LECTURE NOTES OF OBSERVATIONAL COSMOLOGY
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Chapter 1

Chronology of the Universe

1.1 The Big Bang

The Standard Model of cosmology is based on a model of spacetime called the Friedmann-Lemaître-Robertson–Walker (FLRW) metric. A metric provides a measure of distance between objects, and the FLRW metric is the exact solution of Einstein field equations (EFE) if some key properties of space such as **homogeneity** and **isotropy** are assumed to be true. The FLRM metric is:

$$ds^2 = -c^2ct^2 + a(t)^2(dx^2 + dy^2 + dz^2) \tag{1.1}$$

Where $a(t)$ is the scalar factor, an adimensional element that characterizes the expansion of the universe. In particular, the scale factor is defined as:

$$d(t) = a(t)d_0 \tag{1.2}$$

where $d(t)$ is the comoving distance and d_0 is the comoving distance at actual time.

Pay attention! Comoving distance and proper distance are two closely related distance measures used by cosmologists to define distances between objects. *Proper distance* roughly corresponds to where a distant object would be at a specific moment of cosmological time, which can change over time due to the expansion of the universe. *Comoving distance* factors out the expansion of the universe, giving a distance that does not change in time due to the expansion of space

If the FLRW metric equations are assumed to be valid all the way back to the beginning of the universe, they can be followed back in time, to a point where the equations suggest all distances between objects in the universe were zero or infinitesimally small. (This does not necessarily mean that the universe was physically small at the Big Bang, although that is one of the possibilities.) This provides a model of the universe which matches all current physical observations extremely closely. This initial period of the universe's chronology is called the "Big Bang".

After that moment, all distances throughout the universe began to increase from (perhaps) zero because the FLRW metric itself changed over time.

1.2 The very early universe

1.2.1 Planck epoch

Times shorter than 10^{-43} *seconds (Planck time)*

The Planck epoch is an era in Big Bang cosmology immediately after the event which began the known universe. During this epoch, the temperature and average energies within the universe were so high that everyday subatomic particles could not form, and even the four fundamental forces that shape the universe — gravitation, electromagnetism, the weak nuclear force, and the strong nuclear force — were combined and formed one fundamental force. Little is understood about physics at this temperature; different hypotheses propose different scenarios. Traditional big bang cosmology predicts a gravitational singularity before this time, but this theory relies on the theory of general relativity, which is thought to break down for this epoch due to quantum effects.

1.2.2 Grand unification epoch

Between 10^{-43} *seconds and* 10^{-32} *seconds after the Big Bang*

As the universe expanded and cooled, it crossed transition temperatures at which forces separated from each other. The fields which define our universe's fundamental forces and particles also completely change their behaviors and structures when the temperature/energy falls below a certain point. These phase transitions in the universe's fundamental forces are believed to be caused by a phenomenon of quantum fields called "symmetry breaking".

Assuming that nature is described by a so-called Grand Unified Theory (GUT), the grand unification epoch began with a phase transition of this kind, when gravitation separated from the universal combined gauge force. This happened from 10^{-43} to 10^{-36} seconds after the Big Bang. This caused two forces to now exist: **gravity**, and an **electrostrong interaction**. There is no hard evidence yet, that such a combined force existed, but many physicists believe it did.

The grand unification epoch ended with a second phase transition, as the electrostrong interaction in turn separated, and began to manifest as two separate interactions, called the **strong** and the **electroweak interactions**. This happened from 10^{-36} to 10^{-32} seconds after the Big Bang when the temperature of the Universe was low enough (10^{28} K).

1.2.3 Inflationary epoch and the rapid expansion of space

Before c. 10^{-32} *seconds after the Big Bang*

At this point of the very early universe, the metric that defines distance within space suddenly and very rapidly changed in scale, leaving the early universe at least 10^{78} times its previous volume (and possibly much more). This change is known as **inflation** and it happened from 10^{-35} to 10^{-32} seconds after the Big Bang.

It is thought to have been triggered by the separation of the strong and electroweak interactions which ended the grand unification epoch. One of the theoretical products of this phase transition was a scalar field called the inflaton field. As this field settled into its lowest energy state throughout the universe, it generated an enormous repulsive force that led to a rapid expansion of the metric that defines space itself. Inflation explains several observed properties of the current universe that are otherwise difficult to account for, including explaining how today's universe has ended up so exceedingly homogeneous (similar) on a very large scale, even though it was highly disordered in its earliest stages.

The rapid expansion of space meant that elementary particles remaining from the grand unification epoch were now distributed very thinly across the universe. However, the huge potential energy of the inflation field was released at the end of the inflationary epoch, as the inflation field decayed into other particles, known as "reheating". This heating effect led to the universe being repopulated with a dense, hot mixture of quarks, anti-quarks and gluons. Remember that quarks are fundamental elements to create particles and gluons are particles of exchange of strong interactions of quarks.

After inflation ended, the universe continued to expand, but at a much slower rate. About 4 billion years ago the expansion gradually began to speed up again. This is believed to be due to dark energy becoming dominant in the universe's large-scale behavior. It is still expanding today.

1.3 The early universe

1.3.1 Electrowaek epoch and early thermalization

Starting anywhere between 10^{-22} *and* 10^{-15} *seconds after the Big Bang, until* 10^{-12} *seconds after the Big Bang*

Some time after inflation (from 10^{-32} to 10^{-22}), the created particles went through thermalization, where mutual interactions lead to thermal equilibrium. This began at a temperature of around 10^{15} K, approximately 10^{-15} seconds after the Big Bang.

The electroweak epoch was the period in the evolution of the early universe when the temperature of the universe had fallen enough that the strong force separated from the electroweak interaction, but was high enough for electromagnetism and the weak interaction to remain merged into a single electroweak interaction above the critical temperature for electroweak symmetry breaking. This happened around 10^{-12} seconds after the Big Bang.

1.3.2 The quark epoch

Between 10^{-12} *seconds and* 10^{-5} *seconds after the Big Bang*

The Quark epoch was the period in the evolution of the early universe when the fundamental interactions of gravitation, electromagnetism, the strong interaction and the weak interaction had taken their present forms, but the temperature of the universe was still too high to allow quarks to bind together to form hadrons. The quark epoch began approximately 10^{-12} seconds after the Big Bang, when the preceding electroweak epoch ended as the electroweak interaction separated into the weak interaction and electromagnetism. During the quark epoch the universe was filled with a dense, hot quark-gluon plasma, containing quarks, leptons and their antiparticles. Collisions between particles were too energetic to allow quarks to combine into mesons or baryons.

1.3.3 Hadron epoch

Between 10^{-5} *second and* 1 *second after the Big Bang*

The temperature of the universe had fallen sufficiently to allow the quarks from the preceding quark epoch to bind together into hadrons. Initially the temperature was high enough to allow the formation of hadron/anti-hadron pairs, which kept matter and anti-matter in thermal equilibrium. Following the annihilation of matter and antimatter, a nano-asymmetry of matter remains to the present day. Most of the hadrons and anti-hadrons were eliminated in annihilation reactions, leaving a small residue of hadrons. Upon elimination of anti-hadrons, the Universe was dominated by photons, neutrinos and electron-positron pairs.

Pay attention! Hadrons are subatomic particles composed by quark and antiquarks blended with strong nuclear interactions. They can be *baryons*, composed by odd number of quarks like protons and neutrons and *mesons*, composed by even number of quarks like pions and kaons.

1.3.4 Neutrino decoupling and cosmic neutrino background (CνB)

Around 1 *second after the Big Bang*

At approximately 1 second after the Big Bang neutrinos (subatomic particles of very small mass, of the family of leptons and fermions) decouple from previous plasma of particles and begin travelling freely through space. As neutrinos rarely interact with matter, these neutrinos still exist today. The neutrinos from this event have a very low energy, around 10^{-10} times smaller than is possible with present-day direct detection. Even high-energy neutrinos are notoriously difficult to detect, so this cosmic neutrino background (CνB) may not be directly observed in detail for many years, if at all. However, Big Bang cosmology makes many predictions about the CνB, and there is very strong indirect evidence that the CνB exists, both from Big Bang nucleosynthesis predictions of the helium abundance, and from anisotropies in the cosmic microwave background (CMB). One of these predictions is that neutrinos will have left a subtle imprint on the CMB.

1.3.5 Possible formation of primordial black holes

May have occurred within about 1 *second after the Big Bang*

Primordial black holes are a hypothetical type of black hole proposed in 1966, that may have formed during the so-called radiation-dominated era, due to the high densities and inhomogeneous conditions within the first second of cosmic time. Random fluctuations could lead to some regions becoming dense enough to undergo gravitational collapse, forming black holes. Current understandings and theories place tight limits on the abundance and mass of these objects. Typically, primordial black hole formation requires density contrasts (regional variations in the universe's density) of around (10%), where is the average density of the universe. Several mechanisms could produce dense regions meeting this criterion during the early universe, including reheating, cosmological phase transitions and (in so-called "hybrid inflation models") axion inflation. Since primordial black holes didn't form from stellar gravitational collapse, their masses can be far below stellar mass ($\sim 2 \times 10^{33}$ g). Stephen Hawking calculated in 1971 that primordial black holes could have a mass as low as $10^{-}5$ g. But they can have any size, so they could also be large, and may have contributed to the formation of galaxies.

1.3.6 Lepton epoch

Between 1 *second and* 10 *seconds after the Big Bang*

The majority of hadrons and anti-hadrons annihilate each other at the end of the hadron epoch, leaving leptons (such as the electron, muons and certain neutrinos) and antileptons, dominating the mass of the universe. The lepton epoch follows a similar path to the earlier hadron epoch. Initially leptons and antileptons are produced in pairs. About 10 seconds after the Big Bang the temperature of the universe falls to the point at which new lepton–antilepton pairs are no longer created and most remaining leptons and antileptons quickly annihilated each other, giving rise to pairs of highenergy photons, and leaving a small residue of non-annihilated leptons.

1.3.7 Photon epoch

Between 10 *seconds and* $47,000$ *years after the Big Bang*

After most leptons and antileptons are annihilated at the end of the lepton epoch, most of the mass-energy in the universe is left in the form of photons. (Much of the rest of its mass-energy is in the form of neutrinos and other relativistic particles.) Therefore, the energy of the universe, and its overall behavior, is dominated by its photons. These photons continue to interact frequently with charged particles, i.e., electrons, protons and (eventually) nuclei. They continue to do so for about the next $370,000$ years.

1.3.8 Nucleosynthesis of light elements

Between 2 *minutes and* 20 *minutes after the Big Bang*

Big Bang nucleosynthesis (abbreviated BBN, also known as primordial nucleosynthesis) is the production of nuclei other than those of the lightest isotope of hydrogen (hydrogen-1, 1H, having a single proton as a nucleus) during the early phases of the Universe. Primordial nucleosynthesis is believed by most cosmologists to have taken place in the interval from roughly 10 seconds to 20 minutes after the Big Bang, and is calculated to be responsible for the formation of most of the universe's helium as the isotope helium-4 (4He) (2 protons, 2 neutrons and 2 electrons), along with small amounts of the hydrogen isotope deuterium (2H or D) (1 protons, 1 neutron and 1 electron), the helium isotope helium-3 (3He) (2 protons, 1 neutron and 2 electrons), and a very small amount of the lithium isotope lithium-7 (7Li).

The amounts of each light element in the early universe can be estimated from old galaxies, and is strong evidence for the Big Bang. For example, we expect 25% of Helium inside and we observe it. However we observe a different abundance of Lithium. This is an open astrophysical questions.

1.3.9 Matter domination

From $47,000$ *to* $370,000$ *years after the Big Bang*

As the universe cools, from around $47,000$ years (redshift $z = 3600$), the universe's large-scale behavior becomes dominated by matter instead. This occurs because the energy density of matter begins to exceed both the energy density of radiation and the vacuum energy density. Around or shortly after $47,000$ years, the densities of non-relativistic matter (atomic nuclei) and relativistic radiation (photons) become equal, the Jeans length, which determines the smallest structures that can form (due to competition between gravitational attraction and pressure effects), begins to fall and perturbations, instead of being wiped out by free streaming radiation, can begin to grow in amplitude.

According to the Lambda-CDM model, by this stage, the matter in the universe is around 84.5% cold dark matter and 15.5% "ordinary" matter. There is overwhelming evidence that dark matter exists and dominates our universe, but since the exact nature of dark matter is still not understood, the Big Bang theory does not presently cover any stages in its formation.

From this point on, and for several billion years to come, the presence of dark matter accelerates the formation of structure in our universe. In the early universe, dark matter gradually gathers in huge filaments under the effects of gravity, collapsing faster than ordinary (baryonic) matter because its collapse is not slowed by radiation pressure. This amplifies the tiny inhomogeneities (irregularities) in the density of the universe which was left by cosmic inflation. Over time, slightly denser regions become denser and slightly rarefied (emptier) regions become more rarefied. Ordinary matter eventually gathers together faster than it would otherwise do, because of the presence of these concentrations of dark matter.

The properties of dark matter that allow it to collapse quickly without radiation pressure, also mean that it cannot lose energy by radiation either. Losing energy is necessary for particles to collapse into dense structures beyond a certain point. Therefore, dark matter collapses into huge but diffuse filaments and haloes, and not into stars or planets. Ordinary matter, which can lose energy by radiation, forms dense objects and also gas clouds when it collapses.

1.3.10 Recombination, photon decoupling, and the cosmic microwave background (CMB)

About $370,000$ years after the Big Bang, two connected events occurred: the ending of recombination and photon decoupling.

At the beginning, the baryonic matter in the universe was at a temperature where it formed a hot ionized plasma. Most of the photons in the universe interacted with electrons and protons, and could not travel significant distances without interacting with ionized particles. As a result, the universe was opaque or "foggy". However, when the temperature drops down to a certain value, ionized atoms began to combine to produce neutral atoms, in particular a huge amount of neutral Hydrogen atoms. This process is known as recombination.

Directly combining in a low energy state (ground state) is less efficient, so these hydrogen atoms generally form with the electrons still in a high-energy state, and once combined, the electrons quickly release energy in the form of one or more photons as they transition to a low energy state. This release of photons is known as photon decoupling. Some of these decoupled photons are captured by other hydrogen atoms, the remainder remain free. By the end of recombination, most of the protons in the universe have formed neutral atoms. This change from charged to neutral particles means that the mean free path photons can travel before capture in effect becomes infinite, so any decoupled photons that have not been captured can travel freely over long distances. The universe has become transparent to visible light, radio waves and other electromagnetic radiation for the first time in its history.

The photons released by these newly formed hydrogen atoms initially had a temperature/energy of around $\sim 4000\ K$.

Over billions of years since decoupling, as the universe has expanded, the photons have been red-shifted from visible light to radio waves (microwave radiation corresponding to a temperature of about $2.7\ K$). Red shifting describes the photons acquiring longer wavelengths and lower frequencies as the universe expanded over billions of years, so that they gradually changed from visible light to radio waves. These same photons can still be detected as radio waves today. They form the cosmic microwave background, and they provide crucial evidence of the early universe and how it developed.

Around the same time as recombination, existing pressure waves within the electron-baryon plasma—known as baryon acoustic oscillations—became embedded in the distribution of matter as it condensed, giving rise to a very slight preference in distribution of large-scale objects. Therefore, the cosmic microwave background is a picture of the universe at the end of this epoch including the tiny fluctuations generated during inflation.

1.4 The Dark Ages and large-scale structure emergence

370 *thousand to about* 1 *billion years after the Big Bang*

1.4.1 Dark ages

After recombination and decoupling, the universe was transparent and had cooled enough to allow light to travel long distances, but there were no light-producing structures such as stars and galaxies.

This period, known as the Dark Ages, began around $370,000$ years after the Big Bang. During the Dark Ages, the temperature of the universe cooled from some $4000\ K$ to about $60\ K$ ($3727\ C$ degree to about $-213\ C$ degree), and only two sources of photons existed: the photons released during recombination/decoupling (as neutral hydrogen atoms formed), which we can still detect today as the cosmic microwave background (CMB), and photons occasionally released by neutral hydrogen atoms, known as the $21\ cm$ spin line of neutral hydrogen. So, other than perhaps some rare statistical anomalies, the universe was truly dark.

The first generation of stars, known as Population III stars, formed within a few hundred million years after the Big Bang. These stars were the first source of visible light in the universe after recombination. Structures may have begun to emerge from around 150 million years, and early galaxies emerged from around 380 to 700 million years. (We do not have separate observations of very early individual stars; the earliest observed stars are discovered as participants in very early galaxies.) As they emerged, the Dark Ages gradually ended. Because this process was gradual, the Dark Ages only fully ended around 1 billion years, as the universe took its present appearance.

1.4.2 Earliest structures and stars emerge

Around 150 *million to* 1 *billion years after the Big Bang*

The matter in the universe is around 84.5% cold dark matter and 15.5% "ordinary" matter. Since the start of the matter-dominated era, dark matter has gradually been gathering in huge spreadout (diffuse) filaments under the effects of gravity. Ordinary matter eventually gathers together faster than it would otherwise do, because of the presence of these concentrations of dark matter. Unlike dark matter, ordinary matter can lose energy by many routes, which means that as it collapses, it can lose the energy which would otherwise hold it apart, and collapse more quickly, and into denser forms. Ordinary matter gathers where dark matter is denser, and in those places it collapses into clouds of mainly hydrogen gas. The first stars and galaxies form from these clouds. Where numerous galaxies have formed, galaxy clusters and superclusters will eventually arise.

Structure formation in the Big Bang model proceeds hierarchically, due to gravitational collapse, with smaller structures forming before larger ones. The earliest structures to form are the first stars (known as Population III stars), dwarf galaxies, and quasars. Before this epoch, the evolution of the universe could be understood through linear cosmological perturbation theory: that is, all structures could be understood as small deviations from a perfect homogeneous universe.

These Population III stars are also responsible for turning the few light elements that were formed in the Big Bang (hydrogen, helium and small amounts of lithium) into many heavier elements. They can be huge as well as perhaps small—and non-metallic (no elements except hydrogen and helium). The larger stars have very short lifetimes compared to most Main Sequence stars we see today, so they commonly finish burning their hydrogen fuel and explode as supernovae after mere millions of years, seeding the universe with heavier elements over repeated generations.

As yet, no Population III stars have been found, so our understanding of them is based on computational models of their formation and evolution. Fortunately, observations of the cosmic microwave background radiation can be used to date when star formation began in earnest.

Quasars provide some additional evidence of early structure formation. Their light shows evidence of elements such as carbon, magnesium, iron and oxygen. This is evidence that by the time quasars formed, a massive phase of star formation had already taken place, including sufficient generations of Population III stars to give rise to these elements.

1.4.3 Reionization

As the first stars, dwarf galaxies and quasars gradually form, the intense radiation they emit reionizes much of the surrounding universe; splitting the neutral hydrogen atoms back into a plasma of free electrons and protons for the first time since recombination and decoupling.

Reionization began as "bubbles" of ionized hydrogen which became larger over time until the entire intergalactic medium was ionized, when the absorption lines by neutral hydrogen become rare. The absorption was due to the general state of the universe (the intergalactic medium) and not due to passing through galaxies or other dense areas. Reionization might have started to happen as early as $z = 16$ (250 million years of cosmic time) and was mostly complete by around $z = 9$ or 10 (500 million years), with the remaining neutral hydrogen becoming fully ionized $z = 5$ or 6 (1 billion years). The intergalactic medium remains predominantly ionized to the present day, the exception being some remaining neutral hydrogen clouds, which cause Lyman-alpha forests to appear in spectra.

To ionize neutral hydrogen, an energy larger than 13.6 eV is required, which corresponds to ultraviolet photons with a wavelength of 91.2 nm or shorter, implying that the sources must have produced significant amount of ultraviolet and higher energy. Protons and electrons will recombine if energy is not continuously provided to keep them apart, which also sets limits on how numerous the sources were and their longevity. With these constraints, it is expected that quasars and first generation stars and galaxies were the main sources of energy. The current leading candidates from most to least significant are currently believed to be Population III stars (the earliest stars) (possibly 70%), dwarf galaxies (very early small high-energy galaxies) (possibly 30%), and a contribution from quasars (a class of active galactic nuclei).

However, by this time, matter had become far more spread out due to the ongoing expansion of the universe. Although the neutral hydrogen atoms were again ionized, the plasma was much more thin and diffuse, and photons were much less likely to be scattered. Despite being reionized, the universe remained largely transparent during reionization due how sparse the intergalactic medium was. Reionization gradually ended as the intergalactic medium became virtually completely ionized, although some regions of neutral hydrogen do exist, creating Lymanalpha forests.

1.4.4 Galaxies, clusters and superclusters

Matter continues to draw together under the influence of gravity, to form galaxies. The stars from this time period, known as Population II stars, are formed early on in this process, with more recent Population I stars formed later.

1.5 The universe as it appears today

1.5.1 Dark energy dominated era

From about 9.8 *billion years after the Big bang*

From about 9.8 billion years of cosmic time, observations show that the expansion of the universe slowly stops decelerating, and gradually begins to accelerate again, instead.

While the precise cause is not known, the observation is accepted as correct by the cosmologist community. By far the most accepted understanding is that this is due to an unknown form of energy which has been given the name "dark energy". "Dark" in this context means that it is not directly observed, but can currently only be studied by examining the effect it has on the universe. Research is ongoing to understand this dark energy. Dark energy is now believed to be the single largest component of the universe, as it constitutes about 68.3% of the entire mass-energy of the physical universe.