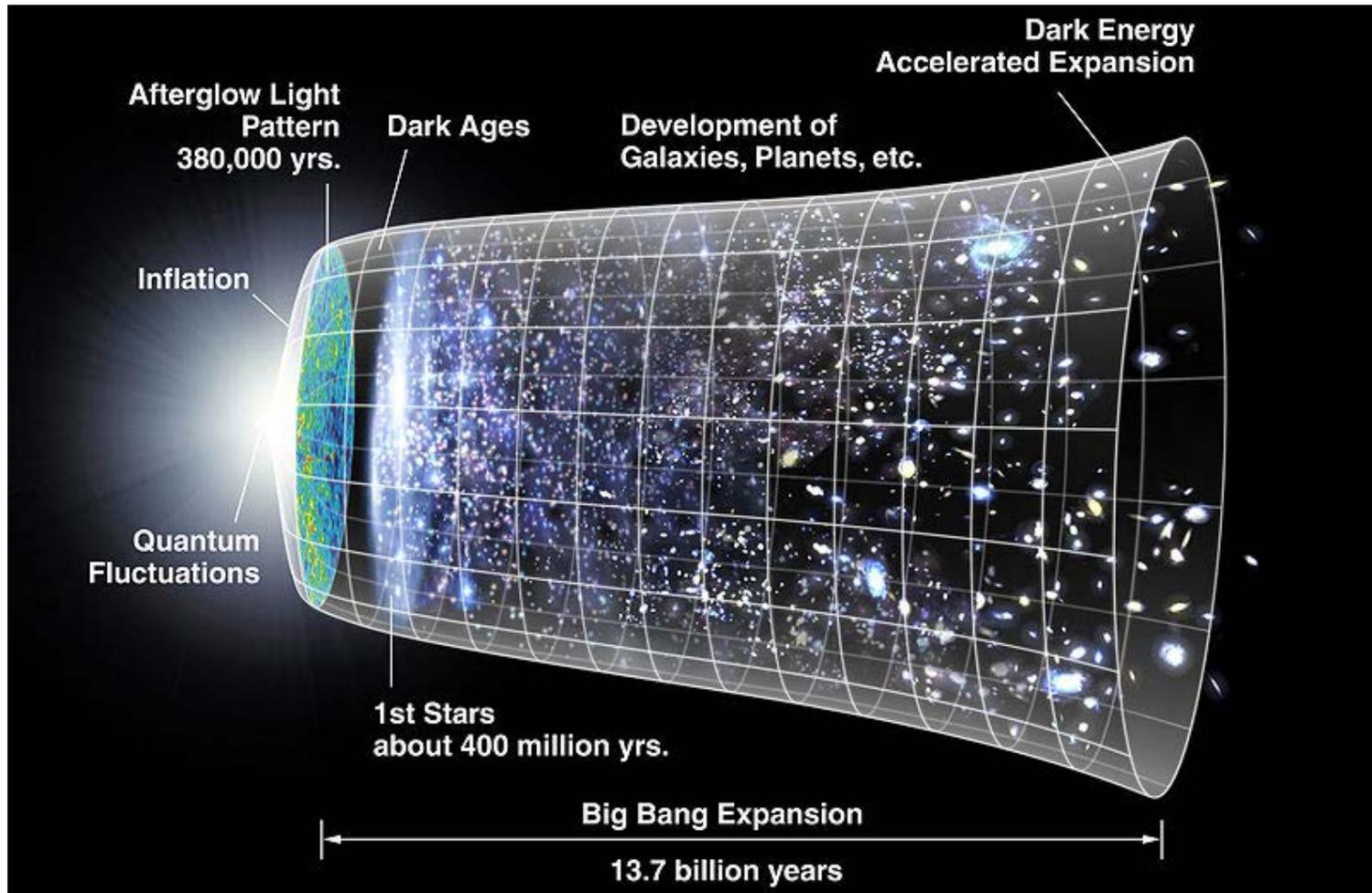


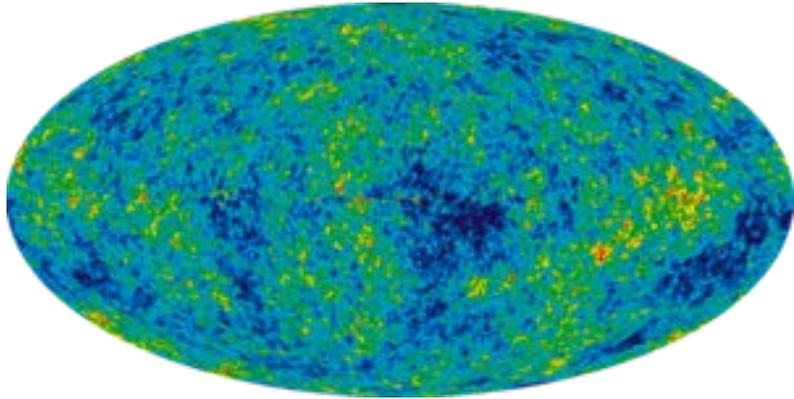
# The Early Universe



# The Early Universe

1. **Inflation Theory**: The early universe expanded enormously in a brief instance in time.
2. The **fundamental forces** change during the first second after the big bang.
3. What happened to **anti-matter**?
4. What **chemicals** were produced in the early universe?
5. When did the **first stars and galaxies** come form?
6. *Theories of everything.*

# The Early Universe



$$T_{\text{then}} \sim 3,000\text{K}$$

$$T_{\text{now}} \sim 2.725\text{ K}$$

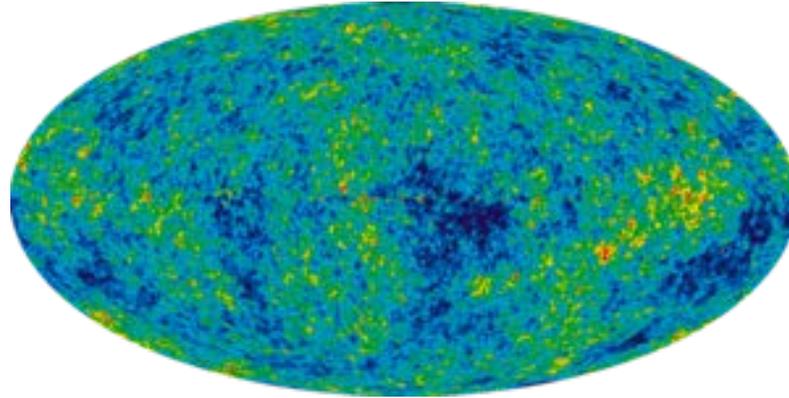
Occurred  $\sim 380,000$  years after big bang

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

A careful analysis of the CMB revealed two strange results:

1. It's too uniform (or isotropic).
2. Why is the Universe so flat today with  $\Omega_0 = 1$

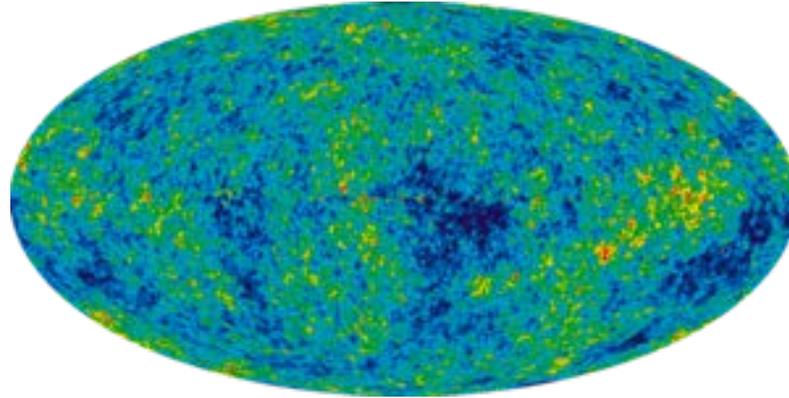
# The Early Universe: The Horizon Problem



Suppose you picked **two locations on the CMB** that were separated by  $180^\circ$  degrees (Two opposite locations in the sky.)

If you use <http://www.astro.ucla.edu/~wright/CosmoCalc.html> and set  $z = 1100$  you find that the age of the universe during decoupling was  $\sim 380,000$  years after the big bang and points  $180^\circ$  apart are separated by  $\sim 40$  Mpc

# The Early Universe: The Horizon Problem



Spots that are  $180^\circ$  apart are separated by  $\sim 40$  Mpc at  $z = 1100$ . How long does it take light to travel between these two spots?

$$t = \frac{\text{distance}}{c} = \frac{40 \text{ Mpc}}{3 \times 10^8 \text{ m/s}} = 1.3 \times 10^8 \text{ years}$$

This is much longer than 380,000 years. So there hasn't been enough time for these two spots since the big bang to have ever physically interacted.

The isotropy problem arose because it is difficult to explain how areas in the CMB that have never been in contact have the same temperature.

## The Early Universe: The Flatness Problem

The geometry of our universe depends on the density parameter  $\Omega_0$ , which is the ratio of the combined mass density in the universe ( $\rho_0$ ) to the critical density ( $\rho_c$ )

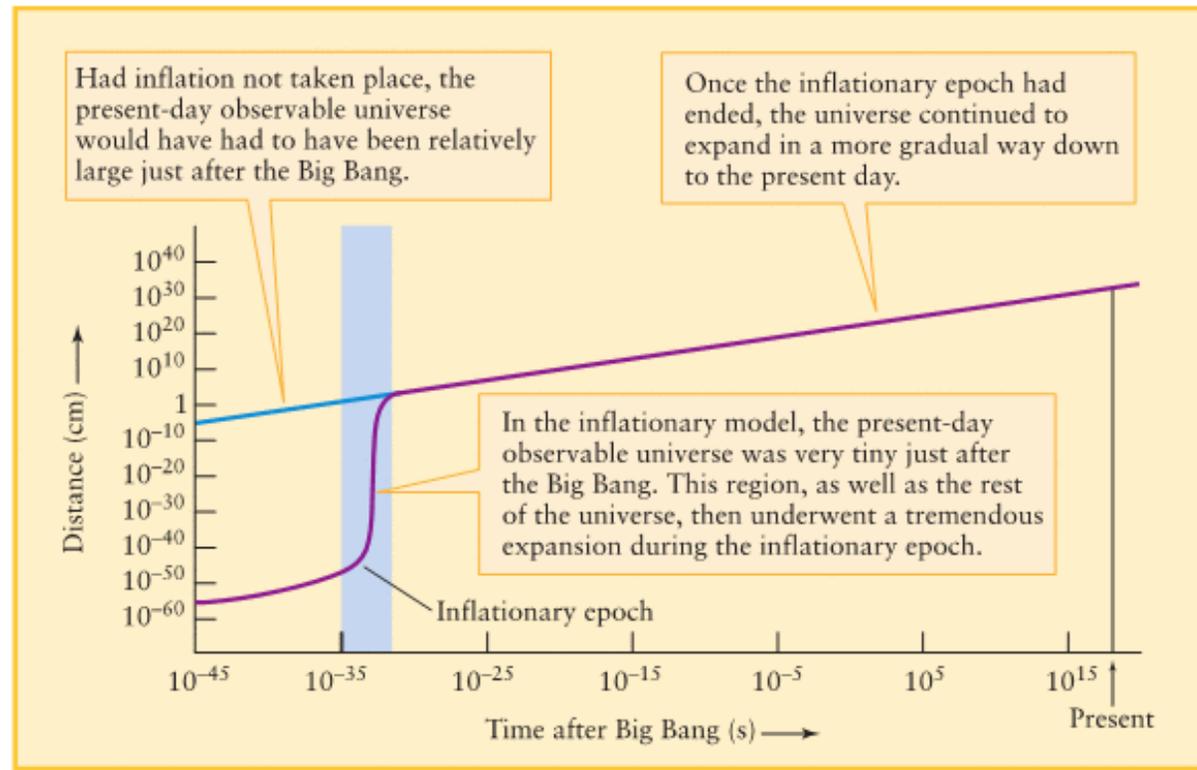
$$\Omega_0 = \rho_0 / \rho_c$$

The analysis of the sizes of the hot spots in the CMB indicates that  $\Omega_0=1$  (flat Universe).

The flatness problem arose because it was difficult to explain how the value of  $\rho_0$  right after the Big Bang was equal to  $\rho_c$  to more than 50 decimal places!

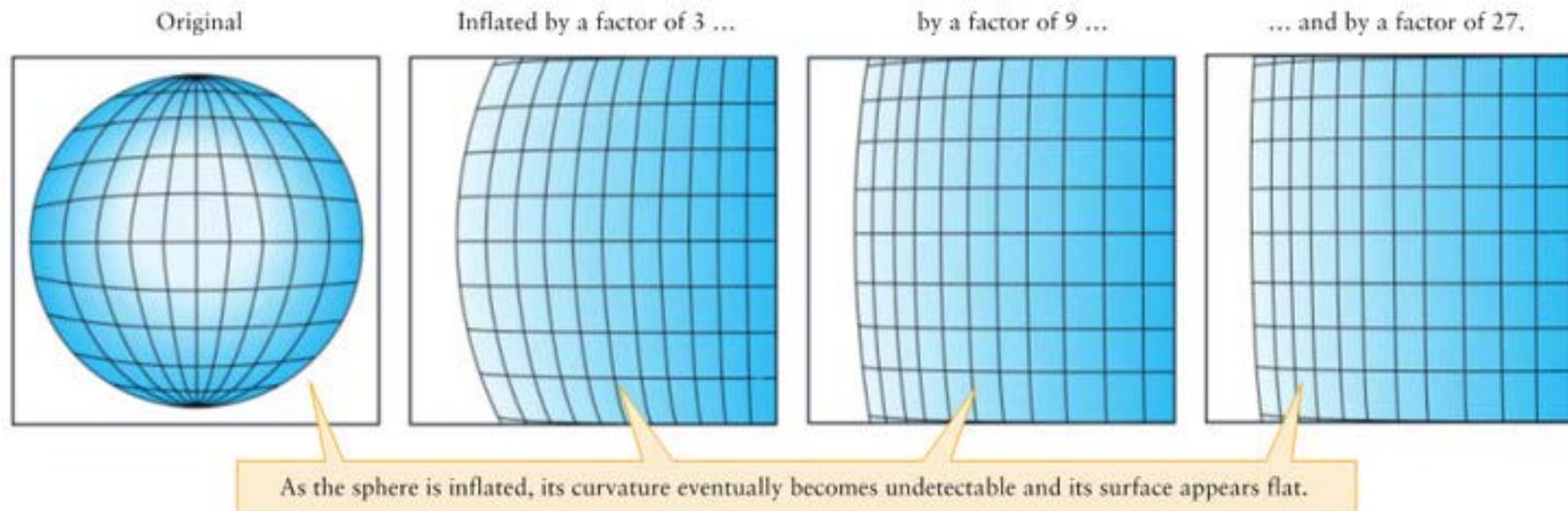
# The Early Universe: Inflation

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 Planck time.



# The Early Universe: Inflation

The equations for an expanding universe show that any deviation of  $\Omega_0$  from exact equality would have mushroomed within a fraction of a second.



# The Early Universe: The 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  $\sim 10^{-15}\text{m}$ )
4. **Weak Force** (force acts on quarks, electrons, neutrinos and involved in certain radioactive decays, short-range force  $\sim 10^{-16}\text{m}$ )

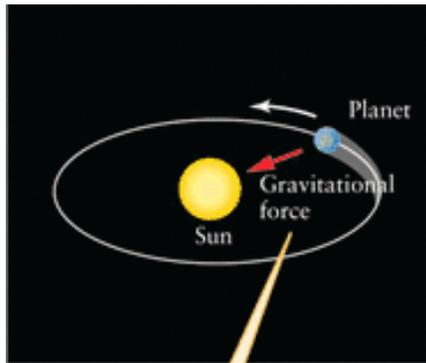
# The Early Universe: The Fundamental Forces

What do we mean by a force between particles :

Particles interact by exchanging particles. Each force has its own **exchange particles**. The exchange particles cannot be directly observed and are called **virtual particles**.

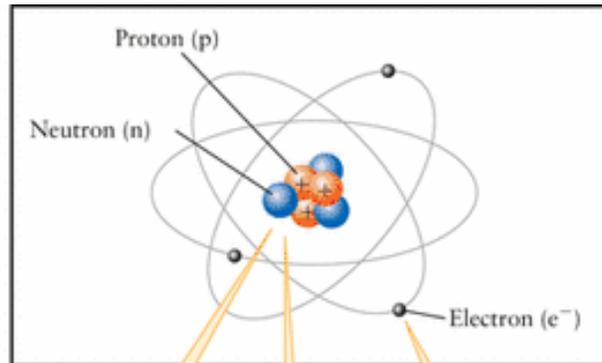
1. **Gravity** (exchange particle=graviton)
2. **Electromagnetism** (exchange particle=photon )
3. **Strong Force** (exchange particle=gluon)
4. **Weak Force** (exchange particles=intermediate vector  $W^+$ ,  $W^-$  and Z bosons)

# The Early Universe: The Fundamental Forces



(a)

The gravitational force is too weak to be important on the subatomic scale. It is *the* most important force on astronomical scales, since stars and planets have no net electric charge and the strong and weak forces do not operate over long distances.

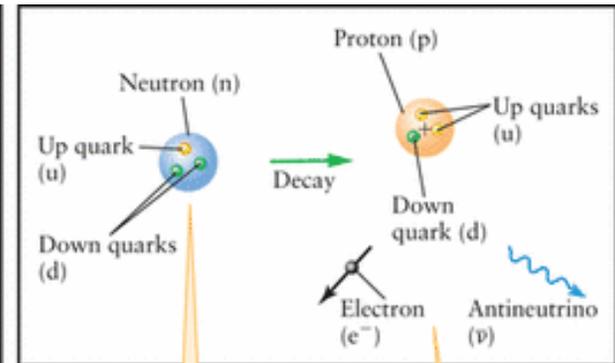


(b)

The strong force binds protons and neutrons together to form nuclei.

The electromagnetic force attracts electrons and nuclei, forming atoms.

The electromagnetic force by itself makes protons repel, but this is overwhelmed by attraction due to the strong force.



(c)

Another aspect of the strong force binds quarks together to form protons and neutrons.

The weak force causes an isolated neutron to decay into a proton, an electron, and an antineutrino. This involves a down quark changing into an up quark.

Force	Relative strength	Particles exchanged	Particles on which the force can act	Range	Example
Strong	1	gluons	quarks	$10^{-15}$ m	holding protons, neutrons, and nuclei together
Electromagnetic	1/137	photons	charged particles	infinite	holding atoms together
Weak	$10^{-4}$	intermediate vector bosons	quarks, electrons, neutrinos	$10^{-16}$ m	radioactive decay
Gravitational	$6 \times 10^{-39}$	gravitons	everything	infinite	holding the solar system together

# The Early Universe: Unification of Forces

Steven Weinberg, Sheldon Glashow, and Abdus Salam proposed that the **weak force is mediated by the  $W^+$ ,  $W^-$  and  $Z$  bosons.**

These three particles were actually discovered in the 1980s, providing strong support for the theory.

They also predicted that the **electromagnetic force and the weak force** between particles **are identical** for particles with energies **greater than 100 GeV!**

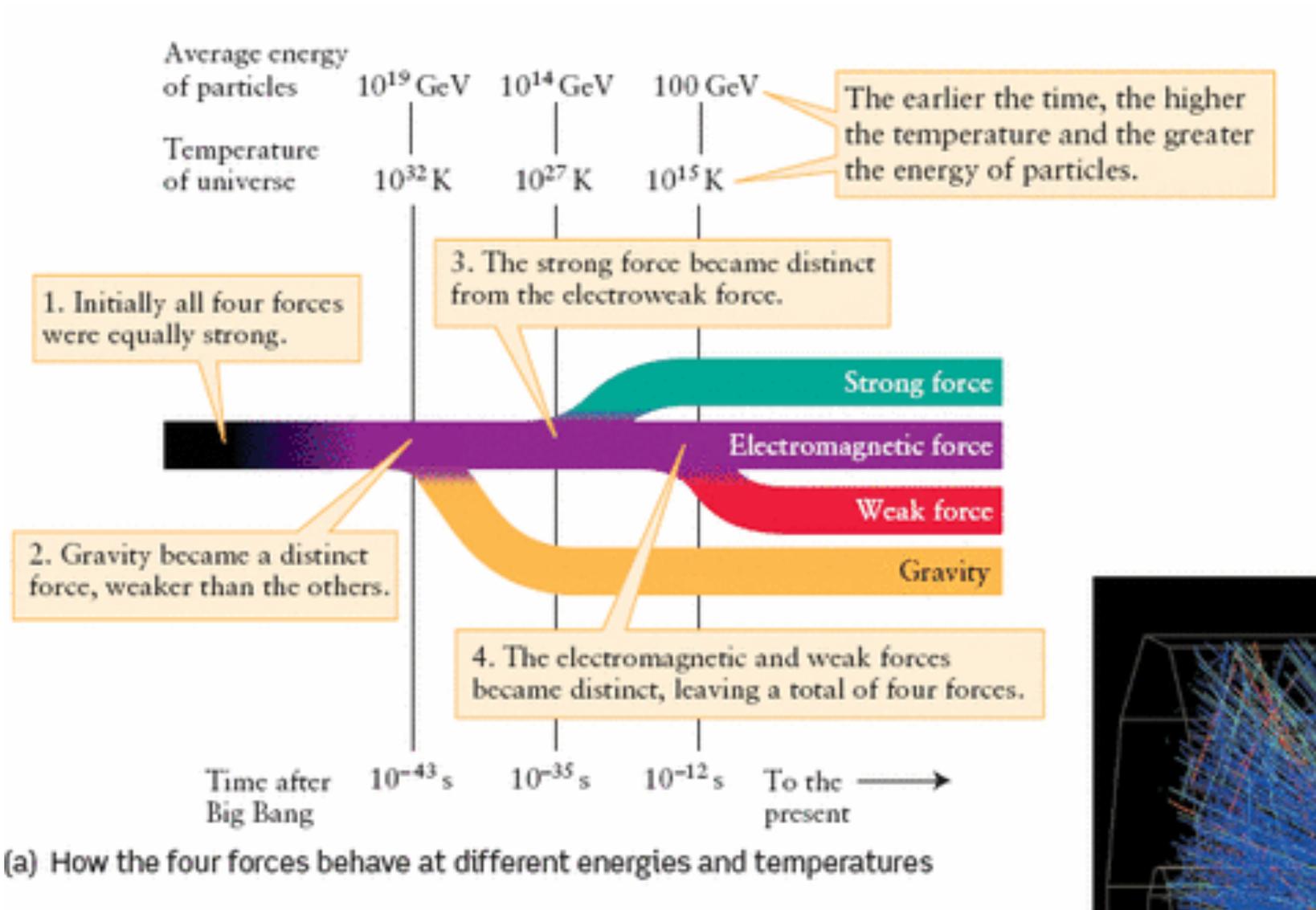
The  $W^+$ ,  $W^-$  and  $Z$  bosons lose their mass at  $> 100$  GeV and behave like photons.

## The Early Universe: GUTs

In the 1970s, scientists proposed **grand unified theories** (or GUTs), which predict that the strong force becomes unified with the weak and electromagnetic forces (but not gravity) at energies above  $10^{14}$  GeV.

No **supergrand unified theory** has been developed yet that can unify all four forces (some theorists think that this happens at  $10^{19}$  eV).

Combining all the forces would require a theory that could combine gravity at the microscopic scales (quantum gravity).



# Matter and Radiation Created During Inflation

To understand **how radiation and matter were created** we need to discuss some quantum mechanics.

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 particles momentum  $p$  ( $p = \text{mass} \times \text{velocity}$ ).

The uncertainty principle between position and momentum states :

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

Where  $\Delta x$  is the uncertainty in the position of the particle and  $\Delta p$  is the uncertainty in its momentum

# Matter and Radiation Created During Inflation

The uncertainty principle between energy and time states :

$$\Delta E \Delta t \geq \frac{\hbar}{2}, \quad \hbar = 1.054 \times 10^{-34} \text{ Js}$$

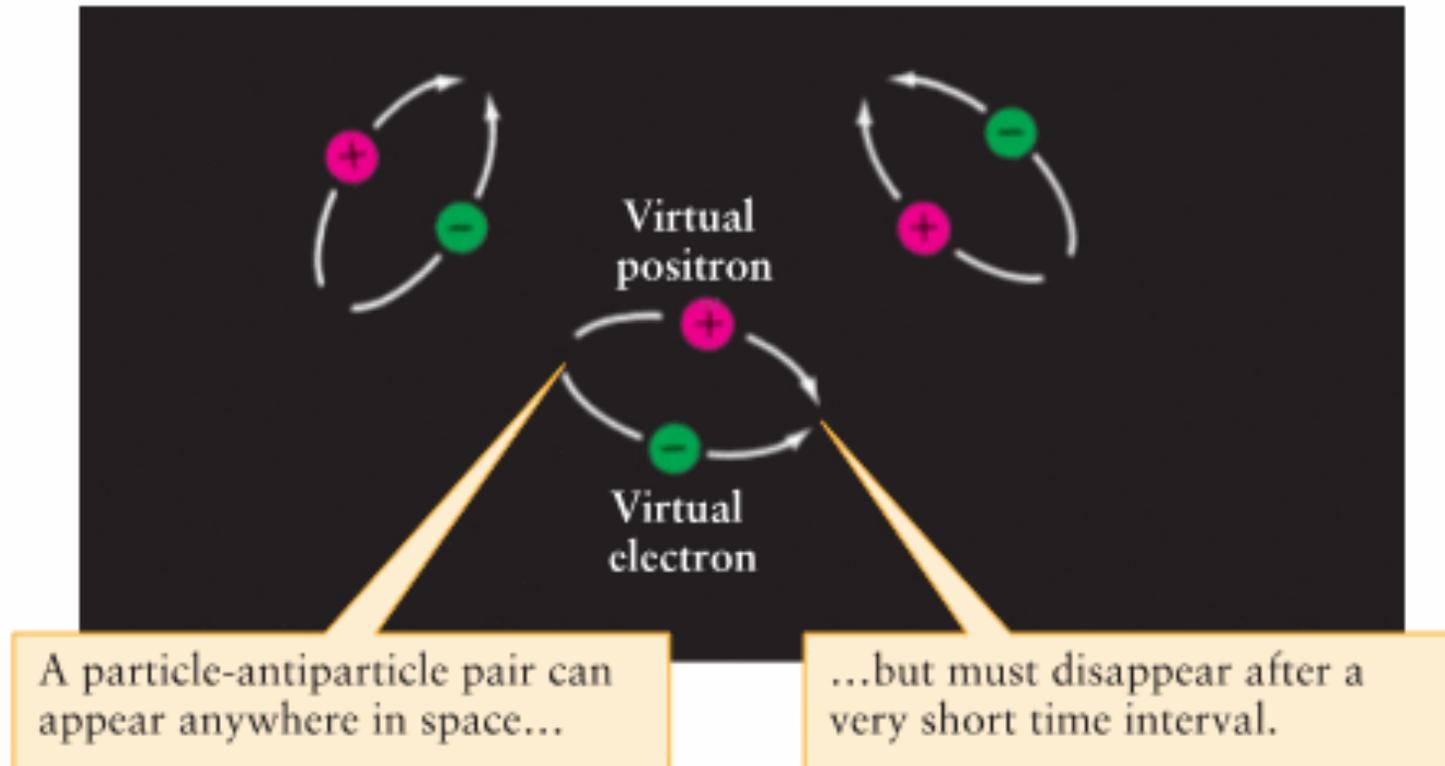
$$\Delta m \Delta t \geq \frac{\hbar}{2c^2}, \quad c = 3 \times 10^8 \text{ m/s}$$

Where  $\Delta E$  is the uncertainty in the energy of the particle and  $\Delta t$  is the uncertainty in the time interval over which the energy is measured.

For very small time intervals large uncertainties in energy (and mass =  $E/c^2$ ) are allowed by nature! This means that 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.

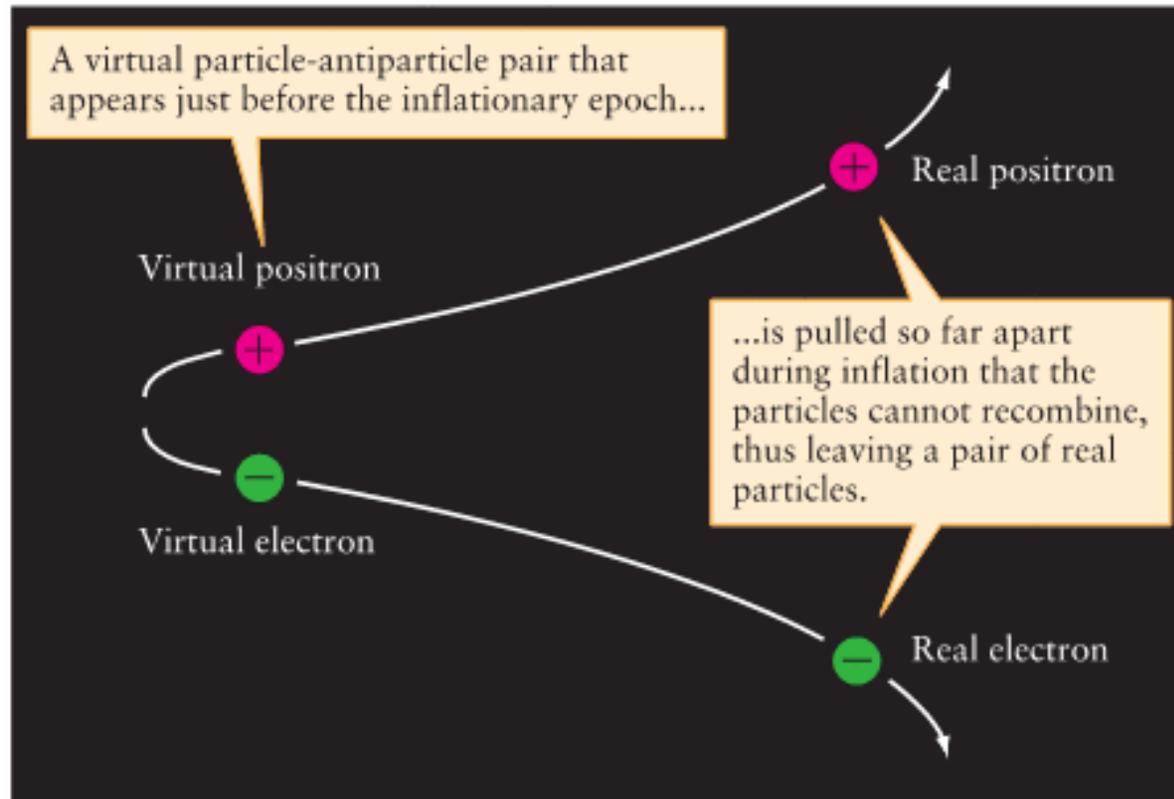
# Matter and Radiation Created During Inflation



**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.

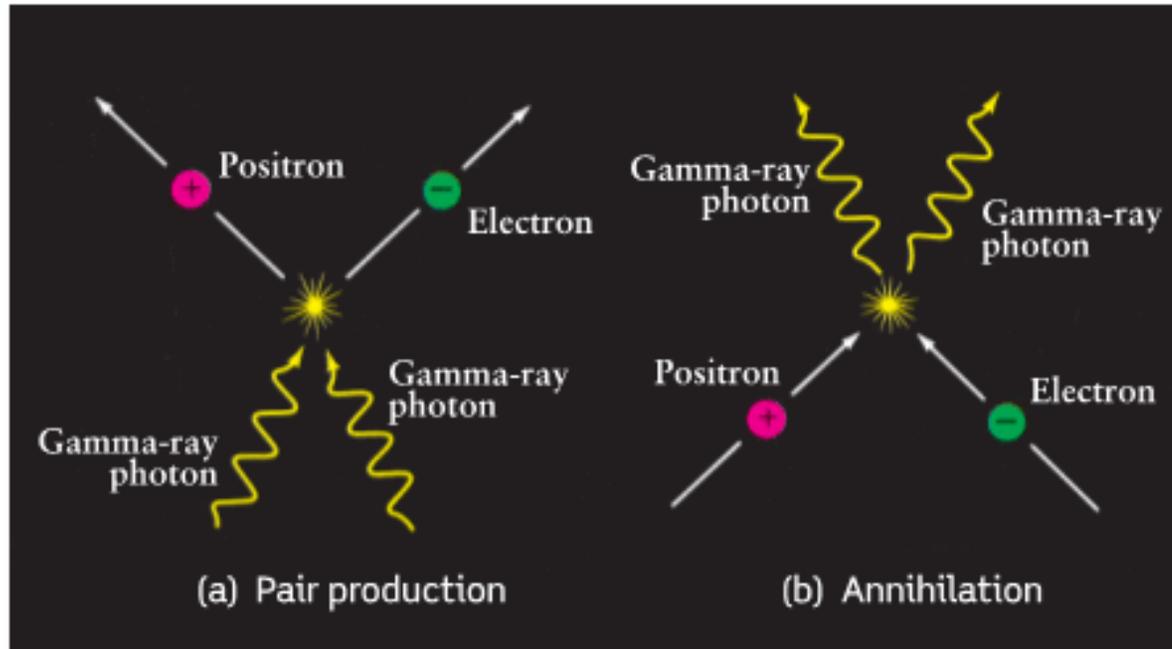
For example an electron positron pair can be created out of vacuum and will exist for about  $3 \times 10^{-22}$  sec without violating the uncertainty principle.

# Matter and Radiation Created During Inflation



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

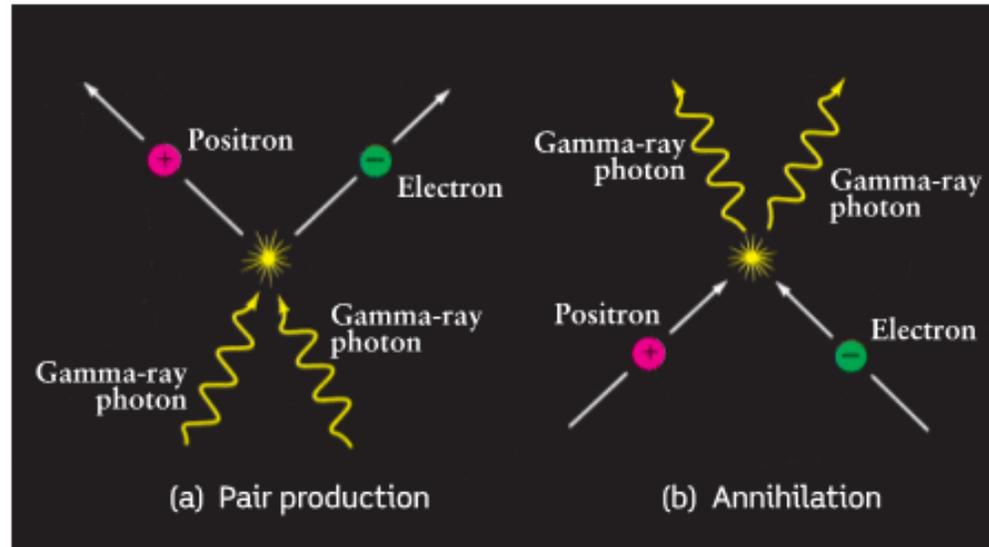
## Most of the Matter and Antimatter Annihilated



Pair production can take place only if the combined energy of the two photons is no less 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...*

# Most of the Matter and Antimatter Annihilated

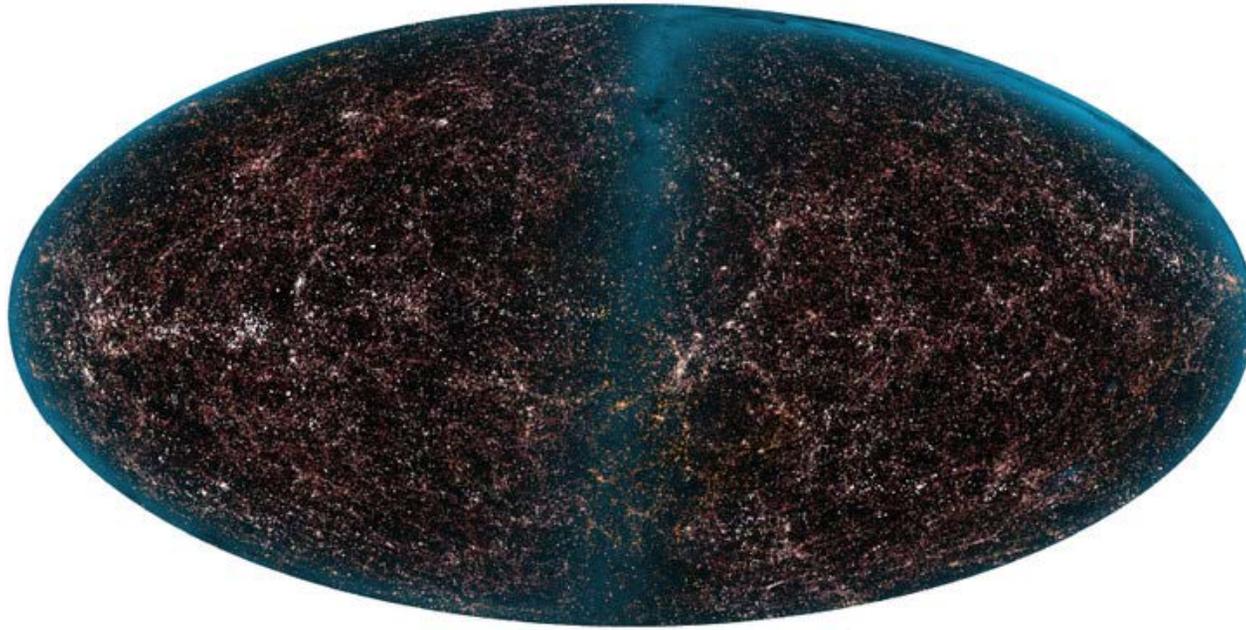


The rate of pair production decreased as the Universe expanded but annihilation continued.

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.*

# Large Scale Structure



How did **large-scale structure** arise from the chaos of the primordial fireball?

When did **stars** first appear in the universe?

And when and how did **galaxies** first form?

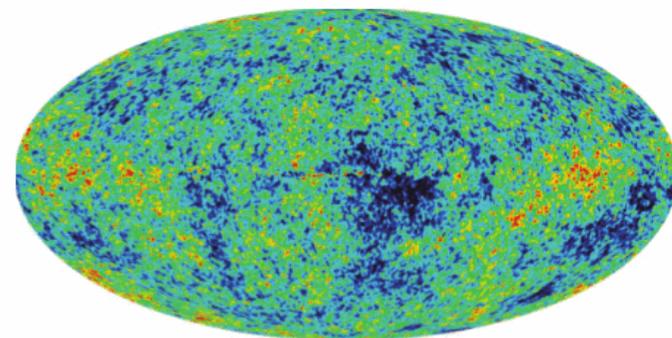
# The Origin of Large Scale Structure

**Density fluctuations** in the distribution of matter are thought to have originated in the very early universe, even before the inflationary epoch.

Very small **quantum fluctuations in density**, which are required by the Heisenberg uncertainty principle, were stretched during inflation to appreciable size.

Through the action of gravity, fluctuations that are longer than some length (**Jeans Length**) initiate the clumping that eventually grew to become the galaxies and clusters of galaxies that we see today throughout the universe.

*The density fluctuations became imprinted on the cosmic background radiation during the era of recombination.*



-200    -100    0    +100    +200  
Temperature difference from average ( $\mu\text{K}$ )

# The Dark Ages and the First Stars

The first stars (**Population III**) are thought to have formed about 400 million years after the big bang.

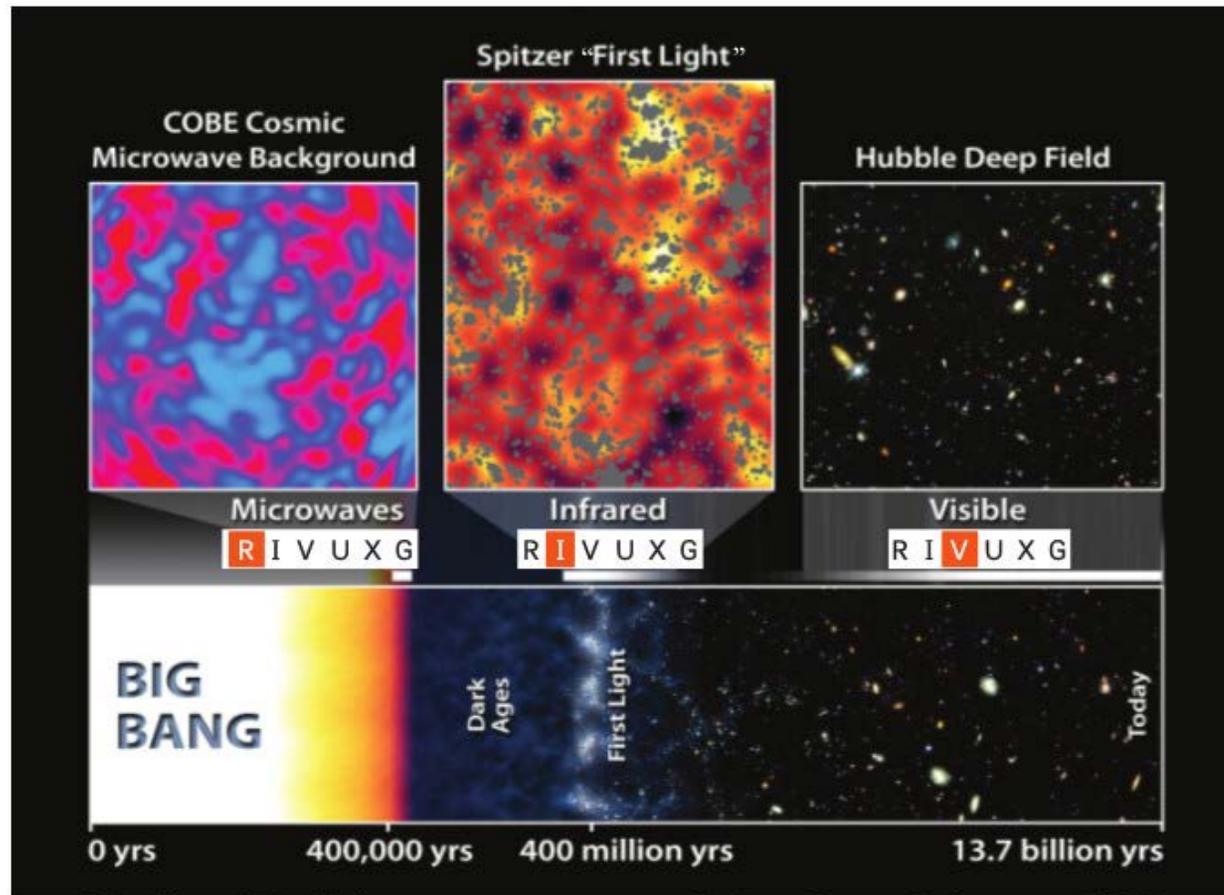
The were composed almost exclusively of hydrogen and helium atoms.

Calculations show that Pop III stars had masses from 30 to 1000  $M_{\odot}$

Between the recombination era (380,000 years after Big Bang) and the formation of the first stars (400 million years after the Big Bang) the Universe was dark (**THE DARK AGES**).

The first stars may have contributed to reionizing the hydrogen in the Universe and making the Universe transparent.

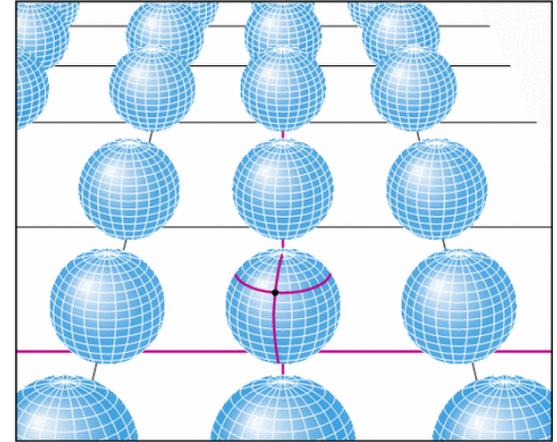
# The Dark Ages and the First Stars



The oldest light that we can see today is the cosmic background radiation, which comes from a time 380,000 years after the Big Bang. This light has  $z = 1100$  and appears in the microwave spectrum. Some 400 million years later at  $z = 11$  the first stars appeared; their light is now redshifted to infrared wavelengths. Galaxies formed more recently and can be seen at visible wavelengths

# A Universe with 11-Dimensions

Membrane theories no longer regard fundamental particles, such as electrons and quarks, as tiny points of mass. Instead, these particles may actually be **multidimensional membranes**, wrapped so tightly around the extra dimensions of space that they appear to us as points.



**M-theory** predicts that space has more than three dimensions.

**Gravity** unlike other forces is expected to **propagate into these extra dimensions** and become stronger at smaller scales.

In three dimensions gravity increases by 4 as you halve the distance between 2 objects. In 9 dimensions the force would increase by 256 as you halved the distance.

# **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**