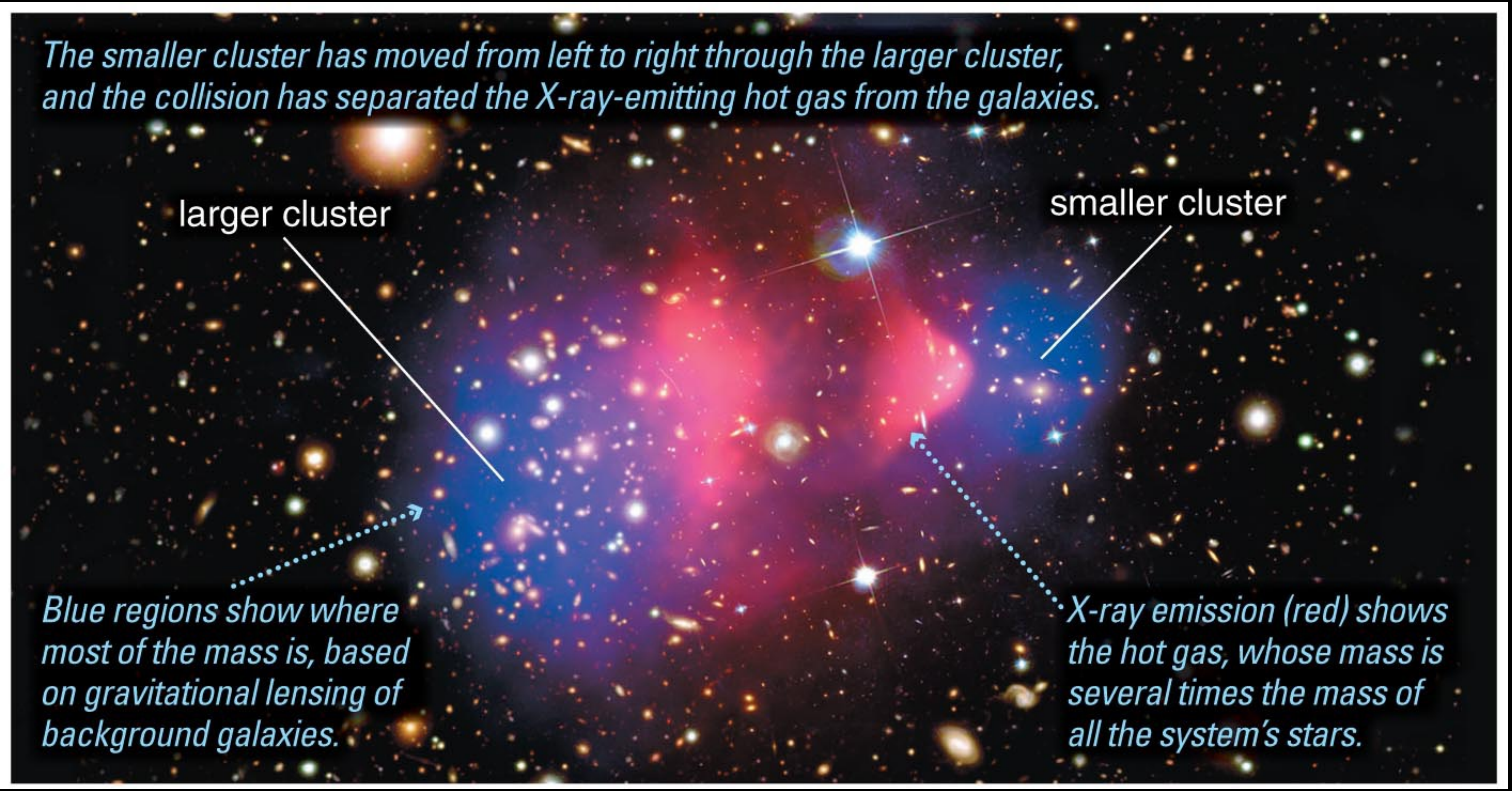
  - Rotation velocities of galaxies are approximately constant, indicating that most of their total mass lies beyond the visible regions
- **What is the evidence for Dark Matter in galaxy clusters?**
  - Masses measured from galaxy motions, temperature of hot gas, and gravitational lensing all indicate that the vast majority of matter in clusters is dark

More fun with dark matter: the "Bullet Cluster"



Ordinary gas in galaxy clusters (red): collides & heats up

Dark matter in galaxy clusters (blue): passes straight through!