Probing Dark Matter from Intact, Disrupting and Disrupted Galaxies

Ting S. Li
University of Toronto

In Collaboration w/
W. Cerny, G. Limberg, A. Pace, S. Smith, N. Sandford,
A. Drlica-Wagner, D. Erkal, A. Ji, S. Koposov, J. Simon, N.Shipp and many more…
(S5, DES, DESI, DELVE, UNIONS Collaborations)

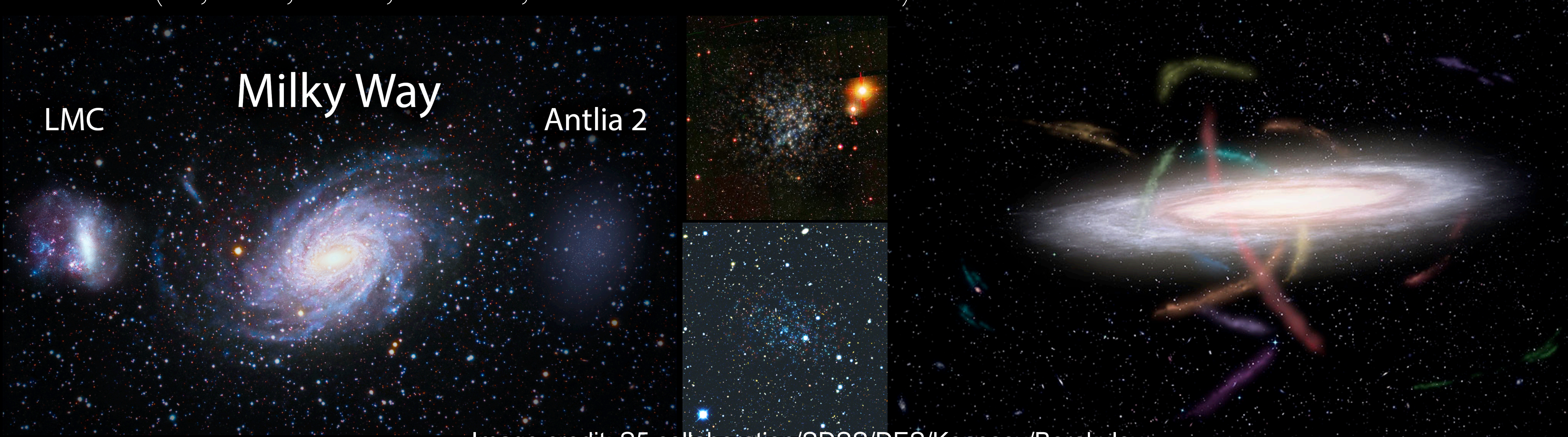

Image credit: S5 collaboration/SDSS/DES/Koposov/Berokulov

Valencia Workshop on the Small-Scale Structure of the Universe and Self-Interacting Dark Matter
Jun 16, 2025, Valencia, Spain

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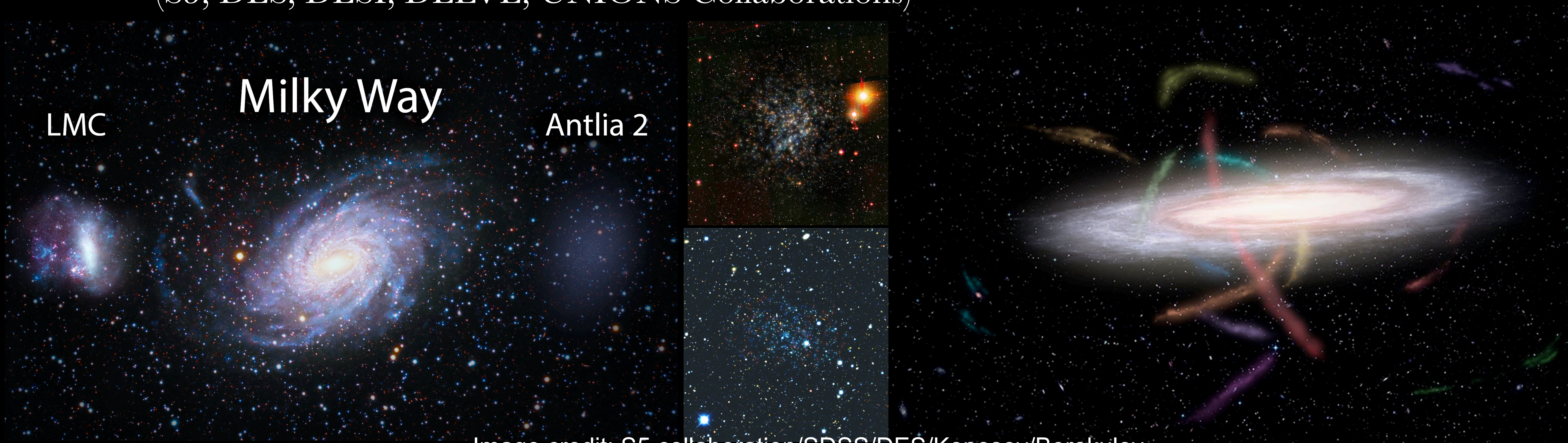

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Valencia Workshop on the Small-Scale Structure of the Universe and Self-Interacting Dark Matter

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Outline

Recent observational results in the Milky Way

- Intact(?) Ultra Faint Dwarf Galaxies (UFDs)
- Intact(?) Ultra Faint Compact Systems (UFCSs)
- Disrupting Dwarf Galaxies — Ultra Diffuse Galaxies (UDGs)?
- Disrupted Dwarf Galaxies — Stellar Streams

Goal: Can we learn anything about dark matter from these observations?

Take away Messages

Our findings

- We find a (tentative) cuspy density profile in the UFDs
- We believe a significant amount of these UFCSs are galaxies.
- We identify tidal tails around some galaxies and measure their kinematics
- We notice a mismatch between observations and simulations in the orbits of the disrupted dwarf galaxies / stellar streams.

Goal: Can we learn anything about dark matter from these observations?

Take away Messages

My wishlist / assignments for you:

- Can we compute the SIDM cross section at UFD scale using stellar kinematics?
- If compact satellites are indeed from SIDM core collapse, what is the expected velocity dispersions and mass to light ratio within half-light radius?
- Can we have tailored simulations for the disrupting dwarfs to probe cusp vs core?
- Is there an over-disruption in the galaxy simulations? Artificial disruption? galaxy too puffy from stellar feedbacks? or SIDM?

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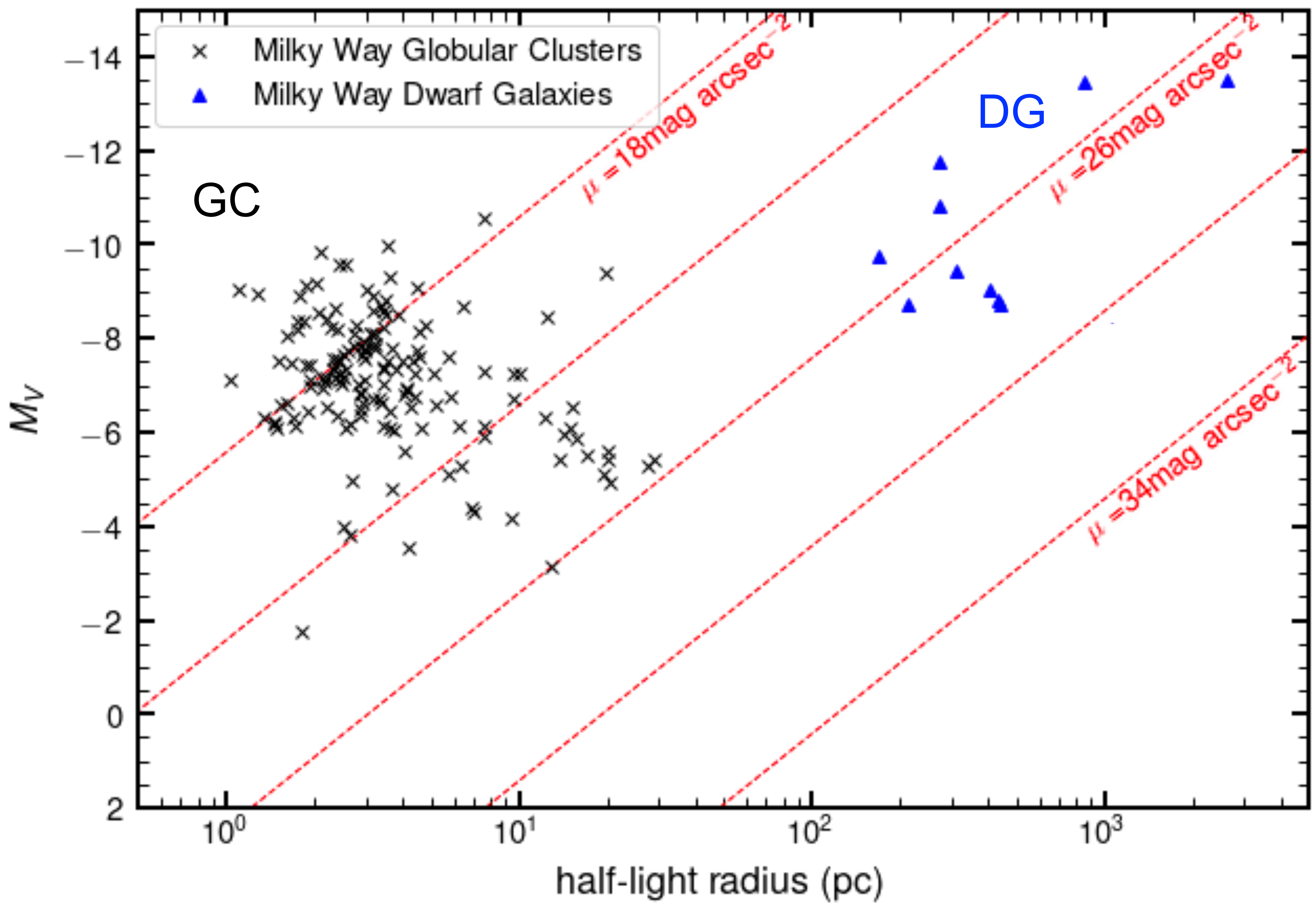
Luminosity vs Size for Galactic Dwarf Galaxies pre-SDSS

GC: Globular Cluster
DG: Dwarf Galaxy



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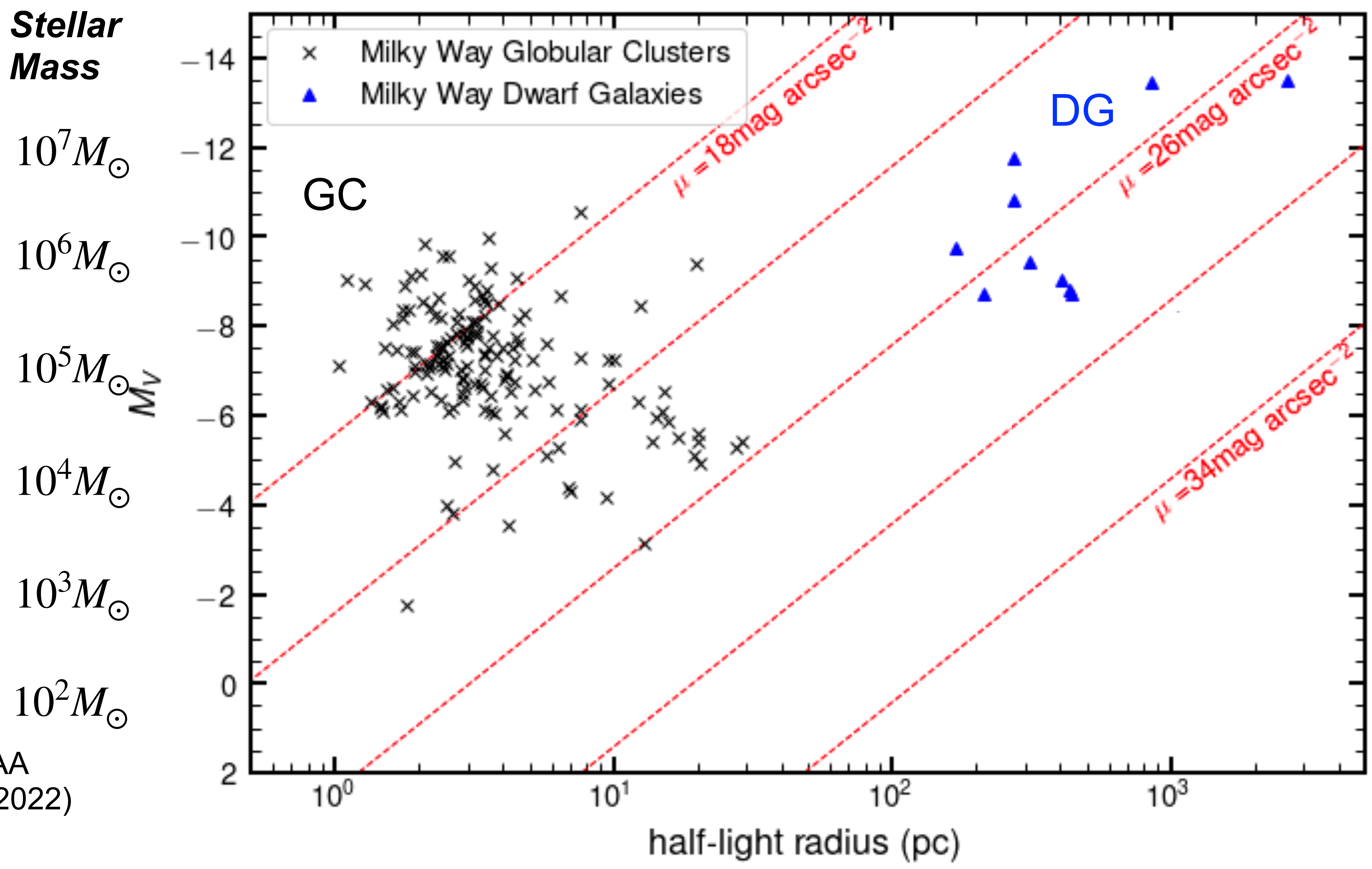

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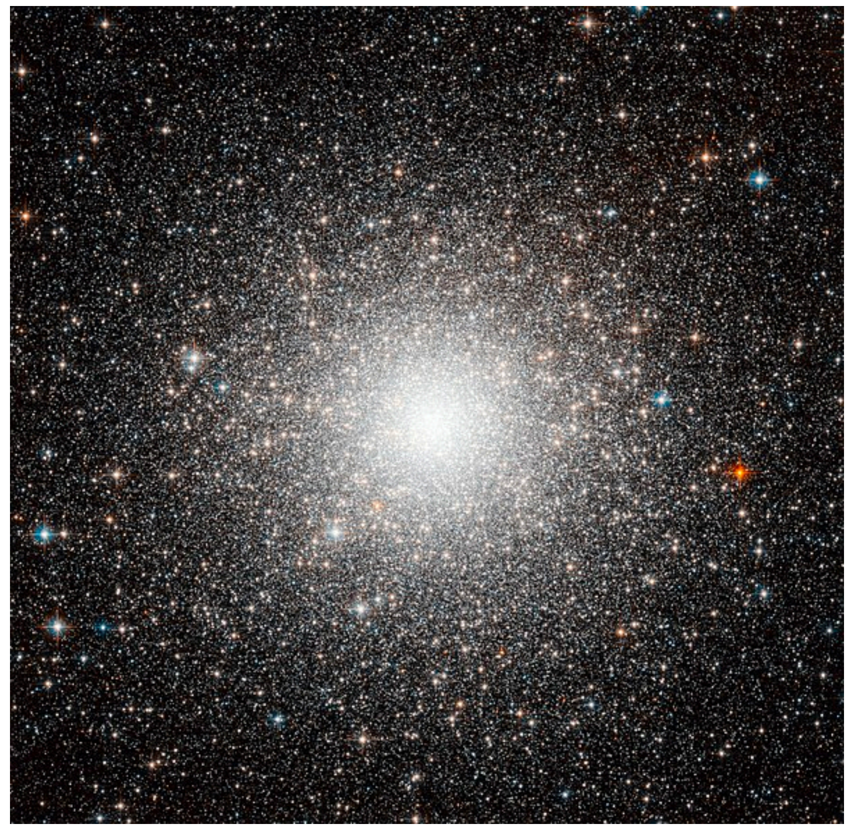
Luminosity vs Size for Galactic Dwarf Galaxies pre-2000



Stellar Mass

$10^7 M_\odot$

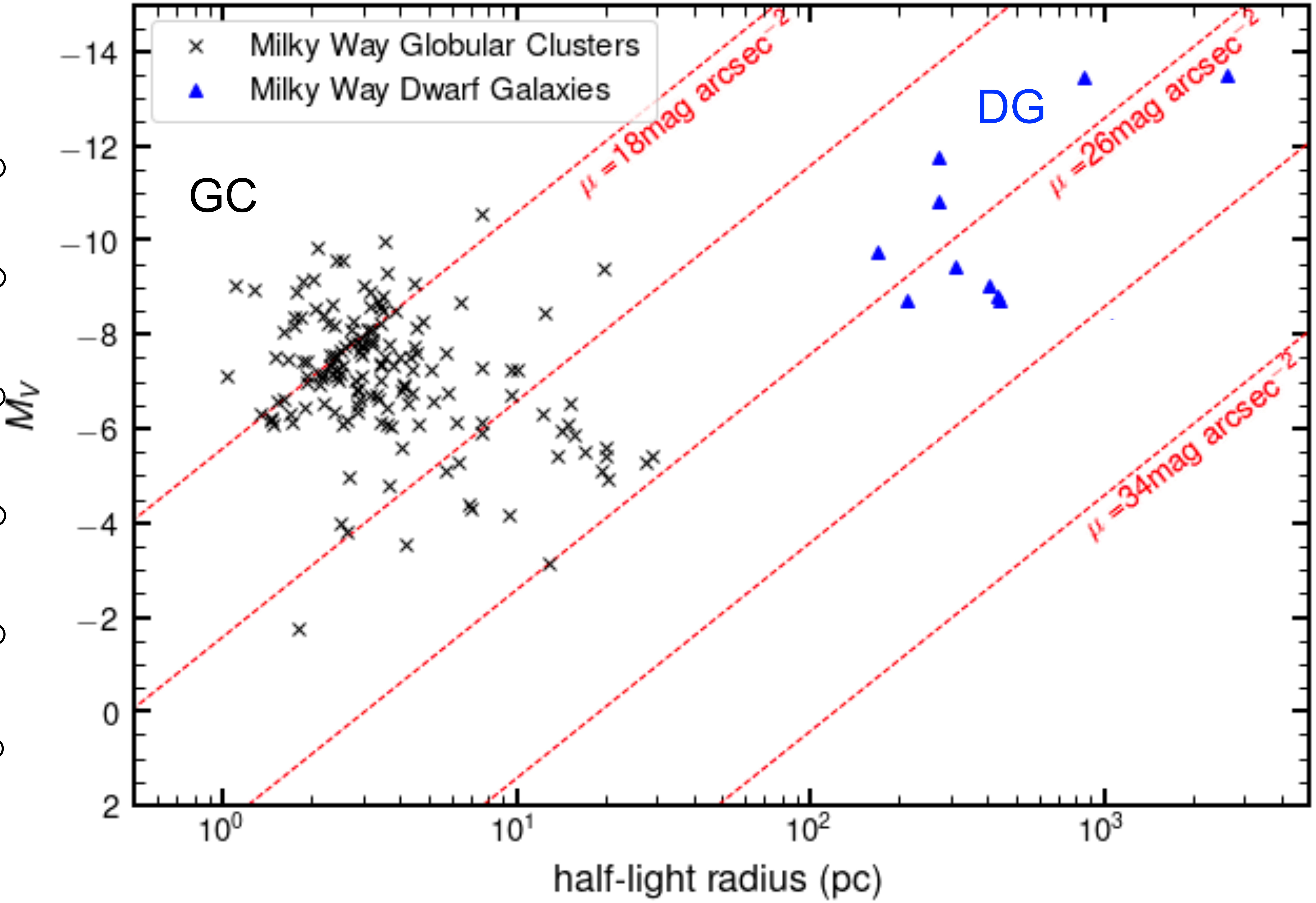
$10^6 M_\odot$

$10^5 M_\odot$

$10^4 M_\odot$

$10^3 M_\odot$

$10^2 M_\odot$



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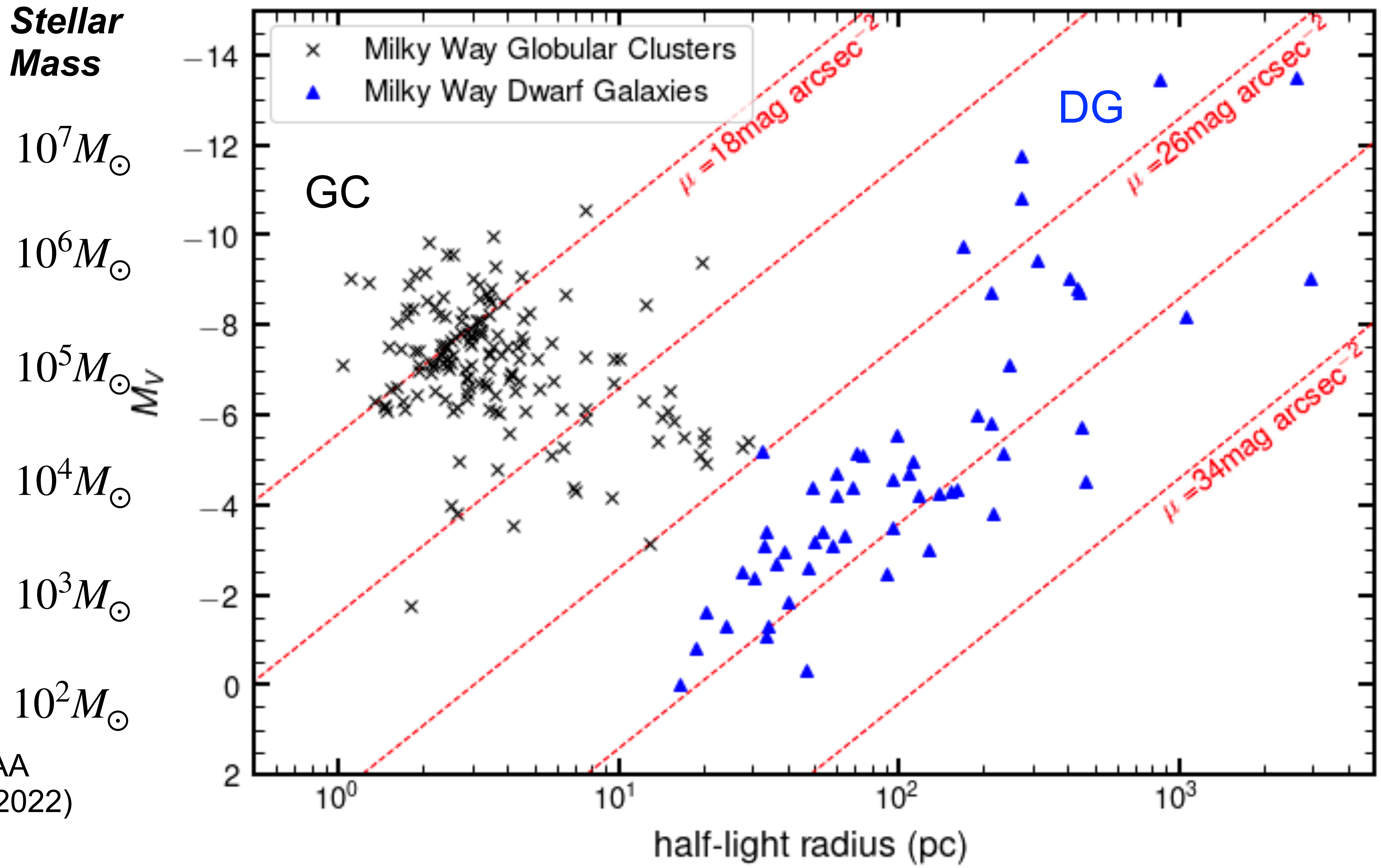

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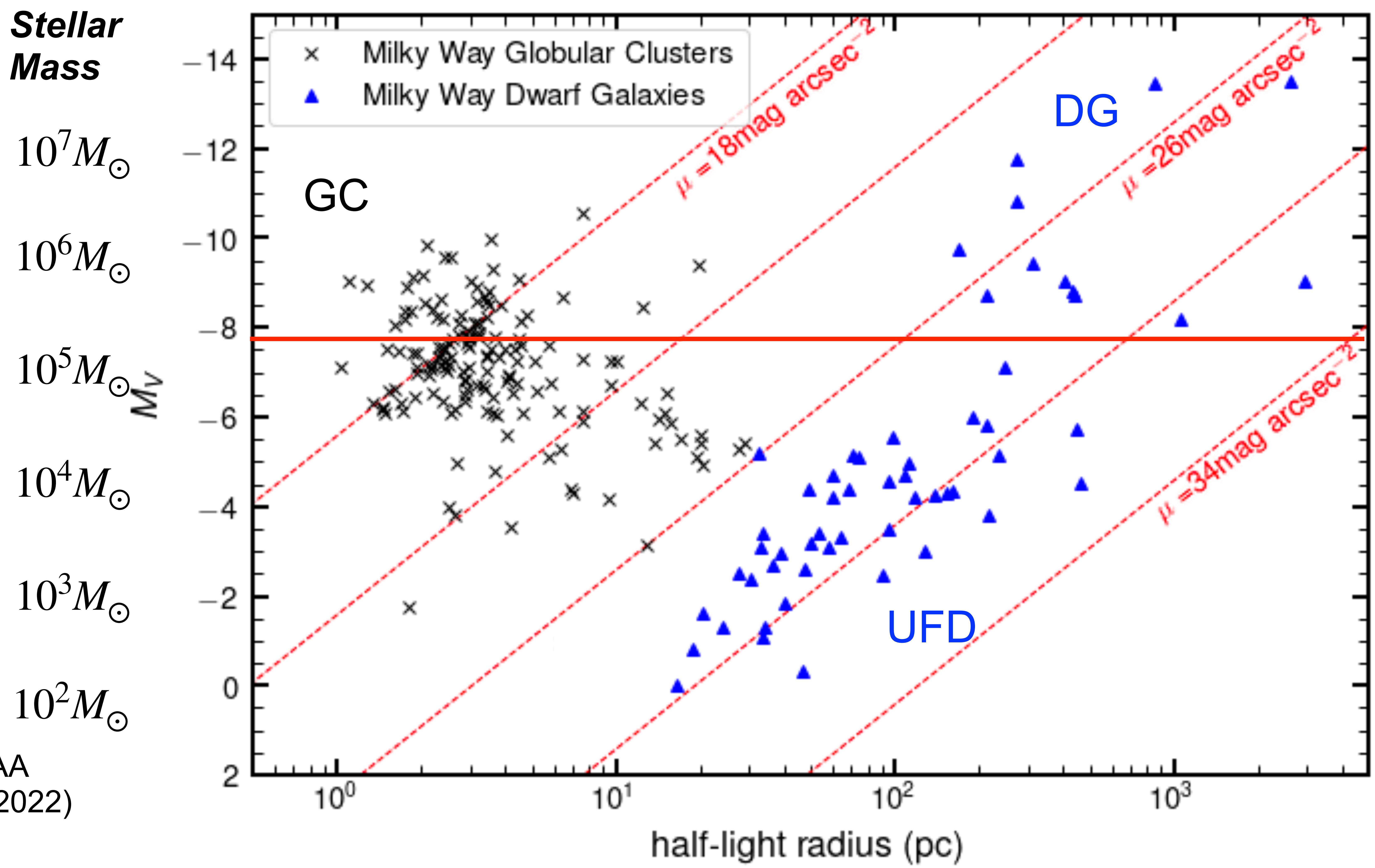

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Milky Way Satellite Galaxies and Cusp/Core

Dwarf Irregular Galaxies

Classical Dwarf Spheroidal Galaxies

Ultra-Faint Dwarf (UFD) Galaxies

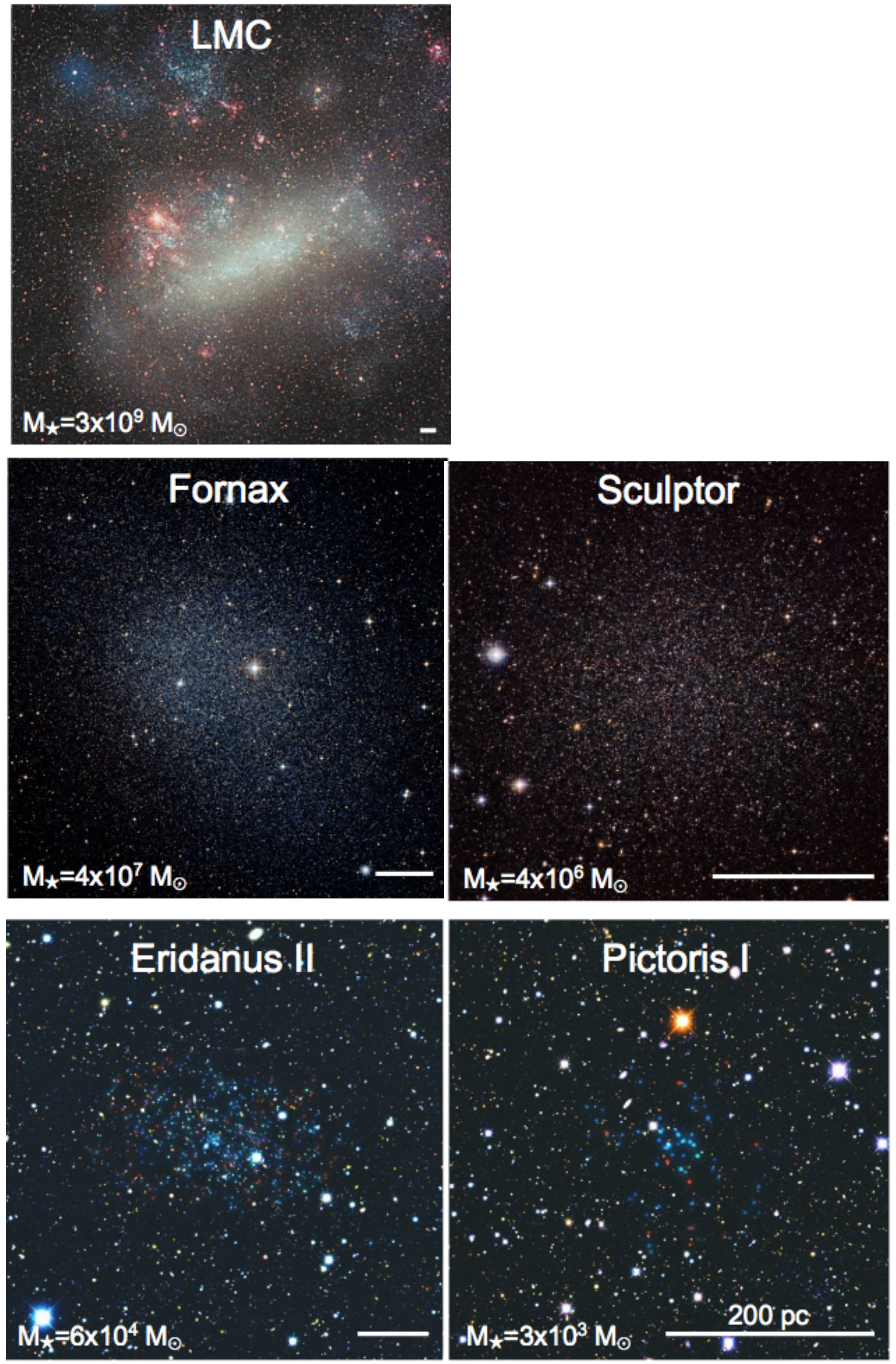

Image credits: Eckhard Slawik (LMC); ESO/Digitized Sky Survey 2 (Fornax);ESO (Sculptor); Vasily Belokurov and Sergey Koposov (Eridanus II, Pictoris I).

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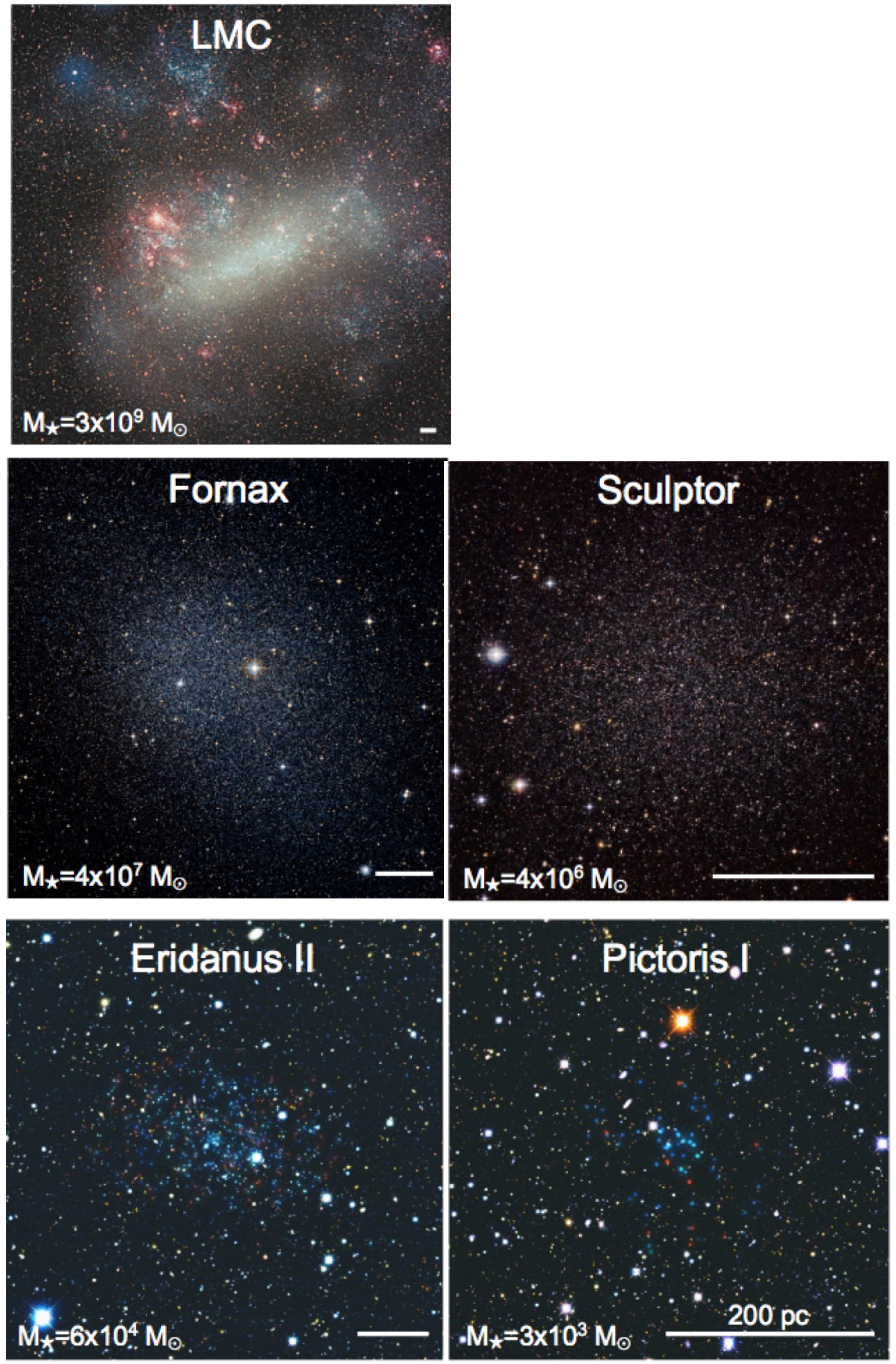

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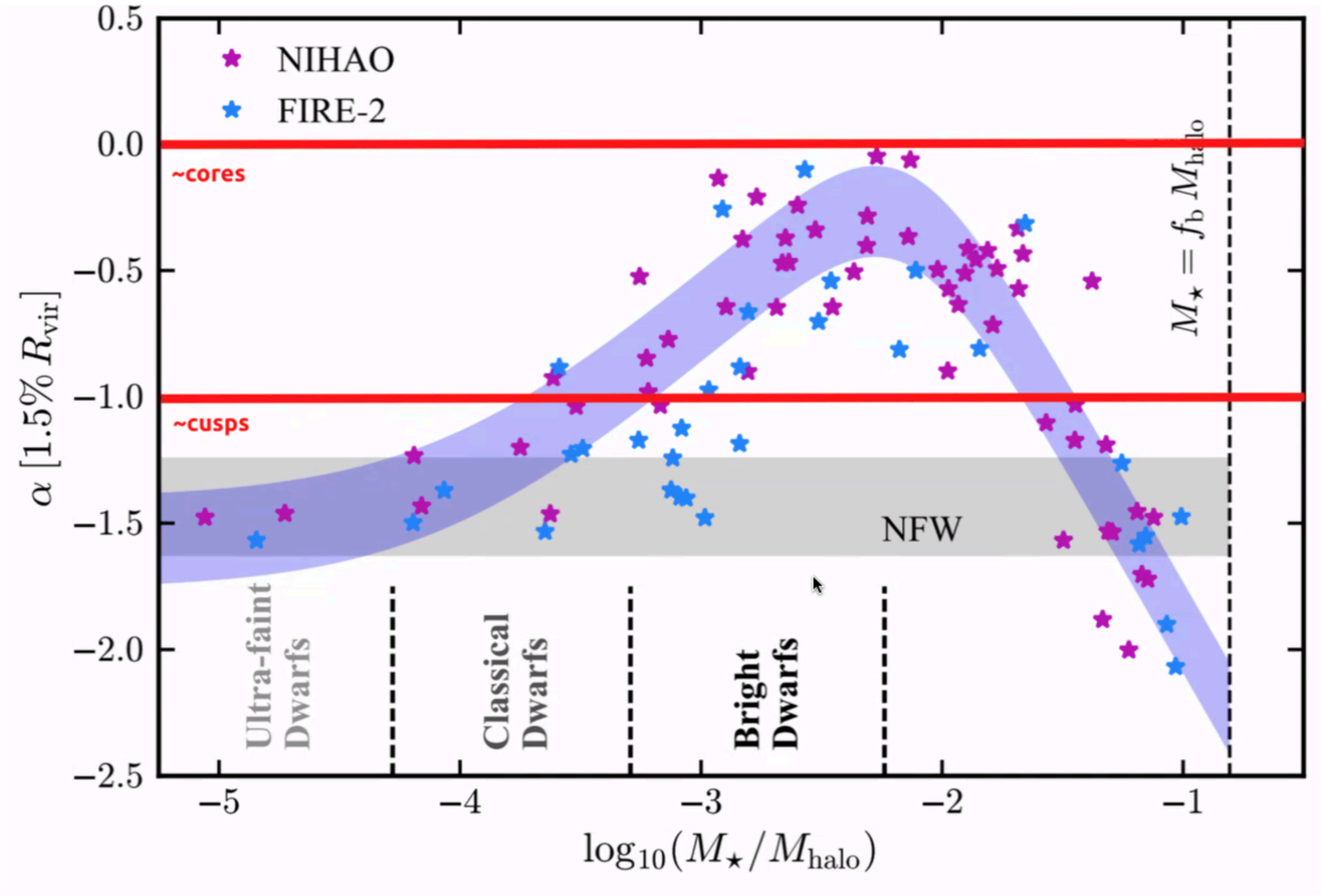
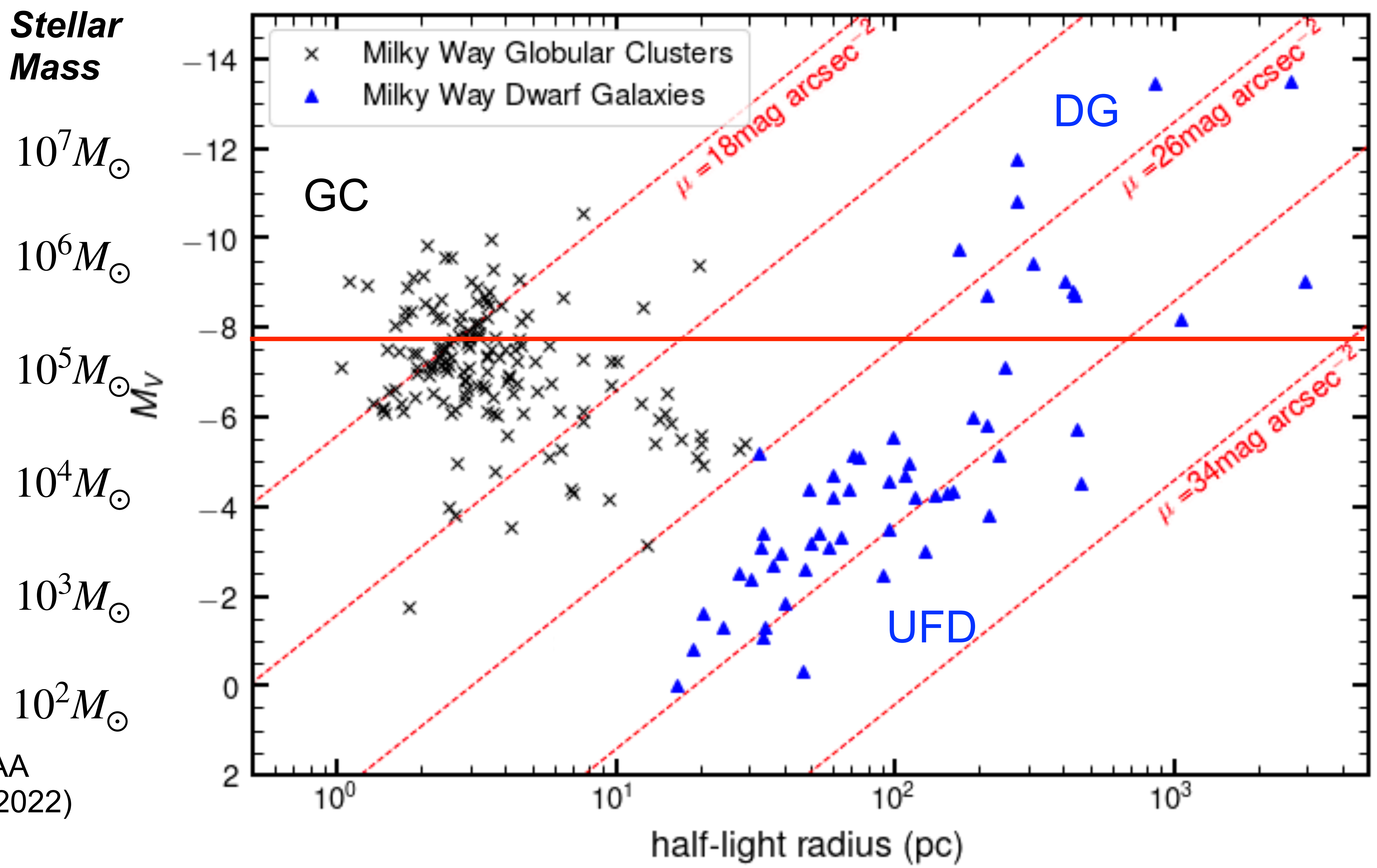


Bullock & Boylan-Kolchin (2017)

$M_{halo} \sim 10^9$ M_{sun}

Luminosity vs Size for Galactic Dwarf Galaxies post-2000



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Bootes I: One of the Brightest UFDs

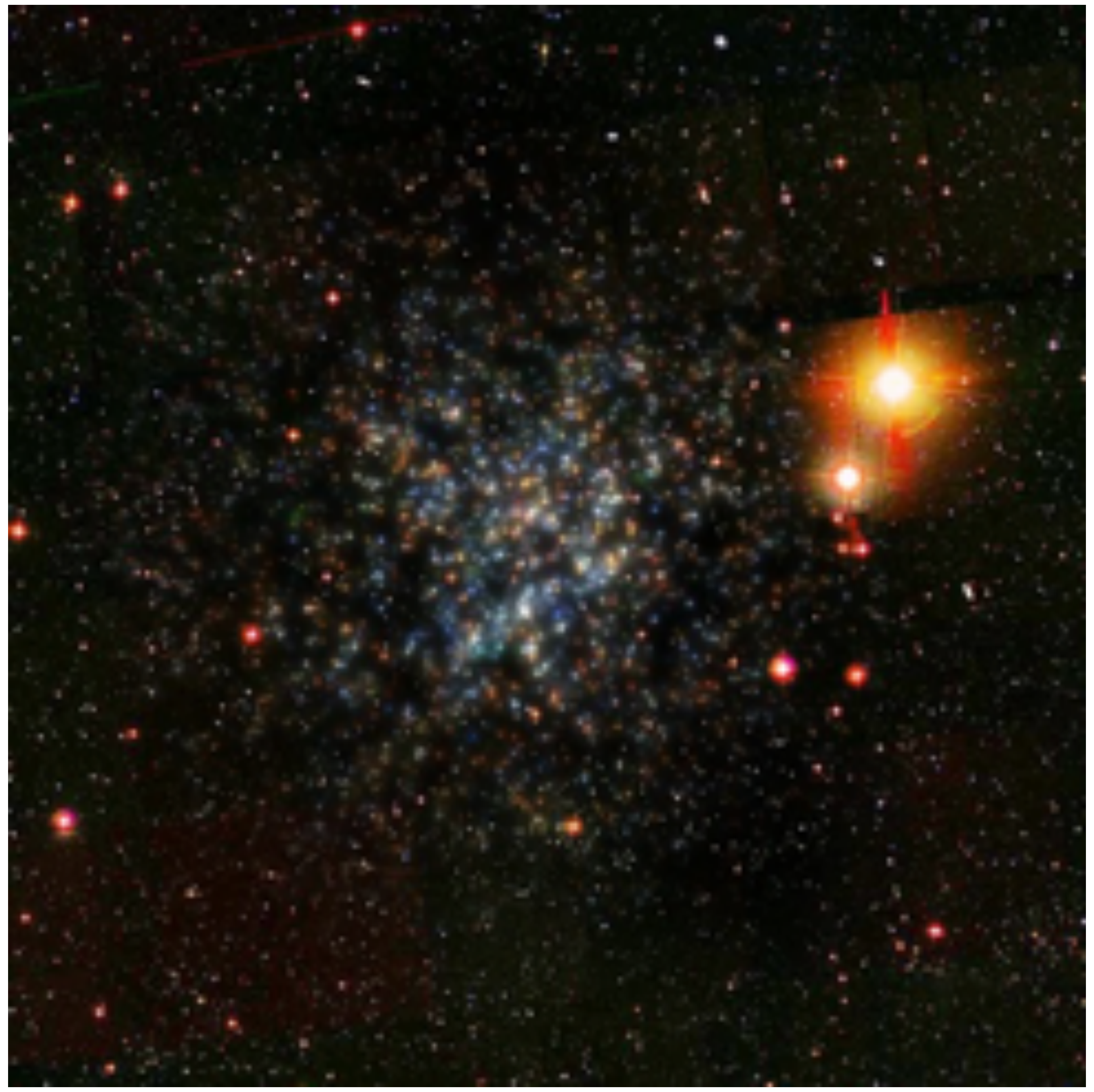
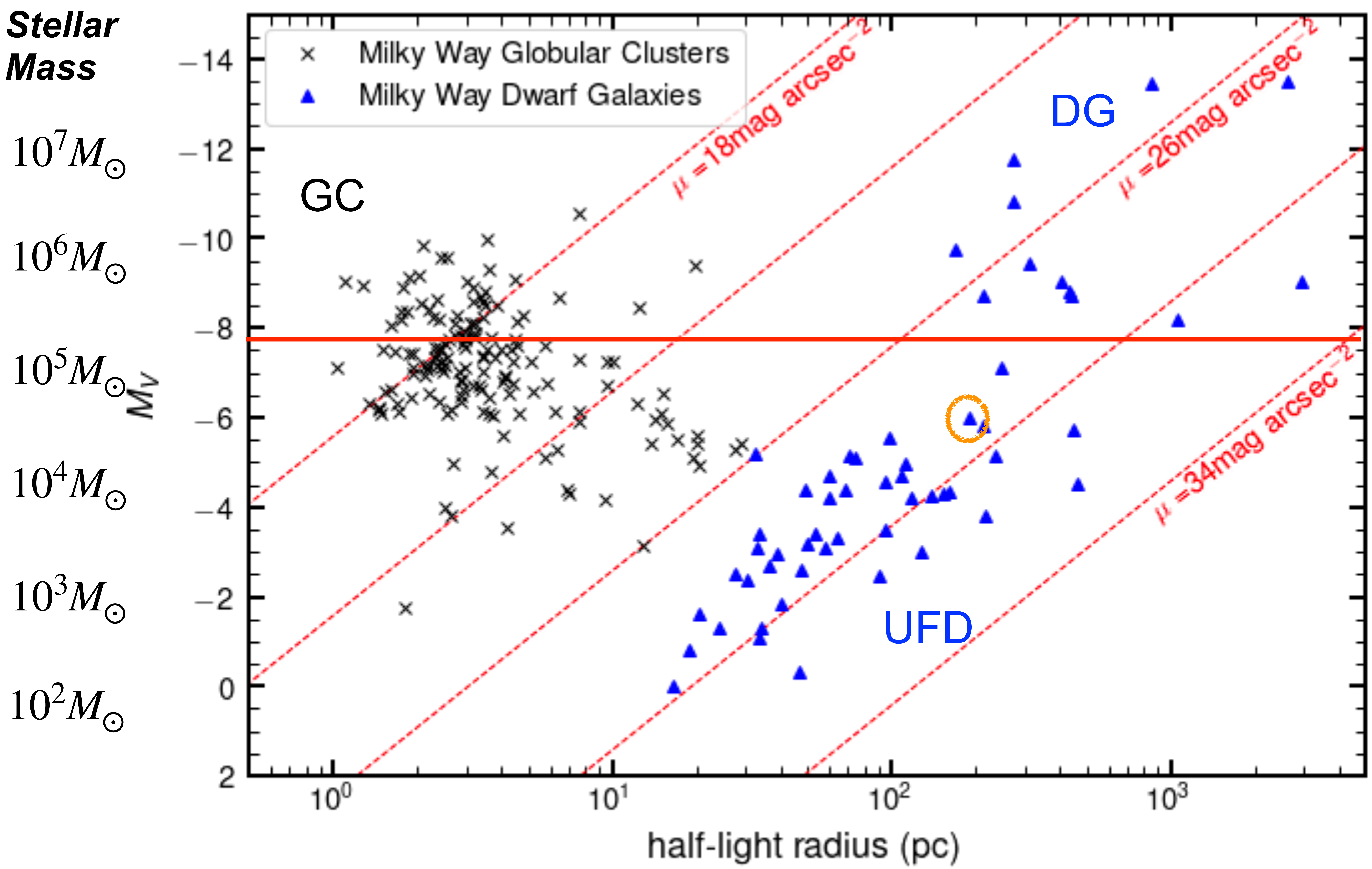
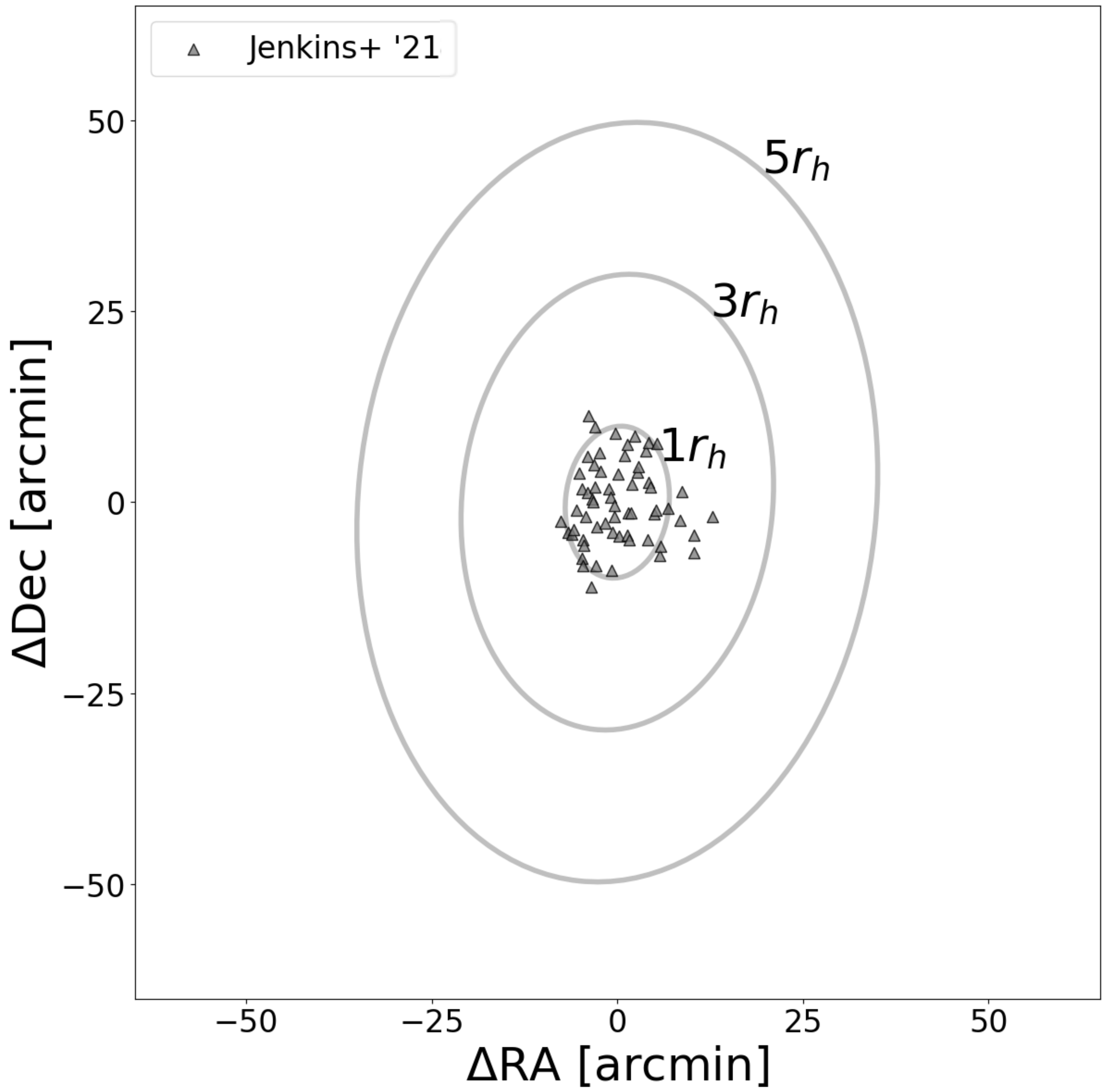
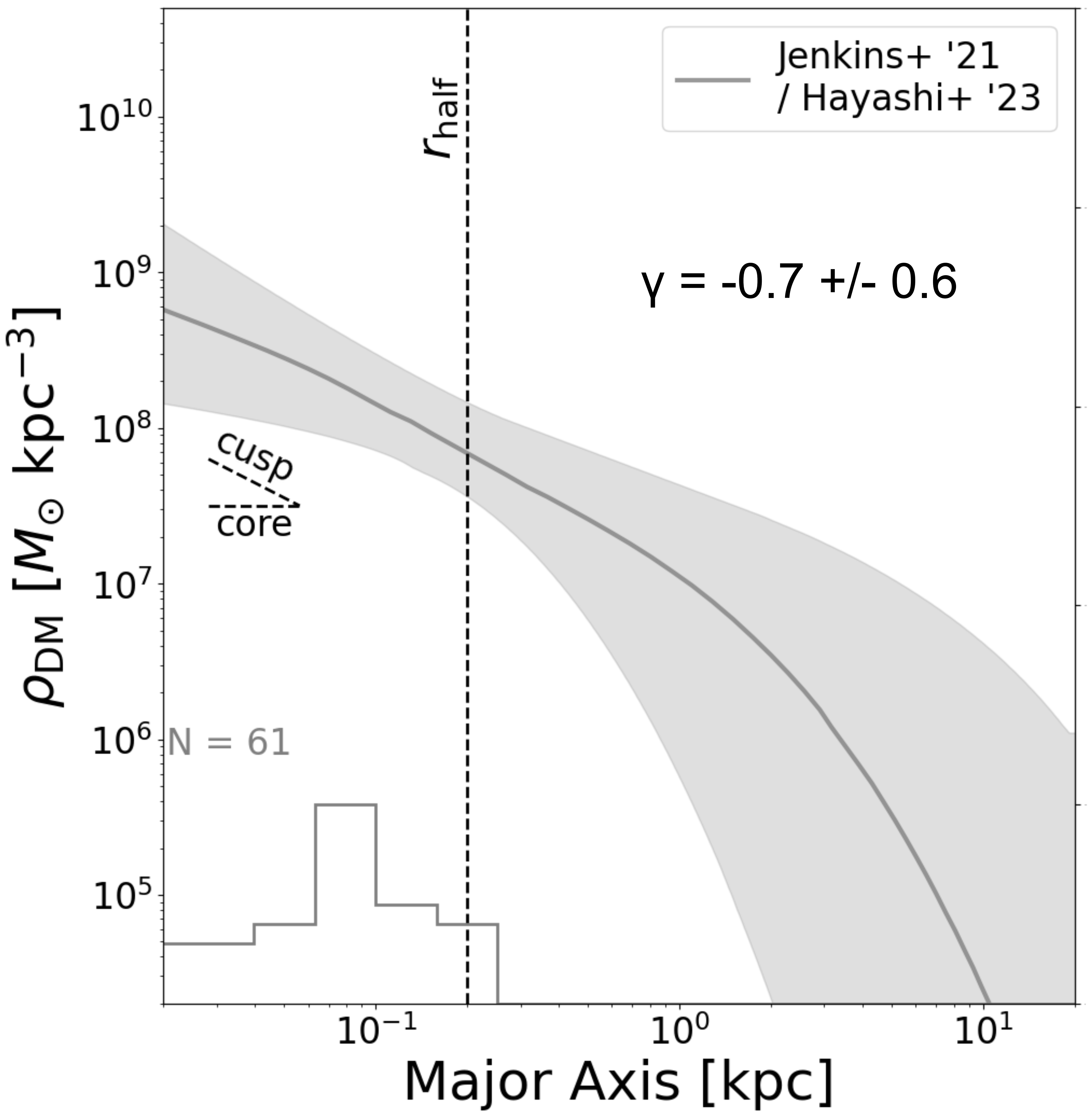


Image Credit: SDSS



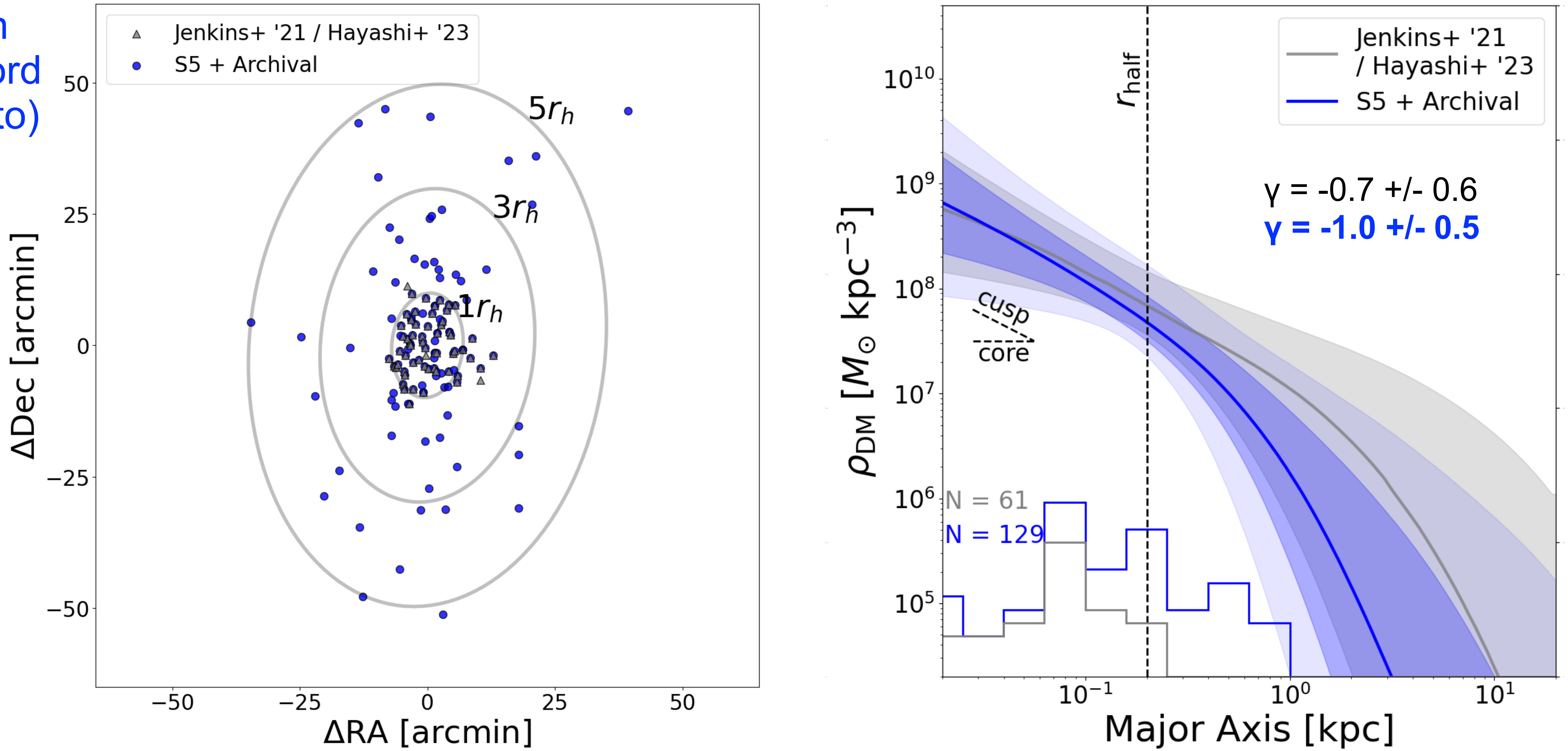
Boötes I: Dark Matter Density Profile





Boötes I: A Cuspy Density Profile? w/ ~15 year archival data + S5 (binary removal)

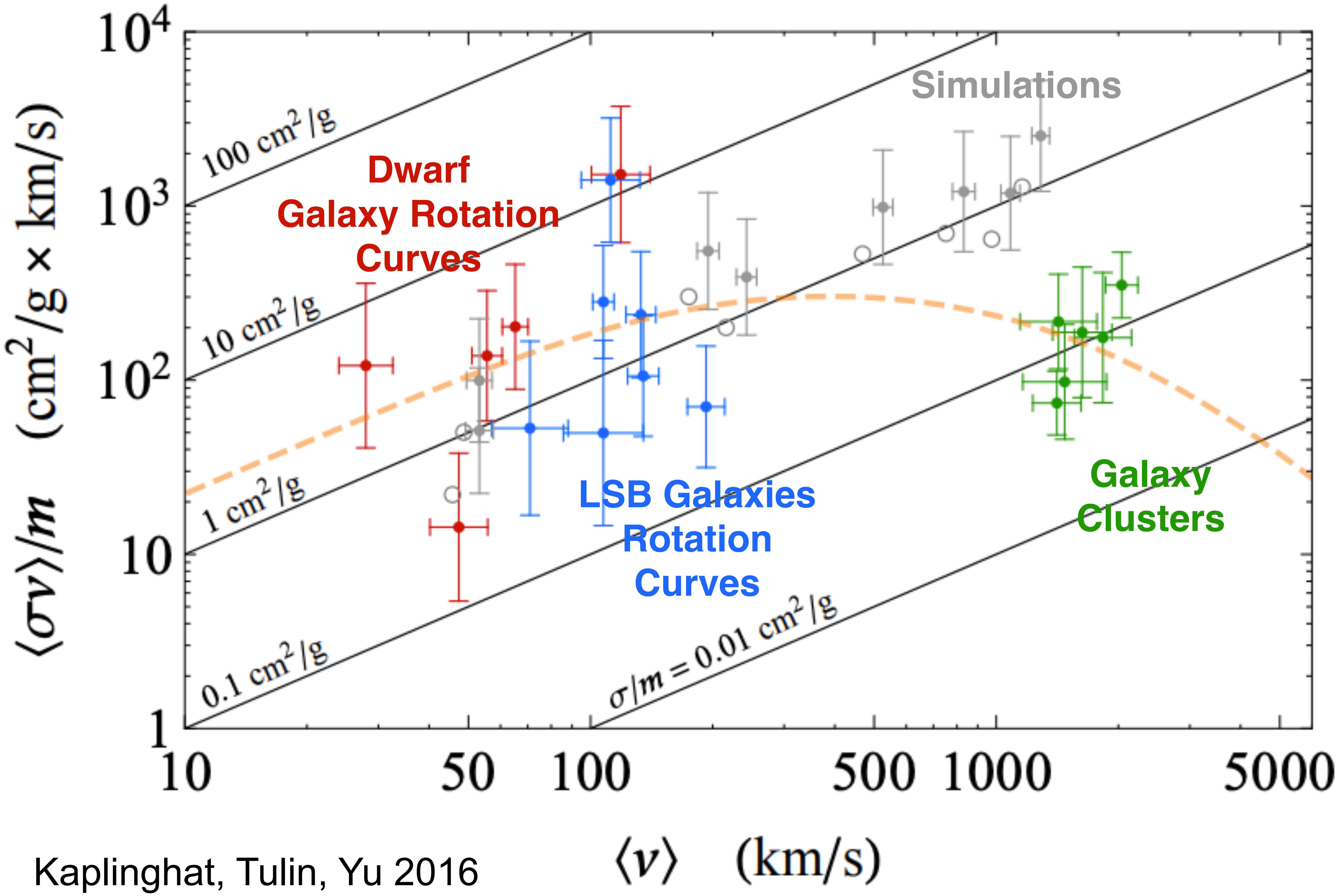
Nathan Sandford (Toronto)



Sandford, TSL et al. to be submitted (S⁵ Collaboration)

Question / Assignment 1

- How to interpret the cuspy profile from SIDM point of view?
- Can we compute the SIDM cross section at UFD scale using stellar kinematics?



Kaplinghat, Tulin, Yu 2016

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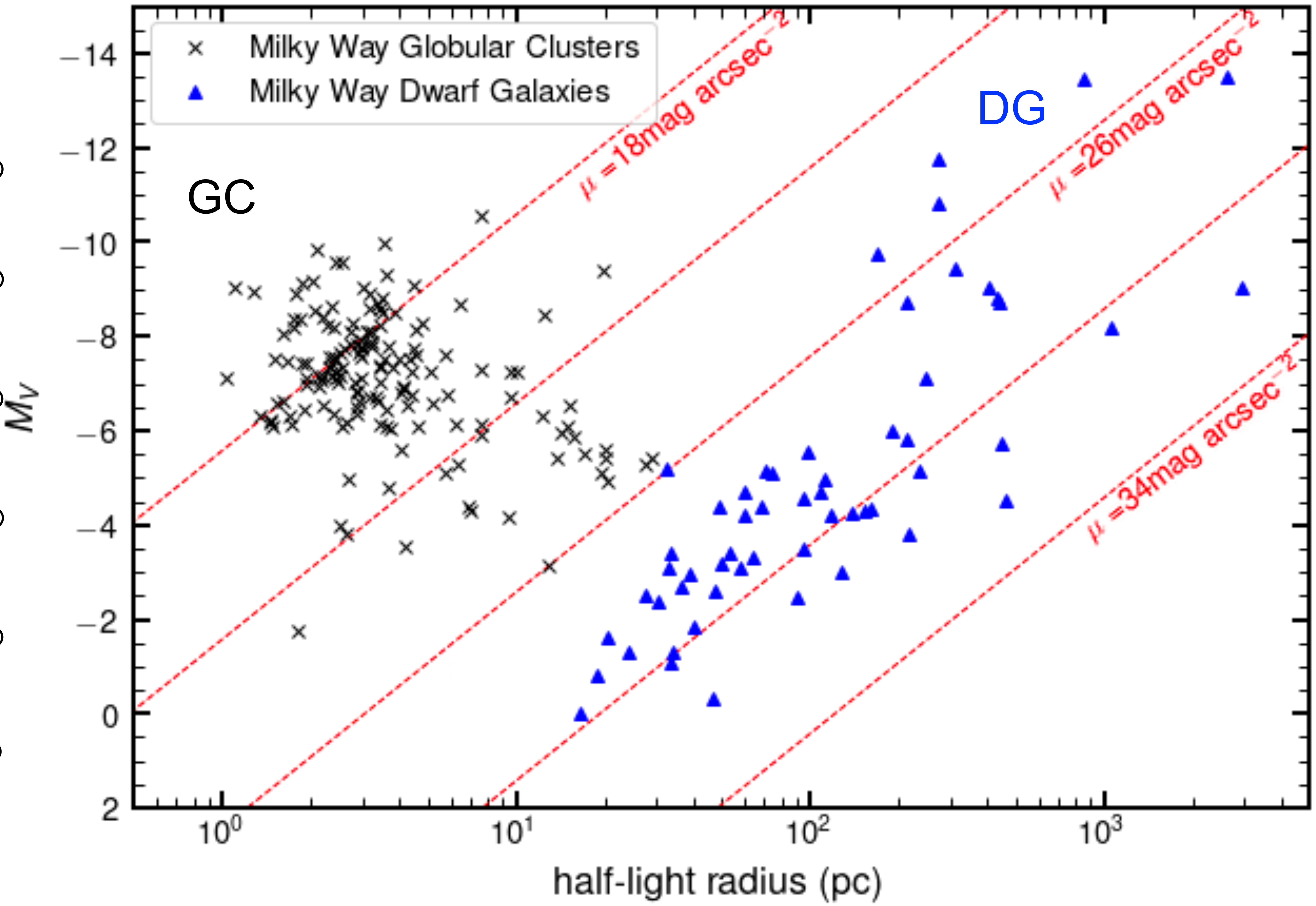

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Ultra Faint Compact Satellites (UFCSs)

~30 systems discovered in the past 20 years!

Discovering papers

Koposov et al. 2007
Fadely et al. 2011
Muñoz et al. 2012
Balbinot et al. 2013
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Cerny et al. 2023
Simon et al. 2024

Andrew Pace (UVa)
Local Volume Database
Pace et al. 2024 arXiv:2411.07424
https://github.com/apace7/local_volume_database

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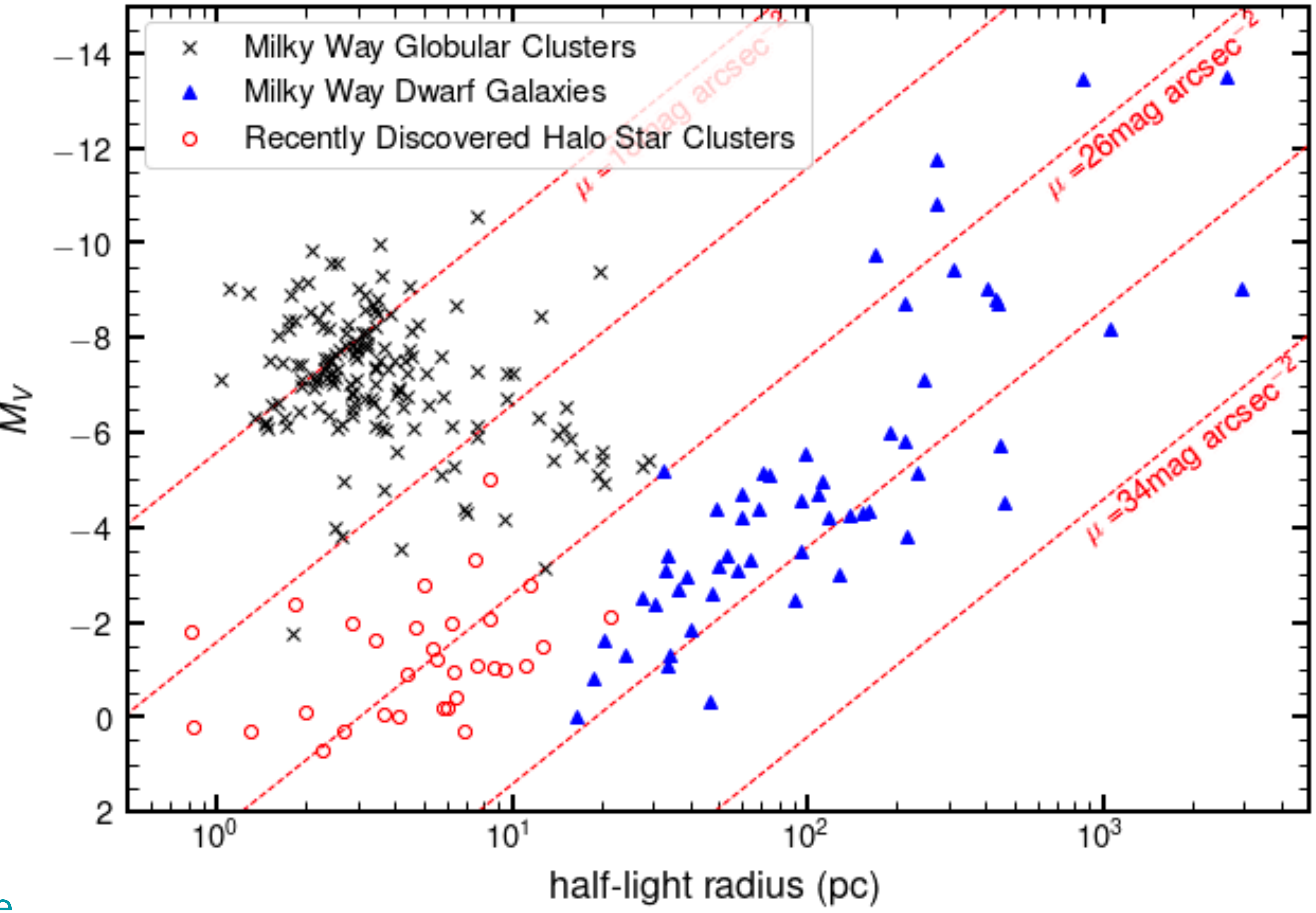
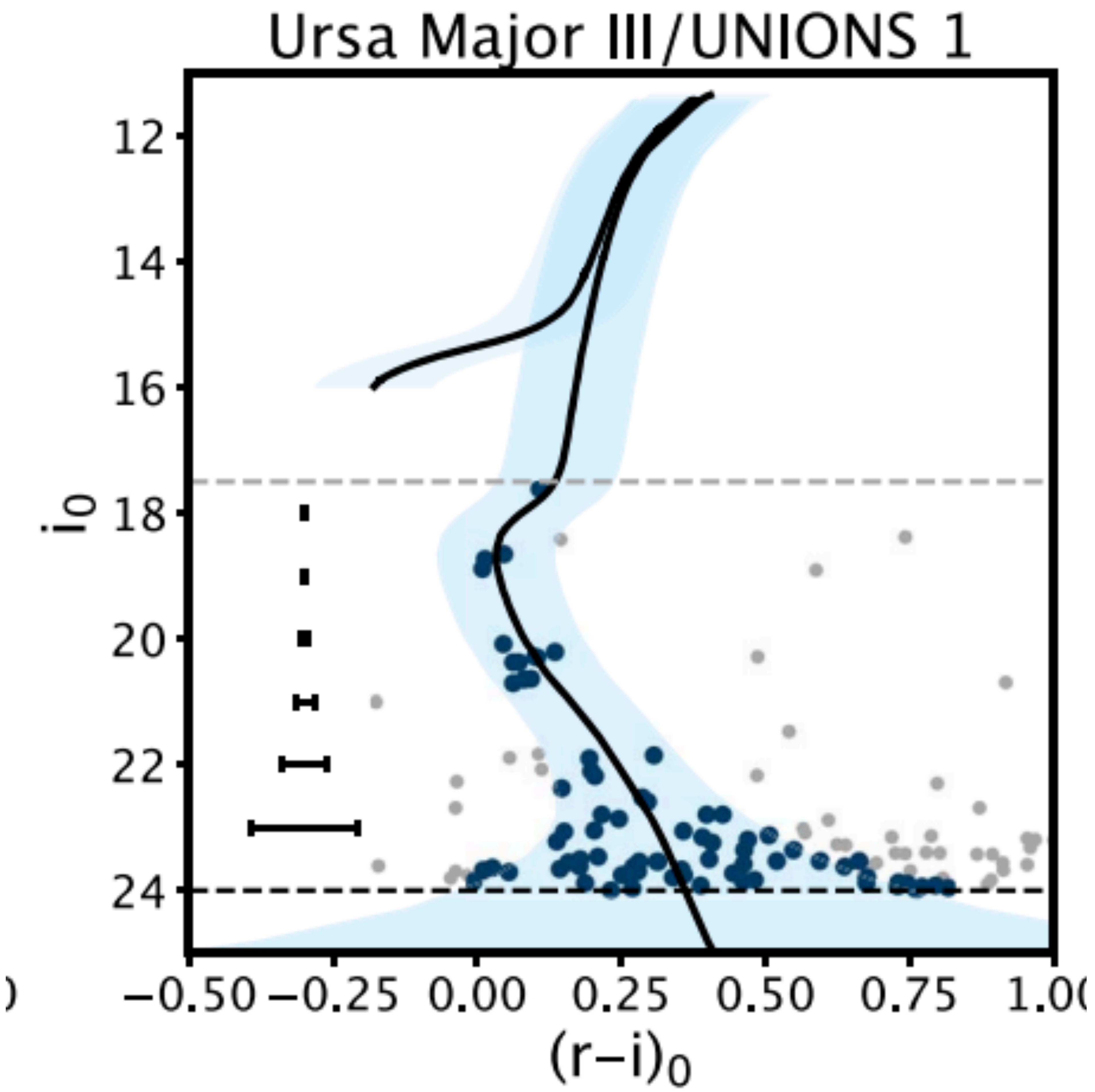
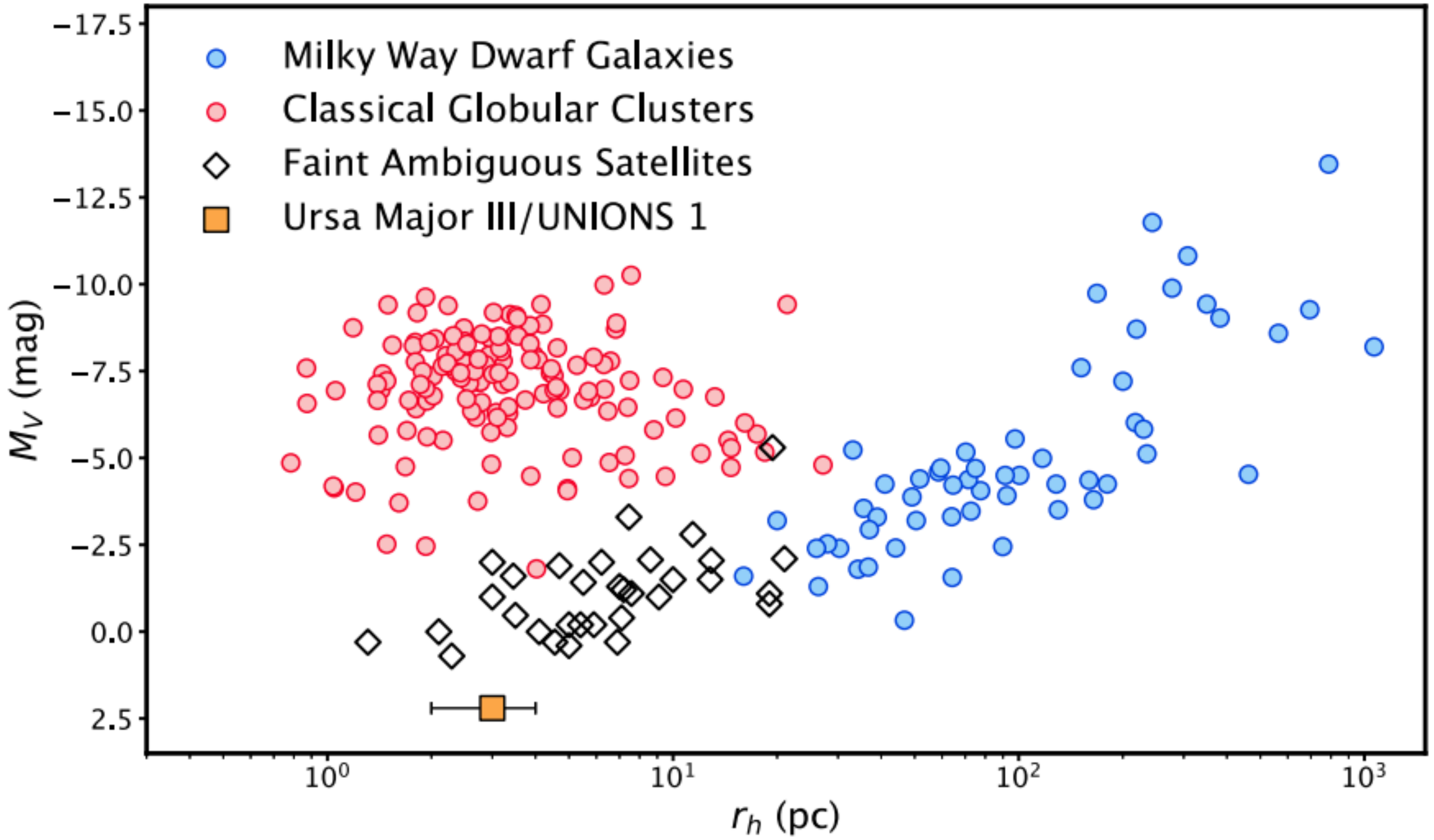


The current record: a galaxy/cluster at 16 Msun?!





Simon Smith (UVic)

Smith w/TSL et al, 2024
(UNIONS Collaborations)

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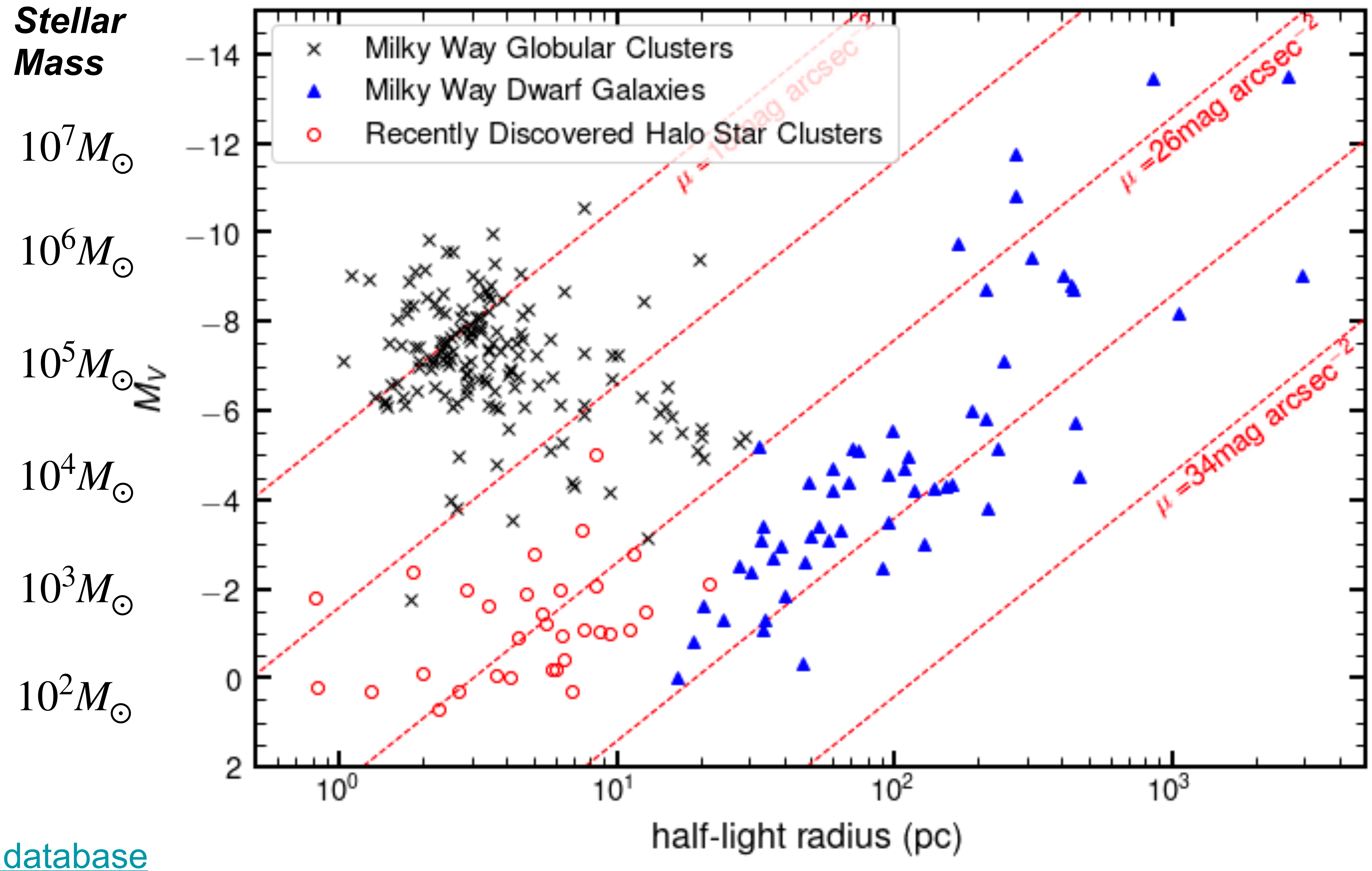


What is the Boundary between clusters and galaxies?

Generally:

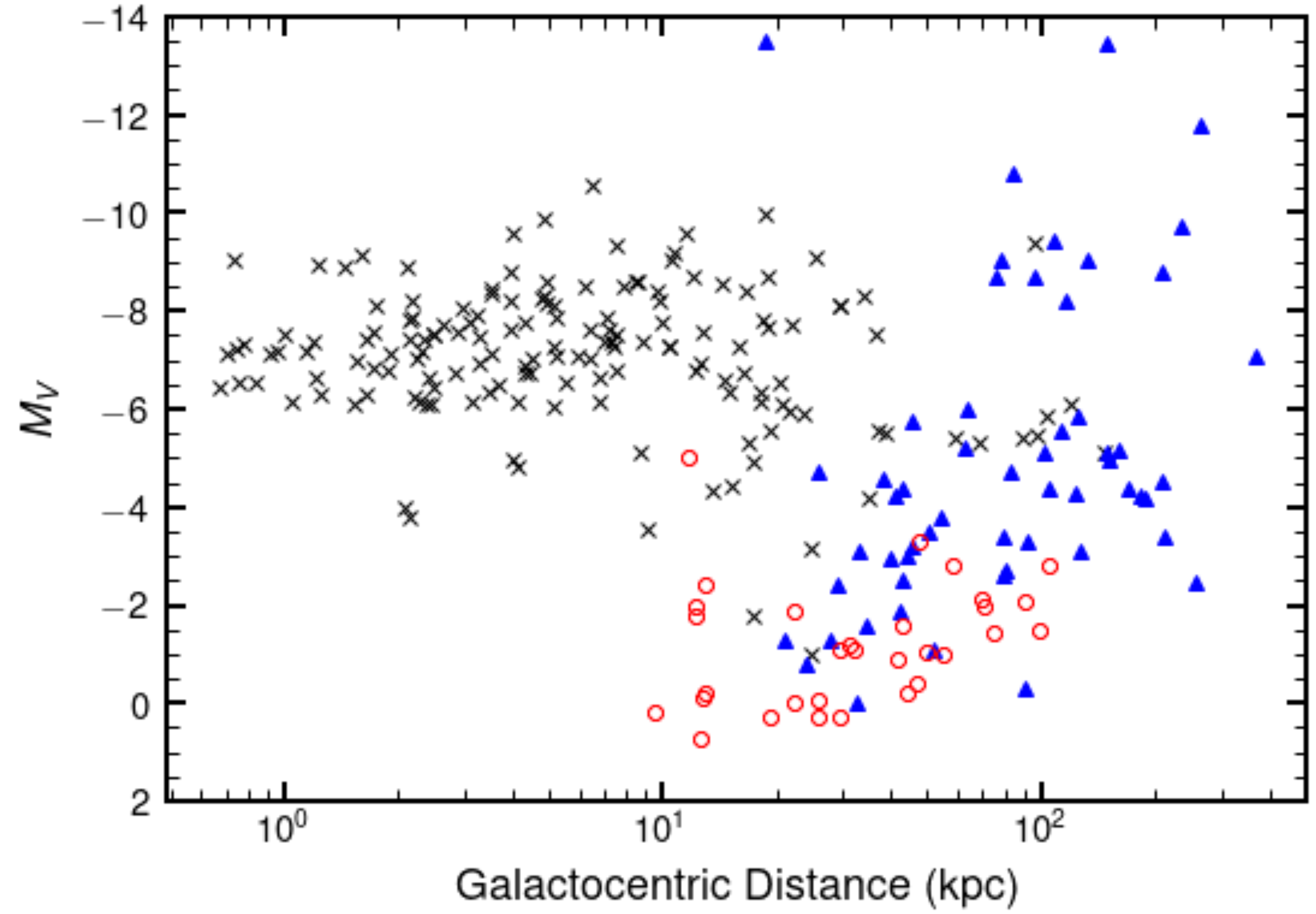
$r_{1/2} \lesssim 10$ pc

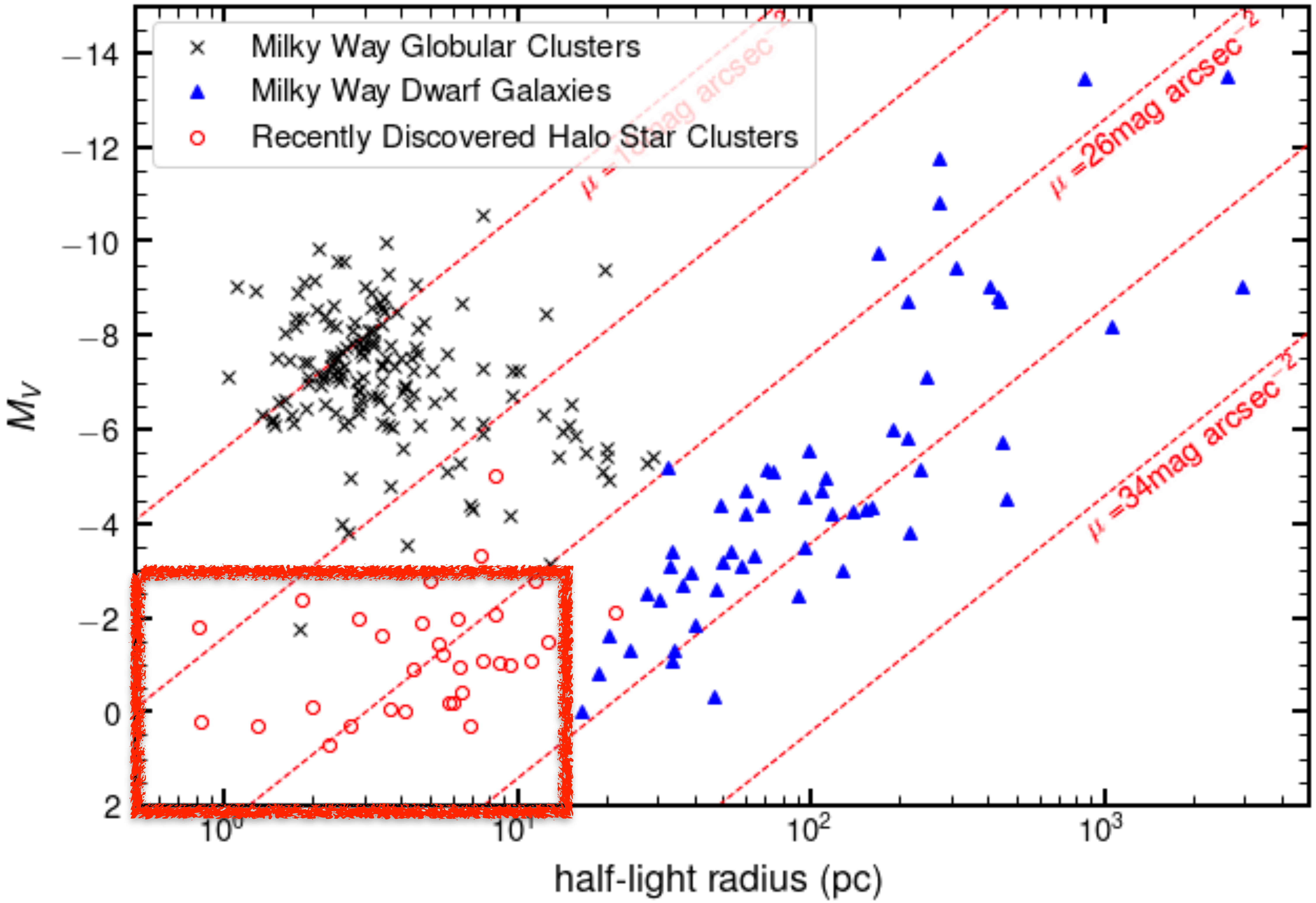
$\mu > 24$ mag/arcsec^2

$M_V \gtrsim -3$ or $M_{star} \lesssim 1000\ M_{sun}$

$r_{Gal} > 10$ kpc

age ~ old (>10 Gyr)





A New Spectroscopic Census of the UFCSs

William Cerny (Yale)

Magellan/IMACS

Keck/DEIMOS

(W. Cerny, TSL, A. Pace et al. in prep)

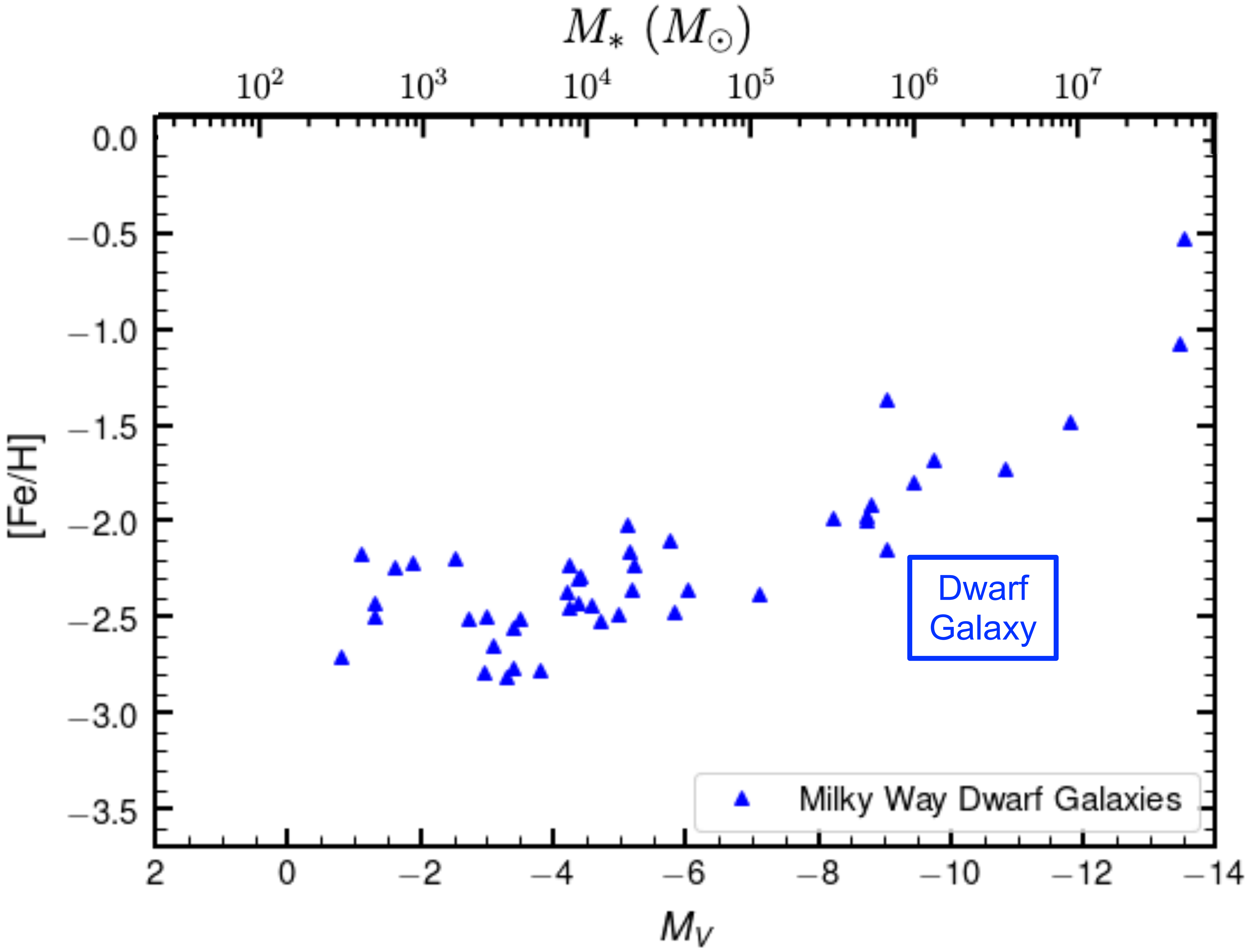
We have collected, reduced, and homogeneously analyzed new and/or archival medium-resolution spectra for ~19 UFCSs!

first population-level chemodynamical insights into these systems

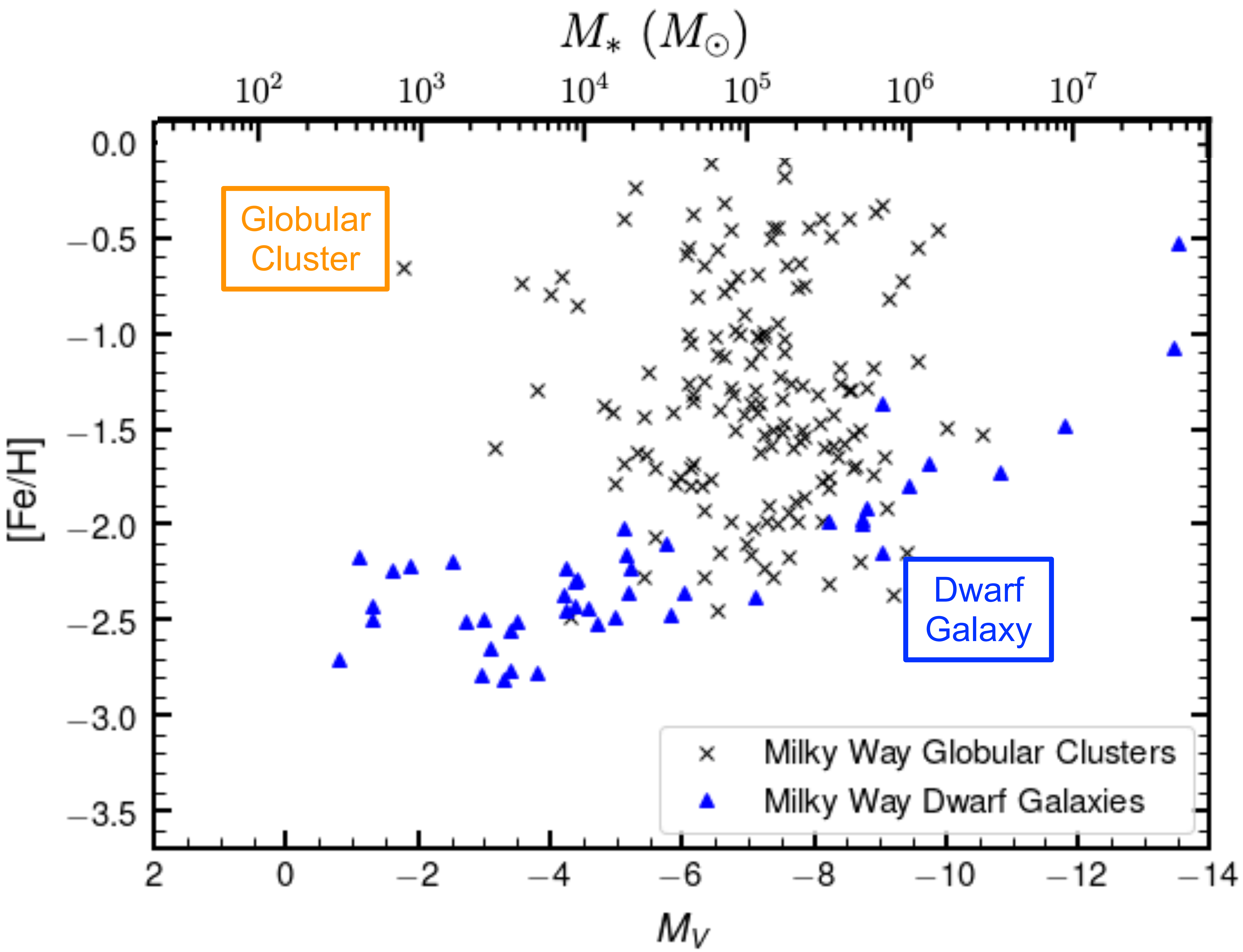
(A 70 page paper!)

Results 1: Metallicities

Galaxy's (stellar) mass-metallicity relation

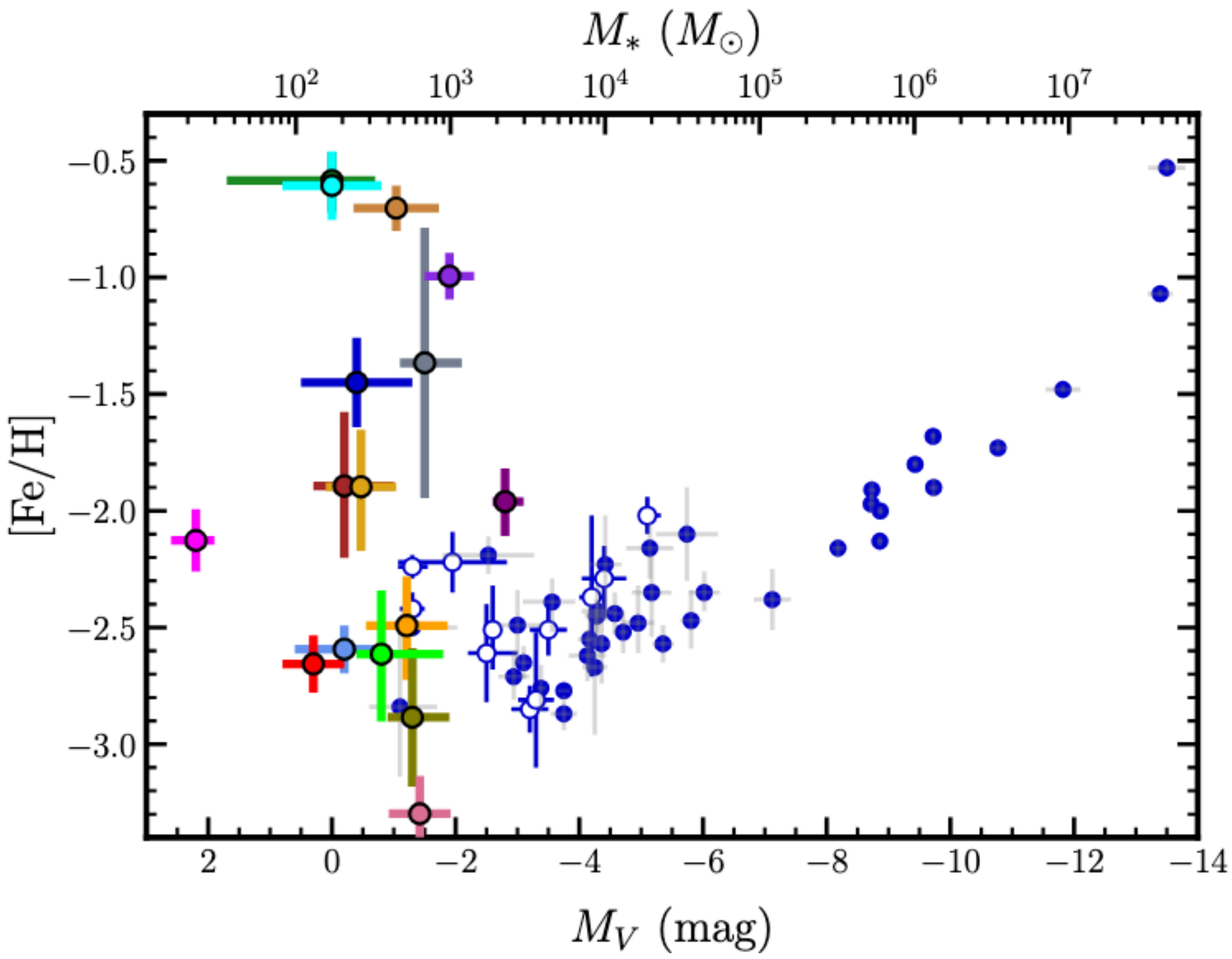


Results 1: Metallicities



Results 1: Metallicities

Metallicities of these systems infer that at least half of them are GC, but the other half are more metal-poor than any known GCs



W. Cerny, TSL, A. Pace et al. in prep

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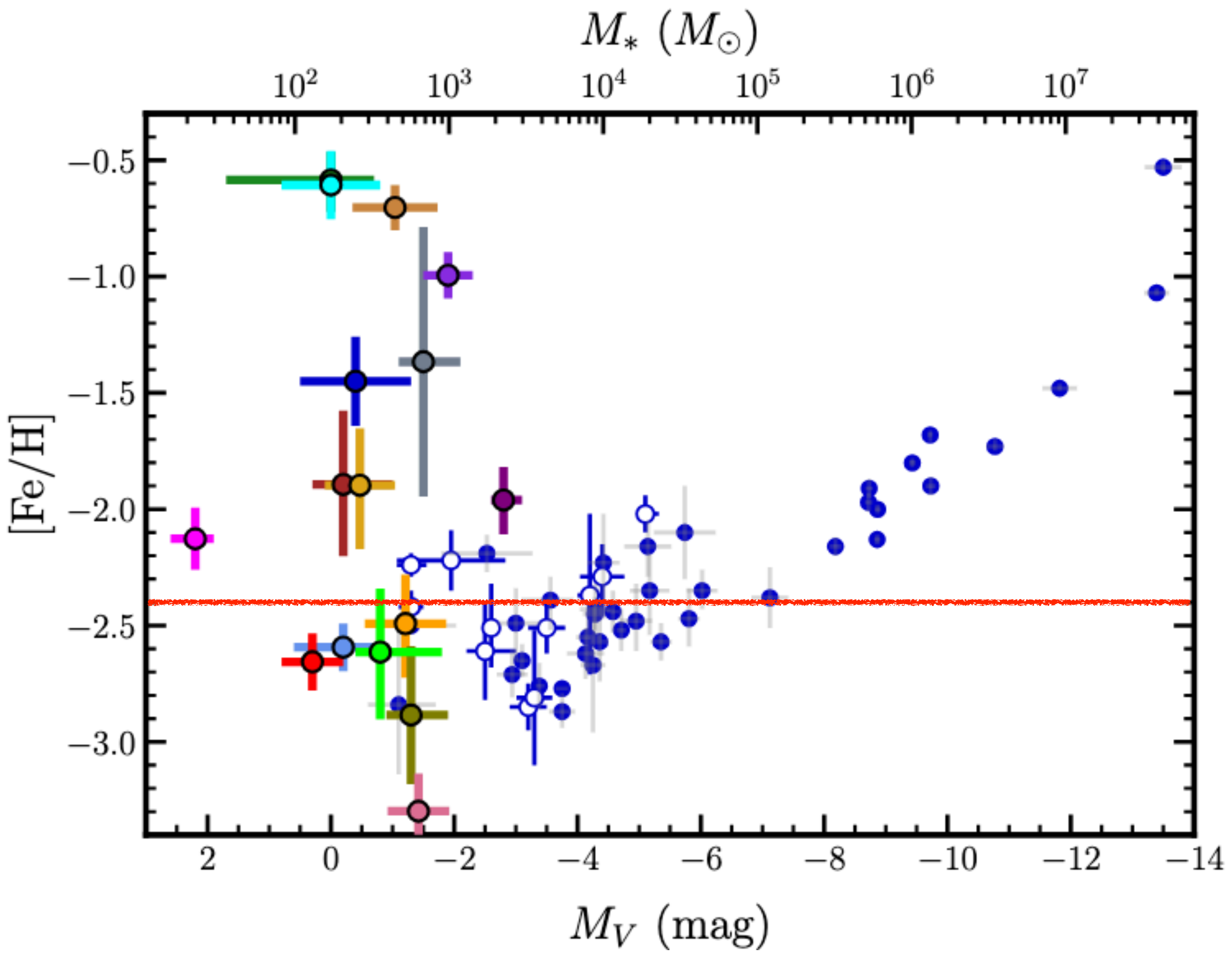
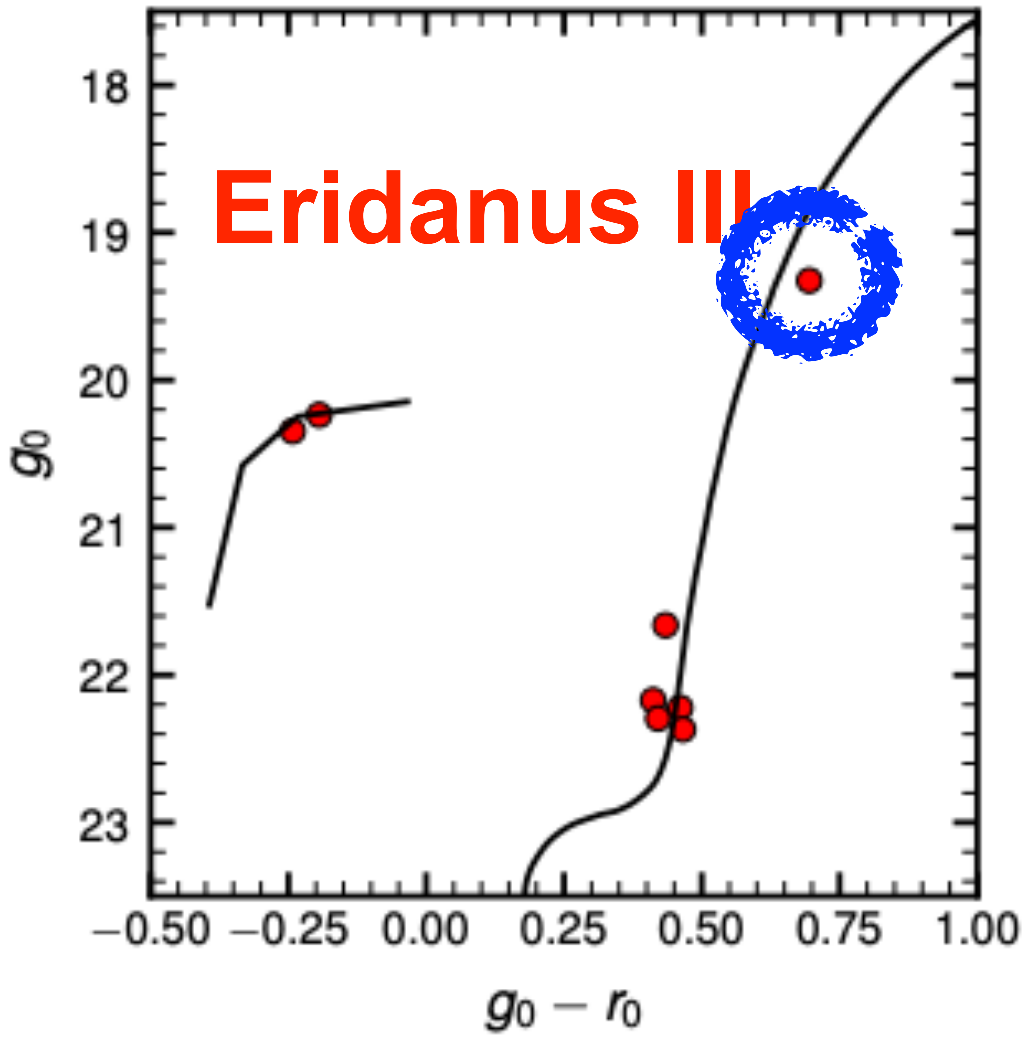


A surprising number of the UFCSs appear to trace the *galaxy* mass-metallicity relation and below "GC metallcity floor"

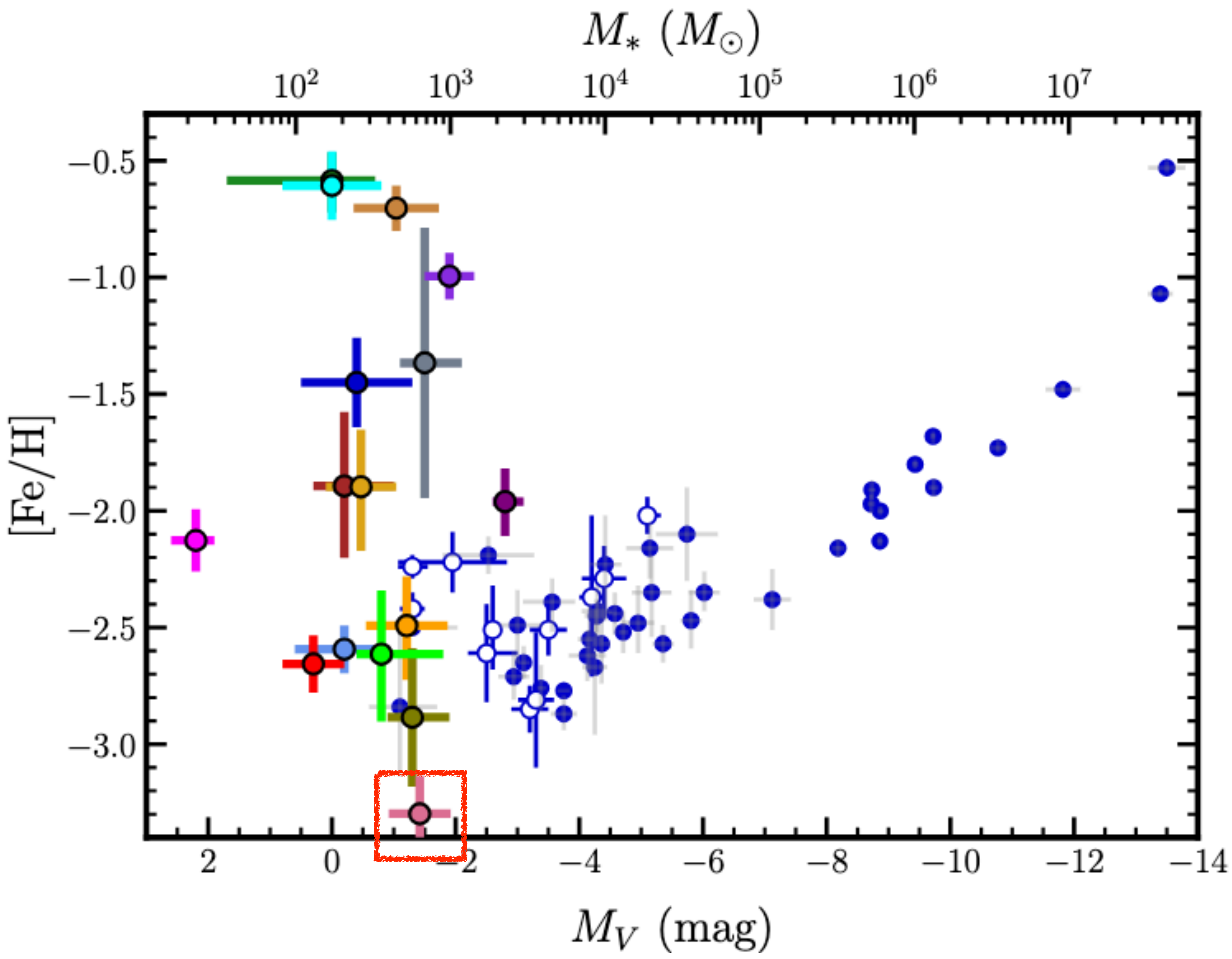
W. Cerny, TSL, A. Pace et al. in prep

Results 1: Metallicities

These metal-poor systems show chemical abundance patterns likes stars in UFDs



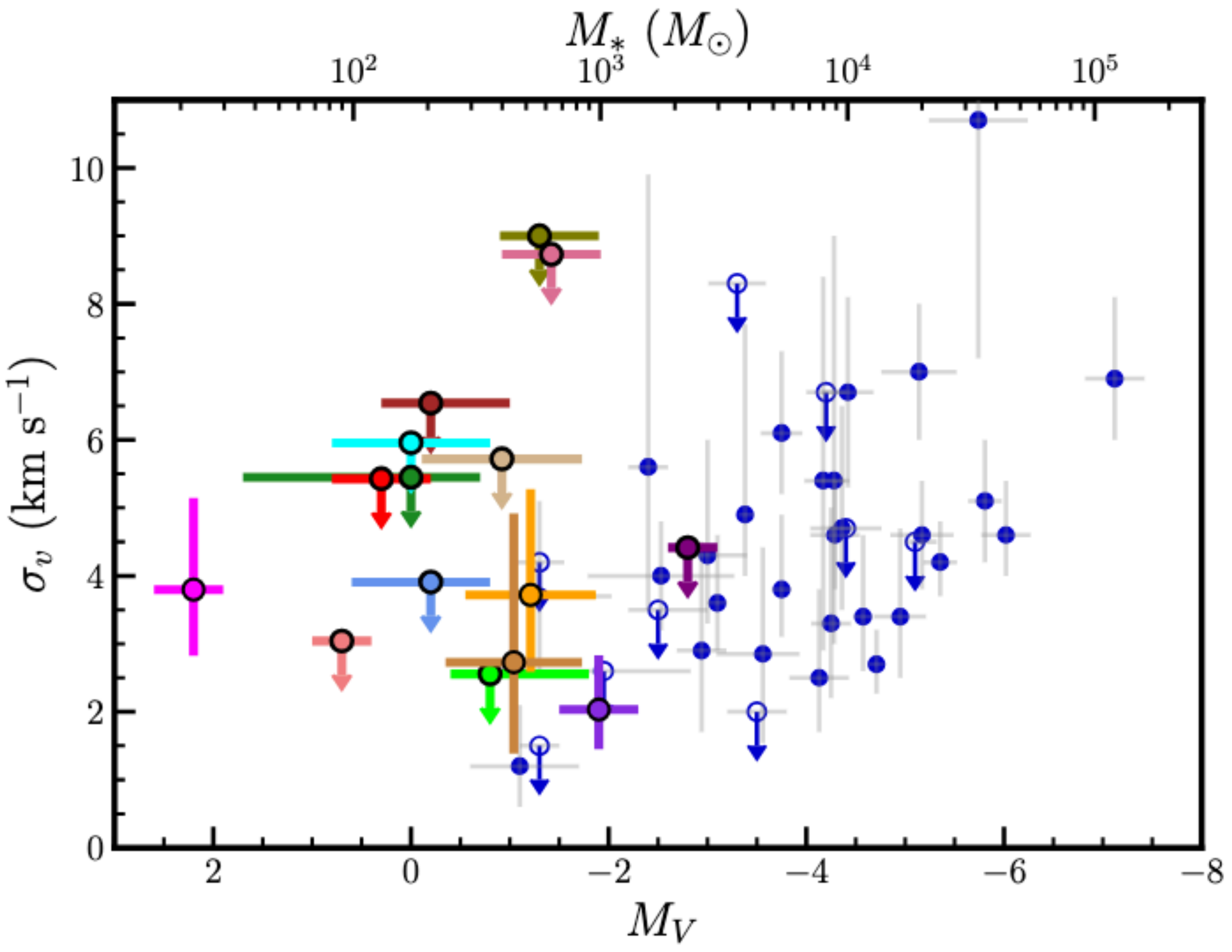
J. Simon, TSL et al. 2024, arXiv:2410.08276



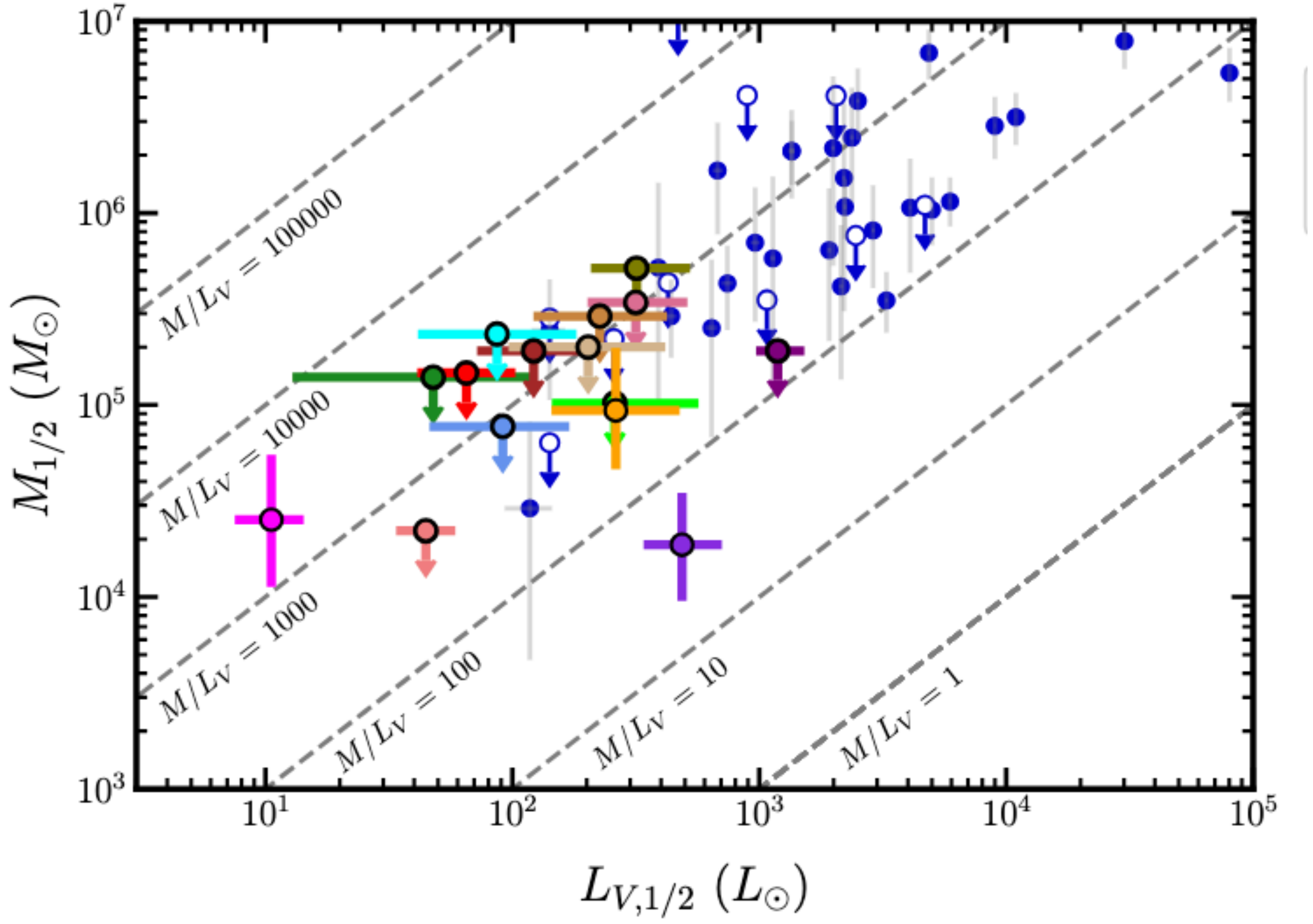
W. Cerny, TSL, A. Pace et al. in prep

Results 2: Kinematics / Dynamical mass

Velocity Dispersions



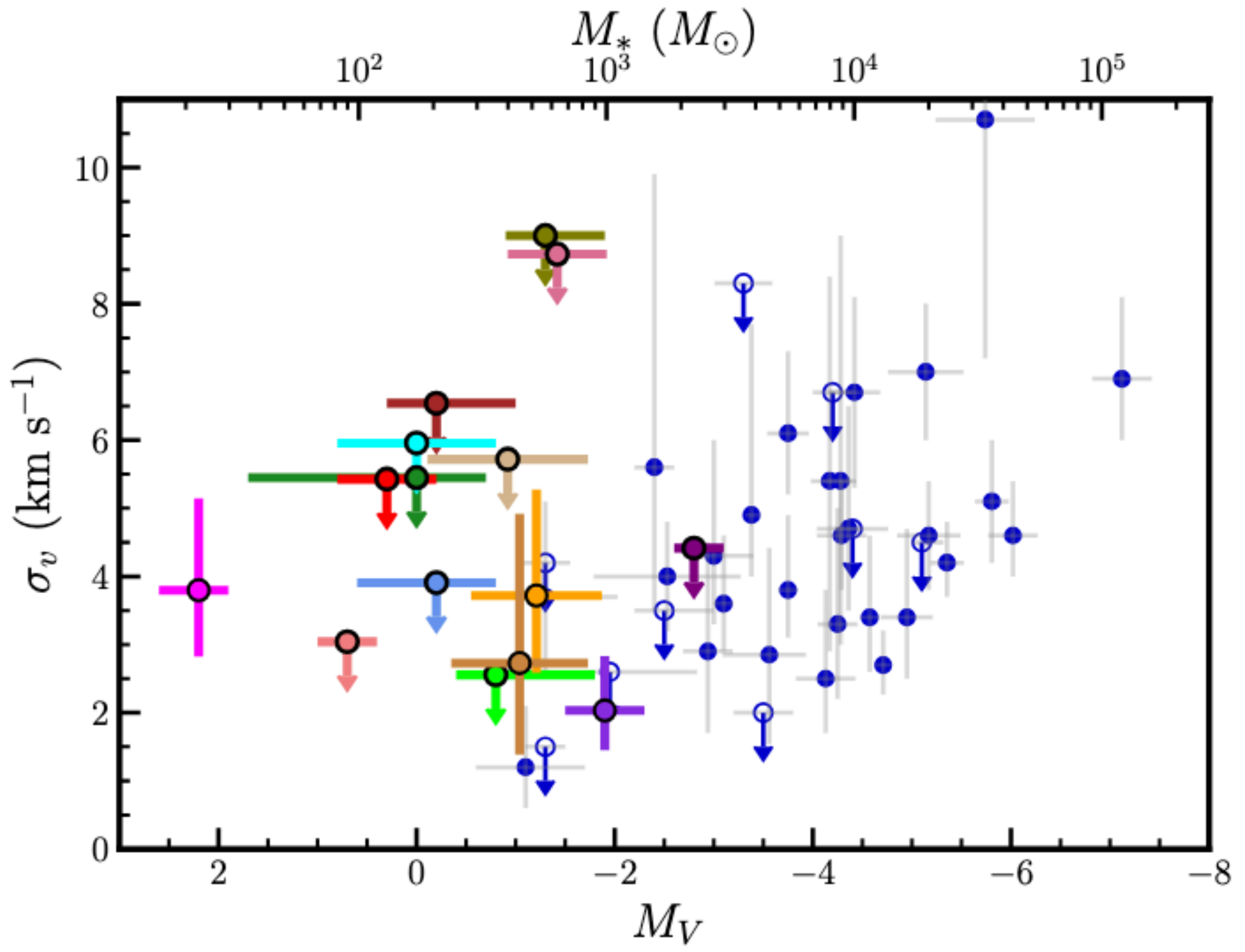
Dynamical Mass to Light Ratio



W. Cerny, TSL, A. Pace et al. in prep

Question / Assignment 2

- If some of these systems are indeed from SIDM core collapse, what is the expected velocity dispersions and mass to light ratio within half-light radius?
- Will the dispersion be different from the CDM predictions?



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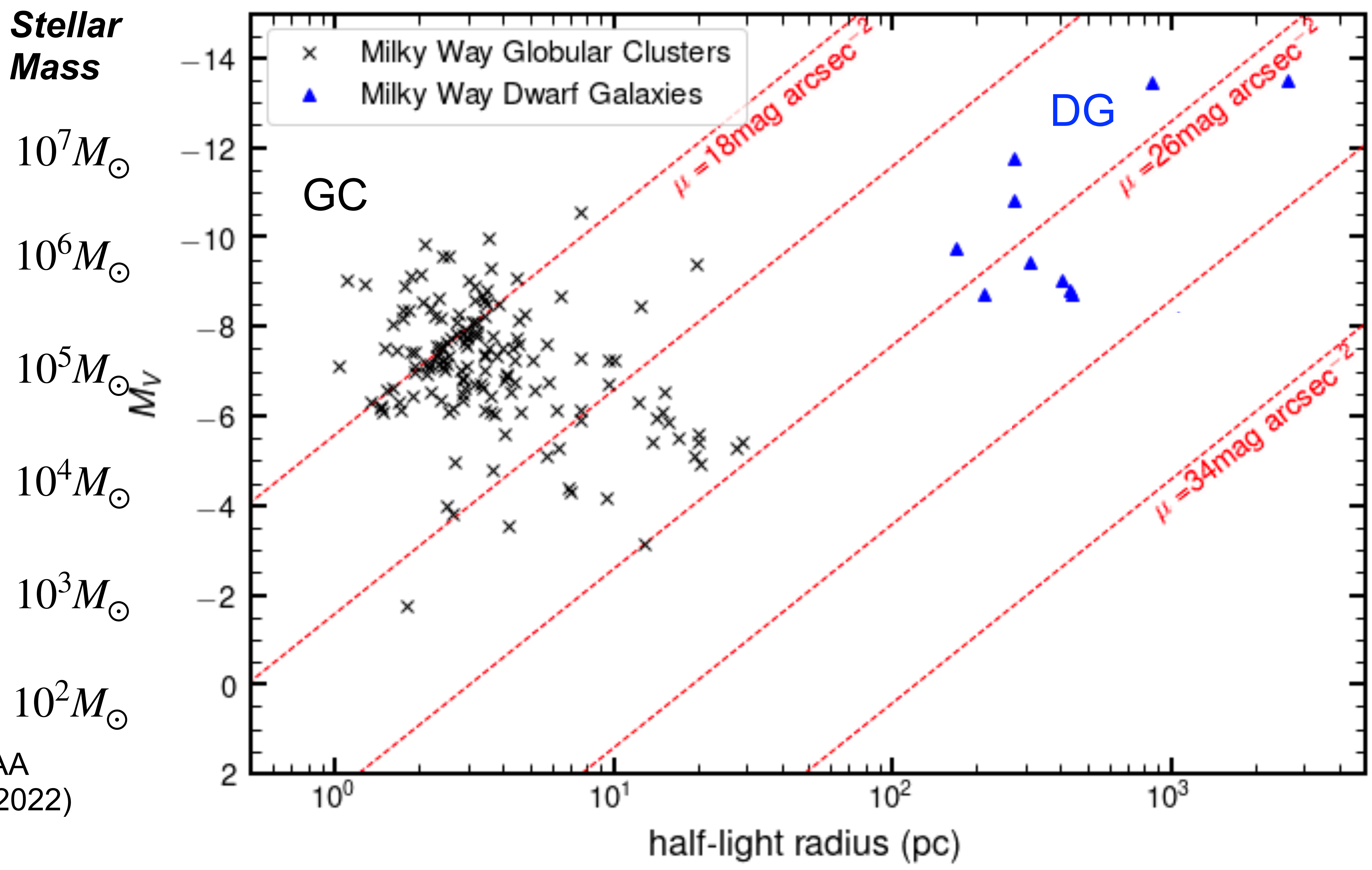

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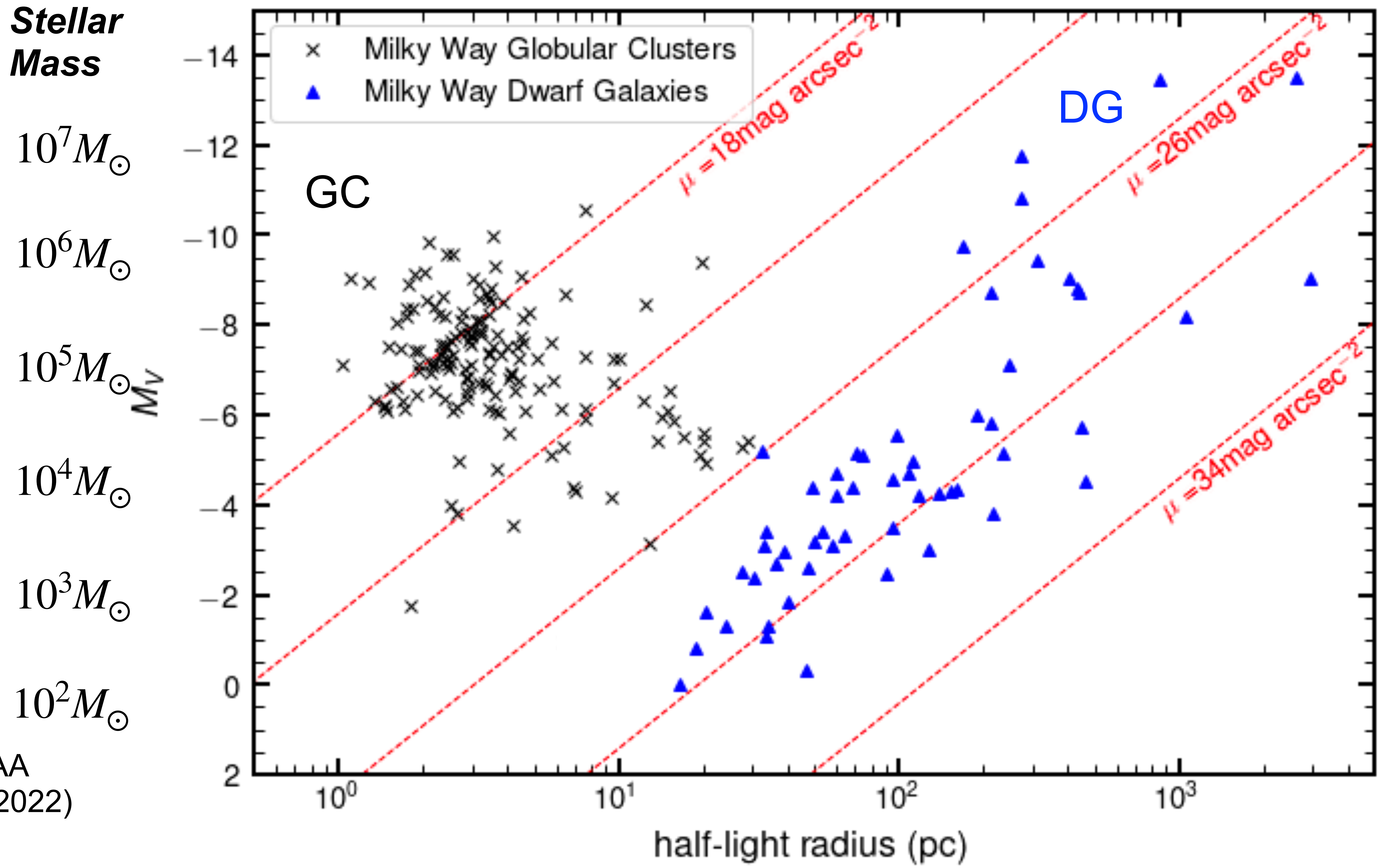

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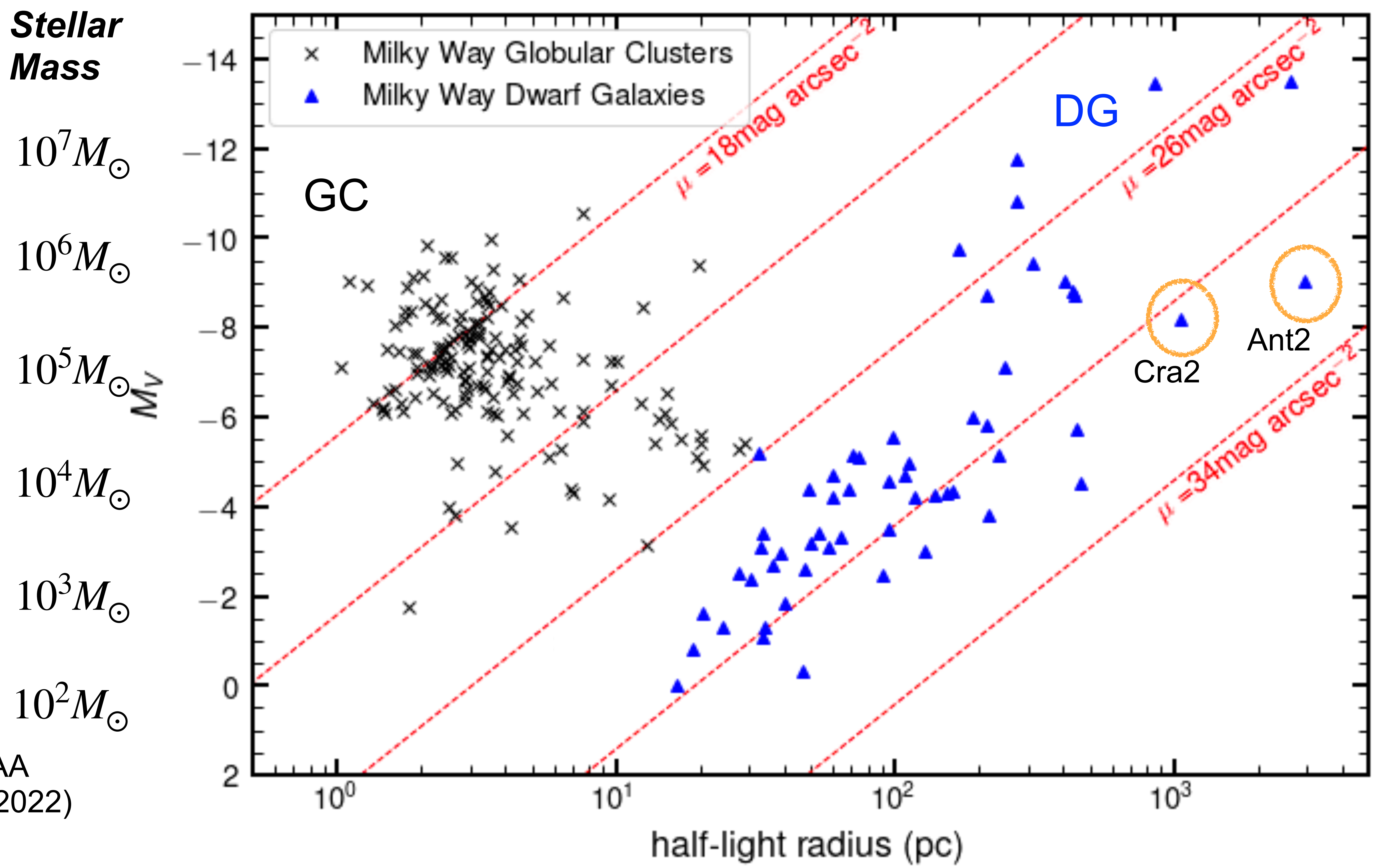

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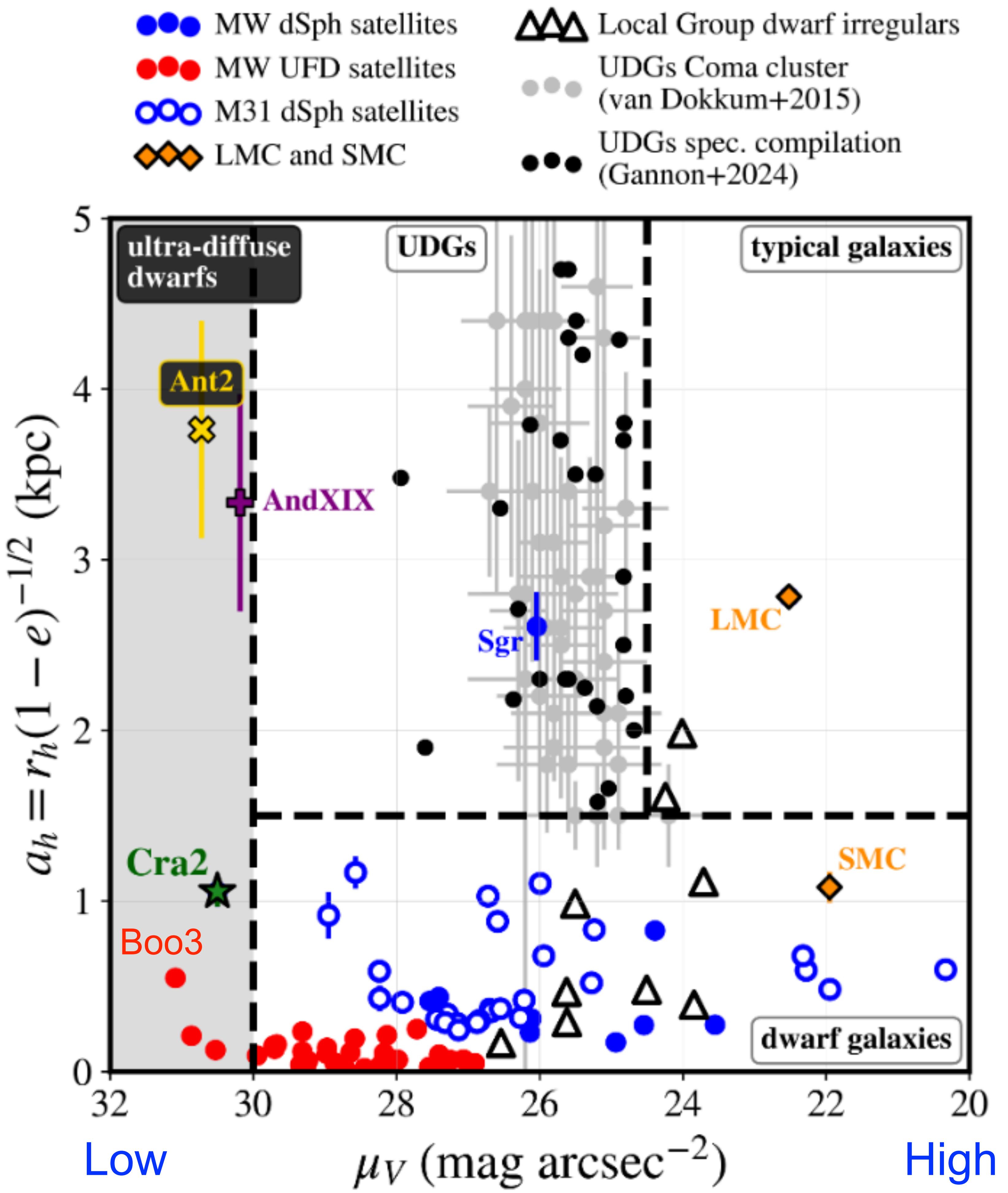
Ultra Diffuse Galaxies in the Milky Way?

Size



Surface brightness

Crater 2 and Antlia 2: UDGs in the Milky Way?

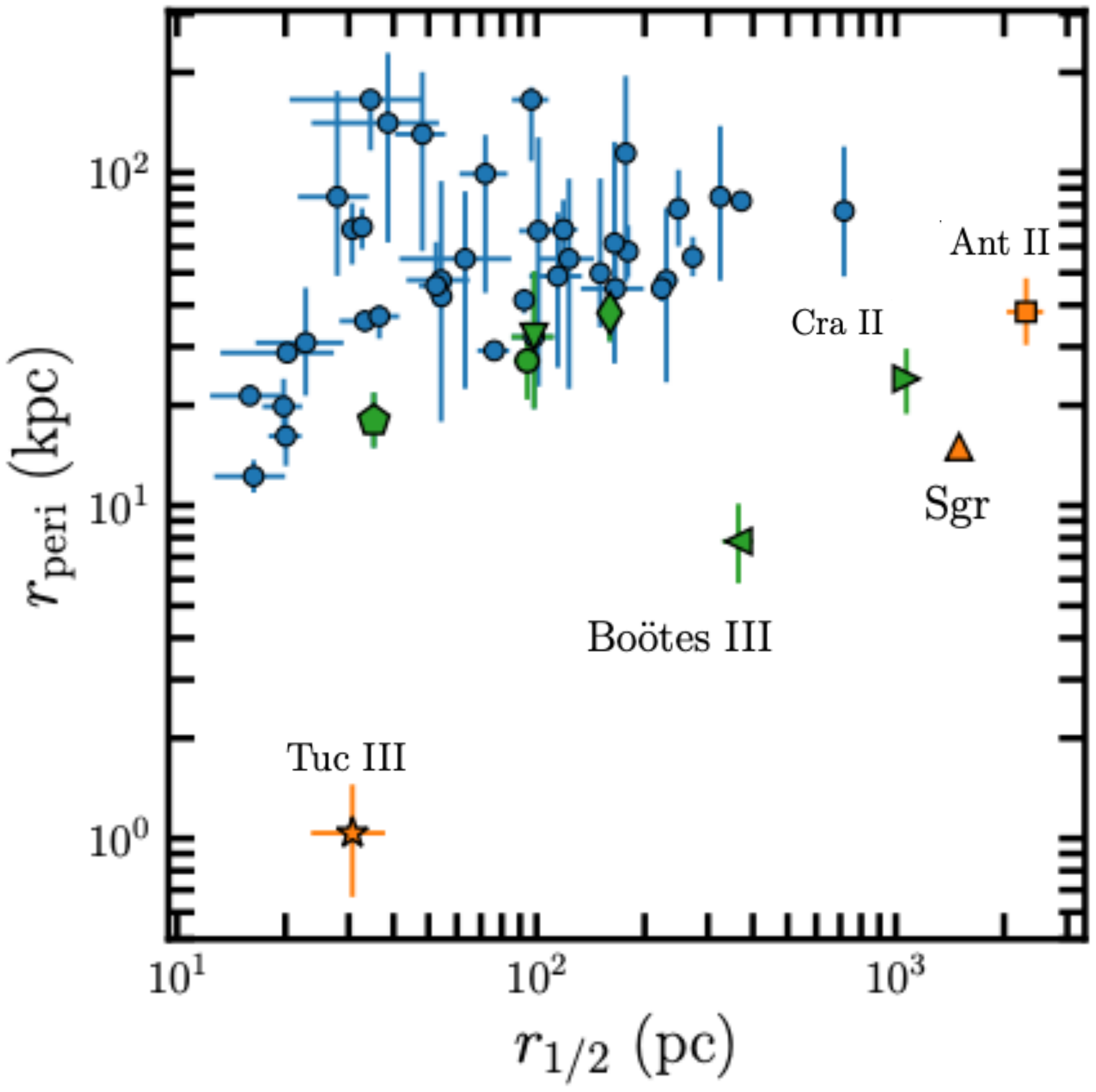
Milky Way UDGs are 5 mag (= 100x) fainter!

G. Limberg, A. Ji, TSL et al. in prep
(S^5 Collaboration)

Ant2 is 1000x fainter than LMC but larger!

Credit: Vasiy Belokurov

5 Milky Way Satellite Galaxies under Tidal Stripping



A. Pace, D. Erkal, TSL, 2022

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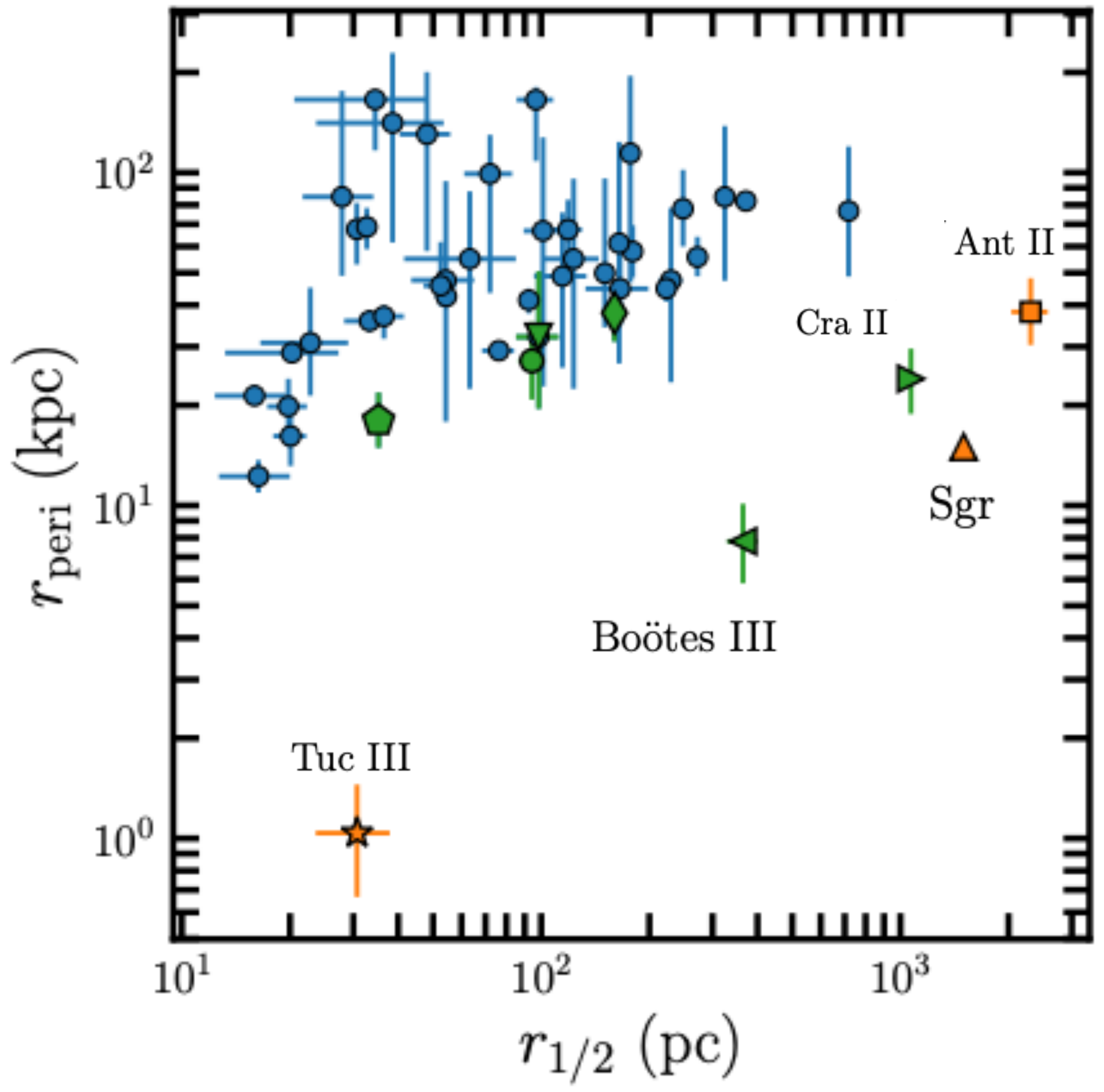
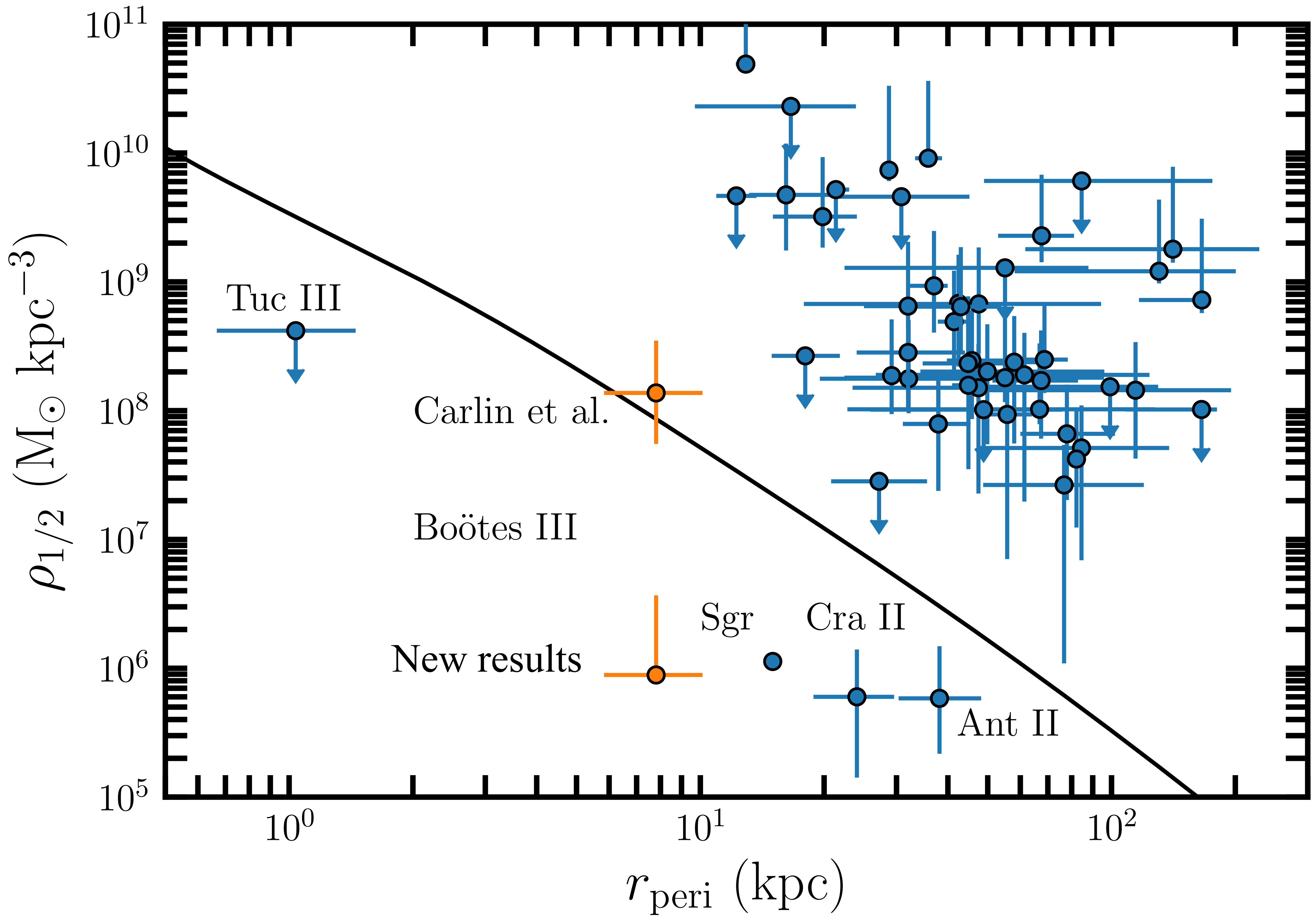


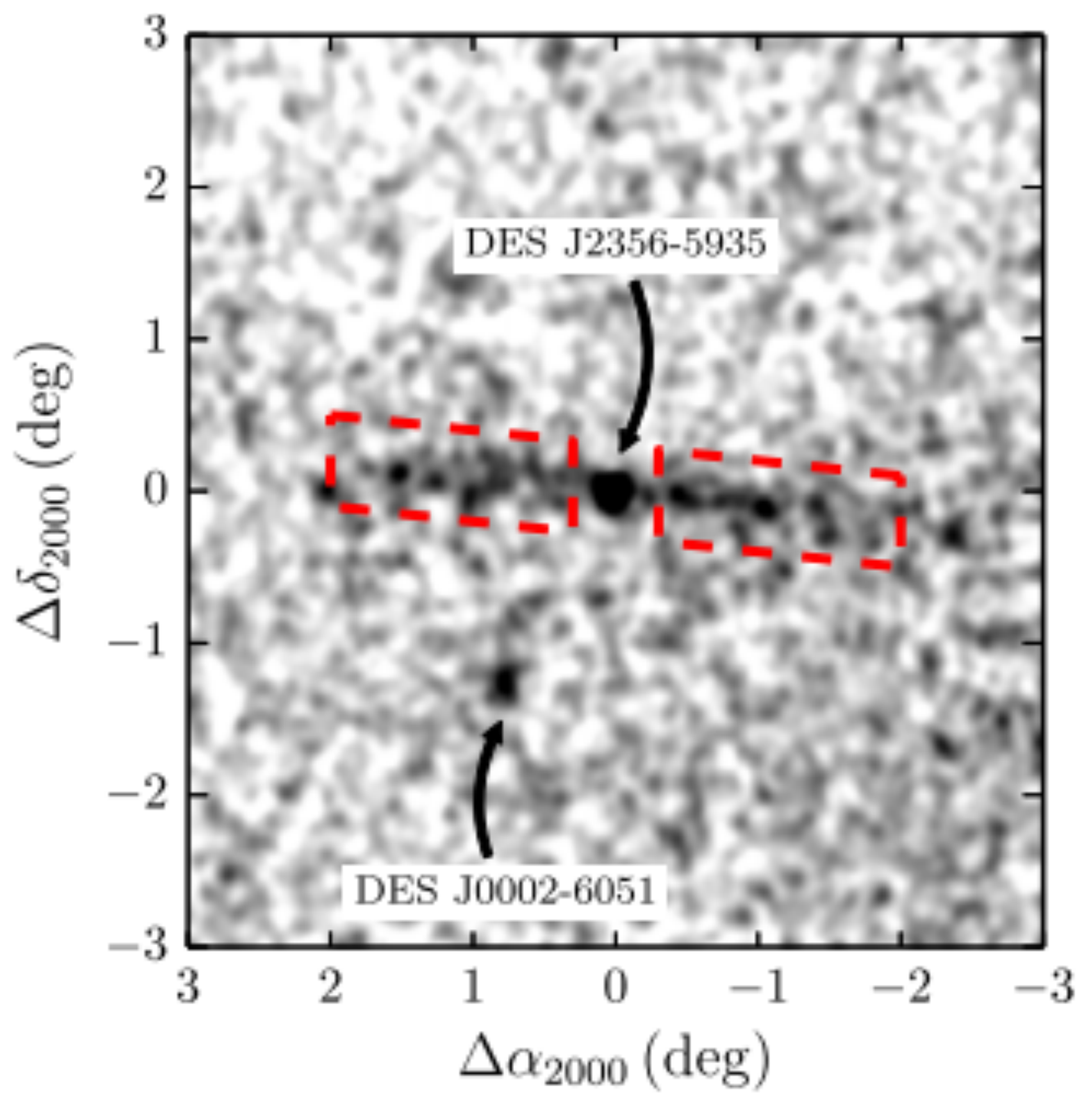
A. Pace, D. Erkal, TSL, 2022



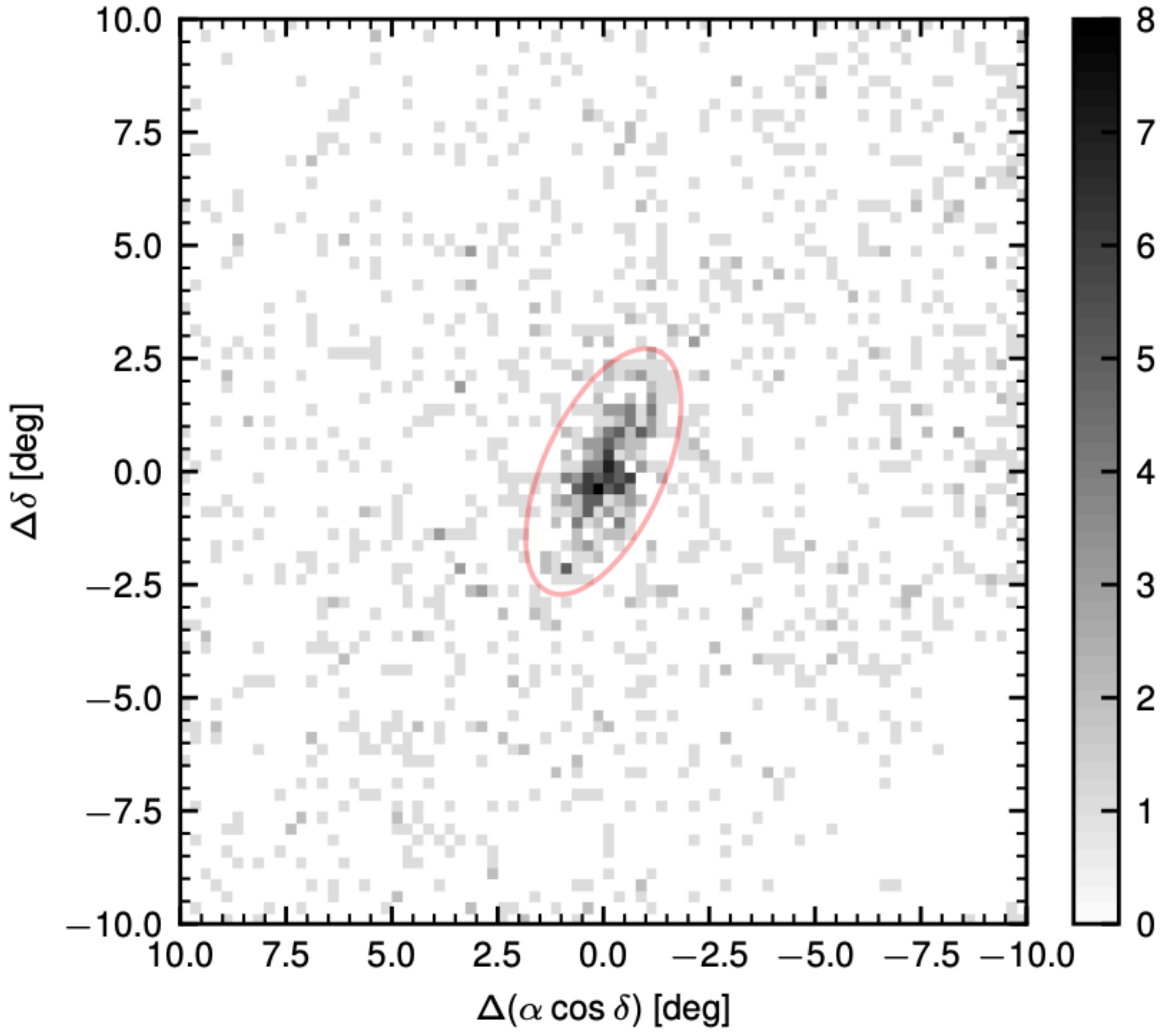
A. Pace, D. Erkal, TSL, 2022
Updated w/ S[5] data

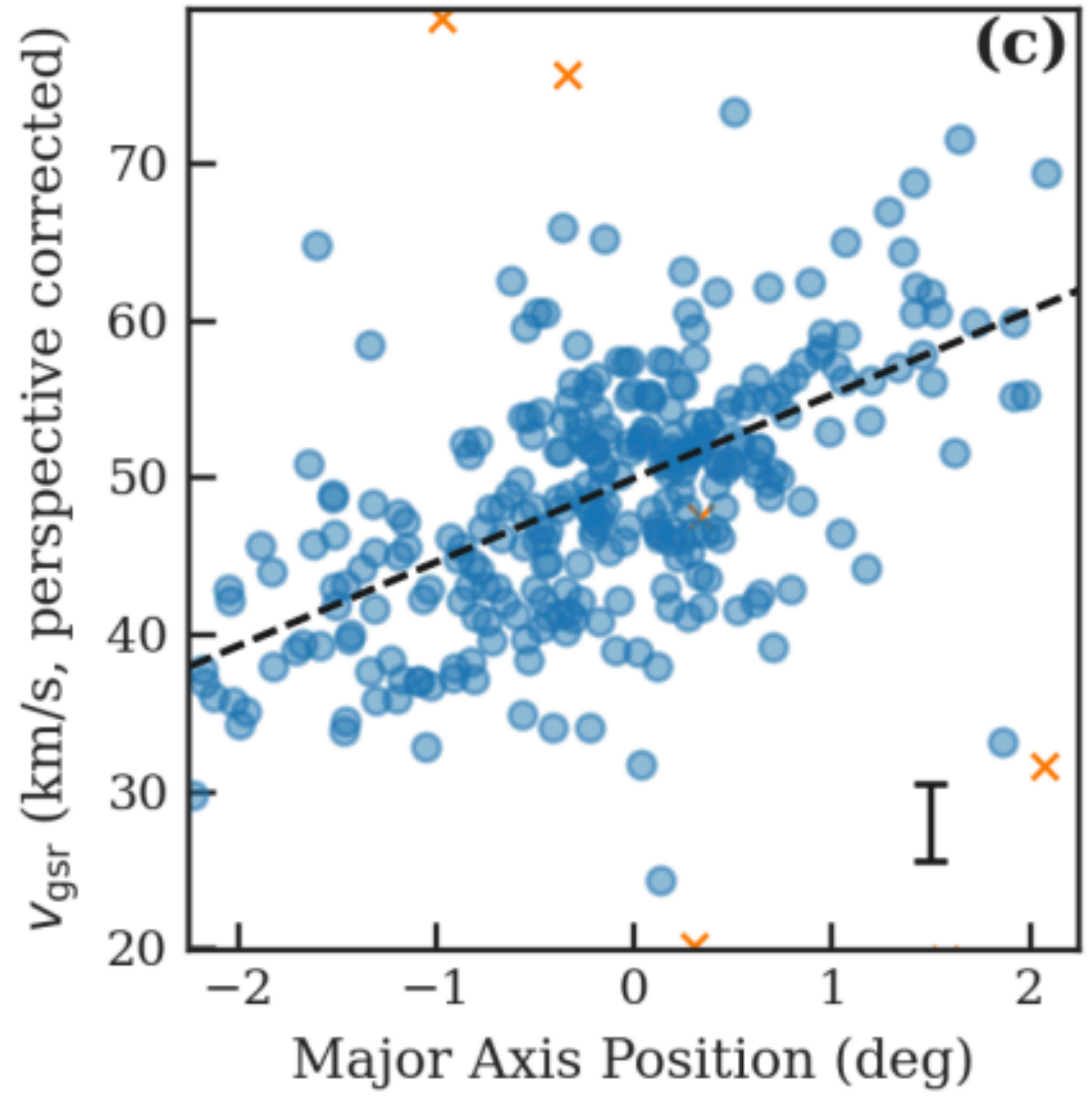
Evidence of Tidal Stripping

Tucana III



Antlia II



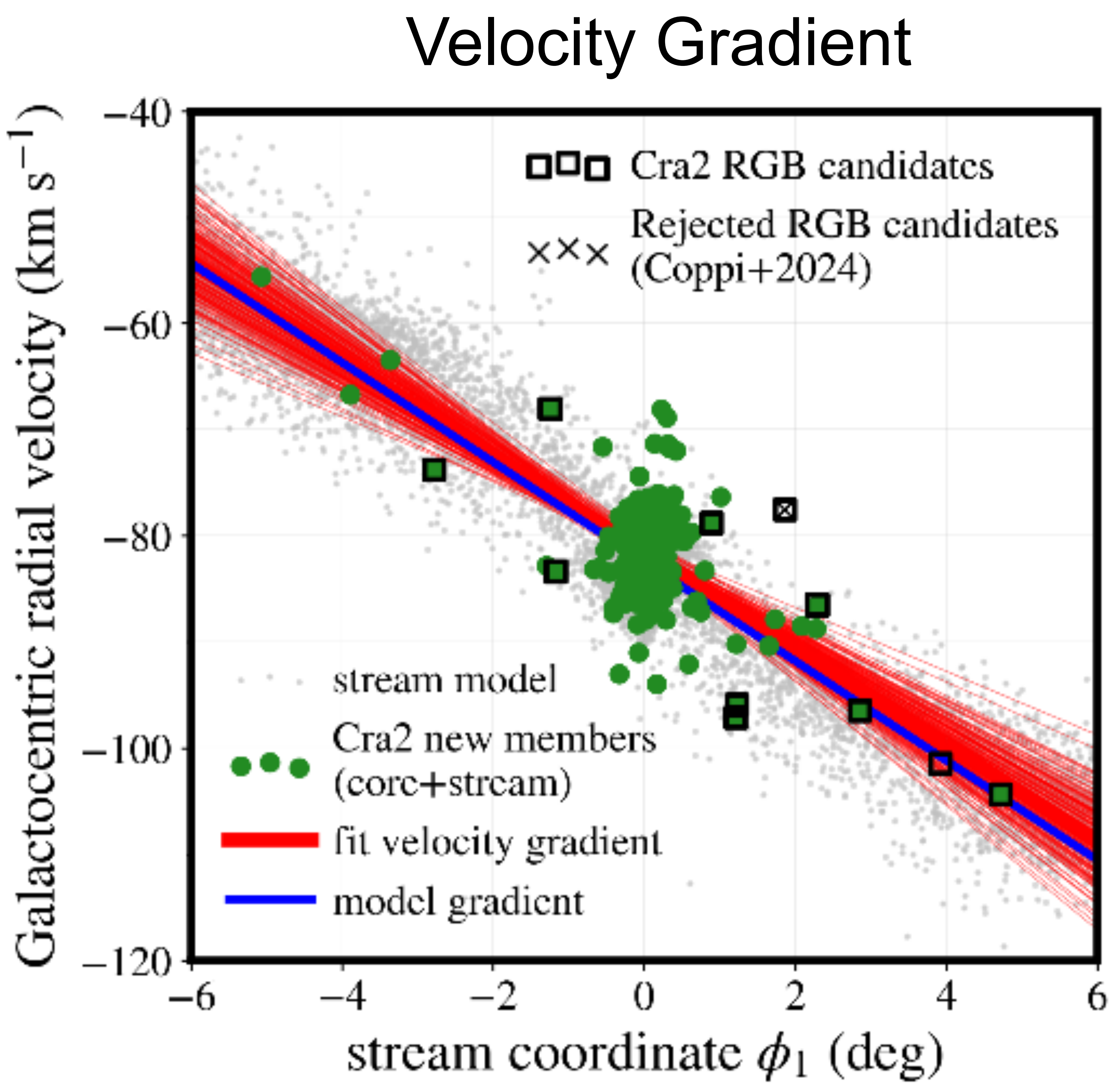


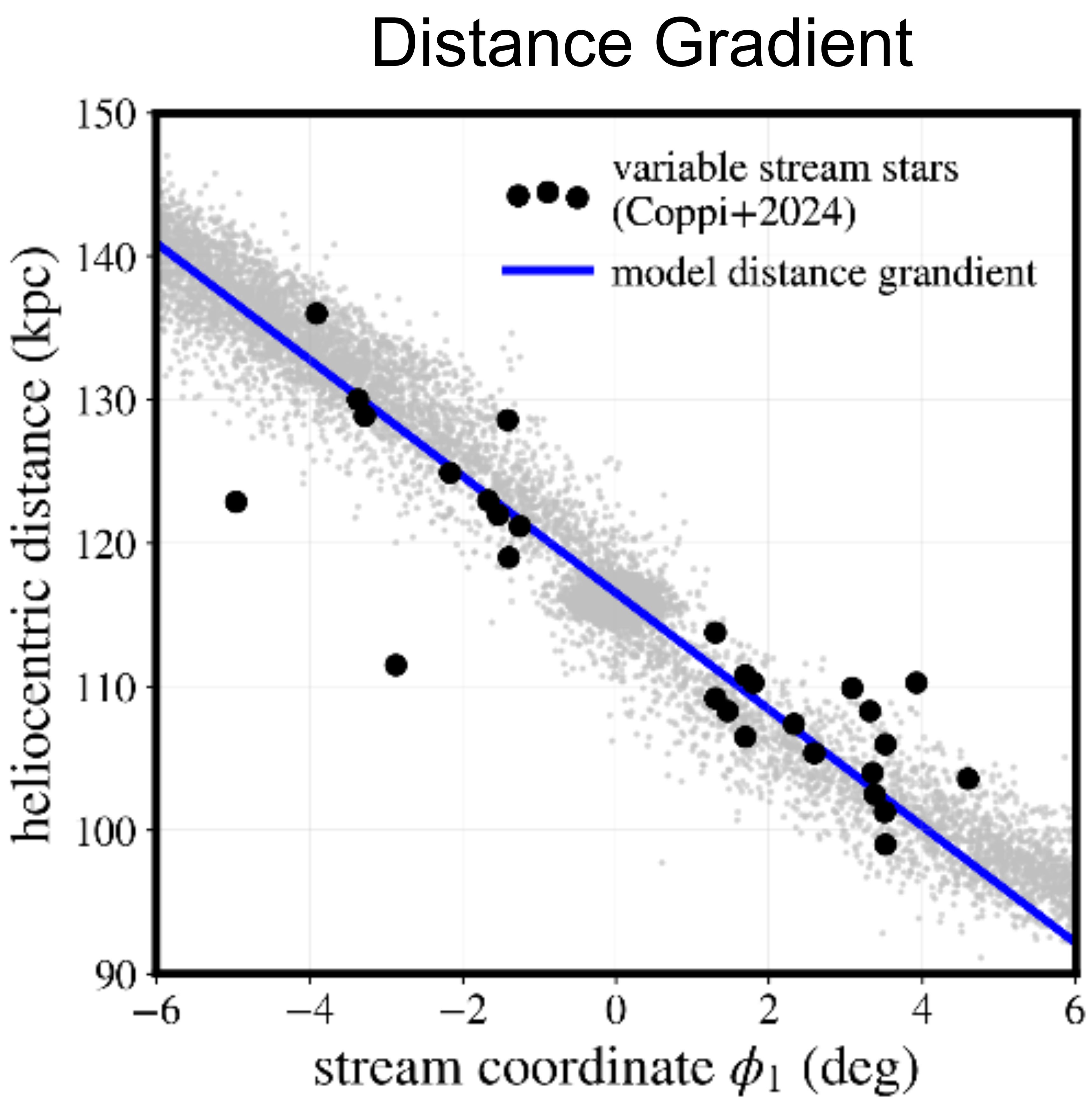
A. Drlica-Wagner et al. w/TSL 2015
TSL et al. 2018
(DES Collaboration)

A. Ji, S. Koposov, TSL et al. 2021
(S^5 Collaboration)

Crater II have tidal tails detected

Guilherme Limberg (UChicago)

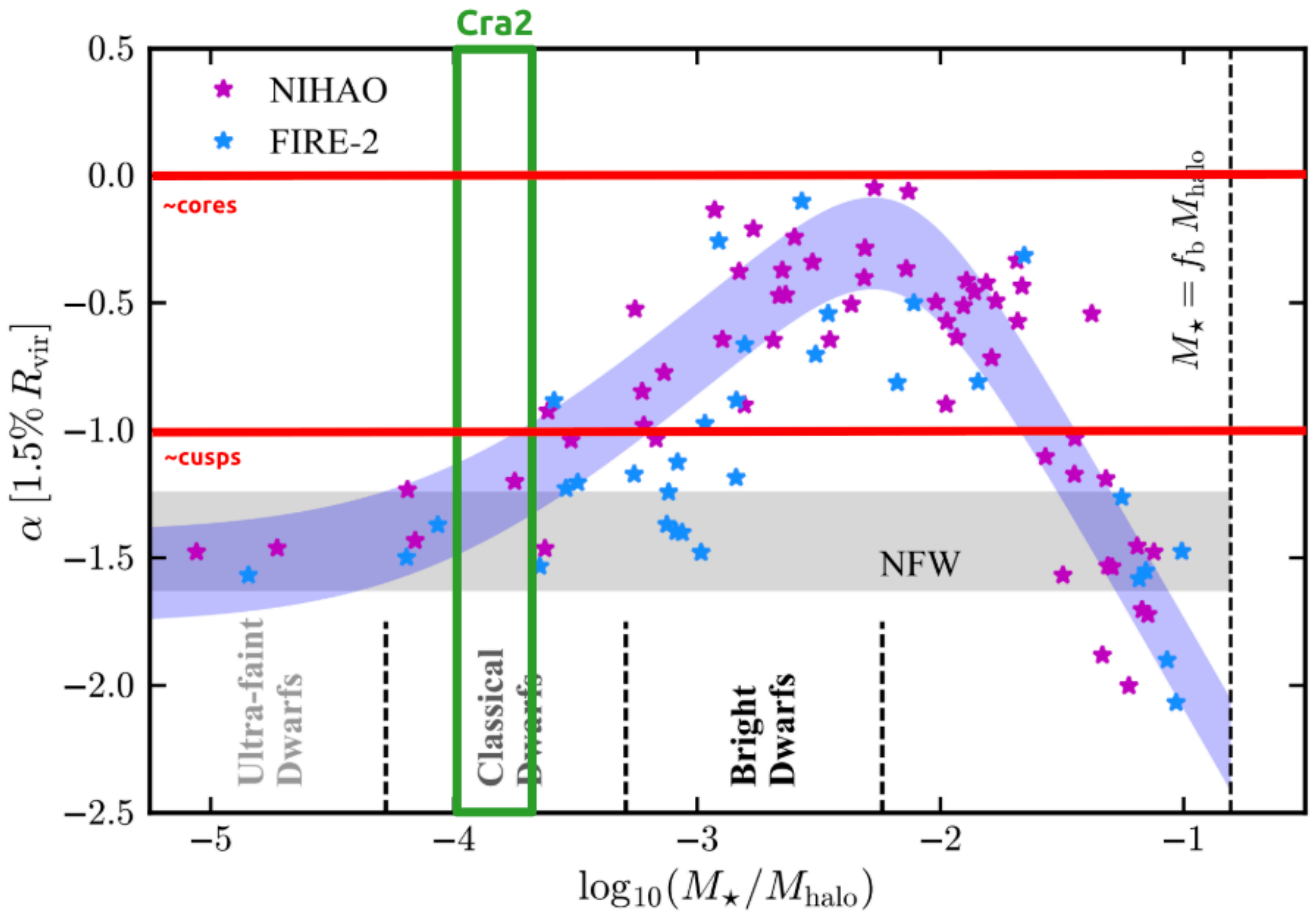




G. Limberg, A. Ji, TSL et al. in prep
(S^5 Collaboration)

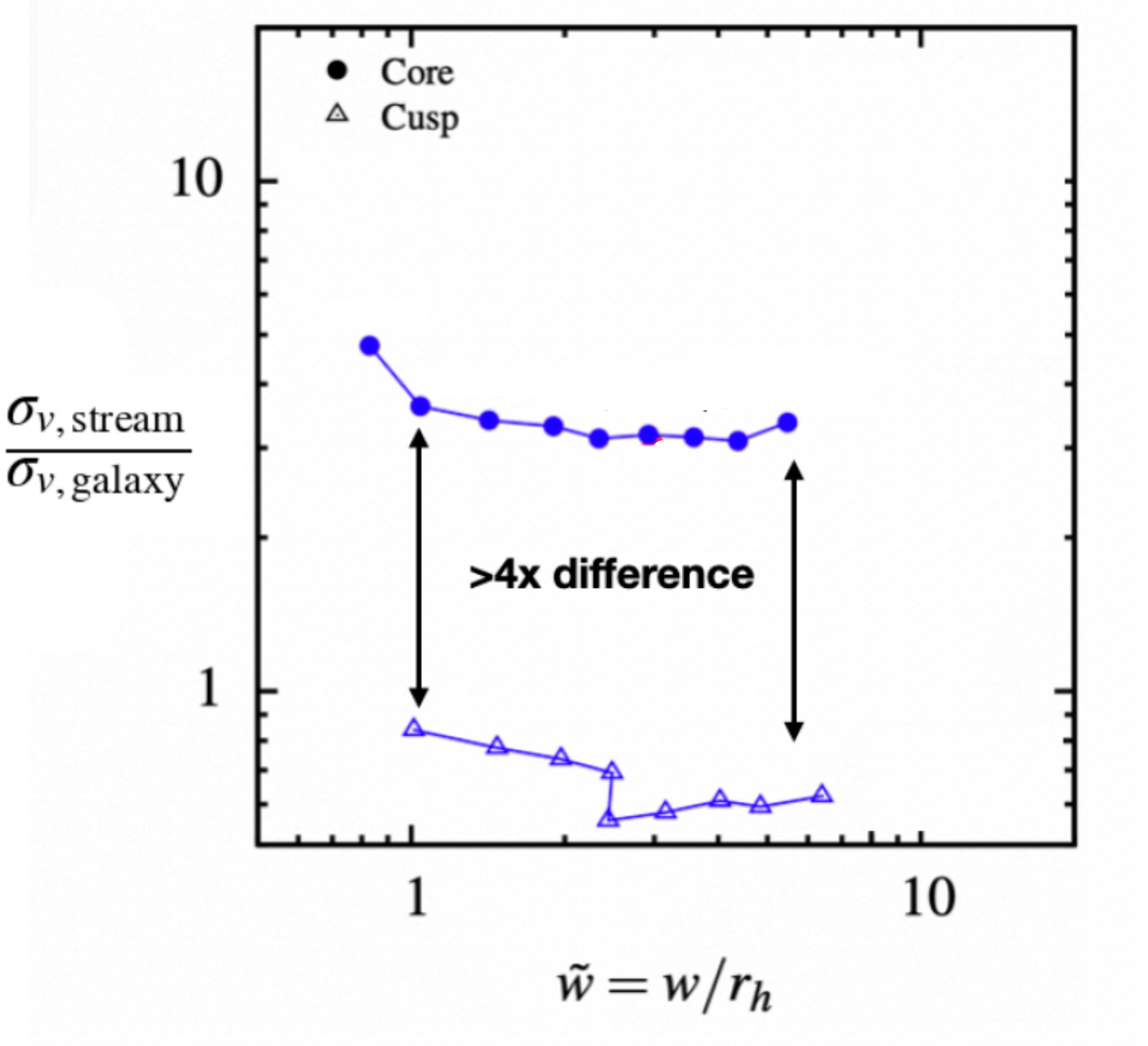
See also Coppi et al. 2024
W/ RRL stars

Milky Way Satellite Galaxies and Cusp/Core

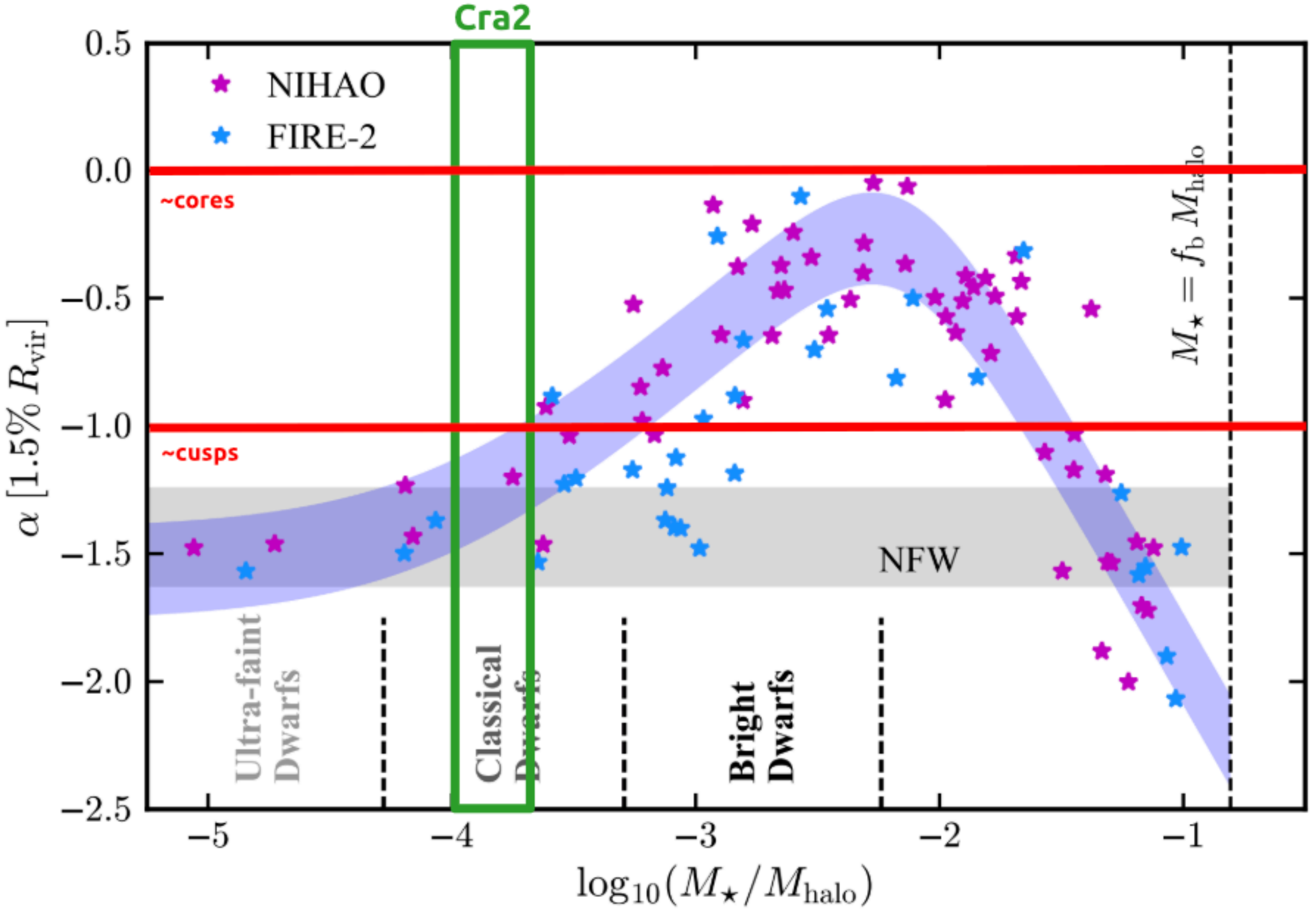


Bullock & Boylan-Kolchin (2017)

Distinguish cusp vs core from tidal tails of Crater 2



Adopted from R. Errani et al. 2015



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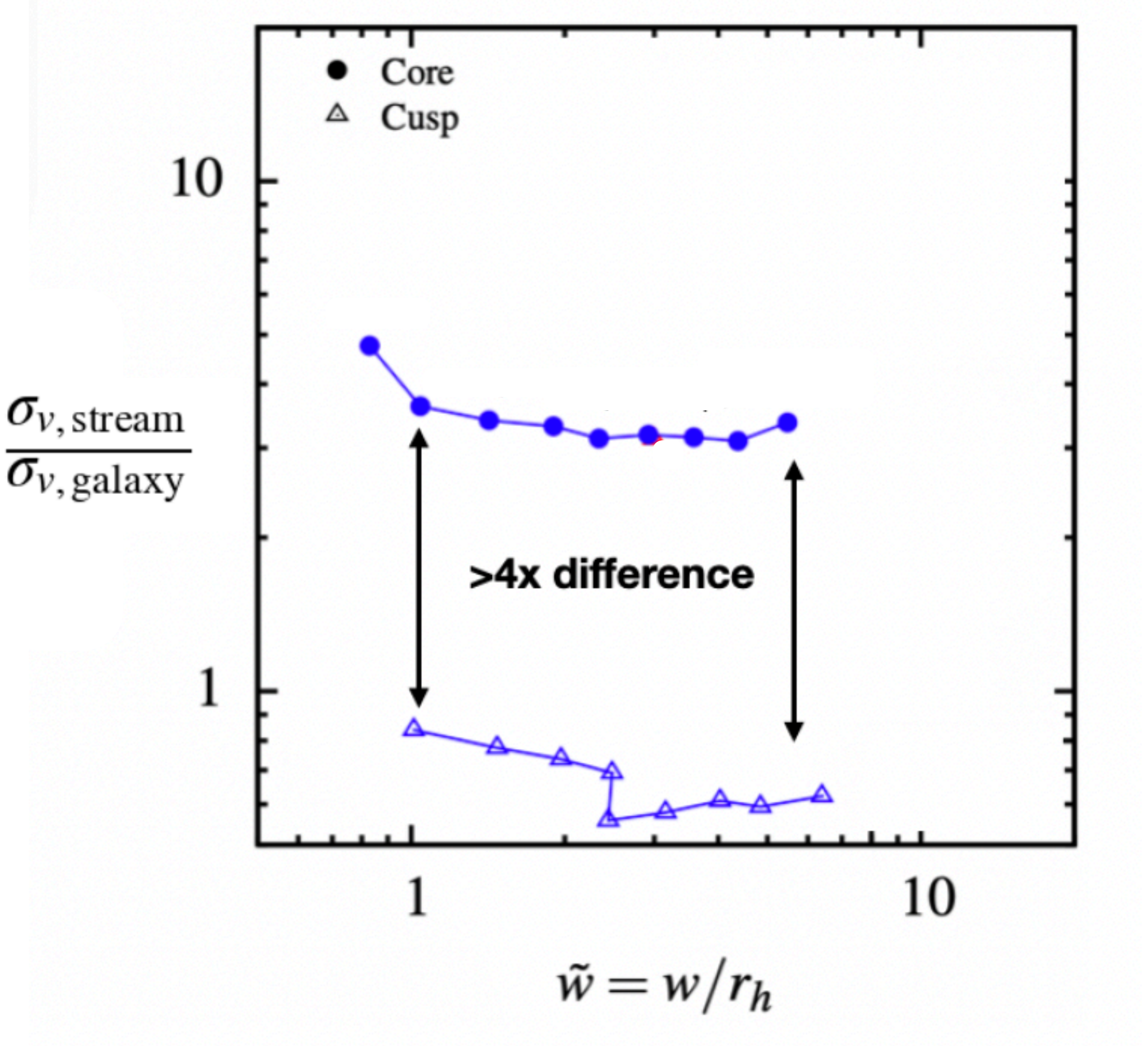

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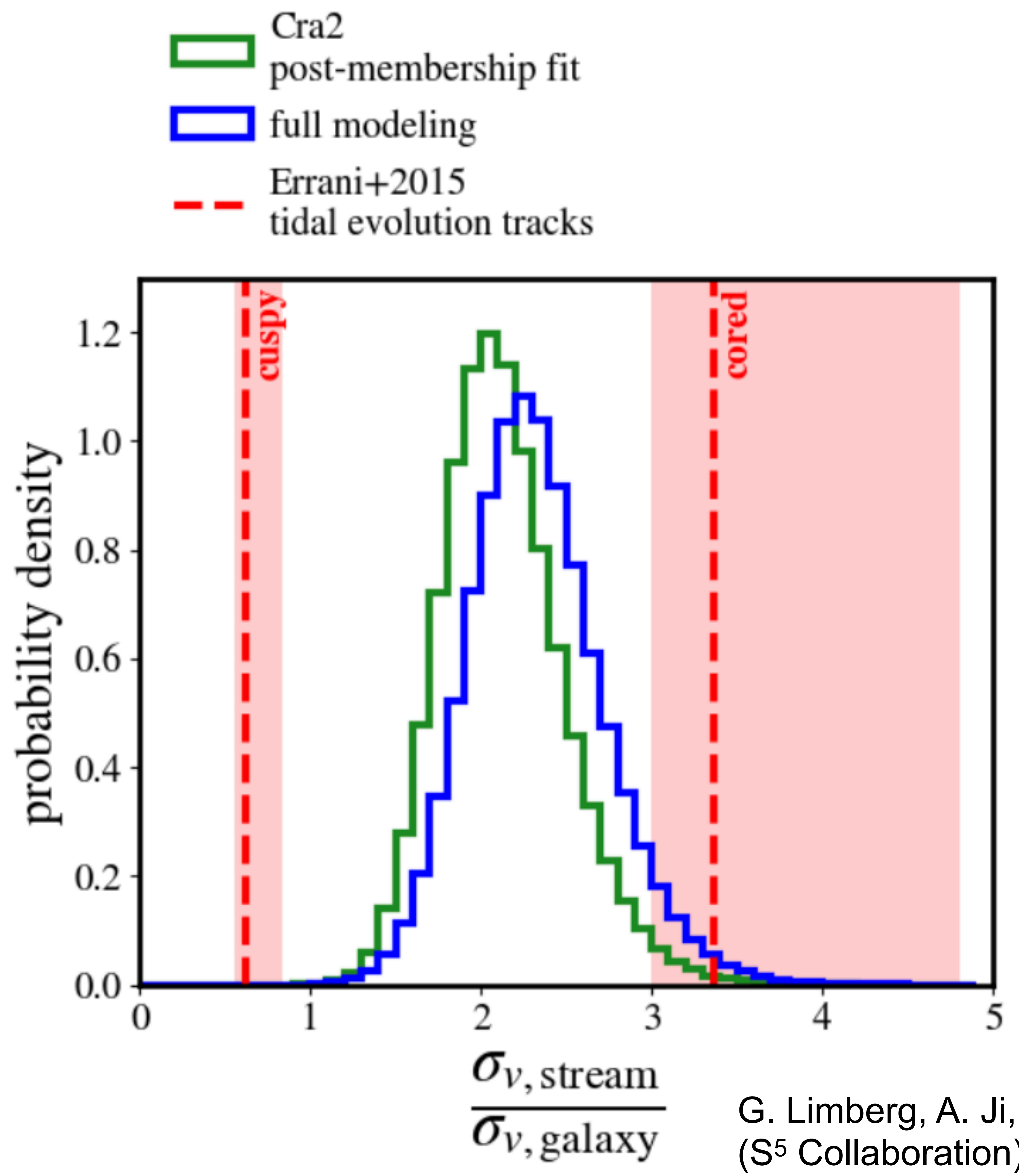
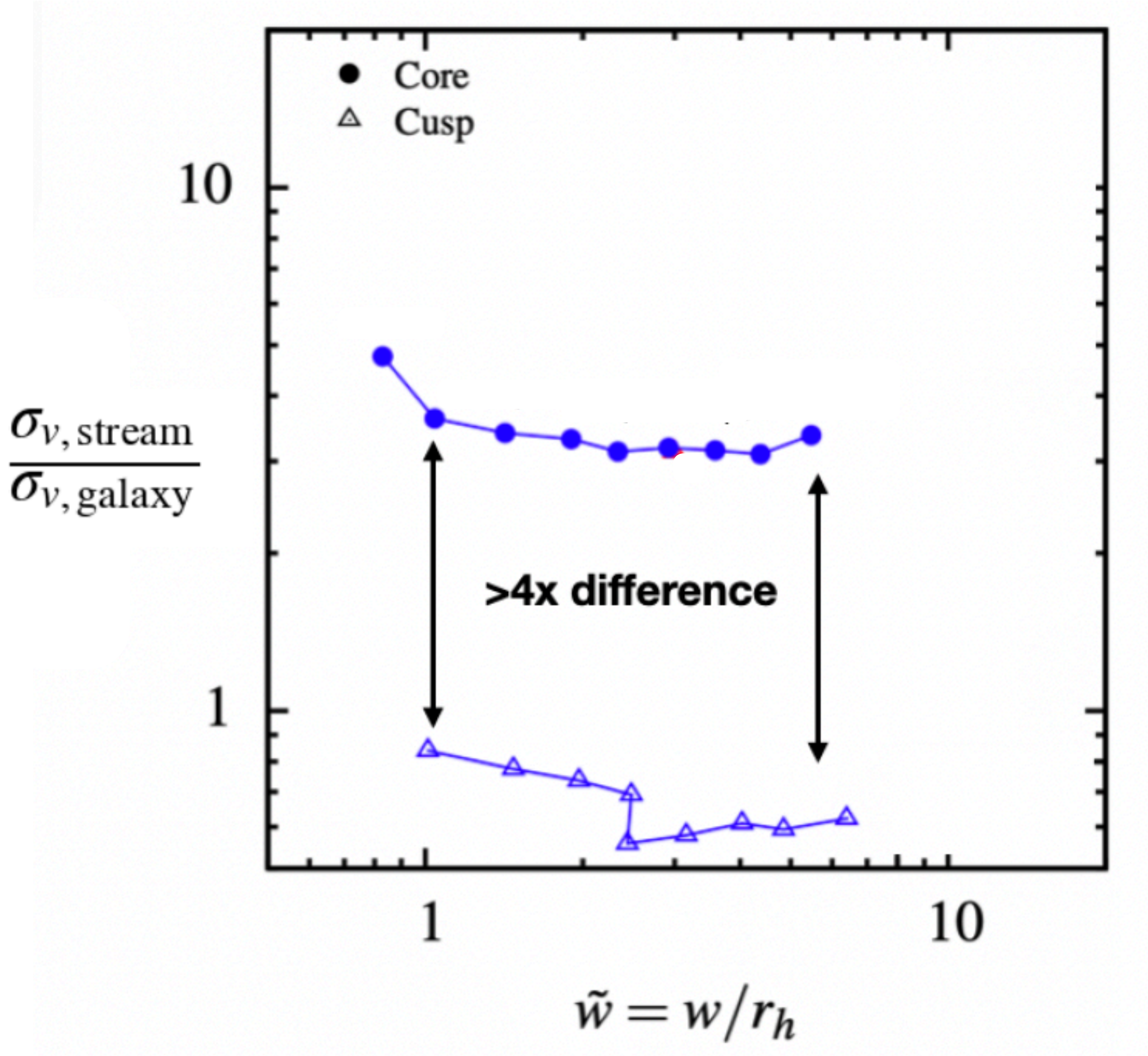


G. Limberg, A. Ji, TSL et al. in prep (S[5] Collaboration)

Question / Assignment 3

- Can we have tailored simulations for the disrupting dwarfs to probe cusp vs core?
- How does this ratio changes vs density profile?



Adopted from R. Errani et al. 2015

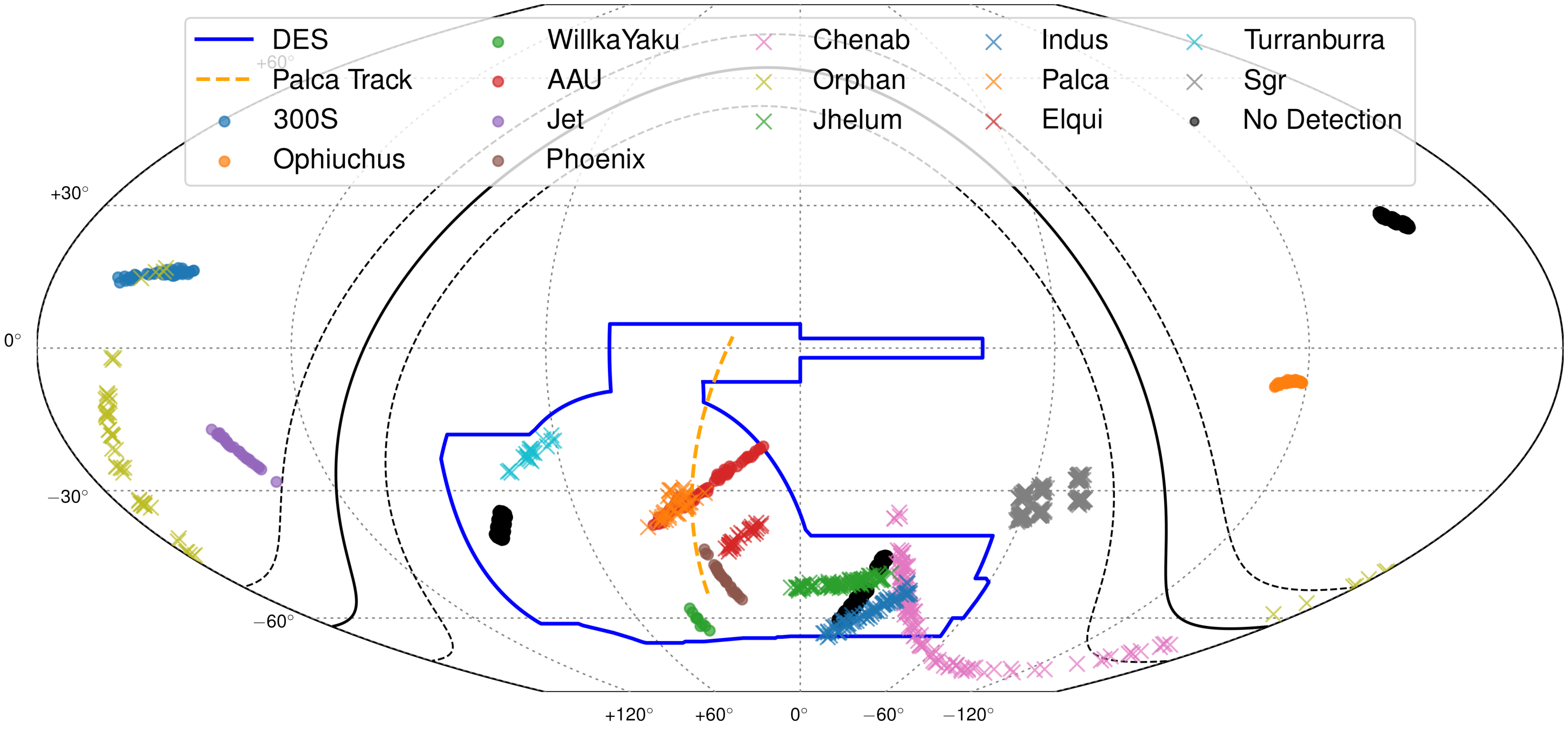
Outline

Recent observational results in the Milky Way

- Intact(?) Ultra Faint Dwarf Galaxies (UFDs)
- Intact(?) Ultra Faint Compact Systems (UFCSs)
- Disrupting Dwarf Galaxies — Ultra Diffuse Galaxies (UDGs)?
- Disrupted Dwarf Galaxies — Stellar Streams

Goal: Can we learn anything about dark matter from these observations?

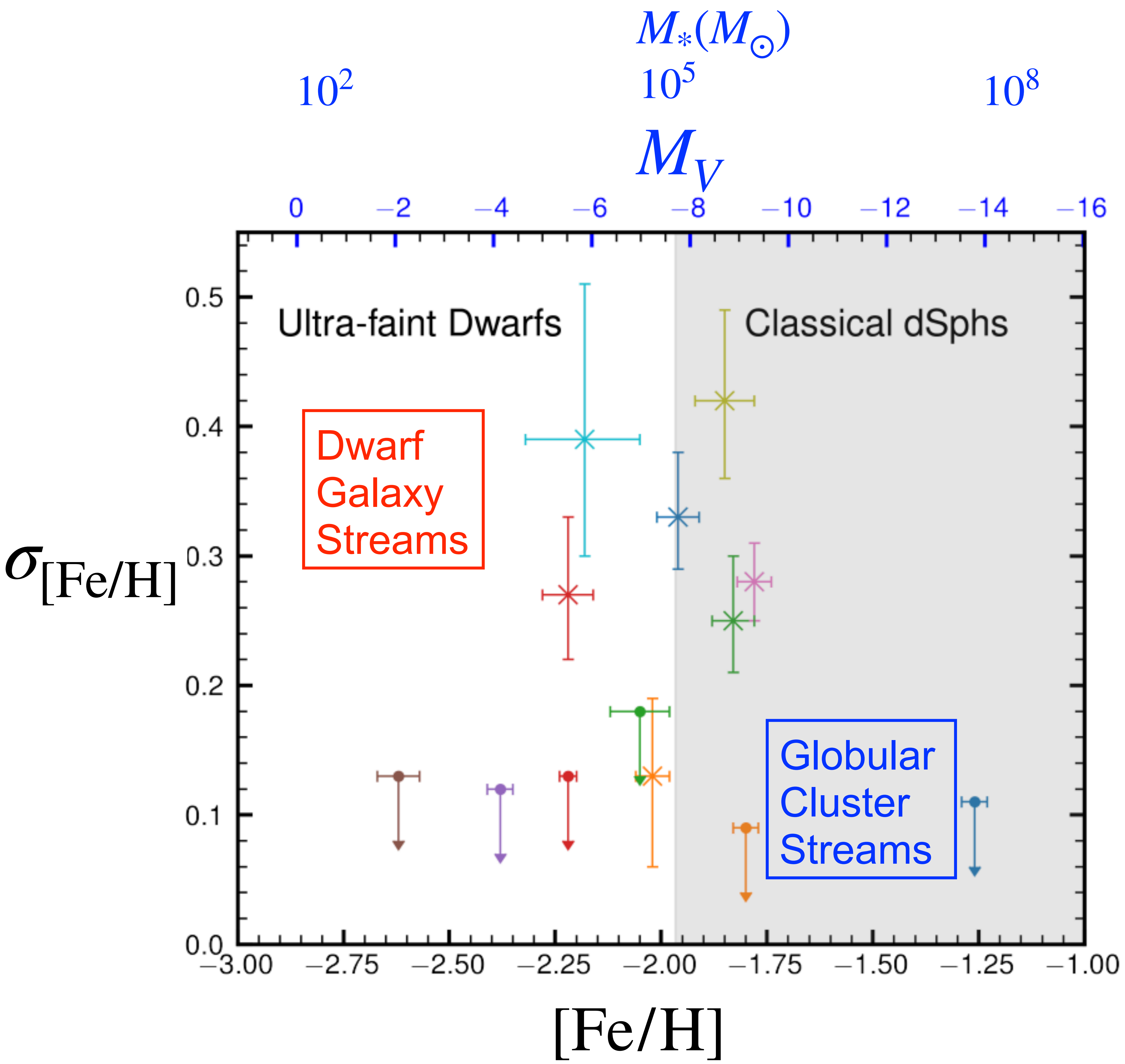
Orbital and Chemical Properties of Stellar Streams



S5: The Orbital and Chemical Properties of One Dozen Stellar Streams
TSL et al (2022), arXiv: 2110.06950
(S^5 collaboration)

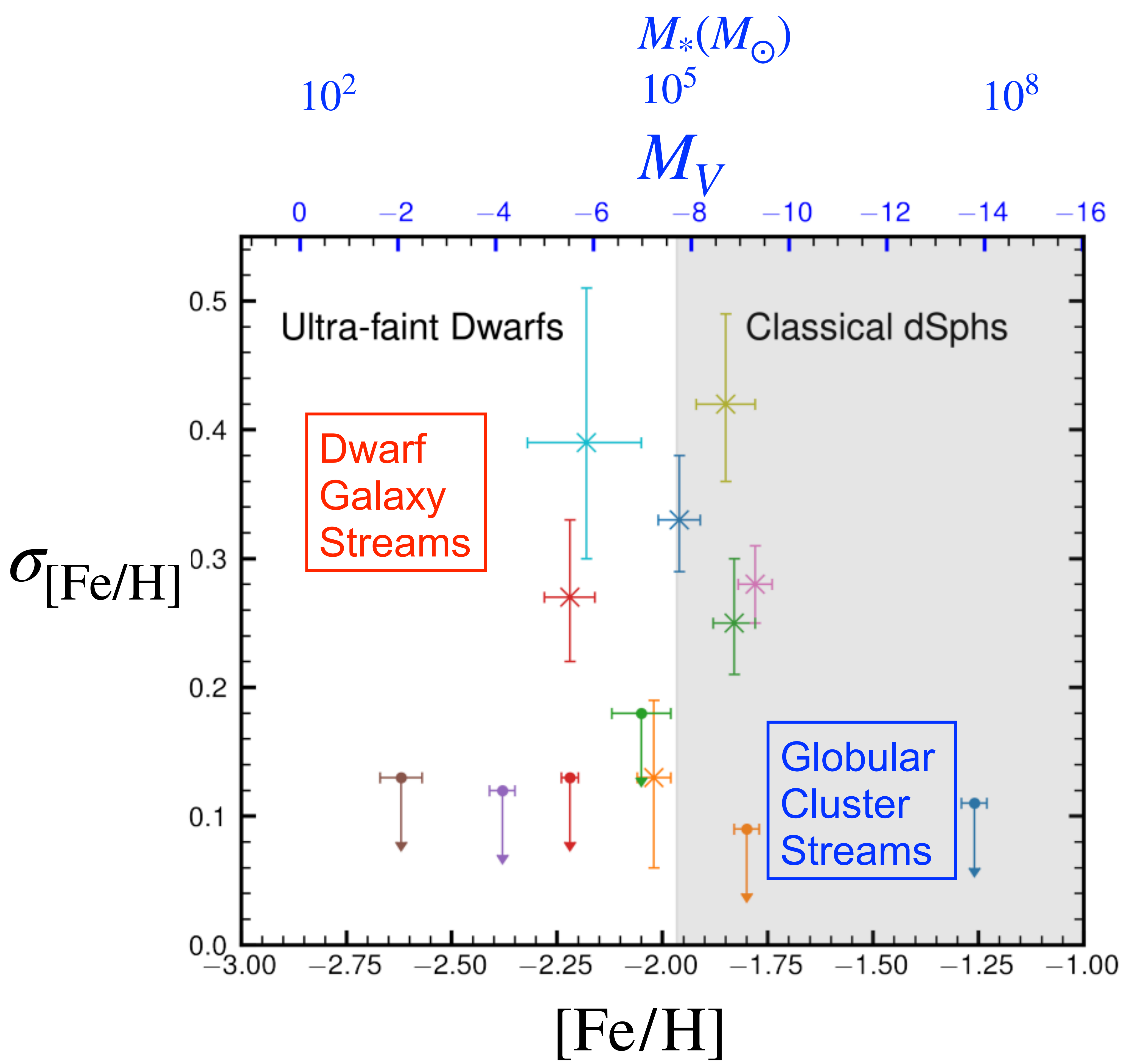
12 progenitor-free stellar streams at ~10-50 kpc
6 of them are dwarf galaxy streams

Luminosity / Stellar Mass of the Stream Progenitors



TSL et al (2022)
(S^5 Collaboration)

Luminosity / Stellar Mass of the Stream Progenitors



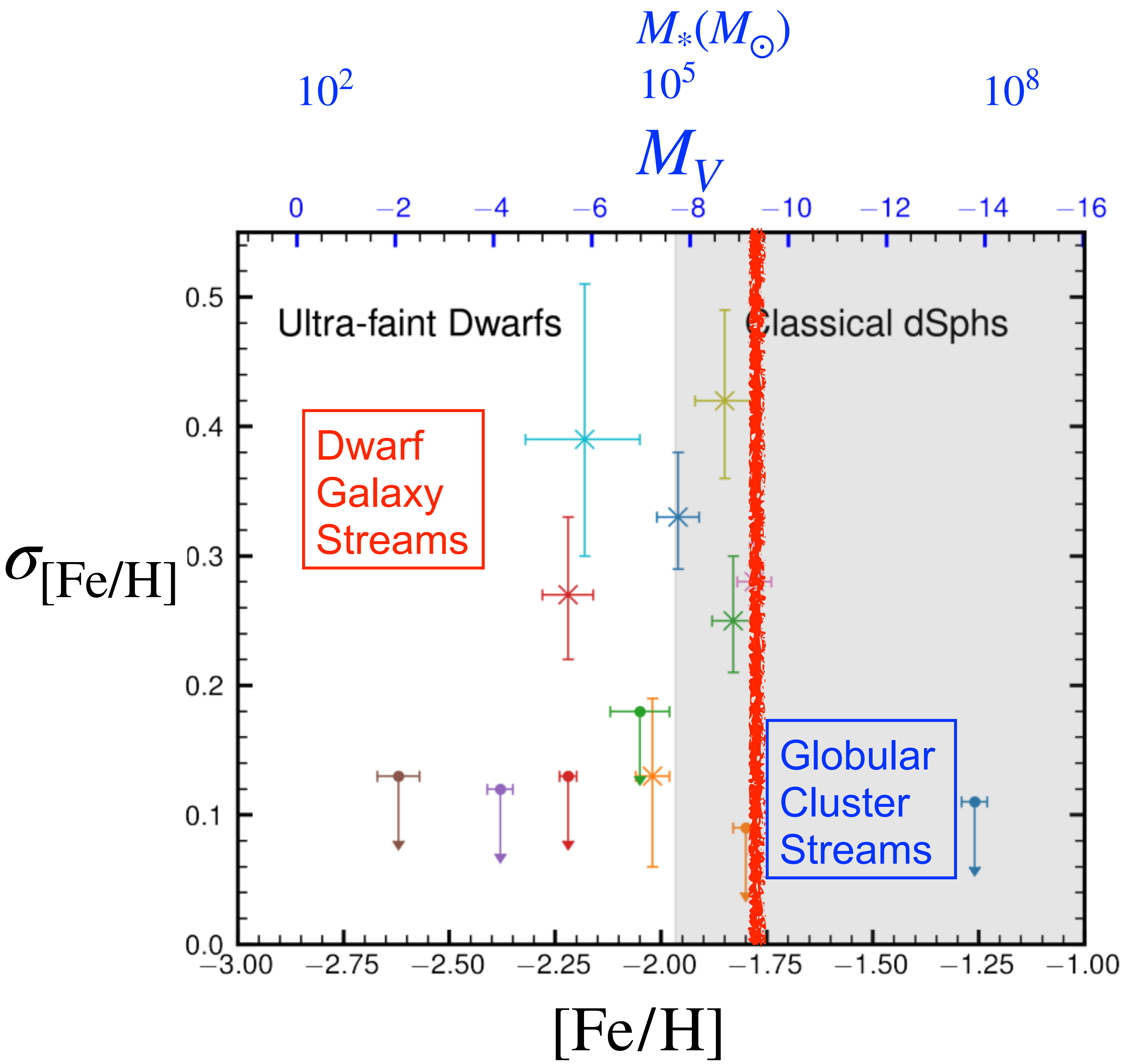
TSL et al (2022)
(S^5 Collaboration)

# of stream at > 5 x10^5 $M_\odot$
Predicted by FIRE-2 simulation

sim name	$m_{200m}[M_\odot]$	r_{200m}[kpc]	N
m12i	1.18×10^{12}	336	9
m12f	1.71×10^{12}	380	8
m12m	1.58×10^{12}	371	8
m12c	1.35×10^{12}	351	7
m12b	1.43×10^{12}	358	8
m12r	1.10×10^{12}	321	3
m12w	1.08×10^{12}	319	3
Romeo	1.32×10^{12}	341	13 [10]
Juliet	1.10×10^{12}	321	12 [6]
Romulus	2.08×10^{12}	406	9 [6]
Remus	1.22×10^{12}	339	8 [5]
Thelma	1.43×10^{12}	358	10 [9]
Louise	1.15×10^{12}	333	8 [8]

Panithanpaisal et al. (2021)

Luminosity / Stellar Mass of the Stream Progenitors



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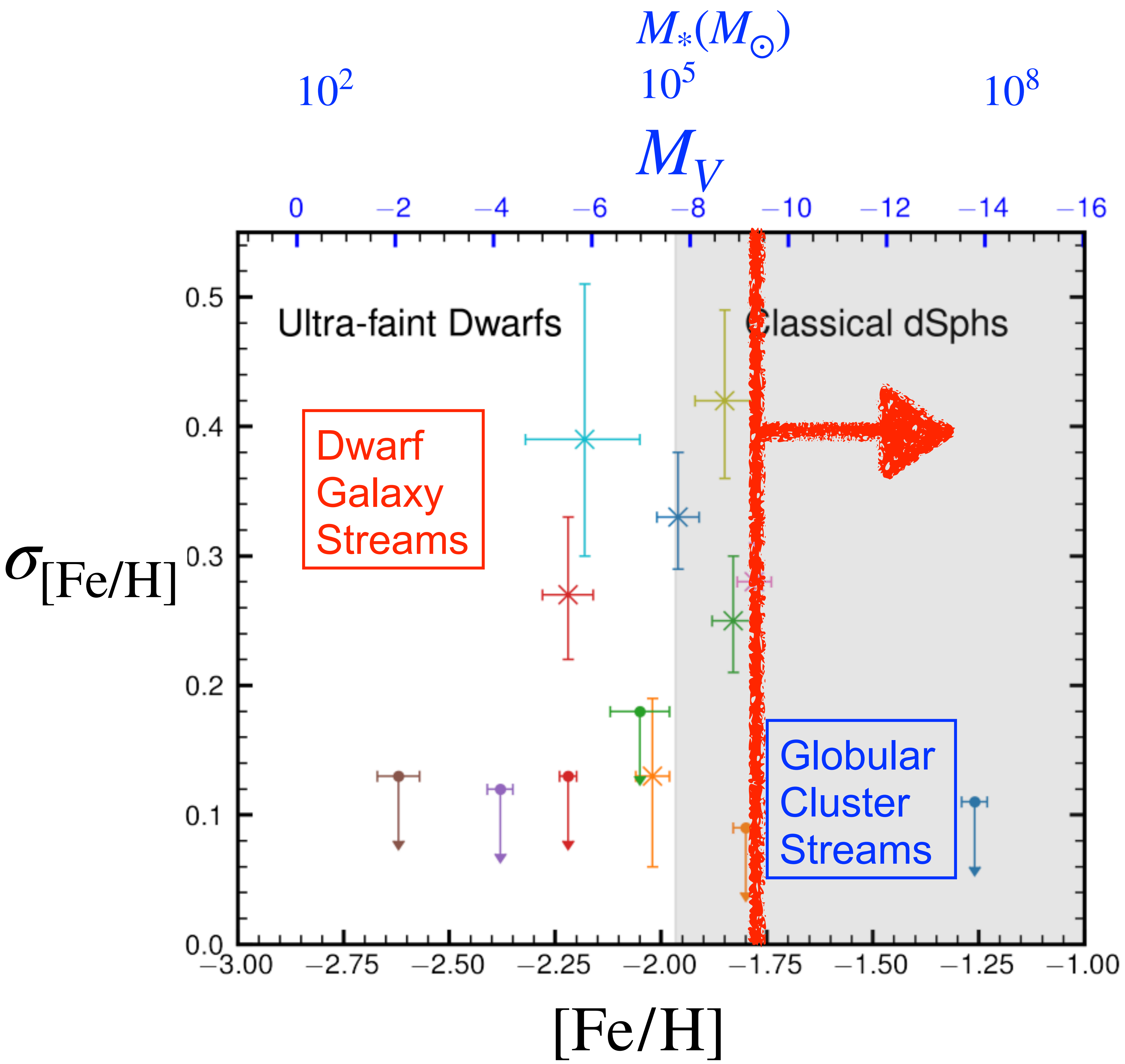
Panithanpaisal et al. (2021)

“Too Big to Fail” in Stream?



Only 1 stream at this mass range — Sagittarius Stream @ [Fe/H] = -0.5

(No galaxy stream between [Fe/H] = -0.5 And [Fe/H] = -1.8)

TSL et al (2022) (S^5 Collaboration)

# of stream at > 5 x10^5 $M_\odot$ Predicted by FIRE-2 simulation

sim name	$m_{200m}[M_\odot]$	r_{200m}[kpc]	N
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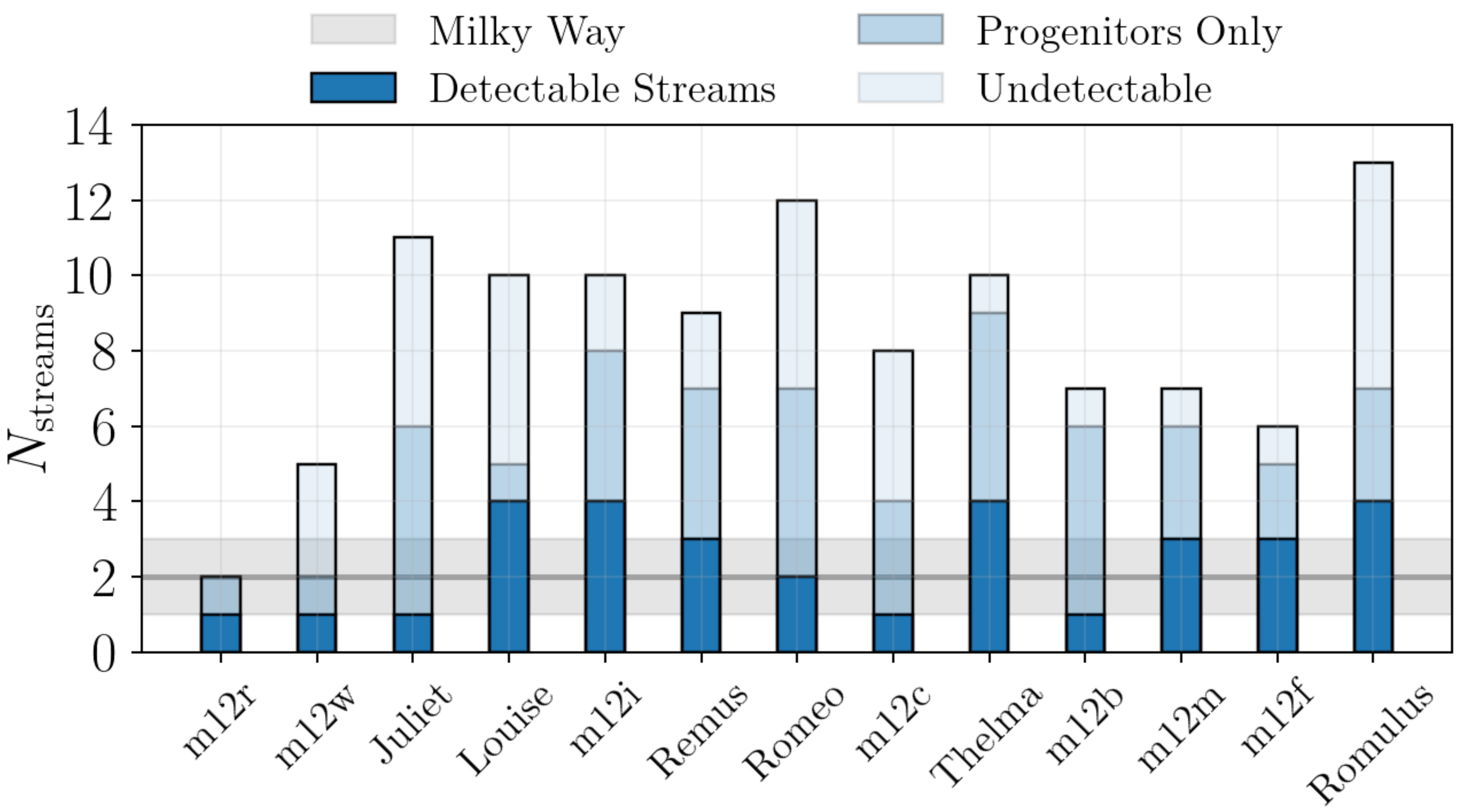
Panithanpaisal et al. (2021)

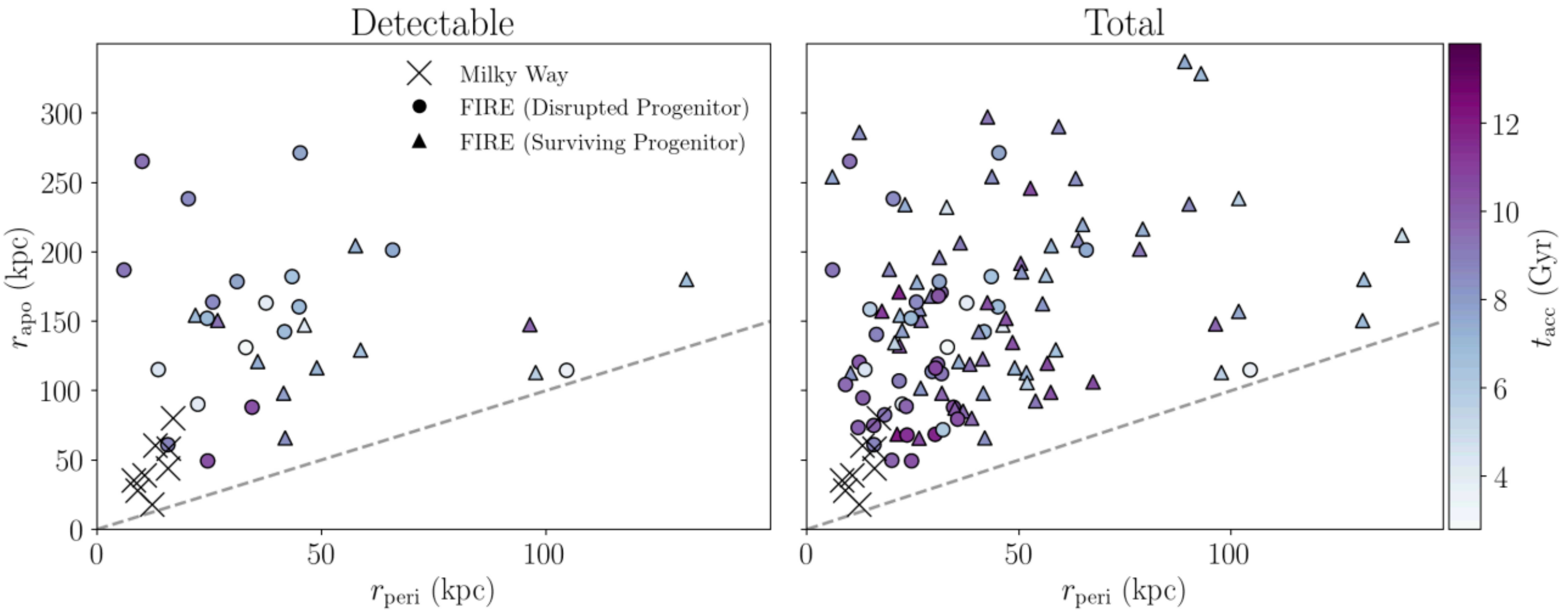
“Too Big to Fail” in Stream?

FIRE-2 matches with observations after detectability is taken into consideration.



N. Shipp et al. w/ TSL (2022)

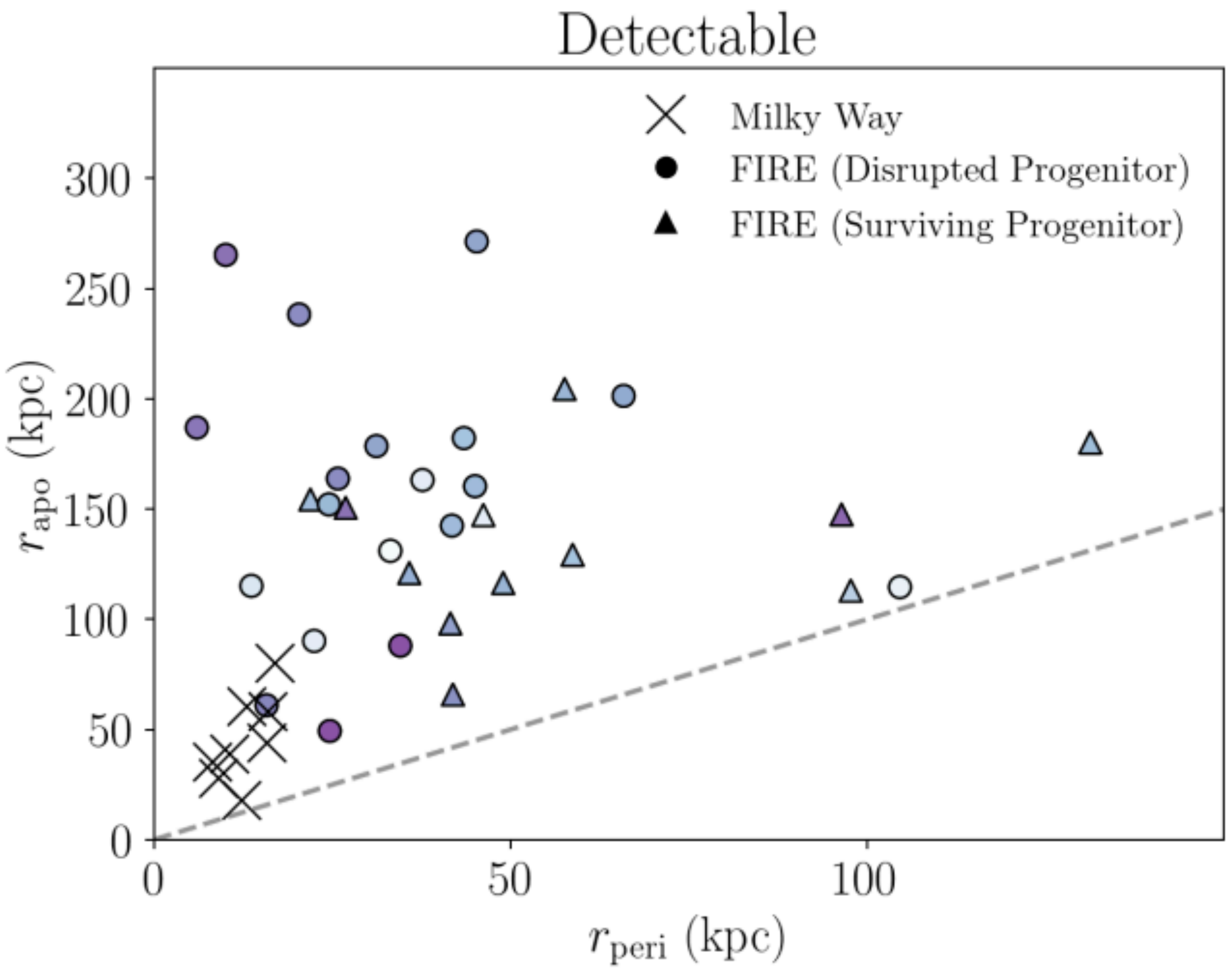
Over-disruption due to Artificial Disruption or Galaxy Too Puffy?



N. Shipp et al. w/ TSL (2022)
Also see A. Riley et al. 2024 & N. Shipp et al. 2024 for comparison w/ Auriga simulation

Question / Assignment 4

- Is there an over-disruption in the galaxy simulations?
- Is it caused by artificial disruption or galaxy too puffy from stellar feedbacks?
- Or SIDM? (e.g dynamical friction, core collapse?)



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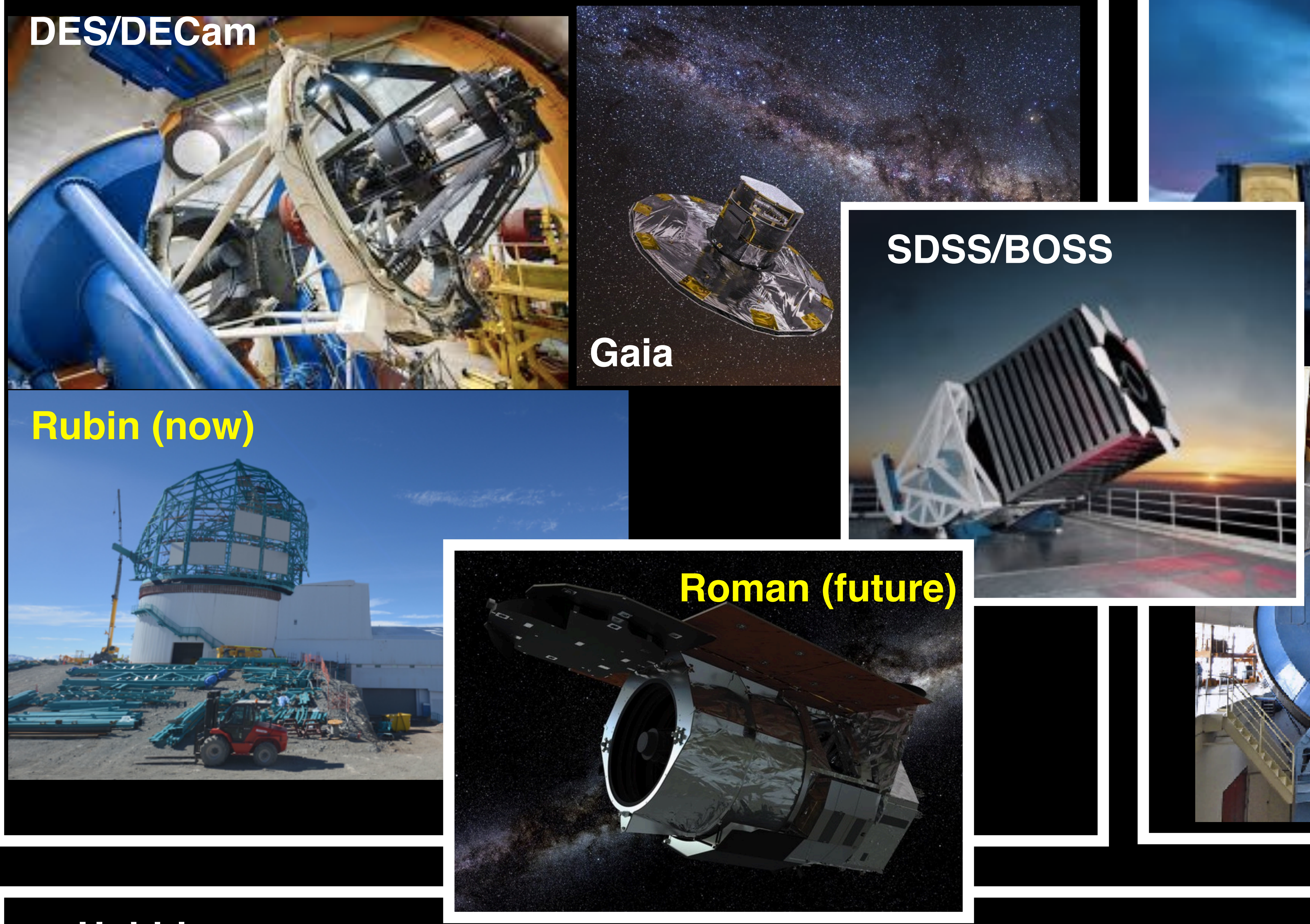
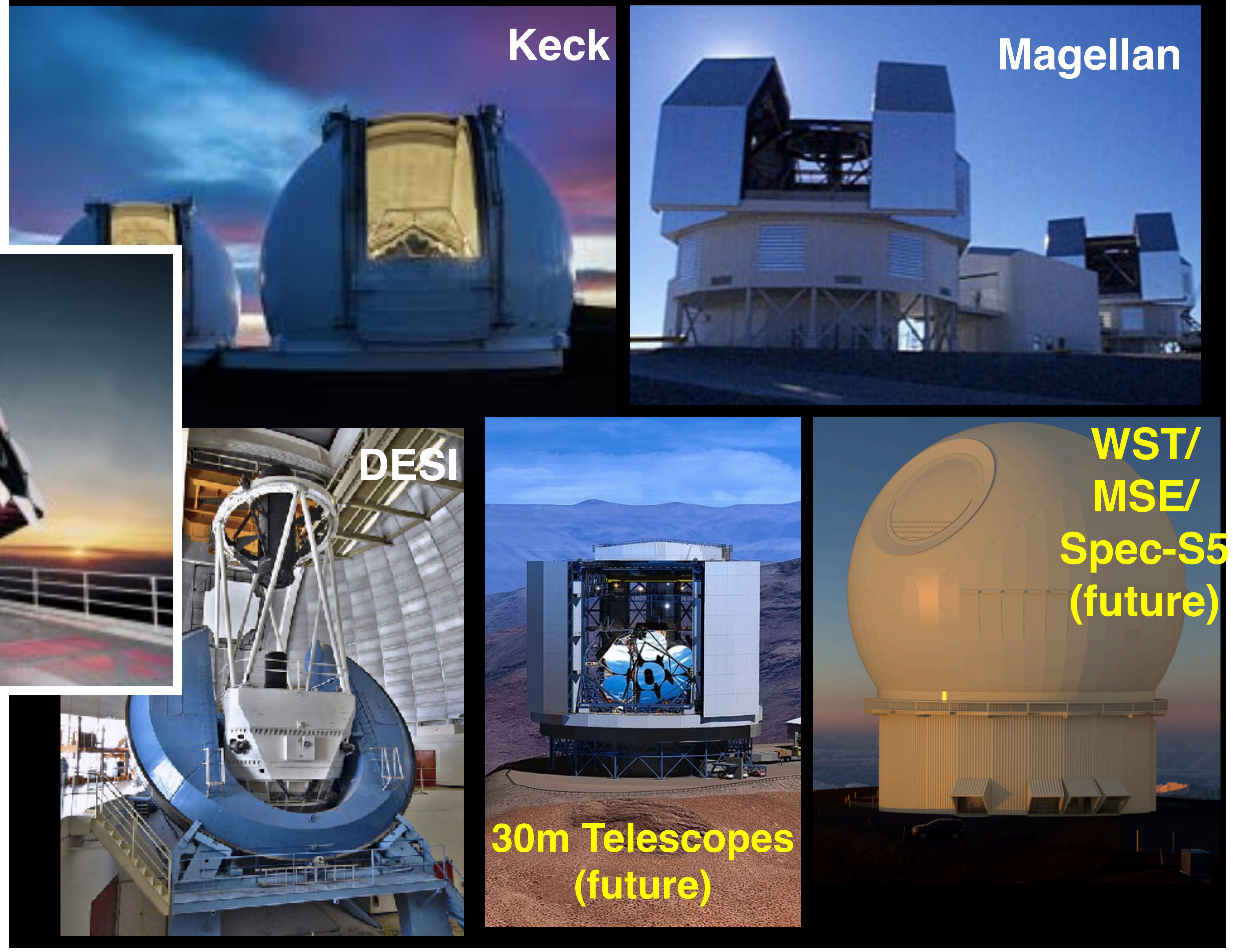
Goal: Can we learn anything about dark matter from these observations?

Current and Near-Future Experiments

Wide-Area Imaging



Spectroscopic Measurements



High Resolution Imaging

Credit:
Alex Drlica-Wagner

Take away Messages

Our findings

- We find a (tentative) cuspy density profile in the UFDs
- We believe a significant amount of these UFCSs are galaxies.
- We identify tidal tails around some galaxies and measure their kinematics
- We notice a mismatch between observations and simulations in the orbits of the disrupted dwarf galaxies / stellar streams.

Goal: Can we learn anything about dark matter from these observations?

Take away Messages

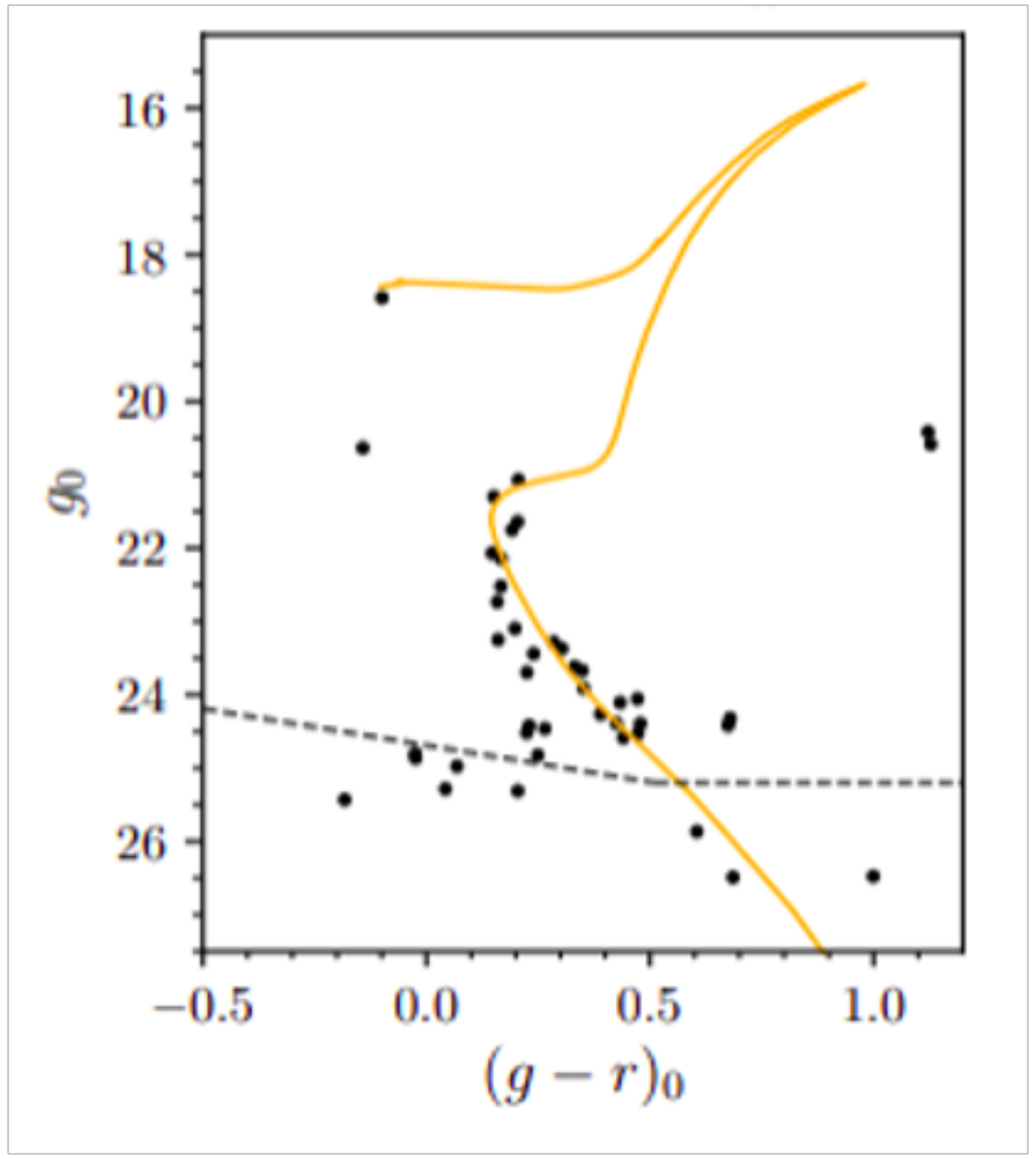
My wishlist / assignments for you:

- Can we compute the SIDM cross section at UFD scale using stellar kinematics?
- If compact satellites are indeed from SIDM core collapse, what is the expected velocity dispersions and mass to light ratio within half-light radius?
- Can we have tailored simulations for the disrupting dwarfs to probe cusp vs core?
- Is there an over-disruption in the galaxy simulations? Artificial disruption? galaxy too puffy from stellar feedbacks? or SIDM?

Backup slides

Some Illustatives of UFSCs

DELVE 5



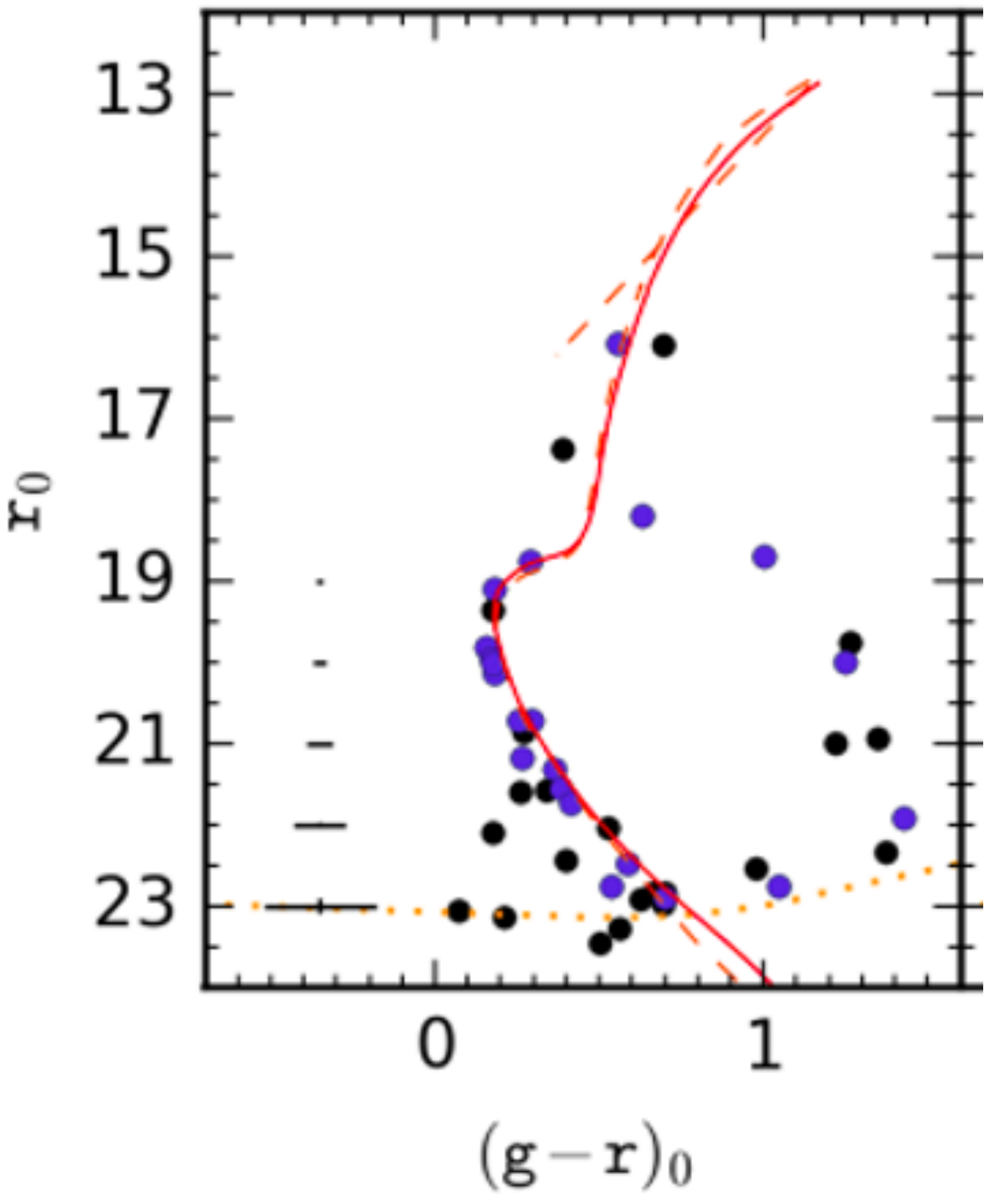
Mstar ~ $100 M_\odot$

rh = 5 pc

d = 39 kpc

Cerny w/ TLS et al. 2023

Kim 3



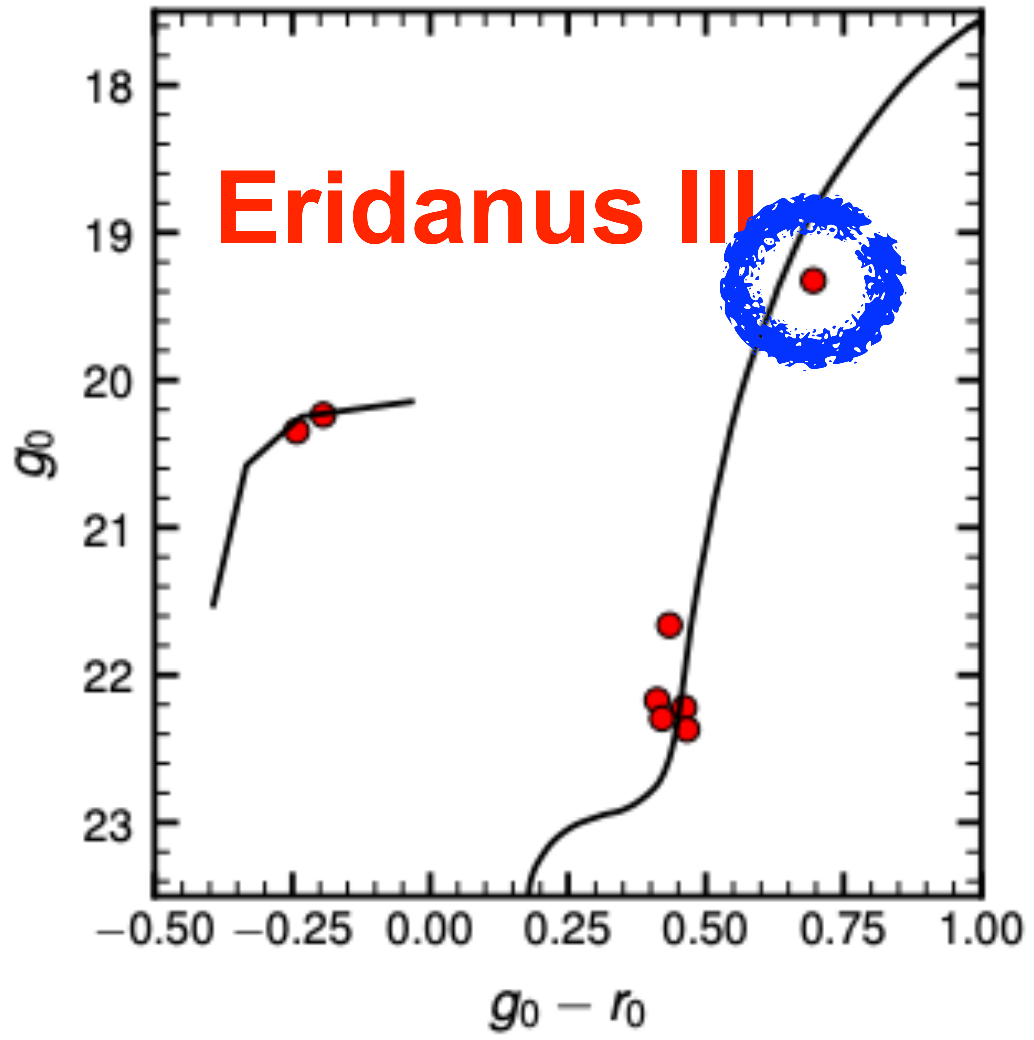
Mstar ~ $50 M_\odot$

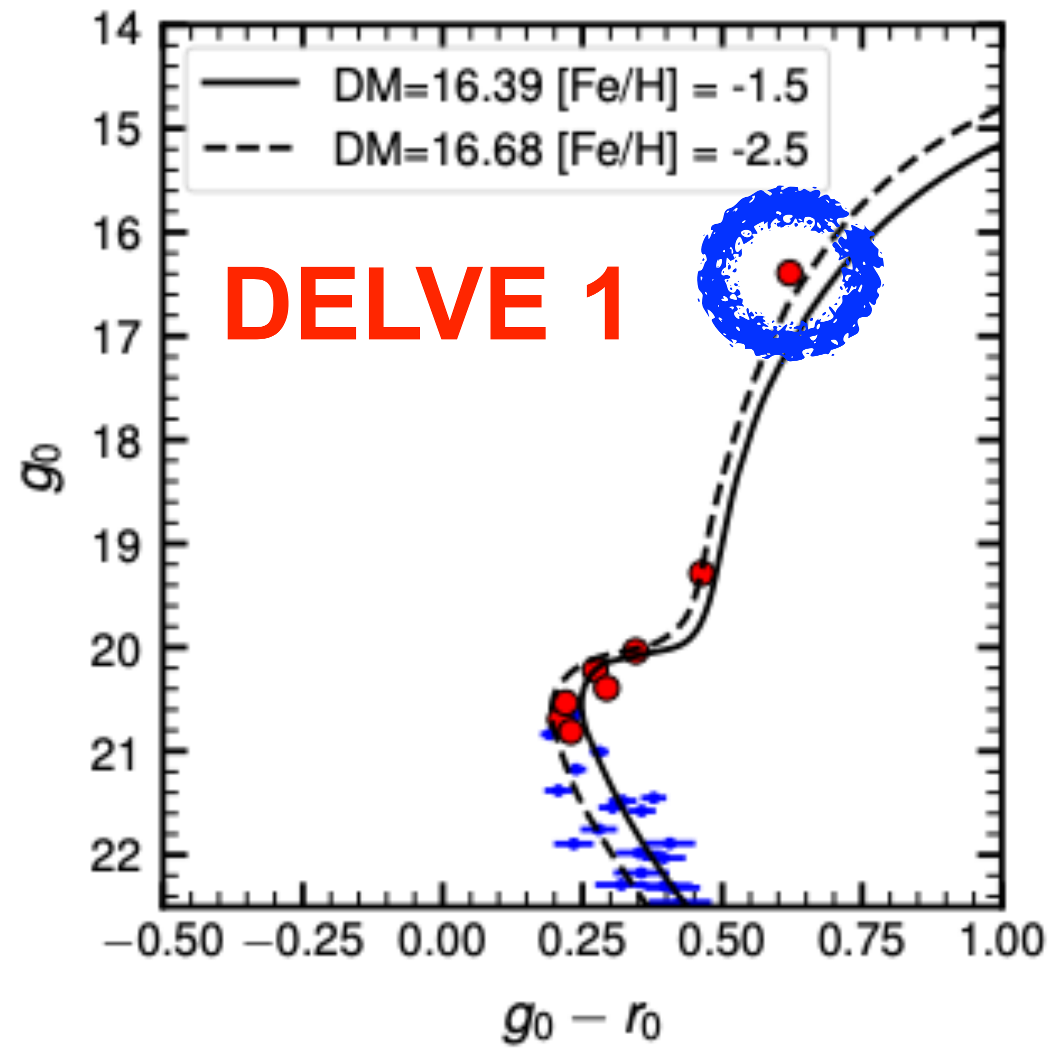
rh = 2 pc

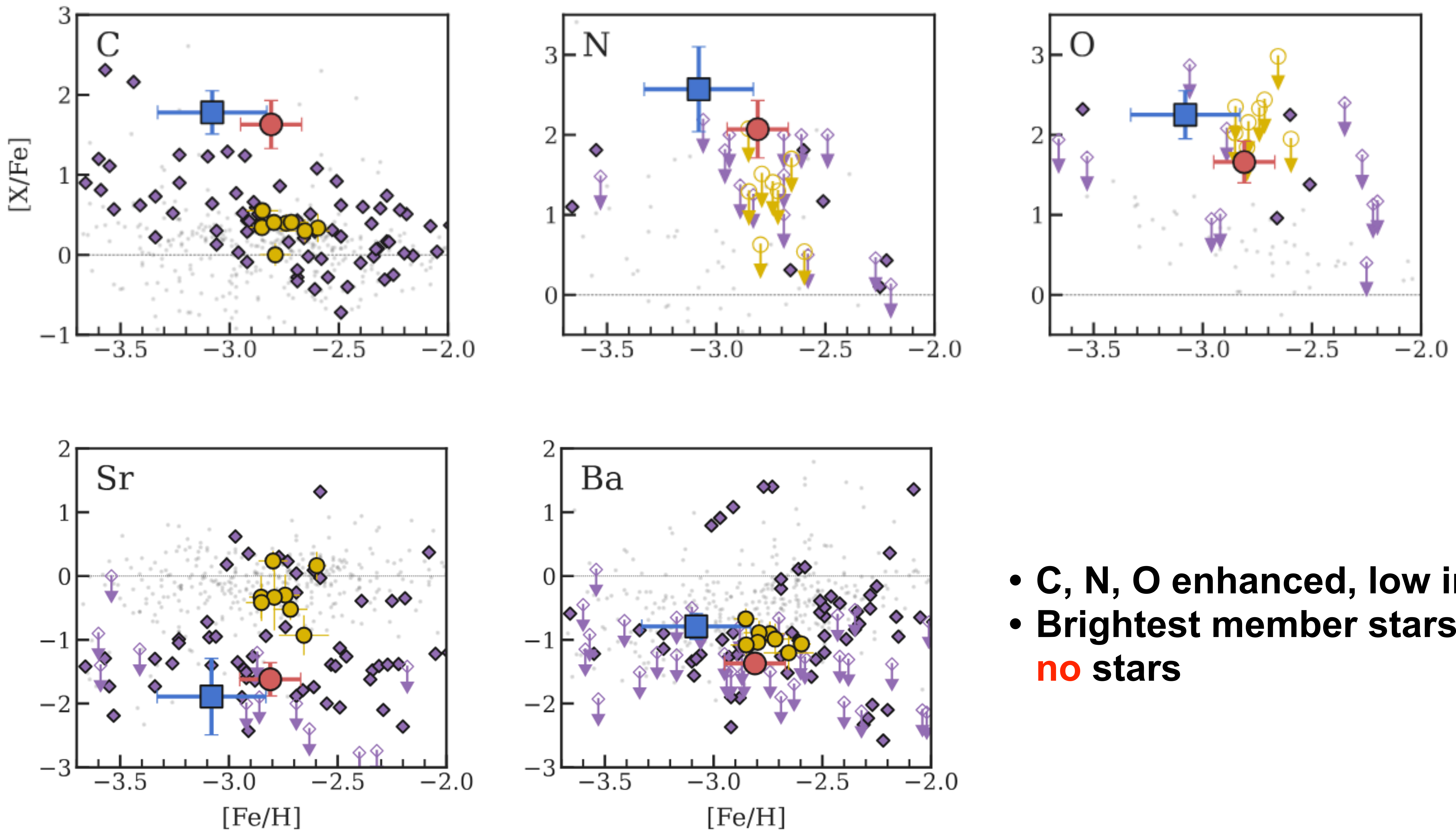
d = 15 kpc

Kim et al. 2016

Carbon-rich Primordial Star Clusters or the Smallest Dwarf Galaxies?



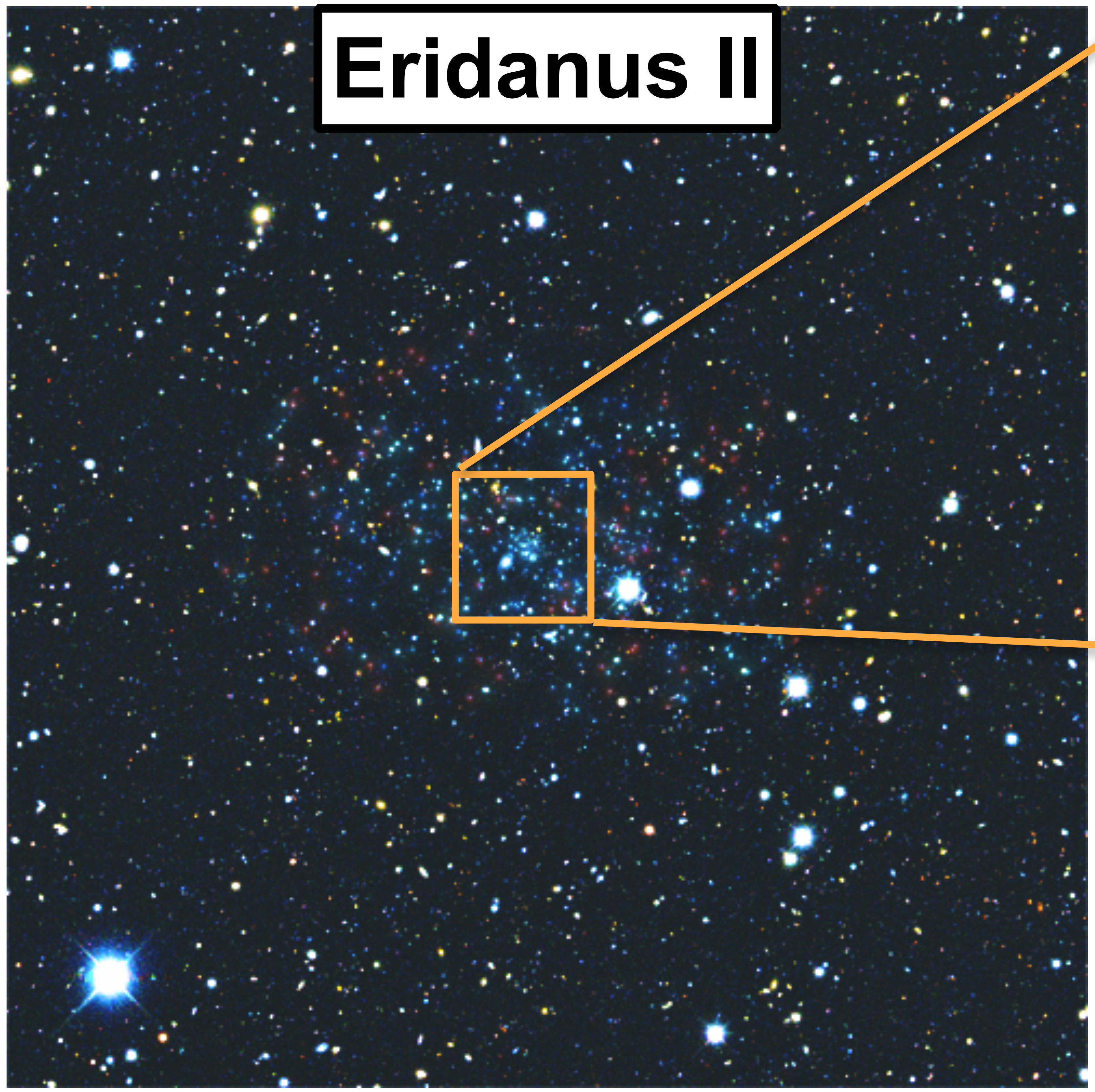




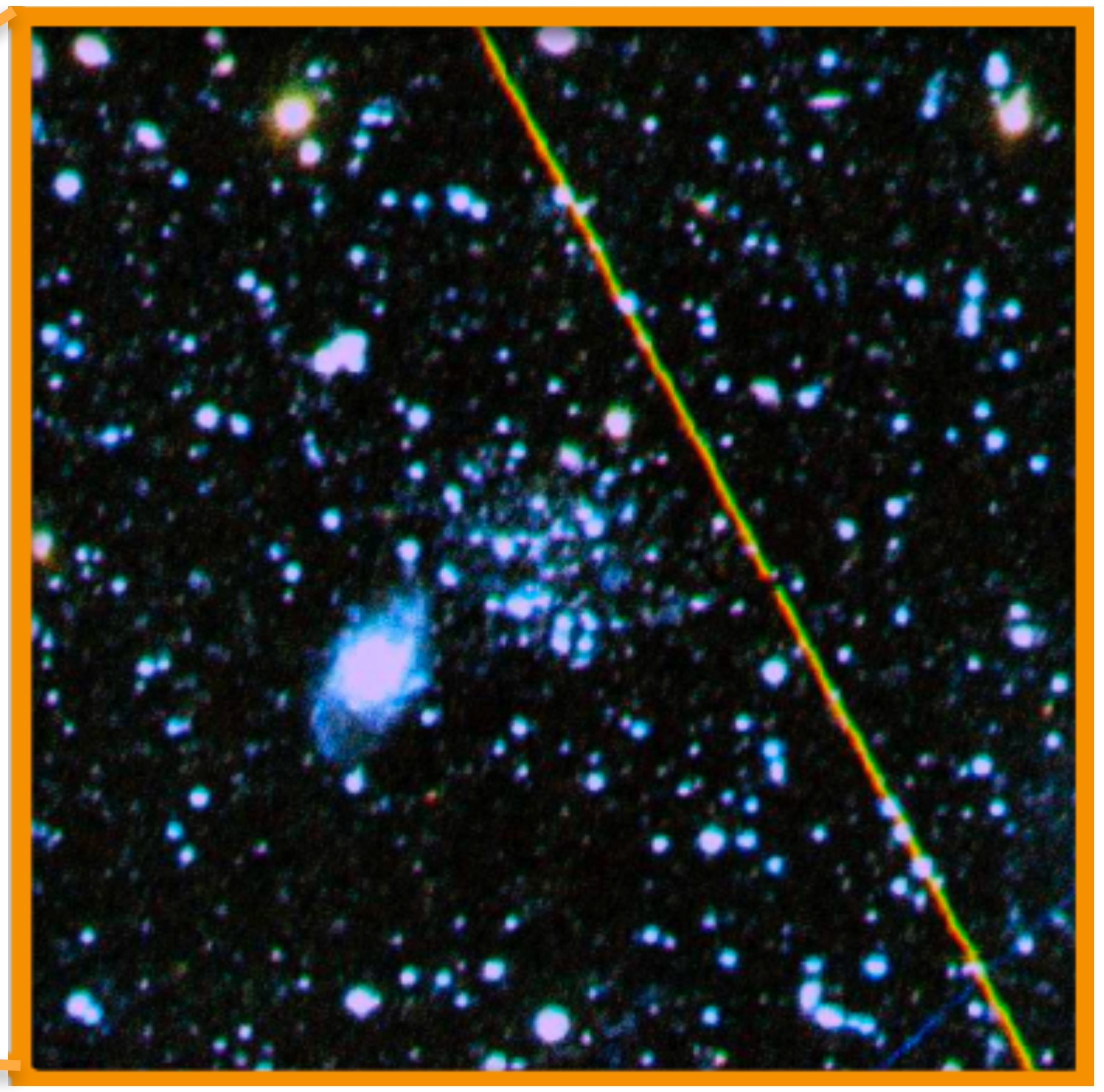
- C, N, O enhanced, low in Sr and Ba
- Brightest member stars are CEMP-no stars

Simon, TSL et al. 2024, arXiv:2410.08276

UFCSs are Remnant of the nuclear star cluster (NSC) of UFD?



Credit: Belokurov & Koposov

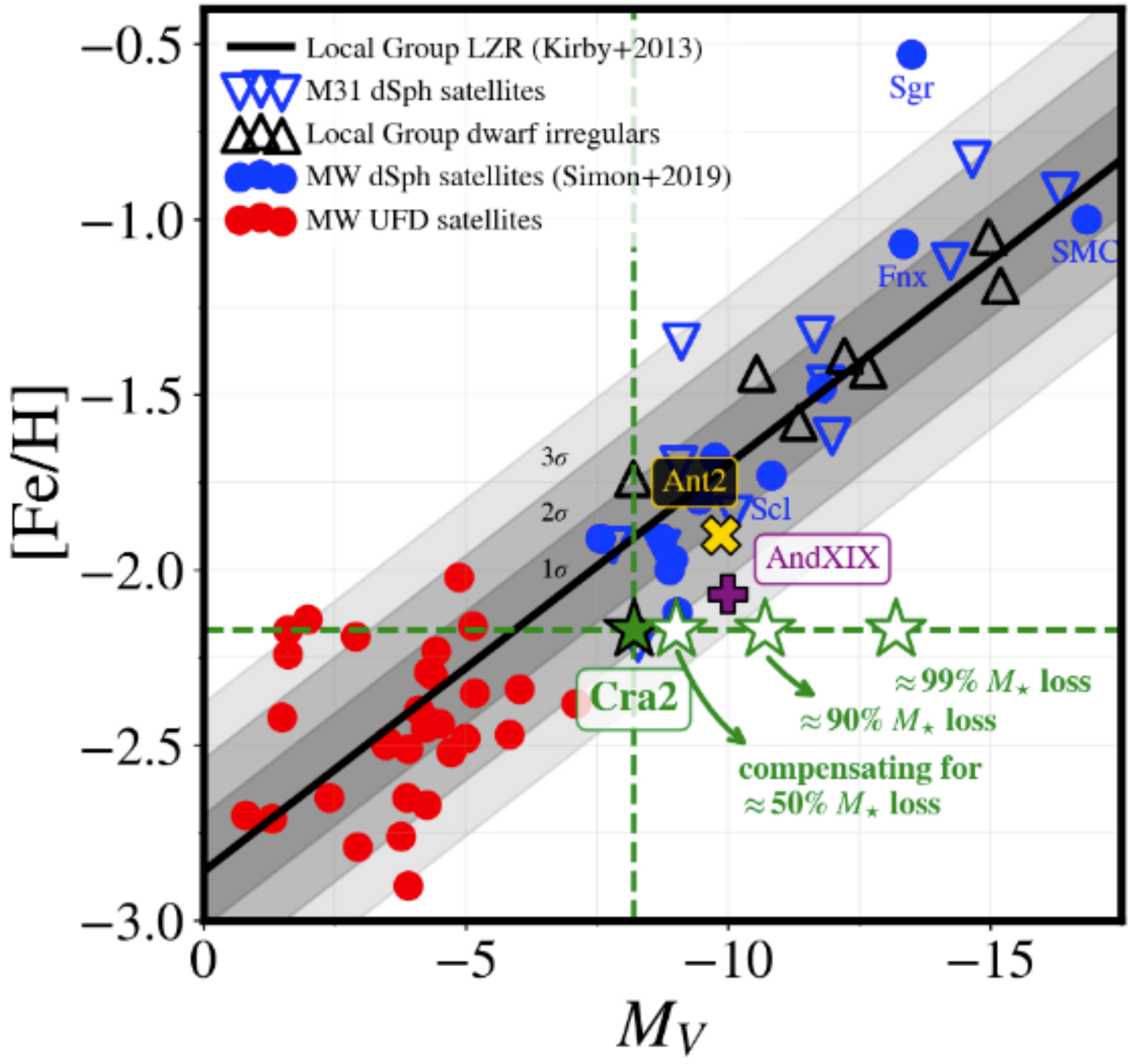


Crnojevic et al. 2016

- Distance ~ 400 kpc
- Galaxy Mstar ~ $10^5 - 10^6 M_\odot$
- (Central) Star Cluster:
  - Mstar ~ $10^3 - 10^4 M_\odot$
  - rh = 15 pc

Weisz et al. 2023
Fu, Weisz et al. 2022
Simon et al. 2021
TSL, Simon et al. 2017
Crnojevic et al. 2016
Bechtol et al. 2015
Koposov et al. 2015
and many more….

Crater 2 is also not following the MZR relation — some weird star formation process?

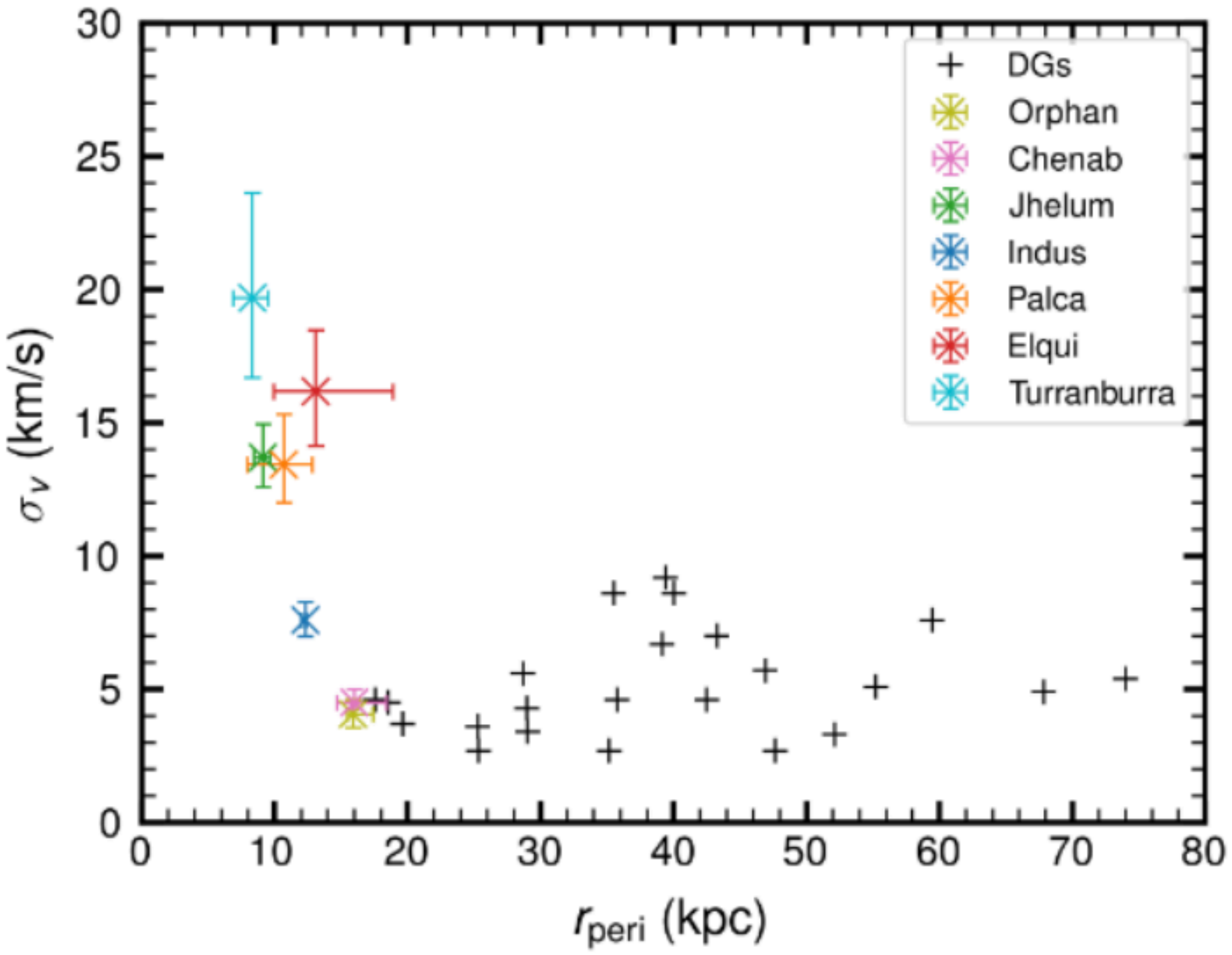


MZR: mass-metallicity relation

Compensating for mass loss makes these galaxies even worse outliers in MZR

G. Limberg, A. Ji, TSL et al. in prep (S[5] Collaboration)

More findings from one dozen stream observations (TSL et al. 2022)



Check more details at https://s5collab.github.io/

- Dwarf Galaxy Streams: increasing velocity dispersion with smaller pericenter
- Observations show fewer massive stellar stream than simulation predicts (TBTF?)
- Observations show smaller pericenter and apocenter than simulation predicts (over-disruption?)
- (Outer halo) Streams have higher orbital eccentricity than intact satellite galaxies (0.55 vs 0.45)
- (Outer halo) Streams prefer prograde than retrograde orbit (similar to massive dwarf galaxies.)