Looking for the fossils of the Galactic bulge formation

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Self-consistent Analysis of Stellar Clusters: An Application to *HST* Data of the Halo Globular Cluster NGC 6752

S. O. Souza[1], L. O. Kerber[1,2], B. Barbuy[1], A. Pérez-Villegas[1], R. A. P. Oliveira[1], and D. Nardiello[3,4,5]

A&A 656, A78 (2021)
https://doi.org/10.1051/0004-6361/202141768

Astronomy & Astrophysics

Photo-chemo-dynamical analysis and the origin of the bulge globular cluster Palomar 6★

S. O. Souza[1], M. Valentini[2], B. Barbuy[1], A. Pérez-Villegas[3], C. Chiappini[2], S. Ortolani[4,5,6], D. Nardiello[7,5], B. Dias[8], F. Anders[9], and E. Bica[10]

Tracing the Galactic Bulge history through its globular clusters metal-poor population

Souza et al. (2020,21,23,24a) among many others

A&A 671, A45 (2023)
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★

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]

A&A, 690, A37 (2024)
https://doi.org/10.1051/0004-6361/202450795

Astronomy & Astrophysics

Combined Gemini-South and HST photometric analysis of the globular cluster NGC 6558

The age of the metal-poor population of the Galactic bulge★

S. O. Souza[1,2,★★], M. Libralato[3,4], D. Nardiello[3,5,6], L. O. Kerber[7], S. Ortolani[3,5,6], A. Pérez-Villegas[8], R. A. P. Oliveira[9], B. Barbuy[1], E. Bica[10], M. Griggio[3,11], and B. Dias[12]

Looking for the fossils of the Galactic bulge formation

Group B.O.B

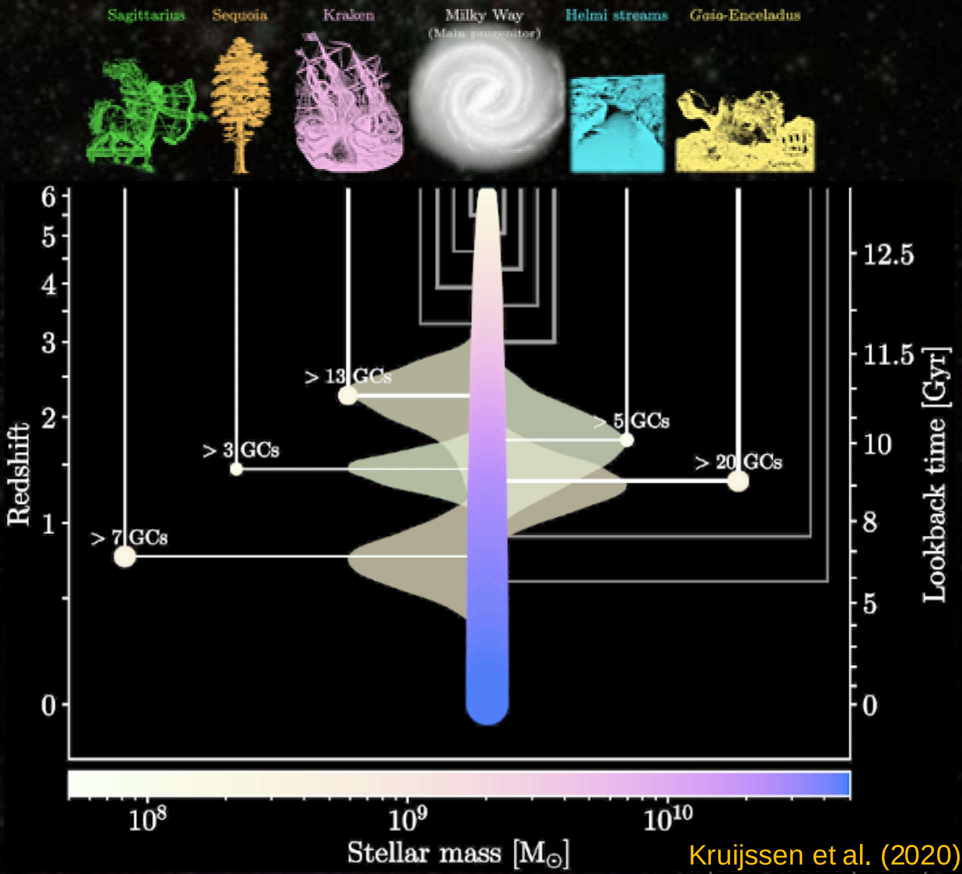
Ortolani

Barbuy

Bica

Why Globular Clusters?

- Galaxy merger tree
  - Kruijssen et al. (2020)
- More than 50 GCs are ex-situ
- The last major merger: GSE
- The Kraken is now in the inner Galaxy
  - Low-energy (Massari et al. 2019)
  - Koala (Forbes 2020)
  - Heracles (Horta et al. 2021)
- The building blocks merger time scale is somewhat unknown and challenging



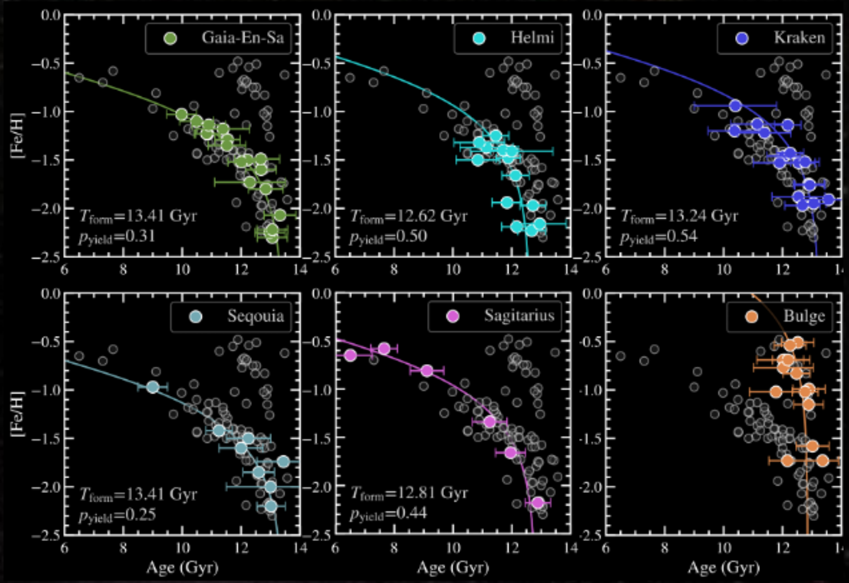
Kruijssen et al. (2020)

Why Globular Clusters?

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

- Two main sequences of GCs
  - The sequence with ages older than ~12Gyr – In-situ
  - The sequence with ages from 6 to 14 Gyr – Ex-situ

Callingham et al. (2022)



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- Two main sequences of GCs
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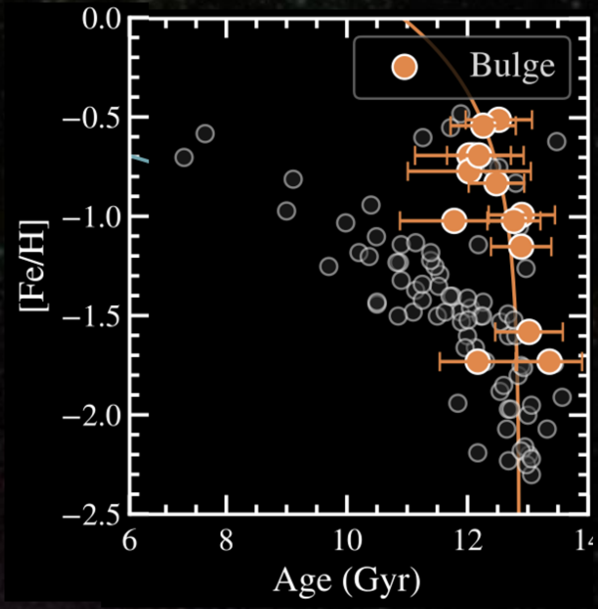
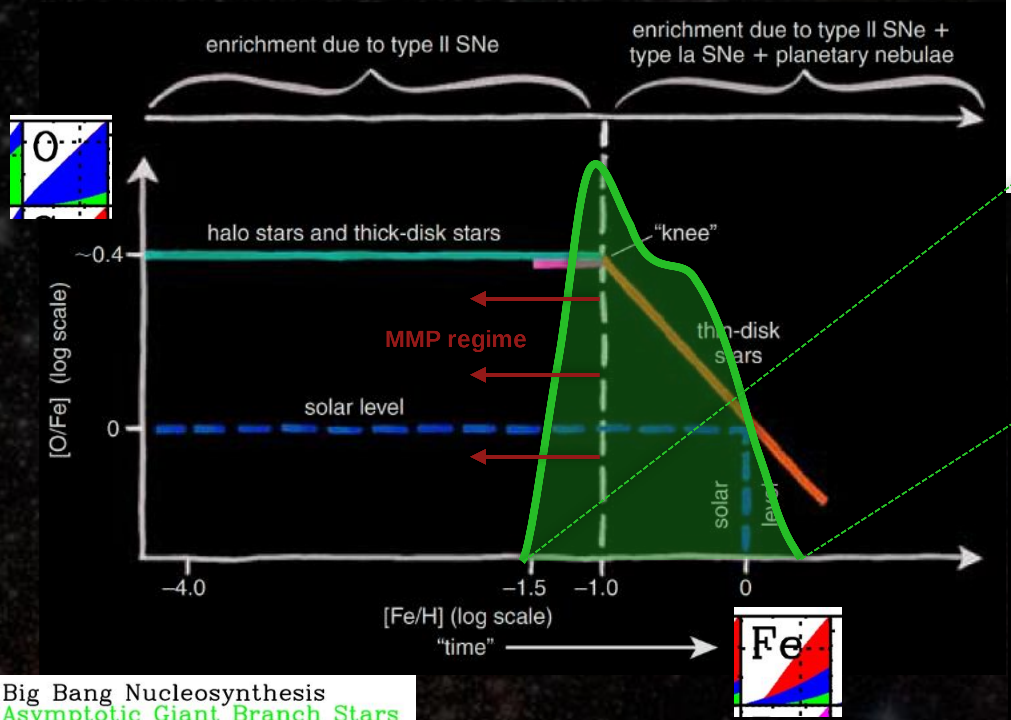
- Is the Bulge AMR constant in Age?

Callingham et al. (2022)



Why MMP GCs?

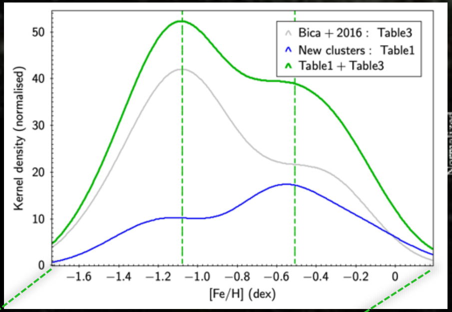
MMP = Moderately metal-poor [Fe/H] ~ -1.2



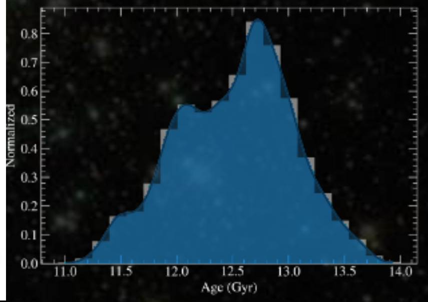
Big Bang Nucleosynthesis
Asymptotic Giant Branch Stars
Core−collapse Supernovae
Type Ia Supernovae
Neutron Star Mergers

Chiappini (2001)
Kobayashi et al. (2022)

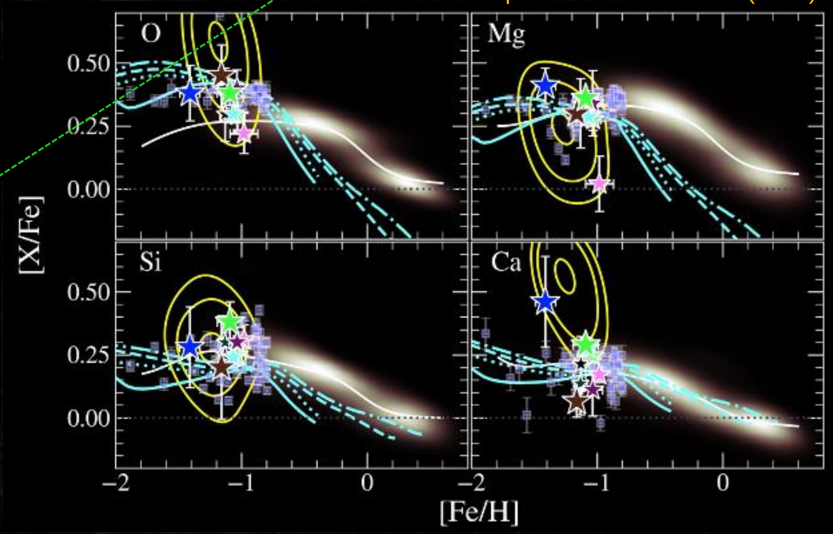
Bica et al. (2024)



Internal analysis



Adapted from Souza et al. (2023)



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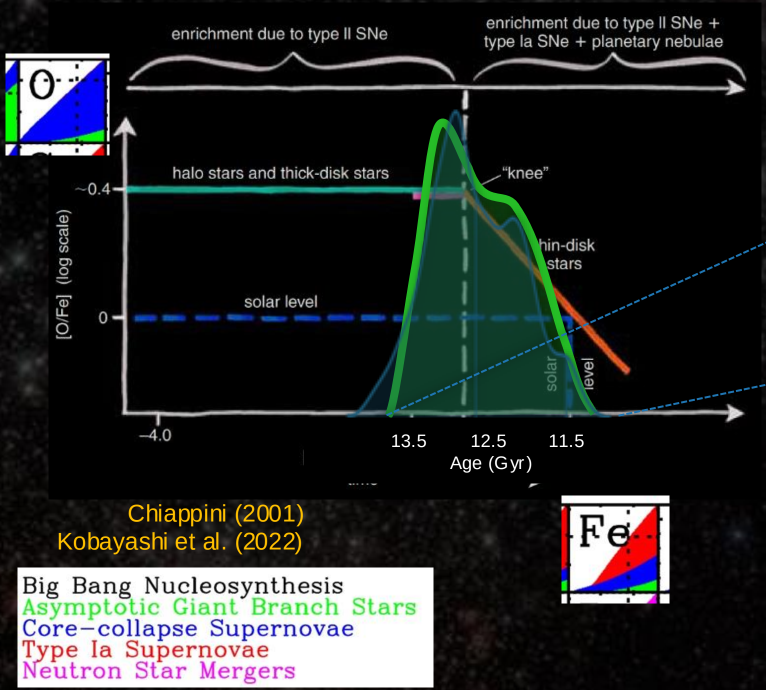

Chiappini (2001)
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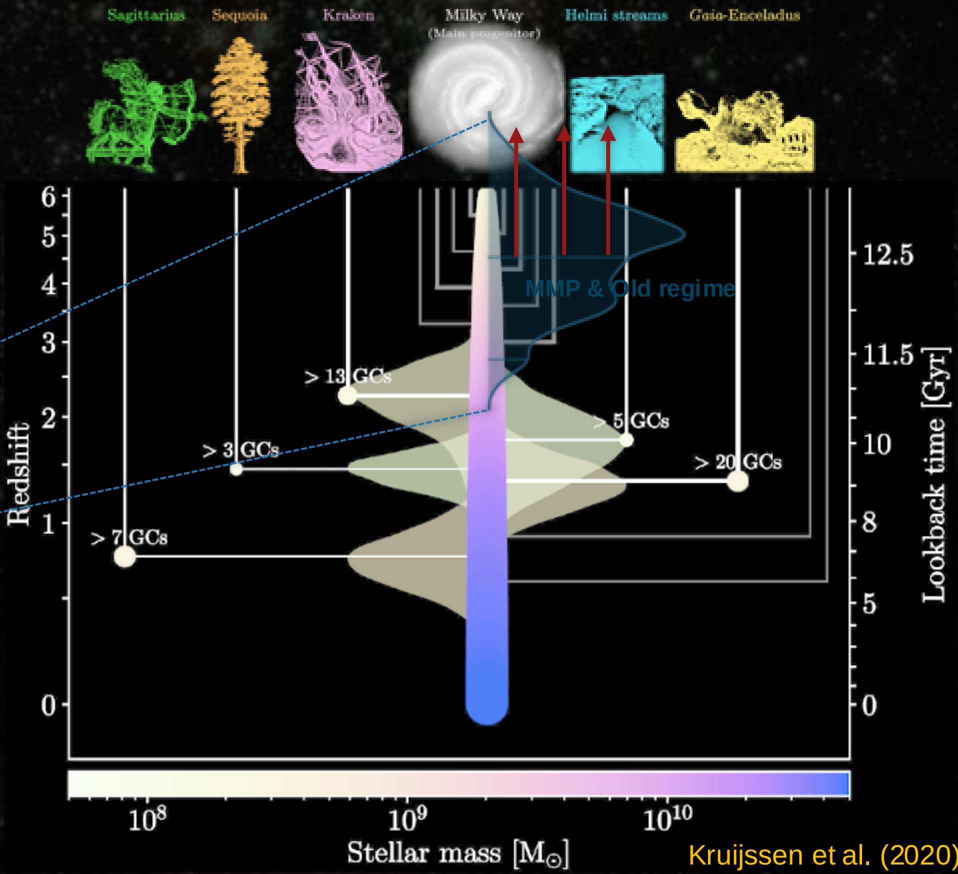


Kruijssen et al. (2020)

How?

Chrono-chemodynamical analysis

Souza et al. (2020,21,23,24)

Ages

Isochrone fitting
SIRIUS code (Souza et al. 2020)
Simple and Synthetic CMD fitting

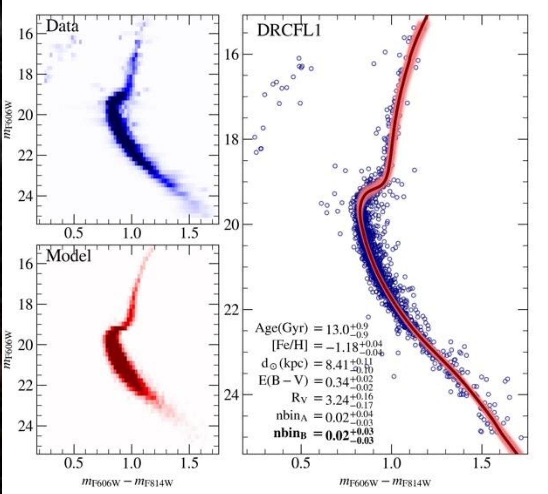
Chemical abundances

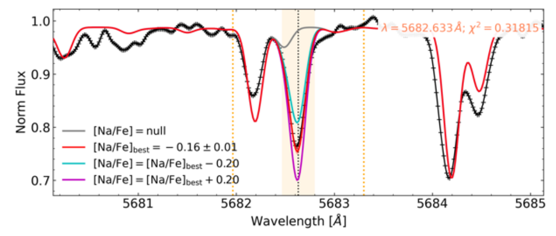
Spectral line fitting
FLAMES-UVES + APOGEE
PFANT code (Barbuy+2018)

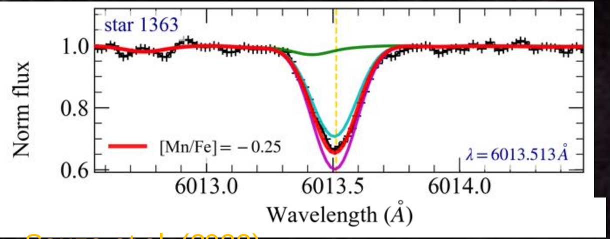
Dynamics

Orbital parameters
AP-Sormani+2022, McMillan17, Perez-Villegas+2020
AGAMA (Vasiliev 2019)

Souza et al. (2024)







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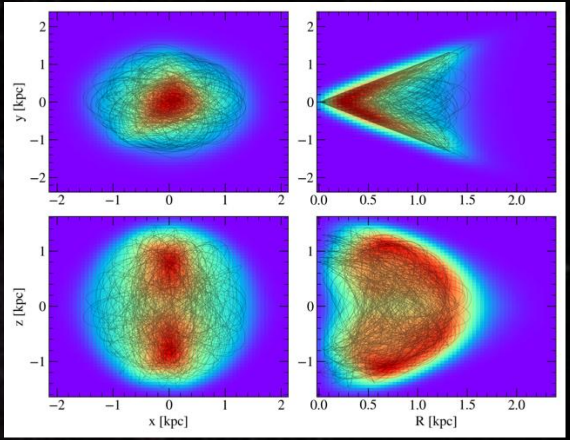
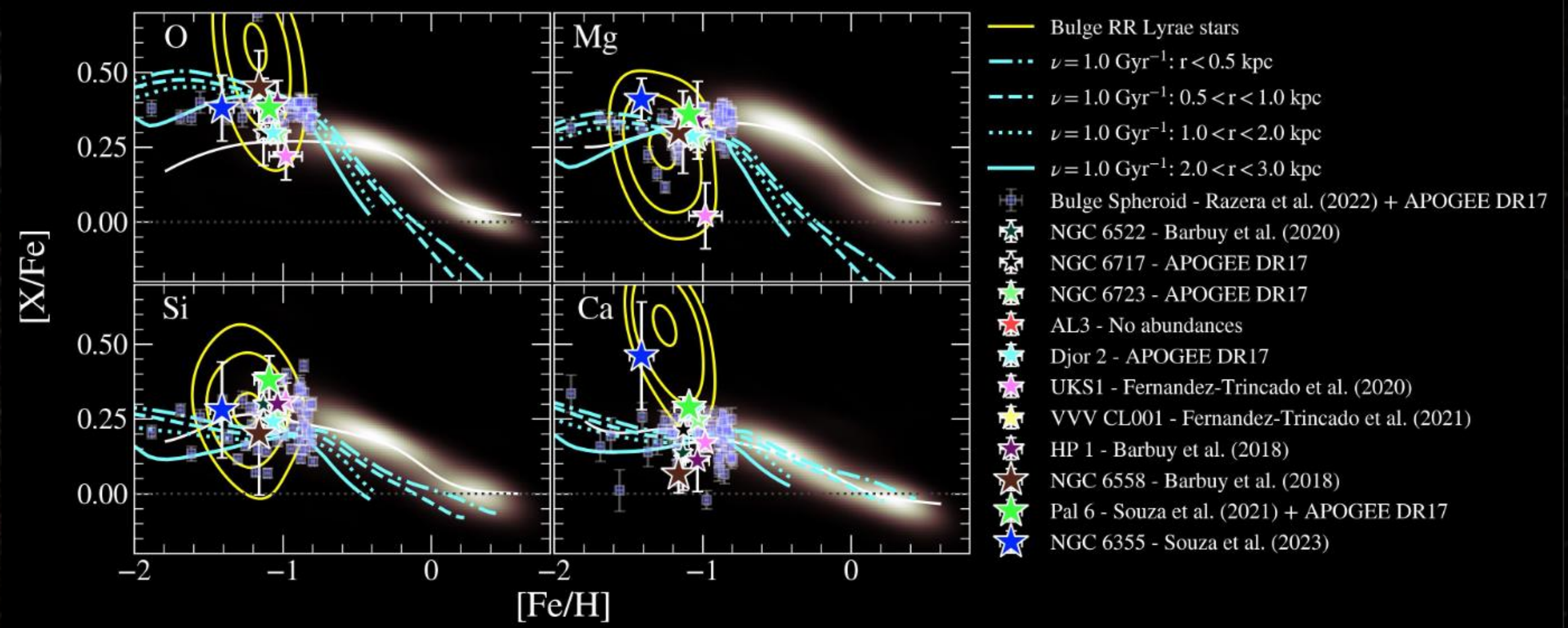


Souza et al. (2024)

Galactic bulge population: α-elements

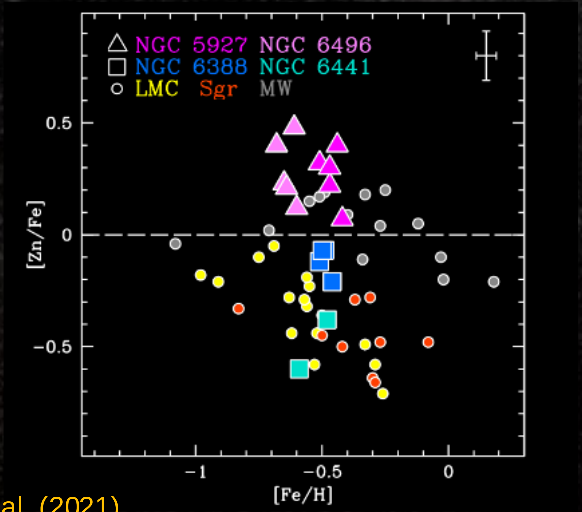
In-situ or Ex-situ?



Galactic bulge population: Zinc

In-situ or Ex-situ?

- Ex-situ indicator – Minelli et al. (2021)
- Moderately metal-rich regime



Minelli et al. (2021)

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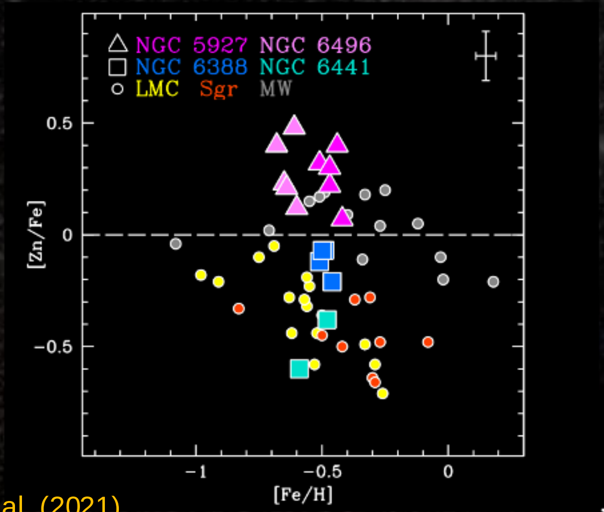
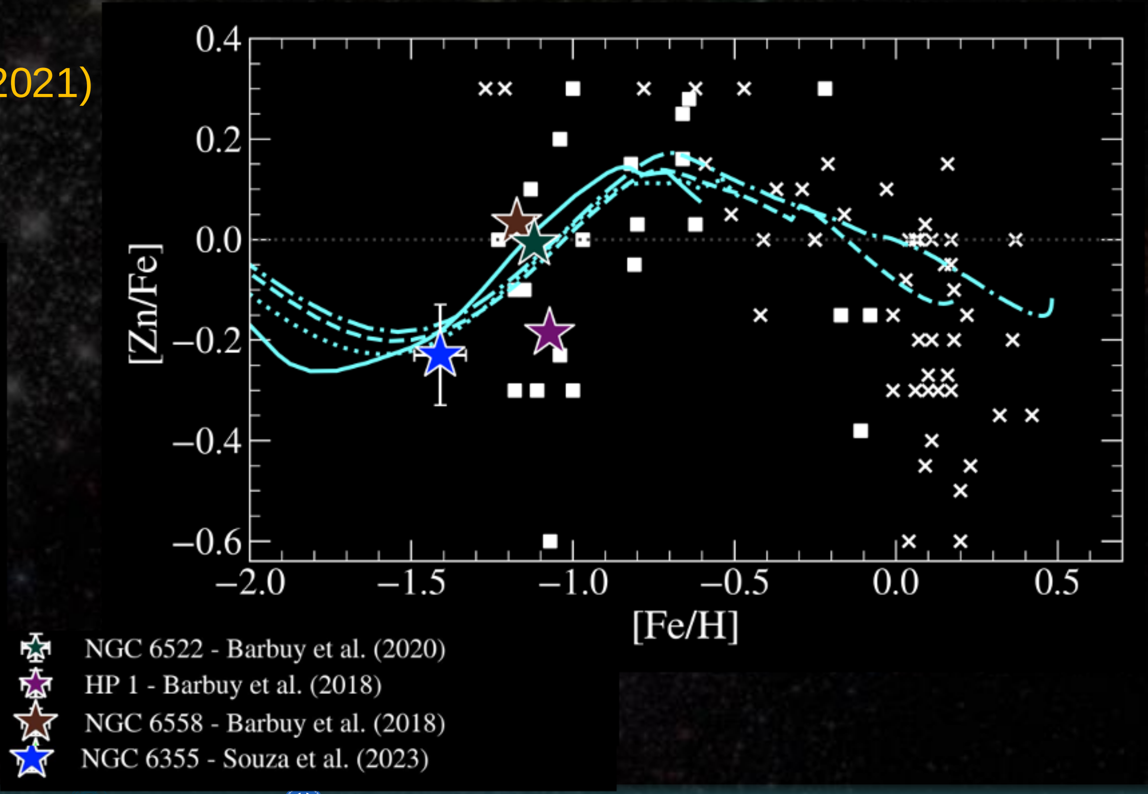


Minelli et al. (2021)



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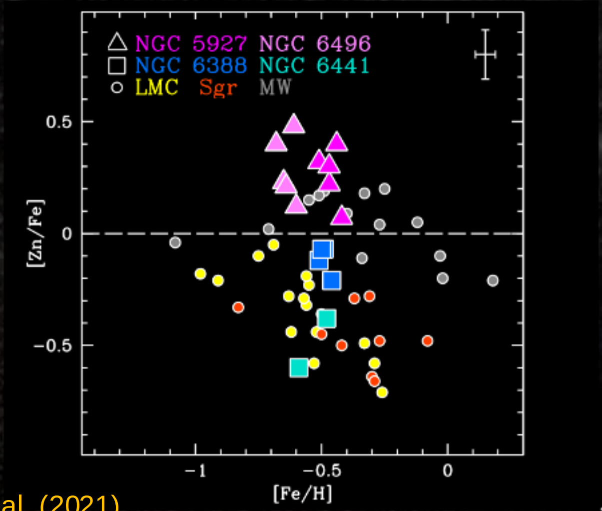
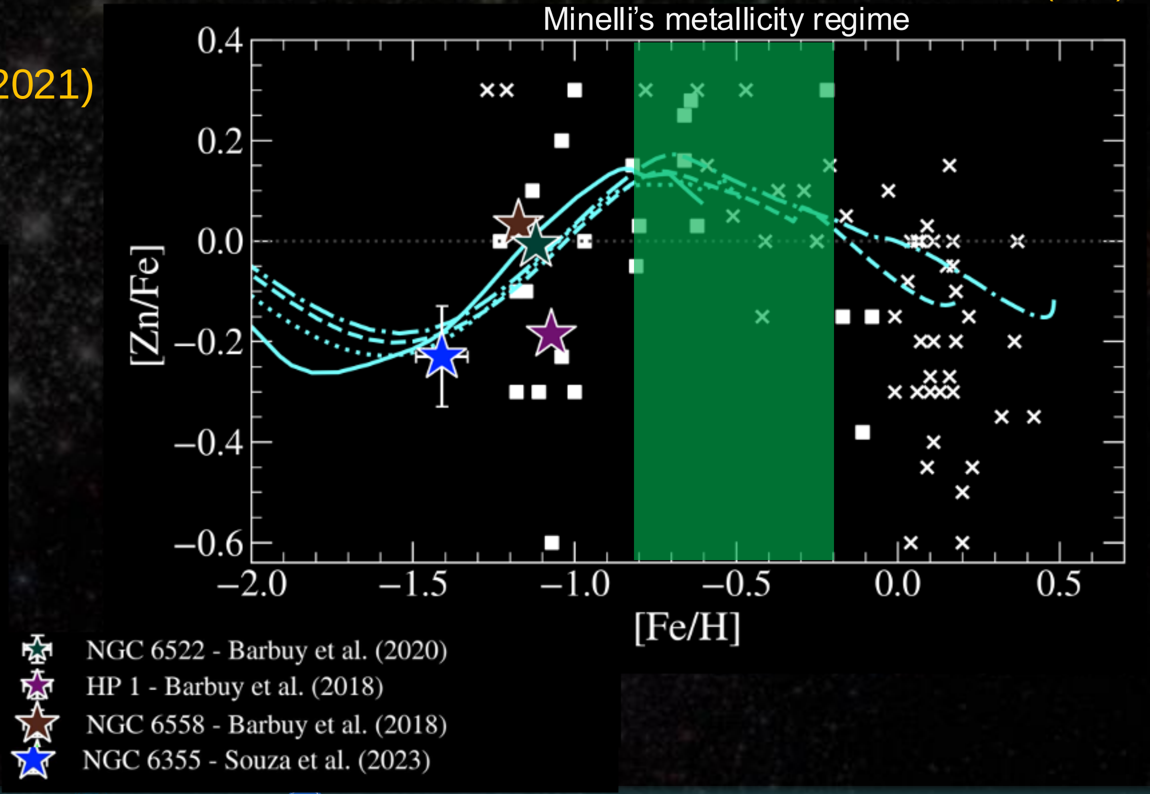


Minelli et al. (2021)

Souza et al. (2023)

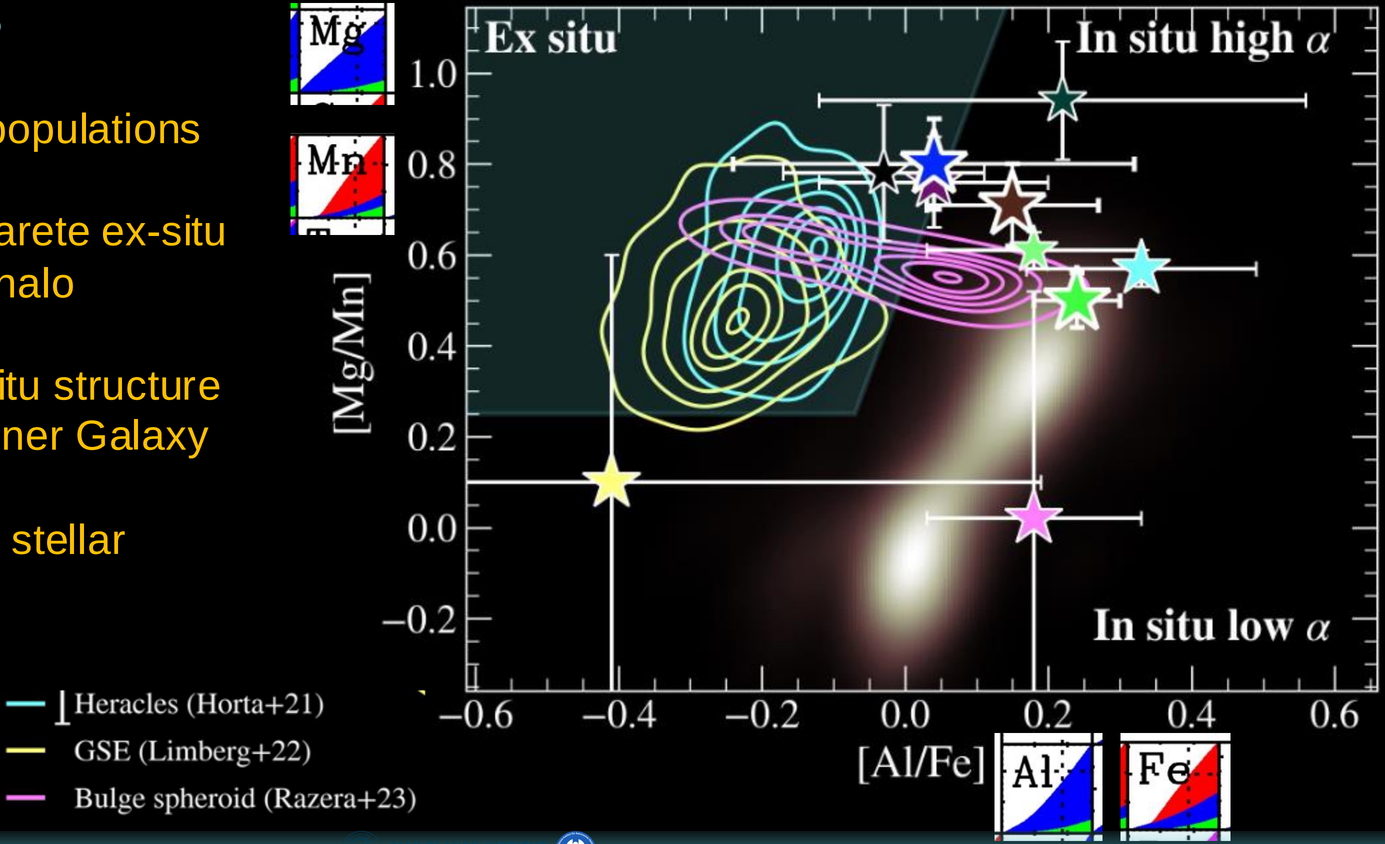


Galactic bulge population: [Mg/Mn] vs [Al/Fe]

Adapted from Souza et al. (2023)

In-situ or Ex-situ?

- Tracers of stellar populations
- Often used to separete ex-situ from in-situ in the halo
- Heracles first ex-situ structure candidate in the inner Galaxy
- For GCs? Multiple stellar populations



Galactic bulge population: IoM space

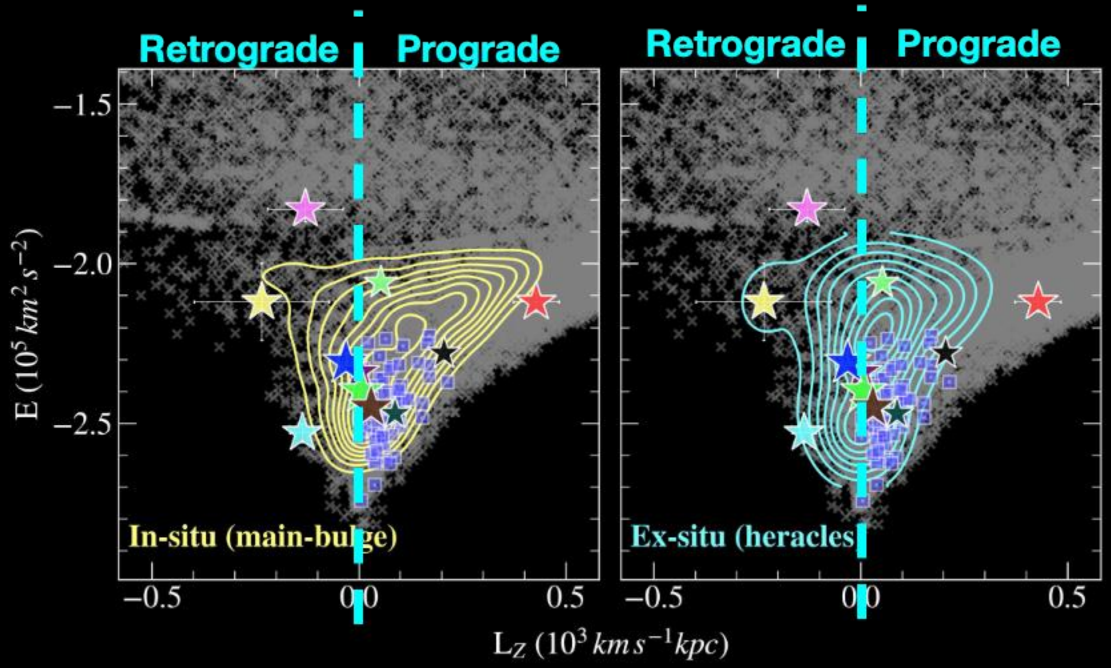
In-situ or Ex-situ?

- Integral of motion space
  - *E* and L_Z
  - Stady state potential

- In-situ and possible ex-situ structure completely mixed

- In-situ more contentrated in prograde orbits

- **NGC6355**, **VVV-CL001**, **UKS1**, and **Djorg 2** are retrograde clusters

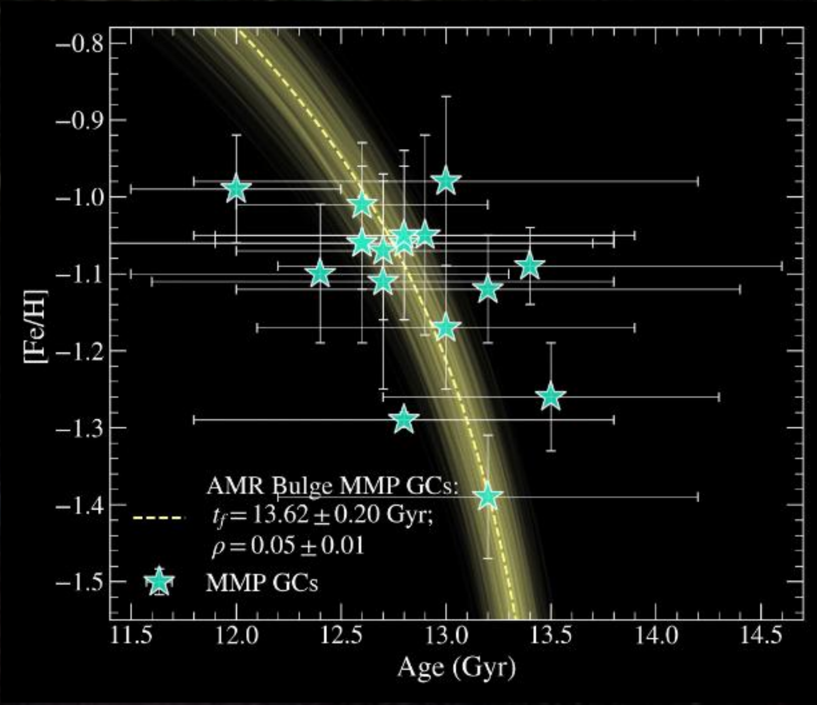


Adapted from Souza et al. (2023)

Galactic bulge population: AMR

- Moderately metal-poor GCs
  - [Fe/H] $\lesssim -1.0$
- Derived AMR:
  - $t_f = 13.62 \pm 0.20$ Gyr
  - $\rho = 0.05 \pm 0.01\ Z_\odot$

Adapted from Souza et al. (2024)



$$t = t_f \cdot exp\left(\frac{-Z_\odot}{\rho} 10^{[Fe/H] + \Delta}\right)$$

$$[\alpha/\mathrm{Fe}] \begin{cases} +0.40 \rightarrow \Delta = 0.312, \text{for in} - \text{situ clusters} \\ +0.00 \rightarrow \Delta = 0.000, \text{for ex} - \text{situ clusters} \end{cases}$$

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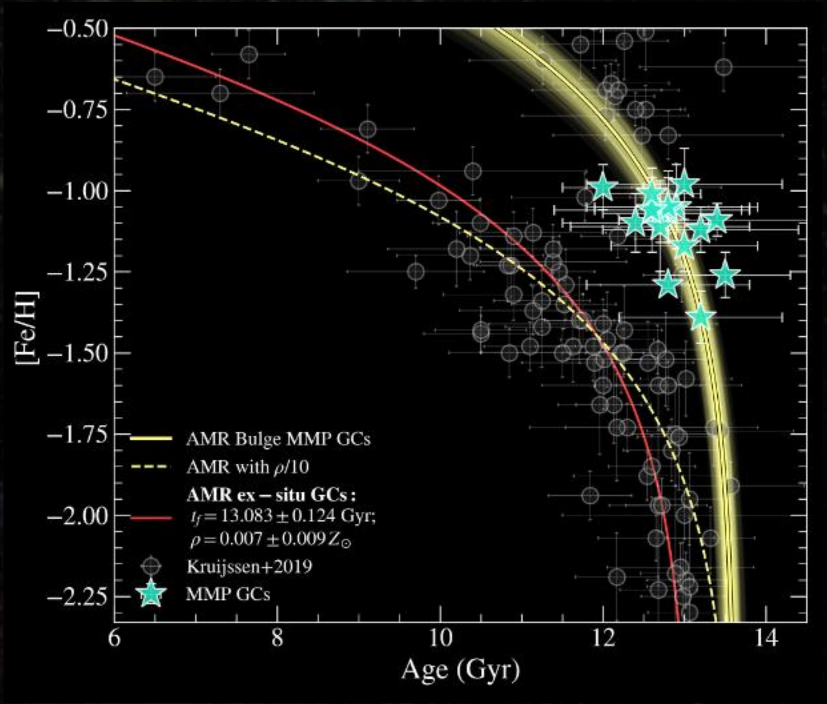
- Derived AMR:
  - $t_f = 13.62 \pm 0.20$ Gyr
  - $\rho = 0.05 \pm 0.01\ Z_\odot$

- The AMR of the MMP GCs is has an chemical enrichment 10x faster than the ex-situ branch.
  - $t_f = 13.08 \pm 0.12$ Gyr
  - $\rho = 0.007 \pm 0.009\ Z_\odot$

Adapted from Souza et al. (2024)



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Key points

- Bulge MMPGCs population started to form approximately **13.6 Gyr** ago

- The effective yield of **0.05 $Z_\odot$** for the MMPGCs and **0.007 $Z_\odot$** for the ex-situ GCs indicate a ten times faster chemical enrichment for the MMPGCs population in the bulge.

- Some clusters could have formed inside the building blocks.

In the bulge, it is all a matter of time!

Bulge GCs with low metallicities and old ages, could compose the sample of GCs that can reconstruct the building blocks of the Galaxy.

Thank you!

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