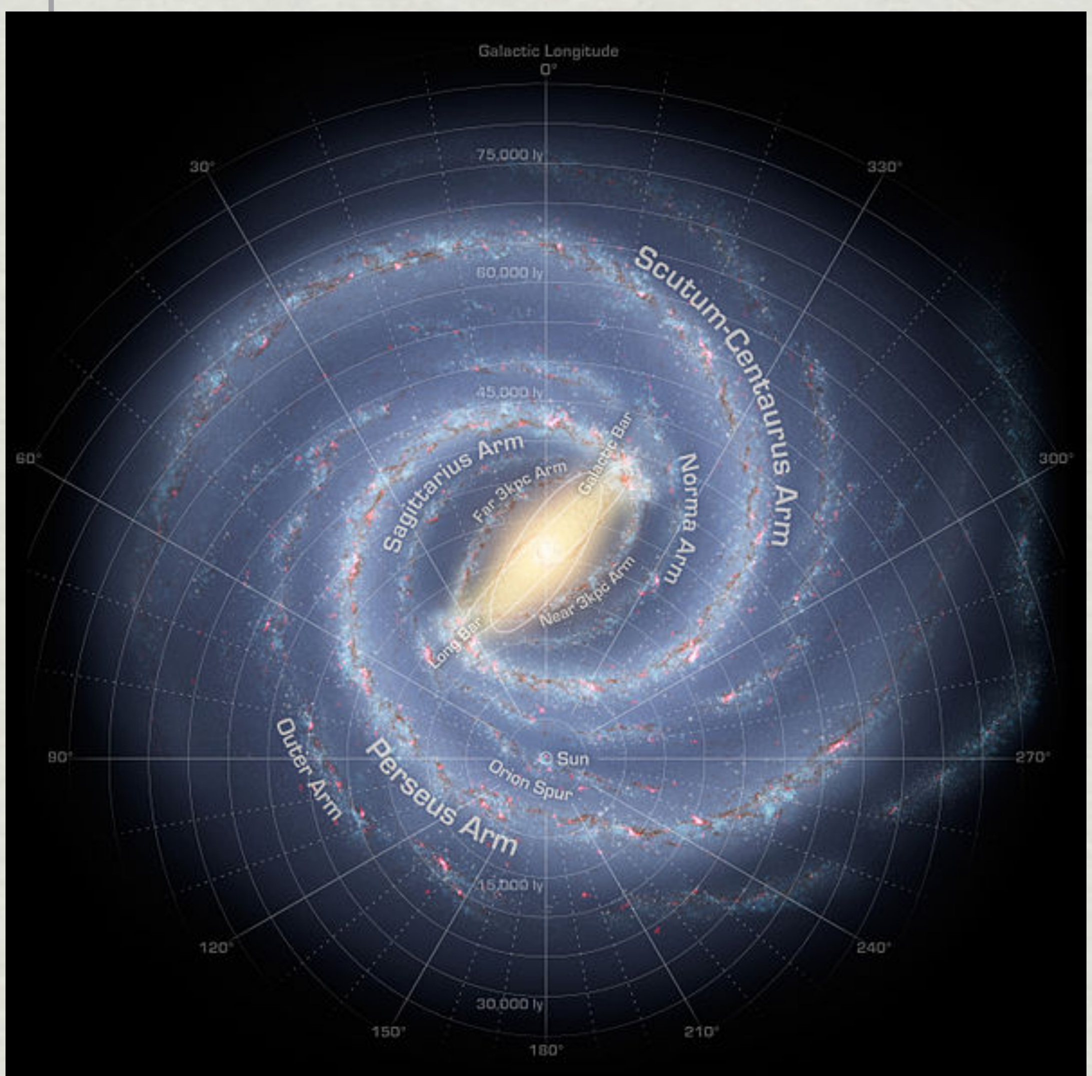
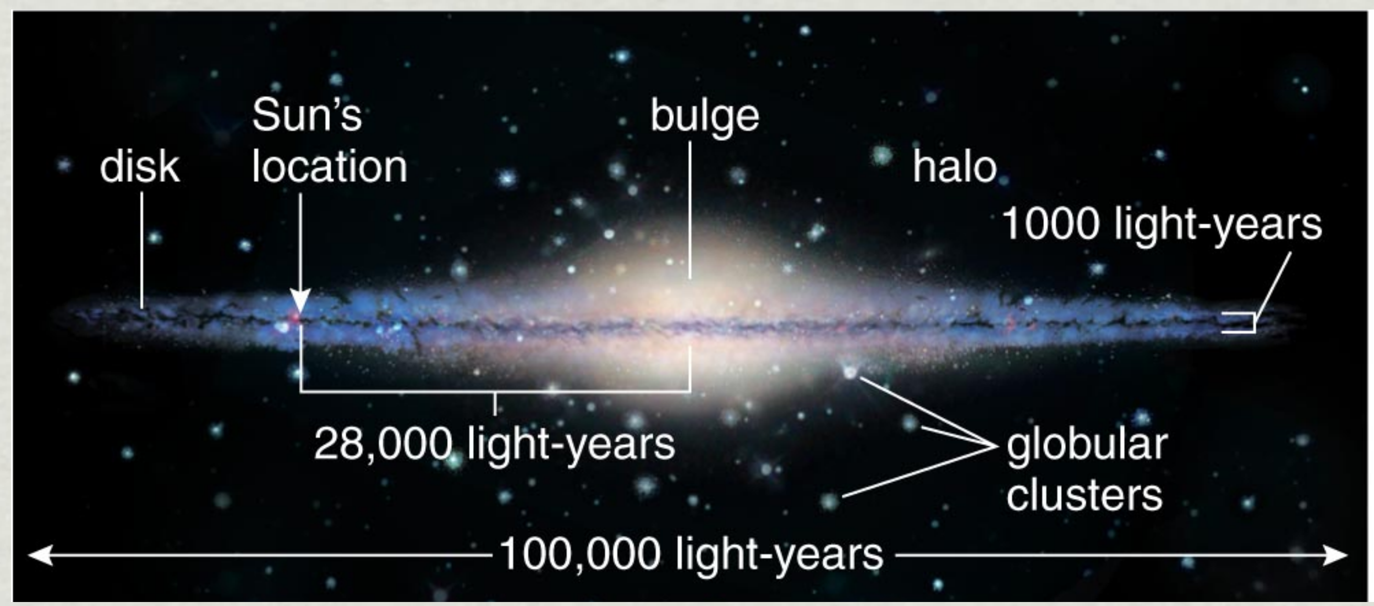
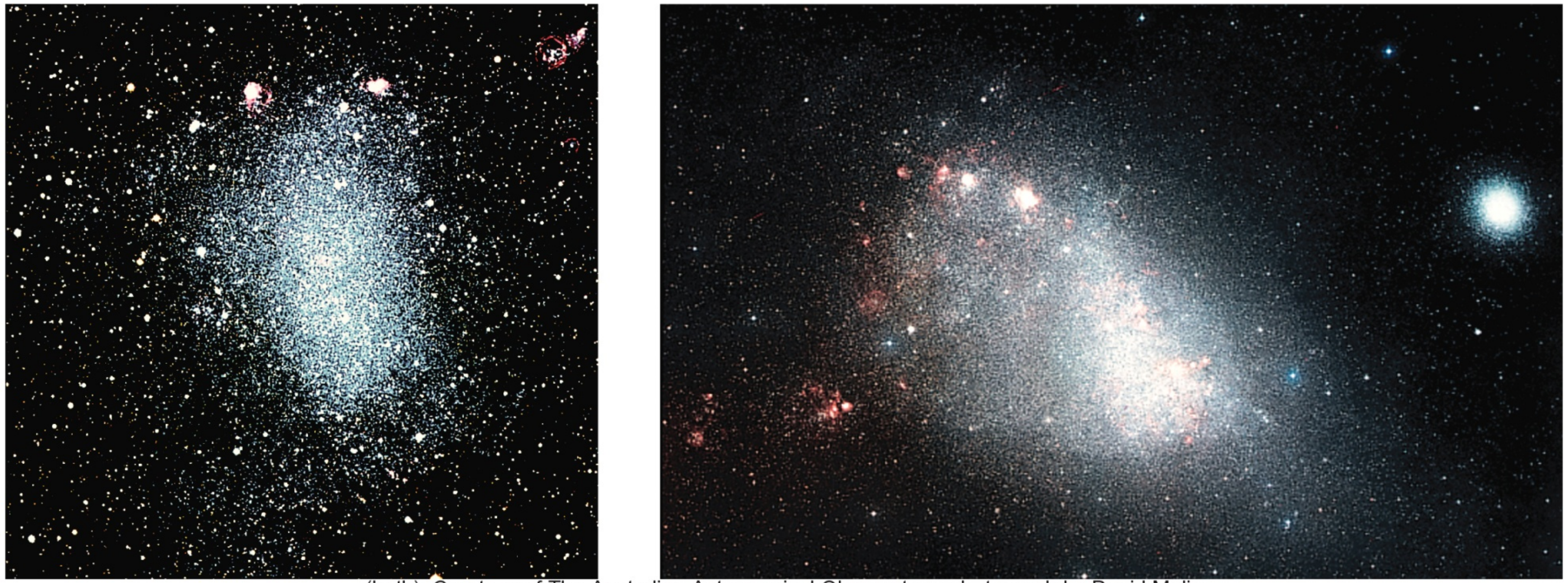
The Milky Way: Cartoon

- Stars: mostly in the disk, some (~10%) in clusters and the halo
- Diffuse gas: in the disk, mostly hydrogen, some helium + other elements
- Dense molecular gas: in the disk, mostly hydrogen again, with some dust





Edge-on (right) and face-on (above) reconstructions of the Milky Way



(both): Courtesy of The Australian Astronomical Observatory; photograph by David Malin

Irregular galaxies.
No neat, tidy disks withs stars moving in circles. But blue, lots of young, hot massive stars. So these galaxies are forming stars now.

Spiral, disk galaxies. Blue, star forming in the disk

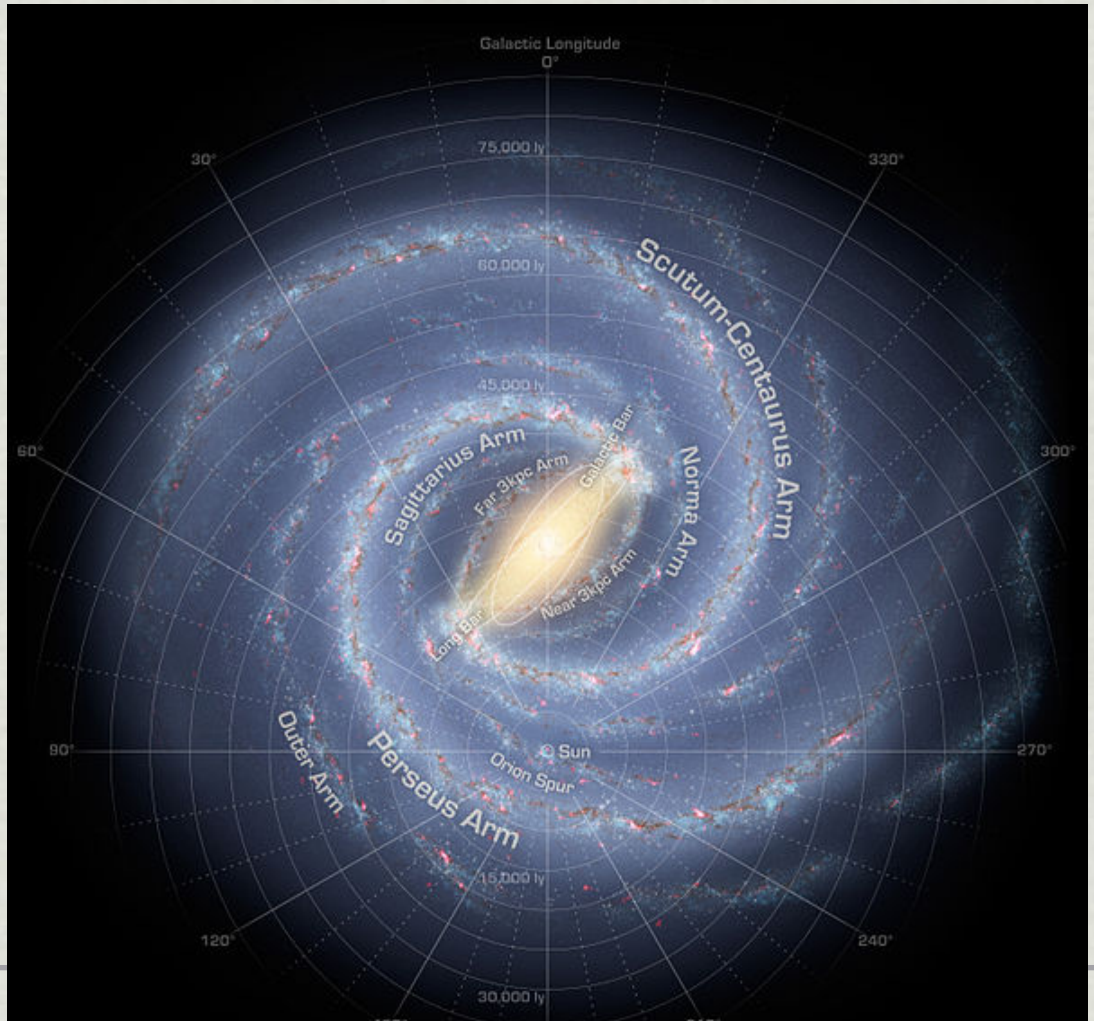
“Elliptical” galaxies: balls of stars with random orbits, like gas molecules in a balloon. Red color means all old stars, no ongoing star formation.

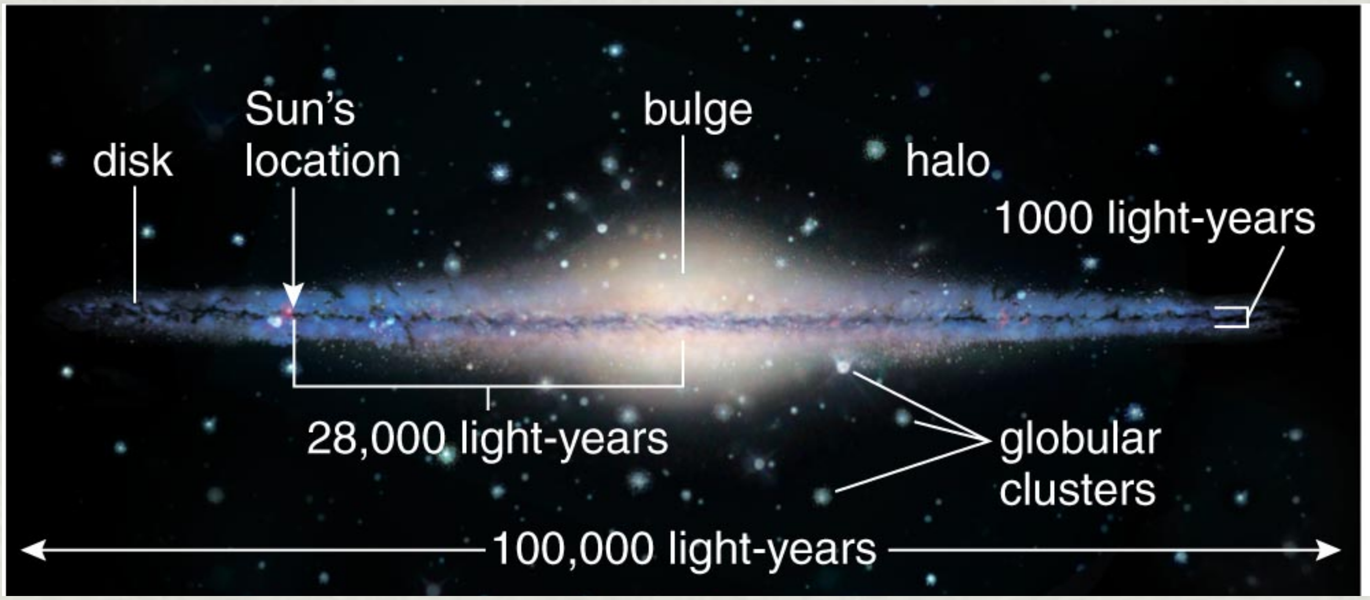
Milky Way: Mass

How is the mass distributed with the Milky Way?
It looks like a disk. Is the mass distributed like the light is?

You'd think so, right? What's making all that light?

Stars! (plus a little bit of H gas emission). And stars have plenty of mass.





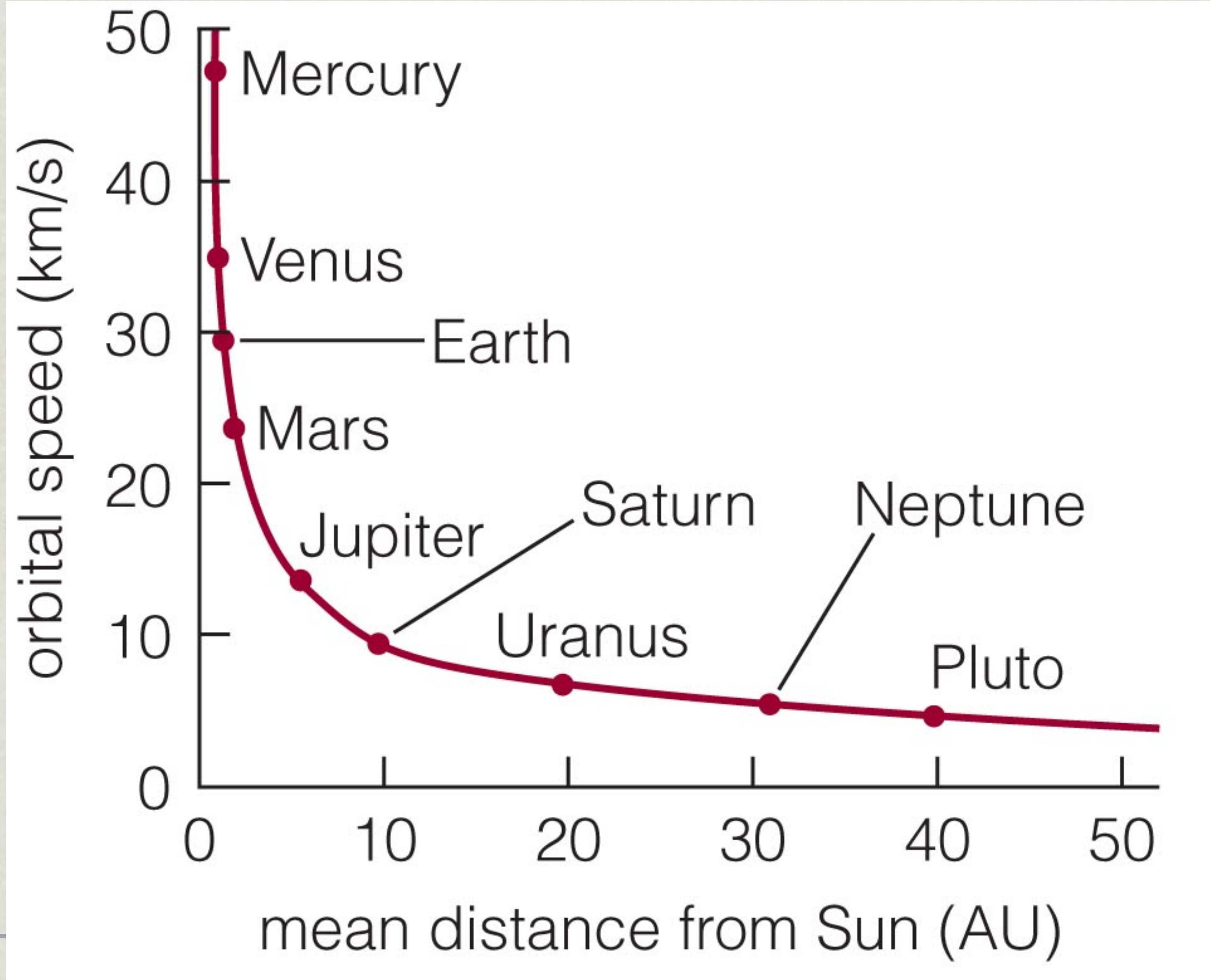
Face-on (left) and edge on (above) schematic views of the Milky Way

Milky Way: Mass

How is mass distributed with the Milky Way?

- Find out by measuring the **rotation curve**: plot velocity vs. radius

Rotation curve for the solar system

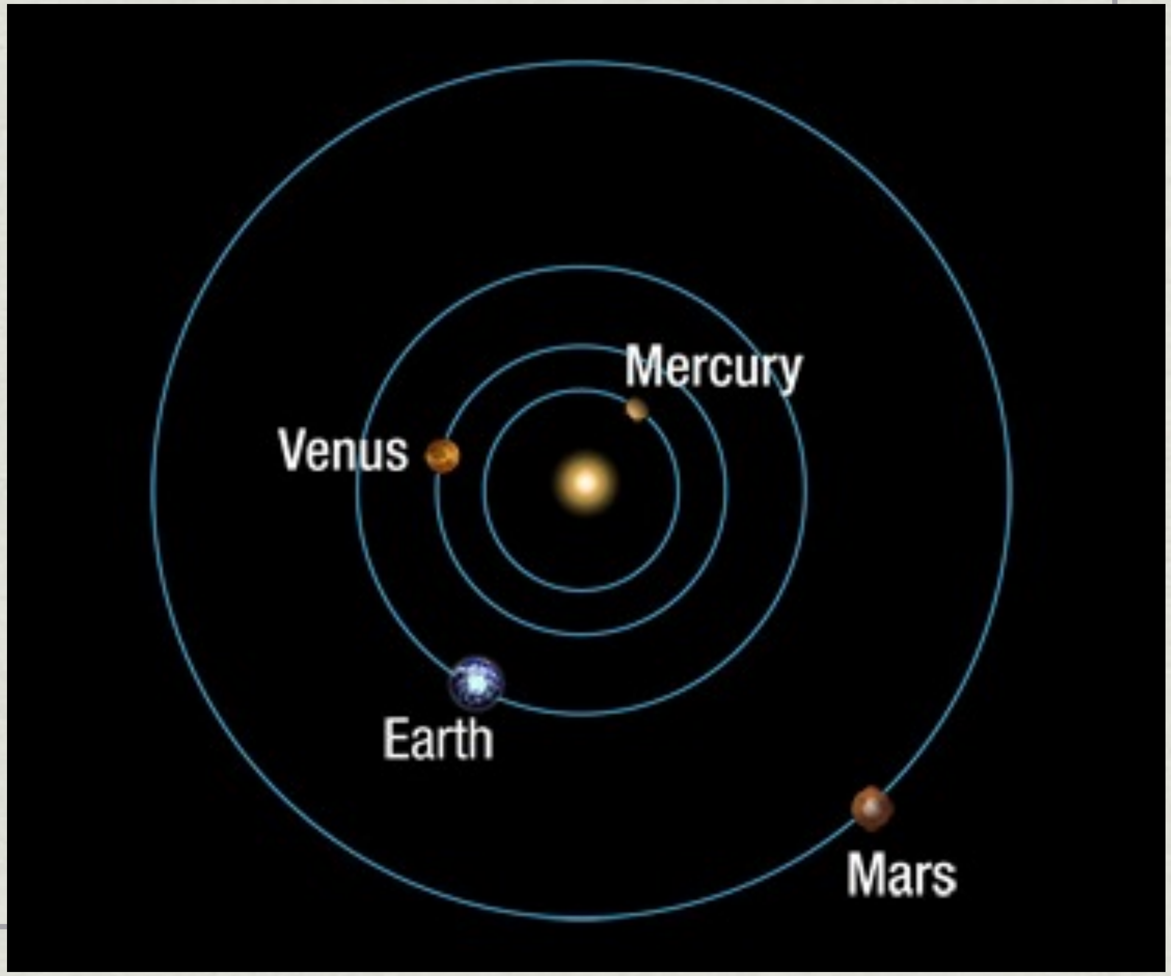


Milky Way: Mass

Equation for a circular orbit around mass M: $v^2 = \frac{GM}{r}$

Rearrange: $M = \frac{v^2 r}{G}$

So if the sun were twice as massive, what would happen to the velocity of the planets if the radii of their orbits stayed the same?



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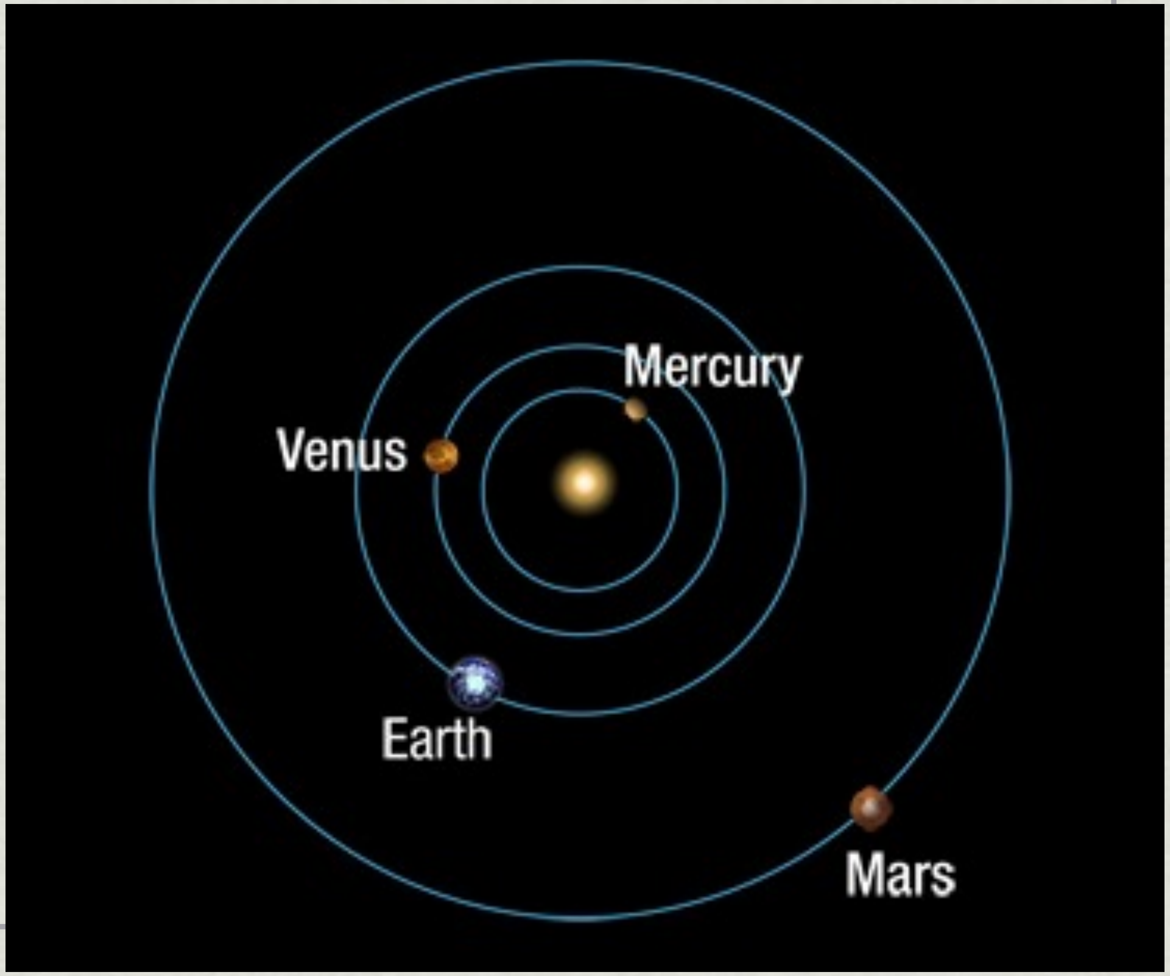
A specific example: what if the mass of the sun increases by a factor of 4?



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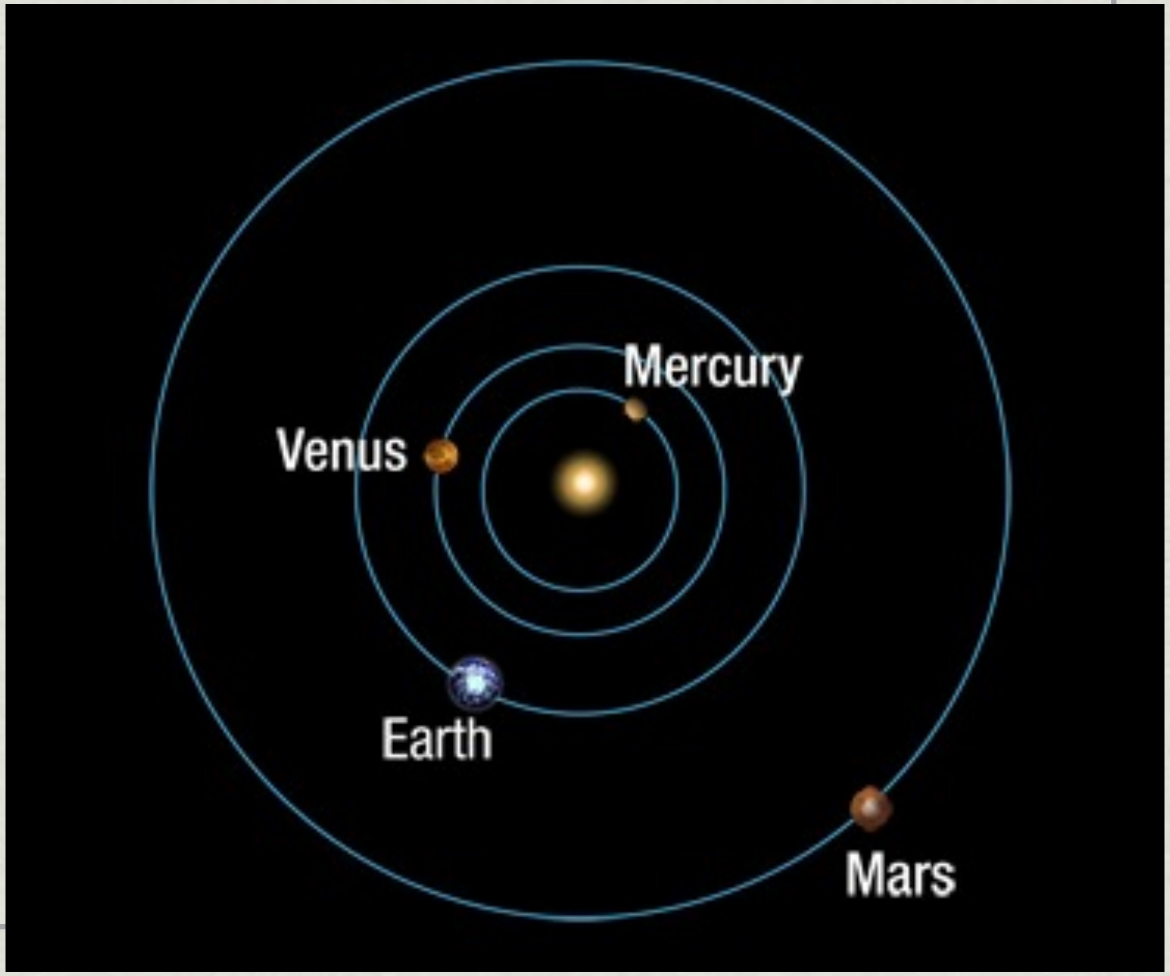
A specific example: what if the mass of the sun increases by a factor of 4?

If M increases by a factor of 4, v must increase by a factor of 2



Milky Way: Mass

Equation for a circular orbit around mass M: $v^2 = \frac{GM}{r}$

Rearrange: $M = \frac{v^2 r}{G}$

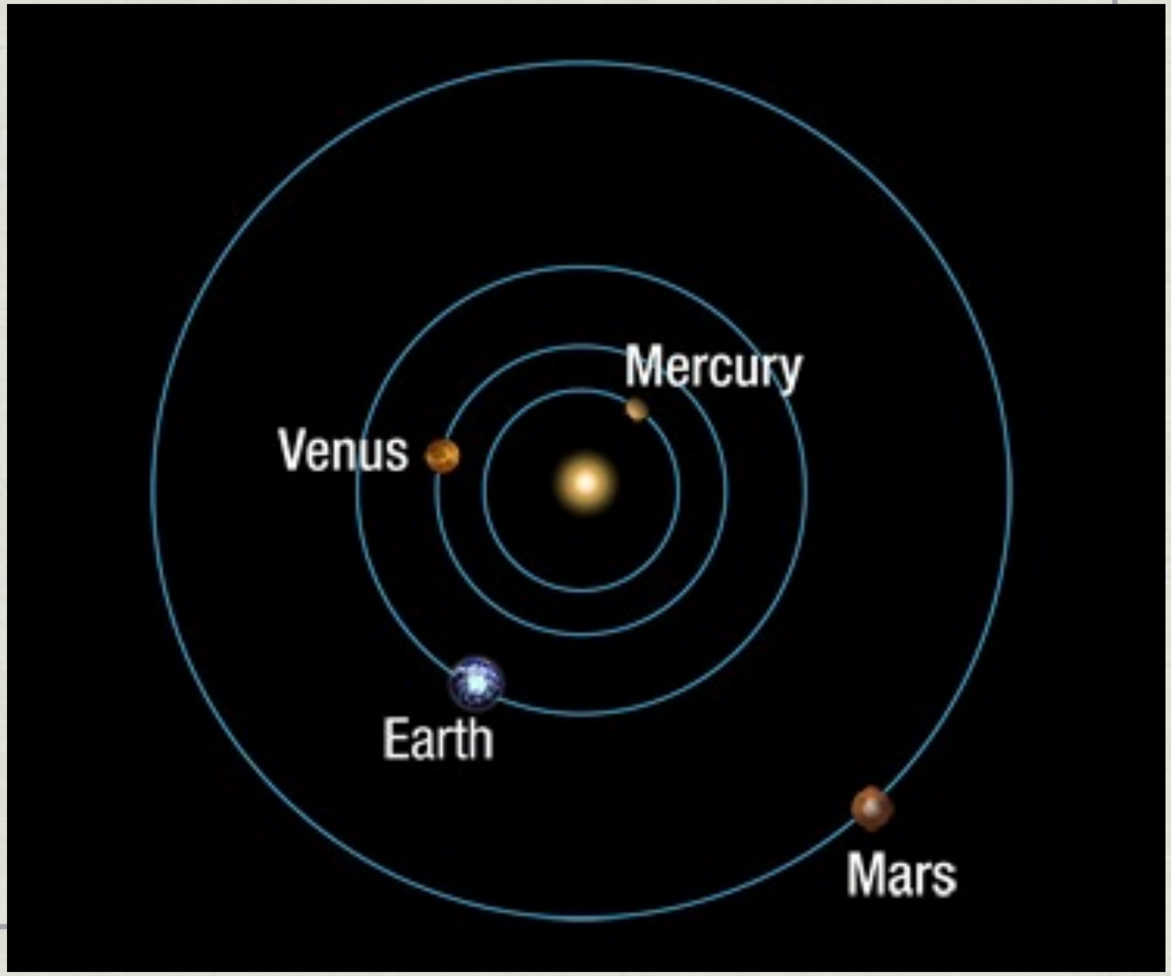
As the orbital radius of the planets increases, what happens to the velocity?

(Assume mass M stays constant)

If **r** increases, **v** must decrease to make the equation balance.

If r goes up by a factor of 4, how much does v decrease?

A factor of 4
B factor of 2
C factor of 8
D factor of 16



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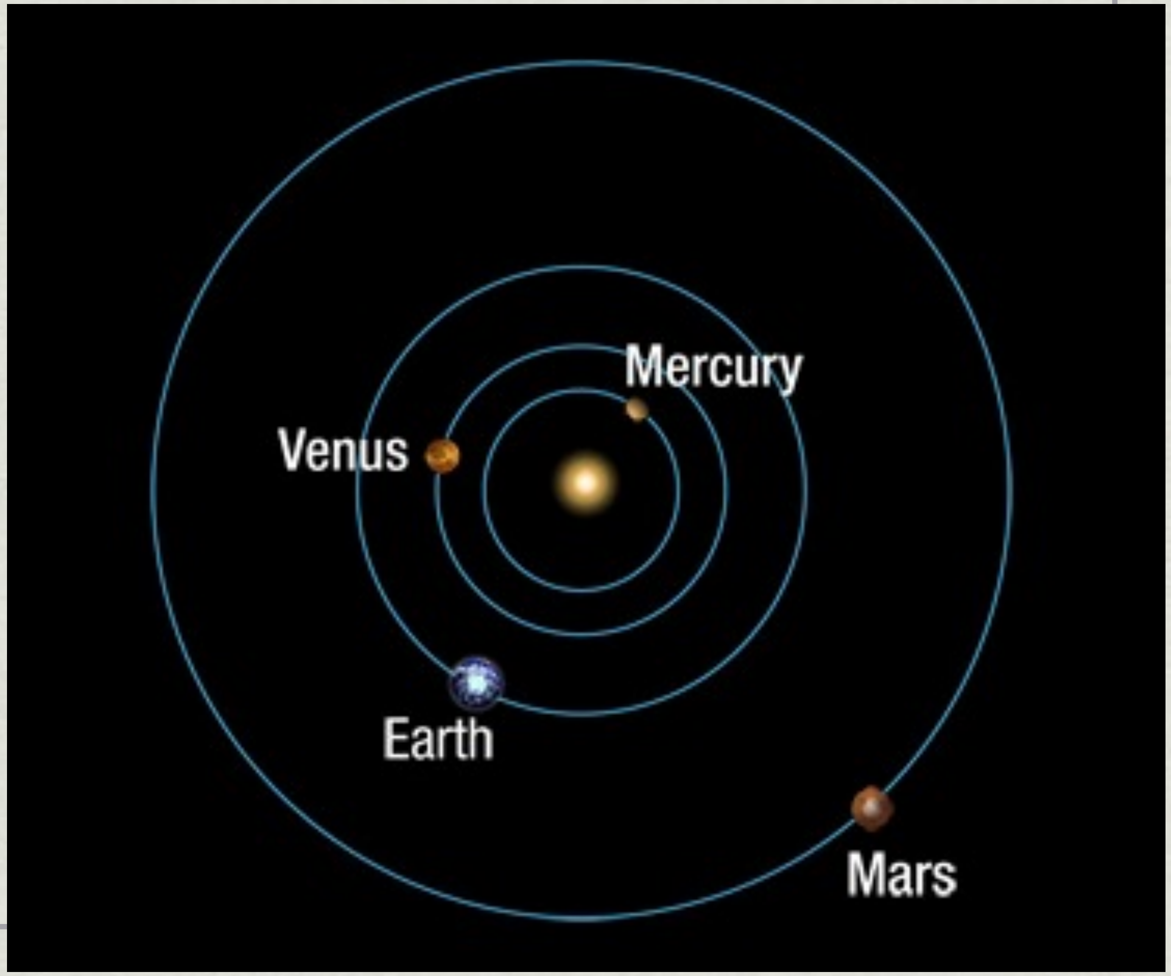

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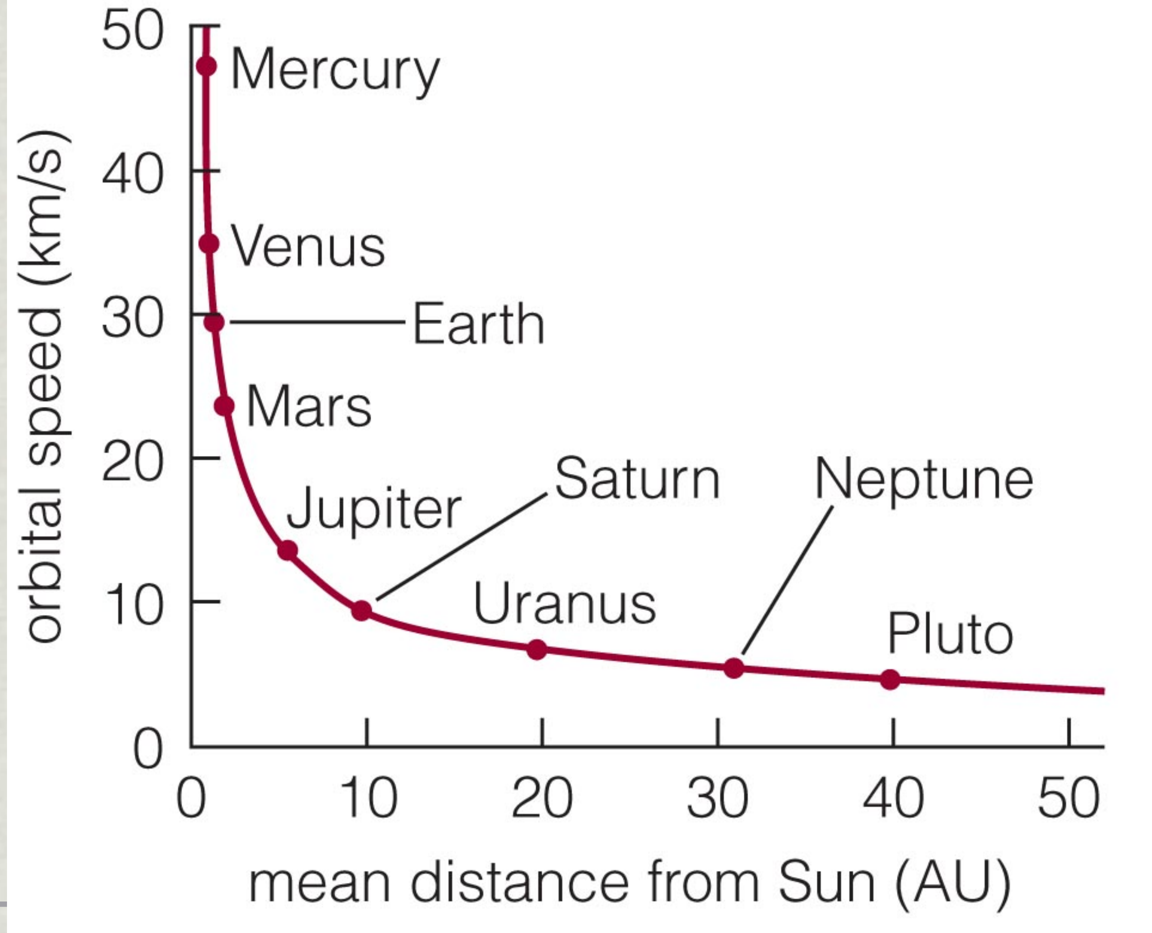

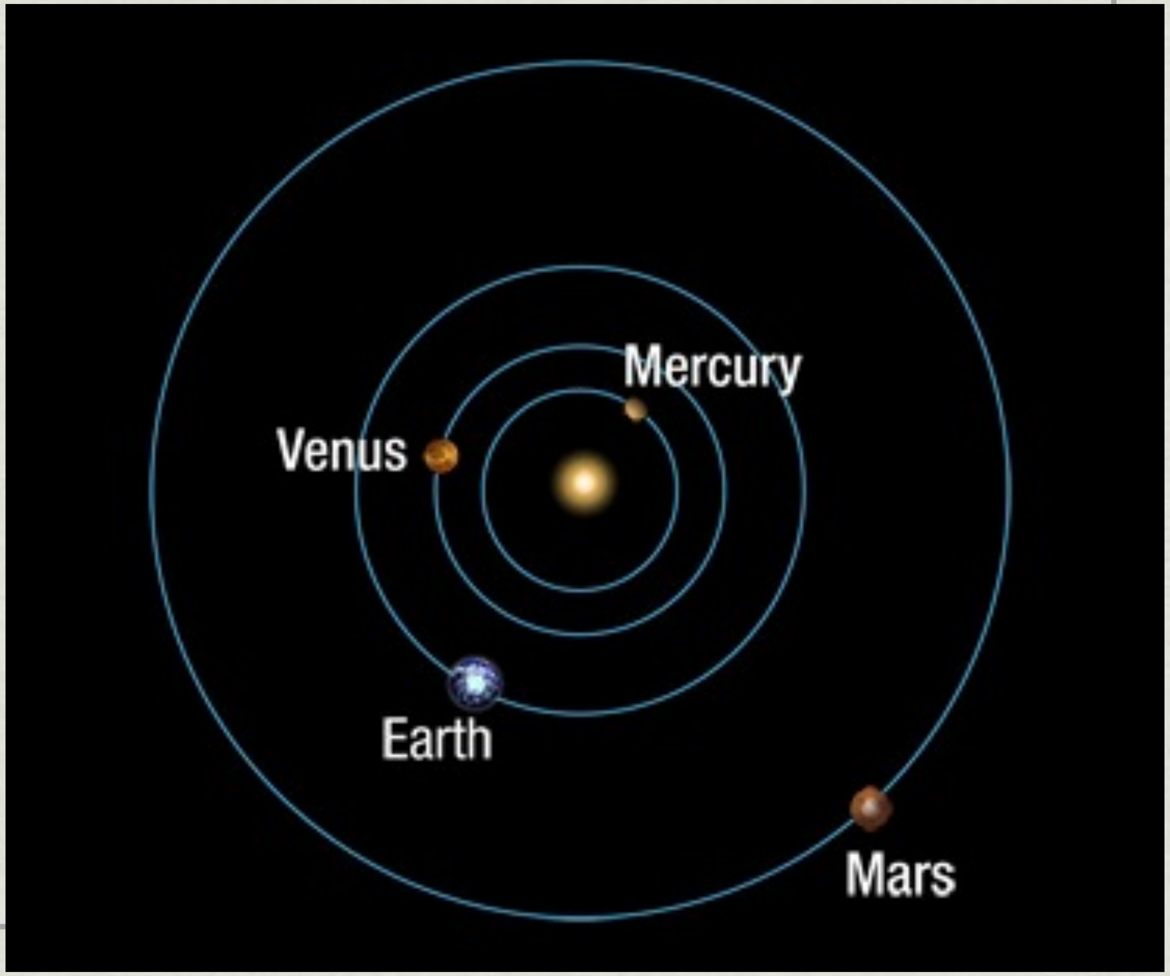

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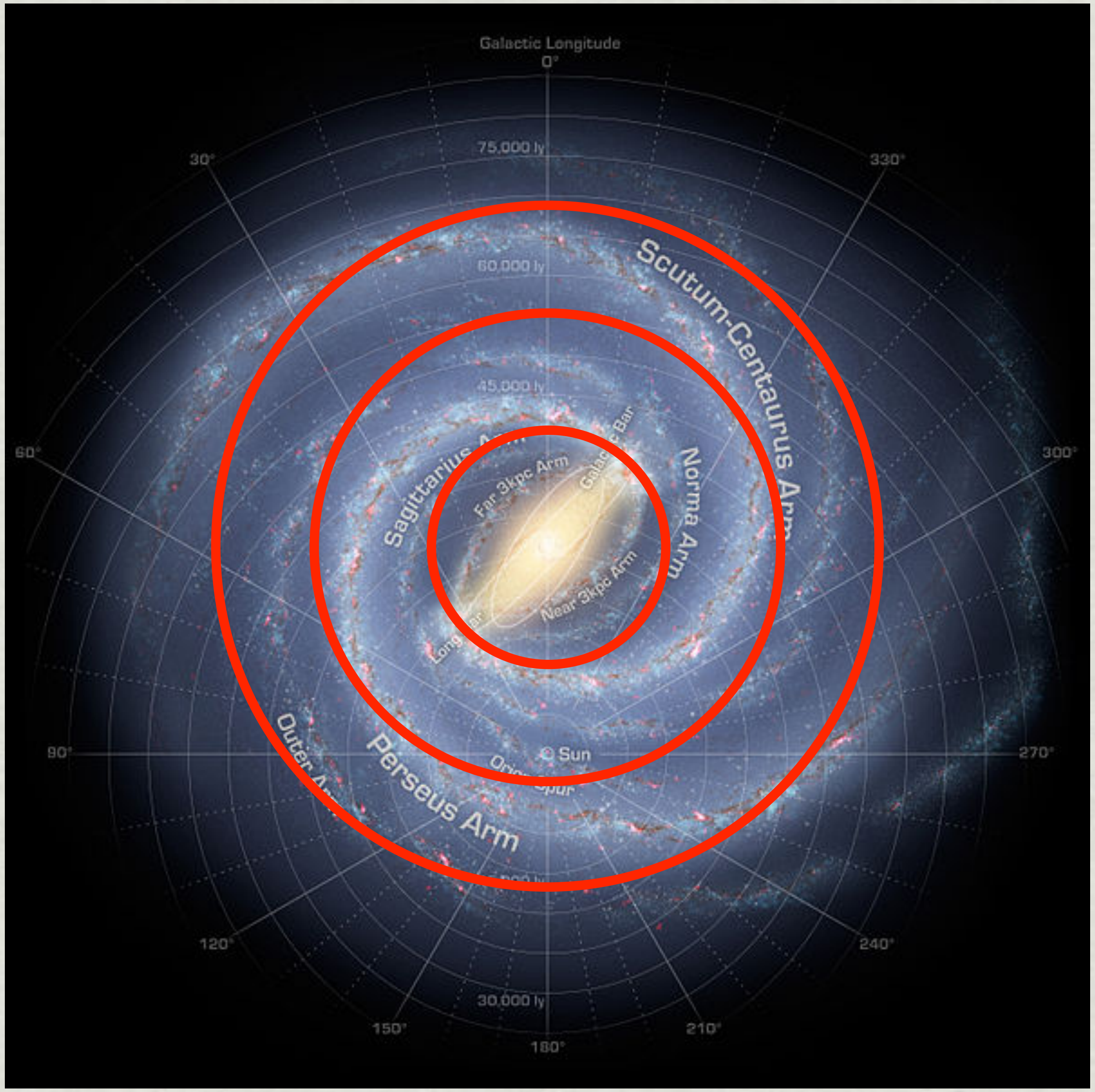
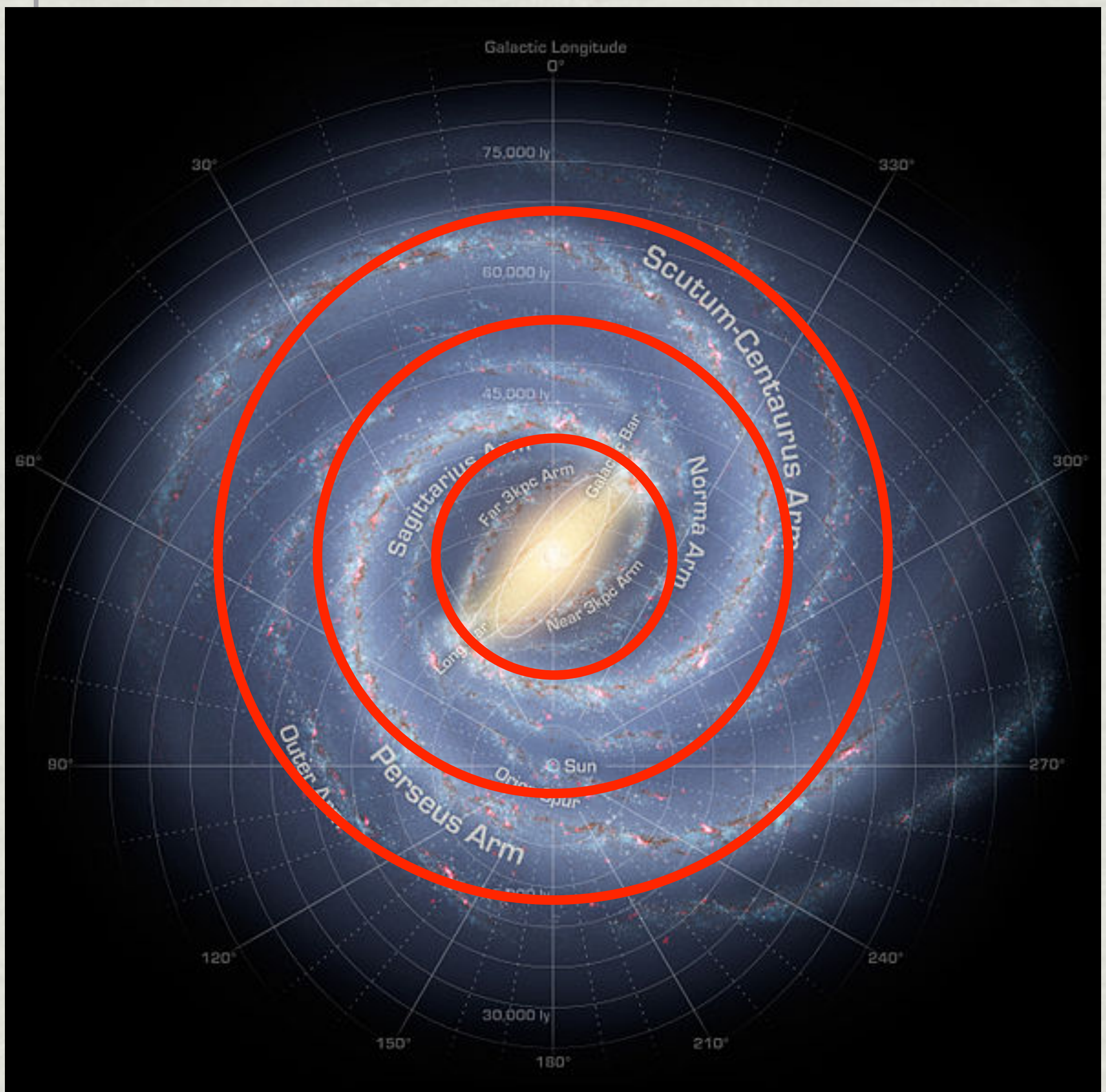


Mass vs radius for a galaxy:

Mass increases as radius gets larger.

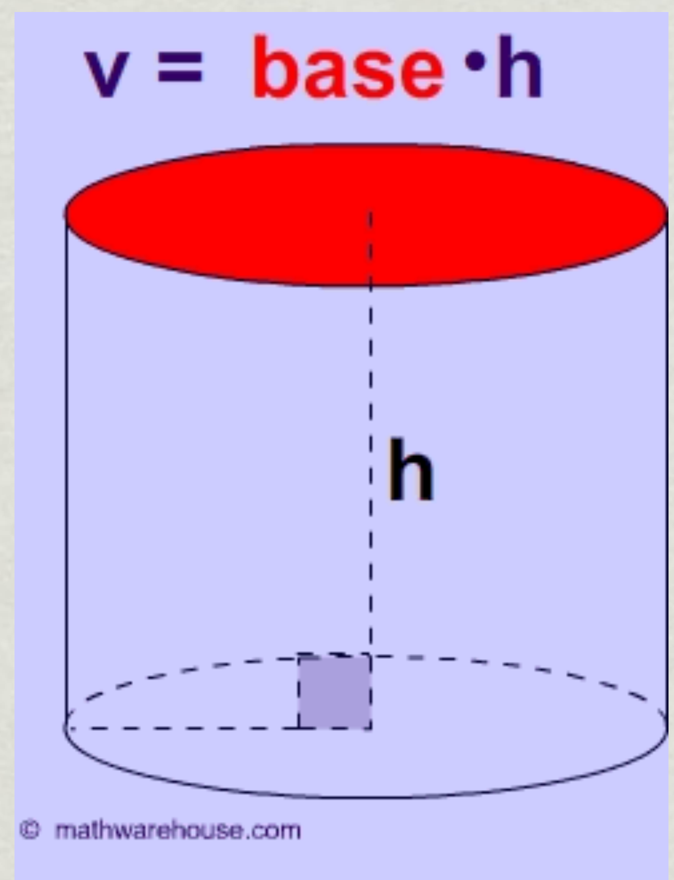
Milky Way: Mass

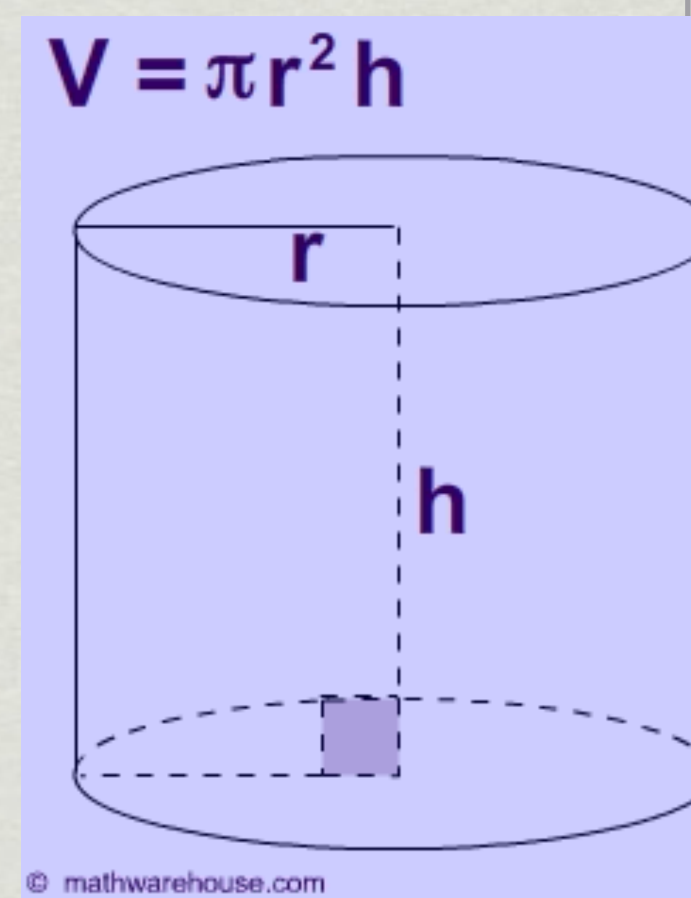


Mass vs radius for a galaxy:
Mass increases as radius gets larger.

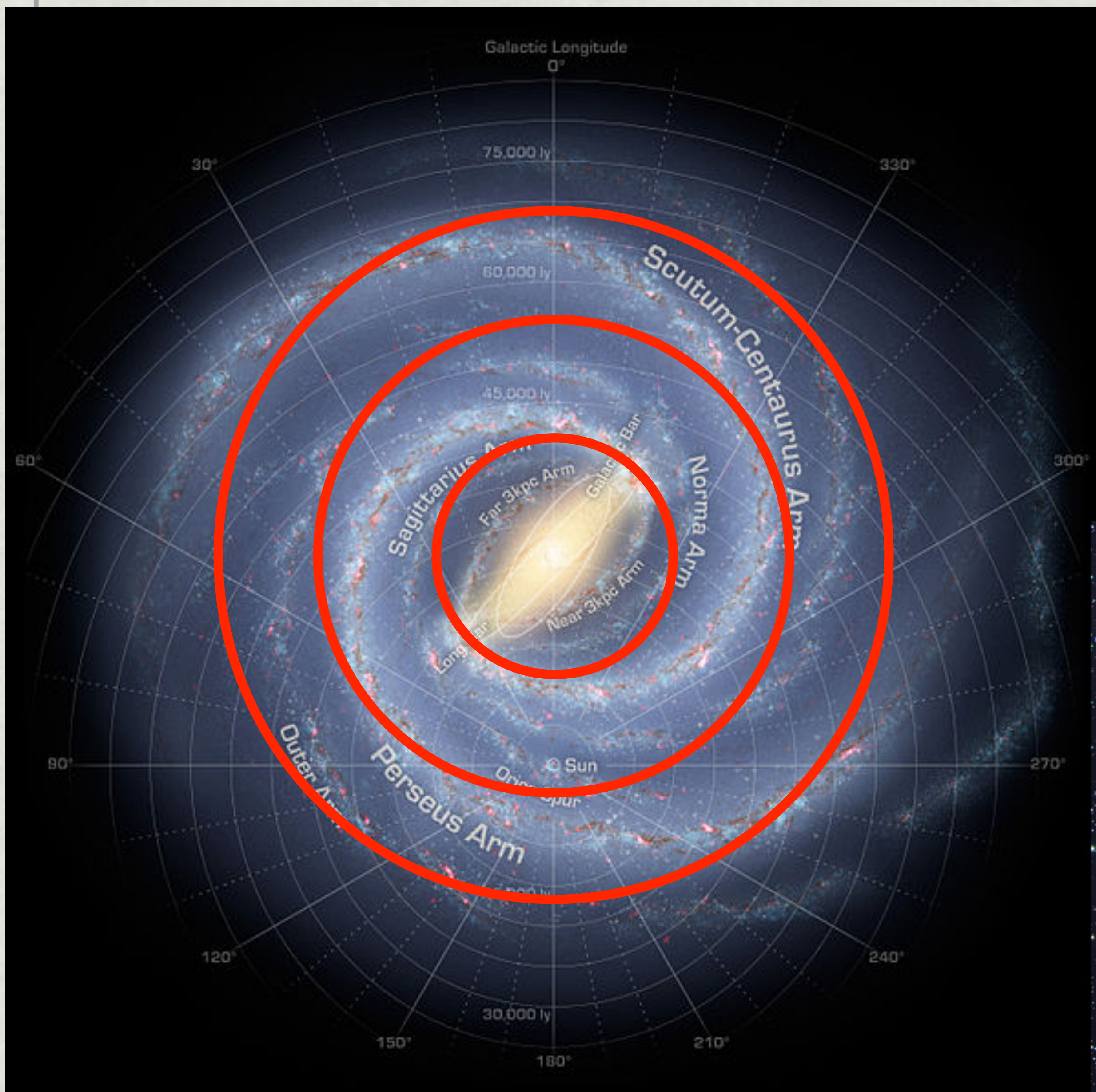
Volume of a cylinder: $4\pi r^2 h$

Mass = density × volume





Milky Way: Mass



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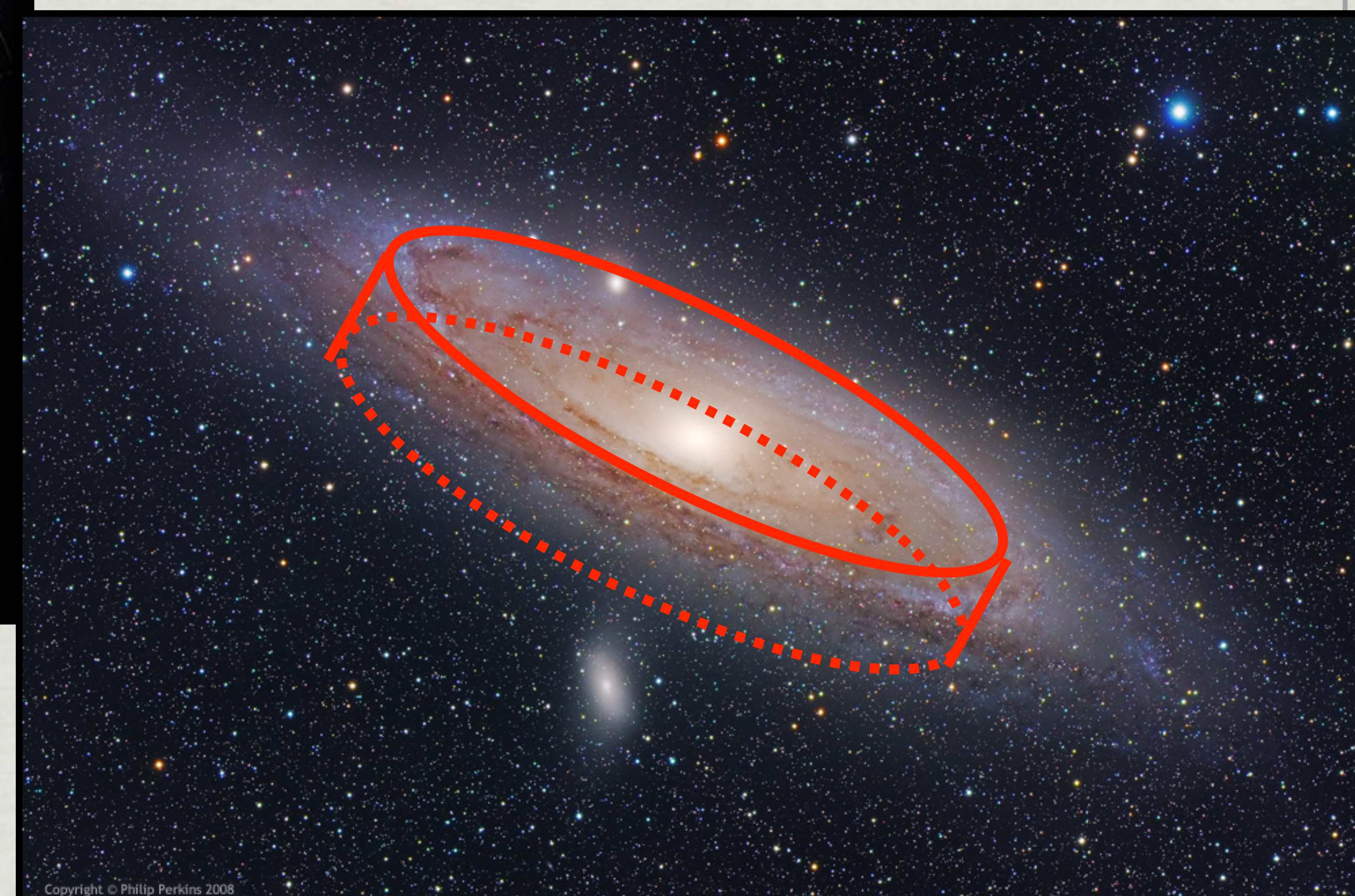

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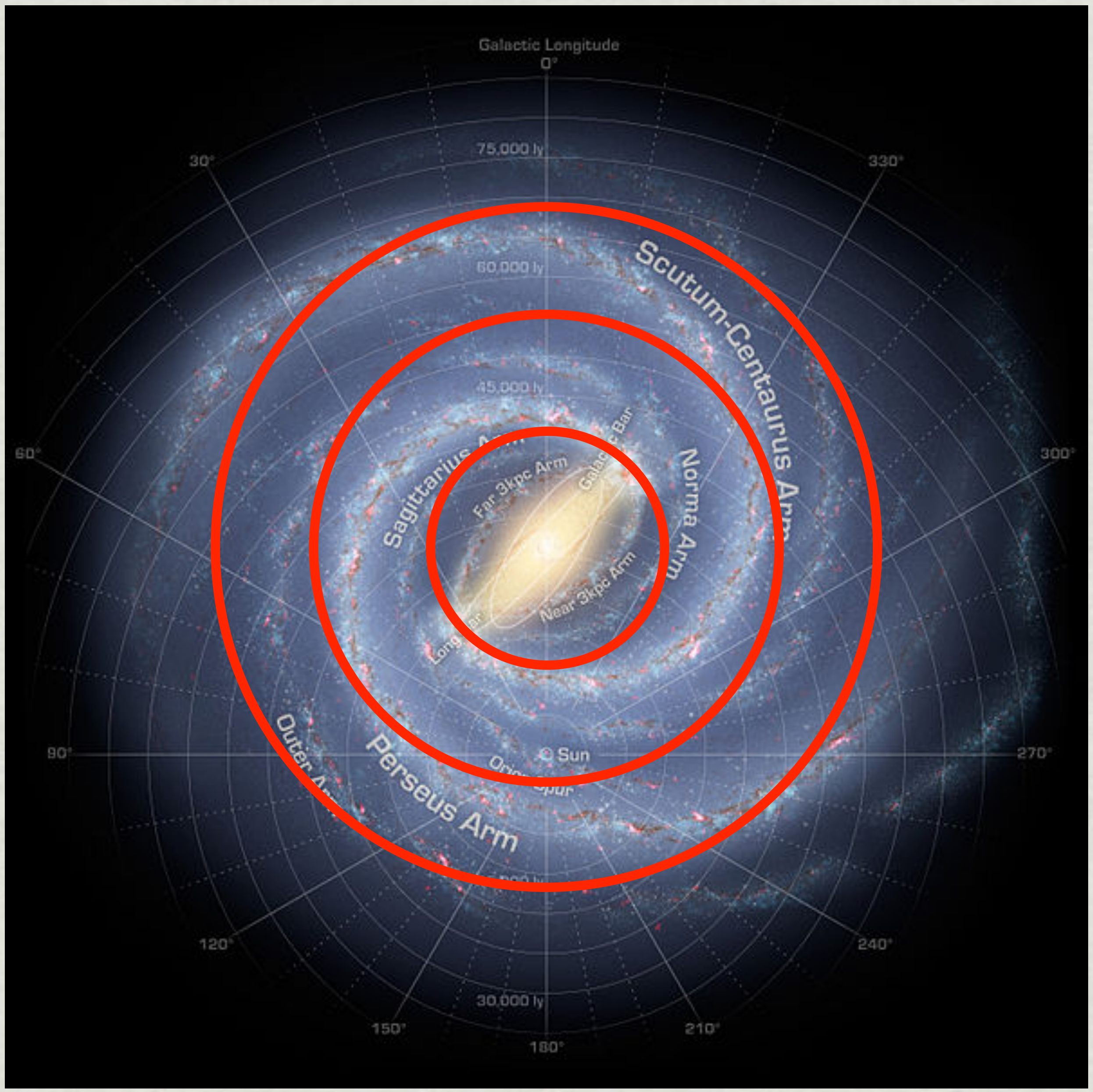

Mass vs radius for a galaxy:

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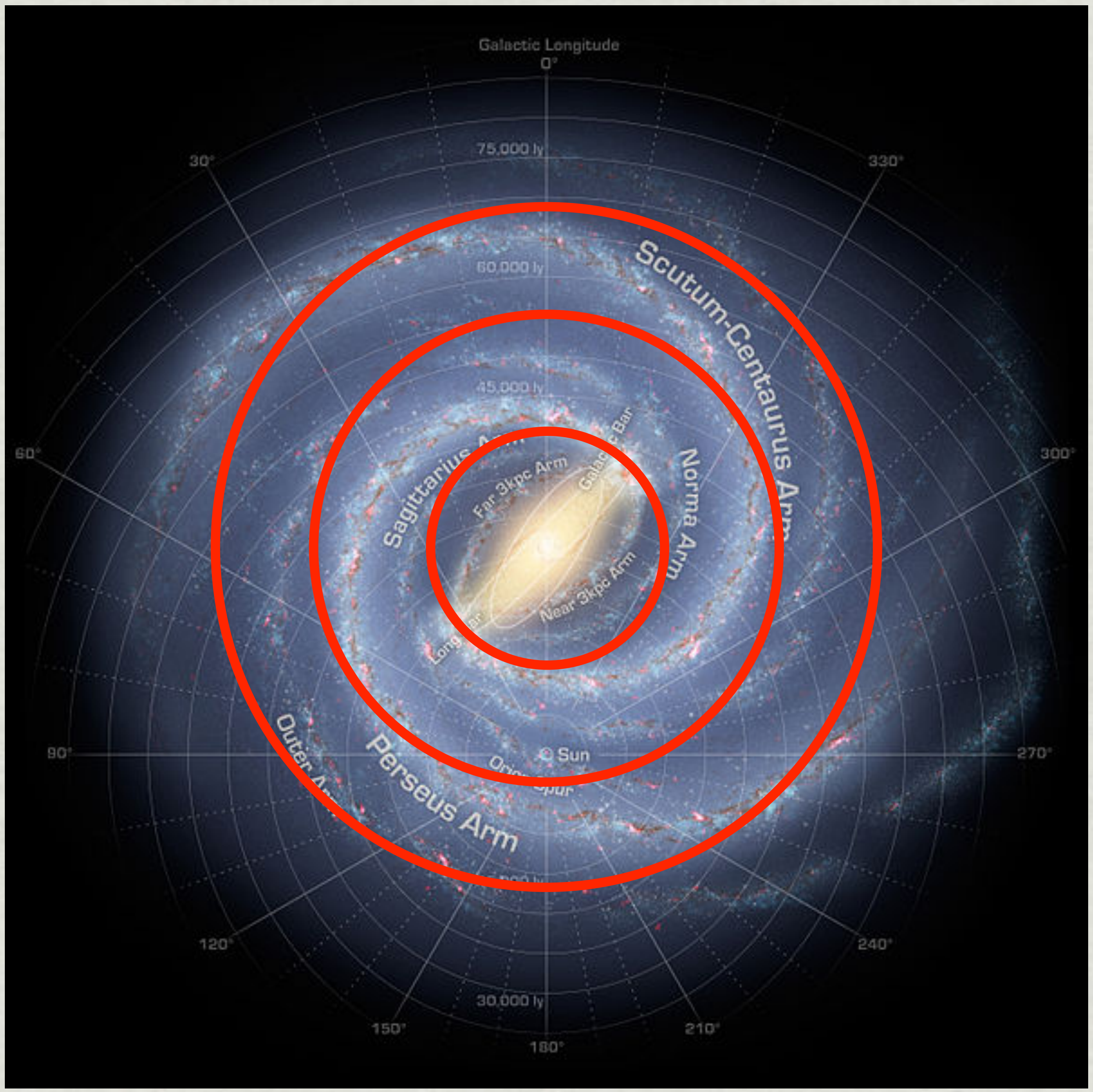
Volume of a cylinder: $4\pi r^2 h$
Mass = density × volume

What matters for the orbital speed is the mass *inside* the radius where you are measuring.

Gravitational pull of mass outside your radius cancels.

Milky Way: Mass



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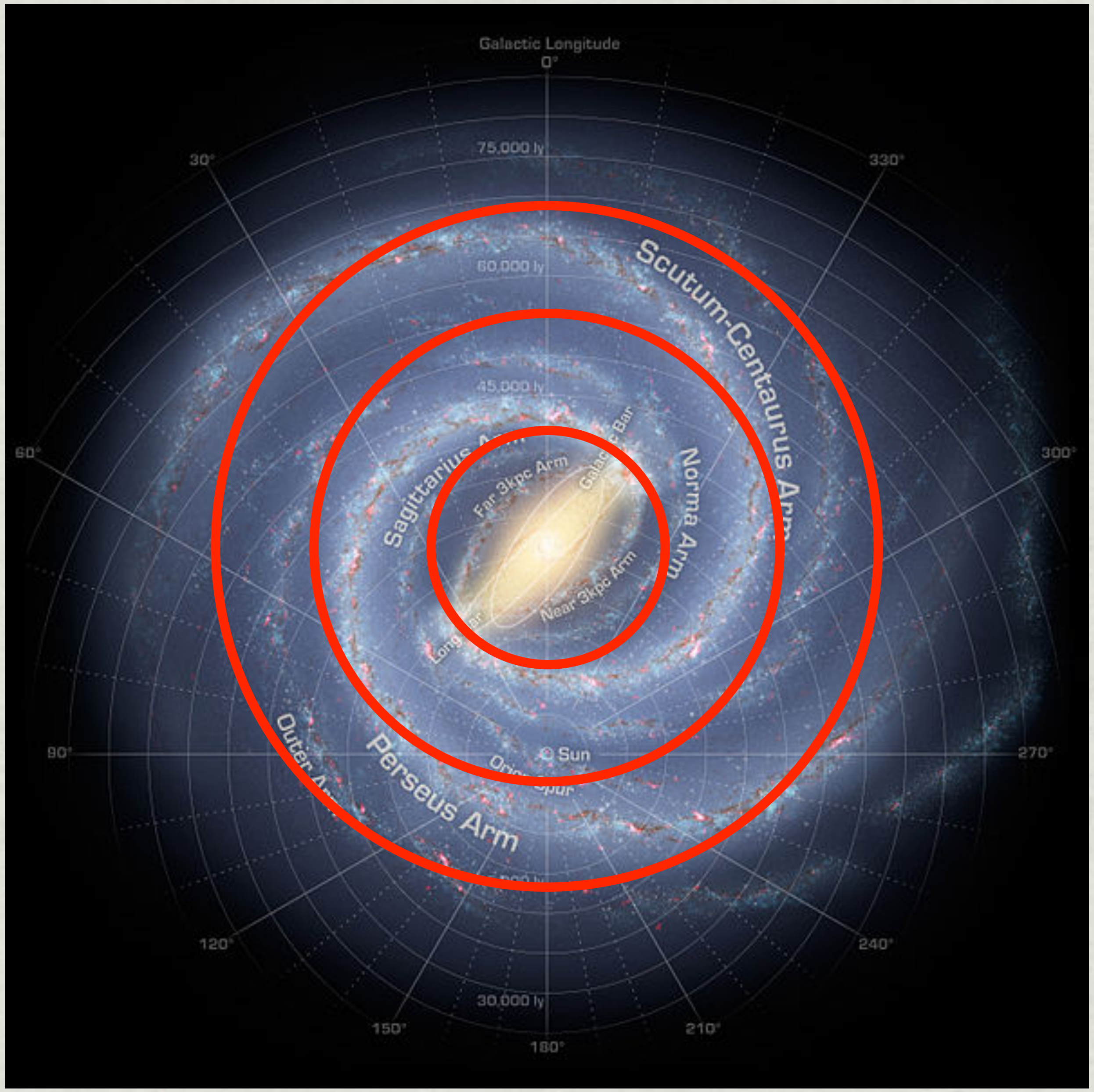
What should happen to the velocity as you measure at the circles drawn here?

Increase as radius gets larger?
Decrease as radius gets larger?

Milky Way: Mass



What matters is mass *inside* the radius. Gravitational pull of mass outside the radius cancels.

Volume of a cylinder: $4\pi r^2 h$

Mass = density × volume

= density x $4\pi r^2 h$

Remember, speed of an orbit around mass M: $v^2 = \frac{GM}{r}$

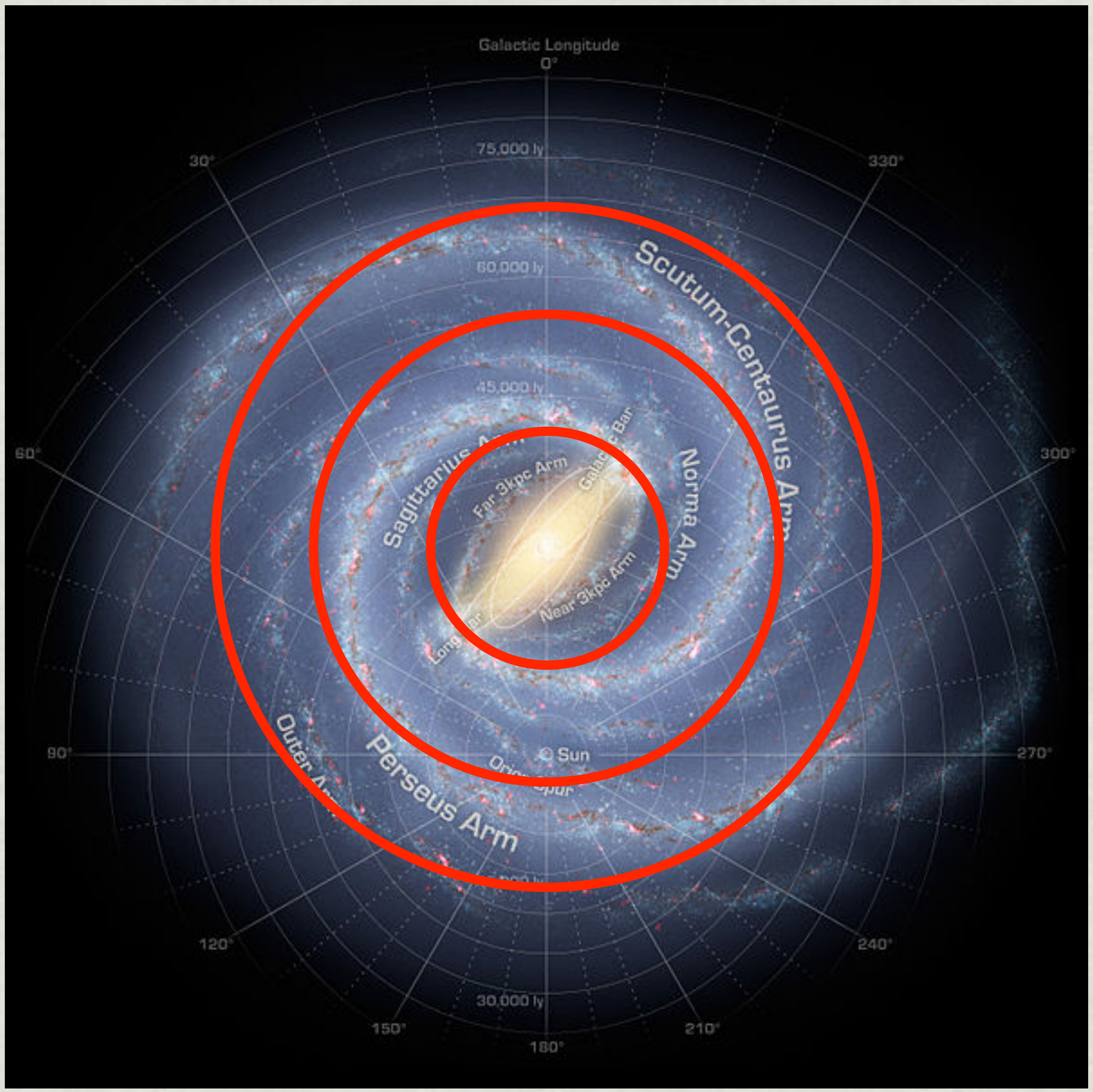
So $v^2 = \frac{G \text{ x density x volume}}{r}$

$v^2 = \frac{G \text{ x density x } 4\pi r^2 h}{r}$

Cancel the powers of r: $v^2 \sim (G4\pi h)$ x density x r

$v^2 \sim r$

Milky Way: Mass



Mass vs radius for a galaxy:

Mass increases as radius gets larger.

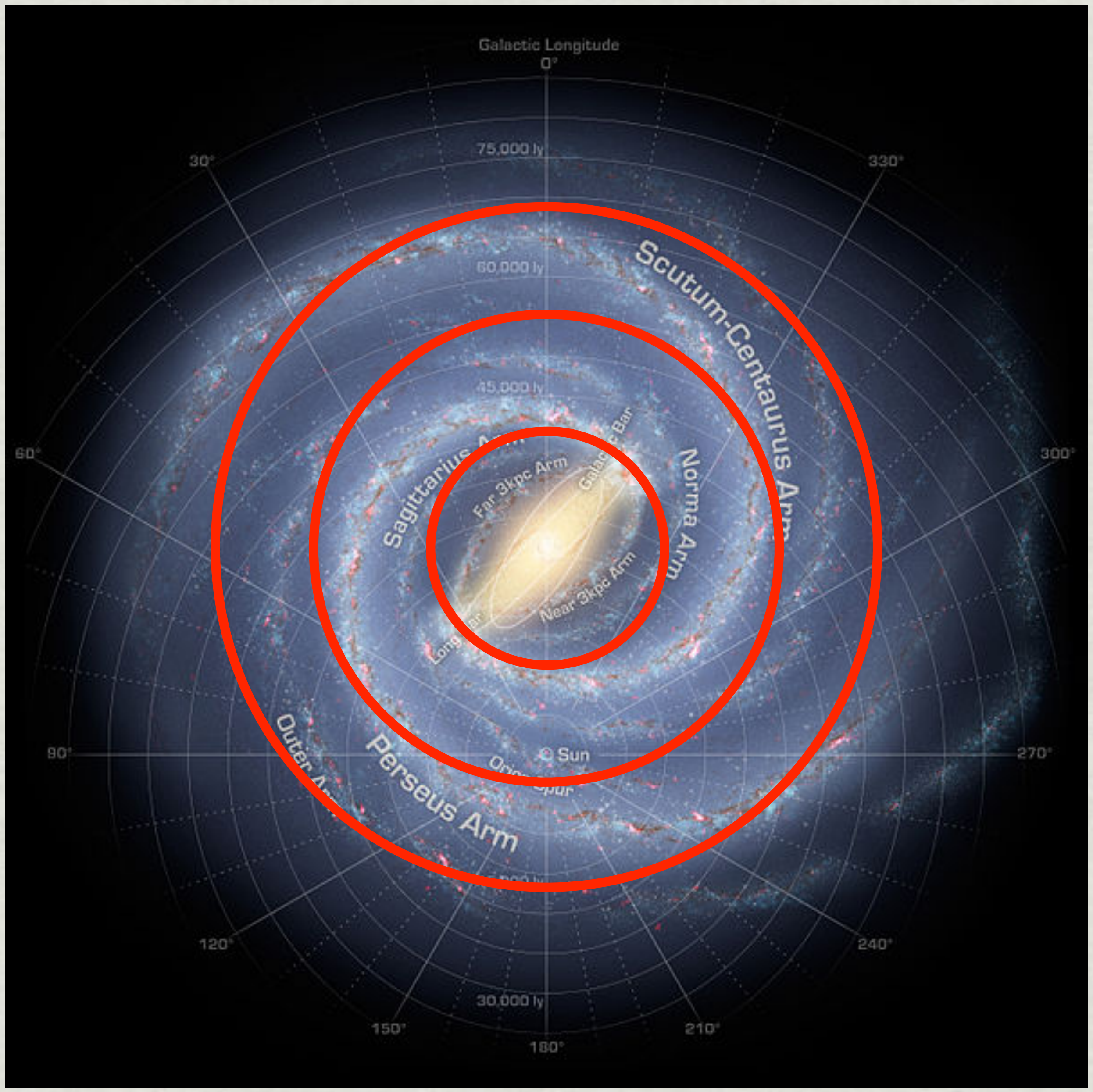
From the previous slide: $v^2 \sim r$

What matters is mass *inside* each radius. Gravitational pull of mass outside the radius cancels.

What should happen to the velocity for as you measure it for all the circles drawn here, starting from the center of the galaxy and working out?

A increase as radius gets larger
B decrease as radius gets larger

Milky Way: Mass



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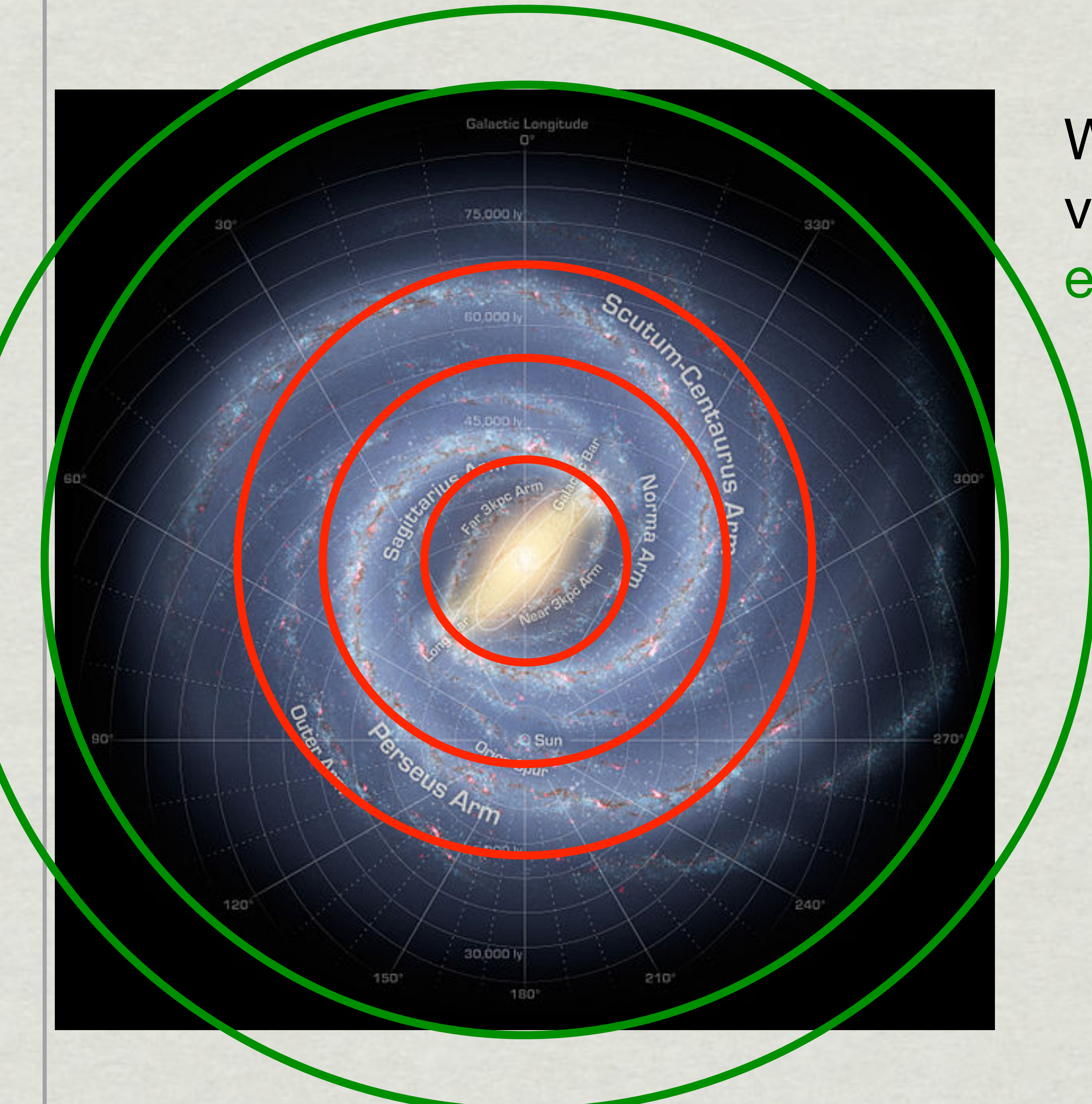
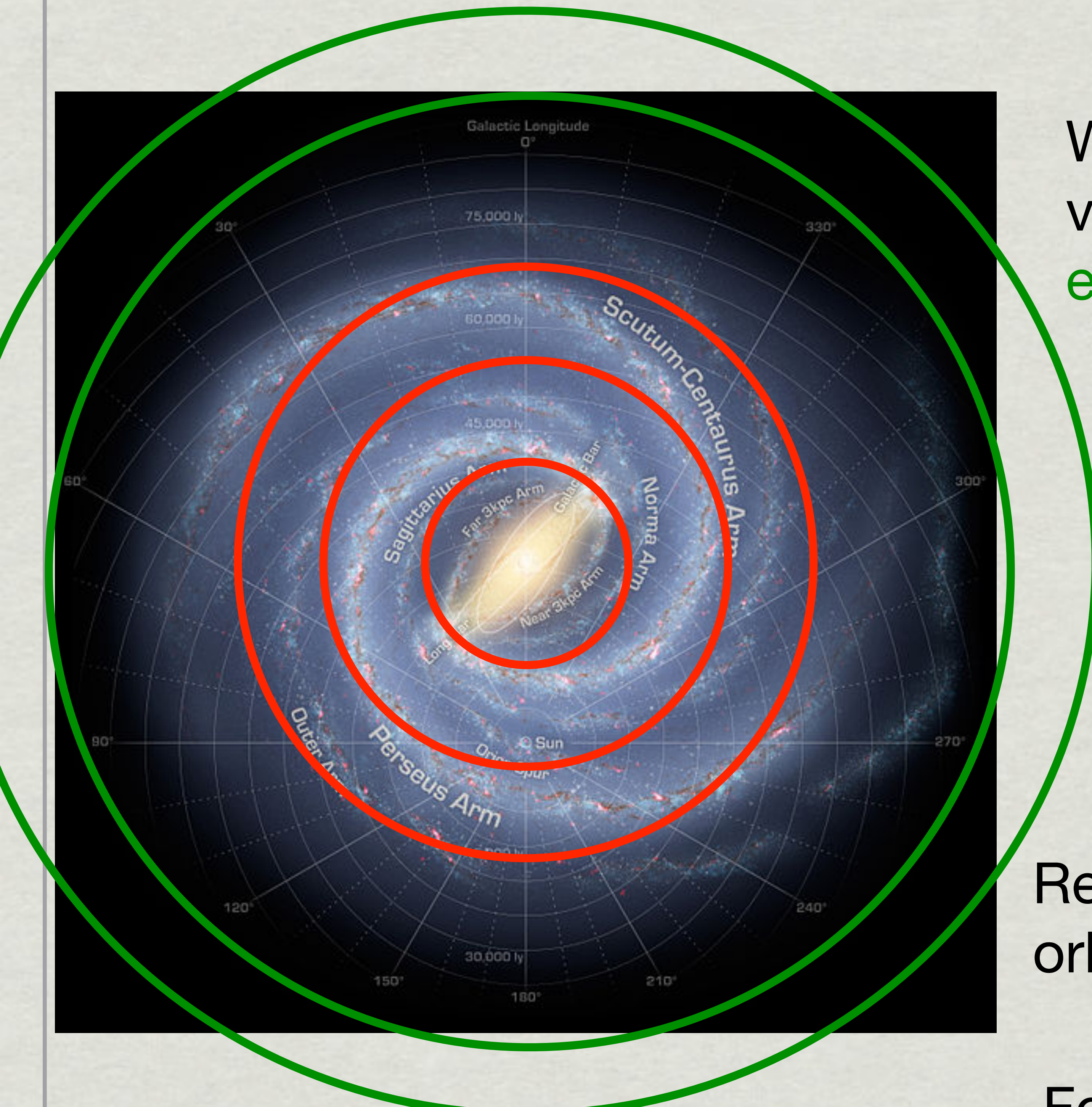


What do you expect will happen to the velocity once the circles get big enough to enclose all the stars?

A) velocity increases as radius gets larger (green circle and beyond)

B) velocity should decrease as radius gets larger (green circle and beyond)

Milky Way: Mass



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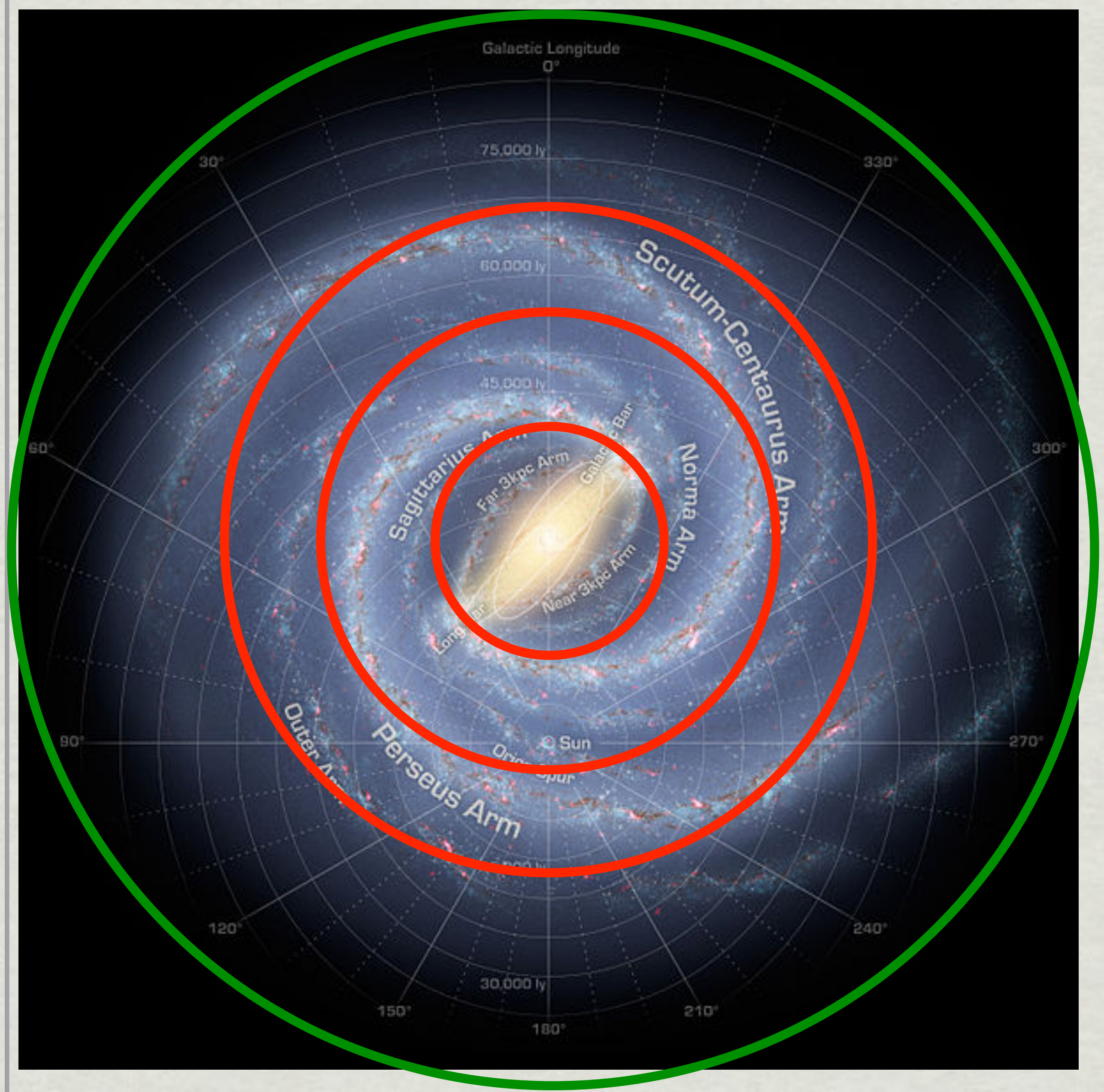
A) velocity increases as radius gets larger (green circle and beyond)

B) velocity should decrease as radius gets larger (green circle and beyond)

Remember, speed of an orbit around mass M: $$v^2 = \frac{GM}{r}$$

For all r large enough to enclose all the stars, expect M to be the same.

Milky Way: Mass



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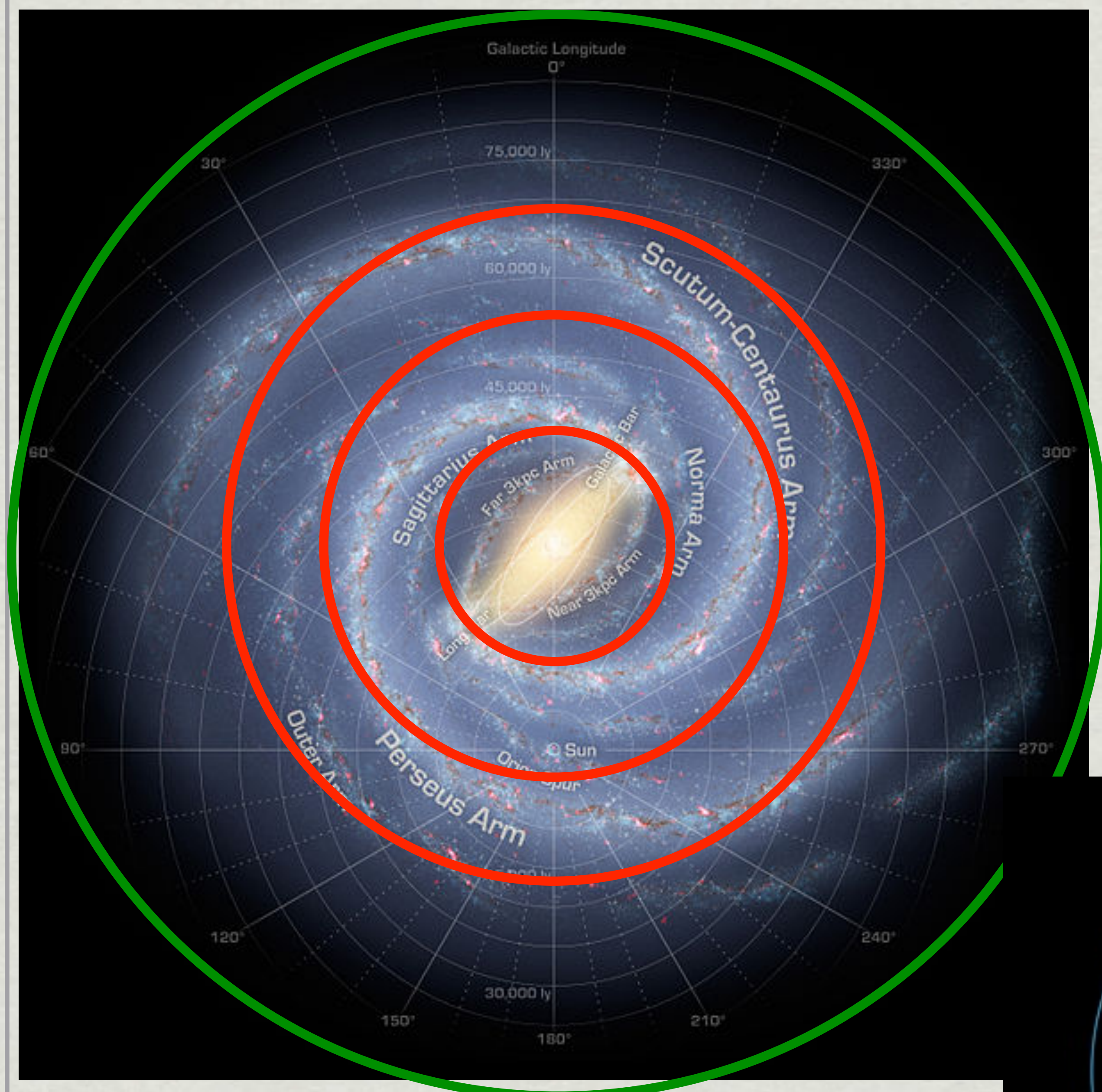
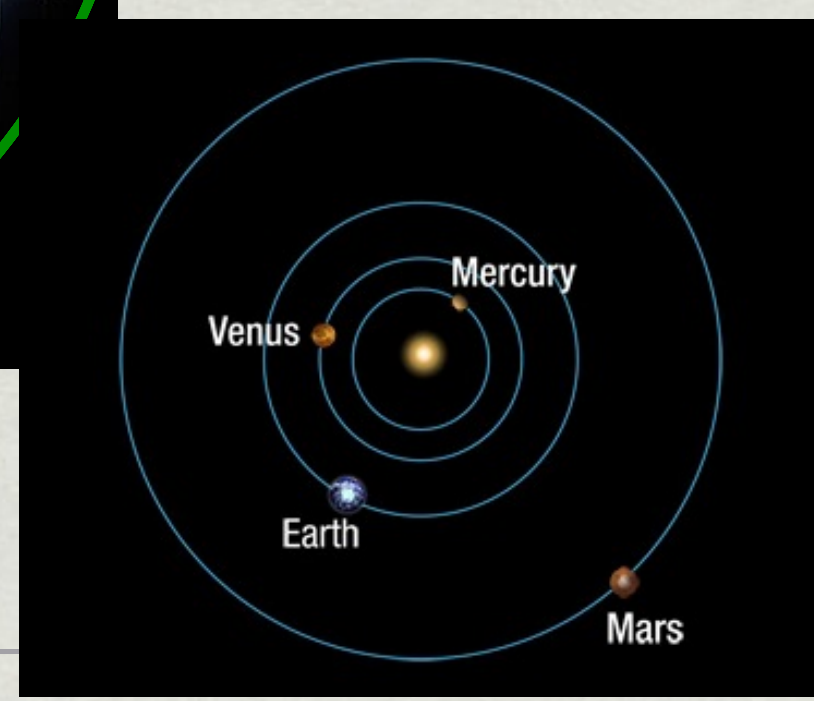
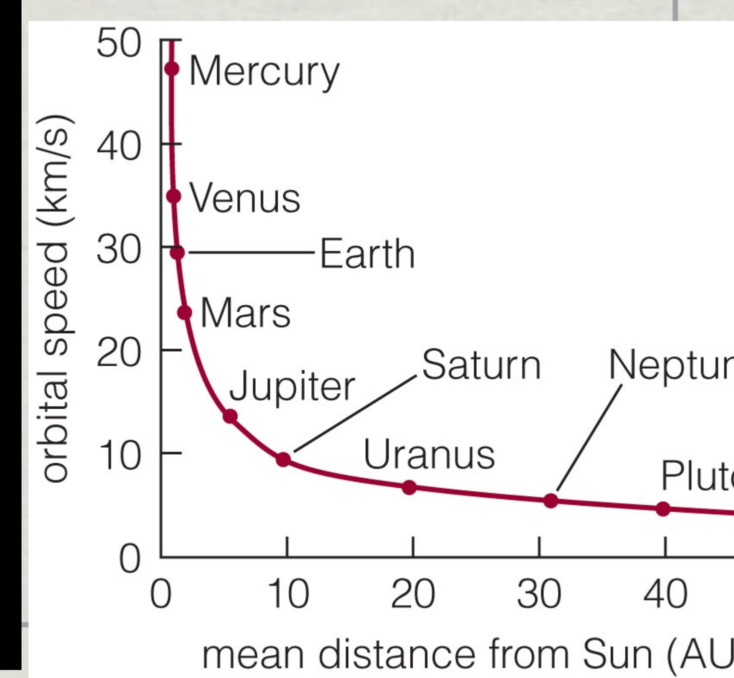


What do you expect will happen to the velocity once the circles get big enough to enclose all the stars?

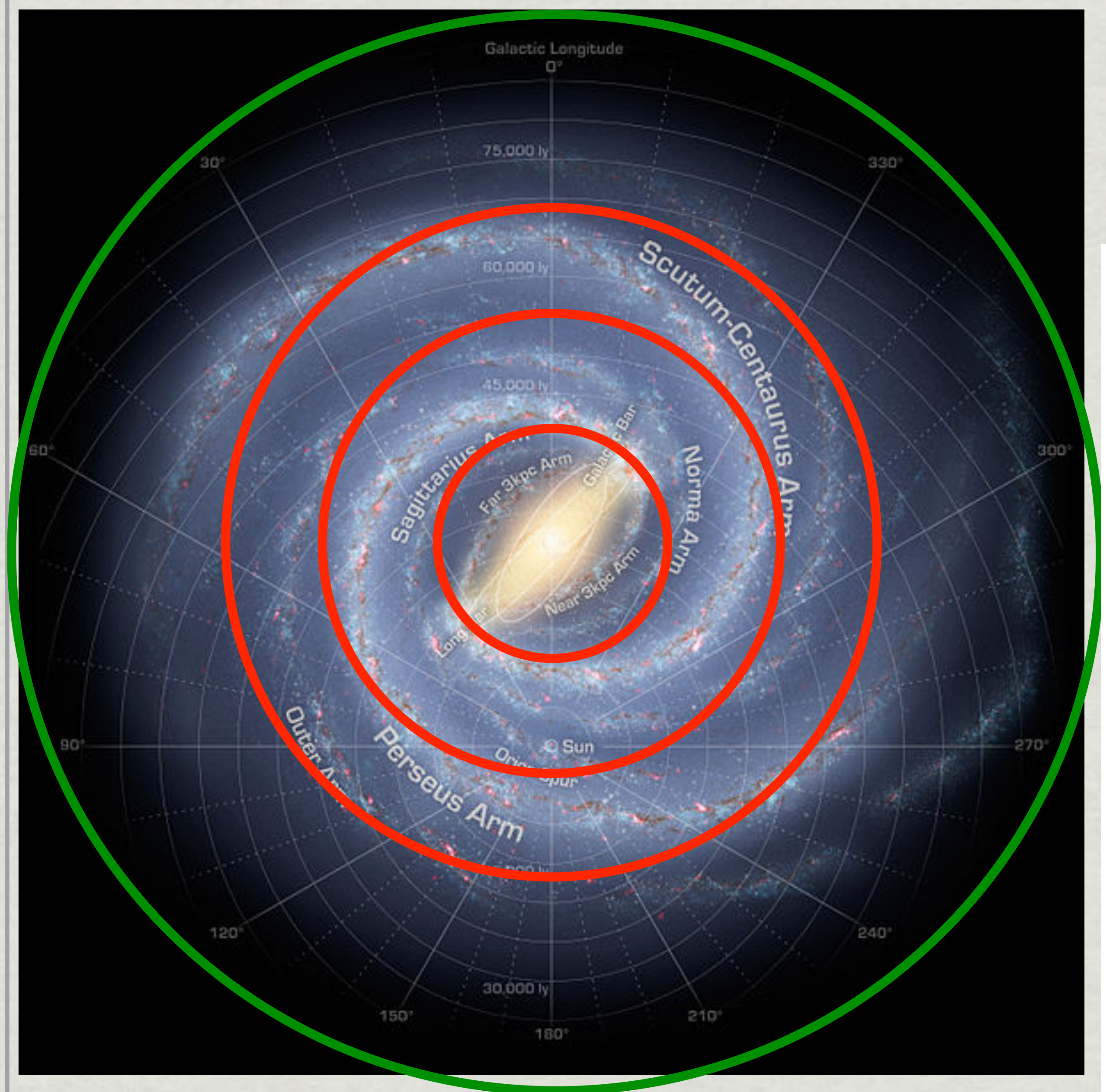
Velocity should decrease at larger radii, just like for the solar system. All the mass is inside the large circles, right?

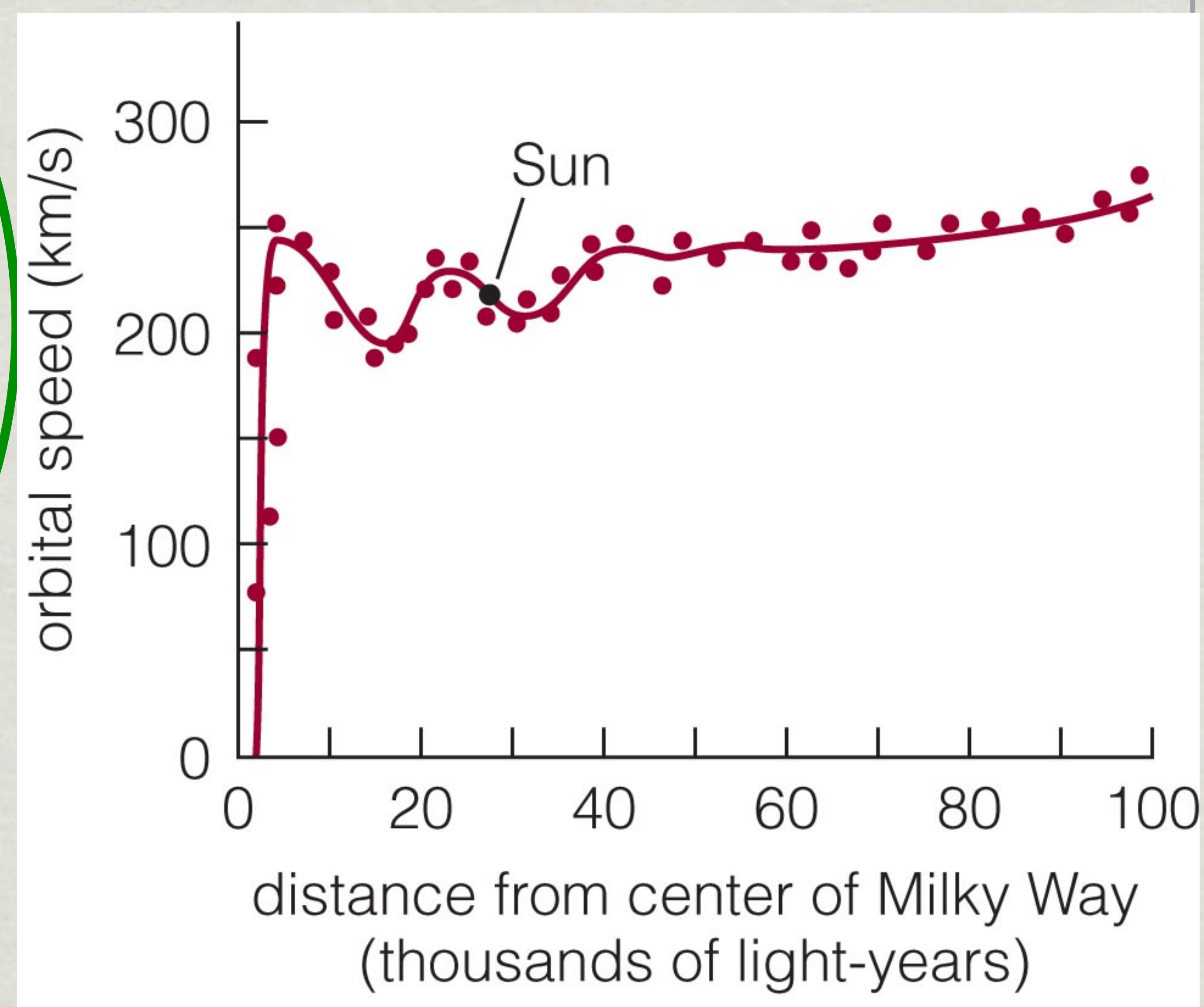




Milky Way: Mass

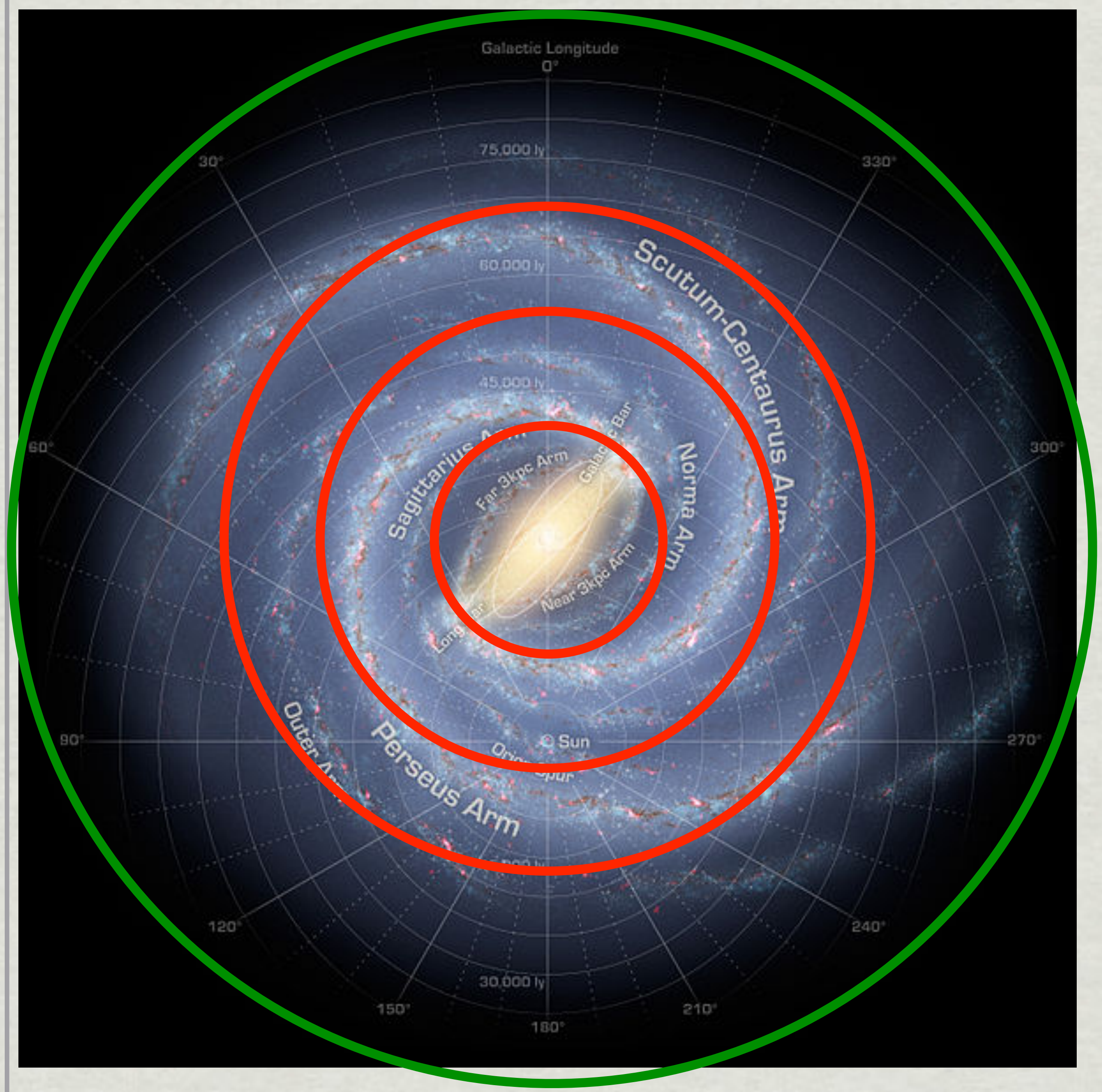
What we measure is wonderfully weird:
the velocity stays constant.



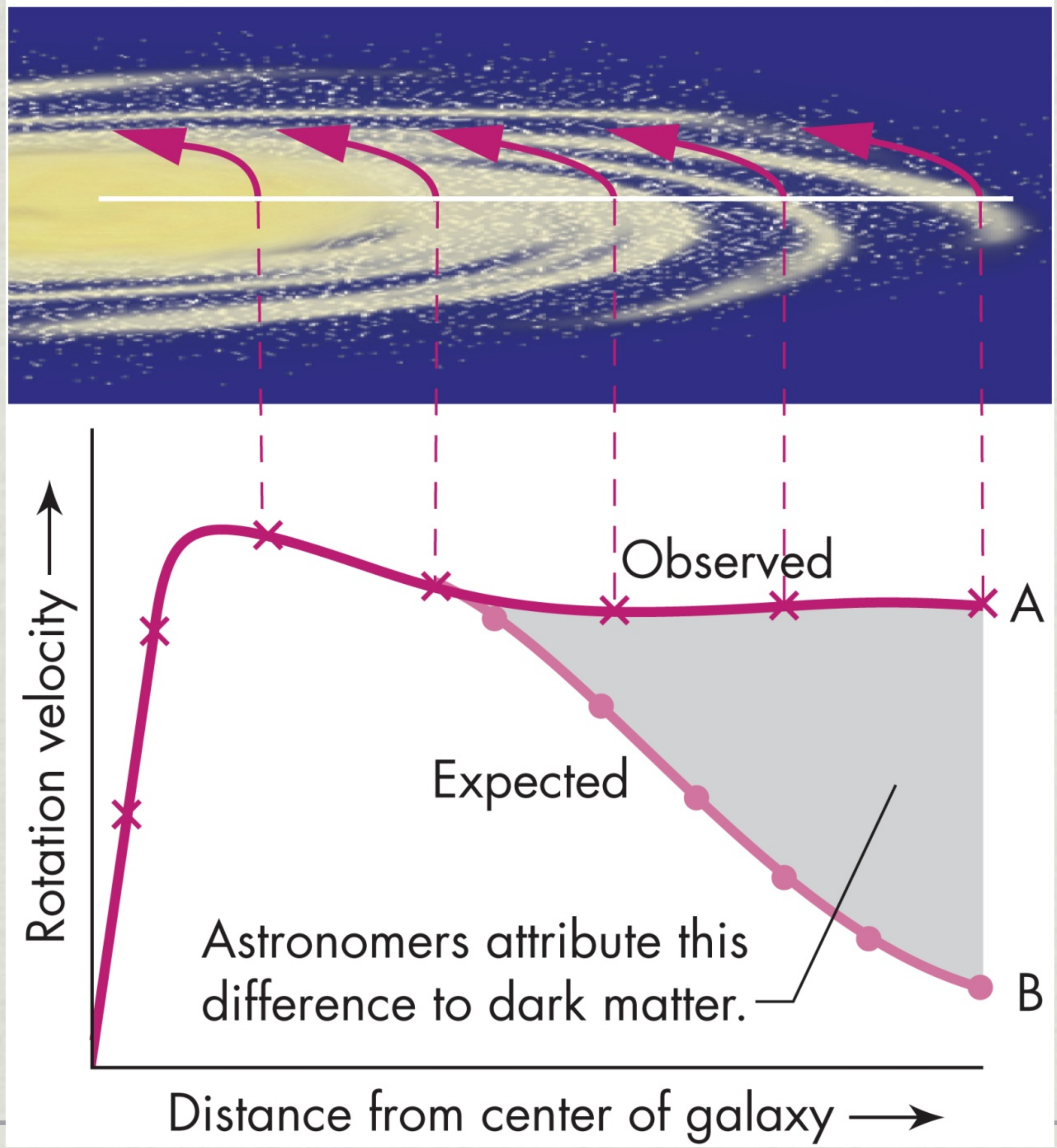


So mass must still be increasing with radius!

Milky Way: Mass



What we measure is wonderfully weird: *the velocity stays constant.*



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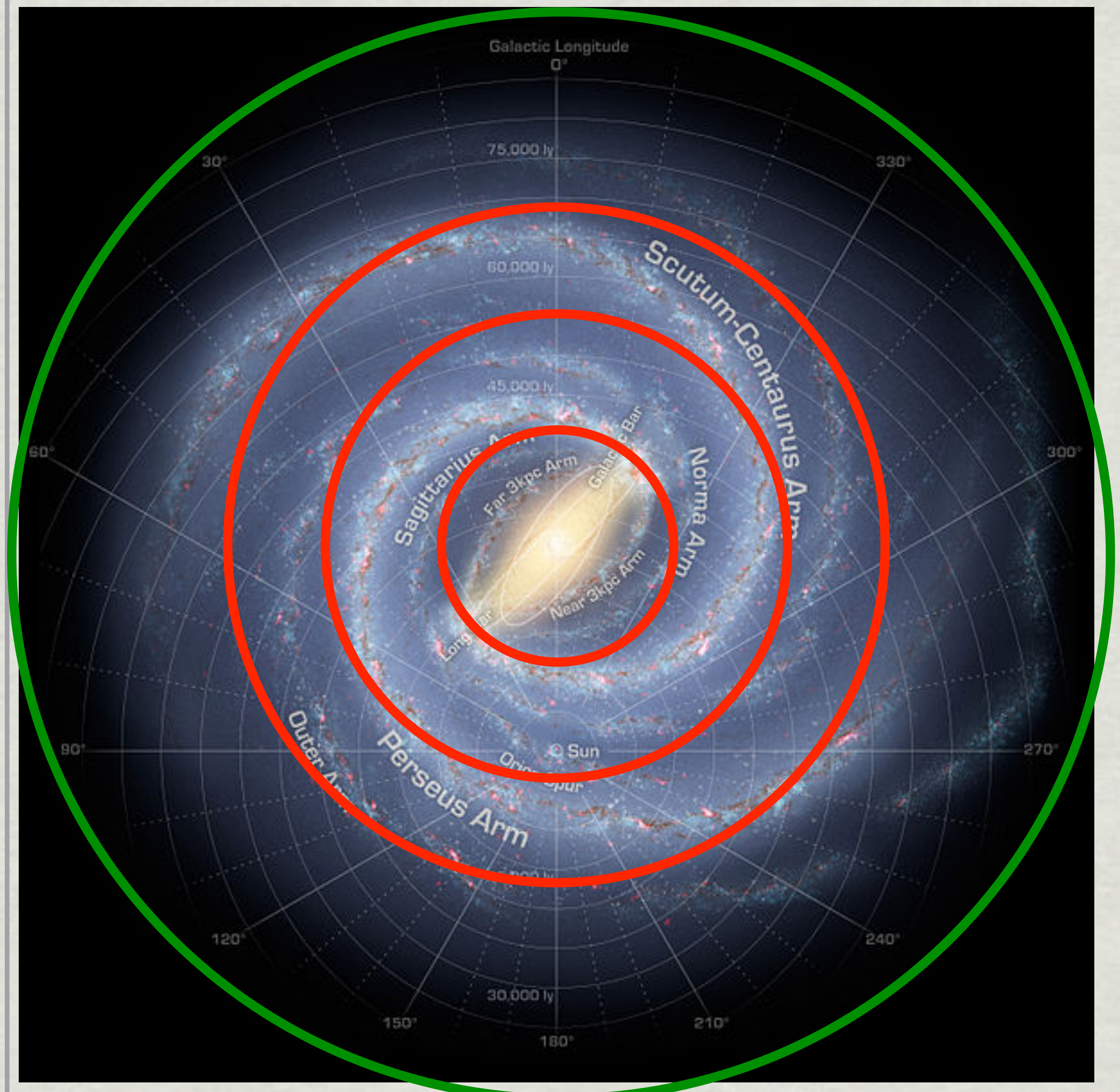
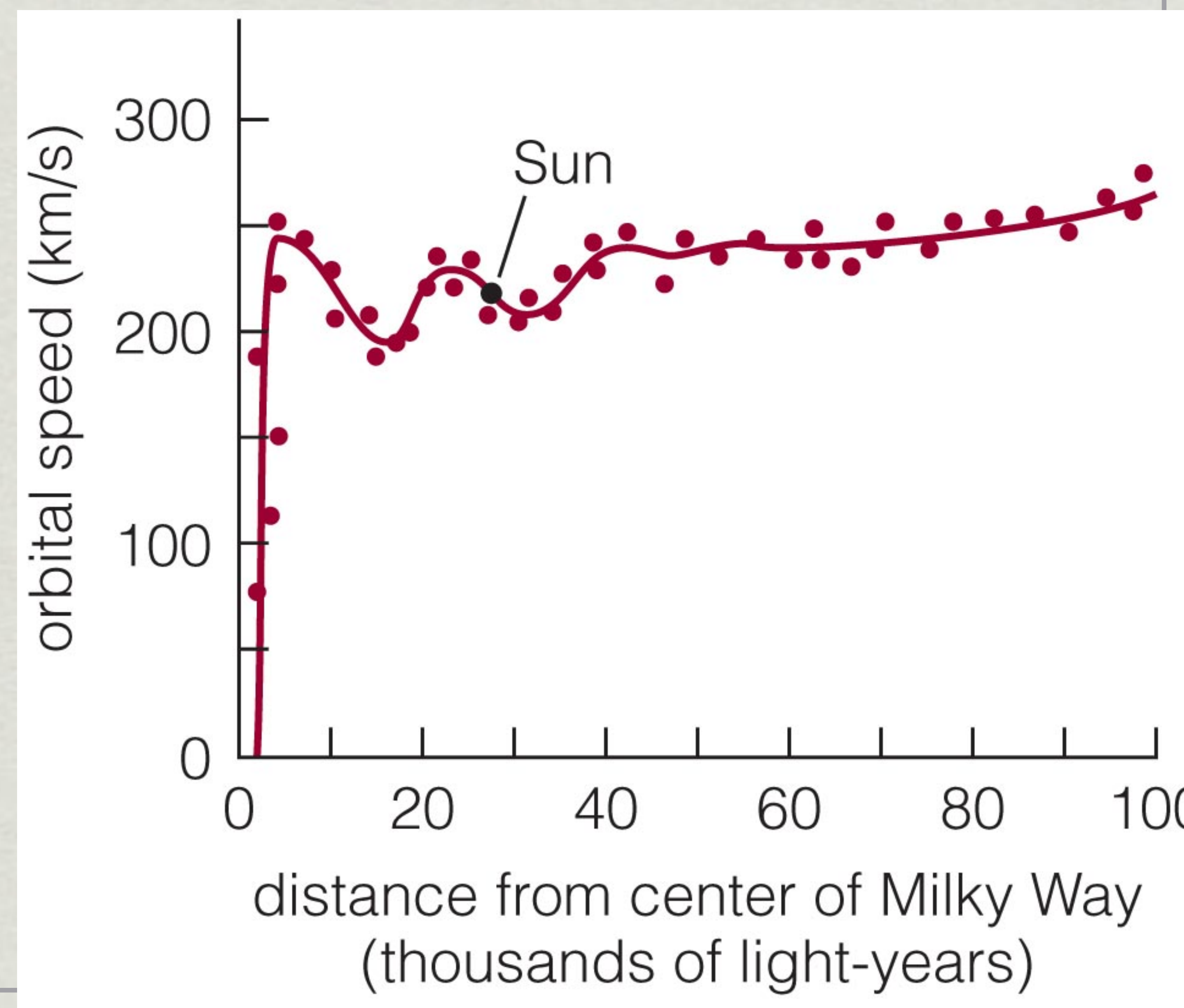


No edge.

No end to the mass.

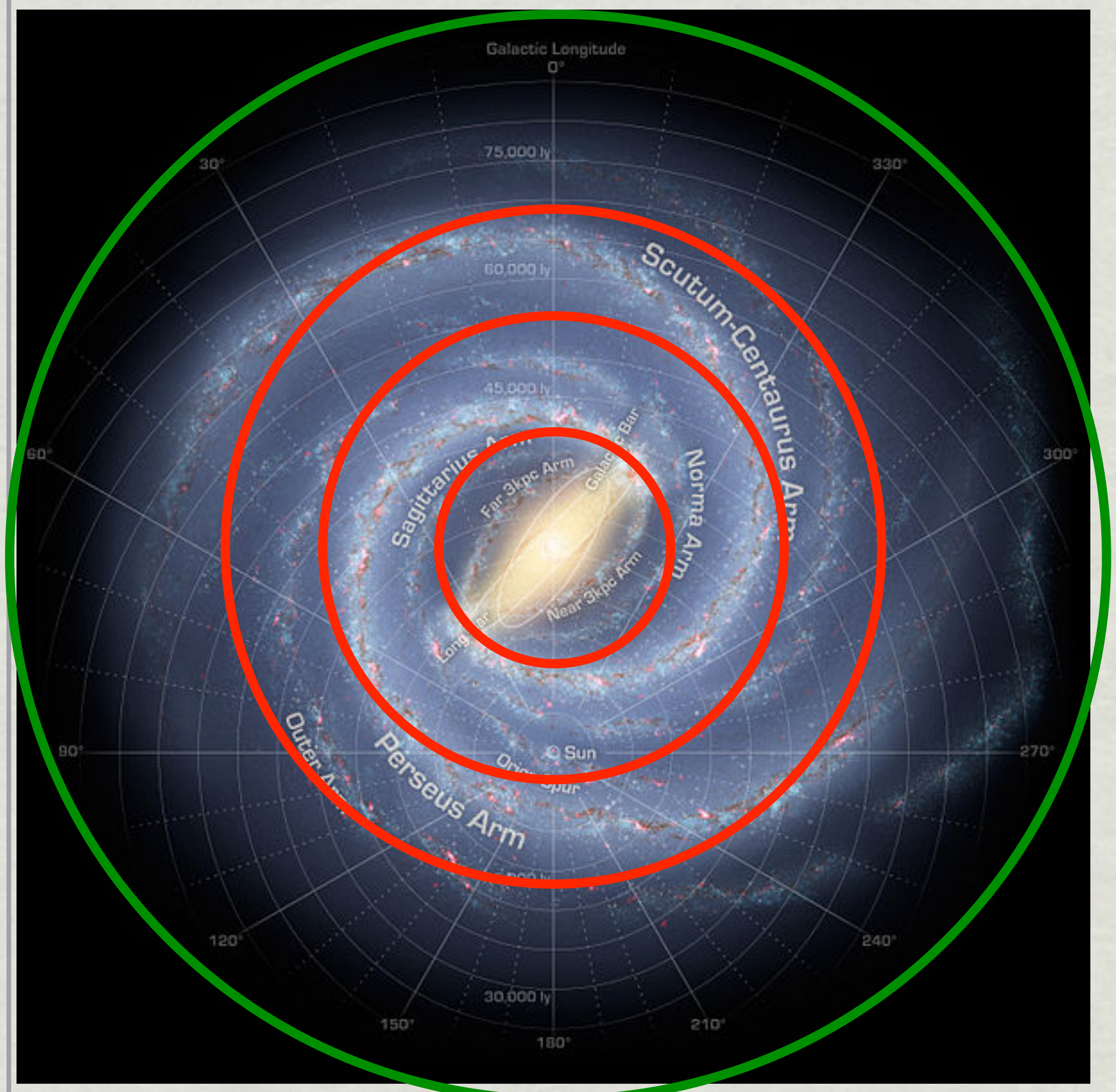
It just keeps on going.



Milky Way: Mass

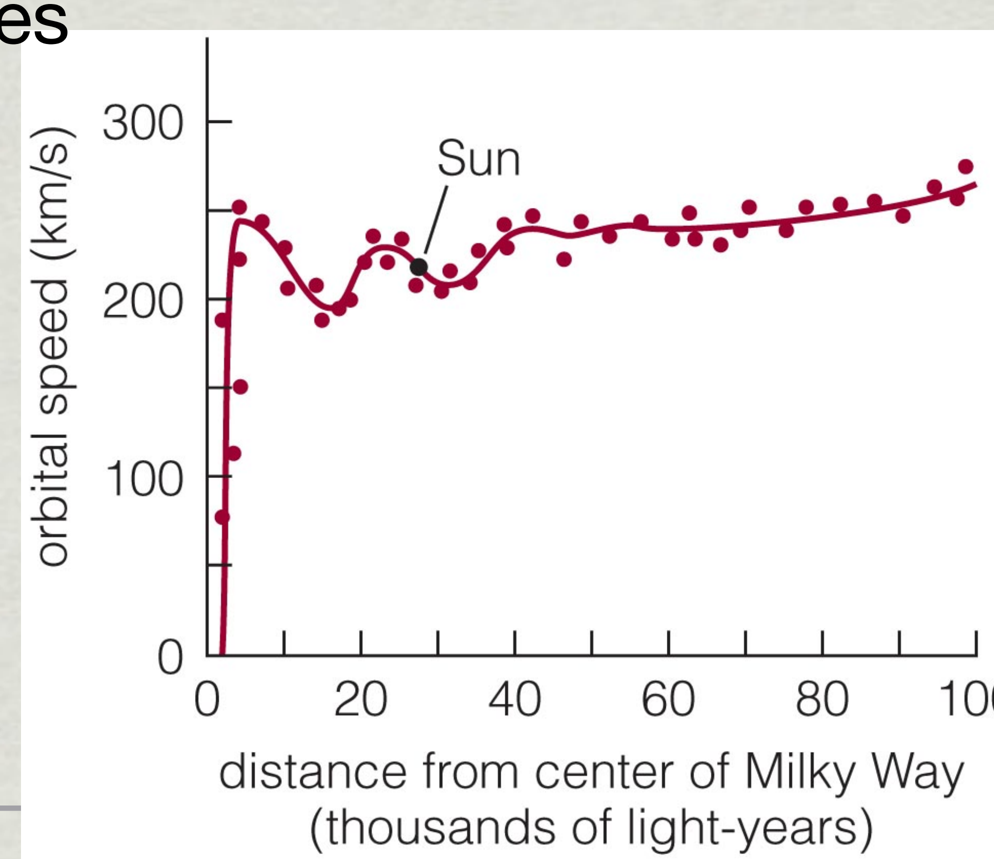
Measure mass (M) inside circle of radius R: measure velocity (v) of stars in circular orbits at R

For circular orbits: $M = \frac{v^2 r}{G}$



Measure V constant as r increases.
Is M inside the green circle:

A) Same as M inside the red circles
B) Greater than M inside the red circles



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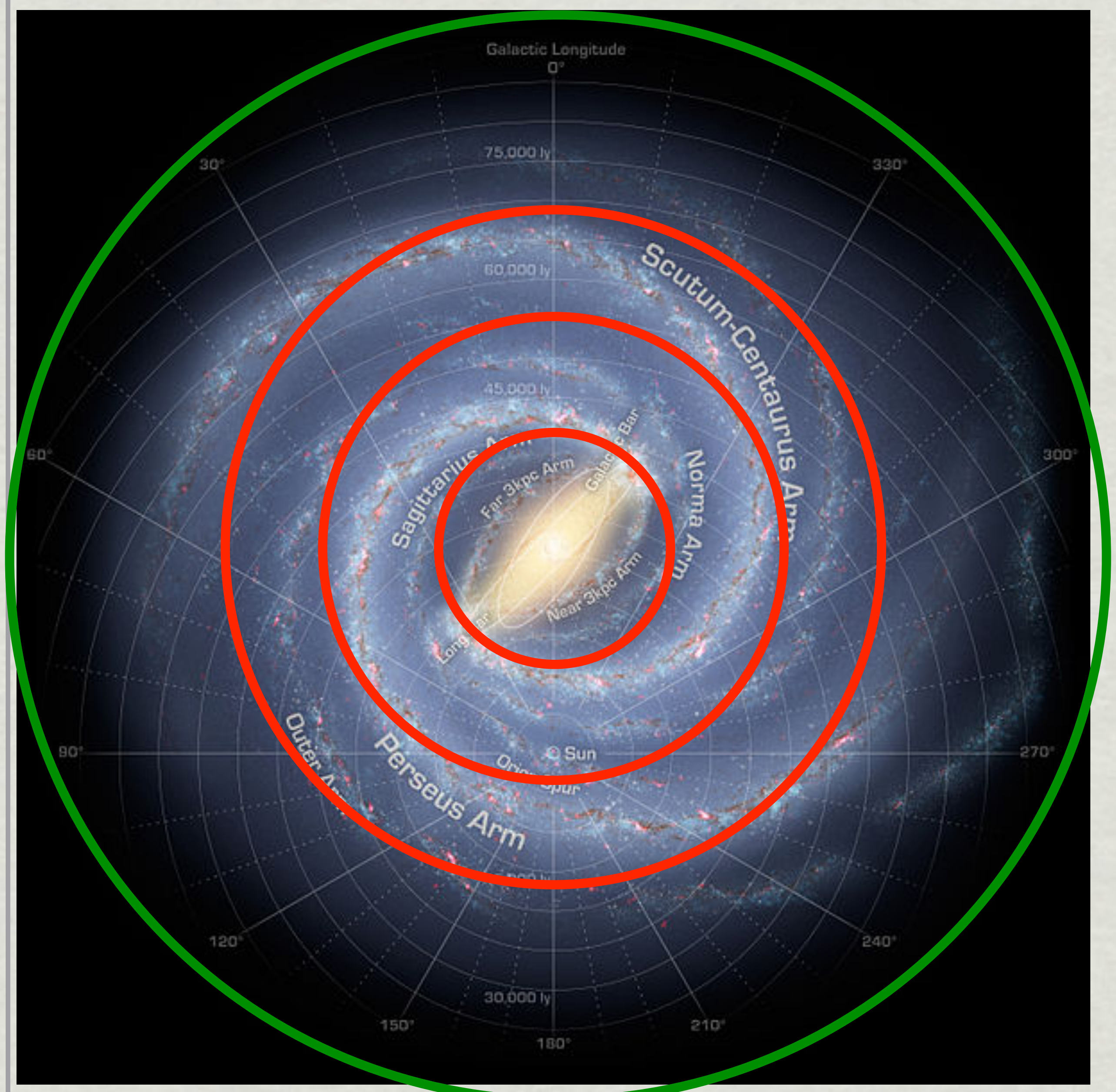

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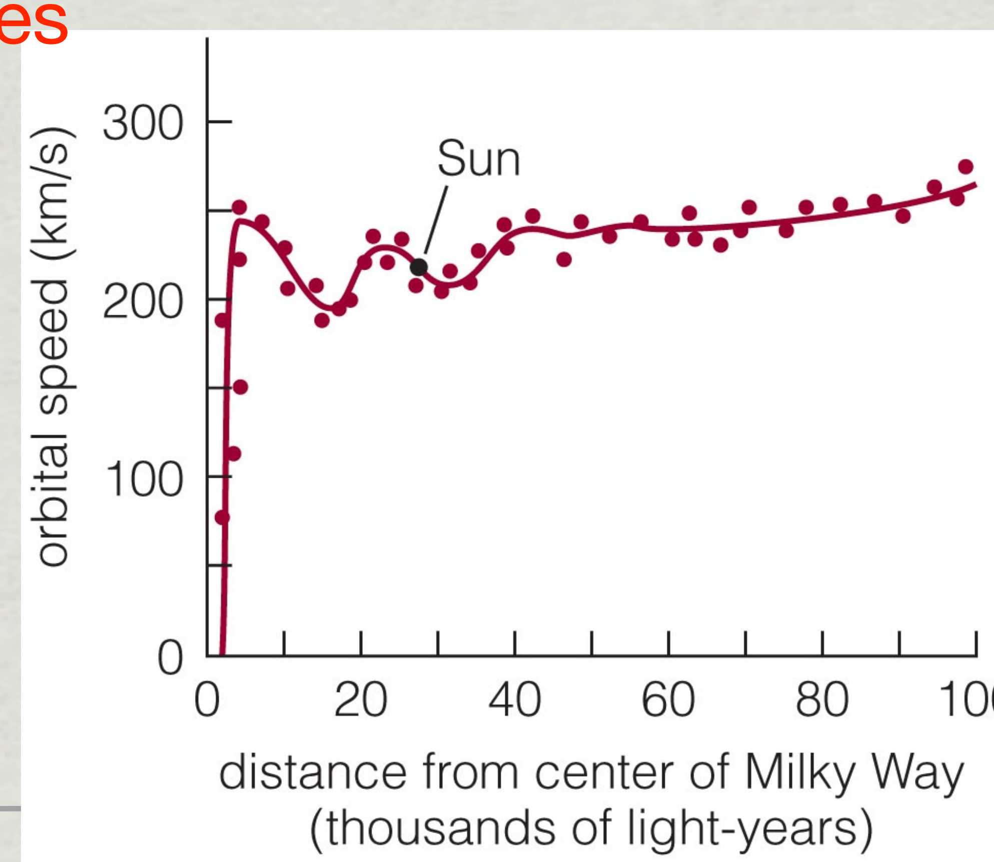

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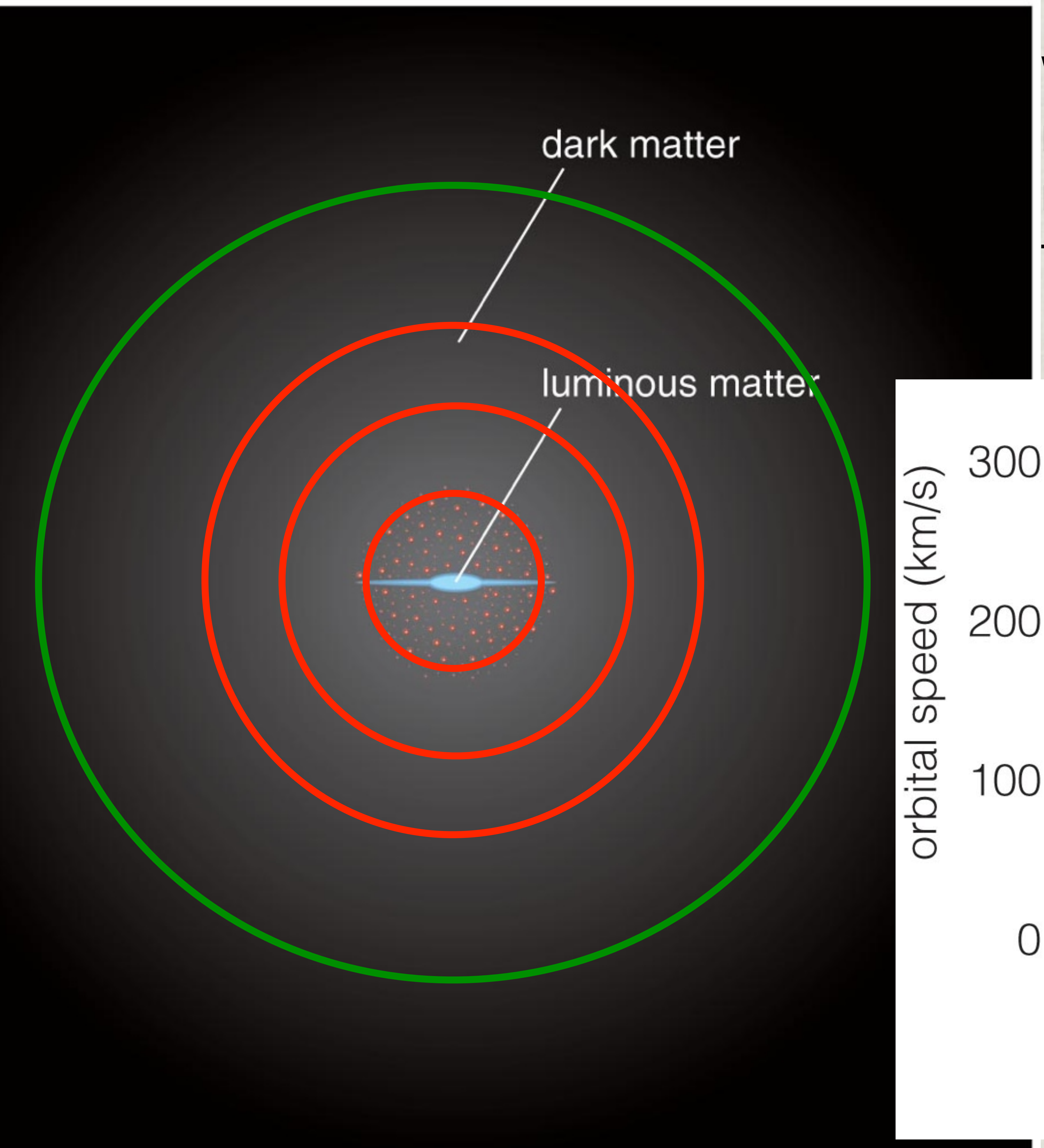
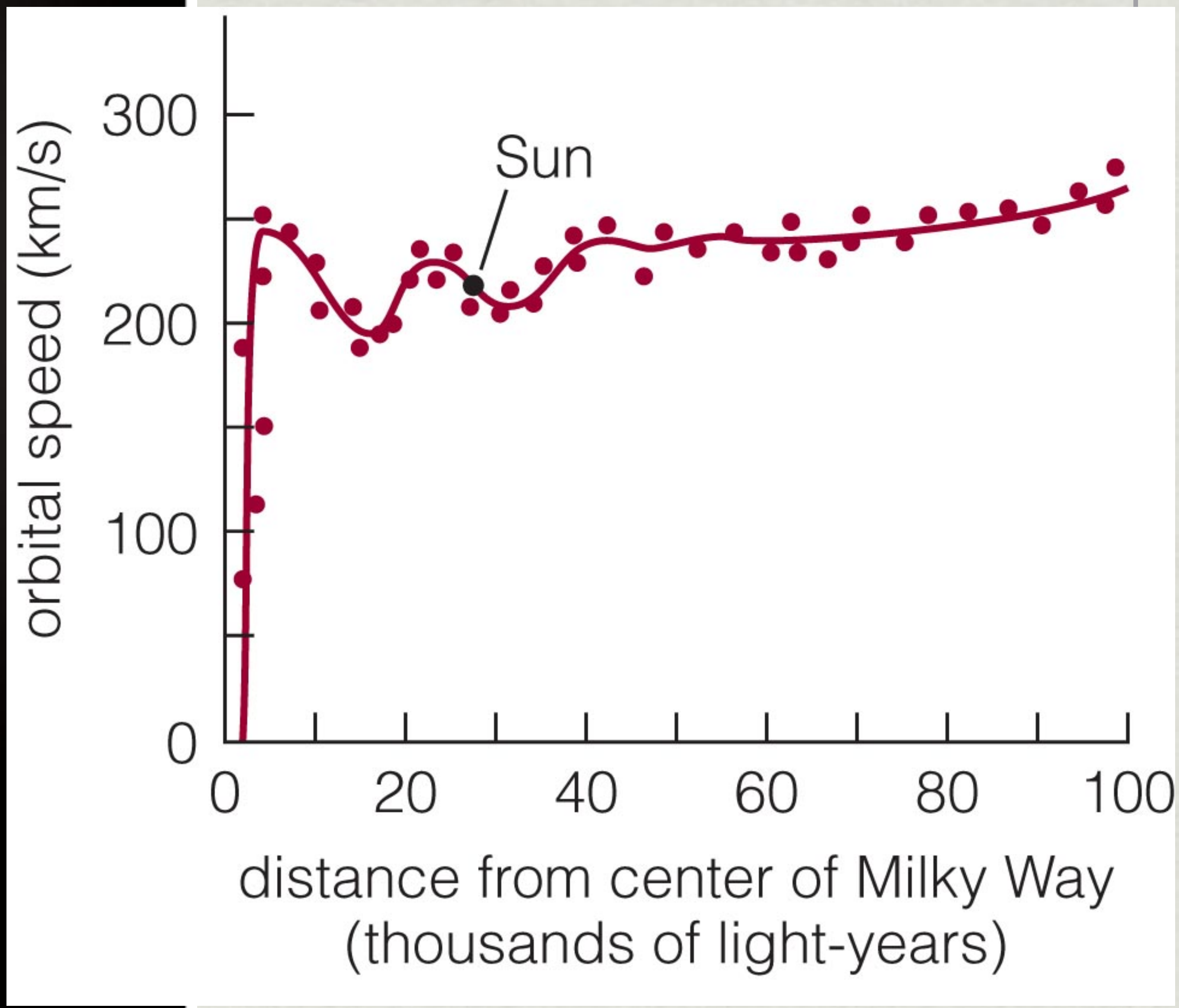
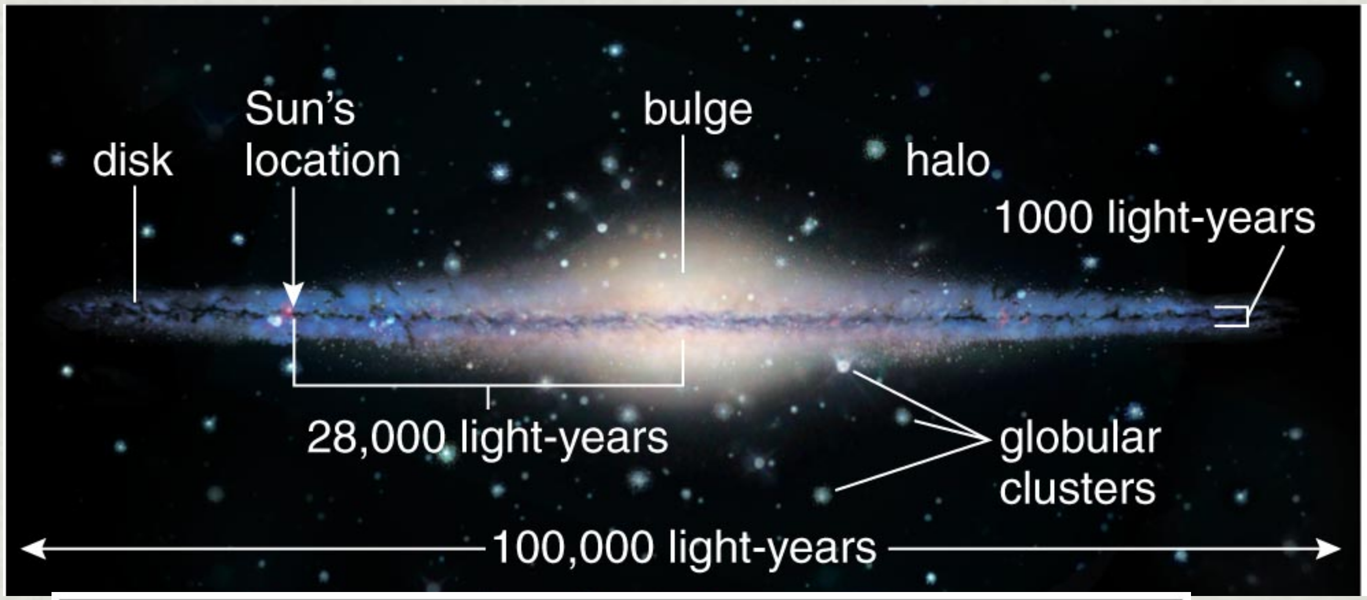


We can't see it, but the velocity measurements tell us there is mass at larger distances than all the mass we can see

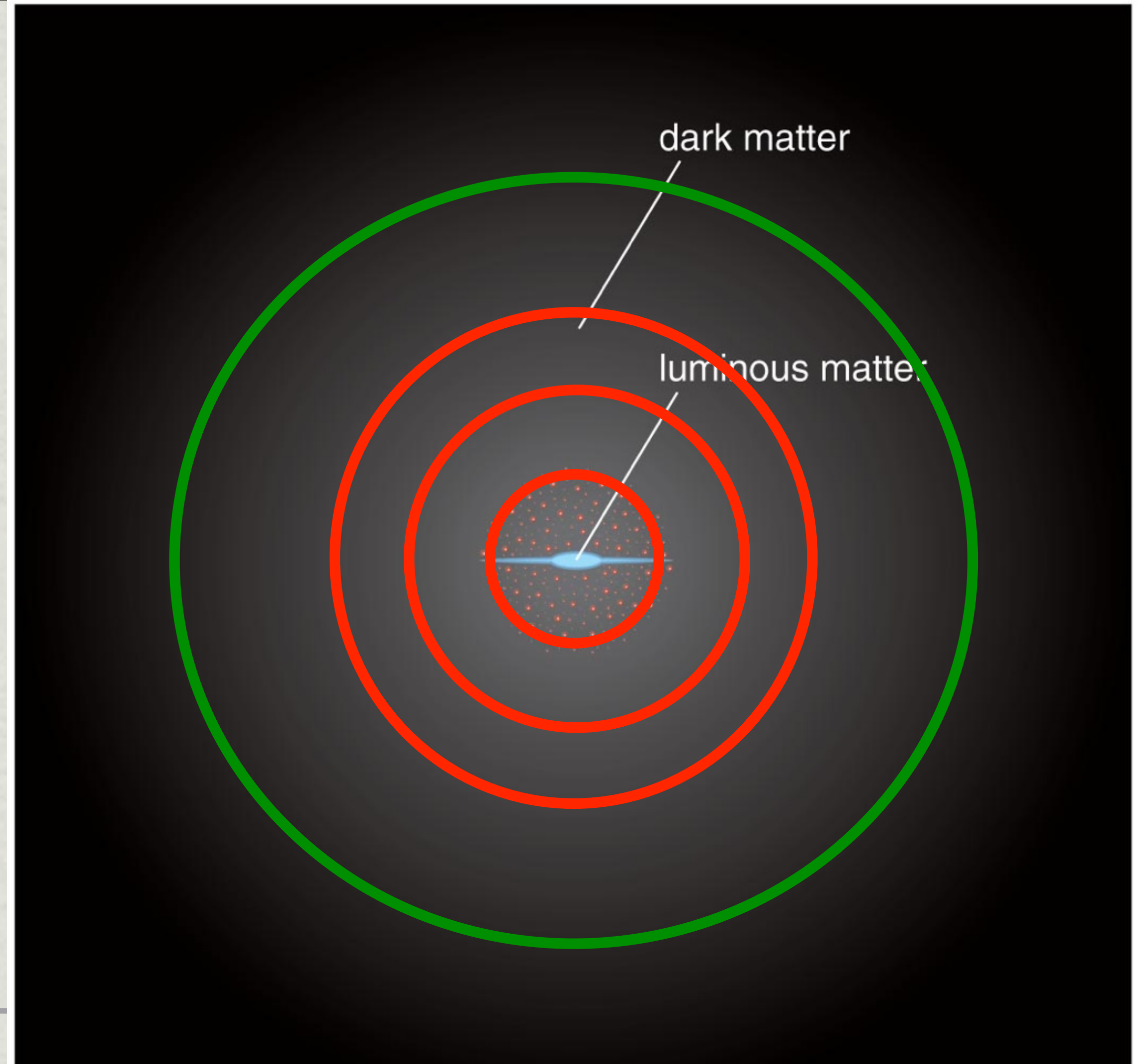


Milky Way: Mass



We don't see the edge of the mass when we look at stars...

...or when we look at gas and dust, or anything else.



A large fraction of the mass of the Galaxy must be "dark"

Which means it doesn't interact with light.

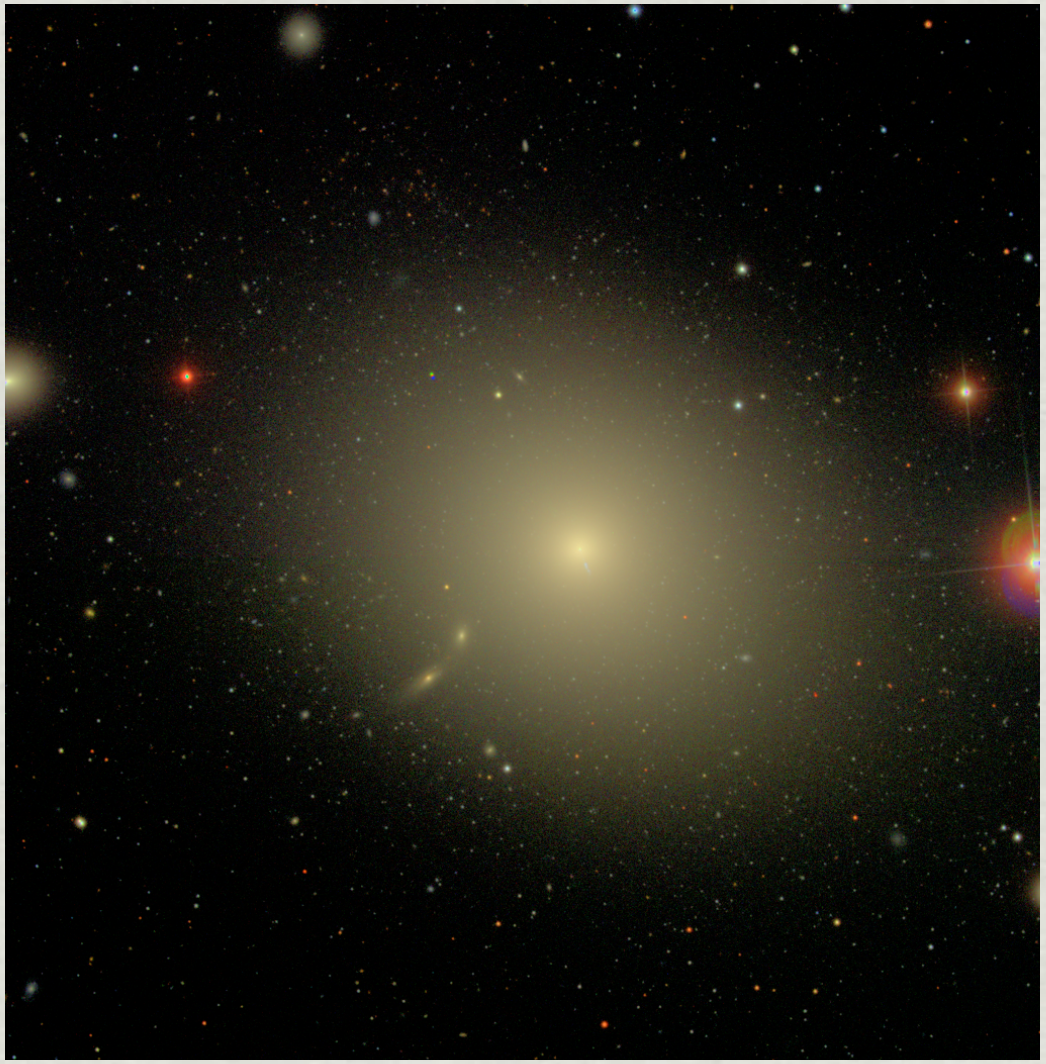
We can't see it, but we know it is there because of gravity.

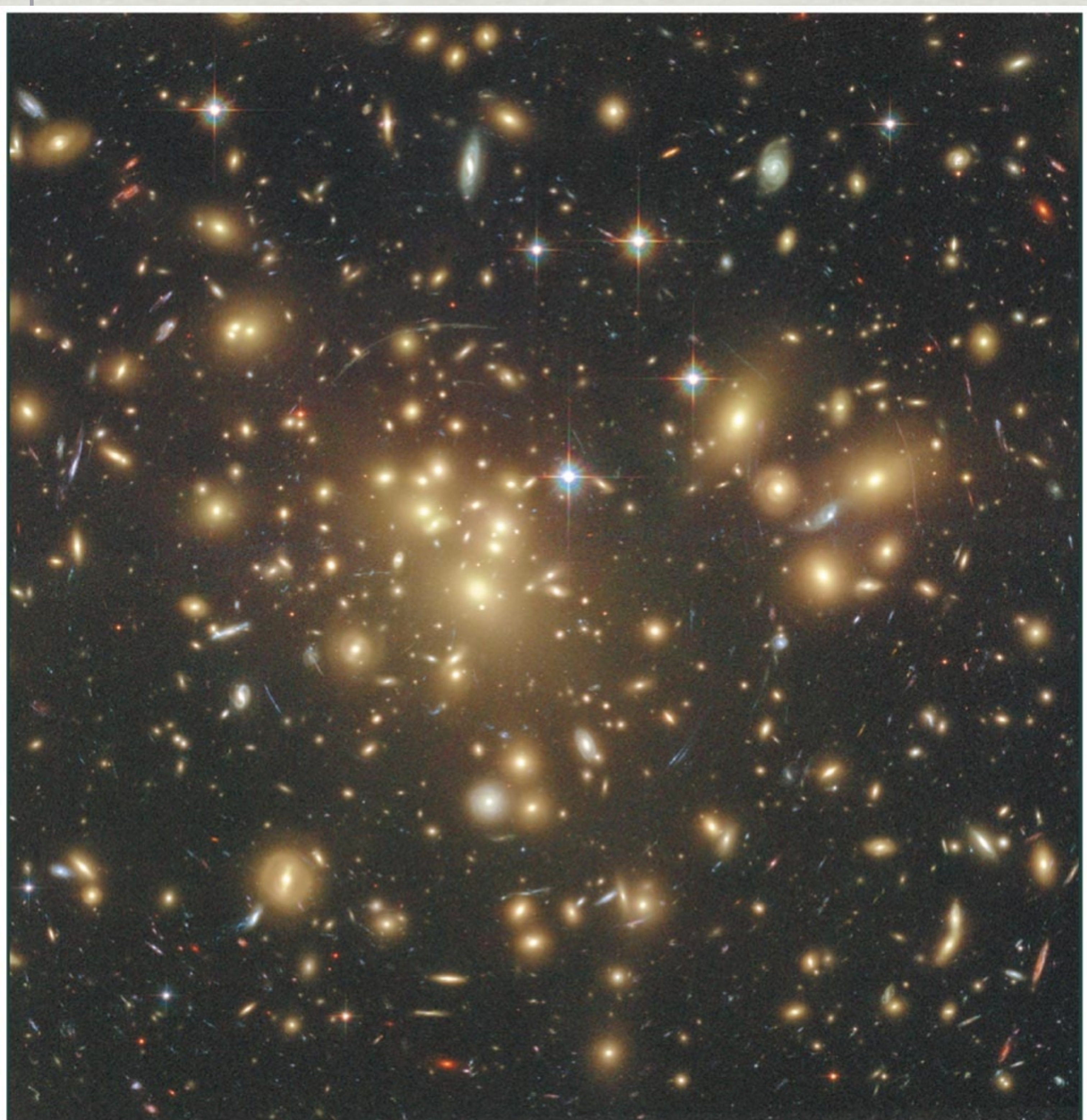
And yes, we call it "Dark Matter" because we don't know what else to call it. We just know it doesn't interact with light.

Galaxies: Mass

It turns out that all other galaxies show the same puzzling difference: the “edge” of where the stars are is much smaller than the edge of where the mass is.

No matter what the galaxy looks like





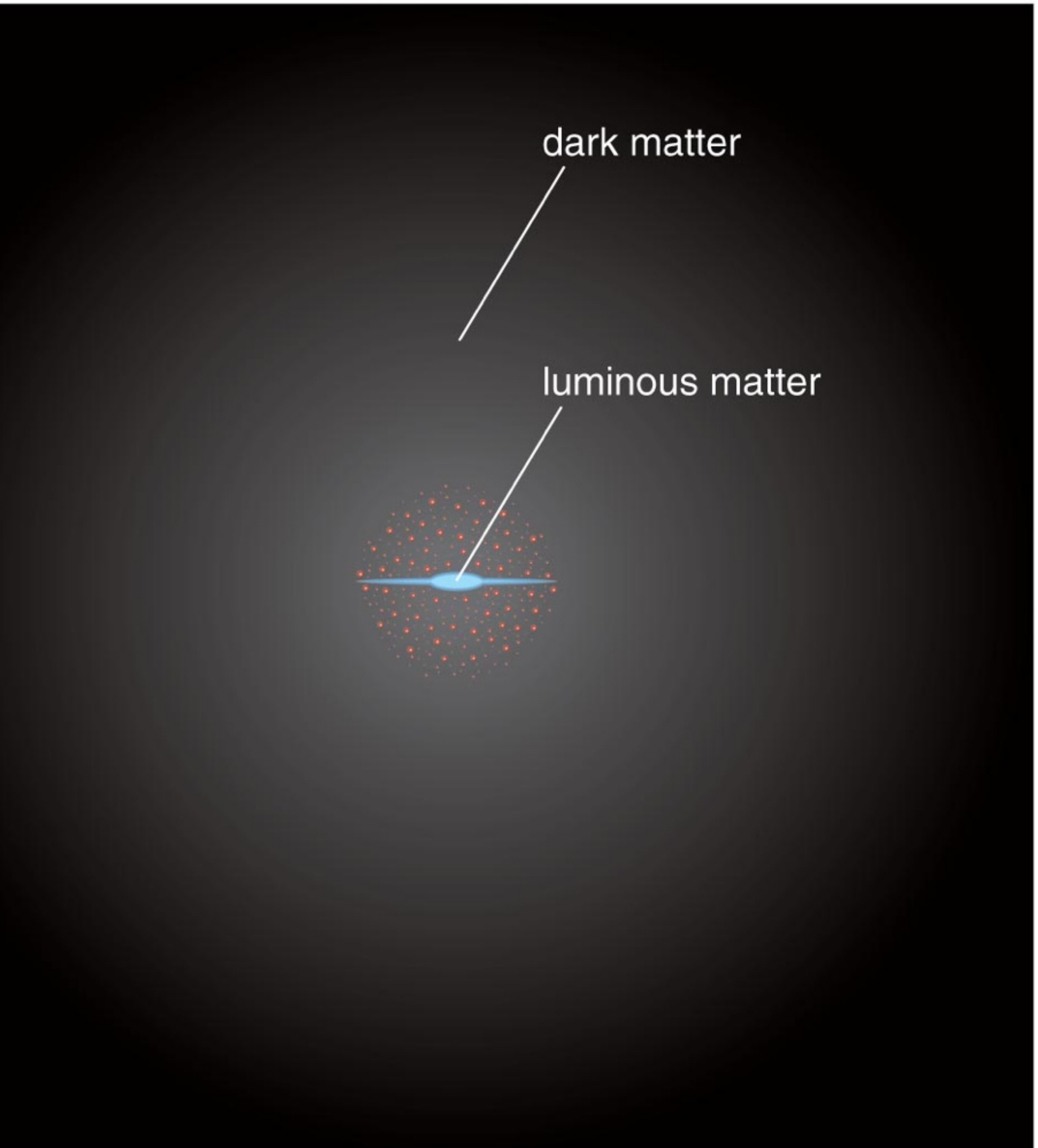
Gravitational lensing by a cluster of many galaxies.

Says there is lots of mass here to curve space-time and force light to follow a curved path.

Just like for galaxies, gravity implies much more mass than all the stars we can see.

More evidence for dark matter.

Milky Way: Mass



What is dark matter?

Rocks?
Planets?
Dead stars?
Small black holes?
Pianos?
Easy chairs?
...

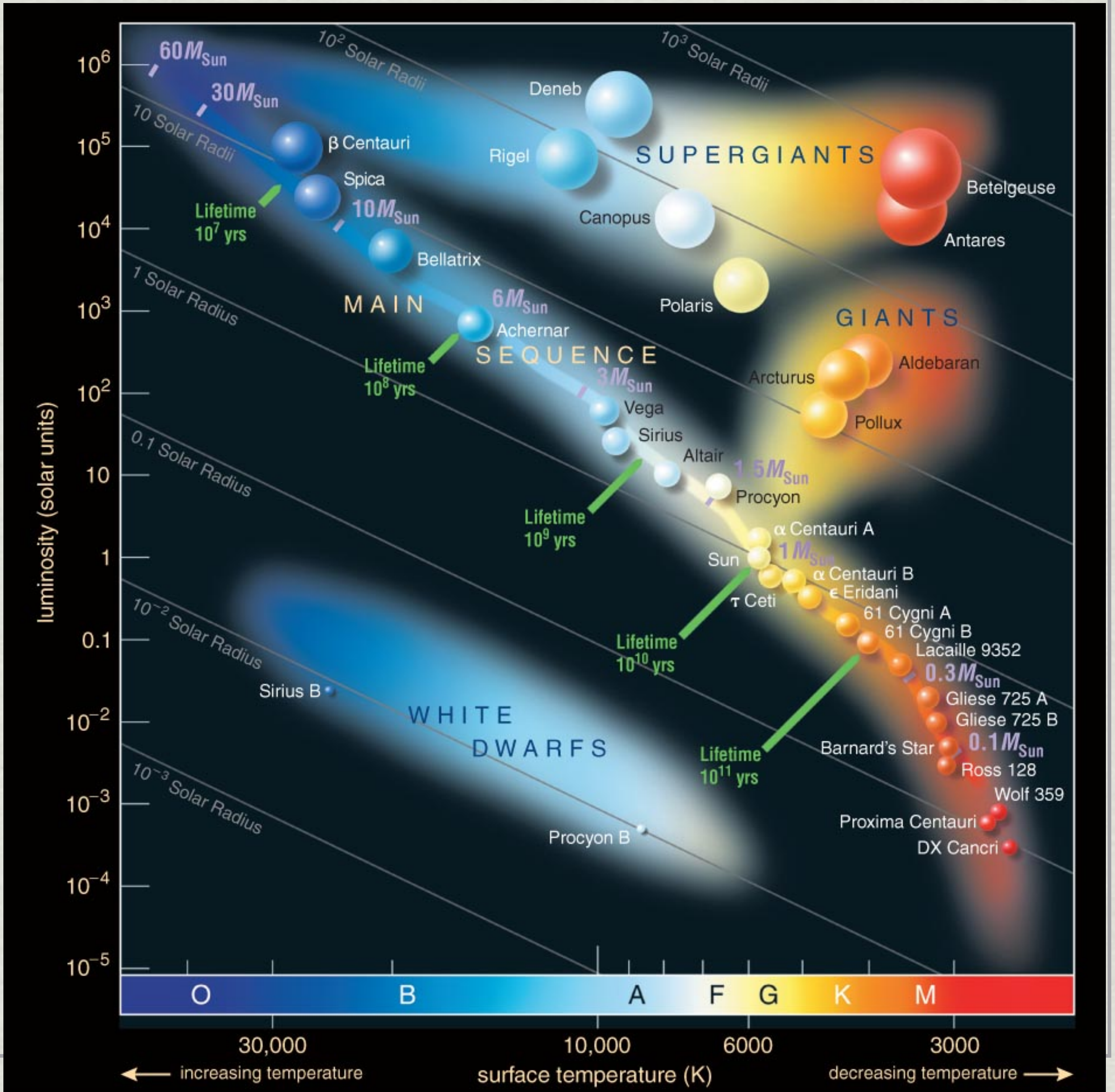
Weakly Interacting Massive Particles (WIMPS) ?

a Massive Compact Halo Object (MACHO) ?

Possible “Halo Objects” that could be “dark matter”

Dim, cool, low-mass stars or cold white dwarfs.

Maybe there are zillions of them out there that are too faint to see



Galaxy Formation

1
2
3
4

Remember this possible sequence for forming spirals like the Milky Way.

Explains data:

Halo is old and not forming stars

Disk is young with gas, dust, and ongoing star formation

Halo stars are less enriched in elements beyond hydrogen and helium

Halo is spherical, star orbits are random

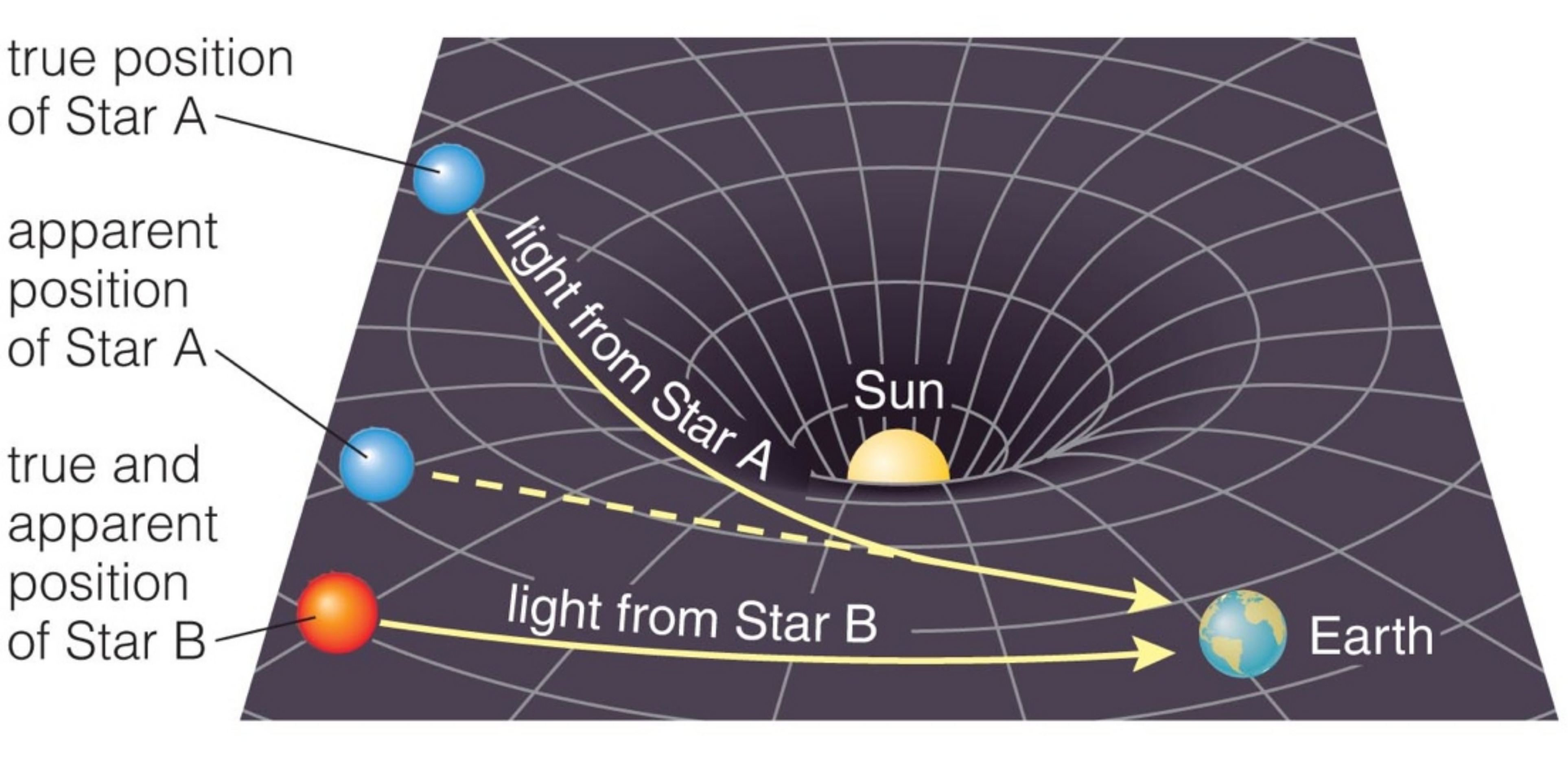
Disk is flattened, star orbits are organized

Maybe the MACHOs are left over from steps 1 and 2?

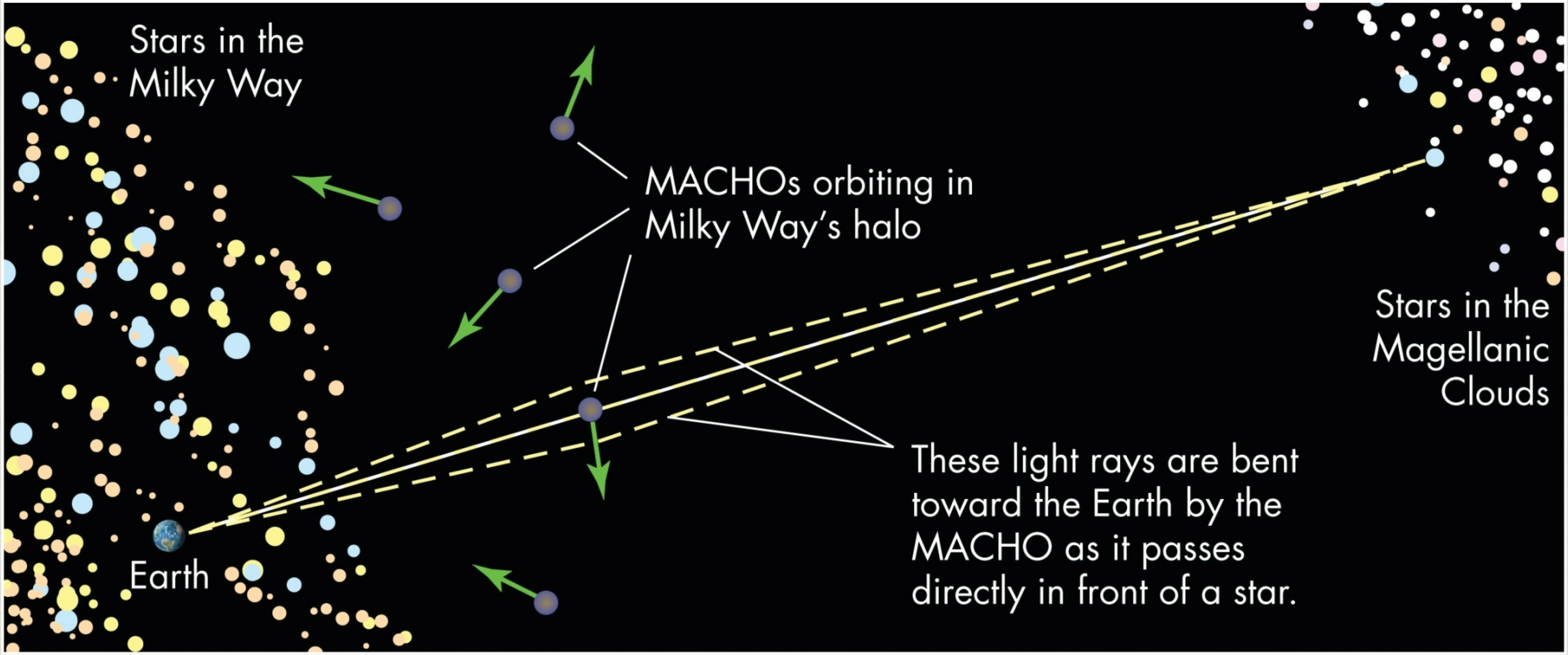
Finding MACHOS we can't see

Recap: Gravitational Lensing: positions of background stars will change when observed along a sight-line near a massive object. Like the sun.

Observation of apparent change in star positions during a solar eclipse (when we can see close to the sun) in 1919 was a first proof of General Relativity.

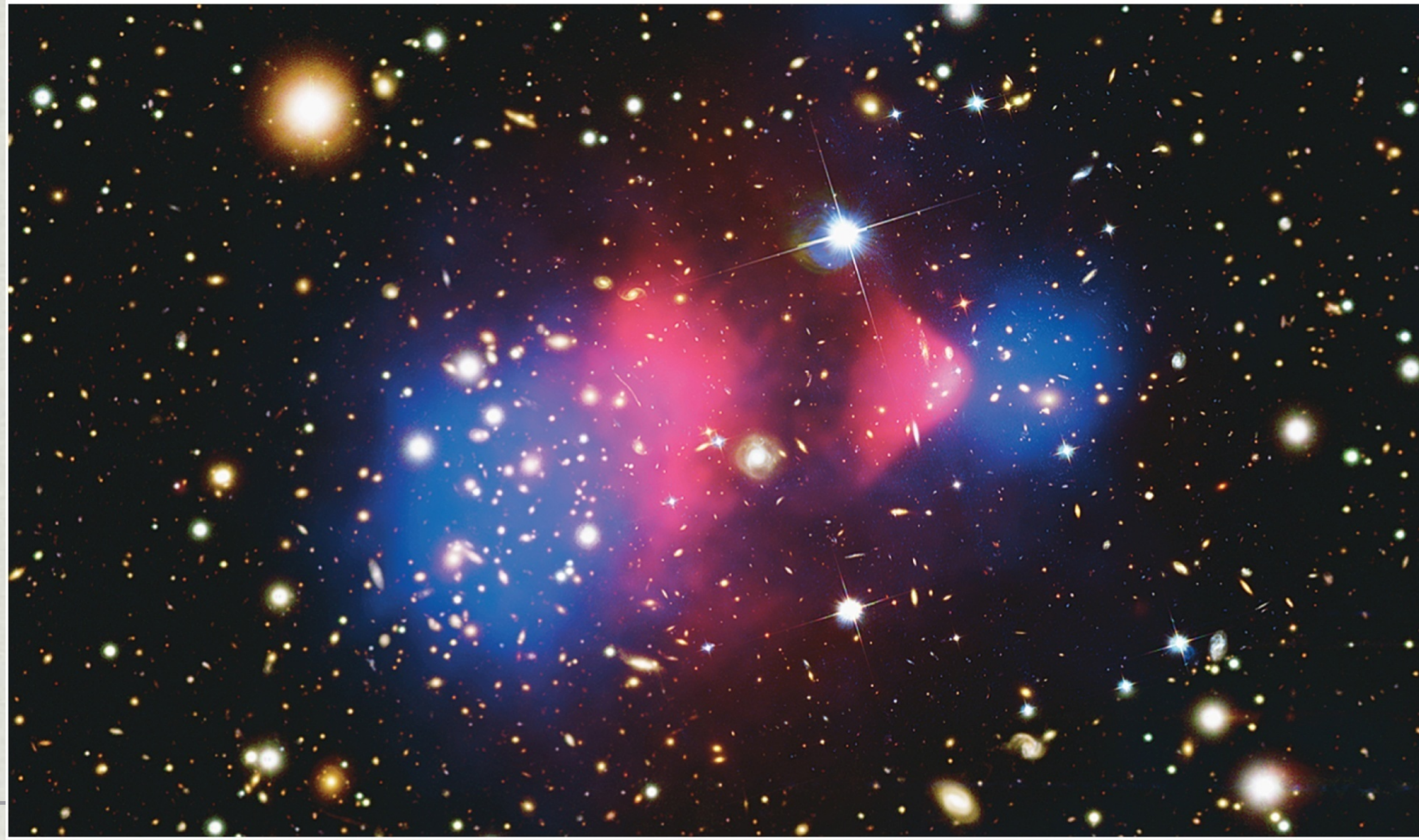


the MACHO project looked for gravitational lensing from stellar leftovers, didn't find enough to explain the rotation curve.



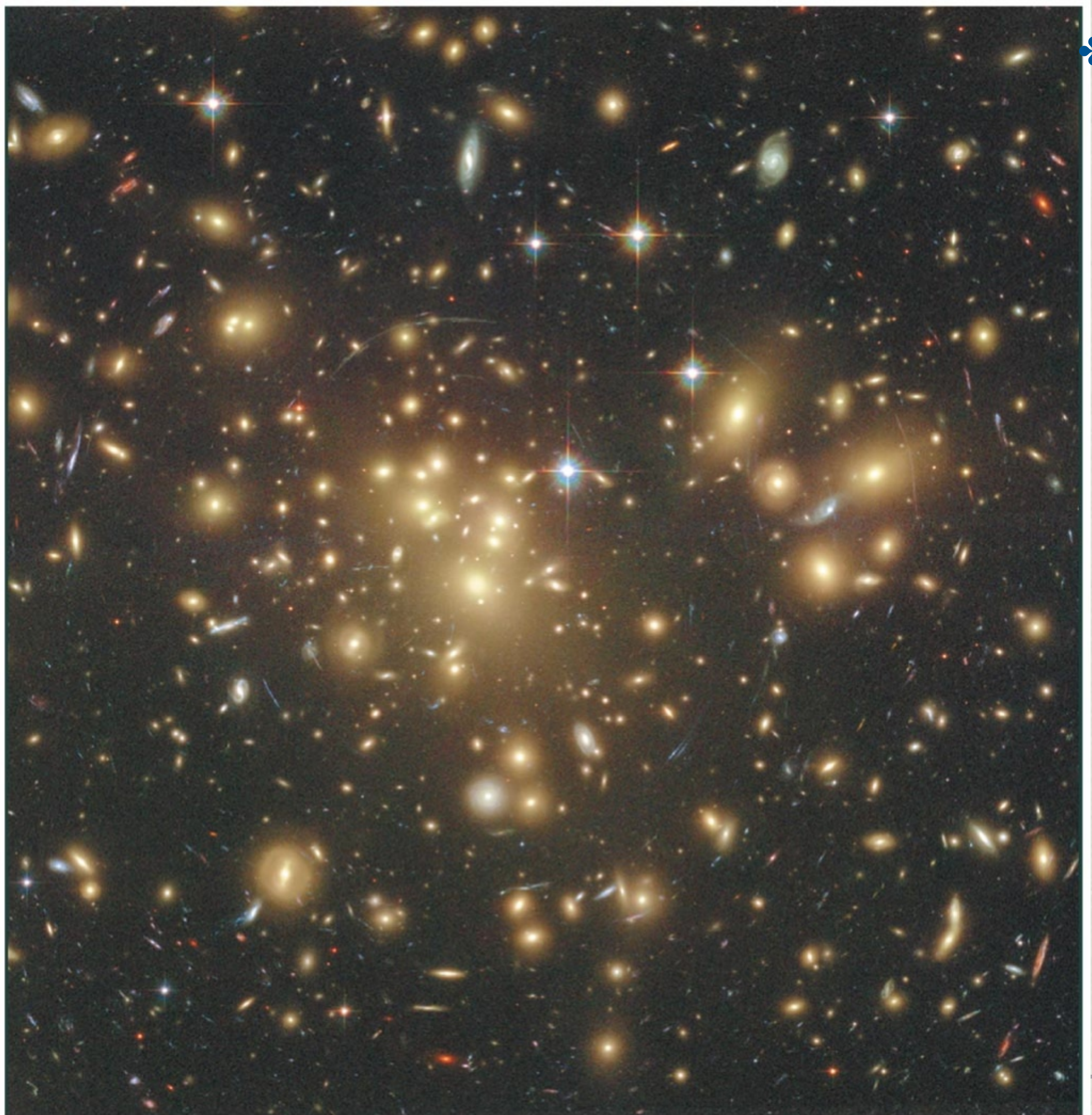
the more we look, the more it seems that dark matter is some new particle, maybe like a WIMP.

Two clusters of galaxies crashing into one another.
Blue: where all the mass is (using gravitational lensing)
Red: X-ray photons from the hot gas



Colliding Clusters of Galaxies

- Clusters contain galaxies, dark matter and gas



- Imagine throwing two handfuls of marbles at each other. Most would pass right through. The galaxies and gas in the cluster collision are like marbles.

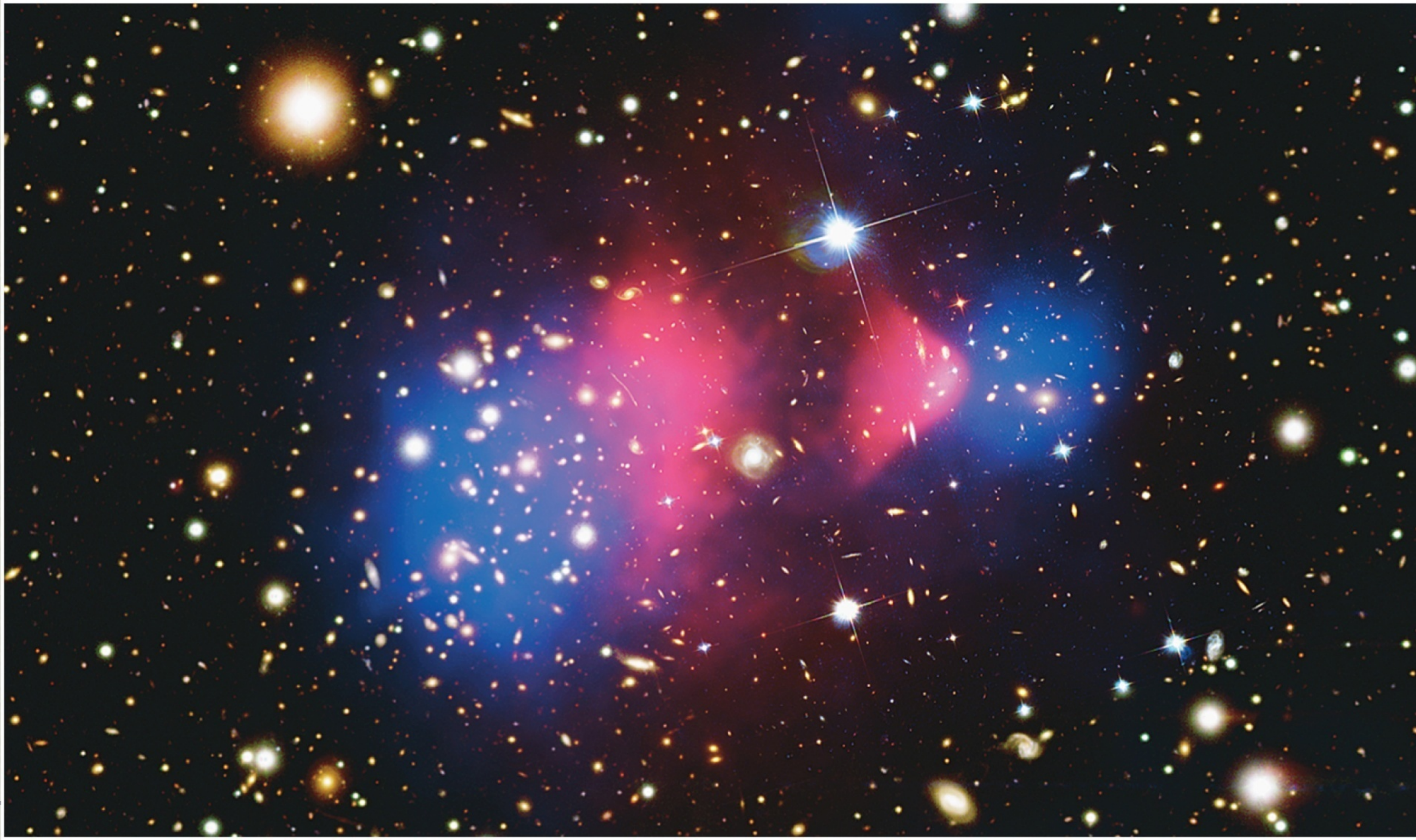
- Now imaging throwing two handfuls of jelly at each other. What do you expect to happen? The gas in the clusters is like jelly.

the more we look, the more it seems that dark matter is some new particle, maybe like a WIMP.

Two clusters of galaxies crashing into one another.
Blue: where all the mass is (using gravitational lensing). Passes right through the collision like marbles.
Red: X-ray photons from the hot gas. Sticks like two colliding blobs of jelly

The gas heats up from the collision, emits energetic photons to cool

The dark matter and galaxies pass right through each other: only interaction is through gravity

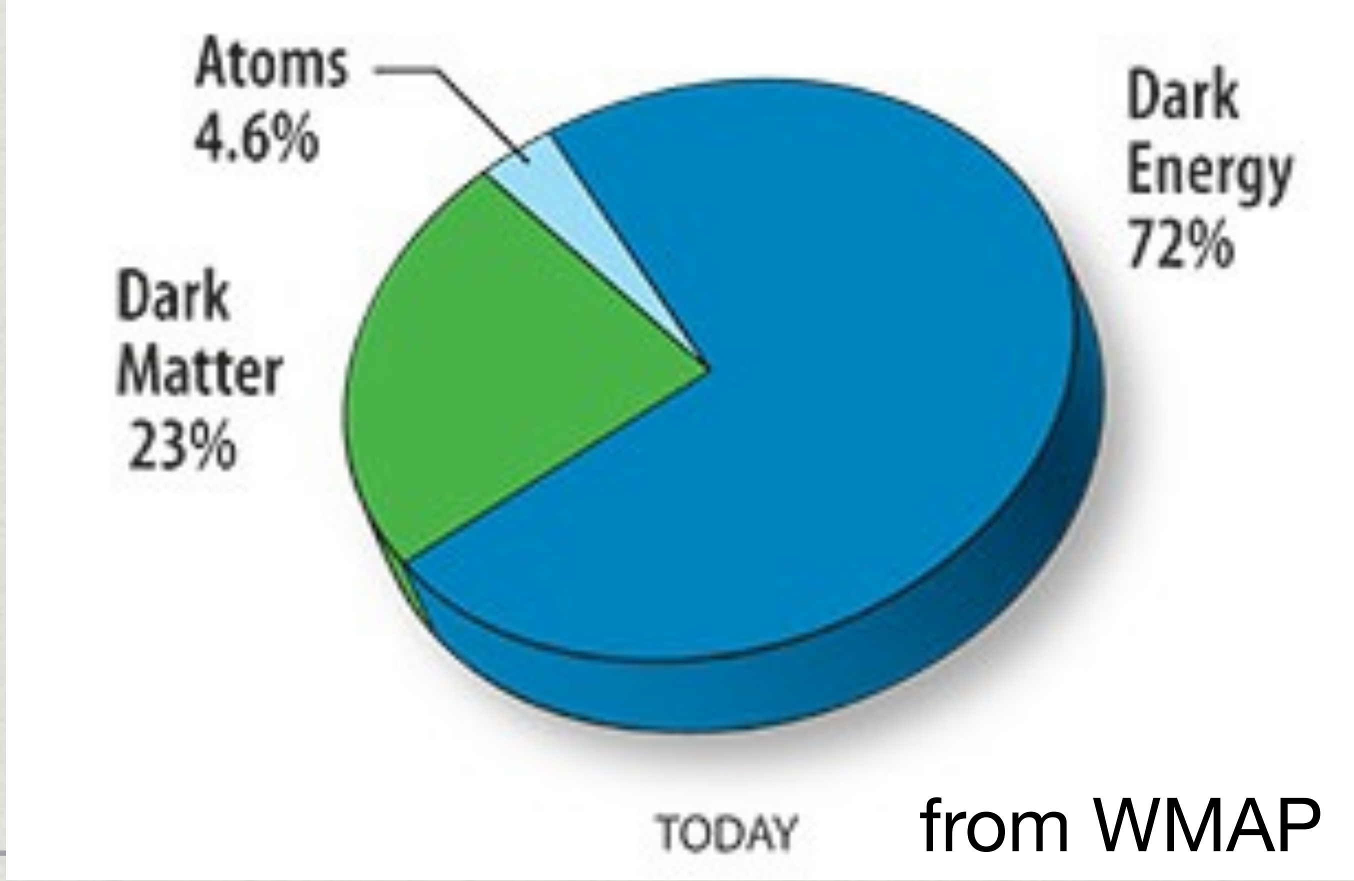


Embarrassing Accounting

We don't know what dark matter is.

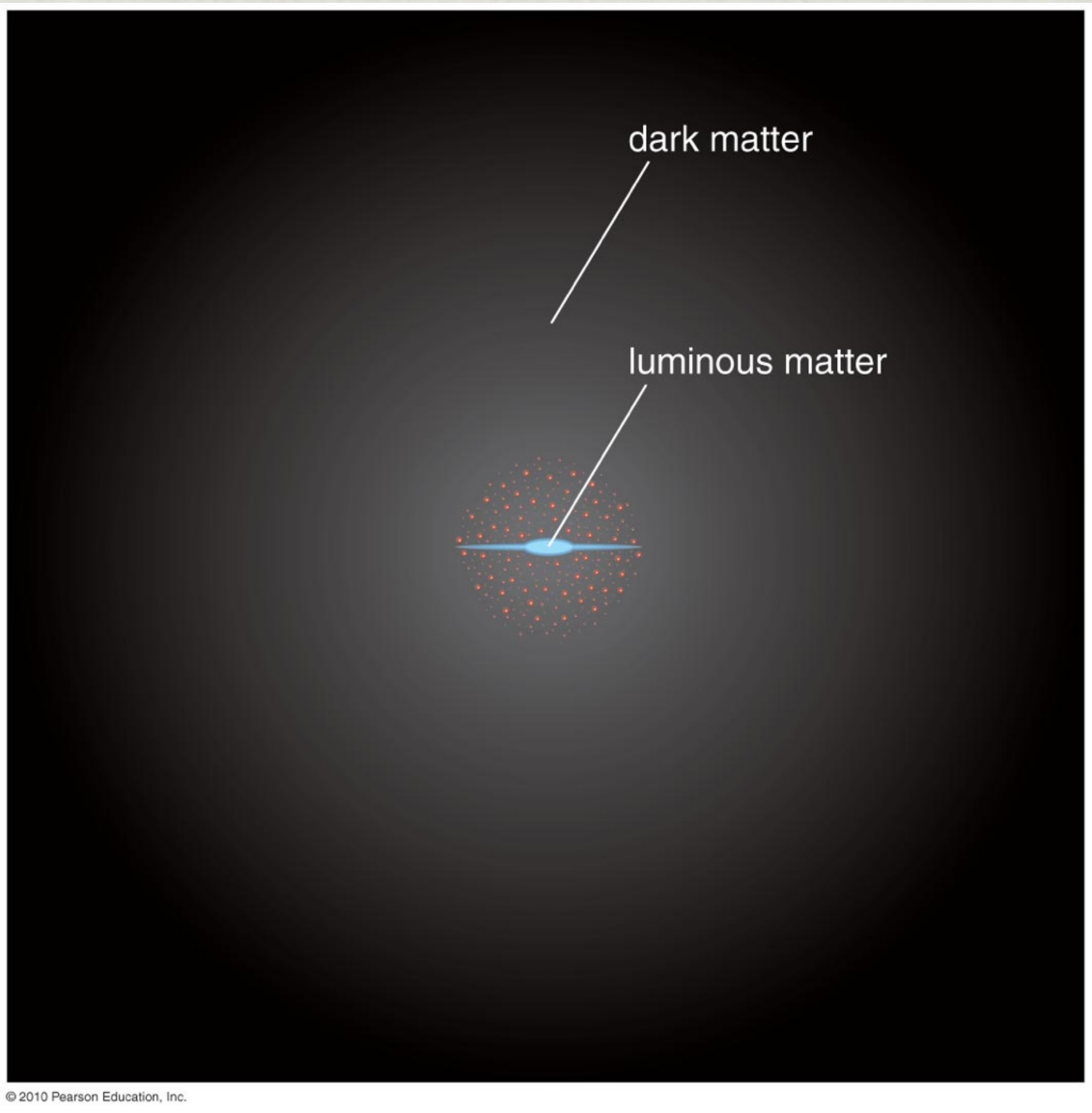
We don't know what dark energy is, either (and we'll talk about that next week)

But those are all but 95.4% of what the universe is made of!



Direct Dark Matter Detection

Looking at how much dark matter must be near the sun to make the mass distribution we measure, there are probably a handful (~10) dark matter particles in the volume of a soda bottle



How can we find individual particles if they don't interact with light?

Wait for them to bump in to things (like the nucleus of another atom)

Direct Dark Matter Detection

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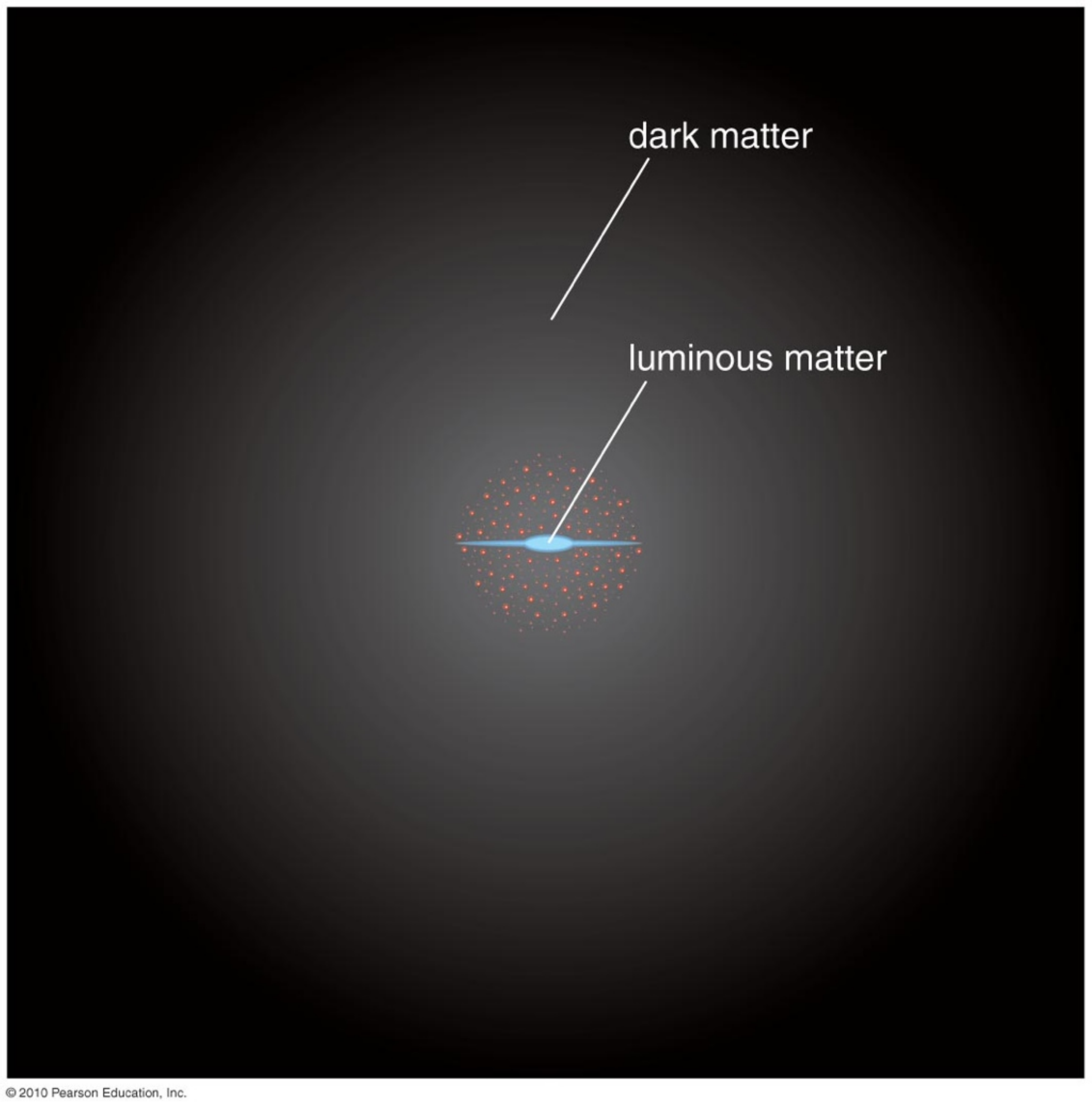
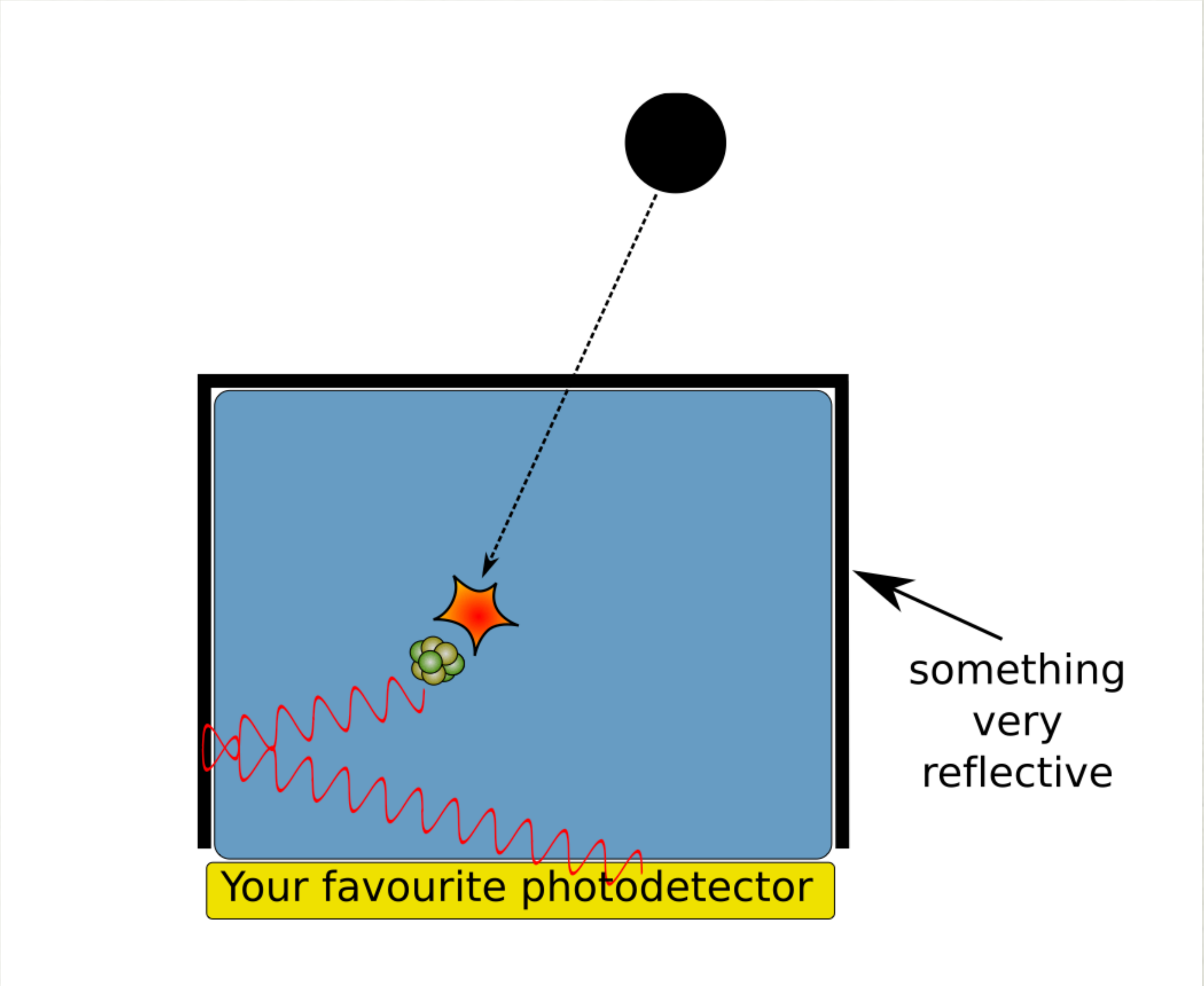
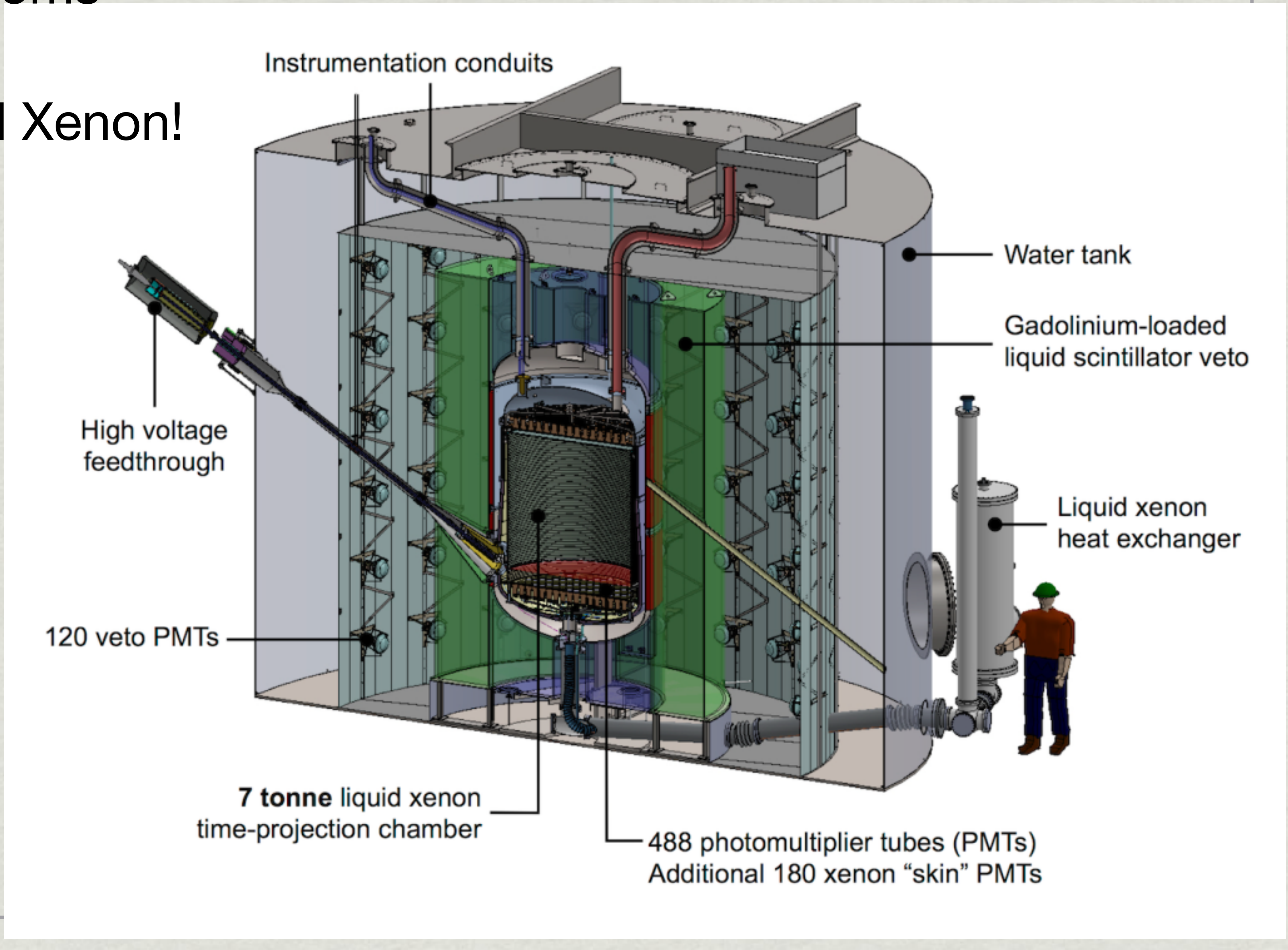




Direct Dark Matter Detection

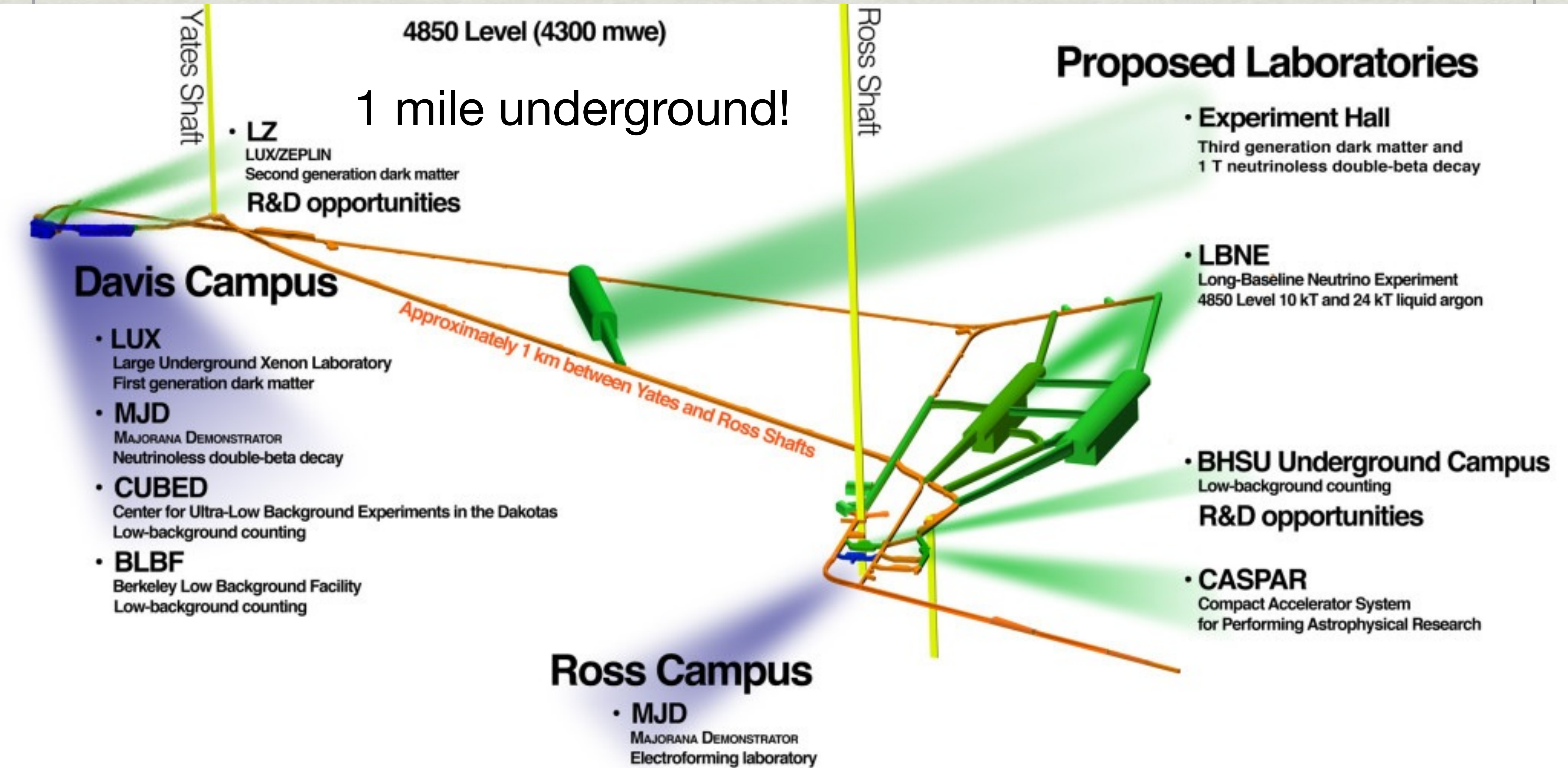
The LZ experiment: looking for WIMP dark matter particles that collide with atoms

7 tons of liquid Xenon!



Direct Dark Matter Detection

One big problem is that there are lots of other particles that could bump into nuclei and confuse the measurement. This is a really, really hard experiment



Light travel time and "lookback time"

Light travels at a fixed speed, 3×10^8 m/s (meters each second)

Because the speed of light is fixed, it takes time for light to travel between any two places, like between the earth and the sun.

1 Astronomical Unit (AU) = distance from sun to earth = 1.5×10^{11} m

How long does it take light to travel that far?

Think about driving. You and your friend both drive at 60 mph. You drive for 30 minutes. Your friend drives for 4 hours.

Who drives a larger distance?

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If you both arrive at your dinner date at the same time, who left first?

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distance = speed x time

Rearrange: time = $\frac{\text{distance}}{\text{speed}}$

➨ It takes $\frac{1.5 \times 10^{11} \text{ m}}{3 \times 10^8 \text{ m/s}}$ = 500 seconds = 8.3 minutes

for light to travel
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- We can use this as a way to measure distance:
  - The distance that light can travel in 1 minute is called a "light-minute"
  - The distance from the earth to the sun is about 8 light-minutes
  - The distance light can travel in 1 year is called a "light-year"
  - What distance is 1 light-second?

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A) 8 m

B) 3×10^8 m

C) 1.5×10^{11} m

D) 9,800,000 m

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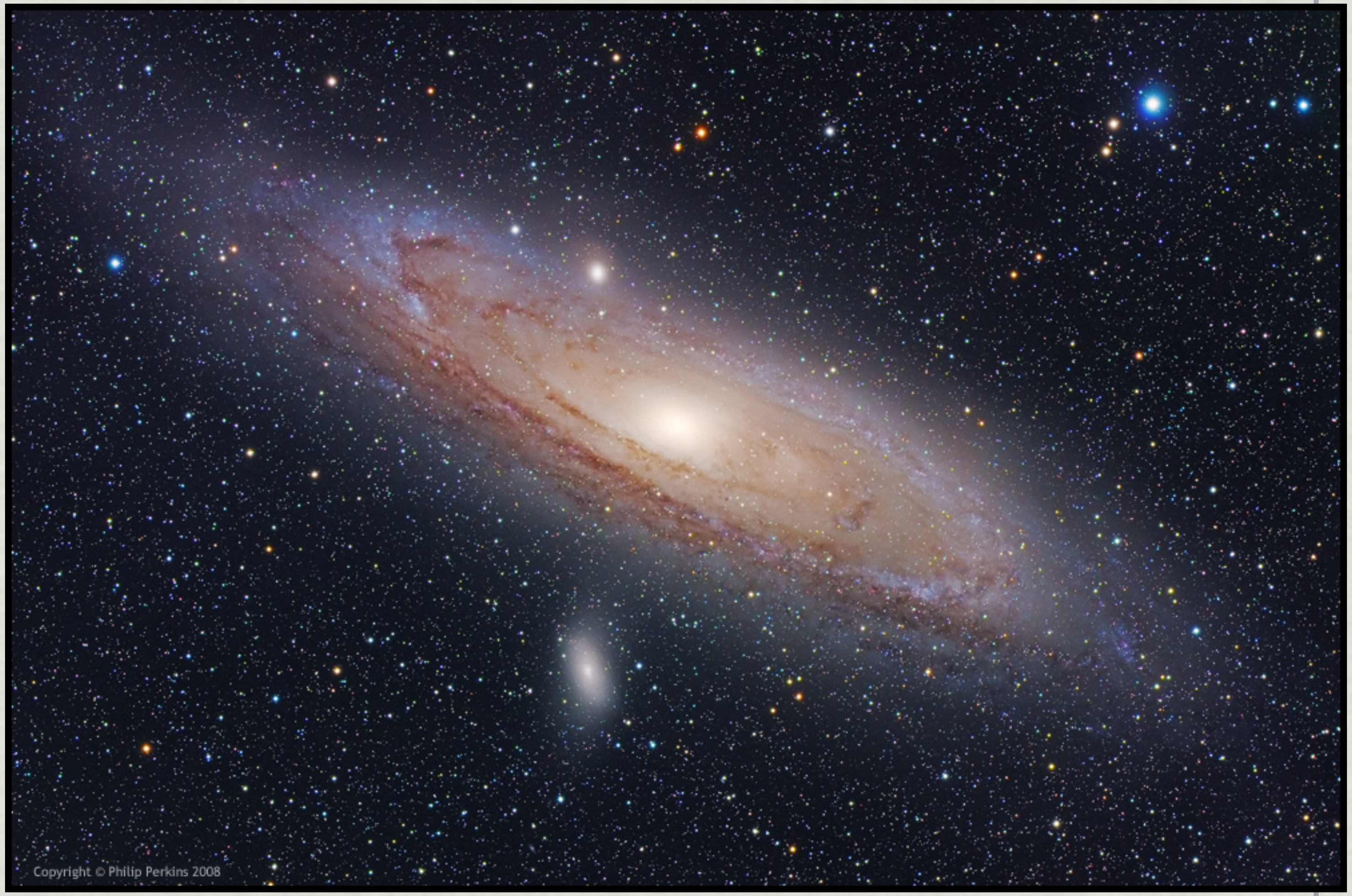
Galaxies in the Universe

- Light travels at a finite speed (300,000 km/s).
- Galaxies at large distances → light left those galaxies a long time ago.
- Large distance = large "look-back time"

The distance to Andromeda, the nearest galaxy to the Milky Way (our galaxy), is 2.5 million light-years.

How long ago did stars in the Andromeda galaxy emit the light we see when we look at Andromeda today?

A) about 8 minutes
B) 13.7 billion years ago
C) 2.5 million years ago
D) 5 billion years ago



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Formula: distance = speed × time

How far does light travel in one year (in a convenient unit...)

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Galaxies in the Universe

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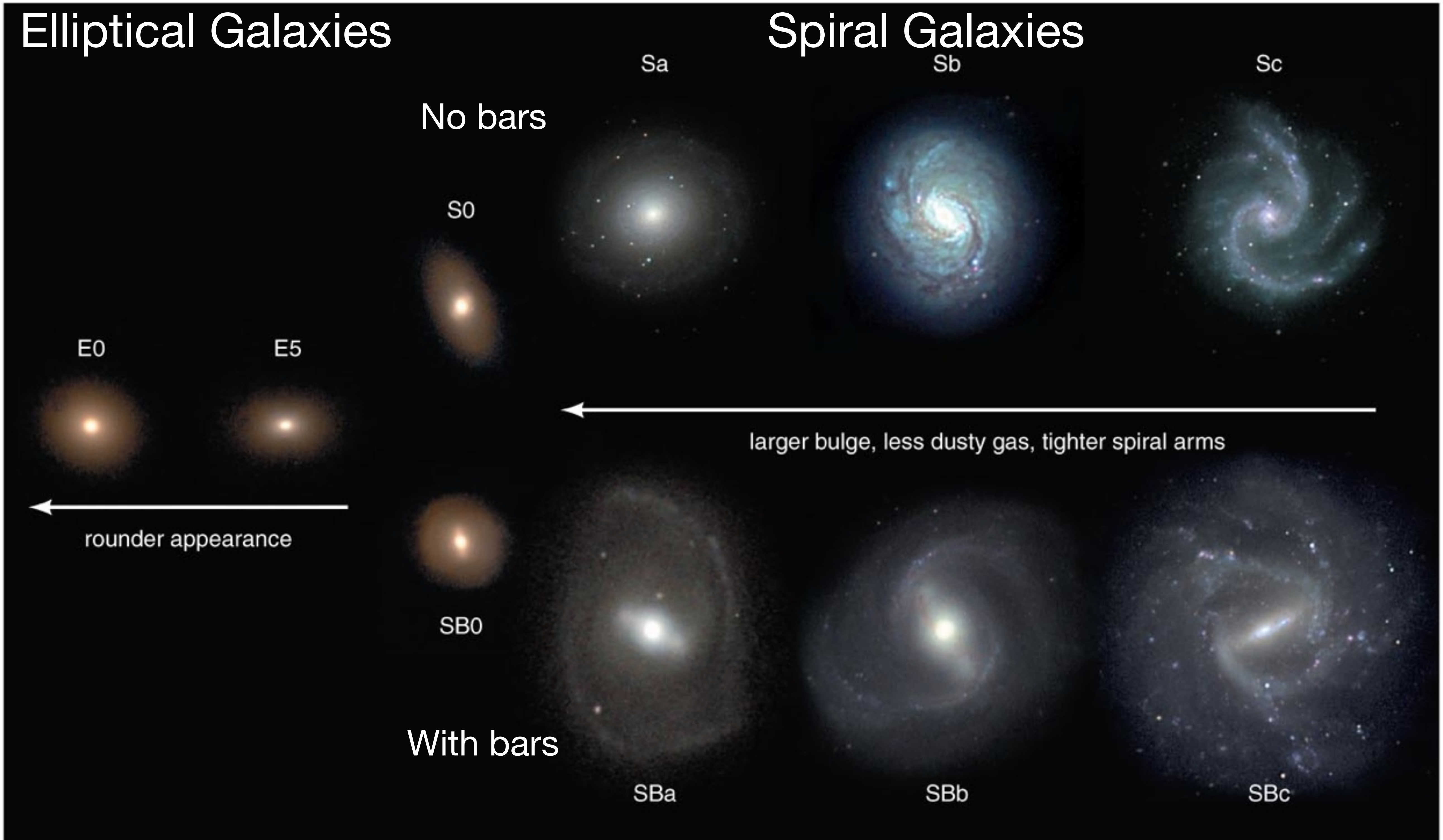
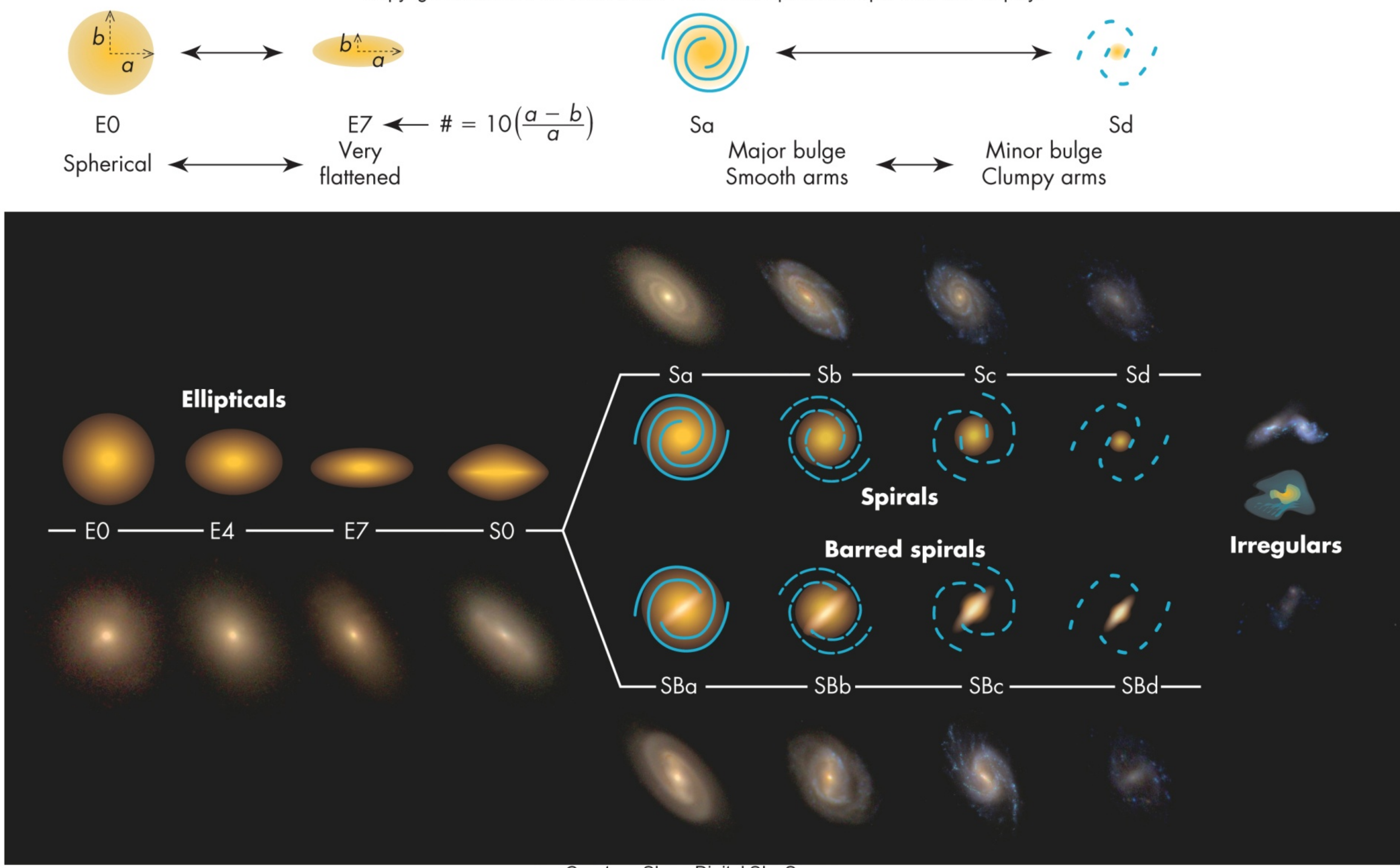
- Distances:
  - Nearest star: 3 light years
  - Center of Milky Way: 25,000 light years
  - Andromeda galaxy (our nearest neighbor): 2.5 million light years
  - Coma cluster (nearest large cluster of galaxies): 340 million light years
  - Most distant galaxies: 10 billion light years
- Look-back time: light left how many years ago?
  - Nearest star: 3 years ago
  - Center of the Milky Way: 25,000 years ago
  - Andromeda galaxy: 2.5 million years ago
  - Coma cluster: 340 million years ago
  - Most distant galaxies: 10 billion years ago

Galaxies in the Universe

Sorting galaxies.
Among the first successful schemes: Edwin Hubble (we'll see him again…)



Galaxies: types and properties



Courtesy Sloan Digital Sky Survey

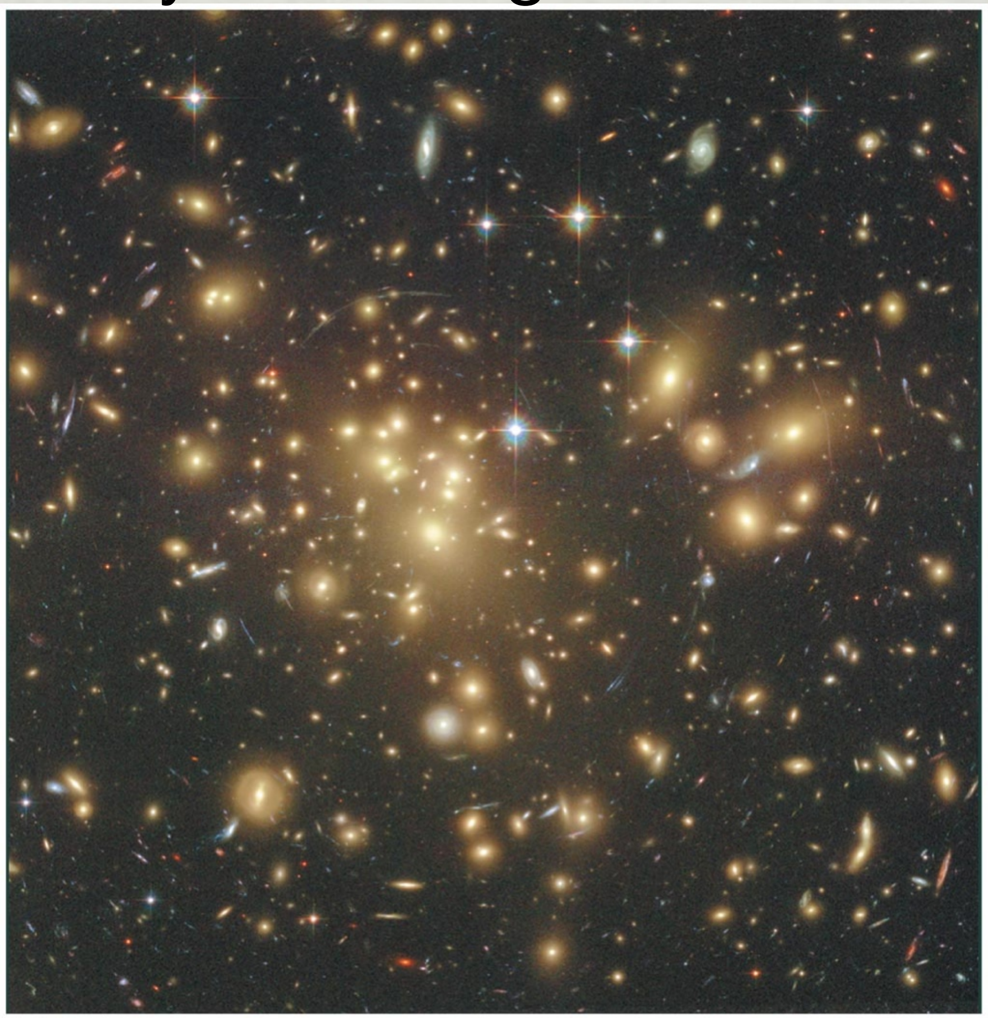
Galaxies in the Universe

100 years after Hubble's first classification diagram, we are still trying to figure out why galaxies look the way they do.

What is important? How many neighbors does a galaxy have?

Spiral (disk) galaxies are often found with few neighbors.

Elliptical galaxies usually have many more neighbors.

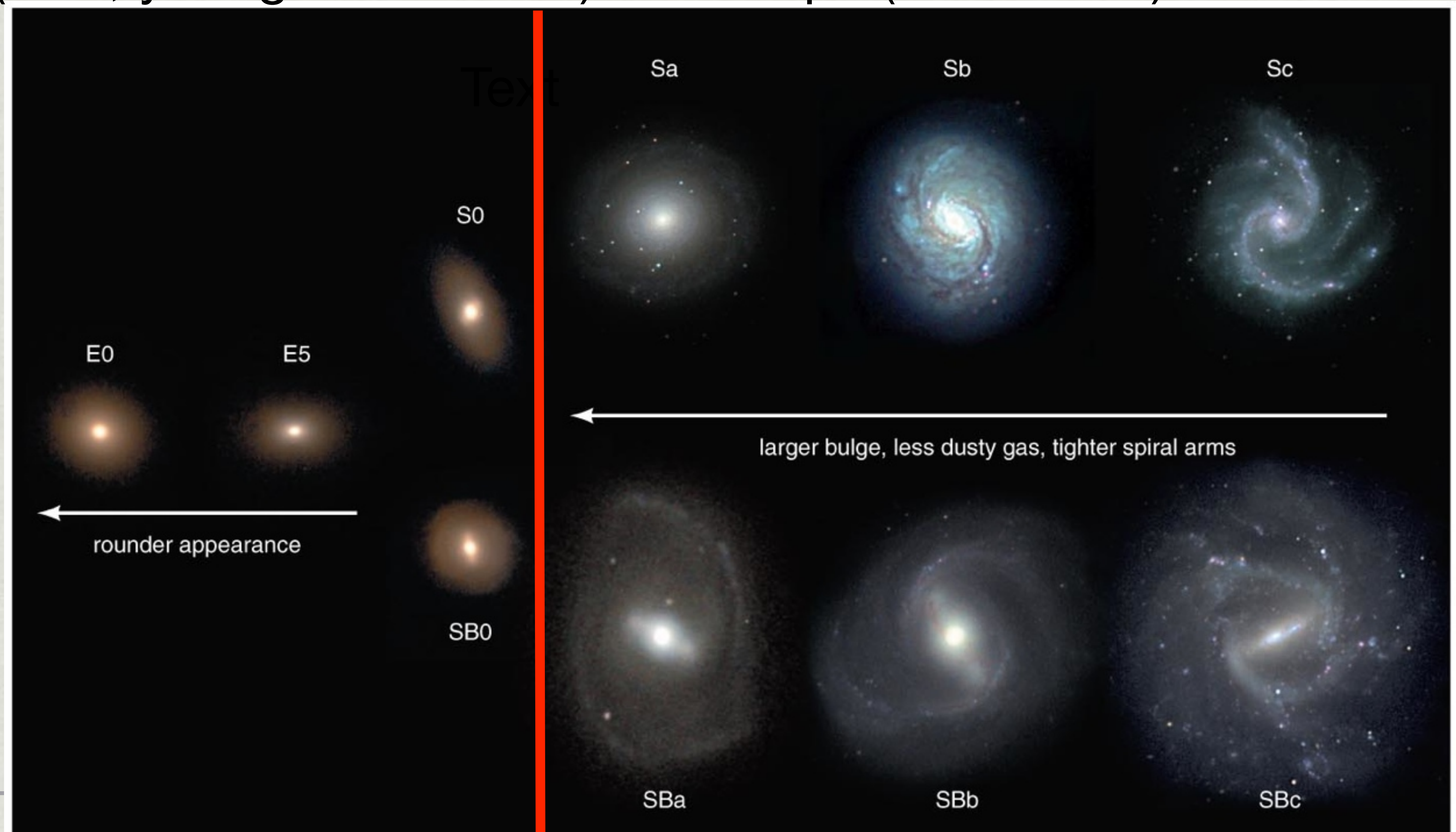


Galaxies in the Universe

100 years after Hubble's first classification diagram, we are still trying to figure out why galaxies look the way they do.

What is important?   Is a galaxy forming stars, or not?

Related to color (blue, young stars or not) and shape (disk or not)



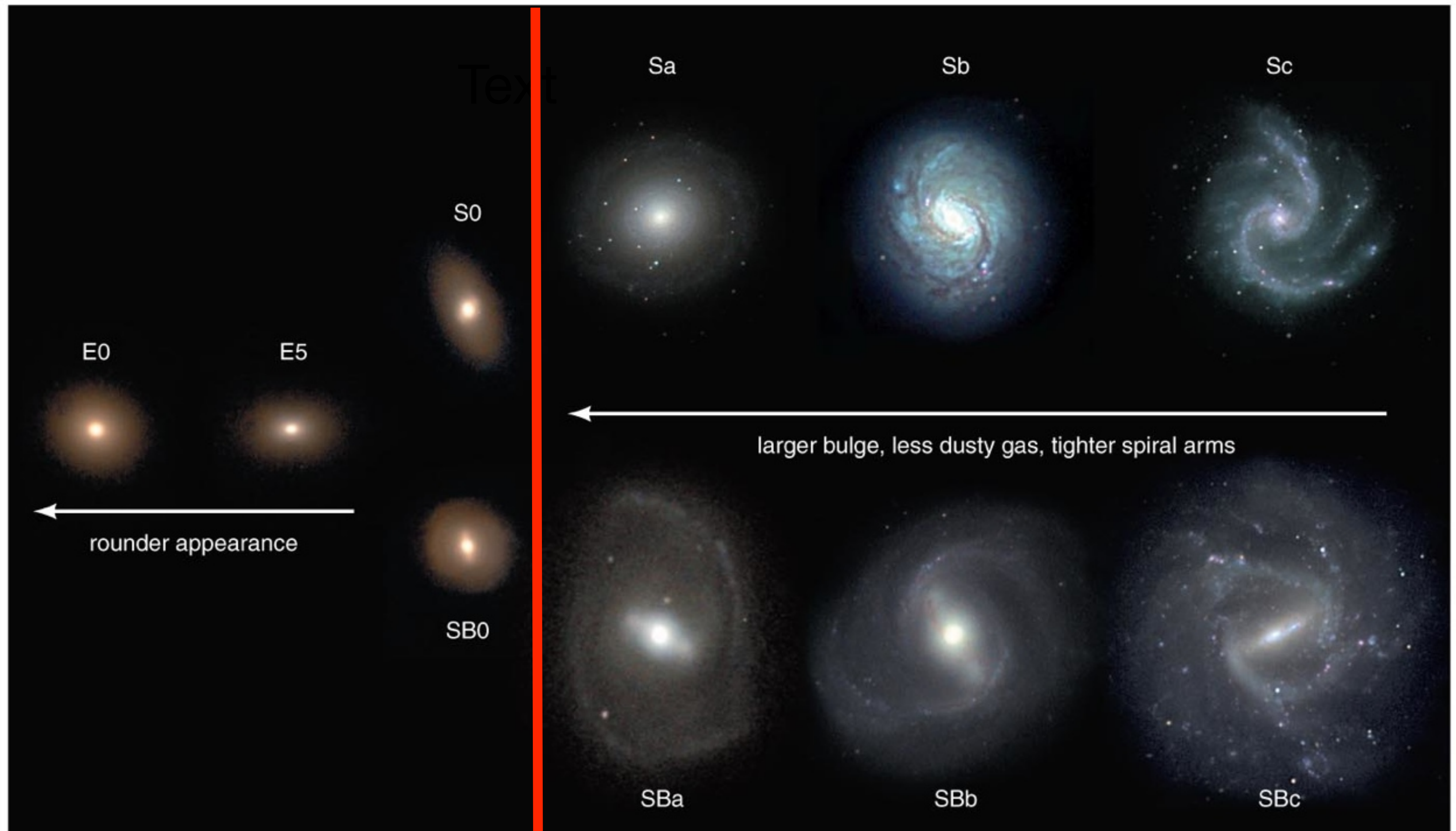
Galaxies in the Universe

100 years after Hubble's first classification diagram, we are still trying to figure out why galaxies look the way they do.

An intriguing related question: what about S0 galaxies? These are disk galaxies not forming stars.

Are they disks that ran out of gas?

Did something take the gas away?



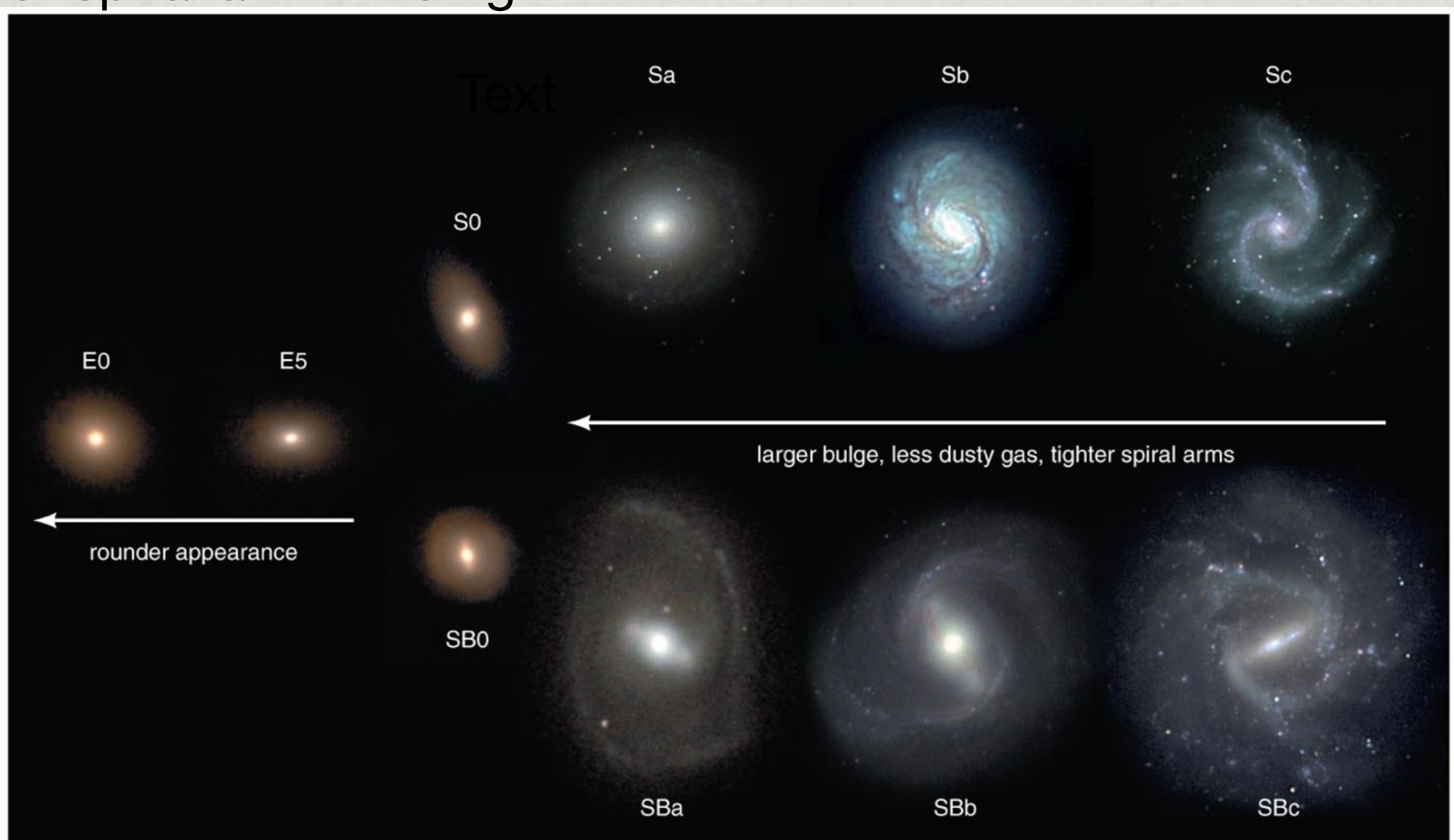
Galaxies in the Universe

100 years after Hubble's first classification diagram, we are still trying to figure out why galaxies look the way they do.

What is important?

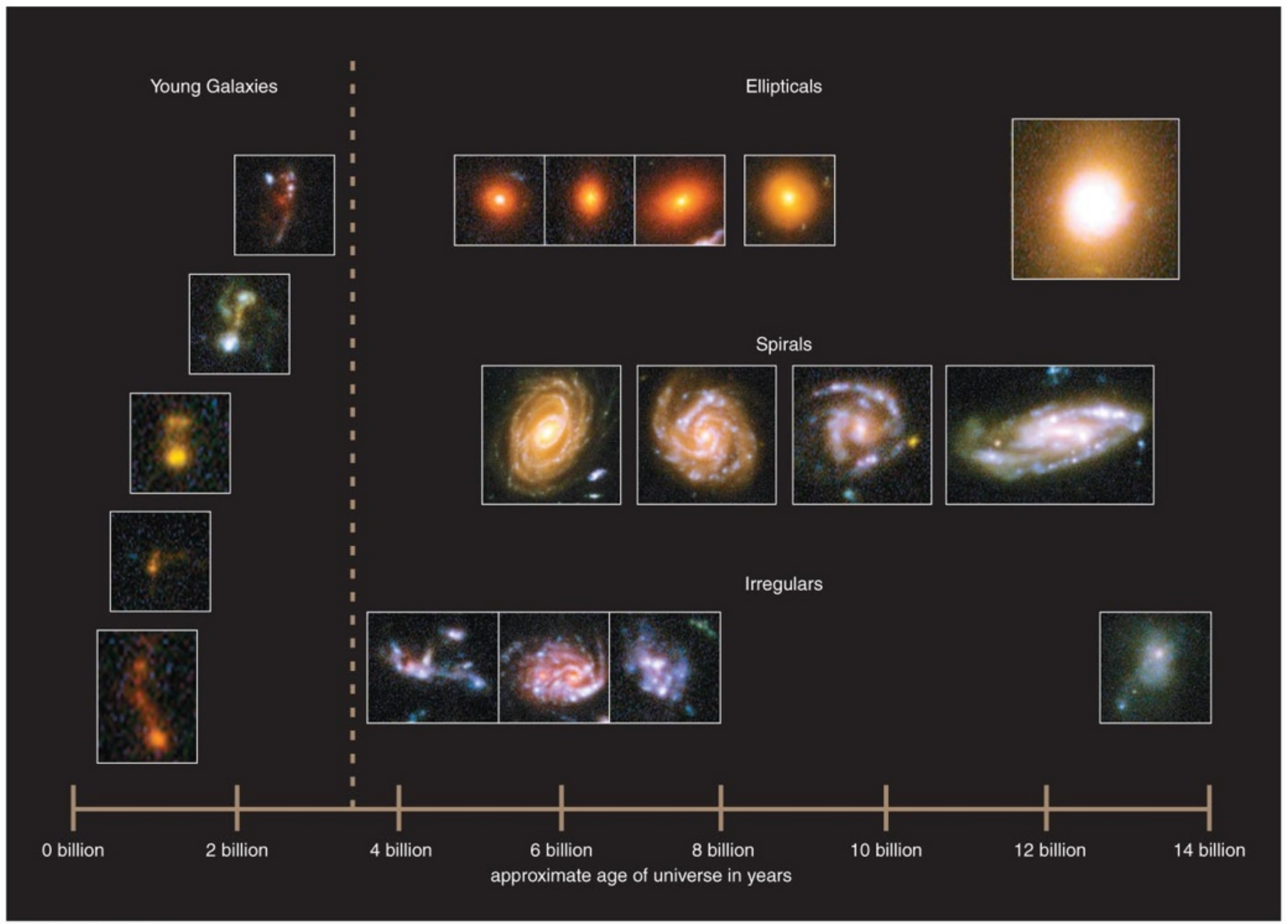
Probably not bars or spiral arm winding.

They have a spectacular effect on what galaxies look like, but are probably transient phases in a galaxy's life.



Galaxy Formation, Growth and Evolution

We see distant galaxies as young galaxies: looking back in time

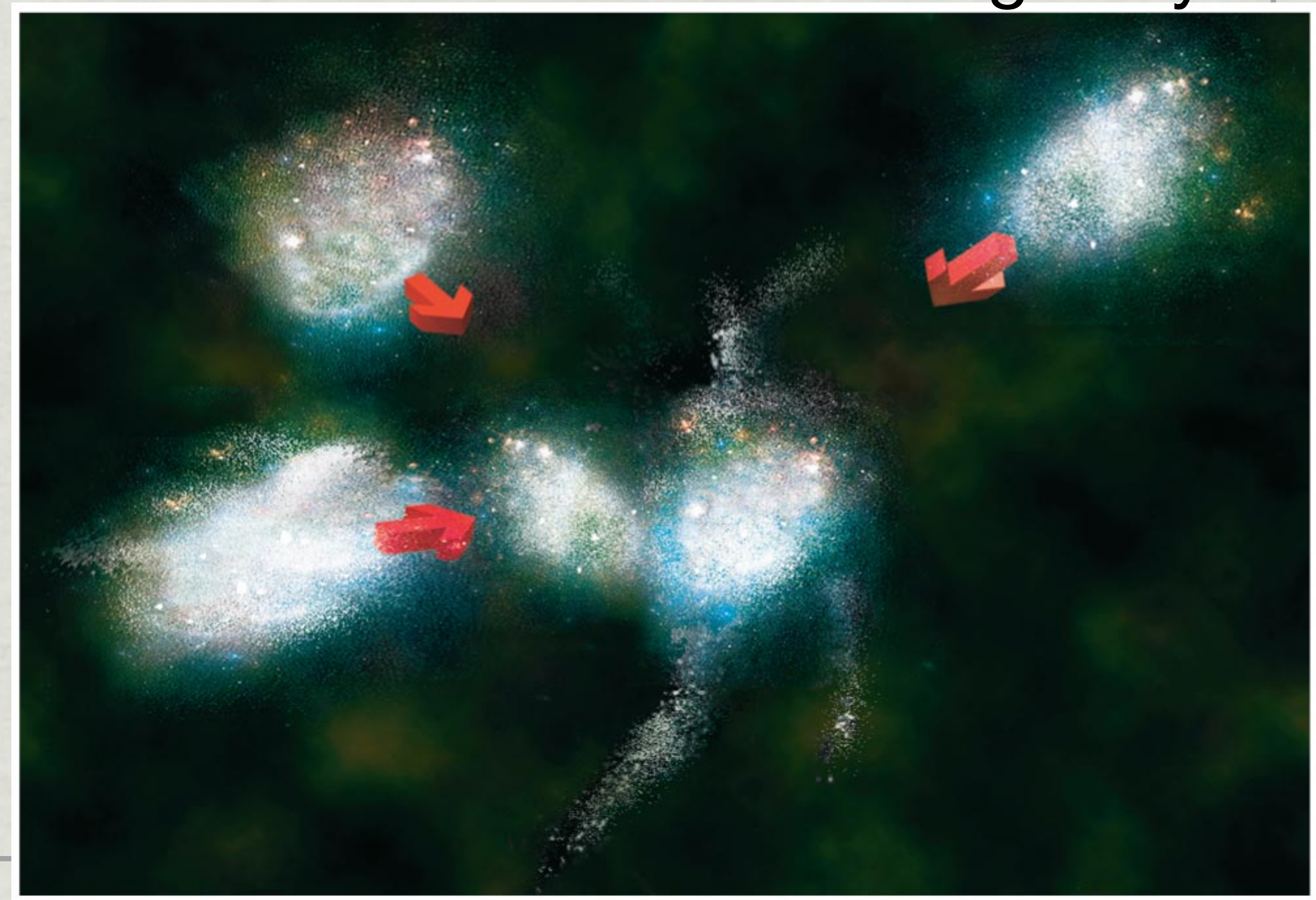


Milky Way: Formation

How it might have happened

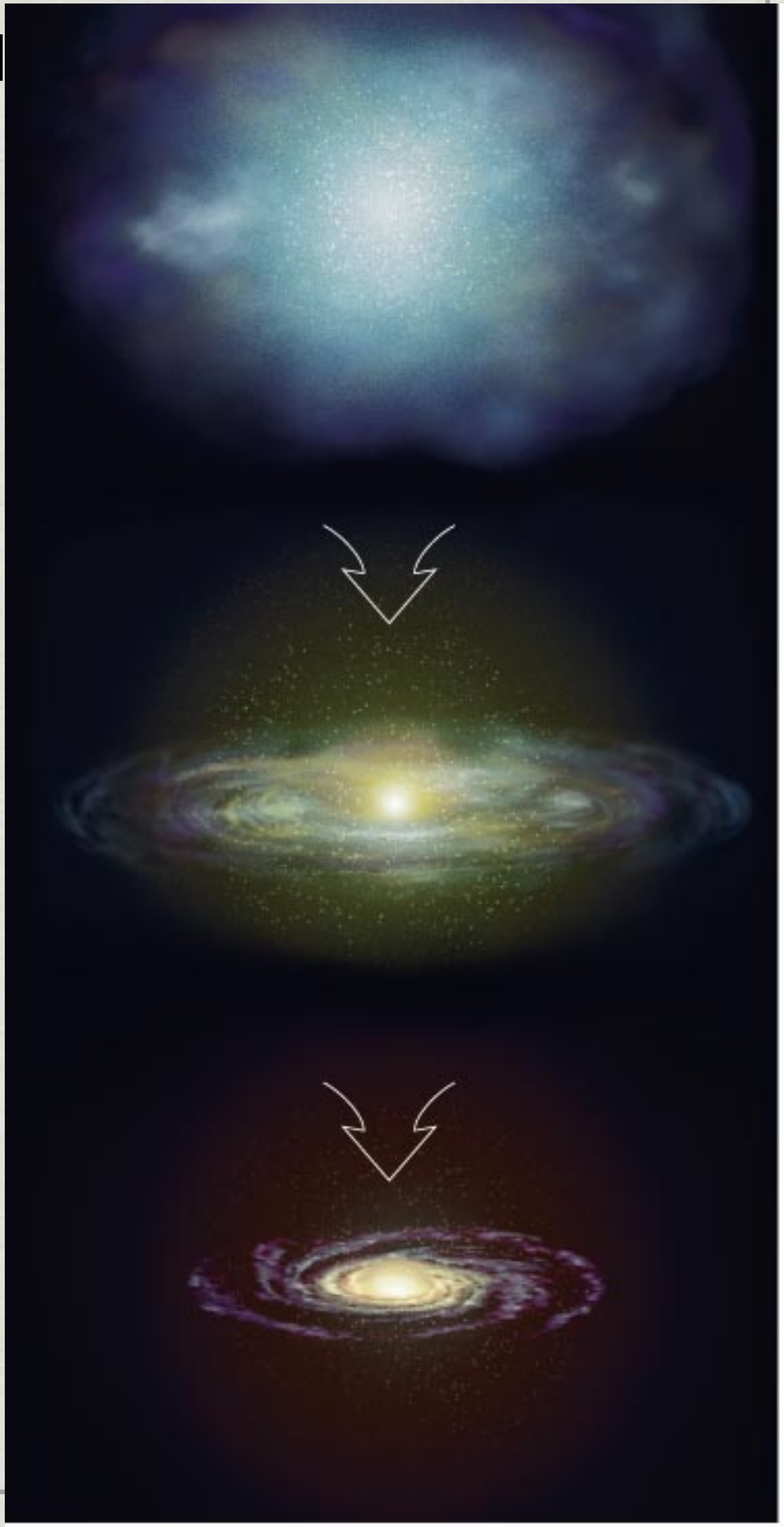
1. Several small blobs of gas started forming stars.
   - gravitationally bound globs of gas
   - Where did the blobs come from? We think the density of gas in early universe was just a little patchy, and those patches grew into distinct blobs under their own self-gravity. We'll get to this next when we talk about cosmology.

2. Those blobs of gas and stars were attracted to each other due to gravity. Fell together and merged to make one big blob of gas and stars.



Milky Way: Formation

How it might have happened



3. Gas can cool and get more dense. The blob gets smaller

How? Kinetic energy of collisions between atoms excites electrons, moves them to higher energy levels. Atoms radiate the energy away as light.

As long as the gas stays transparent, energy escapes as light. Transfer kinetic energy to light, lose thermal energy from the gas.

Kinetic energy goes down, gas gets cooler and can become more dense (like a balloon in the freezer).

Stars can't do this, so they stay in the halo.

Milky Way: Formation

How it might have happened

3. Gas can coo

Kinetic energy c
electrons, move
Atoms radiate t

As long as the g
escapes as ligh
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Kinetic energy g
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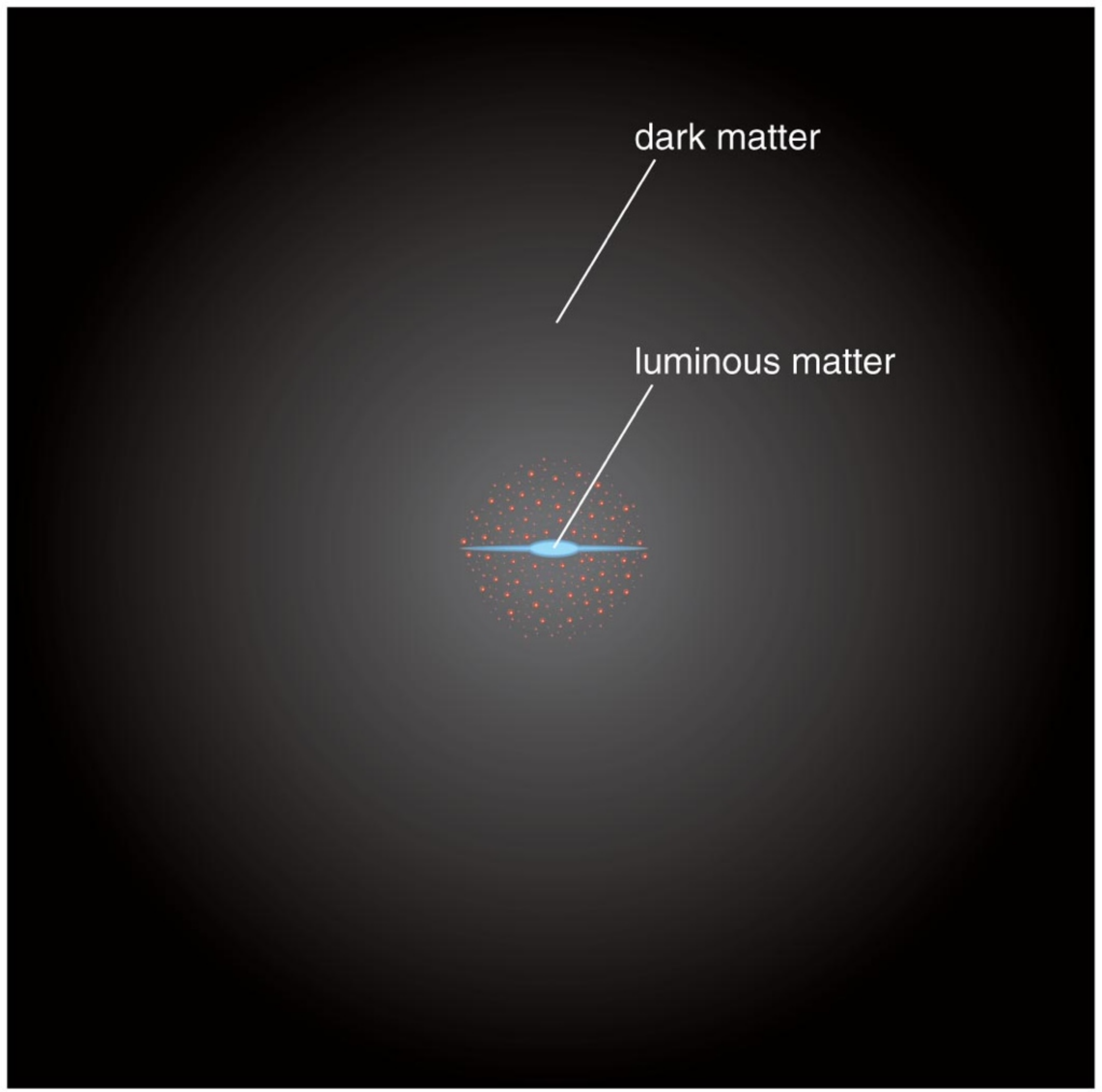
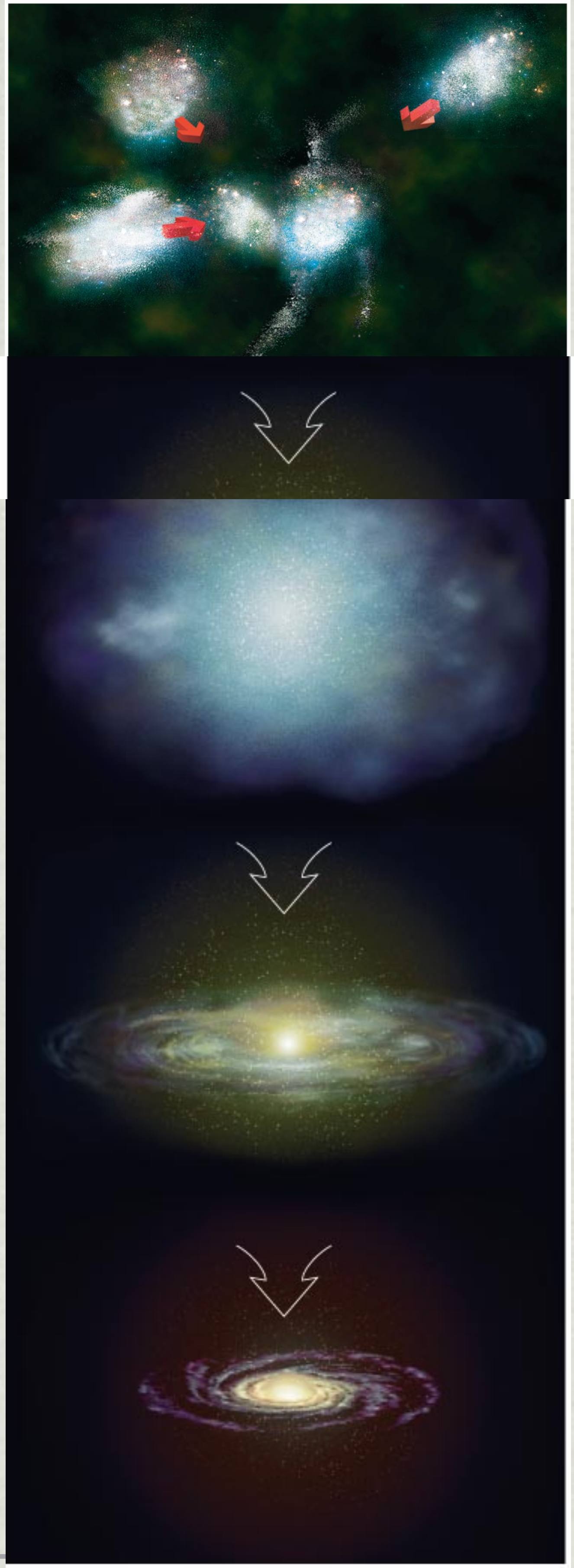
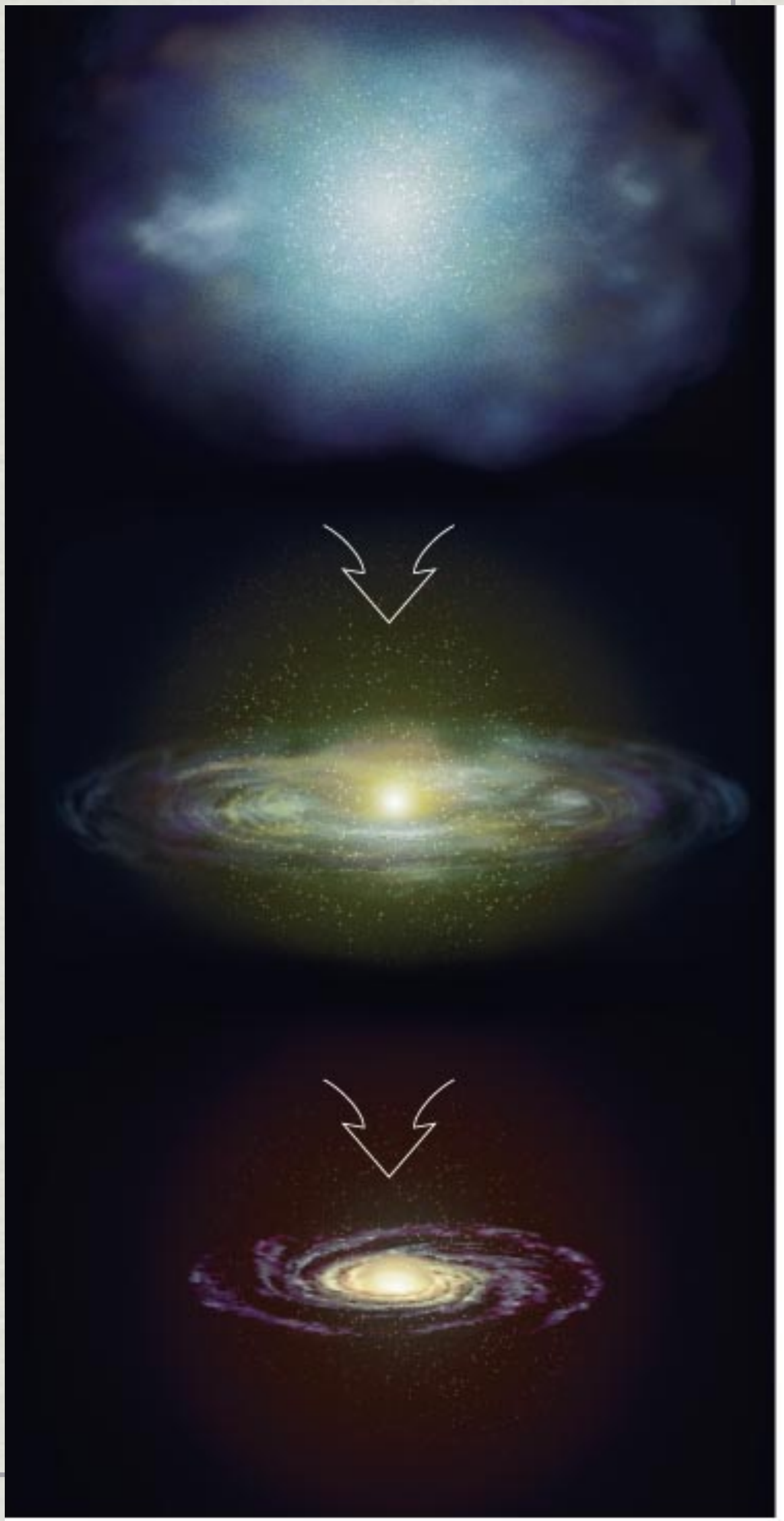




Neither can dark matter: it can't interact with light.
So it stays in a big, diffuse halo, too.

Milky Way: Formation

How it might have happened



4. Conservation of angular momentum means that the gas becomes a disk as it cools and becomes more dense, not a sphere.

5. Star formation continues in the disk up to the present day.

Galaxy Formation

Picture for spirals like the Milky Way.

Explains data:

Halo is old and not forming stars

Disk is young with gas, dust, and ongoing star formation

Halo stars are less enriched in elements beyond hydrogen and helium

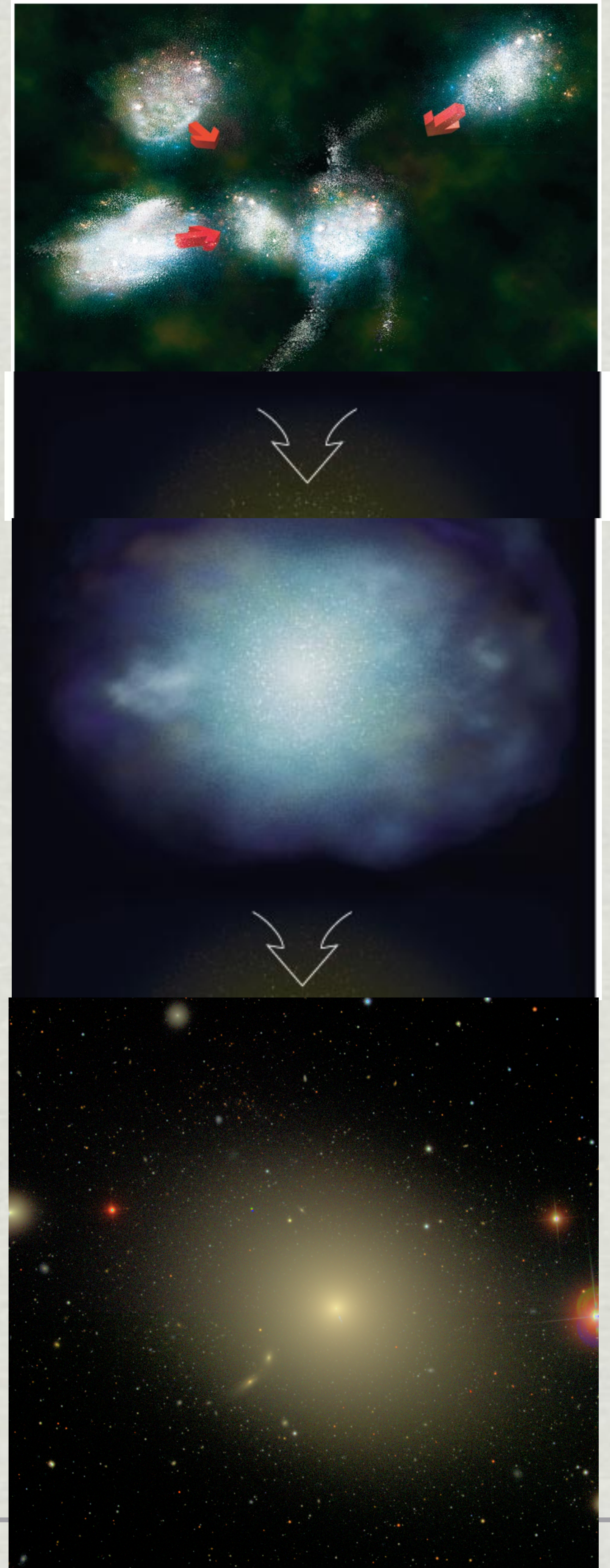
Halo is spherical, star orbits are random

Disk is flattened, star orbits are organized

Galaxies in the Universe

- Elliptical galaxies
  - Structure: round, no disk
  - Old stars, no star formation. Not much gas or dust.
  - Color: red. No hot, young stars.
  - Motions: random motions, like gas molecules in the air.
    - Like the halo of spiral galaxies.
    - Did these galaxies form like the halo of our Galaxy?

Galaxy Formation



What about ellipticals?

Remember:
- No disk, orbits of stars are disorganized. Stars move in all different directions like gas molecules in the air
- No star formation. No hot, young stars. Very little gas or dust

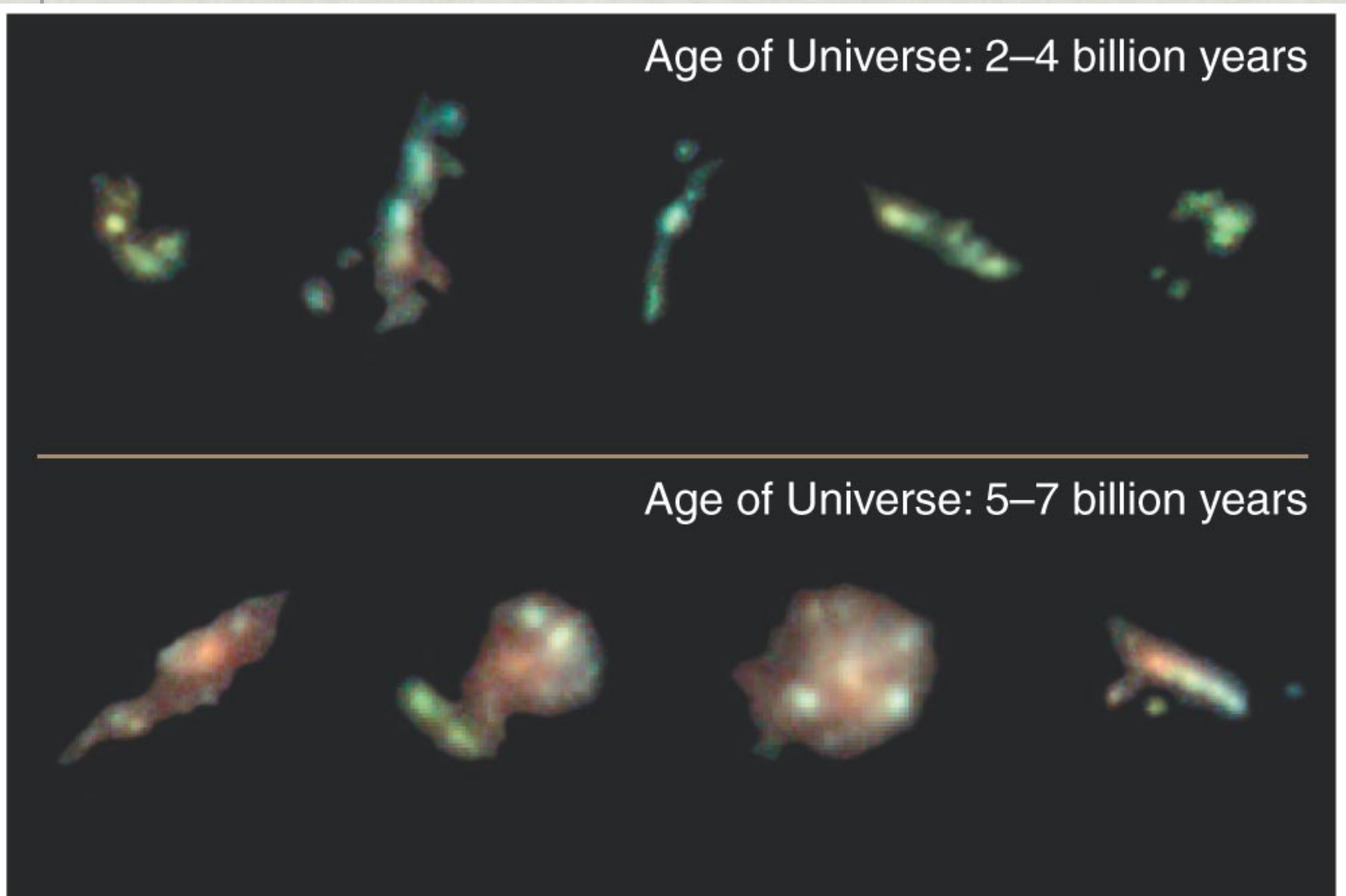
?

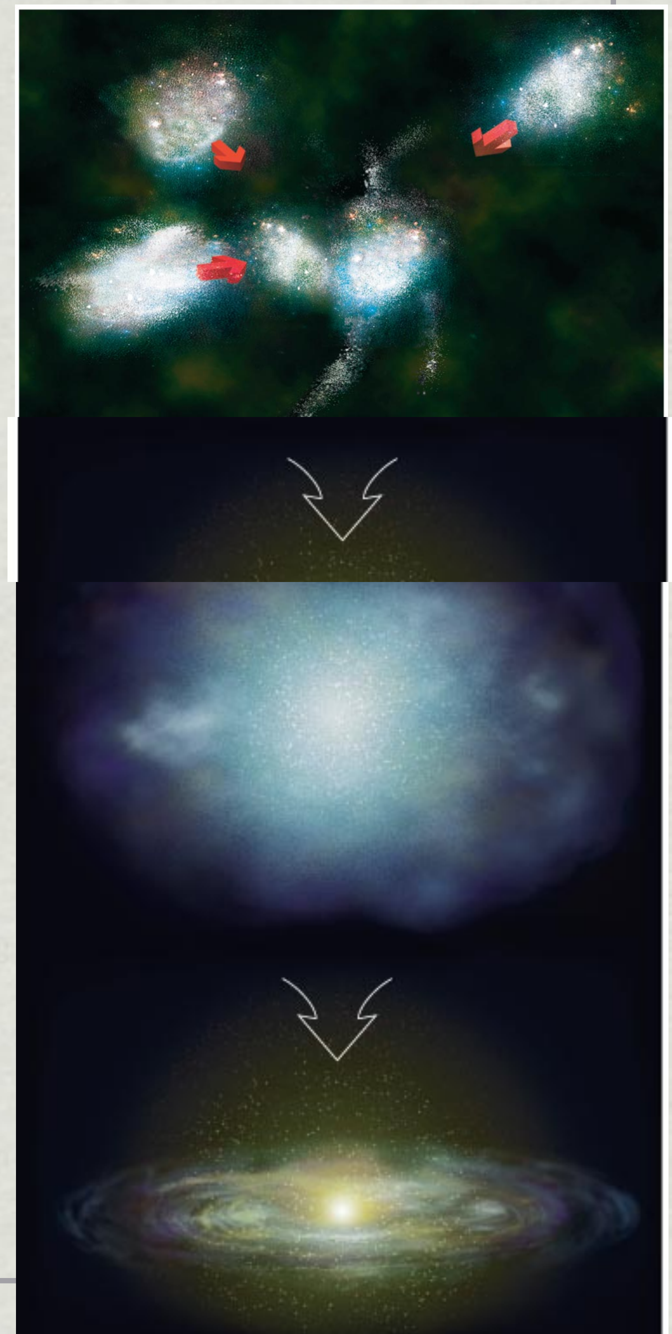
Maybe they formed very fast from a gas cloud that was very dense.

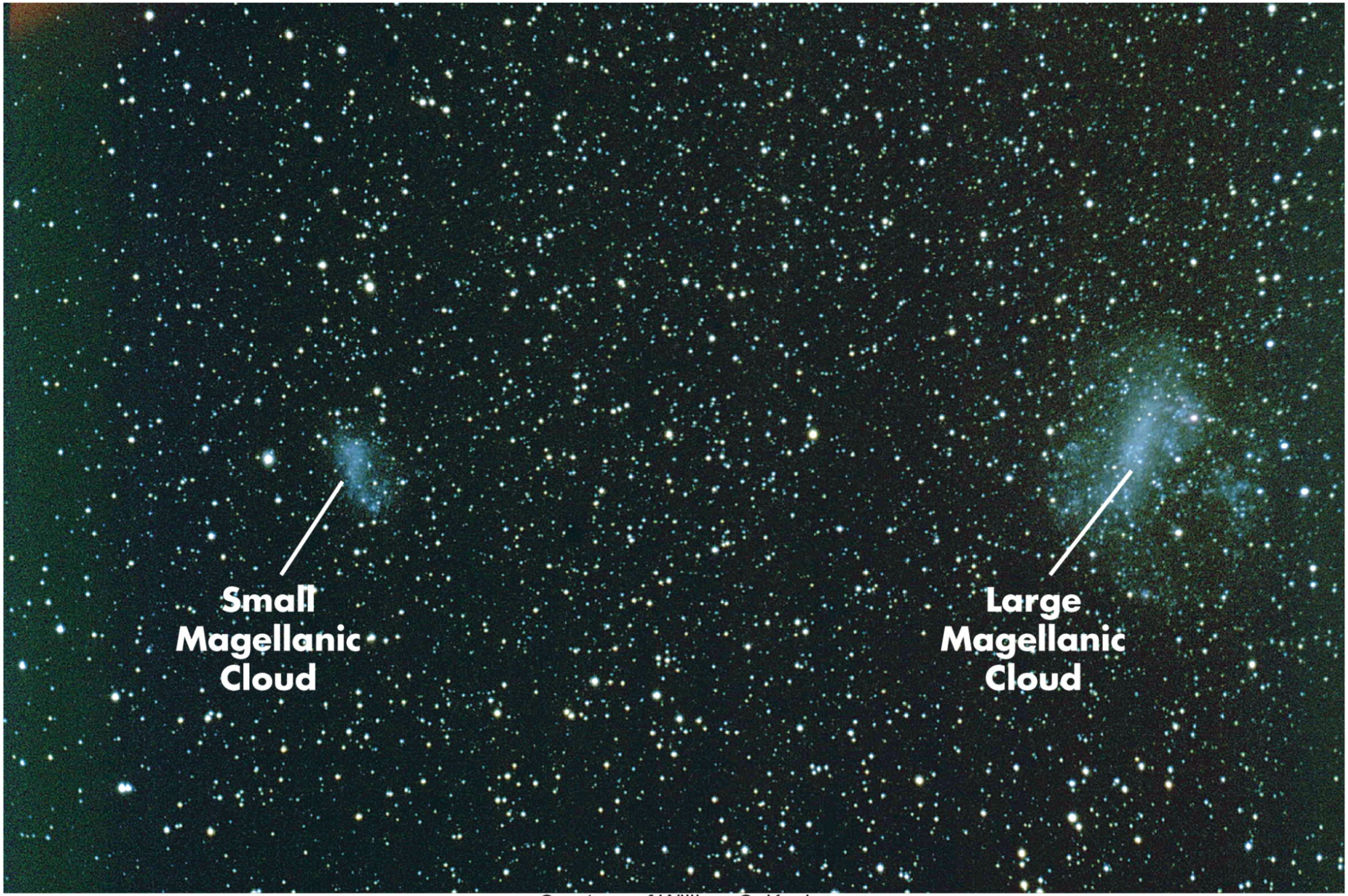
All the gas formed stars before the gas had time to cool and settle into a disk.

Galaxy Evolution

Young galaxies: lumpier, more evidence of individual overdensities that merge together to make galaxies



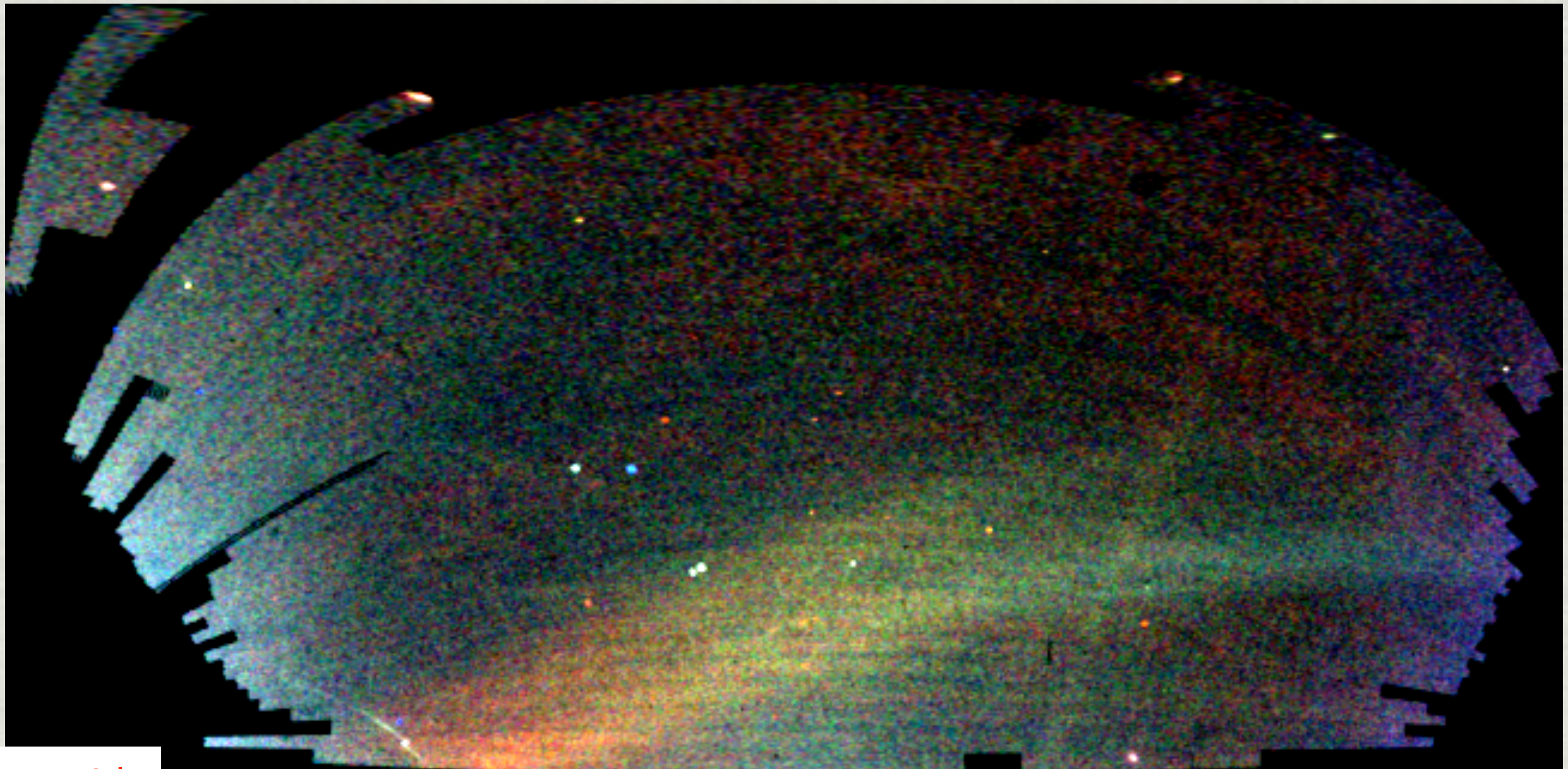




Courtesy of William C. Keel

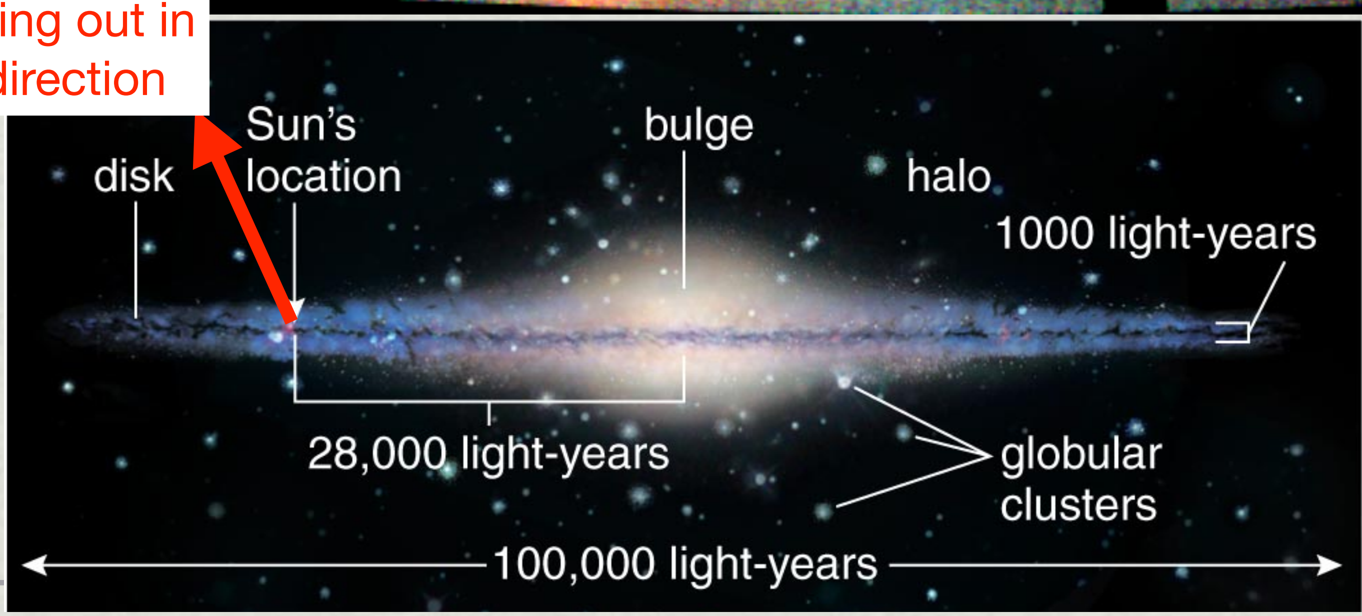
Milky Way Halo

More data: the halo is patchy and lumpy, not a uniform sphere



View of the Milky Way looking out away from the disk. Color coding is by distance.

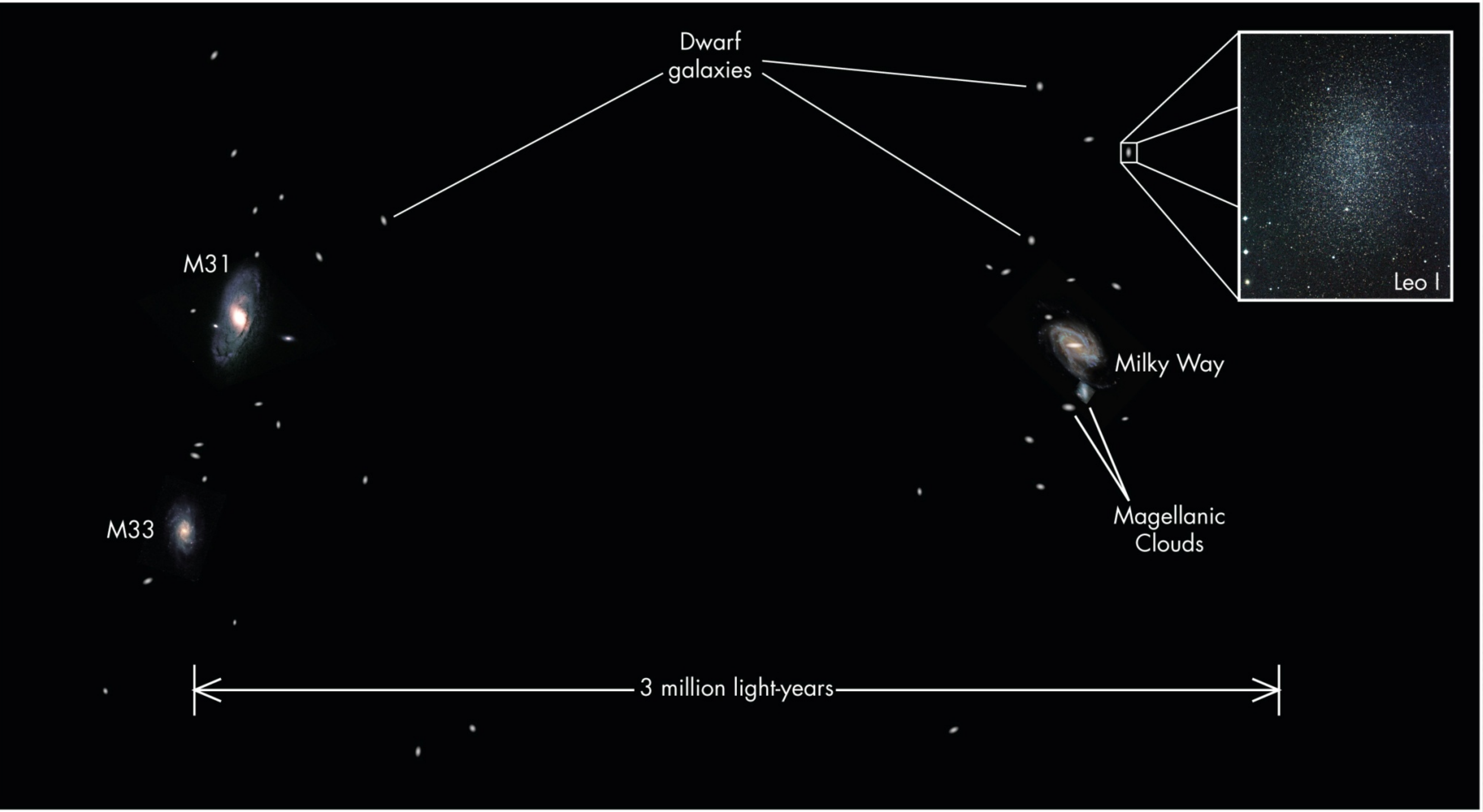
Data from the SDSS www.sdss.org



Evidence that these small lumps of gas, stars (and dark matter!) are still falling in?

In other galaxies, too!

Galaxies are found near each other, in small groups and giant clusters



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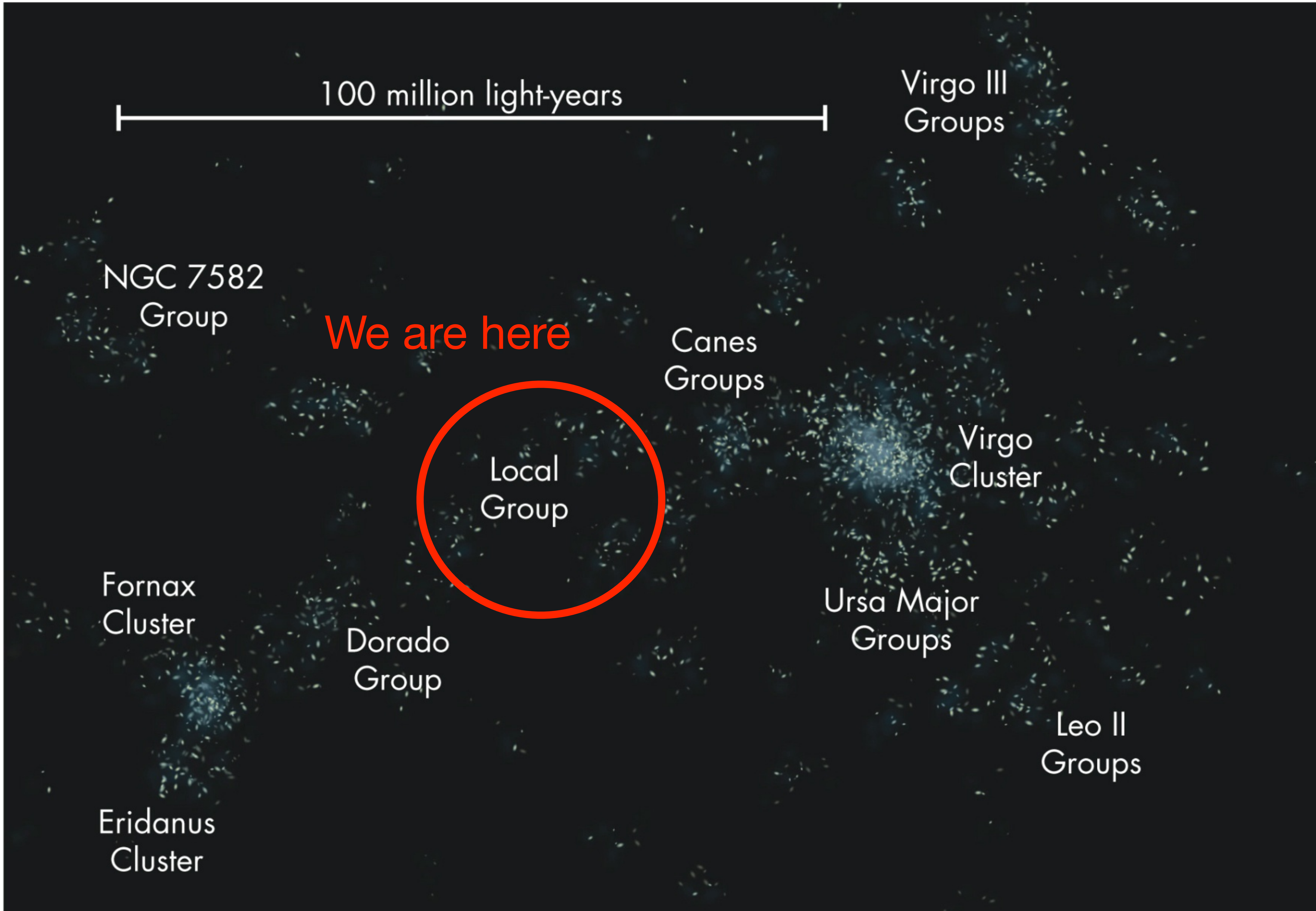
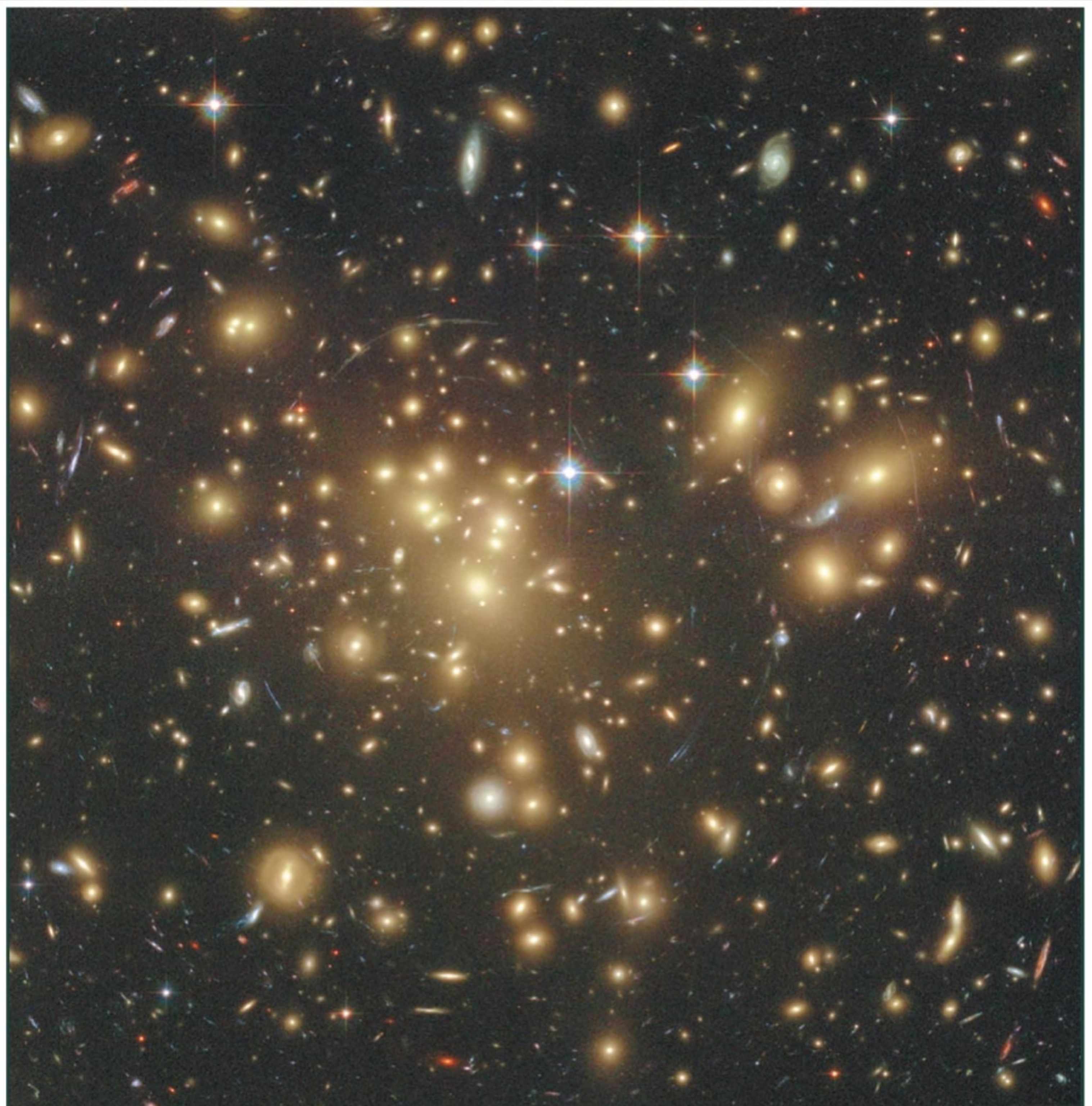


Clusters of Galaxies

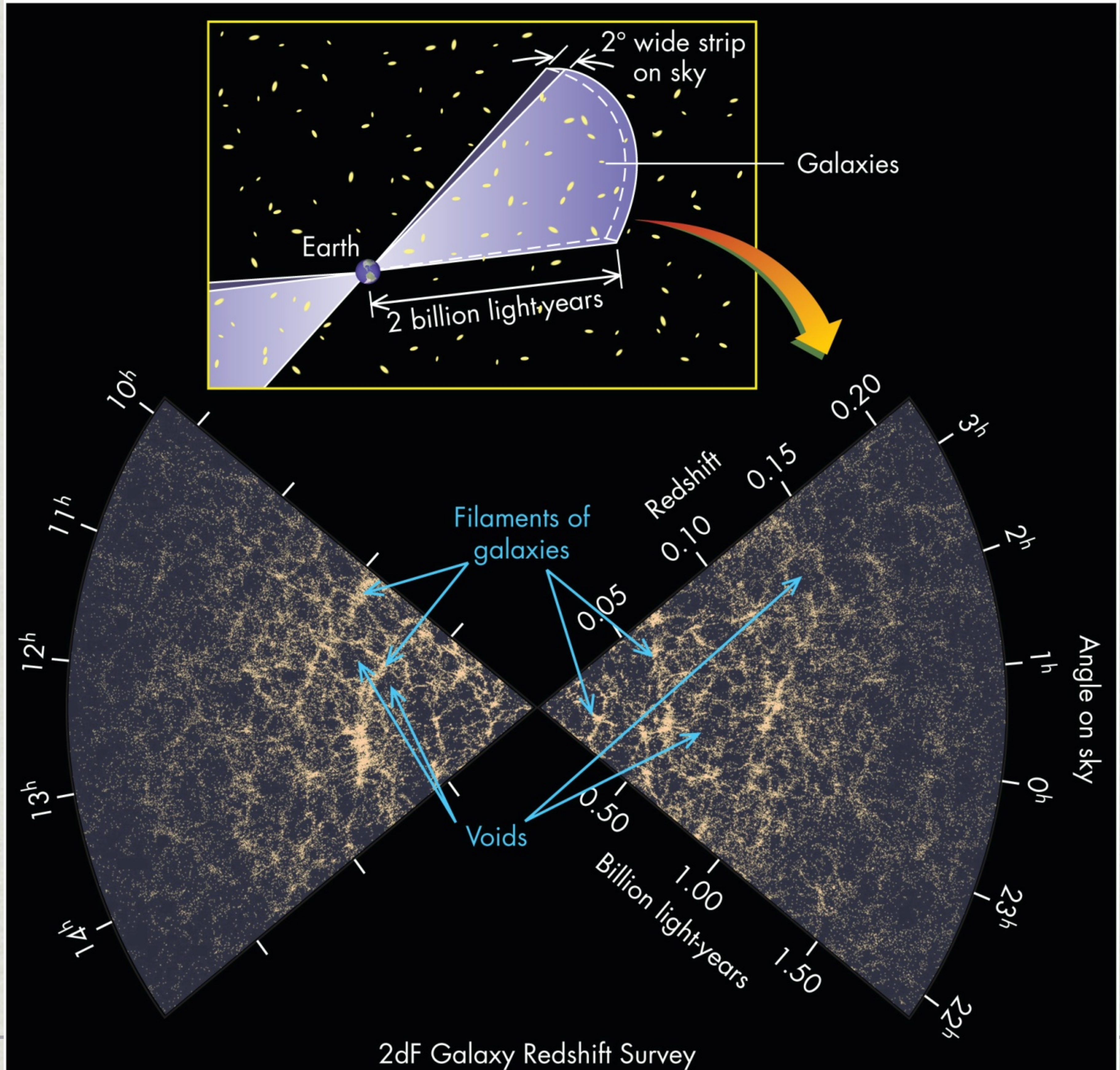
Elliptical galaxies usually have many neighbors.



Number of neighbors related to total mass bound by gravity: note gravitational lensing by this cluster of many galaxies.

Says there is lots of mass here to curve space-time and force light to follow a curved path.

Clusters of Clusters of Galaxies



Quasars, Black Holes and Galaxies

Quasars first discovered in 1963

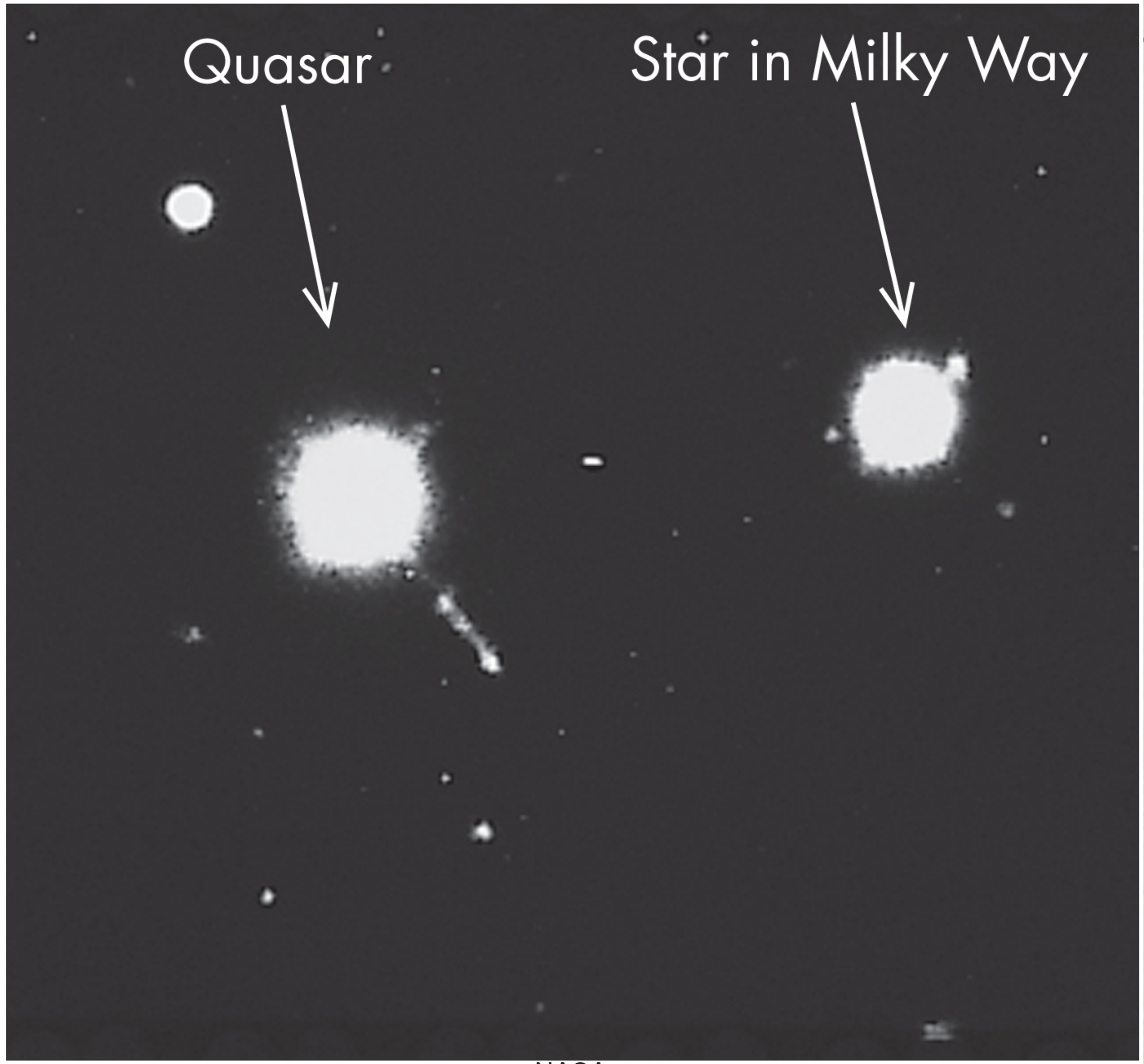
"Quasi-Stellar Radio Source": very bright, star-like objects that also emit in the radio part of the EM spectrum. Not expected for a thermal spectrum.

Realized that the spectra showed chemical fingerprints of hydrogen, but with gigantic Doppler shifts.

Very distant* but still have large observed apparent brightness: must be ***really*** luminous!

$$\text{apparent brightness} = \frac{L}{4\pi d^2}$$

*we'll get to why a big doppler shift means a big distance when we talk about cosmology



NASA

← An image of a Quasar from a telescope on the ground.

Looks a lot like a star!

AURA/STScI/NASA

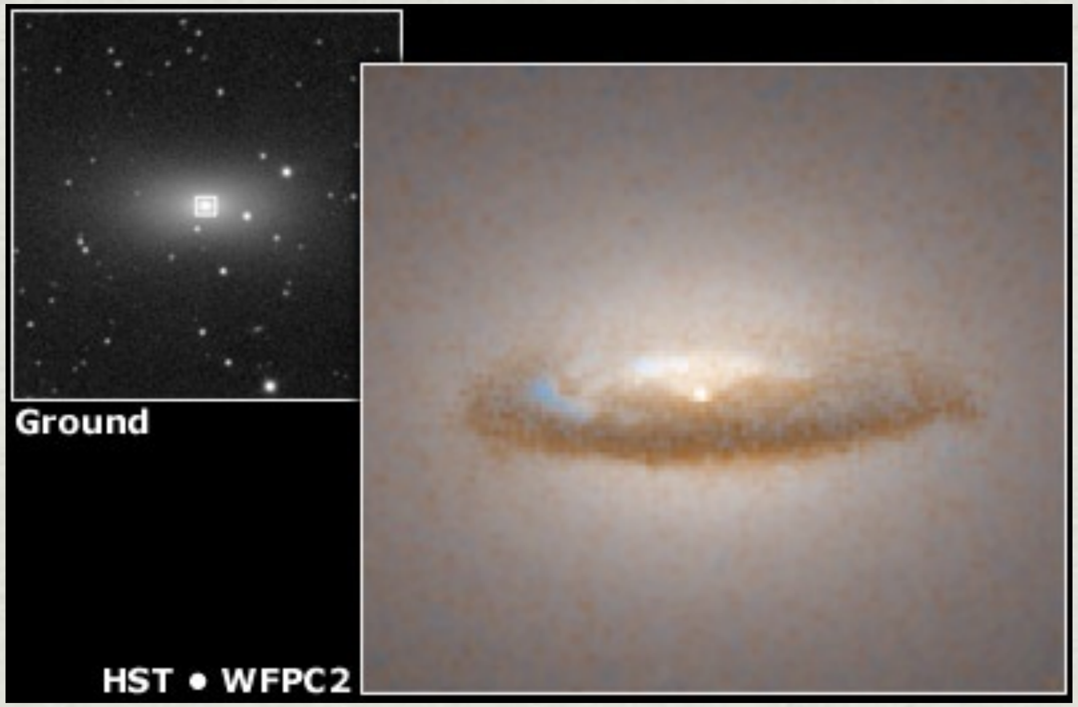
An image of a Quasar (a dim one, called a "Seyfert galaxy") from space. → Can now see the rest of the galaxy around the very bright center

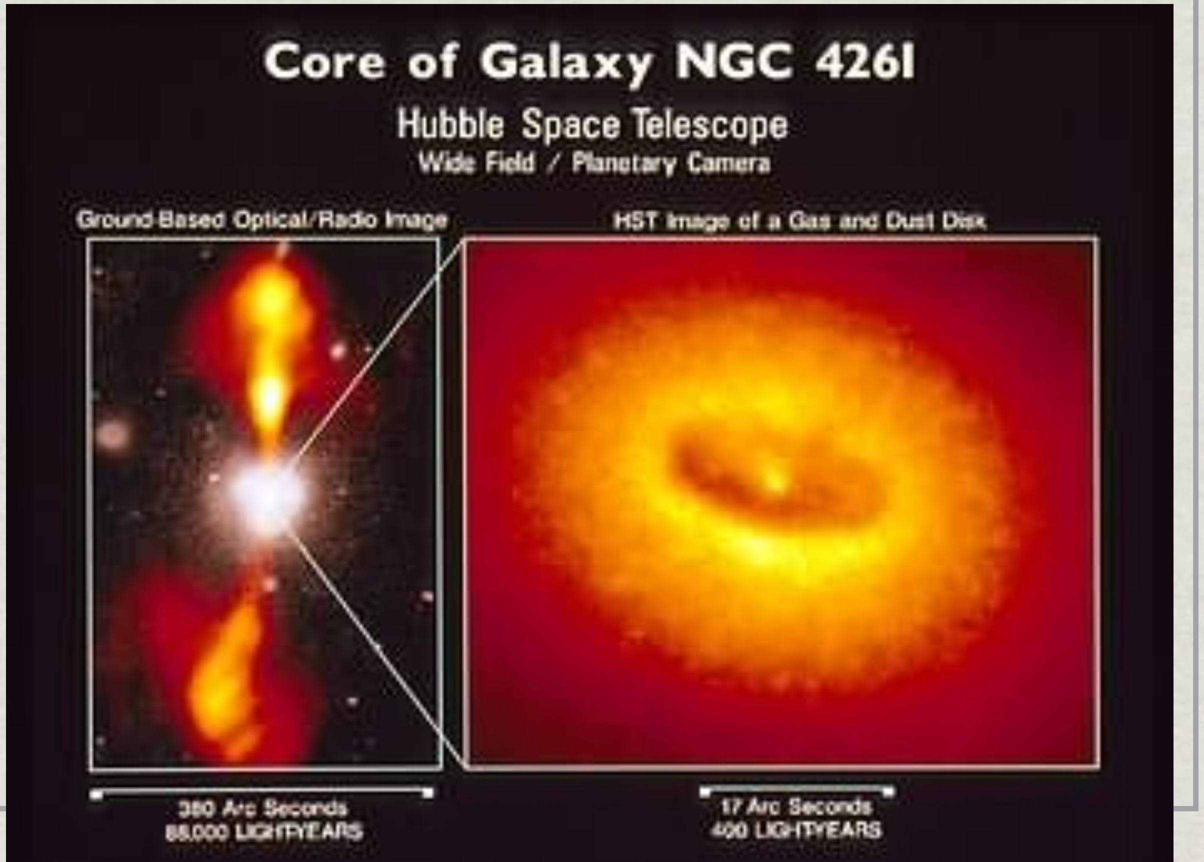
Quasars, Black Holes and Galaxies

Eventually, realized that quasars are black holes in the centers of galaxies.

That huge luminosity is the light from gas that is glowing from the energy it gains as it falls in to the black hole.

Infall converts gravitational potential energy to other kinds of energy. Stored in the energy levels of atoms, released as emission line spectra and other interactions





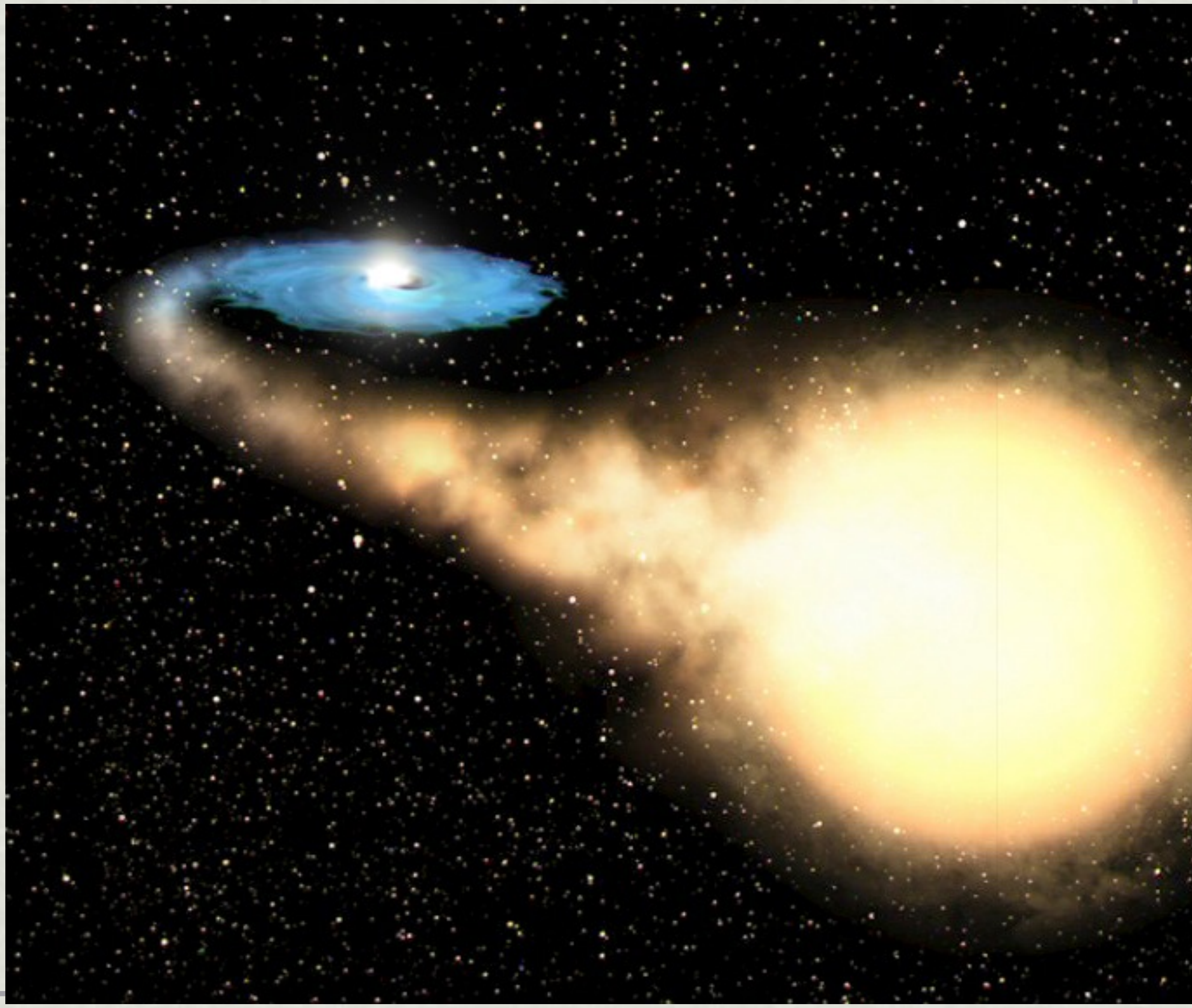
Quasars, Black Holes and Galaxies

Black holes in the centers of galaxies can pull in gas from the rest of the galaxy.

As the gas falls in the atoms collide. The gas heats up due to friction and the release of gravitational potential energy.

The gas emits radiation, though not a thermal spectrum.

Can be incredibly bright, out-shine an entire galaxy.



A Black Hole in Our Galaxy

We observe black holes indirectly, through the influence of their gravity.

Sagittarius A*: a black hole right at the center of our Galaxy

How do we know it's a Black Hole and not just a really heavy star?

Speed in a circular orbit:

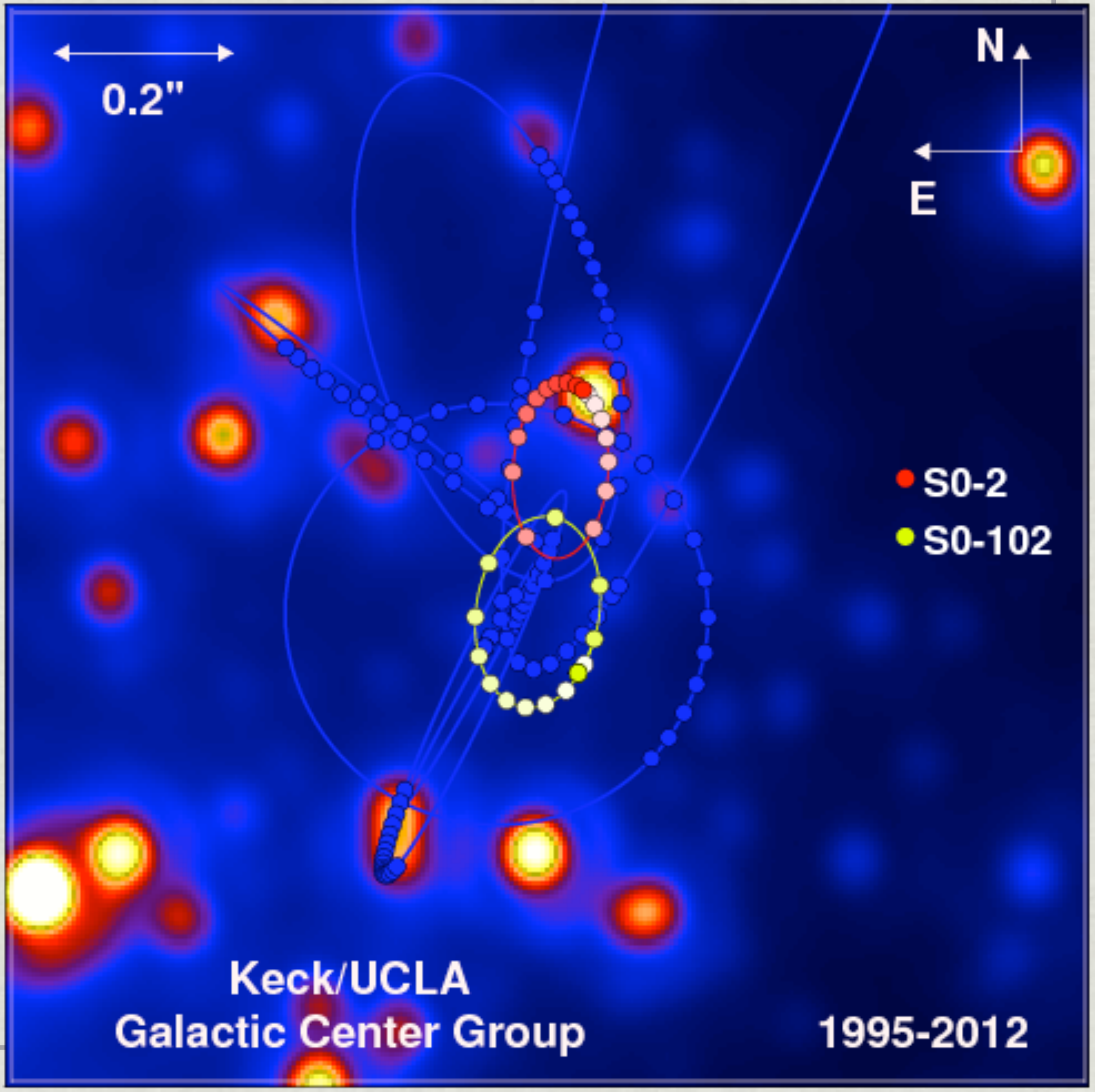
$$v_{orbit} = \sqrt{\frac{G\,M}{d}}$$

Measure d, v_{orbit}, get M

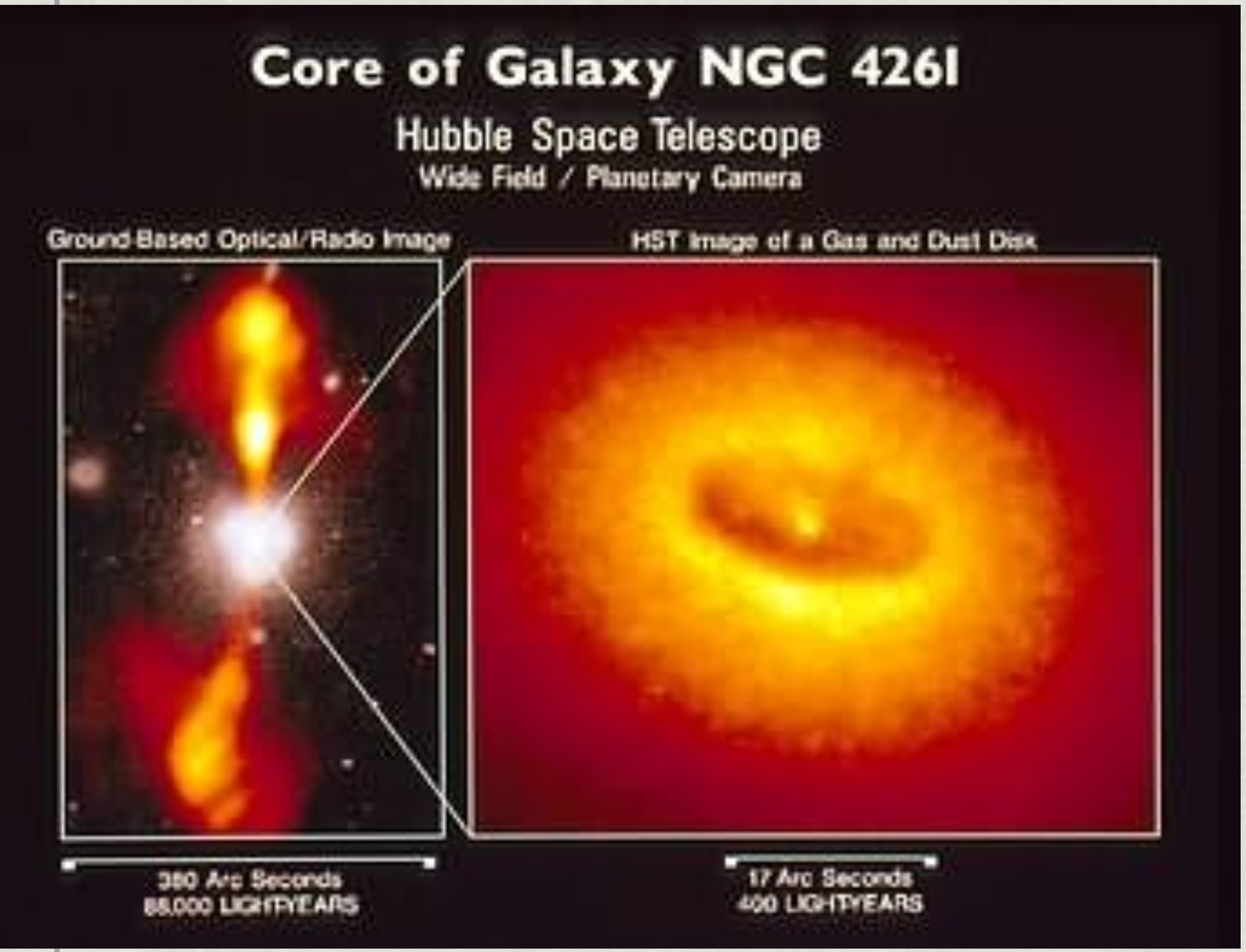
But Black Holes require high density, not just lots of mass.

So need to measure lots of mass in a tiny volume (small d). Want stars as close as possible.

S0-102: 200 AU from GC

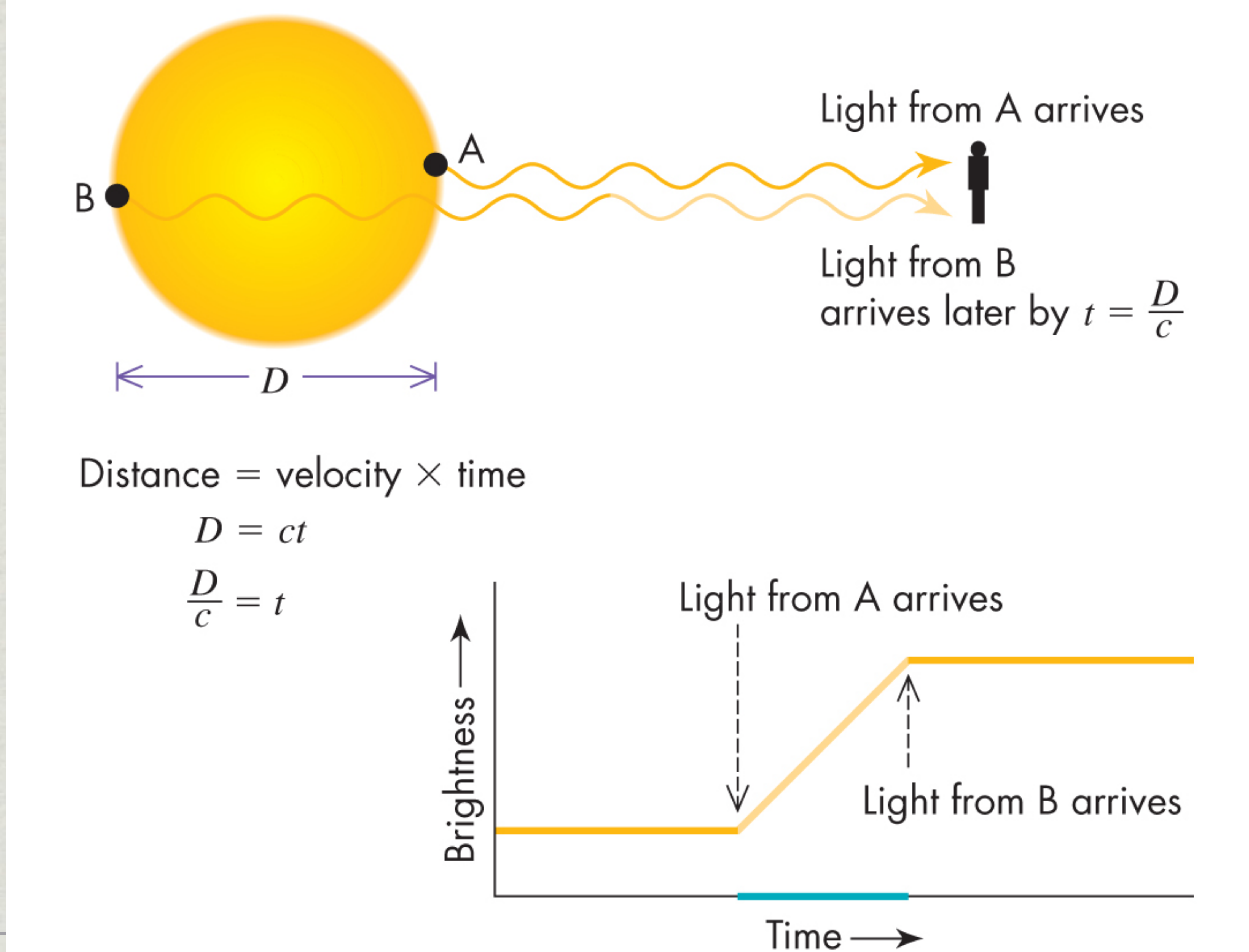


Measuring the Size of Quasars



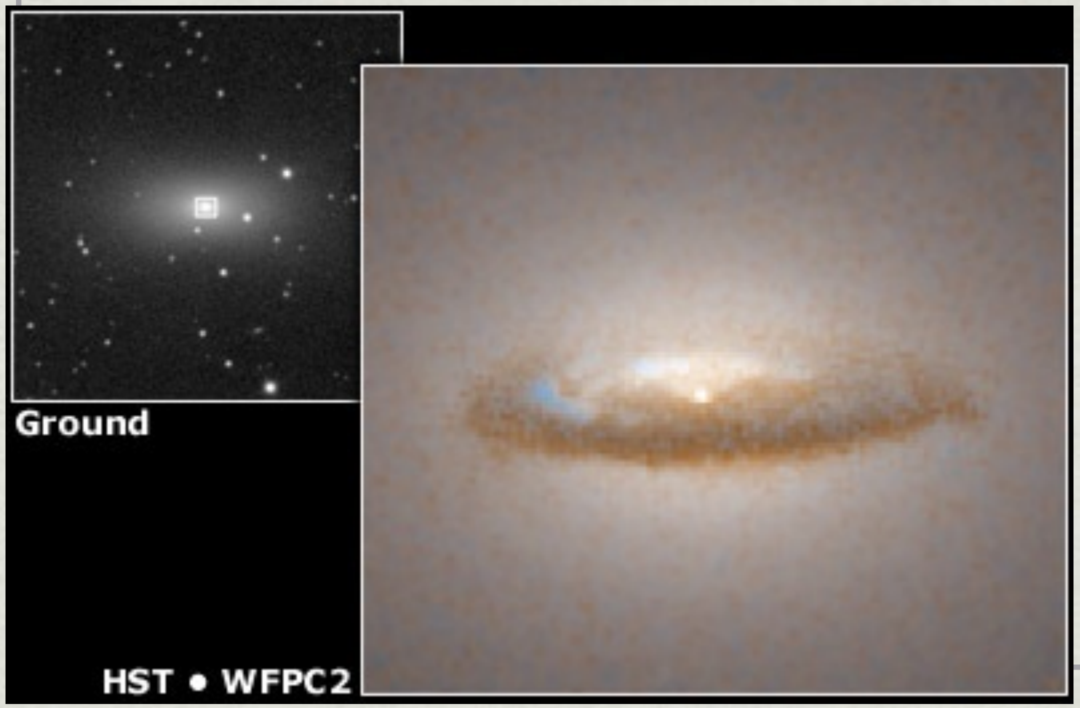
Billions of times the mass of the sun in a volume with radius only a few times the size of the solar system!

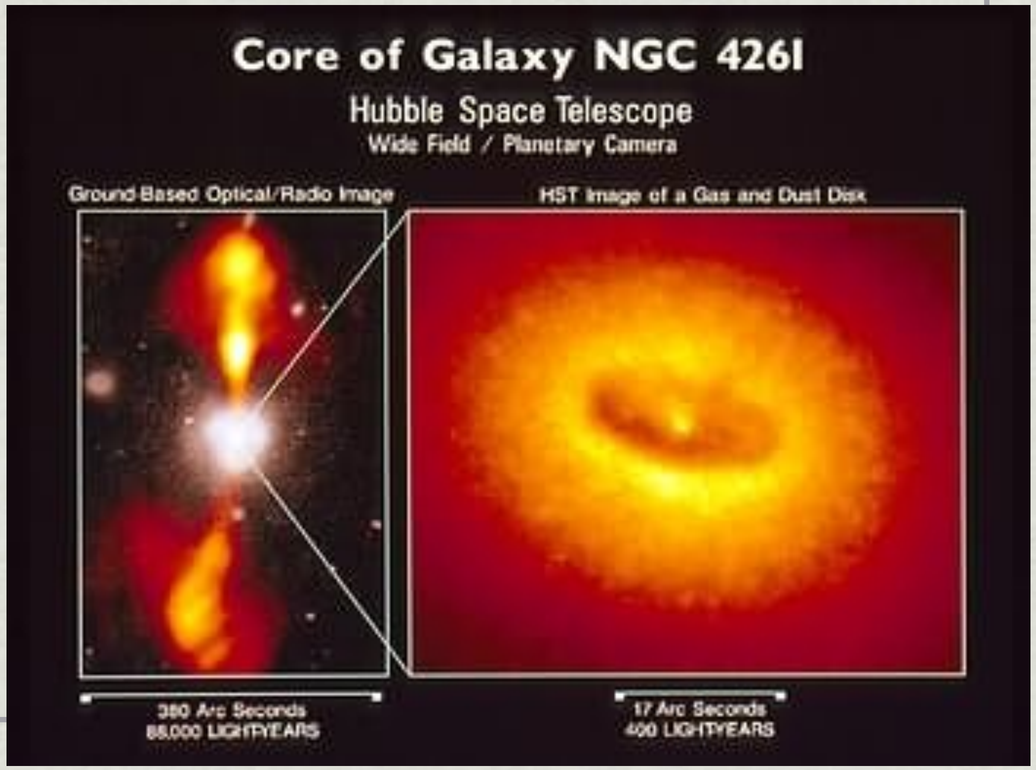
Measuring the Size of Quasars

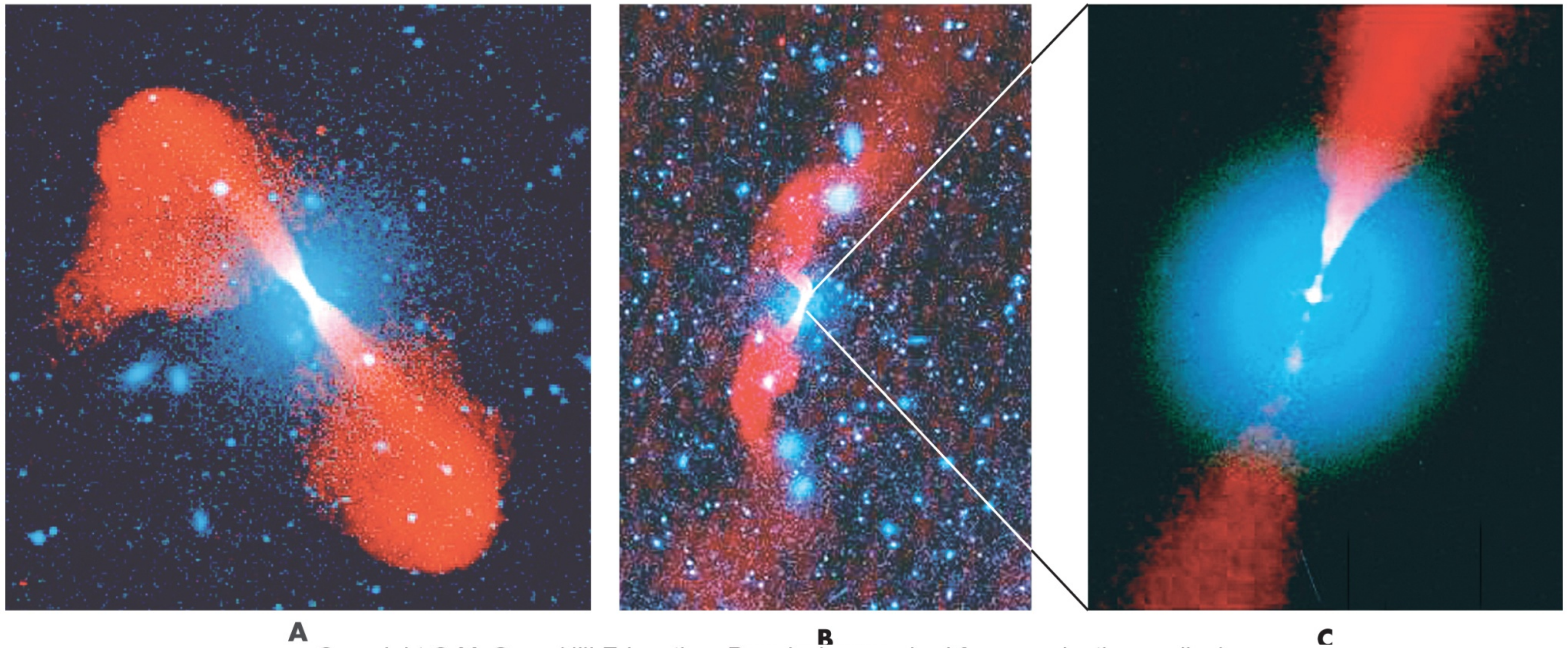


Quasars, Black Holes and Galaxies

Black hole gain mass as gas, stars, etc. fall in
Because Quasars are so luminous, we can see them at very large distances
Constant speed of light means we see distant quasars as they were a very long time ago
Most distant quasar known: seen when the universe was 6% of its current age, 770 million years after the big bang
Quasar masses: billions of times the mass of the sun
If BH start out as the collapsed core of a massive star, there is not a lot of time for a BH grow so much!







Black holes that are pulling in gas from their surroundings also have jets

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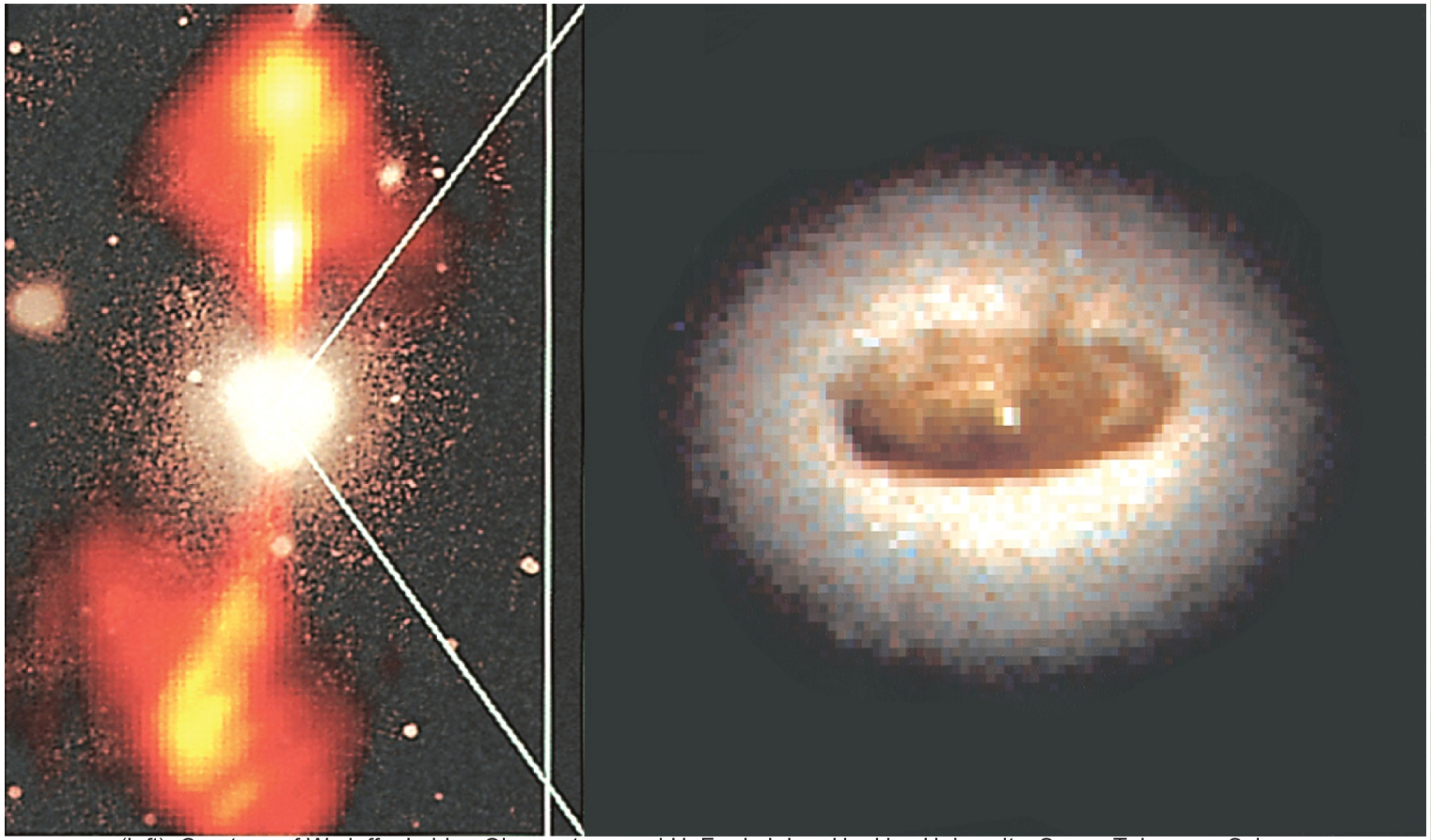
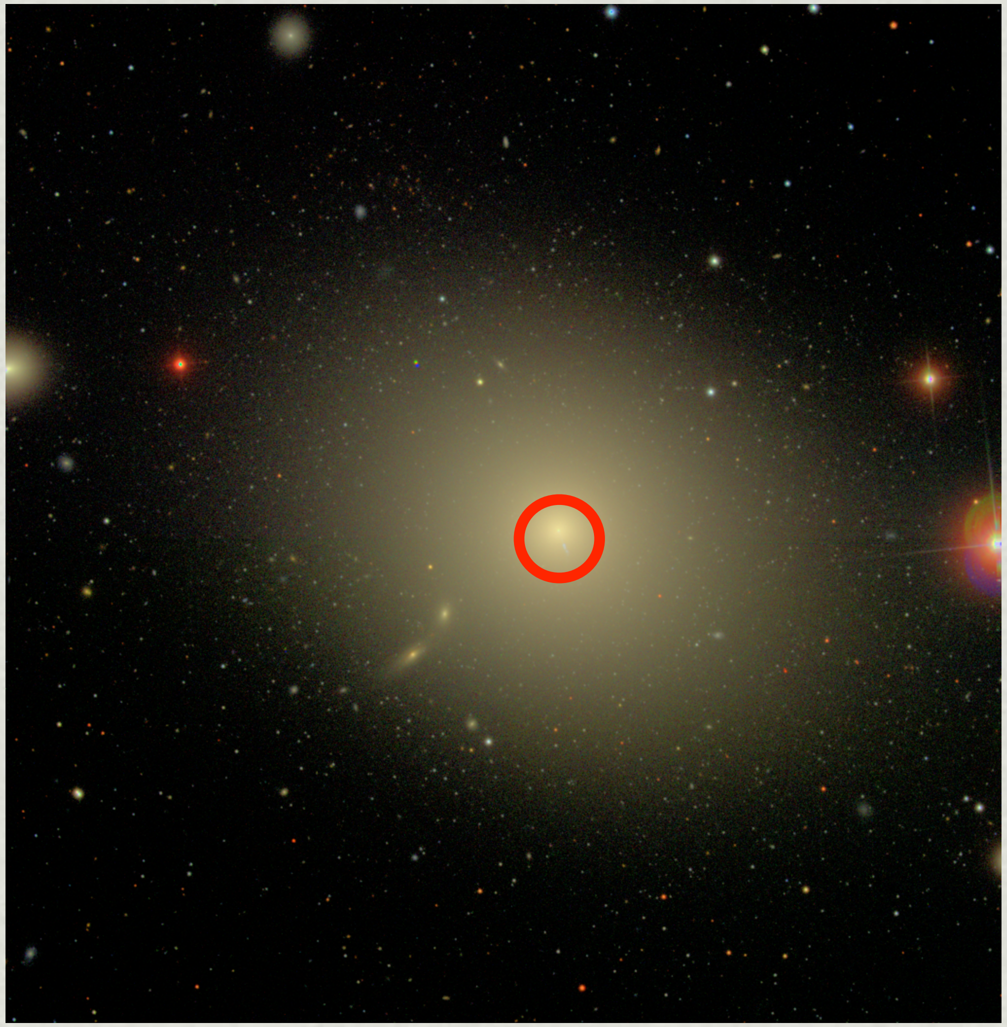


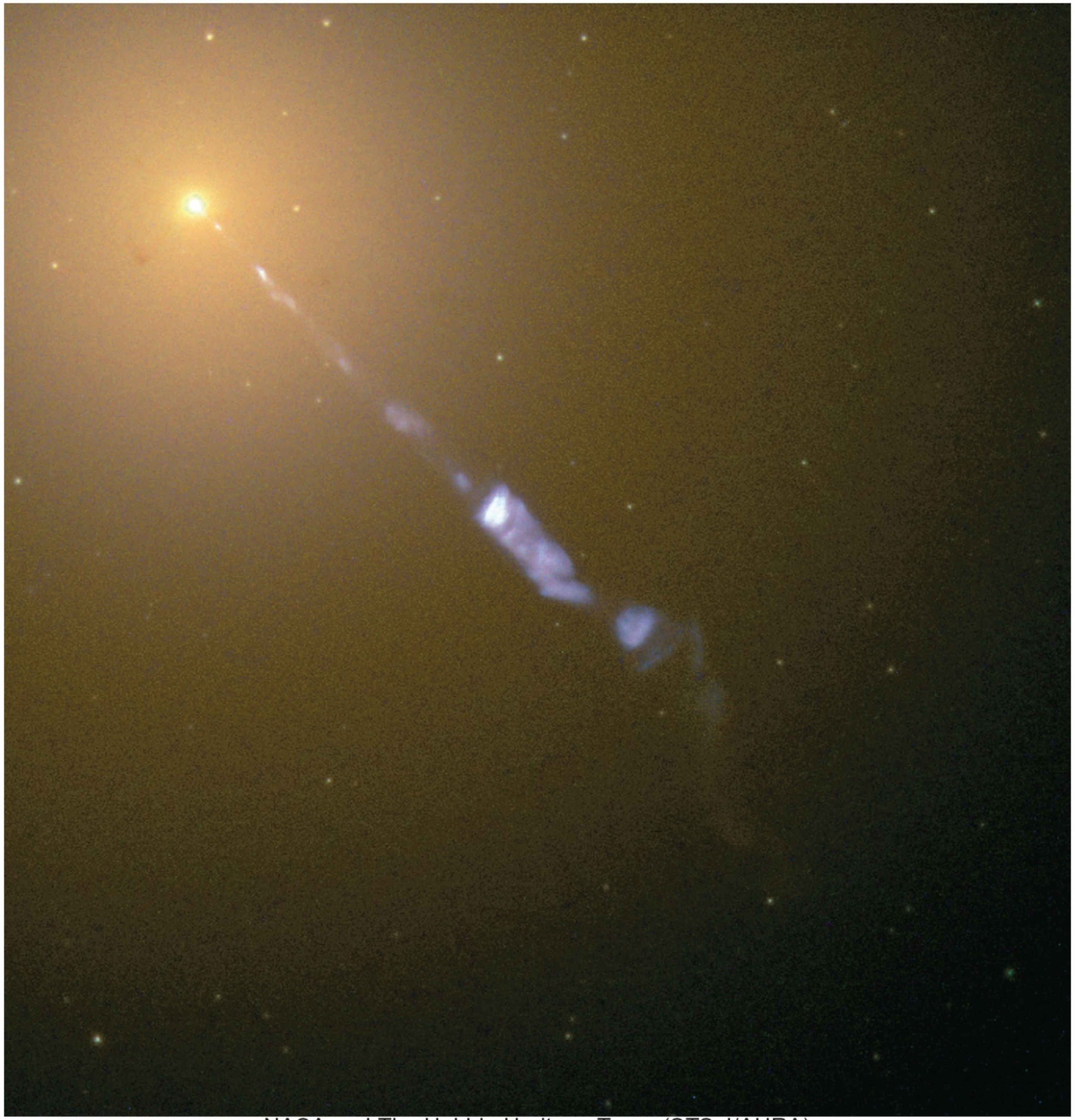
(left): Courtesy of W. Jaffe, Leiden Observatory, and H. Ford. Johns Hopkins University, Space Telescope Science Institute and NASA; (right): ©NRAO/AUI/NSF

Probably material that falls in and gets accelerated back out by the BH magnetic field



These jets might be able to push more gas out of the rest of the galaxy.

Might help explain something very weird…



NASA and The Hubble Heritage Team (STScI/AURA)

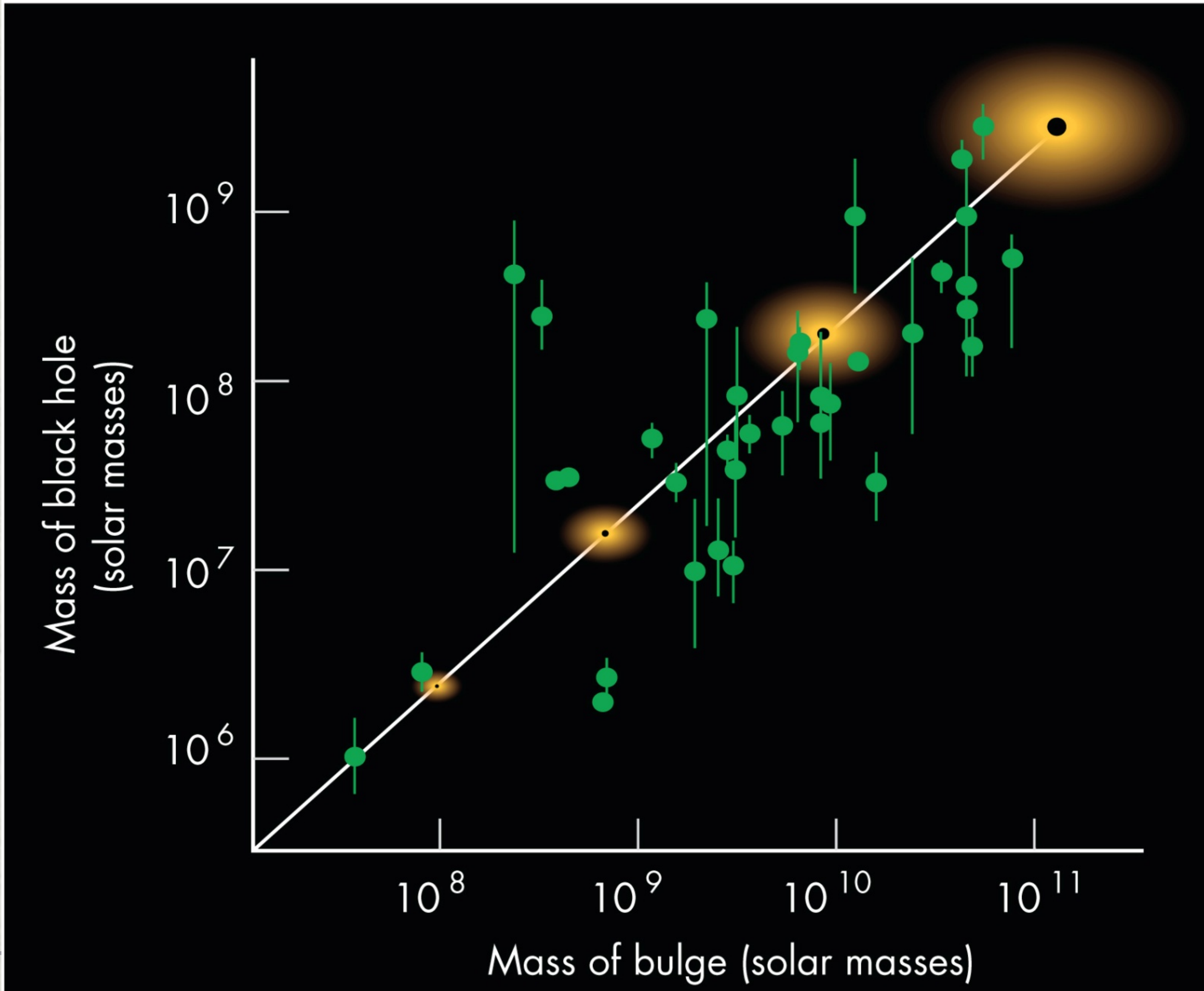
All galaxies seem to have BH in the middle, and the more massive the galaxy the more massive the BH

How does the BH “know”?

BH ~ size of the solar system:
~few x 10^{11} m

Galaxy: size 10^{21}m

10 billion times larger!



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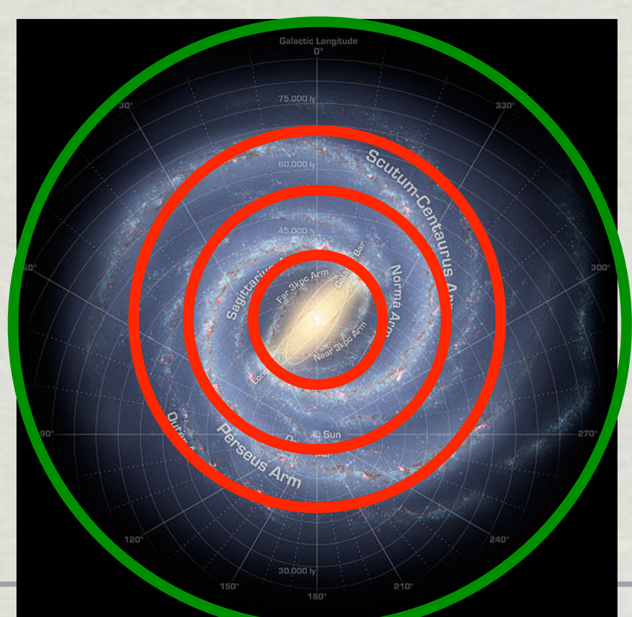

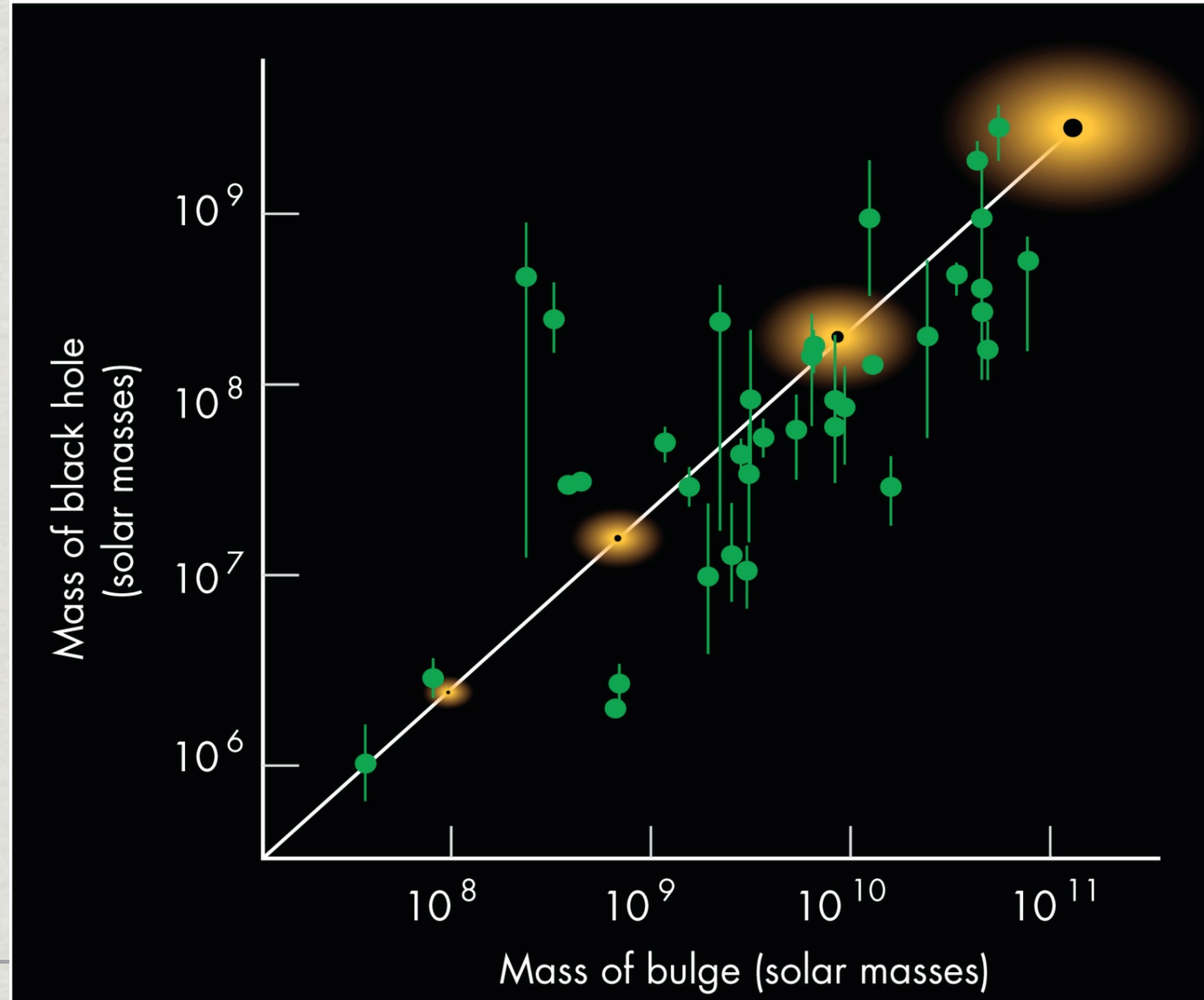

Galaxy Formation

What about ellipticals?

Maybe they are formed when two spiral galaxies smash together: disks collide, destroy the organized structure and ordered orbits of the stars.

Compress the gas so it gets used up in a big batch of star formation (a big version of what happens in spiral arms)

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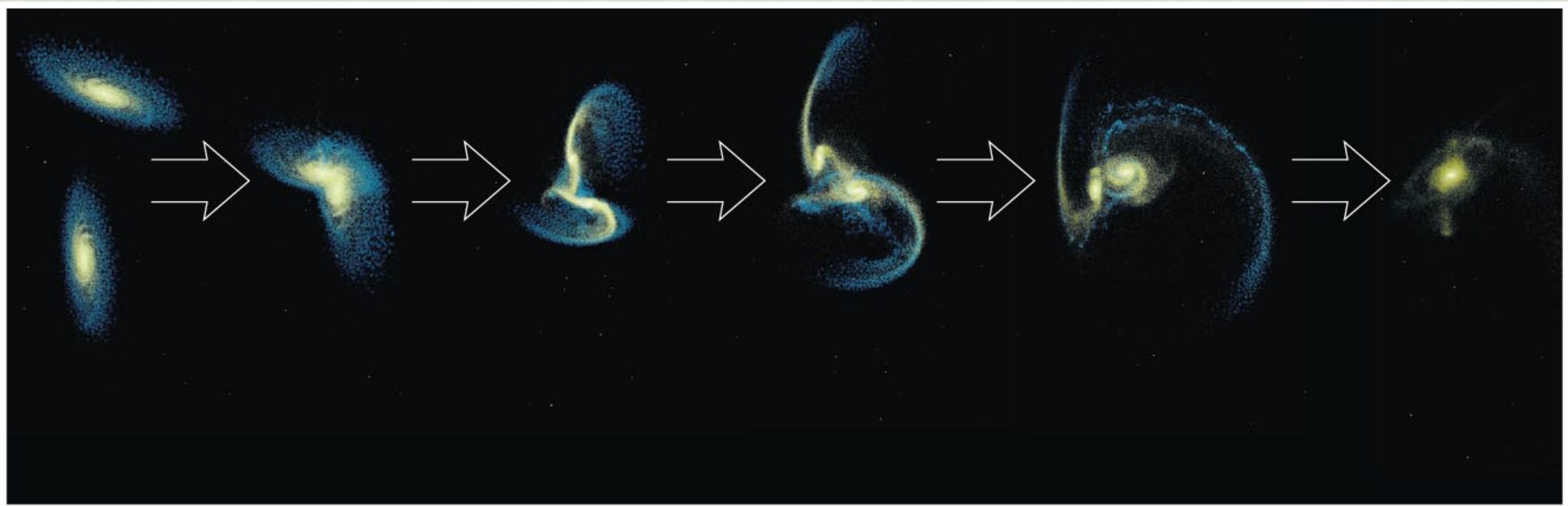
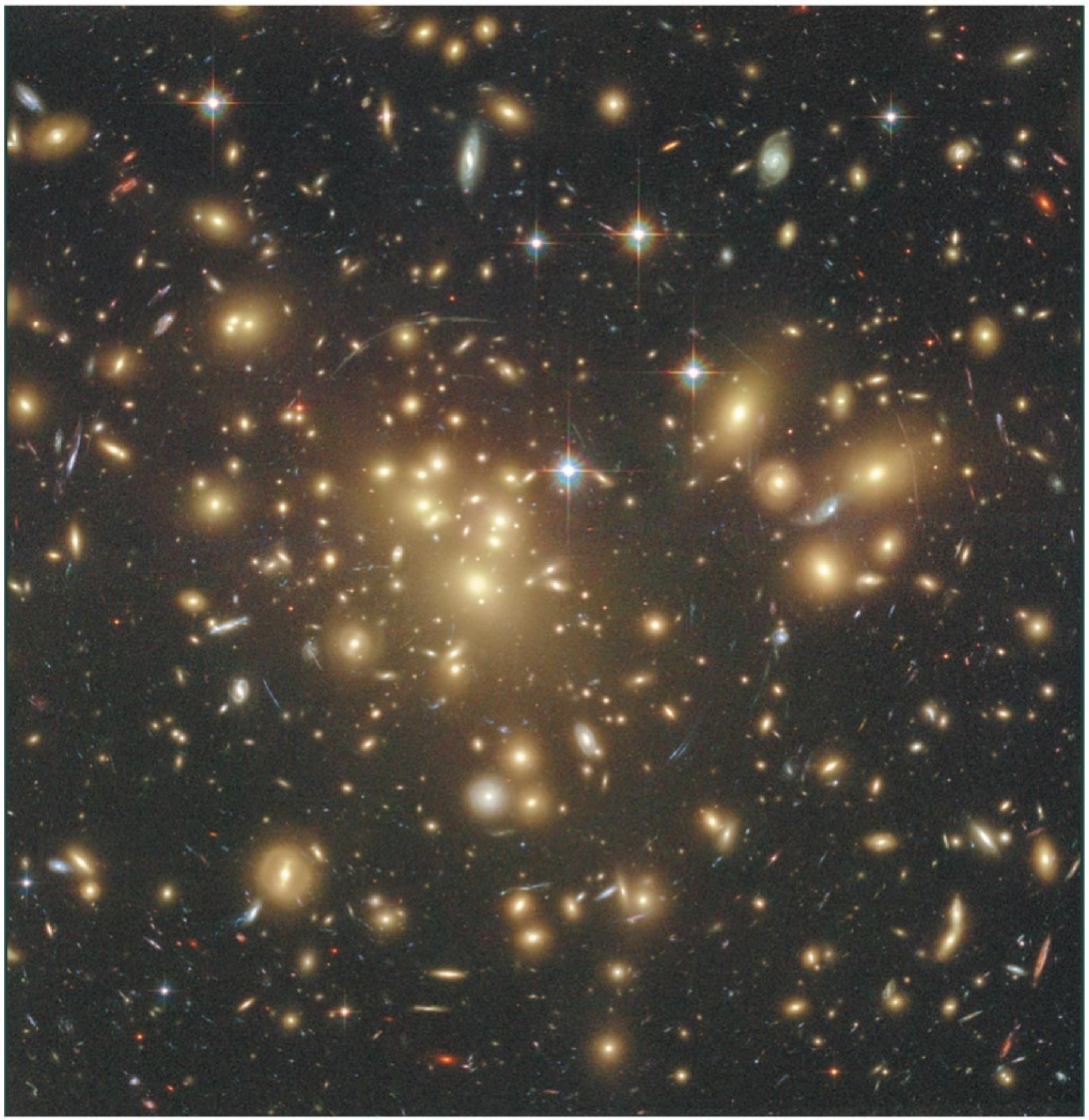


Galaxy Formation

Elliptical galaxies are found with lots of neighbors, in gravitationally bound groups of galaxies with lots of mass: plenty of opportunity for mergers.

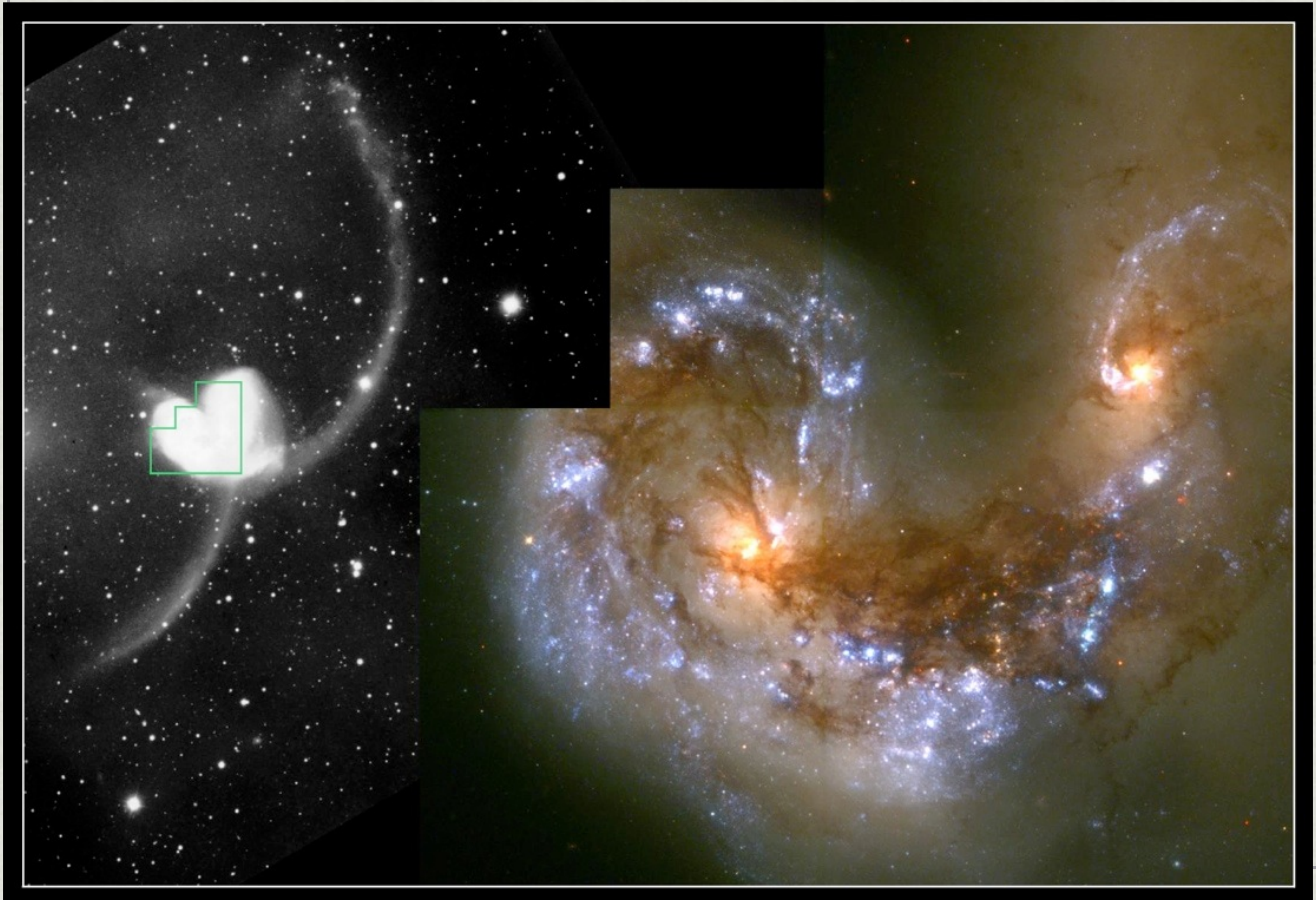
Need lots of mass to have lots of galaxies.

Spiral galaxies are found in less massive systems, so we expect fewer neighbors. So we don't think they "used up" their neighbors in past mergers.



Galaxy Formation

Plenty of evidence that mergers happen.



The antennae galaxies: two spiral galaxies in the process of colliding and merging.

Note lots of new star formation.