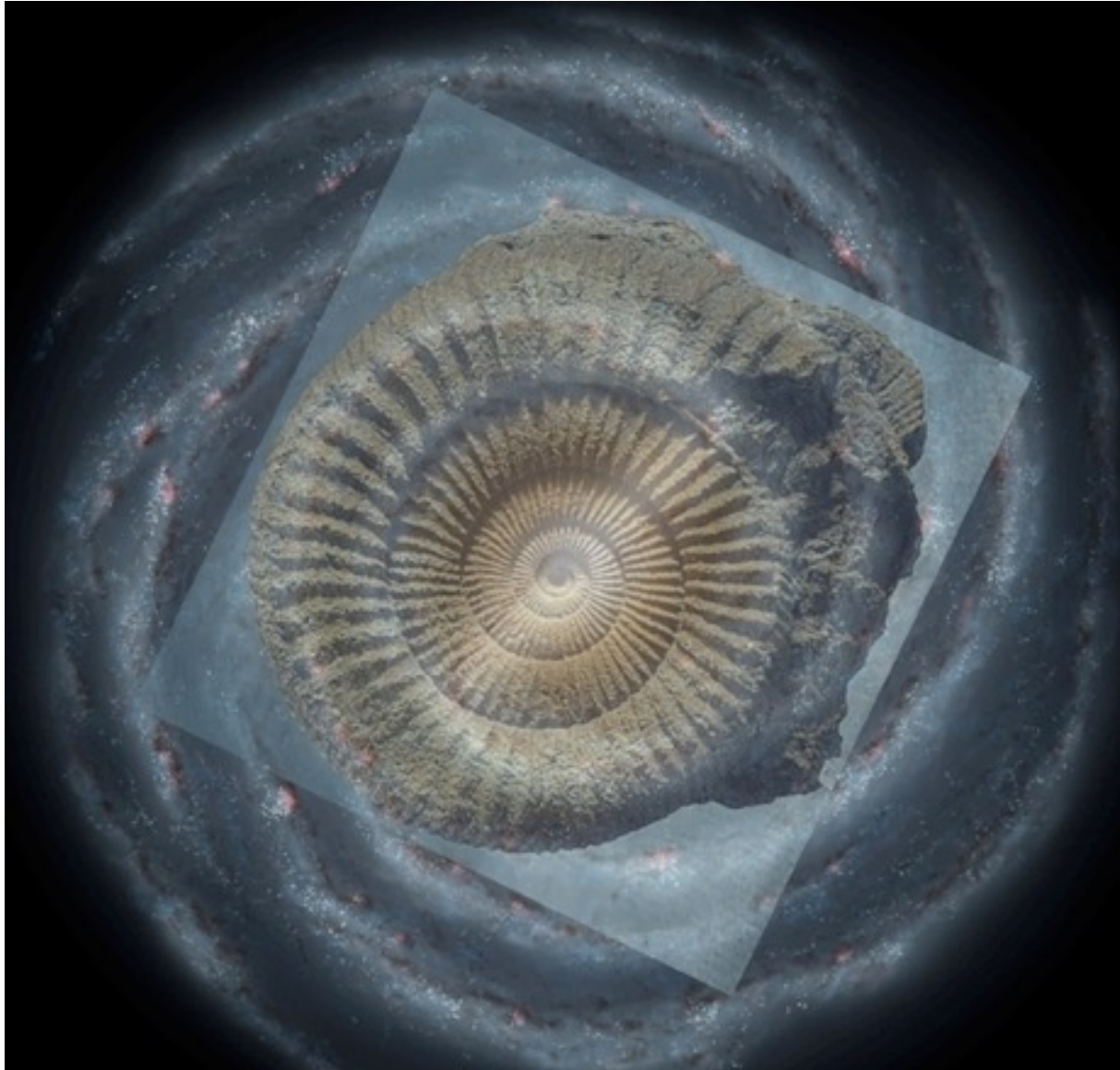


# Galactic Archeology with Bulge Globular Clusters



Doug Geisler  
Univ. de Concepcion  
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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



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Schenectady, New York  
USA

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Angra dos Reis 1991

Edited by B. BARBUY and A. RENZINI

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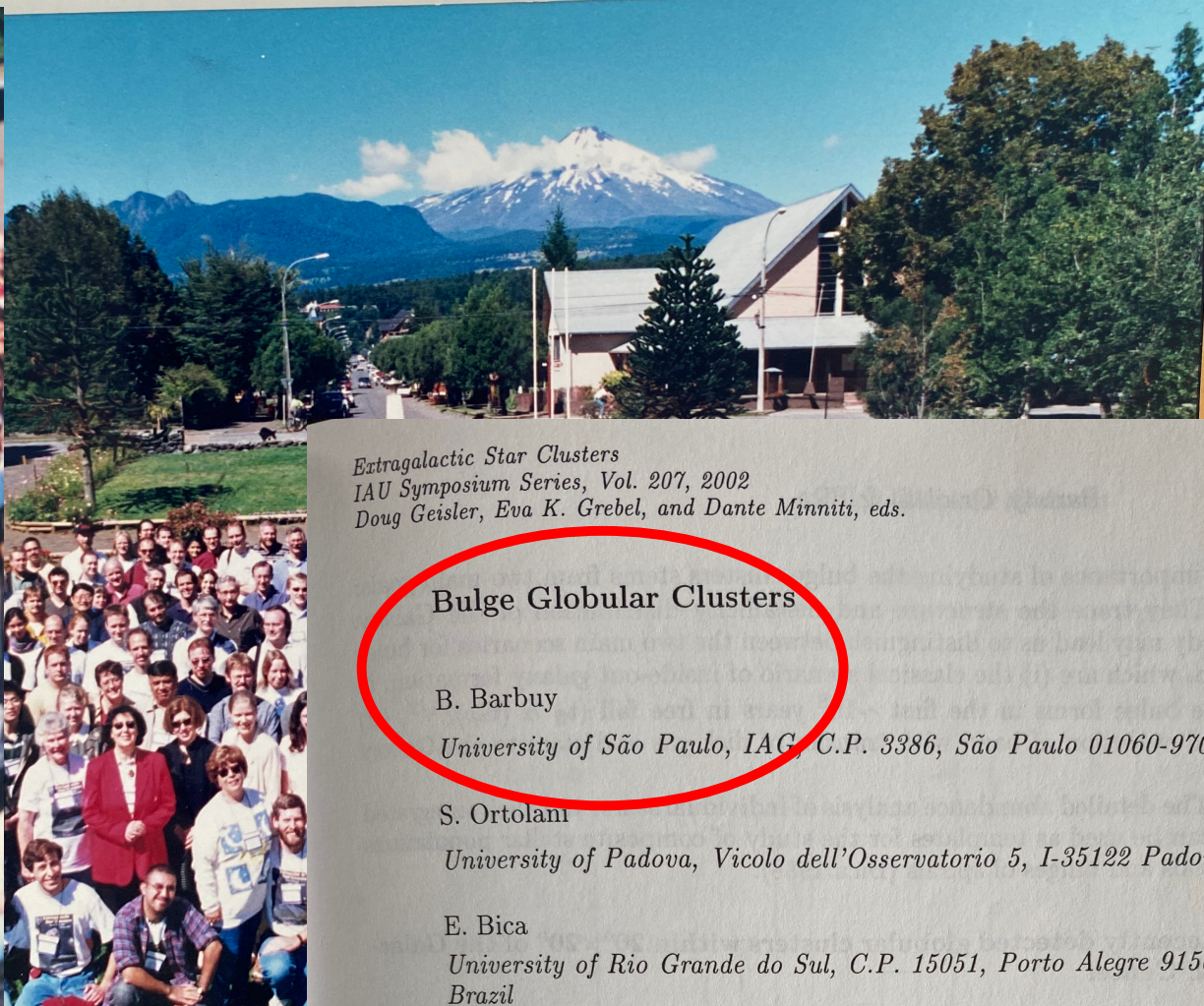


INTERNATIONAL ASTRONOMICAL UNION

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

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*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*

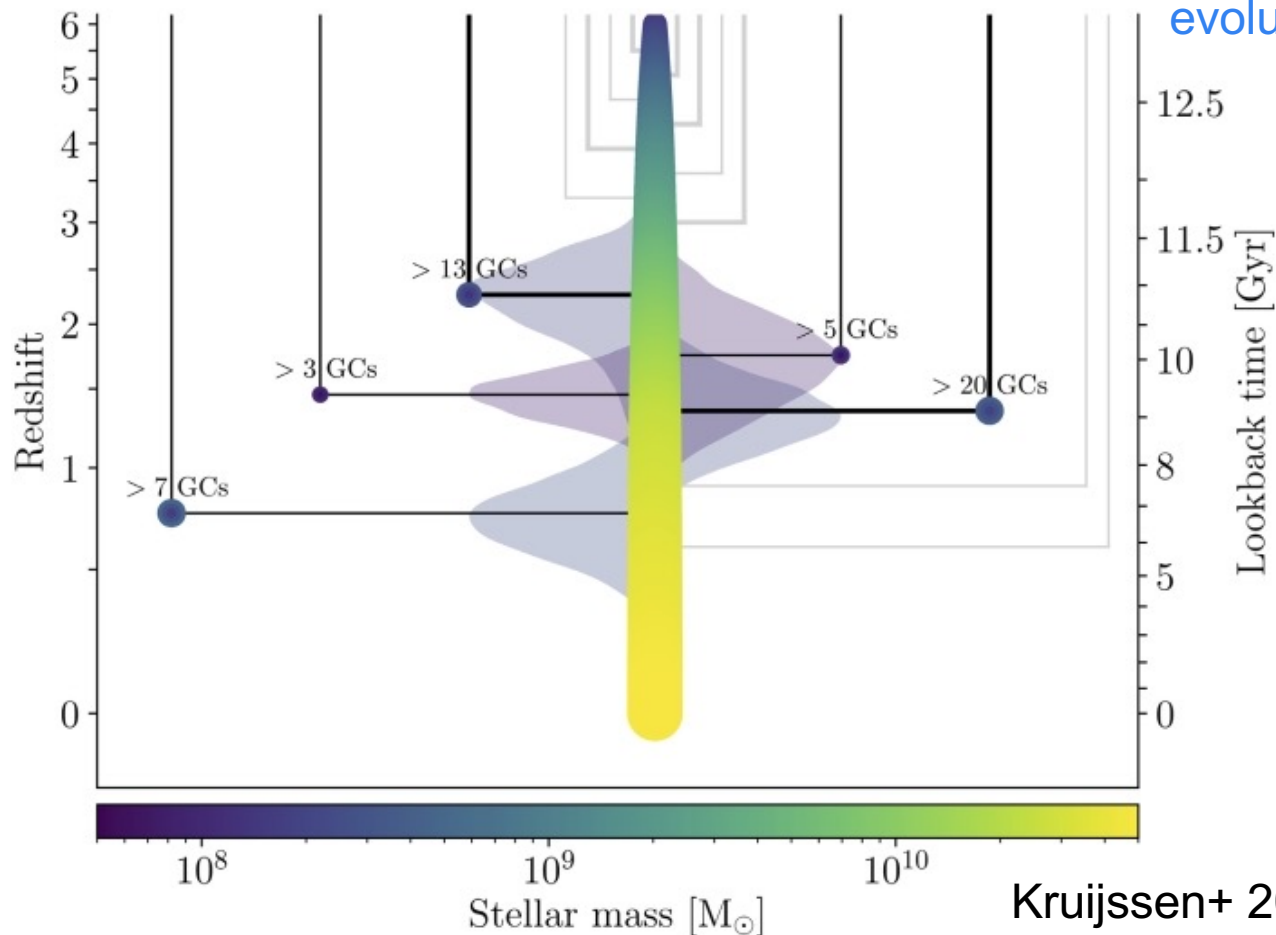
E. Bica

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

# Galactic archeology using GCs

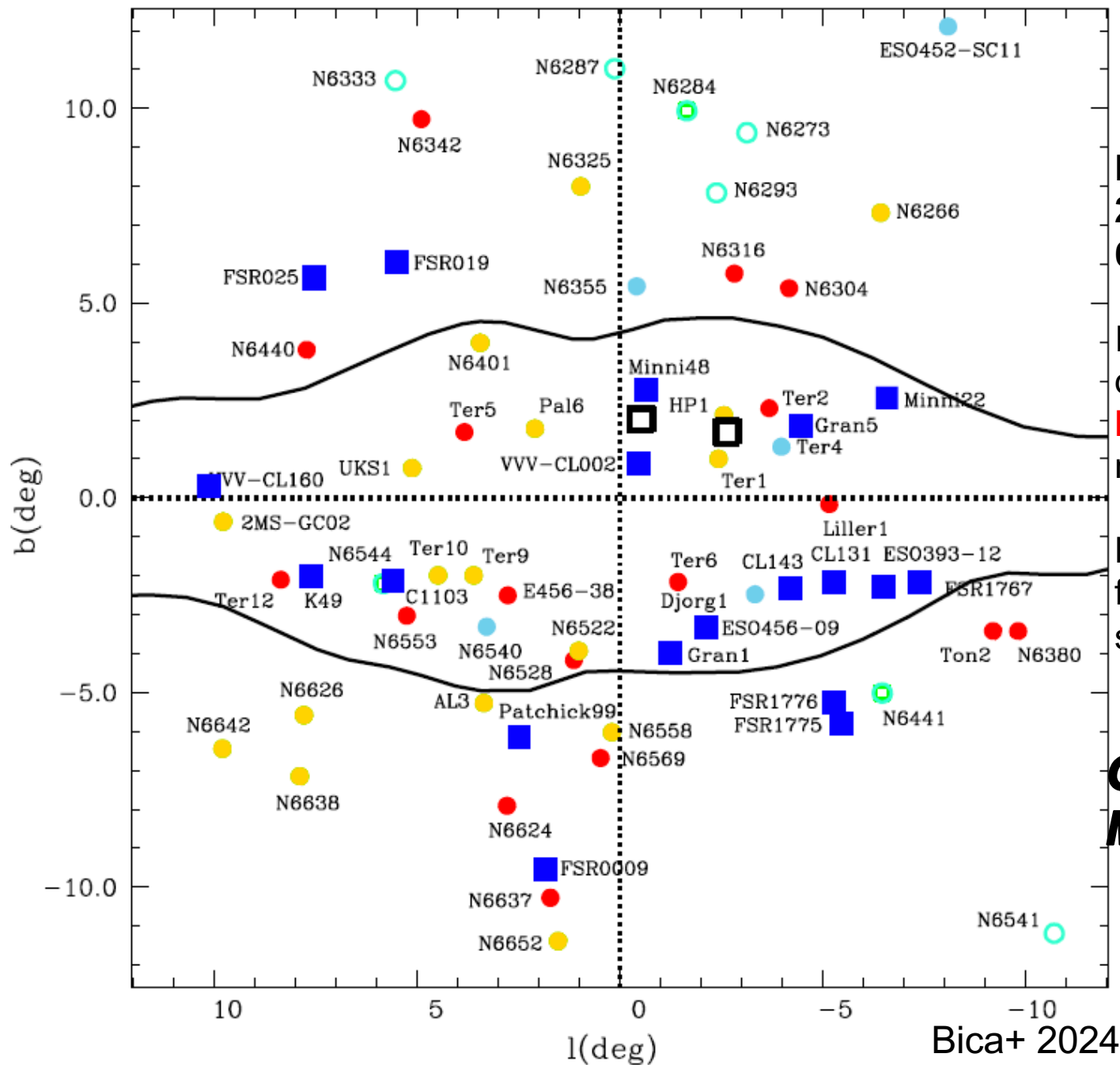


Trace merger history of halo  
Study formation and chemical  
evolution of Main Progenitor (MP)



**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



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

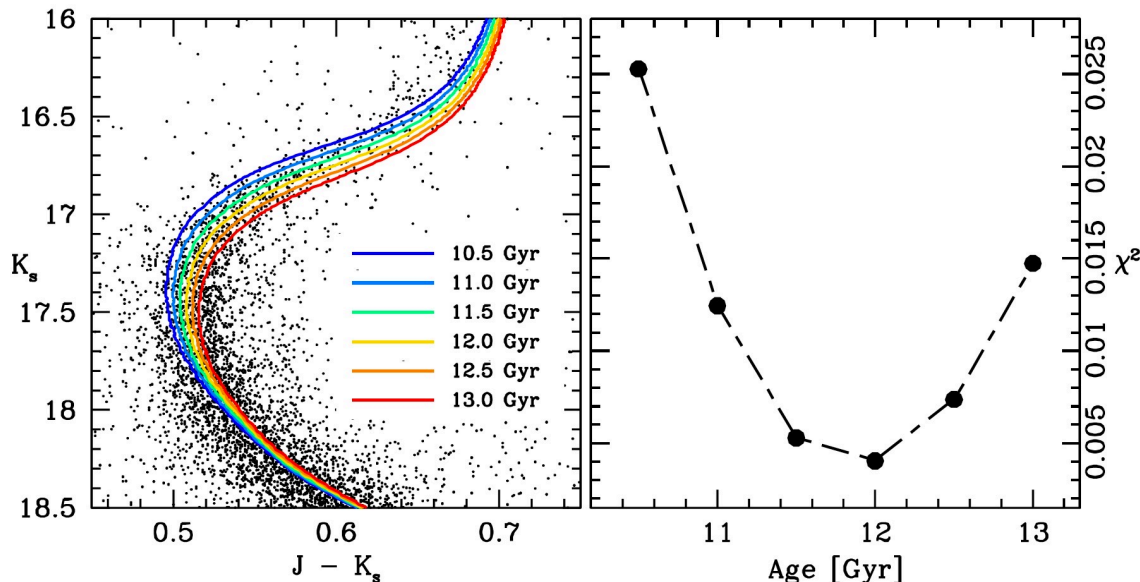
In situ but poorly studied  
 due to dust – require  
**IR observations** –  
 not possible until now.

Need deep photometry  
 for isochrone fitting and  
 spectra for abundances

***Oldest object(s) in  
 MP with good ages***

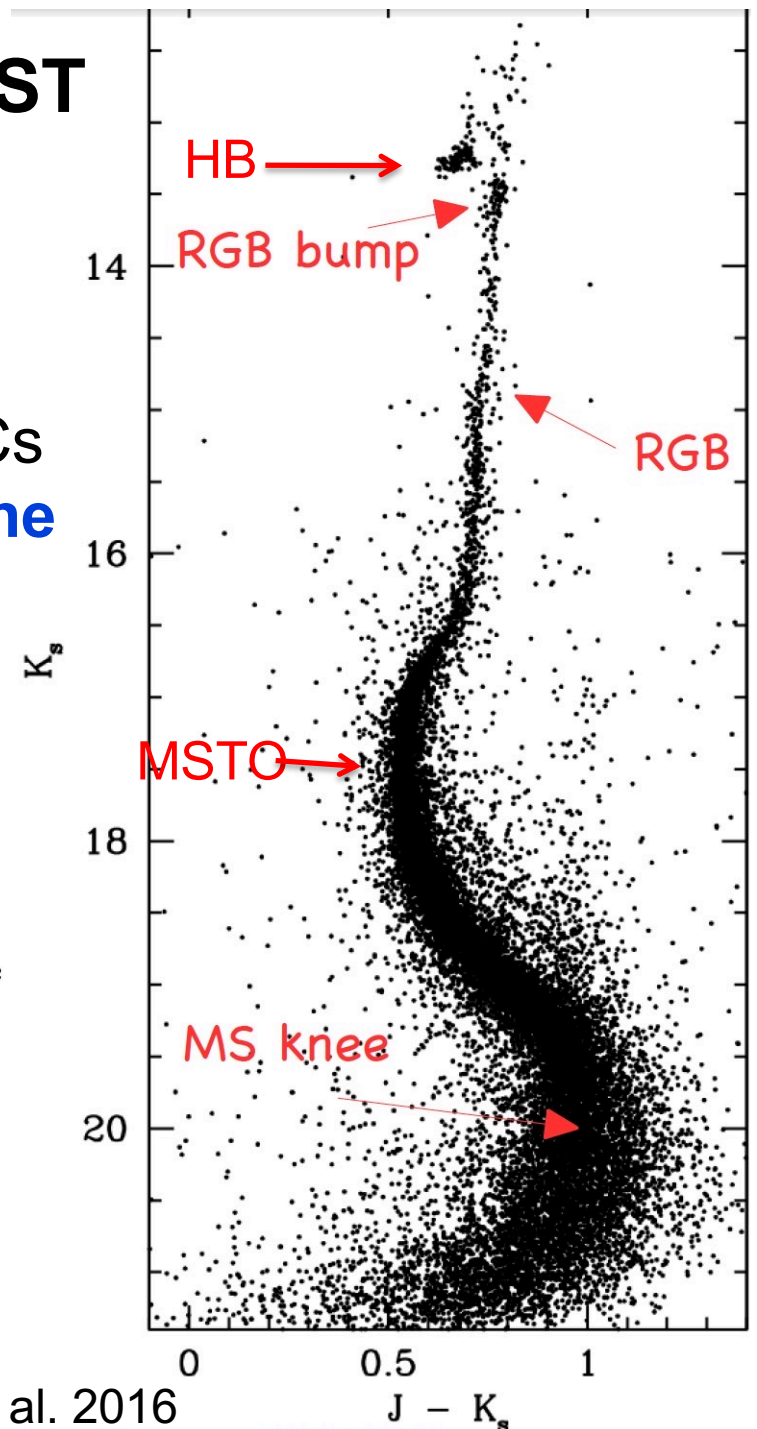
# Deep NIR photometry – GeMS/HST

- 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...



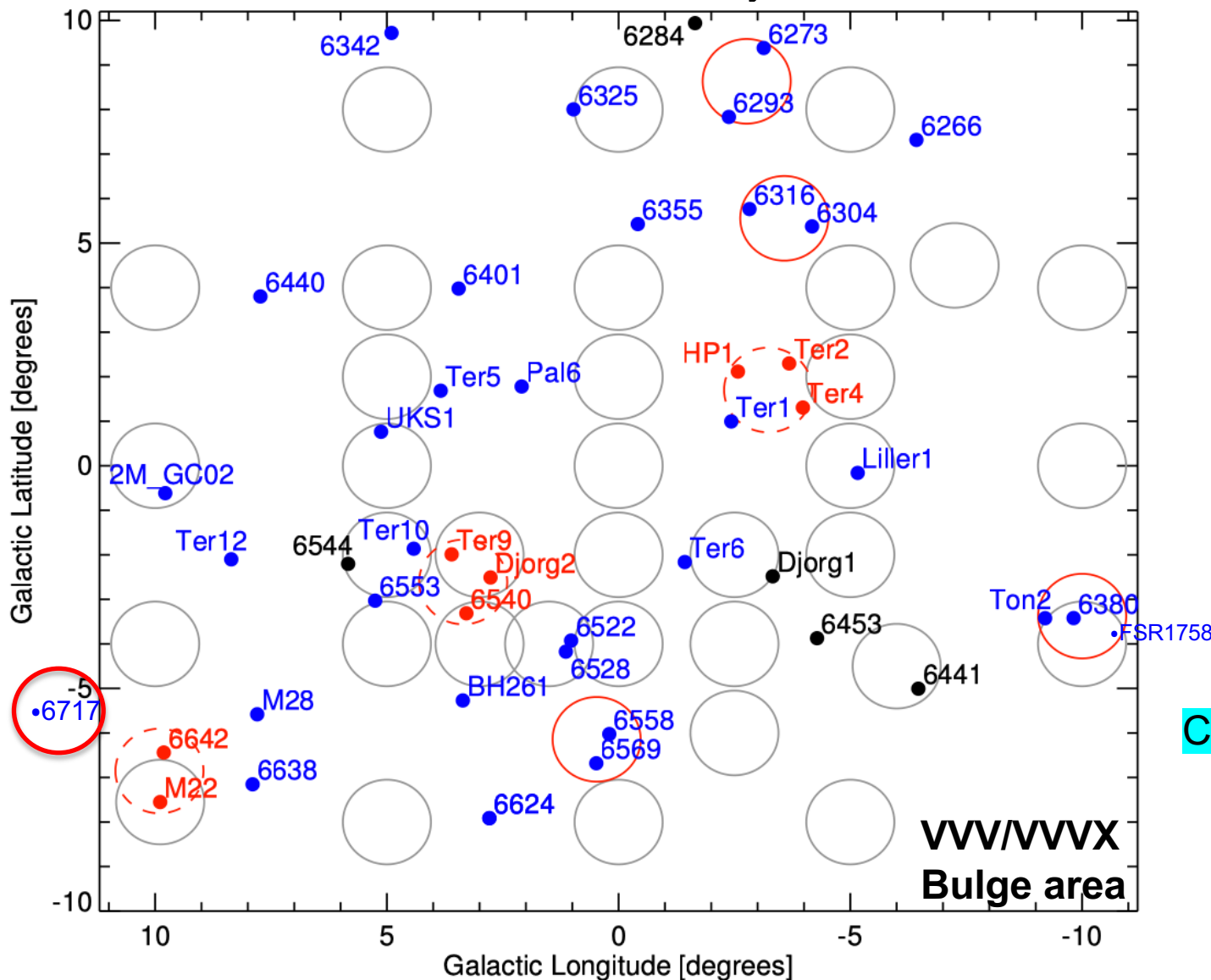
**$12.0 \pm 0.5$  Gyr (5%!)**

Saracino et al. 2016



# CAPOS: *the bulge Cluster APOgee Survey*

Good abundances for many B/D GCs!



## BGCs ( $R_{GC} < 3.5 \text{ kpc}$ )

## 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 <sup>a</sup>	PV 20 <sup>b</sup>	C22 <sup>c</sup>	BK23 <sup>d</sup>	CG24 <sup>e</sup>	[Mg/Mn] vs. [Al/Fe] <sup>f</sup>	Final Classification <sup>g</sup>
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?

<sup>a</sup> Massari et al. (2019). LE = Low Energy, MB = Main Bulge, Seq = Sequoia, MD = Main Disk.

<sup>b</sup> Perez-Villegas et al. (2020). TD = Thick Disk, B/B = Bulge/Bar, OH = Outer Halo.

<sup>c</sup> Callingham et al. (2022). Kra = Kraken, B = Bulge, D = Disk, Ungr = Ungrouped, Seq = Sequoia, GE = Gaia Enceladus.

<sup>d</sup> Belokurov & Kravtsov (2023). 1 = in-situ, 0 = accreted.

<sup>e</sup> Chen & Gnedin (2024). 1 = in-situ, 0 = accreted.

<sup>f</sup> Our assessment from [Mg/Mn] vs. [Al/Fe]. 1 = in-situ, 0 = accreted.

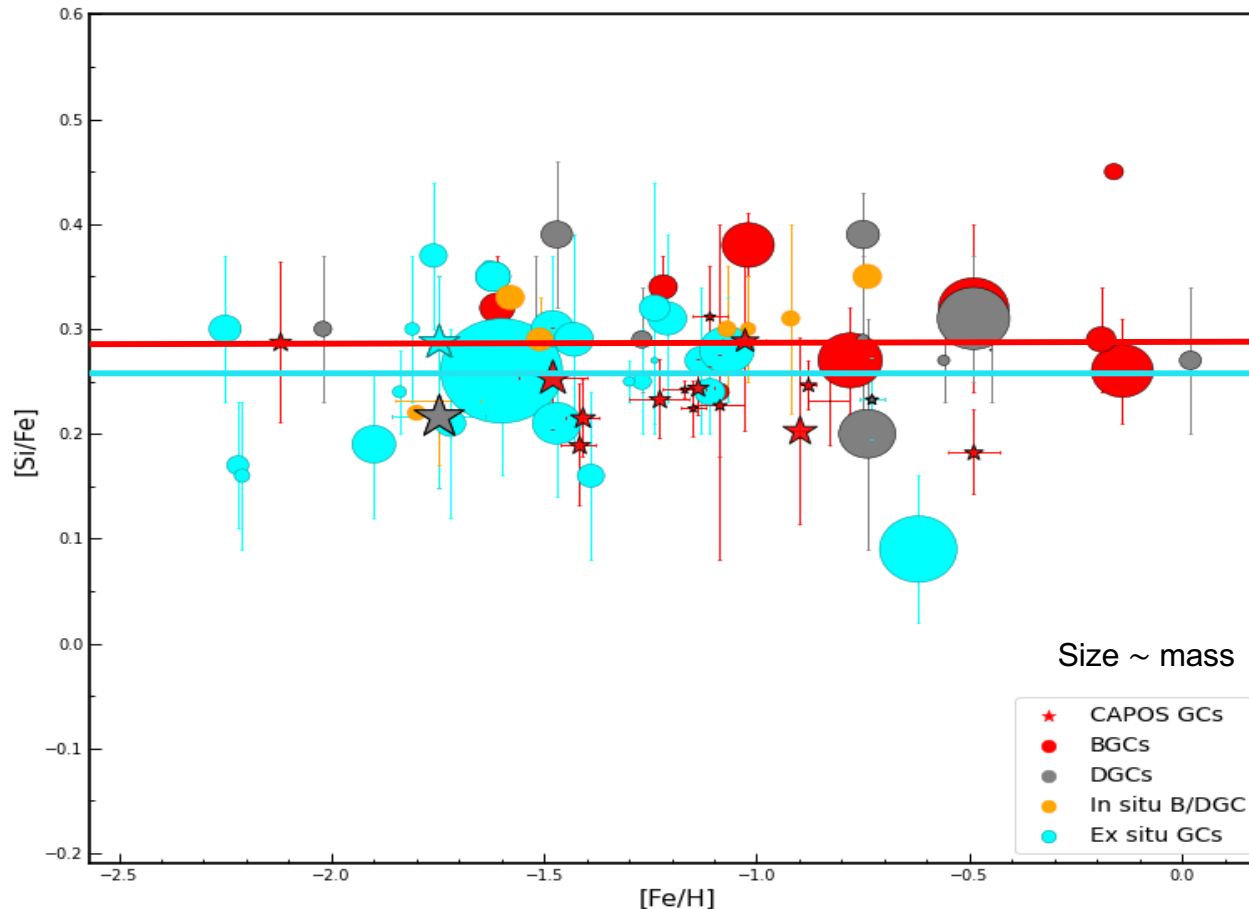
<sup>g</sup> Our final classification: 1B = in-situ bulge, 1D = in-situ disk, 0 = accreted.

Geisler+ 2024

# Chemodynamics of in situ vs. accreted GCs

## 1. $[\alpha/\text{Fe}]$ vs. $[\text{Fe}/\text{H}]$ – SFR/chemical evolution history

CAPOS extends BGCs to lower metallicity



In situ (B and D)  
Accreted

In situ:  $0.28 \pm 0.06$  (44)  
Ex situ:  $0.26 \pm 0.07$  (27)

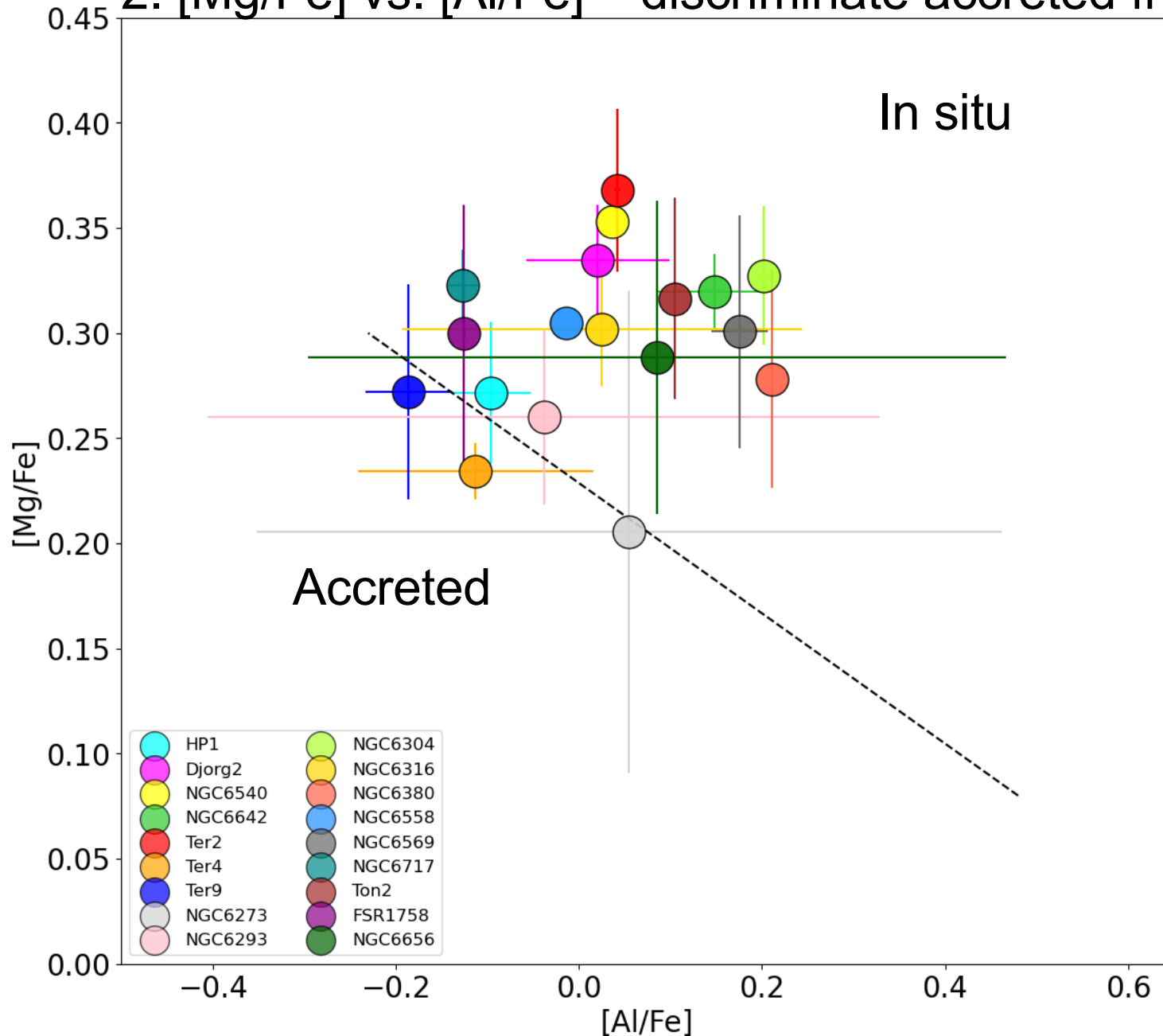
Geisler+ 2024

Very similar  $[\alpha/\text{Fe}]$  at similar  $[\text{Fe}/\text{H}] \rightarrow$

**Similar SFR/chem evol. in deeper potential well of in situ B/D GCs vs accreted!?**

# Chemodynamics of in situ vs. accreted GCs

## 2. $[\text{Mg}/\text{Fe}]$ vs. $[\text{Al}/\text{Fe}]$ – discriminate accreted from in situ



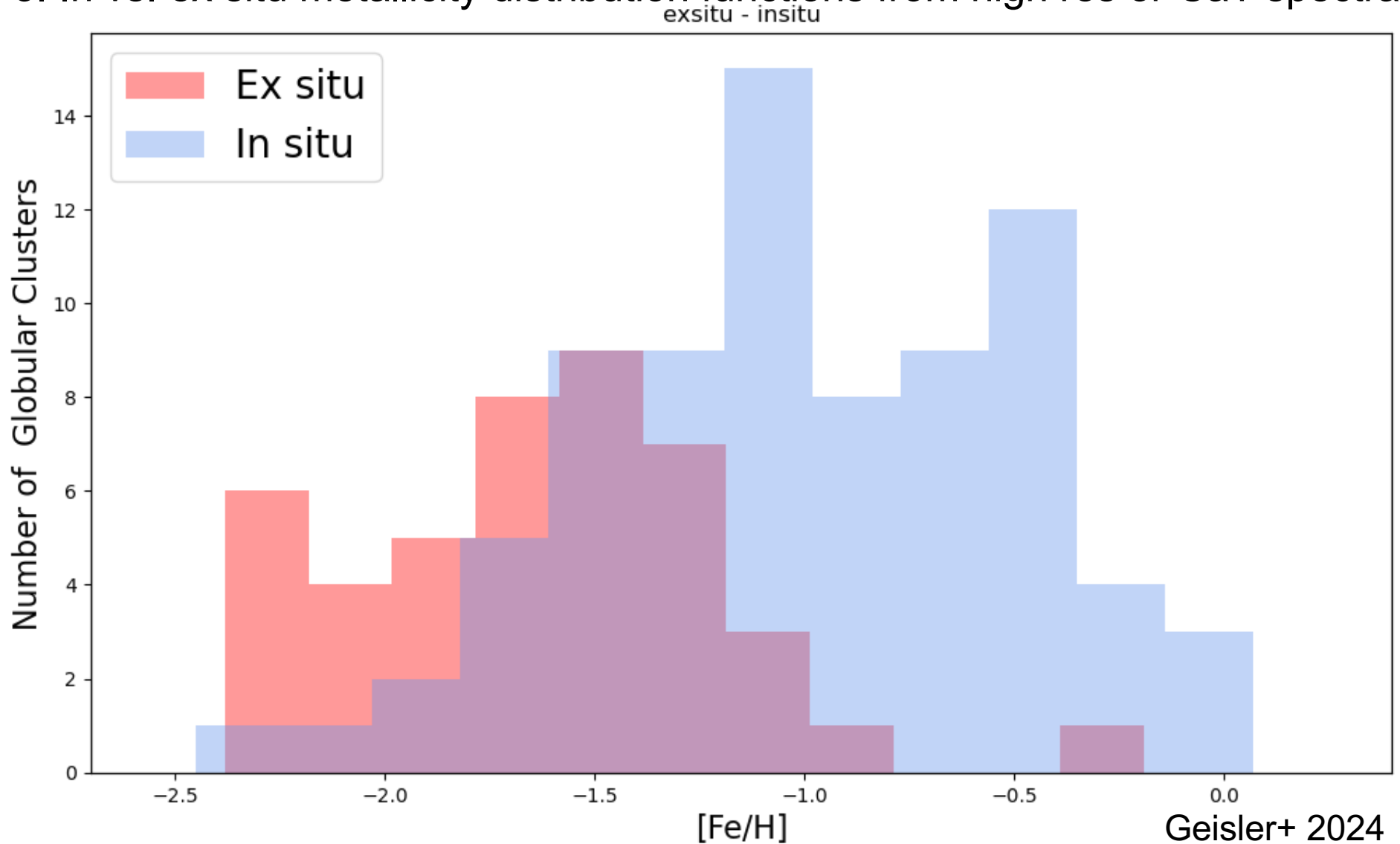
Belokurov+24:  
Nice separation  
between in and ex  
situ in  $[\text{Mg}/\text{Fe}]$  vs.  
 $[\text{Al}/\text{Fe}]$ .

**CAPOS GCs:**  
**Most are in situ**

Geisler+ 2024

# Chemodynamics of in situ vs. accreted GCs

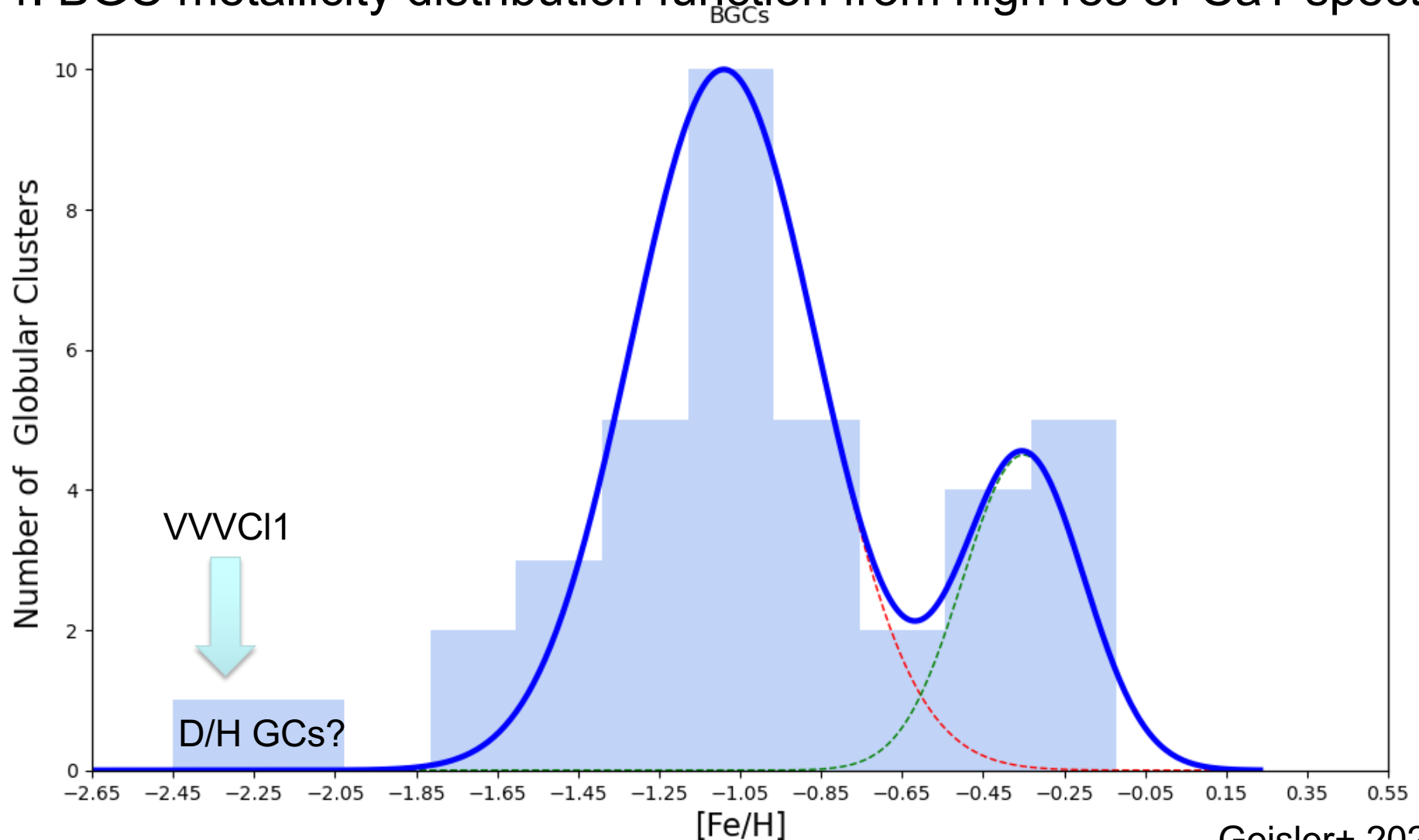
## 3. In vs. ex situ metallicity distribution functions from high res or CaT spectra



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

# Chemodynamics of in situ vs. accreted GCs

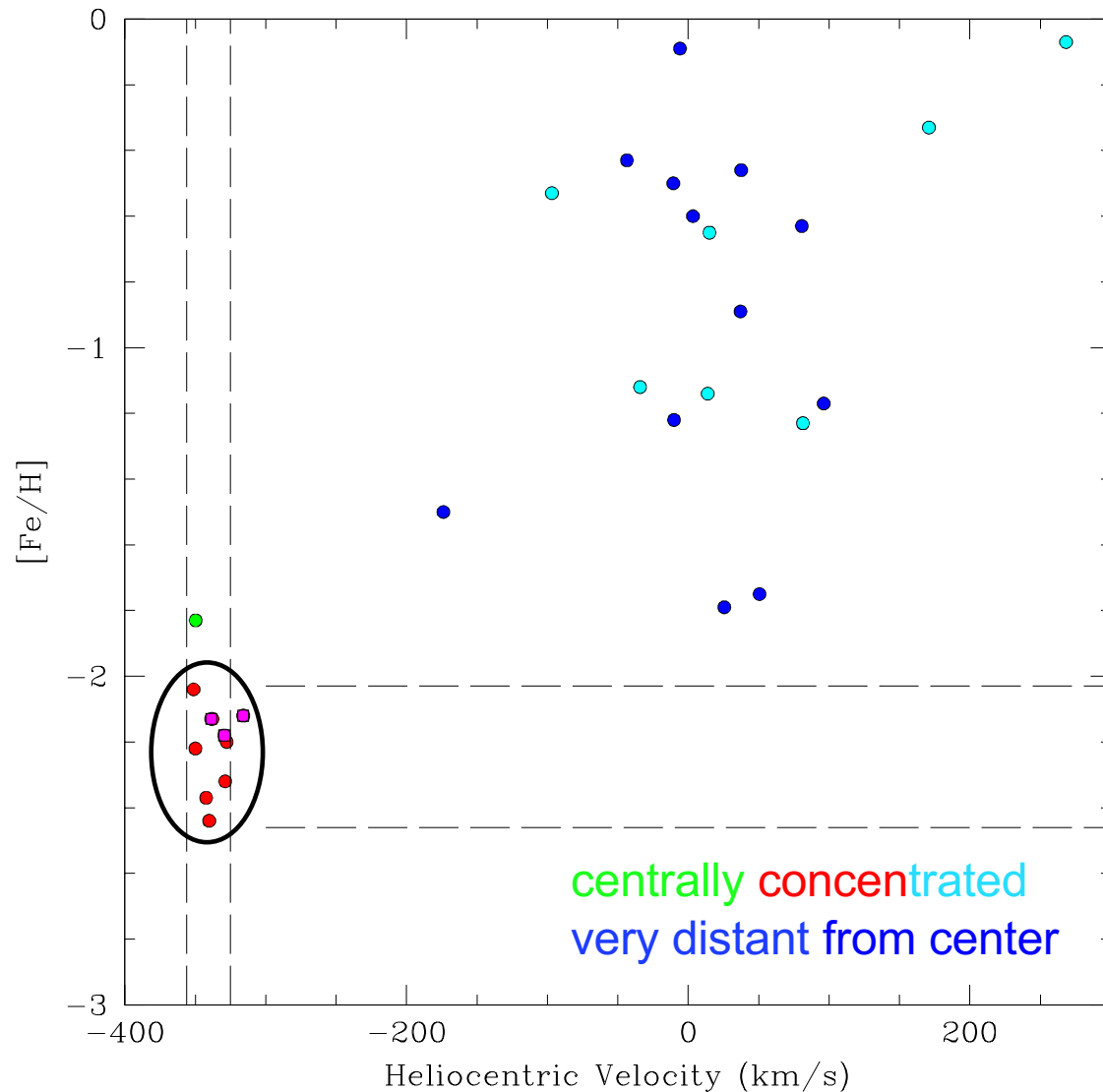
## 4. BGC metallicity distribution function from high res or CaT spectra



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?

# VVCI1: VLT CaT metallicities & velocities



$$\langle [\text{Fe}/\text{H}] \rangle = -2.25 \pm 0.05$$

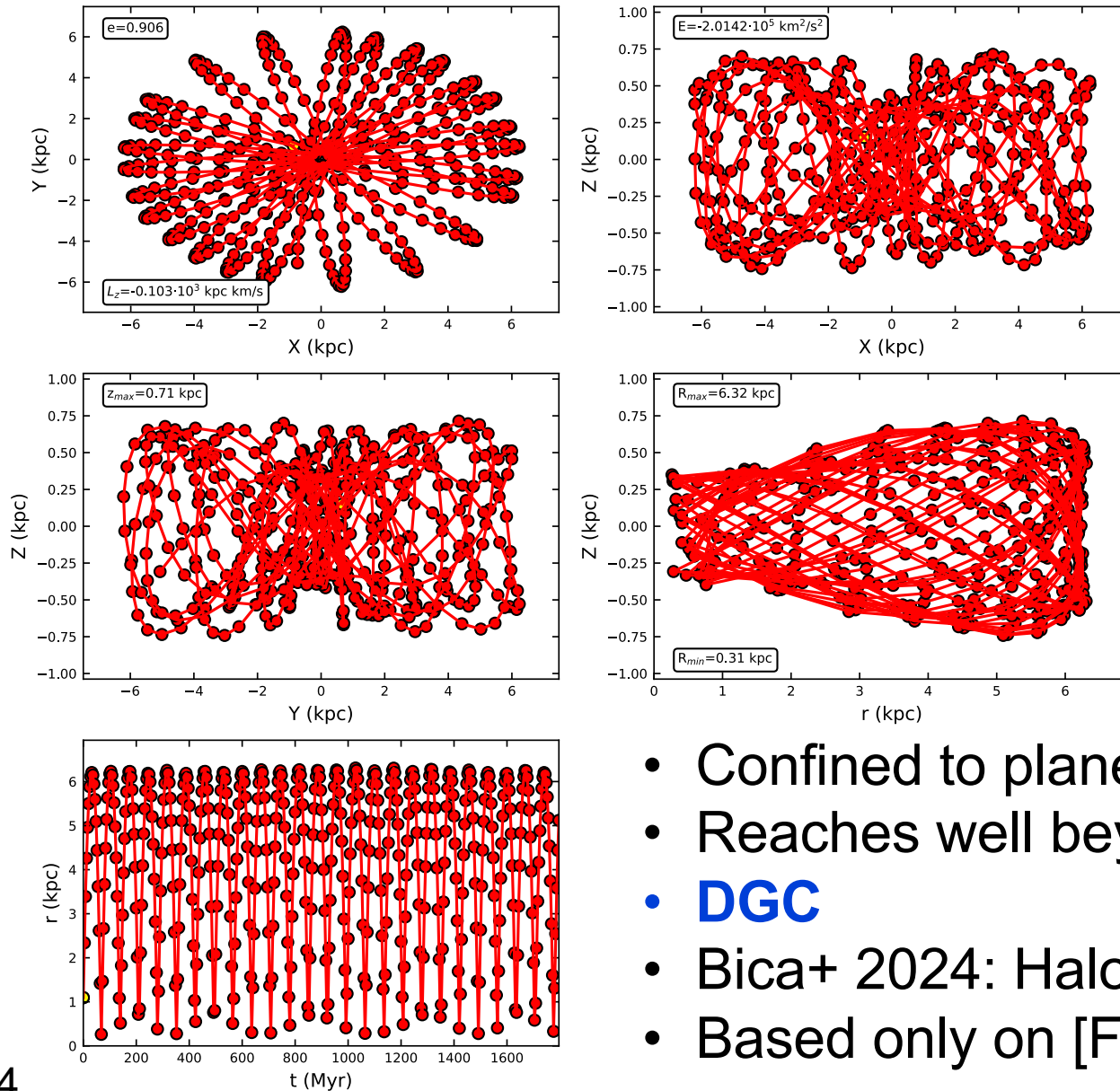
(2 APOGEE stars:  $-2.45 \pm 0.24$   
Fernandez-Trincado+ 2021)

$$\langle v_r \rangle = -339.7 \pm 3.5 \text{ km/s}$$

**EXTREME values!**

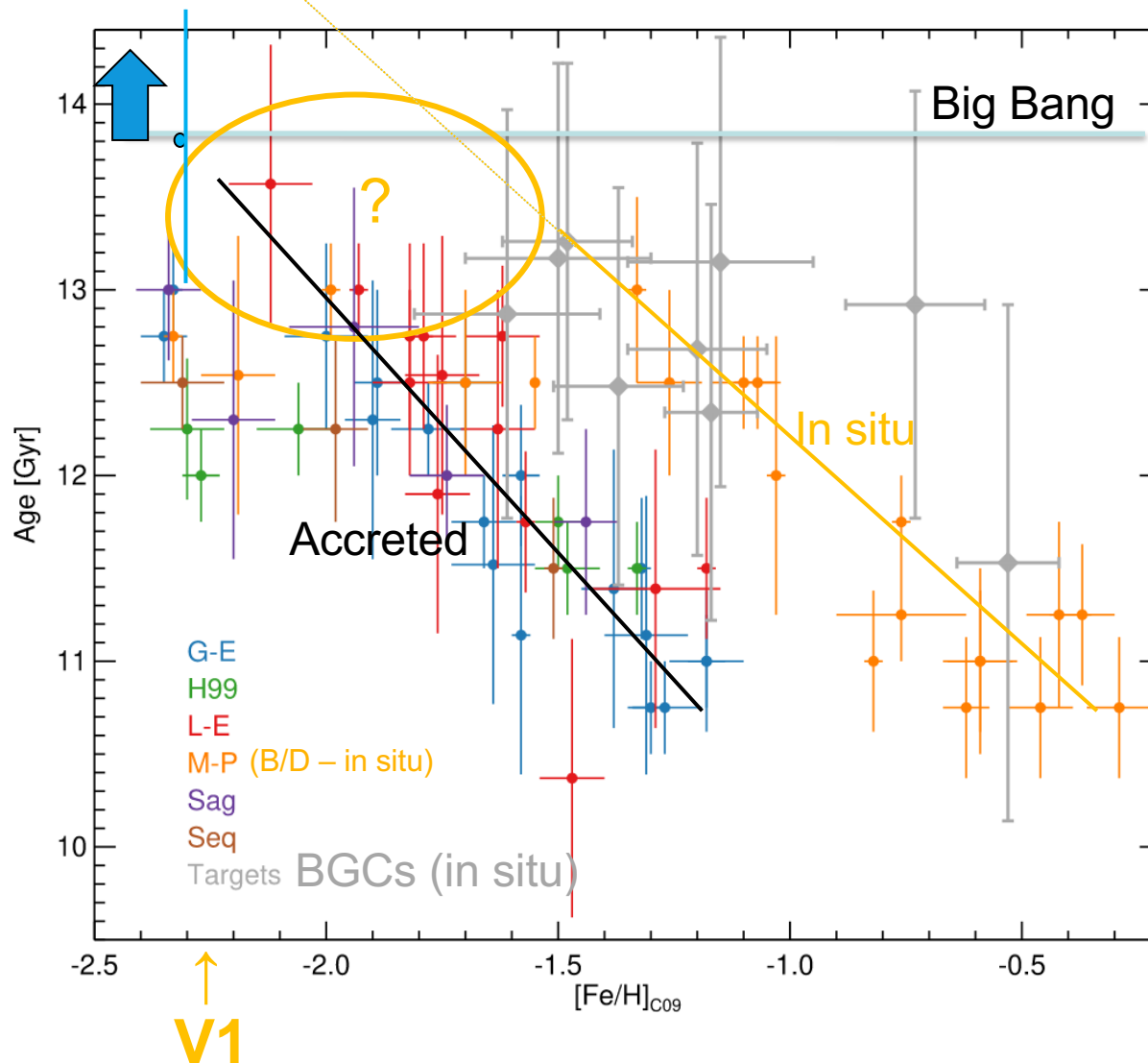
Haro+ 2024

# VVCI1 Preliminary orbit



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

## V1? GC age:metallicity relations



Cohen+ 2021

VVVC11 most metal-poor (?) in situ GC - great candidate for **oldest object in MP for which we can derive good age!**

# ***Conclusions***

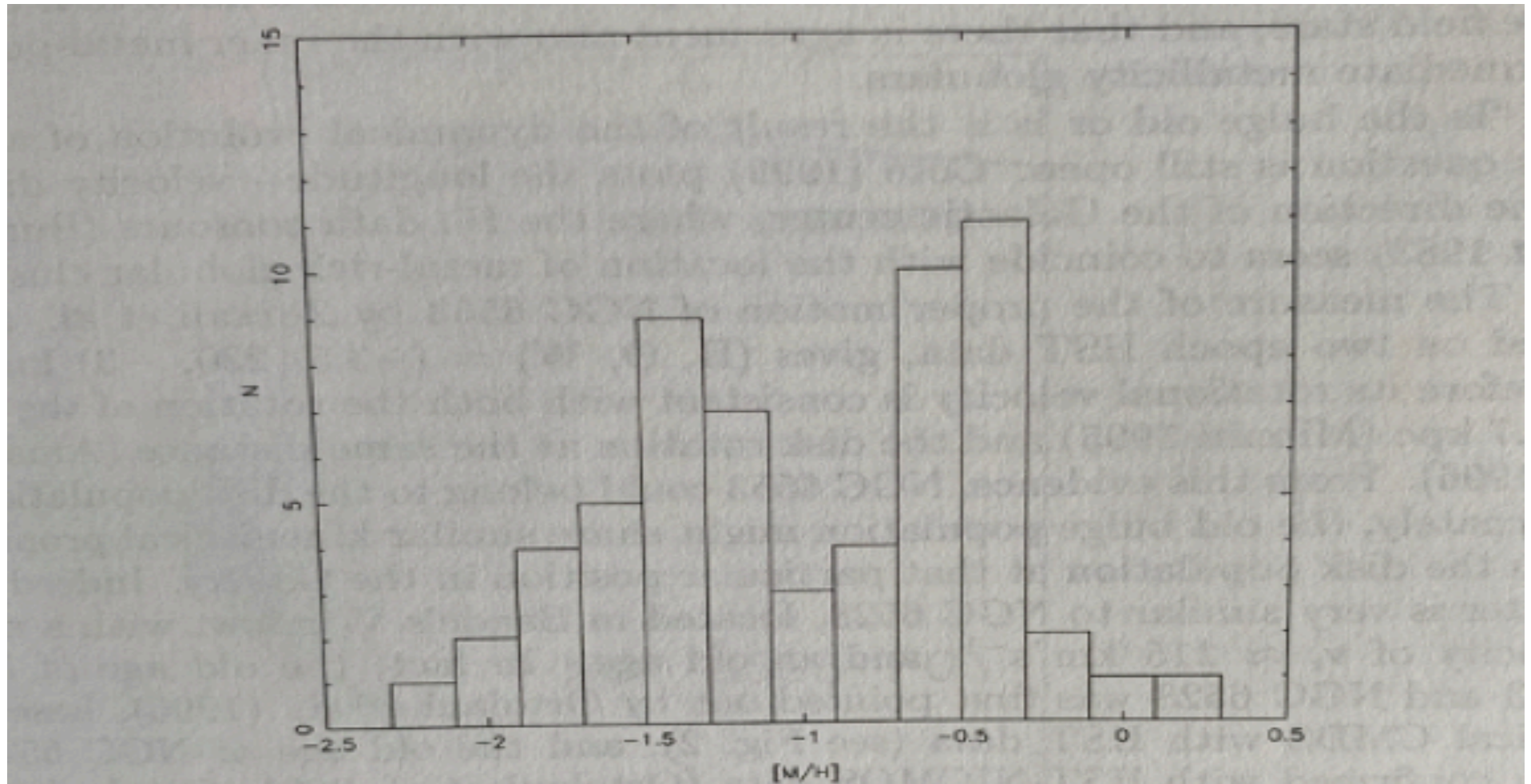


**Need deep GeMS  
data for VVCI1!**

**Happy birthday  
Beatriz!**

## Chemodynamics of in situ vs. accreted GCs

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



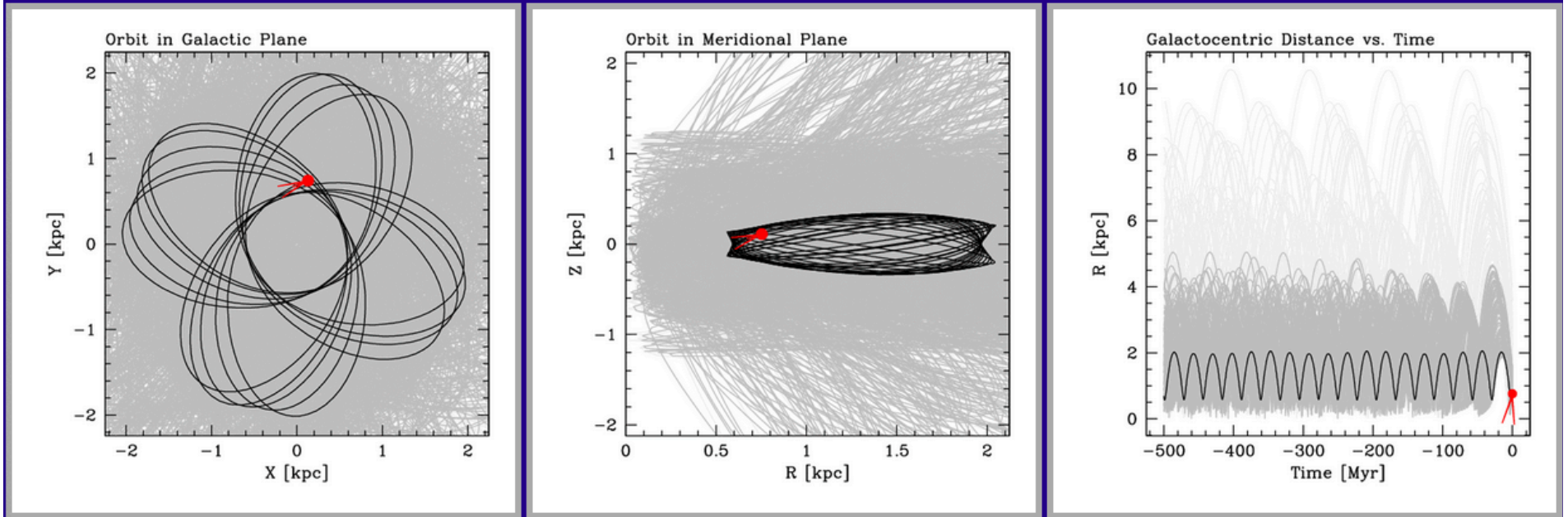
**Bimodal, dominated by -0.5 group, smaller peak -1.4**

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

Barbuy+ 2001

# VVCI1 orbit

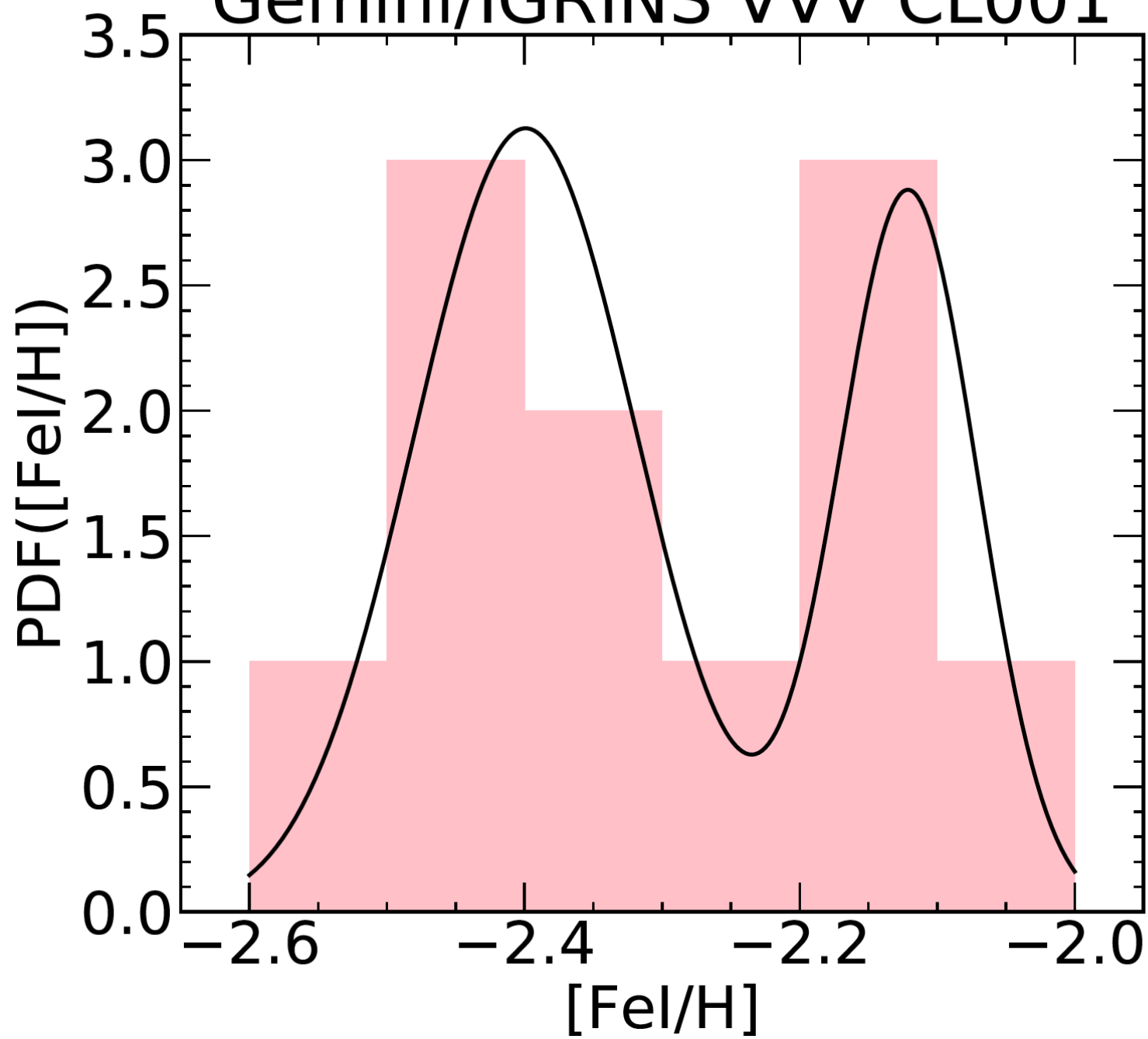
Orbit over the last 500 Myr



Baumgardt database

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

# Gemini/IGRINS VVV CL001

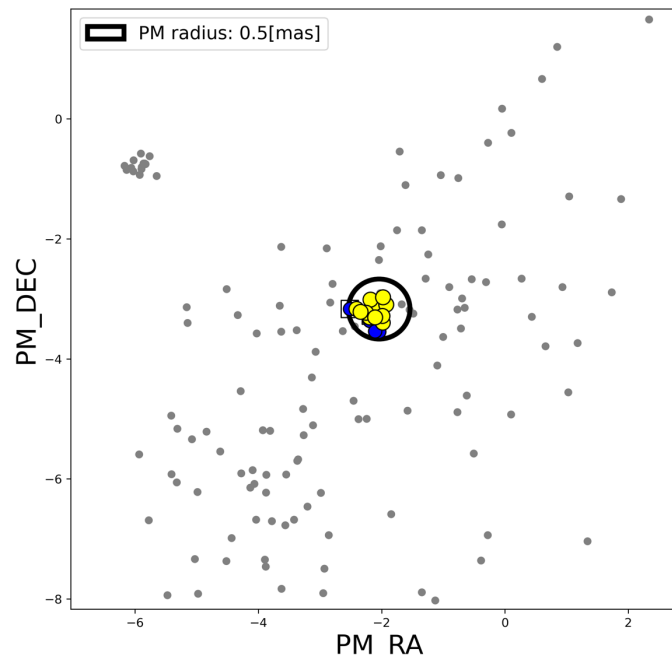
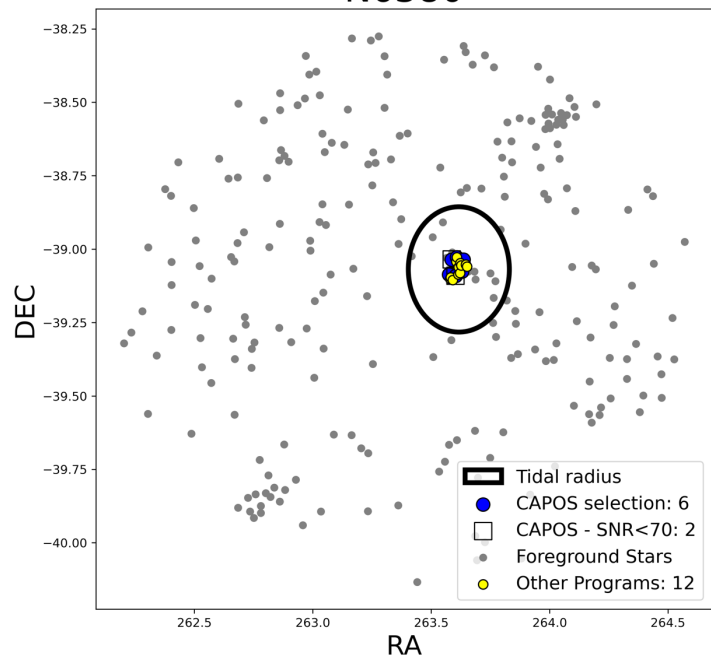


VVCI1 MDF  
11 IGRINS stars

Haro+ 2024

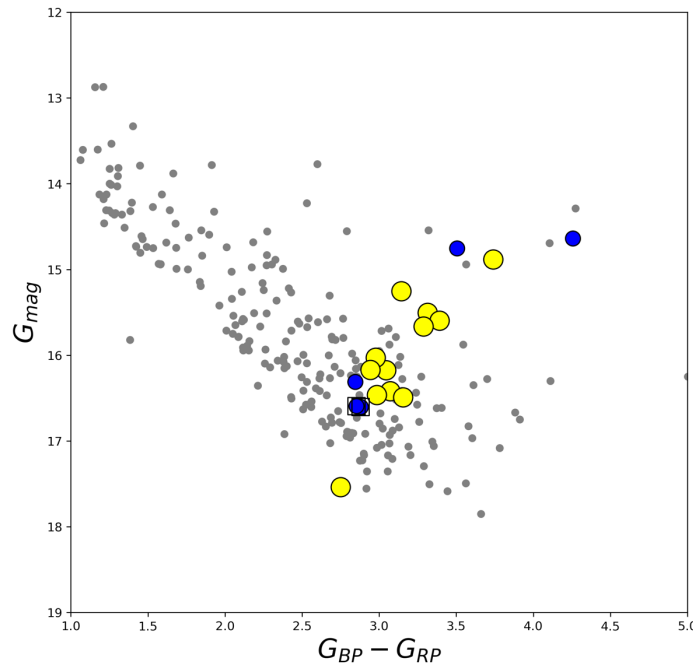
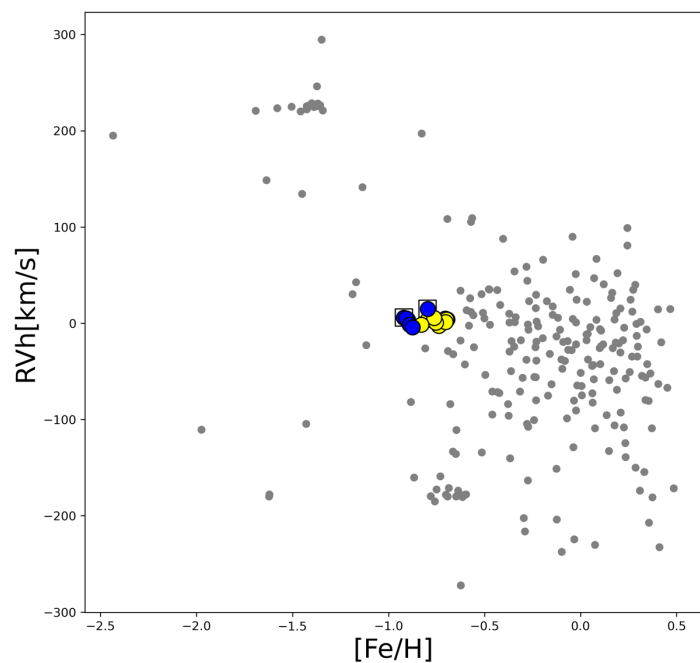


N6380



## 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 assignments 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 Freliij 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 Freliij? Scarlet Ortega UdeC PhD thesis

**2 Masters thesis completed, 3 in progress**

**1 PhD thesis completed, 4 in progress**

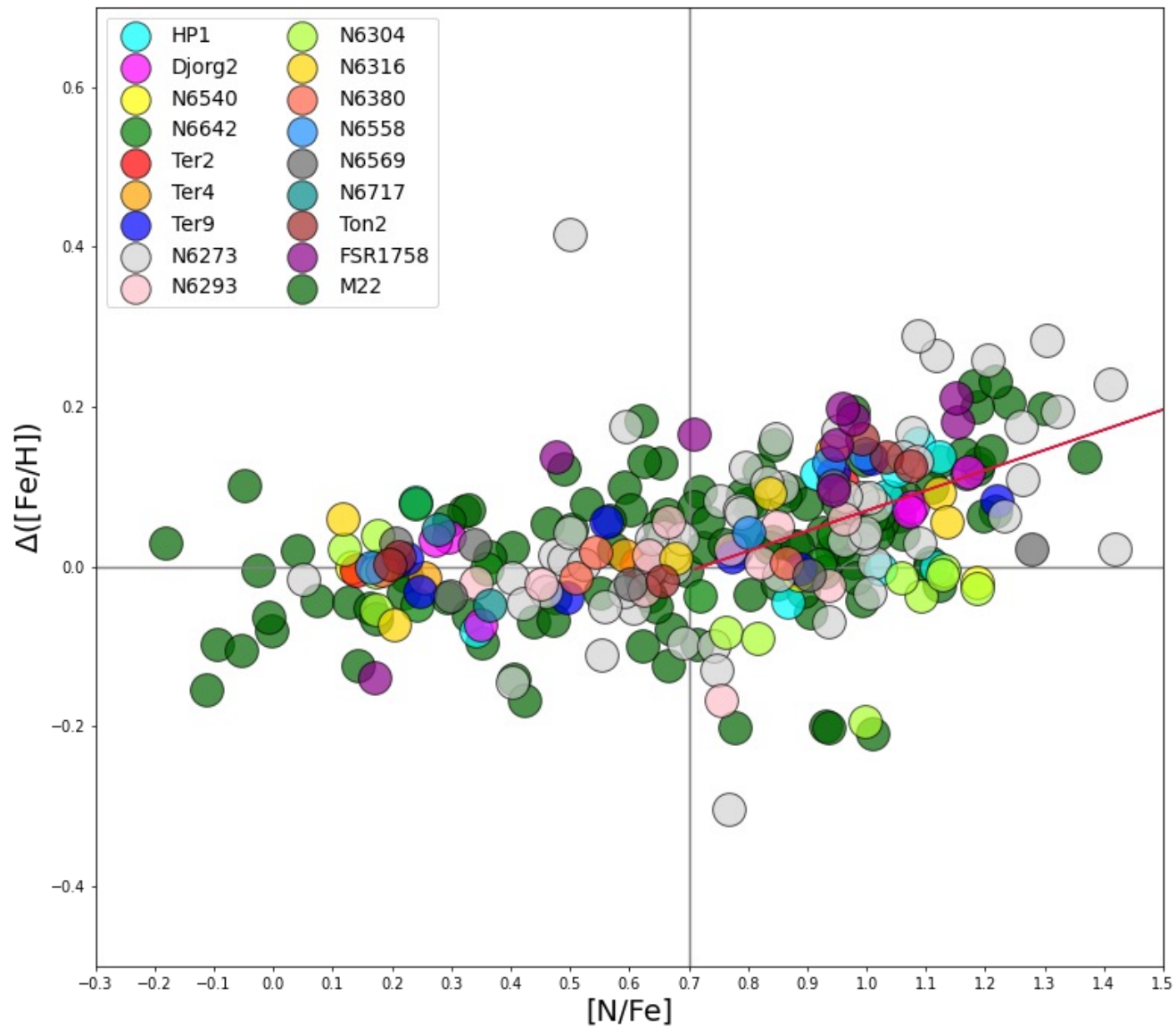
# Final CAPOS Sample (ASPCAP)

**Table 3.** Mean cluster metallicity,  $[\alpha/\text{Fe}]$  and radial velocity for members.

Geisler+ 2024

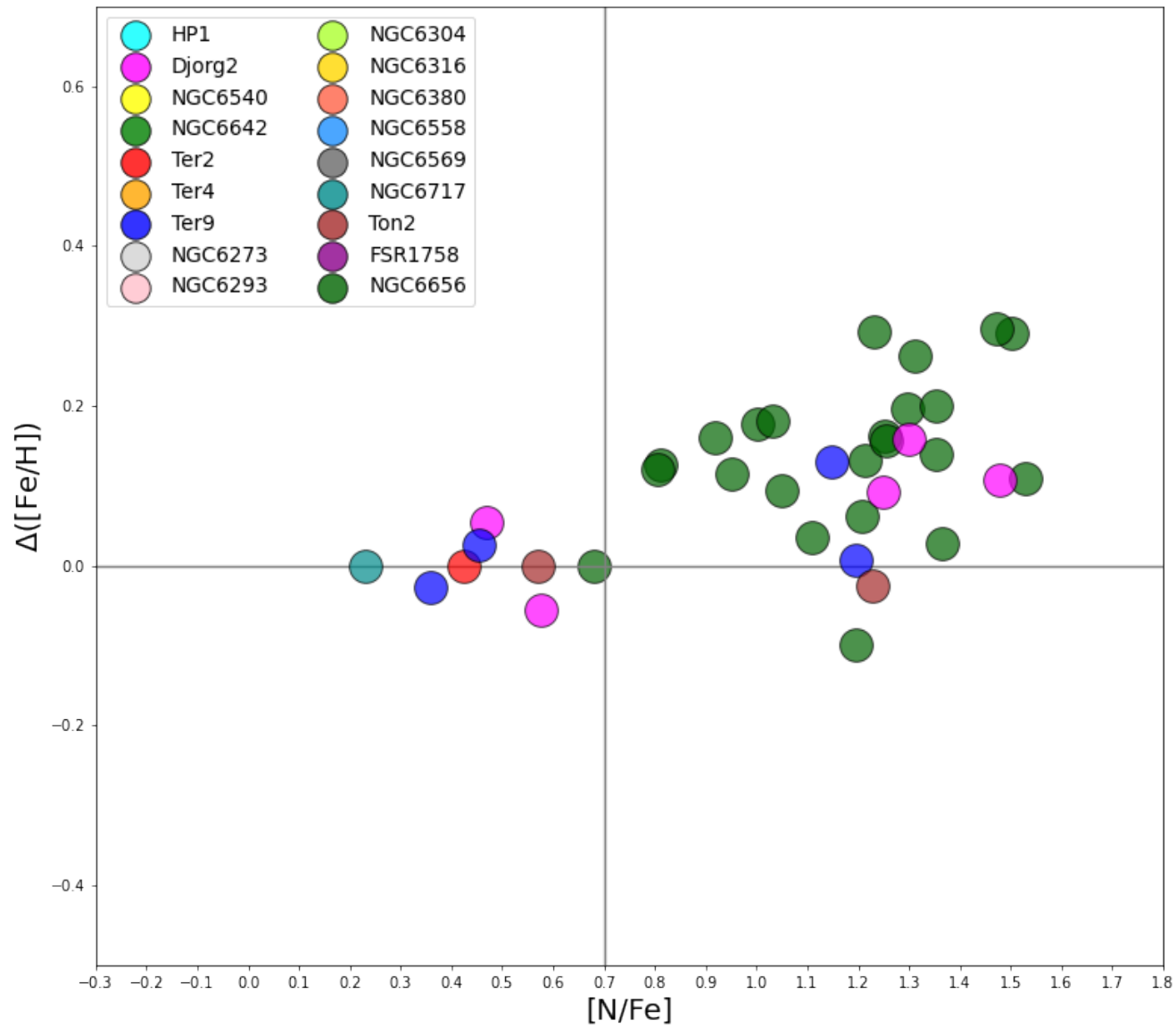
Cluster ID	$[\text{Fe}/\text{H}]^{\text{a}}$ (dex)	$[\alpha/\text{Fe}]^{\text{a}}$ (dex)	$V_r^{\text{a}}$ ( $\text{km s}^{-1}$ )	$N_{\text{members}}$	$N_{1G}$
NGC 6273	$-1.75 \pm 0.11$	$0.20 \pm 0.10$	$144.8 \pm 7.6$	62	23
NGC 6293	$-2.12 \pm 0.08$	$0.26 \pm 0.08$	$-144.1 \pm 5.8$	13	5
NGC 6304	$-0.49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

# ASPCAP

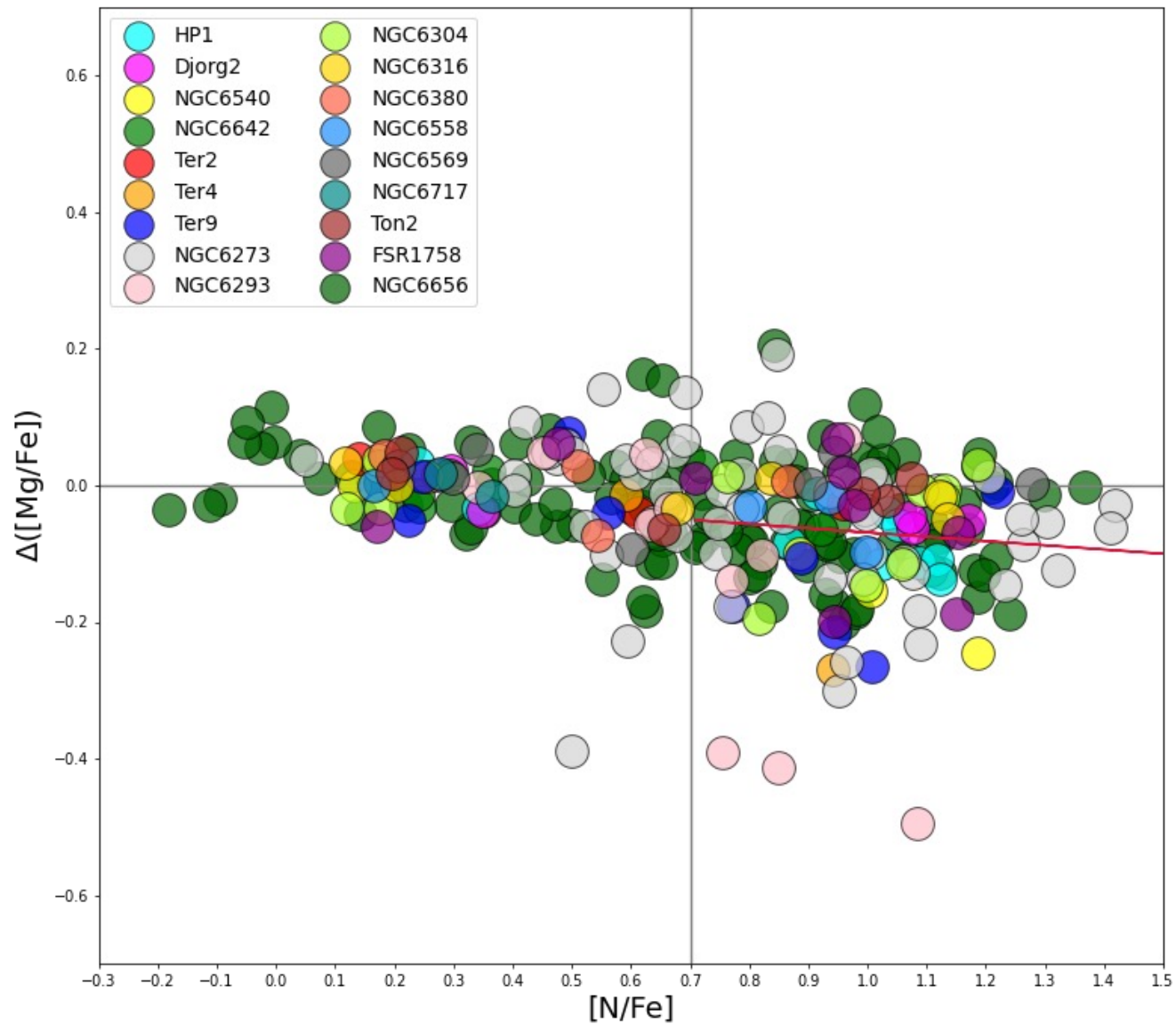


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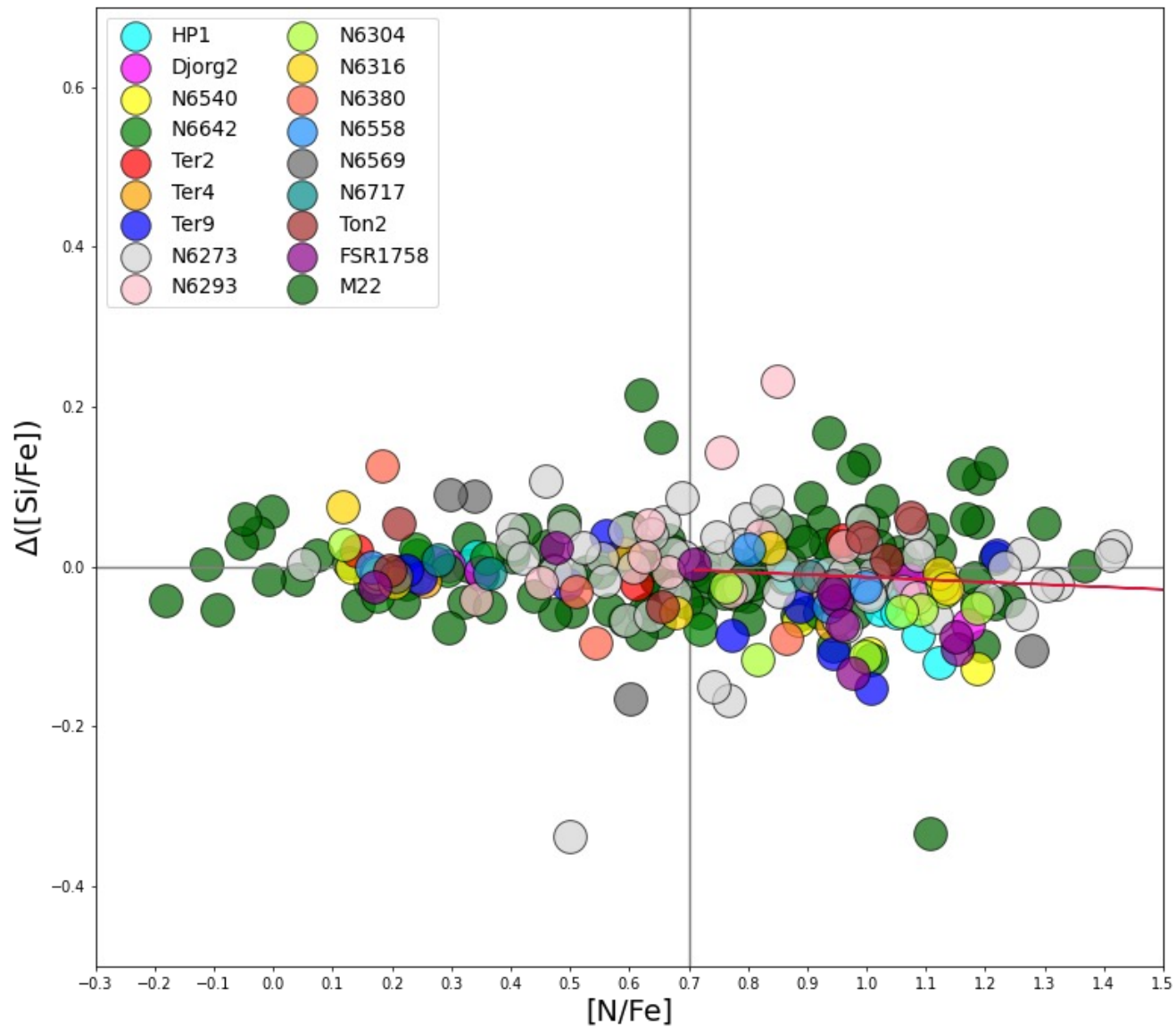
# BAWLAS



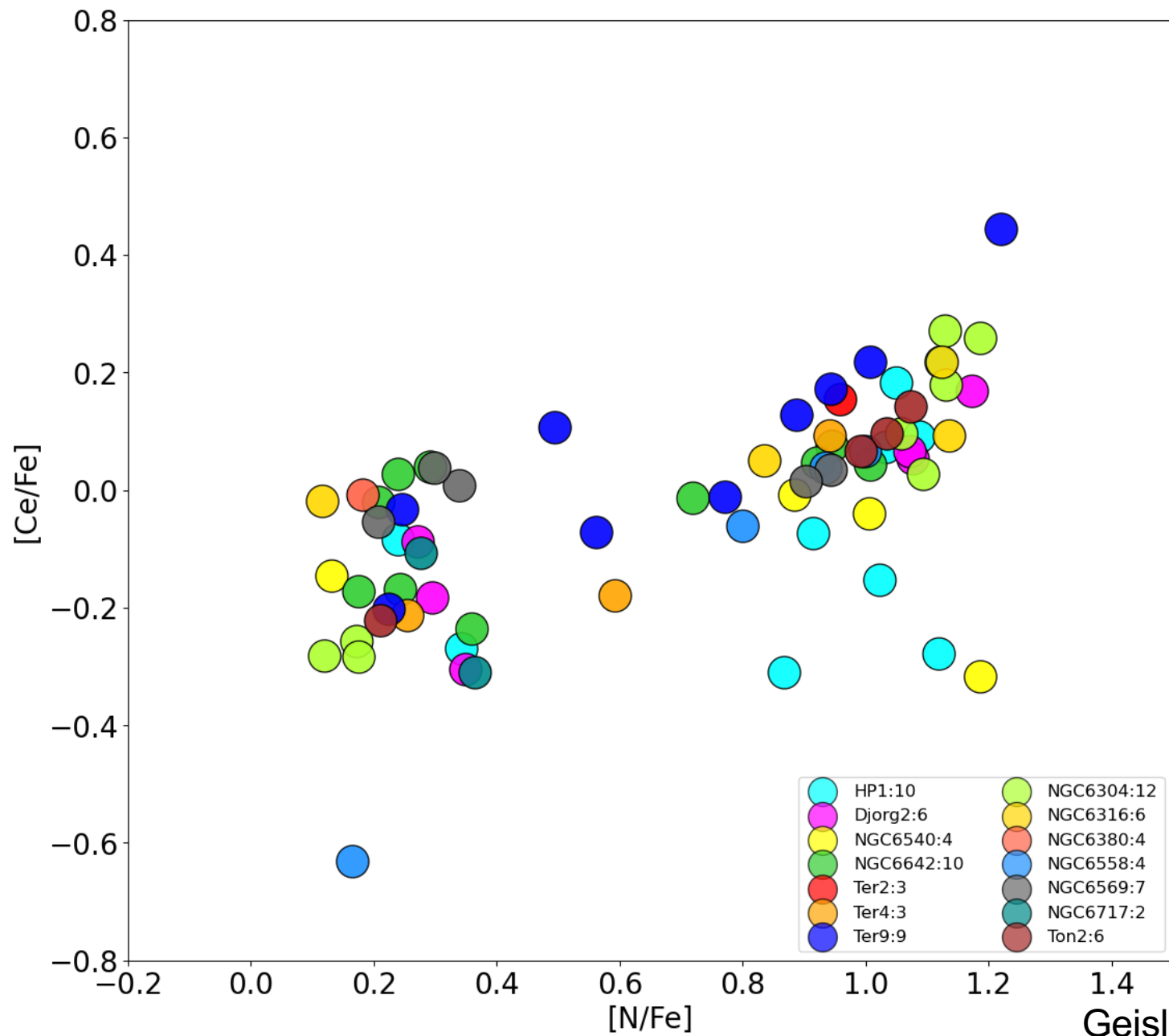
# ASPCAP



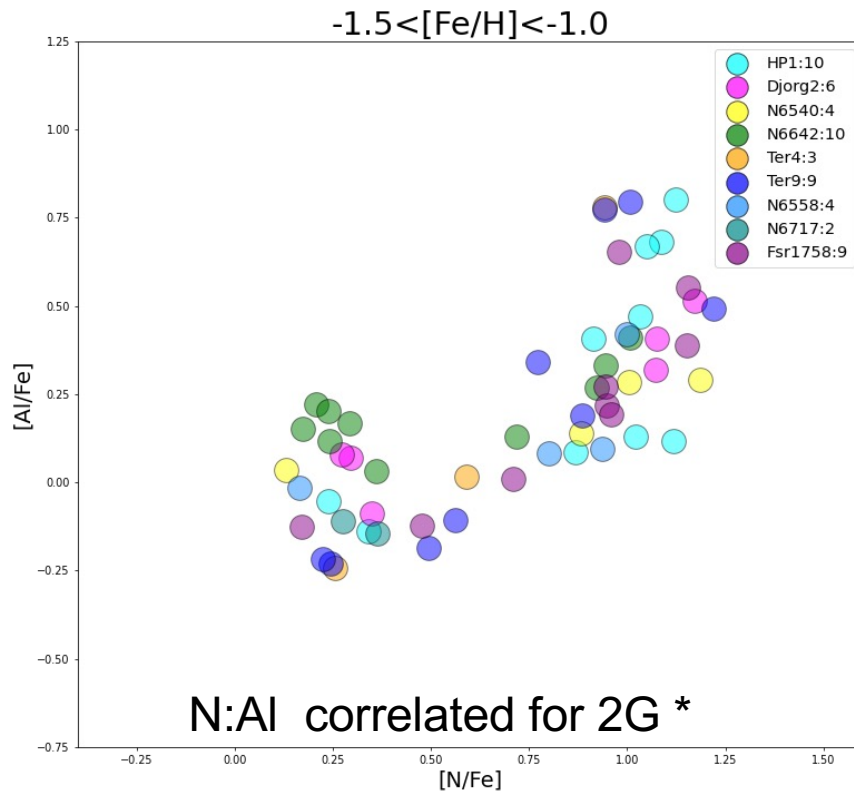
# ASPCAP



# ASPCAP



# Multiple populations in 9 intermediate-metallicity B/D GCs



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

