ΛCDM Model and Hubble Tension

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Outline

1 Introduction

2 ΛCDM Model
   - Λ, Cosmological Constant
   - Cold Dark Matter
   - ΛCDM model

3 Hubble Tension
   - Hubble Constant
   - Measurement from Planck and HST
   - Hubble Tension

4 Summary
The Famous Figure
How our universe looks like?

(assuming dark matter and dark energy)
Occam’s Razor

Entities are not to be multiplied beyond necessity. If there are many ways to explain the phenomena, then the simplest one is likely to correct.
What is the simplest model for our universe?

(assuming dark matter and dark energy)
What is the simplest model for our universe?

(assuming dark matter and dark energy)

Answer: ΛCDM Model
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4 Summary
When Einstein developed his field equation, he wanted a static universe.

But His equation seems to reject static universe.

So he introduced a cosmological constant, $\Lambda$ to make our universe static.

\[
R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}
\]
Later, Hubble discovered that our universe is expanding.

\[ v = H_0 d \]  \hspace{1cm} \text{(Hubble-Lemaître law)}

So the hypothesis of static universe is rejected.

Einstein withdrew his cosmological constant and he called it as his “biggest blunder.”
However, the accelerating expansion of universe is discovered.

To explain this, the notion of dark energy is suggested.
Cosmological constant $\Lambda$ acts as a repulsive force.

By using $\Lambda$, the accelerating expansion can be explained.

Also, quantum field theory suggests the vacuum energy which can be interpreted as a source of cosmological constant.

Due to its simplicity, $\Lambda$ is used to denoting dark energy.
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4. Summary
Galaxy Rotation Curve

Galaxy rotation curve suggests the existence of unknown mass.
Properties of Dark Matter

Dark matter should have these properties.

- **Non-baryonic**
  It consists of matter other than baryons (and electrons).

- **Dissipationless**
  It cannot cool by radiating process.

- **Collisionless**
  It interact with each other and other particles only through gravity and possibly the weak force.

If not, it can interact through electromagnetic process.
Galaxies are surrounded by dark matter halo.
Coldness of Dark Matter

To explain the structure of galaxies, the coldness of dark matter is usually assumed.

It means that the velocity of dark matter is far less than the speed of light.

In this case, the small objects merge into larger objects by gravitational interaction.

To make dark matter halo, we need to assume cold dark matter.
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4. Summary
Constituents of $\Lambda$CDM Model

$\Lambda$CDM model is abbreviation of “$\Lambda$ Cold Dark Matter model”.

It has 3 constituents listed below.

- **Dark energy**
  It behaves just like the energy density of the vacuum and is denoted by $\Lambda$.

- **Cold dark matter**
  It interacts with ordinary matter gravitationally and its velocity is much less than that of light.

- **Ordinary matter**
Assumptions of $\Lambda$CDM Model

$\Lambda$CDM model has a few assumptions.

- Physics is the same throughout the observable universe.
- General Relativity is an adequate description of gravity.
- On large scales the Universe is statistically the same everywhere.
- The Universe was once much hotter and denser and has been expanding since early times.
- The curvature of space is very small.
- Variations in density were laid down everywhere at early times, and are Gaussian, adiabatic, and nearly scale invariant as predicted by inflation.
- The observable Universe has “trivial” topology.
6 Parameters of $\Lambda$CDM Model

- Density of baryons $\Omega_b$
- Density of cold dark matter $\Omega_c$
- Amplitude of a power-law spectrum of adiabatic perturbations $A_s$
- Scalar spectral index of a power-law spectrum of adiabatic perturbations $n_s$
- Angular scale of acoustic oscillations $\theta_*$
- Optical depth to Thomson scattering from reionization $\tau$
6 Parameters of ΛCDM Model

\[ \Omega_b \quad \Omega_c \quad A_s \quad n_s \quad \theta_* \quad \tau \]
Success of ΛCDM Model

The 2011 Nobel Prize in Physics was awarded to Adam Riess, Brian Schmidt, and Saul Perlmutter
(for their discovery of the accelerating expansion of the universe)
The Supernova Cosmology Project & The High-z Supernova Search Team
It’s That Easy

...
No, it’s not that easy.
Unsolved Problem of ΛCDM Model

- Cosmological Constant Problem
- Small Scale Crisis
- Warm Dark Matter
- Hubble Tension
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Hubble Lemaître Law

Hubble Lemaître Law says

\[ v = H_0 d \]

\( v \) is recession velocity, \( d \) is proper distance, and \( H_0 \) is Hubble constant.

According to Friedmann equation, Hubble parameter \( H \) varies with time.

\[ H^2 = \frac{8\pi G}{3} \rho - \frac{kc^2}{a^2} + \frac{\Lambda c^2}{3} \]

When we use the word Hubble constant \( H_0 \), it points out the value of Hubble parameter in this time.
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Planck Mission

Planck was ESA’s mission to observe the cosmic microwave background.

It was designed to image the temperature and polarization anisotropies of the Cosmic Background Radiation Field.
Data from Planck constrain 6 parameters governing $\Lambda$CDM model.

Using these, other cosmological quantities including Hubble constant can be calculated.

In 2018, Planck releases final results and it gives

$$H_0 = 67.66 \pm 0.42 \text{ km/s/Mpc}$$
Hubble constant is the ration between recession velocity and distance.

Although Planck gives the value of $H_0$, the way of measurement is not intuitive.

The direct way to measure $H_0$ is measuring $v$ and $d$ for cosmological objects and calculating $H_0 = v/d$.

$v$ can be measured by measuring red shift but measuring $d$ is difficult.
Tools for Distance Measurement

Type Ia Supernovae

Characteristic Light Curve

Standardized Supernova - Perlmutter

Cepheid Variables

Period Luminosity Relation
Hubble Constant from HST

Hubble Space Telescope can measure the luminosity of Type Ia supernovae and Cepheid variables.

So it can measure the distance of galaxy including them.

HST release its result for $H_0$.

$$H_0 = 74.03 \pm 1.42 \text{ km/s/Mpc}$$
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Hubble Tension

Now we have two result for $H_0$.

\[
H_0 = 67.66 \pm 0.42 \text{ km/s/Mpc} \quad \text{(Planck)}
\]
\[
H_0 = 74.03 \pm 1.42 \text{ km/s/Mpc} \quad \text{(HST)}
\]

There exists the 4.4$\sigma$ difference between local measurements of $H_0$ by HST and the value predicted from Planck + $\Lambda$CDM.

This difference is called Hubble Tension.
Now we have two results for $H_0$.

\[
H_0 = 67.66 \pm 0.42 \text{ km/s/Mpc (Planck)}
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\[
H_0 = 74.03 \pm 1.42 \text{ km/s/Mpc (HST)}
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There exists the $4.4\sigma$ difference between local measurements of $H_0$ by HST and the value predicted from Planck $+$ $\Lambda$CDM.

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Now we have two results for $H_0$.

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There exists the $4.4\sigma$ difference between local measurements of $H_0$ by HST and the value predicted from Planck + ΛCDM.

This difference is called Hubble Tension.
ΛCDM model is not sufficient to explain whole history of universe.
Moreover

Also, $H_0 = 54.4 \pm 4.0$ km/s/Mpc is proposed. (Nature Astronomy (2019)).
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Summary

- ΛCDM model is the simplest model for our universe. It can explain many cosmological phenomena.
- Hubble constant from Planck and HST shows significant difference. It indicates that ΛCDM model is not perfect.
- Our universe is not simple as we expected.
- It is more interesting than we expected.
Thank You for Your Listening
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