Announcements

- Extra credit opportunity this Saturday, November 19, 7:30 p.m., at the Eastern Iowa Observatory and Learning Center, "The Violent Universe" by
  The Violent Universe
  Dr. Daniel Gall, for directions see
  Presenter: Dr. Daniel Gall,
  http://www.cedar-astronomers.org/events.htm

- Review will be Monday after Thanksgiving break, please e-mail questions.
- Remember HW #11 will be due at noon on the Monday after break, November 28.
- Third in-class exam will be Wednesday, November 30.

What is the maximum distance that has been measured via parallax?

A) 1 parsec

B) 1000 parsecs

C) 10^6 parsecs

D) 10^9 parsecs

Stellar Parallax

- Most accurate parallax measurements are from the European Space Agency's Hipparcos mission.
- Hipparcos could measure parallax as small as 0.001 arcseconds or distances as large as 1000 pc.
- How to find distance to objects farther than 1000 pc?

What is the distance to the closest galaxy?

A) 8000 parsecs
B) 24,000 parsecs
C) 50,000 parsecs
D) 790,000 parsecs

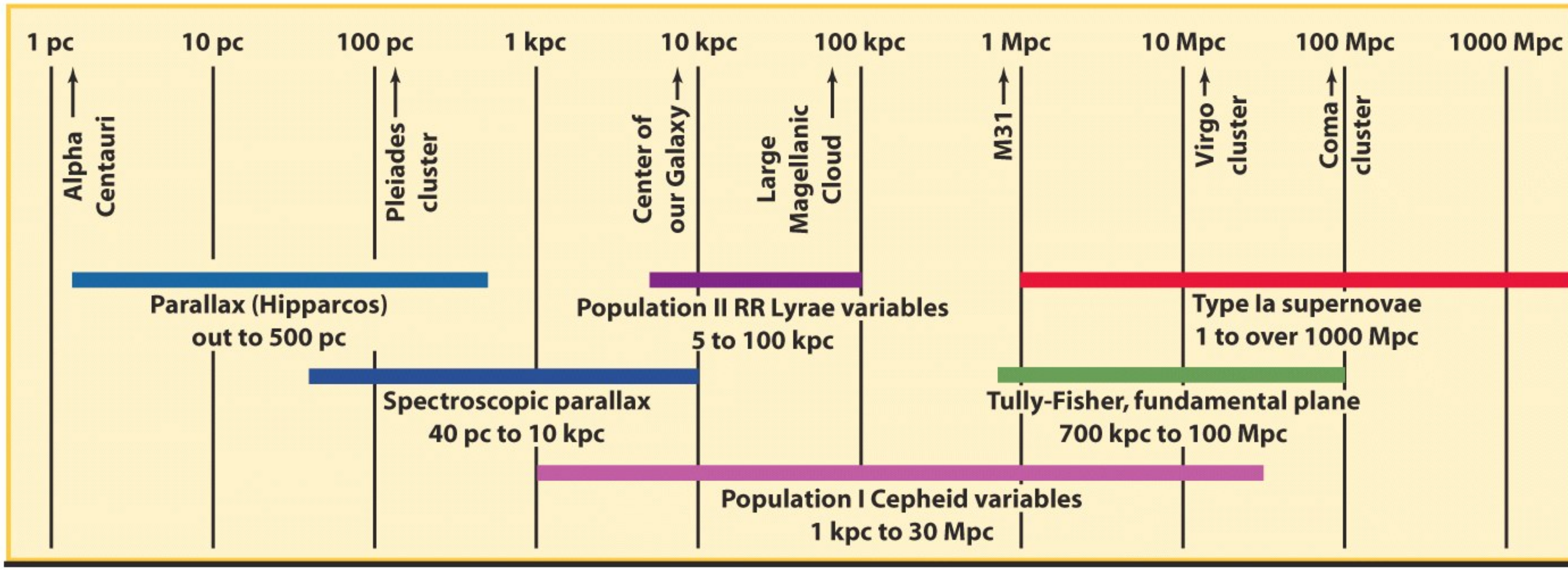
What is the distance to the closest galaxy?

A) 8000 parsecs - Canis Major Dwarf
B) 24,000 parsecs - Sagittarius Dwarf
C) 50,000 parsecs - Large Magellanic Cloud
D) 790,000 parsecs - Andromeda Galaxy

Which of the following would NOT be useful in determining the distance to another galaxy?

A) parallax
B) Cepheid variables
C) the luminosities of globular clusters
D) the brightness of a supernova

The Distance Ladder



- Each stage in the ladder overlaps the previous and next
- Cepheid distances are critical
- Tully-Fisher, fundamental plane apply to whole galaxies
- Supernova are the best estimators at large distances

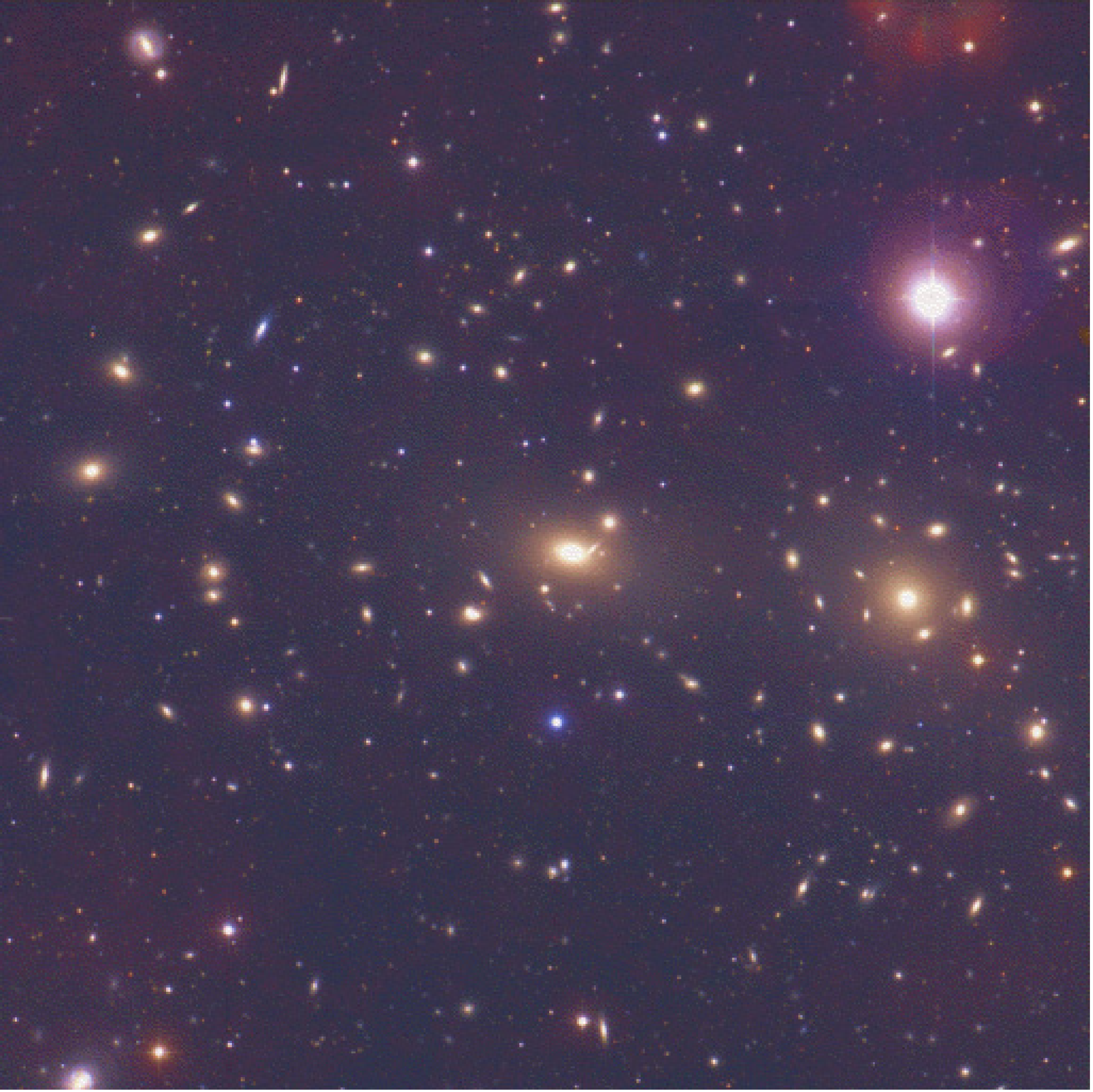
Evidence for matter between galaxies in large galaxy clusters (intracluster matter) is provided by

A) star formation regions between galaxies in clusters.

B) absorption lines in the spectra of cluster members.

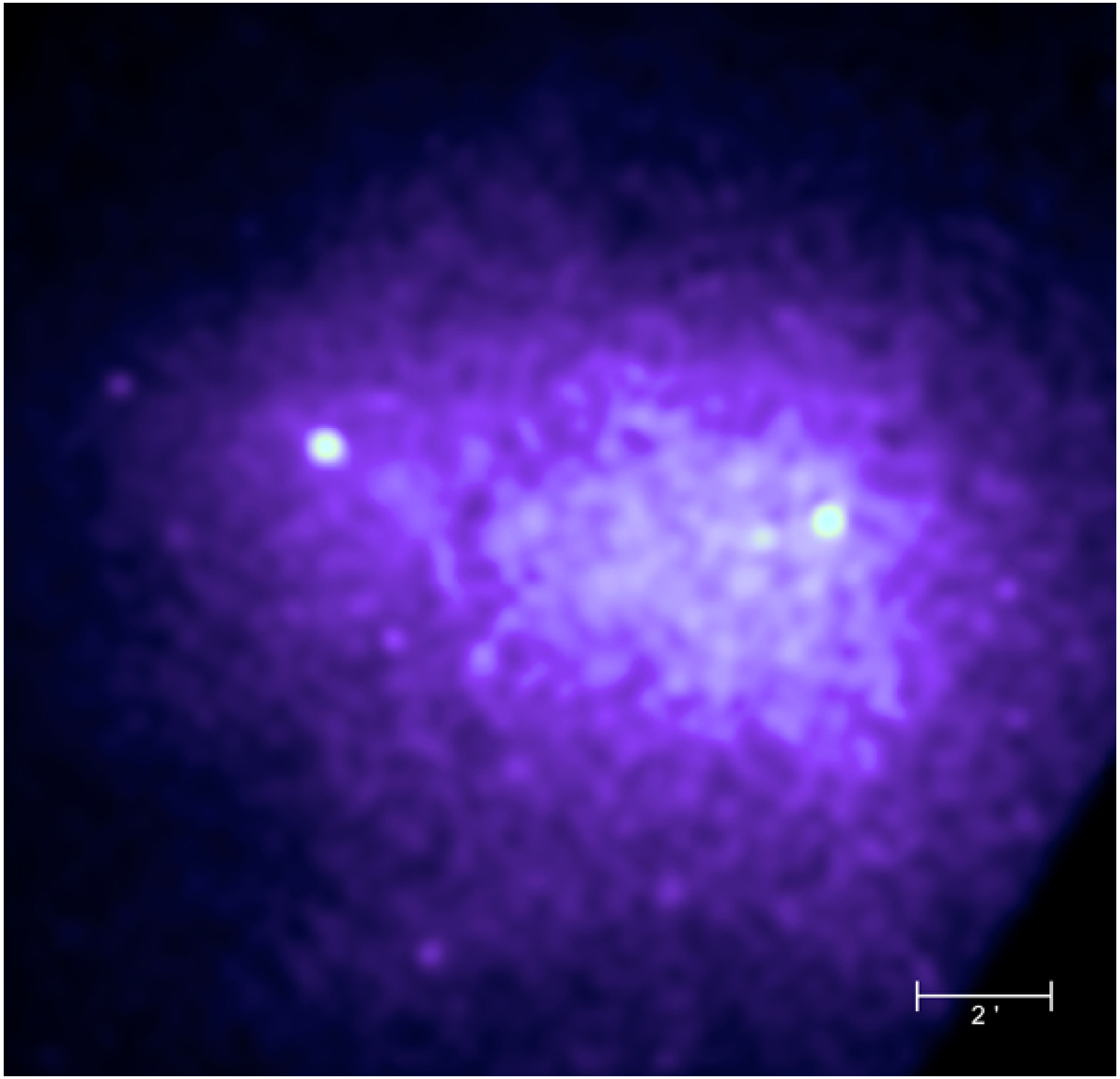
C) the rotation curves of clusters which are flatter than Keplerian.

D) X-ray emission from a halo of gas centered on the cluster.



Coma cluster

Coma cluster in X-rays



Coma cluster

- X-ray emitting gas is at a temperature of 100,000,000 K.
- The total X-ray luminosity is more than the luminosity of 100 billion Suns.

- From this, the amount of X-ray emitting gas can be calculated. The mass of X-ray emitting gas is greater than the mass in all the stars in all the galaxies in the cluster.

There is often a giant, dominant elliptical at the center of galactic clusters. It is thought to arise from

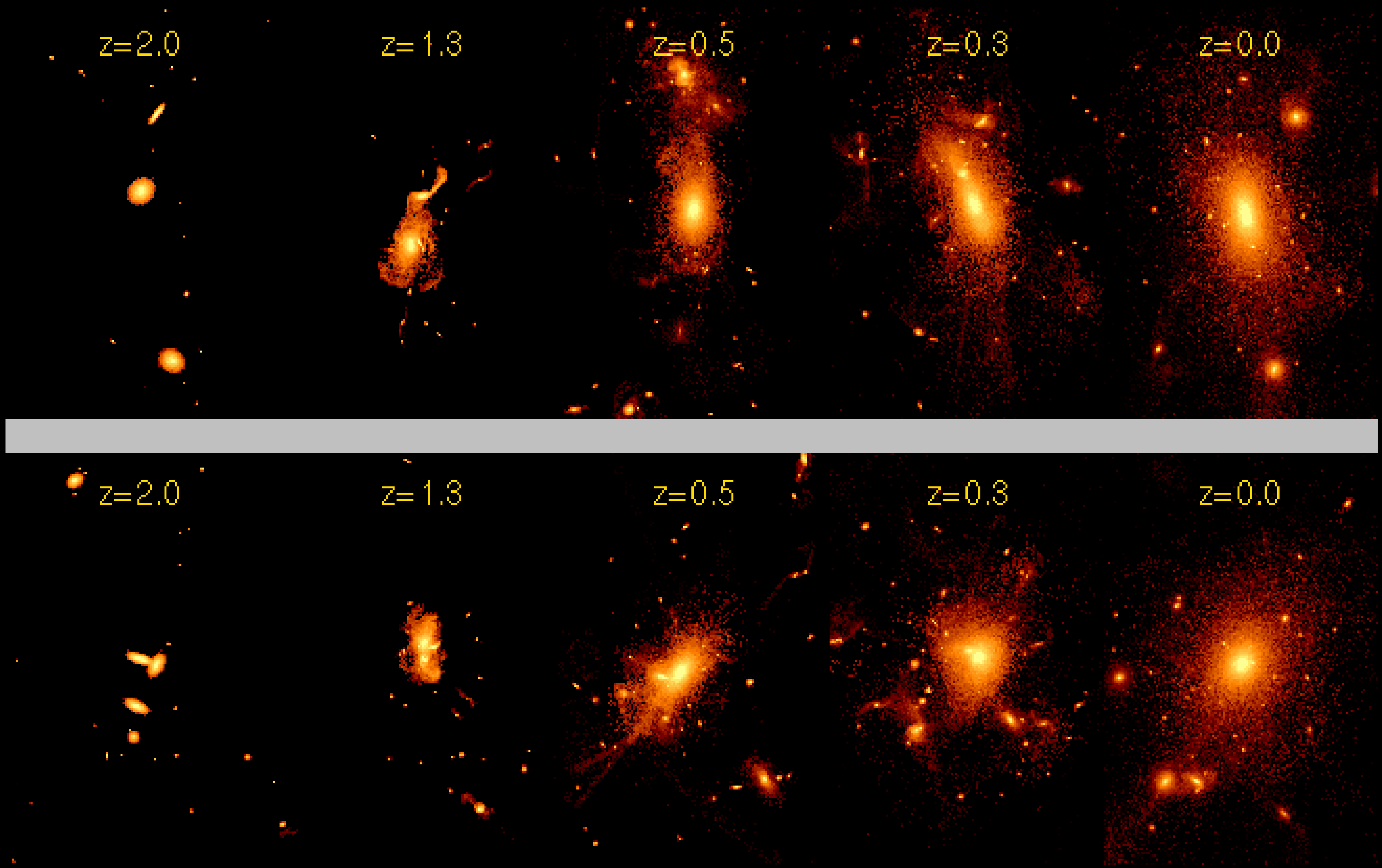
A) large amounts of hydrogen gas collecting in the core.

B) a collection of black holes at the center.

C) gravitational effects of the local supercluster.

D) interactions and collisions among members of the cluster.

Formation of an Elliptical Galaxy



Movie

Cosmology

- Geometry of the Universe
- Accelerating Universe or “Einstein’s greatest blunder”
- The contents of the Universe

The geometry of the Universe

- How many degrees in the angles in a triangle?
- Positively/negatively curved spaces
- Measuring curvature using the cosmic microwave background

Two dimensional geometry

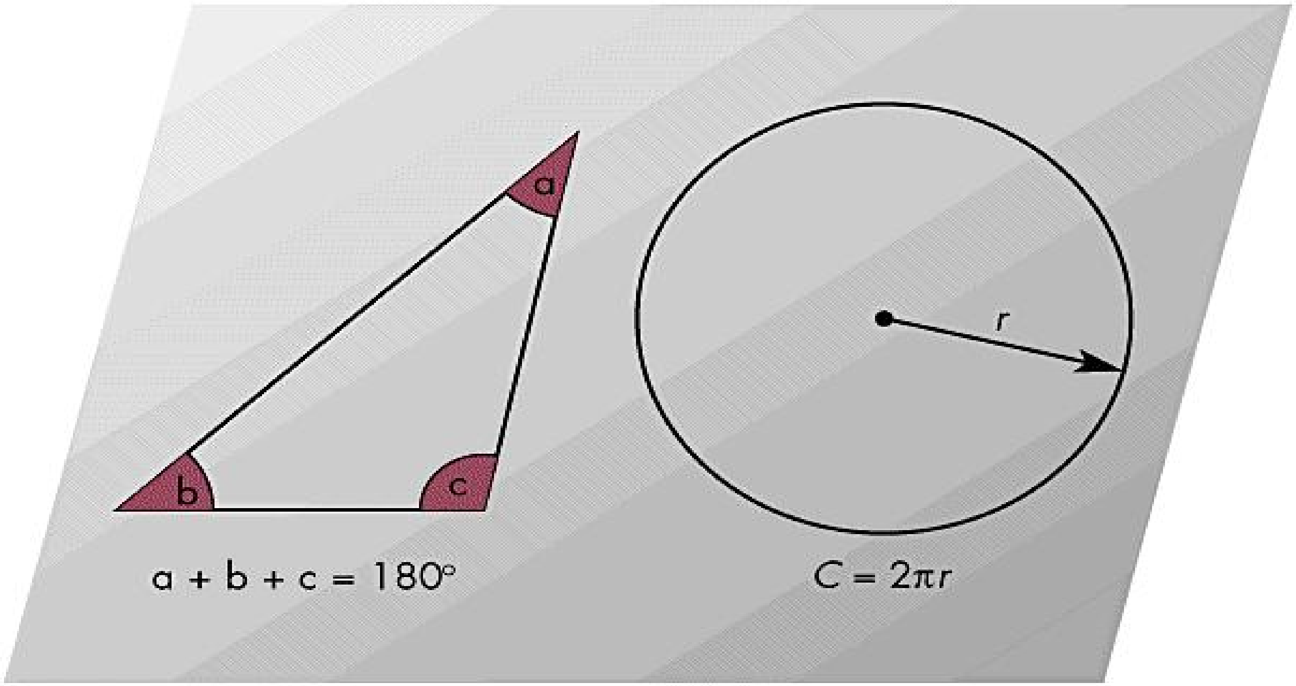
- Only two directions: up/down and left/right
  : north/south and east/west
- All motion of particles, light confined to two dimensions
- Examples: black board, piece of paper, surface of sphere, surface of donut, surface of saddle

Geometry

- How are the diameter and circumference of a circle related?

- What is the sum of all of the angles in a triangle?

Geometry in flat space



- Circumference = $2\pi \times$ radius

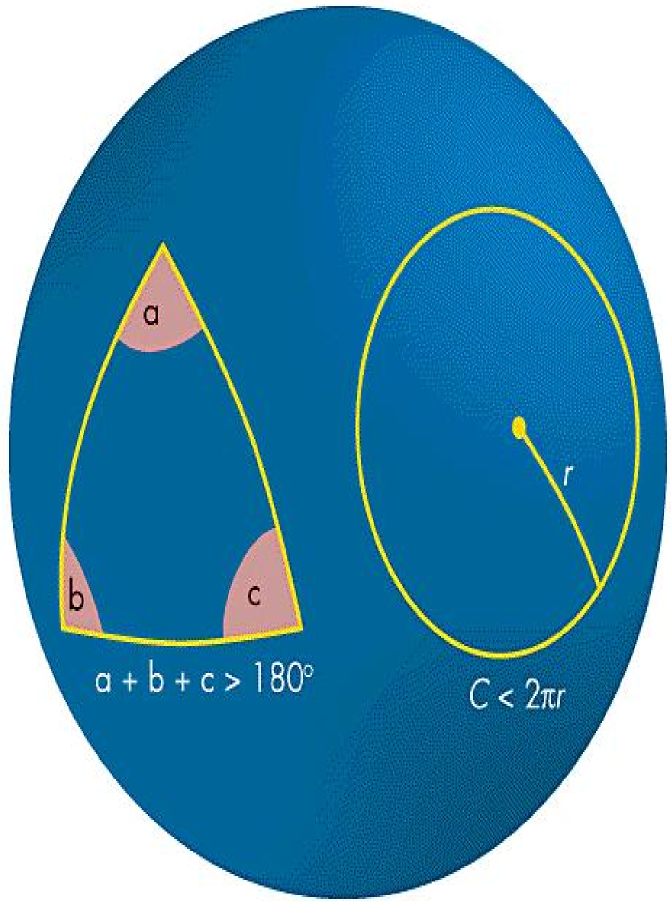
  $\pi = 3.1415926\ldots \qquad 2\pi = 6.28\ldots$

- The sum of the angles in a triangle is 180º

Non-Euclidean Geometry

- How about in a curved space?
- Do demo 8C10.50

Geometry in positively curved space



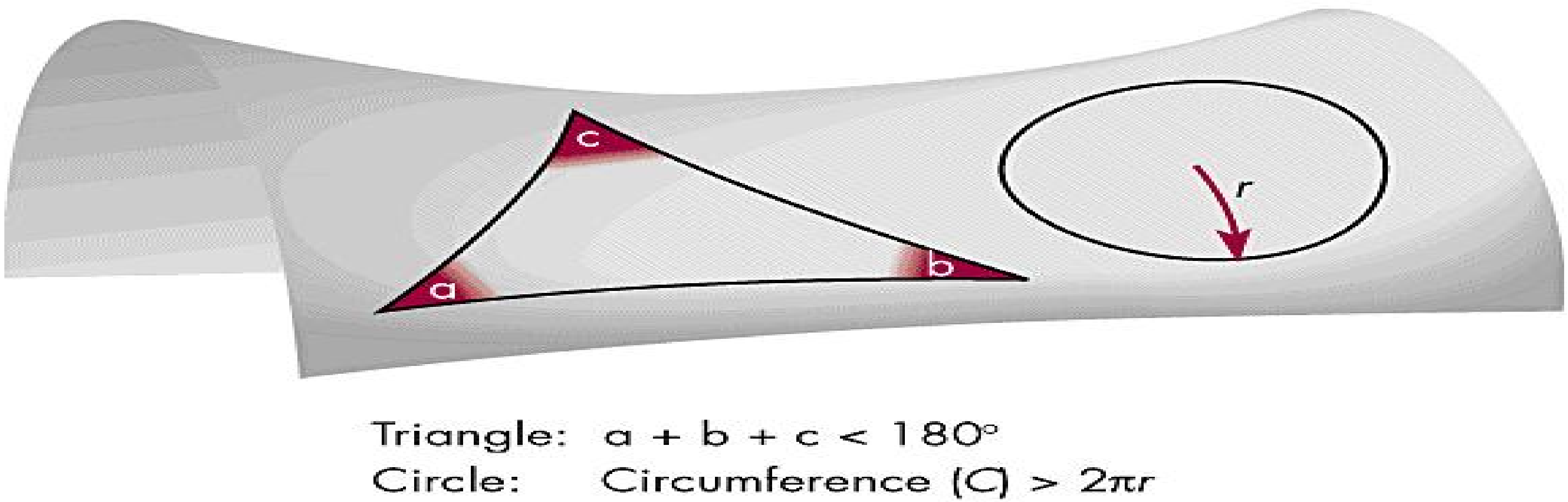
- Circumference < $2\pi \times$ radius
- The sum of the angles in a triangle > 180º

Properties of positively curved space

- Finite
- Unbounded
- No center

How do the properties of positively curved space differ from flat space?

Geometry in negatively curved space



- Circumference > 2π × radius
- The sum of the angles in a triangle < 180º

Curvature of the Universe

The curvature of the Universe is determined by:

- the density of matter and energy
  - higher density produces positive curvature
  - gravity from matter always makes positive curvature
- the expansion of the Universe
  - more rapid expansion produces negative curvature

At the "critical density", expansion exactly balances gravity – universe is flat

Curvature of the Universe

The curvature of the Universe is determined by the density parameter Ω_0

$$\Omega_0 = \frac{\rho}{\rho_C}$$

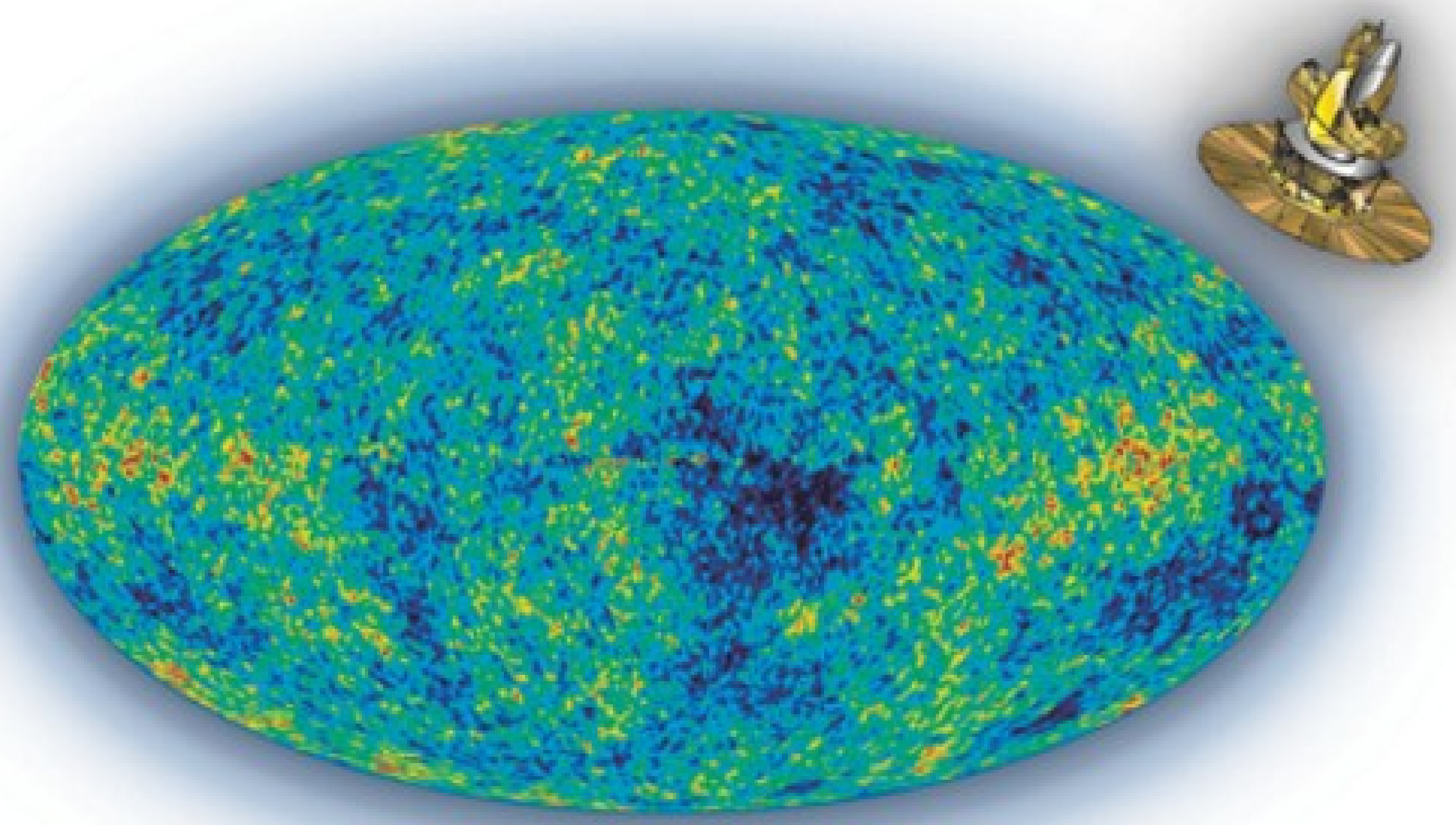
ρ = density of matter/energy

Critical density $\rho_c = 10^{-26}$ kg/m^3

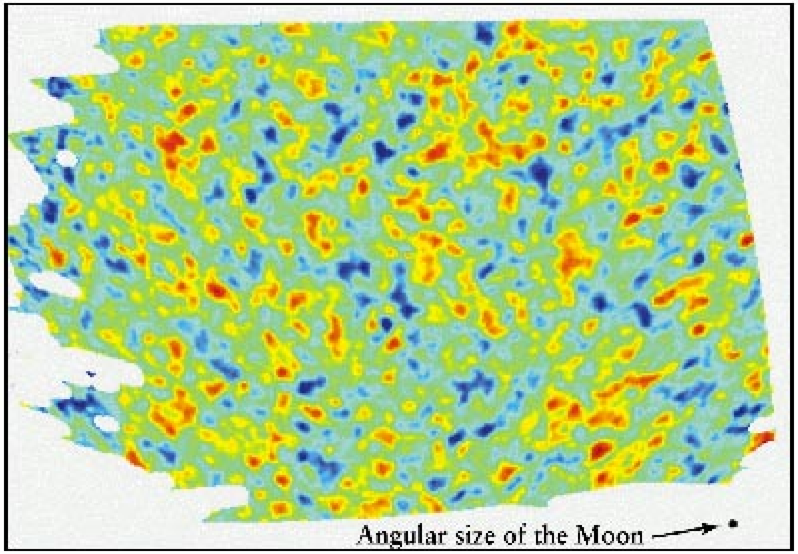
$\Omega_0 < 1 \Rightarrow$ negative curvature

$\Omega_0 > 1 \Rightarrow$ positive curvature

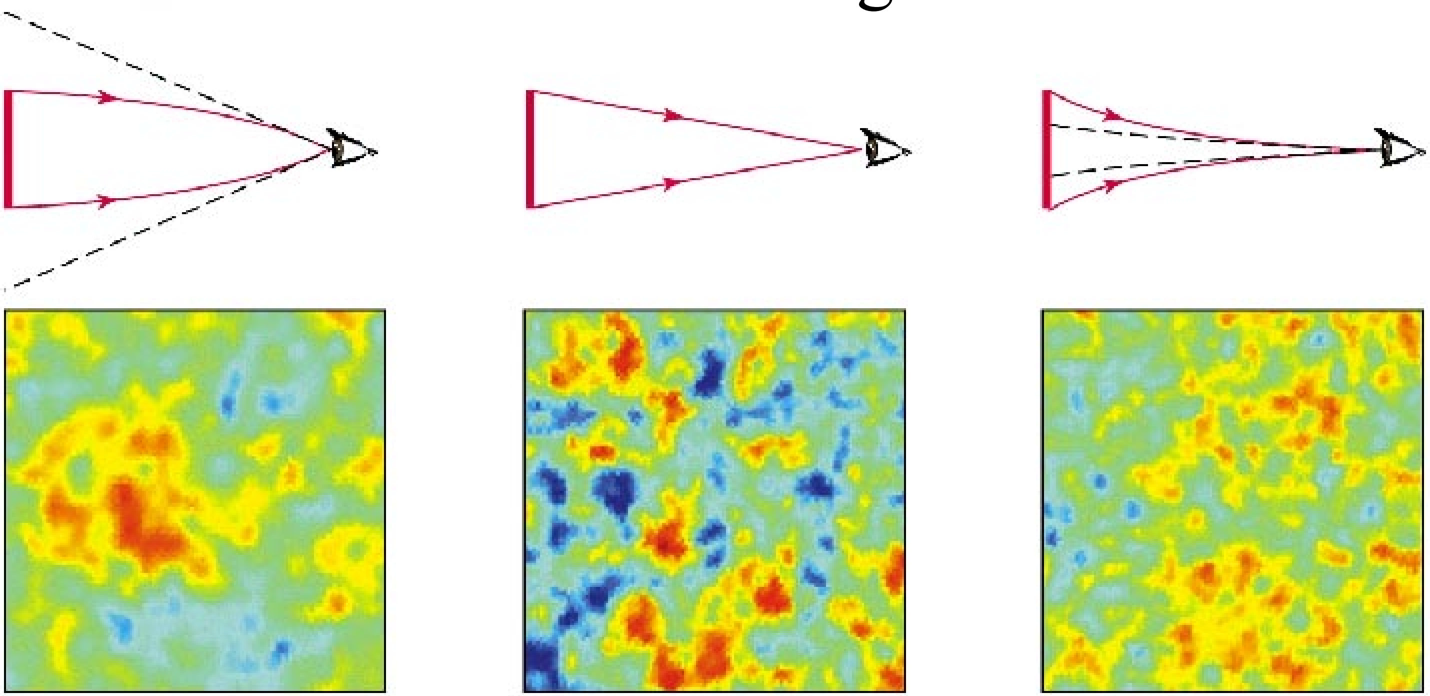
Cosmic Microwave Background



Small fluctuations are due to sound waves at recombination.



Temperature variations in the Cosmic Microwave Background (CMB) are observed to be about 0.0003 K. The expected physical size of the hot/cold regions can be calculated.



a If universe is closed, "hot spots" appear larger than actual size

b If universe is flat, "hot spots" appear actual size

c If universe is open, "hot spots" appear smaller than actual size

Curvature of the Universe

The curvature of the Universe is determined by the density parameter Ω_0

$$\Omega_0 = \frac{\rho}{\rho_C}$$

$\Omega_0 < 1 \Rightarrow$ negative curvature

$\Omega_0 > 1 \Rightarrow$ positive curvature

Measurement of CMB fluctuations gives

$$\Omega_0 = 1.02 \pm 0.02$$

Why can't we see radiation produced during the first 1,000 years after the Big Bang?

A) It was absorbed soon after it was emitted.
B) It hasn't reached us yet.
C) It has been deflected by black holes.
D) It passed by our part of the universe a few billion years ago.

When did the universe first become transparent?

A) 1 year after the big bang
B) 10^3 years after the big bang
C) 10^6 years after the big bang
D) 10^9 years after the big bang
E) 10^{12} years after the big bang

What produced the photons that we see as the 3 degree cosmic background radation?

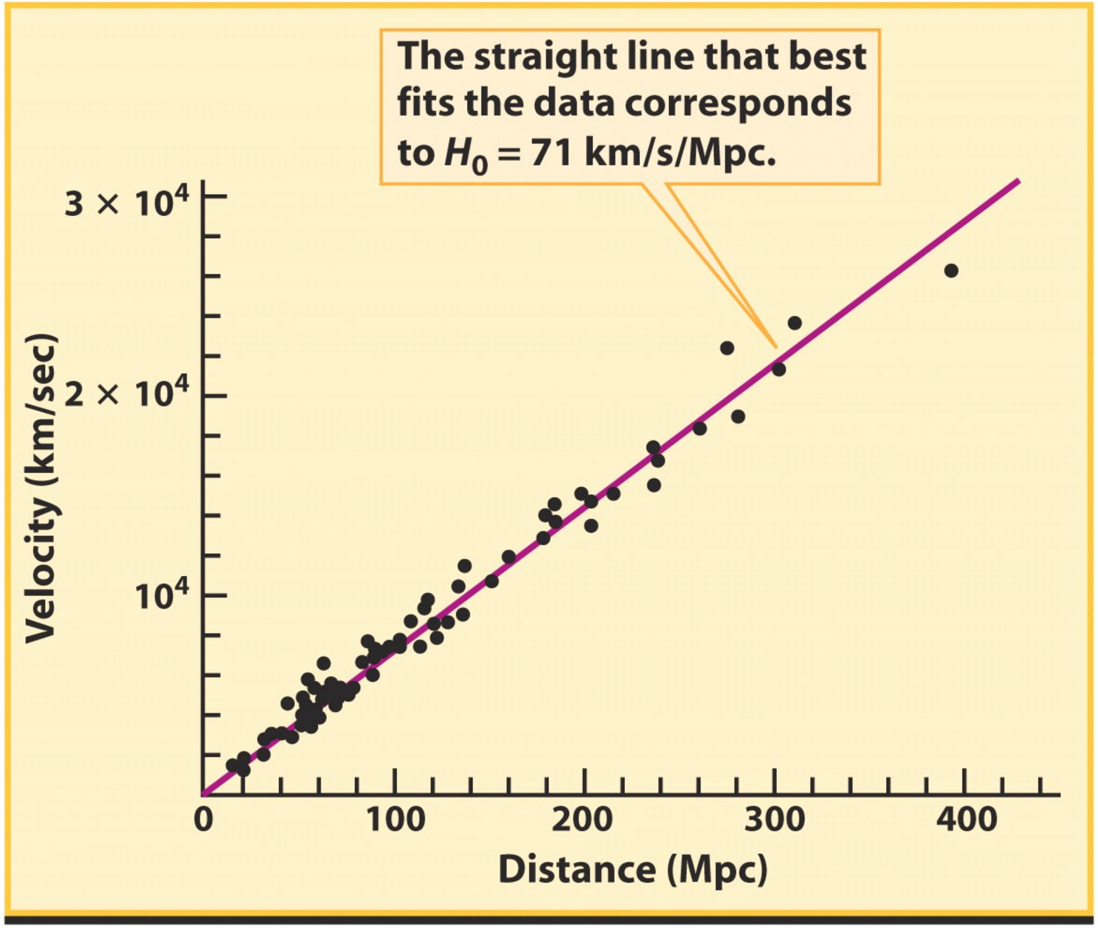
A) Neutrinos

B) Hot gas

C) Stars

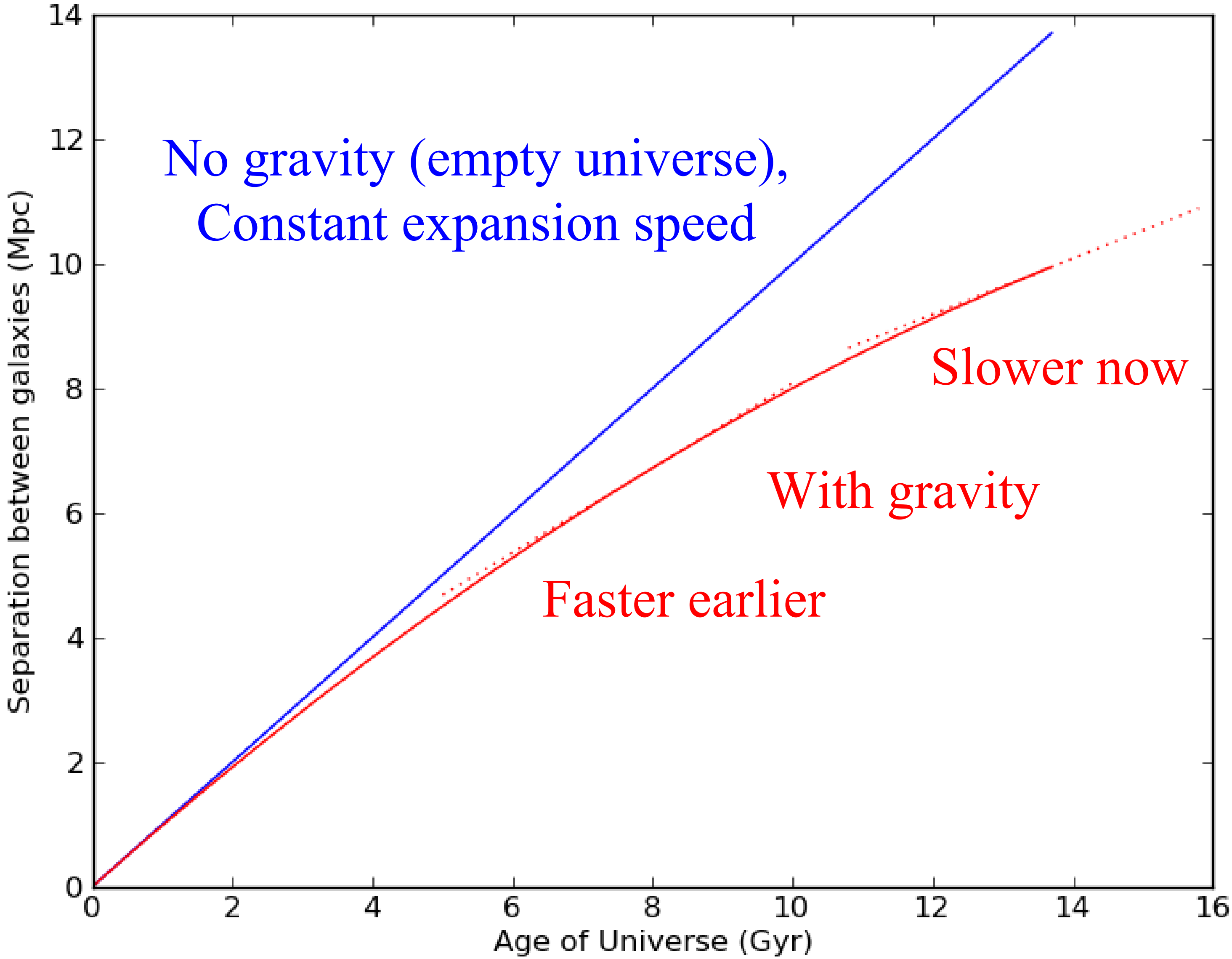
D) Formation of helium nuclei

Hubble expansion



How will gravity of the motion of galaxies?

Matter slows down expansion

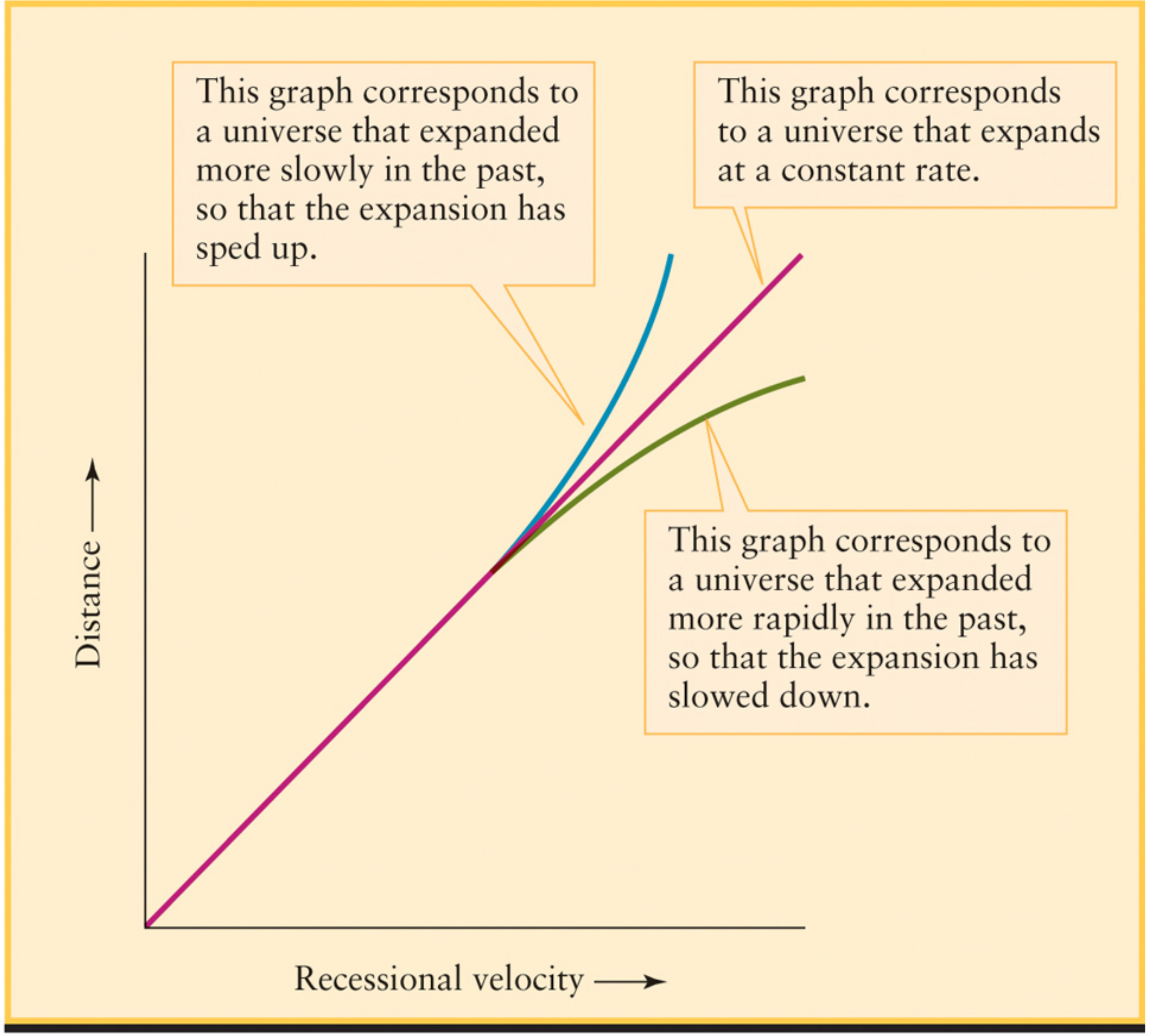


Expansion of the Universe

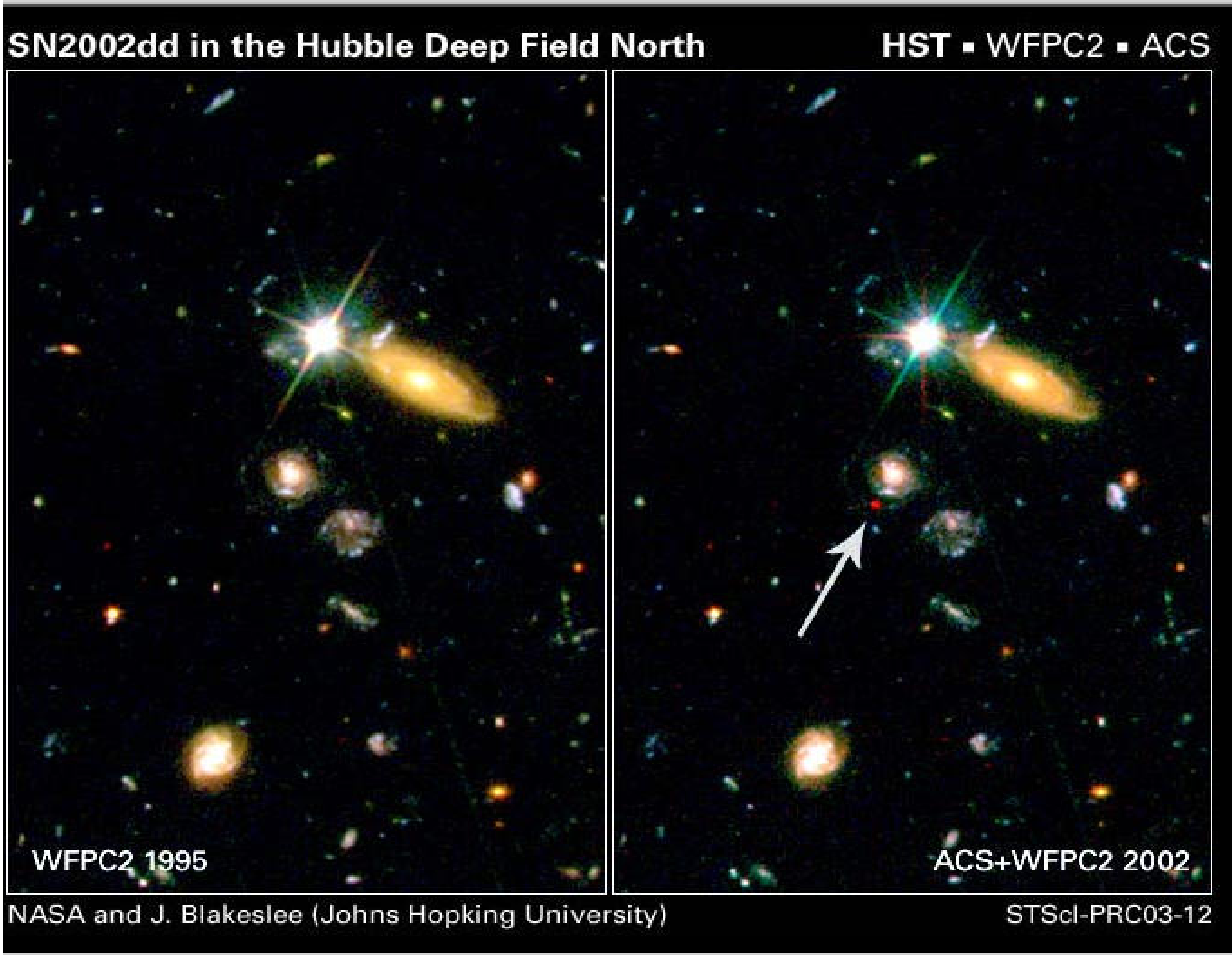
Larger distance means we are looking further into the past.

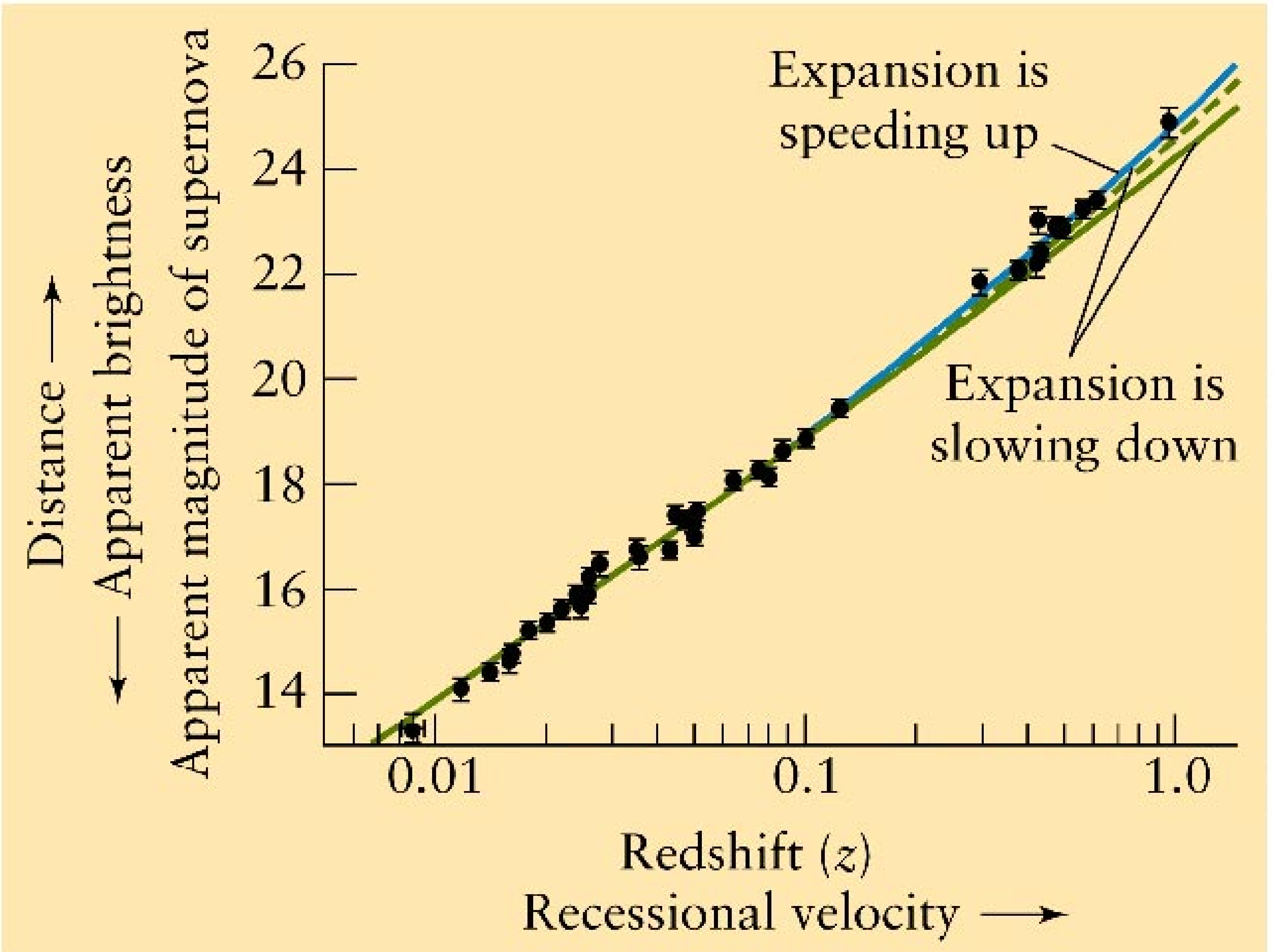
If the rate of expansion of the universe was faster in the past, we should see larger velocities for larger distances.

If the expansion rate was slower in the distant past, we should see lower velocities for large distances.

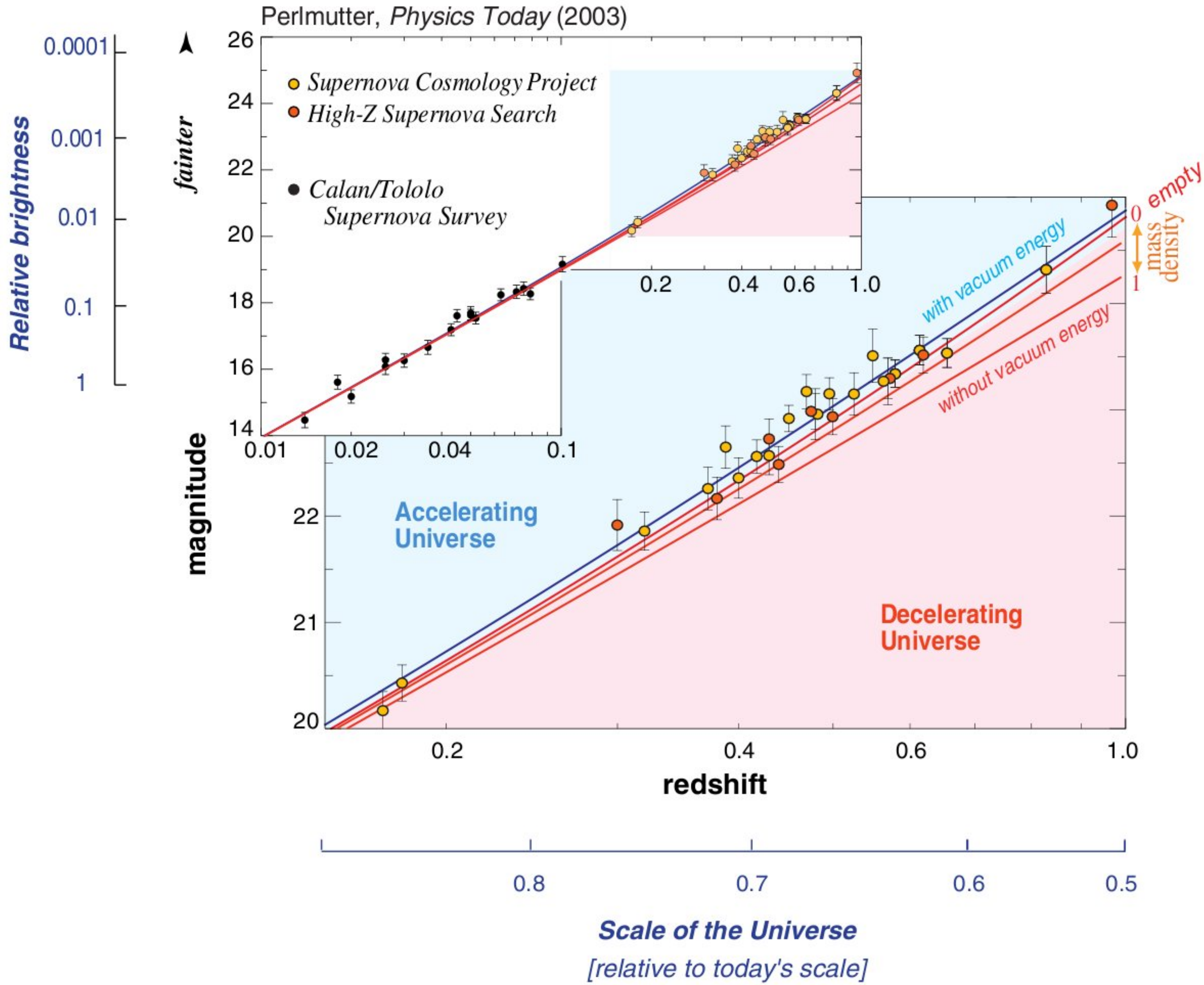


(b) Possible expansion histories of the universe

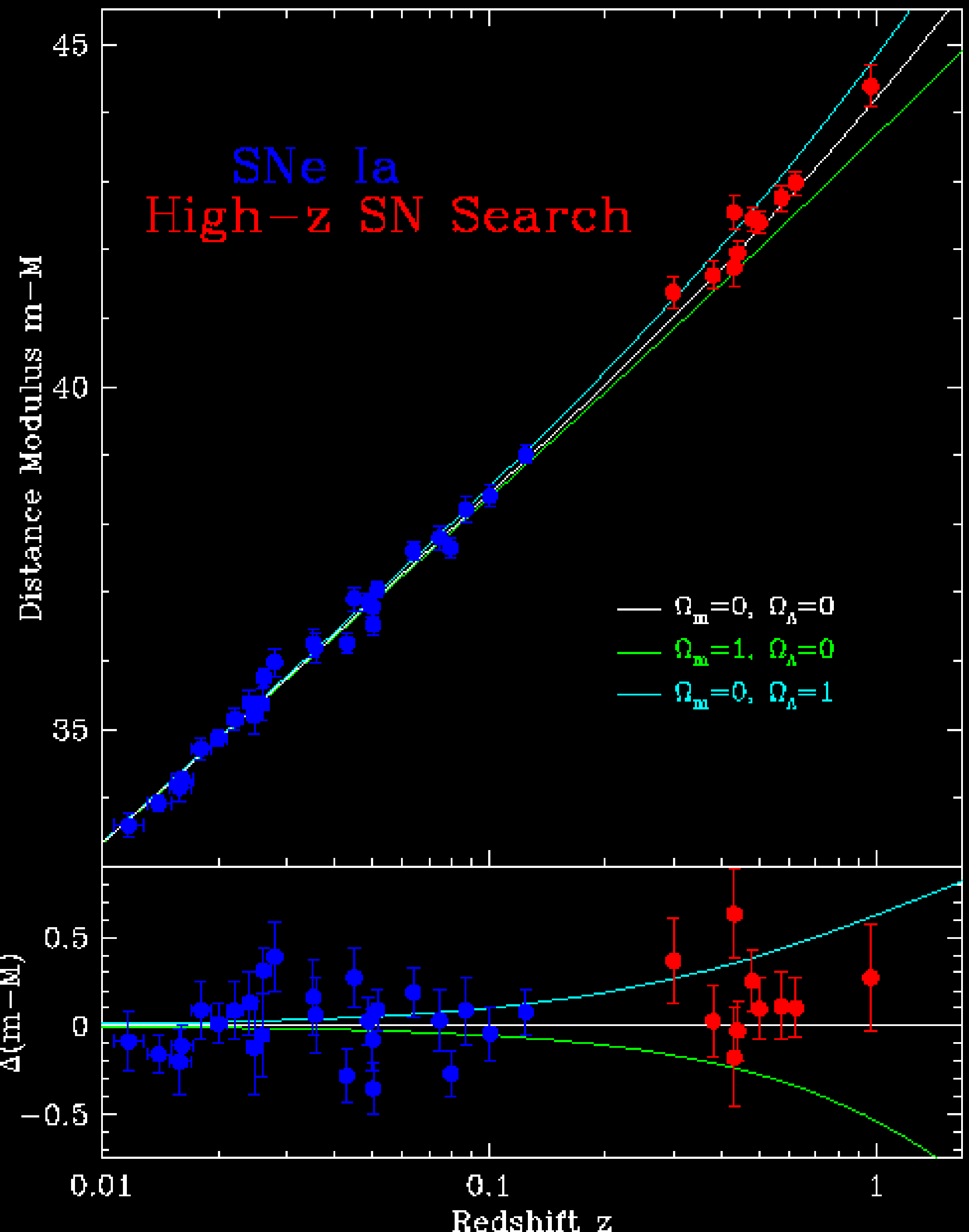

SN2002dd in the Hubble Deep Field North
HST ▪ WFPC2 ▪ ACS
WFPC2 1995
ACS+WFPC2 2002
NASA and J. Blakeslee (Johns Hopking University)
STScI-PRC03-12



Expansion is speeding up
Expansion is slowing down
Distance →
← Apparent brightness
Apparent magnitude of supernova
26
24
22
20
18
16
14
0.01
0.1
1.0
Redshift (z)
Recessional velocity →



Perlmutter, *Physics Today* (2003)
Supernova Cosmology Project
High-Z Supernova Search
Calan/Tololo Supernova Survey
fainter
Relative brightness
0.0001
0.001
0.01
0.1
1
26
24
22
20
18
16
14
0.01
0.02
0.04
0.1
0.2
0.4
0.6
1.0
magnitude
22
21
20
redshift
with vacuum energy
without vacuum energy
0 empty
mass density
1
Accelerating Universe
Decelerating Universe
0.8
0.7
0.6
0.5
Scale of the Universe
[relative to today's scale]



SNe Ia
High-z SN Search
Distance Modulus m−M
45
40
35
Ω_m=0, Ω_Λ=0
Ω_m=1, Ω_Λ=0
Ω_m=0, Ω_Λ=1
Δ(m−M)
0.5
0
−0.5
0.01
0.1
1
Redshift z

Accelerating Universe

- Hubble expansion appears to be accelerating
- Normal matter cannot cause acceleration, only deceleration of expansion
- Dark energy is required
  - may be cosmological constant
  - may be something else
  - major current problem in astronomy

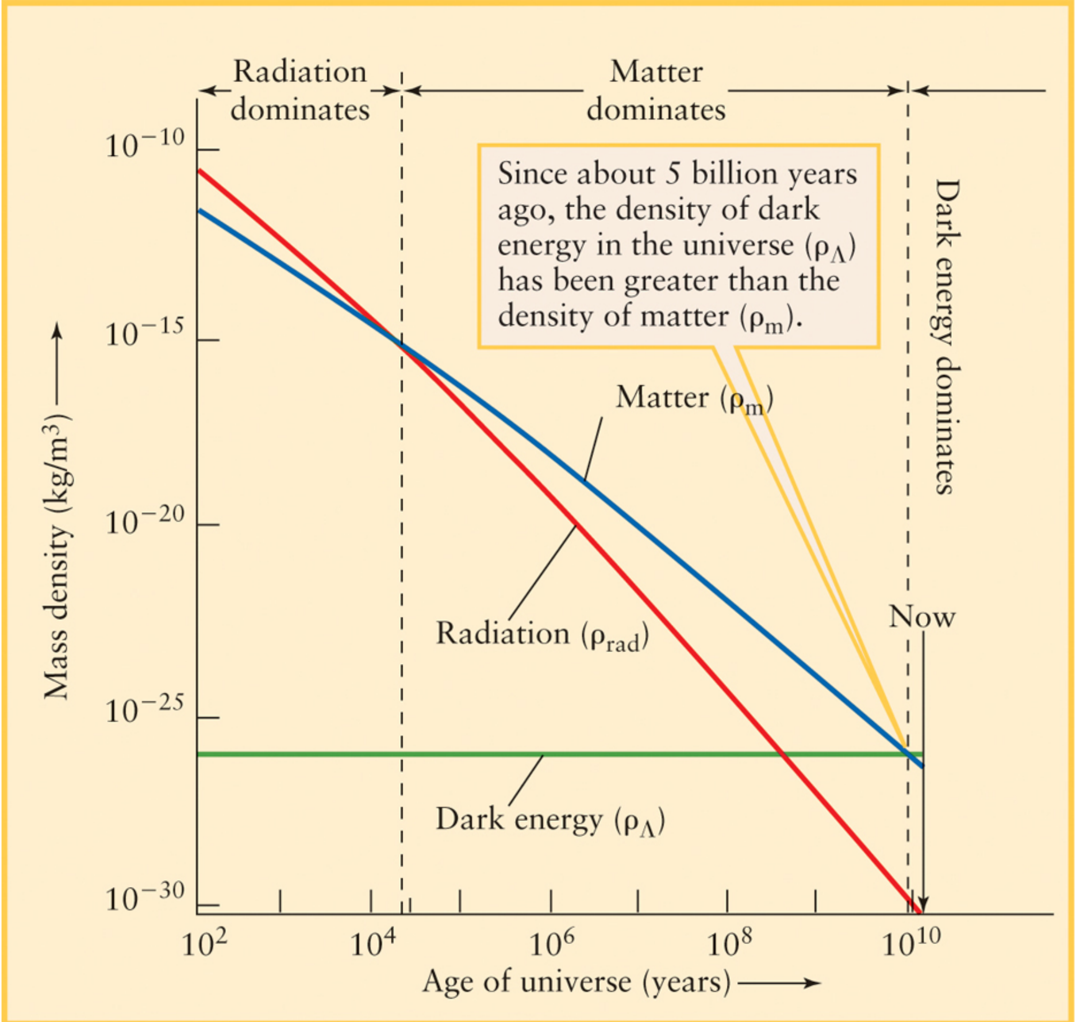
Einstein and Cosmology

- After Einstein wrote down the equations for General Relativity, he made a model of the Universe and found that the Universe had to be either expanding or contracting.
- He introduced a new term, the cosmological constant or Λ, in his equations representing a energy field which could create antigravity to allow a static model.
- After Hubble found the expansion of the Universe, Einstein called Λ his greatest blunder.

Cosmological Constant

- Quantum physics predicts that some energy fields that act like Λ.
- One such field is thought to have caused a rapid expansion of the Universe, called "inflation", when it was very young, less than 10^{-32} seconds old.
- Another such field, the "dark energy", appears to be operating today and causing the expansion of the Universe to accelerate.

Density of the Universe, Revisited



The densities of matter and radiation both decrease as the universe expands. But if the dark energy is due to a cosmological constant, its density remains constant.

Contents of the Universe

- Normal matter
  - Stars
  - hot gas
  - anything made of atoms

- Total is 4% of ρ_C

Dark Matter

- Dark – it doesn’t produce light (any kind)
- Does have mass, produces gravity
- Nature is unknown

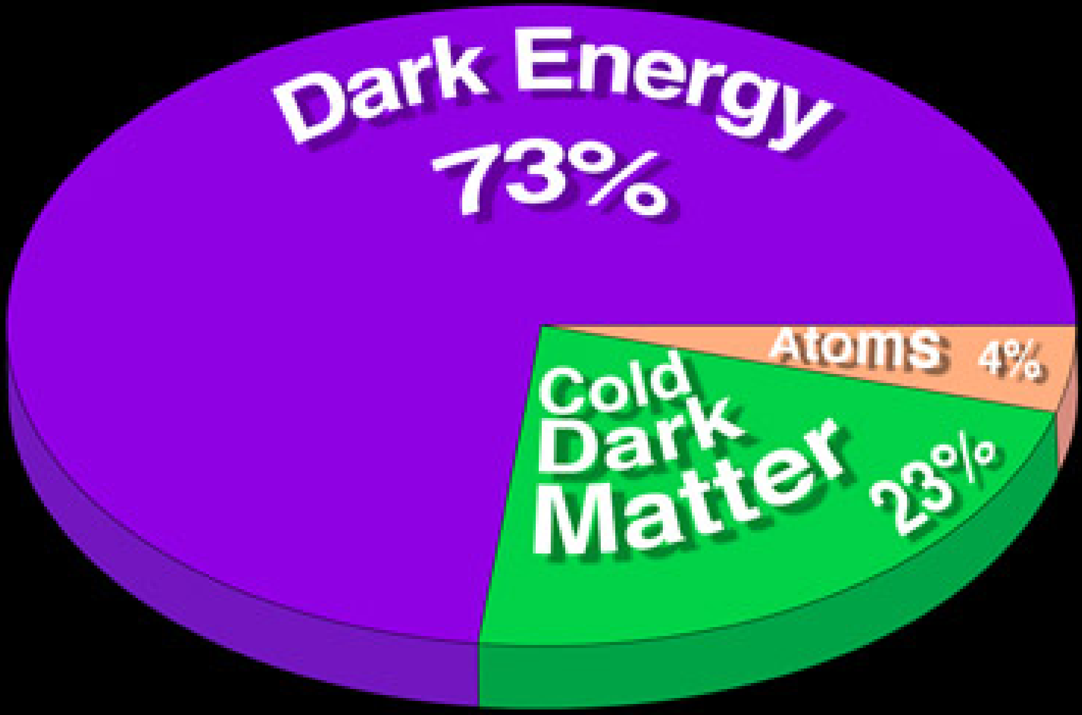
- Most likely it is elementary particles

Contents of the Universe

- Normal matter is 4% of ρ_C
- Dark matter is 23% of ρ_C
- Total of normal and dark matter is $\Omega_M = 0.3$

- But, we need 100% of ρ_C because the Universe is flat
- Remainder, 73%, is dark energy $\Omega_\Lambda = 0.7$

Contents of the Universe



Review questions

- How does the curvature of the Universe relate to the observed size of distant objects?
- What is the geometry of the Universe?
- Is the expansion of the Universe speeding up or slowing down?
- What does this indicate about the contents of the Universe?