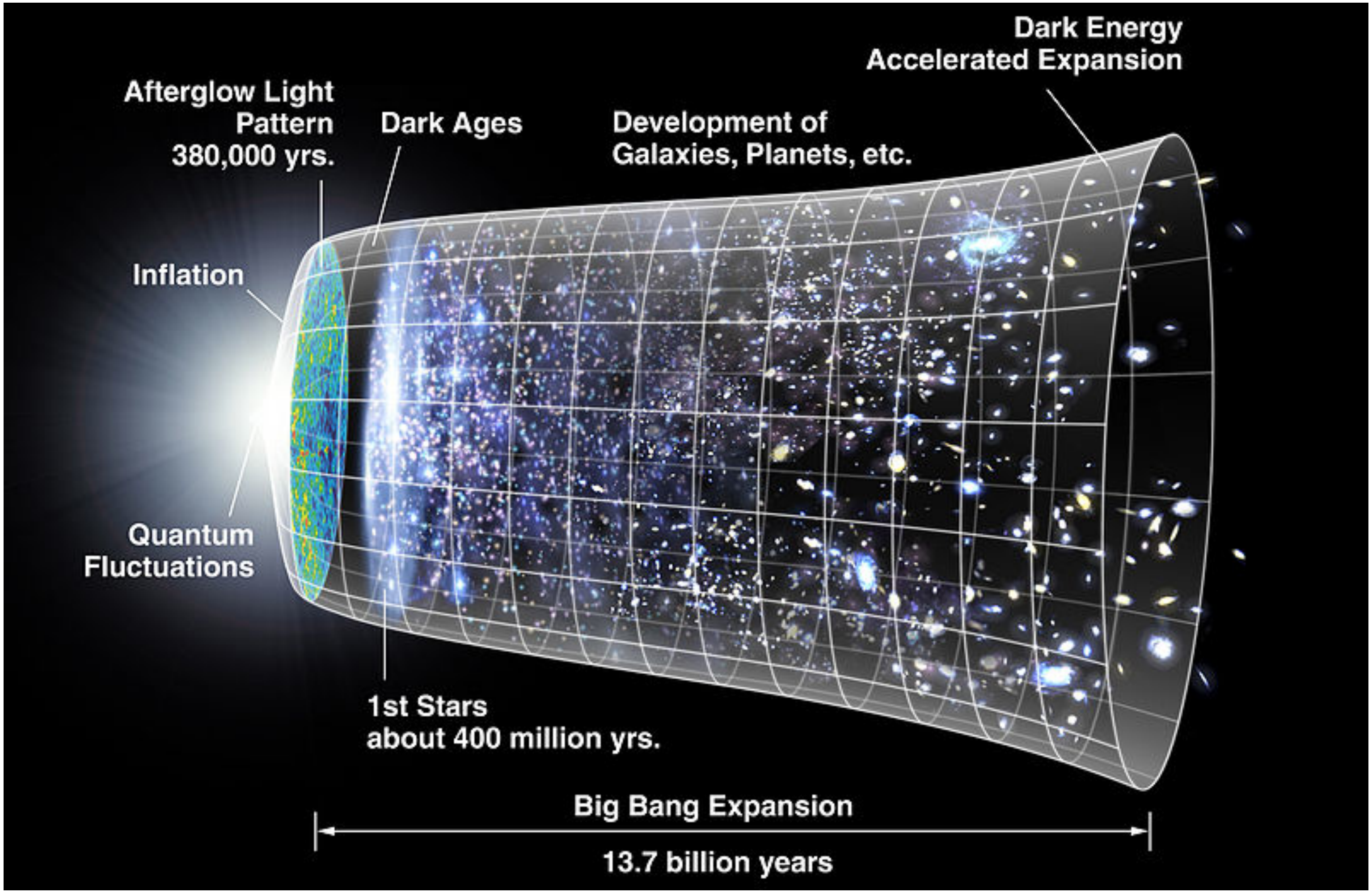
Cosmology


Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
380,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.7 billion years

Cosmological Principle

Cosmological Principle: Observers on Earth do not occupy any special location in the Universe. Two consequences of the cosmological principle are homogeneity and isotropy.

Homogeneous Universe:
The same observational evidence is available from any part of the Universe. It doesn't matter where you are located in the Universe.

Isotropic:
Over sufficiently large distances the Universe looks the same in any direction we look.

Cosmological Redshift

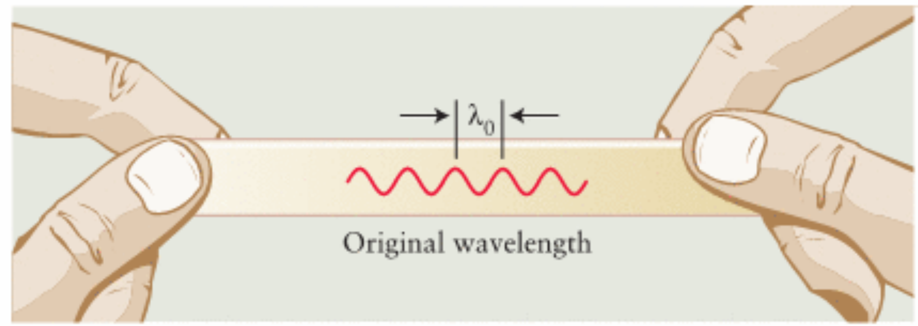
A redshift caused by the expansion of the universe is called cosmological redshift.

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

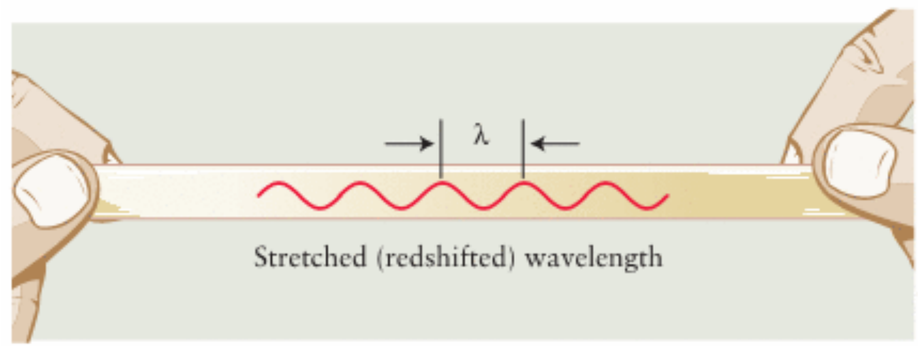
$z = (\lambda_{obs} - \lambda_0)/\lambda_0 \rightarrow \lambda_{obs}/\lambda_0 = (1+z)$

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.

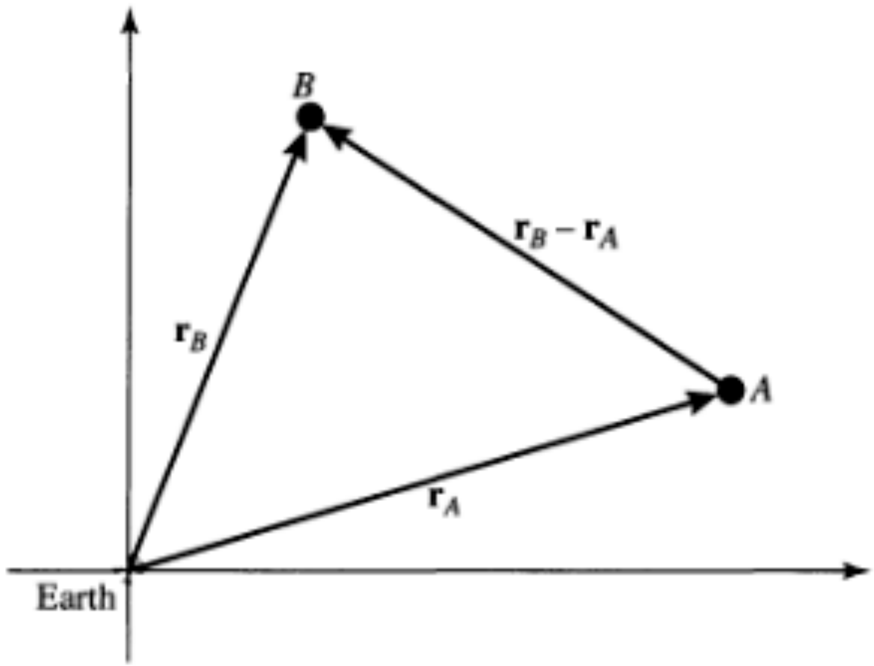


FIGURE 29.1 The expansion of the universe, with Earth at the origin.

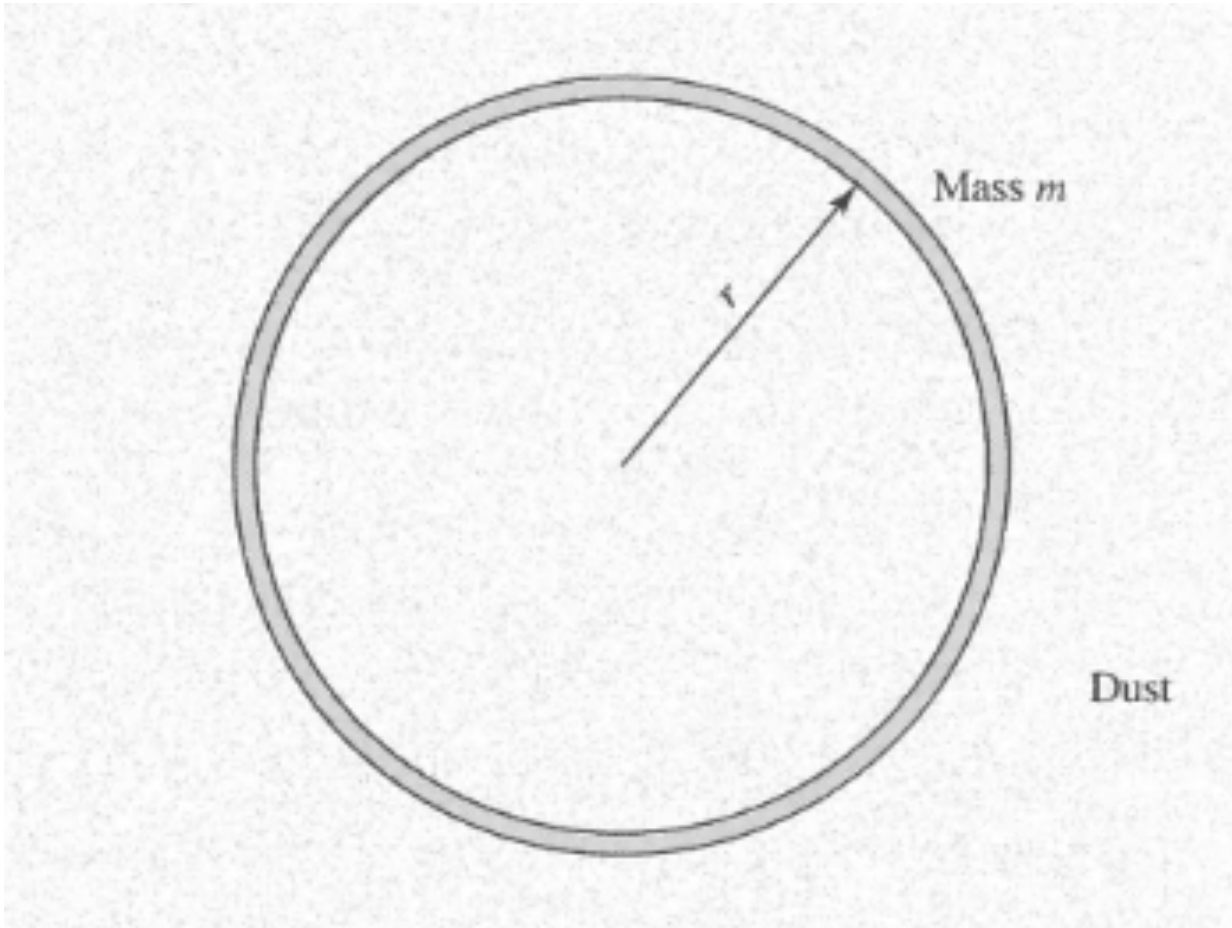


FIGURE 29.2 Spherical mass shell in a dust-filled universe.

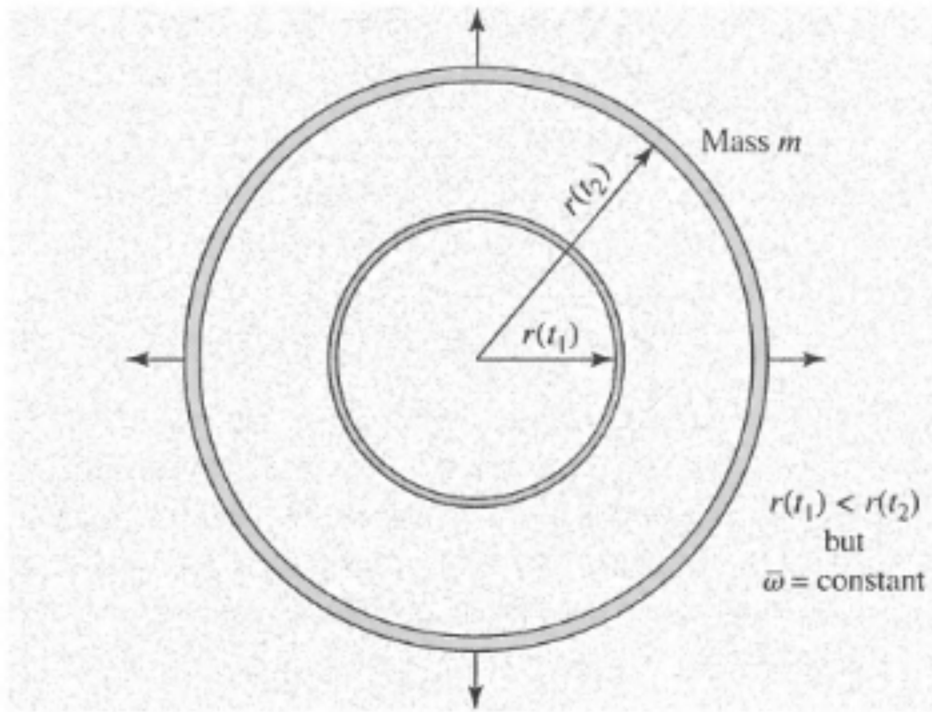


FIGURE 29.3 An expanding mass shell seen at two different times, $t_1 < t_2$. As the mass shell expands, its comoving coordinate, ϖ, is the same at times t_1 and t_2, while $r(t_1) < r(t_2)$.

Curvature of the Universe

The **Density Parameter of the Universe Ω_0** is defined as the ratio of the combined mass density ρ_0 to the critical mass density ρ_c:

$$\Omega_0 = \rho_0/\rho_c$$

Closed Universe: $\rho_0 > \rho_c \rightarrow \Omega_0 > 1$

Flat Universe: $\rho_0 = \rho_c \rightarrow \Omega_0 = 1$

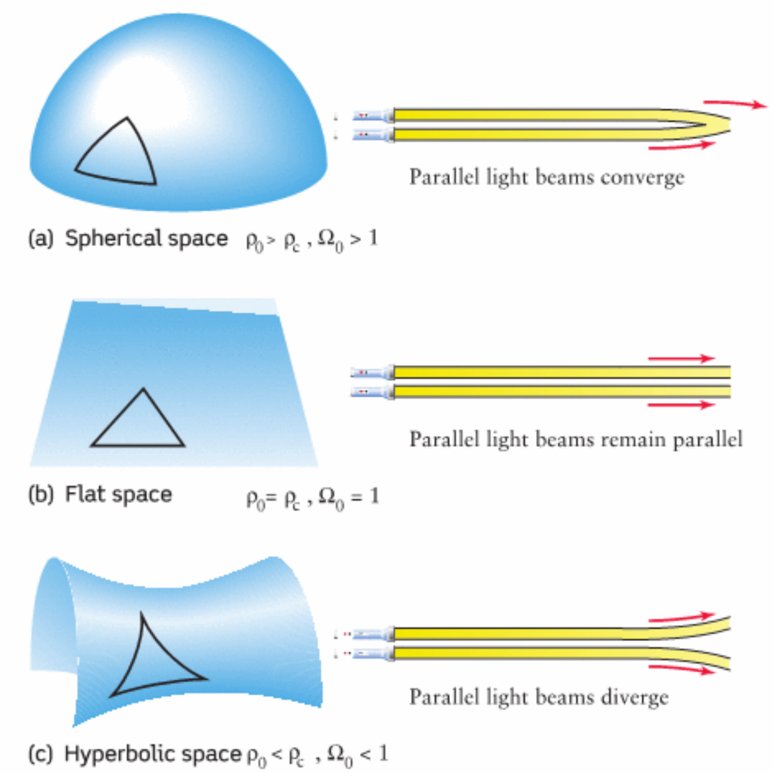
Open Universe: $\rho_0 < \rho_c \rightarrow \Omega_0 < 1$

Where the critical mass density is:

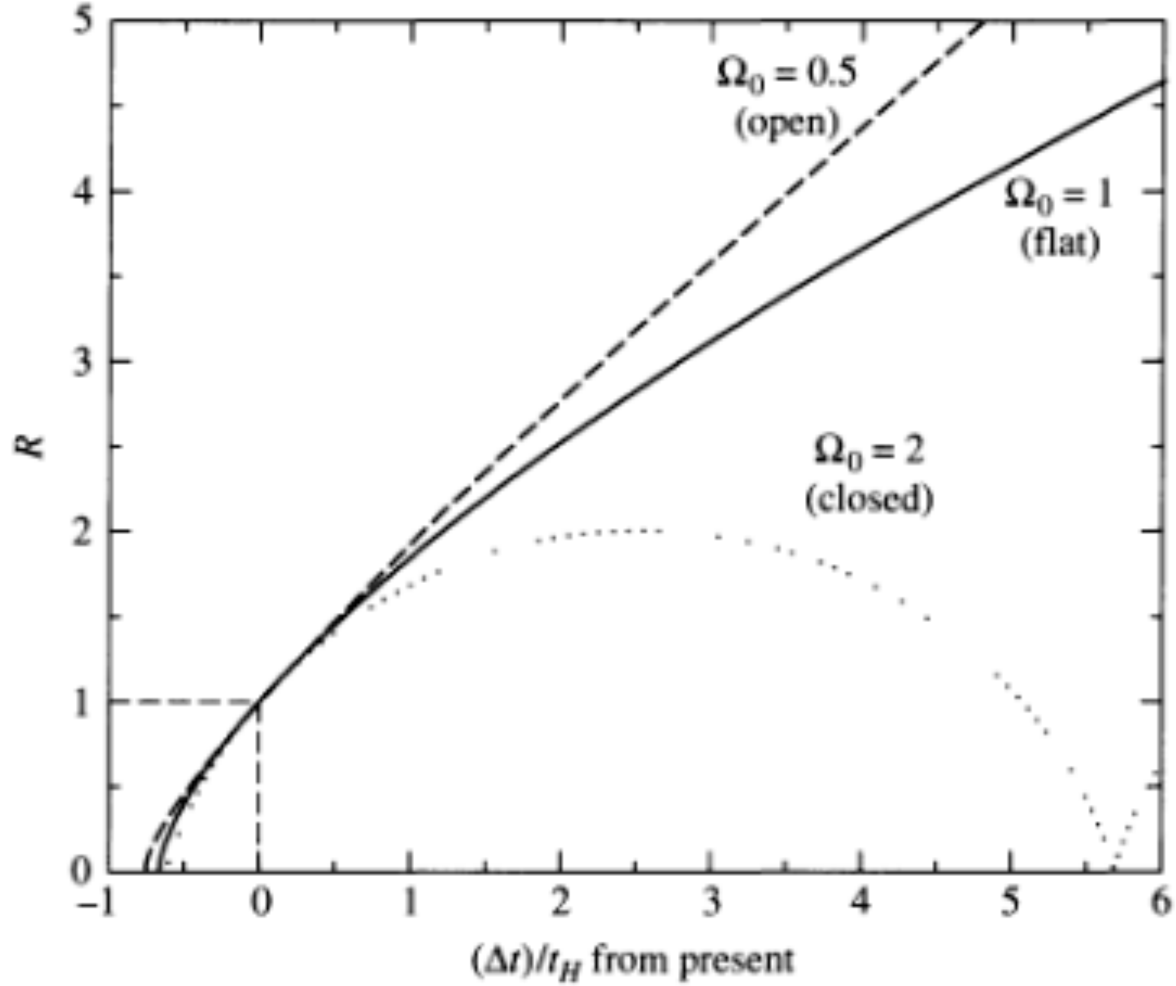
$$\rho_c = \frac{3H_0^2}{8\pi G}$$

ρ_c = critical density of the Universe

For $H_0 = 68$ km/s/Mpc $\rho_c = 1.0 \times 10^{-26}$ kg/m^3



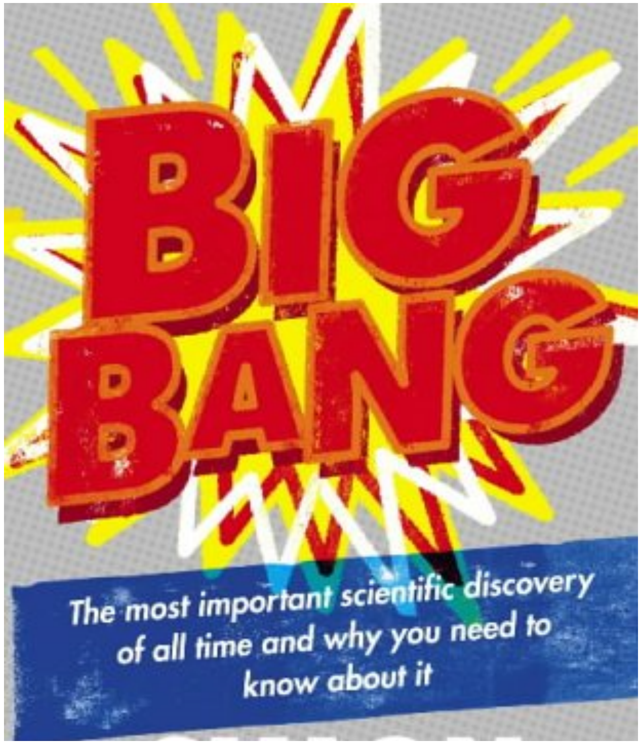
Scale factor for a pressureless dust Universe



Evidence of a Hot Big Bang

(1) **H and He Abundances**
Calculations of the amount of H and Helium expected to have been produced a few minutes just after the Big Bang agrees well with the amounts observed in primordial gas.

In order for the Universe to have produced those $H \rightarrow He$ fusion reactions it must have been extremely hot and dense filled with high energy photons.



(2) **Cosmic Microwave Background**
As the universe expanded the plasma cooled and when it reached T~3000 K electrons combined with protons to form neutral H. At this point (~ 380,000 years after the Big Bang) photons were able to escape and travel freely through space. This radiation is all around us as is called cosmic microwave background.

Radiation of the Universe

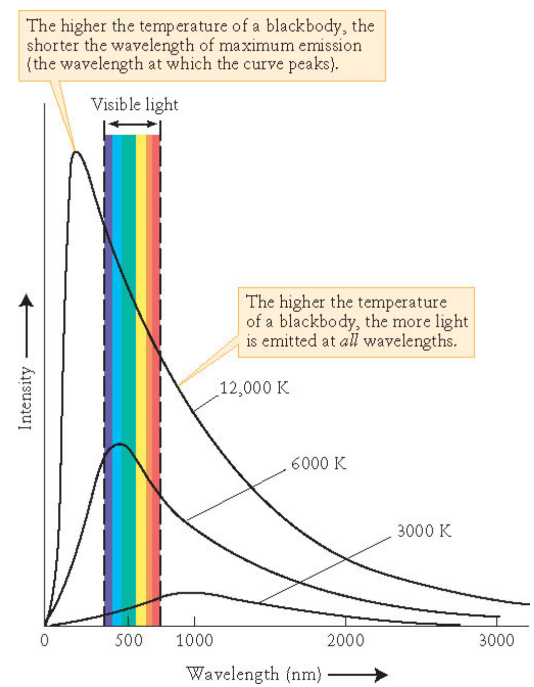
Photons are massless particles that travel across the Universe at the speed of light and constitute a form of radiation. Radiation from the hot plasma produced just after the Big Bang has a **blackbody spectrum**.

Recall that a Blackbody spectrum is characterized by a peak wavelength and a Temperature that follow Wien's Law:

$$\lambda_{max}(m) = \frac{0.0029\ \mathrm{K\,m}}{T(K)}$$

$\lambda_{max}(m)$ = wavelength of maximum emission in meters

T = temperature of object in kelvins



Evidence of a Hot Big Bang

In 1965 Arno Penzias and Robert Wilson while working at Bell Labs on a horn antenna discovered cosmic background radiation left over from the hot Big Bang.

Temperature of the cosmic microwave background (CMB) now $T_{obs} = 2.725$ K

Because of the cosmological redshift the spectrum of the CMB is redshifted making the observed temperature now much cooler than the original one of 3,000 K!

$T_{obs} = 0.0029\text{K}/\lambda_{obs}$

$\lambda_{obs}/\lambda_0 = (1+z) \rightarrow \lambda_{obs} = (1+z)\ \lambda_0 \sim 1100\ \lambda_0$

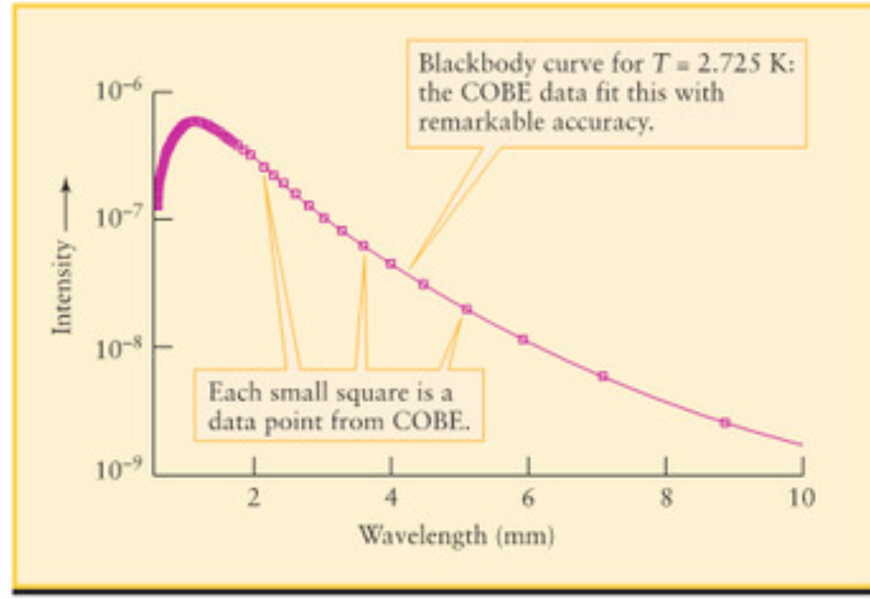
$\lambda_0 = 0.0029/3{,}000\text{K}$

$T_{obs} = 3{,}000\text{K}/1100 \sim 2.73$ K

Penzias and Wilson in front of the Horn Antenna.

Evidence of a Hot Big Bang

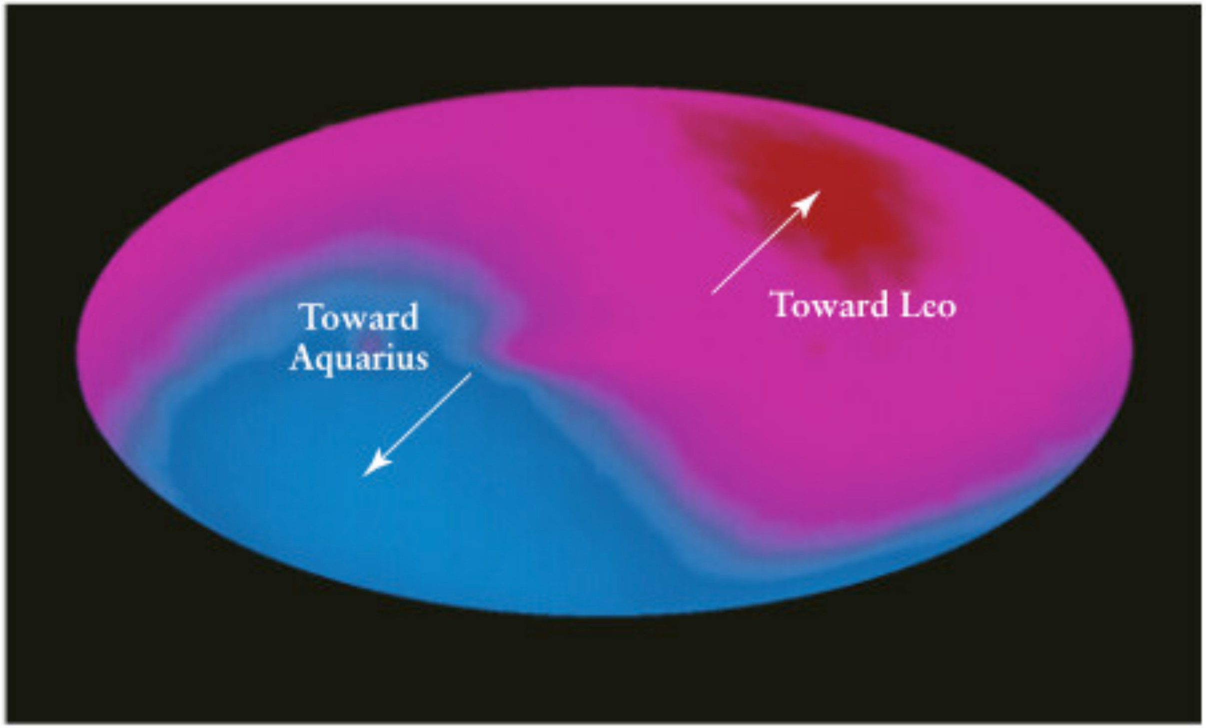
(a) The COBE spacecraft



(b) The spectrum of the cosmic microwave background

The first high-precision measurements of the cosmic microwave background came from the Cosmic Background Explorer (COBE) satellite, which was placed in Earth orbit in 1989. The CMB intensity is almost perfectly isotropic with a slight variation in temperature across the sky.

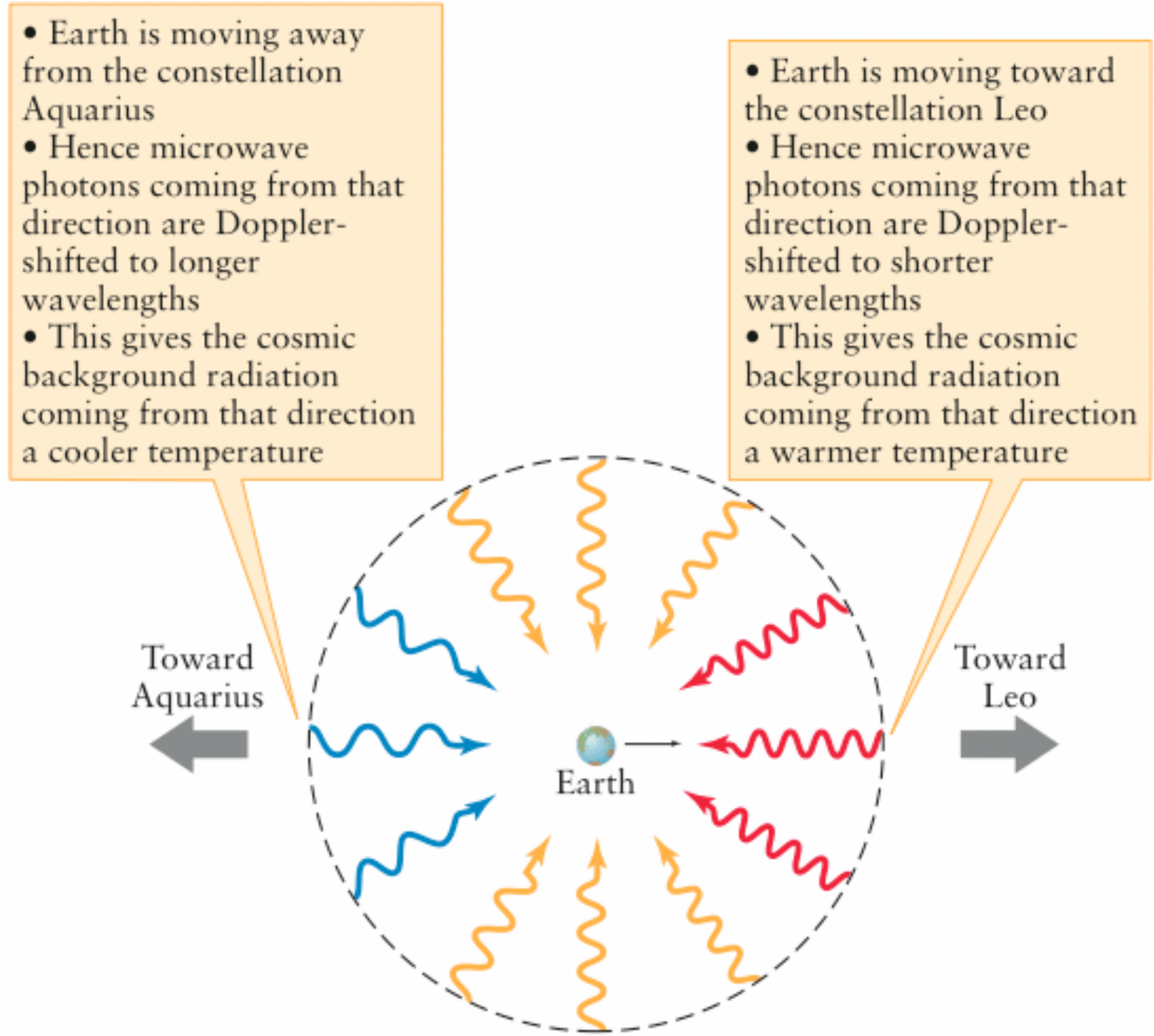
Evidence of a Hot Big Bang



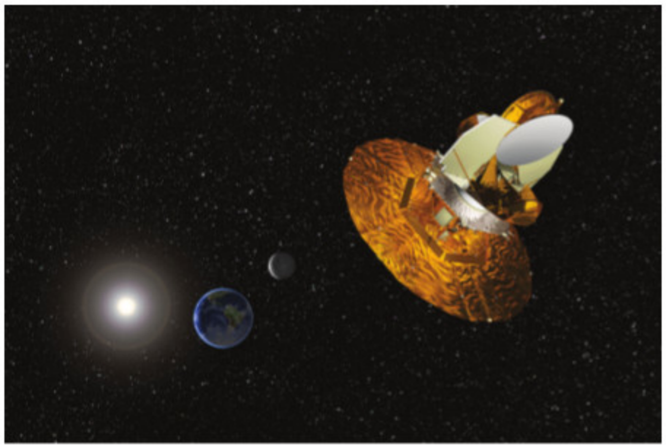
The microwave background appears slightly warmer than average toward the constellation of Leo and slightly cooler than average in the opposite direction toward Aquarius. In this map of the entire sky made from COBE data, the plane of the Milky Way runs horizontally across the map, with the galactic center in the middle. Color indicates temperature—red is warm and blue is cool. The small temperature variation across the sky is caused by Earth's motion through the microwave background.

Evidence of a Hot Big Bang

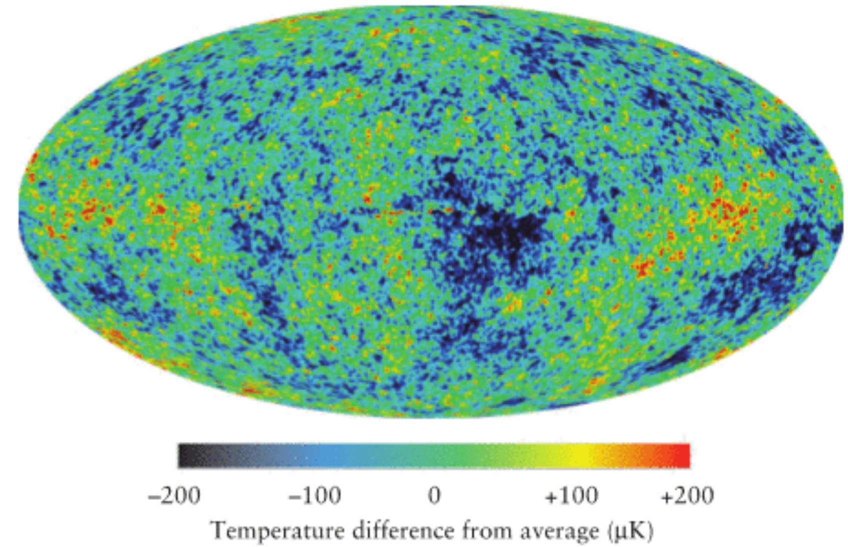
Because of the Doppler effect, we detect shorter wavelengths in the microwave background and a higher temperature of radiation in that part of the sky toward which we are moving. This part of the sky is the area shown in red. In the opposite part of the sky, shown in blue the microwave radiation has longer wavelengths and a cooler temperature.



Temperature Variations in the CMB



The Wilkinson Microwave Anisotropy Probe (WMAP) launched in 2001.

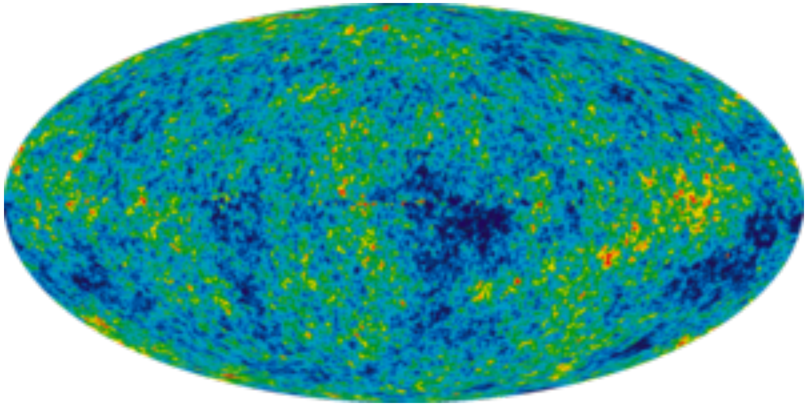


This map from WMAP data shows small variations in the temperature of the cosmic background radiation across the entire sky.

WMAP images show temperature variations of the CMB of the order of 2×10^{-4} K around the average value of 2.725K. The bluer regions a lower temperature and higher density. These denser regions will evolve to become the galaxies and clusters of galaxies in the Universe.

This 2.725K background radiation originates from the recombination era some ~ 380,000 years after the Big Bang.

Cosmic Microwave Background



When H atoms first formed 380,000 years after the Big Bang light was able to freely travel through the Universe.

Temperature of CMB Then ~ 3,000K
Temperature of CMB NOW ~ 2.725 K

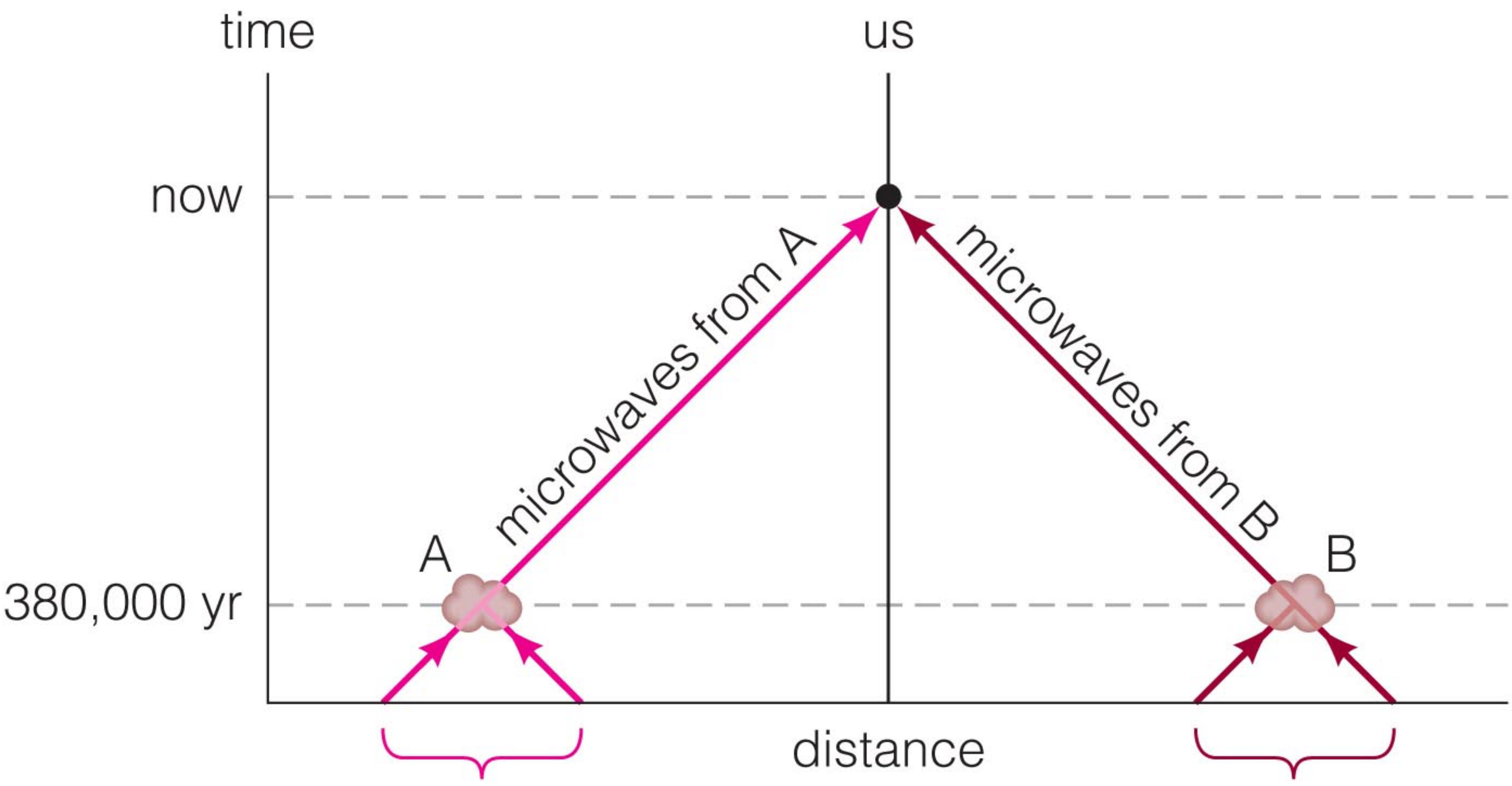
A great discovery that confirmed the big bang theory was the detection of the cosmic microwave background (CMB).

A careful analysis of the CMB revealed two strange results:

1. It’s too uniform (or isotropic).

2. The curvature of space of the Universe is near zero today.

Result 1: Universe is uniform over large scales



- How can microwave temperature be nearly identical on opposite sides of the sky?

Result 2: The Early Universe: The Flatness Problem

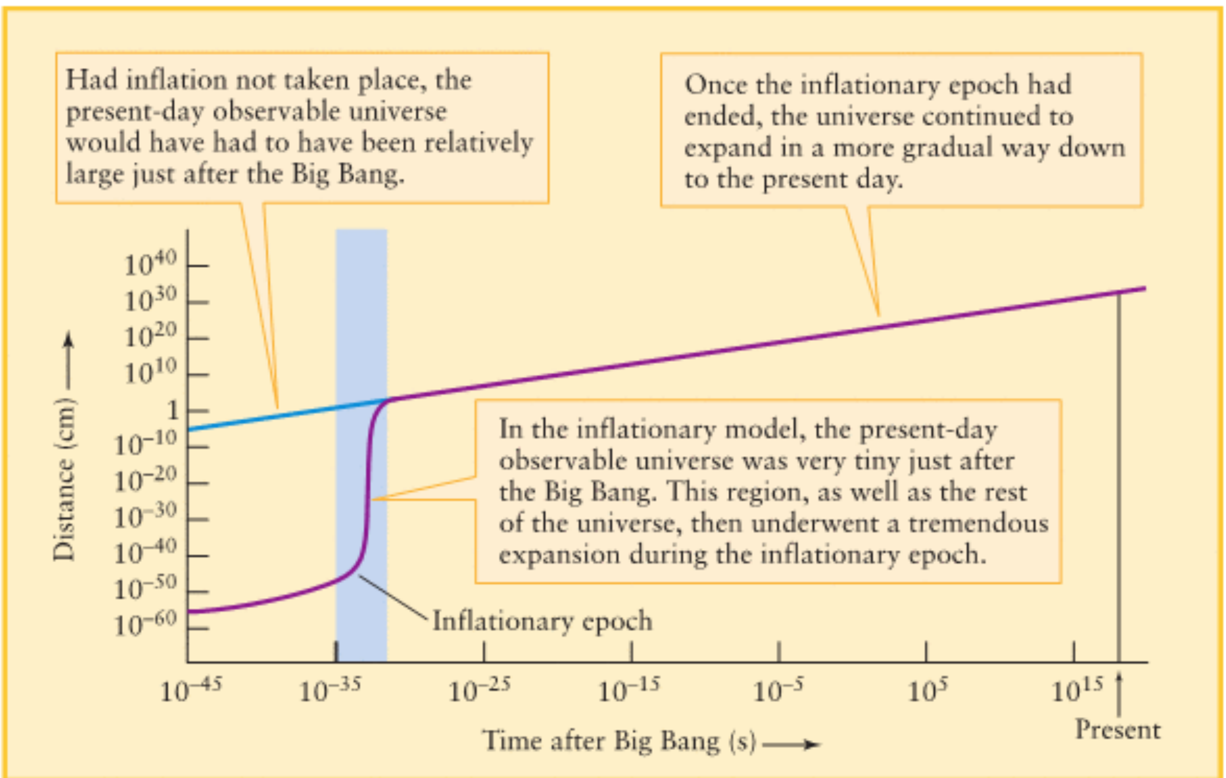
The geometry of our universe depends on the density parameter Ω_0, which is the ratio of the combined mass density in the universe (ρ_0) to the critical density (ρ_c)

$$\Omega_0 = \rho_0/\rho_c$$

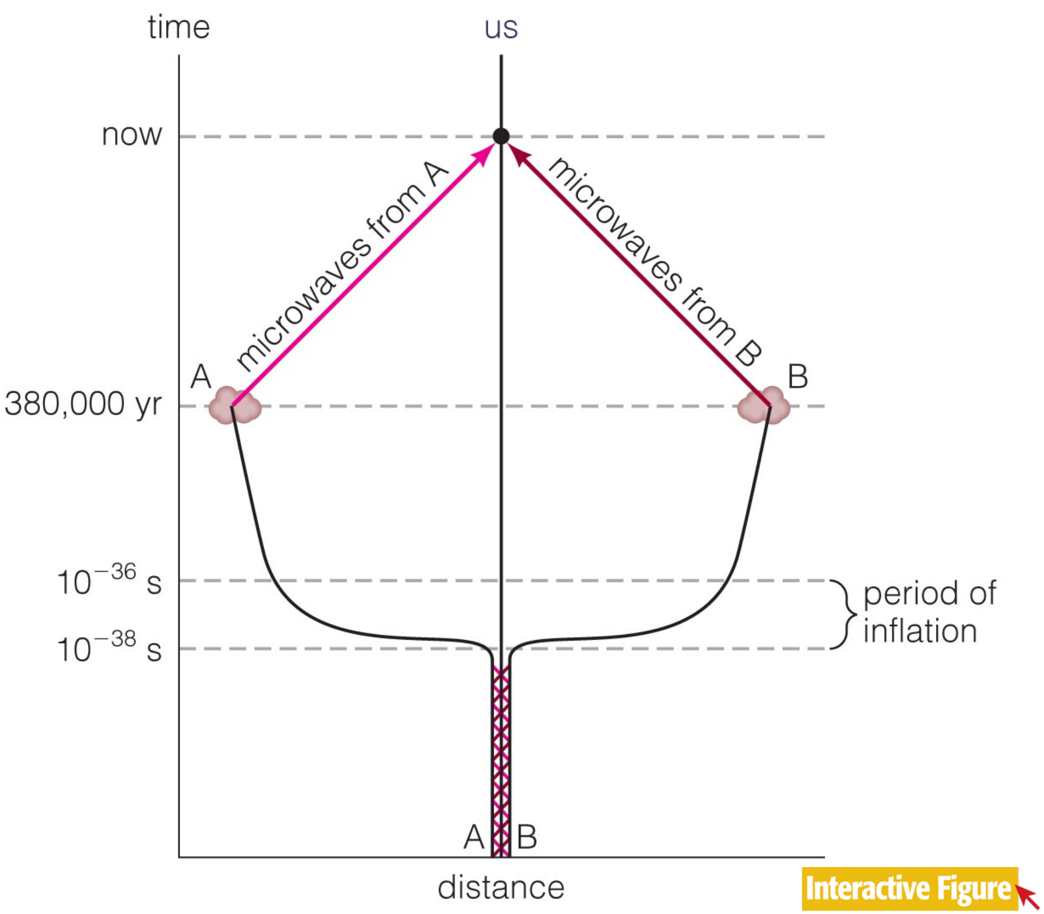
We now know that the density of the Universe is exactly equal to the critical density: $\Omega_0=1$ (flat Universe).

Proposed solution to results (1) and (2): **Inflation**

Independently Alexei Starobinsky and Alan Guth suggested that the universe might have experienced a brief period of inflation, expanded by a factor of 10^{50}, shortly after the big bang.

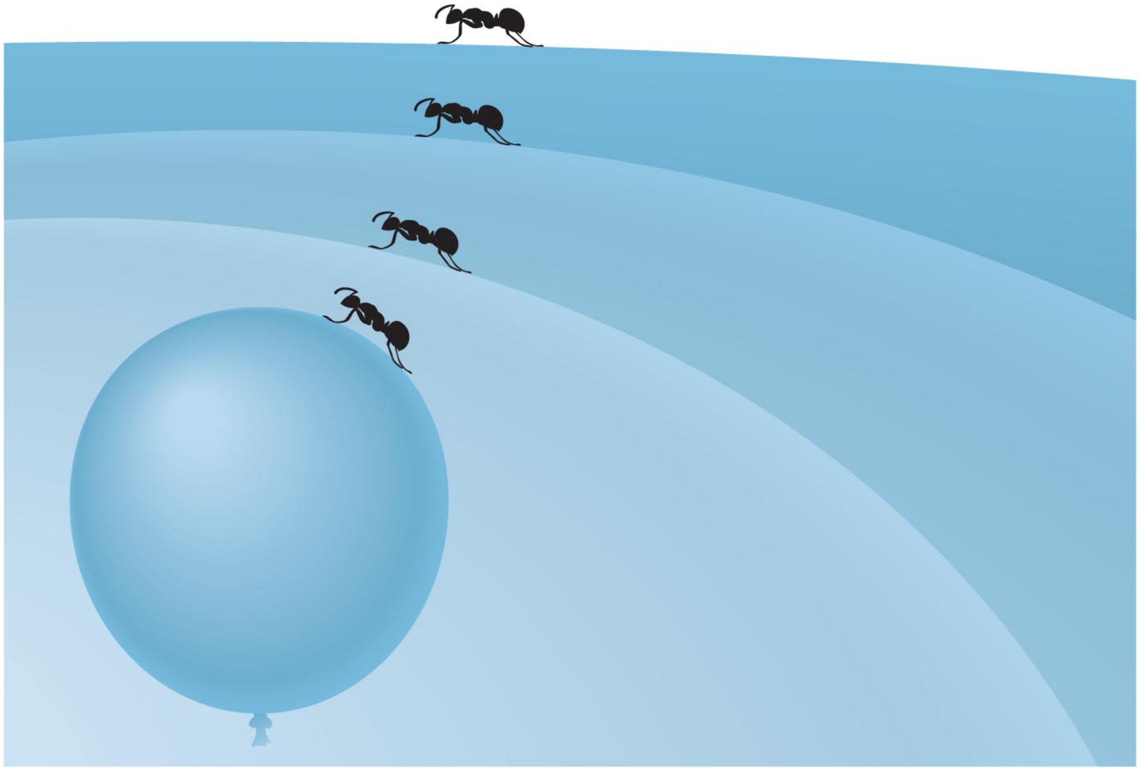


Inflation explains uniformity of Universe



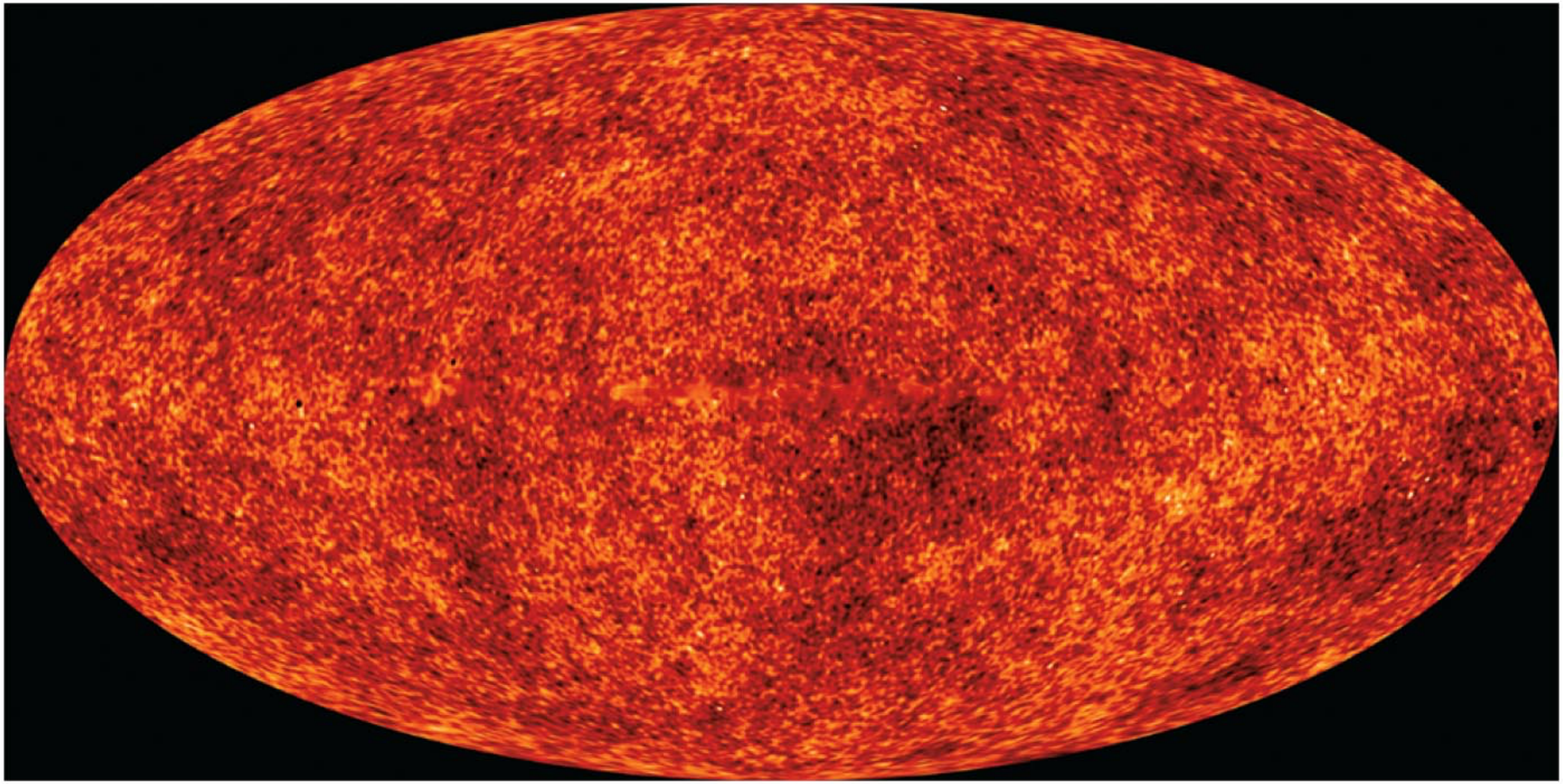
- Regions now on opposite sides of the sky were close together before inflation pushed them far apart.

Inflation explains flatness of Universe

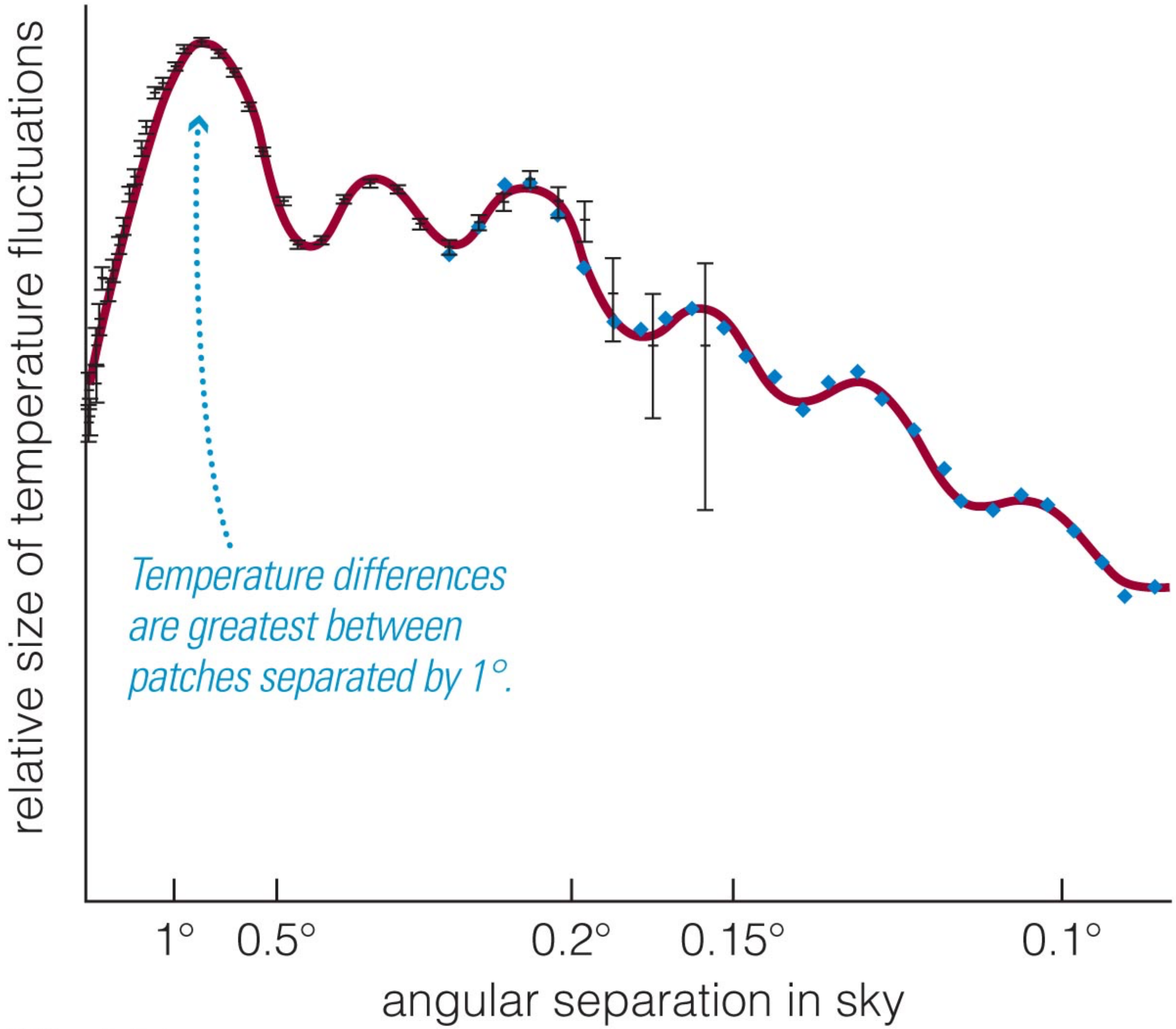


- Inflation of the universe flattens its overall geometry like the inflation of a balloon, causing the overall density of matter plus energy to be very close to the critical density.

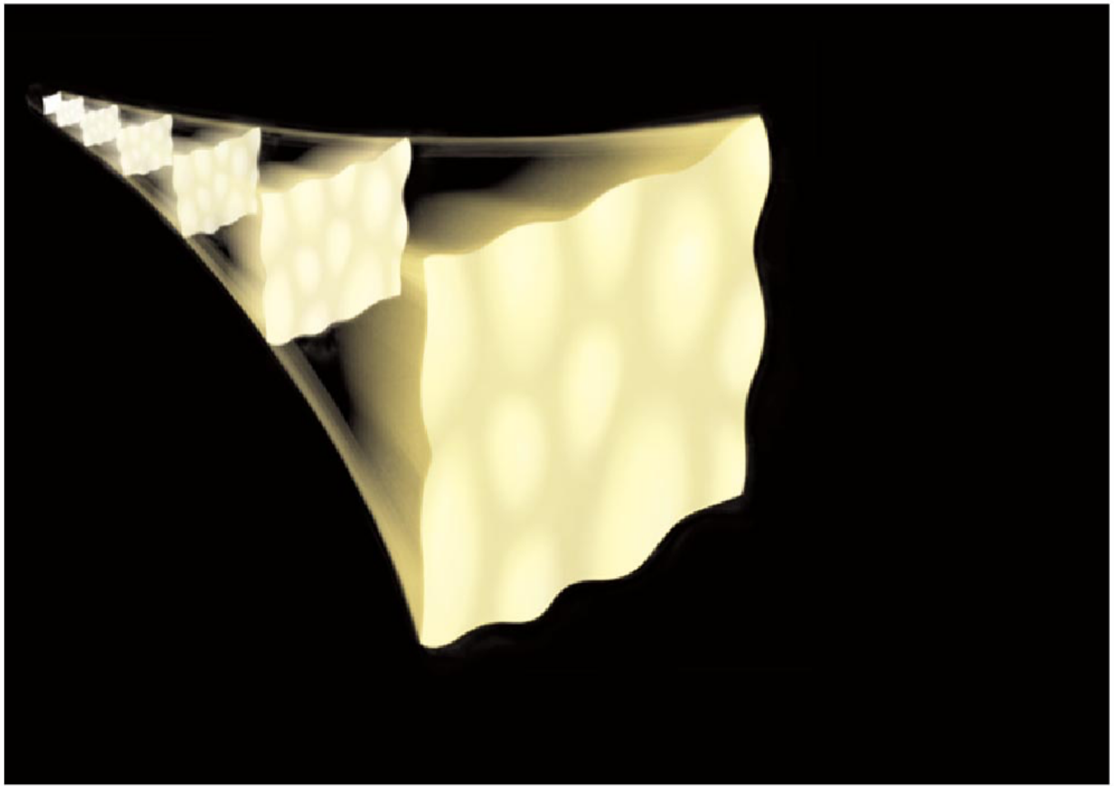
Did inflation really occur?



- Patterns observed by WMAP show us the "seeds" of structure in the universe.



- Observed patterns of structure in universe agree (so far) with the "seeds" that inflation would produce.



- Inflation can make all the structure by stretching tiny quantum ripples to enormous size.
- These ripples in density then become the seeds for all structures in the universe

The Early Universe: Fundamental Forces

To understand what happened in the early universe we need to understand how particles interact at high energies.

Particles interact through four fundamental forces of nature.

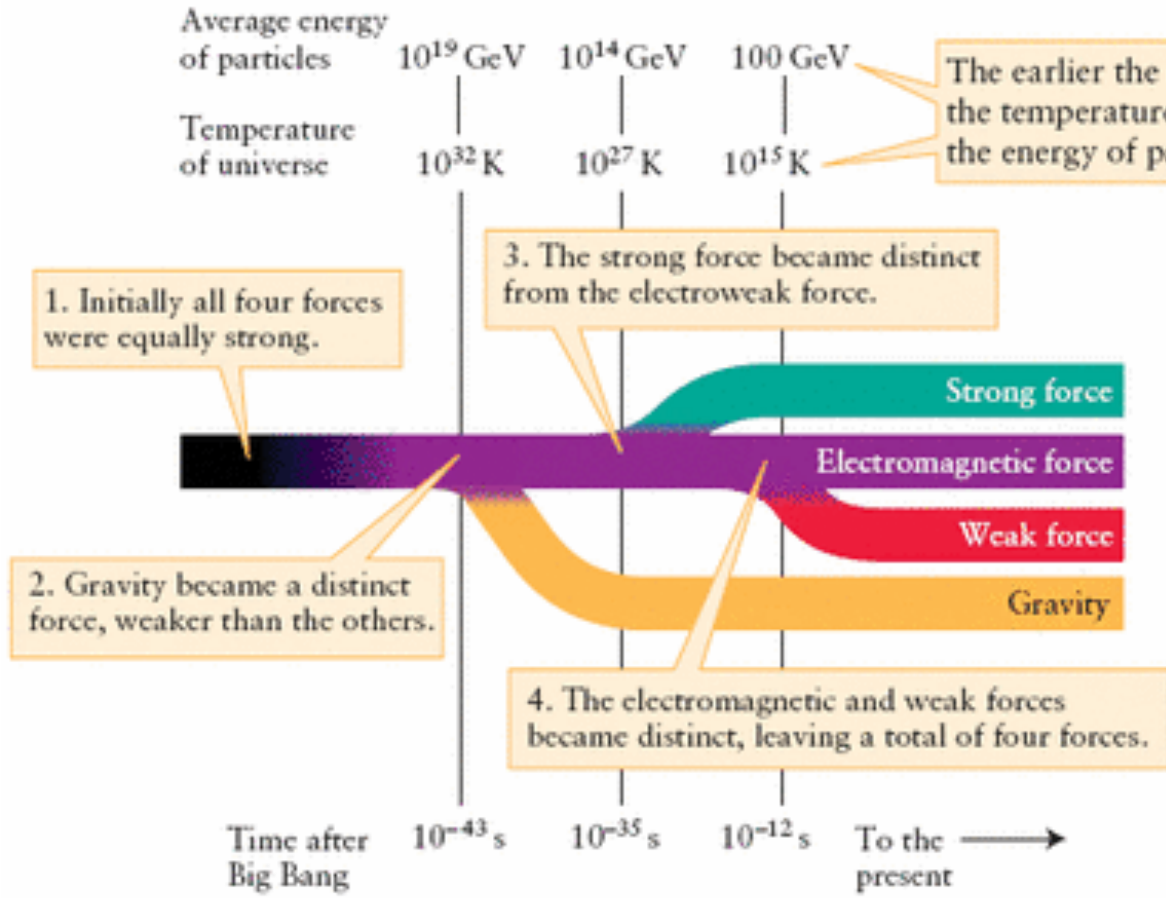
1. Gravity (force between everything including massless objects like photons, infinite range)

2. Electromagnetism (force between charged particles, infinite range)

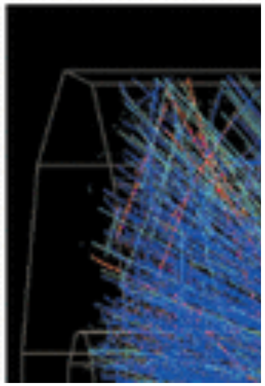
3. Strong Force (force between quarks that make up neutrons and protons, short-range force ~ 10^{-15}m)

4. Weak Force (force acts on quarks, electrons, neutrinos and involved in certain radioactive decays, short-range force ~10^{-16}m)

One Force in the Beginning?



(a) How the four forces behave at different energies and temperatures



Matter and Radiation Created During Inflation

To understand how radiation and matter were created we need to discuss the uncertainty principle.

According to Heisenberg's uncertainty principle the more precisely you try to measure the position x of a particle, the more unsure you become of the particle's momentum p (p = mass $\times$ velocity).

The uncertainty principle between position and momentum states :

$$\Delta x \Delta p \geq \frac{\hbar}{2} \rightarrow \Delta x \geq \frac{1}{2}\left(\frac{\hbar}{mc}\right), \; \hbar = 1.054 \times 10^{-34} \, Js$$

Where Δx is the uncertainty in the position of the particle and Δp is the uncertainty in its momentum.

Matter and Radiation Created During Inflation

The uncertainty principle between mass and time states :

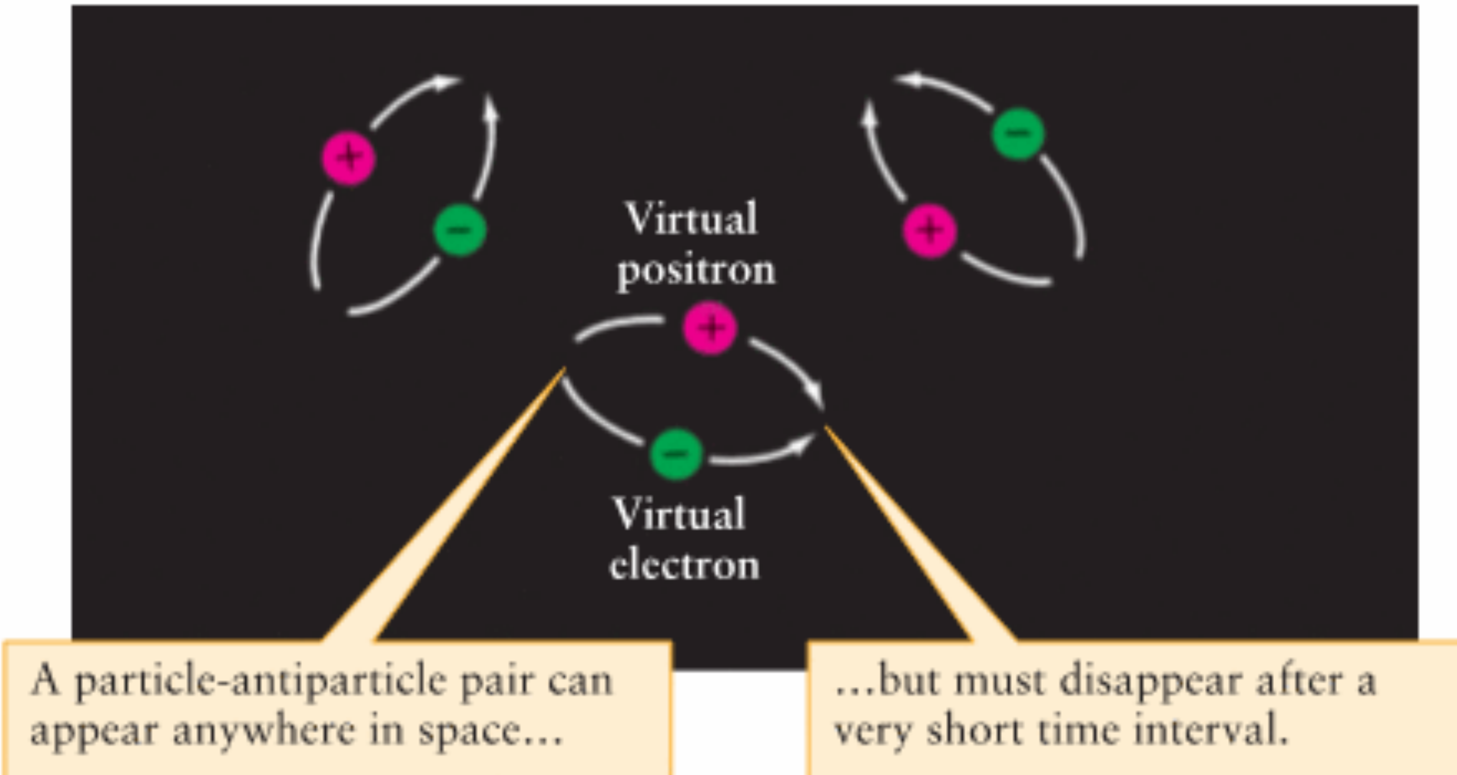
$$\Delta m \Delta \mathrm{t} \geq \frac{\hbar}{2c^2} \quad \text{where } \hbar = 1.054 \times 10^{-34} \text{ Js}$$

Δm is the uncertainty in the mass of the particle and Δt is the uncertainty in the time interval over which the energy is measured.

For very small time intervals large uncertainties in mass are allowed by nature! This means than over a very short time interval matter can just appear and then disappear even in empty space!

No particle can appear by itself, but has to be created with an antiparticle.

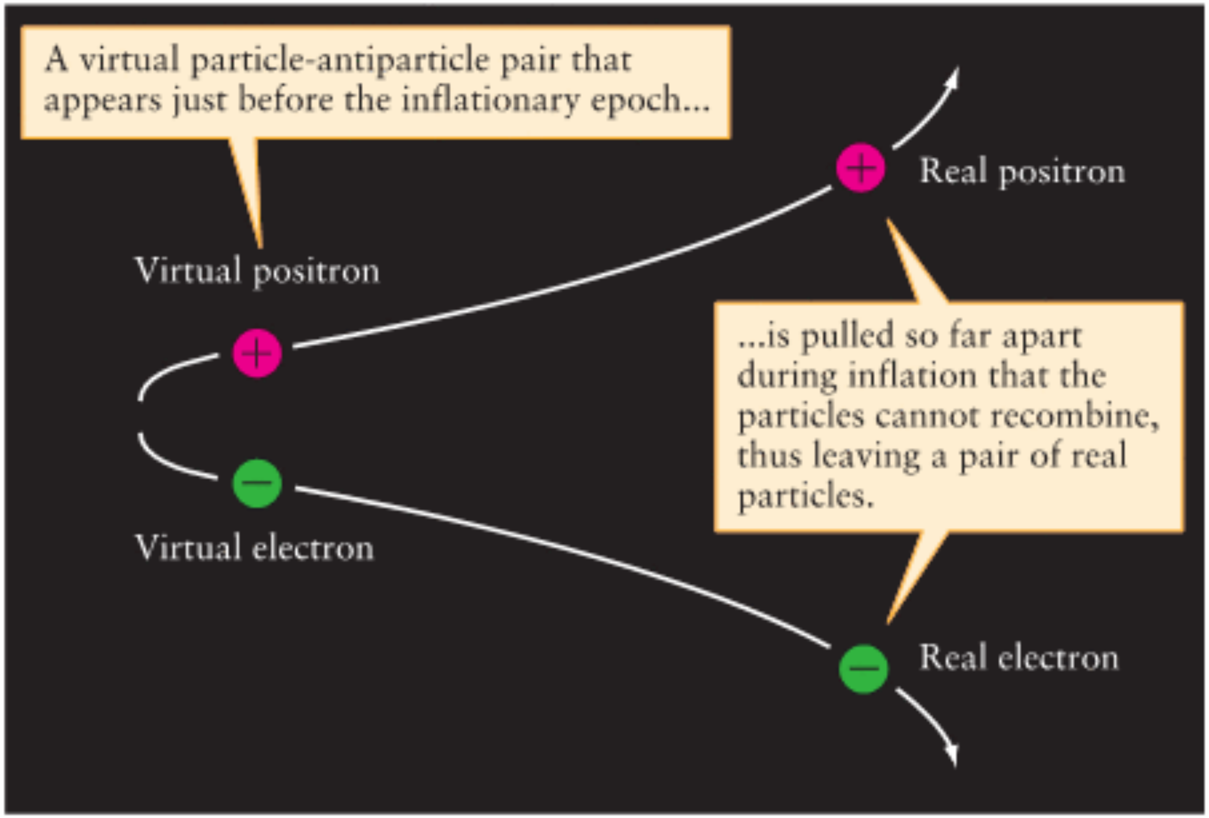
Matter and Radiation Created During Inflation



Virtual Pairs of particles and antiparticles can appear and then disappear in space provided that each pair exists only for a very short time interval, as dictated by the uncertainty principle.

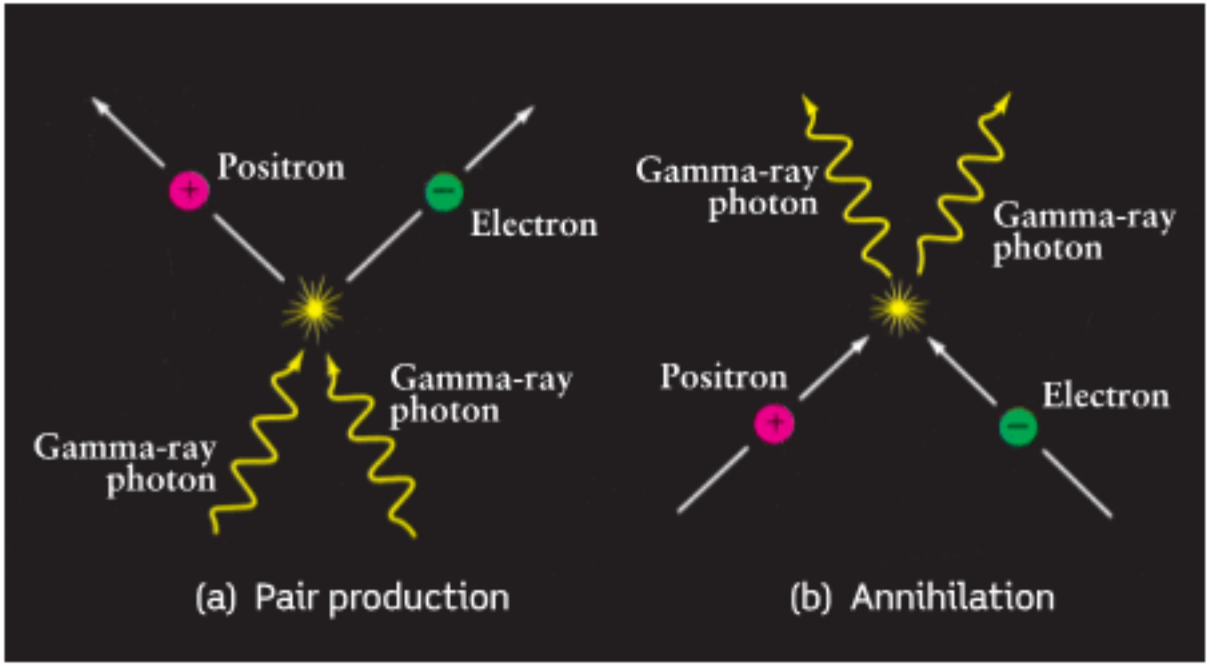
For example, an electron positron pair can be created out of vacuum and will exist for about 3×10^{-22} sec without violating the uncertainty principle.

Matter and Radiation Created During Inflation



Matter is created during Inflation: Virtual Pairs turn into real particles during inflation.

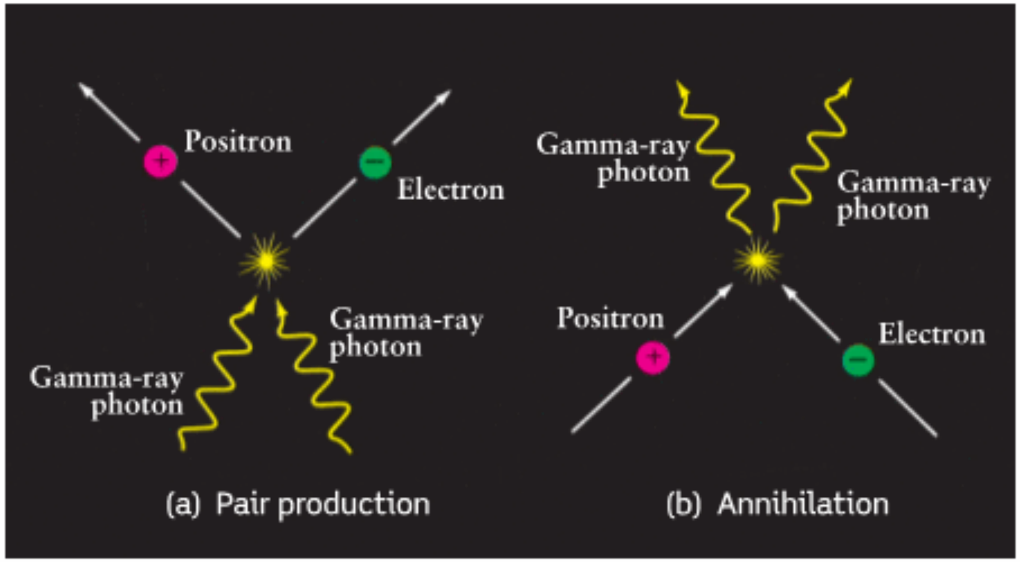
Matter and Radiation Created During Inflation



Pair production can take place only if the combined energy of the two photons is greater than *Mc^2, where M is the total mass of the electron and positron*

In the Early Universe the rate of pair production was equal to the rate of annihilation but as the Universe expanded and the temperature dropped…

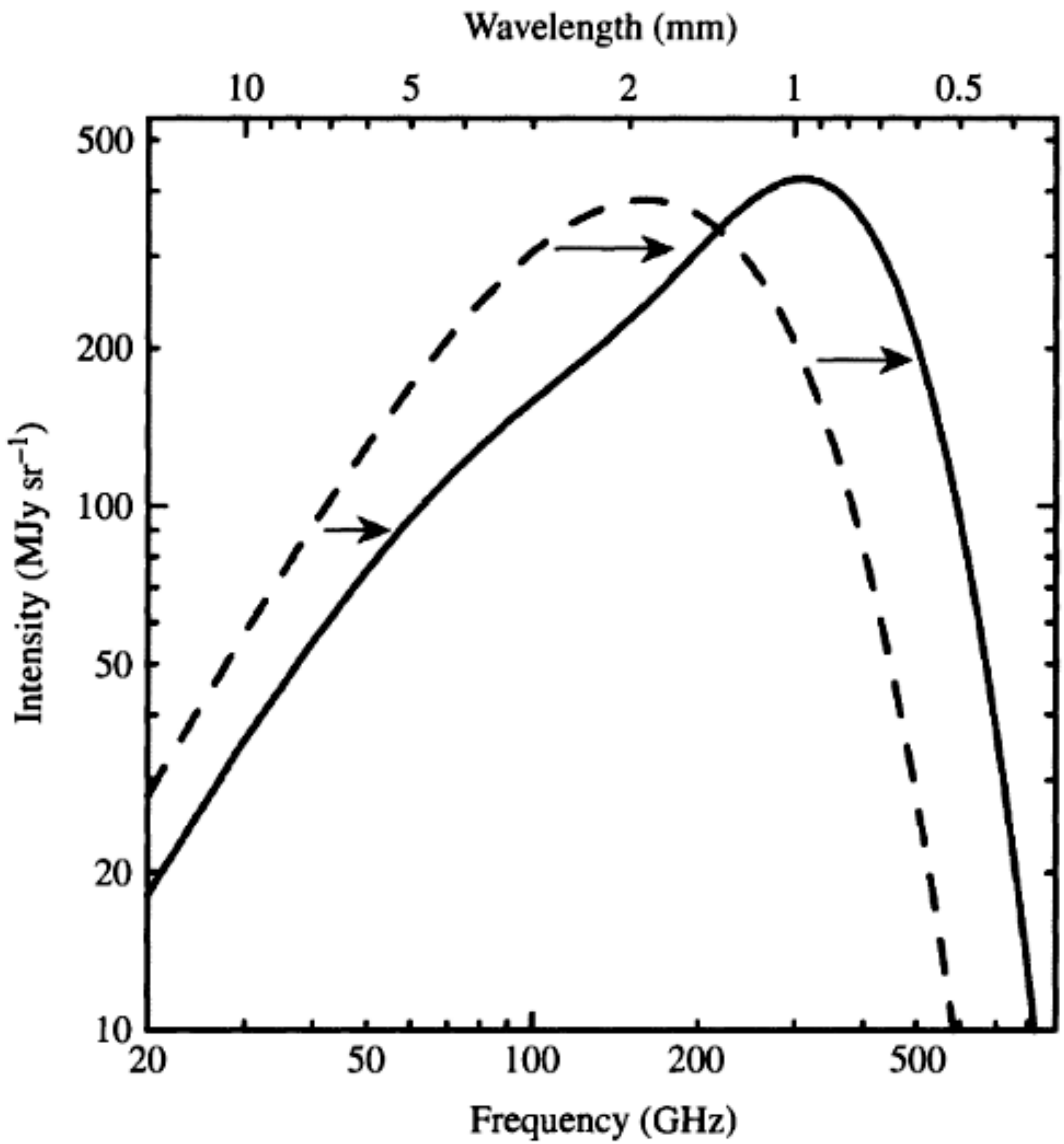
Matter and Radiation Created During Inflation



The rate of pair production decreased as the Universe expanded but annihilation continued.

In the present Universe we mostly find matter and not antimatter. But why did not all matter and antimatter annihilate?

Theories of elementary particles predict an excess of matter over antimatter immediately after the Big Bang, so that the particles outnumbered the antiparticles.



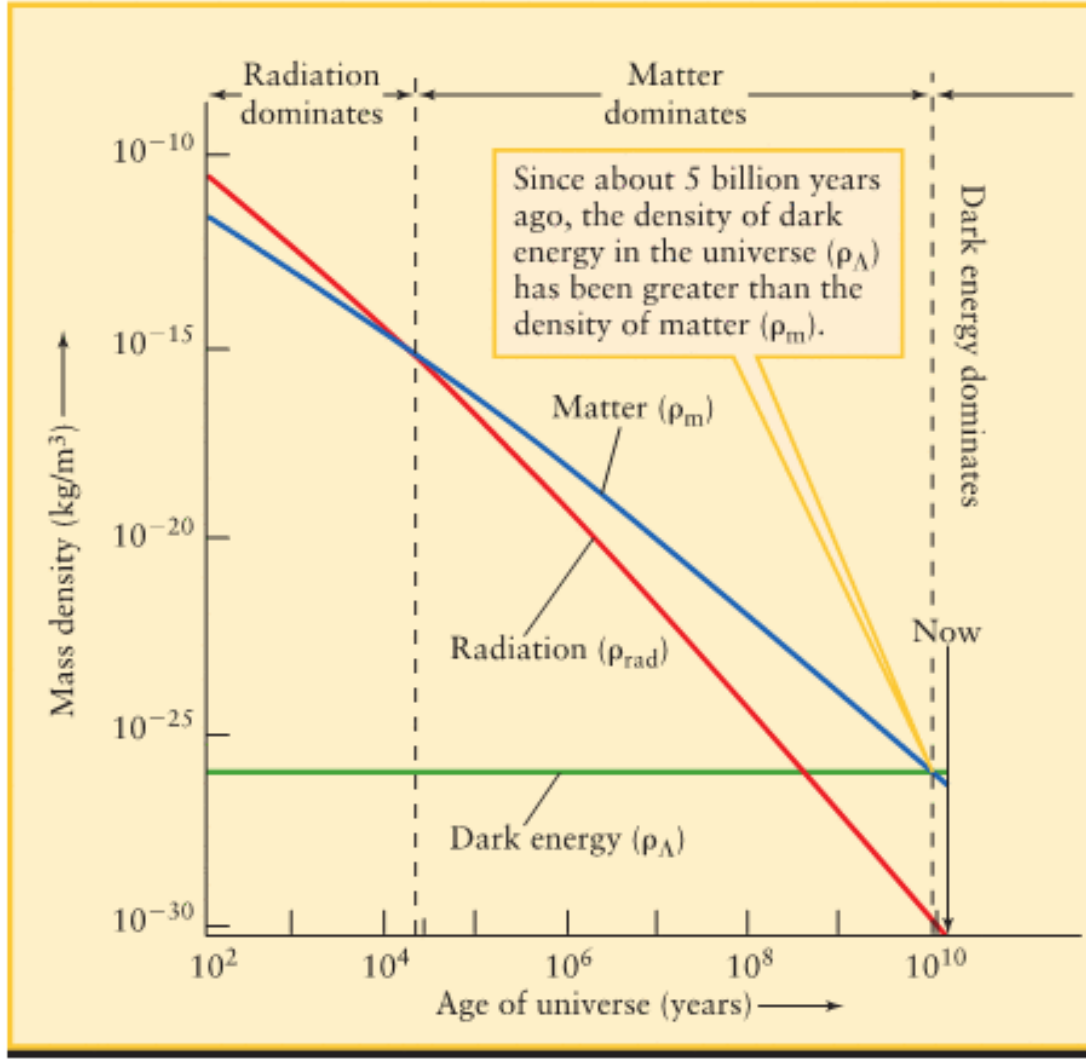
Wavelength (mm)
10
5
2
1
0.5
500
200
100
50
20
10
Intensity (MJy sr^{-1})
20
50
100
200
500
Frequency (GHz)

Why Me? Why Now?

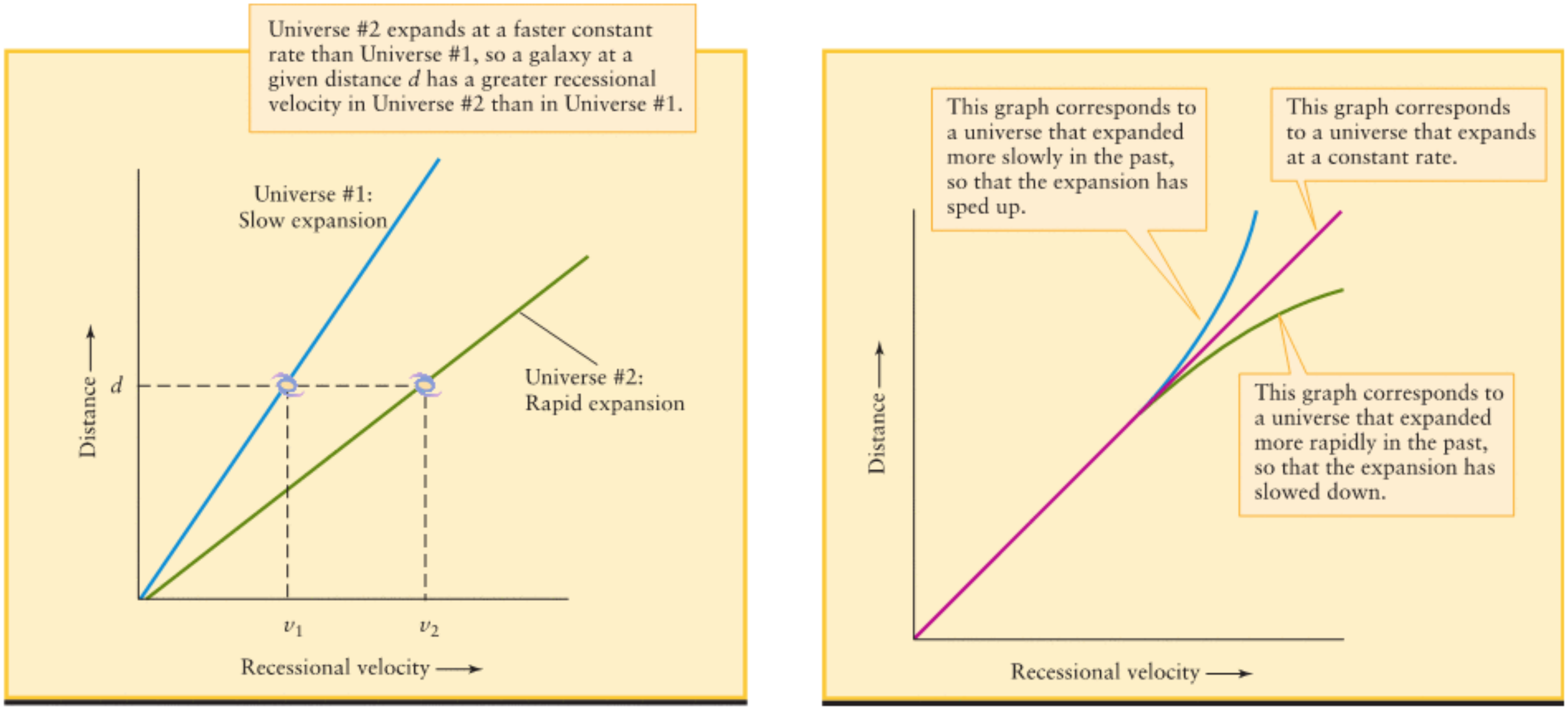
In the past dark energy was unimportant and in the future it will be dominant!

We just happen to live at the time when dark matter and dark energy have comparable densities.

In the words of Olympic skater Nancy Kerrigan, "Why me? Why now?



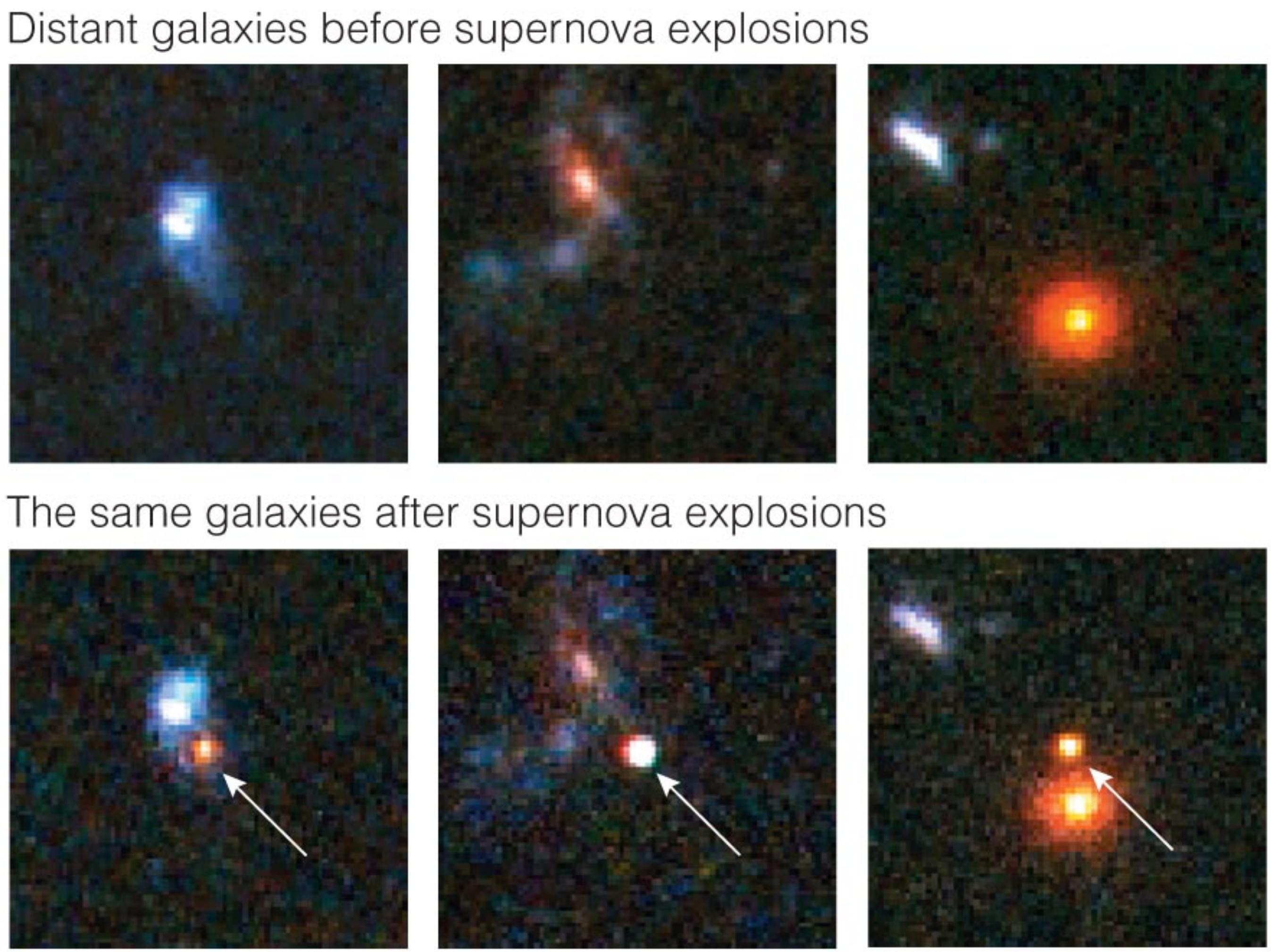
Does The Expansion Rate Change With Time?



(a) Two universes with different expansion rates

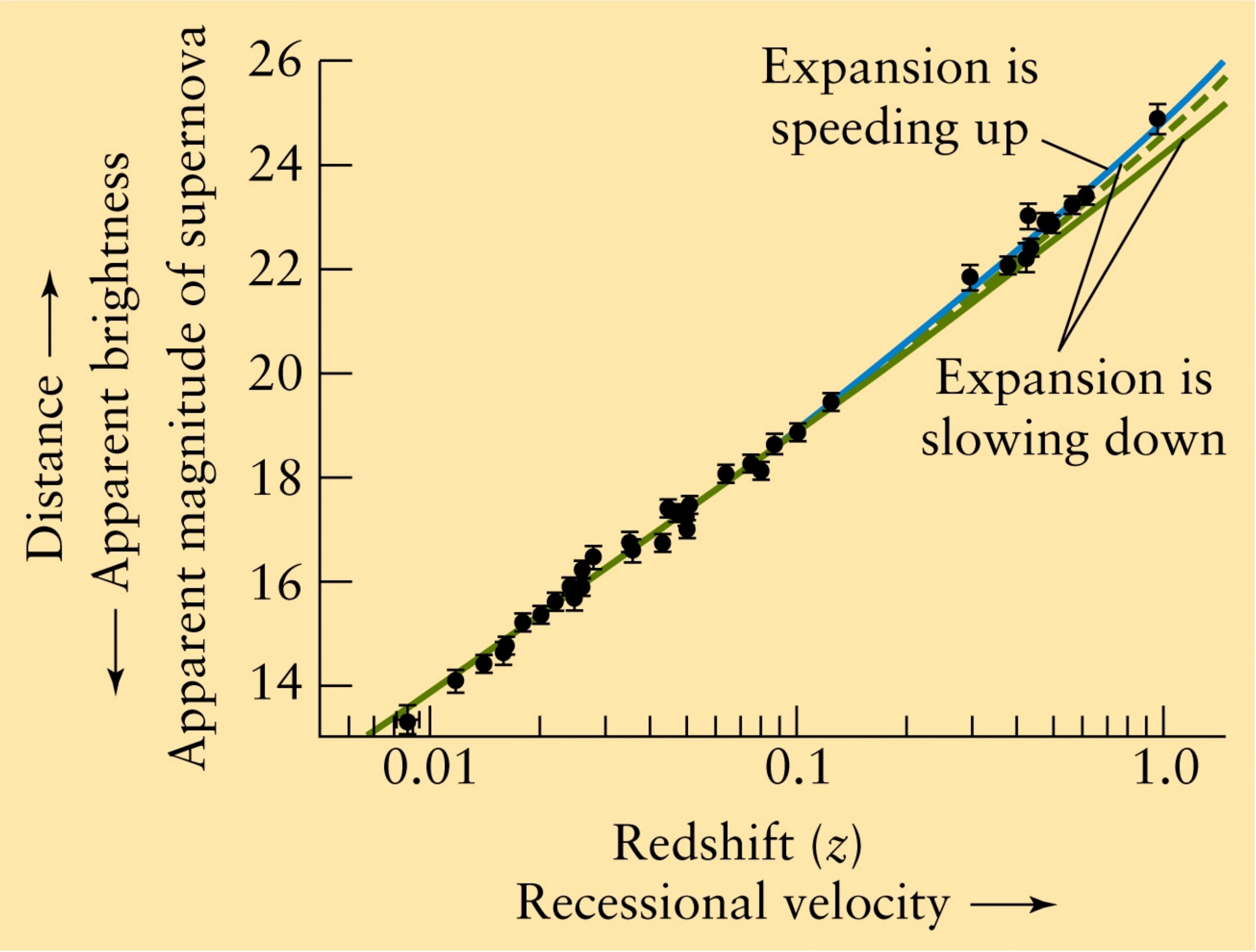
(b) Possible expansion histories of the universe

To address this question we need to look at the distances versus recession velocities of objects and see if the expansion rate changes with redshift. If the expansion rate is slowing down we expect a a steeper slope in the Distance versus velocity plot.



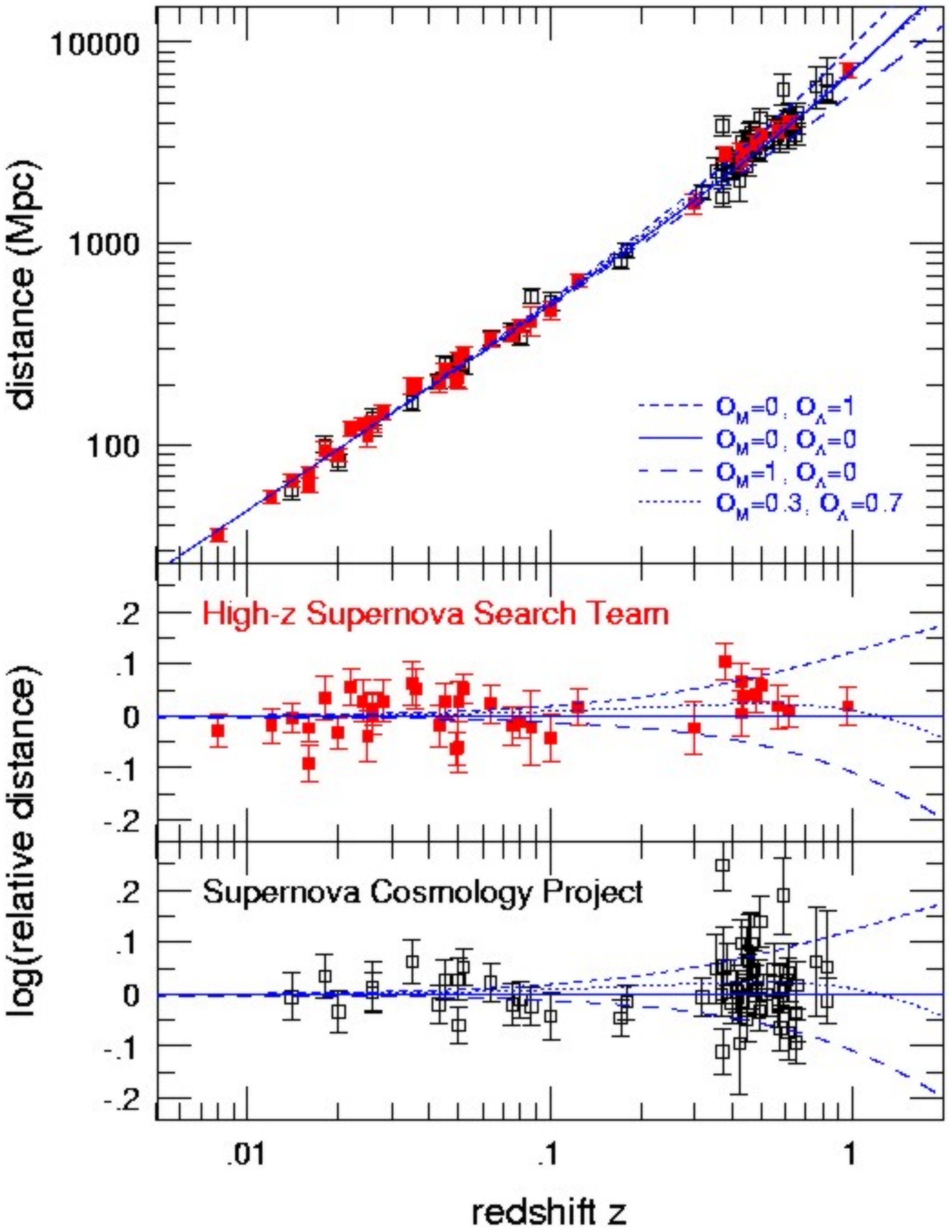
- The brightness of distant white dwarf supernovae tells us how much the universe has expanded since they exploded.

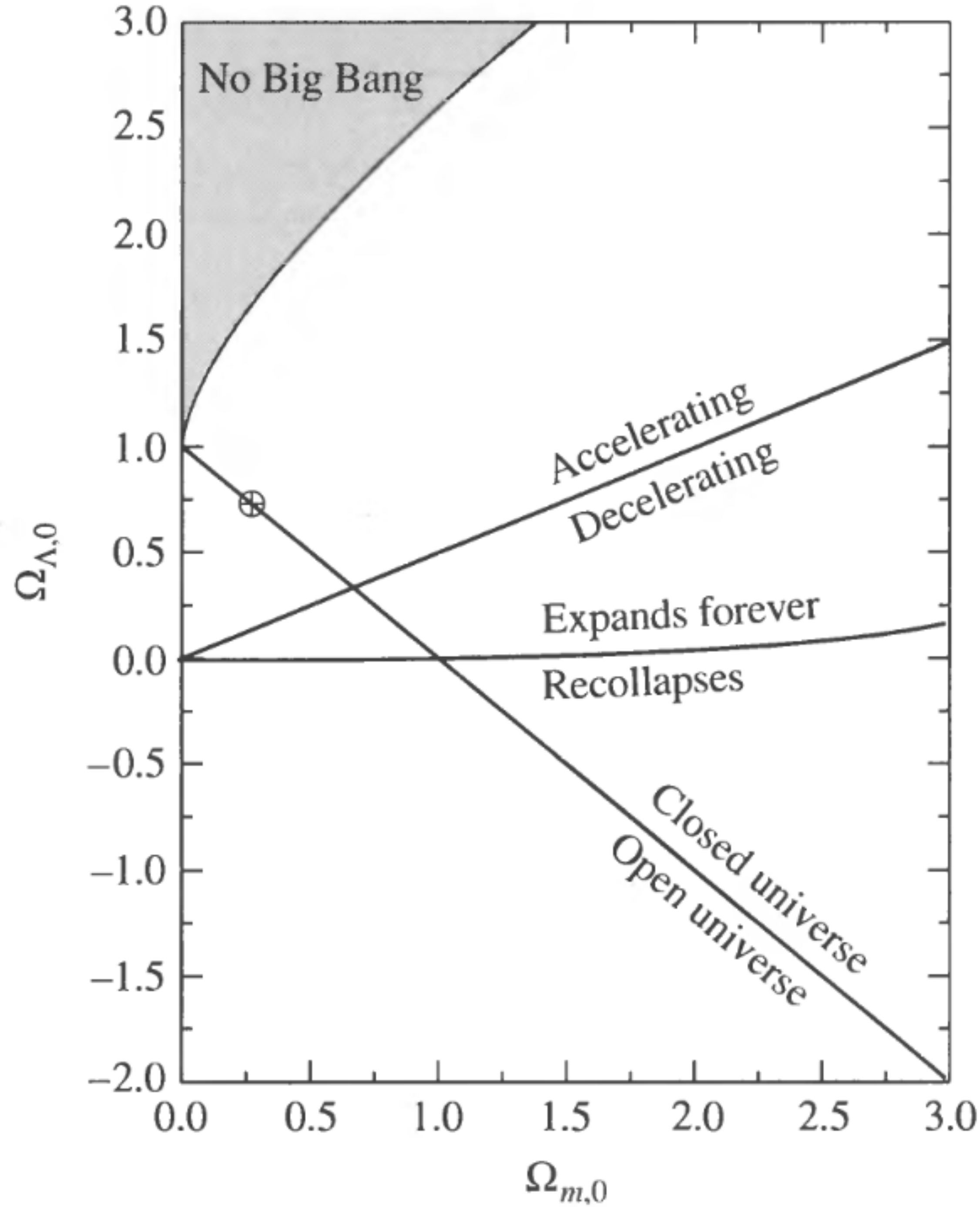
Does The Expansion Rate Change With Time?



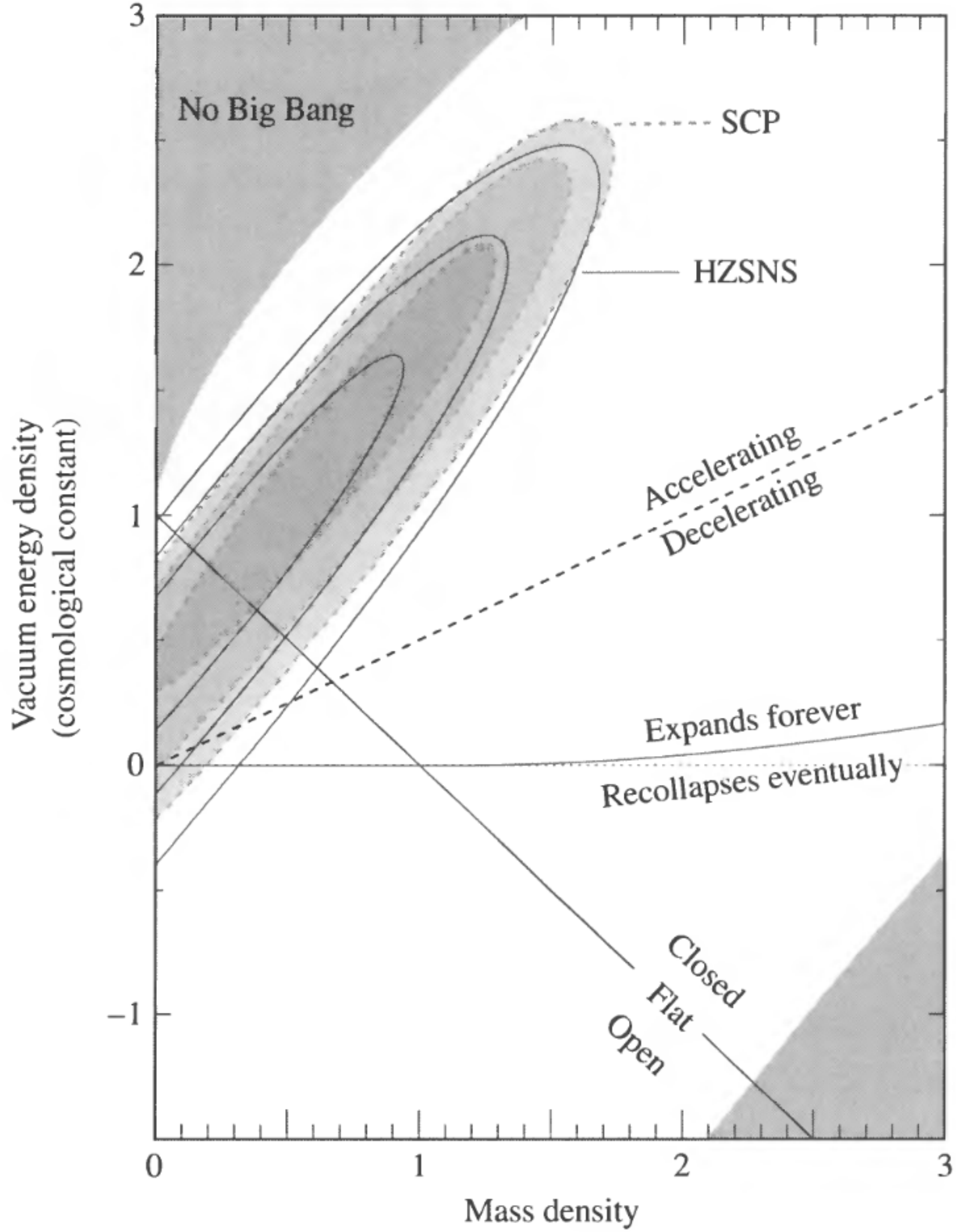
The data from SN Ia follow the blue curve and show that the Universe was expanding at a slower rate in the past. The expansion of the Universe is now speeding up!

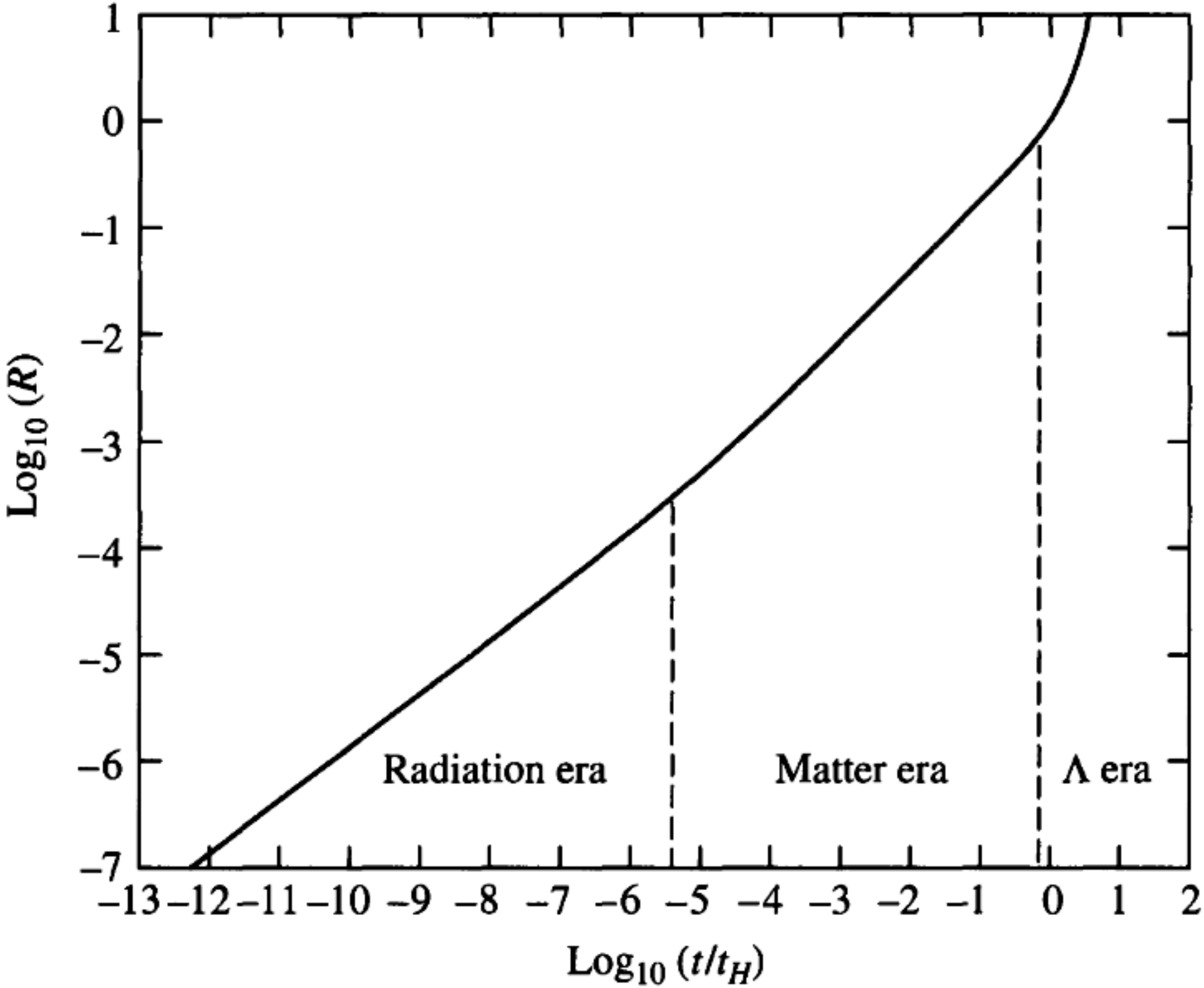
Does The Expansion Rate Change With Time?

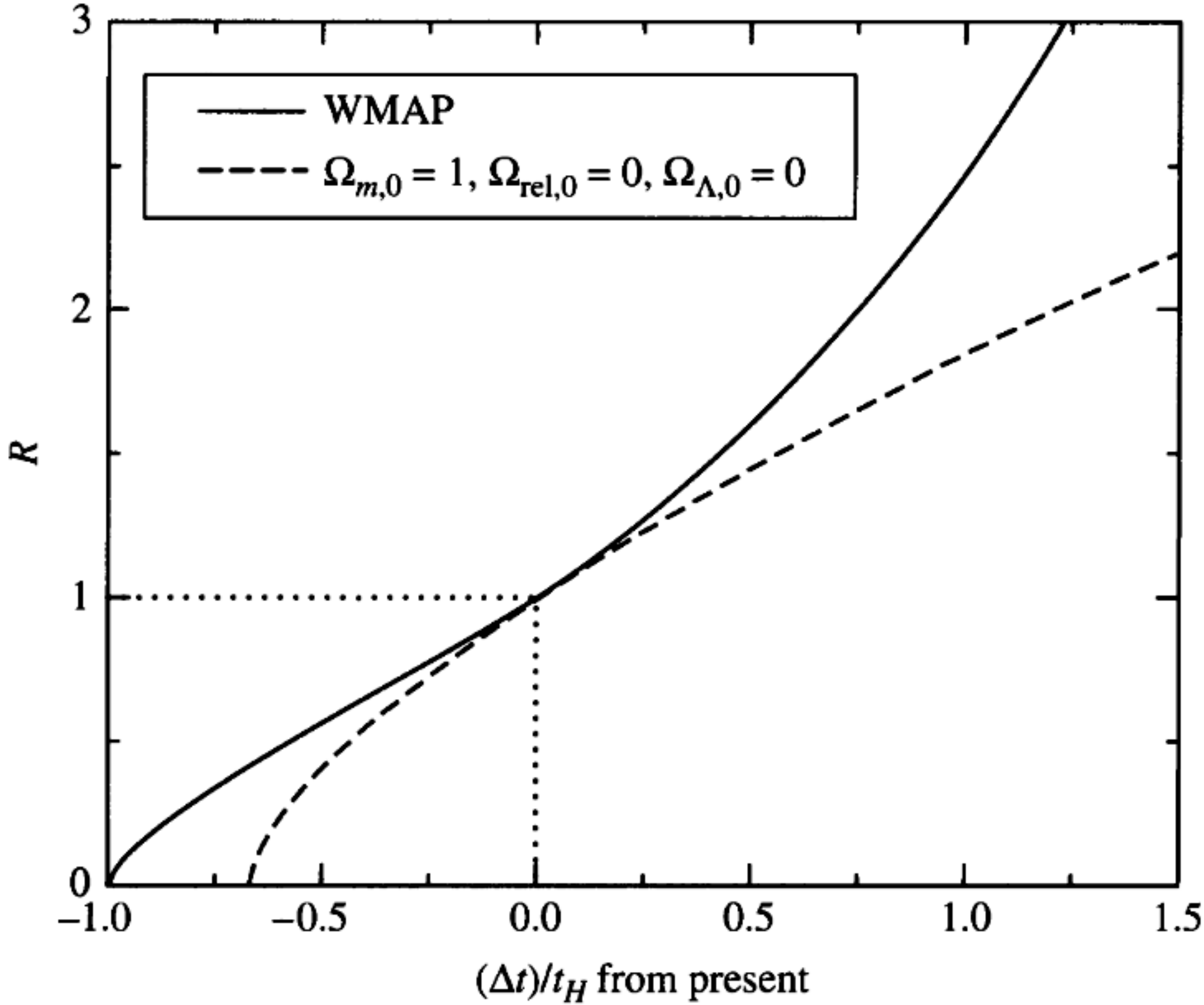




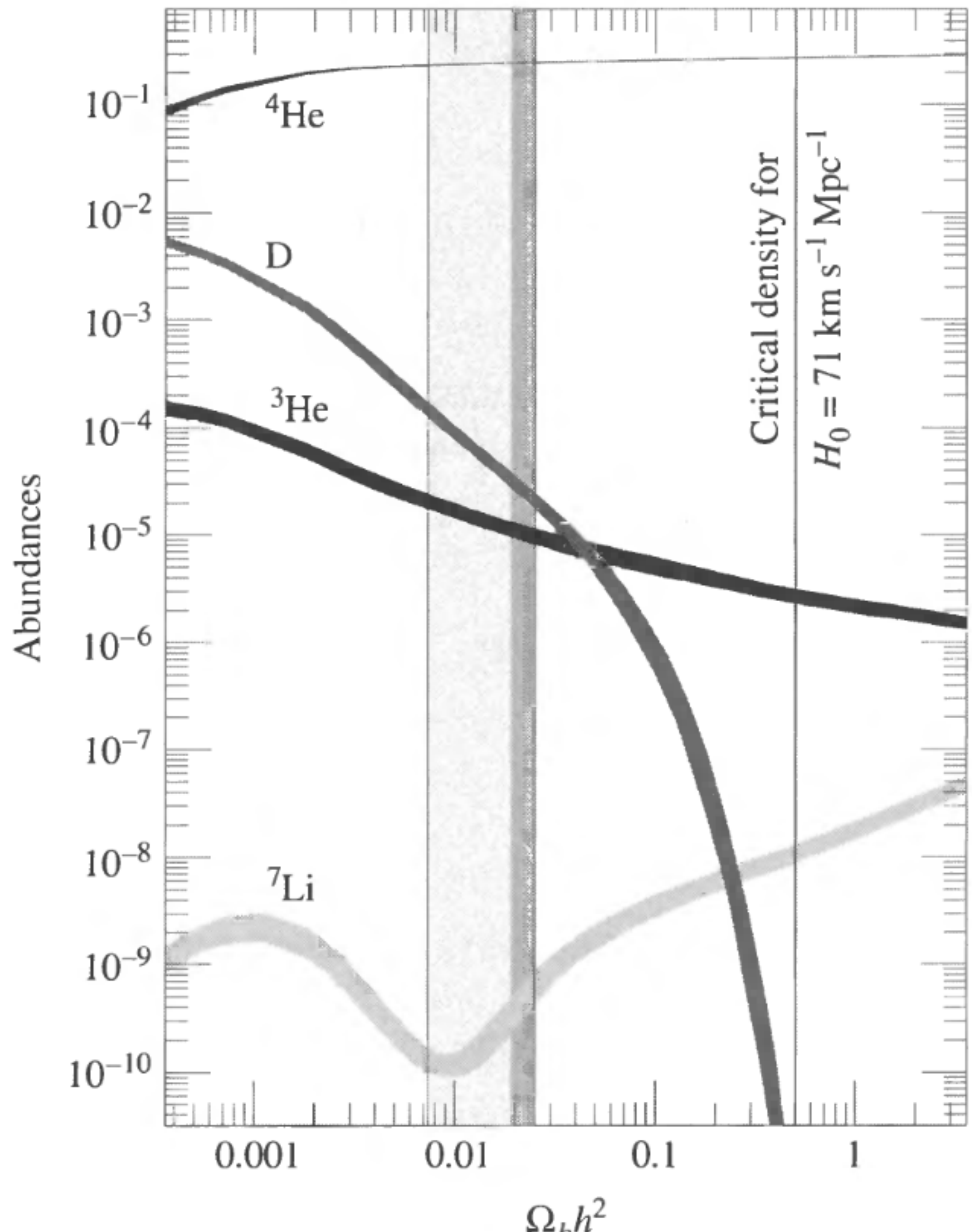
No Big Bang
Accelerating
Decelerating
Expands forever
Recollapses
Closed universe
Open universe
$\Omega_{\Lambda,0}$
$\Omega_{m,0}$
3.0
2.5
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
−2.0
0.0
0.5
1.0
1.5
2.0
2.5
3.0


No Big Bang
SCP
HZSNS
Accelerating
Decelerating
Expands forever
Recollapses eventually
Closed
Flat
Open
Vacuum energy density
(cosmological constant)
Mass density
3
2
1
0
−1
0
1
2
3


1
0
−1
−2
−3
−4
−5
−6
−7
$\mathrm{Log}_{10}(R)$
−13 −12 −11 −10 −9 −8 −7 −6 −5 −4 −3 −2 −1 0 1 2
$\mathrm{Log}_{10}(t/t_H)$
Radiation era
Matter era
Λ era



WMAP
$\Omega_{m,0} = 1$, $\Omega_{rel,0} = 0$, $\Omega_{\Lambda,0} = 0$
R
0
1
2
3
−1.0
−0.5
0.0
0.5
1.0
1.5
$(\Delta t)/t_H$ from present



10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
Abundances
^{4}He
D
^{3}He
^{7}Li
Critical density for
$H_0 = 71$ km s^{-1} Mpc^{-1}
0.001
0.01
0.1
1
$\Omega_b h^2$

Method	M/L ($M_\odot/L_\odot$)	Ω_0
Solar neighborhood	3	$0.002h^{-1}$
Elliptical galaxy cores	$12h$	0.007
Local escape speed	30	$0.018h^{-1}$
Satellite galaxies	30	$0.018h^{-1}$
Magellanic Stream	> 80	$> 0.05h^{-1}$
X-ray halo of M87	> 750	$> 0.46h^{-1}$
Local Group timing	100	$0.06h^{-1}$
Groups of galaxies	$260h$	0.16
Clusters of galaxies	$400h$	0.25
Gravitational lenses	—	$0.1 - 0.3$
Big Bang nucleosynthesis	—	0.065 ± 0.045