Dean&Francis
ISSN 2959-6157

The Role of Galaxy Surveys in Mapping Cosmic Evolution

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Abstract:
Galaxy redshift surveys are one of the main ways of knowing how the universe as evolved. These surveys show how the matter forms a large-scale cosmic web of filaments, galaxy clusters and empty 'voids. Dark matter can be seen to influence this pattern, which can be seen to still have the imprint of an early universe. A key pattern, the baryon acoustic oscillation scale, acts as a length-time tracker for tracking how the universe's expansion has changed over time. In studying how galaxy clustering evolves with distance, surveys show that structure growth has slowed as dark energy began to dominate becoming a greater proportion of the total mass-energy content in the universe, causing the accelerated expansion of the universe. More recently, multi-messenger astronomy featuring gravitational waves, gamma rays and neutrinos have allowed astronomers to observe more cosmic events leading to greater evidence. Galaxy surveys provide some of the strongest evidence for the current model of the universe's evolution from the Big Bang to the present day.

Keywords: Galaxy surveys, cosmic evolution, multi-messenger astronomy.

1. Introduction

Nowadays, the Universe is estimated to be around 13.8 billion years old [1] with the Big Bang model being the most accepted by the scientific world. This model of the universe is often divided into five observationally supported epochs (stages). The inflationary epoch marks the earliest phase, where an exponential expansion of spacetime occurred, concluding with the conversion of vacuum energy into a hot, random distribution of fundamental particles [2]. This was followed by the quark era, during which the universe cooled sufficiently for quarks to bind into hadrons and dark matter to form. In the subsequent 'Big Bang Nucleosynthesis' phase [3, 4], nuclear reactions combined protons and neutrons to produce the light-element nuclei that serve as the cores of the first atoms. As the density dropped, the universe entered the structure formation epoch, in which matter came to dominate over radiation, photons decoupled from matter and consequently formed the CMBR [5], and gravitational collapse of gas lead to the eventual formation of stars [6], galaxies, and galaxy clusters [7]. Lastly, in the cosmic acceleration epoch, the current period, the expansion allowed dark energy to represent large majority of the total energy in the observable universe and therefore overcoming gravity

ISSN 2959-6157

on large scales.

Scientific understanding of these periods has been improved over the course of around 100 years by astronomical observations, with galaxy redshift surveys playing a central role in mapping the large-scale structure and tracking its evolution over billions of years. Recent advancements in galaxy surveys, such as the Sloan Digital Sky Survey (SDSS) and the ongoing Dark Energy Spectroscopic Instrument (DESI) project [8, 9], have enabled precise three-dimensional mapping of millions of galaxies, and have subsequently revealed the large-scale cosmic web and improved measurements of the baryon acoustic oscillation scale.

2. Cosmic Evolution and the Large-Scale Structure of the Universe

2.1 The Early Universe

The universe began with a brief period of cosmic inflation that smoothed spacetime by flattening the universe and making it uniform at large scales. This was followed by the Big Bang, during which the stored energy transformed into a hot, dense mixture of matter and radiation. In the first few minutes, nuclear fusion processes combined protons and neutrons to form hydrogen, helium, and other atomic nuclei in a phase known as Big Bang nucleosynthesis [3, 4]. Around 380,000 years later, the universe had cooled sufficiently for electrons to combine with nuclei to form neutral atoms. This period, called the recombination epoch, allowed photons to travel freely through space and decouple from the matter, producing the cosmic microwave background radiation (CMBR).

2.2 Dark and Light

Following recombination, the cosmos entered a period known as the Dark Ages. During this epoch, which lasted from 380,000 years since the Big Bang to several hundred million years after, there was no light due to no stars being formed yet. However, because of gravity, the highly abundant hydrogen and helium gas gradually caused matter to clump together, forming high density volumes of gas that would eventually collapse and become stars and galaxies.

After several hundred million years, the first stars and galaxies formed, marking the beginning of the universe observed nowadays. The ultraviolet radiation emitted by these objects ionized the surrounding neutral hydrogen in a process called reionization [10], gradually making the universe transparent to ultraviolet light. As time progressed, these early galaxies merged and grew within the constraints of dark matter, giving rise to larger structures such as galaxy clusters and filaments.

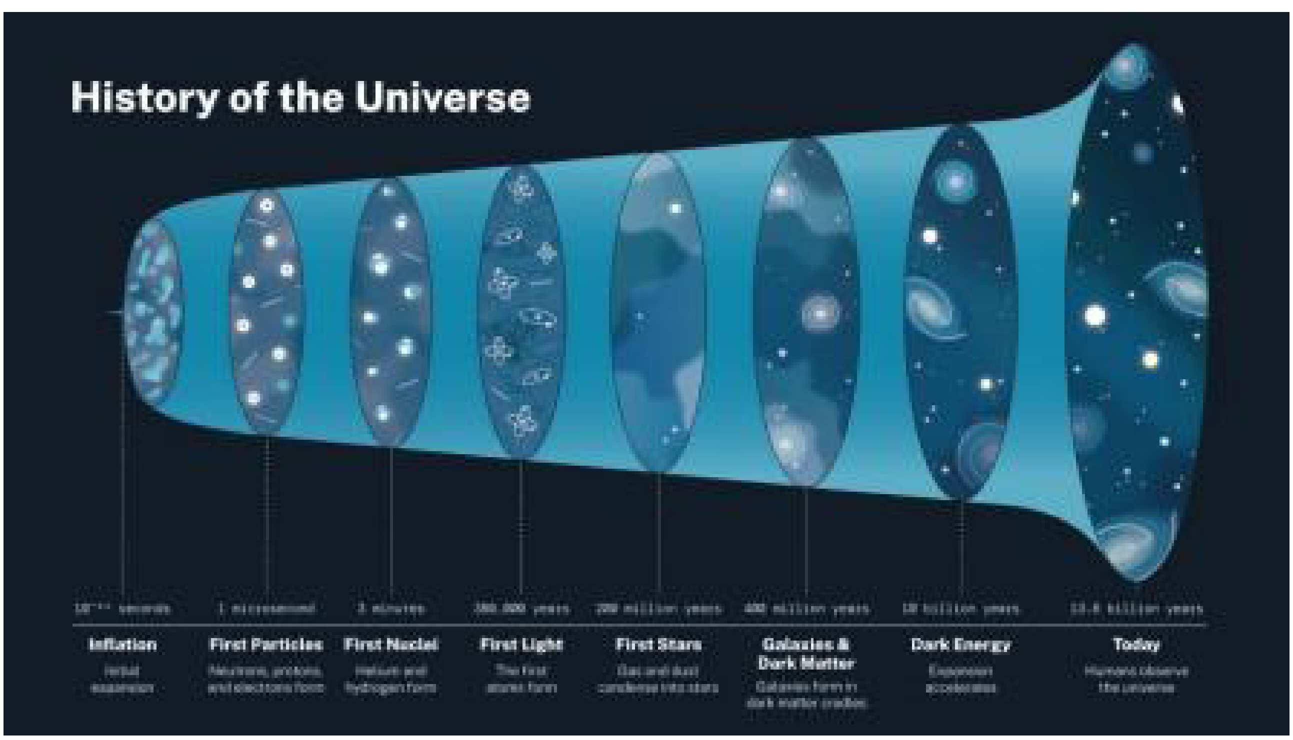


Fig. 1 NASA Infographic on the History of the Universe [1].

2.3 Accelerated Expansion and the Future

Over the past 100 years of astronomical research, it has become increasingly obvious that the universe is indeed expanding at an accelerating rate [11]. Unfortunately, current astronomers understand little to nothing about these phenomena other than dark energy, which comprises about 70% of the universe, being the reason for this accelerated expansion. The evolution of the universe and the future of it is governed also by the amount of dark matter and dark energy it contains, but their densities are affected very differently by the expansion.

Dark energy is described as an intrinsic property of space due to more dark energy being 'created' as the universe expands. Dark matter behaves like the baryonic matter as its density decreases as space grows and makes up roughly 25% of the universe's mass. It does not emit, absorb, or reflect light, making it invisible to electromagnetic observations. Its presence can only be detected due to some gravitational effects such as the galaxy rotation curve and how light bends around supermassive bodies.

The best hypothesis suggests that dark energy drives space-time apart, counteracting the attractive pull of gravity (and driving galaxies apart), while dark matter binds matter together, preventing galaxies from drifting apart under the influence of dark energy. The balance between these dark energy and dark matter is what is keeping the universe stable. However, if this balance is not maintained, the fate of the universe could differ; whether it will expand forever, slow down, or a 'Big Rip' event. Despite these two models, the exact physical nature of both components remains unknown, leaving them as two of the most profound mysteries in modern cosmology.

3. Redshift and Galaxy Mapping

3.1 The z - value

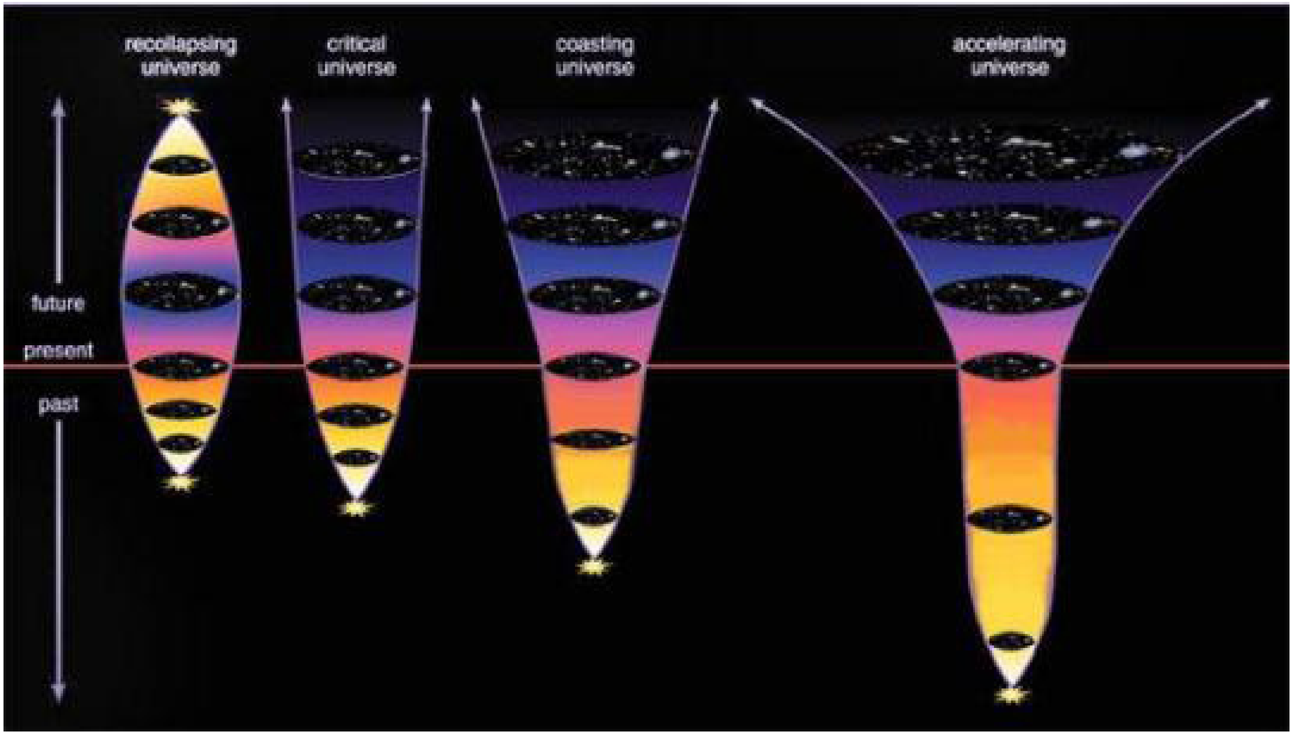


Fig. 2 Various universe evolution scenarios. From left: A universe with too much density collapsesin on itself, a critical density universe stays static, a universe with not enough density keepsexpanding at a steady (coasting) rate. Then there's what seems to be happening: the rate of

expansion is speeding up [12].

Redshift is the stretching of lengthening or shortening of the wavelength of light waves as distant galaxies approach or move away. This effect happens because the universe is expanding, causing most galaxies to move away from the point of observation. By measuring redshift, astronomers can determine how fast objects are receding and how far away they are, which makes it a useful tool for studying the size, age, and evolution of the universe. To use redshift as a reliable measurement, astronomers need to calculate it with the formula

ISSN 2959-6157

$$z = \frac{\lambda_{observed} - \lambda_{emitted}}{\lambda_{emitted}} \quad (1)$$

where λ observed is the wavelength detected on earth λ emitted is the emitted wavelength. A higher redshift value z means that the galaxy is moving faster away and is situated further away from the point of observation. By measuring redshift for millions of galaxies, astronomers can create large 3D maps of the universe that show where galaxies are located and how structures like clusters and voids are arranged in this universe. These maps allow scientists to trace the growth and change of the universe overtime which allows studying of dark matter and dark energy on the largest scales.

3.2 Cross-Correlation

The practical question to ask here is how to measure 'z' at scale. One way that is widely used is the cross-correlation method, which compares the observed spectrum of wavelength O(λ) to template reference spectrum T(λ) which will change as a different trial redshift is used. This cross-correlation function is defined as:

$$C(z) = \sum_1^i O(\lambda_i) T\left(\frac{\lambda_i}{1+z}\right) \quad (2)$$

Where i numbers the wavelengths individually, $O(\lambda_i)$ is the observed flux at the i-th wavelength and $T\left(\frac{\lambda_i}{1+z}\right)$ is the template spectrum shifted according to the value of z that is inputted and is derived from rearranging the above equation for λ observed .

The method works by sliding the template along the wavelength axis and calculating C(z) at each step. When the features of the observed spectrum, such as peaks and absorption troughs, align with those of the shifted template, the product of fluxes is maximized, producing a peak in the redshift that maximizes the cross-correlation. Plotting a graph for C(z) against z will produce a maximum peak for an accurate value for z - allowing identification of how far the galaxy is.

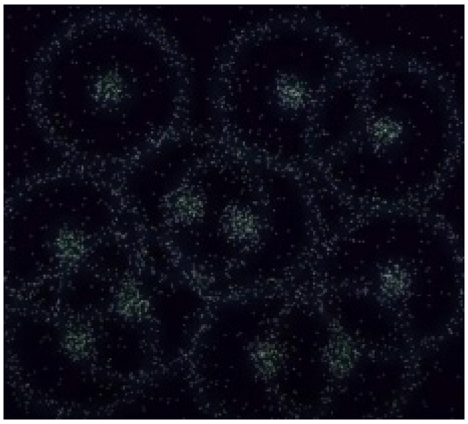
The cross-correlation method, along with other redshift estimation techniques, underpins the success of large-scale galaxy surveys. Two of the most influential projects exemplify how these methods are applied in practice: the Sloan Digital Sky Survey (SDSS) and the Vera C. Rubin Observatory. The SDSS revolutionized observational cosmology by obtaining spectroscopic redshifts for millions of galaxies using spectrographs. Its success demonstrated the power of cross-correlation and template-fitting techniques in building precise 3D maps of galaxies. These maps provided critical insights into large-scale clustering, baryon acoustic oscillations, and the distribution of dark matter, something that will be expanded upon in the following section.

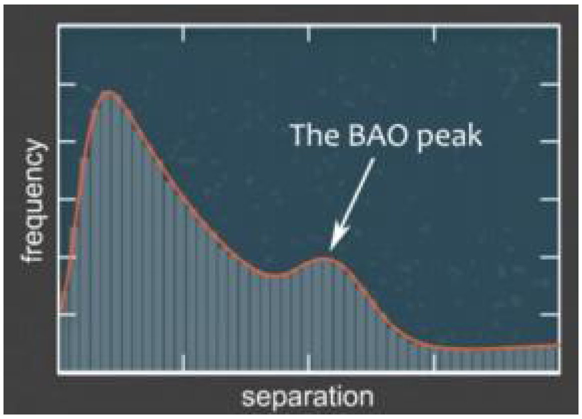
In contrast, the Vera Rubin Observatory will employ a photometric survey model through the Legacy Survey of Space and Time (LSST). Instead of precise spectra for each object, it will record repeated multi-band imaging of billions of galaxies over ten-year period. Redshifts in this context are derived photometrically, using galaxy colors across filters to estimate distances. While individual redshifts will be less precise than in SDSS, the vastly larger sample size enables a huge amount of a data to be collected which is useful for something like investigating dark energy.

4. Contributions to the Cosmic Evolution Model from Surveys

380,000 years after the Big Bang, matter and radiation were coupled together and inseparable. The universe was a medium of hot plasma, photons, electrons and baryons. Because the photons frequently collided with the electrons in this ultra-dense medium, the pressure from radiation was very high. Small areas with high density and a high concentration of particles tried to collapse under gravity, but the overwhelming radiation pressure resisted this collapse, which created oscillations that travelled in the plasma. The reason why they are called acoustic oscillations is due to them being analogous to sound waves, and they were propagating at nearly half the speed of light.

These sound waves continued to travel outwards from the over dense regions in the plasma until the universe cooled enough for recombination at approximately 380,000 years. At which point, photons decoupled and continued to move at the speed of light. This is what can be seen nowadays as the cosmic microwave background (CMB). The baryons were left behind and therefore, the maximum distance the waves travelled before recombination is called the sound horizon, nowadays agreed upon to be about 150 Mpc. This process left a major imprint which can be seen by observers today. In the matter distribution, there is a slight excess probability of finding pairs of galaxies separated by the sound horizon scale (i.e. the chance offending two galaxies around 150 Mpc away is statistically significant compared to other distances).





(a) **(b)**

Fig.3 (a), (b) Clearly visible rings can be shown in the left image, this shows how far the baryons were able to move up to recombination and these rings have a radius of 150 Mpc. From analyzing the frequency and separation, there is a small but significant peak at separation distance of 150 Mpc corresponding to the rings created by BAO [13].

5. Multi Messenger Astronomy

5.1 Gravitational Waves, Gamma Rays and Neutrinos

To investigate how galaxy structure even forms, it is necessary to realize that using observed features such as gravitational waves, gamma radiation and neutrinos, will allow a more complete picture of cosmic evolution. Gravitational waves are ripples in spacetime produced by the merging of ultra dense objects like black holes. The waveform of a gravitational-wave signal carries an absolute measure of distance to the source. If the source galaxy can be identified, either directly through an electromagnetic counterpart or statistically from a galaxy catalogue database, then the source redshift can also be determined. This directly allows calculations for how fast that galaxy is moving away. There are also localized 'hotspots' of high gamma radiation which are easily detectable. Blazar events emit a lot of gamma rays and hence by cross-correlating gamma-ray intensity maps with galaxy catalogues at different redshifts, astronomers can determine which galaxies contribute most to the diffuse extragalactic gamma-ray background radiation. The clustering of gamma rays compared with galaxies provides insight into how these sources trace the dark matter halo distribution. Neutrinos, unlike photons, travel almost unaffected from their sources, carrying information about particle acceleration in extreme environments. However, they are extremely difficult to detect due to them having no electric charge and being virtually massless. If frequent detection is possible, cross-correlation with galaxy surveys makes it more possible to search for statistical associations between neutrino arrival directions and specific galaxy populations, such as active galactic nuclei or starburst galaxies (galaxies with high rate of star formation). Such correlations contest whether neutrinos are produced through hadronic processes involving cosmic rays.

5.2 MMA and its Challenges

In practice, combining these ‚messengers‘ (hence the name multi messenger) with galaxy surveys involves building well-calibrated 3D galaxy maps and comparing them statistically with sky maps of gravitational waves, gamma rays, or neutrinos. The cross-correlation signals can be modelled using the halo framework, which links sources to the dark matter structures traced by galaxies. By jointly analyzing distances, clustering, lensing, and messenger correlations, researchers can reduce any possible inconsistencies in cosmological models and achieve more robust constraints. Despite the effective nature of multi messenger astronomy, there are some significant challenges to overcome for the future of observational astronomy. Gravitational waves and neutrino sources often have large localization uncertainties, making it difficult to pinpoint where they originate from. Statistical methods and more complete galaxy catalogues help address this but are not completely accurate or dependable. Photometric redshift errors in surveys can blur correlations, but future improved calibration techniques mitigate this effect. Selection biases, such as detection thresholds, must be also modelled carefully to avoid any bias when making conclusions of observed data as this could hinder scientific development in astronomy. Foregrounds like Galactic gamma-ray emission also need to be subtracted reliably

ISSN 2959-6157

without omitting the detected data.

6. Conclusion

For future observational astronomers, the future holds many opportunities. New wide and deep optical and infrared surveys such as Rubin Observatory's LSST, Euclid, and Roman will provide vast and precise measurements. Large spectroscopic surveys such as DESI will supply accurate redshifts. At the same time, the global gravitational-wave detector network, next-generation neutrino observatories across the world will start to come online. Alongside with these advances, there will be an undoubtably be an increase in machine computational power soon and hence, applying machine learning will become important. With AI being able to handle magnitudes more data than the current algorithms, machine learning will help identify patterns in clustering and hopefully detect new astronomical phenomena that might otherwise have been missed. The integration of galaxy surveys with multi-messenger astronomy incorporated with more complex machine learning promises to drive a new era of discoveries in cosmology.

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