

## Postprint: Advances in the Search for and Physical Properties of Milky Way Satellite Galaxies

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### Abstract

Over the past decade, searches for Milky Way satellite galaxies have achieved significant progress. As of 2021, more than 60 satellite galaxies have been discovered, and this number will continue to increase with the development of next-generation imaging surveys. A comprehensive census of the satellite galaxy population is not only crucial for accurately characterizing the structure of the nearby Universe, but also serves as a powerful tool for testing galaxy formation models and the nature of dark matter. As an important component of the galaxy population, the study of satellite galaxies' physical properties is also indispensable for understanding galaxy formation and evolution. We first introduce the progress in satellite galaxy searches over the past decade, summarize their physical properties, and finally discuss the opportunities that next-generation surveys will bring to this field.

### Full Text

#### Research Progress on the Search for and Physical Properties of Milky Way Satellite Galaxies

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### Abstract

Over the past two decades, significant progress has been made in the search for Milky Way satellite galaxies. As of 2021, more than 60 satellite galaxies

have been discovered, and this number is expected to continue growing with the advent of next-generation imaging surveys. A complete census of satellite galaxy populations is not only crucial for accurately characterizing the structure of the nearby universe but also provides important constraints for testing galaxy formation models and the nature of dark matter. As important constituents of the galaxy population, satellite galaxies are indispensable for understanding galaxy formation and evolution. This review first summarizes the progress in satellite galaxy searches over the past two decades, then provides an overview of their physical properties, and finally discusses the opportunities that future surveys will bring to this field.

**Keywords:** Milky Way; dwarf galaxies; imaging surveys

**Classification Codes:** P152, P156

## 1 Introduction

The Milky Way is the second-largest galaxy in the Local Group, with a virial radius of approximately 300 kpc. Observations reveal numerous companion galaxies distributed within this virial radius, commonly referred to as Milky Way satellite galaxies (hereafter “satellite galaxies”). The most well-known examples are the Large Magellanic Cloud (LMC) and Small Magellanic Cloud (SMC) in the southern sky, which are also the two largest known satellite galaxies. The vast majority of discovered satellite galaxies have luminosities comparable to globular clusters, but their physical properties—including stellar kinematics, star formation histories, and stellar distribution scales—differ significantly from those of globular clusters.

Studying satellite galaxies holds substantial scientific importance. Because satellite galaxies orbit within the Milky Way’s gravitational potential, their kinematic properties can be combined with models to estimate the Milky Way’s dynamical mass. Furthermore, while the cold dark matter (CDM) model has achieved remarkable success in describing the formation and evolution of large-scale cosmic structures, it encounters several challenges when predicting the properties of small-scale structures. For instance, the CDM model predicts that thousands of sub-dark matter halos within the Milky Way’s dark matter halo should be able to form stars, yet only about 60 satellite galaxies have been discovered to date—one to two orders of magnitude fewer than predicted. This discrepancy is known as the “missing satellite galaxy problem.” Some researchers argue that there is no actual “missing satellite” issue; rather, after cosmic reionization, heating by the ultraviolet background prevented gas from cooling effectively in some dark halos, resulting in extremely low star formation efficiencies that render these systems too faint to detect. Limited by current observational capabilities, the census of satellite galaxies remains incomplete, and more discoveries are anticipated in the future. Therefore, a comprehensive survey of satellite galaxies provides crucial observational constraints for galaxy formation theory. Additionally, dynamical studies indicate that satellite galaxy masses are dominated by invisible matter (dark matter), making them natural “dark matter laboratories” that

offer excellent opportunities for detecting dark matter particle annihilation signals and revealing the nature of dark matter and its distribution within dark halos. Moreover, satellite galaxies represent the smallest observable galaxies. Although their contribution to the total stellar mass of the universe is modest, they far outnumber larger galaxies and constitute an important component of the galaxy population. As galaxies whose individual stars can be resolved, they are ideal laboratories for studying star formation in extremely low-mass dark matter halos. Due to significant stellar feedback effects, satellite galaxy stars are extremely metal-poor and may represent relics of the first generation of stars. Investigating the physical properties and evolutionary histories of these small galaxies contributes to building a complete picture of galaxy formation and evolution.

Over the past two decades, the advent of large-scale digital imaging surveys has ushered astronomy into the era of big data and brought breakthrough progress in satellite galaxy searches, as illustrated in Figure 1 [Figure 1: see original paper]. The Sloan Digital Sky Survey (SDSS) and the Dark Energy Survey (DES) have played particularly crucial roles. In 2005, researchers first identified a new satellite galaxy candidate using SDSS data, which was later spectroscopically confirmed as a genuine satellite galaxy. Subsequent systematic searches using wide-area imaging survey data have discovered over 50 new satellite galaxies and candidates, some with unique properties that have even revolutionized our understanding of galaxies. For example, Torrealba et al. discovered Antlia 2 near the Galactic plane—a satellite galaxy with a scale comparable to the LMC but a surface brightness even lower than that of ultra-diffuse galaxies, making it the lowest surface brightness galaxy known to date.

In this context, this review provides a detailed overview of progress in satellite galaxy searches and physical property studies over the past two decades. Section 2 discusses advances in satellite galaxy searches; Section 3 describes search methodologies; Section 4 covers their physical properties; Section 5 outlines opportunities from next-generation imaging surveys; and Section 6 presents a summary.

## 2 Progress in Satellite Galaxy Searches

Prior to SDSS, only 11 satellite galaxies were known (the “classical” satellites). A typical satellite galaxy appears on the sky as an overdensity spanning tens to hundreds of square arcminutes, with stars in its color-magnitude diagram showing distributions similar to those of metal-poor, old globular cluster stars. In recent years, large-scale digital imaging surveys such as SDSS and DES have provided powerful data support for satellite galaxy searches. As of 2021, astronomers have identified over 60 satellite galaxies and candidates, with their spatial distribution shown in Figure 2 [Figure 2: see original paper] and detailed information provided in Table 1. The following sections describe search progress based on different surveys.

## 2.1 SDSS Satellite Galaxy Searches

SDSS is a survey conducted using a 2.5-meter telescope at Apache Point Observatory in New Mexico. It covers over ten thousand square degrees, providing photometric data in five optical bands (u, g, r, i, z) and millions of stellar spectra. SDSS began operations in 2000, reaching a limiting magnitude of  $r = 22.2$  mag. Through simulations, Willman et al. predicted that SDSS data could reveal a new population of satellite galaxies with surface brightnesses  $0.5 - 3.9 \text{ mag} \cdot \text{arcsec}^{-2}$  fainter than the previously known faintest satellite, Sextans. In 2005, Willman et al. identified a satellite galaxy candidate, SDSS J1049+5103 (later designated Wil 1), whose luminosity and color-magnitude diagram properties closely resembled those of Milky Way globular clusters, but with a half-light radius 4–5 times larger than globular clusters of similar luminosity.

Initially, Willman et al. could not definitively classify this source as a satellite galaxy. It was not until 2007 that Martin et al. obtained high-resolution spectroscopic observations of Wil 1 and several other candidates using the Keck Telescope, studying their stellar metallicity distributions. The results showed that Wil 1's stellar metallicity dispersion was significantly larger than that of typical globular clusters, indicating that it likely did not form in a single starburst event and thus confirming its nature as a satellite galaxy.

As the SDSS survey progressed, additional satellite galaxies were discovered. In 2006, Zucker et al. identified two new satellites, one of which (Ursa Major) appeared particularly unusual, exhibiting several stellar overdensities suggestive of ongoing tidal disruption. Belokurov et al. systematically searched approximately 8,000 square degrees of SDSS DR5 data, discovering five additional satellite galaxies (some shown in Figure 3 [Figure 3: see original paper]). By 2018, scientists had discovered 17 new satellite galaxies or candidates using SDSS data, substantially expanding our understanding of the satellite galaxy population. Some of these faint candidates required follow-up photometric or spectroscopic observations with other telescopes for confirmation, as exemplified by Wil 1 and Segue 2.

## 2.2 DES Satellite Galaxy Searches

While SDSS primarily covered the northern sky, the Dark Energy Survey played a crucial role in satellite galaxy searches in the southern sky. DES covers approximately 5,000 square degrees near the southern Galactic cap in five bands (g, r, i, z, Y), reaching r-band depths about 2 magnitudes deeper than SDSS, enabling searches for fainter satellite galaxies. In 2015, Bechtol et al. systematically searched 1,800 square degrees of DES Year 1 data, discovering eight new candidates. Later that year, Drlica-Wagner et al. used DES Year 2 data to identify eight additional candidates.

Interestingly, a substantial fraction of these newly discovered candidates clustered near the Large Magellanic Cloud. Two possible explanations have been proposed for this concentration. The first suggests that the LMC was not orig-

inally a Milky Way satellite but belonged to a galaxy system outside the Milky Way' s virial radius that was later accreted and tidally disrupted, with the debris forming the LMC and surrounding dwarf galaxies. Numerical simulations support this scenario. The second explanation posits that as the Milky Way' s most massive satellite, the LMC' s relatively deep gravitational potential can capture smaller surrounding galaxies, eventually forming a sub-gravitationally bound system centered on the LMC.

Different search methods exhibit varying sensitivity to satellite galaxy signals (e.g., some are insensitive to diffuse galaxies), making the final results highly dependent on the methodology employed. Despite systematic searches by the DES team, other researchers have continued mining DES data to discover additional candidates. Kim & Jerjen developed a new method to re-analyze DES Year 1 data, confirming previously discovered satellites and identifying a new candidate, Hor II. Luque et al. conducted a deep search of DES Year 1 data, discovering the faint candidate DES 1. As with other surveys, these DES candidates require spectroscopic follow-up for confirmation, and by 2021 approximately half of the 18 candidates had been spectroscopically confirmed as satellite galaxies.

### 2.3 Satellite Galaxy Searches in Other Imaging Surveys

While SDSS and DES have been instrumental in satellite galaxy discoveries, with most new finds over the past two decades originating from these surveys, researchers have also utilized other imaging survey data for search efforts.

**Pan-STARRS1.** The Panoramic Survey Telescope and Rapid Response System 1 (Pan-STARRS1) is a multi-band survey using a 1.8-meter telescope, covering 75% of the entire sky with r-band depth comparable to SDSS. Its primary advantage lies in its larger sky coverage. Using Pan-STARRS1 data, Laevens et al. discovered four new satellite galaxies.

**ATLAS.** The ATLAS survey, conducted with the 2.6-meter VST telescope at the European Southern Observatory, covers approximately 5,000 square degrees in the southern Galactic cap in five bands (u, g, r, i, z) with depth similar to SDSS. In 2015, Torrealba et al. discovered two satellite galaxies, one of which (Crater 2) was notably large, ranking just below the Magellanic Clouds and the Sagittarius dwarf galaxy in size at the time of discovery.

**HSC-SSP.** The Hyper Suprime-Cam Subaru Strategic Program (HSC-SSP) is a survey conducted with the Japanese Subaru Telescope. Its HSC-Wide component plans to observe 1,400 square degrees with depth approximately two magnitudes deeper than DES, enabling detection of extremely faint satellite galaxy signals. Although the project is ongoing, Homma et al. have already identified three new satellite galaxy candidates using early HSC-SSP data. These newly detected systems are either more distant or less luminous than those found in DES and SDSS, indicating that a significant population of satellite galaxies remains undiscovered. Upon completion, HSC-SSP is expected to discover an additional five to six satellite galaxies.

**DECam.** The DES is a large-scale multi-band survey conducted using the DECam camera on the 4-meter Blanco telescope. Astronomers have also used this instrument for a series of smaller-scale imaging surveys, including the Survey of the Magellanic Stellar History (SMSH) and the Magellanic Satellites Survey (MagLiteS). Using SMSH data, Martin et al. discovered one satellite galaxy near the SMC, while Drlica-Wagner et al. used MagLiteS data to find a satellite near the LMC that may be gravitationally bound to it. The MagLiteS project subsequently discovered two additional satellites, and the DECam Local Volume Exploration survey (DELVE) team discovered another satellite in 2020.

## 2.4 Gaia Satellite Galaxy Searches

Most discovered satellite galaxies are located at intermediate to high Galactic latitudes (Figure 2 [Figure 2: see original paper]) because the high stellar density and severe dust extinction in the low-latitude Galactic plane make it difficult to extract satellite signals using only multi-band photometric data. Since 2016, Gaia data have helped address this issue. The Gaia satellite, launched by the European Space Agency, aims to measure proper motions, positions, and temperatures for one billion stars in the solar neighborhood. Using Gaia's proper motion measurements helps remove contamination from Milky Way foreground stars. In 2019, Torrealba et al. used Gaia data to discover Antlia 2, an extremely low surface brightness satellite galaxy near the Galactic plane. More recently, Darragh-Ford et al. employed wavelet analysis methods with Gaia DR2 data to systematically search for satellite galaxies, providing a list of promising targets for follow-up studies.

## 3 Satellite Galaxy Search Methodologies

Except for a few relatively large satellites such as the Magellanic Clouds that are visible to the naked eye, most satellite galaxies cannot be directly identified in optical images. Current search methods primarily rely on these galaxies' stellar spatial clustering characteristics and their distinctive features in color-magnitude diagrams (CMDs), such as prominent red giant branches and blue horizontal branches. However, satellite galaxies are located at distances of tens to hundreds of kiloparsecs from the Milky Way and have relatively low luminosities, resulting in few spatially resolvable bright stars. The primary challenge in search efforts is simultaneously extracting satellite signals from both spatial positions and CMDs.

Early SDSS studies employed relatively simple and direct search methods. The typical procedure involved: (1) selecting stars brighter than a given apparent magnitude threshold and dividing them into grid cells with side lengths of 0.5 -3 based on their spatial distribution; (2) calculating the stellar surface density in each cell and comparing it to the background density (averaged over all cells in a  $\sim 1$  square degree region surrounding the cell) to identify significant overdensities—cells with the most significant excesses were selected and matched against known clusters or satellites, with unmatched cells considered preliminary new

candidates; and (3) constructing CMDs for stars in the candidate regions and visually inspecting them for excess main sequence, red giant, or blue horizontal branch stars compared to background regions, then comparing with population synthesis models to constrain the candidate's distance modulus. A typical example is shown in Figure 4 [Figure 4: see original paper]. Following candidate selection, deeper follow-up imaging or spectroscopic observations with other telescopes were typically conducted to confirm their nature as genuine satellite galaxies.

This straightforward method was used to discover most early SDSS satellites. However, it suffers from several drawbacks. First, without pre-filtering to eliminate foreground Milky Way stellar contamination, the method is severely affected by projection effects—many regions with high stellar concentrations result from projection of foreground stars rather than genuine satellite signals. Second, the background subtraction treatment is overly simplistic. For a satellite galaxy placed at greater distances, the number of observable bright stars decreases, reducing the signal significance relative to the background. Therefore, distance considerations must be incorporated into background subtraction to identify more satellite candidates.

In recent years, astronomers have improved search methods to address these issues. Since satellite galaxy stellar populations tend to be old and metal-poor, specific color criteria are now applied first to remove relatively metal-rich Milky Way disk stars. Then, for different distance moduli, color-magnitude filter windows are defined to exclude stars outside these windows, leaving only stars that could be members of a satellite at that specific distance. Recent searches in DES and HSC-SSP have employed these improved methods.

Beyond imaging photometry, some researchers have attempted to use Gaia data for satellite galaxy searches. In Torrealba et al.'s work, they first selected RR Lyrae variable stars with known distances as central tracers, then examined whether surrounding stars showed clustering in proper motion parameter space. RR Lyrae stars are chosen because they are metal-poor and old, similar to satellite galaxy stellar populations, and their distances can be relatively easily estimated. Detecting clustering in proper motion space around a central RR Lyrae star suggests that the stellar group likely belongs to the same system at the same distance. This method's advantages include relatively straightforward distance determination and applicability to searches for dwarf galaxies near the Galactic plane. However, since Gaia's limiting magnitude is 20 mag, it is difficult to apply this method to satellite galaxies lacking RR Lyrae stars brighter than this limit.

## 4 Physical Properties of Satellite Galaxies

As the smallest known galaxies, satellite galaxies provide important observational constraints for understanding the complete physical picture of galaxy formation and evolution. With increasing sample sizes, our knowledge of their

properties has grown substantially.

#### 4.1 Sizes

Compared to globular clusters of similar luminosity, satellite galaxies are one to two orders of magnitude larger, with half-light radii ranging from tens to thousands of parsecs (Figure 5 [Figure 5: see original paper]). Consequently, the size-luminosity diagram serves as an important diagnostic for distinguishing satellite galaxies from globular clusters. However, the distributions of globular clusters and satellite galaxies in this diagram are not completely separate, with some overlap remaining. Sources in the overlapping region are difficult to classify as genuine satellites without additional criteria. Similar to more massive galaxies, satellite galaxies exhibit a significant positive correlation between size and luminosity.

#### 4.2 Luminosity Function

The satellite galaxy luminosity function describes their luminosity distribution. Before SDSS, the sample size and completeness of classical satellites were insufficient for detailed luminosity function studies. In 2008, Koposov et al. combined classical satellites with newly discovered SDSS satellites and, after completeness corrections, performed the first systematic study of the satellite luminosity function, finding a flattening trend at the faint end. They also noted that the observed luminosity function shape did not perfectly match numerical simulations. In the same year, Tollerud et al. concluded that the bright-end luminosity function was consistent with simulations, but the faint end showed a significant deficit, predicting that future large-scale surveys would find hundreds of faint satellites.

In 2018, Newton et al. used SDSS+DES data to estimate the satellite luminosity function with new methods, concluding that the Milky Way should host approximately 125 satellite galaxies with  $M_V < 0$  mag (Figure 6 [Figure 6: see original paper]). This number is substantially lower than Tollerud et al.'s earlier estimate but more reliable, as their work used only SDSS DR5 data covering a relatively small sky area, leading to large uncertainties in completeness corrections. Comparing with hydrodynamical simulations that incorporate baryonic physics, Wetzell et al. found excellent agreement between observed and simulated luminosity functions at the bright end ( $M_V < -6$  mag), suggesting no “missing satellite galaxy problem” when baryonic processes are properly included.

#### 4.3 Initial Mass Function

The initial mass function (IMF) describes the mass distribution of stars formed in a single burst and has wide applications in galaxy physics research. The IMF is typically expressed as  $dN/dM \propto M^{-\alpha}$ , where  $N$  represents the number of stars and  $M$  represents stellar mass. Studies of Milky Way clusters and field stars find an IMF index of  $\alpha = 2.35$ , largely independent of environment. Using

high-resolution Hubble Space Telescope images, researchers can count stars of different masses in satellite galaxies to determine their IMFs for comparison with the Milky Way.

Geha et al. found that the low-mass-end IMF indices for Hercules and Leo were  $\alpha = 1.16$  and  $\alpha = 1.31$ , respectively—significantly smaller than the Milky Way value of 2.35 (Figure 7 [Figure 7: see original paper]). Kalirai et al. studied the SMC's IMF, obtaining  $\alpha = 1.90$ , also lower than the Milky Way value. Expanding the sample, Gennaro et al. studied six satellite galaxies, finding  $\alpha$  values ranging from 1.01 to 1.87, significantly different from the Milky Way. Additionally, Gennaro et al. discovered that more metal-rich galaxies have larger  $\alpha$  values, suggesting that metallicity influences and regulates star formation, consistent with findings from other studies.

#### 4.4 Stellar Velocity Dispersion

Stellar velocity dispersion is crucial for understanding the mass composition of satellite galaxies. Using high-resolution spectroscopic observations, Kleyna et al. performed the first stellar velocity dispersion measurement for a satellite galaxy, obtaining  $\sigma = 9.3_{-1.2}^{+11.7}$  km  $\cdot$  s $^{-1}$  for Ursa Major I. If UMa I contained only stars without dark matter, its stellar velocity dispersion would be  $\sigma < 0.1$  km  $\cdot$  s $^{-1}$ , implying that its mass is dominated by dark matter. To date, velocity dispersion measurements have been obtained for over 20 satellite galaxies, yielding values in the range of 3 – 10 km  $\cdot$  s $^{-1}$ .

Converting stellar velocity dispersion to dynamical mass requires several assumptions, most importantly that the system is in dynamical equilibrium. Some satellite galaxies, particularly those within 40 kpc of the Milky Way, show signs of tidal disruption and may not satisfy this condition. For these systems, velocity dispersion may not accurately trace their dynamical mass.

#### 4.5 Metallicity

Kirby et al. studied the metallicity distributions of eight satellite galaxies, finding  $-3 < [Fe/H] < -0.5$ . Comparing observations with model predictions, they found that simple closed-box passive evolution models could not explain the data, requiring gas accretion or outflow. For lower-luminosity galaxies, gas accretion models better fit the observations, while for higher-luminosity systems, gas outflow models are more appropriate.

Studies of large nearby galaxy samples from SDSS reveal a significant positive correlation between galaxy metallicity and stellar mass (or luminosity). This correlation persists for satellite galaxies (Figure 8 [Figure 8: see original paper]). Using spectroscopic data, Kirby et al. fit the metallicity-luminosity relation for satellite galaxies:

$$[Fe/H] = (-1.68 \pm 0.03) + (0.29 \pm 0.02) \log(L/10^6 L_{\odot})$$

with a dispersion of  $\sigma = 0.16$  dex. The tightness of this relation suggests that most satellite galaxies have not experienced severe tidal stripping, which would reduce luminosity without changing metallicity. If tidal stripping were significant, the metallicity-luminosity relation would not be so tight.

#### 4.6 Stellar Populations and Gas

High-quality Hubble Space Telescope imaging enables resolution of numerous stars in satellite galaxies, allowing detailed study of their CMDs. By comparing with model CMDs, constraints can be placed on their stellar population properties and star formation histories. Brown et al. studied six satellite galaxies, finding predominantly old stellar populations with most stars forming at redshift  $z \approx 6$ . Weisz et al. studied three satellites, finding stellar populations older than 11 Gyr, consistent with Brown et al.'s results.

Currently, neutral hydrogen gas has been detected only in the LMC, SMC, Fornax, Sculptor, and Leo T; the vast majority of satellite galaxies show no gas detection. Since most satellite galaxies are old and quiescent, their gas deficiency is not surprising. The cause of gas loss remains unclear. One possibility is ram-pressure stripping by hot gas in the Milky Way's dark matter halo, though this hypothesis requires further confirmation.

### 5 Satellite Galaxy Searches with Next-Generation Imaging Surveys

Both theoretical studies and completeness analyses of existing surveys indicate that many satellite galaxies remain undiscovered, a conclusion supported by deep observations from HSC-SSP. Future breakthroughs in satellite galaxy searches will depend on next-generation large-scale imaging surveys. Over the next decade, the primary imaging survey facility in the southern hemisphere will be the Large Synoptic Survey Telescope (LSST). With an 8.4-meter primary mirror (6.4-meter effective aperture), LSST is substantially larger than the telescopes used for SDSS and DES. Its design specifications achieve  $r = 24$  mag depth in a single exposure and an astounding  $r = 27$  mag in coadded images over ten years, covering 20,000 square degrees in the southern sky. Based on LSST data, we expect to find a large population of more distant or fainter satellite galaxies, achieving completeness within the Milky Way's virial radius down to  $M_V = -2$  mag.

Even in the SDSS era, researchers estimated the discovery potential of future surveys. In 2008, Tollerud et al. predicted that DES would find 19–37 satellite galaxies, single-exposure LSST data would reveal 93–179, and LSST coadded images would uncover 145–283. Subsequent work indeed discovered 18 satellite galaxies in DES, consistent with these estimates. However, Tollerud et al. may have overestimated the total number of Milky Way satellites. As discussed in the luminosity function section, early numerical simulations without baryonic

physics produced excessive satellite galaxies. Recent studies suggest the Milky Way hosts only about 120 satellites with  $M_V < 0$  mag (Figure 6).

While LSST offers powerful capabilities, it cannot cover the northern sky. In the north, the under-construction Wide Field Survey Telescope (WFST) will conduct next-generation optical time-domain surveys. WFST is a 2.5-meter optical telescope jointly built by the University of Science and Technology of China and Purple Mountain Observatory, featuring a 7 square degree field of view and exceptional survey capability (6,000 square degrees per night). Located at the Lenghu observatory site in Qinghai Province, the telescope is expected to be completed in December 2022 and begin observations in 2023. With  $r = 25.1$  mag depth from six years of coadded observations, WFST's depth is comparable to DES but with larger sky coverage. Based on DES results, WFST should discover 30–40 satellite galaxies in the 10,000 square degrees near the northern Galactic cap. Considering that SDSS and other surveys have already found about 20 satellites in the north, WFST is expected to yield 10–20 new discoveries.

China plans to launch the China Space Station Telescope (CSST) around 2024. CSST's survey includes four components, with multicolor imaging covering 17,500 square degrees to  $r = 26$  mag depth, making it ideal for satellite galaxy searches. As a space-based facility, CSST will provide superior seeing and high-quality imaging data, expected to discover new satellite galaxies and resolve numerous individual stars for detailed follow-up studies. Additionally, Europe and the United States plan to launch the EUCLID and WFIRST satellites for wide-area near-infrared observations. These future large-scale surveys will not only dramatically improve the completeness of satellite galaxy censuses but also bring new breakthroughs in studying their stellar properties, particularly at the low-mass end, thanks to high spatial resolution data.

## 6 Summary

This review has summarized recent progress in Milky Way satellite galaxy research over the past two decades, focusing on search methodologies and physical properties, and has outlined opportunities from future surveys. The main conclusions are:

1. **Search Progress:** Multi-band, wide-area imaging surveys have brought breakthrough advances, with SDSS and DES playing primary roles in the northern and southern skies, respectively. Deeper surveys such as HSC-SSP have discovered fainter or more distant satellites, indicating that the current census remains incomplete. Gaia data have opened new opportunities for searches near the Galactic plane. As of 2021, over 60 satellite galaxies and candidates have been discovered.
2. **Physical Properties:** Most satellite galaxies have luminosities comparable to globular clusters, with half-light radii of tens to thousands of parsecs and stellar velocity dispersions of  $3 - 10 \text{ km} \cdot \text{s}^{-1}$ . Like more mas-

sive galaxies, they exhibit a tight positive correlation between metallicity and luminosity, are dark matter-dominated, and have IMF low-mass-end slopes shallower than the Milky Way's. The vast majority contain very old stellar populations that formed primarily at  $z \approx 6$ , with quenched star formation and undetectable cold gas components.

3. **Future Prospects:** Next-generation large-scale imaging surveys over the next decade will bring new opportunities. LSST is expected to discover numerous new satellites in the southern sky, while WFST should find 10–20 new satellites in the north. Space missions including CSST, EUCLID, and WFIRST will provide high-quality data that will greatly advance both the detection of satellite galaxies and studies of their physical properties.

## References

- [1] Klypin A, Zhao H, Somerville R S. MNRAS, 2002, 573: 597
- [2] McConnachie A W. AJ, 2012, 144: 4
- [3] Simon J D. ARA&A, 2019, 57: 375
- [4] Watkins L L, Evans N W, An J H. MNRAS, 2010, 406: 264
- [5] Callingham T M, Cautun M, Deason A J, et al. MNRAS, 2019, 484: 5453
- [6] Fritz T K, Di Cintio A, Battaglia G, et al. MNRAS, 2020, 494: 5178
- [7] White S D M, Rees M J. MNRAS, 1978, 183: 341
- [8] Springel V, Wang J, Vogelsberger M, et al. MNRAS, 2008, 391: 1685
- [9] Griffin B F, Ji A P, Dooley G A, et al. ApJ, 2016, 818: 10
- [10] Klypin A, Kravtsov AV, Valenzuela O, et al. ApJ, 1999, 522: 82
- [11] Moore B, Ghigna S, Governato F, et al. ApJL, 1999, 524: L19
- [12] Bullock J S, Boylan-Kolchin M. ARA&A, 2017, 55: 343
- [13] Boylan-Kolchin M, Bullock J S, Kaplinghat M. MNRAS, 2011, 415: L40
- [14] Boylan-Kolchin M, Bullock J S, Kaplinghat M. MNRAS, 2012, 422: 1203
- [15] Kleya J T, Wilkinson M I, Evans N W, et al. ApJ, 2005, 630: L141
- [16] Spekkens K, Mason B S, Aguirre J E, et al. ApJ, 2013, 773: 61
- [17] Malyshev D, Neronov A, Eckert D. PhRvD, 2014, 90: 103506
- [18] Nadler E O, Gluscevic V, Boddy K K, et al. ApJL, 2019, 878: L32
- [19] Nadler E O, Drlica-Wagner A, Bechtol K, et al. PRL, 2021, 126: 091101
- [20] Weisz D R, Boylan-Kolchin M. MNRAS, 2017, 469: L83
- [21] Jeon M, Besla G, Bromm V. ApJ, 2017, 848: 85
- [22] Mashchenko S, Wadsley J, Couchman H M P. Sci, 2008, 319: 174
- [23] Wheeler C, Onorbe J, Bullock J S, et al. MNRAS, 2015, 453: 1305
- [24] York D G, Adelman J, Anderson J E, et al. AJ, 2000, 120: 1579
- [25] The Dark Energy Survey Collaboration, 2005, astro-ph/0510346
- [26] Martin N F, Ibata R A, Chapman S C, et al. MNRAS, 2007, 380: 281
- [27] Torrealba G, Belokurov V, Koposov S E, et al. MNRAS, 2019, 488: 2743
- [28] Stoughton C, Lupton R H, Bernardi M, et al. AJ, 2002, 123: 485
- [29] Willman B, Dalcanton J, Ivezić Ž, et al. AJ, 2002, 123: 848
- [30] Willman B, Blanton M R, West A A, et al. ApJ, 2005, 129: 2692
- [31] Zucker D B, Belokurov V, Evans N W, et al. ApJL, 2006, 643: L103

- [32] Zucker D B, Belokurov V, Evans N W, et al. *ApJL*, 2006, 650: L41
- [33] Belokurov V, Zucker D B, Evans N W, et al. *ApJ*, 2007, 654: 897
- [34] Newton O, Cautun M, Jenkins A, et al. *MNRAS*, 2018, 479: 2853
- [35] Kirby E N, Boylan-Kolchin M, Cohen J G, et al. *ApJ*, 2013, 770: 16
- [36] Bechtol K, Drlica-Wagner A, Balbinot E, et al. *ApJ*, 2015, 807: 50
- [37] Drlica-Wagner A, Bechtol K, Rykoff E S, et al. *ApJ*, 2015, 813: 109
- [38] Lynden-Bell D. *MNRAS*, 1976, 174: 695
- [39] Deason A J, Wetzel A R, Garrison-Kimmel S. *MNRAS*, 2015, 453: 3568
- [40] Jethwa P, Erkal D, Belokurov V. *MNRAS*, 2016, 461: 2212
- [41] Walsh S M, Willman B, Jerjen H. *AJ*, 2009, 137: 450
- [42] Kim D, Jerjen H. *ApJ*, 2015, 808: 39
- [43] Luque E, Queiroz A, Santiago B, et al. *MNRAS*, 2016, 458: 603
- [44] Laevens B P M, Martin N F, Bernard E J, et al. *ApJ*, 2019, 813: 44
- [45] Torrealba G, Koposov S E, Belokurov V, et al. *MNRAS*, 2016a, 463: 712
- [46] Torrealba G, Koposov S E, Belokurov V, et al. *MNRAS*, 2016b, 459: 2370
- [47] Homma D, Chiba M, Okamoto S, et al. *ApJ*, 2016, 832: 21
- [48] Homma D, Chiba M, Okamoto S, et al. *PASJ*, 2018, 70: S18
- [49] Homma D, Chiba M, Komiyama Y, et al. *PASJ*, 2019, 71: 94
- [50] Martin N F, Nidever D L, Besla G, et al. *ApJL*, 2015, 804: L5
- [51] Drlica-Wagner A, Bechtol K, Allam S, et al. *ApJL*, 2016, 833: L5
- [52] Koposov S E, Walker M G, Belokurov V, et al. *MNRAS*, 2018, 479: 5343
- [53] Torrealba G, Belokurov V, Koposov S E, et al. *MNRAS*, 2019, 475: 5085
- [54] Mau S, Cerny W, Pace A B, et al. *ApJ*, 2020, 890: 136
- [55] Gaia C, Prusti T, de Bruijne J H J, et al. *A&A*, 2016, 595: A1
- [56] Darragh-Ford E, Nadler E O, McLaughlin S, et al. *ApJ*, 2021, 915: 48
- [57] Munoz R R, Cote P, Santana F A, et al. *ApJ*, 2018, 860: 66
- [58] Grillmair C J. *ApJ*, 2009, 693: 1118
- [59] Carlin J L, Sand D J, Munoz R R, et al. *AJ*, 2017, 154: 267
- [60] Luque E, Pieres A, Santiago B, et al. *MNRAS*, 2017, 468: 97
- [61] Longeard N, Martin N, Starkenburg E, et al. *MNRAS*, 2018, 480: 2609
- [62] Cerny W, Pace A B, Drlica-Wagner A, et al. 2021, astro-ph/2107.09080
- [63] Kim D, Jerjen H, Geha M, et al. *ApJ*, 2016, 833: 16
- [64] Makarov D, Prugniel P, Terekhova N, et al. *A&A*, 2014, 570: A13
- [65] Mutlu-Pakdil B, Sand D J, Carlin J L, et al. *ApJ*, 2018, 863: 25
- [66] Martinez-Vazquez C E, Monelli M, Bono G, et al. *MNRAS*, 2015, 454: 1509
- [67] Graczyk D, Pietrzynski G, Thompson I B, et al. *ApJ*, 2014, 780: 59
- [68] Belokurov V, Zucker D B, Evans N W, et al. *ApJL*, 2006, 647: L111
- [69] Koposov S E, Belokurov V, Torrealba G, et al. *ApJ*, 2008, 686: 279
- [70] Tollerud E J, Bullock J S, Strigari L E, et al. *ApJ*, 2008, 688: 277
- [71] Wetzel A R, Hopkins P F, Kim J hoon, et al. *ApJL*, 2016, 827: L23
- [72] Salpeter E E. *ApJ*, 1955, 121: 161
- [73] Bastian N, Covey K R, Meyer M R. *ARA&A*, 2010, 48: 339
- [74] Geha M, Brown T M, Tumlinson J, et al. *ApJ*, 2013, 771: 29
- [75] Kalirai J S, Anderson J, Dotter A, et al. *ApJ*, 2013, 763: 110
- [76] Gennaro M, Tchernyshyov K, Brown T M, et al. *ApJ*, 2018, 855: 20
- [77] Martin-Navarro I, Vazdekis A, La Barbera F, et al. *ApJL*, 2015, 806: L31

- [78] Parikh T, Thomas D, Maraston C, et al. MNRAS, 2018, 477: 3954
- [79] Kirby E N, Lanfranchi G A, Simon J D, et al. ApJ, 2011, 727: 78
- [80] Tremonti C A, Heckman T M, Kauffmann G, et al. ApJ, 2004, 613: 898
- [81] Kirby E N, Cohen J G, Guhathakurta P, et al. ApJ, 2013b, 779: 102
- [82] Brown T M, Tumlinson J, Geha M, et al. ApJ, 2014, 796: 91
- [83] Weisz D R, Dolphin A E, Skillman E D, et al. ApJ, 2014, 789: 147
- [84] Irwin M J, Belokurov V, Evans N W, et al. ApJ, 2007, 656: L13
- [85] Spekkens K, Urbancic N, Mason B S, et al. ApJL, 2014, 795: L5
- [86] Westmeier T, Staveley-Smith L, Calabretta M, et al. MNRAS, 2015, 453: 338
- [87] Ivezić Z, Kahn S M, Tyson J A. ApJ, 2019, 873: 111
- [88] Zhan H. Chinese Science Bulletin, 2021, 66: 1290
- [89] Beaulieu J P, Bennett D P, Batista V, et al. Pathways Towards Habitable Planets, 2010, 430: 266
- [90] Spergel D, Gehrels N, Baltay C, et al. 2015, astro-ph/1503.03757

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