Spectroscopic Frontiers and Observational Challenges in Studying Dwarf Galaxies

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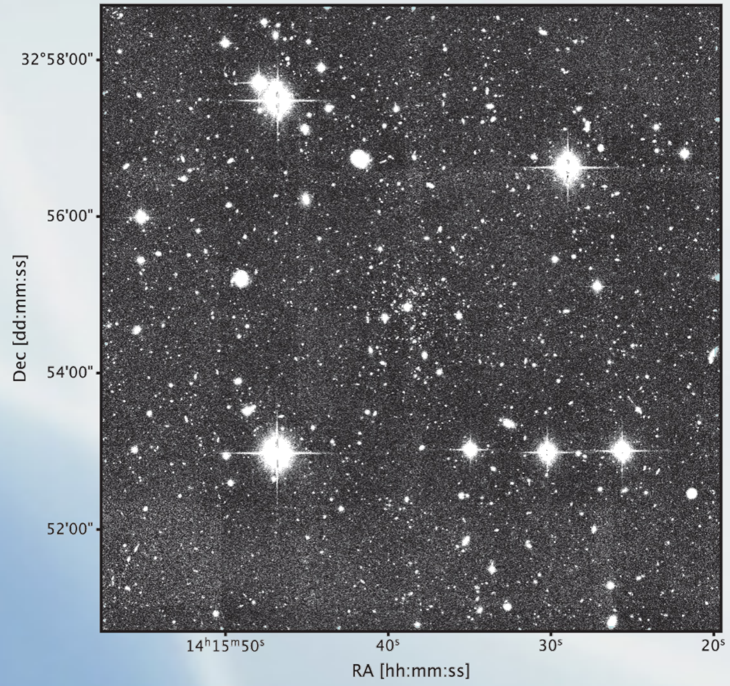
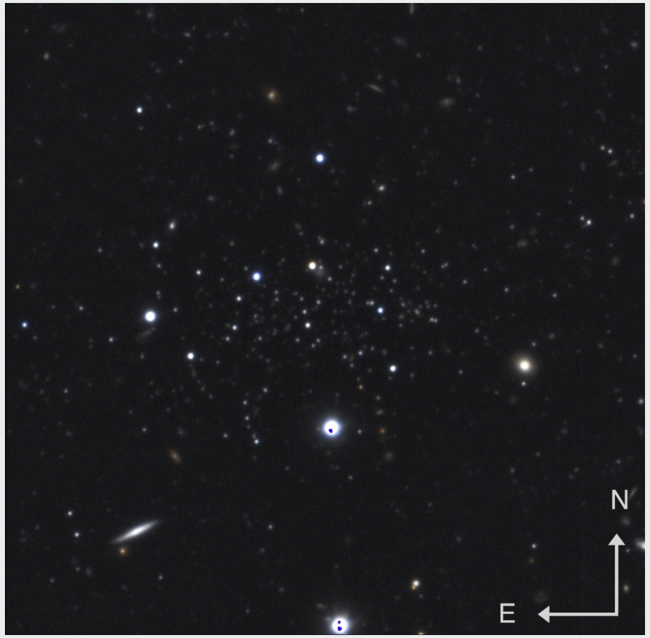
Why are dwarfs interesting?

- Smallest DM halos that contain stars
- Windows to early galaxy formation processes

Bootes V



Eridanus III

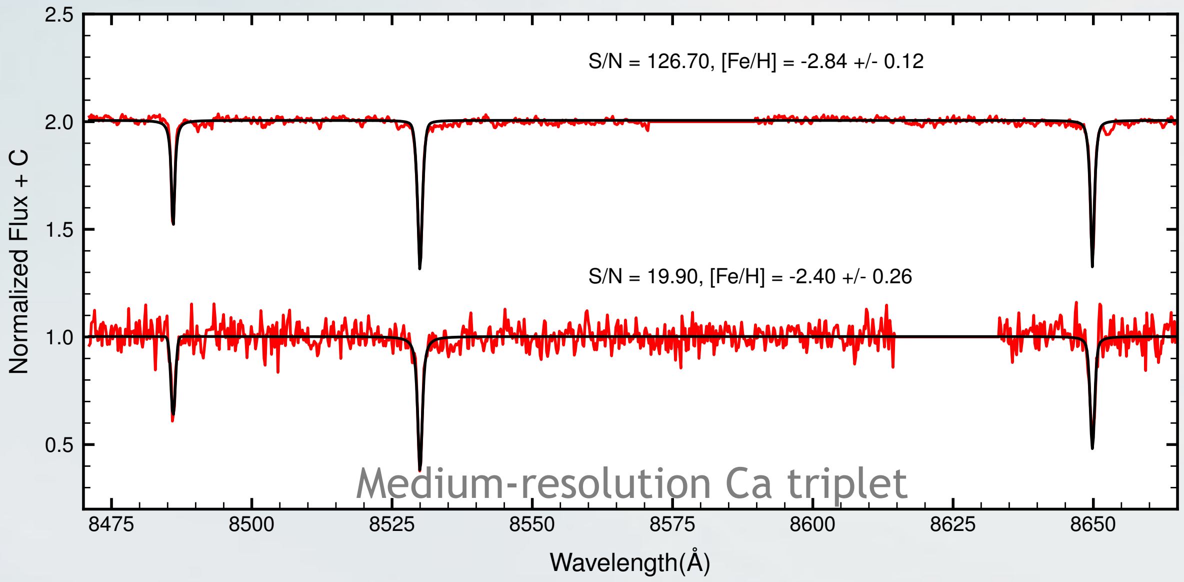


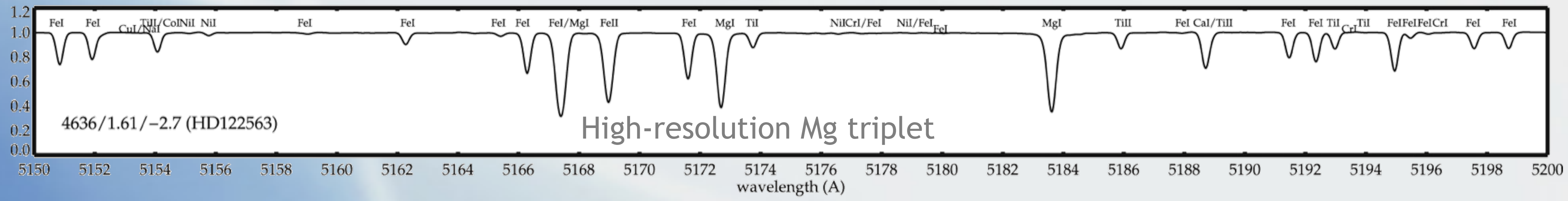
Smith et al. (2023)

Conn et al. (2018)

Why do we need spectra?

- Masses, metallicities, and chemical abundances

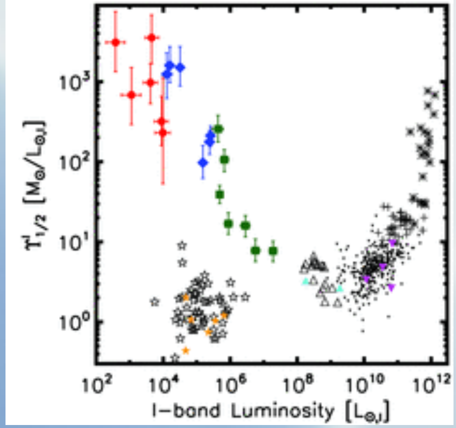


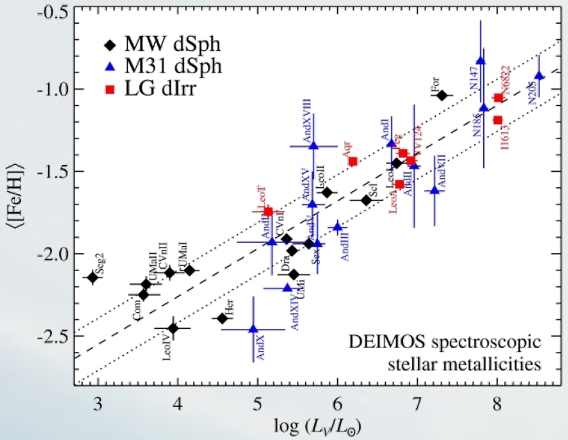


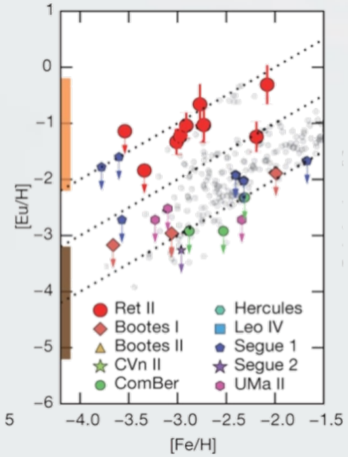
Conroy et al. (2019), Simon et al. (submitted)

Why do we need spectra?

- Masses, metallicities, and chemical abundances
- Some key results these data have provided:
  - Dwarfs are (usually) highly dark matter-dominated (Wolf et al. 2010)
  - Metallicity-luminosity relation extends at least down to L~1000 $L_\odot$ (Kirby et al. 2013)
  - Extreme r-process enrichment in Reticulum II (Ji et al. 2016)







What is the state of the art*?

- Stellar velocities with a precision of $\lesssim$ 1 km s^{-1} (dispersions down to σ ~ 2 km s^{-1})
- Metallicities from medium-resolution spectra with a precision of $\lesssim$ 0.15 dex
- Abundances for ~20 elements from high-resolution spectra

*for metal-poor stars at magnitude ~19-22

Characterizing the Milky Way satellite population

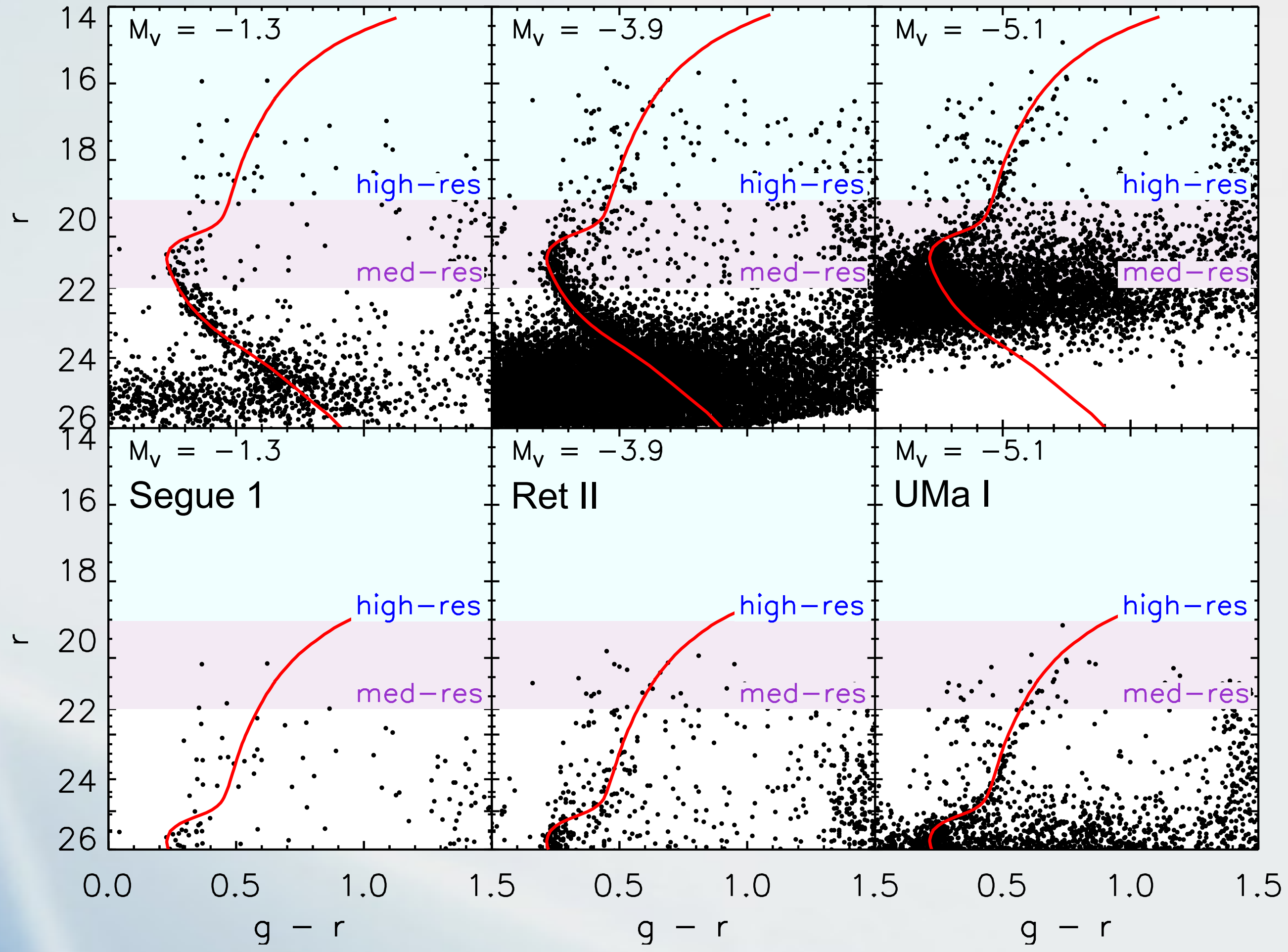
- Currently 63 confirmed/likely/possible dwarfs
  - 79% have a measured radial velocity
  - 79% have a velocity dispersion or upper limit
  - 78% have a mean metallicity
  - 48% have high-resolution chemical abundances
  - 62% have a high-confidence classification

Observational challenges

(1) There aren't very many stars

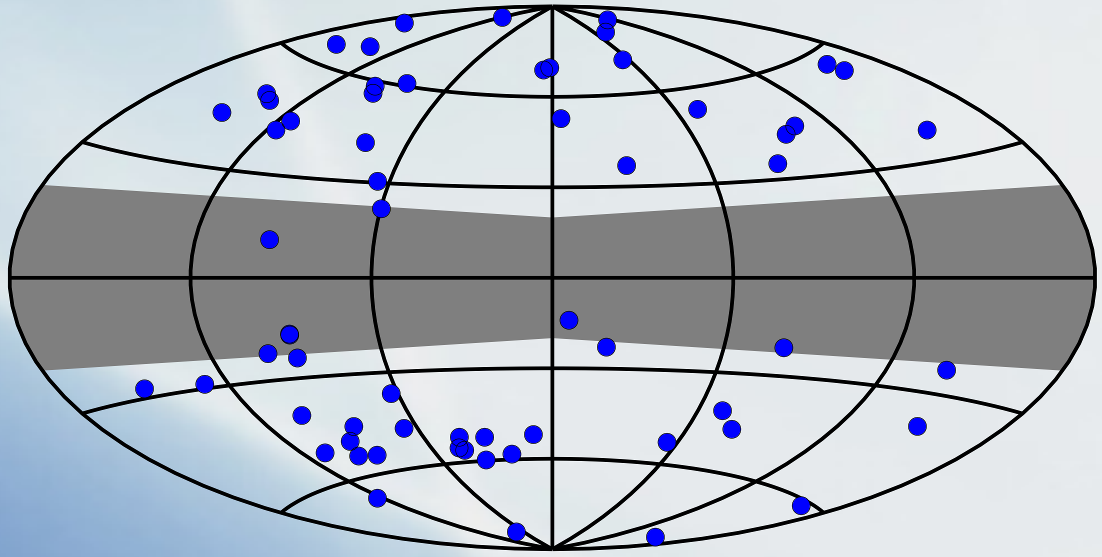
D = 30 kpc

D = 250 kpc

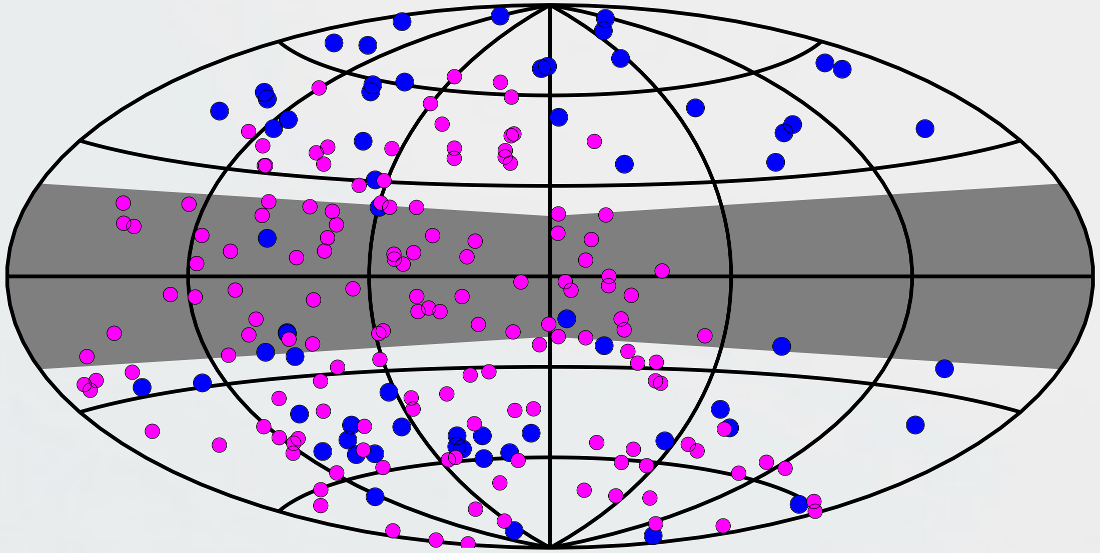


Observational challenges

(2) There are going to be a lot of Rubin satellite candidates to follow up



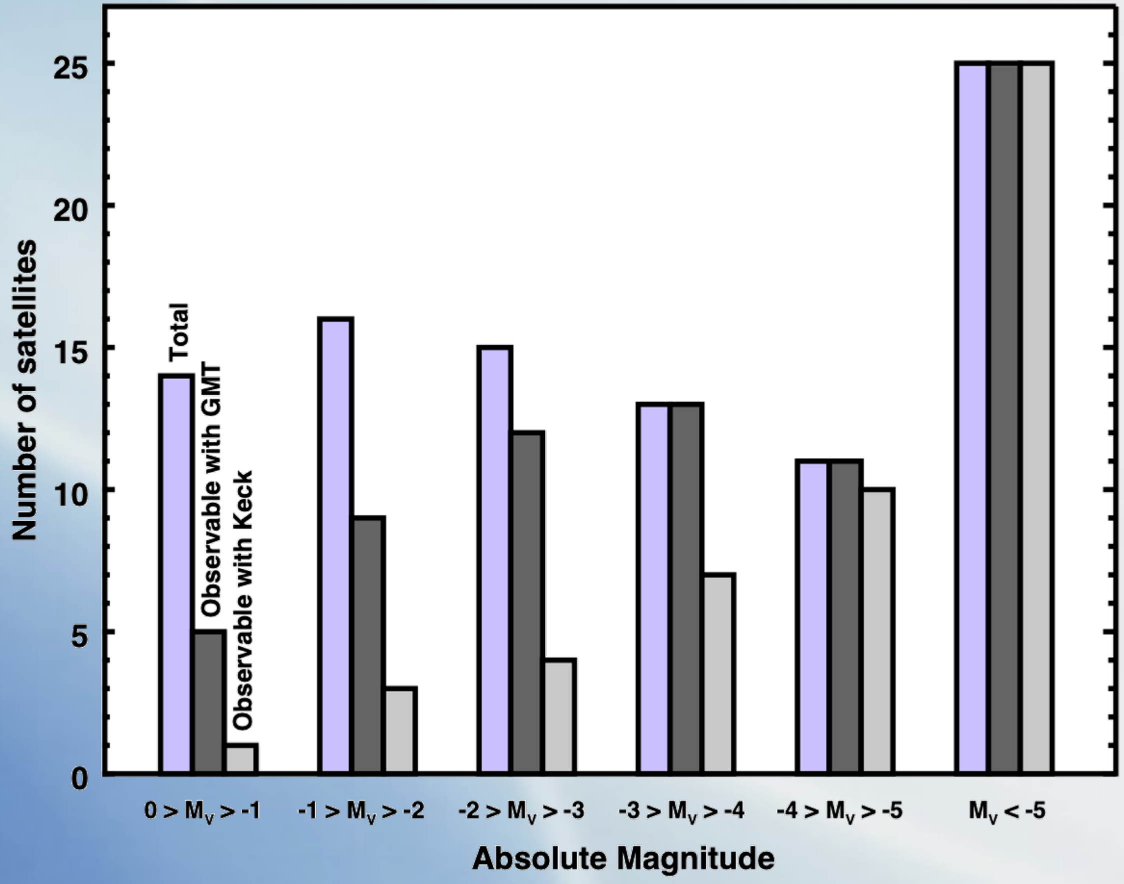
• MW satellites as of 2024

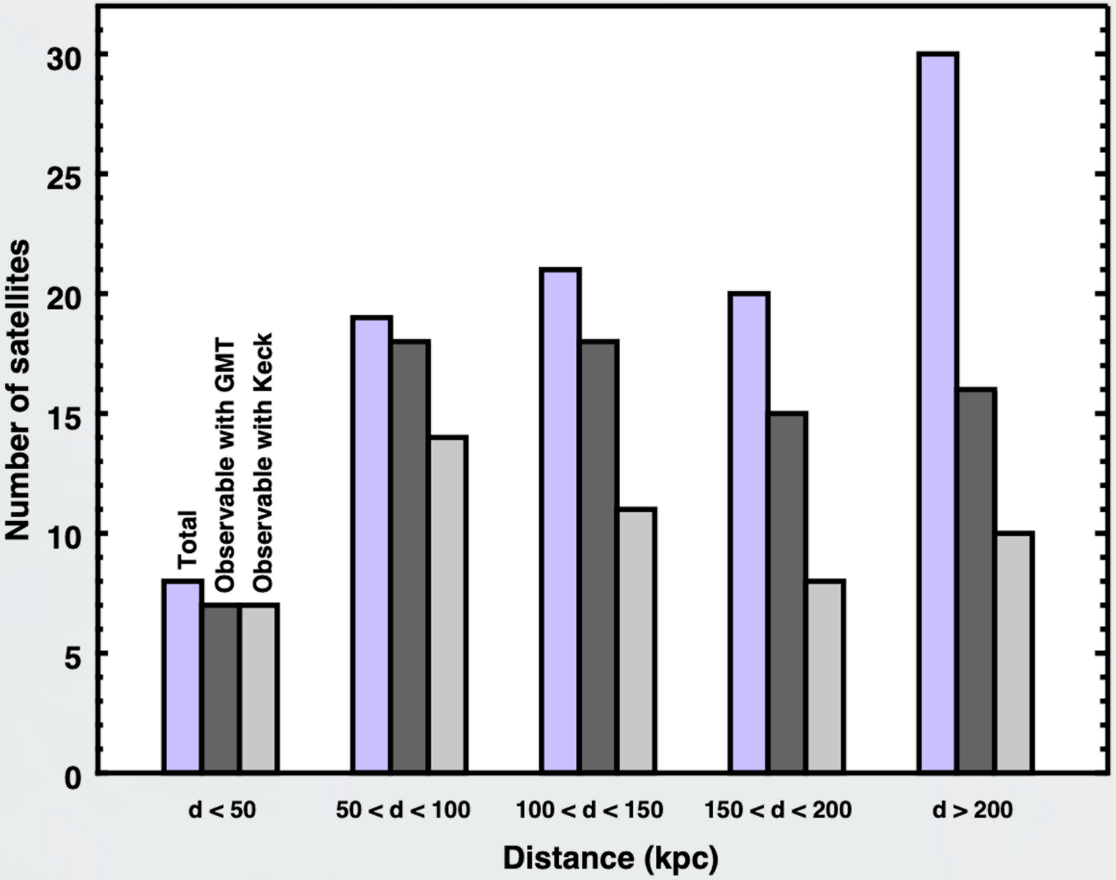


• Toy model of what LSST may find

Observability of future MW satellite discoveries

- Spectroscopy of faint/distant satellites requires ELTs





Drlica-Wagner et al. (2019)

Forecasted spectroscopic resource use

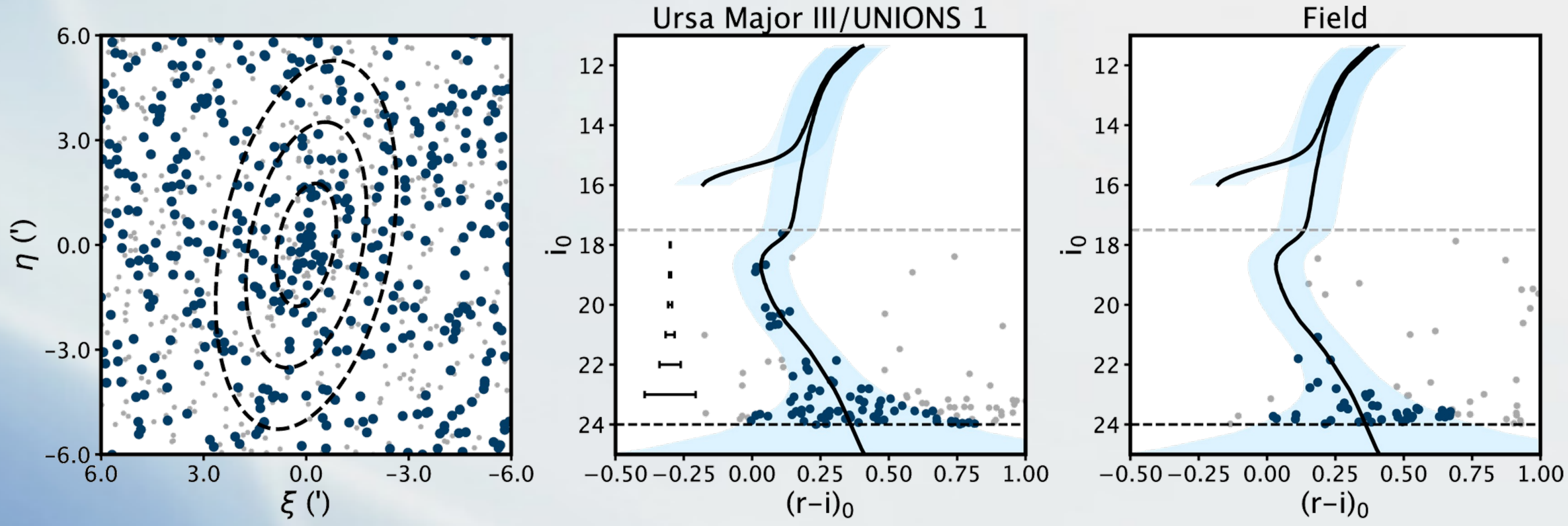
- Milky Way satellite follow-up in the Rubin era will take ~1.5 years of dedicated time on an 8m telescope

	Infrastructure	< 3m	3–5m	8m	25m
Dark Matter				**Multi-object spectroscopy: 4000 hrs** *Near-IR imaging: 300 hrs* *Single-object spectroscopy: 1200 hrs*	**Multi-object spectroscopy: 400 hrs**
Milky Way Halo Formation			Medium-band imaging: 5300 hrs	**Multi-object spectroscopy: 6700 hrs**	**Multi-object spectroscopy: 670 hrs**
Total On Sky Time			~ 1.5 years	~ 3.3 years	~ 0.3 year

Najita et al. (2016)

The low-luminosity frontier

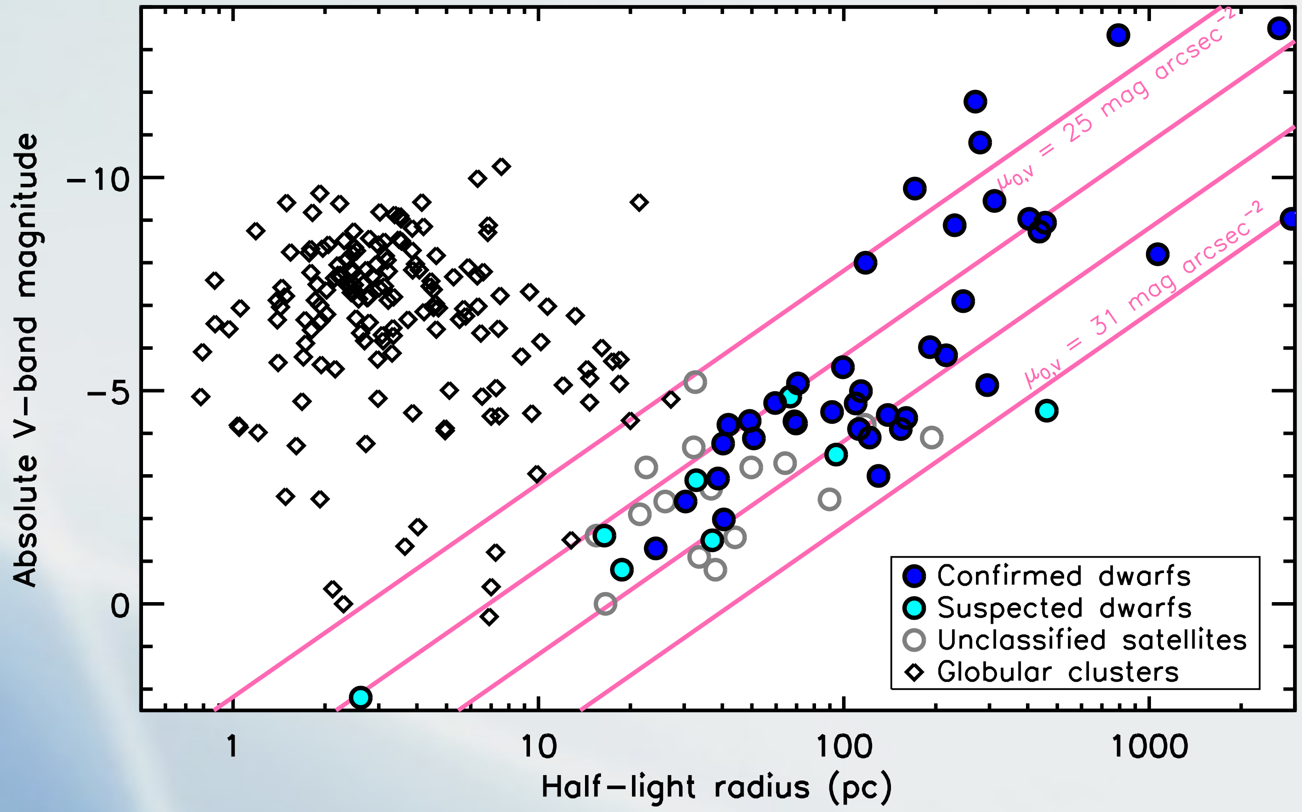
- Luminosity function may extend to L=0
  - UNIONS 1/Ursa Major III: $M_V = 2.2$ ($M_* = 16\ M_\odot$)



Smith et al. (2024)

The low-luminosity frontier

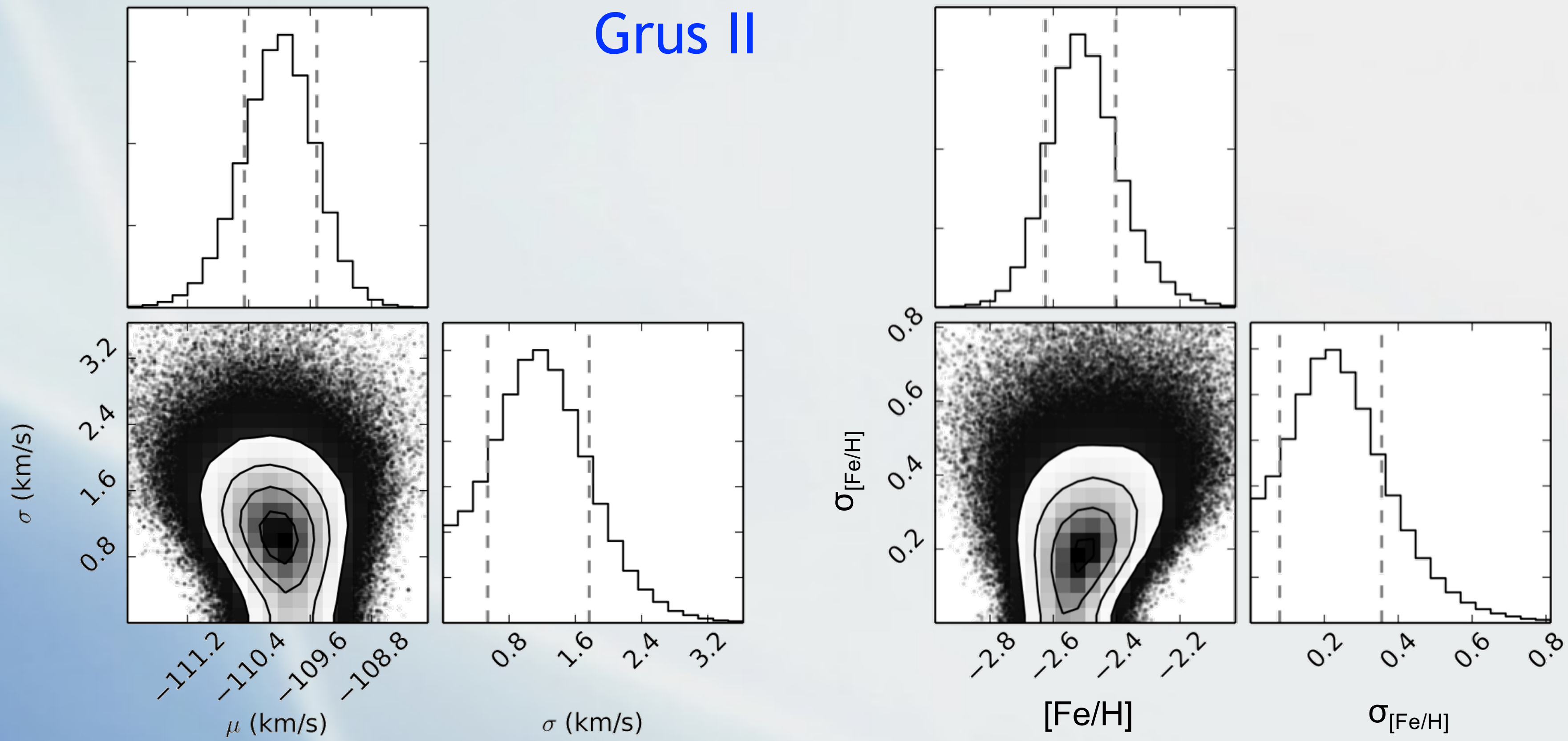
- A majority of satellites at $M_V > -3.5$ do not have firm classifications



Simon (2019, updated)

The classification challenge

- What is the nature of faint satellites with unresolved velocity and metallicity dispersions?



Simon et al. (2020)

The classification challenge

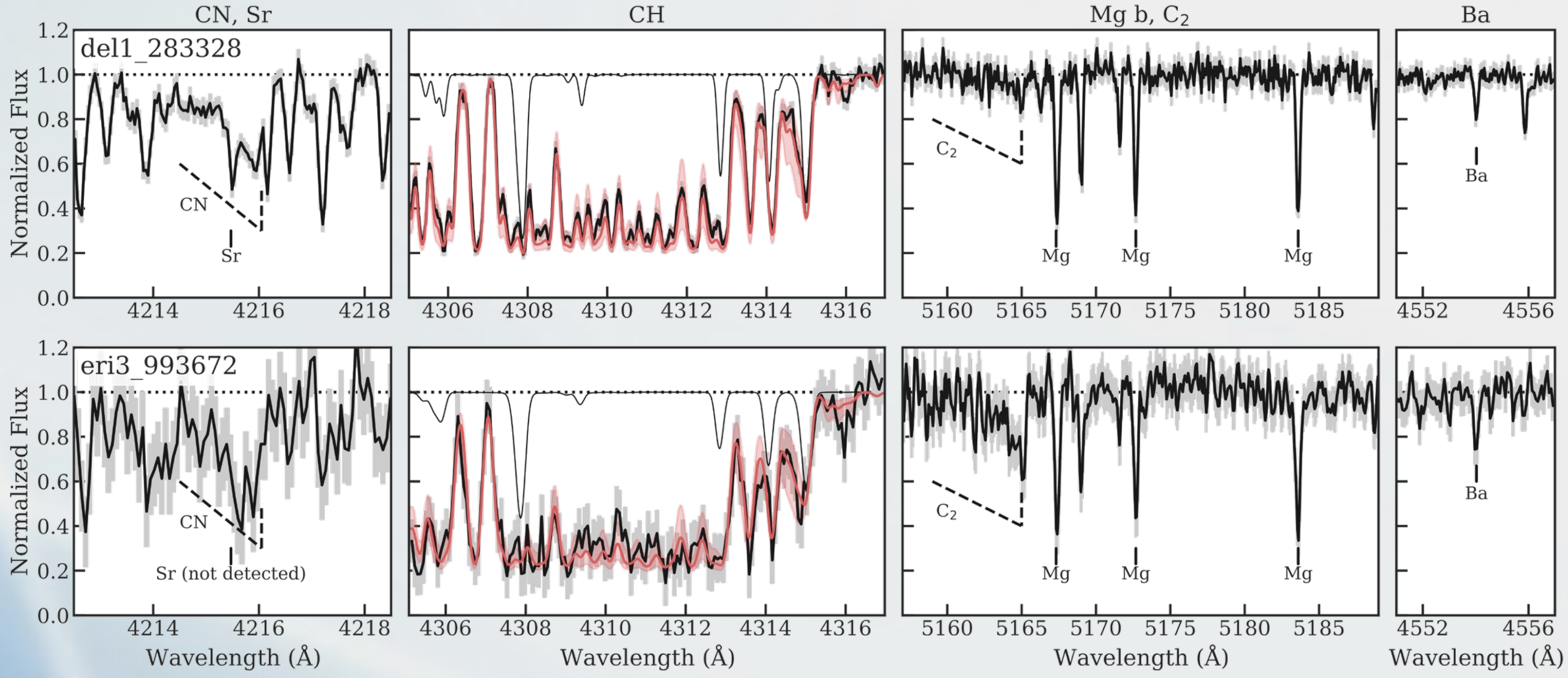
- Can other chemical information robustly distinguish dwarf galaxies from clusters?

DELVE 1:

[Fe/H] = -2.8
[C/Fe] = +1.6
[N/Fe] = +2.1
[Ba/Fe] = -1.4

Eri III:

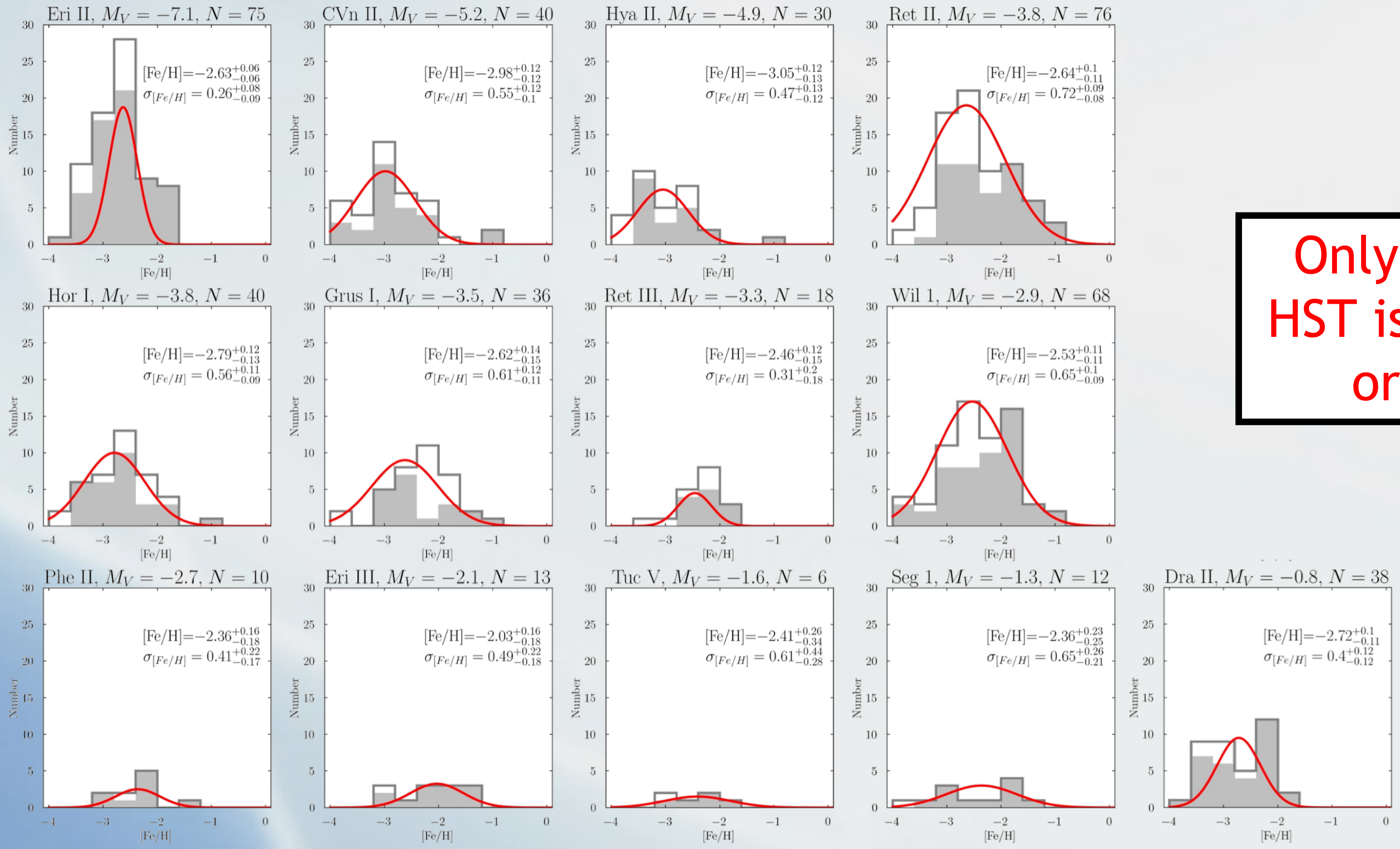
[Fe/H] = -3.1
[C/Fe] = +1.8
[N/Fe] = +2.6
[Ba/Fe] = -0.8



Simon et al. (submitted)

Non-spectroscopic classifications

- Metallicity distributions from narrow-band imaging

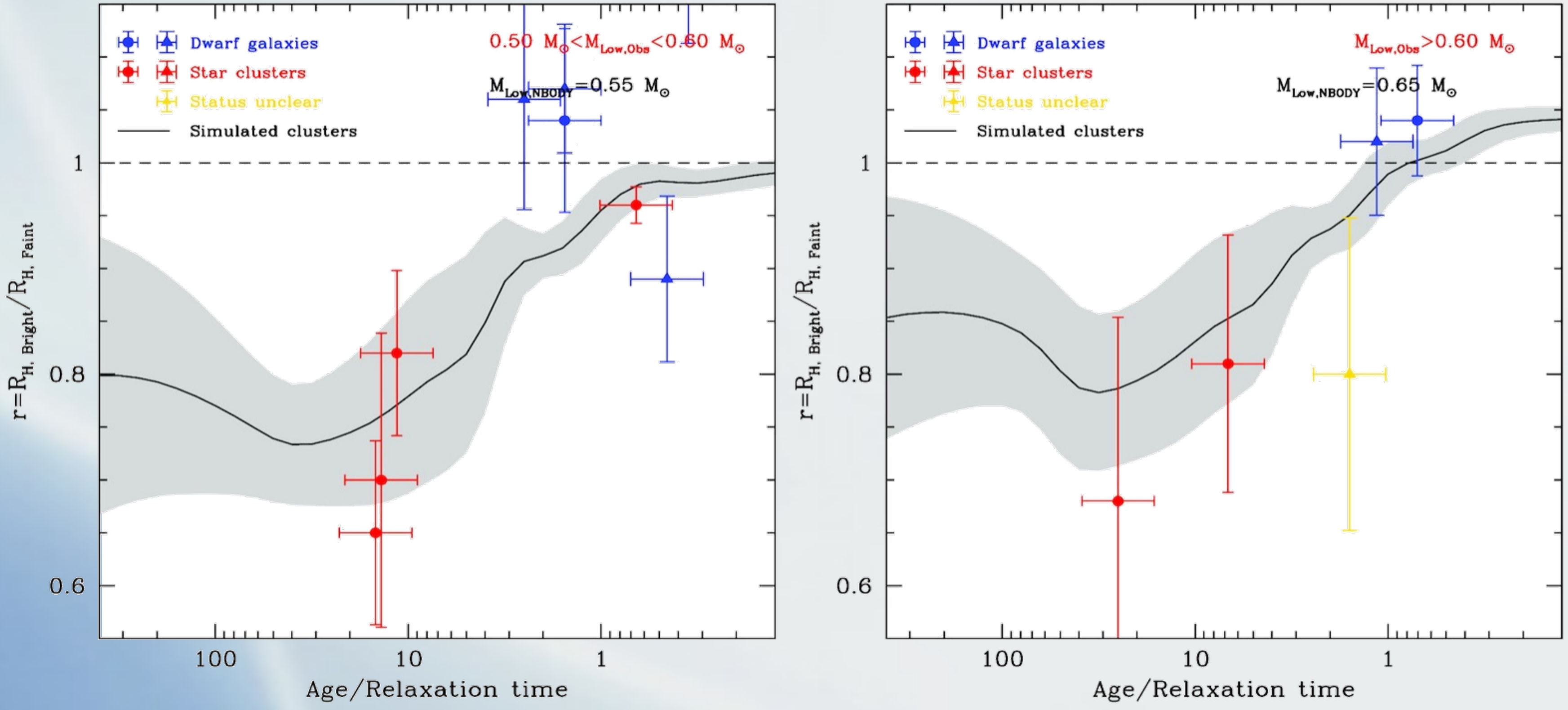


Only as long as HST is in working order . . .

Fu et al. (2023)

Non-spectroscopic classifications

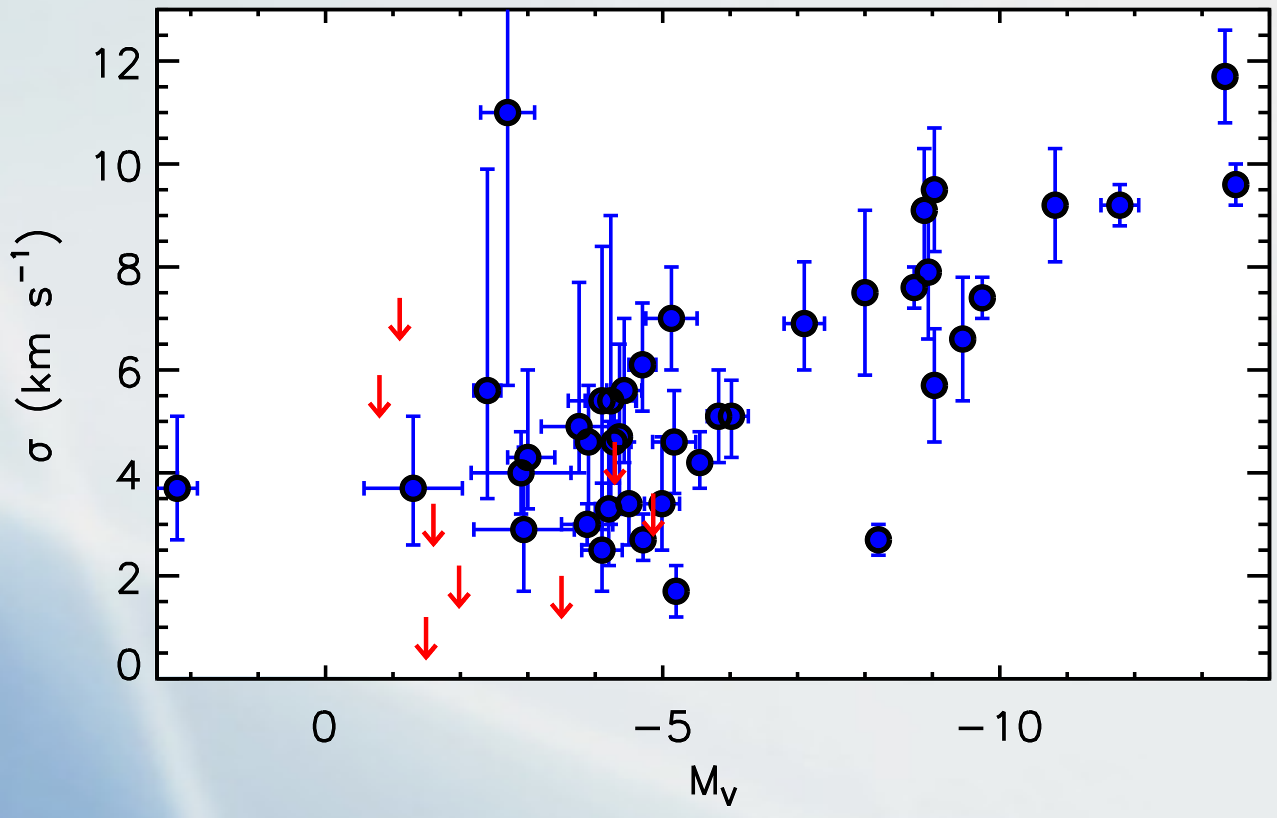
- Separating DM-dominated from DM-free systems via mass segregation



Baumgardt et al. (2022)

The low-velocity dispersion frontier

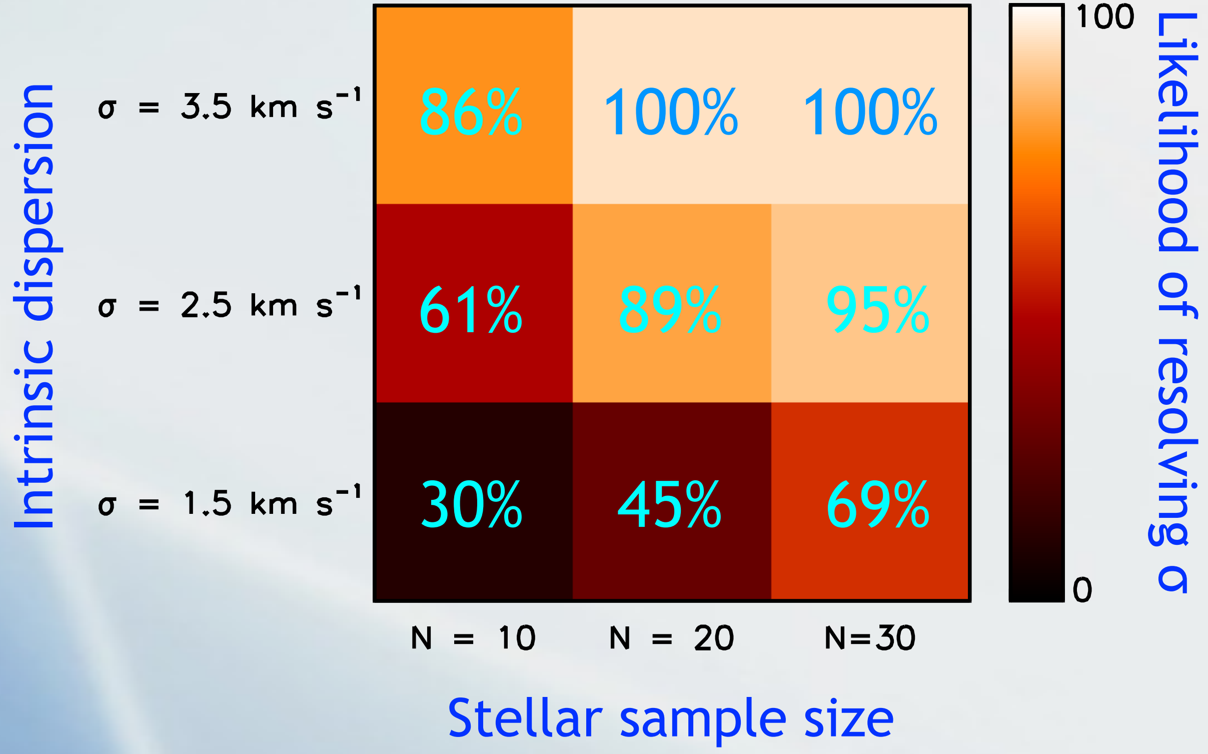
- Velocity dispersions have been resolved down to ~2 km s^{-1} (Sagittarius II, Crater II)



Simon (2019, updated)

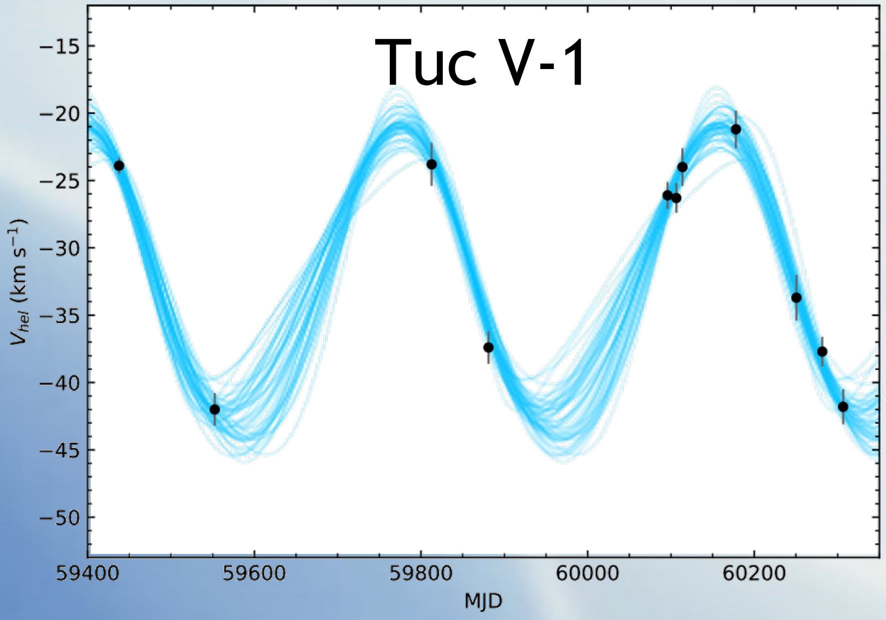
What's required to resolve cold systems?

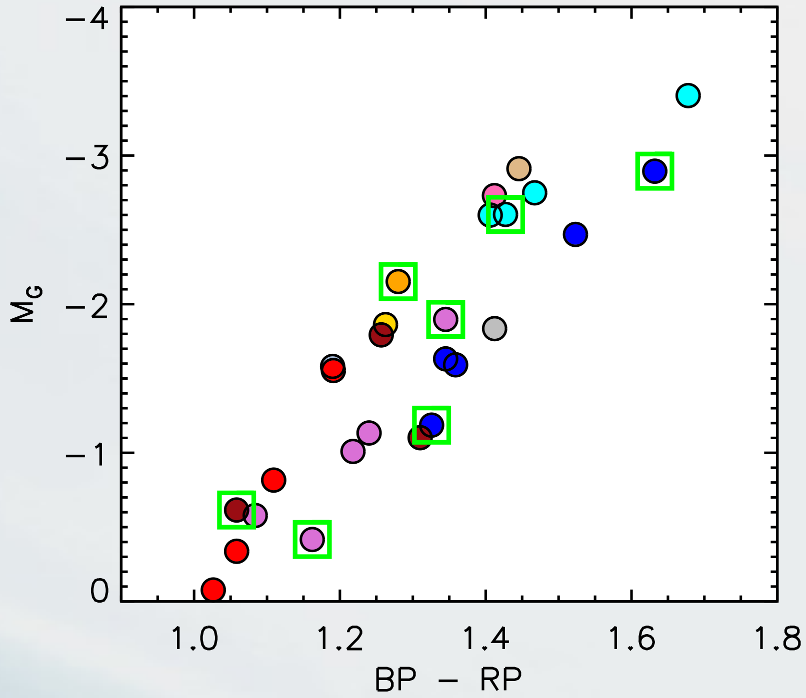
- For the faintest/coldest satellites, need >20 stars
- For systems with σ < 2 km s^{-1}, need better velocity precision



The binary frontier

- Long-term monitoring of 27 bright UFD stars
- 26% are binaries
- Implied binary fraction ~100%





Domani Sharkey

Hansen et al. (2024)

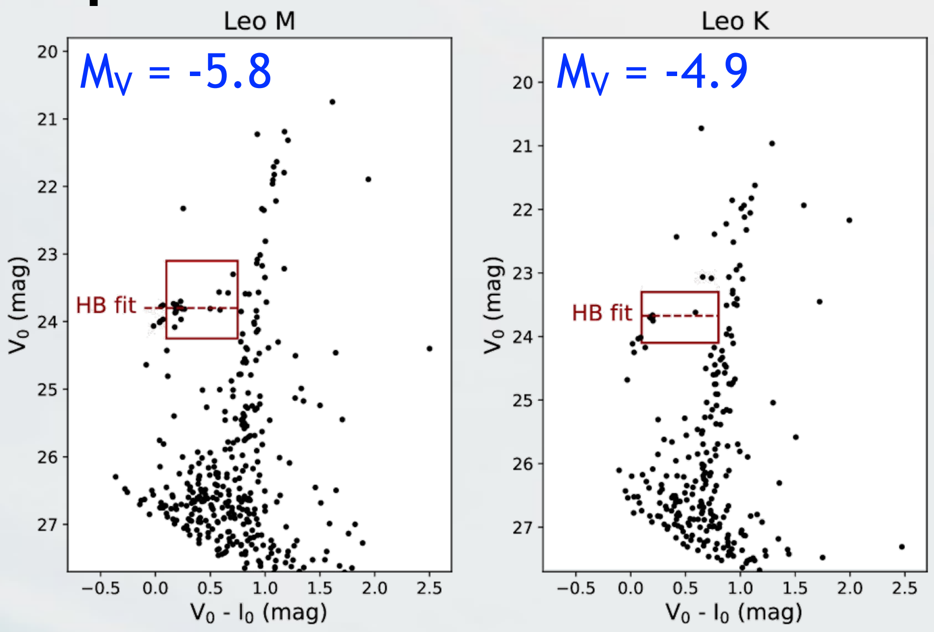
Sharkey et al. (in prep.)

The distance frontier

Coming soon

~~A long time ago~~ in a galaxy far, far away….

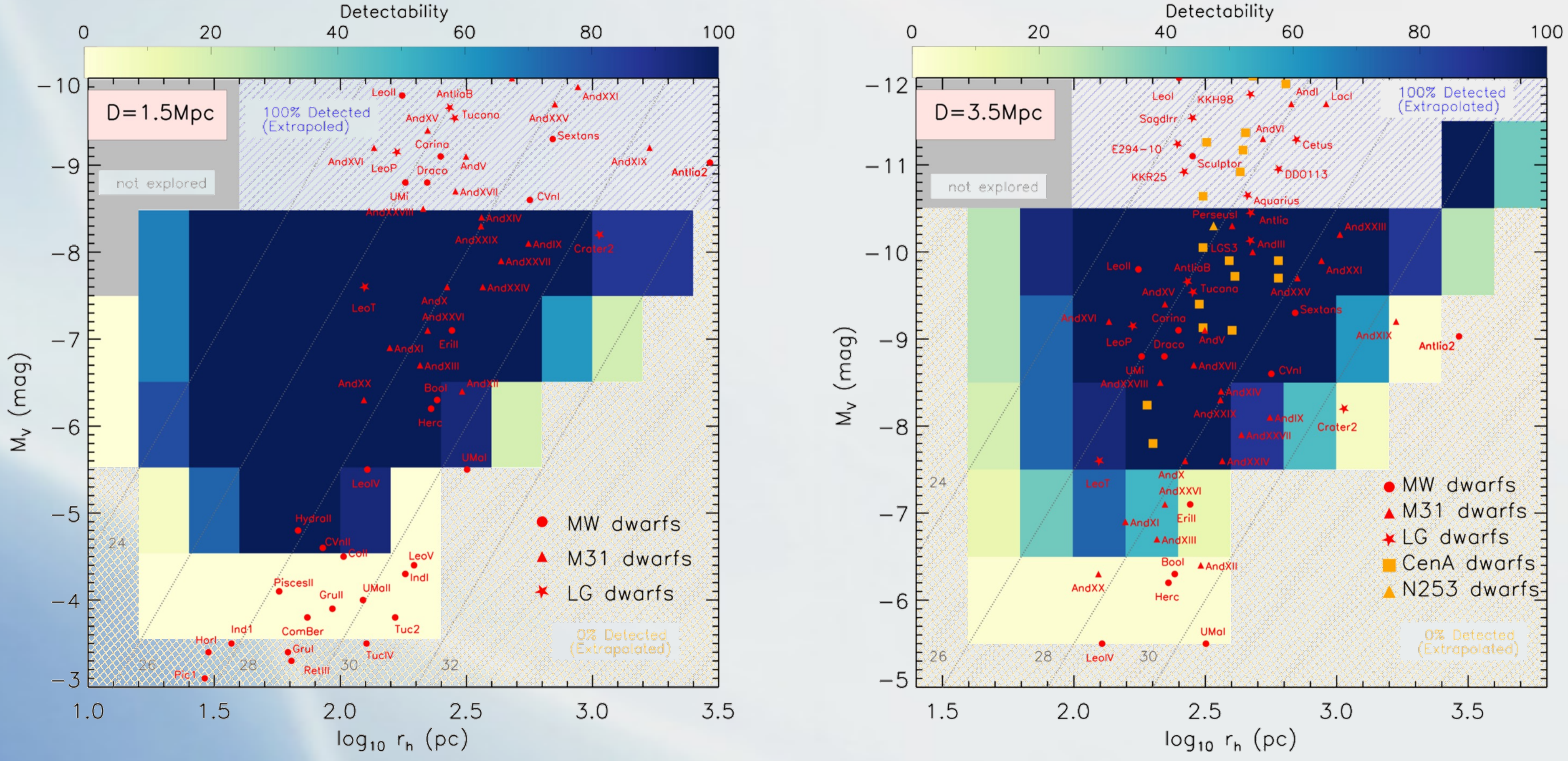
- Pre-Rubin searches for ultra-faint satellites are limited to the Local Group
  - Only a handful of objects fainter than M_V ~ -7 are known beyond the Milky Way



McQuinn et al. (2024)

The distance frontier

- Ultra-faint dwarfs will be discoverable to ~1.5 Mpc

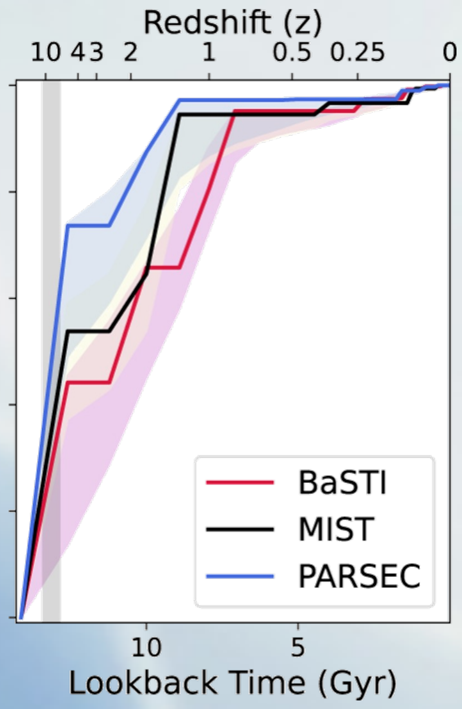


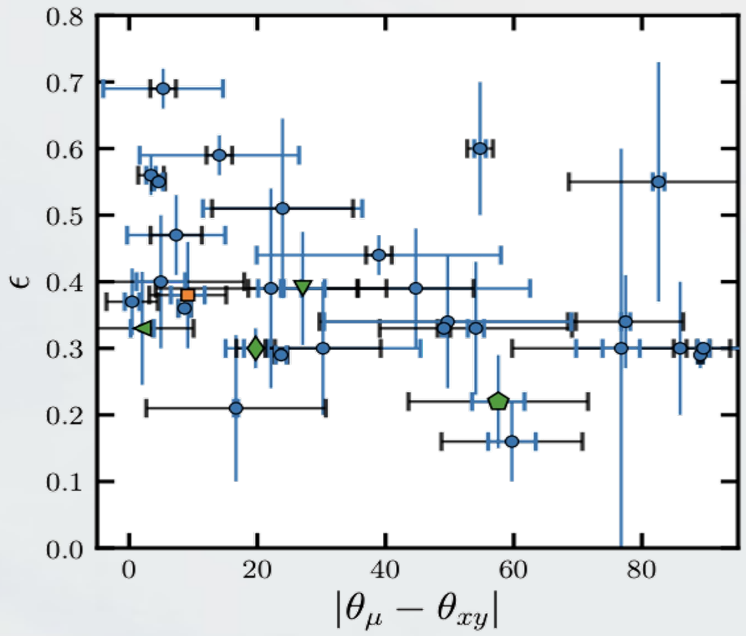
Mutlu-Pakdil et al. (2021)

The distance frontier

- What can we learn from more distant dwarfs?
  - Environmental influence on star formation
  - Tidal effects

Isolated dwarf Peg W was not quenched at reionization





Elliptical satellites are aligned with their orbital motion

McQuinn et al. (2023)

Pace et al. (2022)

Key future goals for spectroscopy

- Characterize the full Milky Way satellite population
- Understand the connection between ultra-faint dwarfs and more compact faint satellites
- Determine the behavior of the faint end of the L-[Fe/H] relation
- Investigate the properties of truly isolated ultra-faint dwarfs

Summary

- We are already struggling to get adequate spectroscopy of the faintest stellar systems
  - Follow-up of Rubin discoveries will be a challenge!
  - Need more efficient spectrographs and a lot of time

- Need to continue developing methods for classifying faint satellites

- We have a lot left to learn about the formation, evolution, and dark matter content of dwarf galaxies!