THE BIG BANG

Sept. 12, 1997

NEEP602 Ed Churchwell

I. Observational Basis

1) Universal Expansion (The Hubble Law)

a) History-By 1912 V. M. Slipher noted that the radial velocities of many "spiral nebulae" had Doppler shifts greater than 300 km/s, the maximum found for stars in the Milky Way. K. Lundmark had also found similar results. In 1929 Hubble and in 1931, Hubble and Humason published their classic papers on the redshifts of remote galaxies. It was shown that the farther away a galaxy is from us, the greater is its redshift. Interpreted in terms of velocity, the further away a galaxy is the faster it appears to be moving away from us. Stated mathematically,

$$V_r = H_o r$$

where H_o is Hubble's constant and has units of inverse time (usually in km/s/Mpc), r is the distance of the galaxy from us, and V_r is the radial velocity of the galaxy measured from the Doppler effect.

This discovery has far reaching consequences.

1) The entire universe is expanding in the sense that the separation of galaxies increases with time.

2) It does not imply a center of the universe, only that all galaxies and clusters of galaxies are increasing their separation with time. A center would imply a preferred coordinate frame which would violate a key precept of relativity theory.

3) The Universe was earlier denser, hotter, and smaller than today.

4) Hubble's constant H_{O}, represents a maximum age of universe

Figures Here
Slide 1

2) The Abundance's of the Light Elements D, He, and Li imply the present mean density of baryons (primarily protons, neutrons) in the universe. The idea here is that during the first few

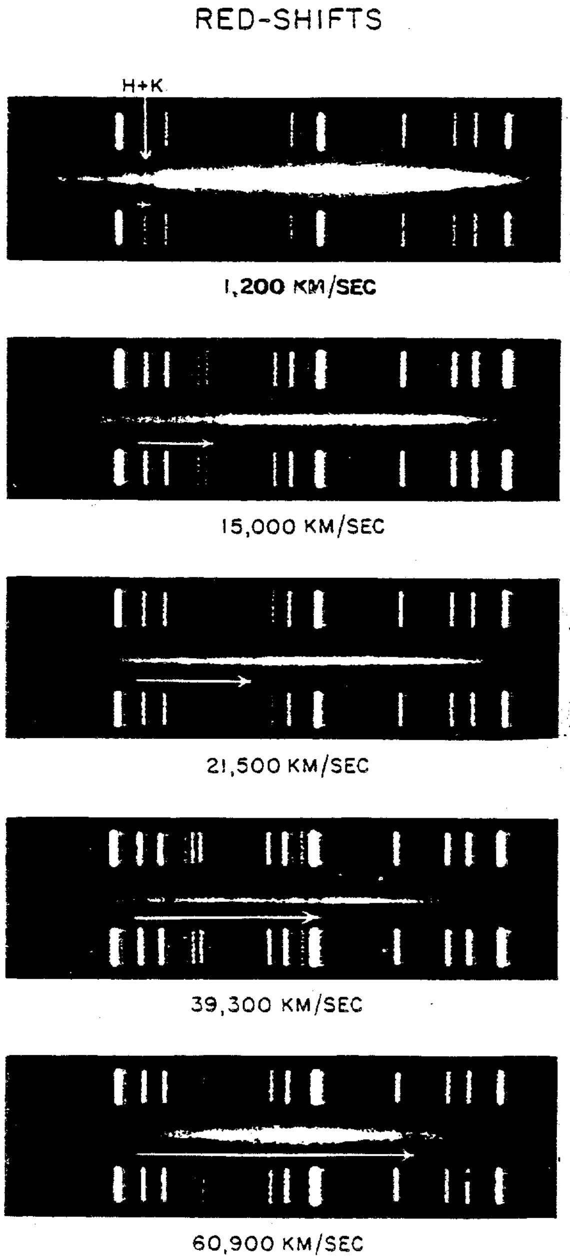


Fig. 238. The spectra of five galaxies, showing redshifts between 1,200 km/sec (23 million light-years distant) and 60,900 km/sec (1 billion light-years distant), photographed by M. L. Humason. (*Mount Wilson and Palomar Observatories*)

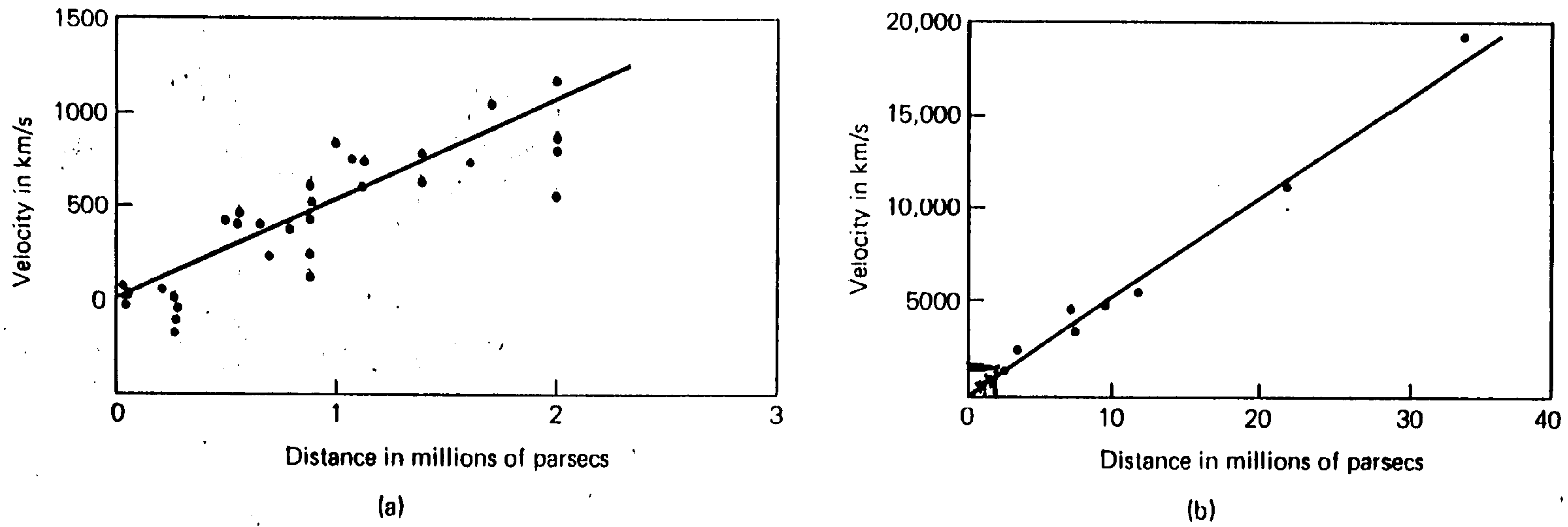
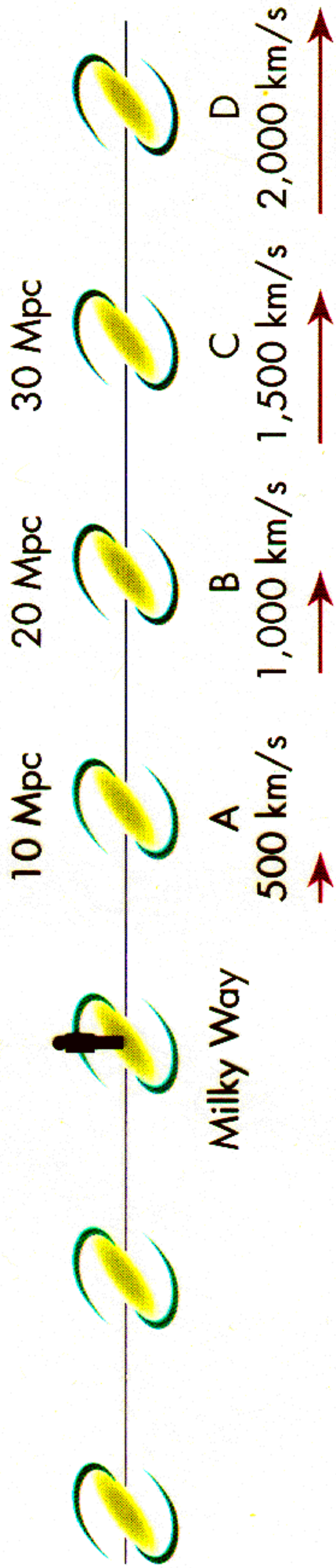


Figure 37.2 (a) Hubble's original velocity-distance relation, adapted from his 1929 paper in the *Proceedings of the National Academy of Sciences.* (b) Hubble and Humason's velocity-distance relation, adapted from their 1931 paper in the *Astrophysical Journal.* The small dots at the lower left are the points in the diagram in the 1929 paper (a).

T 226

Expanding Universe and the Hubble law (Fig. 16-4)



minutes after the cosmic fireball (Big Bang) was initiated, the universe was hot enough to initiate nuclear burning (build-up of subnuclear particles (protons and neutrons) to synthesize atomic nuclei of the lightest elements. The universe itself was literally a nuclear furnace. During this period the ratio of neutrons to protons was very sensitive to the temperature determined the relative abundance's of D, ^{3}He, ^{4}He, and Li. Determination of the cosmic relative abundance's of these elements tells us the early temperature history of the universe, it final neutron to proton ratio, and the confirms the fact that the universe went through a very hot phase at the beginning.

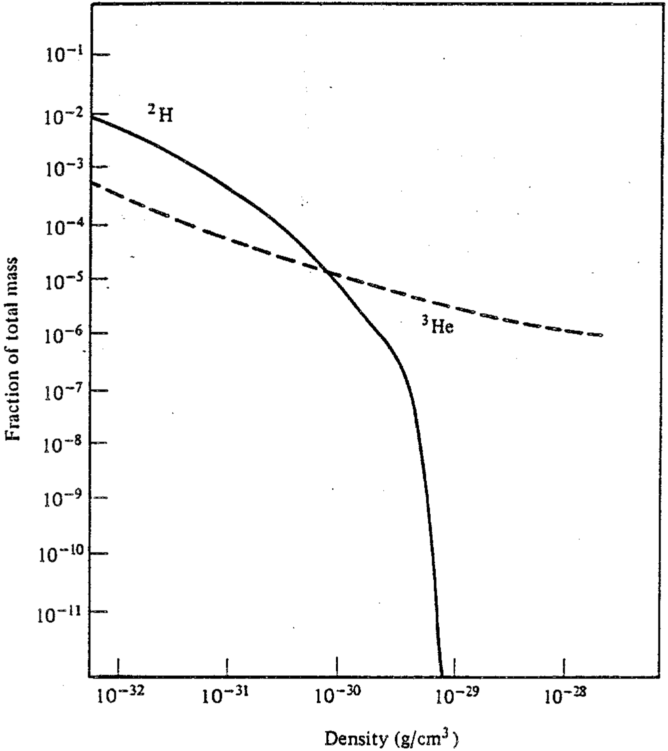
D can only be destroyed (by stellar nuclear burning) but is not created in significant abundance by any natural process. He can be made in stars and in the first few minutes of the birth of the universe. The trick is to determine the primordial abundance's of these two elements. This has been done using various clever tricks and it is found that $He/H \approx 0.10$ and $D/H \approx 1\text{-}2x10^{-5}$. These values imply that the baryonic density in the universe today is too low to close the universe. That is, the universe will continue to expand indefinitely It does not have enough self gravity to stop the expansion although the rate of expansion has been slowing down from the beginning. The universe appears to be unbound. This is true even if one adds in the "dark" matter which accounts for 90% of all the mass in the universe. One can also show that the observed abundance's of the light elements cannot have been primarily produced in stars and therefore had to have been produced in the Big Bang which required that the early universe had to have been very hot and very dense.

2 overheads

3) The cosmic background radiation (CBR)

In 1965 Penzias & Wilson of Bell Labs reported detection of an approximately 3 K background radiation that seemed to be the same in all directions in the sky. In the meantime this has been refined and frequency coverage extended by many other observers, the most recent and spectacular is that of the COBE (Cosmic Background Experiment satellite) results which shows that this radiation field which fills the entire universe has a present day temperature of 2.785± 0.005 K. Its

Figure 21.10 Relationship between the abundances of deuterium (^2H) and ^3H and the density of matter in the universe. Though the actual relationship comes from the density in the first three minutes of the universe, we can relate that to the current density, so the horizontal axis is the current density. It is important to note that this is only the density of matter that participate in nuclear reactions, and doesn't include certain types of particles that have been suggested for dark matter.



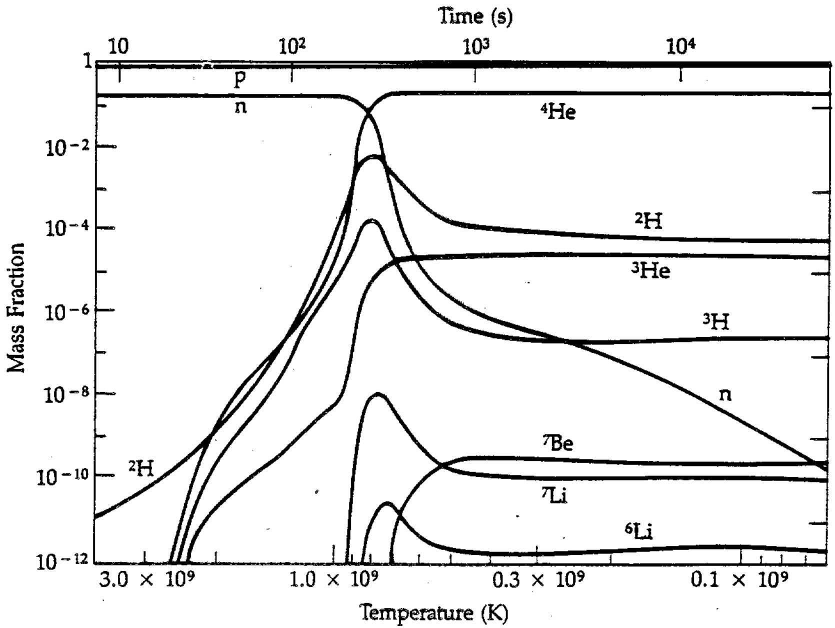


FIGURE 26–1 Nucleosynthesis in the Big Bang. The top axis gives the age of the Universe; the bottom gives temperature; the vertical axis is abundance in terms of the fraction of total mass. *(Adapted from a diagram by R. V. Wagoner)*

For a short period the Universe was a nuclear furnace.

deviations from a Planck curve (i.e. black body) is less than about a milliKelvin. This radiation is now interpreted as the doppler shifted radiation from the Big Bang at the time when the universe became transparent to optical light (about a redshift of 1000). The significance of this discovery is that it tells us the photon/baryon ratio ($\approx 10^9$ which does not change with time) and it also confirms that the universe went through an enormously hot and dense phase during its early history.

overhead

4) Deep observations of galaxies and quasars have shown that visible matter is not distributed uniformly on fairly large scales. There are superclusters of galaxies and voids where almost no matter is found. These pose some very interesting problems for cosmology.

slide

II. Assumptions

Finally, it is generally assumed that if one includes a large enough volume, that the universe would look the same to all observers no matter where they are in the universe. This is called the **cosmological principle** and is an assumption not a proven fact.

III. The Standard Model

Using the above observational constraints, and solving Einstein's field equations (equivalent to the equation of motion) with the assumption of the cosmological principle plus the application of basic physics, a model of the evolution of the universe, which has become known as a the standard model, has been constructed. This model seems to be consistent with present observational constraints. I want now to describe the predictions of this model.

First, we have to understand a little bit about the physics of annihilation and creation of matter. Einstein has shown in his theory of relativity that matter and energy are different forms of the same thing. That is, matter and energy are equivalent through his now famous equation, $E=mc^2$ where E is energy, m is mass, and c is the speed of light. However, there are strict rules on how matter and energy can be interchanged. Conversion from matter to energy occurs through the annihilation of a particle of matter and its antiparticle. For example,

$$e^- + e^+ = \text{two photons each of energy 0.511 Mev}$$

and

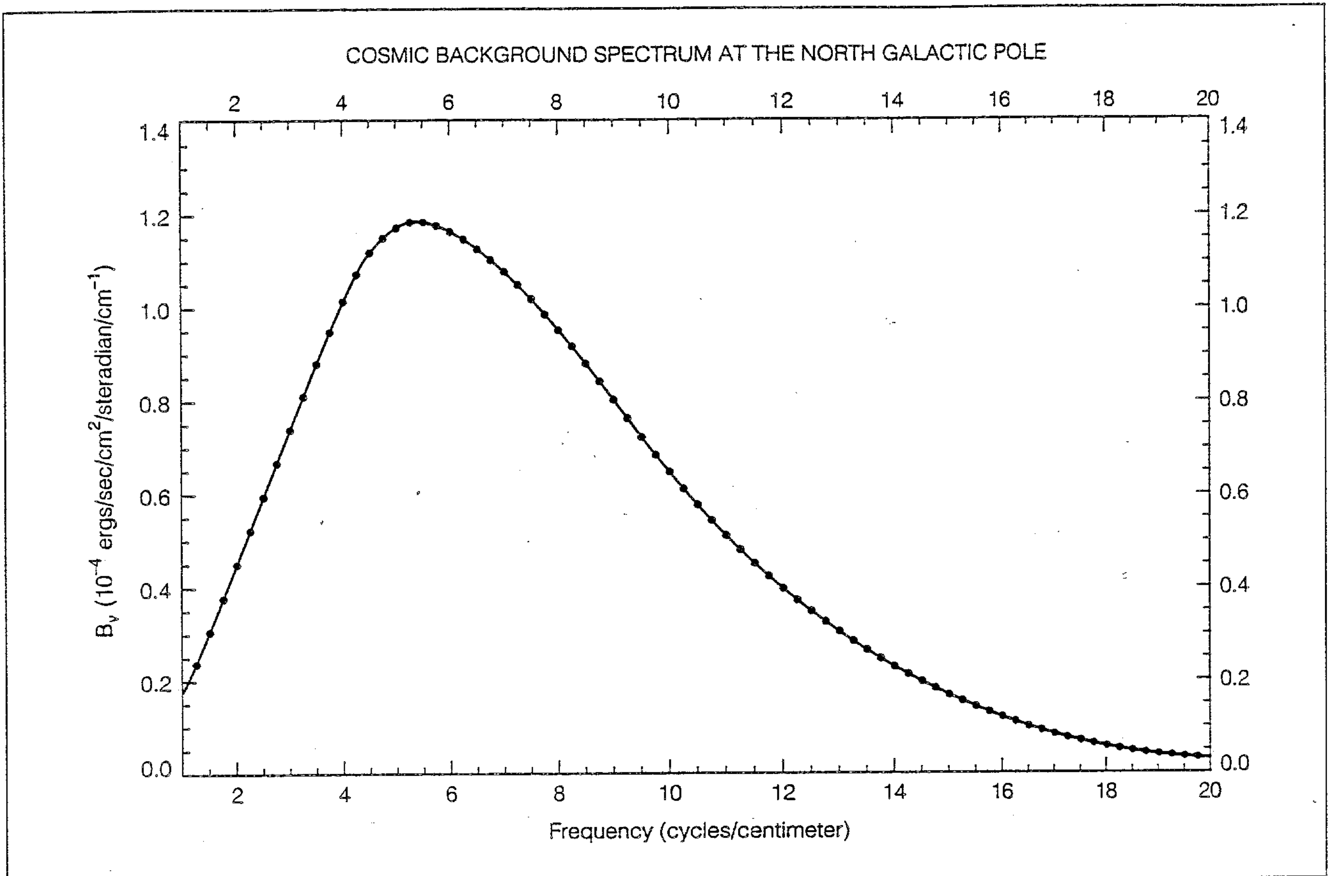
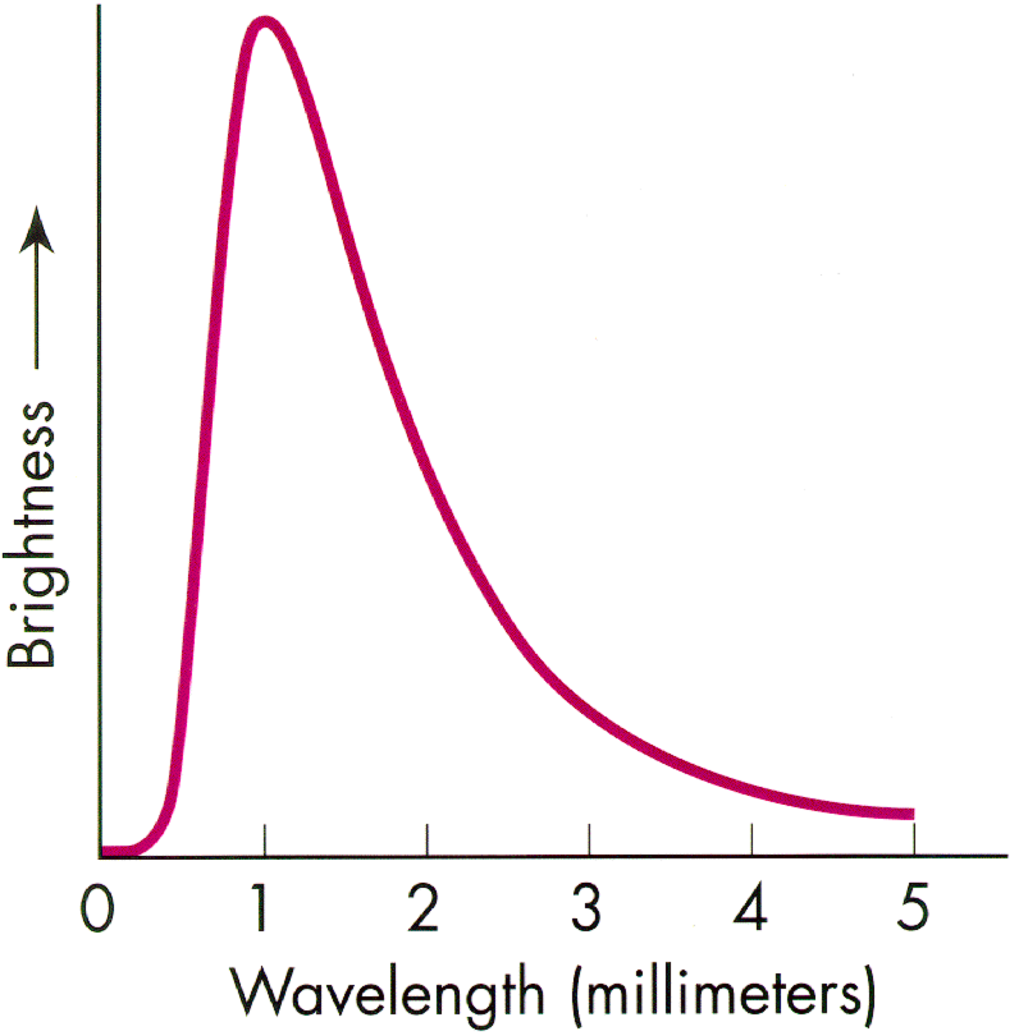


Figure 29.15 The revised cosmic background spectrum from *COBE*. *The* Cosmic Background Explorer (COBE) *has measured the background radiation at many wavelengths, as indicated by the points. The result is the most accurate measurement yet of the temperature of the radiation, which is found to be 2.735 K, derived by fitting a theoretical thermal radiation spectrum (solid line) through the points. (NASA, courtesy of the COBE Science Working Group)*

$\Rightarrow$ photon/baryon $\simeq 10^9$

T 227

Spectrum of the cosmic background radiation (Fig. 16-6)



$$p^- + p^+ = \text{two photons each of energy 938.2 Mev}$$

and

$$n + \bar{n} = \text{two photons each of energy 939.5 Mev}$$

Annihilation of matter to form energy can occur at any temperature as long as there are matching pairs of matter and antimatter particles present. The other direction, in which photons are converted to matter-antimatter pairs of particles cannot occur in empty space and can only occur if the photons have energies at least equal to the rest energy of the individual particles. This is called pair production. Here the energy of the photons have to have an energy ,

$$h\nu = 2m_0c^2 + (E^+ + E^-)$$

where $h\nu$ is the photon energy and E is the kinetic energies of the matter-antimatter particles. The important point here is that there is a threshold energy below which pair production cannot occur. Cosmologists usually denote this in terms of the equivalent temperature of the radiation field.

$\bar{E}_{rad} = \bar{E}_{th} \geq E_{rest}$ **but** $\bar{E}_{rad} = h\nu$**,** $\bar{E}_{th} = kT$ **, and so that** $T \geq m_o c^2 / k$

The threshold temperature for pair production of neutrons is 1.090E13 K and for protons it is 1.088E13 K, and for electrons it is 5.930E9 K. Once the temperature of the universe drops below any of these thresholds, it becomes impossible for more of that particular particle to be produced by the universe. As the cosmologists say, they "freeze out" of the universe. Then the matter and antimatter particles will annihilate each other until there are no more of one or the other particle. That remaining represents the initial imbalance in the number of matter and particles. In this case, we know from the CBR that the net imbalance was about 1 more matter than antimatter particle for every billion pairs. Now let's look at the conditions in the universe as a function of time according to the current best model of the Big Bang.

IV. Evolution of the Universe

Reference: "The First Three Minutes" by Steven Weinberg
Basic Books, NY

"Introductory Astronomy & Astrophysics" Zeilik, Gregory, and Smith, 3rd Edition, 1992
Saunders College Pub.

Problem: At the very beginning of the universe, temperatures and densities were so high that we are not sure how particles interacted with each other, also the four forces (electromagnetic, strong, weak, and gravity) were probably a single unified force rather than the 4 separate forces that we know today. Gravity is believed to have separated out as a separate force at about 10^{-45} s. Before this, there was only one force that controlled the interactions of particles. We will begin the story at 10^{-35} secs after the initial fireball.

<u>Time=10^{-35} s</u>
$T \approx 10^{27}$ K

The universe is a soup of matter, antimatter and radiation which interact freely and rapidly with each other. It is in a state of ~perfect thermal equilibrium (i.e. all particles including radiation are at the same temp). Total charge, baryon number, and lepton number are all very very small or zero. All particles freely interact with each other. The rate between pair production and annihilation are equal.

Contents: photons, electrons, positrons, quarks, antiquarks, neutrinos, and antineutrinos

At this time the quarks and antiquarks begin to annihilate, leaving behind a small residual of quarks but no antiquarks. These will later combine to form neutrons and protons. The imbalance between matter quarks and antiquarks is believed to have occurred due to several processes that violated charge-parity conservation.

<u>Time=10^{-32} s</u>
$T \approx 10^{21}$ K

The temp is still too high for protons and neutrons to be stable. Period of inflation ends. The universe has increased in size by a factor of 10^{24}. In some theories it went from 10^{-23} cm to about 10 cm in the period from 10^{-35} sec to 10^{-32} sec.

<u>Time=10^{-12} s</u>
$T \approx 10^{15}$ K

The weak nuclear and electromagnetic forces separate. Neutrons and protons are stable and freely interact with radiation.

<u>Time=0.01s</u>

The universe has cooled to a temp of 10^{11} K (100,000 million). The temp is already below the threshold temps of neutron, and proton pair production and they and their antiparticles are rapidly disappearing from the universe (freezing out).

$\rho \approx 3.8 \times 10^{9}$ gm/cm^3 (energy plus matter)-if Mt Everest were made of matter this dense, it would destroy the Earth by tidal forces.

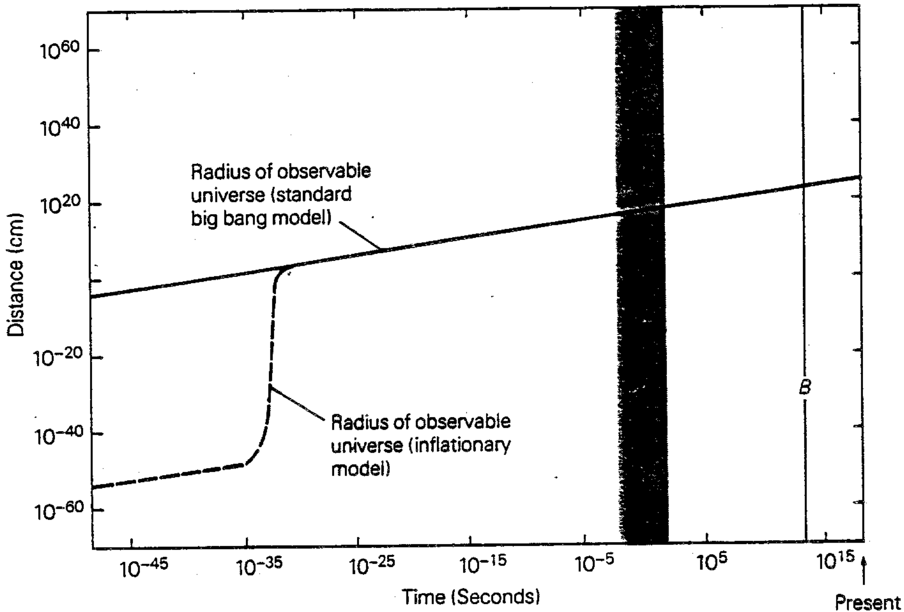


Figure 37.13 Radius of the observable universe as a function of time for the standard big bang model (solid line) and for the inflationary model (dashed line). The two models are the same for all times after 10^{-30} second. Electrons, positrons, and the lightest atomic nuclei are formed during the time interval labeled *A*. The universe becomes transparent to radiation at the time designated *B*.

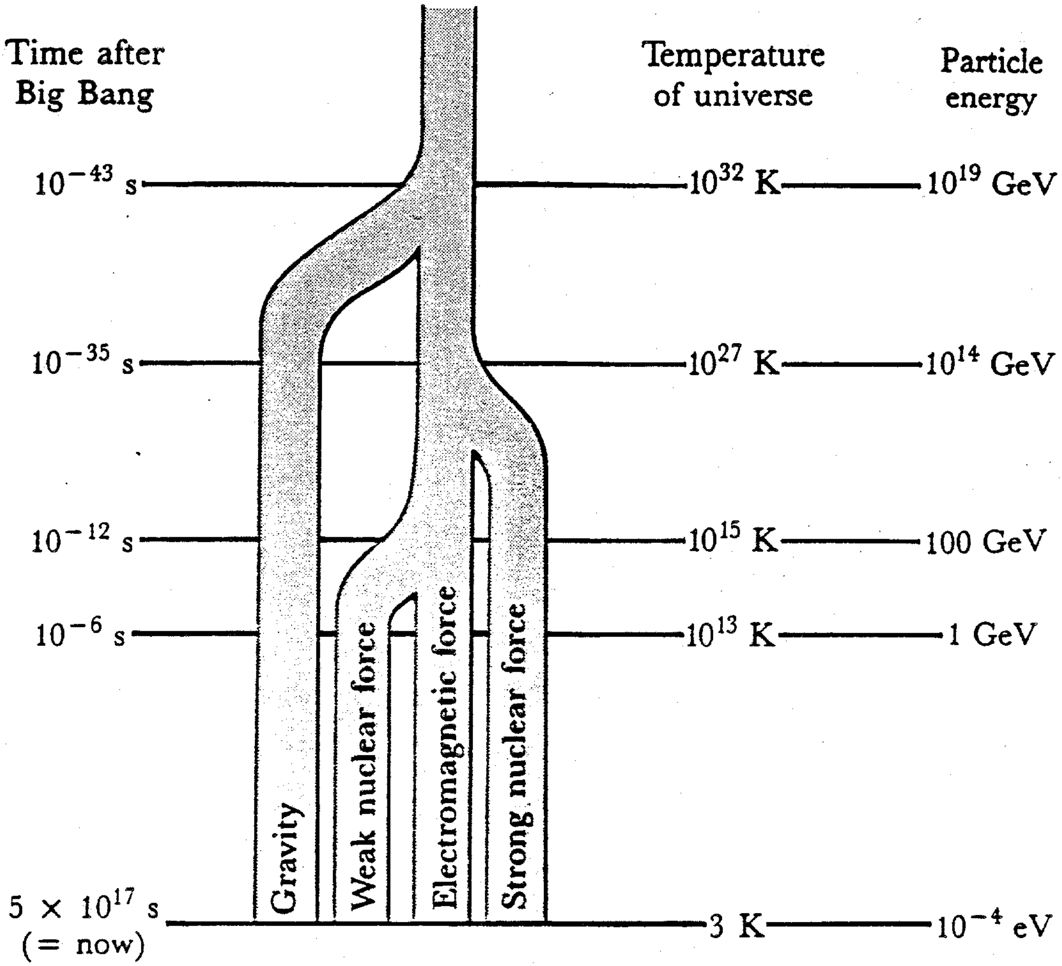


Figure 29-6 Unification of the four forces The strength of the four physical forces depends on the speed or energy with which particles interact. As shown in this schematic diagram, the higher the energy, the more the forces resemble each other. Also included here are the temperature of the universe and the time after the Big Bang when the strengths of the forces are thought to have been equal.

The doubling time for the universe is about 0.02 secs.

At this time there are about 10^9 photons, electrons, and neutrinos for every proton and every neutron.

$N(n) \sim N(p)$

Size of universe? Don't really know, but if use present value of H and assume present density is about 2 time critical, then present circumference is about 1.25×10^{11} ly and the size at 0.01 s would be $3K/10^{11}K$ times smaller then than now (~4 ly)

<u>Time=0.11s</u>

$T = 3 \times 10^{10}\ K$

Contents of universe = electrons, positrons, neutrinos, antineutrinos, and photons

All particles are in thermal equilibrium and all above their threshold temps (except for the small number of neutrons & protons).

Energy density $\propto T^4 \Rightarrow \rho \approx 3 \times 10^7$ gm/cm^3 (30 million times denser than water)

Doubling time of universe is about 0.2 secs.

Rate of expansion continues to slow down.

As T decreases, it becomes easier for heavier neutrons to turn into protons than vice versa $\Rightarrow$ the number of neutrons decrease relative to the number of protons. N(n)~38% of nuclear particles and N(p)~62%.

<u>Time=1.09 s</u>

$T = 10^{10}\ K$ This is about twice the threshold temp of electrons and positrons and they are beginning to annihilate more rapidly than they can be created out of radiation. It is still too hot for neutrons and protons to bind into atomic nuclei.

$\rho \approx 3.8 \times 10^5$gm/cm^3. At this density and temp. the mean free path of neutrinos and antineutrinos have become large enough that they are beginning to decouple from the rest of the matter and radiation in the universe and they therefore are no longer in thermal equil with the electrons, positrons, and photons.

Doubling time ~2 secs

Decreasing temp has allowed the proton-neutron balance to become ~24% neutrons and ~76% protons.

Time=13.82 secs

$T=3x10^9\ K$ This is below the threshold for electrons and positrons and they are rapidly disappearing from the universe (via annihilation). This adds 0.511 Mev of energy per annihilation and slows the rate of cooling of the universe until the process is completed.

Since the neutrinos have decoupled from the rest of the particles in the universe, they do not share in the heating by elec-pos annihilation and are therefore about 8% cooler than the rest of the particles in the universe. From this point on when we refer to the temp of the universe, we will mean the temp. of the photons only.

Temp is still too high for D nucluclei to be stable $\Rightarrow$ no atomic nuclei yet.

Neutrons are still being converted to protons and the present values are N(n)~17% and N(p)~83%

Time=3 min and 2 secs

$T=10^9\ K$ (about 70 times hotter than the center of the Sun). The temp is now low enough that stable nuclei such tritium, ^3He, and ^4He can exist but deuterium is still too short-lived to allow significant amount of heavier atomic nuclei to be built up. Thus, still not atomic nuclei exist.

$\rho \approx 38$ gm/cm^3, about 38 times that of water.

By this time the electrons and positrons have mostly disappeared and the main constituents of the universe are neutrinos, antineutrinos, and photons. A tiny trace (one for every 10^9 photons) of neutrons, protons, and electrons are also present but they are insignificant relative to the photons and neutrinos.

The energy released by electron-positron annihilation has given the photons a temperature 35% higher than that of the neutrinos.

Free neutrons are beginning to decay to protons, electrons, and antielectron neutrinos, further reducing the neutron/proton ratio which has been decreasing all along via the reactions

$$\bar{v} + p \leftrightarrow e^- + n \quad \text{and} \quad v + n \leftrightarrow e^- + p$$

both of which favor formation of the neutron at lower temperatures because it takes more energy to form the neutron which is slightly more massive than the proton.

The n/p balance is now 14% neutrons and 86% protons

Time=3 min and 46secs

$T=9\times10^8\ K$ The temperature has now declined to a low enough value that deuterium is stable. Once this occurs, it is possible for heavier atomic nuclei such as Li, helium, Be, and B to be formed. Because of the formation deuterium and synthesis of heavier nuclei, the free neutrons are rapidly incorporated into atomic nuclei where they are safe from further decay and so the n/p ratio is fixed. The n/p ratio at this point will determine how much He and D can be made in the Big Bang. If n/p is about 0.15 and most neutrons -> He, then $He/H \approx 2x(n/p) \approx 26-28\%$ by mass.

Time=34 min 40 secs

$T=3\times10^8\ K$ The density is now too low to support nuclear processing, even though the temperature is high enough. All elements capable of being produced in the Big Bang have been made.

$e^- - e^+$ are completely annihilated leaving only the small residual of e- (1 in 10^9 of the original number). The same is also true of neutrons and protons, all that is left is the small matter-antimatter imbalance.

The main constituents of the universe are photons, neutrinos, and antineutrinos. The number of electrons=number of protons. No stable, neutral atoms exist yet because it is too hot.

$T_{photon} \cong 1.40 T_V$

$\rho \approx 9.9$ gm/cm^3 About 31% of the energy density is in neutrinos and antineutrinos and about 69% is in photons.

The doubling time of the universe at this time is about 1.5 hours

Time= 7×10^5 years

T~3000 K At this temperature the universe is cool enough for electrons to combine with atomic nuclei to form stable atoms. At this time the universe becomes transparent to photons and matter decouples from the radiation. This marks the change from a radiation to a matter dominated universe.

$\rho \approx 9.9\times10^{-20}$ gm/cm^3

Time= 10^8-10^{10} years

Galaxies formed including stars and planets.

The universe becomes very cold and the average density is at least 19 orders of magnitude less than the air we breath.

V. Problems with the Standard Model

1) Why the imbalance between matter and antimatter in the early universe? That is why are we here? This is believed to have occurred at about 10^{-36} sec after the Big Bang in the period when quarks were annihilating (which initiated inflation). It is believed that a number of processes that violated charge-parity conservation rules resulted in the annihilation of most of the quarks. Only about 1 in 10^9 quarks survived and no antiquarks survived. This, however, still requires more experimental confirmation.

2) The horizon problem: This has to do with the incredible constancy of the CBR. It is the same temperature in every direction in the sky to a very high accuracy. If one looks back at the universe at earlier times, one realizes that two patches separated by large angular distances could never have been in "causal contact". That is, there is no way that one patch could have communicated its temperature to that of the other patch and there is absolutely no reason why they should be precisely the same temperature. One way around this is the suggestion that the early universe went through a period of rapid expansion called the **inflation period**. During this period from about 10^{-35}-10^{-33} secs the universe expanded by a factor of about 10^{50}! Prior to this period all parts of the universe were in causal contact.

3) The flatness problem: This has to do with the question of why the universe appears to be so near the critical density for closure. The name comes from the fact that at the critical density, the curvature of the universe (which specifies its geometry) would be zero, hence a "flat" universe. Any departure from flatness in the early universe would be magnified by many orders of magnitude due to expansion. In fact, the density found today must have been within 1 part in 10^{49} of the critical density. If an inflationary epoch did occur, it requires flatness and it would therefore solve the flatness problem as well as the horizon

problem, but inflation is not yet confirmed by observations at the moment.

4) Where did galaxies come from? The CBR is so smooth, it is very difficult to understand how galaxies began to form. To form a galaxy it is necessary to have matter coagulate or clump into clouds of density greater than the ambient average density. One would expect to see some evidence of this in the CBR distribution on the sky. Until recently this was not detected. Now it appears that there are some "ripples" in the brightness distribution of the CBR. The question now is: are the fluctuations in the CBR large enough to possibly understand galaxy formation.

5) Grand Unified Theories (GUTs)
Prior to about 10^{-35} secs, it is postulated that the four forces of nature that we know today were combined or unified into a single force. That is the forces today are different aspects of a single unified force which under extreme density and temperature operates as a single force. These were decoupled into separate forces as the universe expanded. What is the nature of this force and is there any way we can establish the validity of this hypothesis?

6) What is the role and nature of dark matter in the evolution of the universe?

7) Age of the universe? This is tied up with evaluating the Hubble constant. It has to be larger than the ages of the oldest stars but less than that implied by the minimum experimental value of H.

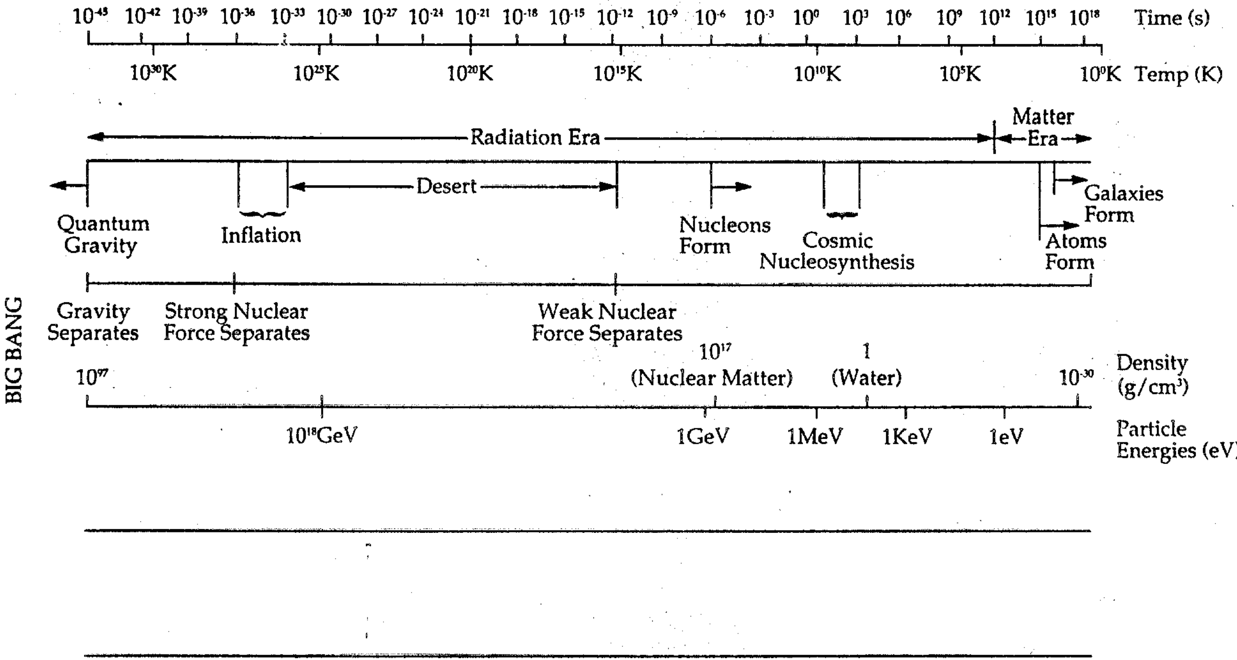
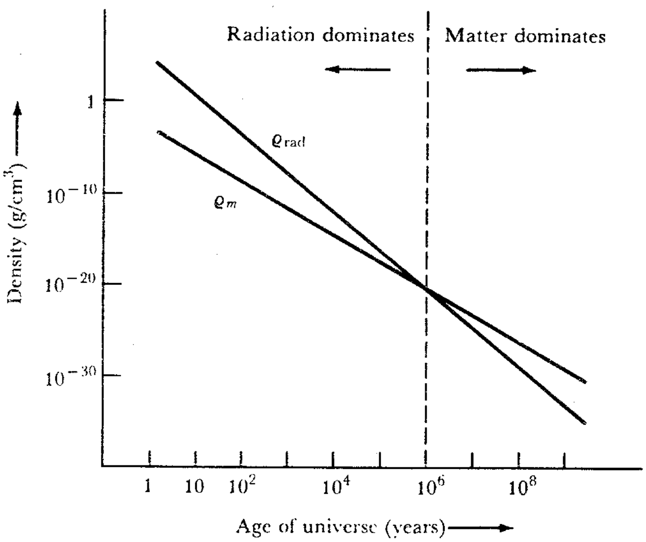


FIGURE 26–2 History of the Universe. All the horizontal axes are actually coincident. The history proceeds from the Big Bang on the left to today on the right.

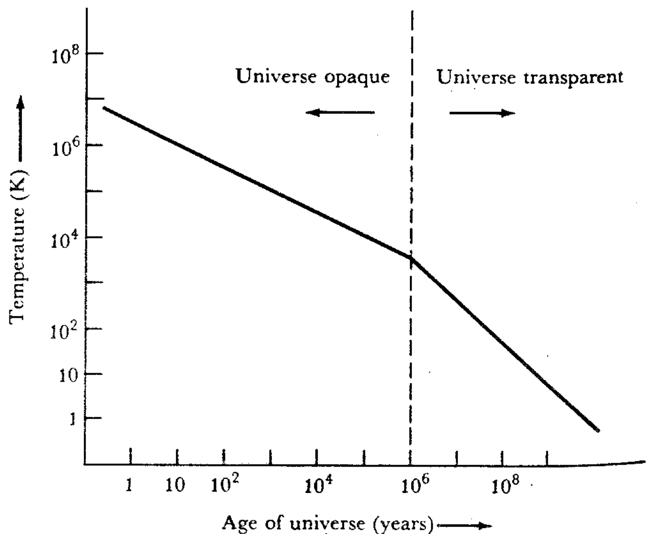
Figure 28-8 [left] The evolution of density
During the first million years, the mass density of radiation (ρ_{rad}) exceeded the matter density (ρ_m), and the universe was radiation dominated. At later times, however, continued expansion of the universe caused ρ_{rad} to become less than ρ_m and the universe became matter-dominated.

Figure 28-9 [right] The evolution of temperature
As the universe expands, the photons of the radiation background become increasingly redshifted, and thus the temperature of the radiation falls. Roughly 1 million years after the Big Bang, when the temperature fell below 3000 K, hydrogen atoms formed, and the radiation field "decoupled" from the matter in the universe.

$z = 1000$



$z \simeq 1000$



$\rho_{rad} \propto \frac{1}{R^4}$

$T \propto \frac{1}{R} \propto t^{-1/2}$ rad.

$t^{-2/3}$ matter

$\rho_{mat} \propto \frac{1}{R^3}$

$R \propto t^{2/n} = t^{1/2}$ - rad.

$t^{2/3}$ - matter

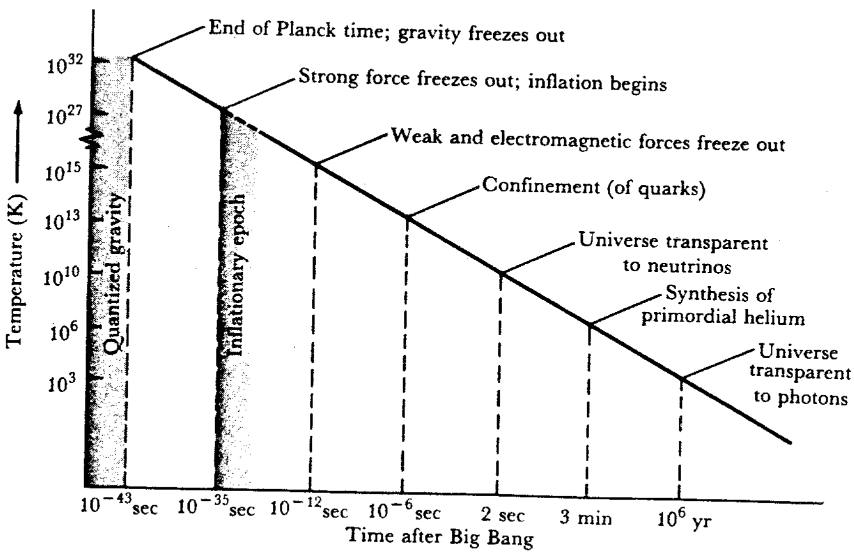


Figure 29-7 The early history of the universe
As the universe cooled, the four forces "froze out" of their unified state as a result of the spontaneous symmetry breaking described in the text. The inflationary epoch lasted from 10^{-35} sec to 10^{-24} sec after the Big Bang. (Adapted from David Schramm)

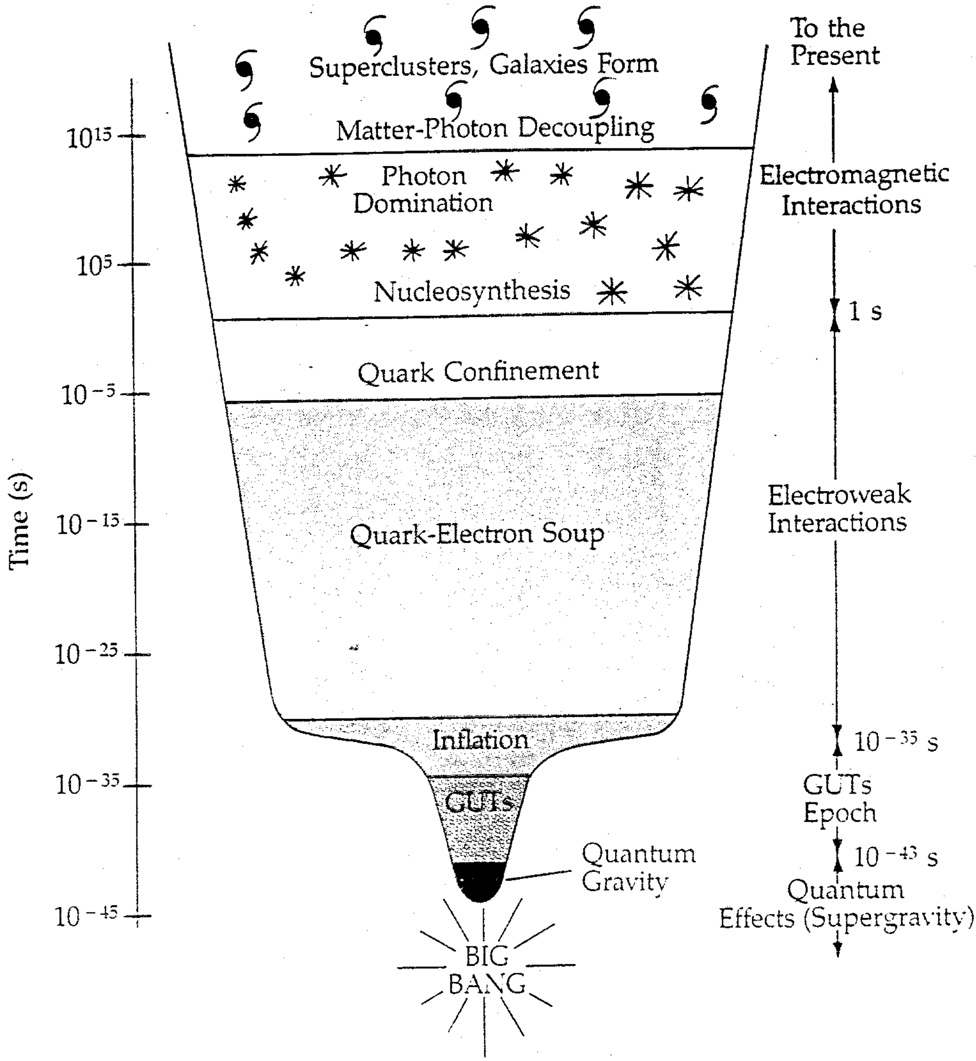


Figure 24–9

A schematic history of the early Universe. The first second of the Universe's history involved uncertain physical processes. General relativity and quantum mechanics have not yet been unified; that attempt is called supergravity. During the first 10^{-43} s, quantum fluctuations of spacetime may have generated the seeds for the growth of later structures. After this time, gravity froze out, while the other three forces remained unified. After 10^{-35} s, the electroweak forces froze out; this process somehow drove the inflation. After the inflation era, the Universe contained a hot soup of interacting quarks and electrons. At 10^{-6} s, the quarks became confined in protons that then partook in nucleosynthesis. *(J. Burns)*