A Universe of Galaxies

Chapter 15


light-years
years
time
nuclei
energy
away
star
brightness
Galaxy
period
collision
distant
Disk
Spiral
space
centers
spiral
distance
large
quasars
disk
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matter
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gas
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age
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elliptical
halo
Elliptical
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13.7 billion years
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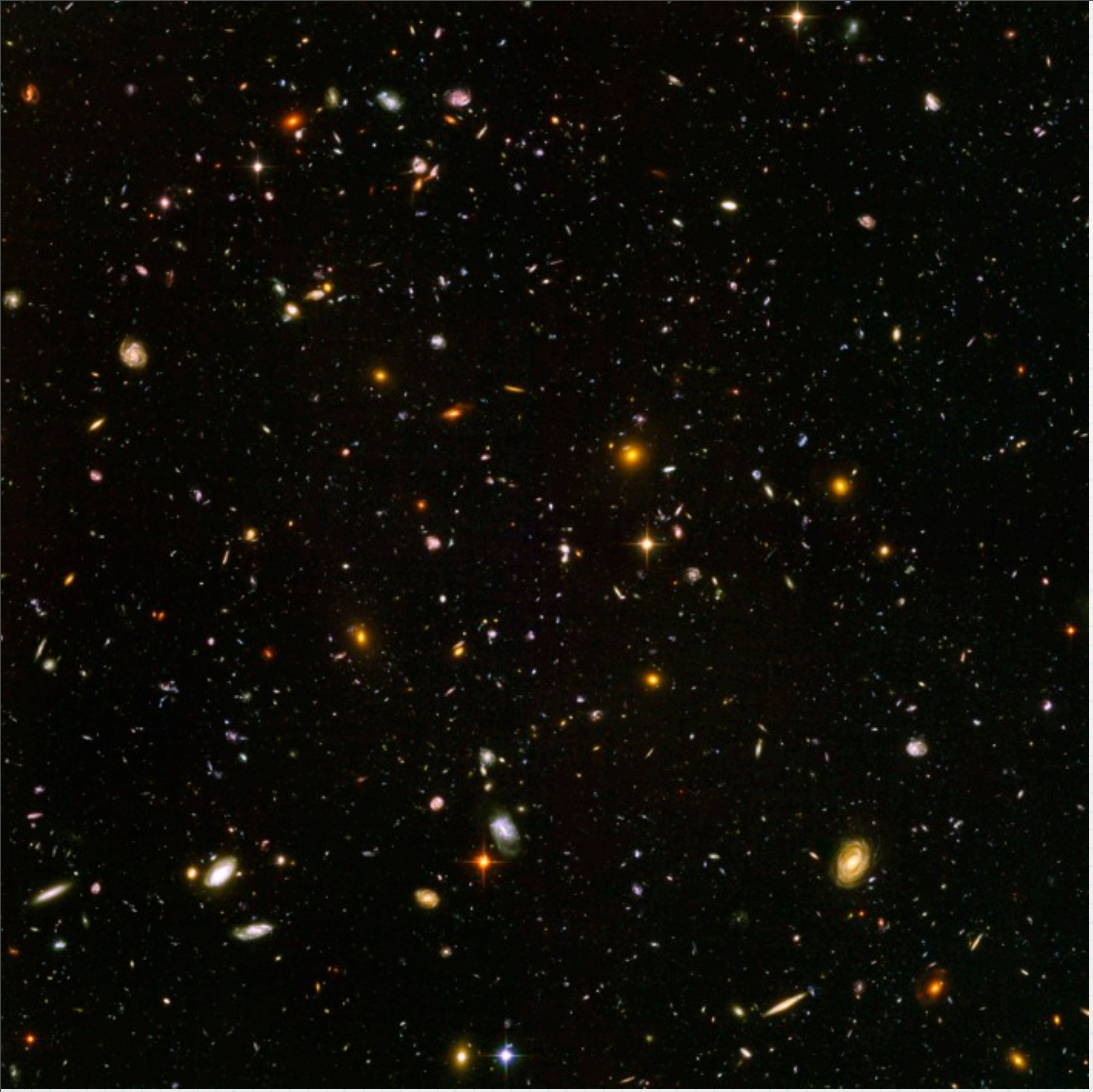
measuring
Black Hole
Cepheid
accretion
supermassive
universe
Hubble's Constant
Hubble
young
Distances
redshift
Component
regions
distances
center
galaxies

Islands of Stars

* Galaxies come in many sizes, colors and shapes
* We cannot see a galaxy age but by looking at many galaxies we can understand how they evolve

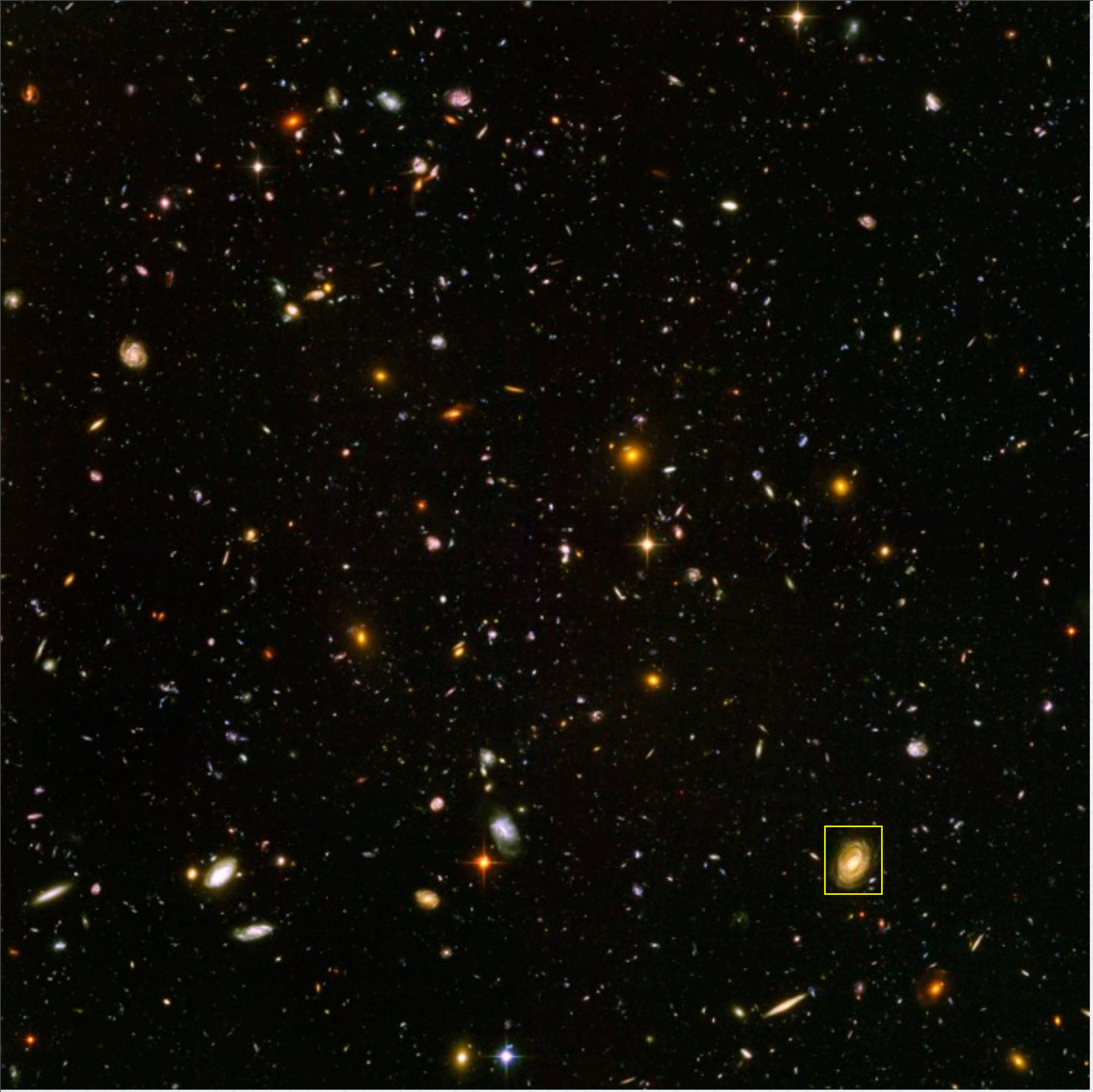


Hubble Ultra Deep Field

This is a tiny patch of sky containing 10 days of light

Almost every blob of light is a galaxy

≈ over 500 billion galaxies in the visible Universe



Hubble Ultra Deep Field

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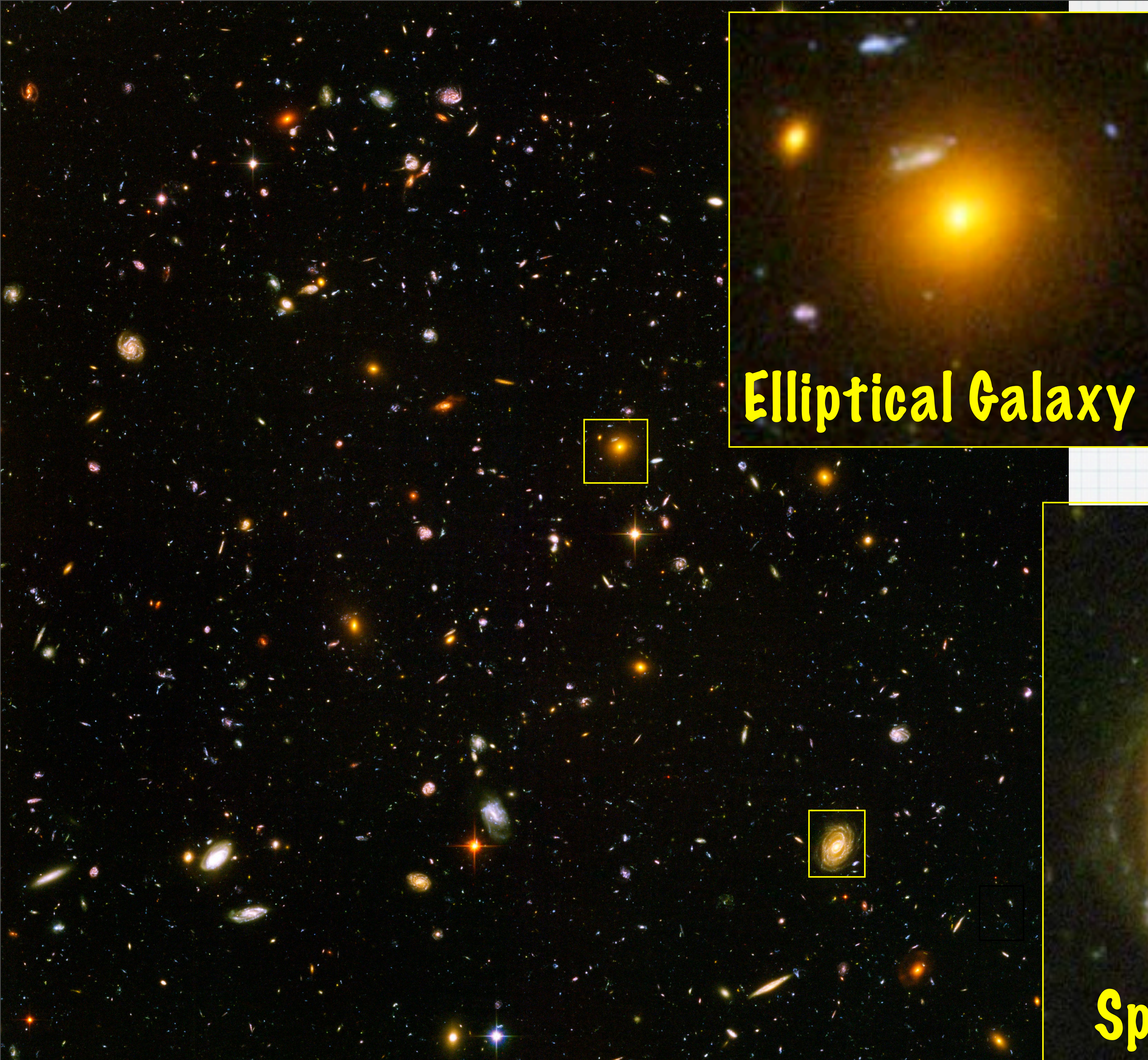
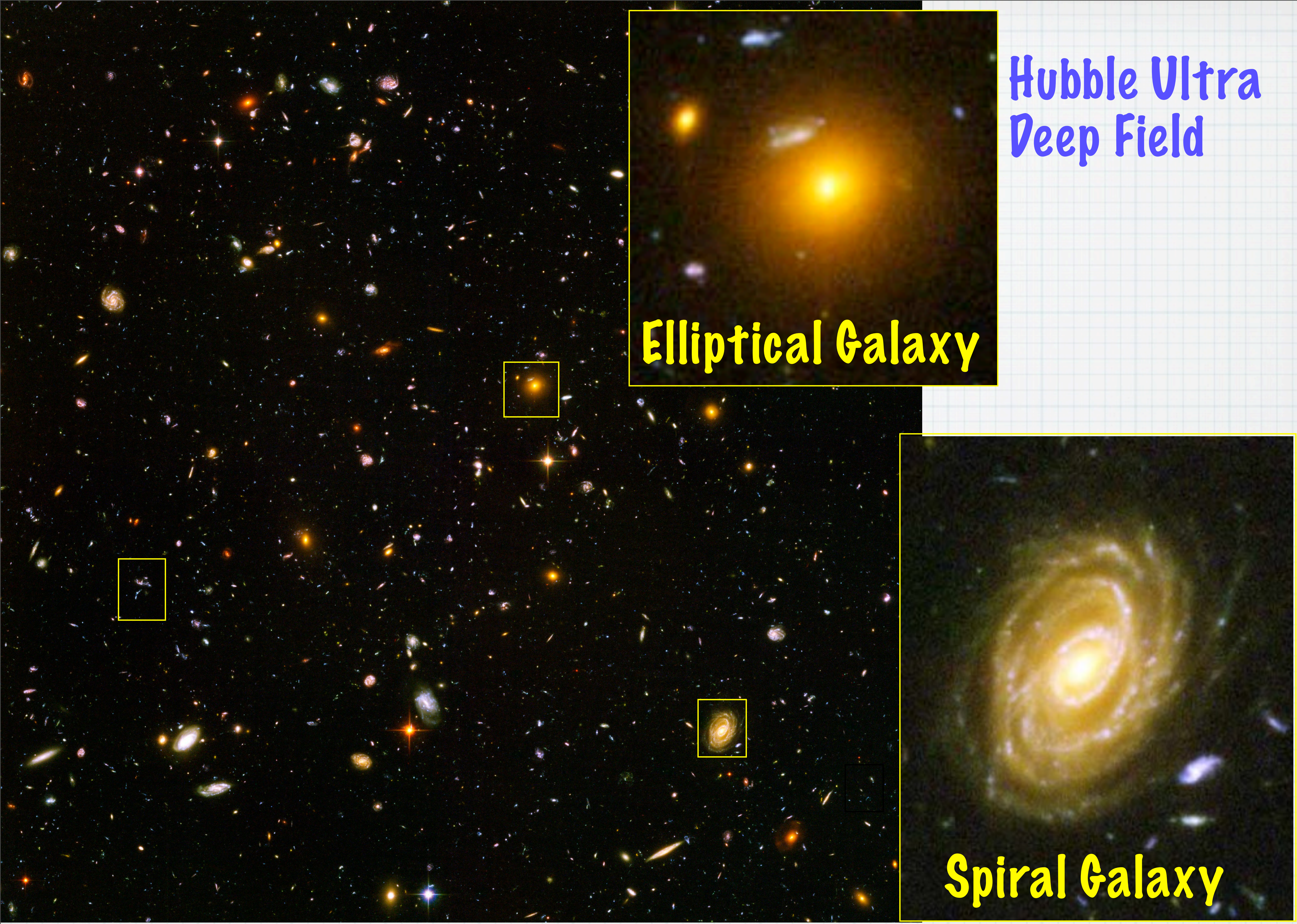
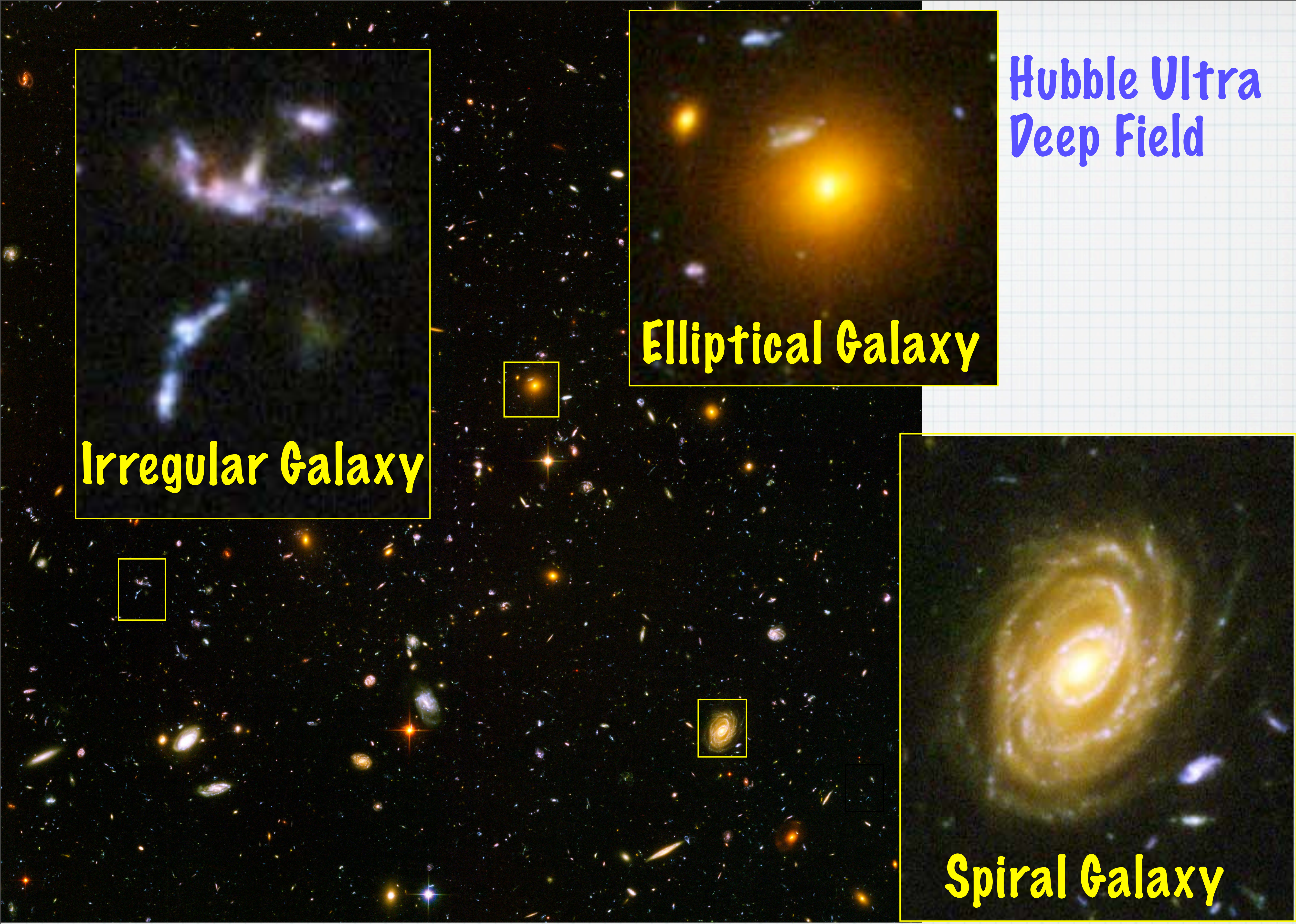


Hubble Ultra Deep Field




Hubble Ultra
Deep Field
Irregular Galaxy
Elliptical Galaxy
Spiral Galaxy

The three major types of galaxies

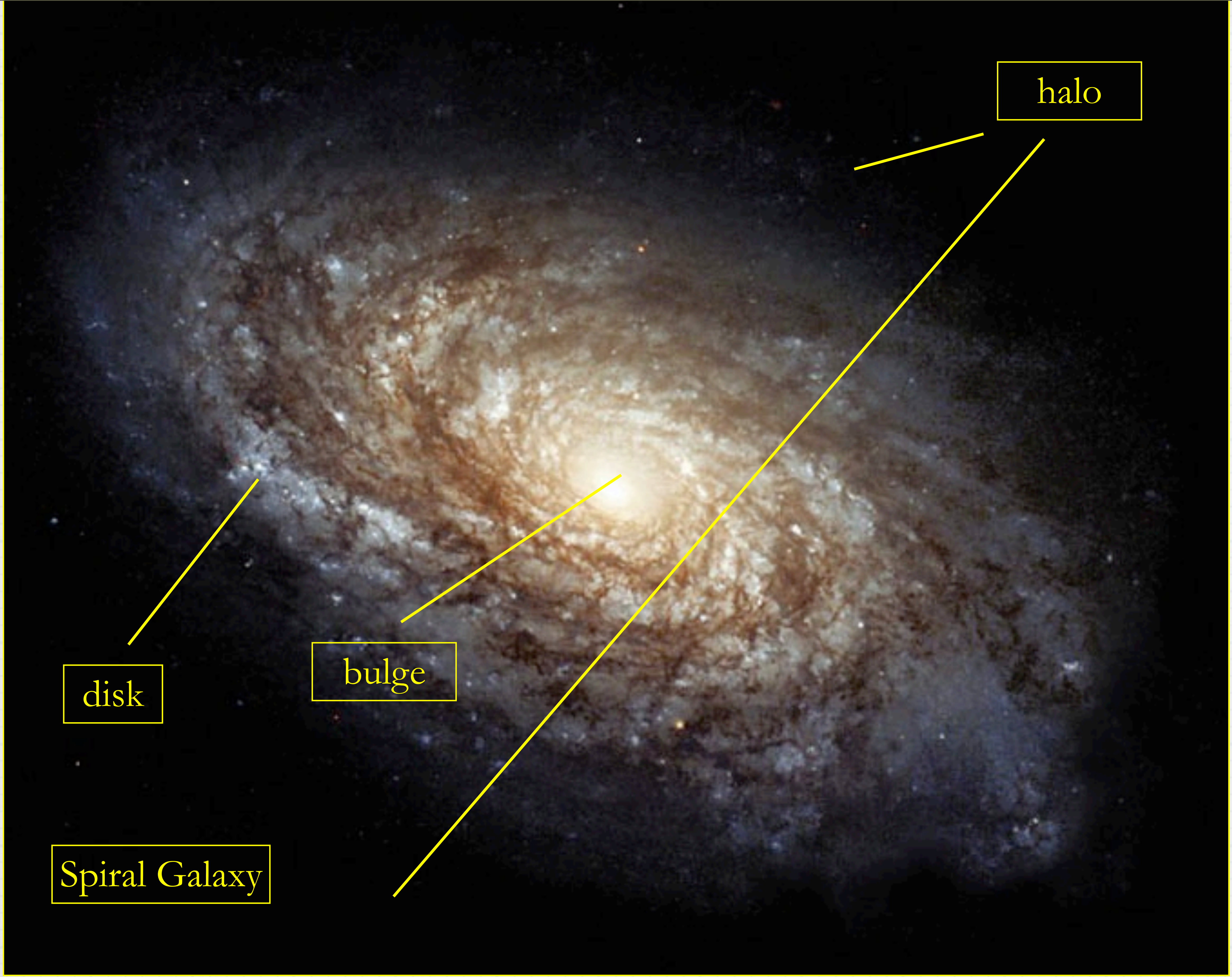
1. Spiral

   Lenticular (in-between)

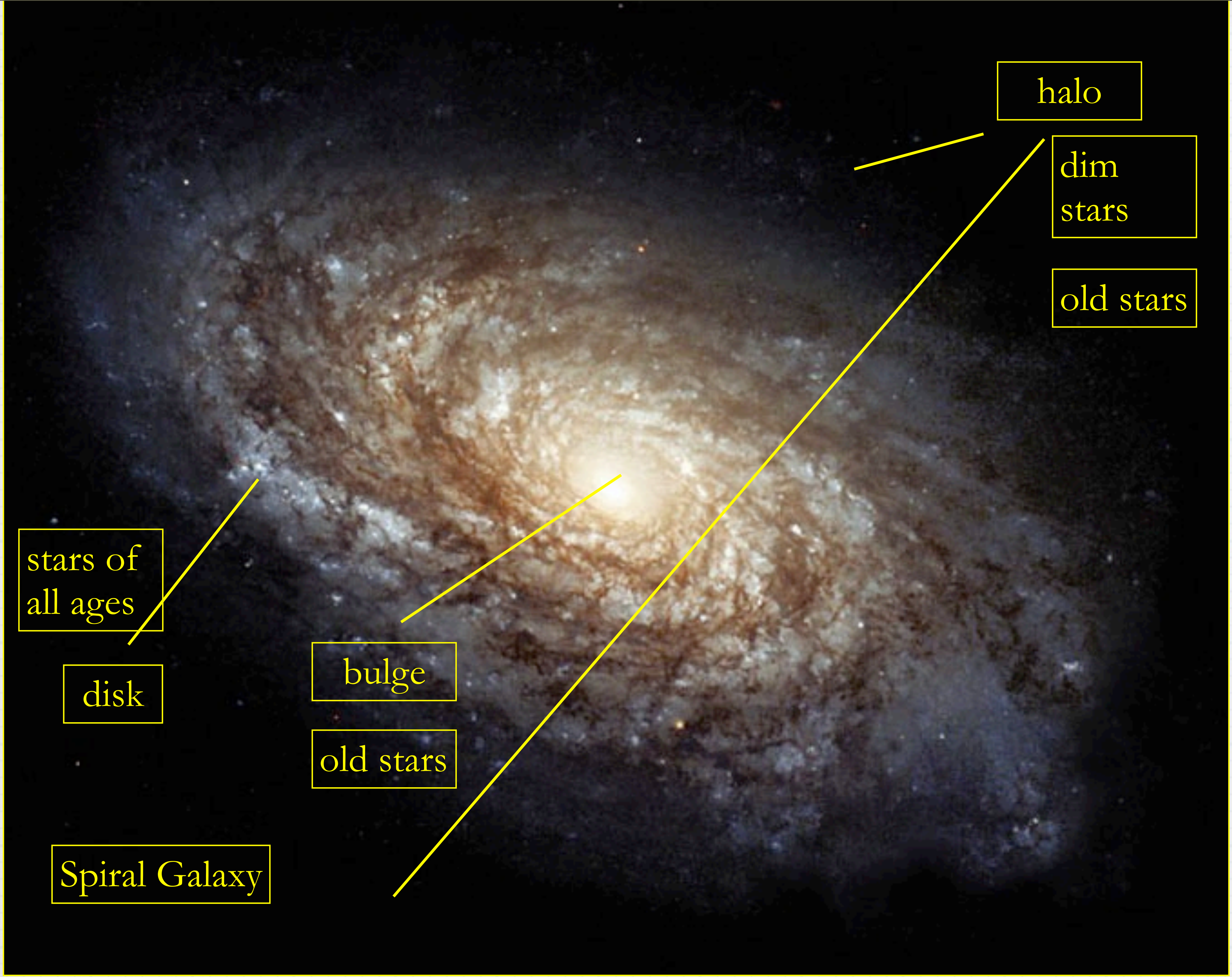
2. Elliptical
3. Irregular

Dwarf: 10 million to 100 million stars

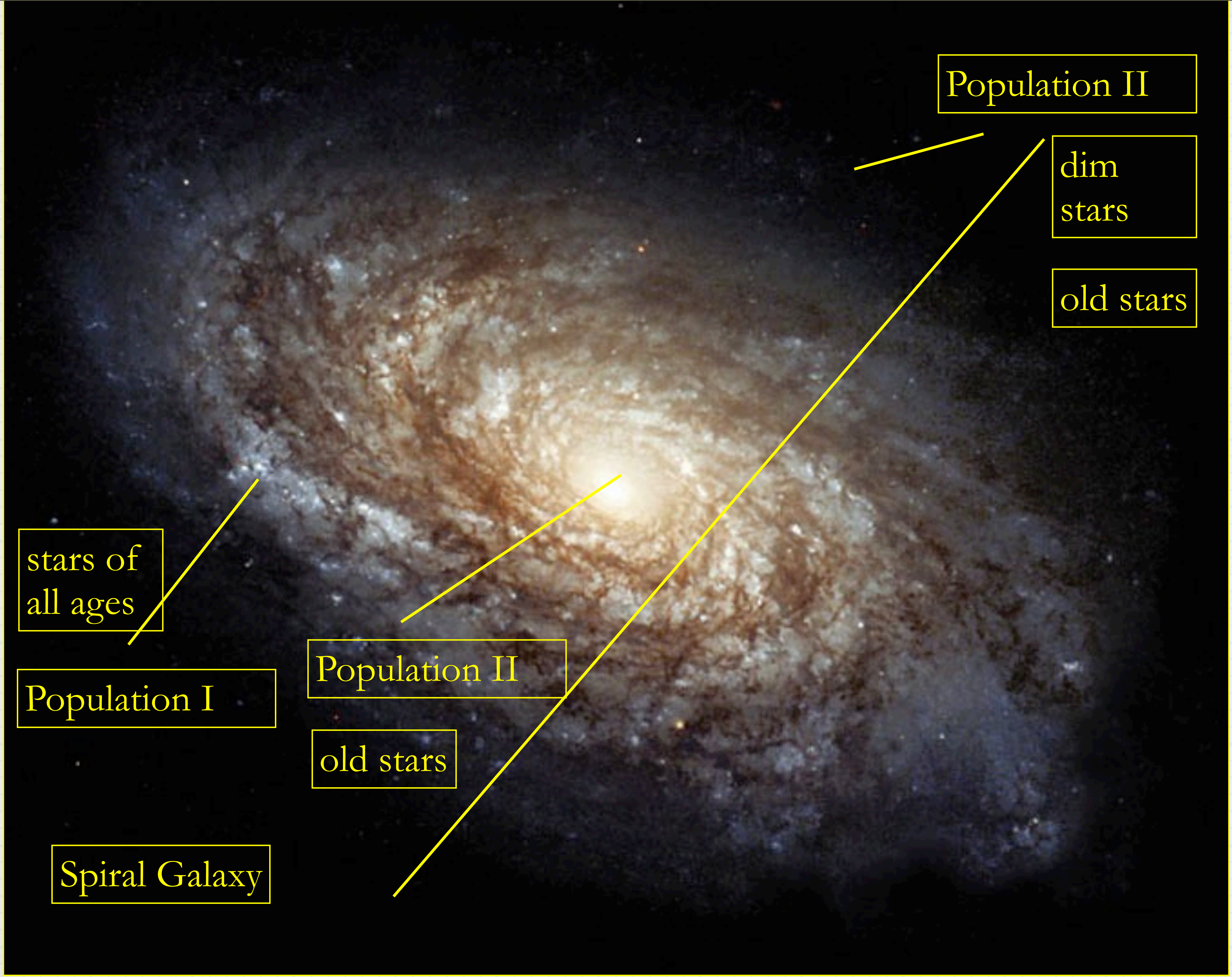
Giant: more than 1 trillion stars



Spiral Galaxy: NGC 4414, 100,000 light-years ∅



Spiral Galaxy: NGC 4414, 100,000 light-years ∅



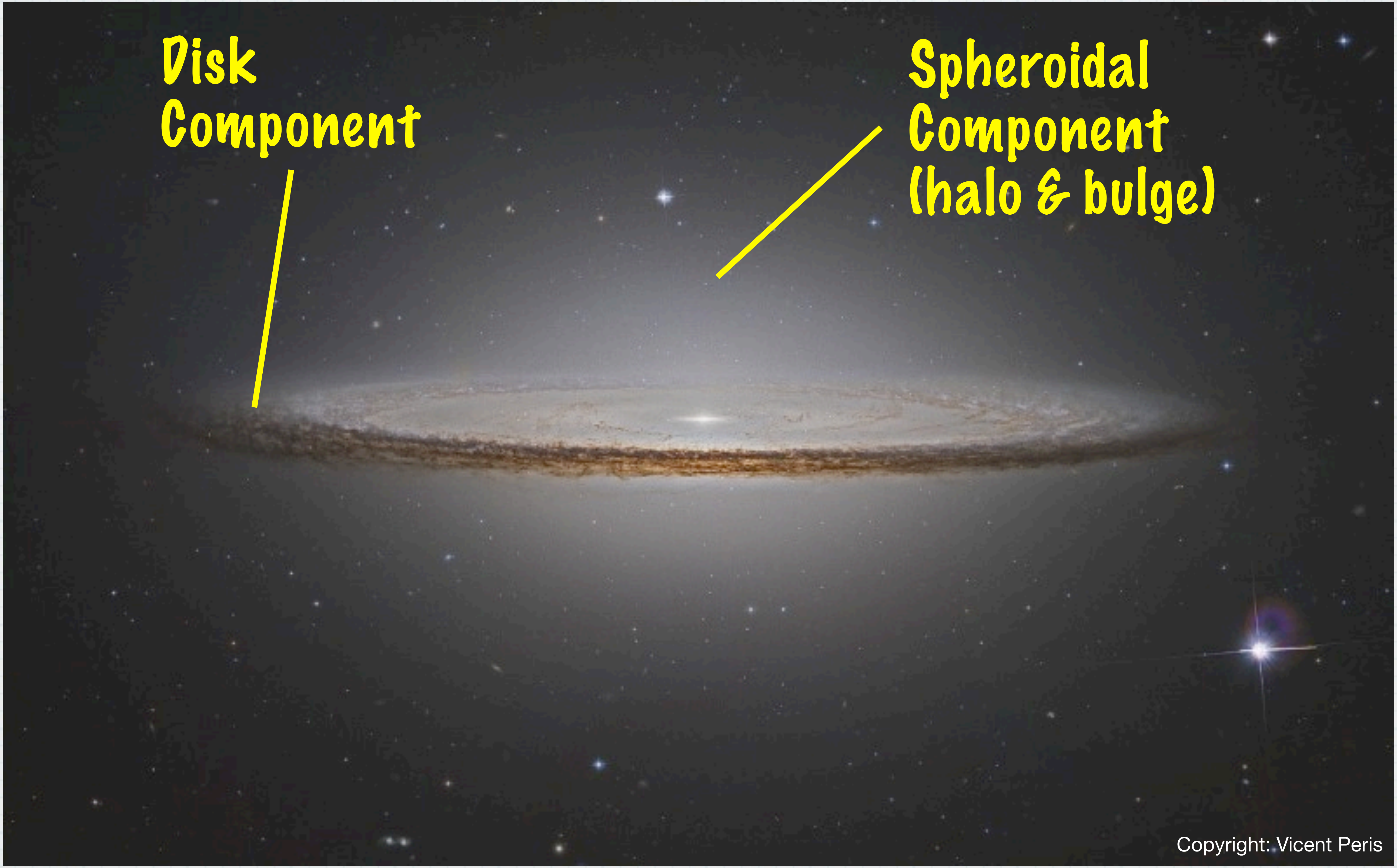
Spiral Galaxy: NGC 4414, 100,000 light-years ∅

Barred Spiral Galaxy NGC 1365

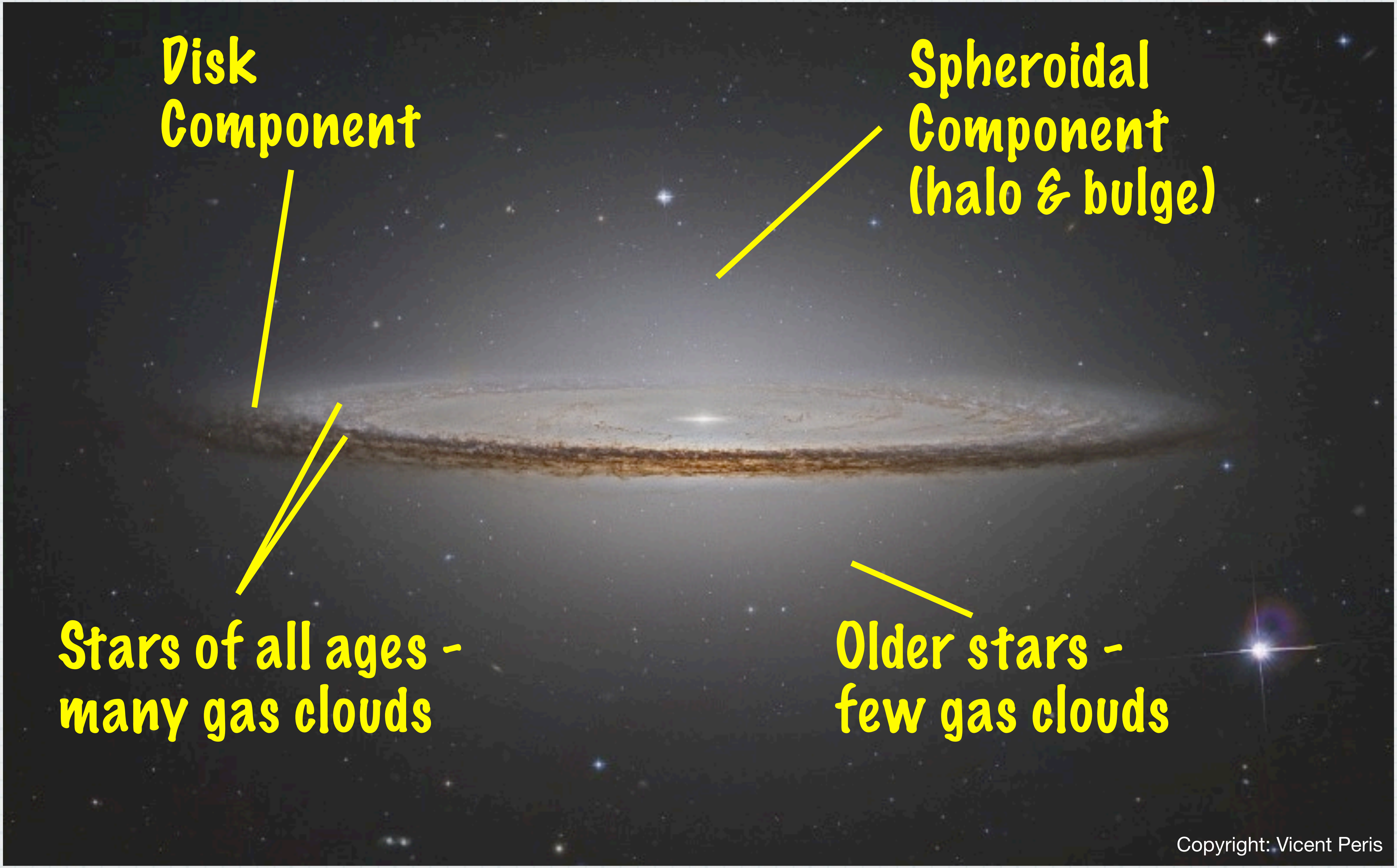
A bar is a sign of maturity (there are more nearby barred spirals than far away ones)

200,000 light-years ∅,
60 million light-year away

Credit & Copyright: SSRO-South (R.Gilbert,D.Goldman,J.Harvey,D.Verschatse) - PROMPT (D.Reichart)



NGC 4594 - The Sombrero Galaxy - 50,000 light-years ∅
aka Messier 104 - 28 million light-years away



NGC 4594 - The Sombrero Galaxy - 50,000 light-years ∅
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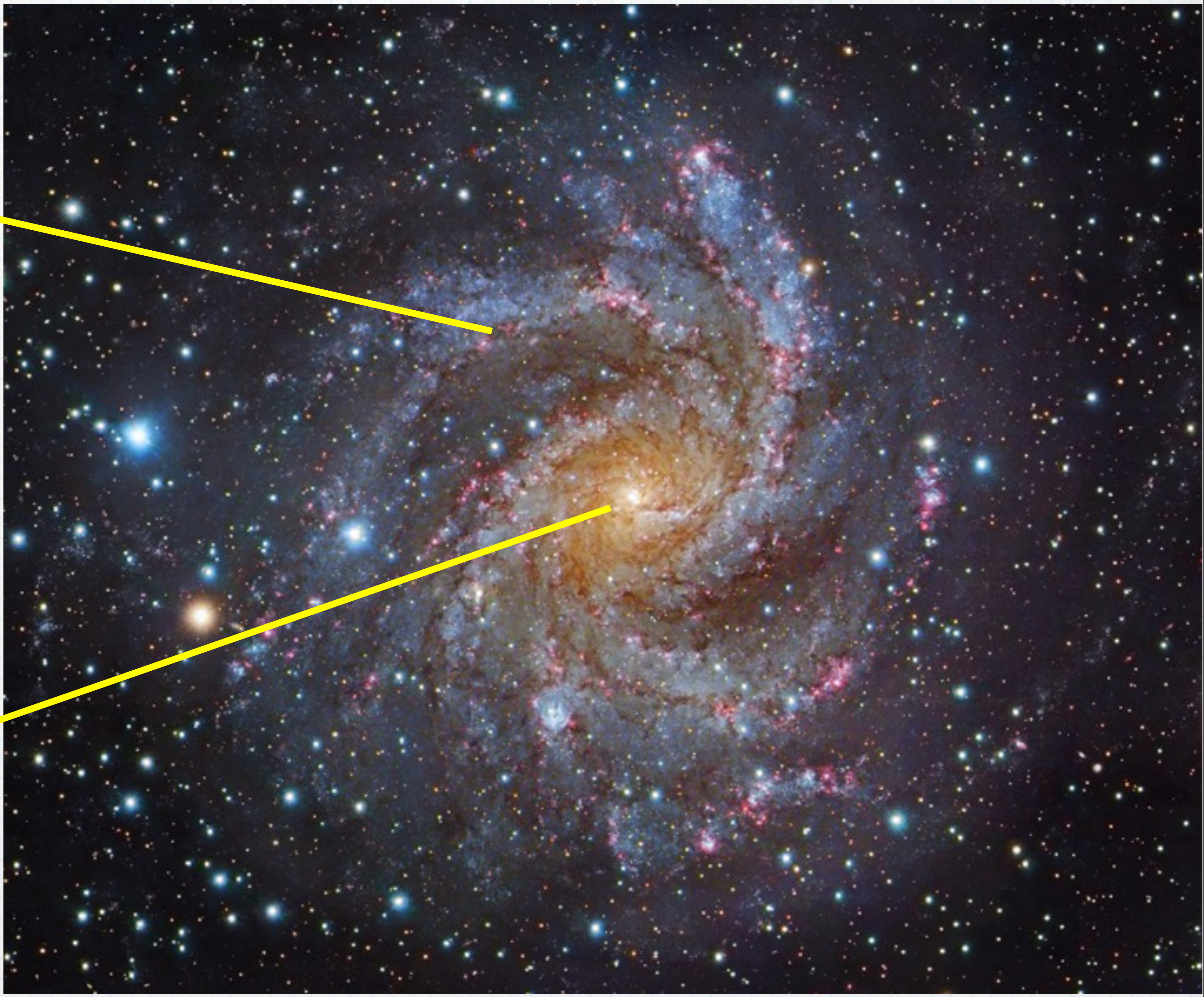
NGC 6946

Disk Component:
stars of all ages,
many gas clouds



Composite Image Data - Subaru Telescope (NAOJ) and Robert Gendler; *Processing* - Robert Gendler

Spheroidal Component:
bulge & halo:
old stars,
few gas clouds

NGC 6946

Disk Component:
stars of all ages,
many gas clouds

Spheroidal Component: bulge & halo:
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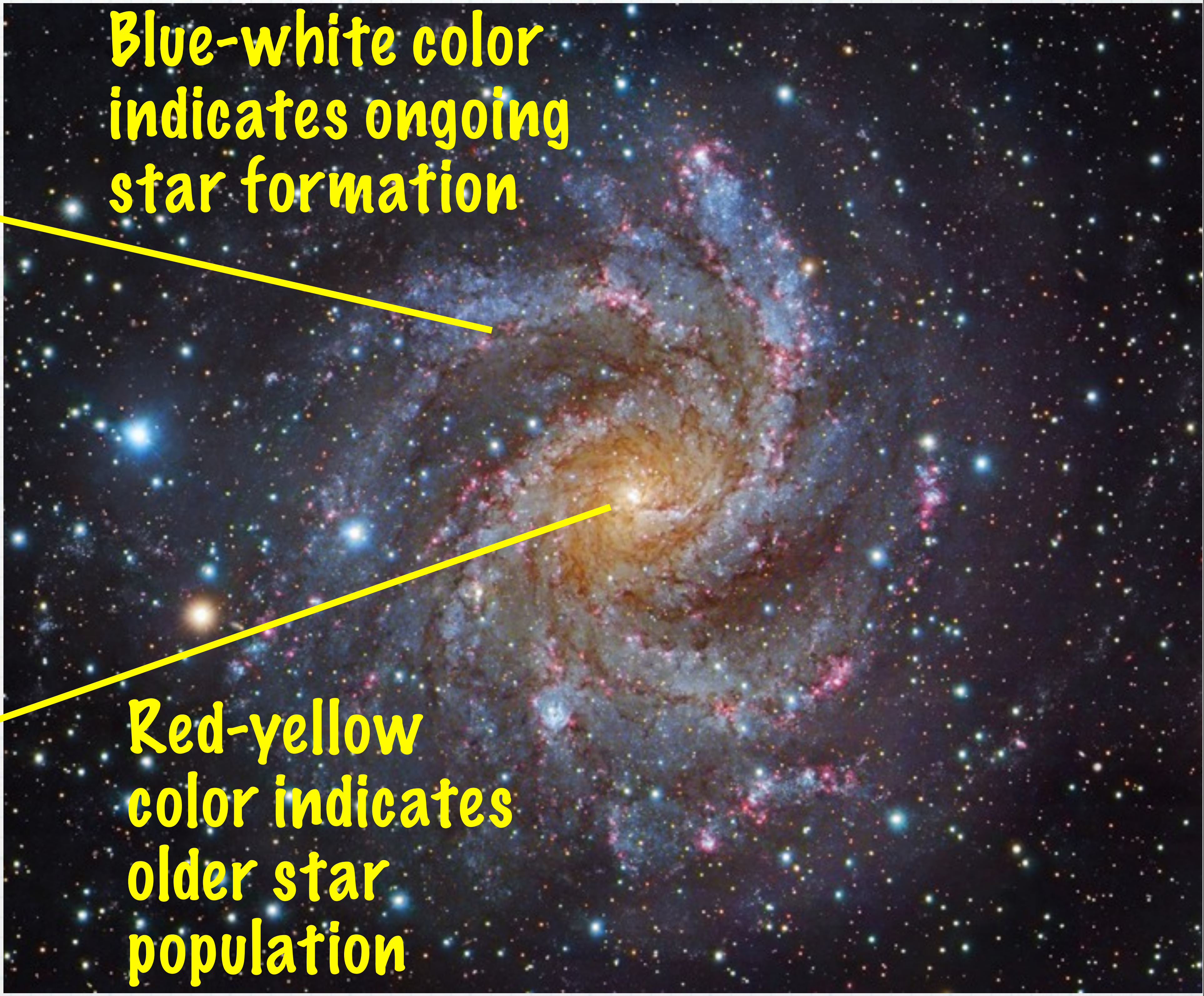

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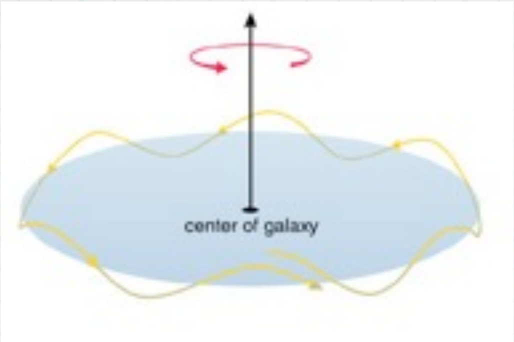
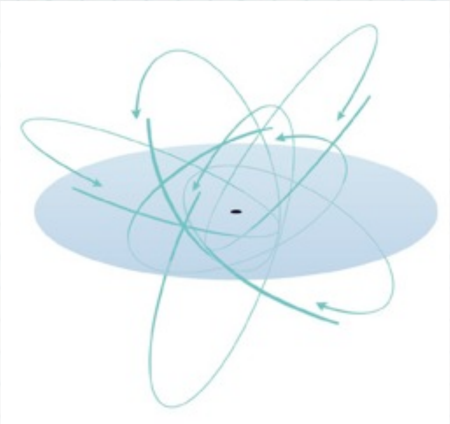
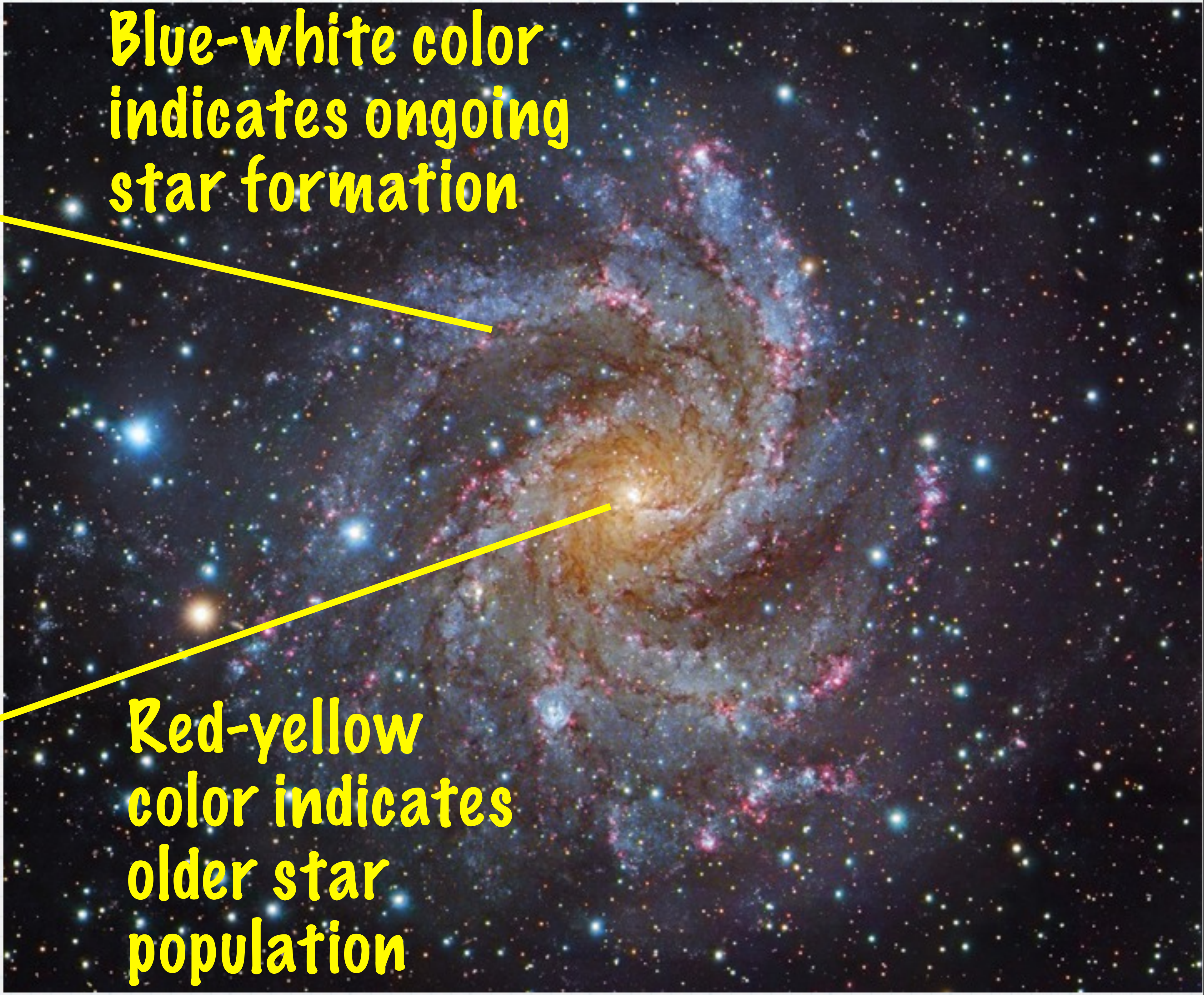


Disk Component: stars of all ages, many gas clouds



Spheroidal Component: bulge & halo: old stars, few gas clouds

NGC 6946



Composite Image Data - Subaru Telescope (NAOJ) and Robert Gendler; *Processing* - Robert Gendler

Beautiful Spiral NGC 7331

Question

* Why does ongoing star formation lead to a blue-white appearance?

A. There aren't any red or yellow stars

B. Short-lived blue stars outshine others

C. Gas in the disk scatters blue light

Question

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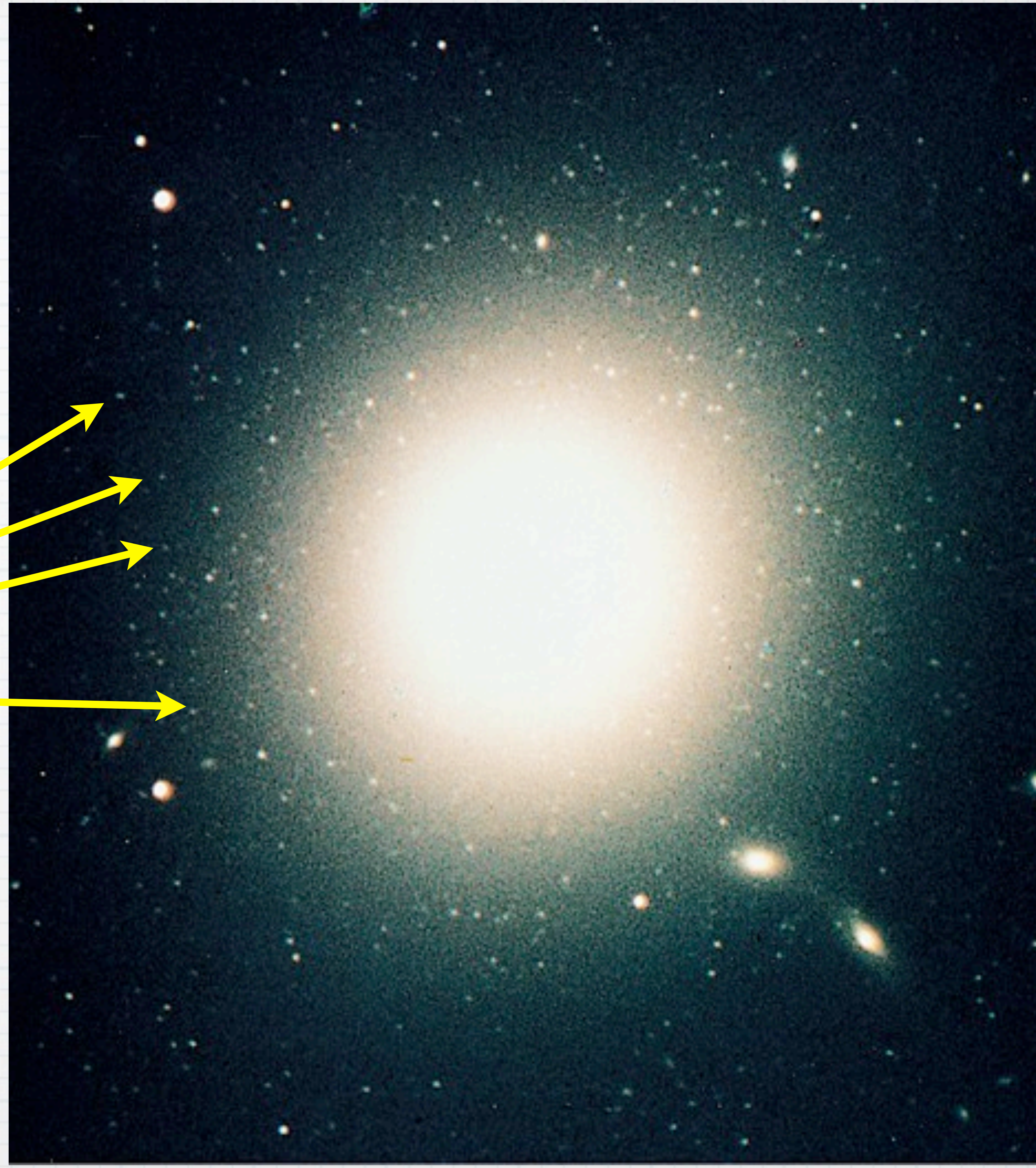
Elliptical Galaxy



numerous globular clusters

M 87, a giant elliptical galaxy in the Virgo Cluster
120,000 light-years ∅

Elliptical Galaxy

All spheroidal component, virtually no disk component

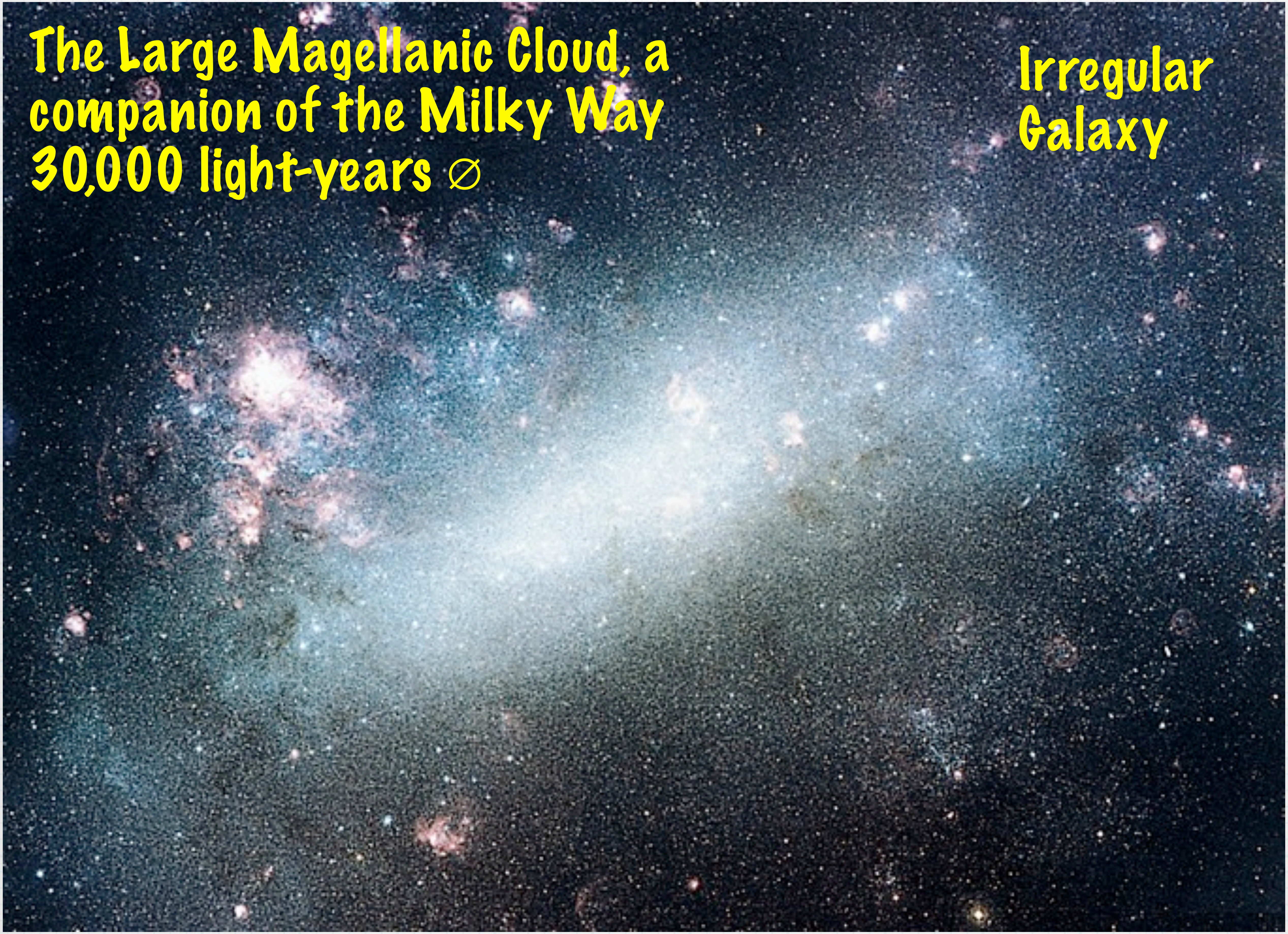
M 87, a giant elliptical galaxy in the Virgo Cluster 120,000 light-years ∅

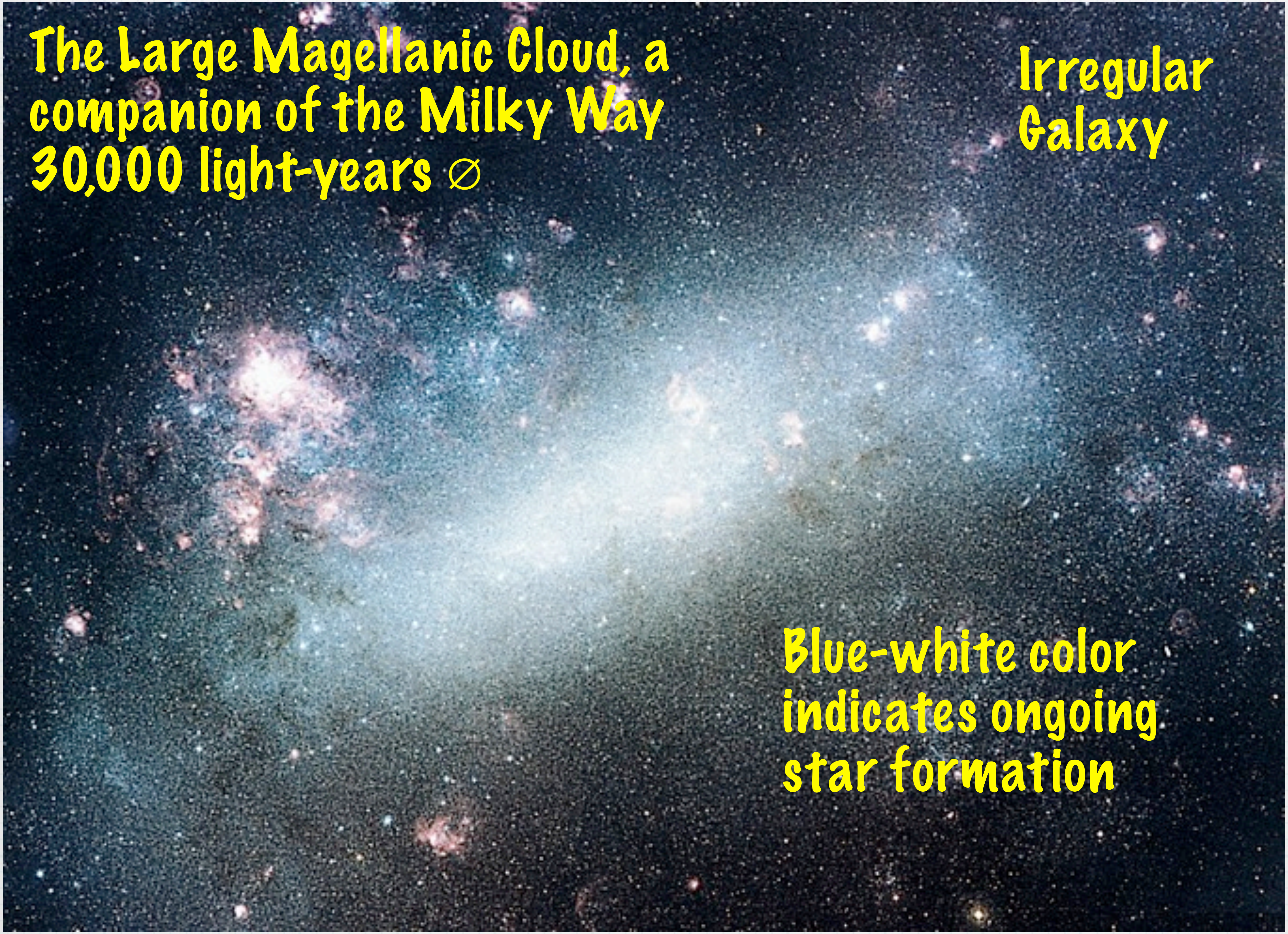
Elliptical Galaxy

All spheroidal component, virtually no disk component

Red-yellow color indicates older star population

M 87, a giant elliptical galaxy in the Virgo Cluster
120,000 light-years ∅


The Large Magellanic Cloud, a companion of the Milky Way
30,000 light-years ∅
Irregular Galaxy


The Large Magellanic Cloud, a
companion of the Milky Way
30,000 light-years ∅
Irregular
Galaxy
Blue-white color
indicates ongoing
star formation

Galactic Size

* Galaxies are bigger than they seem:
* A UV space telescope shows early-generation stars forming at the extreme ends of galaxies
* Astronomers thought these regions were devoid of star forming matter
* Hence, our current mass calculations are too small

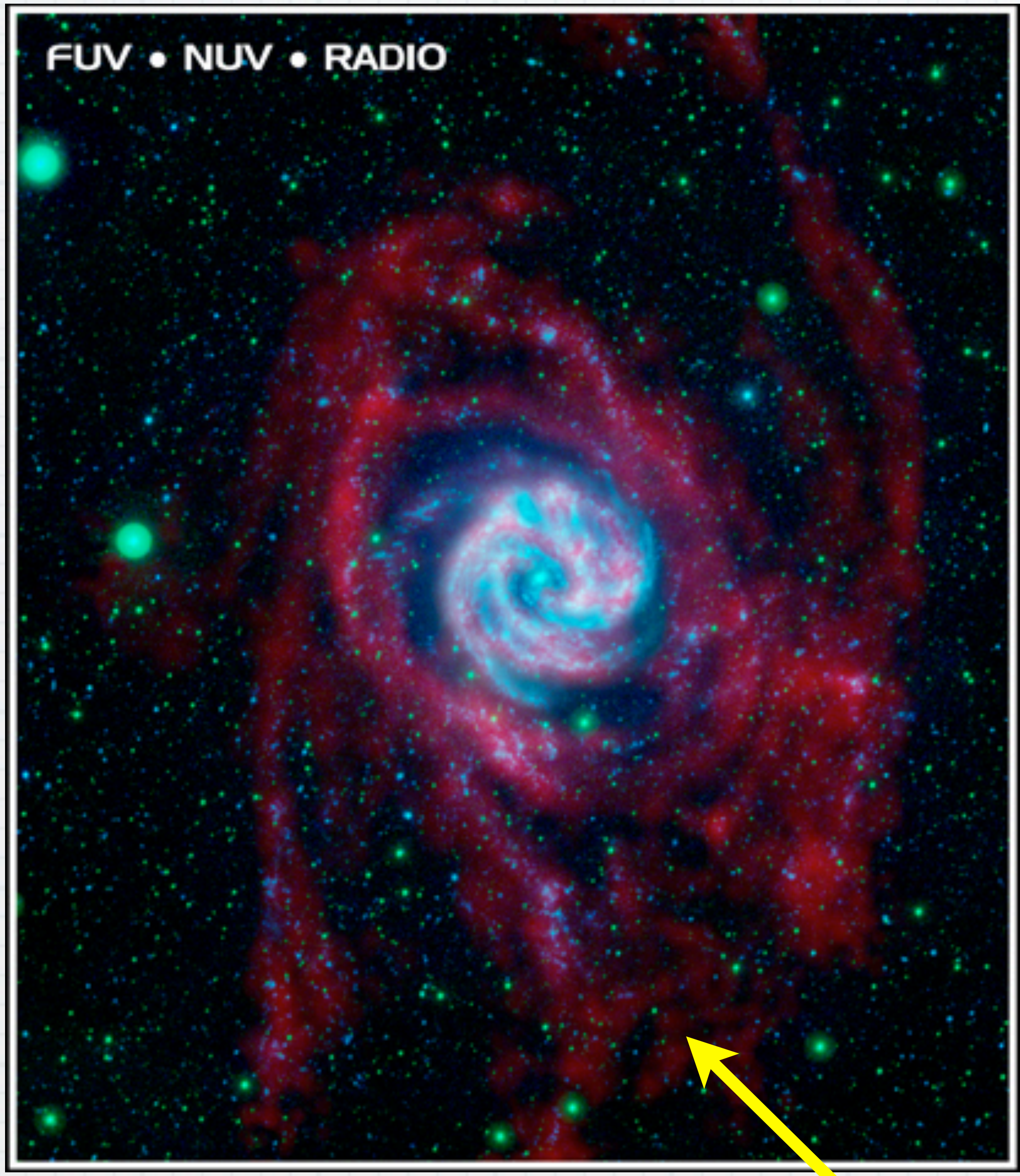
How big galaxies really are?

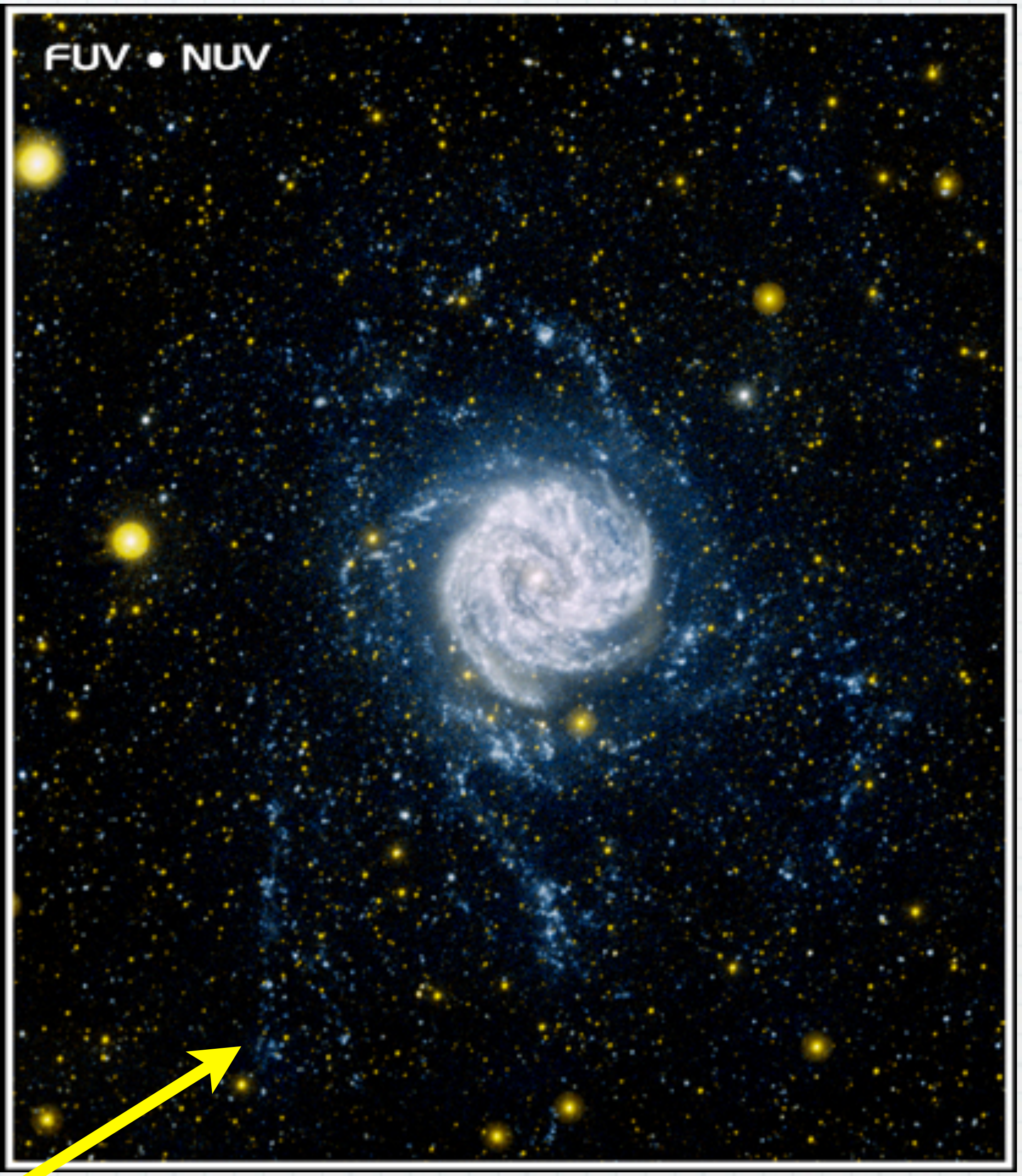
Messier 83

How big galaxies really are?

Messier 83

Far, Near UV & Radio **Far & Near UV**



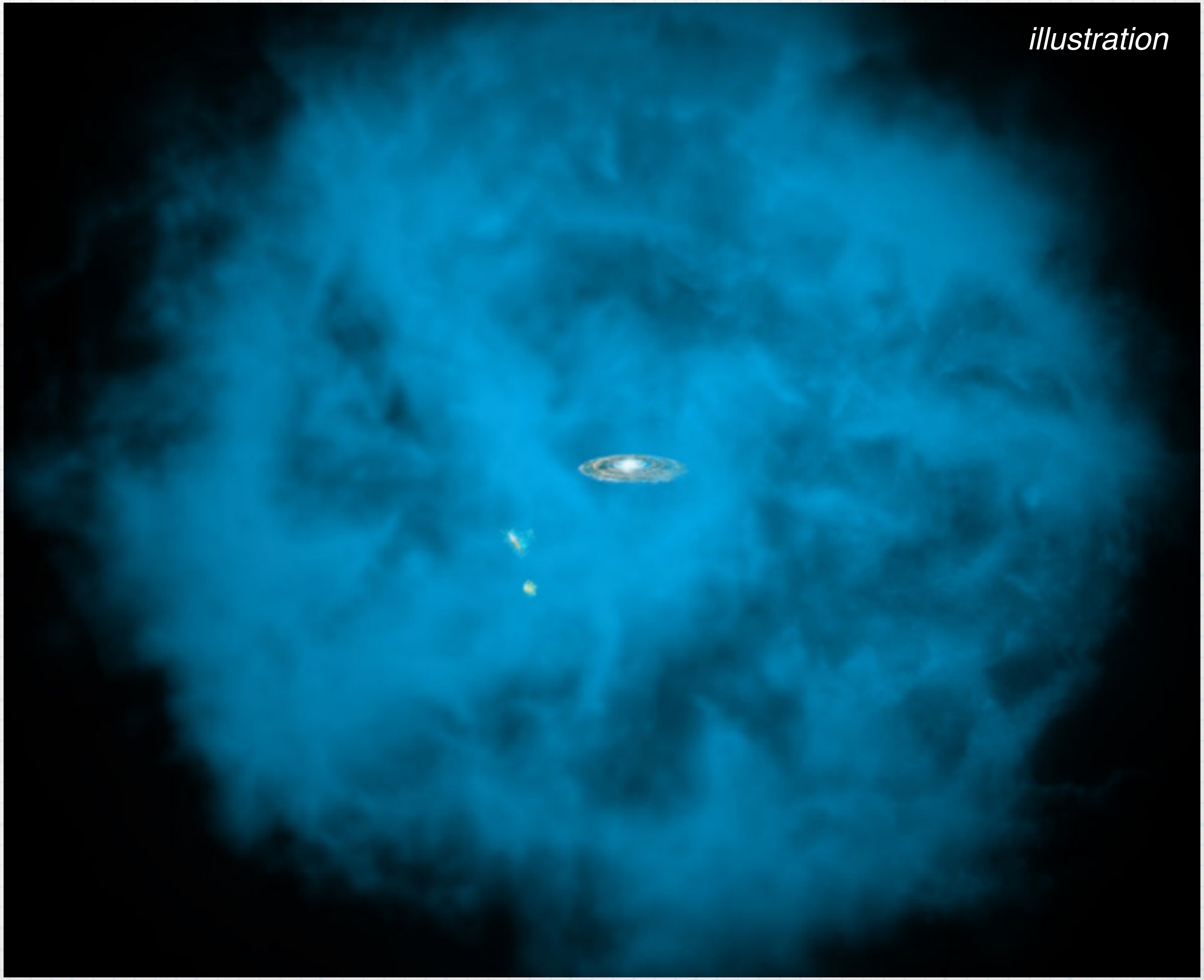


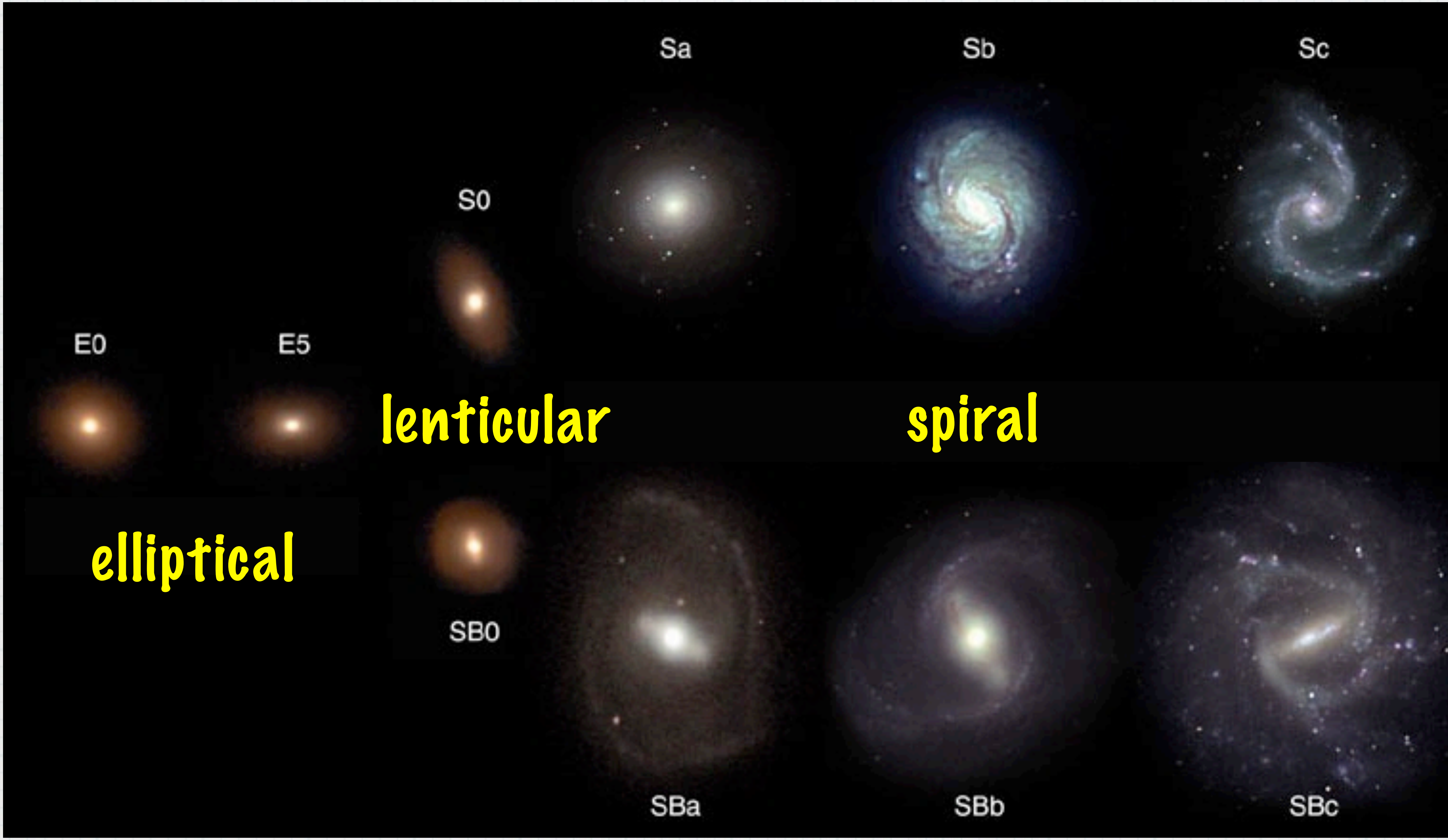
Extended disk

Half of Milky Way's mass found in million-Kelvin gas cloud

Posted in [Science](), [25th September 2012]()

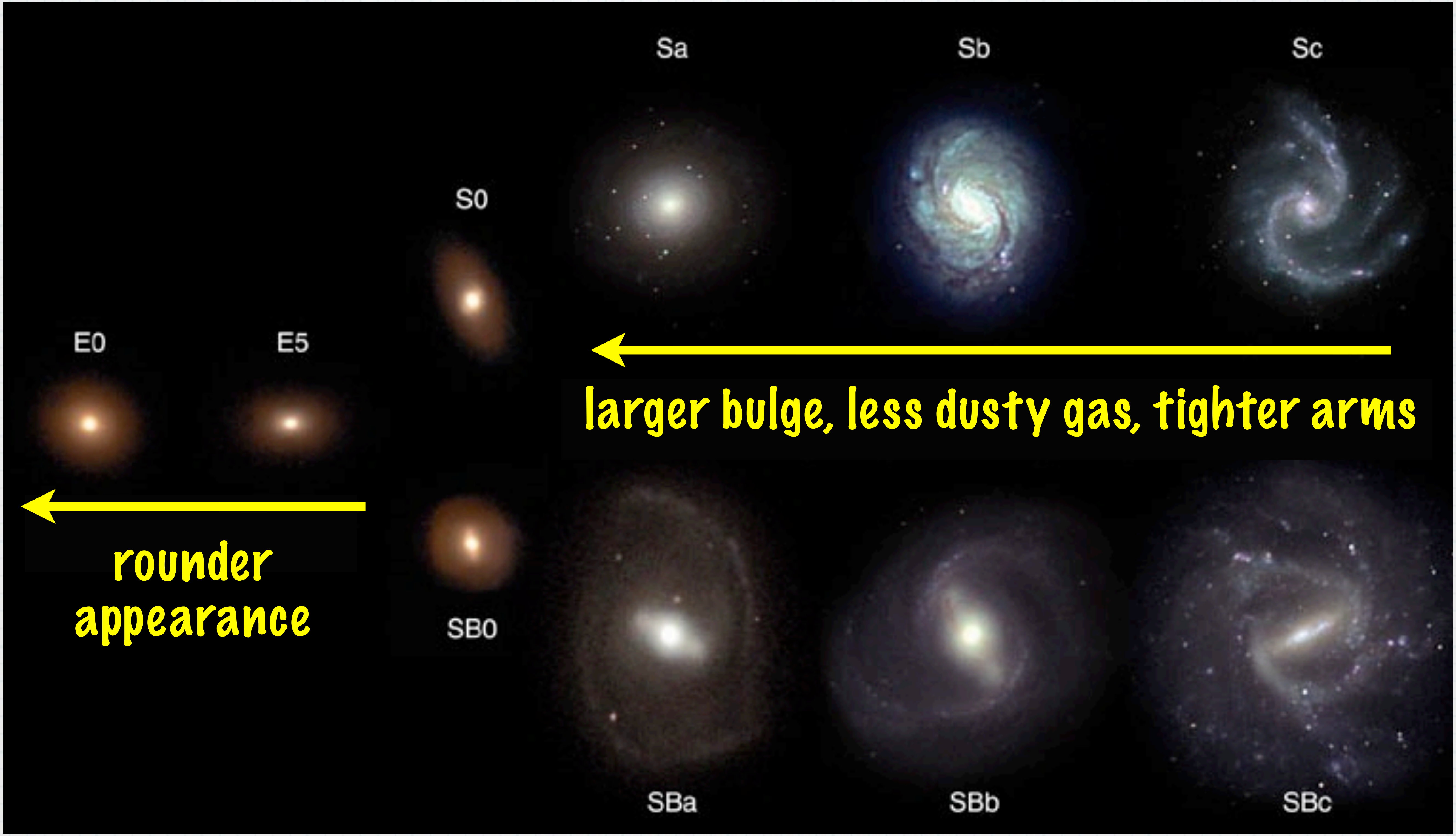
A massive, highly diffuse, hence undetected gas cloud, simmering away at somewhere between 1 million and 2.5 million °K and composed of protons and neutrons





Spheroid Dominates

Disk Dominates



Spheroid Dominates

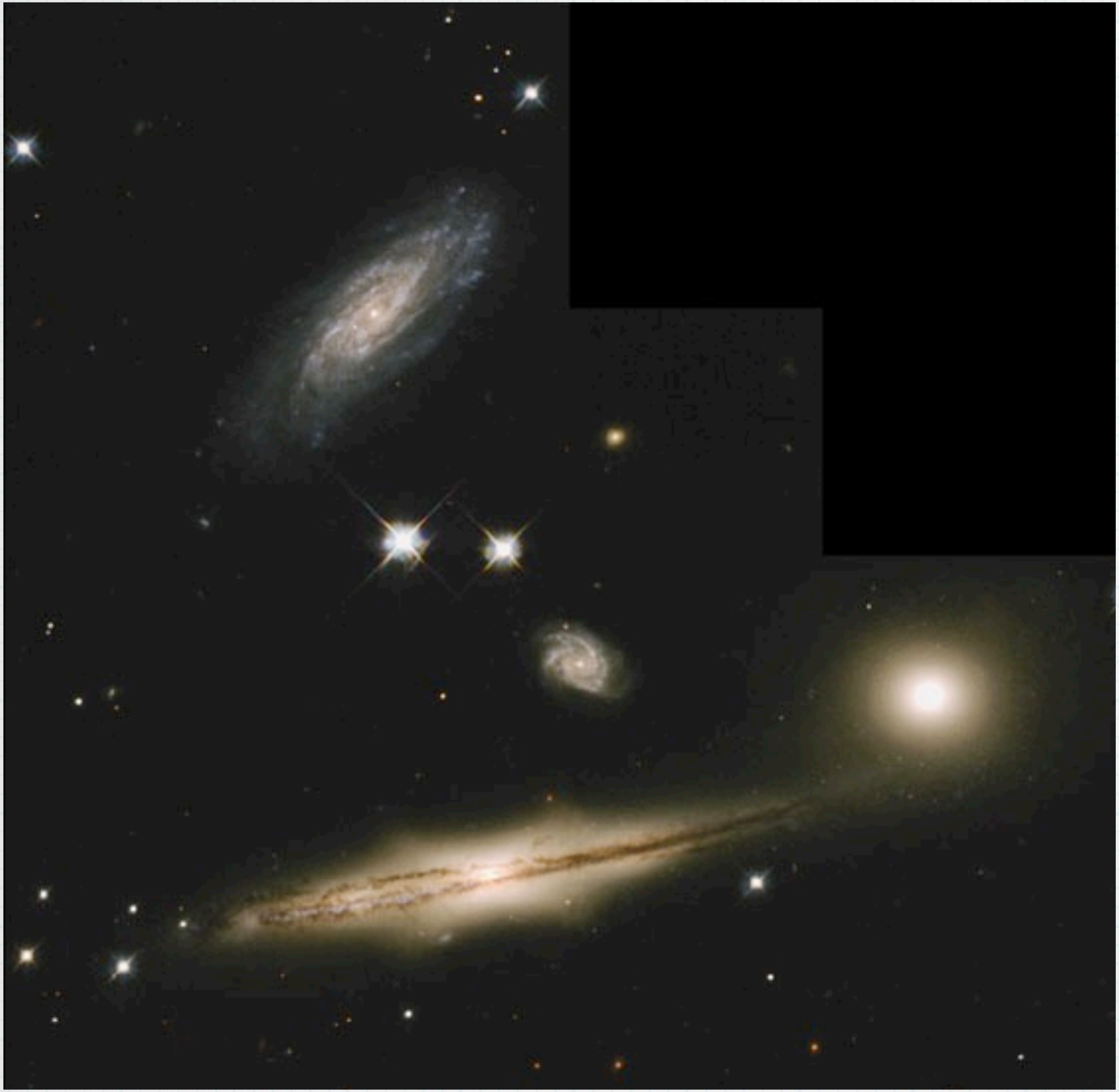
Disk Dominates

Hubble's classification

* It was hoped the galaxy classification would help understand them (like the stellar classification.) Maybe it was an evolutionary path?
* However, galaxies are far more complex than stars and this classification brought no light in understanding them

How are galaxies grouped together?

* **Groups:** loose collections of up to a few dozens of spiral galaxies
* **Clusters:** collections of hundreds or thousands of elliptical galaxies



Spiral galaxies are often found in groups of galaxies

(up to a few dozen galaxies)

Elliptical galaxies are much more common in huge clusters of galaxies

(hundreds to thousands of galaxies)

Snapshot

* What are the three major types of galaxies?

1. **Spiral** galaxies have prominent disks and spiral arms.

2. **Elliptical** galaxies are rounder and redder than spiral galaxies and contain less cool gas and dust.

3. **Irregular** galaxies are neither disk-like nor rounded in appearance.

Snapshot

* How are galaxies grouped together?
* Spiral galaxies tend to collect in groups of galaxies, which contain up to several dozen galaxies

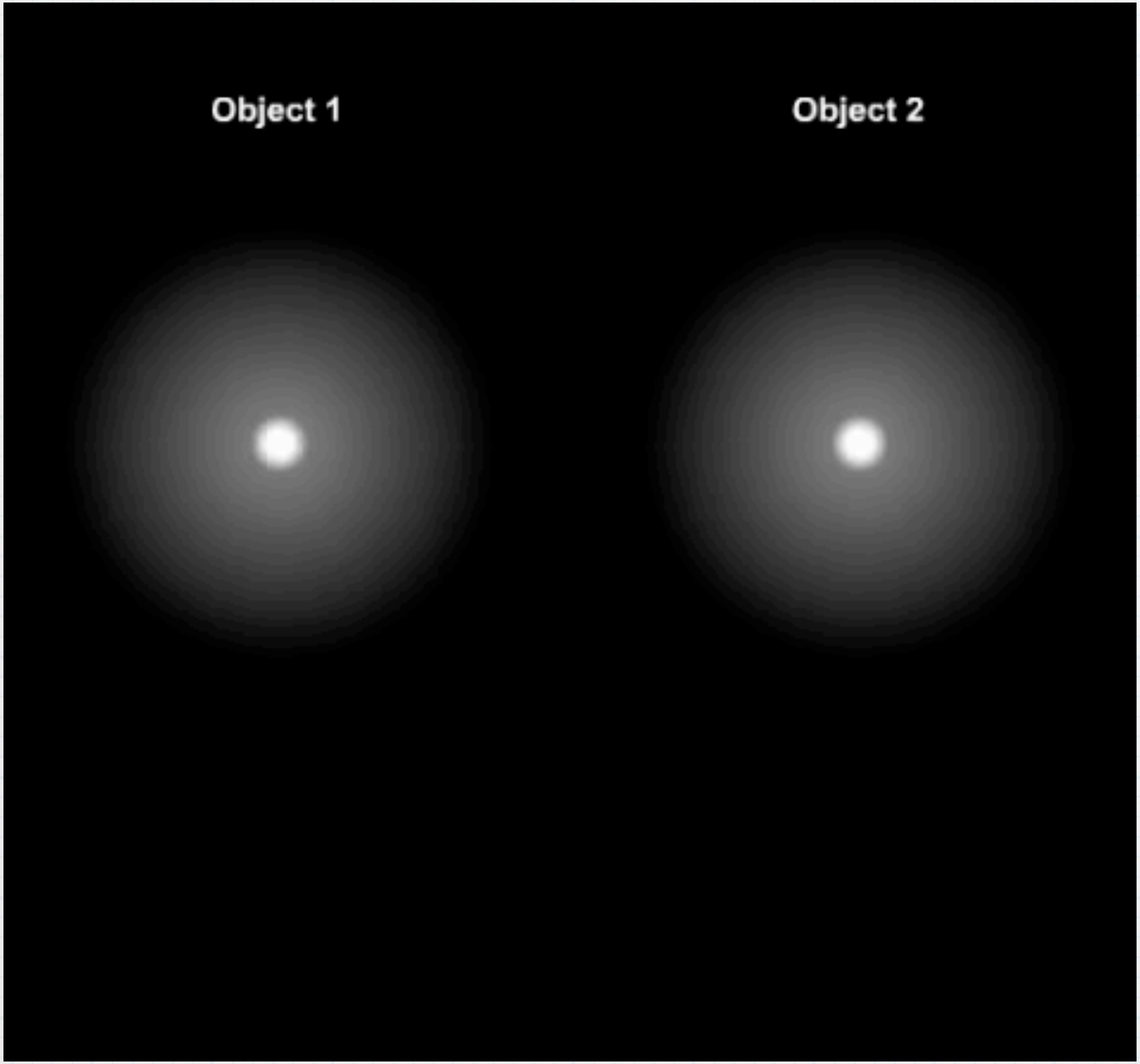
* Elliptical galaxies are more common in clusters of galaxies, which contain hundreds to thousands of galaxies, all bound together by gravity

Distances of Galaxies

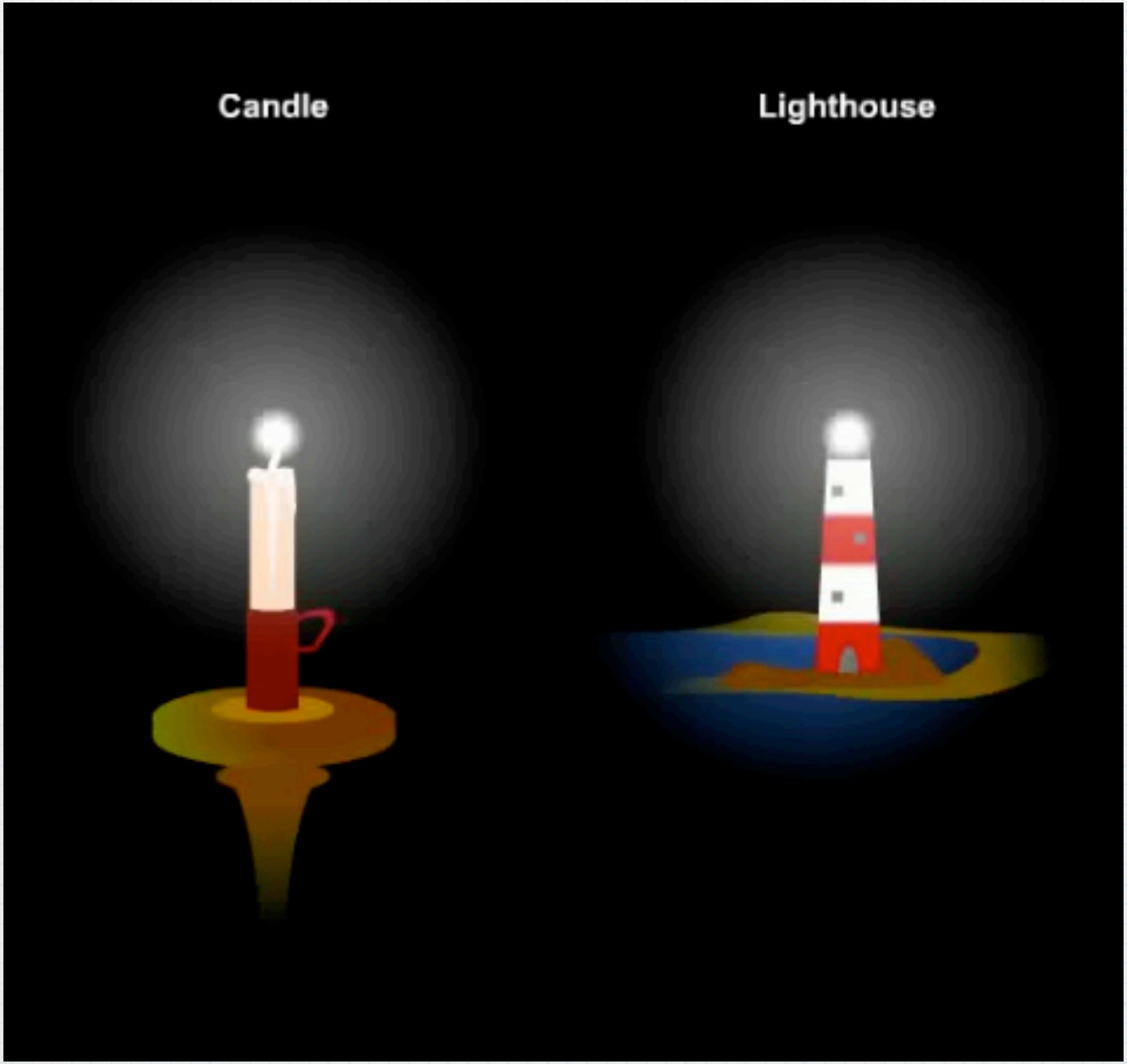
* This is one of the most challenging tasks
* We cannot hope to understand galaxies and the Universe they reside in without knowing how far they are
* Such measurements will also tell us the size and the age of our observable Universe

How do we measure the distances to galaxies?

* Astronomers use different methods to measure objects that are more and more distant
* Like a chain, each method is calibrated on the preceding one



Brightness alone does not provide enough information to measure distance



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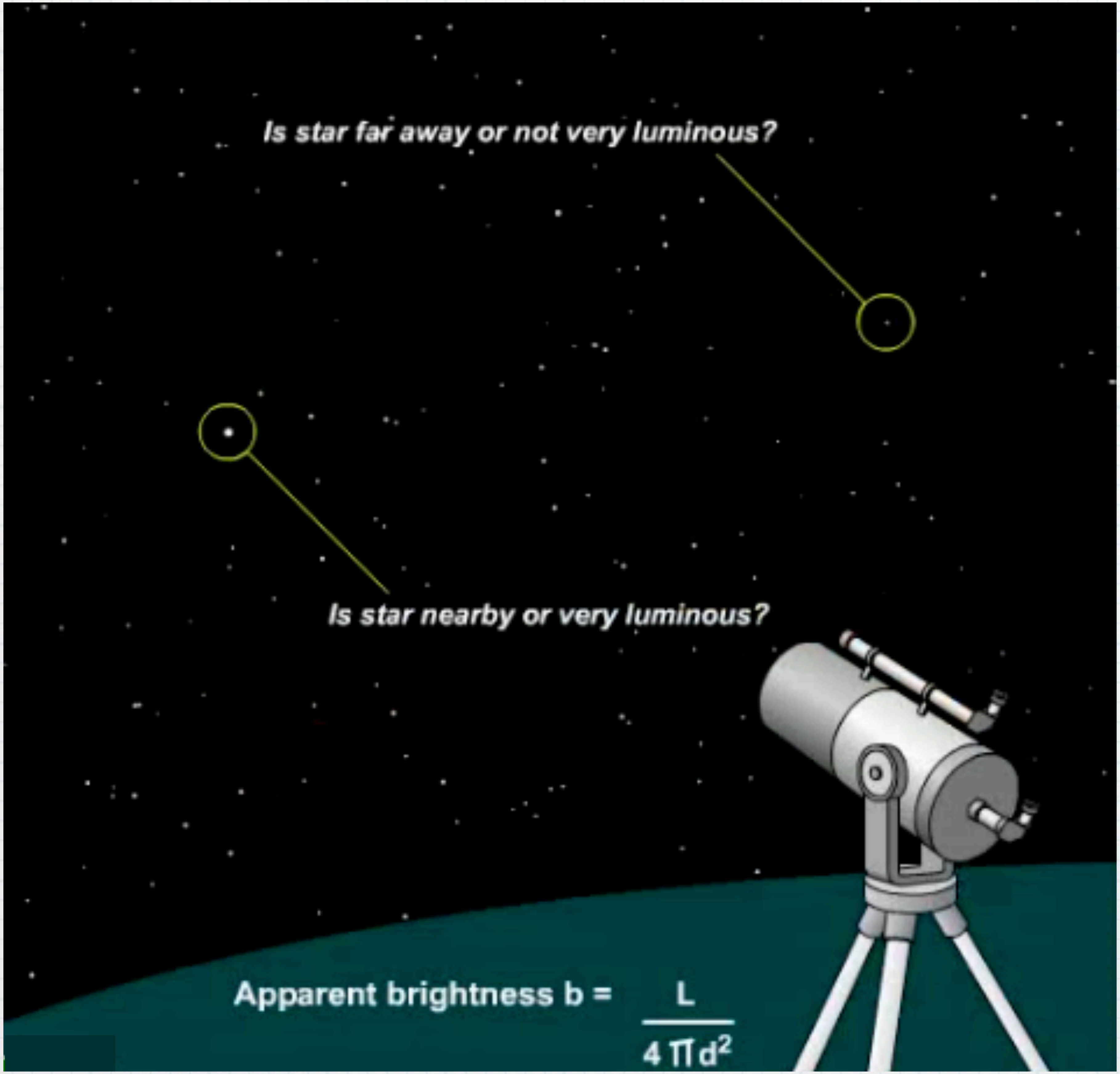
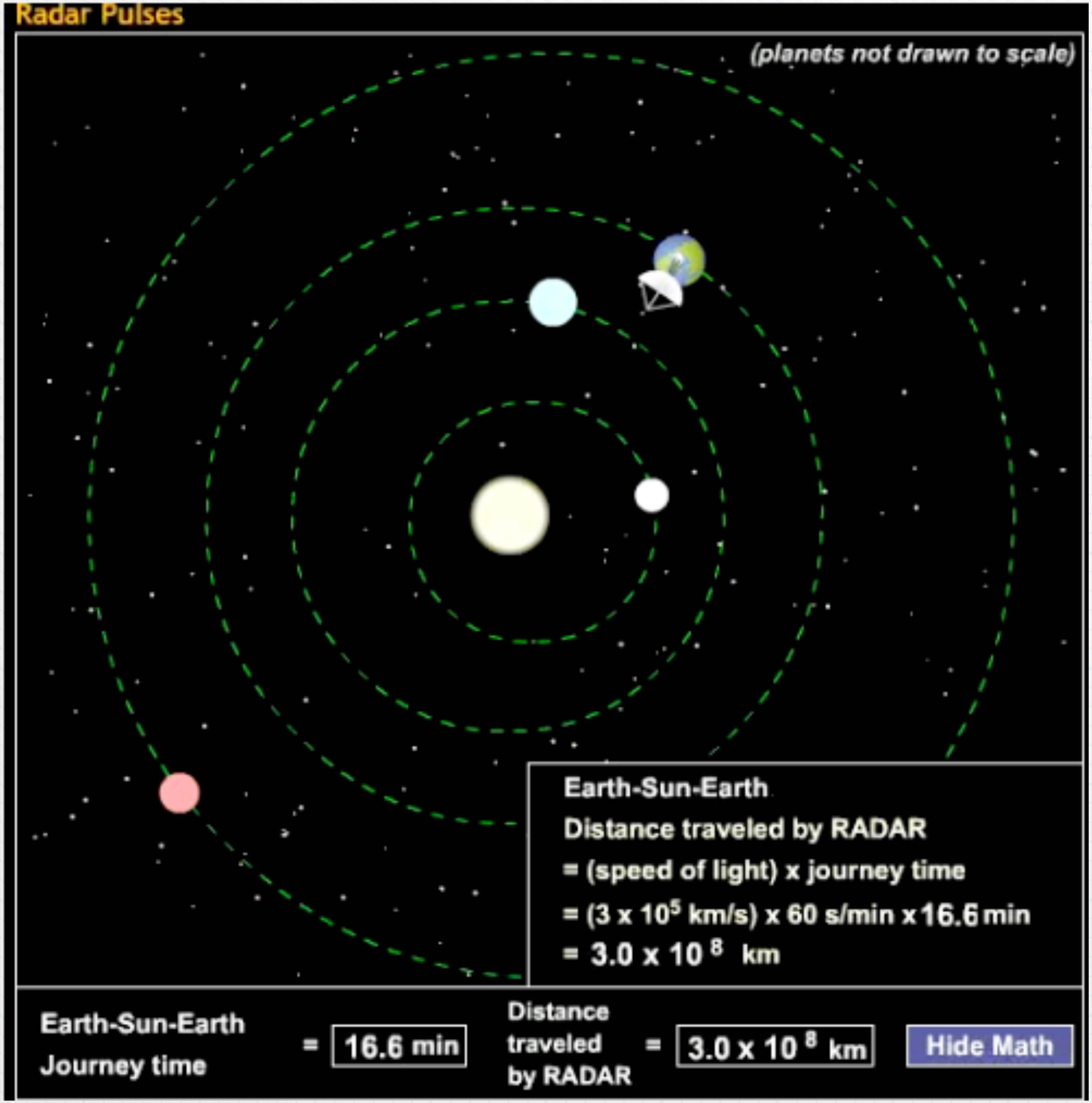
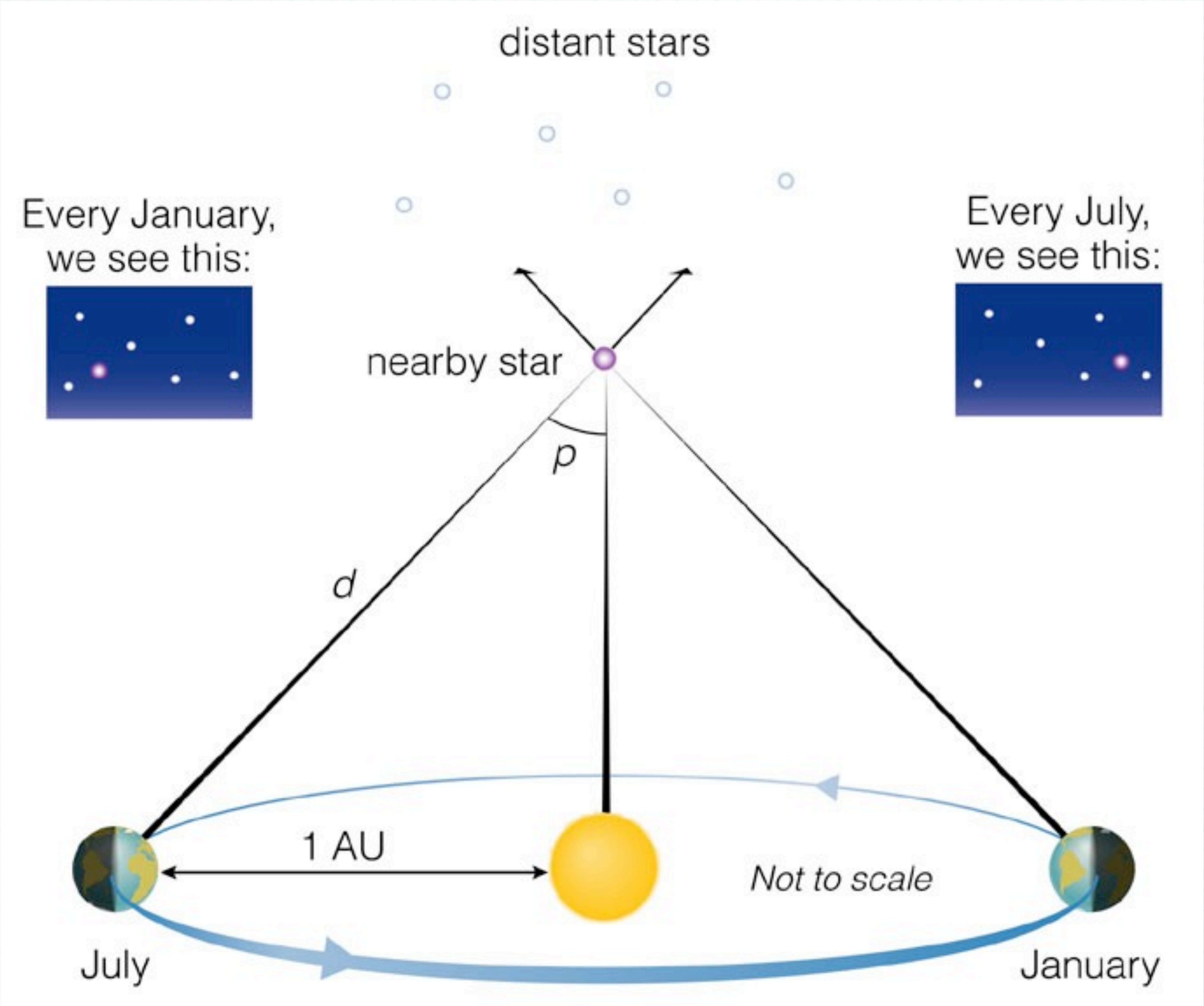


Brightness alone does not provide enough information to measure distance

Step 1

Determine size of solar system using radar





Step 2

Determine distances of stars out to a few hundred light-years using parallax

Standard Candles

* A standard candle is an object whose luminosity we can determine without measuring its distance
* Stars whose properties are well understood and are predictable can be used as "standard candles"

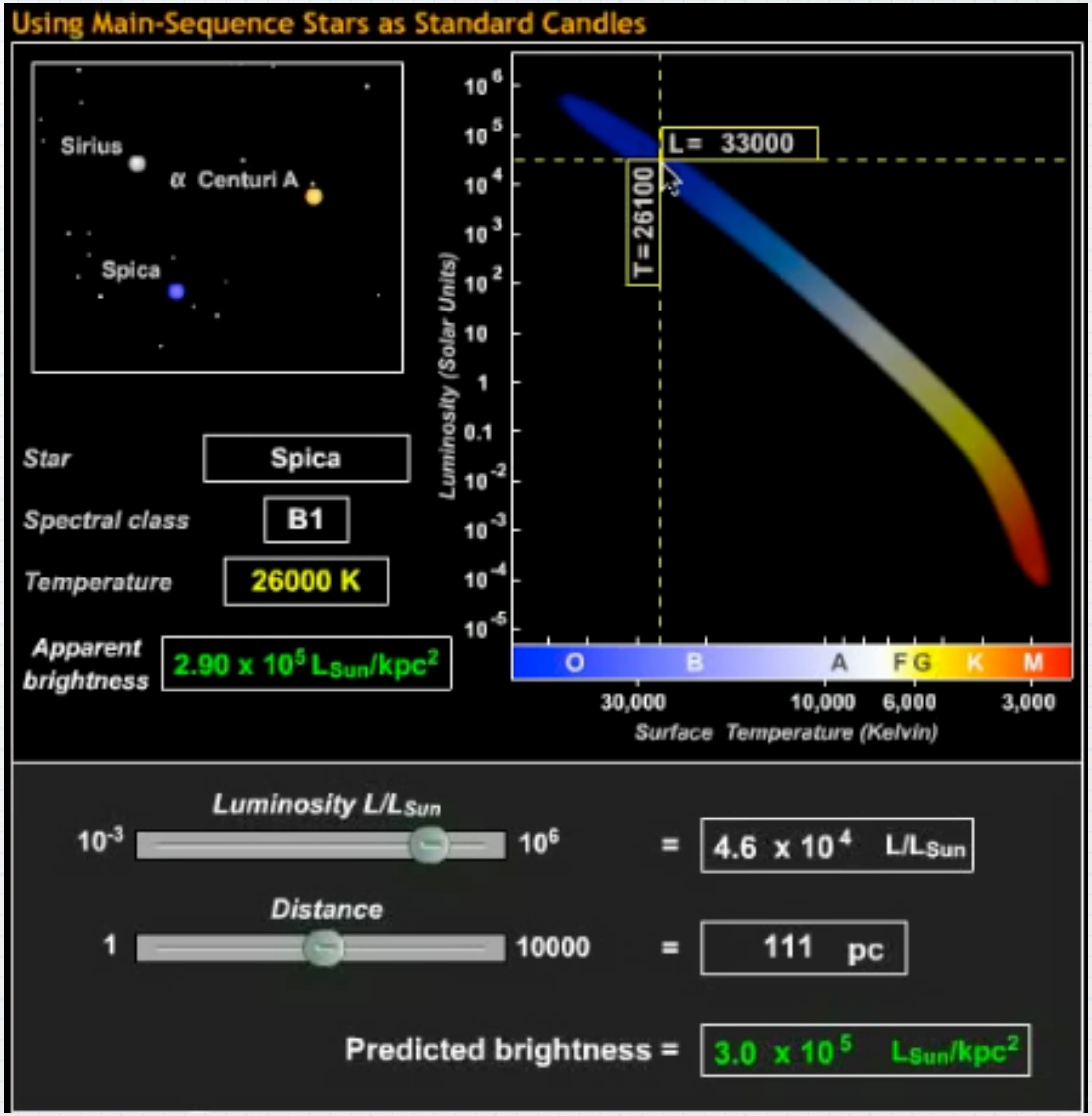
Using main-sequence stars as standard candles

1) find star's surface temperature

2) from H-R diagram, find its Luminosity

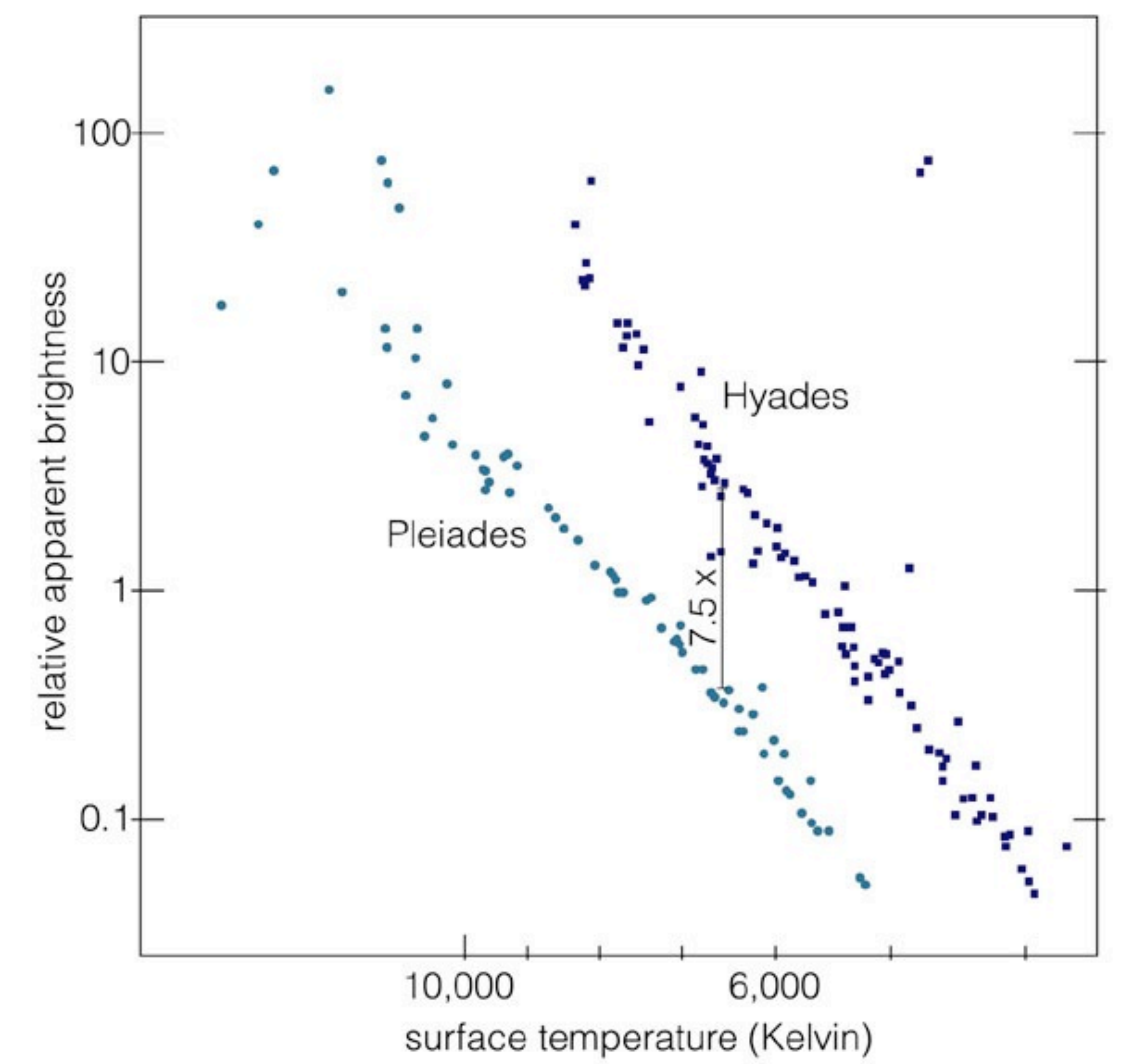
3) set Luminosity

4) get distance from measuring its brightness



Main-sequence fitting

Step 3



Apparent brightness of star cluster's main sequence tells us its distance (Pleiades are 2.75 farther than Hyades)

Knowing a star cluster's distance, we can determine the luminosity of each type of star within it

M45

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Question

Which kind of stars are best for measuring large distances?

A. High-luminosity stars

B. Low-luminosity stars

Question

Which kind of stars are best for measuring large distances?

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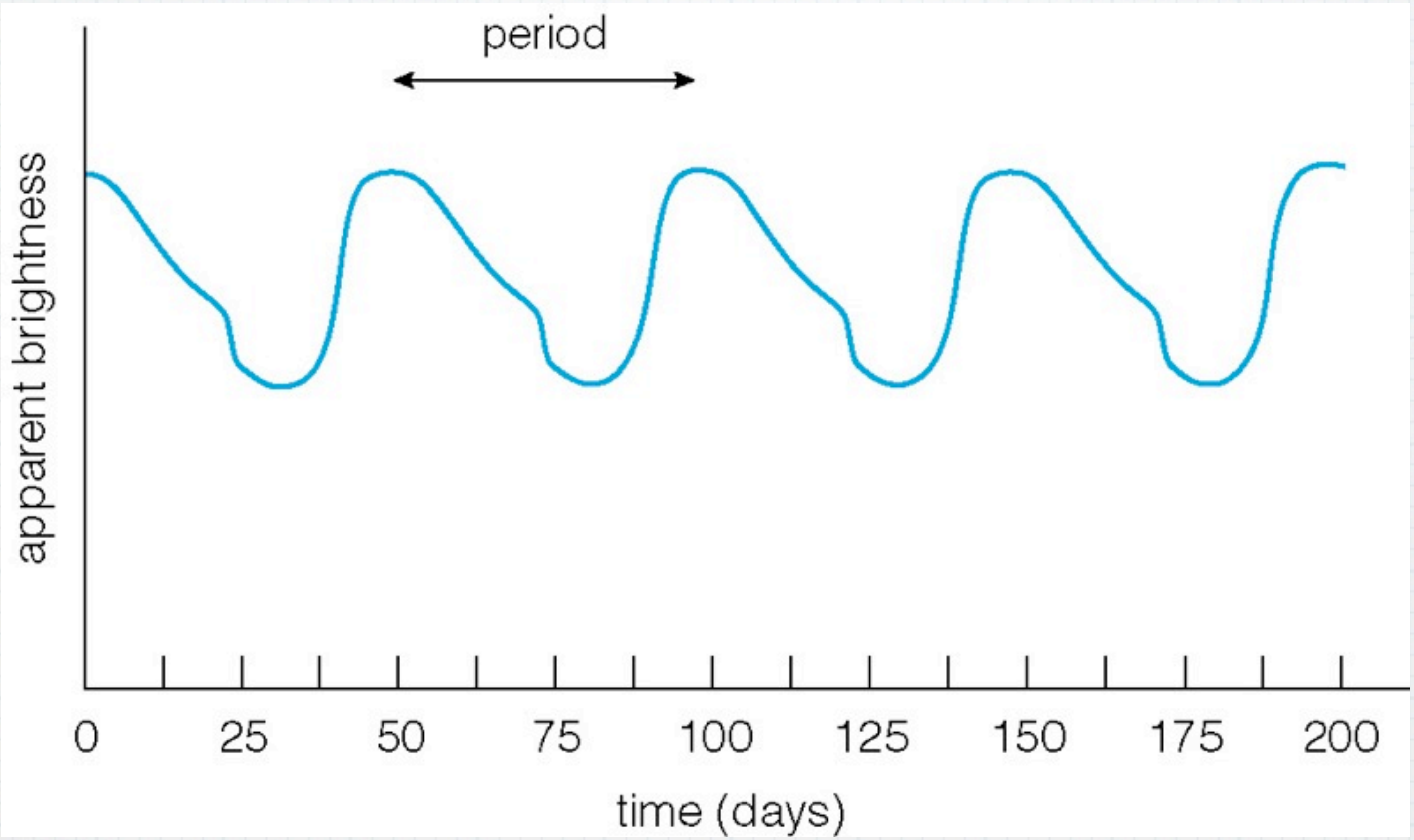
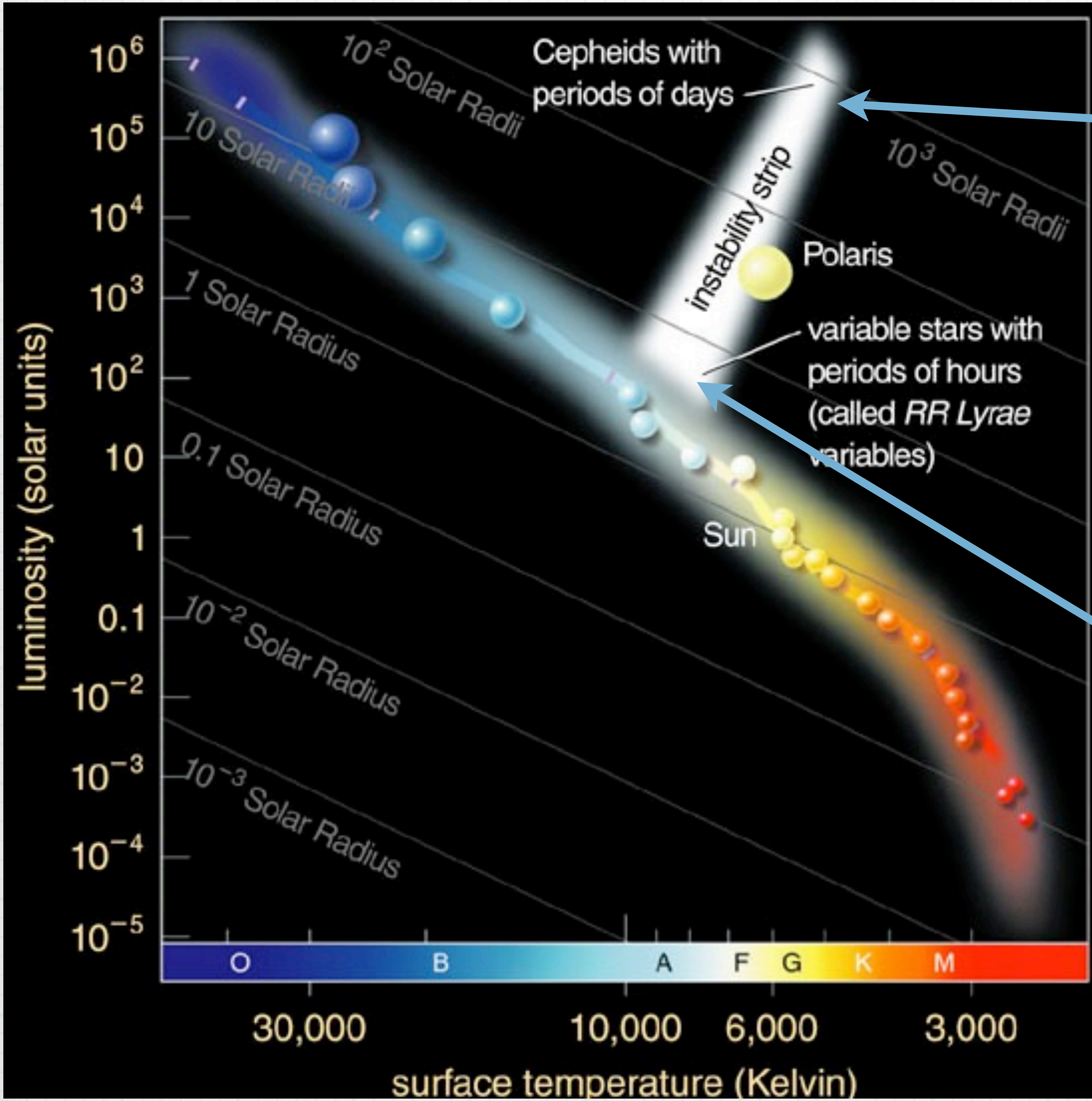
B. Low-luminosity stars

Cepheid Variable Stars

* **Cepheid variable** stars vary in brightness with periods ranging from a few hours to a few months
* Their periods are very closely related to their true luminosity!
* The longer the period, the more luminous the star is

How a Cepheid's brightness varies with time (50 days here)

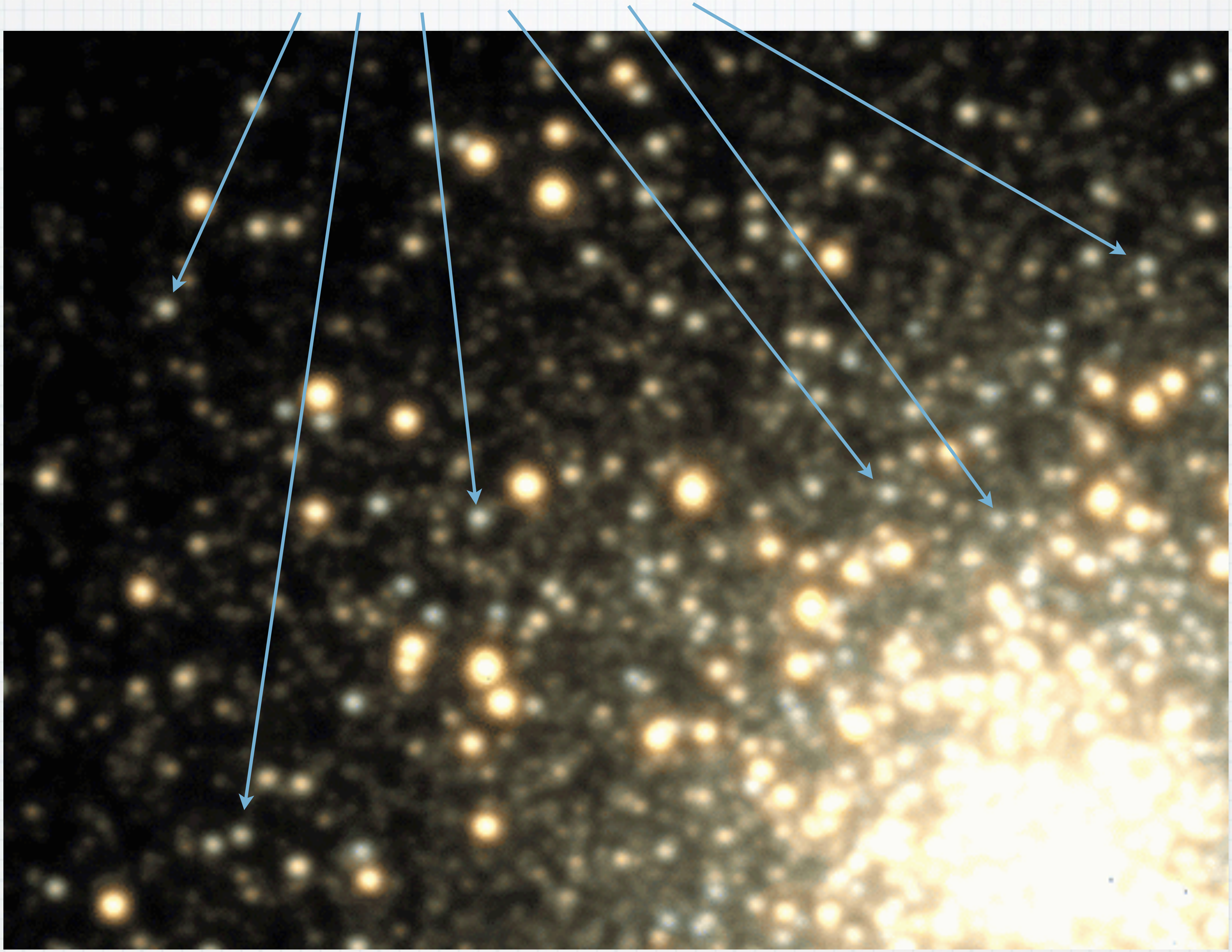




These Cepheid variable stars are very luminous

RR Lyrae have a very short period (lower luminosity)

RR Lyrae - Cepheids with a period of a few hours



M3 - oldest and brightest globular cluster orbiting our Milky Way

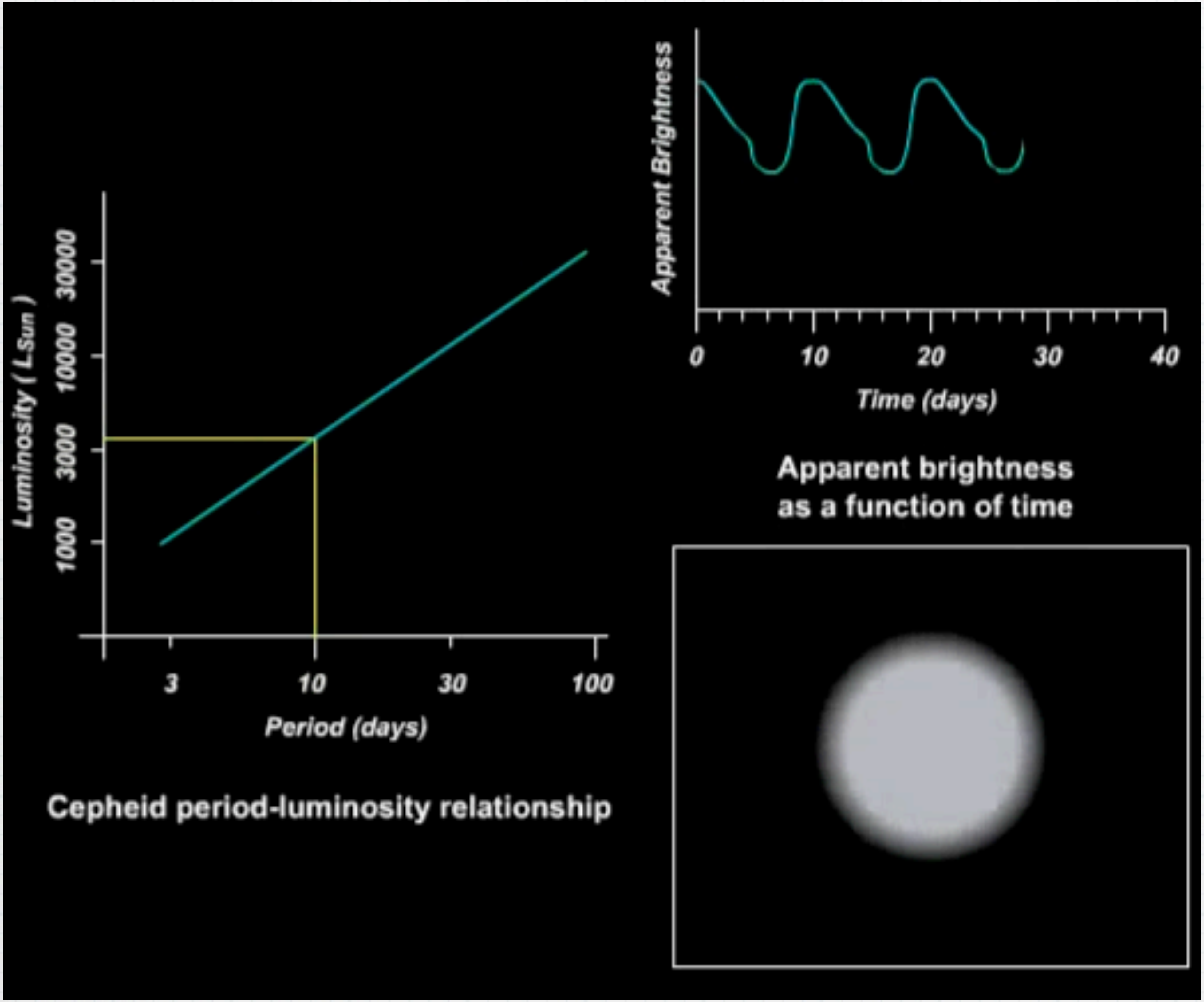
Cepheid Variable Stars...

* The variability arises from a non-steady equilibrium between the amount of energy generated by the fusion shell surrounding the core and the amount of energy radiated by the star's surface

➡ **Their surface expands and contracts causing the star's luminosity to rise and fall**

Cepheid Variable Stars...

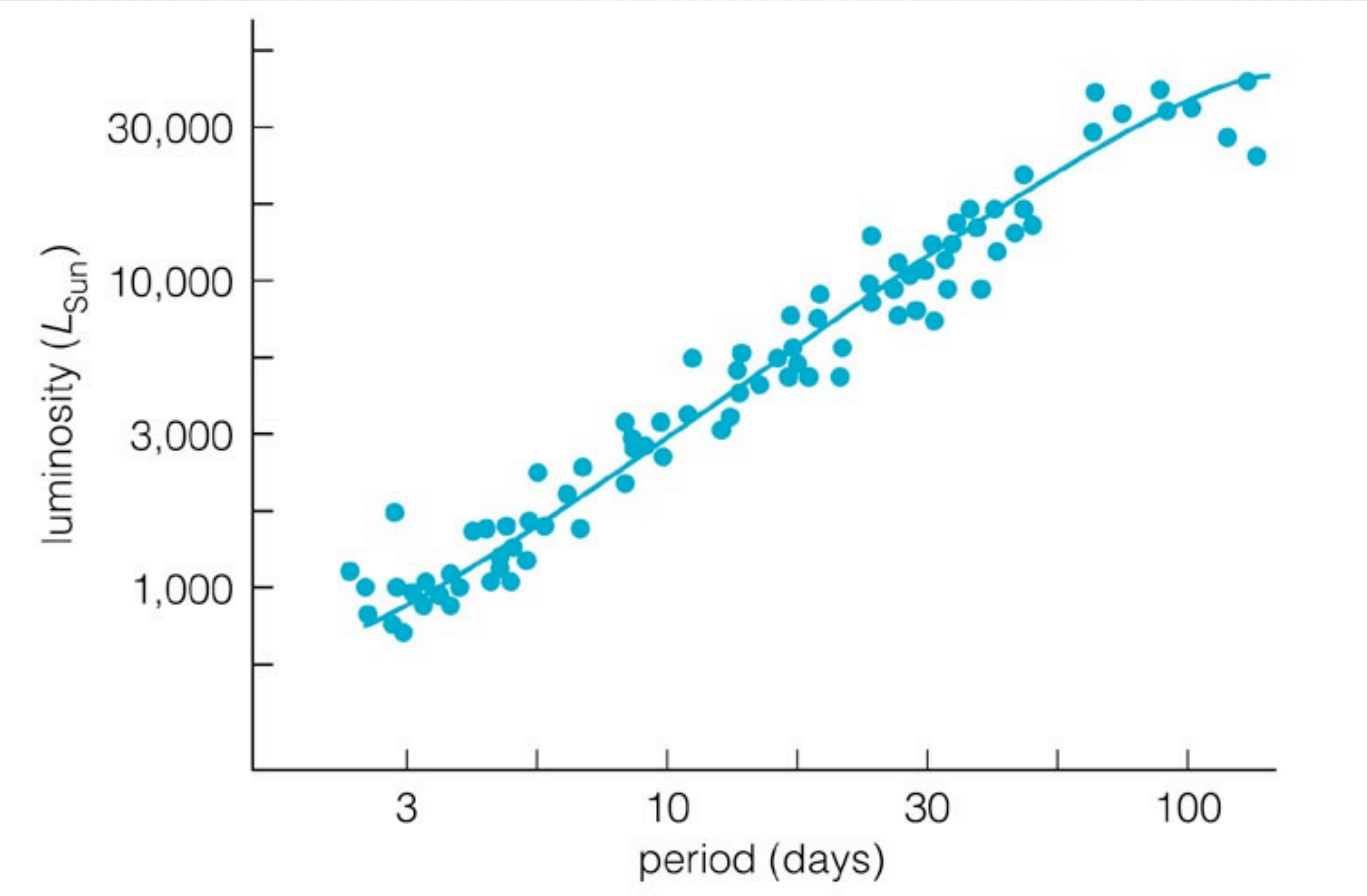
* Cepheids are useful for measuring distances because we can determine a Cepheid's luminosity from the period between peaks of brightness

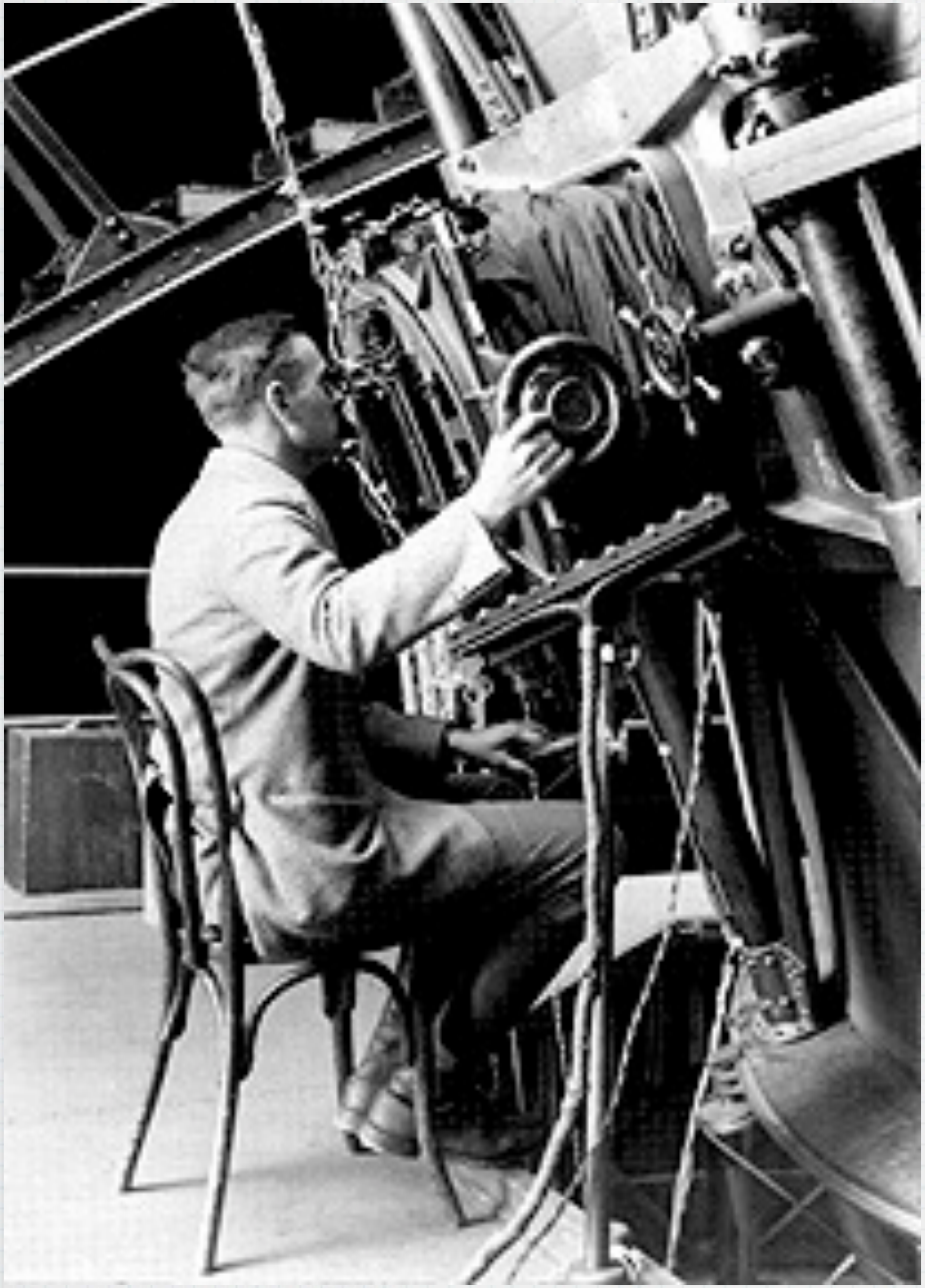


Step 4

Because the period of a Cepheid variable star tells us its luminosity, we can use these stars as standard candles

Cepheid variable stars with longer periods have greater luminosities





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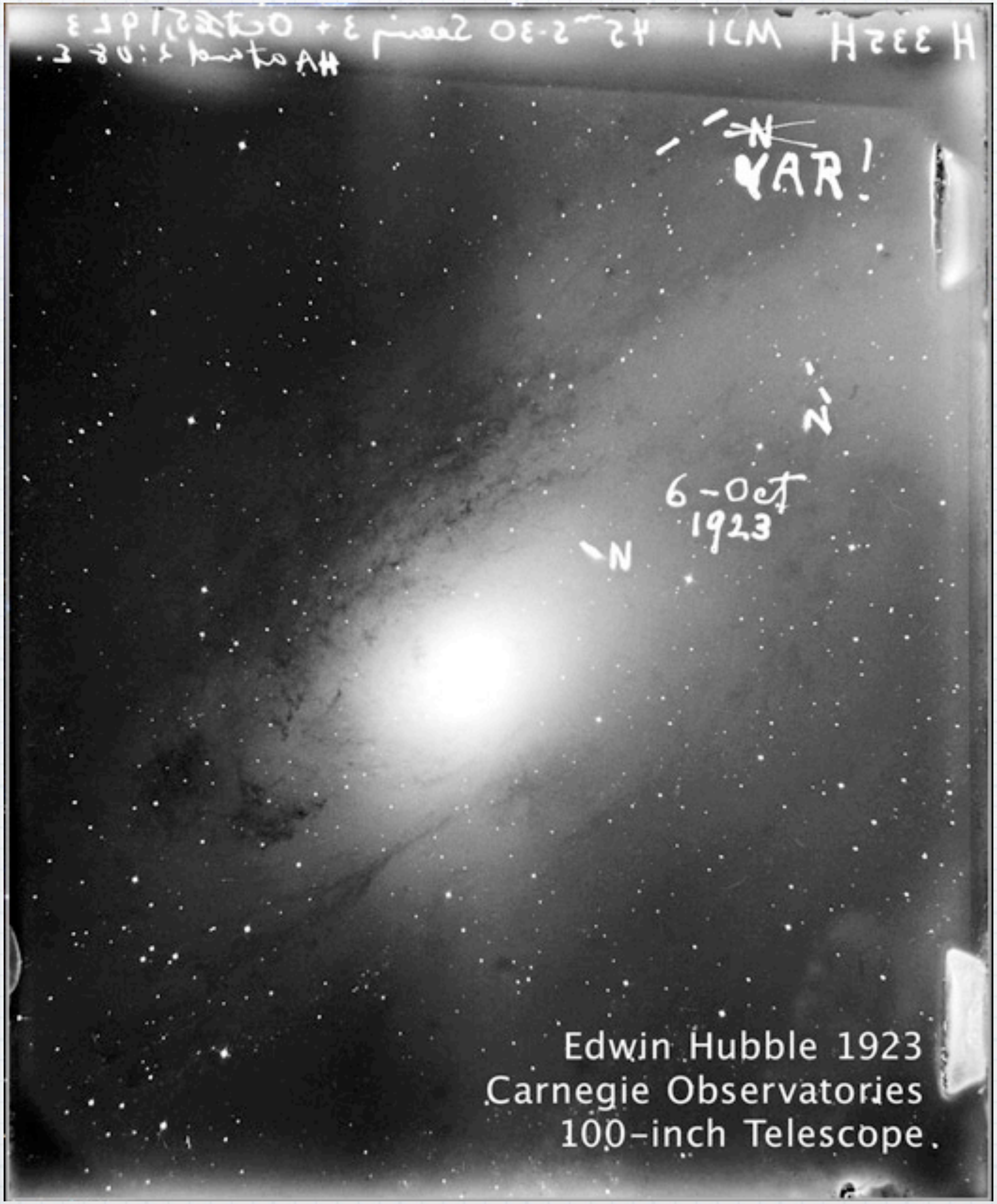
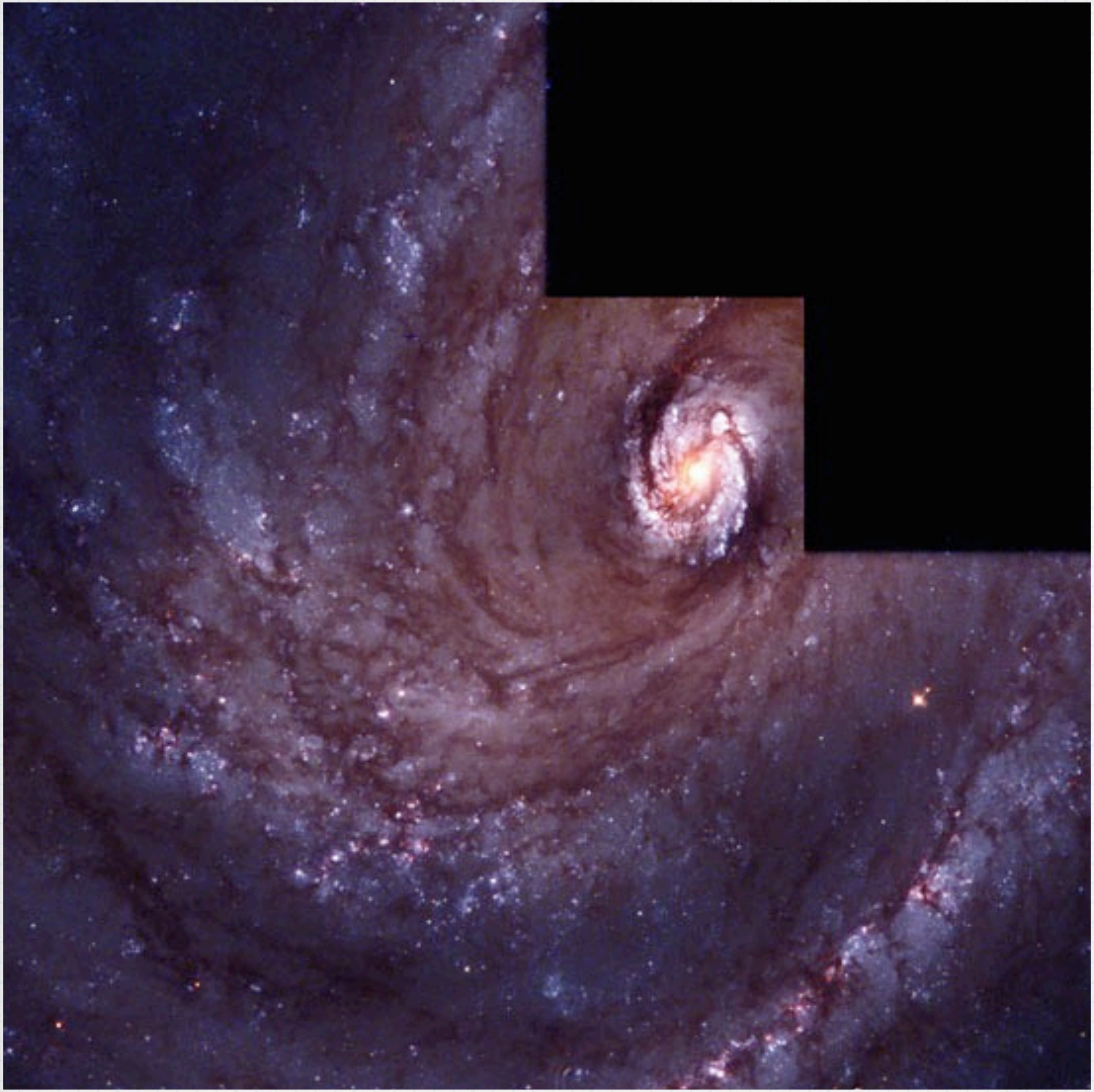
Edwin Hubble, using Cepheids as standard candles, was the first to measure distances to other galaxies

Hubble discovers a Cepheid in Andromeda

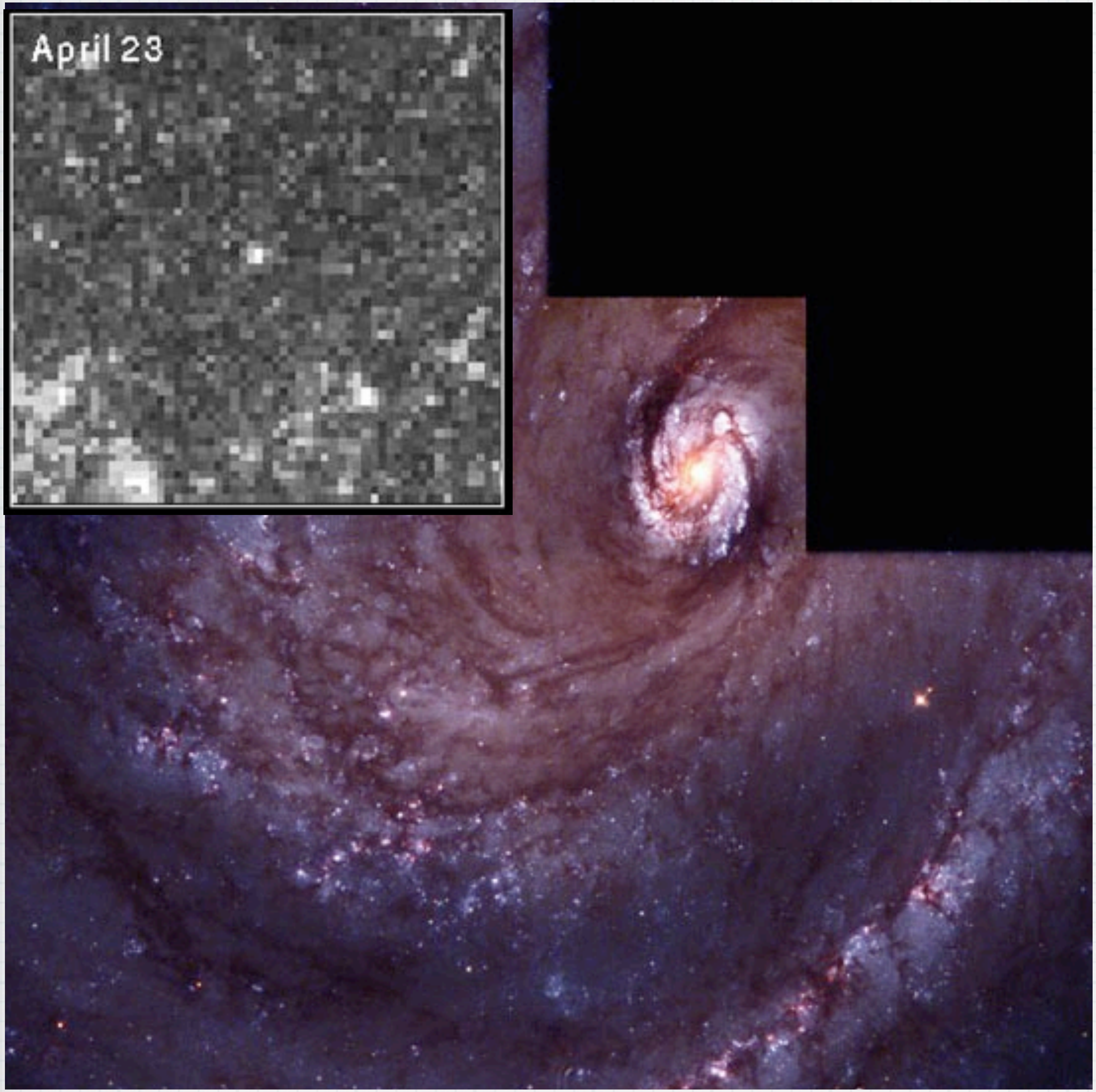


Measuring distances using Cepheids has been a key mission of the Hubble Space Telescope



Galaxy M100

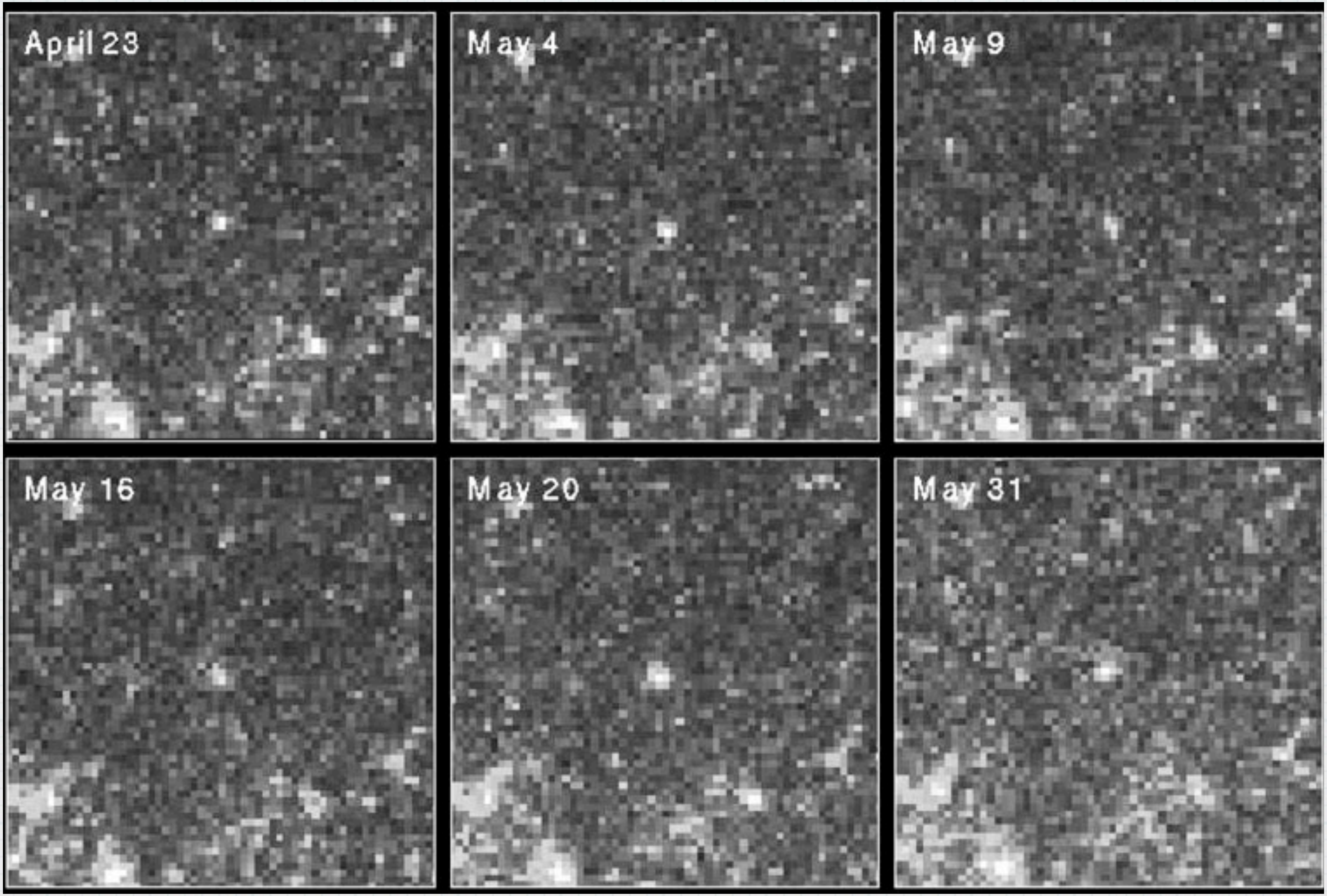
Hubble's extra-sharp vision allows us to observe individual Cepheid variable stars in galaxies up to 100 million light-years away

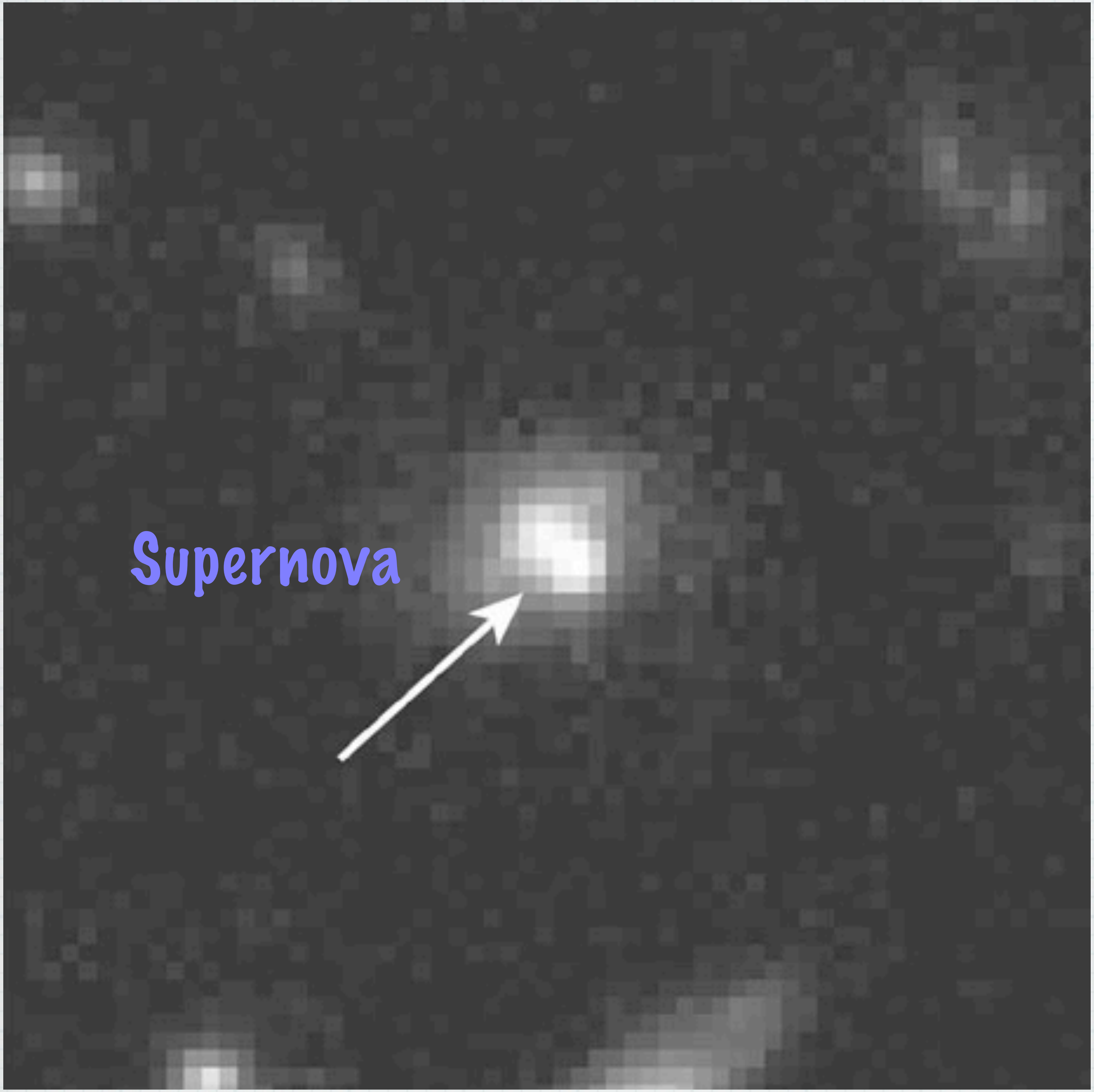


Hubble's extra-sharp vision allows us to observe individual Cepheid variable stars in galaxies up to 100 million light-years away

Galaxy M100

Cepheid variable star in M100 with period ≈ one month

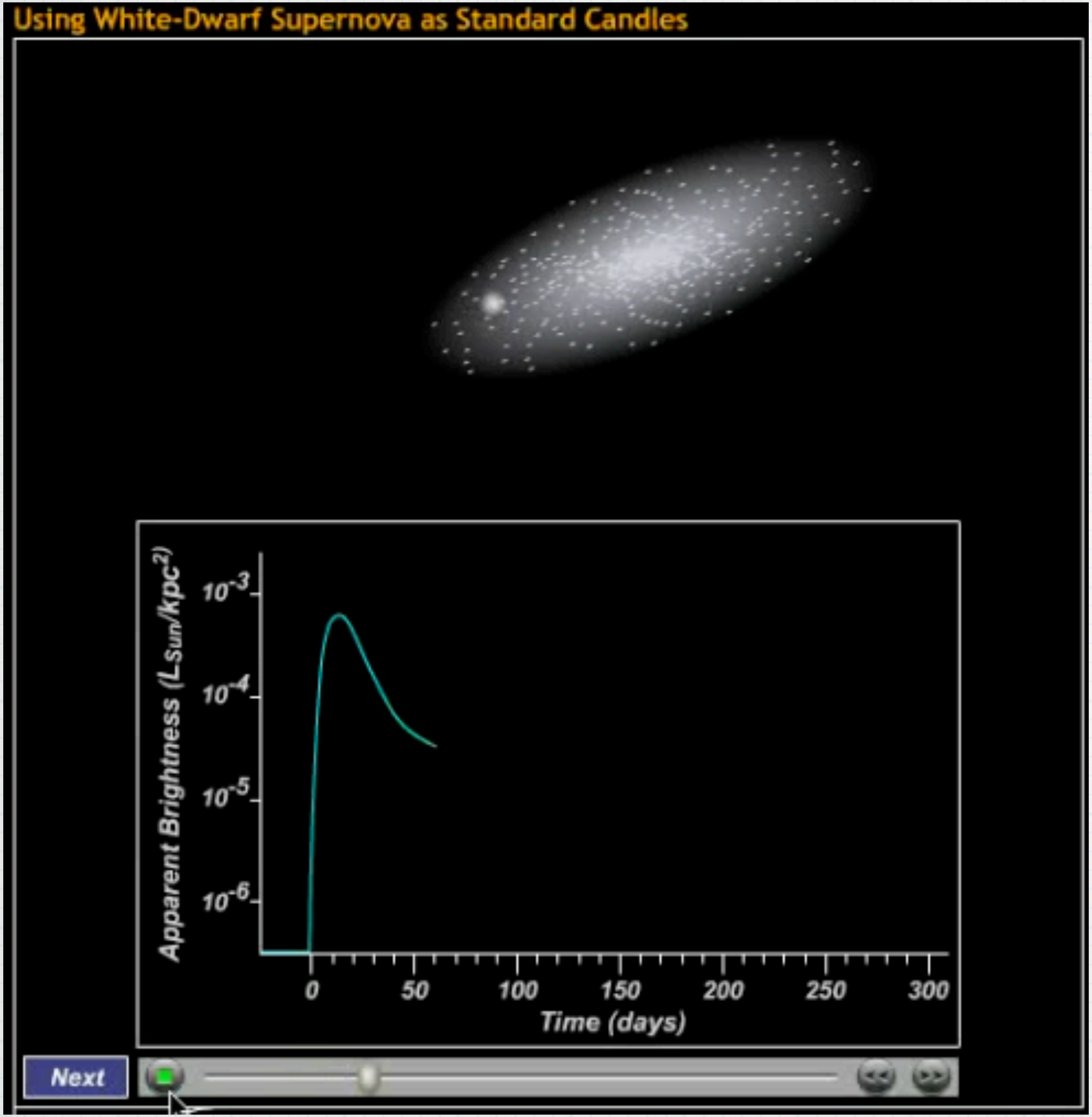




Step 5

Apparent brightness of white-dwarf supernova tells us the distance to its galaxy

(up to 10 billion light-years)



White-dwarf supernovae can also be used as standard candles

George Lemaître

(July 17, 1894 - June 20, 1966)

* Analyzed Einstein General Theory of Relativity and came up with a new theoretical solution (which Einstein did not like)
* The equations showed that the Universe could expand. If if it did, then there was a beginning. And in the beginning, the entire Universe fit in the size of an atom

George Lemaître
Father of the Big Bang

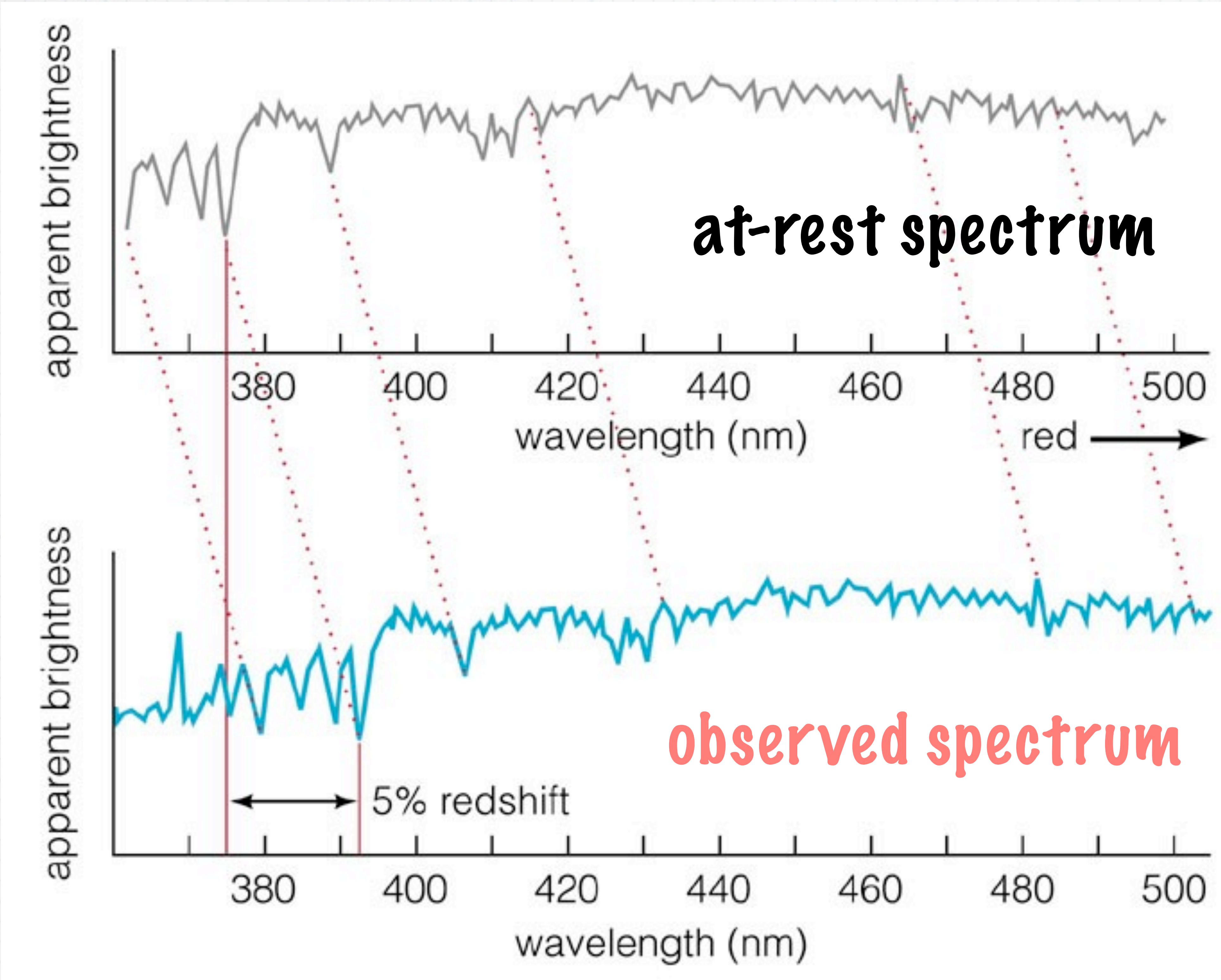
* Lemaître decided that the Universe was expanding. He came to this conclusion after observing the redshift surrounding objects outside of our galaxy
* He published his results in an obscure Belgian scientific journal which was not noticed. But Hubble's paper was

Hubble's Law

* By measuring the redshift of faraway galaxies, Edwin Hubble was able to make some bold statements, soon after Lemaître published his results

1. The Universe is expanding, it has no center nor any edges
2. The Universe has a beginning in time
3. The Universe has a spacetime geometry which will dictate its future

* Let's see how



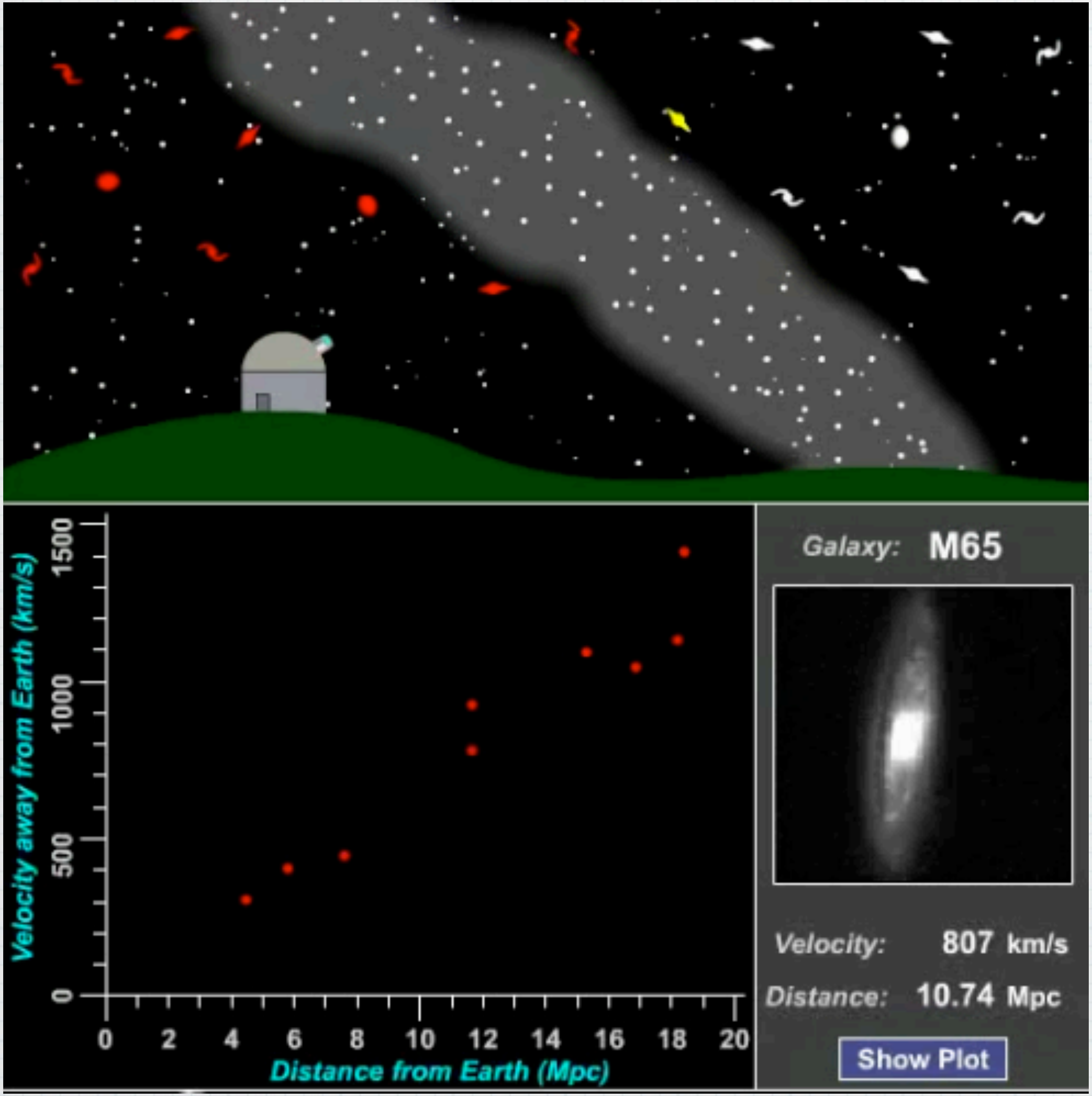
Hubble observed this:

The spectral features of virtually all galaxies are redshifted

⇒ They're all moving away from us

Galactic Distances

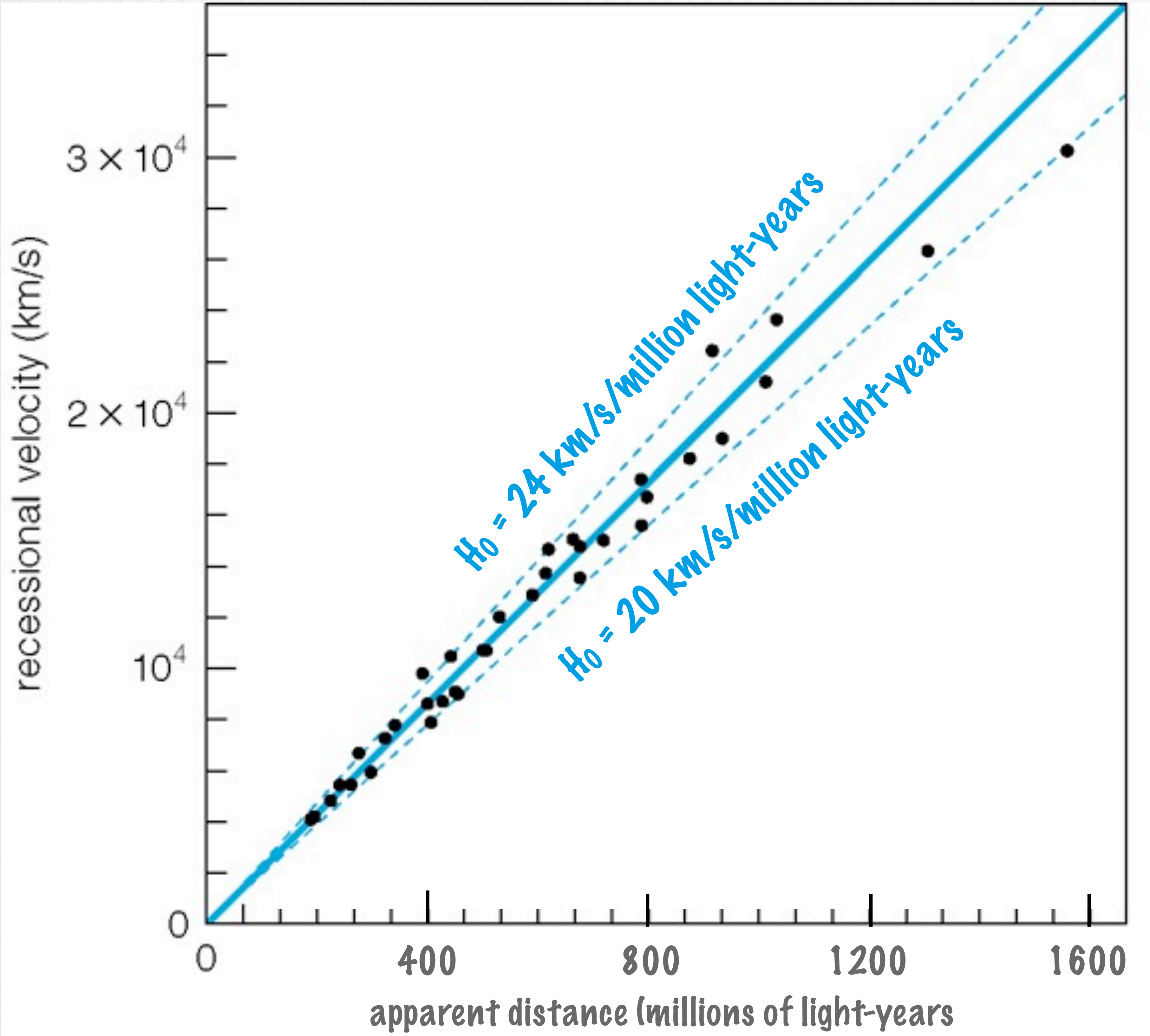
* Hubble assumed that the brightest object he could see in each galaxy had the same intrinsic luminosity
* He then calculated our distance (a best guess) to each of those galaxies
* Comparing all the spectrums, he noticed that their redshifts (giving their radial velocities) were linked to these estimated distances!



By measuring distances to galaxies, Hubble found that redshift and distance are related in a special way:

The more distant the galaxy, the fastest it is moving away from us

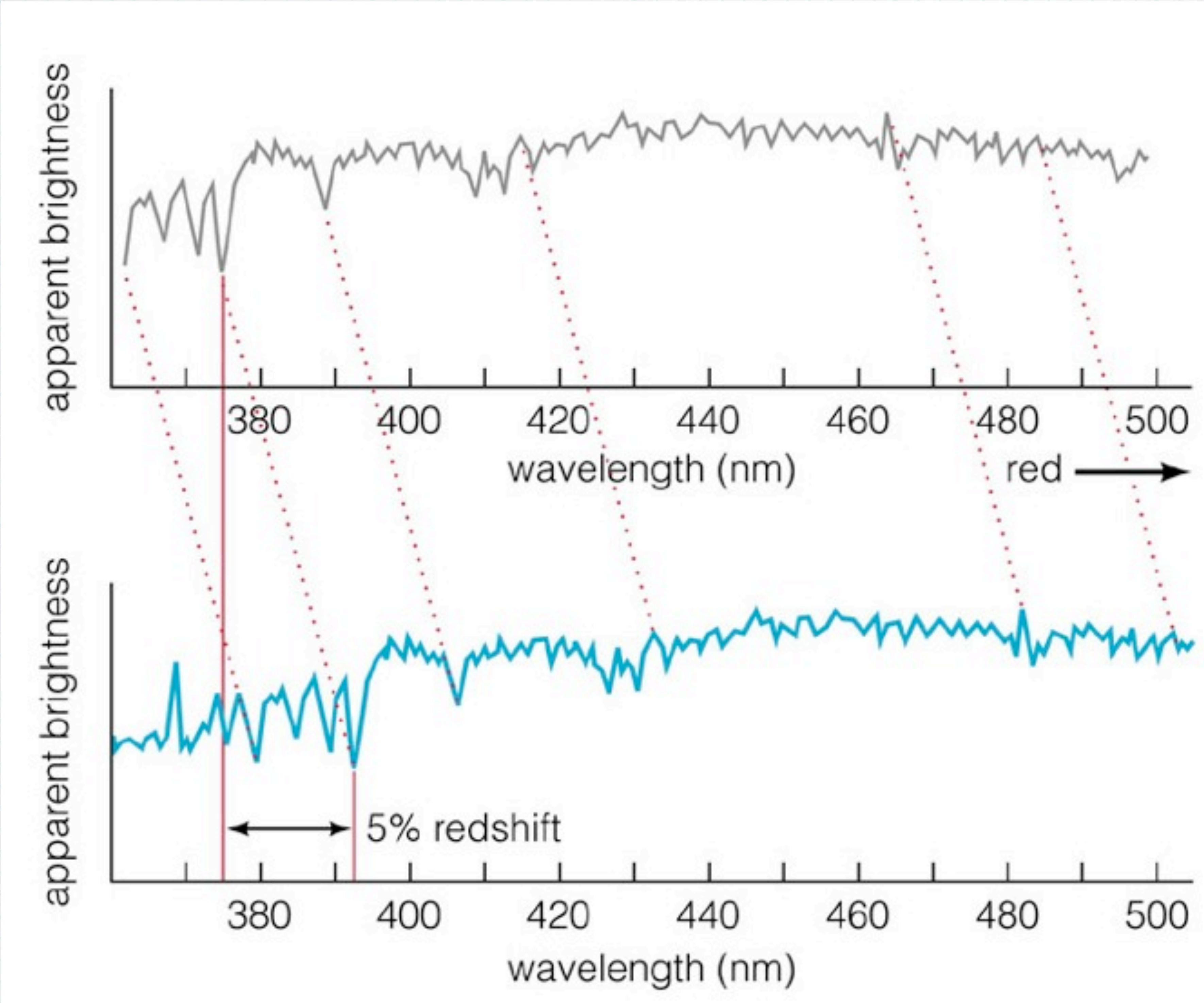
Step 6 Hubble's Law: velocity = H_0 x distance



H_0 =
Hubble's constant

velocity =
recession velocity

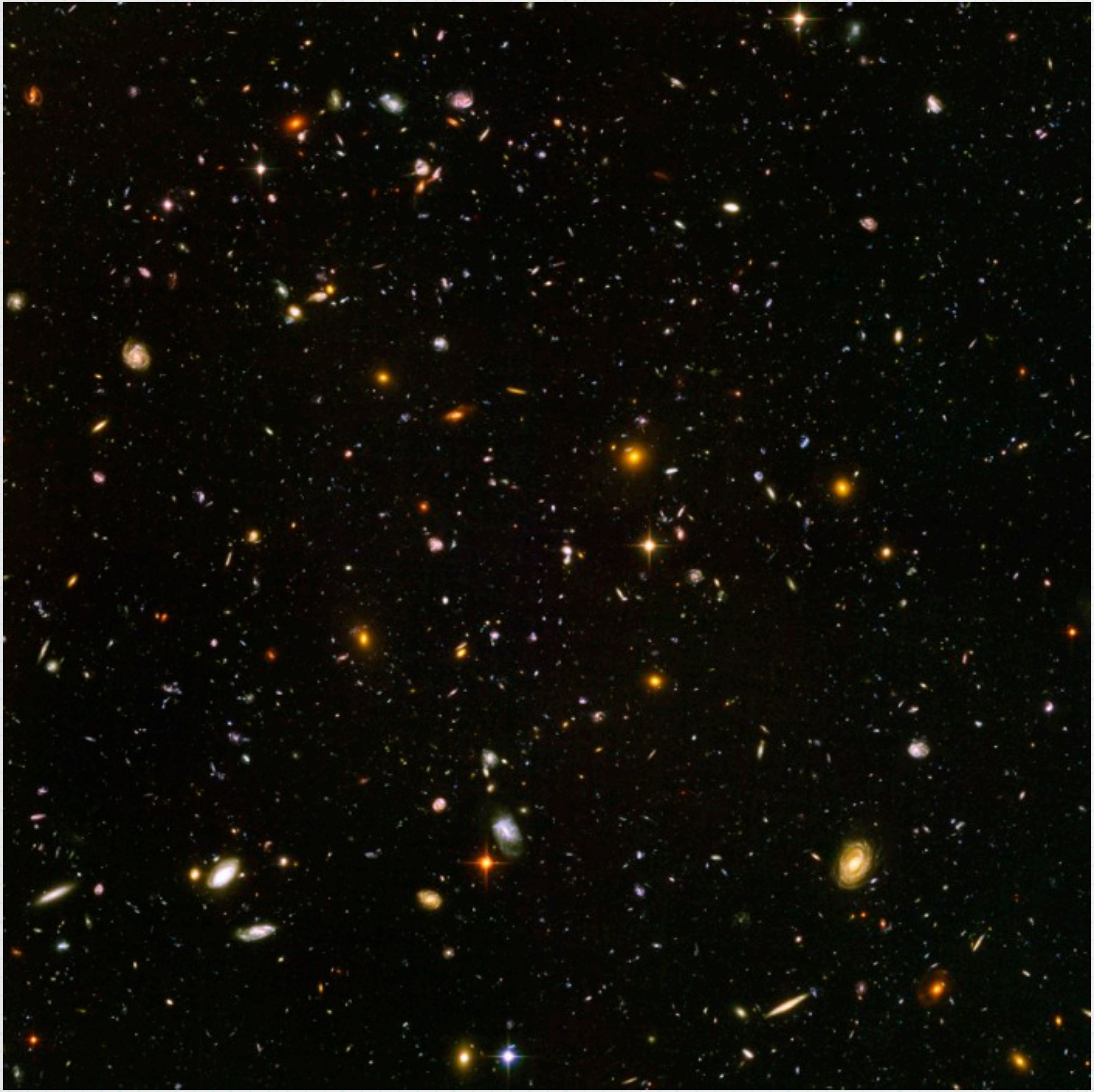
An easy way to calculate the distance to a faraway galaxy:



The redshift of a galaxy tells us its distance through Hubble's Law:

$$\text{distance} = \frac{\text{velocity}}{H_0}$$

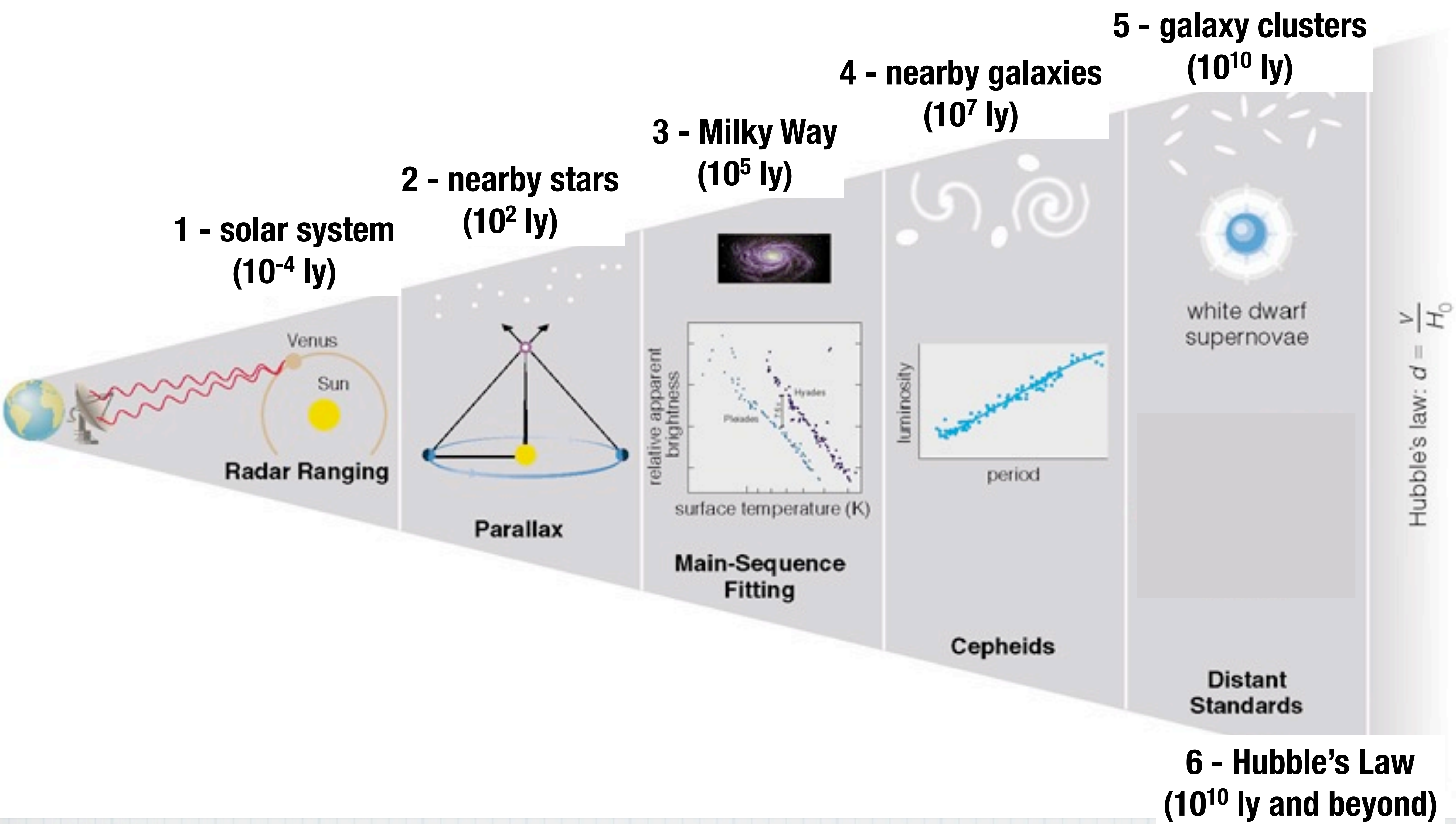
velocity is calculated from the redshift



The distances of farthest galaxies are measured from their redshifts

However, galaxies do not obey Hubble's law perfectly as they are gravitationally tugged by galaxies in their local neighborhoods

We measure galactic distances using a chain of techniques



Measuring Distances Summary

1) Radar ranging (Solar System)

* bouncing radio waves off planets

2) Parallax (nearby stars)

* measuring star position changes

Measuring Distances Summary

3) Main-sequence fitting (Milky Way)

* comparing star clusters apparent brightness

4) Cepheids (nearby galaxies)

* Period/Luminosity relationship
* comparing brightness

Measuring Distances Summary

5) White Dwarf Supernovae (galaxy clusters)

* comparing supernovae apparent brightness

6) Hubble's Law (all the way back to the Universe's beginning - but not local)

* measure galactic redshifts

Problems with Hubble's Law

1. Hubble's law only works for galaxies which are not in our vicinity (local group)
2. Until we can pin down the true value for H_0, the distances we get via Hubble's law are only relative

Hubble's Constant

(which should be known as Lemaître's Constant)

- As best we know it now, Hubble's constant, H_0, is between 20.28 and 21.01 km/s per million light-years

➡ For every million light-years of distance away from us, a galaxy's speed away from us is between 20.28 and 21.01 km/s

Question

* Say H_0 is 20 km/s/million light-years
* What is the recession speed of a galaxy which is located 100 million light-years from us?

A. 20 km/s

B. 200 km/s

C. 2,000 km/s

Question

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From Receding Galaxies to the Age of the Universe

* Receding galaxies means an expanding Universe

➡ Expanding Universe means a size

➡ It also means a beginning and a current age

Expanding Universe

* Faraway galaxies are moving away from us
* What is the mechanism behind this expansion?
    * are galaxies speeding away in existing space?
    * or is existing space stretching and carrying galaxies away?

Problems:

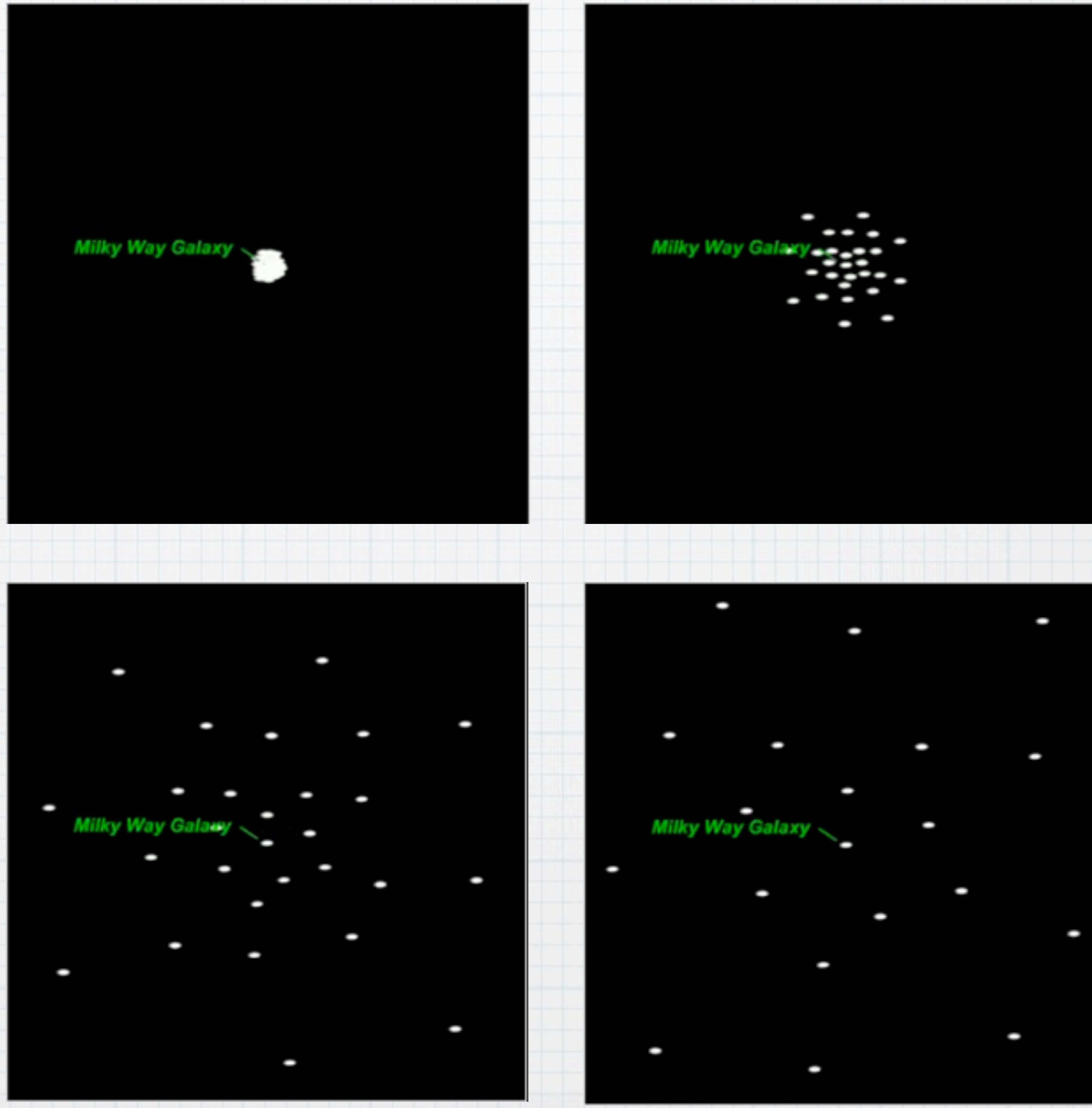
Speeding away in existing space

a) why were all the galaxies in one place? (center?)

b) why are they moving away from each others?

c) where does the empty space comes from?

d) how much of it is there?

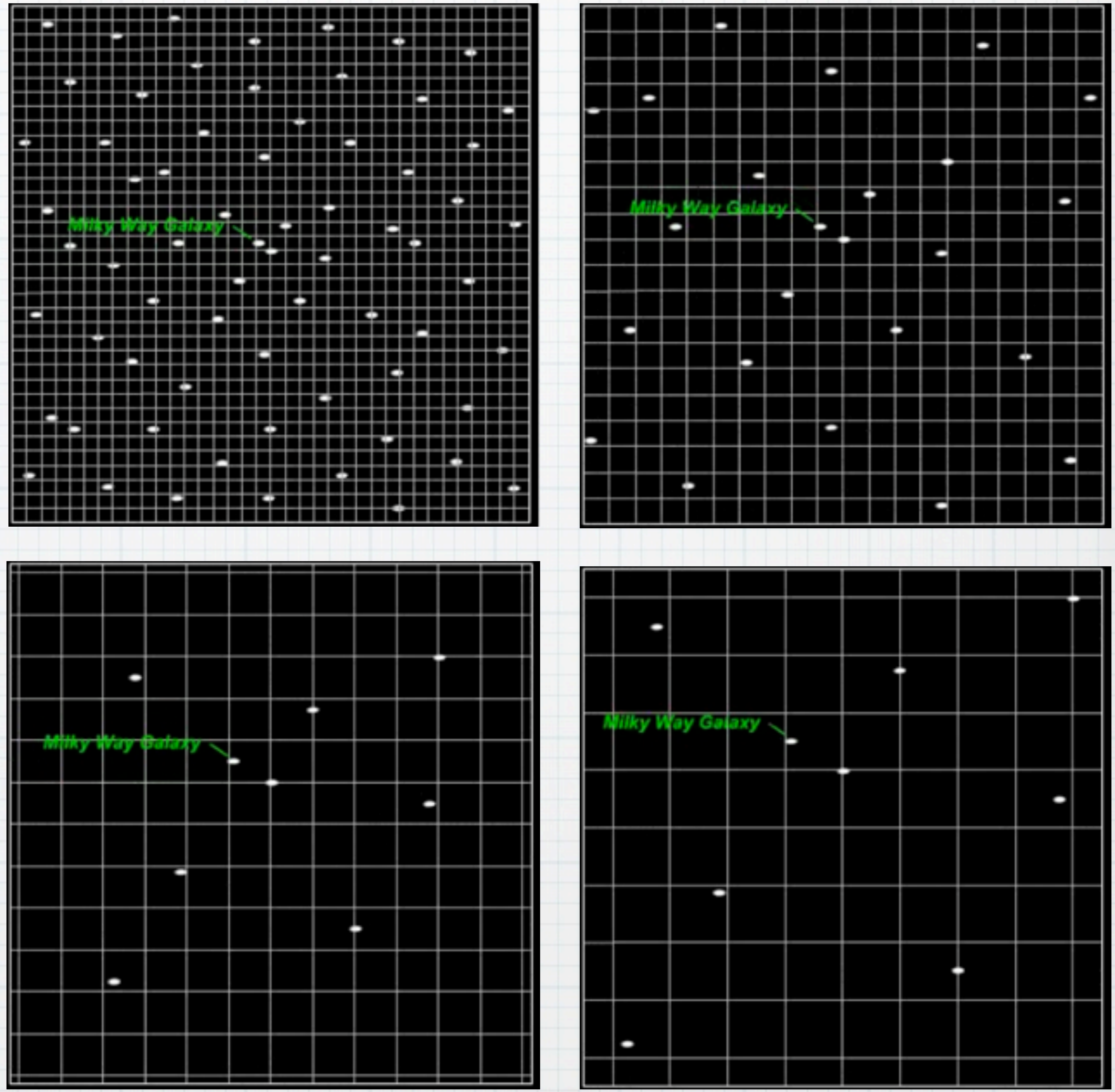


Existing space stretching

Problems:

a) what causes space to stretch?

b) will it stretch forever? will it rip?



This explanation makes more sense but it does not explains everything

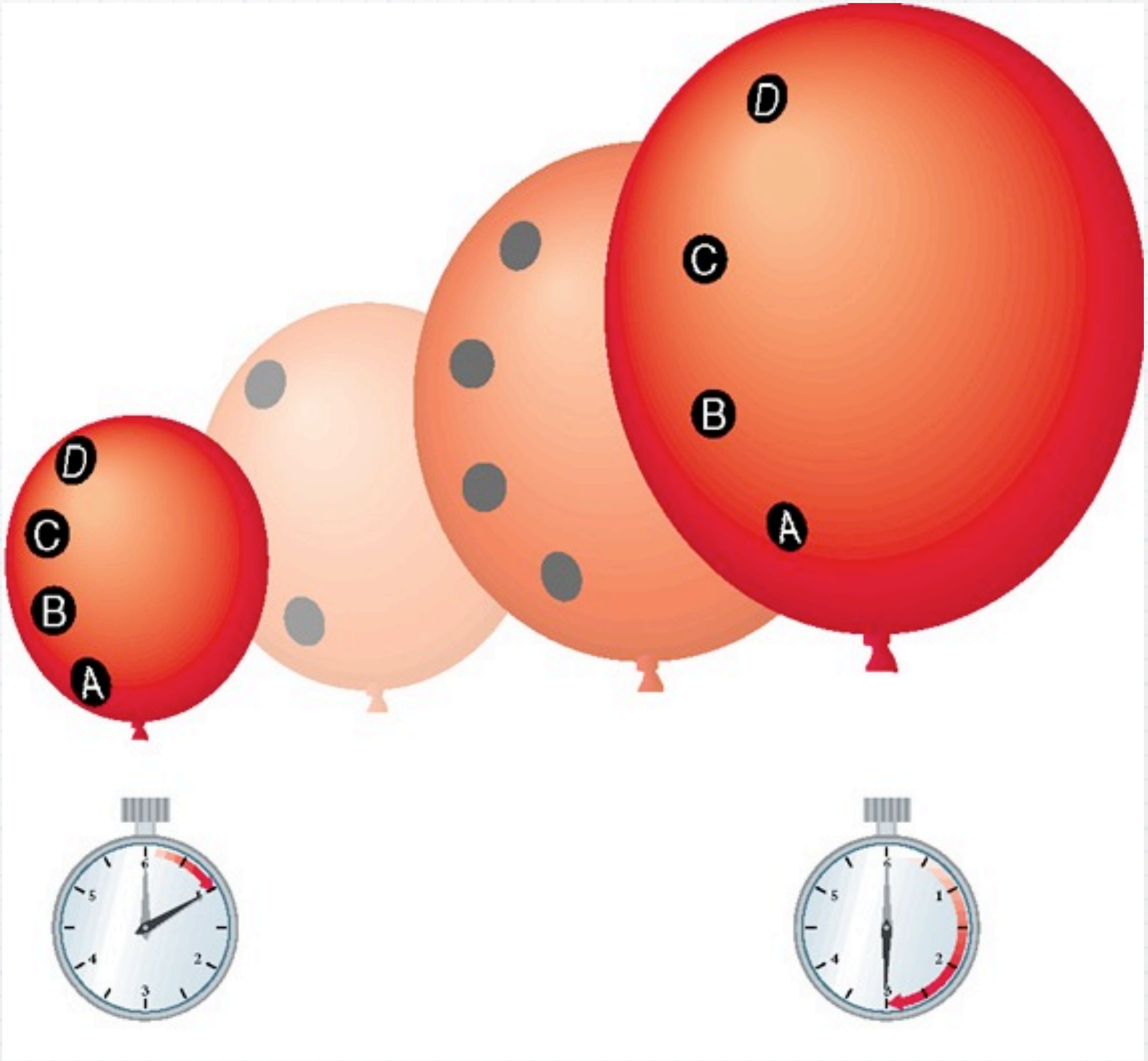
Universal Expansion

* The Universe is not expanding into anything
* The Universe has no center and no edge (as far as we can tell)
* Spatial galaxy distribution looks uniform on the very large scales (it looks the same wherever we look)

Surface of a balloon expands but has no center or edge

Imagine that the surface of the balloon represents the 3 dimensions of space

As time goes forward, the balloon expands and the dots move away from one another



The Cosmological Principle

* The Cosmological Principle states the following: the Universe looks about the same no matter where you are within it. Its laws are the same everywhere

1. Matter is evenly distributed on very large scales in the Universe

2. No center & no edges

* Not (yet) proven but consistent with all observations to date

The Age of the Universe

* Based on the cosmological principle of uniformity, if we look back in time, galaxies were closer together

➡ There is a beginning of time and space

Thought Question

* Your friend leaves your house. She later calls you, saying that she's been driving at 60 mph directly away from you the whole time and is now 60 miles away. How long has she been gone?

A. 1 minute

B. 30 minutes

C. 60 minutes

D. 120 minutes

Thought Question

* Your friend leaves your house. She later calls you, saying that she's been driving at 60 mph directly away from you the whole time and is now 60 miles away. How long has she been gone?

A. 1 minute

B. 30 minutes

C. 60 minutes

D. 120 minutes

$d = v\ t \Rightarrow t = d/v$

Thought Question

* You observe a galaxy moving away from you at 0.1 light-years per year, and it is now 1.4 billion light-years away from you. How long has it taken to get there?

A. 1 million years

B. 14 million years

C. 10 billion years

D. 14 billion years

Thought Question

* You observe a galaxy moving away from you at 0.1 light-years per year, and it is now 1.4 billion light-years away from you. How long has it taken to get there?

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C. 10 billion years

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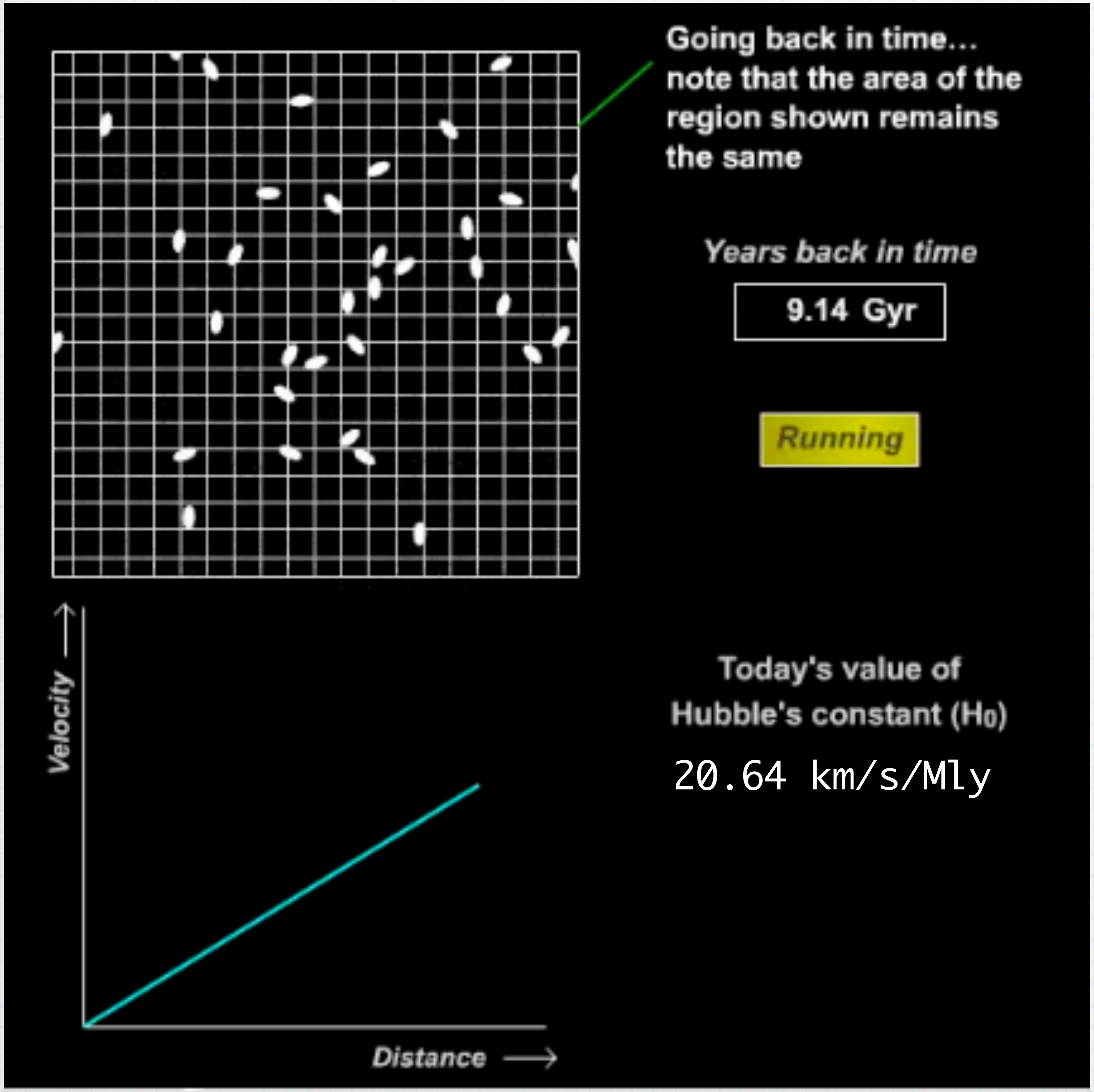
$d = v\ t \Rightarrow t = d/v$

$t = 1.4x10^9/10^{-1} = 1.4x10^{(9+1)}$

Estimating the age of the Universe



Hubble's constant tells us the age of the Universe because it relates the velocities and distances of all galaxies

$$\text{Age} = \frac{\text{Distance}}{\text{Velocity}} \approx \frac{1}{H_0}$$

Age ≈ 13.798 billion years

The Age of the Universe

* The Universe is 13.798 billion years old (± 37 million years)
* This number is correct as of our latest theoretical understanding of our best data obtained by specialized telescopes - which we will talk about next week

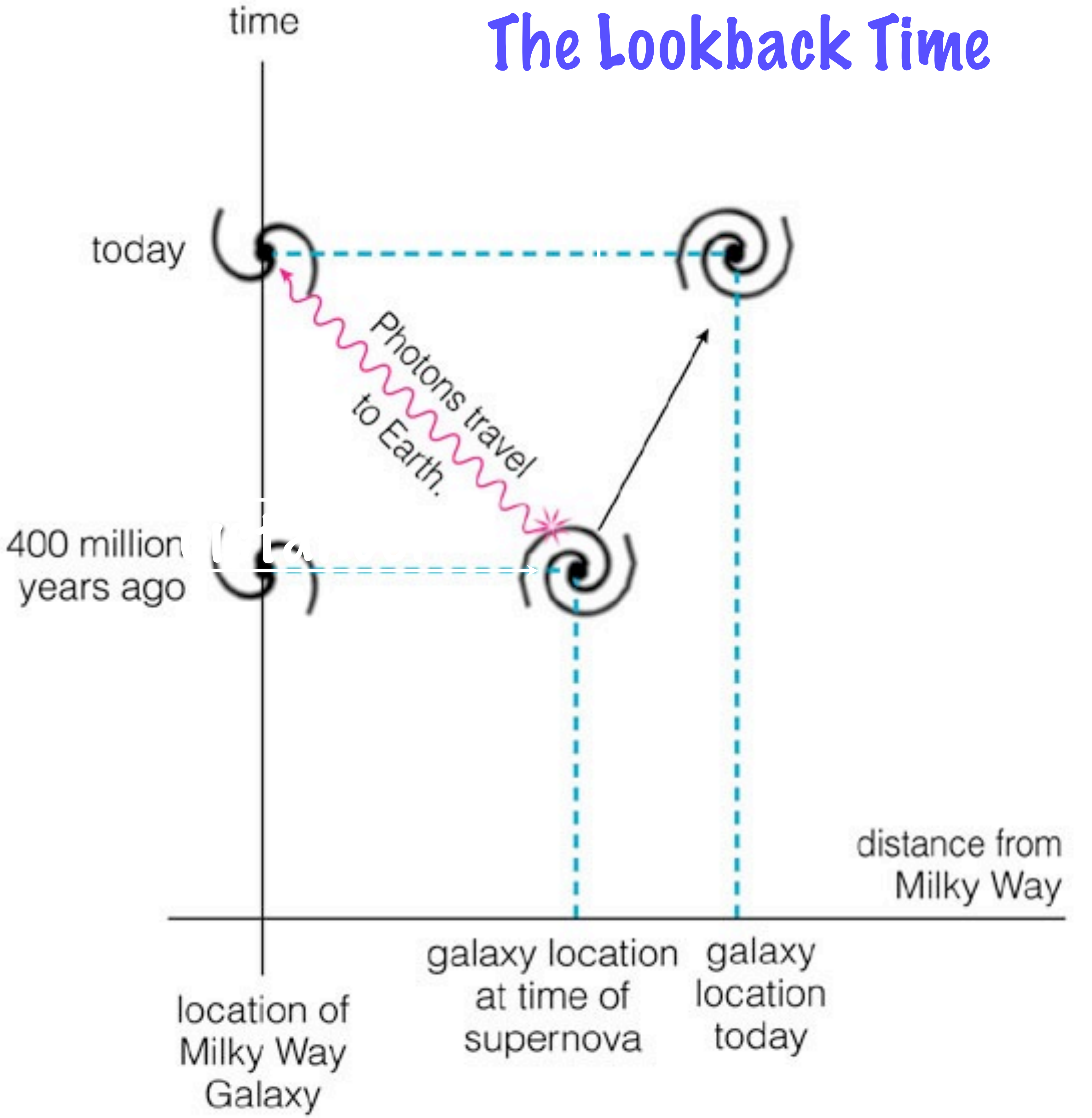
Lookback Time

* When we see a supernova in a galaxy which is 400 million light-years away, what is it true distance to us?
* the distance now?
* the distance when the supernova happened?
* something in between?

Lookback Time...

* Introducing the lookback time
* Since galactic distances are constantly changing, a galaxy's lookback time is the time it took for its light to reach us

The Lookback Time

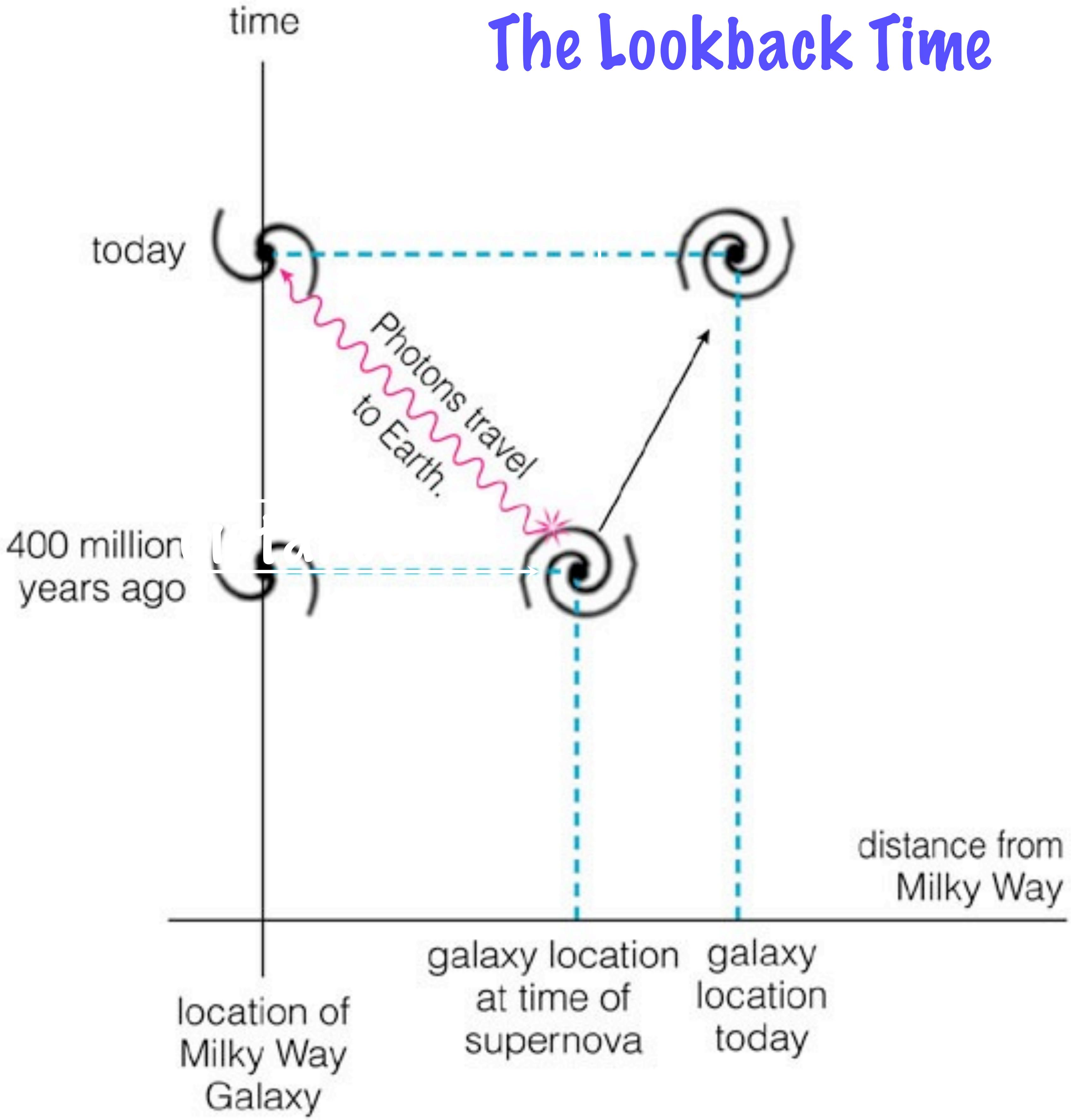


Distances between faraway galaxies change while light travels

We see a galaxy as it was, not as it now is

When the light was emitted, our Milky Way was also closer to that galaxy

The Lookback Time

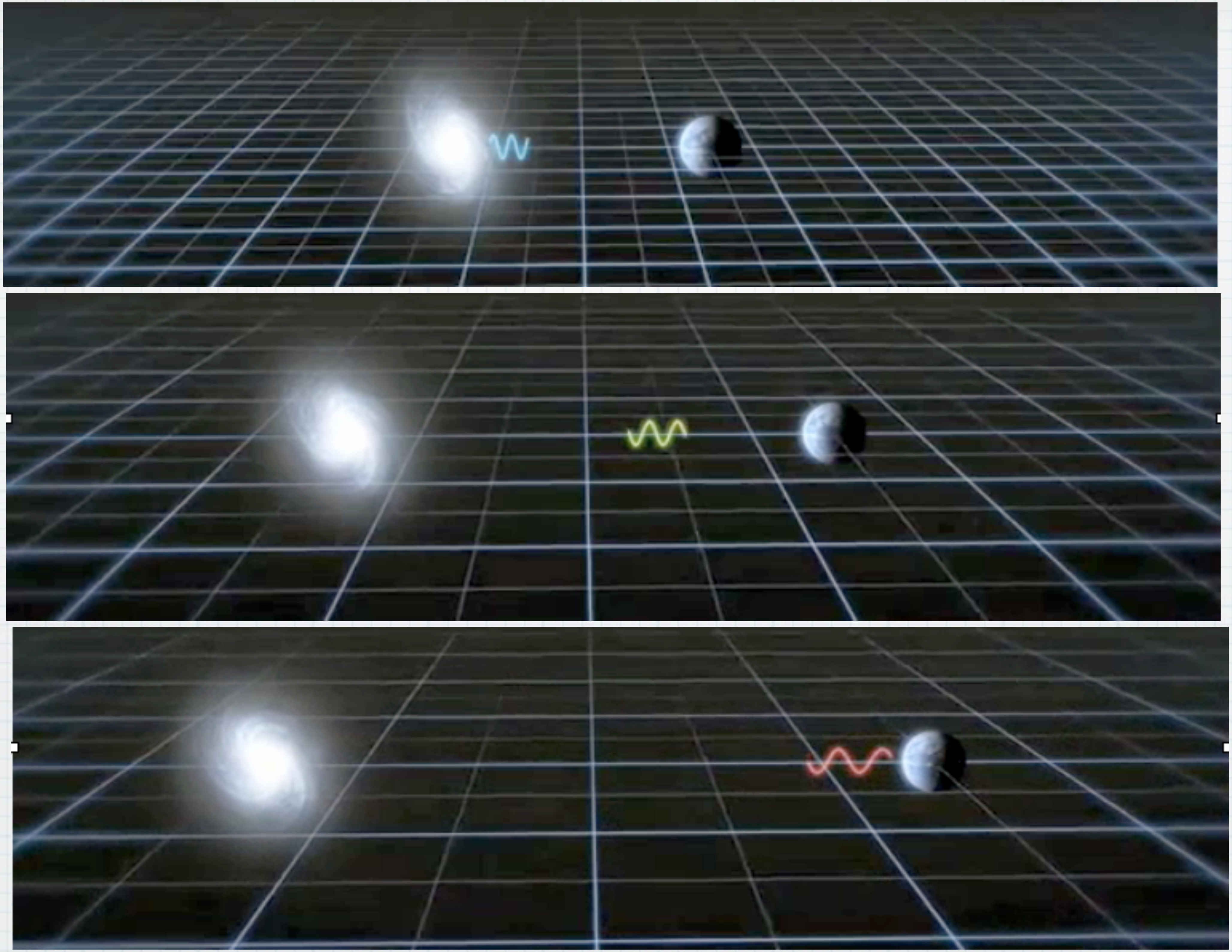


Distances between faraway galaxies change while light travels

Astronomers think in terms of lookback time rather than distance

The Cosmological Redshift

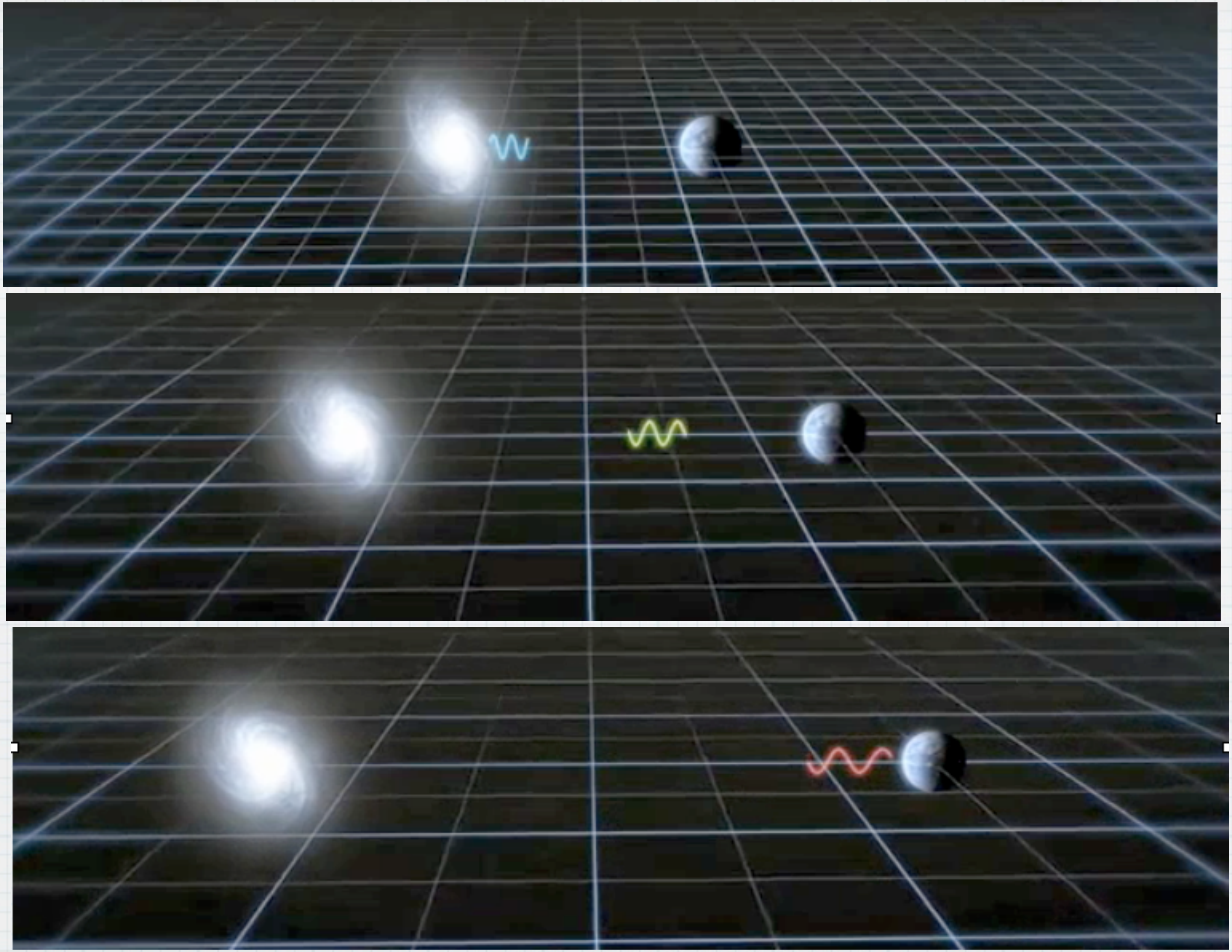
* An object's lookback time is directly related to its redshift
* Recall that a galaxy's redshift tells us how fast it is moving away from us
* But the space in between is being stretched - what happens to photons as they travel through it?



The redshift can be seen as

a) doppler effect due to galaxy moving away

b) a photon's wavelength being stretched as it travels

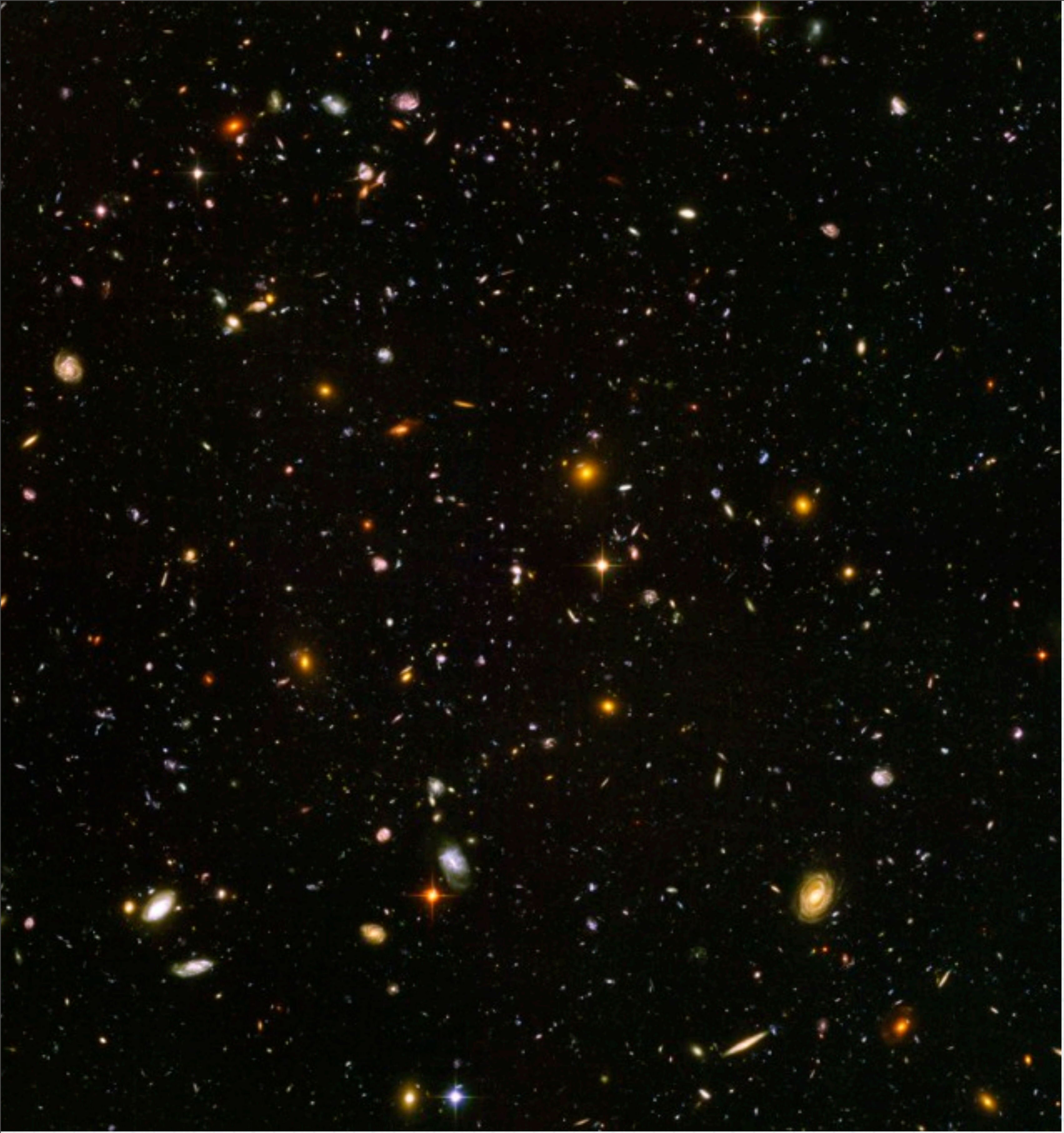


Since distance is now ambiguous it is preferable to state that **the expansion of the Universe stretches photon wavelengths which causes a cosmological redshift**

The Cosmological Horizon

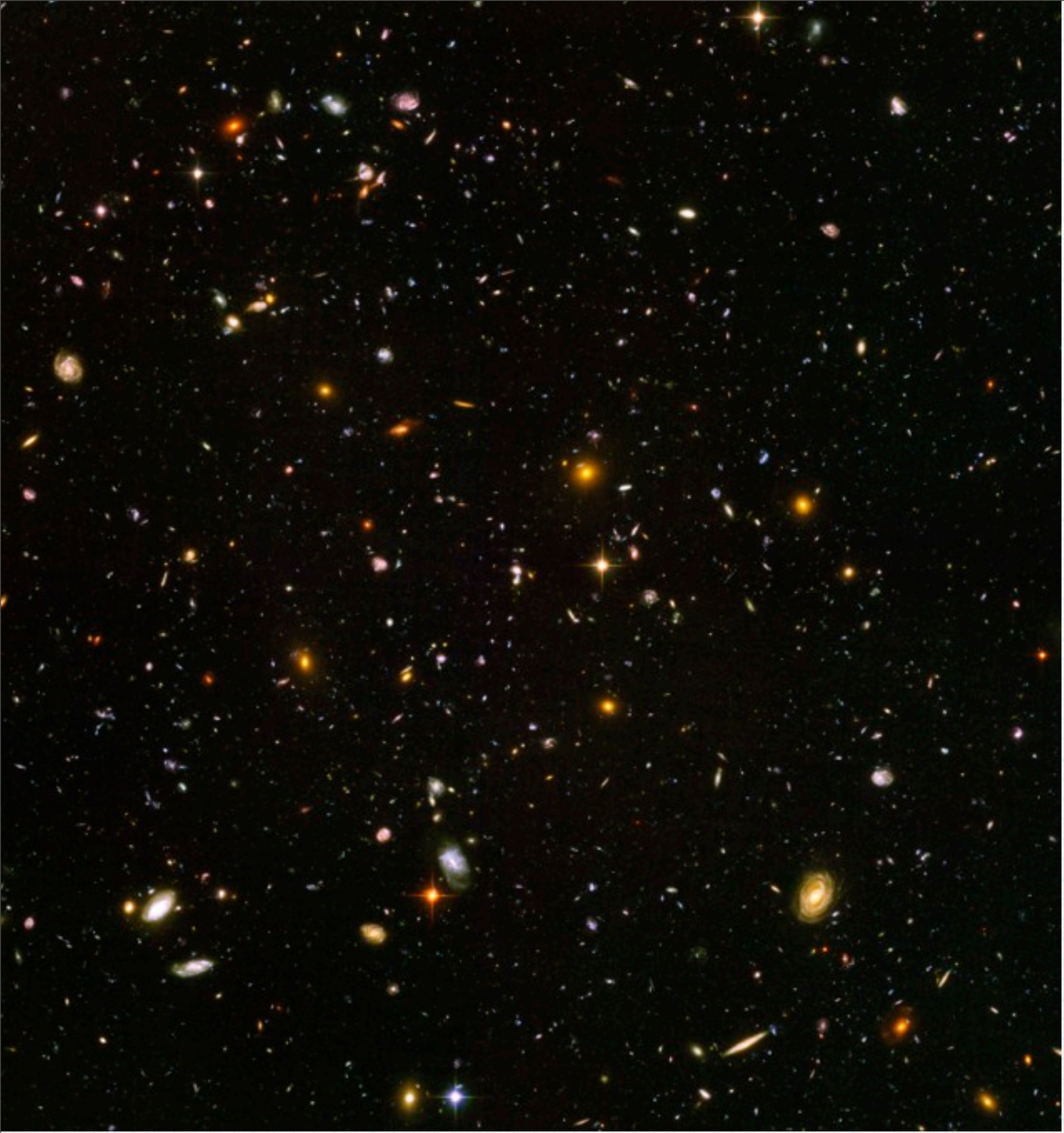
* The Universe does not have edges, **but it has an horizon**
* **The cosmological horizon is a boundary in time**

➡ **We cannot look further than the age of the Universe (about 13.798 billion years)**



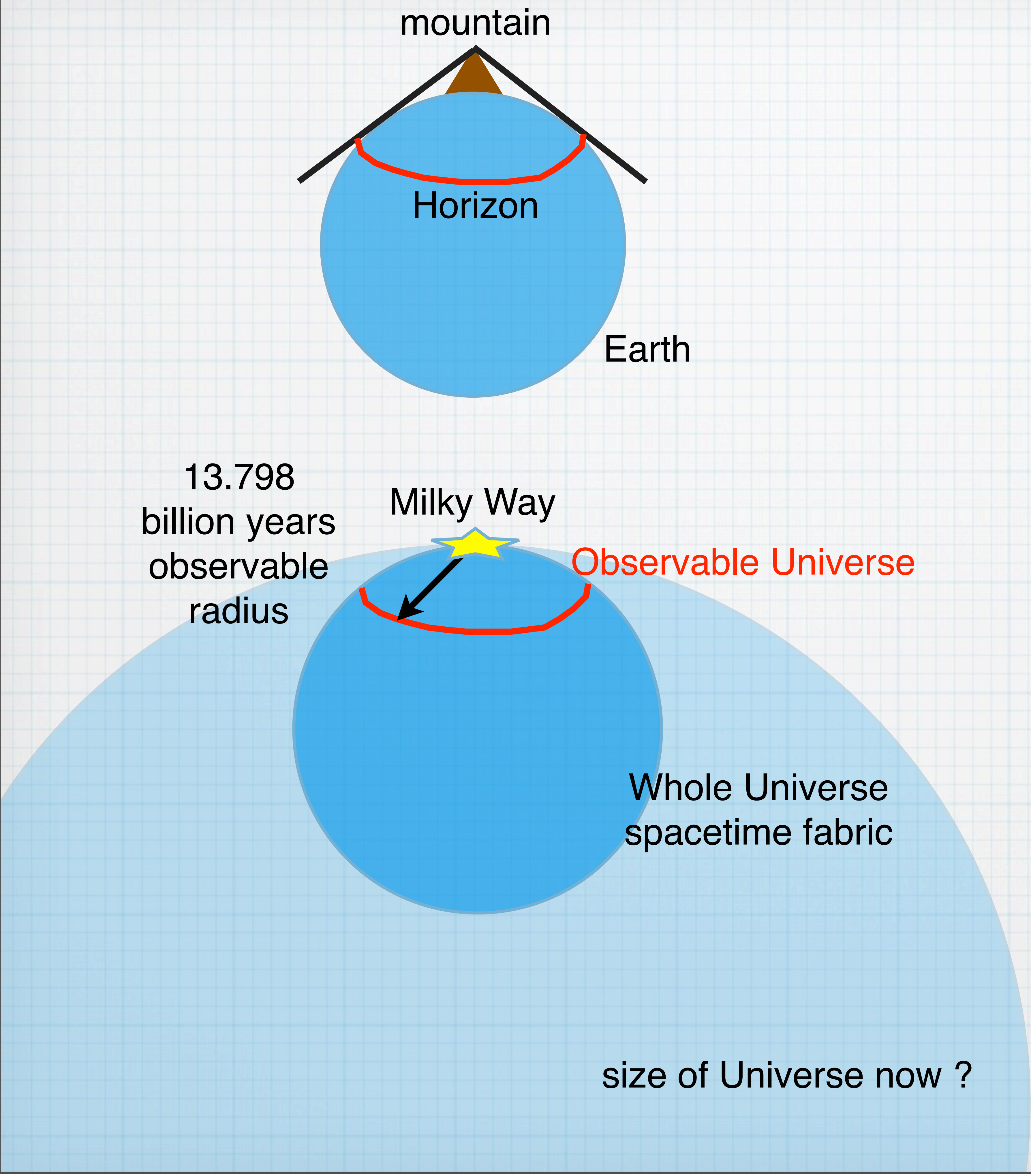
Cosmological Horizon

Maximum lookback time of 13.798 billion years limits how far we can see



Cosmological Horizon

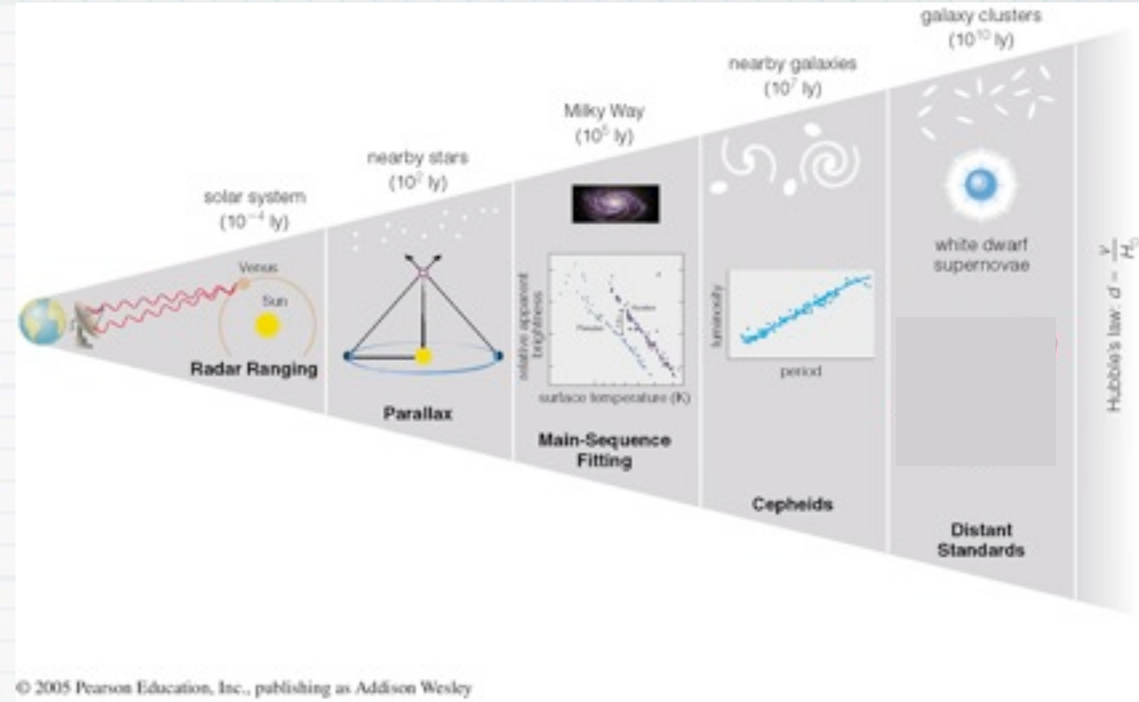
Due to the expansion of space, the **current radius** of the **visible Universe** is estimated to be around 46 billion light-years away



From the top of the mountain, one cannot see nor size the entire Earth

From our Milky Way, we can only see a portion of the whole Universe. How big is it really????

Snapshot

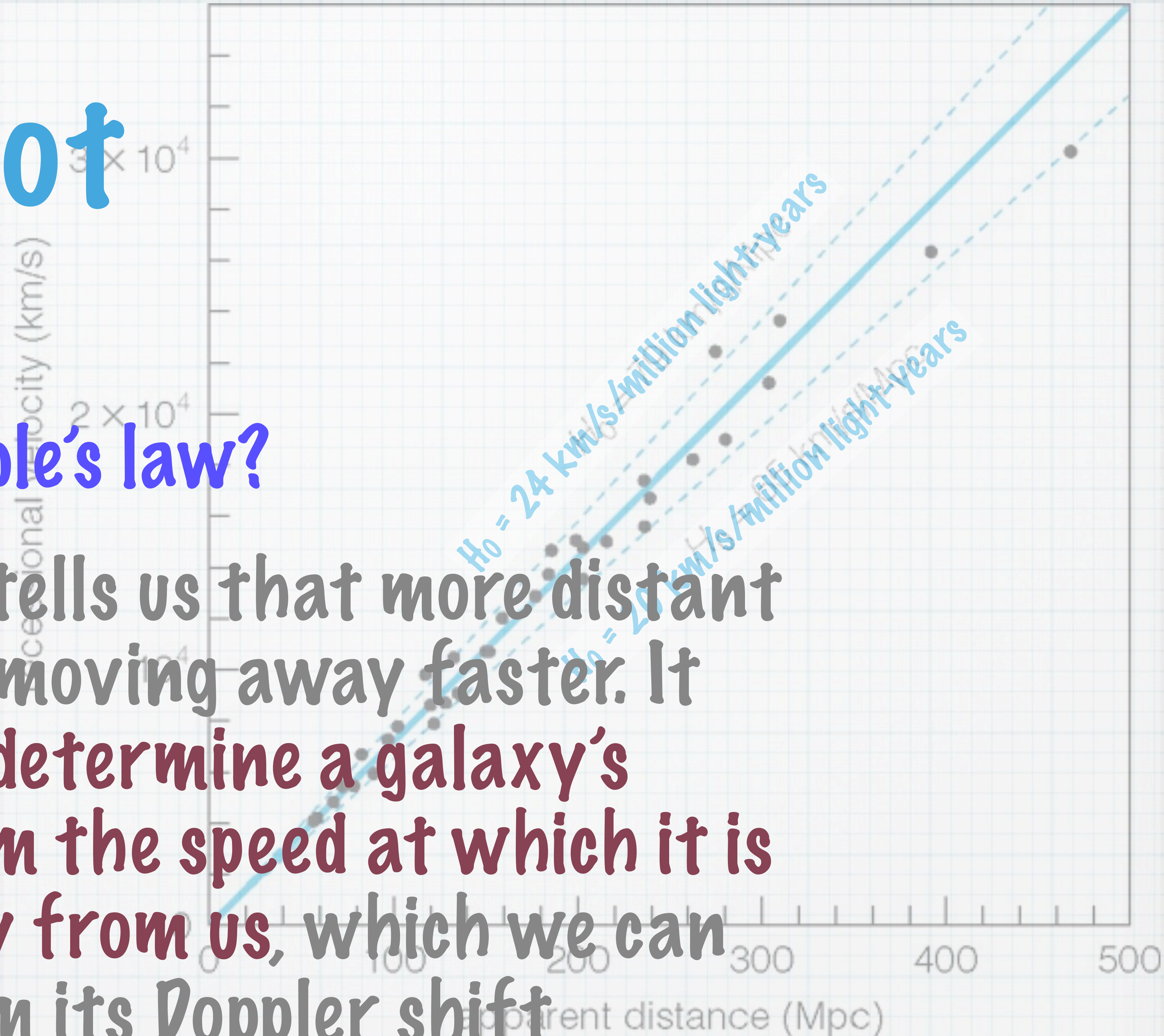


* How do we measure the distances to galaxies?

* Our measurements of galaxy distances depend on a chain of methods. The chain begins with radar ranging in our own solar system and ends with measuring the Doppler effect of receding galaxies

Snapshot

* What is Hubble's law?
* Hubble's law tells us that more distant galaxies are moving away faster. It allows us to determine a galaxy's distance from the speed at which it is moving away from us, which we can measure from its Doppler shift



Snapshot

* How do distance measurements tell us the age of the Universe?
* Combining distance measurements with velocity measurements tells us Hubble's constant, and the inverse of Hubble's constant tells us how long it would have taken the Universe to reach its present observable size if the expansion rate had never changed

Snapshot

* **How do distance measurements tell us the age of the Universe?**

* Based on Hubble's constant we now estimate the age of the Universe at **about 13.798 billion years**, which restricts our view of the Universe to lookback times smaller than that age

* The radius of the current Universe is greater (3 times at least) because it has been expanding ever since

Galaxy Evolution

* We understand a lot less about galaxy evolution than we know about the lives of stars
* Regardless, progress is being made

Observing the life histories of galaxies

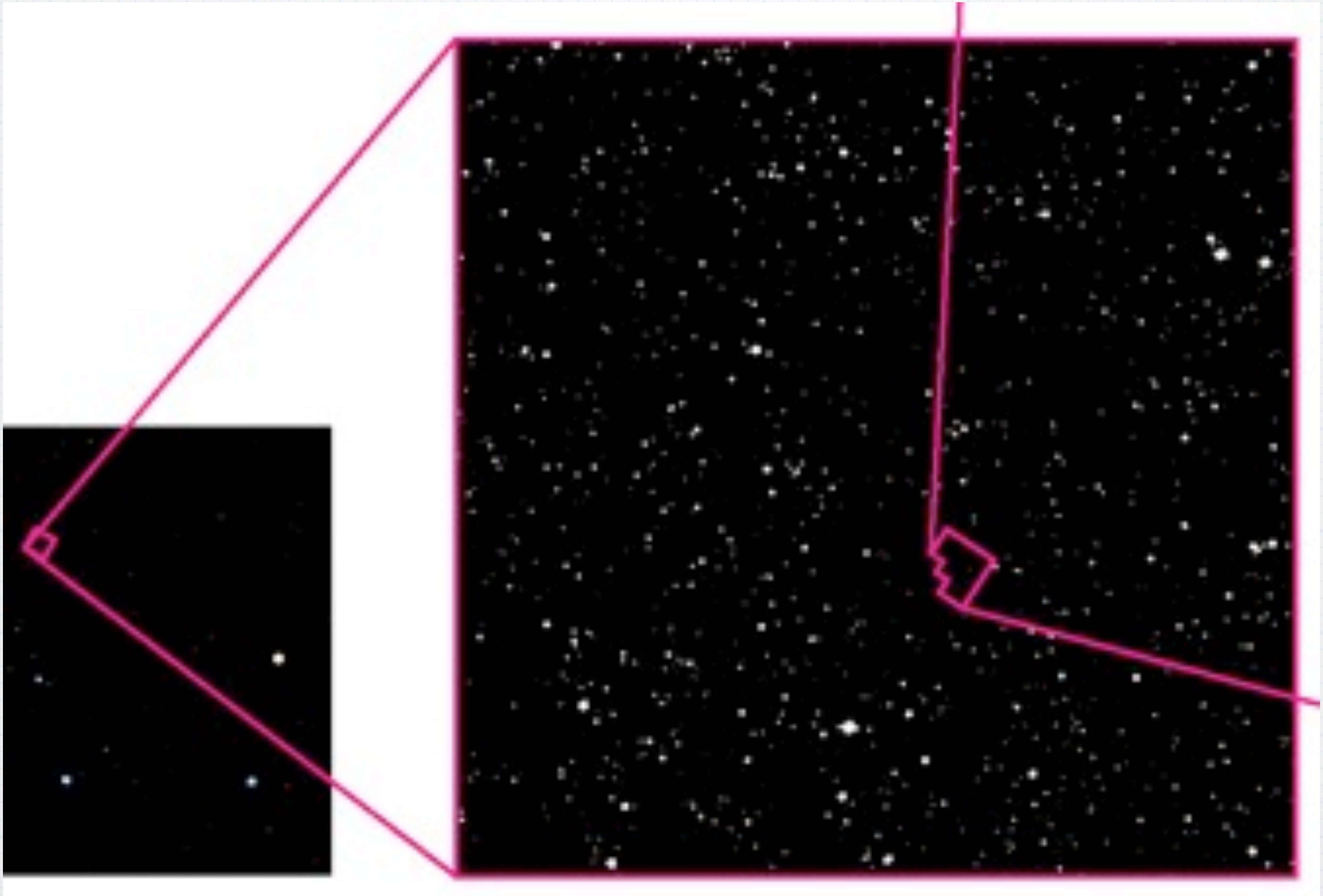
* The most distant galaxies we can see had stars 13 billion years ago
* This is when our galaxy formed
* We can assume virtually most galaxies formed around that time

Observing the life histories of galaxies

* Looking farther in space is like looking in the past
* The more distant the galaxy, the younger it is (as we see it)
* With these assumptions, we can study galaxy evolution

Let's look at a dark patch of sky near the Big Dipper

And zoom in

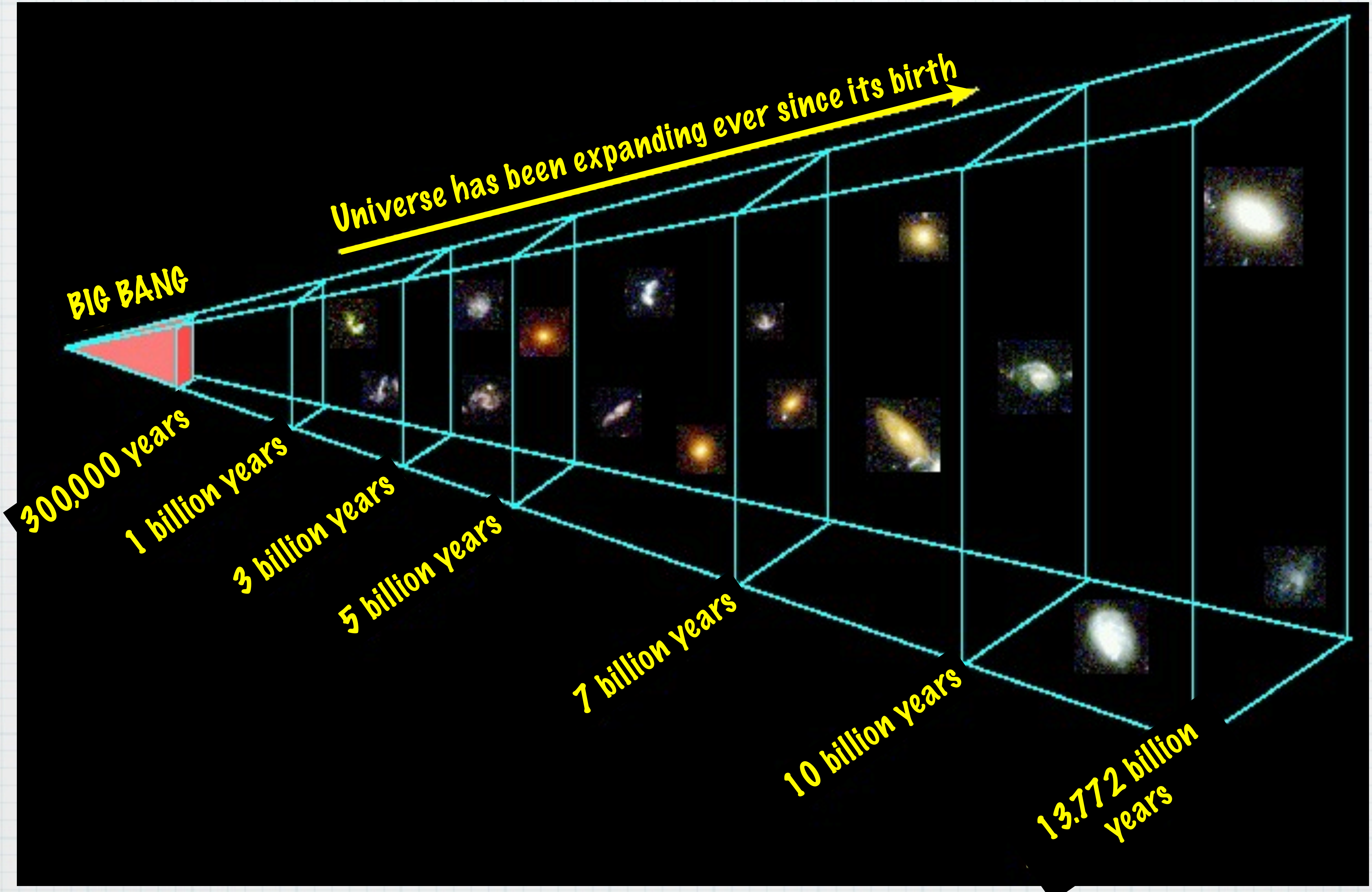


And zoom some more...

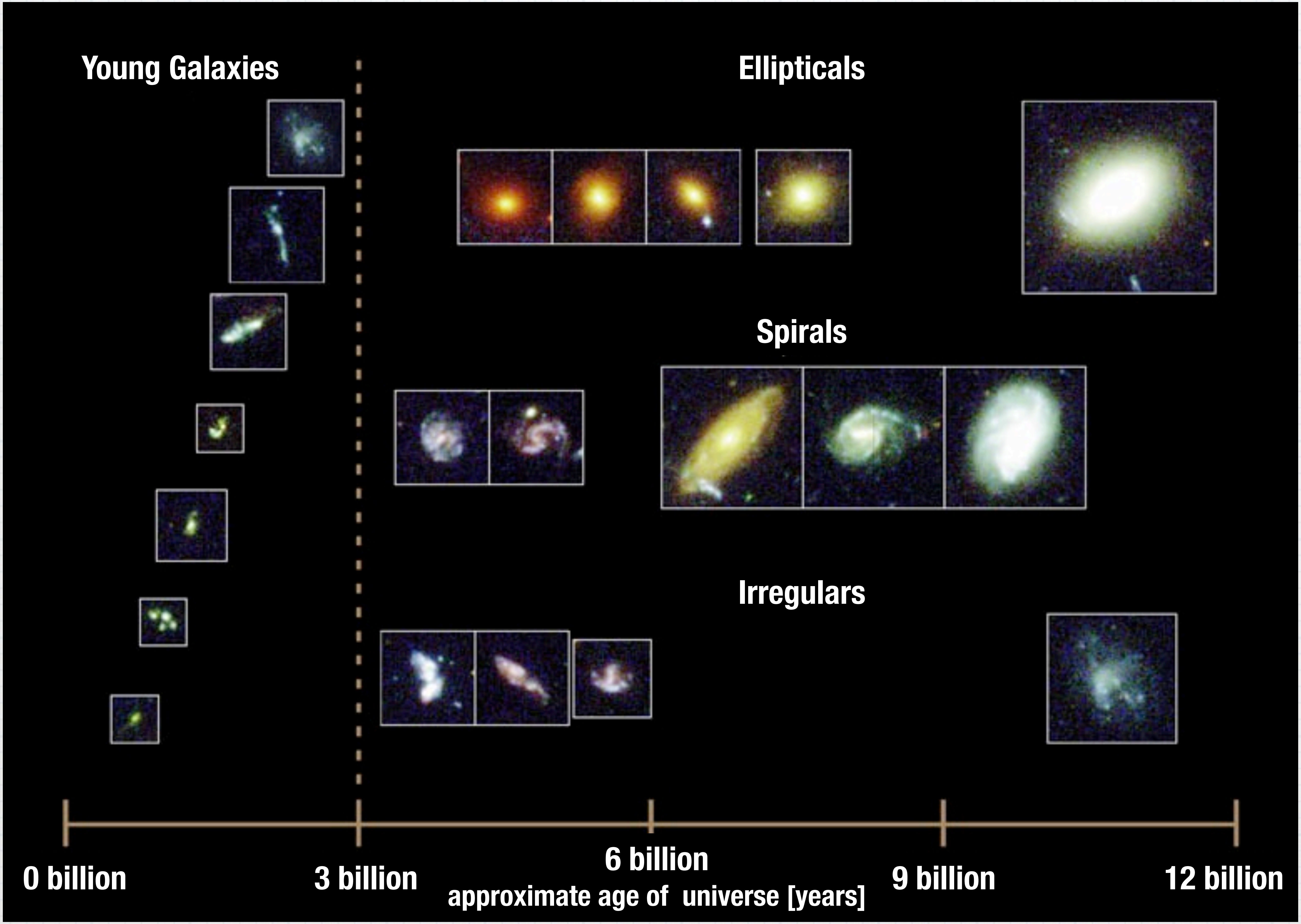
Deep observations show us very distant galaxies as they were much earlier in time

(Old light from young galaxies)

Looking back in time...

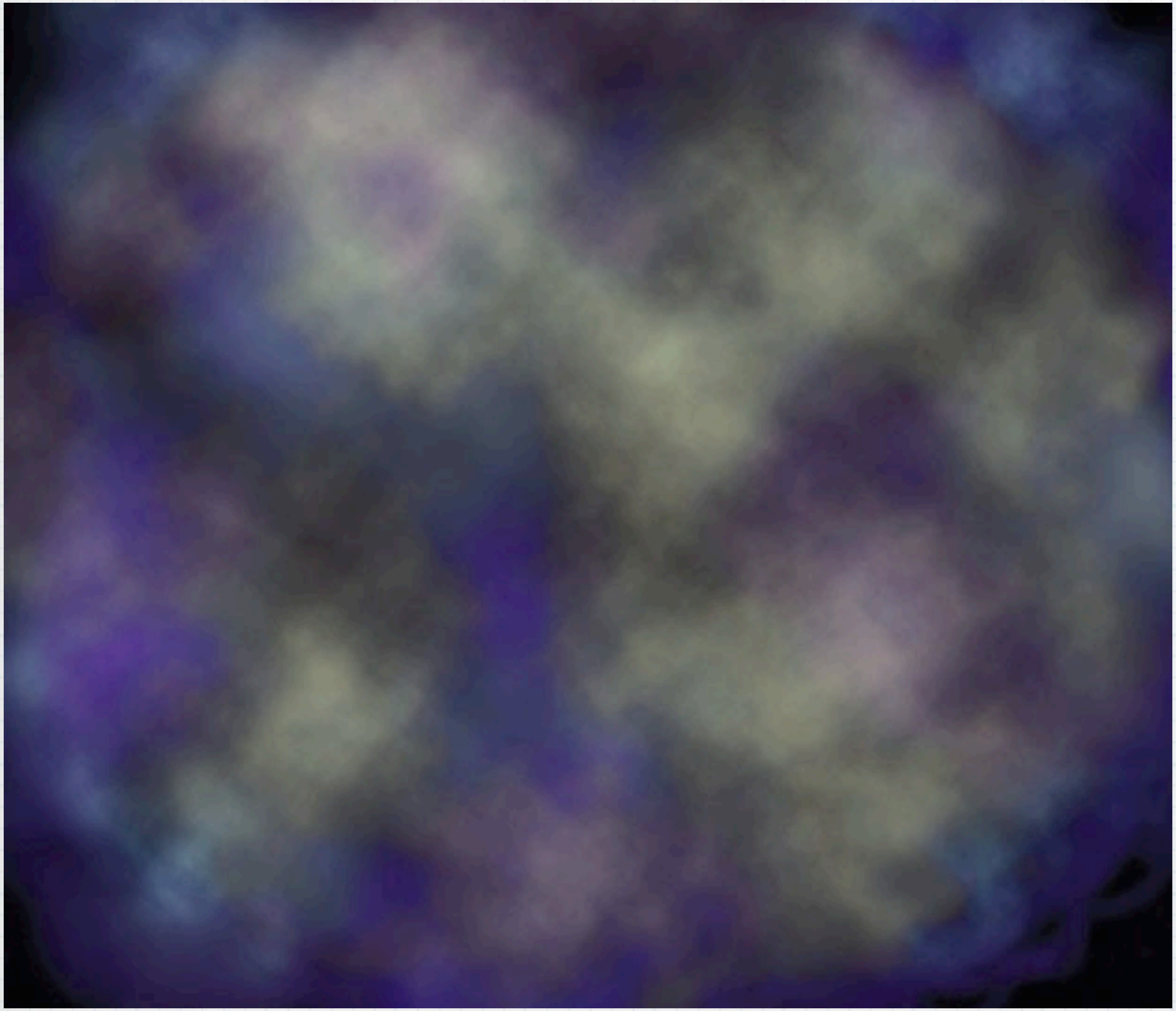


Galactic Family Album from previous image



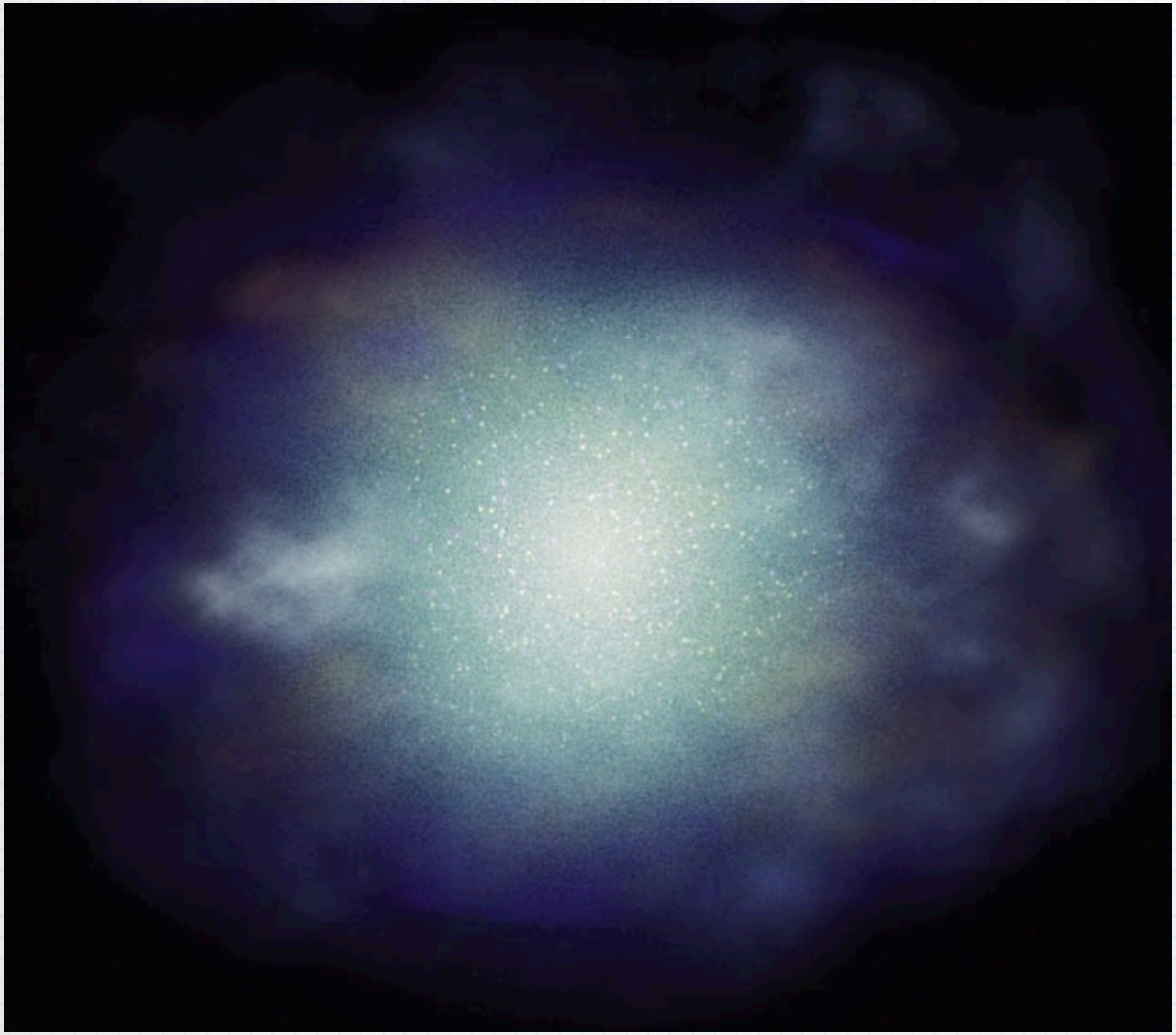
How did galaxies form?

* Theoretical modeling is needed as our best telescopes cannot yet see when galaxies formed their first stars
* Assumptions 1 & 2
  * Hydrogen & helium gas filled all of space more or less uniformly
  * e.g.: some regions slightly denser than others



Matter originally filled all of space almost uniformly

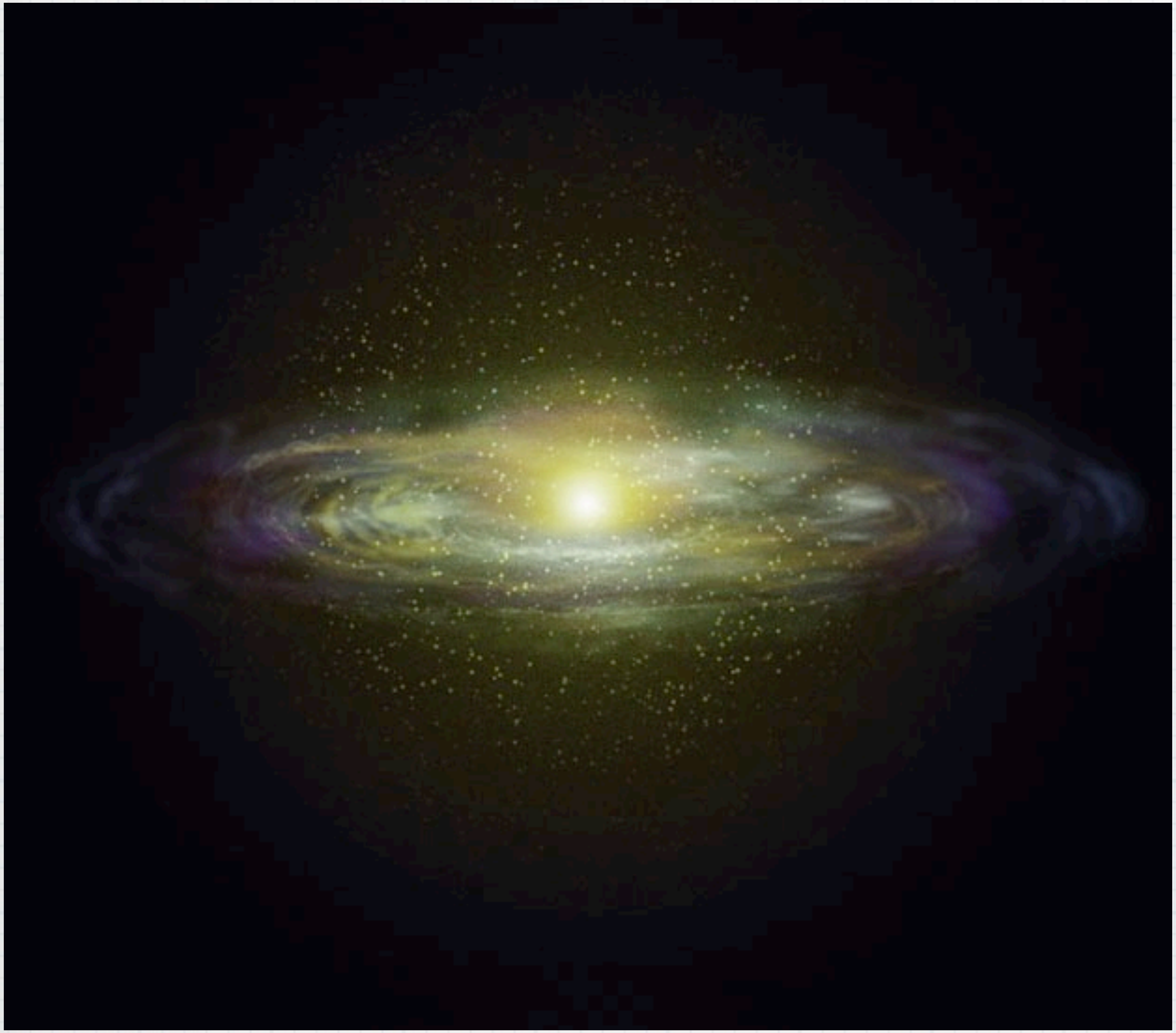
Gravity of denser regions pulled in surrounding matter despite the expansion



Within 400 million years, denser regions contracted, forming protogalactic clouds

H and He gases in these clouds formed the first stars which were likely quite massive (over 100 solar masses)

Spiral galaxy formation



Supernova explosions from first stars
- slowed the galactic contraction,
- disrupted star formation,
- yet seeded the galaxy with heavier elements

Leftover gas settled into spinning disk (conservation of angular momentum)

Galaxy Formation (incomplete theory)

* The previous modeling works quite well but for two things
* 1) why were there slight differences in region densities? (answer: formed as a result of tiny quantum fluctuations in the wake of the Big Bang, to be seen in 2 weeks)
* 2) model does not explain elliptical and irregular galaxy formations

But why do some galaxies end up looking so different?

NGC 4414

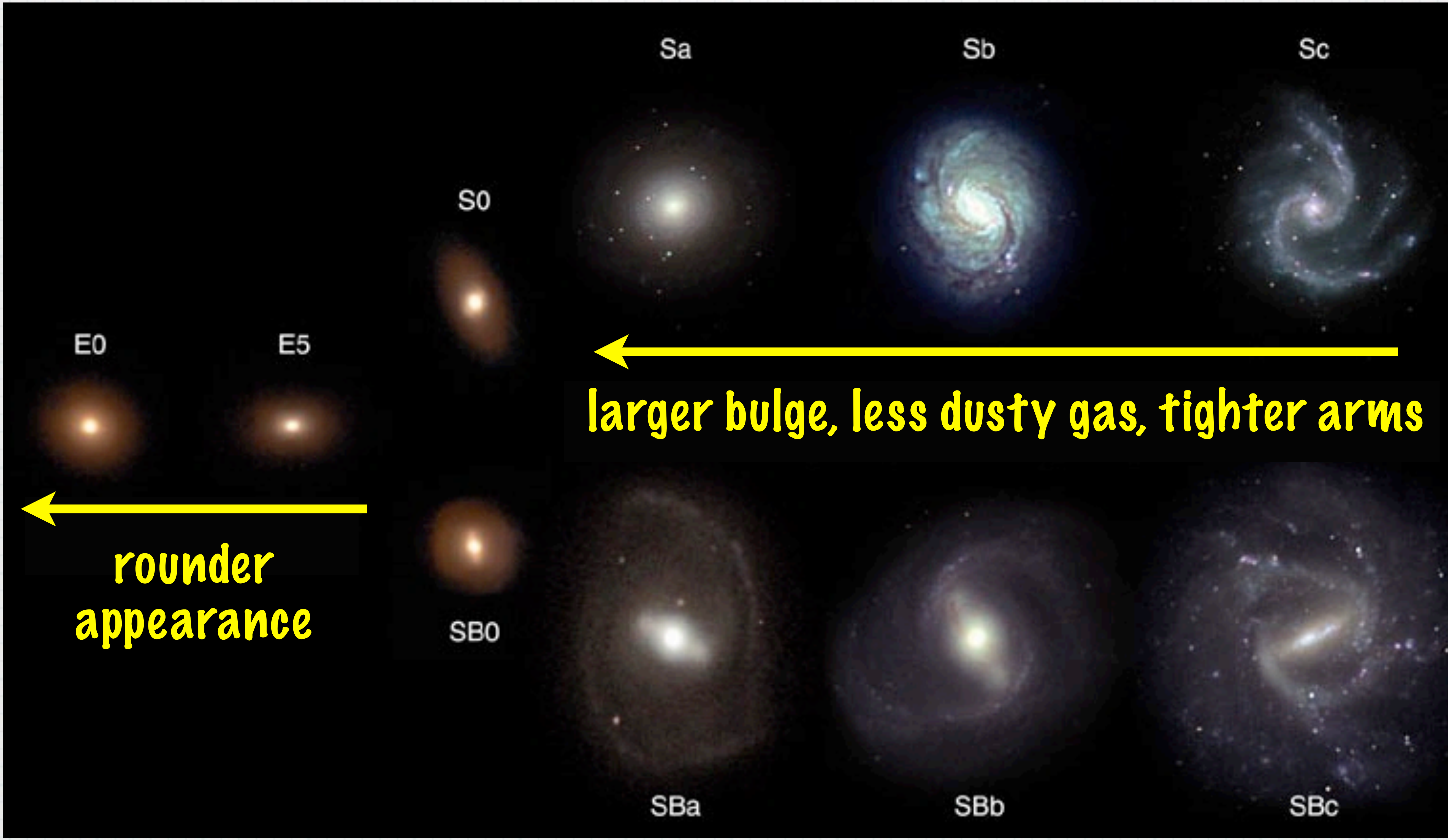
M87

Why do galaxies differ?

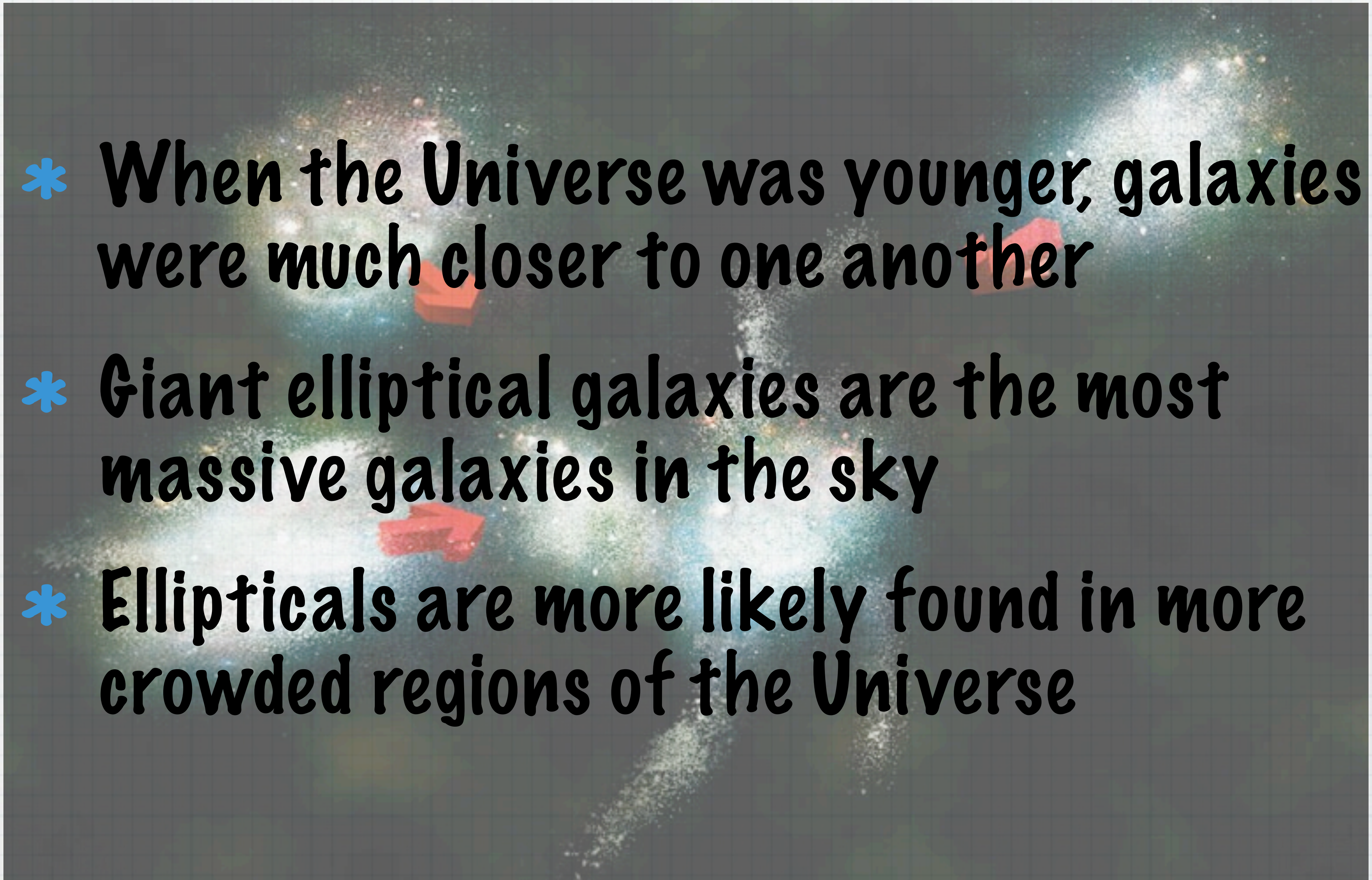
* It is thought that all protogalactic clouds started the same way
* The later differences must have arisen from

1. differing conditions in the cloud
2. interactions with other galaxies

Why do spiral galaxies have gas-rich disks, while ellipticals do not?



Galactic Mergers



* When the Universe was younger, galaxies were much closer to one another
* Giant elliptical galaxies are the most massive galaxies in the sky
* Ellipticals are more likely found in more crowded regions of the Universe

Galactic Mergers...

* Astronomers now see ellipticals as some of the most evolved systems in the Universe
* Elliptical galaxies are due to the mergers of smaller galaxies (best current explanation)

Galactic Mergers / Collisions?

* Galaxies are much closer to one another than stars (in proportion)

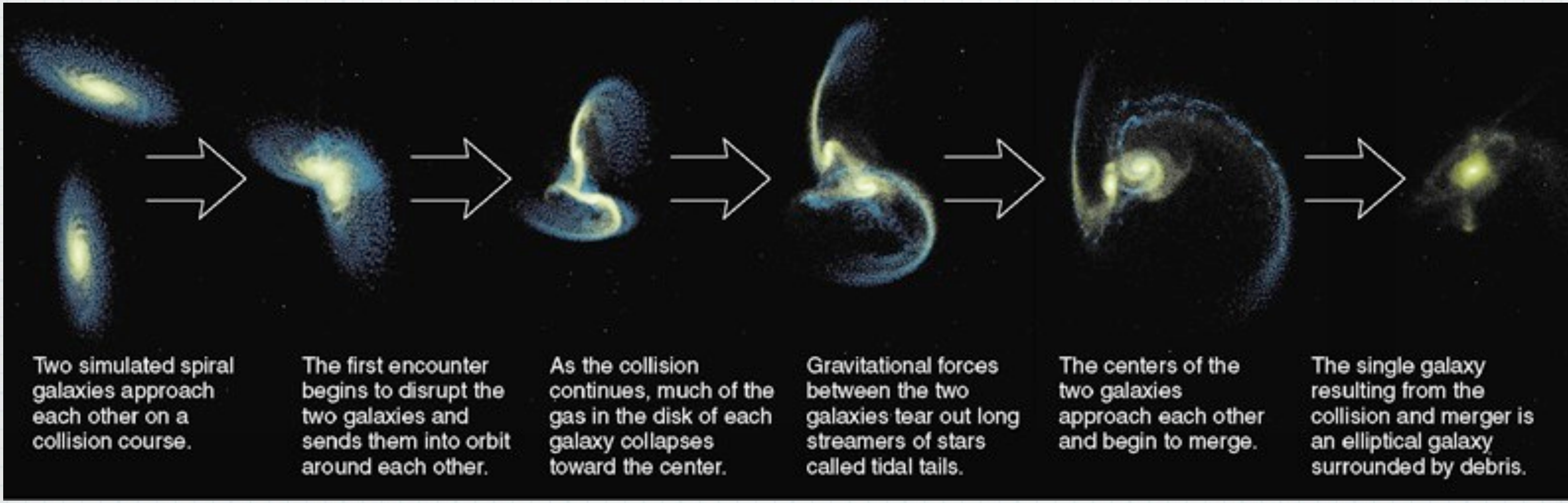
➡ Collisions between galaxies are unavoidable and many are observed

* Collisions between stars is a very rare event (lots of space between them)

Galactic Mergers / Collisions?...

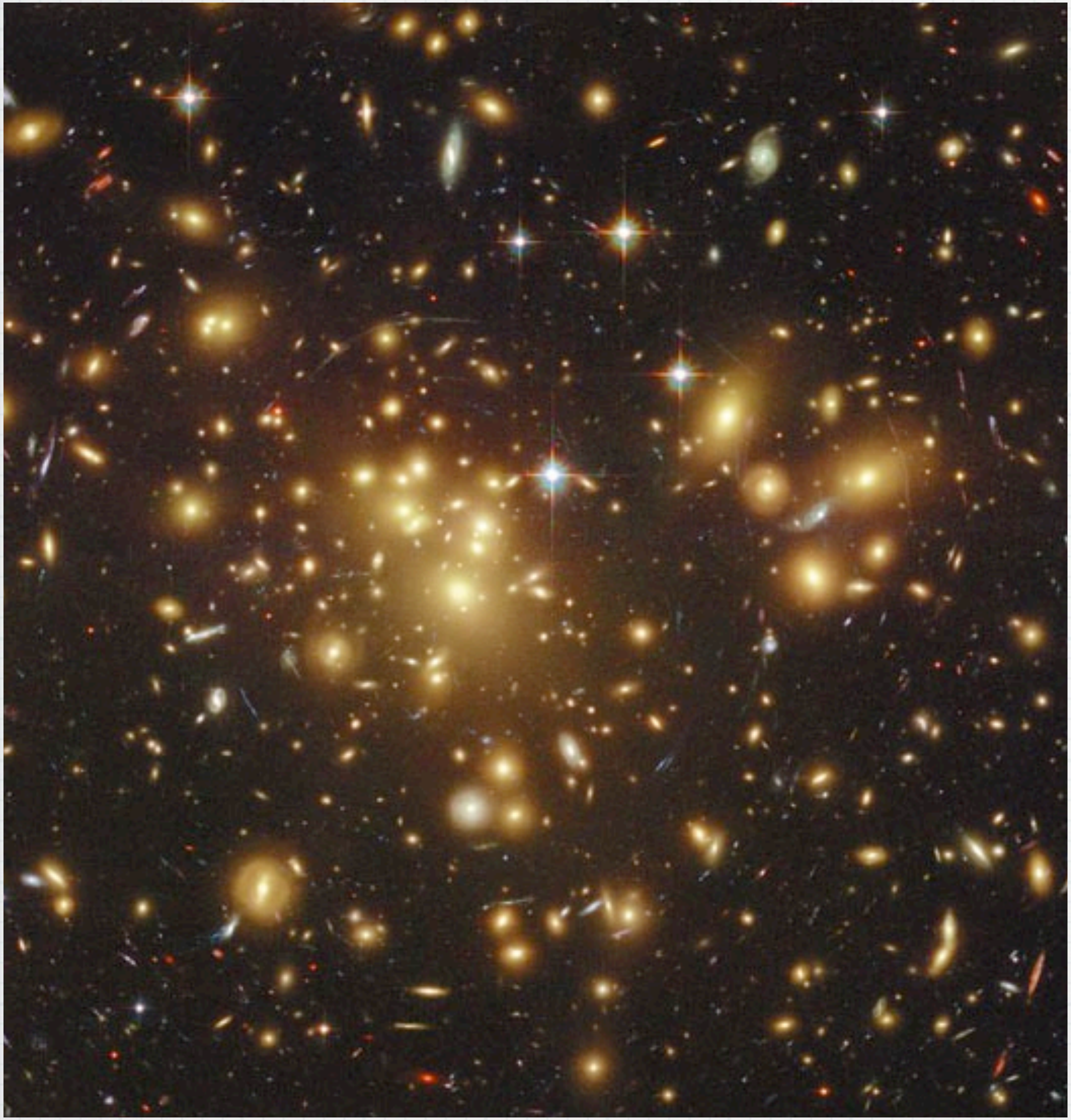
* A single collision takes over several hundred million of years to unfold
* Looking back in time, observations confirm galaxy collisions were more common in the early Universe than they are today

Modeling such collisions on a computer shows that two spiral galaxies can merge to make an elliptical



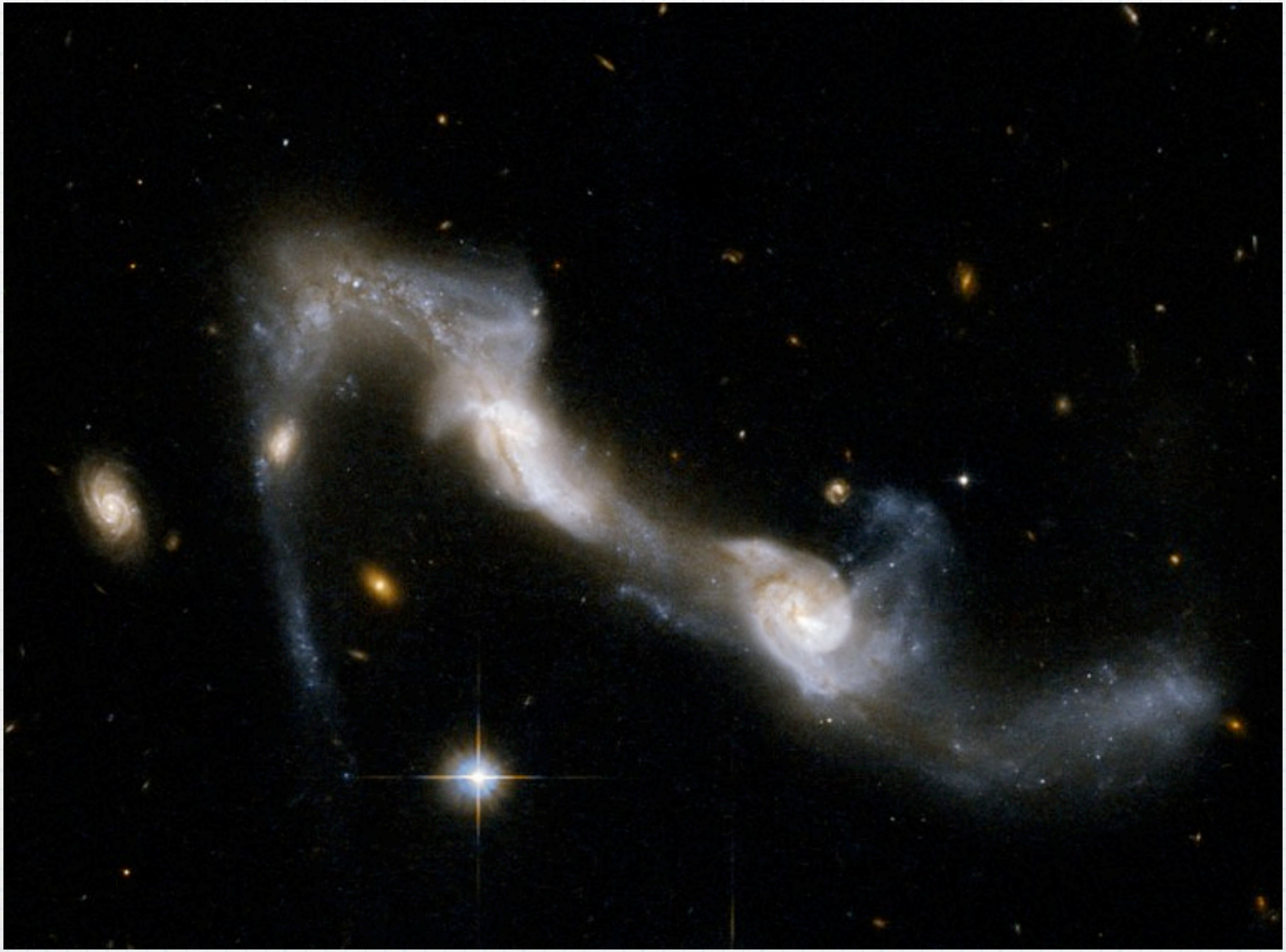
Modeling the collision shows

1. tremendous tidal forces tear both disks apart
2. the orbits of stars are randomized
3. large amount of gas sinks to the collision center and forms new stars at an accelerated rate
4. supernovae and stellar wind blow the rest of the gas away
5. a single elliptical galaxy can emerge

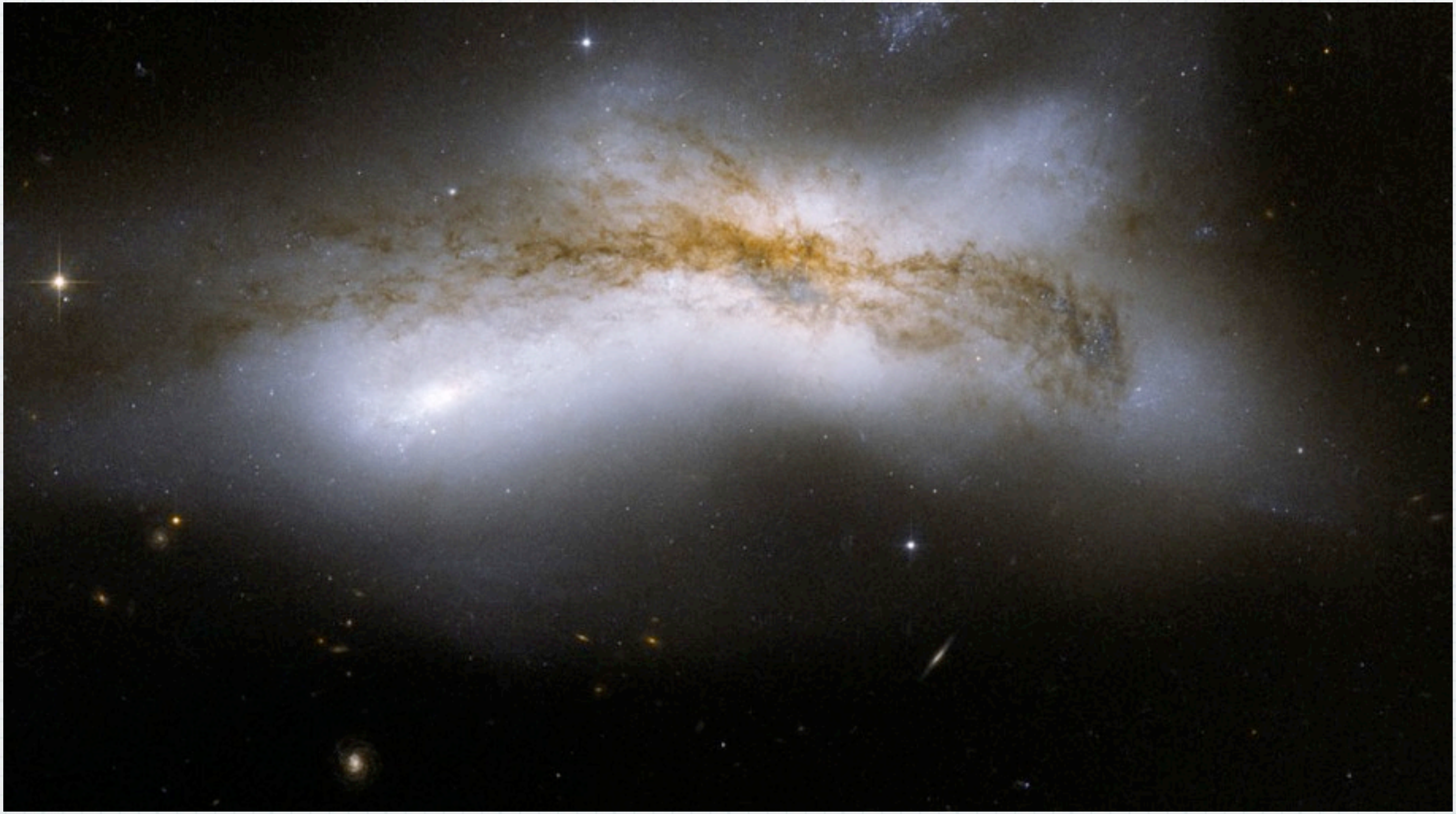


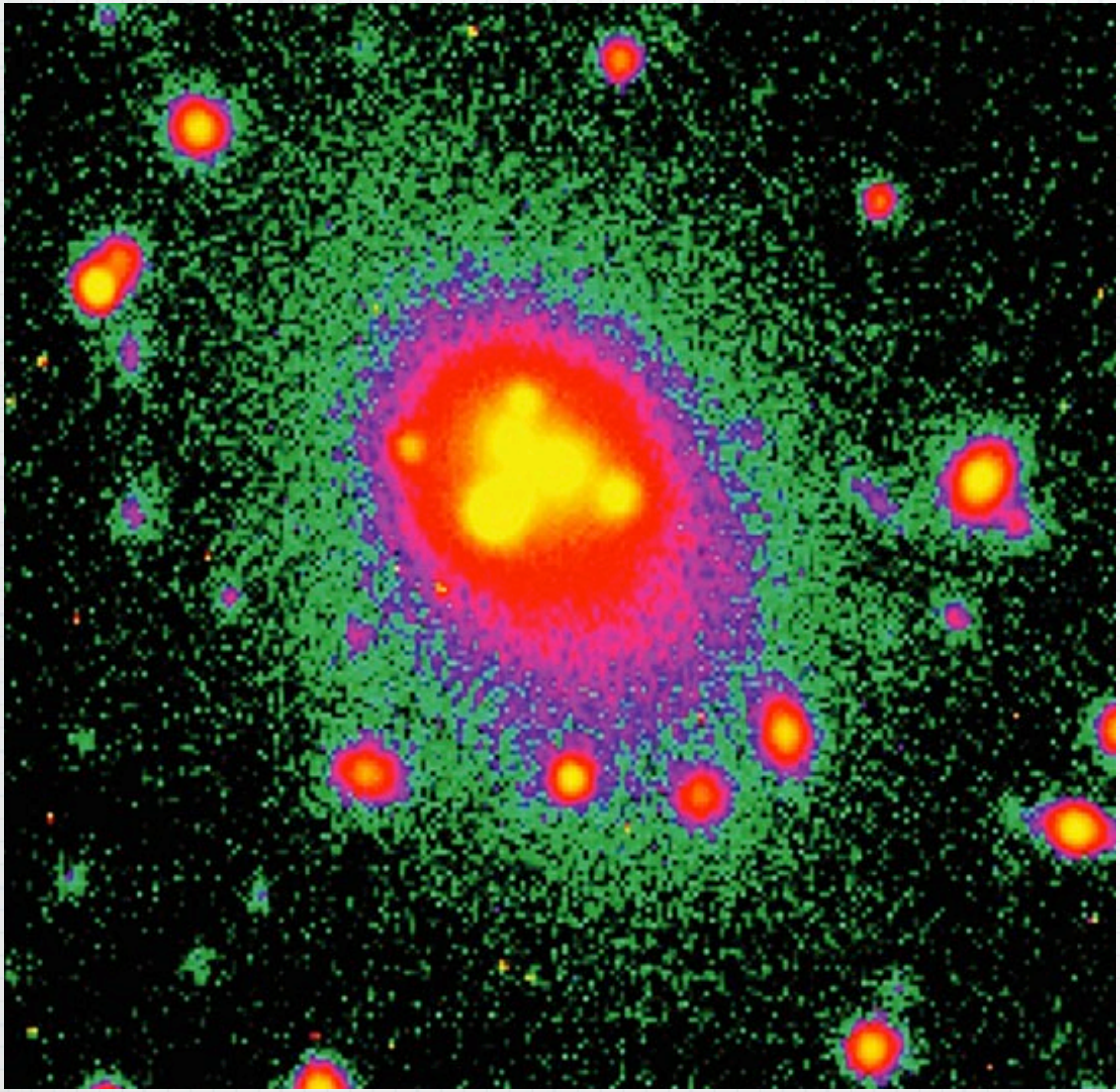
Collisions explain why elliptical galaxies tend to be found where galaxies are closer together

UCG 8335 - early stage of a collision: galaxies are united by a bridge of material



NGC 520 - middle stage of a collision: disks have merged but not the nuclei

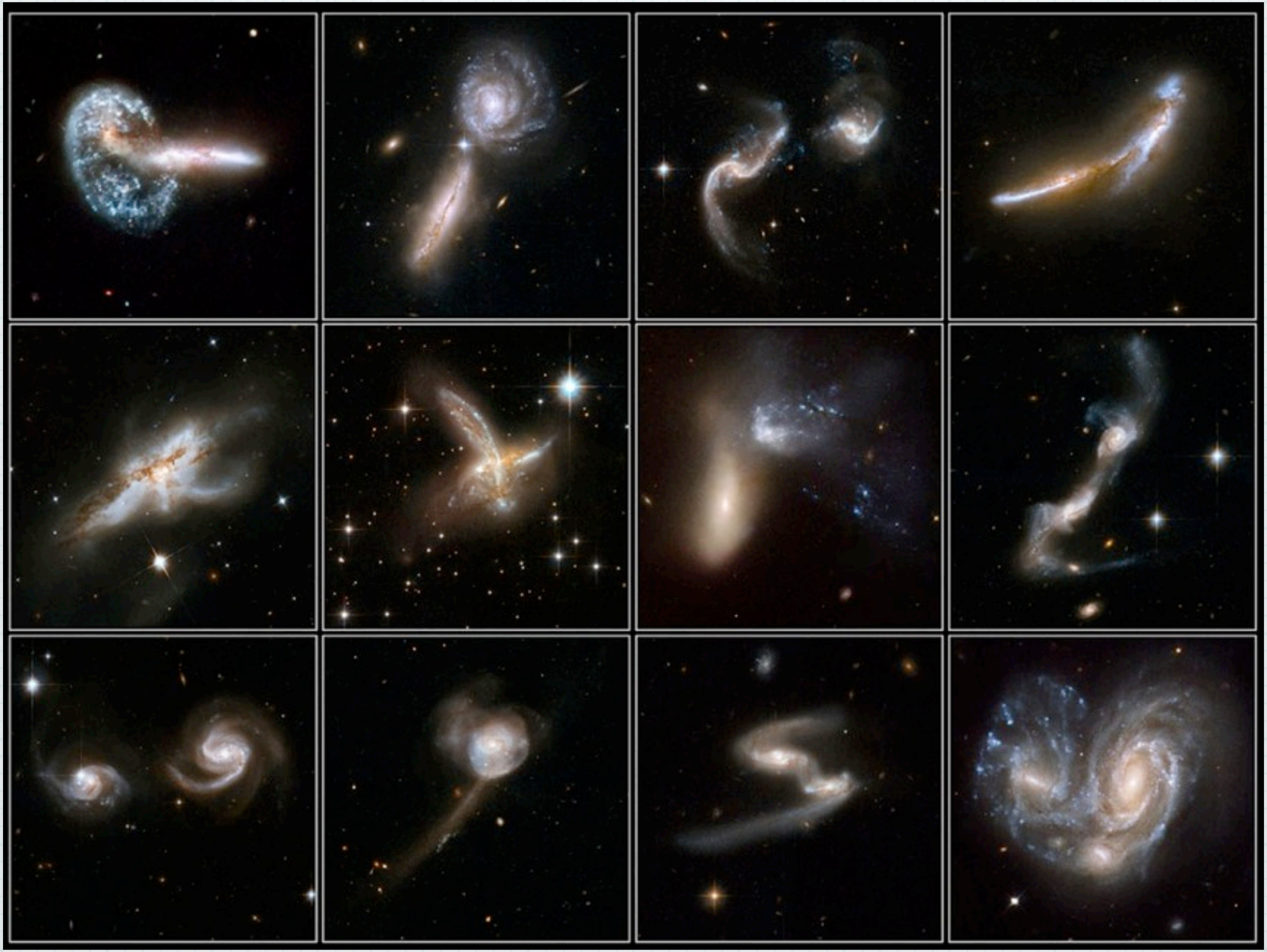




Observations support the idea that elliptical galaxies result from collisions

Giant elliptical galaxies at the centers of clusters (where collisions should be most frequent) seem to have consumed a number of smaller galaxies

Interacting galaxies is common throughout the Universe



The collisions we observe trigger bursts of star formation

Starburst Galaxies

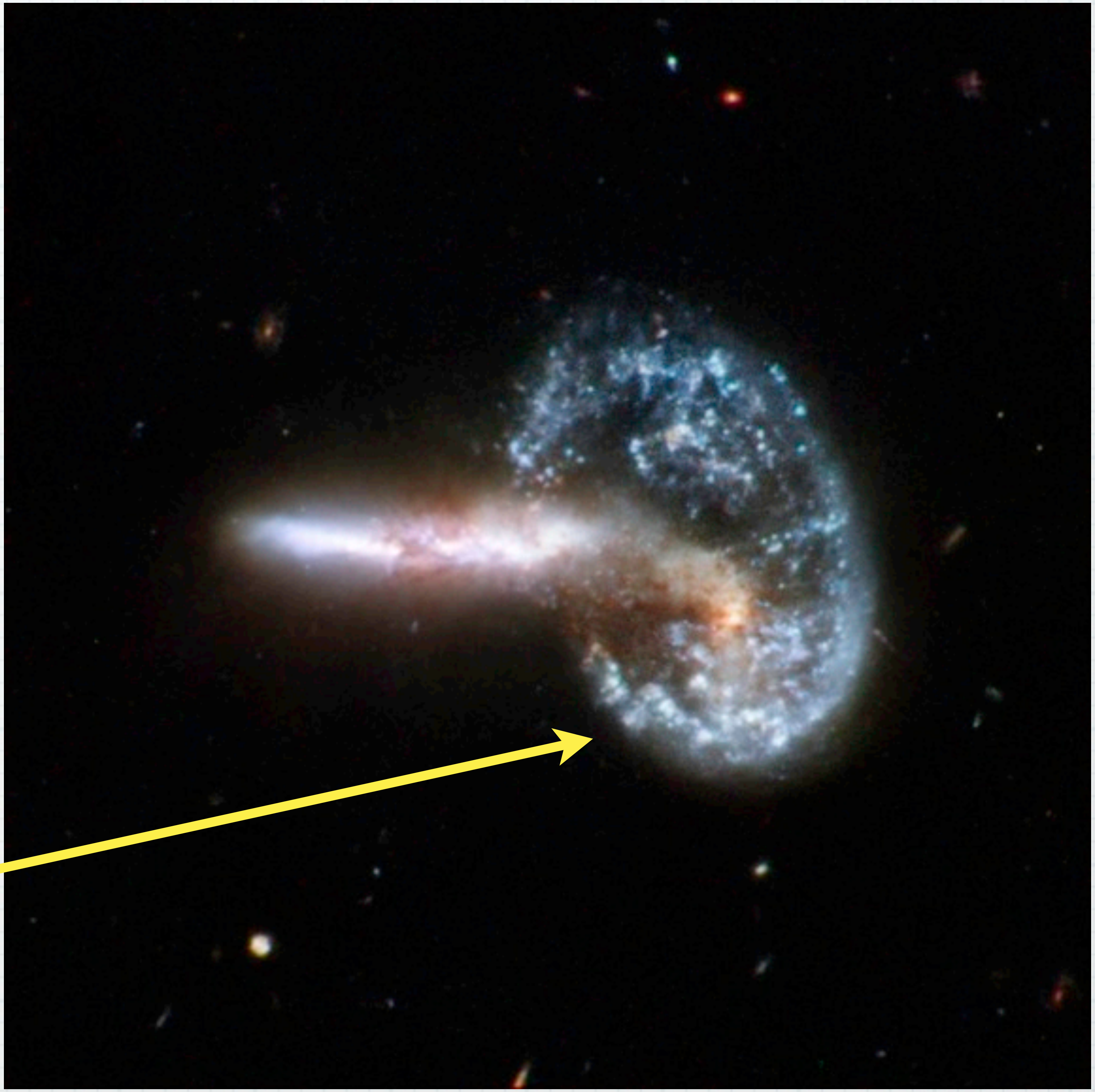
* Galactic collision computer models suggest that a huge ignition of rapid star formation is triggered by the collision
* Most of the gas is consumed, too little is left to form a disk afterwards
* Observations supports this idea

Starburst Galaxies...

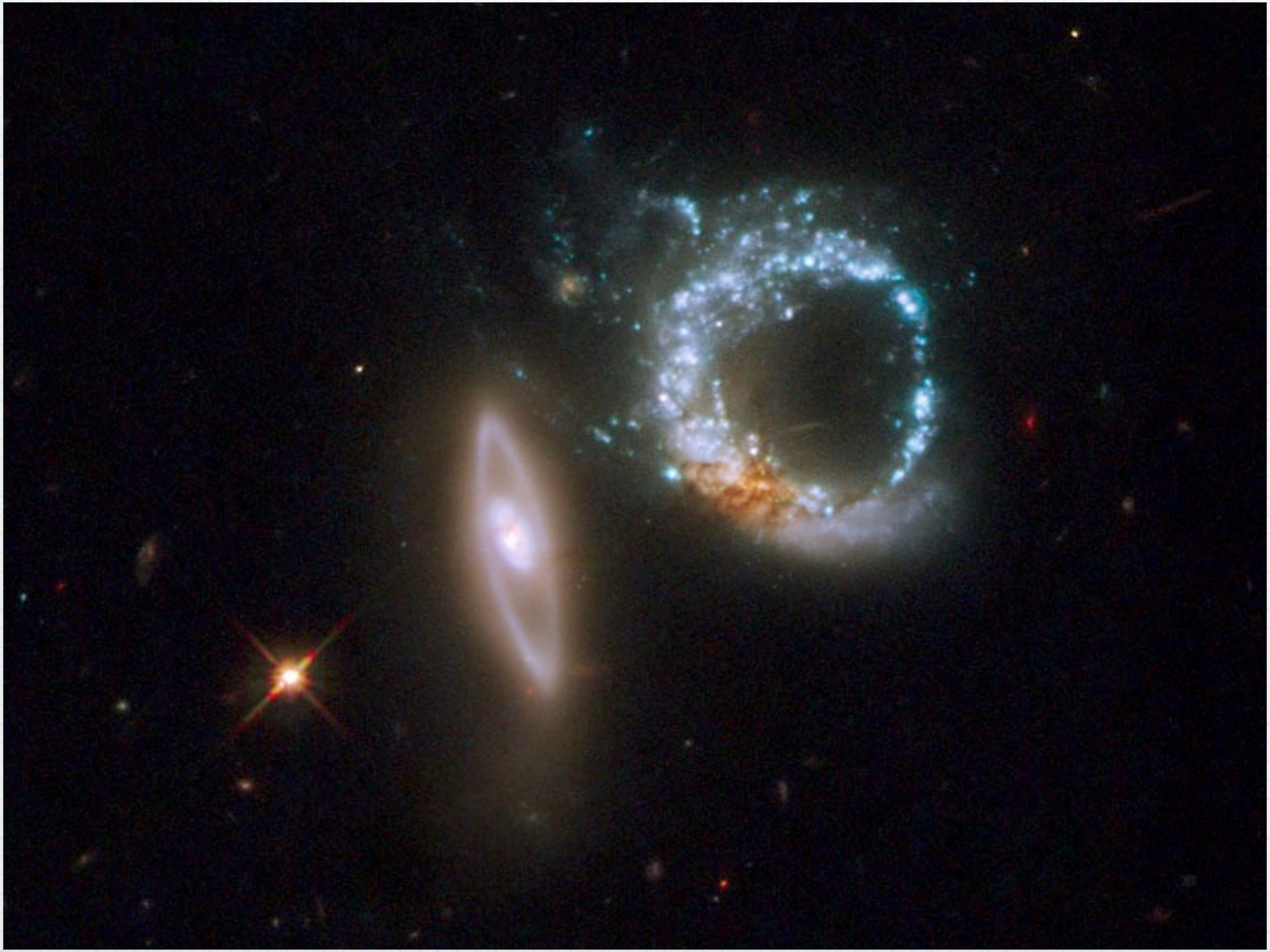
* Galaxies undergoing rapid star formations are called starburst galaxies
* Starburst galaxies are forming stars so quickly that they will run out of star-forming gas in just a few hundred million years

Arp 148 - aftermath of a collision:
a ring-shaped galaxy and a long-tailed companion

The collision produced a shockwave effect that first drew matter into the center and then caused it to propagate outwards in a ring



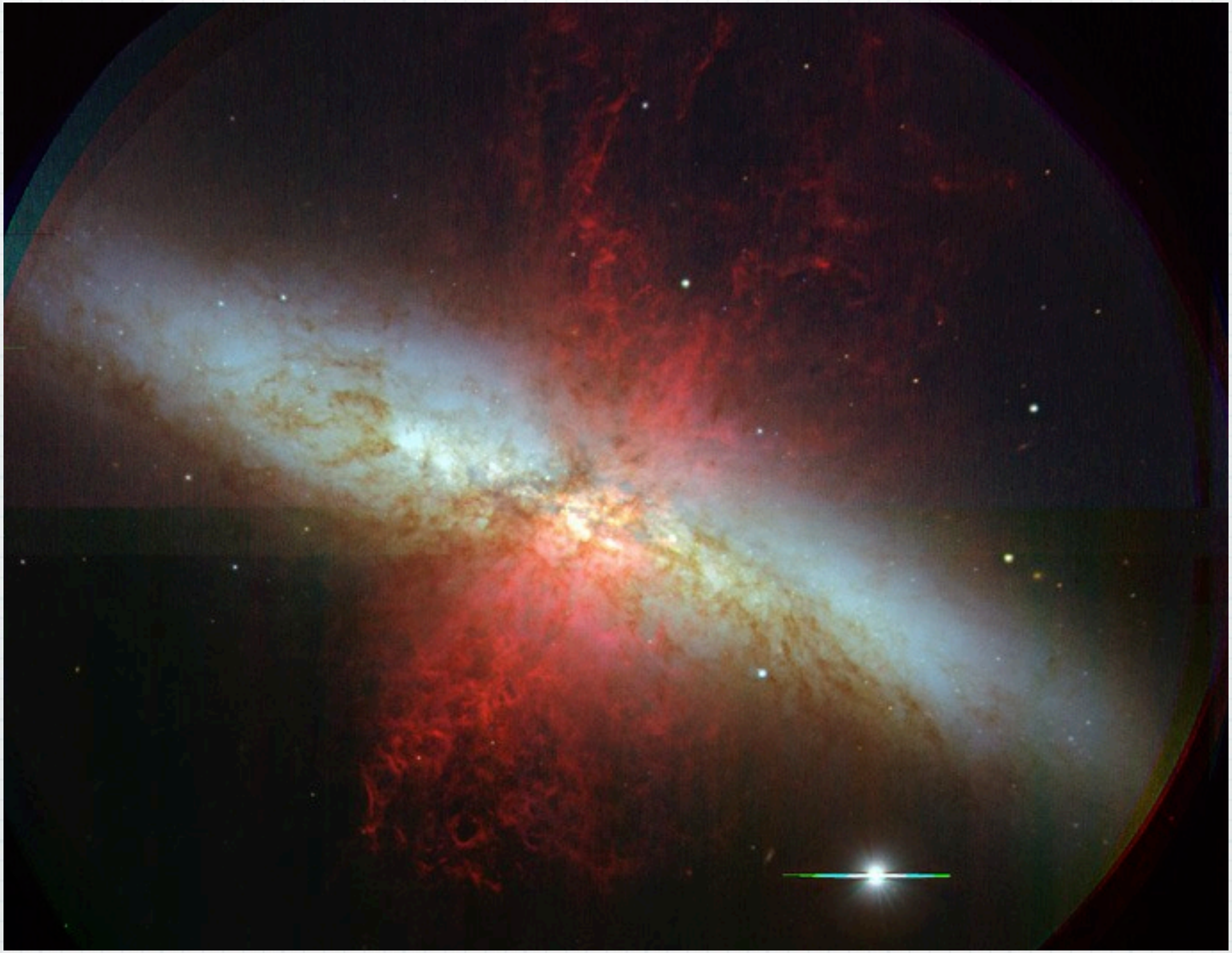
Arp 147 - aftermath of a collision: the Double Ring Galaxies



Star rate formation increase means increase rate of supernova explosions in starburst galaxies which can drive hot gas into intergalactic space via galactic winds

M82 (16,000 light-years across)

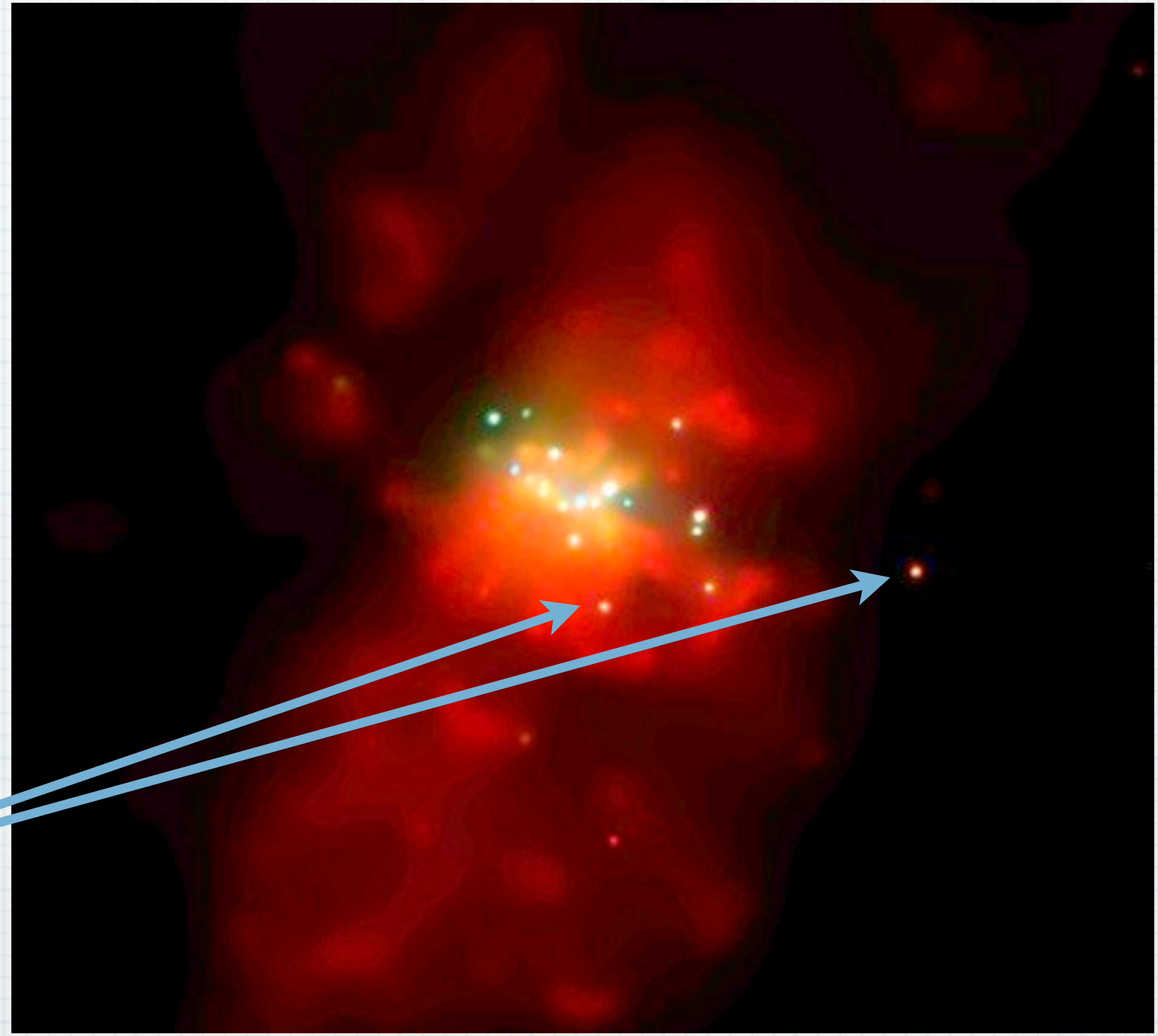
Violently disturbed hot gas (red) blowing out both above and below the disk



Same region and scale as previous image

Reddish region shows X-ray emission from very hot gas blowing out of the disk

X-ray emission from accretion disks (black holes & neutron stars



M82 X-ray image

Snapshot

* How do we observe the life histories of galaxies?
* Today's telescopes enable us to observe galaxies of many different ages because they are powerful enough to detect light from objects with lookback times almost as large as the age of the universe
* We can therefore assemble "family albums" of galaxies at different distances and lookback times

Snapshot

* How did galaxies form?
* The most successful models of galaxy formation assume that galaxies formed as gravity pulled together regions of the universe that were ever so slightly denser than their surroundings. Gas collected in protogalactic clouds, and stars began to form as the gas cooled

Snapshot

* Why do galaxies differ?
* Differences between present-day galaxies probably can arise both from conditions in their protogalactic clouds
* Ellipticals form through the collision and merger of two or more spiral galaxies

Active Galactic Nuclei (Seyfert, Quasars, Blazars)

* Some galaxies display phenomena emanating from their centers that are so powerful and spectacular that they are named **active galactic nuclei (AGN)**
* Most are **Seyfert galaxies:** their centers produce spectral line of highly ionized gas
* The brightest of them all are called **quasars**
* Quasars shine in the **visual** and **radio spectrum**

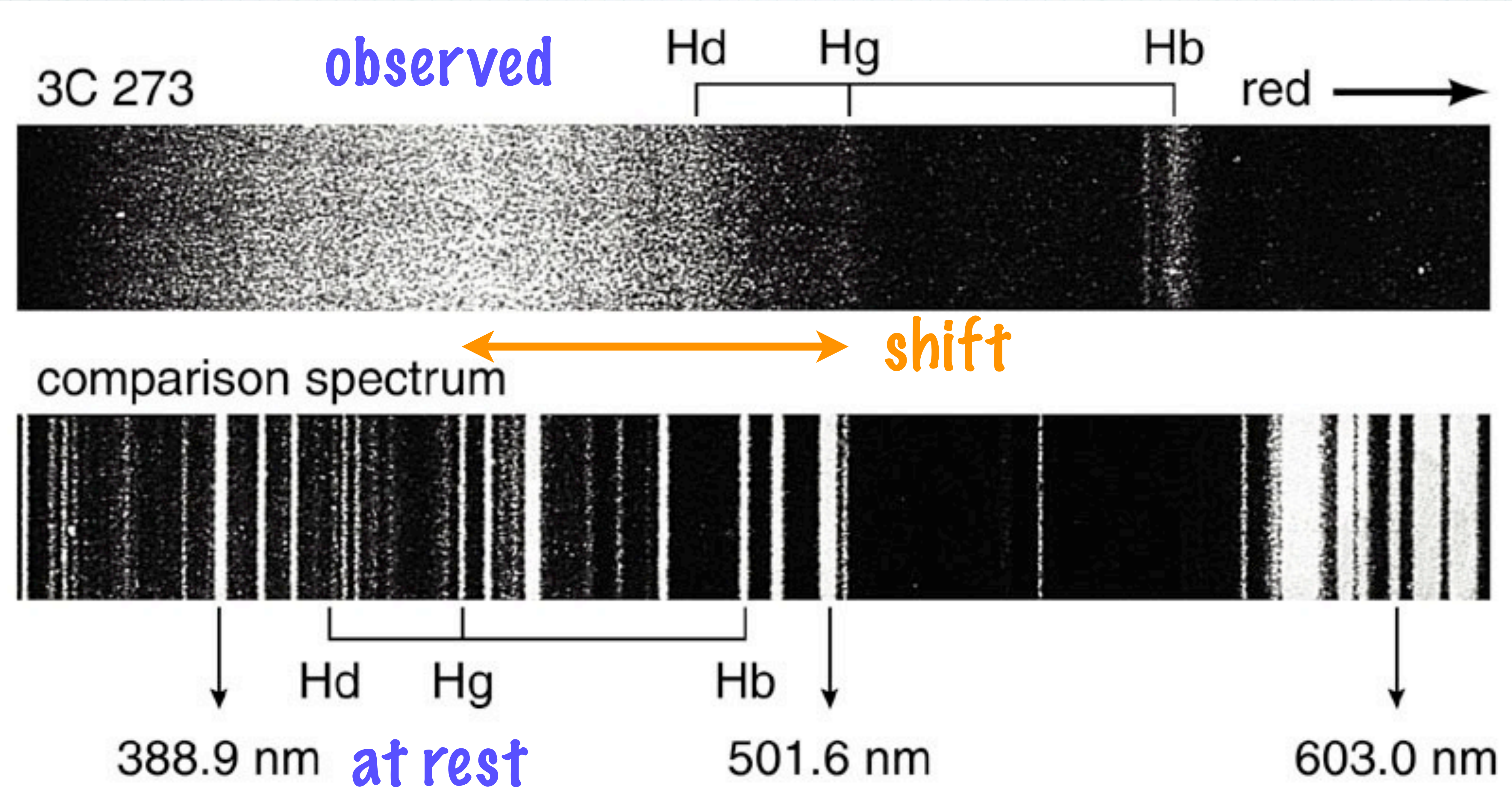
Seyfert Galaxies

* Named after Carl Seyfert
* They are characterized by extremely bright nuclei, and spectra which have very bright emission lines of hydrogen, helium, nitrogen, and oxygen
* These emission lines are believed to originate near an accretion disk surrounding the massive central black hole

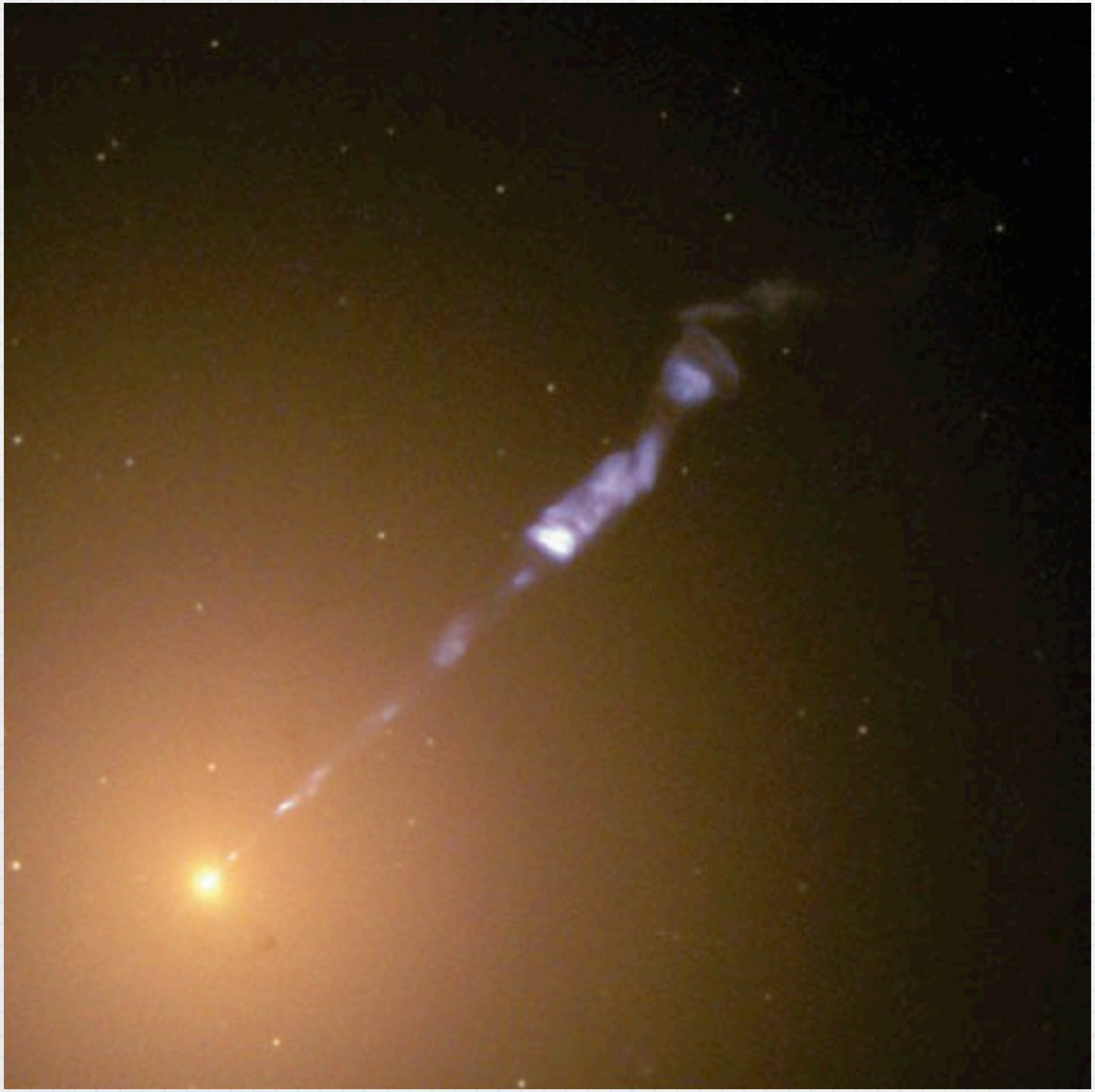
Quasars
(quasi-stellar radio sources)

* They were first discovered as very localized intense radio sources but their centers looked like powerful stars
* The brightest quasars shine with the luminosity of 1,000 galaxies the size of the Milky Way, but the parent galaxy is very faint
* They are relics of the past: they are not seen in any nearby galaxy but only on the very distant ones

The highly redshifted spectra of quasars indicate large distances (Hubble's law)



Active Nucleus in M87



If the center of a galaxy is unusually bright we call it an **active galactic nucleus (AGN)**

Quasars are the most luminous examples

What are quasars?

* Being seen only in distant galaxies tells us that quasars were common billions of years ago - when galaxies were young
* Whatever shone as a quasar in young galaxies must become dormant as galaxies age

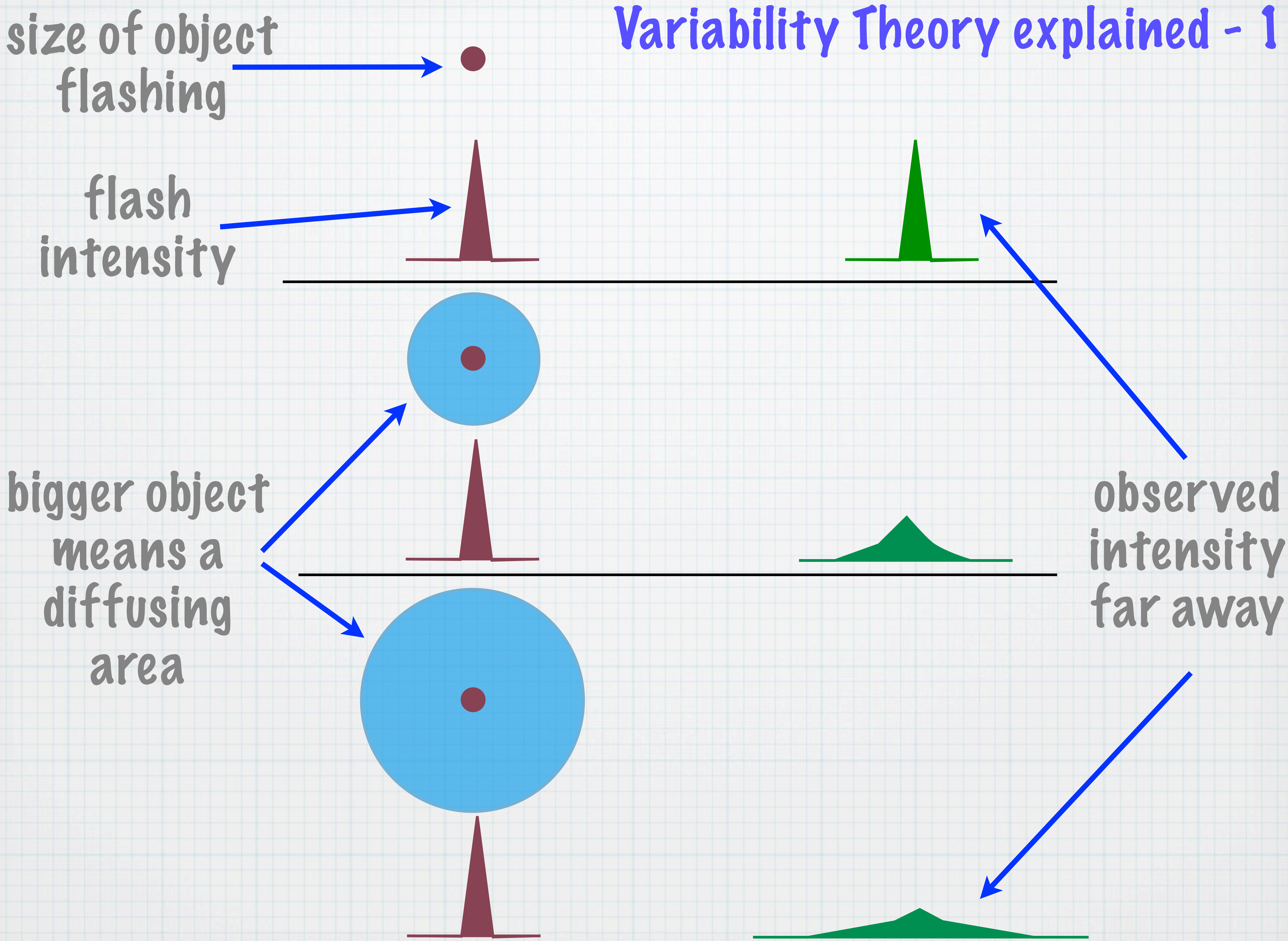
Quasar Evidence

* From brightness and distance we find that luminosities of some quasars are greater than 10^{12} L_{Sun} (1 trillion Suns)
* Variability theory shows that all this energy comes from region smaller than Solar System

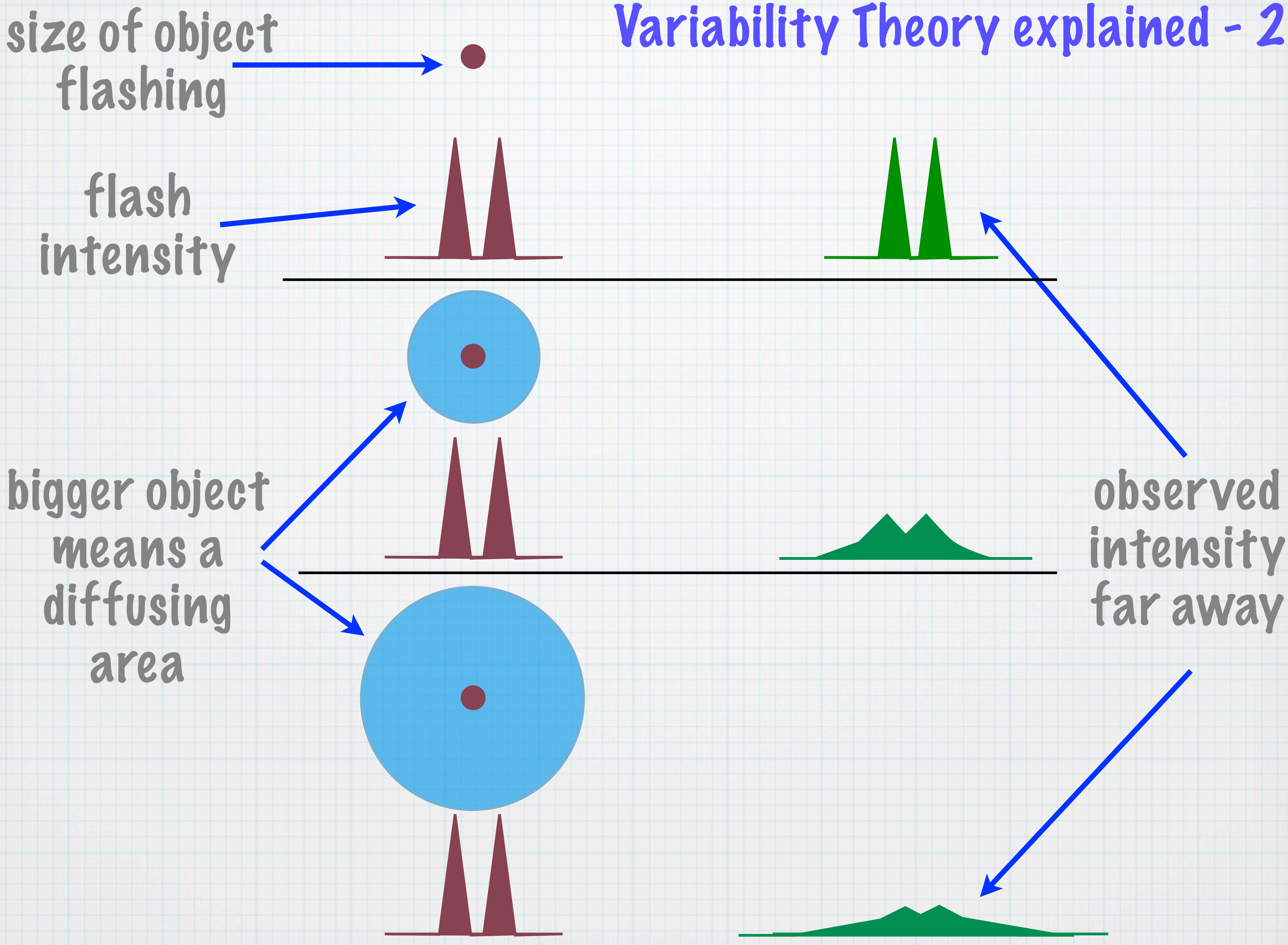
Variability Theory

* Variability theory: the variations in luminosity gives clues about an object's size
* If we see an object whose luminosity varies in a 1-hour cycle, it cannot be bigger than one light-hour. If it were bigger, we would not be able to see the variations as they would be smeared out by light coming from the close and far side of the object

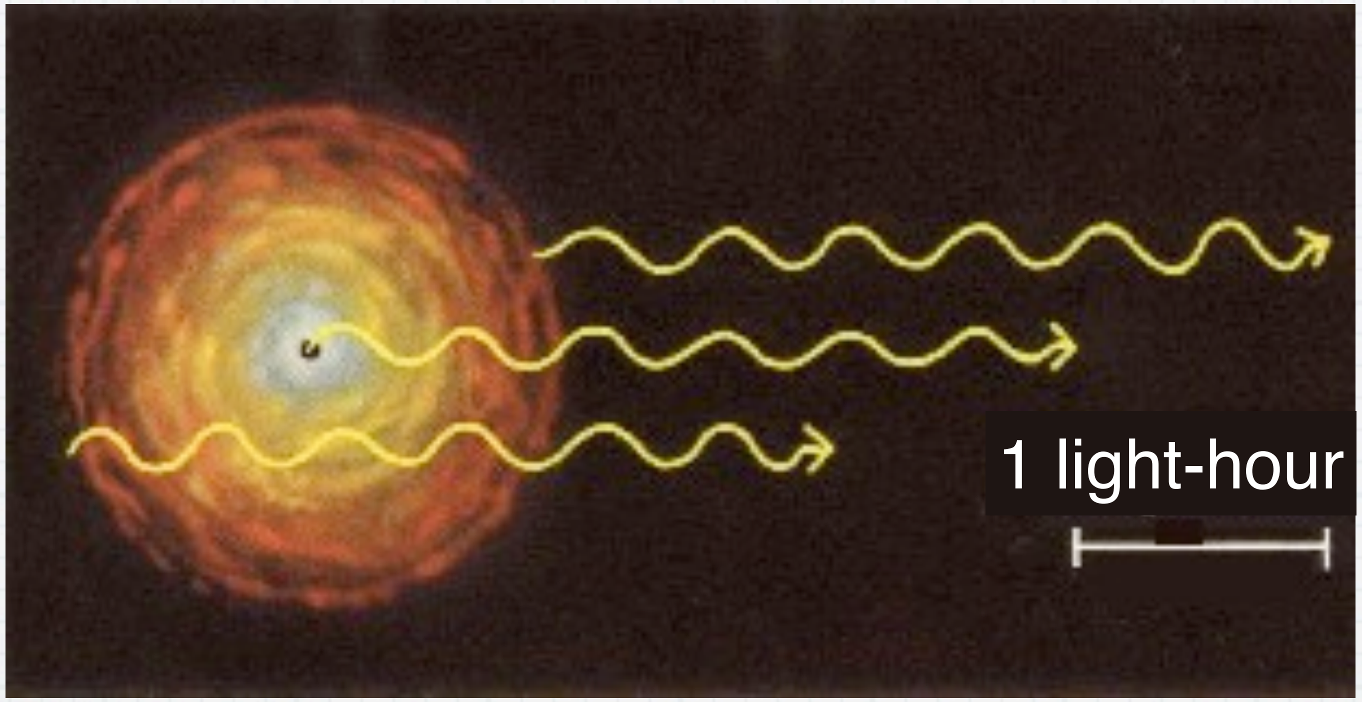
Variability Theory explained - 1



Variability Theory explained - 2



Variability Theory...



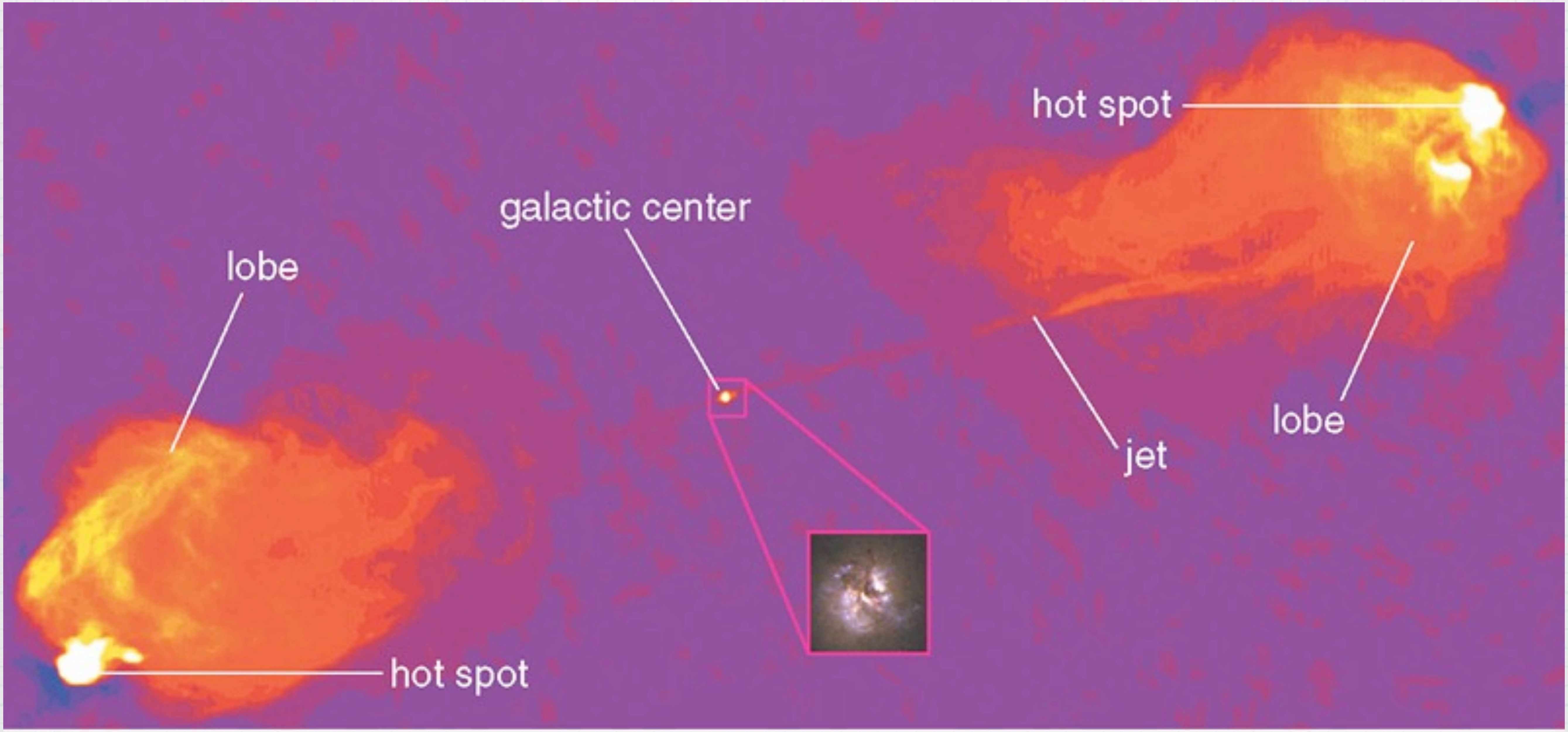
The Variability Timescale of a quasar limits the size of its light emitting region

This "flash" would be observed as a rise and fall in the brightness over a two hour period

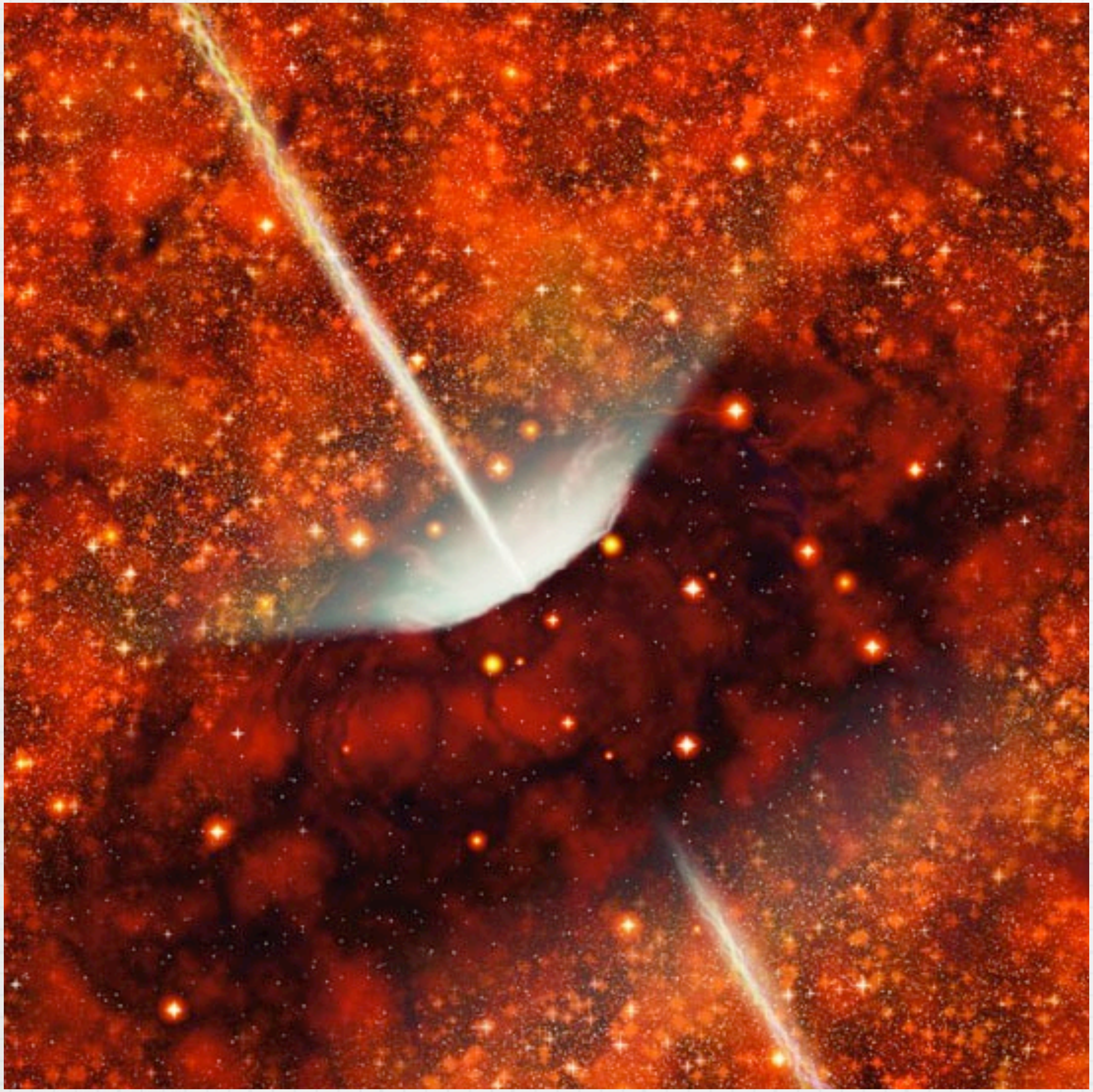
Radio Galaxies

* Radio galaxies are another type of active galaxy that are very luminous at radio wavelengths, but not in the visual
* The observed structure in radio emission is determined by the interaction between twin jets and the external gas happening at relativistic speeds

Radio galaxies contain active nuclei shooting out vast jets of plasma that emits radio waves



The lobes are created when the jets hit surrounding intergalactic gas



Astronomers suspect that quasars and radio galaxies are the same type of object seen in different ways:

Many quasars have jets and radio lobes and radio galaxies don't appear as quasars because dusty gas clouds block our view of accretion disk

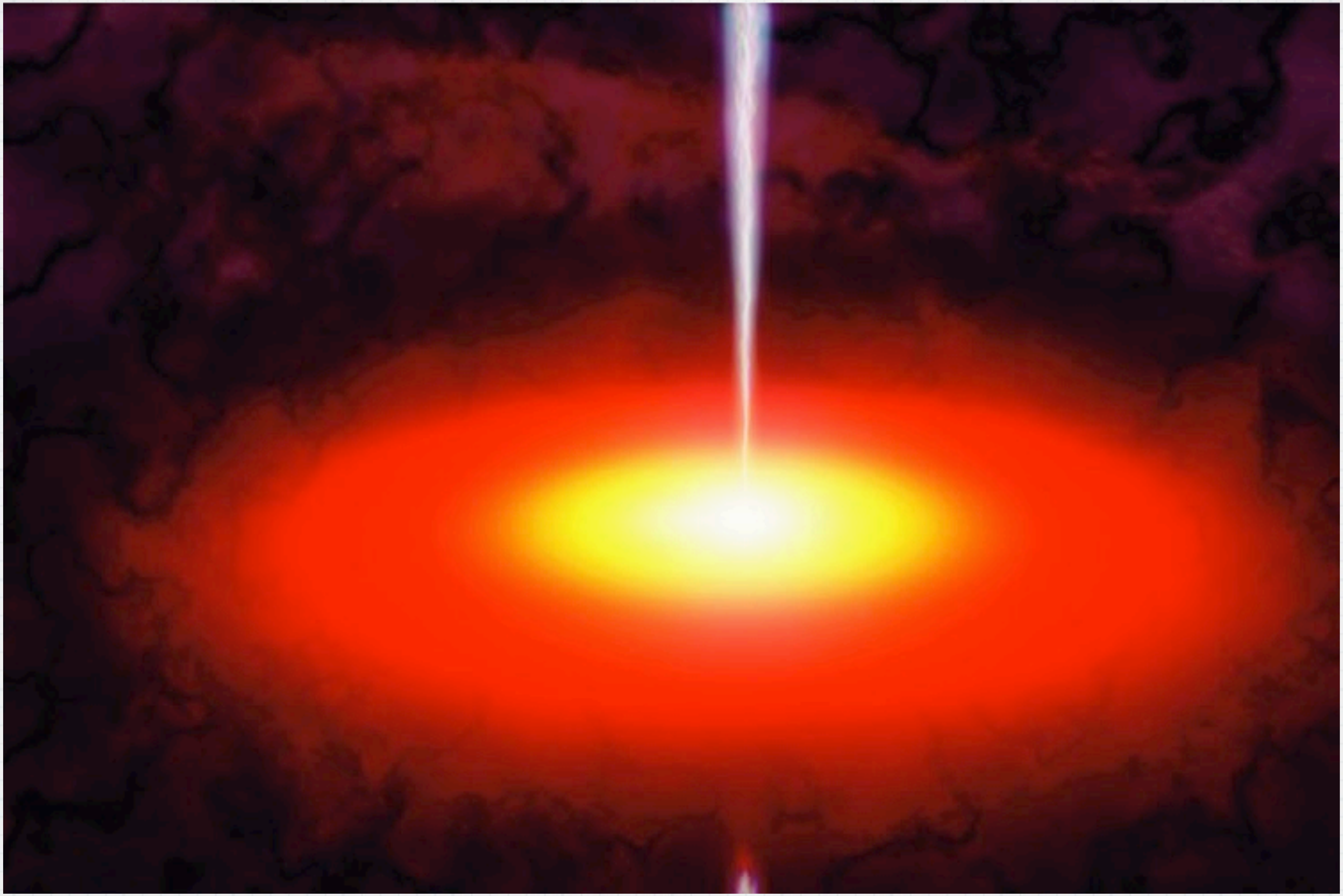
What Powers an AGN?

* So much energy in such small volumes...

➡ The energy must be coming from matter falling into supermassive black holes via an accretion disk

Back to Seyfert Galaxies and Quasars

* So what are Seyfert galaxies and quasars and why did they fade away?
* The suspected answer: the energy of these objects was a gigantic accretion disk surrounding a supermassive black hole (a black hole with a mass of millions to billions that of our Sun) When the accretion disk disappeared, so did the quasar



Accretion of gas onto a supermassive black hole appears to be the only way to explain all the properties of Seyfert galaxies, quasars and blazars

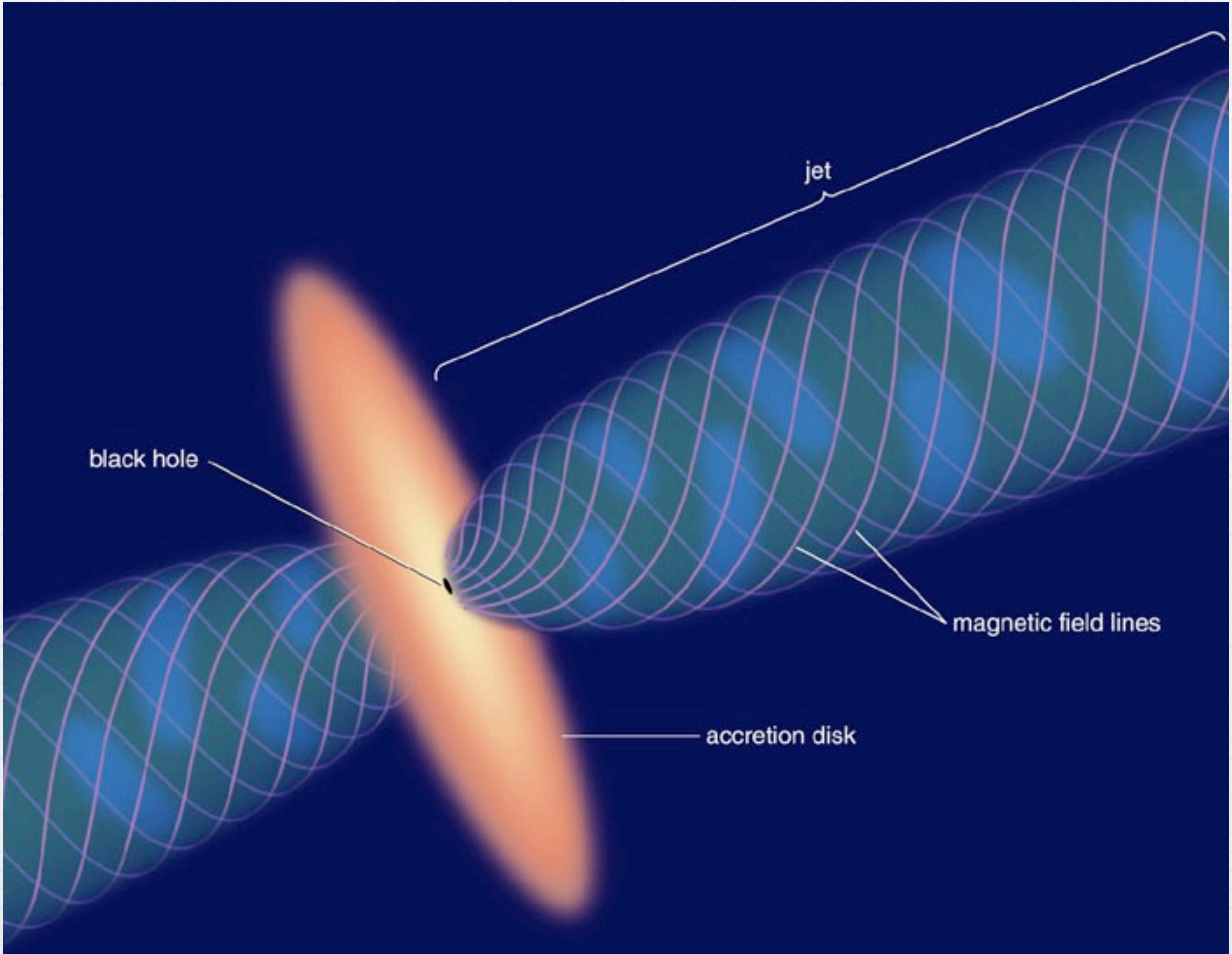
Blazars

- A blazar is a quasar relativistic jet which happens to be pointing in the general direction of the Earth
- (like a pulsar but with a lot more energy)

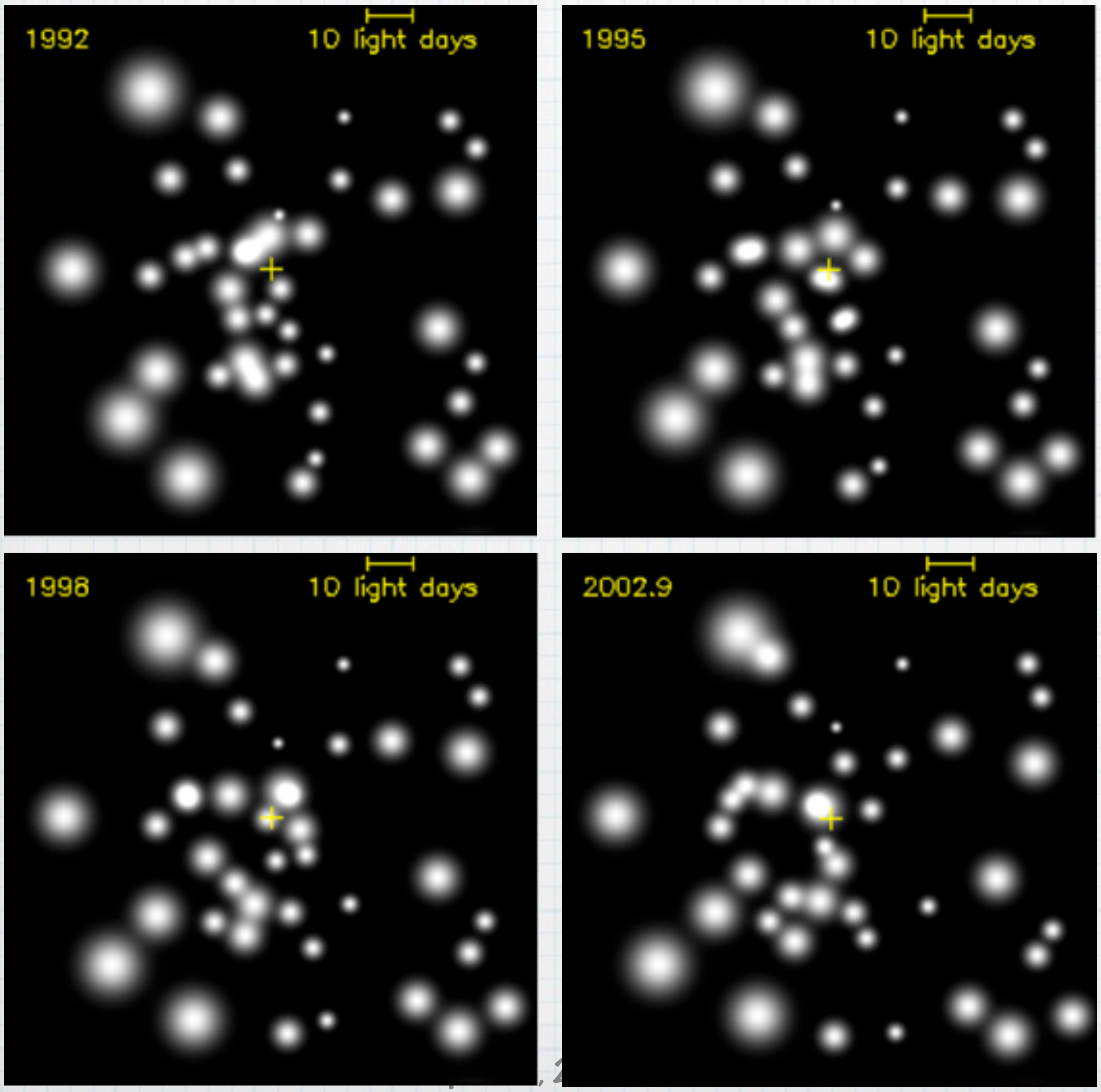
Energy from a Black Hole

* Gravitational potential energy of matter falling into black hole turns into kinetic energy
* Friction in accretion disk turns kinetic energy into thermal energy (heat)
* Heat produces thermal radiation (photons)
* This process of accretion is one of the most efficient energy producing process known
* It can convert up to 40% of the accretion disk's mass into radiation

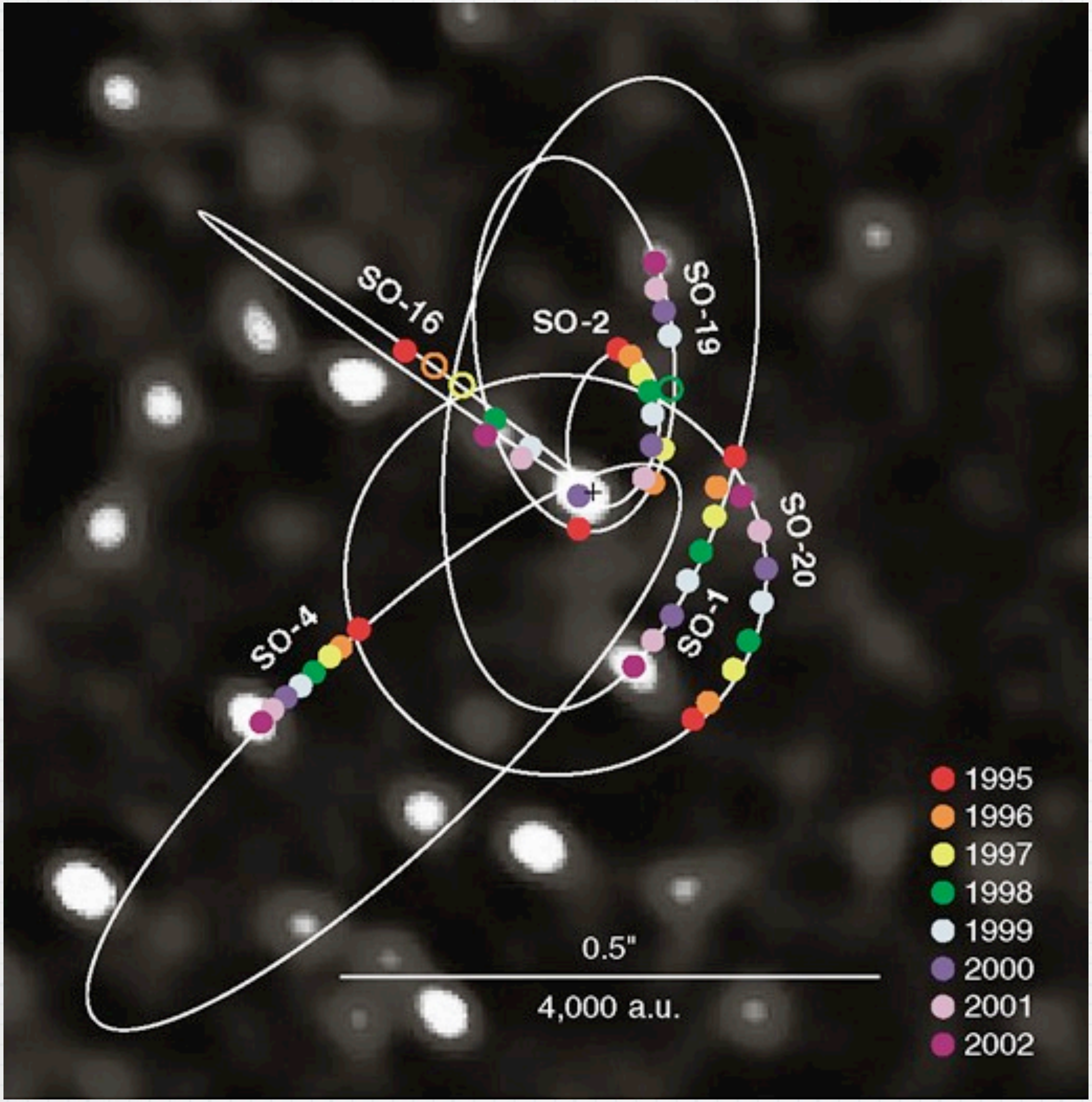
Jets are thought to come from twisting of magnetic field in the inner part of accretion disk



Do supermassive black holes really exist?



This series of images is off our galactic center from 1992 to 2003

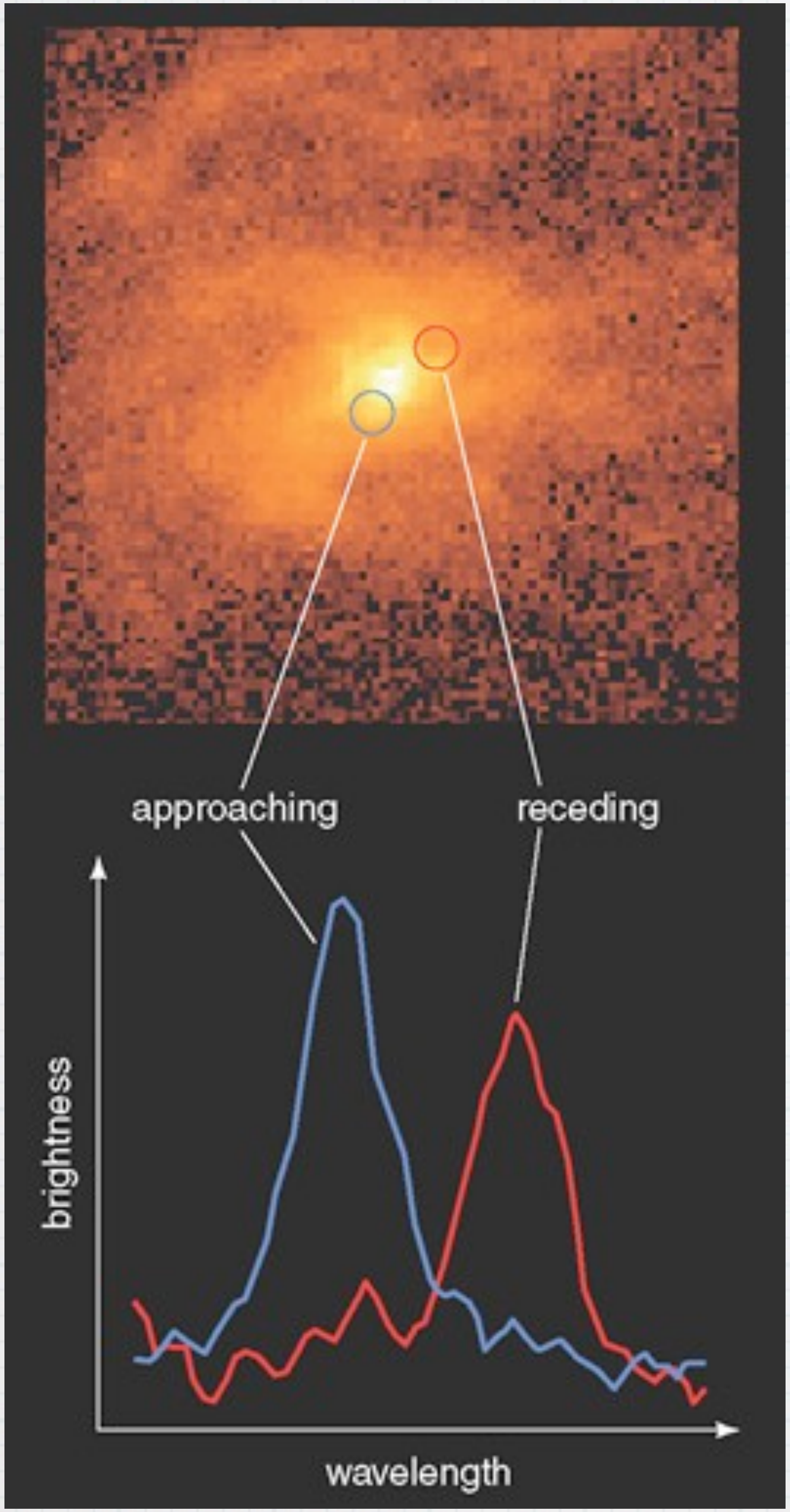


Orbits of stars at center of Milky Way stars indicate a black hole with mass of 4.1 million M_{Sun}

A 2008 study measured the diameter of Sagittarius A* to be 0.3 AU (44 million km)

Do supermassive black holes really exist?

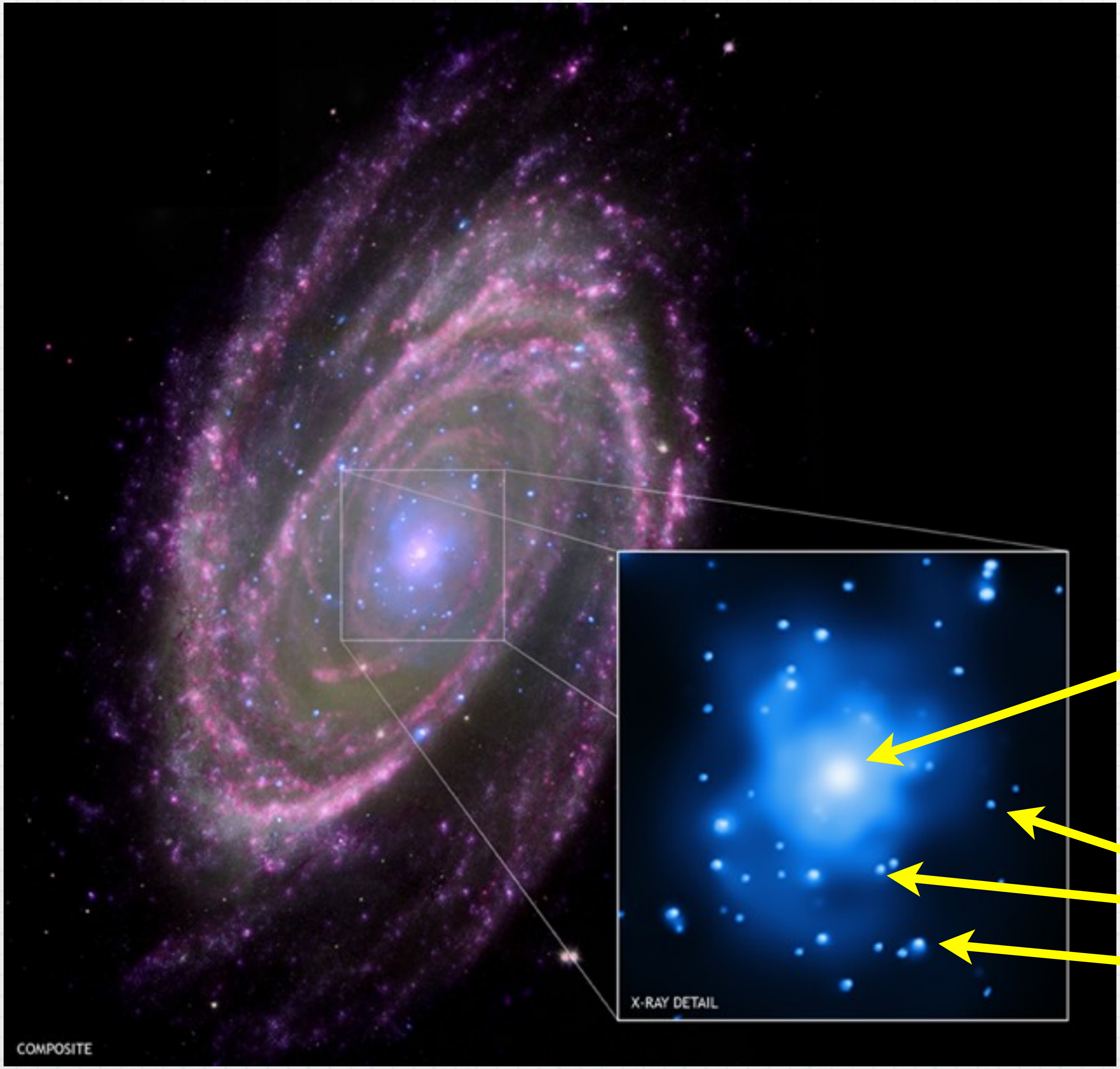
* We have evidence of a supermassive black hole in our galaxy
* Is that an exception or the rule?



Orbital speed and distance of gas orbiting center of the nearby M87 galaxy indicate a black hole with mass of 3 billion M_{Sun}

Actually, similar observations on other nearby galaxies also indicate the presence of a supermassive black hole at their centers too

M81: one supermassive black hole and many smaller ones



Composite color shot including
X-ray (blue)
IR (pink)
UV (violet)
visible (green)

X-ray data highlights central supermassive (70 million M_{Sun}) black hole

and many black holes in binary star systems

Black Holes in Galaxies

* Many nearby galaxies – perhaps all of them – have supermassive black holes at their centers
* These black holes seem to be dormant active galactic nuclei
* All galaxies may have passed through a quasar-like stage when they were young and forming

Illustration of the 9.7 billion M_{sun} black hole lurking in the center of NGC 3842

Solar System shown to scale

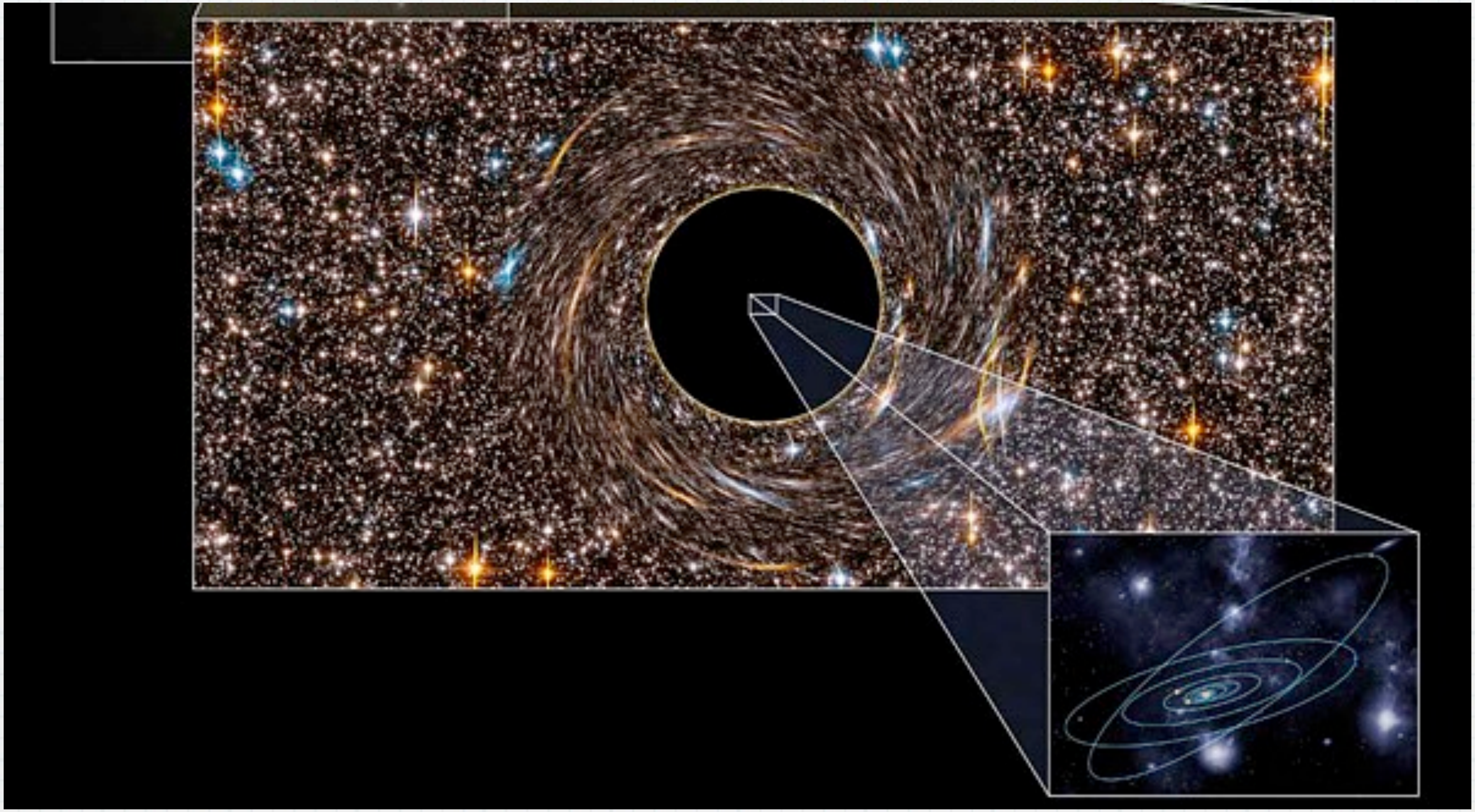
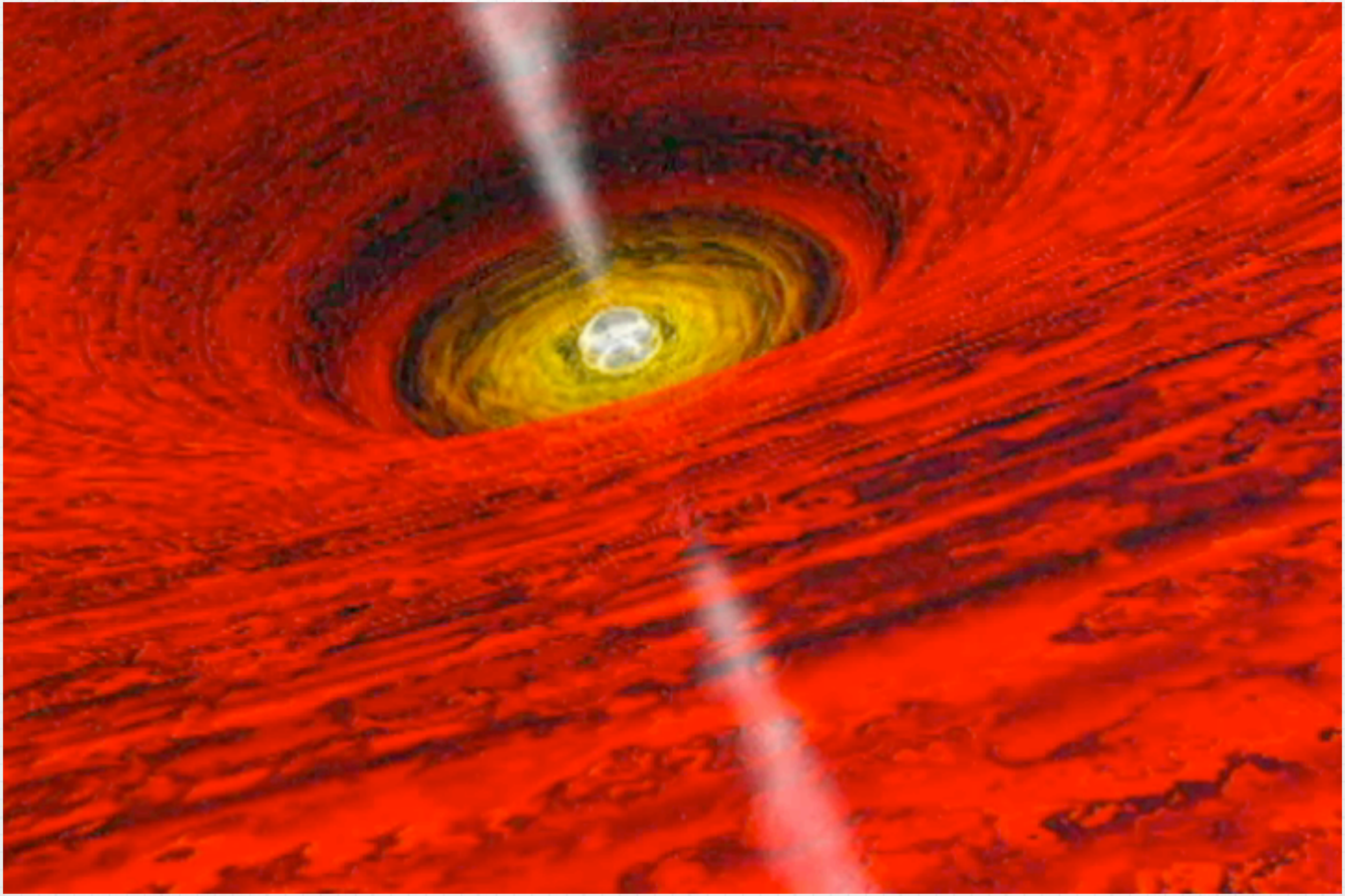


Illustration by Pete Marenfeld/National Optical Astronomy Observatory

Another one weighs as much as 21 billion Suns, is in the galaxy known as NGC 4889

Supermassive Black Hole in Galaxies

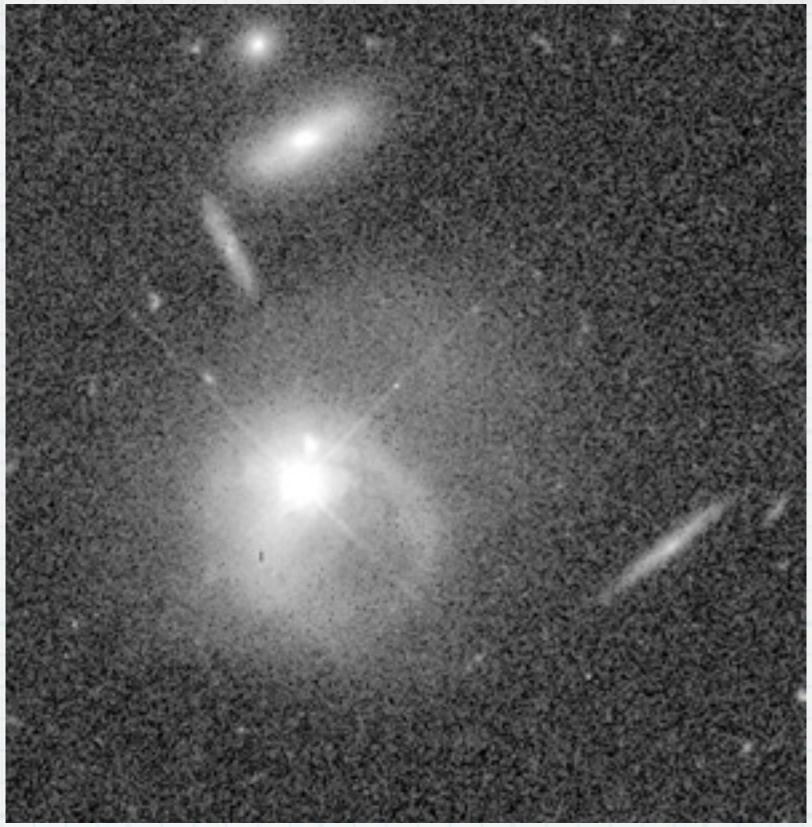


Finding the Mass of Black Holes

1. By observing the motion of stars or of gas near such large black holes (works only for 30 or 40 nearby spirals)
2. By measuring a temperature peak of hot gas in the center of a galaxy
3. By measuring how tightly the spiral arms of a galaxy wind up

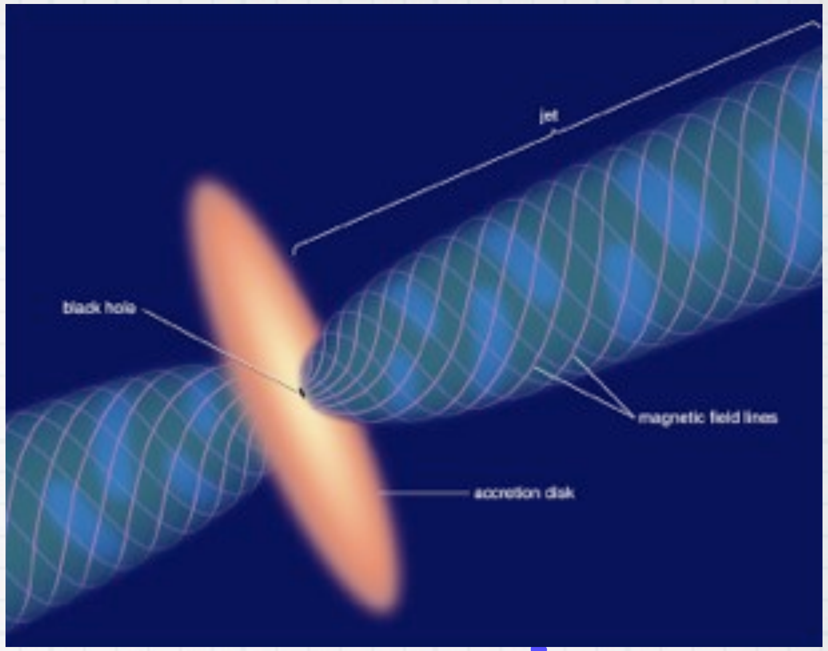
* These 3 methods are independent and their results agree

Snapshot



* What are quasars?
* Some galaxies have unusually bright centers known as active galactic nuclei. **A quasar is a particularly bright active galactic nucleus**. Quasars are generally found at very great distances, telling us that they were much more common early in the history of the Universe

Snapshot



* What is the power source for quasars and other active galactic nuclei (radio galaxies and blazars)?
* Supermassive black holes are thought to be the power sources for active galactic nuclei. As matter falls into a supermassive black hole through an accretion disk, its gravitational potential energy is transformed into thermal energy and then into light with enormous efficiency

Snapshot

* Do supermassive black holes really exist?
* Observations of orbiting stars and gas clouds in the nuclei of galaxies suggest that all galaxies may harbor supermassive black holes at their centers

Age of Galaxies

* Most major galaxies were created early in the Universe's history (about 11 to 13 billion years ago)
* For a long time, astronomers thought large galaxies were no longer being born
* But recent discoveries suggest that the Universe is still spawning large galaxies like our own

Snapshot

* How old are galaxies?
* Most were born about 11 to 13 billion years ago
* New telescope data suggests that few large galaxies were born 100 million to 1 billion years ago suggesting that some galaxies may still be forming now

How Many Galaxies?

* An average galaxy contains between 100 billion and 1 trillion stars
* There are approximately 300 billion to 1 trillion galaxies in the visible Universe

References

* http://www.youtube.com/watch?v=kV33t8U6w28
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