1 Introduction

1.1 Large-scale structure

Solar System: The sun, which is an average star is approximately 6.96×10^5 km in radius, about $109\times$ earth's radius. It weighs 1.9891×10^{30}kg, which is almost 330000 times the mass of the earth. Our solar system is roughly 9.1 billion km in diameter (taking Neptune as the farthest planet).

Star Clusters: A large group of starts that are gravitationally bound. May contain from a few hundreds to a million of starts, for example the Globular Cluster for example Omega Centuri (6 million). If a cluster contains fewer than hundred stars then gravitationally it is loosely bound and is called an open cluster. Open clusters span about a few light-years to about tens of ligh-years in radius. Other clusters may span to few hundreds light-years, for example Omega Centuri has 200 light-years radius. One light-year is 9.461×10^{12}Km.

Galaxy: It is a gravitationally bound system of stars, stellar remnants, interstellar gas clouds and dusts, dark matter etc. In the observable universe, there are estimated to be several hundred billion (two trillion 2×10^{12} according to previous estimates) galaxies. Galaxies are estimated to contain from a less than a few hundred million (100×10^6) stars (dwarf galaxies) to hundred trillion (100×10^{12}) stars (known as supergiants) with an average of 100 billion. The diameter of galaxies range from 300 light-years to about 300,000 light years across. Mass estimated to be 10^{12} the solar mass or more.

Milky Way: This is the galaxy that we live in. Estimated number of stars is 100-400 billion and the radius is about 90000 light-years. It has. also a thickness of about 700-1400 light-years.

Group, Cluster and Supercluster of galaxies: A galaxy group comprises of about 50 or fewer galaxies that are gravitationally bound. The Miliky Way is a part of the so called Local Group which contains about 50-80 galaxies. A galaxy cluster may contain from a few hundreds to about a thousands gravitationally bound galaxies, dark matter, gas clouds etc. The Virgo Cluster and the Coma Cluster are examples of galaxy clusters. The diameters of galaxy clusters range from about a million light yers $(\sim 3.26 \times 10^6)$ to about 15 million (16×10^6) light years. The galaxy superclusters may range from few hundred million to nearly thousand million light years across. Between superclusters there are voids containing only a few galaxies to no galaxies at all. These voids are spread across several hundred million light years. Due to their large distance scales, the galaxy clusters and super clusters expands with the Hubble expansion. This kind of distance scales is what we mean by "large" in the Large Scale Structure of Universe. See figure 1.

Galaxy Filaments: These are the largest known structure in the universe. It is a thread-like structure of countless galaxies, gas, dark matter, stretching million of light-years to few billion light-years. Examples include the Super-Virgo Wall (which includes our Milky Way) that stretches to about 100 million light-years, and Hercules–Corona Borealis Great Wall, ranging approximately 10 billion (10^{12}) light year across.

1.2 Units

It is probably clear to you by now that in the discussion of large scale structure of the universe, km, kg, light years, etc units are inconvenient. We will now introduce few new units of measurements. These are of mainly two classes – cosmology and astronomy units, and units of elementary particle physics.

Natural Units:

Natural units, often used in particle physics, the speed of light $c = 1$, Planck's constant $\hbar = 1$ and the Boltzmann constant $k_B = 1$. In the SI units the values are (approximately)

$$c = 2.99 \times 10^8 m/s\,, \qquad \hbar = 6.62 \times 10^{-34} Js\,, \qquad k_B = 1.38 \times 10^{-23} J/K\,. \tag{1}$$

The consequences of setting $c = 1, \hbar = 1, k_B = 1$ is that the units of time (s), length (cm in CGS), temperature (K), and mass (g in CGS) are expressible in the units of energy (erg in the CGS). In particle physics, instead of erg, the commonly used unit of energy is electron-volt or eV (1 ev $= 1.60 \times 10^{-12}$ erg). We get

$$1s = 1.52 \times 10^{15} eV^{-1}\,, \quad 1cm = 5.06 \times 10^4 eV^{-1}\,, \qquad 1g = 5.06 \times 10^{14} eV\,, \qquad 1K = 8.62 \times 10^{-5} eV \tag{2}$$

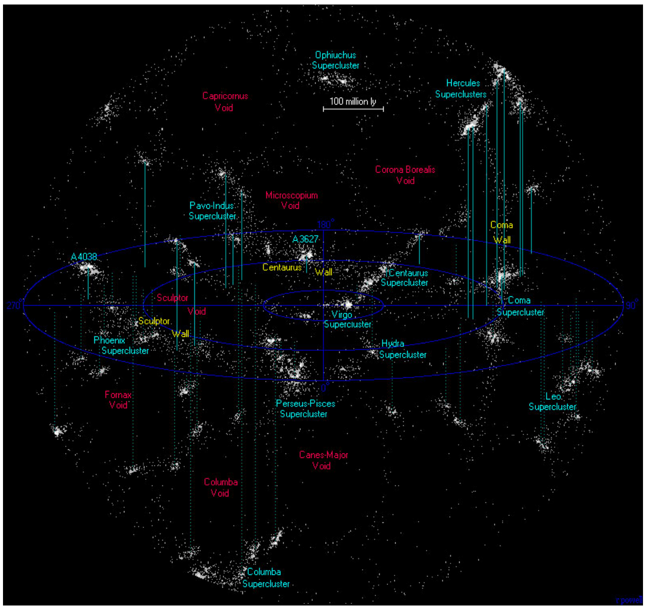

Figure 1: Super clusters and voids

Planck Units:

In the Planck units, the Newton's gravitational constant

$$G = 6.67 \times 10^{-8} cm^3 g^- 1s^{-2} = 6.70 \times 10^{-21} eV^{-2} \tag{3}$$

is set to unity, *i.e.*, $G = 1$. The fundamental units then become dimensionless. For example

$$1s = 1.85 \times 10^{43}\,, \quad 1cm = 6.18 \times 10^{32}\,, \quad 1g = 4.59 \times 10^{4}\,, \quad 1K = 7.05 \times 10^{-33}\,. \tag{4}$$

We introduce Planck time, Planck mass, Plank length, and Plank temperatures – these are the scales where the effect of quantum mechanics and (quantum) gravity both becomes important

$$t_{\rm Pl} = 5.39 \times 10^{-44} s\,, \quad \ell_{\rm Pl} = 1.16 \times 10^{-33} cm\,, \quad m_{\rm Pl} = 2.17 \times 10^{-5} g\,, \quad T_{\rm Pl} = 1.14 \times 10^{32} K\,. \tag{5}$$

It is customary to use following Plank mass unit expresses in terms of the natural units

$$m_{\rm Pl} = \frac{1}{\sqrt{G_N}} = 1.22 \times 10^{28} eV\,, \quad M_{\rm Pl} = \frac{1}{\sqrt{8\pi G_N}} = \frac{m_{\rm Pl}}{\sqrt{8\pi}} = 2.43 \times 10^{27} eV\,. \tag{6}$$

Cosmology/Astro Units:

Solar mass and luminosity are the units of mass and luminosity

$$M_\odot = 1.98 \times 10^{33} g\,, \quad L_\odot = 3.85 \times 10^{33} erg/s\,. \tag{7}$$

The units of distance measurements in solar system is Astronimical Unit (AU)

$$1AU = 1.49 \times 10^{13} cm\,. \tag{8}$$

For distance measurement beyond the solar system, light year (ly) is more convenient

$$1ly = 9.46 \times 10^{17} cm\,. \tag{9}$$

In the discussion of the large-scale structure of the universe, cosmologist use the unit of persec (pc). One pc is defined as the distance at which a 1AU subtends an angle of 1 arc-second or $1/3600^o$. With this definition

$$1pc = 3.26ly \tag{10}$$

Finally, remember the higher denomonations

$$1Mega - parsec(Mpc) = 10^6 pc\,, \quad 1GeV = 10^9 eV\,. \tag{11}$$

The universe is considered *large* at the scale of 100Mpc and beyond.

1.3 A brief History

It is observed that the universe is expanding – galaxies and galaxy clusters are moving away from each other. This observation, when extrapolated back in time, indicates that any finite volume of the universe was smaller, denser, and obviously hotter. This give rise to a 'scenario' called the Big Bang Theory. Though the word "theory" is there, it is not a a theory – it is a plausible scenario verified by experiments.

There are few misconceptions about Big Bang Theory– lets clarify them first.

- "it is the American television series" – yes, but there is more
- "universe started from Big Bang" – not true, universe was there to begin with, Big Bang was a early stage of the universe that physics can not yet explain because of high density, extreme temperture etc
- "Big Bang was an explosion at some point in space" – not true, Big Bang is not a point in space, but moment in the universe in time – Big Bang stage was everywhere. Space is itself part of the universe. Universe is infinitely large today, was infinitely large during the Big Bang. However, any finite region of the universe was extremely small during the Big Bang. For example, the observable universe is estimated to be about a few mili-meter during Big Bang.
- "universe is expanding into open space since the Big Bang" – no, universe is not expanding into anything, the space is itself a part of the universe.

There are/were scenarios other than the Big Bang Theory, for exapmle the Steady State Cosmology proposed by Hoyle, Narlikar and others. But only the Big Bang scenario is still consistent with many experimental observations.

Since we do not know anything at the Big Bang or before it, we take $t = 0$ at Big Bang. Following are important stages of the universe since $t = 0$. We will soon see that time t is not a good for tracking time – temperature (and some other observale) is more convenient – so in the following chronology we will give the temperature in the unit of GeV

- Planck time $t \sim 10^{-43}s$, $T = 10^{19}$ GeV: Physics as we know it fails at this high temperature. Quantum gravity, string theory, etc are expected to play a role at this stage. Highly active area of research – so far everything is speculative
- Inflationary stage begins, $t \sim 10^{-37}s, T = 10^{17}GeV$: Exponential expansion of the universe, governed by a unstable "inflaton" field starts. The universe expands by a factor of 10^{60} to 10^{100} between $t \sim 10^{-37}$s to $t \sim 10^{-35}$s.
- $10^{-35} - 10^{-5}s$ Quark-gluon plasma: Universe dominated by the elementary subatomic particles, quarks, gluons, phots, gauge bosons etc. Temperature is $T \sim 10^{27}$K. This stage is still speculative. Infact, no direct evidence of inflation till now.
- QCD phase transition 10^{-5}s, $T \sim 100 - 300$MeV: Quark-hadron phase transition takes place – *i.e.,* quarks bind together to form hadrons like the protons and the neutrons etc. We are almost certain that the universe had this phase – but the details are unclear.

- Big-bang nucleosynthesis, few seconds to about 3 mins: The protons and the neutrons combine for the first time to form nuclei of lightest elements D, ^{4}He, ^{3}He, ^{3}Li. Nuclei higher than the berilium was not formed at this stage. Heavier elements like iron etc where mostly synthesised in the stars that did not form until about 400 million years.
- $t \sim 10^5$s (1.2days), $T \sim$ few KeV: Photons fell out of chemical equilibrium, *i.e.,* photon's number changing reactions became slower than the rate of the expansion of the universe. The number of photons would not change rapidly following this stage
- $t \sim 10^{4-5}$yrs, $T \sim$ 3eV: Not much happens. Matter and radiation energy densities become equal. The universe starts to become matter dominated afterwards
- Recombination $t \sim 400,000$ yrs, $T \sim$eV: Recombination is the stage when the first atoms, the Hydrogen atoms, were formed. The cosmic microwave background (CMB) formed shortly after. There is a picture of this stage of the universe, see figure 2. Picture of the earlier stage of the universe is yet to exist. Probably we will have one in the future through neutrinos, and gravitational waves. Careful, though it is called recombination, no combination happened before that.
- First stars formed about 400 million years, and it took about a billion years to form galaxies. Solar system was formed 9 billion years. Today is about 13.7 billion years since the time of the big-bang – temperature is $T = 2.7$K. We will calculate this temperature

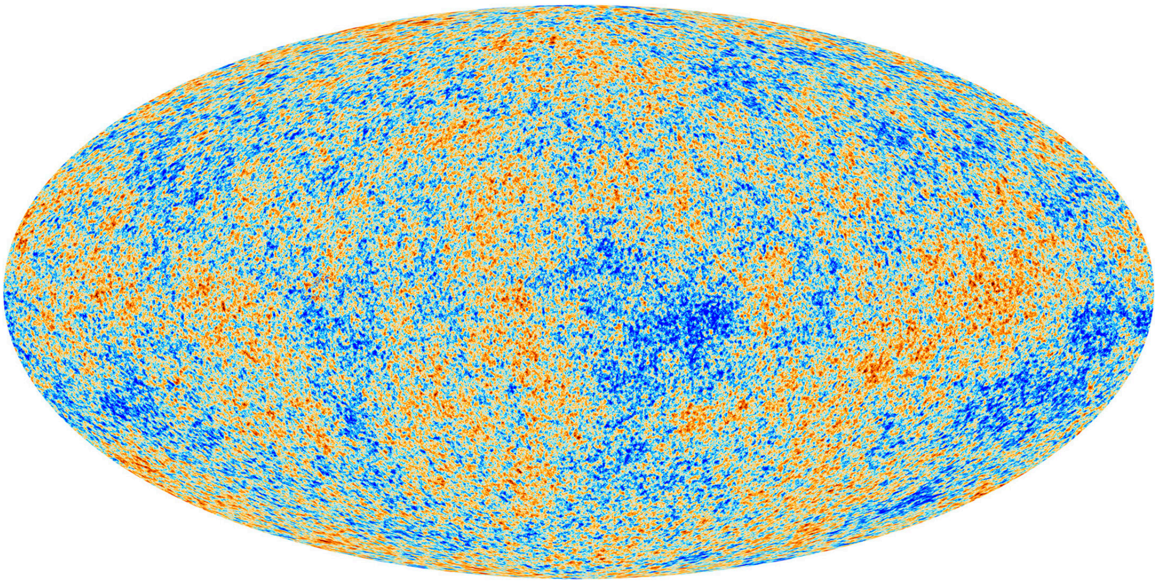

Figure 2: The cosmic microwave background (CMB) – this is how the universe looked 13.7 billion years ago. Courtesy the ESA's Planck mission.