Galactic Archaeology in the Gaia era

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Lecture III

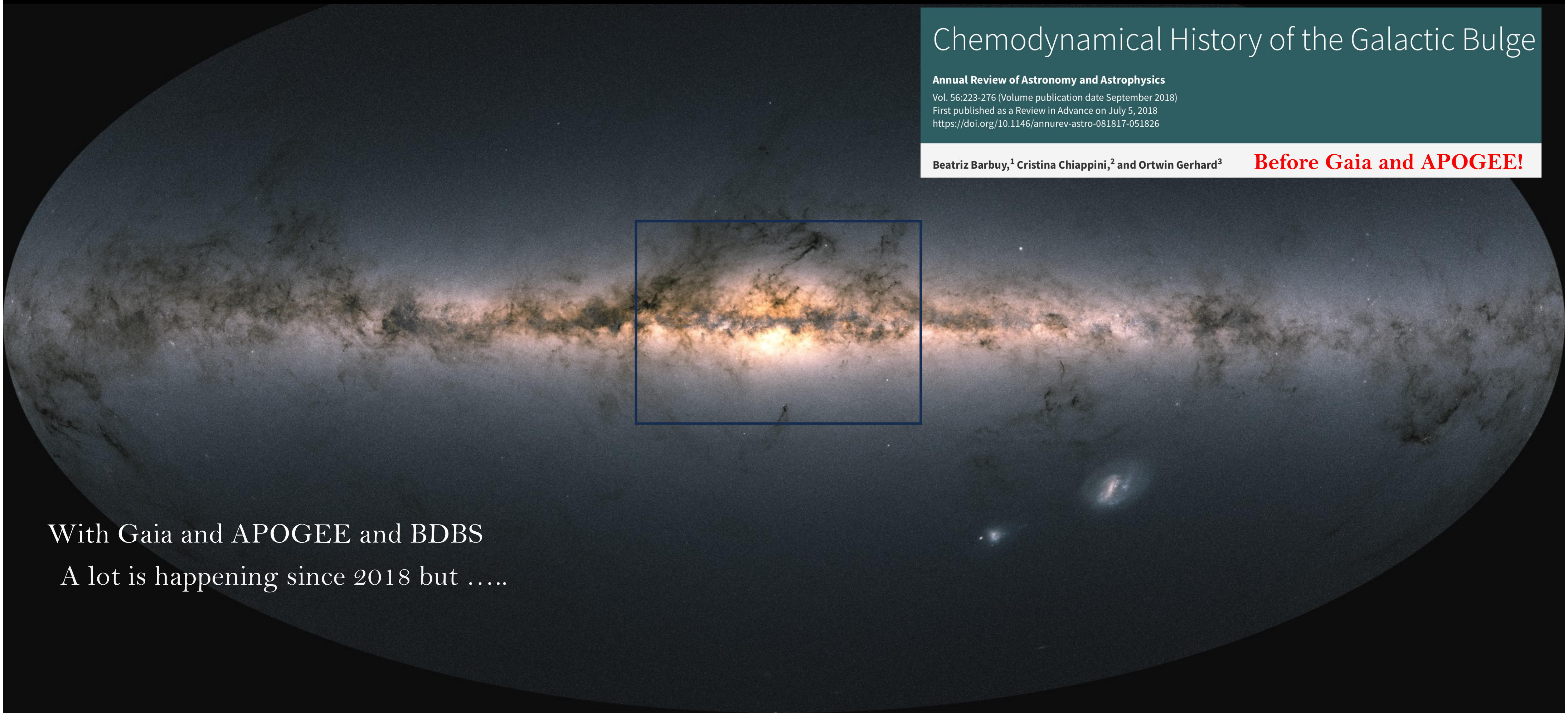
AIP

XXV CCE at ON – Rio de Janeiro – Brazil
06-10 November 2023

Galactic Archaeology in the Gaia era

1. Mapping the Milky Way: Gaia, Spectroscopic Surveys and asteroseismology
2. The Galaxy is complex: finding debris and culprits of radial migration by combining ages, chemistry and kinematics
3. The galactic bulge I
4. The galactic bulge II and future outlook

Stellar Populations in the MW Bulge



A&A 673, A147 (2023)
https://doi.org/10.1051/0004-6361/202245673

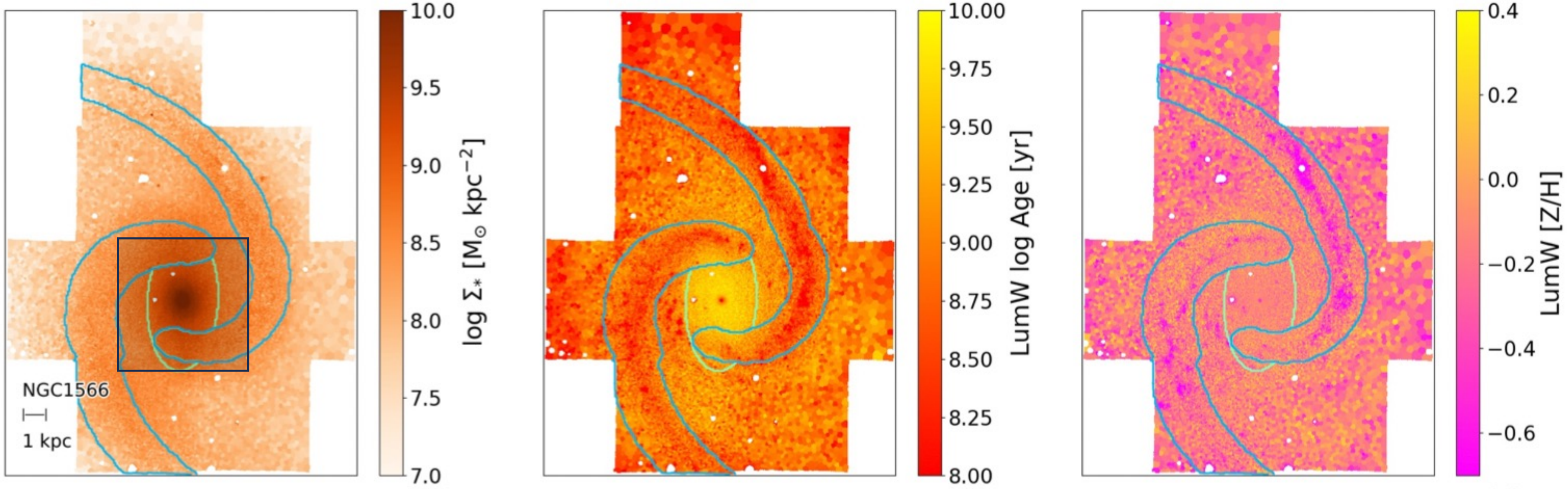
Astronomy & Astrophysics

Resolved stellar population properties of PHANGS-MUSE galaxies

I. Pessa[1,2], E. Schinnerer[2], P. Sanchez-Blazquez[3], F. Belfiore[4], B. Groves[5,6], E. Emsellem[7,8], J. Neumann[2,9], A. K. Leroy[10], F. Bigiel[11], M. Chevance[12,13], D. A. Dale[14], S. C. O. Glover[12], K. Grasha[6], R. S. Klessen[12,15], K. Kreckel[16], J. M. D. Kruijssen[13], F. Pinna[2], M. Querejeta[17], E. Rosolowsky[18], and T. G. Williams[2,19]

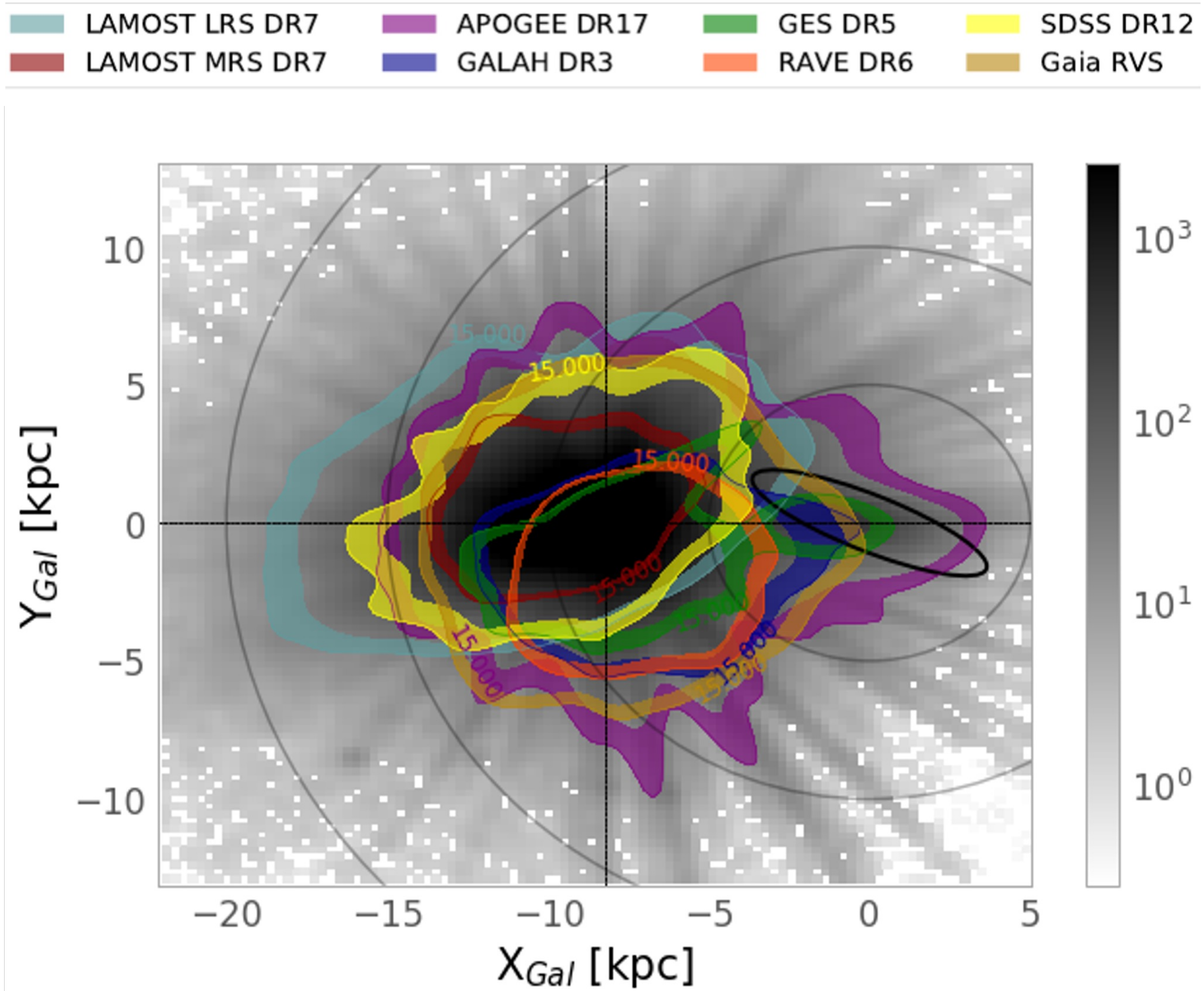
100 pc spatial resolution!

(previously, in kpc scales, blurred mix pops)



+ JWST bulges at redshift > 5 (e.g. Carnall et al. 2023) – but what is ``the bulge``?

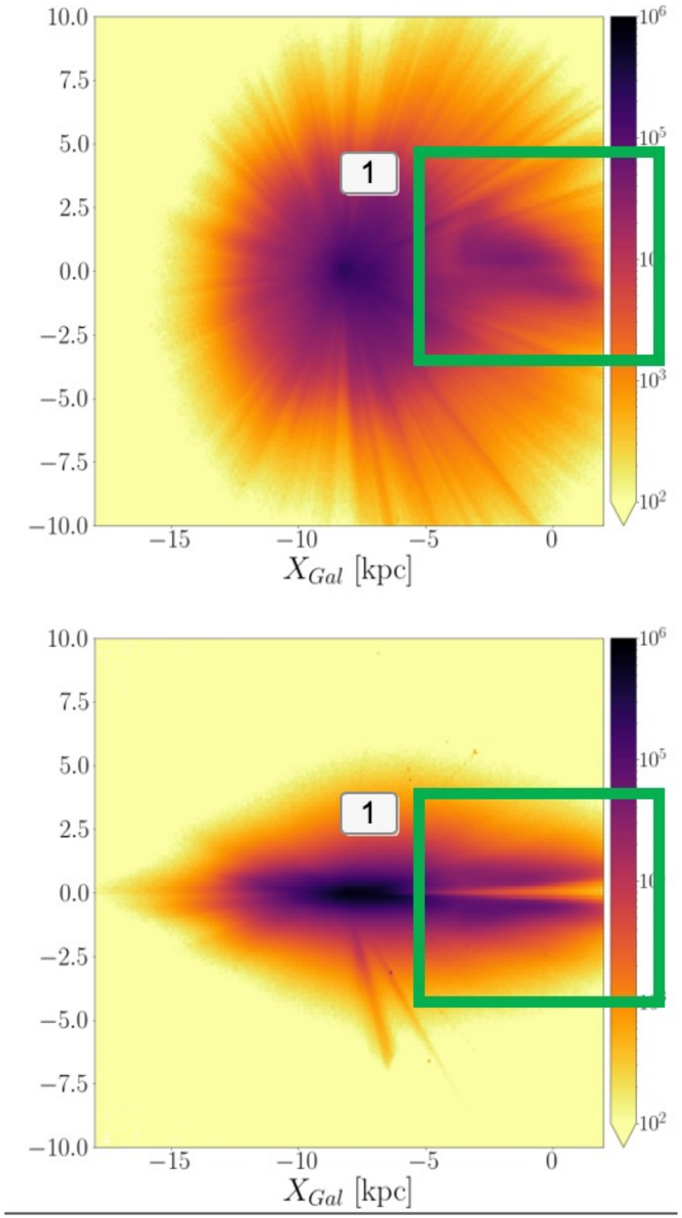
Gaia + photometry + spectroscopy + SH



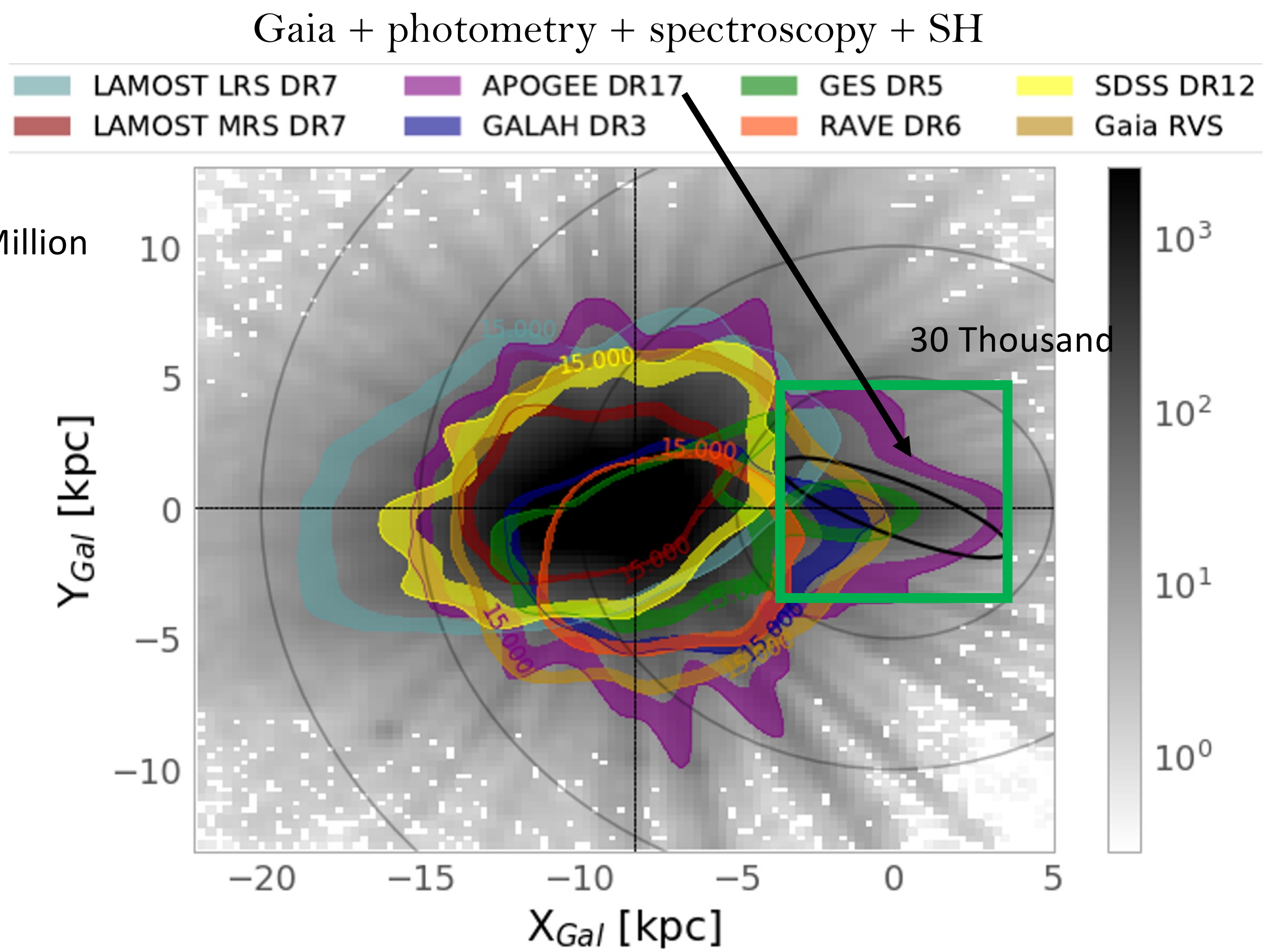
Precise Distances
are essential for
precise orbital
parameters
computation

https://data.aip.de/projects/aqueiroz2023.html

Queiroz et al. 2023, 11 Million targets with distances, 2.5 Million with ages



30 Million

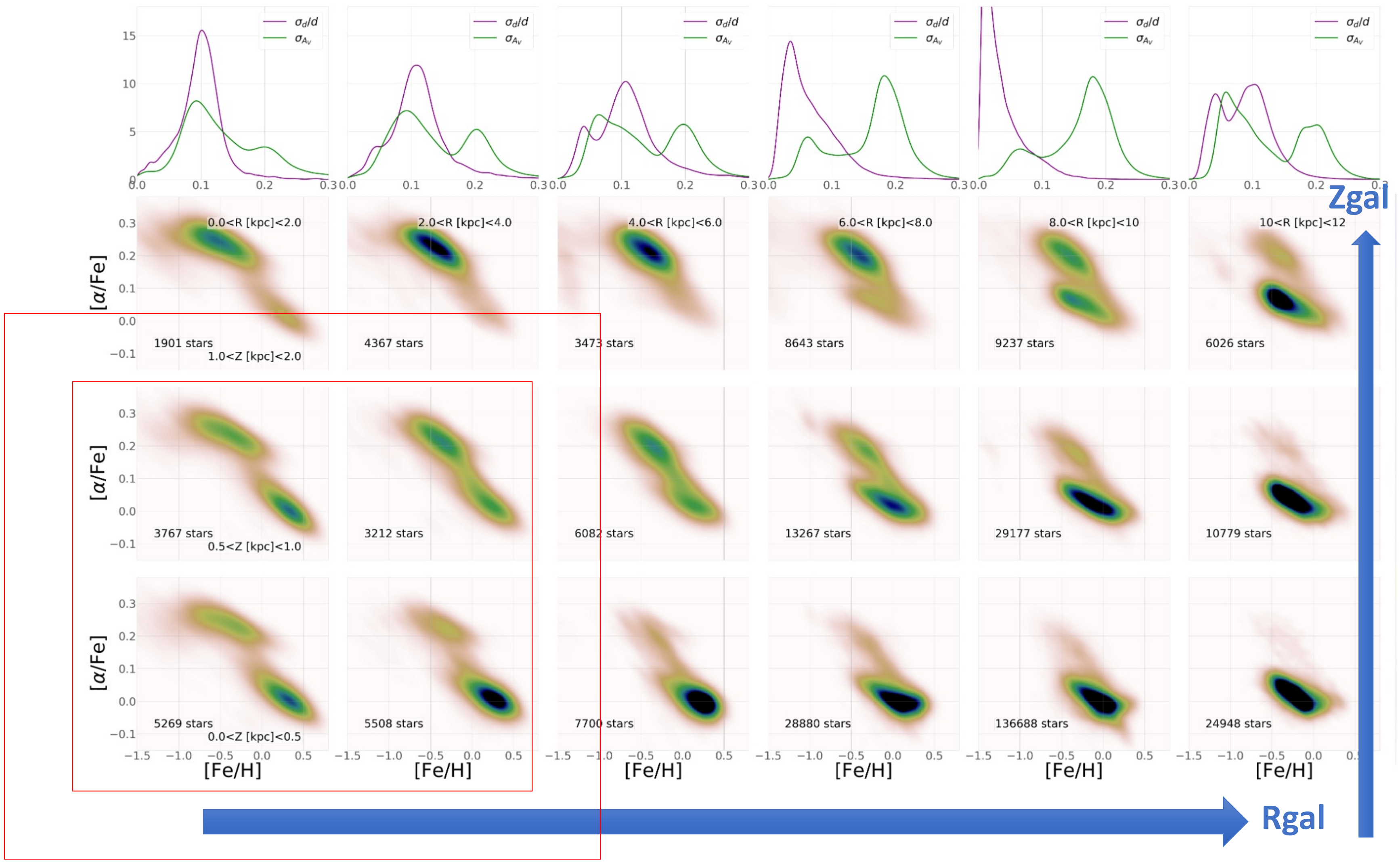


https://data.aip.de/projects/aqueiroz2023.html

Queiroz et al. 2023

Queiroz et al. 2020 – **APOGEE DR16** + Gaia DR2 + Complementary photometry

Inner disk – not one sequence, but two, extending into bulge



A&A 656, A156 (2021)
https://doi.org/10.1051/0004-6361/202039030

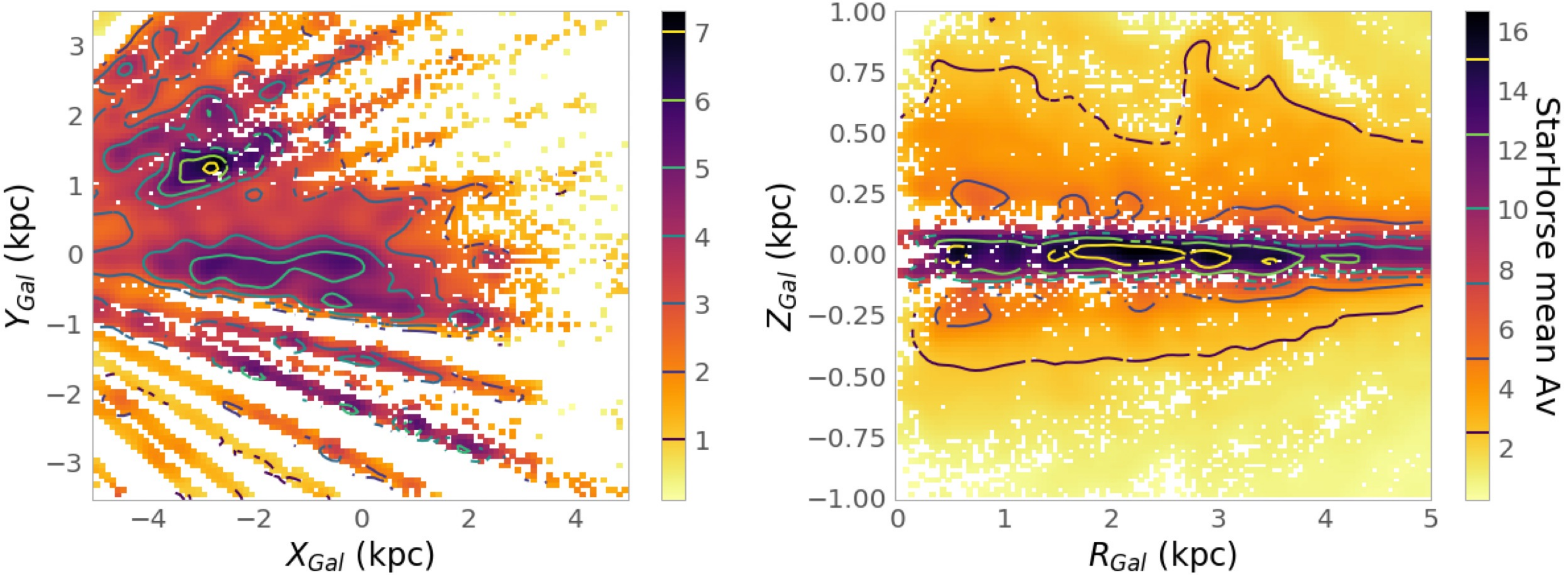
Astronomy & Astrophysics

26 500 stars within |*X*Gal| < 5 kpc, |*Y*Gal| < 3.5 kpc, |*Z*Gal| < 1 kpc

Foreground-cleaned subsample of **8000 stars that is more representative of the bulge–bar populations**

The Milky Way bar and bulge revealed by APOGEE and *Gaia* EDR3

A. B. A. Queiroz[1,2], C. Chiappini[1,2], A. Perez-Villegas[3,4], A. Khalatyan[1], F. Anders[5,2], B. Barbuy[3], B. X. Santiago[6,2], M. Steinmetz[1], K. Cunha[7,8], M. Schultheis[9], S. R. Majewski[10], I. Minchev[1], D. Minniti[11,12], R. L. Beaton[13], R. E. Cohen[14], L. N. da Costa[2], J. G. Fernández-Trincado[15,16], D. A. Garcia-Hernández[17,18], D. Geisler[19,20,21], S. Hasselquist[22,⋆], R. R. Lane[16], C. Nitschelm[23], A. Rojas-Arriagada[24,25], A. Roman-Lopes[21], V. Smith[26], and G. Zasowski[22]



Improvements from DR2 to EDR3 in the studied bulge region

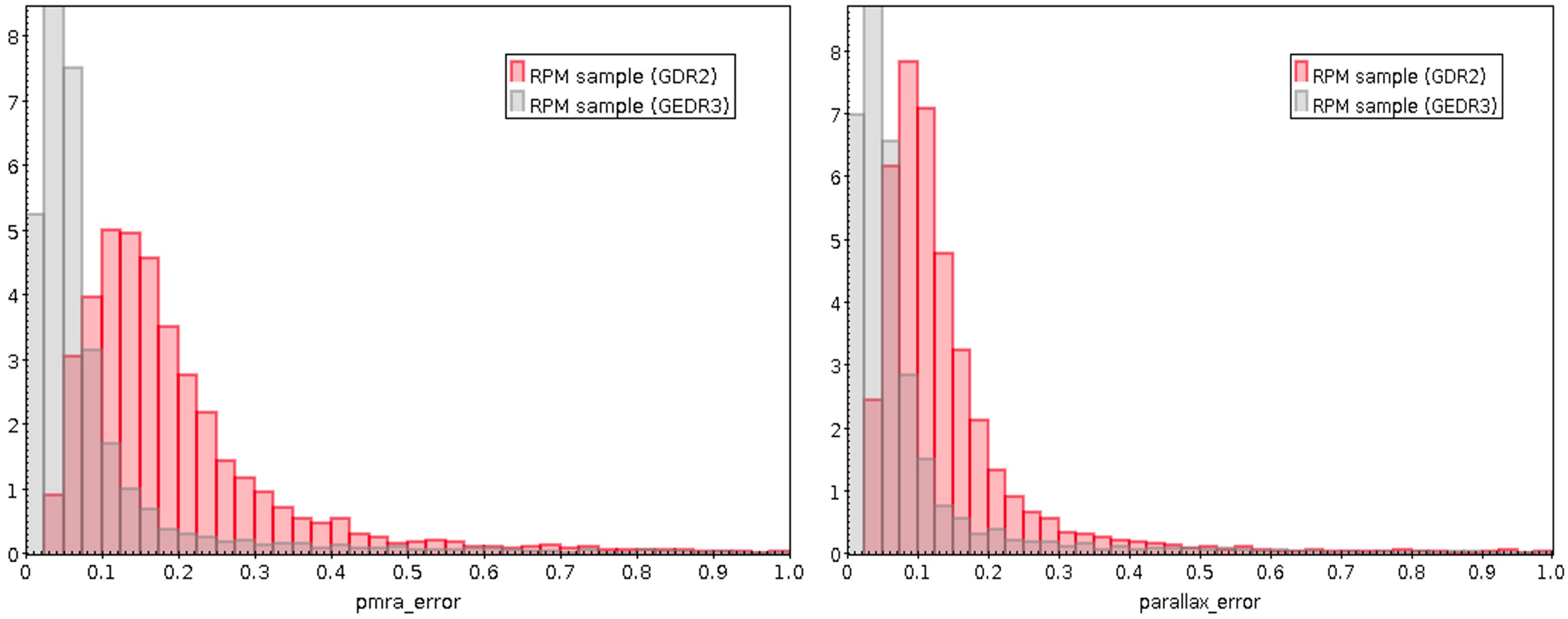
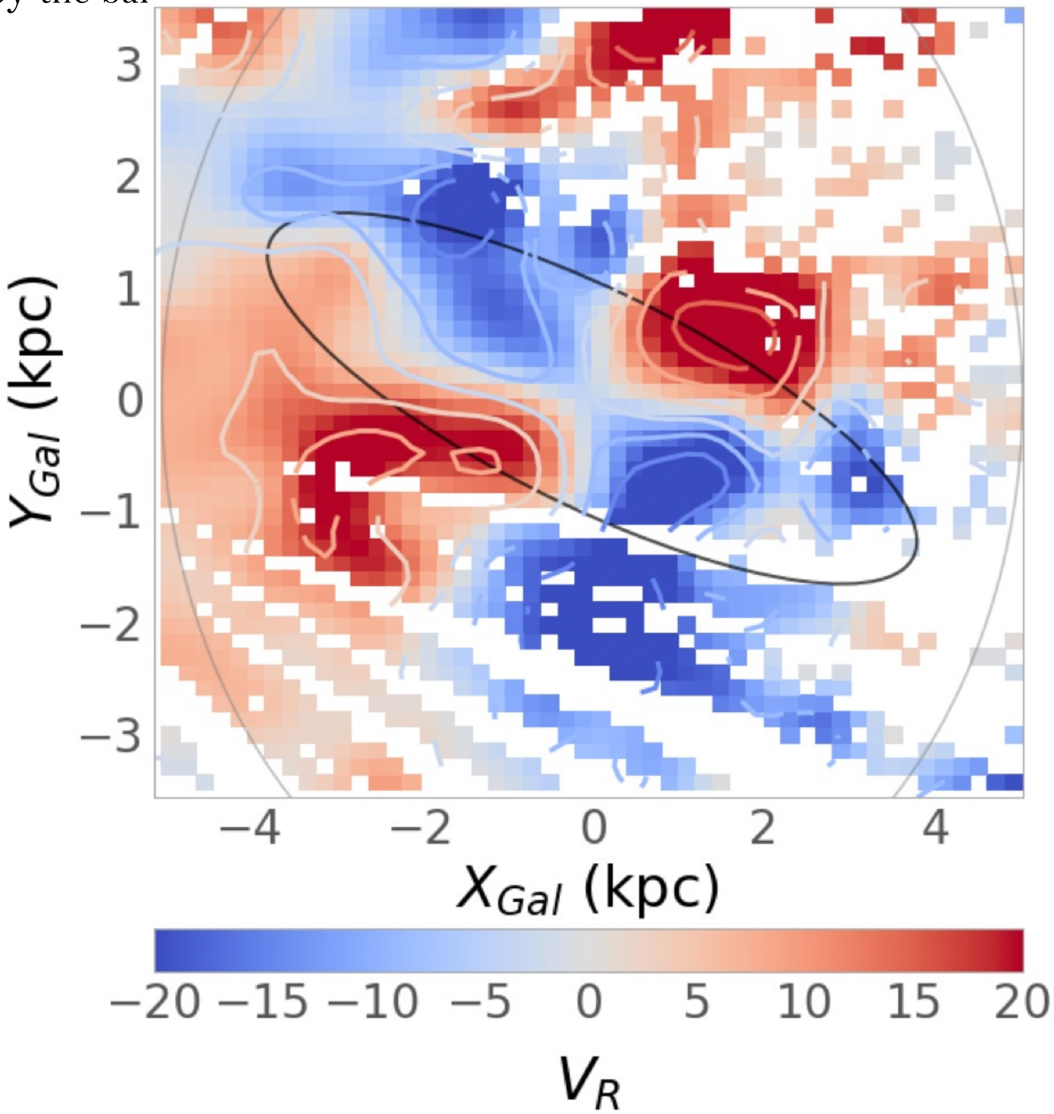
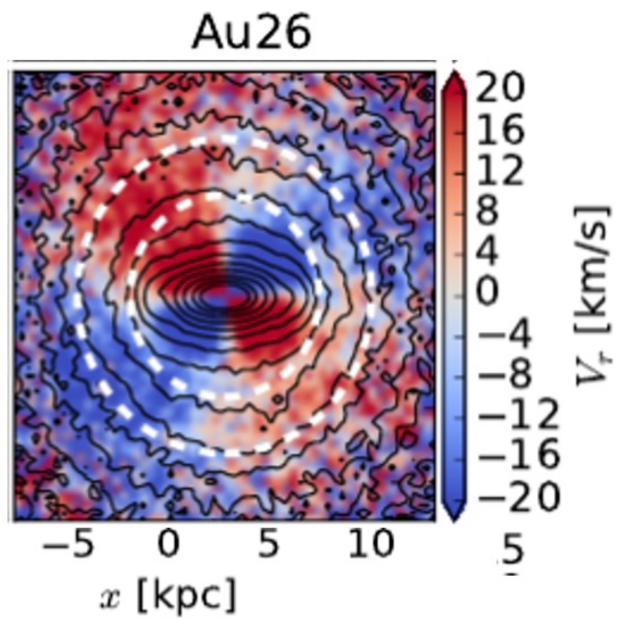


Figure Credit: Queiroz

Precise kinematical maps (Queiroz et al. 2021) unveils quadrupole feature characterizing the mean streamimg motion induced by the bar

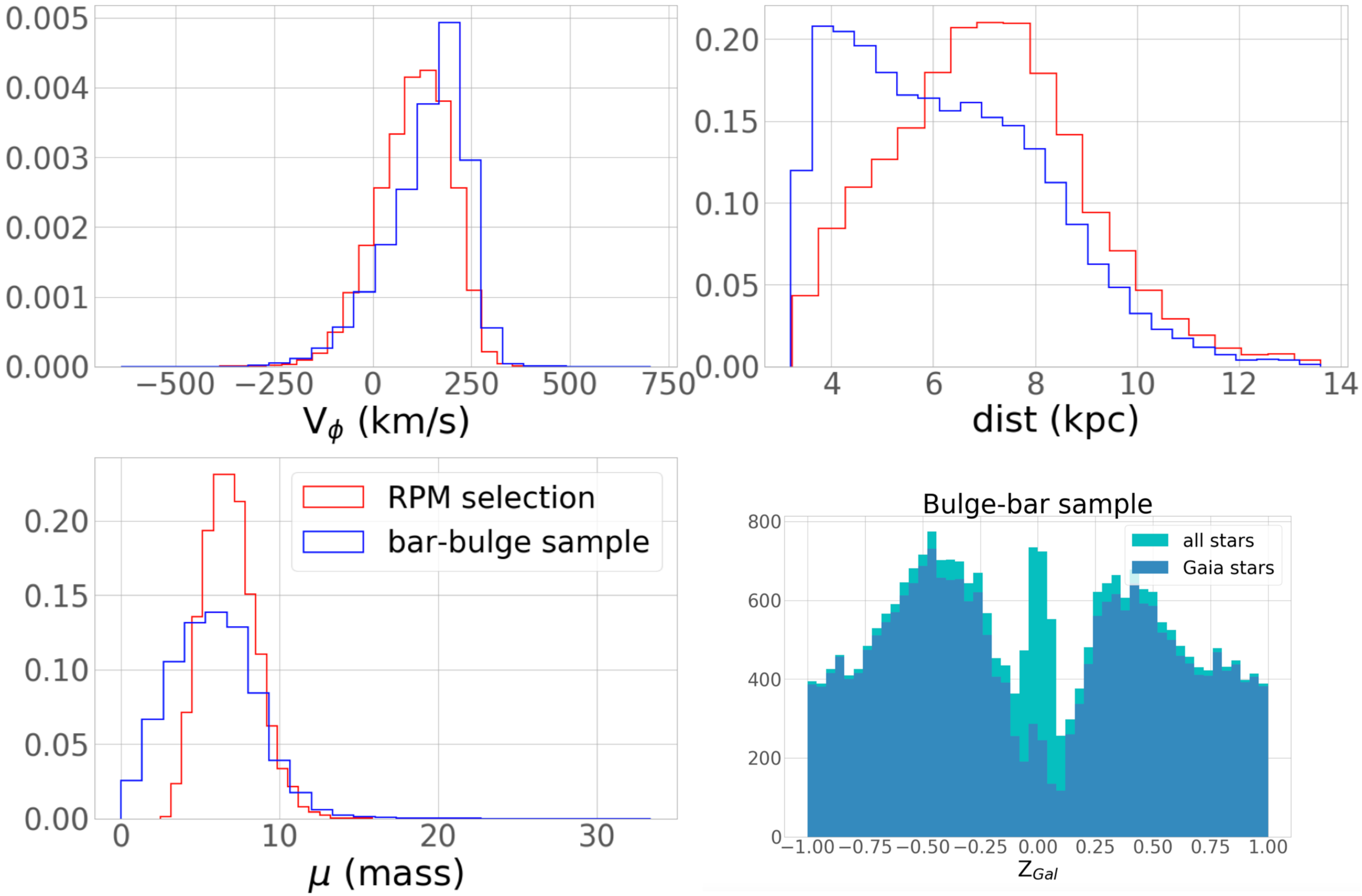


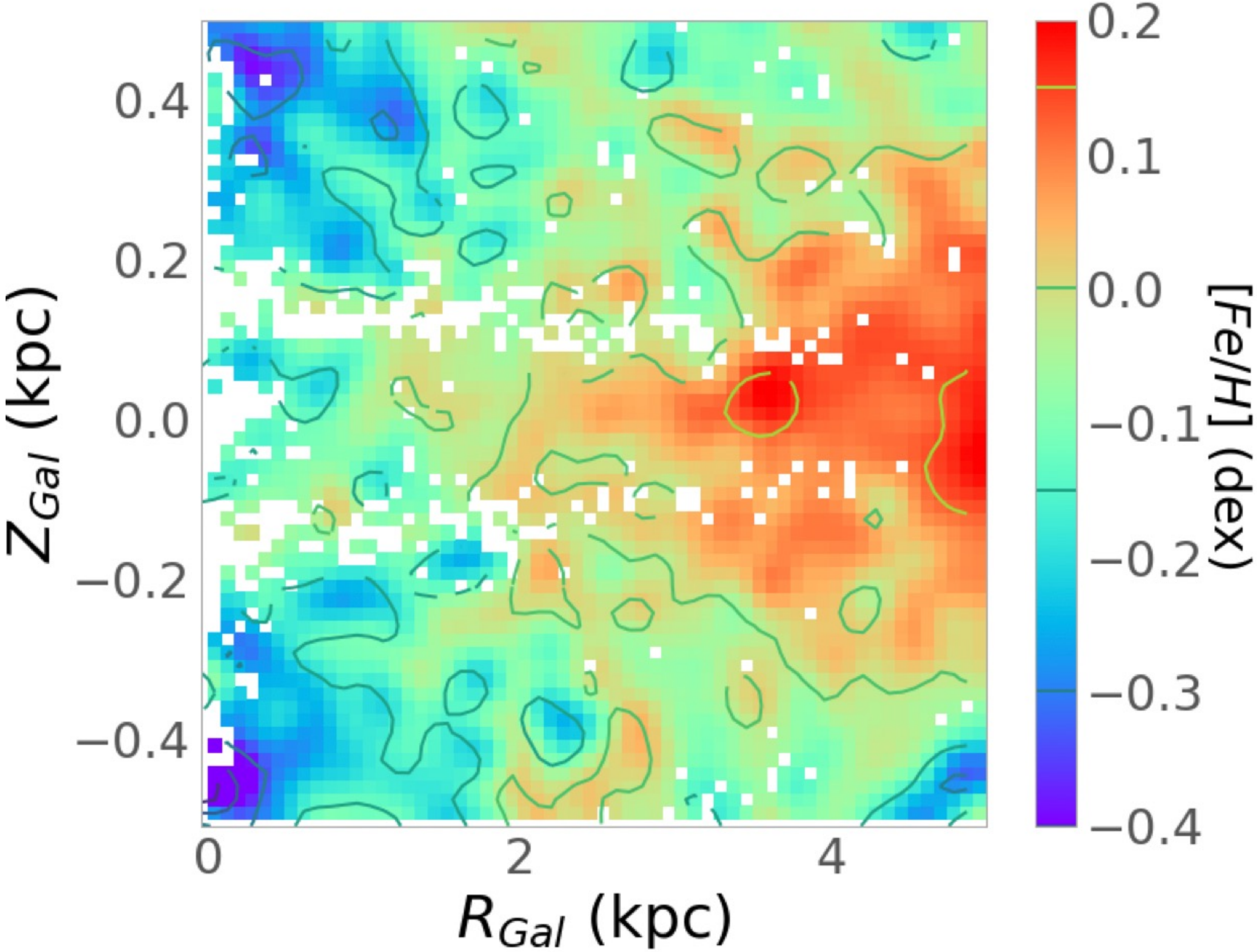


Auriga simulations-Fragkoudi et al. 2019

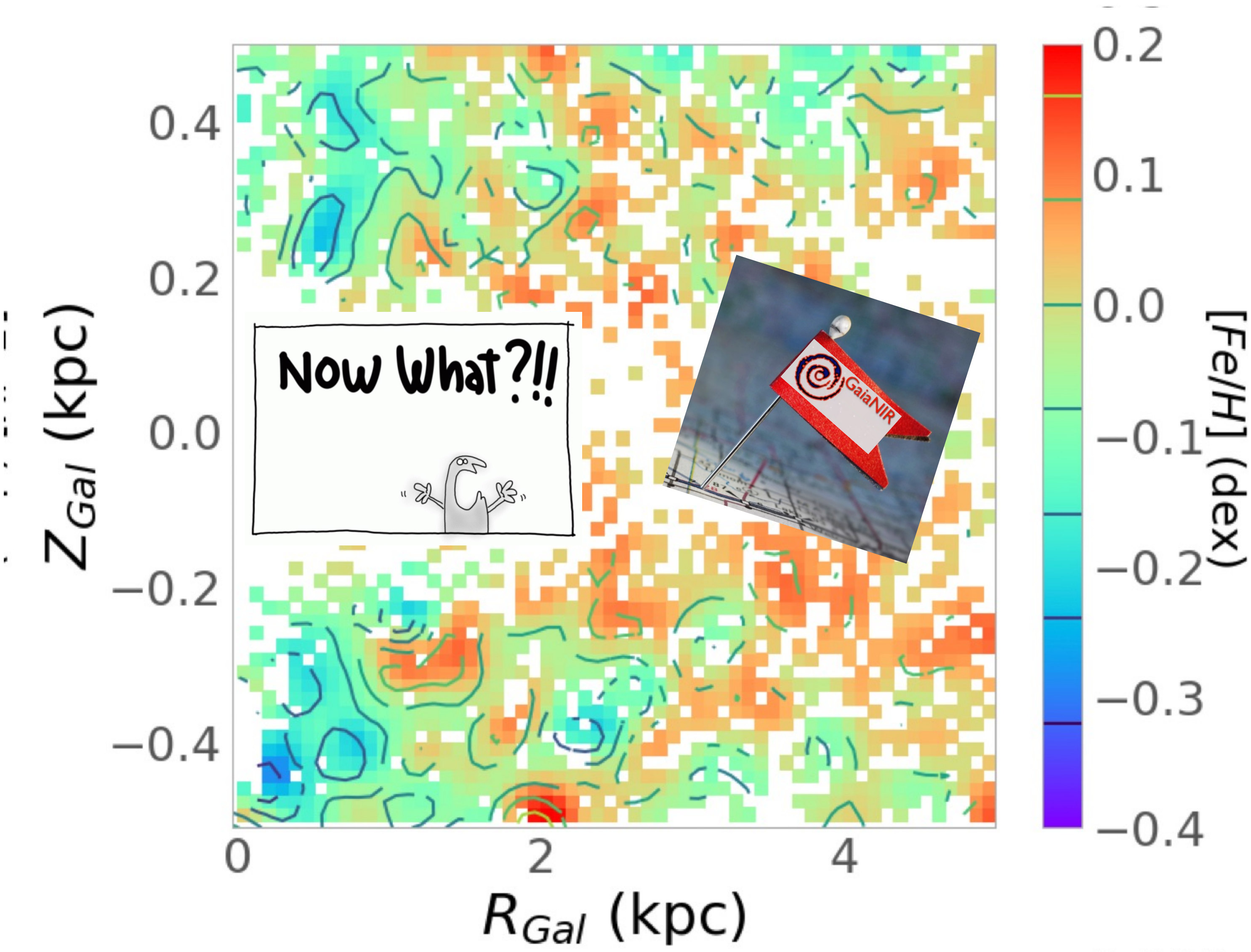
Earlier results by Bovy+2019 did not reach the far side.
Recently confirmed by Hey et al. 2023

$$M_{H'} = H_{2mass} + 5.0 + \log_{10}(\sqrt{\mu^2_{\rm RA} + \mu^2_{\rm DEC}}).$$



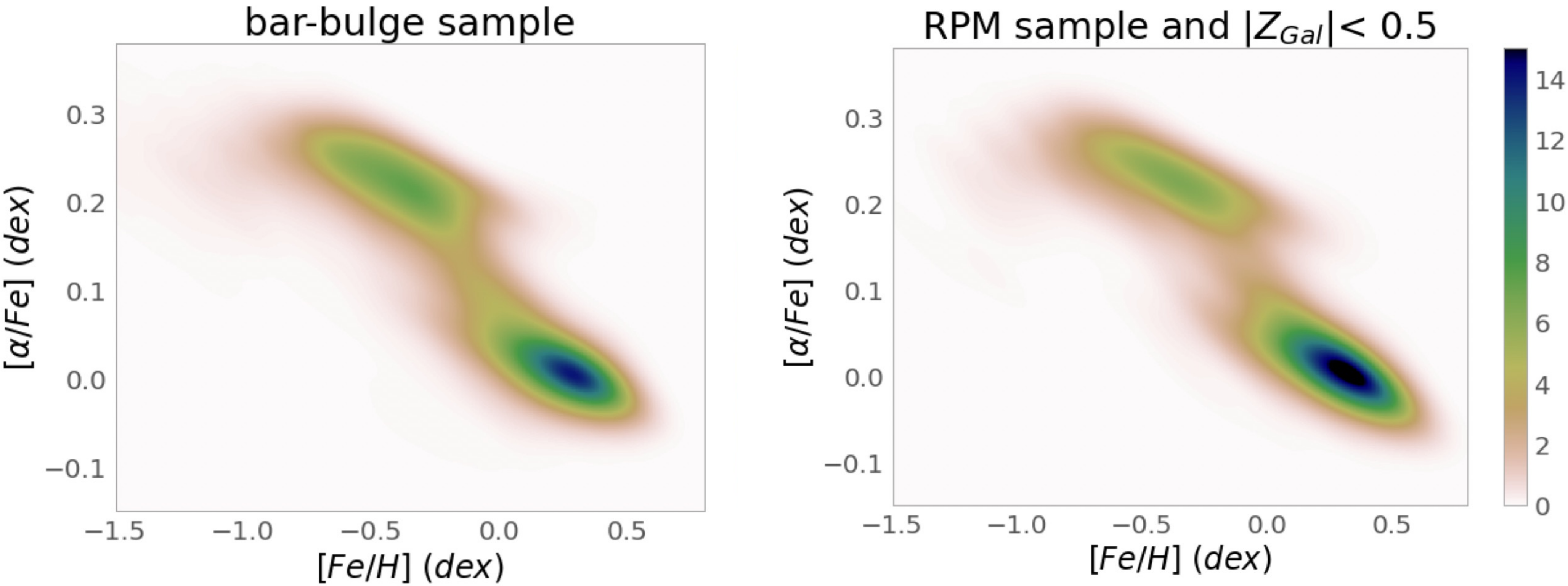


0.4
0.2
0.0
−0.2
−0.4
Z_{Gal} (kpc)
0
2
4
R_{Gal} (kpc)
0.2
0.1
0.0
−0.1
−0.2
−0.3
−0.4
[Fe/H] (dex)


Now What?!!
GaiaNIR
0.4
0.2
0.0
−0.2
−0.4
Z_{Gal} (kpc)
0
2
4
R_{Gal} (kpc)
0.2
0.1
0.0
−0.1
−0.2
−0.3
−0.4
[Fe/H] (dex)

26,500 stars

3,800 stars

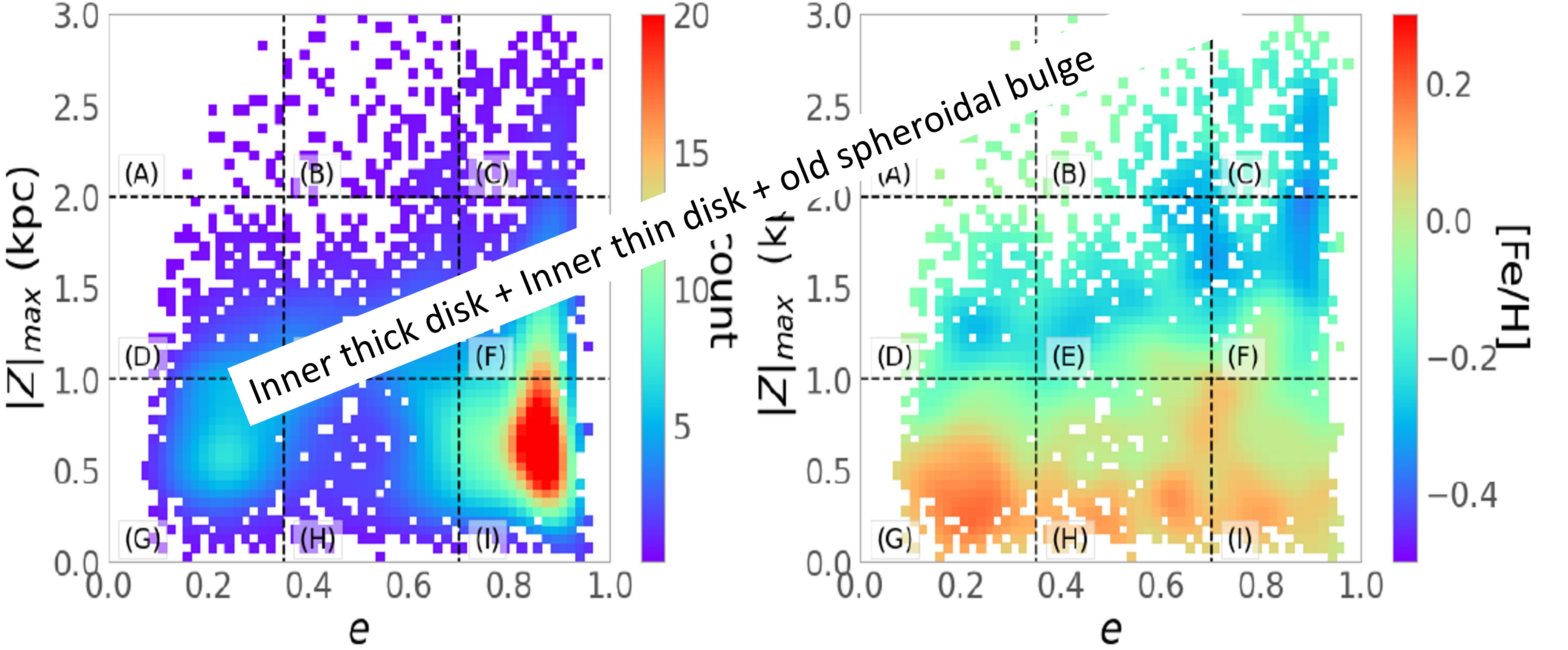


Less foreground + orbital analysis possible!

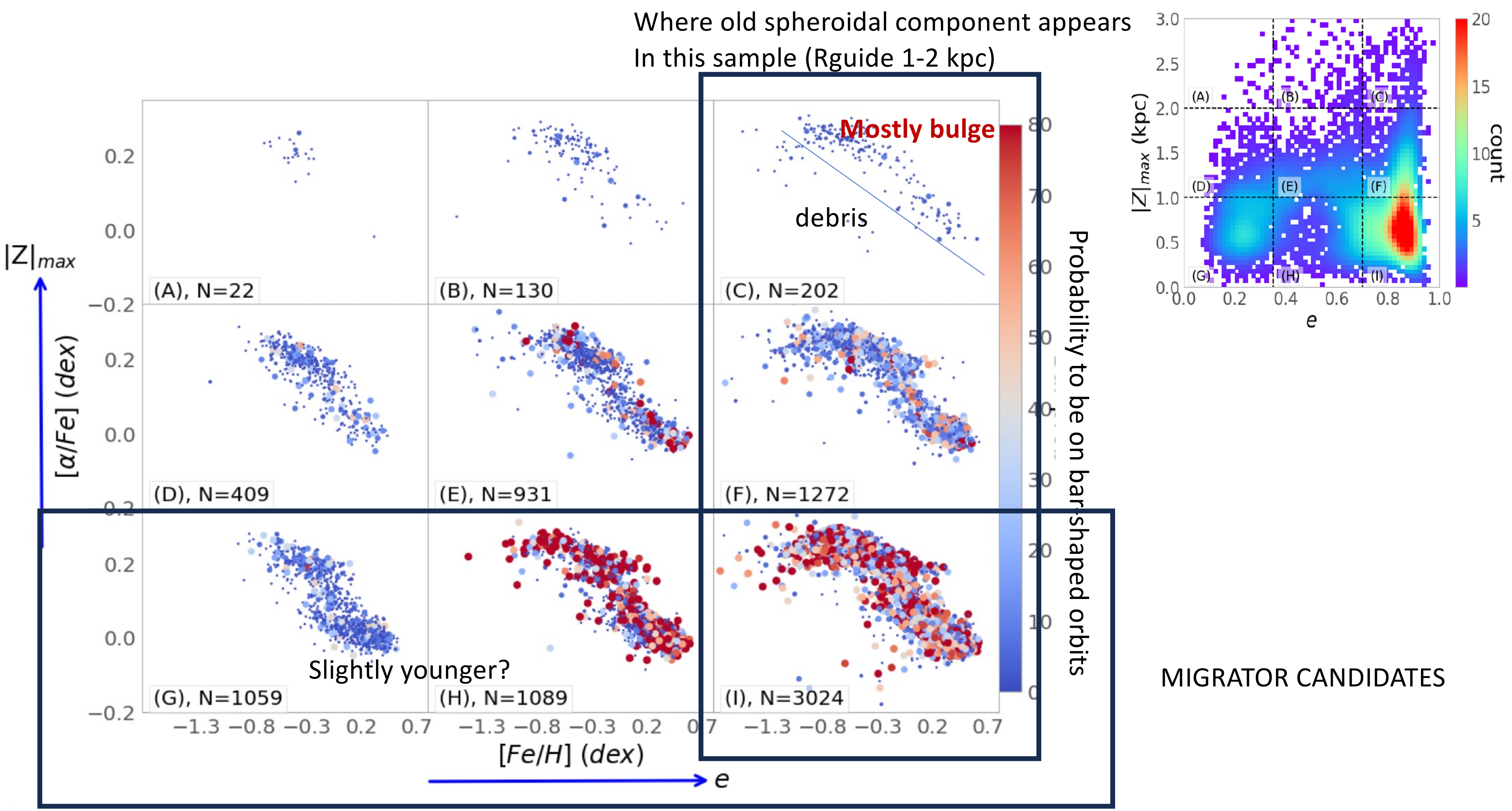
Queiroz, CC et al. 2021

7D+

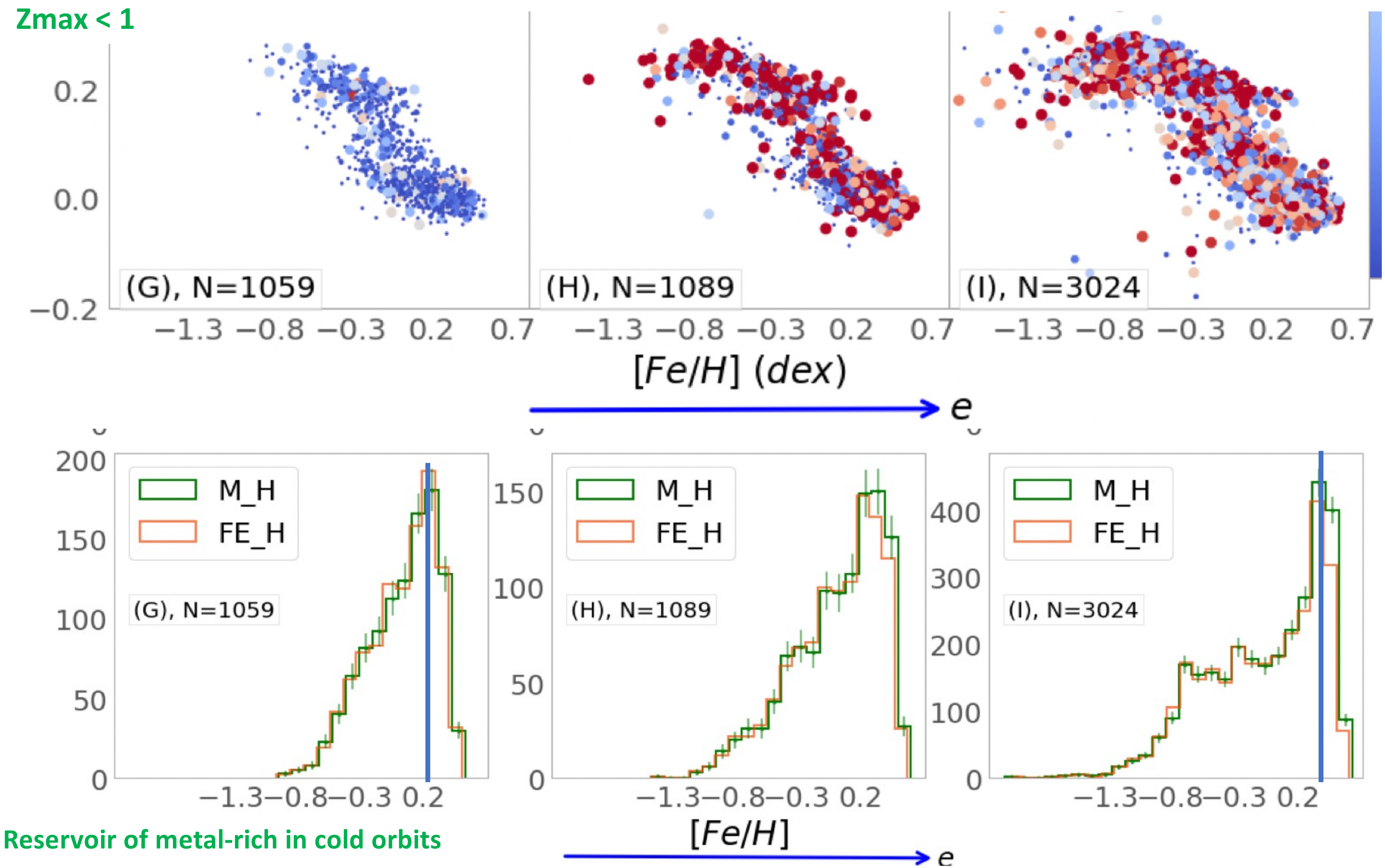
We can finally make an orbital space analysis but for around 8000 stars...
(from box of 30Million -> 30Thousand – Thousands...)



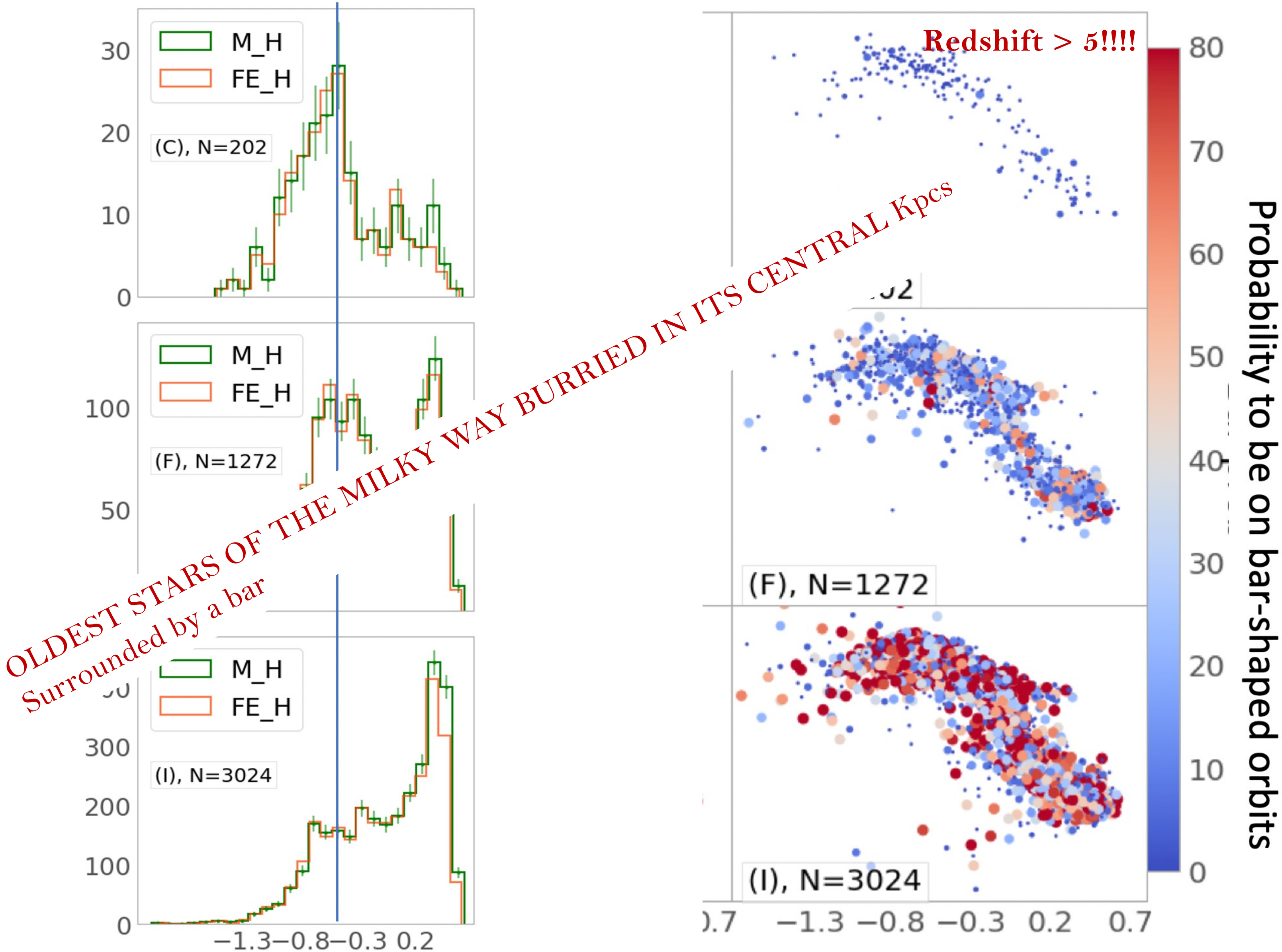
Queiroz et al. 2021



Where old spheroidal component appears
In this sample (Rguide 1-2 kpc)
Mostly bulge
debris
Slightly younger?
MIGRATOR CANDIDATES
|Z|max
[α/Fe] (dex)
[Fe/H] (dex)
e
(A), N=22
(B), N=130
(C), N=202
(D), N=409
(E), N=931
(F), N=1272
(G), N=1059
(H), N=1089
(I), N=3024
Probability to be on bar-shaped orbits
|Z|max (kpc)
count

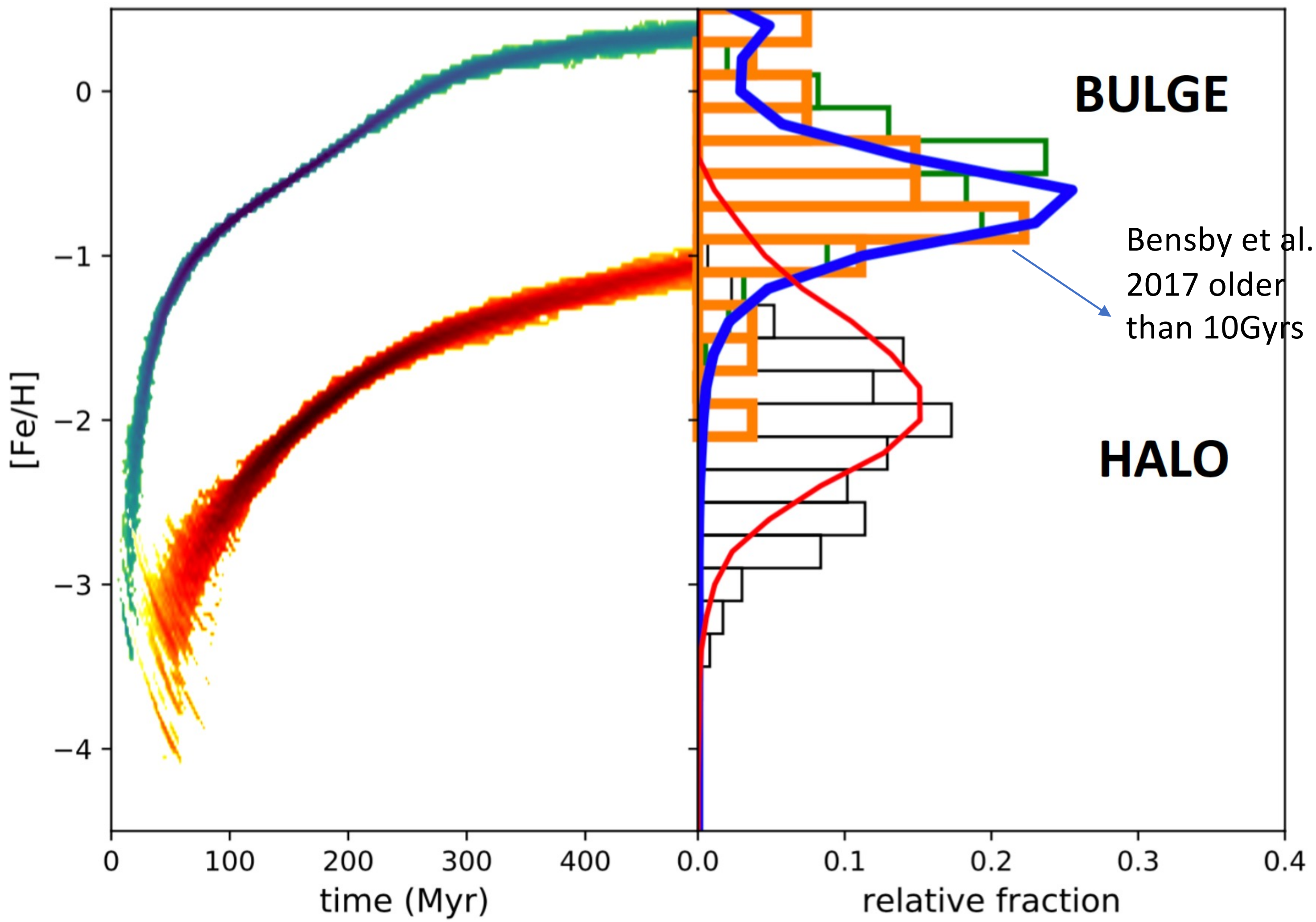


Zmax < 1
0.2
0.0
−0.2
(G), N=1059
(H), N=1089
(I), N=3024
−1.3 −0.8 −0.3 0.2 0.7
[Fe/H] (dex)
e
200
150
100
50
0
M_H
FE_H
(G), N=1059
(H), N=1089
(I), N=3024
400
300
−1.3−0.8−0.3 0.2
[Fe/H]
Reservoir of metal-rich in cold orbits
e



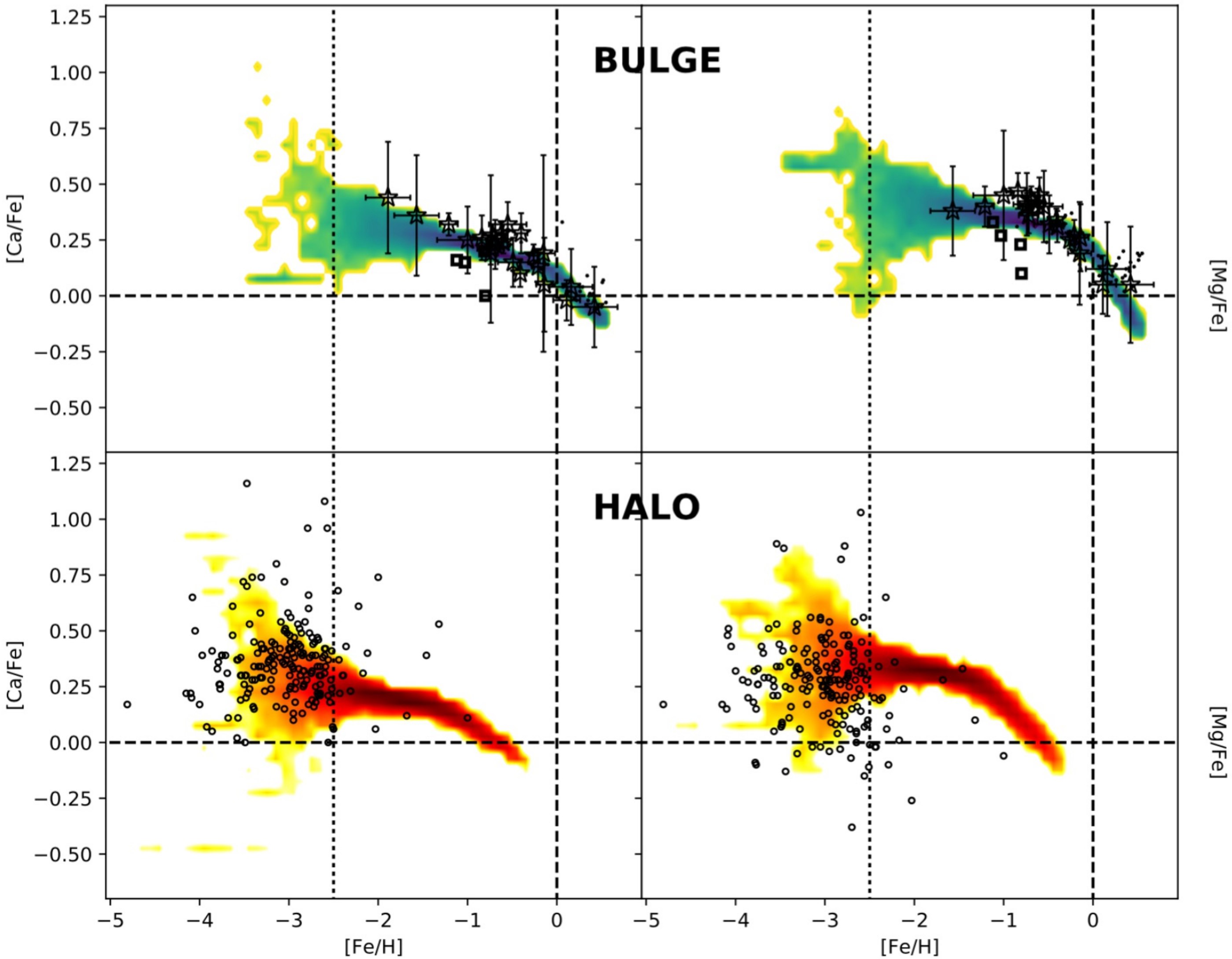
Dangerous to use chemical or kinematical criteria to select bar vs. non bar

Modelling only an old, fast formation, component

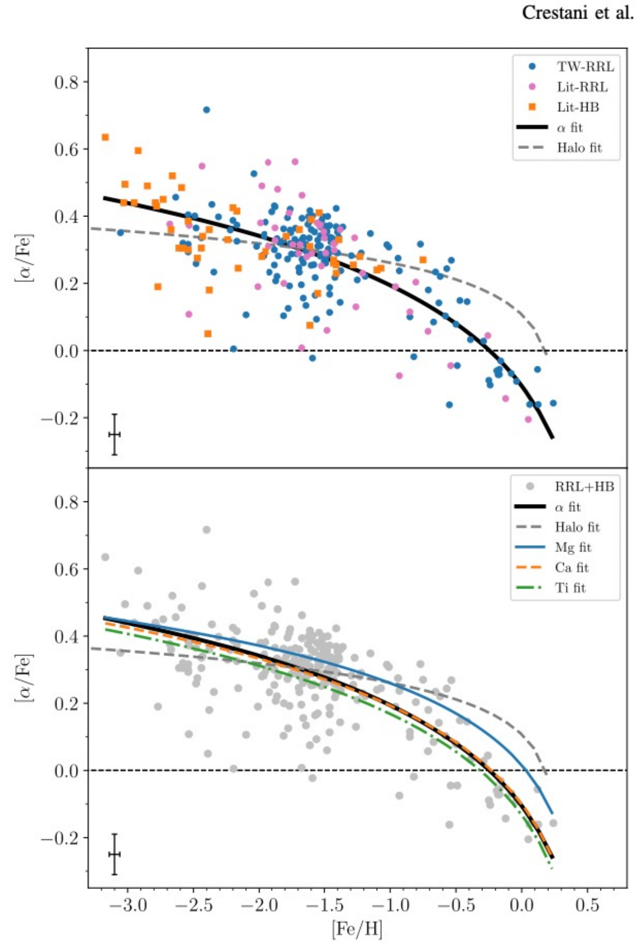


Cescutti, Chiappini et al. In prep.

See Crestani et al. 2021, RRLyrae: alpha elements



Cescutti, CC et al. In prep., see also Scannapieco, Cescutti, Chiappini 2022



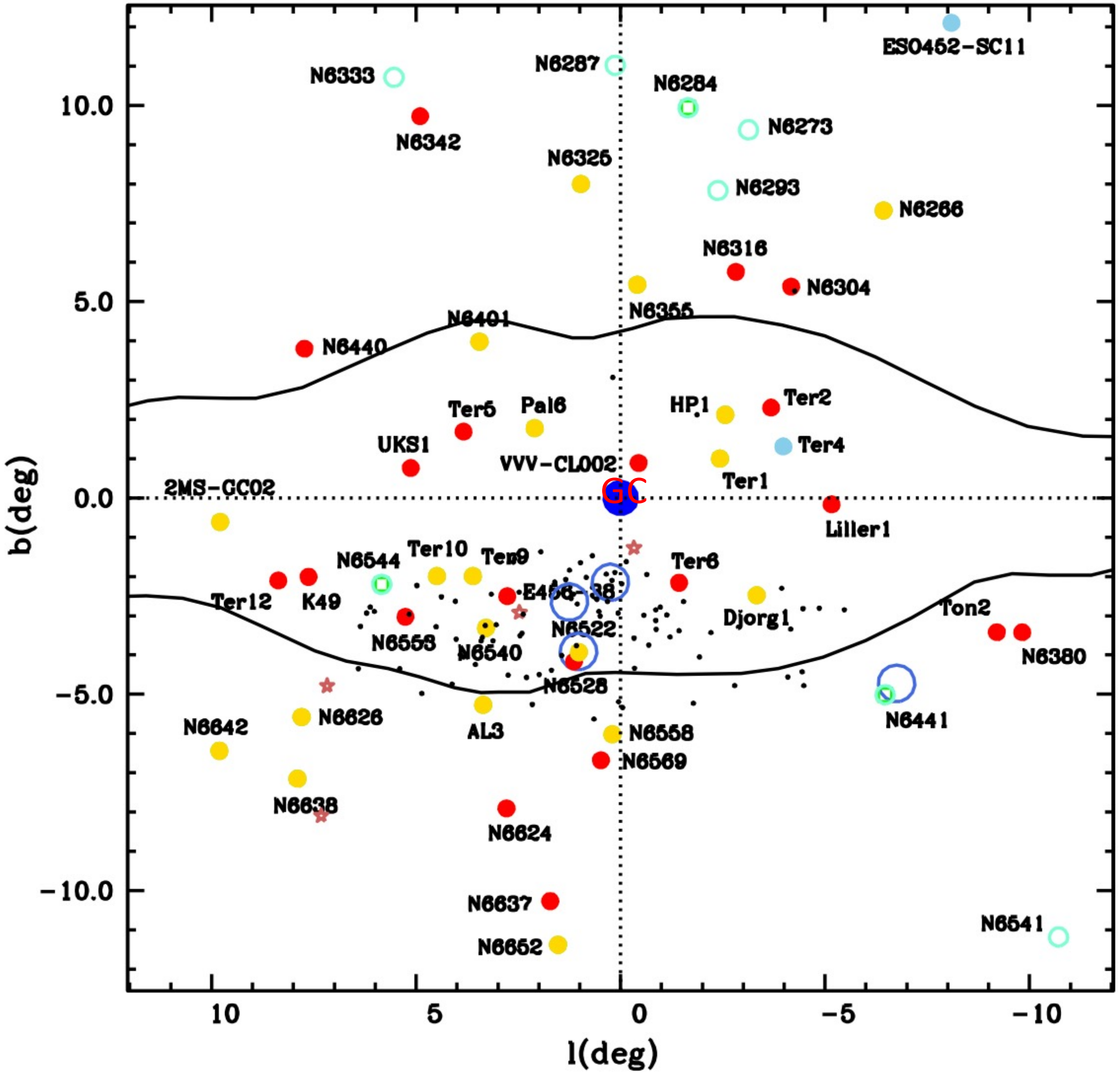
See also Kunder et al. 2016, Clarkson et al. 2018, Savino et al. 2020, Marchetti et al. 2022, Ages (Meridith et al. 2023, old miras Prudil´s talk)

Chemodynamical History of the Galactic Bulge

Annual Review of Astronomy and Astrophysics
Vol. 56:223-276 (Volume publication date September 2018)
First published as a Review in Advance on July 5, 2018
https://doi.org/10.1146/annurev-astro-081817-051826

Beatriz Barbuy,[1] Cristina Chiappini,[2] and Ortwin Gerhard[3]

Clusters from 2018 to now (recent update by Barbuy squares – empty squares are candidates, blue are confirmed GCs). Full compilation to appear in Bica et al. (submitted)



- Dots – Microlensed Dwarfs (Bensby et al. 2017)
- Filled circles – Projected bulge GCs (Bica et al. 2016)
  [Fe/H]>−0.8 (red)
  −1.3<[Fe/H]<−0.8 (gold)
  [Fe/H]<−1.3 (blue)
  Halo GCs (cyan) and Rgal > 4.5 kpc (green open squares)
- Halo ClustersFilled circles – GCs (Bica et al. 2016)
- COBE/DIRBE contour (Weiland et al. 1994) (line)
- Low extinction windows: BW, SWEEPS, OGLE29 (blue circles)
- 4 C-rich Miras - stars

Chemodynamical History of the Galactic Bulge

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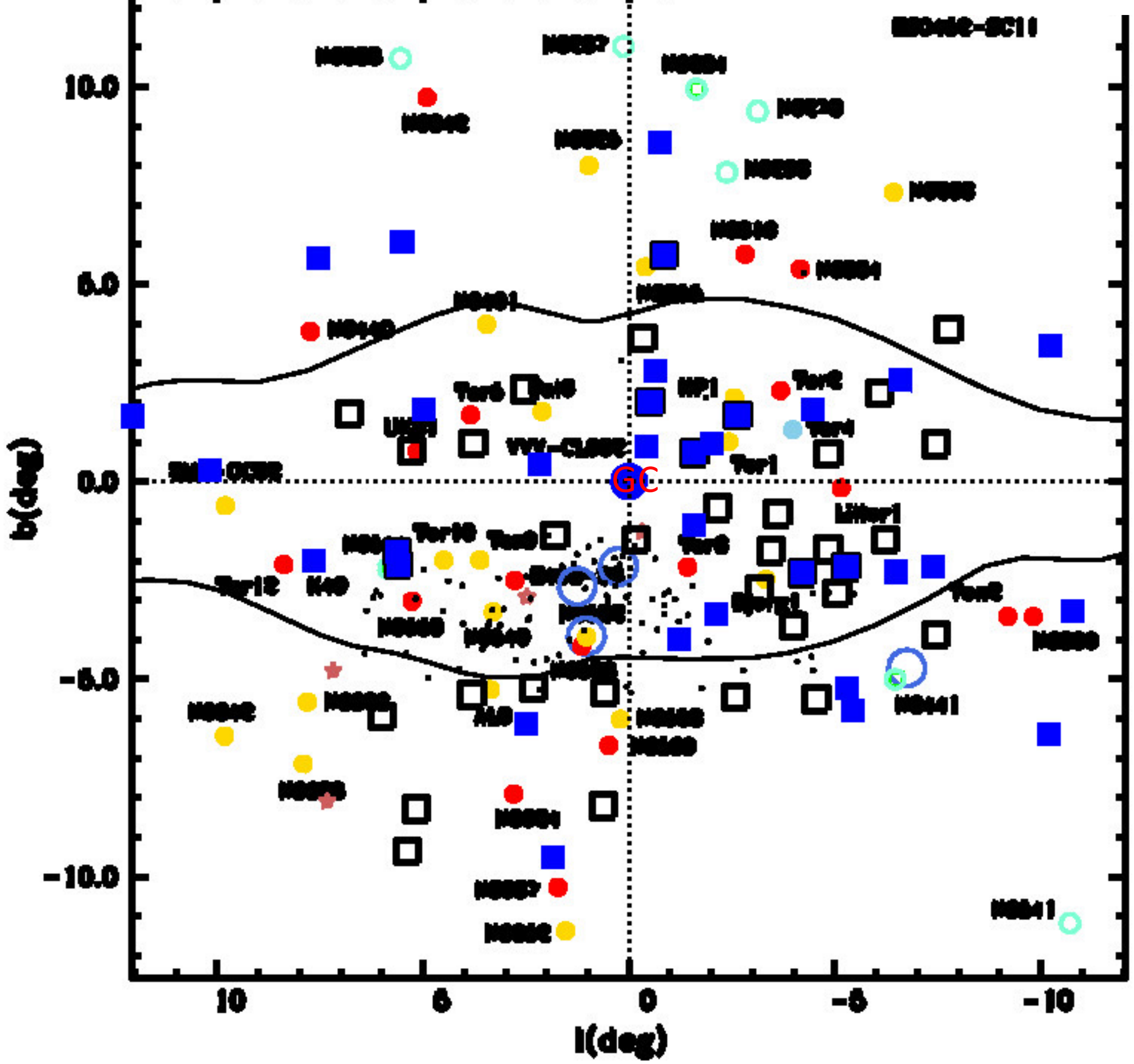
Beatriz Barbuy,[1] Cristina Chiappini,[2] and Ortwin Gerhard[3]

Most of the new ones come from VVV (e.g. Gran et al. 2019, Minniti et al. 2020, Garro et al. 2022)

Clusters from 2018 to now (recent update by Barbuy squares – empty squares are candidates, blue are confirmed GCs). Full compilation to appear in Bica et al. (submitted)



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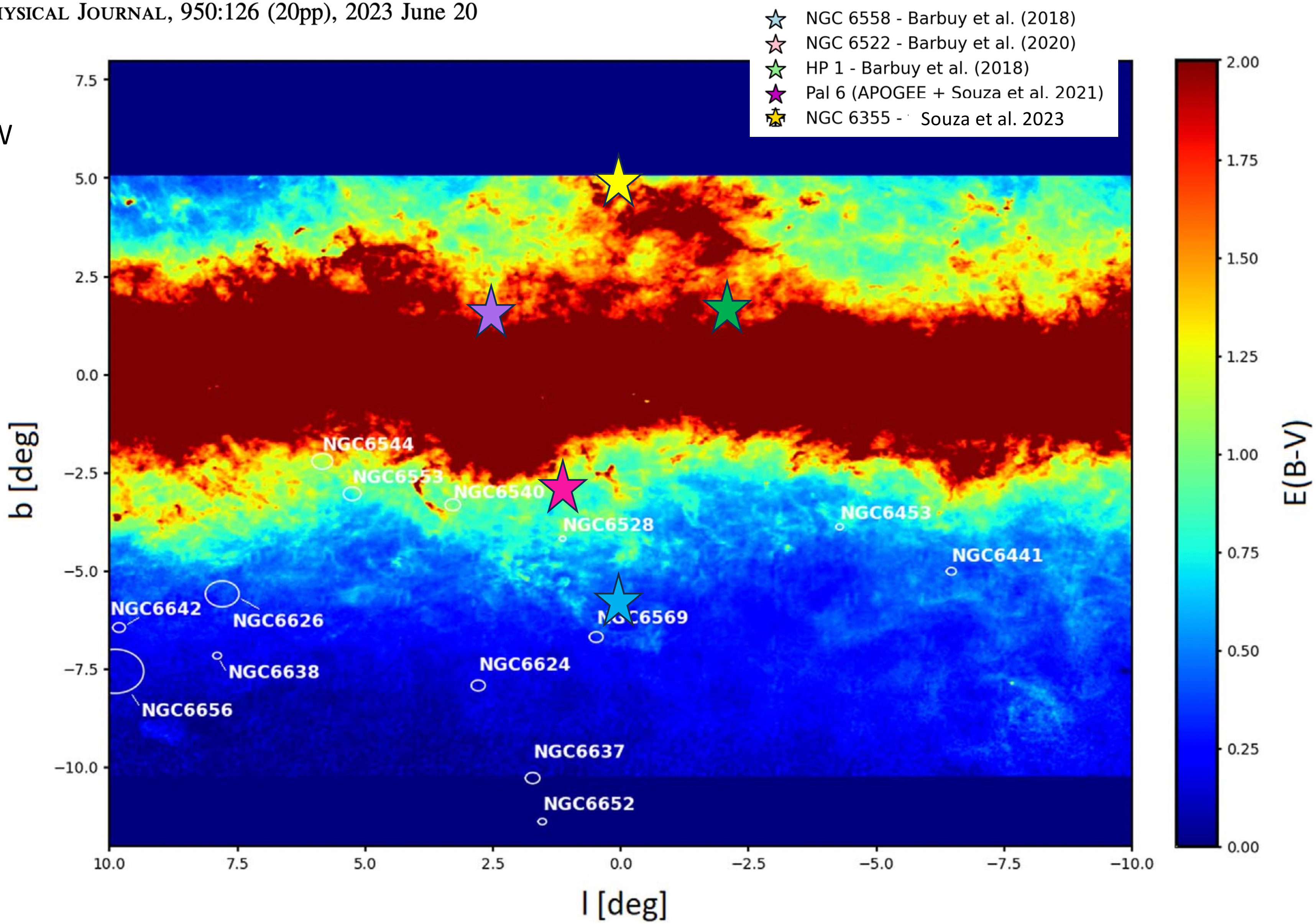
- 4 C-rich Miras - stars

GCs view
Oldest MW



https://doi.org/10.1051/0004-6361/202245286

Astronomy & Astrophysics

Chrono-chemodynamical analysis of the globular cluster NGC 6355: Looking for the fundamental bricks of the Bulge★

AROUND 13 Gyr old

S. O. Souza[1,2], H. Ernandes[3,2], M. Valentini[1], B. Barbuy[2], C. Chiappini[1], A. Pérez-Villegas[4], S. Ortolani[5,6,7], A. C. S. Friaça[2], A. B. A. Queiroz[1,8], and E. Bica[9]

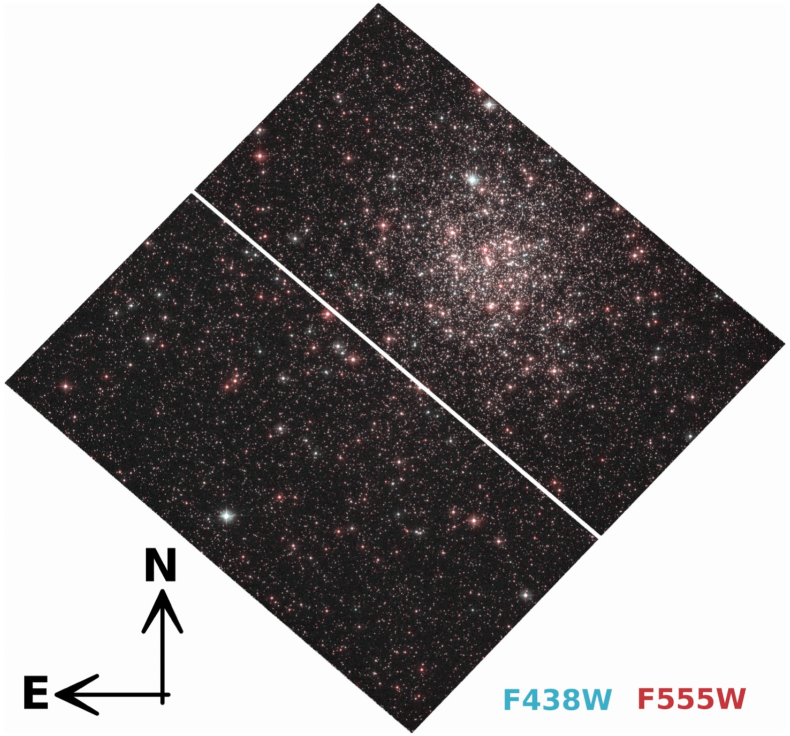


Fig. 1. *F438W/F555W* combined colour image from the HST WFC3 camera for NGC 6355.

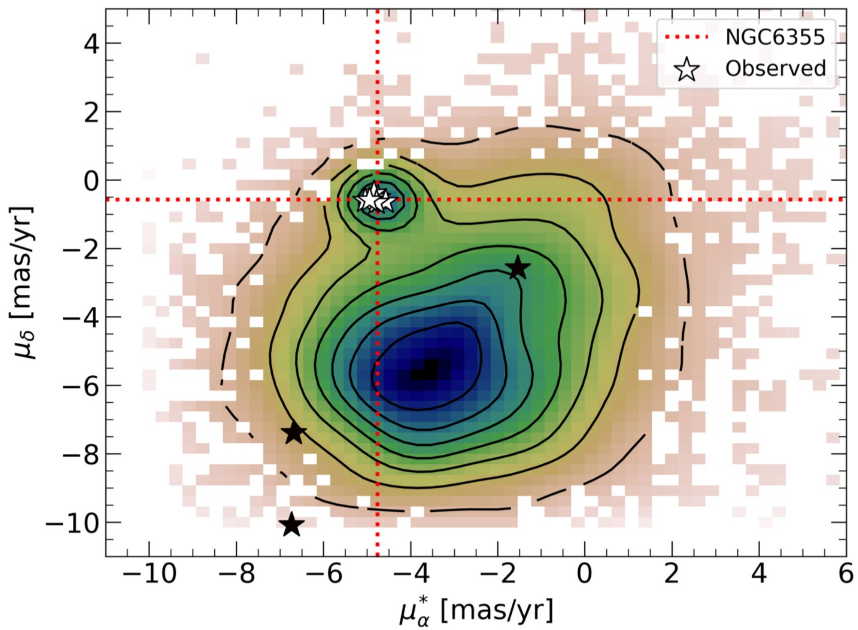
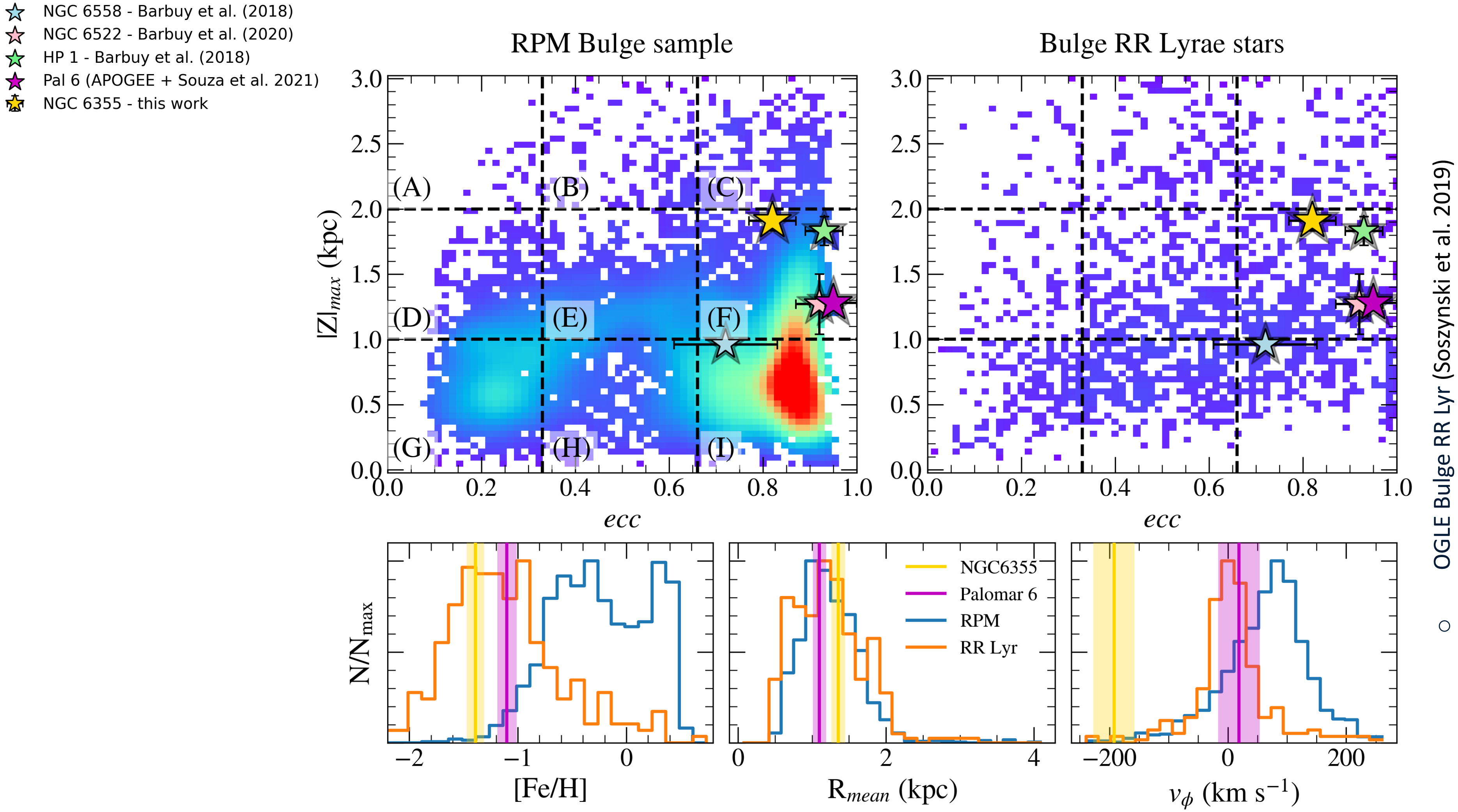
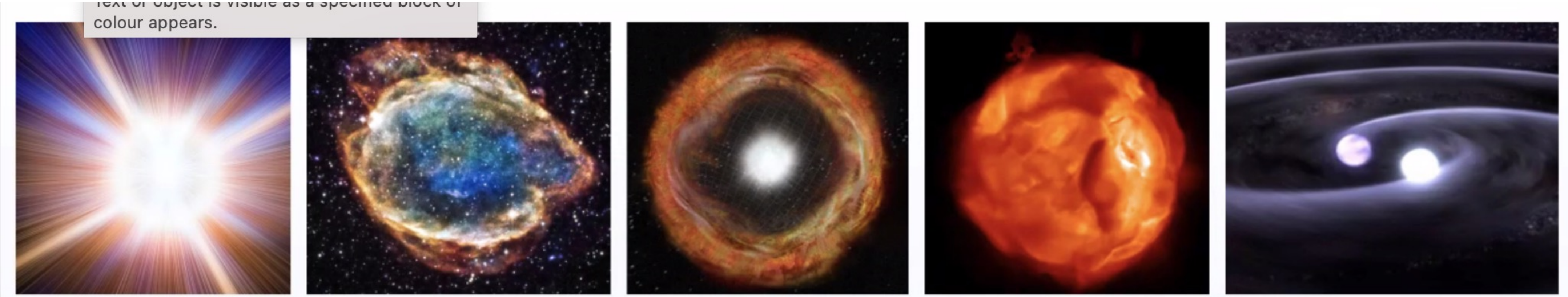


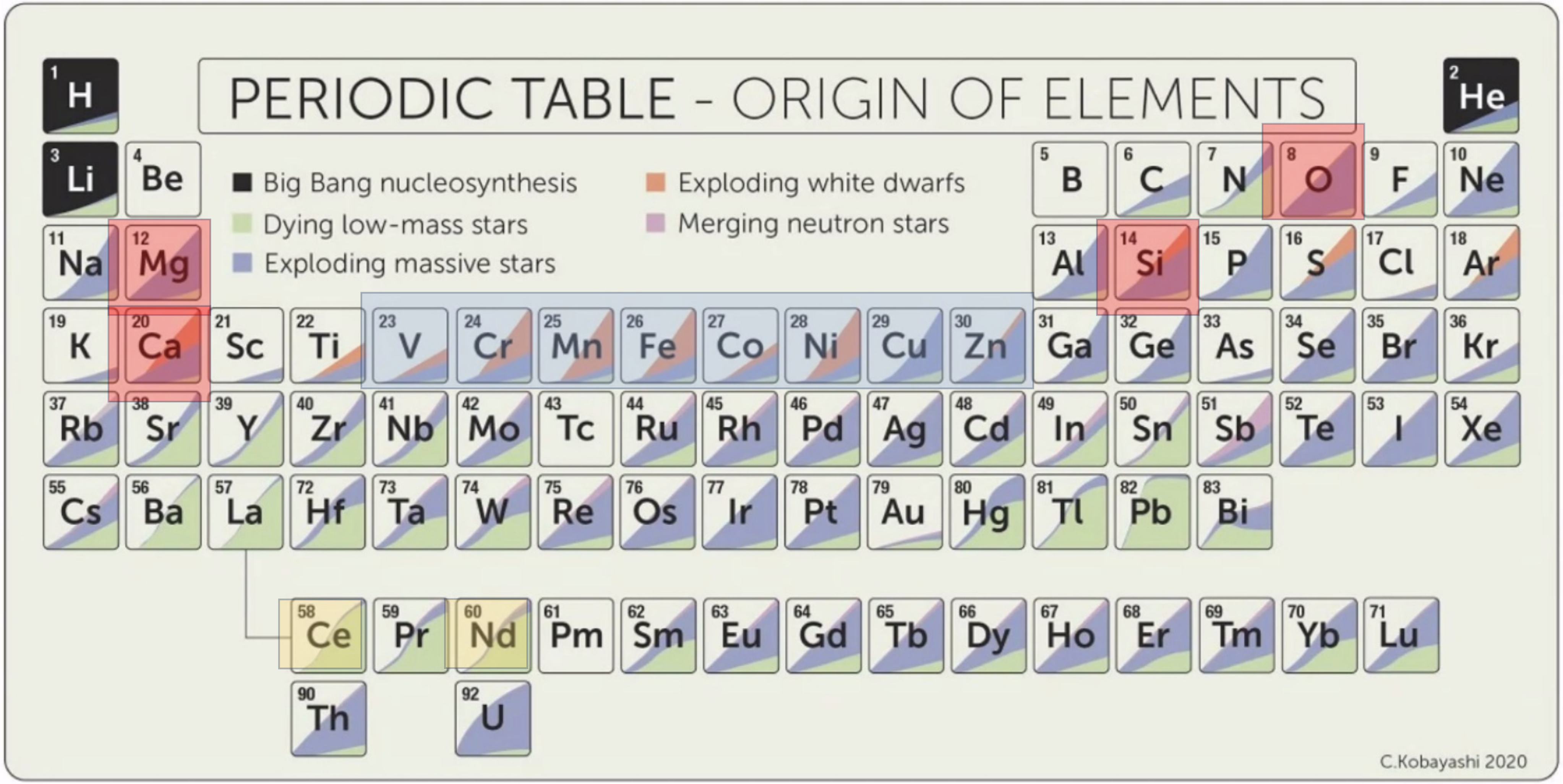
Fig. 3. Proper-motion density map from *Gaia* DR3. The stars show all the observed stars in both programs (members are plotted in white, and non-members are given in black). The red lines show the position of the mean proper motion of NGC 6355.



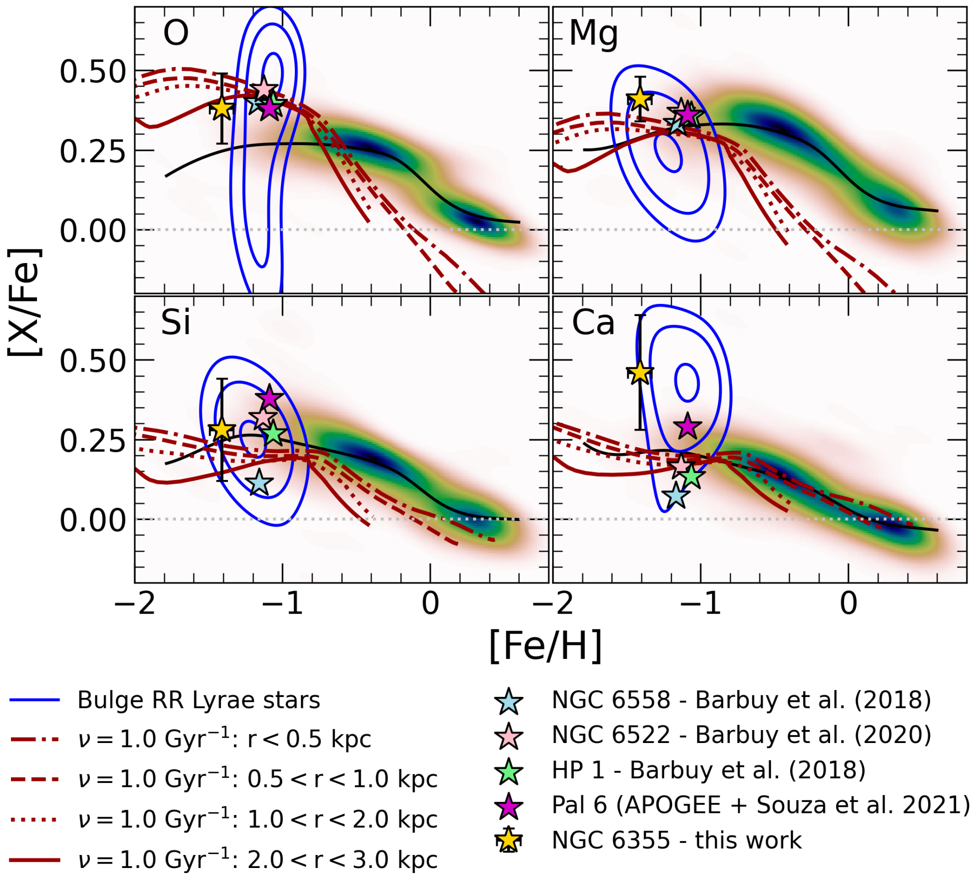
NGC 6355 (Souza et al. 2023)

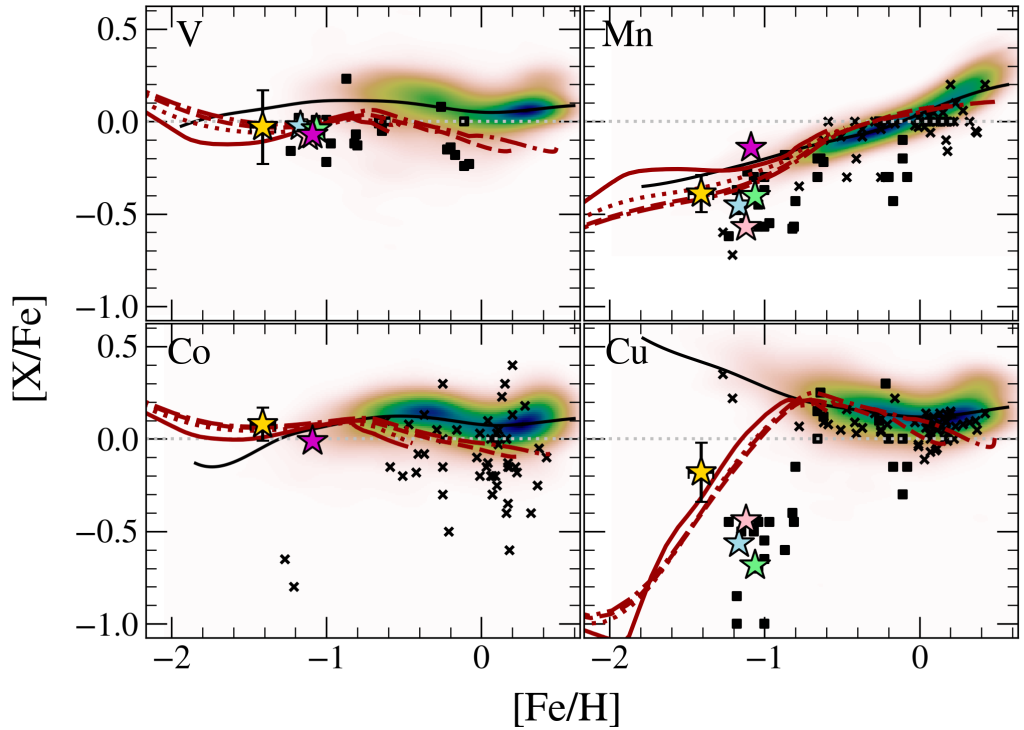
Small detour…




PERIODIC TABLE - ORIGIN OF ELEMENTS
Big Bang nucleosynthesis
Dying low-mass stars
Exploding massive stars
Exploding white dwarfs
Merging neutron stars
1 H
2 He
3 Li
4 Be
5 B
6 C
7 N
8 O
9 F
10 Ne
11 Na
12 Mg
13 Al
14 Si
15 P
16 S
17 Cl
18 Ar
19 K
20 Ca
21 Sc
22 Ti
23 V
24 Cr
25 Mn
26 Fe
27 Co
28 Ni
29 Cu
30 Zn
31 Ga
32 Ge
33 As
34 Se
35 Br
36 Kr
37 Rb
38 Sr
39 Y
40 Zr
41 Nb
42 Mo
43 Tc
44 Ru
45 Rh
46 Pd
47 Ag
48 Cd
49 In
50 Sn
51 Sb
52 Te
53 I
54 Xe
55 Cs
56 Ba
57 La
72 Hf
73 Ta
74 W
75 Re
76 Os
77 Ir
78 Pt
79 Au
80 Hg
81 Tl
82 Pb
83 Bi
58 Ce
59 Pr
60 Nd
61 Pm
62 Sm
63 Eu
64 Gd
65 Tb
66 Dy
67 Ho
68 Er
69 Tm
70 Yb
71 Lu
90 Th
92 U
C.Kobayashi 2020

Souza et al. abundances (FLAMES/UVES) + APOGEE for Pal 6



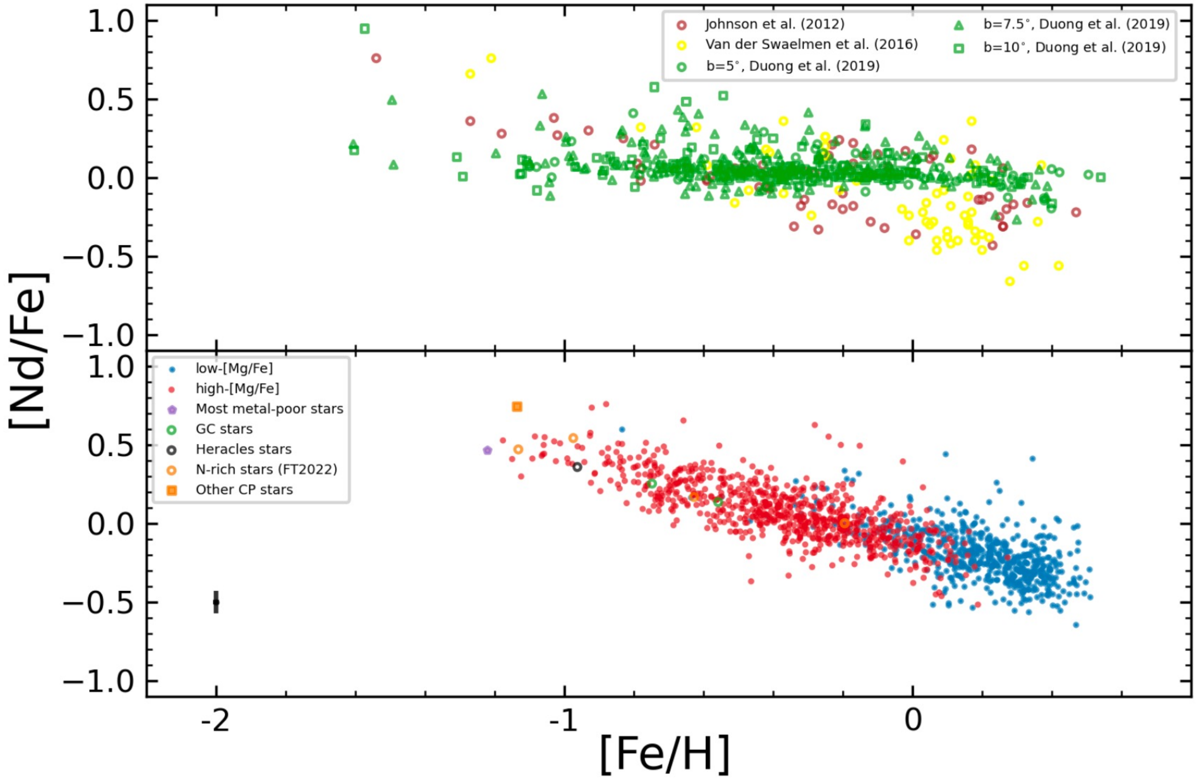


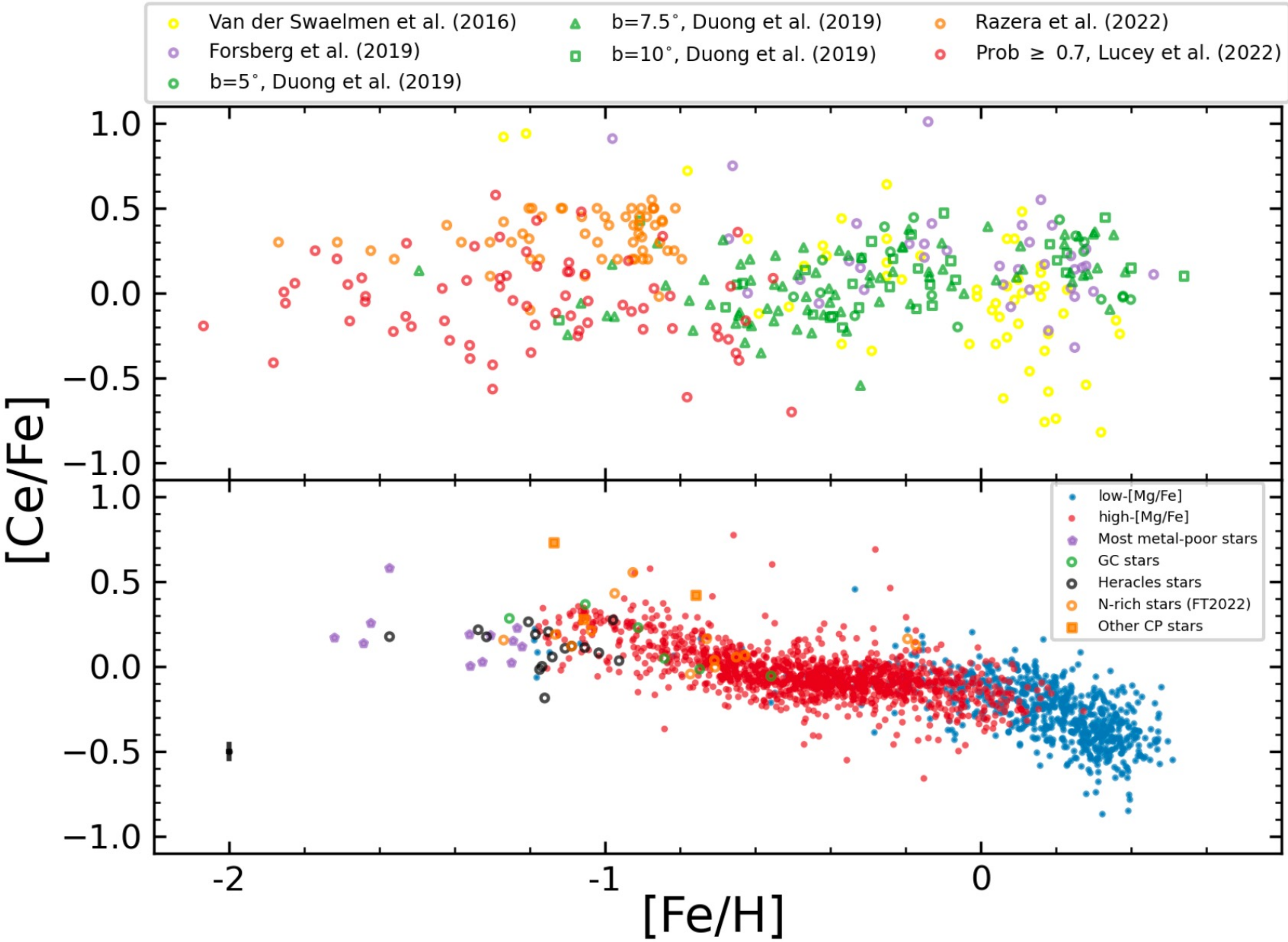
NGC 6355 (Souza et al. 2023)

A perspective on the Milky Way Bulge-Bar as seen from the neutron-capture elements Cerium and Neodymium with APOGEE

J. V. Sales-Silva,[1] K. Cunha,[1,2,3] V. V. Smith,[4,3] S. Daflon,[1] D. Souto,[5] R. Guerço,[1] A. Queiroz,[6] C. Chiappini,[7] C. R. Hayes,[8] T. Masseron,[9,10] Sten Hasselquist,[11] D. Horta,[12] C. Allende Prieto,[9,10] B. Barbuy,[13] R. Beaton,[11] D. Bizyaev,[14,15] J. G. Fernández-Trincado,[16] P. M. Frinchaboy,[17] J. A. Holtzman,[18] J. A. Johnson,[19] Henrik Jönsson,[20] S. R. Majewski,[21] D. L. Nidever,[22] N. Prantzos,[3] R. P. Schiavon,[23] M. Schultheis,[24] and G. Zasowski[25]

Ce and Nd are s-process-dominated elements;
their s-/r- contributions to the pre-solar composition are estimated, respectively, as 85/15 % for Ce and 62/38 % for Nd




Van der Swaelmen et al. (2016)
Forsberg et al. (2019)
b=5°, Duong et al. (2019)
b=7.5°, Duong et al. (2019)
b=10°, Duong et al. (2019)
Razera et al. (2022)
Prob ≥ 0.7, Lucey et al. (2022)
low-[Mg/Fe]
high-[Mg/Fe]
Most metal-poor stars
GC stars
Heracles stars
N-rich stars (FT2022)
Other CP stars
[Ce/Fe]
[Fe/H]
1.0
0.5
0.0
−0.5
−1.0
-2
-1
0

Key points

- Gaia + spectroscopy made possible precise distances – Velocity quadripole beatifully seen
- Bulge now can be studied in orbital-chemical space (caveats potential)
- Objects confined to the innermost 4 kpc show a metal-rich thin disk, a thick disk and a population with large velocity dispersion (old bulge) burried inside bar/inner disk
- GCs in the Bulge – possibility to age-date and we find some of the oldest stars in our Galaxy (suggesting the stars with similar orbital-chemical parameters are also old
- We find no chemical segregation of stars in bar shape orbits. The ones with low Zmax are migrator candidates- they present the largest metallicities but an important component metal-poor is also present – We see at Solar Neighbourhood stars migrated
- Need to move on in the future beyond 4MOST and PLATO
- Gaia NIR

Stay Tuned for two important conference next year
Workshop in honor of Francesca Matteucci, Italy, July 2024
IAU Symposium on Stellar Populations, MAYBE RIO DE JANEIRO, November 2024 in honor of Beatriz Barbuy

NEXT LECTURE – ACCRETED DEBRIS – HALO – BULGE and FUTURE DIRECTIONS