OLDEST STARS IN THE GALACTIC BULGE

Beatriz Barbuy

IAG - Universidade de São Paulo

OUTLINE

- Bulge Formation
- Age of bulge globular clusters
- Orbits: bulge vs. halo/thick disk intruders
- Metallicity distribution function
- Metal-poor stars in the Galactic bulge
- CEMP stars
- Fast star formation rate
- Abundances in field and GC stars

Kormendy & Kennicutt ARA&A 2004:

BULGES OF SPIRALS:

Sa, Sb = high mass = bulges

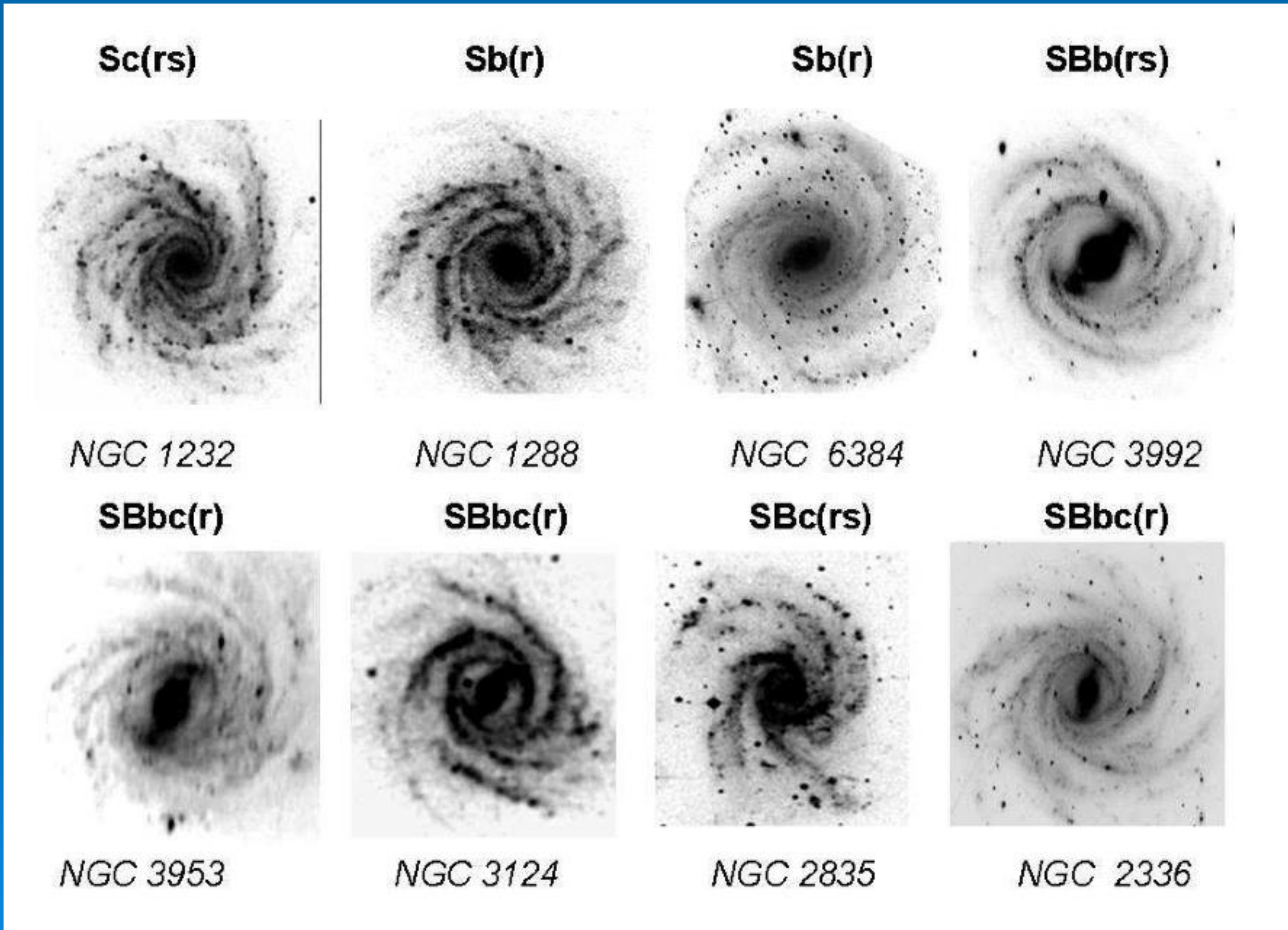
Sc = pseudobulges formed from the bar

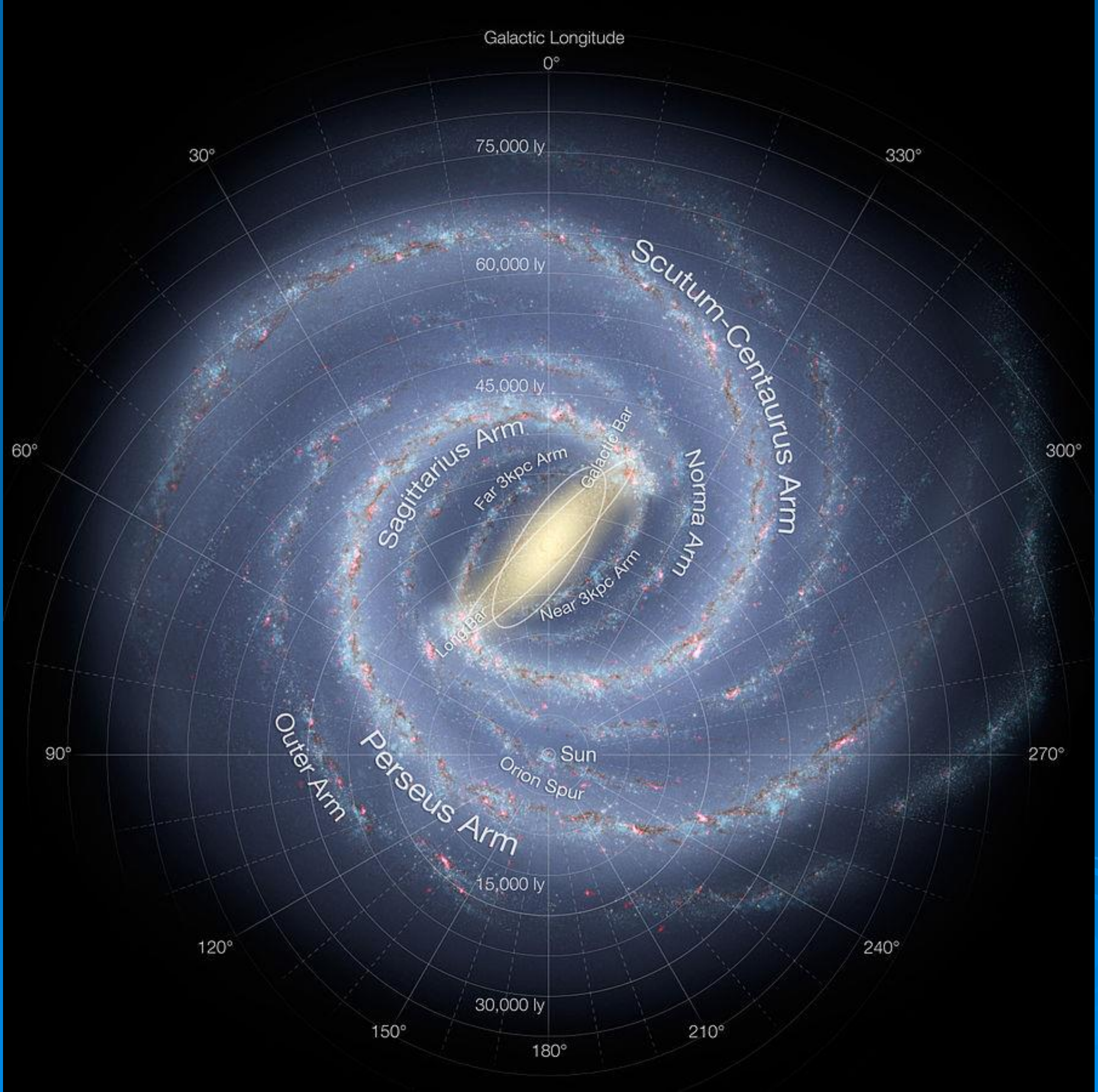
Milky Way

Barred:
SABbc(rs) ➔ SABb(rs)

Classical bulge or
Pseudobulge formed entirely
from the bar?

Bland-Hawthorn & Gerhard 2016, ARA&A





Galactic Longitude
0°
30°
330°
60°
300°
90°
270°
120°
240°
150°
180°
210°
75,000 ly
60,000 ly
45,000 ly
15,000 ly
30,000 ly
Scutum-Centaurus Arm
Sagittarius Arm
Far 3kpc Arm
Galactic Bar
Norma Arm
Near 3kpc Arm
Long Bar
Outer Arm
Perseus Arm
Sun
Orion Spur

Formation of bulges

Redshift z~2 → 10 Gyr → bulges in formation

Evidence show bulges already formed, with no star formation in the center, only in the surrounding disk (Tacchella+15, Nelson+16)

Disks had much more gas than now, of the order of 50% →

Tacconi+18: quantity of gas scales with redshift: $(1+z)^{2.6}$

galaxies are more compact, effective radius scaling with $(1+z)^{-1}$ (Newman+12)

Therefore surface gas density scales with: $(1+z)^{4.6}$

➔ Probably the property of galaxies that evolve most rapidly (Renzini+18).

Scenarios of bulge formation

1. Classical = central collapse

$t_{free\text{-}fall} \sim (G\rho)^{-1/2}$

→ bulge forms first, in $\sim 10^8$ yr

→ this was a super-simplification → but several recent models with bulge forming first

2. Evolution of the bar → transfer of gas and stars to the center of the Galaxy, leading to bulge formation

Several models in the lines of option 1:

Bulges form first

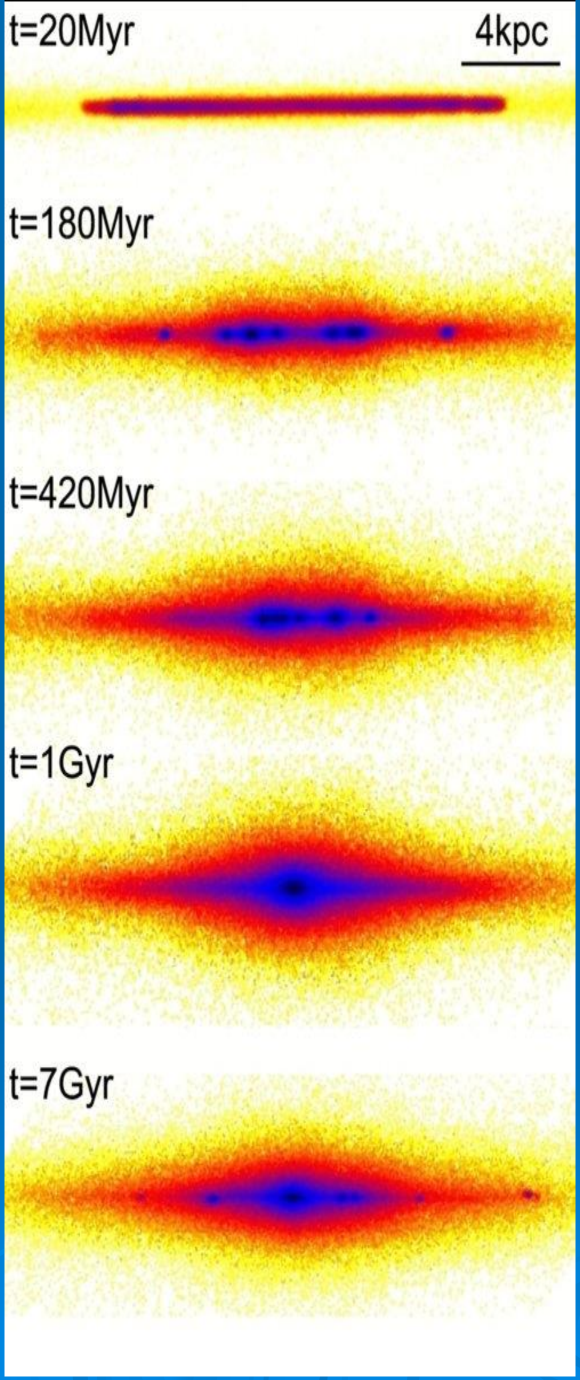
➔ old bulge (13 Gyr)

Clumps migrate and coalesce in the centers of protogalaxies (Bournaud)

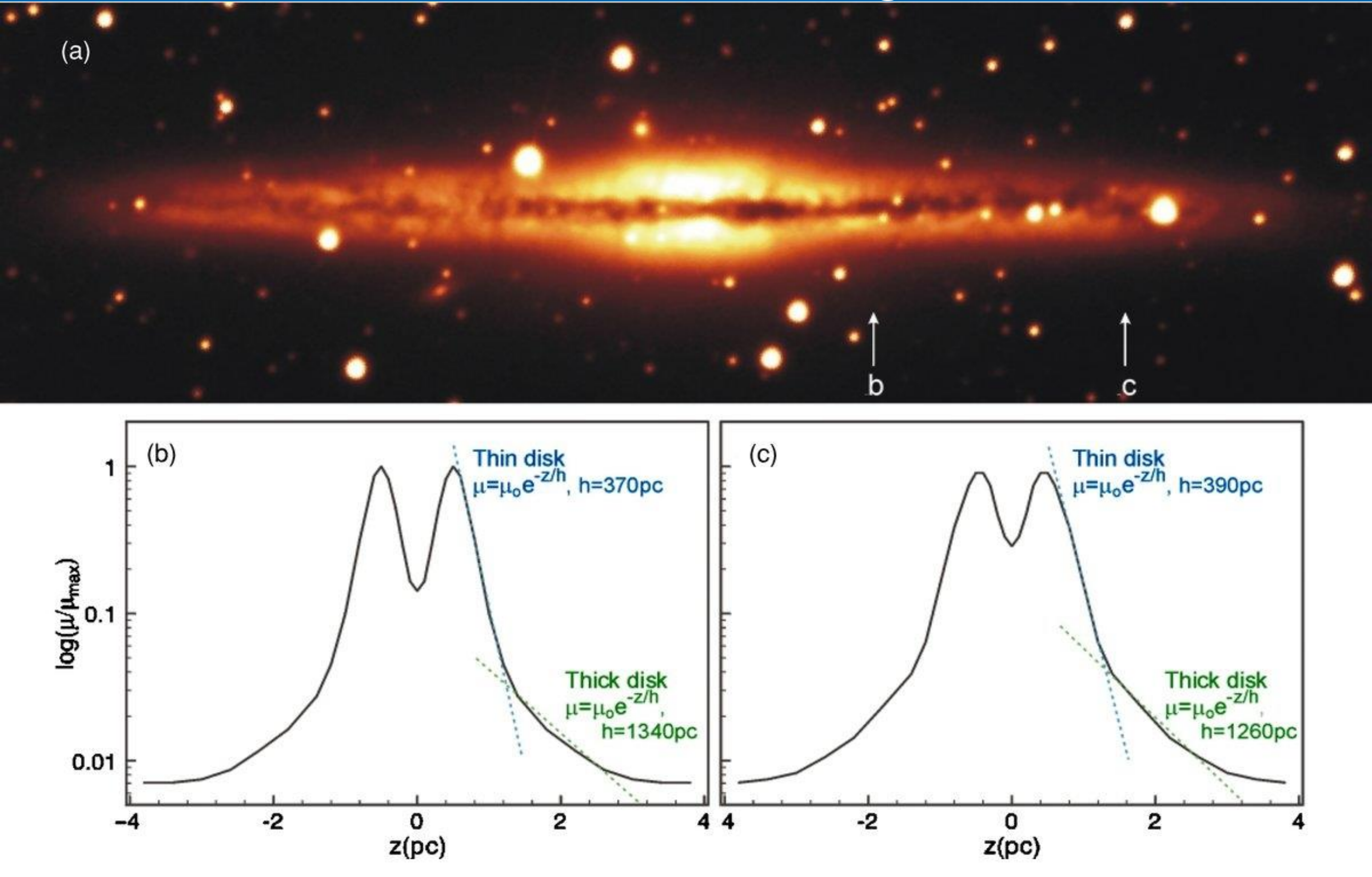
Turbulent instabilities of disks, leading to intense star formation (Dekel & Burkert14, Tacchella+16).

Bournaud et al. 2009

Clouds of gas coalesce



Bournaud, Elmegreen, Martig 2009, ApJ 707, L1
NGC 891 – analog to Via Lactea

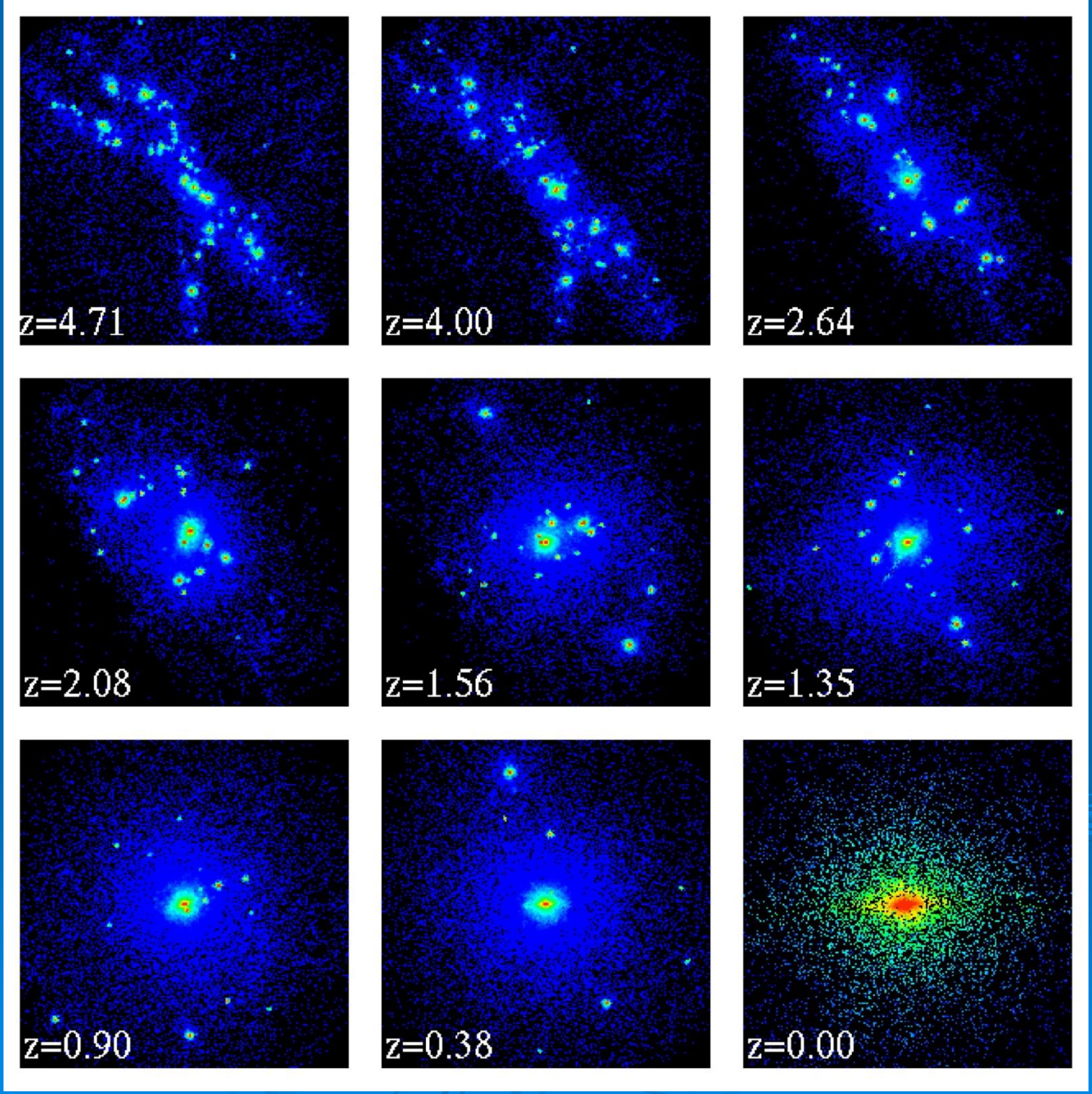


Cosmological simulations in ΛCDM:

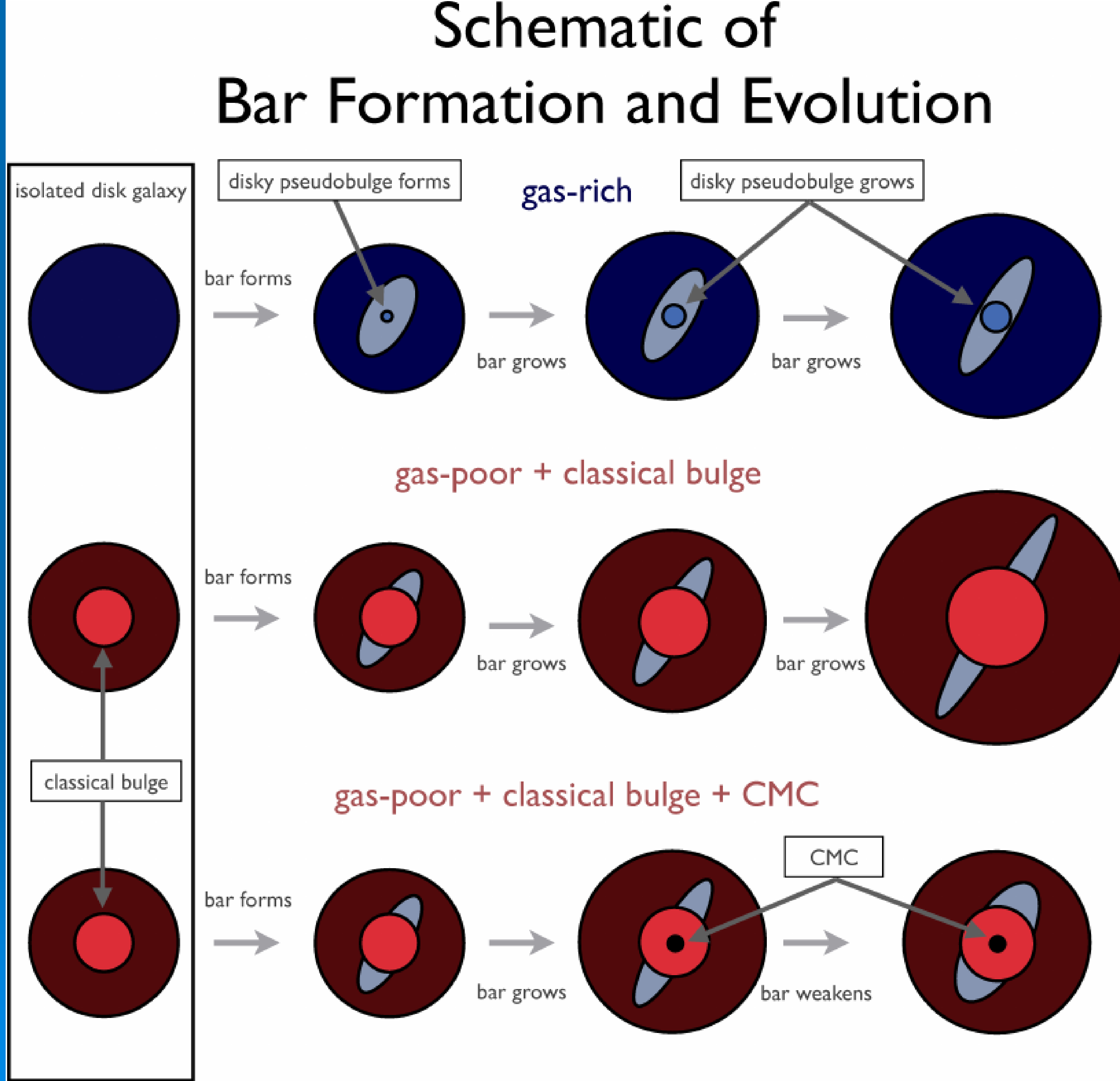
Formation of small disks of dark matter:

→ these disks coalesce
→ gas falls in these potential wells due to gravity
→ bulges form first

Abadi



CMC = Central Mass Concen- tration



The formation of the bar and buckling in the MW are confirmed, given its box/peanut shape.

But this has probably occurred more recently, when there was already little gas → in this case bulge was already formed (Renzini+18)

Age of MW bar:

Buck+2018: models

Bovy+2019:Gaia+APOGEE

➔ 8 Gyr

Oldest stars: 13 Gyr

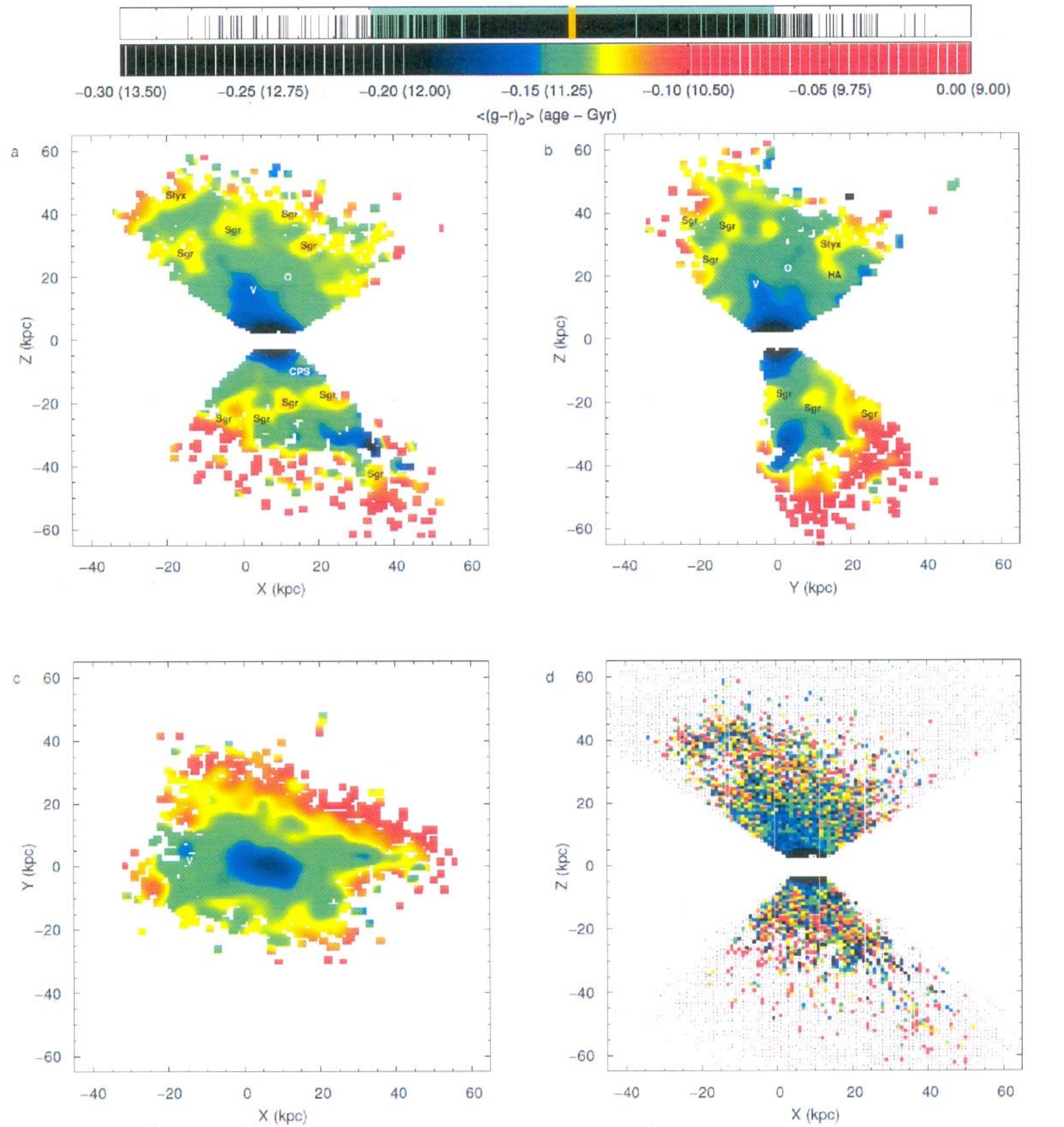
OLD BULGE: OLDEST STARS

Miralda-Escudé 2000

Tumlinson 2010, ApJ 708, 1398:
Oldest most metal-poor stars in the very center of the Galaxy, in the bulge (not of the bulge)

Carollo+2016

Gradient in age
→Oldest in
the center



1 | Chronographic map for photometrically-selected BHB stars from the SDSS. The adopted

Globular Clusters in the Galactic bulge

Bica, Ortolani, Barbuy 2016, PASA, 33, 16

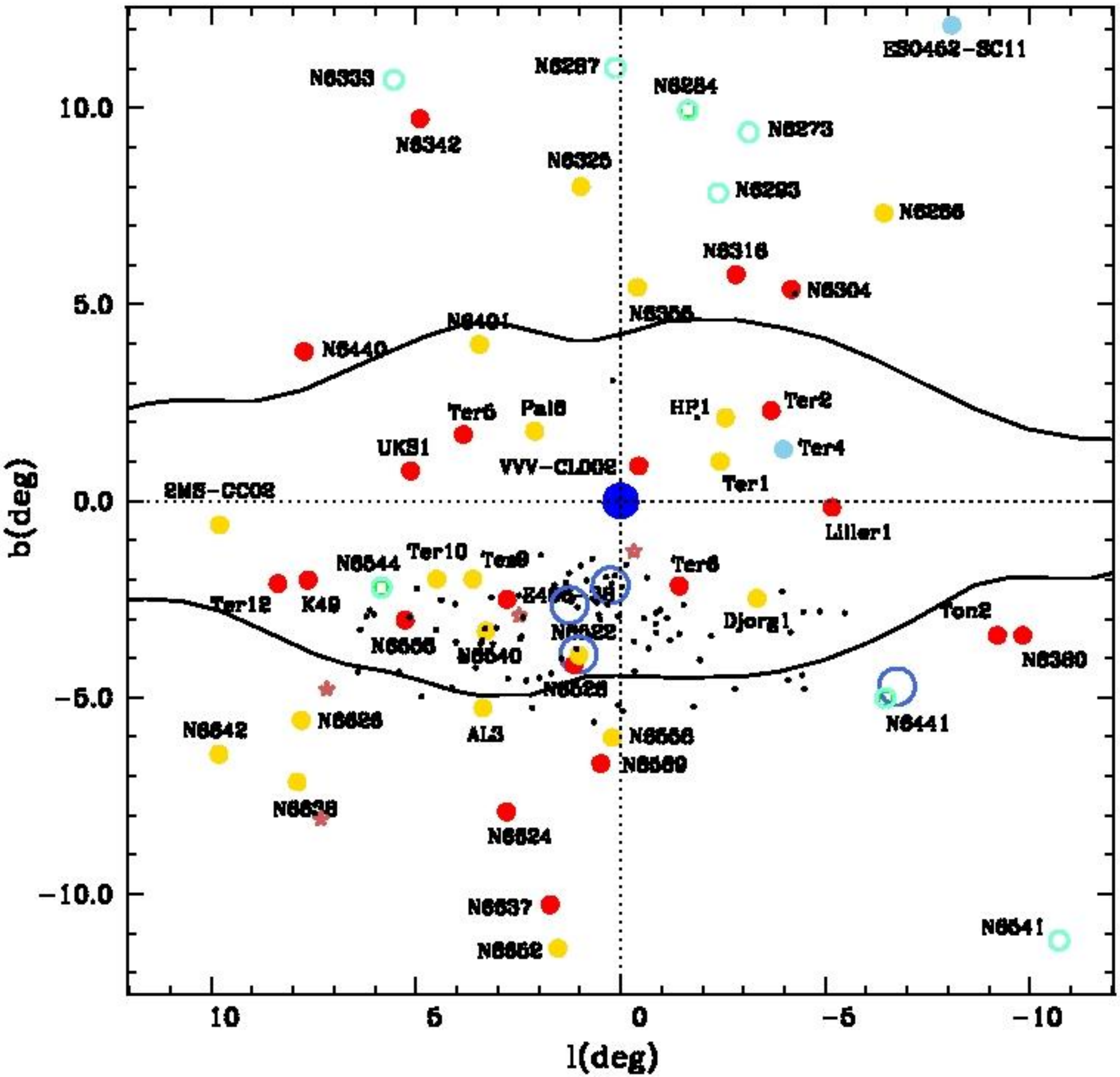
43 genuine bulge globular clusters
(RGC<3.5 kpc, l,b< 20º)

plus:
40 including halo intruders, outer bulge shell, ¨disk¨ clusters (metal-rich, R>4.5kpc)

Barbuy
Chiappini
Gerhard
2018

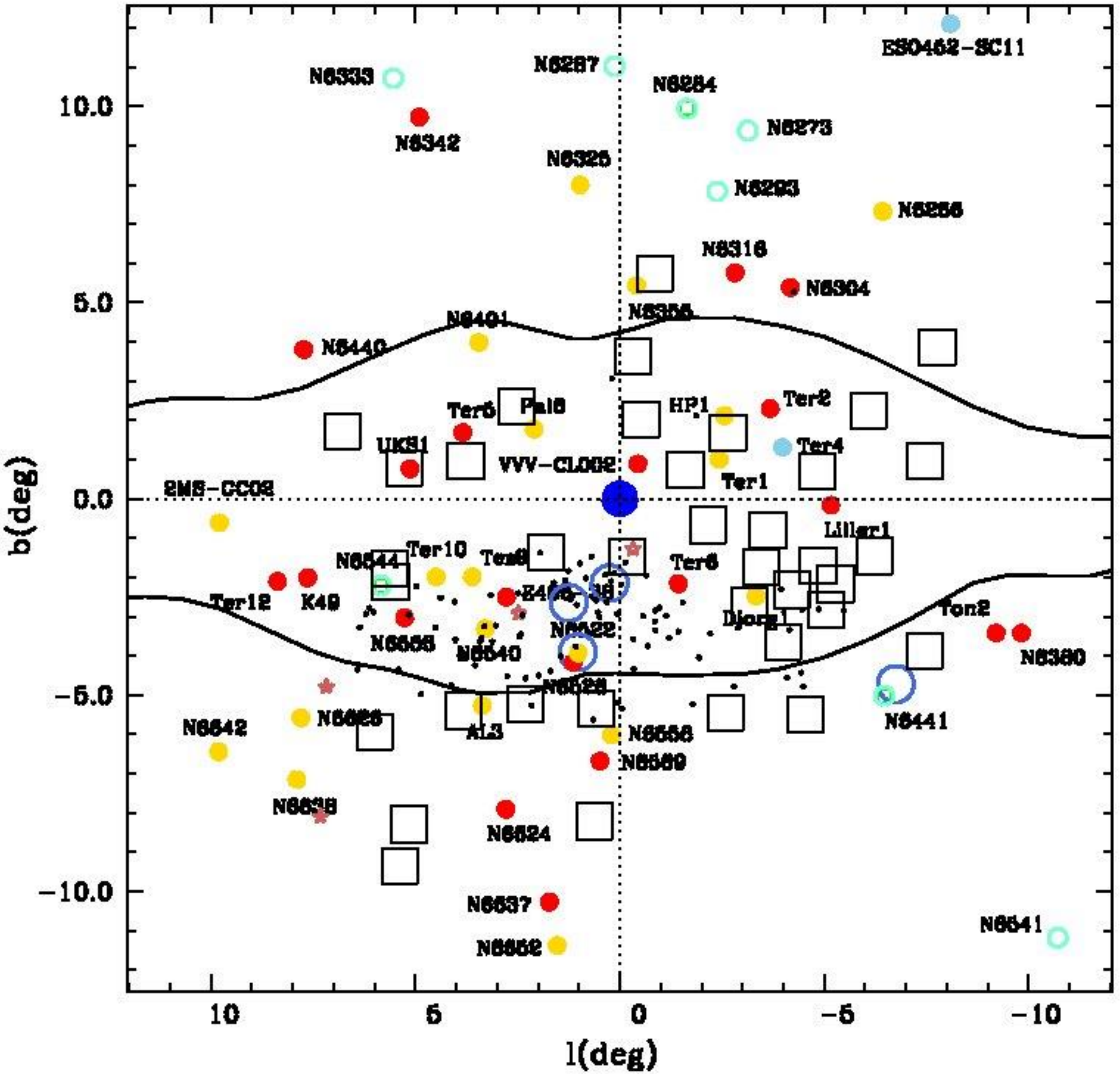
ARA&A

Yellow dots:
[Fe/H]~-1.0



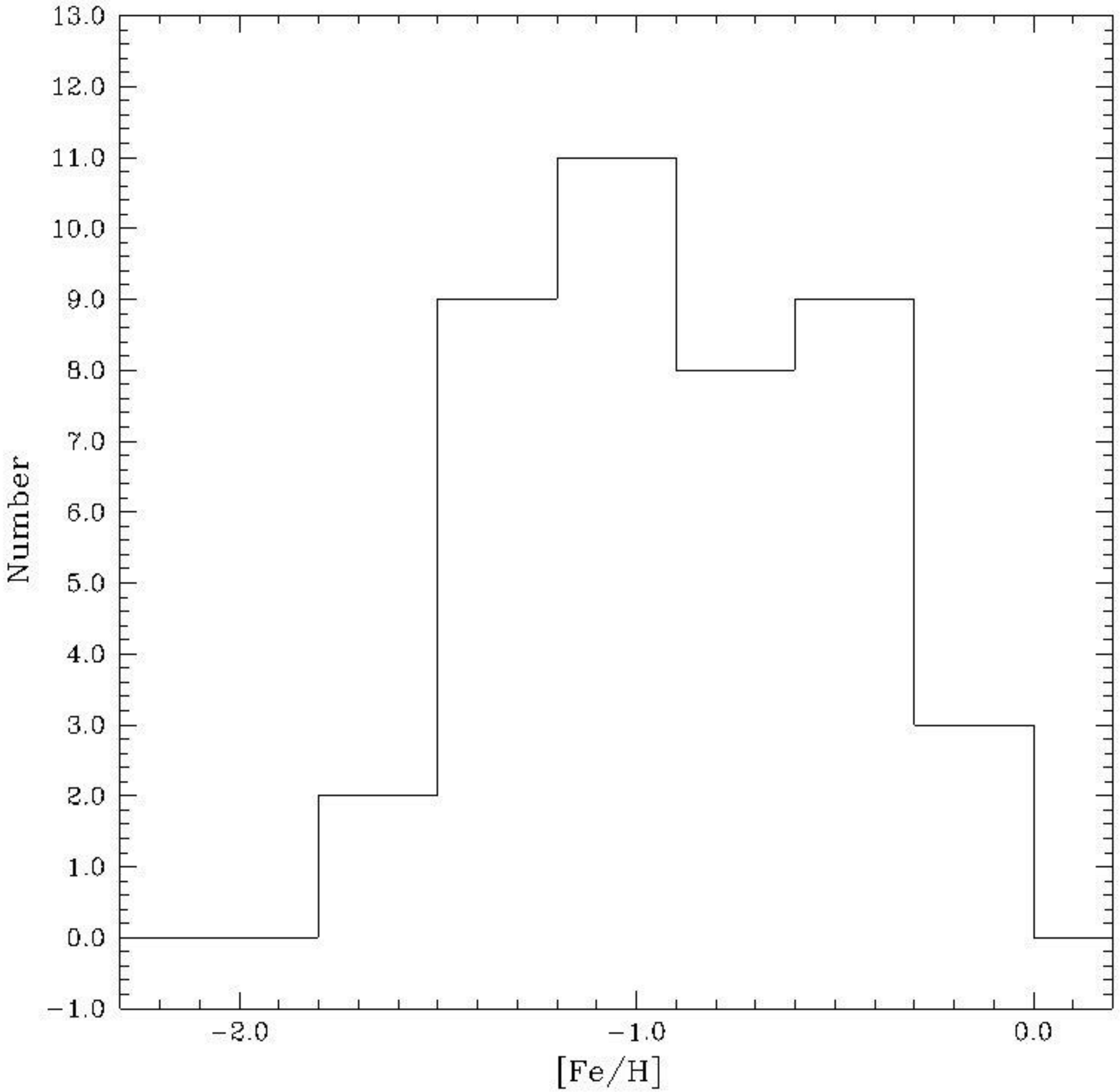
squares:

newly identified GCs
 or candidates

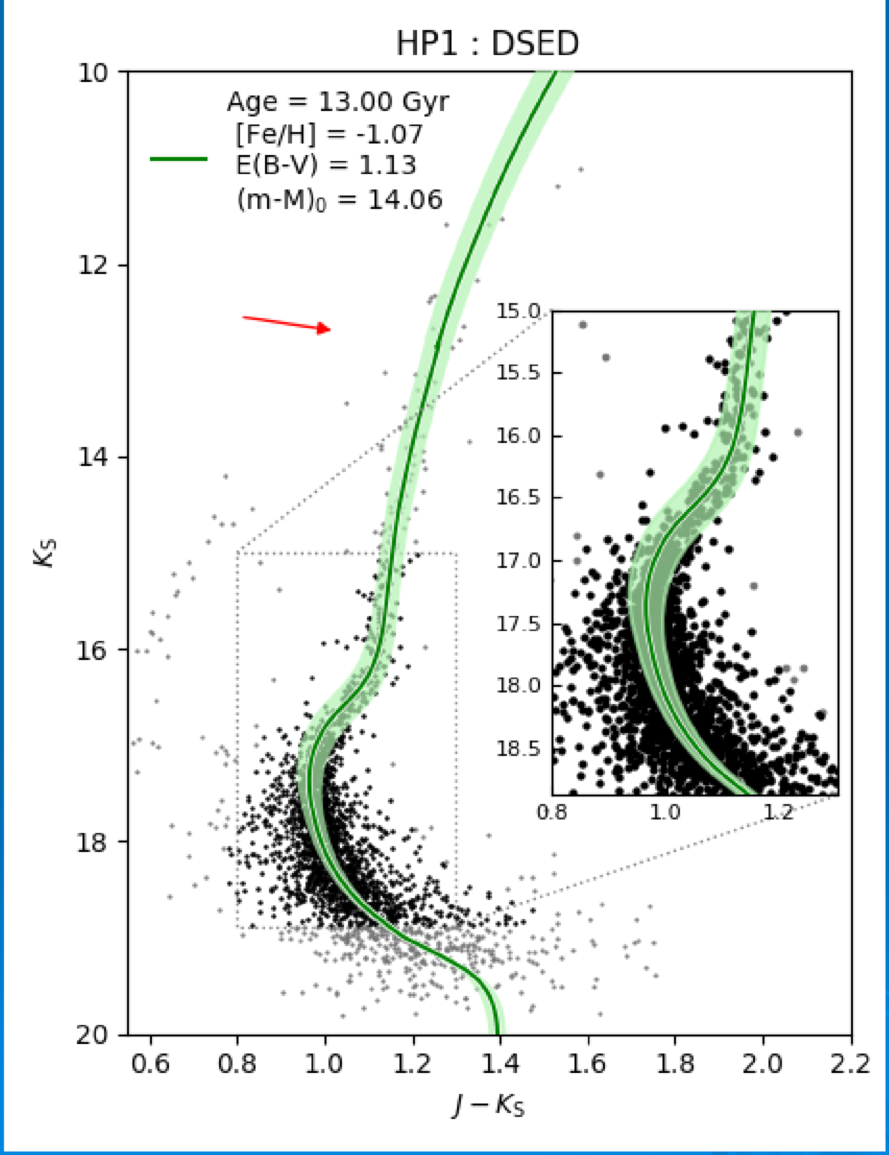


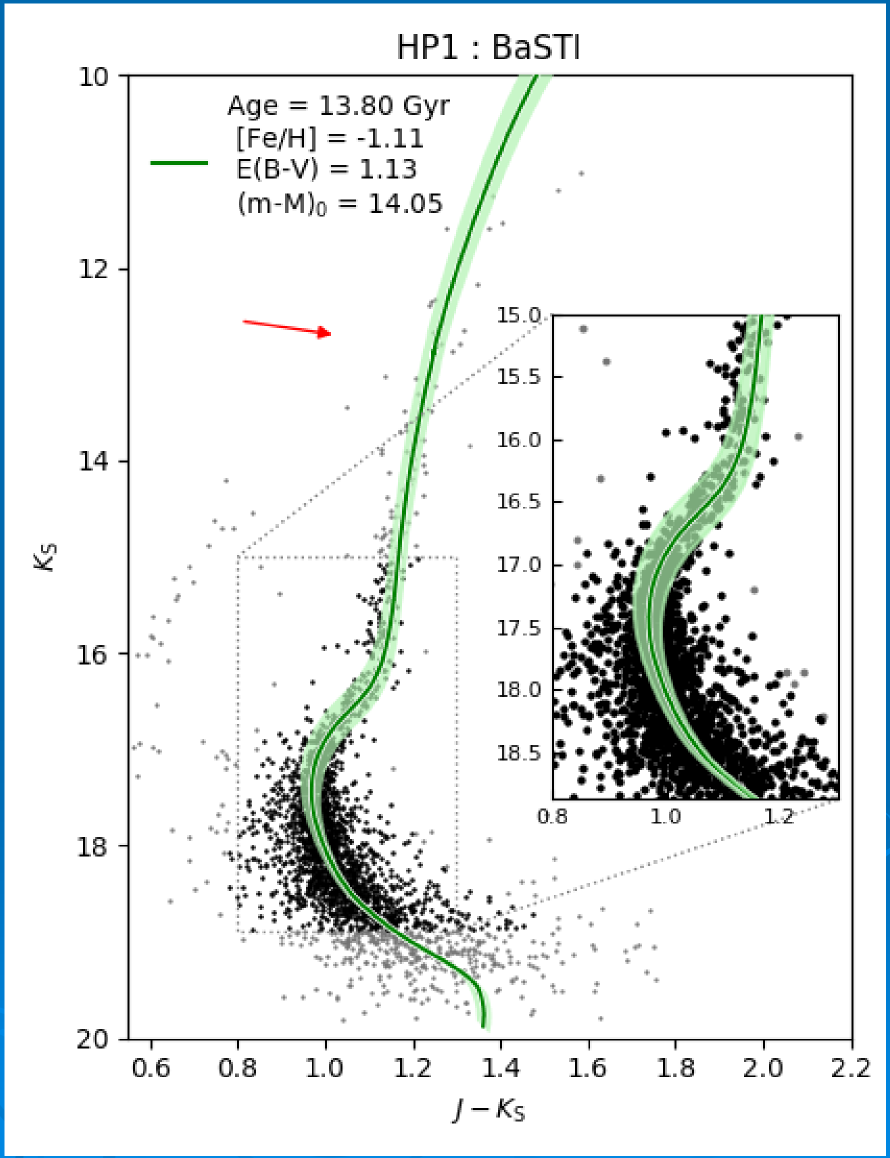
Bica+16

MDF

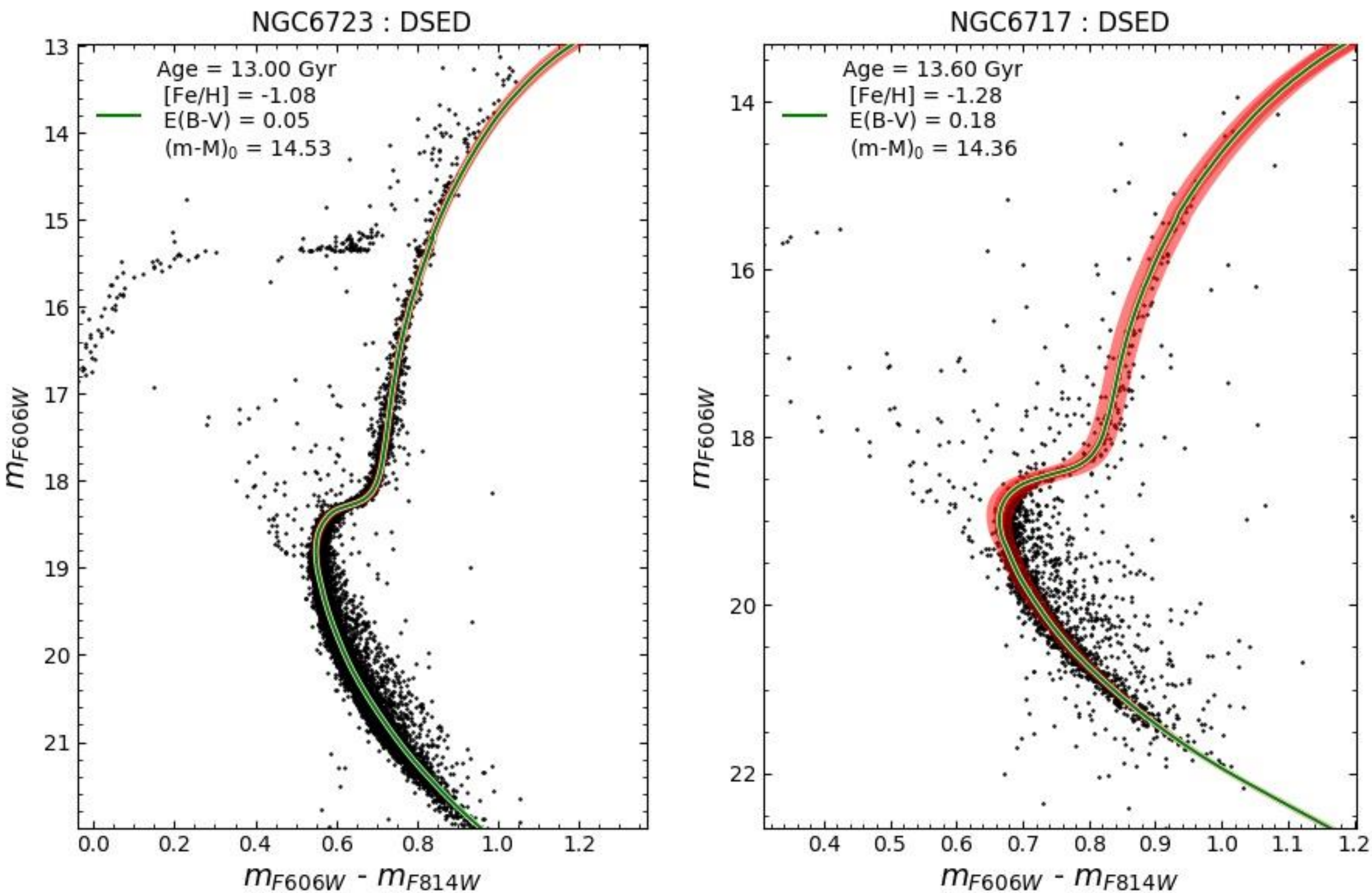


AGES: HP1: 13 GYR (Kerber+19)





Oliveira, Souza+2019



REDSHIFT	AGE
z = 2	10.6 Gyr
z = 4	12.4 Gyr
z = 7	13.2 Gyr
Reionization:	
z=8.8 (Planck)	13.4 Gyr
z = 10	13.5 Gyr

Could even have formed before reionization

RECENT ORBIT ANALYSIS:

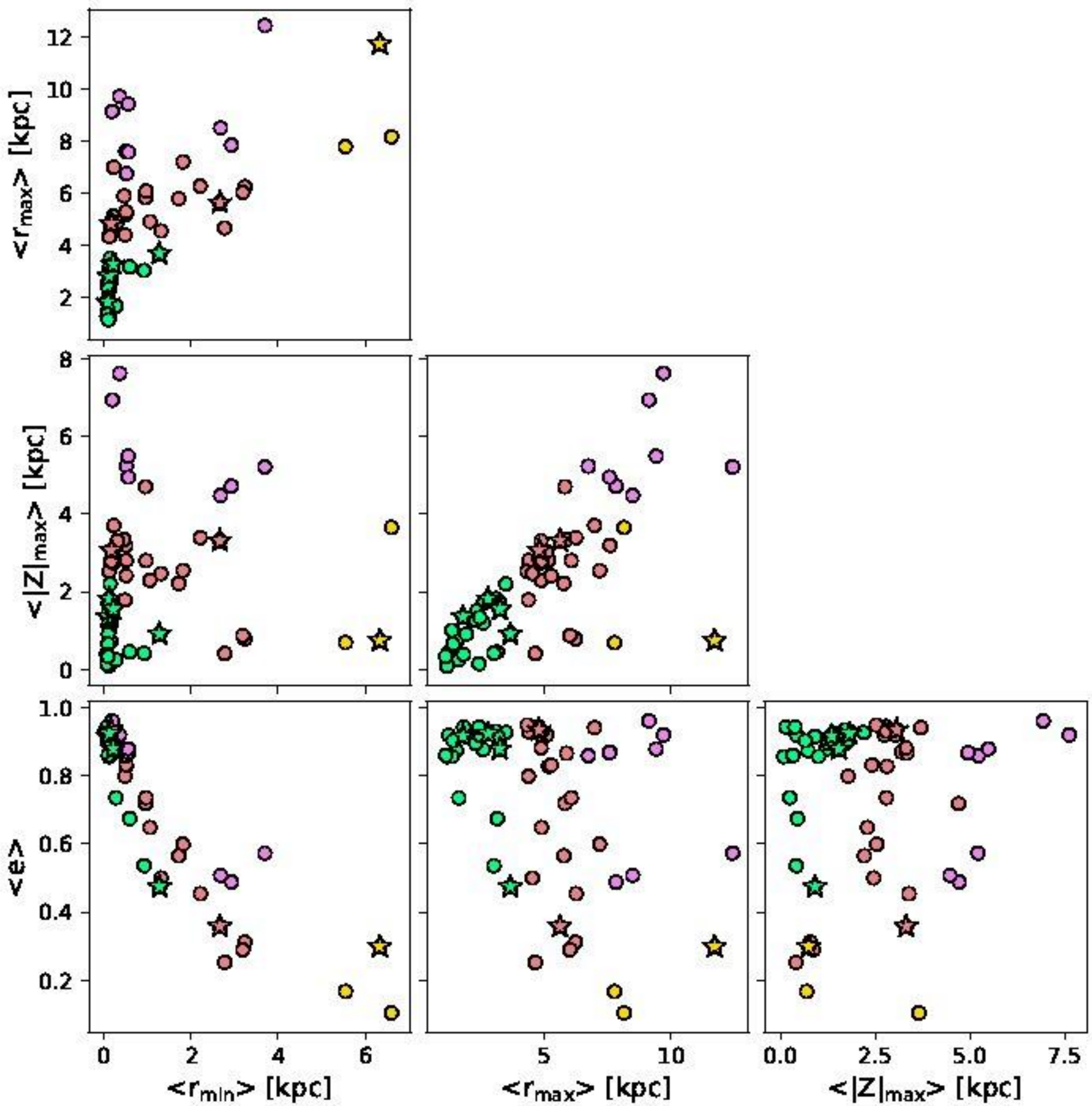
Terzan 10, Djorgovski 1

→New radial velocities, and proper motions -> Halo intruders (Ortolani+2018)

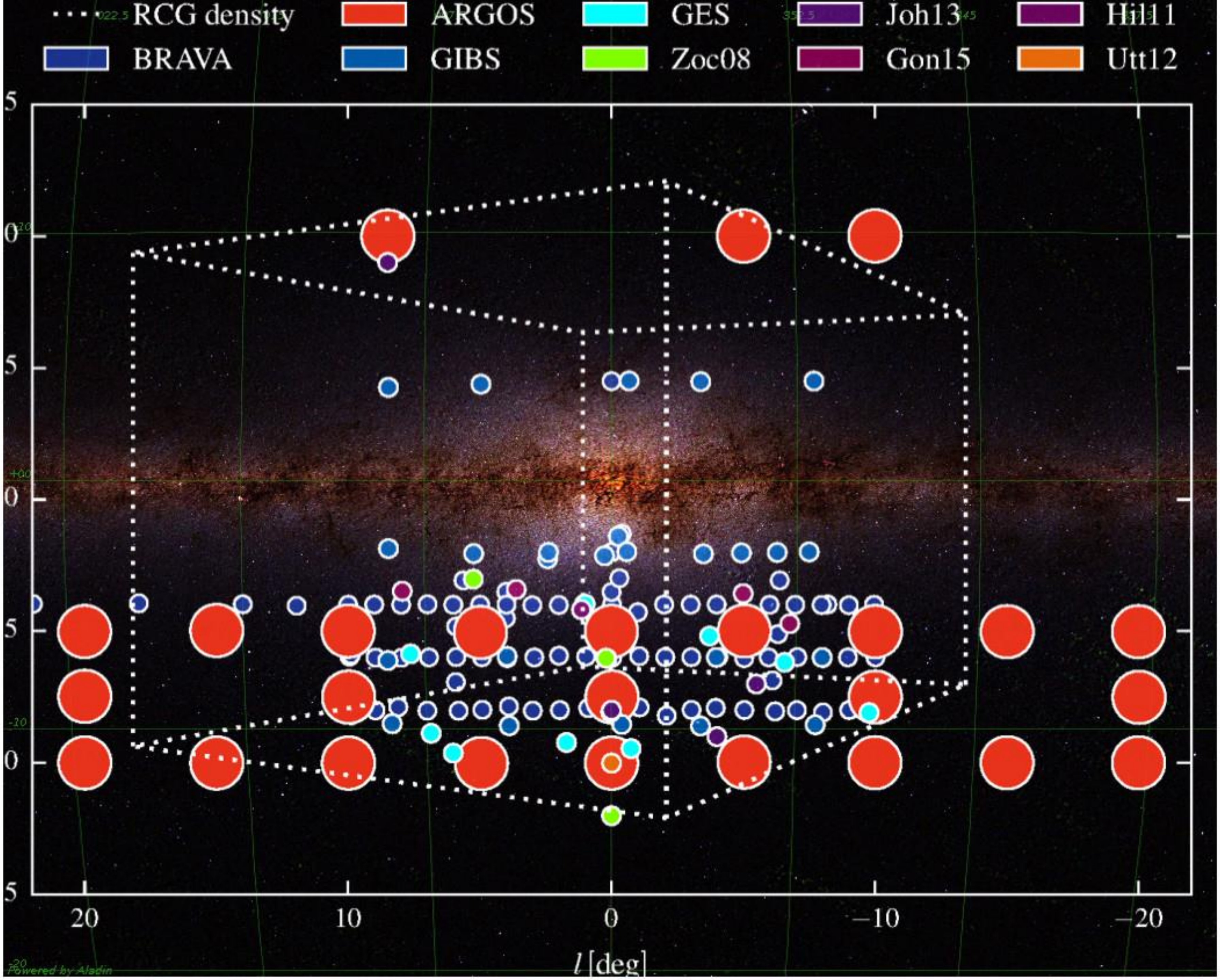
Pérez-Villegas+19

Orbit-driven selection

green circles = Bulge GCs



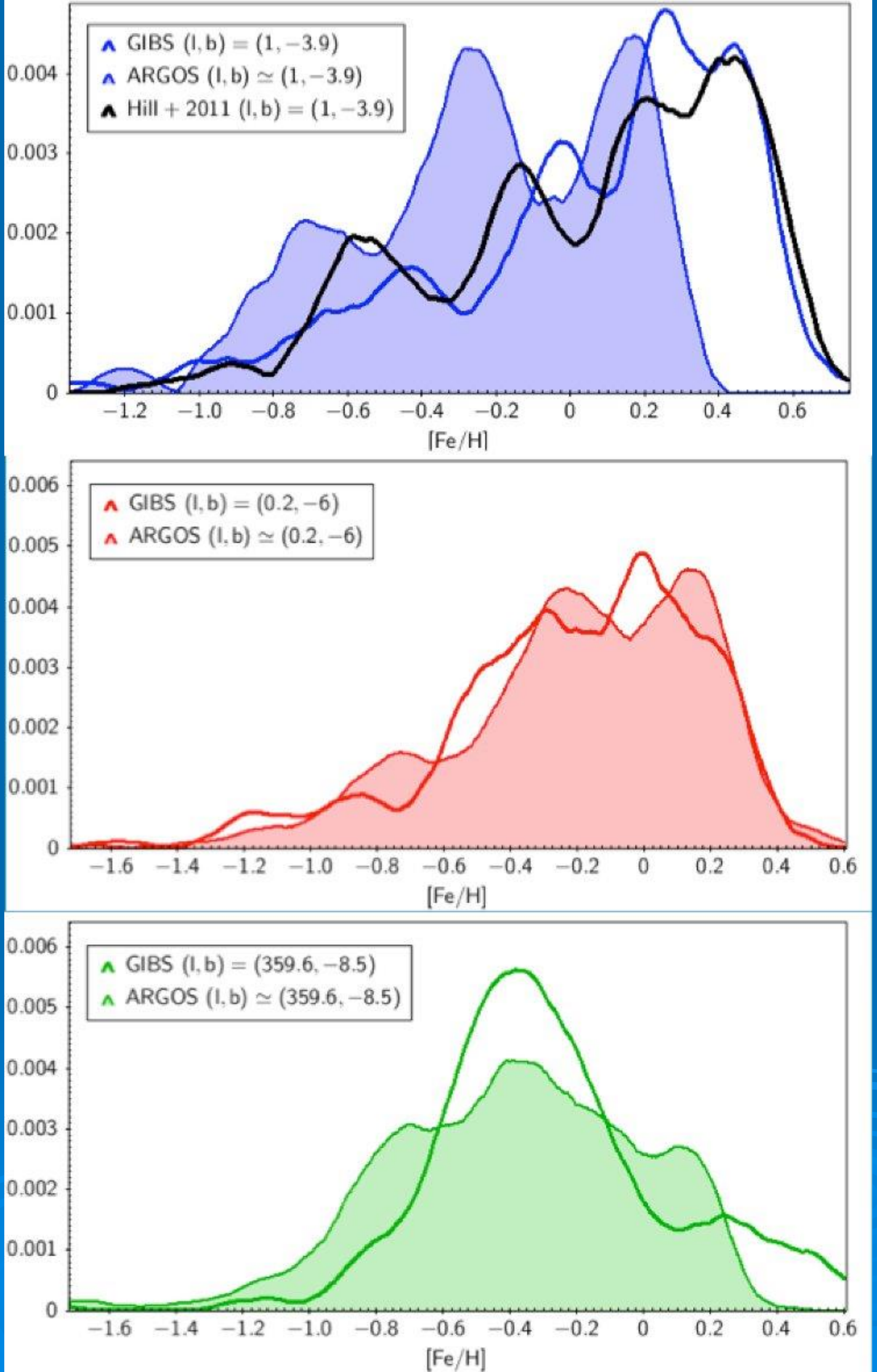
METALLICITY DISTRIBUTION FUNCTION OF BULGE FIELD STARS



RCG density
ARGOS
GES
Joh13
Hill1
BRAVA
GIBS
Zoc08
Gon15
Utt12
20
10
0
−10
−20
l [deg]
Powered by Aladin

ARA&A 2018

Barbuy, Chiappini Gerhard



Percentages of metal-poor stars in the bulge:

Rojas-Arriagada et al. 2014 .... 1.1%
Rojas-Arriagada et al. 2017 .... 0.2%
Ness et al. 2013 .... 0.7%
Zoccali et al. 2017 ....0.2%

Note: use of Red Clump Stars prevents finding very metal-poor stars

In any case: very low number of stars with $[Fe/H] < -1.0$

García-Pérez+2013: APOGEE: **5** stars with -**2.1<[Fe/H]<-1.6**

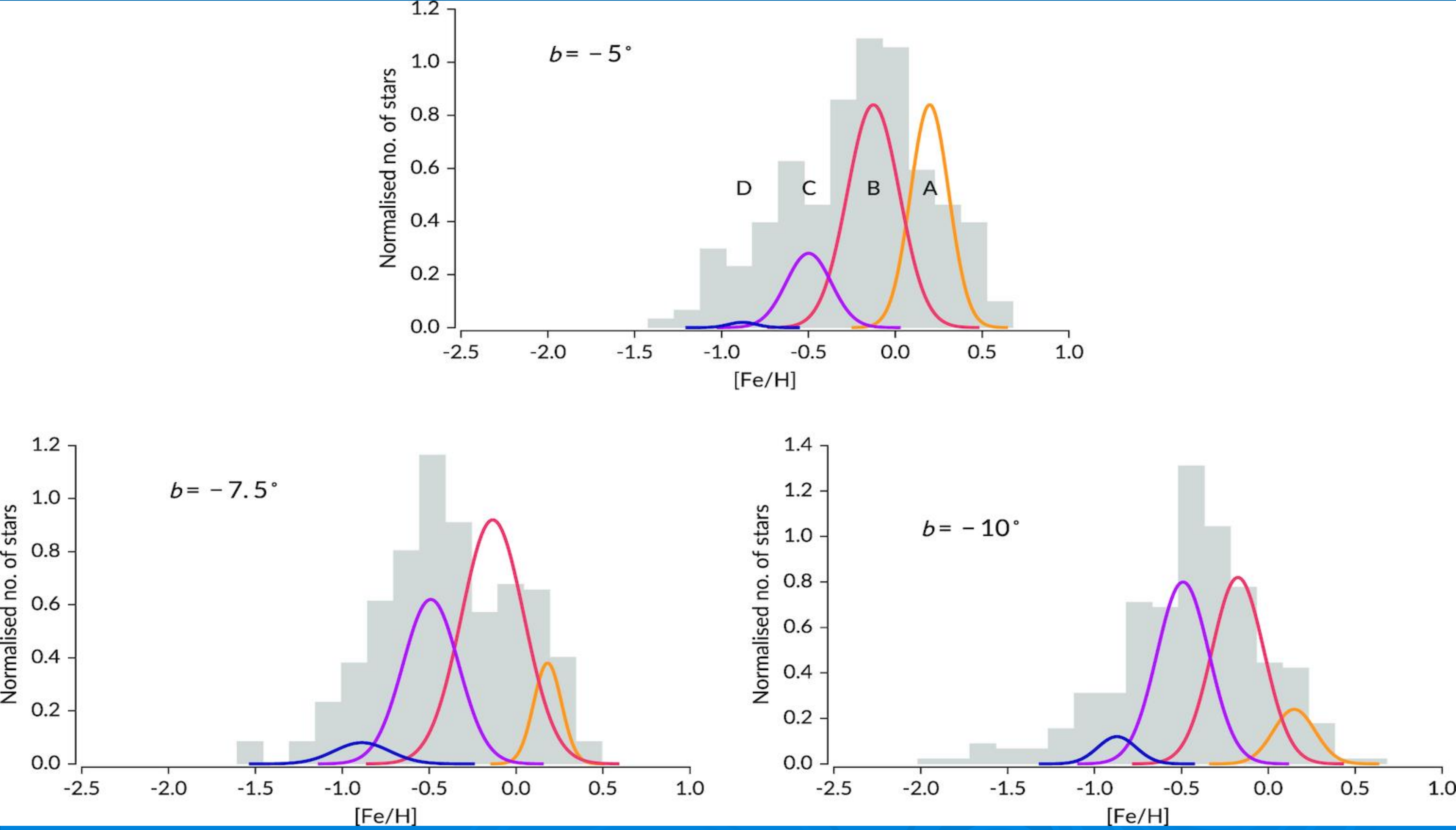
Howes+2016: EMBLA: 300 candidates with [Fe/H]**<-2.0 ➔ 24** stars: -**3.94 < [Fe/H] < -1.83**

Lamb+2017: EMBLA: [Fe/H]**=-1.51, -2.06**

Schlaufman+Casey2014,2015: **3** stars with -**3.1 < [Fe/H] < -2.7**

Koch+2016: 1 CEMP-s **[Fe/H] = -2.52,**
1 [Fe/H] = -1.53 CH, 4 -2.66<[Fe/H] < -2.07

Duong et al. 2019 – HERBS survey



Duong+2019: 47 stars with [Fe/H]<-0.8

7 stars with [Fe/H]<-1.5

1 star with [Fe/H]=-2.0

Lucey+2019**: 26 -** 16 stars with [Fe/H]<-0.8

9 stars with [Fe/H]<-1.0

6 stars with [Fe/H]<-1.5

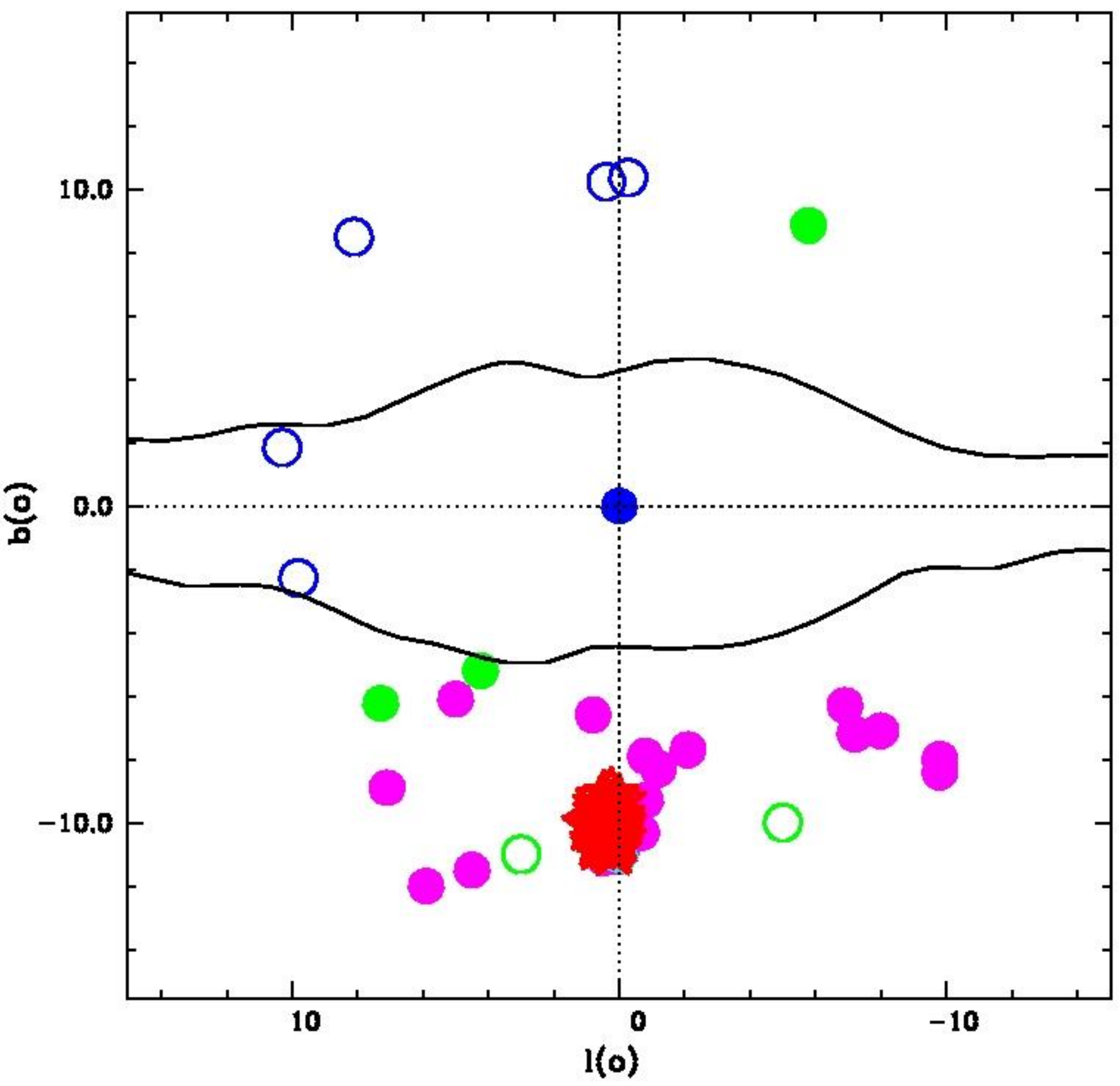
2 stars with [Fe/H]<-2.0

with [Fe/H]=-2.3, -2.31

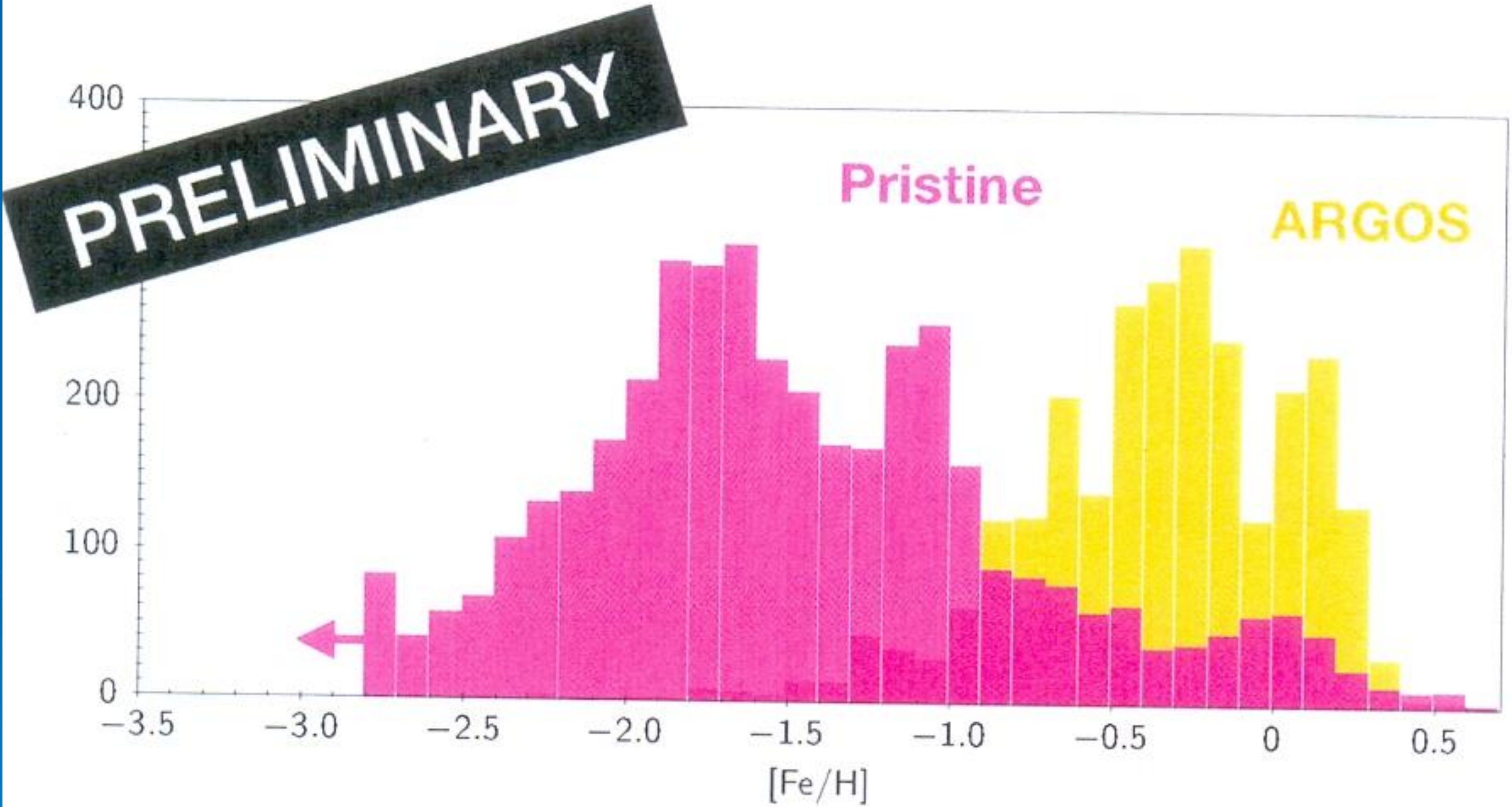
Koch+2019: 2 C-rich, neutron-capture-rich with **[Fe/H]=-1.5, -2.5**

¨bulge¨ metal-poor stars

→ Outer bulge



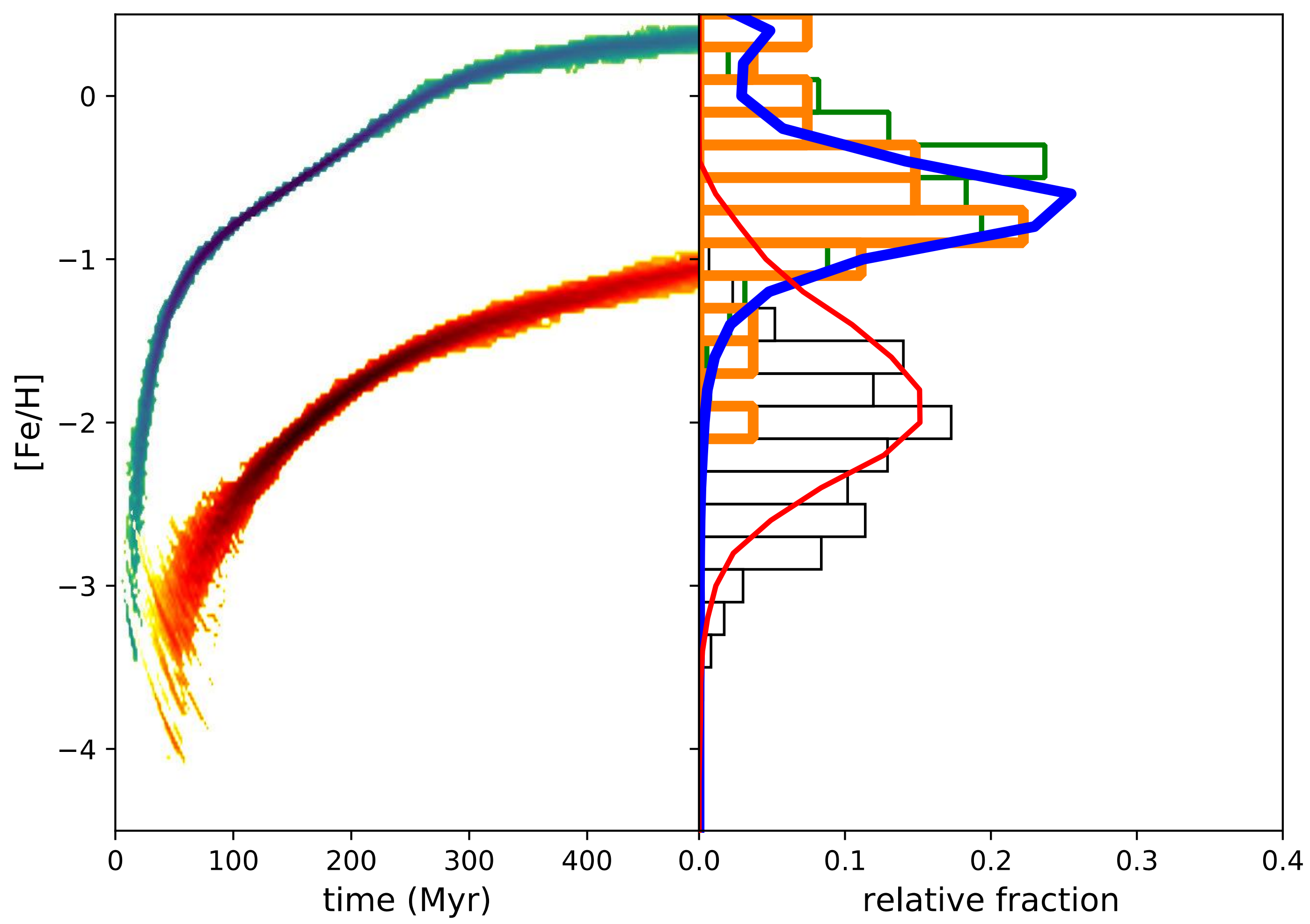
Pristine + Gaia (meeting Pucón 2018)



Reason why there are so few metal-poor stars in the Galactic bulge:

Fast chemical enrichment – e.g. SFR 20 times that of solar neighbourhood (Matteucci et al. 2012)

Cescutti, Chiappini, Hirschi, Barbuy, Meynet 2019, in prep.:
Metal-poor halo vs. metal-poor bulge: [Fe/H]=-2.5 vs. -1.0



ABUNDANCES

Why oxygen abundances are important ➔ high oxygen-to-iron ➔ fast enrichment by the first supernovae – Fe comes later from SNIa

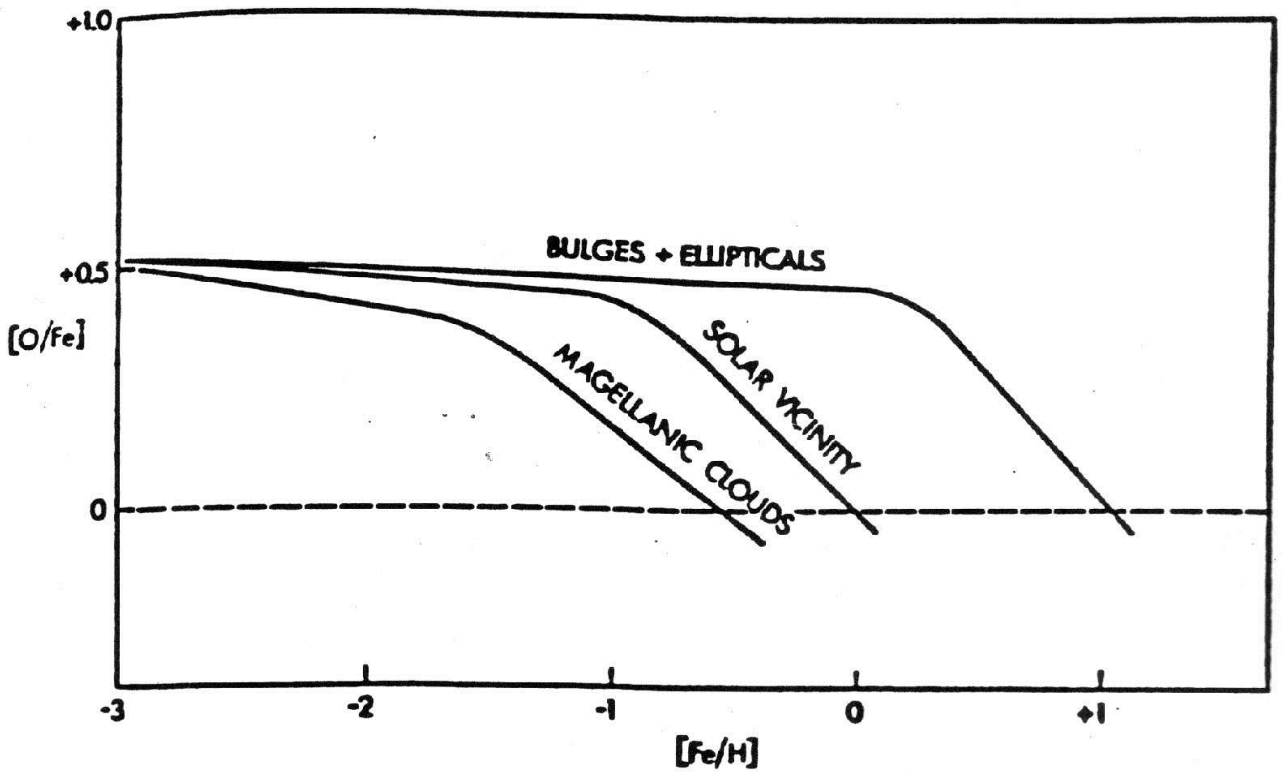
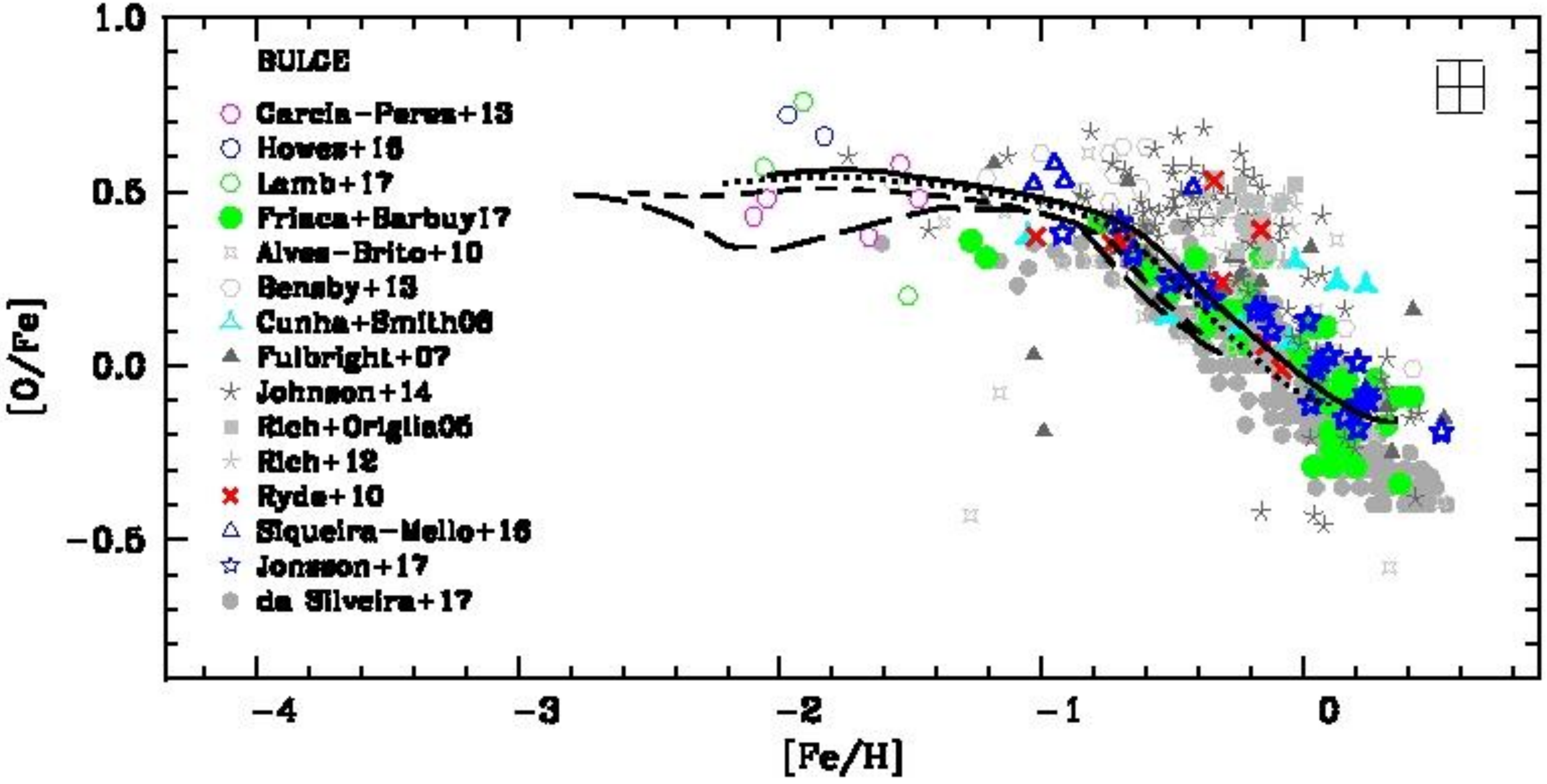


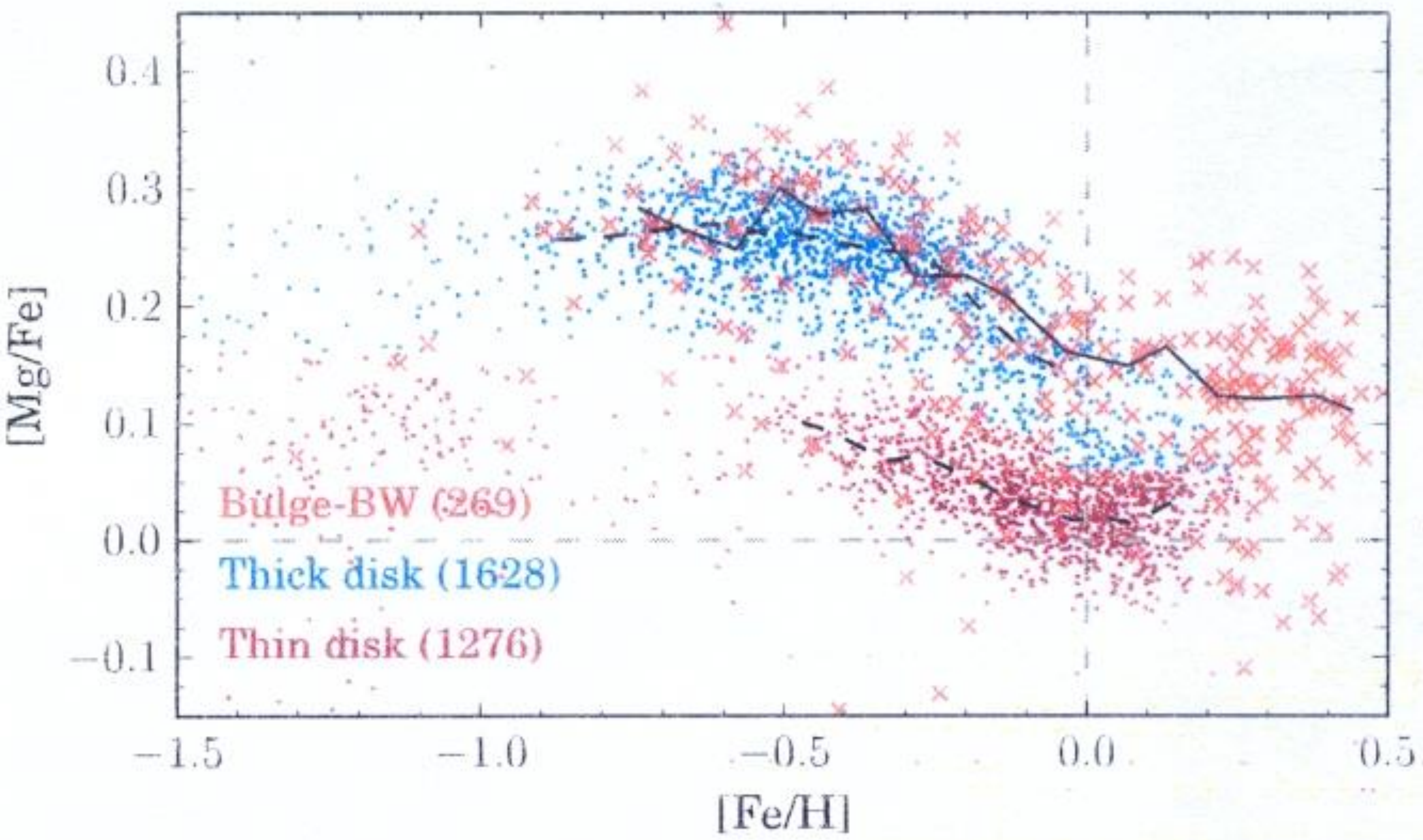
FIG. 4.—A sketch of the predicted [O/Fe] vs. [Fe/H] relations in different systems as a consequence of their different [Fe/H]-*t* relations.

Matteucci & Brocato 1990, ApJ, 365, 539

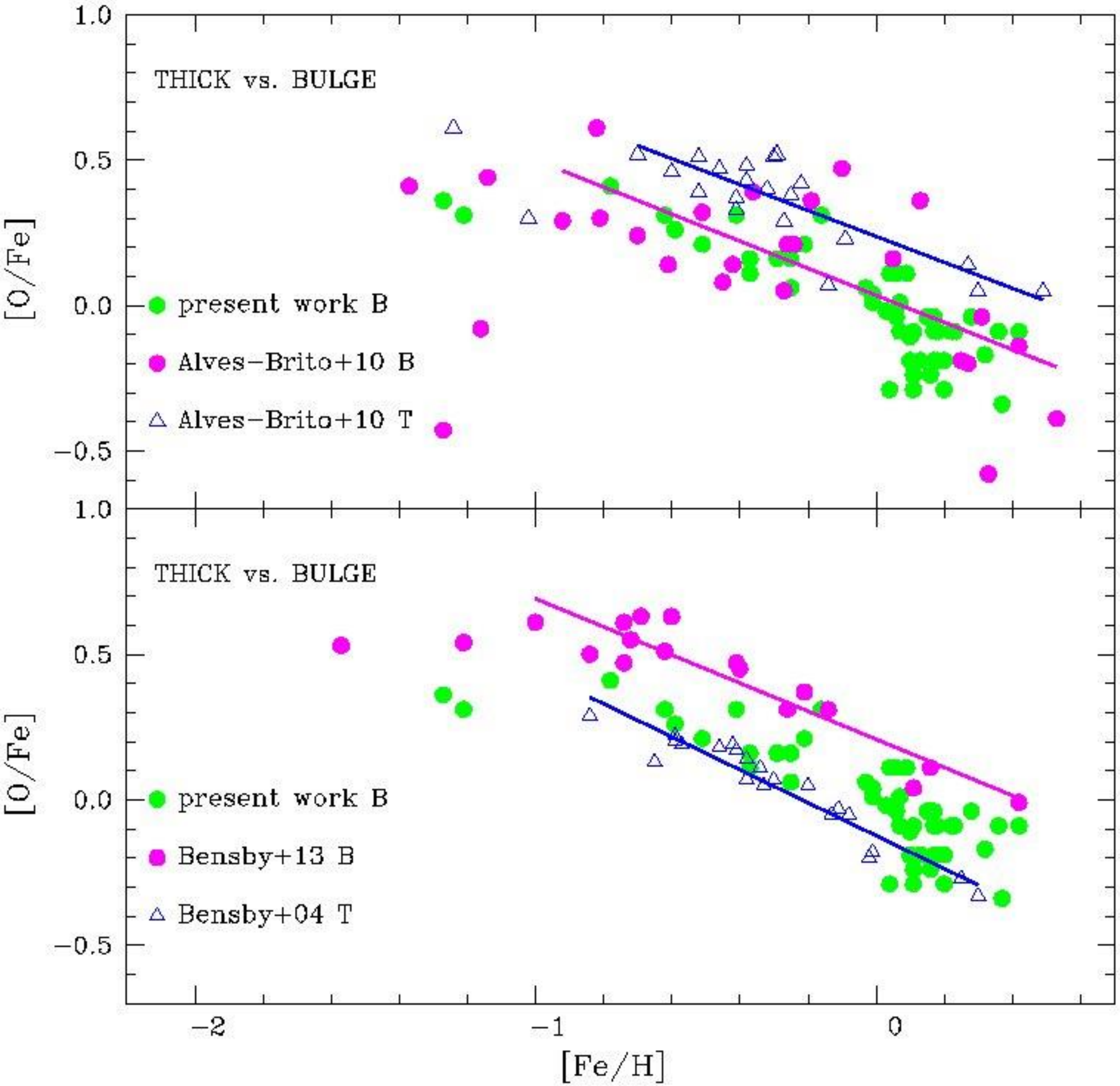
Barbuy Chiappini Gerhard 2018 ARA&A



Bulge vs. Thick disk – different or the same?
APOGEE: Schultheis+2018



Friaça
Barbuy
2017



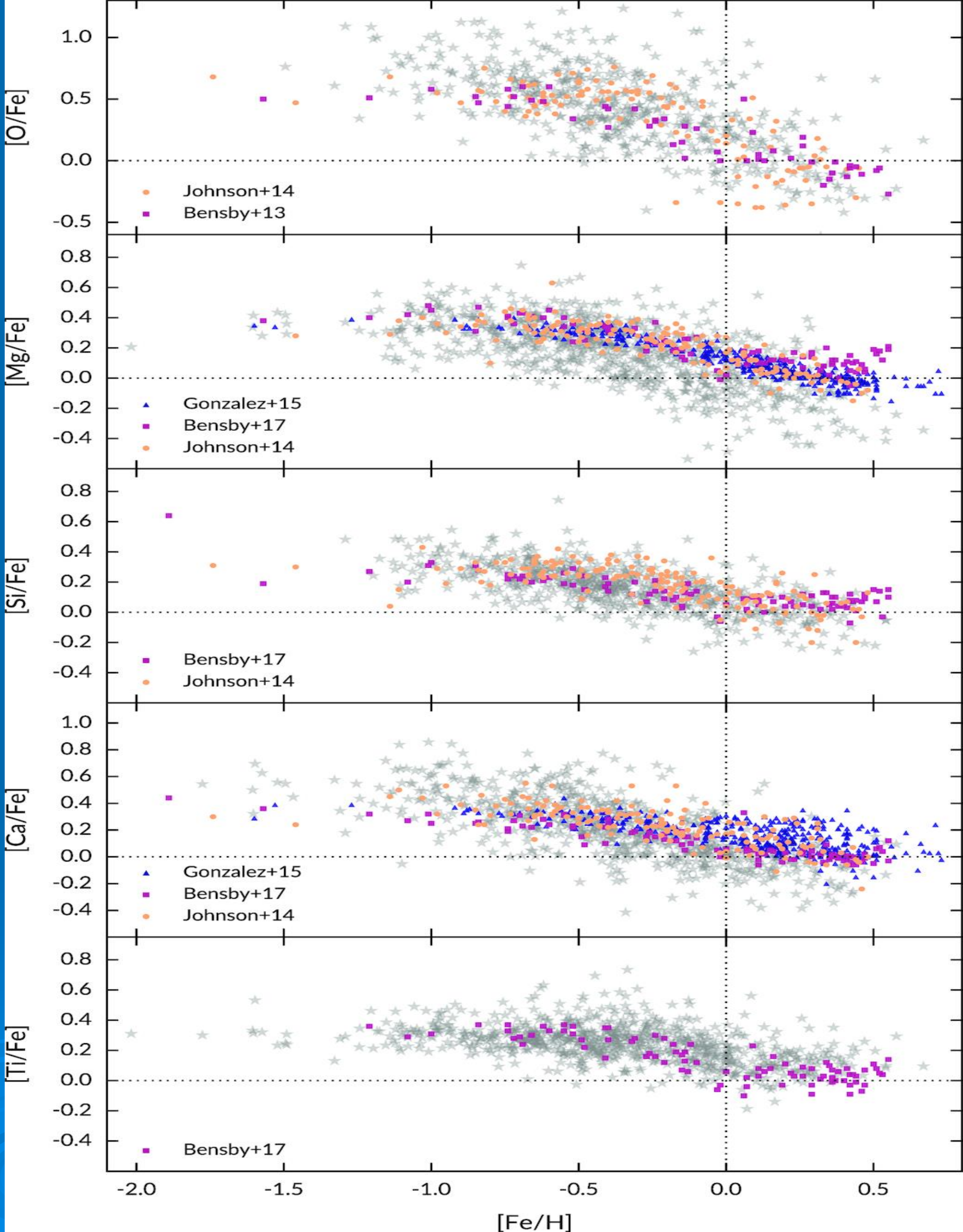
Differences Bulge vs. Thick Disk

Table 3 Level of abundance ratio plateau, and knee when it starts to drop, for comparable populations of Bulge (B) and thick-disk (TD) stars

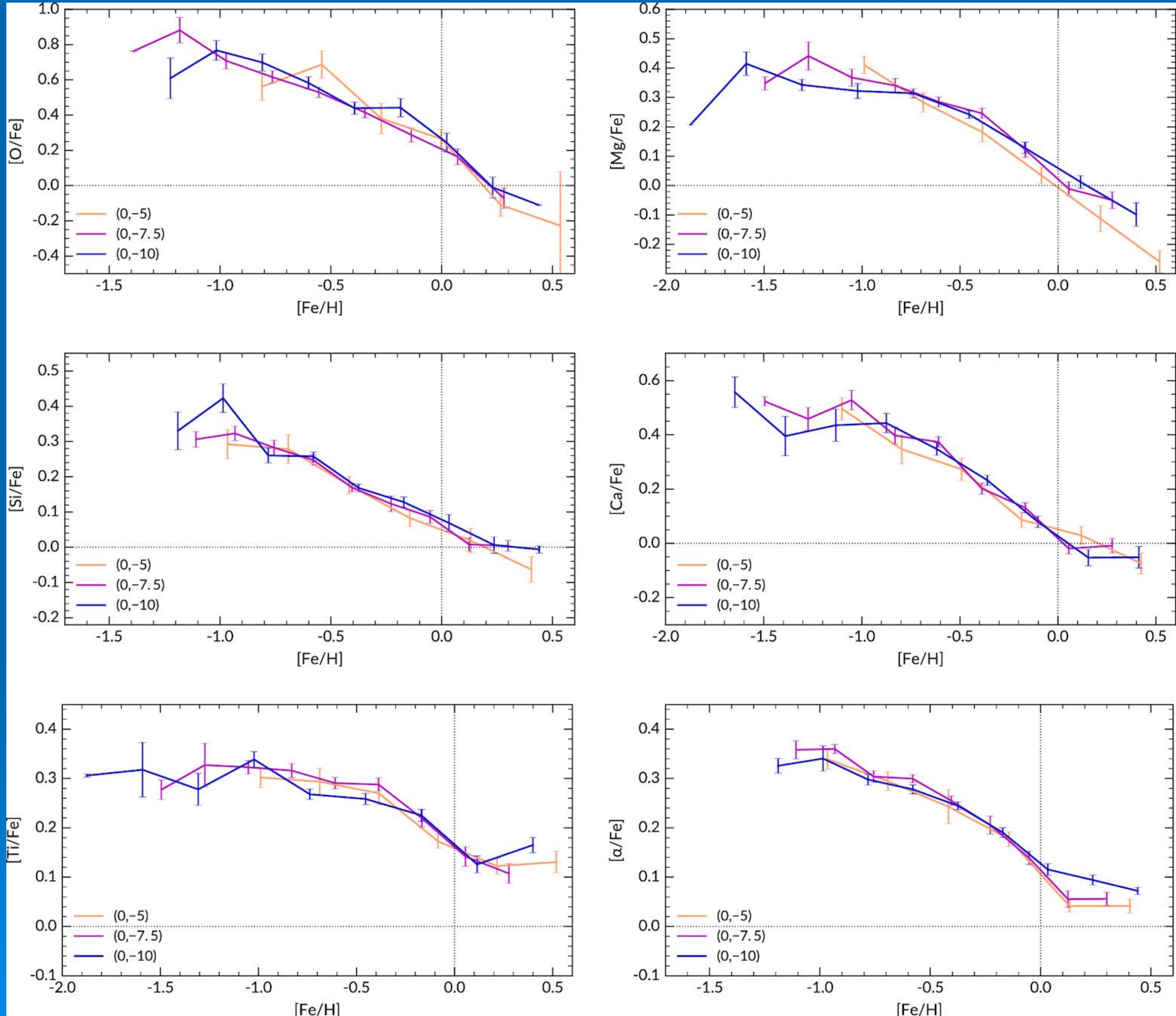
Reference	Stars B/TD	[O, Mg/Fe] Plateau	[Fe/H] Knee	Reference	Stars B/TD	[Mg/Fe] Plateau	[Fe/H] Knee
Friaça & Barbuy (2017)	B	+0.30	-0.55 ± 0.03	Hill et al. (2011)	B	+0.36	−0.4 to −0.5
Bensby et al. (2013, 2017)	B	+0.41	−0.45 to −0.05	Bensby et al. (2017)	TD	+0.36	−0.6
Rojas-Arriagada et al. (2017)	B	$+0.310 \pm 0.11$	−0.37	Rojas-Arriagada et al. (2017)	TD	$+0.304 \pm 0.07$	−0.43

Barbuy, Chiappini, Gerhard 2018

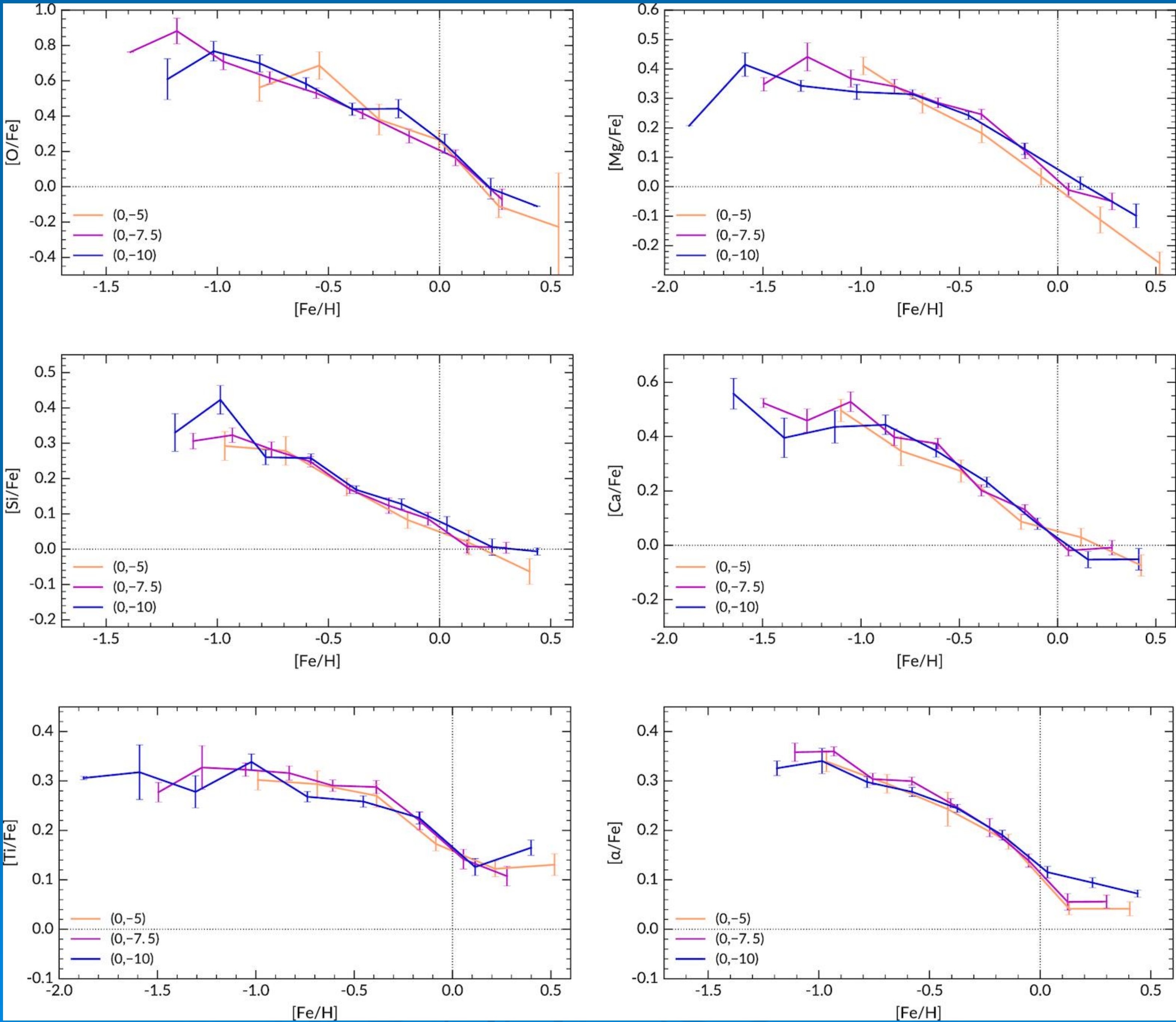
Duong+2019: alpha-enhancement for [Fe/H]<-1.0



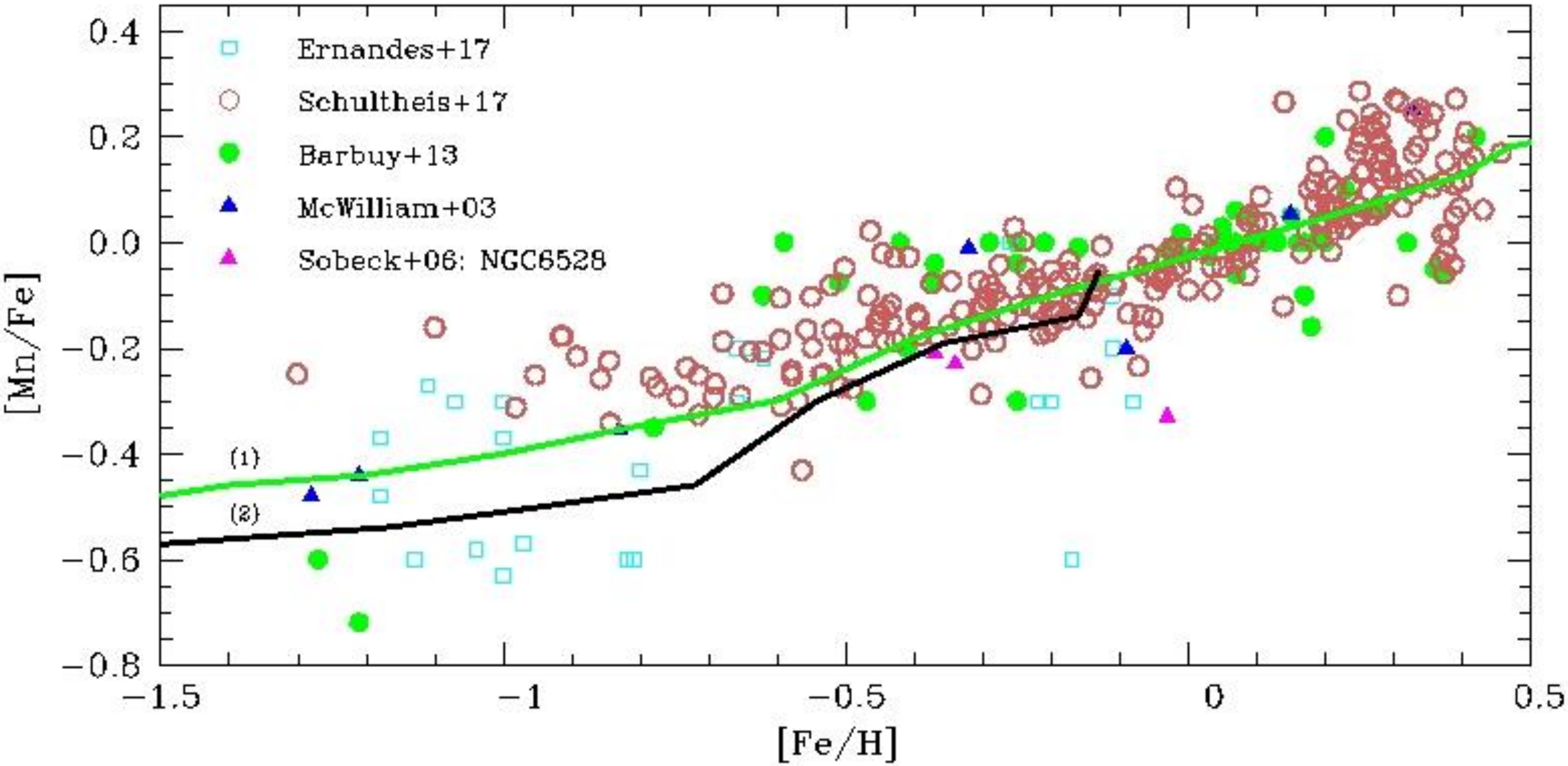
Duong +2019



Duong +2019

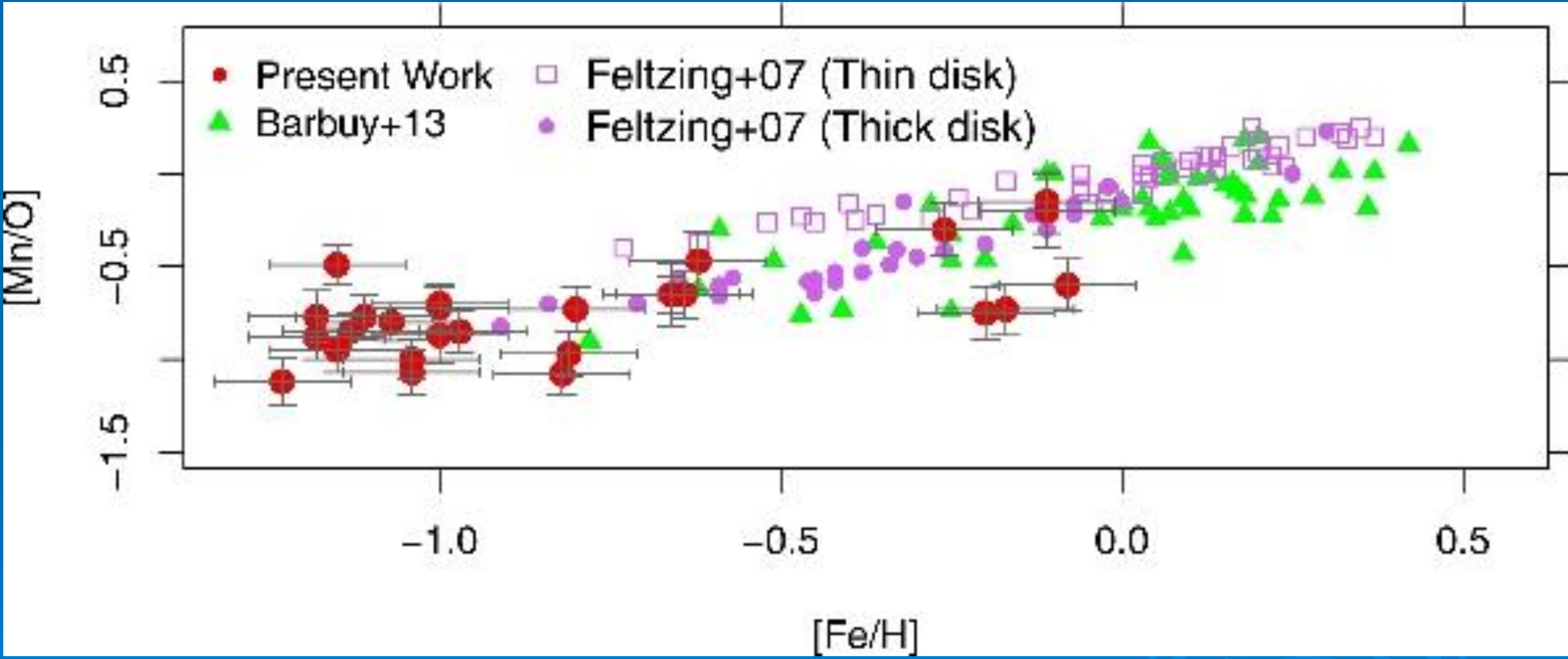


Duong+2019: metal-poor bulge populations do not share the same similarity with the disk, as the metal-rich populations

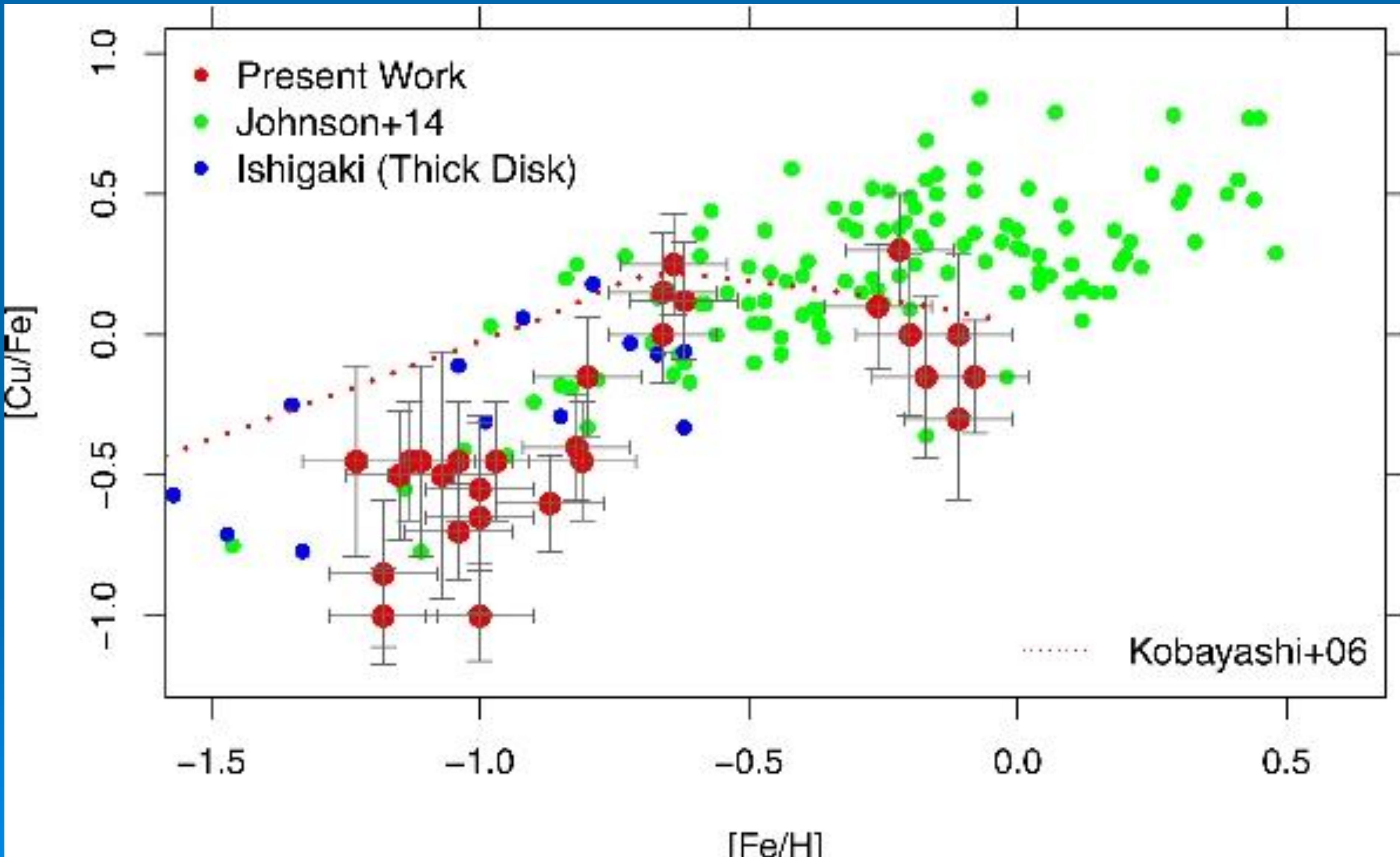


Ernandes+17
Schultheis+17
Barbuy+13
McWilliam+03
Sobeck+06: NGC6528
(1)
(2)
[Mn/Fe]
[Fe/H]
0.4
0.2
0.0
−0.2
−0.4
−0.6
−0.8
−1.5
−1
−0.5
0
0.5

Ernandes+18; [Mn/O] distinguishes thin-thick disk field bulge + GCs slightly more [Mn/O]-poor



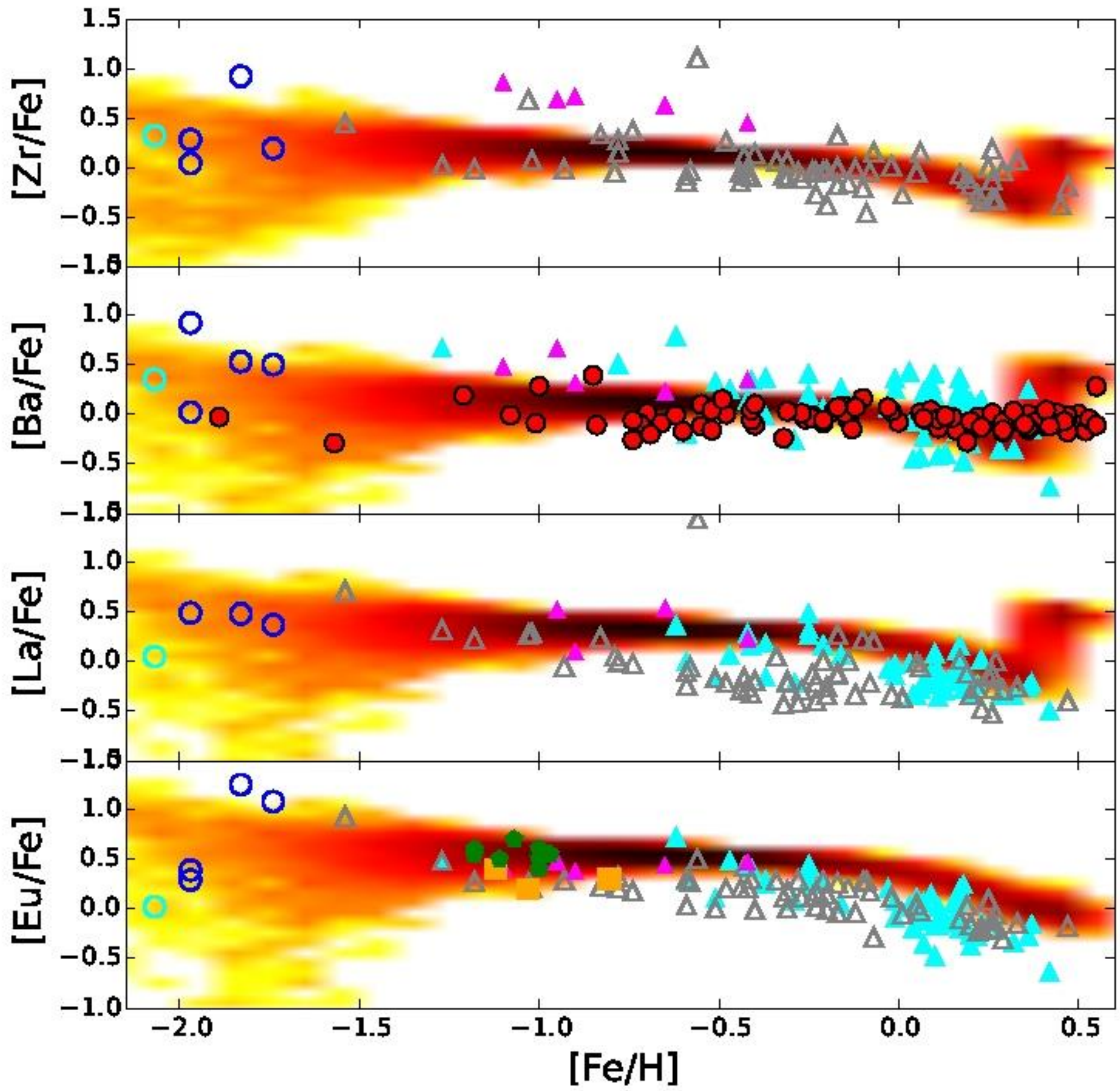
Ernandes+18: GCs more Cu-poor



Cescutti+19

Includes magneto-rotationally driven SN

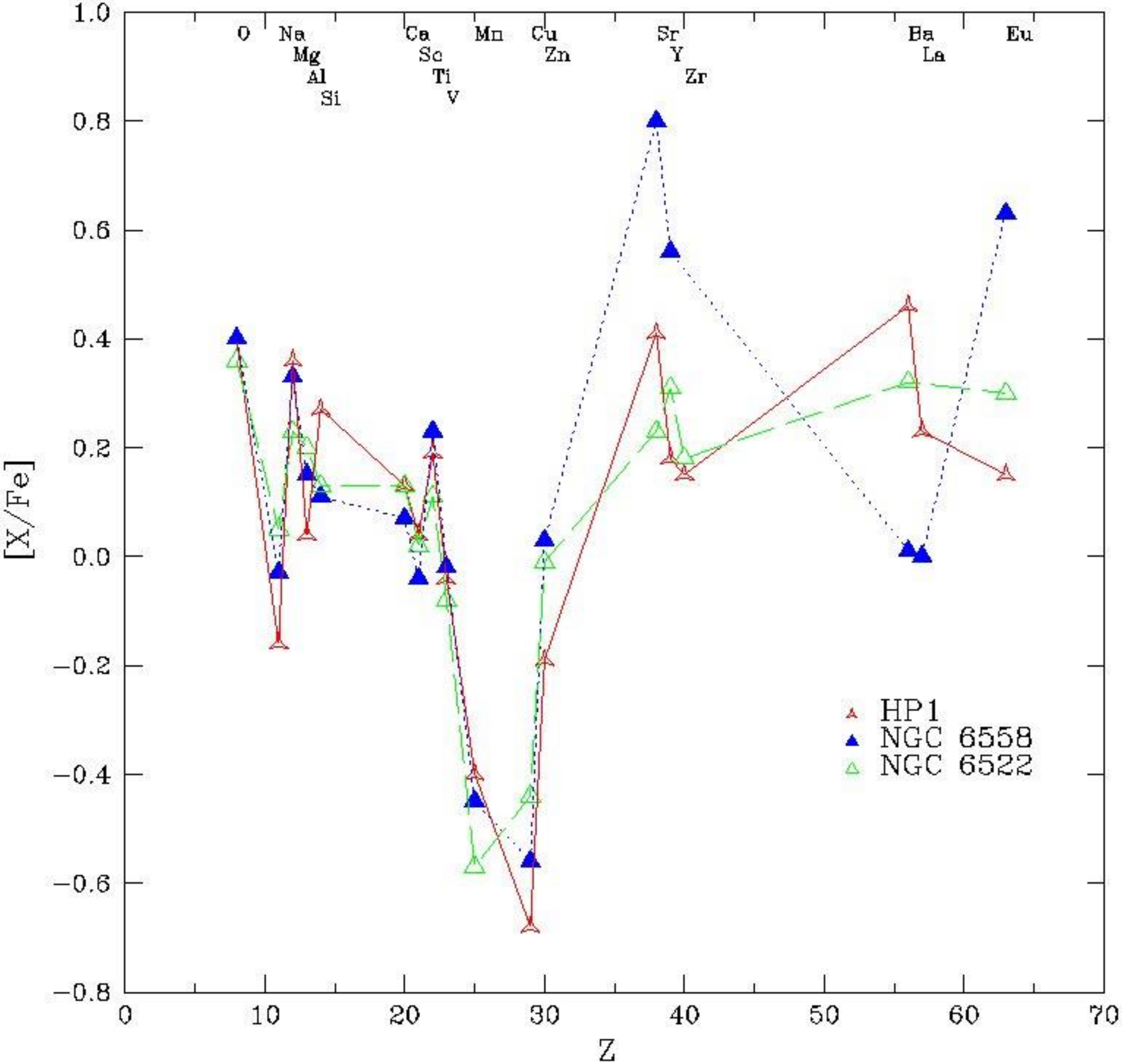
-connexion w/ spinstars in pre-SN phase



Abundances in Globular clusters:
we have been looking for:

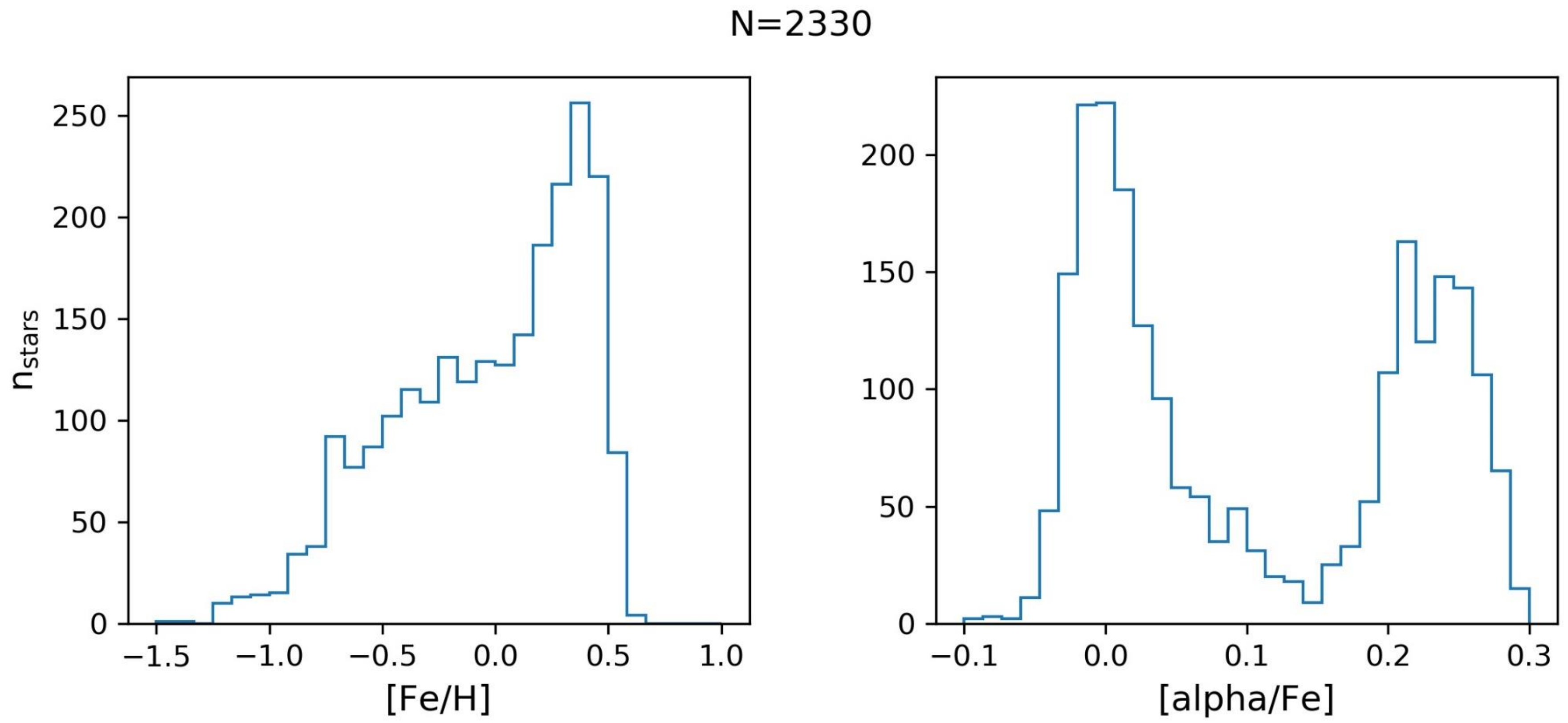
Bulge GCs characterized by:
- [Fe/H] ~ -1.0
- BHB (and/or + RHB)
- Old age (~13Gyr)

A typical abundance pattern?


O
Na
Mg
Al
Si
Ca
Sc
Ti
V
Mn
Cu
Zn
Sr
Y
Zr
Ba
La
Eu
[X/Fe]
Z
HP1
NGC 6558
NGC 6522
1.0
0.8
0.6
0.4
0.2
0.0
−0.2
−0.4
−0.6
−0.8
0
10
20
30
40
50
60
70

Queiroz, Chiappini, Perez-Villegas+2019

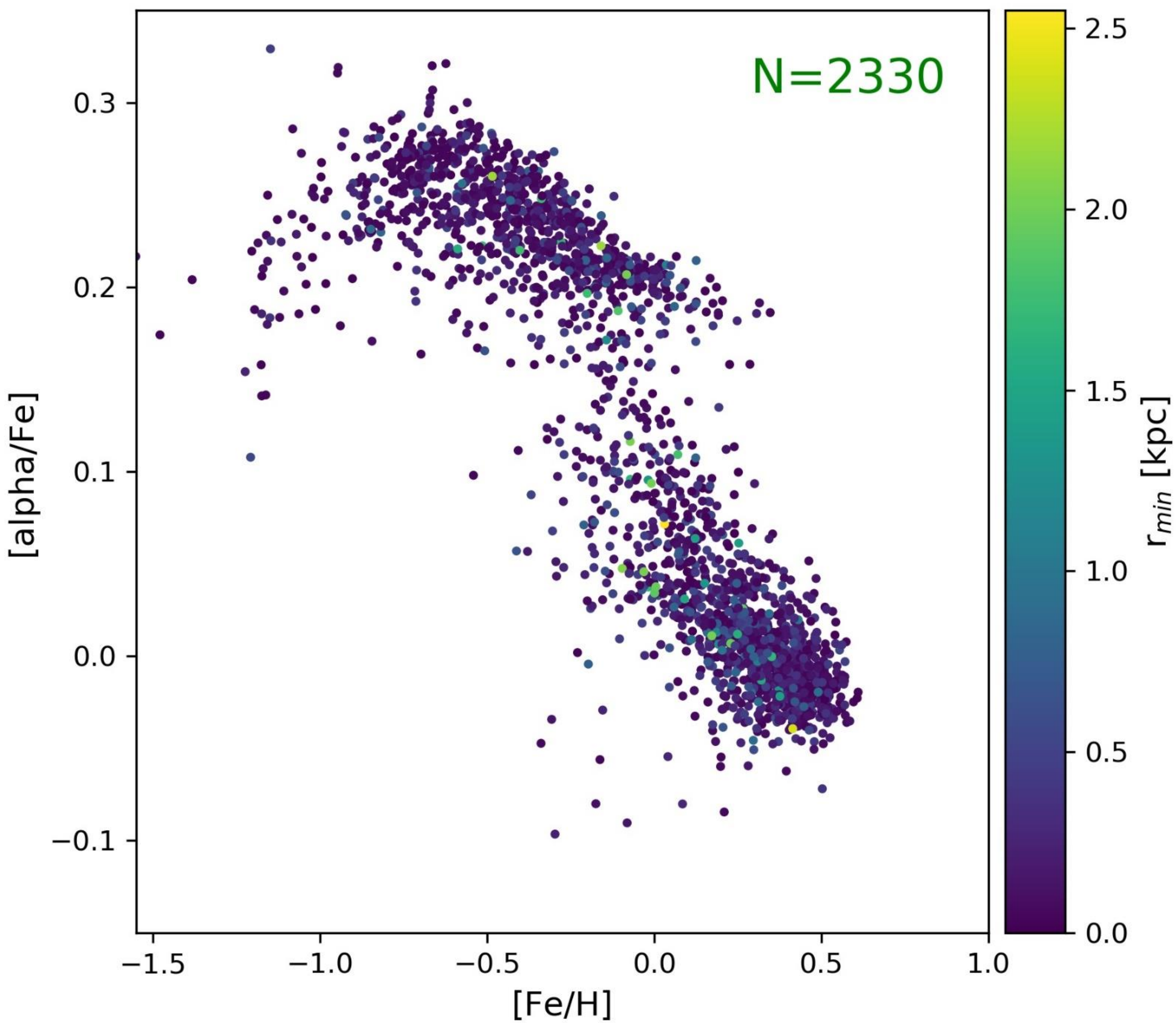
APOGEE: distance selected 2330 bona-fide bulge stars



Metal-poor,
High-alpha

Dominated by

Low Rmin
(in prep.)



Conclusions

1. Very few metal-poor stars are found.
2. MDF -1.3 < [Fe/H] < +0.5
3. Predominantly old – fraction of young < 3.5 % → controversies
4. [alpha/Fe],[Al/Fe],[Eu/Fe]=+0.3 to 0.5 dex → enrichment by SN II
5. Evidence for Fast Chemical Enrichment
   - ➔ OLD, but Moderately Metal-poor
   - ➔ Magneto-rotationally driven Snae + spinstars in the pre-SN phase
6. Very few CEMP stars (Koch+19)

The End