Review

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Review

Dwarf Galaxies in Focus: A Survey of Observational and Theoretical Studies

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Abstract

This paper presents provides a comprehensive survey of dwarf galaxies, which represent the most numerous and diverse systems in the Universe. We discuss their definitions and morphological classifications, emphasizing the unique properties that distinguish them from globular clusters and giant galaxies. Special attention is given to their formation and evolutionary processes in the framework of hierarchical structure formation and ΛCDM cosmology, including the role of environmental mechanisms and stellar feedback. Star formation histories are explored based on observations and simulations, highlighting both bursty and extended activity across different dwarf types. We further examine the crucial role of dark matter in shaping the dynamics and structure of dwarf galaxies, as well as the core–cusp and missing satellites problems. Finally, we summarize insights from numerical simulations and theoretical models, which provide a bridge between observations and cosmological predictions. This synthesis demonstrates that dwarf galaxies remain essential laboratories for testing galaxy formation theories and probing the nature of dark matter.

Keywords: dwarf galaxy; catalog; universe; local group; local volume; galaxy; evolution; star formation; population; mass of galaxy; cosmology

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1. Introduction

Dwarf galaxies, particularly the ultra-faint variety, are primarily composed of dark matter, often outweighing their visible matter by hundreds or thousands of times [1]. This makes them ideal for studying dark matter and its gravitational effects. By observing the movement of stars within these galaxies, scientists can collect crucial data to test and improve theoretical models of dark matter [2]. Dwarf galaxies serve as important tools for testing the Cold Dark Matter (CDM) model, which is currently the most widely accepted framework in cosmology. There are ongoing challenges because simulations don't always match what we observe. For instance, there's the missing satellite problem, where we see fewer dwarf galaxies than predicted, and the core-cusp problem, which is a discrepancy in how dark matter is distributed within galaxy halos [3]. These issues are crucial for improving our understanding of both dark matter behavior and galaxy formation processes [4,5].

Dwarf galaxies are regarded as the foundational components from which larger galaxies are assembled. According to the hierarchical model of galaxy formation, massive systems like the Milky Way have developed over time by merging with and absorbing numerous smaller dwarf galaxies [6]. Due to their shallow gravitational potential wells, dwarf galaxies are particularly vulnerable to environmental influences such as tidal stripping and rampressure stripping caused by nearby massive galaxies [7]. Examining these interactions provides valuable insights into how external conditions influence galaxy evolution. Dwarf galaxies also display diverse star formation histories from inactive to highly bursty phases and their low metal content and structural simplicity make them excellent subjects for exploring star formation processes, especially under extreme conditions [1].

Dwarf galaxies offer crucial insights into the early Universe. Many of the oldest stars in our galactic neighborhood reside in these systems. These stars act as "living fossils" that hold chemical clues from the epoch of reionization [8]. These galaxies have a low amount of normal matter and a weak gravitational pull, which makes them very susceptible to powerful stellar events like supernovae and stellar winds. This "feedback" can either control or completely halt star formation within them [9]. Thanks to new powerful instruments like the James Webb Space Telescope (JWST) and upcoming surveys from the Vera C. Rubin Observatory, we are now better equipped to find faint dwarf galaxies and study their stars in remarkable detail [10].

2. What are Dwarf Galaxies?

Dwarf galaxies are currently a hot topic in astronomy because they offer crucial insights into several fundamental areas [11,12]. They were instrumental in developing the idea of stellar populations (groups of stars with similar origins), and they are key to understanding how elements evolve within galaxies and how dark matter is distributed. Furthermore, studying dwarf galaxies could be vital for unraveling the mysteries of galaxy formation and evolution. As a working definition all galaxies fainter than $M_B \leq -16$ m (H_0=50) and more extended than global clusters are considered here as dwarfs. But this definition is artificial; the high-surface brightness elliptical M32 (M_B=-15.5 m) is rather an underluminous giant, and SMC (M_B=-17.0 m) may be classified as an overluminous dwarf. Indeed the physical meaning of dwarfs is probably much deeper. It seems that dwarfs form a separate class of galaxies [13].

Dwarf galaxies differ from larger "giant" galaxies in several key ways. They have less stellar mass, are not as bright, and their stars are more spread out, making them look different [14]. Because of these variations, the precise definition of a dwarf galaxy can differ slightly across scientific studies, depending on the specific property being examined. Figure 1 illustrates these differences using an optical Color-Magnitude Diagram (CMD) for galaxies in the Coma cluster.

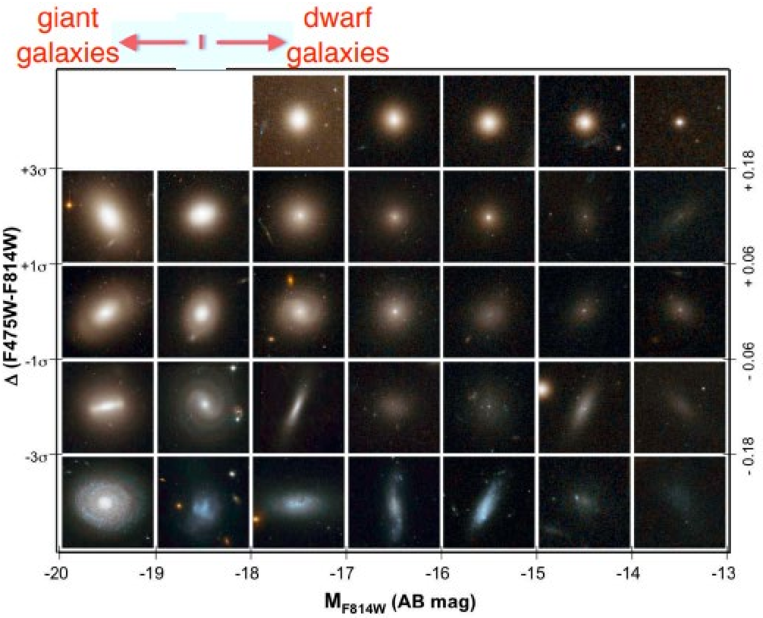

Figure 1. Dwarf galaxies are difficult to observe as they are intrinsically faint and tend to have lower surface brightness at fainter magnitudes.

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This CMD replaces data points with actual image cutouts from high-resolution Hubble Space Telescope observations, showcasing typical examples across various regions of color space. The middle row of the CMD represents the "red sequence" of galaxies. Detecting and analyzing dwarf galaxies is difficult because they get dimmer as they get fainter, making their surface brightness less intense [15].

An examination of the Palomar Sky Survey images of galaxy clusters reveals a group of faint objects that can be identified based on two main features:

A) they have low surface brightness, and

B) they show little or no central light concentration on the red images.

Since these objects appear more commonly in galaxy clusters than in the general field, it is likely that they are dwarf galaxies. This assumption is further supported by their resemblance to known dwarf galaxies in the Local Group. Most objects meeting both criteria A and B are likely dwarf galaxies. However, it's important to note that not all known or suspected dwarf galaxies meet both conditions [16].

Dwarf galaxies are key to studying galaxy formation, dark matter, and stellar evolution.They are characterized by low luminosity, low mass, and diffuse structure. Classification is complex, with overlaps between dwarfs and underluminous giants. Observational challenges arise from their faintness, requiring advanced detection methods. More research is needed to understand their full significance in astrophysics.

Globular clusters and dwarf galaxies are both systems of stars held together by gravity, yet they differ notably in terms of structure, composition, and development. Globular clusters are dense, spherical groupings of stars, generally only a few parsecs in size, and contain up to a few million ancient, metal-poor stars [17]. They typically have low mass-to-light ratios and show minimal signs of dark matter [18]. Dwarf galaxies, on the other hand, are much larger—ranging from hundreds to thousands of parsecs—and have more intricate star formation histories, often including multiple stellar generations and a broad range of metallicities. A key trait of dwarf galaxies is their high mass-to-light ratios, suggesting significant dark matter content [19]. Unlike the more compact and dynamically evolved globular clusters, which often show signs of mass segregation, dwarf galaxies are more diffuse and evolve more slowly, with less evidence of internal mass sorting. While globular clusters are usually thought to have formed within larger galaxies, dwarf galaxies are believed to have originated independently within their own dark matter halos. Some objects, like Omega Centauri, challenge this classification and may actually be the stripped cores of former dwarf galaxies [20]. Thus, for example, if the absolute magnitude M_V of the host galaxy is equal to or brighter than -22.5 m, then its globular cluster systems can be assigned to the brightest systems, while if it is fainter than -17.5 m, then it is among the faintest or dwarf systems [21].

Recent advances in observational technology have greatly improved our ability to detect and study dwarf galaxies. Deep wide-field imaging from surveys such as the Vera C. Rubin Observatory's LSST, precise astrometry from Gaia, and near-infrared capabilities of the James Webb Space Telescope now allow astronomers to detect fainter and more distant dwarfs than ever before. When scientists use new tools and high-resolution computer simulations, they can more precisely measure things like the number of stars, the amount of dark matter, and the history of dwarf galaxies. This helps us better understand the role these galaxies play in how the universe evolves.

The locations of dwarf galaxies are key to understanding how they evolve and are affected by their surroundings. In our Local Group, many dwarf spheroidals (dSph) and dwarf elliptical (dE) galaxies are grouped around the Milky Way and Andromeda. It's believed that the strong gravitational pull and gas stripping from these larger galaxies removed the dwarfs' gas, stopping them from forming stars. Conversely, some dwarf irregular (dIrr) and blue compact dwarf (BCD) galaxies exist in more isolated areas, which lets them continue to form stars for longer periods. This distribution gives us direct evidence that a dwarf galaxy's shape, gas content, and star formation history are all linked to its environment (Figure 2).

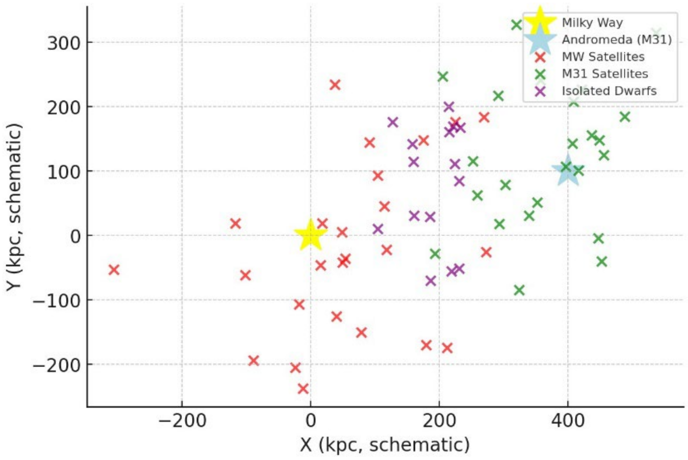

Figure 2. Schematic Sky Distribution of Local Group Dwarf Galaxies.

3. Morphological Types of Dwarf Galaxies

Dwarf galaxies are classified into three main types: dwarf spheroidal, dwarf irregular, and dwarf elliptical galaxies. Among these, dSphs are particularly distinctive, as their stellar masses are comparable to those of Galactic globular clusters, yet they possess significantly larger spatial extents. The shallow gravitational potentials and low average densities of dSphs render them highly susceptible to environmental influences; even low levels of star formation can substantially affect the structural evolution of their gaseous progenitors. Consequently, this study focuses on examining the mech-anisms of star formation within these systems [22].

3.1. Dwarf Spiral Galaxies

Dwarf spiral galaxies are a type of galaxy that falls within the S0 to Sd range. They are characterized by a low central surface brightness ($\mu_V \geq 23$ mag arcsec^{-2}), low hydrogen (HI) mass ($M_{HI} \leq 10^9\ M_\odot$), and high mass-to-light ratios. These galaxies are at the heavier end of the dwarf galaxy spectrum. Earlier types of these galaxies have rotation curves that are typical of rotating disks, while later types either spin slowly or rotate as a single solid body. These galaxies typically experience gradual, ongoing star formation. Later-type dwarf spirals generally contain less gas and metals compared to earlier types. The most extreme late-type spirals might be evolving into irregular galaxies. Dwarf spirals can be found both in galaxy clusters and in isolated (field) environments [23].

3.2. Blue Compact Dwarf Galaxies (BCD)

Blue compact dwarf galaxies (BCDs) are small galaxies known for their rapid star formation, which is concentrated in the center. This concentration of gas and stars makes them look very compact, powers their starburst activity, and gives them a high central surface brightness ($\mu_V \geq 19$ mag arcsec^{-2}). Some BCDs are also classified as HI-rich galaxies, blue amorphous galaxies, or low-mass Wolf-Rayet galaxies. They have hydrogen (HI) masses of $M_{HI} \leq 10^9\ M_\odot$, which can be greater than their stellar mass. While the inner regions of BCDs rotate like a solid body, the extended gas around them may move independently. These galaxies are often found in relatively isolated areas, away from crowded galaxy clusters [23].

3.3. Dwarf Irregular Galaxies (dIrr)

Dwarf irregular galaxies (dIrr) have a disorganized appearance. In optical images, they often feature scattered bright H II regions. When observed using hydrogen (HI) data, these galaxies reveal a complex, fractal-like structure of gas, containing many shells and clumps. In more massive dIrrs, the HI gas typically extends far beyond even the oldest stars. Some of these galaxies also show signs of gas accretion. In lower-mass dIrrs, the HI gas may be misaligned with the distribution of starlight—

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either shifted from the center or forming a ring-like shape with a central gap. dIrr are characterized by ($\mu_V \geq 23$ mag arcsec^{-2}, $M_{HI} \leq 10^9\ M_\odot$), and $Mtot \leq 1010\ M_\odot$. In more massive dwarf irregular galaxies (dIrrs), chemical enrichment tends to increase in younger stellar populations. In contrast, low-mass dIrrs often show clear differences between the spatial distribution and motion of gas and stars. Solid-body rotation is typical in higher-mass dIrrs, while some low-mass ones may lack any detectable rotation. dIrrs are found in various environments, including clusters, groups, and isolated (field) regions, but they are not strongly clustered around large galaxies. Massive dIrrs can sustain star formation over the course of a Hubble time, whereas very low-mass, gas-deficient dIrrs might be transitioning into dwarf spheroidal galaxies [23].

Dwarf irregular (dIrr) galaxies share several characteristics with dwarf spheroidal (dSph) galaxies, yet they are distinguished by the presence of neutral hydrogen (HI) gas—often comprising a significant portion of their mass and ongoing or recent star formation activity. Both types of galaxies harbor an older stellar population. It has been suggested that dIrr galaxies might represent dSph galaxies in a more active evolutionary phase. A small dIrr galaxy that ceases star formation for several hundred million years could resemble a dSph. Nonetheless, dIrr galaxies generally exhibit a more continuous and stable star formation rate (SFR) over time and tend to reach higher metallicities compared to dSph. This may be due to their greater mass, allowing them to retain their interstellar medium (ISM) despite supernova-driven outflows, or due to reduced environmental disruption, as they are often located farther from massive galaxies. These factors enable dIrr galaxies to maintain prolonged, albeit low-level, star formation throughout their evolution [24].

3.4. Dwarf Elliptical Galaxies (dE)

Dwarf elliptical (dE) galaxies are small, spherical or oval-shaped galaxies with a high concentration of stars at their center. They are typically fainter than M_V=-17 mag, with a surface brightness of $\mu_V \geq 21$ mag arcsec^{-2}, a hydrogen (HI) mass of $M_{HI} \leq 10^5\ M_\odot$, and a total mass of $M_{tot} \leq 10^9\ M_\odot$. These galaxies are usually found close to larger galaxies, contain very little to no gas, and generally lack rotational support. If gas is present, it might be unevenly distributed, less extended than the starlight, and may move differently from the main galaxy structure. Some dEs have a noticeable nucleus, which can account for up to 20% of the galaxy's light. More luminous dEs are more likely to have a nucleus. The surface density profiles of dEs and their nucleated counterparts (dE(N)s) are best described by Sersic's [25] generalization of a de Vaucouleurs $r^{1/4}$ law and exponential profiles [23].

3.5. Dwarf Spheroidal Galaxies (dSph)

Dwarf spheroidal galaxies (dSphs) are very faint, low-mass galaxies with little central light concentration and almost no gas. They have a total magnitude of $M_V \geq$-14 mag, a surface brightness of $\mu_V \geq 21$ mag arcsec^{-2}, and a total mass of $M_{tot} \approx 10^9\ M_\odot$. These are the faintest and least massive galaxies we know of. They are typically found near larger galaxies and don't show signs of rotation. Their velocity dispersions suggest that they contain a lot of dark matter. The different locations of dSphs and dEs compared to dwarf irregular galaxies (dIrrs) is called morphological segregation, which suggests that their environment plays a role in how they evolve [23].

Dwarf spheroidal (dSph) galaxies are the smallest and dimmest galaxies discovered so far. In the Local Group, they are typically found orbiting larger galaxies like the Milky Way and M31, acting as their satellites. While some dSph galaxies formed the entirety of their stellar content over 10–12 billion years ago and have remained inactive since, others formed most of their stars during intermediate epochs, approximately 6–8 billion years ago. A small subset has undergone star formation as recently as 1–2 billion years ago. Despite this diversity, all dSph galaxies contain a population of ancient stars. Even those considered the oldest and most quiescent exhibit complex star formation histories (SFHs), and despite similarities in their SFHs, their color–magnitude diagrams (CMDs) often differ, possibly due to variations in environmental conditions. The evolution of dSph galaxies is likely shaped, perhaps significantly, by their interactions with the Milky Way. Orbital dynamics, particularly dynamical friction, may influence their star formation rates. Currently, none of the Milky Way's dSph satellites shows clear evidence of retaining inter-stellar medium (ISM) [24,26].

3.7. Ultra-Faint Dwarf Galaxies (UFD)

Ultra-faint dwarf galaxies (UFDs) are the faintest galaxies known in the Universe, with, by definition, a V-band luminosity of fainter than $L_V=10^5\ L_\odot$, $M_V<-7{,}7$. Some of these galaxies, such as Triangulum II or Segue II, can be extremely faint—just a few hundred times the luminosity of the Sun. Ultra-faint dwarf galaxies (UFDs) are composed mainly of very old stars, older than 10 billion years. Their structure and shape have been the subject of ongoing debate for more than 15 years. It was soon discovered that UFDs are generally elongated, with an average ellipticity of around 0.4. Such a relatively elongated shape has been postulated to result from tidal interaction with the Milky Way [27].

Table 1 summarizes the principal physical and morphological characteristics of various dwarf galaxy types, including their typical stellar masses, gas content, star formation activity, structural morphology, and representative examples. Dwarf galaxies are a very diverse group, ranging from those that are rich in gas and actively forming stars (like dwarf irregulars and blue compact dwarfs) to those with little gas that have stopped forming stars (dwarf spheroidals and dwarf ellipticals). At the very dimmest end of the spectrum are ultra-faint dwarfs (UFDs), which are mostly made of dark matter. Another unique type, tidal dwarf galaxies (TDGs), form from the leftover material created when large galaxies collide.

Table 1. Key physical and morphological properties of dwarf galaxy types.

Morphological type	Typical stellar mass ($M_\odot$)	Gas content	Star formation activity	Shape / structure	Example galaxies
Dwarf Elliptical (dE)	10^7–10^9	Very low	None	Smooth, spheroidal	NGC 205, M32
Dwarf Spheroidal (dSph)	10^5–10^7	Extremely low	None	Faint, diffuse	Draco, Sculptor
Dwarf Irregular (dIrr)	10^7–10^9	High	Ongoing	Irregular, clumpy	IC 1613, WLM
Blue Compact Dwarf (BCD)	10^7–10^9	High	Intense bursts	Compact, blue	I Zw 18, Henize 2-10
Ultra-Faint Dwarf (UFD)	10^3–10^5	Negligible	None	Very faint, DM-dominated	Segue 1, Bootes I
Tidal Dwarf Galaxy (TDG)	10^8–10^9	Moderate	Possible	Formed from tidal debris	NGC 5291 TDGs

4. Mass of Dwarf Galaxies and Methods for Determining Mass

To estimate the kinematic mass of a galaxy, one must measure either its velocity dispersion in pressure-supported systems or its rotation speed in rotation-supported systems. We also need to determine an appropriate scale length and the galaxy's luminosity density or total luminosity to calculate its mass-to-light ratio [28,29]. The scale length chosen for the calculation depends on the dynamic model. For non-rotating dwarf galaxies, the King core radius or exponential scale length is used, while for rotating galaxies, the scale is derived from the rotation curve [30,31].

dSph galaxies. Because they generally lack an ISM component, and because they have such low surface brightnesses, the internal kinematics of most LG dSph galaxies are based on high precision spectroscopic radial velocities of individual stars. At least four ongoing criticisms have been raised regarding the reliability of dSph kinematic measurements obtained using this approach.

dIrr galaxies. Established methods are available for constructing rotation curves of dwarf irregular (dIrr) galaxies both within and outside the Local Group. We only see dwarf irregular galaxies (dIrrs) in the Local Group where rotation isn't the primary force governing their movement at every radius. For example, GR 8 shows rotational motion in its inner parts but shifts to pressure support in the outer regions. In gas-rich dIrr galaxies that lack rotation, velocity dispersion is typically measured using the width of the 21-cm hydrogen line [32].

Precisely mapping the mass distributions of low-mass dwarf spheroidal (dSph) galaxies provides a way to test predictions from dark matter (DM) theories. So far, most of these studies have focused on the satellite galaxies of the Milky Way. In contrast, although the Andromeda Galaxy (M31) hosts 35 known dwarf galaxies, only two have been thoroughly mass modeled. To gain deeper insights into the nature of dark matter, a broader investigation of Local Group dwarf galaxies is needed. In this context, the authors have conducted a dynamical analysis of two relatively luminous Andromeda satellites: Andromeda VI (And VI) and Andromeda XXIII (And XXIII). Author's infer an enclosed mass for And XXIII of $M(r < r_h) = (3.1 \pm 1.9) \times 10^7 M_\odot$, corresponding to a mass-to-light ratio of $[M/L]r_h = (90.2 \pm 53.9) M_\odot/L_\odot$. Using the dynamical Jeans modeling tool, GravSphere, we determine And VI and And XXIII's dark matter density at 150 pc, finding ρDM,VI (150 pc) = $(1.4 \pm 0.5) \times 10^8 M_\odot\, \mathrm{kpc}^{-3}$ and ρDM,XXIII (150 pc) $=0.5+0.4 -0.3 \times 10^8 M_\odot\, \mathrm{kpc}^{-3}$. The authors' findings identify Andromeda VI (And VI) as the first M31 satellite to exhibit a cuspy central dark matter profile based on mass modeling, whereas Andromeda XXIII (And XXIII) shows a lower central density. The low dark matter density in the galaxy And XXIII might be due to a "core" in its dark matter distribution or a decrease in density caused by tidal interactions. Because And XXIII stopped forming stars early on, a dark matter core likely didn't form from gas moving in and out, which is a common process.This low central density makes And XXIII similar to other dwarf galaxies orbiting M31, but different from most of the dwarfs orbiting the Milky Way, and also less dense than what is predicted by standard cosmological models for isolated dwarfs. A possible reason for this is that the dwarf galaxies orbiting M31 have experienced stronger tidal forces than those orbiting the Milky Way [33].

Dwarf galaxies come in many sizes, with different amounts of stars, ordinary matter, and dark matter halos. This variety is a result of their unique histories and the environments they've lived in. This text will describe the usual mass ranges for different types of dwarf galaxies, and then explain the main techniques used to calculate these masses. It will focus on how each method works, what observations are needed, its advantages, and its potential for errors. The mass of a dwarf galaxy can be defined in several ways:

Stellar mass (M^*) – derived from stellar population synthesis.
Baryonic mass (M_{bar}) – the sum of stellar and cold gas masses.
Dynamical mass – enclosed mass within a given radius inferred from kinematics.
Halo mass ($M_{(200)}$) – the mass within a sphere of mean density 200 times the critical density.

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Table 2 presents representative stellar, dynamical (or baryonic), and halo mass ranges for various classes of dwarf galaxies, expressed in logarithmic solar mass units. Ultra-faint dwarf spheroidals (UFDs) exhibit the lowest stellar masses, typically in the range log(M*) ≈ 2–5, with dynamical masses within the half-light radius of log(M_{<r_{half}) ≈ 6–7.5, and inferred halo masses of log(M_{halo}) ≈ 8–10. Classical dwarf spheroidals (dSphs) occupy a higher stellar mass regime (log(M*) ≈ 5–7.2) and dynamical masses within r_{half} of log(M) ≈ 7–8.5, corresponding to halo masses of ≈ 9–10. Dwarf irregulars (dIrrs) display stellar masses of log(M*) ≈ 6–9.2, baryonic masses of log(M) ≈ 7–9.6, and more extended halo masses of ≈ 9–11. Dwarf ellipticals and lenticulars (dE/dS0) are typically more massive, with stellar masses in the range log(M*) ≈ 7–9.5, dynamical masses within the effective radius of ≈ 8.5–10.5, and halo masses ≈ 9.5–11. Ultra-diffuse galaxies (UDGs) show stellar masses of ≈ 7–8.5, dynamical masses within a few kiloparsecs of ≈ 9–11.2, and halo masses of ≈ 10–12, consistent with their extended, low-surface-brightness structure. Finally, transition-type dwarfs (dTrans) possess stellar masses of log(M*) ≈ 5–7, dynamical masses within r_{half} of ≈ 7–8.3, and halo masses of ≈ 9–10, representing systems with mixed morphological and star formation properties.

Table 2. Typical stellar (upper bar) and halo (lower bar) mass ranges for selected dwarf galaxy types. Upper bars correspond to stellar masses, lower bars to halo masses.

Type	Stellar mass	Dynamical/ Baryonic mass	Halo mass
Ultra-faint dSph (UFD)	2–5	M(<r_{half}) = 6–7.5	8–10
Classical dSph	5–7.2	M(<r_{half}) = 7–8.5	9–10
dIrr	6–9.2	Baryonic = 7–9.6	9–11
dE/dS0	7–9.5	M(<R_e) = 8.5–10.5	9.5–11
UDG	7–8.5	M(few kpc) = 9–11.2	10–12
dTrans	5–7	M(<r_{half}) = 7–8.3	9–10

Table 3 compares the main methods used to figure out how mass is distributed in galaxies. It covers what is used to trace the mass, the data needed, the pros of each method, and the main sources of error. H I rotation curves, derived through tilted-ring fitting or full 3D modelling, trace the enclosed mass profile to large galactocentric radii, enabling discrimination between core-like and cuspy dark matter distributions, as well as consistency checks via the baryonic Tully–Fisher relation. Their application, however, is subject to limitations arising from beam smearing, asymmetric drift, warps, and inclination uncertainties. Optical H α or IFU gas kinematics offer high central spatial resolution of rotational and dispersion components through emission-line modelling, though the method is sensitive to patchy emission and pressure support effects. Stellar mass-to-light ratios inferred from stellar population synthesis (SPS) modelling of broadband photometry or spectral energy distributions (SEDs) allow rapid stellar mass estimation but are constrained by uncertainties in the IMF, SPS models, and age–metallicity degeneracies. Abundance matching and stellar-to-halo mass relations (SHMR) provide a cosmologically motivated framework linking stellar and halo masses, with the advantage of broad applicability, albeit with significant intrinsic scatter and susceptibility to environmental biases. Globular cluster (GC) or tracer kinematics extend mass measurements well beyond the stellar extent of galaxies by exploiting velocity distributions and anisotropy, but their interpretation is hindered by uncertainties in the dynamical connection between GC systems and their host galaxies. Weak gravitational lensing analyses directly probe the underlying gravitational potential via stacked measurements of large galaxy samples; however, they require extensive datasets and are limited by low signal-to-noise ratios for individual systems. Finally, satellite dynamics and tidal feature analyses constrain the global gravitational potential and the influence of environmental tides, although these approaches remain model-dependent and require detailed knowledge of a system's interaction history.

Table 3. Outlines the various observational methods for calculating the mass of dwarf galaxies.

Method	Traces	Key Inputs	Strengths	Weaknesses / Systematics
Stellar LOS velocity dispersions (Jeans/DF/GravSphere)	Dynamical mass within rhalf; inner DM slope	Member selection; σ_los(R); surface brightness; anisotropy model	Works for gas-poor dSphs; robust M(r_half); chemo-dynamic info	β–mass degeneracy; binaries; tides; contamination; small-N
HI rotation curves (tilted-ring, 3D)	Enclosed mass profile; core/cusp	HI datacube; inclination; distance; M*+gas maps; pressure support	Extended radii; spatial resolution; BTFR check	Beam smearing; asymmetric drift; warps; inclination errors
Optical H_α / IFU gas kinematics	Inner rotation/dispersion	IFU cubes; emission-line modelling	High central resolution	Patchy emission; pressure support
SPS M*/L from colours	Stellar mass	Broadband colours/SED; IMF; SPS model	Fast; photometry-based	IMF/SPS systematics; age–metallicity degeneracy
Abundance matching / SHMR	Statistical halo mass ($M_{(200)}$)	Stellar mass; SHMR model	Cosmological context; easy to apply	Large scatter; environmental bias
GC/tracer kinematics	Potential at large radii	GC velocities; distribution; anisotropy	Reaches beyond stellar body	Small-N; GC–galaxy link uncertain
Weak lensing (stacking)	Mean halo mass of samples	Large sample; shapes; redshifts	Direct gravitational probe	Requires huge samples; low S/N
Satellite dynamics / tidal features	Global potential; stripping	Orbits; streams; asymmetries	Constrains environment & tides	Model-dependent; needs history
Stellar LOS velocity dispersions (Jeans/DF/GravSphere)	Dynamical mass within rhalf; inner DM slope	Member selection; σ_los(R); surface brightness; anisotropy model	Works for gas-poor dSphs; robust M(r_half); chemo-dynamic info	β–mass degeneracy; binaries; tides; contamination; small-N

The choice of mass determination method depends strongly on the morphology and gas content of the galaxy.

Gas-poor systems (dSph, UFD) – use line-of-sight stellar velocity dispersions. The [34] estimator is robust to anisotropy at the half-light radius. High-quality spectroscopy allows more advanced models (Jeans, DF, GravSphere).

Global halo mass – often inferred via abundance matching between the stellar mass function and ΛCDM halo mass function. Large scatter exists for dwarfs, and results may be biased in dense environments.

Alternative tracers – globular cluster kinematics in UDGs, satellite orbits, and weak lensing in large statistical samples complement the above methods by probing larger scales or ensemble properties.

5. Formation and Evolution of Dwarf Galaxies

Dwarf galaxies rank among the smallest and most numerous galactic systems in the cosmos and play an essential role in the hierarchical process of galaxy formation. The ΛCDM model suggests that they originated from the early gravitational collapse of localized dark matter concentrations, which subsequently attracted baryonic matter that cooled and triggered star formation [35]. These systems typically underwent brief, intense bursts of star formation early on, leading to the creation of metal-poor stars [19]. However, mechanisms like cosmic reionization and stellar feedback often curtailed further star formation by heating or expelling the gas needed to form new stars [36]. Environmental influences, such as tidal forces and ram pressure from larger galaxies, also played a significant role in reshaping these systems, frequently halting star formation altogether and converting gas-rich dwarf irregular galaxies into gas-poor dwarf spheroidals [37]. Although small in mass, dwarf galaxies possess rich and varied chemical evolution patterns, including evidence for multiple generations of stars and complex enrichment processes. Their dark matter-dominated structures, vulnerability to feedback, and diverse developmental paths make them powerful tools for studying galaxy evolution and the nature of dark matter on smaller cosmic scales.

The formation and evolution of dwarf galaxies appear to diverge significantly from that of “normal” galaxies. However, the standard theory of galaxy evolution suggests that all galaxies, except for the very smallest, are constructed through the successive mergers and accretions of smaller collections of stars, gas, and dark matter. A major component of the universe, 90% of its matter, is dark matter detectable only through its gravitational effects and still largely a mystery. If this dark matter is “cold” and present when Big Bang light propagated across galactic distances, then the universe’s expansion would have caused initial density fluctuations to become gravitationally bound and stable. Unlike dark matter, the gas in these early proto-galaxies can cool down by releasing energy. This allows the gas to gather and form dense cores within the dark matter halos. Once this gas becomes dense and cool enough, star formation begins, marking the birth of a galaxy. The hierarchical growth of cosmic structures like galaxies and galaxy clusters occurs as these small, dense regions merge. The matter we see in a bright galaxy today is actually a collection of many smaller, original fragments that merged together over time [38].

The dwarf galaxies that exist today are essentially "survivors" that avoided being consumed by larger galaxies. It's possible these remaining dwarf galaxies are fundamentally different from the early galactic fragments that merged to form today's massive galaxies. Nonetheless, studying the features of contemporary dwarf galaxies provides vital data for evaluating the theory of hierarchical structure formation. A rapid onset of star for motion after gravitational collapse of dense regions would imply that the stars in these surviving local dwarf galaxies are very old, given that their surrounding dark matter halos would have been among the universe’s earliest formations [39].

Explaining the disparities between observed dwarf galaxies and the standard model of galaxy evolution necessitates unique astrophysical explanations for dwarf galaxy development compared to giant galaxies. Their low masses and shallow gravitational potential make dwarf galaxies inherently fragile. Processes such as radiation and supernovae from their earliest stars can lead to the breakdown, heating, and expulsion of gas, thus suppressing future star formation. Moreover, the strong background of ultraviolet photons during the universe's early “re-ionization” phase might have photo-ionized or even “photo-evaporated” their small gaseous halos. Finally, the history of star formation within dwarf galaxies can be shaped by their surrounding environment and interactions with other galaxies [39].

Comparative Theoretical Frameworks: While the ΛCDM model successfully explains many aspects of dwarf galaxy formation, alternative dark matter models such as Warm Dark Matter (WDM) and Self-Interacting Dark Matter (SIDM) predict different structural properties, especially in the central density profiles of dwarf galaxies [40,41]. The cusp–core problem, where simulations predict steep dark matter density cusps but observations show flatter cores, is a key area where these models diverge in predictions.

Observations vs. Simulations: Hydrodynamical simulations like FIRE, IllustrisTNG, and NewHorizon provide detailed star formation histories and chemical enrichment patterns in dwarf galaxies, yet discrepancies remain when compared with high-precision observations from HST,

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JWST, and Gaia [1,42]. For example, simulations often overpredict the number of luminous satellites (the “missing satellites” problem) or their central velocity dispersions (the “too big to fail” problem).

Environmental Effects in Greater Detail: Environmental quenching mechanisms, such as ram-pressure stripping in galaxy clusters or tidal stirring in the halos of massive galaxies, have varying efficiencies depending on the dwarf galaxy's mass and orbit [43]. Recent studies show that ultra-faint dwarf galaxies near the Milky Way may have had their star formation suppressed primarily by reionization, while more massive dwarfs were affected by late-time environmental processes.

Despite significant advances, several key puzzles remain unsolved:

- The origin of ultra-faint dwarfs and their extremely low metallicities.
- The role of bursty star formation in shaping dark matter density profiles.
- The extent to which early feedback vs. environmental effects dominate quenching in different environments.

Local dwarf galaxies serve as unique laboratories where the imprint of early structure formation can still be observed, making them key objects for studying galaxy evolution [44].

Dwarf galaxies have complicated chemical histories despite their small size. Even within a single dwarf galaxy, there's a wide range of metal content, which suggests they've had multiple periods of star formation. The very small, "ultra-faint" dwarfs contain ancient stars with specific abundance patterns, like a high ratio of alpha elements to iron, which helps us understand how the first elements were formed. Larger dwarf galaxies, like Fornax and Sagittarius, show that they've been forming stars for a long time and have been enriched by different types of supernovae and AGB stars. Overall, the chemical makeup of dwarf galaxies makes them great for studying how small systems create, use, and lose their metals [19,44].

Chemical enrichment and feedback processes are closely related and determine how efficiently dwarf galaxies form stars. Due to their weak gravitational pull, these galaxies are very vulnerable to being affected by stellar winds, ionizing radiation, and gas expelled by supernovae. According to computer simulations, strong, repetitive events like stellar explosions can expel a significant amount of gas from a dwarf galaxy, halting its star formation and even smoothing out the dense center of its dark matter [60]. Finally, the universe's ultraviolet background during the reionization period probably heated up or evaporated the gas in the smallest dwarf galaxies, which stopped them from forming more stars. Therefore, feedback processes don't just control a dwarf galaxy's internal development; they also link its observable characteristics—like its metal content, amount of gas, and star types—to larger cosmic events [36].

Future Research Directions: Next-generation instruments such as JWST, ELT, and LSST are expected to detect even fainter dwarf galaxies and measure their detailed chemical abundances, enabling discrimination between competing formation models [10]. Furthermore, high-resolution cosmological zoom-in simulations will help refine predictions for the internal structure and star formation history of dwarf galaxies.

6. Dwarf Galaxy Catalogs

One of the first catalogs of dwarf galaxies was created by Sidney van den Bergh [16]. A catalog of dwarf galaxies located north of declination −23° was created using images from the Palomar Sky Survey. The results show that dwarf galaxies are not evenly spread across the sky. A notable cluster of dwarf irregular galaxies is observed near the galaxy M94 in the Canes Venatici constellation.

A catalog containing 846 dwarf galaxies within a 200 square degree area of the Virgo region has been compiled. Among them, 634 (75%) are classified as dwarf ellipticals, 137 (16%) as IC 3475 types, and 73 (9%) as dwarf spirals or irregulars. Additionally, two entries are identified as jets from typically bright galaxies. Notably, at least 20% of the dwarf ellipticals and 29% of the IC 3475 types exhibit stellar or quasi-stellar nuclei. The catalog is derived from nine deep-exposure images taken with the Palomar 48-inch (1.2 m) Schmidt telescope using IIIa-J plates, capturing galaxies with apparent diameters as small as 0.3 arcminutes and down to a limiting magnitude of approximately 19. For each galaxy, the catalog provides position coordinates (epoch 1950.0), apparent size, morphological type, an estimate of central light concentration, and a brightness assessment. The spatial distribution of the dwarf ellipticals and IC 3475 types closely resembles that of the standard galaxies comprising the Virgo Cluster, suggesting that these dwarf types are genuine members of the cluster. In contrast, dwarf spirals and possibly dwarf irregulars do not seem to be associated with the cluster. The catalog also briefly mentions the discovery of two new GR 8-type extreme dwarf irregular galaxies [45].

A catalog presents 145 dwarf elliptical galaxies within the Fornax cluster and is considered complete down to a blue magnitude of 18.5, although some galaxies with luminosities two magnitudes fainter have also been identified. Compared to brighter galaxies, the dwarf ellipticals show a less concentrated distribution toward the cluster center. The proportion of dwarf ellipticals relative to normal ellipticals is notably lower in Fornax than in the Virgo cluster. However, the ratio of dwarf ellipticals to actively star-forming galaxies (such as spirals and irregulars) is comparable in both clusters. Interestingly, the velocity distribution of both the dwarf ellipticals and the star-forming galaxies in Fornax deviates from a Gaussian profile, whereas the velocity distribution for elliptical and lenticular (E/S0) galaxies does follow a Gaussian pattern. The E/S0 galaxies also show a relatively low velocity dispersion of around 300 km s^{-1} [46].

The dwarf galaxies within the Local Group provide an exceptional opportunity to study the detailed characteristics of the most prevalent galaxy type in the Universe. This review presents an updated census of Local Group dwarf galaxies, incorporating the latest measurements of distances and radial velocities. It explores various aspects of these systems, including: (a) their integrated photometric properties and optical structures, (b) the composition, nature, and spatial distribution of their interstellar medium (ISM), (c) heavy-element abundances inferred from both stellar populations and nebulae, (d) their diverse and complex star formation histories, (e) internal kinematics, with particular attention to their significance for the dark matter problem and alternative frameworks, and (f) evidence of interactions past, present, and potential future with other galaxies within and beyond the Local Group. In support of this discussion and to aid future research, the review includes comprehensive tables summarizing current observational data and knowledge gaps regarding these nearby dwarf galaxies. Despite significant advancements over the past decade, many unresolved questions remain, ensuring that the Local Group will continue to play a central role in the study of galaxy evolution [32].

The Local Volume Database (LVDB) is introduced as a comprehensive catalog encompassing observed properties of dwarf galaxies and star clusters within the Local Group and the broader Local Volume. It compiles data on positional, structural, kinematic, chemical, and dynamical characteristics of these systems. Special attention is given to catalogs featuring faint and compact Milky Way systems with ambiguous classifications, newly identified Milky Way globular clusters and candidates, as well as globular clusters residing in nearby dwarf galaxies. The LVDB currently offers full coverage of known dwarf galaxies within approximately 3 megaparsecs, with ongoing efforts to extend its scope to include resolved stellar systems across the Local Volume. Publicly accessible examples and use cases of the LVDB are presented, focusing on the census and statistical properties of Local Group populations, alongside some theoretical implications. The coming decade is expected to be transformative for near-field cosmology, with upcoming missions and surveys including the Legacy Survey of Space and Time (LSST) at the Vera C. Rubin Observatory, the Euclid mission, and the Nancy Grace Roman Space Telescope anticipated to both discover new systems and provide unprecedented detail on known dwarf galaxies and star clusters [47].

This catalog [48] presents a detailed compilation of the positional, structural, and dynamical properties of dwarf galaxies located within and around the Local Group. It includes over 100 nearby galaxies with reliably determined distances placing them within 3 Mpc of the Sun. These systems span a diverse range of environments, including satellites of the Milky Way (MW) and Andromeda (M31), quasi-isolated galaxies with-in the Local Group outskirts, and numerous isolated dwarfs beyond its boundaries. Galaxies associated with nearby groups such as Maffei, Sculptor, and IC 342 are intentionally excluded. The catalog compiles key observational parameters distances, velocities,

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luminosities, mean stellar metallicities, structural dimensions, and dynamical characteristics which have been homogenized where possible and organized into standardized tables. The provenance and potential uncertainties of the tabulated values are critically discussed. Addition-ally, the spatial structure and membership of the MW and M31 subgroups, as well as the Local Group as a whole, are explored. The morphological variety of the dwarf galaxy population and its subgroups is analyzed, along with estimated timescales related to orbital motions and interaction histories. Scaling relations and trends in mean stellar metallicity are examined, and a potential floor in central surface brightness and possibly in stellar metallicity at low luminosities is considered.

Researchers have compiled a substantial collection of observational data on dwarf galaxies, leading to the creation of a composite catalog covering systems located within 121 megaparsecs. This catalog documents key physical properties of 413 dwarf galaxies, including equatorial coordinates, distances, absolute stellar magnitudes, masses (in solar masses), redshifts, and apparent magnitudes in the X-ray spectrum. Statistical analysis of the dataset has revealed empirical correlations among major galaxy characteristics. In particular, linear relationships were identified between galaxy mass and absolute magnitude, as well as between mass and distance. The findings demonstrate that galaxy mass increases linearly with both distance and absolute magnitude. However, the study found no significant correlation between redshift and apparent magnitude. Additionally, the spatial distribution of dwarf galaxies shows two prominent groupings—within 10–40 Mpc and 95–120 Mpc—likely linked to the influence of nearby massive galaxies [49].

7. Star Formation in Dwarf Galaxies

Consistent star formation histories (SFHs) for 40 dwarf galaxies in the Local Group have been reconstructed by analyzing color-magnitude diagrams (CMDs) generated from archival HST/WFPC2 imaging data. The study reports several key findings based on this analysis. A galaxy's lifetime star formation history (SFH) can be reliably determined even from a color-magnitude diagram (CMD) that does not extend to the oldest main sequence turnoff (MSTO). When systematic uncertainties in stellar evolution models are properly accounted for, SFHs derived from such shallower CMDs remain consistent with those obtained from deeper CMDs that reach below the oldest MSTO. Nevertheless, only CMDs that include the oldest MSTO allow for precise constraints on the earliest periods of star formation. In the case of sparsely populated systems, such as ultra-faint dwarf galaxies, expanding the survey area or increasing the number of stars near the oldest main sequence turnoff (MSTO) provides more reliable constraints on star formation histories (SFHs) than extremely deep CMDs covering smaller regions. CMDs that extend significantly below the oldest MSTO exhibit similar levels of systematic uncertainty in SFH determination as those reaching the MSTO with moderate signal-to-noise (approximately 1 magnitude below the oldest MSTO). This similarity arises because stars below the oldest MSTO are not strongly sensitive to variations in SFH. Therefore, in low-density systems, the primary limitation on SFH precision is the number of stars present in age-sensitive regions of the CMD such as the subgiant branch (SGB) and MSTO. Consequently, CMDs that include a greater number of stars—usually obtained by covering wider regions—provide more precise and representative star formation histories (SFHs) compared to ultra-deep CMDs confined to smaller fields. On average, the SFHs of dwarf spheroidal (dSph) galaxies exhibit an exponentially decreasing trend, with a typical timescale of around 5 billion years [50]. In contrast, dwarf irregulars (dIrrs), transition-type dwarfs (dTrans), and dwarf ellipticals (dE) are more accurately described by an exponentially declining star formation history (SFH) up to roughly 10 billion years ago, with characteristic timescales of approximately 3–4 billion years, after which they experienced a period of constant or rising star formation activity. Dwarf galaxies in the Local Group (LG) with stellar masses below 10^5 solar masses formed over 80% of their total stellar content before redshift z ~ 2, which corresponds to approximately 10 billion years ago. In contrast, more massive LG dwarfs with stellar masses exceeding 10^5 solar masses—had formed only about 30% of their stars by that same time [51]. The study explores how this apparent "upsizing" trend could be influenced by observational selection effects and environmental factors within the Local Group. Dwarf spheroidal galaxies

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(dSphs) with lower luminosities tend to have less extended star formation histories (SFHs) compared to their more luminous counterparts. Nevertheless, the relatively small variation in SFHs among dSphs indicates that stellar mass alone does not fully explain this trend, and that external factors—such as a galaxy's interaction history—have likely played a significant role in shaping their evolution [52]. Interestingly, some ultra-faint and classical dSph exhibit similar SFHs, suggesting that the distinction between these two categories is somewhat artificial. Furthermore, dwarf irregular galaxies (dIrr) in the Local Group formed a larger proportion of their stellar mass before redshift z = 2 than the star-forming galaxy population observed in the SDSS sample by Leitner [53]. Although systematic uncertainties and selection effects were considered, no clear explanation was found for this inverse downsizing trend. Additionally, before z = 2, Local Group dIrrs had formed more stellar mass than predicted by the abundance matching models of Behroozi et al. [54]. These findings highlight the limitations of extrapolating the properties of low-mass galaxies based on trends observed in more massive systems. One possible explanation for the observed discrepancy is that low-mass galaxies may have experienced higher-than-expected star formation efficiencies during the early stages of their evolution [10].

Star formation in dwarf galaxies is influenced by a range of both external and internal processes. External mechanisms such as ram-pressure stripping, tidal interactions, and exposure to ultraviolet (UV) radiation from the surrounding environment play a significant role, with the latter potentially inhibiting star formation in the lowest-mass systems. Internally, feedback from massive stars through UV radiation, stellar winds, and supernova explosions can suppress star formation efficiency. This suppression may help ad-dress various theoretical and observational challenges in galaxy formation. In this study, we present recent investigations into the relative significance of these diverse influences on the evolutionary pathways of dwarf galaxies [55].

Comparisons with cosmological simulations such as FIRE, APOSTLE, and NIHAO show that simulated dwarfs reproduce many observed trends, including the bursty SFHs of low-mass systems and extended SFHs in higher-mass, isolated dwarfs. However, discrepancies remain, especially in sustaining late-time star formation in isolated dIrrs, suggesting that simulations may underestimate late gas accretion or feedback regulation.

8. The Role of Dark Matter in Dwarf Galaxies

Dwarf spheroidal (dSph) galaxies, found near us in space, are excellent for studying dark matter since they are composed almost entirely of it. These galaxies have very few stars and gas (baryonic content) but have a surprisingly large mass, which we can figure out by observing the movement of their stars [32,56]. This makes them ideal for testing different dark matter theories.

Astronomical surveys that measure light from stars have shown that many dwarf spheroidal (dSph) galaxies have high stellar velocity dispersions. This means that even though they don't have many stars, the stars are moving very fast, which suggests a large mass. A galaxy's mass-to-light ratio ($M_\odot/L_\odot$), which compares its total mass to its visible light, helps us understand this. For instance, the Draco dSph has a remarkably high $M_\odot/L_\odot$ ratio of about 94, while the Fornax dSph has a lower but still significant ratio of around 5.7 [32]. These high ratios indicate that most of the mass is invisible and not from stars, suggesting these galaxies are surrounded by large, extended dark matter halos. These observations align with the Lambda Cold Dark Matter (ΛCDM) model, which predicts that dark matter halos extend well beyond a galaxy's visible stars [57].

A significant puzzle in studying dwarf galaxies is the core–cusp problem. Computer simulations of cold dark matter predict that galaxies should have a dense, sharply-peaked center, or a "cusp" [58]. However, observations of how stars move in many dwarf spheroidal galaxies suggest the opposite—that their centers have a more uniform density, or a "core" [59]. Researchers have proposed two main types of solutions to this discrepancy:

- Astrophysical Solutions: One idea is that supernova explosions in dwarf galaxies repeatedly push gas out. This process, known as baryonic feedback, could transfer energy to the surrounding dark matter, "puffing up" the dense central cusp and transforming it into a less dense core [60].

- Particle physics solutions: Another possibility is that the standard cold dark matter model is incomplete. Alternative theories, such as warm dark matter or self-interacting dark matter, suggest that dark matter particles don't behave as we've assumed. In these models, the particles naturally create a core-like distribution on their own, without needing the effects of supernovae [61].

Dwarf galaxies can also be used to place direct astrophysical constraints on the nature of dark matter particles. For example, [62] used stellar dynamics of the Leo II dSph to constrain the mass of ultra-light bosonic dark matter, finding m> 2.2×10^{-21} eV 95% confidence. Such limits are among the most stringent for fuzzy dark matter models and complement constraints from cosmological structure formation studies. Because of their high dark matter densities and low astrophysical backgrounds, dSph galaxies are prime targets for indirect dark matter searches via gamma-ray emission. The expected flux depends on the so-called “J-factor,” the line-of-sight integral of the squared DM density. Observations from the Fermi Large Area Telescope (LAT) have been used to set some of the strongest upper limits on the annihilation cross-section of weakly interacting massive particles (WIMPs), with no significant detection to date [63].

Bulge components were once thought to be equivalent to elliptical galaxies, but their properties and formation histories are more diverse, leading to a distinction between “classical bulges” and “pseudobulges” [64].

The distribution of dark matter in dwarf galaxies is a highly debated topic in modern cosmology. According to computer simulations based on the Cold Dark Matter (CDM) model, dwarf galaxies should have a dense, sharply-increasing concentration of dark matter at their core, which is called a cuspy profile. However, what has actually been observed, particularly in dwarf spheroidal (dSph) galaxies, shows a much flatter, less dense central region, or a cored profile. This conflict, called the core–cusp problem, has led scientists to develop models that include strong internal processes like supernova explosions and stellar feedback. These processes could redistribute dark matter, effectively smoothing out the central density and creating a cored profile (Figure 3; [58,59]).

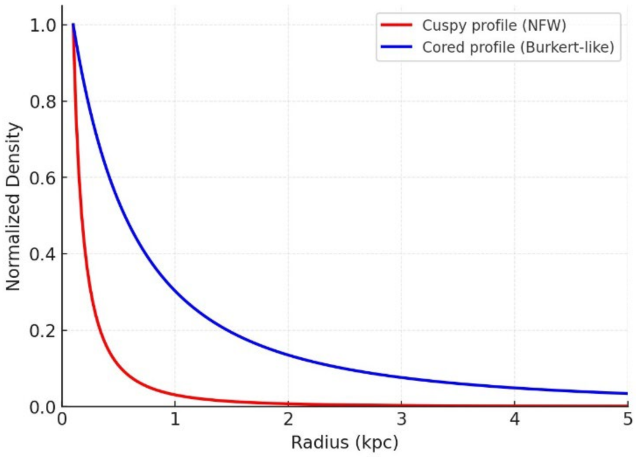

Figure 3. Dark Matter Density Profiles in Dwarf Galaxies: Cuspy vs. Cored.

9. Simulations and Theoretical Models

Dwarf galaxies, despite their relatively small masses and luminosities, play a pivotal role in testing cosmological models and galaxy formation theories [19,32]. The combination of theoretical frameworks and high-resolution numerical simulations has significantly advanced our understanding of their structural properties, star formation histories, and dark matter content.

State-of-the-art cosmological hydrodynamical simulations are now able to reproduce key observational scaling relations of dwarf galaxies, such as the stellar mass–halo mass relation,

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metallicity–luminosity trends, and size–mass correlations [65]. These simulations vary in feedback prescriptions, but often converge toward similar predictions, reinforcing the robustness of theoretical models.

One of the most debated issues in dwarf galaxy theory is the core–cusp problem, where ΛCDM simulations predict steep central dark matter cusps, while observational data favor flat (cored) profiles [56,66]. Stellar feedback—particularly supernova-driven outflows—has emerged as a leading explanation for transforming cusps into cores by inducing fluctuations in the gravitational potential [60].

N-body simulations coupled with smoothed particle hydrodynamics (SPH) codes, such as GADGET-2 and GADGET-4, have been extensively used to model the gravitational and hydrodynamical evolution of dwarf galaxies [67,68]. In parallel, semi-analytic models, including regulator-type frameworks like GRUMPY, provide computationally efficient tools for exploring parameter space and connecting halo assembly histories to observed galaxy properties [69].

Another long-standing challenge is the missing satellites problem, where simulations predict an order of magnitude more low-mass dark matter halos than the number of observed dwarf galaxies in the Local Group. Recent simulations suggest that many of these predicted satellites remain undetected due to their low surface brightness and extremely faint stellar populations, a prediction that upcoming surveys such as the Vera C. Rubin Observatory's LSST aim to test [70].

While the majority of theoretical work assumes that dwarf galaxies are dark matter–dominated systems, alternative hypotheses have been proposed. For instance, some models explore the possibility that massive black holes could dominate the gravitational potential in certain ultra-faint systems traditionally classified as dark matter–rich (Silk, 2017). State-of-the-art simulations and theoretical frameworks of dwarf galaxies have achieved remarkable sophistication, allowing scientists to better connect observational data with cosmological predictions. Nonetheless, unresolved issues—such as the precise impact of feedback mechanisms, the census of satellite systems, and the fundamental properties of dark matter—guarantee that dwarf galaxies will continue to play a central role in galaxy formation studies for the foreseeable future [56,70].

Different computer simulations of dwarf galaxies both agree with and contradict what we see in space. For example, FIRE simulations accurately recreate the sudden bursts of star formation and the formation of galactic cores in small dwarfs, which are caused by gas being pushed out [42,60]. In contrast, the APOSTLE simulations, which focus on our local cosmic neighborhood, do a better job of matching the number of observed satellite galaxies and how they move, helping to solve the "missing satellites" and "too-big-to-fail" problems [43]. The NIHAO simulations, which cover a wider range of galaxy sizes, successfully reproduce the long-term star formation histories of isolated dwarfs and provide better chemical evolution models that align with what we see in observations [55].

Ultimately, no single simulation can perfectly explain all the properties of dwarf galaxies. However, by looking at all of them, we get a more complete picture of how these small galaxies form and evolve.

10. Conclusions

Despite their relatively small masses, dwarf galaxies are crucial for advancing our understanding of cosmic evolution. Their diverse morphological types, star formation histories, and interactions with the environment make them one of the most relevant topics in astrophysics. In recent years, dynamical and photometric methods have been widely used to determine mass. However, there are significant differences between some of these methods, which may be related to observational accuracy and model parameters.

The amount and distribution of dark matter in dwarf galaxies is still not fully understood. In addition, it is important to study the evolutionary processes of dwarf galaxies. Therefore, during our current research, observational data on more than 600 dwarf galaxies up to 121 Mpc were collected and a catalog was created. In our previous studies, regression equations and correlation coefficients between various physical parameters of dwarf galaxies were calculated using catalog data [71,72].

Comparable analyses have also been carried out on various other astrophysical systems [73–75]. Such comparative research helps confirm the effectiveness of statistical approaches across diverse astronomical objects and offers a wider framework for understanding the findings related to dwarf galaxies.

In addition to these findings, it is important to emphasize that dwarf galaxies continue to pose several unresolved challenges for both observational astronomy and cosmological theory. The discrepancies between the predicted and observed numbers of satellites (the "missing satellites problem"), the internal mass distribution (the "core–cusp [73–75problem"), and the difficulty of sustaining star formation in isolated dwarfs highlight the complexity of these systems.

Moreover, the sensitivity of dwarf galaxies to feedback and environmental processes makes them unique probes for testing models of galaxy–environment interaction. Their shallow gravitational potentials ensure that even moderate supernova activity or tidal interactions can dramatically reshape their structures and star formation histories. Such features underline the importance of treating dwarfs not merely as scaled-down versions of massive galaxies but as fundamentally distinct systems with their own evolutionary pathways.

In the future, the James Webb Space Telescope and other advanced observational instruments will enable a deeper study of the star formation history and chemical evolution of dwarf galaxies. Additionally, the creation of new catalogs of ultra-faint dwarf galaxies is expected to expand the current classification. The results discussed in this paper summarize existing knowledge on dwarf galaxies and serve as a methodological basis for future research.

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