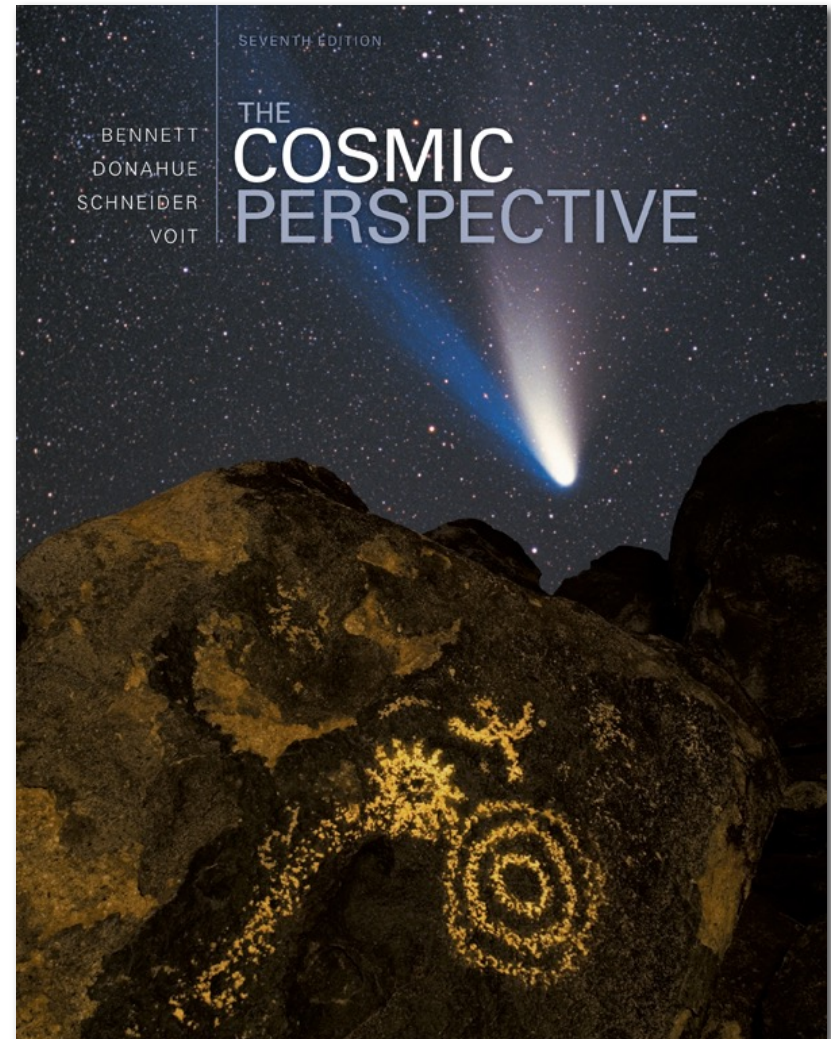# The Cosmic Perspective

Seventh Edition
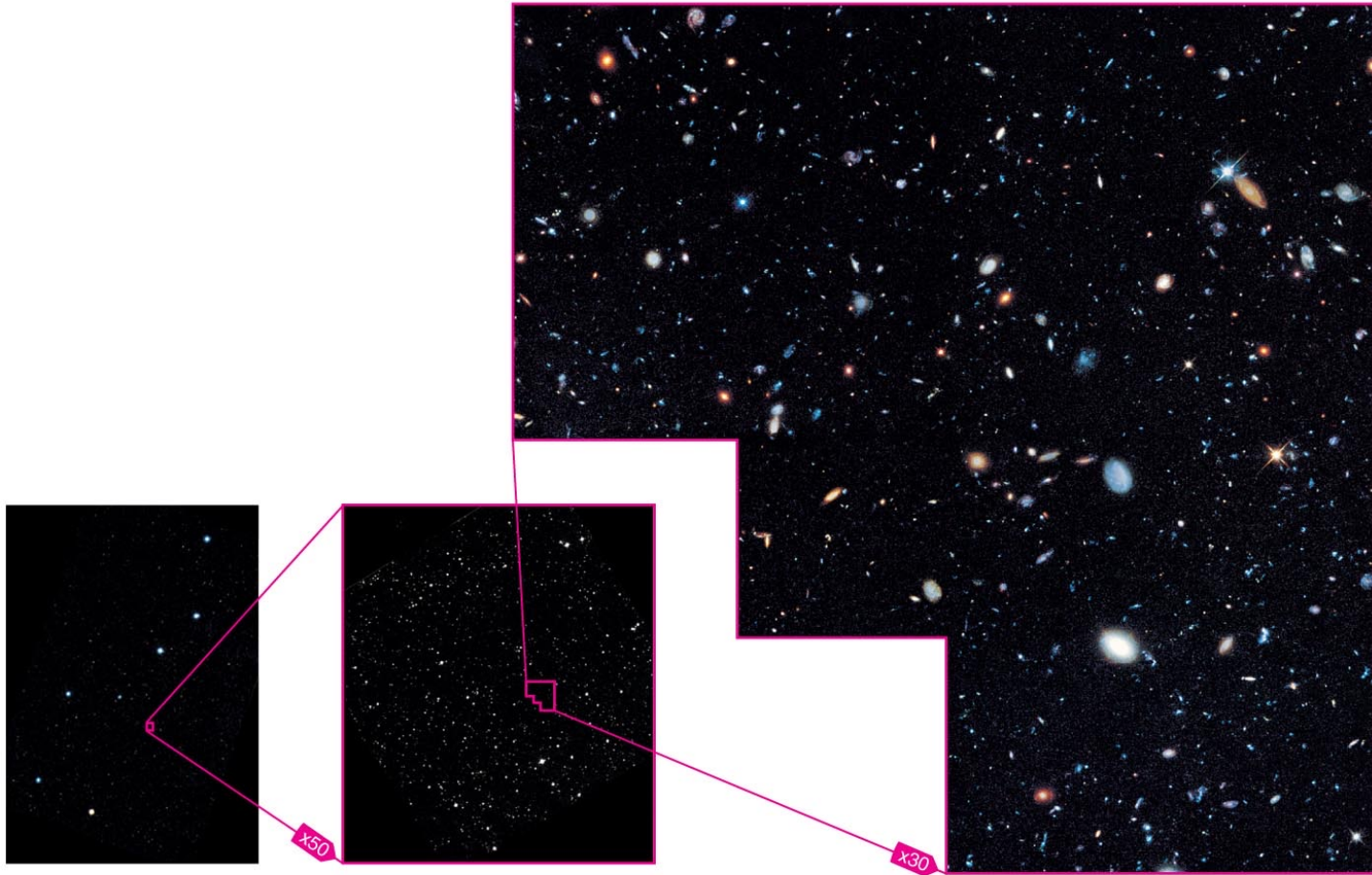
Galaxies and the Foundation of Modern Cosmology
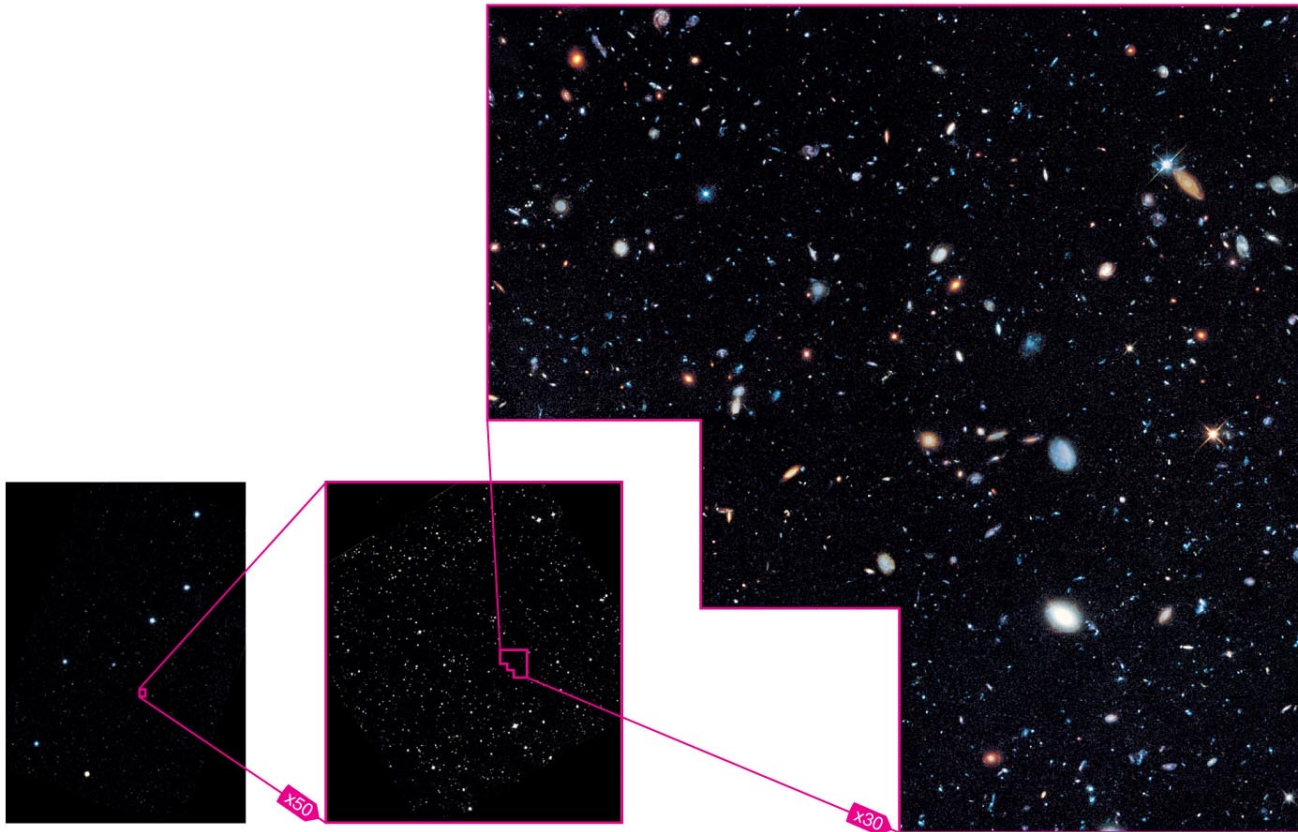
20.1 Islands of Stars

- Our goals for learning:
  - **How do galaxies evolve?**
  - **What are the three major types of galaxies?**
  - **How are galaxies grouped together?**

How do galaxies evolve?

Hubble Deep Field

- Our deepest images of the universe show a great variety of galaxies, some of them billions of light-years away.

- Number of galaxies in the observable universe~100 billion

Galaxies and Cosmology

- The **first galaxies** are thought to have formed about 13 billion years ago.

- **Galaxy evolution** depends on their **environment** which changes as the Universe evolves.

- We can study their evolution by measuring their properties as a function of distance which is equivalent to **looking back in time.**
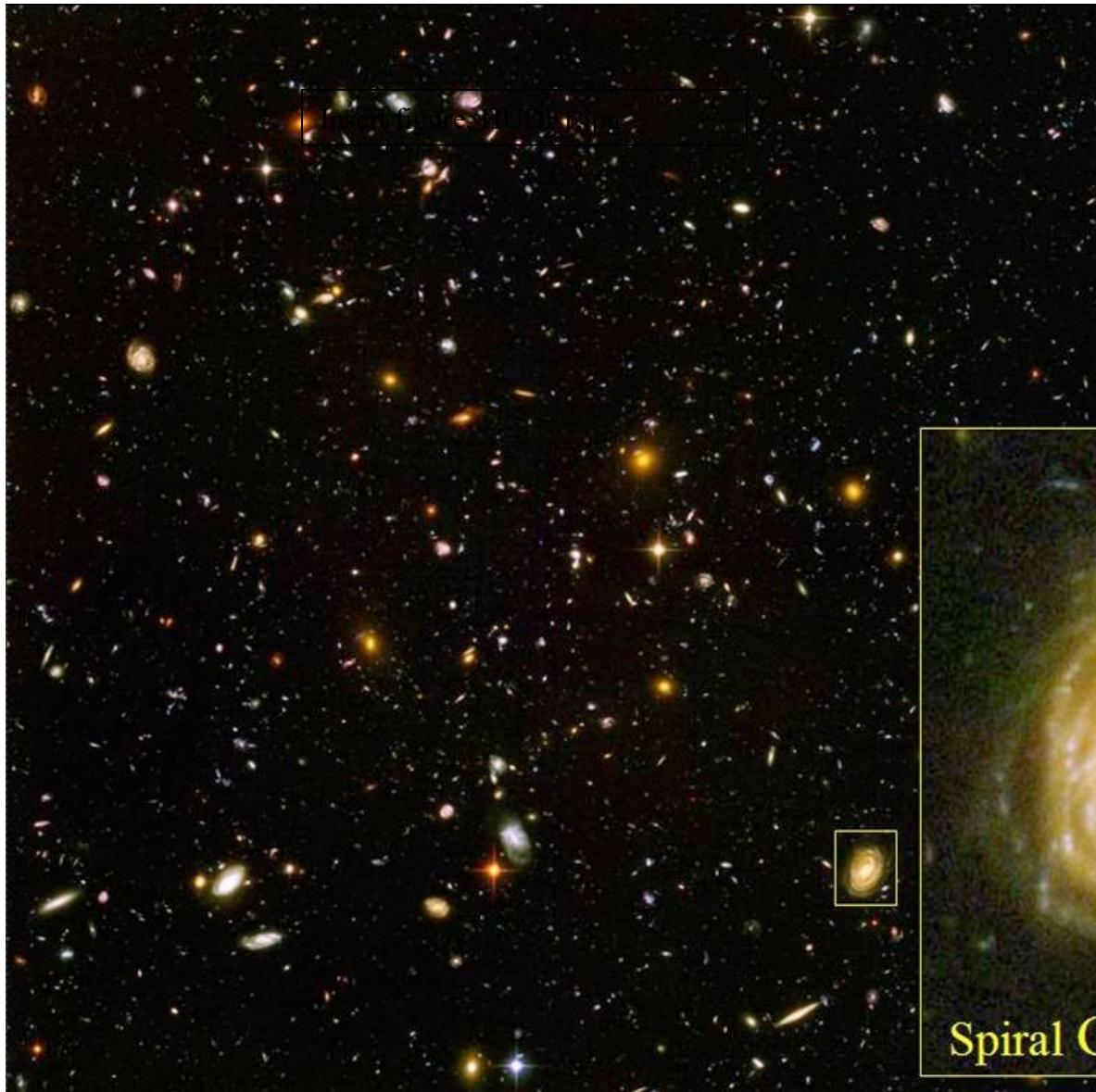
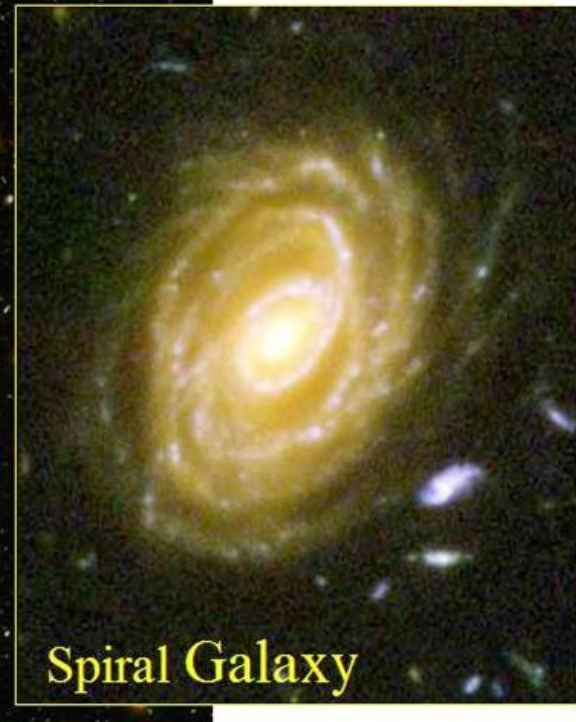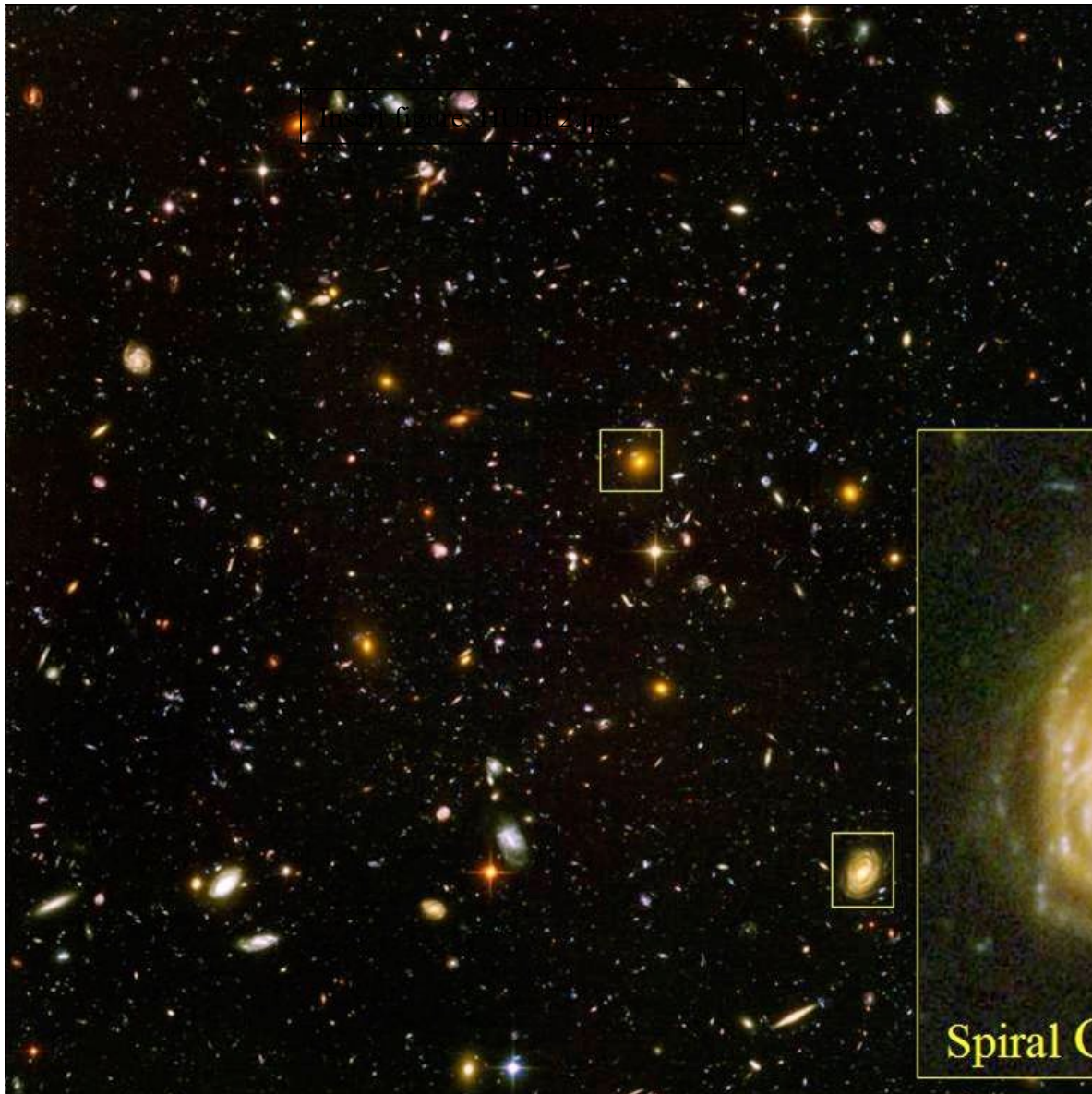# What are the three major types of galaxies?
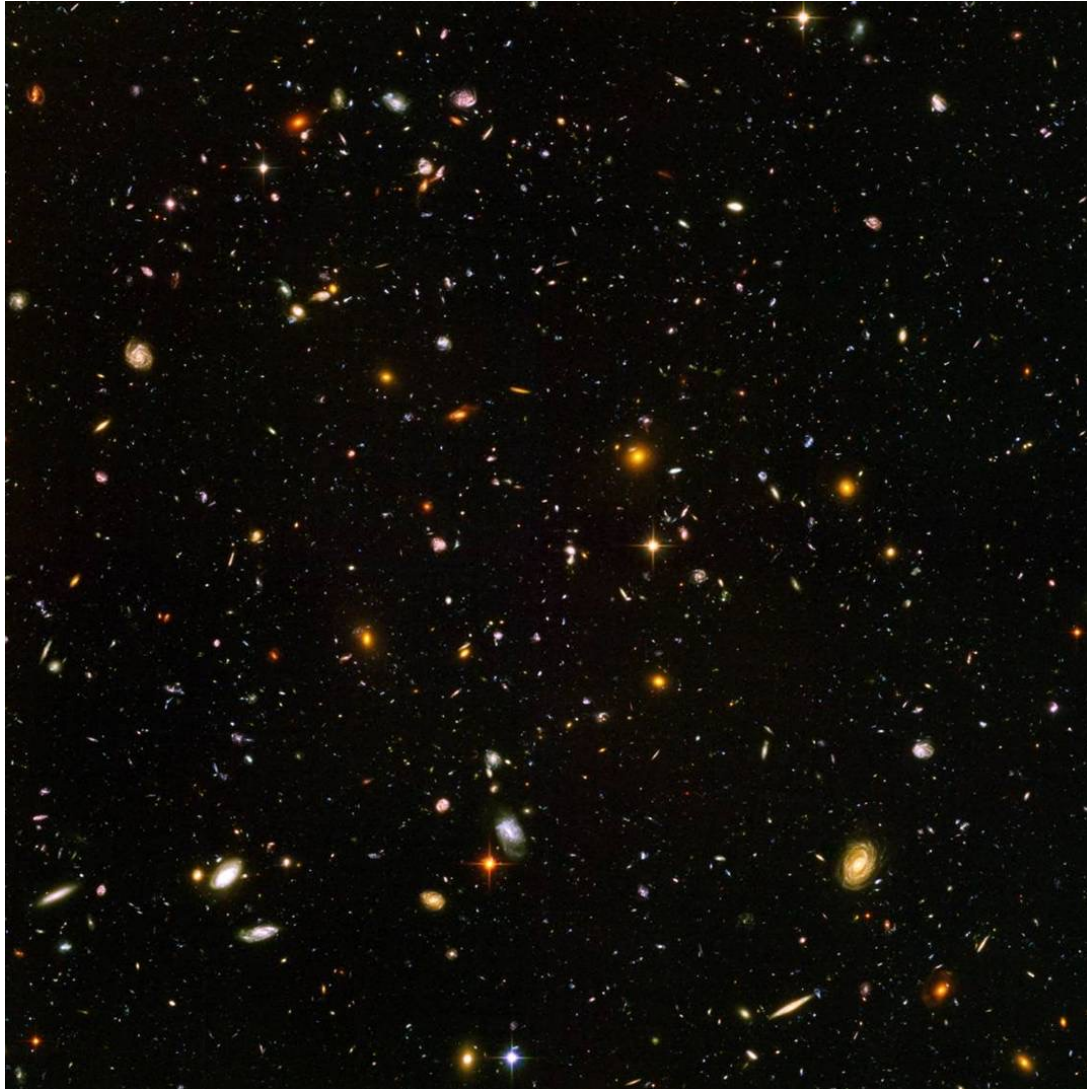
- Hubble Ultra Deep Field

- Hubble Ultra Deep Field

Spiral Galaxy

- Hubble Ultra Deep Field
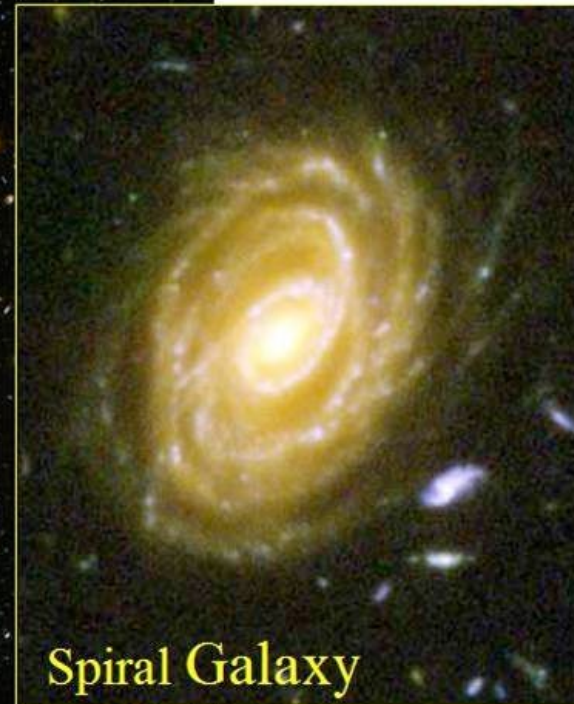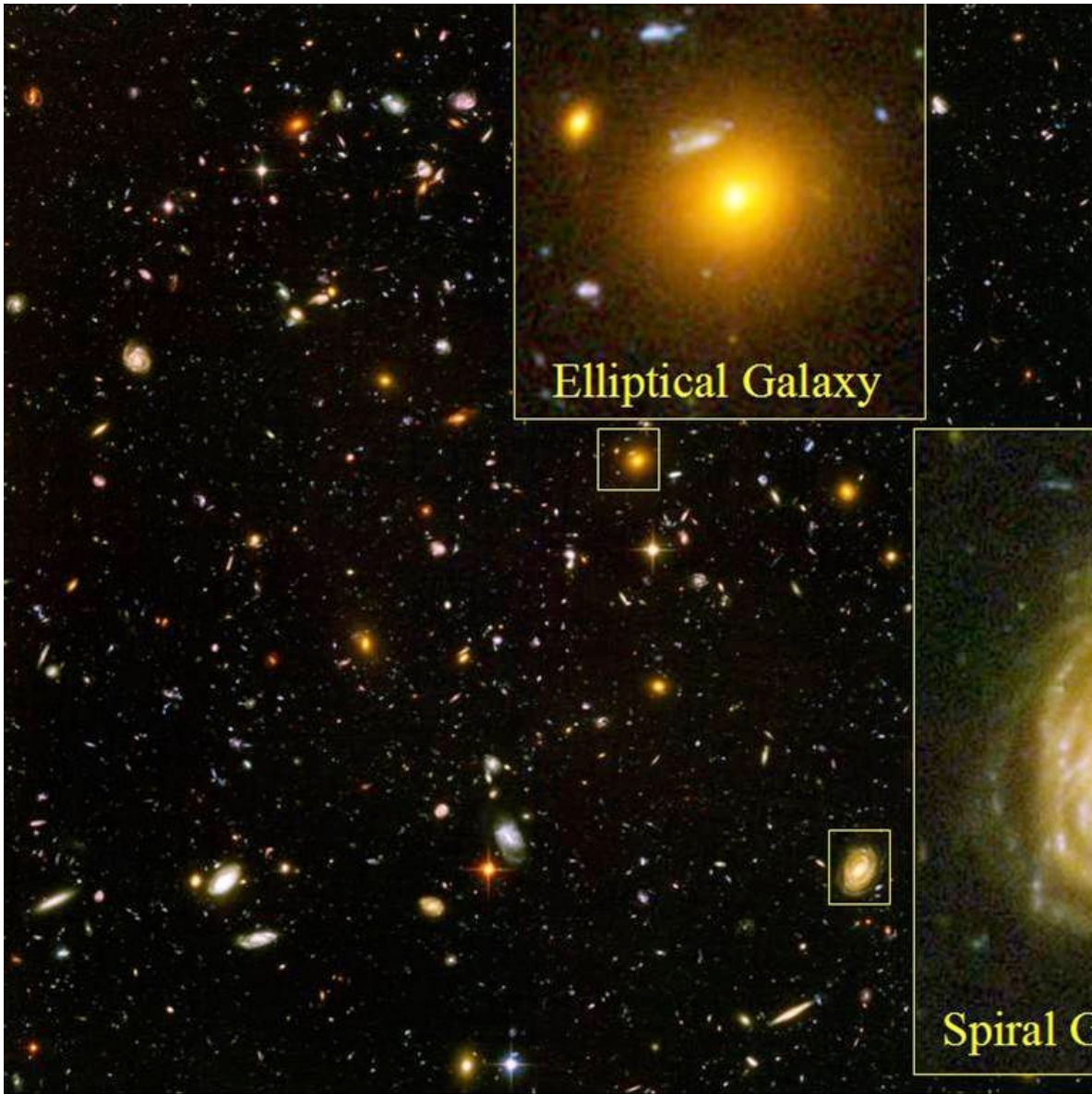
Spiral Galaxy

Elliptical Galaxy

Spiral Galaxy

- Hubble Ultra Deep Field
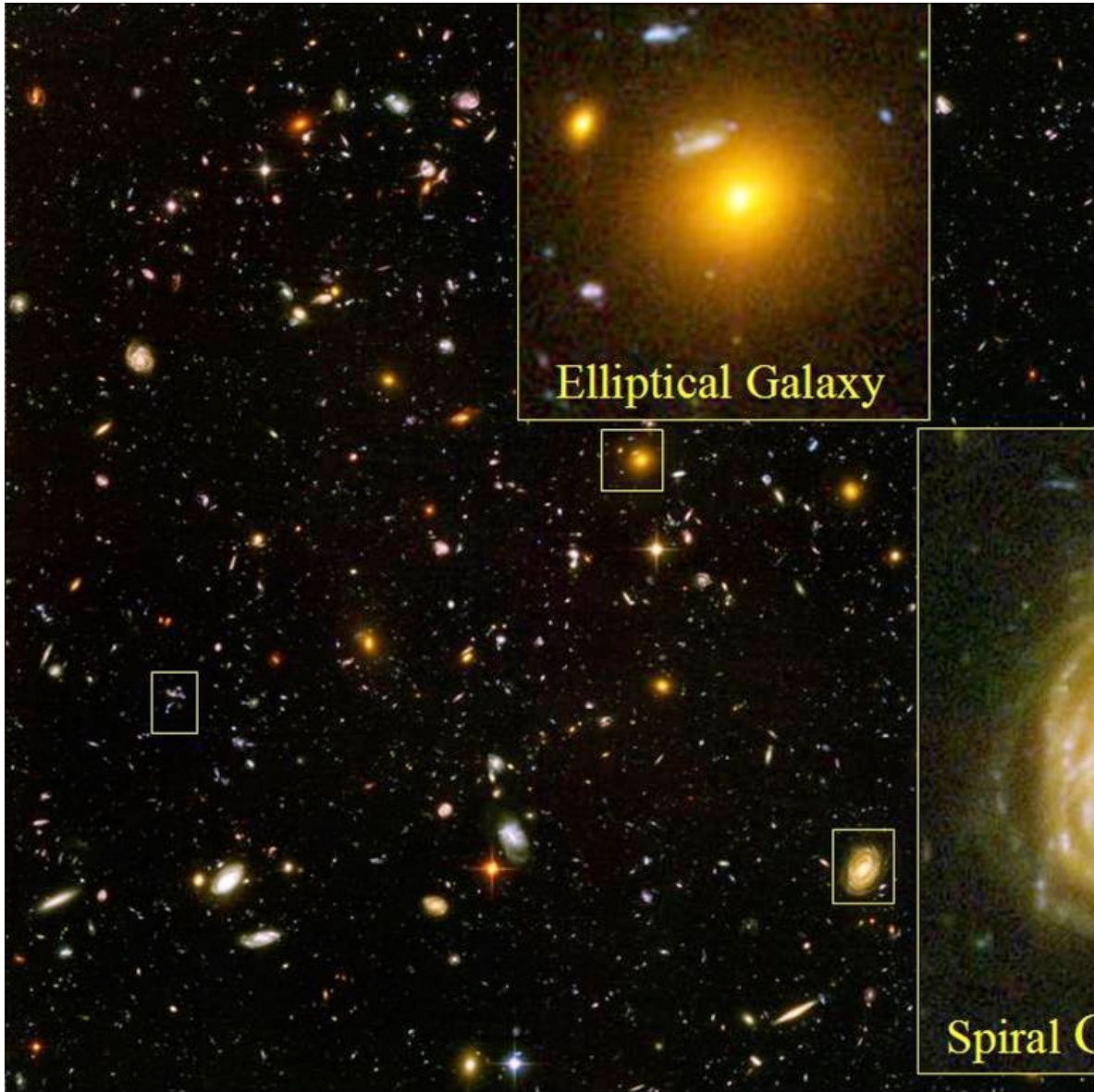
Elliptical Galaxy

Spiral Galaxy

- Hubble Ultra Deep Field
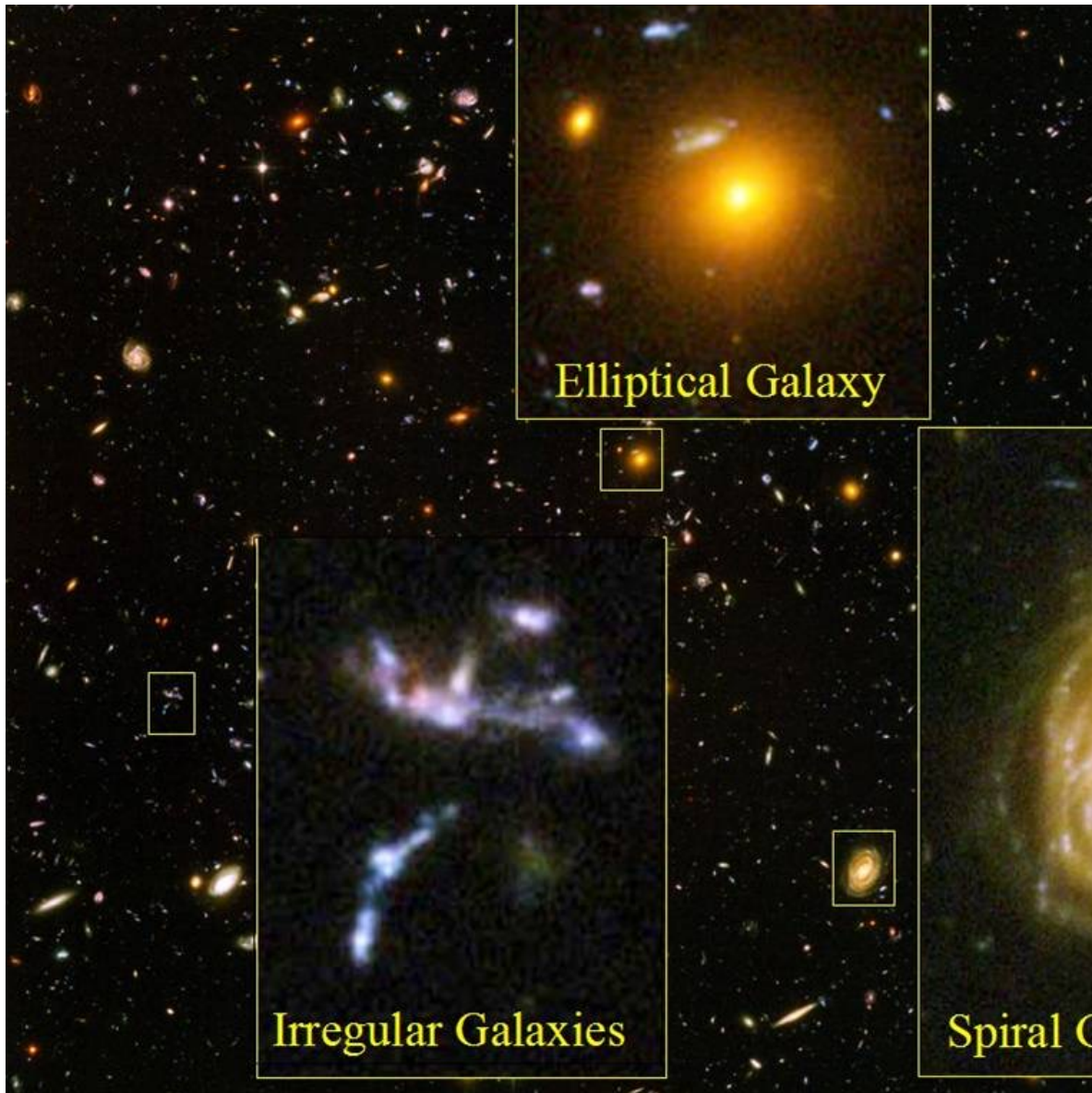
Elliptical Galaxy

Irregular Galaxies

Spiral Galaxy

- Hubble Ultra Deep Field
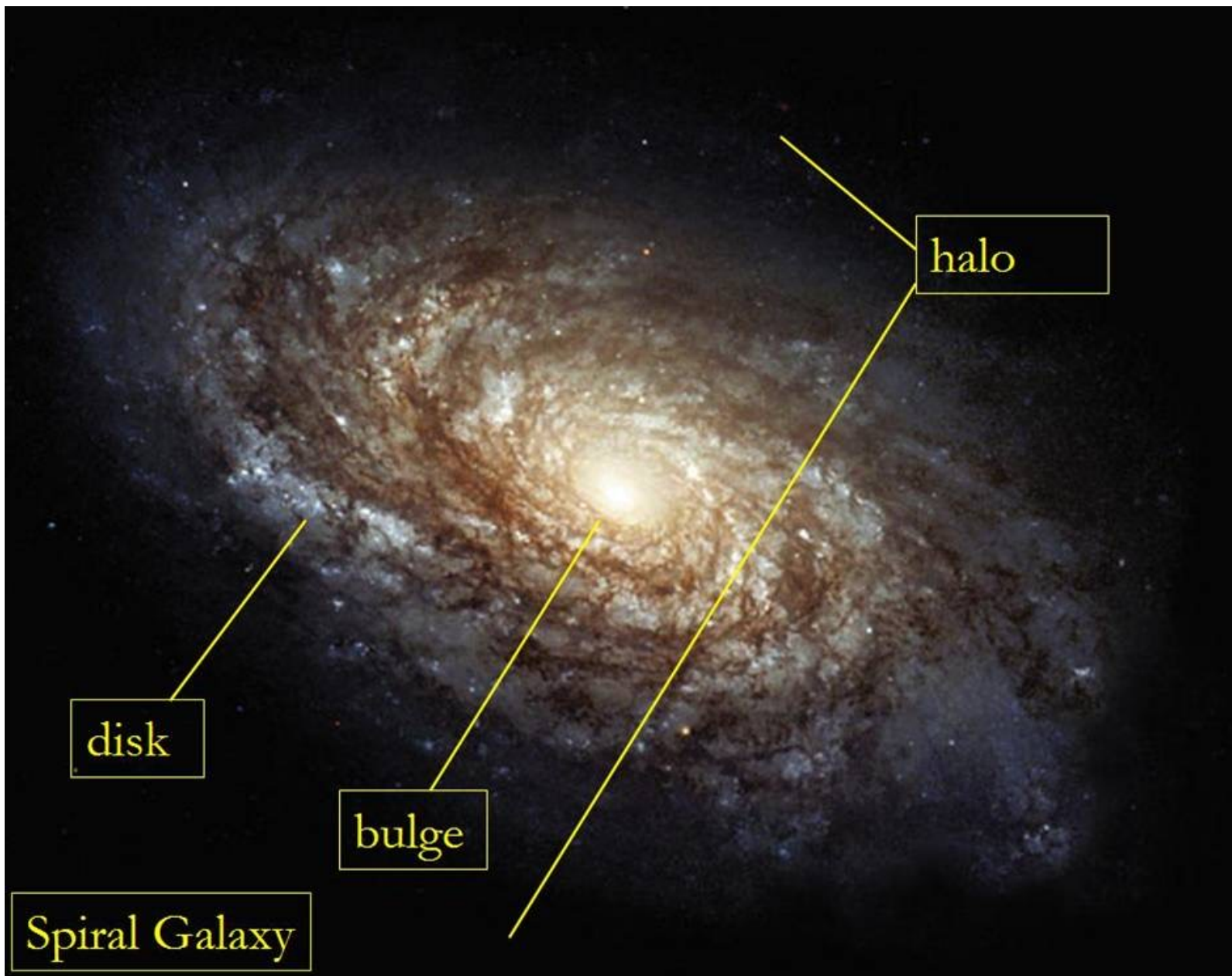
halo

disk

bulge

Spiral Galaxy

Disk component:
stars of all ages, many gas clouds

Spheroidal component:
bulge and halo, old stars, few gas clouds

Disk component: stars of all ages, many gas clouds

Spheroidal component: bulge and halo, old stars, few gas clouds
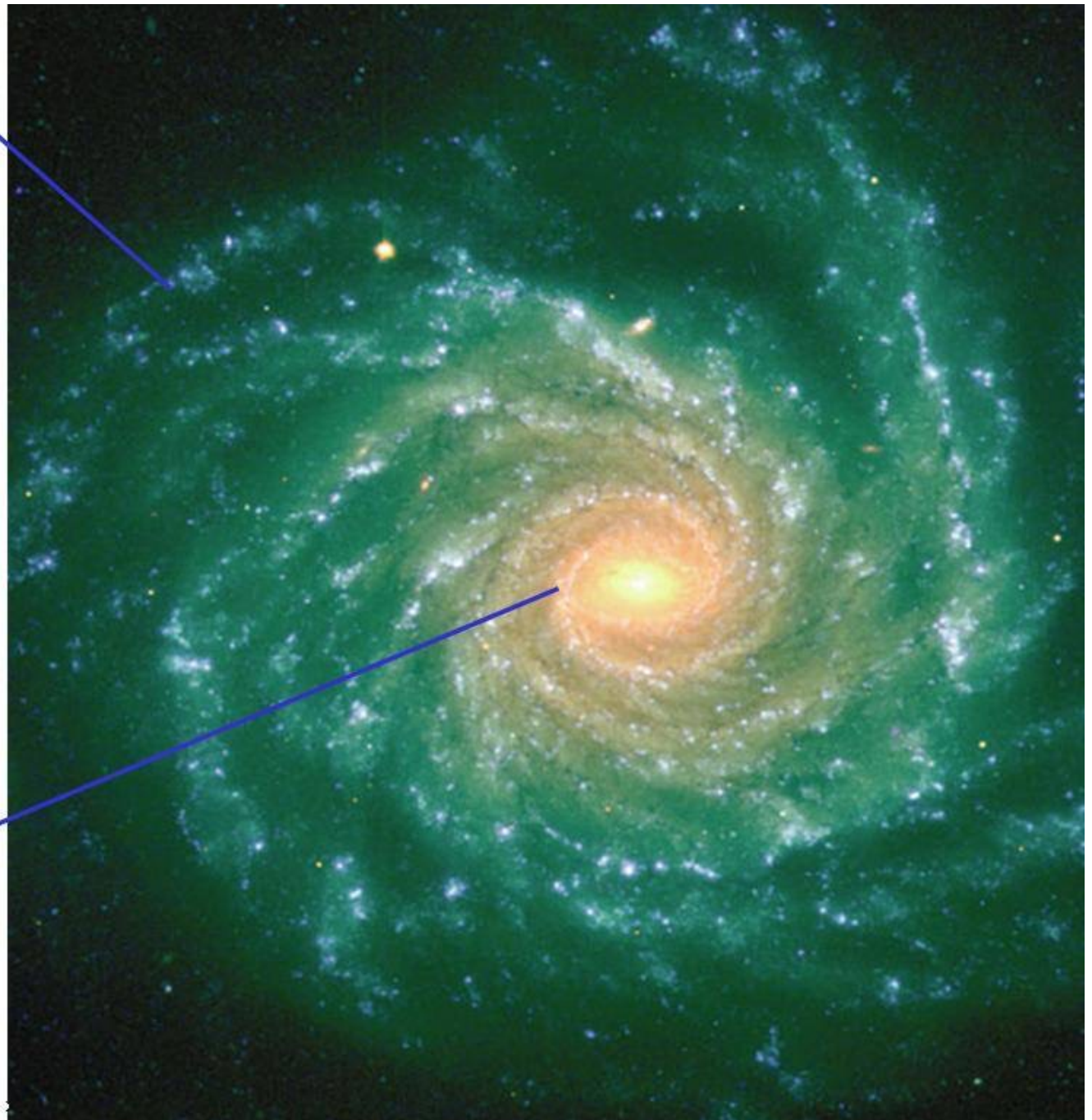
Disk component: stars of all ages, many gas clouds

Spheroidal component: bulge and halo, old stars, few gas clouds
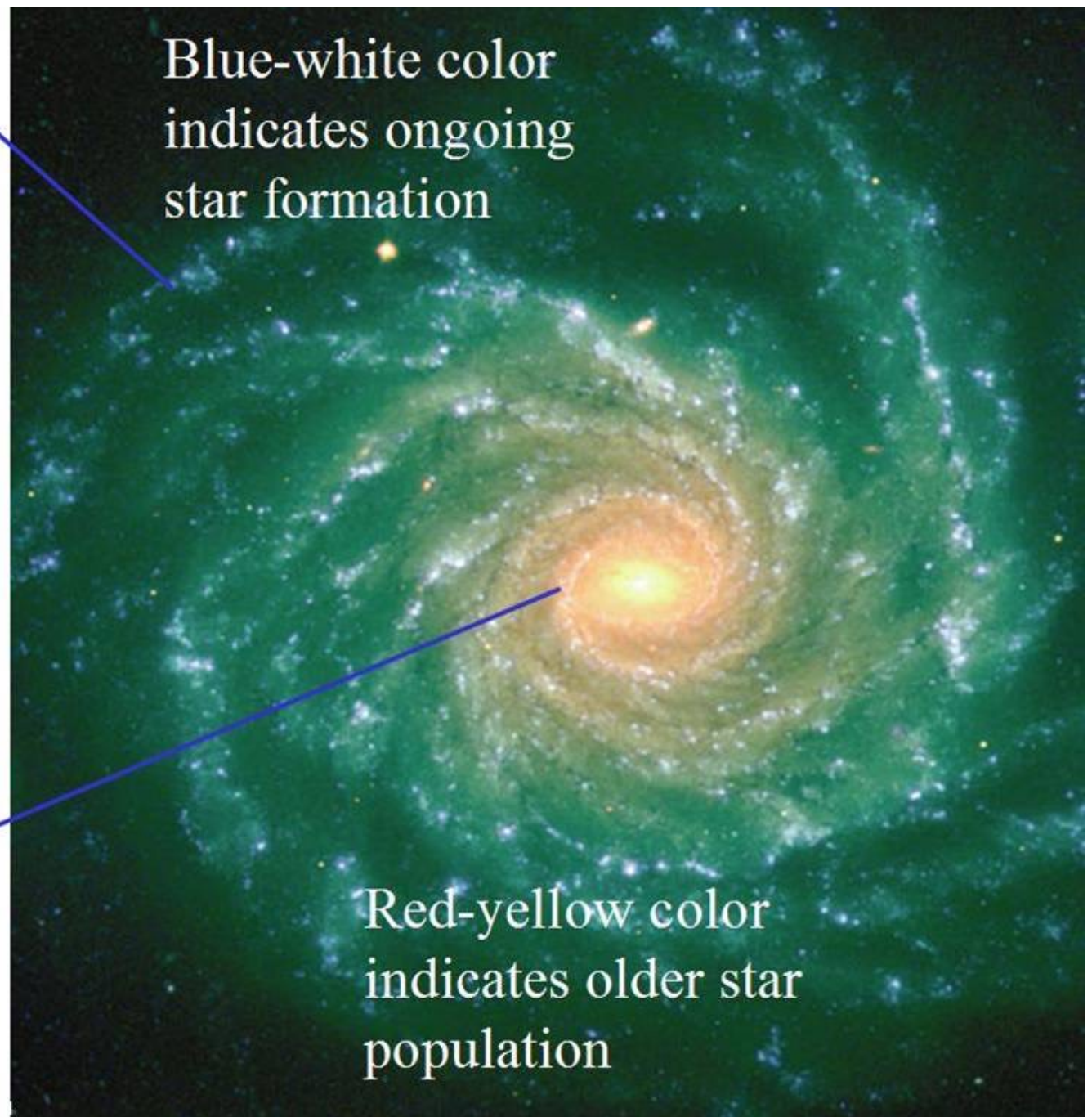
Blue-white color indicates ongoing star formation

Red-yellow color indicates older star population

Disk component: stars of all ages, many gas clouds

Spheroidal component: bulge and halo, old stars, few gas clouds

Blue-white color indicates ongoing star formation

center of galaxy
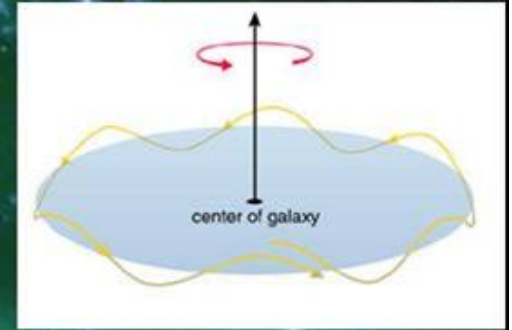
Red-yellow color indicates older star population
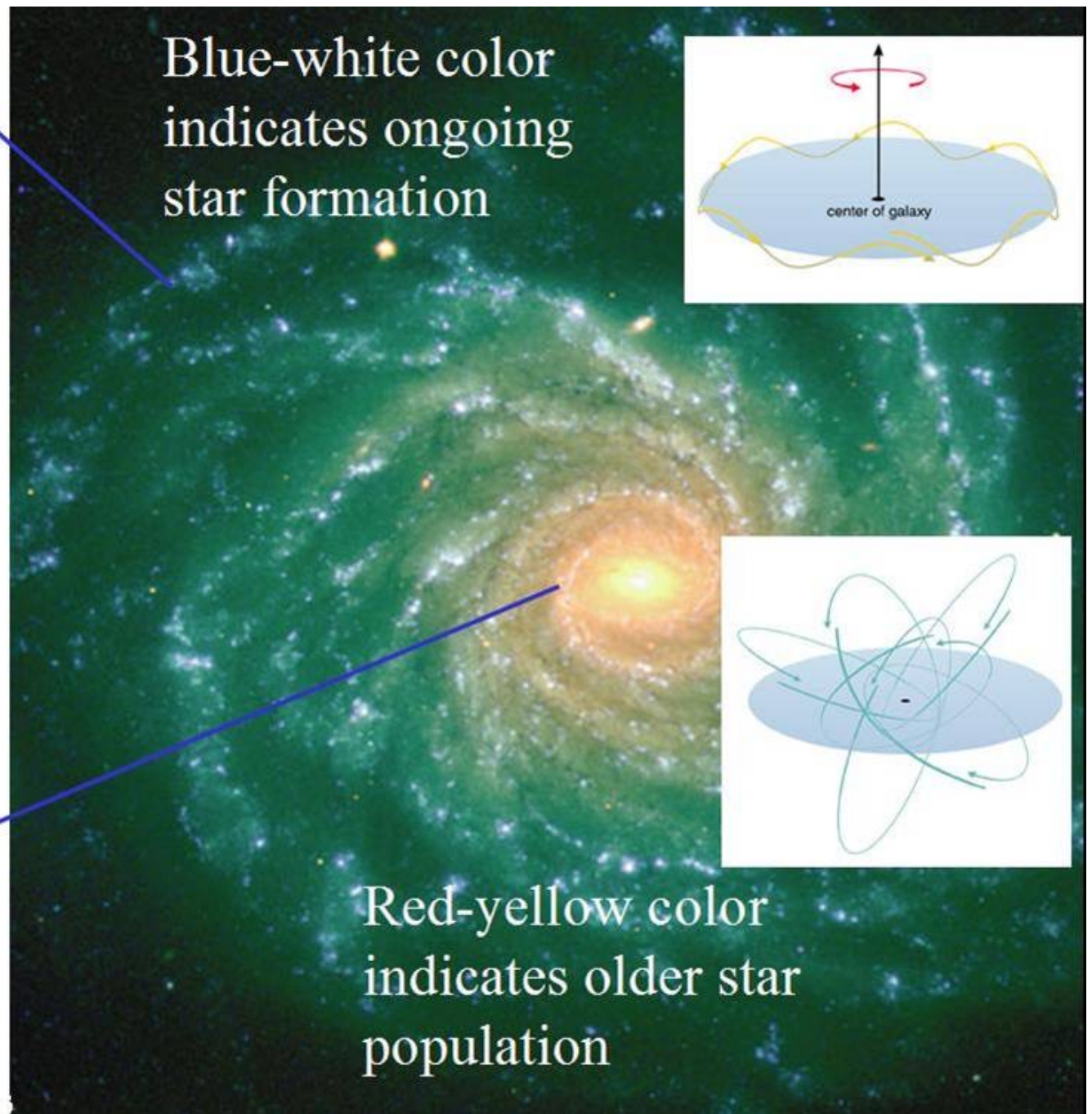
Spiral Galaxies

(a) Sa (NGC 1357)   (b) Sb (M81)   (c) Sc (NGC 4321)

Hubble further classified spirals into :

Sa galaxies: smooth broad and tightly wrapped spiral arms with a large bulge (~4% of baryonic mass in dust and gas)

Sb galaxies: moderate-sized spirals and bulge (~8% of mass in dust and gas)

Sc galaxies: narrow loosely wrapped spirals and small bulge (~25% of mass in dust and gas)

Spiral Galaxies

Spiral galaxies

The spiral arms contain **young, hot, blue stars** and their associated H II regions, indicating **ongoing star formation**.

As the stars in the disk evolve, they enrich the interstellar medium (ISM) with metals through AGB winds and Supernova explosions. This metal enriched ISM will be used to form the next generation of stars that will therefore be metal rich. This is why **most stars in the disks of Spirals are Population I stars**.

The main difference between Sa, Sb and Sc galaxies is the relative amounts of gas and dust in them. **The proportion of dust, gas and young stars increases from Sa to Sc galaxies**.

Barred Spiral Galaxies

(a) SBa (NGC 1291)   (b) SBb (M83)   (c) SBc (NGC 1365)

A barred spiral galaxy is a spiral galaxy with a central bar-shaped structure composed of stars. About 20 % of the spiral galaxies in the distant past possessed bars, compared with nearly 70 % of their modern counterparts.

The bar is thought to act as a mechanism that channels gas inwards from the spiral arms, in effect funneling the flow to create new stars and feeding the central supermassive black hole.

Thought 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 the others.

C. Gas in the disk scatters blue light.

Thought 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 the others.

C. Gas in the disk scatters blue light.

- **Lenticular galaxy (S0):** has a disk like a spiral galaxy but much less dusty gas (intermediate between spiral and elliptical)

a M87, a giant elliptical galaxy in the Virgo Cluster, is one of the most massive galaxies in the universe. The region shown is more than 300,000 light-years across.

- **Elliptical galaxy:** all spheroidal component, virtually **no disk component**

- Red-yellow color indicates older star population.

Elliptical Galaxies

Elliptical galaxies contain very little amounts of gas, dust and star formation. They are composed of mostly old red Population II stars.
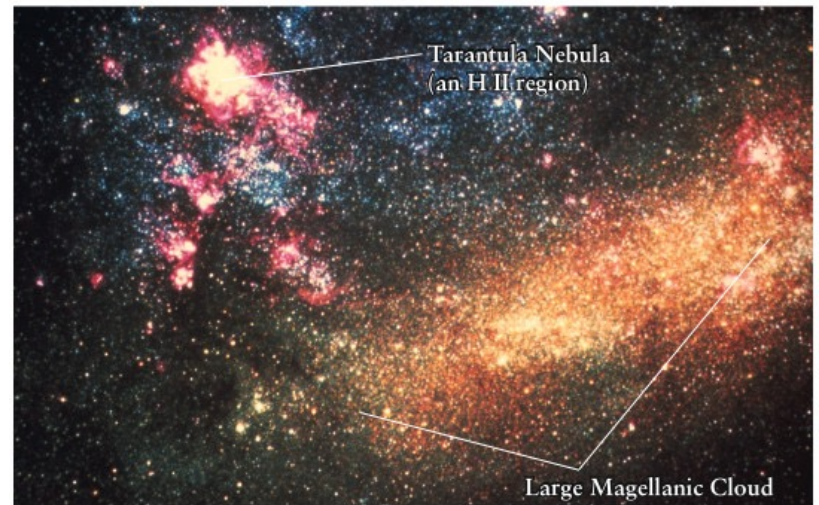
Giant elliptical galaxies are about 20 times larger than typical elliptical galaxies and often found in clusters of galaxies.

Dwarf elliptical galaxies contain only about a few million stars compared to 100 billion in the Milky way.

Irregular Galaxies

Galaxies that do no fit into the scheme of elliptical or spiral galaxies are referred to as irregulars. They contain old and young stars and are in general rich in gas and dust.

The distorted shapes of some irregular galaxies is likely the result of collisions.

The Large Magellanic Cloud is a Irr I galaxy located at a distance of 179,000 ly.

Sc

Sb

Sa

S0

E0   E5

SBc   SBb   SBa   SB0

larger bulge, less dusty gas, tighter spiral arms

rounder appearance
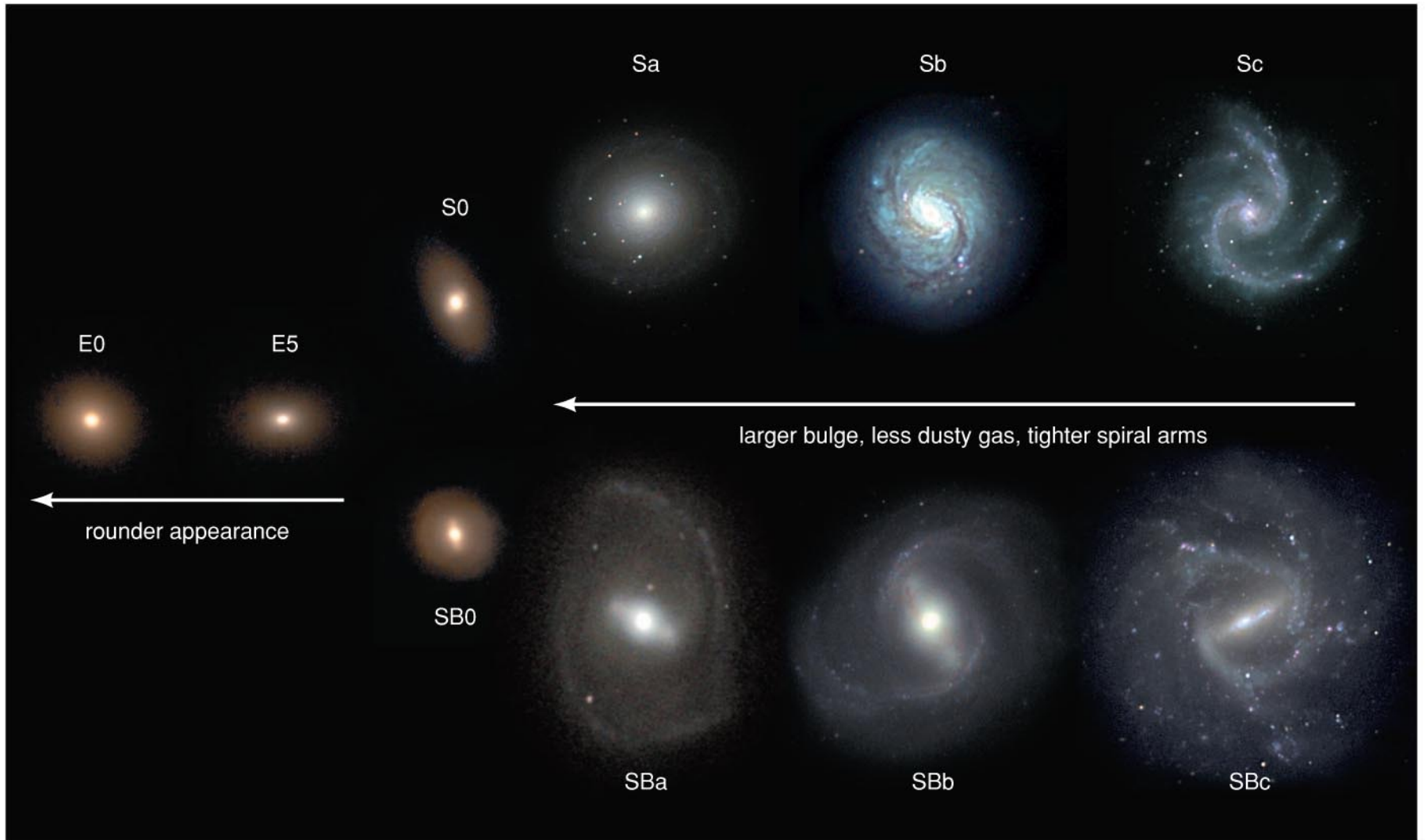
Spheroid dominates

Hubble's galaxy classes

Disk dominates

How are galaxies grouped together?

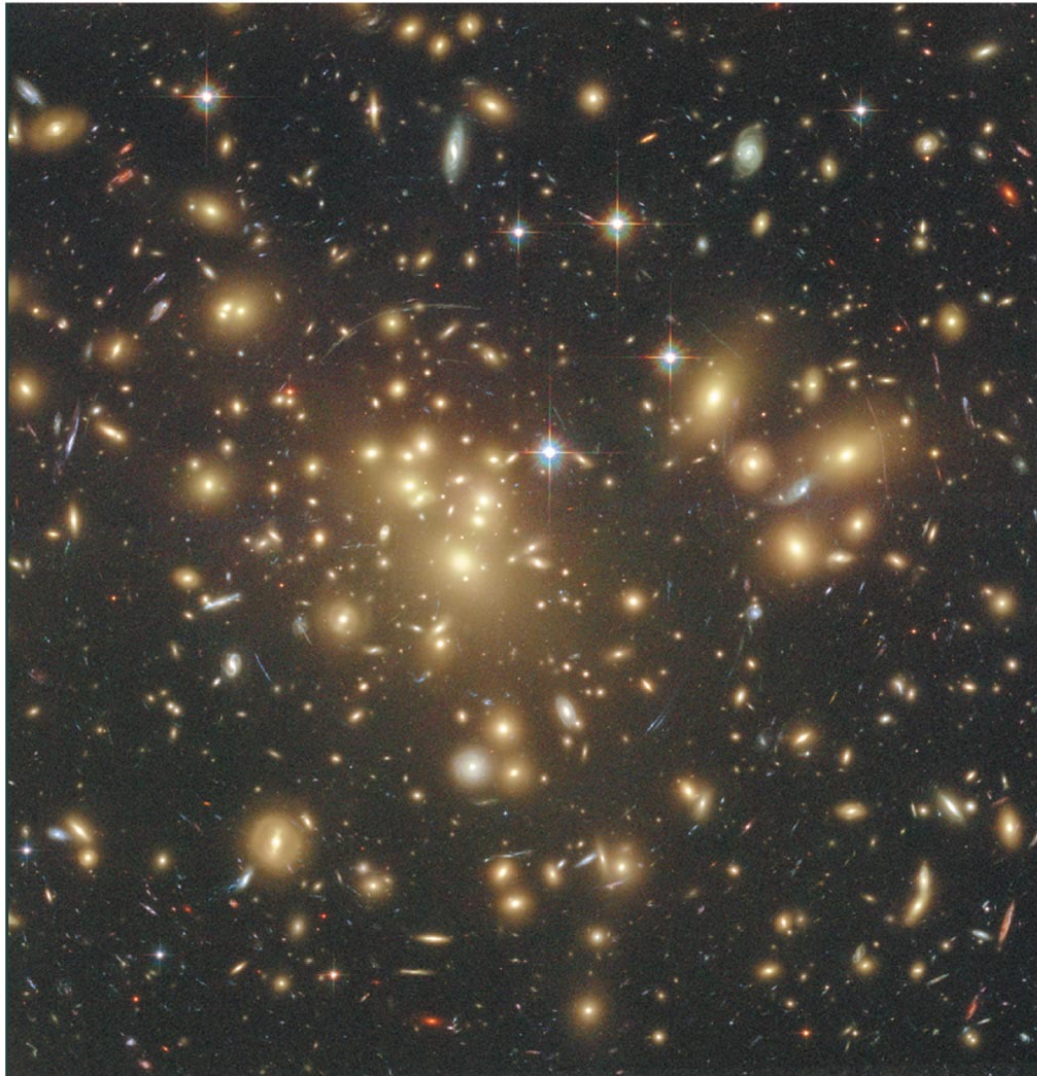- Spiral galaxies are often found in **_groups_** of galaxies (up to a few dozen galaxies).
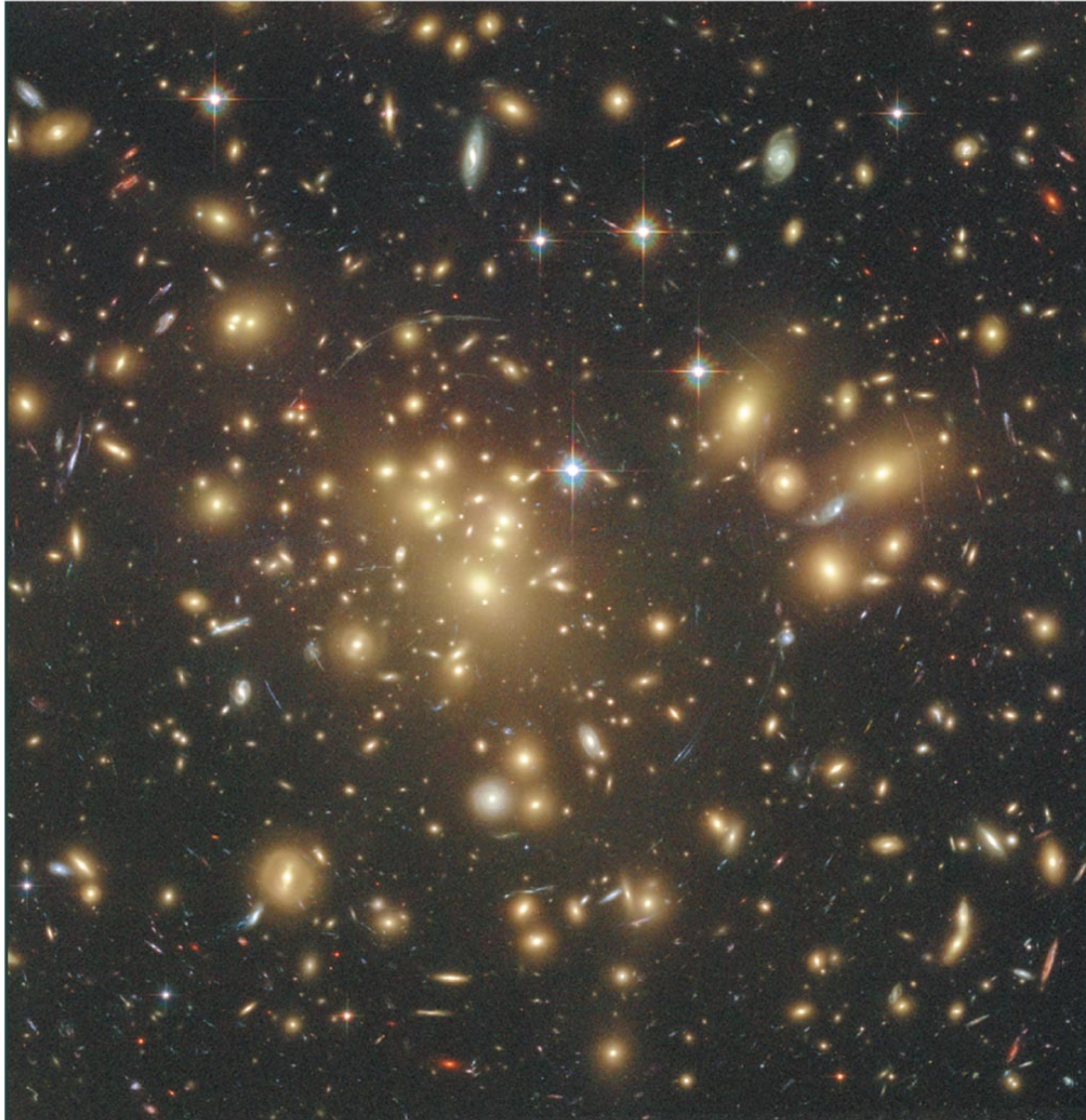
- Elliptical galaxies are much more common in huge *clusters* of galaxies (hundreds to thousands of galaxies).

Clusters of Galaxies

The Hercules cluster of galaxies just 650 million ly away.

Clusters of galaxies are the largest gravitationally bound objects in the Universe. Based on simulations the smallest structures collapsed first and eventually build the largest structures, such as clusters of galaxies.

Properties of Clusters of Galaxies

Clusters of Galaxies contain between 100 - 2000 galaxies, hot X-ray emitting gas and dark matter. **Mass distribution:**
~5% in galaxies, ~10% in hot gas and ~85 % in dark matter.

- Total mass $\sim 10^{14} - 10^{15}$ M$_\odot$
- Diameter of $1- 2$ Mpc
- Velocity dispersion (spread of galaxy velocities) of ~ 1000 km/s

Clusters are classified as **rich or poor** (< 100 members) depending on the number of member galaxies. **Poor Clusters are also called groups**. The Milky Way belongs to the Local Group.

Clusters are also classified as **regular** (spherical shape) and **irregular** (non-spherical shape).

Properties of Clusters of Galaxies

Giant elliptical galaxies dominate the center of **Virgo** (56 million light years away).
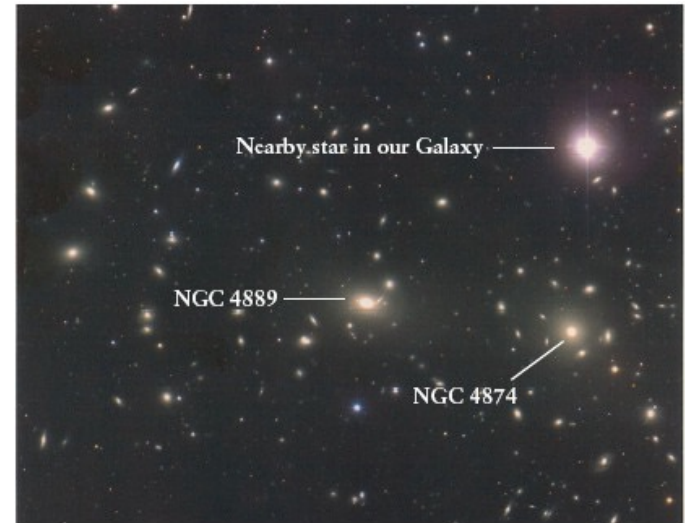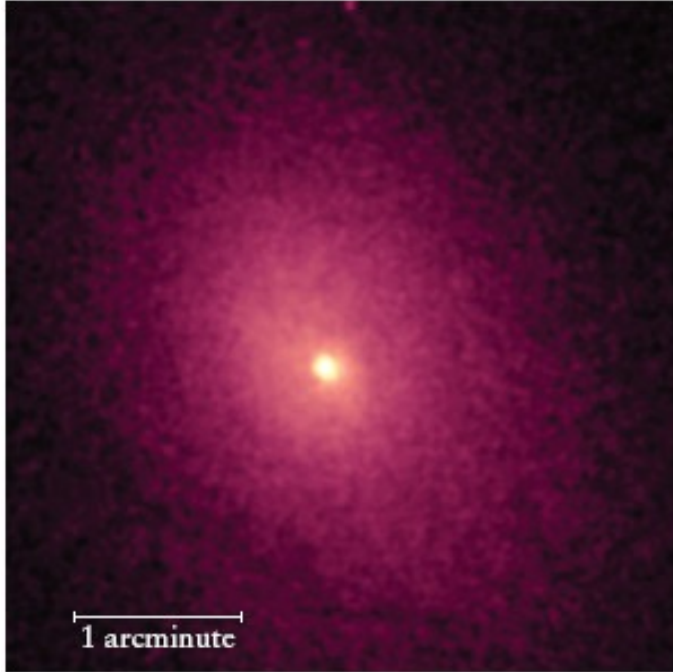

Coma Cluster (300 million light years away)

Irregular clusters like Virgo and Hercules contain an even mixture of elliptical and spiral galaxies.

Rich and regular clusters like Coma contain mostly elliptical and lenticular galaxies.
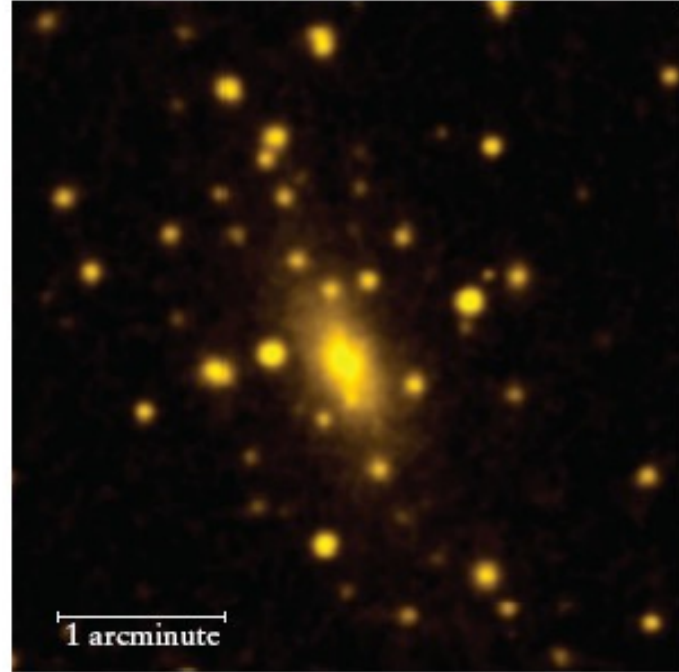
Heating of Intracluster Gas

(a) An X-ray image of Abell 2029 shows emission from hot gas.

R I V U **X** G

(b) A visible-light image of Abell 2029 shows the cluster's galaxies.

R I **V** U X G

The **Intracluster Medium is heated** to high temperatures **primarily by** the **gravitational energy** released during the formation of the cluster from smaller structures. Additional heating is provided by (a) winds from supernovae in the galaxies interacting with the ICM (b) by heating provided by the active galactic nucleus at the center of the cluster (c) collisions between galaxies and galaxies and the ICM.

Collision of Galaxies and Starburst Galaxies

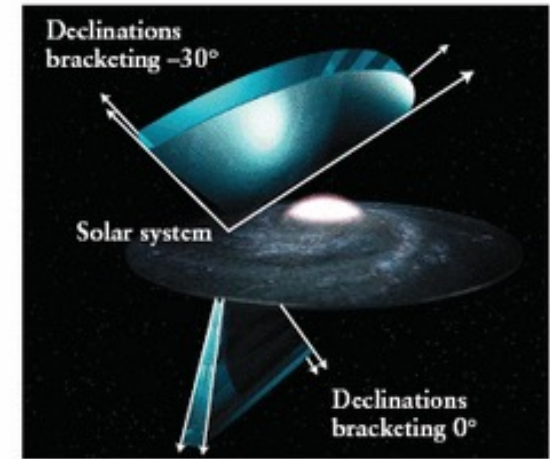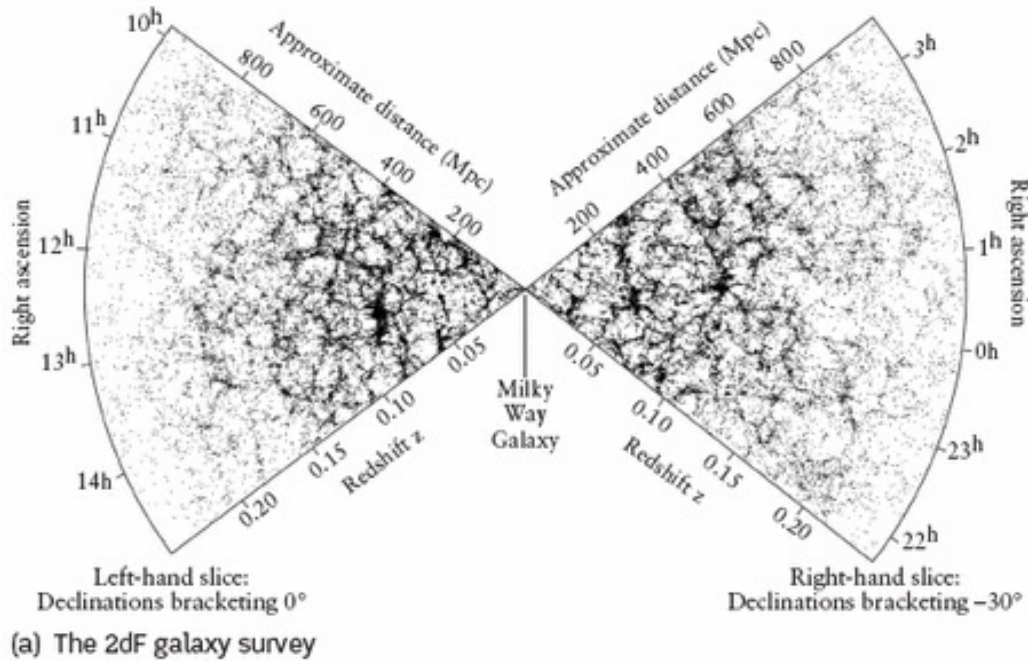Powerful winds from young stars cause M82 to expel gas and dust at a prodigious rate.

The large number of young, hot, blue stars in the disk of M82 is evidence of intense star formation.

1 arcminute = 1000 pc
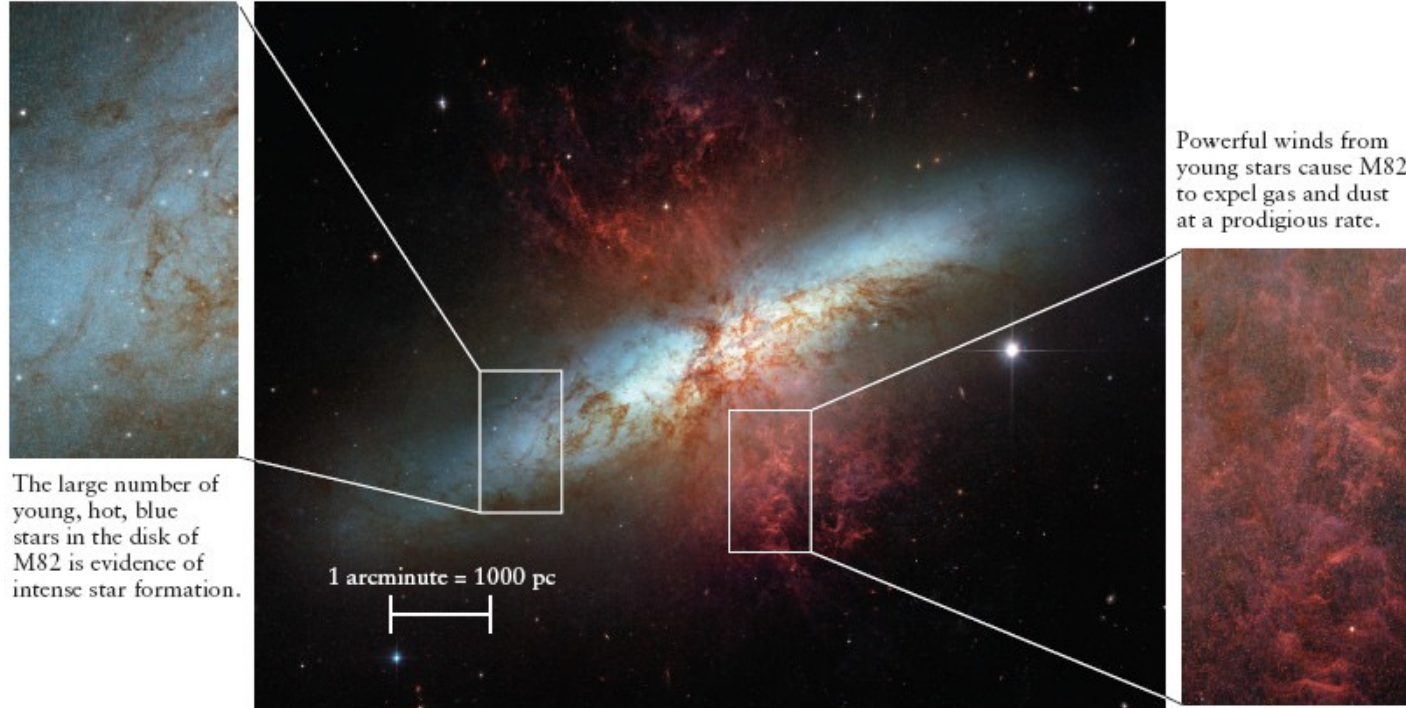
During the collision of two galaxies gas from both galaxies is brought into the central region of the merged galaxy where it is compressed thus triggering star formation.

Star formation can also be triggered by less violent collisions where the galaxies pass very near each other. A galaxy with a bright center produced by vigorous star formation surrounded by clouds of warm interstellar dust is called a **starburst galaxy**. An example of a starburst galaxy is M82.

Large Scale Distribution of Galaxies: Voids and Sheets

(a) The 2dF galaxy survey

Left-hand slice:
Declinations bracketing 0°

Right-hand slice:
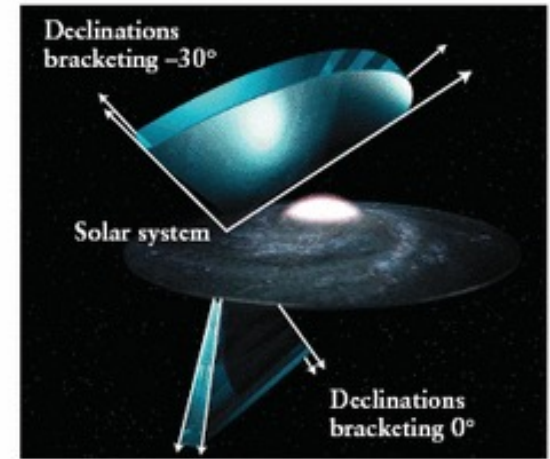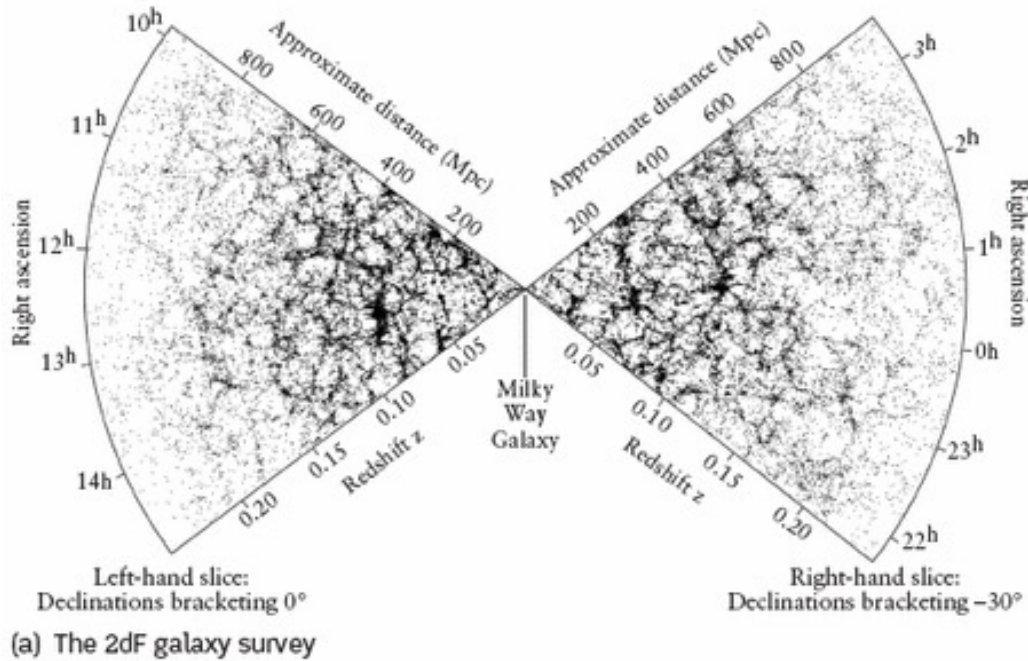Declinations bracketing –30°

(b) Fields of view in the 2dF survey

Three dimensional maps of galaxies in the nearby Universe are now available from the Sloan Digital Sky Survey (SDSS) and the two degree field galactic redshift survey (2dFGRS).

These maps indicate that most galaxies are located on sheets several Mpc thick and separated by voids of sizes ~ 100 Mpc.

Large Scale Distribution of Galaxies: Voids and Sheets

(a) The 2dF galaxy survey

Left-hand slice:
Declinations bracketing 0°

Right-hand slice:
Declinations bracketing −30°

(b) Fields of view in the 2dF survey

This pattern is similar to that of soapsuds in a kitchen sink, with sheets of soap film (analogous to galaxies) surrounding air bubbles (analogous to voids). Voids contain very few galaxies but may contain hydrogen clouds.

On scales much larger than 100 Mpc, the distribution of galaxies in the universe appears to be roughly uniform.

What have we learned?

- **How do galaxies evolve?**
  - Galaxies generally formed when the universe was young and have aged along with the universe.

- **What are the three major types of galaxies?**
  - The major types are spiral galaxies, elliptical galaxies, and irregular galaxies.
  - Spirals have both disk and spheroidal components; ellipticals have no disk.

What have we learned?

- **How are galaxies grouped together?**
  - Spiral galaxies tend to collect into groups of up to a few dozen galaxies.
  - Elliptical galaxies are more common in large clusters containing hundreds to thousands of galaxies.
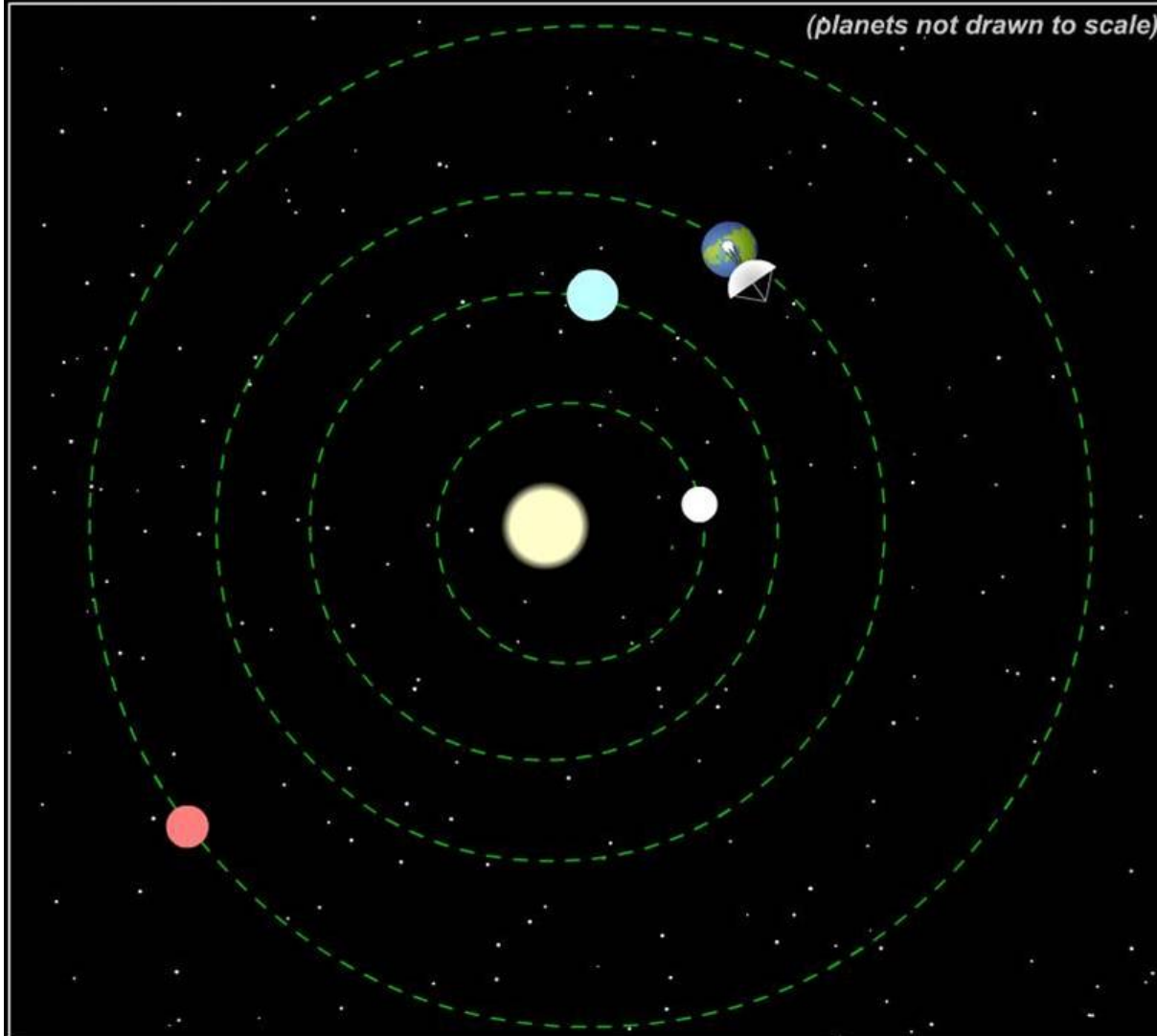
20.2 Measuring Galactic Distances

- Our goals for learning:
  - **How do we measure the distances to galaxies?**
  - **How did Hubble prove that galaxies lie far beyond the Milky Way?**
  - **What is Hubble - Lemaître law?**

How do we measure the distances to galaxies?
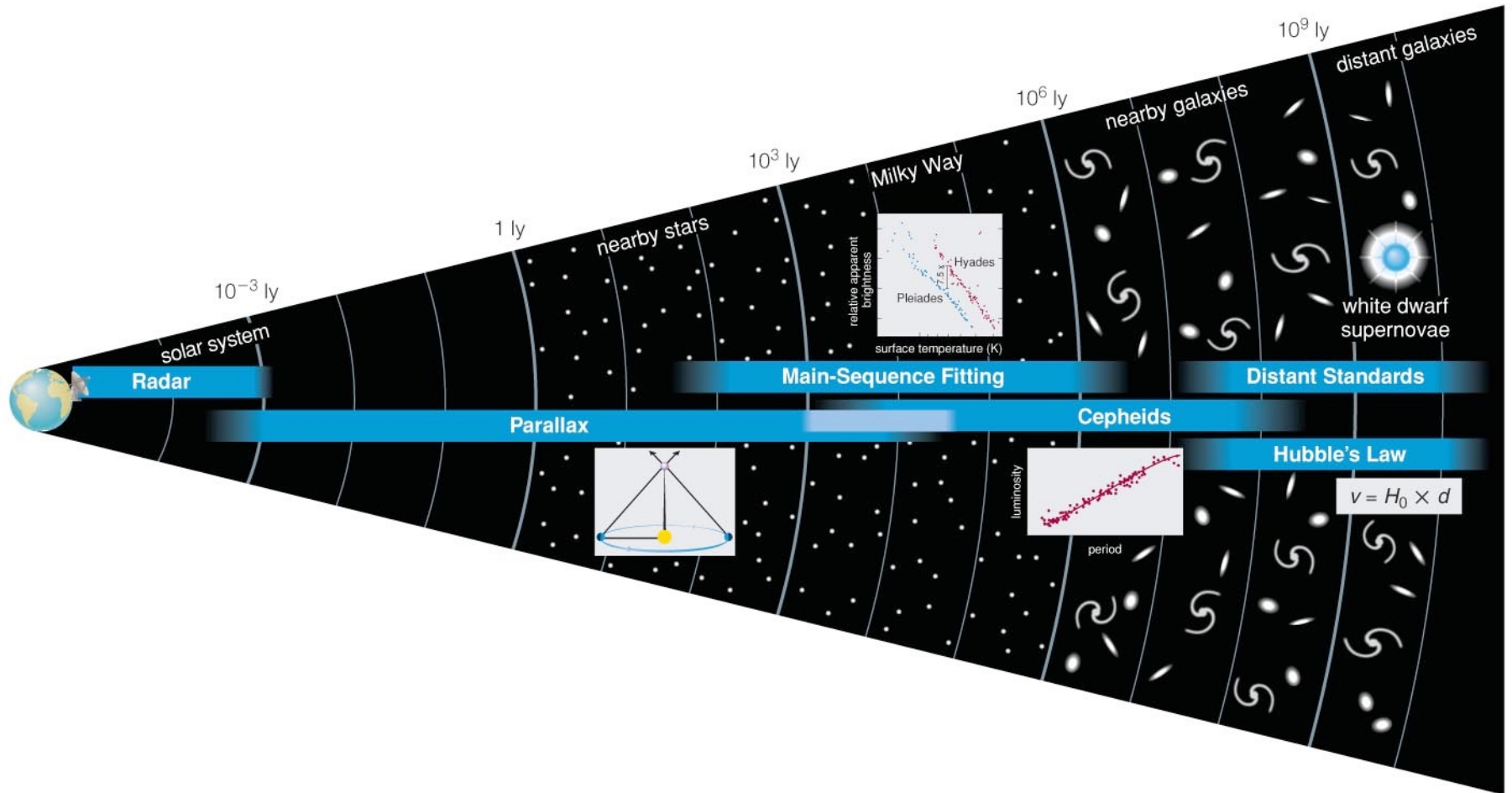
- ***Step 1***

- Determine size of the solar system using radar.

Distance to Nearby Stars from Parallax

Every January, we see this: distant stars

Every July, we see this:

nearby star

p

d

1 AU

Not to scale

July

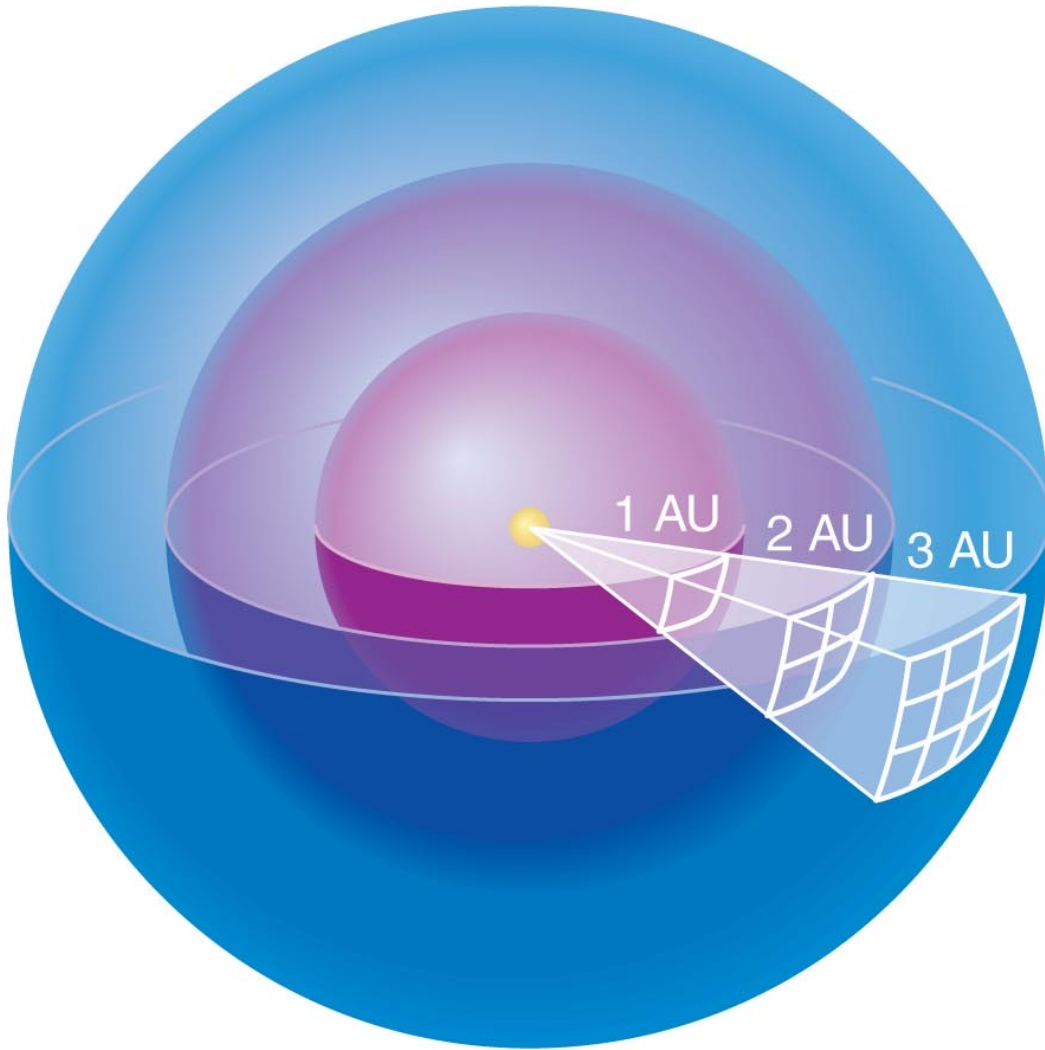January
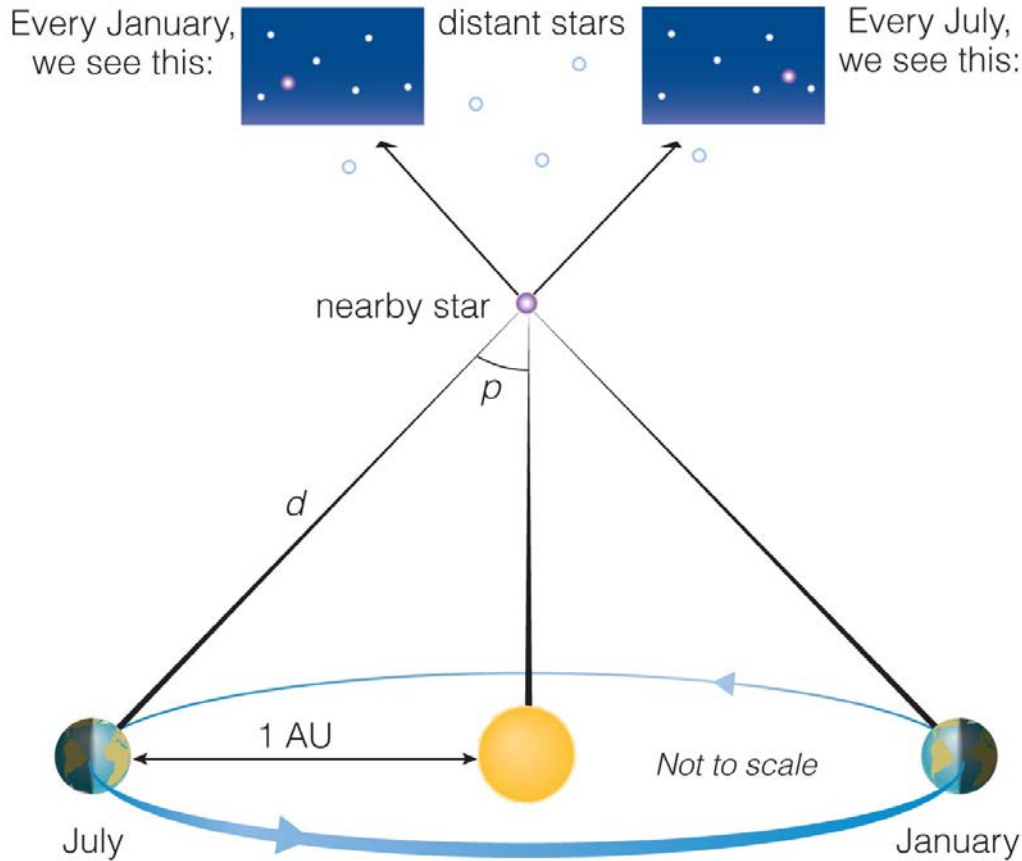
- *Step 2*

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

- $d = (1/p)$ parsec, p in arcsec.

- Luminosity passing through each sphere is the same.

- Area of sphere:

    4π (radius)^2

- Divide luminosity by area to get brightness.

Distance from brightness and luminosity

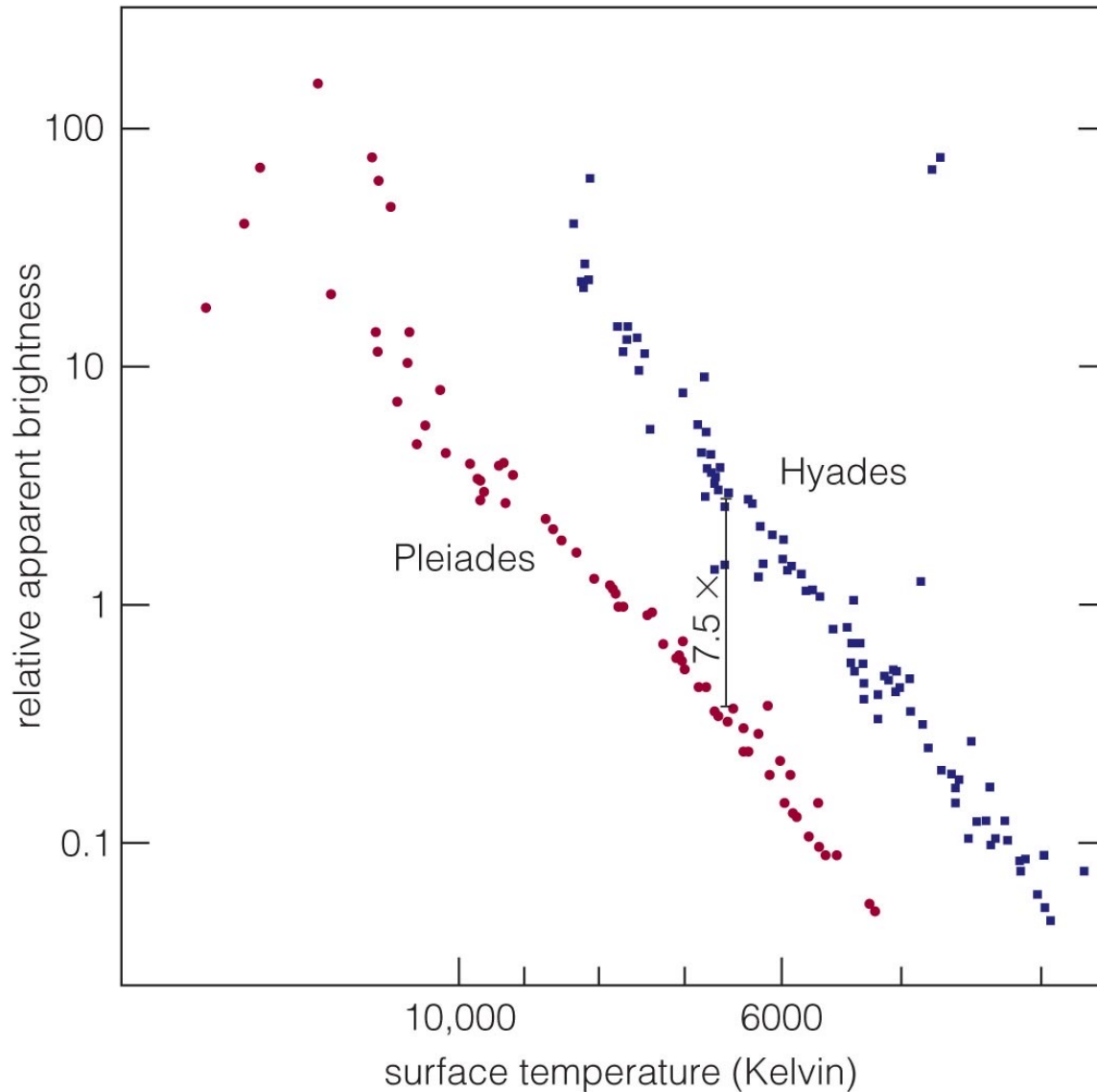The relationship between apparent brightness and luminosity depends on distance:

$$Brightness = \frac{Luminosity}{4\pi(distance)^2}$$

We can determine a star's distance if we know its luminosity and can measure its apparent brightness

$$distance = \sqrt{\frac{Luminosity}{4\pi(Brightness)}}$$

Distance from main sequence fitting

- ***Step 3***

- The apparent brightness of a star cluster's main sequence tells us its distance.

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

Thought Question

Which kind of stars are best for measuring large distances?

A. high-luminosity stars
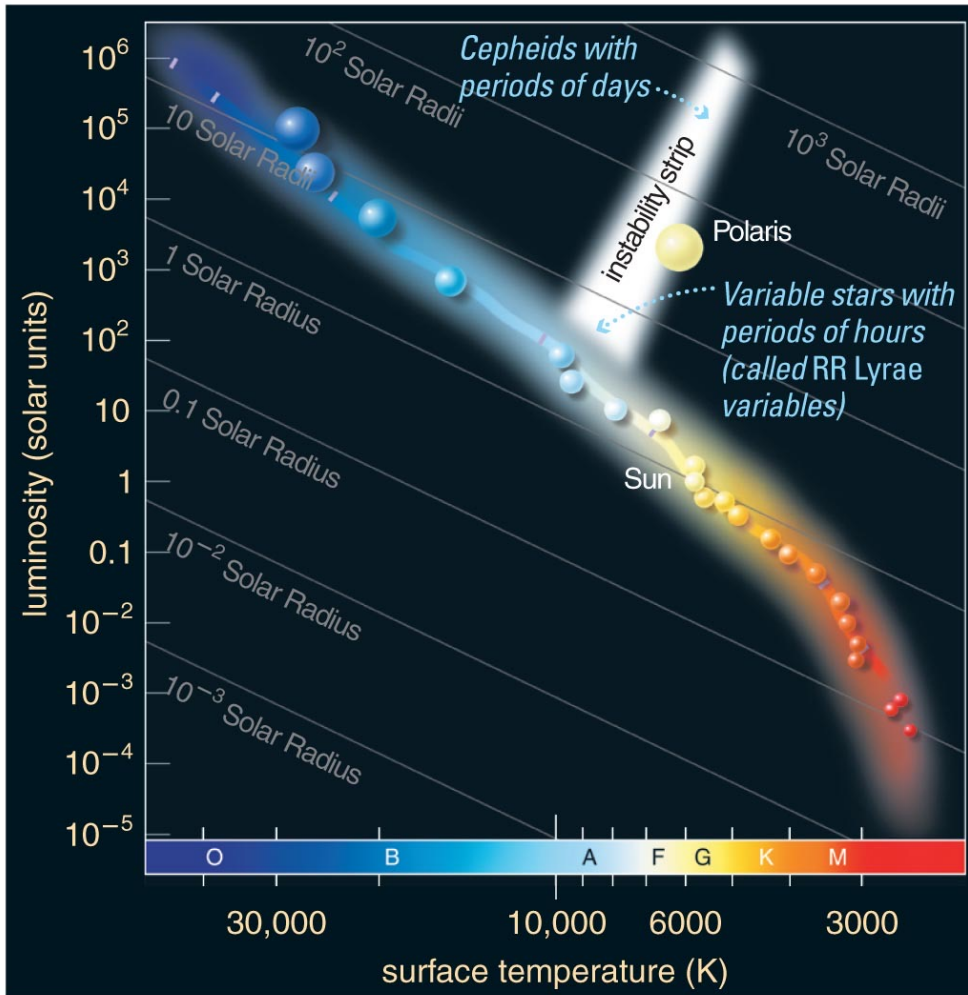B. low-luminosity stars

Thought Question

Which kind of stars are best for measuring large distances?

A. high-luminosity stars

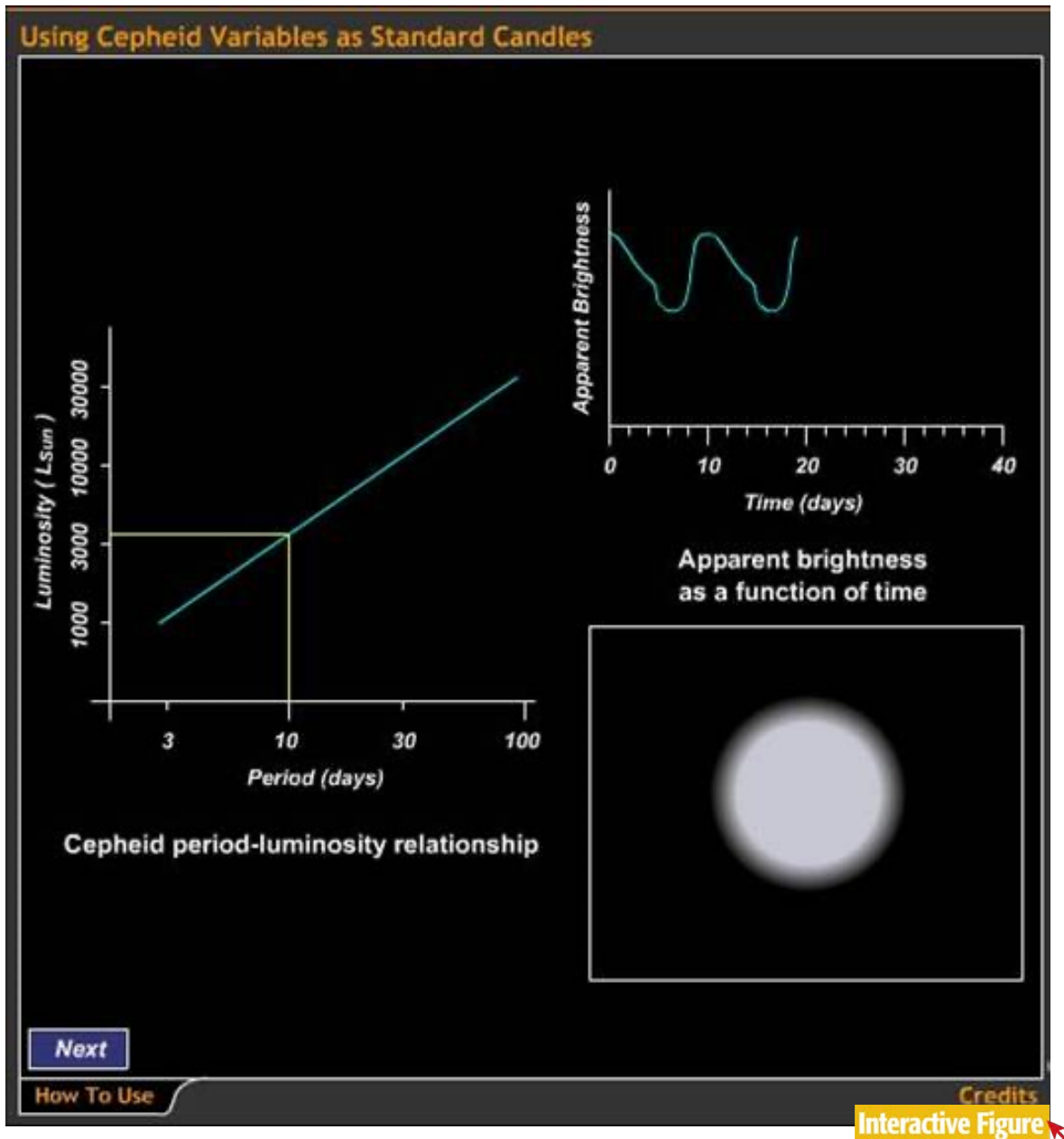B. low-luminosity stars

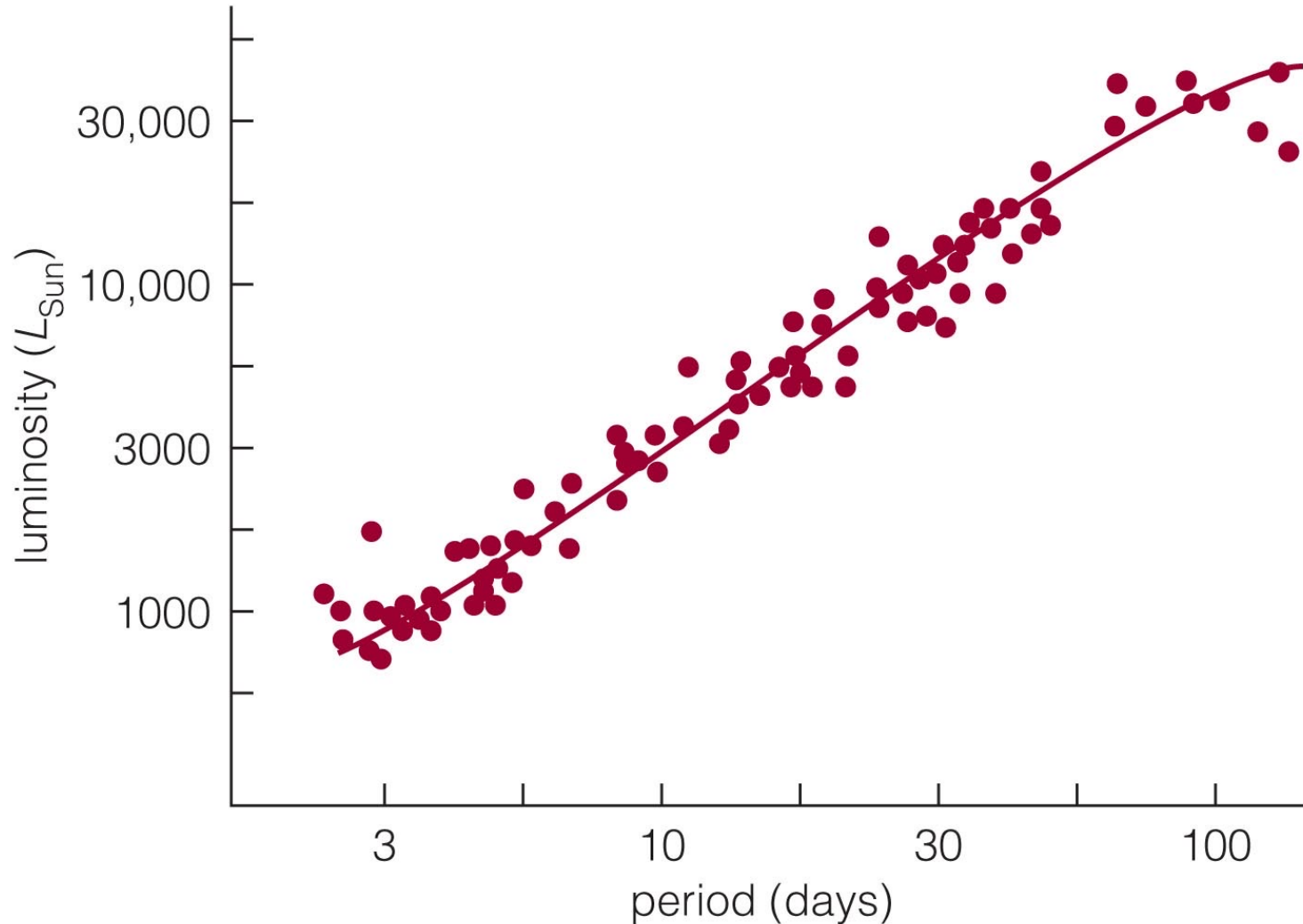# Distances to Cepheid Variables

- Cepheid variable supergiant stars are very luminous.
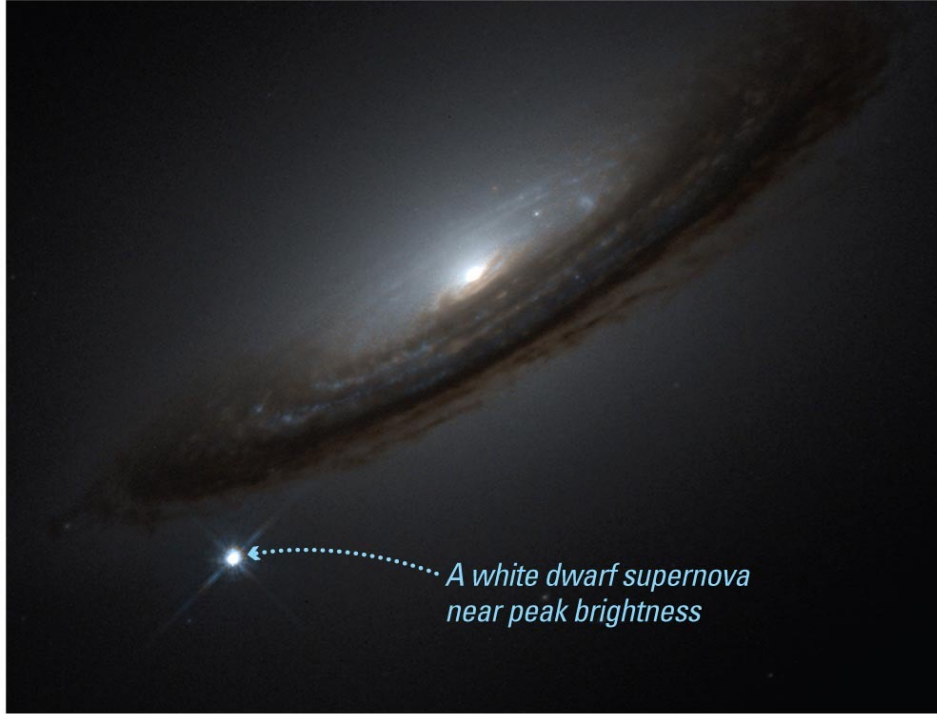
Distances to Cepheid Variables

- ***Step 4***

- Because the period of Cepheid variable stars tells us their luminosities, we can use them as standard candles.

Distances to Cepheid Variables

- Cepheid variable stars with longer periods have greater luminosities. Can be used to determine distances up to 100 Mly.
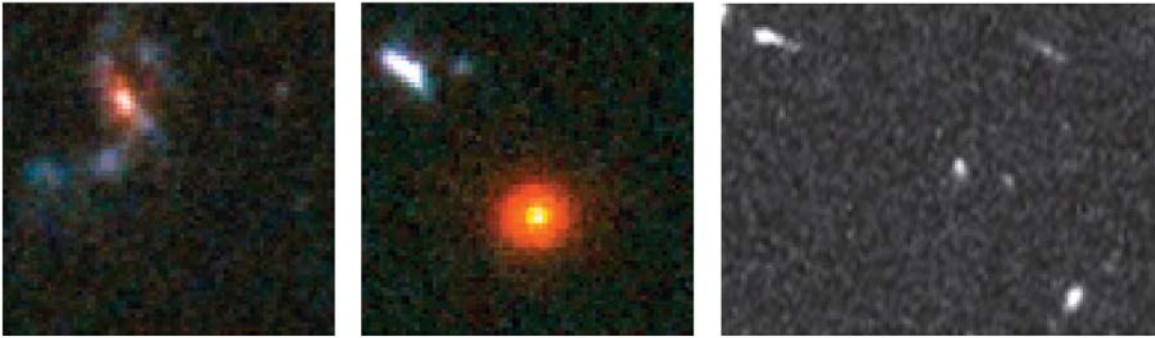
Distances to Type Ia Supernovae

A white dwarf supernova near peak brightness

- White-dwarf supernovae can also be used as standard candles.

- These supernovae occur when a white dwarf in a close binary system accretes enough matter from its companion to blow itself apart when M > 1.4 $M_{\odot}$
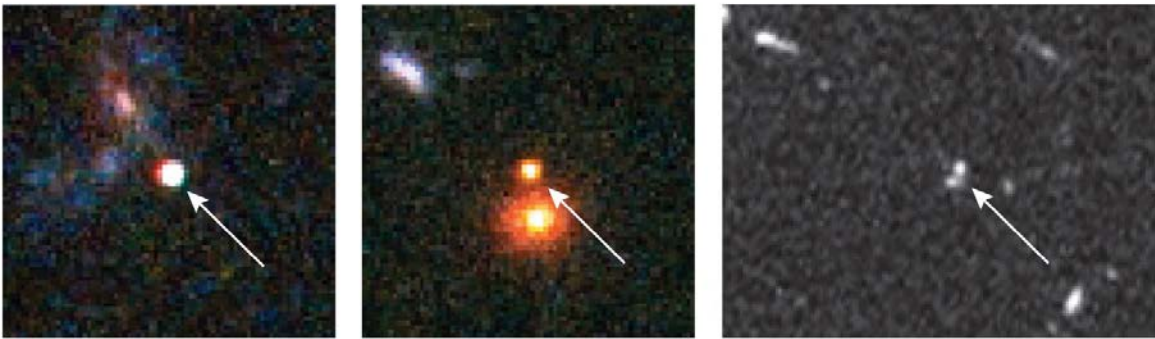
Distances to Type Ia Supernovae

Distant galaxies before supernova explosions

The same galaxies after supernova explosions

- *Step 5*

- The apparent brightness of a white dwarf supernova tells us the distance to its galaxy (up to 10 billion light-years).

How did Hubble prove that galaxies lie far beyond the Milky Way?
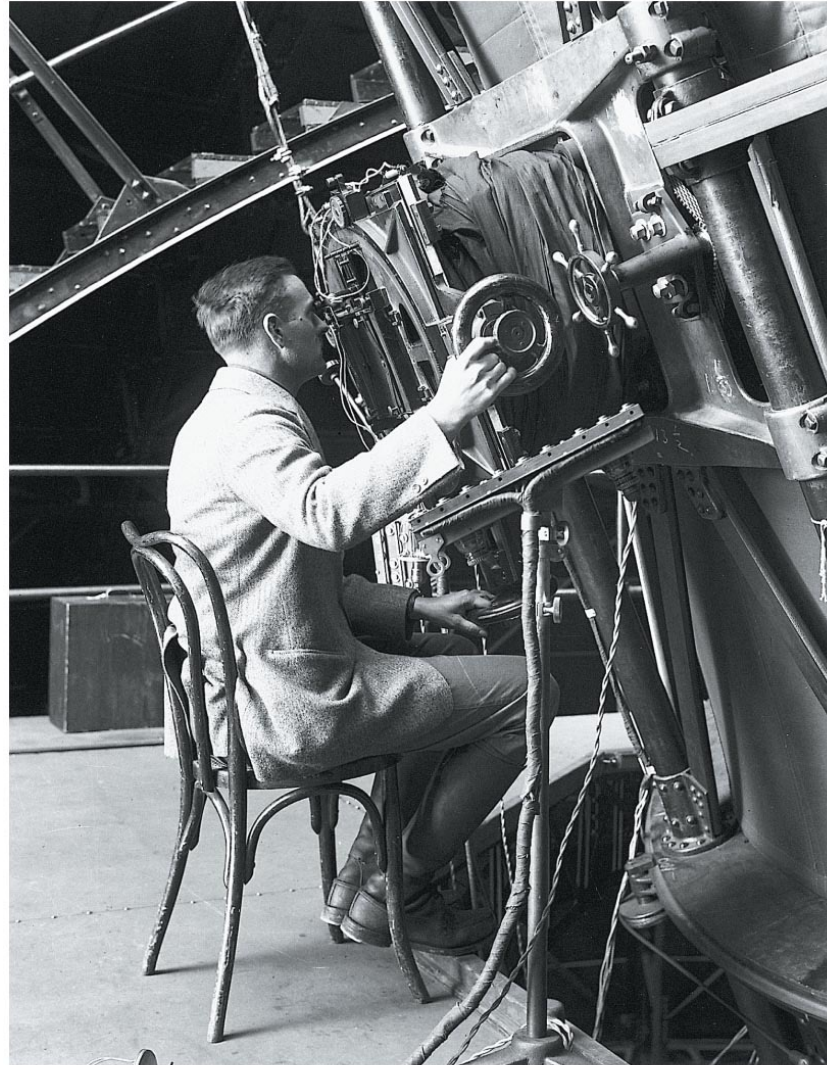
The Puzzle of "Spiral Nebulae"

- Before Hubble, some scientists argued that "spiral nebulae" were entire galaxies like our Milky Way, while others maintained they were smaller collections of stars within the Milky Way.

- The debate remained unsettled until Edwin Hubble finally measured their distances.
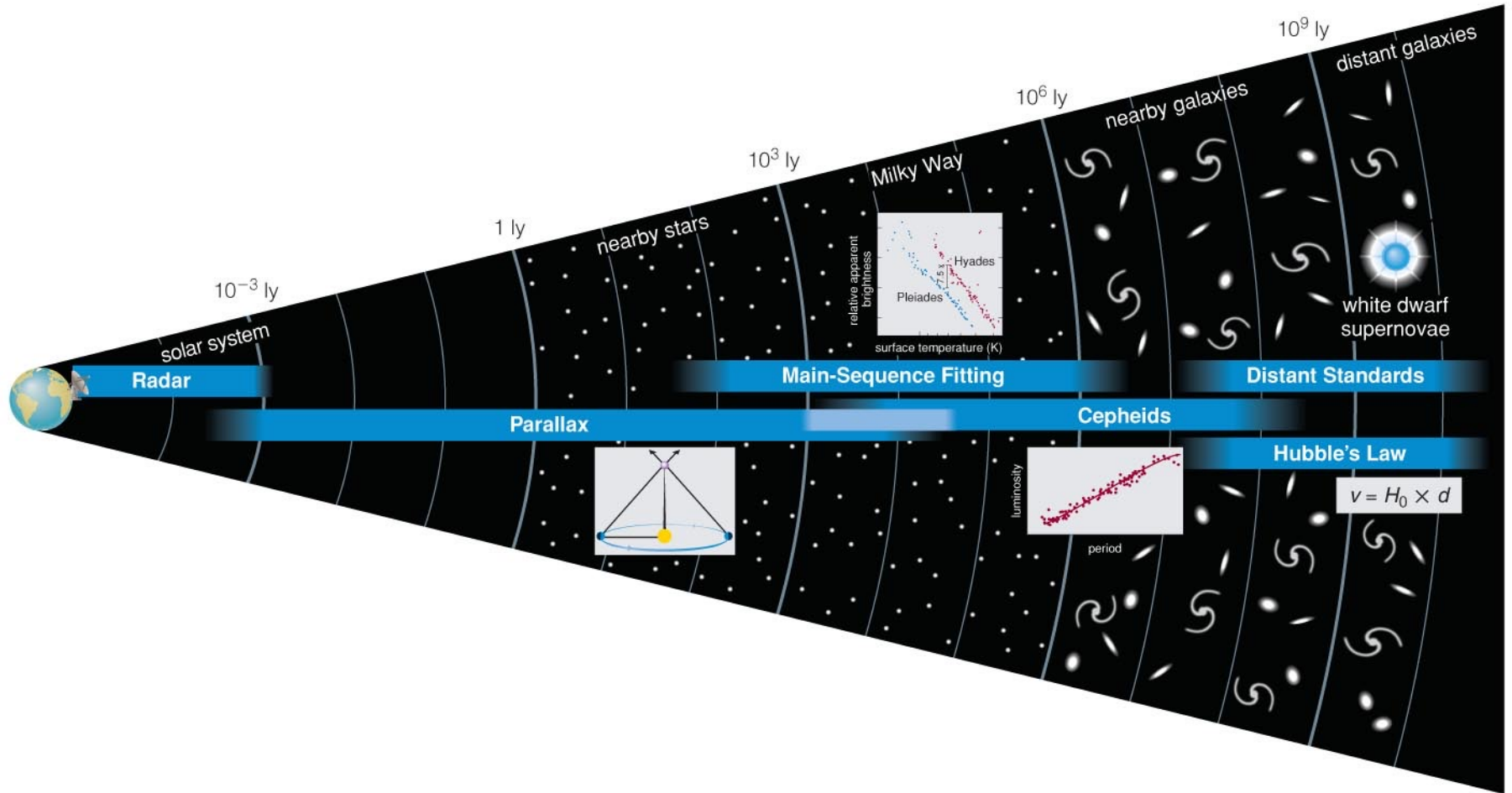
- Hubble settled the debate by measuring the distance to the Andromeda Galaxy using Cepheid variables as standard candles.

What is the Hubble–Lemaître Law
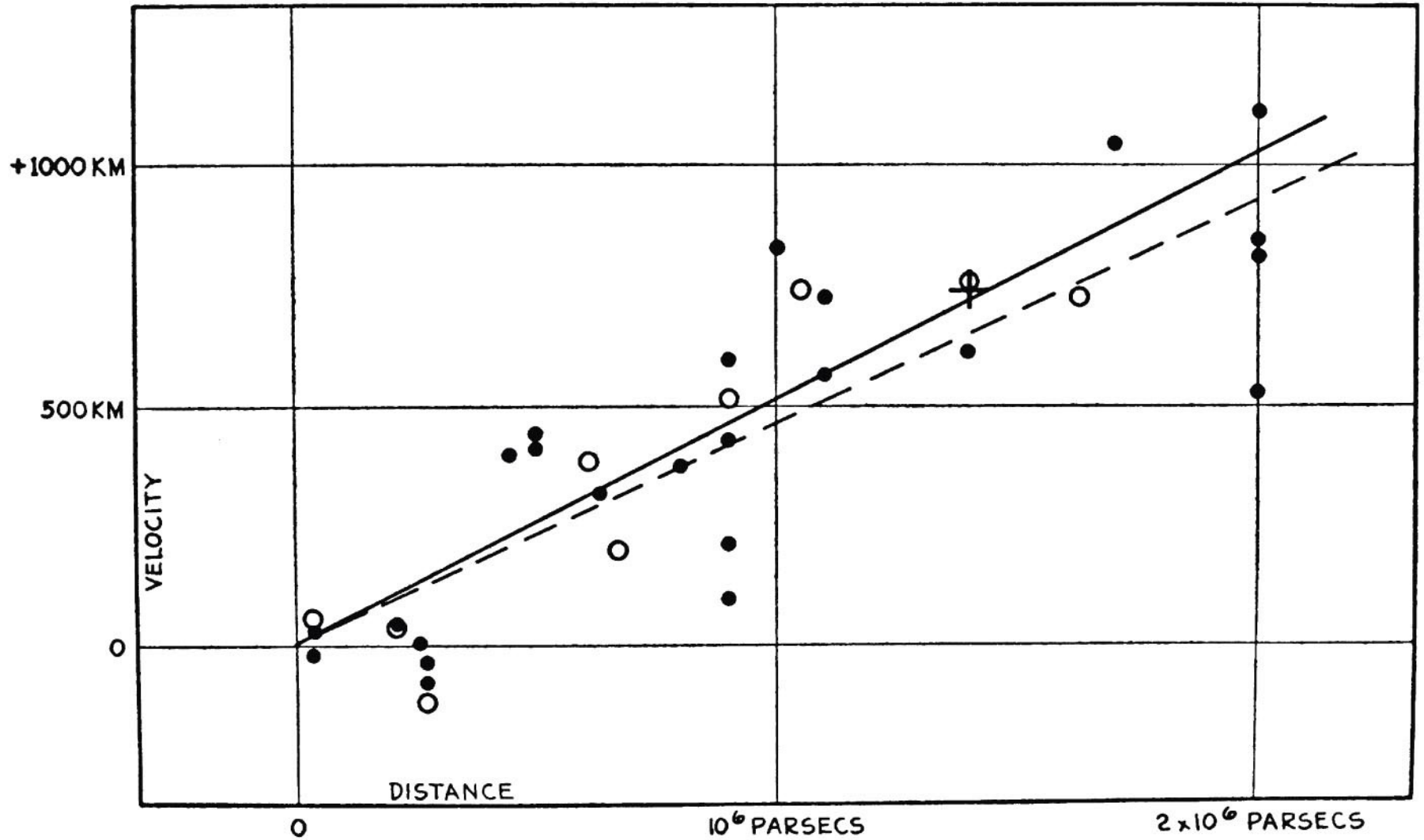
- The spectral features of virtually all galaxies are redshifted, which means that they're all moving away from us.

Cosmological Redshift

$$\frac{\lambda_{obs} - \lambda_0}{\lambda_0} = z$$

λ_{obs} = the observed wavelength

λ_0 = the rest frame wavelength

z = redshift of object

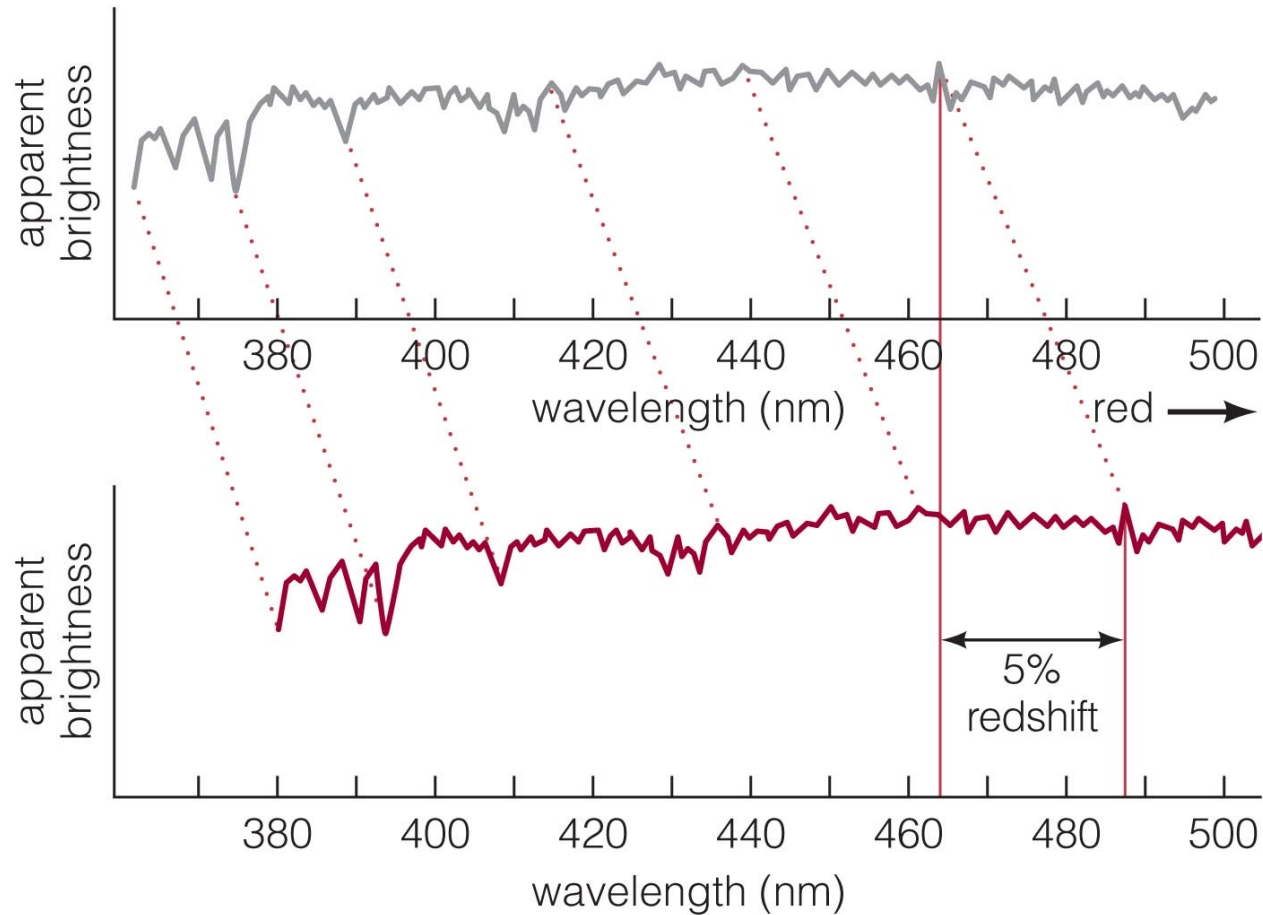Figure: Each galaxy's spectrum is a bright band with dark absorption lines.

The bright lines above and below it are a comparison spectrum taken on Earth. The horizontal red arrows show how much the H and K lines of singly ionized calcium are redshifted in each galaxy's spectrum. Below each spectrum is the recessional velocity calculated from the redshift.

GALAXIES in

Virgo

Ursa Major

Corona Borealis

Boötes

Hydra

The more distant the galaxy…

REDSHIFTS

H + K

1200 km/s

15,000 km/s

22,000 km/s

39,000 km/s

61,000 km/s

…the greater its redshift and the more rapidly it is receding from us.

Cosmological Redshift

We can easily calculate the factor by which the Universe has expanded from some previous time as follows:

$$z = (\lambda_{obs} - \lambda_0)/\lambda_0 \rightarrow \lambda_{obs}/\lambda_0 = (1+z)$$

This means that if you observe an object to have a redshift of $z = 1$ the distance between us and the object has increased by a factor of 2 from the time the photon left that object and arrived to Earth.

How does the volume and density change?
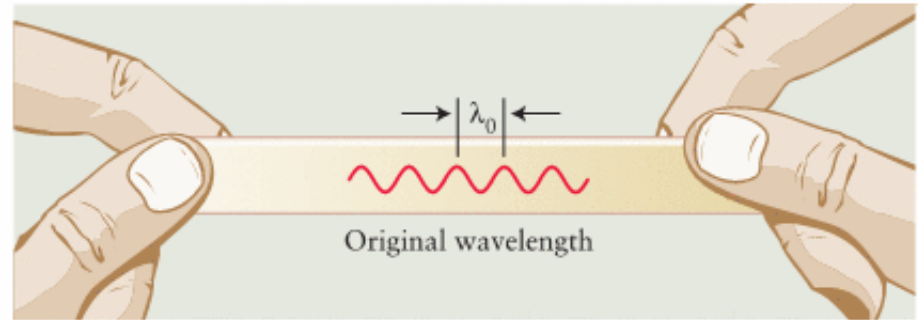
(a) A wave drawn on a rubber band ...
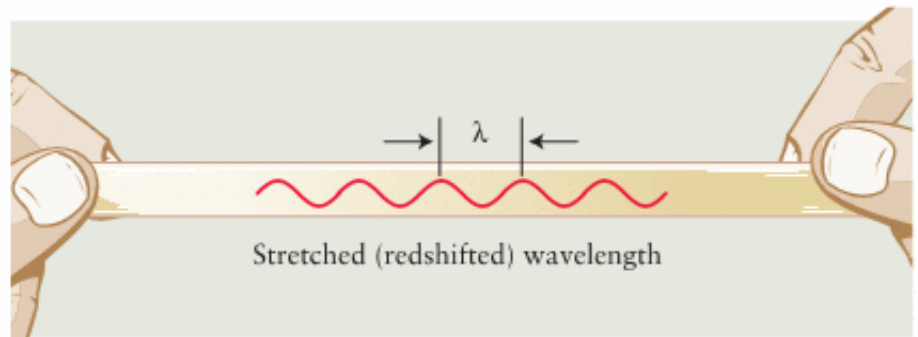
(b) ... increases in wavelength as the rubber band is stretched.

Cosmological Redshift

$$z = \frac{\lambda_{obs} - \lambda_0}{\lambda_0}$$

Example: The rest-frame wavelength of the hydrogen H_α line is : $\lambda_{H_\alpha} = 656\ nm$

You observe a distant galaxy where hydrogen H_α has an observed wavelength of $\lambda_{obs} = 787\ nm$

What is the redshift to this galaxy?

Cosmological Redshift

Example: The rest-frame wavelength of the hydrogen H_α line is : $\lambda_{H_\alpha} = 656 \, nm$

You observe a distant galaxy where hydrogen H_α has an observed wavelength of $\lambda_{obs} = 787 \, nm$

The redshift to this galaxy is:

$$z = \frac{\lambda_{obs} - \lambda_{H_\alpha}}{\lambda_{H_\alpha}} = \frac{787 - 656}{656} = 0.2$$
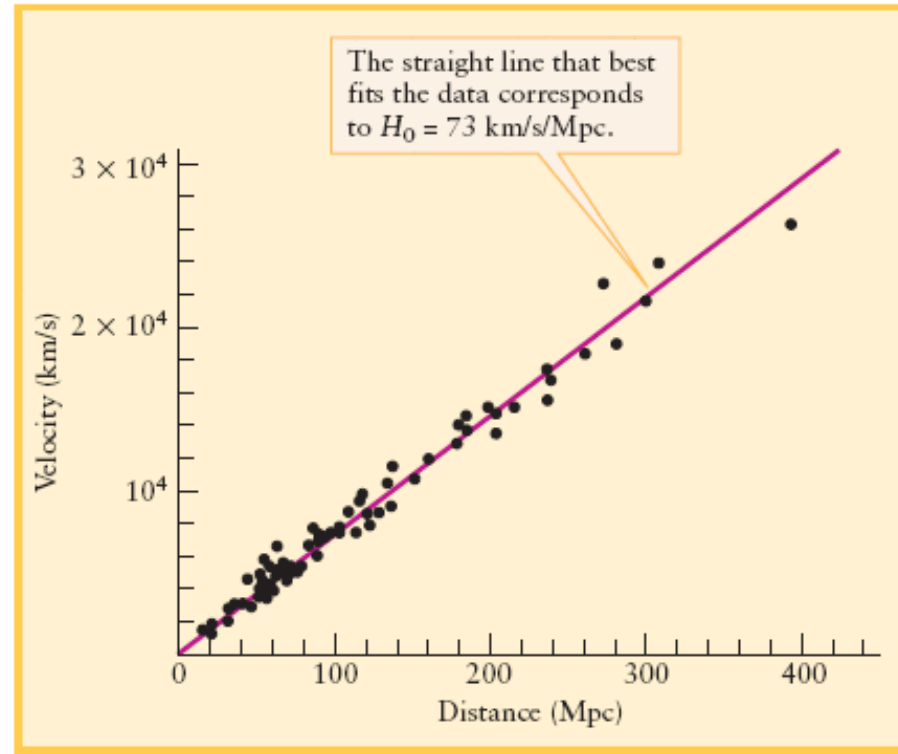
The Hubble–Lemaître Law

The Hubble–Lemaître Law:

$$v = H_0 \, d$$

v = recessional velocity of a galaxy, H_0 = Hubble constant
d = distance to the galaxy

$$H_0 = 68 \text{ km/s/Mpc}$$

Note that this is not a real velocity as in the Doppler effect but the apparent velocity due to the expansion of space. For low redshift ($z < 0.1$) $z \sim v/c$ ➡ $v \sim zc$

The straight line that best fits the data corresponds to $H_0 = 73$ km/s/Mpc.

Hubble and Lemaître measured the recession velocities (from redshifts) and distances to galaxies (using Cepheid variable stars) and found that the more distant the galaxy the greater its recession velocity.

Distance from the Hubble-Lemaître law
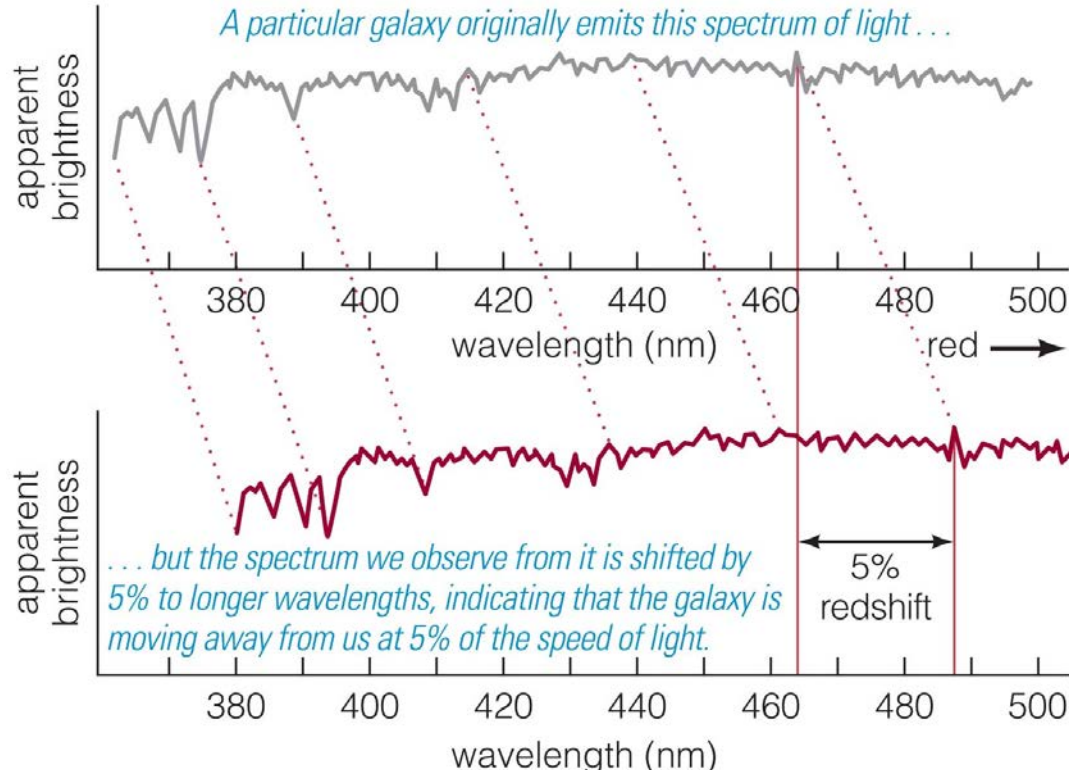
Redshift of a galaxy tells us its distance through the Hubble - Lemaître law:

$$Distance = \frac{velocity}{H_0} = \frac{zc}{H_0} \text{ (valid approximation for } z < 0.1)$$

Distance from the Hubble-Lemaître law

Redshift of a galaxy tells us its distance through the Hubble - Lemaître law:

$$Distance = \frac{velocity}{H_0}$$

Example: The recessional velocity of a galaxy is v = 10,000km/s. What is the distance to this galaxy. Assume $H_0 = 70$ km/s/Mpc ?
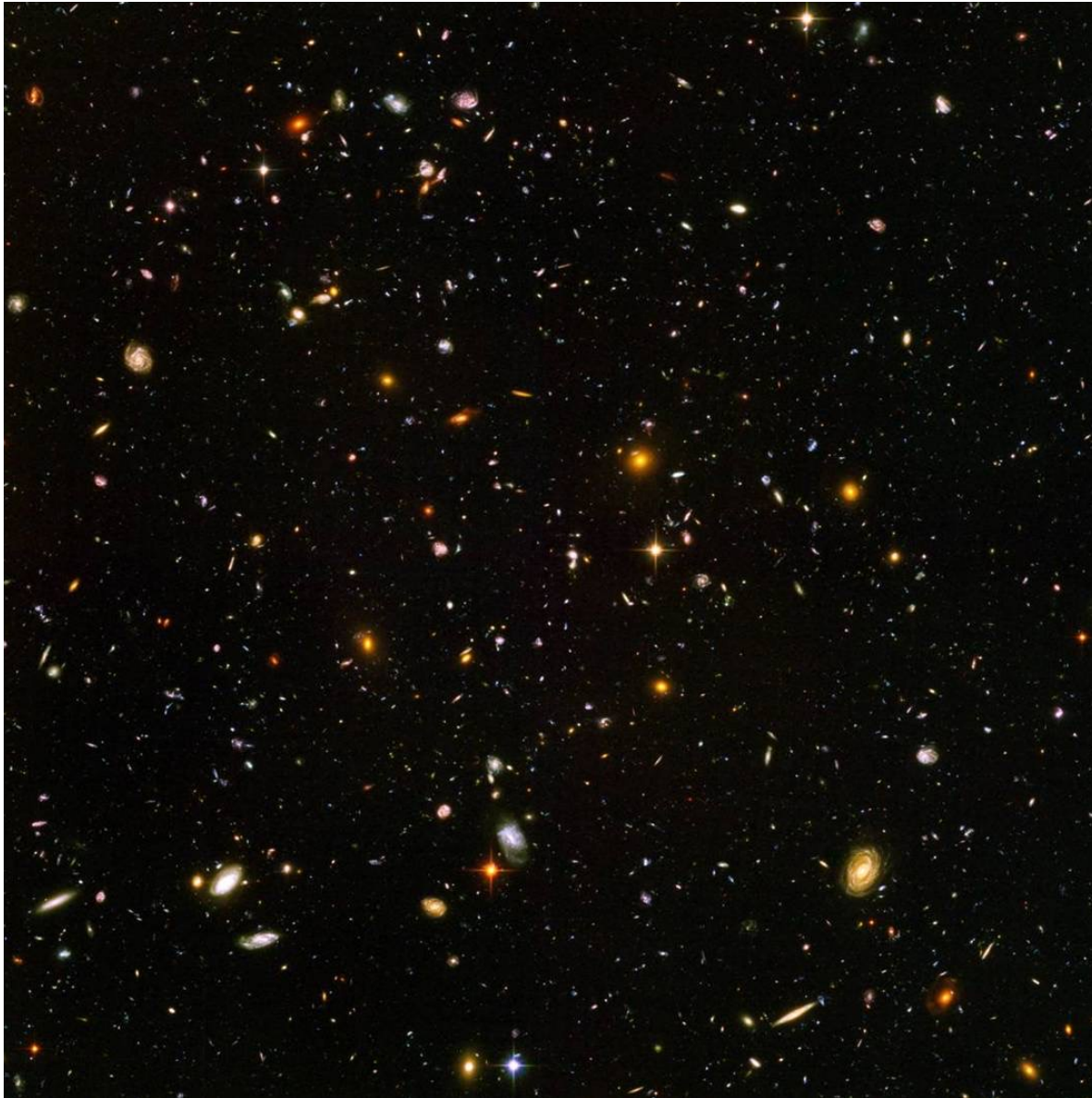
Distance from the Hubble-Lemaître law

Redshift of a galaxy tells us its distance through the Hubble - Lemaître law:

$$Distance = \frac{velocity}{H_0}$$
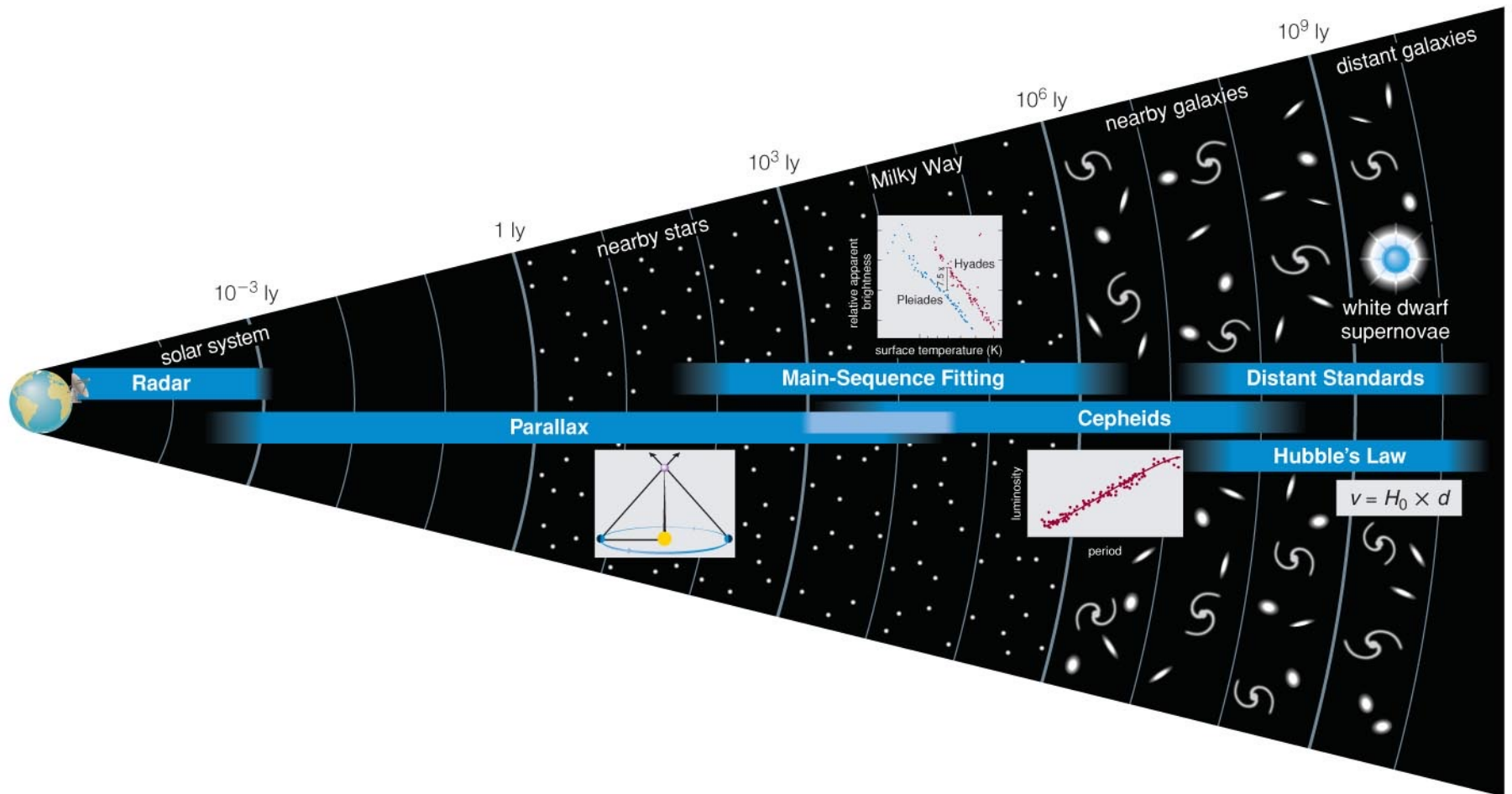
Example: The recessional velocity of a galaxy is v = 10,000km/s. What is the distance to this galaxy. Assume H_0 = 70 km/s/Mpc ?

$$distance = \frac{10000 \; km/s}{70 \frac{km}{sMpc}} = 142.9 \; Mpc$$

- Distances of the farthest galaxies are measured from their redshifts.

- We measure galaxy distances using a chain of interdependent techniques.

Distances

lookback time (or light travel time) indicates how far into the past we are looking when we see a particular object.

comoving radial distance: **d**(which goes into the H-L law : $v = H_0 d$) is the **distance now** between the object and us. During the time that it takes a photon to reach us from a distant object, that object has moved farther away due to the expansion of the universe.

luminosity distance (which goes into the inverse square law)

Several online cosmology calculators can be found at:

http://lambda.gsfc.nasa.gov/toolbox/tb_calclinks.cfm

The Age of the Universe

- Our goals for learning
  - **How does Hubble-Lemaître Law tell us the age of the universe?**
  - **How does expansion affect distance measurements?**
  - **Why does the observable universe have a horizon?**

The Age of the Universe

The expansion of the Universe is an expansion of space. As we go back in time we find the density of the Universe increasing. About 13.8 billion years ago all matter was concentrated in a singularity of infinite density. Space and time were created 13.8 billion years ago in an event that is called the **Big Bang**.

How long ago did the Big Bang take place?

$T_0 = d/v = d / H_0 d = 1 / H_0 = 1 / 70$ km s^{-1} Mpc^{-1}
→ $T_0 \sim 14$ billion years 1 (1 Mpc = 3.09 × 10^{19} km)
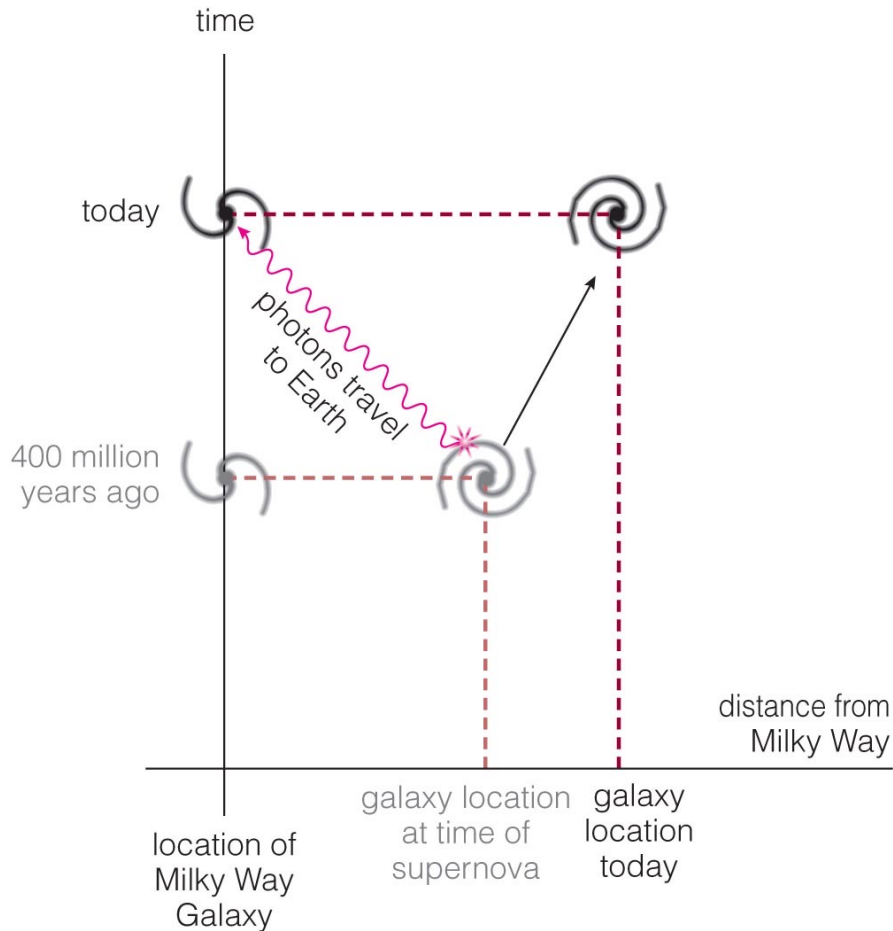
We have assumed that the Universe expands at a constant rate which is not true. Doing the calculations assuming a ΛCDM cosmology gives: $T_0 = 13.8$ Billion years
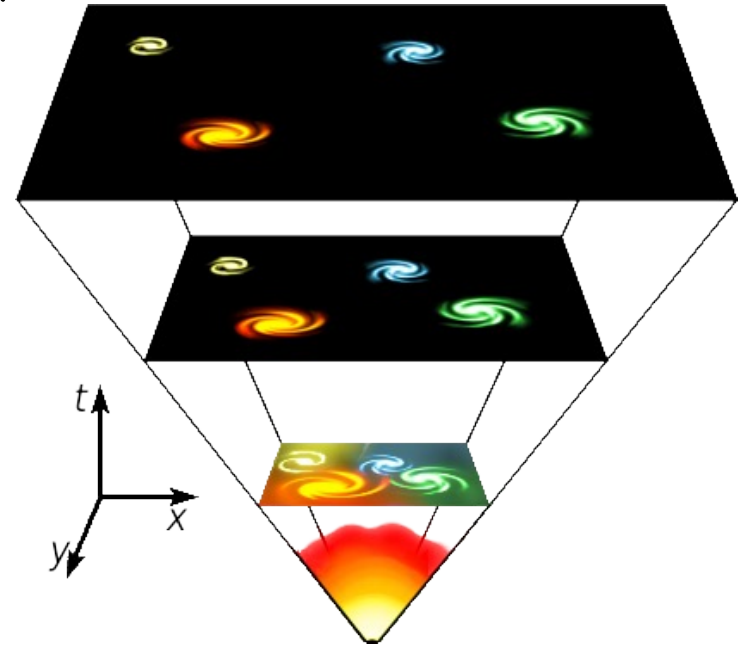
According to the Big Bang Model the Universe expanded from an extremely dense and hot state and continues to expand today.
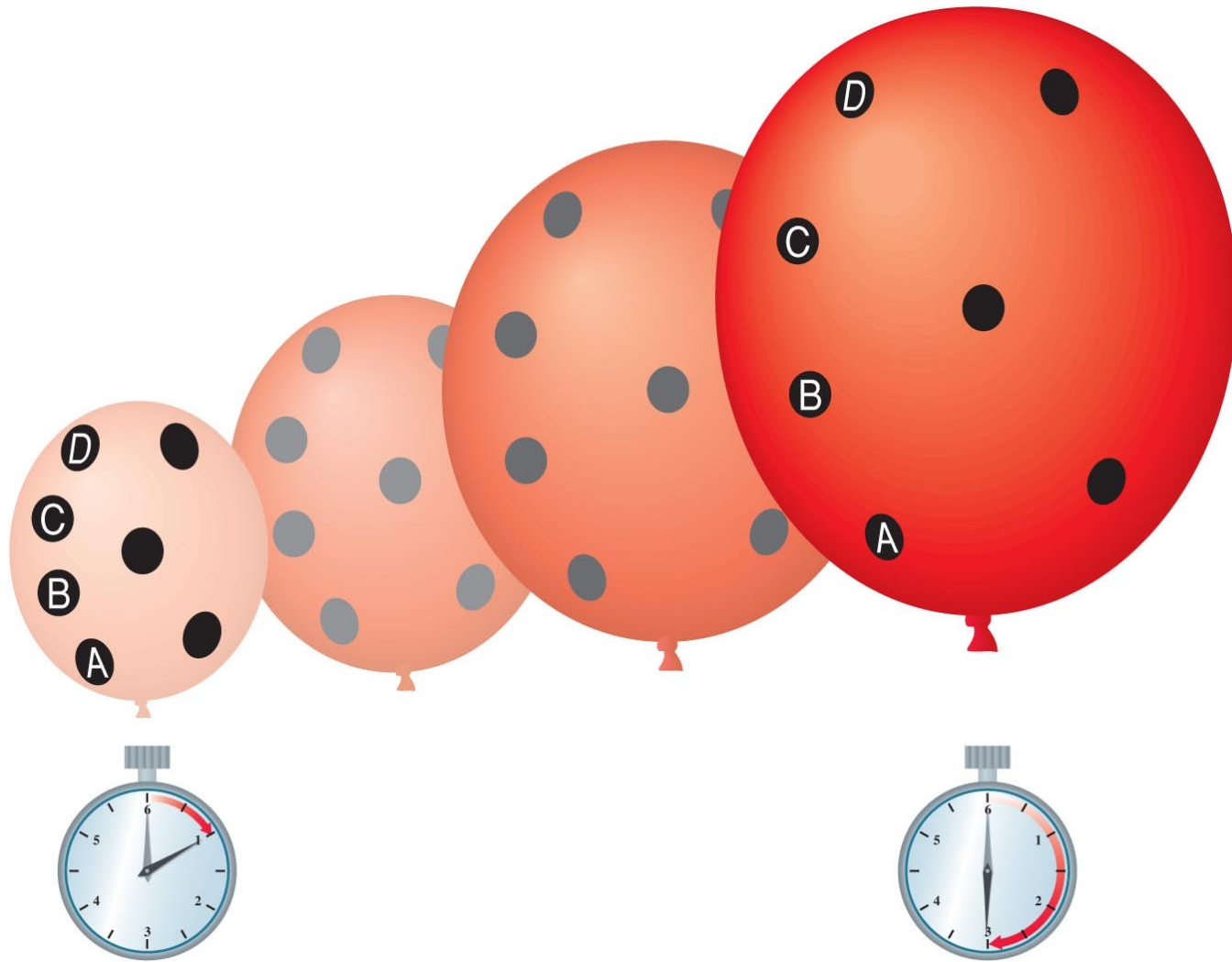
How does expansion affect distance measurements?
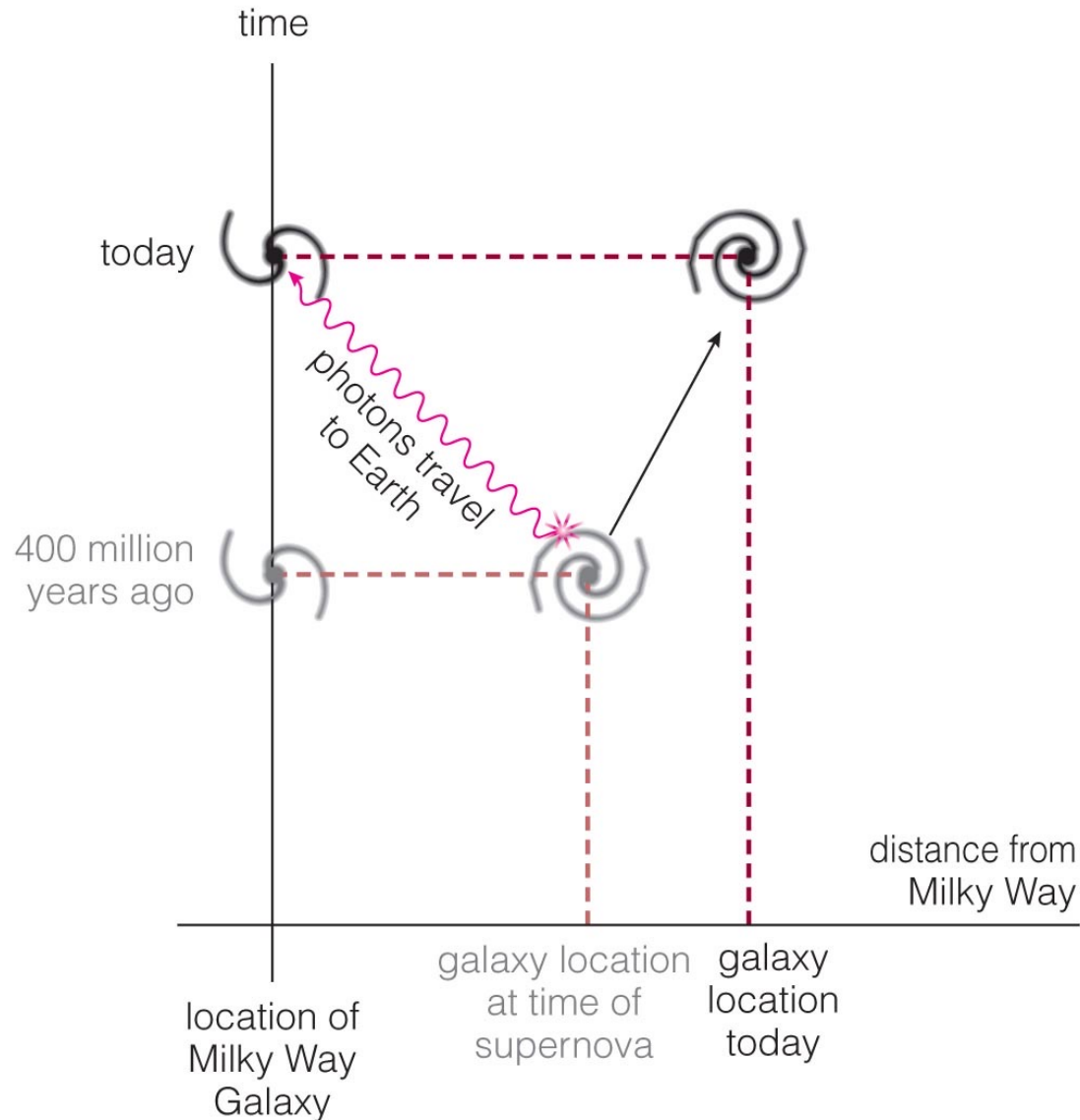
- Distances between faraway galaxies change while light travels. The distance now between us and a galaxy is larger than the distance during the time the photon left the galaxy.

- Astronomers use the term *lookback time* that indicates how far into the past we are looking when we see a particular object.

- One example of something that expands but has no center or edge is the surface of a balloon.

Cosmological Principle

*The universe looks about the same no matter where you are within it.*

- Matter is evenly distributed **on very large scales** in the universe.

- It has no center or edges.

- The Universe is **homogeneous and isotropic**.

- The cosmological principle is consistent with all observations to date.

Cosmological Principle

Homogeneous
Not isotropic

Isotropic
Not homogeneous

(a)

Homogeneous
Not isotropic

Isotropic
Not homogeneous

(b)
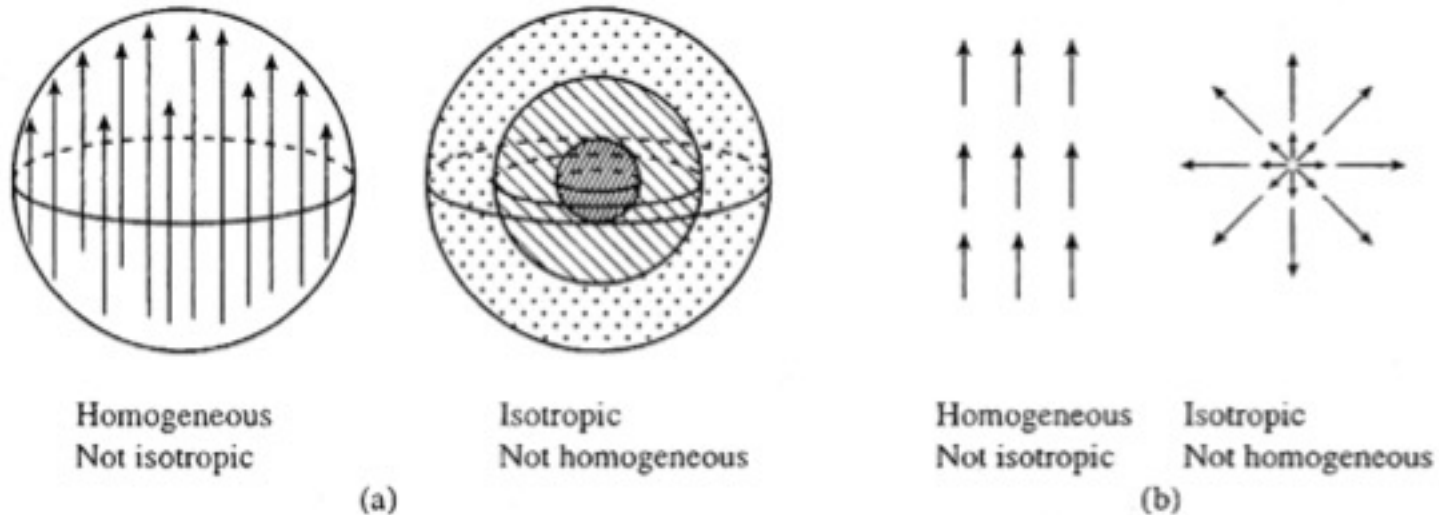
Figure 1.5 Illustrations of how homogeneity and isotropy are not equivalent in (a) three dimensions and (b) two dimensions. In the first example of each, a unique direction is picked out but translation invariance is maintained. In the second example of each, all directions are the same (rotation invariance) but a radial gradient exists.

Why does the observable universe have a horizon?
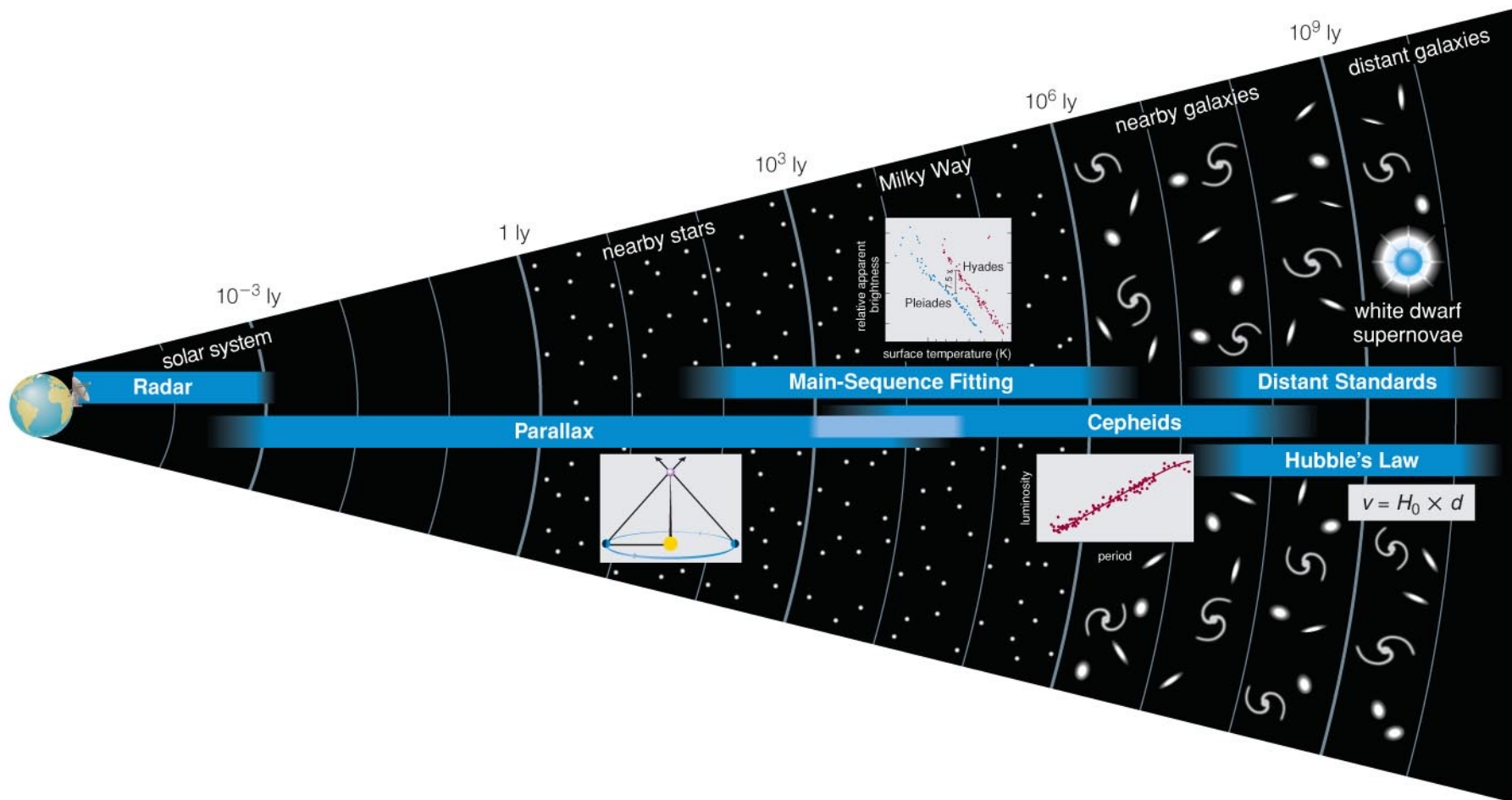
- The **Cosmological Horizon** marks the limits of the observable universe.

- We can only observe the parts of the Universe where the lookback time is less than the age of the Universe.

The Observable Universe

The dashed circle represents our cosmic light horizon, a sphere centered on Earth. Light from objects on this horizon is only now reaching us.

These galaxies lie within our cosmic light horizon, and so are part of our observable universe.

R I V U X G

All of the objects that we can see with even the most powerful telescopes lie within our observable universe.

Because the universe has continued to expand over the past 13.7 billion years, the radius of our cosmic light horizon is greater than 13.7 billion light-years. The present radius is about 47 billion light-years.

These galaxies lie outside our cosmic light horizon. Their light has been traveling toward us for 13.7 billion years, but they are so far away that the light has not yet reached us. Hence they are outside our present-day observable universe.
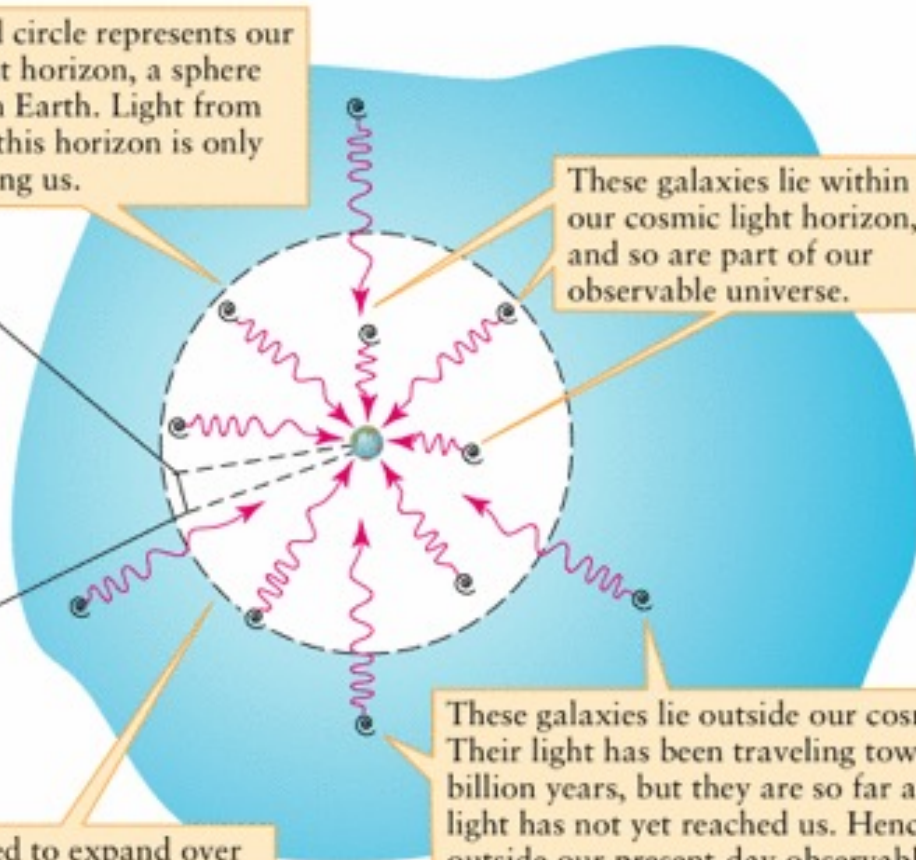
What have we learned?

- **How do distance measurements tell us the age of the universe?**

  – Measuring a galaxy's distance and speed allows us to figure out how long the galaxy took to reach its current distance.

  – Measuring Hubble's constant tells us that amount of time: about 14 billion years.

- **How does the universe's expansion affect our distance measurements?**

  – Lookback time is easier to define than distance for objects whose distances grow while their light travels to Earth.

What have we learned?

- **Why does the observable universe have a horizon?**
  - We cannot see back to a time before the beginning of the universe!

EXTRA SLIDES

- Brightness alone does not provide enough information to measure the distance to an object.

- Irregular galaxy

Blue-white color indicates ongoing star formation.

How does the Hubble-Lemaître Law tell us the age of the universe?