Galaxy Evolution and Cosmology

Chapter 21

Recap of last time: Hubble's Law

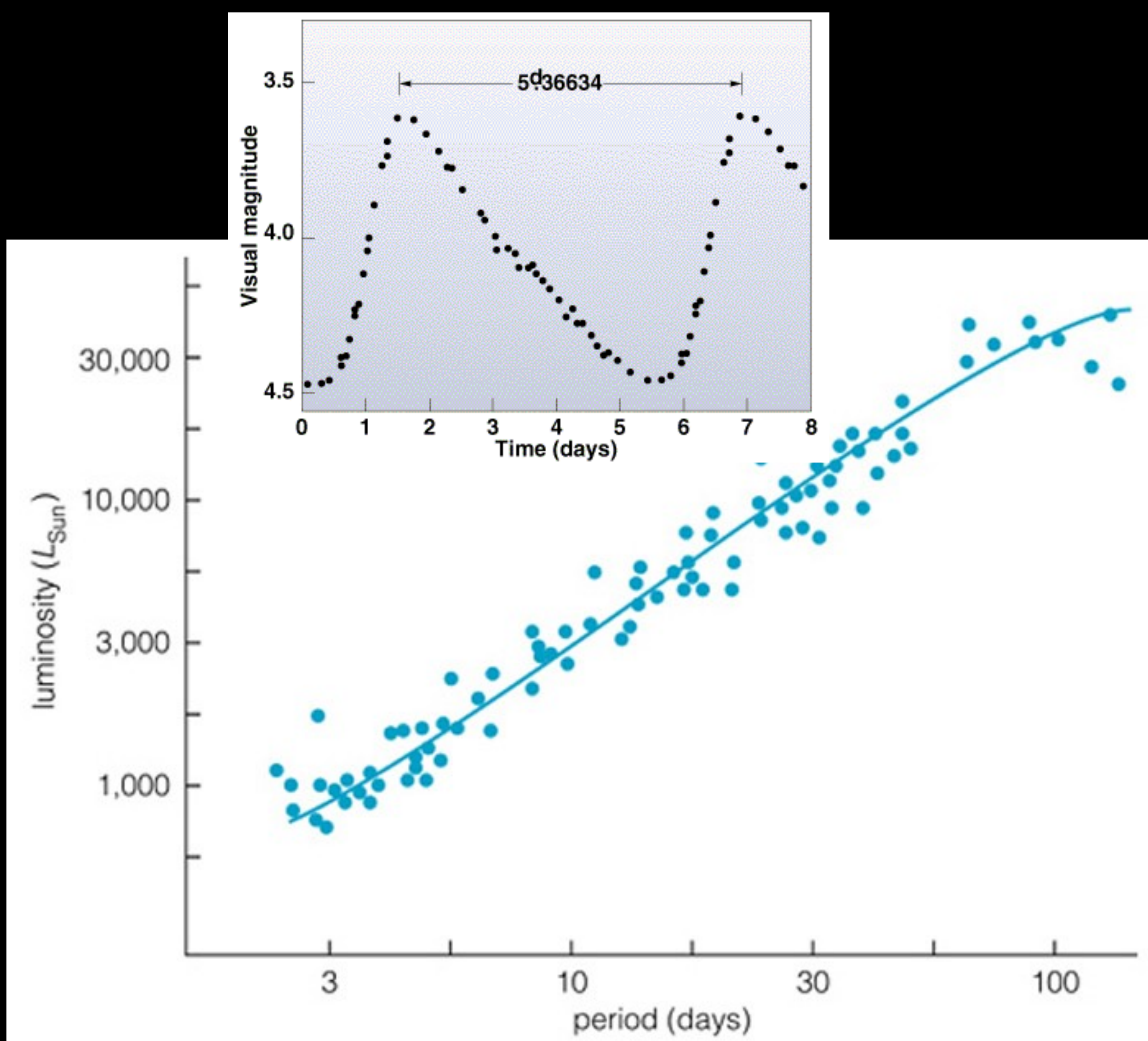
How do we measure distances to galaxies?

How do we measure velocities of galaxies?

Recap of last time: Hubble's Law

How do we measure distances to galaxies?

Standard candles!
(Cepheid variable stars)

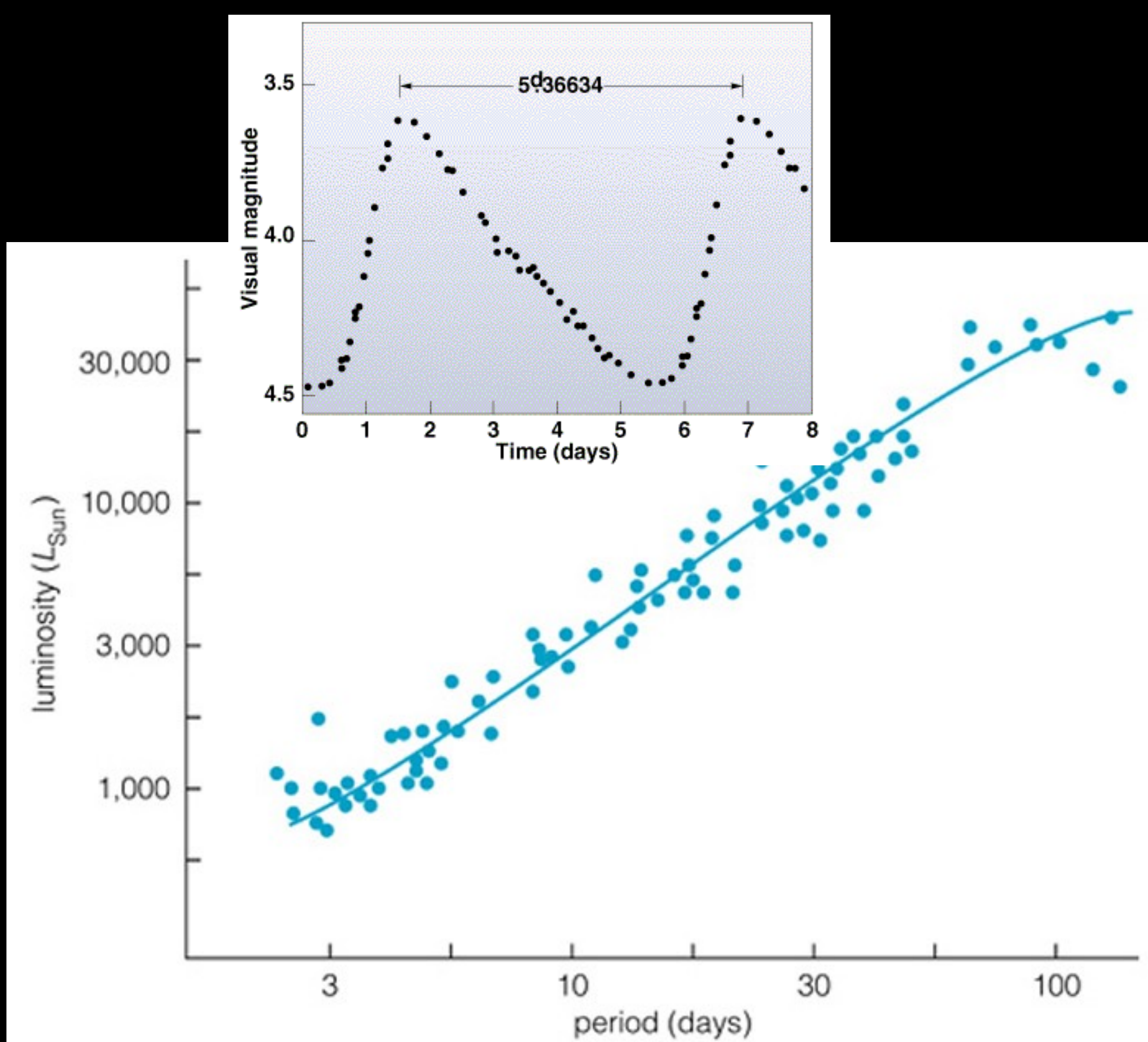


How do we measure velocities of galaxies?

Recap of last time: Hubble's Law

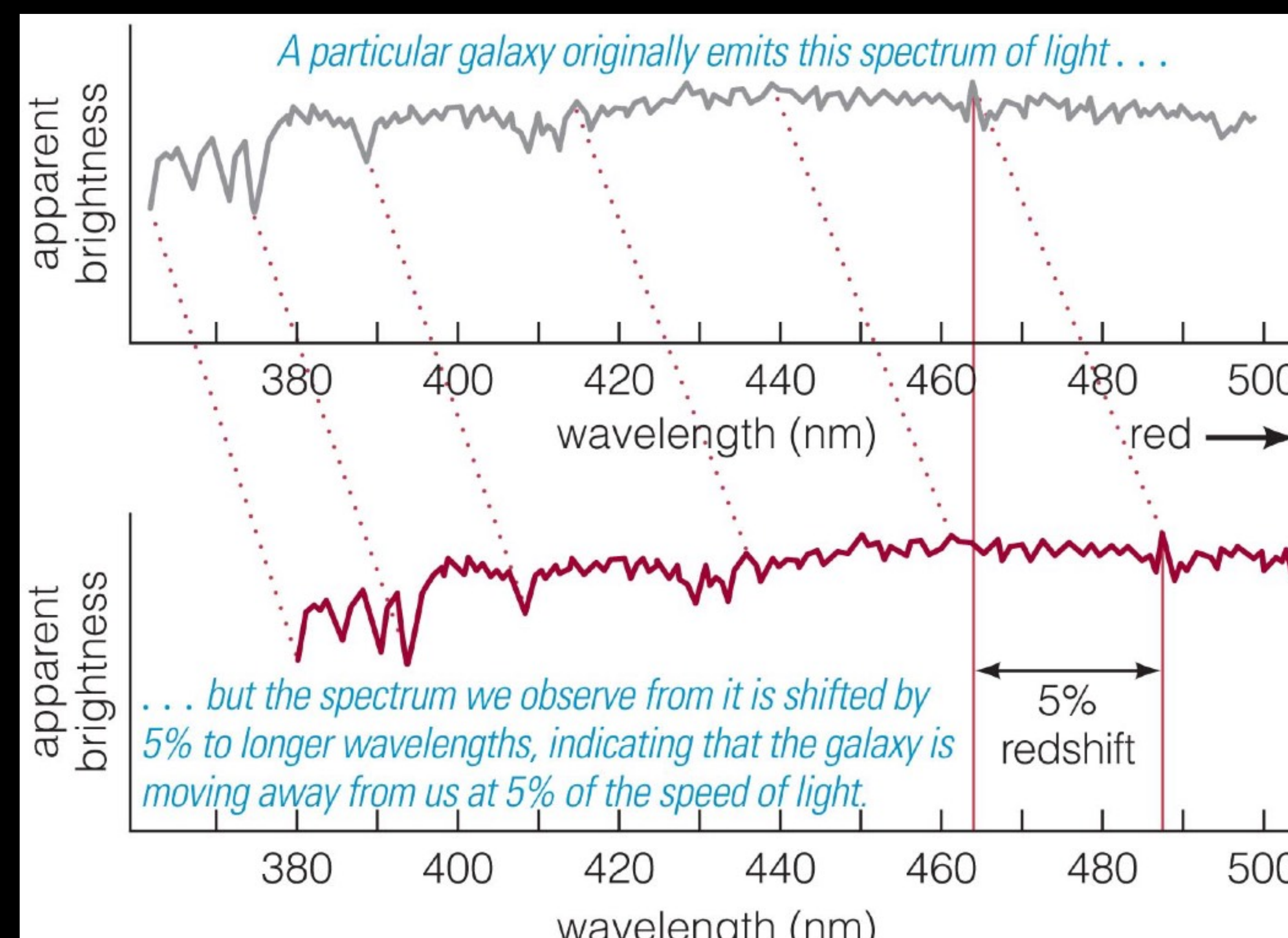
How do we measure distances to galaxies?

Standard candles! (Cepheid variable stars)



How do we measure velocities of galaxies?

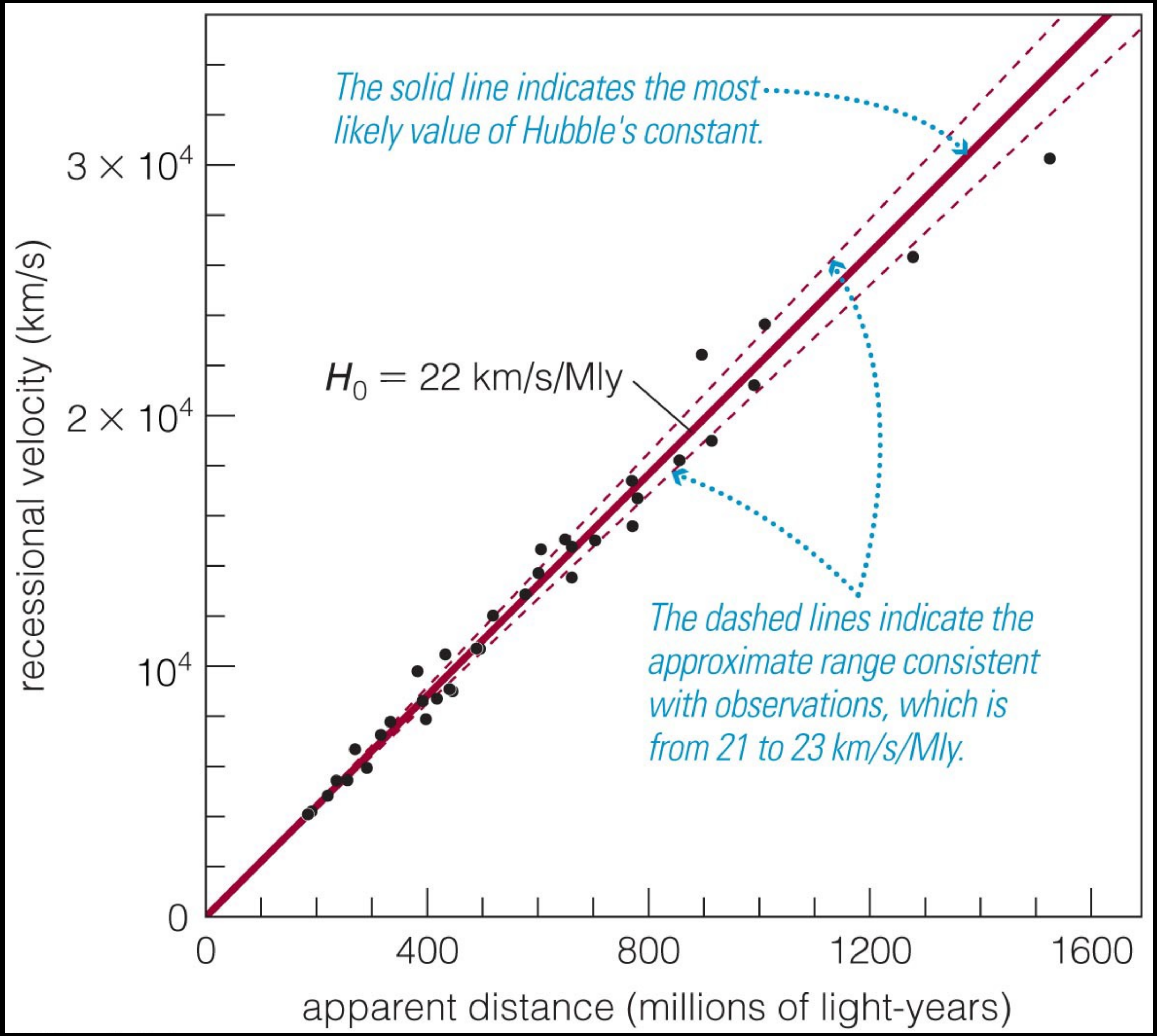
Doppler shift!



$$\frac{v}{c} = \frac{\Delta\lambda}{\lambda_0}$$

"Hubble's Law"

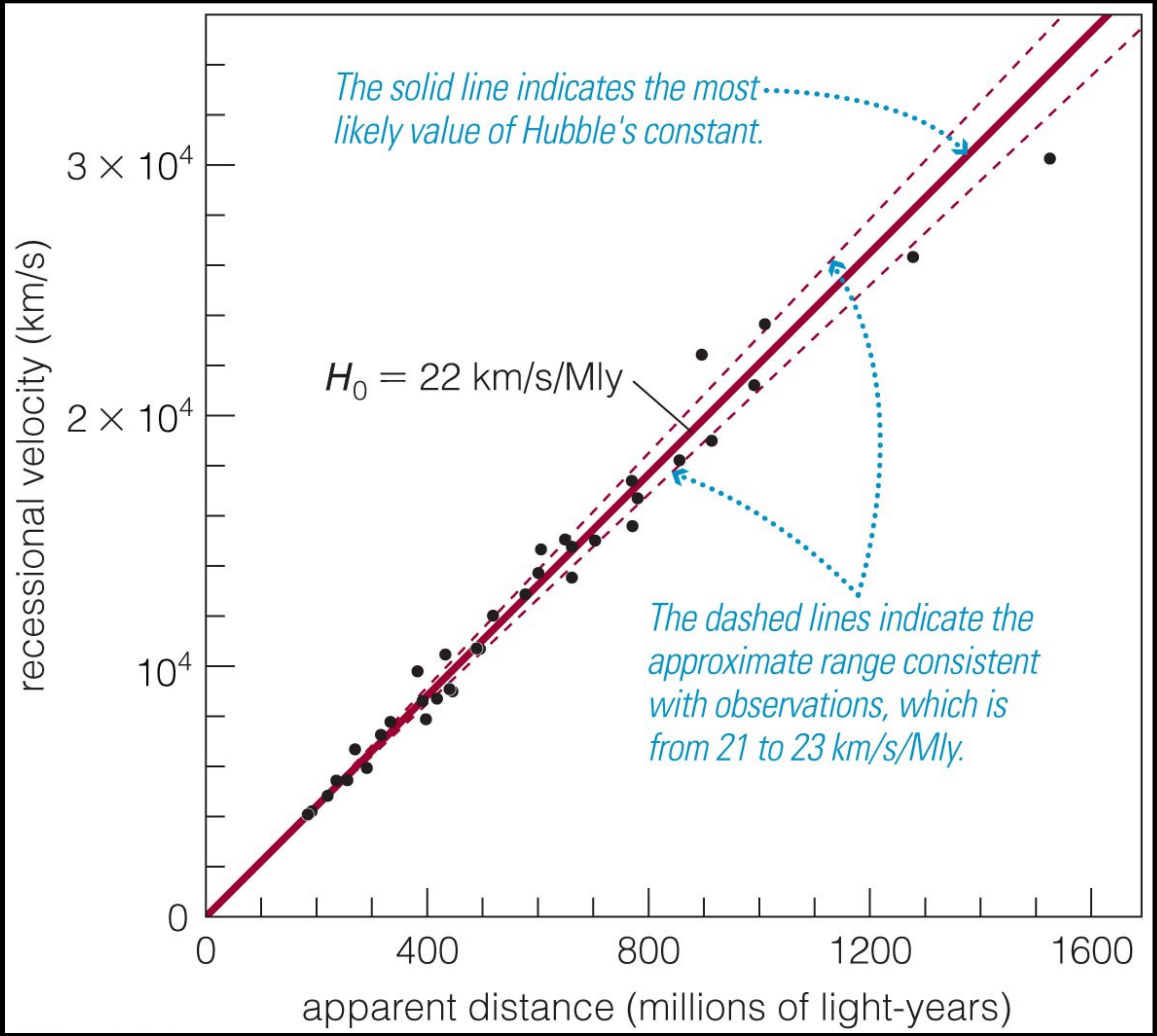
- Recessional velocity is proportional to distance
- $v = H_0 \times D$
- H_0 is the "Hubble Constant". Units are km/s / Mpc.



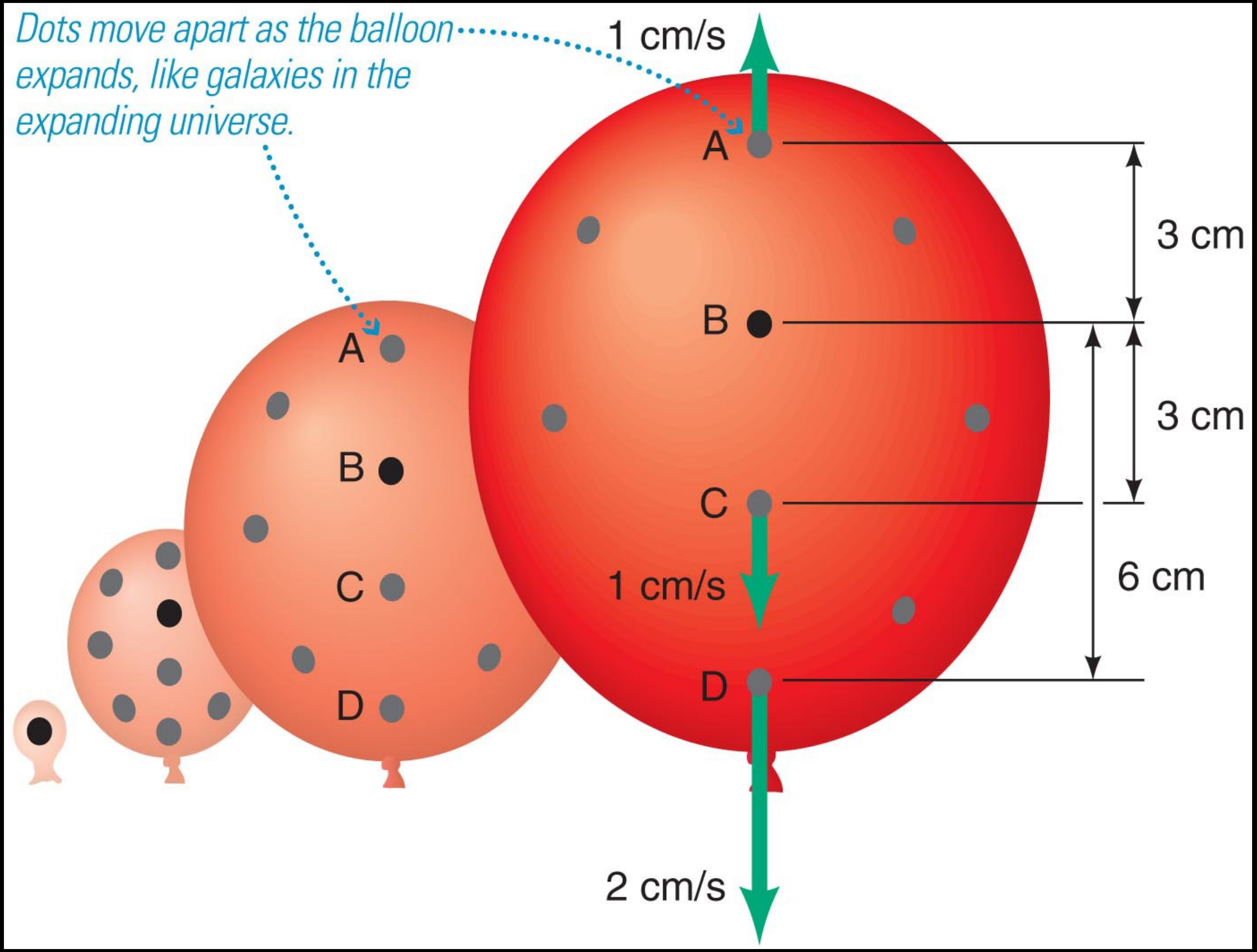
p.s. Distance is hard to measure, but velocity is easy.
Now we can measure velocity, and use Hubble's Law to find distance!

Hubble's Law tells us the age of the Universe (sort of)

- Nearly all galaxies are moving away from us
- They must have been closer together in the past
- If we extrapolate into the past, it suggests that all galaxies have a common origin: same place at a certain time
  - "Beginning" of the Universe!



Galaxies were closer together in the past



- Galaxies are all moving apart from one another
- Analogous to blowing up a balloon

Recap: Hubble's law

- **What is Hubble's Law?**
  - The faster a galaxy is moving away from us, the greater its distance
    - $v = H_0 \times D$
  - We can use this to determine distances to galaxies! Measure the velocity (redshift), and use Hubble's Law to calculate distance.

- **How does Hubble's Law tell us the age of the Universe?**
  - By measuring a galaxy's current distance and speed, we can deduce how long it must have been traveling to reach its current distance
  - Measuring the "Hubble Constant" H_0 tells us the approximate amount of time: 14 billion years

Consequence of Hubble's Law: (almost) all galaxies are moving away from us!

- In all directions, galaxies are moving **away** from us

- More distant galaxies are moving away **faster**

Are we at the center of a big explosion?!

No! The whole Universe is expanding!

What is an “expanding universe”???

On large scales, every point in space is getting further away from every other point in space

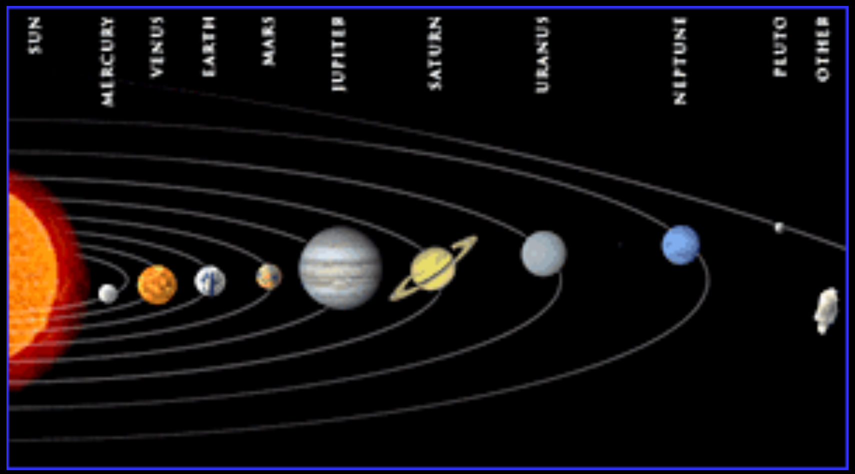
So, are we at the center?

- NO! We are not that special!
- The **cosmological principle** states that:
  - We do not live in a special place in the Universe
  - We do not live at a special time in the history of the Universe

We are not at the center of the Solar System, or the Milky Way, and we are not at center of the Universe either….

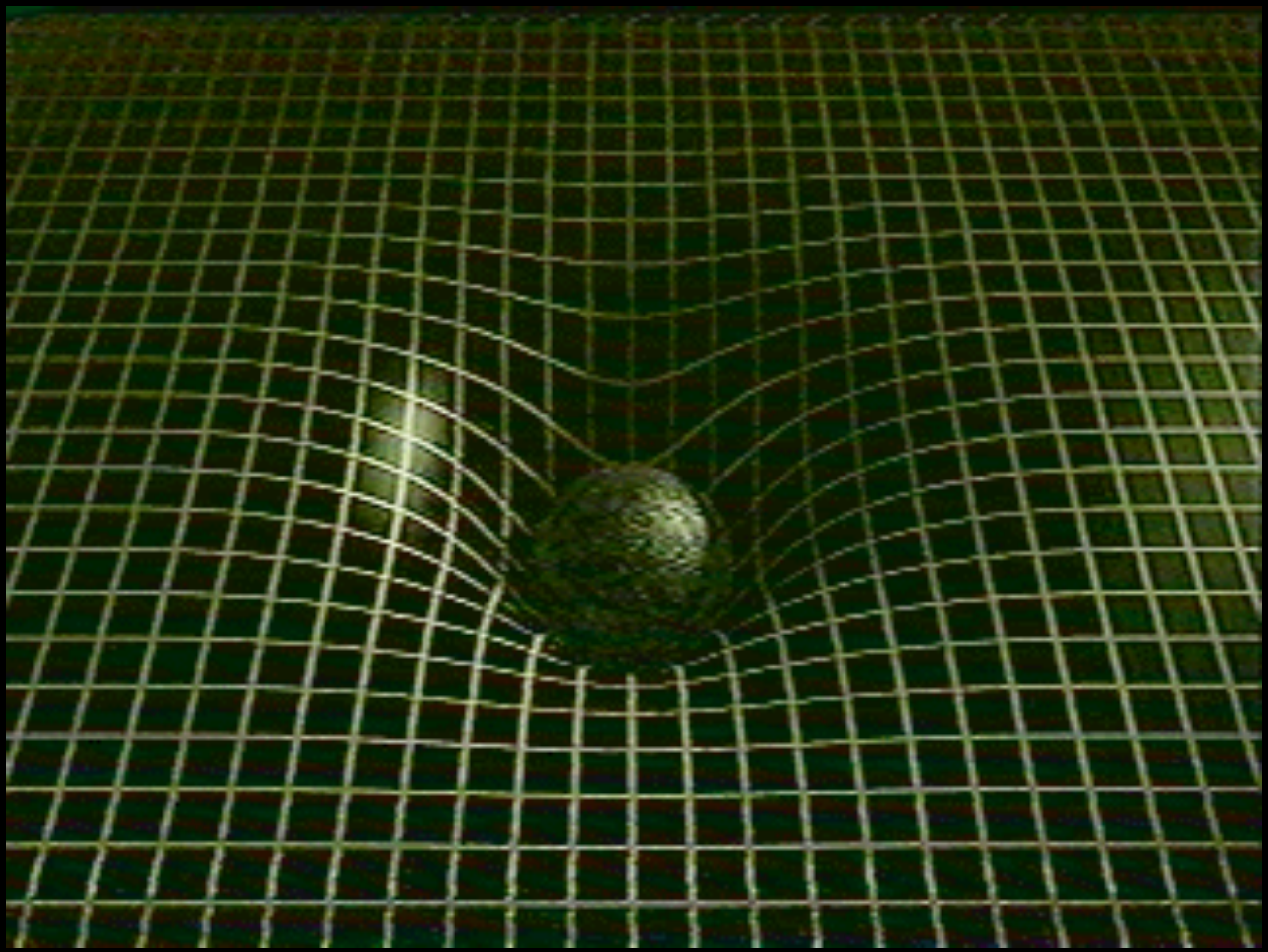
But if the universe is expanding, why am I not expanding?

- It is not difficult for other forces to be stronger than the push of expansion



None of these are expanding. They are bound together by electricity and/or molecular forces

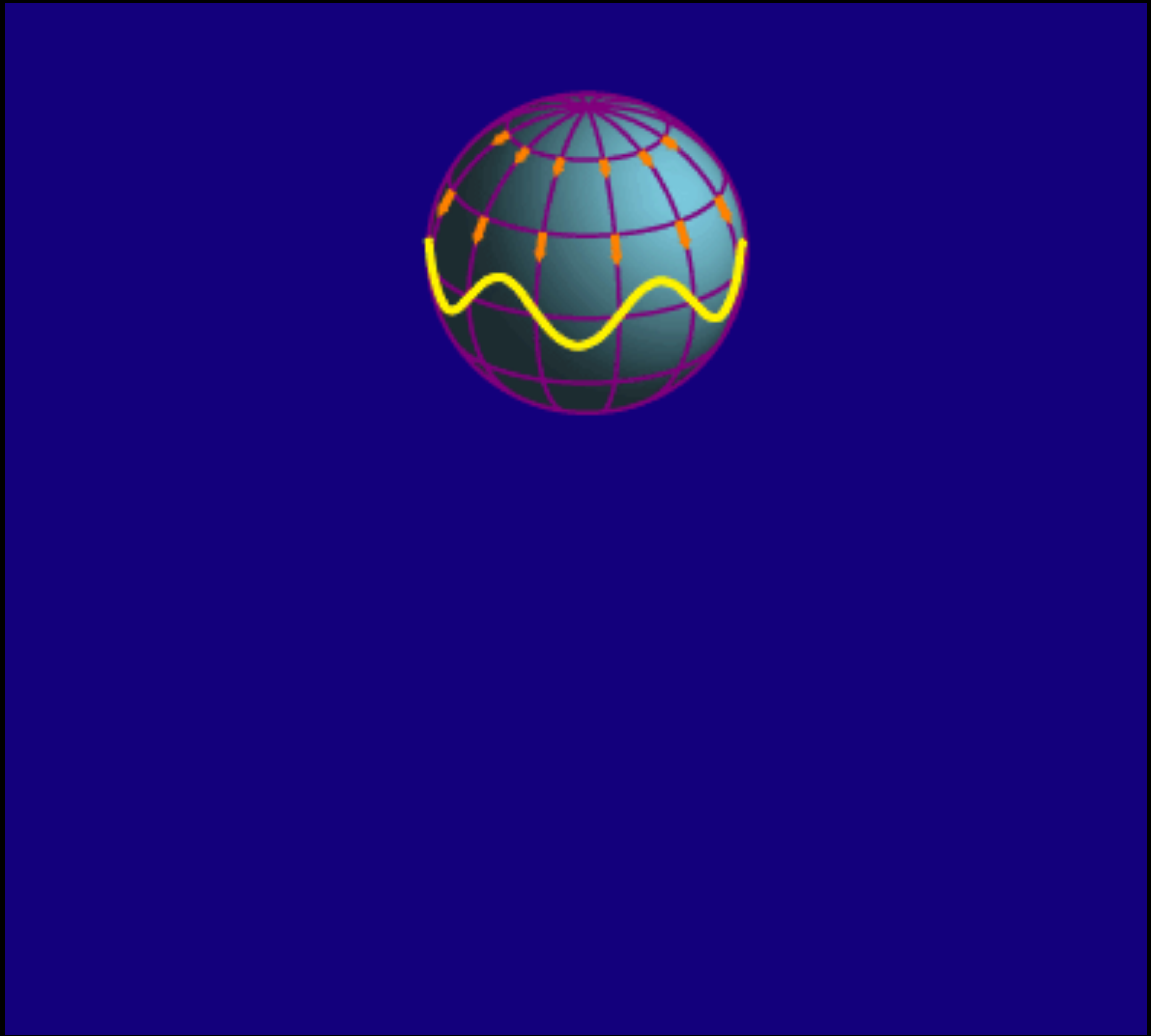
Remember curved spacetime?



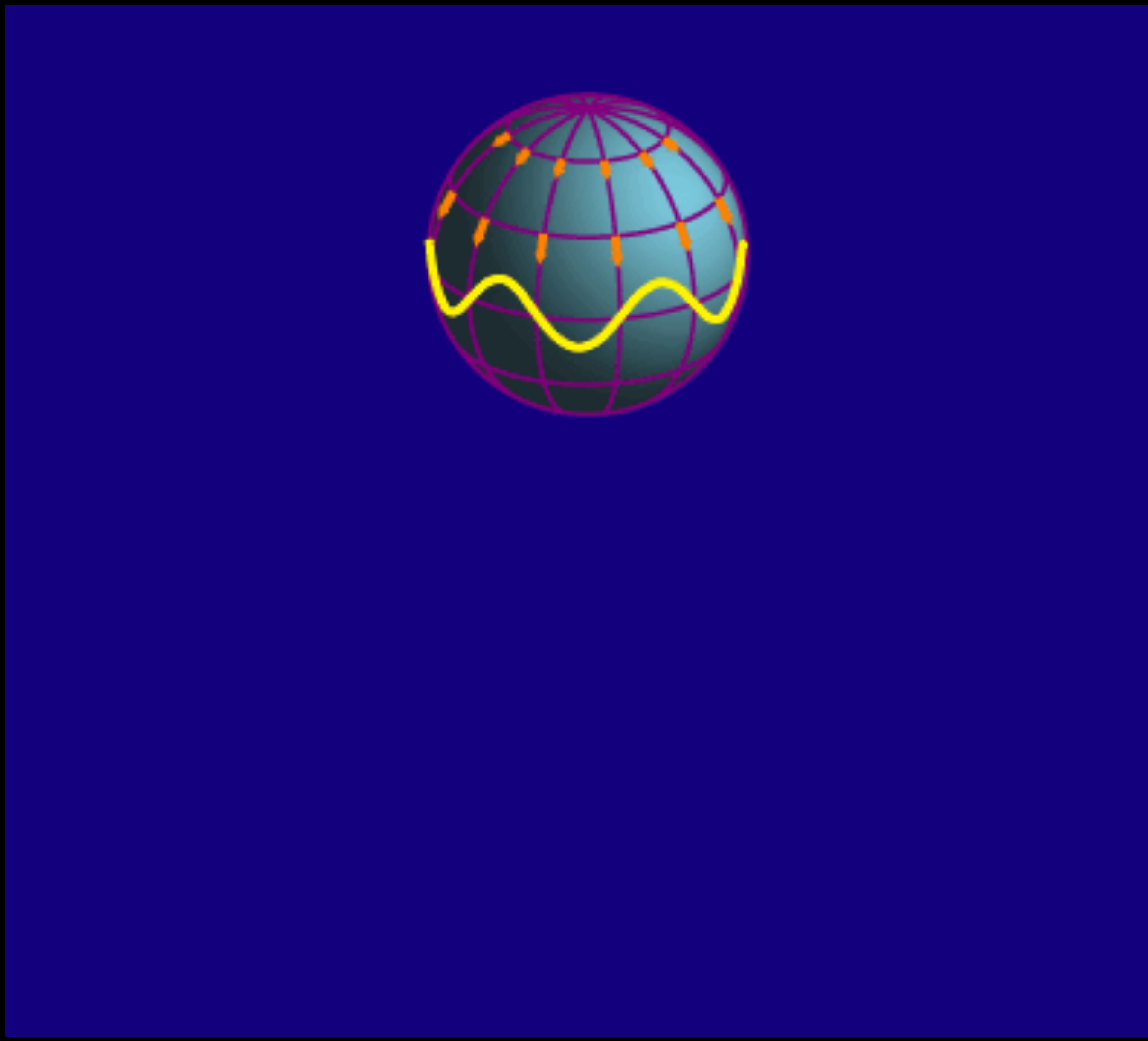
- Spacetime is malleable
- It curves and stretches!
- Galaxies get carried along as spacetime expands
- Most of their "motion" is due to the expansion of spacetime rather than any motion through space

The surface of an expanding sphere (balloon) is a reasonable 2-D analog of what our 3-D space is doing…

- There is no special place on the ball
- Everyone sees the same thing
- Everyone sees expansion in all directions

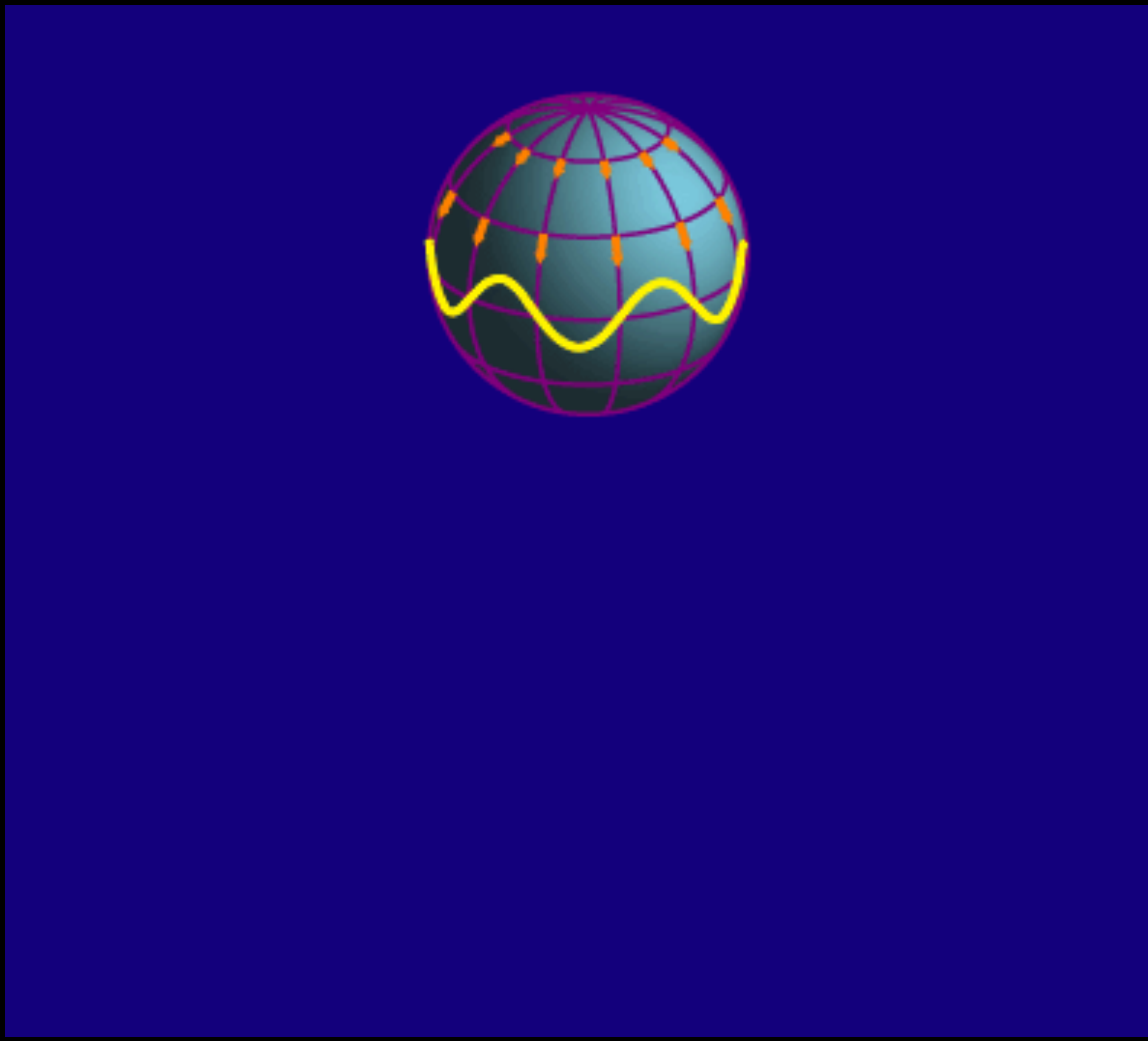


Where is the center of the expansion?



- It is happening everywhere!
- If there were a “center” (which there may not be), it would be in a higher dimension that we cannot perceive

What is the Universe expanding into?



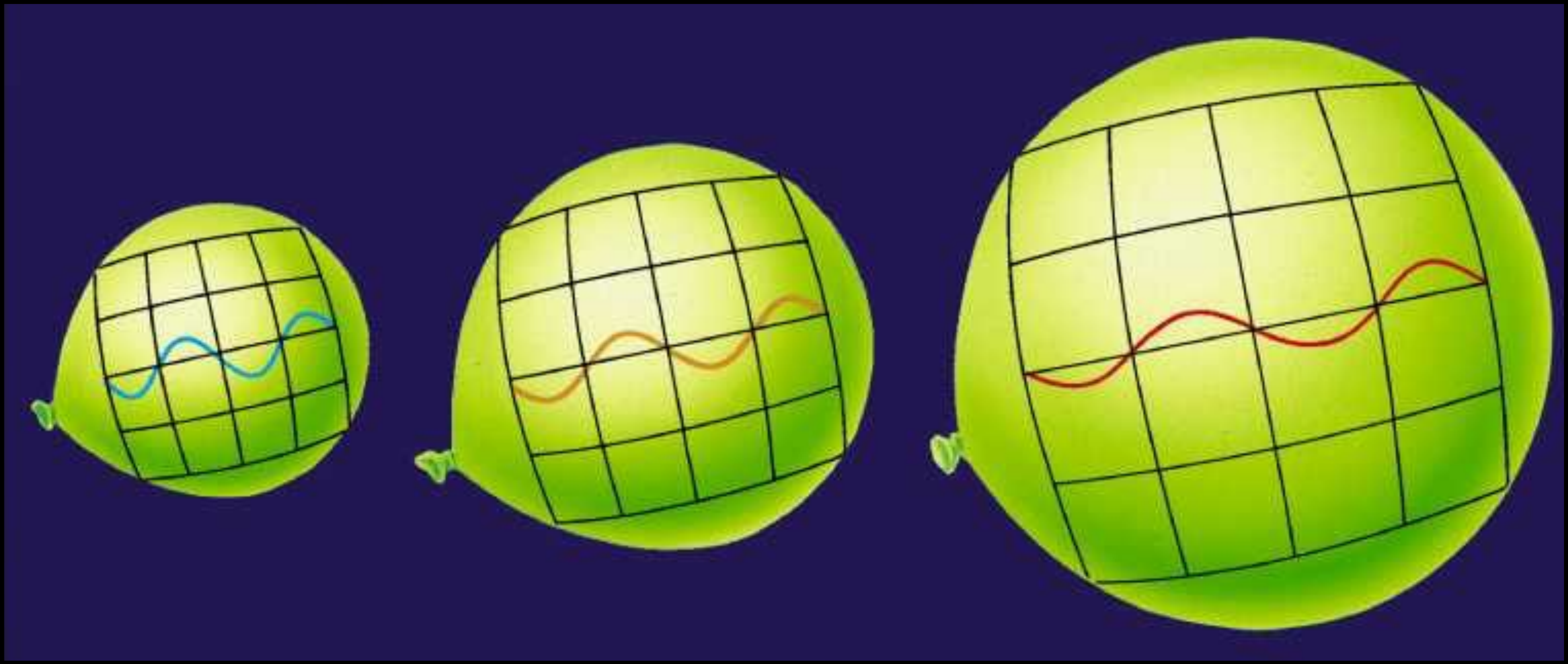
- There is no ‘edge’!
- If there were something the Universe is expanding into (which there may not be), it would be into a higher dimension that we cannot perceive

What about redshifts?

- Don’t redshifts tell us that the galaxies are moving?
- We thought the redshift was due to the Doppler effect (motion)
- Instead, the redshift is caused by the wavelength of photons being stretched along with the expansion of the universe

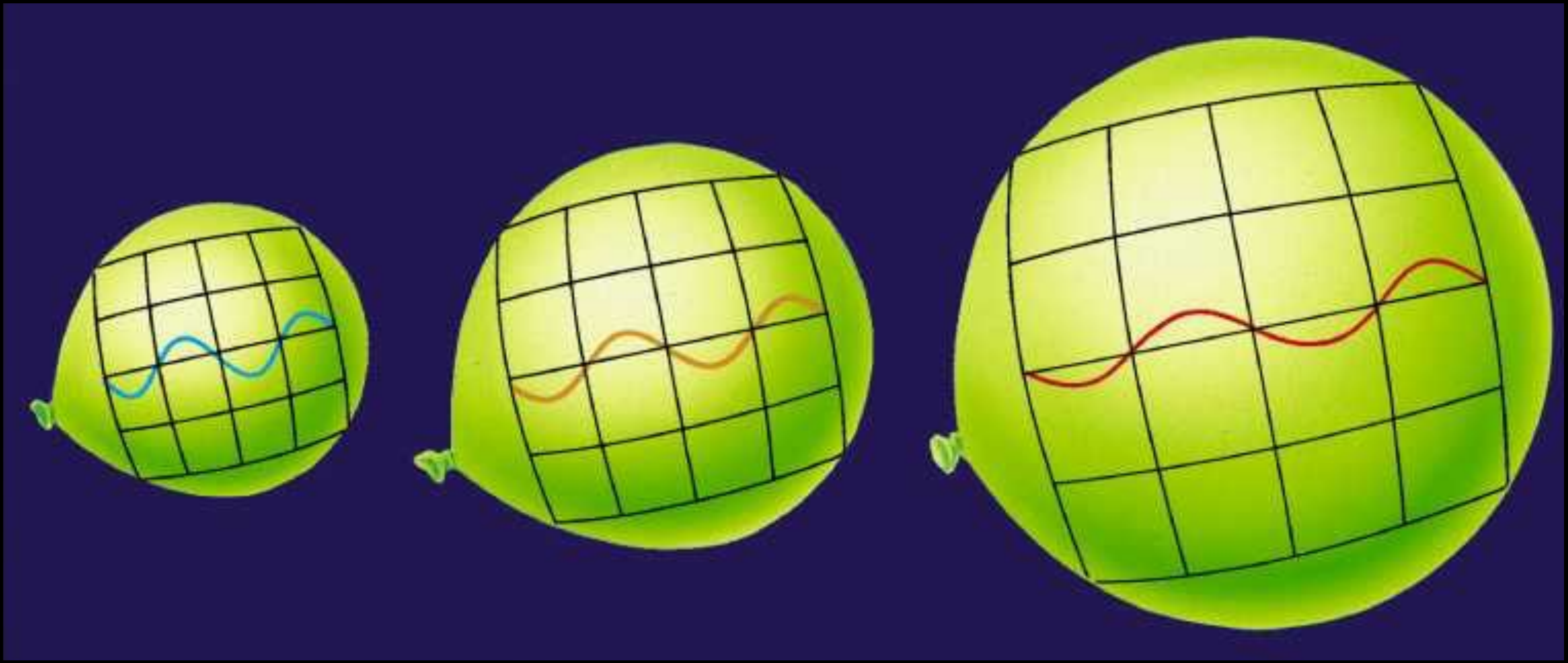
Cosmological redshift

The “Cosmological Redshift”



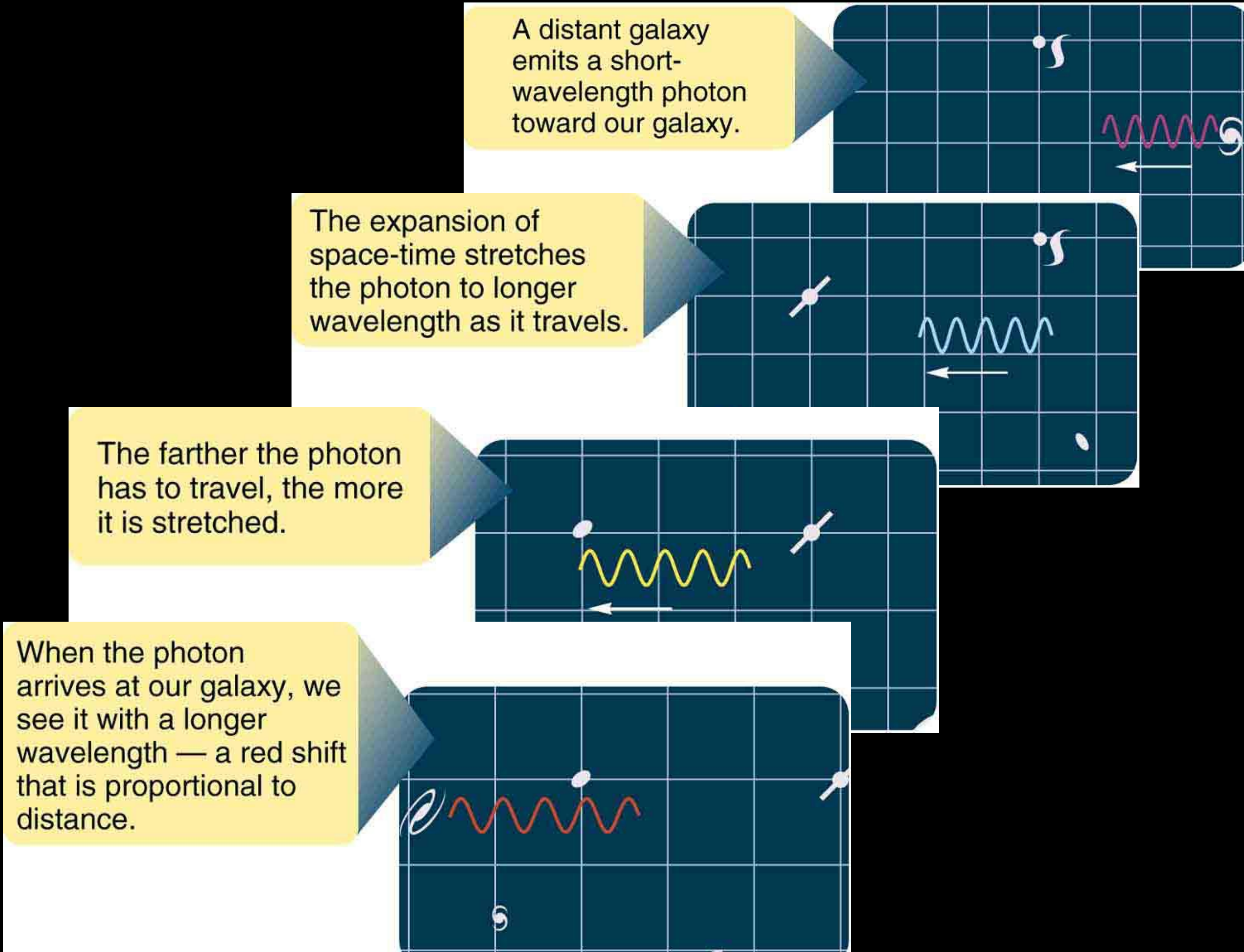
- As the Universe expands, the wavelength of photons do too! → **REDDER**!

The "Cosmological Redshift"



- Photons that travel longer (from further away), have experienced more expansion.

Bigger Distance = Bigger Redshift


A distant galaxy emits a short-wavelength photon toward our galaxy.
The expansion of space-time stretches the photon to longer wavelength as it travels.
The farther the photon has to travel, the more it is stretched.
When the photon arrives at our galaxy, we see it with a longer wavelength — a red shift that is proportional to distance.

The Age of the Universe

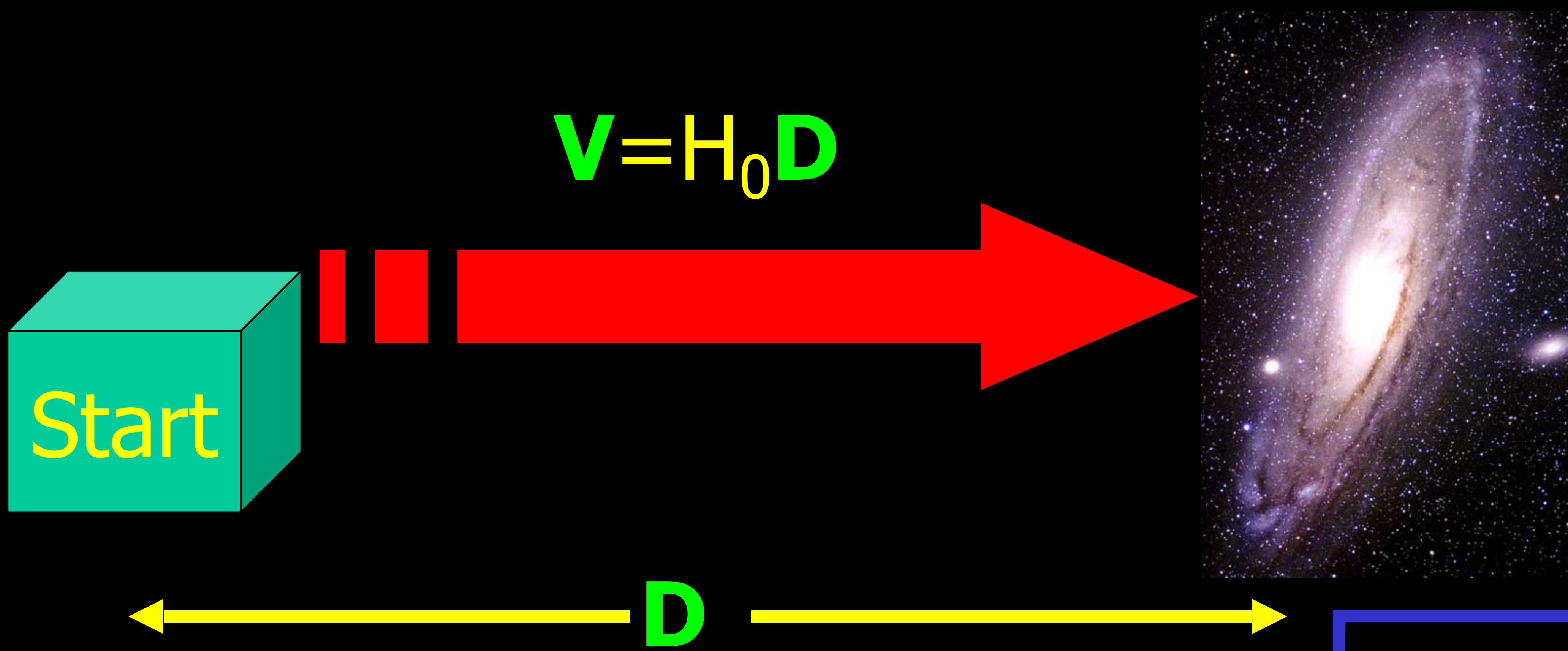
- The Universe was smaller yesterday
- Smaller the day before that
- Et cetera
- At some point the Universe was an infinitely small point!

The Universe had a Beginning!

“The Big Bang”

How long has it been since the Beginning?

- We know how far apart galaxies are today (**D**), and how fast they're moving apart (**V**)



Duration= **D**/**V**
$= 1/H_0$

The value of the Hubble Constant reveals the age of the Universe!

- H_0 ~ 70 km/s/Mpc
- $1/H_0$ ~ 14 billion years

$$v = H_0 \times D$$

(not exactly the age of the Universe, because the rate of expansion wasn't always the same!)

Measurements from the Planck satellite give precise age: 13.80 +/- 0.02 billion years!

Galaxy Evolution

Chapter 21

Questions of the day

- How do we observe the histories of galaxies?
- How do we study galaxy formation?

Disk (spiral) galaxies

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!

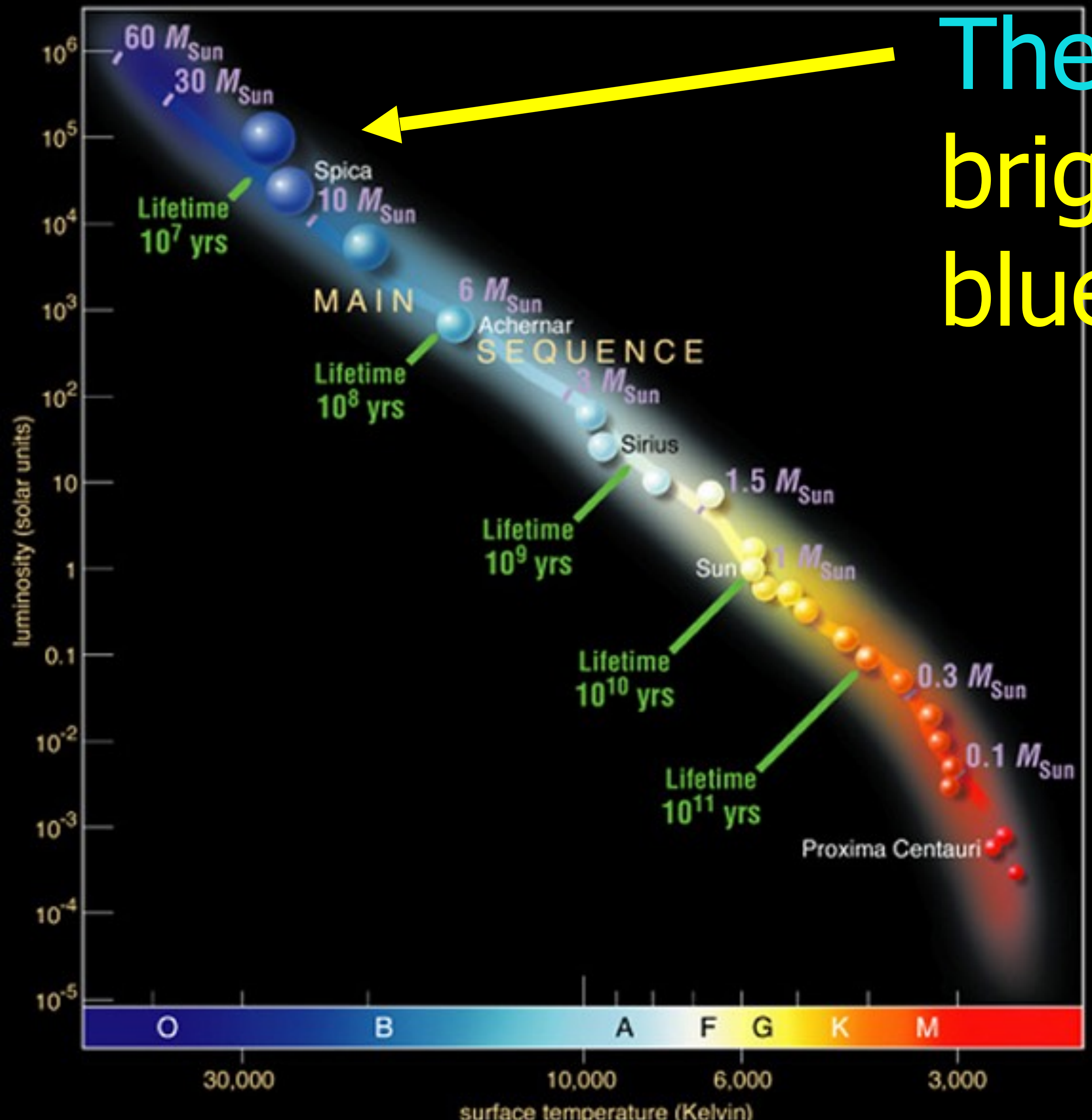
Galaxies change and evolve!

- Start as mostly gas…
- End up as mostly stars…

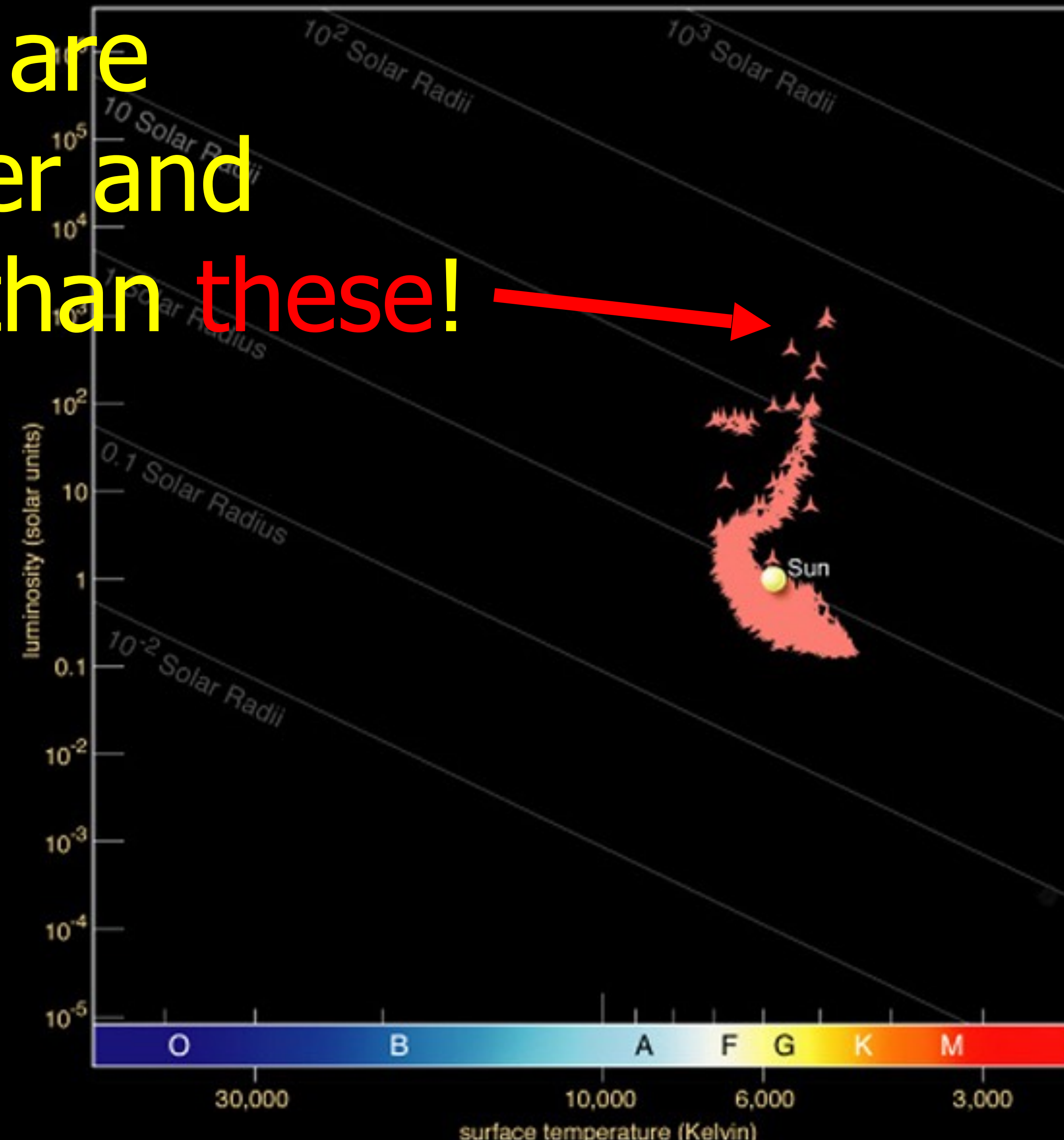
Different galaxies form stars at different rates

Galaxies which are actively forming stars look different

Galaxies that are forming stars are **BRIGHT and BLUER**!



These are brighter and bluer than these!



Young

Old

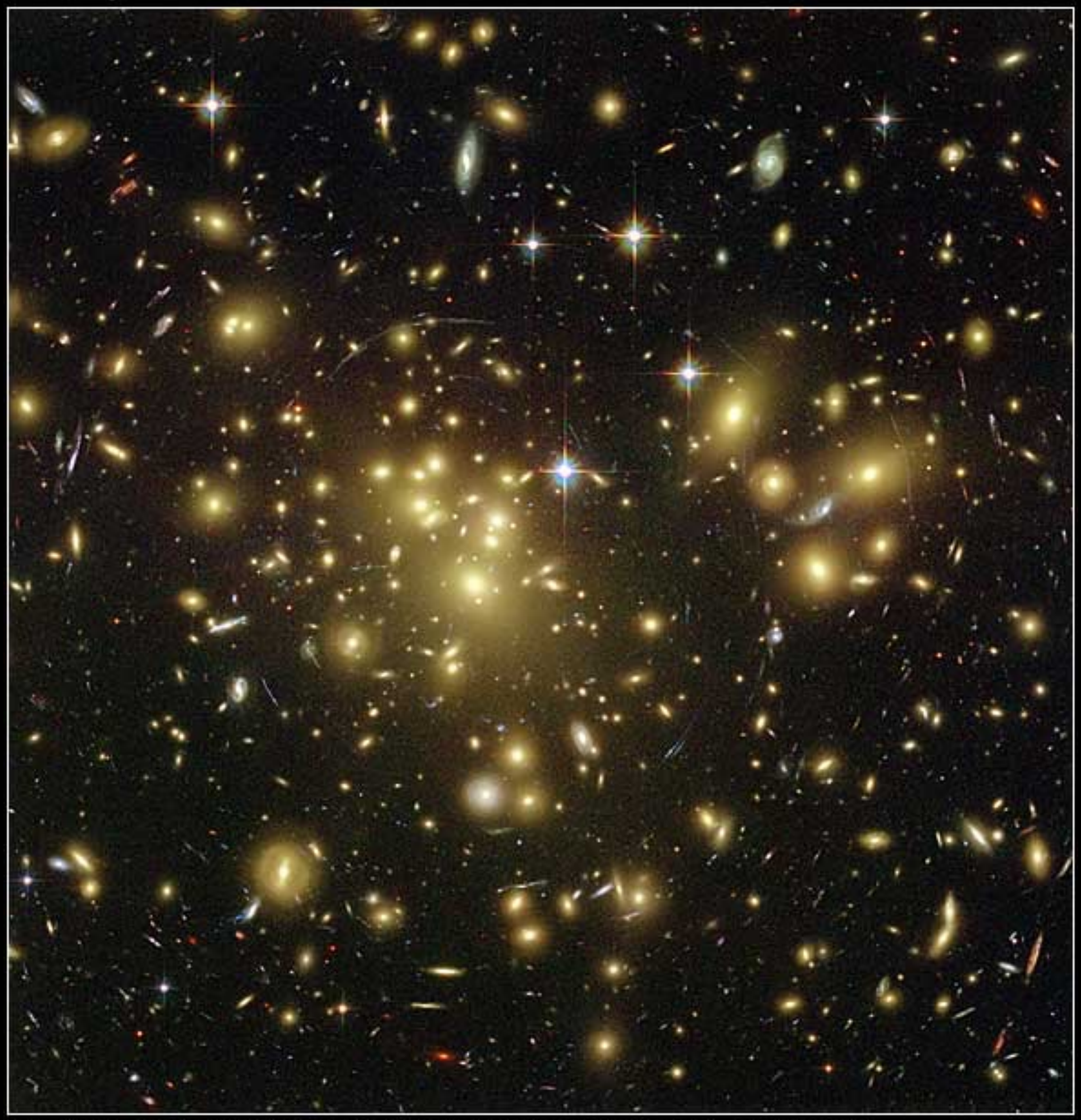
Disk galaxies (in their spiral arms) are actively forming stars

They have bluer colors!

Elliptical galaxies, and the bulges of spirals, are no longer forming stars

They look yellow or red

Galaxy Cluster Abell 1689 HST ▪ ACS



NASA, N. Benitez (JHU), T. Broadhurst (Hebrew Univ.), H. Ford (JHU), M. Clampin(STScI), G. Hartig (STScI), G. Illingworth (UCO/Lick Observatory), the ACS Science Team and ESA STScI-PRC03-01a

The process of star formation and evolution fundamentally changes galaxies

- Steadily adds new stars
- Removes gas, overall
- Changes the phase of the gas (molecular, atomic, or ionized)
- Changes the elemental abundances ("metallicity") of gas and of subsequent generations of stars

The Universe is a Time Machine!

- Speed of light is not infinite

  1 light year – Distance light travels in a year

  - Nearest Star: 3 light years
  - Center of Milky Way: 25,000 lyr
  - Andromeda Galaxy: 2.5 million lyr
  - Coma Cluster: 340 million lyr
  - Most Distant galaxies: 13 billion lyr

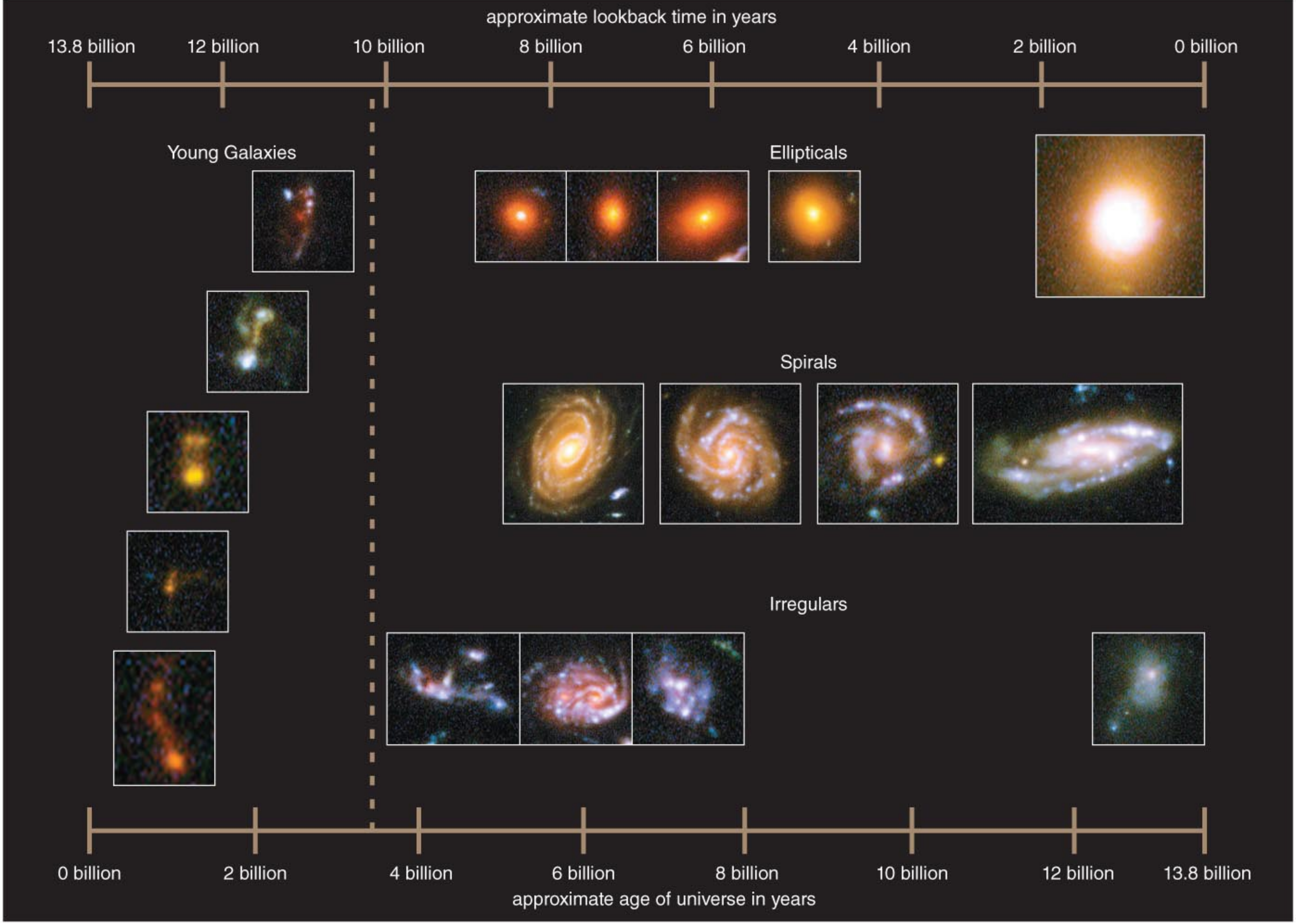
The Universe is a Time Machine!

- Speed of light not infinite
- **Distant = Younger!**
  - The light we see from distant galaxies was emitted many, many years ago
  - So, we see these galaxies as they were when the Universe was younger
- This means that we can take snapshots of the Universe and learn how galaxies were formed

We learn about galaxy formation by observing galaxies at different distances

BUT…

- This process is harder than we would like
  - Remember, we can not see the **same** galaxy at different distances
  - Distant galaxies appear fainter, so harder to detect
  - Distant galaxies appear smaller (in angular size), so harder to resolve features
  - Worst of all, measuring distances to galaxies is **DIFFICULT**

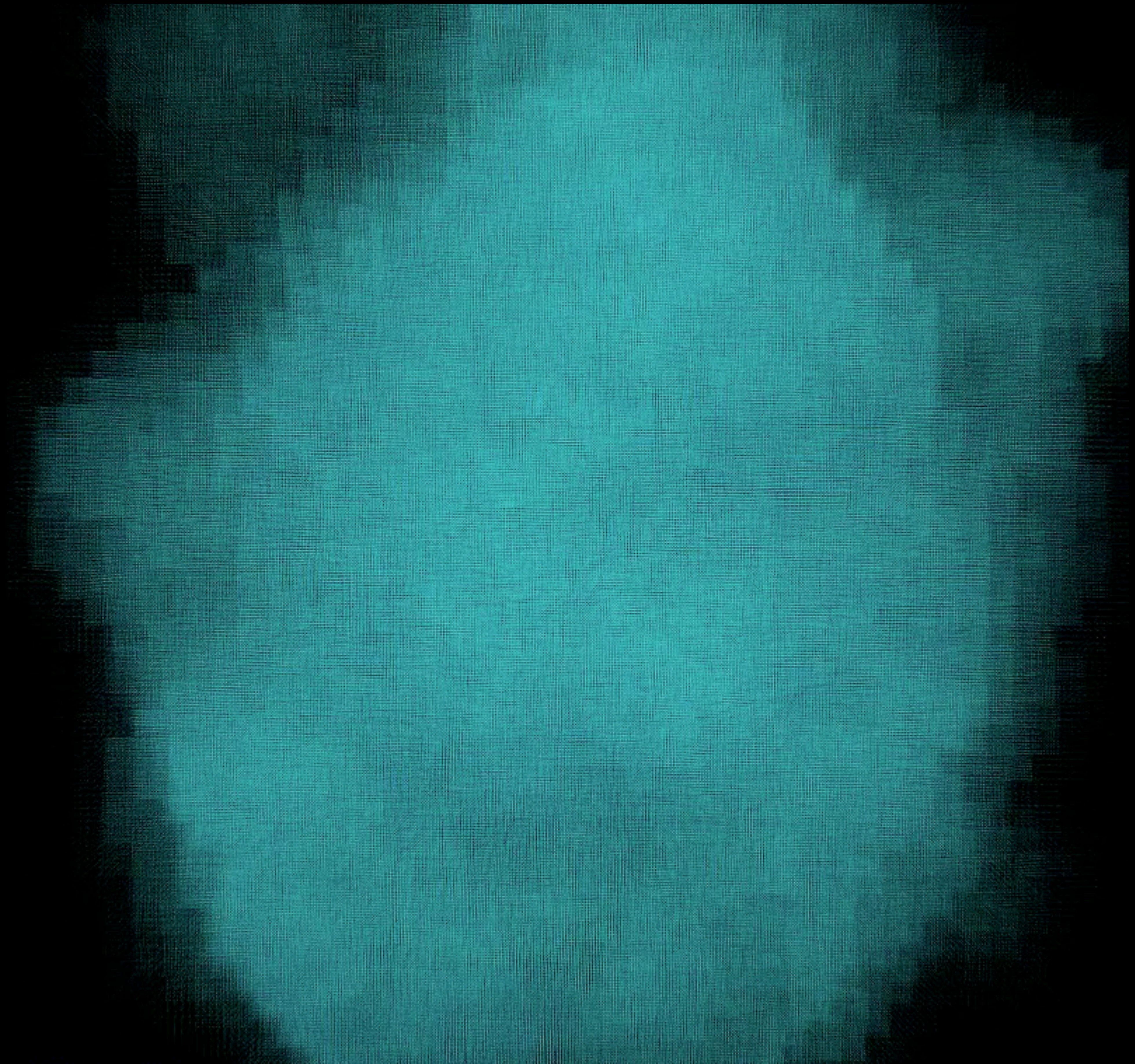


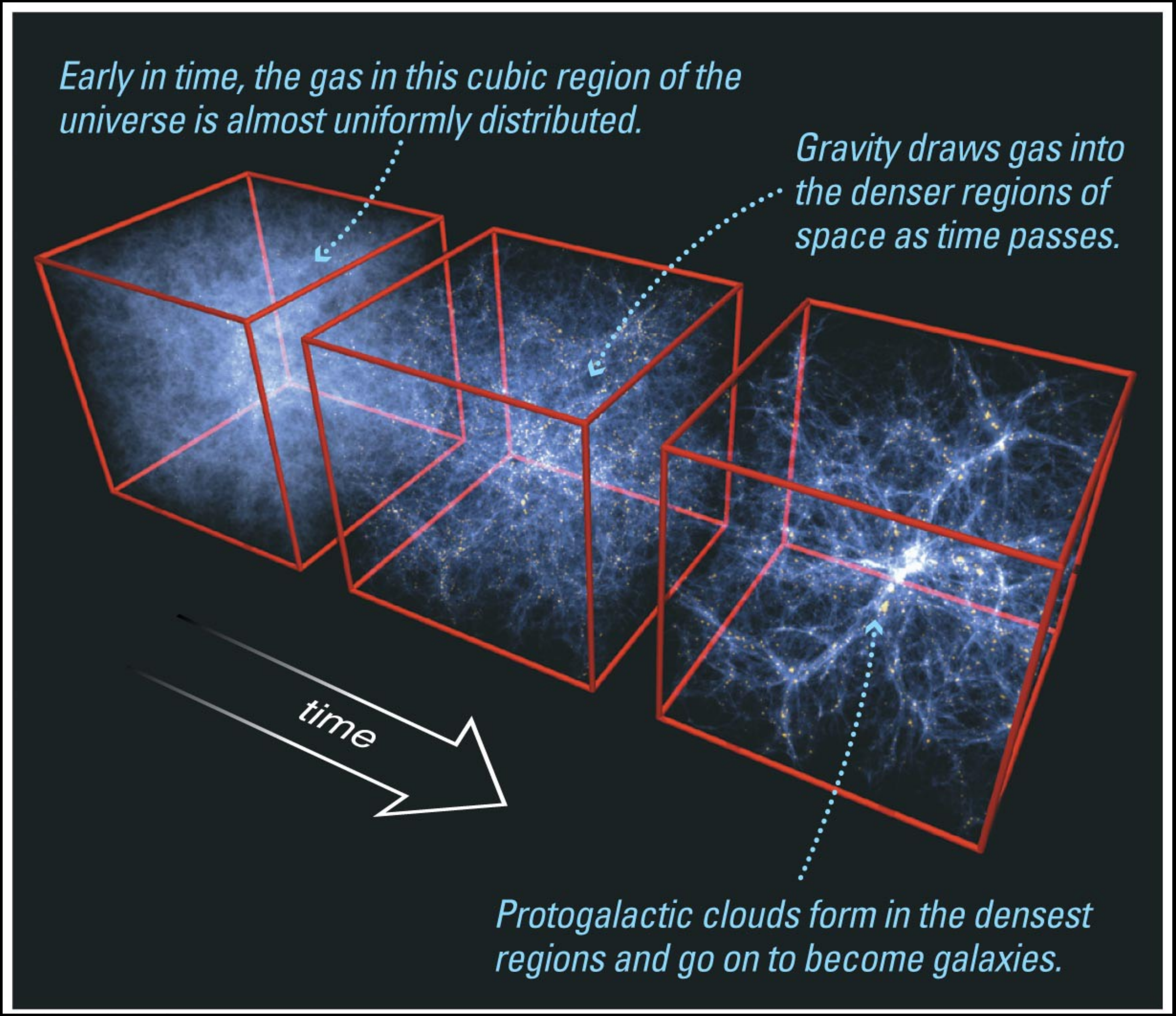
← Big Bang Today→

How did galaxies start out?

- H and He filled space more or less uniformly ~1 million years after Big Bang
- However, uniformity was not perfect
- Regions of enhanced density expanded with rest of Universe, but…
  - Greater pull of gravity in these regions eventually slowed, halted, and reversed their expansion
  - Material within them began to contract into protogalactic clouds which eventually form galaxies

Cosmic structure formation in action

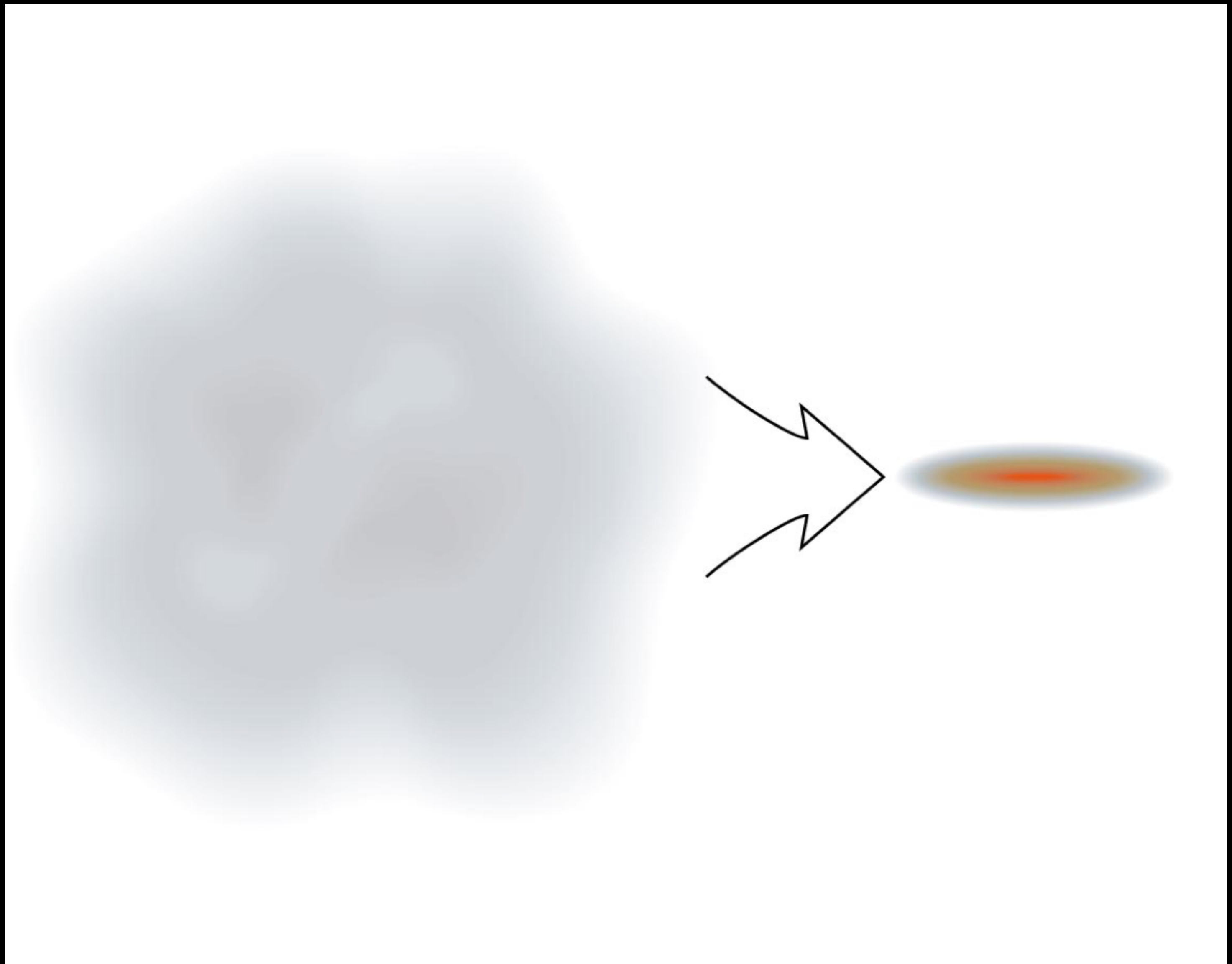



Early in time, the gas in this cubic region of the universe is almost uniformly distributed.
Gravity draws gas into the denser regions of space as time passes.
time
Protogalactic clouds form in the densest regions and go on to become galaxies.

The formation of galaxies

Elliptical
vs
spiral galaxies

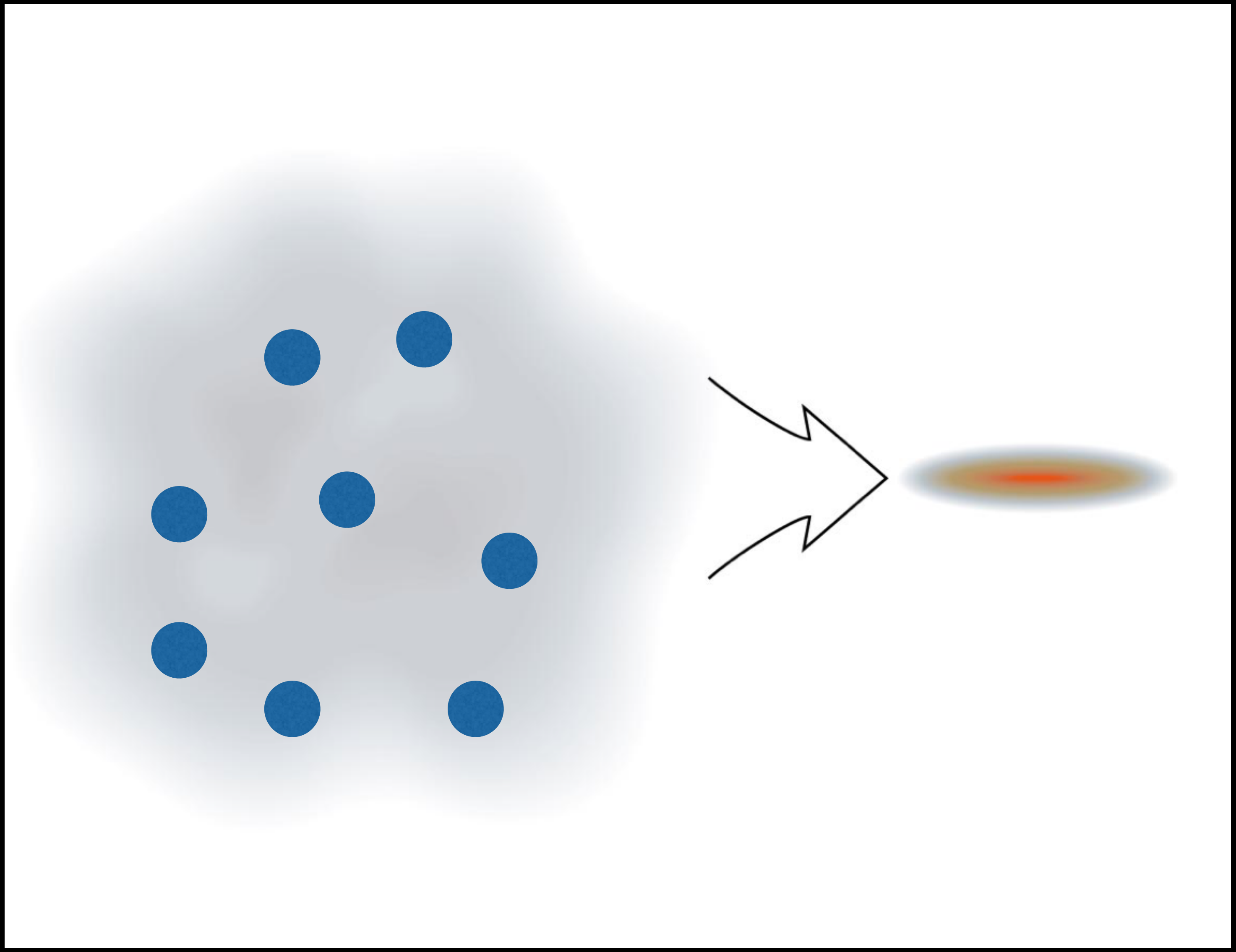
Gas



b A cloud of interstellar gas contracting because of its own gravity has more gravitational potential energy when it is spread out than when it shrinks in size.

- Gas can lose energy and “fall” inward
- Conservation of angular momentum causes gas to flatten into a disk as it contracts
- Collisions among gas particles tend to average out random motions

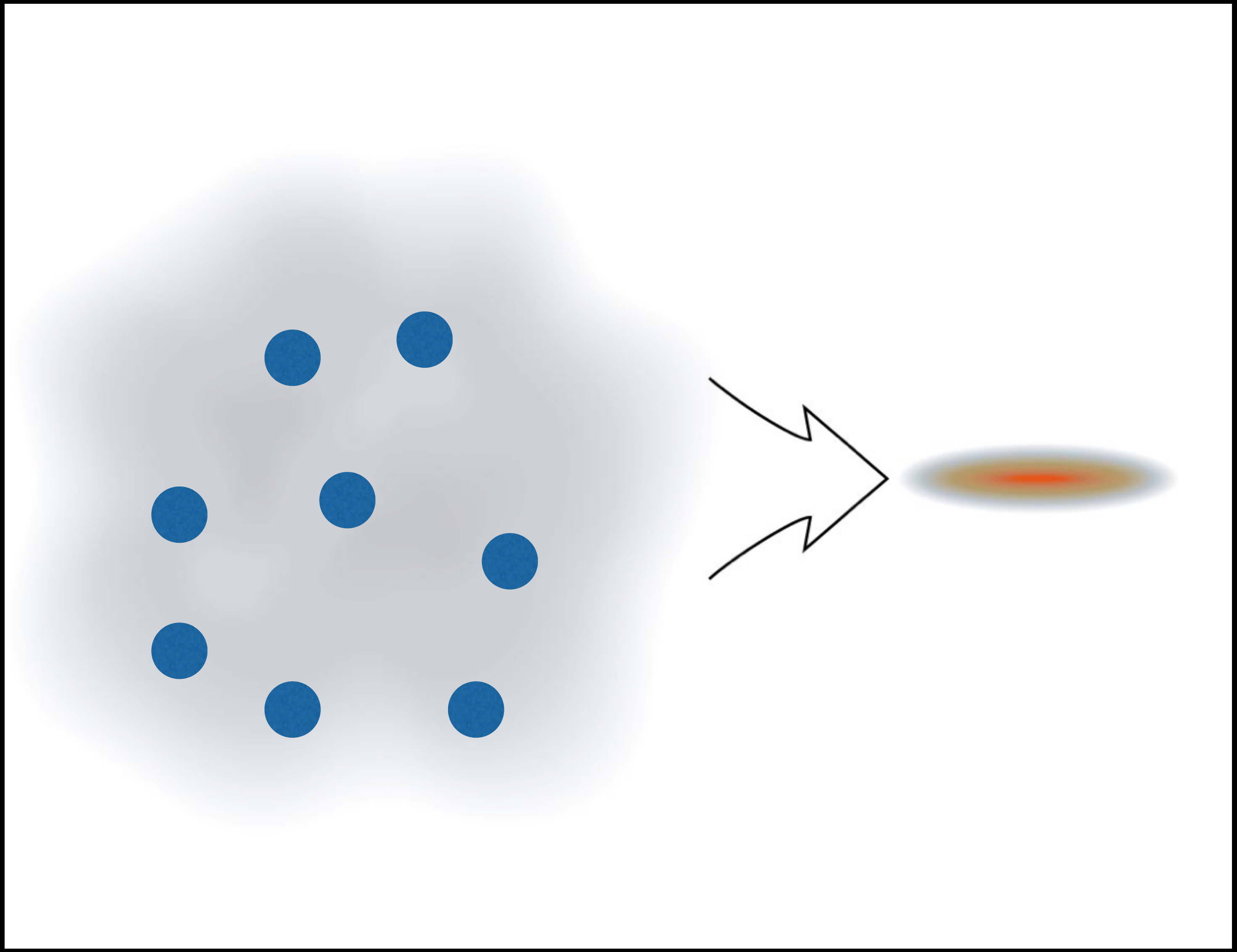
Gas



- Gas can lose energy and "fall" inward
- Conservation of angular momentum causes gas to flatten into a disk as it contracts
- Collisions among gas particles tend to average out random motions

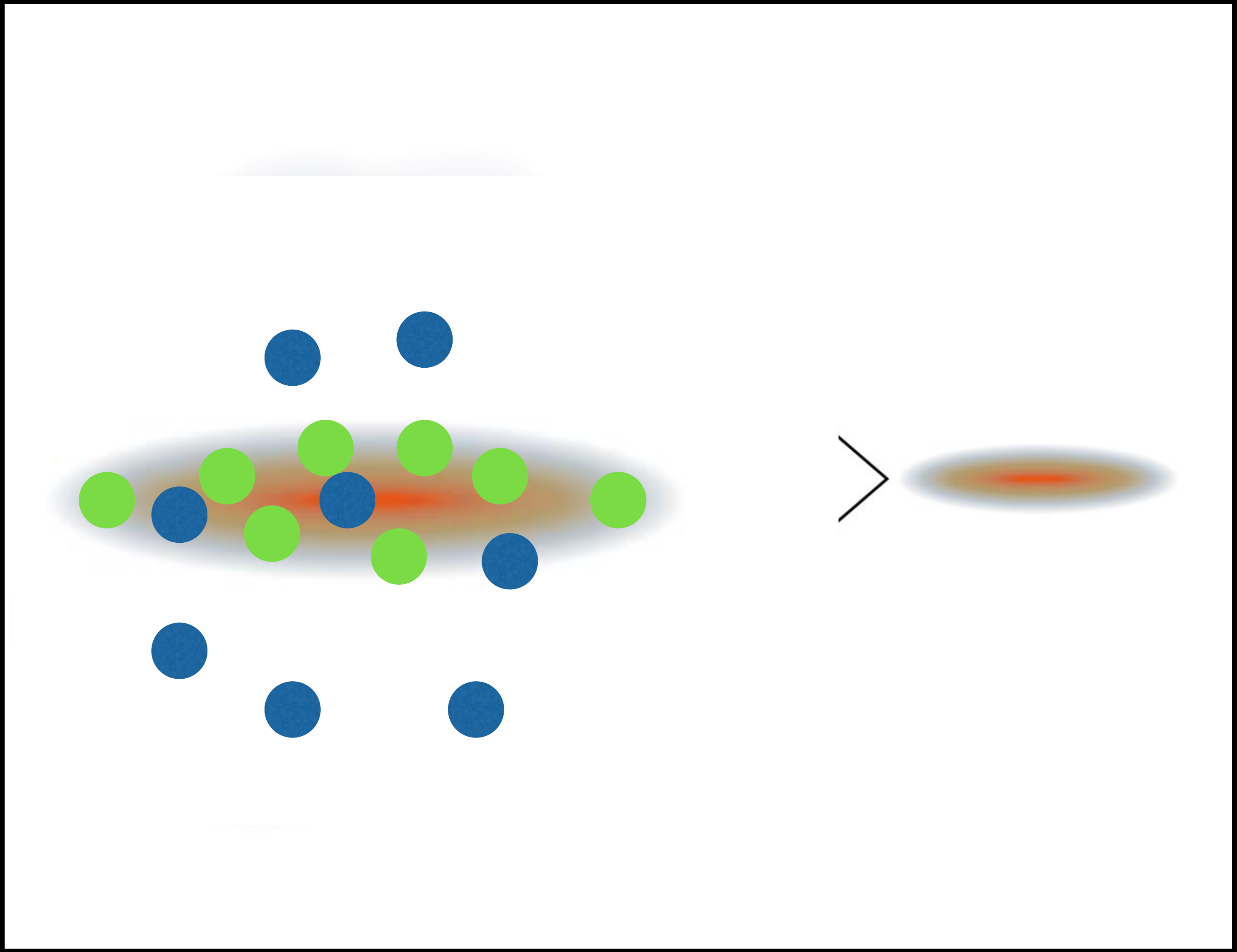
Part of the mass is used to form new stars

Stars



- Star do not collide
- Space is essentially empty
- Preserve the random motion they had at formation (Halo stars)

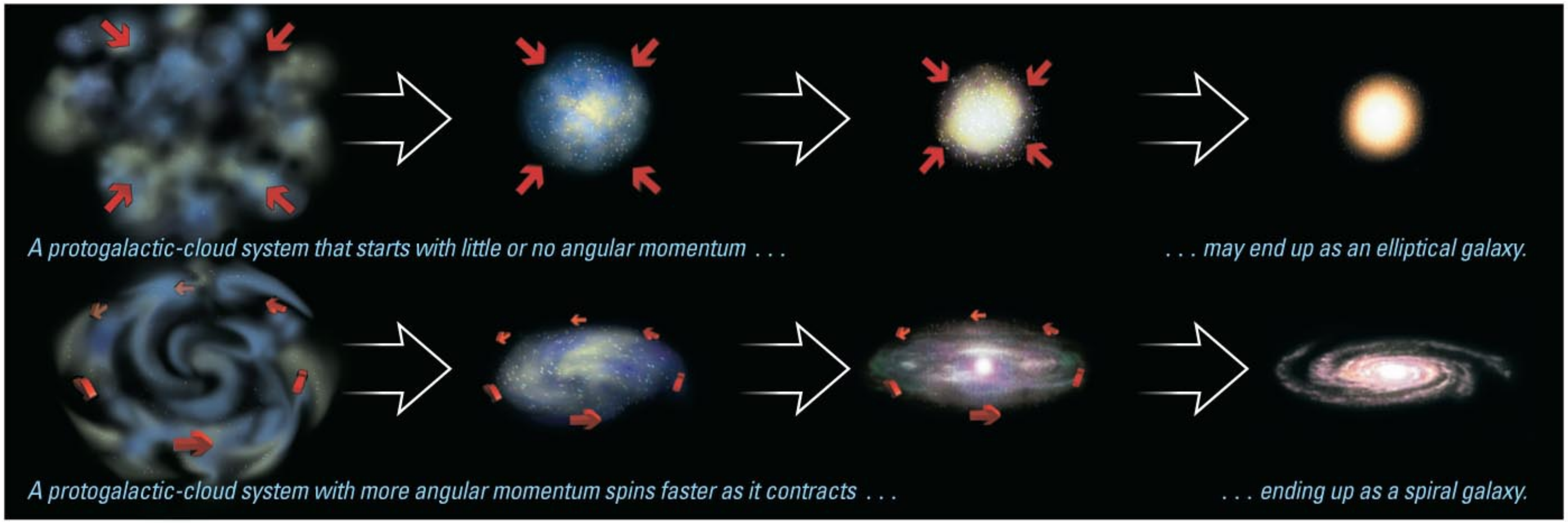
Spiral Galaxy



- Star do not collide
- Space is essentially empty
- Preserve the random motion they had at formation (Halo stars)

You still have gas around (once the gas flattened) to form new stars in the disk

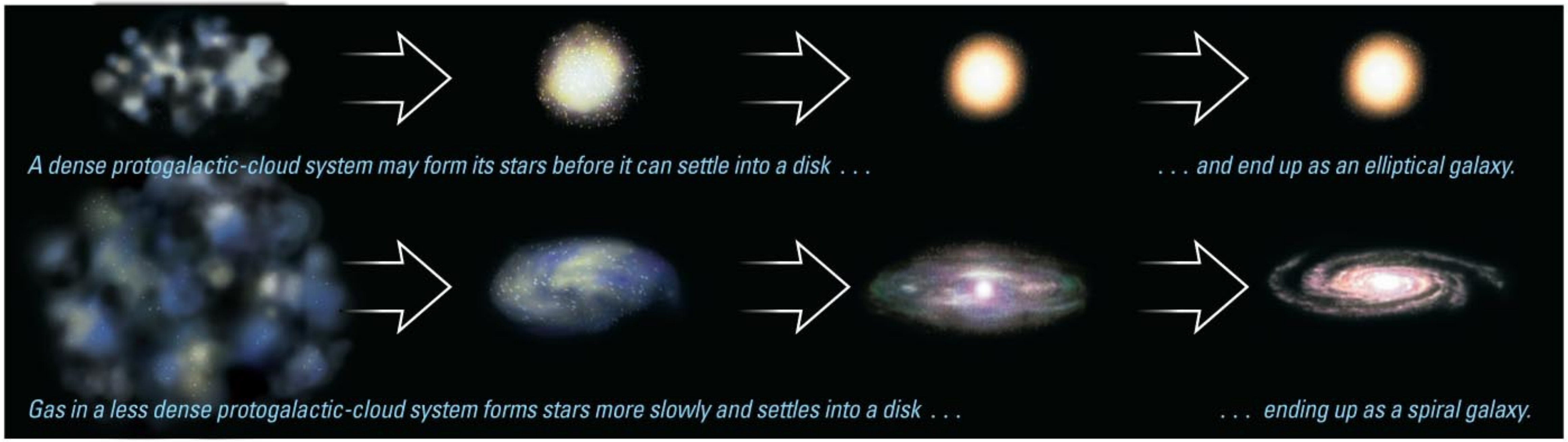
Elliptical galaxies



a The angular momentum of a galaxy's protogalactic-cloud system may determine whether it ends up spiral or elliptical.

Protogalactic cloud with low angular momentum will not flat producing elliptical galaxies

Elliptical galaxies



b The gas density of a galaxy's protogalactic clouds may determine whether it ends up spiral or elliptical.

Protogalactic cloud with high density gas may use all the gas to quickly form stars before flattening

No gas left to form the disk

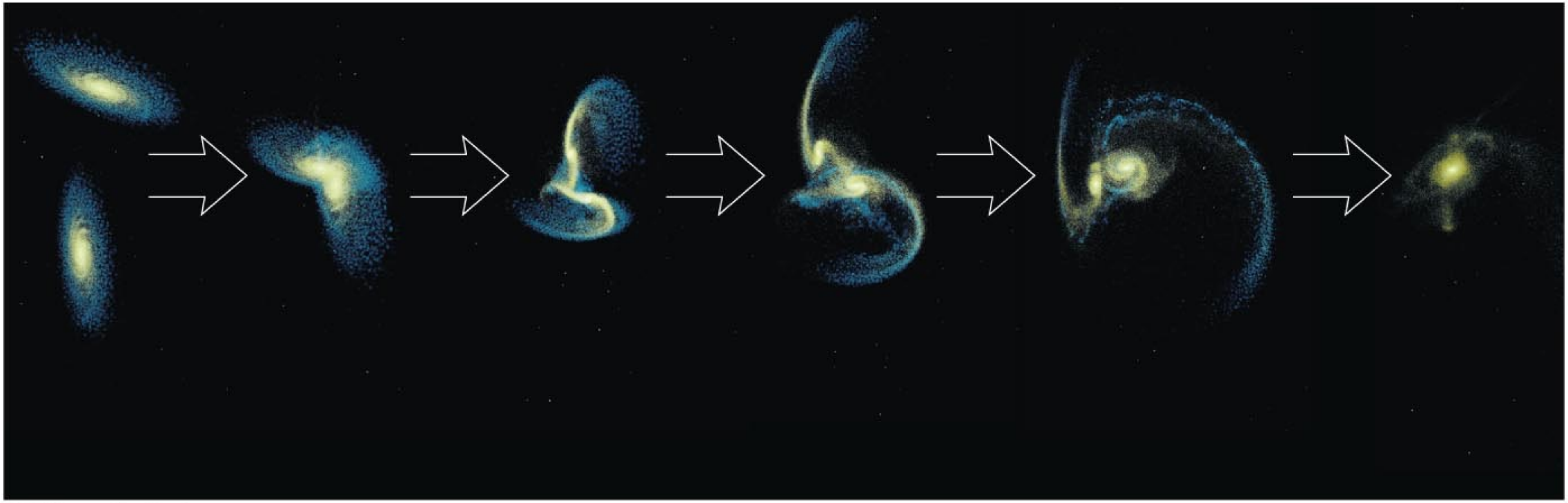
The formation of galaxies

Protogalactic cloud birth condition may be responsible of the type of galaxy we see today

The formation of disk galaxies

Protogalactic cloud birth condition may be responsible of the type of galaxy we see today

Some of the elliptical galaxies today are probably coming from the collision of spiral galaxies



Putting it all together: computer simulations of galaxies over time

Pleiades Supercomputer


z=30.0
z=30.0
$(< 10^4\ K)$
$(> 10^6\ K)$

Recap: what have we learned?

- **How do we observe the histories of galaxies?**
  - Light takes a long time to reach us from distant galaxies
  - By looking at galaxies at different distances, we see them at different ages
  - We can see galaxies as far back as ~13 billion years ago!
- **How do we study galaxy formation?**
  - We observe how galaxies change over time, and use our knowledge of the laws of nature to construct models for how they behave
  - We can run these models on supercomputers, and compare them with actual galaxies