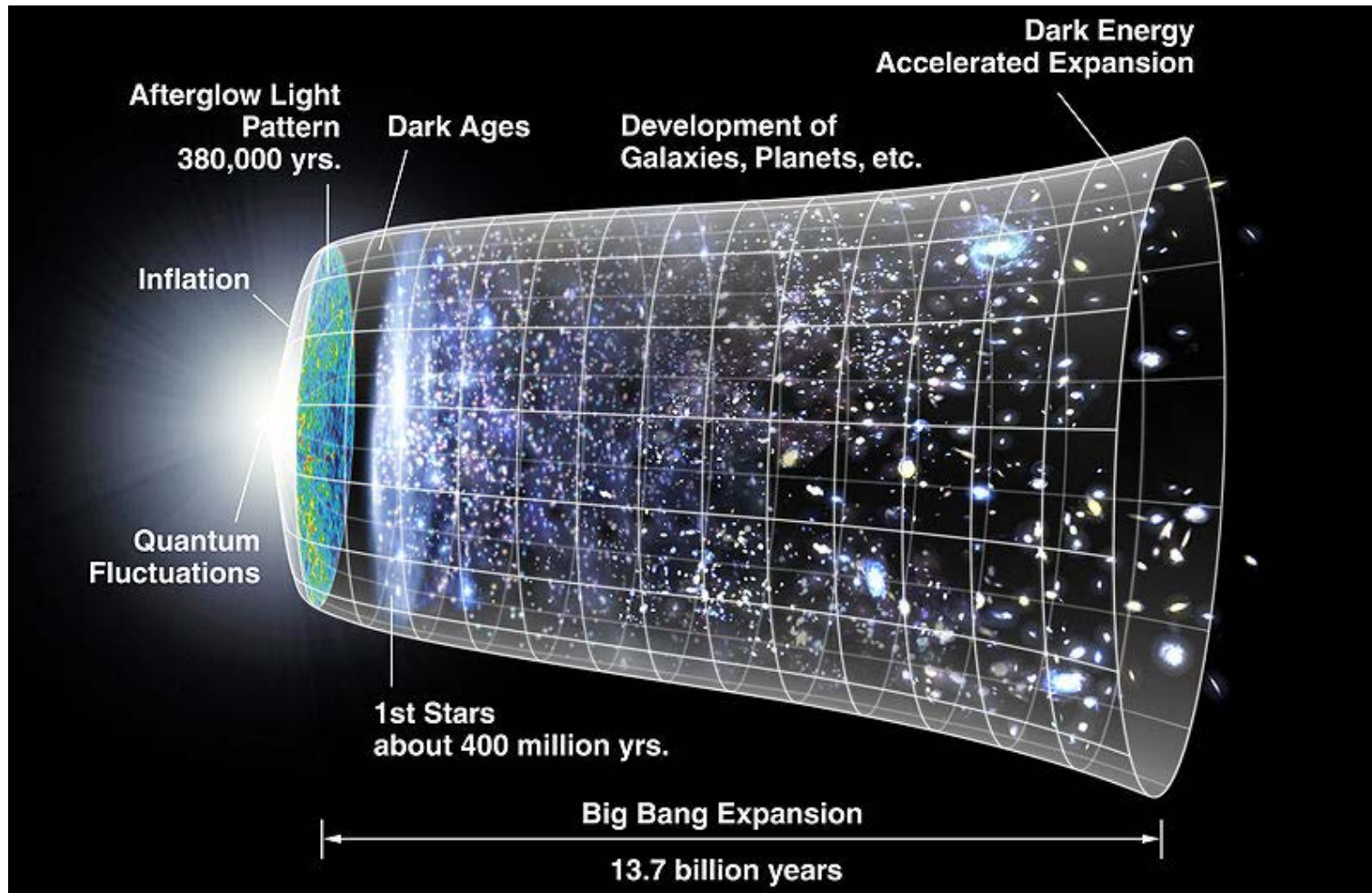


Cosmology



Cosmology



Olders' Paradox. An infinite static Universe would imply that any line of sight would eventually hit a star and the night sky should be bright!

Einstein's Biggest Blunder?

Einstein's initial formulation of General Relativity implied an **expanding Universe**.

The prevailing theory at the time, however, was that the Universe was static and infinite. Einstein included a constant (Λ) in his equations to make his theory predict a non expanding and static Universe.

Einstein later stated that the inclusion of this constant was the **greatest blunder of his life**.



Hubble showed with observations that the Universe was expanding. Later Einstein visited Hubble and congratulated him on this remarkable discovery.

Hubble's Law and the Expanding Universe

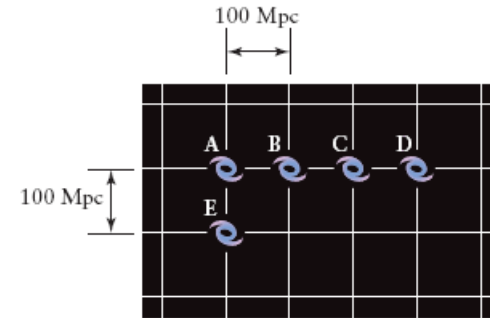
The **Hubble law** states that the recession velocity of a galaxy is proportional to its distance from Earth.

$$v = H_0 d$$

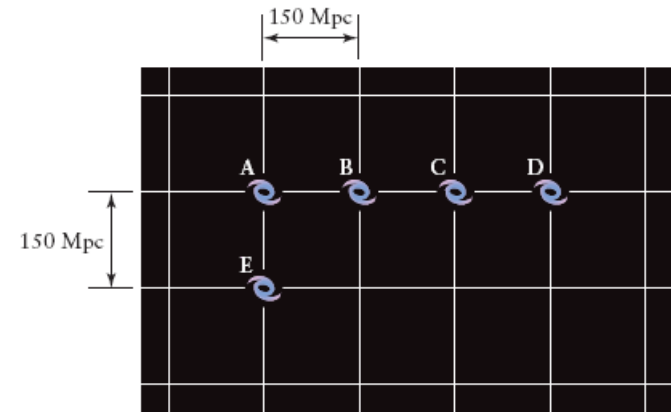
This law applies to any object participating in the expansion of the Universe and for an observer at any location in the Universe.

The currently accepted value of the Hubble constant is :

$$H_0 = (68 \pm 1) \text{ km/s/Mpc}$$



(a) Five galaxies spaced 100 Mpc apart



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

	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

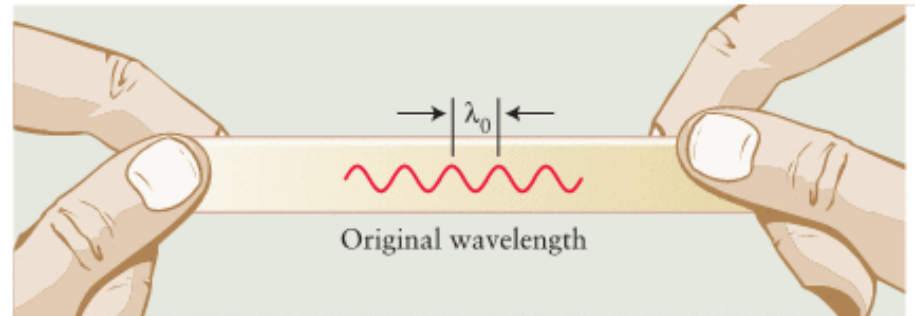
A redshift caused by the expansion of the universe is called cosmological redshift.

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

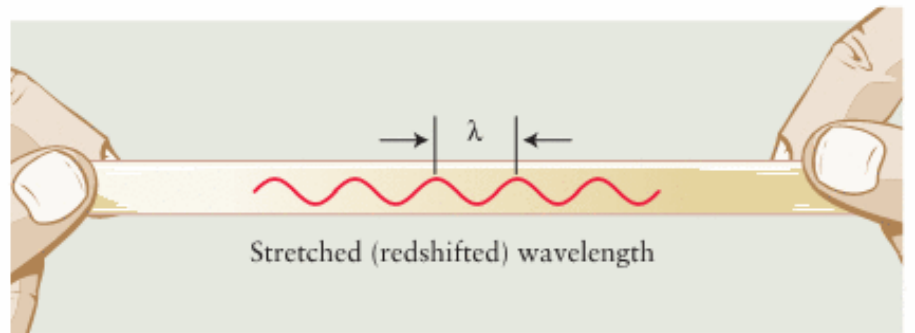
$$z = (\lambda_{\text{obs}} - \lambda_0) / \lambda_0 \rightarrow \lambda_{\text{obs}} / \lambda_0 = (1+z)$$

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 ...



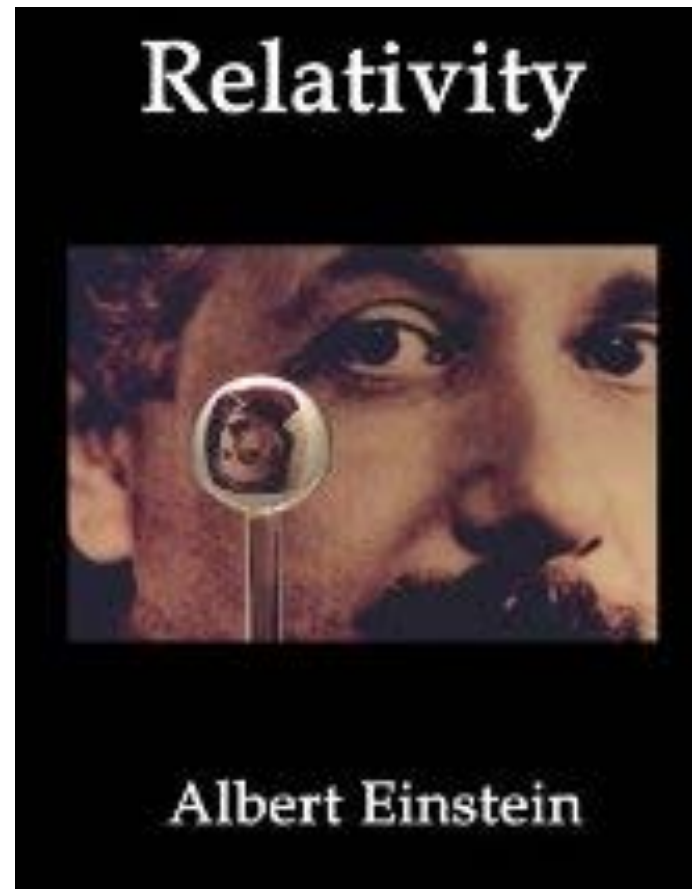
(b) ... increases in wavelength as the rubber band is stretched.

Cosmological Time Dilation

$$\Delta t_{emit} = \frac{\Delta t_{obs}}{1+z},$$

where Δt_{obs} is a time interval in the observers frame and

Δt_{emit} is a time interval in the emitted frame.



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 Hubble 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

Cosmological Principle

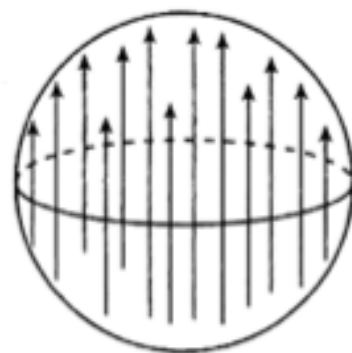
Cosmological Principle: Observers on Earth do not occupy any special location in the Universe. Two consequences of the cosmological principle are homogeneity and isotropy.

Homogeneous Universe:

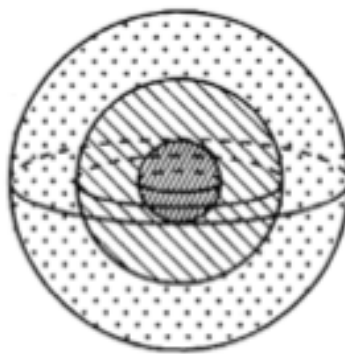
The same observational evidence is available from any part of the Universe. It doesn't matter where you are located in the Universe.

Isotropic:

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

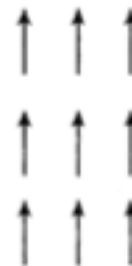


Homogeneous
Not isotropic

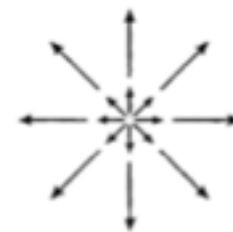


Isotropic
Not homogeneous

(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.

The Big Bang

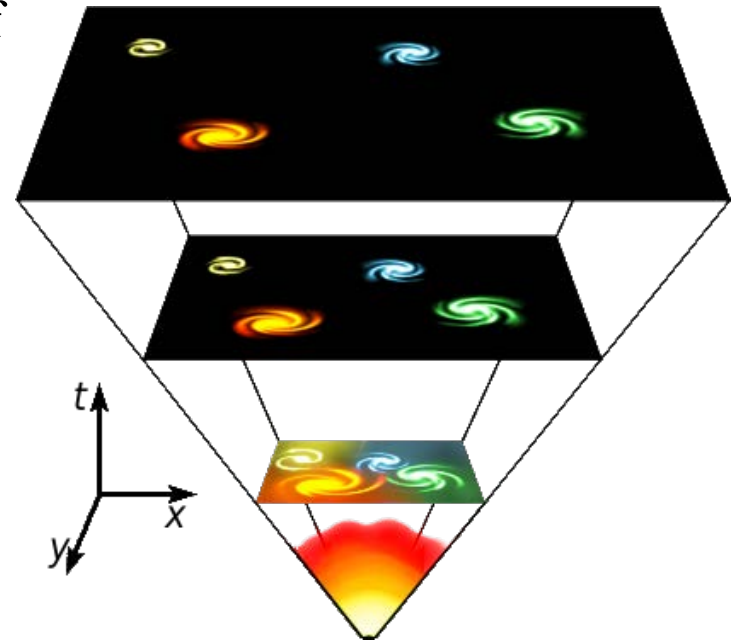
The expansion of the Universe is an expansion of space. As we go back in time we find the density of the Universe increasing. About 13.8 billion years ago all matter was concentrated in a singularity of infinite density. Space and time were created 13.8 billion years ago in an event that is called the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

How long ago did the Big Bang take place?

$$T_0 = d/v = d / H_0 d = 1 / H_0 = 1 / 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$$

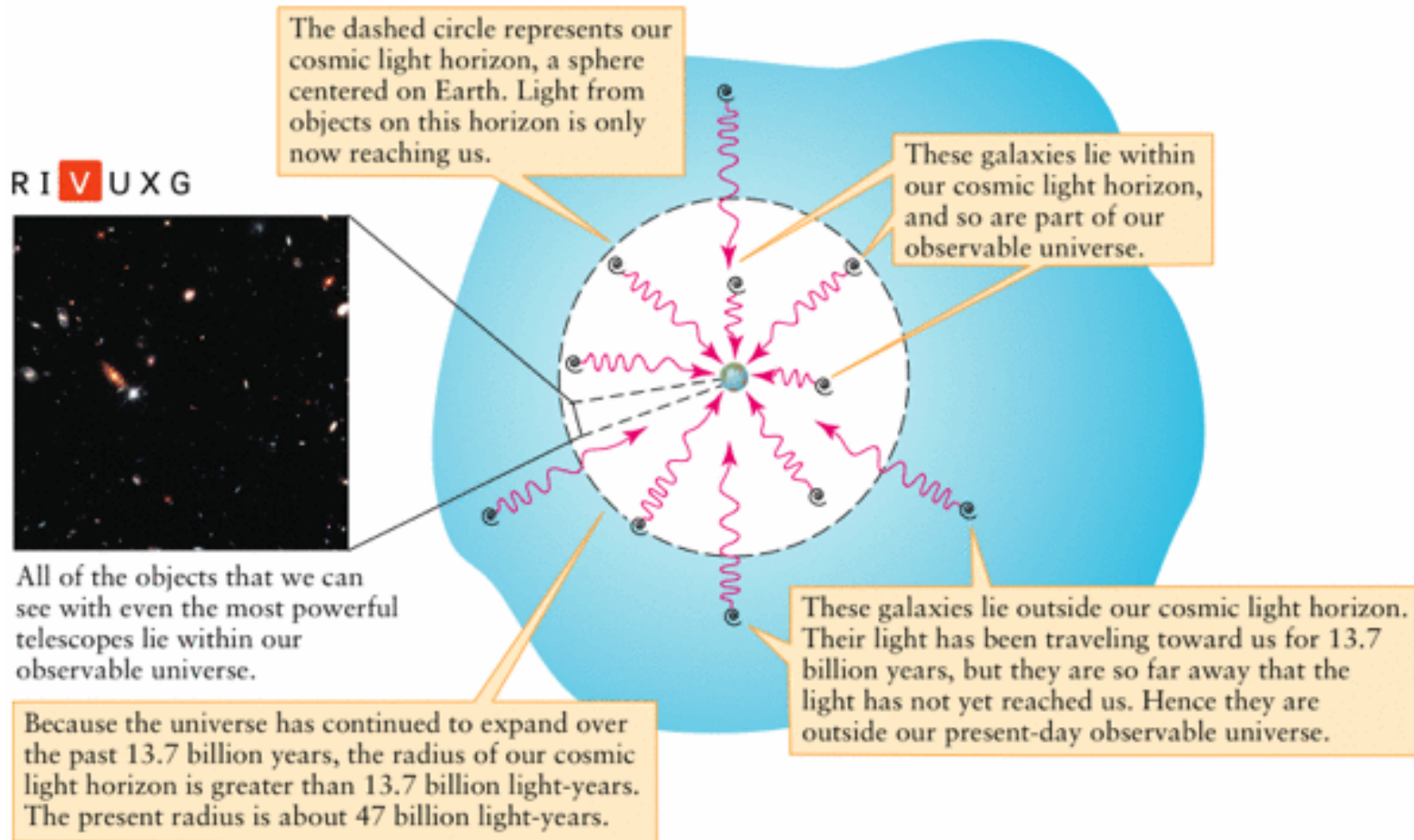
→ $T_0 \sim 14$ billion years (1 Mpc = 3.09×10^{19} km)

We have assumed that the Universe expands at a constant rate which is not true. Doing the calculations assuming a Λ CDM 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.

The Observable Universe



Resolving Olders' Paradox

Olders' Paradox: An infinite static Universe would imply that any line of sight would eventually hit a star and the night sky should be bright!

Resolution:

1. The observable universe is not static and infinite. In our observable universe stars are distributed sparsely enough that one does not expect to find stars along every line of sight.
2. Because of the redshift effect the light from very distant stars will be redshifted out of the visible range.

Planck Time

Quantum mechanical effects become important at very small scales. Some theories indicate that the structure of space-time is dominated by quantum mechanical effects at lengths less than the **Planck length** which is:

$$l_P = \sqrt{\frac{\hbar G}{c^3}} = 1.616 \times 10^{-35} \text{ m}$$

The time light takes to travel this distance is the **Planck time** $= 5.39 \times 10^{-44} \text{ s}$.

Understanding the universe before a Planck time would require a theory that combines both gravity and quantum mechanics which does not exist at the moment ...

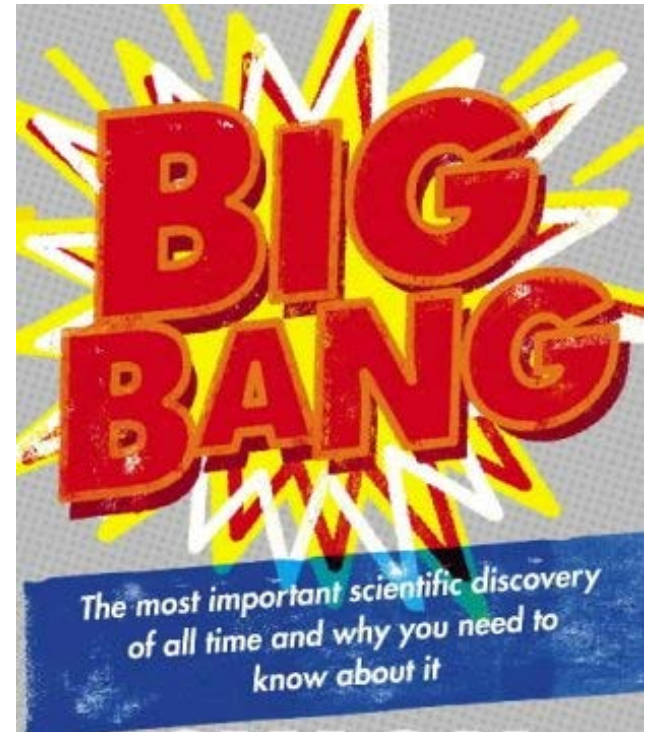
Evidence of a Hot Big Bang

Calculations of the **amount of Helium expected** to have been produced a few minutes **just after the Big Bang agrees well with** the amounts of **He 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.

As the universe expanded the plasma of protons and electrons cooled. When it reached $T \sim 3000 \text{ K}$ the electrons combined with protons to form neutral H.

A prediction of the Big Bang theory is that about 380,000 years after the beginning of our Universe photons were able to escape and travel freely through space.



Radiation of the Universe

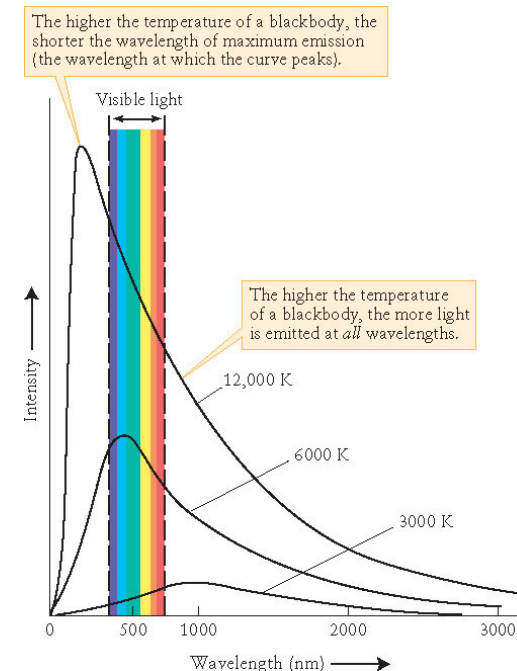
Photons are massless particles that travel across the Universe at the speed of light and constitute a form of radiation. Radiation from the hot plasma produced just after the Big Bang has a **blackbody spectrum**.

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

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

$\lambda_{\max}$ = 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 $T_{\text{obs}} = 2.725 \text{ K}$

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!

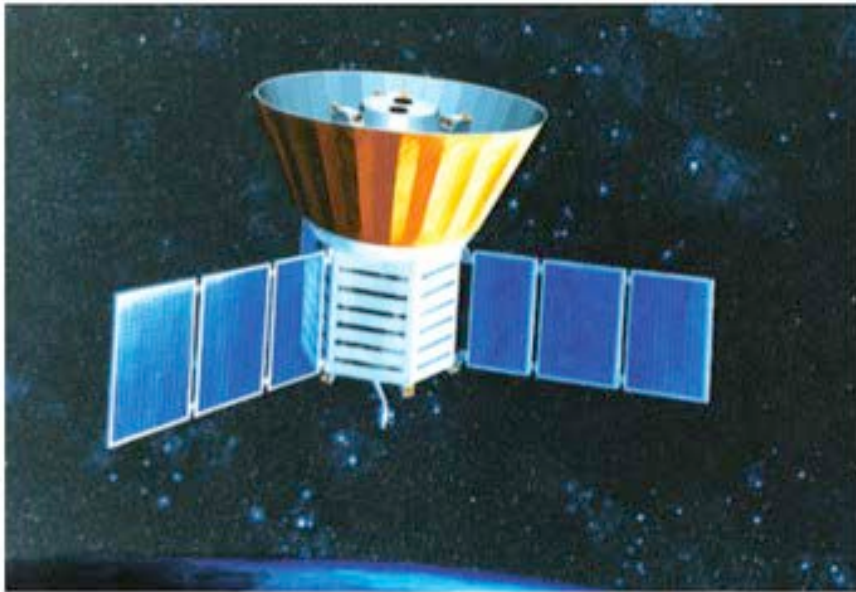
Since the temperature decreased by a factor of $3,000 \text{ K} / 2.725 \text{ K} = 1100$ the wavelength increased by 1100.

The redshift of this emitted radiation is about $z \sim 1100$

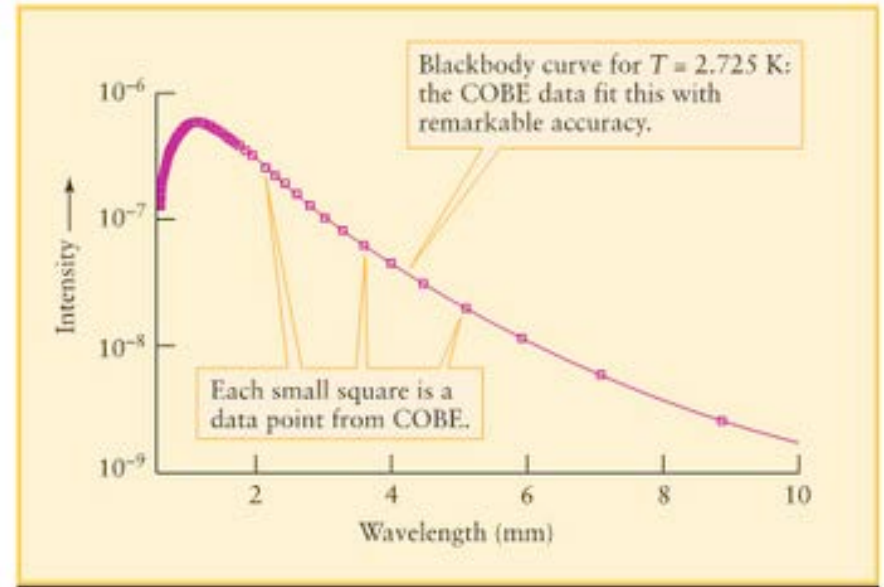


Penzias and Wilson in front of the Horn Antenna.

Evidence of a Hot Big Bang



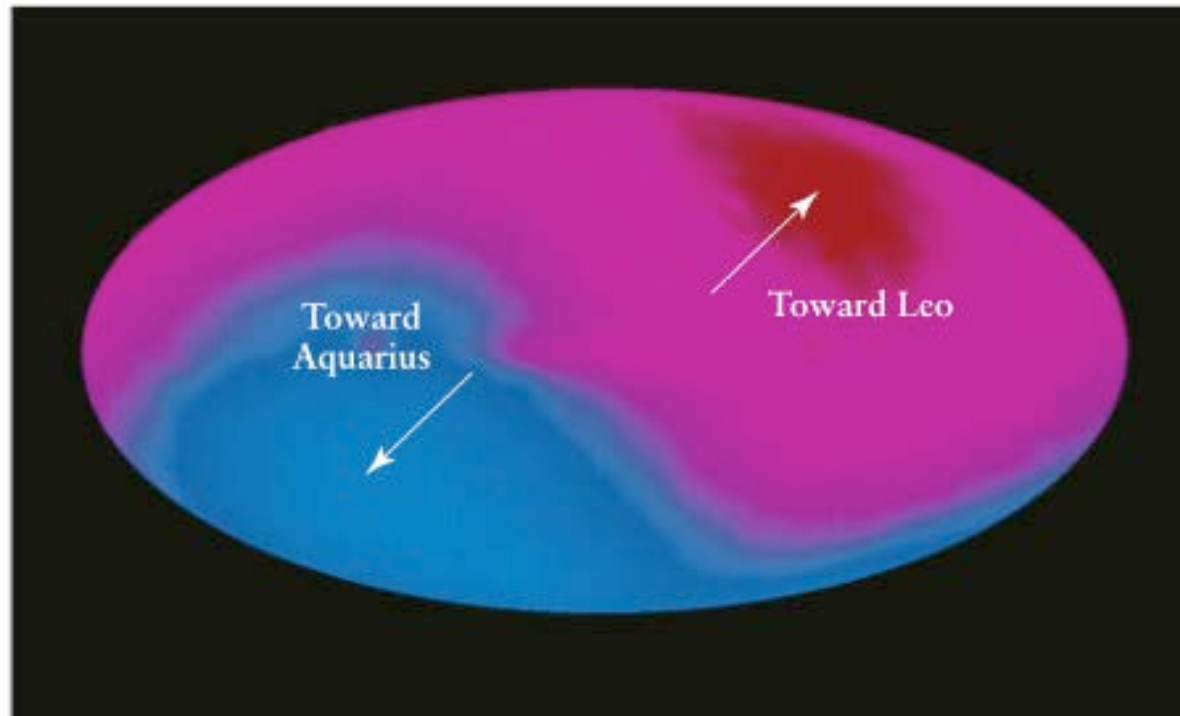
(a) The COBE spacecraft



(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.

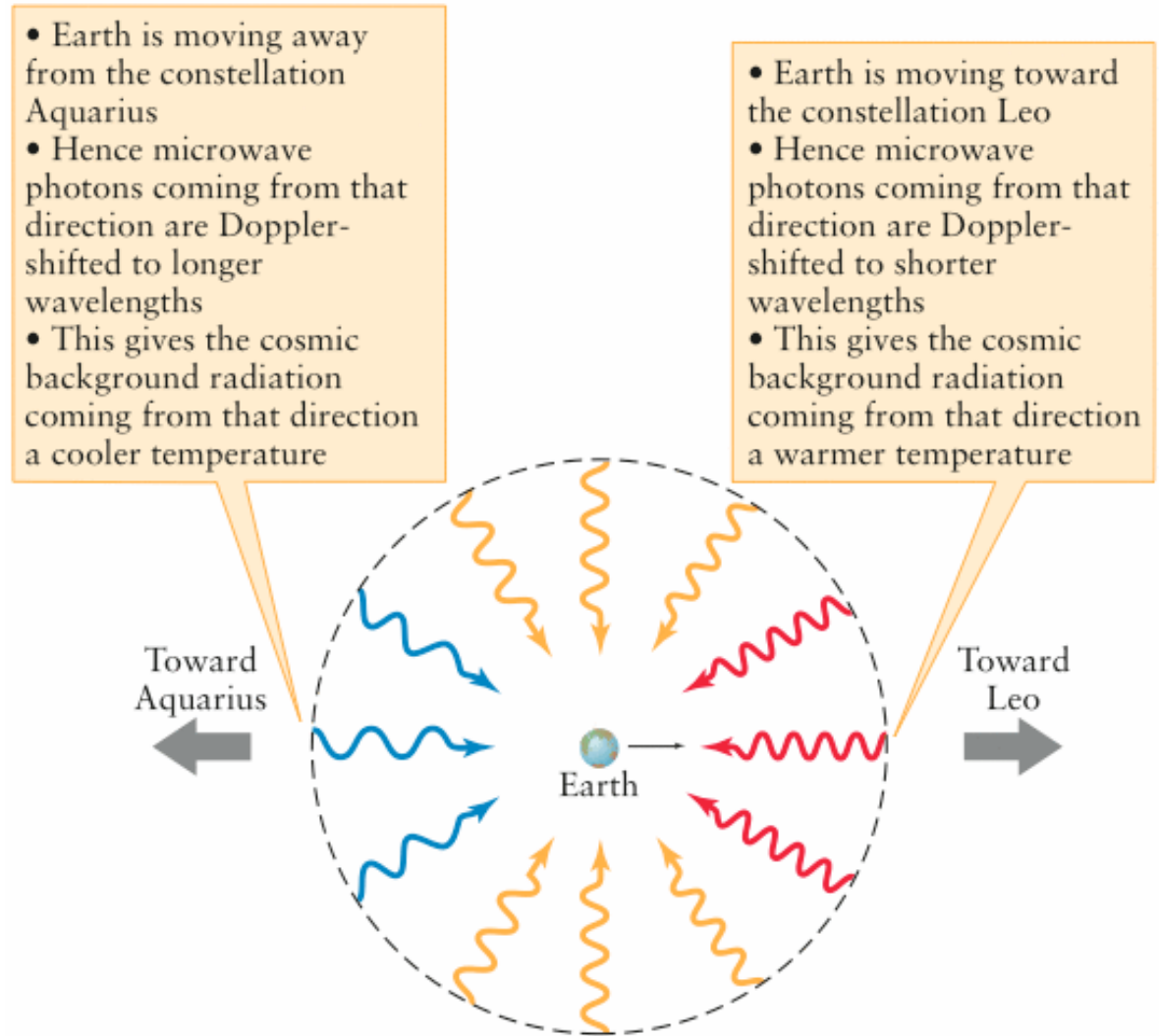
Evidence of a Hot Big Bang



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 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.



Density of Radiation and Matter of the Universe

From Einstein's famous equation $E = mc^2$ one can associate an energy to a photon that is equal to some **equivalent mass** times the speed of light squared. The mass density ρ of the radiation in some volume is just the ratio of this equivalent mass to the volume $\rho = (\text{equivalent mass})/\text{Volume}$.

1. Density of Radiation

We can define a **mass density of radiation** of the photons :

$\rho_{\text{rad}} = 4\sigma T^4/c^3$, where T is the temperature of the blackbody radiation and σ is the Stefan-Boltzmann constant.

$$\rho_{\text{rad}} = 4.6 \times 10^{-31} \text{ kg/m}^3 \text{ (density of radiation **today**)}$$

2. Density of Matter

Observations of clusters of galaxies provide the total mass (luminous and dark matter in a volume) today.

$$\rho_{\text{mass}} = 2.4 \times 10^{-27} \text{ kg/m}^3 \text{ (all luminous and dark matter **today**)}$$

$$\rho_{\text{mass}} = 4.2 \times 10^{-28} \text{ kg/m}^3 \text{ (all luminous matter **today**)}$$

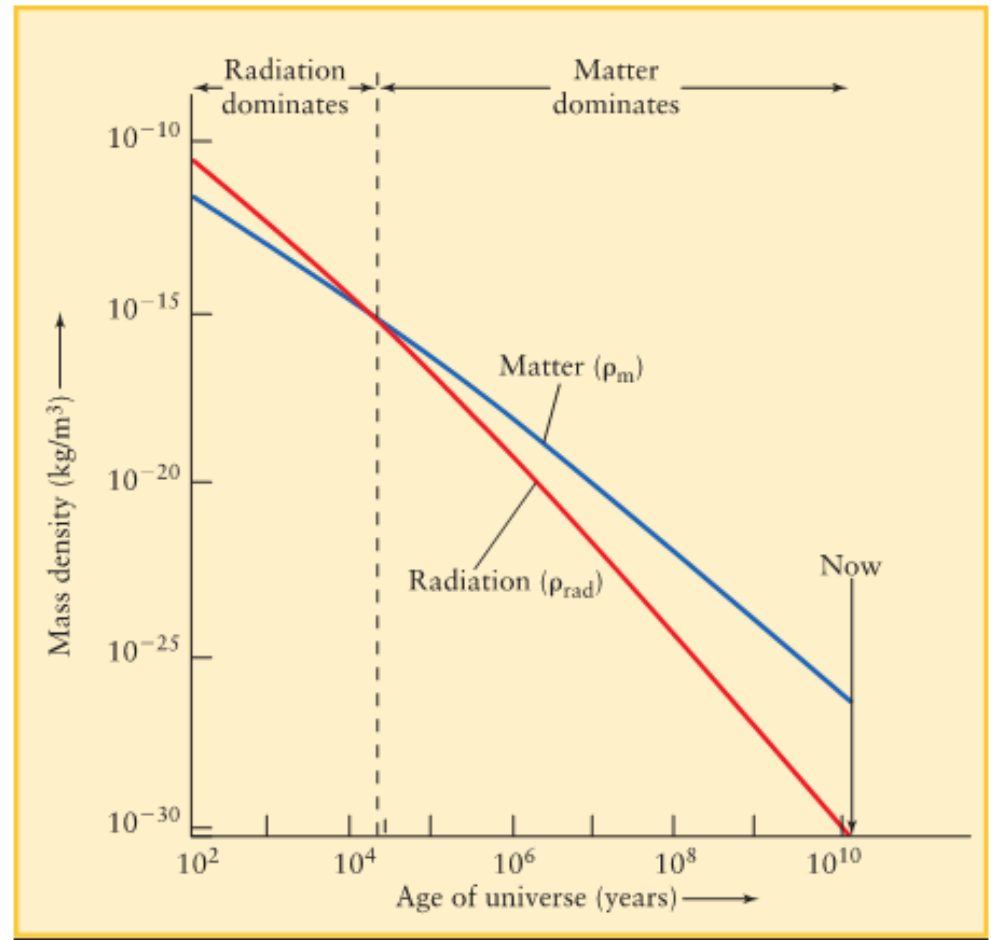
Radiation and Matter Density of the Universe

The density of all baryonic matter is larger by a factor of 1000 than the density of radiation at the current time.

$\rho_{\text{mass}} > \rho_{\text{rad}}$, matter dominated

$\rho_{\text{rad}} > \rho_{\text{mass}}$, radiation dominated

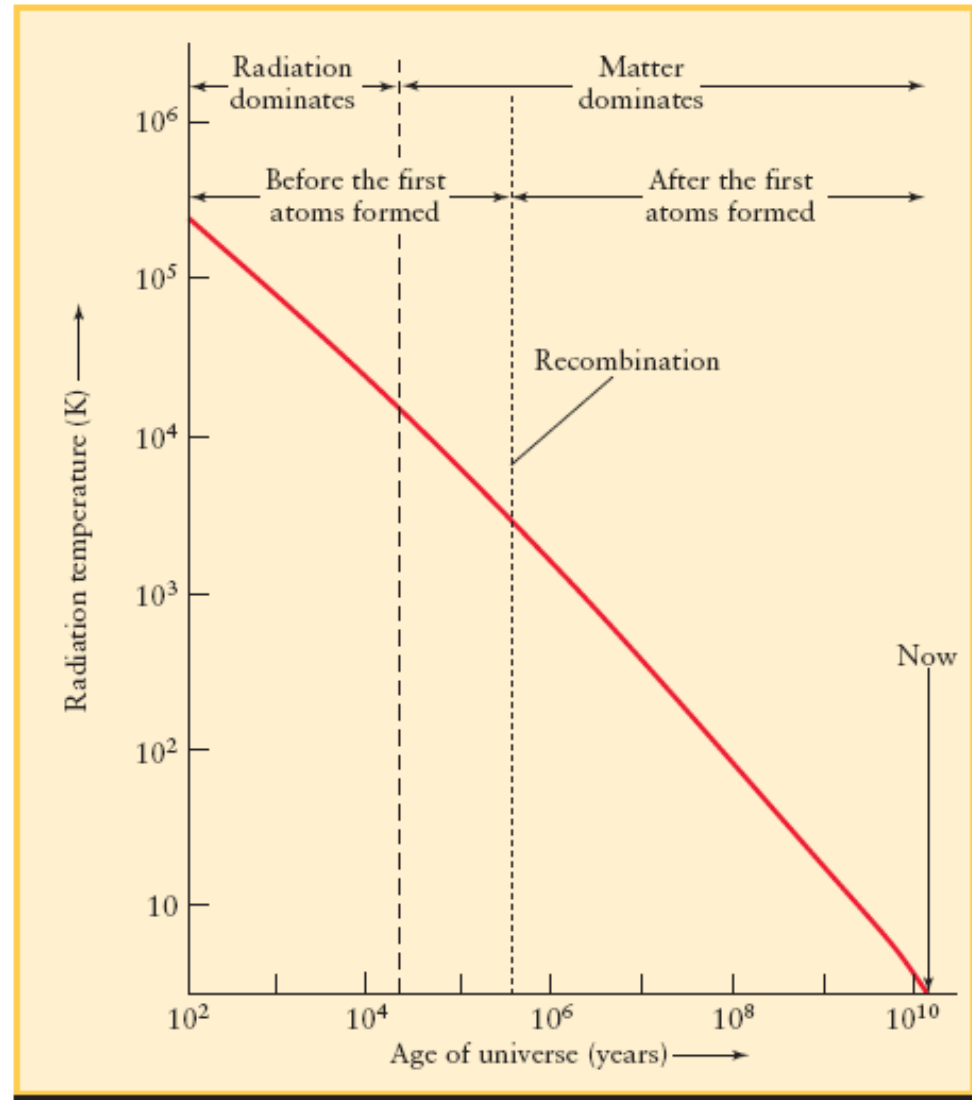
Today the cosmic background spectrum peaks at about 1mm but when $\rho_{\text{mass}} = \rho_{\text{rad}}$ at $z = 5200$ it peaked at $1\text{mm}/(1+z) = 160\text{ nm}$.



Radiation and Matter Density of the Universe

Today the cosmic background has a temperature of $T = 2.725 \text{ K}$ but when $\rho_{\text{mass}} = \rho_{\text{rad}}$ it had a temperature of $2.725 \text{ K} \cdot (1+z) = (1+5200) = 14,170 \text{ K}$.

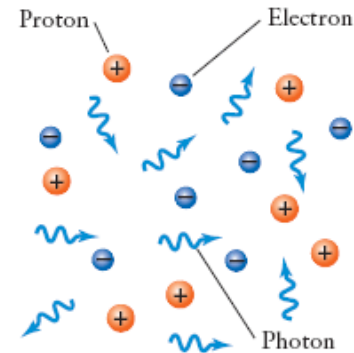
This is because the temperature of a blackbody is inversely proportional to λ . When λ was smaller by a factor of $(1+z) = (1 + 5200)$ than today about 24,000 years after the Big Bang the temperature of the cosmic background was larger by a factor of $(1+z) = (1+5200)$.



Recombination Era

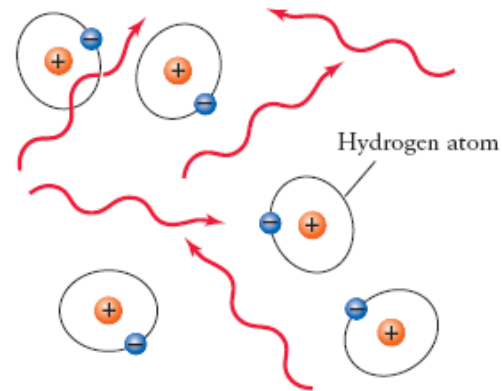
Shortly after the Big Bang the Universe was filled with photons, electrons, protons and other elementary particles. The temperature of this **plasma** decreased as the Universe expanded. Photons up to this time would scatter vigorously with electrons and be trapped within this plasma.

When the temperature got to about 3,000K the electrons were able to combine with the protons and form stable hydrogen atoms for the first time. These atoms do not absorb low-energy photons, and so photons were able to escape and travel freely through space. This event occurred ~380,000 years after the Big Bang and is called the **era of recombination**.



(a) Before recombination:

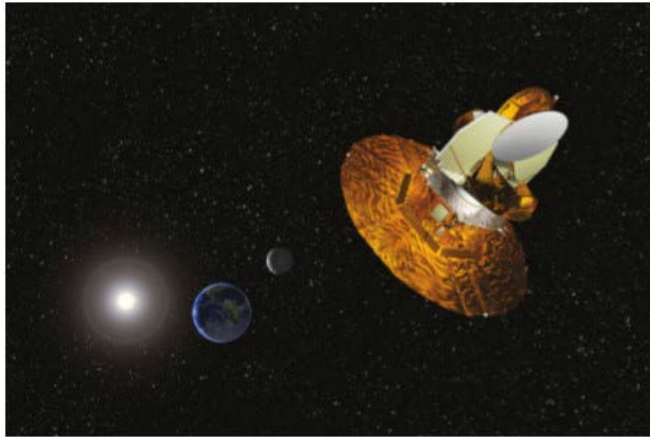
- Temperatures were so high that electrons and protons could not combine to form hydrogen atoms.
- The universe was opaque: Photons underwent frequent collisions with electrons.
- Matter and radiation were at the same temperature.



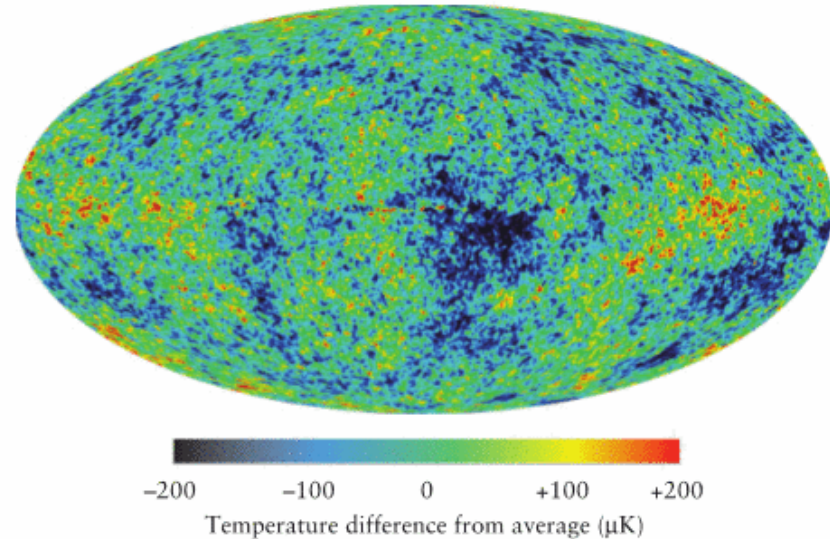
(b) After recombination:

- 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.

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 are 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 $\sim 380,000$ years after the Big Bang.

The Curvature of the Universe

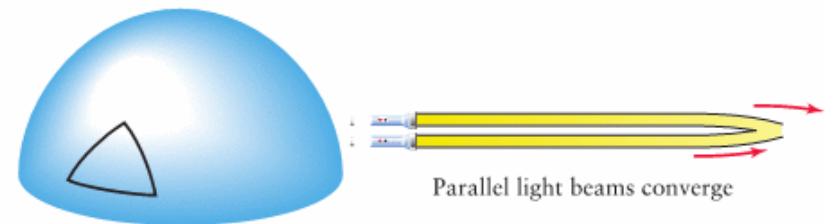
The **Universe curves** according to General Relativity **in the presence of any form of matter or energy**. The curvature of the Universe therefore depends on the **combined average mass density ρ_0** of all forms of matter and energy.

Imagine 2 light beams that start off parallel.

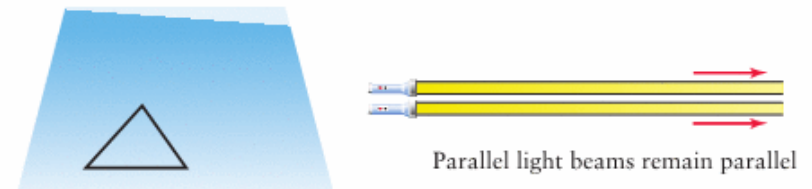
1. If the beams converge we say the Universe has positive curvature, it is closed and space is spherical.

2. If the beams remain parallel the Universe has zero curvature and space is flat.

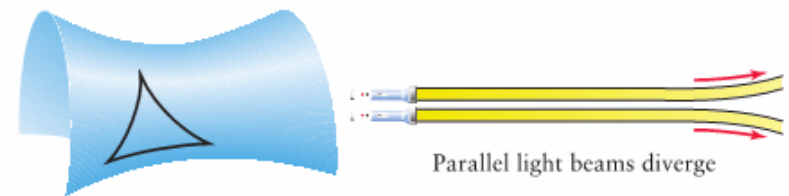
3. If the beams diverge the Universe has negative curvature, is open and space is hyperbolic.



(a) Spherical space $\rho_0 > \rho_c$, $\Omega_0 > 1$



(b) Flat space $\rho_0 = \rho_c$, $\Omega_0 = 1$



(c) Hyperbolic space $\rho_0 < \rho_c$, $\Omega_0 < 1$

The Curvature of the Universe

The curvature of the Universe is determined by the value of the **combined mass density** ρ_0 compared to the **critical mass density** ρ_c .

When:

$\rho_0 > \rho_c$ Spherical Space

$\rho_0 = \rho_c$ Flat Space

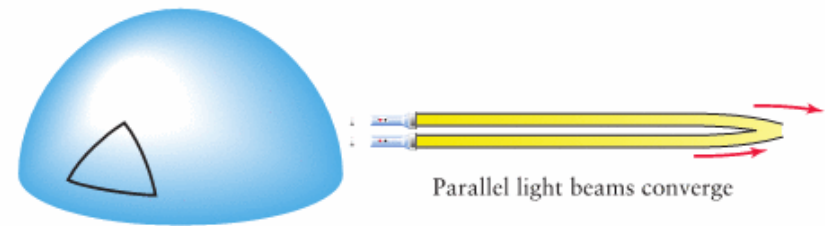
$\rho_0 < \rho_c$ Hyperbolic Space

Where the critical mass density is:

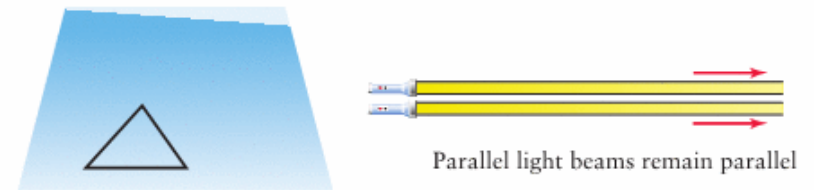
$$\rho_c = \frac{3H_0^2}{8\pi G}$$

ρ_c = critical density of the Universe

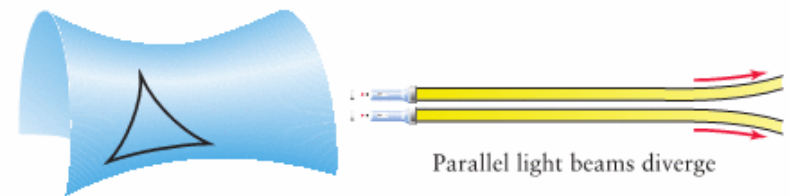
For $H_0 = 68 \text{ km/s/Mpc}$ $\rho_c = 1.0 \times 10^{-26} \text{ kg/m}^3$



(a) Spherical space $\rho_0 > \rho_c$, $\Omega_0 > 1$



(b) Flat space $\rho_0 = \rho_c$, $\Omega_0 = 1$



(c) Hyperbolic space $\rho_0 < \rho_c$, $\Omega_0 < 1$

Curvature of Universe

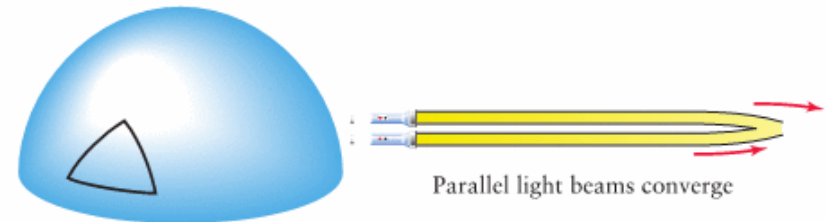
The **Density Parameter of the Universe Ω_0** is defined as the ratio of the combined mass density ρ_0 to the critical mass density ρ_c :

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

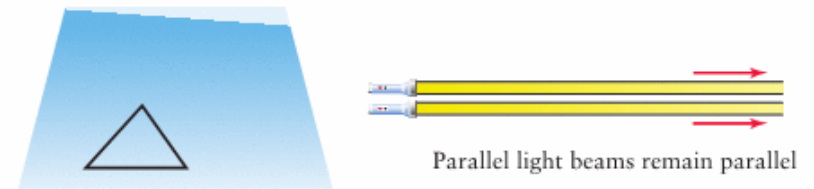
Closed Universe: $\rho_0 > \rho_c \rightarrow \Omega_0 > 1$

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

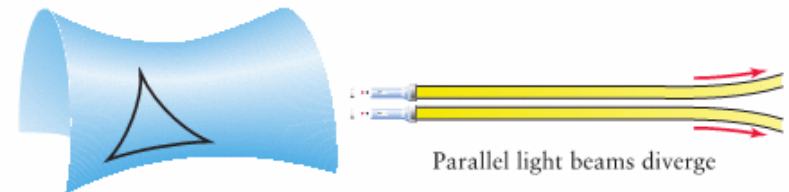
Open Universe: $\rho_0 < \rho_c \rightarrow \Omega_0 < 1$



(a) Spherical space $\rho_0 > \rho_c$, $\Omega_0 > 1$

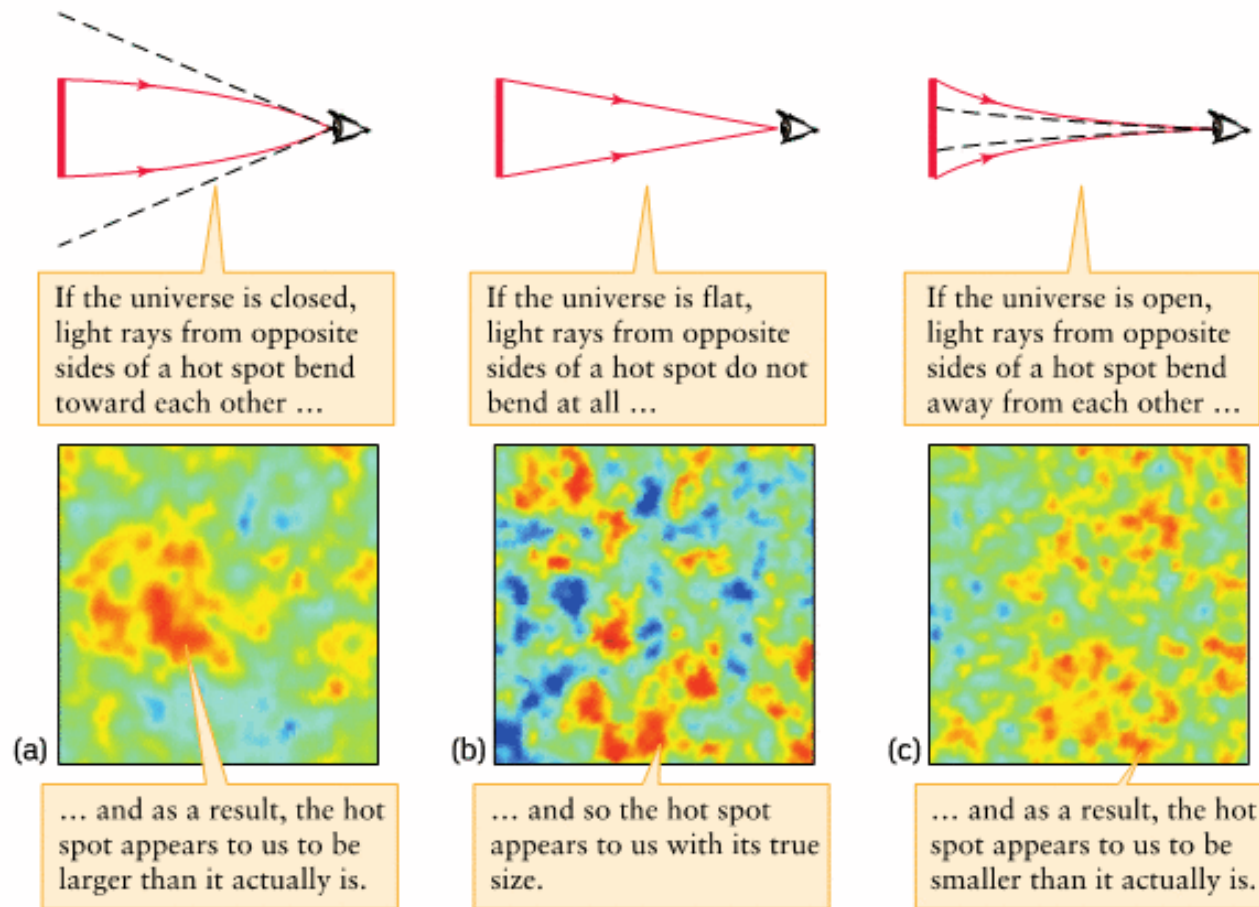


(b) Flat space $\rho_0 = \rho_c$, $\Omega_0 = 1$



(c) Hyperbolic space $\rho_0 < \rho_c$, $\Omega_0 < 1$

Measuring the Curvature of the Universe



The method relies on finding a distant object with a known size and estimating how its angular size would appear in an open, flat and closed Universe. This can be done by looking at hot spots in the CMB. For a flat Universe the angular size of a hot spot is expected to be about 1° and that's what we find!

Dark Energy

Density Parameter: $\Omega_0 = \rho_0/\rho_c = 1$ (from CMB hot spots)

Matter Density Parameter : $\Omega_m = \rho_m/\rho_c = 2.4 \times 10^{-27}/1 \times 10^{-26} = 0.24$ (from clusters of galaxies)

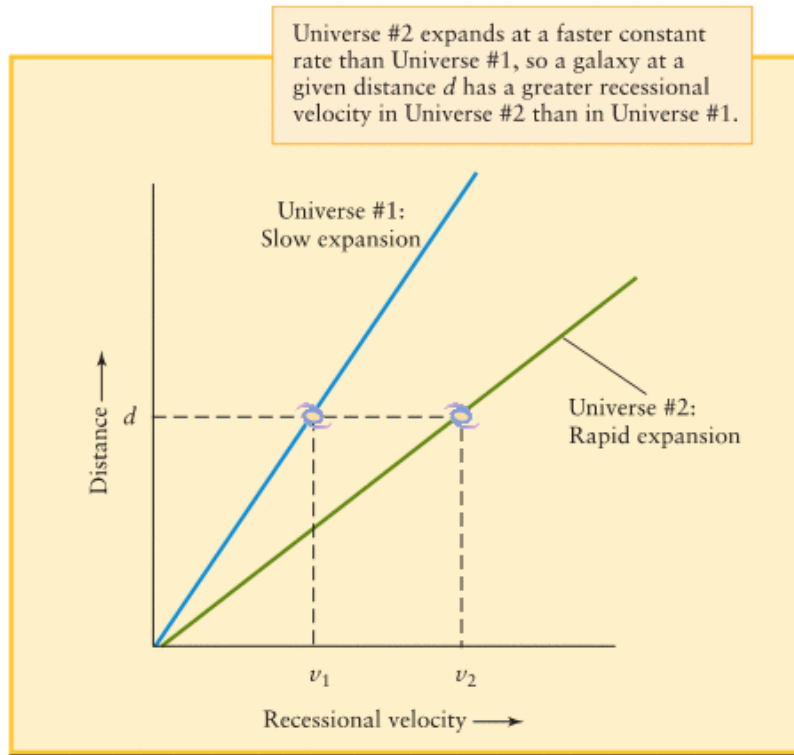
By taking into account all the mass (visible and dark) and radiation in the Universe we obtain a Density Parameter of 0.24 that is significantly less than 1. This means that there must be some additional energy source in the Universe to make up for a density parameter equal to 1. This mysterious energy source is called **Dark Energy**. With this dark energy we associate an average mass density of dark energy of ρ_Λ and a dark energy density parameter Ω_Λ .

Dark Energy Density Parameter : $\Omega_\Lambda = \rho_\Lambda/\rho_c$

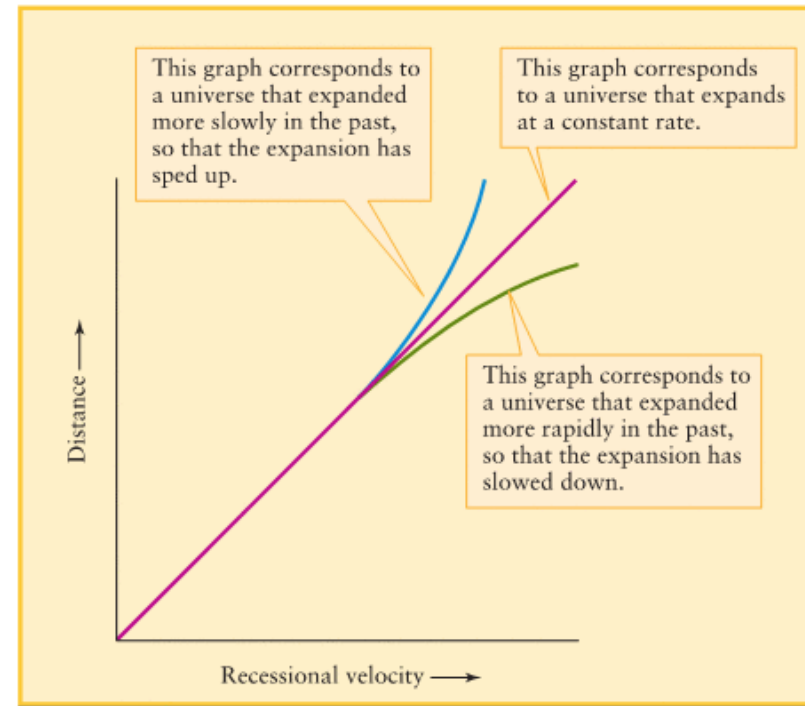
$$\Omega_0 = \Omega_m + \Omega_\Lambda = 1 \text{ (from CMB hot spots)}$$

This implies that the dark energy density parameter is $\Omega_\Lambda = 0.76$

Does the Expansion Rate Change with Time?

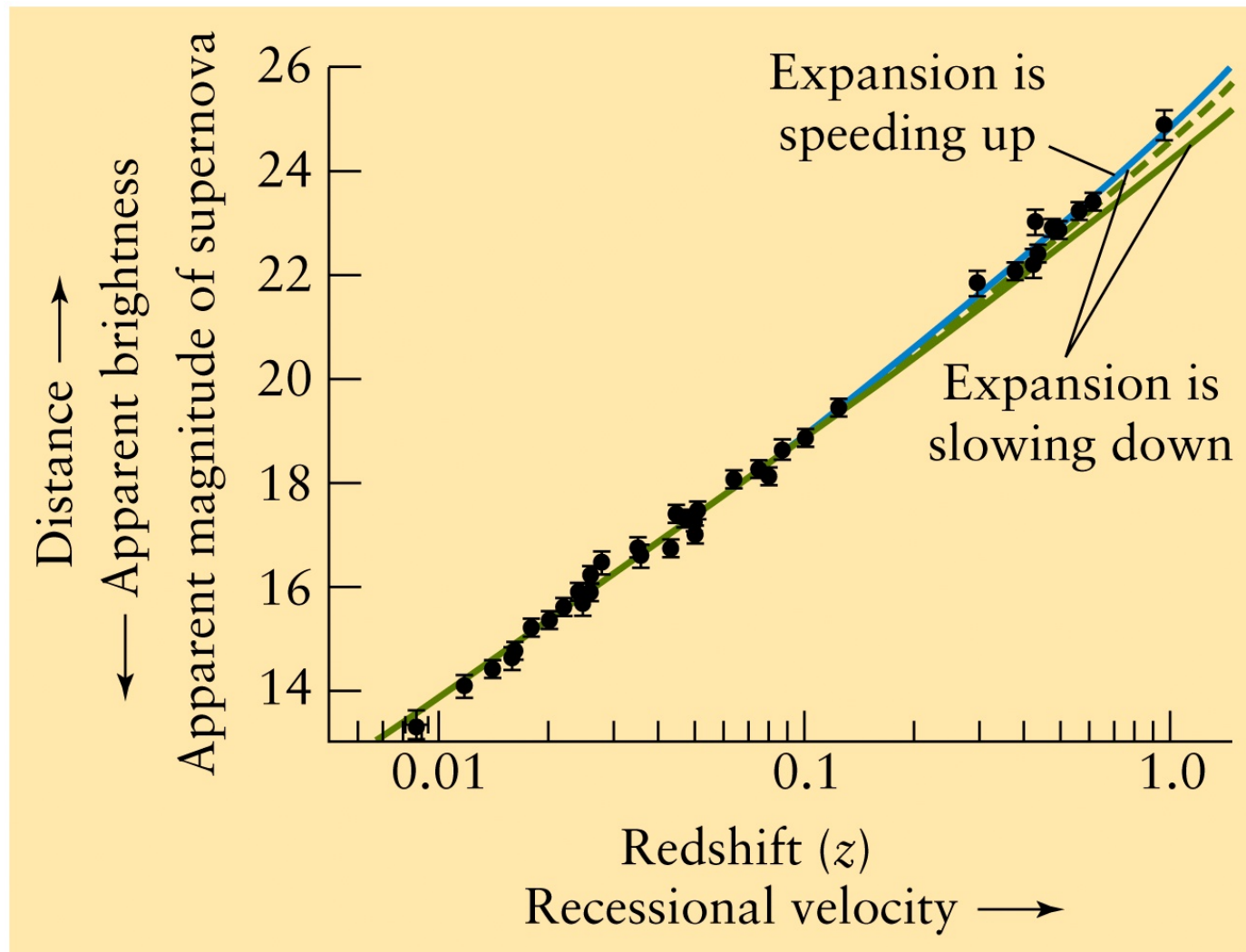


(a) Two universes with different expansion rates



(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 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!

Constraints on Ω_Λ and Ω_m ?

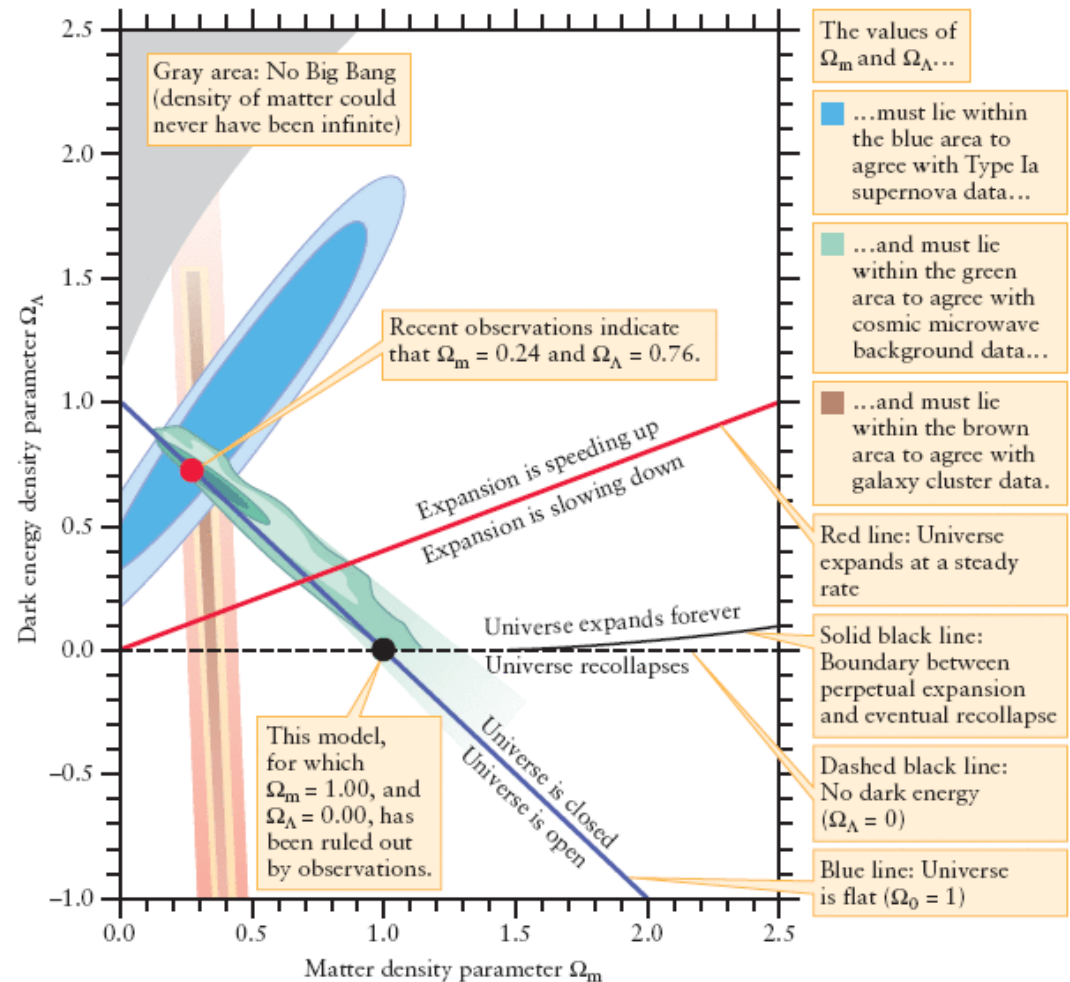
The analysis of the WMAP data indicates:

$$\Omega_\Lambda + \Omega_m = 1$$

The analysis of data from Clusters of Galaxies tells us that $\Omega_m \sim 0.24$

The analysis of SN type Ia data constrain the relative contribution of Ω_Λ and Ω_m

We can place these constraints on the same plot to obtain tighter constraints on Ω_Λ and Ω_m

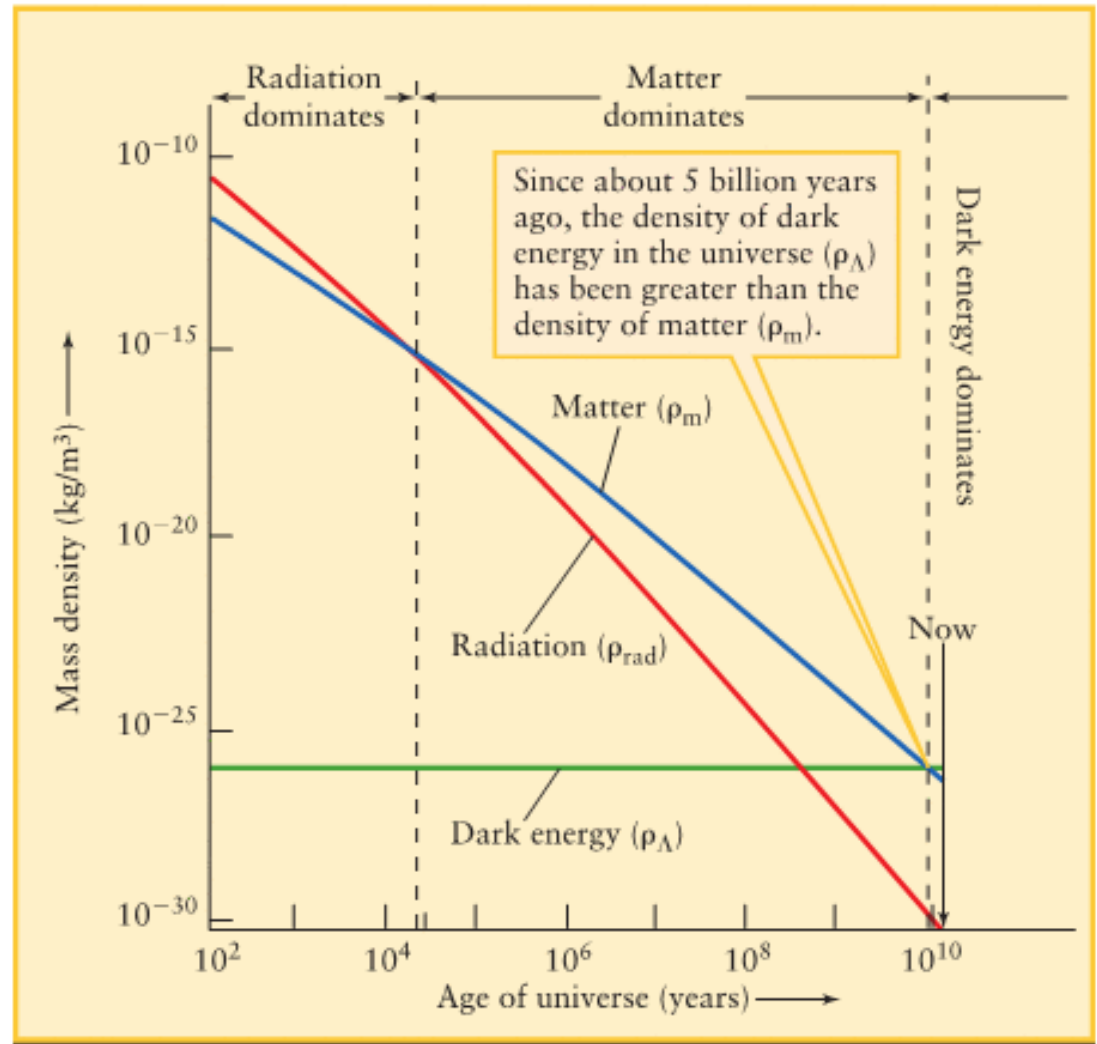


Why Me? Why Now?

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?”



Sound Waves in the Early Universe

Sound waves can travel through any type of fluid including plasmas like the one formed just after the Big Bang.

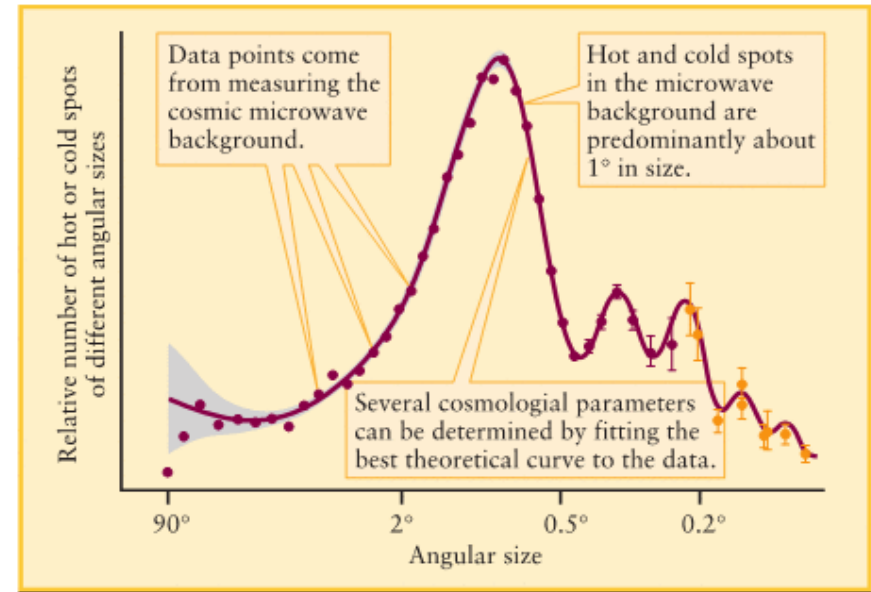
380,000 years after the Big Bang this fluid was made up mostly of electrons, protons and photons.

As a wave propagates through a fluid it creates compressions and rarefactions(medium is spread out).

Because there is more mass in a compressed region radiation emitted from this region is gravitationally redshifted (cold spot).

hot spot → rarefaction

cold spot → compression



Number of hot or cold spots of the CMB of different angular sizes.

Observations of the cosmic background radiation show that hot and cold spots of certain angular sizes are more common than others. A model that describes these observations helps to constrain the values of important cosmological parameters.

ASTRO 130, Fall 2014 FINAL EXAM

Date/time/place: Dec 6, 8:00 -11:00 am, HWWE rm 112

Chapters covered on the final exam:

Chapter 5 : The Nature of Light

Chapter 19 : Stellar Evolution I

Chapter 20 : Stellar Evolution II

Chapter 25: Quasars and Active Galaxies

Chapter 26 : Evolution of the Universe

Chapter 27 : The Early Universe