Lec 1: 08/19/2013

Intrduction:

The subject of cosmology is our universe as a whole. There are fondamental questions arising from observation of structures of different size (galaxies, clusters, superclusters, etc), such as:

(1) How big is the observable part of the universe?

(2) How old is the universe?

(3) How did these structures form and evolve in time?

One would like to know whether these questions can be addressed within a consistent model that is based on the know laws of physics.

Cosmology undertakes the ambitious task of answering these questions within a theoretical framework describing the laws of physics.

As a "physical science", it is based on observations and measurements. The influx of high quality data, made possible by advances in technology, has revolutionized cosmology in the past few decades. Cosmology has now become an "experimental subject" where we can talk about error bars in a meaningful way. One often hears that we have now entered an era of "precision cosmology".

As theoretical framework, we use Einstein theory of general relativity. This theory provides an acceptable and well tested description of gravity, which is the main force acting at large distances relevant to cosmology.

Observational milestones that have played crucial role in leading to modern cosmology are:

(1) Expansion of the universe: Hubble, 1920's. Observation of redshift of distant galaxies confirmed a receding velocity between galaxies that linearly increases with their distance.

It estabished the notion of an expanding universe and led to the so-called "hot big-bang cosmology". Expansion means that the universe was smaller, denser and hotter at earlier times. At sufficiently early times, the universe was very small and extremely hot, such that it consisted of the most fundamental constituents of matter (i.e., elementary particles). Extrapolating back in time, such a hot universe had to start from an infinite density, which amounts to an initial singularity. General relativity breaks down at this singolarity, and a new theory (of quantum gravity) is needed to resolve this. But general relativity can nicely explain the universe right after the singularity (called big-bang) and its evolution afterwards.

(2) Cosmic Microwave Background (CMB): 1960's, 1990's, 2000's.

The discovery in the 1960's that the universe is filled with a highly isotropic background of microwave photons provided an observational pillar of big-bang cosmology. The temperature of CMB photons is 2.72°K, and the relic microwave radiation is isotropic at the level of 1 in 10^5. The anisotropy was found by COBE in 1990's, which also confirmed that the CMB photons have a black-body spectrum.

Further CMB experiments in the 2000's (notably WMAP and PLANCK) have led to considerable improvement. The CMB has turned into the holy grail of modern cosmology, which can be used to determine various parameters such as the geometry of the universe and the contribution of atoms to its density.

(3) Primordial synthesis of light elements, aka Big Bang Nucleosynthesis (BBN): calculations made in 1940's, observations started in 1970's. This is another observational pillar of the big-bang cosmology. It predicts that light elements were

synthesized in the first 3 minutes after the big-bang (~75% Hydrogen, ~25% Helium, and negligible amounts of Deutrium/Helium-3/Lithium-7). The BBN can be used to gain information about the contribution of atoms to the density of the universe, which is in very good agreement with observations and the value inferred from the CMB.

(4) Missing matter in the universe, aka Dark Matter (DM): 1930's, 1970's, 2000's. Rotation curves of the satellites of the Coma cluster (by Zwicky) and the Andromeda galaxy (by Rubin) were used as indicators that there exists more matter in the universe thant the luminous matter. There are now various pieces of evidence (weak gravitational lensing, large scale structure, and CMB) that support the existence of DM. In fact, the CMB data can now be used to infer the contribution of DM to the density of the

universe with high accuracy.

(5) Accelerated expansion of the universe (aka Dark Energy (DE)): 1990's. The luminosity-redshift relation of type Ia supernovae at high redshift $z \lesssim 1$ revealed a surprising fact about the universe: the expansion of the universe has been accelerating lately. An accelerated expansion cannot be due to know distribution of energy (such as atoms and photons). It requires a new, mysterious component that has dominated the density of the universe lately, called DE. Observations indicate tha this mysterious component makes the dominant contribution to the density of the universe at the present time.

Various observations have led to the emergence of the "Standard Model of Cosmology". This model, which is largely in agreement with data, describes the universe and its evolution by 6 parameters: baryon (atoms) density, DM, DE density, geometry of the universe (quantified by a parameter corresponding to flat, open, and closed cases), amplitude of anisotropy in the CMB temperature, and spectral index of the CMB anisotropy.

The latest results from PLANCK imply a flat universe (up to few %) with ~5% baryons, 27% DM, and 68% DE. The anisotropy in the CMB temperature is $\sim 10^{-5}$, and has a spectral index slightly less than one ~96% (hence called nearly scale-invariant).

The standard model of cosmology is currently the leading model that is in agreement with all data. There are alternatives to DM (like modified newtonian dynamics) and DE (like modified theories of gravity). However, the standard cosmological model is the simplest and leading model that can explain a broad range of observations.

That said, while being a triumph for cosmology, this model is not completely understood at a fundamental level. The nature of DM and DE are important open questions. Also, although there exists a dominant paradigm (called cosmic inflation) to explain the small and nearly scale-invariant anisotropy in the CMB, its microphysical origin still remains to be estabished. These are questions at the interface of cosmology and fundamental physics, and further data from both ends of the distance/energy spectrum can help us find answers to them.