<u>The Big Bang Theory</u> Paragraph
(Freely modified from various Wikipedia pages)

The **Big Bang** theory is the prevailing cosmological model for the early development of the
universe. The key idea is that the universe is expanding. Consequently, the universe was
denser and hotter in the past. Moreover, the Big Bang model suggests that at some moment
all matter in the universe was contained in a single point, which is considered the beginning
of the universe. Modern measurements place this moment at approximately 13.8 billion years
ago, which is thus considered the age of the universe. After the initial expansion, the universe 1
cooled sufficiently to allow the formation of subatomic particles, including protons, neutrons,
and electrons. Though simple atomic nuclei formed within the first three minutes after the
Big Bang, thousands of years passed before the first electrically neutral atoms formed. The
majority of atoms produced by the Big Bang were hydrogen, along with helium and traces
of lithium. Giant clouds of these primordial elements later coalesced through gravity to form
stars and galaxies, and the heavier elements were synthesized either within stars or during
supernovae.

The Big Bang theory offers a comprehensive explanation for a broad range of observed
phenomena, including the abundance of light elements, the cosmic microwave background
radiation (CMBR), large scale structure, and Hubble's Law. Today, the distances between
galaxies is increasing hence, in the past, galaxies were closer together. The known laws
of nature can be used to calculate the characteristics of the universe in detail back to a
time when densities and temperatures were extreme. While large particle accelerators
can replicate such conditions, resulting in confirmation and refinement of the details of 2
the Big Bang model, these accelerators can only probe so far into high energy conditions.
Consequently, the state of the universe in the earliest instants of the Big Bang expansion
is poorly understood and still an area of open investigation. The Big Bang theory does not
provide any explanation for the initial conditions of the universe; rather, it describes and
explains the general evolution of the universe going forward from that point on.

Belgian Catholic priest and scientist Georges Lemaître proposed what became the Big Bang
theory in 1927. Over time, scientists built on his initial idea of cosmic expansion, which, his
theory went, could be traced back to the origin of the cosmos and which led to the formation
of the modern universe. The framework for the Big Bang model relies on Albert Einstein's
theory of general relativity and on simplifying assumptions such as homogeneity and isotropy
of space. In 1929, Edwin Hubble discovered that the distances to faraway galaxies were 3
strongly correlated with their red shifts. Hubble's observation was taken to indicate that
all distant galaxies and clusters have an apparent velocity directly away from our vantage
point: that is, the farther away, the higher the apparent velocity, regardless of direction. The
interpretation is that all observable regions of the universe are receding from each other.

While the scientific community was once divided between supporters of two different
expanding universe theories – the Big Bang and the Steady State theory – observational
confirmation of the Big Bang scenario came with the discovery of the CMBR in 1964, and 4
later when its spectrum was found to match that of thermal radiation from a black body.

The History of the Universe

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Inflation

The earliest phases of the Big Bang are subject to much speculation. In the most common models the universe was filled homogeneously and isotropically with an incredibly high energy density and huge temperatures and pressures and was very rapidly expanding and cooling. Approximately 10^{-37} seconds into the expansion, a phase transition caused a cosmic inflation, during which the universe grew exponentially. After inflation stopped, the universe consisted of a quark-gluon plasma, as well as all other elementary particles. Temperatures were so high that the random motions of particles were at relativistic speeds, and particle-antiparticle pairs of all kinds were being continuously created and destroyed in collisions. At some point baryogenesis, a reaction that we know little about, violated the conservation of baryon number, leading to a very small excess of quarks and leptons over antiquarks and antileptons – of the order of one part in 30 million. This resulted in the predominance of matter over antimatter in the present universe.

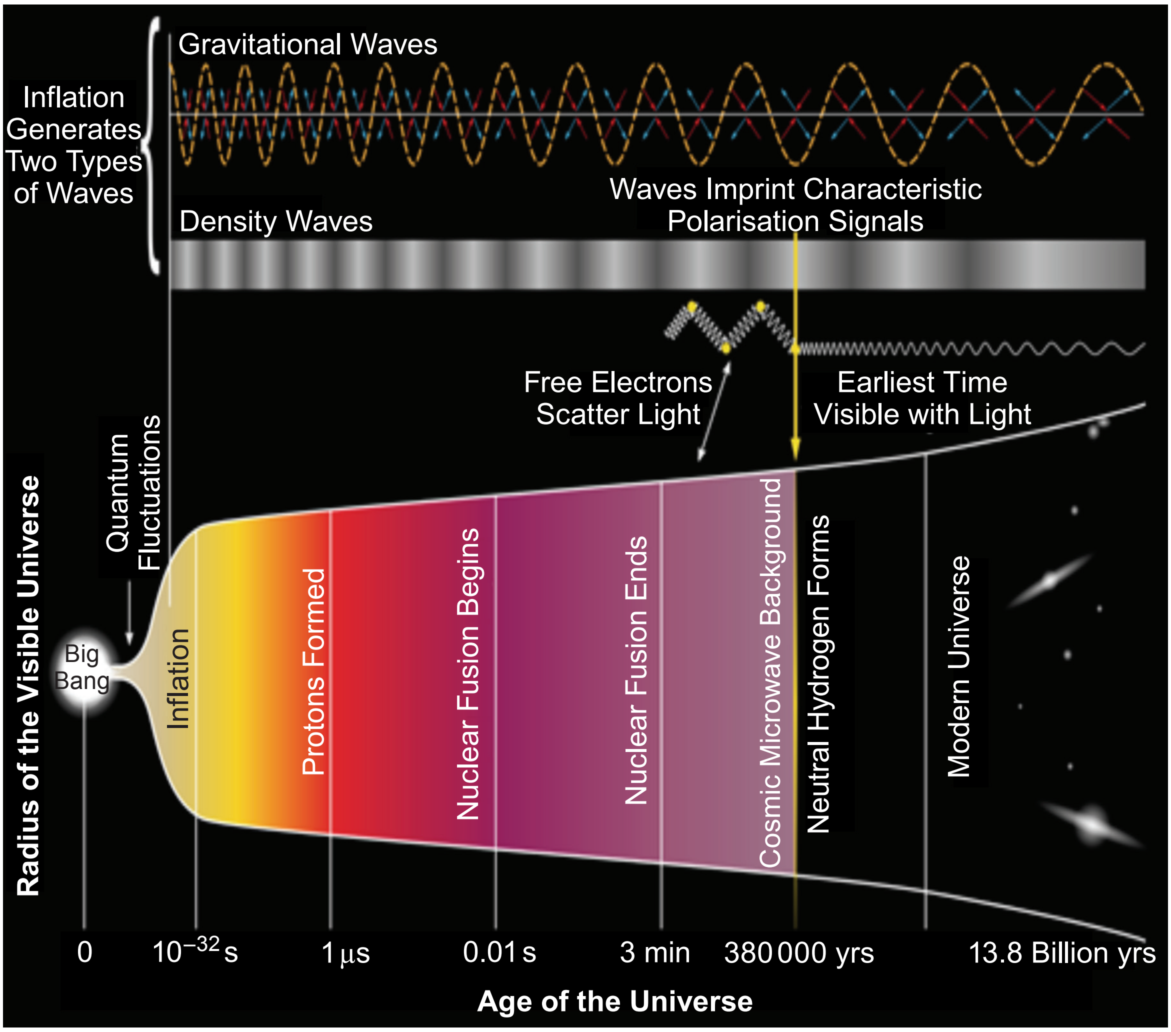

Figure 1

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Protons Forming

Paragraph

The universe continued to decrease in density and fall in temperature, hence the typical energy of each particle was decreasing. After about 10^{-11} seconds, the picture becomes less speculative, since particle energies drop to values that can be attained in particle physics experiments. At about 10^{-6} seconds, quarks and gluons combined to form baryons such as protons and neutrons. The small excess of quarks over antiquarks led to a small excess 6 of baryons over antibaryons. The temperature was now no longer high enough to create new proton-antiproton pairs (similarly for neutrons-antineutrons), so a mass annihilation immediately followed, leaving just one in 10^{10} of the original protons and neutrons, and none of their antiparticles. A similar process happened at about 1 second for electrons and positrons. After these annihilations, the remaining protons, neutrons and electrons were no longer moving relativistically and the energy density of the universe was dominated by photons (with a minor contribution from neutrinos).

Nuclear Fusion Begins and Ends

A fraction of a second into the expansion, when the temperature was about a hundred billion kelvin (100 GK), neutrons combined with protons to form the universe's deuterium and helium nuclei in a process called Big Bang nucleosynthesis. However, around 3 minutes after the Big Bang the universe had cooled further so that fusion was no longer possible. The Big Bang 7 theory itself predicts mass abundances of about 75% of hydrogen-1, about 25% helium-4, about 0.01% of deuterium, trace amounts (in the order of 10^{-10}) of lithium and beryllium, and no other heavy elements. That the observed abundances in the universe are generally consistent with these abundance numbers is considered strong evidence for the Big Bang theory.

The Universe Becomes Transparent

After about 380 000 years the universe cooled to a temperature of around 3 000 K. The electrons and nuclei combined into atoms (mostly hydrogen). This meant that radiation could travel freely without forcing free charges to oscillate and continued through space largely unimpeded. This relic radiation is known as the CMBR. It is frequently stated that the CMBR that is detected today started as gamma radiation shortly after the Big Bang. This is not 8 strictly true because these photons were scattered and absorbed a long time ago. The CMBR that we can detect now started as mainly infra-red radiation 380 000 years after the Big Bang when the universe suddenly became transparent. Although the universe previously had been hot enough to emit gamma rays (as a black body radiator), this radiation was not able to travel very far.

The Modern Universe and The Big Bang Theory

In today's universe, the earliest and most direct observational evidence of the validity of the theory are the expansion of the universe according to Hubble's law (as indicated by the red shifts of galaxies), discovery and measurement of the CMBR and the relative abundances of light elements produced by Big Bang nucleosynthesis. More recent evidence includes 9 observations of galaxy formation and evolution, and the distribution of large-scale cosmic structures. These are sometimes called the "four pillars" of the Big Bang theory.

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Observations of distant galaxies and quasars show that these objects are red shifted – the
light emitted from them has been shifted to longer wavelengths. This can be seen by taking
a frequency spectrum of an object and matching the spectroscopic pattern of emission lines
or absorption lines corresponding to atoms of the chemical elements interacting with the light.
These red shifts are distributed evenly among the observed objects in all directions. If the red 10
shift is interpreted as a Doppler shift, the recessional velocity of the object can be calculated.
When the recessional velocities are plotted against these distances, a linear relationship
known as Hubble's law is observed:

$$v = H_0 D$$ **Equation 1**

where:
- v is the recessional velocity of the galaxy or other distant object;
- D is the distance to the object;
- H_0 is the Hubble constant, measured to be $2.2685 \times 10^{-18}\ \text{s}^{-1}$.

If Hubble's law, $v = H_0 D$, is combined with a simple calculation for the escape velocity from a spherical universe, the so-called critical density of the universe can be calculated:

$$\frac{1}{2}mv_{\text{esc}}^2 - \frac{GMm}{R} = 0$$ **Equation 2**

where v_{esc} is the escape velocity of an arbitrary mass, m, which is a distance, R, from the
'centre' of the universe and M is the mass of the universe contained inside the sphere of 11
radius R (upon whose surface the arbitrary mass lies). When the volume of the sphere of
radius R is also included, this leads to:

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

The critical density, ρ_c, of the universe can be calculated from this equation and corresponds 12
to 5 hydrogen atoms per cubic metre. The observed mass of the universe (based on counting
stars) also leads to a similar value of density.

Not only can we calculate a mean density for the modern universe, we can also calculate a
mean temperature. From the CMBR, if the universe is assumed to be a black body then a 13
temperature of (2.725 ± 0.001)K is obtained. Moreover, the microwave spectrum follows a
perfect black body spectrum shape.

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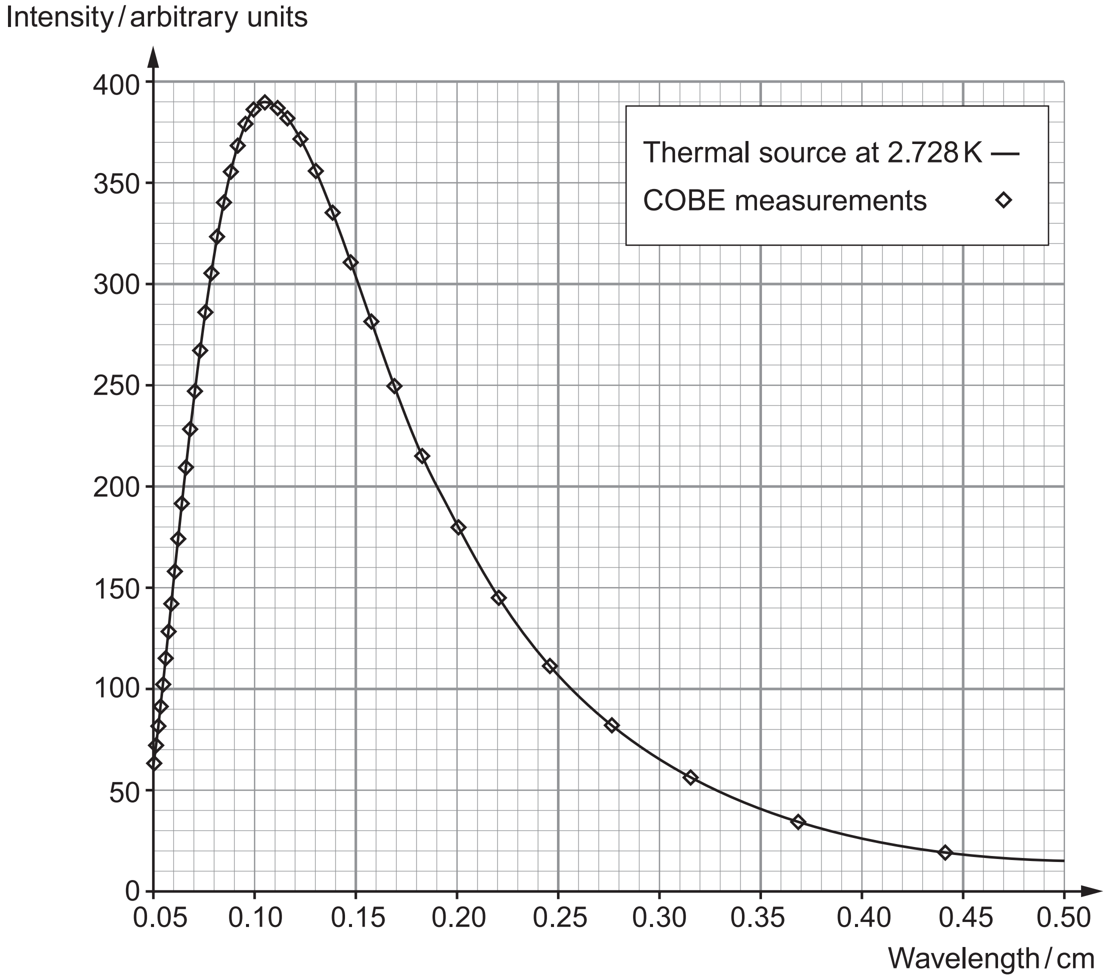

Figure 2

Since the early 1980s more and more evidence for larger scale order of matter in the universe has been discovered. Stars are organised into galaxies, which in turn form galaxy groups, galaxy clusters, superclusters, sheets, walls and filaments, which are separated by immense voids, creating a vast foam-like structure sometimes called the “cosmic web”. All these enormous scale structures have been simulated by computer and all seem to agree with the Big Bang theory. 14

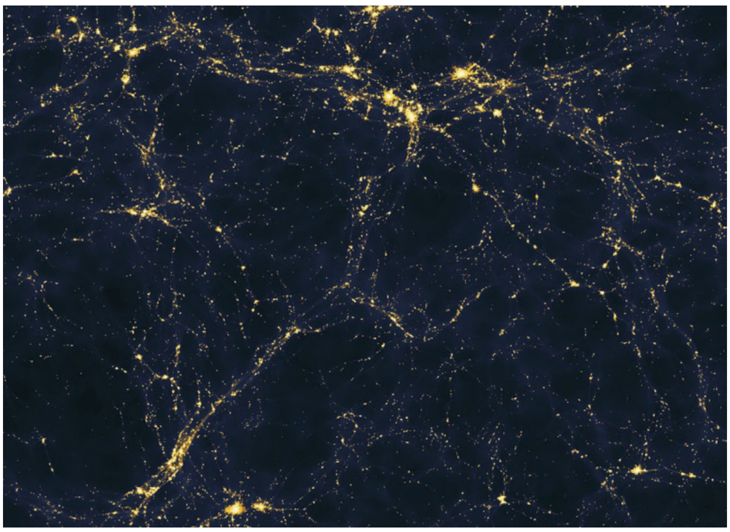

Figure 3