Note For Cosmology 1

Contents

1 Introduction

Cosmology is the study of the universe as a whole, its structure, its origin, and its evolution.

Fundation:	(i) Observations	(ii) Laws of physics
Restriction:	(i) Only one universe	(ii) Single location
Open questions:	(i) Dark matter	(ii) Dark energy

The fundamental observation is the redshift of spectra which can be described by a time-dependent *scale factor* $a(t)$.

1.1 Cosmological Principle

The universe is homogeneous and isotropic.

- Homogeneous means that all locations are equal, so that the observed properties of universe are independent of your locations(x, y, z).

- Isotropic means that all directions are equal, so that the observed properties of universe are independent of the direction(θ, ϕ, ψ) you look at.

When applied to real universe, there are two variants of the cosmological principle.

- A homogeneous and isotropic model of the universe is a good approximation to the real universe at *large scales*(larger than the scale of galaxy clusters 2$\sim$10 Mpc).
- Small-scale deviations from this model are *statistically* homogeneous and isotropic.

1.2 Structure formation

There are two parts to structure formation:

- The origin of the *primordial density fluctuations* is the "seeds of galaxies".

- The *growth* of these fluctuations as we approach the present time.

1.3 Dark matter and Dark energy

Dark matter(1930s)

- Baryonic dark matter(BDM)consist of protons, neutrons and electrons. BDM is only a small fraction of DM for the fundalmental reasons of BBN and structure formation(or not enough amount loosly).
- Cold dark matter(CDM) consists of unknown particles with nonrelativistic velocity and weakly EW and Strong interaction. Hierarchically structure formation requires that most of the dark matter is CDM, or possibly WDM.

- Hot dark matter(HDM) consists of particles that travel with ultrarelativistic velocities. HDM is highly constrained by structure formation.
- Warm dark matter(WDM) is an intermediate case.

Dark energy(1990s) Unlike dark matter, which is clustered, the dark energy should be relatively uniform in the observable universe. DE can do contributions to determine the geometry and expansion history of the universe accurately with astronomical data relevant to cosmology. But DE is much more obscure than DM since there're fewer relevant observed facts to explain and subsequently less constrains.
Some possible explanation:

- Cosmological constant or vacuum energy.
- Modification of the law of gravity at large distances.

1.4 Observable Universe

The observations relevant to cosmology are mainly astronomical. There're are some observation channel:

- Electromagnetic radiation (light, X ray, 21cm line etc.)
- Cosmic rays(protons, elec- trons, nuclei)
- Neutrinos
- Gravitational wave

1.4.1 Big bang and the steady-state theory

- Steady state model(no evolution): the density of matter in the expanding universe remains unchanged due to a continuous creation of matter, thus adhering to the perfect cosmological principle.
- Big bang model(has evolution): the universe had a beginning at a finite time ago in the past; the universe started at very high density, and as the universe expands its density goes down.

1.4.2 Redshift and the Hubble law

- Definitio of *redshit* z,
$$z = \frac{\lambda}{\lambda_0} - 1 \tag{1}$$
where λ is the observed wavelength and λ_0 is the original wavelength.
- *Hubble law*
$$z = H_0 d = v \tag{2}$$
where H_0 is the Hubble constant with value $72 \pm 8km/s/Mpc$, d is the distance to the galaxy and v is receding velocity of galaxy.
- For the case $z << 1$, we have consider the *peculiar motion* v_{gal} of galaxy,
$$z = H_0 d + v_{gal}. \tag{3}$$

1.4.3 Distance, luminosity, and magnitude

- *apparent luminosity* l and *absolute luminosity* L

$$l = \frac{L}{4\pi d^2}, \tag{4}$$

  where d is our distance to the object.

- *apparent magnitude* m and *absolute magnitude* M

$$m = -2.5 \log \frac{l}{l_0}, \quad M = -2.5 \log \frac{L}{L_0}, \tag{5}$$

  where L_0 and l_0 are reference luminosities.

1.4.4 Horizon

Because of the finite speed of light and the finite age of the universe, only a finite part of the universe is observable. There're several concepts of horizon.

- *Practicle horizon* is the limit what we can *see* since the universe has been transparent only for ($z < 1090$) after recombination.

- *Particle horizon* is the distance that photon has passed in conformal time since the Big bang in terms of comoving distance. In general, the conmoving distance at a certain time t is given by

$$d_c = c\eta = c \int_0^t \frac{cdt'}{a(t')}. \tag{6}$$

  We can also express particle horizon in proper distance which means the maximum distance from which particles have traveled to the observer in the age of the universe.

$$d_p = a(t) d_c \tag{7}$$

- *Event horizon* is the largest comoving distance from which light emitted now can ever reach the observer in the future.

$$d_e = c \int_t^{t_{max}} \frac{cdt'}{a(t')}. \tag{8}$$

1.4.5 Electromagnetic channel

Earth's atmosphere is opaque except for two wavelength ranges, the *optical window* ($\lambda = 300$–$800nm$), which includes visible light, and the *radio window* ($\lambda = 1mm$–$20m$).
Observations at other wavelengths have become possible only during the past few decades, from space (satellites) or at very high altitude in the atmosphere (planes, rockets, balloons).

1.4.6 Optical astronomy and the large scale structure

There is a large body of data relevant to cosmology from optical astronomy.

- Counting the number of stars and galaxies can determine the matter density they contribute to the universe.
- Counting the number density of galaxies as a function of their distance can determine the geometry of space by using general relativity.
- Different redshifts of galaxies within the same galaxy cluster can determine their relative motions, which reflect the gravitating mass within the system(for instance, pointing to the existence of dark matter).
- Spectral lines of stars and gas clouds can determine the relative amounts of different elements and their isotopes in the universe.
- Distribution of galaxies in space and their relative velocities can tell us about the *large scale structure* of the universe.

1.4.7 Radio astronomy

Radio astronomy is a subfield of astronomy that studies celestial objects at radio frequencies.
Cold gas clouds can be mapped using the 21 cm spectral line of hydrogen, which is from the energy level transition in the hyperfine structure. The redshift of this kind of spectral line shows that redshift is independent of wavelength.

1.4.8 Cosmic microwave background

At microwave frequencies the sky is dominated by the *cosmic microwave background* (CMB), which is highly isotropic.
The electromagnetic spectrum of the CMB is the black body spectrum with a temperature of $T_0 = 2.725 \pm 0.001K$.
The redshift of the photons causes the temperature of the CMB to fall as $(1+z)^{-1}$, so that its original temperature was about $T = 3000K$. With sensitive instruments a small anisotropy can be observed in the microwave sky. This is dominated by the *dipole anisotropy*, with an amplitude of $3362.1 \pm 1.0\mu K$, or $\Delta T/T_0 = 0.001234$.