THE GALACTIC BULGE

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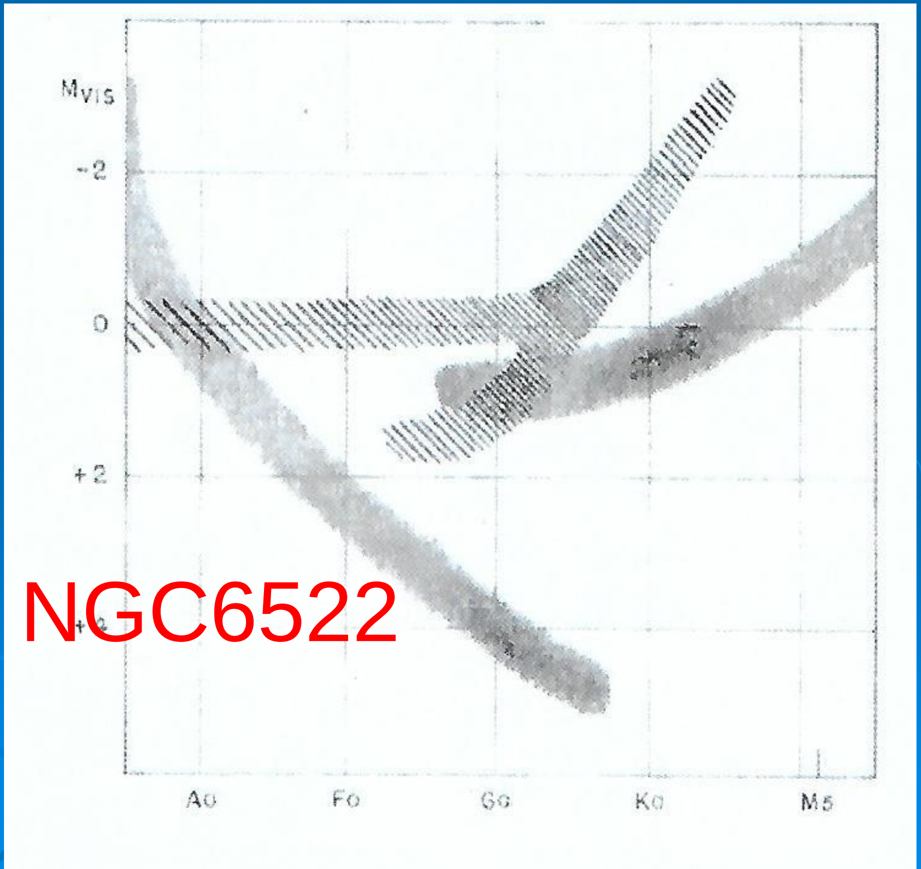
OUTLINE

- History along our lifetime
- First structures, Bulge formation
- Accretion: in-situ, ex-situ:AMR
- Bulge globular clusters
- Metallicity Distribution Function
- Abundances, Chemical evolution
- Conclusions, Challenges

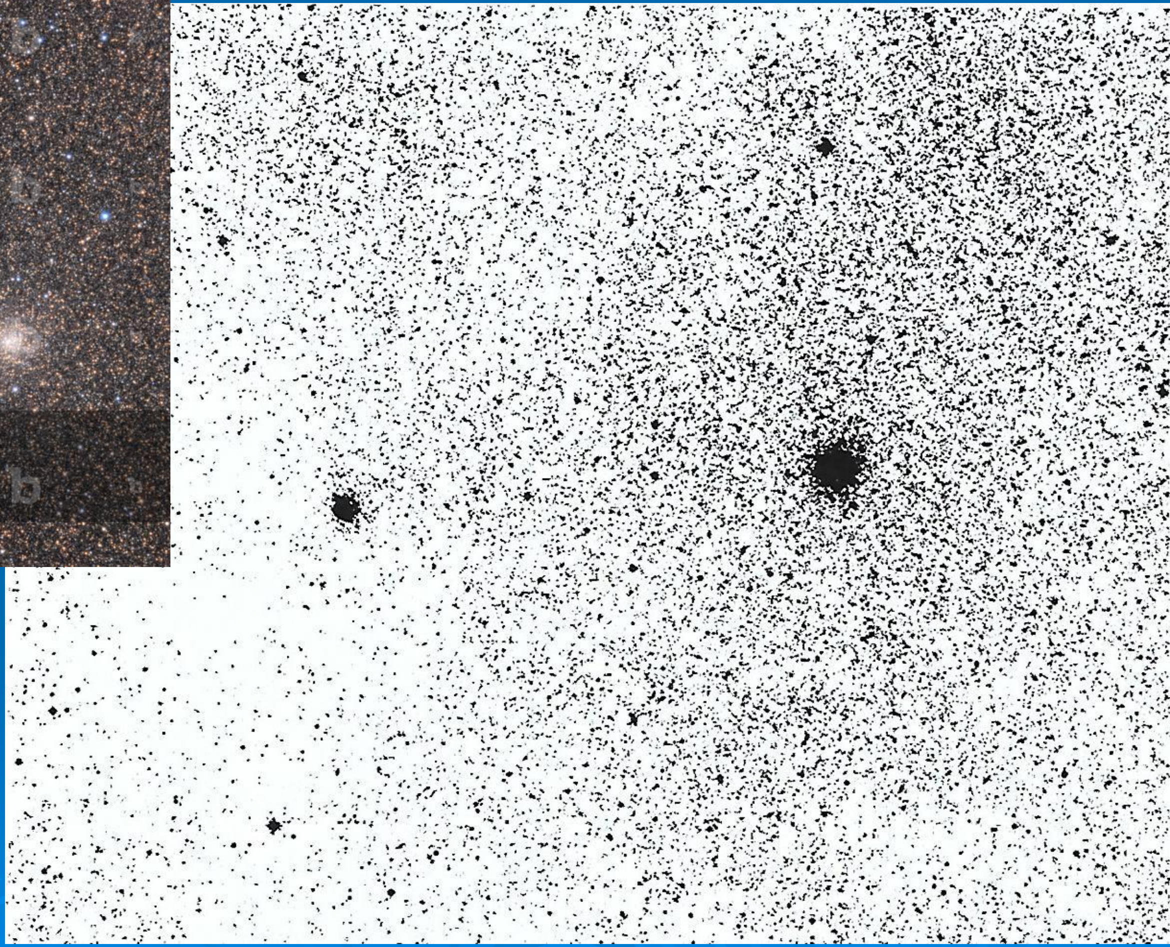
HISTORY: First studies on the Bulge

Baade 1944 a,b =ApJ, 100, 137,147
Direction of NGC 6522 = bulge has Pop. II

Baade's hypothesis:
nuclear bulge of the Galaxy consisting of globular cluster-like stellar population



Nassau+Blanco 1958,Van den Bergh 1972
Bulge dominated by metal-rich M stars



N6528-N6522

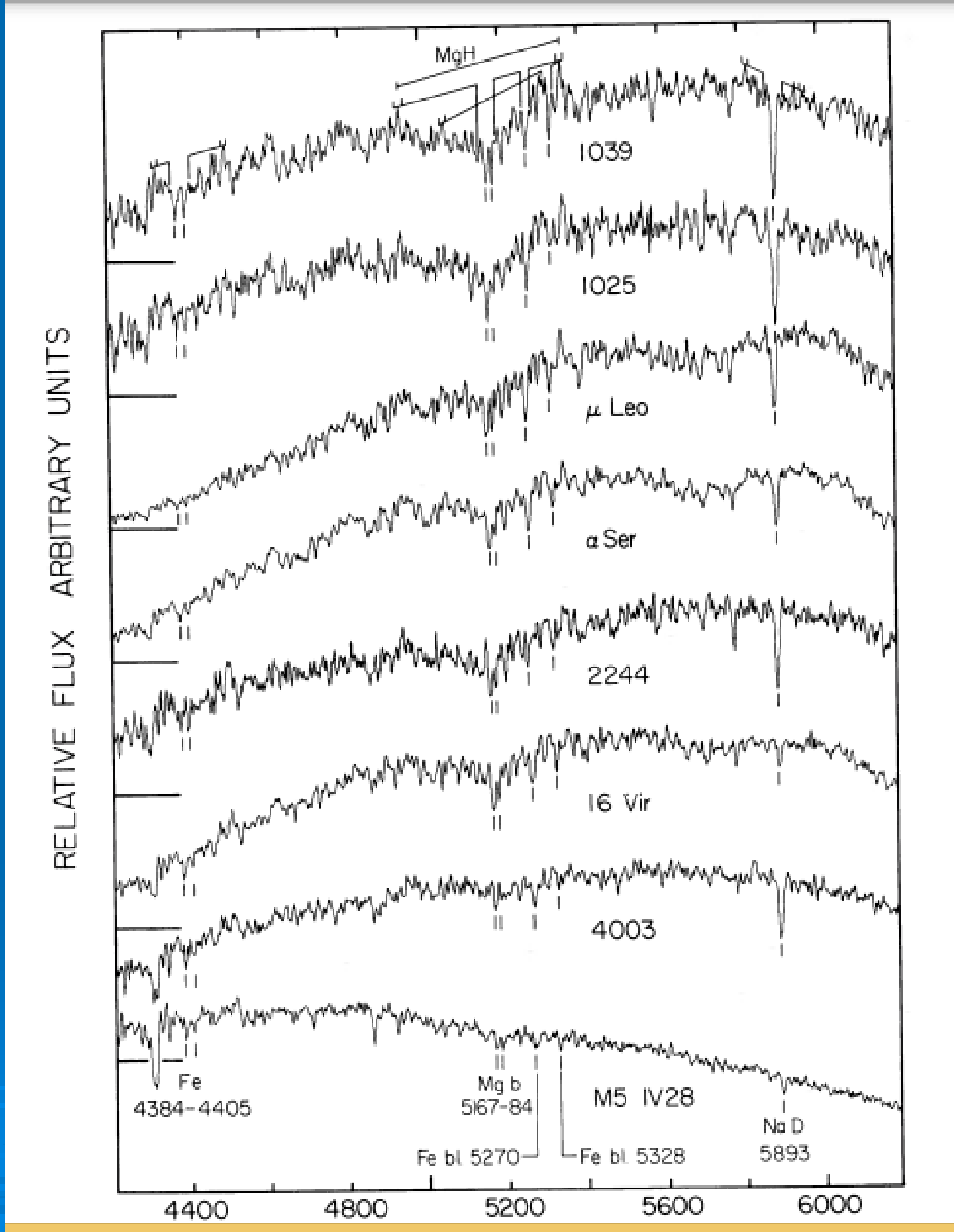
Bulge field
in BW

NGC 6528

Whitford & Rich
1983, ApJ, 274, 723

Bulge stars are
metal-rich

McWilliam+Rich94
First high-res
abundances:
-1.5<[Fe/H]<+0.5



History: First studies bulge clusters

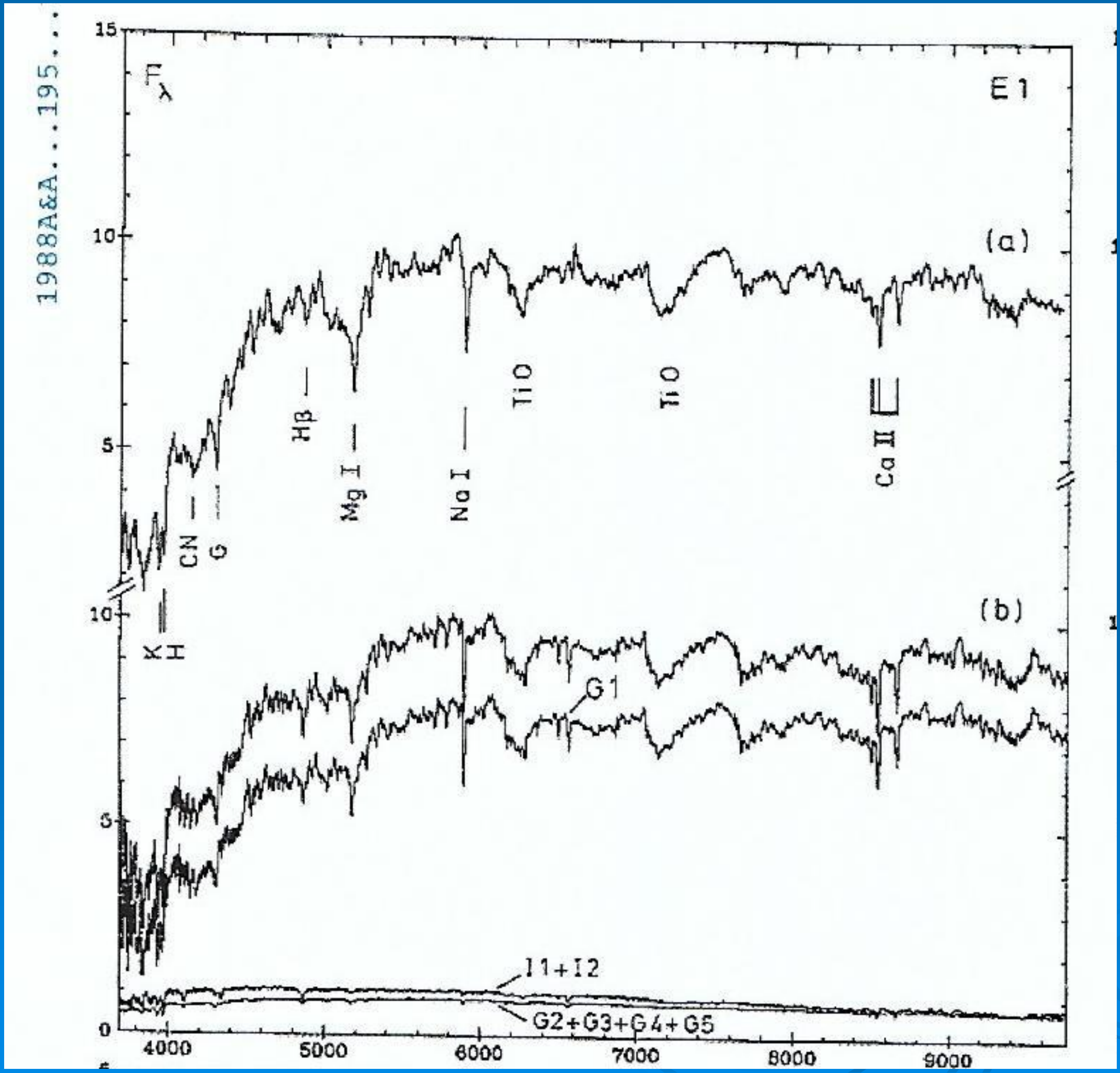
- Bica & Alloin 1986, A&A, 162, 21:

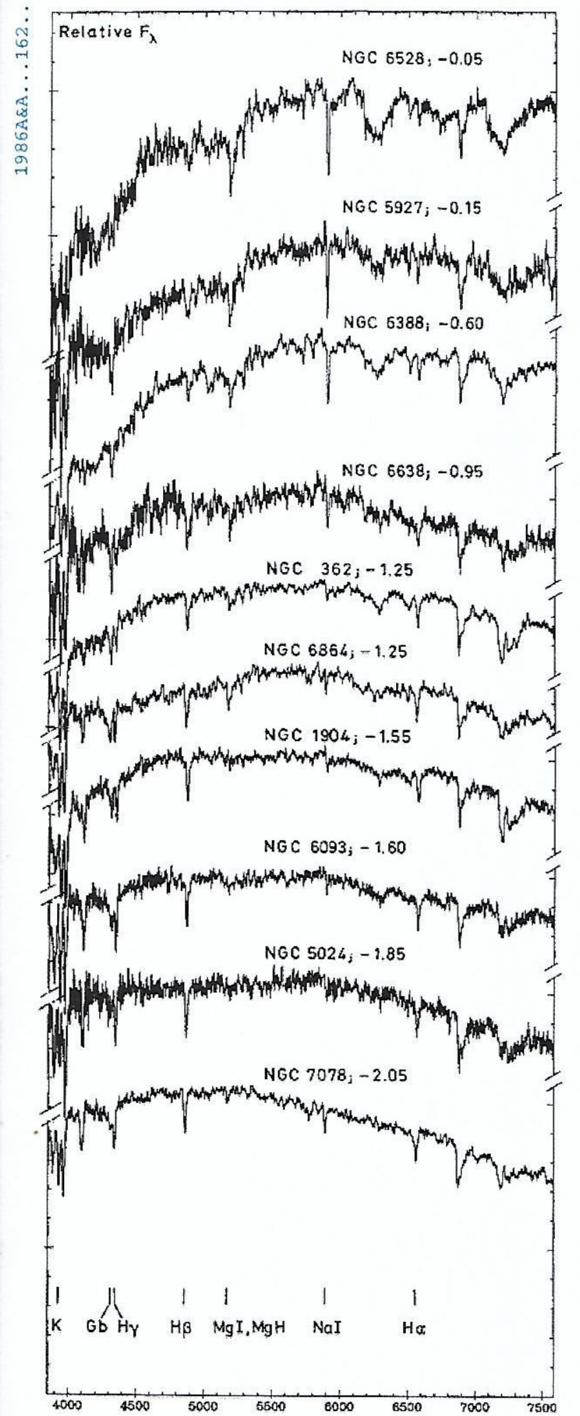
Library of integrated spectra of star clusters

- Bica 1988:

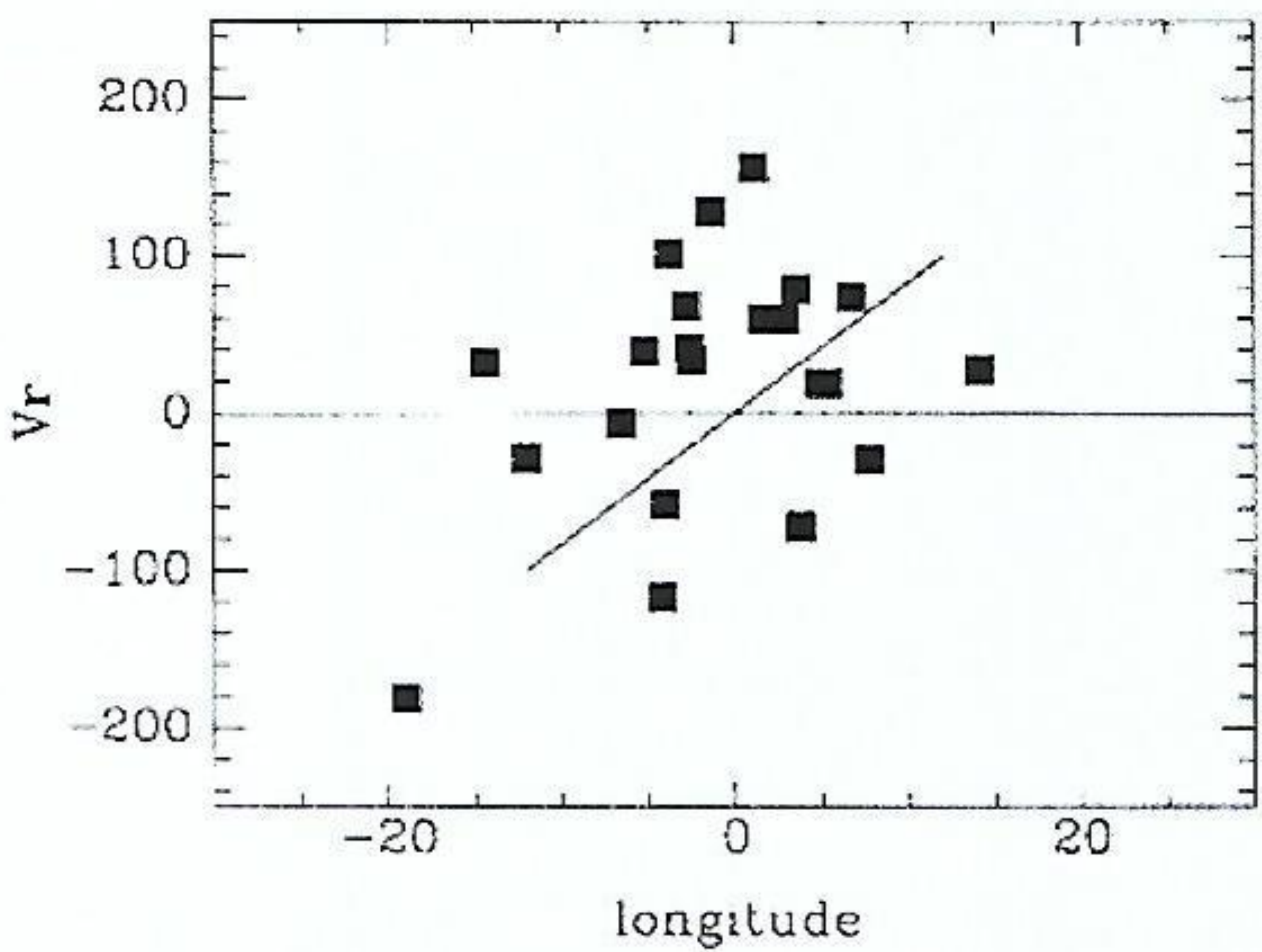
spectra of metal-rich clusters vs.
spectra of Ellipticals, and bulges
of spirals.

Bica Alloin 86, Bica 88





Minniti95: inner metal-rich clusters associated with the bulge

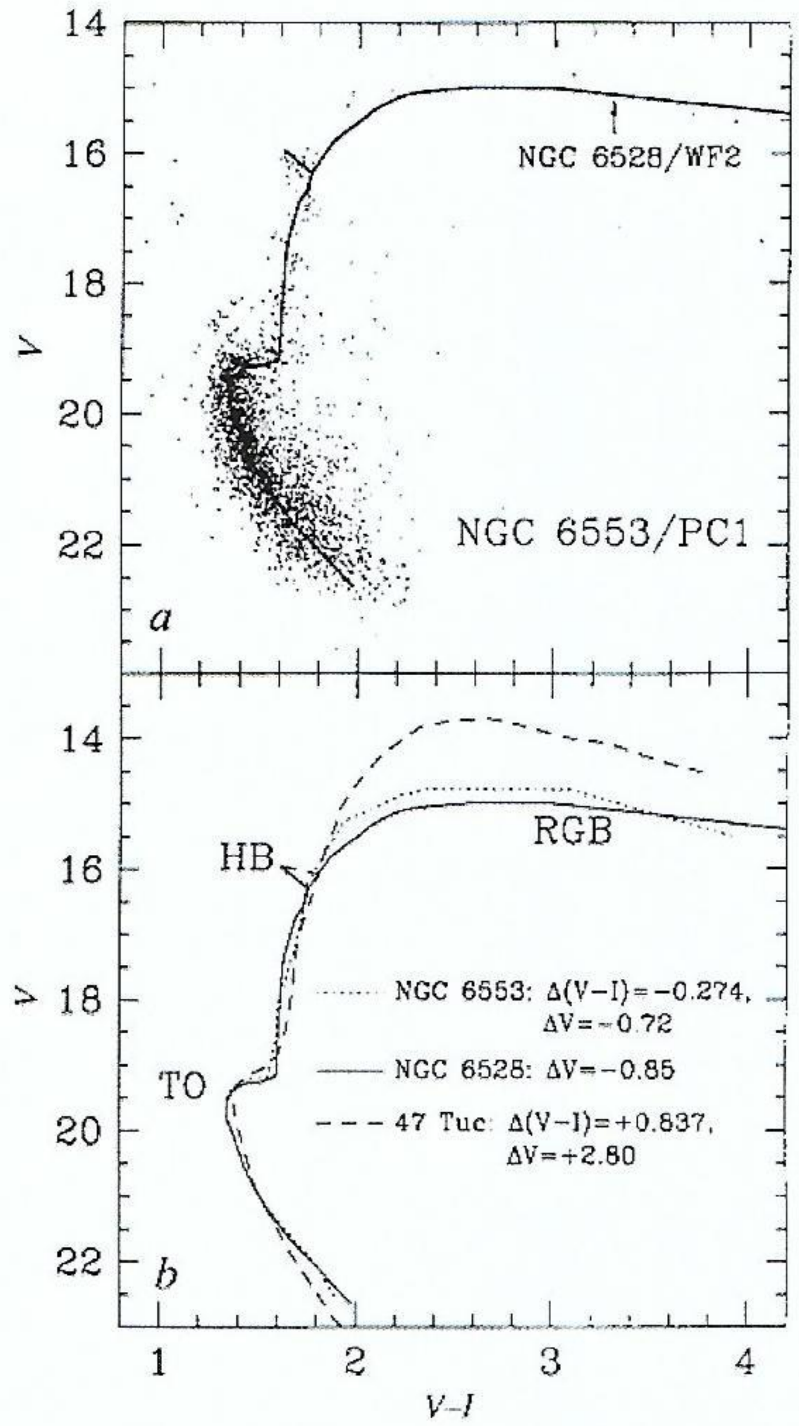


Ortolani, Renzini, Gilmozzi, Marconi, Barbuy, Bica, Rich 1995, Nature 377,701

Near-coeval formation of Galactic bulge and halo

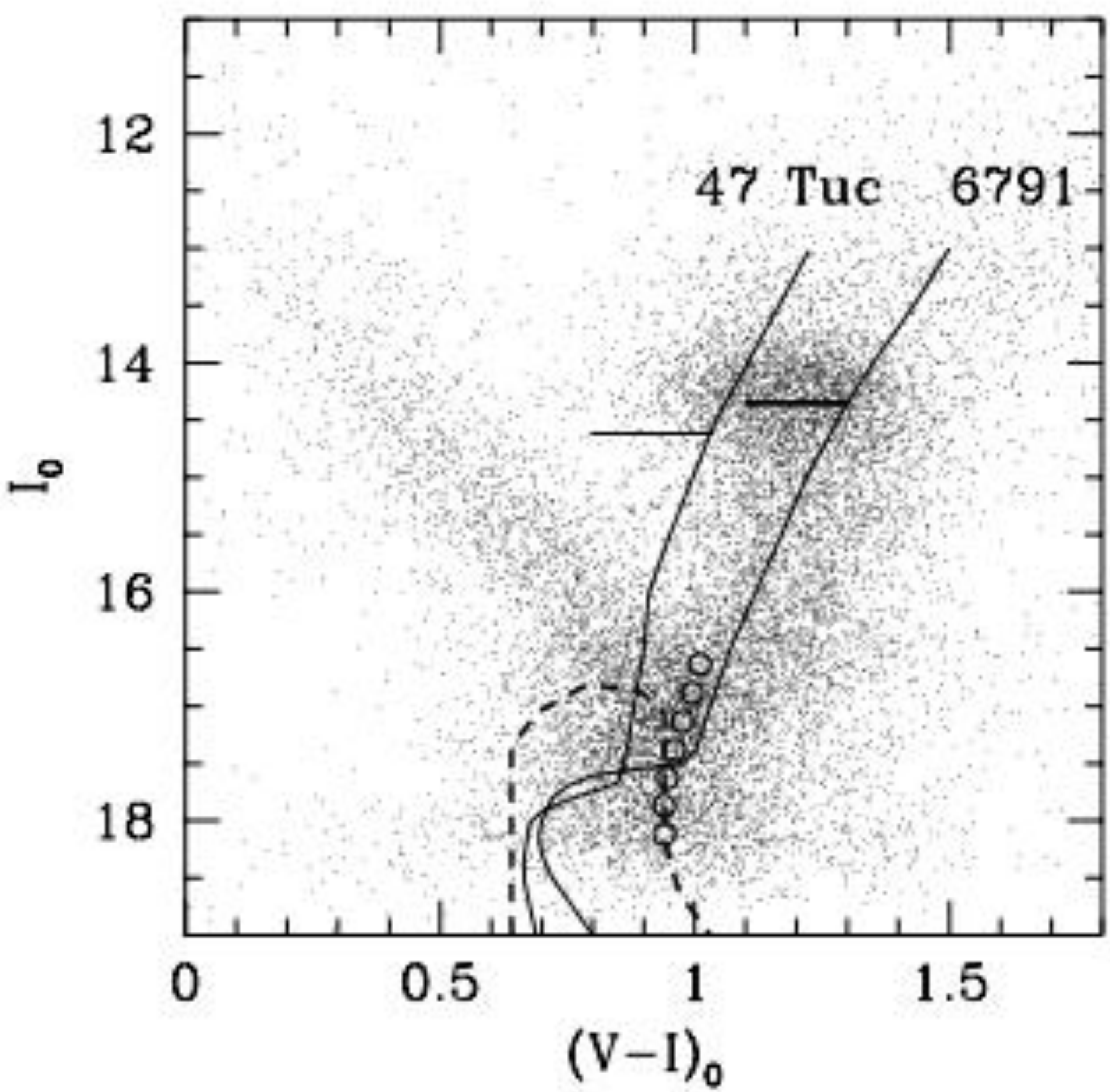
first data with HST: NGC 6528, 6553 coeval with 47 Tuc

→ Bulge is old



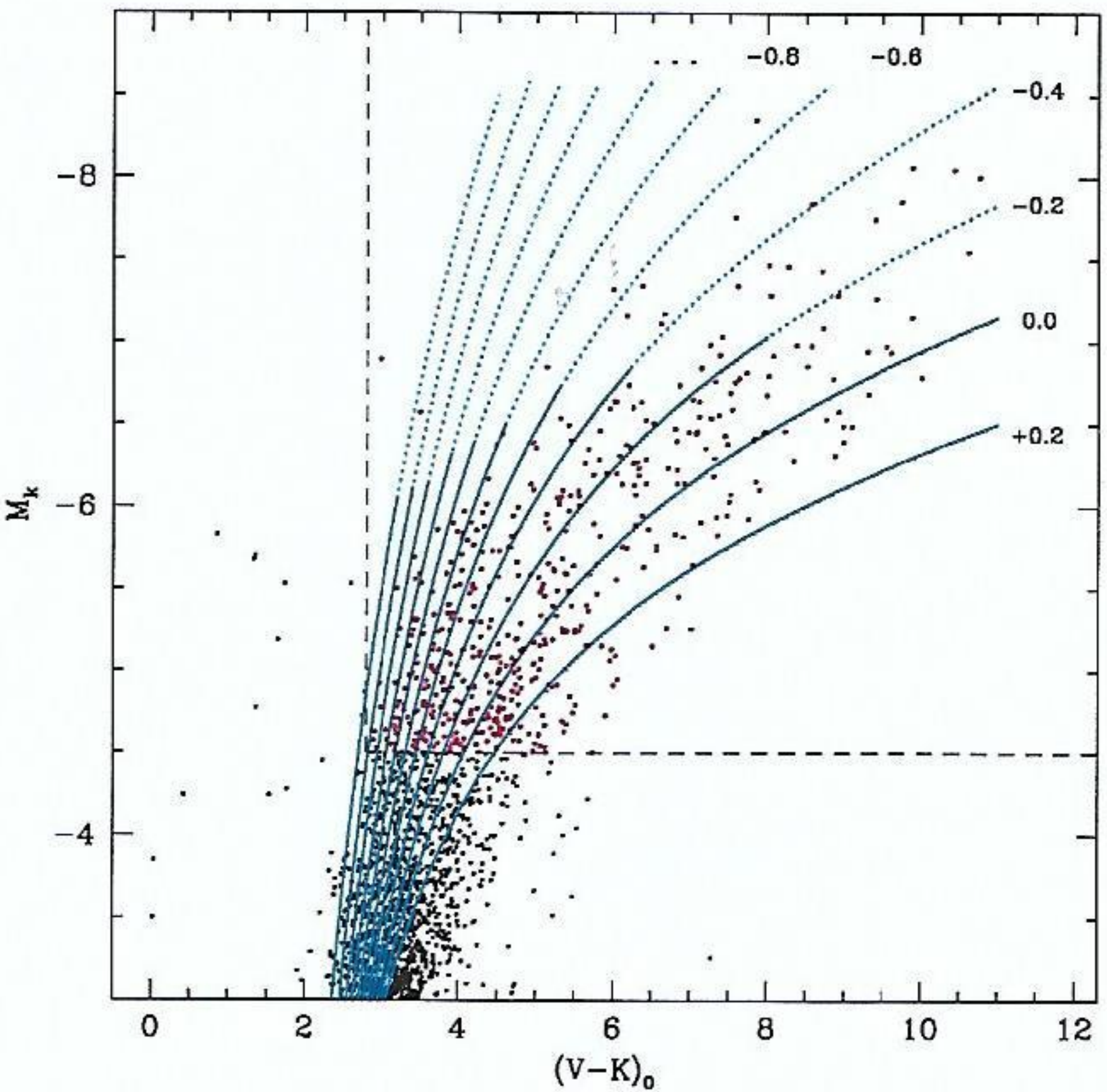
Kiraga, Paczynski & Stanek 1997, ApJ 485, 611

Bulge field is Young!

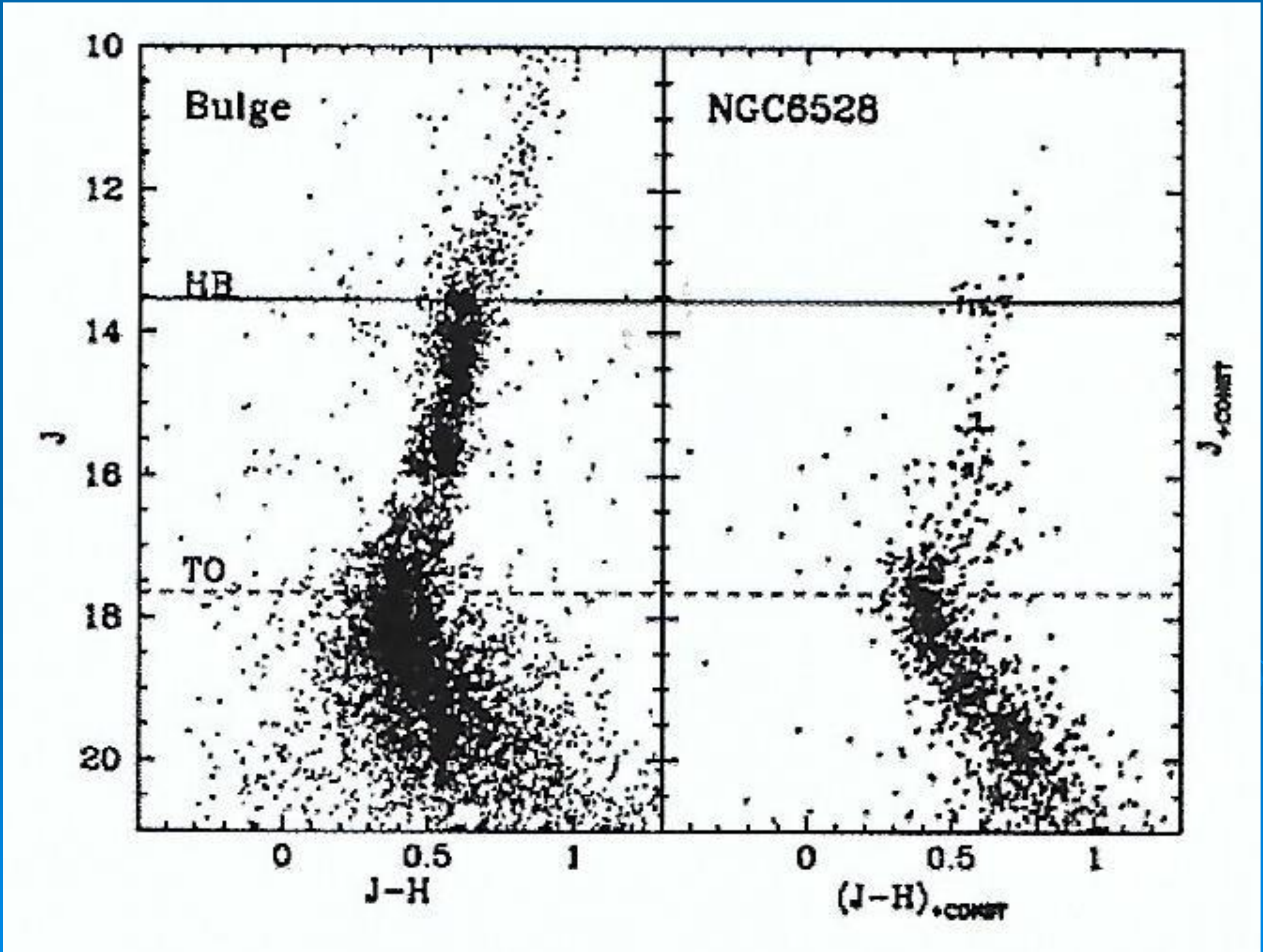


Zoccali+03 A&A, 399, 931

NTT-SOFI +NICMOS

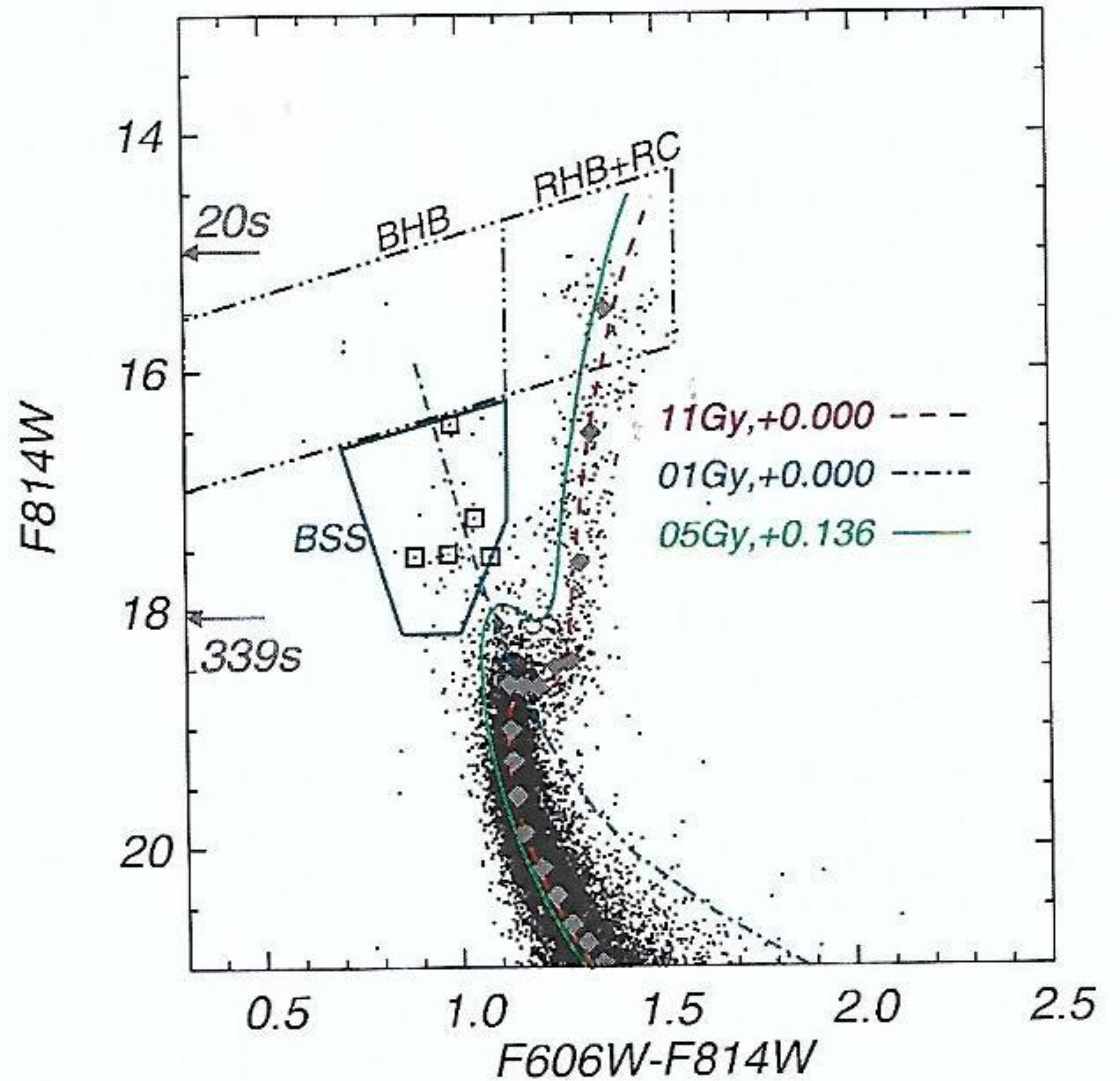


Zoccali+03 ➔ bulge is old



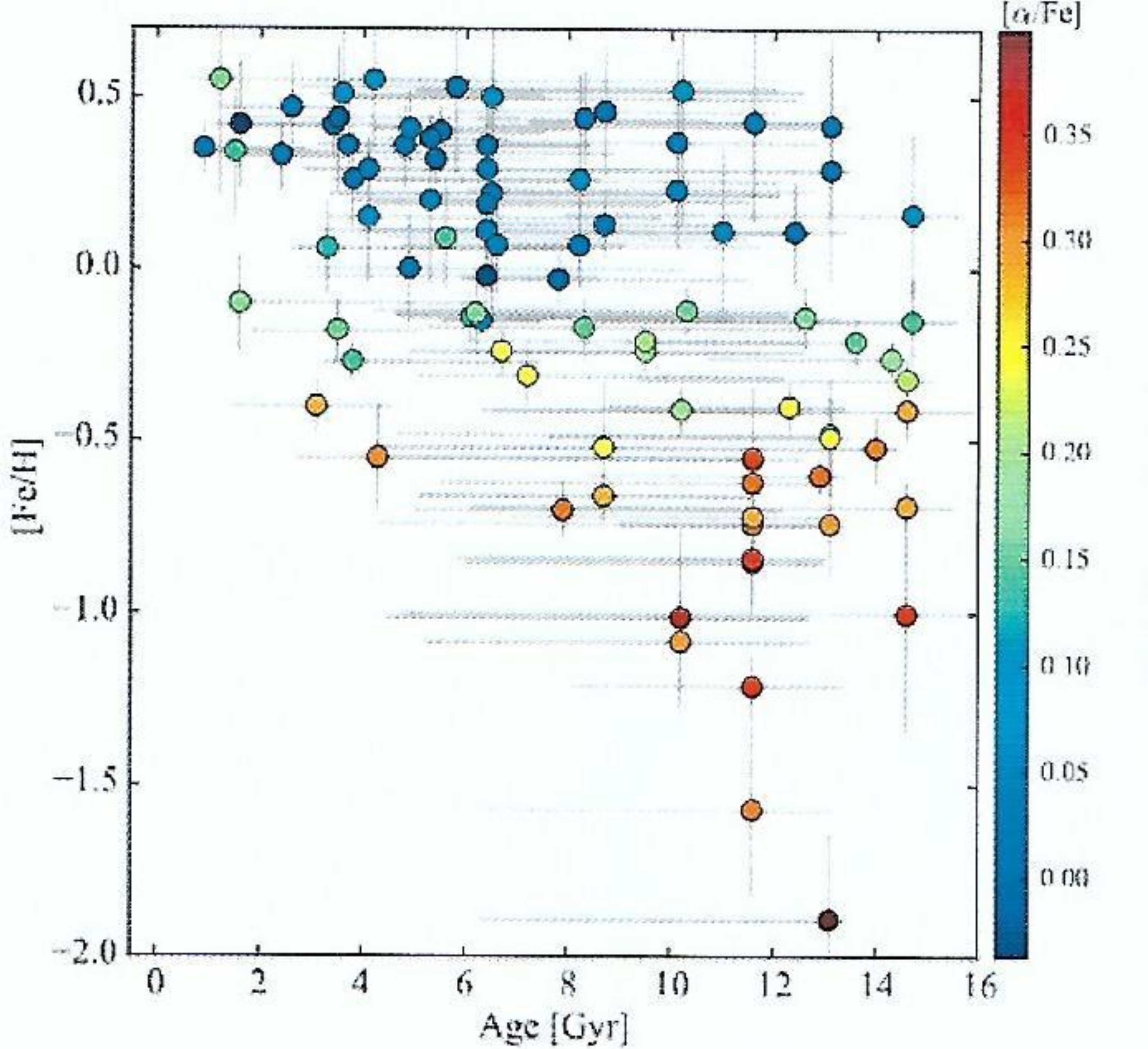
Clarkson+08
ApJ, 684,
1110

Bulge is old



Bensby 2017, A&A, 605, 89

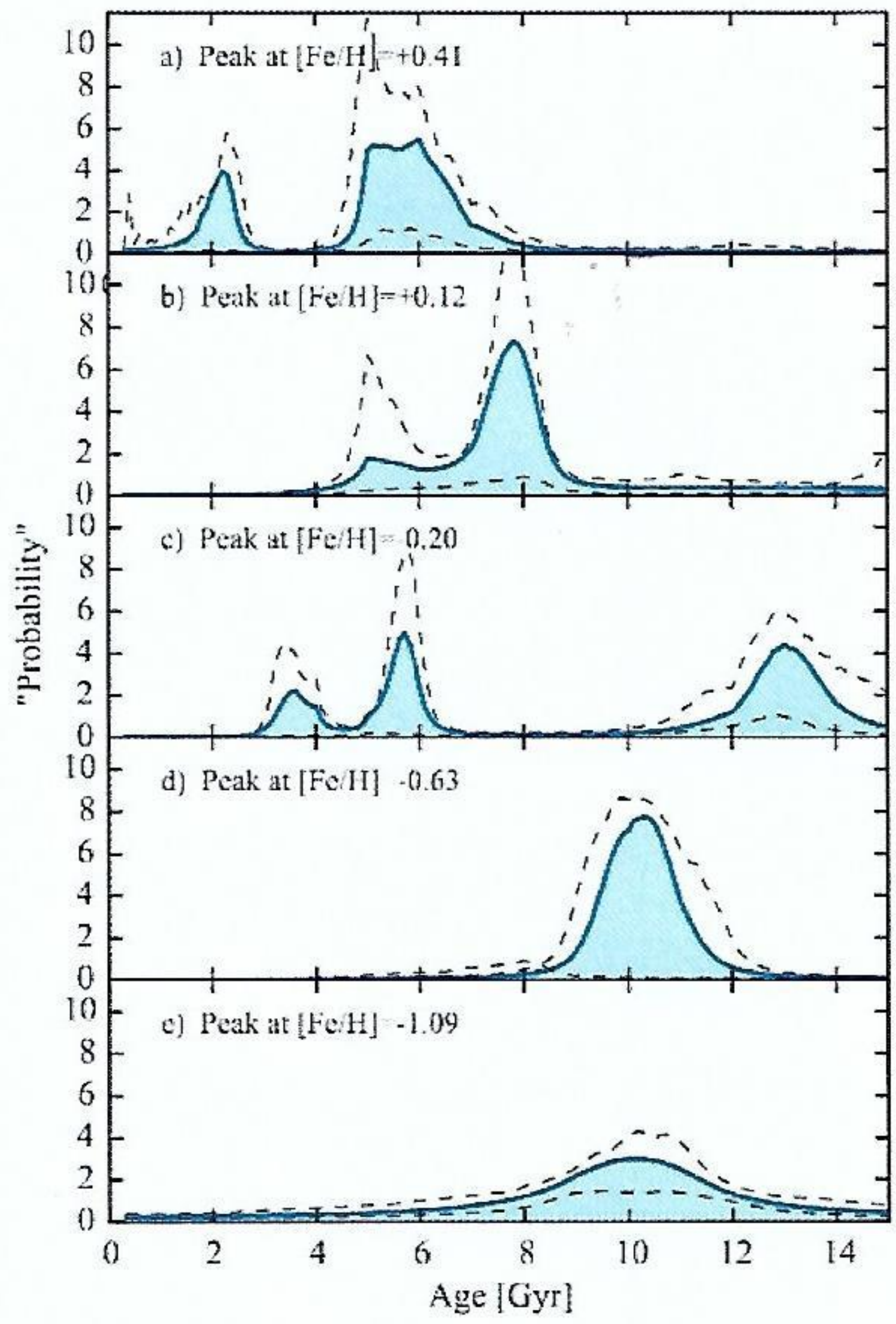
Fraction of young stars



Bensby+17

[Fe/H] vs. age

Peak at -1 is old →



Renzini+18: 4 bulge windows

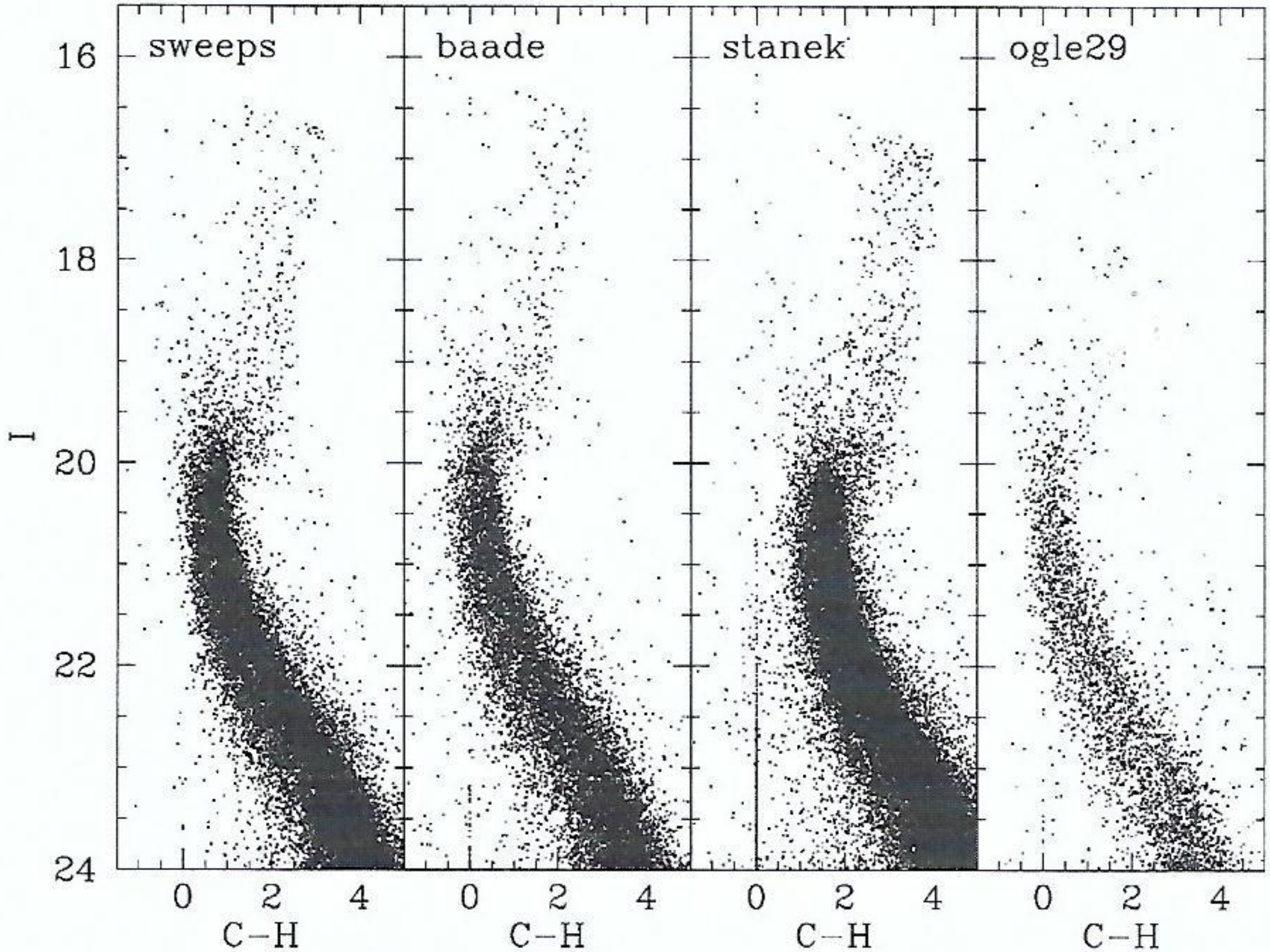


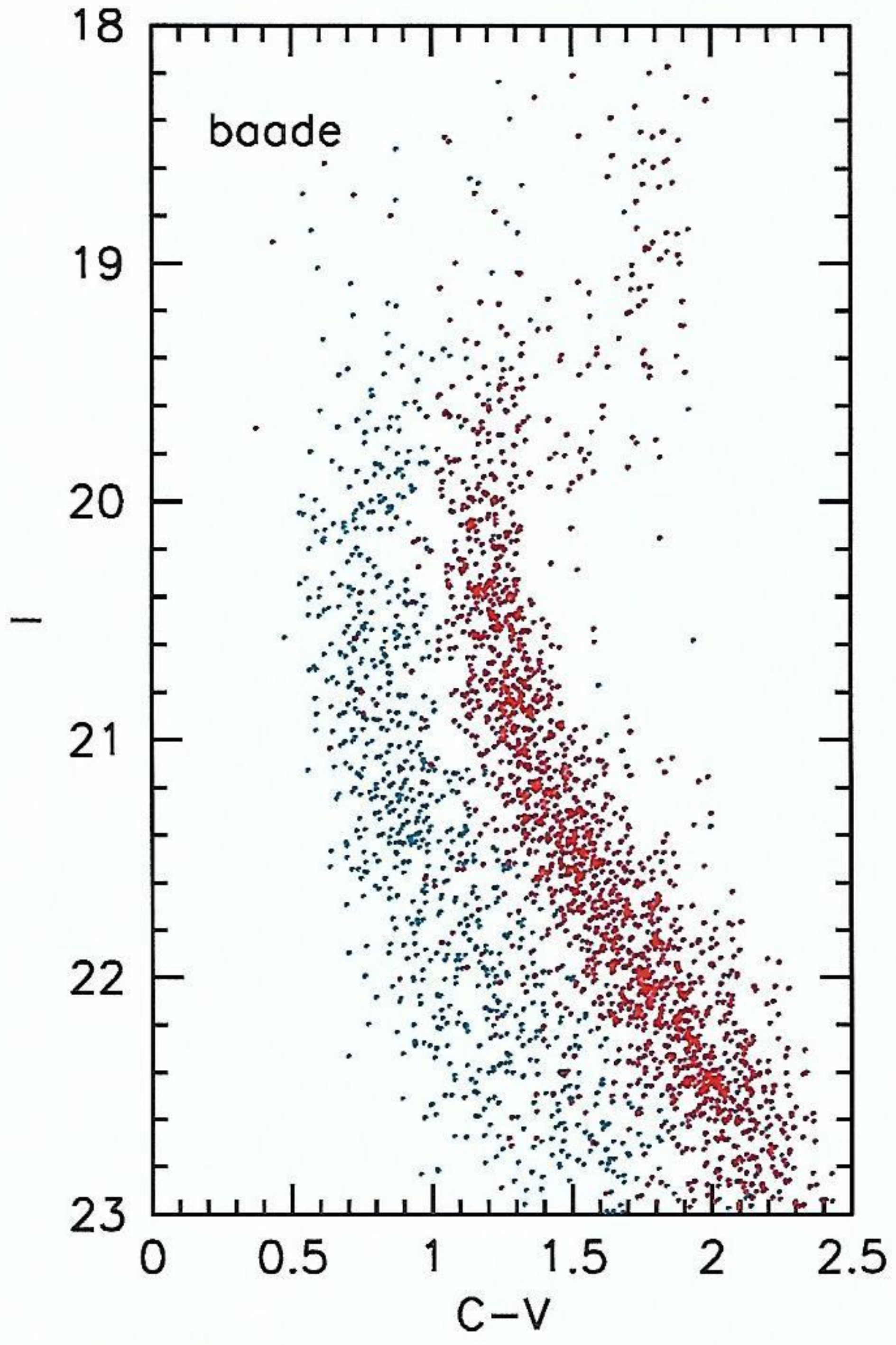
Figure 2. I – (C–H) CMD of the four bulge fields after disk decontamination.

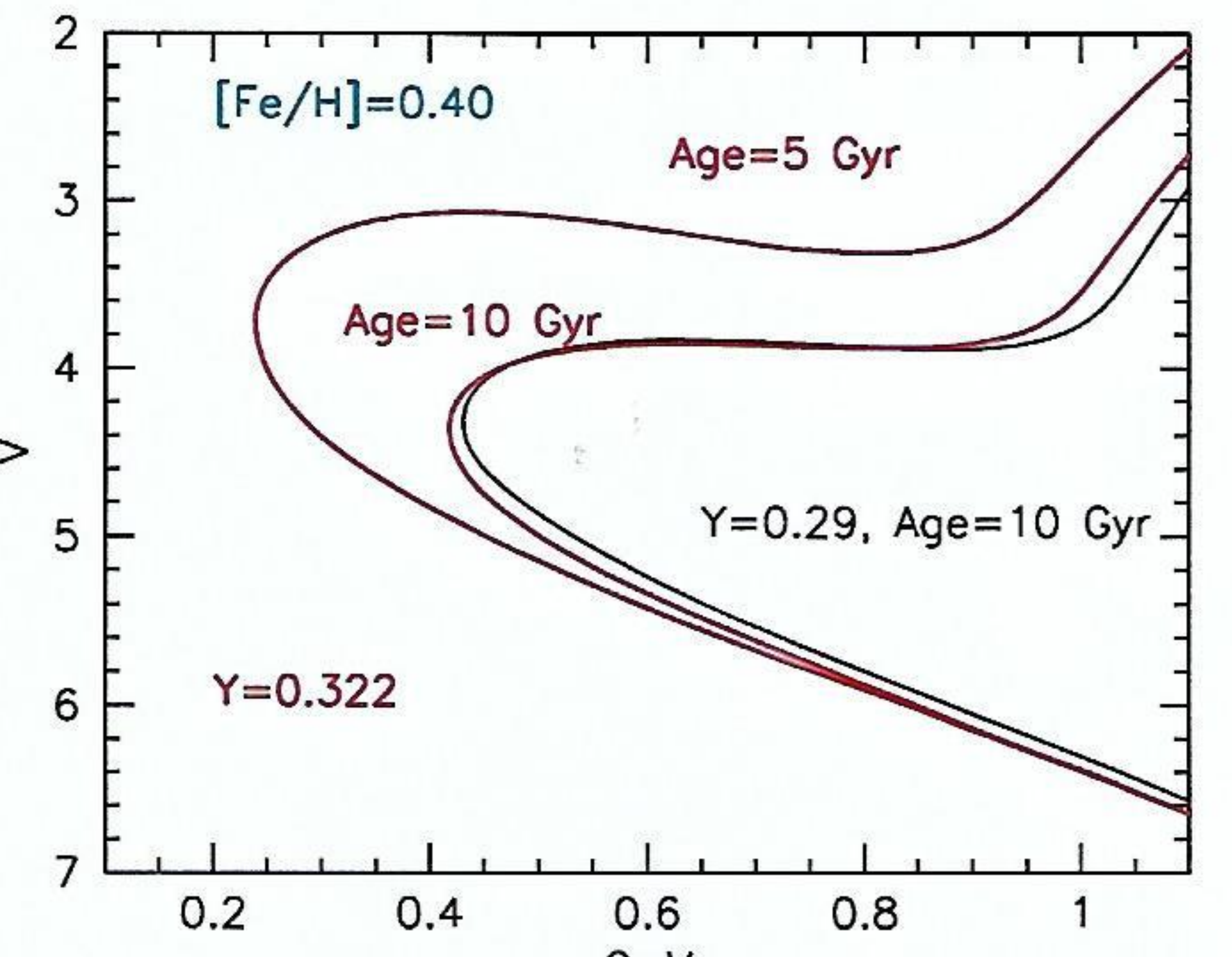
Renzini+18

distinguishing metal-poor and metal-rich bulge field stars

➔

Helium has to be taken into account (Bensby used Y2 Demarque Y=0.29 for metal-rich *s)




[Fe/H]=0.40
Age=5 Gyr
Age=10 Gyr
Y=0.29, Age=10 Gyr
Y=0.322
V
2
3
4
5
6
7
0.2
0.4
0.6
0.8
1

He in the bulge should be higher than in the solar neighbourhood:
enrichment by massive stars/SNII only

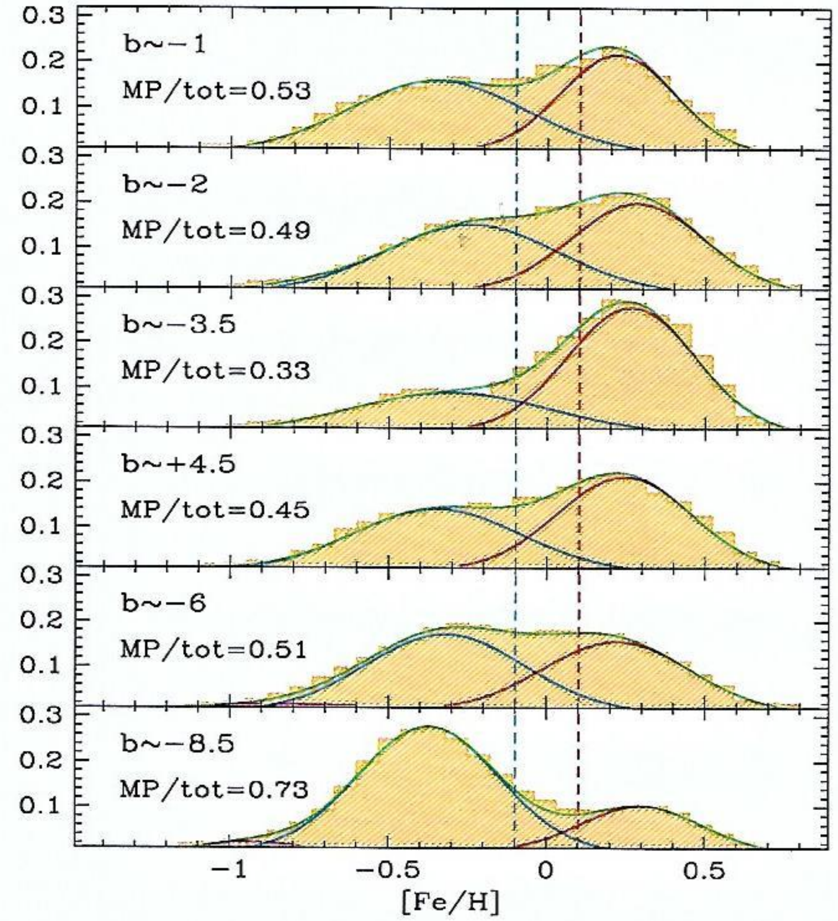
Also, uncertainties on mixing-length parameter in models: Li+2024
(Alvio on Friday)

Table 5. SEMMUL Gaussian components decomposition of field $b = -6°$.

Pop	[Fe/H]	$\sigma_{[Fe/H]}$	%	σ_r
C	-1.09 ± 0.07	0.24 ± 0.01	6 ± 2	127 ± 26
A	-0.27 ± 0.02	0.24 ± 0.01	64 ± 3	83 ± 5
B	0.14 ± 0.02	0.13 ± 0.01	30 ± 3	70 ± 6

Notes. The radial velocity dispersion σ_r is gi

Babusiaux+10,Hill+11



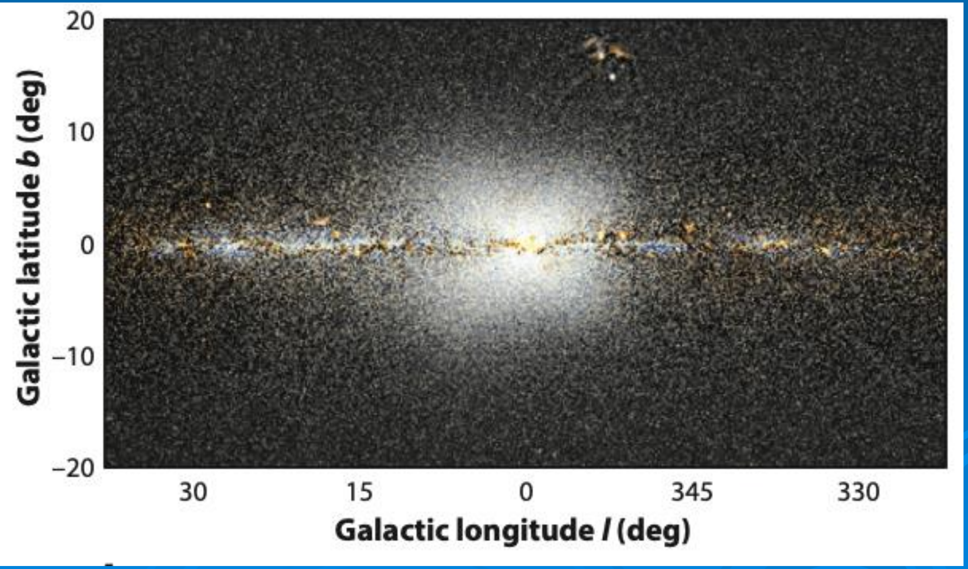
Zoccali+17

(also Ness+13)

Formation of the Galactic bulge

ESA; layout: ESA/ATG medialab

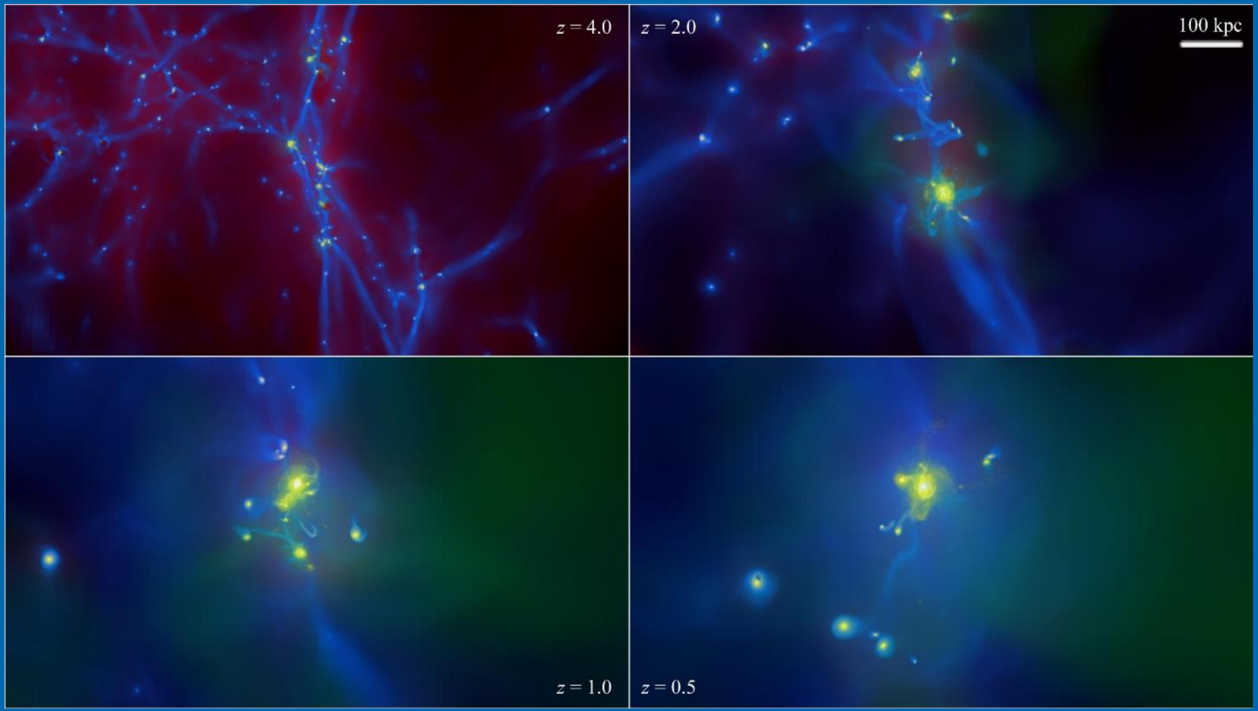
1.Merger scenario = bulge formation by hierarchical merging (White Rees 1978)
➔ early classical bulge



Ness & Lang (2016)

WISE =Ness+Lang16

Filaments, first structures



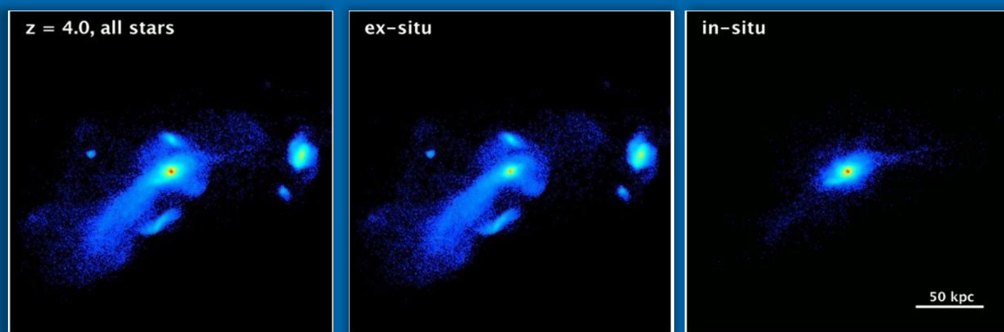
Renaud+17

From: The origin of the Milky Way globular clusters

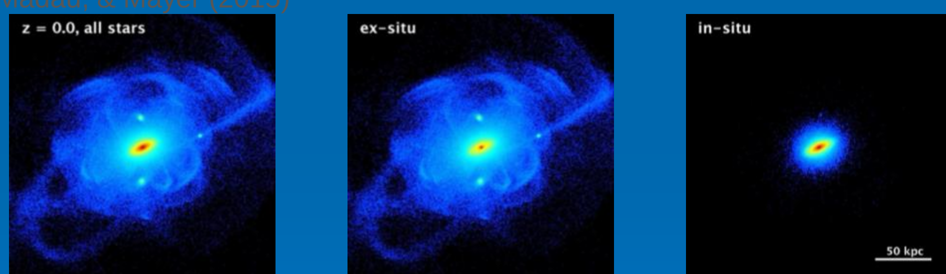
Mon Not R Astron Soc. 2016;465(3):3622-3636. doi:10.1093/mnras/stw2969

Formation of early bulges

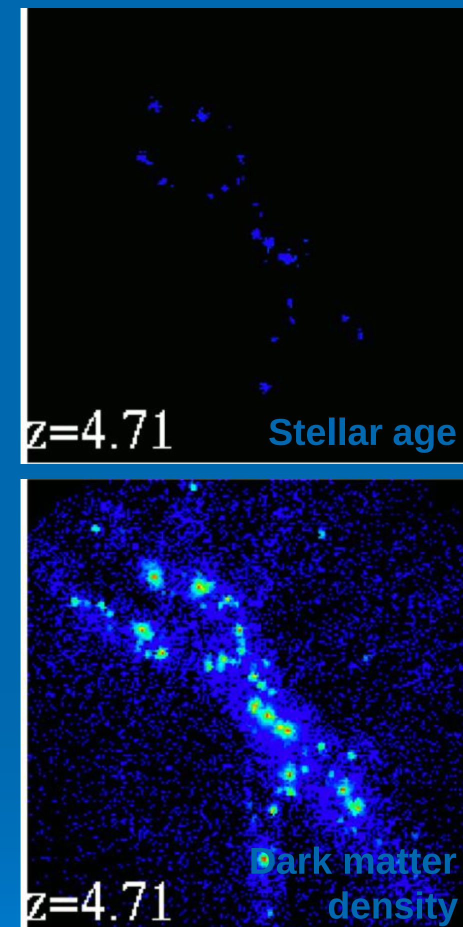
Pillepich, Madau, Mayer 2015



Pillepich, Madau, & Mayer (2015)



- From the merger of the building blocks, the proto-Galaxy is formed first composed of a spheroidal bulge and a halo.



Abadi et al. (2003)

2. In situ bulge (and thick disk) form early via strong gas accretion

Tacchella+16, Dekel & Burkert+14:

The discs, fed by cold streams, undergo violent disc instability that drives gas into the centre (along with mergers).

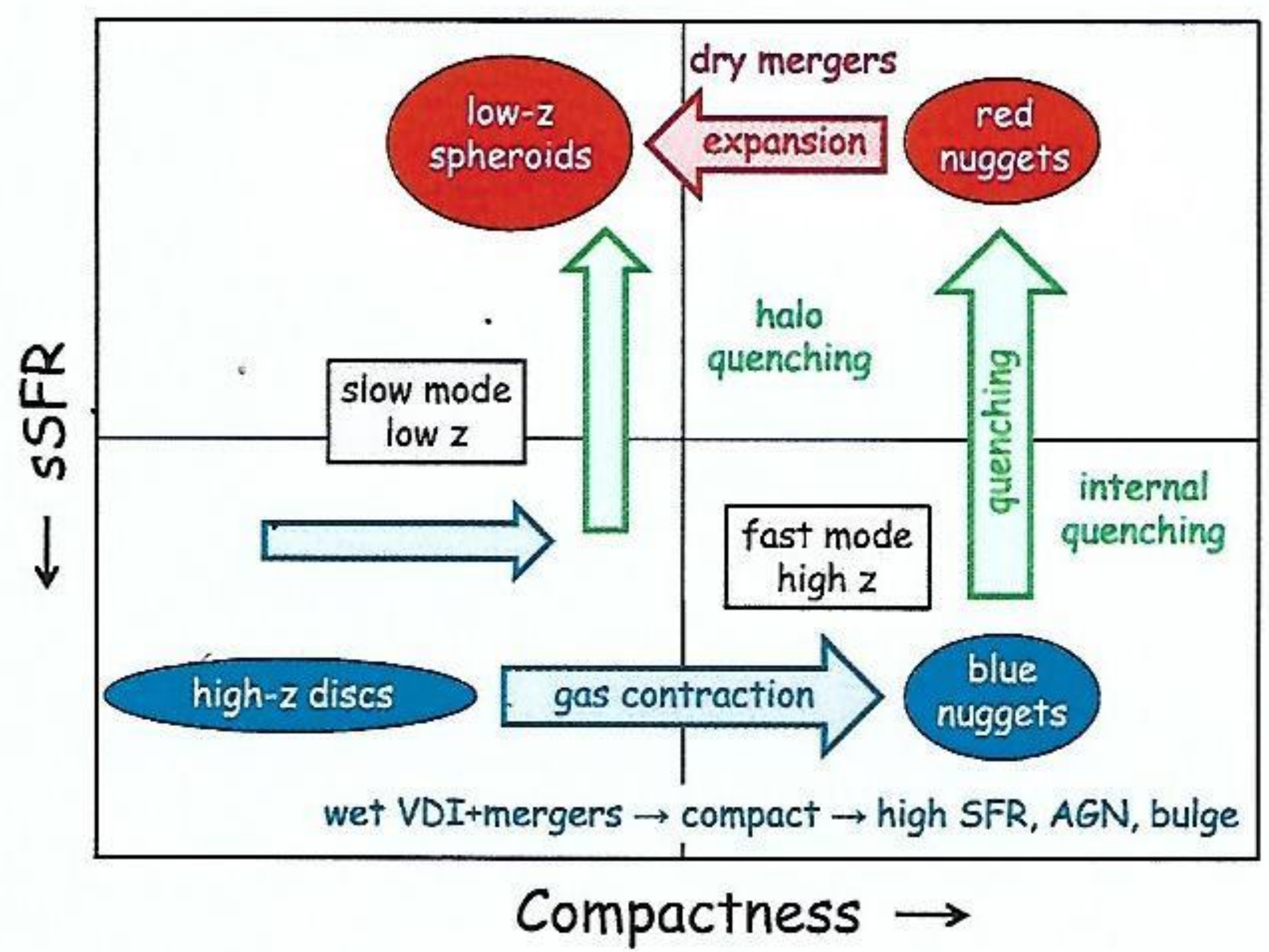
➔

compact star-forming systems: blue nuggets

compact, quenched spheroids: red nuggets

Early disk and simultaneous formation of globulars

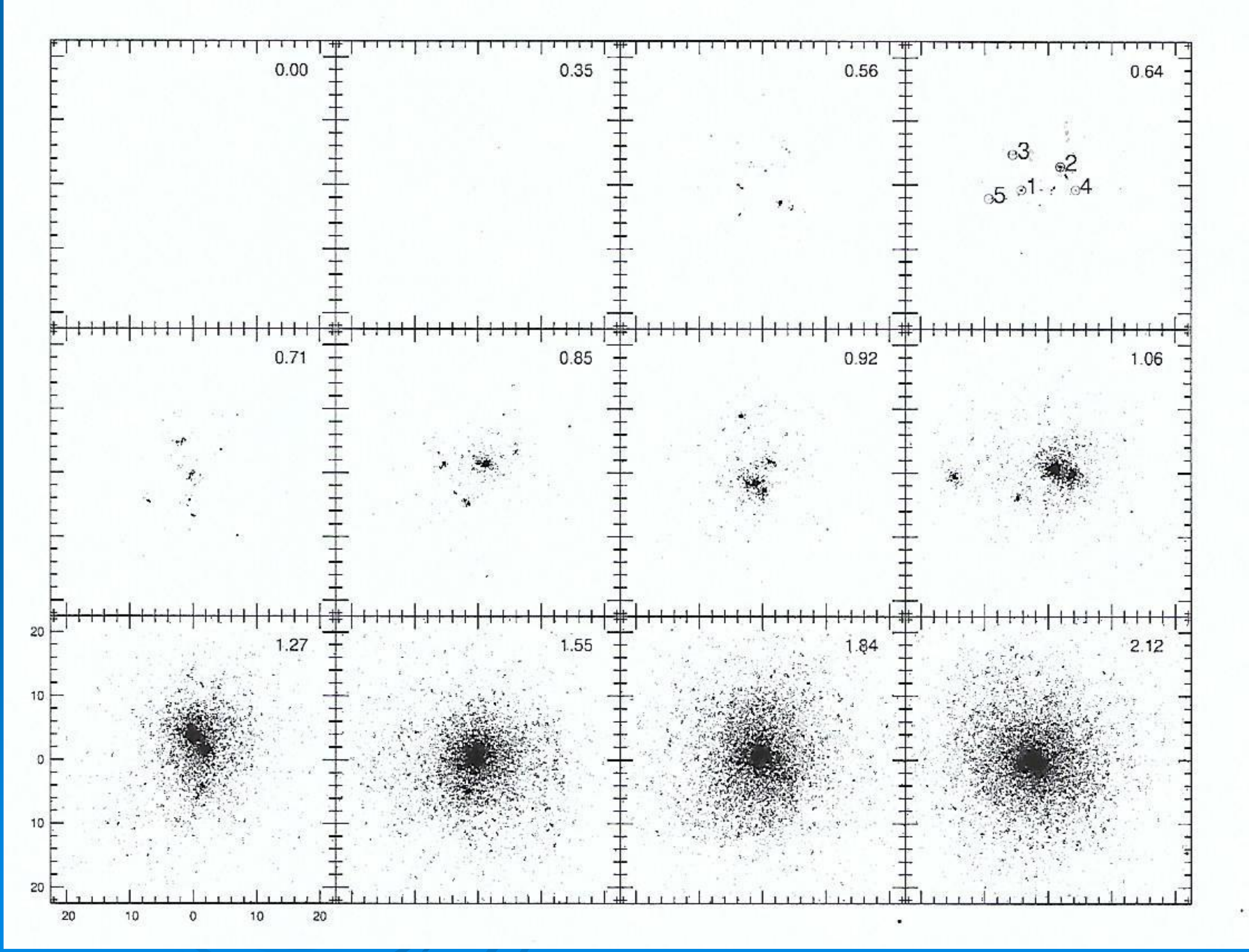
Tacchella+15, Science, 348,314



3. Clump scenario – migration of star forming clumps to center of early disk galaxies

Noguchi 99

also: Immeli+04, Mandel-ker+16



4. Secular Evolution scenario = formation of bulge from the disk through bar instability

Combes 2000,KK04, Shen10, Debattista14

Brava survey – Rich+07➔ cylindrical rotation

Bar instability and buckling instability ➔ two-step heating ➔

Radial gradient transforms into vertical gradient

Conclusion:

ALL IS TRUE (?)

Shakespeare

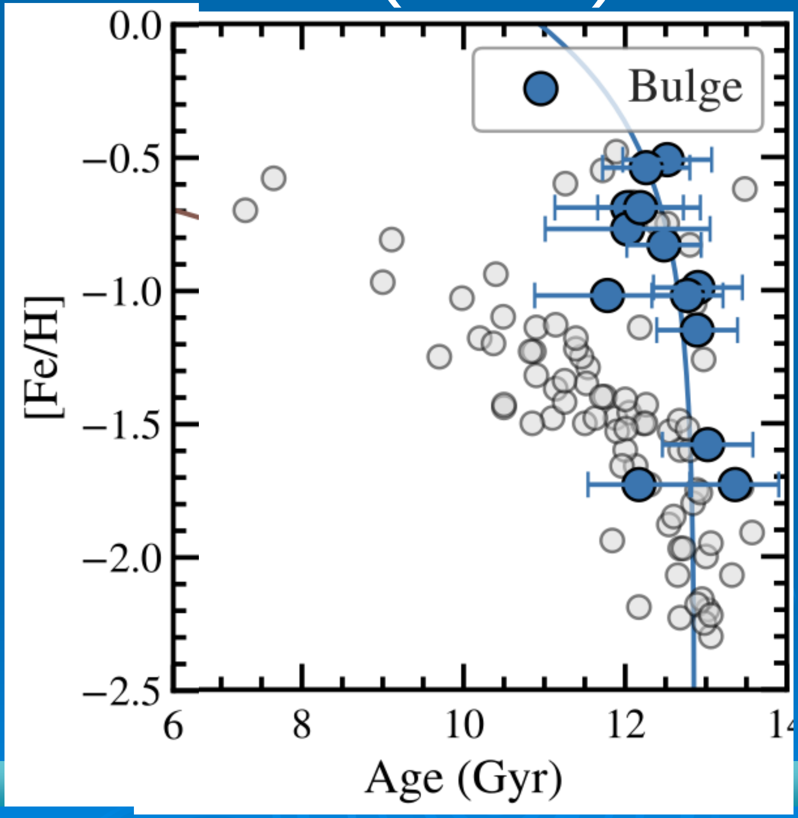
Accretion of Dwarf Galaxies

Identification of accreted structures:
Gaia-Enceladus-Sausage -10 Gyr ago
+ many others

➔ Globular Clusters are tracers of early bulge and accreted structures

- **Age-metallicity relation (AMR)**
  - Forbes (2010), Massari (2019), Forbes (2020), Kruijssen et al. (2020), Callingham et al. (2022), Belokurov & Kravtov (2024).

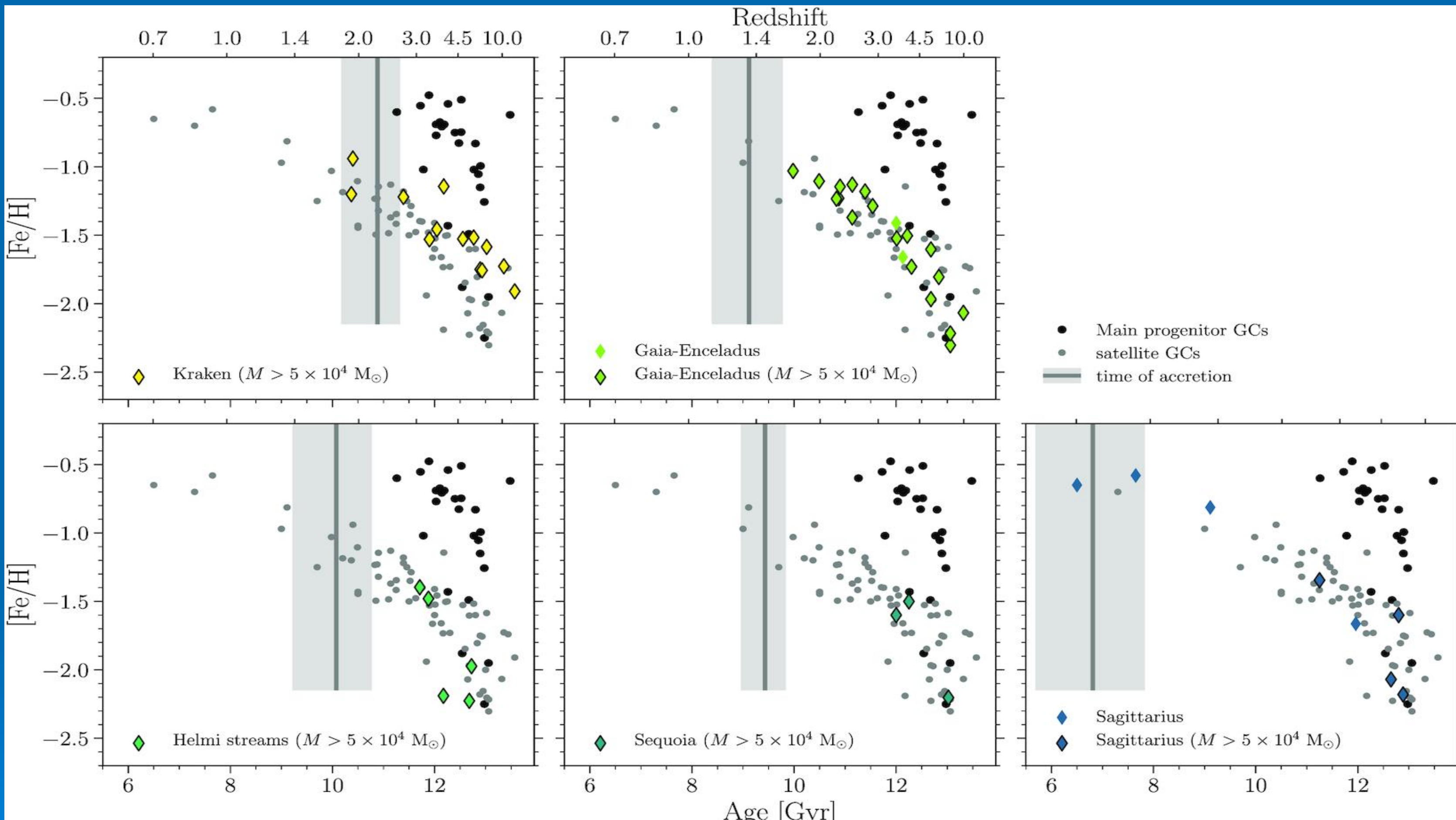
Callingham et al. (2022)



- Two sequences of GCs
  - Old ages >~12Gyr
    ➔ in-situ
  - ages from 6 to 14 Gyr –
    ➔ ex-situ

Figure 3. Age–metallicity distribution of the Galactic GC population. In all the panels, we distinguish GCs that formed ...

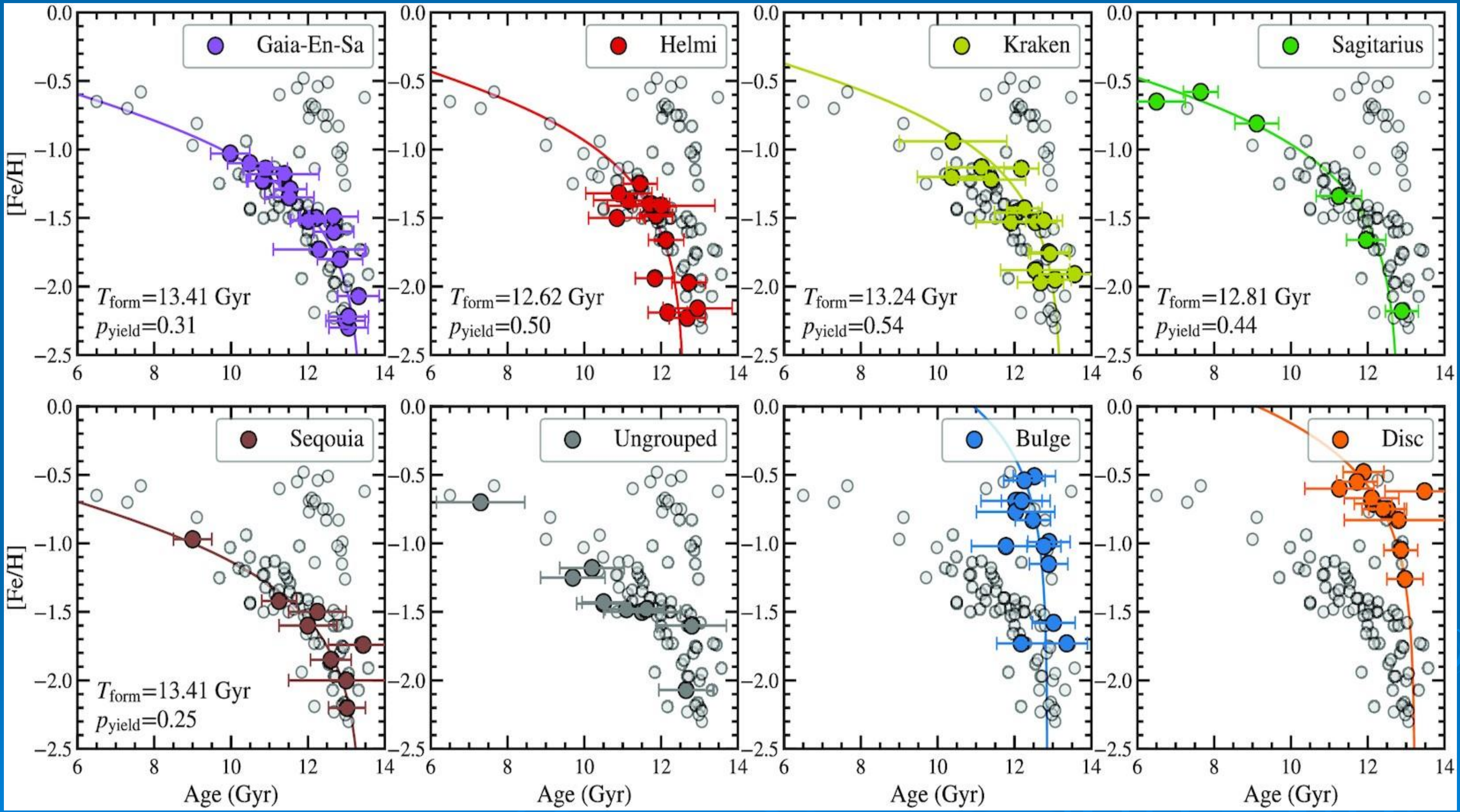
Kruijssen+2020



Mon Not R Astron Soc, Volume 498, Issue 2, October 2020, Pages 2472–2491, https://doi.org/10.1093/mnras/staa2452

Figure 9. The AMR for the Galactic GCs split according to the component with which they are associated. The solid lines ...

Callingham+22



Mon Not R Astron Soc, Volume 513, Issue 3, July 2022, Pages 4107–4129, https://doi.org/10.1093/mnras/stac1145

Galaxy merger structures

Kruijssen+2020:
Sagittarius, Helmi, GSE and others

Inner bulge – to be confirmed as accreted:

Heracles, Kraken, Koala, Aurora

Kruijssen et al. (2020)

Globular clusters: fossils of the Galactic bulge

-

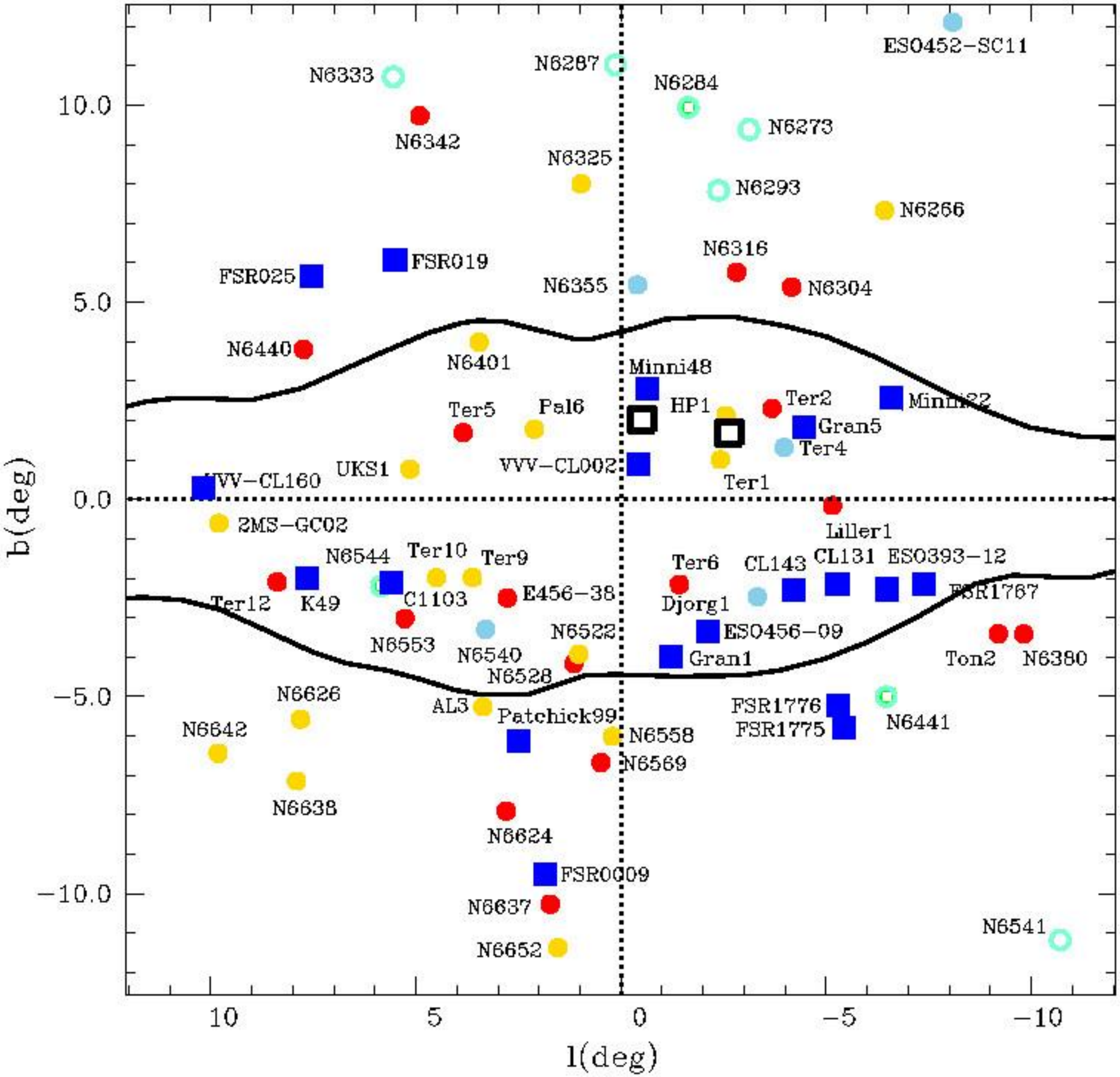
HP-1
Image:
Survey
VVV

Barbuy
+2016

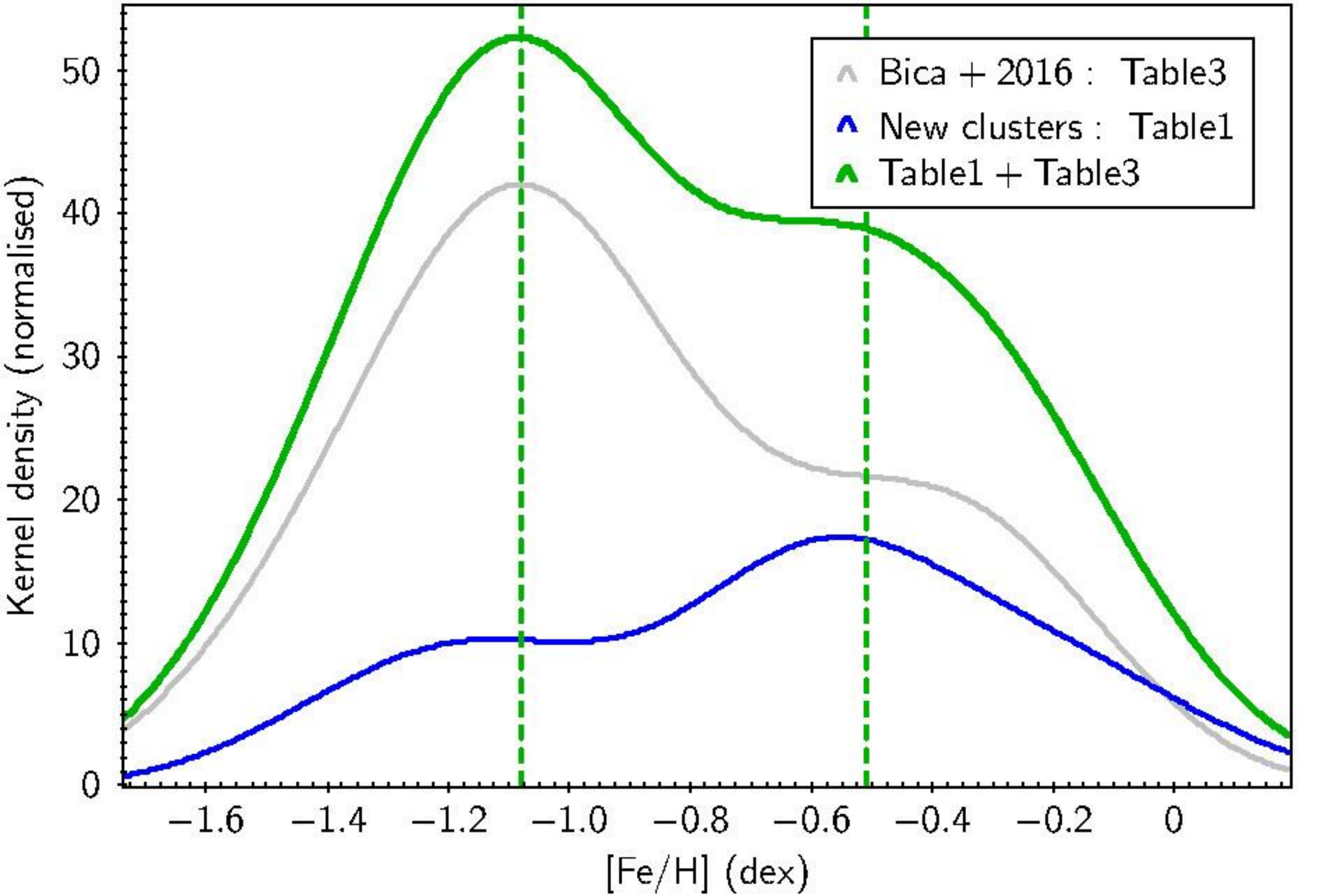
Kerber+
2019
12.8Gyr

Bica+24

61 bulge in-situ globular clusters

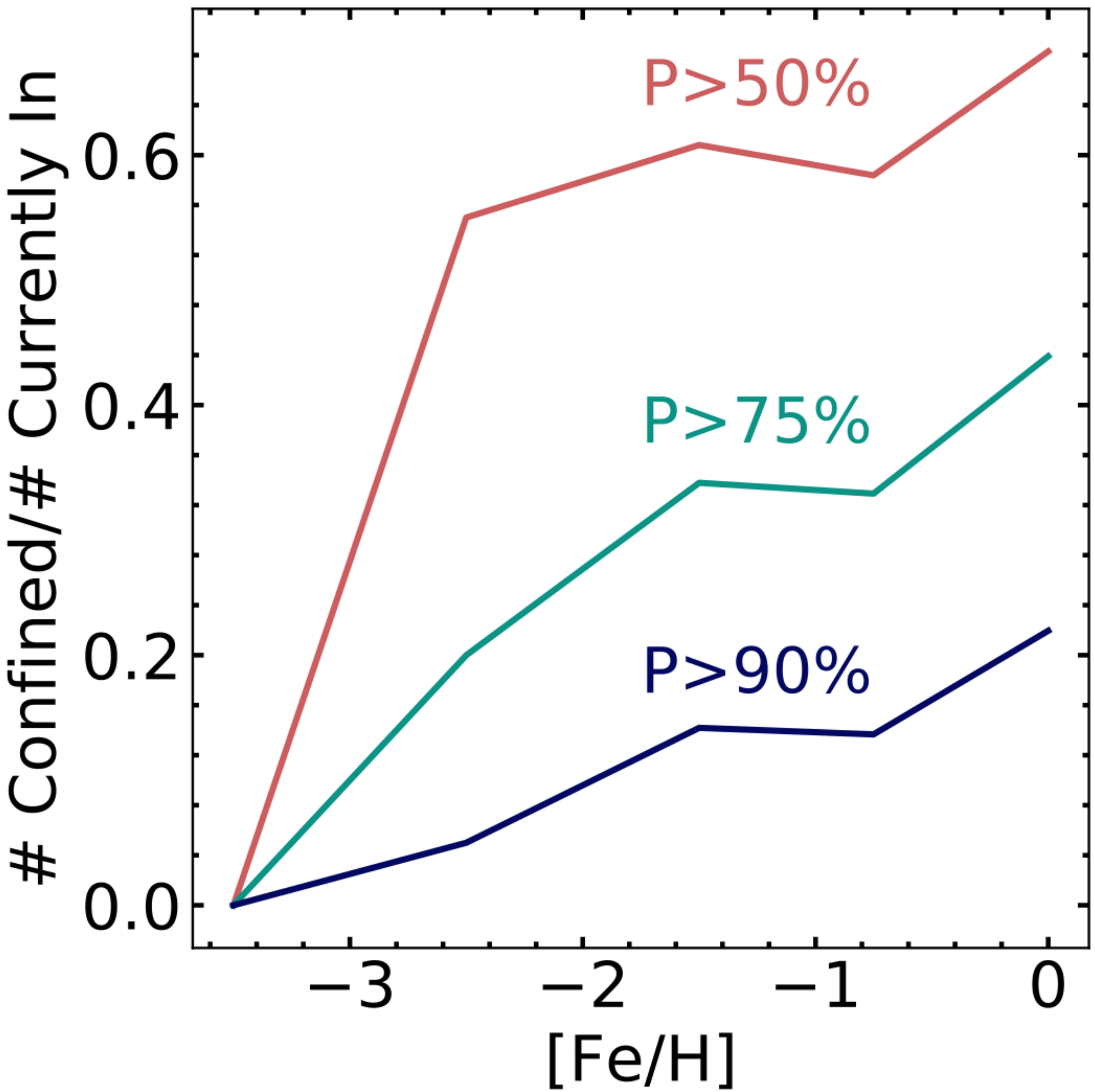


Bica+2024, A&A, 687, A201 ([Fe/H]>-1.5)



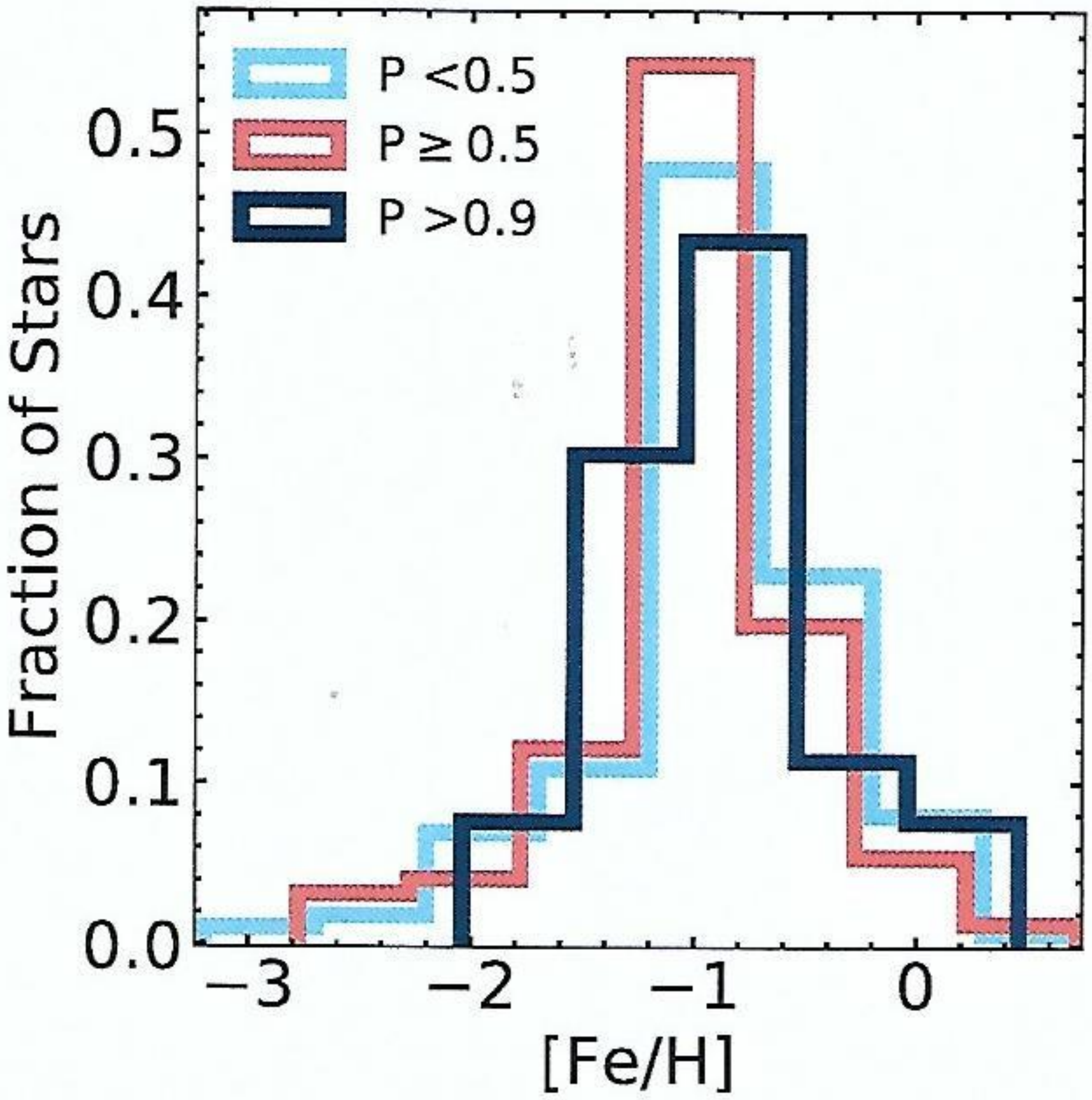
Lucey+21

Bulge field:
extracting
only
bulge *s



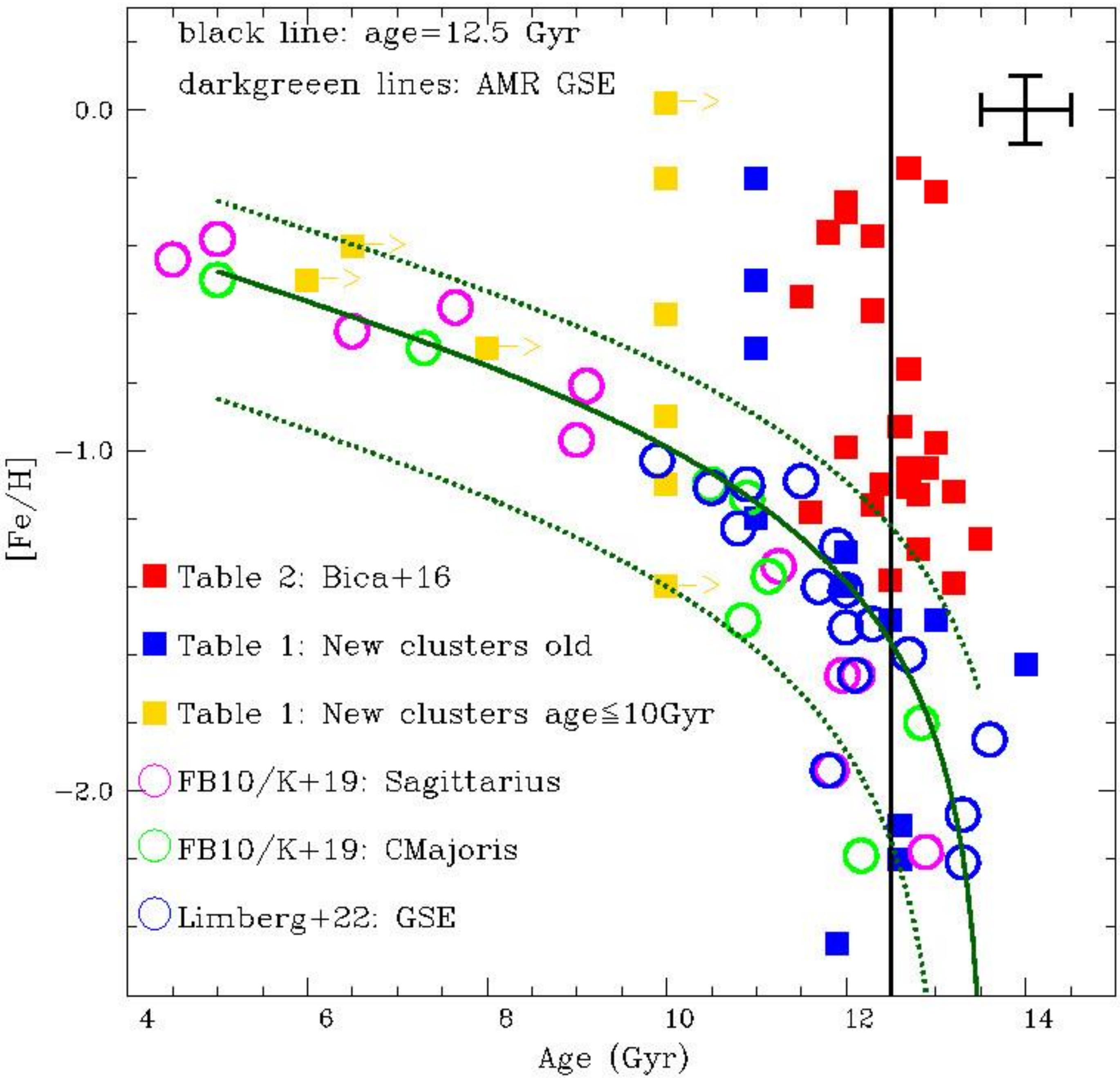
Lucey+21
[Fe/H]<-0.8:

Bulge field:
extracting only bulge *s i.e. excluding inner halo stars

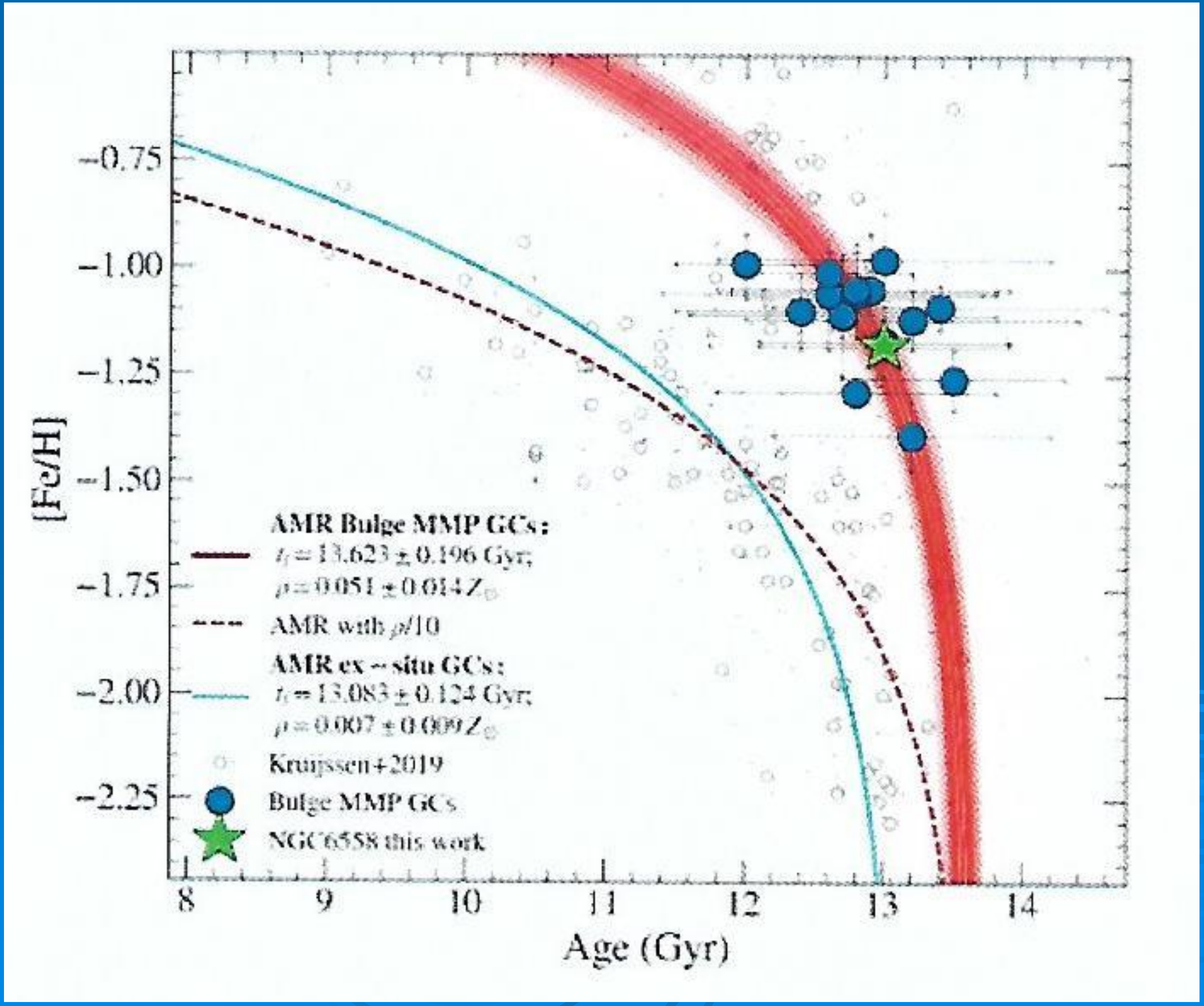


Bica+2024

All bulge clusters with age



AMR of 15 old (12.3-13.5Gyr) moderately metal-´poor ([Fe/H] -1)
Souza+2024, earliest = 13.57 Gyr



Example of GC accreted

Located in inner bulge: VVV CL001:

R_V=-326 km/s, E(B-V)=2.20
[Fe/H]=-2.45 ➔ most metal-poor GC in the Galaxy (halo ESO280-SC06 [Fe/H]=-2.45)
Both possibly associated with GES, or Sequoia

Fernández-Trincado+2021,ApJ, 908, L42:
Gemini/IGRINS: [Fe/H]=-2.4, -2.1 (11 stars)

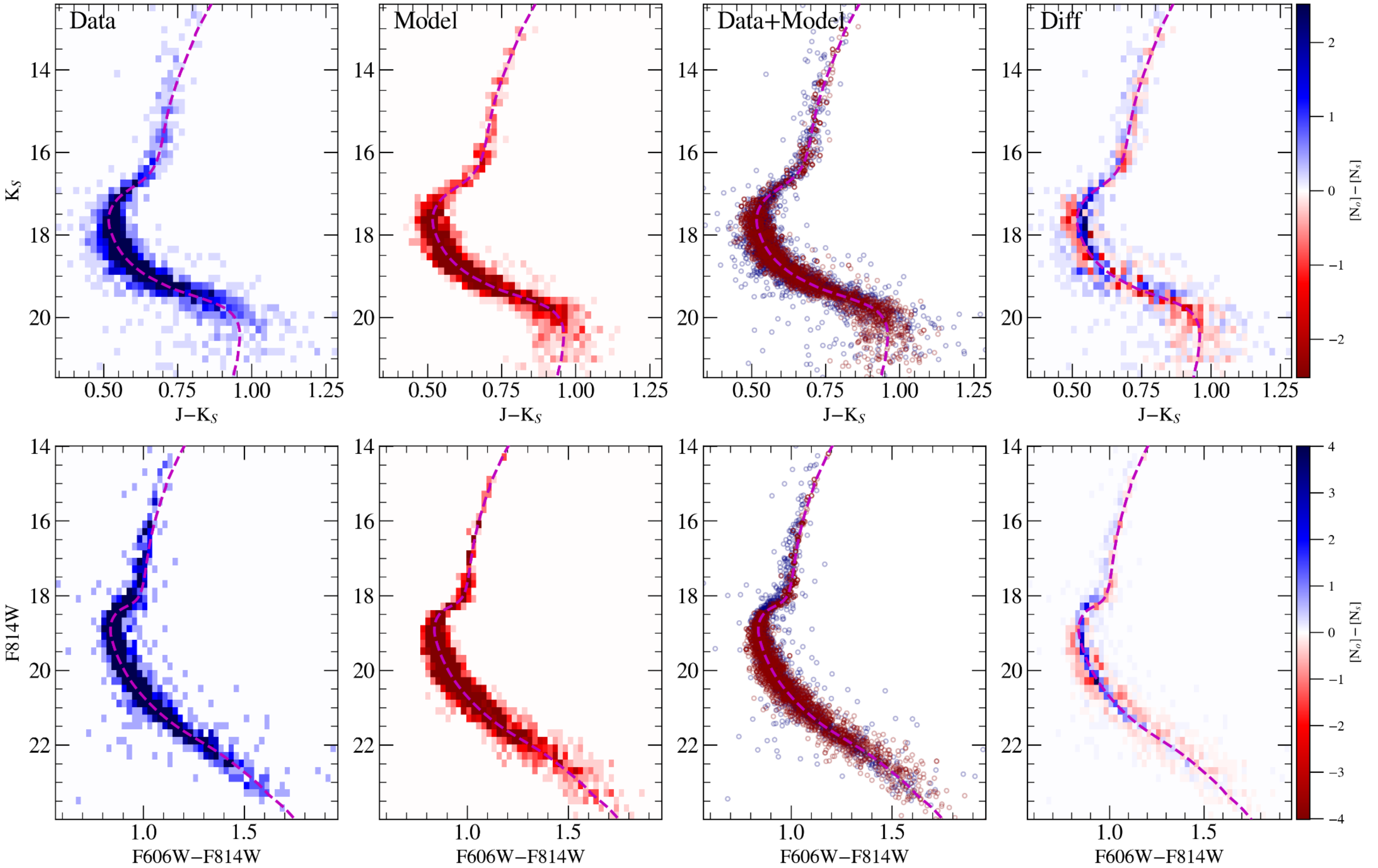
A main uncertainty: distances

Example:
Palomar 6: = d_{Sun} = **5.8** kpc (Harris)→ thick disc
d_{Sun} = **8.9** kpc (Ortolani+95) → bulge.

Using Harris=Baumgardt +19, Pérez-Villegas+20
→thick disc with a probability of 98%.

Souza+21: Age=12.4 ± 0.9 Gyr,
d_{Sun} = **7.67** ± 0.19 kpc → bulge

The same discrepancy with NGC 6558: Gaia BV21: 7.47 kpc,Souza+24: 8.5 kpc



➔ Deep Optical and NIR isochrone fitting needed

Gaia distances are uncertain for distances above ~6 kpc

Gaia data – Orbits + chemistry

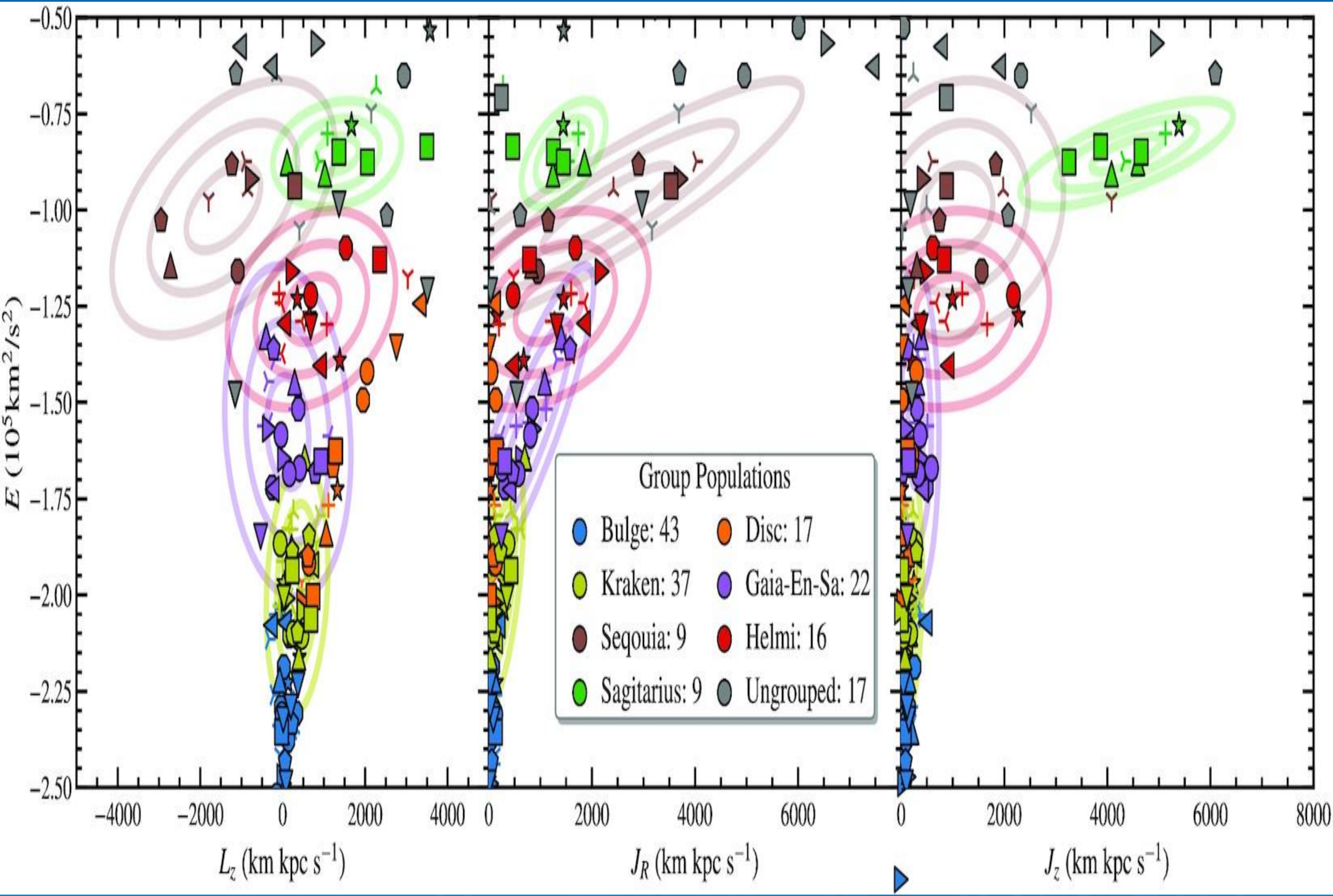
Six-dimensional phase space, calculation of Integrals of Motion (IOM):

Studies on orbits and corresponding Energy vs. Angular momentum L_Z.

Massari+2019, Kruijssen+2019,2020, Forbes(2020),Callingham+2022.

Orbits: Pérez-Villegas+2020.

➔ Classification of clusters to progenitors



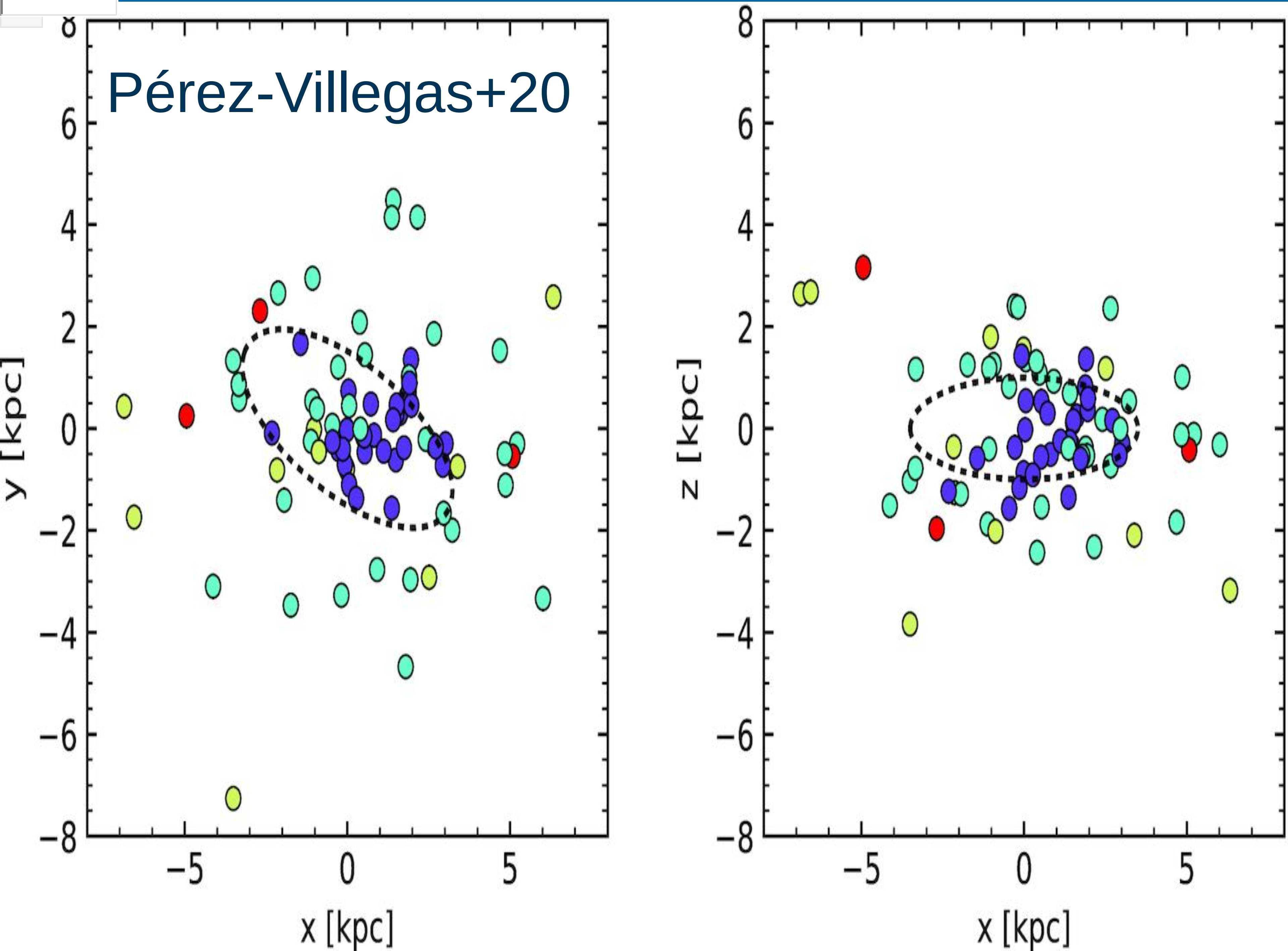
Integrals of motion -Callingham et al. 2022

The BAR

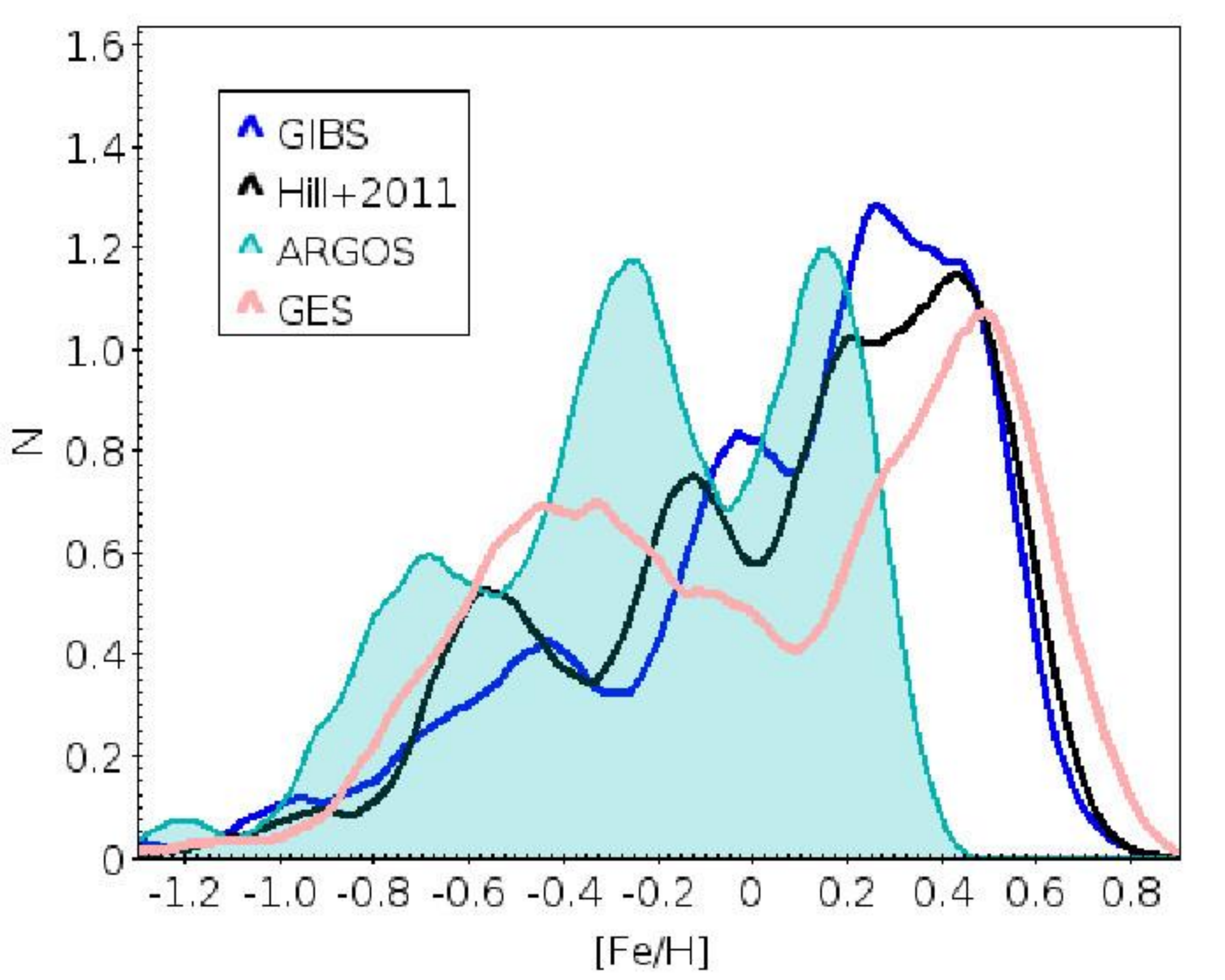
Buck+18: Galaxy’s bar 8 ± 2 Gyr ago.
Bovy+18 : ~8 Gyr ago.
Nepal+24: ~3 Gyr ago.
Sanders+24: ~8-11 Gyr ago (Mira´s in NSD)

Pérez-Villegas+20:
GCs are in the bar ➔ trapped by the bar
Most are not supporting the bar structure

7 clusters that are supporting the bar ➔ do not necessarily support the X-shape.


Pérez-Villegas+20
y [kpc]
x [kpc]
z [kpc]
x [kpc]
8
6
4
2
0
−2
−4
−6
−8
−5
0
5

Metallicity distribution function - MDF

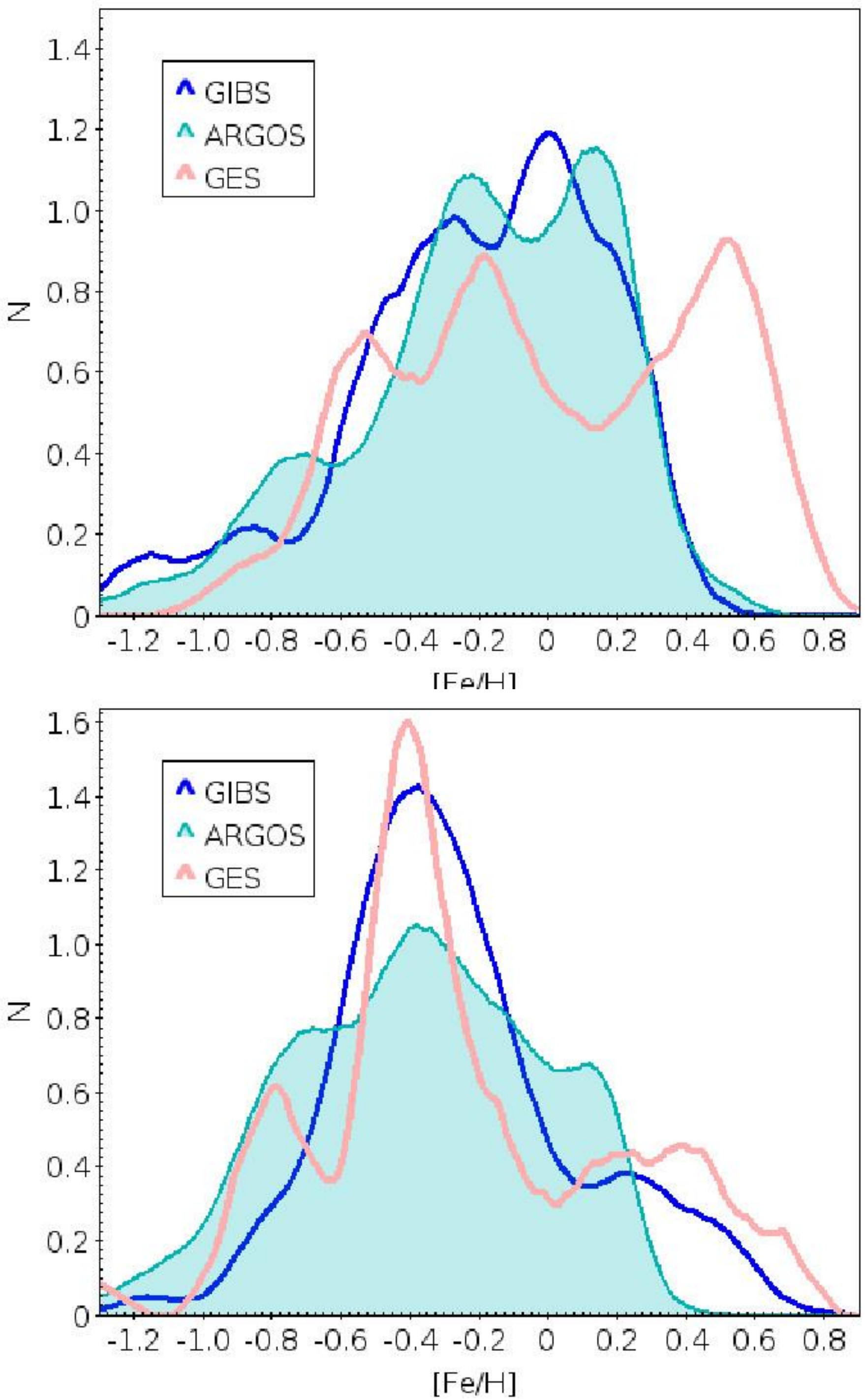


BW

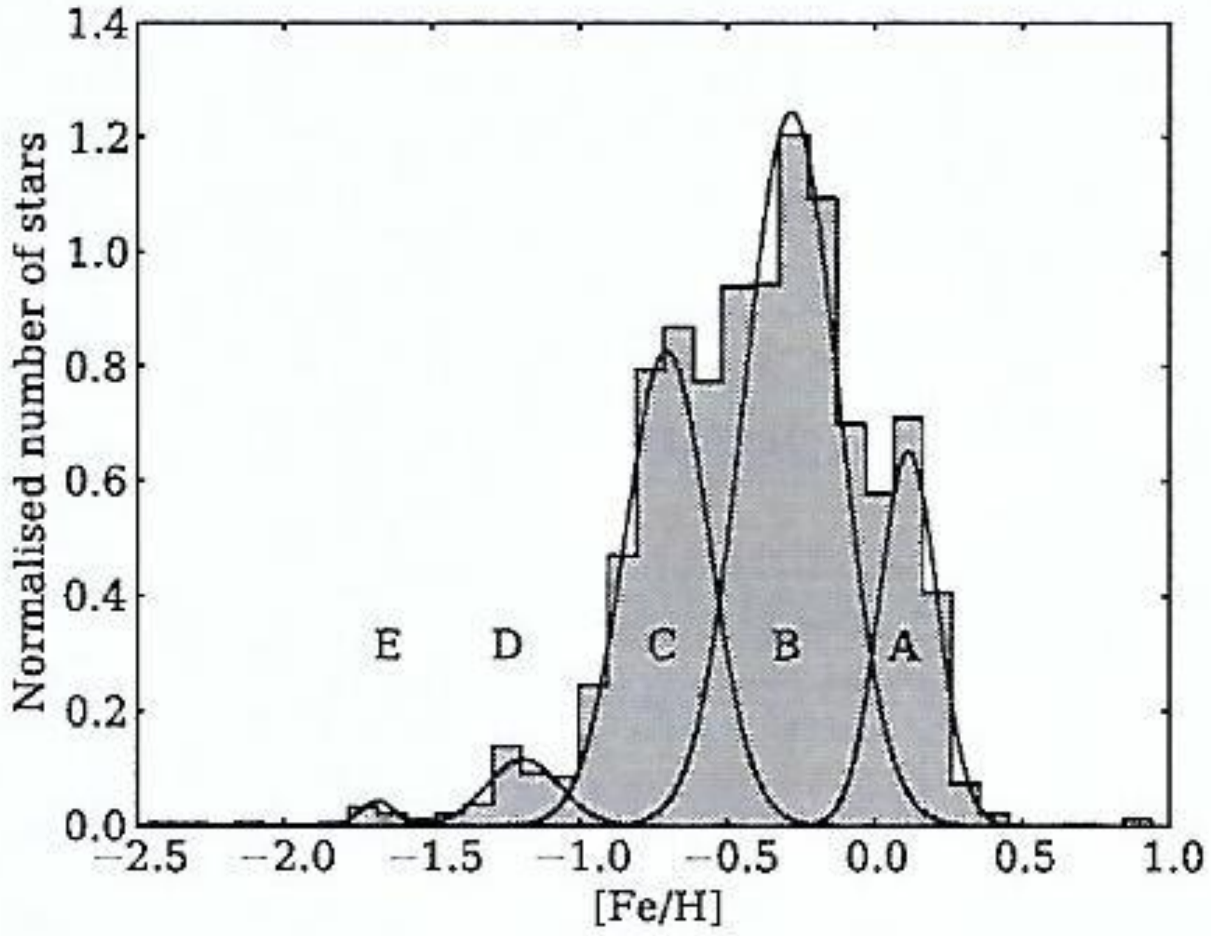
Barbuy, Chiappini, Gerhard18

-6º

-8º



Ness+13

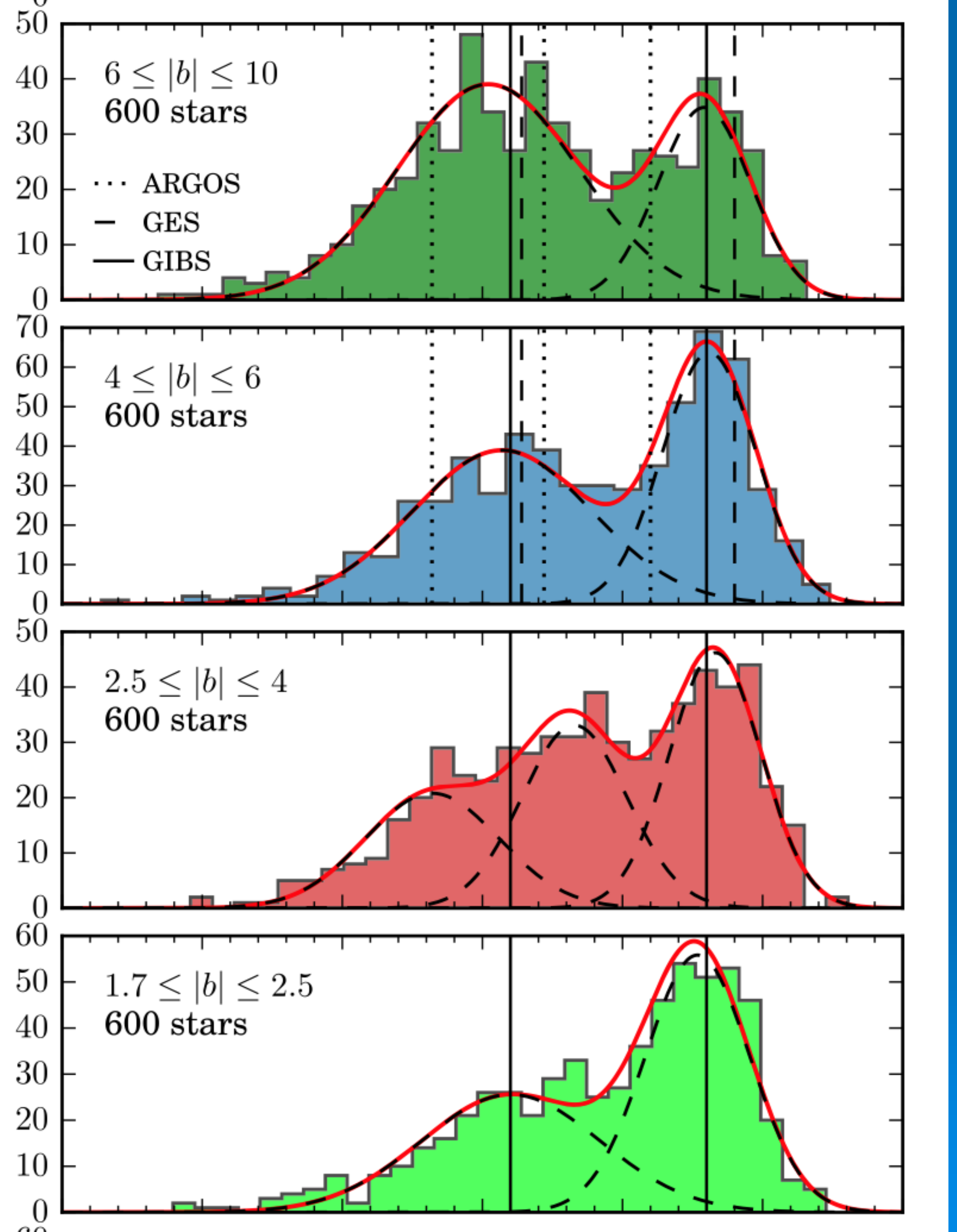


(b) $l \pm 15°, b = -7.5°$

Rojas-Arriagada+20

APOGEE MDF
vs
Surveys

[Fe/H] = +0.32, −0.17, −0.66 dex



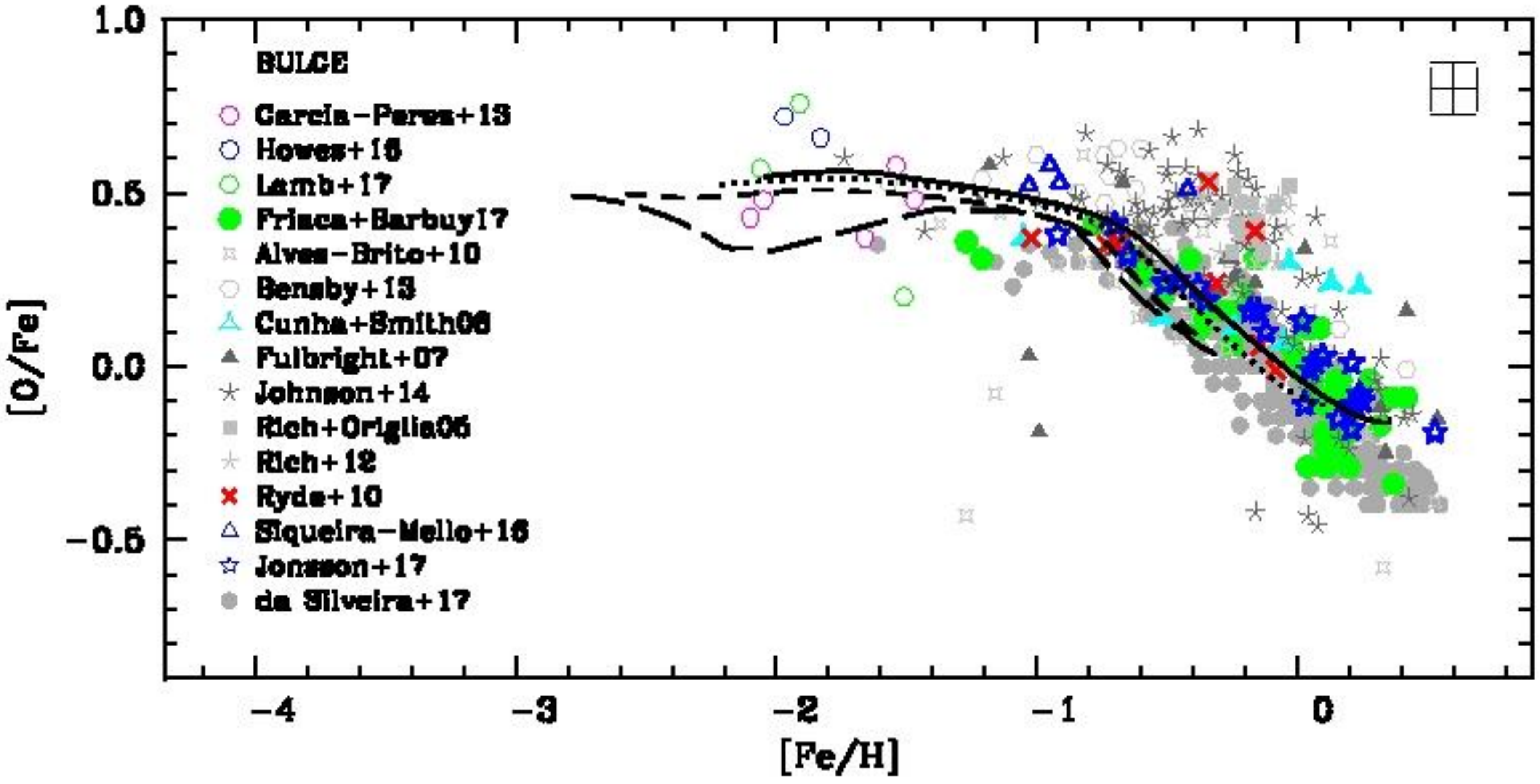
Chemical enrichment & Nucleosynthesis

α-elements: O, Mg, Si, Ca, Ti:
Supernovae type II = CCSNae

Iron-peak: Fe, Ni → Supernovae type Ia (+1/3 from SNII)

Heavy elements: SNII at explosion, merging of NS, BHs (r-elements)

Bulge field – Barbuy+18 ARA&A, 56, 223
SFR = 2 Gyr



Looking closer →

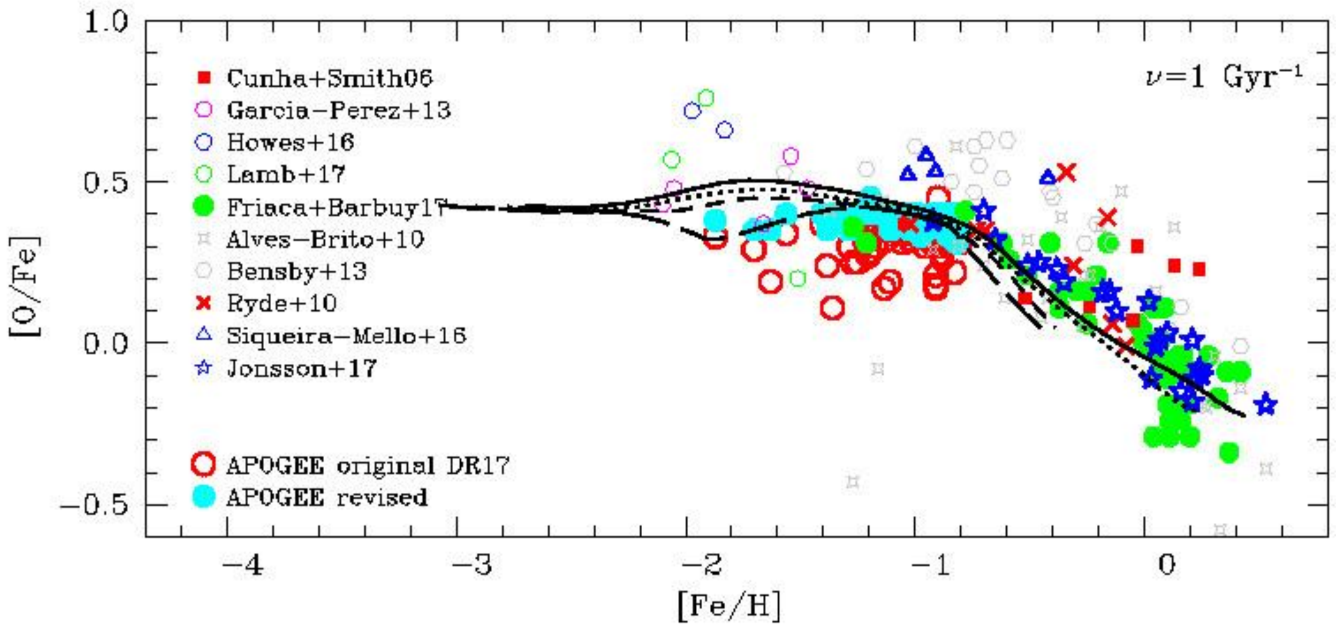
58 stars of Bulge spheroid

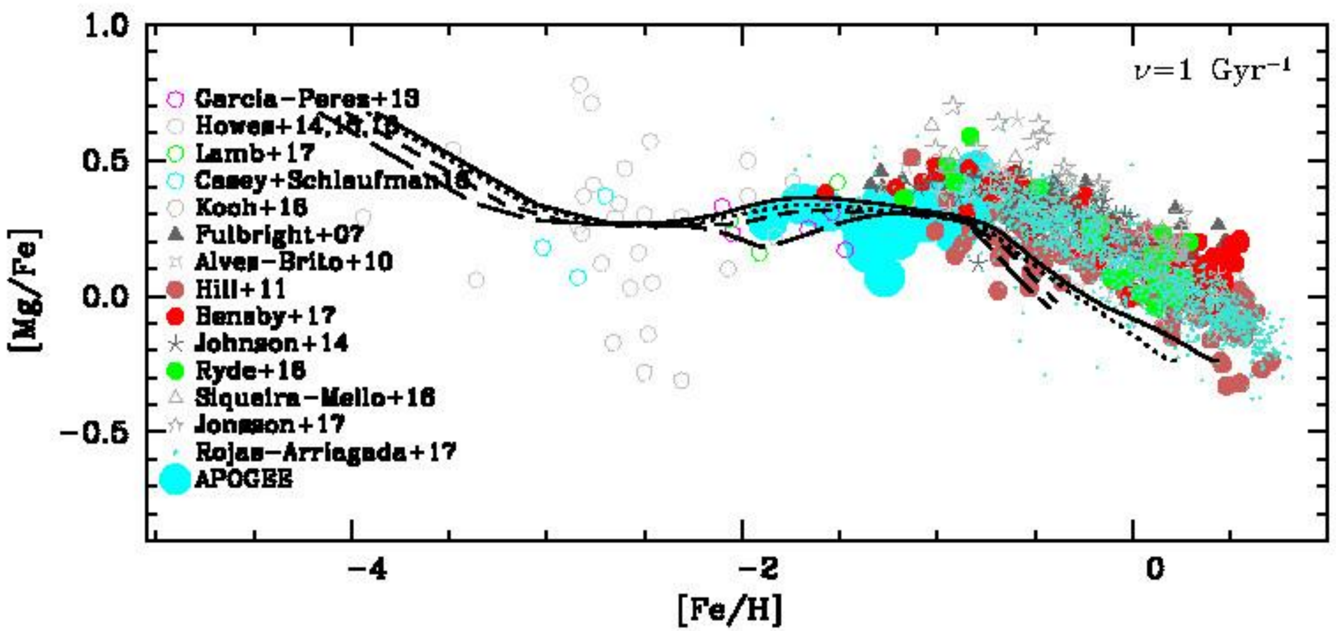
SFR = 1 Gyr

sSFR

v = 1Gyr^{-1}

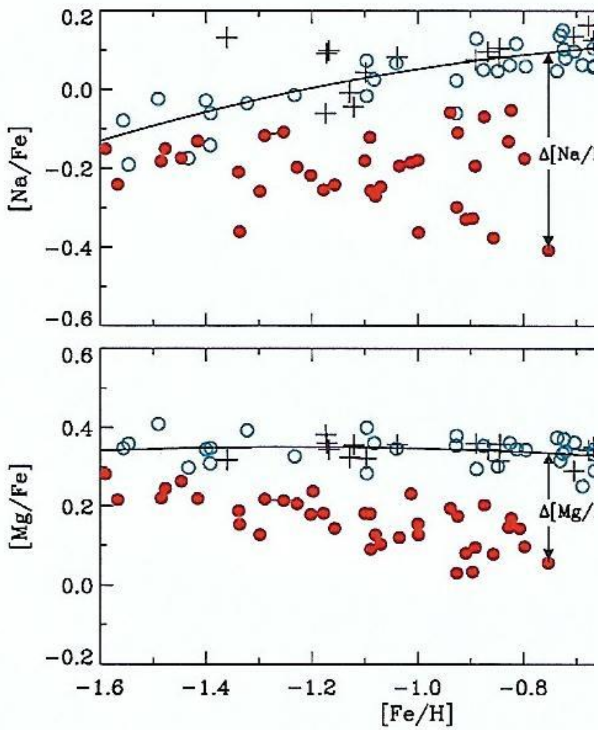
Models from A. Friaça

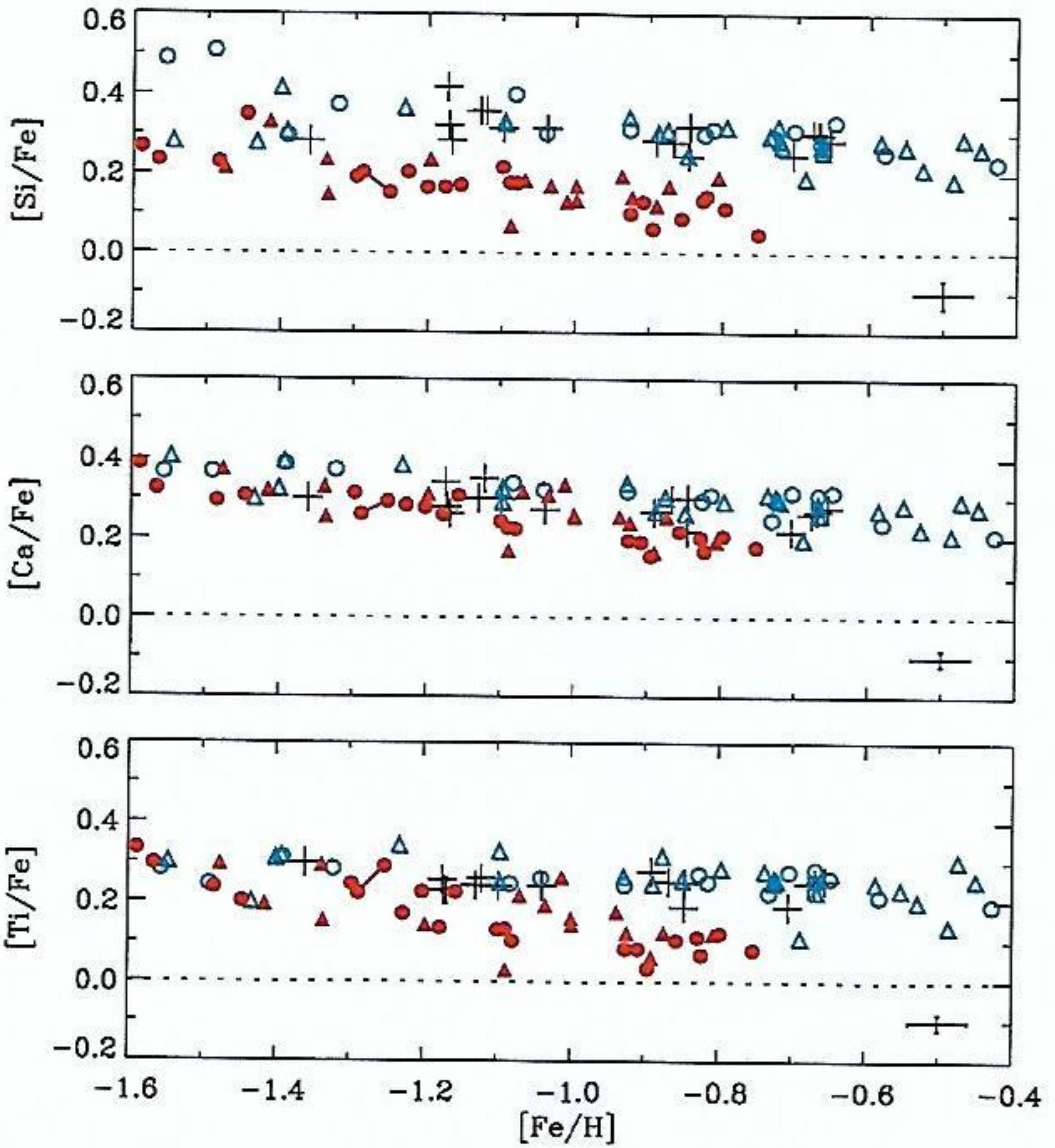




Nissen+ Schuster10

α´s Mg,Si,Ca, "Ti"





Nissen+ Schuster10

Odd-Z Na

Iron-peak
 Cr, Ni

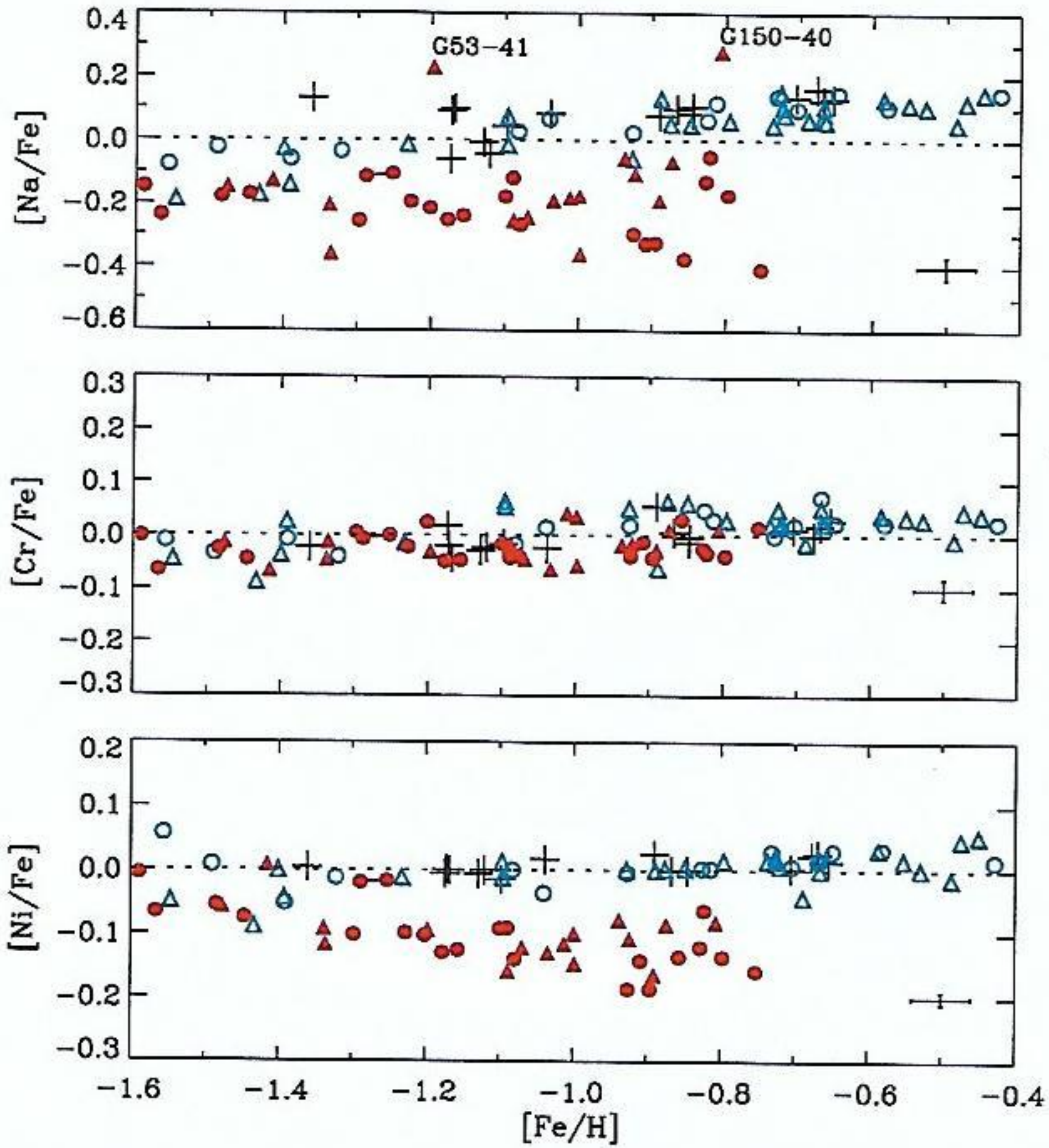
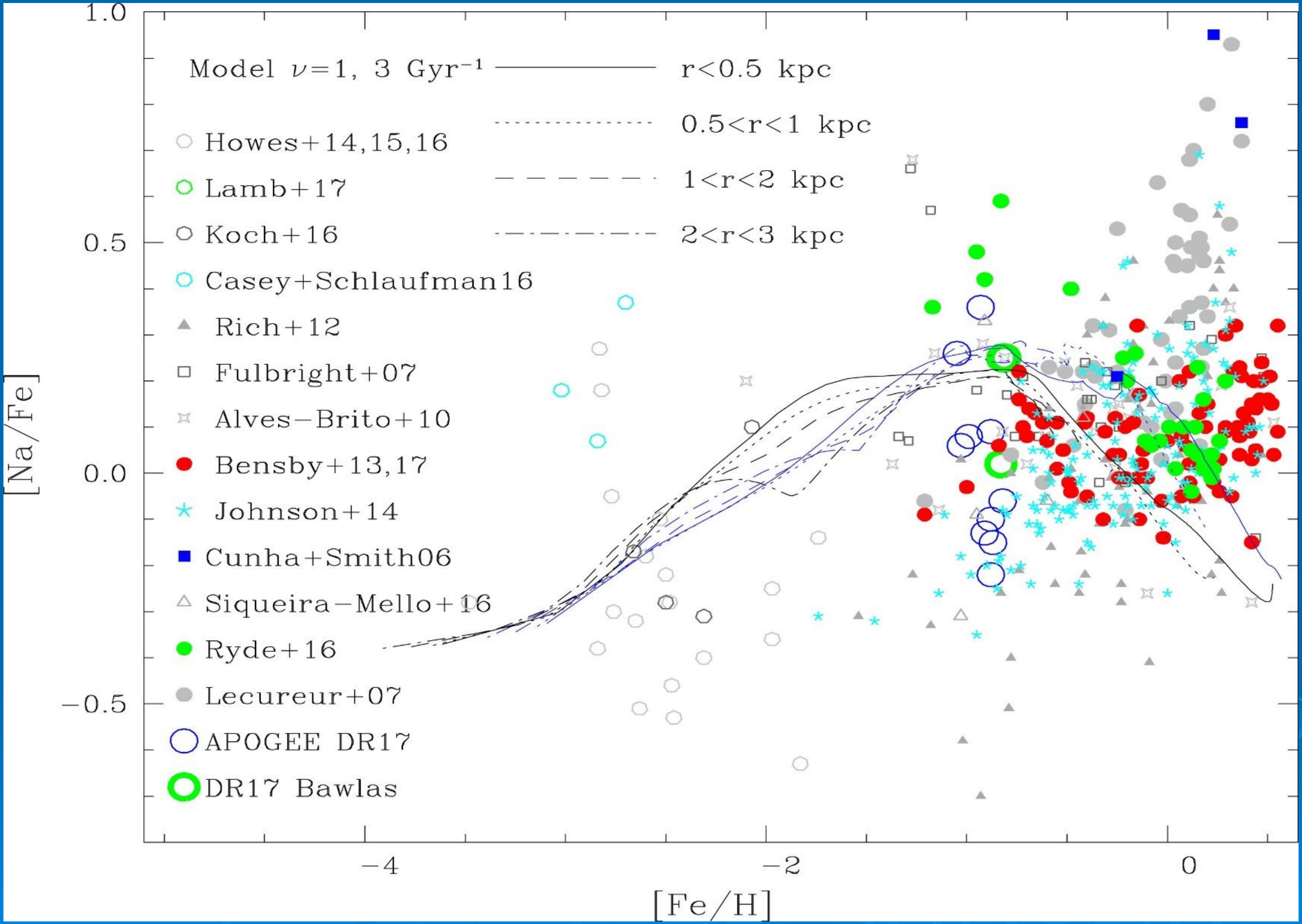


Figure 4. Na/Fe] versus [Fe/H] for literature bulge field stars and 11 APOGEE aspcap DR17 abundances, plus 4 BAWLAS ...

Barbuy +2023



Mon Not R Astron Soc, Volume 526, Issue 2, December 2023, Pages 2365–2376, https://doi.org/10.1093/mnras/stad2888

OXFORD UNIVERSITY PRESS

Smiljanic+16: over 1000 disk stars (Gaia-ESO)

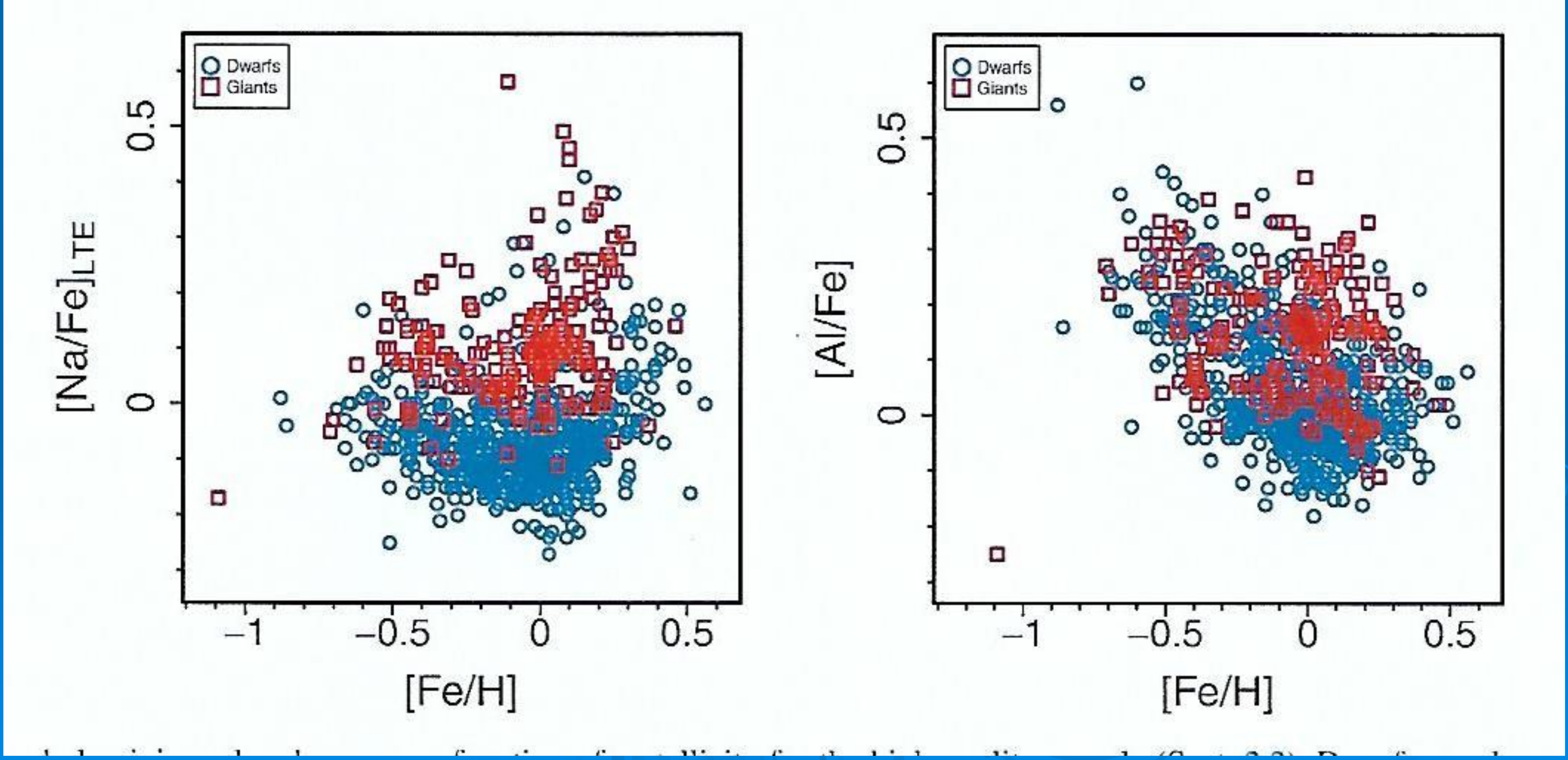
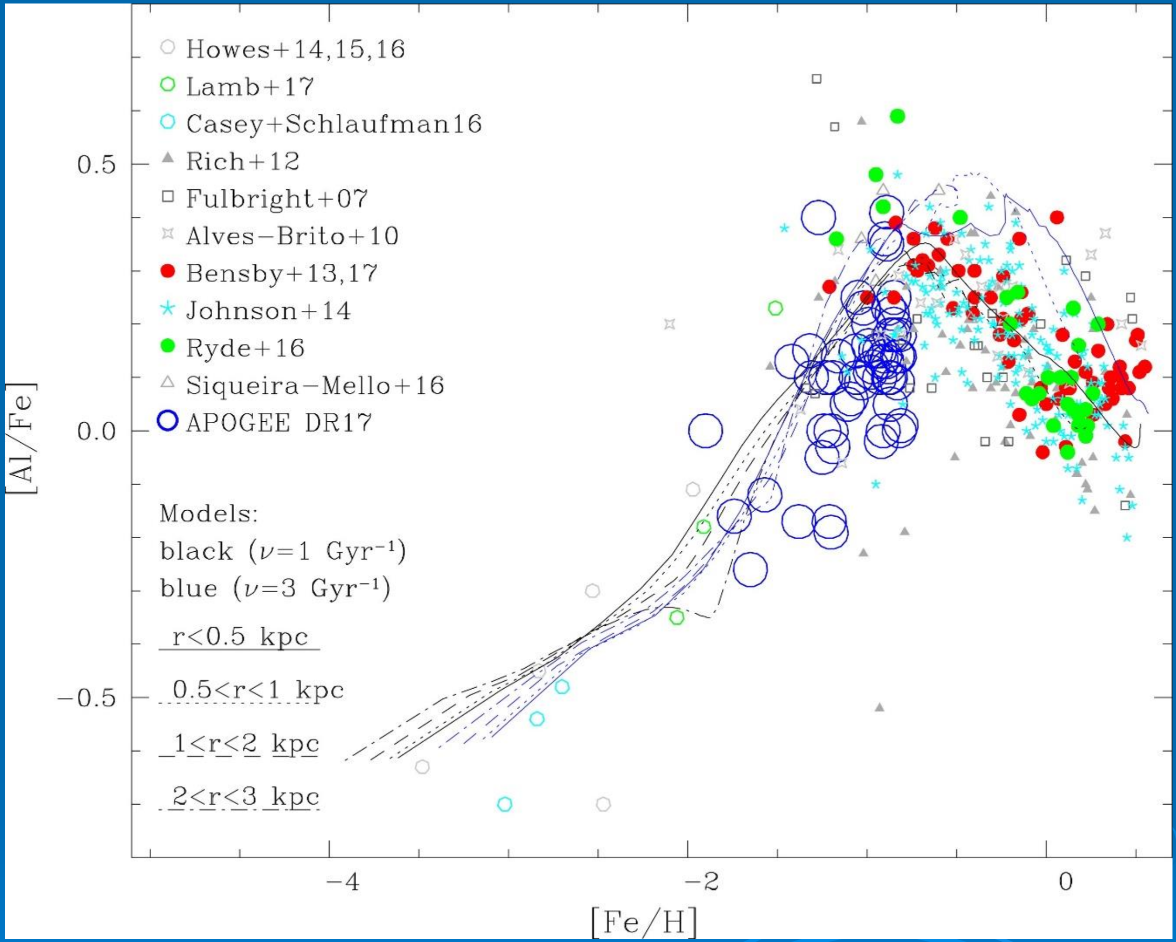


Figure 5. [Al/Fe] versus. [Fe/H] for literature bulge field stars and the APOGEE abundances (original DR17) for the 58 ...

v = 1,3 Gyr^{-1}

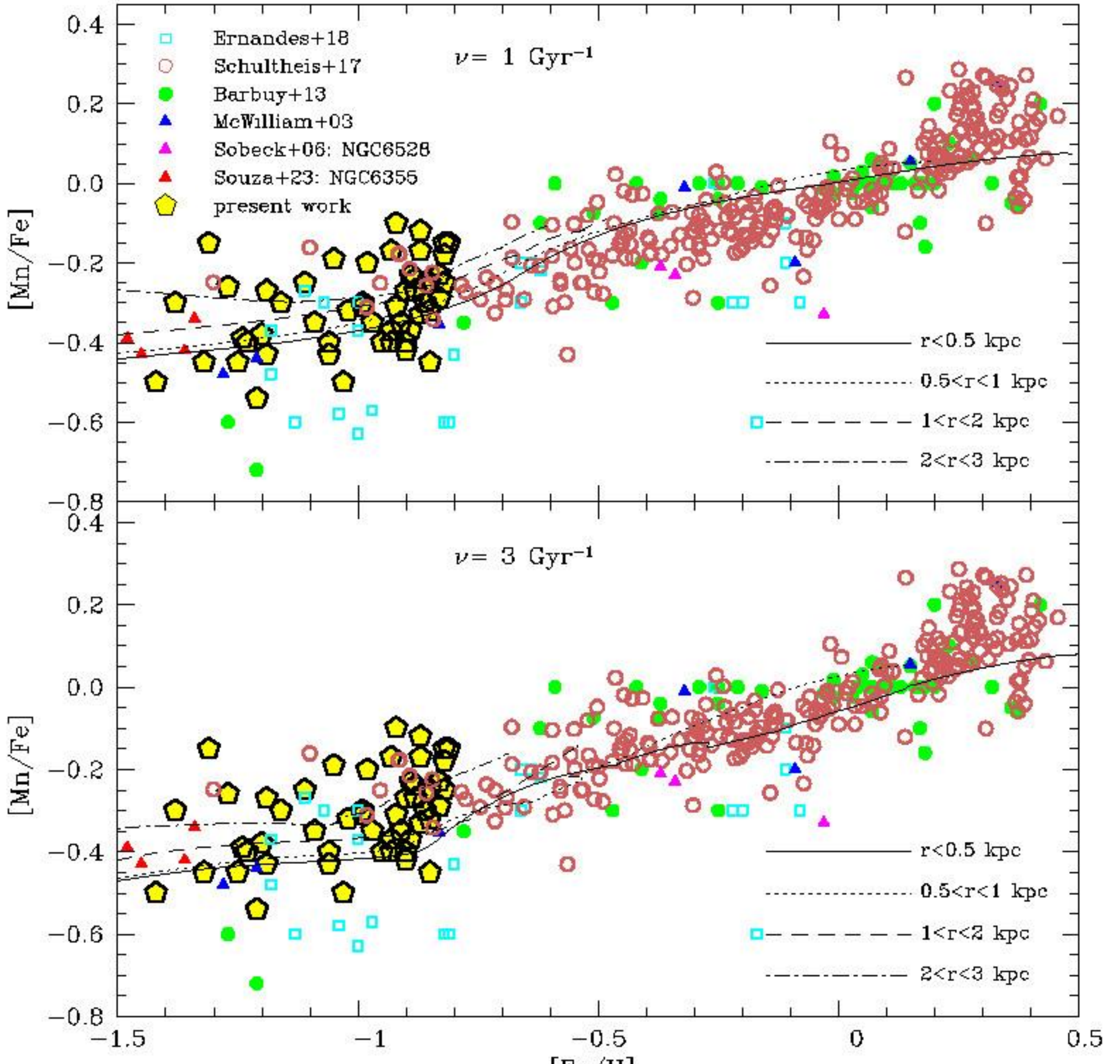
SFR in Mo Gyr−1 M gas

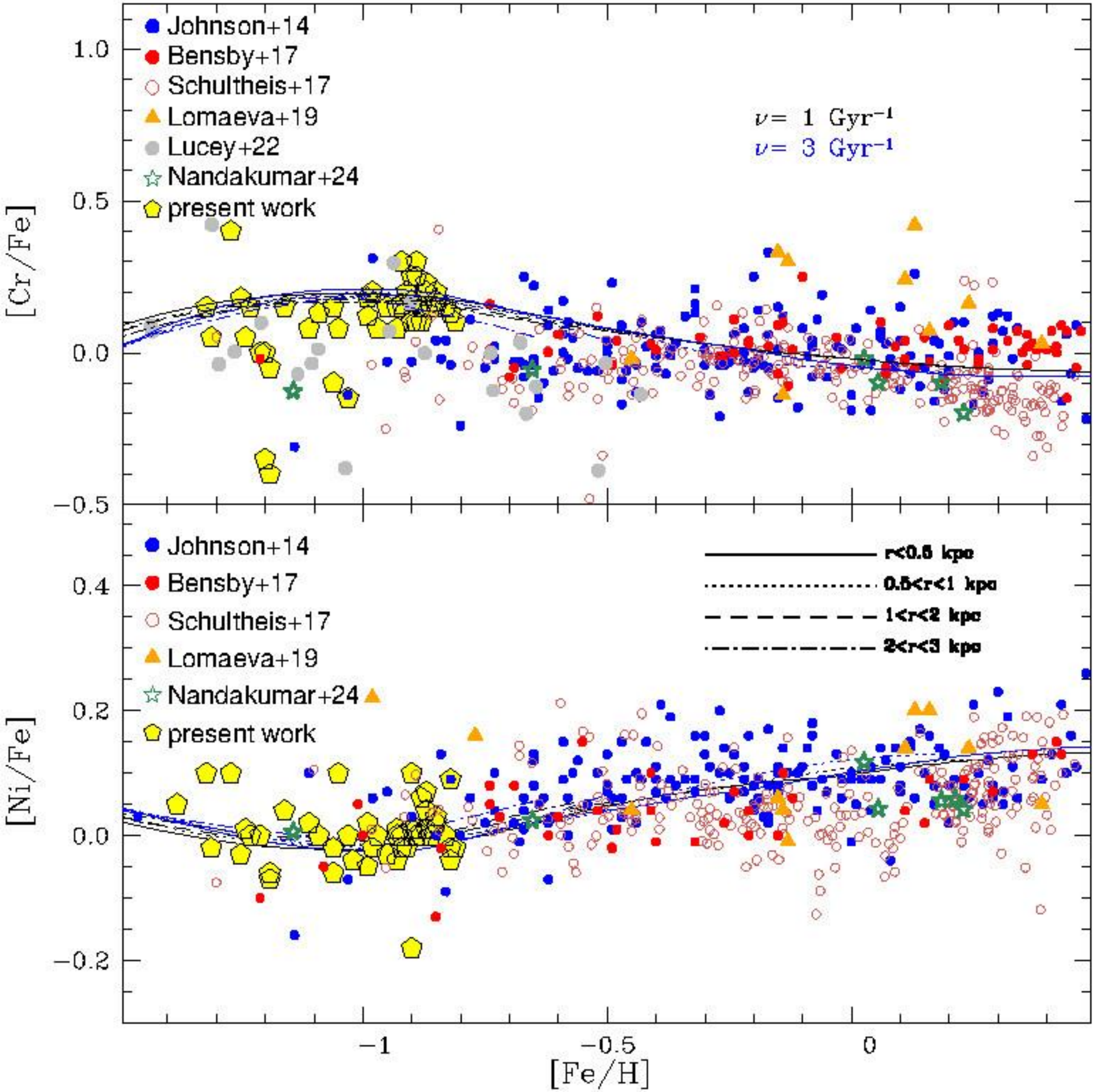


Mon Not R Astron Soc, Volume 526, Issue 2, December 2023, Pages 2365–2376, https://doi.org/10.1093/mnras/stad2888

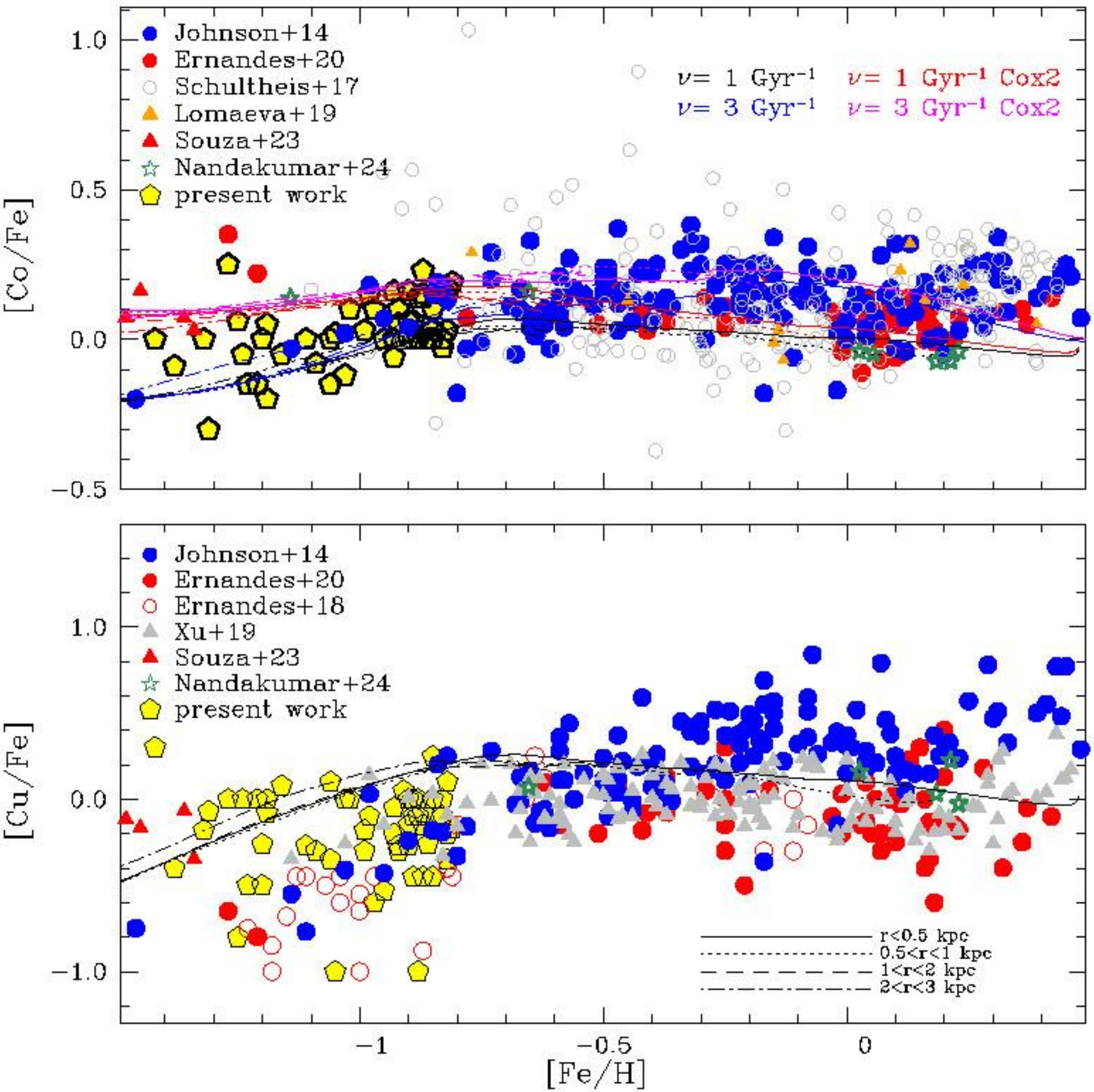
Barbuy, Friaça+24

58 bulge stars

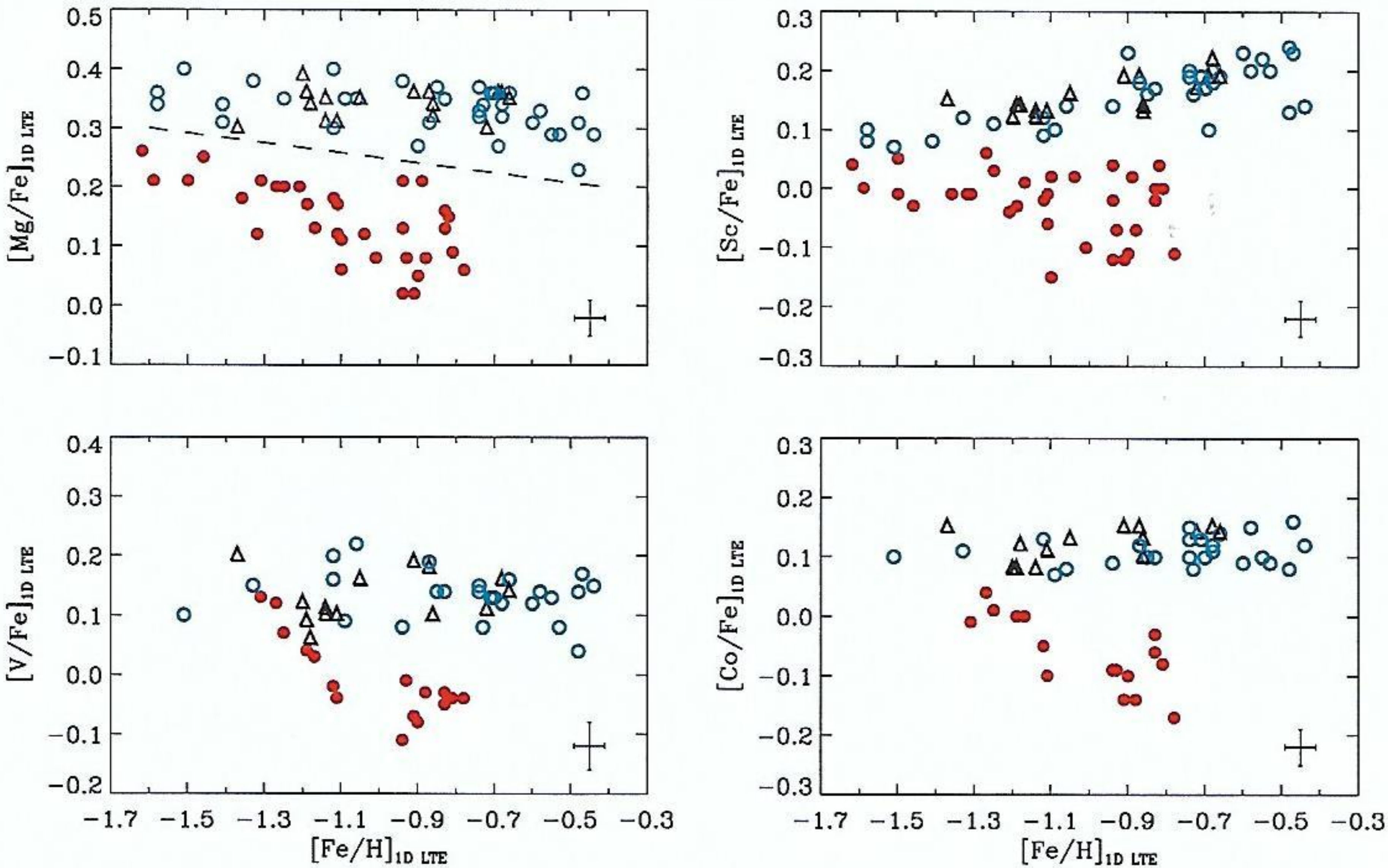


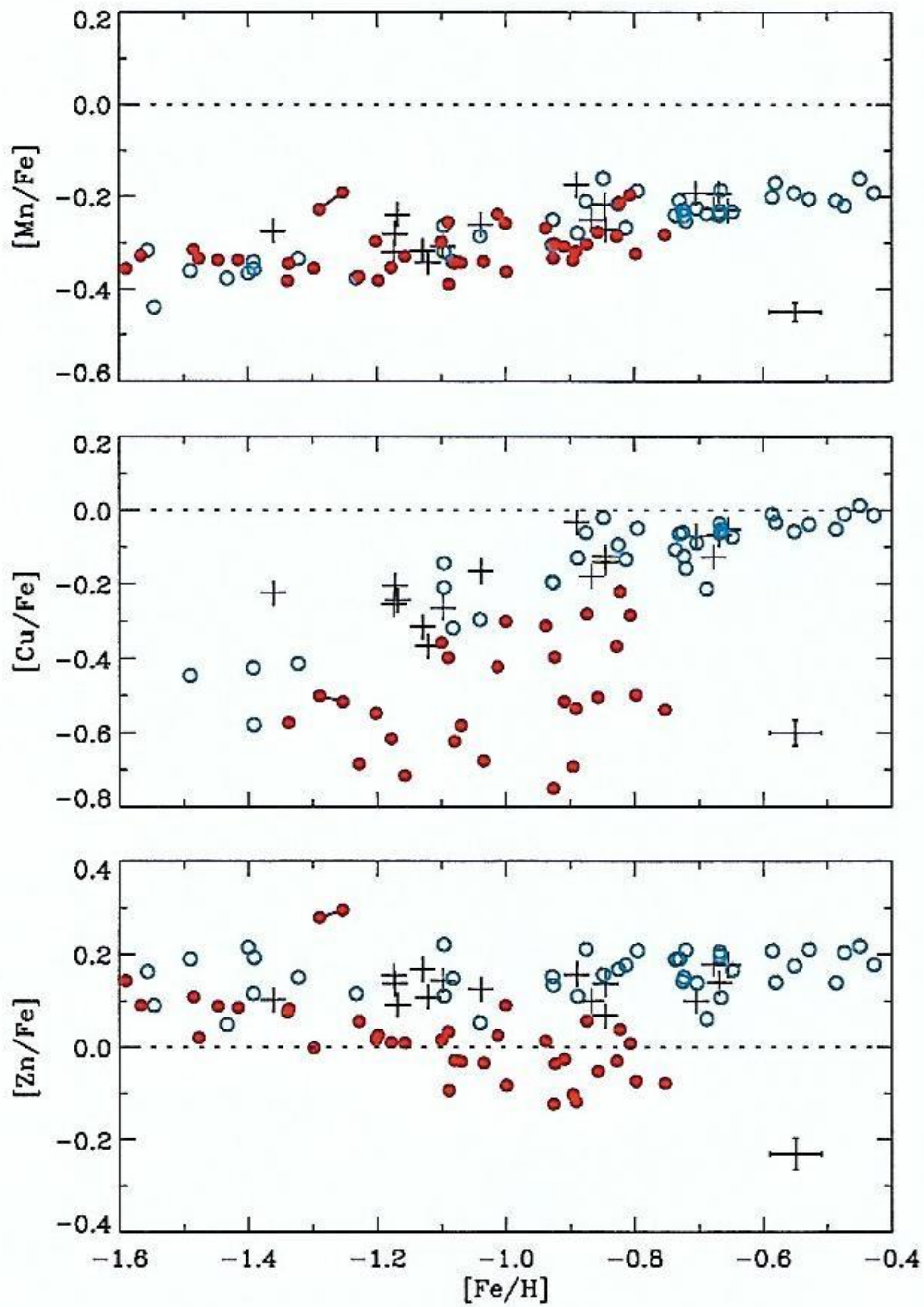


Johnson+14
Bensby+17
Schultheis+17
Lomaeva+19
Lucey+22
Nandakumar+24
present work
ν= 1 Gyr⁻¹
ν= 3 Gyr⁻¹
[Cr/Fe]
1.0
0.5
0.0
−0.5
Johnson+14
Bensby+17
Schultheis+17
Lomaeva+19
Nandakumar+24
present work
r<0.5 kpc
0.5<r<1 kpc
1<r<2 kpc
2<r<3 kpc
[Ni/Fe]
0.4
0.2
0.0
−0.2
−1
−0.5
0
[Fe/H]

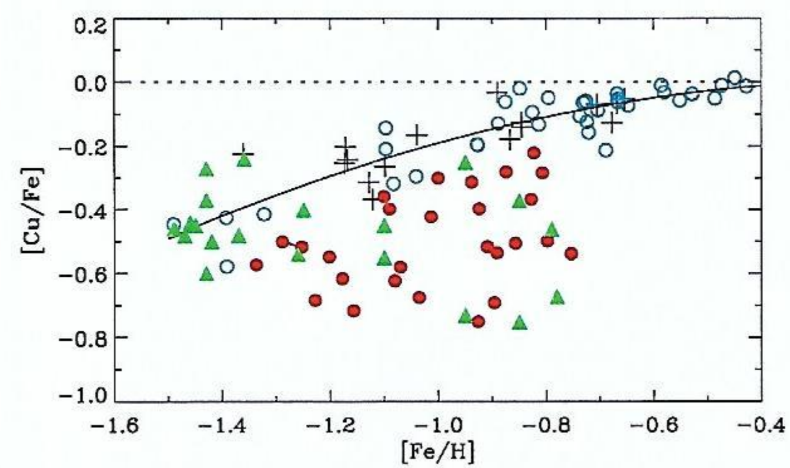

Johnson+14
Ernandes+20
Schultheis+17
Lomaeva+19
Souza+23
Nandakumar+24
present work
ν= 1 Gyr^{-1}
ν= 3 Gyr^{-1}
ν= 1 Gyr^{-1} Cox2
ν= 3 Gyr^{-1} Cox2
[Co/Fe]
1.0
0.5
0.0
−0.5
Johnson+14
Ernandes+20
Ernandes+18
Xu+19
Souza+23
Nandakumar+24
present work
[Cu/Fe]
1.0
0.0
−1.0
r<0.5 kpc
0.5<r<1 kpc
1<r<2 kpc
2<r<3 kpc
−1
−0.5
0
[Fe/H]

Nissen+24: α:Mg, iron-peak: Sc, V,Co



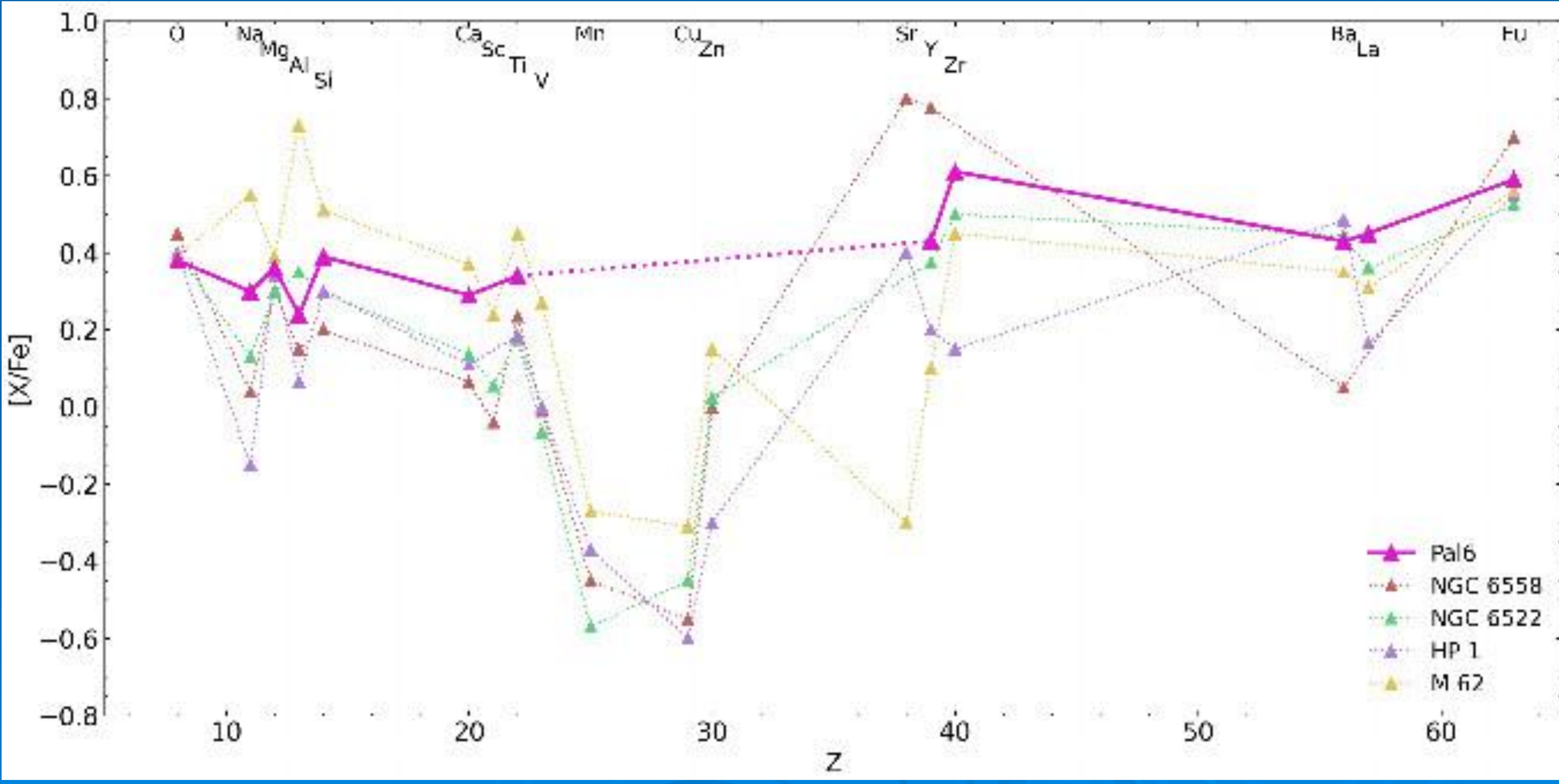


[Mn/Fe]
[Cu/Fe]
[Zn/Fe]
[Fe/H]



[Cu/Fe]
[Fe/H]

Abundance pattern bulge GCs (Souza+21)



Conclusions:

Bulge formation: probably a mix of scenarios

Stellar populations: a mix of a small early bulge, inner thin & thick disk, halo, + accreted dwarfs + bar (Queiroz+20,21)

Bulge is old but a fraction of younger stars is possible, mainly among metal-rich bar ones
➔ but He is not know, and needed for age

Continued Conclusions:

Bulge GCs are old: 12.3 to 13.5 Gyr.

Old globular clusters: formed in-situ very early

Later trapped in the bar (Pérez-Villegas+2020)
➔ possibility to have formed the
GCs in the bar? ➔only if bar formed very early

MDF: +- agreement on metallicity peaks

Continued Conclusions:

Abundances of α´s: Mg, Si, Ti (not Ca), Na, iron-peak:Sc, V, Mn, Co, Ni, Cu, Zn (not Cr) can indicate in-situ or ex-situ origin

Chemical Evolution models with a fast star formation rate of 1 Gyr do reproduce the observed abundances.

Challenges:

Measurement of He abundances vs. age

High-resolution spectroscopy of turn-off stars (and subgiants) => crowding

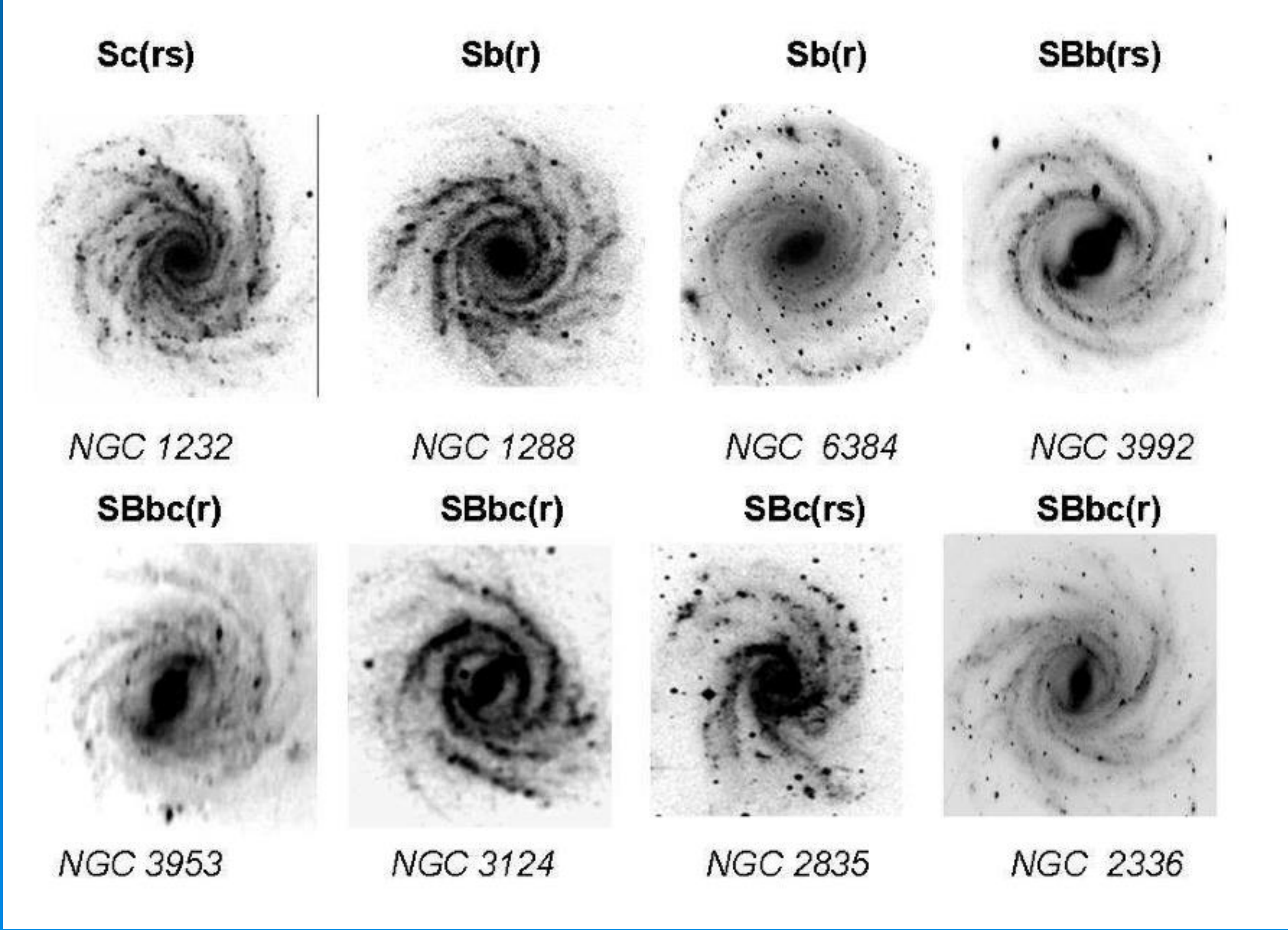
Most primitive stars in the proto-MW: metal-poor ? or in fact the moderately metal-poor? Inner halo vs bulge

More important mechanism to form the bulge?

Early bulge (1Gyr) vs. accreted ? in situ vs. ex situ

MW: SBbc(rs)
Sb ?

Bland-Hawthorn+Gerhard ARA&A 2017



The End