Hubble showed that certain “nebulae” are actually whole galaxies by

A) measuring the distance to them
B) showing that they have spiral arms like the Milky Way
C) measuring their recession speed
D) measuring their mass

Most of the normal matter in clusters of galaxies is

A) in stars within the galaxies
B) in hot gas between the galaxies
C) in cool gas within the galaxies
D) in black holes at the centers of the galaxies

The Universe

- Assumption in cosmology
- Why is the night sky dark?
- Hubble expansion
- The Big Bang
- Geometry of the Universe
- Cosmic microwave background

Assumptions in Cosmology

Copernican principle:

- We do not occupy a special place.
- There are no special places.
- The universe is homogeneous if viewed at sufficiently large scales.
- The laws of physics are the same everywhere.

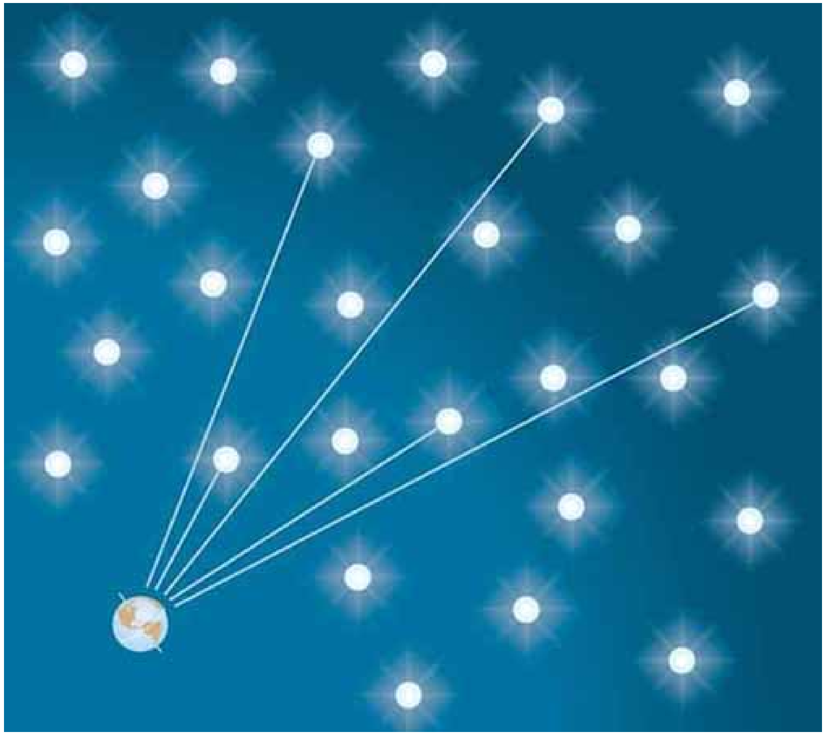
- Can we test the Copernican principle?

How can we test the Copernican principle?

- Does the Universe look the same in all directions? (Isotropy)
- Are the spectral lines from atoms the same in distant galaxies?
- Do the same laws of gravity apply in other galaxies?

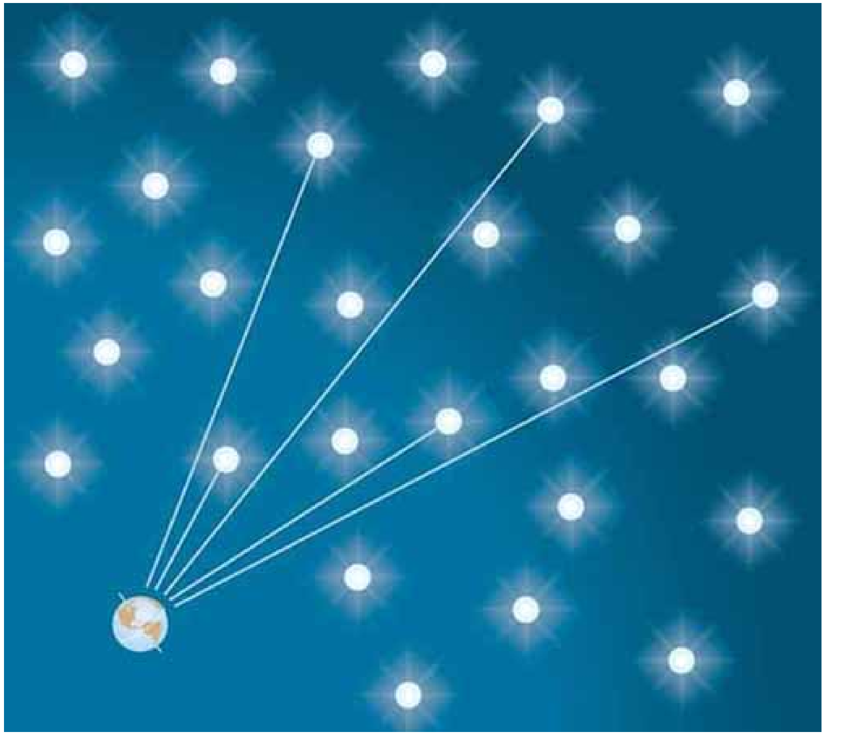
Why is the night sky dark? (Olber's Paradox)

- Or what is the temperature of the sky?
- Assume universe is static, infinite, and full of stars like the Sun.
- Then every ray extending out from the Earth will eventually intersect a star.
- So, the brightness of the sky at that point will be determined by the surface temperature of that star.
- So, any where we look, the sky should be as bright as the Sun.



Why is the night sky dark? (Olber's Paradox)

- One of the assumptions (static, infinite, and full of stars like the Sun) must be incorrect.
- Thus, to have a dark night sky, the Universe must be some combination of
    - dynamic
    - finite in time
    - finite in extent

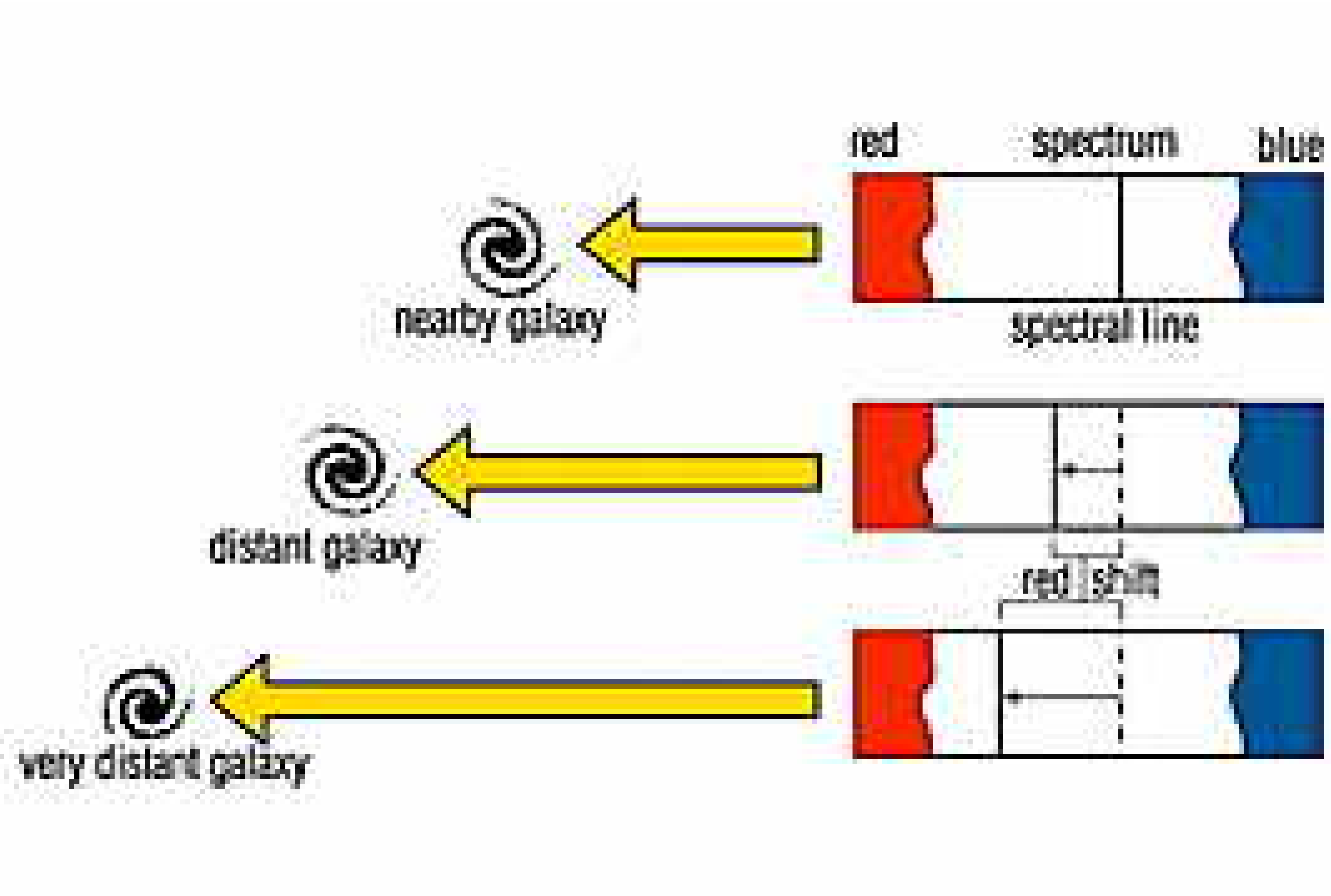


Doppler effect for light

Distances and velocities of galaxies

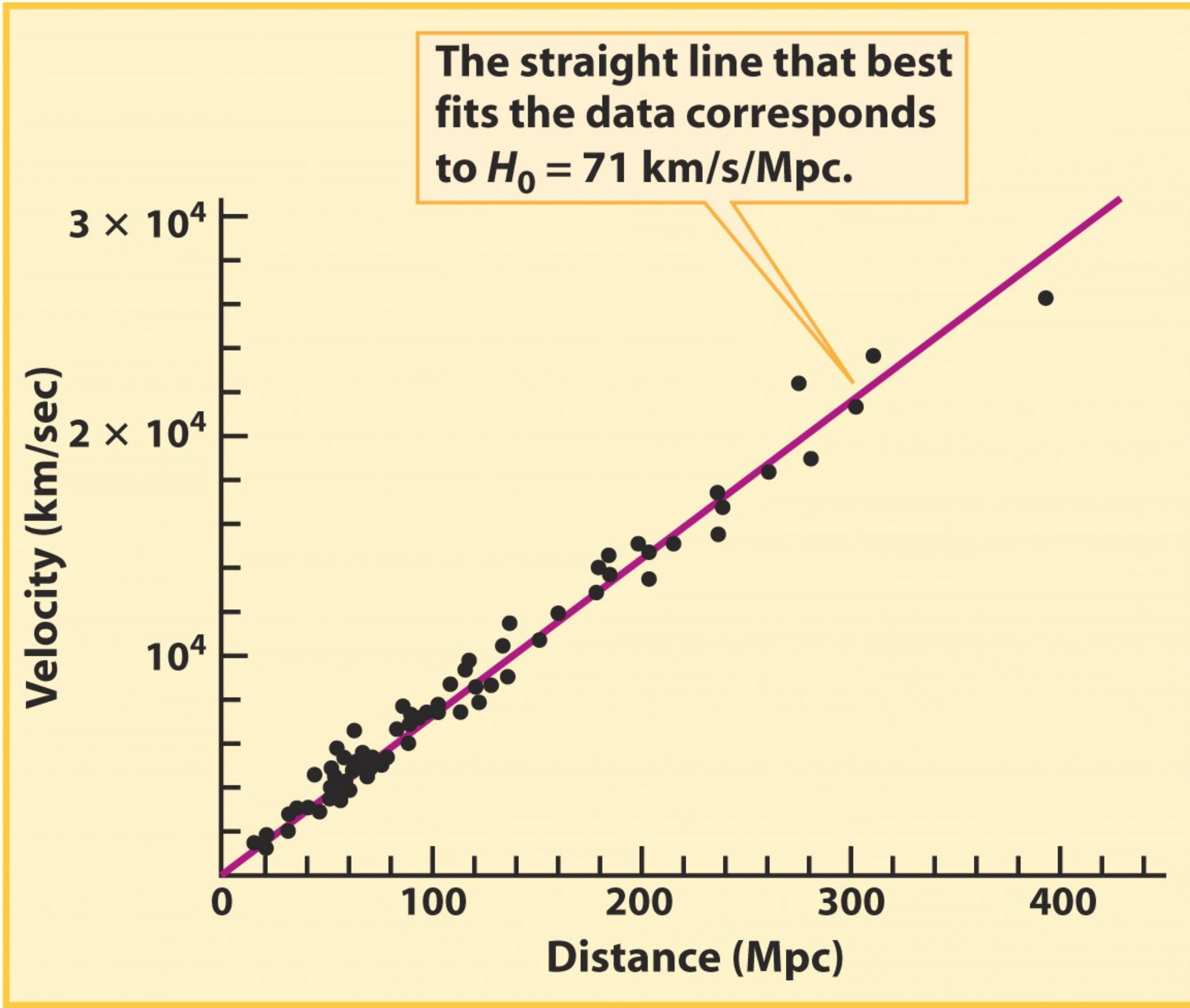
- If you measure the distances to a large set of galaxies and also measure the speed of the galaxies using the redshift, what do you find?

Light from distant galaxies is redshifted



Hubble expansion

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



What would be the recession speed of a galaxy at a distance of 7 Mpc?

A) 0.1 km/s

B) 10 km/s

C) 245 km/s

D) 490 km/s

E) 980 km/s

$\text{Speed} = H_0 \times \text{distance} \qquad H_0 = 70 \text{ km/s/Mpc}$

What would be the recession speed of a galaxy at a distance of 14 Mpc?

A) 0.1 km/s

B) 10 km/s

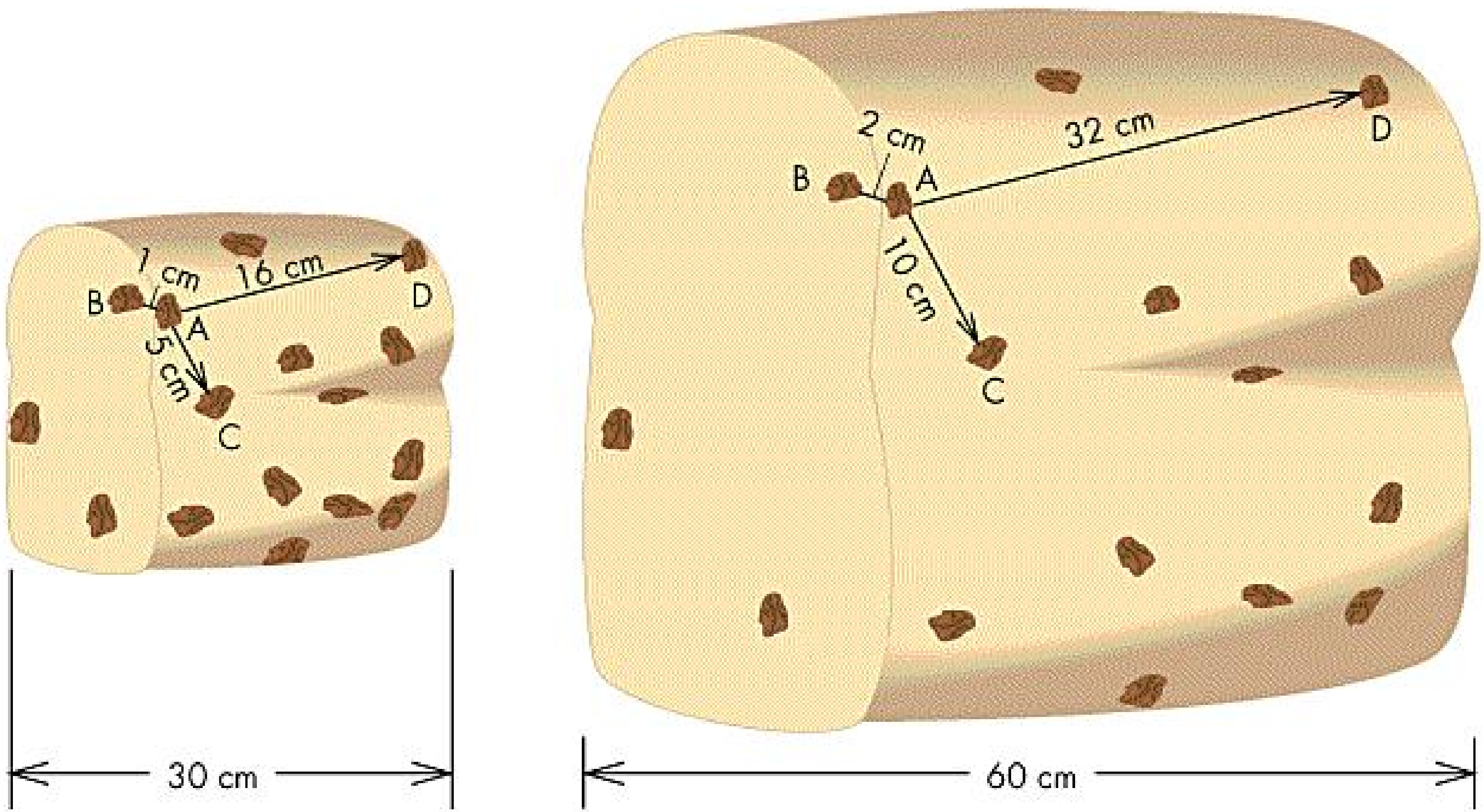
C) 245 km/s

D) 490 km/s

E) 980 km/s

$\text{Speed} = H_0 \times \text{distance}$ $\quad H_0 = 70$ km/s/Mpc

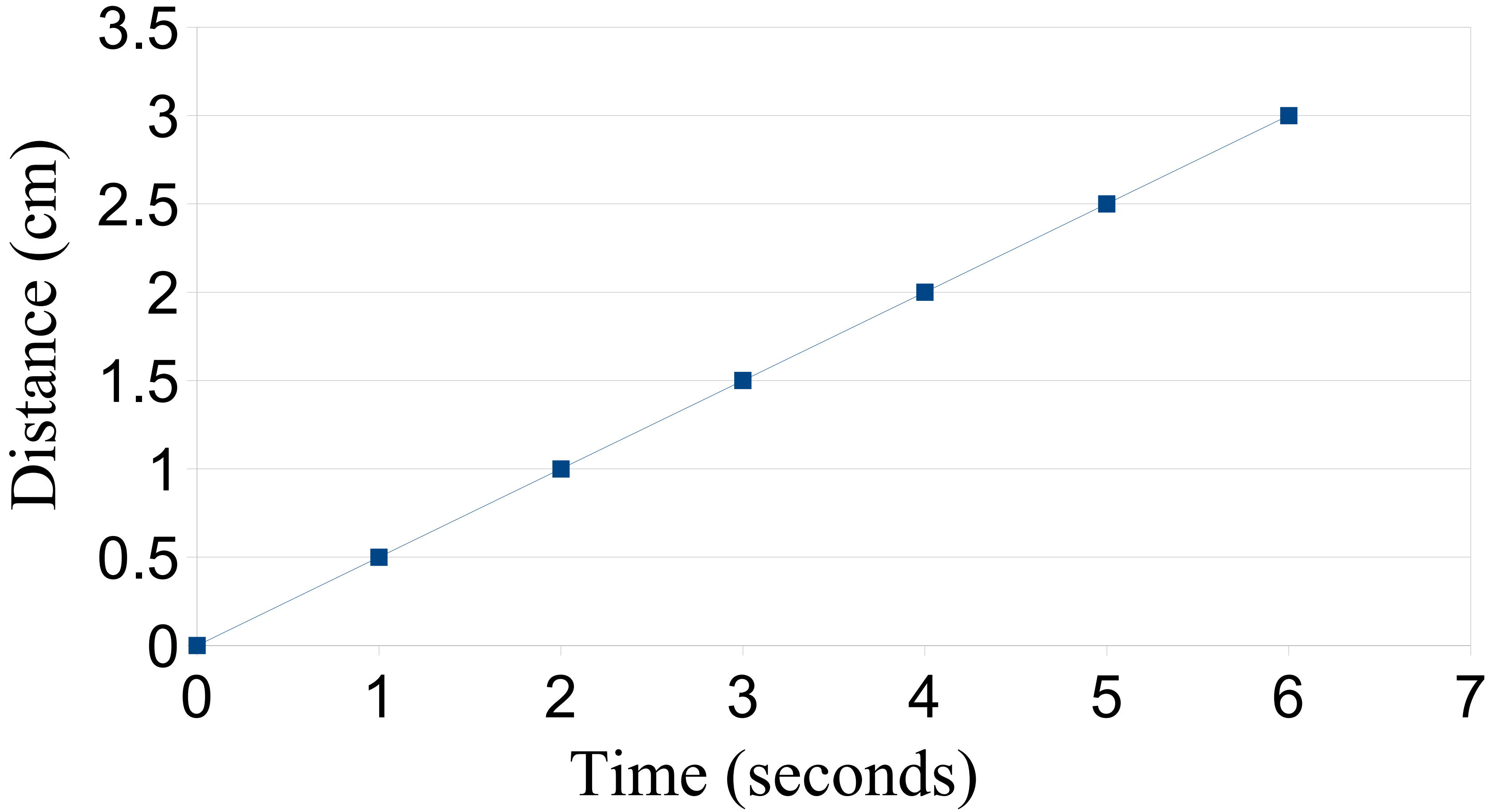
Expansion of the Universe



A Raisin bread dough before rising

B Raisin bread dough after rising

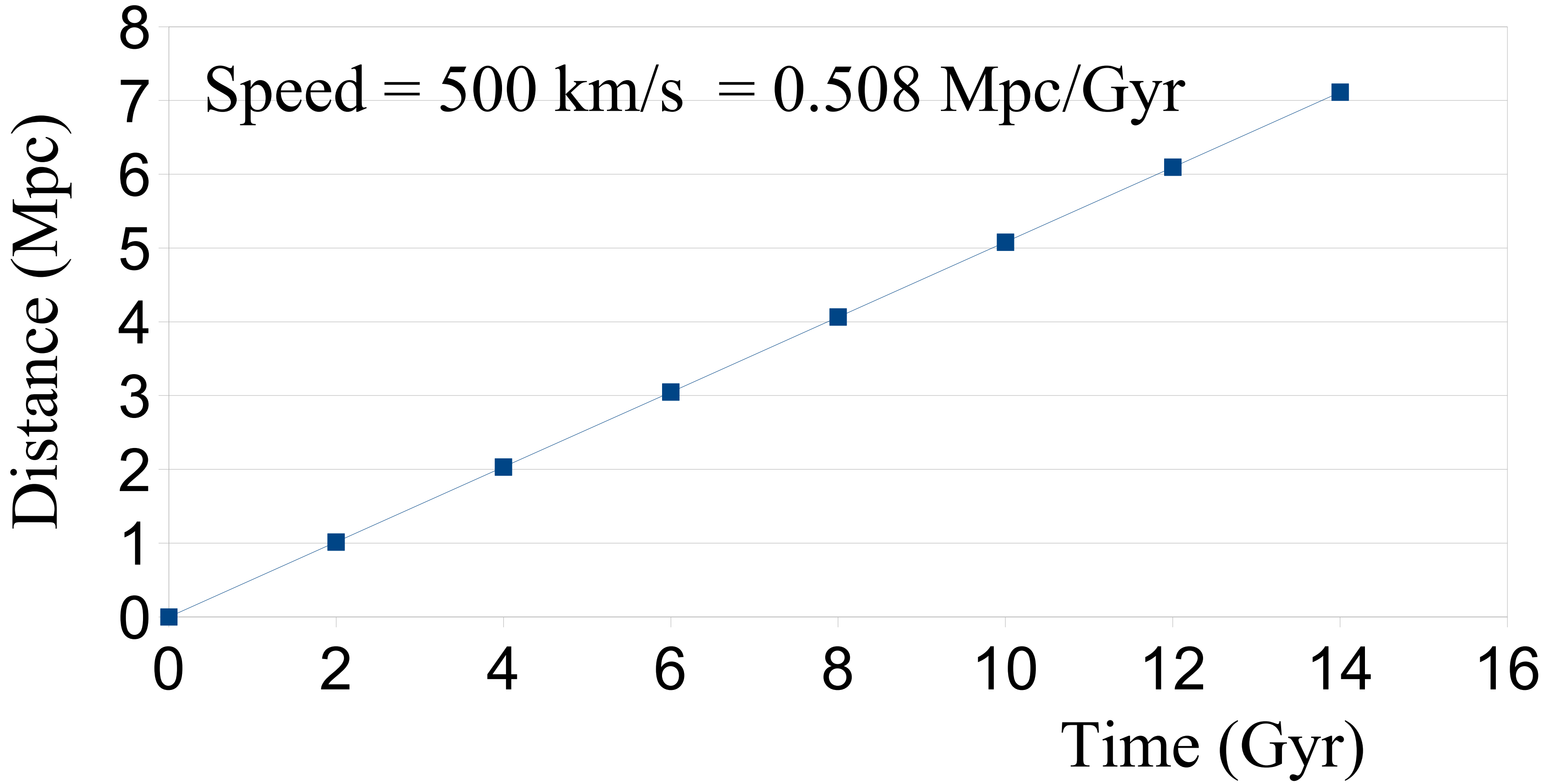
Motion at constant speed



distance = velocity × time velocity = 0.5 cm/s

time = distance / velocity = 3 cm/(0.5 cm/s) = 6 s

Receding galaxy

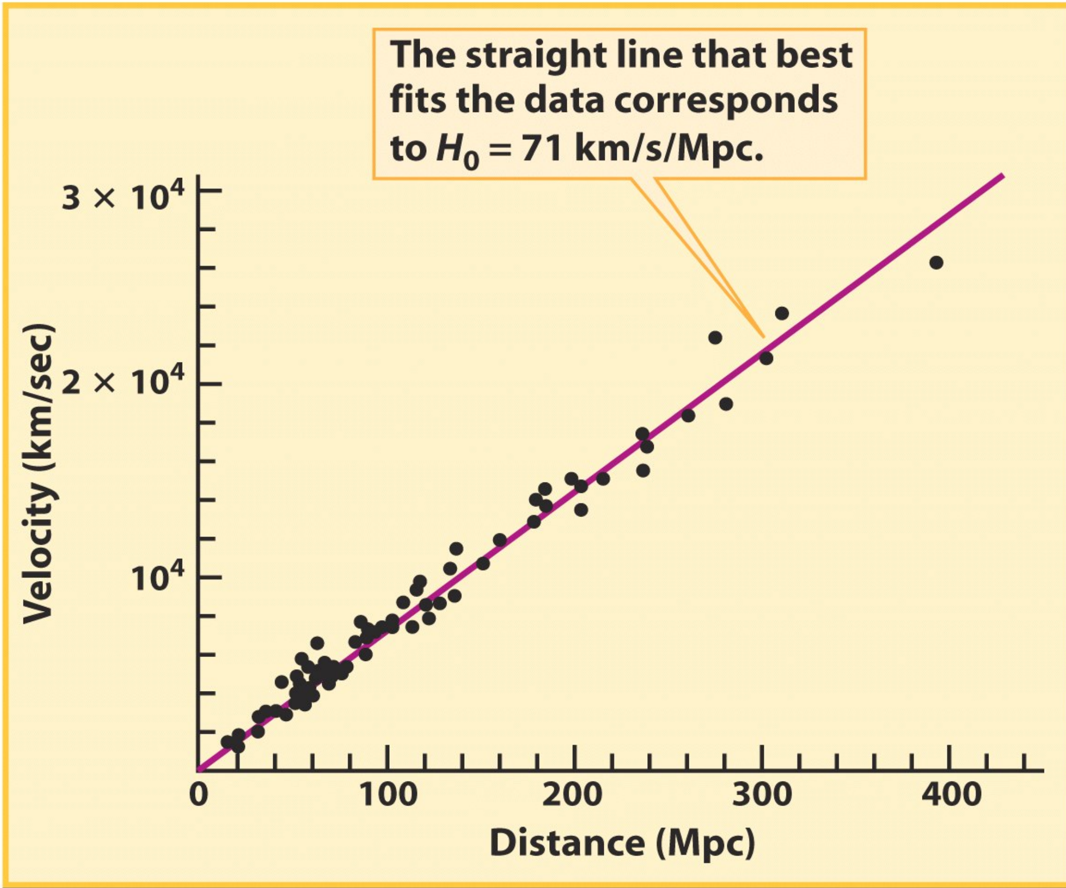


When were galaxies in the same place?

time = distance / velocity

= 7 Mpc/(0.508 Mpc/Gyr) = 13.8 Gyr ago

Hubble expansion $v = H_0 d$



Time = distance/velocity

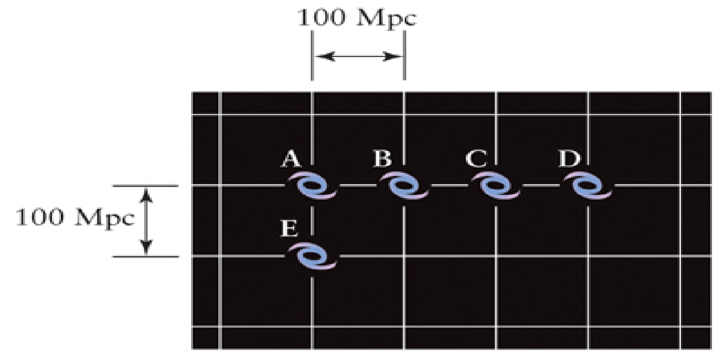
$= d/H_0 d$

$= 1/H_0$

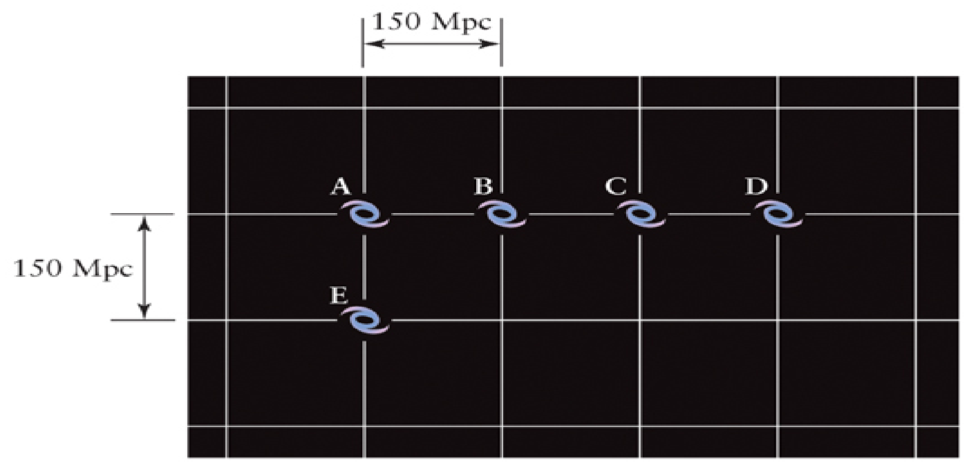
$= 1/(71\ \text{km/s/Mpc})$

$= 13.8$ Gyr

The Expanding Universe



(a) Five galaxies spaced 100 Mpc apart

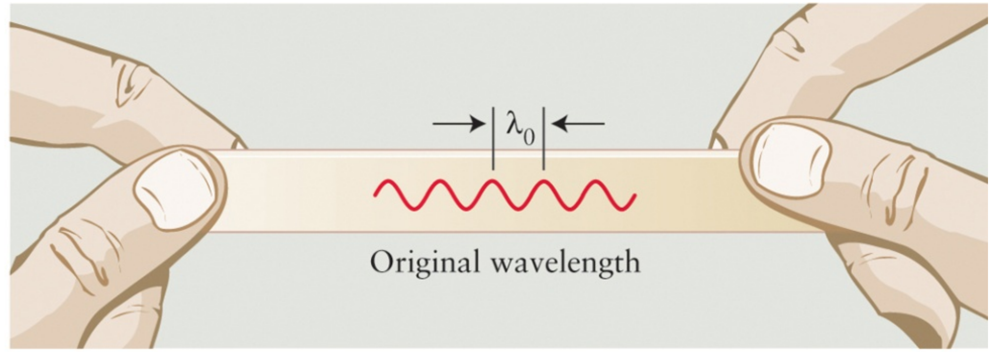


(b) The expansion of the universe spreads the galaxies apart

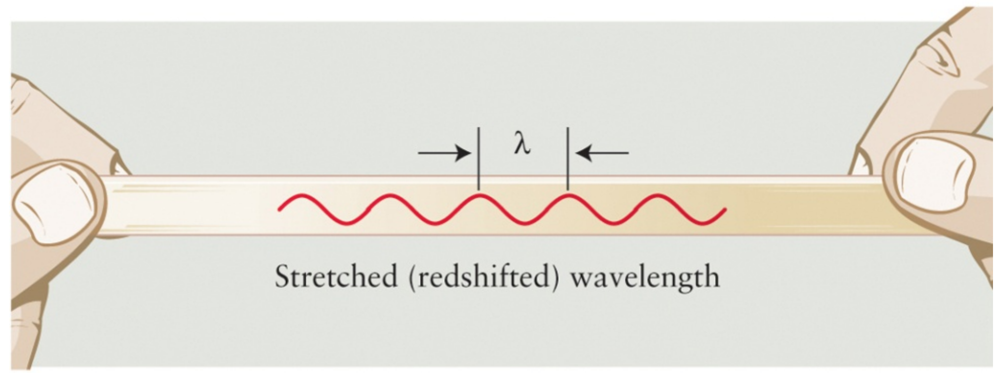
- As the universe expands, the space between adjacent galaxies increases.
- The greater the original distance between galaxies, the greater the increase in distance.
- The Hubble law arises from the expansion of space itself.

	Original distance (Mpc)	Later distance (Mpc)	Change in distance (Mpc)
A–B	100	150	50
A–C	200	300	100
A–D	300	450	150
A–E	100	150	50

Cosmological Redshift



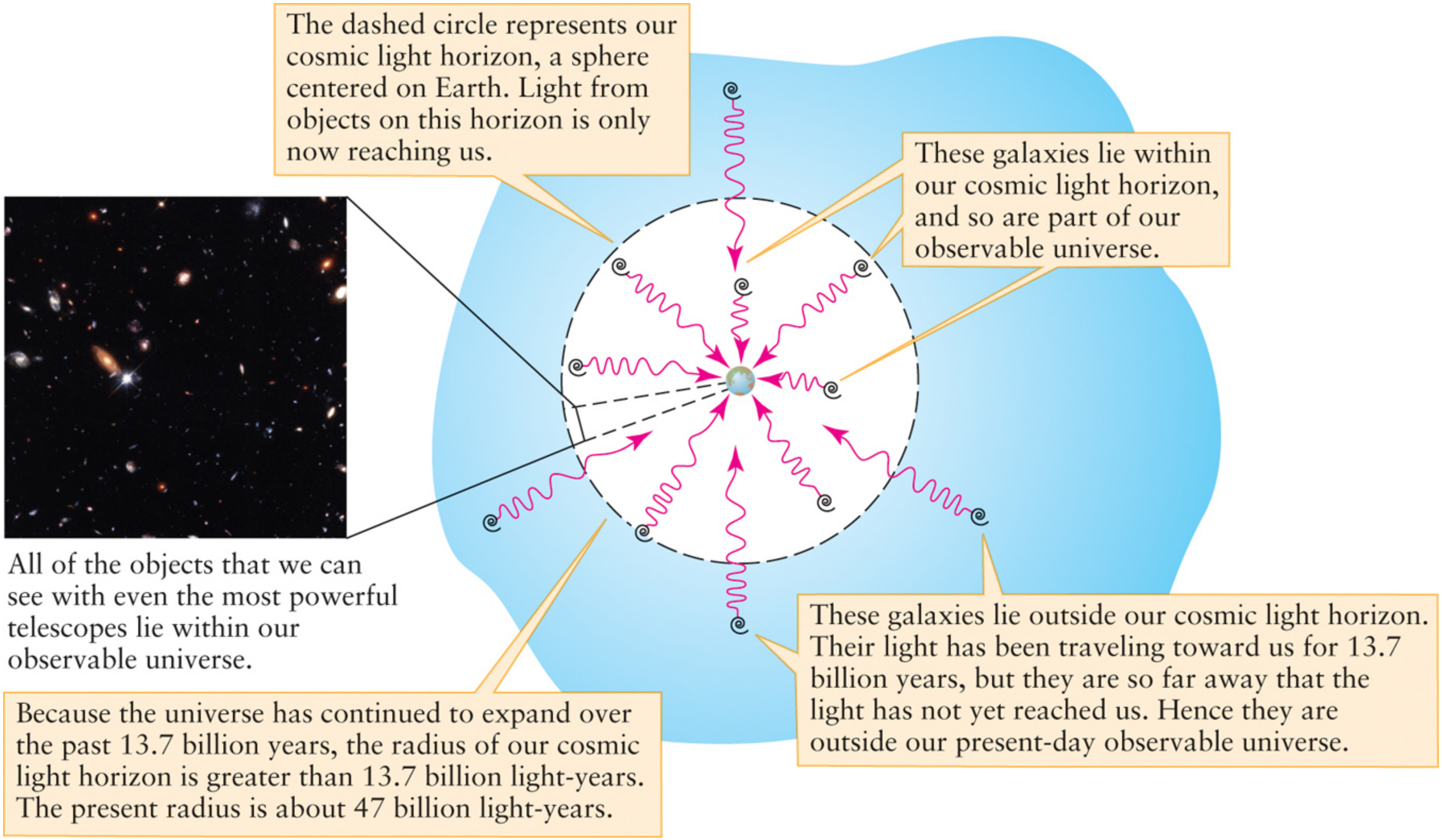
(a) A wave drawn on a rubber band ...



(b) ... increases in wavelength as the rubber band is stretched.

- A light wave traveling through an expanding universe "stretches," that is, its wavelength increases.
- A redshift caused by the expansion of the universe is a cosmological redshift.
- Doppler shifts are caused by an object's motion through space, whereas cosmological redshift is caused by the expansion of space.

Our Observable Universe



If the Hubble constant were doubled, what would be the recession speed of a galaxy at a distance of 7 Mpc?

A) 0.1 km/s
B) 10 km/s
C) 250 km/s
D) 500 km/s
E) 1000 km/s

Speed = $H_0 \times$ distance $H_0 = 2 \times 71$ km/s/Mpc

If Hubble's constant were twice as large as we now think it is, our estimate of the age of the universe would

A) be unchanged
B) increase by a factor of 2
C) increase by a factor of 4
D) decrease by a factor of 2
E) decrease by a factor of 4

Big Bang

- Our conclusion that the Universe actually began at some point in time is based on extrapolating back the observed Hubble expansion of galaxies

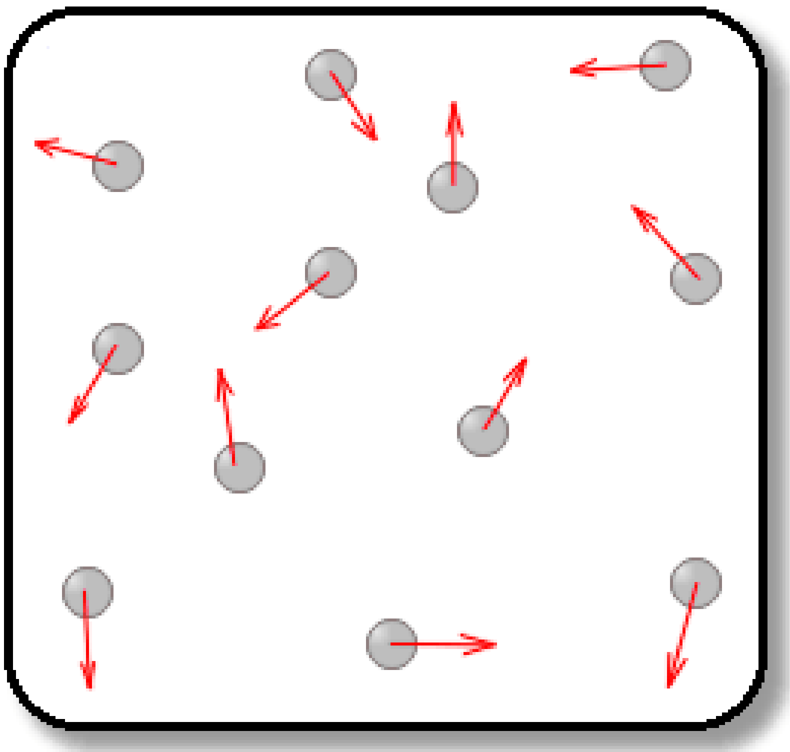
- Is there any other evidence?

Big Bang

- The universe is now expanding.
- In the past, the Universe was denser than it is today. Also, the energy density and therefore the temperature was higher.
- If we keep going backwards in time, the density and temperature must have been extremely high.
- Some sort of tremendous event caused this extremely hot, ultra-dense matter to begin the expansion that continues to the present day.
- This event, the ***Big Bang*,** marks the start of our Universe.

Temperature

- Temperature measures how fast atoms in a gas move



- Hotter

→ atoms move faster

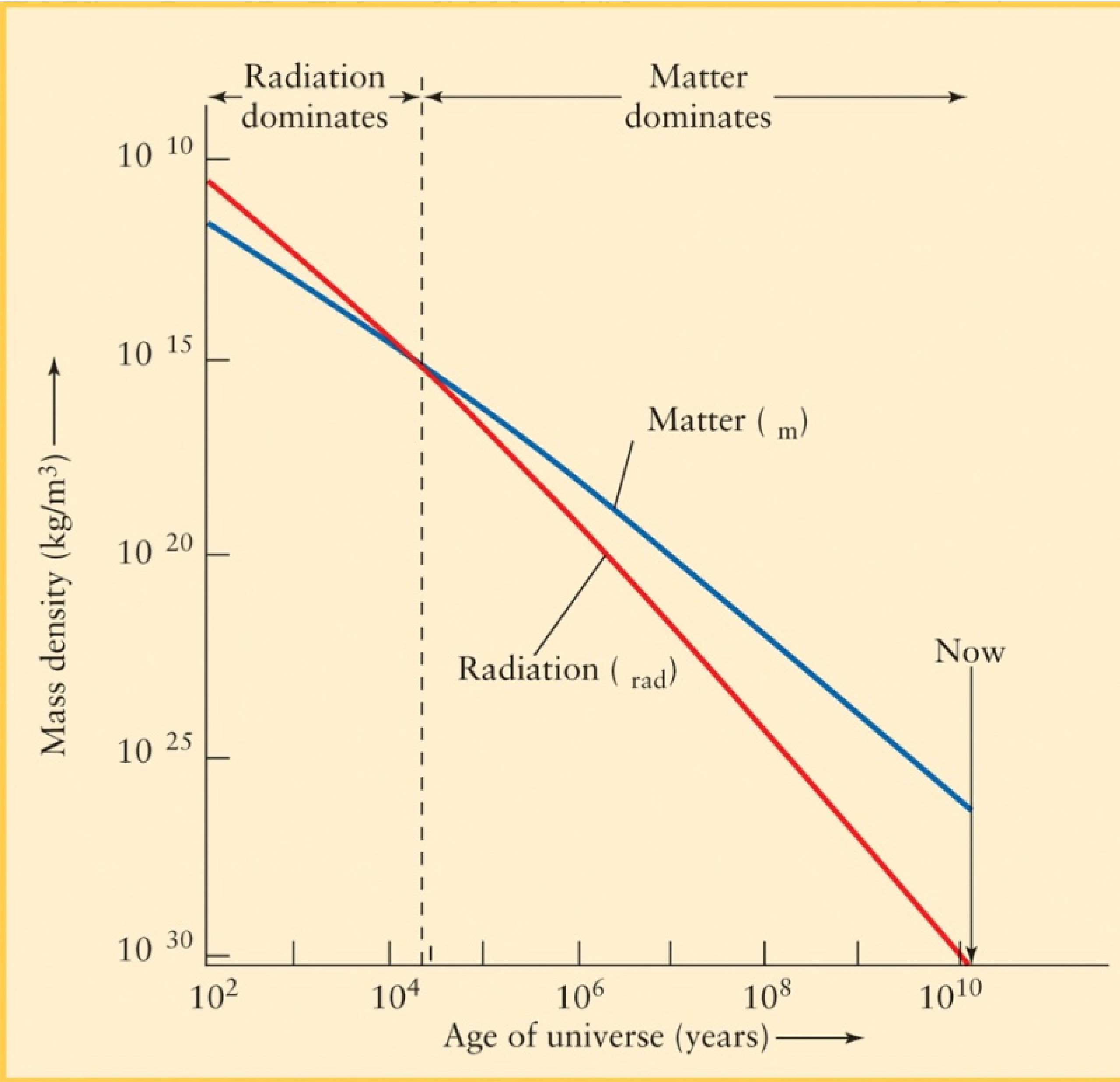
→ higher energy density

- Cooler

→ atoms move slower

→ lower energy density

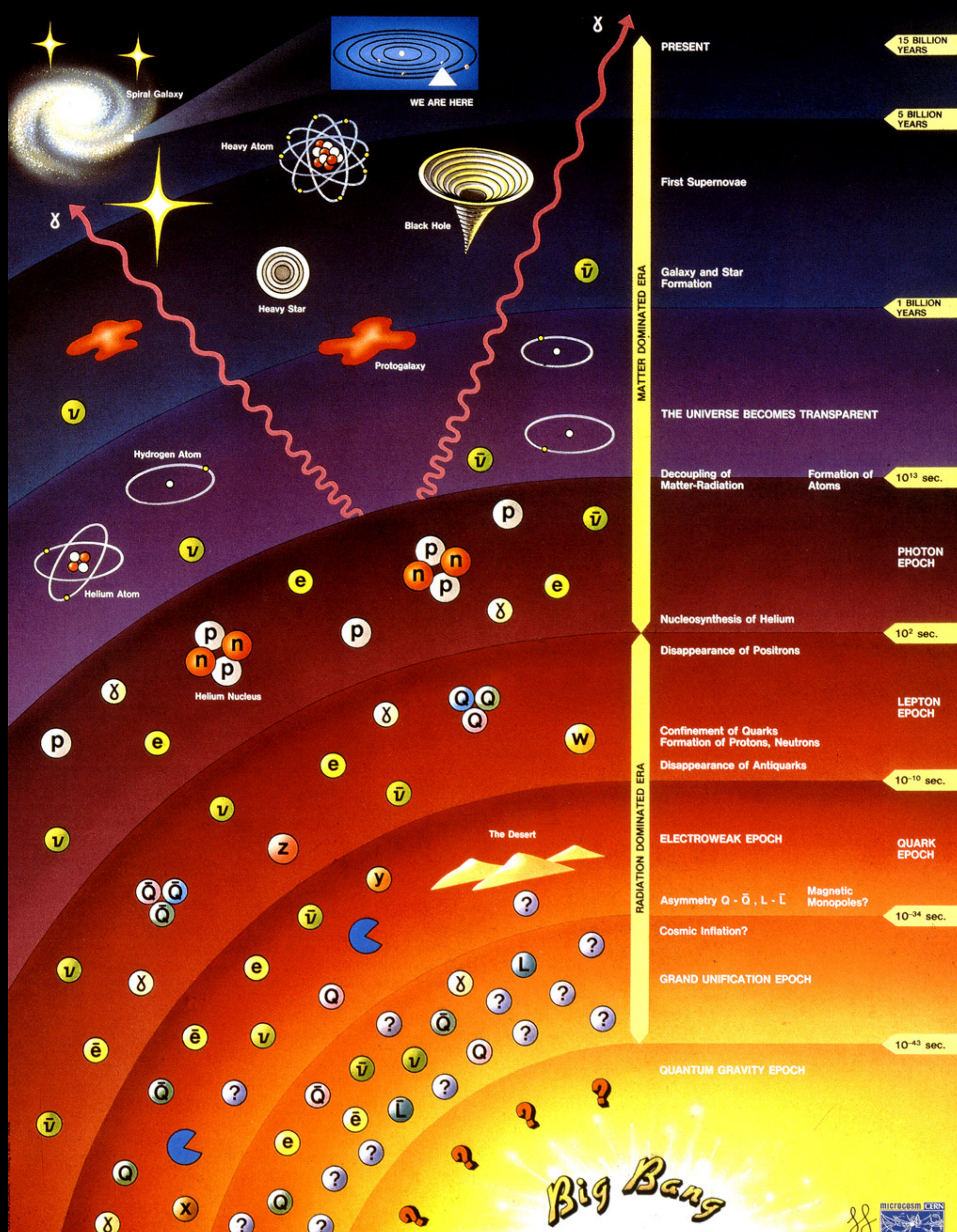
Anything will melt if the temperature is high enough



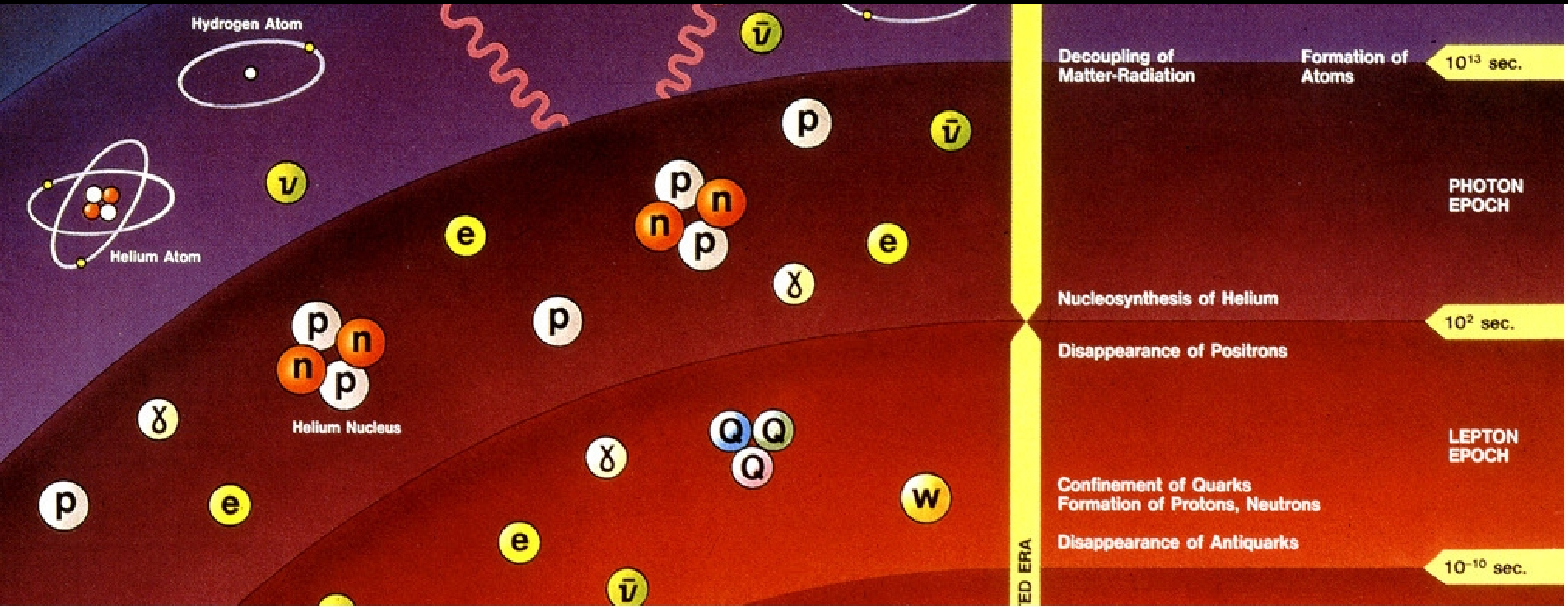
Big Bang

If the Universe was smaller in the past, but had roughly the same amount of matter and energy, then the density of matter and energy must have been higher in the past.

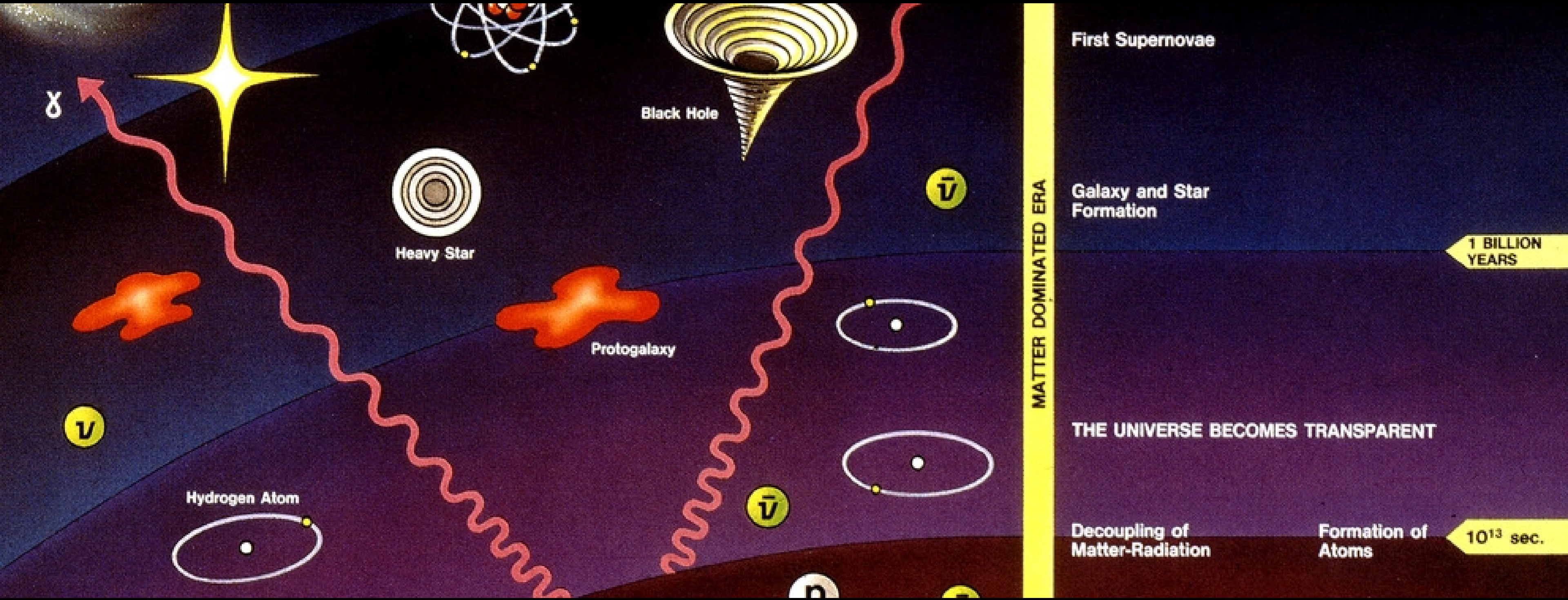
History of the Universe



Disappearance of Antiquarks
10^{-10} sec.
RADIATION DOMINATED ERA
The Desert
ELECTROWEAK EPOCH
QUARK EPOCH
Asymmetry $Q - \bar{Q}$, $L - \bar{L}$
Magnetic Monopoles?
10^{-34} sec.
Cosmic Inflation?
GRAND UNIFICATION EPOCH
10^{-43} sec.
QUANTUM GRAVITY EPOCH
Big Bang
microcosm CERN

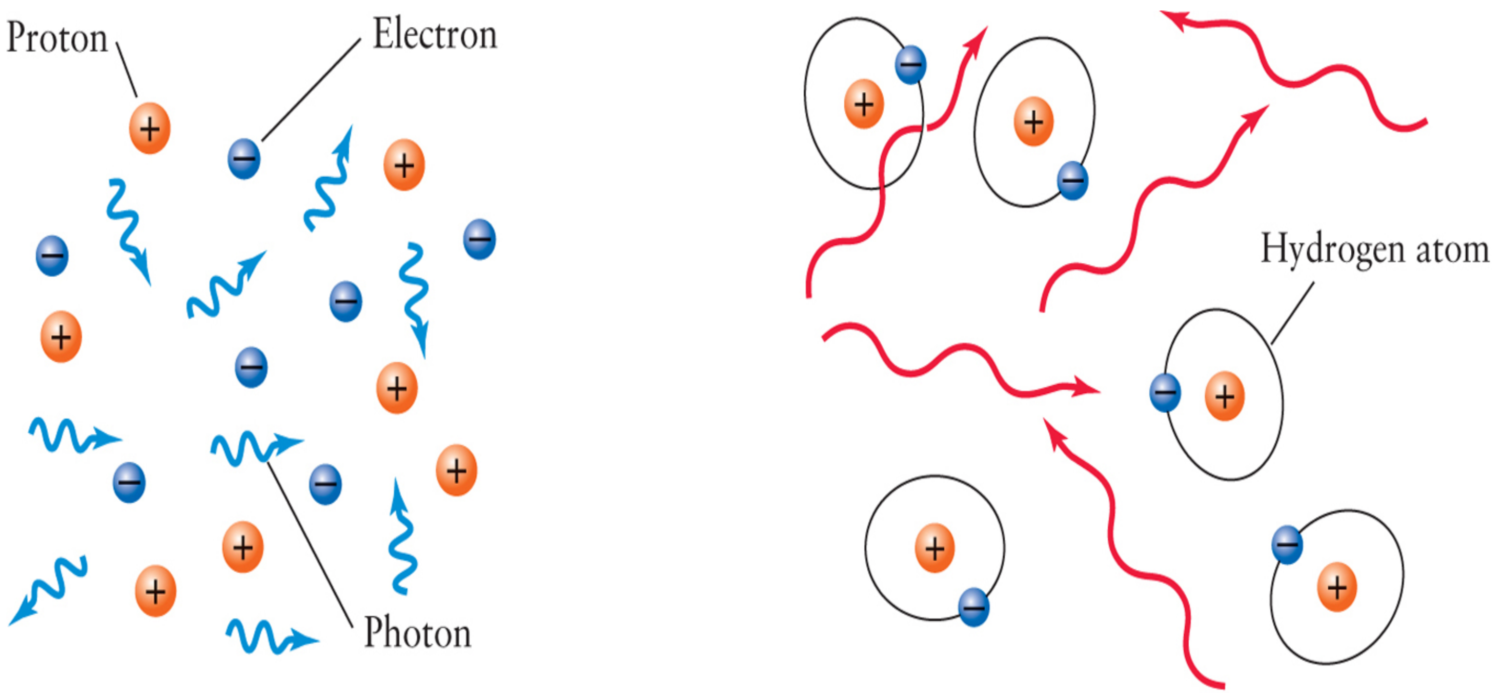


First protons and neutrons at about 1 second.
Helium nuclei formed at about 100 seconds.
Observed ratio of Helium/Hydrogen matches Big Bang prediction.
Universe is opaque.



At one million years, electrons combine with nuclei and atoms form.
Universe becomes transparent – this is called "Recombination".

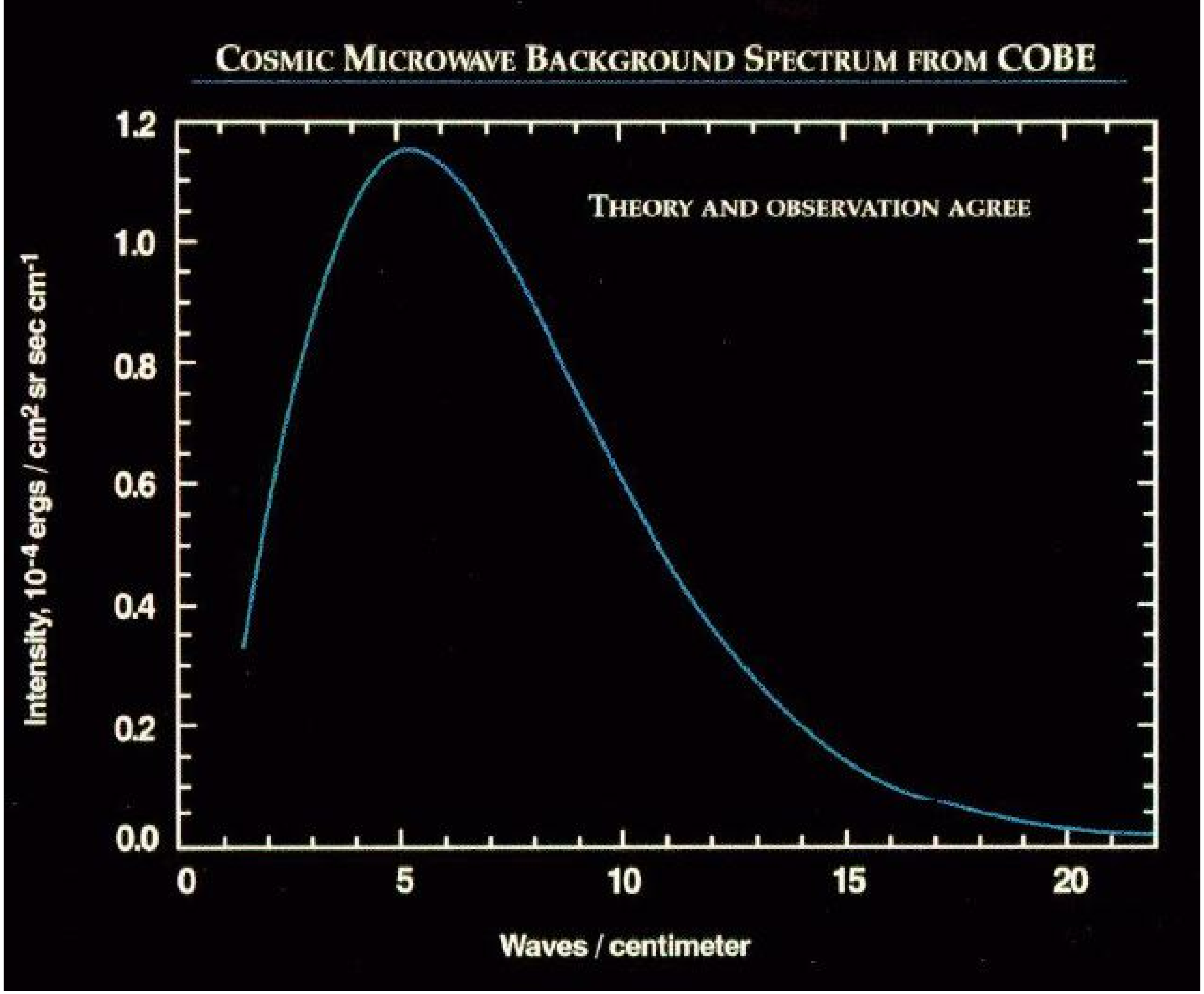
Recombination



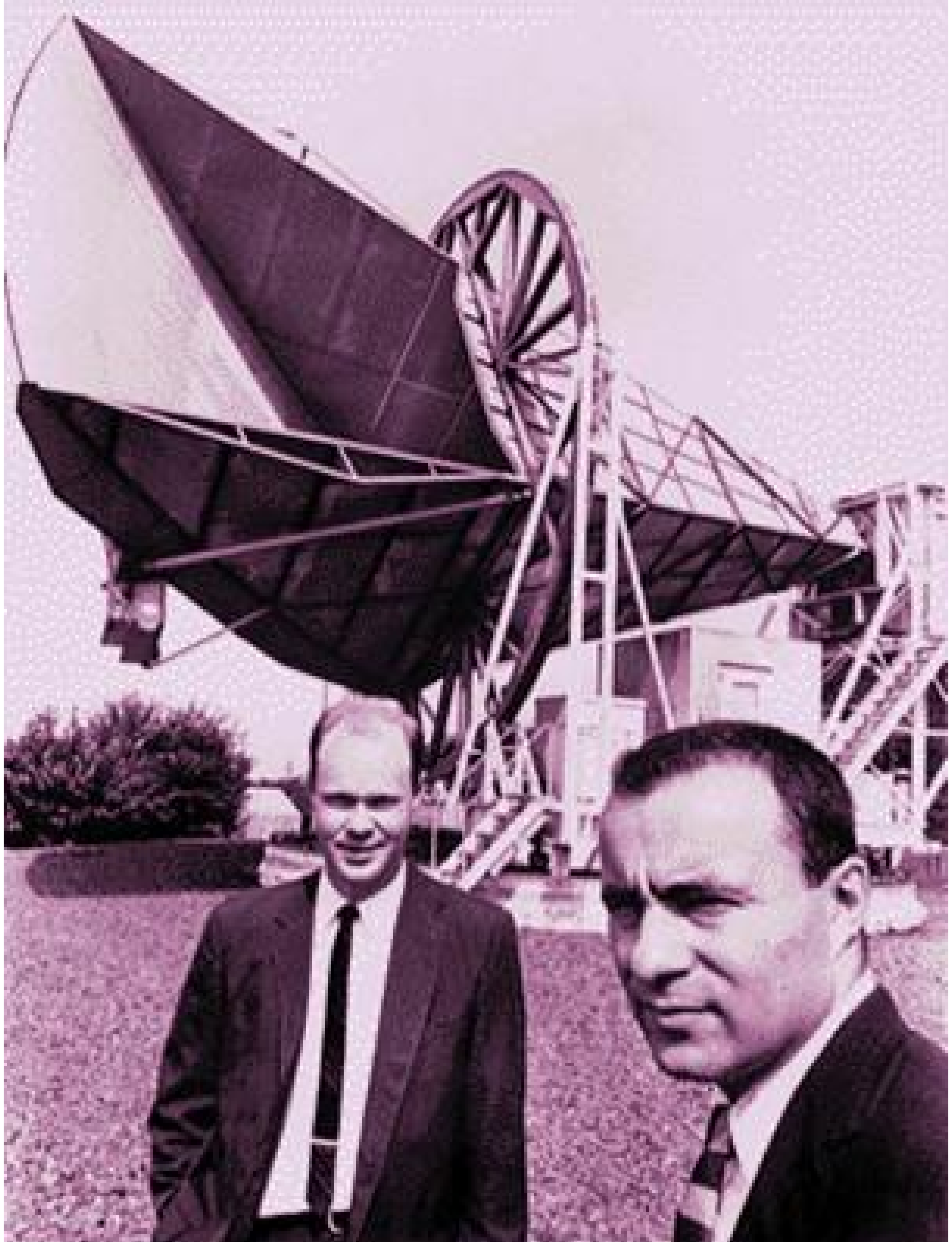
(a) Before recombination:
- Temperatures were so high that electrons and protons could not combine to form hydrogen atoms.
- The universe was opaque: Photons underwent frequent collisions with electrons.
- Matter and radiation were at the same temperature.

(b) After recombination:
- Temperatures became low enough for hydrogen atoms to form.
- The universe became transparent: Collisions between photons and atoms became infrequent.
- Matter and radiation were no longer at the same temperature.

Photons present at recombination can travel extent of the Universe



Radiation is a blackbody spectrum originally emitted at 3000 K but red shifted by a factor of 1000.

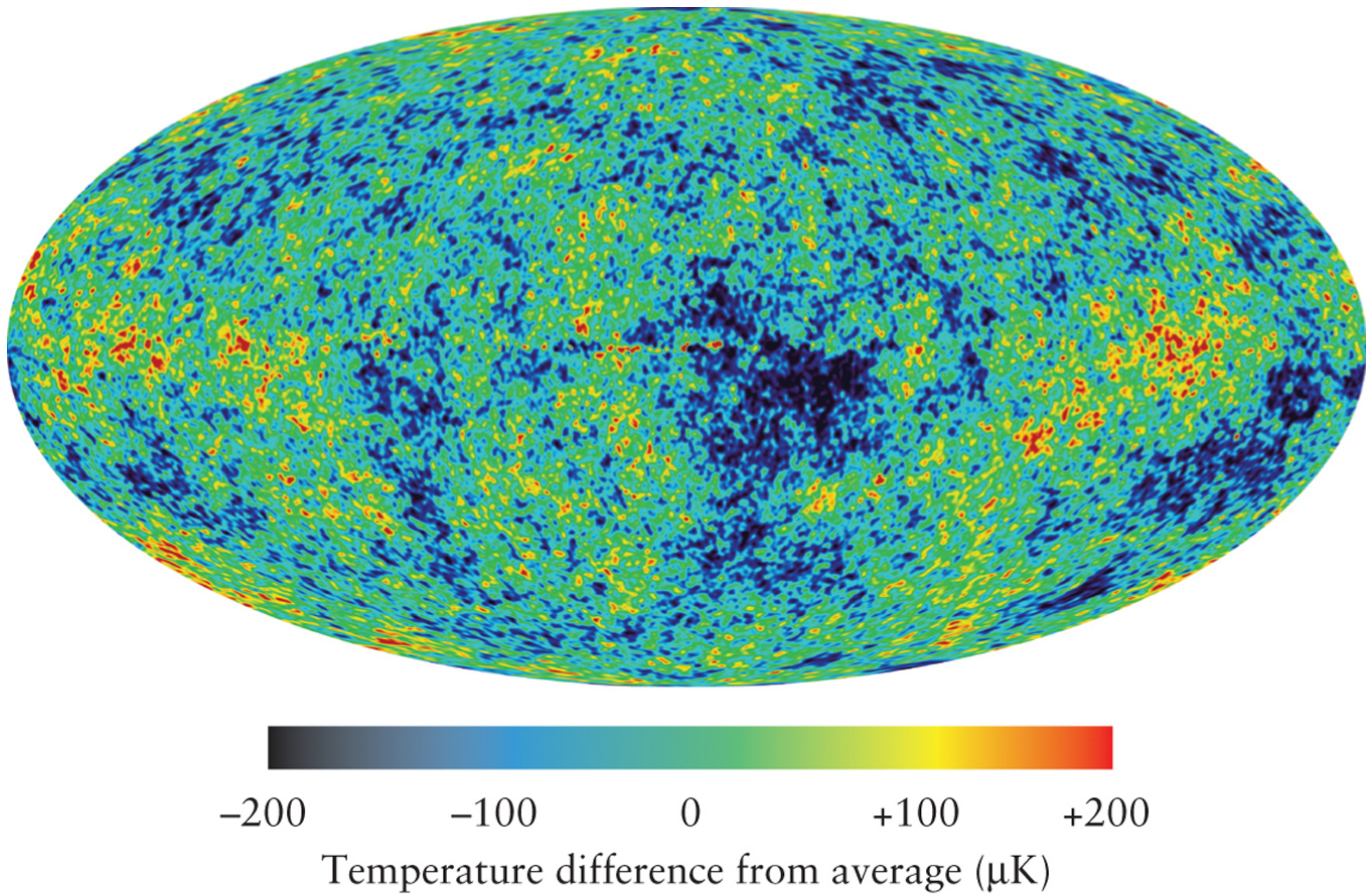


Discovered by Arno Penzias and Robert Wilson in 1960s while at AT&T and attempting to find the source of noise in an antenna used to bounce telephone signals off metallic balloons high in the atmosphere.

The whole sky glows with at a temperature of 3 K.

They won the Nobel prize in 1978.

Temperature Variations in the Cosmic Microwave Background



There are small variations in the temperature of the cosmic background across the sky. Cooler spots show where the early universe was slightly denser than average.

Three pieces of evidence for the Big Bang model

- Hubble expansion: galaxies are moving away from us with speed proportional to distance.
- The ratio of Helium to Hydrogen in gas clouds unaffected by stars matches with that predicted.
- The cosmic microwave background: a 2.7 K glow seen in all directions.

Review Questions

- In a universe that is expanding more quickly, will the slope of a Hubble plot be steeper or shallower?
- Why does our observable universe get larger over time?
- The early universe was filled with high-energy, short-wavelength photons. Why are these observed today to be low-energy, long-wavelength microwave photons?