DESI: Dark Energy Spectroscopic Instrument

Bhavya Jaiswal
BS-MS Physics
Indian Institute of Technology, Kanpur

Dark Energy is a mysterious component of our universe, which causes our universe to expand faster over time. It works in opposition to gravity: it stretches space-time and thus pulls objects away. However, we still need to learn more about it. The leading model that describes our universe, the ΛCDM model, includes matter (ordinary and dark) as well as dark energy. Both matter and dark energy govern how our universe expands, but in opposite ways. Ordinary matter and dark matter slow the expansion; however, dark energy accelerates it. Thus, the amount of matter/dark energy influences how our universe evolves.

What is DESI?

The Dark Energy Spectroscopic Instrument (DESI) is a scientific research instrument that will measure the effect of dark energy on the expansion of the universe by obtaining positions and optical spectra of millions of galaxies and quasars, constructing a 3D map of our universe. The instrument was built and is operated with funding from the DOE Office of Science. It is situated at the U.S. National Science Foundation's Nicholas U. Mayall 4-meter Telescope at Kitt Peak National Observatory.
In its observing lifetime of 5yrs, DESI will measure the spectra of more than 30 million galaxies and quasars covering an area of 14,000 square degrees with the highest accuracy ever achieved. In its first year, DESI measured the positions of about 6.5 million galaxies and quasars, creating the largest 3D map of our universe. The data helps us get a picture of the expansion history of our universe over the past 10 billion years and thus allows researchers to study dark energy.

Baryon Acoustic Oscillations(BAO) and Evolving Dark Energy

The key feature extracted from DESI data is Baryon Acoustic Oscillations (BAO). Our early universe was a soup of ionized plasma. Tiny fluctuations in this early soup caused pressure waves, creating ripples. It set up patterns in the density of baryons in the universe. As the universe expanded and cooled, these pressure waves stopped and froze the ripples in 3-dimensions. This density contrast increased the clustering of galaxies in the dense areas. These density variations persist for billions of years, and we observe them now as a faint pattern of 3D bubbles. This feature is what we call Baryon Acoustic Oscillations (BAO).
Due to this, the galaxies are separated by a preferred distance. This distance acts as a cosmic ruler, which gets stretched as the universe expands. Measuring the size of these bubbles (the cosmic ruler) over various epochs, we can measure how fast the universe was expanding at each time in the past, thus modeling how dark energy affects expansion.
The leading model of our universe, the ΛCDM model, assumes non-evolving dark energy (cosmological constant). This model describes the results of previous experiments very well. This model also explains the DESI data well. However, when DESI data was combined with other studies, the combined data fit better to an evolving dark energy model. Thus, DESI data, along with other data sets, tells us that the equation of the state of dark energy might actually vary with time. However, this is just the first year of DESI, and future data will reveal more information.

DESI and Neutrino Mass

Neutrinos are neutral subatomic particles that interact via the weak force and gravity. Earlier, they were thought to be massless particles. However, from neutrino oscillation experiments, we know that they have extremely small non-zero masses. There are three generations of neutrinos (ν_e, ν_μ, ν_τ) which differ in their masses. From these laboratory experiments, we know that $\sum m_\nu > 0.06$ eV for normal ordering (NO), where the lightest neutrino mixes most with ν_e or $\sum m_\nu > 0.10$ eV for inverse ordering (IO), where the lightest neutrino mixes least with ν_e.

Neutrinos were produced in large numbers after the Big Bang, and they decoupled from the background plasma when the universe was only about 1 second old, producing the Cosmic Neutrino Background. These neutrinos modify the expansion rate and also affect the rate at which structures form in our universe. These two effects are directly proportional to the energy density of neutrinos and, thus, their mass. Large neutrino energy density results in an enhanced expansion rate and a decrease in the rate of formation of large-scale structures.

Using the existing Planck CMB data with the DESI Y1 BAO measurements, researchers reported a powerful bound on the sum of neutrino masses of $\sum m_\nu < 0.073$ eV at a 95% confidence level. This bound is very strong as it is very close to the mass constraint obtained from lab experiments of $\sum m_\nu > 0.06$ eV. This bound provides strong evidence against the IO hypothesis.

However, this result depends on the planck data set used and thus can be weakened by about 40%. Also, DESI data has some outliers, which put the bound to much smaller masses. Considering both things, the bound relaxes to $\sum m_\nu < 0.11$ eV with 95% confidence level. This is compatible with both the NO and IO hypothesis. Also, the bound depends on the cosmological model used. When a model with evolving dark energy is used, the bound becomes $\sum m_\nu < 0.2$ eV. Thus, only future data can give a clearer picture of neutrino mass bound.

Summary

DESI represents a remarkable leap forward in cosmology, providing unprecedented insights into the nature of dark energy, the universe's expansion history, and fundamental properties like neutrino masses. By mapping millions of galaxies with unparalleled precision, DESI illuminates cosmic evolution and sets the stage for answering some of science's most profound questions. As the survey progresses, it will bring even more exciting discoveries and help us unveil the mysteries of Our Universe.

References

1. DESI 2024 Y1 Results
2. https://www.sciencenews.org/article/map-universe-dark-energy-cosmology-desi
3. https://newscenter.lbl.gov/2024/04/04/desi-first-results-make-most-precise-measurement-of-expanding-universe/
4. https://ep-news.web.cern.ch/content/desi-y1-and-mystery-neutrino-mass