

Paradigm Shifts in Cosmology

The paradigm shift, as put forward by Thomas Kuhn, means revolutionary changes in the normative concepts and principles occurring in the stages of scientific development. A most easily understandable example is the transition from the Ptolemaic (geocentric) theory to the Copernican (heliocentric) theory. It is well known that in the 17th century Galileo Galilei's era, a revolution abruptly occurred from the idea that the Earth is the center of the Universe to a completely different idea or a new paradigm that the Earth revolves around the Sun. Such paradigm shifts that thoroughly changed mankind's view of the Universe have repeatedly occurred and are still going on in the 20th century and thereafter. Developments in the field of cosmology are strongly shaking mankind's view of the Universe again.

The Milky Way was found not the sole galaxy

At the beginning of the 20th century, it was not understood whether celestial objects called *nebulae* lay within the Milky Way or if they were independent groups of stars (*island universes*). It was in 1920 that the famous *Great Debate* between Harlow Shapley and Heber Curtis took place at the Smithsonian National Museum of Natural History. In the debate, Shapley argued that all the nebulae lay within the Milky Way, and Curtis on the other hand argued that spiral nebulae such as Andromeda lay

outside the Milky Way.

This debate was settled in 1922 when Edwin Hubble determined the distance to Andromeda. Since it was far beyond the distance across the Milky Way, it turned out that the Andromeda Nebula lay outside the Milky Way, and it was an independent group of stars, namely a galaxy. It would be an irony of history that it was Shapley—loser in the debate—that measured the size of the Milky Way Galaxy for the first time.

We could call it a paradigm shift in mankind's view of the Universe that the Milky Way to which the Sun belongs turned out to be but one of the immense number of galaxies in the Universe. Hubble's measurement, which caused this paradigm shift, was inspired by Henrietta Swan Leavitt's discovery of how to measure the distance in the Universe. She found that the Cepheid variables have a correlation between the period and the luminosity—the longer the period of the variable star, the greater the intrinsic luminosity. Therefore, the measurement of the period gives the true luminosity. It is possible, then, to determine the distance by comparing the observed apparent luminosity with the true one. It was her finding that opened the door to the cosmology as an objective of scientific research. Finally mankind obtained the means to measure the distance beyond the solar system to the Milky Way and further to galaxies. In fact, Hubble measured the distance to the Andromeda Nebula using this means.

Expanding Universe

At around the same time as the recognition of island universes other than the Milky Way, an expanding dynamic nature of the universe was found. Here, Vesto Slipher should be mentioned. From the 1910's to the 1920's he made spectroscopic observations of the spiral nebulae (galaxies) and found that almost all the galaxies showed the shift of spectral lines toward the red side of the spectrum. This phenomenon is known as *redshift*. He thought that this phenomenon was due to the Doppler shift arising from the high-speed movement of nebulae (galaxies) away from us, but he did not make further attempts to relate it with the expansion of space.

The universe that allows the expansion of space is possible only in terms of the general theory of relativity completed by Albert Einstein in 1915. The reason is that this theory shows the possibility for the space-time structure to vary due to the effects of gravity. Until that time, it had been considered to be absolutely stable.

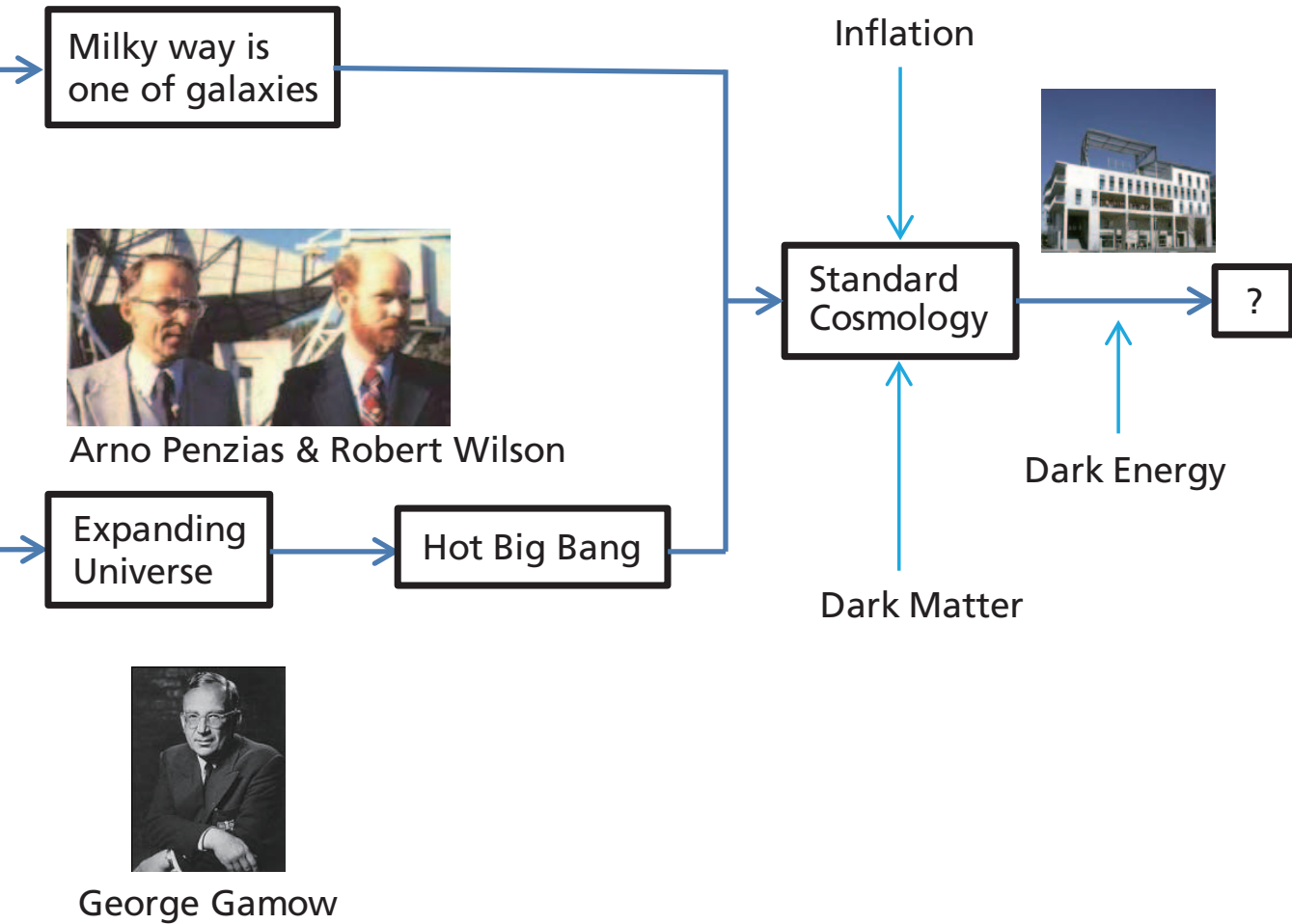
A cosmological model based on the theory of general relativity was published by Einstein himself in 1917. However, Einstein, being influenced by preconceptions that space should be static, introduced a repulsive force into his basic equation in order to balance out the gravity and prevent the evolution of space with time. This is a cosmological constant. It acts as anti-gravity that expands space. It

is said that Einstein later regretted the introduction of a cosmological constant and remarked that it was "the biggest blunder of his life," when the dynamic nature of space became clear.

In 1922, Alexander Friedmann proposed a model of the universe which allows for the expansion or contraction of space. A model of an expanding universe can naturally explain the results of Slipher. Suppose that the surface of an expanding balloon represents the space of our universe. Then, it is easy to imagine that the expansion of the balloon, i.e., the expansion of space with time, means that all galaxies move away from each other. The general theory of relativity can also explain redshift by thinking that the wavelength of light expands with space while it has been propagating from a galaxy to us.

However, the mere fact that galaxies are moving away cannot be decisive evidence for the expansion of space. It should be verified based on an accurate law and *Hubble's law* is the very thing. It states that the velocity of expansion is proportional to the distance from us. Let's assume that the entirety of space expands uniformly independent of point and direction. The distance between any celestial bodies, then, will be multiplied by the same amount. As a result, if a distance is large, its increment is proportionally large, and the velocity of expansion is also large because it is proportional to the increment of the distance

It was in 1929 when Hubble found the



background radiation (CMBR) by Arno Penzias and Robert Wilson that settled this debate. It is expected that the hot universe was filled with light having a temperature-dependent spectrum. That light remains without disappearing as the temperature of the universe has cooled down in accordance with its expansion. This is CMBR. The radio wave discovered by Penzias and Wilson by chance was found to have an absolute temperature of about 3K. Although Hoyle was defeated in the debate, his name has been known to the public as the godfather of *Big*

Bang. This also may be an irony of history. It was Hoyle that called Gamow's theory Big Bang *with derision in his radio broadcast lectures*. On the other hand, it turned out later that hydrogen and helium were produced in the Big Bang, and heavy elements were produced by stars—both Gamow and Hoyle were right.

Failures of the standard cosmological paradigm

A cosmological paradigm newly established in

the 20th century, with pictures of the expanding universe, the beginning of the hot universe, and the universe brimming over with galaxies, led us to the view of Standard Cosmology. However, as the 20th century advanced into the latter half, failures started to show up also in the Standard Cosmology.

The mechanism proposed to solve the difficulties in the Big Bang and to produce seeds of a variety of structures seen in the present universe is a rapid expansion of the early universe, *inflation*. According to the inflation scenario, the huge vacuum energy caused the rapid expansion of space and converted vacuum quantum fluctuations into matter density fluctuations. The expansion made the universe once almost empty, and then the Big Bang started with conversion of vacuum energy into heat and particles. In 1992, the COBE satellite discovered the temperature fluctuations in CMBR and the spatial pattern of fluctuation almost completely agreed with the expectation of inflation. Because of this, it is not too much to say that now inflation is one of the pieces incorporated into the Standard Cosmology.

Dark matter is also one of the pieces incorporated into the Standard Cosmology. Dark matter was “discovered” by Fritz Zwicky in the 1930’s. He investigated the peculiar motions of galaxies in a cluster of galaxies and found that visible matter cannot provide enough gravity to hold these galaxies in the cluster. To hold them together, there must be a large quantity of invisible matter—dark matter.

Since then, the existence of dark matter has nearly been established by observations of the rotational speeds of galaxies and gravitational lensing. Yet, we do not know what dark matter is. Now, searches are performed extensively for unknown particles that are candidates for dark matter. For instance, IPMU is conducting a direct search experiment XMASS in the Kamioka mine. Also, at the Swiss-French border, experiments are going on at the Large Hadron Collider (LHC) to produce candidate particles for dark matter.

Dark energy could be the most dangerous failure of the Standard Cosmology Paradigm, which might be collapsed by it. Dark energy was “discovered” in 1998 through a survey of distant supernovae. It is possible to determine the true luminosity of a supernova (in particular, that called type Ia) from the time variation of its decrease in brightness. By comparing the true luminosity with the apparent one, the distance to the distant galaxy where the supernova appeared can be determined. Once the distance is determined, it is possible to determine the rate of expansion of space at that point from the relation between the redshift and the distance. Along these lines, investigations showed that the distant (i.e., past) universe had a slower rate of expansion than the present universe. This means an accelerating expansion.

The accelerating expansion is an extremely strange phenomenon. Ordinary gravity exerts only attractive

force so that its effect on the expansion rate is only deceleration. In order to accelerate the expansion, a sort of repulsive force, namely, something that exerts anti-gravity is needed. What we can readily think of is Einstein's cosmological constant. The vacuum energy that caused inflation is also a strong candidate. So, the unknown energy that accelerates the expansion of the universe has been called dark energy. This, however, means that we have only named it without knowing its real nature at all. Unlike dark matter, dark energy spreads out over the entire universe—it is so much diluted. This makes its direct detection almost impossible. For now, the only possibility to approach dark energy is precise measurements of the expansion rate of the universe. If we could determine the time variation of the expansion rate as a function of redshift, we would be able to know the time evolution and physical properties of dark matter to some extent. For that purpose, large-scale survey projects of supernovae and galaxies have been planned and carried out.

For measurements of dark energy using galaxies, there are two methods. One is a method to use gravitational lensing effects on the images of distant galaxies. The size of the effects is dependent on the degree of structure growth. On the other hand, since dark energy acts as a repulsive force accelerating the expansion of space, it would impede the growth of structure due to gravity if its amount increases. So, it is possible to obtain the time evolution of

dark energy from the degree of structure growth. The other method is the one using an effect called *Baryon Acoustic Oscillations*. The galaxy distribution has a special-size structure which was caused by the acoustic oscillation in the early universe. The physical scale of this size can be theoretically predicted. On the other hand, the observed apparent scale varies depending on the amount of dark energy which dominates the space in between. Therefore, it is possible to determine the amount of dark energy by measuring this structure at great distances

At IPMU, a survey project of dark energy is under way in collaboration with the Subaru Telescope. First, gravitational lensing effects on distant galaxies will be measured using a very wide-field camera HSC (Hyper-Suprime Cam) which will be commissioned in FY2011. Next, a project to obtain more detailed information about dark matter by measuring Baryon Acoustic Oscillations with a next-generation multi-object spectrograph PFS (Prime-Focus Spectrograph) is being planned

Might dark energy be only one of the pieces which can be incorporated into the Standard Cosmology? Or, might it be a vanguard to urge a shift into a completely new paradigm, overturning the Standard Cosmology which has been developed over 100 years until now? It would be an important mission of IPMU to quest for the answer to this problem.