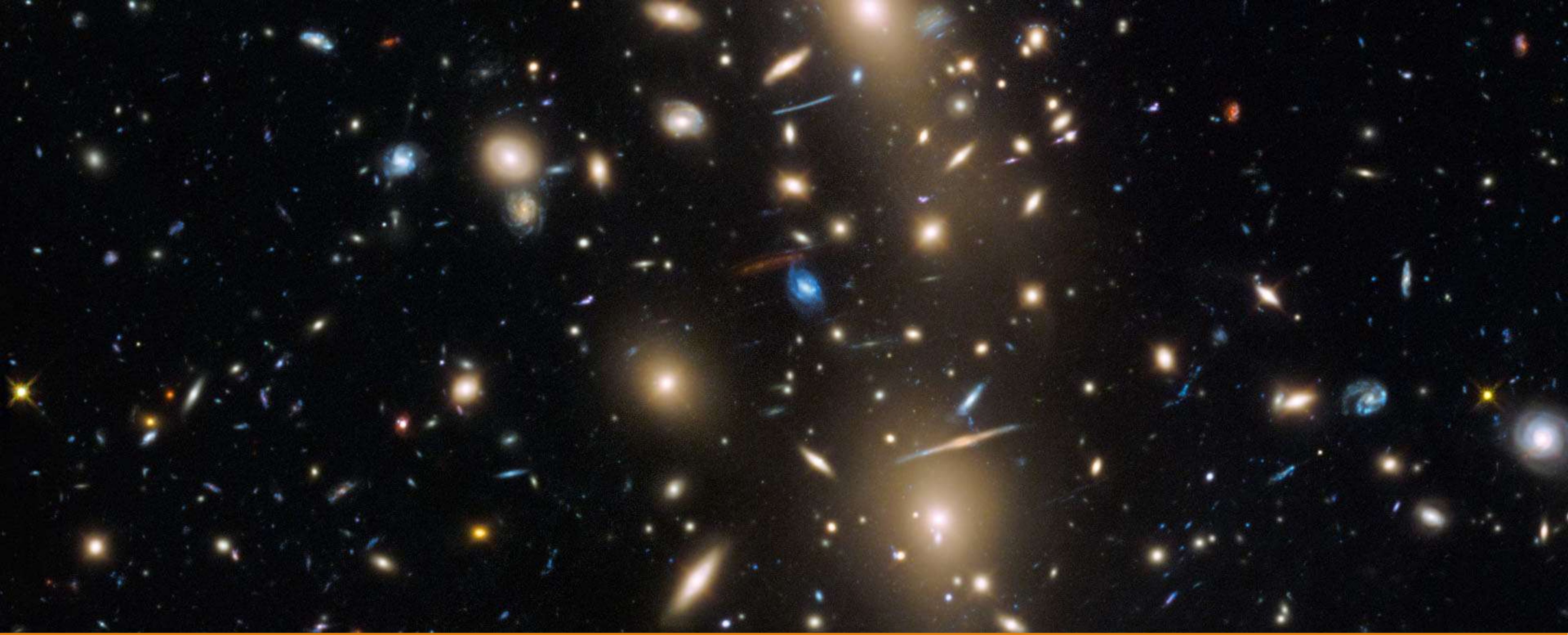

Ultra-Faint Dwarf Galaxies

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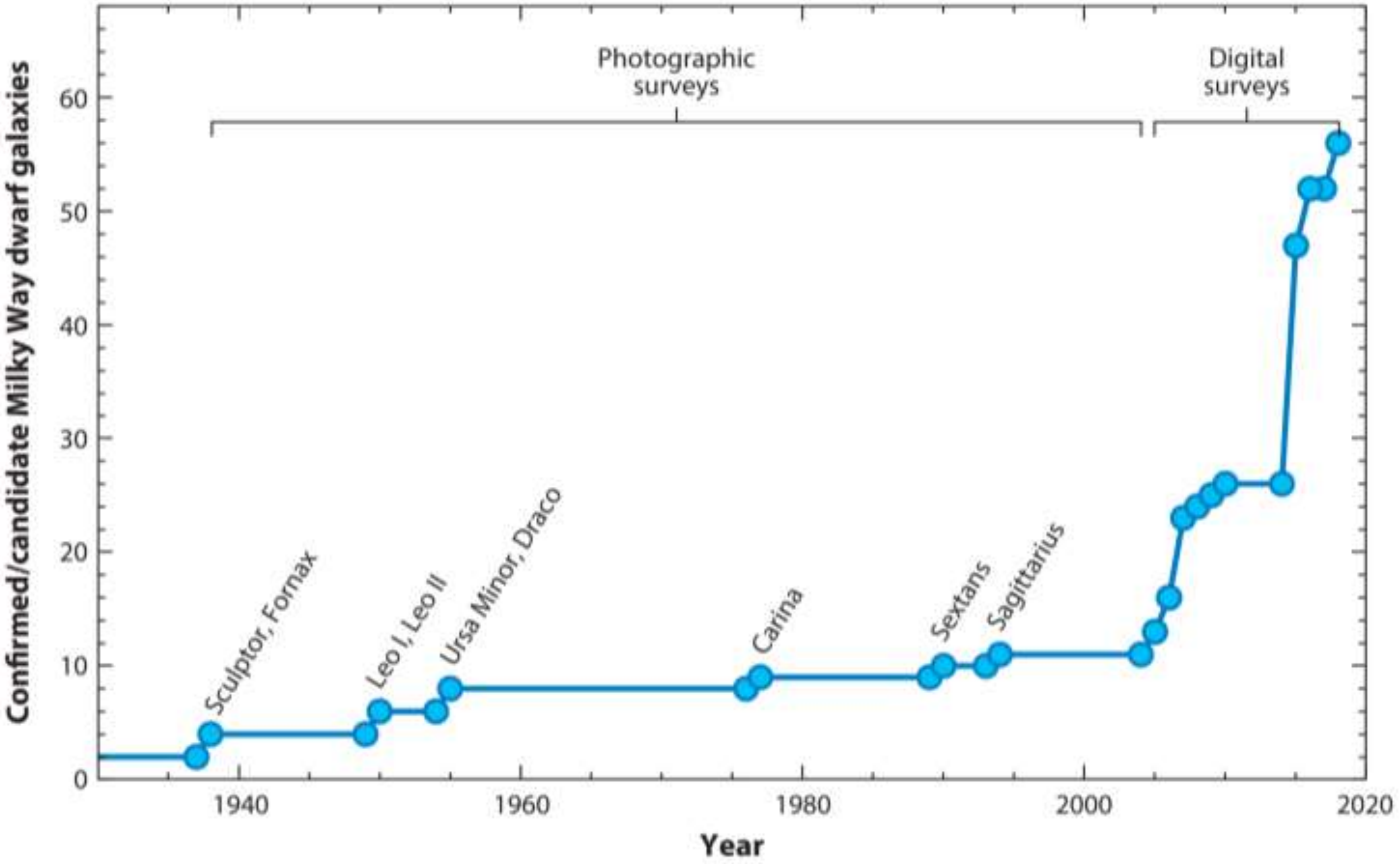
INTRODUCTION

- Dwarf galaxies are extremely faint, and until the emergence of the Sloan Digital Sky Survey (SDSS), so many of them were undetected, however, they were suspected to exist by astronomers.



INTRODUCTION

Ultra-faint dwarf galaxies (UFD) resemble globular clusters but there are some main differences:

1. Based on stellar kinematics, UFDs demonstrate that they contain a significant amount of dark matter,
2. Most of the dwarf galaxies except very low luminary UFD extent larger than any known globular clusters.
3. Within each UFD, the abundance of Fe, and α-elements exhibit substantial spread which is a result of extended star formation and internal chemical enrichment.
4. Similarity between the abundances of certain elements in UFD similar to brighter dwarfs

The Large Magellanic Cloud

https://en.wikipedia.org/wiki/Dwarf_galaxy

Messier 2

https://en.wikipedia.org/wiki/Globular_cluster

Cosmological Significance of UFDs

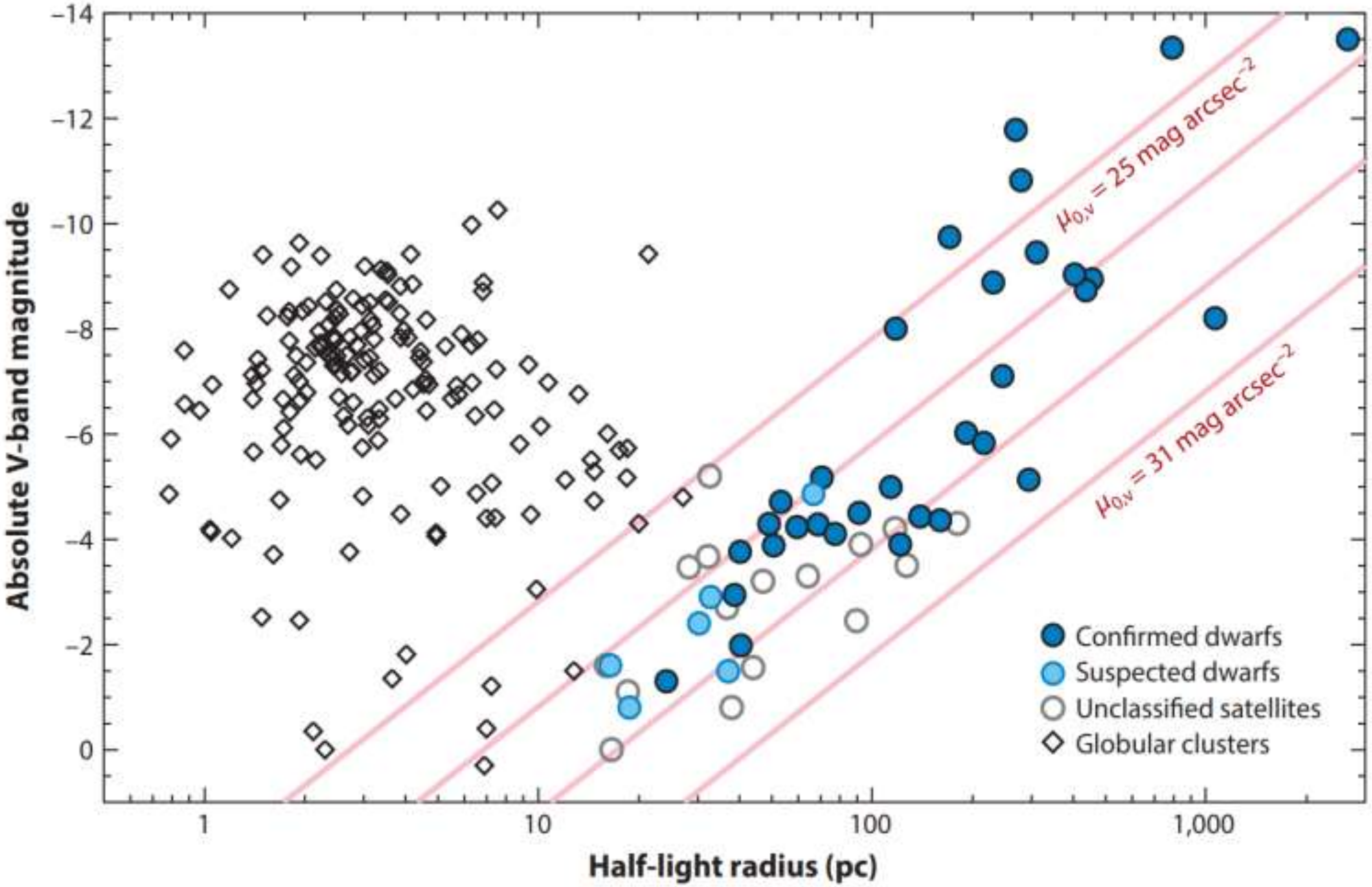
1. UFDs reside in the smallest DM halos yet found, with the virial mass of $\sim 10^9 M_\odot$. UFDs are also the most DM-dominated system we know. The combination of these two factors can constrain the nature of DM. Possibly by counting them around MW, can limit the mass of DM particles, and can point us to the direction of solving the long-lasting missing satellite problem.

2. UFDs are the extreme limit of the galaxy formation process. They have the lowest metallicities, oldest ages, smallest sizes, smallest stellar masses, and simplest assembly histories of all galaxies. UFDs formed at high redshift and before the epoch of reionization, so little to no further evolution after that time, and this means they are pristine relics from the early universe.

Definition of Ultra-Faint Dwarfs

- Before SDSS, dwarf galaxies were brighter than $M_{v} = -8.7$, and a Plummer half-light radii of $\geq 200\ pc$, but the dwarfs detected through SDSS were ~ 1000 less luminous and with a half-light radii of $20pc$.
- However, in the first papers released their nature wasn't clear and only after several years of spectroscopy did they find them to be dwarf galaxies rather than globular clusters, and that was when the term "ultra-faint" dwarfs was used for the first time by Willman.
- It is important to note that detailed spectroscopic characterization of UFDs is only limited to the MW.
- A possible but not yet proven distinction between UFDs and dwarfs can be the start formation. It is believed that in UFD their star formation was shut off by reionization at z $\geq$ 6 and did not continue to lower redshift. But our bright enough samples are too small to draw a conclusion.

Definition of Ultra-Faint Dwarfs

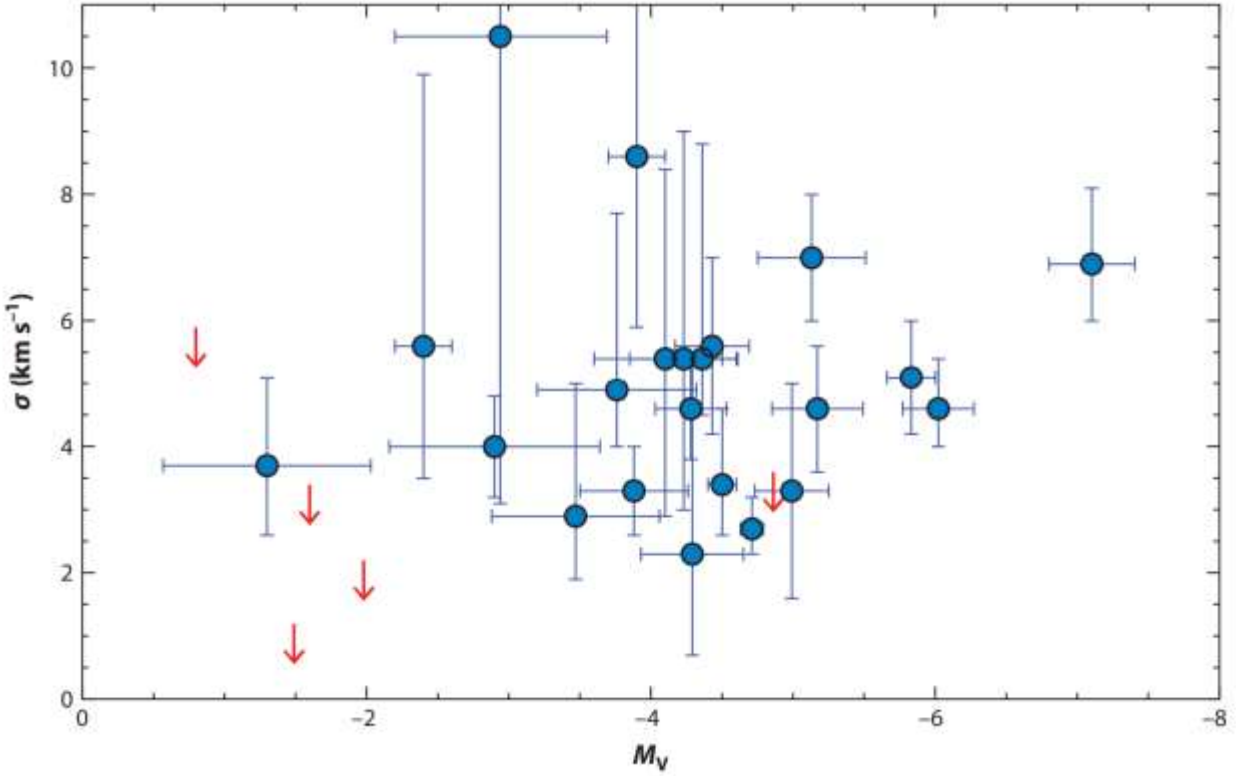


- Unclassified satellites are due to insufficient spectroscopy
- Globular clusters mostly have $R_{1/2} < 20pc$ and dwarf galaxies have $R_{1/2} > 100pc$
- It is suggested that to call the dwarf galaxies fainter that $M_v = -7.7$ to be considered UFDs.

Only 4 galaxies in surveys have been within 1 magnitude of this boundary. The reasons for those is that they are mostly more metal-rich, more extended. These are the galaxies that resemble dwarf spherical transition-type dwarfs in the local group.

Stellar Kinematics

- Following the discovery of UFDs, astronomers began measuring their stellar velocity dispersions by measuring the velocities of individual stars.
- Two separate studies done in 2005 and 2006, measured the velocity dispersion of galaxies to be of order 10 $km.s^{-1}$
- However if we take the stellar mass-to-light ratio to be $\approx 2\ M_{\odot}/\ L_{\odot}$ as it is expected for an old stellar population, the expected velocity dispersion should be $< 0.1\ km.s^{-1}$
- This caused astronomers to believe that UFDs can't be purely baryonic systems.



- Line of sight velocity dispersion of Milky Way satellites as a function of absolute magnitude.

- Here we can see a clear trend of decreasing velocity dispersion toward the fainter dwarfs.

- We also can see a larger scatter toward the fainter dwarfs.
- Their values are between 1 to 8

Mass Modeling and Dark Matter Content

Assumptions required for determining the mass:

1. Mass should be measured under dynamical equilibrium, so for example not after tidal interactions. However, there have been some studies showing that in the case of dwarf galaxies, their velocity dispersion does not change substantially so it would be safe to assume that most of the dwarf galaxies are under equilibrium.
2. If spectroscopy is not over multiple, well-separated observations, we should be aware of it not being infected by binary stars. Taking into account that at low metallicities binary fraction is quite large, there can be a high chance of our spectroscopy being infected by them. However, studies have shown that only for systems with a low number of stars, this has proven to increase the velocity dispersion drastically, and the rest won't be affected drastically.
3. Especially for galaxies with velocities close to the median velocity of Milky Way stars along the line of sight, we should be aware of them not being contaminated by foreground stars. In some studies, it has been shown that even though for a few galaxies this effect has almost no effect, for some galaxies it has changed the value drastically, so the uncertainty regarding this matter must be always taken into account. Because of the low number of stars, unlike dwarf spheroidal galaxies with around 100000 members, we can't assign a membership probability to the stars. However, in recent years, the advent of Gaia astrometry has made it much easier to correctly classify the membership of the stars.

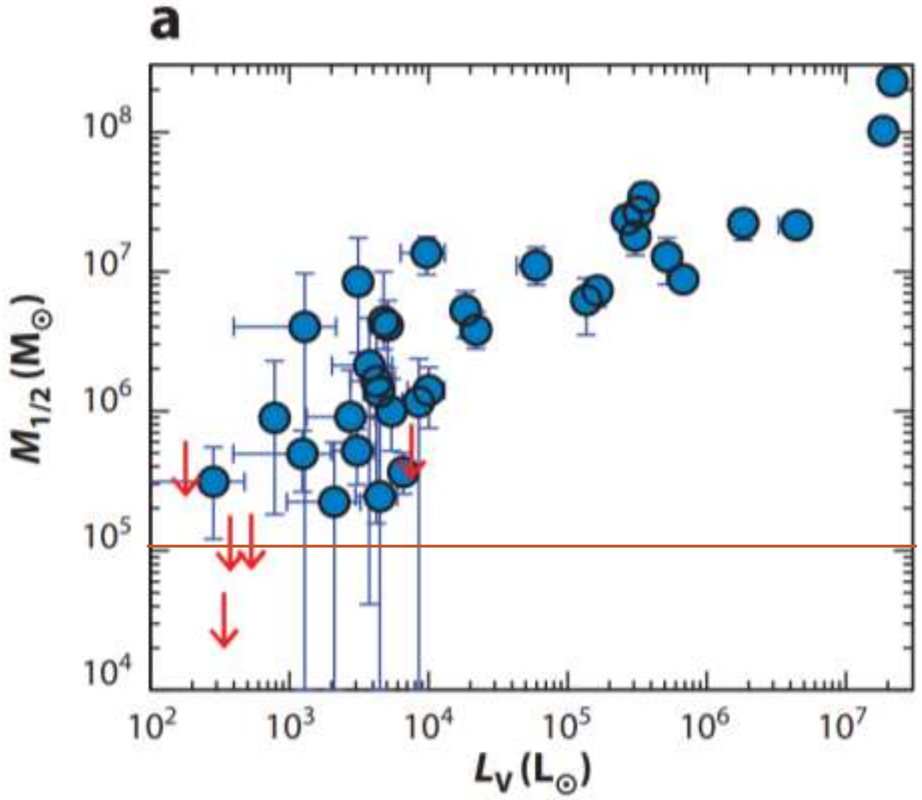
Mass Modeling and Dark Matter Content

- After taking into account all these assumption, we would be ready to measure the mass.
- A study at 2010, showed that, the mass that is constrained by stellar velocity measurements is the mass eclosed within the three-dimensional half-light radius of the system.
- On the other hand, the 3D half light radius $r_{\frac{1}{2}}$ is related to the 2D half light $R_{\frac{1}{2}}$ radius by: $r_{\frac{1}{2}} = \frac{4}{3} R_{\frac{1}{2}}$

So the dynamical mass is given by the equation:

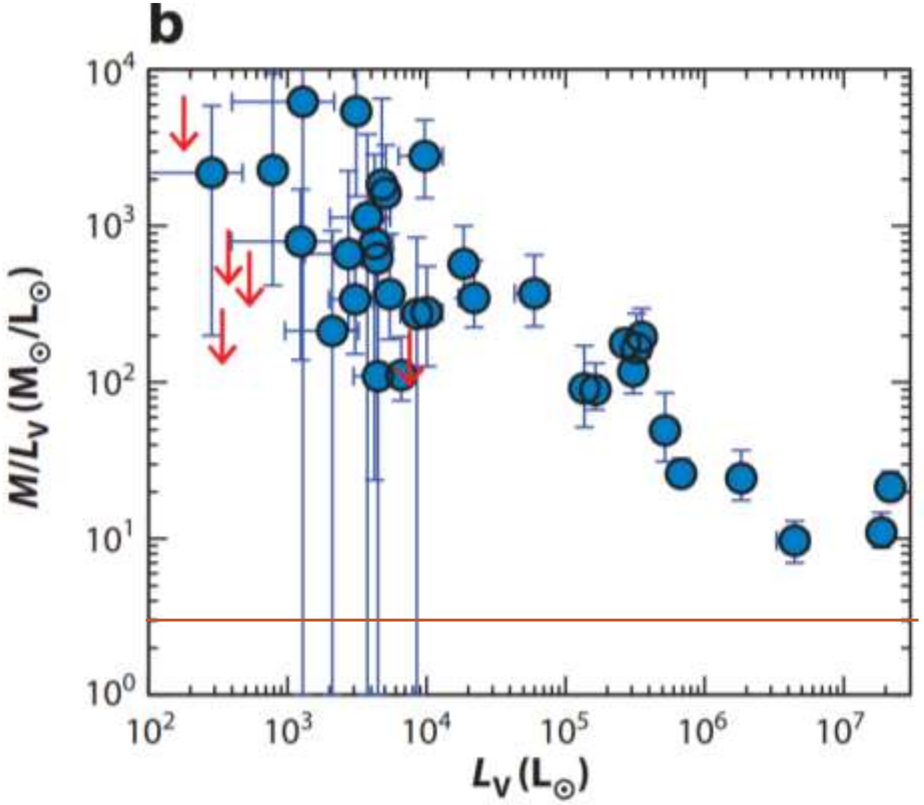
$$M_{\frac{1}{2}} = 930 \left(\frac{\sigma}{km\ s^{-1}}\right)^2 \left(\frac{R_{\frac{1}{2}}}{pc}\right) M_{\odot}$$

Mass Modeling and Dark Matter Content



Dynamical masses of ultra-faint MW satellites as a function of luminosity

Every UFD here measured has a mass measured higher than $10^5 M_\odot$



Mass to light ratios within the half-light radius for ultra-faint MW satellites as a function of luminosity.
As we can see, the supposed $2\ M_\odot / L_\odot$ based on Salpeters IMF for old stars is at least an order of magnitude below the values observed here

Identification as Galaxies

- In the beginning, size was enough distinction between globular clusters and dwarfs, but as less luminous and smaller objects were detected, size was no longer sufficient to distinguish them.
- Willman put it as: “A galaxy is a gravitationally bound collection of stars whose properties cannot be explained by a combination of baryons and Newton’s laws of gravity.”
- If we apply this to UFDs, we require a dynamical mass significantly larger than its baryonic mass. This suggests that the object must be embedded in a dark matter halo massive enough that supernova ejecta can be retained for subsequent generations of star formation.
- In the beginning of SDSS, early UFDs had $\sigma > 3\ km.s^{-1}$ implying that they are mostly DM dominated and can straight forward be known as galaxies. They were some disagreements in the beginning, which were solved later using stellar kinematics, metallicities, and chemical abundances.
- However, sometimes even using stellar kinematics, metallicities or chemical abundances is not sufficient, so we have to accept the uncertainty or rely more on the circumstantial facts such as size.
- This uncertainty can get worse as we discover less luminous system.

Metallicities and Chemical Abundances

- For finding the metallicities, we use the same spectrum that was used for kinematics, because higher resolution is difficult due to the very faint stars.
- A study for UFDs found that:

  1- they have very low metallicity: [Fe/H] < -2

  2- they span a range in metallicity, which is what can distinguish dwarfs from globular clusters. This also indicates that:

  a. Their star formation lasted long enough for SN enrichment to occur.

  b. their gravitational potential was deep enough so not all SN ejecta could escape.

  3- According to some studies, most of them have extremely-metal-poor stars with [Fe/H] < -3 which is distinct from globular clusters.
- Why do we use Dwarf galaxies for chemical evolution?

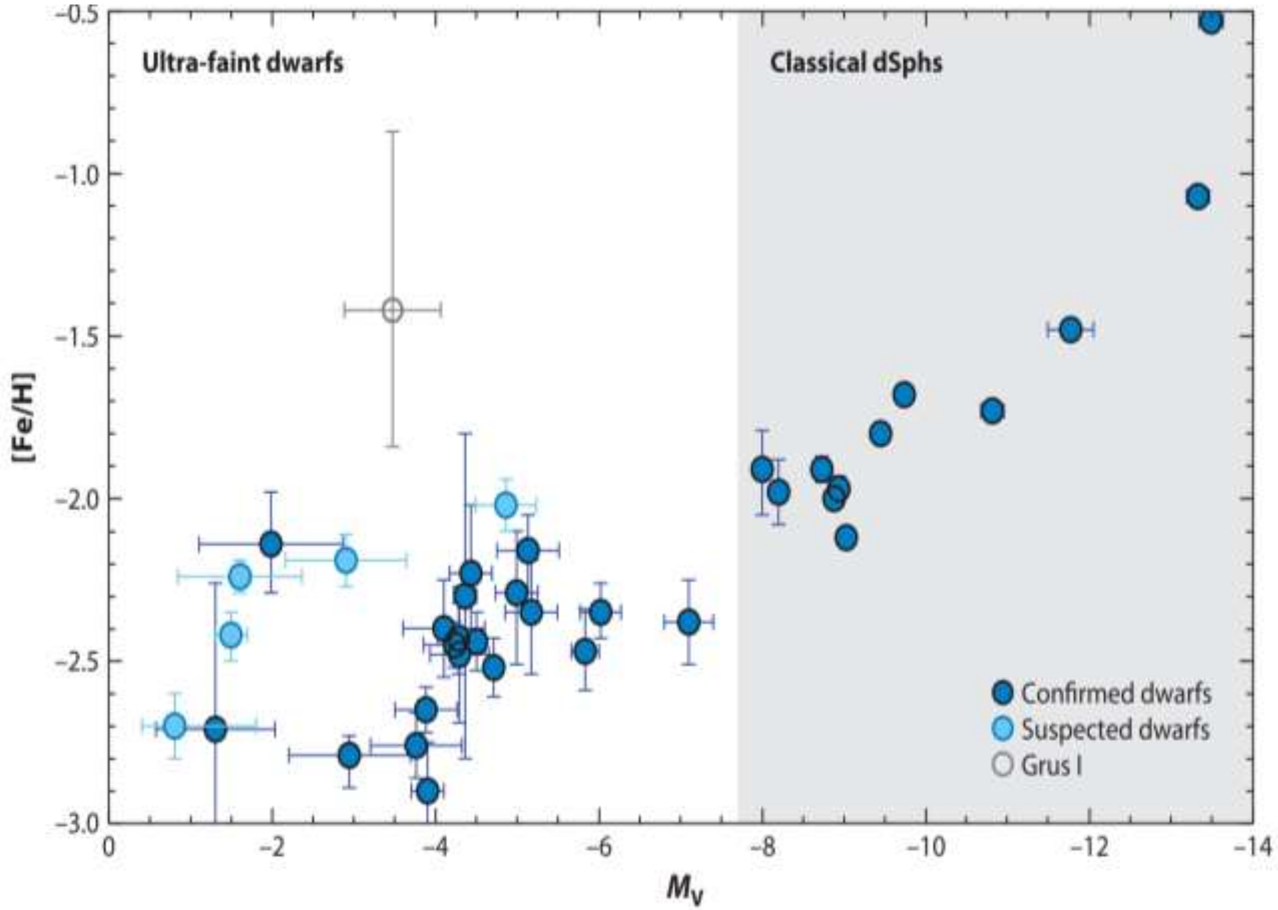
  1- Due to their small mass, it is believed they went through relatively few supernova explosion

  2- Due to their short periods of star-forming, they preserved the chemical signature of the nucleosynthesis era

The Mass-Metalicity Relation

In a study it was shown that, a single relation holds for all types of dwarf galaxies throughout the local group:

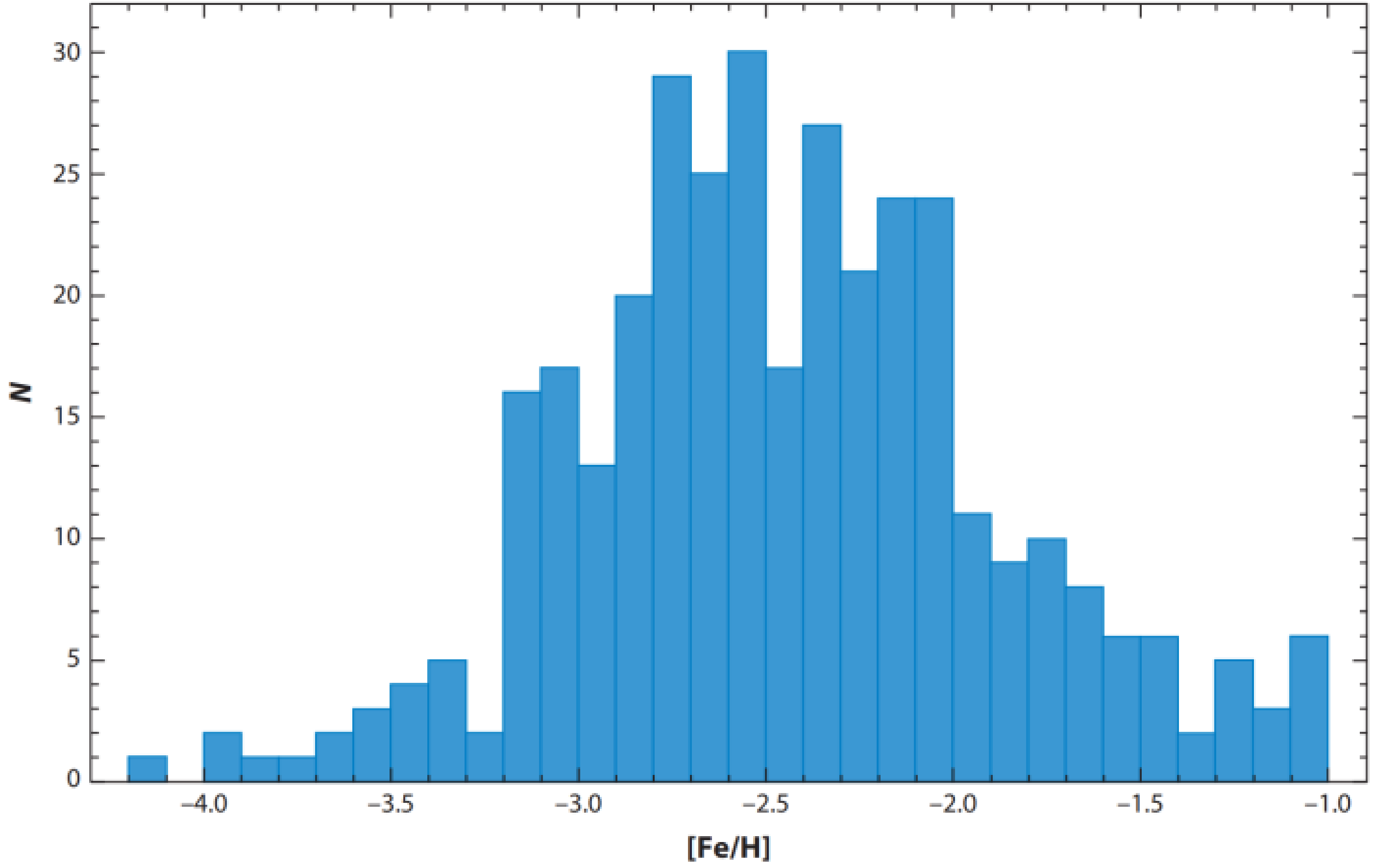
$$[Fe/H] = (-1.68 \pm 0.03) + (0.29 \pm 0.02)\log\left(\frac{L_v}{10^6 L_\odot}\right)$$



- The existence of a tight correlation between luminosity and metallicity argues against severe tidal stripping of stellar components of dwarf galaxies. Because Tidal stripping, reduces the luminosity, but not the metallicity. Using this we can put an upper limit on the amount of stripping.
- There is a scatter around $M_v \geq -4.5$, because:
  1. Faintest dwarfs have suffered more stripping than classical dwarf spheroidal.
  2. There is an observational uncertainty for low luminosity, because their brightest stars might not be representative, and can even be foreground contribution.

Metallicity Distribution Functions

Relatively little research has been done in UFDs compared to dwarf spheroidal, due to their small sample sizes of metallicity measurements, and very few astronomers draw conclusions about UFD evolutionary history from observed MDFs.



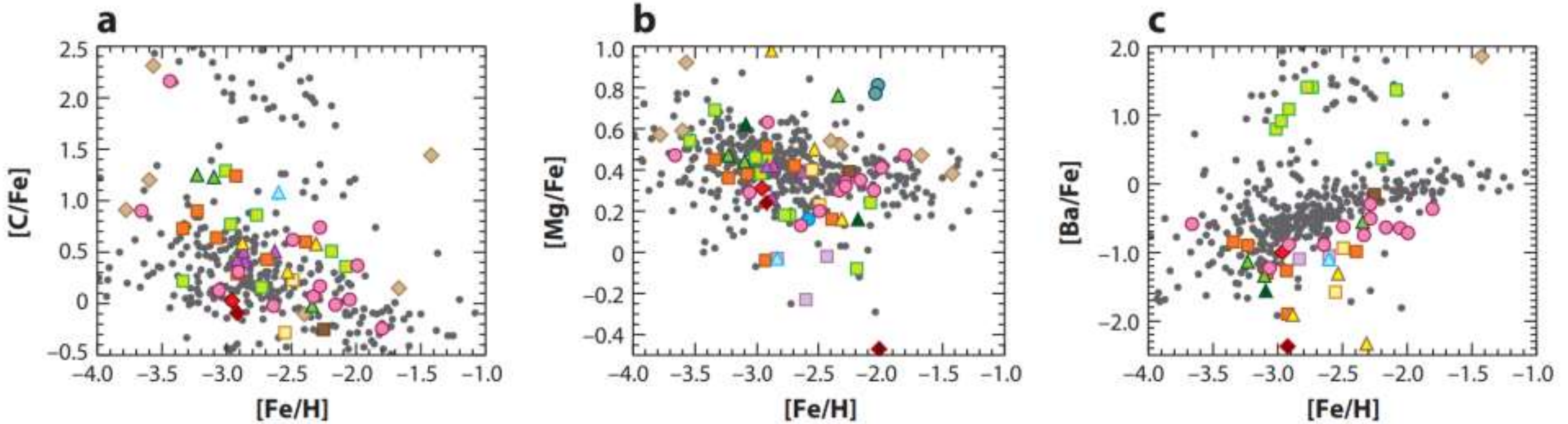
using the very few data published, we can draw a combined MDF including all the UFD stars.
The bulk of UFD stars have metallicities ranging from -2 and -3.2, with the tails of distribution extending to -4 and -1.

However, for many of the lowest and highest stars, the metallicity distribution function should be interpreted with caution, because they may have large uncertainty, and possible foreground contamination respectively.

Chemical Evolution Histories

- Beyond MDF, the most basic feature of galactic chemical evolution is the dependence of α elements on metallicity: $[\alpha/Fe]$
- At low metallicities we have high $[\alpha/Fe]$, and at high metallicities low $[\alpha/Fe]$ are observed, which is a result of different chemical yields from different SNe.
  - Core-Collapse SN, happens quickly after star formation from massive stars and produces large quantities of $\alpha-$elements
  - Type Ia SNe explodes later producing Fe and therefor lowering the $[\alpha/Fe]$ ratio.
- The time for transition from Core-Collapse SN and SNe Ia, depends on the star formation rate and varies among galaxies.
- One study has shown the transition happening at $[Fe/H] = -2.3$ indicating that their Star formation lasted over 100Myr so some SNe Ia had exploded before the end of star formation and therefor had contributed
- The more recent study suggests that UFDs were predominantly enriched by core-collapse SNe, with only one galaxy showing no evidence of a transition, which means that its star formation was ended before SNe Ia occurred.

Chemical Abundances Patterns



- A sample of MW metal-poor halo stars has been shown in gray circles and UFD stars are the colored points.
- The abundance pattern of different UFDs resemble each other, making it difficult to discern the galaxy only based on it.
- At the lowest metallicities, a significant fraction of UFD stars have high carbon abundances, similar to findings in the Milky Way halo.
- The only clear distinction between UFDs and halo stars is seen in the heaviest elements such as Ba which is significantly lower on average compared to halo stars, suggesting a possible characteristic for distinguishing UFDs from globular clusters.

Structural Properties

- Previous studies have described the radial profiles of UFDs using exponential or Plummer profiles. On average UFDs have smaller half-light radii compared to classical dSphs, however, there are some overlaps, and this is not the only distinguishing fact.
- The weighted average ellipticity for UFDs is larger than the one classical dSphs, it's 0.350 ± 0.003. However, statistical tests show no significant evidence that UFDs have always more elongated shapes.
- The irregular or distorted isophotes have been shown by simulations to be the result of Poisson fluctuations rather than tidal stripping and disturbed morphology.

The Formation of UFDs

- Simulating the formation of UFDs is challenging due to the high resolution and dynamic range required. Various approaches are used, including ultrahigh-resolution (which is very expensive to run), simulations of isolated dwarf galaxies (but you lose the physics of satellite dynamics and stripping), and simulation of MW-like galaxies (may include all the relevant Physics but currently doesn't have sufficient resolution).
- UFDs may form in either dark matter minihaloes of relatively low mass or atomic cooling halos of higher mass. The cooling mechanisms for these halos differ, with molecular hydrogen playing a significant role in the former and atomic hydrogen lines in the latter which leads to its collapse. DM Minihalos are suspected to host the first Population III stars.
- Understanding the relationship between the stellar masses of galaxies and the masses of their dark matter halos is crucial because DM halos control the amount of UFD gas content and their resilience to heating. This relationship, known as the stellar mass-halo mass (SMHM) relation, is important for addressing challenges to the standard cosmological model (ΛCDM). While the SMHM relation is relatively well-understood for larger galaxies, its behavior at lower stellar masses, particularly for UFDs is not yet known.
- Observational data and hydrodynamic simulations provide conflicting results regarding the scatter in the SMHM relation at low masses, however, discoveries of additional satellites and completeness analyses of surveys are expected to provide further constraints on these relationships.

Galactic Orbits and Tidal Evolution

- With the orbits of some UFDs now known, it's possible to discuss the possibility of tidal stripping more quantitatively. While some dark matter stripping is expected on almost any orbit, substantial loss of stars requires closer approaches to the Milky Way.
- The tidal radius of a dwarf galaxy can be approximated as the Jacobi radius:

$$r_t = \left(\frac{m_{dwarf}}{3M_{MW}}\right)^{1/3} d.$$

Using this approximation, it's found that the tidal radius is currently beyond 3 times the half-light radius for most UFDs.

- For most other UFDs with published kinematics, significant stripping appears unlikely. Their pericenter distances and tidal radii suggest that only minimal stripping of stars is possible.
- For UFDs with elongated shapes and velocity gradients, alternative explanations such as formation through mergers should be considered before attributing these properties solely to Milky Way tides.

UFDs as Dark Matter Laboratories

- UFDs offer unique opportunities to study dark matter for several reasons:
  1. They are the most DM-dominated systems known, their baryonic components are likely to have been always dynamically negligible.
  2. Because of their small sizes, UFDs provide insights into dark matter on smaller scales than anywhere else, with their small sizes enabling investigations at scales of about 20-30 parsecs.
  3. The abundance of dwarf galaxies around the Milky Way sets on the allowed mass of warm DM particles.
  4. UFDs are among the closest dark matter halos to us, making them promising targets for indirect detection experiments.
  5. The internal dynamics of UFDs are so gentle that heating by very weak effects is potentially measurable. This offers the opportunity to measure the DM constraint.

- The conclusive measurement of the inner density profile of highly dark matter-dominated UFDs is considered a holy grail for dark matter research, although the limited number of stars in these galaxies poses challenges for such measurements.
- Despite the challenges, advancements in observational techniques, such as combining radial velocities and proper motions, offer prospects for more accurate measurements of dark matter properties in UFDs using ground-based and space-based facilities.

Summary

- The initial discovery of UFDs was in the Sloan Digital Sky Survey (SDSS) Observations, and then there was an agreed-upon magnitude of -7.7 for them.
- They are described as the oldest, least luminous galaxies known, most dark matter–dominated, most metal-poor, and least chemically evolved stellar systems known. These properties make them unique probes of early galaxy formation, and the behavior of dark matter on small scales.
- By measuring their velocity dispersion, we found out that they are dark matter-dominated, also indicating that they are galaxies rather than globular clusters. We also saw that it is mostly robust against systematic uncertainties such as binary stars and foreground contamination.
- Their chemical abundance taught us that most of their stars have formed before the reionization, and they are mostly enriched by core-collapsed supernovas, however, some of them are enriched by SN Ia as well.
- Even under conservative assumptions, only a small fraction of UFDs may have suffered significant tidal stripping of their stellar components.
- Challenges remain, including incomplete spectroscopy for a third of the current ultra-faint satellite population, limited star-formation histories for only a few galaxies, and no sufficient resolution in theoretical simulations.
- The census of Milky Way satellites is significantly incomplete, with potentially twice as many dwarf satellites yet to be found. Ongoing and future surveys such as DESI Legacy Imaging Surveys may reveal missing satellites.