Gravitational lensing of Pop III star explosion by a foreground dark matter halo of a high redshift galaxy

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ABSTRACT

Radiation from PopIII star explosions taking place around redshifts z ~ 15-20 are likely to be gravitationally lensed by the foreground high redshift galaxies. In this study, we consider gravitational lensing caused by two distinct kinds of dark matter halos - standard cold dark matter halo and dark matter halo constituted of Bose-Einstein condensates (BECs) of ultralight pseudo scalars. In the latter case, depending on the mass of the pseudo scalar bosons, oscillation of BEC due to perturbation may leave significant imprint in the lensed images. We discuss the possibility of detecting such signatures using James Webb Space Telescope data.

A Comprehensive Analysis of Galaxy Types: Classification, Formation, and Evolution

Galaxies are fascinating cosmic structures that serve as the building blocks of the universe, and understanding their diverse nature is crucial for unraveling the mysteries of our cosmos. This research will explore the major galaxy types, such as spiral galaxies, elliptical galaxies, irregular galaxies, and peculiar galaxies, and investigate their properties, morphology, and the underlying physical mechanisms governing their formation and evolution. By delving into the latest observational and theoretical advancements in the field, this study seeks to contribute to our knowledge of the vast range of galaxies that populate the universe.

I. Introduction

a) Introduction:

Galaxies, sprawling cosmic systems composed of stars, gas, and dust, have captivated astronomers for centuries. One of the fundamental aspects of studying galaxies is their classification based on their morphological features. Morphological classification provides a way to categorize galaxies into distinct types, aiding in the understanding of their formation, evolution, and overall properties. This chapter serves as an introduction to the thesis, providing background information on galaxy classification, outlining the objectives and scope of the research, and describing the methodology and data sources utilized.

b) Background and Significance:

The concept of galaxy classification dates back to the early 20th century when astronomers first realized that galaxies exhibited various shapes and structures. Notably, Edwin Hubble's groundbreaking work in the

1920s established the Hubble sequence, a classification scheme that organized galaxies into distinct types based on their visual appearance. The Hubble sequence, often referred to as the "tuning fork diagram," remains a cornerstone of galaxy classification today.

The classification of galaxies is of significant importance for several reasons. Firstly, it provides a framework for organizing the immense diversity of galaxies, allowing astronomers to make sense of their observed properties and distributions. Secondly, morphological classification offers insights into the physical processes that govern galaxy formation and evolution. By identifying common characteristics within galaxy types, scientists can discern patterns and establish connections between morphology and other properties, such as stellar populations, gas dynamics, and environmental factors. Furthermore, understanding galaxy morphology is crucial for studying the larger-scale structure of the universe and its evolution over cosmic time.

c) Objectives and Scope:

The primary objective of this thesis is to provide a comprehensive analysis of galaxy types, focusing on their morphological classification and the underlying physical processes responsible for their appearance. The thesis aims to explore the major galaxy types, including elliptical galaxies, spiral galaxies, lenticular galaxies, and irregular galaxies. It also delves into the subtypes and extensions within these broad categories, elucidating the nuances and variations within each type.

The paper further investigates the relationship between galaxy morphology and various physical processes, such as gas dynamics, star formation, galaxy interactions, and environmental effects. By examining these connections, the research aims to deepen our understanding of the formation and evolution of galaxies and shed light on the factors that shape their morphological characteristics.

d) Methodology and Data Sources:

To achieve the objectives of this thesis, a comprehensive approach will be employed, combining theoretical analyses, observational data, and computational techniques. The primary data sources will include large-scale surveys, such as the Sloan Digital Sky Survey (SDSS), Hubble Space Telescope (HST) observations, and other relevant astronomical databases. These datasets will provide the necessary observational data, images, and spectra for studying galaxy morphology.

In addition to observational data, the thesis will draw upon theoretical models and simulations of galaxy formation and evolution. These models, based on principles of astrophysics and cosmology, will provide insights into the physical processes driving the observed morphologies.

The paper will also explore the advancements in machine learning and automated classification techniques, highlighting their role in facilitating galaxy classification on a large scale.

By employing a multi-faceted methodology and utilizing a wide range of data sources, this research aims to provide a comprehensive analysis of galaxy types, deepening our understanding of their morphological classification and the underlying physical processes shaping their appearances.

II: Early Attempts at Classification

a) Introduction:

Galaxy classification has a rich historical background, with early astronomers making significant contributions to organizing and categorizing the diverse range of galactic structures. This chapter explores the development of galaxy classification, starting from early attempts to more refined systems that laid the foundation for the modern understanding of galaxy types. The chapter also discusses the emergence of the Hubble sequence and its profound impact on the field of galaxy morphology.

b) Historical Development of Galaxy Classification:

Early astronomers, such as William Herschel and Lord Rosse, made important observations of galaxies in the 18th and 19th centuries. However, it was not until the early 20th century that systematic efforts were made to classify galaxies based on their morphological features. Astronomers like Vesto Melvin Slipher and Heber Curtis began to identify distinct types of galaxies, noting differences in their shapes, sizes, and apparent structures.

c) The Shapley-Curtis Debate:

The Shapley-Curtis Debate in 1920 marked a significant milestone in galaxy classification. Harlow Shapley and Heber Curtis presented contrasting views on the nature of "spiral nebulae" and their relationship to the Milky Way. Shapley argued that these objects were part of our own galaxy, while Curtis proposed that they were separate "island universes." The debate highlighted the need for a systematic classification scheme to better understand the nature of these enigmatic objects.

d) The Hubble Sequence:

Edwin Hubble's work in the 1920s revolutionized our understanding of galaxies and established the Hubble sequence, a classification scheme that organized galaxies into distinct types based on their visual appearance. Hubble's observations revealed a continuum of galaxy shapes, ranging from elliptical to spiral, with intermediate types in between. He arranged these galaxies along a diagram resembling a tuning fork, hence the term "Hubble tuning fork diagram."

e) Elliptical Galaxies:

Hubble recognized elliptical galaxies as a major category in his classification scheme. These galaxies are characterized by their smooth, featureless appearance and lack of spiral arms. Hubble further categorized ellipticals into different classes based on their elongation and symmetry.

f) Spiral Galaxies:

Spiral galaxies became a prominent category within the Hubble sequence. Hubble identified two main types of spiral galaxies: "normal" spirals, later denoted as Sa, Sb, and Sc, and barred spirals, classified as SBa, SBb, and SBc. Spirals are characterized by their prominent spiral arms, central bulges, and often a rotating disk of gas and dust.

g) Lenticular and Irregular Galaxies:

Hubble also recognized other galaxy types, including lenticular (S0) galaxies, which exhibit a disk-like structure but lack the prominent spiral arms, and irregular galaxies, which lack a well-defined shape and exhibit chaotic or distorted structures. Irregular galaxies often arise from interactions and mergers between galaxies.

h) Limitations of Early Classification Schemes:

While the Hubble sequence provided a groundbreaking framework for organizing galaxies, it had its limitations. The classification was primarily based on visual appearance and did not take into account the underlying physical processes driving the galaxy's morphology. Additionally, the Hubble sequence did not account for galaxies that deviated from the primary categories, leading to the development of further subtypes and extensions in subsequent studies.

Despite these limitations, the Hubble sequence laid the foundation for subsequent advancements in galaxy classification and served as a starting point for understanding the diverse range of galaxy types. It remains a fundamental aspect of galaxy morphology and has influenced the field for decades.

This chapter provides an overview of the early attempts at galaxy classification, highlighting the contributions of astronomers and the emergence of the Hubble sequence. It sets the stage for further exploration of the major galaxy types and their characteristics in subsequent chapters.

III: Hubble Sequence and Major Galaxy Types

a) Introduction:

The Hubble sequence, proposed by Edwin Hubble in the 1920s, revolutionized the field of galaxy classification. This chapter delves into the major galaxy types identified within the Hubble sequence and explores their distinct morphological features, formation processes, and properties. The chapter focuses on elliptical galaxies, spiral galaxies, lenticular galaxies, and irregular galaxies, providing an in-depth analysis of each type.

b) The Hubble Tuning Fork Diagram:

The Hubble sequence, often depicted as a tuning fork diagram, is a classification scheme that arranges galaxies based on their visual appearance. At one end of the tuning fork are elliptical galaxies, characterized by their smooth, rounded shapes and absence of spiral arms. At the other end are spiral galaxies, distinguished by their prominent spiral arms and central bulges. Intermediate between the two are lenticular galaxies, which possess a disk-like structure but lack prominent spiral arms. Irregular galaxies, which do not conform to a regular shape, occupy a separate branch on the diagram.

c) Elliptical Galaxies:

Elliptical galaxies are generally spheroidal or ellipsoidal in shape, lacking the flattened disk structure observed in spiral galaxies. They are categorized according to their apparent elongation and symmetry, often denoted by the labels E0 to E7. Elliptical galaxies are predominantly composed of older stars and contain little interstellar gas and dust. They are thought to form through various processes, including mergers of smaller galaxies, and are commonly found in dense environments such as galaxy clusters.

d) Spiral Galaxies:

Spiral galaxies are characterized by their prominent spiral arms, central bulges, and rotating disk structure. They are further classified based on their level of spiral arm tightness, the size and prominence of the central bulge, and the presence of a central bar. Spiral galaxies are rich in interstellar gas and dust, fostering active star formation. They exhibit a wide range of properties, from tightly wound grand design spirals to loosely wound flocculent spirals. Spiral galaxies are believed to form through the collapse and subsequent evolution of rotating gas-rich protogalactic clouds.

e) Lenticular Galaxies:

Lenticular (S0) galaxies represent an intermediate type between ellipticals and spirals. They possess a disk-like structure similar to spirals but lack the prominent spiral arms. Instead, they often exhibit a featureless, smooth disk with a central bulge. Lenticular galaxies are generally gas-poor, indicating a lack of ongoing star formation. They are thought to form through a combination of processes, including the transformation of spiral galaxies in dense environments or the cessation of gas supply to an active galactic nucleus.

f) Irregular Galaxies:

Irregular galaxies do not conform to a regular shape and exhibit chaotic or distorted structures. They are often characterized by an irregular distribution of gas, dust, and young stars. Irregular galaxies can be further classified as Magellanic-type irregulars, which resemble the Large and Small Magellanic Clouds, or as peculiar/interacting galaxies resulting from interactions or mergers between galaxies. These interactions can trigger intense star formation and produce peculiar morphologies.

g) Properties and Formation Mechanisms:

Each galaxy type possesses unique properties that provide insights into their formation and evolution. Elliptical galaxies, for instance, tend to have older stellar populations, lower gas content, and a dominance of random stellar motions. Spiral galaxies showcase a range of features, from tightly wound grand design spirals with prominent bulges to loosely wound flocculent spirals with smaller bulges. Lenticular galaxies bridge the gap between ellipticals and spirals, exhibiting disk-like structures without pronounced spiral arms. Irregular galaxies exhibit a diverse range of morphologies resulting from interactions, mergers, or ongoing star formation.

Formation mechanisms for different galaxy types involve a combination of factors such as gas dynamics, mergers, interactions, and environmental influences. Understanding the underlying physical processes driving the formation and evolution of galaxies is crucial for unraveling their observed morphological characteristics.

h) Conclusion:

This chapter explored the major galaxy types within the Hubble sequence, including elliptical galaxies, spiral galaxies, lenticular galaxies, and irregular galaxies. It highlighted their distinct morphological features, formation processes, and properties. By examining these galaxy types, astronomers gain valuable insights into the diversity of galactic structures and the underlying physical mechanisms shaping their appearances. The subsequent chapters will delve further into subtypes and extensions within these major categories, as well as explore the physical processes and environmental effects influencing galaxy morphology.

IV. Subtypes and Extensions

a) Introduction:

Building upon the major galaxy types discussed in the previous chapter, Chapter 4 explores the subtypes and extensions within each category. This chapter delves deeper into the nuances and variations within elliptical, spiral, lenticular, and irregular galaxies. It explores the subcategories and rare types that exist within these major classifications, shedding light on their unique features, formation processes, and properties. Additionally, the chapter examines the role of galaxy interactions in shaping morphology and introduces rare and peculiar galaxy types.

b) Subtypes within Elliptical Galaxies:

Elliptical galaxies exhibit a range of morphological features, leading to the subdivision of this category into subtypes. These subtypes are often denoted by labels ranging from E0 to E7, representing variations in the ellipticity, elongation, and structure of the galaxies. Understanding the subtypes provides insights into the formation mechanisms and evolutionary processes that lead to different elliptical galaxy morphologies. Additionally, the chapter discusses the properties and characteristics specific to each subtype, such as stellar populations, metallicity, and luminosity profiles.

c) Spiral Galaxy Subcategories:

Spiral galaxies also exhibit a variety of subcategories based on the characteristics of their spiral arms, central bulges, and the presence of a central bar. The subcategories, often labeled as Sa, Sb, Sc, and sometimes Sd, represent a continuum of properties within the spiral category. Each subcategory showcases distinct features, such as the tightness and winding of the spiral arms, the prominence of the central bulge, and the presence or absence of a central bar. The chapter explores the differences between these subcategories, their implications for galaxy evolution, and their connection to other properties, such as gas content and star formation rates.

d) Additional Subclasses and Rare Types:

Beyond the main subcategories, there exist additional subclasses and rare types of galaxies that do not fit neatly into the traditional classifications. For example, ring galaxies feature a ring-like structure of stars and gas encircling a central core. Polar-ring galaxies possess an outer ring or disk of gas and stars perpendicular to the central galactic plane. These unique structures often result from specific interactions, such as galaxy collisions or mergers. The chapter explores these rare galaxy types, discussing their formation mechanisms, properties, and their significance in understanding galaxy evolution.

e) The Role of Galaxy Interactions:

Galaxy interactions play a crucial role in shaping the morphology and properties of galaxies. Interactions between galaxies can trigger disturbances in gas and dust, initiate star formation, and lead to the formation of tidal tails, bridges, and other features. The chapter examines the effects of galaxy interactions on morphological transformations, including the creation of peculiar galaxies and the potential for merging galaxies to form ellipticals. It explores the interplay between interactions, mergers, and galaxy morphology, shedding light on the dynamic nature of galaxy evolution.

f) Conclusion:

Chapter 4 delves into the subtypes and extensions within major galaxy types, including elliptical, spiral, lenticular, and irregular galaxies. It explores the subcategories and rare types within each classification, providing insights into their unique features, formation processes, and properties. The chapter also highlights the role of galaxy interactions in shaping morphology and introduces rare and peculiar galaxy types resulting from specific interactions or mergers. Understanding the diversity within galaxy types and the influence of interactions is crucial for comprehending the complexity of galactic structures and their evolutionary pathways.

V. Physical Processes and Environmental Effects

a) Introduction:

Chapter 5 focuses on the physical processes and environmental effects that influence galaxy morphology. It explores the interplay between these factors and the observed characteristics of different galaxy types. The chapter examines the role of gas dynamics, star formation, galaxy mergers, and environmental factors in shaping the morphological properties of galaxies. By understanding these processes, astronomers gain insights into the formation and evolution of galaxies and the factors that contribute to their diverse appearances.

b) Gas Dynamics and Star Formation:

Gas dynamics play a critical role in galaxy evolution and morphology. The chapter discusses the influence of gas in fueling star formation and driving the formation of different galaxy types. Gas-rich environments are conducive to active star formation, leading to the formation of young, blue stars and the emergence of spiral arms in disk galaxies. The interplay between gas dynamics, such as accretion, outflows, and feedback processes, shapes the distribution of gas and its role in determining the overall morphology of galaxies.

c) Galaxy Mergers and Interactions:

Galaxy mergers and interactions have a profound impact on the morphology and evolution of galaxies. The chapter explores the effects of mergers on the transformation of galaxy types, such as the formation of elliptical galaxies through major mergers. It discusses the disruption of spiral structures, the creation of tidal features, and the triggering of intense star formation during galaxy interactions. The role of minor mergers, flybys, and close encounters in influencing the morphological properties of galaxies is also examined.

d) Environmental Effects:

The environment in which galaxies reside can significantly influence their morphology and evolution. The chapter explores the effects of dense environments, such as galaxy clusters, on the formation of different galaxy types. It discusses the processes of galaxy harassment, ram pressure stripping, and strangulation, which can lead to the transformation of spirals into lenticular or elliptical galaxies. The impact of galaxy interactions within these environments, including galaxy cannibalism and cluster mergers, is also explored.

e) Galaxy Groups and Galaxy Formation:

In addition to galaxy clusters, galaxy groups provide unique environments for studying galaxy formation and morphology. The chapter discusses the properties of galaxies in group environments, including the prevalence of interacting systems and the role of tidal interactions in shaping morphology. It also explores the impact of group dynamics on gas stripping, star formation rates, and the transformation of galaxies.

f) Galaxy Evolutionary Pathways:

By examining the physical processes and environmental effects discussed in this chapter, astronomers can establish evolutionary pathways for galaxies. The chapter highlights the connections between these processes and the observed morphological properties of galaxies. It also discusses the interplay between gas content, star formation activity, mergers, and environmental factors in driving galaxy evolution along different pathways.

g) Conclusion:

Chapter 5 delves into the physical processes and environmental effects that influence galaxy morphology and evolution. It explores the role of gas dynamics, star formation, galaxy mergers, and environmental factors in shaping the observed characteristics of galaxies. By understanding these processes, astronomers gain insights into the formation and transformation of different galaxy types. The chapter emphasizes the interconnected nature of these factors and their contributions to the rich diversity of galactic structures.

VI. Multiwavelength and Observational Techniques

a) Introduction:

Chapter 6 focuses on the multiwavelength observations and observational techniques used to study galaxies. It explores how different wavelengths of light provide unique insights into various aspects of galaxies, including their morphology, stellar populations, interstellar medium, and active galactic nuclei. The chapter discusses the telescopes, instruments, and observational methods employed to collect data across the electromagnetic spectrum, enabling a comprehensive understanding of galaxy properties.

a) Overview of the Electromagnetic Spectrum:

The electromagnetic spectrum spans a broad range of wavelengths, from radio waves to gamma rays. The chapter provides an overview of the different regions of the spectrum and the types of observations possible at each wavelength. It highlights the importance of multiwavelength observations in obtaining a complete picture of galaxies and their physical processes.

b) Optical and Infrared Observations:

Optical observations play a crucial role in studying galaxy morphology and stellar populations. The chapter discusses the use of ground-based telescopes and space-based observatories to capture optical images of galaxies. It explores the advantages of high-resolution optical imaging for characterizing spiral arms, bars, and other structural features. Additionally, the chapter explores the significance of infrared observations, which can penetrate dust clouds and provide insights into star formation rates, dust content, and the presence of obscured active galactic nuclei.

c) Radio and Submillimeter Observations:

Radio observations allow astronomers to study various phenomena, including synchrotron emission, molecular gas, and radio jets from active galactic nuclei. The chapter delves into the use of radio telescopes and interferometry techniques to study galaxy properties, such as the presence of magnetic fields, supernova remnants, and interactions between galaxies. It also explores the emerging field of submillimeter astronomy, which probes the cold dust and molecular gas in galaxies, providing information about star formation and the early universe.

d) X-ray and Gamma-ray Observations:

X-ray and gamma-ray observations provide insights into the most energetic processes in galaxies. The chapter discusses the use of X-ray telescopes to study active galactic nuclei, hot gas in galaxy clusters, and X-ray binaries in galaxies. It explores the techniques employed to detect and analyze gamma-ray emissions from sources such as pulsars, gamma-ray bursts, and active galactic nuclei, shedding light on high-energy phenomena and particle acceleration processes.

e) Multiwavelength Surveys and Large-scale Projects:

The chapter explores the significance of large-scale surveys and projects conducted across multiple wavelengths. It discusses examples such as the Sloan Digital Sky Survey (SDSS) and the Hubble Space Telescope (HST) observations, which provide comprehensive datasets for studying galaxy populations, evolution, and large-scale structures. It also introduces upcoming projects, including the James Webb Space Telescope (JWST), which promises to revolutionize our understanding of galaxies with its enhanced infrared capabilities.

f) Data Analysis and Techniques:

The chapter covers various data analysis techniques used in multiwavelength observations, including image processing, photometry, spectroscopy, and source identification. It explores methods for combining data from different wavelengths to create composite images and extract valuable information about galaxy properties. The chapter also discusses advanced analysis techniques, such as spectral energy distribution fitting and machine learning algorithms, which aid in understanding complex datasets and identifying patterns within multiwavelength observations.

g) Conclusion:

Chapter 6 provides an overview of multiwavelength observations and observational techniques used to study galaxies. It explores the range of wavelengths across the electromagnetic spectrum and the insights provided by each. The chapter highlights the significance of combining data from multiple wavelengths to obtain a comprehensive understanding of galaxy properties, morphology, and physical processes. By employing advanced telescopes, instruments, and analysis techniques, astronomers can unravel the intricacies of galaxies and unlock the mysteries of the universe.

VII. Galaxy Evolution and Cosmology

a) Introduction:

Chapter 7 delves into the field of galaxy evolution and its connection to cosmology. It explores the processes and mechanisms that drive the transformation of galaxies over cosmic time, leading to the rich variety of galaxy types observed today. The chapter discusses the theoretical frameworks, observational evidence, and computational simulations that contribute to our understanding of galaxy evolution. It also examines the link between galaxy evolution and the larger-scale structure and evolution of the universe.

b) Hierarchical Structure Formation:

The chapter begins by discussing the concept of hierarchical structure formation, which is central to understanding galaxy evolution. It explores the growth of structures in the universe from small density fluctuations in the early universe to the formation of galaxy clusters and superclusters. The chapter also examines the role of dark matter and dark energy in shaping the large-scale structure of the universe and influencing galaxy evolution.

c) Formation and Evolution of Galaxies:

The chapter delves into the various processes involved in galaxy formation and evolution. It discusses the early universe and the formation of the first galaxies during the cosmic dark ages. It explores the growth of galaxies through gas accretion, mergers, and interactions. The chapter also examines the interplay between star formation, feedback mechanisms, and the regulation of gas supply in shaping galaxy properties over time.

d) Observational Evidence:

Observational evidence plays a crucial role in understanding galaxy evolution. The chapter discusses the observations of distant and high-redshift galaxies, which provide insights into the early stages of galaxy formation and the evolution of galaxy populations. It explores the use of spectroscopy, photometry, and imaging techniques to study galaxy properties, such as stellar populations, metallicity, star formation rates, and morphological transformations. The chapter also highlights the importance of studying galaxy clusters and the cosmic microwave background radiation in constraining galaxy evolution models.

e) Simulations and Computational Modeling:

Computational simulations are vital tools for studying galaxy evolution. The chapter discusses the use of numerical simulations to model the formation and evolution of galaxies within the framework of hierarchical structure formation. It explores the challenges and complexities of simulating galaxy-scale processes, including gas dynamics, star formation, and feedback mechanisms. The chapter also examines the comparison between simulations and observations, highlighting the successes and limitations of current models.

f) Galaxy Evolution and Cosmology:

The chapter explores the intimate connection between galaxy evolution and cosmology. It discusses the role of galaxy surveys, such as the Sloan Digital Sky Survey (SDSS) and the Hubble Space Telescope (HST) observations, in constraining cosmological parameters and understanding the growth of structures in the universe. The chapter also examines the impact of cosmological simulations and theoretical frameworks, such as the ΛCDM (Lambda Cold Dark Matter) model, on our understanding of galaxy evolution and its connection to the broader cosmic context.

g) Future Directions and Challenges:

The chapter concludes by discussing future directions and challenges in the field of galaxy evolution and cosmology. It highlights upcoming observatories and missions, such as the James Webb Space Telescope (JWST) and the Large Synoptic Survey Telescope (LSST), which will provide unprecedented data for studying galaxy evolution. The chapter also explores current challenges, including understanding the role of baryonic physics, improving the accuracy of simulations, and reconciling observations with theoretical predictions.

h) Conclusion:

Chapter 7 explores the fascinating field of galaxy evolution and its connection to cosmology. It examines the theoretical frameworks, observational evidence, and computational simulations that contribute to our understanding of galaxy formation, growth, and transformation over cosmic time. By studying the processes that shape galaxies and their connection to the larger-scale structure of the universe, astronomers gain insights into the intricate interplay between galaxies, dark matter, dark energy, and the evolution of the cosmos.

VIII: Active Galactic Nuclei (AGN) and Quasars

a) Introduction:

Chapter 8 focuses on the fascinating phenomena of active galactic nuclei (AGN) and quasars. These energetic sources at the centers of galaxies exhibit highly luminous and variable emission across multiple wavelengths. This chapter explores the nature, properties, and physical processes associated with AGN and quasars, shedding light on their origins, accretion mechanisms, and their role in galaxy evolution.

b) AGN and Quasar Classification:

The chapter begins by providing an overview of AGN and quasar classification schemes. It discusses the various observational characteristics and properties used to differentiate different types of AGN, including Seyfert galaxies, radio galaxies, blazars, and quasars. It explores the connection between AGN and their host galaxies, highlighting the differences in their properties and the potential links between AGN activity and galaxy evolution.

c) Accretion Processes and Central Engines:

The chapter delves into the physical processes responsible for the immense luminosity of AGN and quasars. It discusses the accretion of matter onto supermassive black holes at the centers of galaxies, forming a central engine that powers the energetic emission. The chapter explores the mechanisms of accretion disks, jets, and the role of magnetic fields in shaping the observed properties of AGN. It also discusses the role of gravitational waves and their potential in studying supermassive black hole mergers.

AGN and quasars exhibit distinctive spectral energy distributions (SEDs) and emission features across the electromagnetic spectrum. The chapter examines the different emission mechanisms involved, such as thermal emission from accretion disks, non-thermal emission from jets, and the contribution of ionized gas clouds. It explores the characteristic features seen in AGN spectra, such as broad emission lines, narrow emission lines, and the presence of high-ionization states. The chapter also discusses the use of spectroscopy to probe the physical conditions and kinematics of the gas surrounding AGN.

d) Variability and Time-domain Astronomy:

AGN and quasars are known for their significant variability in brightness and spectral properties over different timescales. The chapter explores the nature of AGN variability and its implications for understanding the physical processes occurring in the central engine. It discusses time-domain astronomy and the importance of monitoring AGN and quasars to capture their transient events, such as flares, outbursts, and microlensing effects. The chapter also examines the use of photometric and spectroscopic observations to study AGN variability and its connection to accretion disk instabilities and interactions with surrounding matter.

e) Feedback and the Role of AGN in Galaxy Evolution:

AGN are believed to play a significant role in regulating star formation and the growth of galaxies. The chapter discusses the feedback mechanisms associated with AGN activity and their impact on the host galaxy. It explores the injection of energy, momentum, and ionizing radiation from AGN into the surrounding medium, influencing gas dynamics, suppressing star formation, and potentially triggering galaxy-wide outflows. The chapter also examines the interplay between AGN feedback and other galaxy evolution processes, such as mergers, and the implications for understanding the co-evolution of supermassive black holes and their host galaxies.

f) Observational Techniques and Surveys:

The chapter explores the observational techniques and surveys used to study AGN and quasars. It discusses the use of large-area surveys, such as the Sloan Digital Sky Survey (SDSS) and the upcoming Large Synoptic Survey Telescope (LSST), to identify and characterize AGN populations. It also examines multiwavelength observations and the importance of coordinated campaigns to capture the broad spectral energy distributions of AGN. The chapter explores the challenges of AGN selection, source classification, and the need for follow-up observations to probe the physical properties of these energetic sources.

g) Conclusion:

Chapter 8 provides a comprehensive overview of active galactic nuclei (AGN) and quasars. It explores their classification, accretion processes, emission mechanisms, and spectral properties. The chapter discusses the variability of AGN and its implications, as well as the role of AGN feedback in galaxy evolution. It also explores the observational techniques and surveys used to study AGN and the challenges in understanding these intriguing and powerful sources at the centers of galaxies. By unraveling the nature of AGN and their connection to galaxy evolution, astronomers gain insights into the dynamics of supermassive black holes and their impact on the cosmic landscape.

By delving into the major galaxy types, their subtypes, and the underlying physical processes responsible for their formation and evolution, this thesis aims to enhance our understanding of the rich tapestry of galaxies in the universe. Furthermore, it highlights the importance of morphological classification as a powerful tool for studying cosmic evolution and paves the way for future advancements in this field of research.

IX. The Coevolution of Supermassive Black Holes and Their Host Galaxies: A Multifaceted Analysis

The relationship between supermassive black holes (SMBHs) and their host galaxies is a fundamental aspect of galactic evolution and astrophysical research. This thesis investigates the coevolutionary processes and interactions between SMBHs and galaxies, aiming to shed light on the underlying mechanisms and their implications for the cosmos. Through a multifaceted analysis encompassing observational, theoretical, and computational approaches, this study explores the key aspects of SMBH-galaxy coevolution and their mutual influence.

Dark matter halos are vast, gravitationally bound structures that form the backbone of the cosmic web, shaping the distribution of matter in the universe. They are composed predominantly of dark matter, a non-luminous and elusive form of matter that interacts weakly with ordinary matter and electromagnetic radiation.

a) Formation and Hierarchical Growth:

Dark matter halos form through the gravitational collapse of overdense regions in the early universe. According to the prevailing cold dark matter (CDM) paradigm, small perturbations in the initial density field grow over time, leading to the hierarchical growth of structures. Small halos merge to form larger ones, culminating in the formation of massive galaxy clusters.

b) Mass Distribution and Density Profiles:

Dark matter halos exhibit a characteristic density profile known as the NFW (Navarro-Frenk-White) profile, named after the researchers who first proposed it. The NFW profile describes a halo's density as a function of its distance from the center, with a steep central cusp and a shallower outer slope. However, recent observations and simulations have suggested that alternative density profiles, such as the Einasto profile, might provide a better fit to the data in certain cases.

c) Substructure and Halo Profiles:

Dark matter halos are not smooth and featureless; they contain numerous subhalos, which are smaller clumps of dark matter orbiting within the larger halo. These subhalos are thought to be the sites where galaxies form and reside. The abundance and properties of subhalos provide valuable information about the underlying cosmological model and the physics of dark matter.

d) Merging History:

As dark matter halos grow, they undergo mergers with other halos of comparable or smaller sizes. These mergers can significantly affect the properties and structure of the resulting halo, redistributing mass and altering its substructure. Understanding the merging history of dark matter halos is crucial for deciphering the large-scale structure of the universe and for predicting the formation of galaxy clusters.

e) Correlation with Galaxy Formation:

Dark matter halos provide the gravitational potential wells in which ordinary matter, such as gas and galaxies, accumulates. The formation and evolution of galaxies are intimately connected to the properties of the hosting dark matter halos. The relationship between dark matter halos and galaxies is a topic of intense research and involves understanding processes such as galaxy assembly, star formation, and the impact of feedback mechanisms from active galactic nuclei.

f) Observational Signatures:

Directly detecting dark matter remains a significant challenge. However, indirect evidence of dark matter halos can be obtained through various observational methods. Gravitational lensing, for instance, can reveal the presence of dark matter halos by distorting the light from background objects. Additionally, the statistical analysis of galaxy surveys can provide insights into the clustering and distribution of dark matter halos.

In summary, dark matter halos are fundamental structures in the universe, shaped by the gravitational pull of dark matter. Studying their properties, density profiles, substructure, merging history, and connection to galaxy formation is crucial for unraveling the nature of dark matter, understanding the formation of cosmic structures, and refining our knowledge of the universe's evolution.

X. Unraveling the Mysteries of Population III Stars

Population III stars, the first generation of stars in the universe, hold the key to understanding the early stages of cosmic evolution. Born from primordial gas clouds devoid of heavy elements, these stars have unique characteristics and played a vital role in shaping the subsequent evolution of galaxies. This thesis aims to explore the properties, formation mechanisms, and impact of Population III stars on the early universe, employing a combination of theoretical models, numerical simulations, and observational constraints.

It begins with a comprehensive review of the theoretical frameworks and observational evidence related to Population III stars. It covers topics such as the primordial gas composition, the formation mechanisms of the first stars, and the expected properties of Population III stellar populations.

Next, we focus on the development and implementation of numerical simulations to model the formation and evolution of Population III stars. This includes incorporating the effects of radiative transfer, hydrodynamics, and chemical enrichment to accurately capture the unique physical processes involved in the formation of these stars. The simulations aim to elucidate the conditions under which Population III stars form, their initial mass distribution, and their subsequent evolution.

We then present the findings of the research, addressing various aspects of Population III stars. This includes the determination of their mass range, spectral properties, and lifetimes, as well as the investigation of their influence on the surrounding interstellar medium and the subsequent generations of stars. The results are compared with observational data, such as the cosmic microwave background and the elemental abundance patterns in metal-poor stars, to validate the theoretical models and simulations.

Furthermore, the thesis explores the role of Population III stars in the process of cosmic reionization, which marks the transition from the dark ages to the universe we observe today. It investigates their contribution to the ionizing radiation budget and the impact on the intergalactic medium, shaping the formation and evolution of subsequent galaxies and their stellar populations.

Finally, we conclude with a summary of the key findings, their implications for our understanding of the early universe, and potential avenues for future research. It highlights the importance of continued investigation into the properties and formation mechanisms of Population III stars, as well as the need for improved observational techniques and upcoming missions to detect and characterize these elusive stellar relics.

Gravitational lensing is a phenomenon that occurs when the gravitational field of a massive object, such as a galaxy or a galaxy cluster, bends the path of light passing through it. This distortion of light provides a unique tool for studying the properties of both the lensing objects and the background sources being lensed. A comprehensive analysis of gravitational lensing involves several key aspects, including the types of gravitational lensing, observational techniques, theoretical modeling, data analysis, and applications in astrophysics and cosmology.

a) Types of Gravitational Lensing:

Gravitational lensing can be classified into different types based on the characteristics of the lens and the observed effects. These include:

- Strong Lensing: In strong lensing, multiple images, arcs, or rings of the background source are formed due to significant bending of light rays by the lensing object.

- Weak Lensing: Weak lensing refers to the subtle distortion of background galaxies that provides statistical information about the mass distribution of the lens.

- Microlensing: Microlensing occurs when a compact object, such as a planet or a star, passes in front of a background star, causing a temporary brightening or magnification.

b) Observational Techniques:

Various observational techniques are used to detect and study gravitational lensing:

- Imaging: Imaging observations capture the distorted images or extended structures caused by lensing.

- Spectroscopy: Spectroscopic measurements provide information about the redshifts, velocities, and chemical compositions of lensing objects and background sources.

- Time-Delay Measurements: Time delays between multiple lensed images can be measured to determine the Hubble constant and probe the expansion rate of the universe.

c) Theoretical Modeling:

Theoretical models are developed to describe the gravitational lensing phenomenon and predict its observable consequences. These models include:

- General Relativity: Gravitational lensing is primarily described by the principles of general relativity, which provide the mathematical framework for understanding the bending of light in a curved spacetime.

- Mass Distribution Models: Models of the lensing objects are constructed to determine their mass distribution and gravitational potential, which influence the lensing effects.

- Ray-Tracing Simulations: Numerical simulations based on ray-tracing techniques are used to predict and interpret the observed lensing phenomena, enabling the comparison of theoretical predictions with observational data.

d) Data Analysis and Parameter Estimation:

Analyzing gravitational lensing data involves extracting information about the lensing object and the background sources. This includes:

- Mass Reconstruction: Methods are employed to reconstruct the mass distribution of the lensing object using the observed lensing effects, such as the positions and shapes of lensed images.

- Statistical Analysis: Statistical techniques are applied to weak lensing data to infer the distribution and properties of dark matter, as well as cosmological parameters.

- Model Fitting: Theoretical models are fitted to the observational data to estimate the lensing parameters and validate the theoretical predictions.

e) Applications in Astrophysics and Cosmology:

Gravitational lensing has a wide range of applications in astrophysics and cosmology:

- Dark Matter Studies: By mapping the distribution of dark matter using lensing effects, researchers gain insights into the nature and properties of this elusive component of the universe.

- Cosmological Probes: Gravitational lensing provides a means to study the large-scale structure of the universe, constrain cosmological parameters, and investigate the expansion rate and geometry of the cosmos.

- Exoplanet Detection: Microlensing can be used to detect and characterize exoplanets by observing their gravitational influence on background stars.

In conclusion, a comprehensive analysis of gravitational lensing involves understanding the different types of lensing, employing observational techniques, developing theoretical models, performing data analysis, and applying lensing to various areas of astrophysics and cosmology. This multidisciplinary approach allows scientists to probe the properties of lensing objects, study the distribution of matter in the universe, and gain insights into fundamental aspects of our cosmos.

XI. DM condensates and uncertainty principle

When light, non-relativistic and weakly interacting bosons of mass m constitute DM halo of size R_h a fraction of them with very low momenta p can form a condensate provided,

$$\lambda_{DB} \sim \frac{h}{p} \gtrsim \left(\frac{3N}{4\pi R_h^3}\right)^{-1/3} = R_h \left(\frac{3M}{4\pi m}\right)^{-1/3}$$

Energy of a typical boson

$$E \sim \frac{p^2}{2m} + \frac{l^2}{2mR_h^2} - \frac{GMm}{R_h} < 0$$

$$p^2 < \frac{2GMm^2}{R_h} - \frac{n^2\hbar^2}{R_h^2}$$

$$L \sim nN\hbar = n\hbar\left(\frac{M}{m}\right) \qquad \Delta p \sim p \gtrsim \frac{\hbar}{2R_h}.$$

$$\frac{h}{4\pi p} \lesssim R_h \lesssim \frac{h}{p}\left(\frac{3N}{4\pi}\right)$$

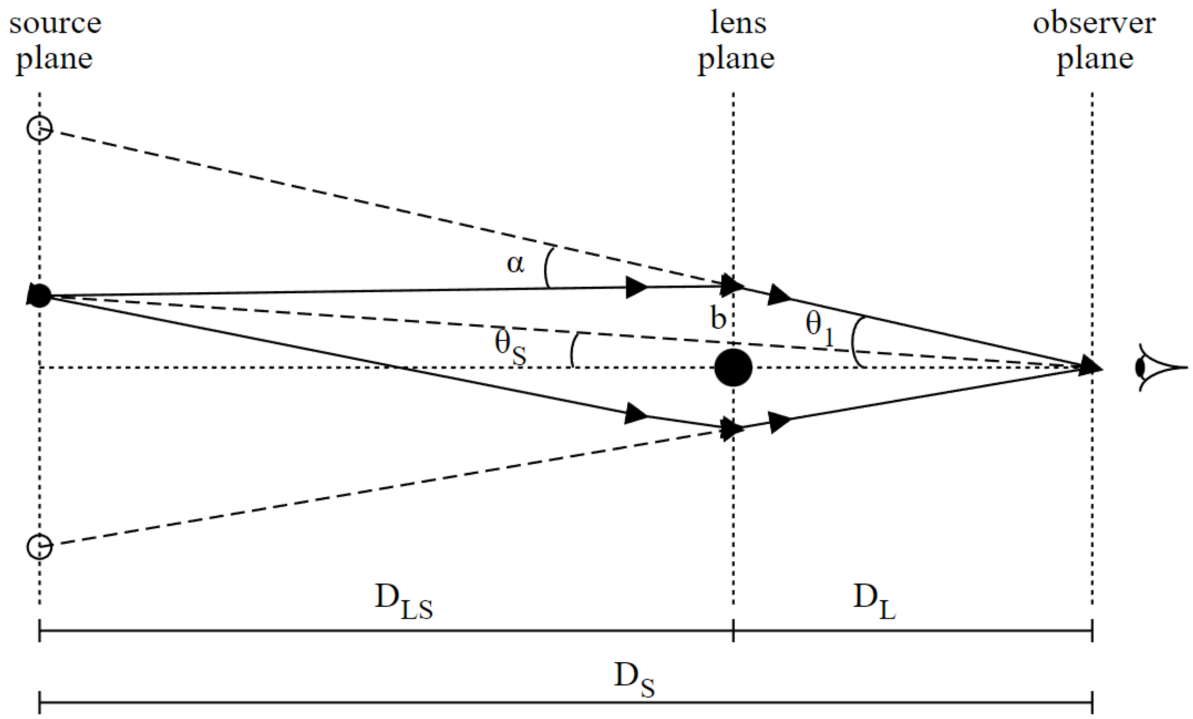
$$E \sim \frac{\hbar^2}{8mR_h^2} + \frac{n^2\hbar^2}{2mR_h^2} - \frac{GMm}{R_h} < 0$$

$$R_h \gtrsim \left(n^2 + \frac{1}{4}\right)\frac{\hbar^2}{2GMm^2} = 0.5\left(n^2 + \frac{1}{4}\right)\left(\frac{m_{Pl}^2}{m\ M}\right)\left(\frac{\hbar}{mc}\right)$$

$$= 4.3\left(n^2 + \frac{1}{4}\right)\left(\frac{10^7 M_\odot}{M}\right)\left(\frac{10^{-22}\ \mathrm{eV}}{m}\right)^2\ \mathrm{kpc}$$

$$\frac{\partial E}{\partial R_h} = \frac{GMm}{R_h^3}\left[R_h - \left(n^2 + \frac{1}{4}\right)\frac{\hbar^2}{GMm^2}\right] = 0$$

$$R_{h0} = \left(n^2 + \frac{1}{4}\right)\frac{\hbar^2}{GMm^2} \cong 86\ \left(n^2 + \frac{1}{4}\right)\left(\frac{10^9 M_\odot}{M}\right)\left(\frac{10^{-22}\ \mathrm{eV}}{m}\right)^2\ \mathrm{pc}$$



$$\alpha = \frac{4GM}{c^2 b}$$

a) Lensing from a BEC halo

BEC phase transition happens when the particles are correlated with each other quantum mechanically.

This happens when their wavelengths overlap, that is, the thermal de-Broglie wavelength λ_{DB} becomes greater than or equal to the mean inter-particle distance.

BEC transition temperature,

$$T < \left(\frac{2\pi\hbar^2}{mk_B}\right) n^{2/3}$$

For a non-rotating BEC ($\omega = 0$), the density distribution is given by

$$\rho(r) = \rho_c \frac{\sin kr}{kr}$$

which is simply the general solution of Poisson equation

$$\nabla^2\rho + k^2\rho = 0$$

$$k = \sqrt{\frac{4\pi G m_\chi^2}{U_0}}$$

$$U_0 = \frac{4\pi\hbar^2 l_a}{m}$$

l_a = s-wave scattering length

n = 1 polytropic Bose-Einstein condensate DM density profile has a sharp radius of boundary R so that $\rho(R) = 0$

$$kR = \pi$$

$$R = \frac{\pi}{k} = \pi\sqrt{\frac{\hbar^2 l_a}{G m_\chi^3}}$$

b) Thin lens approximation:

Lens equation for axially symmetric lens is

$$\eta = \frac{D_S}{D_L}\xi - D_{LS}\tilde{\alpha}$$

By introducing the quantities of dimensionless position and angle, the thin lens equation can be rewritten as

$$\beta = \theta - \alpha(\theta)$$

In circular symmetric case, the deflection angle is given by

$$\begin{aligned} D_L\alpha(\xi) &= \frac{2}{\xi}\int_0^{\xi}\frac{\Sigma(\xi')}{\Sigma_{crit}}d\xi' = \frac{2}{\xi}\int_0^{\xi}\xi'\kappa(\xi')\,d\xi' \\ &= \frac{1}{\pi\Sigma_{crit}}\frac{M_\xi(\xi)}{\xi}, \end{aligned}$$

Where convergence is defined as

$$\kappa(\xi) = \Sigma(\xi)/\Sigma_{crit}$$

Central convergence can describe the lensing properties of a BEC DM halo

$$\kappa_c = \frac{1.17357\rho_c R}{\Sigma_{\text{crit}}} = \frac{1.17357\pi M(R)}{4R^2\Sigma_{\text{crit}}}$$

c) Magnification factor

Gravitational lensing changes the shape and solid angle of the source.

Magnification factor (by which the luminosity of source S would be amplified) is given by

$$\mu = \frac{1}{(1-\kappa)^2 - \gamma^2}$$

$$\gamma(\xi) = \bar{\kappa} - \kappa = \frac{\bar{\Sigma}(\xi) - \Sigma(\xi)}{\Sigma_{crit}}$$

$$\bar{\Sigma}(\xi) = \frac{2}{\xi^2}\int_0^{\xi} \xi' \Sigma(\xi')\, d\xi'$$

Magnification by a spherically symmetric lens is given by

$$\mu = \frac{1}{(1-\bar{\kappa})(1+\bar{\kappa}-2\kappa)} = \frac{1}{\left(1-\bar{\Sigma}(\xi)/\Sigma_{crit}\right)\left(1+\bar{\Sigma}(\xi)/\Sigma_{crit}-2\Sigma(\xi)/\Sigma_{crit}\right)}$$

The lensing profile has 2 critical curves

$$1 - \bar{\kappa} = 0$$

$$1 + \bar{\kappa} - 2\kappa = 0$$

The model can explain the formation and existence of SMBHs at the nuclei of high redshift galaxies, which current models struggle to explain. In the near future, the data provided by James Webb telescope is likely to support this model.

If such a DM halo still exists (albeit at very high redshifts), it would cause gravitational lensing. If the same is detected, this model is confirmed.

If confirmed by gravitational lensing because of such a diffuse DM halo in future, it will prove to be crucial in the field of astrophysics and cosmology since it can directly explain the existence of SMBHs at the centers of galaxies with z >=10, and simultaneously confirm the existence of dark matter.

References:

1. Aspects of Black Hole Physics and Formation of Super-massive Black Holes from Ultra-light Dark Bosons
   -Patrick Das Gupta, Fazlu Rahman
2. Gravitational, lensing, and stability properties of Bose-Einstein condensate dark matter halos
   -Tiberiu Harko, and Francisco S. N. Lobo