How Fast Is the Universe Expanding?

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What do we know and what do we not know about the universe? It has only been during the last several decades out of the long history of humanity that we have finally begun to construct scientifically justified ways to describe it. The present concordance model which describes the universe, however, contains many open questions to be answered. One of the most serious problems is the *Hubble tension*.

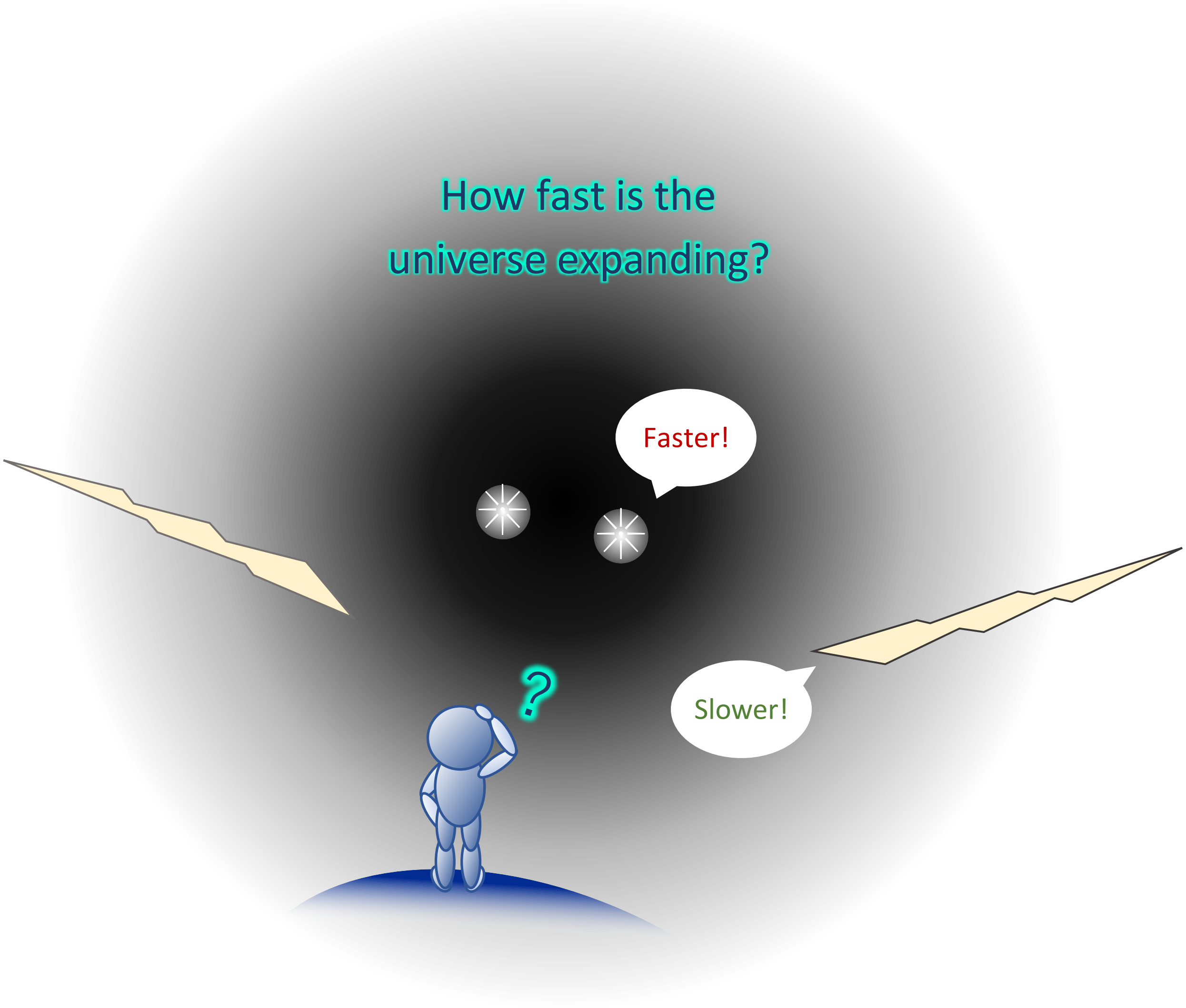
Since the era of myth, we have tried to describe the mechanism which governs the universe and sometimes experienced striking paradigm shifts. Some of the most important work was done in 1915-16, by Albert Einstein. He established the theory of *general relativity*. This theory reveals that the notions of time and space are not unique at all but rather transformed in such a way that they are mixed. Moreover, the structure of time and space is not static but dynamic. The Einstein equations determine the dynamics of time and space. In 1922, Alexander Friedmann found a solution for the equations, according to which time and space can be expanding. Georges Lemaitre first claimed in 1927 that this possibility is realized in our universe. The most famous paper related to such a claim was written by Edwin Hubble in 1929. He observed that a certain kind of astrophysical object is receding and that their speeds are proportional to their distance from us. The proportionality constant of speed and distance is the *Hubble constant*, which describes how fast our universe is expanding. Based on the concept of an expanding universe, we have recently established a concordance model of cosmology. It claims that the universe experienced the *inflation* first, then *Big Bang*, some essential transitions of the nature of physics during them, and later formation of astrophysical objects. Here the term of astrophysical objects includes stars, galaxies, and the distribution of them on large scales. These processes of cosmic history are almost completely explained by general relativity with the assumption that *dark energy*, *dark matter*, and familiar matter are filling a large fraction of the universe. This so-called *ΛCDM model* well describes most of the observed global properties of the universe.

Many observations have been done after Hubble and they confirm that our universe is expanding. However, there has been a serious discrepancy among the reported values of the Hubble constant. We call this problem the Hubble tension, which we have to overcome if we want to know the true value of the Hubble constant and to make further progress in understanding the universe.

Approaches to measuring the value of the Hubble constant can be classified into two classes. One is local measurements, in which we observe astrophysical objects around us, and the other is global measurements, which do not need any specific astrophysical objects. They show the trend of yielding larger values in local measurements compared to values yielded in global measurements. One of the latest examples of the former class is H0LiCOW collaboration, which measures the distances of *quasars* from us. Quasars are very bright astrophysical objects and are located very far from us. The light emitted from them come along paths distorted by gravity which massive objects between quasars and us generate. Because of the distortion of light paths, we see multiple images of a quasar although the quasar itself is a single object. This is the *strong gravitational lensing*. By precisely measuring to what extent this effect occurs, we can estimate the distances of quasars from us. Another example for the former class of measurements is SH0ES collaboration, which measures the brightness of the images of *Cepheids*. Cepheids are

also astrophysical objects and are not so distant as quasars. They change their brightness periodically, and we can estimate their actual brightness by observing the periodicity.
As we can easily imagine, the further they are located, the fainter their brightness appears. By comparing their actual and apparent brightness, how far they are located from us is estimated. The estimated values of the Hubble constant are about 73±2 km/s/Mpc for H0LiCOW and about 74±2 km/s/Mpc for SH0ES. These values mean that if we observe a galaxy one megaparsec (Mpc, about 3.3 million light years) away from us, it is receding with a speed of 73-4km/s by the cosmic expansion. On the other hand, an example of the latter class is Planck collaboration, which is an observation project on the *cosmic microwave background*. Cosmic microwave background is photons emitted from everywhere in the universe at a certain time in the early universe, roughly 13.8 billion years ago. The energy of CMB photons coming from whichever directions is almost the same but with a very tiny fluctuation. If we accept the ΛCDM model, we can determine a set of values for cosmological parameters, one out of which is the Hubble constant, by measuring the fluctuations of the CMB photon energy. The reported value of the Hubble constant by this method is 67.4±0.5km/s/Mpc. As we can notice, the estimated values for the Hubble constant disagree with each other.

The Hubble tension is a very serious and important problem. The discrepancy between the two major reported values of the Hubble constant is more than 4 times larger than the standard deviation and is statistically very large. It indicates that there exists a new physics. New physics might be some modifications to general relativity or the ΛCDM model. In whichever case, we have to give up persisting in very widely accepted theories and come up with completely new ideas. Historically such a situation often leads to important progress in physics. Thus, the Hubble tension could play a role as a key to a deeper understanding of our universe.


How fast is the universe expanding?
Faster!
?
Slower!