Metal-poor stars of the Milky Way and ultra-faint dwarf galaxies

Ting S. Li
University of Toronto

IAU Symposium 395: Stellar populations in the Milky Way and beyond
Paraty, Brazil, Nov 18, 2024

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[Fe/H] < -1?
[Fe/H] < -2? — VMP
[Fe/H] < -3? — EMP

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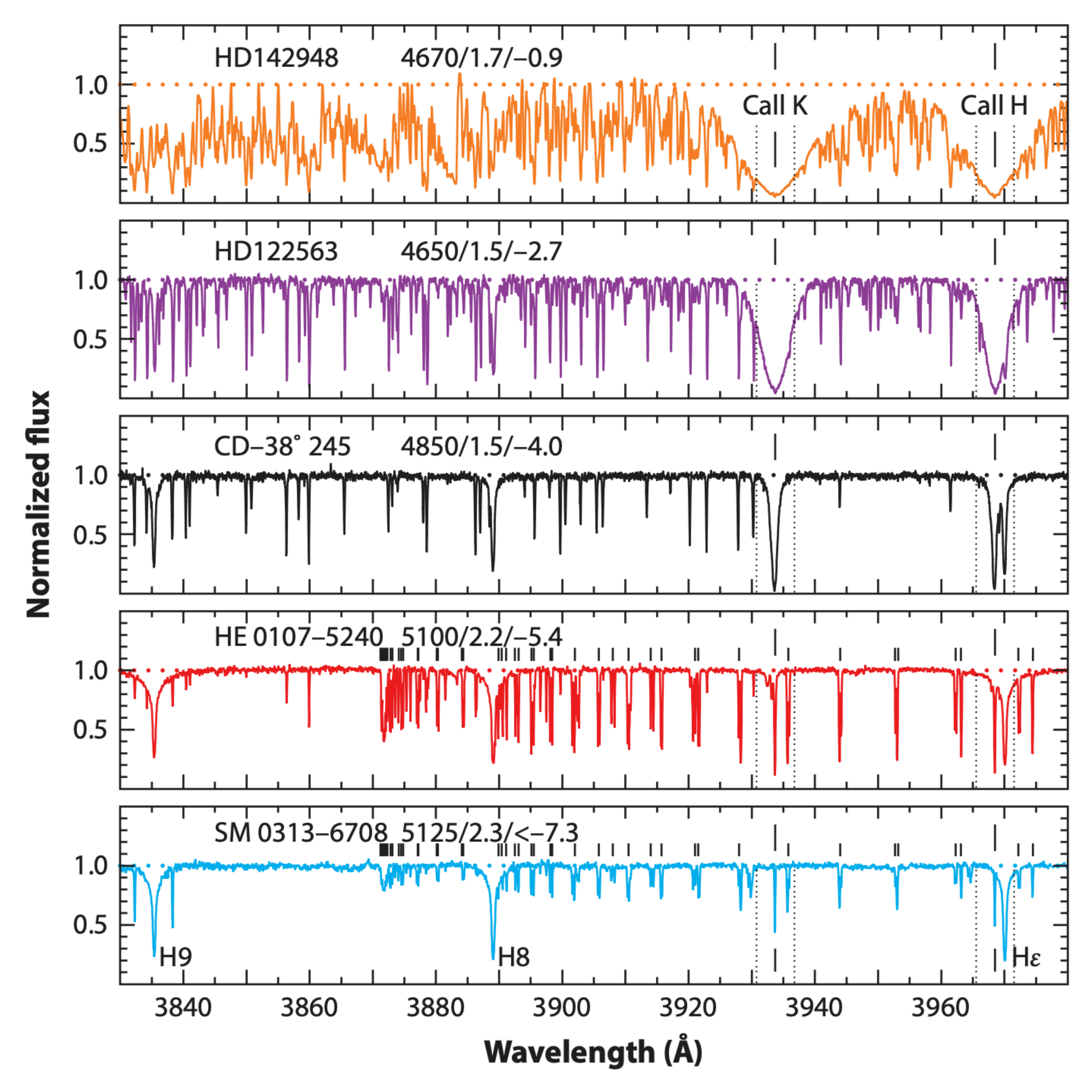

[Fe/H] = -0.9

[Fe/H] = -2.7

[Fe/H] = -4.0

[Fe/H] = -5.4

[Fe/H] < -7.3 but [C/H]=[O/H]=-2.5 Keller et al. 2014

- ~54 Stars with [Fe/H] < -4 (UMP)
- ~700 Stars with [Fe/H] < -3 (EMP)

Frebel & Norris 2015

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16 paper series: First Stars

The extreme r-element rich, iron-poor halo giant CS 31082-001

Implications for the r-process site(s) and radioactive cosmochronology ⋆

V. Hill[1], B. Plez[2], R. Cayrel[3], T. C. Beers[4], B. Nordström[5,6], J. Andersen[6], M. Spite[1], F. Spite[1], B. Barbuy[7], P. Bonifacio[8], E. Depagne[1], P. François[3], and F. Primas[9]

First Stars II. Elemental abundances in the extremely metal-poor star CS 22949–037 ⋆

A diagnostic of early massive supernovae

E. Depagne[1], V. Hill[1], M. Spite[1], F. Spite[1], B. Plez[2], T. C. Beers[3], B. Barbuy[4], R. Cayrel[1], J. Andersen[5], P. Bonifacio[6], P. François[1], B. Nordström[7,5], and F. Primas[8]

First Stars. III. A detailed elemental abundance study of four extremely metal-poor giant stars⋆,⋆⋆

P. François[1], E. Depagne[1], V. Hill[1], M. Spite[1], F. Spite[1], B. Plez[2], T. C. Beers[3], B. Barbuy[4], R. Cayrel[1], J. Andersen[5], P. Bonifacio[6], P. Molaro[6], B. Nordström[7,5], and F. Primas[8]

First stars IV. CS 29497-030: Evidence for operation of the s-process at very low metallicity ⋆

T. Sivarani[1], P. Bonifacio[1], P. Molaro[1], R. Cayrel[2], M. Spite[2], F. Spite[2], B. Plez[3], J. Andersen[4], B. Barbuy[5], T. C. Beers[6], E. Depagne[7], V. Hill[2], P. François[2], B. Nordström[8,4], and F. Primas[9]

First stars V - Abundance patterns from C to Zn and supernova yields in the early Galaxy ⋆

R. Cayrel[1], E. Depagne[1], M. Spite[1], V. Hill[1], F. Spite[1], P. François[1], B. Plez[2], T. Beers[3], F. Primas[4], J. Andersen[5,9], B. Barbuy[6], P. Bonifacio[7], P. Molaro[7], and B. Nordström[5,8]

First stars VI - Abundances of C, N, O, Li, and mixing in extremely metal-poor giants. Galactic evolution of the light elements ⋆

M. Spite[1], R. Cayrel[1], B. Plez[2], V. Hill[1], F. Spite[1], E. Depagne[3], P. François[1], P. Bonifacio[4], B. Barbuy[5], T. Beers[6], J. Andersen[7,8], P. Molaro[4], B. Nordström[7,9], and F. Primas[10]

First stars XVI. STIS/HST abundances of heavy-elements in the uranium-rich star CS 31082-001⋆

C. Siqueira Mello Jr.[1,2], M. Spite[2], B. Barbuy[1], F. Spite[2], E. Caffau[3,2], V. Hill[4], S. Wanajo[5], F. Primas[6], B. Plez[7], R. Cayrel[8], J. Andersen[9,10], B. Nordström[9], C. Sneden[11], T.C. Beers[12], P. Bonifacio[2], P. François[8], and P. Molaro[13]

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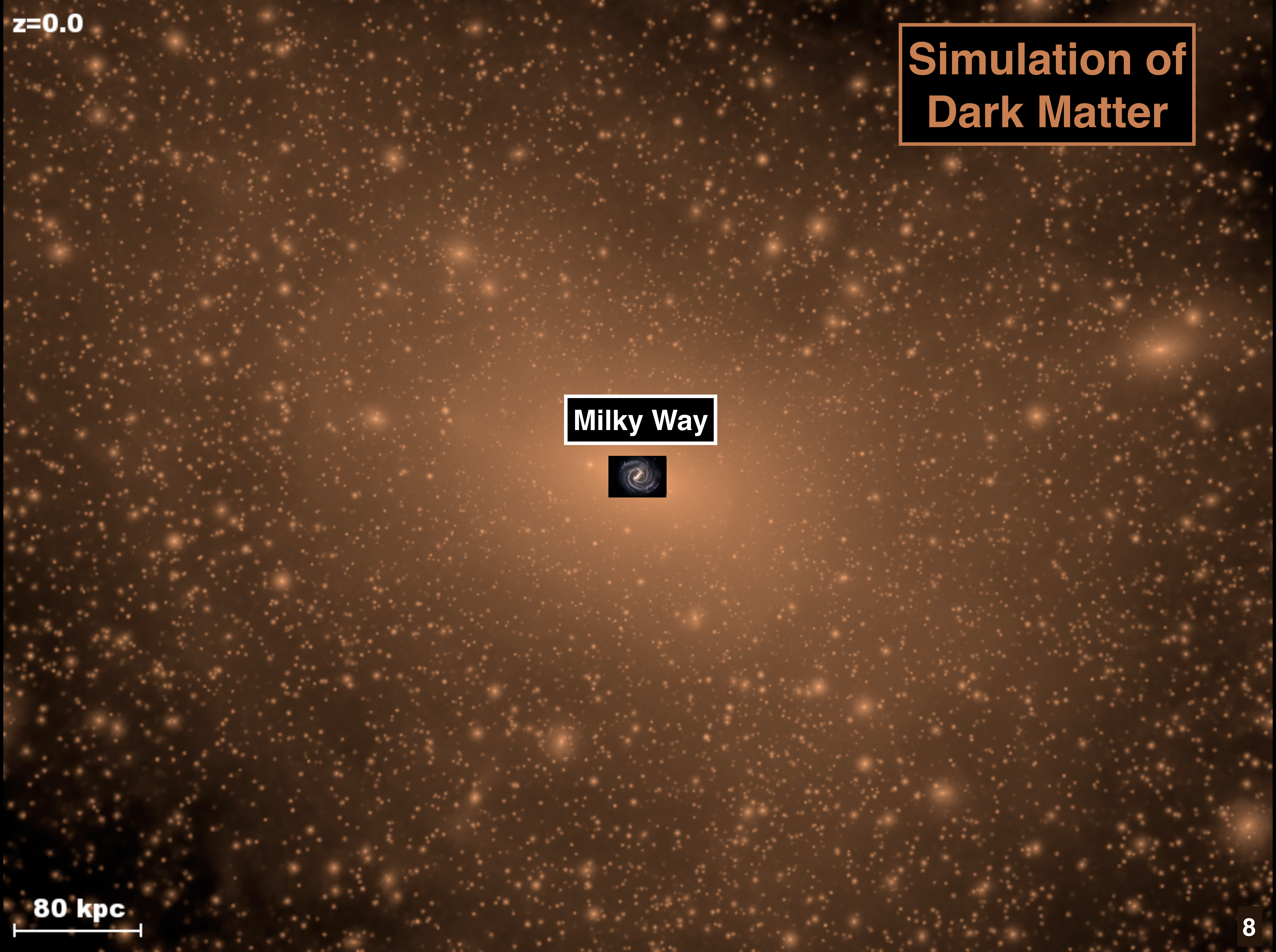
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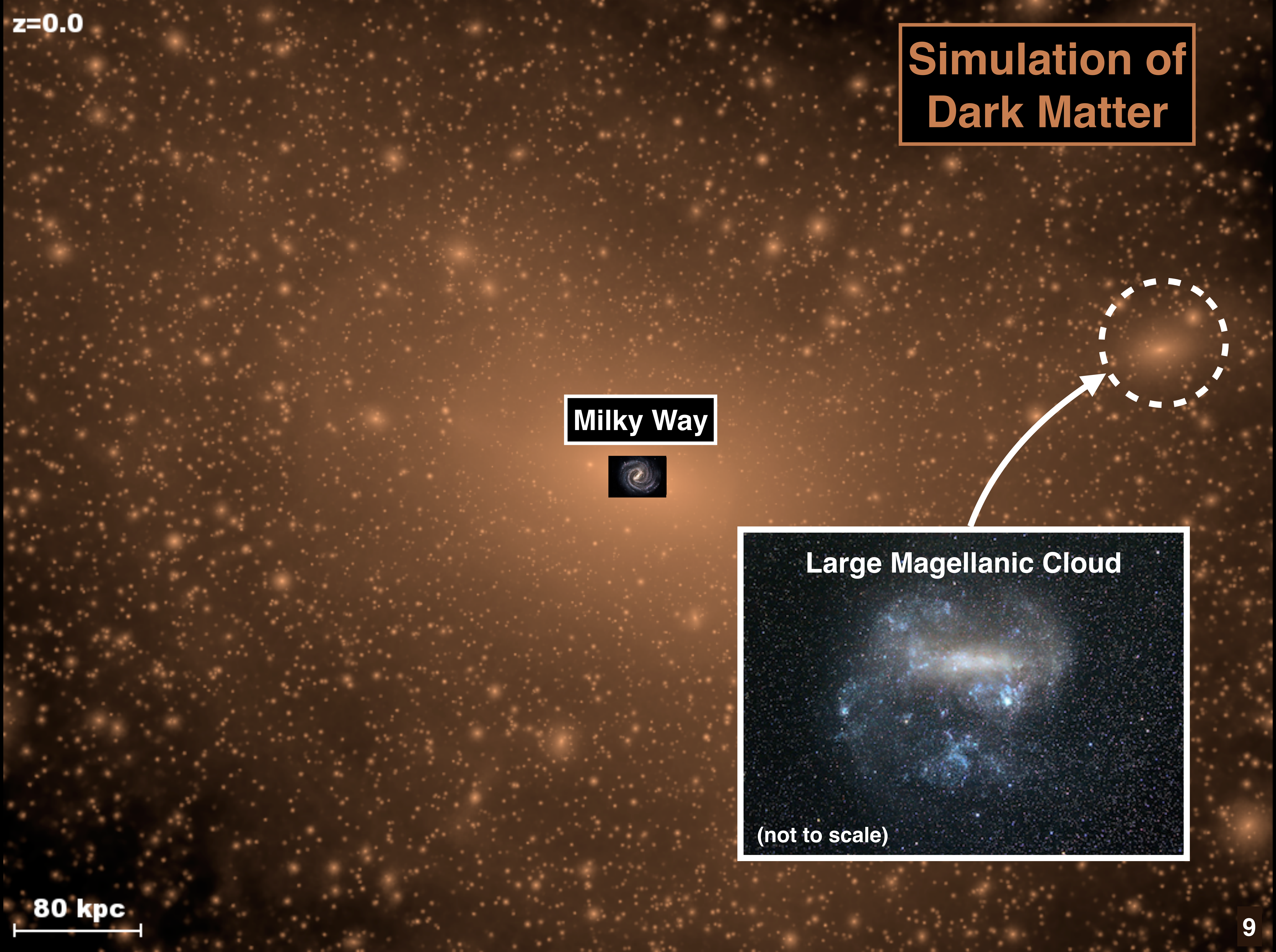
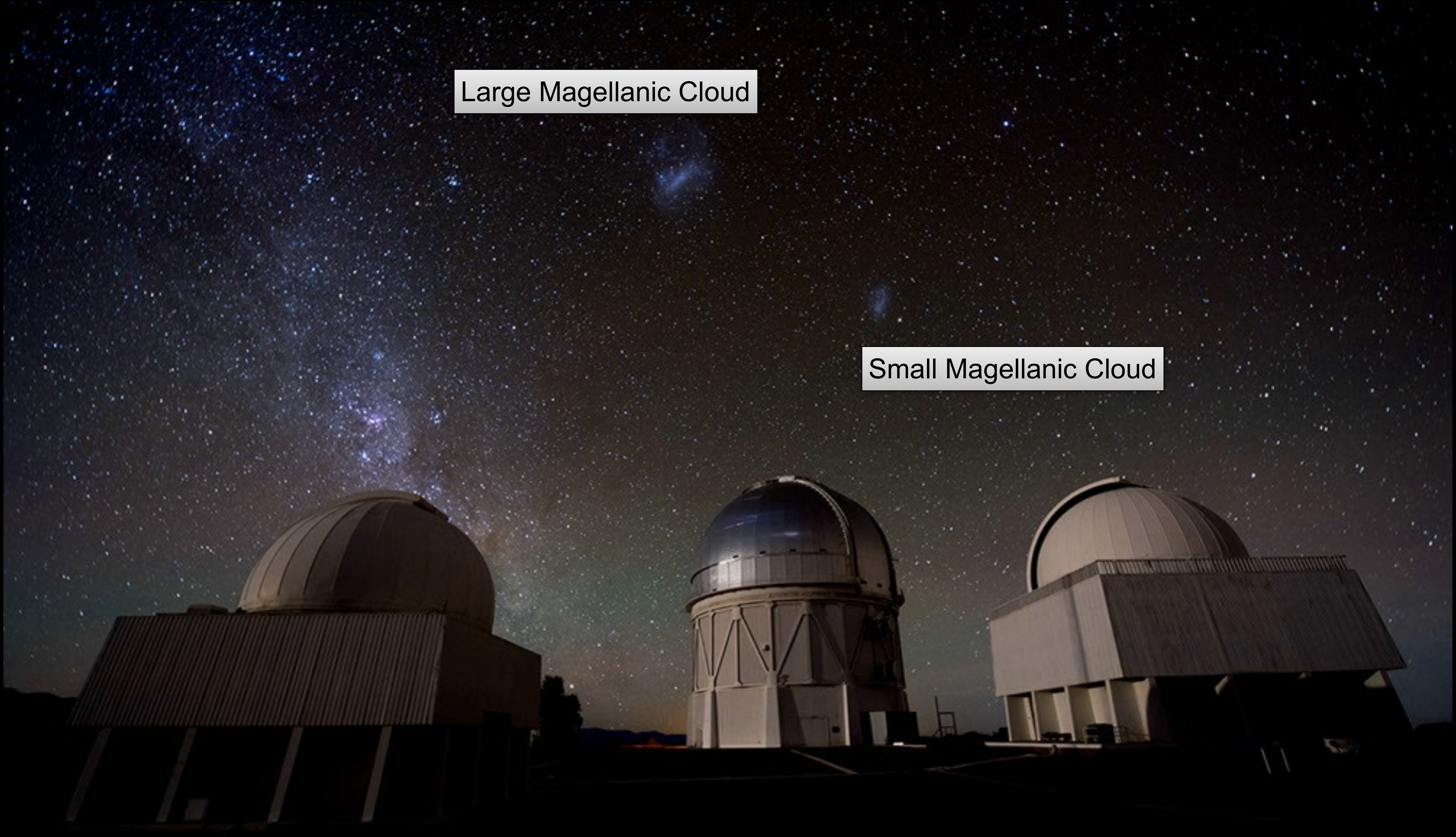
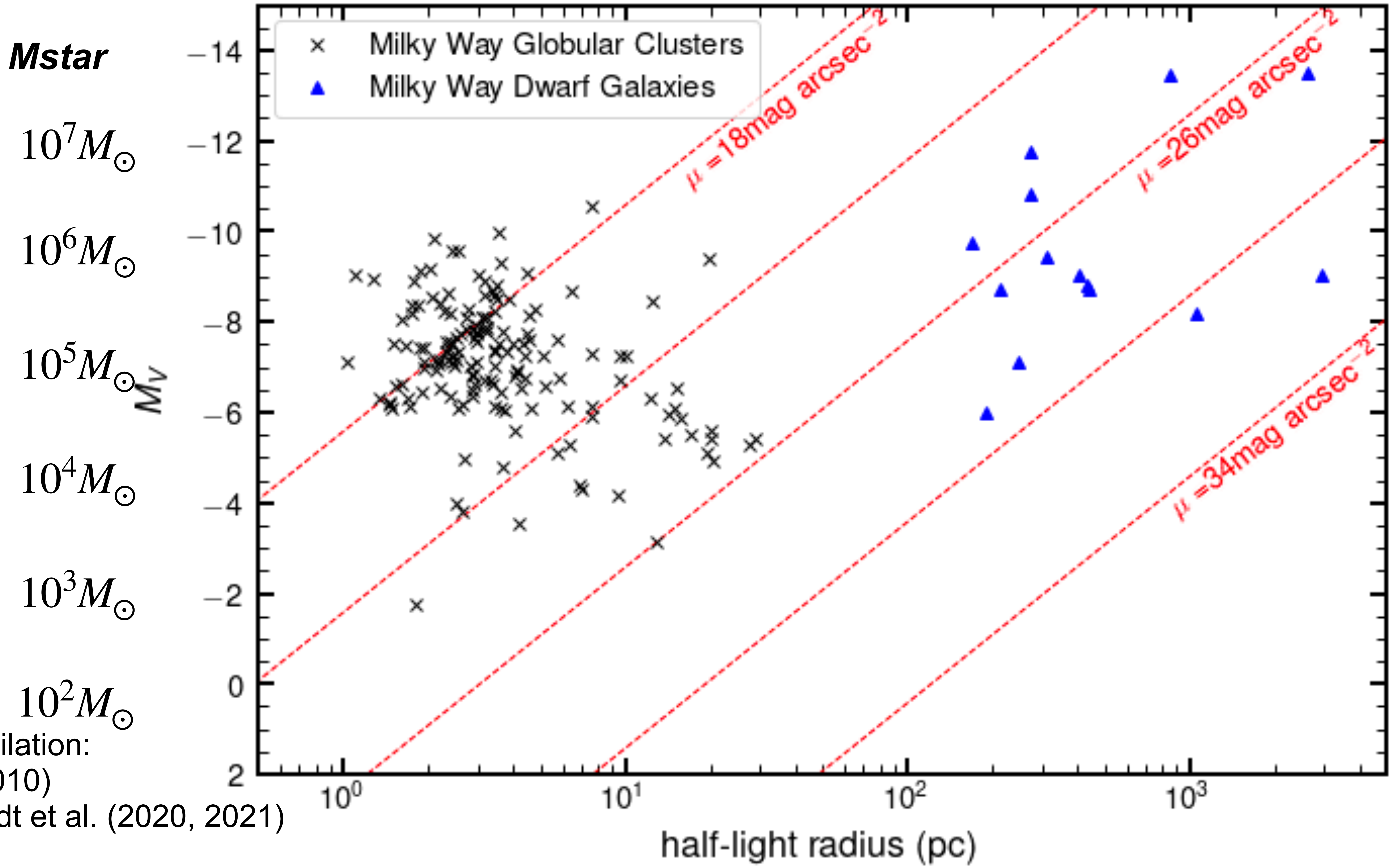
Simulation of Dark Matter
Milky Way
80 kpc


z=0.0
Simulation of Dark Matter
Milky Way
Large Magellanic Cloud
(not to scale)
80 kpc

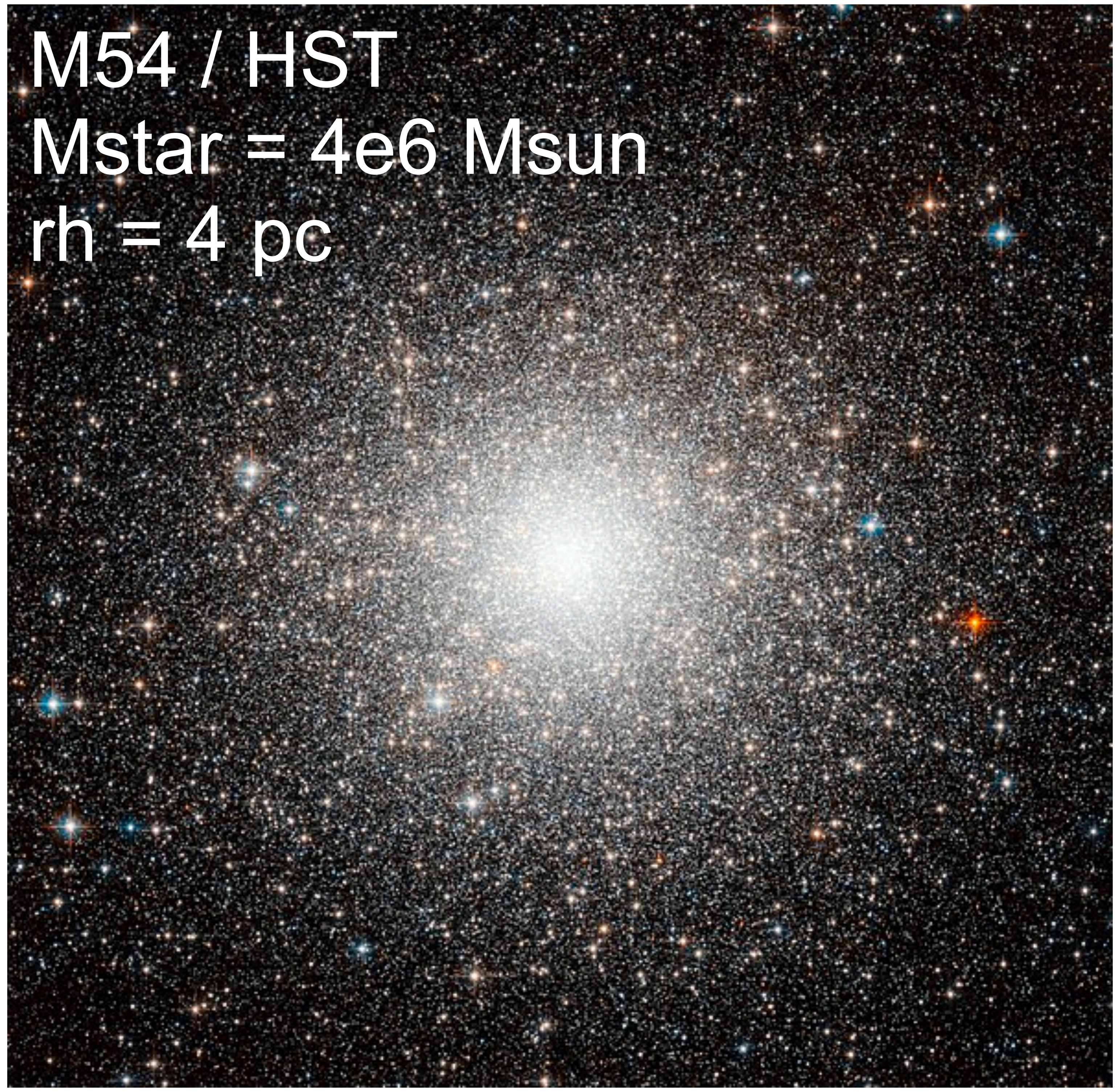

Large Magellanic Cloud
Small Magellanic Cloud

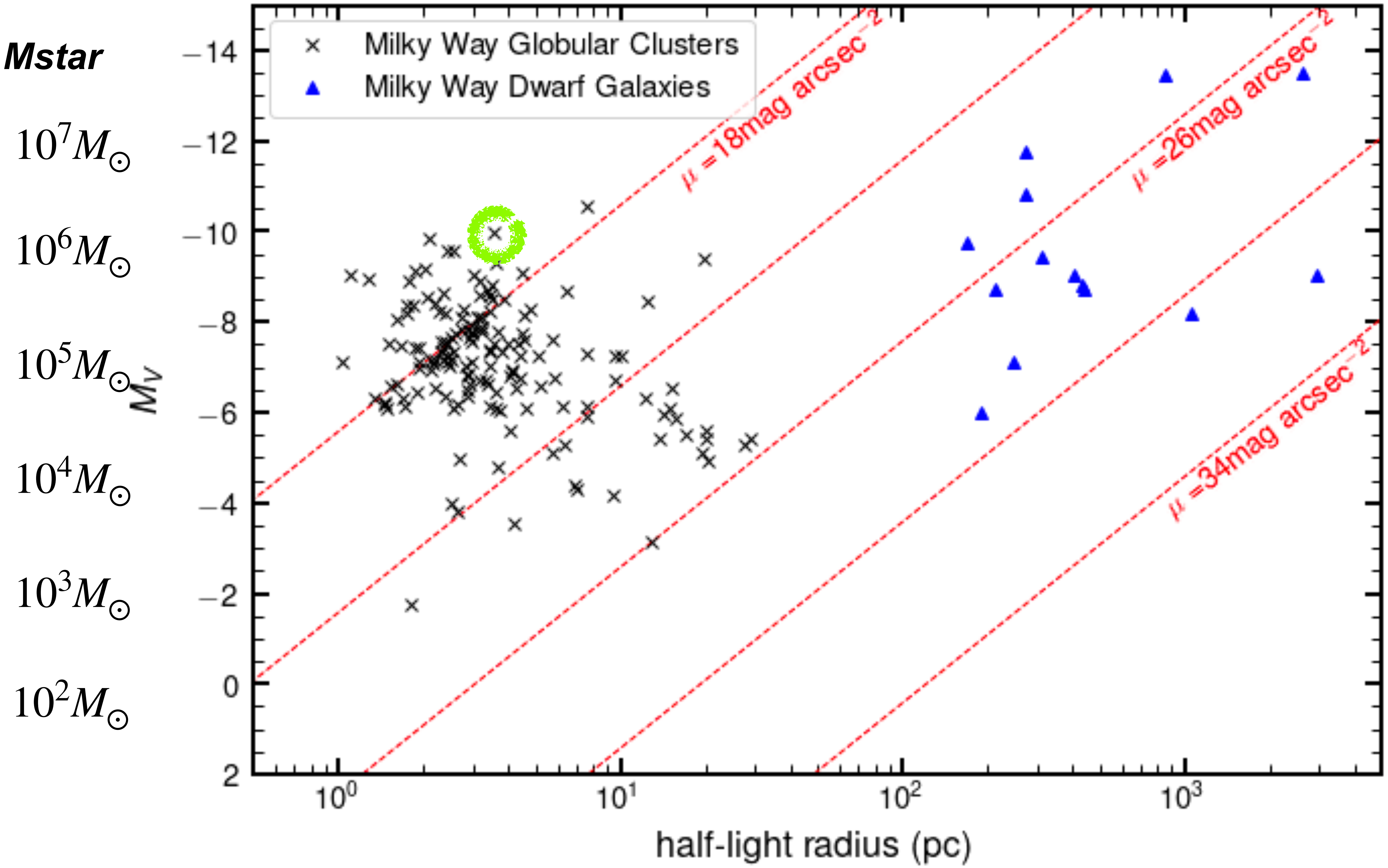
Luminosity vs Size for Galactic Satellites



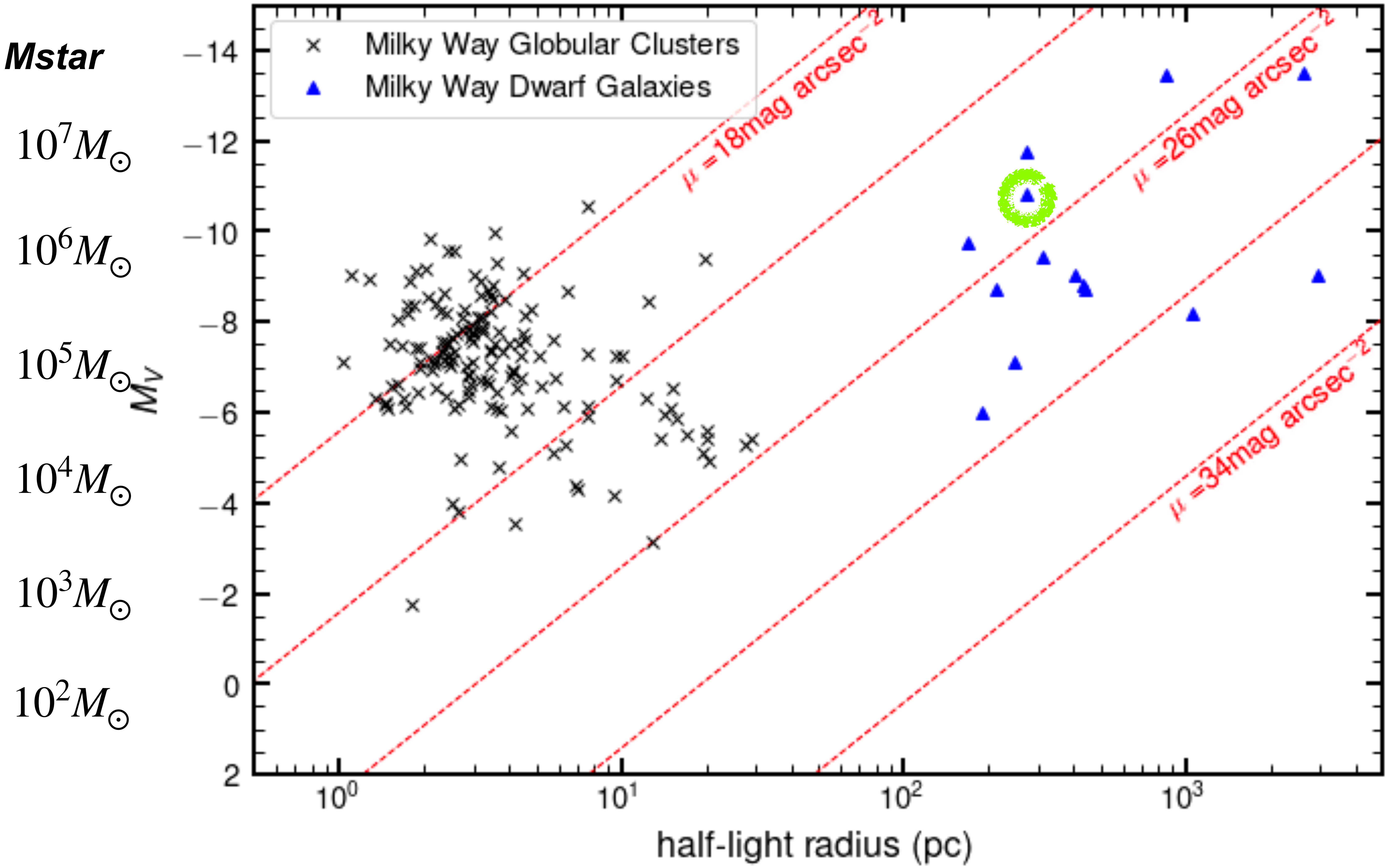
GC compilation:
Harris (2010)
Baumgardt et al. (2020, 2021)

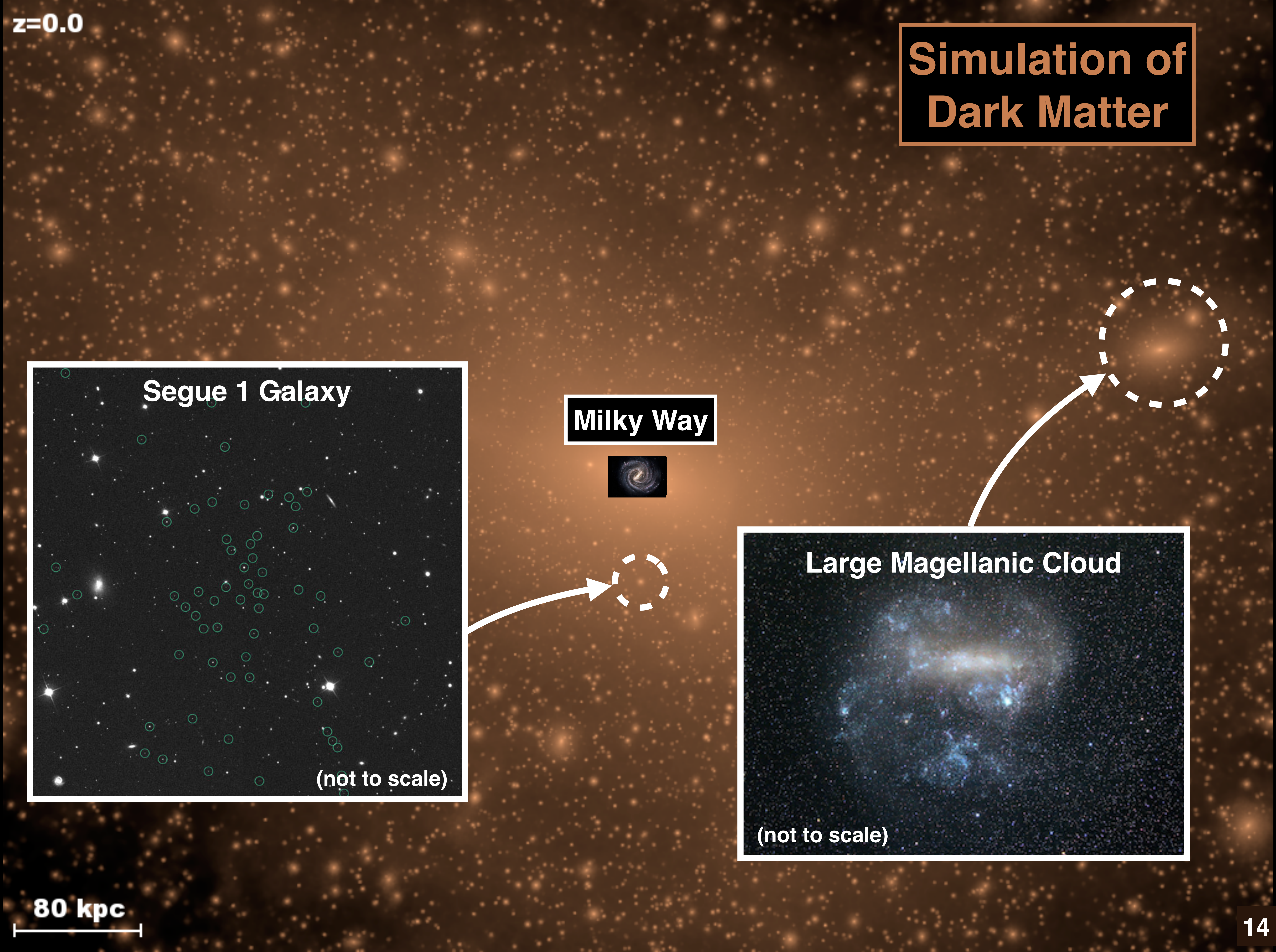
Luminosity vs Size for Galactic Satellites





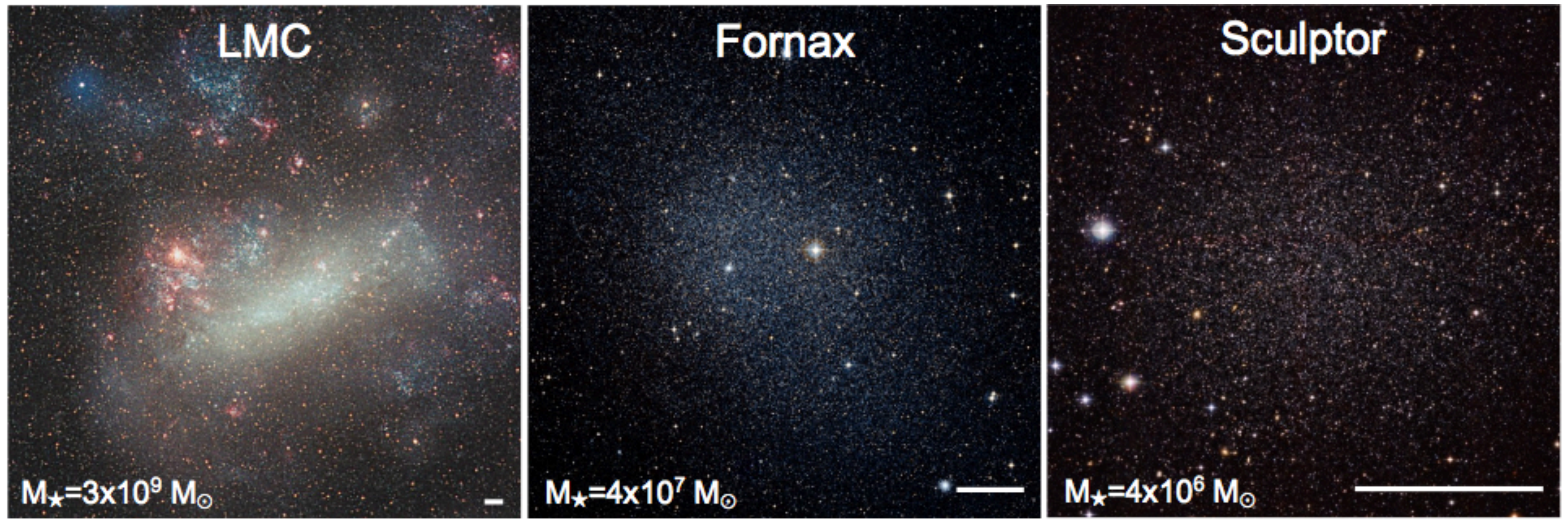
Luminosity vs Size for Galactic Satellites



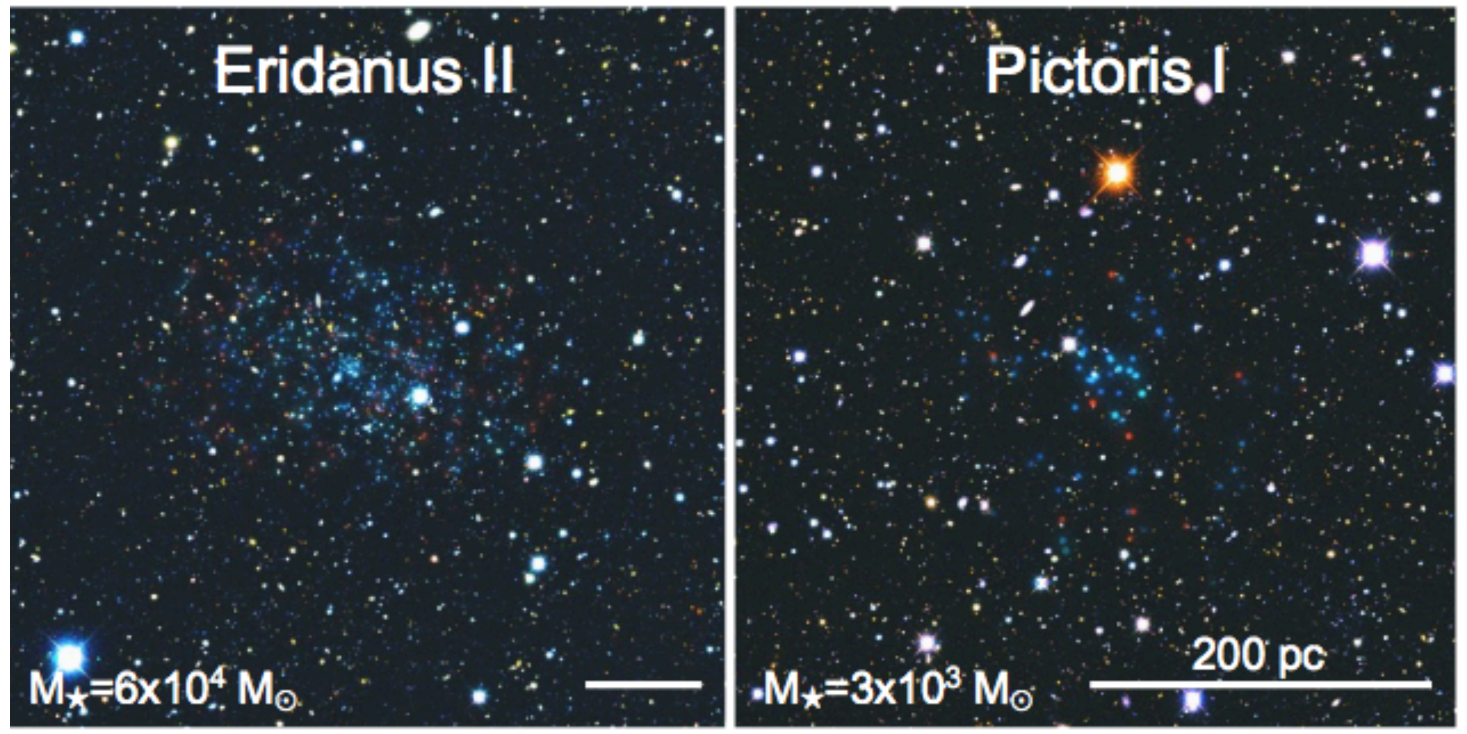

z=0.0
Simulation of Dark Matter
Segue 1 Galaxy
(not to scale)
Milky Way
Large Magellanic Cloud
(not to scale)
80 kpc

Milky Way Satellite Galaxies

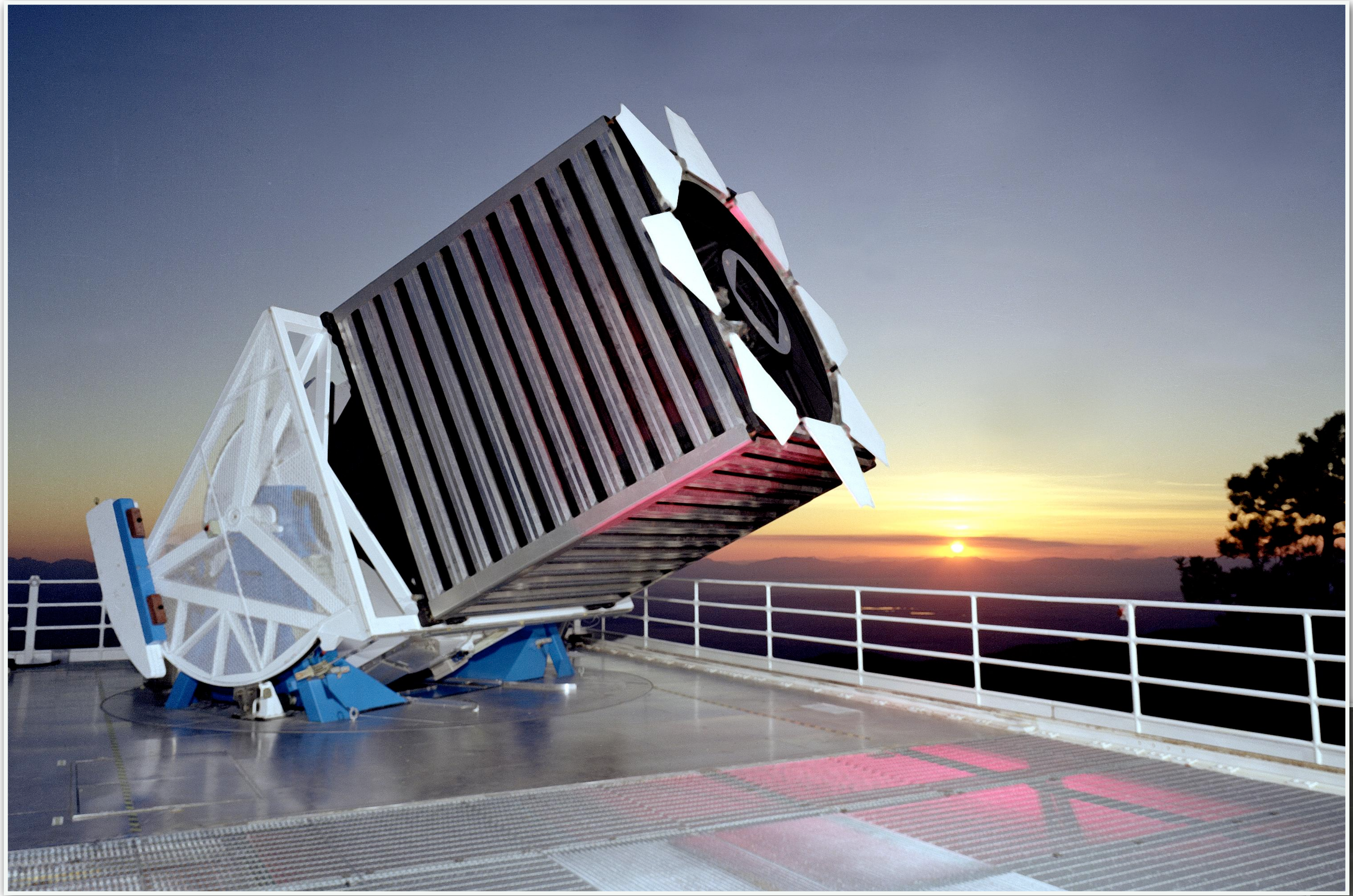
Classical Dwarf Galaxies



Ultra-Faint Dwarf (UFD) Galaxies



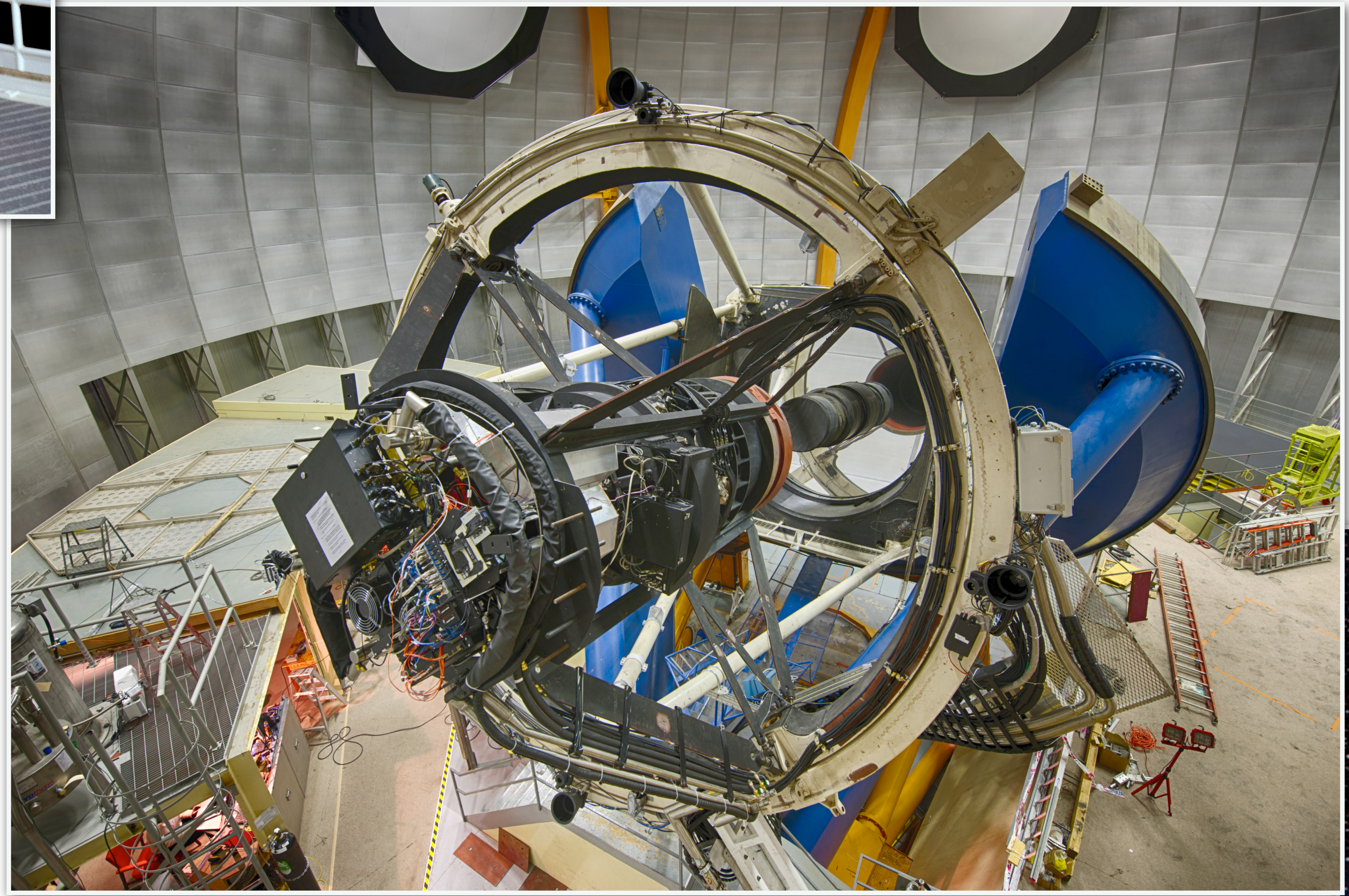
Progression of Wide-field Optical Imaging Surveys



$r \sim 22$

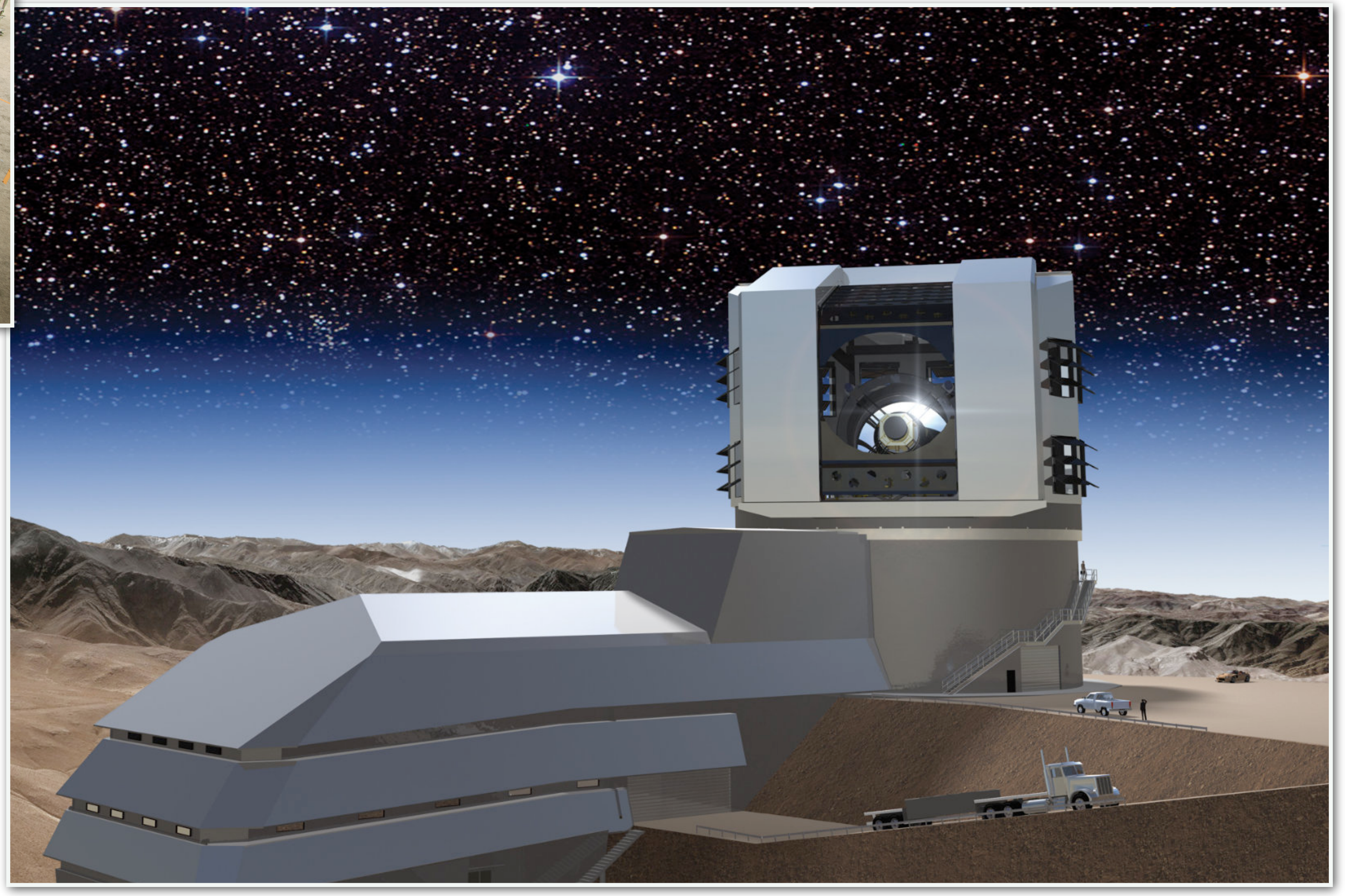
Past: SDSS

$r \sim 24$



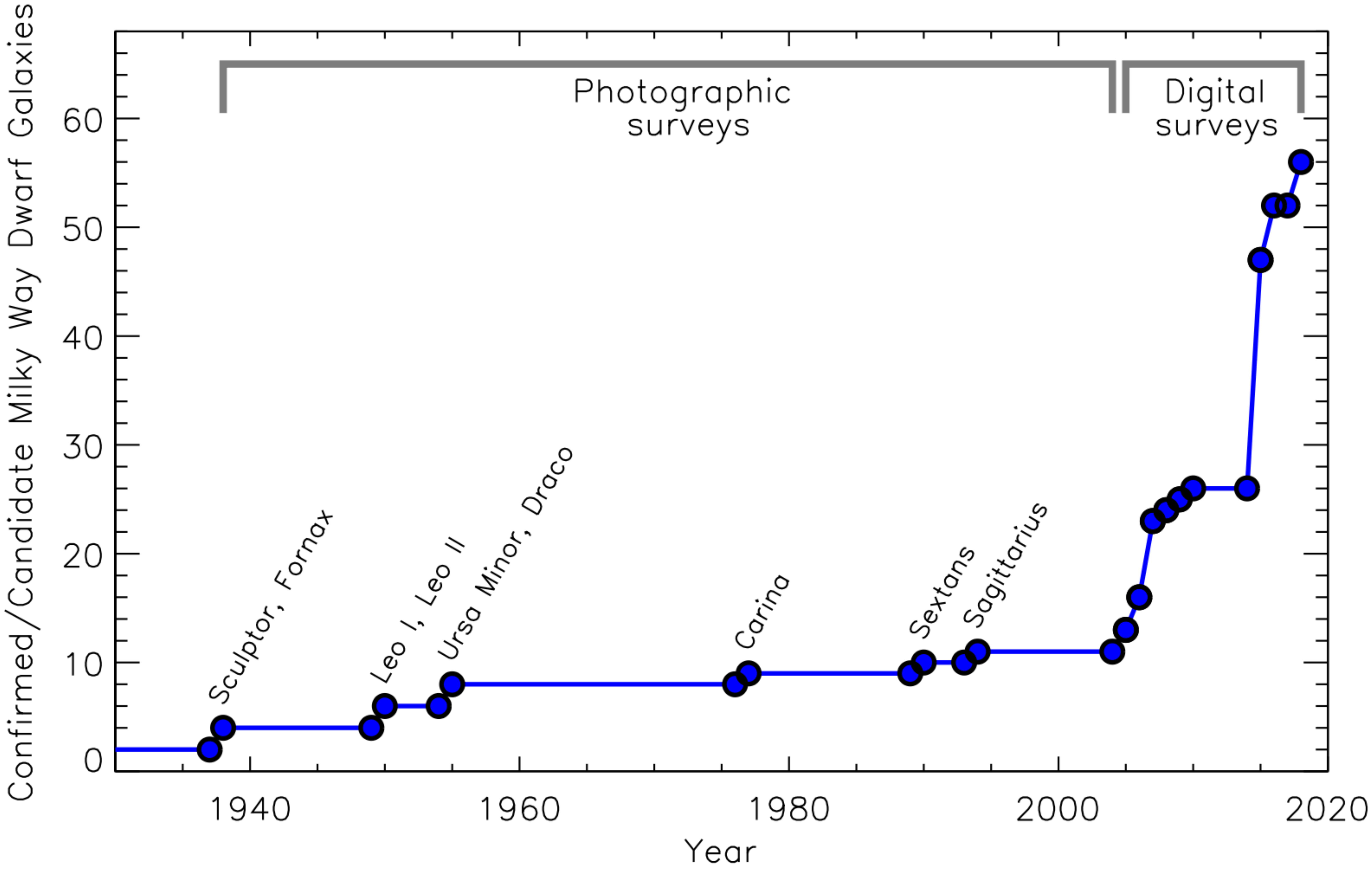
Current: DECam, Pan-STARRS, HSC, SkyMapper

$r \sim 26$



Future: Rubin/LSST

Dwarf Galaxy Discovery Timeline



Simon et al. 2019, ARAA

Luminosity vs Size for Galactic Dwarf Galaxies pre-SDSS

Mstar

$10^7 M_\odot$

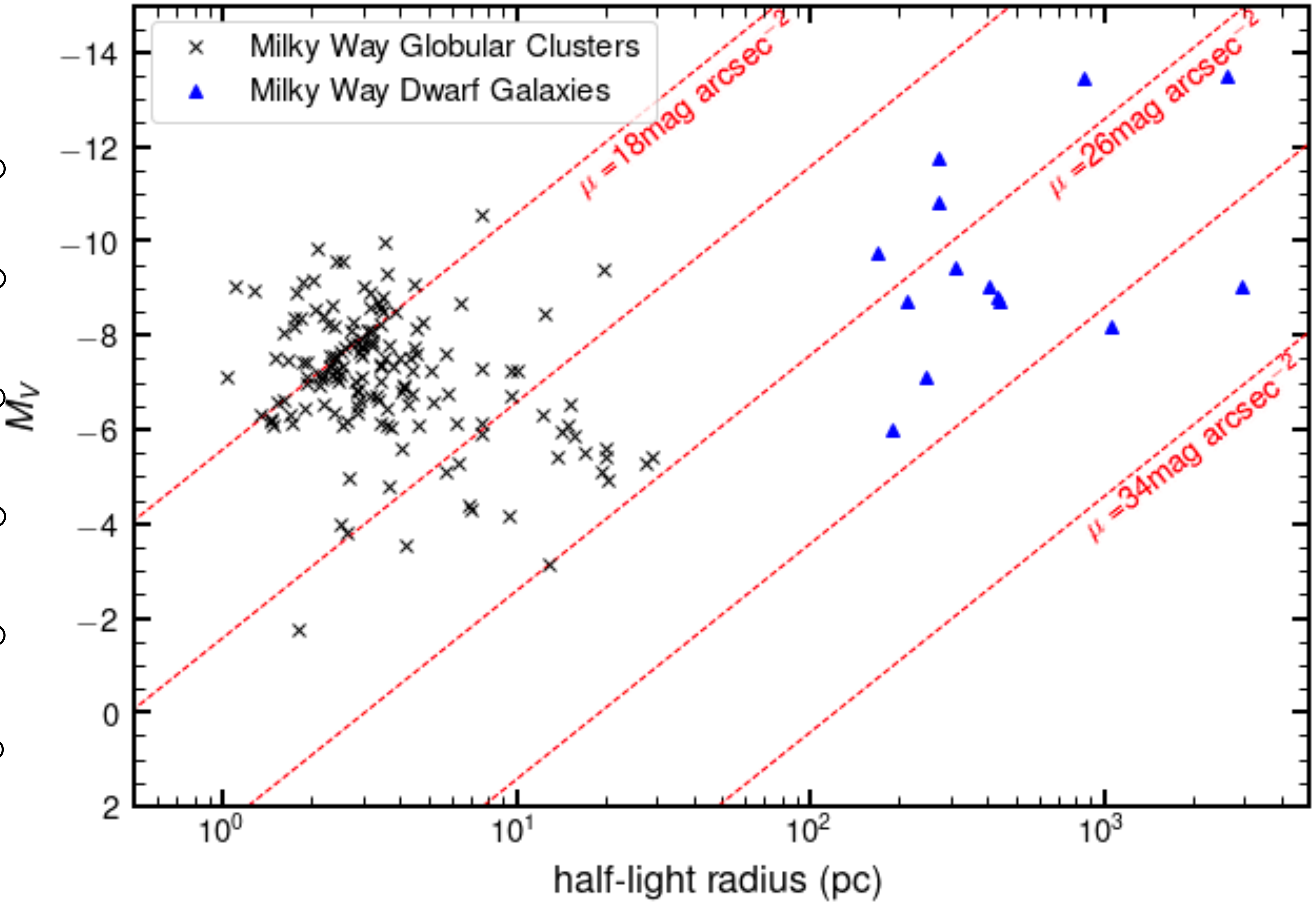
$10^6 M_\odot$

$10^5 M_\odot$

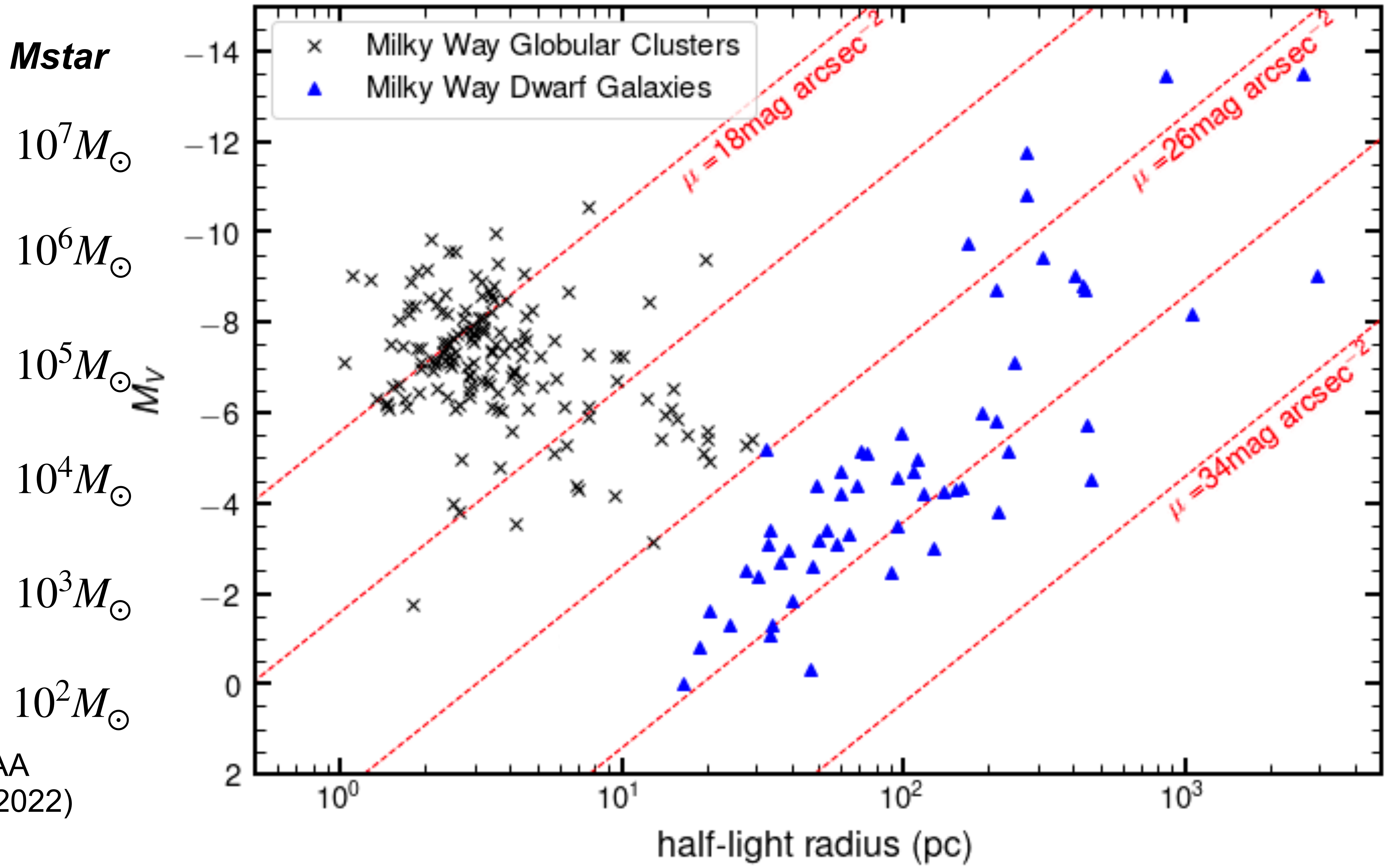
$10^4 M_\odot$

$10^3 M_\odot$

$10^2 M_\odot$



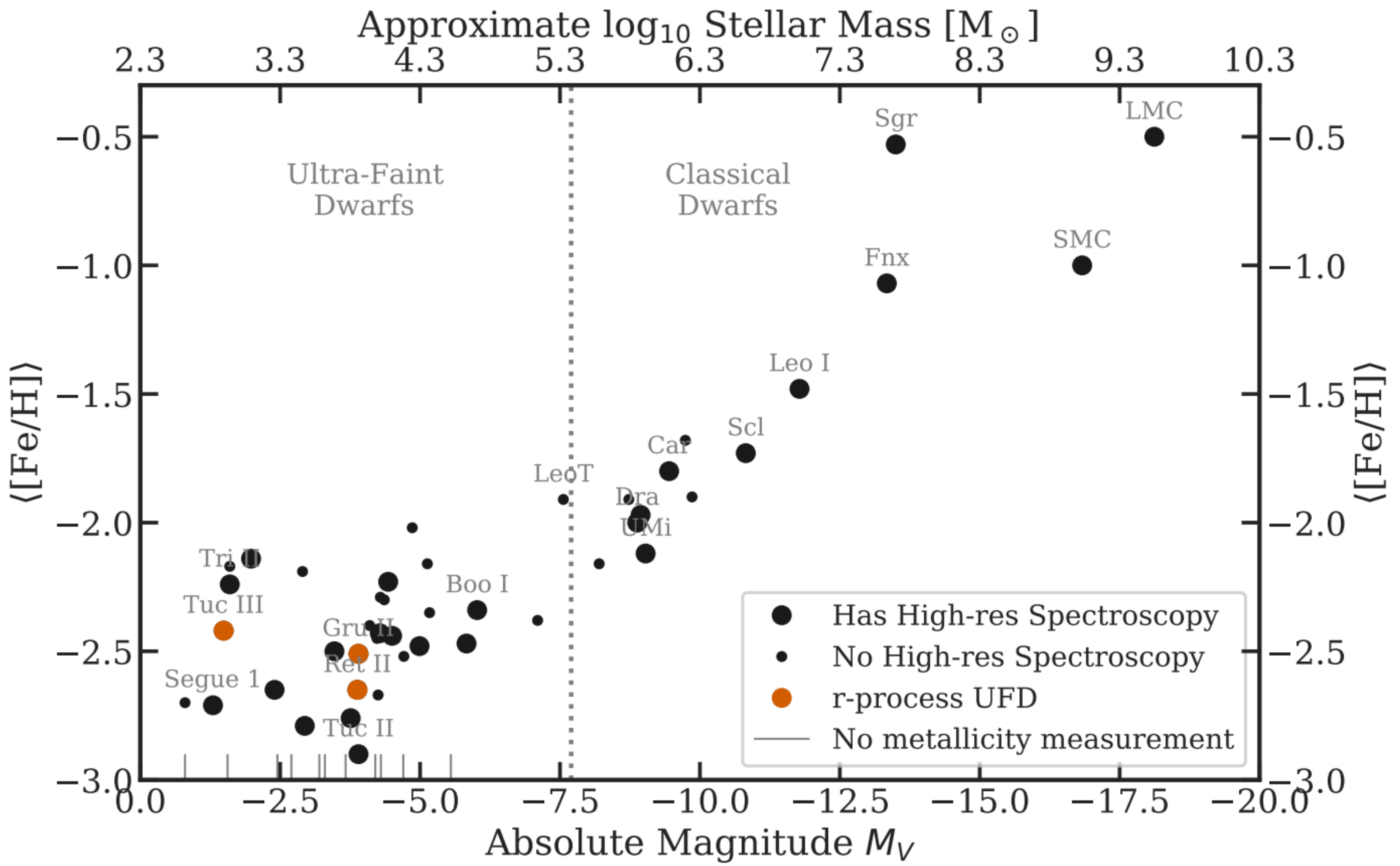
Luminosity vs Size for Galactic Dwarf Galaxies post-SDSS



GC compilation:
Harris (2010)
Baumgardt et al. (2020, 2021)

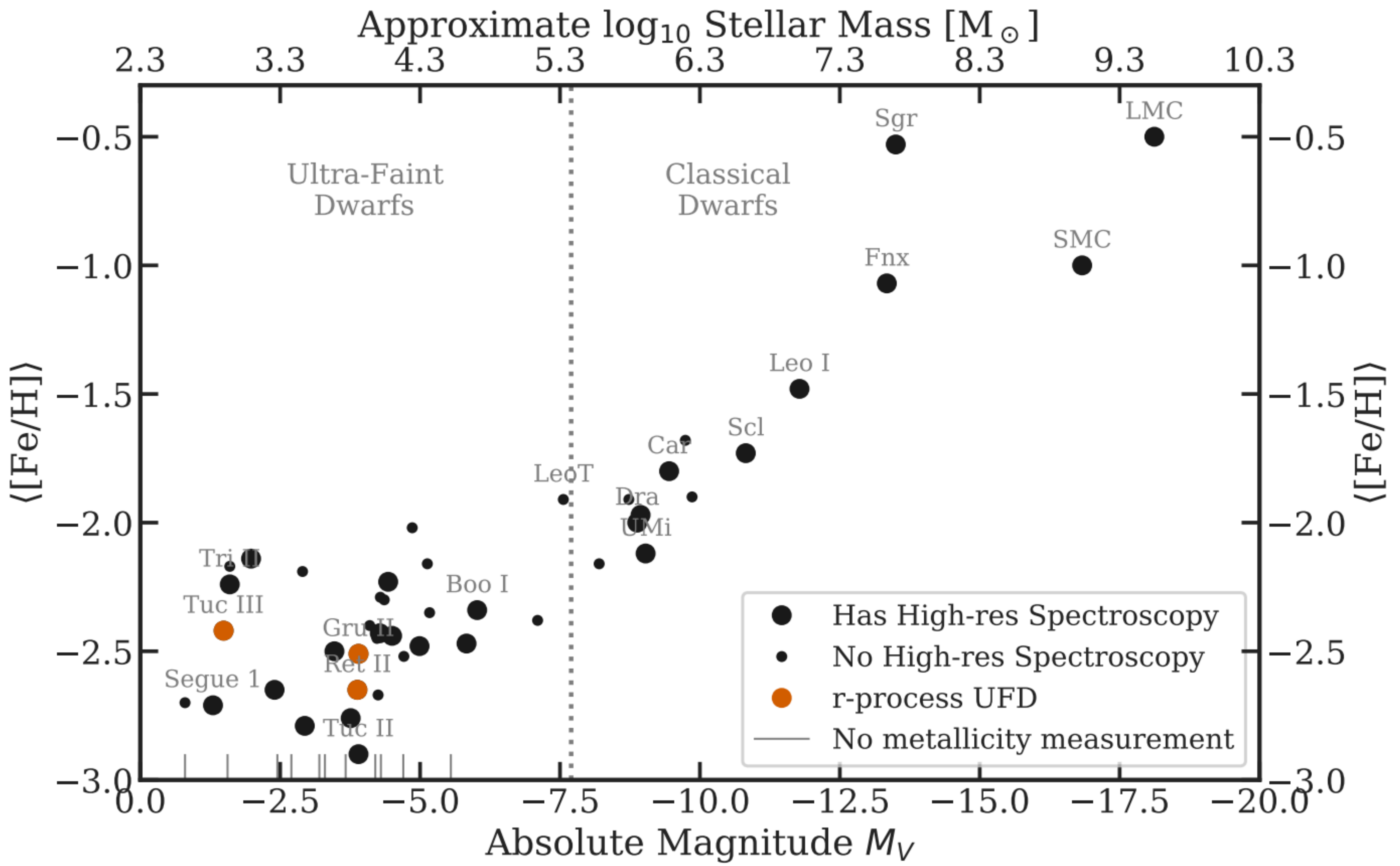
UFD compilation:
Simon (2019), ARAA
Pace, Erkal, TSL (2022)

Luminosity Metallicity Relation / Mass Metallicity Relation (LZR/MZR)

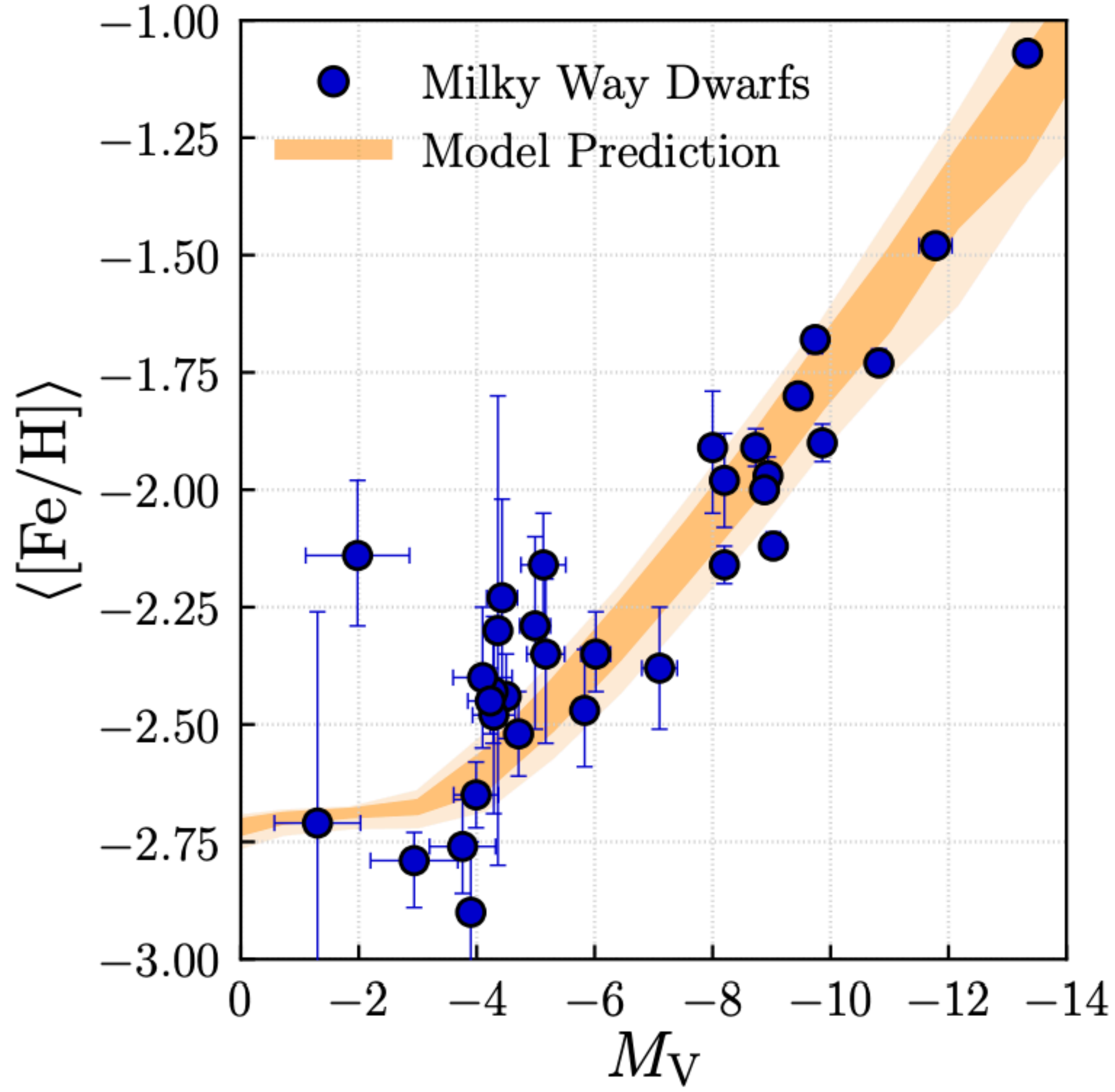


Frebel & Ji 2024
Handbook of Nuclear Physics – Part III Section 15 “Supernovae and Neutron Star Mergers”

Luminosity Metallicity Relation / Mass Metallicity Relation (LZR/MZR)



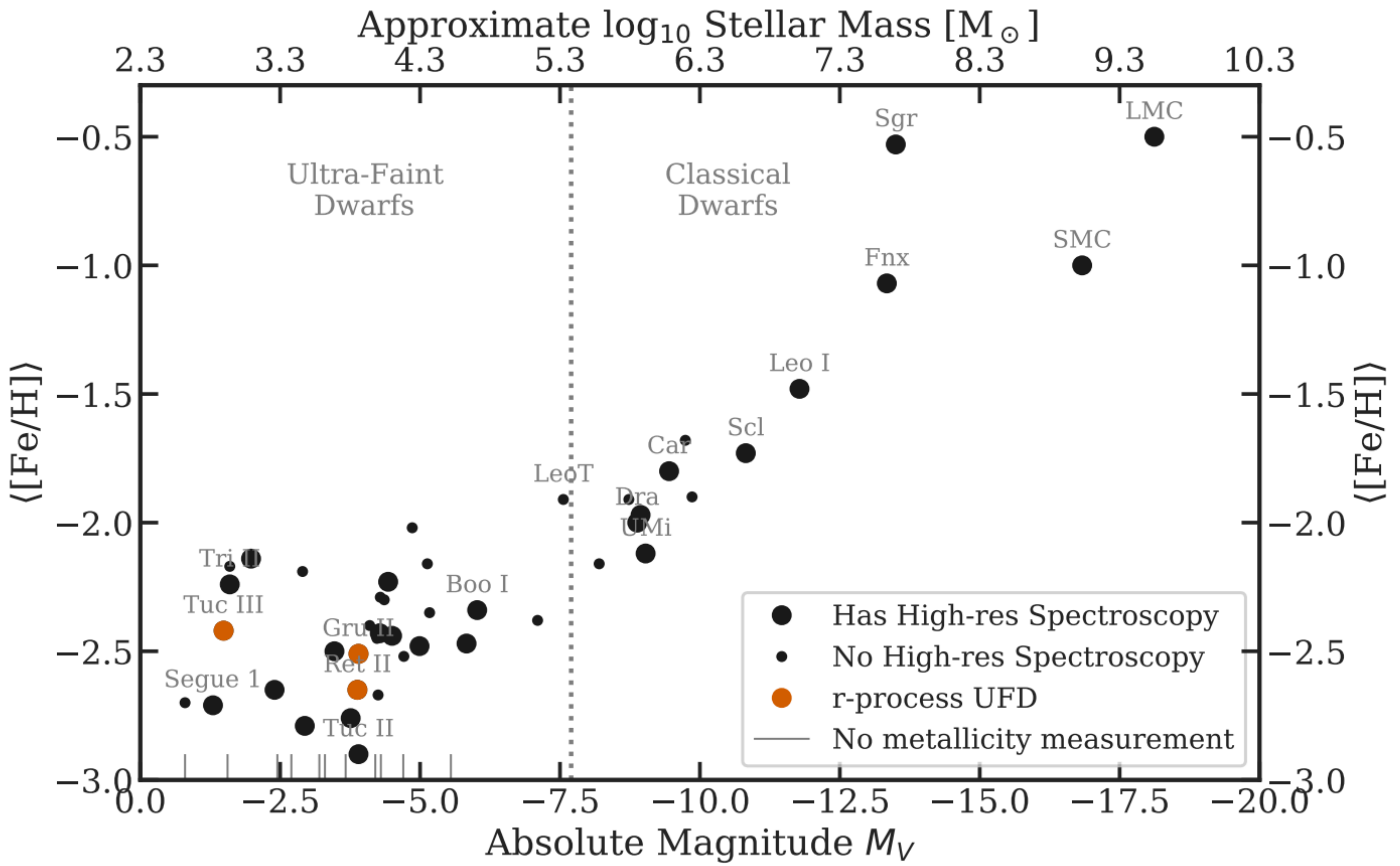
A metallicity plateau?

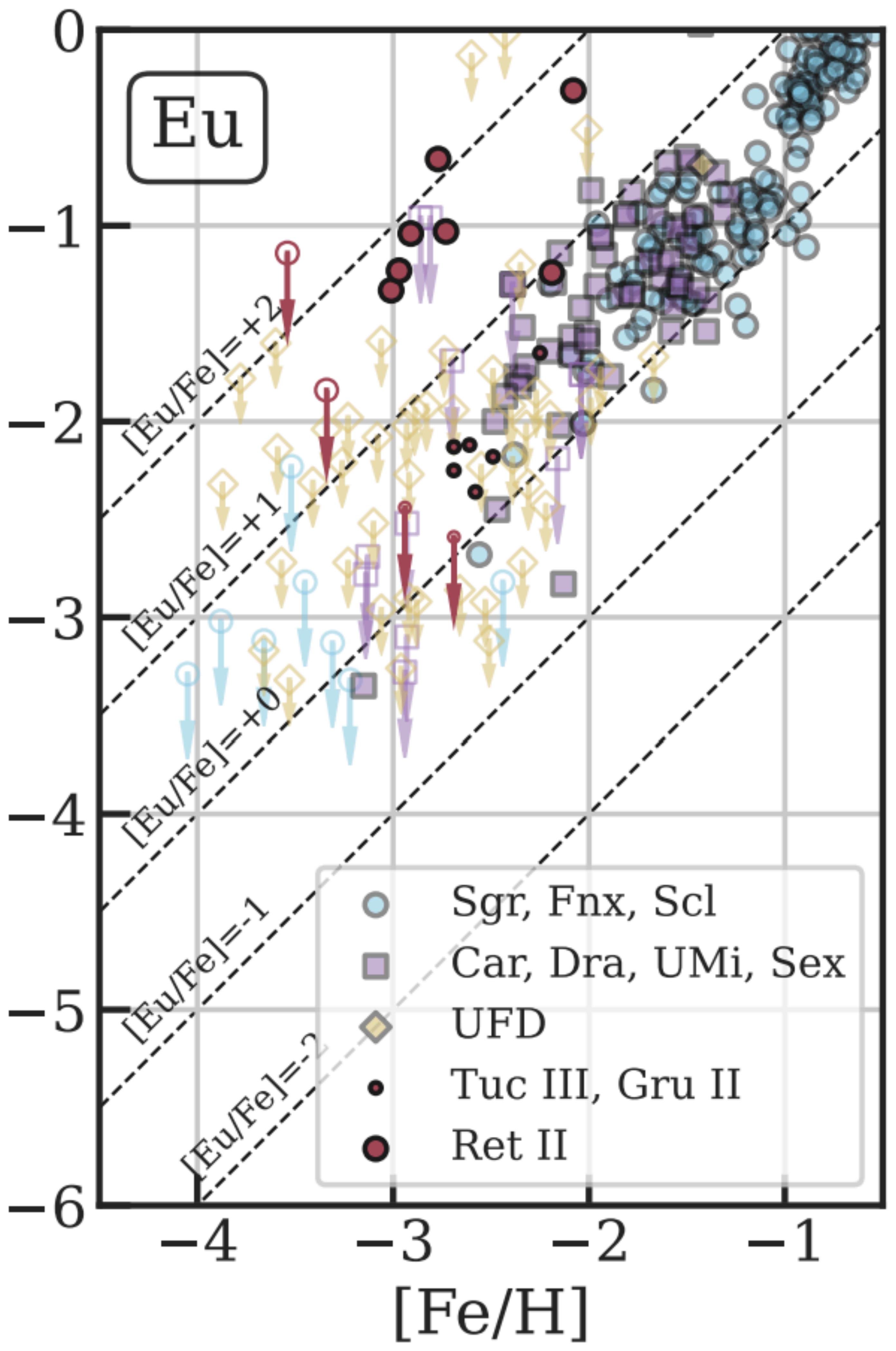


Frebel & Ji 2024
Handbook of Nuclear Physics – Part III Section 15 "Supernovae and Neutron Star Mergers"

Manwadkar & Kravtsov 2022

Astrophysical site for r-process elements?

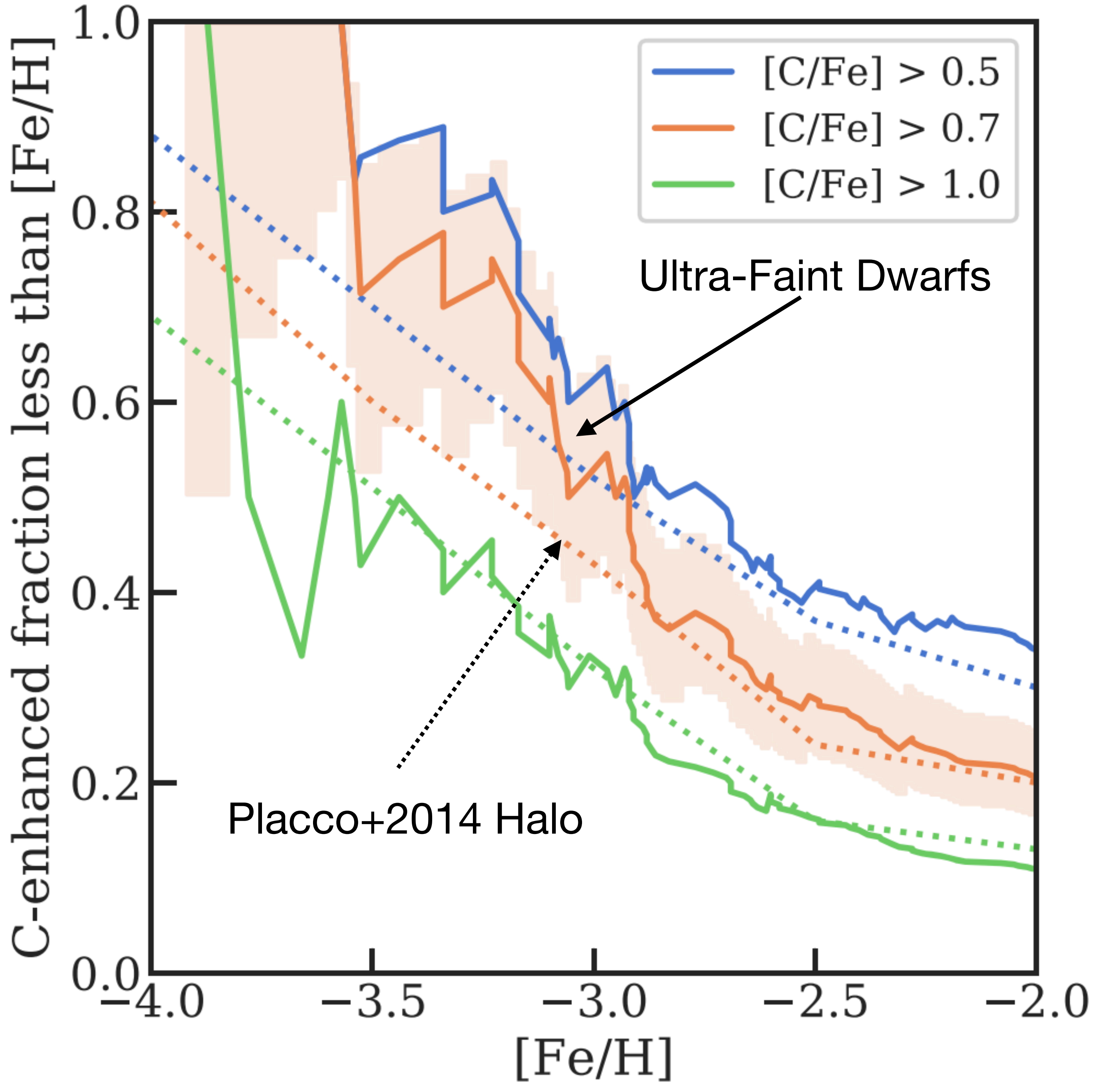




Frebel & Ji 2024
Handbook of Nuclear Physics – Part III Section 15 “Supernovae and Neutron Star Mergers”

CEMP Fraction in different environment
Carbon-Enhanced Metal-Poor

UFDs vs MW Halo

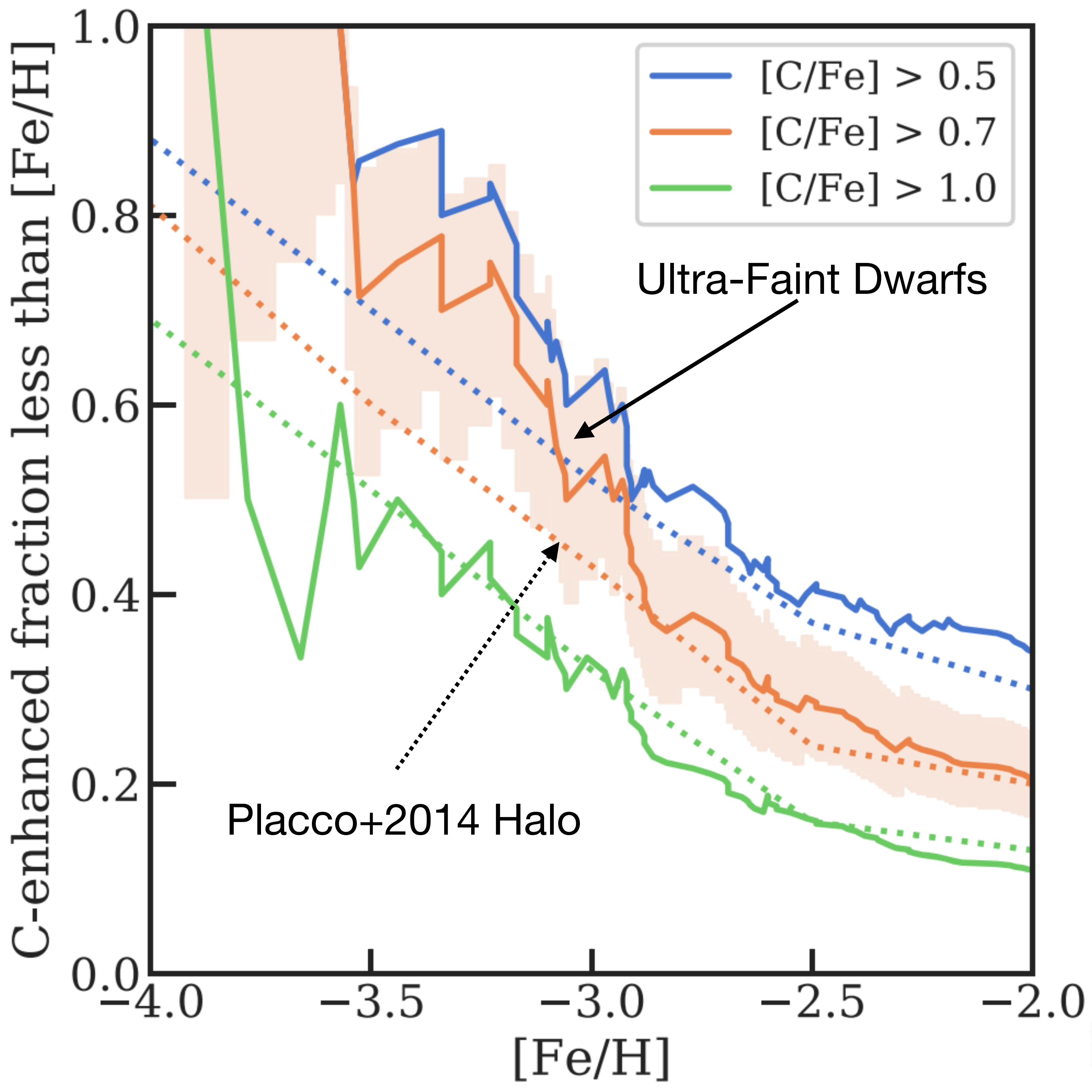


Ji, TSL et al. 2020

CEMP Fraction in different environment

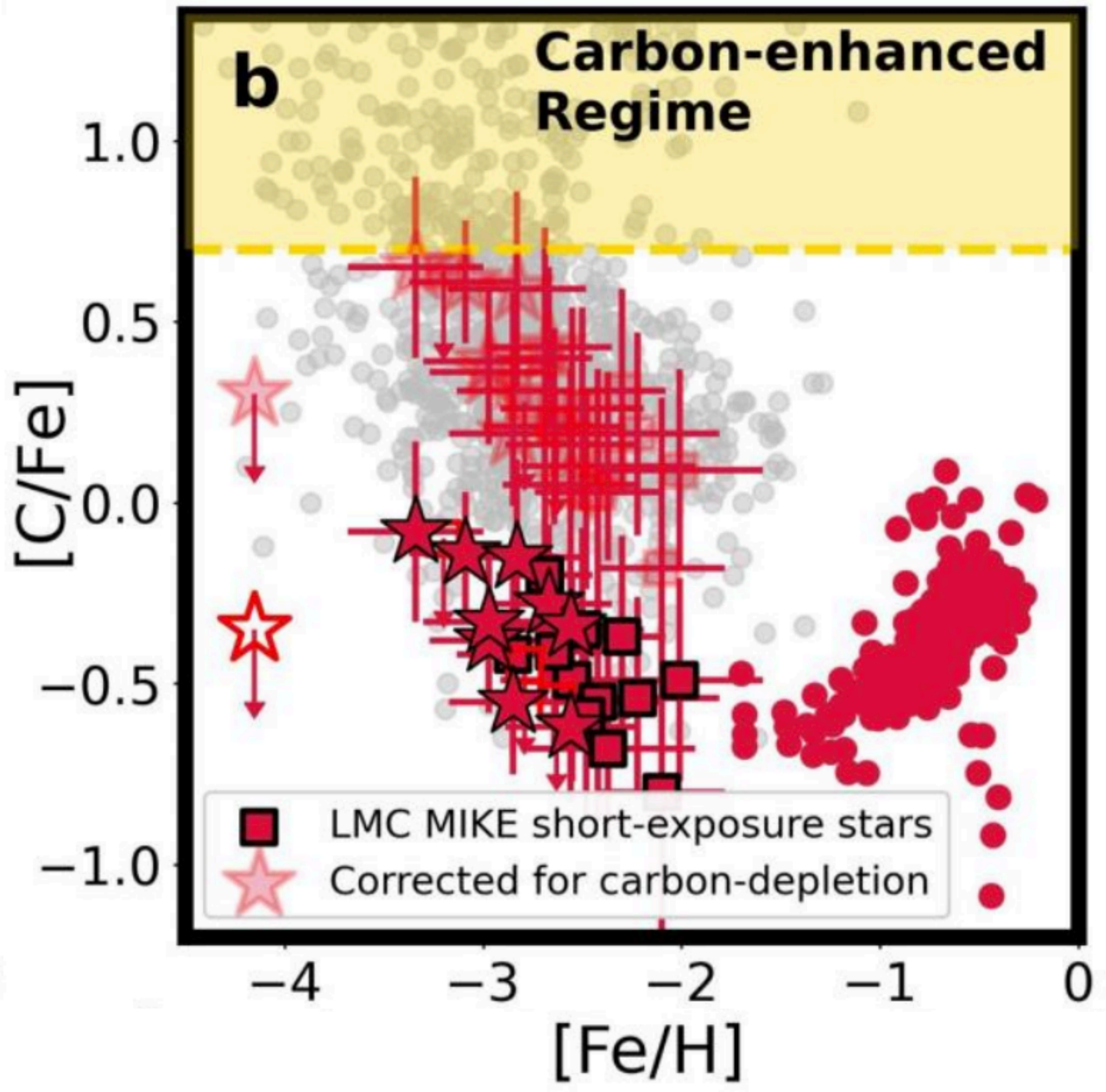
Carbon-Enhanced Metal-Poor

UFDs vs MW Halo



Ji, TSL et al. 2020

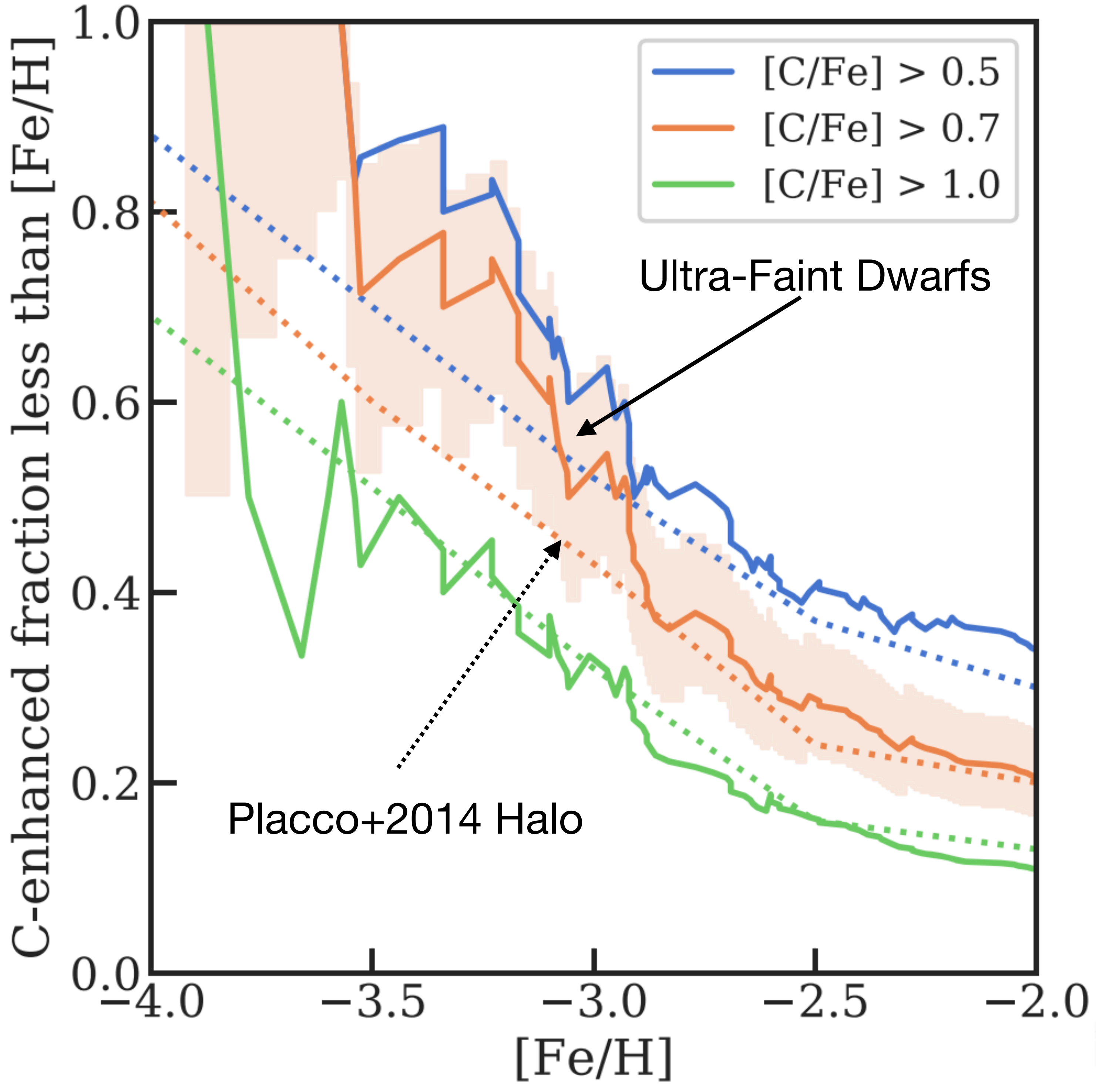
LMC vs MW Halo



Chiti w/ TSL et al. 2024

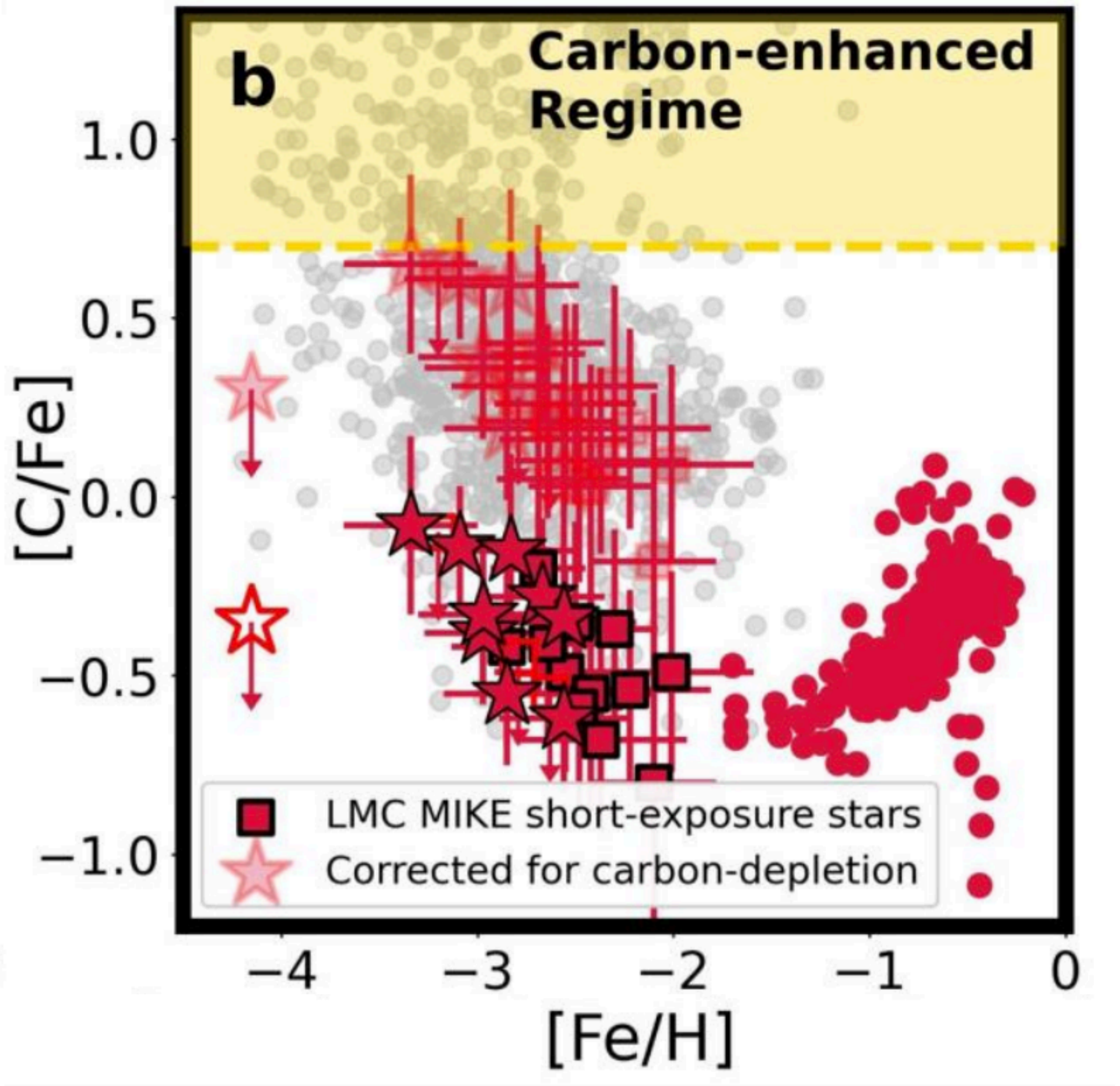
CEMP Fraction in different environment
Carbon-Enhanced Metal-Poor

UFDs vs MW Halo



Ji, TSL et al. 2020

LMC vs MW Halo



Chiti w/ TSL et al. 2024

UFDs have similar CEMP fractions as halo

Higher-mass systems (Classical dSphs, LMC, Bulge) may have lower CEMP fractions than halo

Also see Skúladóttir+2015, Salvadori+2015, Howes+2015, Arentsen+2021, Skúladóttir+2023, Oh+2024

Metal-poor stars of the Milky Way and ultra-faint dwarf galaxies

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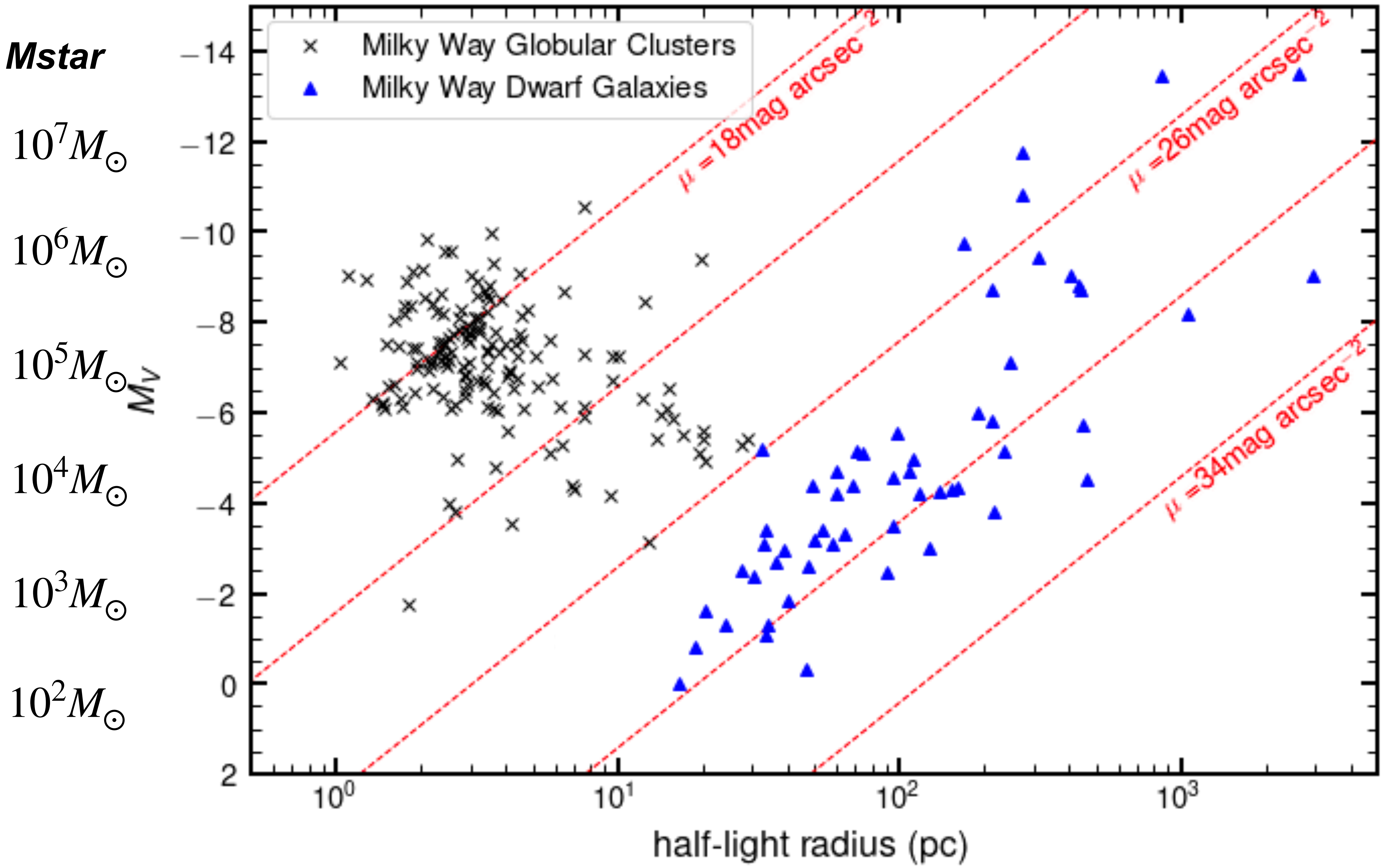
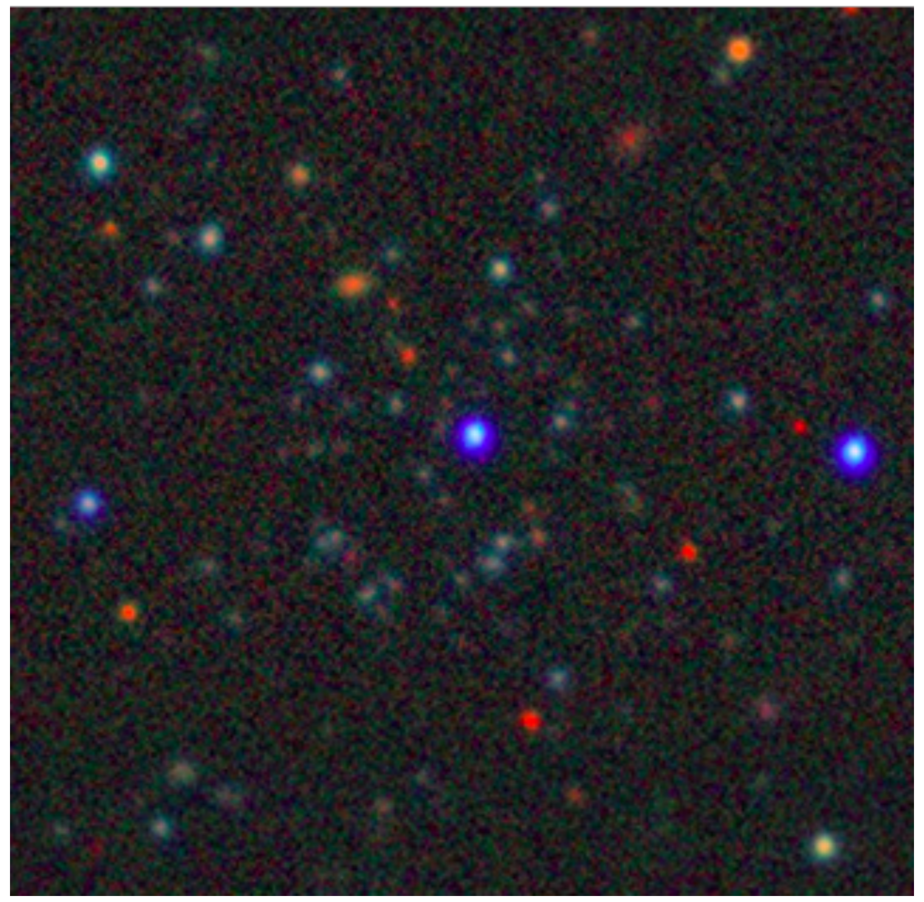
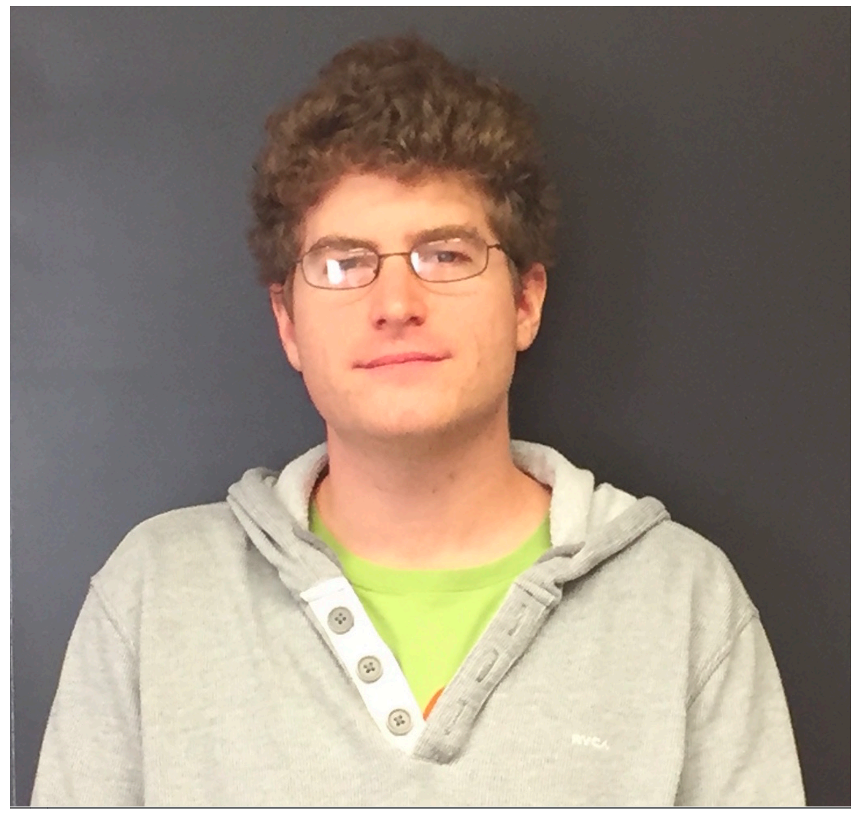
Are these all the Milky Way (intact) satellites in the halo?



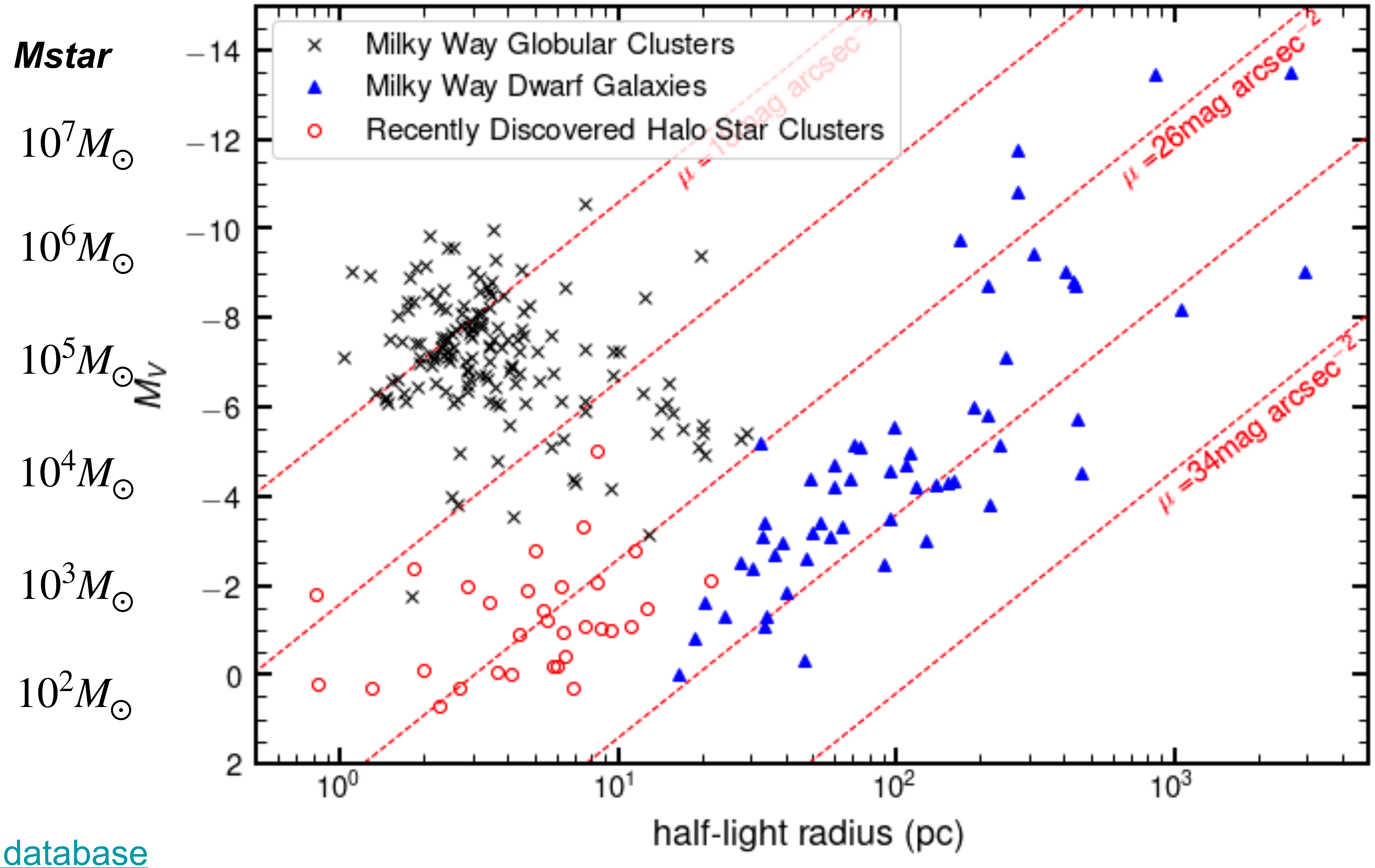
Ultra Faint Star Clusters (UFSCs) / Ultra Faint Compact Systems (UFCSs)

~30 systems discovered in the past 10 years!





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



What is the Boundary between clusters and galaxies?

Generally:

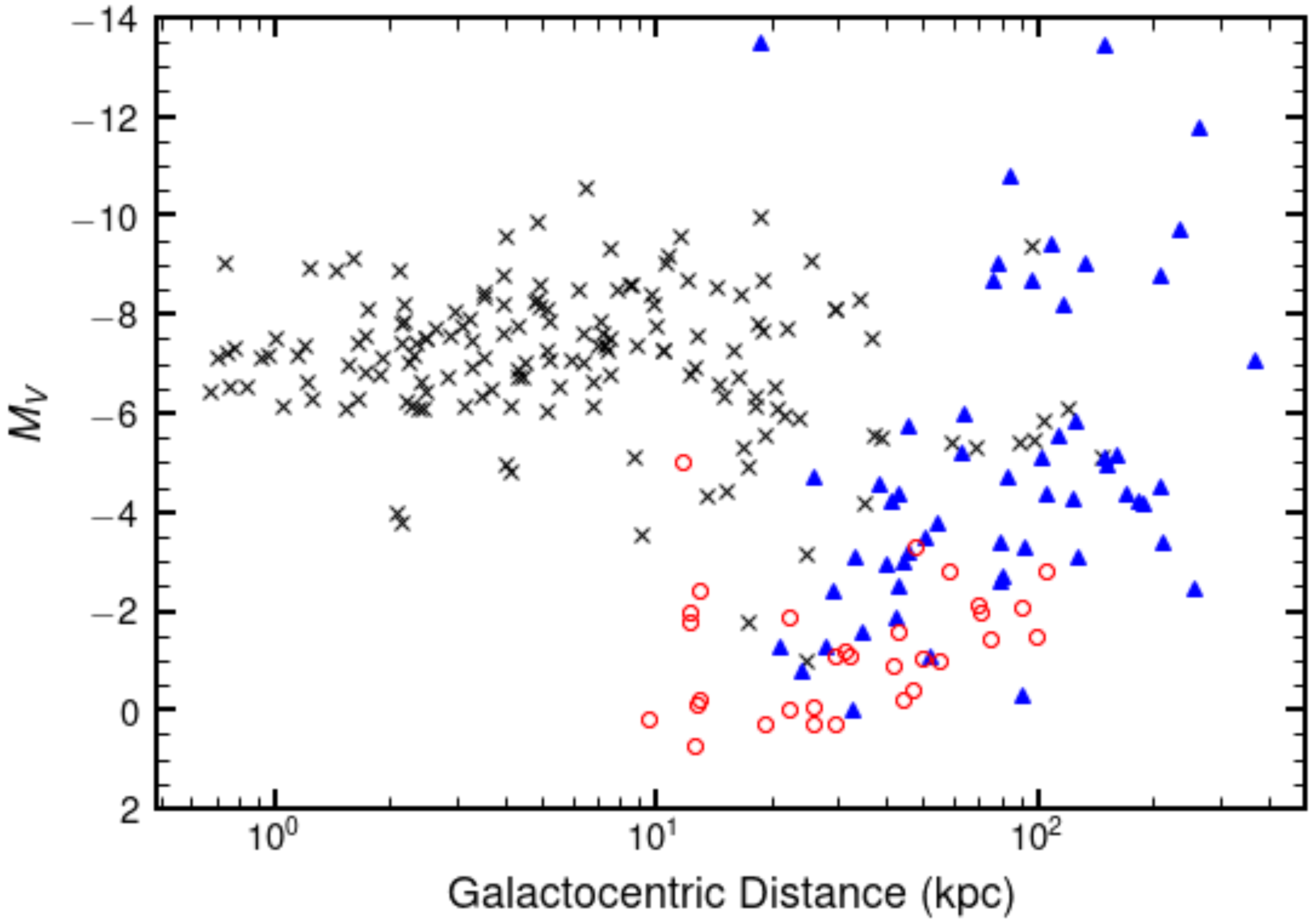
$r_{1/2} \lesssim 10$ pc

$\mu > 24$ mag/arcsec^2

$M_V \gtrsim -3$

$r_{Gal} > 10$ kpc

age ~ old (>10 Gyr)



Mstar

$10^7 M_\odot$

$10^6 M_\odot$

$10^5 M_\odot$

$10^4 M_\odot$

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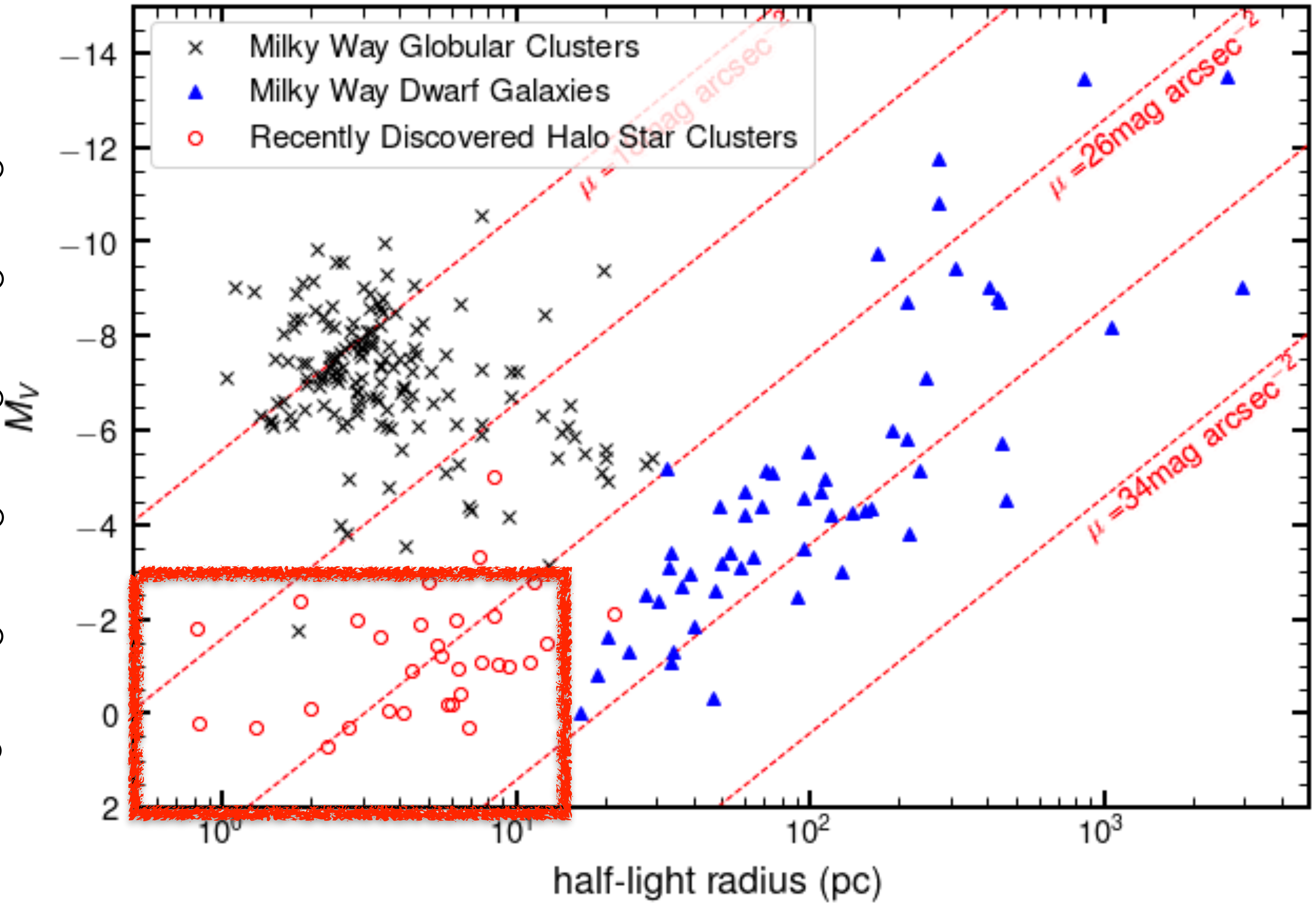
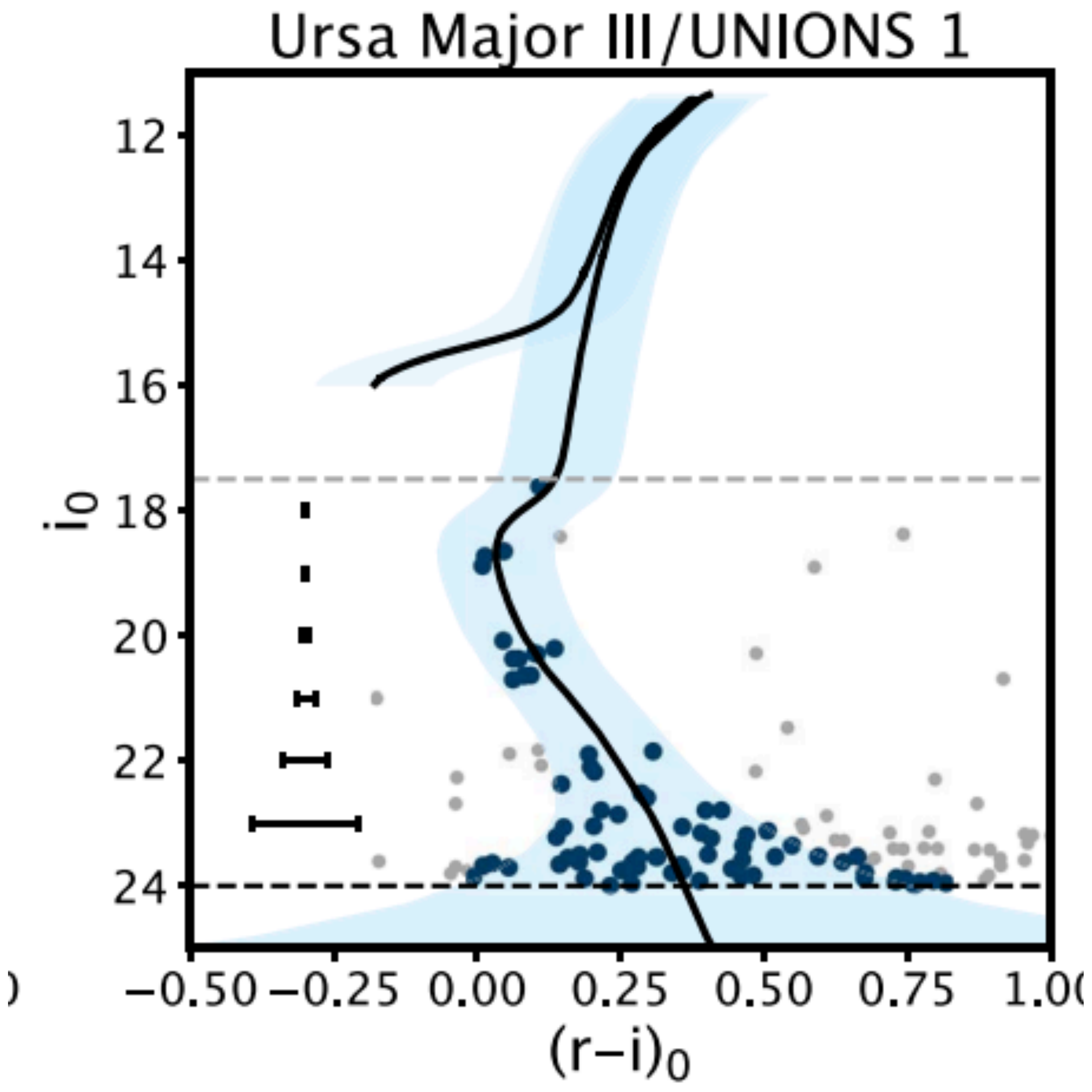
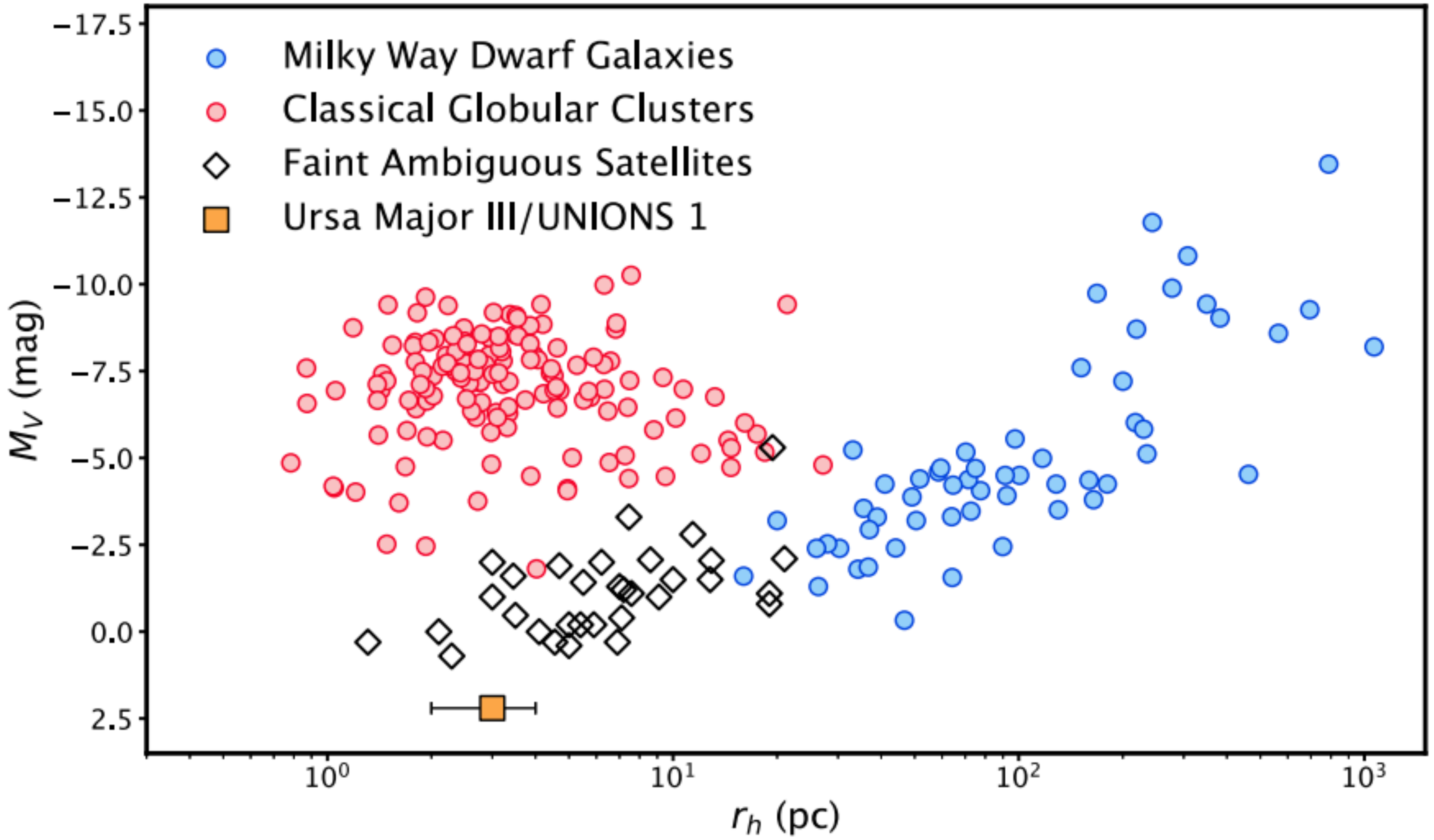
$10^2 M_\odot$



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





Smith w/TSL et al, 2024

A New Spectroscopic Census of the UFCSs

Magellan/IMACS

Keck/DEIMOS

William Cerny (Yale)

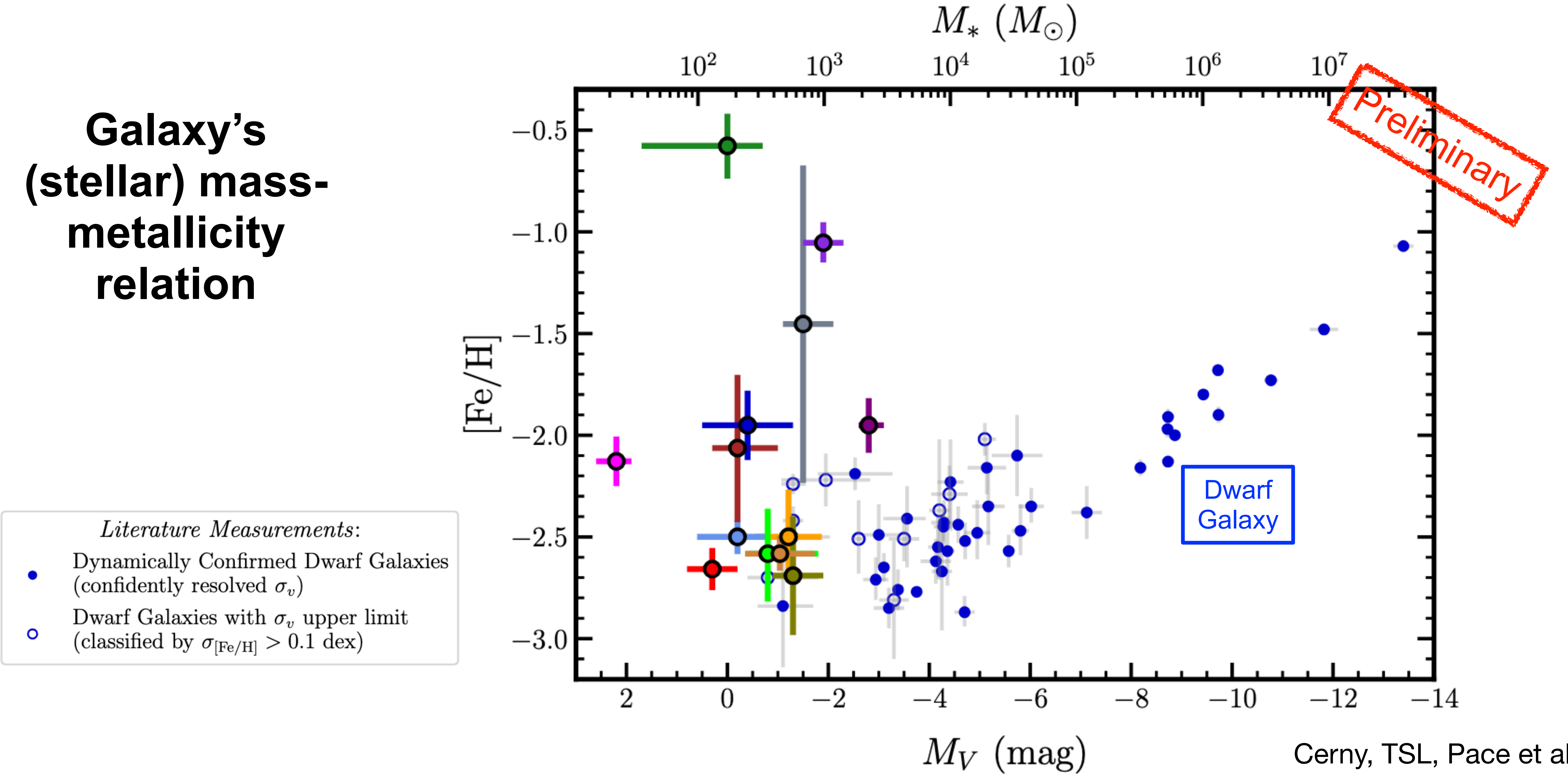
(Cerny, TSL, Pace et al. in prep)

We have collected, reduced, and homogeneously analyzed new and/or archival medium-resolution spectra for ~18 UFCSs!

first population-level chemodynamical insights into these systems

Results 1: Metallicities

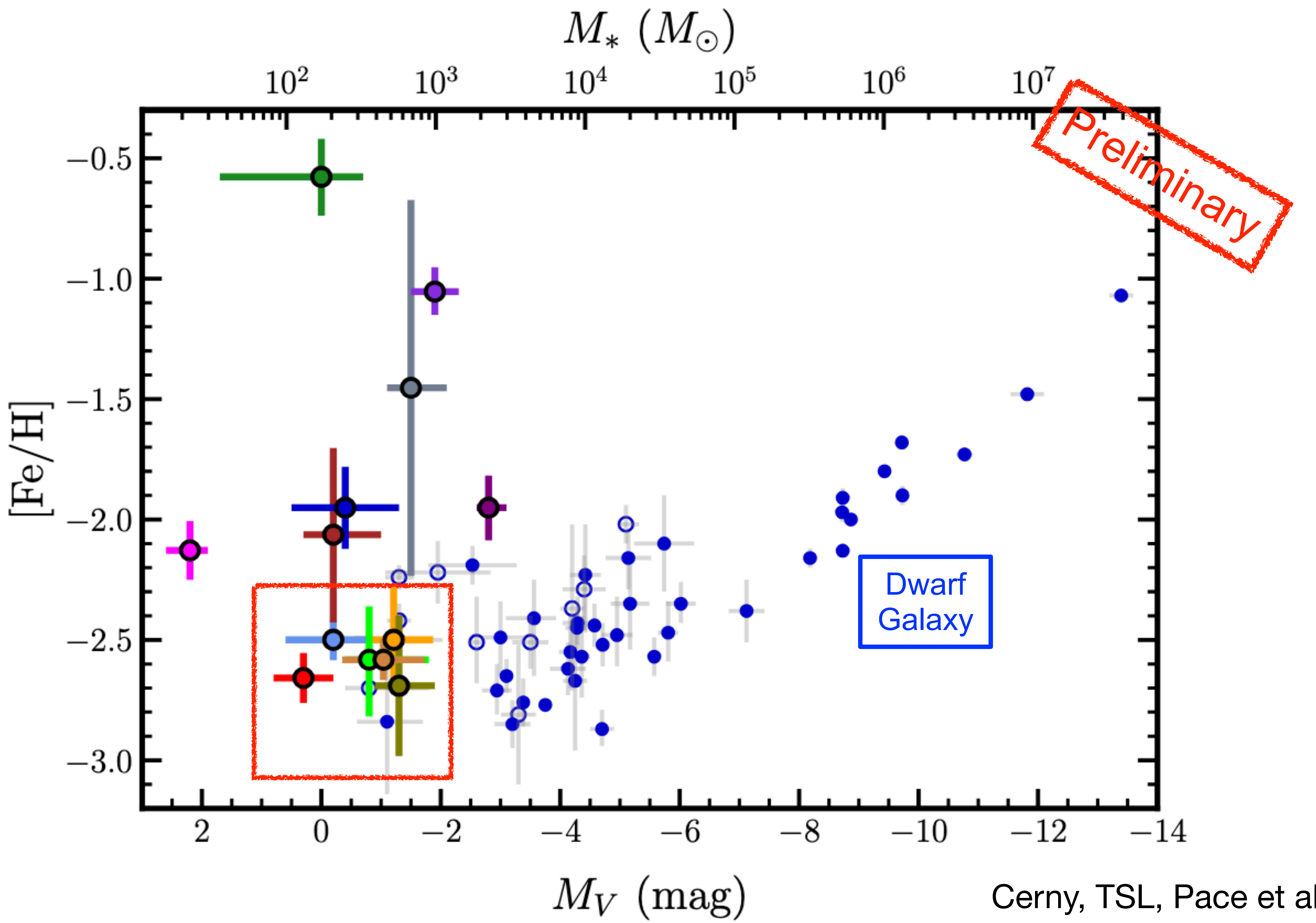
Galaxy's (stellar) mass-metallicity relation



Cerny, TSL, Pace et al. in prep

Results 1: Metallicities

Galaxy's (stellar) mass-metallicity relation

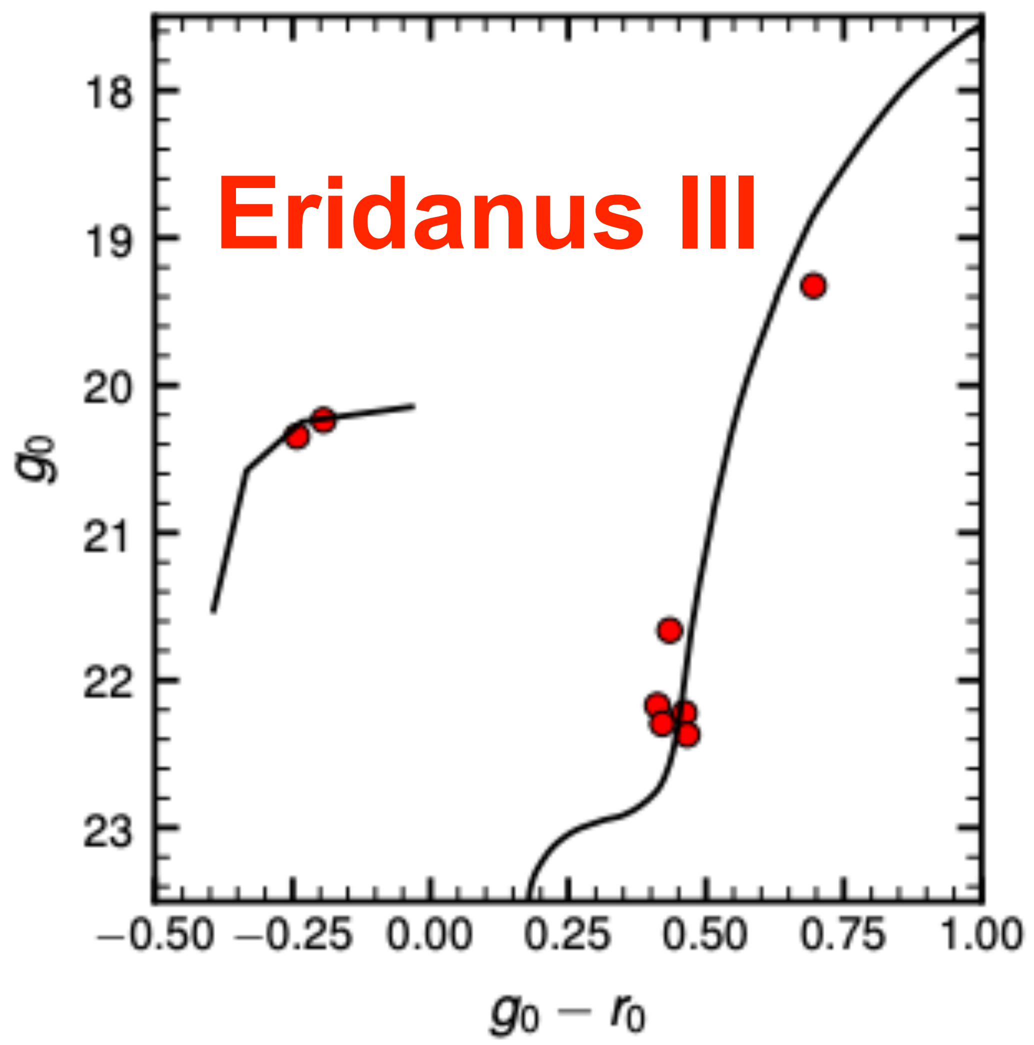


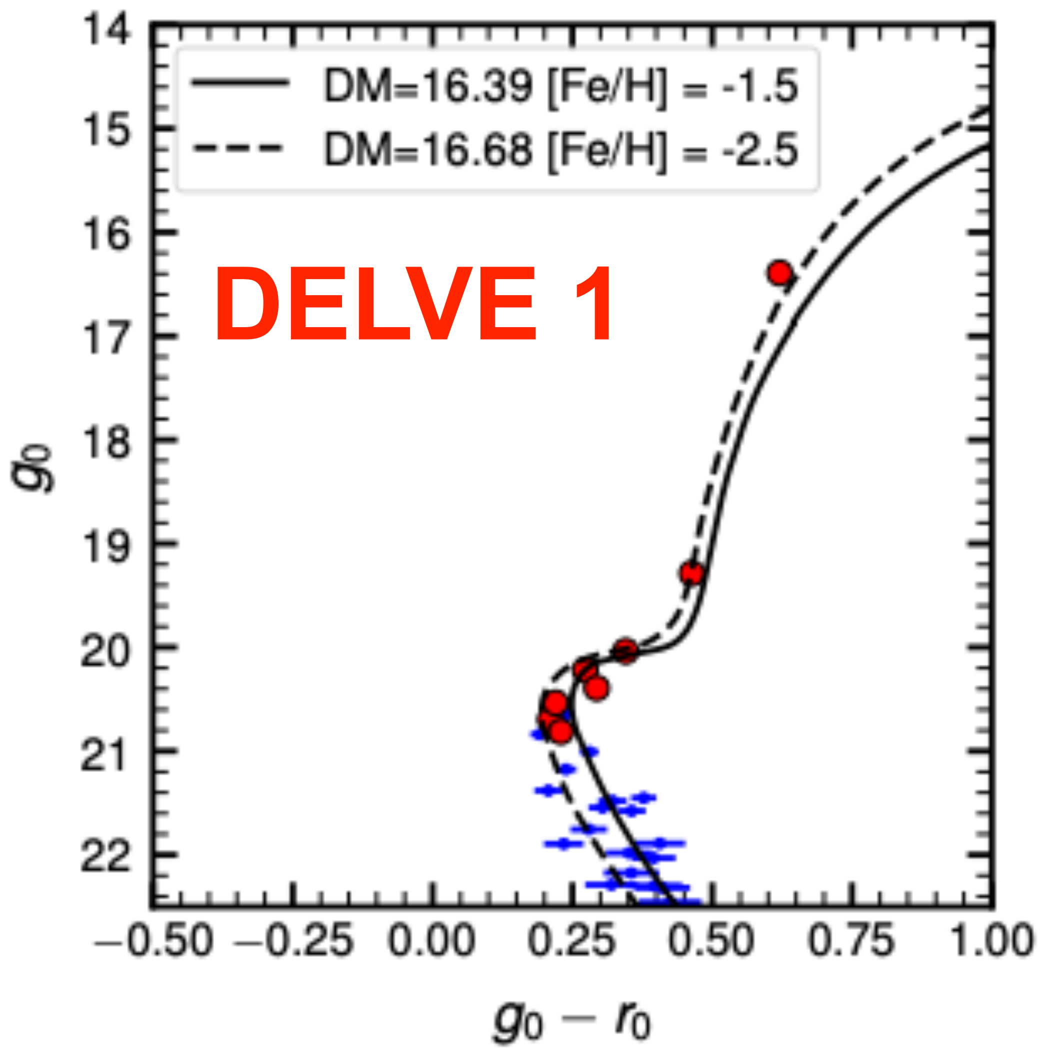
A surprising number of the UFCSs appear to trace the *galaxy* mass-metallicity relation

and below "GC metallcity floor"

Cerny, TSL, Pace et al. in prep

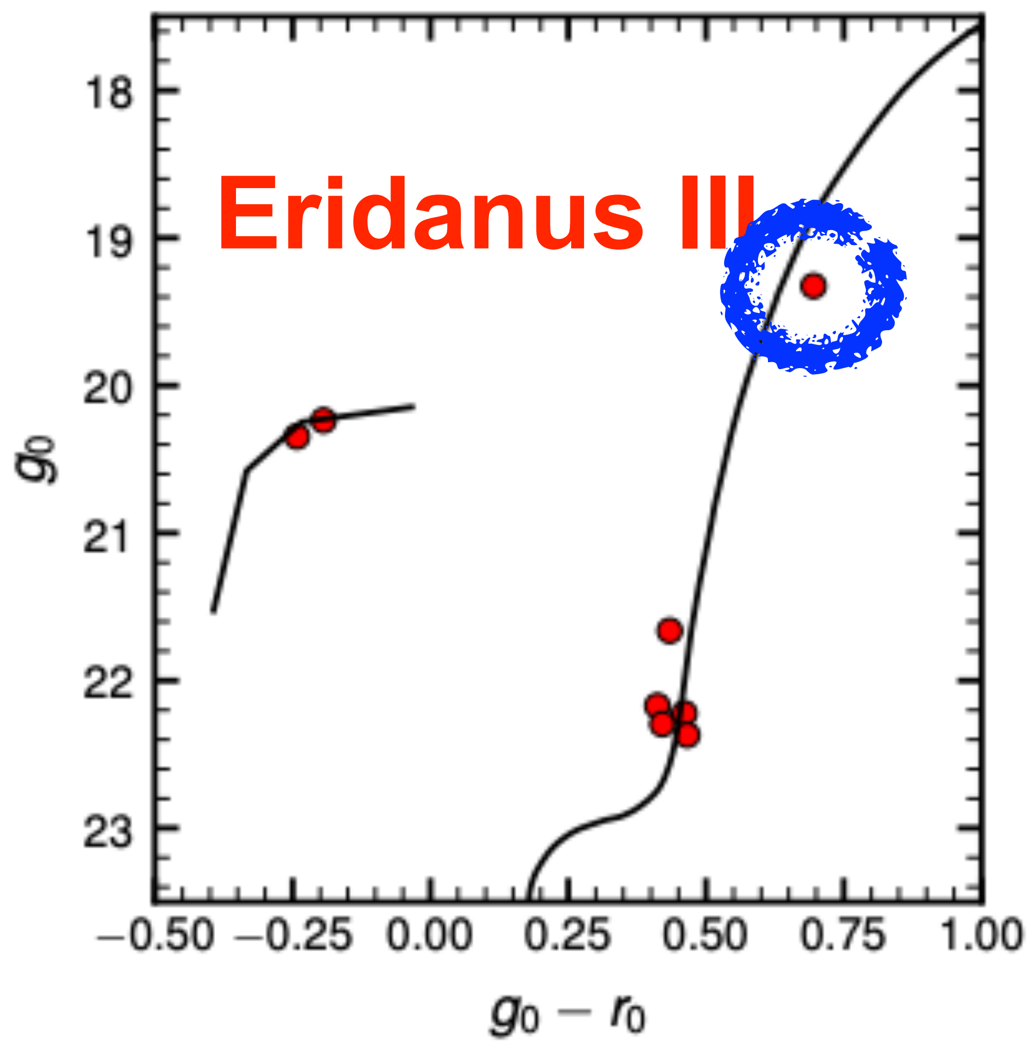
Results 2:
Carbon-rich Primordial Star Clusters or the Smallest Dwarf Galaxies?



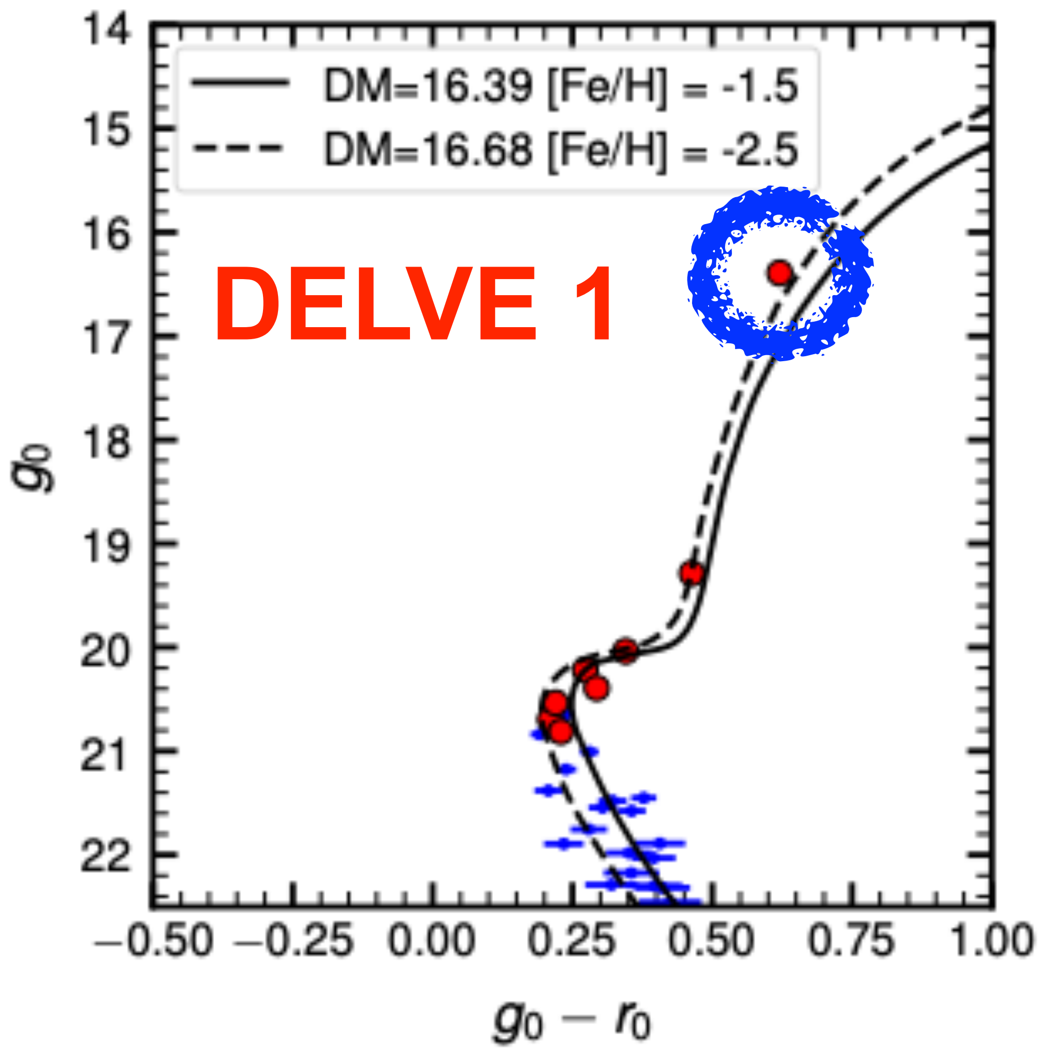


Simon, TSL et al. 2024, arXiv:2410.08276

Results 2:
Carbon-rich Primordial Star Clusters or the Smallest Dwarf Galaxies?



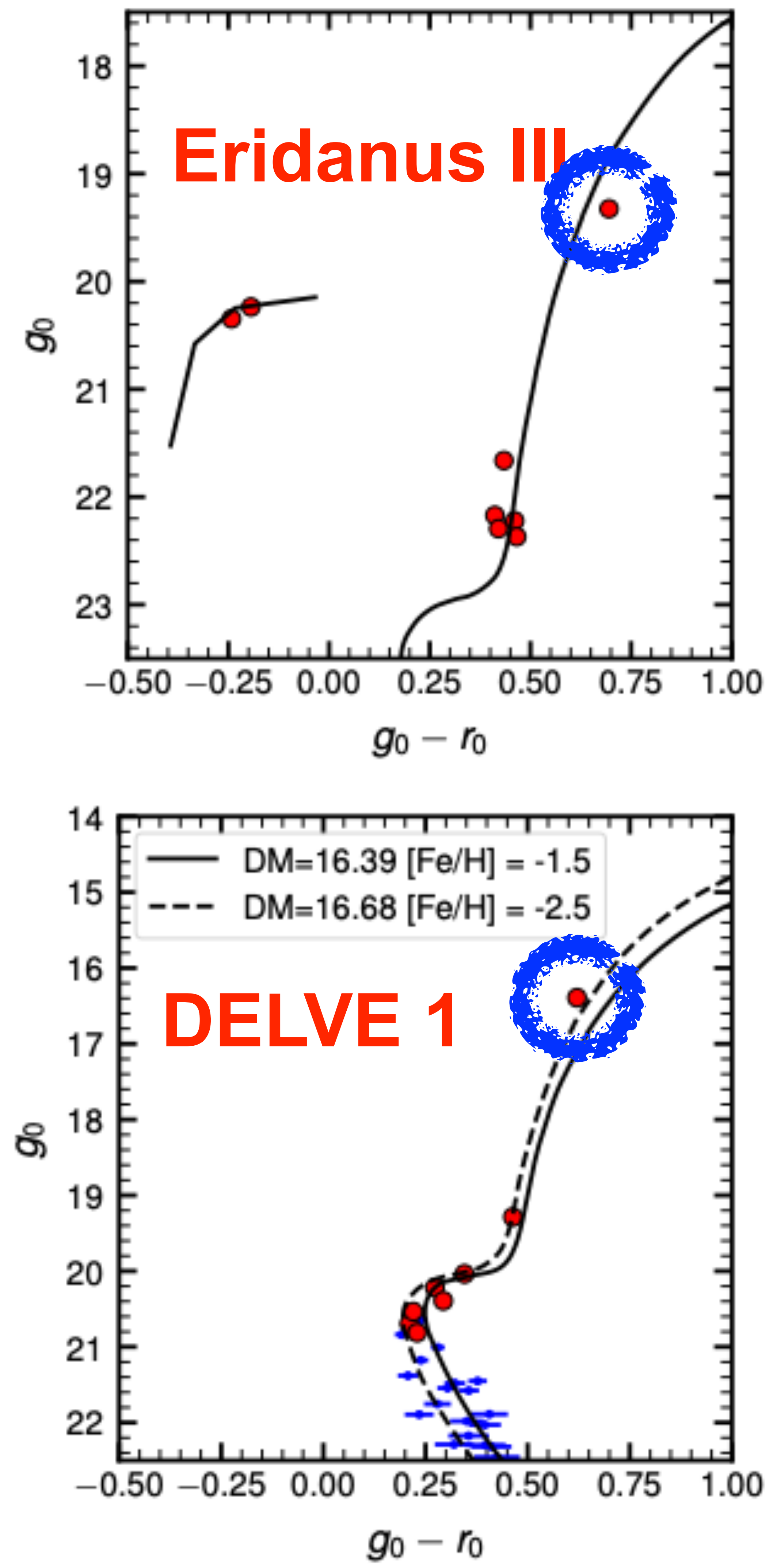
[Fe/H] = -3.1

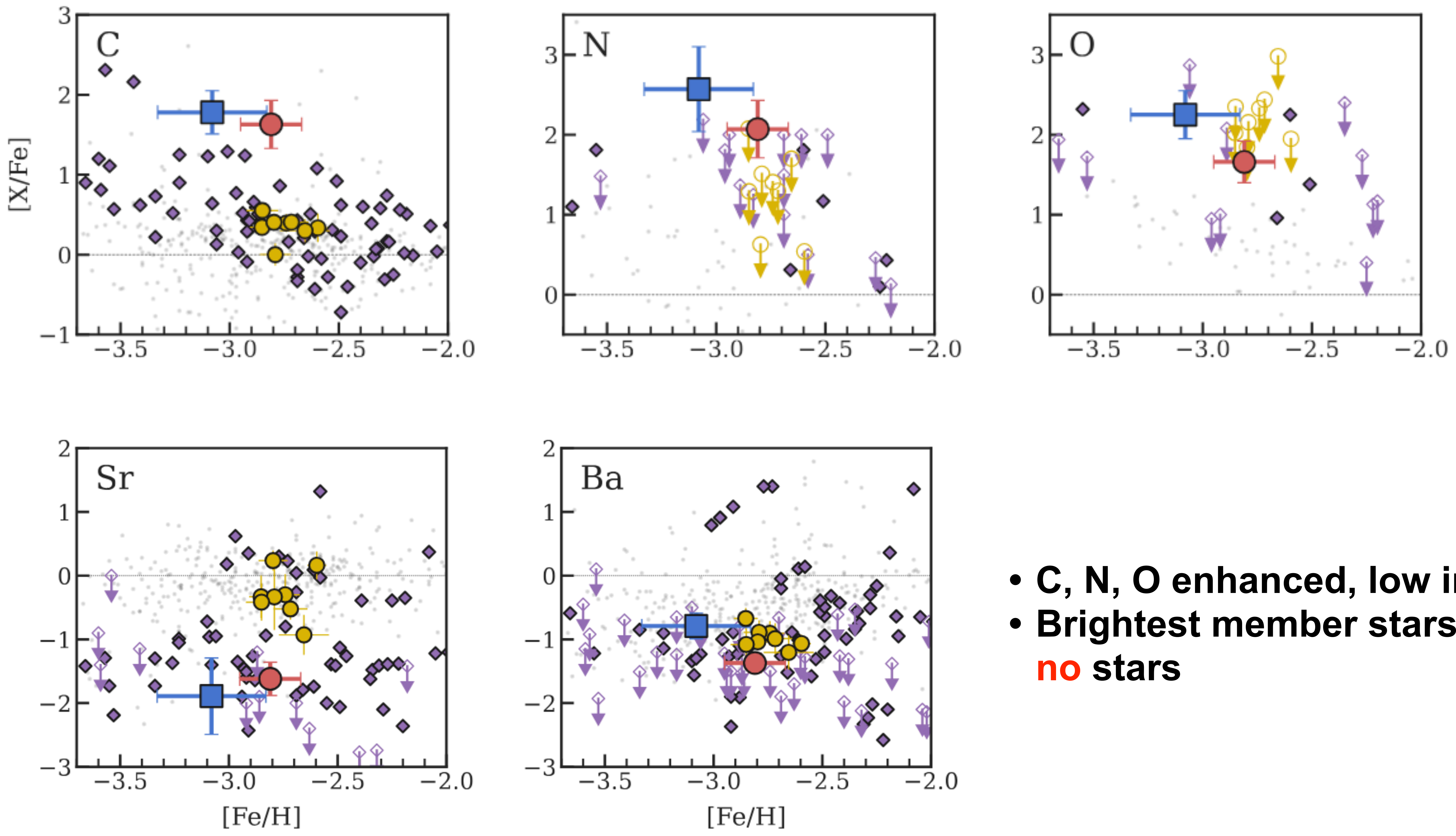


[Fe/H] = -2.8

Simon, TSL et al. 2024, arXiv:2410.08276

Results 2:
Carbon-rich Primordial Star Clusters or the Smallest Dwarf Galaxies?



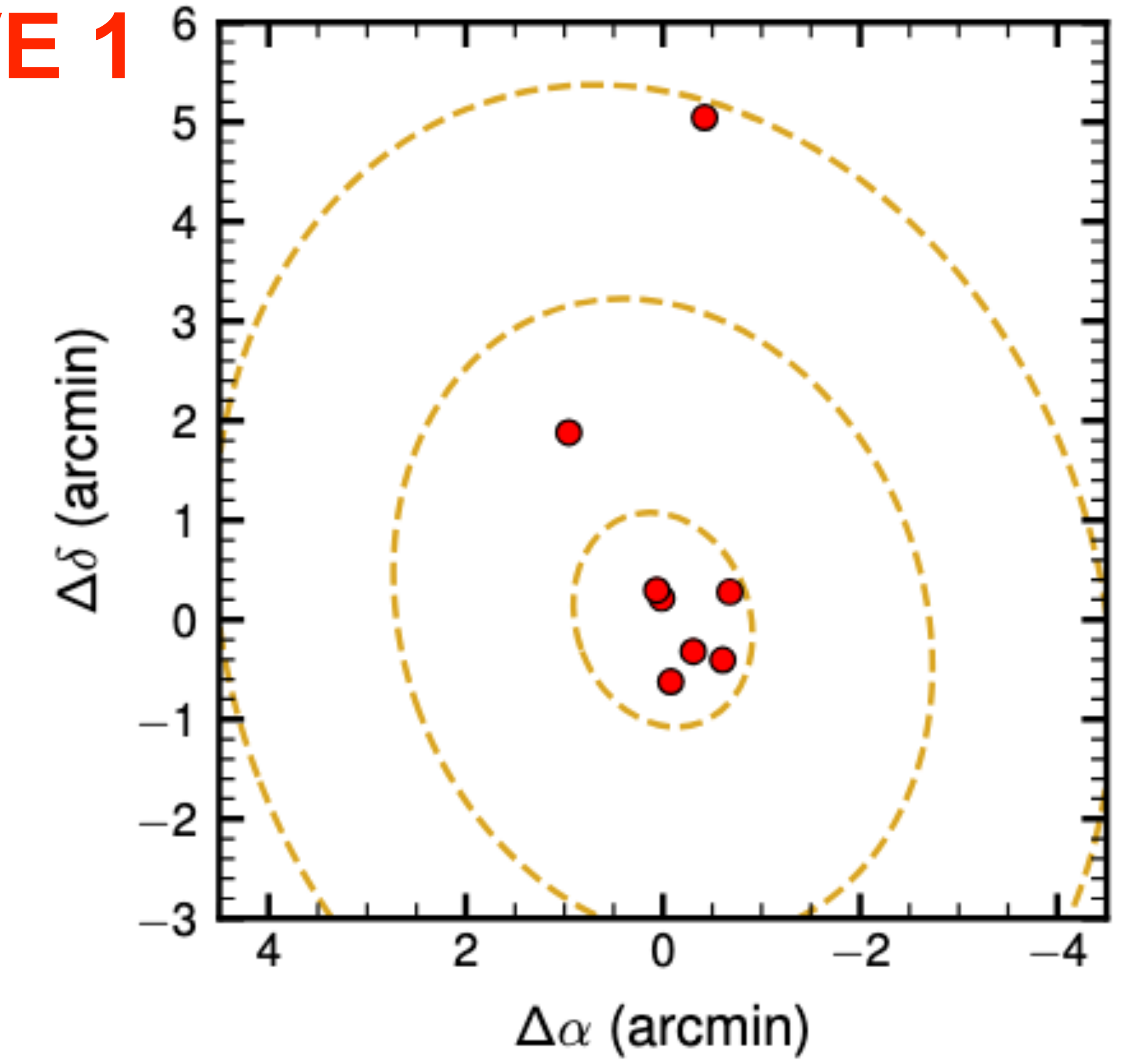


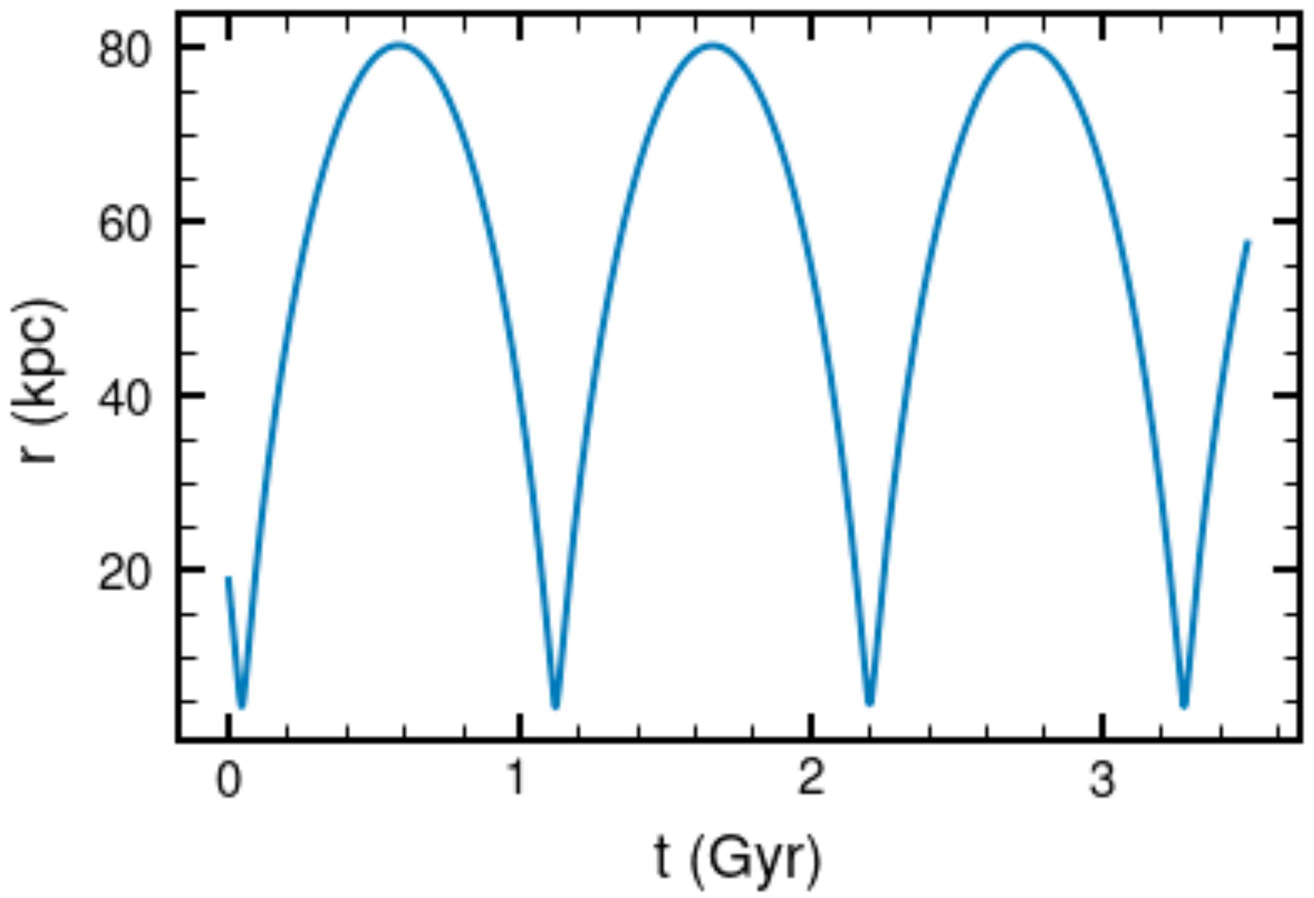
- **C, N, O enhanced, low in Sr and Ba**
- **Brightest member stars are CEMP-no stars**

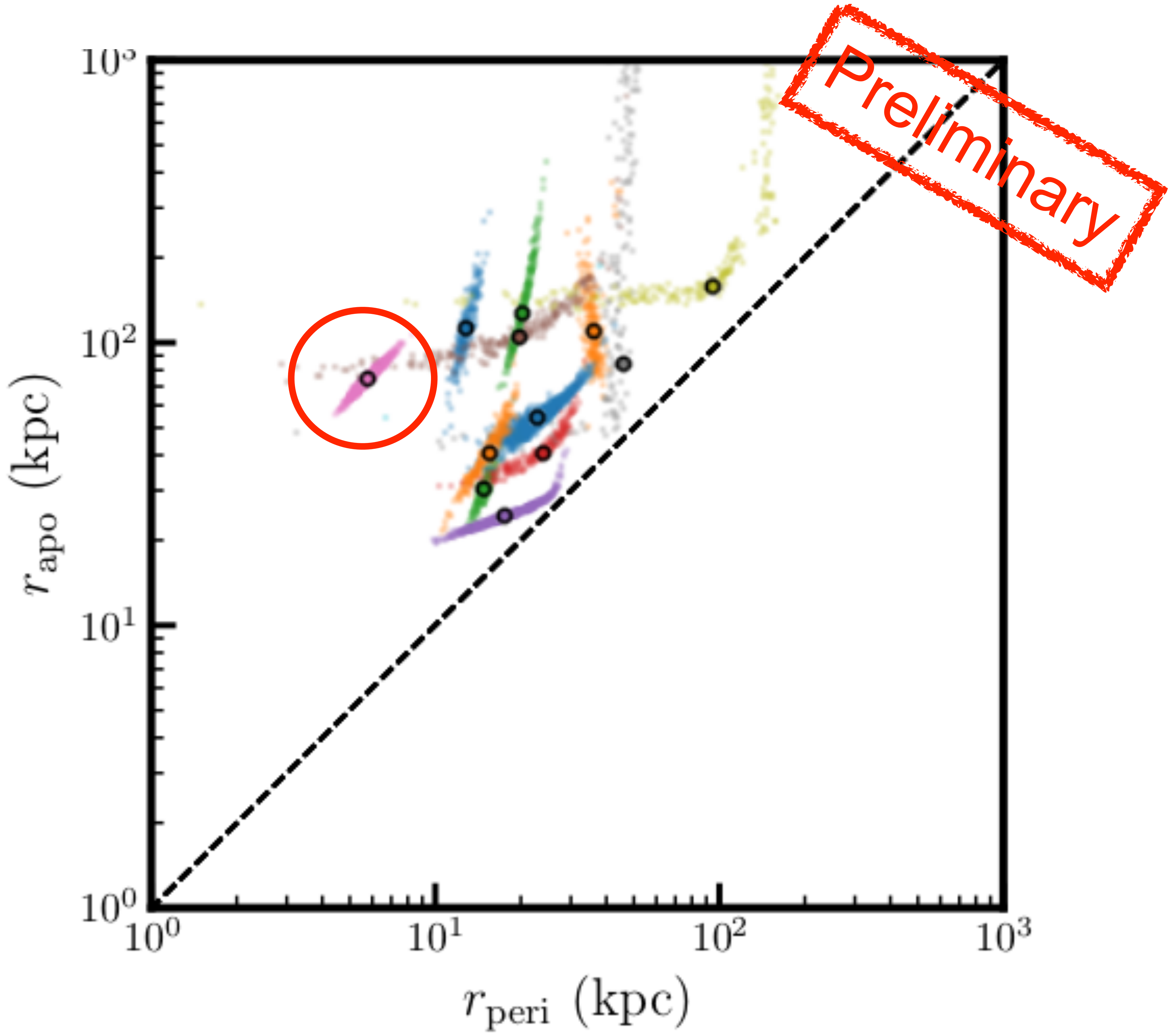
Simon, TSL et al. 2024, arXiv:2410.08276

Preliminary Results 3: Orbital Properties — Survivability

DELVE 1



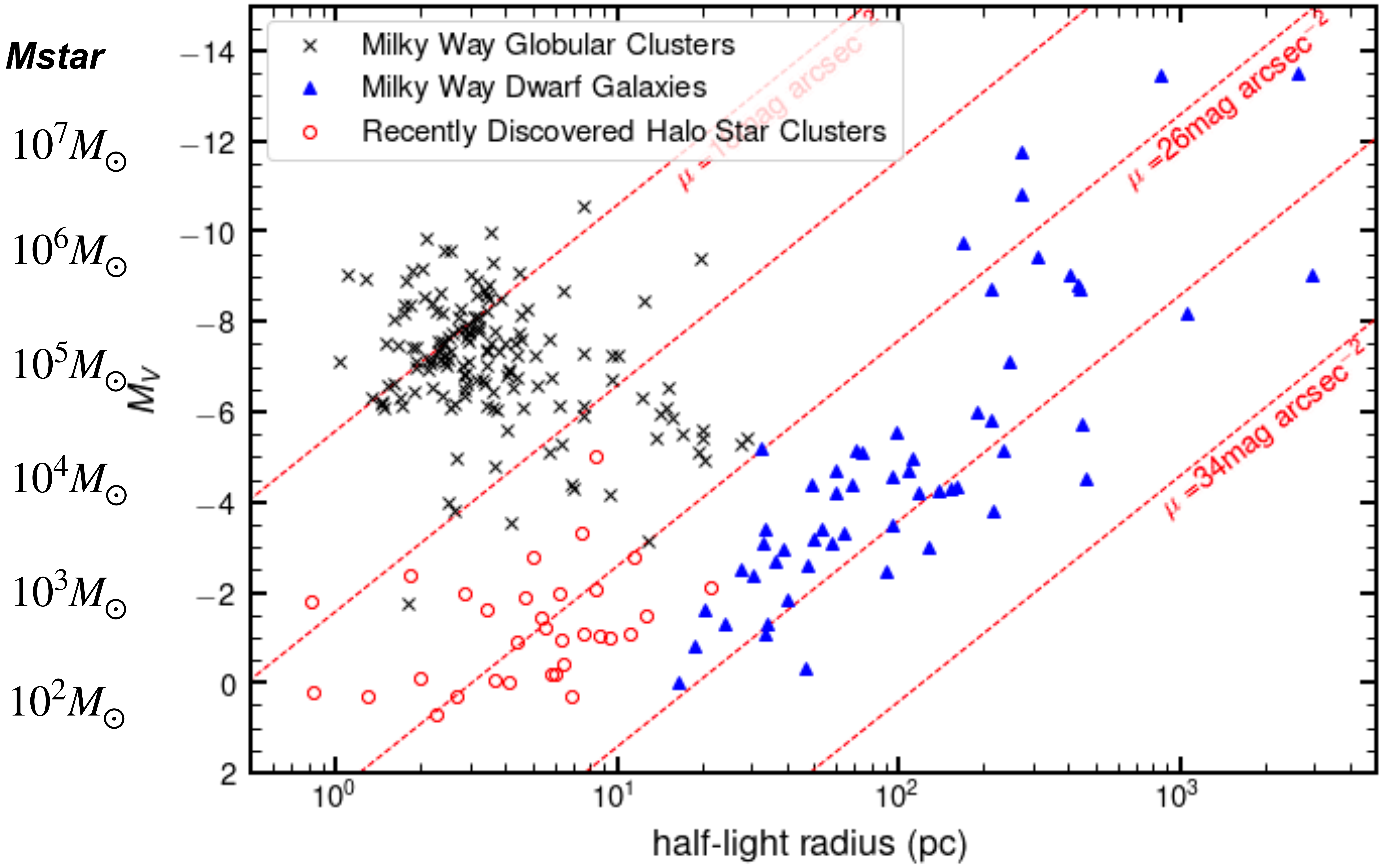




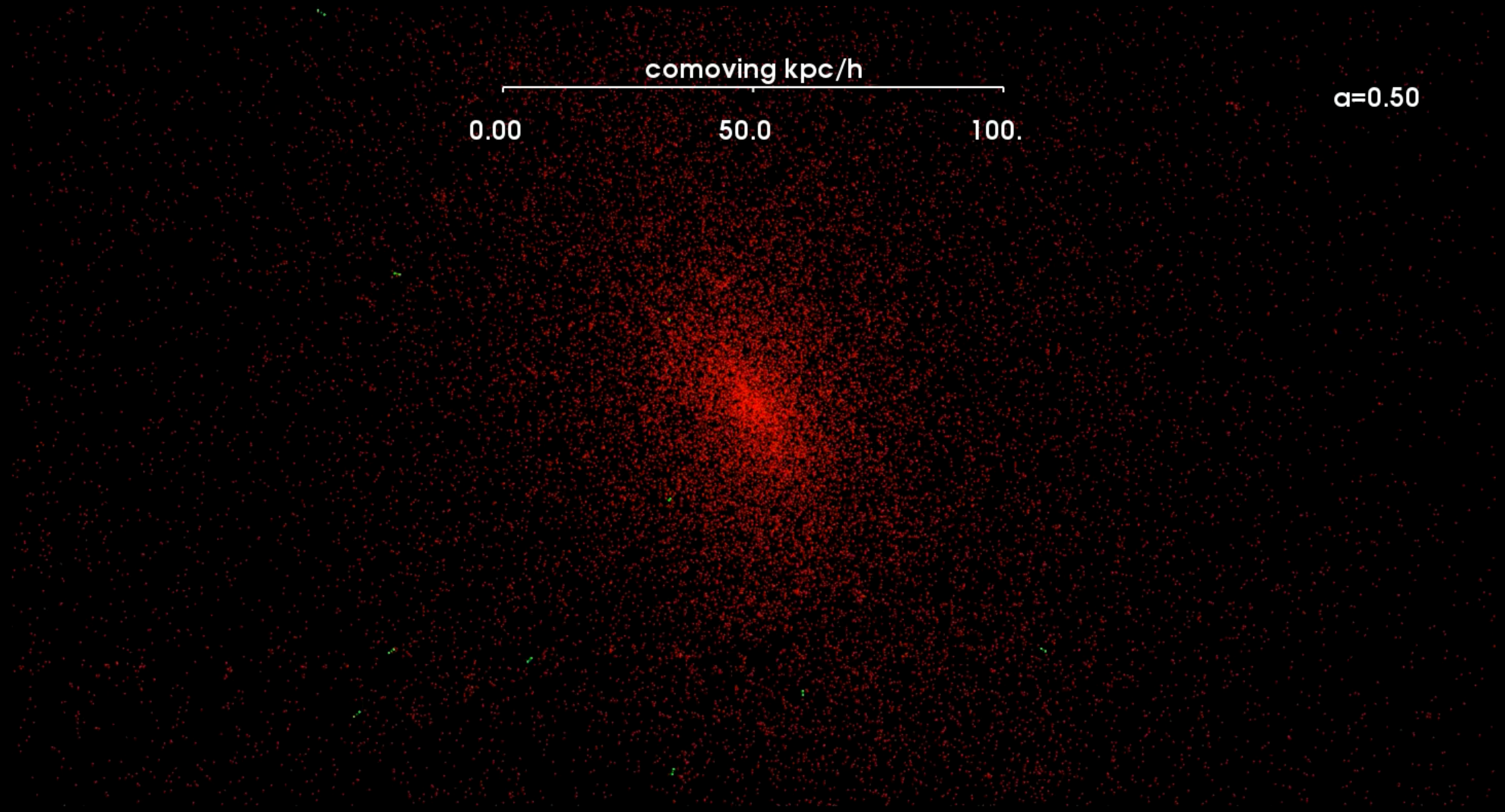
Pericenter ~ 4 kpc, Apocenter ~ 80 kpc
Last peri: ~ 40 Myr

Cerny, TSL, Pace et al. in prep
See also in Errani et al 2024 for UNIONS 1

Are these all the Milky Way ~~(intact)~~ satellites in the halo?



Cold Stellar Streams in the Milky Way



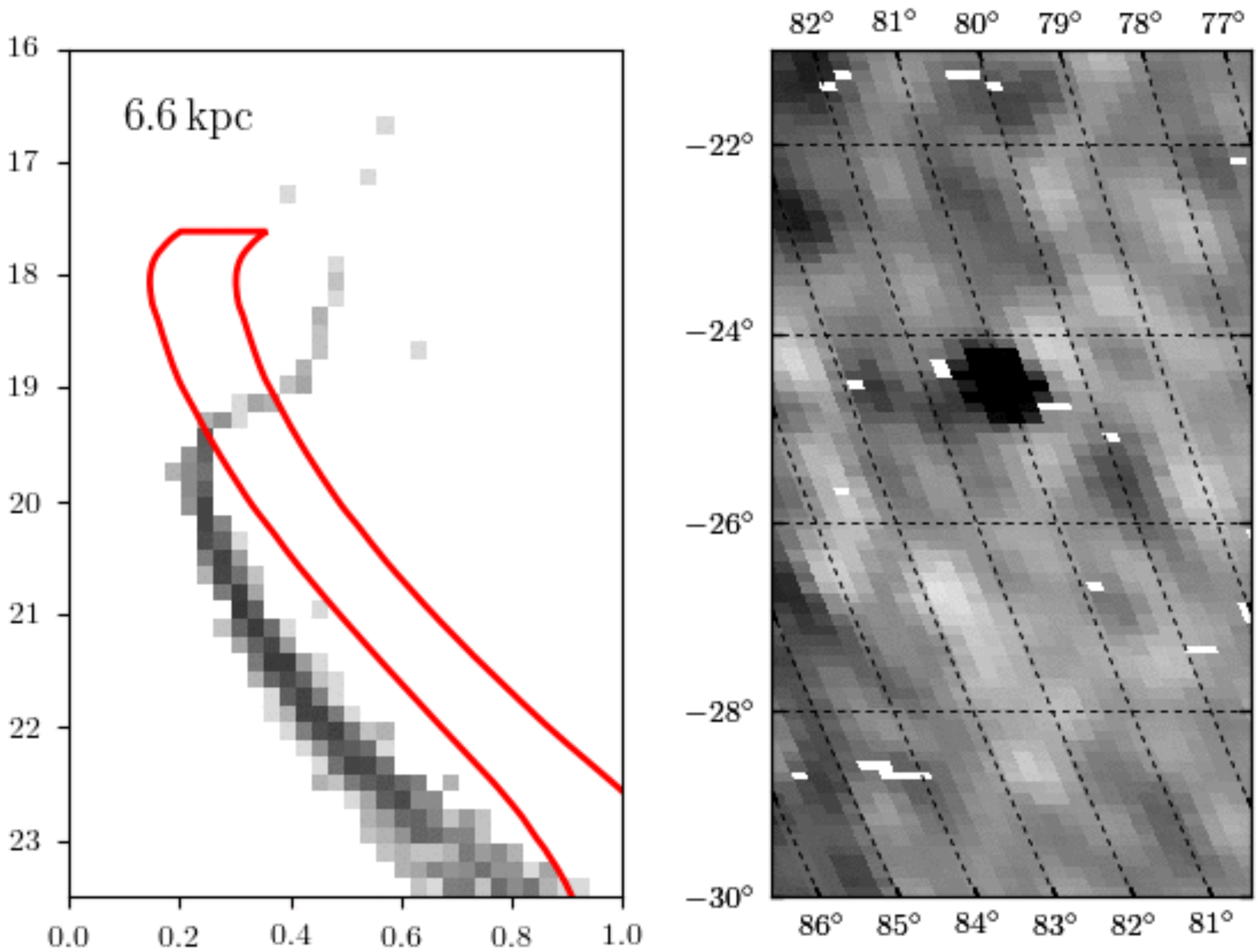
Milky Way like galaxies are assembled by accretion and disruption of many smaller systems

Stellar Streams:

- tidally disrupted
  - dwarf galaxies
  - globular clusters
- but not fully mixed

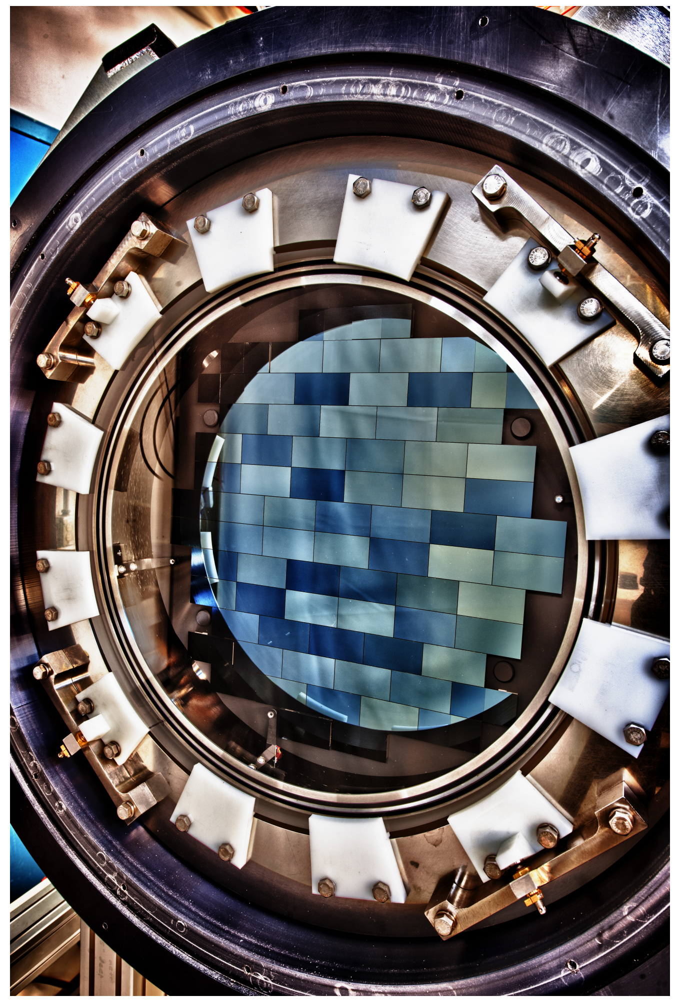
Credit: Denis Erkal

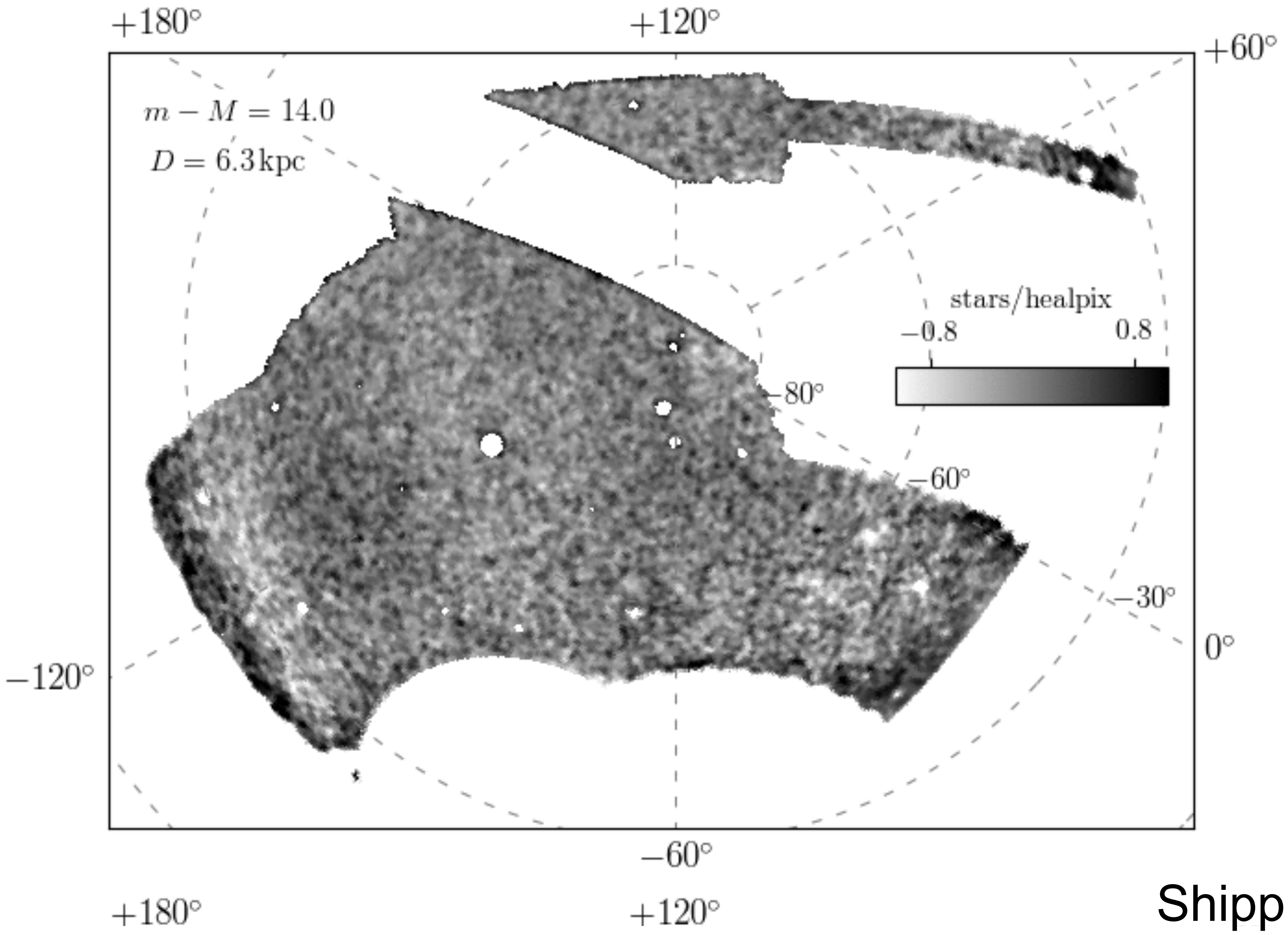
Isochrones Scanning through in distance



Credit: Alex Drlica-Wagner

Streams in the Dark Energy Survey

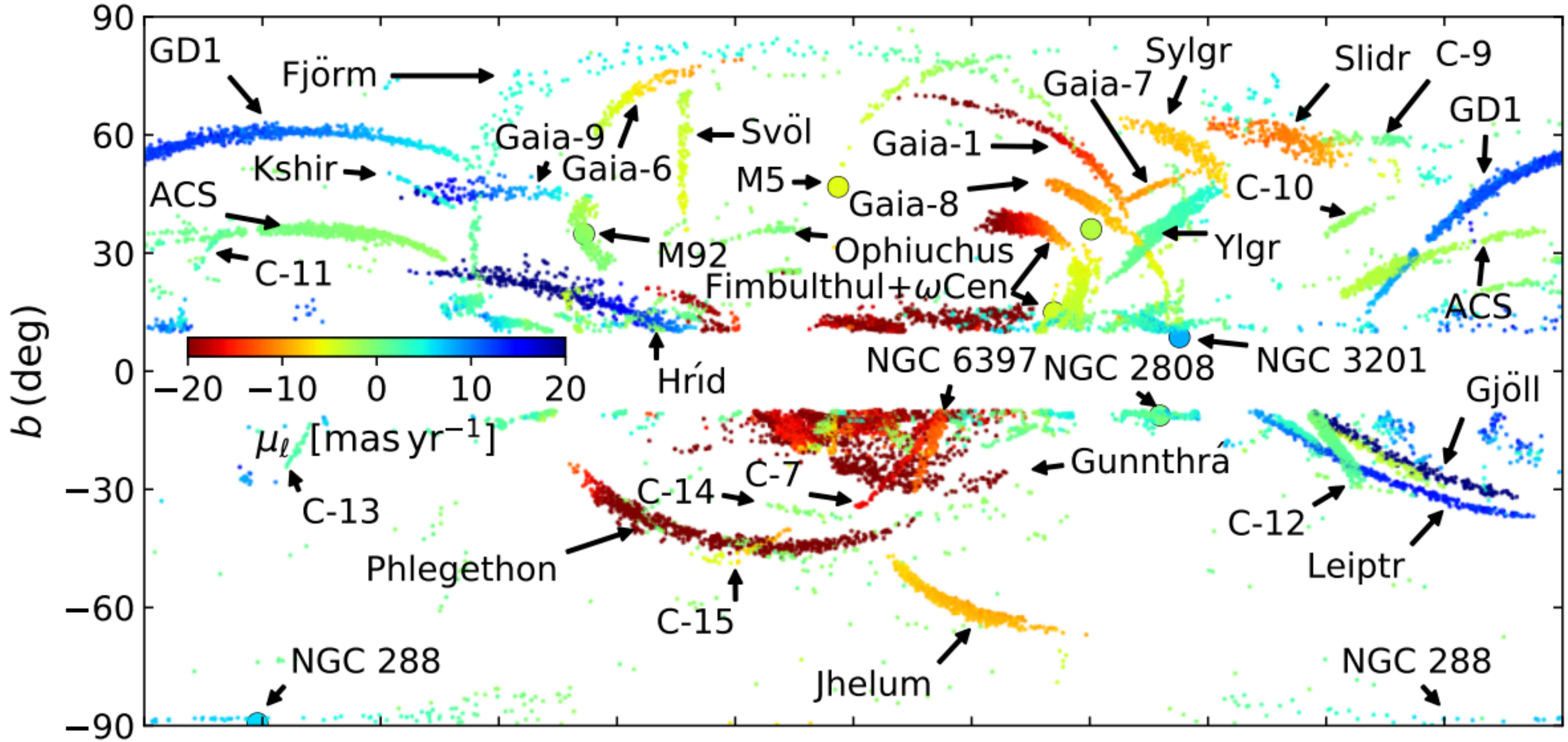




13 new streams from DES + 2 previous known

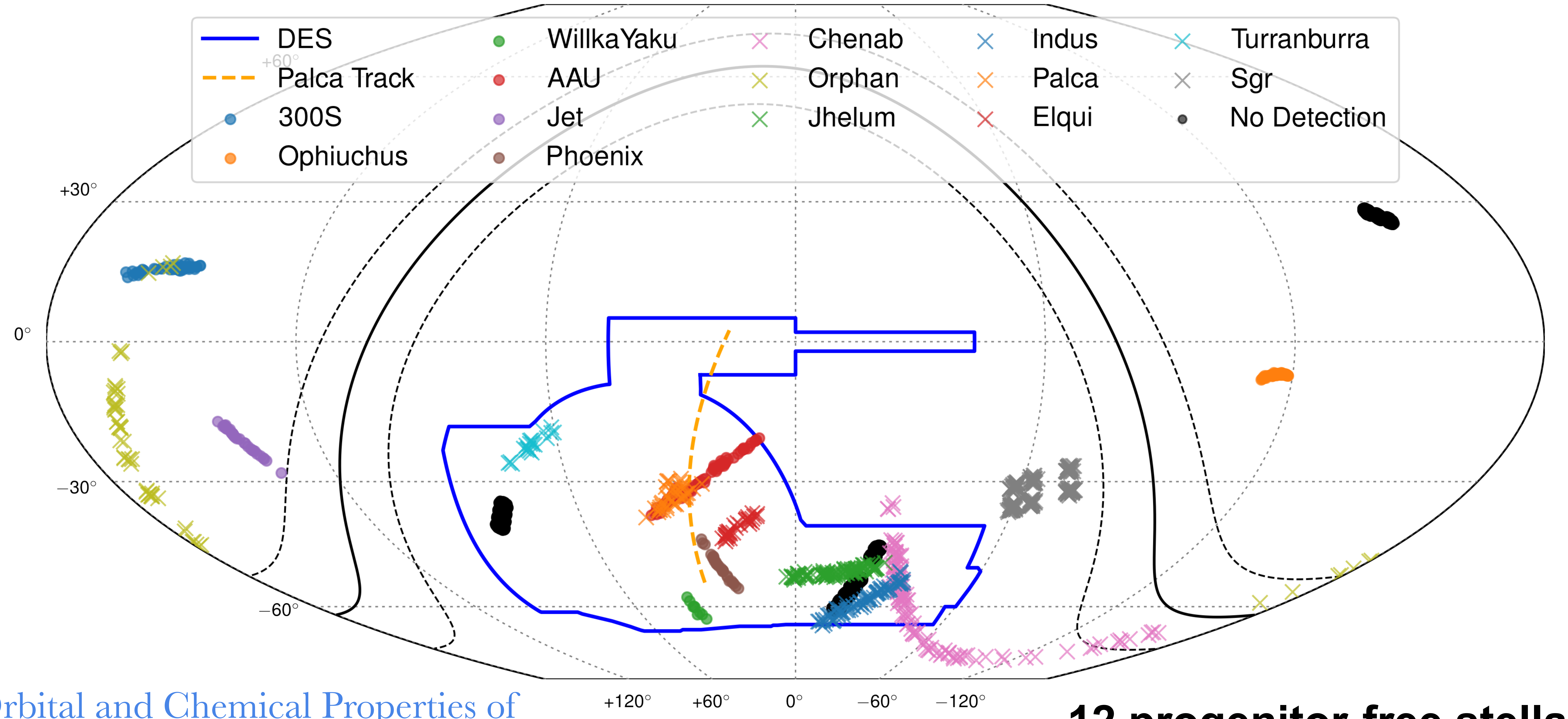
Shipp et al. 2018
(DES Collaboration)

Gaia EDR3 detections, [3, 12] kpc



Gaia EDR3 / Ibata et al. 2021

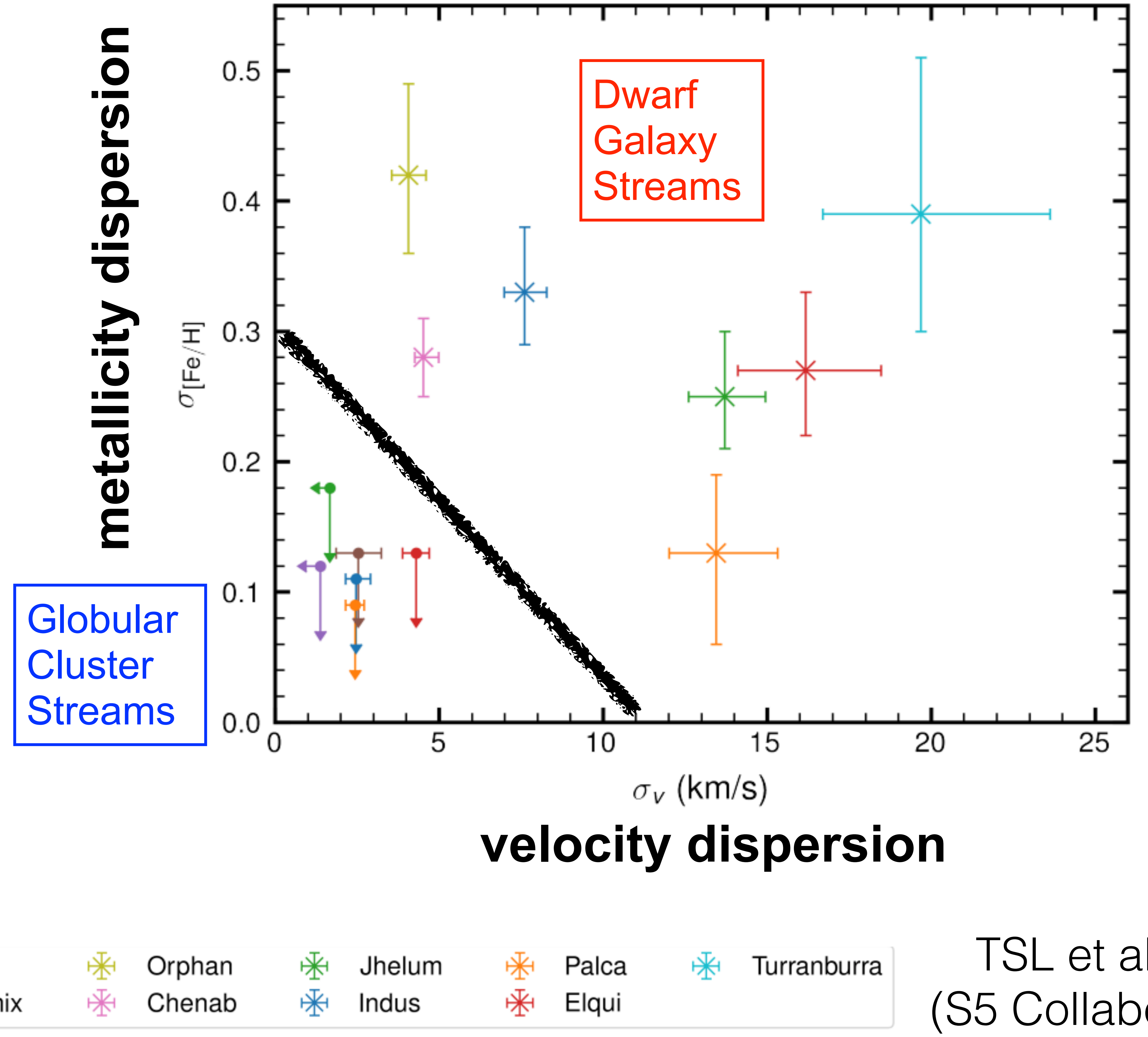
S5: Southern Stellar Stream Spectroscopic Survey



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

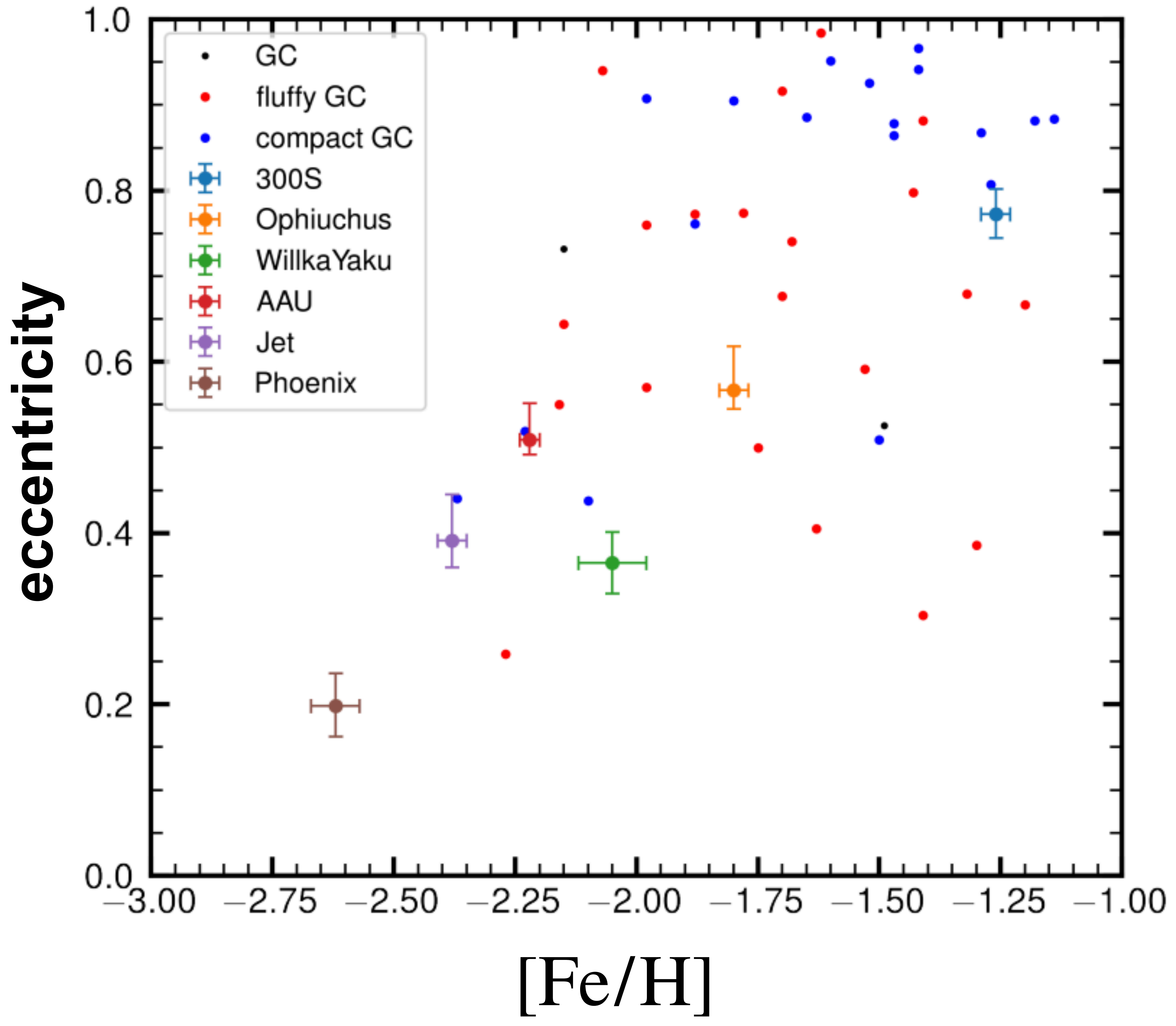
12 progenitor-free stellar streams at ~10-50 kpc observed in 2018-2020

Progenitors — globular cluster vs dwarf galaxy: 50%-50%



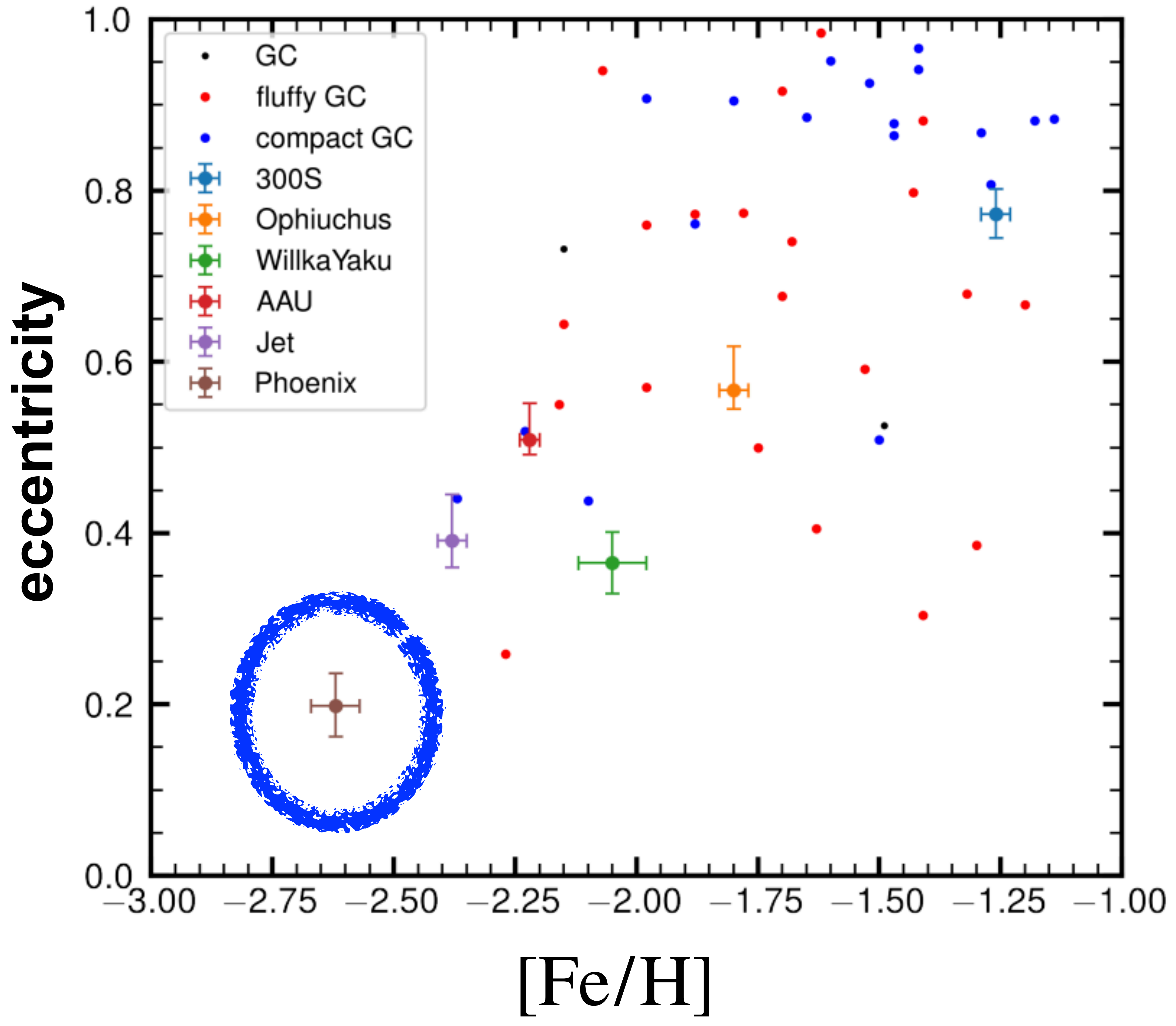
TSL et al (2022)
(S5 Collaboration)

Globular cluster streams:
Lower metallicity, more circular orbit



TSL et al (2022)
(S5 Collaboration)

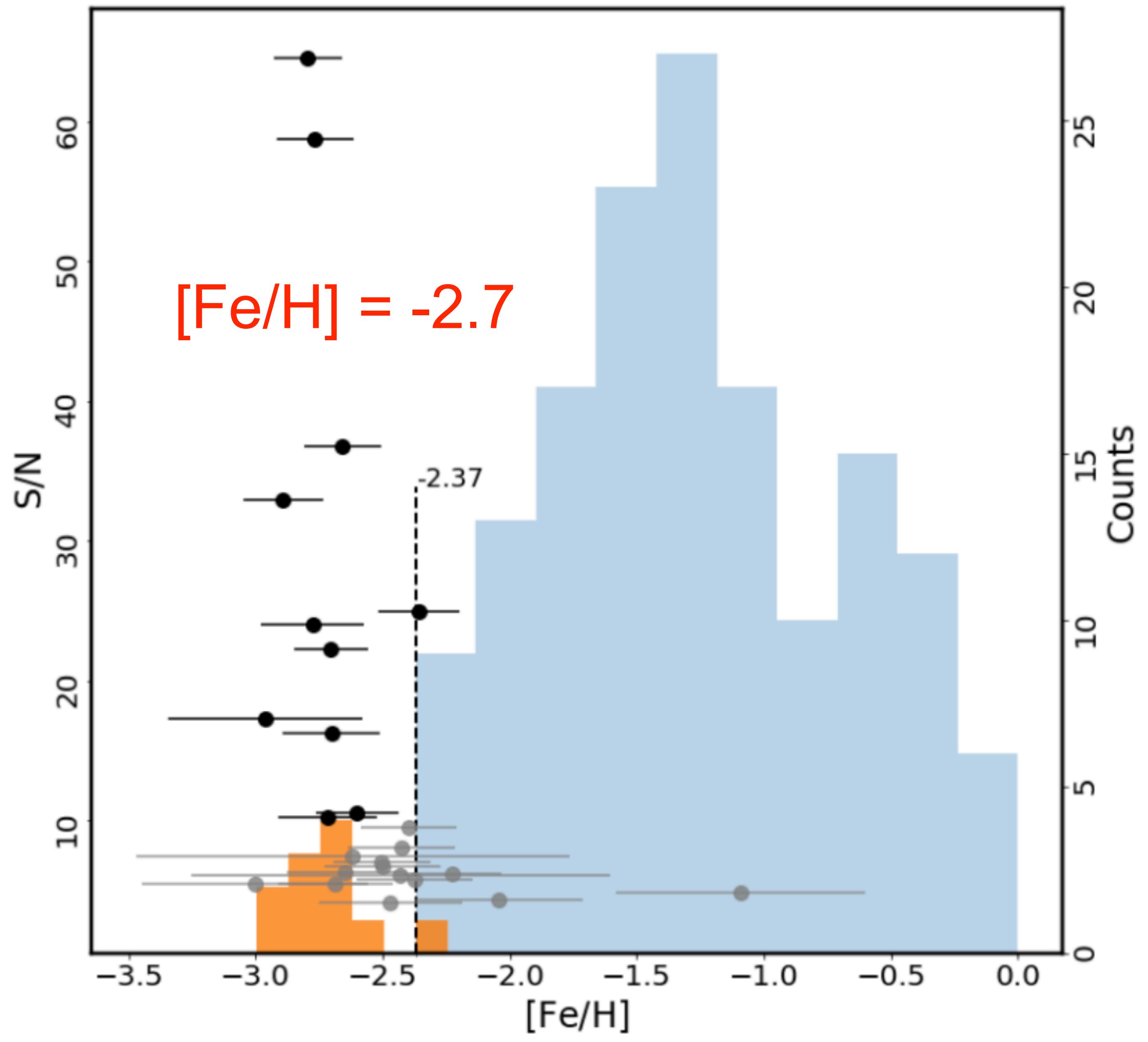
Globular cluster streams: Lower metallicity, more circular orbit



TSL et al (2022)
(S5 Collaboration)

Globular cluster streams below [Fe/H] < -2.5

Phoenix Stream: more metal-poor than any known globular cluster



Cyan: globular cluster in Milky Way
Orange: stars in Phoenix Stream

Wan, Lewis, TSL et al. (2020) Nature (S5 Collaboration)

Globular cluster streams below [Fe/H] < -2.5

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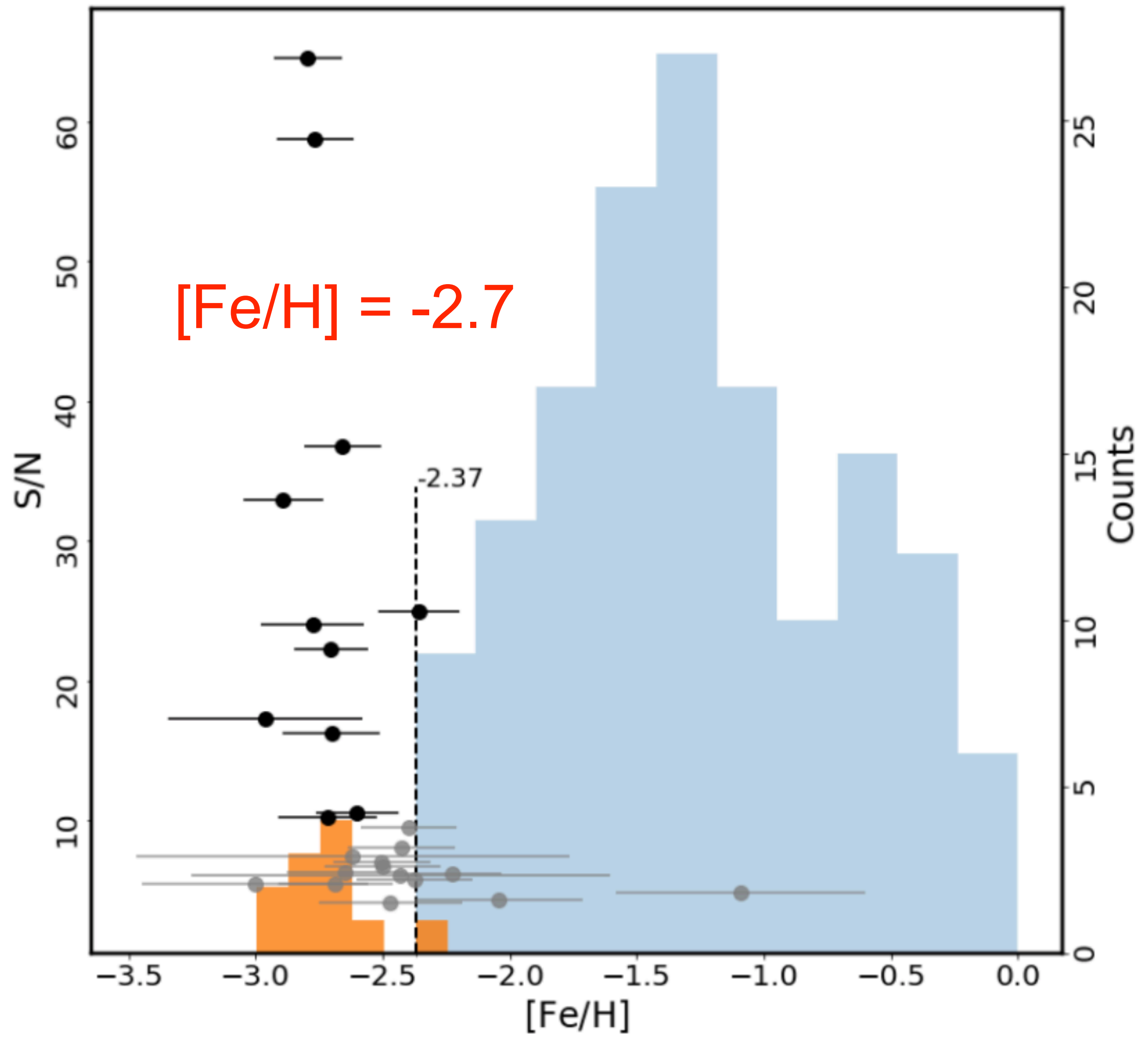
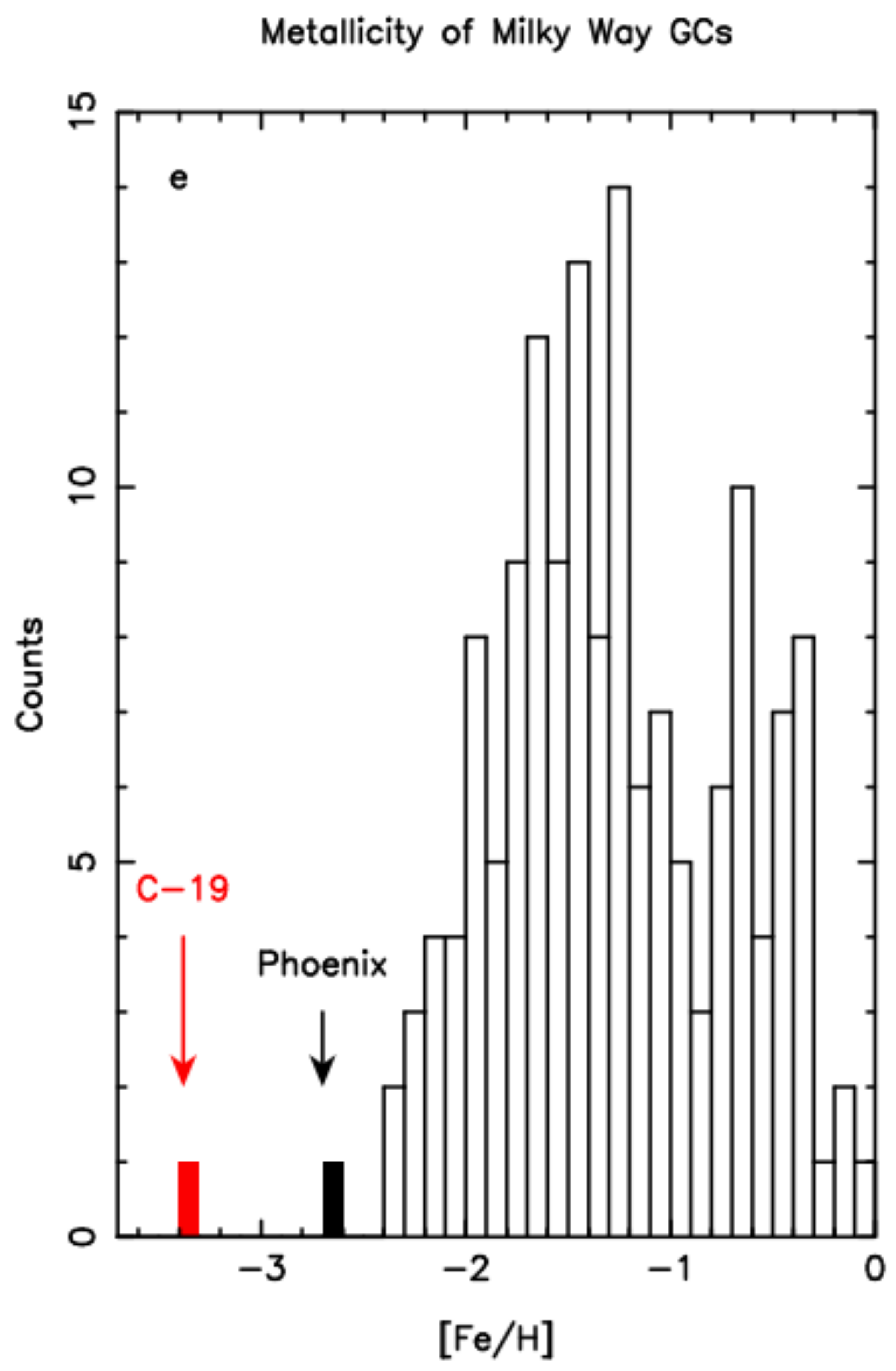


Cyan: globular cluster in Milky Way
Orange: stars in Phoenix Stream

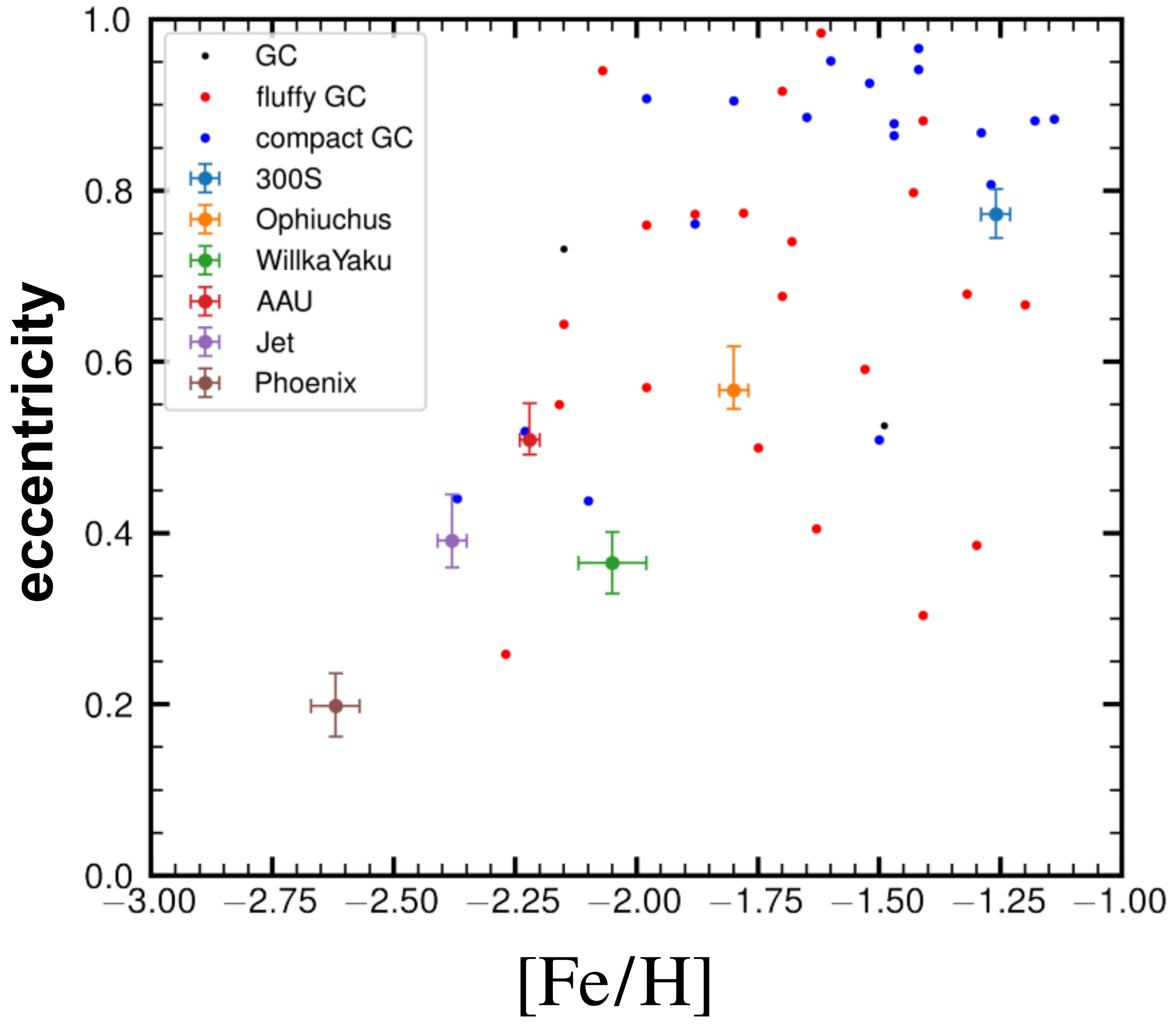
Wan, Lewis, TSL et al. (2020) Nature
(S5 Collaboration)

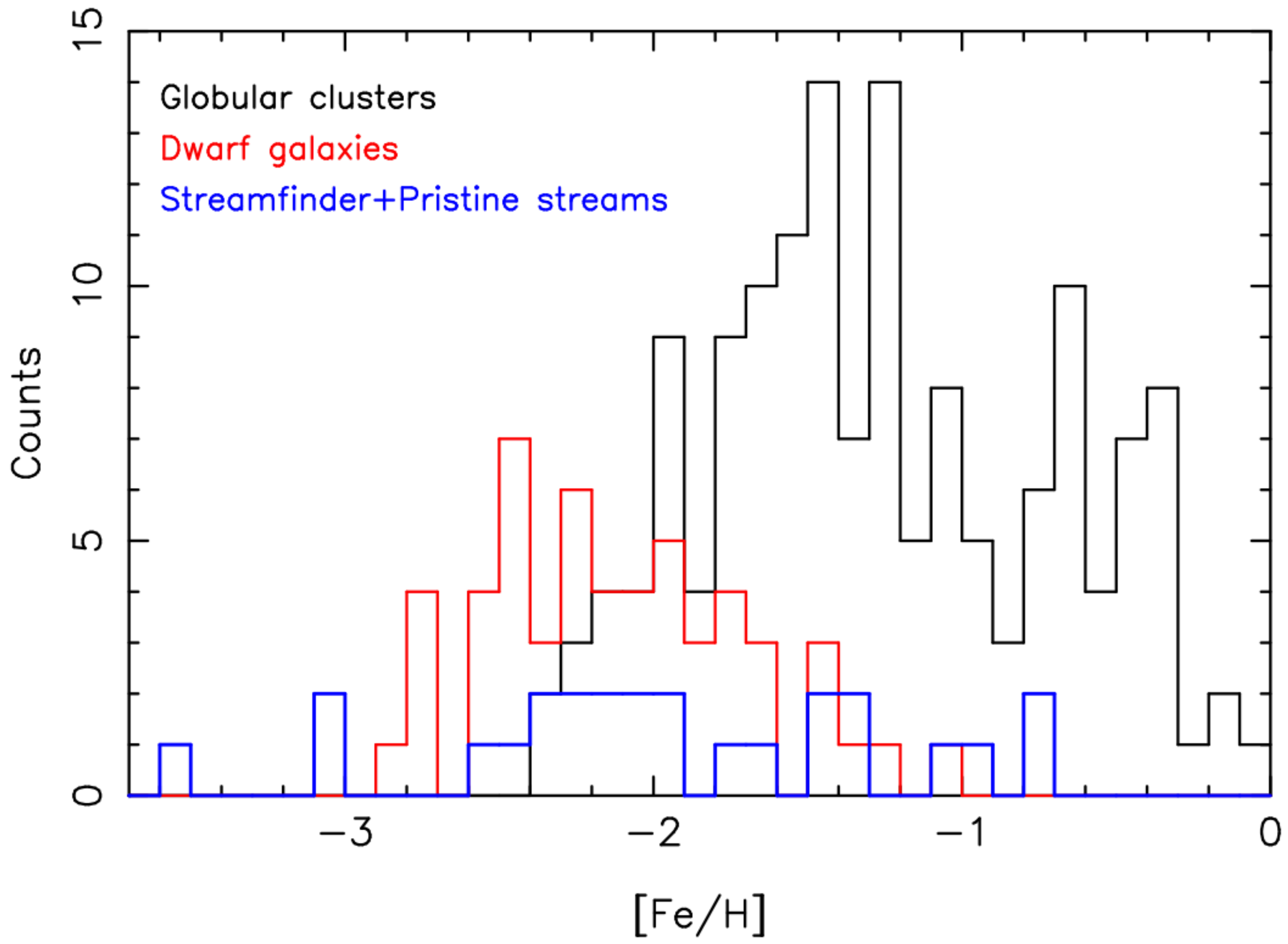
C-19 Stream — [Fe/H] = -3.4!



Martin et al. (2022) Nature
(Pristine Collaboration)

Globular cluster streams: More metal-poor than intact ones





TSL et al (2022)
(S5 Collaboration)

Martin et al (2022)
(Pristine Collaboration)

Metal-poor stars in the Milky Way, ultra faint dwarf galaxies, ultra faint compact systems, and cold stellar streams

IAU Symposium 395: Stellar populations in the Milky Way and beyond
Paraty, Brazil, Nov 18, 2024

Metal-poor stars in the Milky Way, ultra faint dwarf galaxies, ultra faint compact systems, and cold stellar streams

What’s next?

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Most Metal-Poor Stars Search

Photometric Narrow-band (CaHK) Surveys

SkyMapper
da Costa+2019

Pristine
Starkenburg+2017
See Else Starkenburg's talk later today

J/S-PLUS
Galarza+2022, Placco+2022

DELVE-MAGIC
Chiti+2021
See Ani Chiti's talk later today

Gaia XP
See Anthony Brown's talk tomorrow

Most Metal-Poor Stars Search

Spectroscopic Surveys

LAMOST	Check Haining Li’s talk on Wednesday
SDSS-V	Check Ricardo Schiavon's & Jennifer Johnson’s talks on Wednesday
DESI	
PFS	Check Evan Kirby’s poster
4MOST	Check Marica Valentini’s talk on
WEAVE	

Most Metal-Poor Stars Search

Spectroscopic Surveys

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- WEAVE

DESI — Dark Energy Spectroscopic Instrument

MWS — Milky Way Survey

Co-chairs: Leandro Beraldo e Silva (U Arizona)
Ting Li (U of Toronto)

DARK ENERGY SPECTROSCOPIC INSTRUMENT

U.S. Department of Energy Office of Science

DARK ENERGY SPECTROSCOPIC INSTRUMENT

U.S. Department of Energy Office of Science

DEPARTMENT OF ENERGY · UNITED STATES OF AMERICA

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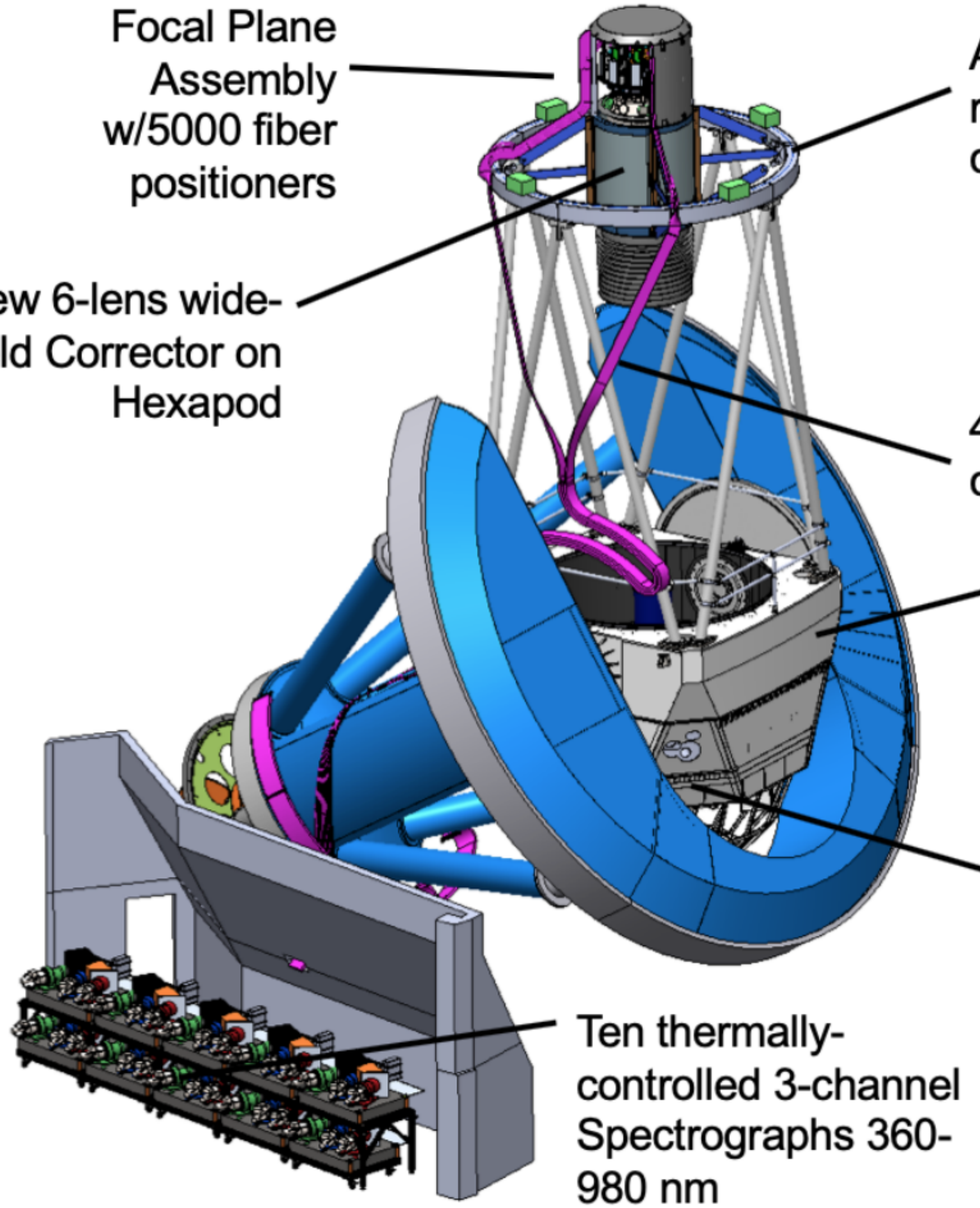
Thanks to our sponsors and
72 Participating Institutions!

DESI, the instrument in a nutshell

DARK ENERGY SPECTROSCOPIC INSTRUMENT
U.S. Department of Energy Office of Science

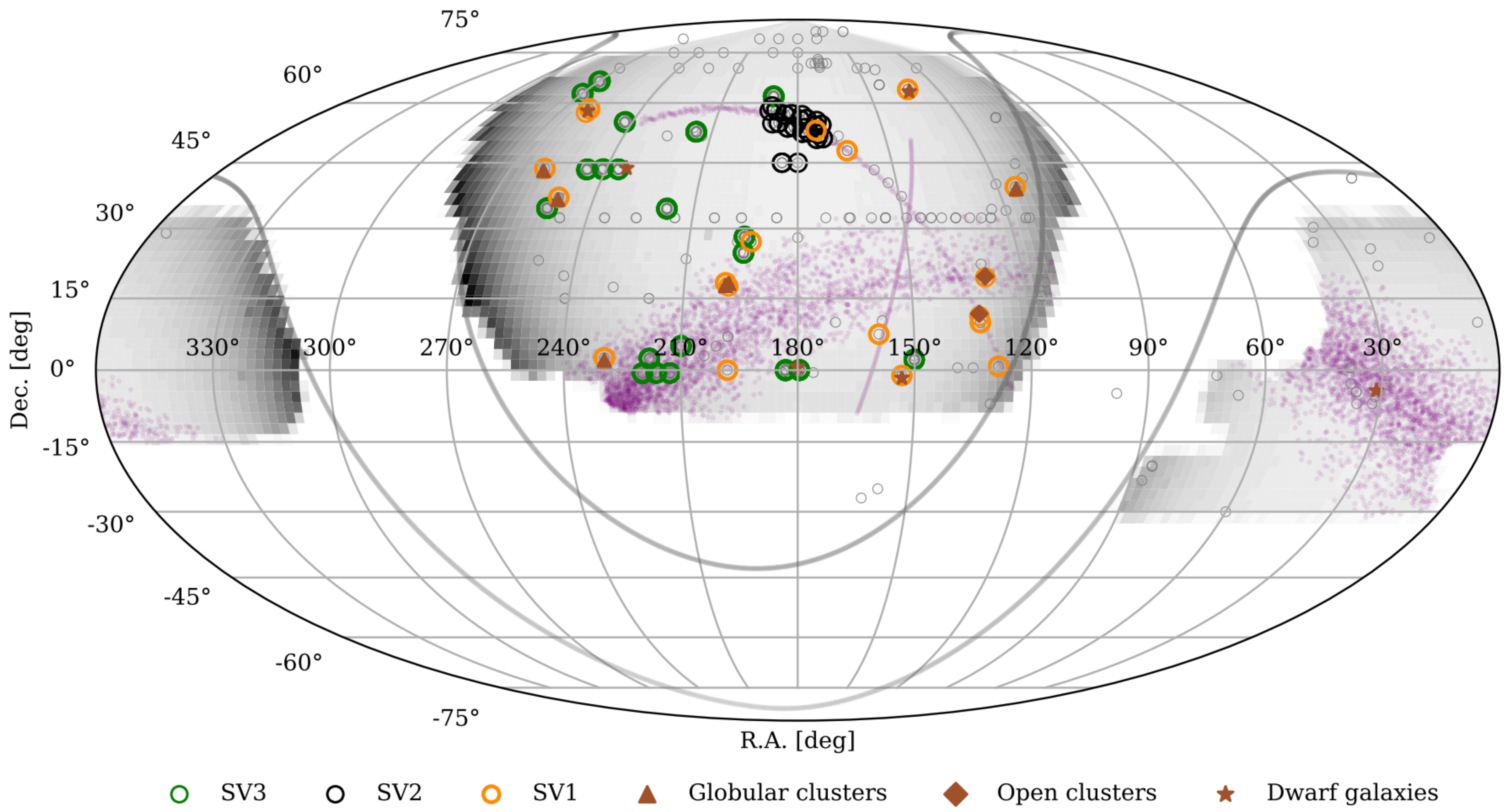


- 4-m Mayall Telescope at KPNO
- 8 sq. deg field-of-view
- 5000 Robotic Fibers
- 10 3-Channel Spectrograph
- Wavelength: 3600-9800 A
- R ~ 2000-5000

Overview of the Instrumentation for the Dark Energy Spectroscopic Instrument
DESI Collaboration et al. 2022, arXiv:2205.10939

DARK ENERGY SPECTROSCOPIC INSTRUMENT
U.S. Department of Energy Office of Science

Milky Way Survey in a nutshell



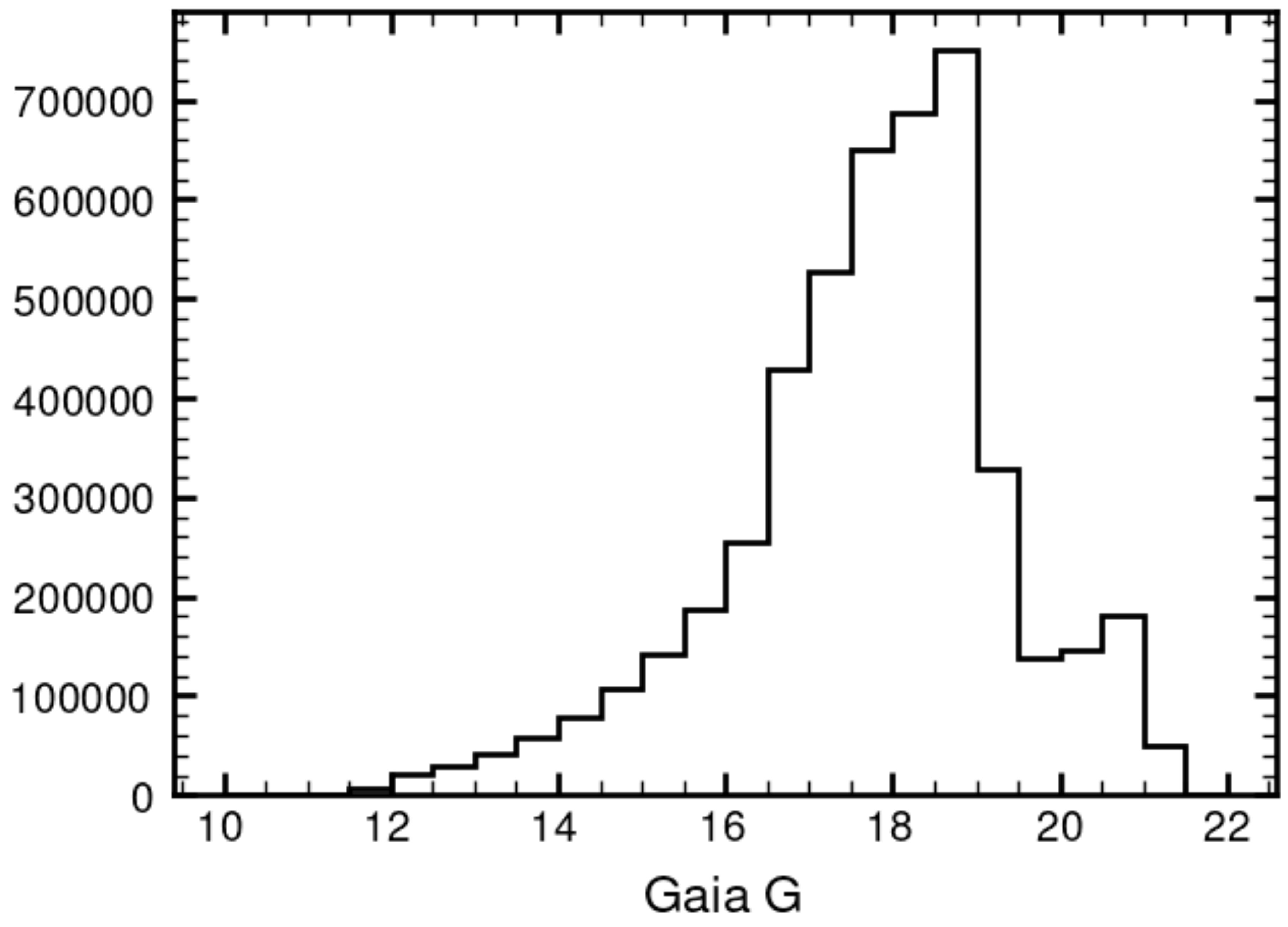
- DESI Bright Time Survey
- ~14k sq deg
- ~180s effective exposure time
- 5 passes over 5 year
- Goal: stars at |b|>20
  - 7M Main 16<r<19
  - 0.6M Faint
  - 6M Backup

Velocity error: ~0.9 km/s

Overview of the DESI Milky Way Survey
Cooper et al. 2023 arXiv:2208.08514
(DESI Collaboration et al)

DESI Milky Way Survey

Year 1 Stellar Sample



- Early Data Release in June 2023
  - Commission + SV: Dec 2020 - May 2021
  - ~600k stars observed (400k w/ RVerr < 10 km/s)

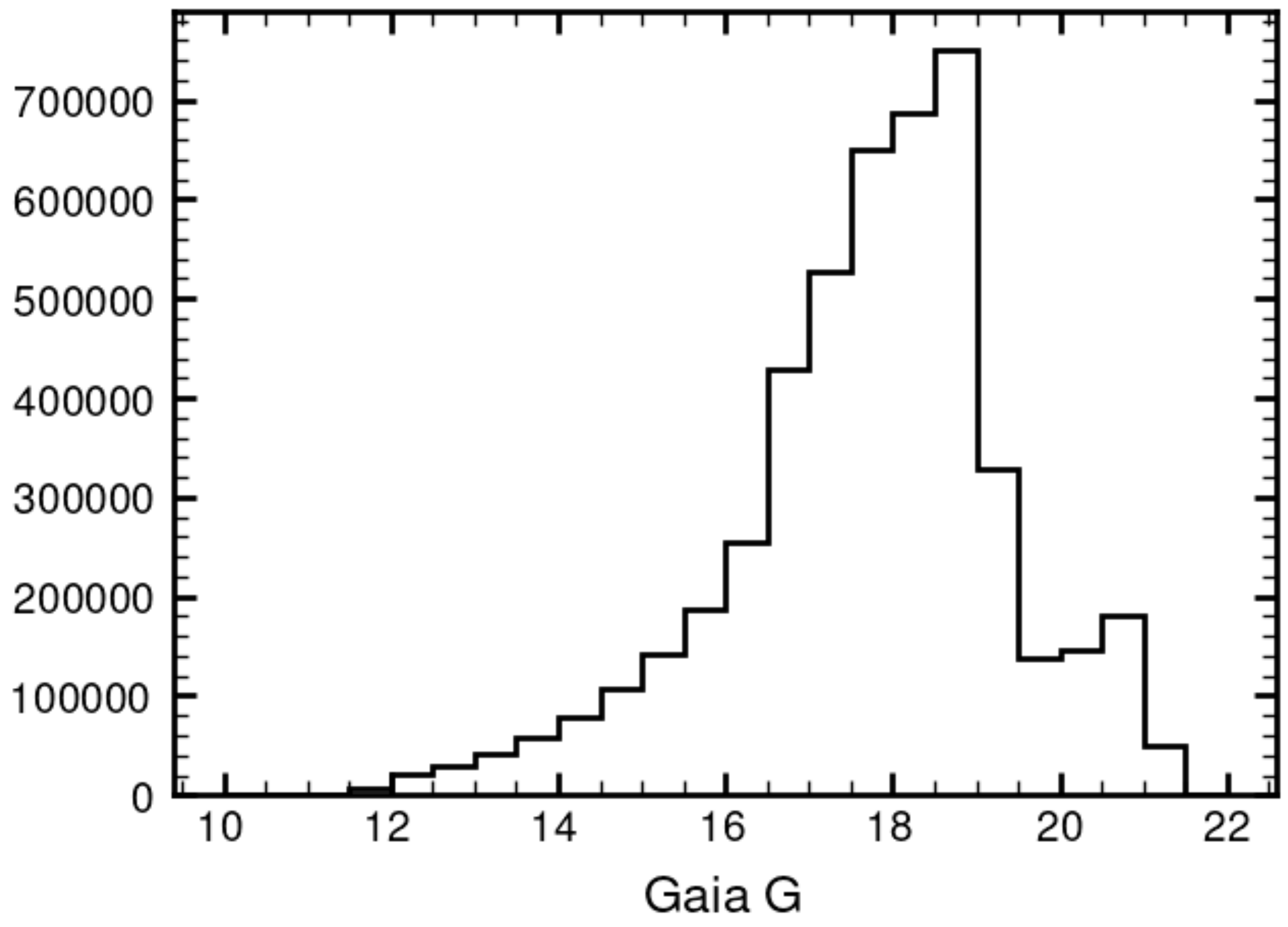
DESI Early Data Release Milky Way Survey Value-Added Catalogue
Koposov et al. 2024, arXiv: 2407.06280
(DESI Collaboration)

- DR1 (expected March 2025)
  - EDR + Year 1: May 2021 - June 2022
  - 5M stars observed (4M w/ RVerr < 10km/s)

DARK ENERGY SPECTROSCOPIC INSTRUMENT
U.S. Department of Energy Office of Science

DESI Milky Way Survey

Year 1 Stellar Sample



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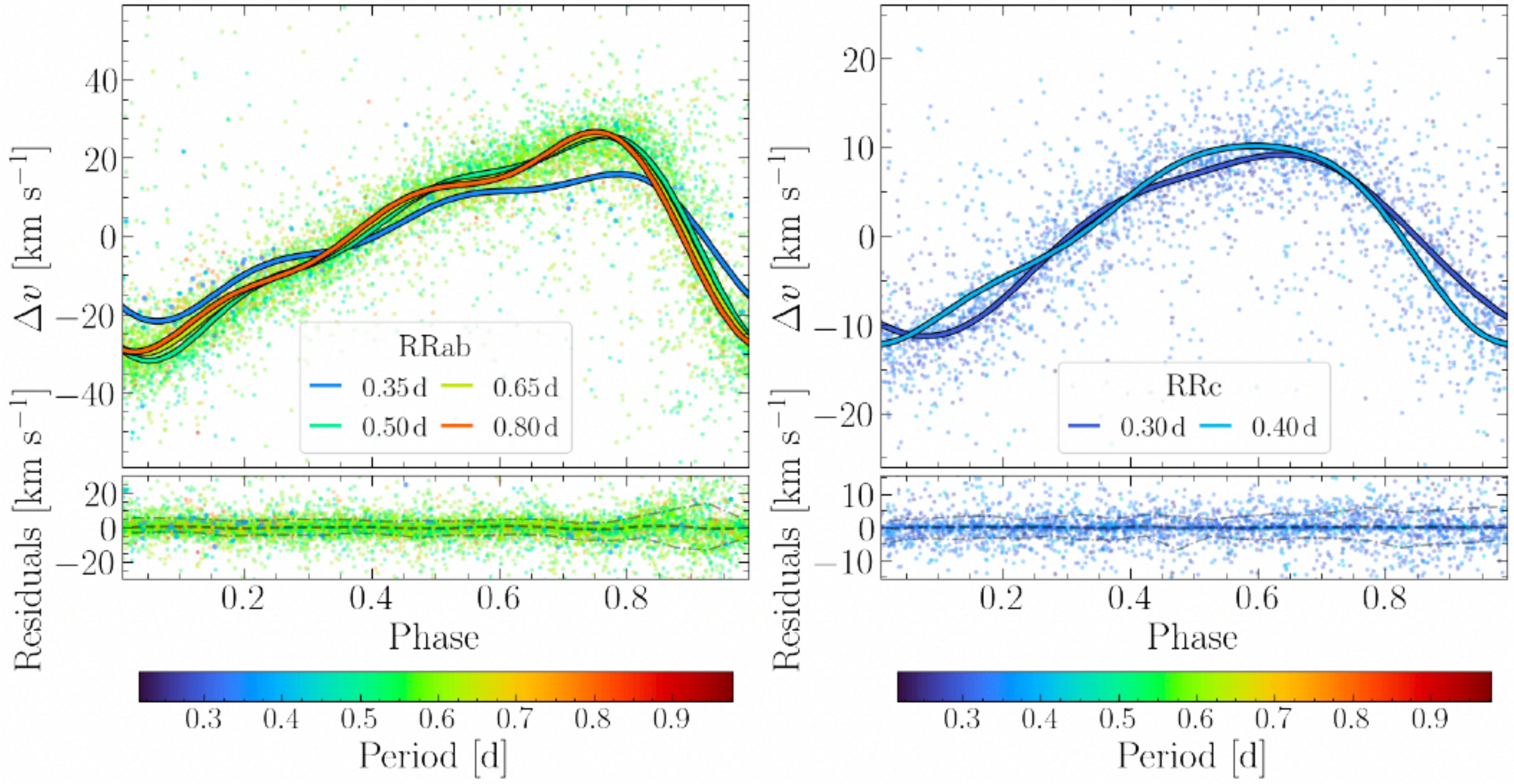
- DR1 (expected March 2025)
  - EDR + Year 1: May 2021 - June 2022
  - 5M stars observed (4M w/ RVerr < 10km/s)

Year 1-3: ~16M stellar spectra

DESI: 2021-2026
DESI Extension: 2026-2028 (TBC)
DESI 2: 2029-2034 (TBC)

RR Lyrae in DESI Year 1



6000+ RR Lyrae
With 12,000 individual epochs

Medina, TSL, et al. in prep
(DESI Collaboration)

DESI on Ursa Minor (UMi) dSph

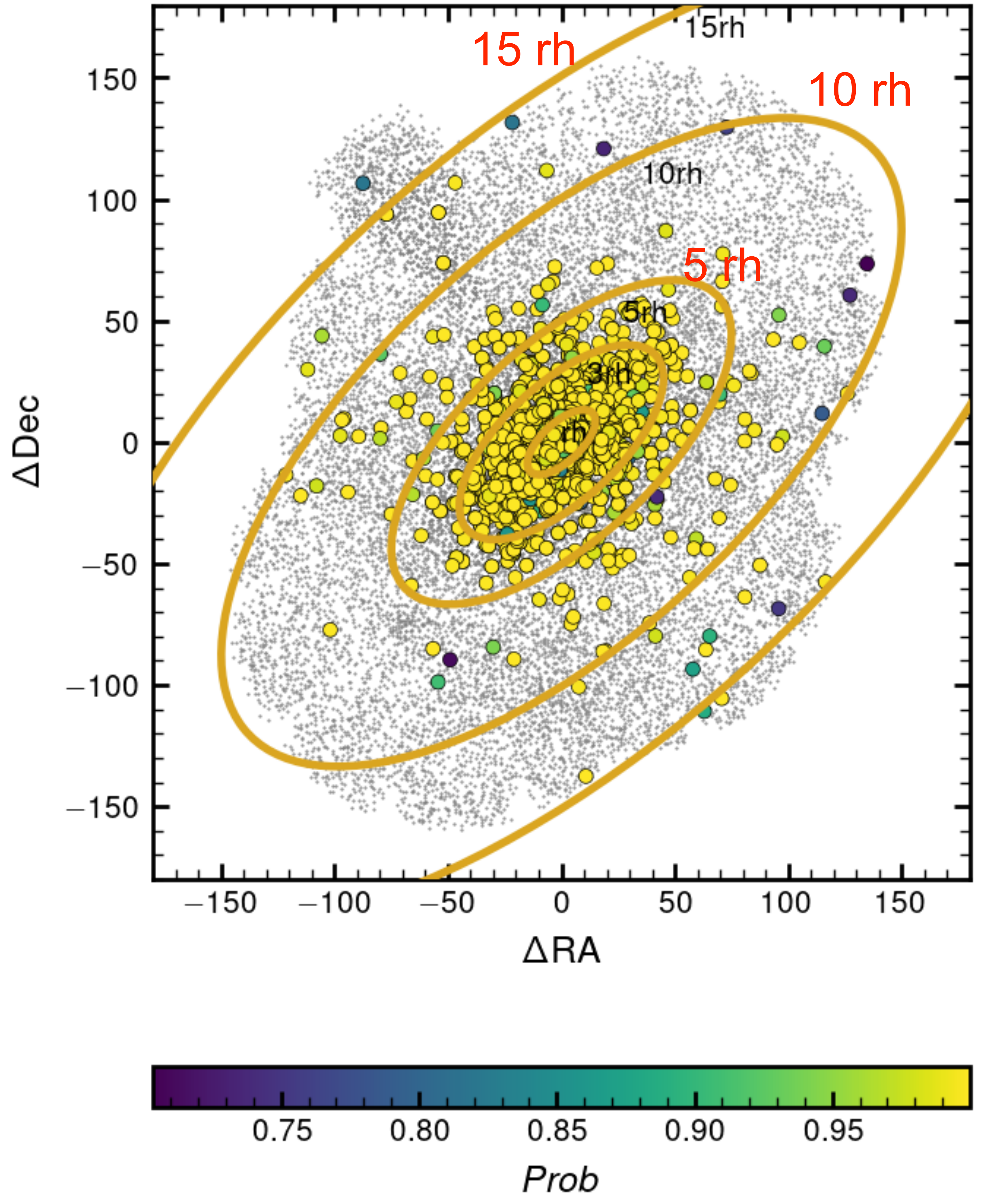
DARK ENERGY SPECTROSCOPIC INSTRUMENT
U.S. Department of Energy Office of Science

892 UMi member from 10 hr Keck time

Slitmask	No. of Targets	Date	Airmass	Seeing	Exposures
uss-1	68	2012 April 19	1.58	1.1″	3×1020 s
	68	2012 April 23	1.60	0.8″	1×1020 s
uss-2	57	2012 April 19	1.74	1.0″	2×1020 s, 600 s
uss-3	74	2012 April 21	1.55	0.5″	3×960 s
uss-4	66	2012 April 21	1.70	0.7″	3×960 s, 480 s
uss-5	27	2012 April 21	1.49	0.5″	2×960 s
uss-6	13	2012 April 22	1.49	0.7″	2×960 s, 900 s
uss-7	17	2012 April 23	1.49	0.9″	2×1020 s
uss-8	57	2012 April 22	1.56	0.9″	2×1080 s, 1170 s
uss-9	24	2012 April 23	1.55	0.7″	1×1080 s, 1020 s
uss-10	65	2012 April 22	1.47	0.8″	3×1020 s
uss-11	56	2012 April 21	1.48	0.5″	3×960 s
uss-12	54	2012 April 23	1.47	0.9″	3×1020 s

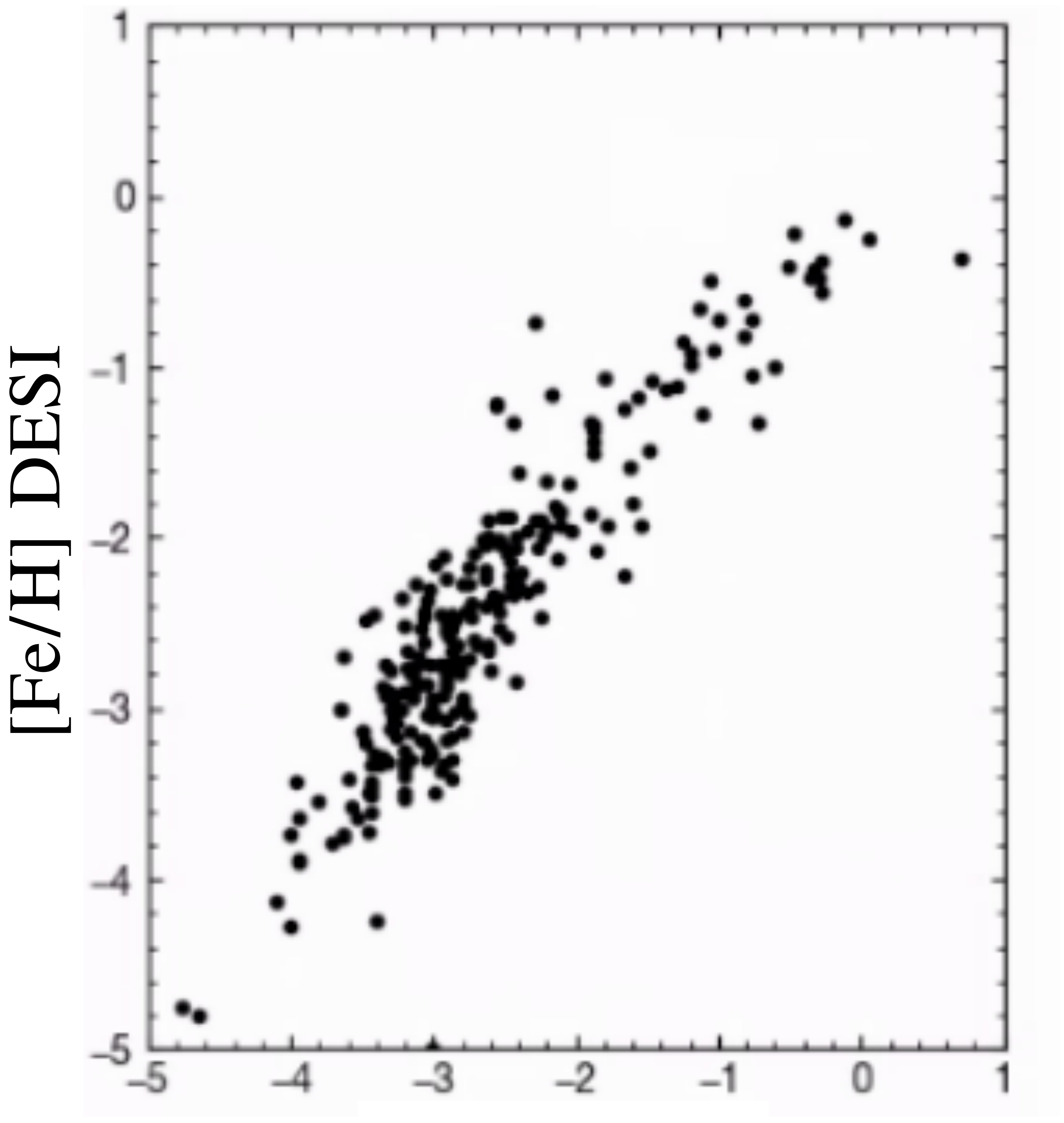
Pace et al. 2020

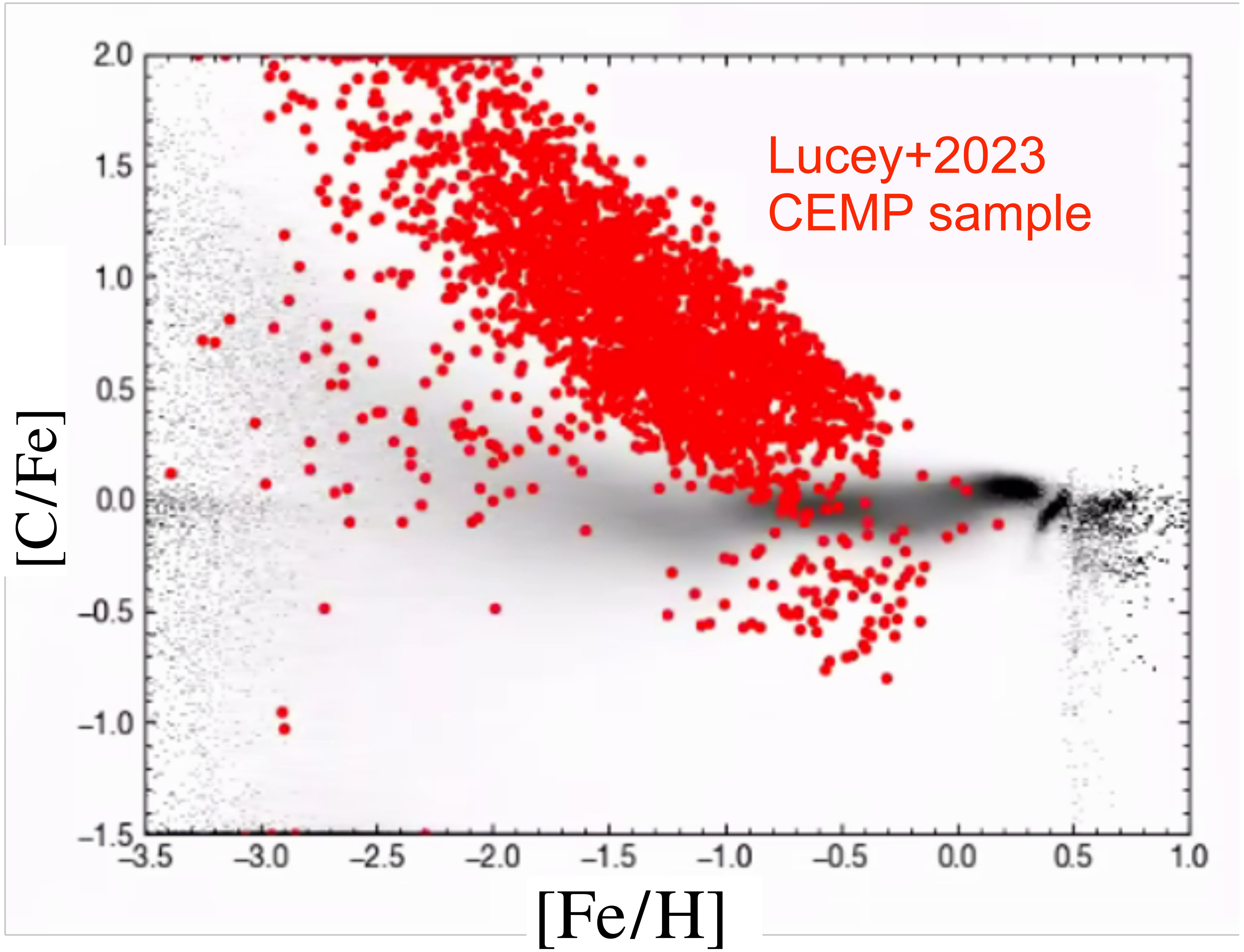
~3000 members w/ 2 hr DESI time



korg-based DESI pipeline (under development)

DARK ENERGY SPECTROSCOPIC INSTRUMENT
U.S. Department of Energy Office of Science





SAGA database: Suda et al. 2008, http://sagadatabase.jp/

Credit: Sergey Koposov

Most Metal-Poor Stars Search

Spectroscopic Surveys

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SDSS-V — Check Ricardo Schiavon's & Jennifer Johnson’s talks on Wednesday

DESI

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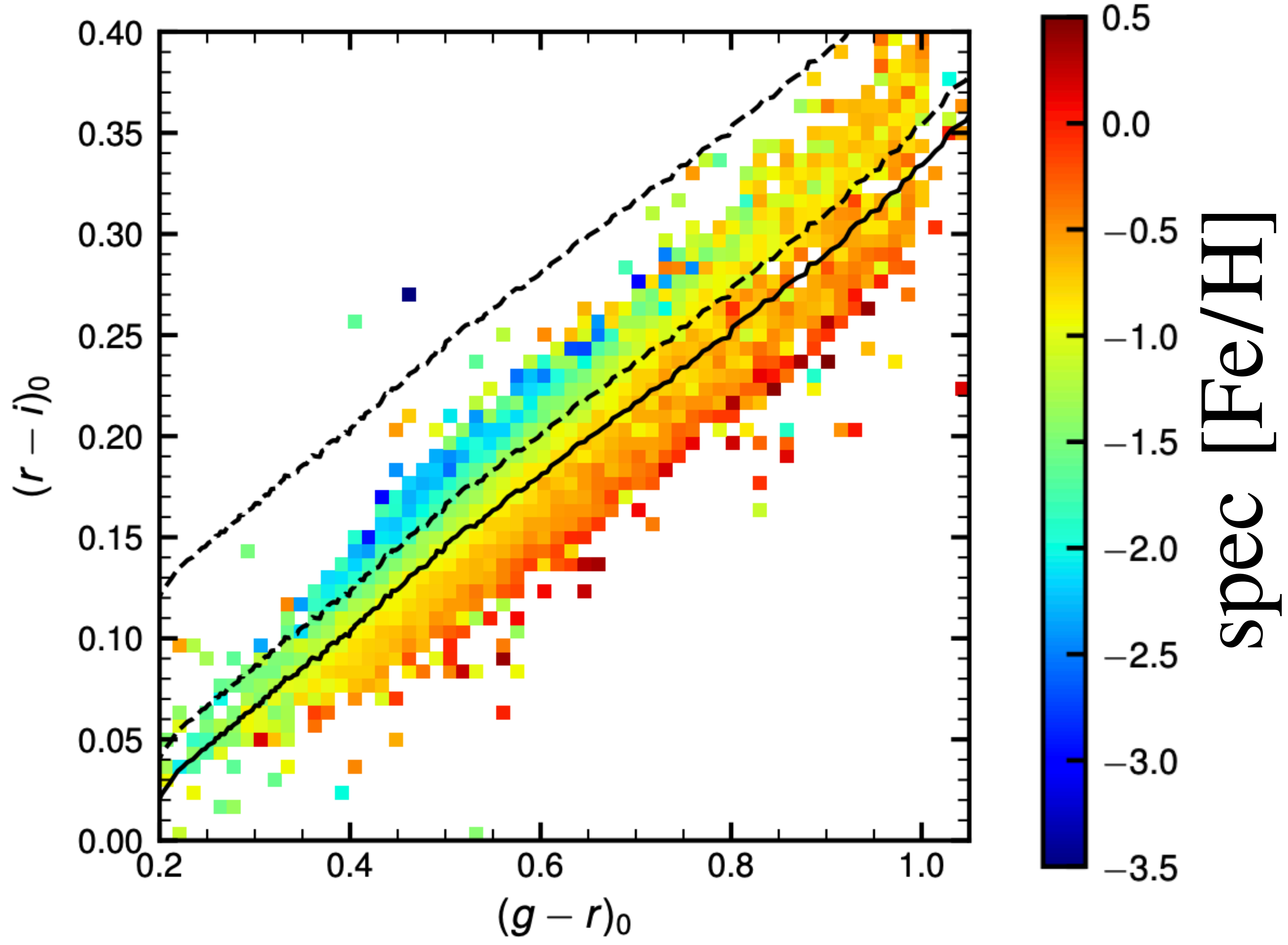
WEAVE

Do not forget broad band photometry either

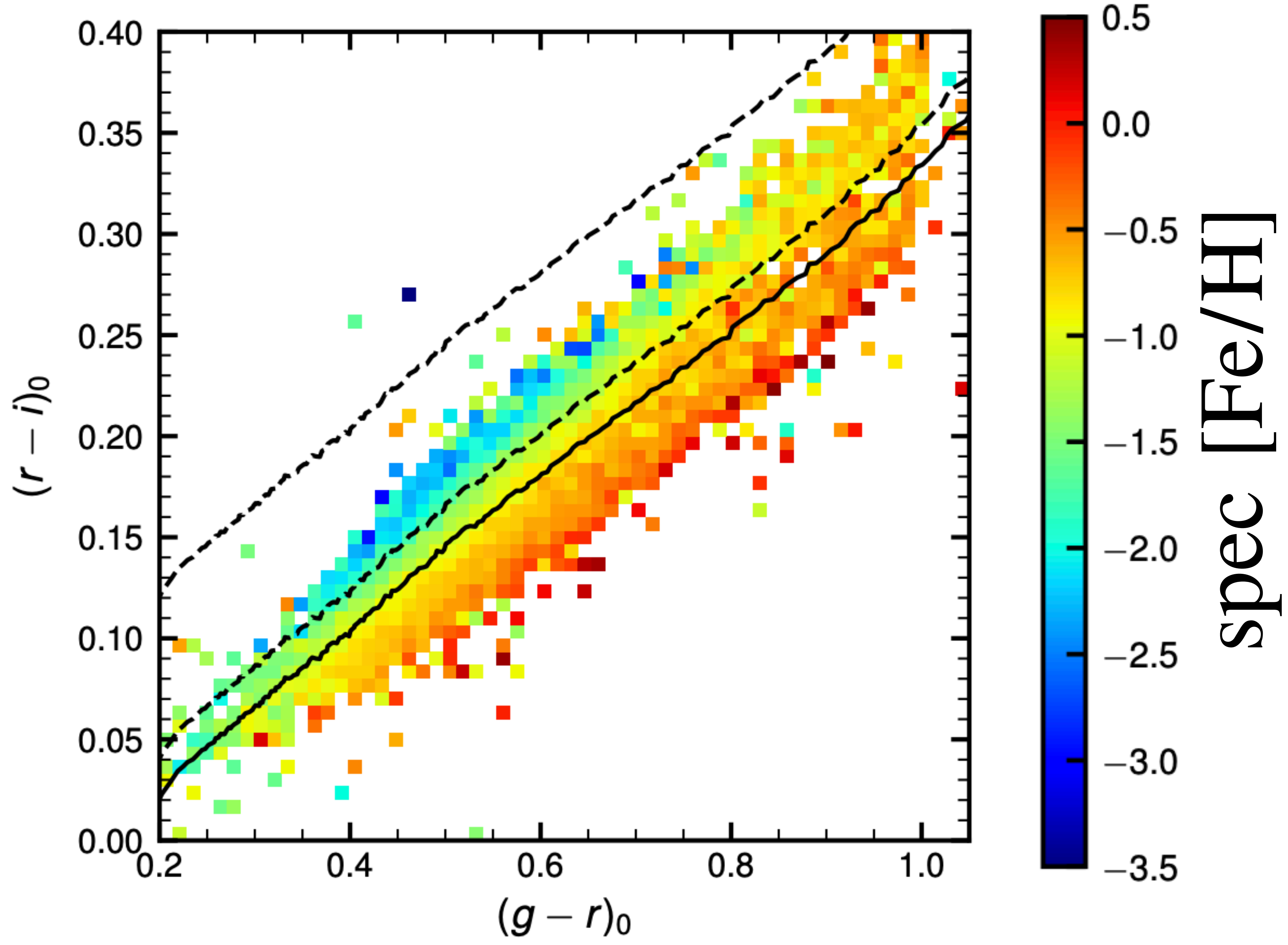
Metal-poor stars ([Fe/H] ~ - 2) with gri photometry from the Dark Energy Camera



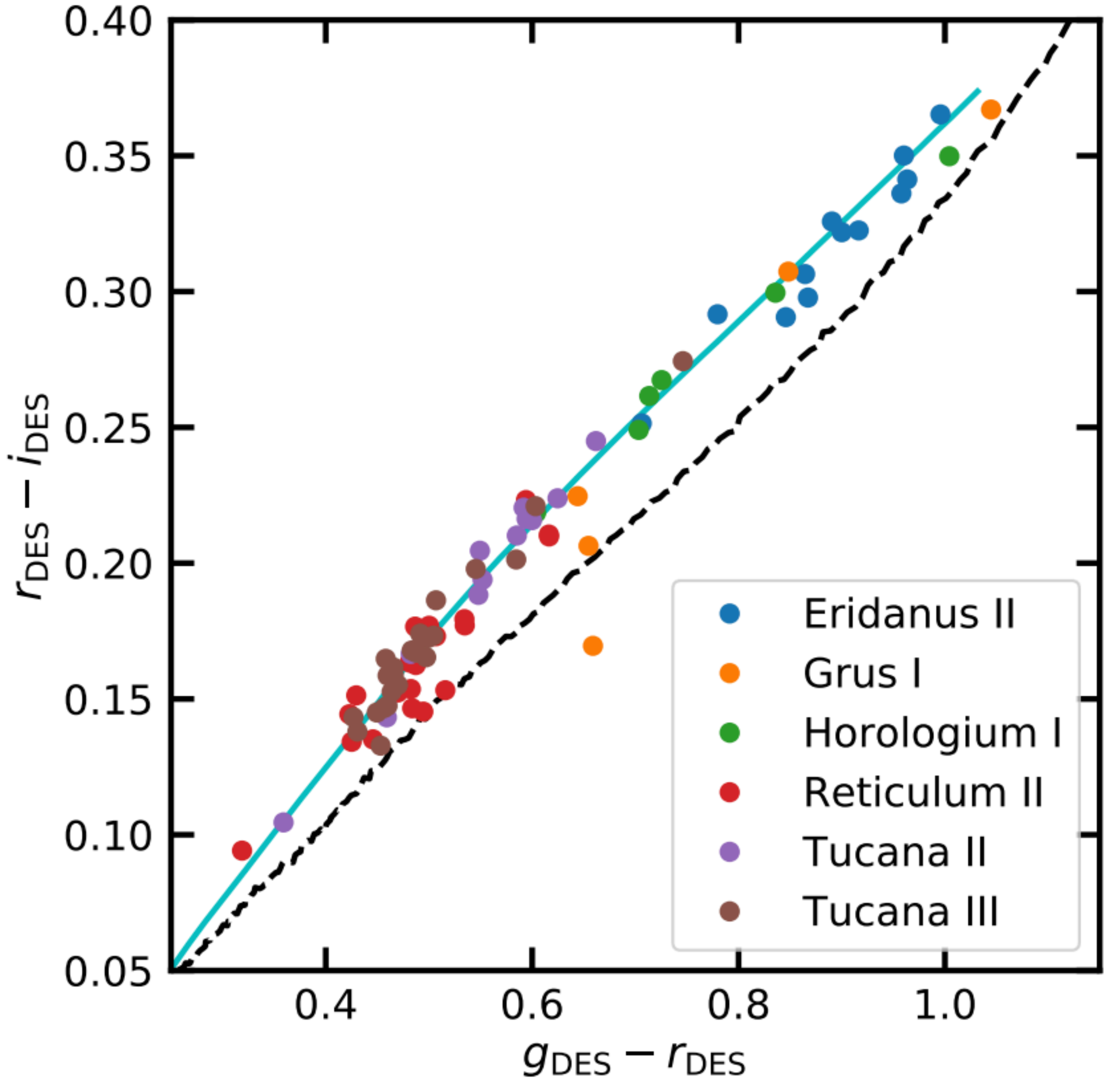
TSL et al. 2019, arXiv:1907.09481
(S5 Collaboration)

Do not forget broad band photometry either

Metal-poor stars ([Fe/H] ~ - 2) with gri photometry from the Dark Energy Camera

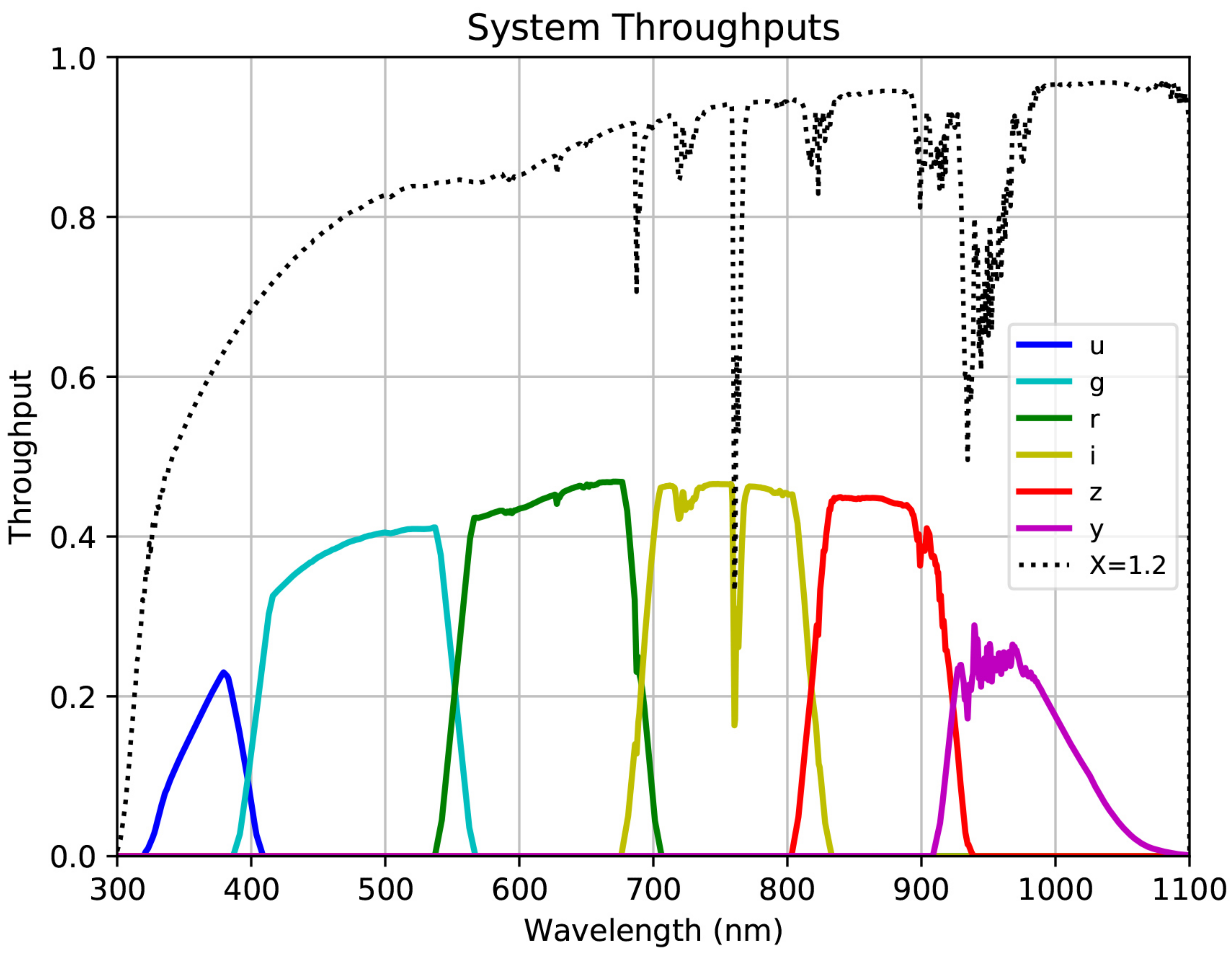


TSL et al. 2019, arXiv:1907.09481 (S5 Collaboration)



Pace & TSL et al. 2019, arXiv:1806.02345

Rubin will start next year!



5-sigma point source depth

u : 23.8, 25.6

g : 24.5, 26.9

r : 24.03, 26.9

i : 23.41 , 26.4

z : 22.74, 25.6

y : 22.96, 24.8

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Spectroscopic Surveys

Rubin/LSST

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