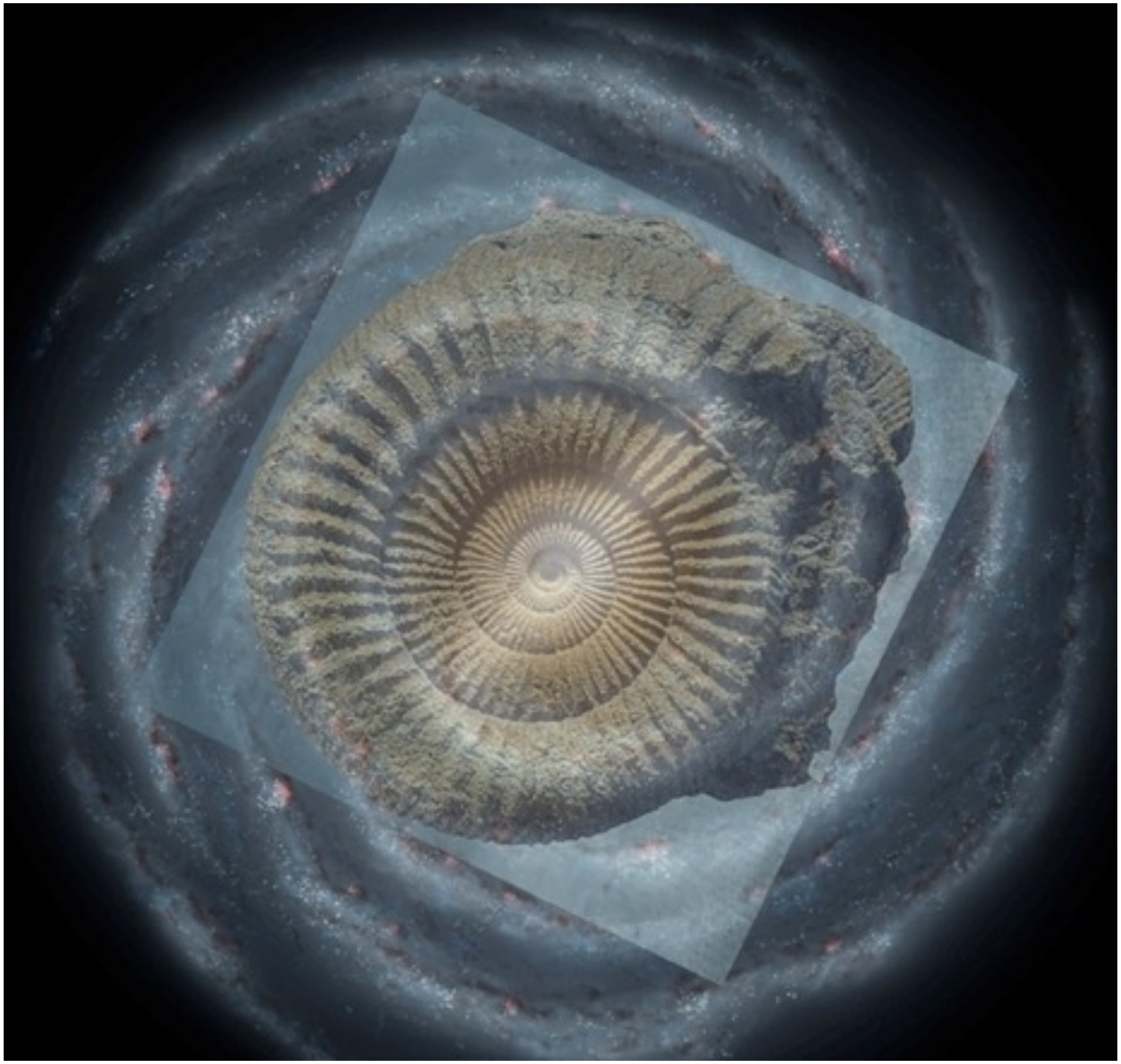
Galactic Archeology with Bulge Globular Clusters



Doug Geisler
Univ. de Concepcion
Univ. de La Serena
Chile

With S. Villanova, C. Muñoz, J.Fernandez-Trincado, D. Minniti. R. Cohen, B. Tang, J. O’Connell, A. Monachesi, C. Montecinos, W. Haro, N. Barrera, …

1981

INTERNATIONAL ASTRONOMICAL UNION
COLLOQUIUM NO. 68

ASTROPHYSICAL PARAMETERS FOR GLOBULAR CLUSTERS

Edited by A.G. Davis Philip and D.S. Hayes

L. DAVIS PRESS, INC.
Schenectady, New York
USA

II. CLUSTER ABUNDANCES

INTERNATIONAL ASTRONOMICAL UNION

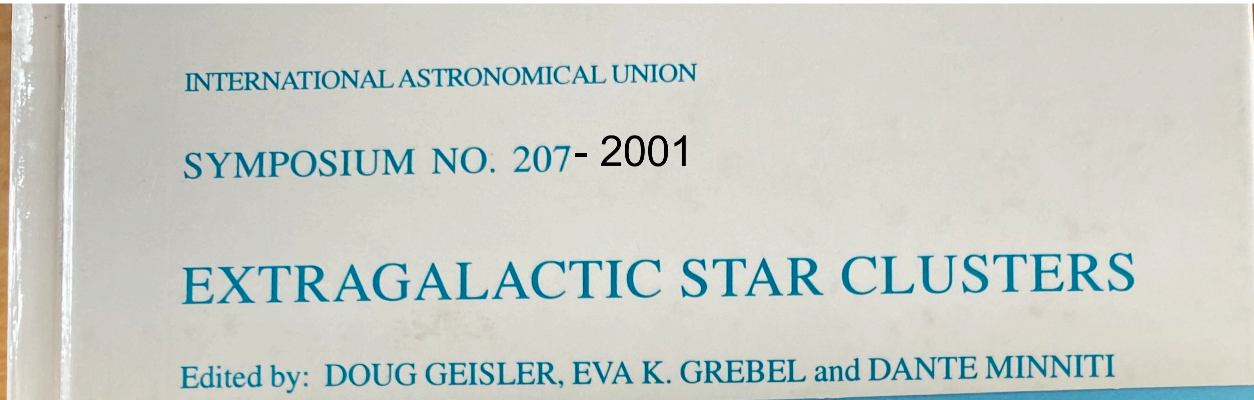
SYMPOSIUM No. 149

THE STELLAR POPULATIONS OF GALAXIES

Angra dos Reis 1991

Edited by B. BARBUY and A. RENZINI

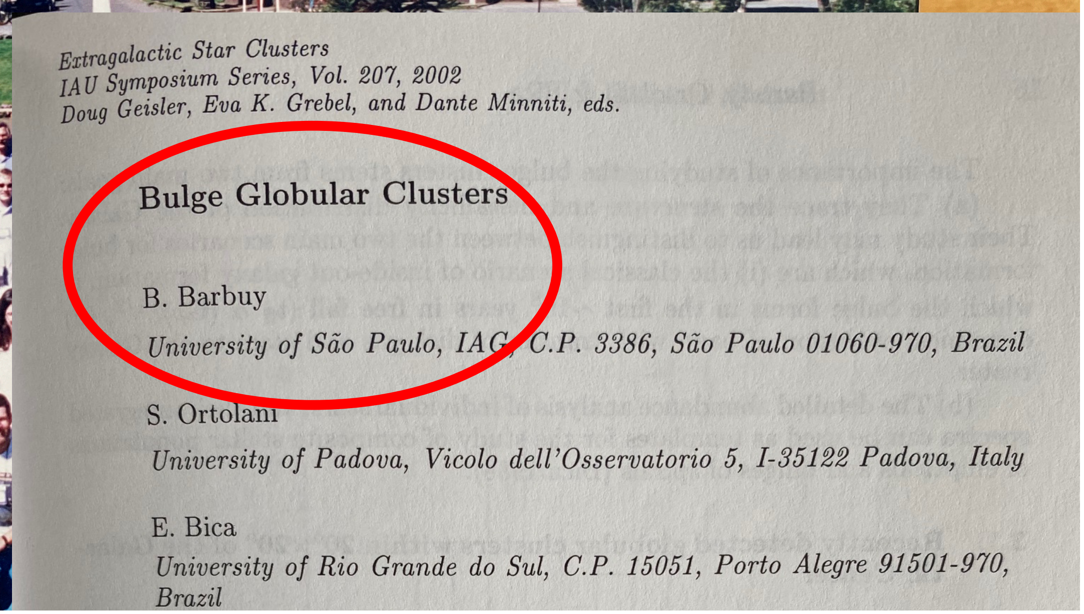
I. THE STELLAR POPULATIONS IN THE MILKY WAY


INTERNATIONAL ASTRONOMICAL UNION

SYMPOSIUM NO. 207- 2001

EXTRAGALACTIC STAR CLUSTERS

Edited by: DOUG GEISLER, EVA K. GREBEL and DANTE MINNITI


Extragalactic Star Clusters
IAU Symposium Series, Vol. 207, 2002
Doug Geisler, Eva K. Grebel, and Dante Minniti, eds.

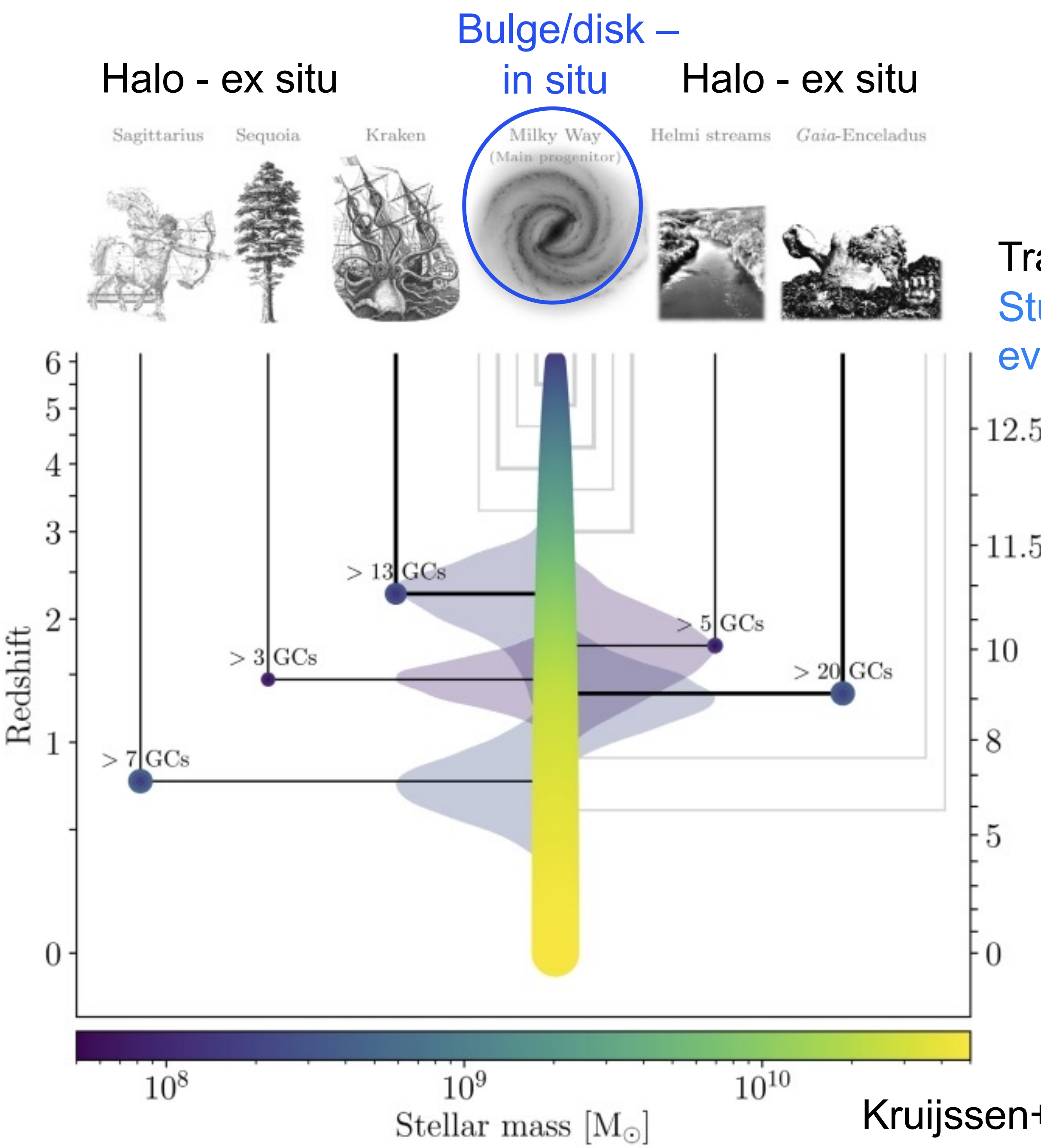
Bulge Globular Clusters

B. Barbuy
University of São Paulo, IAG, C.P. 3386, São Paulo 01060-970, Brazil

S. Ortolani
University of Padova, Vicolo dell'Osservatorio 5, I-35122 Padova, Italy

E. Bica
University of Rio Grande do Sul, C.P. 15051, Porto Alegre 91501-970, Brazil

Galactic archeology using GCs

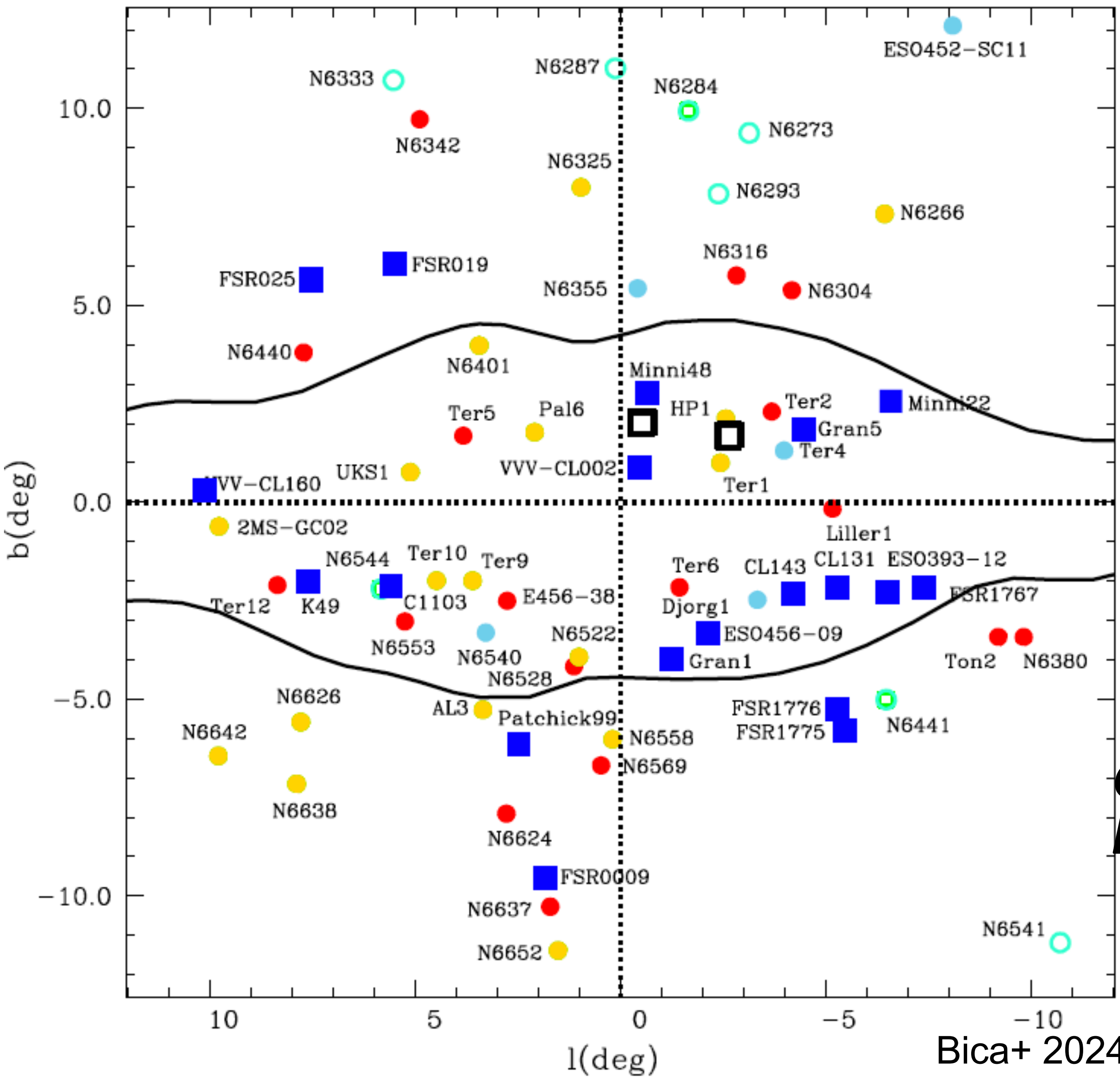


Kruijssen+ 2020

Trace merger history of halo
Study formation and chemical evolution of Main Progenitor (MP)

Goal: derive accurate and precise age for Galaxy, or at least **find oldest in situ object in MP with good age estimate!**
GCs perfect because old and yield excellent ages!

BGCs



Bica+ 2024

Bulge/disk (B/D GCs)
2/3 of all MW GCs!
61 BGCs in Bica+2024

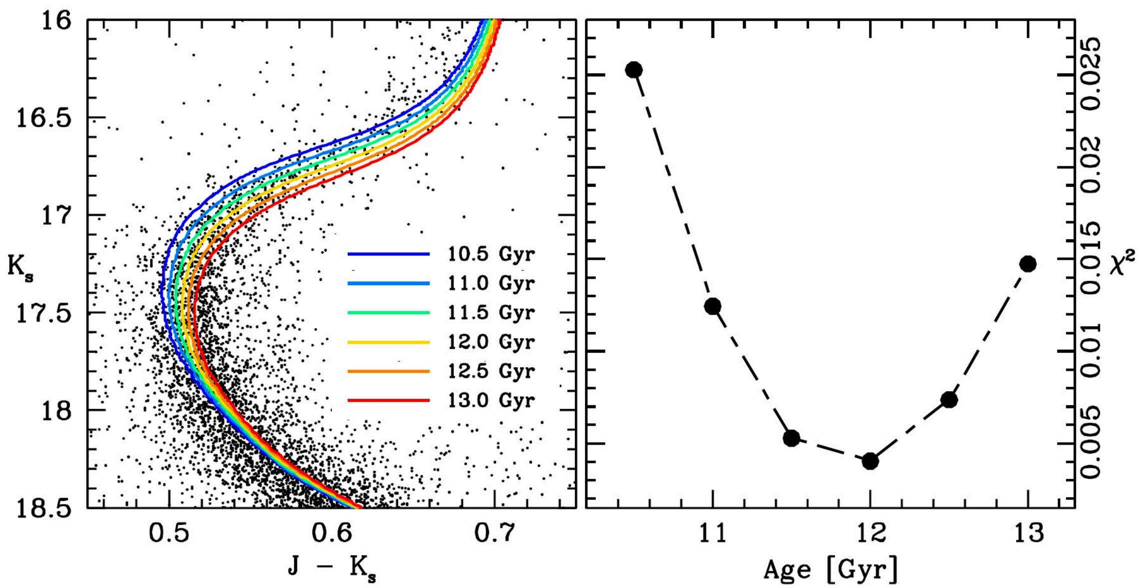
In situ but poorly studied due to dust – require **IR observations** – not possible until now.

Need deep photometry for isochrone fitting and spectra for abundances

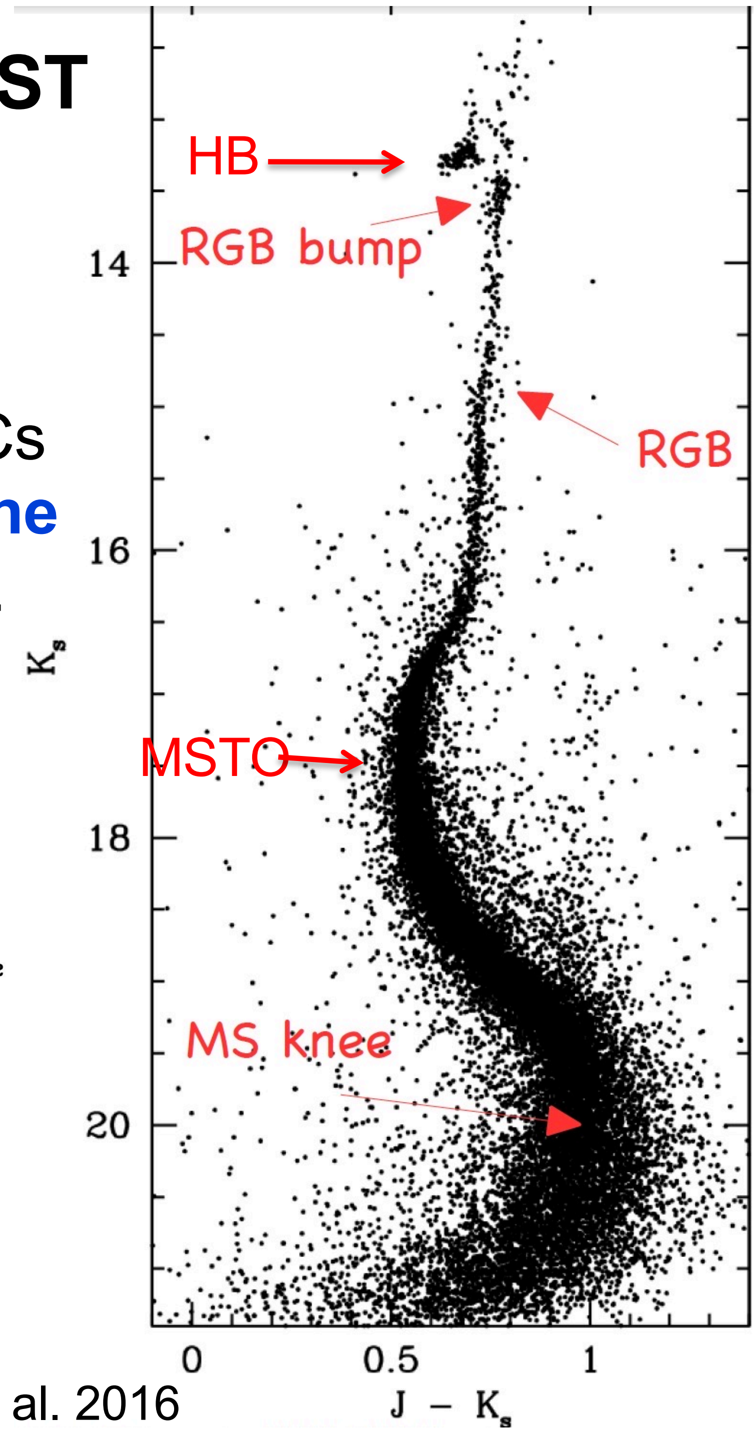
Oldest object(s) in MP with good ages

Deep NIR photometry – GeMS/HST

- ➢GeMS: Gemini S MCAO system
- ➢4 mags below MSTO of NGC 6624!
- ➢Derive **accurate age** – scarce for BGCs
- ➢**Need good abundances for isochrone**
- ➢GeMS data for 11 BGCs, HST for 16…



12.0±0.5 Gyr (5%!)

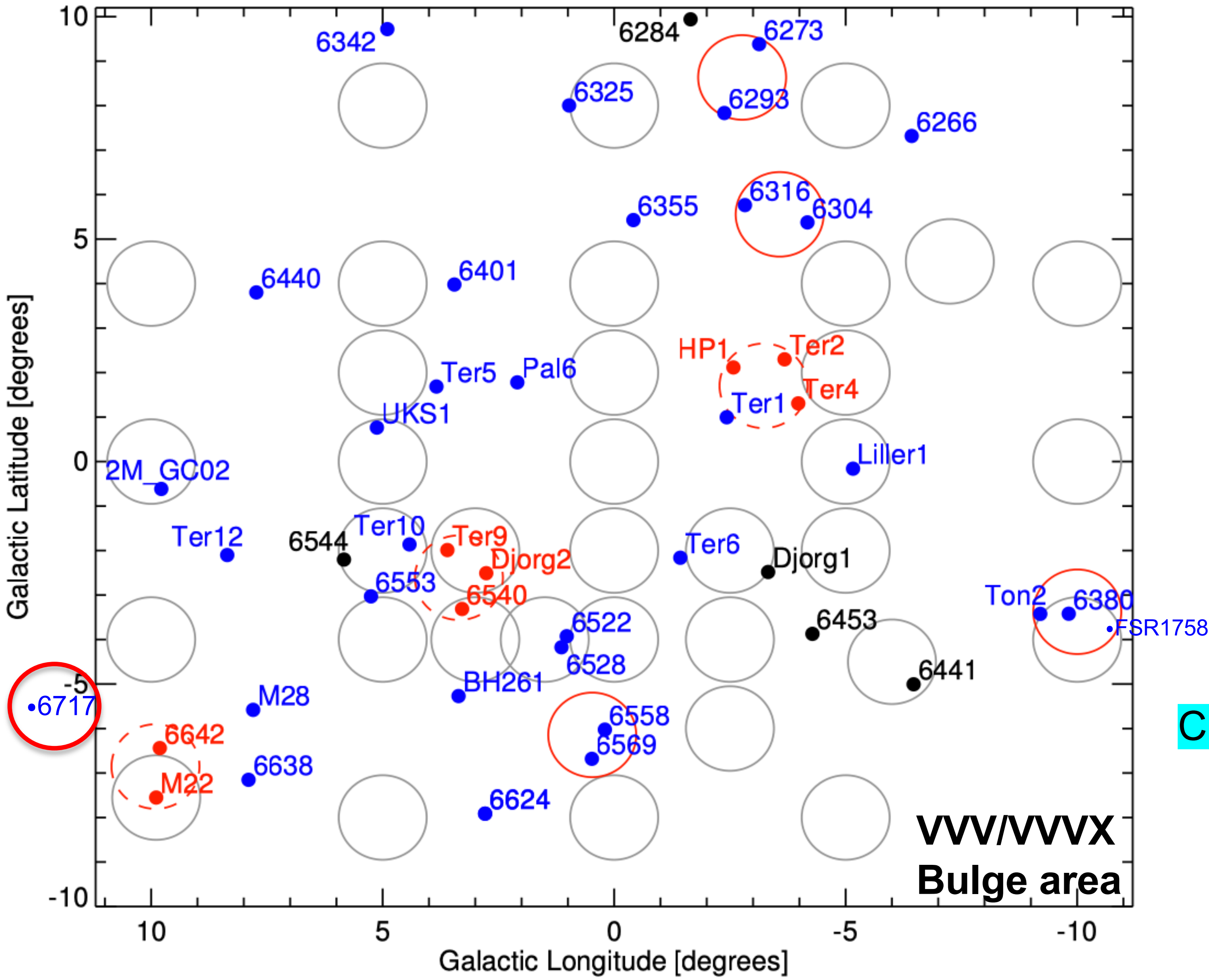


Saracino et al. 2016

High resolution NIR spectroscopy – APOGEE

CAPOS: *the bulge Cluster APOgee Survey*

Good abundances for many B/D GCs!



BGCs (R_{GC}<3.5kpc)

Non BGCs

SDSSIV

CAPOS

DR16

DR17

18 BGCs!

C. Montecino poster 11

Geisler+ 2021

New chemo-dynamical classification of GCs

averaging prior classifications

Table 6. Cluster classifications for CAPOS clusters

Cluster ID	M19 [a]	PV20 [b]	C22 [c]	BK23 [d]	CG24 [e]	[Mg/Mn] vs. [Al/Fe] [f]	Final Classification [g]
NGC 6273	LE	TD	Kra 0.90 / B 0.10	1	1	1	1?D?
NGC 6293	MB	TD	B 0.95 / Kra 0.05	1	1	1?	1B?
NGC 6304	MB	B/B	B 0.99 / D 0.01	1	1	1	1B
NGC 6316	MB	TD	Kra 0.92 / B 0.07	1	1	1	1?B?
Terzan 2	MB	B/B	B 1.00	1	1	1	1B
Terzan 4	MB	B/B	B 1.00	1	1	0	1B?
HP 1	MB	B/B	B 1.00	1	1	0	1B?
FSR 1758	Seq	-	Ungr 0.62 / Seq 0.28	0	-	0	0
NGC 6380	MB	B/B	B 1.00	1	1	1	1B
Ton 2	LE	TD	Kra 0.96 / B 0.03	1	1	1	1?D?
Terzan 9	MB	B/B	B 1.00	1	1	0	1B?
Djorg 2	MB	B/B	B 1.00	1	1	1?	1B
NGC 6540	MB	B/B	B 0.97 / D 0.03	1	1	1?	1B
NGC 6558	MB	B/B	B 1.00	1	1	1?	1B
NGC 6569	MB	B/B	Kra 0.84 / B 0.12	1	1	1	1?B
NGC 6642	MB	B/B	B 1.00	1	1	1	1B
NGC 6656	MD	OH	GE 0.85 / D 0.15	1	1	1?	0?
NGC 6717	MB	B/B	B 0.97 / D 0.03	1	1	0	1B?

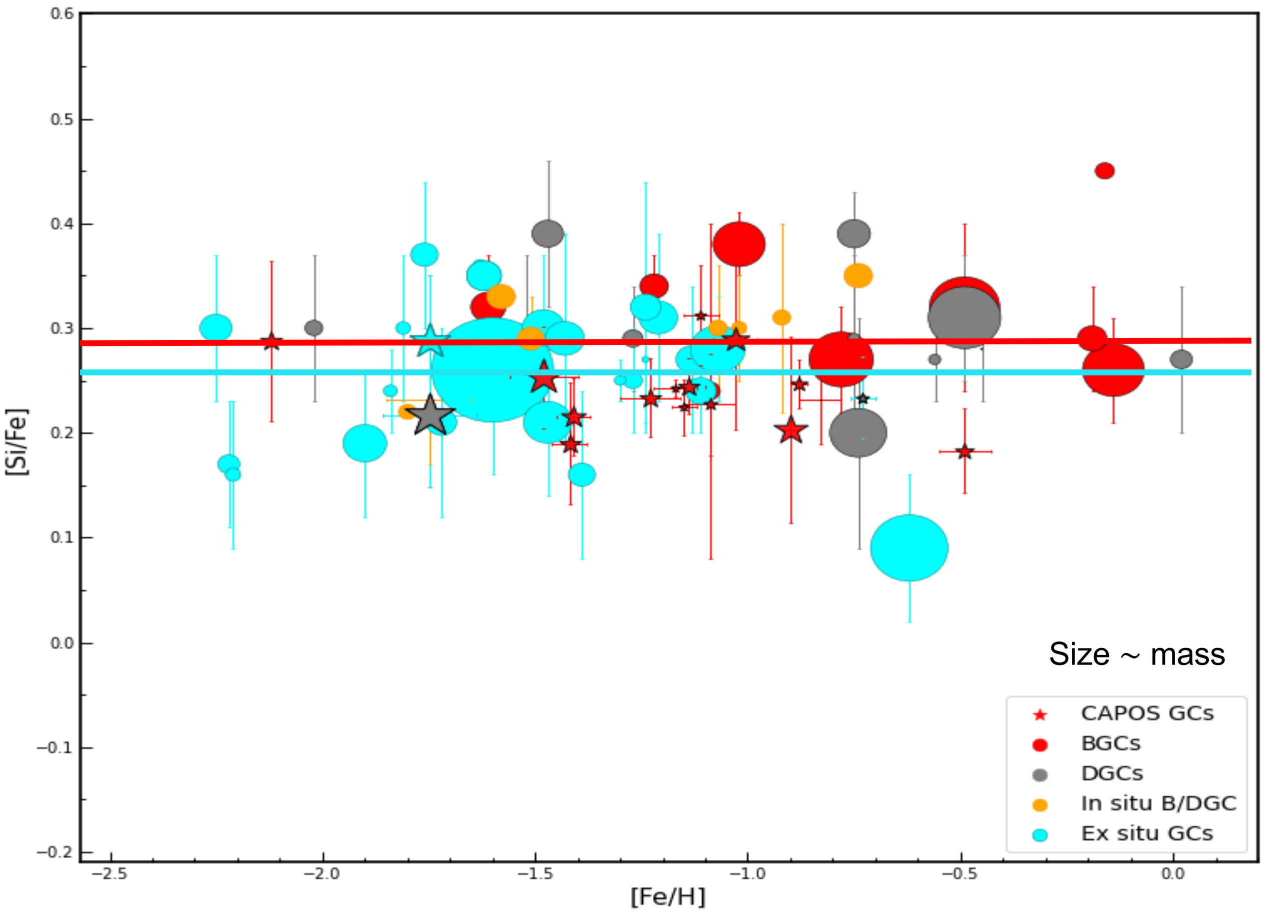
[a] Massari et al. (2019). LE = Low Energy, MB = Main Bulge, Seq = Sequoia, MD = Main Disk.
[b] Perez-Villegas et al. (2020). TD = Thick Disk, B/B = Bulge/Bar, OH = Outer Halo.
[c] Callingham et al. (2022). Kra = Kraken, B = Bulge, D = Disk, Ungr = Ungrouped, Seq = Sequoia, GE = Gaia Enceladus.
[d] Belokurov & Kravtsov (2023). 1 = in-situ, 0 = accreted.
[e] Chen & Gnedin (2024). 1 = in-situ, 0 = accreted.
[f] Our assessment from [Mg/Mn] vs. [Al/Fe]. 1 = in-situ, 0 = accreted.
[g] Our final classification: 1B = in-situ bulge, 1D = in-situ disk, 0 = accreted.

Geisler+ 2024

Chemodynamics of in situ vs. accreted GCs

1. [α/Fe] vs. [Fe/H] – SFR/chemical evolution history

CAPOS extends BGCs to lower metallicity



In situ (B and D)
Accreted

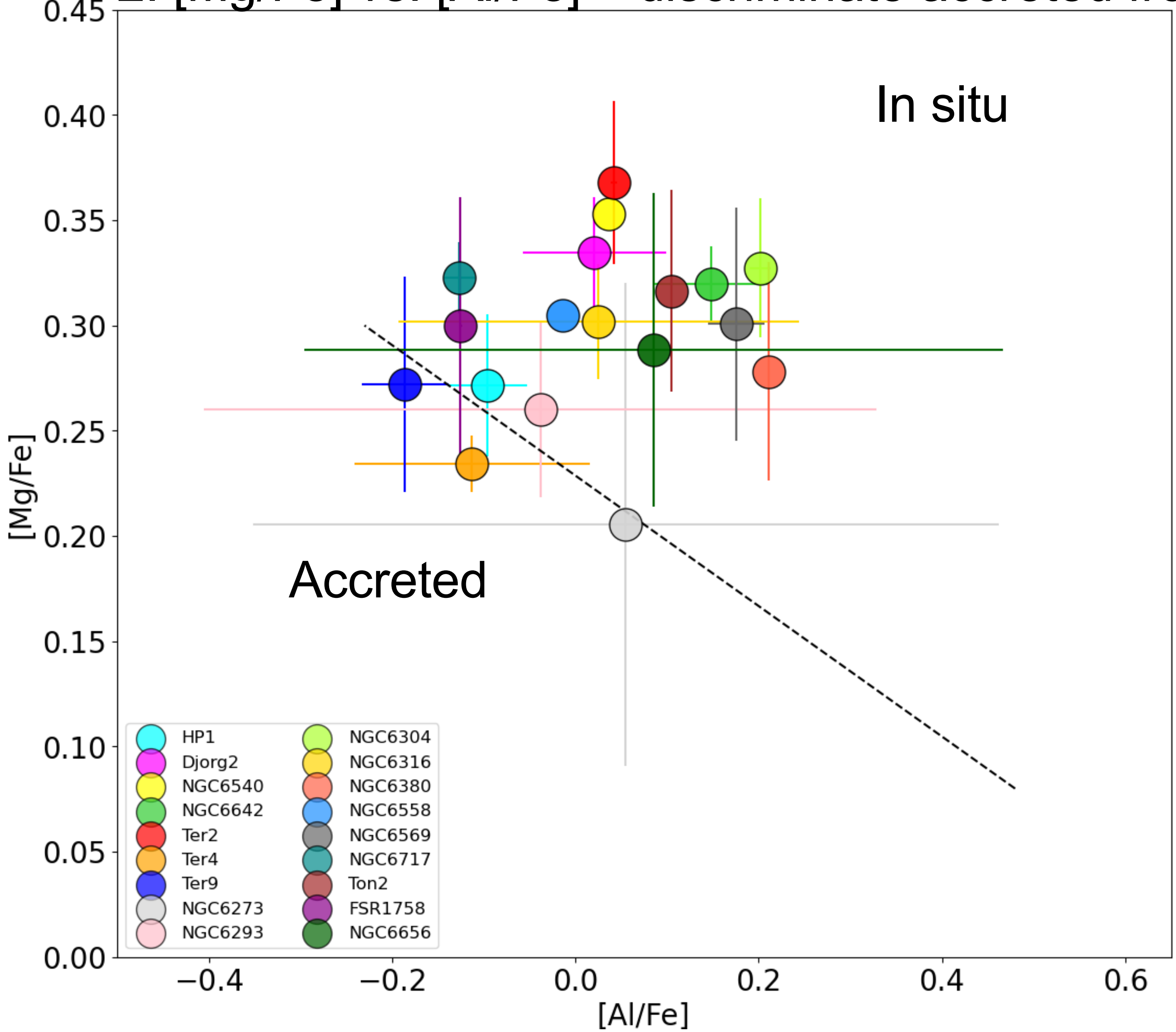
In situ: 0.28+/-0.06 (44)
Ex situ: 0.26+/-0.07 (27)

Geisler+ 2024

Very similar [α /Fe] at similar [Fe/H] ➜
Similar SFR/chem evol. in deeper potential well of in situ B/D GCs vs accreted!?

Chemodynamics of in situ vs. accreted GCs

2. [Mg/Fe] vs. [Al/Fe] – discriminate accreted from in situ



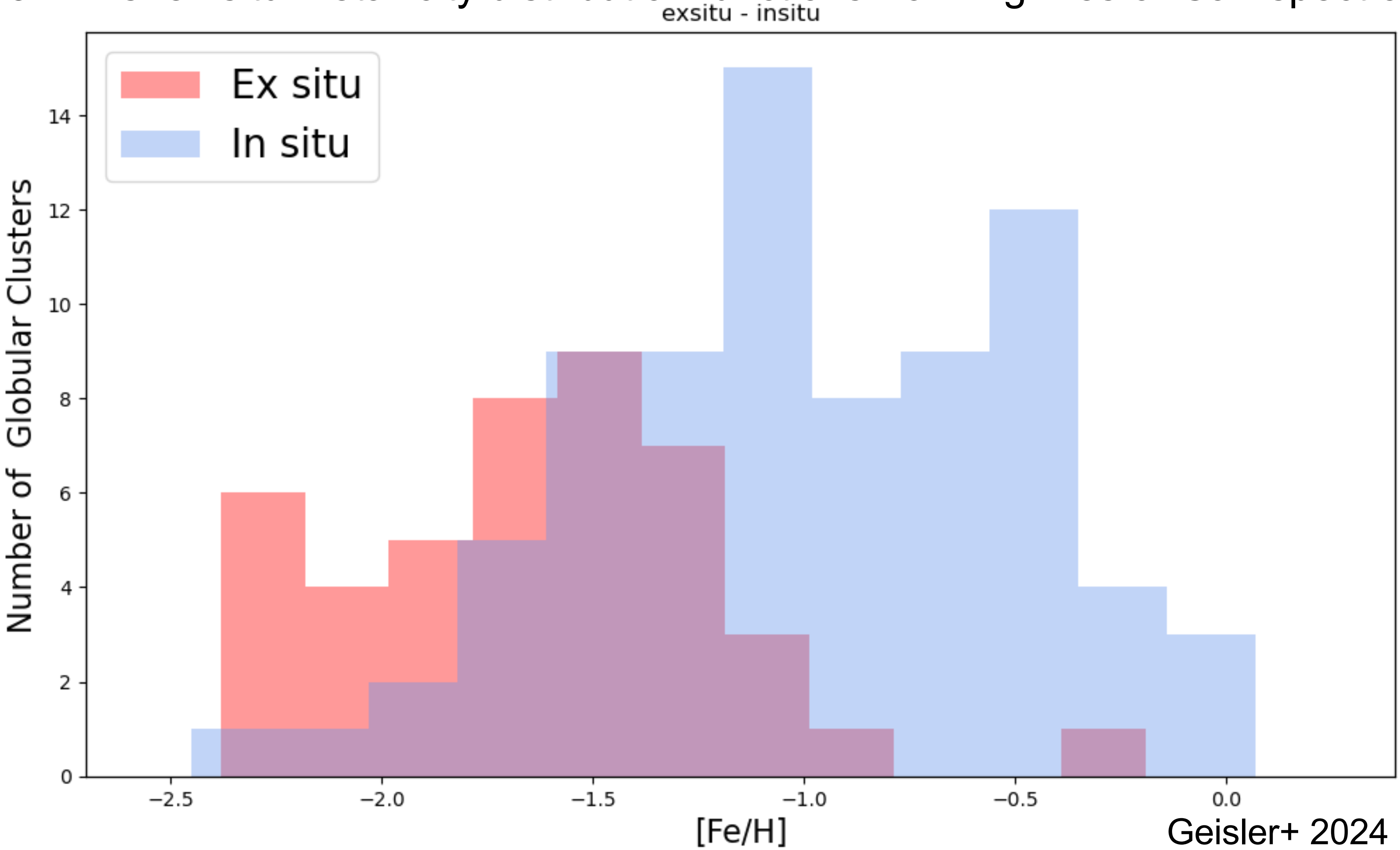
Belokurov+24: Nice separation between in and ex situ in [Mg/Fe] vs. [Al/Fe].

CAPOS GCs: Most are in situ

Geisler+ 2024

Chemodynamics of in situ vs. accreted GCs

3. In vs. ex situ metallicity distribution functions from high res or CaT spectra

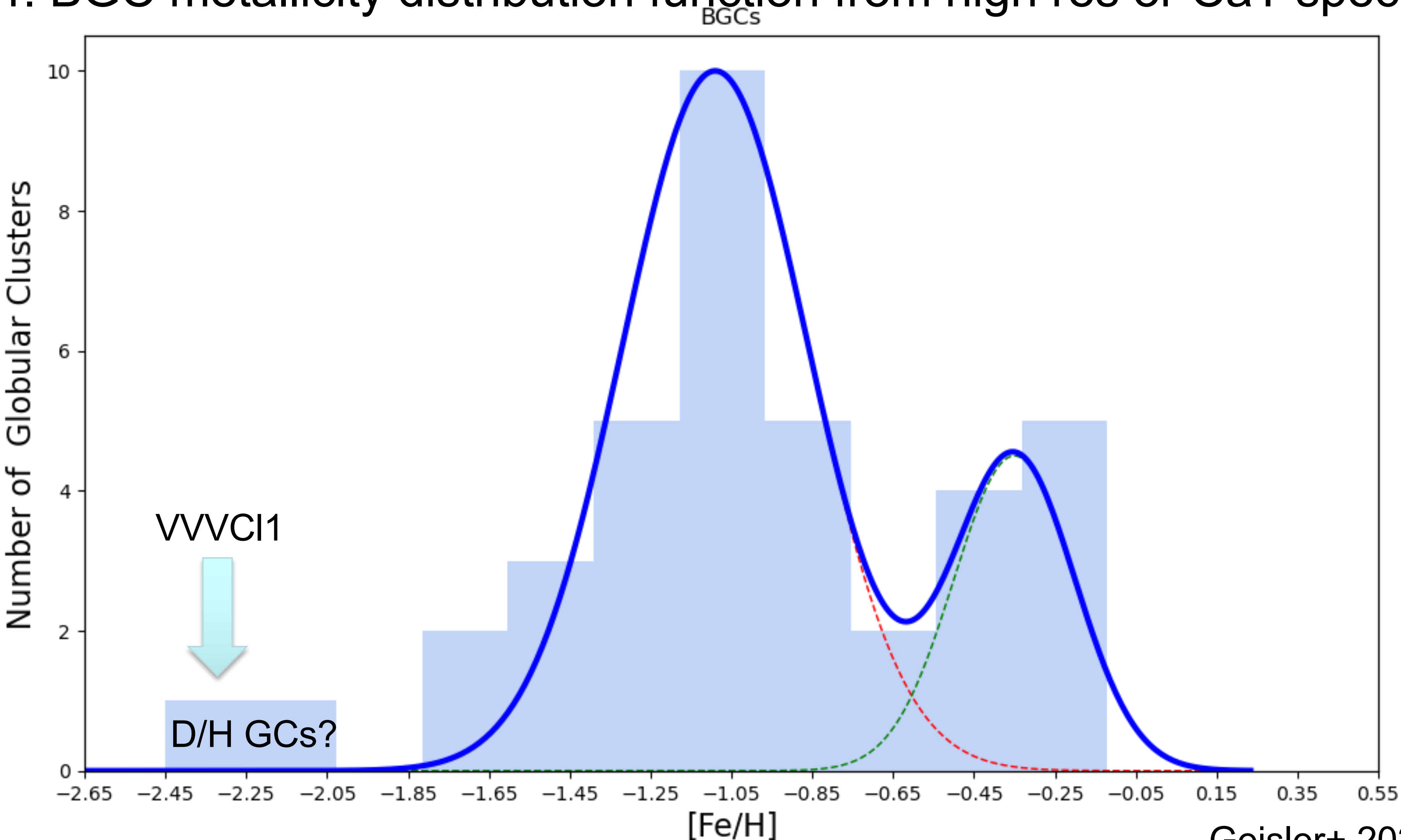


Geisler+ 2024

In situ cover full metallicity range while ex situ almost exclusively <-1

Chemodynamics of in situ vs. accreted GCs

4. BGC metallicity distribution function from high res or CaT spectra



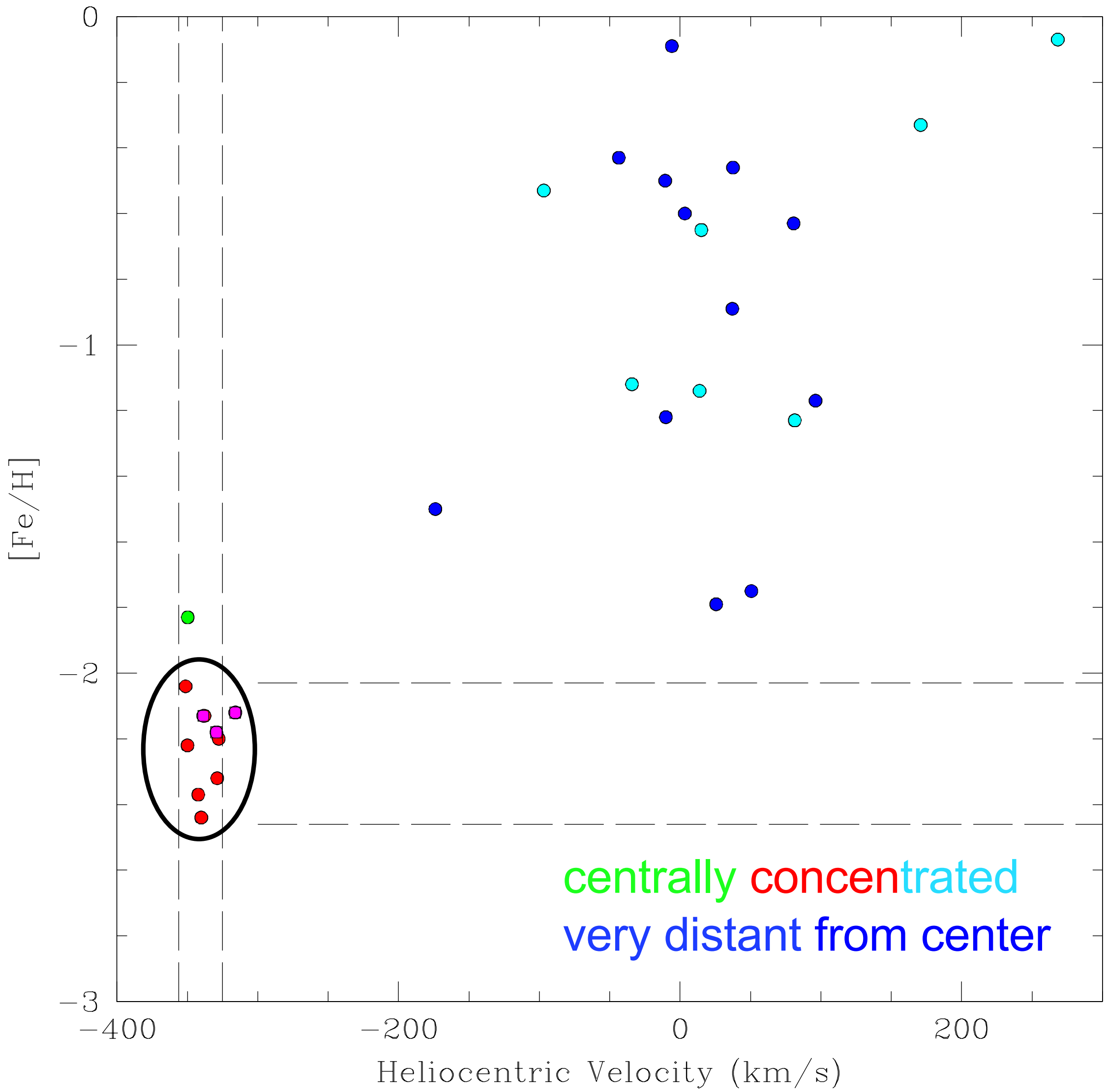
Geisler+ 2024

Bimodal, dominated by -1.1 group, minor peak -0.4. Good agreement with Bica+ 2024.

Lowest metallicity B/D GCs best candidates for oldest in situ MW objects!

2 very low metallicity BGCs – Disk? Halo intruders?

VVVCl1: VLT CaT metallicities & velocities



Haro+ 2024

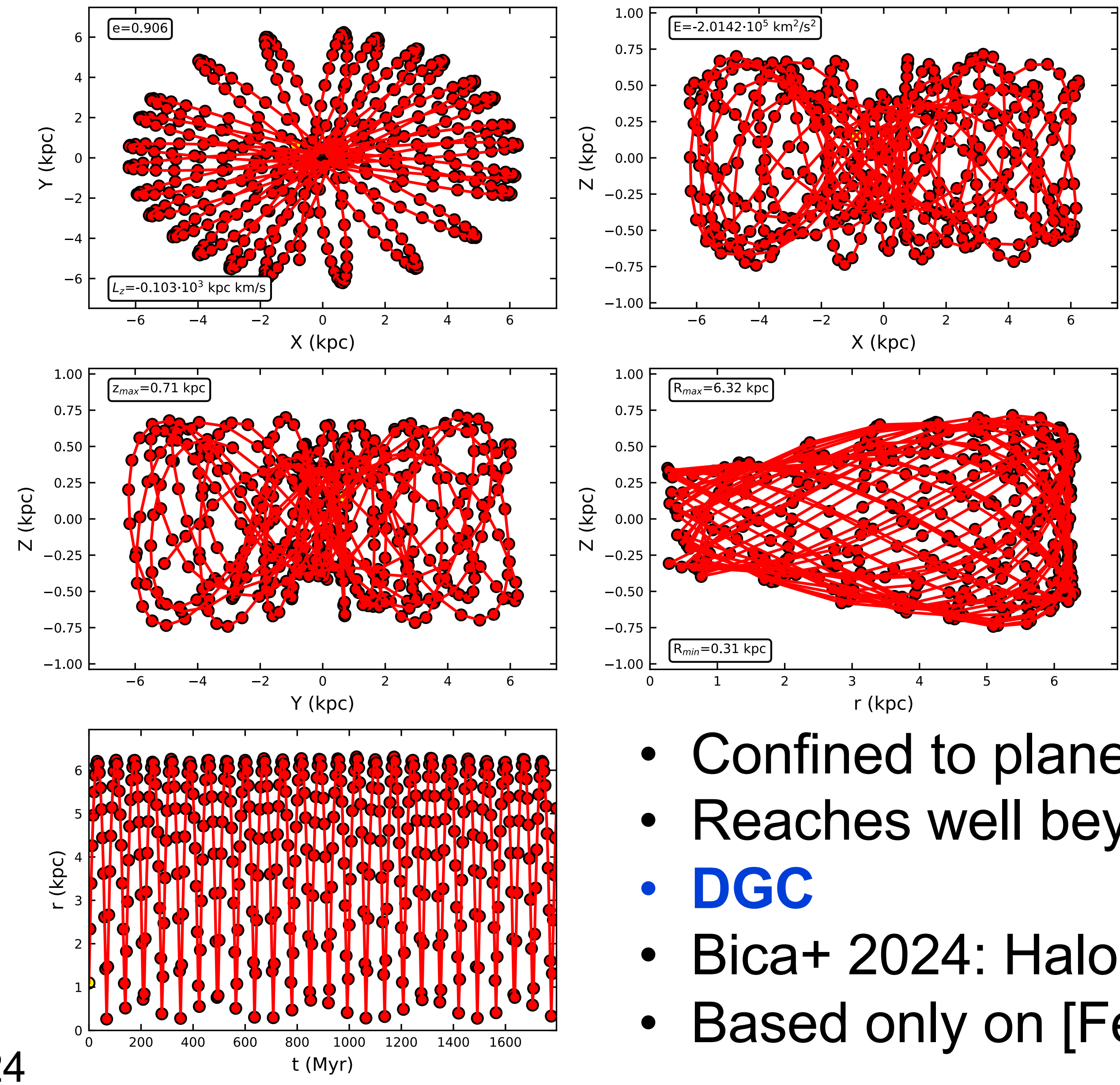
<[Fe/H]> = -2.25±0.05

(2 APOGEE stars: -2.45±0.24 Fernandez-Trincado+ 2021)

$\langle v_r \rangle$ = -339.7±3.5 km/s

EXTREME values!

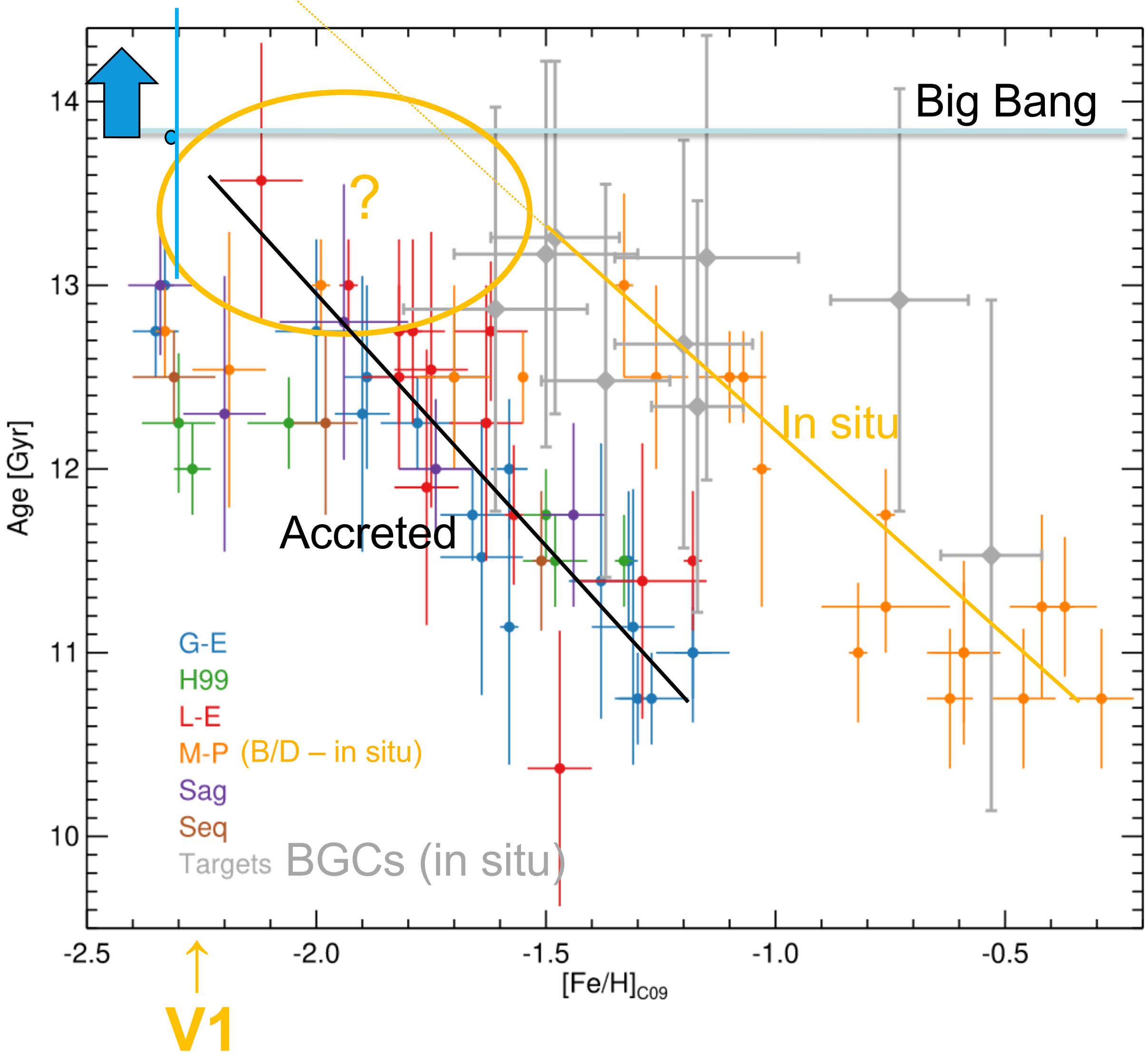
VVVCl1 Preliminary orbit



- Confined to plane
- Reaches well beyond bulge
- **DGC**
- Bica+ 2024: Halo intruder
- Based only on [Fe/H] <-1.5

Haro+ 2024

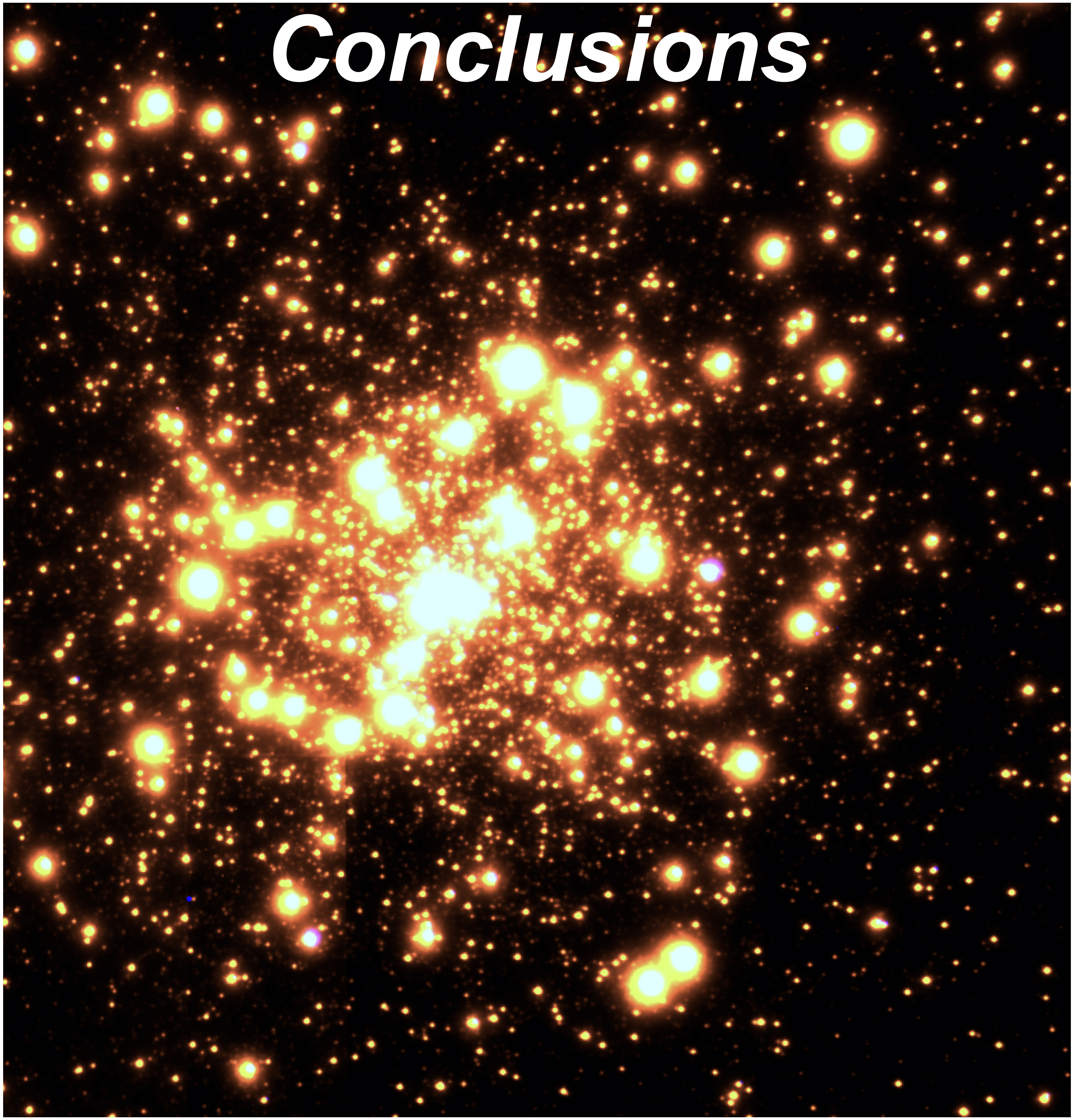
V1? GC age:metallicity relations



Cohen+ 2021

VVVCl1 most metal-poor (?) in situ GC - great candidate for
oldest object in MP for which we can derive good age!

Conclusions

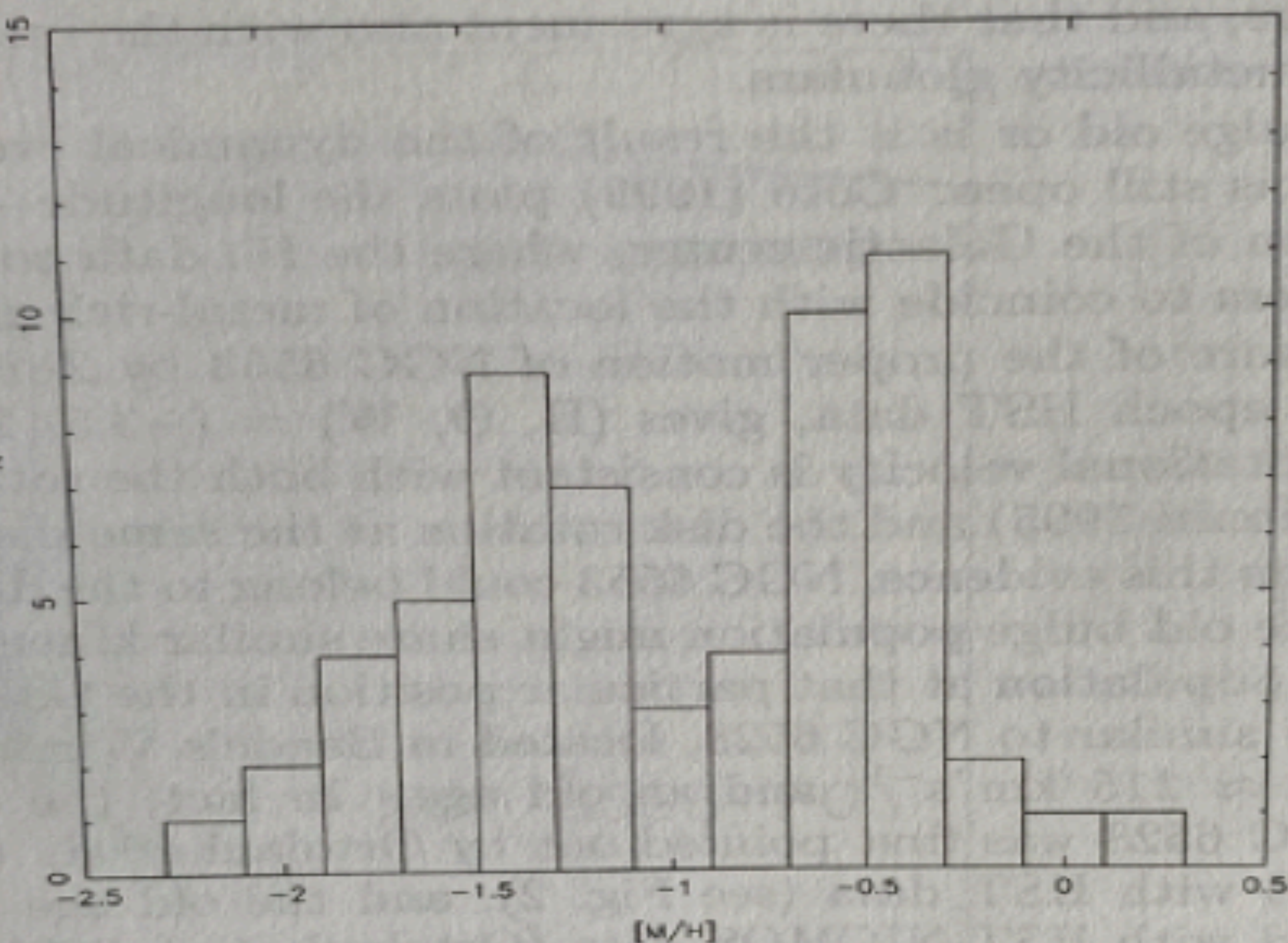


Need deep GeMS data for VVVCl1!

Happy birthday Beatriz!

Chemodynamics of in situ vs. accreted GCs

4. Old “BGC” metallicity distribution function from many techniques

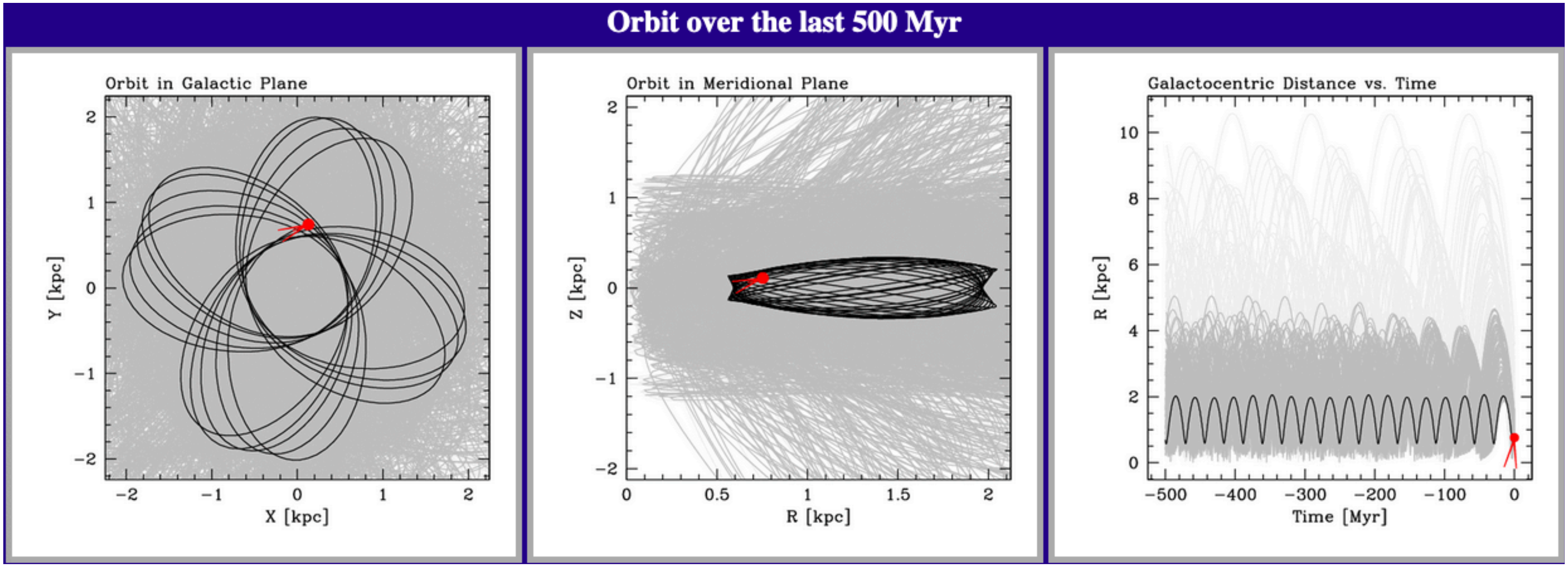


Bimodal, dominated by -0.5 group, smaller peak -1.4

Figure 1. Histogram of metallicities of 60 globular clusters within $R_{GC} < 4$ kpc and $20° \times 20°$ of the Galactic center, where metallicity values are adopted from Harris (1996).

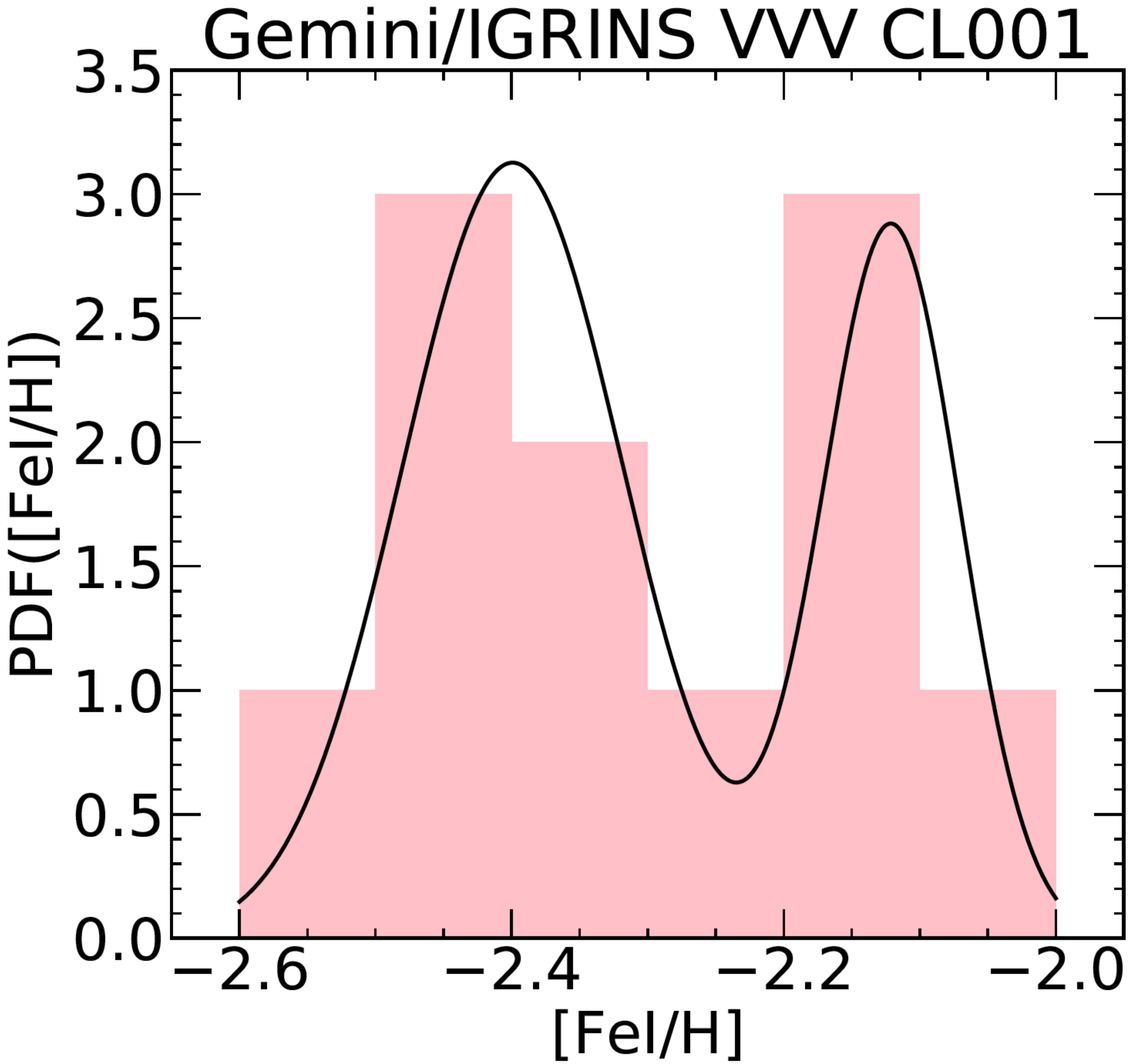
Barbuy+ 2001

VVVCl1 orbit



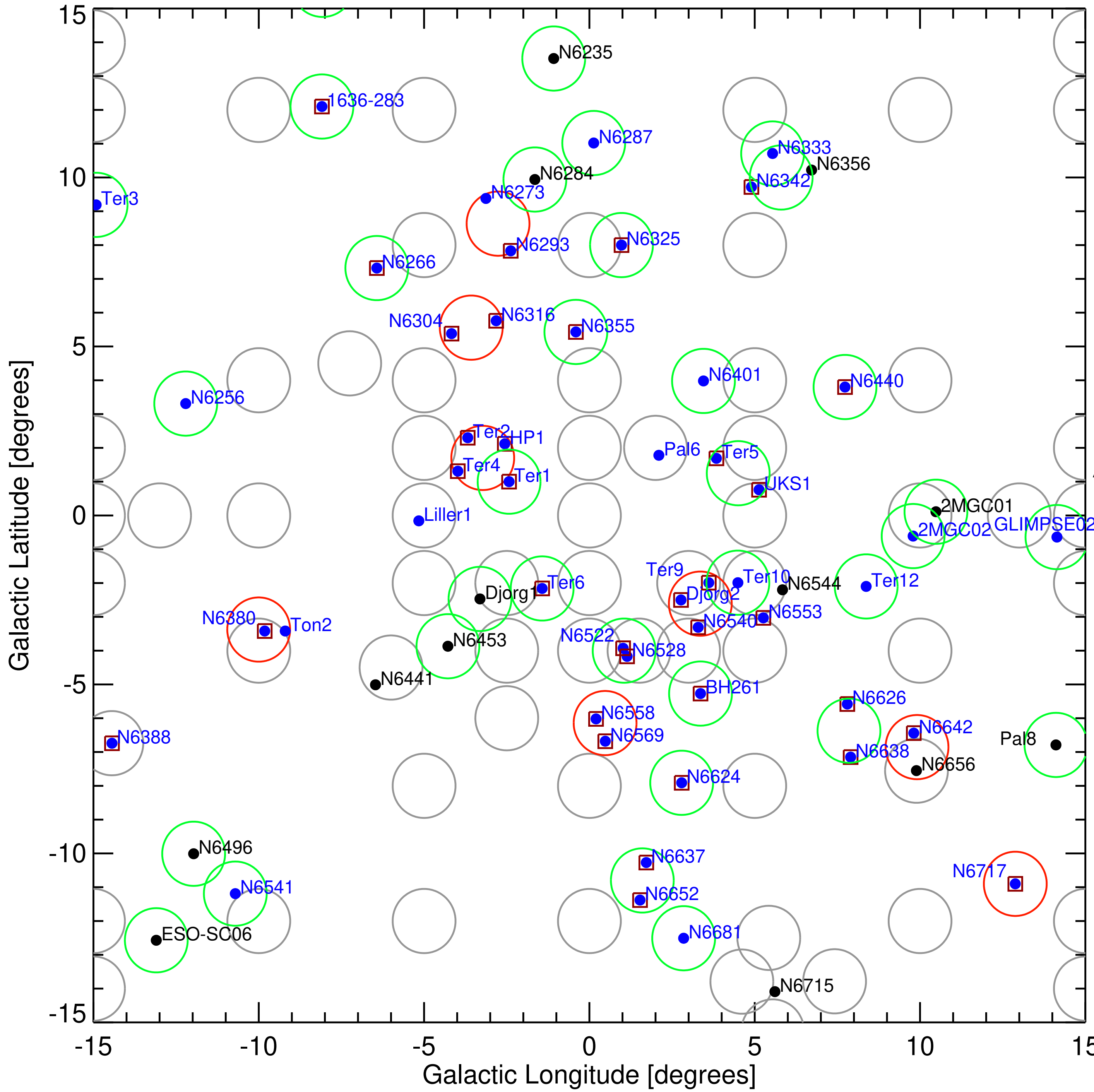
Baumgardt database

- Confined to plane
- Stays within bulge
- Current R_{GC} = 760 ± 680 pc
- **BGC**
- Bica+ 2024 - halo intruder?!
- But based only on [Fe/H]<-1.5



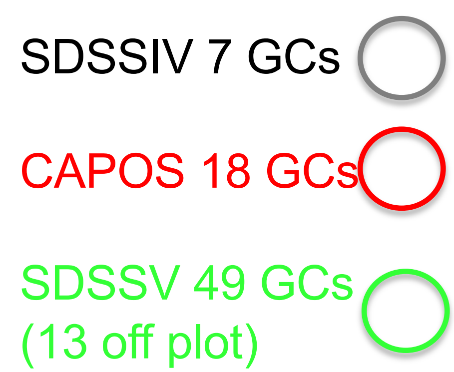
VVVCl1 MDF
11 IGRINS stars

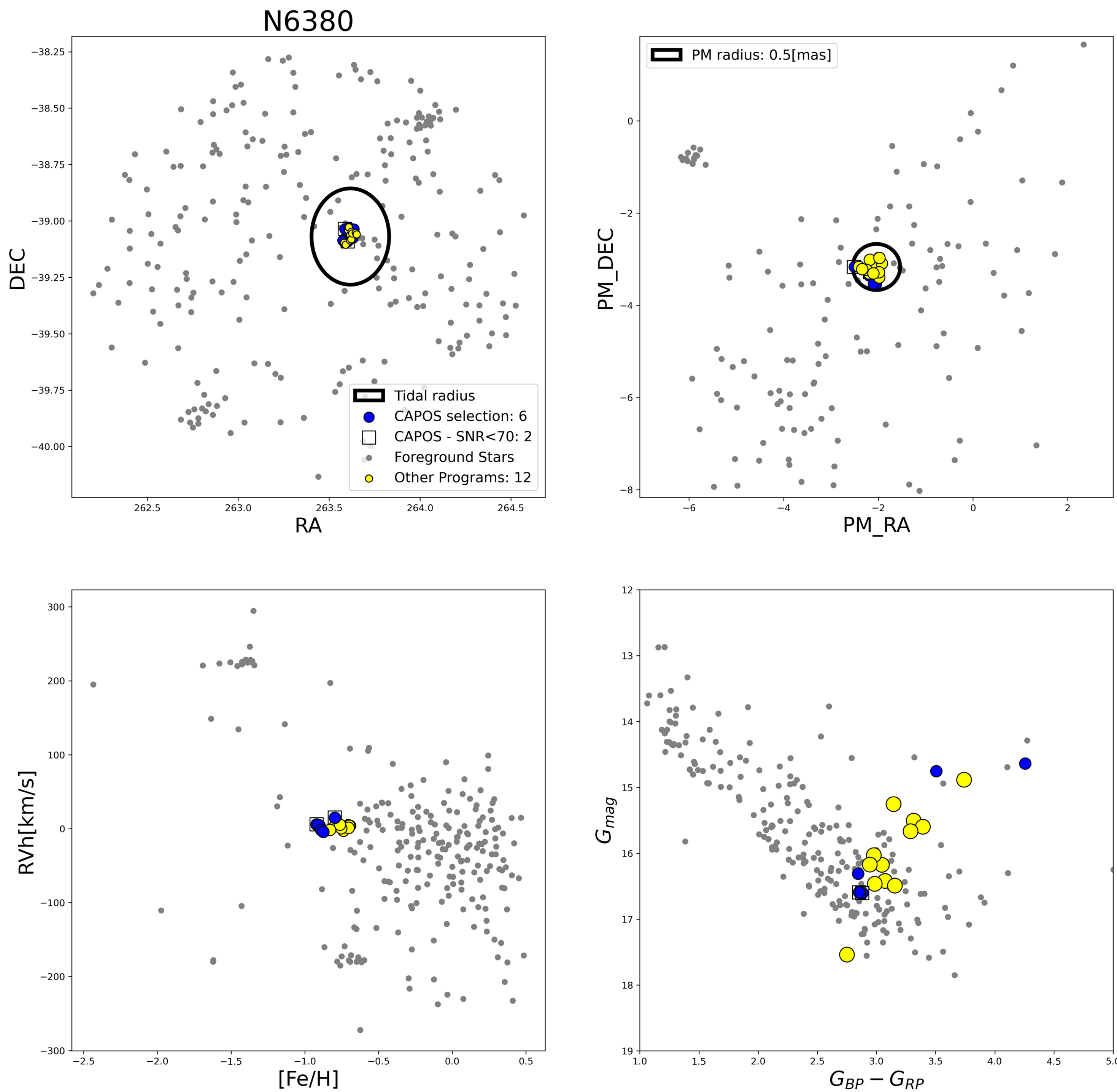
Haro+ 2024



SDSSV Open Fiber project to observe all remaining BGCs not observed by APOGEE: **complete sample!** Geisler PI

Combined with Frinchaboy prop to **get Apogee data for ALL GCs without it - ~100!!**





Cesar Muñoz:
Member Selection

- Position in GC
- Proper motion
- Radial velocity
- Metallicity
- Position in CMD

Very high probability for a good number of members/GC

Note multiple GCs per APOGEE field

Geisler+ 2024

CAPOS B/D GC Hands-on Abundance Analysis projects

Cluster assigments and status

C. Montecino poster 11

Spectroscopy - CAPOS members

Cluster	Ntot	N(SN>70)	[Fe/H]	Worker
Djorg 2	6	6	-1.09	Thaiz Pino UdeC Masters thesis started 23
FSR1758	15	9	-1.42	Maria Romero UCN Masters thesis ended 21 - Romero+21 DONE!
HP 1	10	10	-1.16	Lady Henao UdeC PhD thesis - Paper submitted
M22	178	125	-1.70	Nicolas Barrera PhD thesis ULS started 24 - NB: also 119 good stars from other program!
N6273	75	62	-1.70	Margaret Castro UCN undergrad thesis ended 22 - ?? Left astro. JFT redoing all - finish sem1 24
N6293	20	13	-2.07	Caro Montecinos ULS PhD thesis started 22
N6304	29	12	-0.49	Caro Montecinos ULS PhD thesis started 22
N6316	17	6	-0.79	Heinz Frelijj UCN postdoc - in progress - 2 stars from other program included – paper submitted
N6380	6	4	-0.89	Fernandez-Trincado+ 22 - but 11 SDSS stars and only 2 CAPOS stars - 7 (6?) total - OPEN - LH
N6540	4	4	-1.03	Wisthon Haro - Taller with Cesar - Ilaria Petralia UCN PhD thesis with JFT
N6558	5	4	-1.11	Danilo Gonzalez+ 23 DONE
N6569	9	7	-1.00	Nicolas Barrera UdeC Masters thesis started 22 - paper submitted
N6642	11	10	-1.09	Caro Montecinos ULS PhD thesis started 22
N6717	4	2	-1.17	OPEN
Ter 2	3	3	-0.86	Macarena Parra UdeC Titulo thesis started 23
Ter 4	3	3	-1.39	Franco Sepulveda UdeC Titulo thesis started 23
Ter 9	9	9	-1.38	Caro Montecinos ULS PhD thesis started 22
Ton 2	12	6	-0.69	Fernandez-Trincado+22 DONE!

Metal-poor field stars — Carolina Salgado UdeC postdoc

Photometry

16 BGCs HST and 11 GeMS data — Wisthon Haro ULS PhD thesis started 23, Heinz Frelijj? Scarlet Ortega UdeC PhD thesis

2 Masters thesis completed, 3 in progress

1 PhD thesis completed, 4 in progress

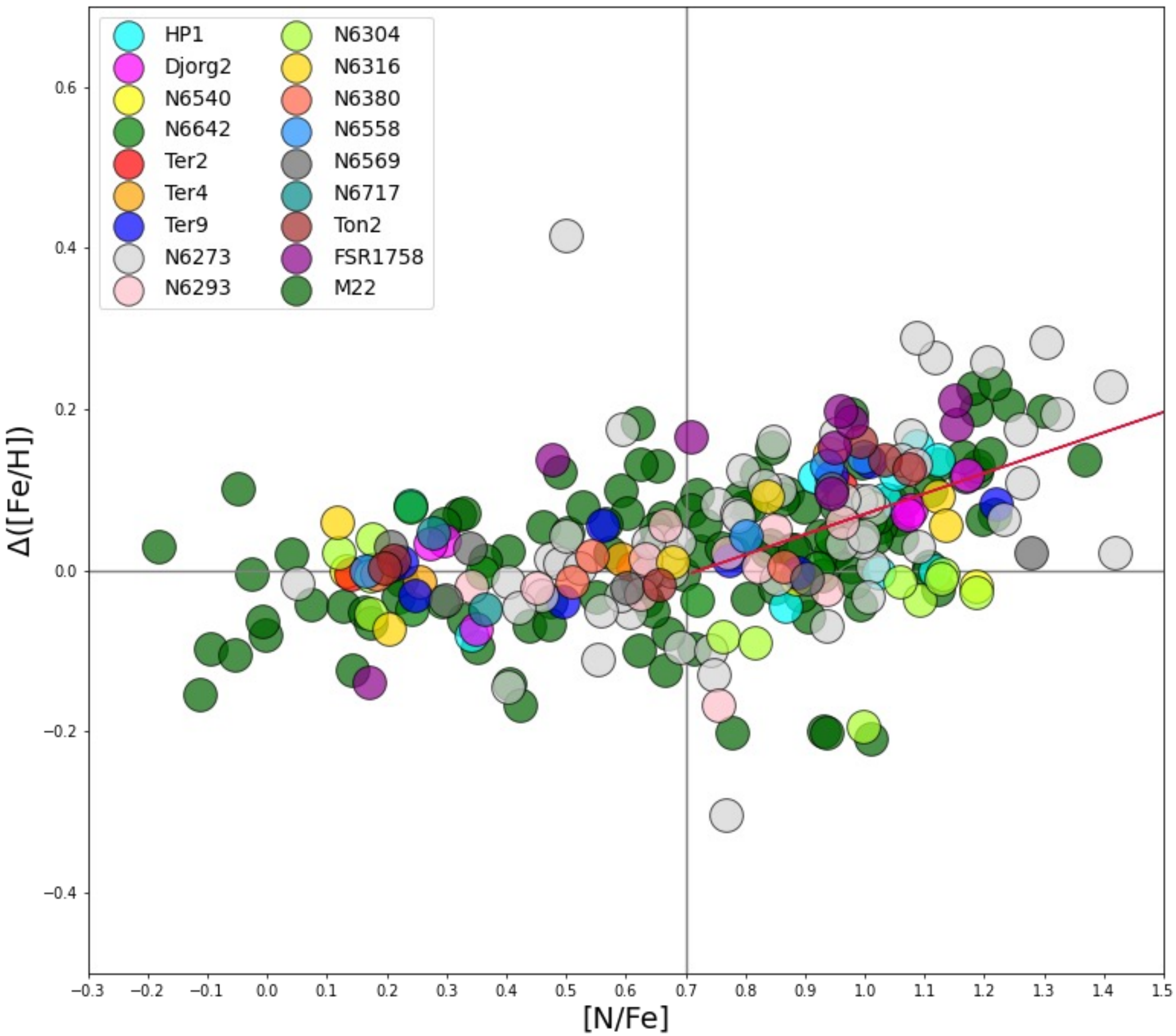
Final CAPOS Sample (ASPCAP)

Table 3. Mean cluster metallicity, [α/Fe] and radial velocity for members.

Geisler+ 2024

Cluster ID	[Fe/H] [a] (dex)	[α/Fe] [a] (dex)	V_r [a] (km s^{-1})	$N_{members}$	N_{1G}
NGC 6273	−1.75± 0.11	0.20±0.10	144.8±7.6	62	23
NGC 6293	−2.12± 0.08	0.26±0.08	−144.1±5.8	13	5
NGC 6304	−0.49± 0.06	0.27±0.02	−108.6±5.4	12	4
NGC 6316	−0.83± 0.05	0.22±0.05	101.5±1.3	6	3
Terzan 2	−0.88± 0.02	0.28±0.01	134.1±1.1	3	2
Terzan 4	−1.41± 0.04	0.26±0.01	−48.2±3.7	3	2
HP 1	−1.23± 0.07	0.27±0.00	40.1±4.0	10	2
FSR 1758	−1.48± 0.08	0.32±0.01	224.8±3.2	9	2
NGC 6380	−0.90± 0.02	0.22±0.10	0.7±3.9	4	3
Ton 2	−0.73± 0.03	0.26±0.05	−177.9±4.0	6	3
Terzan 9	−1.42± 0.04	0.22±0.01	69.8±5.1	9	4
Djorg 2	−1.14± 0.04	0.30±0.02	−152.0±1.2	6	3
NGC 6540	−1.09± 0.06	0.32	−14.4±1.1	4	1
NGC 6558	−1.15± 0.03	0.28	−192.4±1.4	4	1
NGC 6569	−1.03± 0.05	0.26±0.09	−49.9±4.2	7	4
NGC 6642	−1.11± 0.04	0.31±0.02	−55.4±2.4	10	6
NGC 6656	−1.75± 0.10	0.26±0.09	−147.4±6.3	125	58
NGC 6717	−1.17± 0.05	0.28±0.01	27.3±1.0	2	2

ASPCAP



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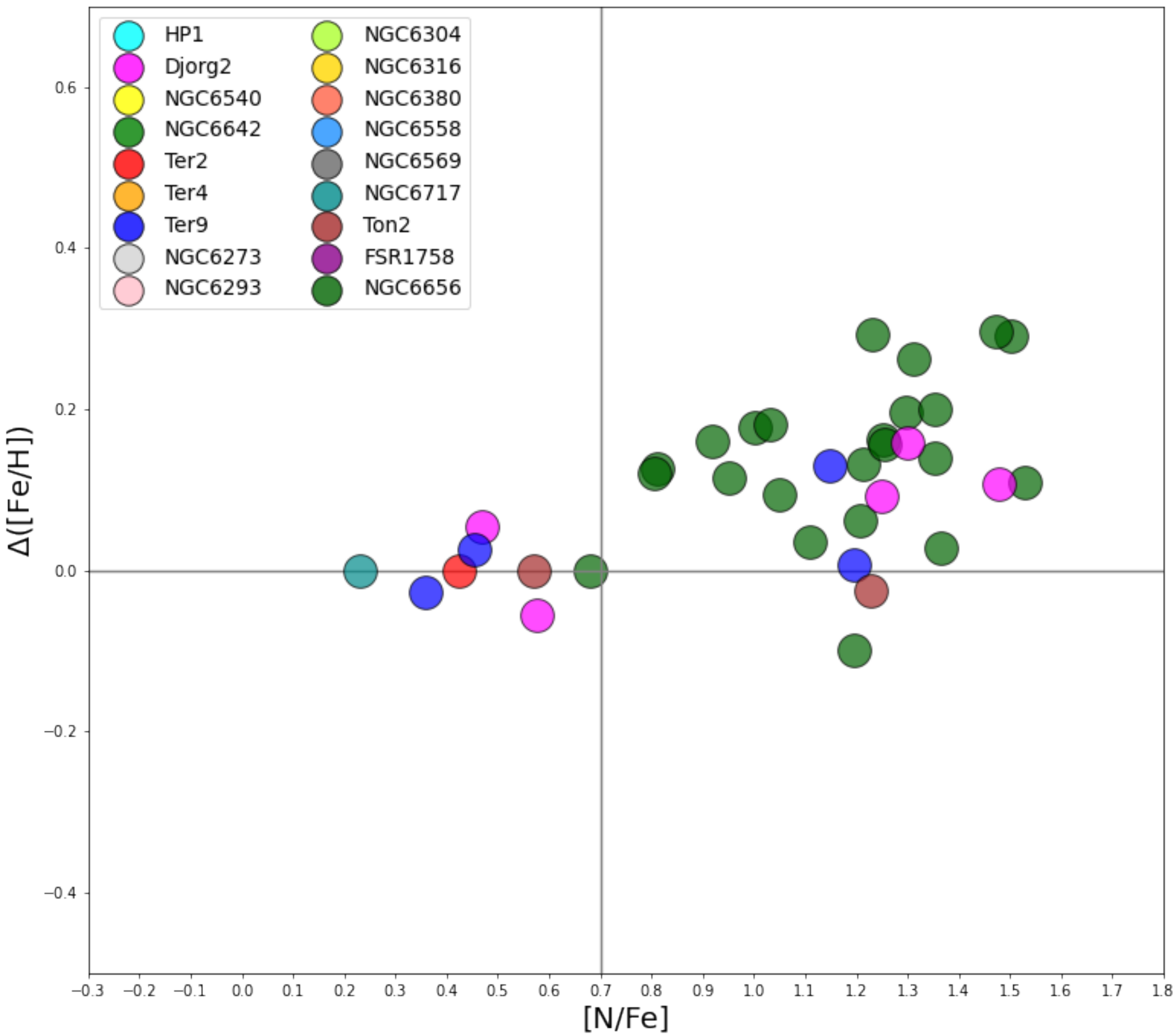
BAWLAS



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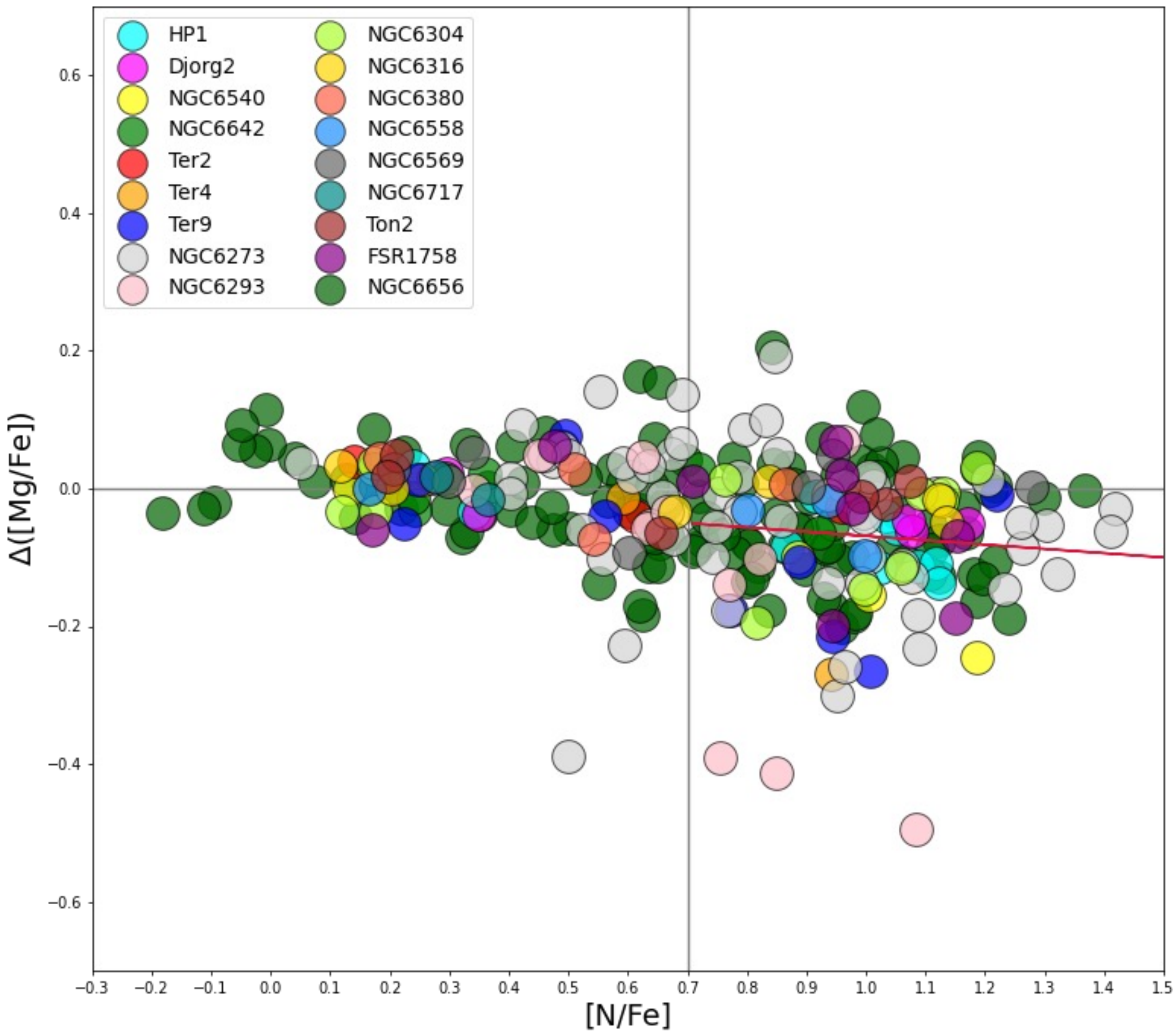
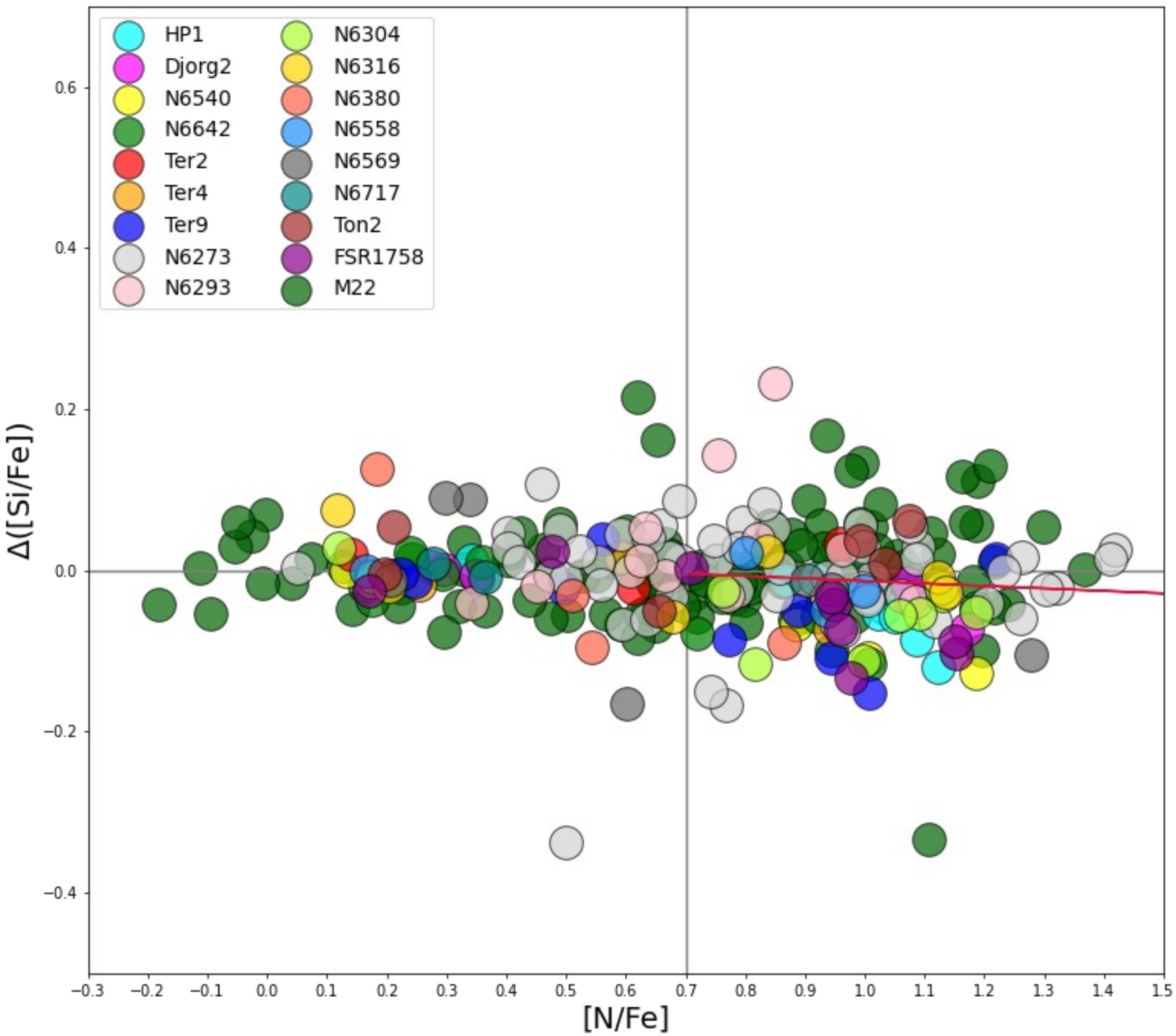
ASPCAP



Geisler+ 2024

ASPCAP



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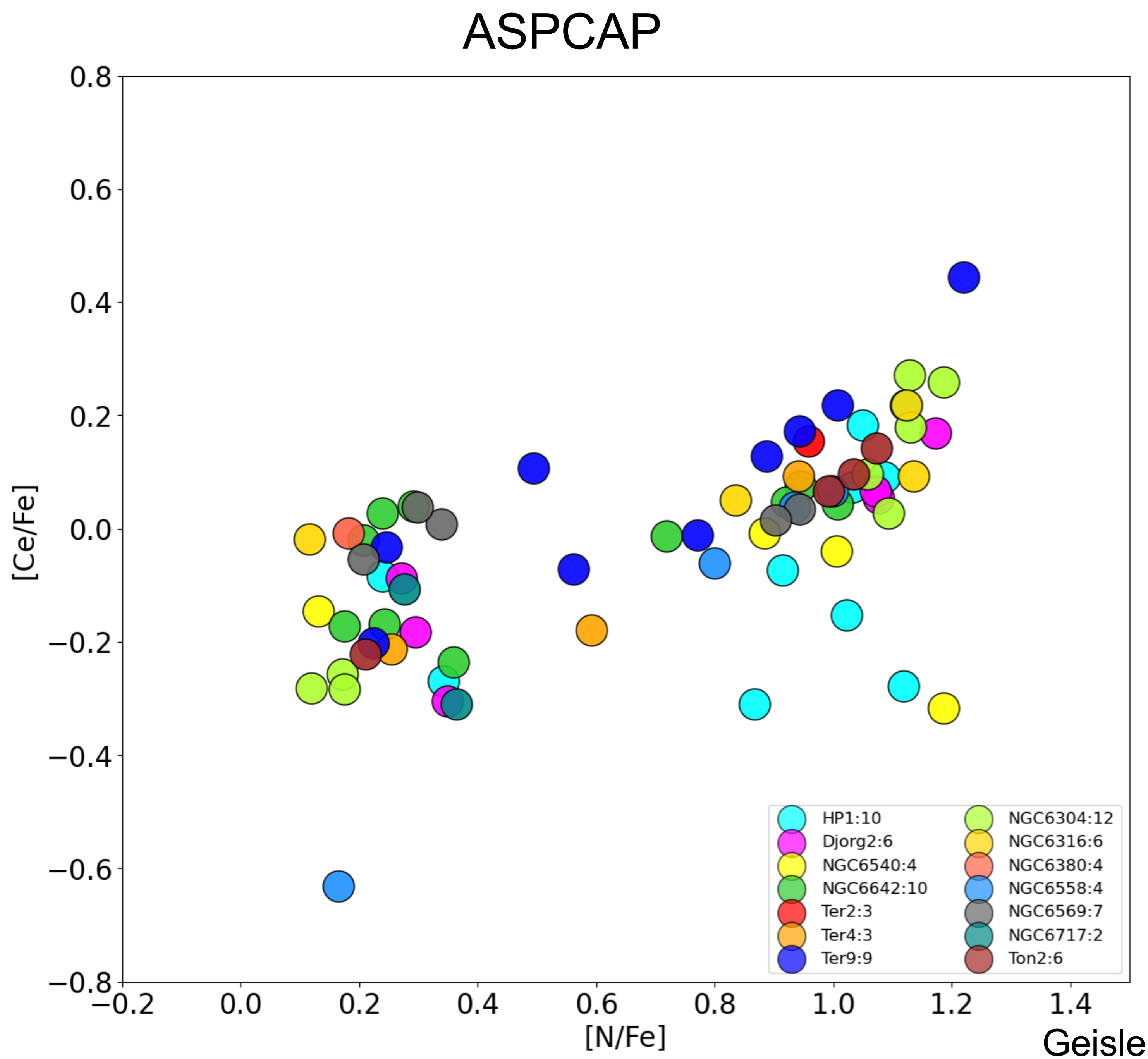

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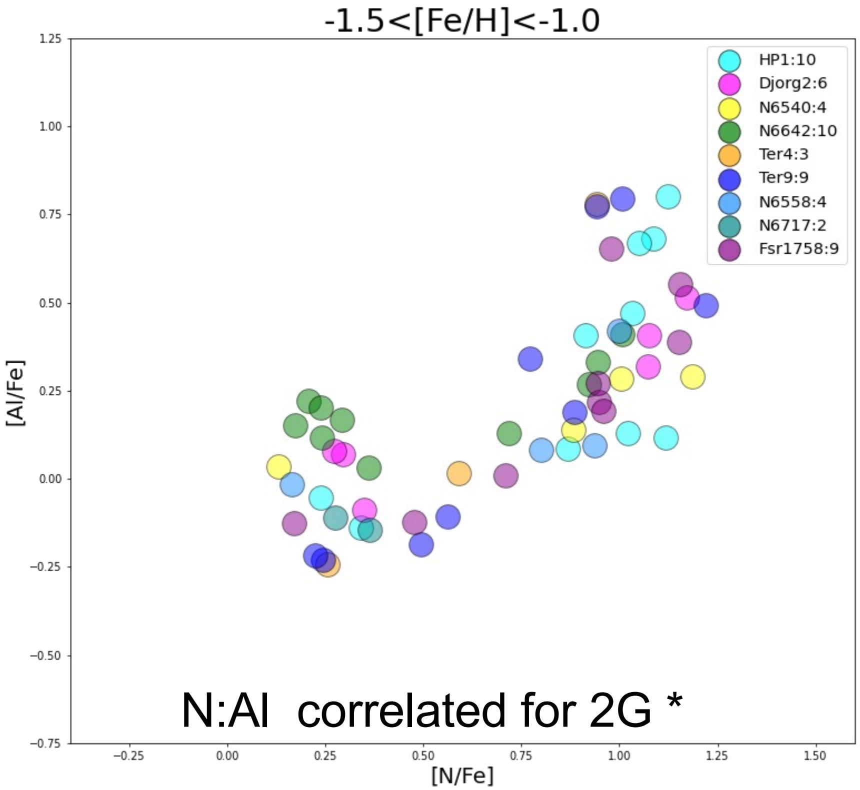
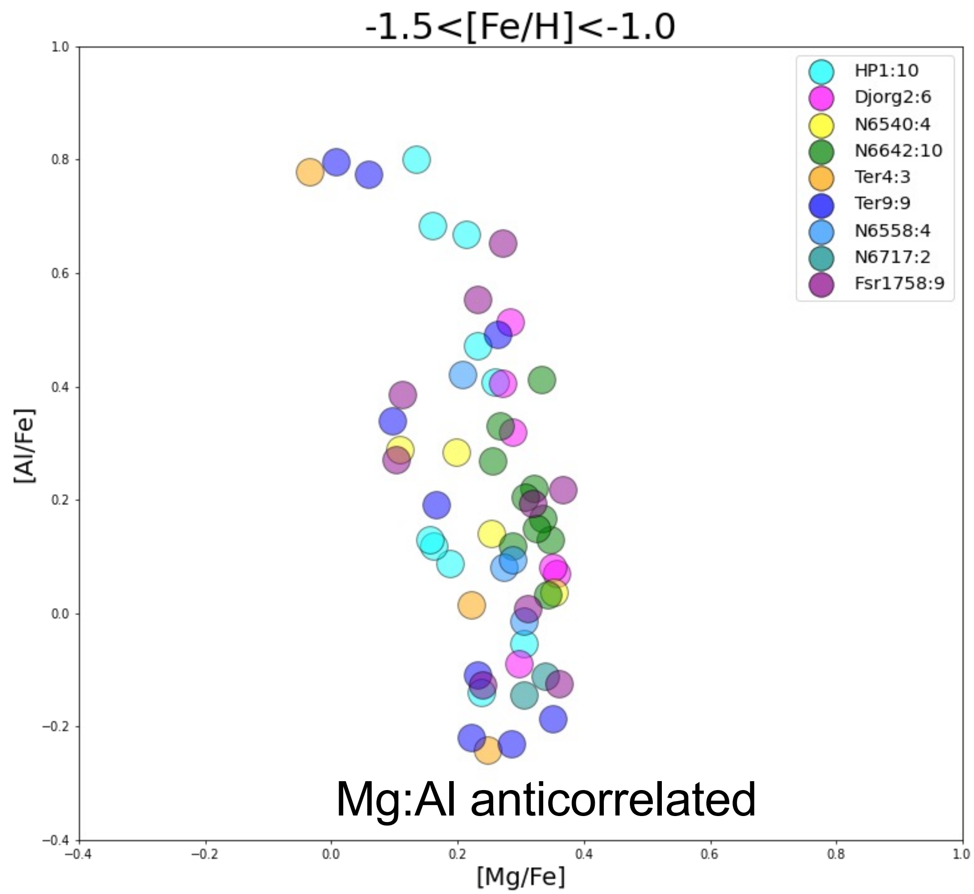
Multiple populations in 9 intermediate-metallicity B/D GCs



Rich variety of MP behavior – poorly studied in metal-rich GCs which are only in the bulge



Geisler+ 2024