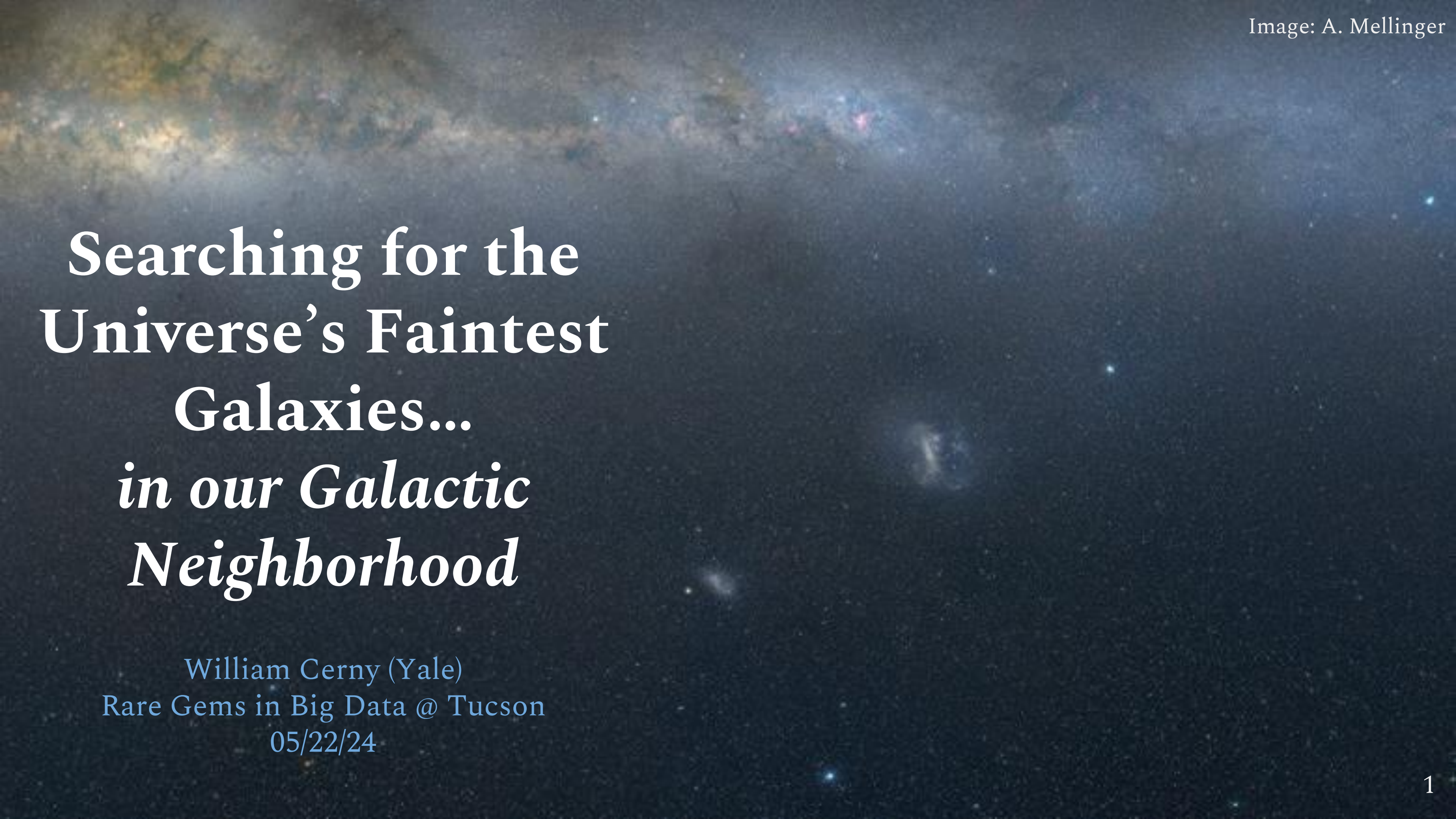


Image: A. Mellinger

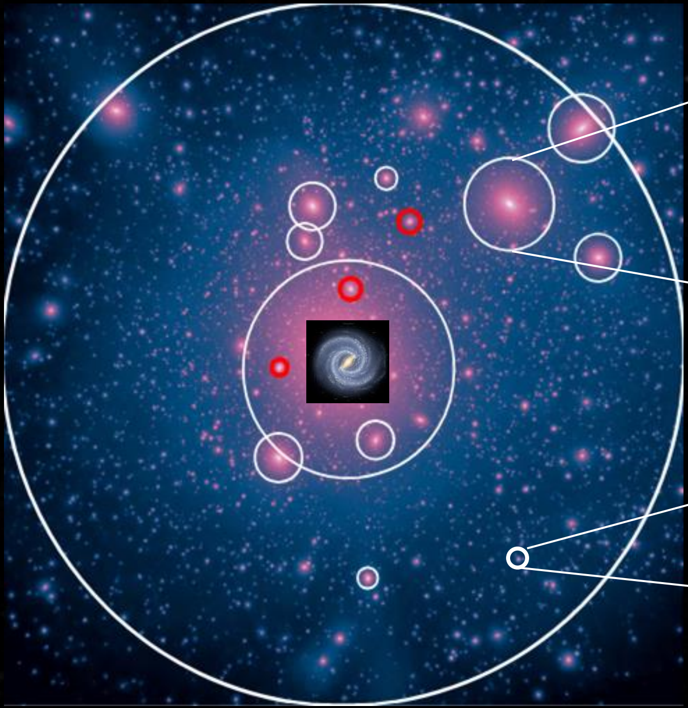
Searching for the Universe's Faintest Galaxies...
in our Galactic Neighborhood

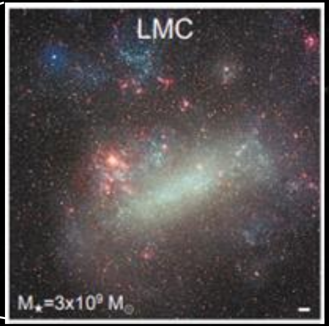
William Cerny (Yale)
Rare Gems in Big Data @ Tucson
05/22/24

Galaxies like the Milky Way – and their host dark matter halos – assemble through the hierarchical merging and accretion of smaller galaxies/(sub)halos.

High-resolution, dark-matter-only simulations of MW mass hosts from the Caterpillar suite (Griffen+ 2016)

As a result of this assembly process, the Milky Way is expected to be surrounded by an entourage of *faint dwarf galaxy satellites spanning a large range in mass*





Factor of 10^7 difference in stellar mass!

Images adapted from Griffen+ (2016), Bullock and Boylan-Kolchin (2017); Sloan Digital Sky Survey

At the low mass extreme are the "ultra-faint dwarfs" (UFDs)

usually defined by $M_V > 7.7$; $M_* < 10^5\ M_\odot$ (Simon 2019)

The UFDs are the...

- Least Luminous and Least Massive
- Oldest and Least Chemically Enriched
- Most Dark-Matter-Dominated

galaxies in the universe!

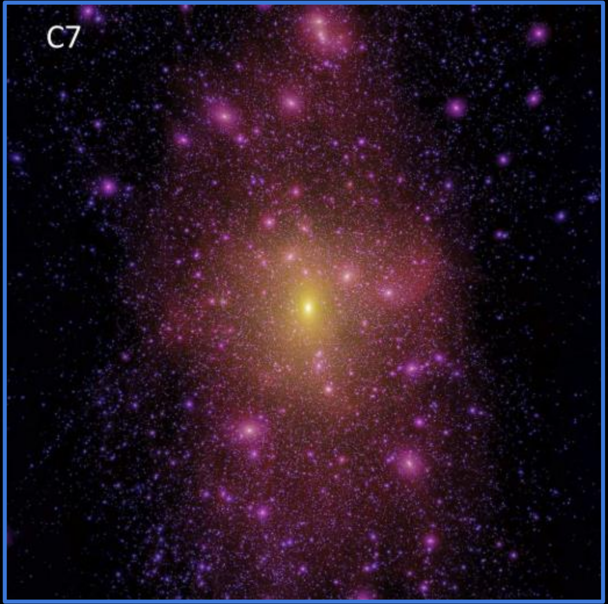
Their faint and diffuse nature make them elusive "rare gems" --> even though they're likely the most common class of galaxy in the universe!

At the low mass extreme are the “ultra-faint dwarfs” (UFDs)

(usually defined by $M_V > 7.7$; $M_* < 10^5\ M_\odot$ (Simon 2019)

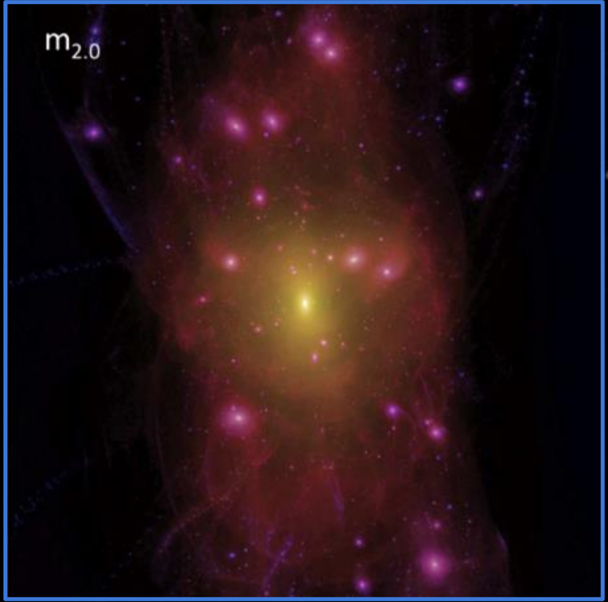
Background: SDSS image of the UFD “Segue I”!

Exactly how many of these ultra-faint galaxies there are around the MW depends on the nature of dark matter



Cold Dark Matter simulation

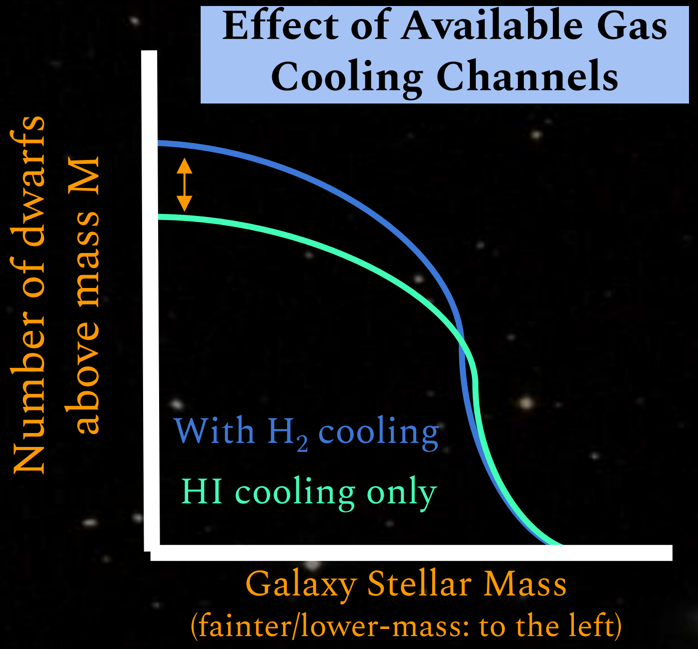
DMO simulations from Lovell+ (2014)

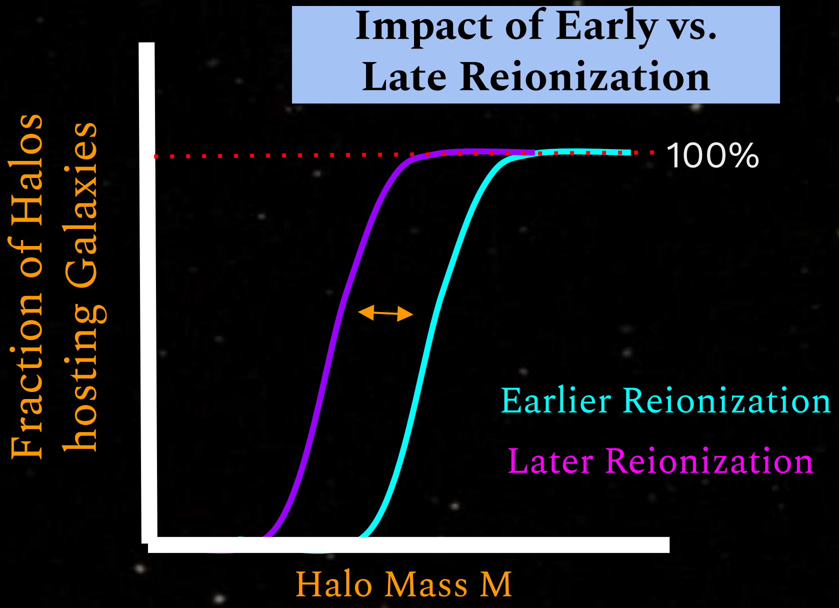


Warm Dark Matter simulation

e.g., "warmer" DM particles suppress small scale structure → expect fewer faint dwarf galaxies around the Milky Way!

In addition, the number of dwarfs at the low-mass end is strongly sensitive to baryonic processes regulating galaxy formation → highly uncertain in many cases!





Cartoon inspired by Munshi+2019, Nadler+2019, Manwadkar & Kravtsov+2021, Weerasooriya+2022, Ahvazi+2023, etc.

Takeaway:

A complete, well-characterized census of Milky Way satellite galaxies *extending down to the faintest dwarfs*

can provide strong constraints on the nature of dark matter and the processes governing galaxy formation in low-mass halos

Takeaway:

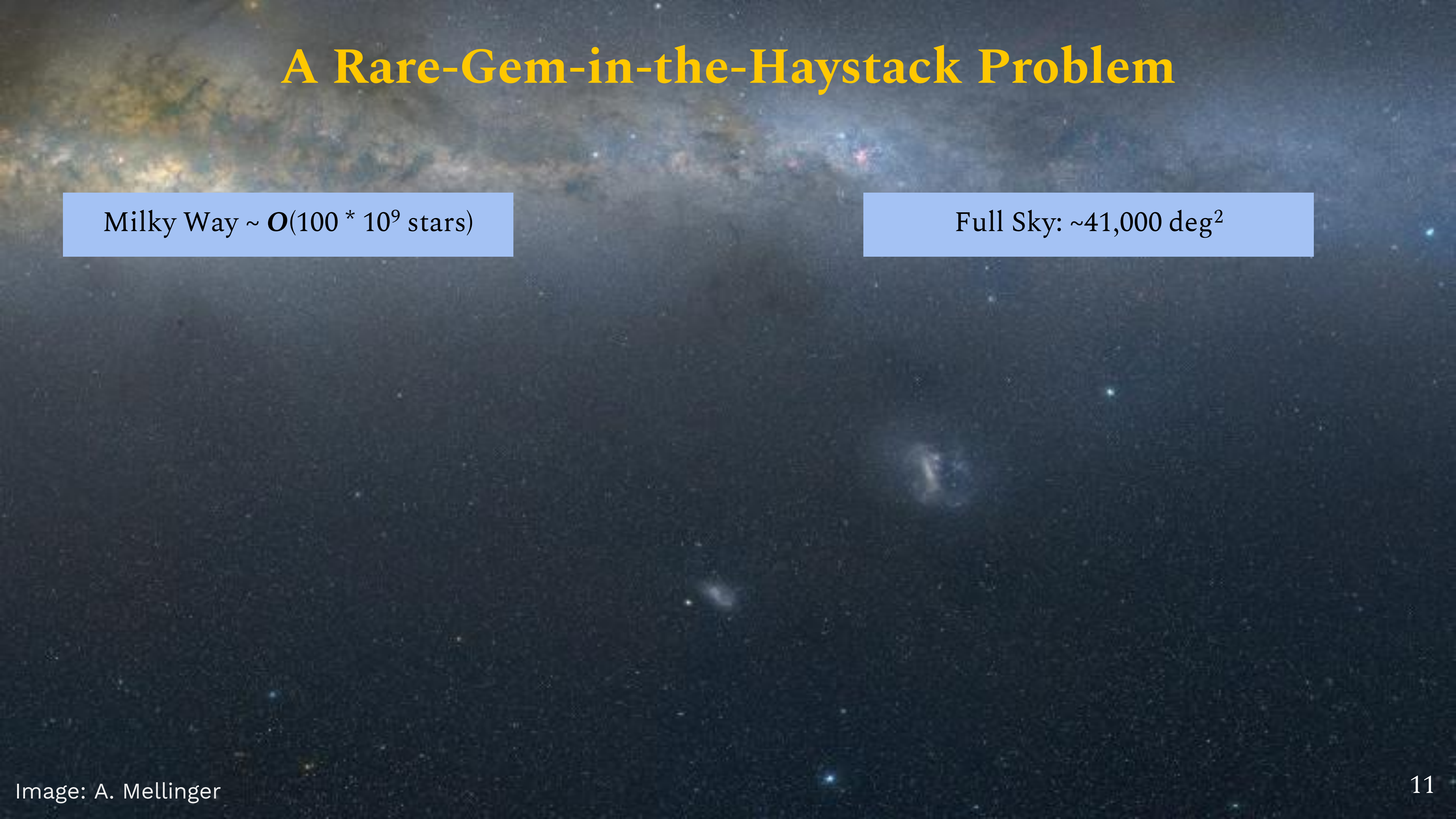
A complete, well-characterized census of Milky Way satellite galaxies *extending down to the faintest dwarfs* can provide strong constraints on the nature of dark matter and the processes governing galaxy formation in low-mass halos

.... so how can we find these very-low-mass, ultra-faint dwarf galaxy satellites?

A Rare-Gem-in-the-Haystack Problem

Image: A. Mellinger

A Rare-Gem-in-the-Haystack Problem



Milky Way ~ $\boldsymbol{O}(100 * 10^9$ stars)

Full Sky: ~41,000 deg^2

Image: A. Mellinger

A Rare-Gem-in-the-Haystack Problem

Milky Way ~ $\boldsymbol{O}(100 * 10^9$ stars)

Factor of ~10^{-8}

UFDs ~ $\boldsymbol{O}(10^2$ detectable stars)

Full Sky: ~41,000 deg^2

Factor of ~10^{-9}

UFDs: $\lesssim$ few arcmin^2

Image: A. Mellinger

A Rare-Gem-in-the-Haystack Problem

Milky Way ~ ***O***(100 * 10^9 stars)

Factor of ~10^{-8}

UFDs ~ ***O***(10^2 detectable stars)

Full Sky: ~41,000 deg^2

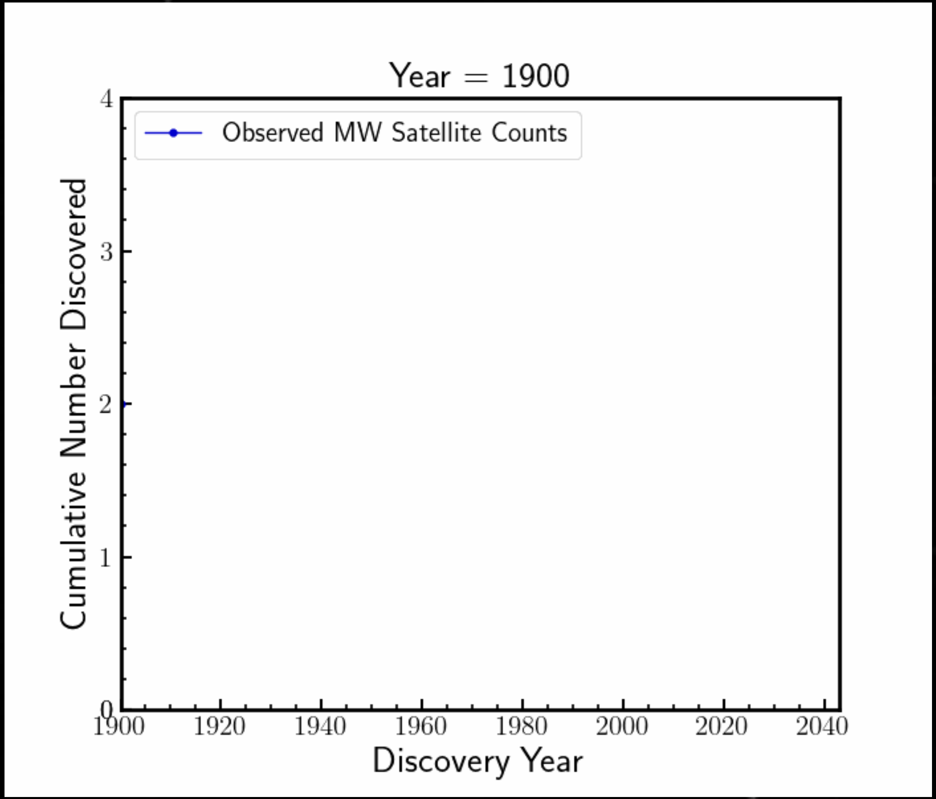
Factor of ~10^{-9}

UFDs: $\lesssim$ few $arcmin^2$

And this is ignoring the orders-of-magnitude more serious contamination from background galaxies!

Image: A. Mellinger

Seven decades of progress in one animation



Based on literature data compiled by Andrew Pace

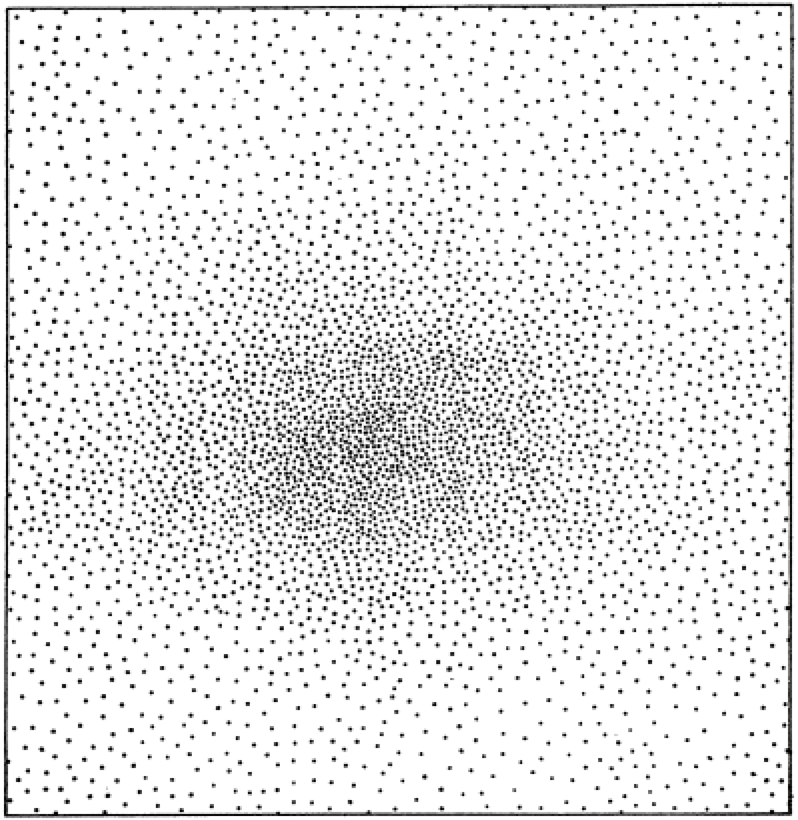


FIGURE 2.— DISTRIBUTION OF STARS IN CENTRAL SQUARE DEGREE

Discovery of the Sculptor dSph by Shapley (1938)

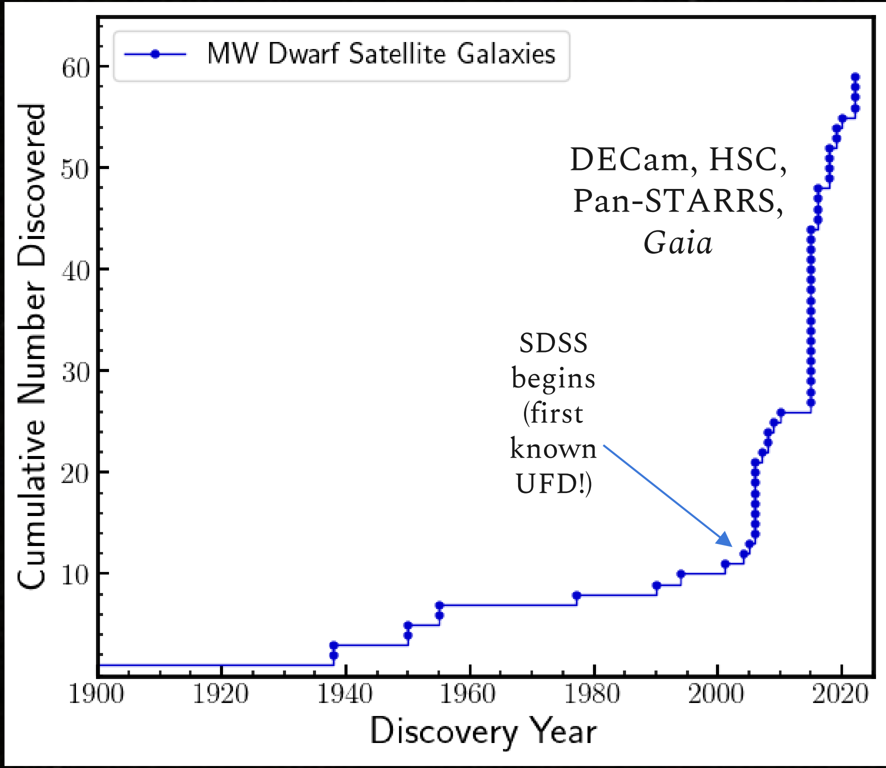
The "classical dwarfs" ($M_* > 10^5\ M_\odot$) around the MW were primarily discovered through a combination of photographic plate surveys, visual inspection, and luck

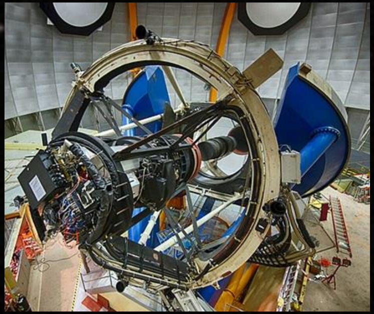
March 1, 1938

A Stellar System of a New Type. — A large rich cluster with remarkable characteristics appears on photographs received from the Boyden Station. Since nothing quite like it is now known, a detailed though preliminary description is given in the following pages. First noted on a long-exposure Bruce plate, the assembly of hazy images near the plate limit was thought to be an extended cluster of galaxies, such as the well-known system in Coma. Subsequent photographs made with the southern 60-inch reflector show, however, that the individual members are stars rather than spheroidal galaxies.

The advent of sensitive wide-field imagers and digital sky surveys catalyzed the ultra-faint dwarf galaxy revolution

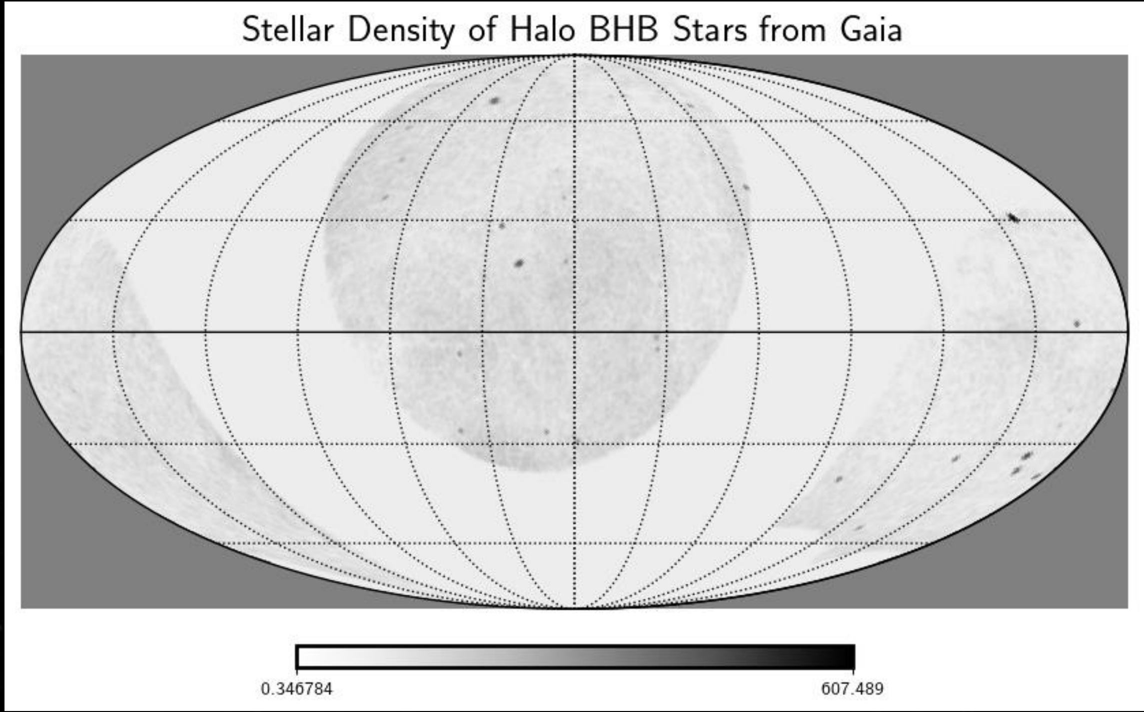
Based on data compiled by Andrew Pace





Images from SDSS, DES, and HSC Collaborations

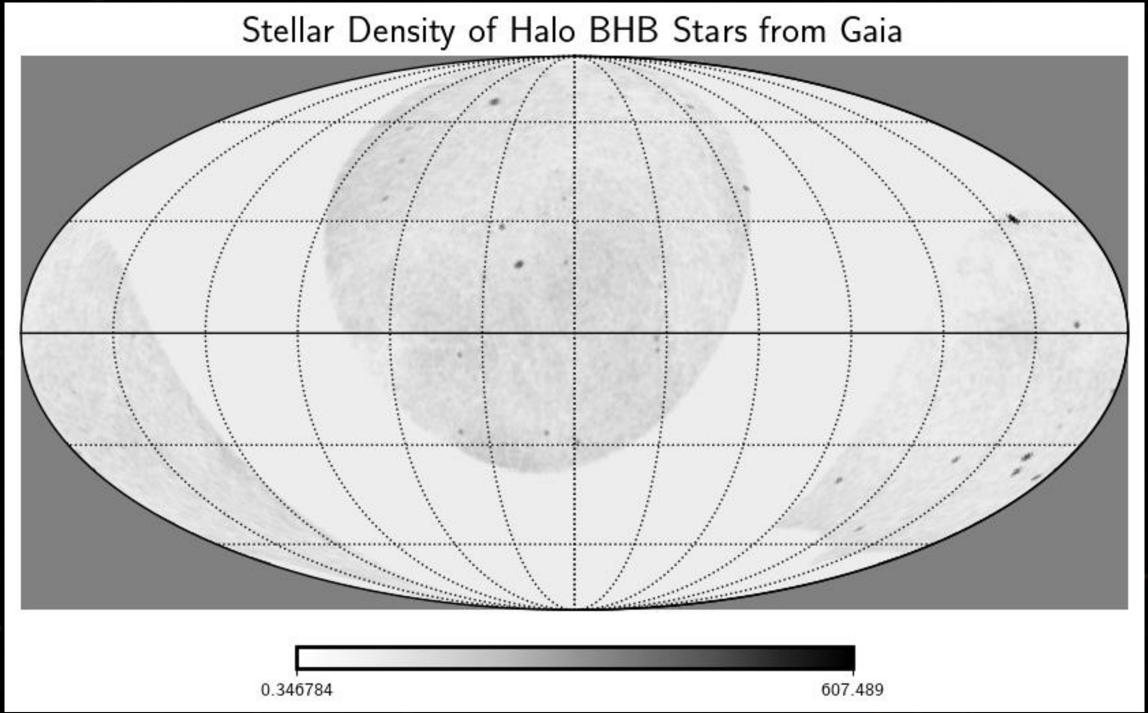
Modern scheme: Milky Way satellite galaxy candidates are detected as spatially-localized "overdensities" of resolved, old, metal-poor halo stars



1. Survey large swaths of sky
2. Separate stars from galaxies
3. Filter for old, metal-poor stars
4. Construct stellar density maps
5. Smooth with a spatial kernel
6. Identify overdensities with high Poisson significance
7. Visually triage detections into real/junk/need more data to confirm

Many variations on this theme: see, e.g. Willman+2005, Koposov+2008, 2015, Walsh+2009, Bechtol+2015, Drlica-Wagner+2020

Modern scheme: Milky Way satellite galaxy candidates are detected as spatially-localized "overdensities" of resolved, old, metal-poor halo stars



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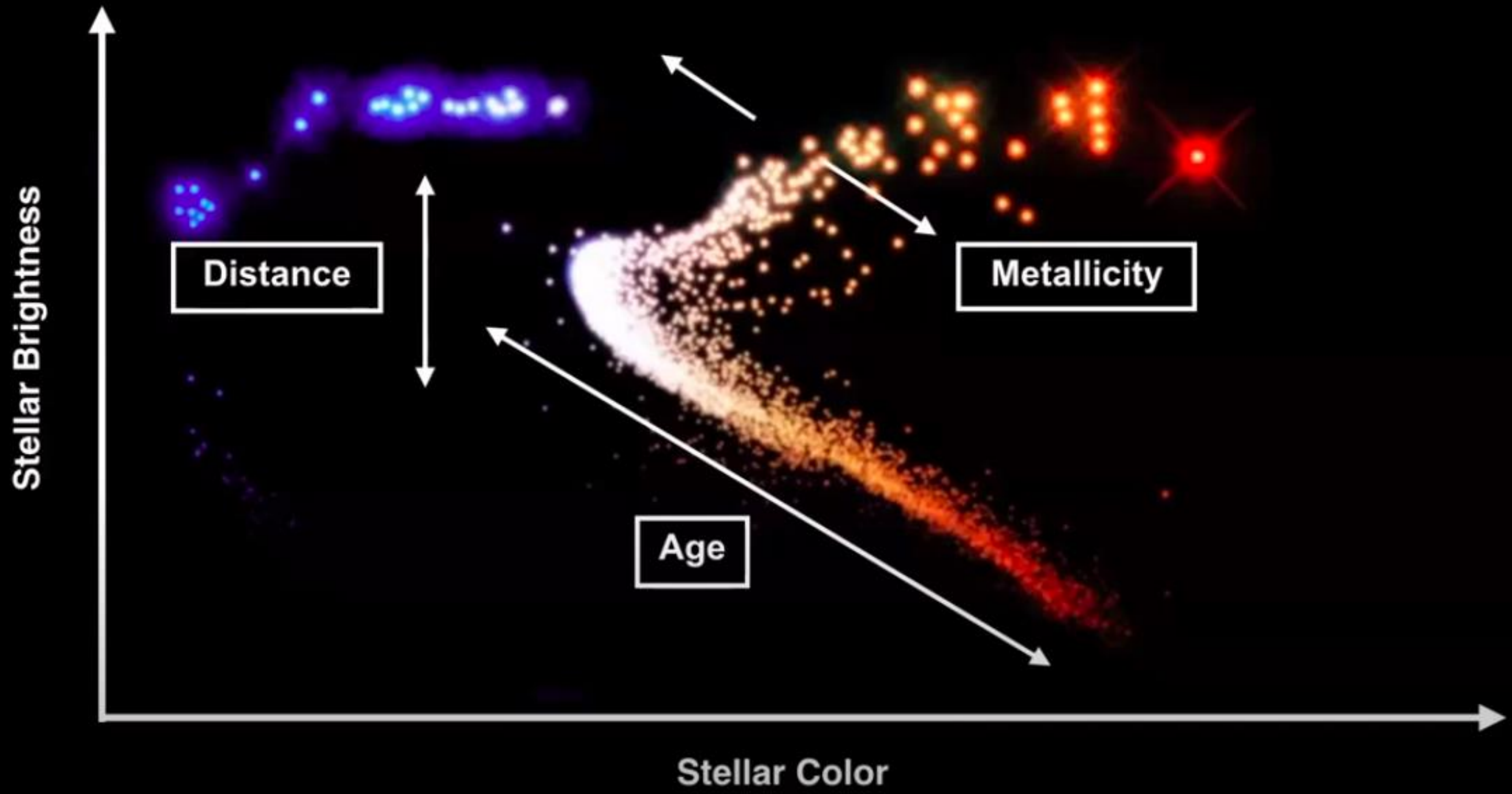
Many variations on this theme: see, e.g. Willman+2005, Koposov+2008, 2015, Walsh+2009, Bechtol+2015, Drlica-Wagner+2020

UFDs are ancient, metal-poor stellar populations, and we can exploit these properties to find them

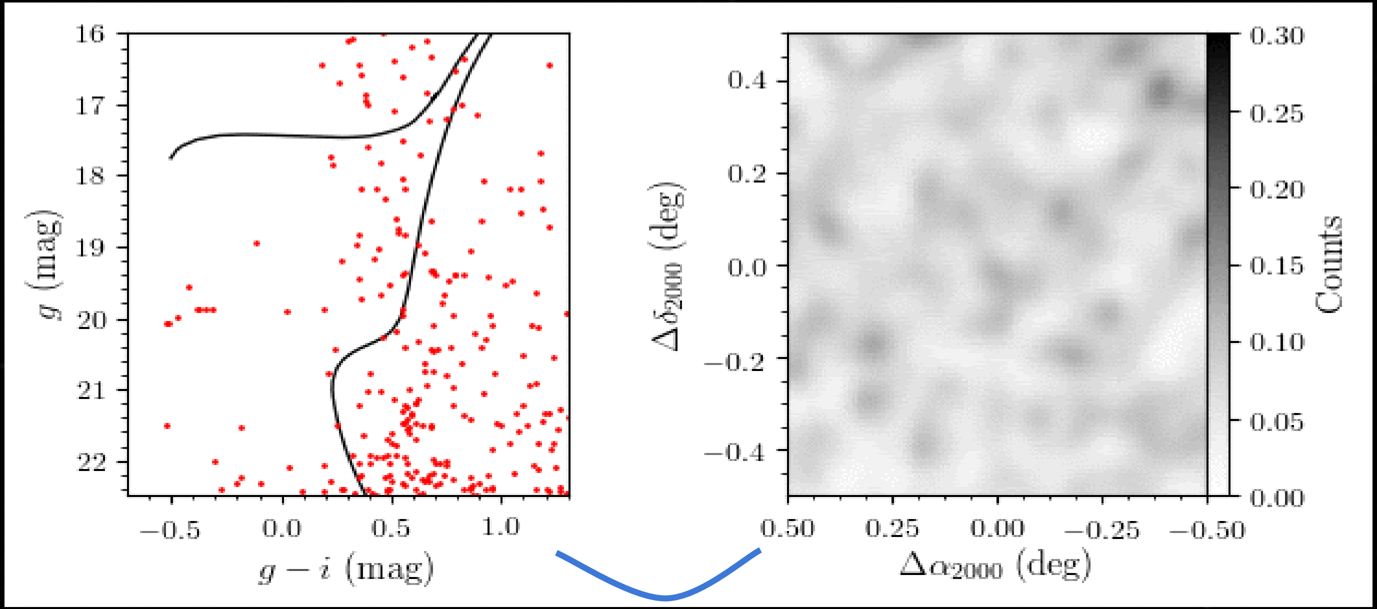


NASA/ESA, Anderson and van der Marel (STScI); adapted by Alex Drlica-Wagner

Key Technique: Isochrone Matched-Filtering

Discovery of Eridanus IV with DECam (Cerny+DELVE Collaboration 2021)

Brightness

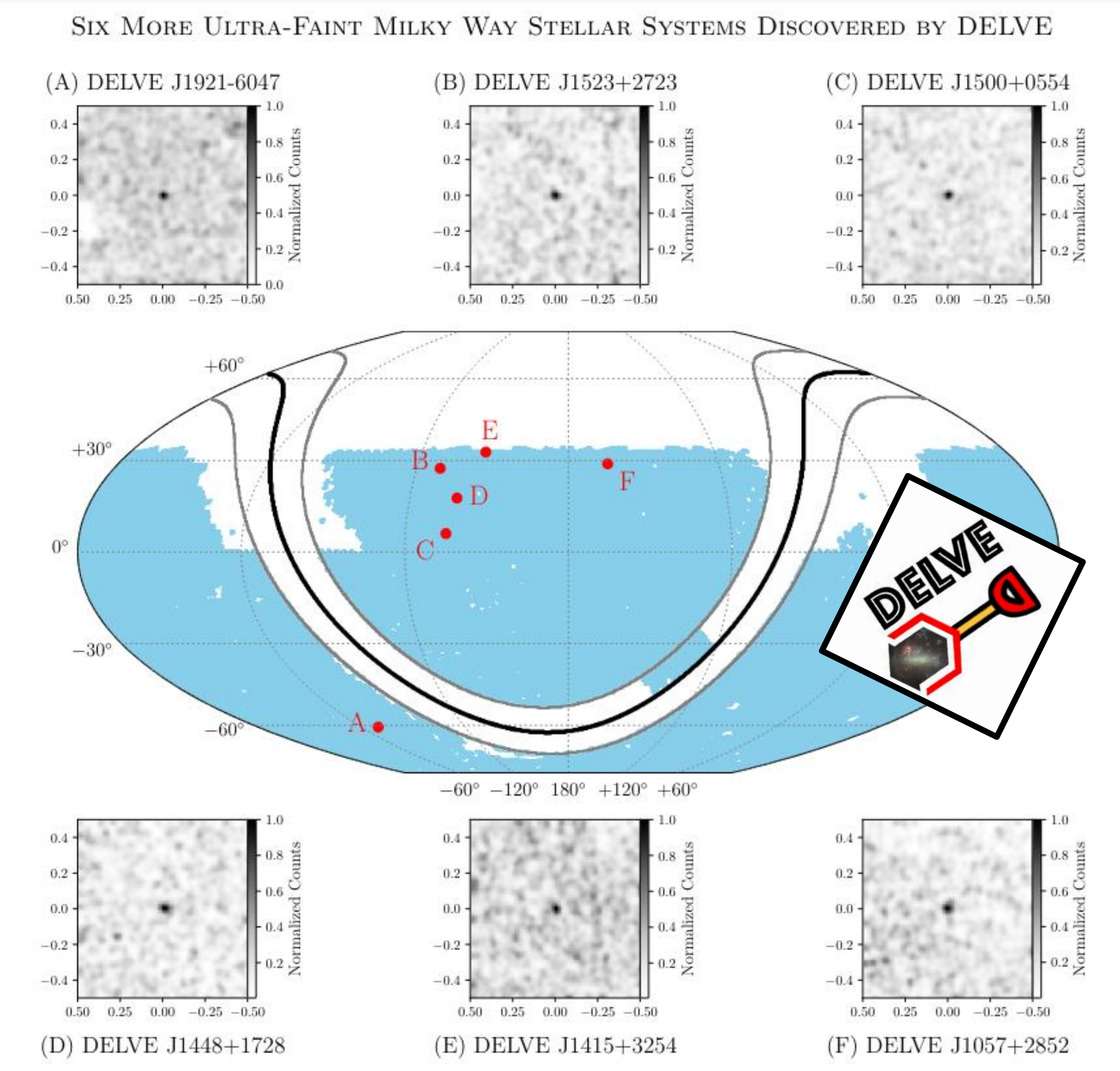


(not shown here: a few tricks to weight filtered stars)

Color

Smoothed, isochrone-filtered stellar density map

→ scan isochrone at a range of distances and select for detection of maximum signal

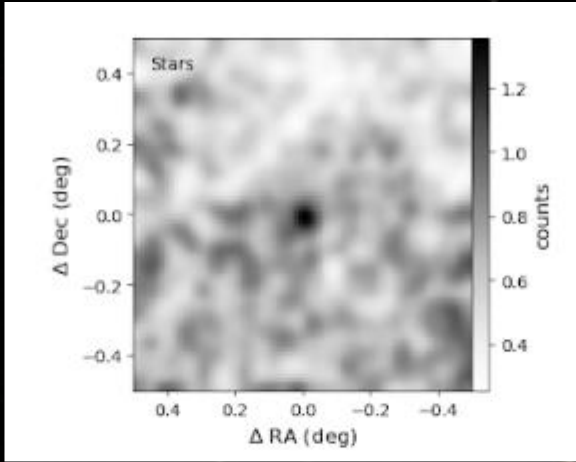


We parallelize by splitting the sky into ~3 deg^2 HEALPix pixels and running the matched-filtering over each pixel independently

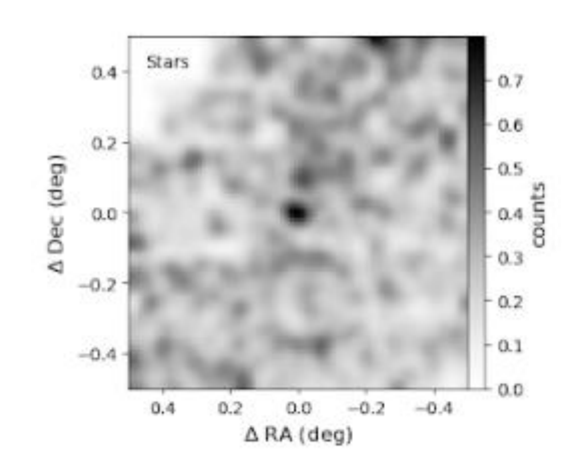
→ later concatenate into a single detection catalog

Most recent tranche of new MW satellites with DECam (Cerny+DELVE Collab. 2023b)... can look pretty marginal even here!

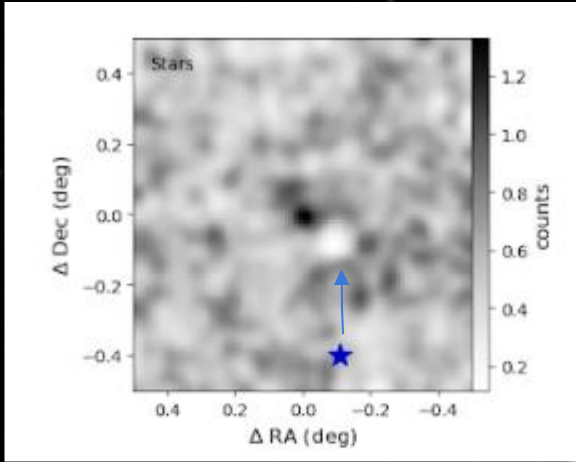
False Positives (can) pose a significant challenge



Likely Galaxy Group/Cluster



Faulty source detection near Galactic cirrus(?)

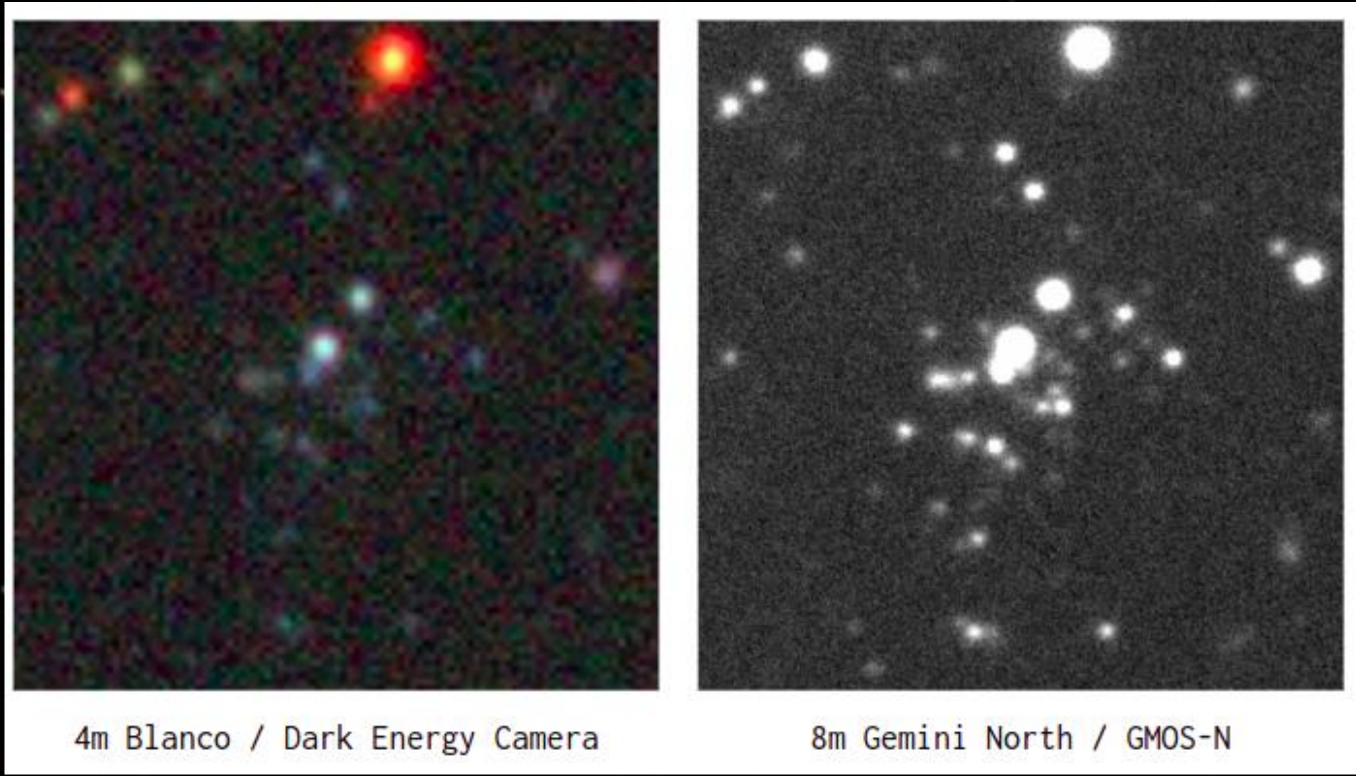


Compromised by nearby bright star

All exceed a nominal ~5σ Poisson significance threshold but are false positives.. not necessarily trivial to reject these cases!

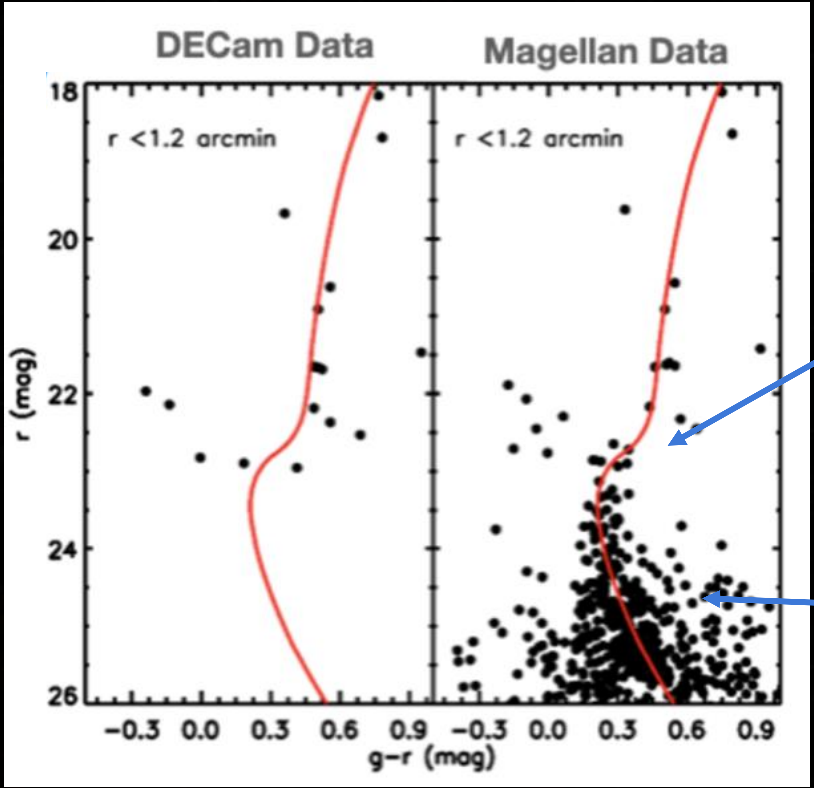
Deeper follow-up imaging on ~8m telescopes is critical for robustly confirming new discoveries (1/2)

Lefthand Image from DESI LIS / Dustin Lang



The ultra-faint star cluster “DELVE 4” (Cerny+23), at only D~40 kpc!

Deeper follow-up imaging on ~8m telescopes is critical for robustly confirming new discoveries (2/2)

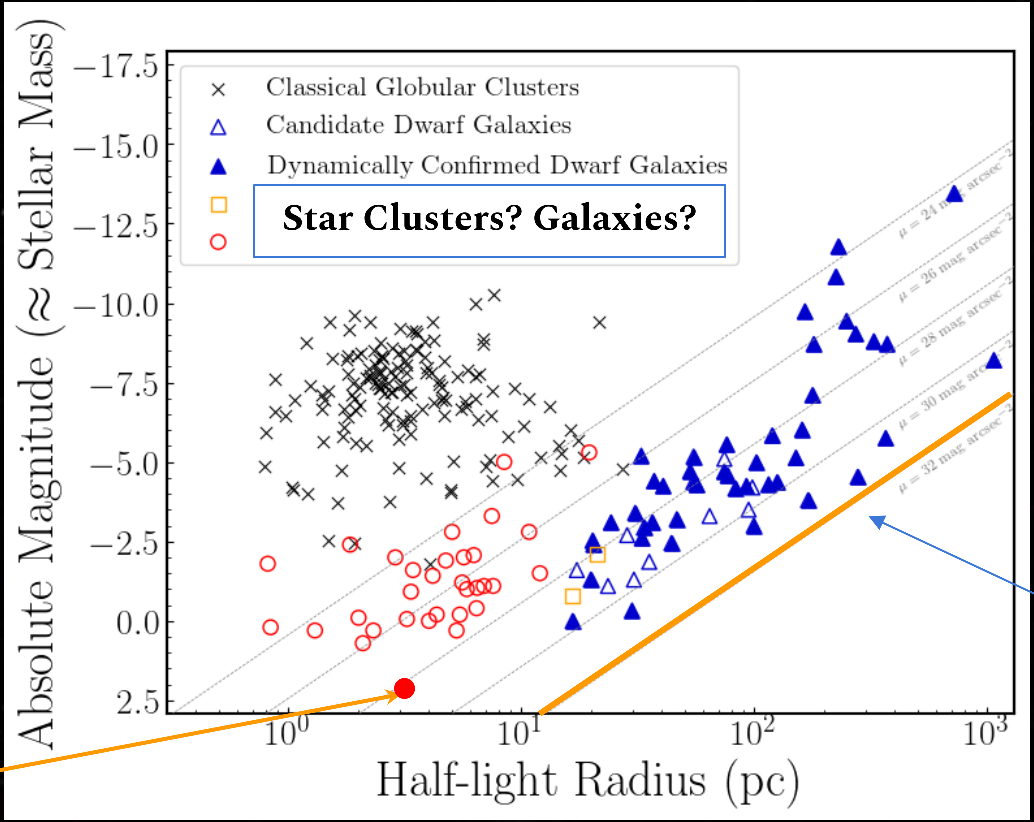


The UFD Phoenix II, at D ~ 85 kpc
(see Mutlu-Pakdil+ 2018)

Deeper data resolves the old Main-Sequence Turn Off (oMSTO) feature - very useful for isochrone fitting

Large sample of low-mass stars improves constraints on the system's morphology (size, ellipticity, etc.)

The Current Frontiers in the Luminosity-Size Plane

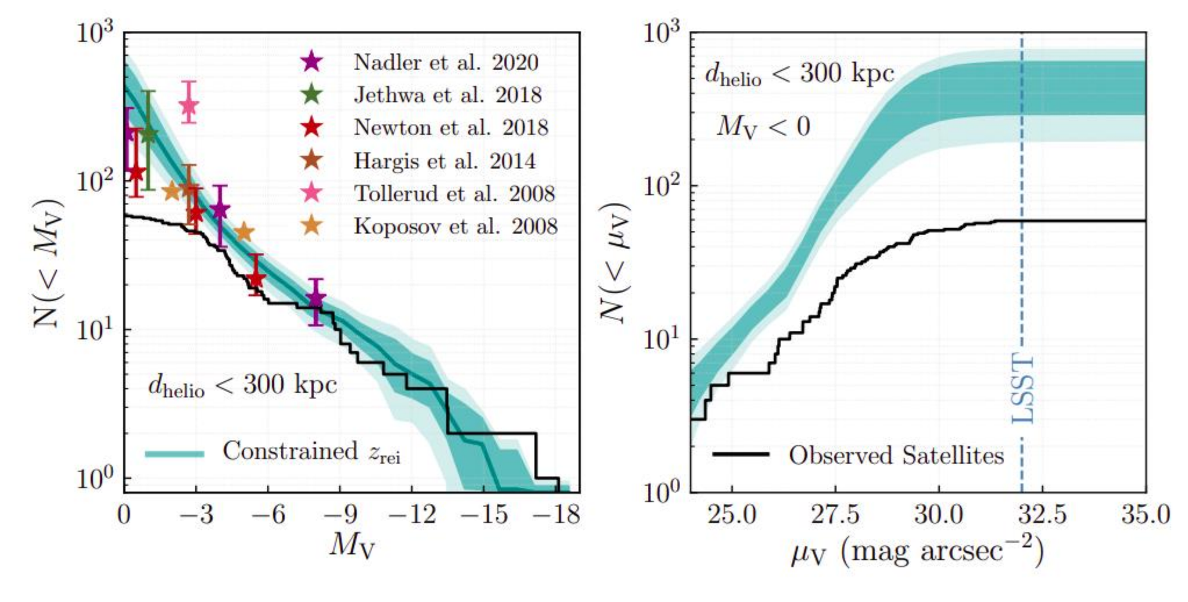


Are systems this faint common? (record as of 2024: M_V = +2.2!)

Apparent cutoff in surface brightness: real, or a detection limit?

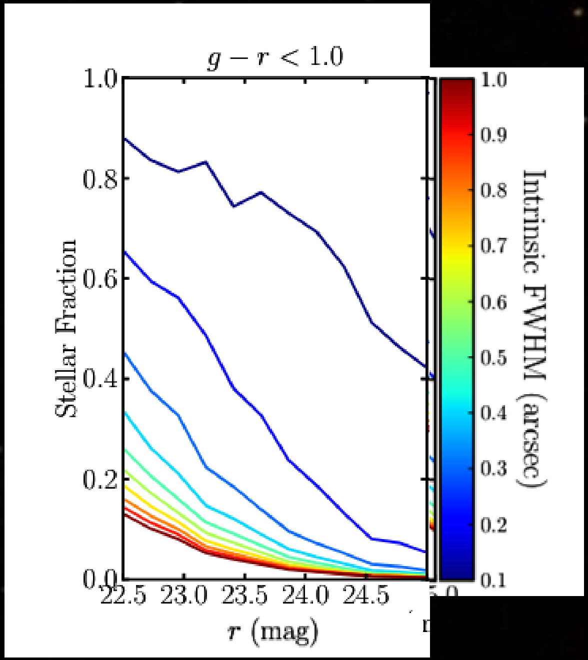
The Vera C. Rubin Observatory will catalyze a new wave of discovery

Image: Rubin Observatory



Forecasts based on semi-analytical modelling; from Manwadkar and Kravtsov (2022) (= same as the earlier animation)

... so long as we can tackle the issue of star/galaxy separation!



Adapted from Fadely, Hogg, and Willman (2012)

At the faint limiting magnitudes probed by Rubin/LSST, compact blue galaxies outnumber blue stars >>10:1

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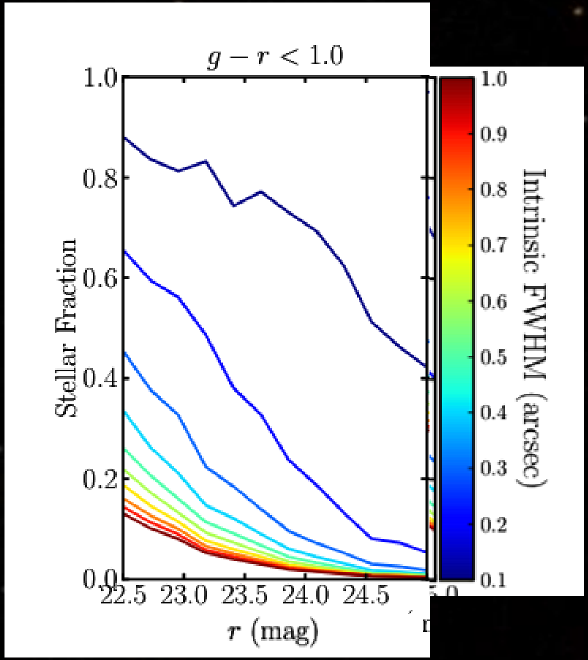


Adapted from Fadely, Hogg, and Willman (2012)

At the faint limiting magnitudes probed by Rubin/LSST, compact blue galaxies outnumber blue stars >>10:1

This is *already* the main limiting factor for current surveys/dwarf searches.. and even was an issue for Shapley in 1938!

in the following pages. First noted on a long-exposure Bruce plate, the assembly of hazy images near the plate limit was thought to be an extended cluster of galaxies,

Closing thoughts about where ML may play a role (and has already)

1. Star/Galaxy separation, of course!
   a. Given a set of morphological parameters, we already often estimate p(star) vs. p(galaxy) → how can we use this *probabilistically* and avoid hard cuts?

1. Candidate Triaging: how do we go from O(10000?) detections -> O(~100) likely candidates, at 100% completeness, without requiring human visual inspection?
   b. Can we use the image plane + CNNs to hone candidate pools? (e.g. Jones+23)
   c. What "metadata" should we collect with each detection that might help a ML model be able to sort true detections from false positives?

1. Quantifying and Interpreting Sensitivity / Completeness:
   b. Example: Dark Energy Survey used simulated dwarf injection to understand sensitivity, then trained a RF classifier over those results to predict satellite detection probability as a function of distance, size, absolute magnitude, etc. (Drlica-Wagner+ 2020)

Summary

1. The number / luminosity function of ultra-faint dwarf galaxies around the MW is a strong probe of dark matter and galaxy formation physics

1. Deep, wide-field imagers have unveiled ~50 ultra-faint MW satellites to date, primarily using non-ML-based isochrone matched filter searches

1. There are scores to hundreds of ultra-faint galaxies within reach of the upcoming Vera C. Rubin Observatory / LSST

1. Maximizing the UFD/satellite yield from Rubin will require tackling the challenges of star/galaxy separation and false positives - role of ML?

Bonus Slides

Satellite Discoveries (as of 2020)

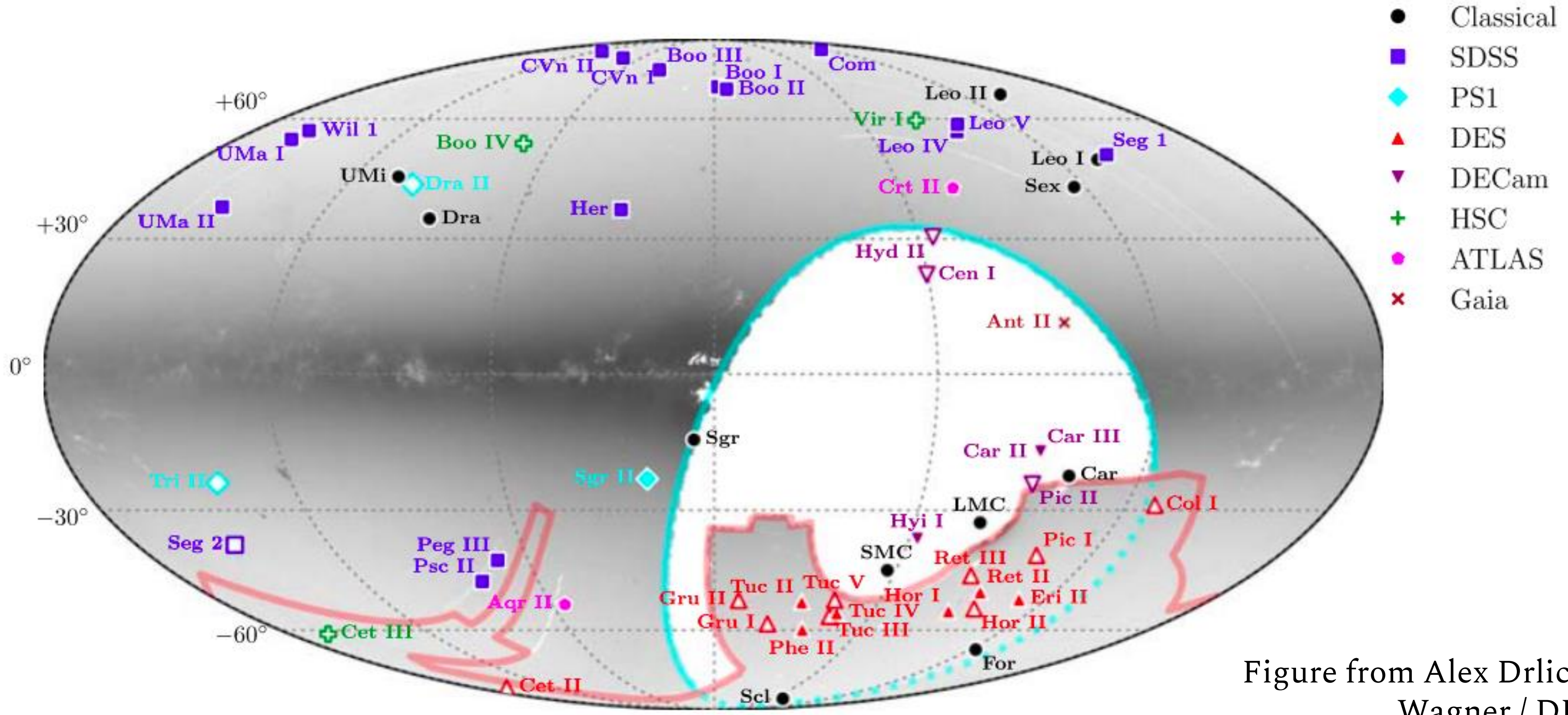
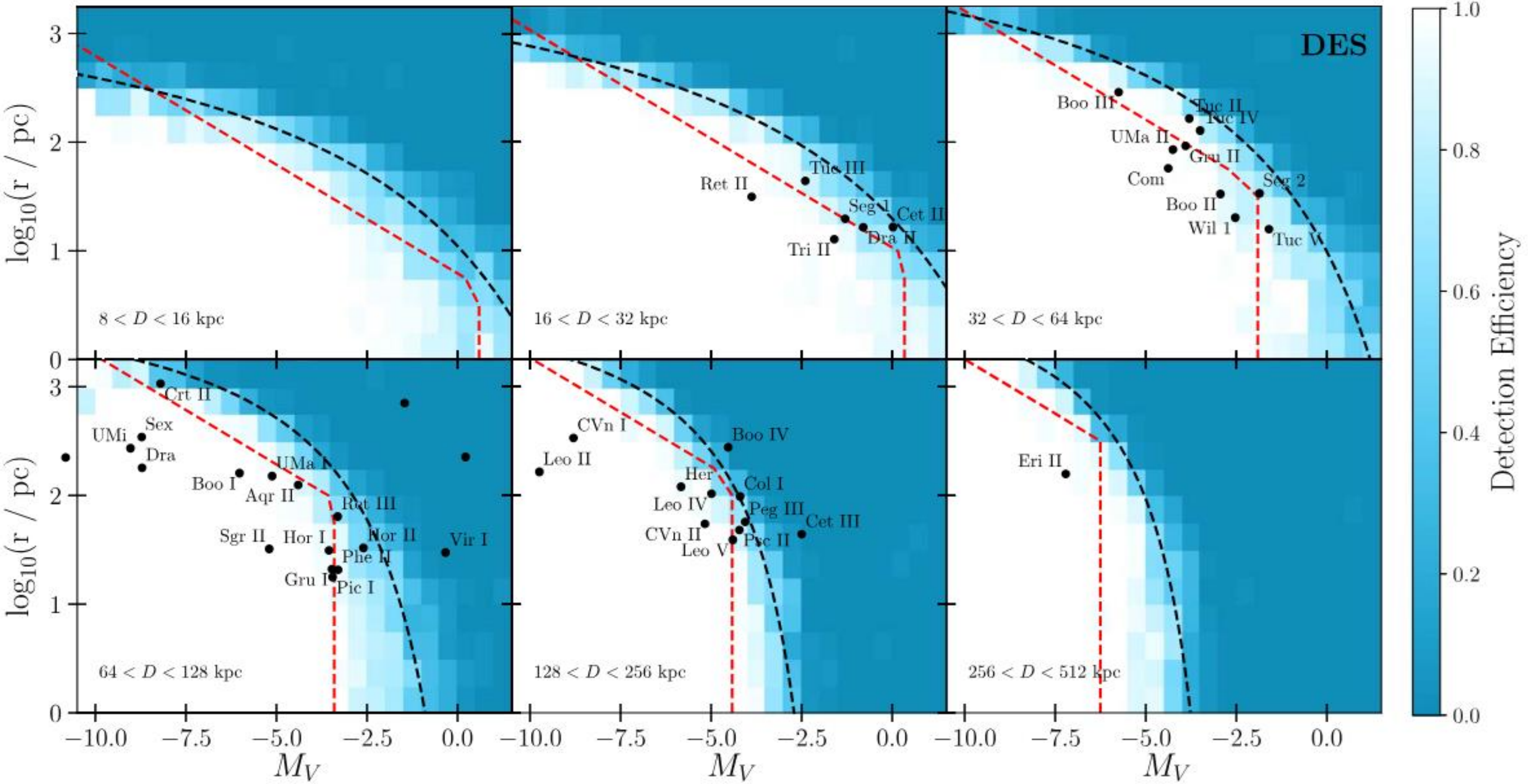
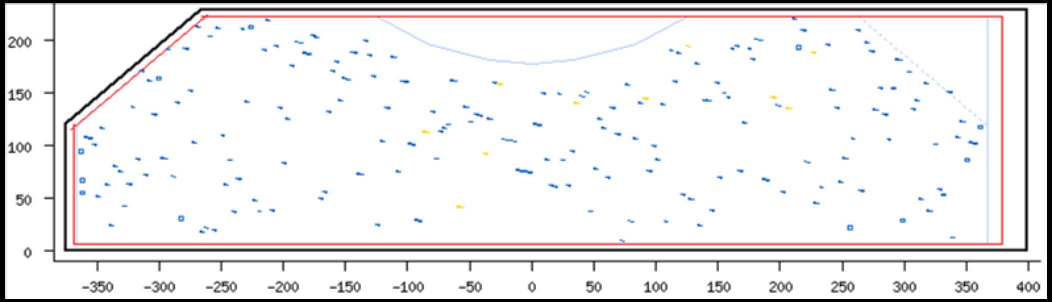


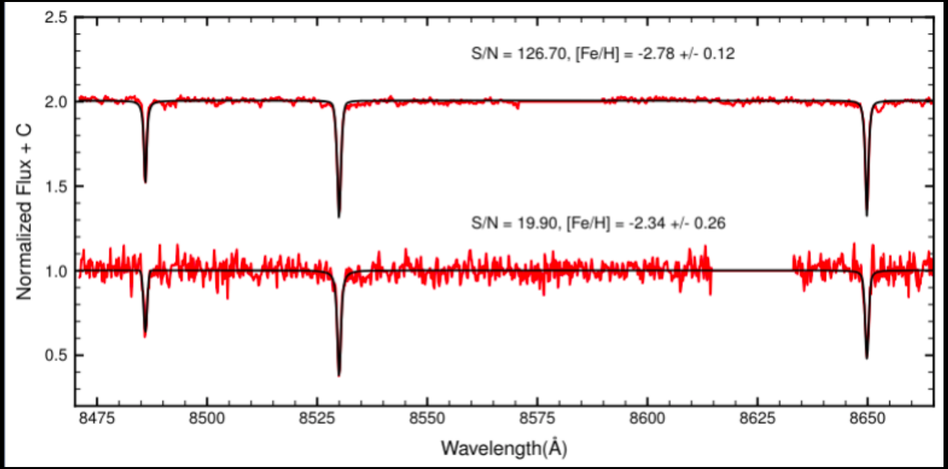
Figure from Alex Drlica-Wagner / DES


DES
8 < D < 16 kpc
16 < D < 32 kpc
32 < D < 64 kpc
64 < D < 128 kpc
128 < D < 256 kpc
256 < D < 512 kpc
log10(r / pc)
M_V
Detection Efficiency
Ret II
Tuc III
Seg 1
Cet II
Dra II
Tri II
Boo III
Tuc II
Tuc IV
UMa II
Gru II
Com
Seg 2
Boo II
Wil 1
Tuc V
Crt II
UMi
Sex
Dra
Boo I
UMa I
Aqr II
Ret III
Sgr II
Hor I
Hor II
Phe II
Gru I
Pic I
Vir I
CVn I
Leo II
Boo IV
Her
Col I
Leo IV
Peg III
Cet III
CVn II
Psc II
Leo V
Eri II

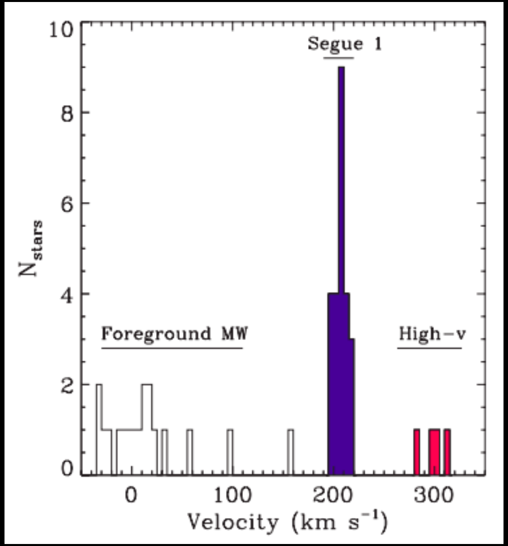
The Role of Multi-Object Spectroscopy



Keck Observatory



Example spectra of red giant stars in an ultra-faint (Simon+2024; submitted)



Geha et al. (2011)

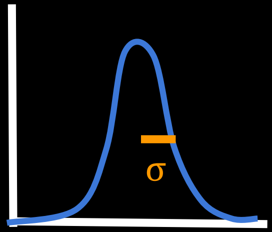
Star Clusters or Dwarf Galaxies?

For our purposes:
Dwarf galaxies have dark matter, while star clusters do not

Two Main Observational Diagnostics:

(Line-of-sight) Velocity Dispersions

Assume dynamical equilibrium —> large enclosed mass → DM



Metallicity Dispersions

Implies retention of supernova ejecta → deep potential well -> DM

Are the faintest MW satellites dwarfs or star clusters?