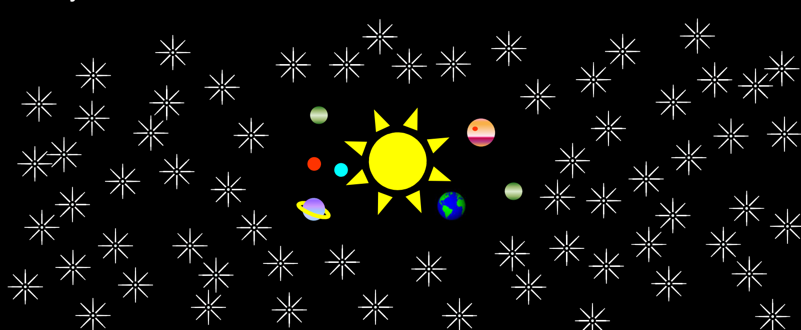
COSMOLOGY

The Beginning and the End of the Universe.

The 17-19th Century Universe

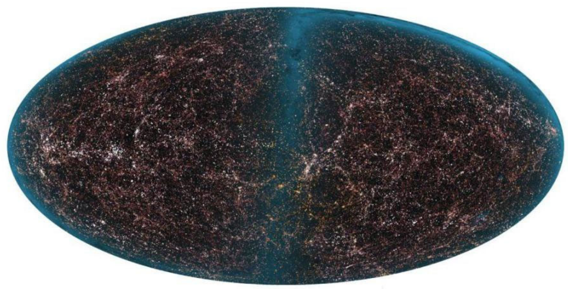
Aside from the few nearby planets and moons, 17 - 19th-century scientists thought that the Earth and Sun were surrounded by infinitely many "fixed stars," roughly uniformly spaced and extending out to infinity in all directions.



In addition, they thought the Universe was static and unchanging. It has existed forever, with no beginning and presumably no end.

Starting Supposition

The Universe is Infinite.



Cosmological Principle

Initially astronomers found that on the large scale the distribution of galaxies is **isotropic** − we find as many galaxies in one direction as in any other.

Moreover, they found that the number of galaxies increased with faintness about as fast as we would expect if they were distributed uniformly in depth.

These findings indicated that the Universe is isotropic and homogeneous − the same in all directions and at all distances. The part we can see around us is representative of the whole.

This idea of uniformity is called the **Cosmological Principle** and it is the starting assumption for nearly all theories of cosmology.

Why is the Night Sky Dark?

If the Universe is infinite, then in any direction one looks, one will eventually see a star. Because of the **Cosmological Principle**, the number of stars would increase at the same rate as the inverse square law (d^2). So the night sky should be as bright as the surface of an average star.

This worried Kepler in the 1600's.

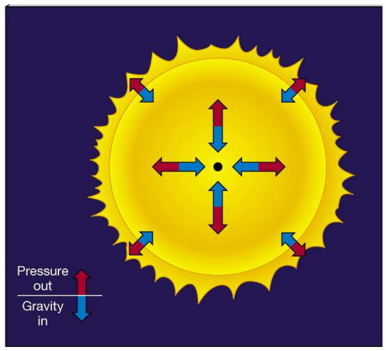
Today it is known as *Olber's Paradox.*

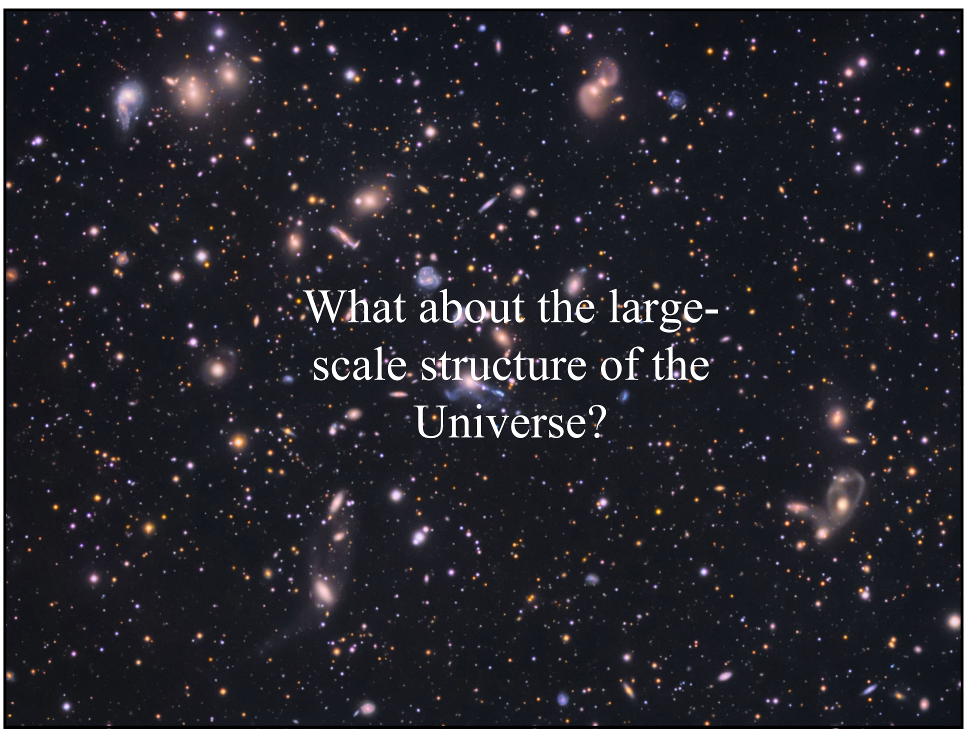
What Else Can One Deduce?

"Because it is Infinite, then it must be Static" – Isaac Newton.

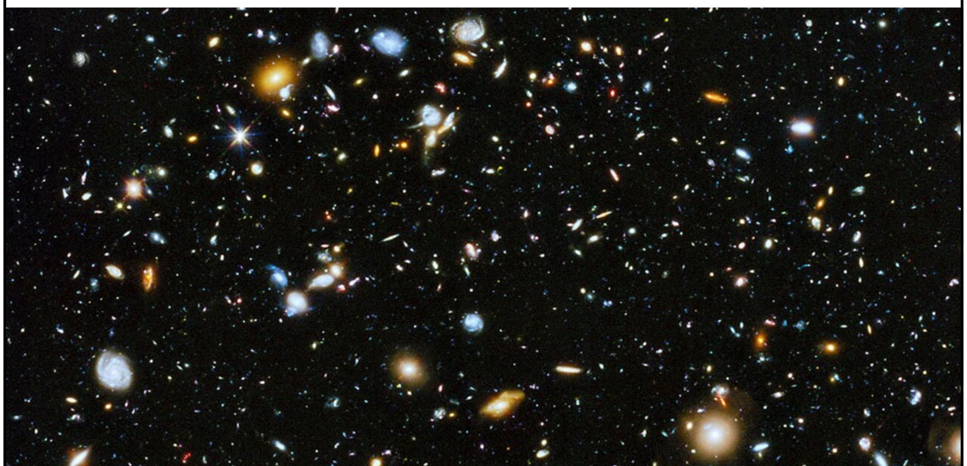
What Does General Relativity Say?

General Relativity concludes that the Universe would either be **Expanding** or **Contracting** (either gravity or pressure would win). So Einstein "fixed" his General Relativity equations with a **Cosmological Constant** (Λ) so that he got a Static Result.





Structure of the Universe



The Universe is made up of galaxies. We can see about a trillion of them.

What Do the Observations Indicate?

Slipher & Hubble: "The Universe is Expanding!"

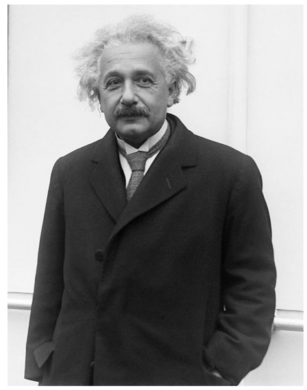
Einstein: "Aw $%!@#*"

"Biggest mistake of my life [adding a Cosmological Constant]."

New Deductions

The Universe is Expanding.

The Universe is Finite.

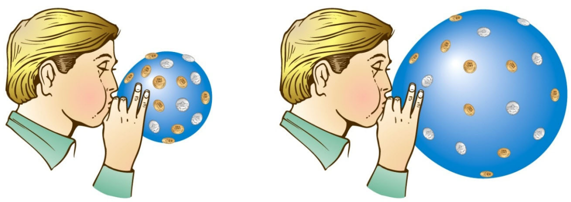


Is Any Place Special in the Universe?

No The Expansion is seen from ALL locations.

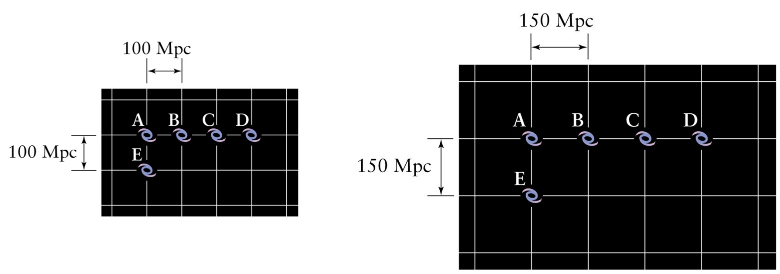
(Let's see how this is possible.)

Cosmological Redshift



The fabric of space is expanding. As photons travel through space, they are redshifted by this expansion.

The Expanding Universe



	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

$v = H_o\, d$

Is Any Place Special in the Universe?

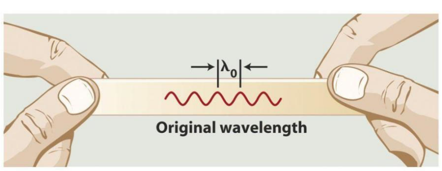
No The Expansion is seen from ALL locations.

No There is NO Center of the Universe.

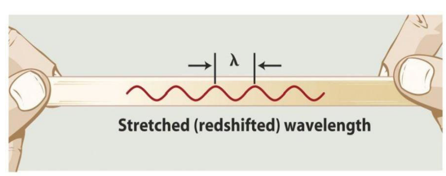
Can We Measure the Growth?

If the Redshift is given by $z = (\lambda - \lambda_o) / \lambda_o$

then the **Stretching** has been $\lambda / \lambda_o = 1 + z$



A wave drawn on a rubber band ...



... increases in wavelength as the rubber band is stretched.

Stretching Factor

Example

$z = 2, \quad \lambda / \lambda_o = 3$

The Universe has expanded by a factor of 3
since the time when the redshifts were $z = 2$.

When Did the Expansion Start?

Hubble-Lemaitre Law

$\mathbf{v = H_o\, d = d / T_o}$

therefore $\mathbf{T_o = 1 / H_o}$

Example: if $H_o = 65$ km/s/Mpc, then

$T_o = 1 / \{ (65 \text{ km/s/Mpc}) / [(10^6 \times 3.09 \times 10^{13} \text{ km/Mpc})] \times (60 \times 60 \times 24 \times 365.25 \text{ s/yr}) \}$

$T_o = 15$ billion years

(Or, How Old is the Universe?)

H_o = 100 km/s/Mpc	T_o = 10 billion years
H_o = 75 km/s/Mpc	T_o = 13 billion years
H_o = 70 km/s/Mpc	T_o = 14 billion years
H_o = 65 km/s/Mpc	T_o = 15 billion years
H_o = 50 km/s/Mpc	T_o = 20 billion years

This assumes the expansion rate has been constant and the Hubble-Lemaitre Law is valid for all times and distances.

What Started the Expansion?

What Started the Expansion?

The Big Bang

Comparing the Big Bang to the center of a black hole can help one to appreciate certain aspects of the creation of the Universe. Matter at the center of a black hole is crushed to infinite density.

At this singularity, the curvature of space and time is infinite, and the very distinction between space and time becomes muddled.

Without a clear background of space and time, such concepts as "past," "future," "here," and "now" cease to have meaning.

A better name for the Big Bang is

The Cosmic Singularity.

Planck Time

At the moment of the Big Bang, a state of infinite density filled the Universe. Throughout the Universe, space and time were completely jumbled up in a condition of infinite curvature. Thus we cannot use the known laws of physics to tell us what happened at the moment of the Big Bang.

A very short time after the Big Bang, space and time began to behave in the way we think of them today. This time interval is called the **Planck Time** (t_p).

$$t_p = \mathrm{sqrt}\{ G\, h / c^5 \} = 1.35 \times 10^{-43}\ \mathrm{s}$$

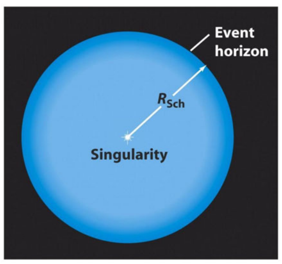
From the beginning of the Big Bang to the Planck time, all known science fails us. We do not know how space, time, and matter behaved in that brief interval.

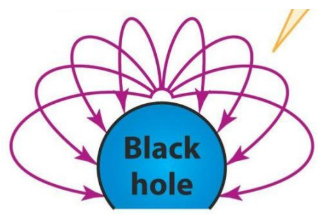
What is it Expanding Into?

There is **NOTHING** outside of the Universe.

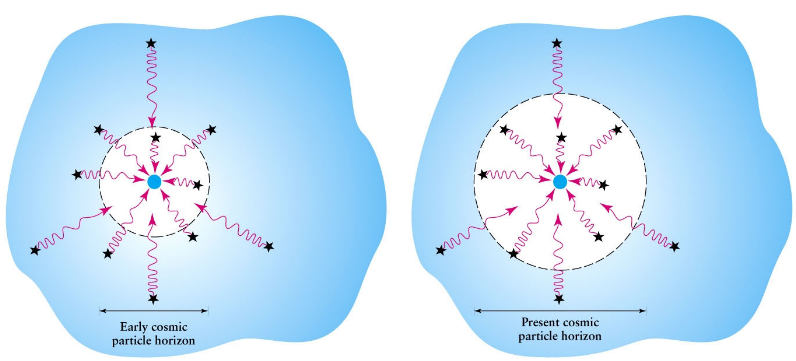
There is no edge to the Universe.

(Think of a black hole and an event horizon.)





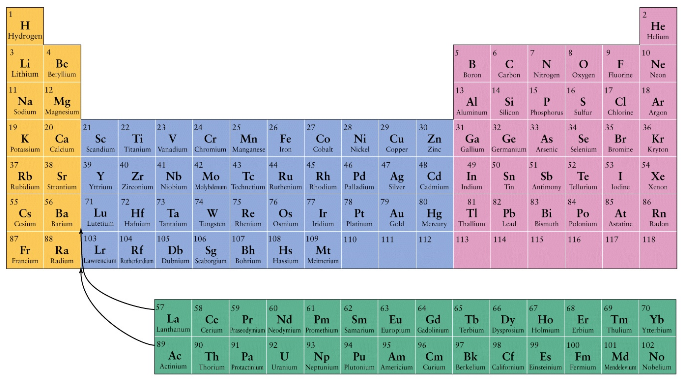
The Observable Universe



The part of the Universe that we can observe lies within a sphere centered on the Earth called the **Cosmic Particle Horizon**. Its radius is equal to the distance that light has traveled since the start of the expansion.

Any Evidence for the Big Bang?

1. **Problem with He Abundance** – there is too much He in the Universe to have been created by stars. Therefore, the early Universe had to have had conditions (temperature, pressure) similar to that of stellar interiors.

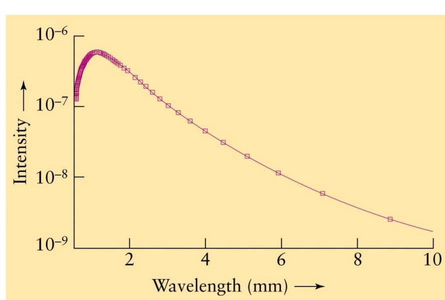


Any Evidence for the Big Bang?

2. **Cosmic Microwave Background** (3K background radiation)

Discovered by Penzias & Wilson

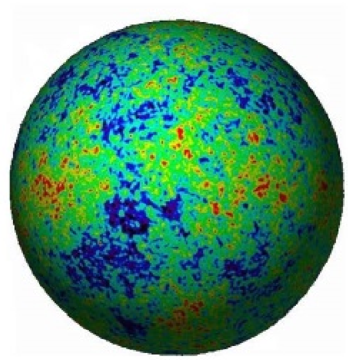
Confirmed by COBE to be 2.726 K



Any Evidence for the Big Bang?

The Cosmic Microwave Background Radiation

Non-terrestrial radiation in the microwave region of the spectrum that is highly uniform on the sky with small fluctuations (10 parts in 1 million).

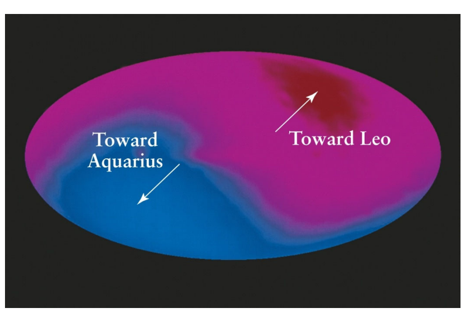


Any Evidence for the Big Bang?

Cosmic Microwave Background (cont.)

Slightly blueshifted toward “The Great Attractor”

v = 370 km/s ΔT = 0.0033 K



COSMOLOGY

The Beginning and the End of the Universe.

What Was The Early Universe Like?

Average Density of Matter − **Today**

$\rho_m = 2 - 6 \times 10^{-27}$ kg/m^3

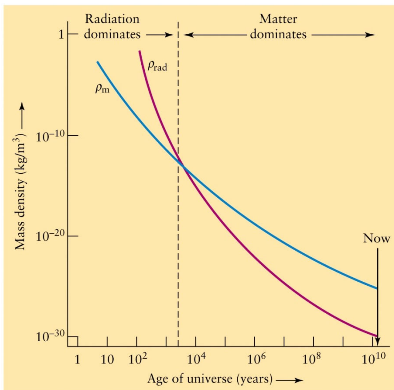
$m_H = 1.7 \times 10^{-27}$ kg

Mass Density of Radiation − **Today**

$\rho_{rad} = 4\,\sigma\,T^4 / c^3 = 4.6 \times 10^{-31}$ kg/m^3

$\sigma = 5.67 \times 10^{-8}$ W m^{-2} K^{-4}

What Was The Early Universe Like?



Currently *Matter* Dominated

Previously *Radiation* Dominated

Switched at τ = 2,500 years
when z = 25,000

λ = 40 nm (then) → λ = 1 mm (now)

T = 25,000 x 3 K = 75,000 K

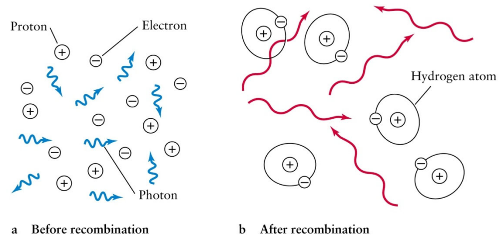
What Was The Early Universe Like?

Era of Recombination

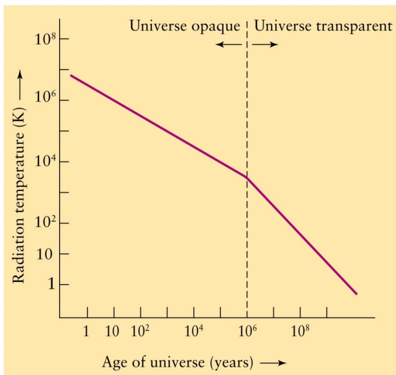
τ = 300,000 years z = 1000

T = 1000 x 3 K = 3,000 K (starlike)

At this time, H atoms were formed (electrons were bound to protons).



What Was The Early Universe Like?



Era of Recombination

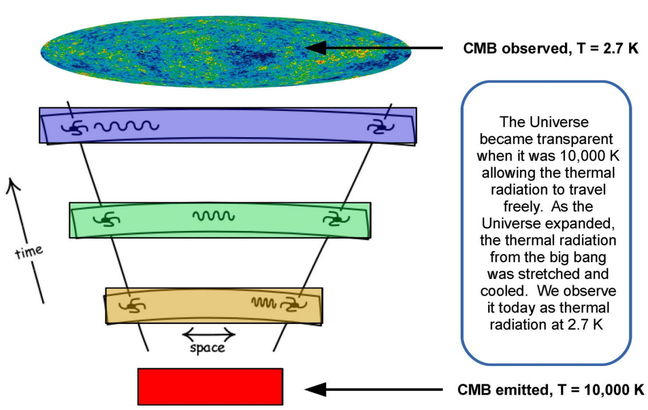
τ = **300,000 years** z = 1000

T = 1000 x 3K = 3,000 K (starlike)

Photons were no longer inhibited, so they decoupled from matter, creating the **Cosmic Microwave Background Radiation** (which was subsequently redshifted).

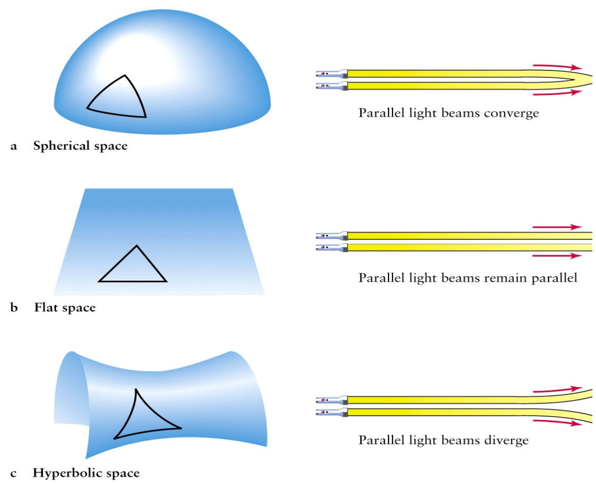
Cosmic Microwave Background

If the CMB was emitted when the Universe was hot (10,000 K), why do we observe it as cold (2.7 K) ?



The Shape of the Universe

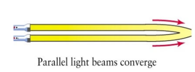
Use two parallel laser beams to determine the Shape of the Universe.



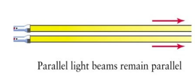
The Shape of the Universe

Use two parallel laser beams to determine the Shape of the Universe.

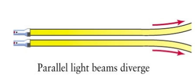
Converge positive curvature spherical space



Parallel zero curvature flat space

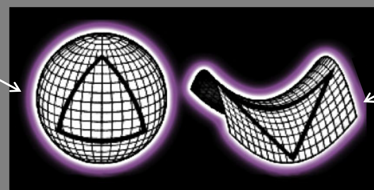


Diverge negative curvature hyperbolic space



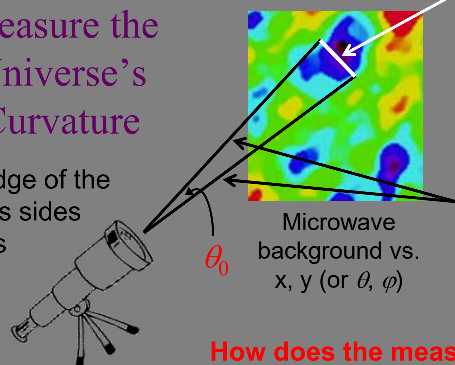
How to Use the Microwave Background Fluctuations to Measure the Universe's Curvature

Angles add up to >180º



Angles add up to <180º

Size of main fluctuation component = ct, where t = 300,000 yrs (when it was emitted). But we must also correct for the universe's expansion: multiply by $1 + z \sim 1000$.



Knowledge of the triangle's sides yields its angles.

Microwave background vs. x, y (or θ, φ)

Distance to microwave emission source = $c\tau$, where $\tau = T - 300{,}000$ yrs $\sim T$ (where T = age of universe).

How does the measured θ_0 compare to that computed from the sides of the triangle?

The Shape of the Universe

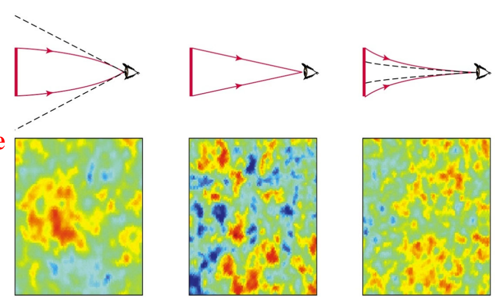
Look at non-uniformities in 3K Cosmic Background Radiation

Warmer regions – more dense

- Positive curvature
- Spherical space
- Closed Universe

Warmer regions – less dense

- Negative curvature
- Hyperbolic space
- Open Universe



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

Observations indicate the Universe is Flat.

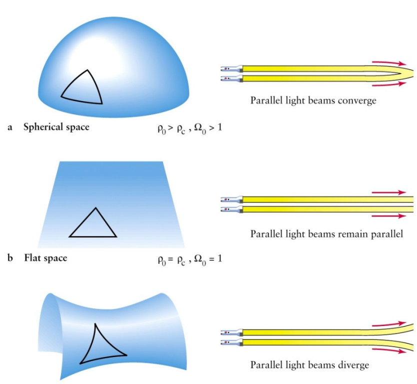
The Critical Density of the Universe

$$\rho_{crit} = 3\,H_o^2 / 8\,\pi\,G$$

high ρ_m	bounded, closed
$\rho_m = \rho_{crit}$	marginally bounded
low ρ_m	unbounded, open

For $H_o = 70$ km/s/Mpc $\quad \rho_{crit} = 9.2 \times 10^{-27}$ kg/m^3

The Average Density of the Universe



Density Parameter

$$\Omega_o = \rho_m / \rho_{crit}$$

$\Omega_o > 1$	bounded, closed
$\Omega_o = 1$	marginally bounded
$\Omega_o < 1$	unbounded, open

Possible Geometries of the Universe

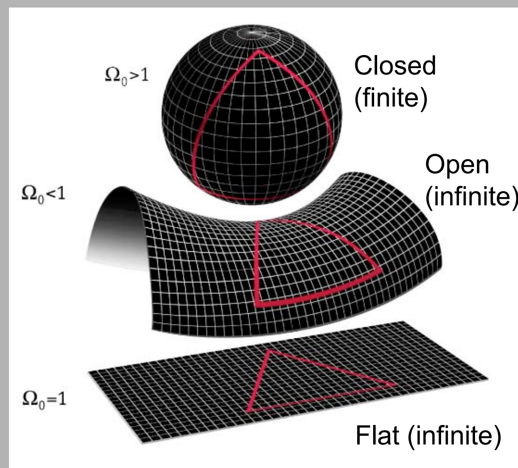
The total density, ρ, of all matter in the Universe determines its shape.

$\Omega_0 \equiv \rho / \rho_{crit}$

where

$\rho_{crit} = 3H^2/8\pi G$

is the **critical density** for which the Universe is flat.



Luminous matter accounts for only ~5% of the critical density.

Mass Density Parameter

The 3K small-scale observations tend to indicate that the Universe is **Flat**, but this poses a major dilemma. The average *mass density* of all matter in the Universe, ρ_m, is in the range 2 – 6 x 10^{-27} kg/m^3. This is about **0.2 to 0.4** of the value of the critical density ρ_{crit} = 9.2 x 10^{-27} kg/m^3.

Mass Density Parameter $\Omega_m = \rho_m / \rho_{crit} = 0.2 – 0.4$

If **matter** and **radiation** is all there is in the Universe, the combined average mass density would be equal to ρ_m. Then the density parameter Ω_o would be equal to Ω_m – in the range of 0.2 to 0.4 – so the Universe would be **Open**.

But the temperature variations in the Cosmic Microwave Background clearly show the Universe is either **Flat** or nearly so.

What Else Is There?

Besides **matter** (luminous and dark) and **radiation**, what else could there be to make the Universe flat?

The source of the missing density is believed to be some form of ***Energy***.

It cannot be detected from its gravitational effects.

It must also not emit detectable radiation of any kind.

This mysterious energy is called **Dark Energy**.

What Else Is There?

Dark Energy Density Parameter $\Omega_\Lambda = \rho_\Lambda / \rho_{crit}$

$$\Omega_o = \Omega_\Lambda + \Omega_m$$

$$1 - \text{“}0.2 - 0.4\text{”} = \Omega_\Lambda = 0.6 - 0.8$$

This is like a Cosmological Constant!

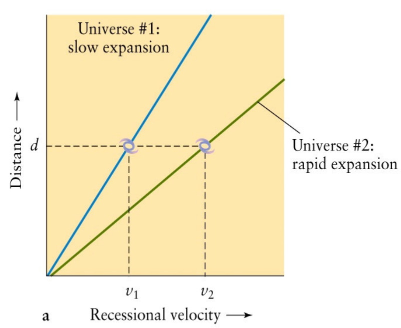
Observational Evidence?

Gravity pulls matter together, so we would expect that the expansion of the Universe should slow down with time. If there is a Cosmological Constant or Dark Energy, though, it would **exert a pressure that accelerates the expansion**.

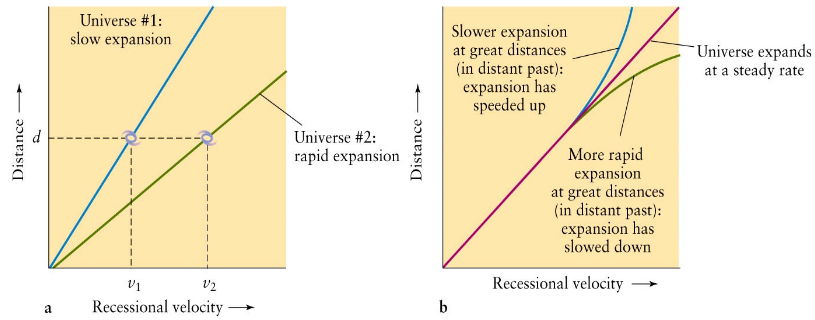
To determine which of these effects is more important, one studies the relationship between redshift and distance for *extremely* remote galaxies. We see these galaxies as they were billions of years ago.

If the rate of expansion was the same in the distant past as it is now, the same Hubble-Lemaitre Law would apply at all times. But if the expansion rate has either increased or decreased, we would see deviations from the linear Hubble-Lemaitre Law.

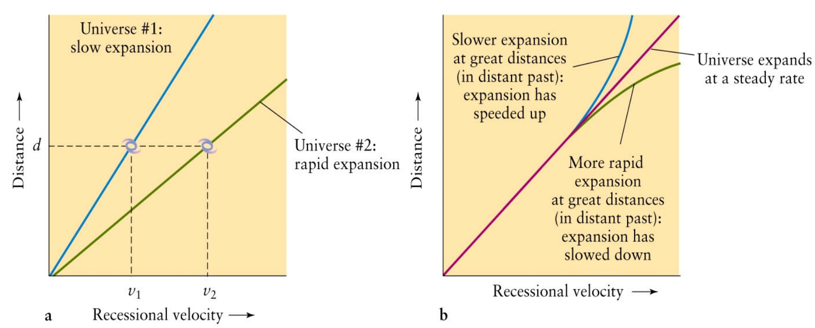
Different Expansion Rates

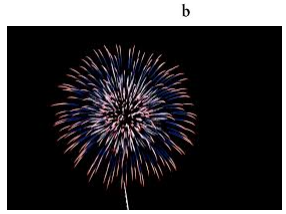


Different Expansion Rates

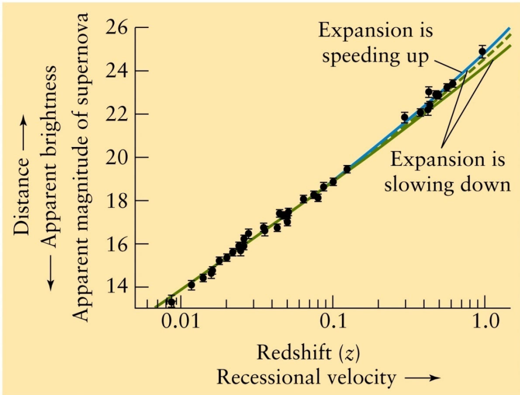


Different Expansion Rates



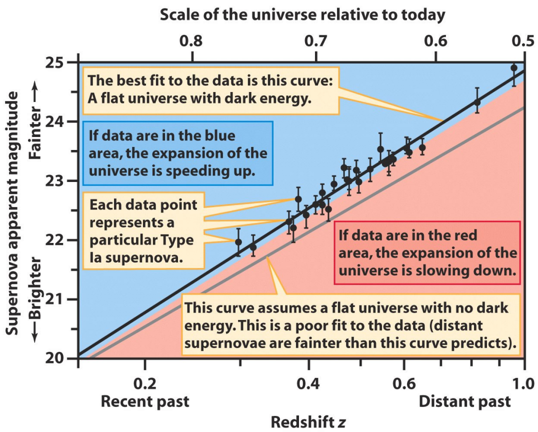


Observations of Remote Galaxies



Type Ia Supernovae are fainter at great distances.

Observations of Remote Galaxies



Limited data of distant galaxies indicate the today's expansion is *faster* than what it was in the past. That is, the expansion of the Universe is speeding up.

Current Cosmological Model

The previous graph shows the relative importance of Dark Energy (which makes the expansion speed up) and Gravitational Attraction between galaxies (which makes the expansion slow down).

1. Basically, we know the difference between the values of Ω_m and Ω_Λ.

2. Measurements of the Cosmic Microwave Background give the sum of Ω_m and Ω_Λ (= Ω_O).

3. Measurements of galaxy clusters give the value of Ω_m.

Current Cosmological Model

The data agree very well with the blue curve on the previous slide. The blue curve assumes **(1) a flat Universe (2) with a Cosmological Constant due to Dark Energy.**

$$\mathbf{\Omega_m = 0.27, \quad \Omega_\Lambda = 0.73,}$$

$$\mathbf{\Omega_O = \Omega_m + \Omega_\Lambda = 1.00}$$

In this model, the Cosmological Constant has made the expansion speed up over time; i.e., the expansion was slower in the distant past.

The Cosmological Constant Rules!

The Cosmological Constant appears to be the dominant effect!

But why?

And what is it really?

Dark Energy Dominance

The data provide compelling evidence of the existence of **Dark Energy**; however, it does not directly determine the value of the Dark Energy density parameter Ω_Λ.

Unlike matter or radiation, whose average densities *decrease* as the Universe expands, the average density of Dark Energy *remains constant.*

Today, we live in a

Dark-Energy-Dominated Universe.