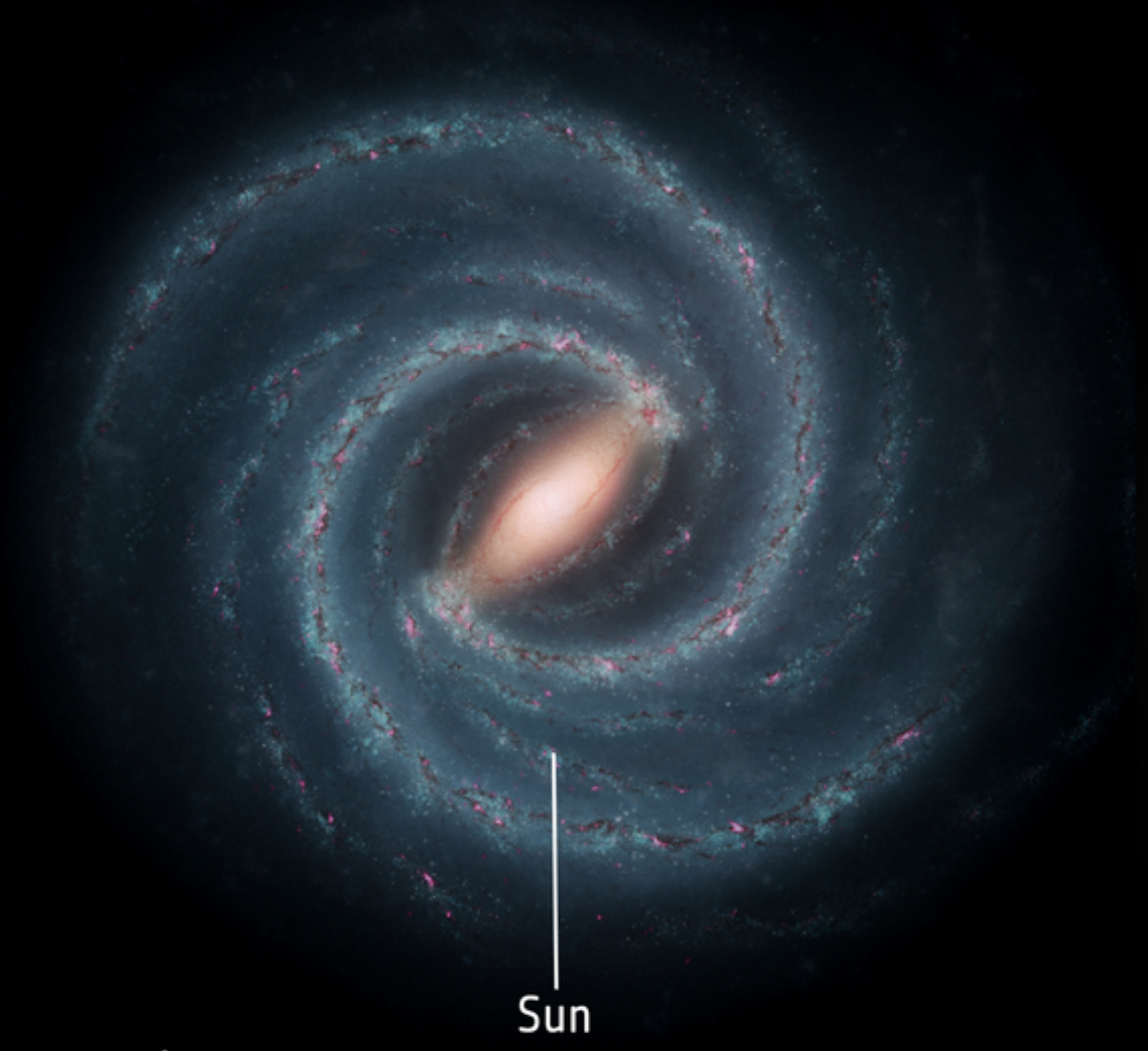
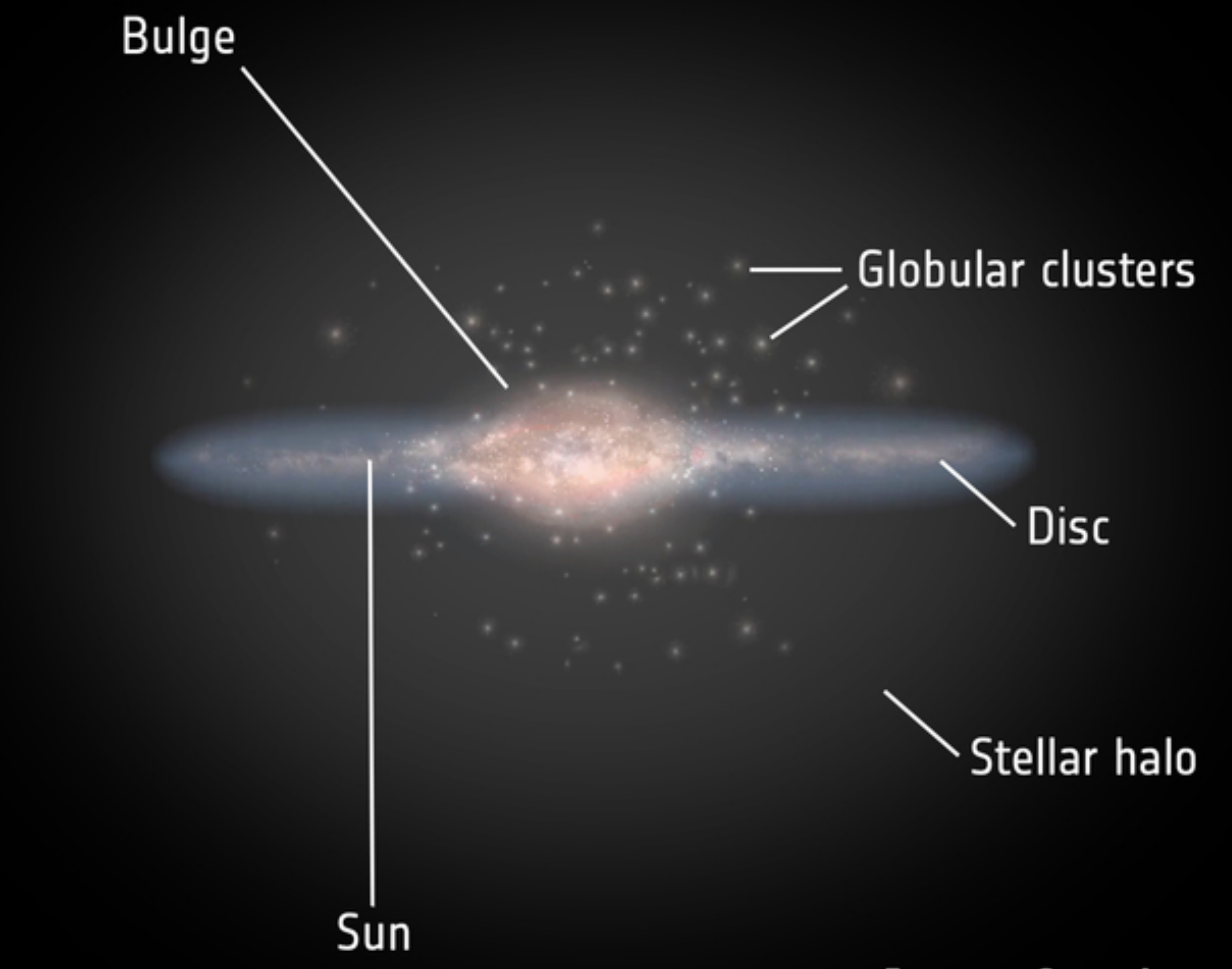
Homogeneous abundances in the LMS-1 dwarf galaxy stream and its globular clusters NGC 5024 & NGC 5053

Stephanie Monty (Institute of Astronomy, Cambridge, sm2744@cam.ac.uk)
Primarily In Collaboration with:
Tadafumi Matsuno (University of Heidelberg), Zhen Yuan (Nanjing University) and Vasily Belokurov (Cambridge)

→ ANATOMY OF THE MILKY WAY





→ ANATOMY OF THE MILKY WAY
esa
Sun
Bulge
Globular clusters
Disc
Stellar halo
Sun
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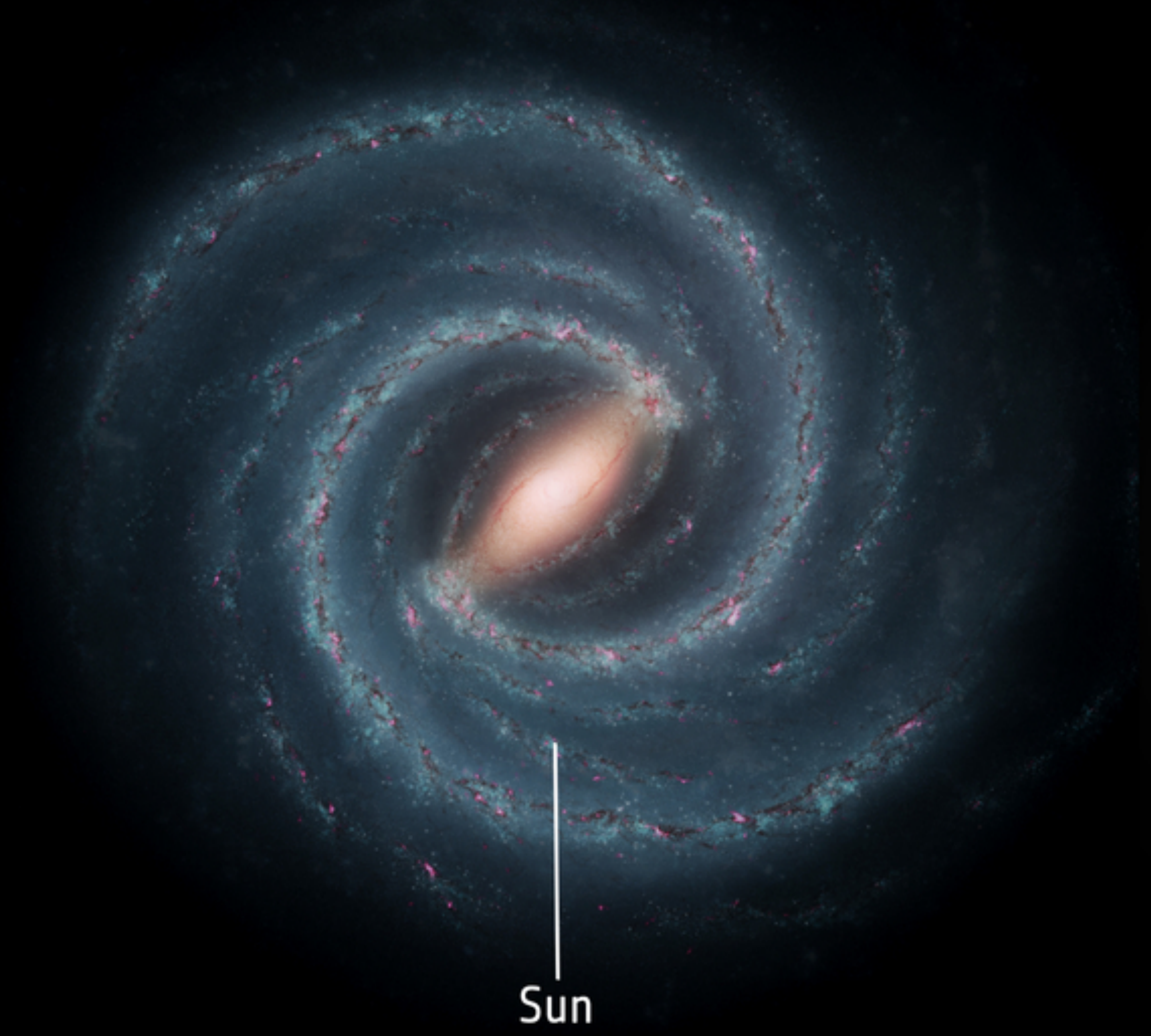

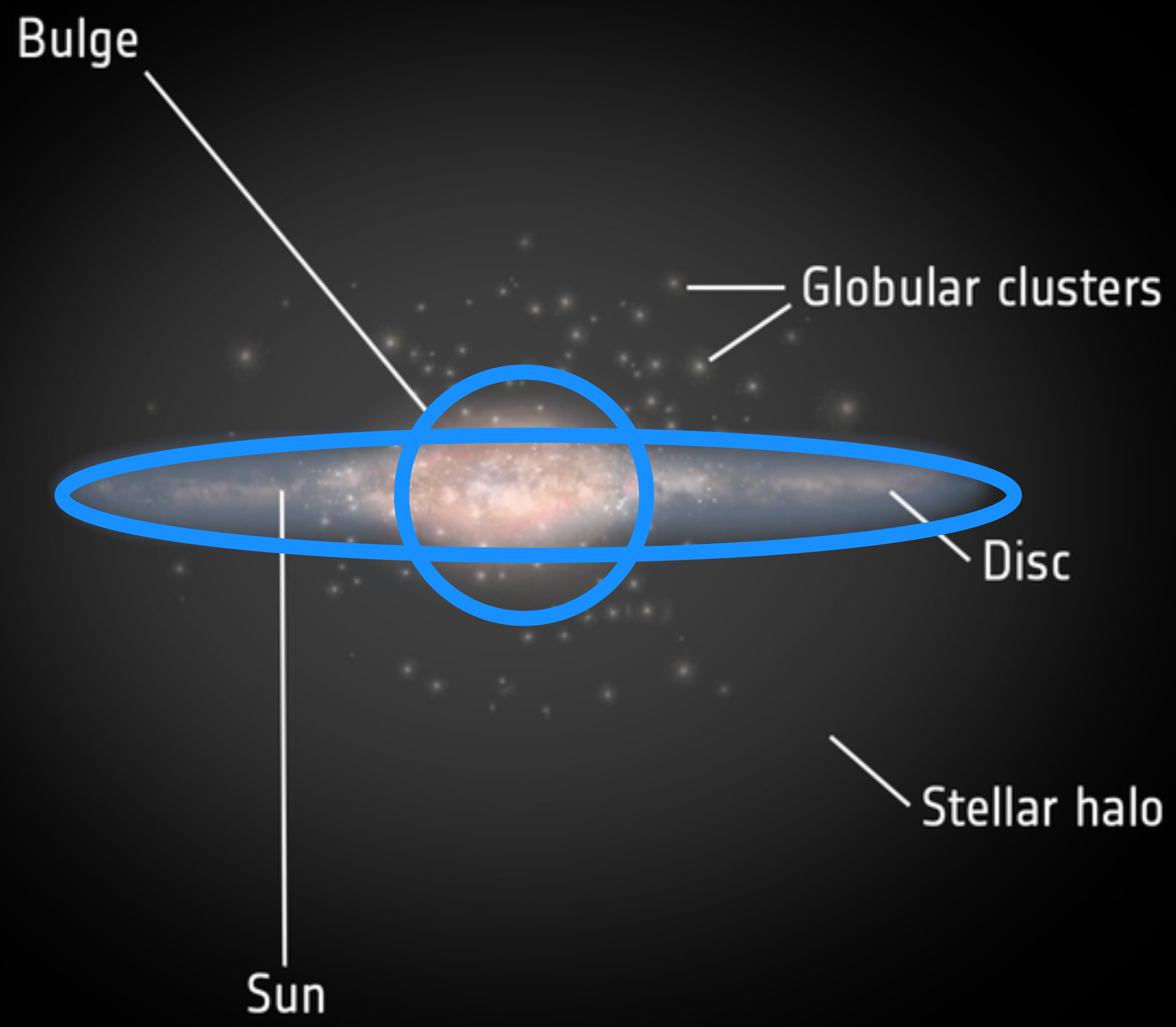

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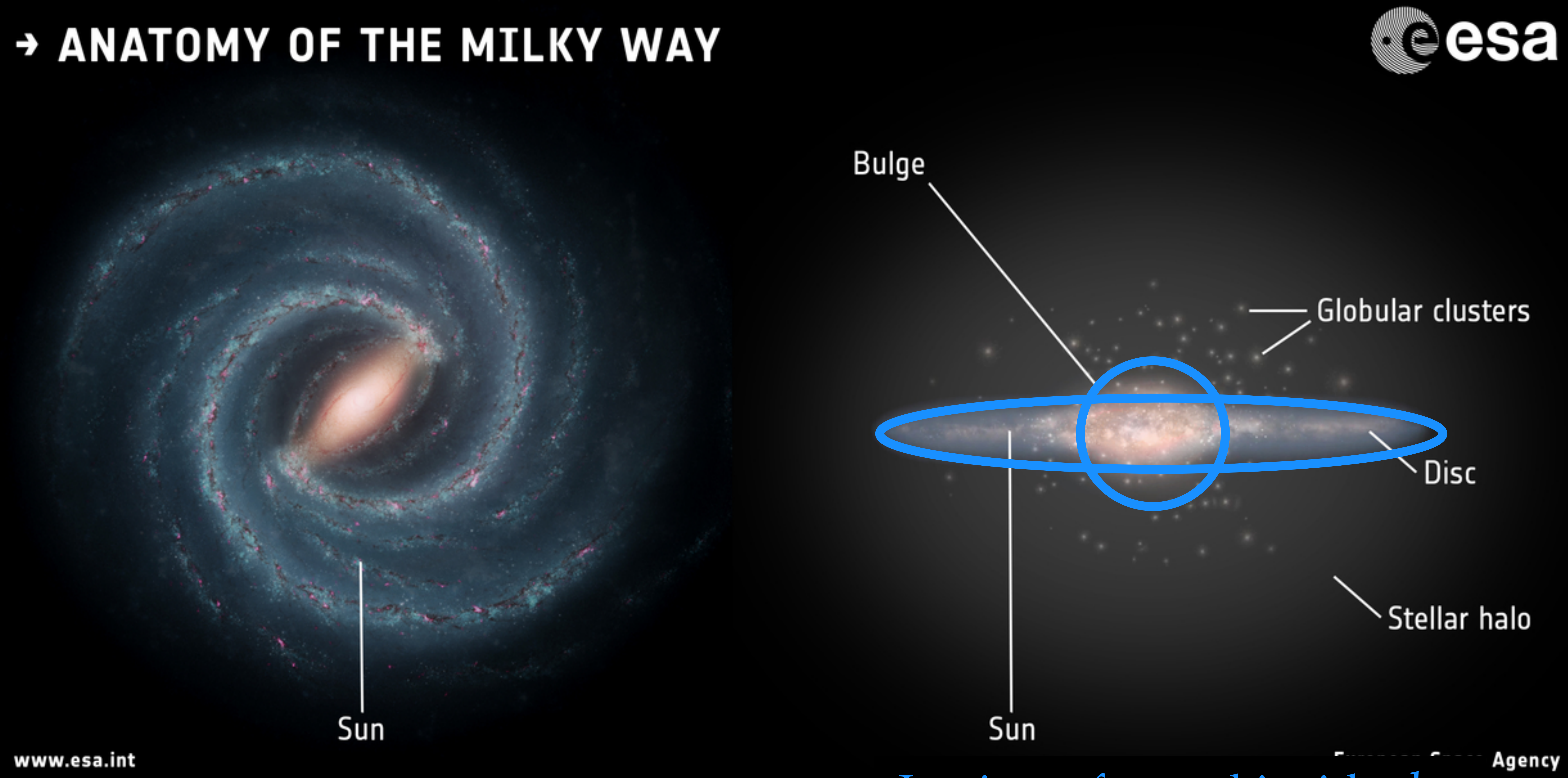
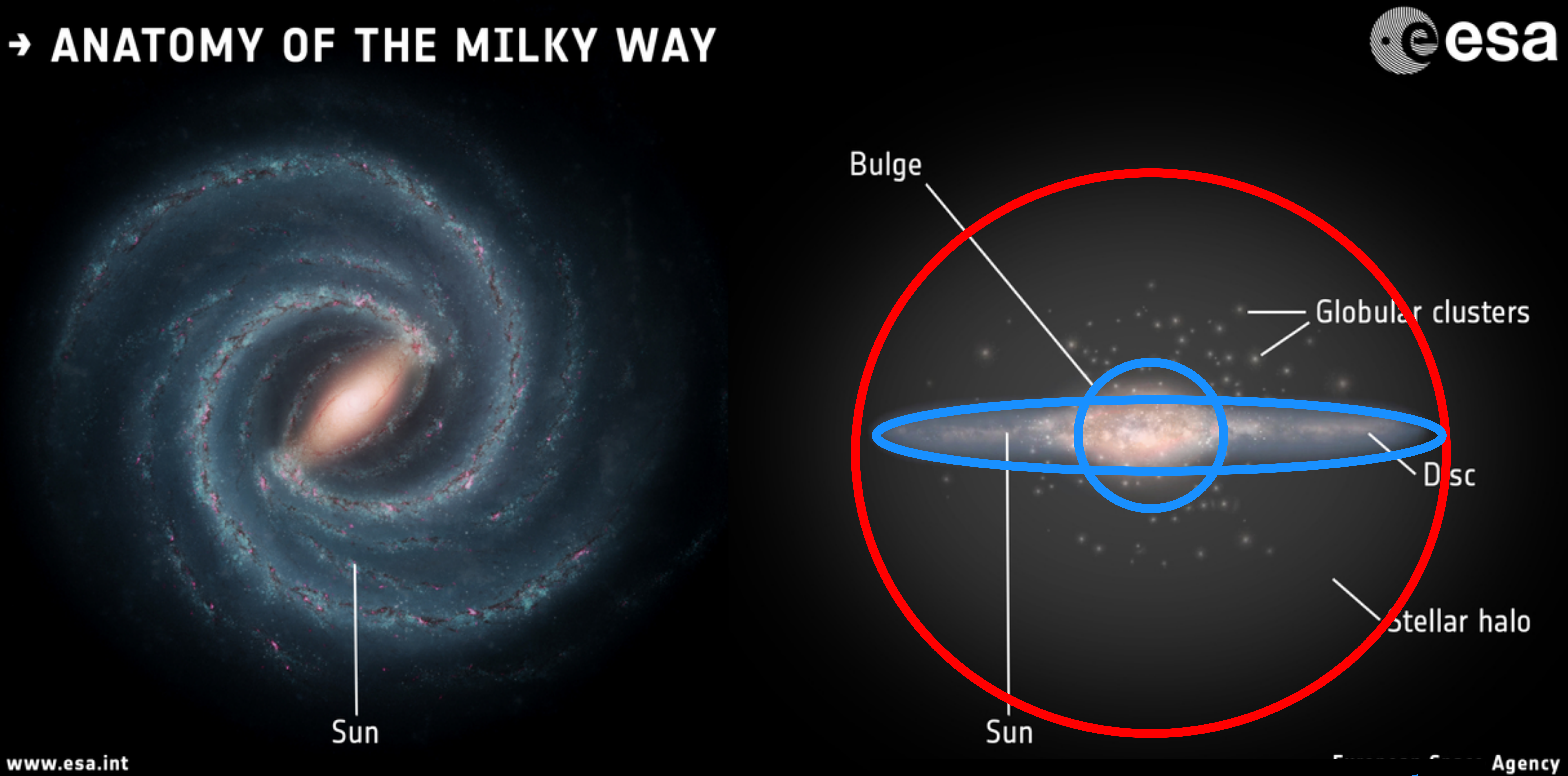
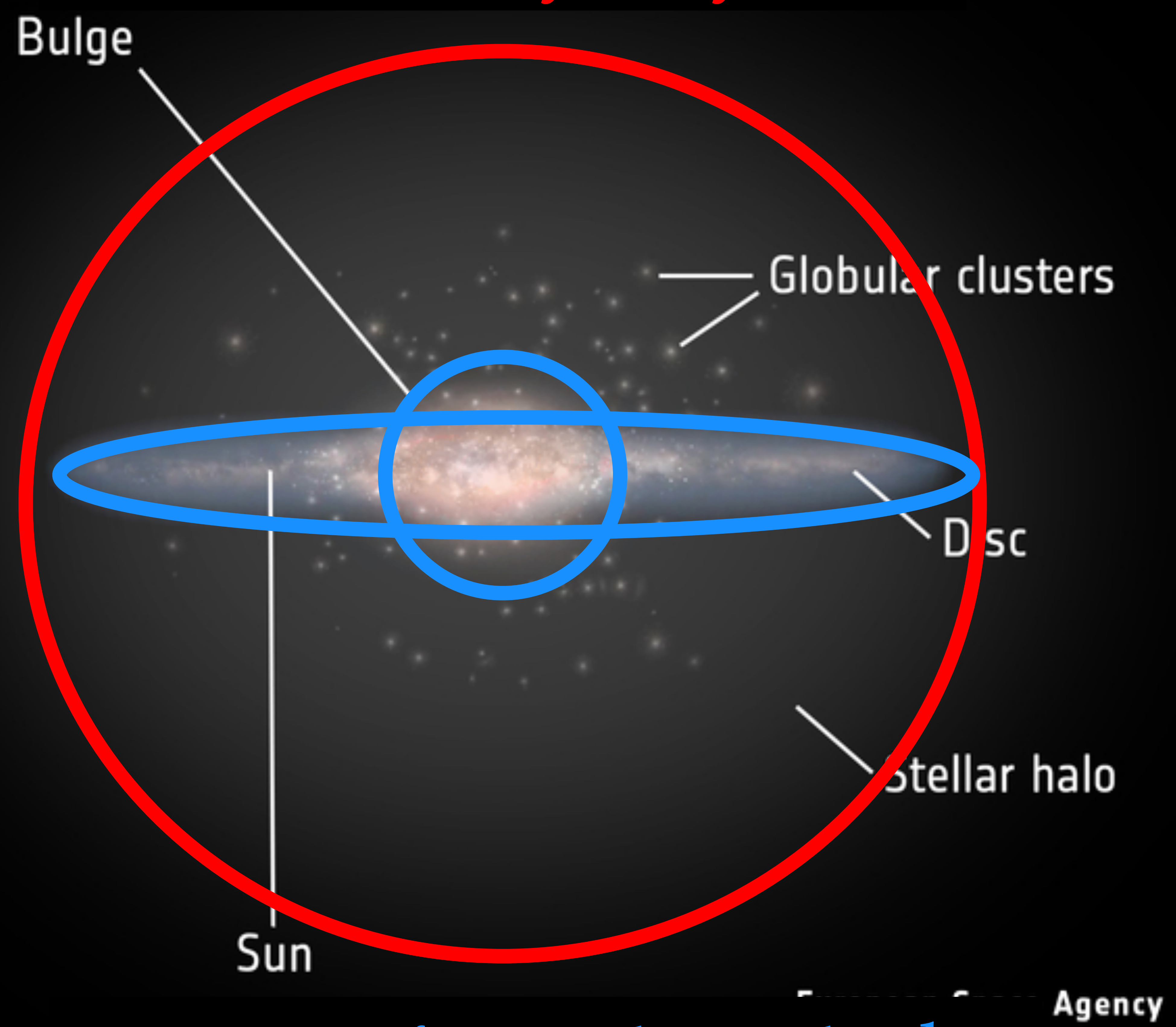


In-situ = formed inside the Milky Way



In-situ = formed inside the Milky Way

Accreted = formed outside the Milky Way



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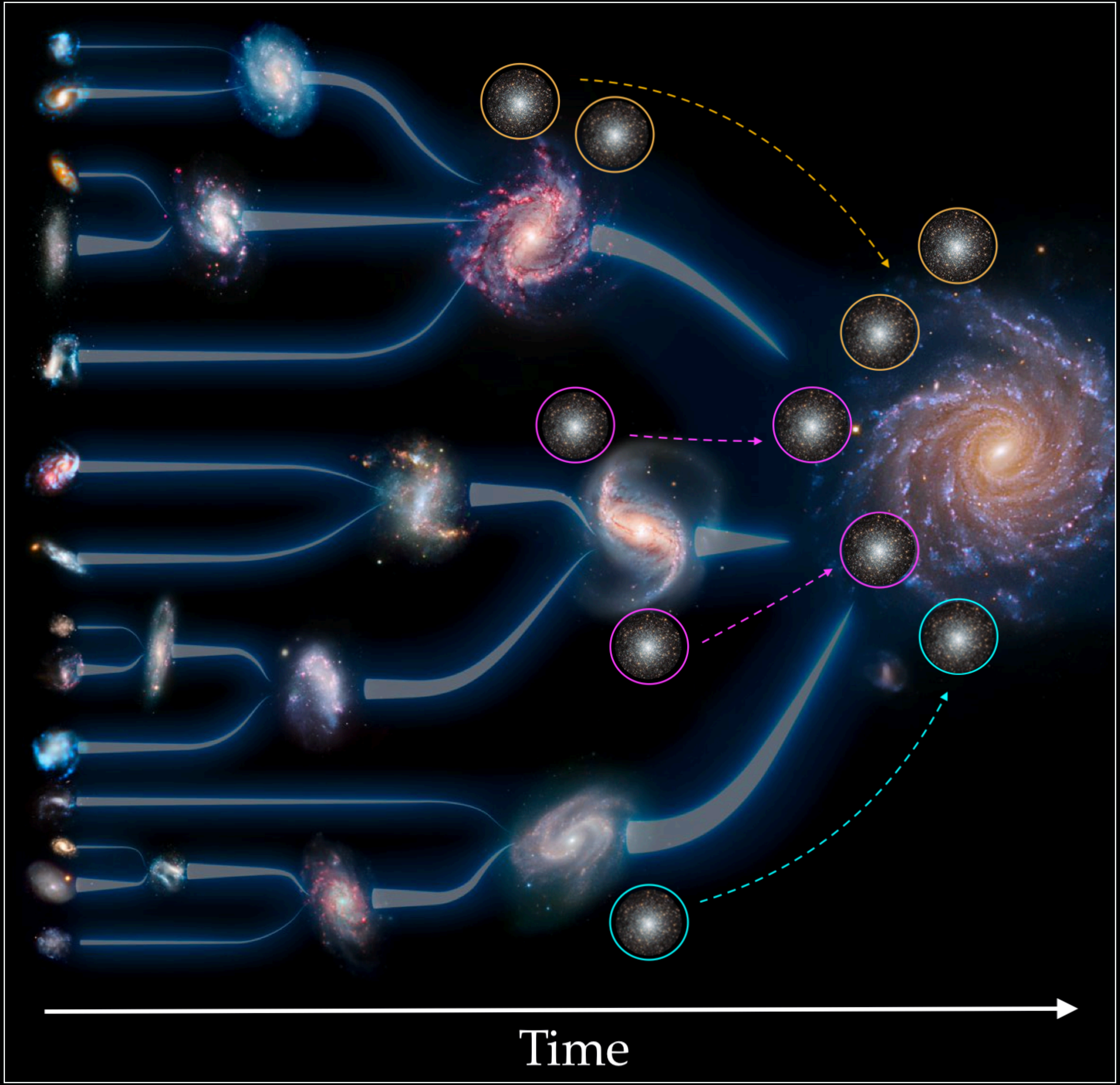

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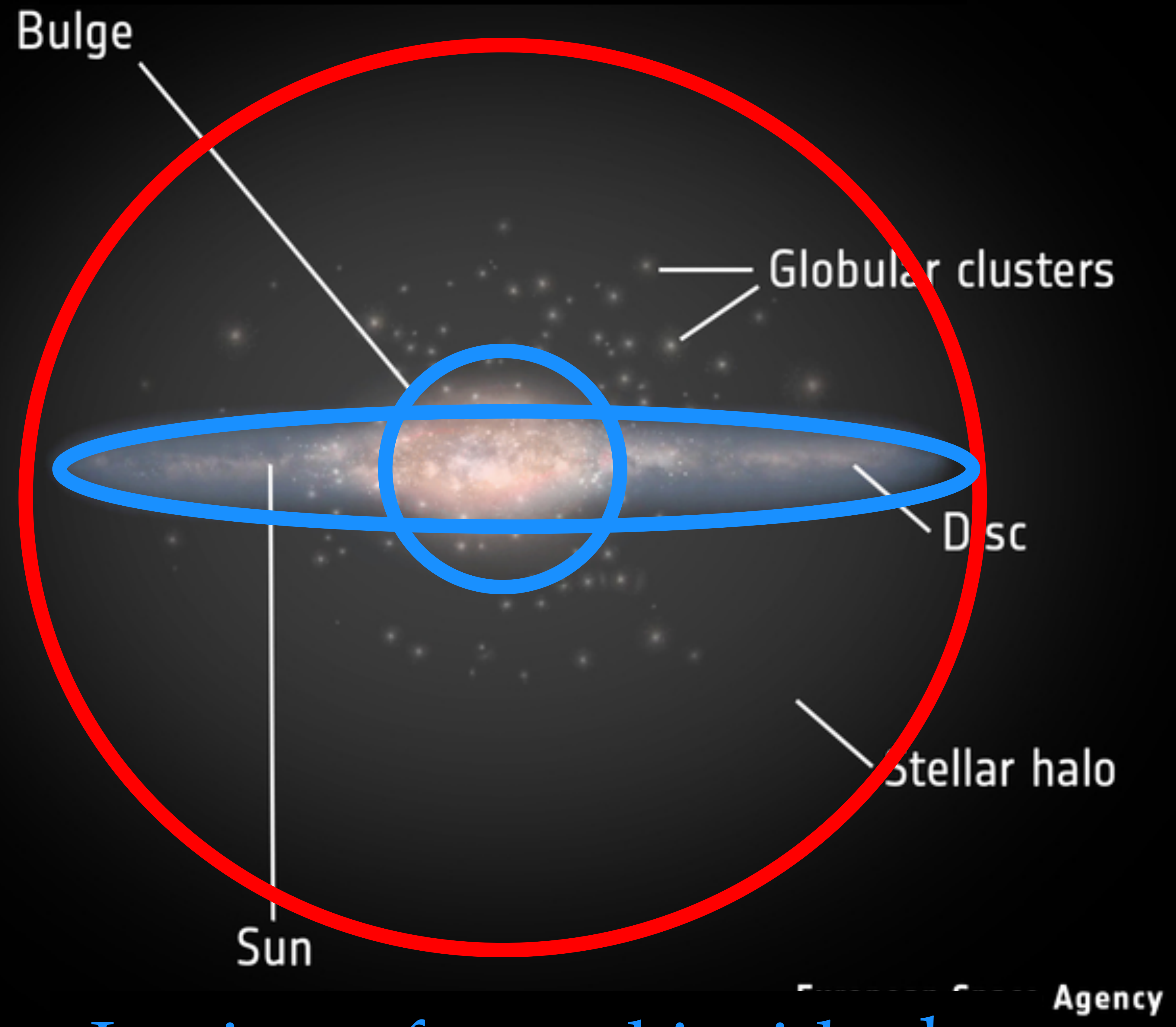
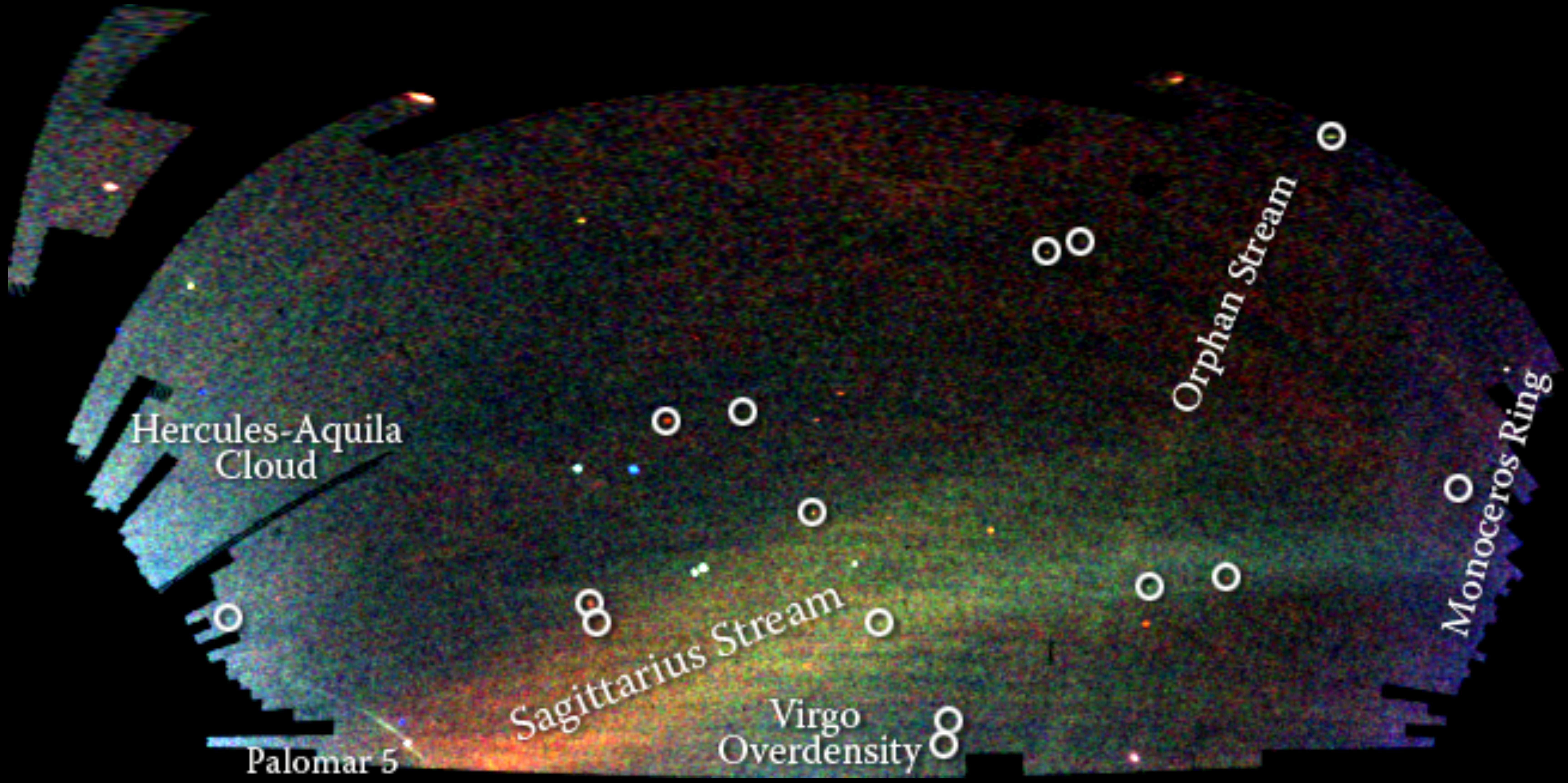


In-situ = formed inside the Milky Way

The Galactic halo has a memory: energy and angular momentum are constants under certain assumptions



V. Belukurov, SDSS Collab.

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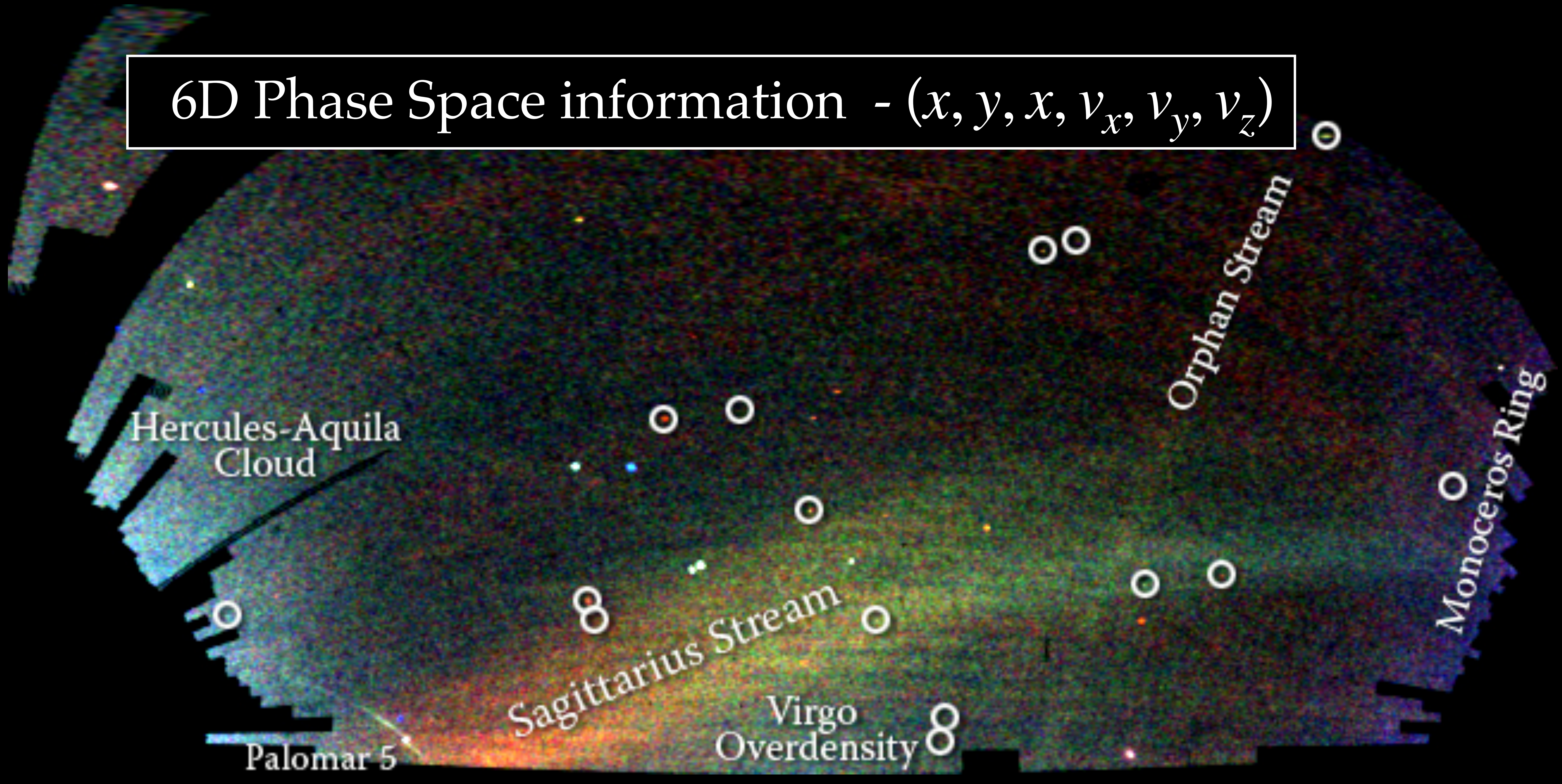
6D Phase Space information - (x, y, x, v_x, v_y, v_z)



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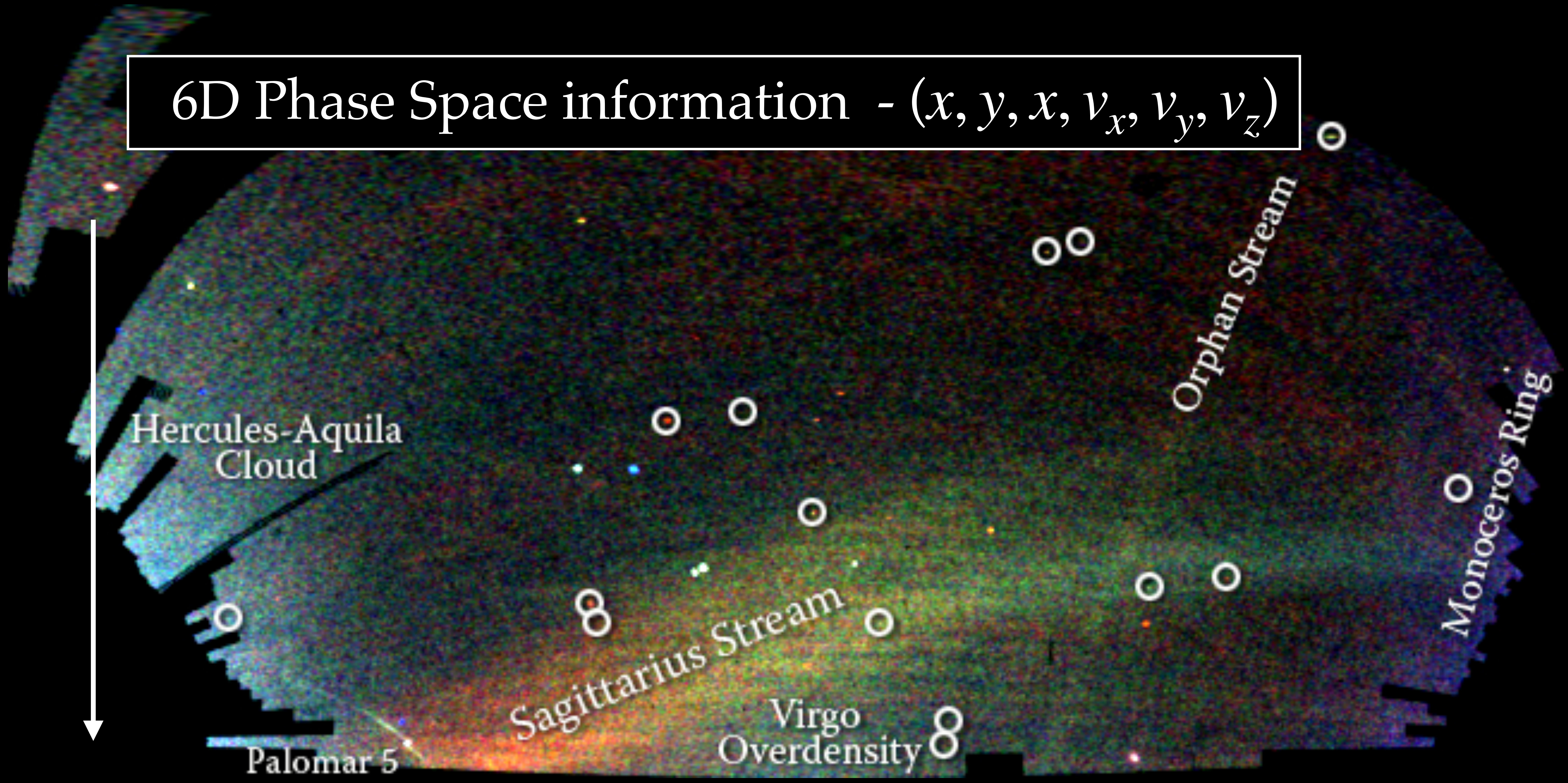

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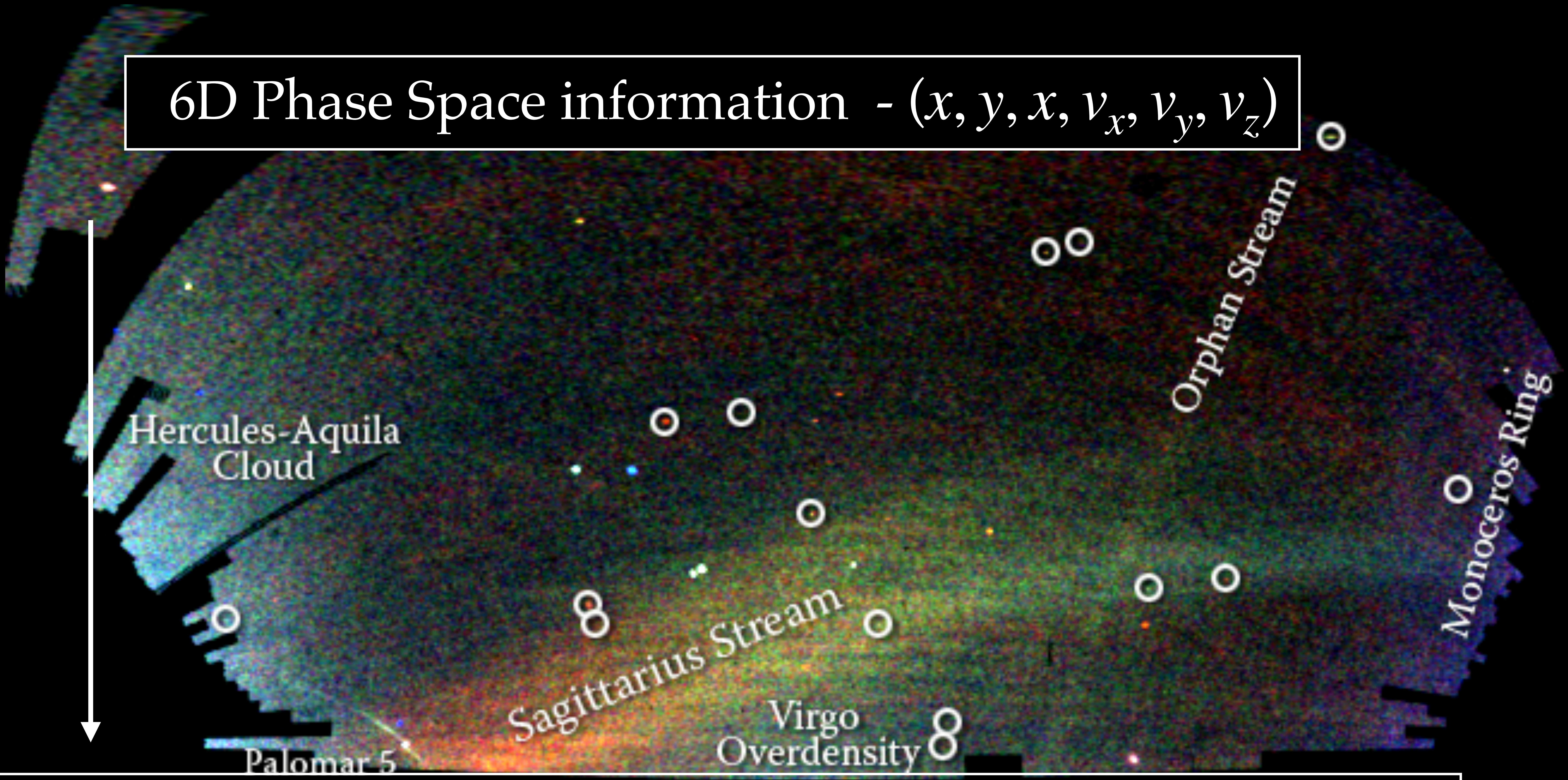

Energy conservation and symmetry - (E, L_z)

(Helmi & de Zeeuw, 2000) - see arXiv 2506.09117 for counter argument

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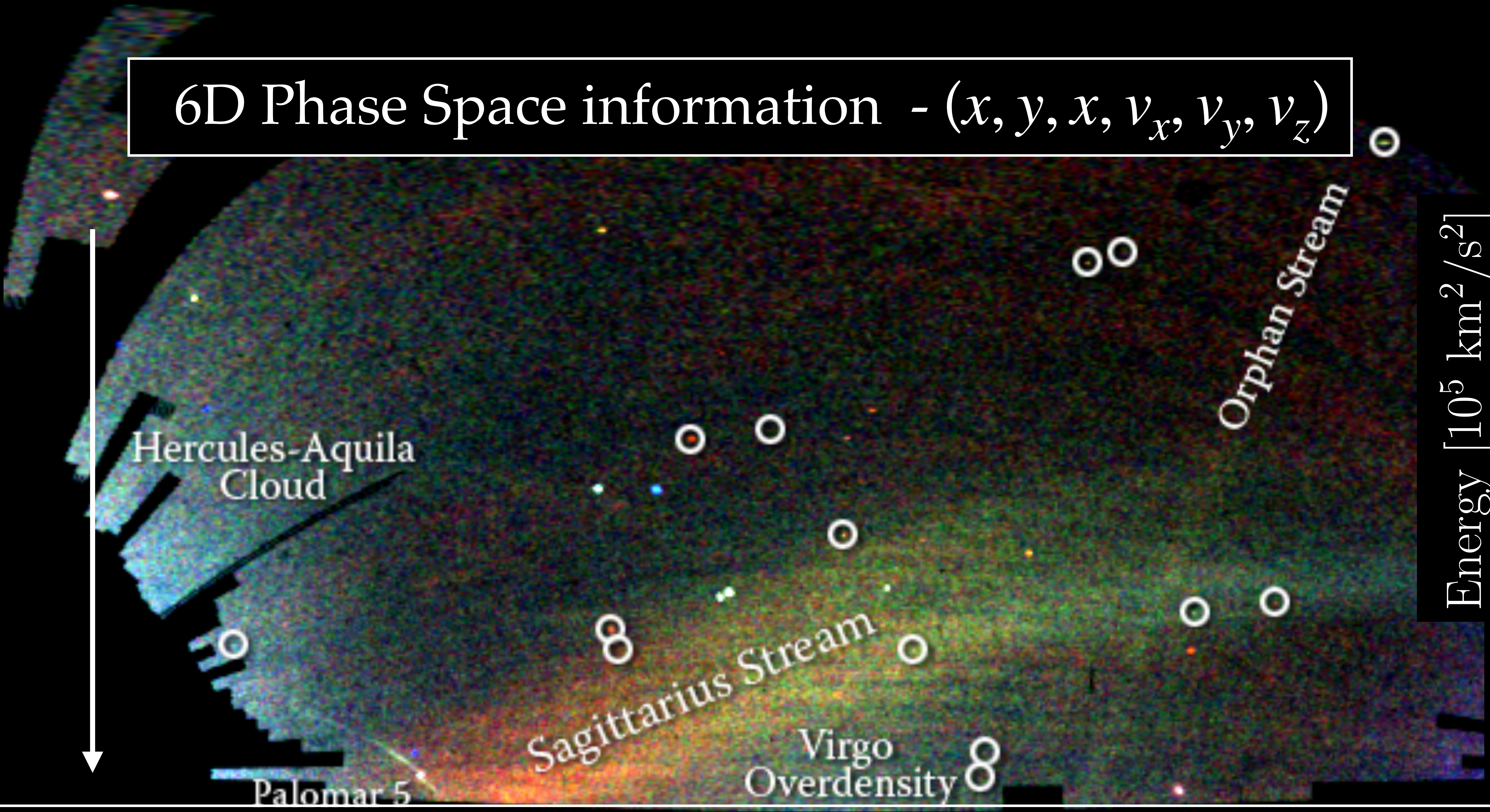

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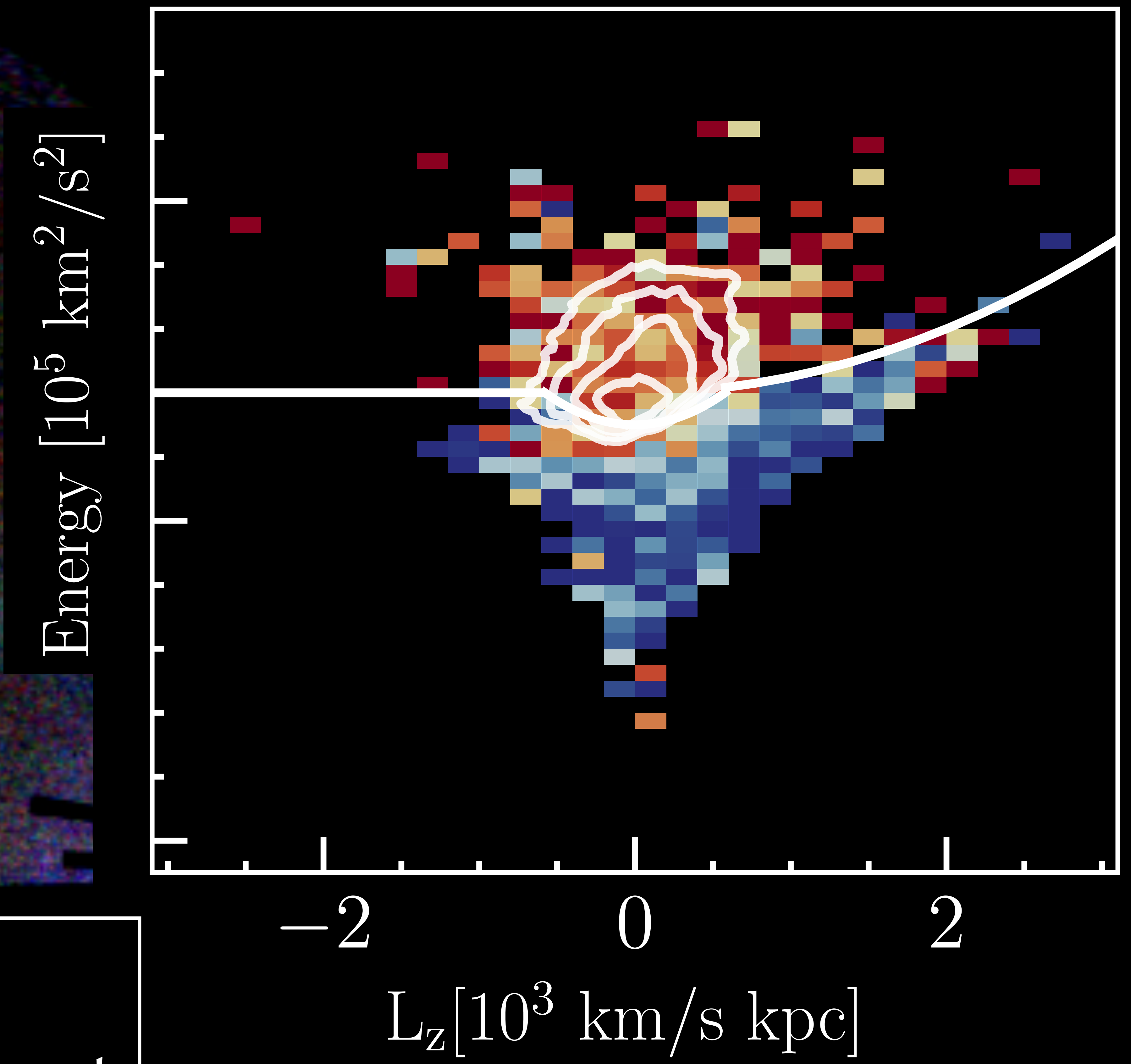

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Monty+ 2024

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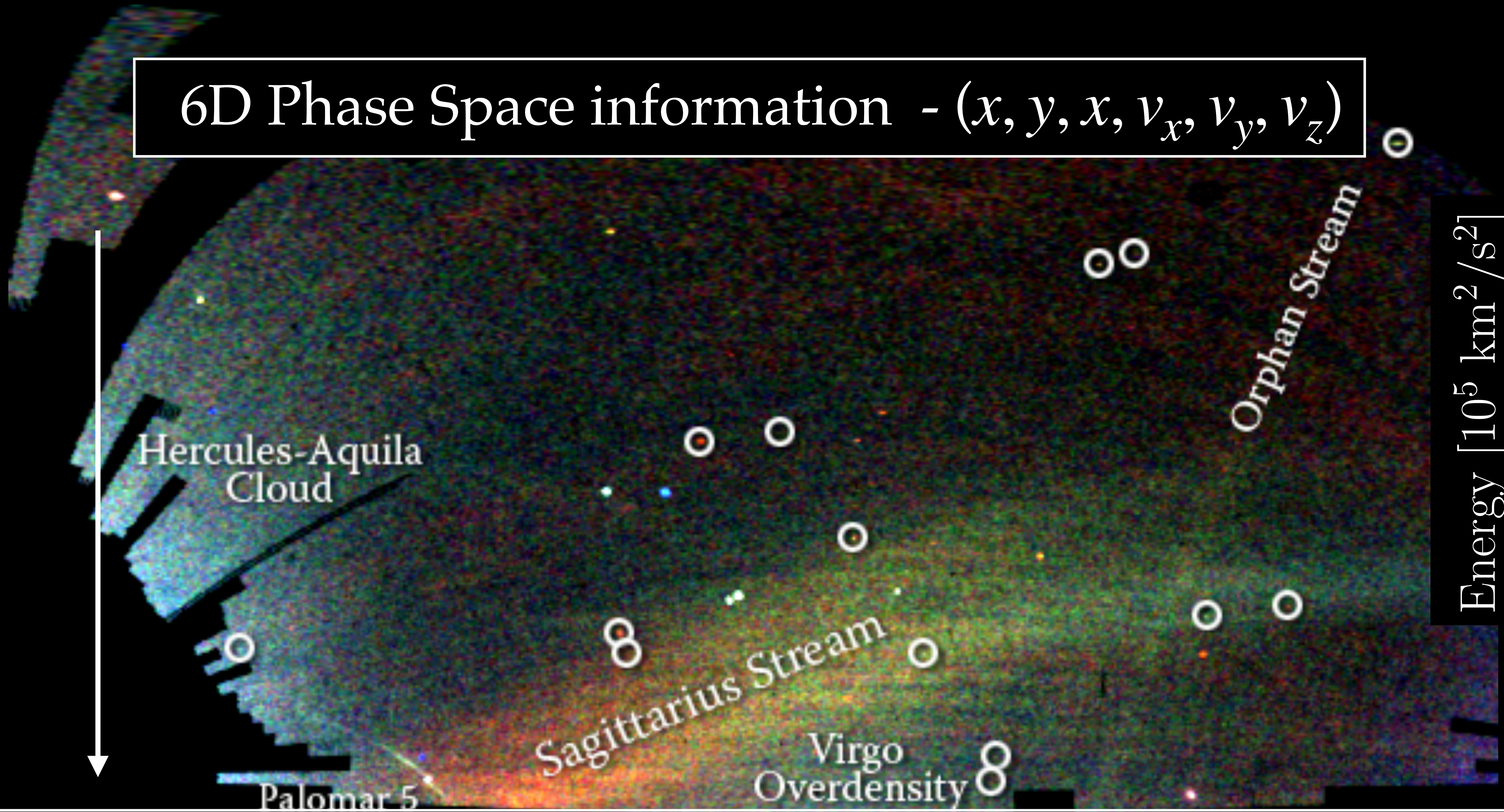

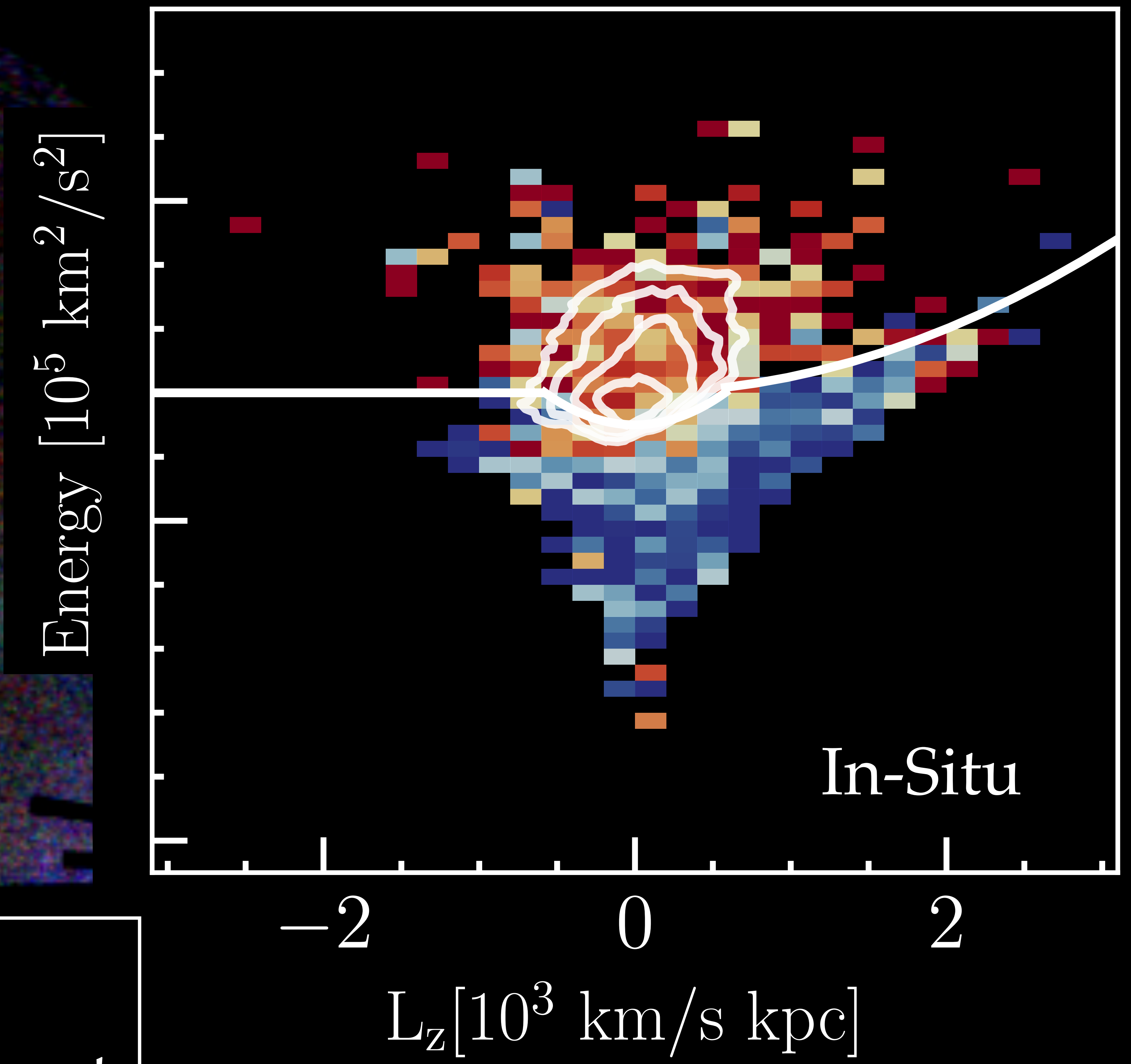

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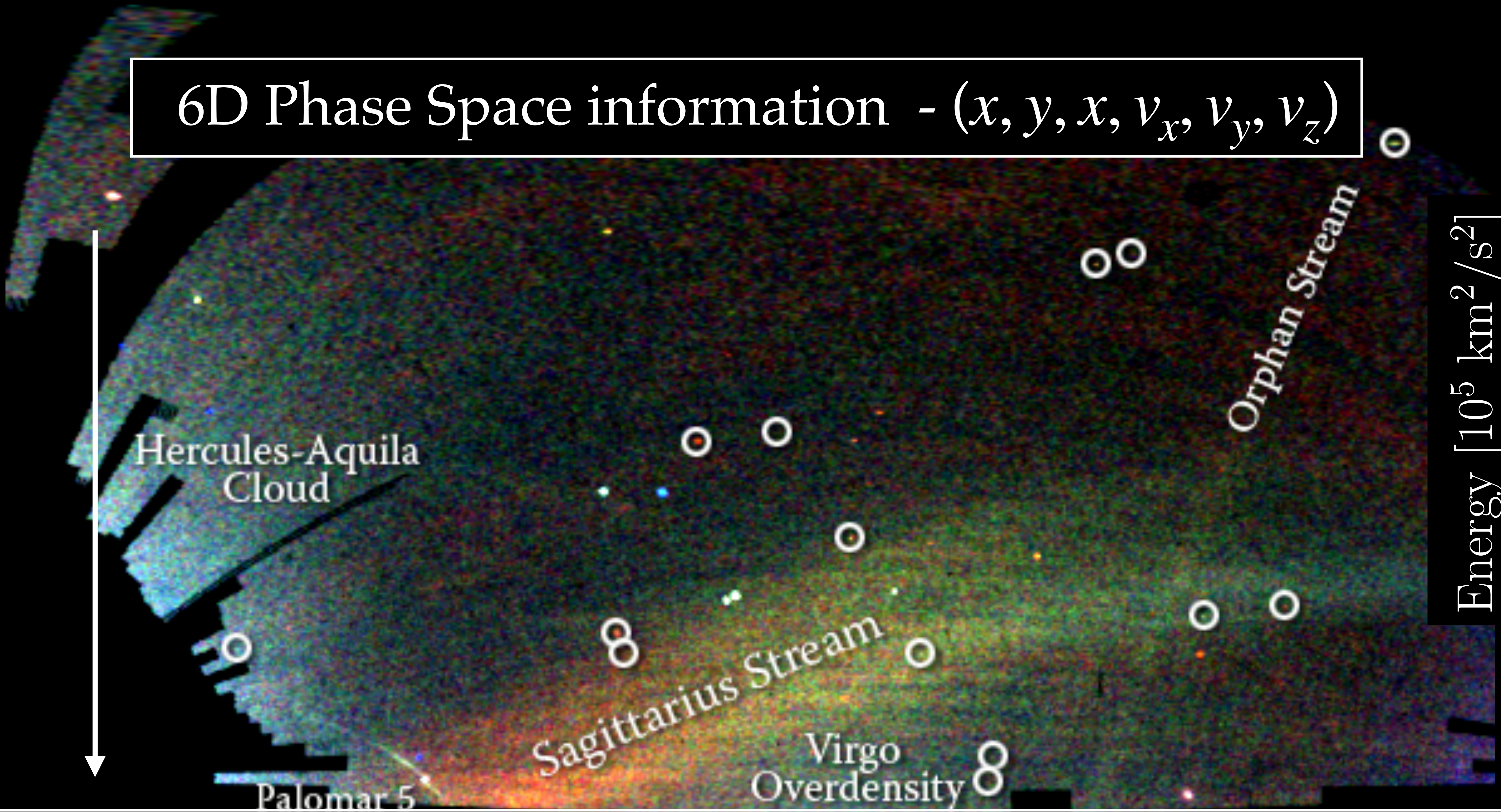

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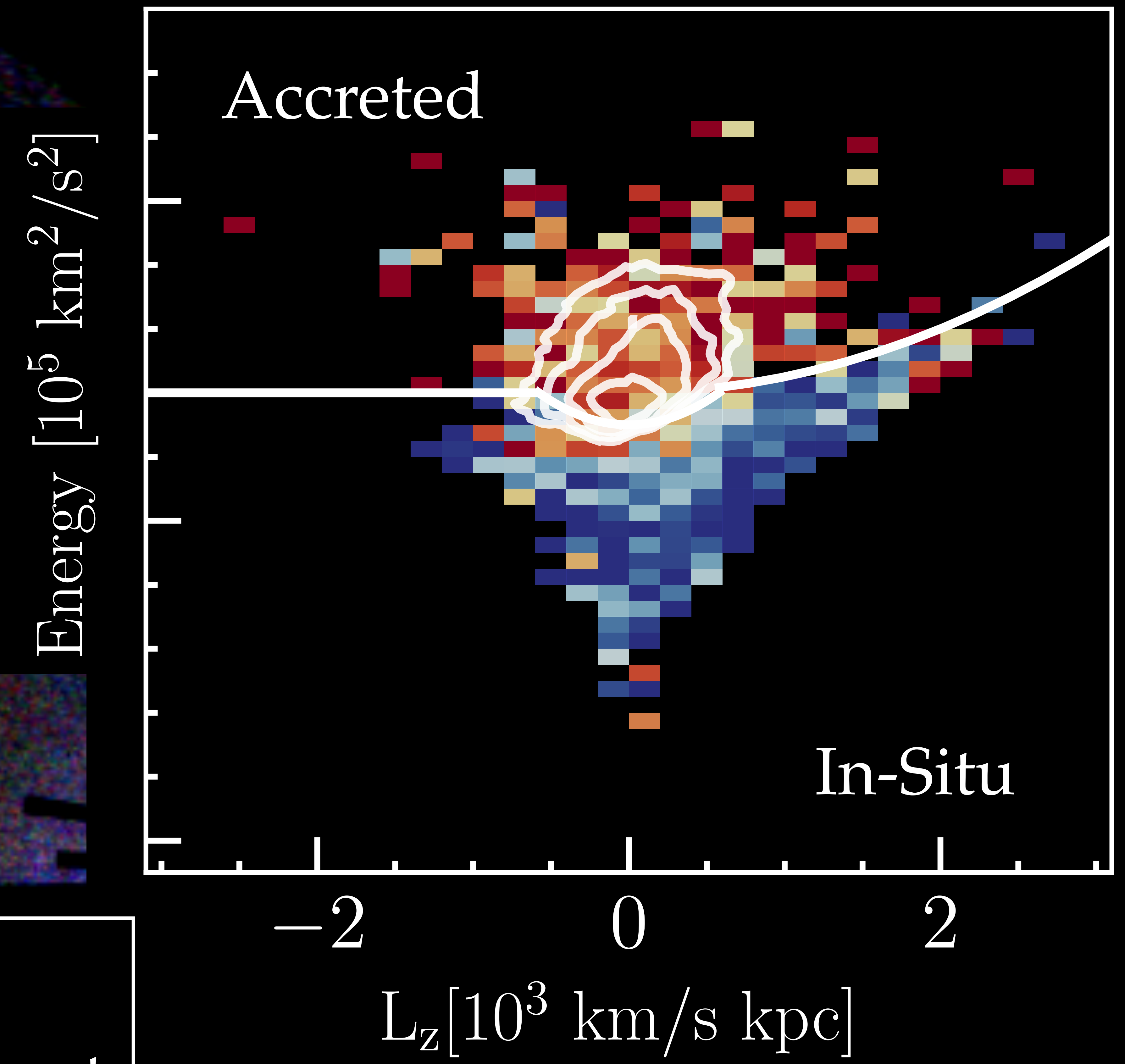

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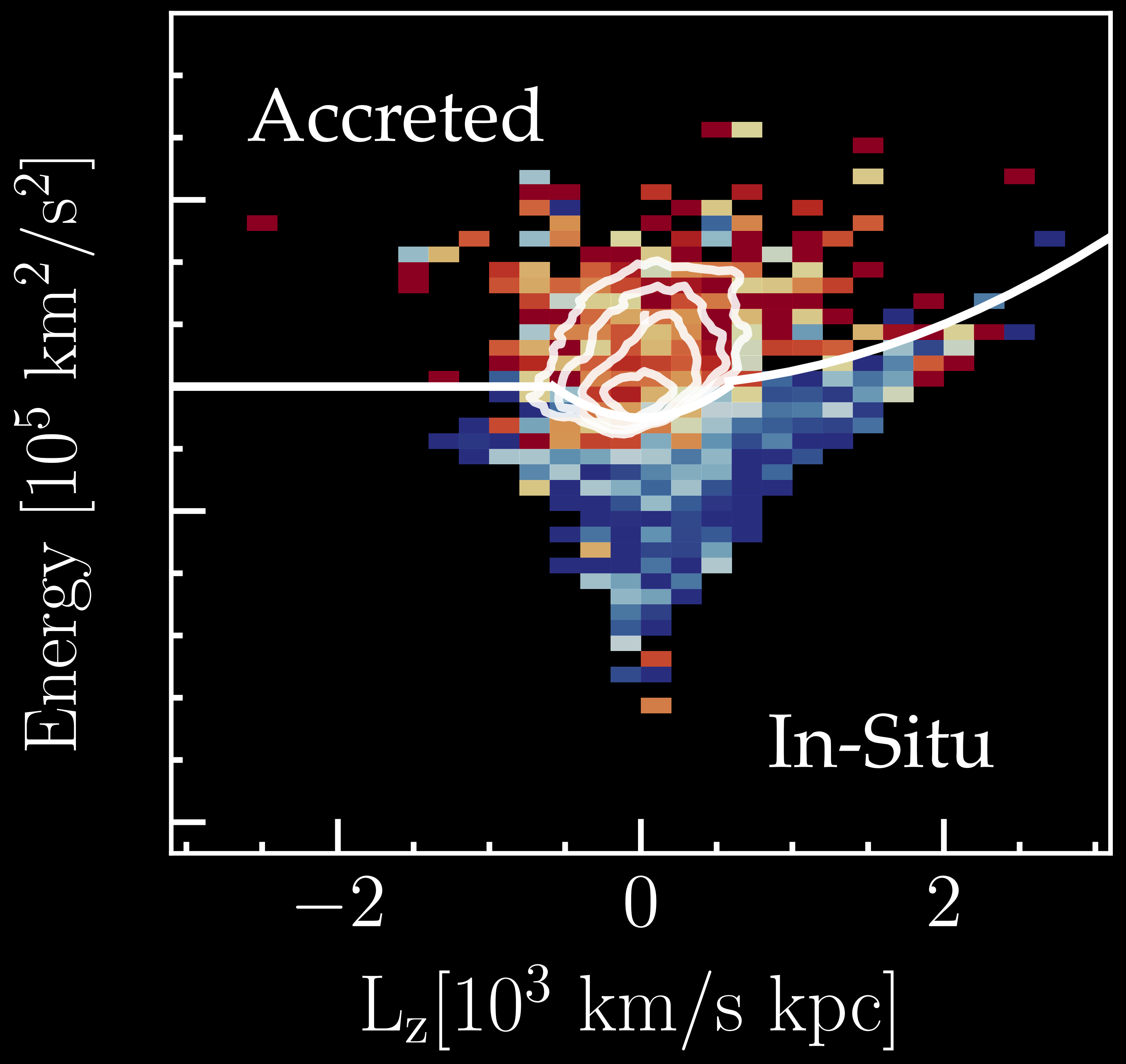

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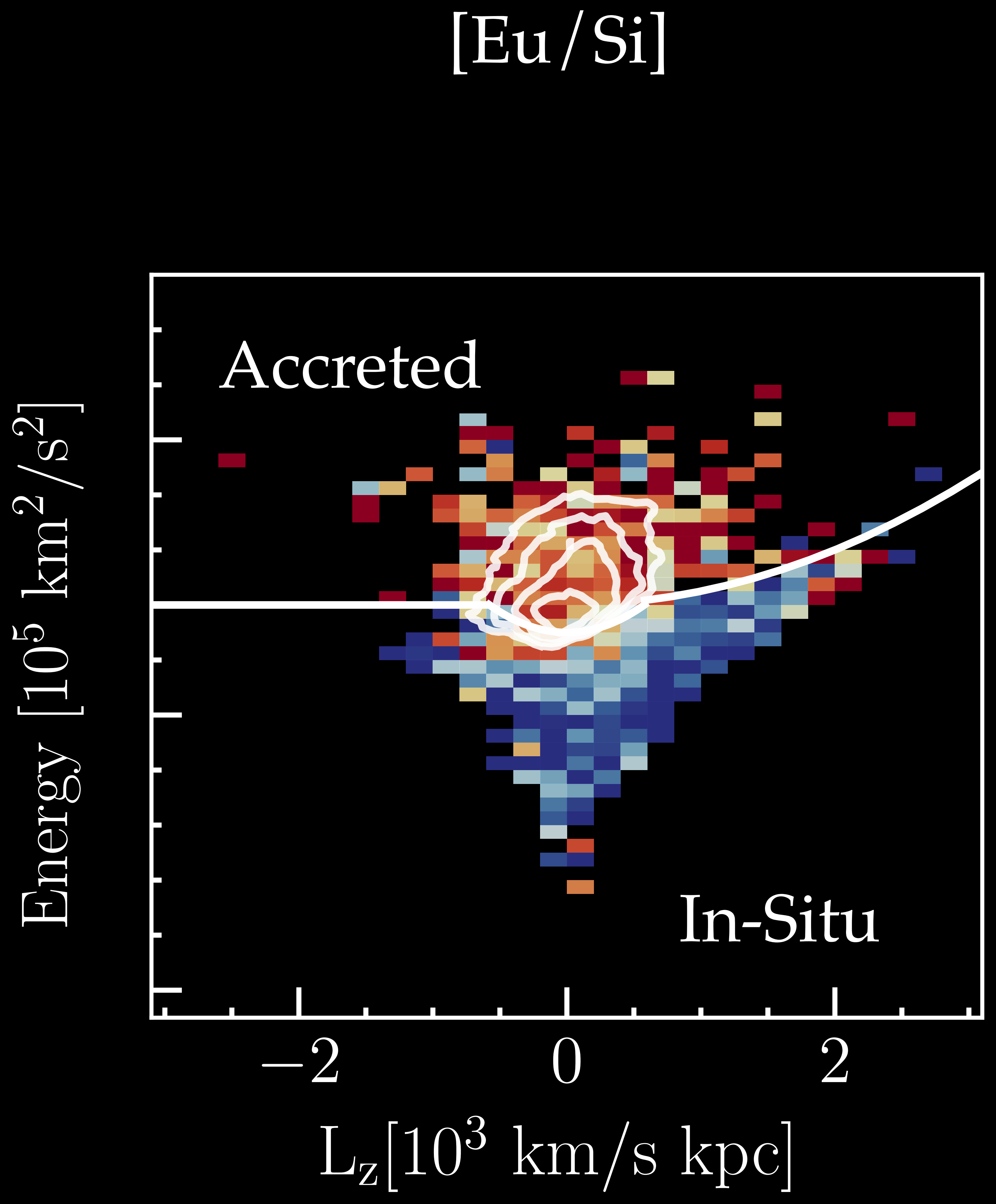

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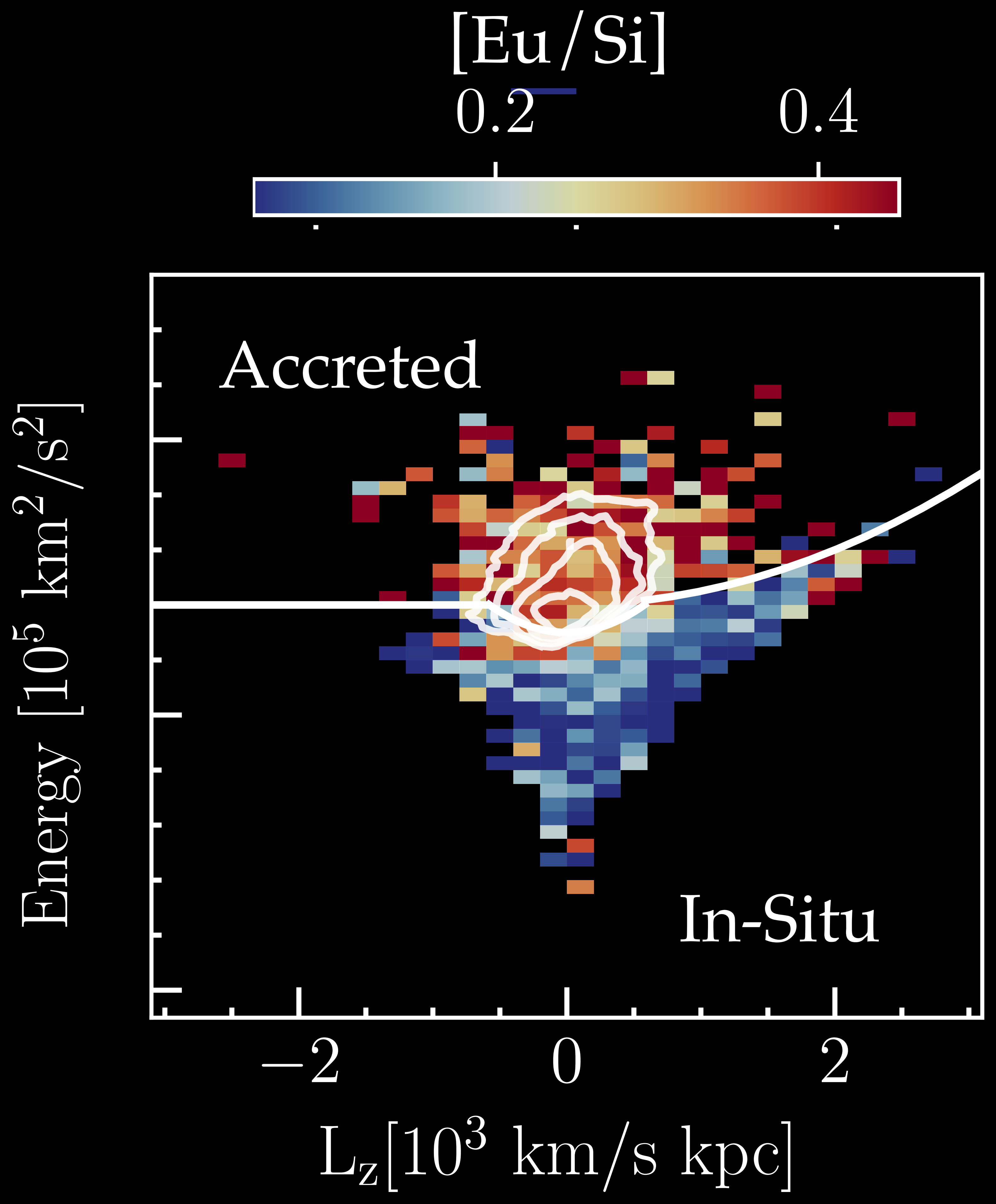

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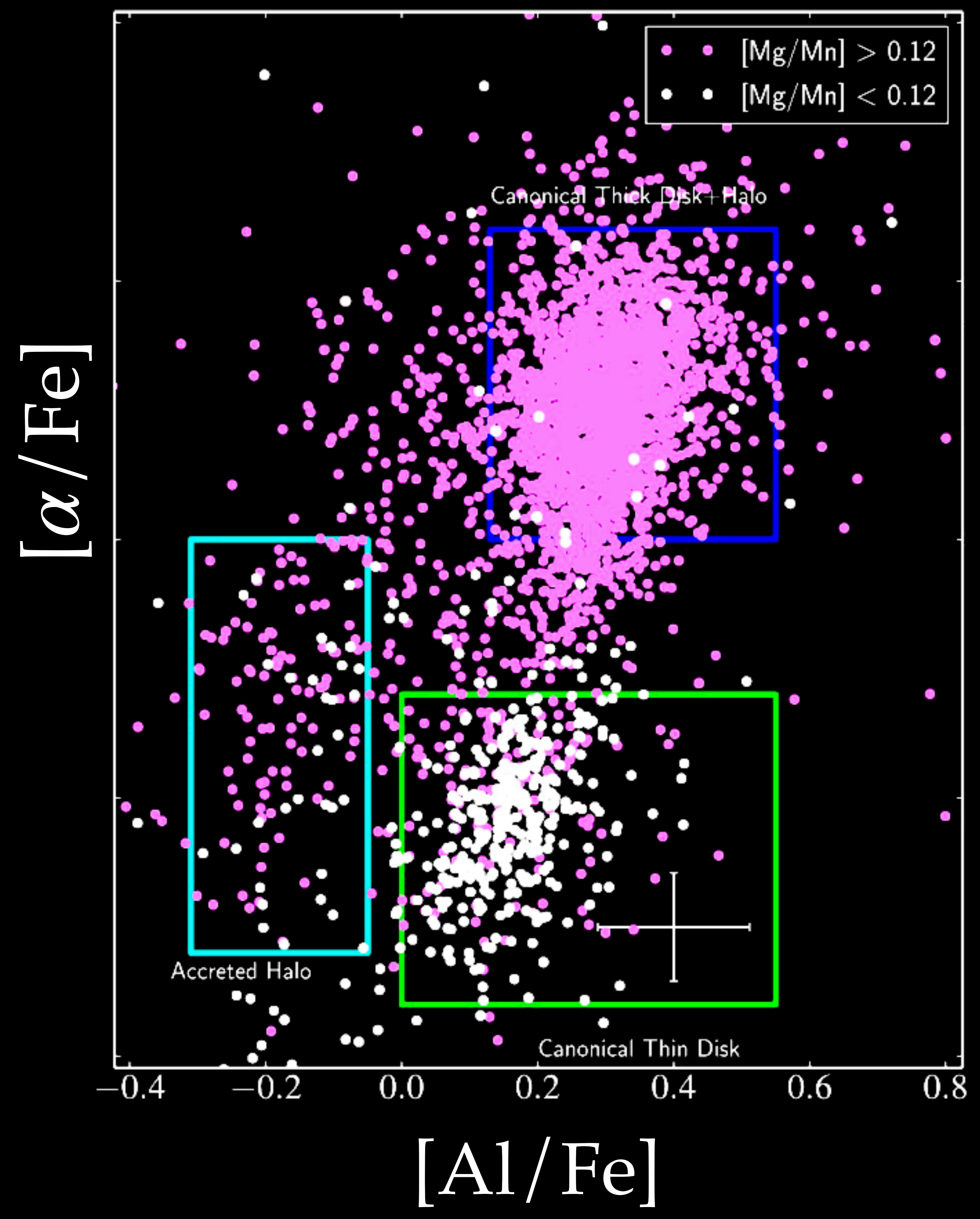

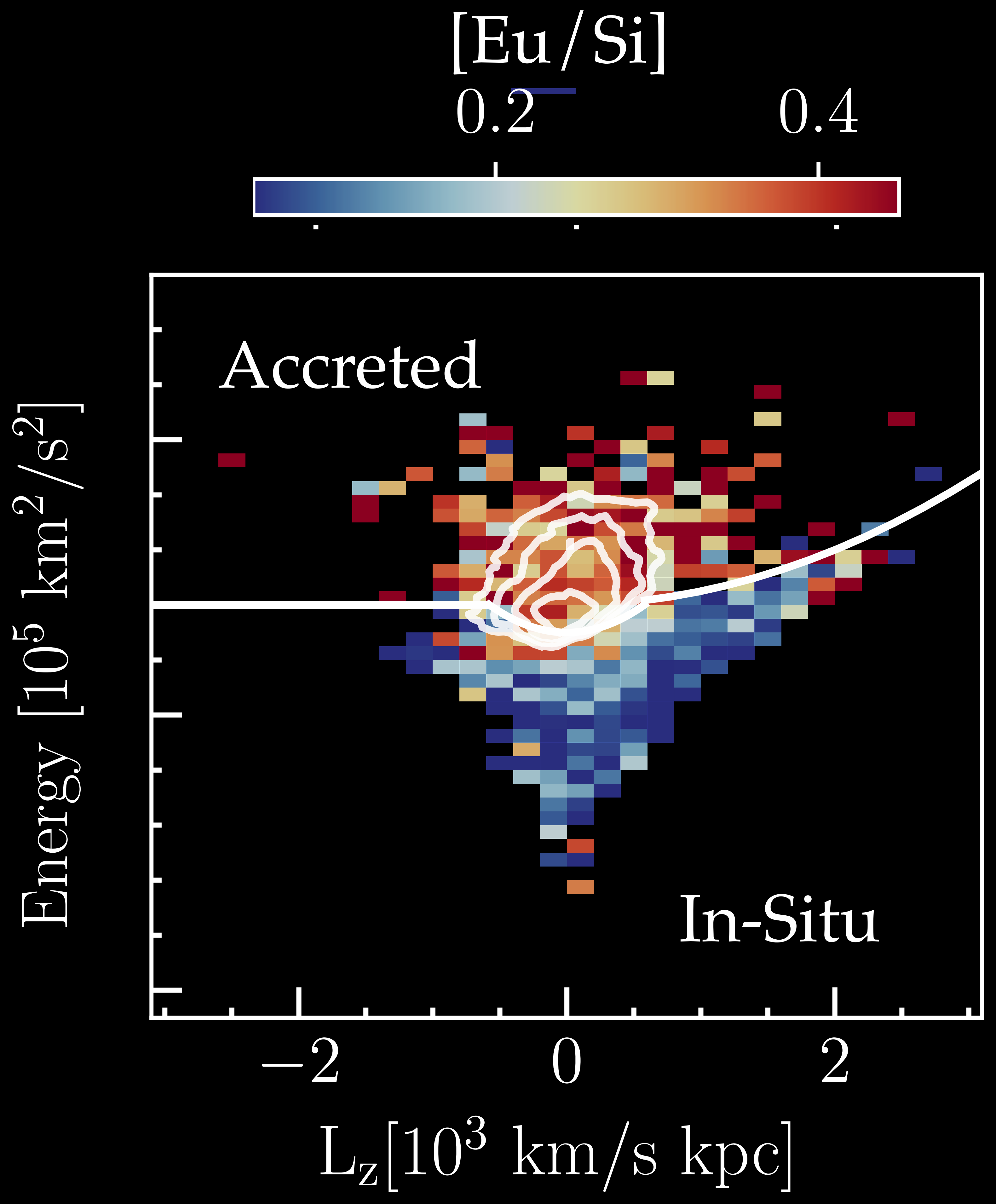

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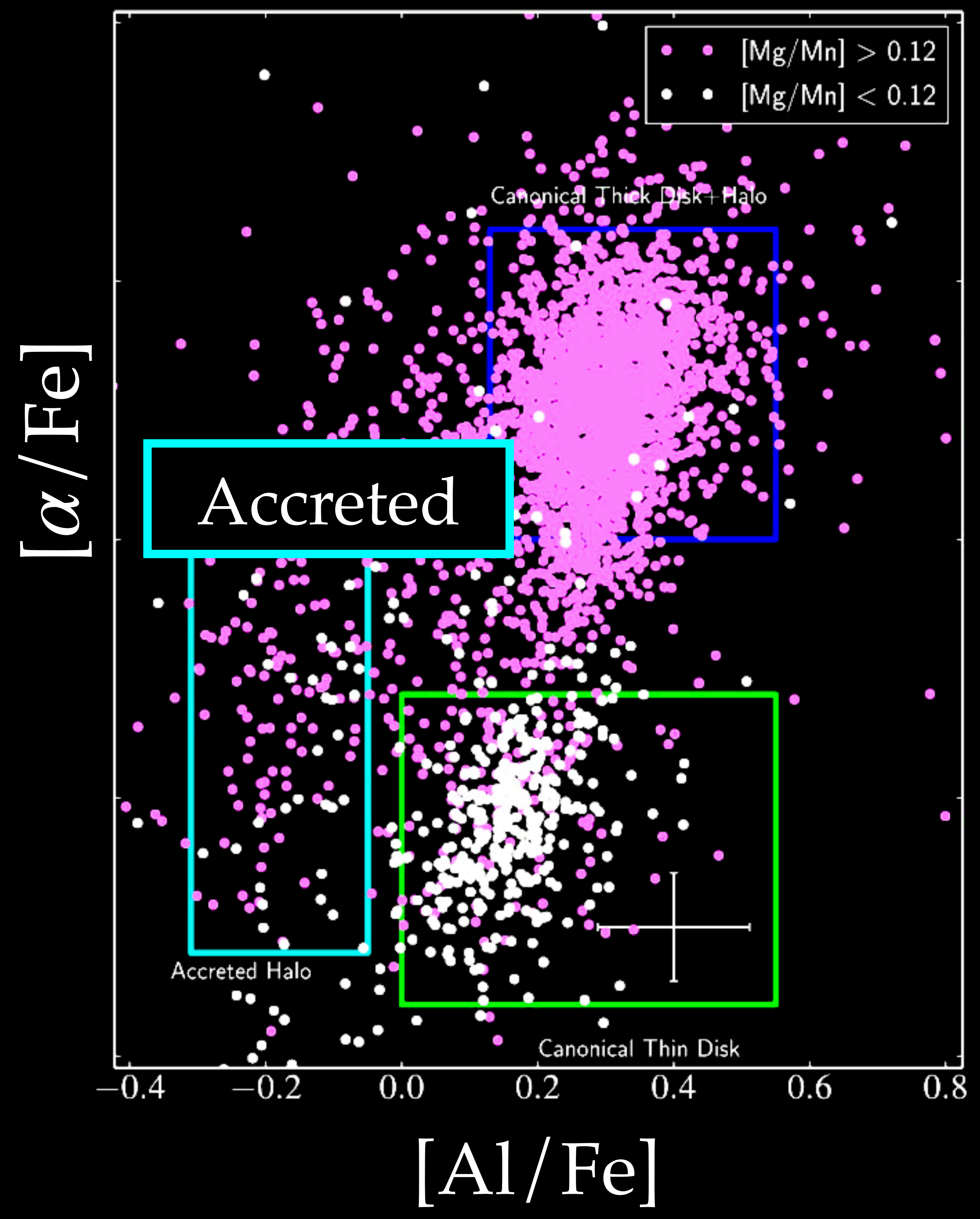

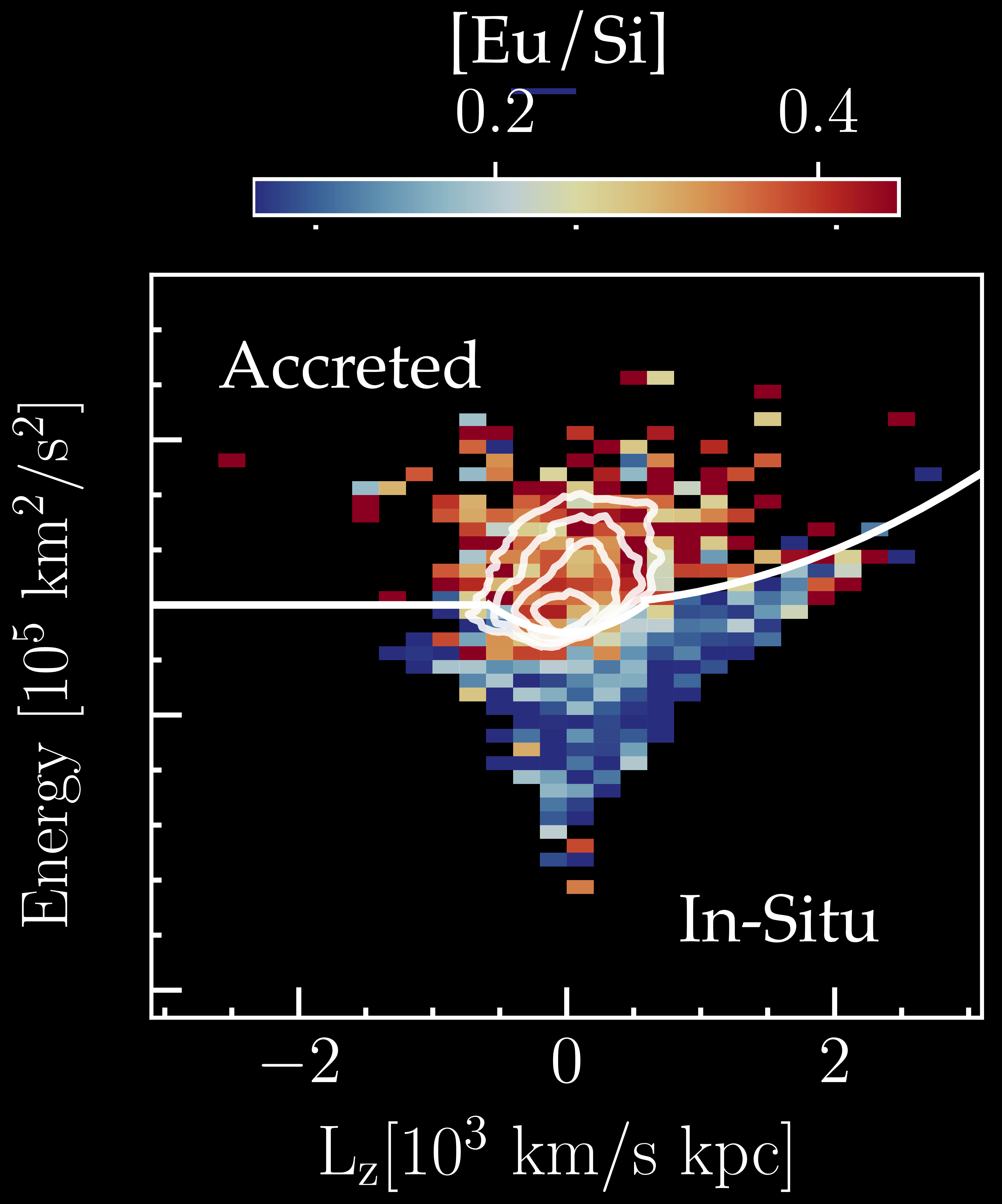

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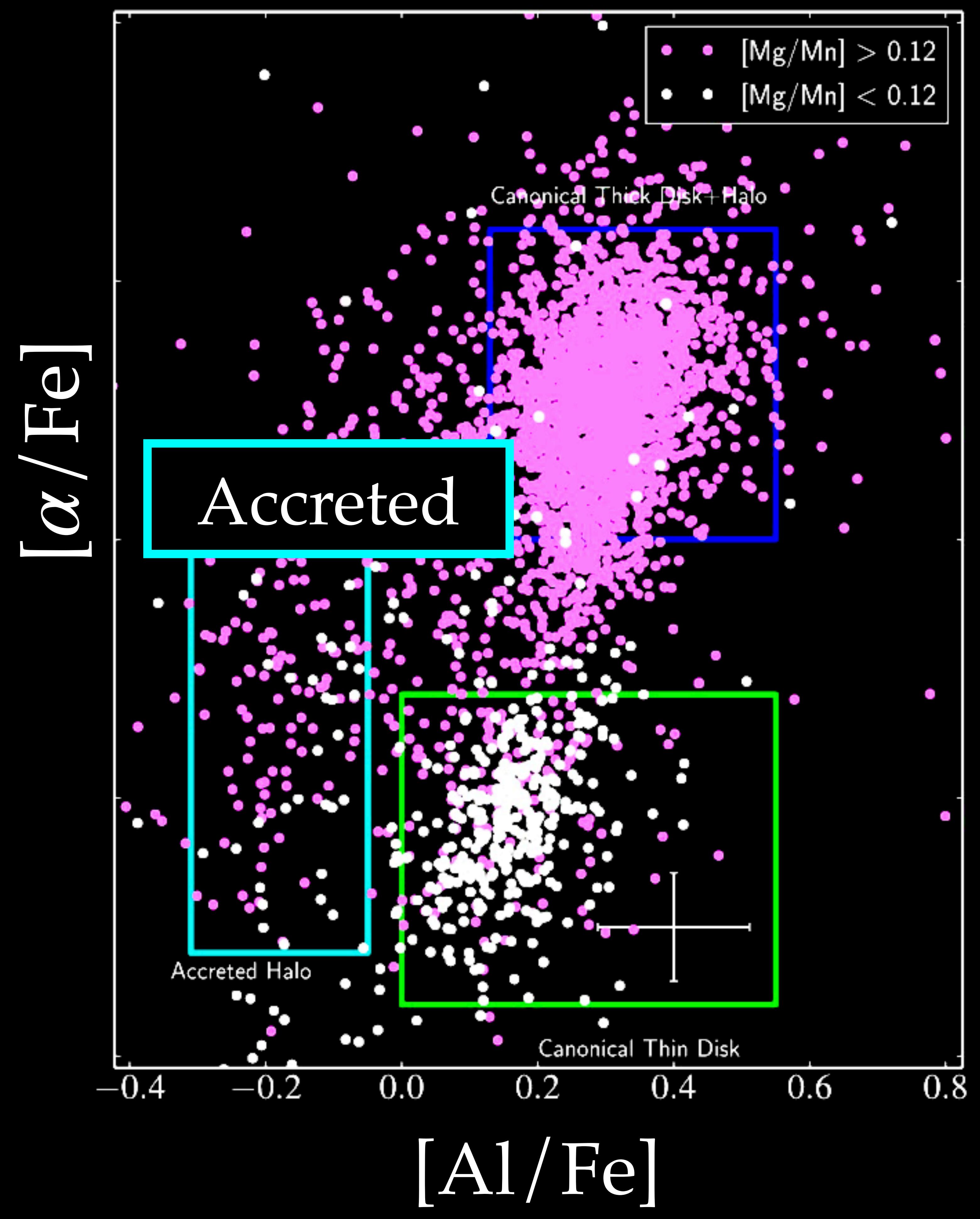

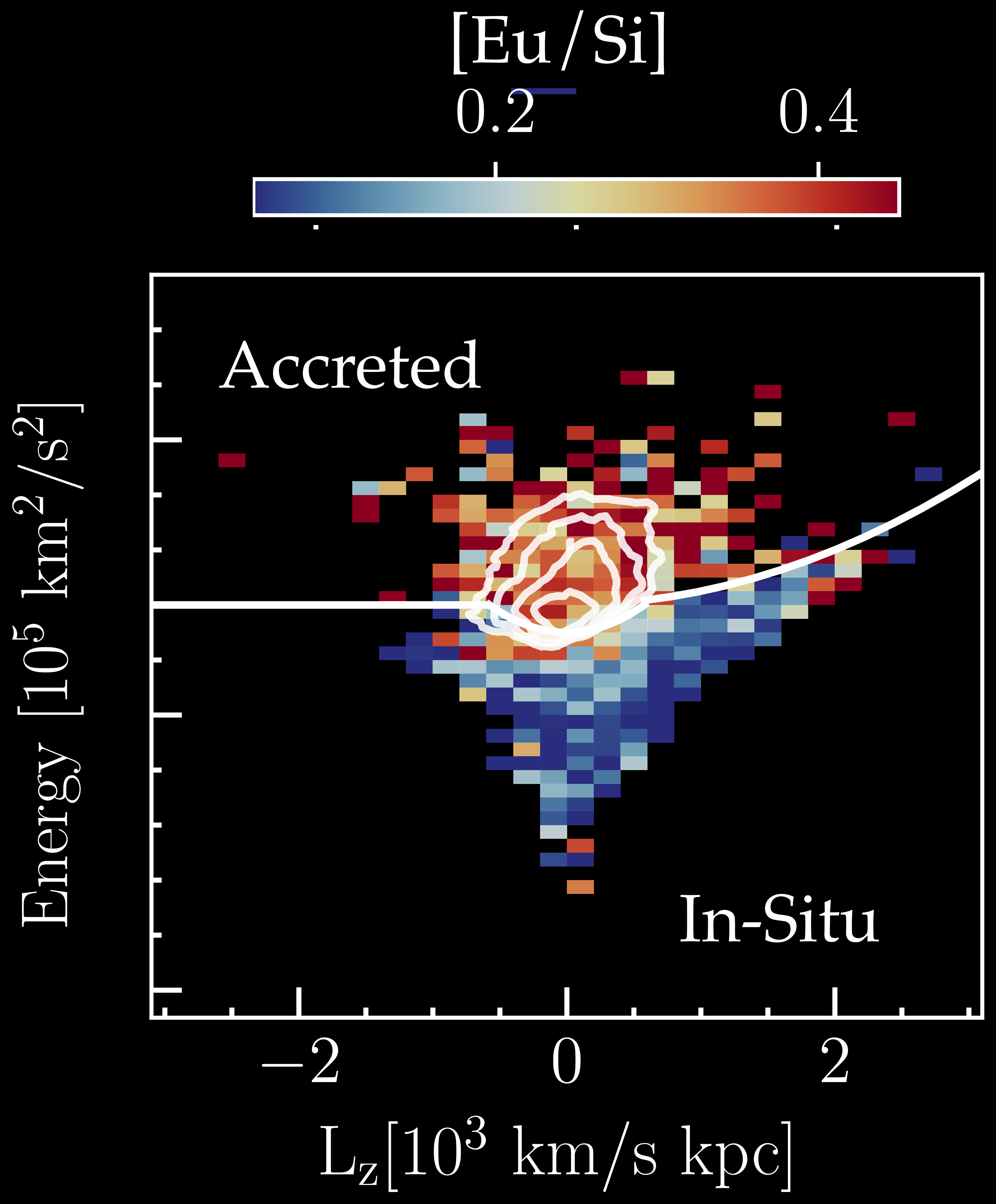

Hawkins+2015, Buder+2022, Nissen & Schuster 2011

+talks this week by Lucertini, Lombardo, Hansen, Holmbeck

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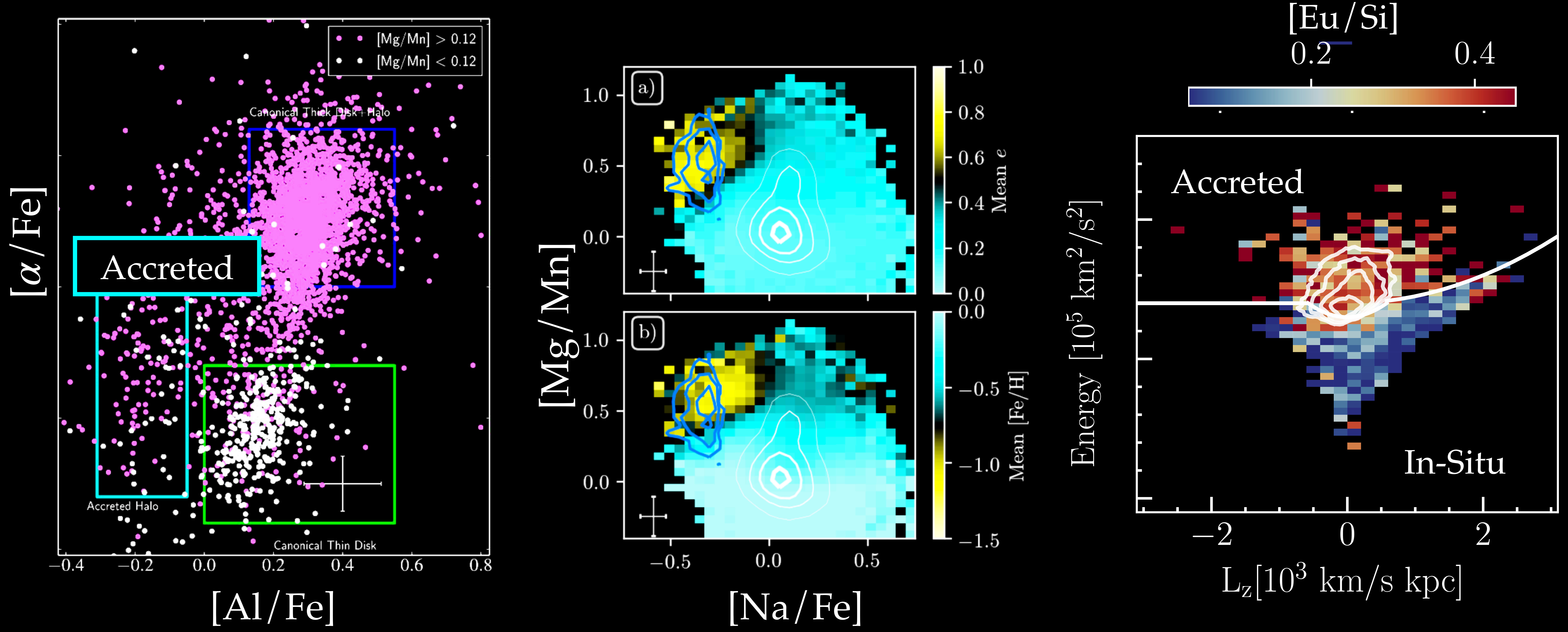

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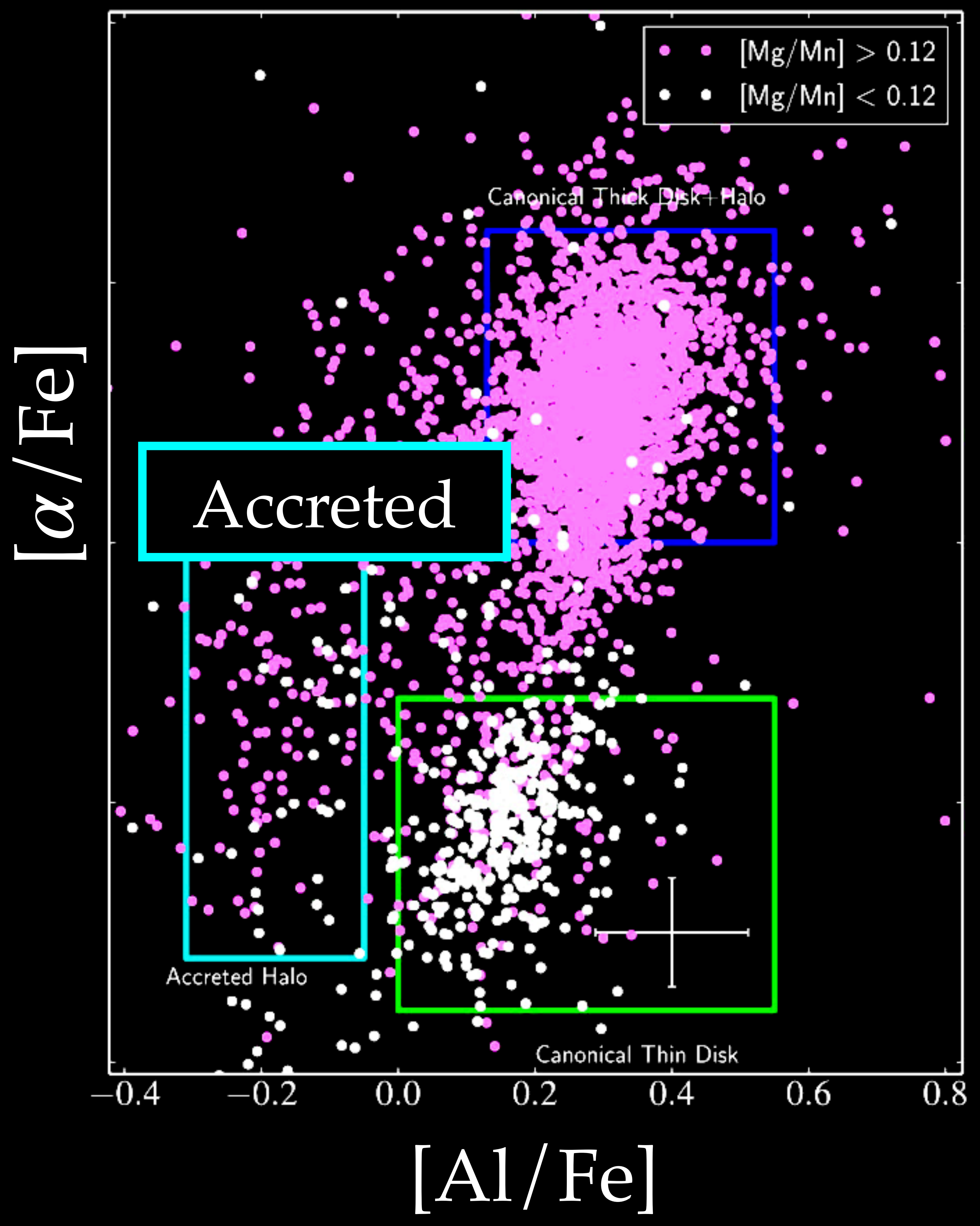

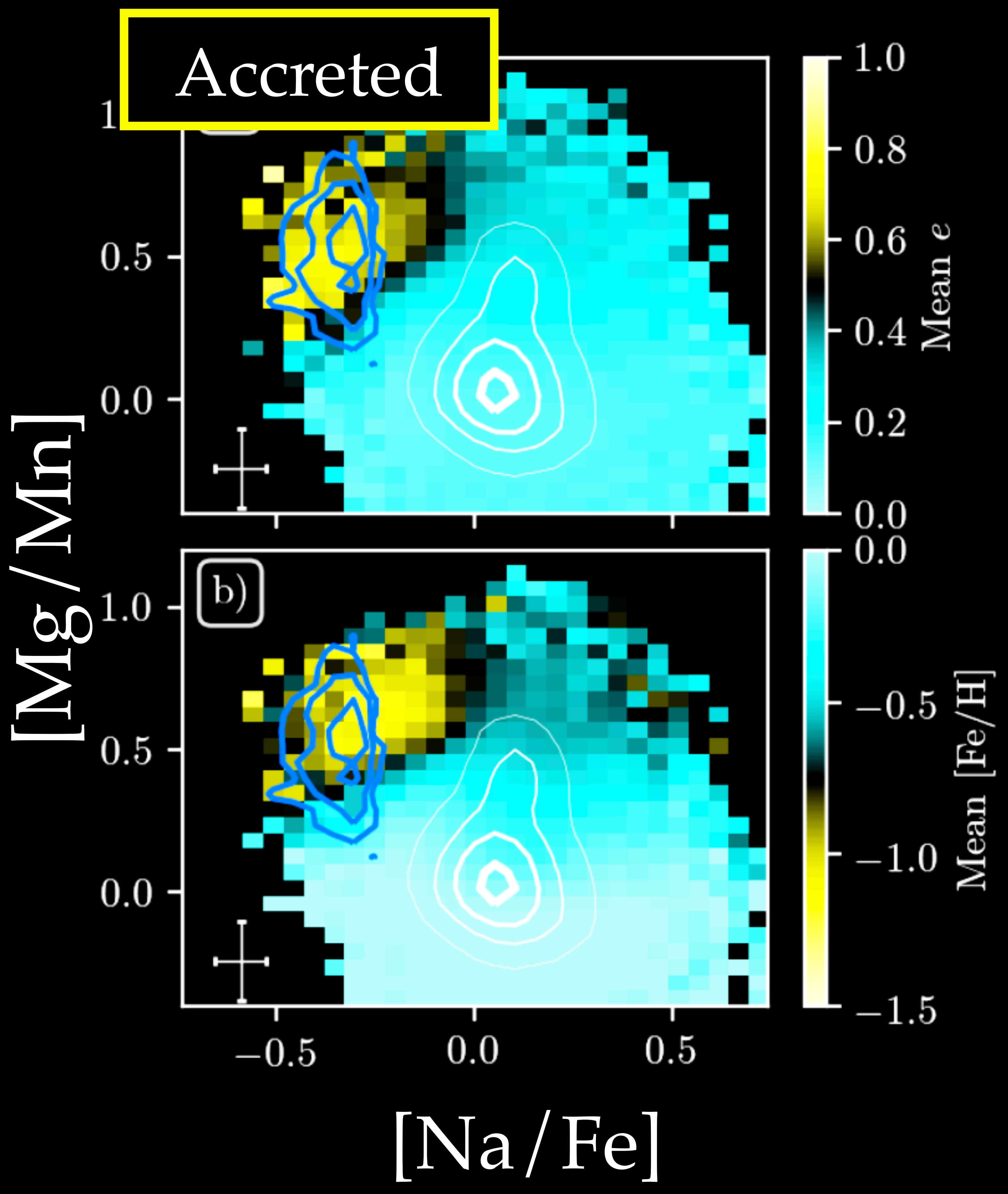

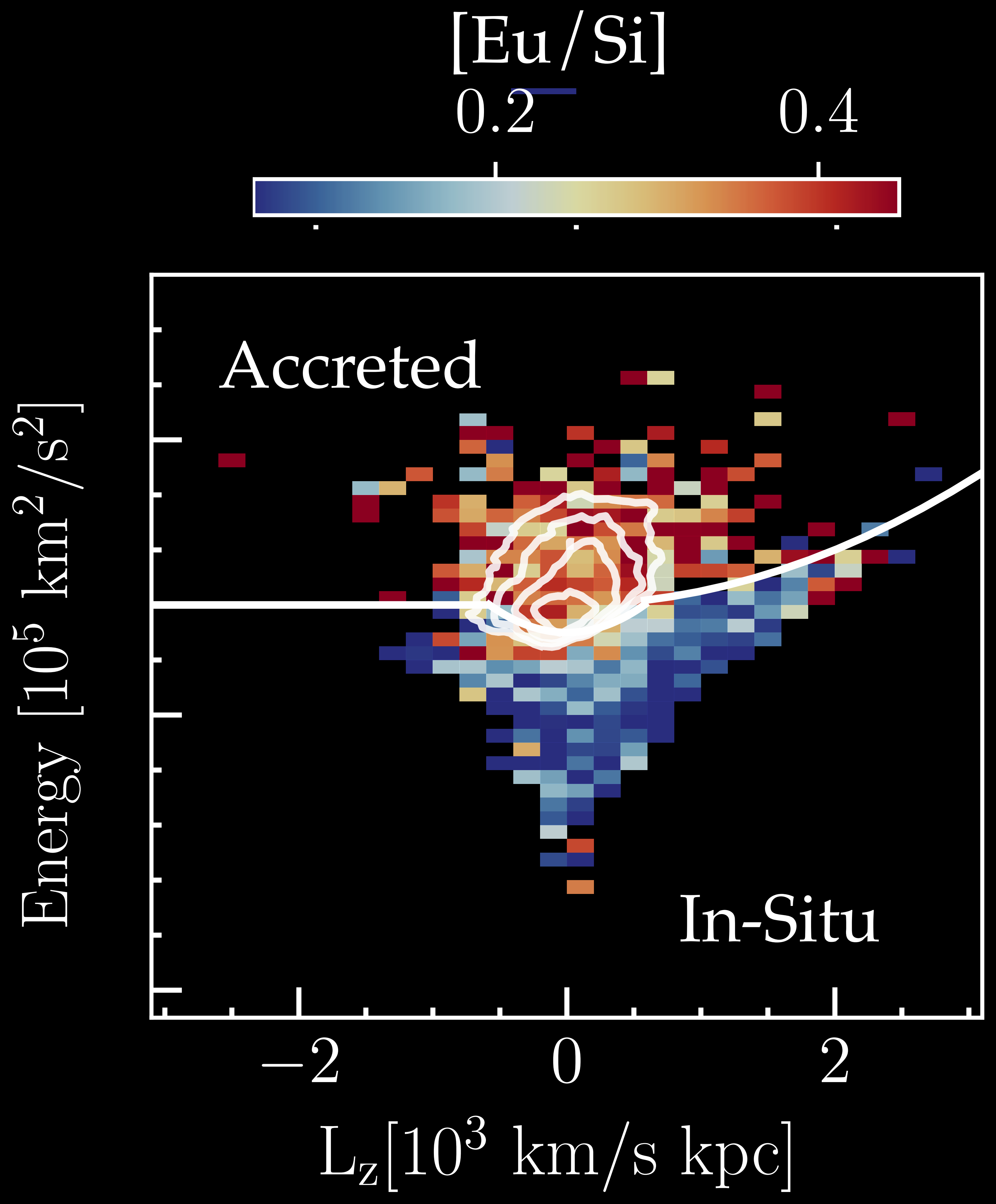

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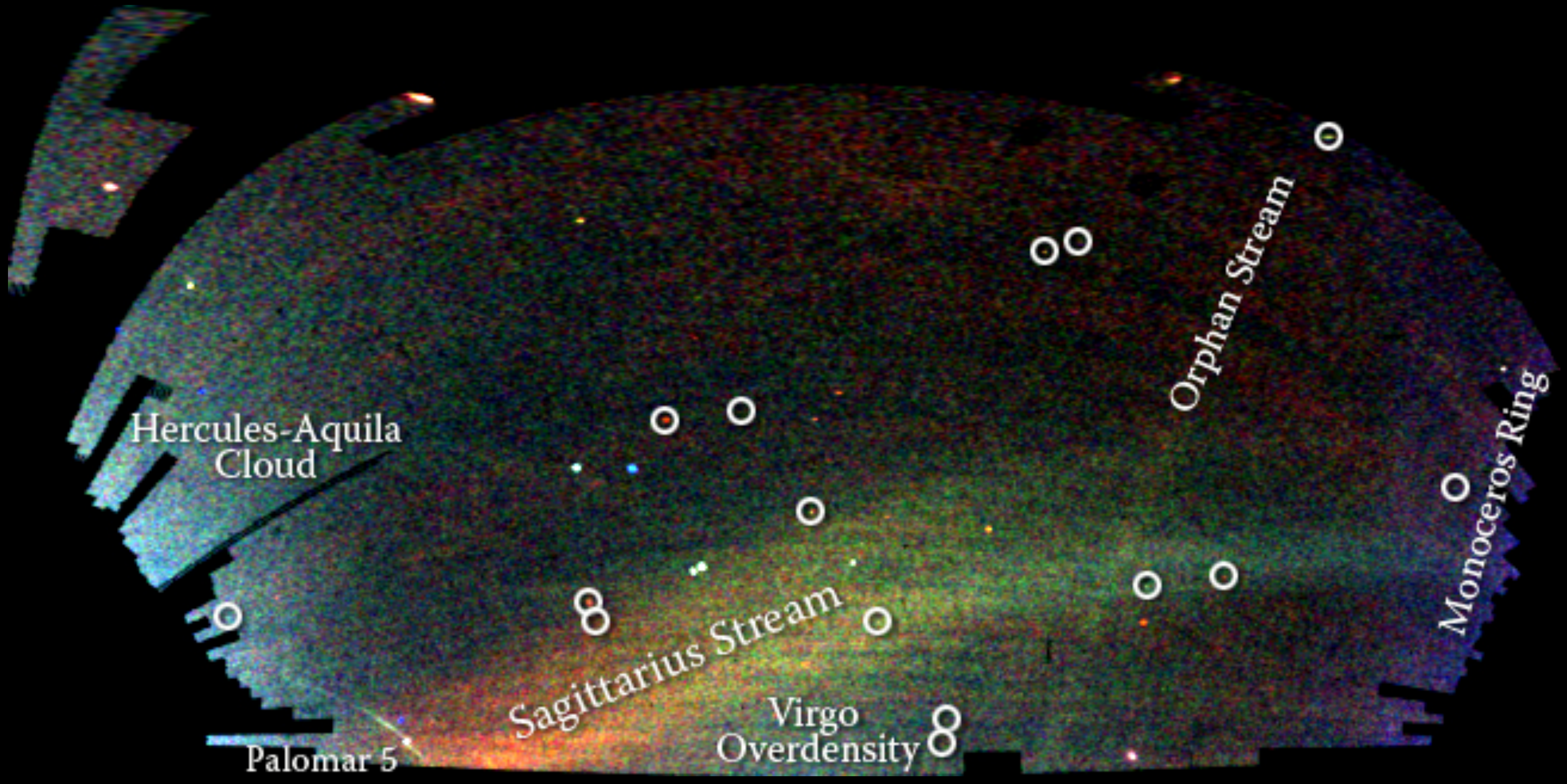
The search for stellar streams in the era of Gaia



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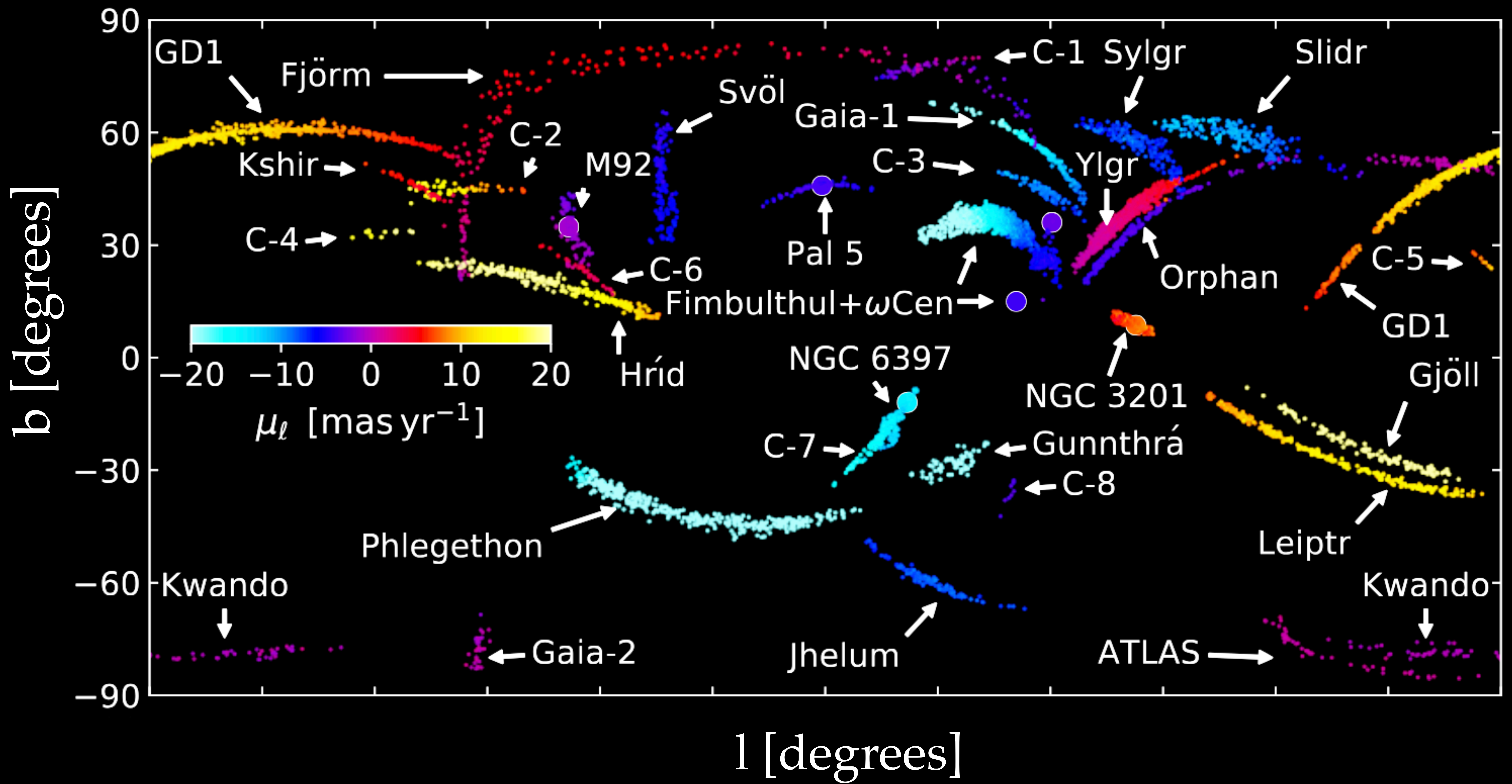

Ibata+ 2021

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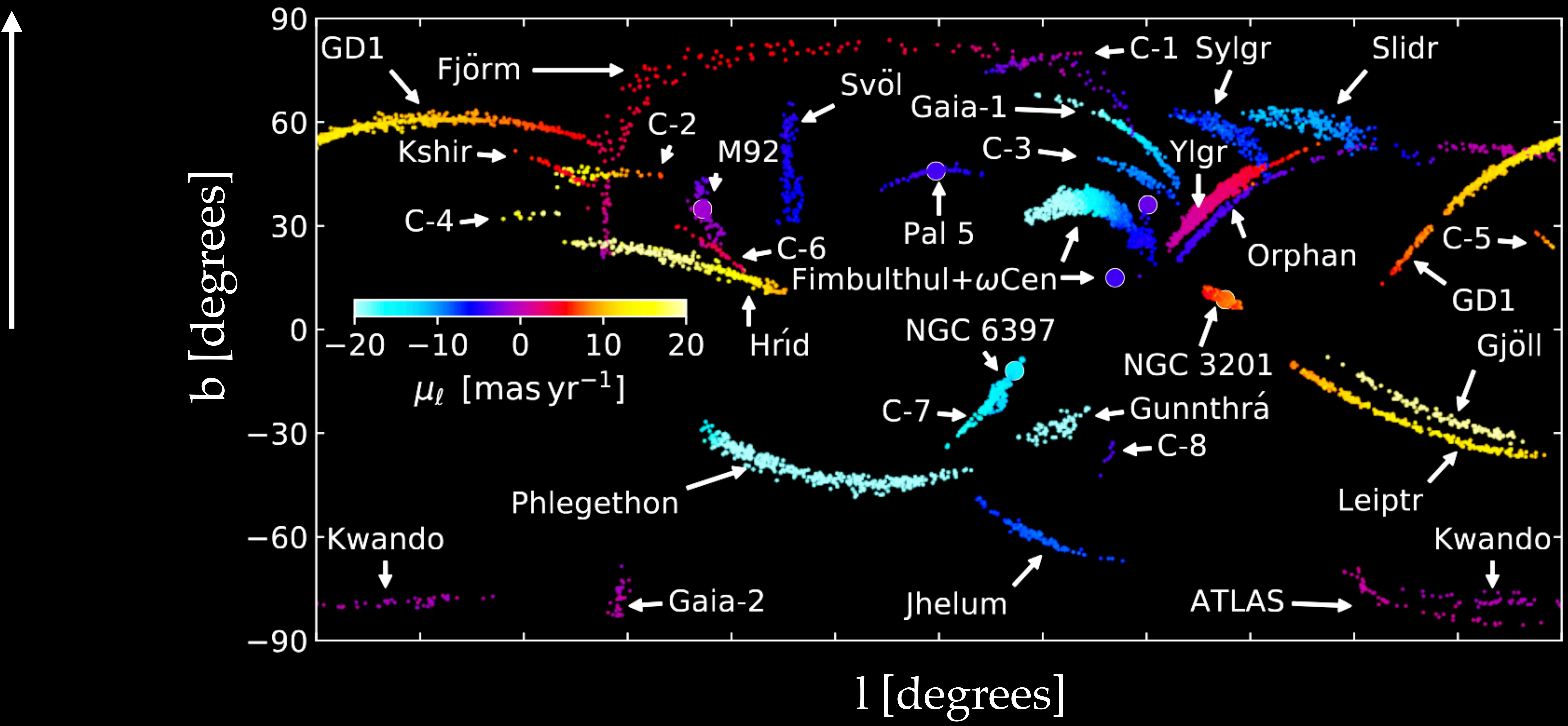

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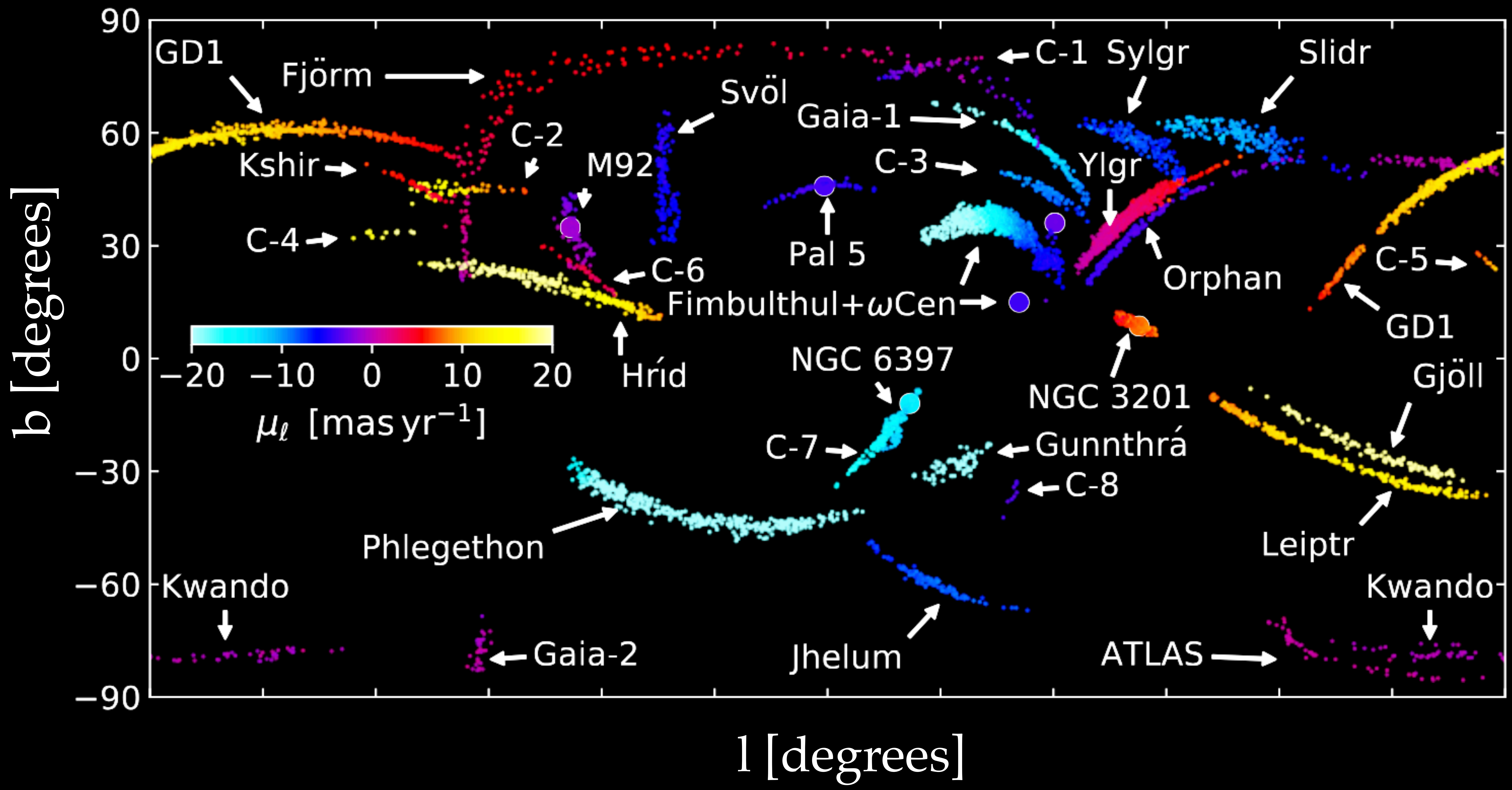
Above the Galactic plane



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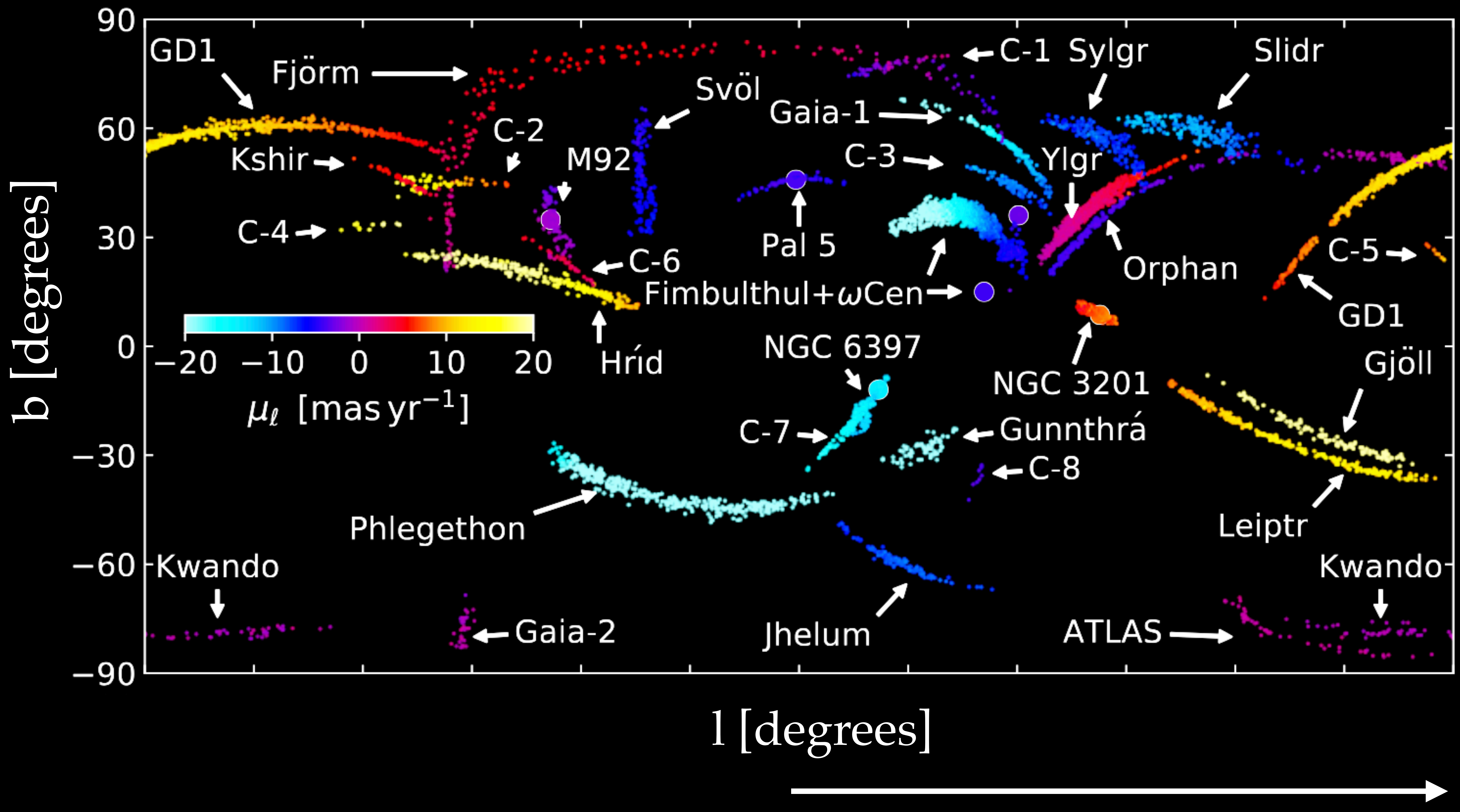

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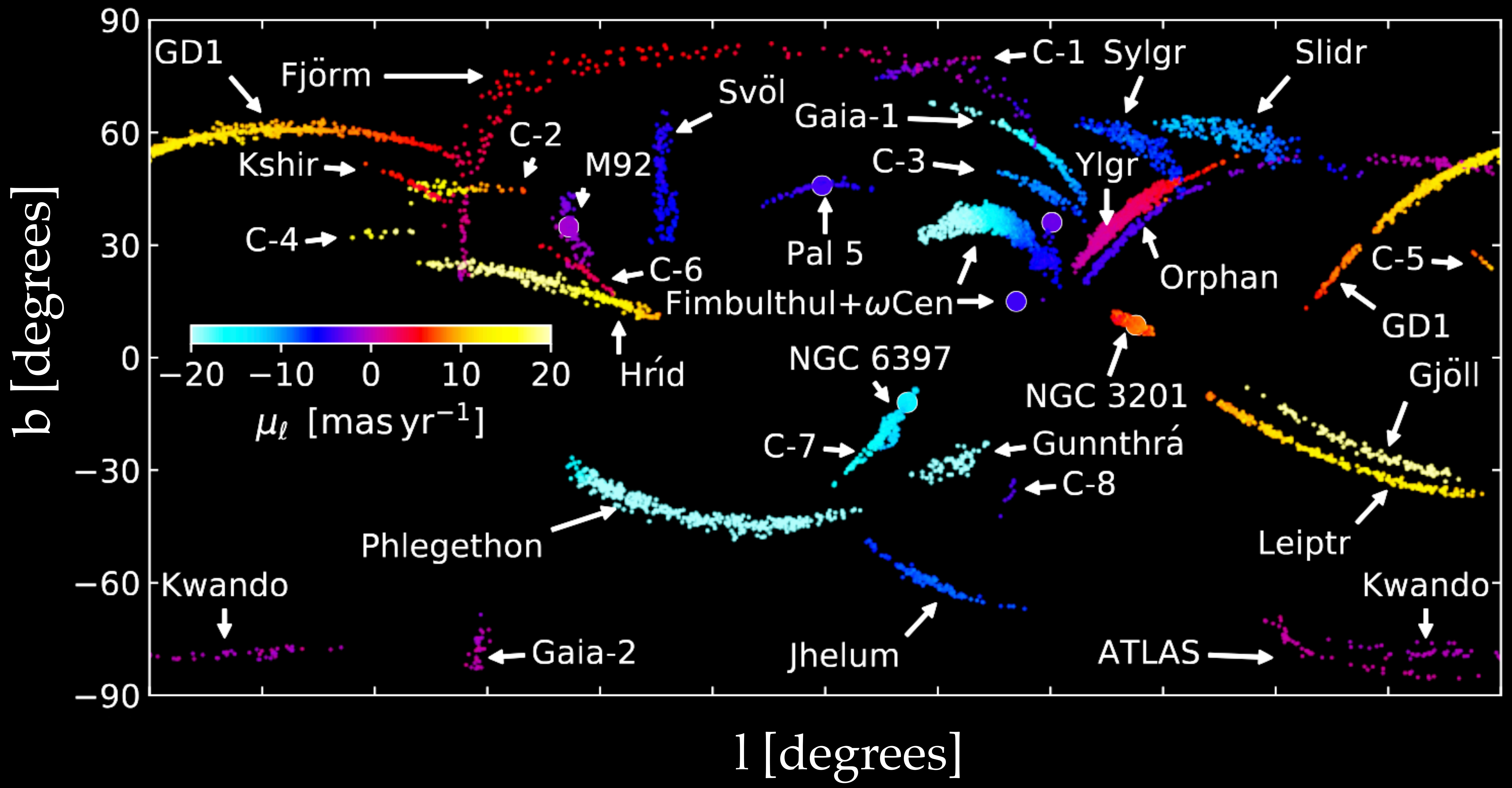

Away from the Galactic centre

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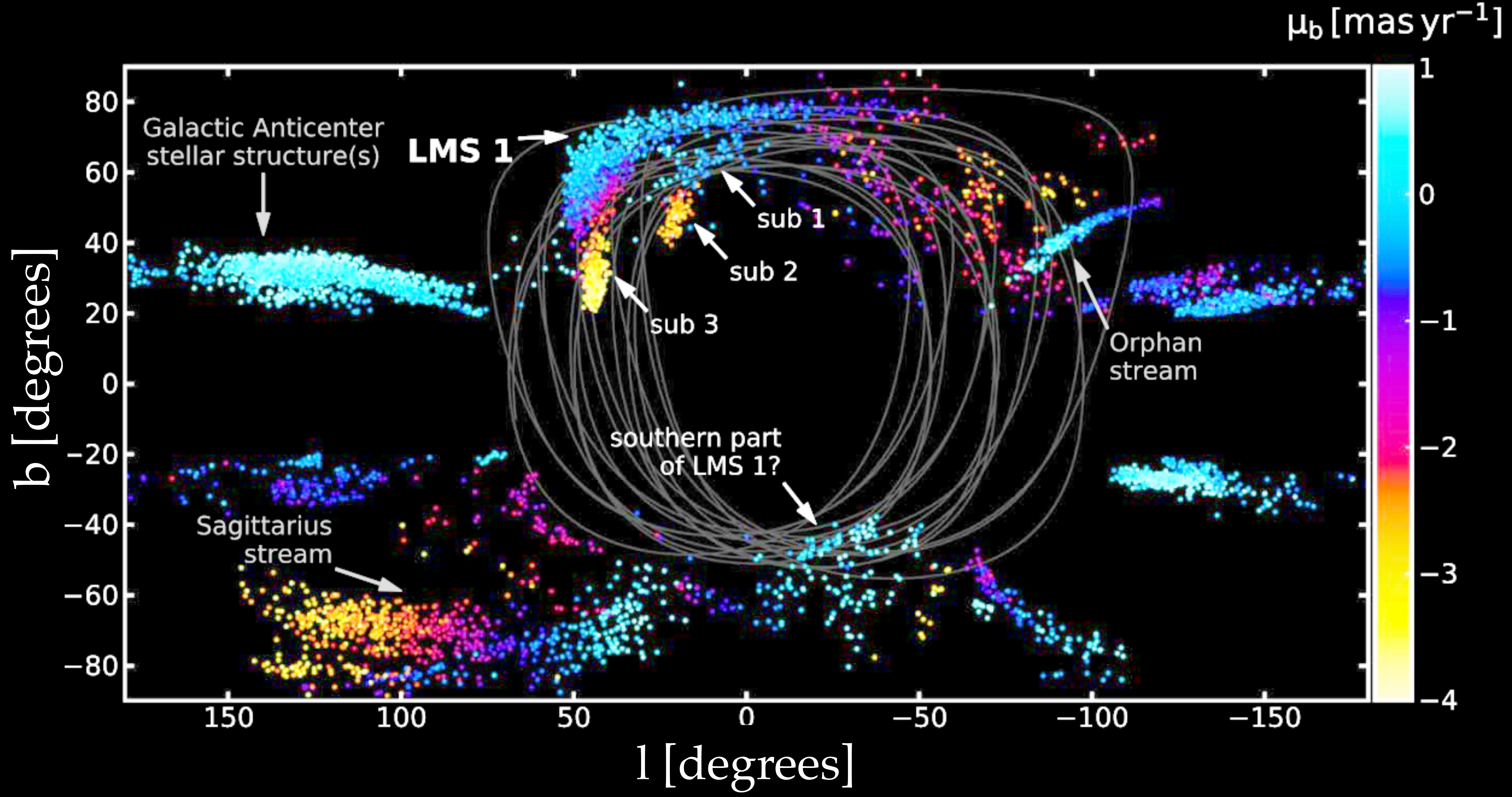

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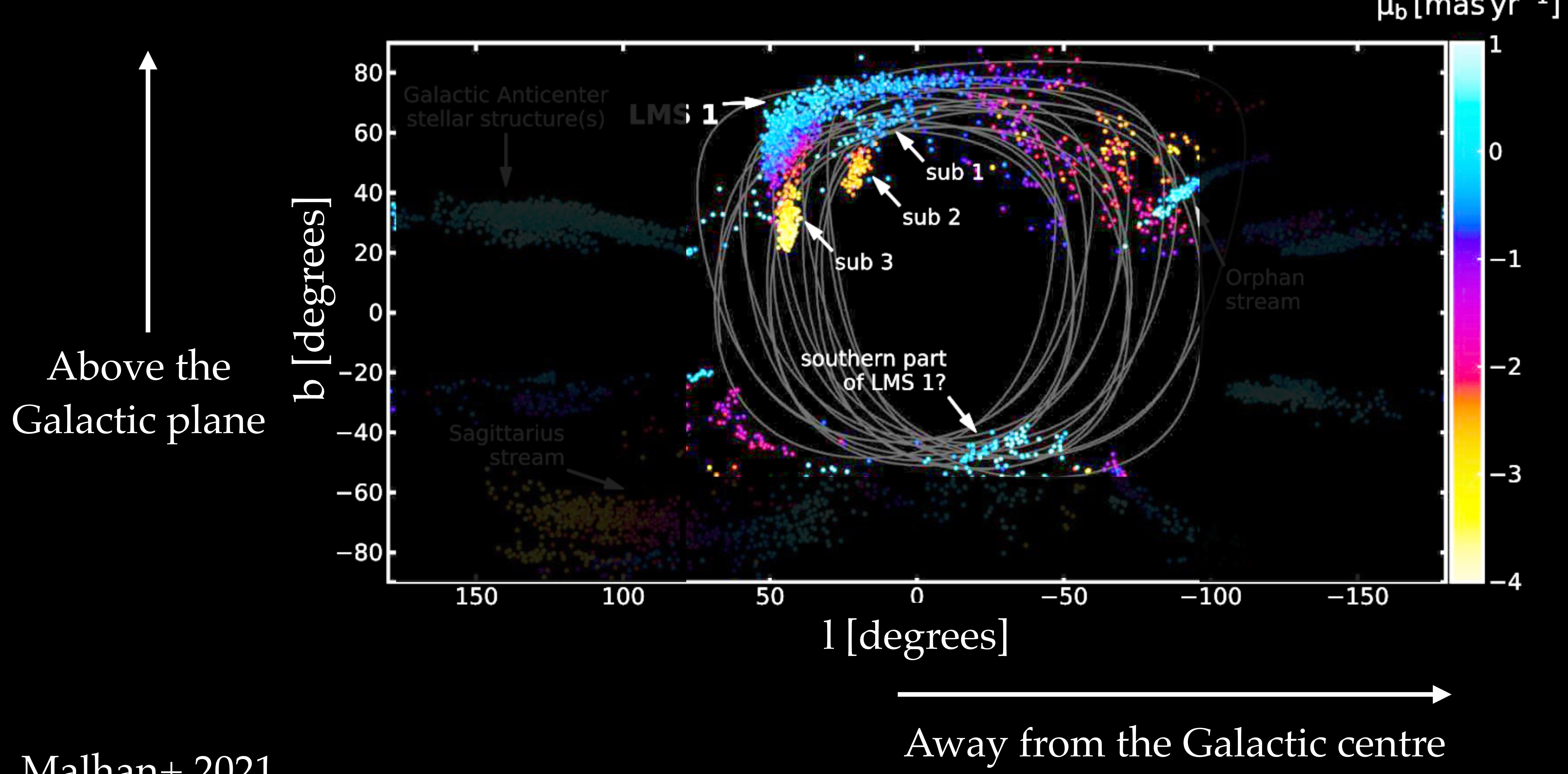

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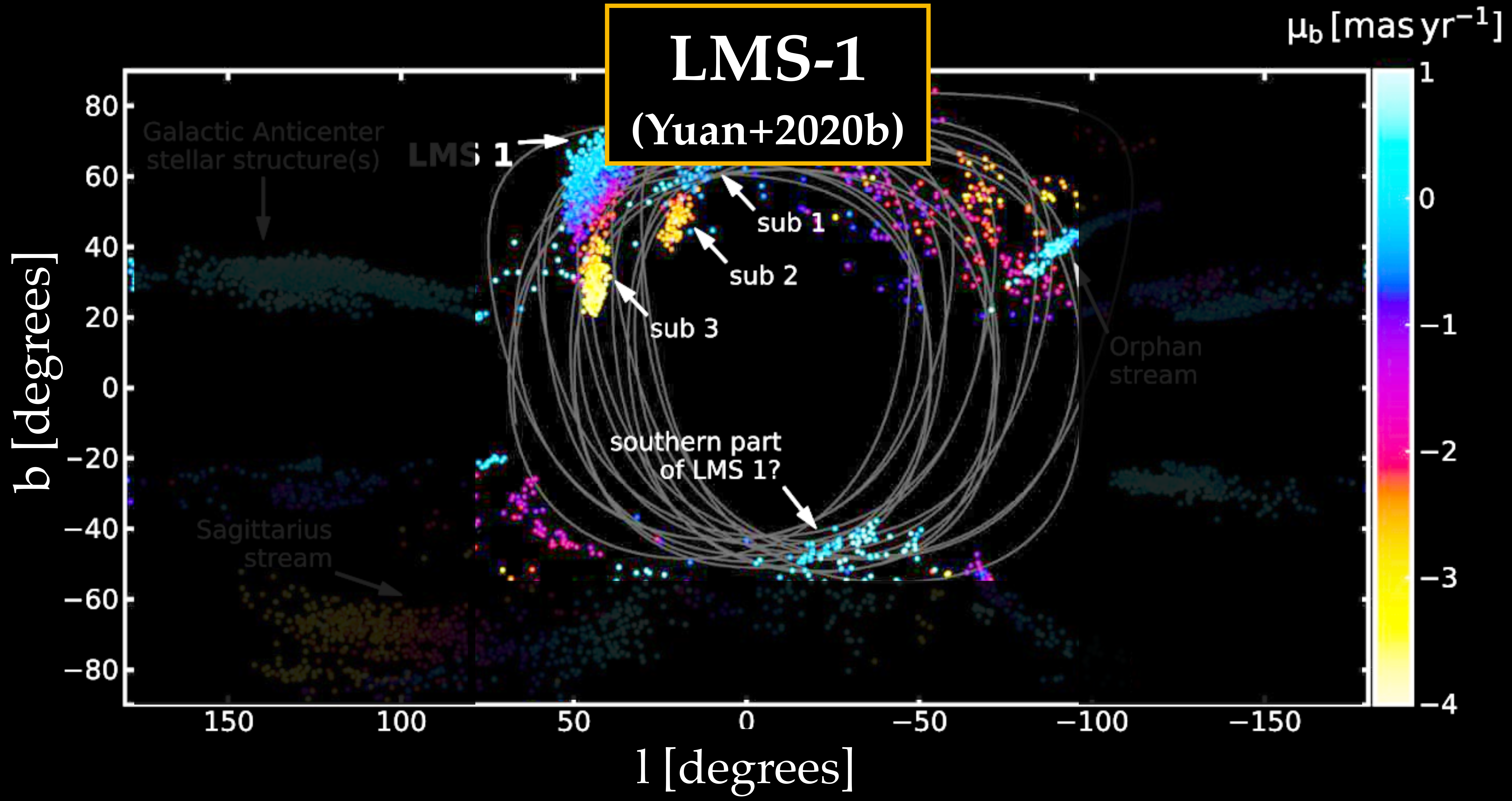

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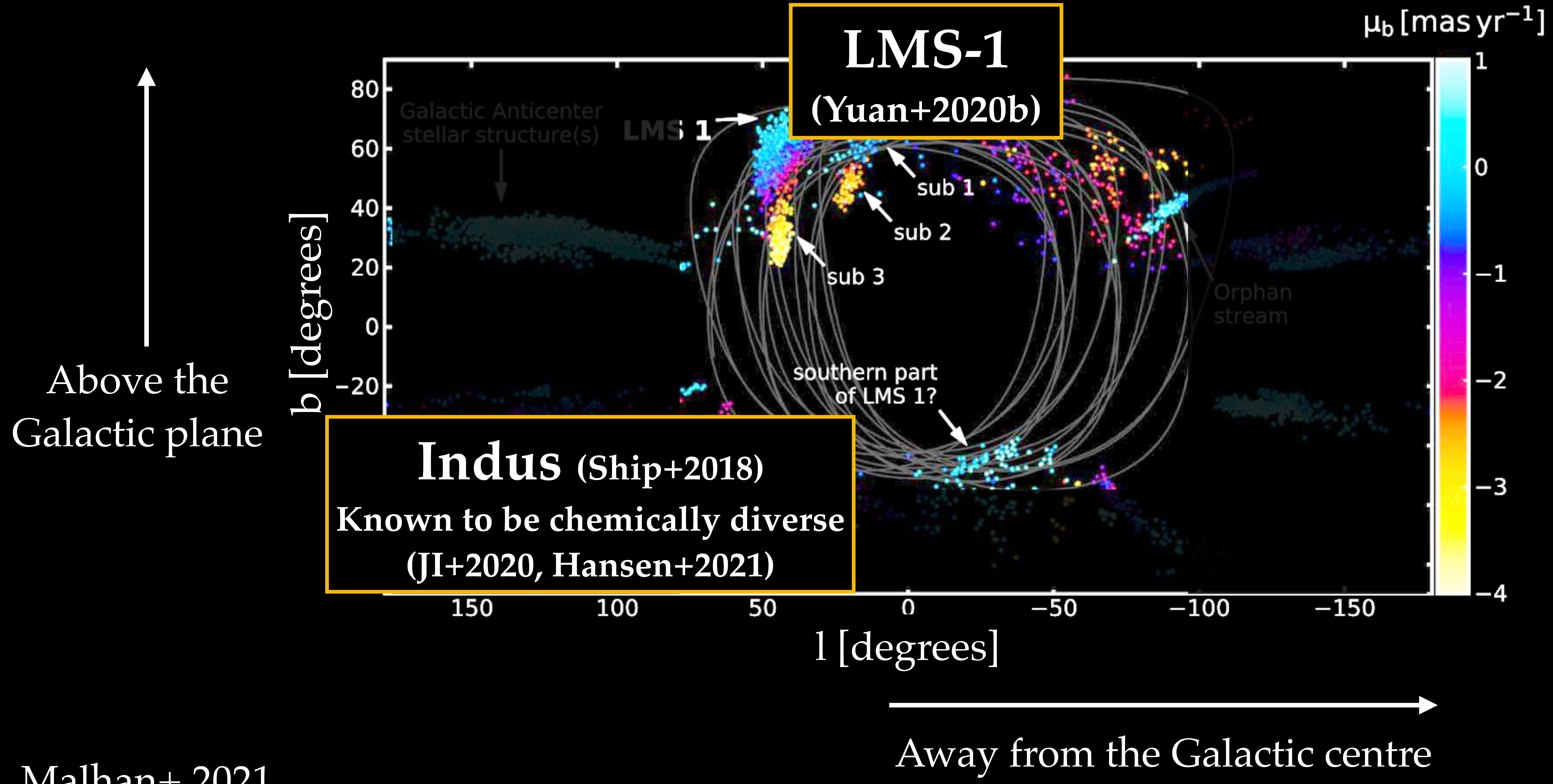

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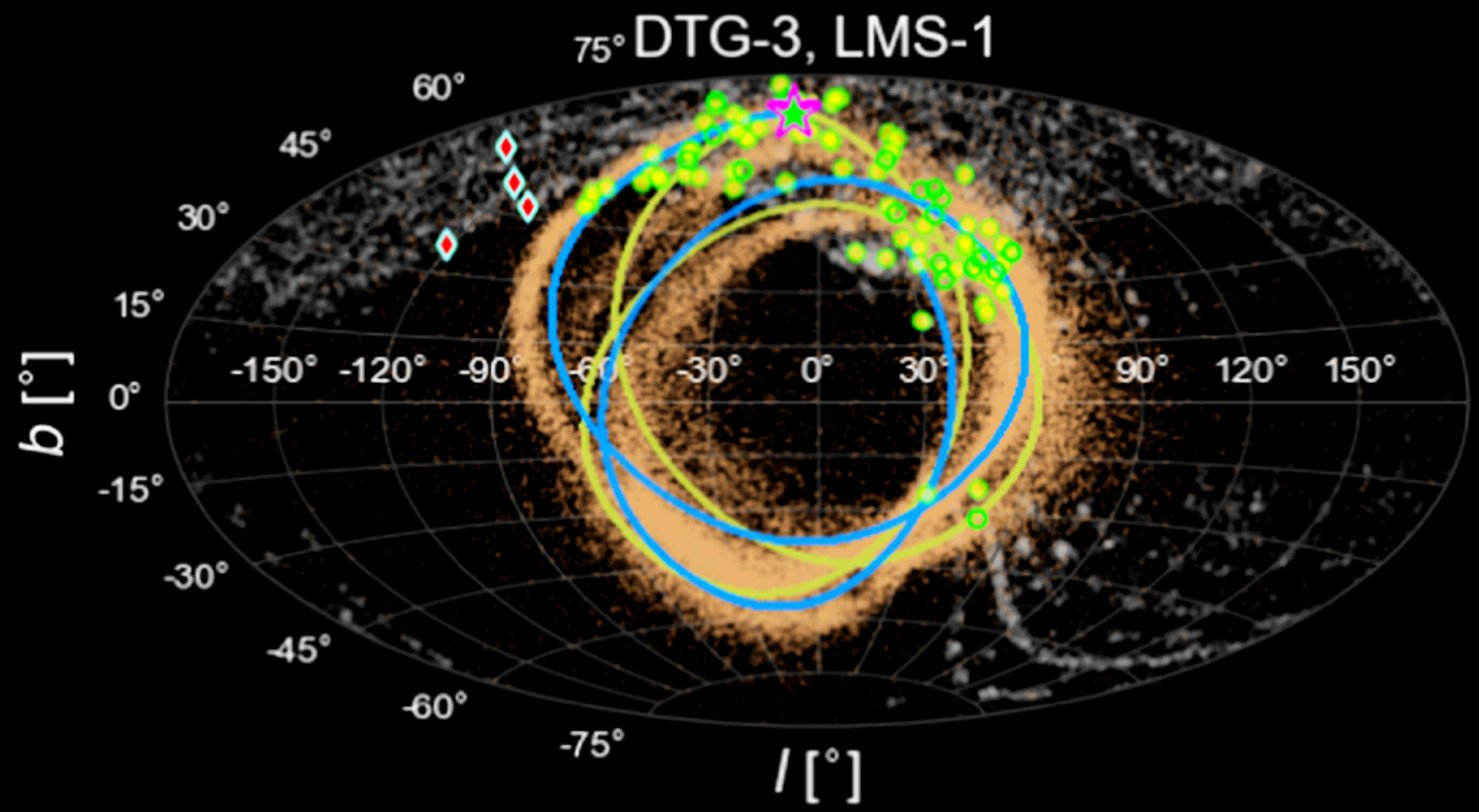
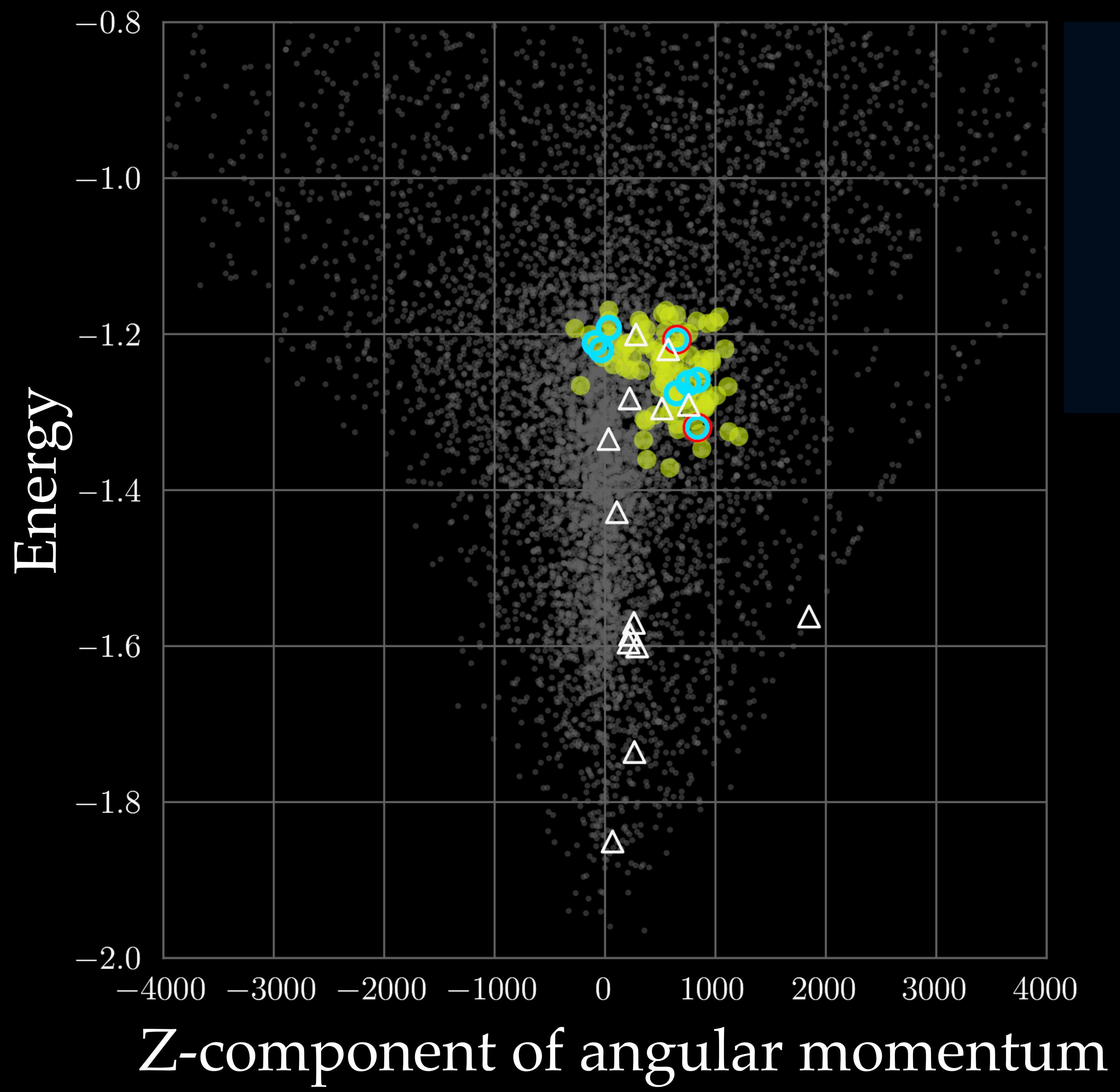
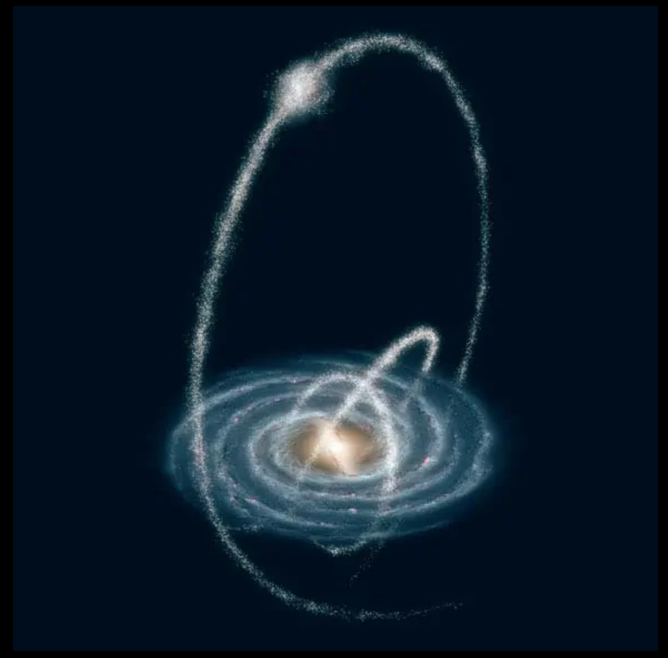
Low-mass stellar-debris stream (LMS-1) system discovery







Monty, Matsuno & Yuan in-prep

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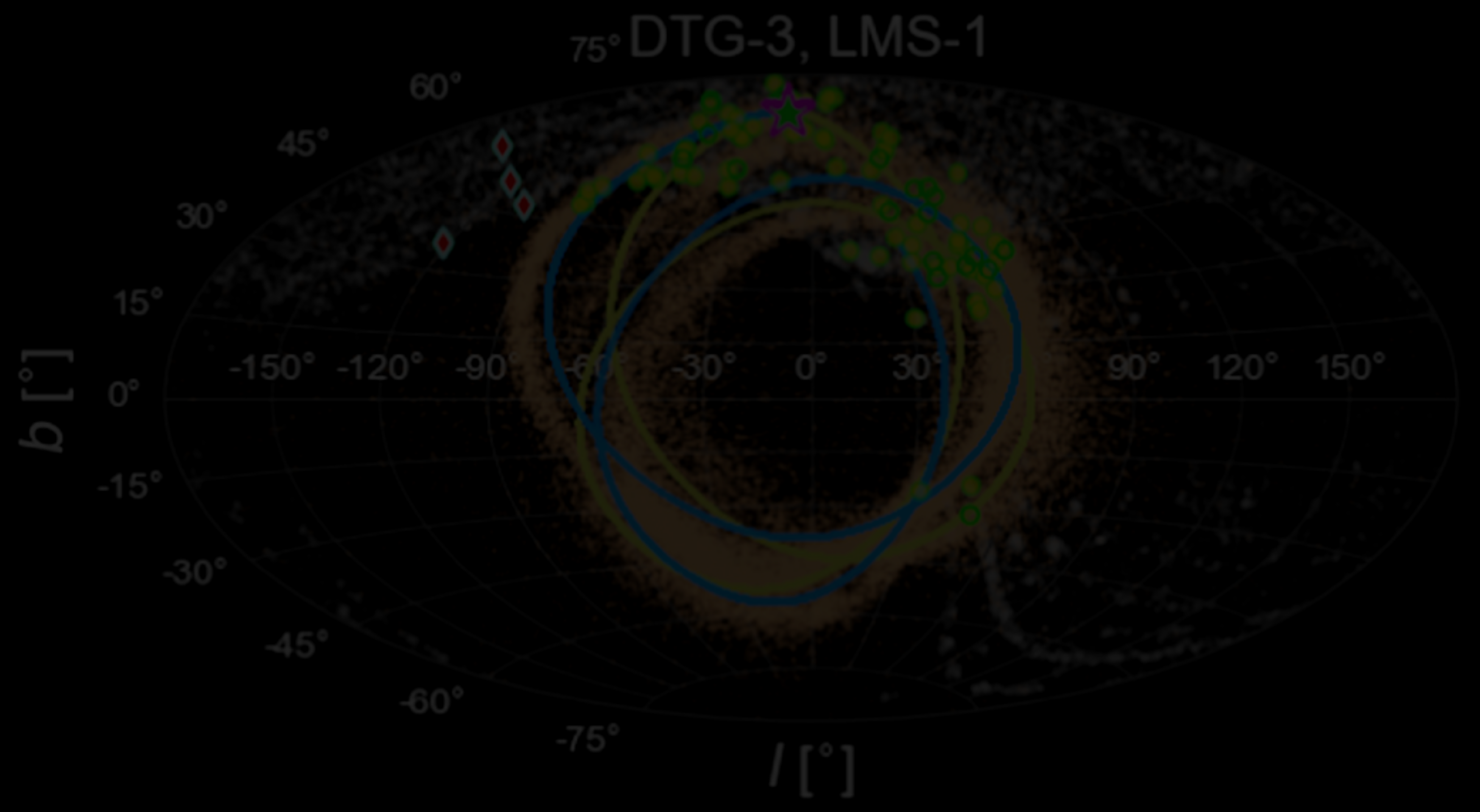

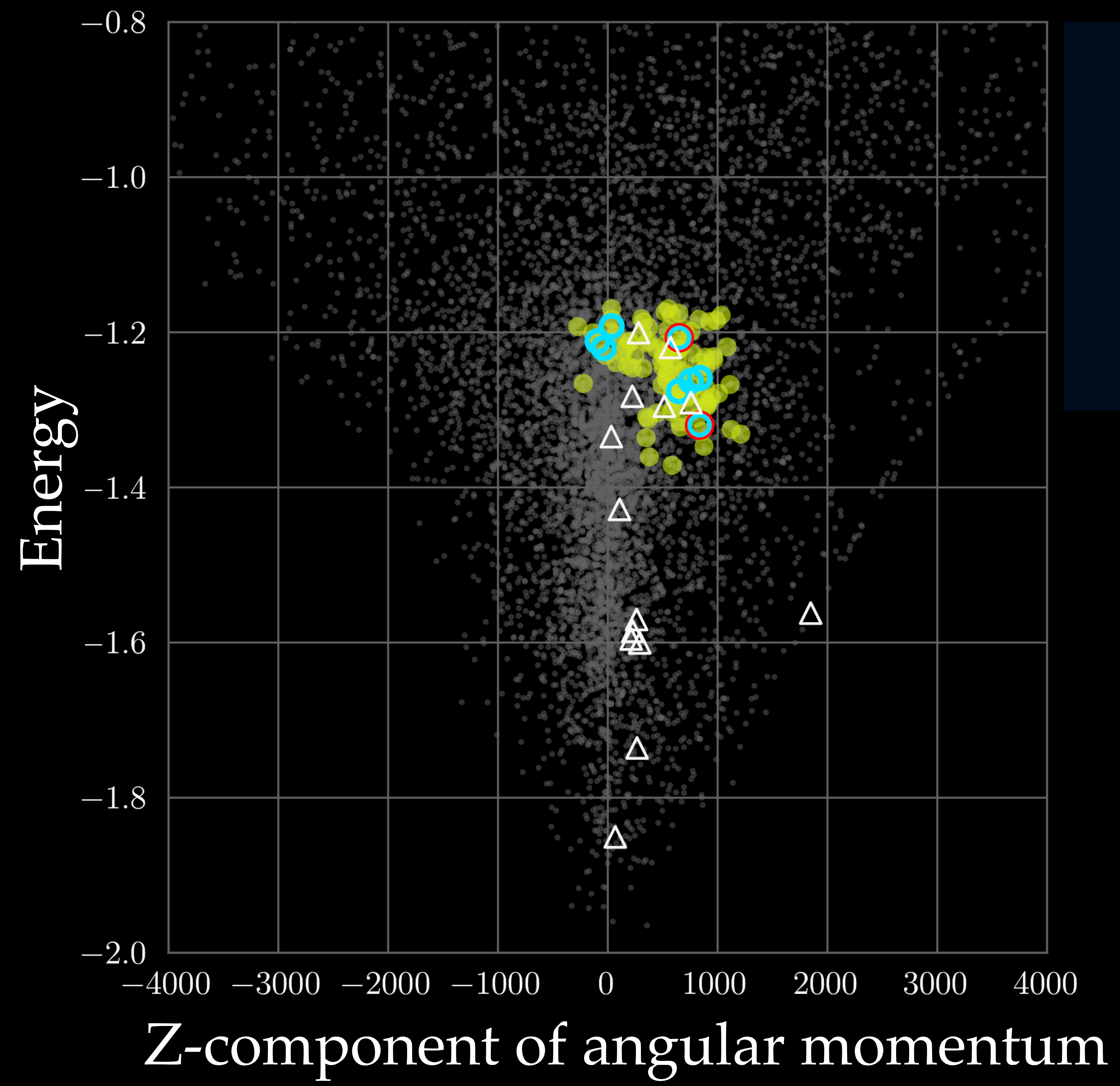

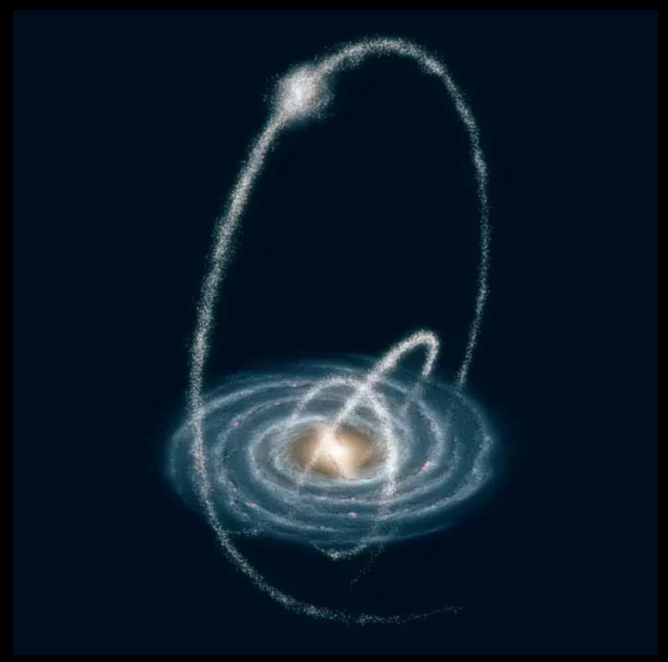

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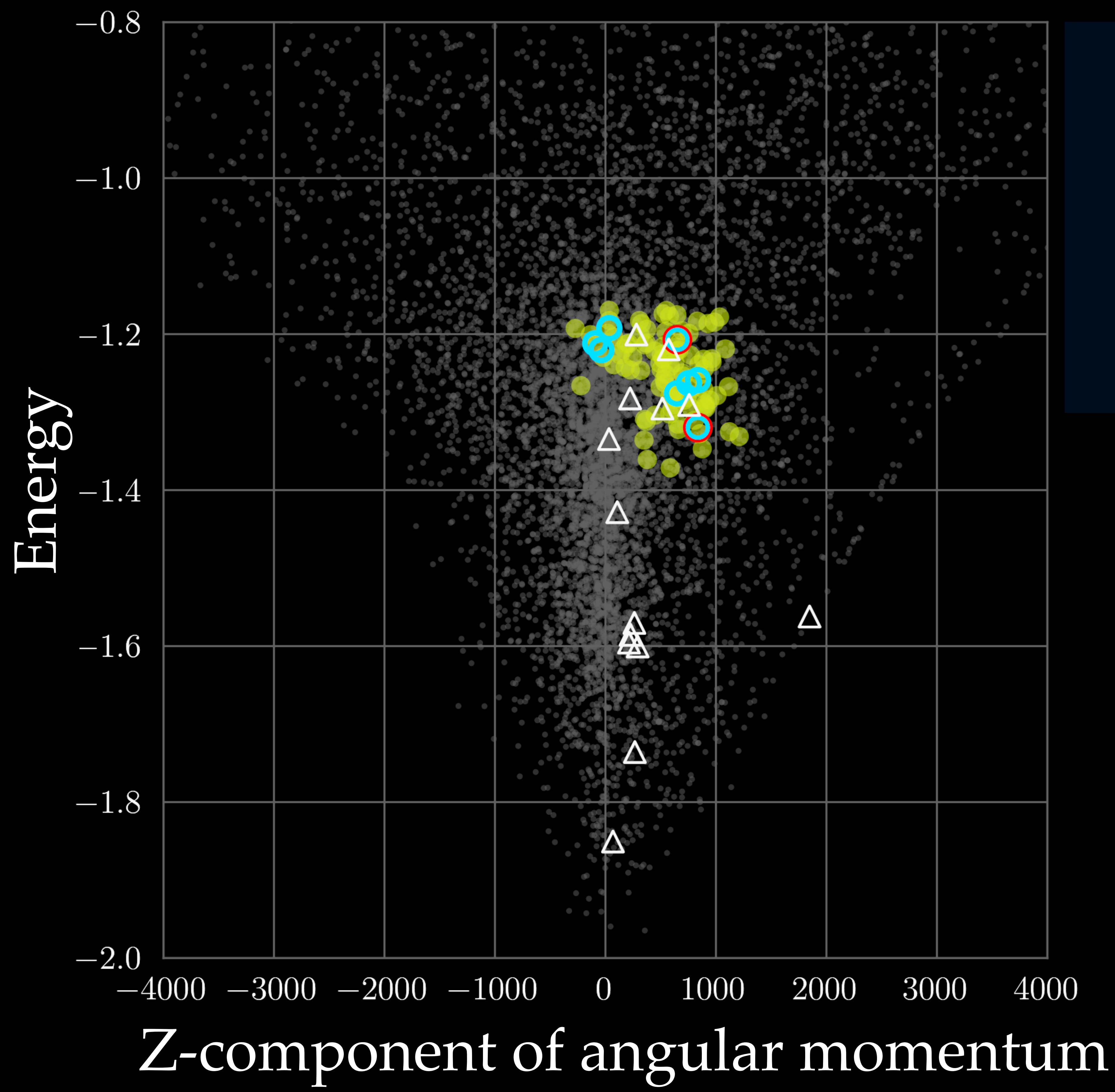

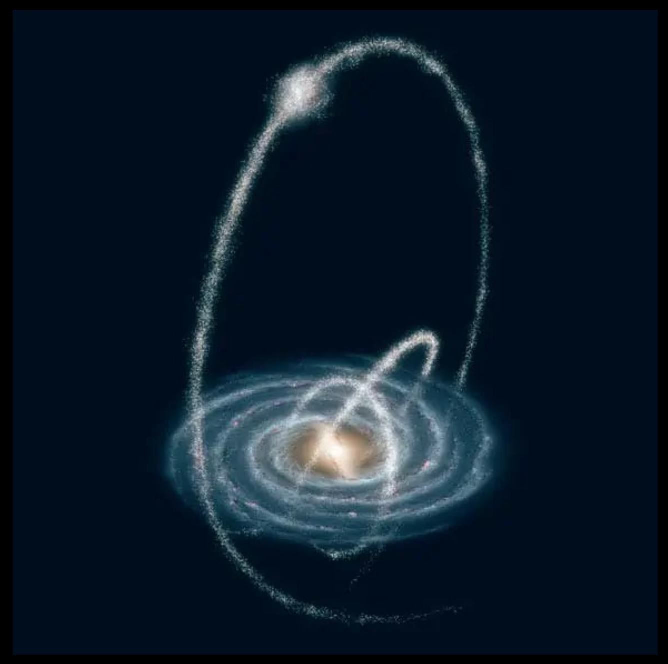

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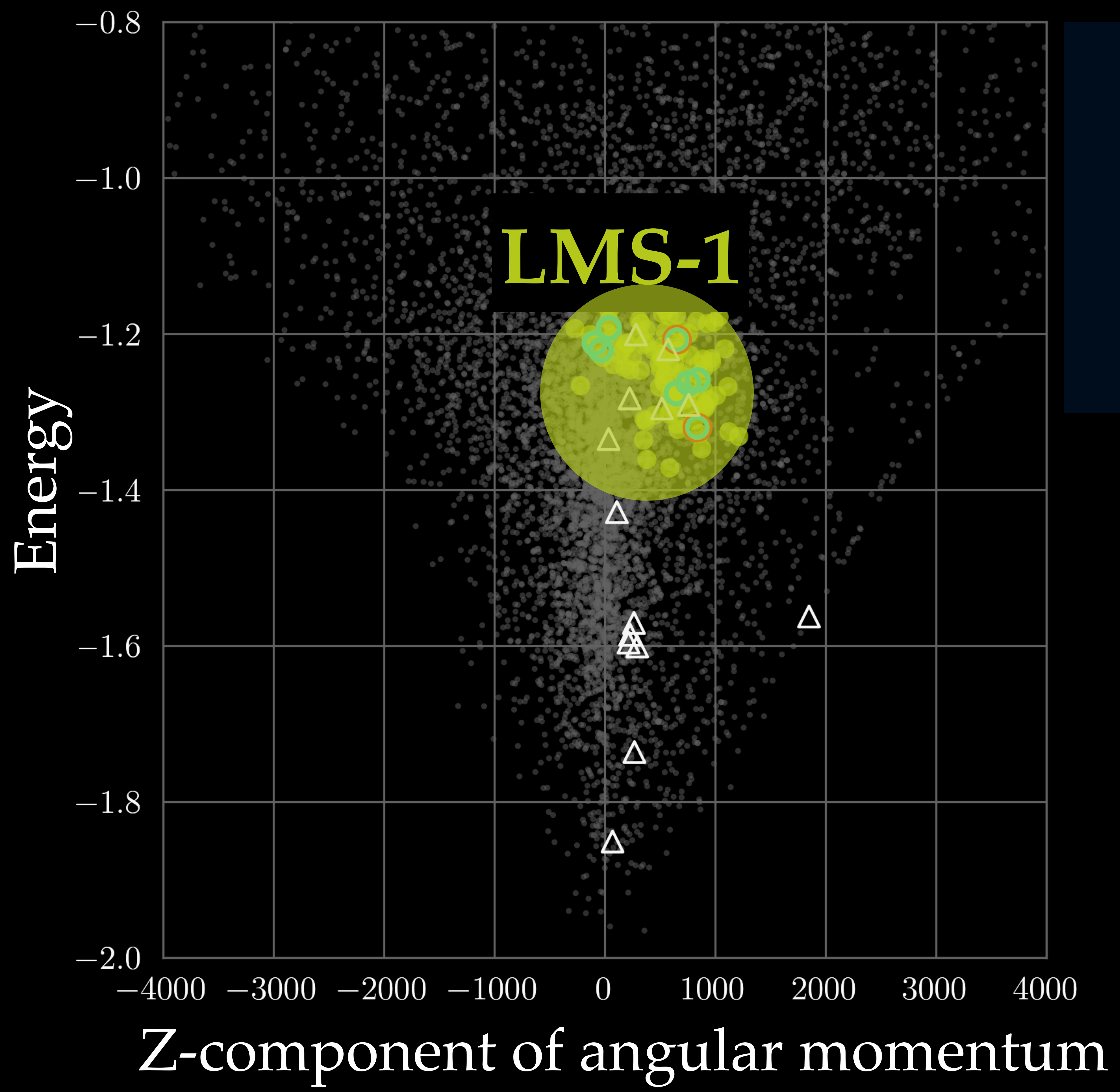

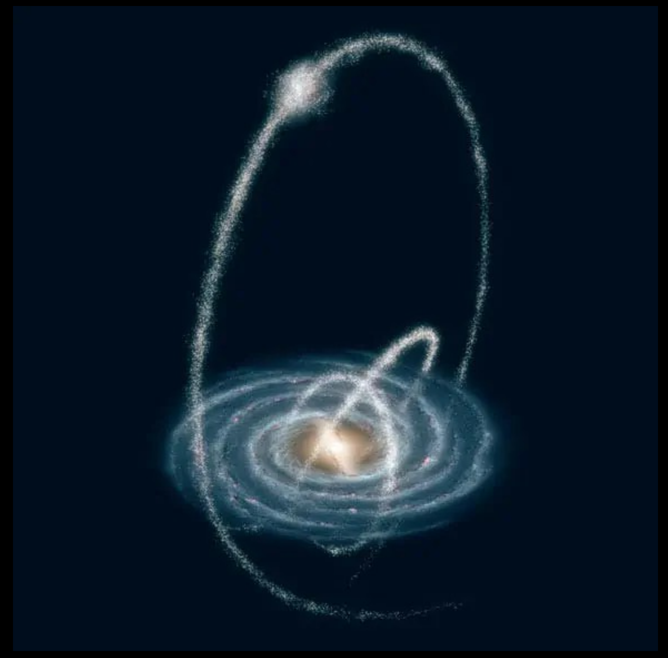

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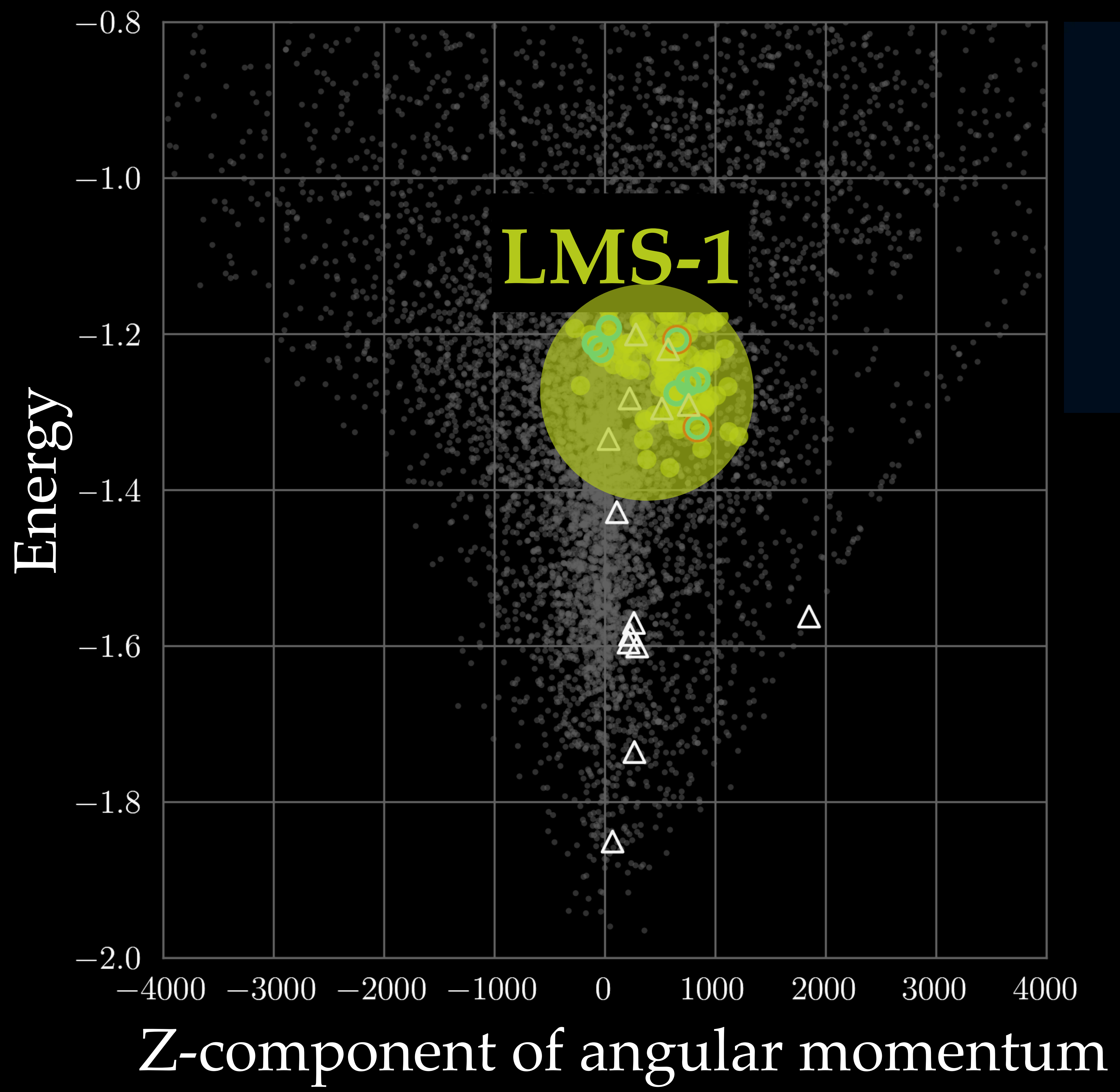

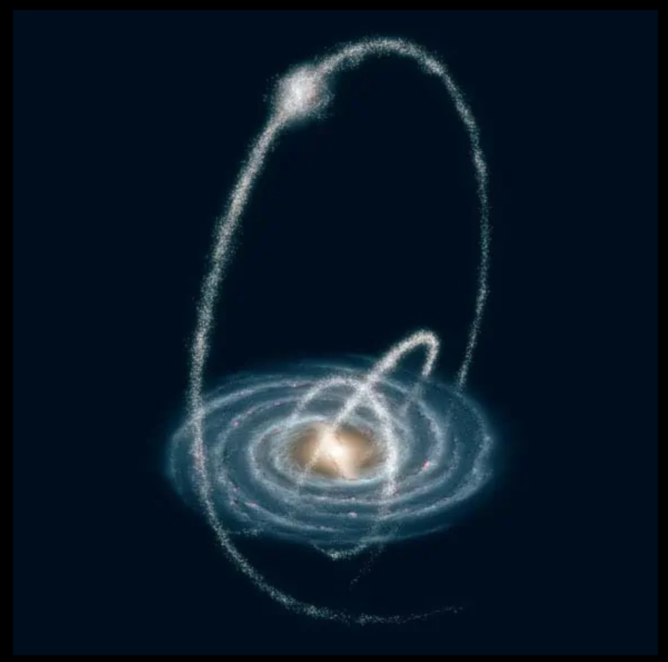

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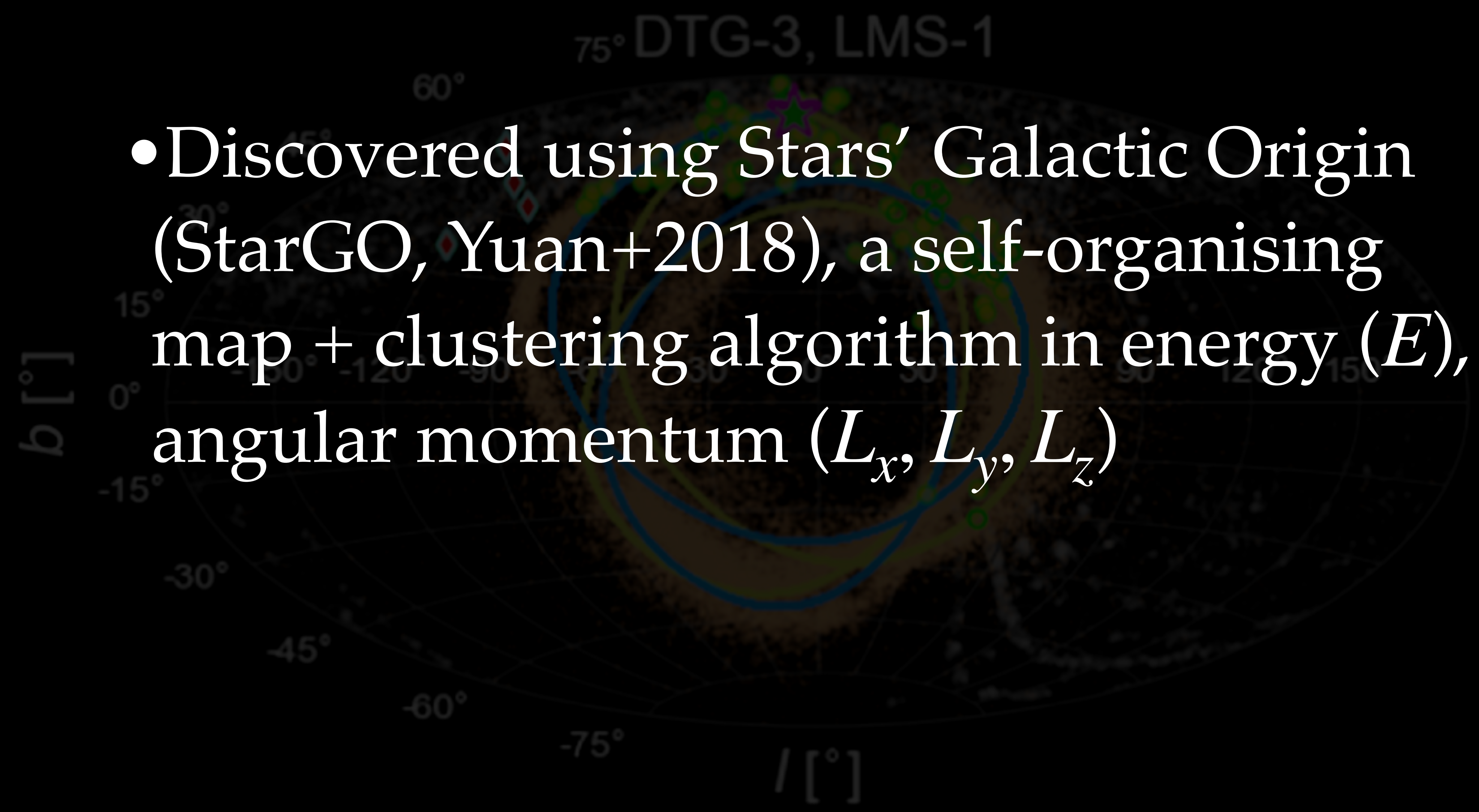

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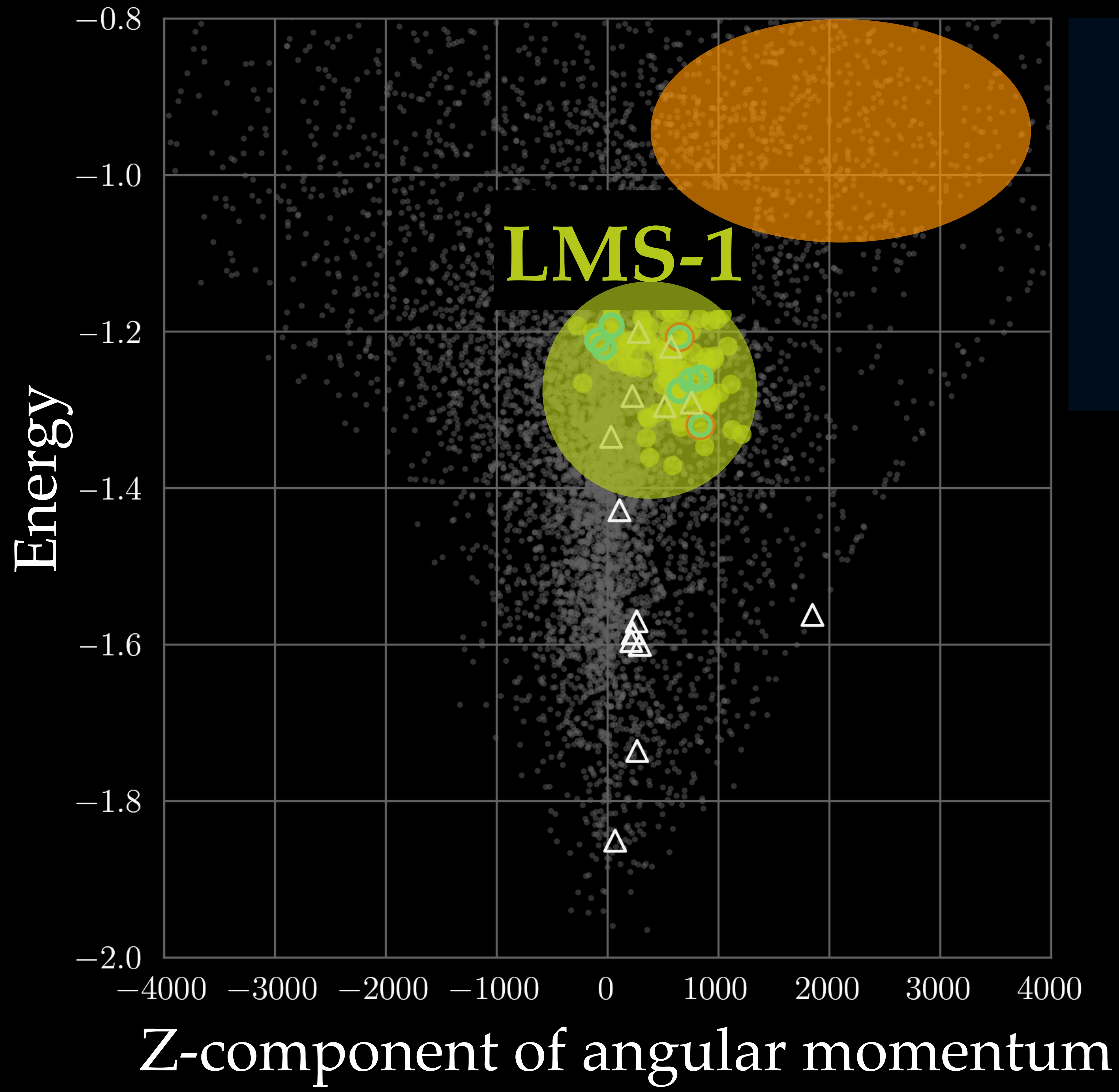
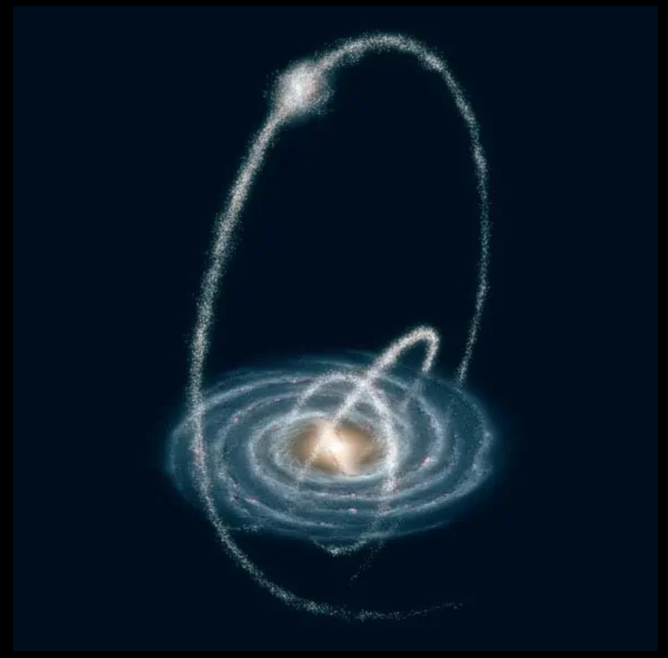
Sagittarius, ongoing

(F. Sestito, Tuesday talk)





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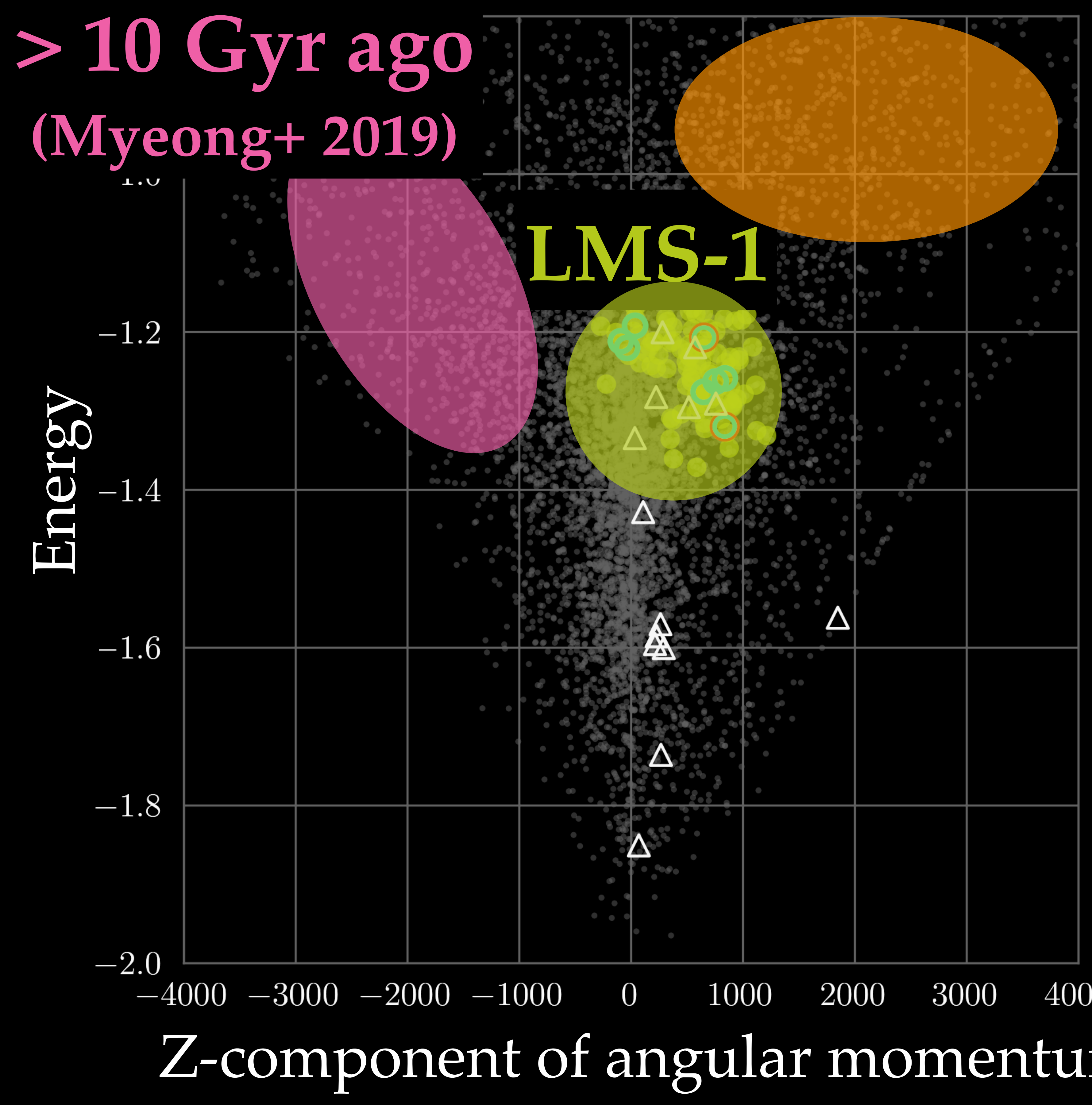

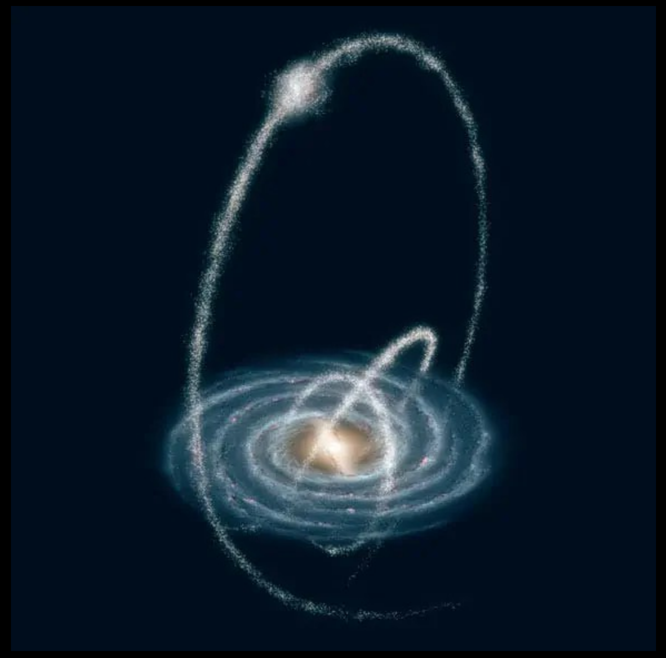

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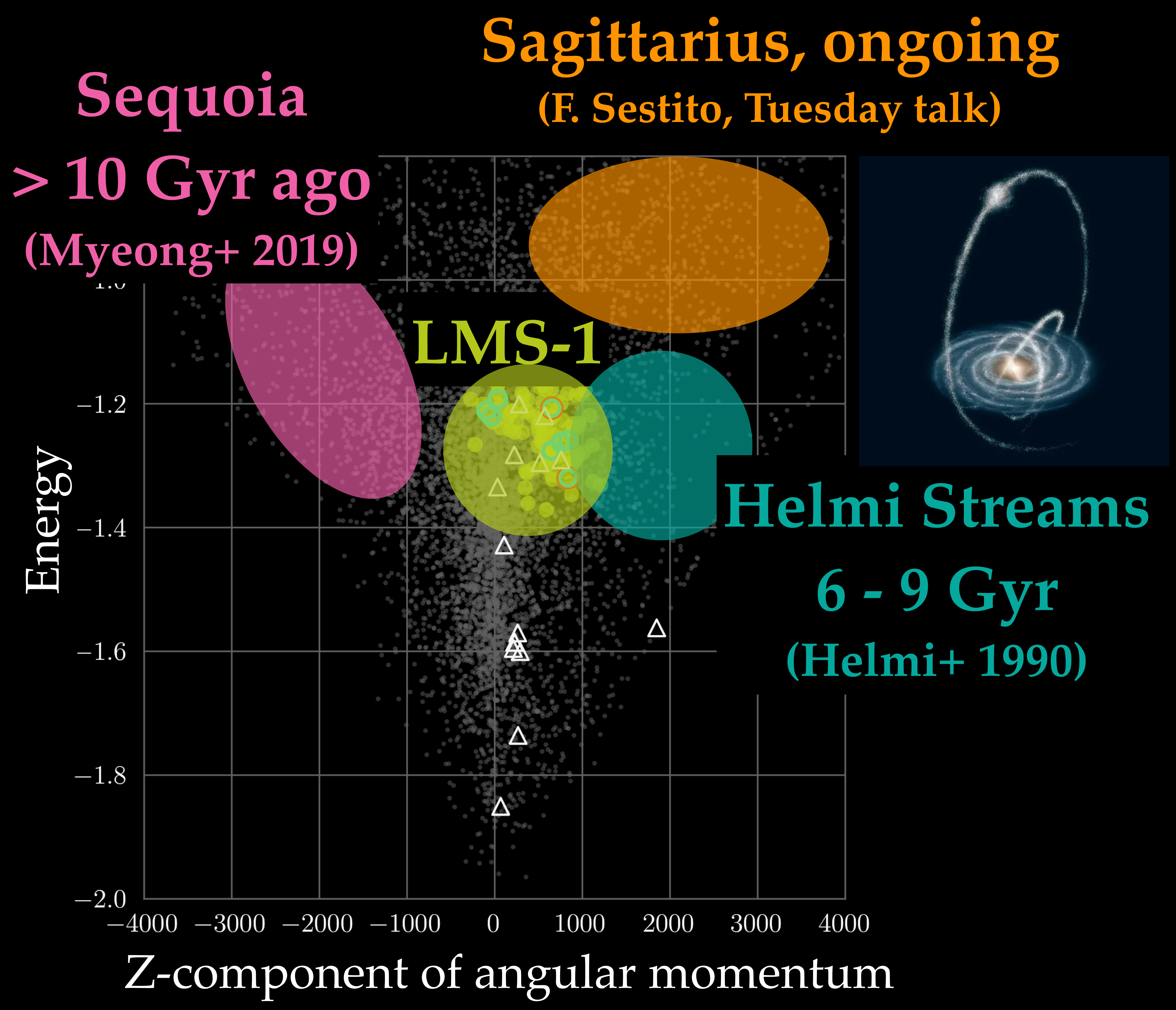

Monty, Matsuno & Yuan in-prep

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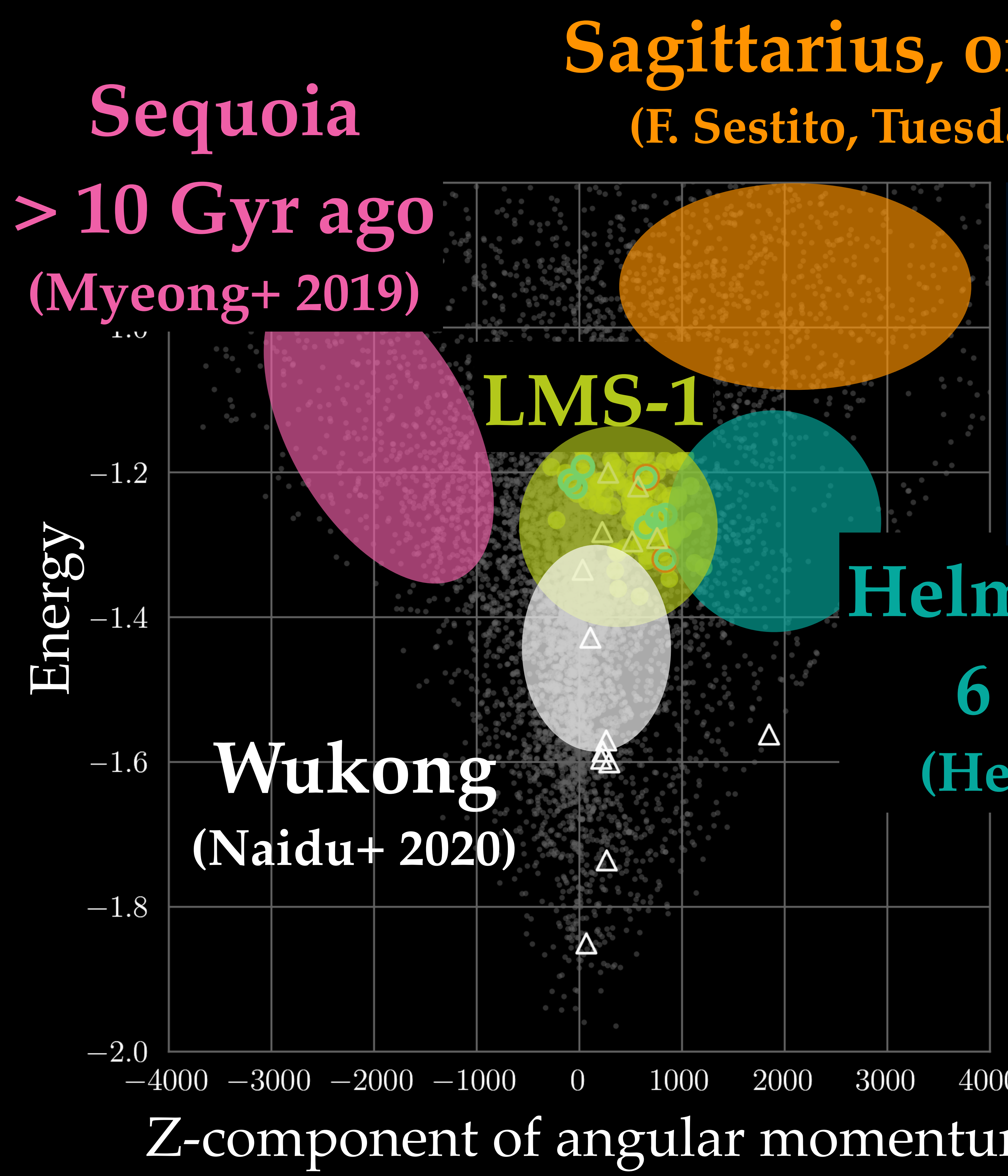
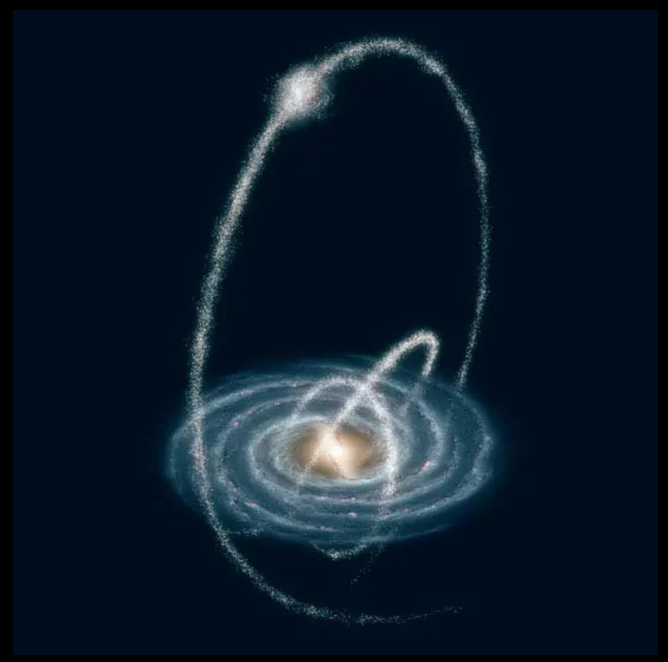
- Discovered using Stars' Galactic Origin (StarGO, Yuan+2018), a self-organising map + clustering algorithm in energy (E), angular momentum (L_x, L_y, L_z)





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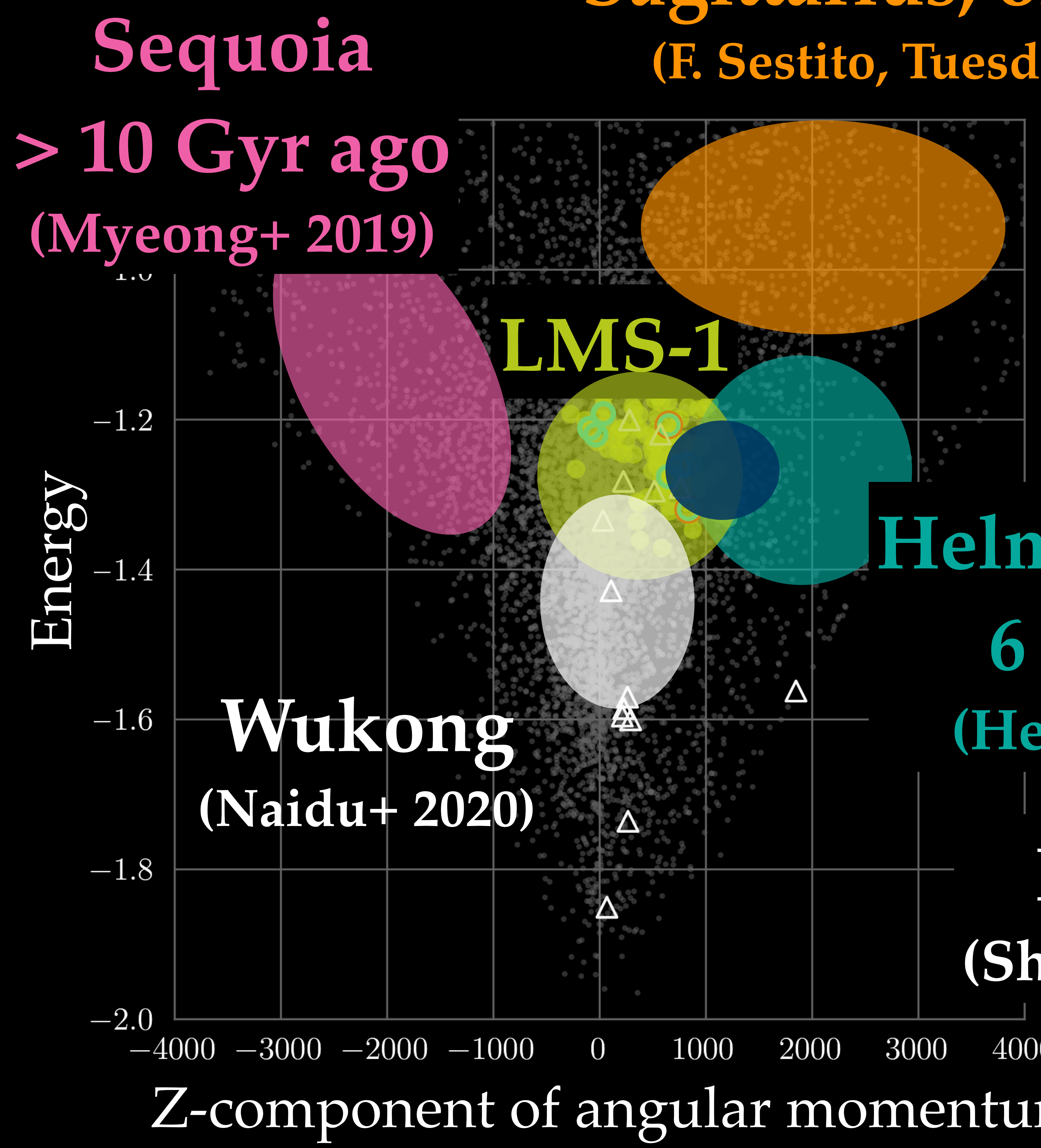
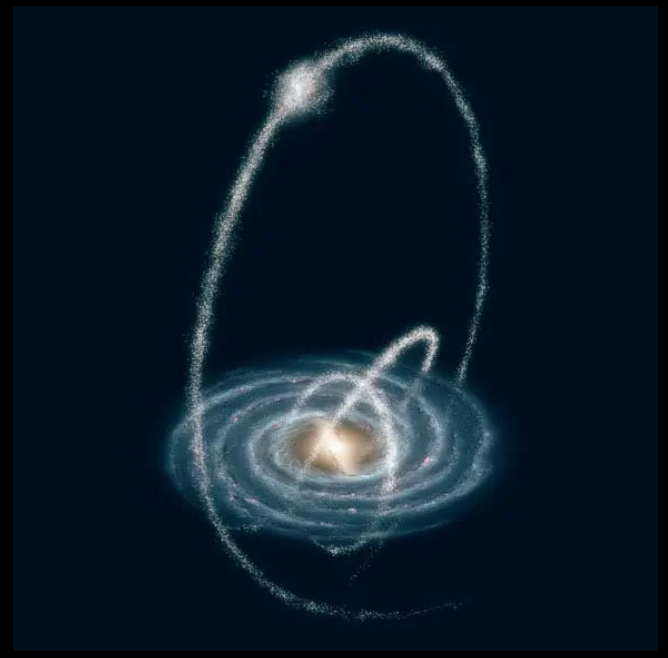
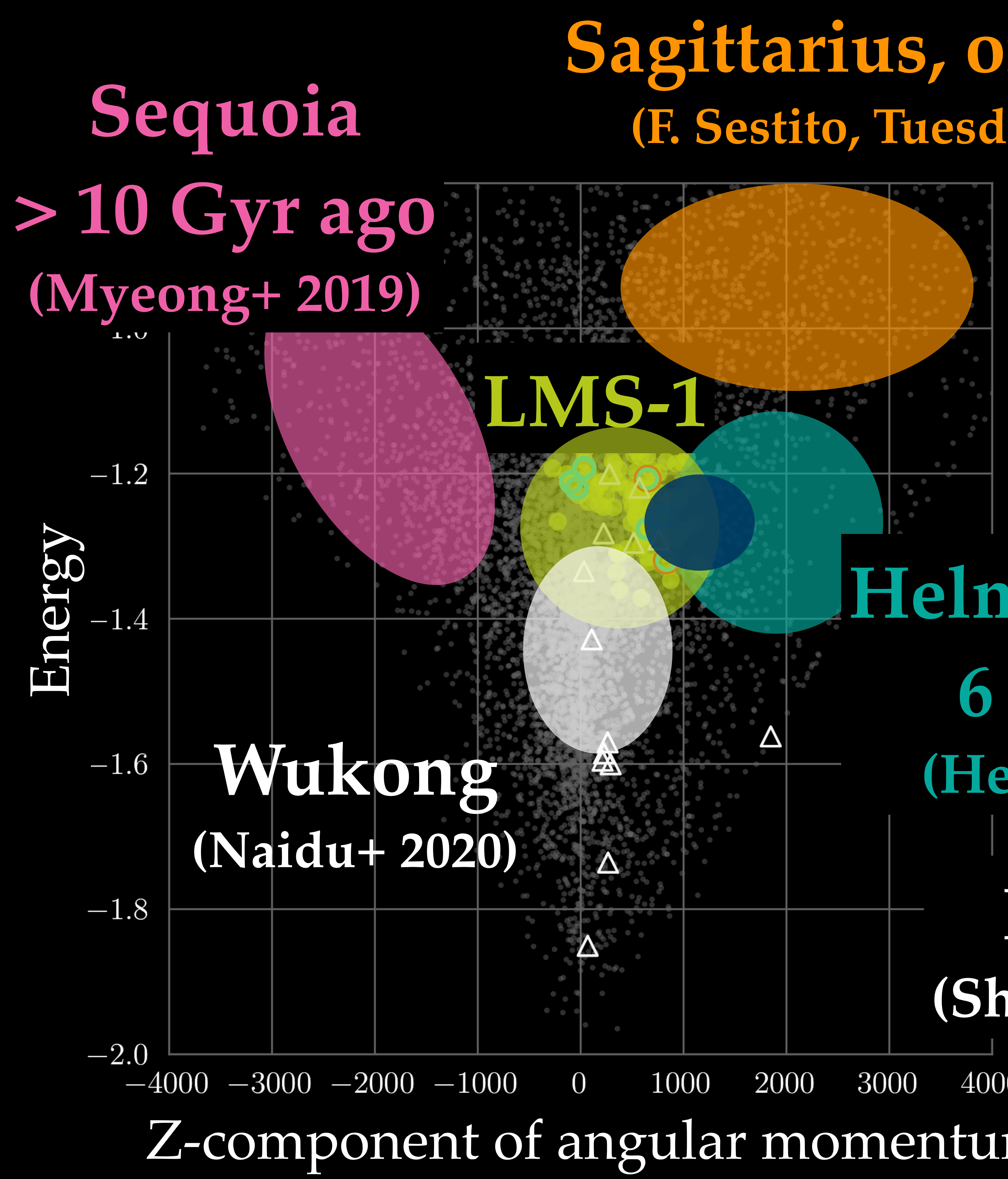


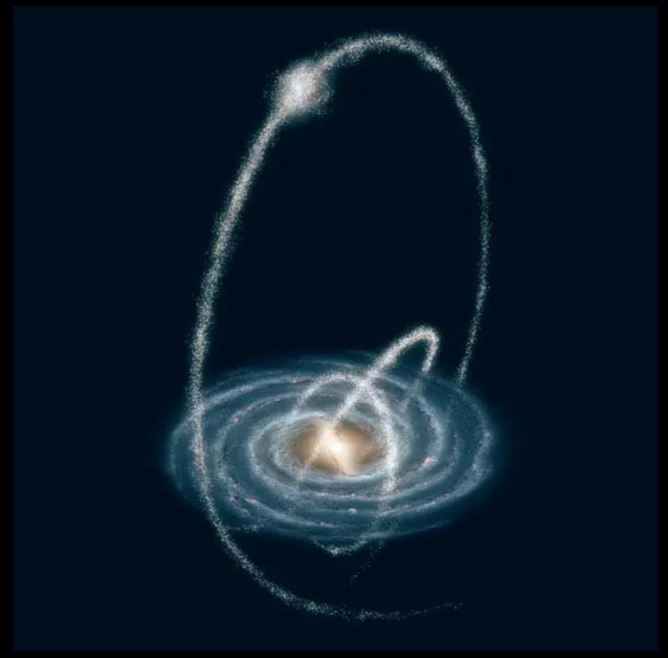


Monty, Matsuno & Yuan in-prep

Low-mass stellar-debris stream (LMS-1) system discovery

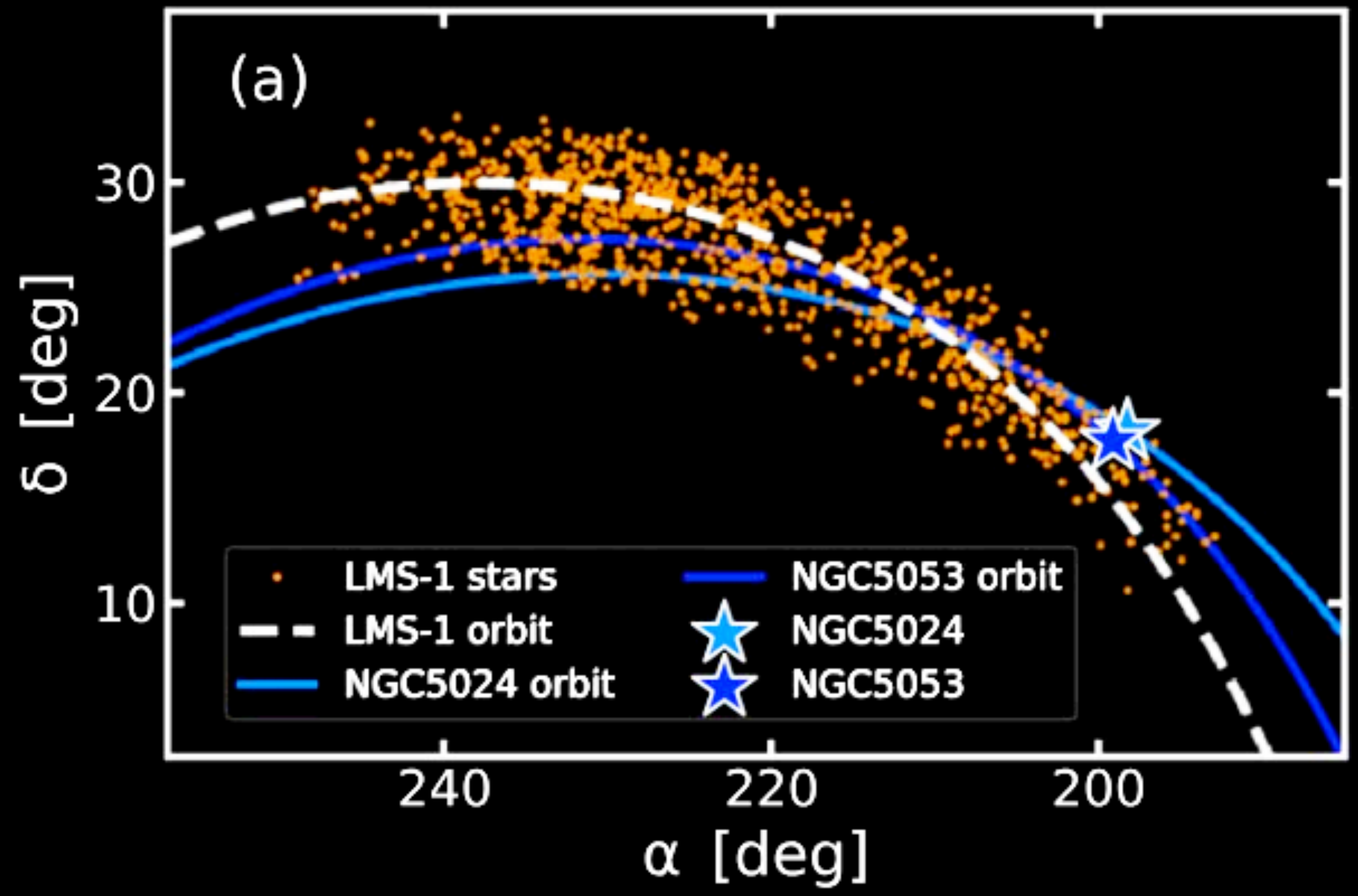
- Discovered using Stars' Galactic Origin (StarGO, Yuan+2018), a self-organising map + clustering algorithm in energy (E), angular momentum (L_x, L_y, L_z)
- LMS-1 overlaps with the Helmi Streams and Wukong in E, L_z -> **Are they all part of the same accreted dwarf galaxy?**





Monty, Matsuno & Yuan in-prep

LMS-1 is the only low-mass stream with companion globular clusters



Malhan+2021

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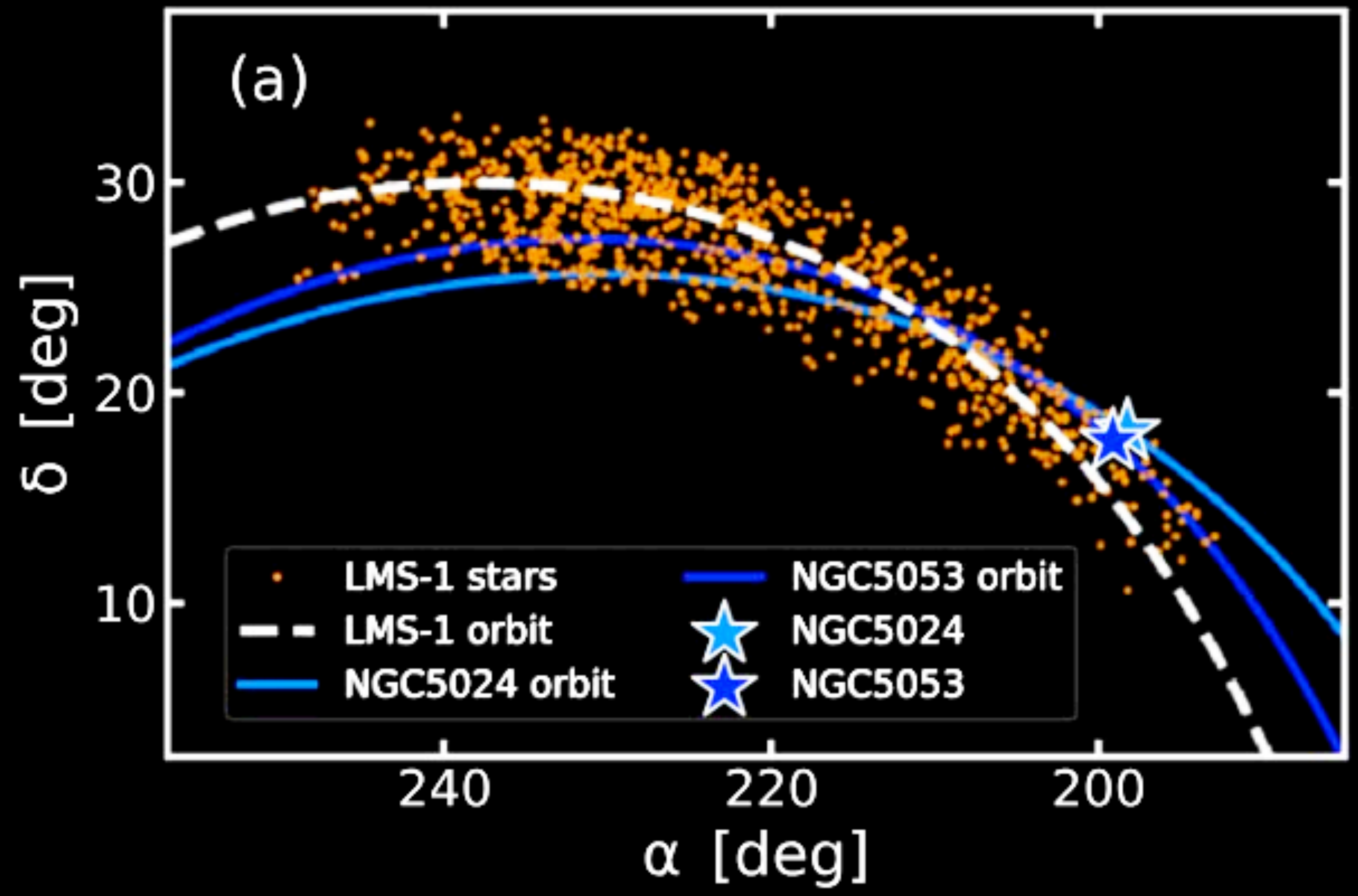

Malhan+2021

AnaTa Starfront Observatories

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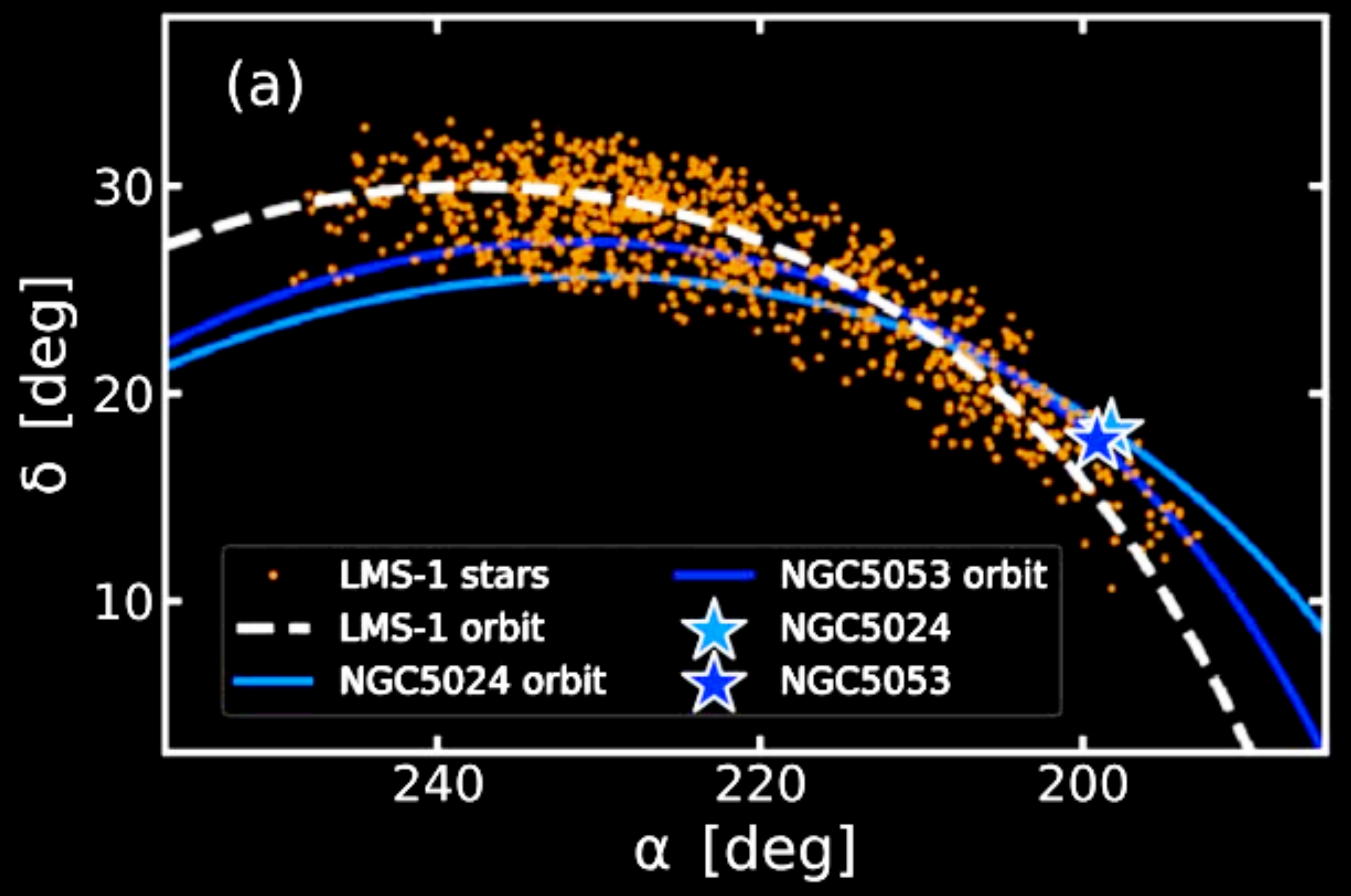

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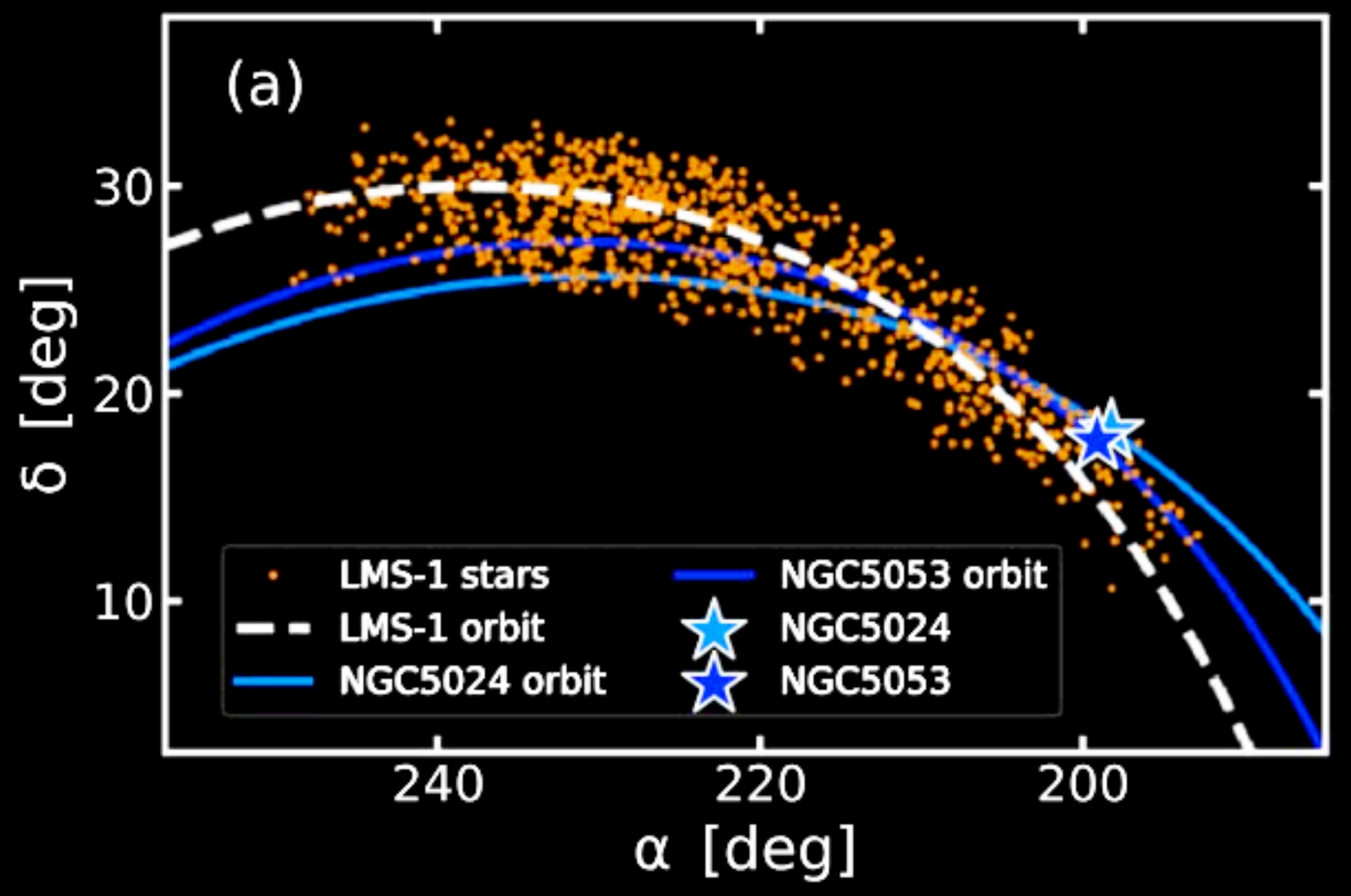

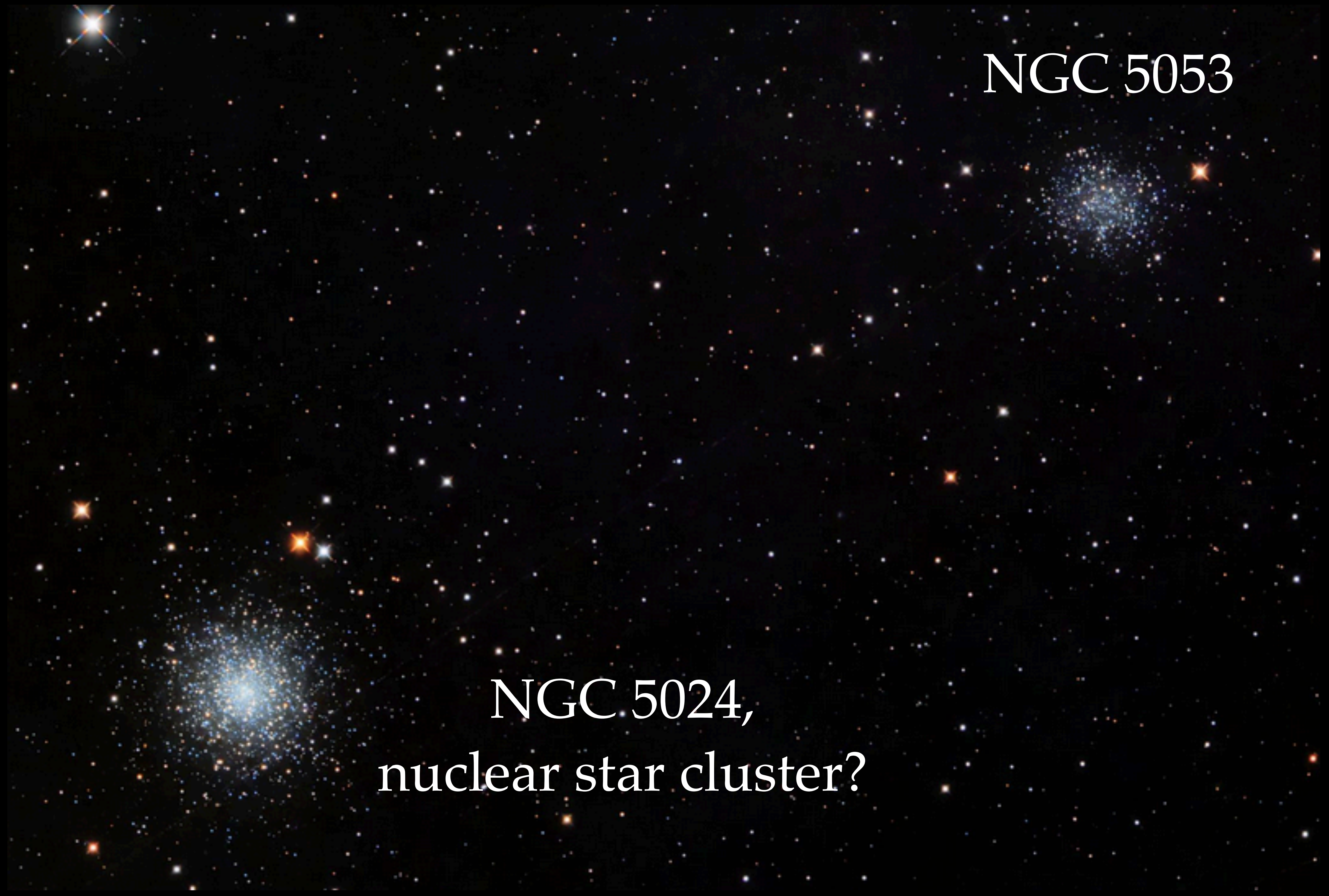

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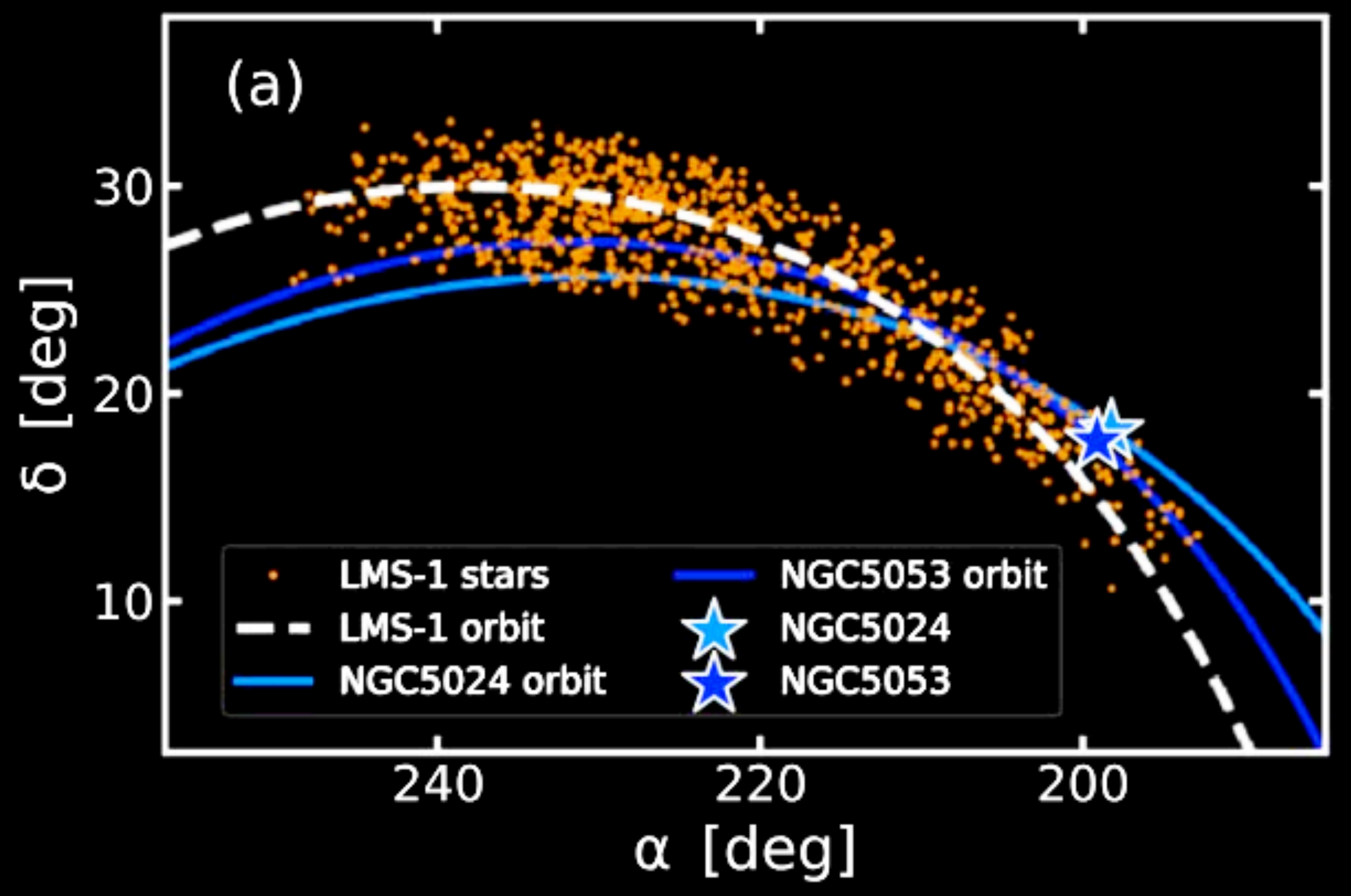

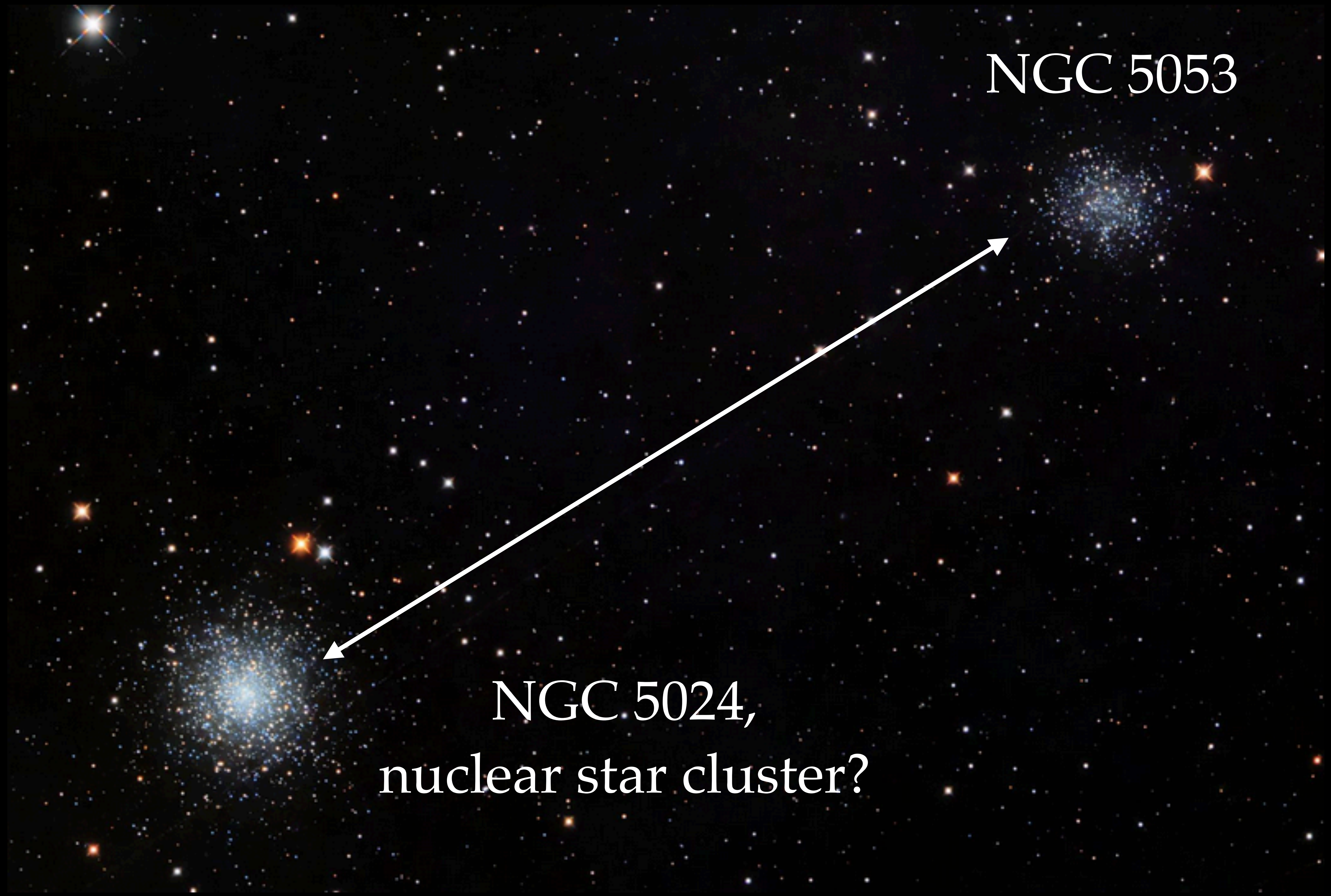

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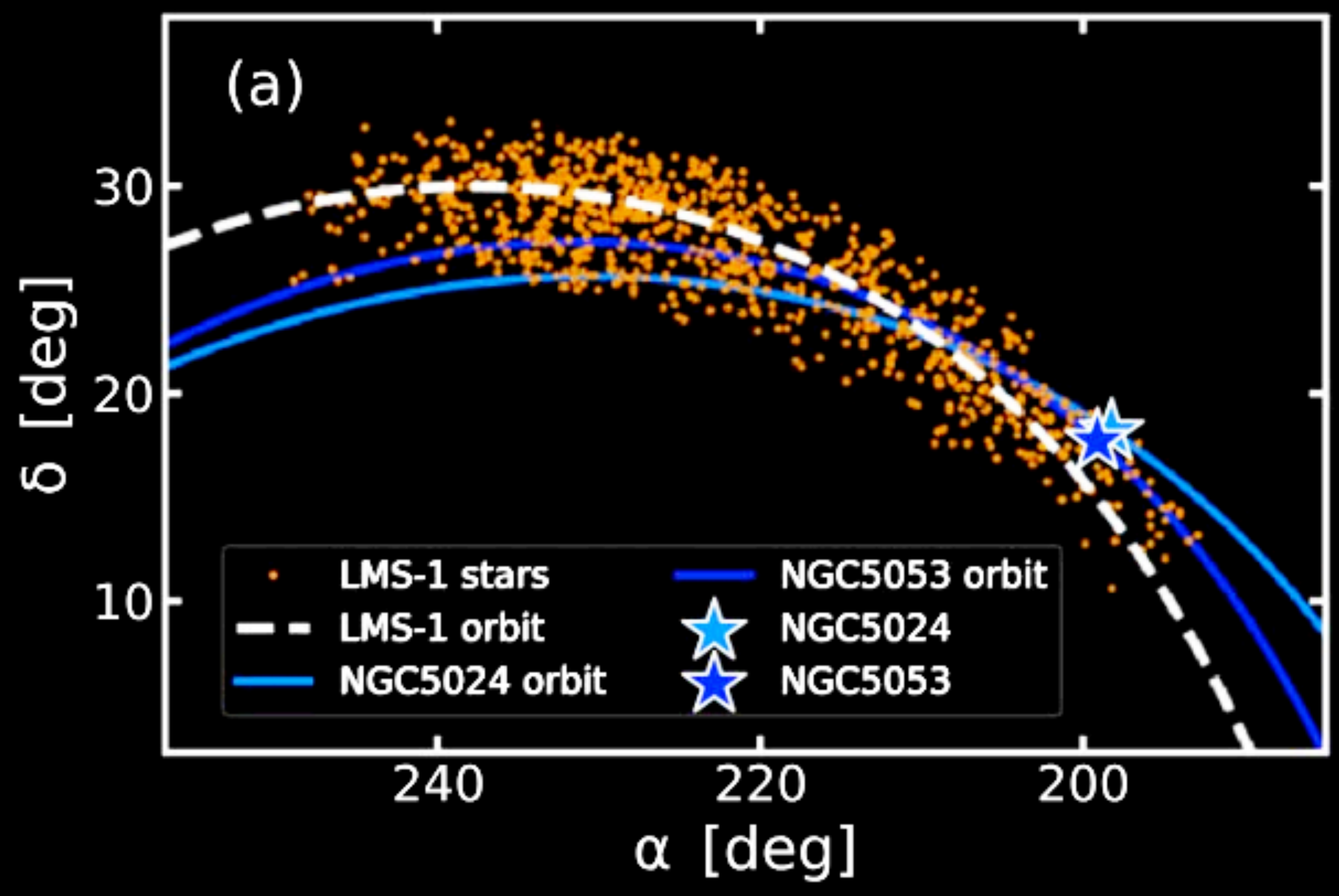
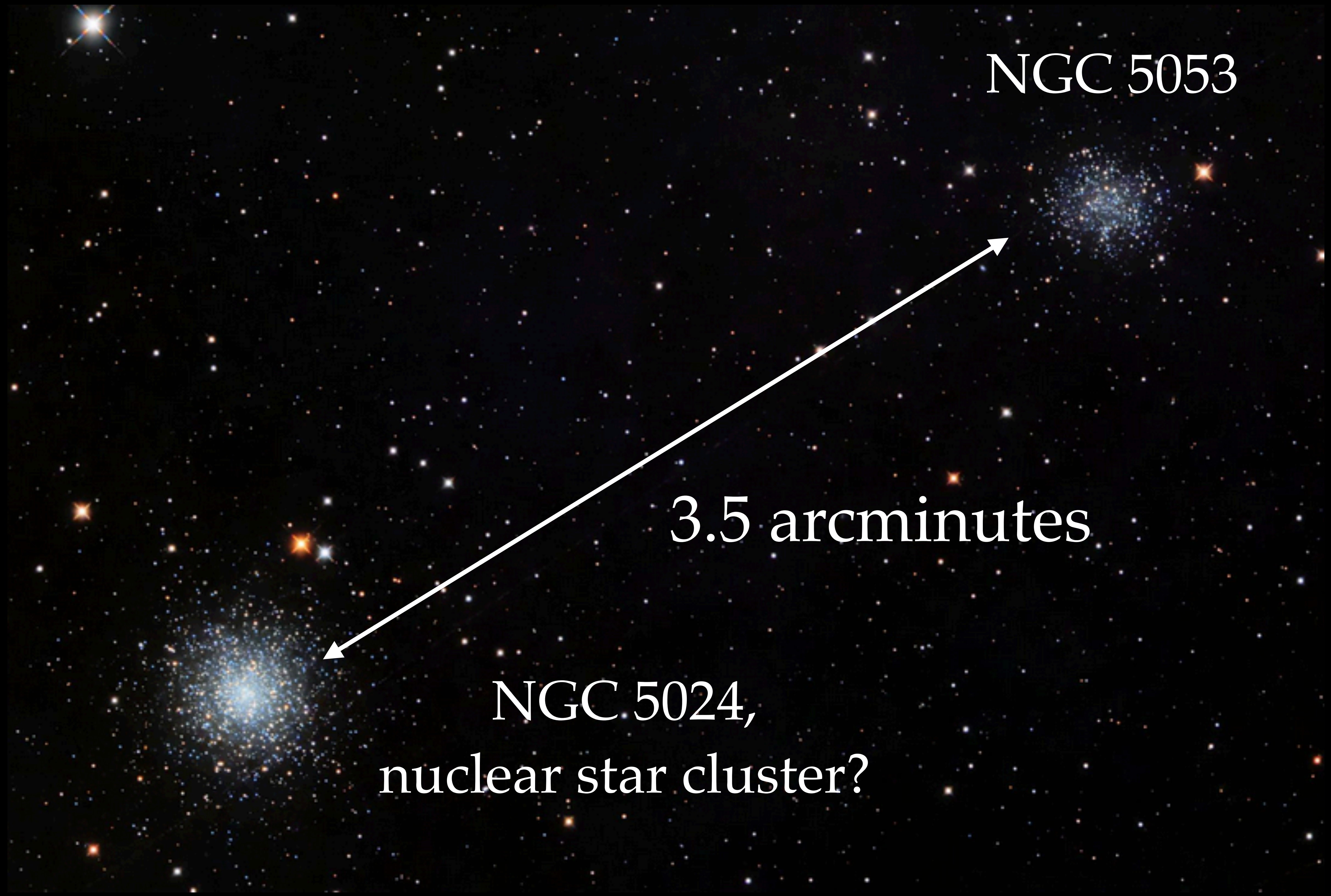


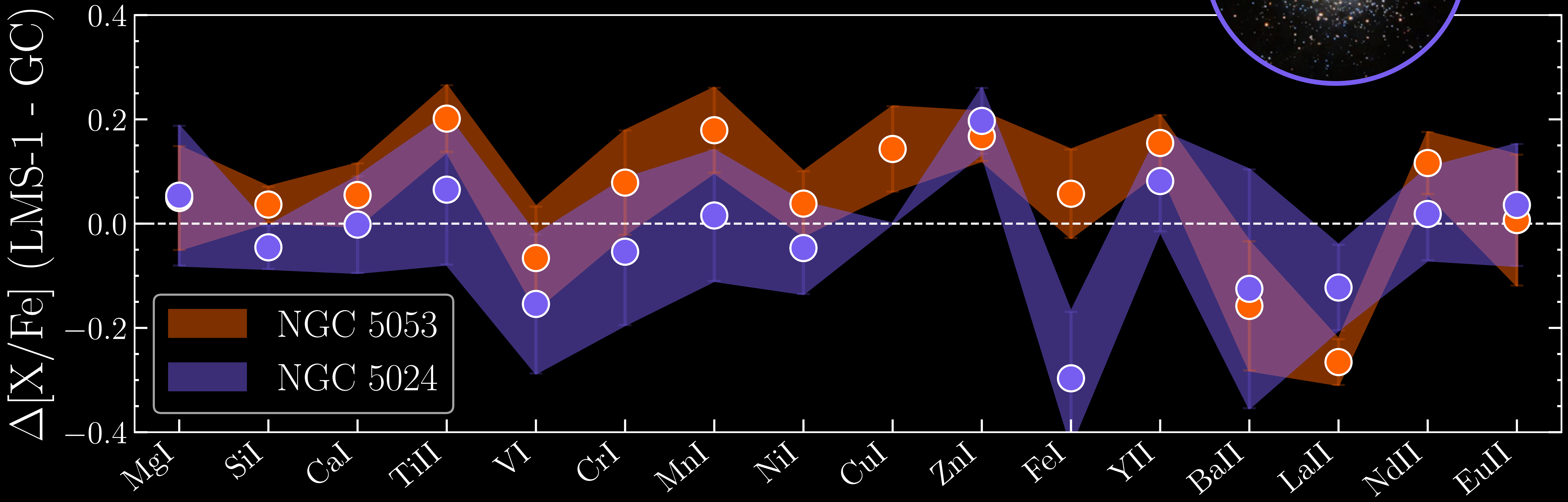


Malhan+2021

AnaTa Starfront Observatories

How similar are the clusters to the stream?

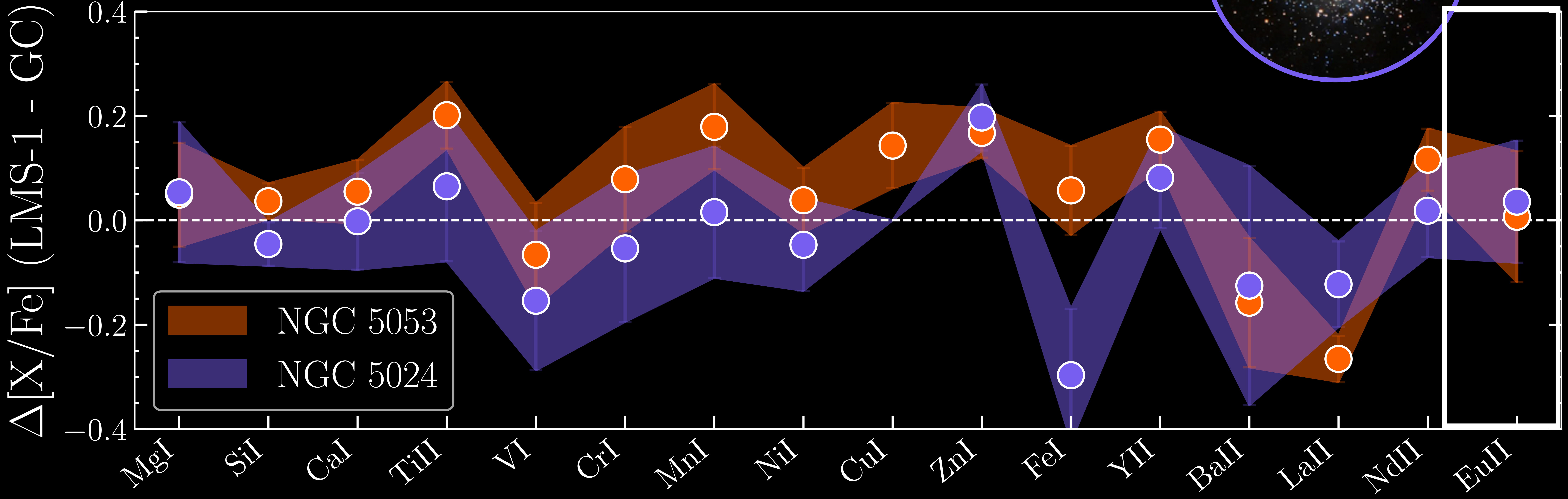
Difference between LMS-1 and the two GCs, considering first generation stars only

Monty, Matsuno & Yuan in-prep

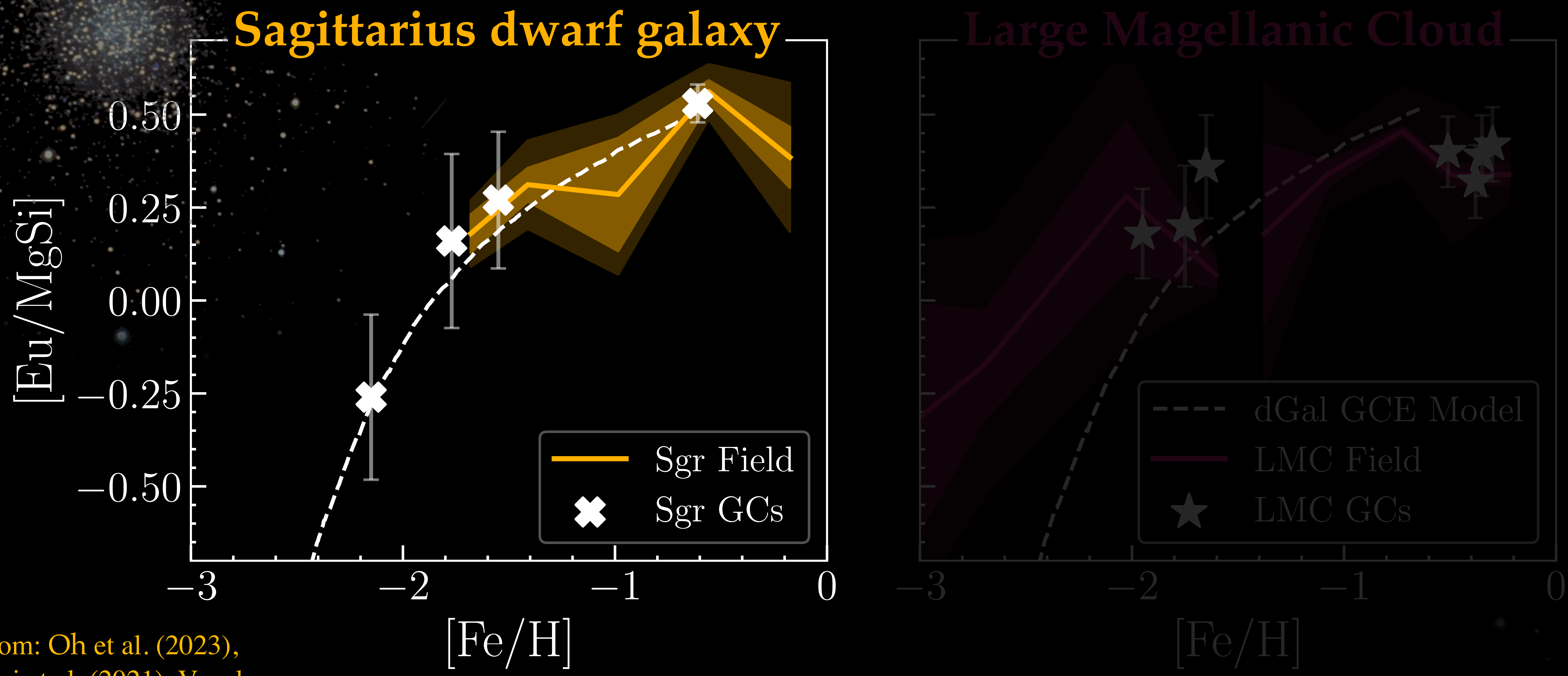
How similar are the clusters to the stream?

Difference between LMS-1 and the two GCs, considering first generation stars only



Monty, Matsuno & Yuan in-prep

Globular clusters trace the r-process evolution of their hosts



Data from: Oh et al. (2023), Reggiani et al. (2021), Van der Swaelmen et al. (2013), Pompéia et al. (2008), Mucciarelli et al. (2008), Mucciarelli et al. (2010), Reichart et al. 2020

Monty et al. 2024

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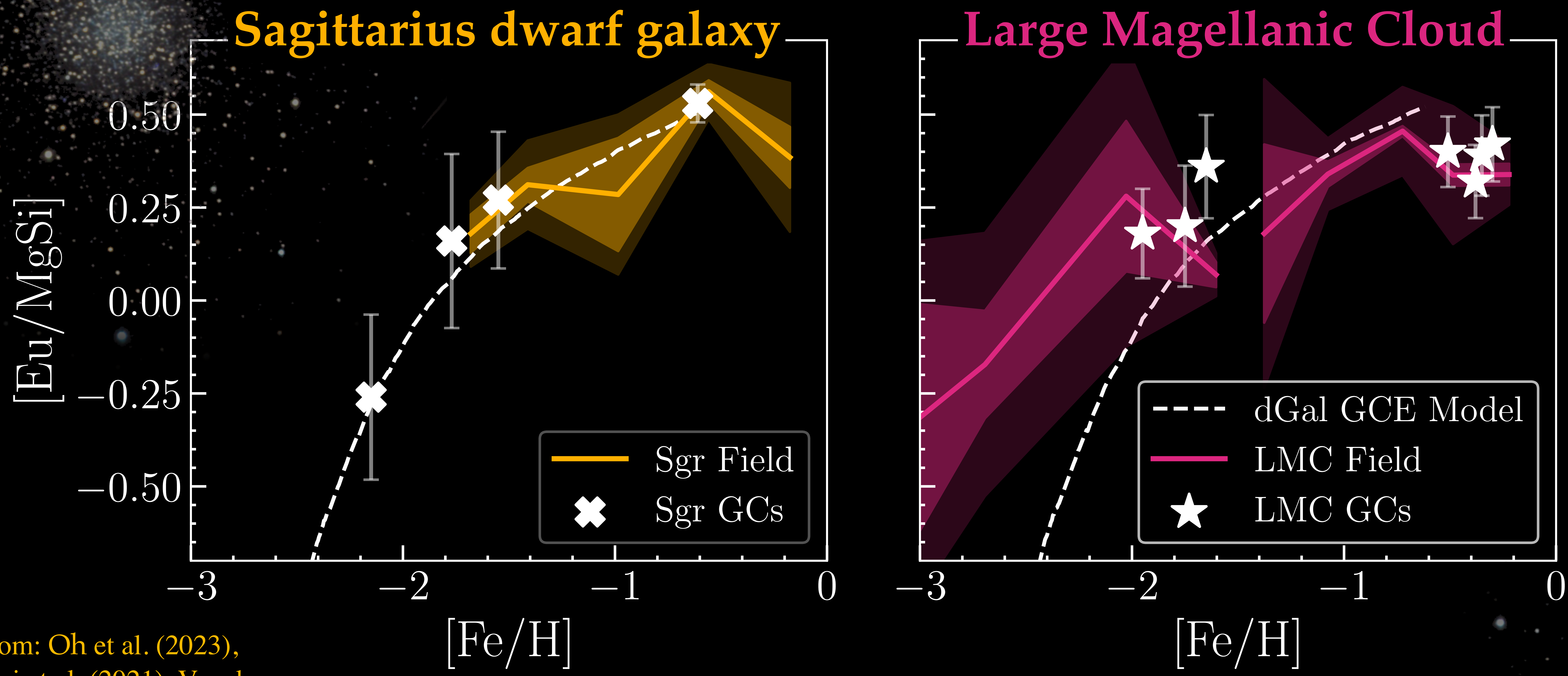

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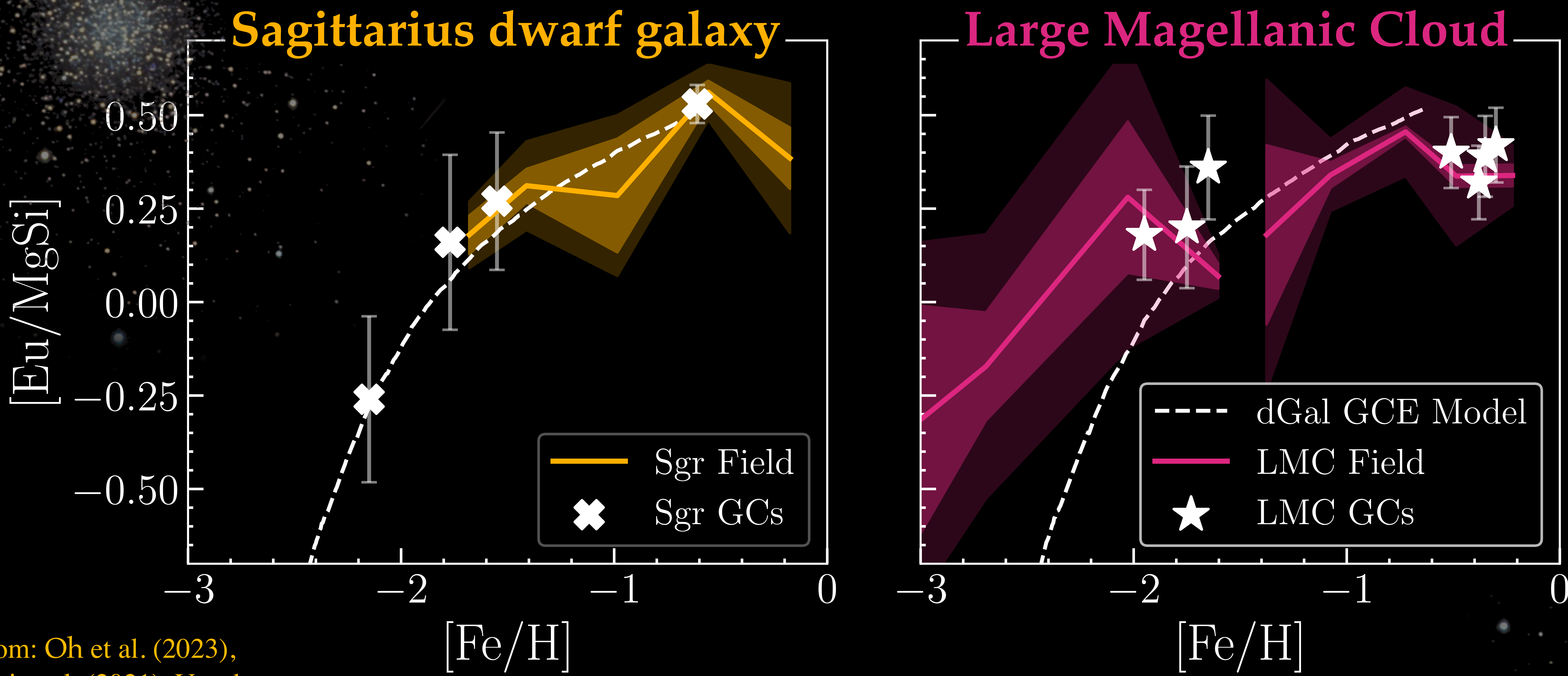

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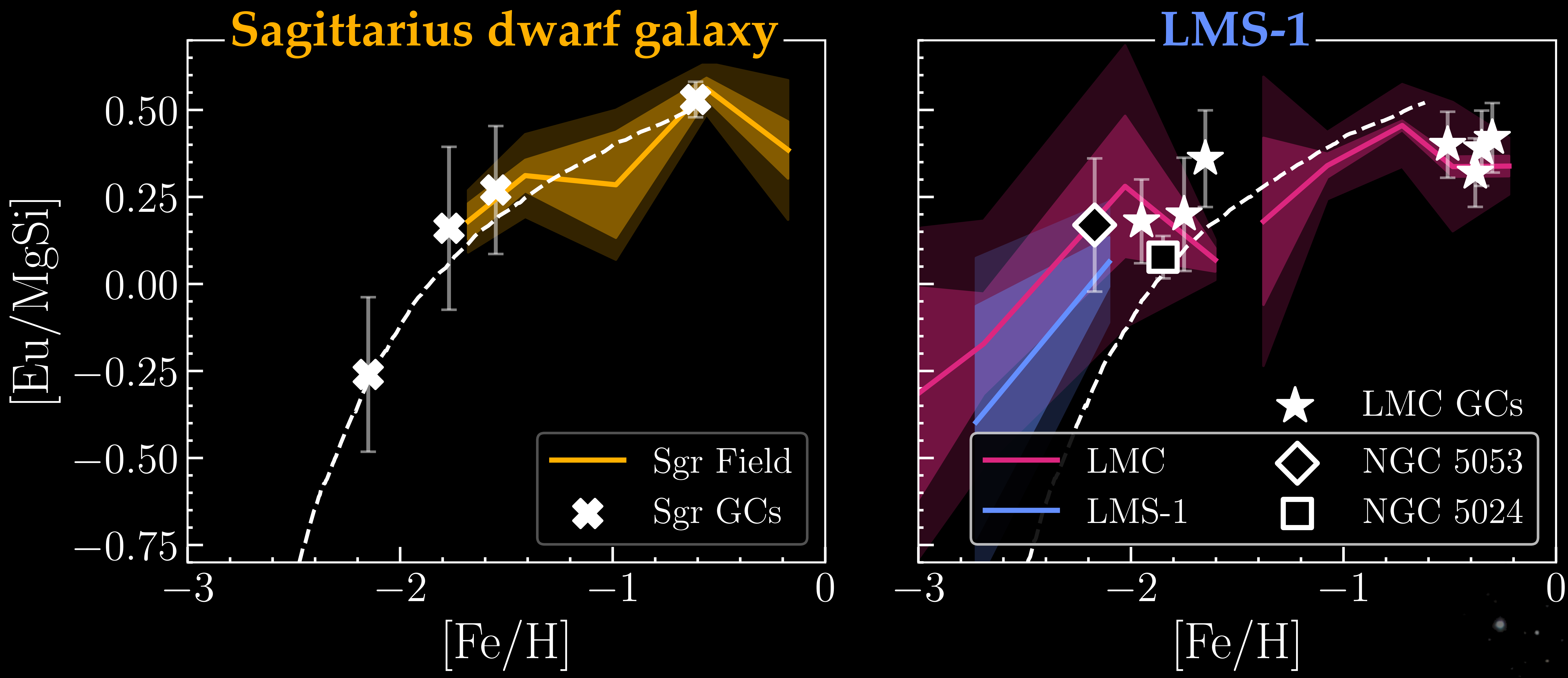
Globular clusters trace the chemical evolution of their hosts in [Eu/α] (see for e.g. talk by J.L. Schiappacasse)

Monty et al. 2024

LMS-1 continues the trend of agreement between GCs and their hosts!



Monty, Matsuno & Yuan in-prep

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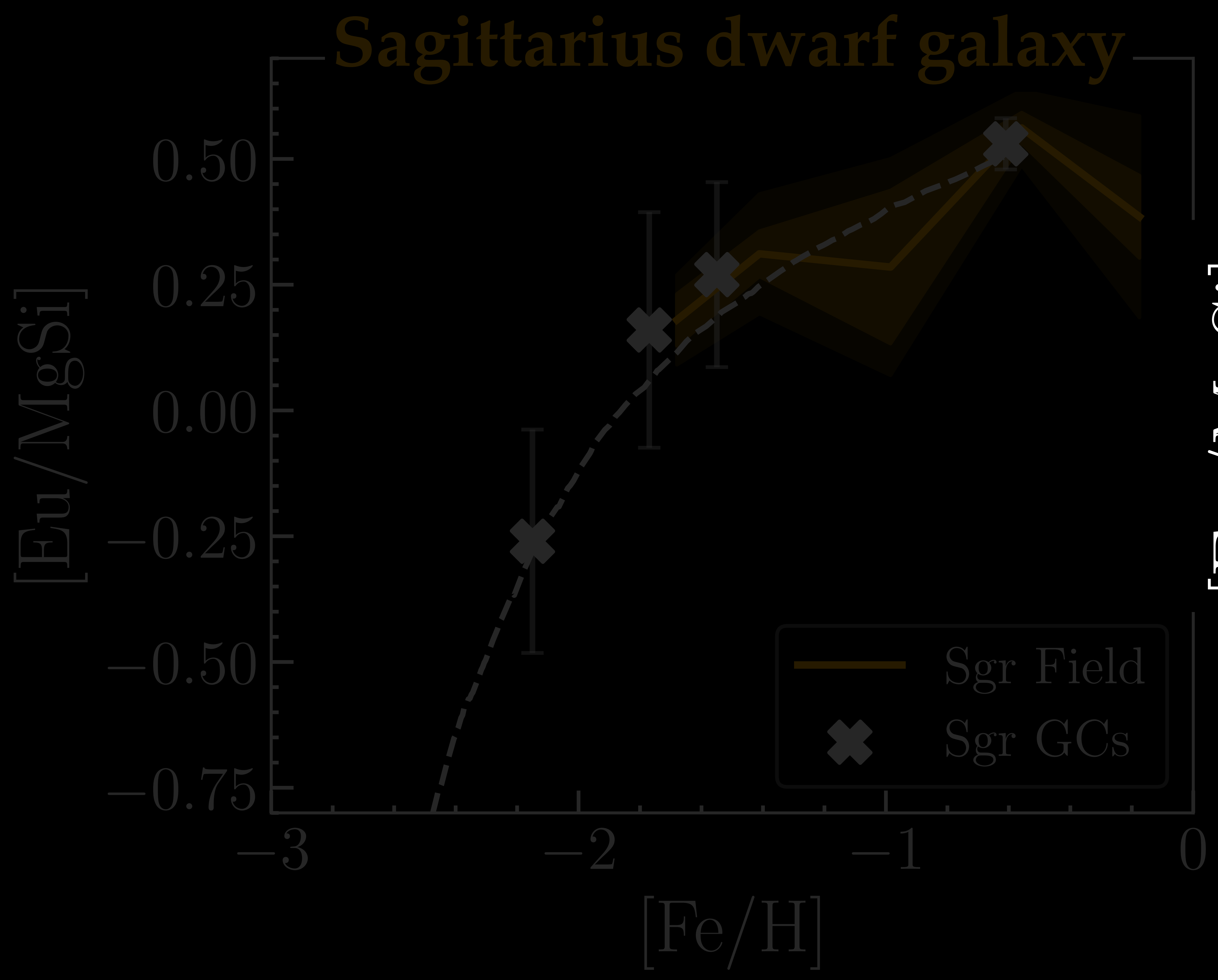
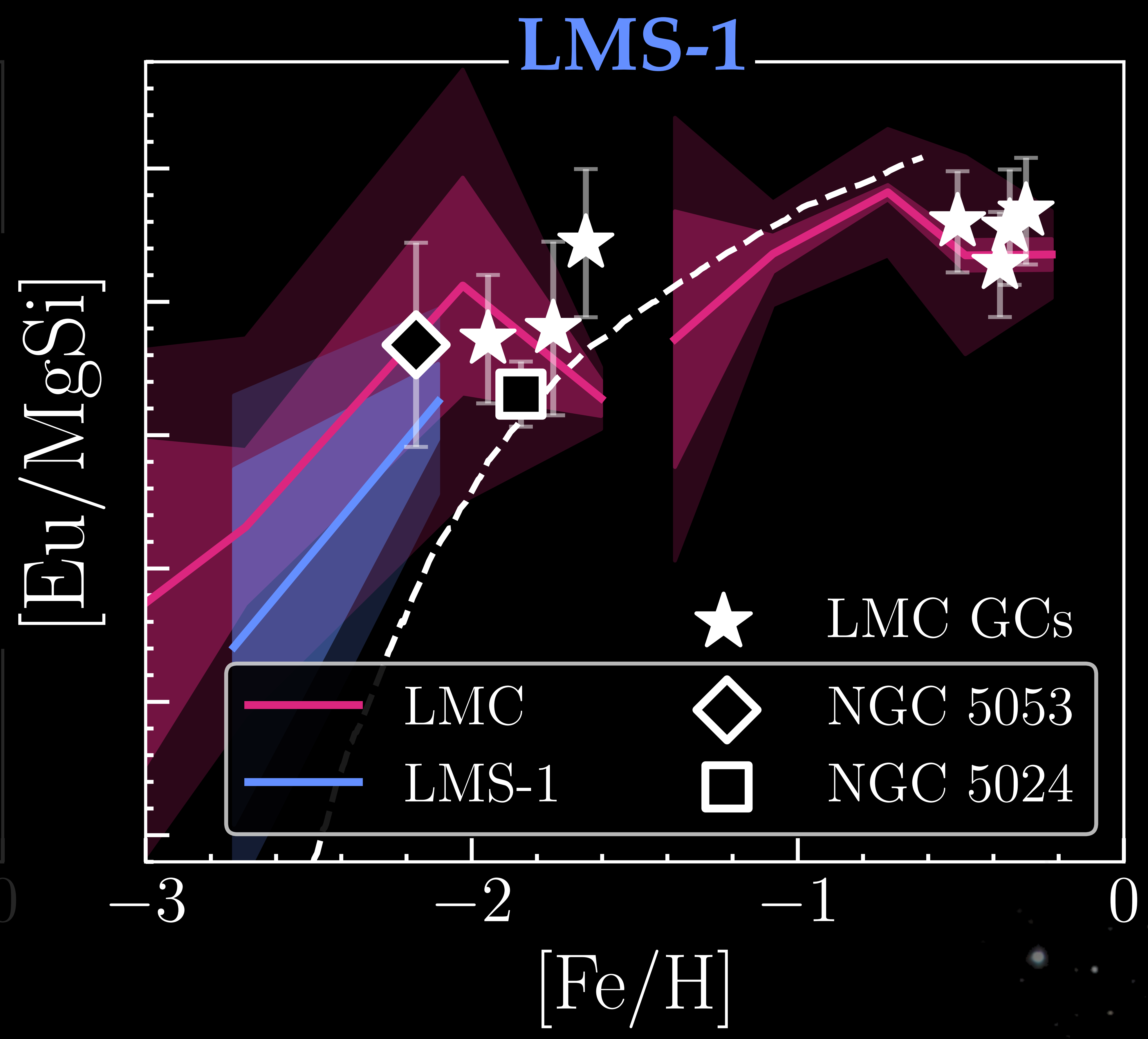
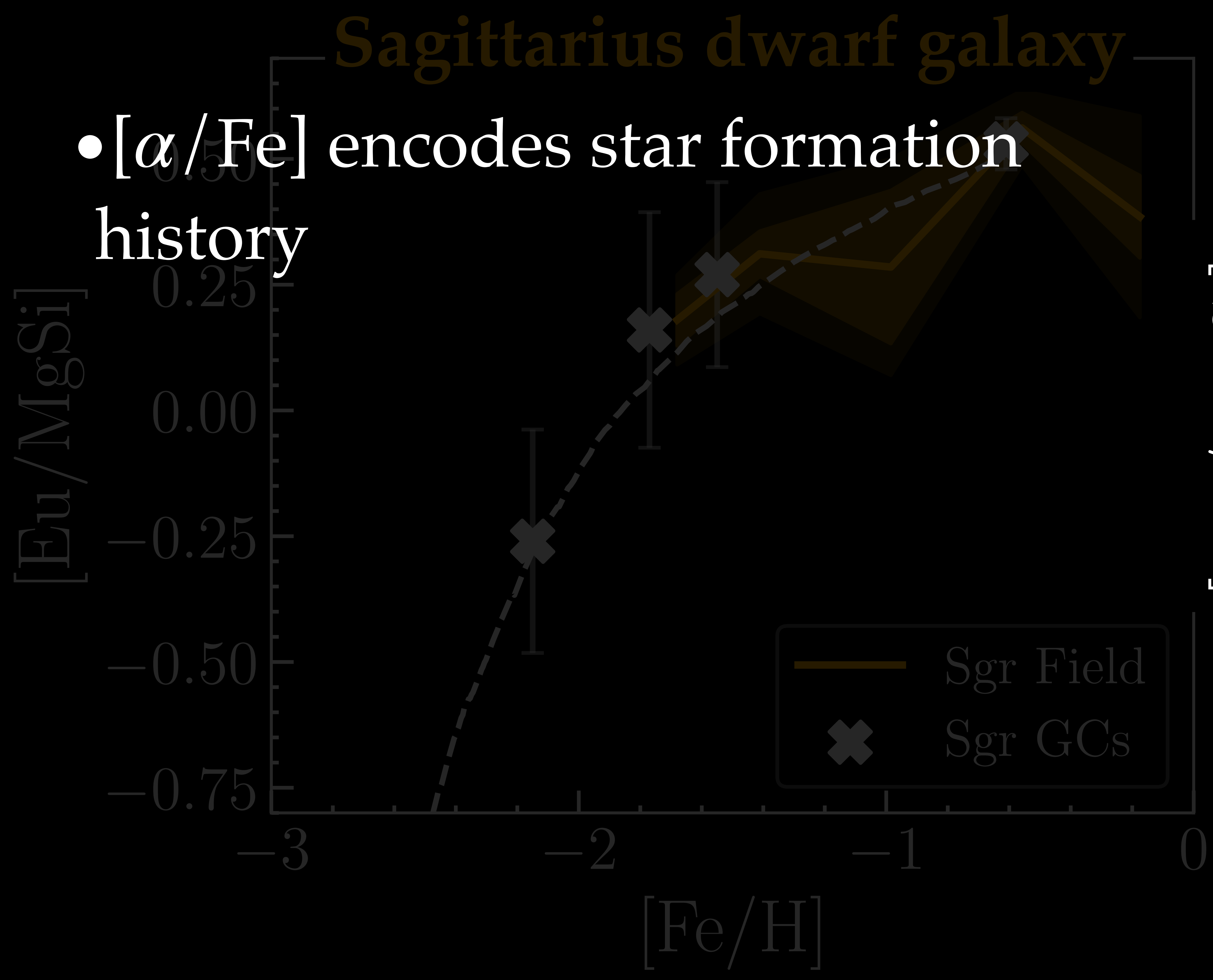


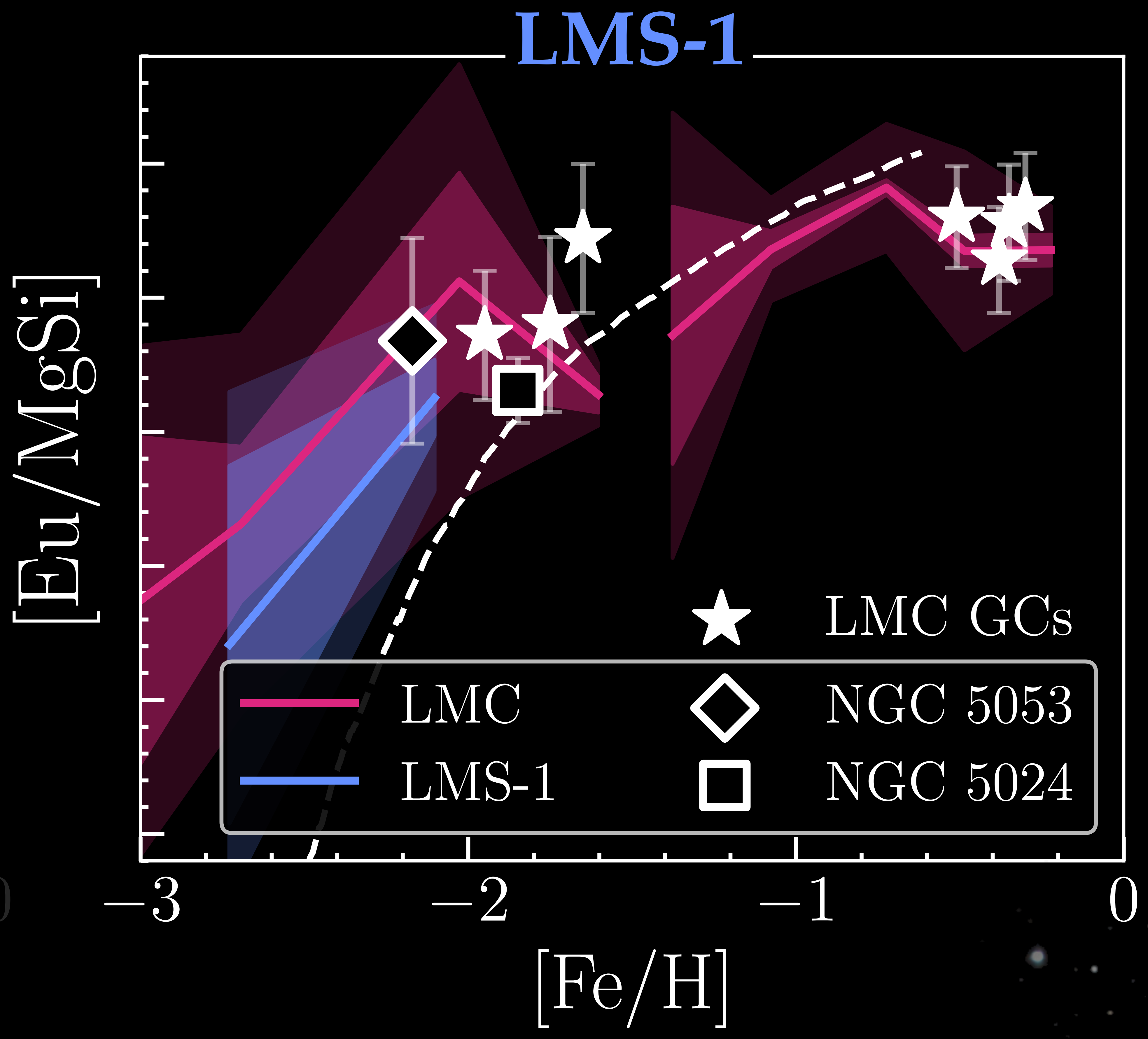


Monty, Matsuno & Yuan in-prep

LMS-1 continues the trend of agreement between GCs and their hosts!

- [α/Fe] encodes star formation history





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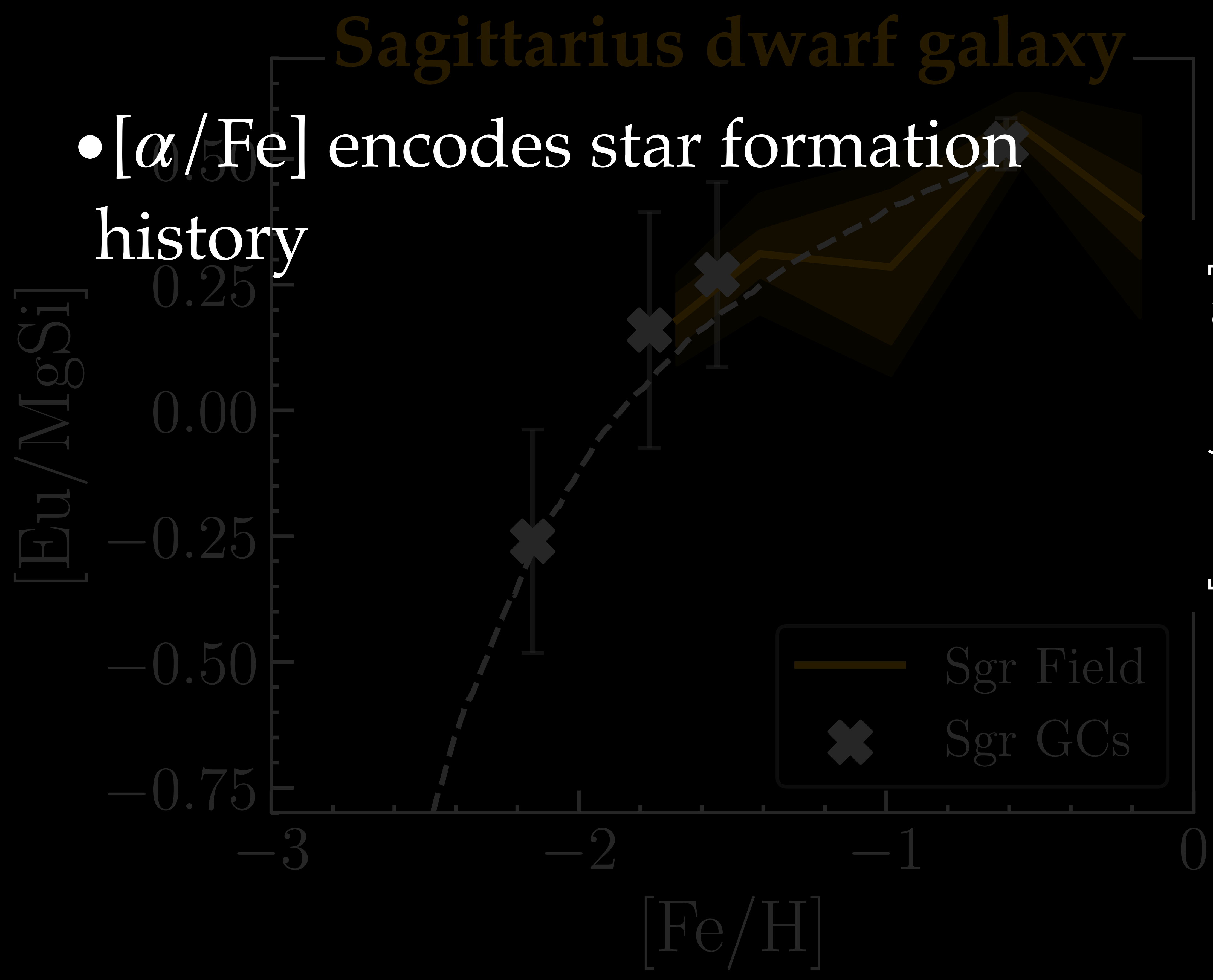
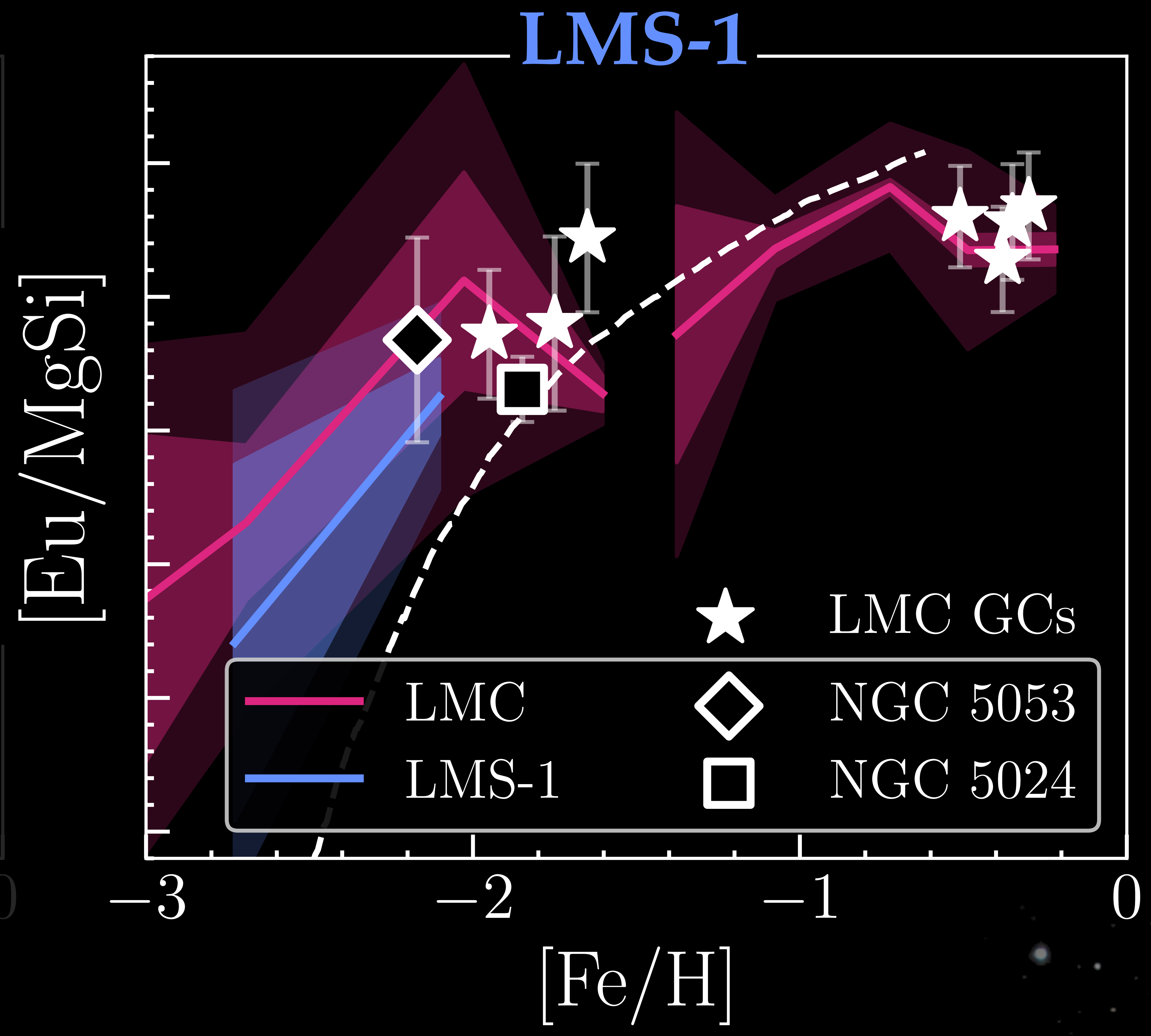
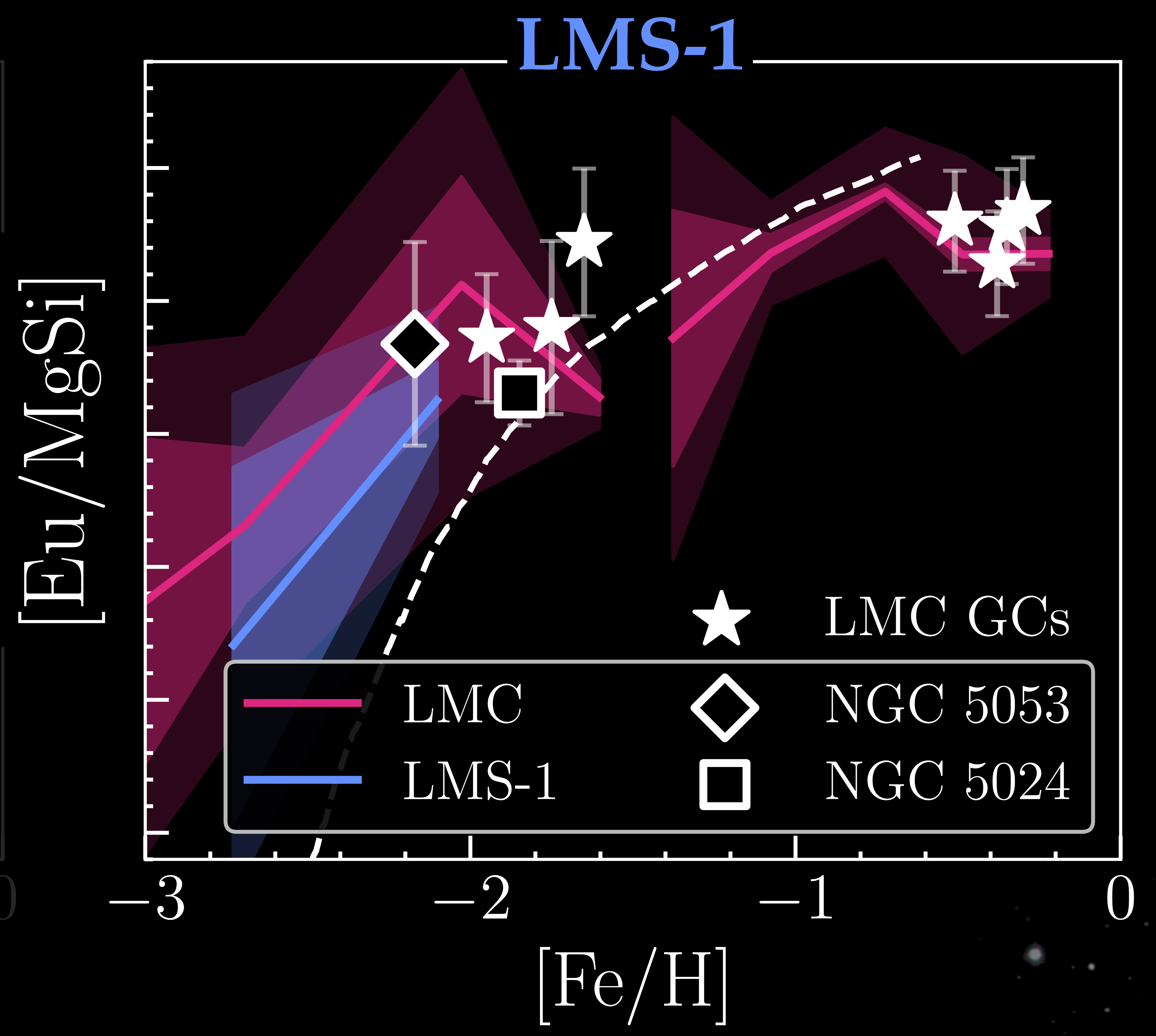




Monty, Matsuno & Yuan in-prep

LMS-1 continues the trend of agreement between GCs and their hosts!

- $[\alpha/\mathrm{Fe}]$ encodes star formation history
- [Eu/Fe] encodes information on rare channels, delay times and mixing timescales (Skúladottir+2020, Aguado+2021, Matsuno+2021, Ernandes+2024, Monty+2024)



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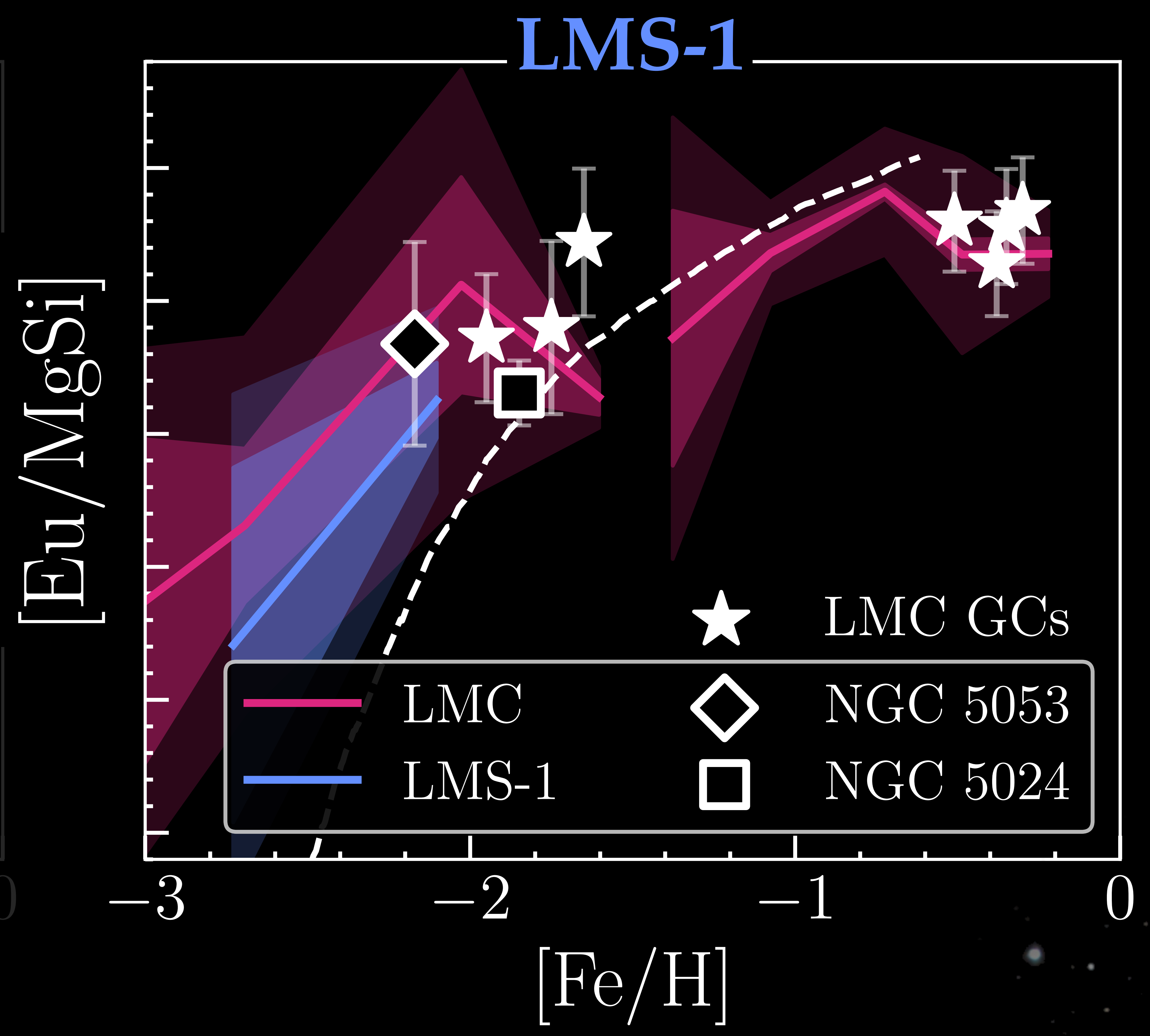
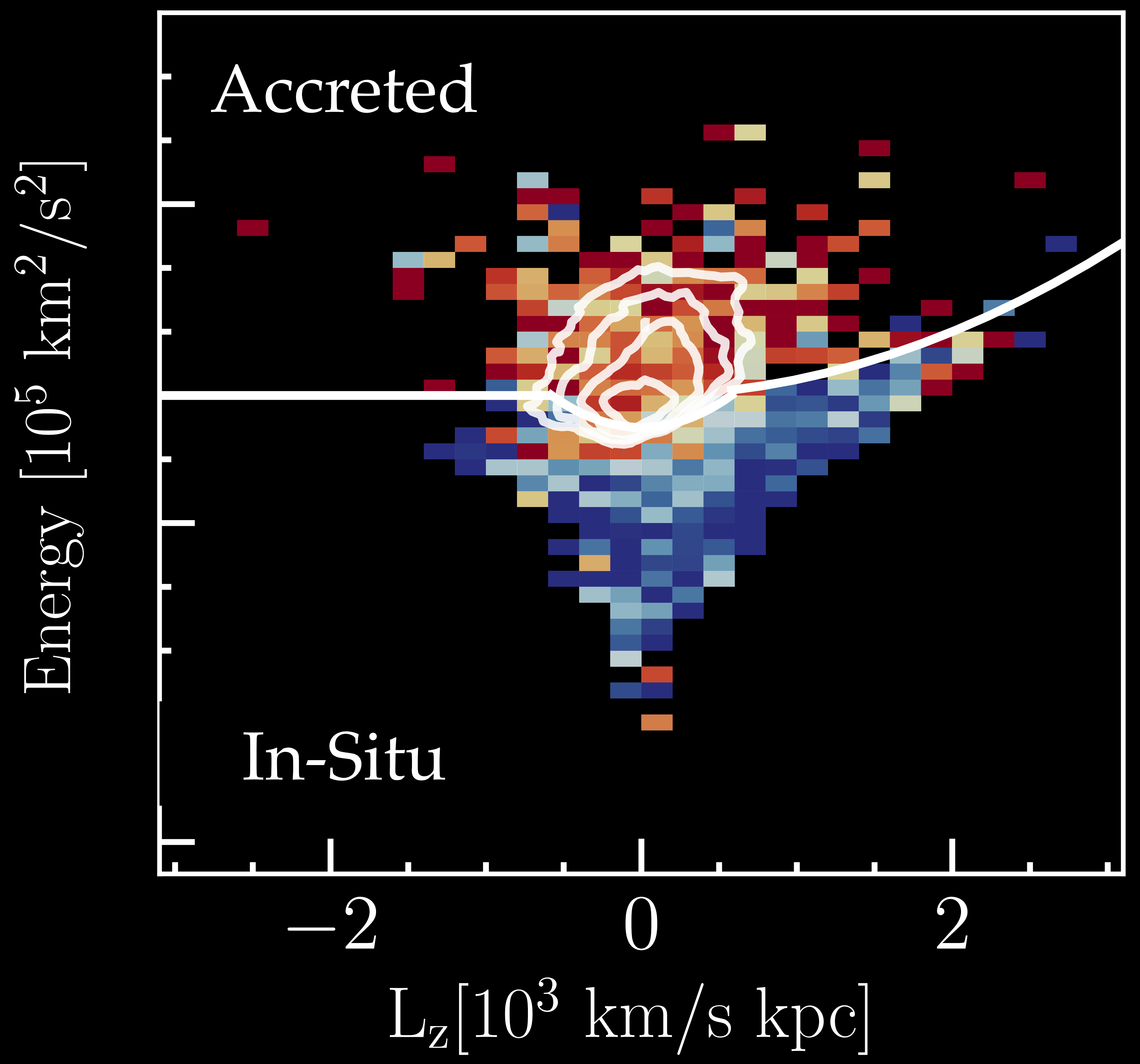


Monty, Matsuno & Yuan in-prep

Globular clusters *time* the r-process evolution of their hosts



Monty et al. 2024

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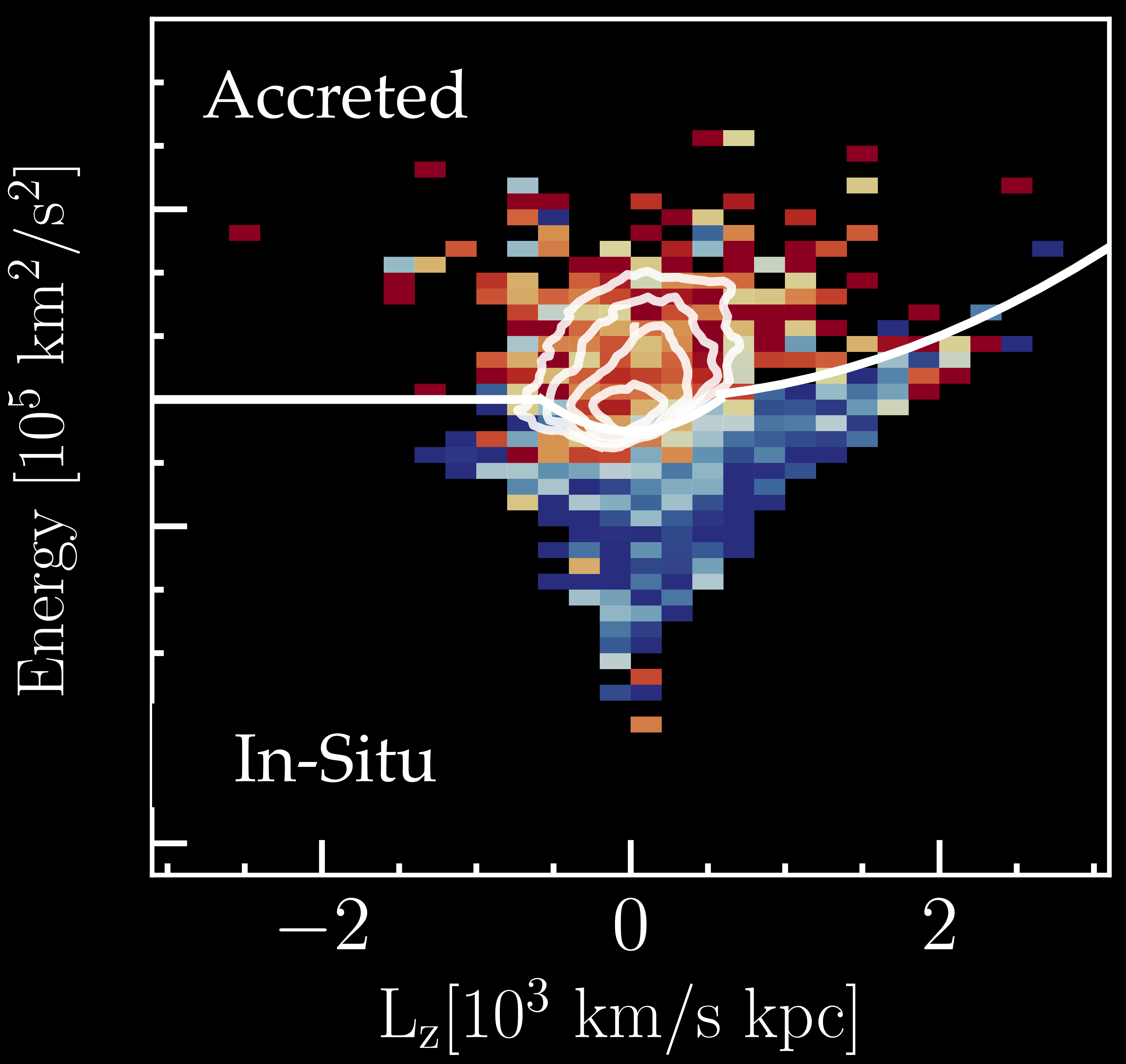

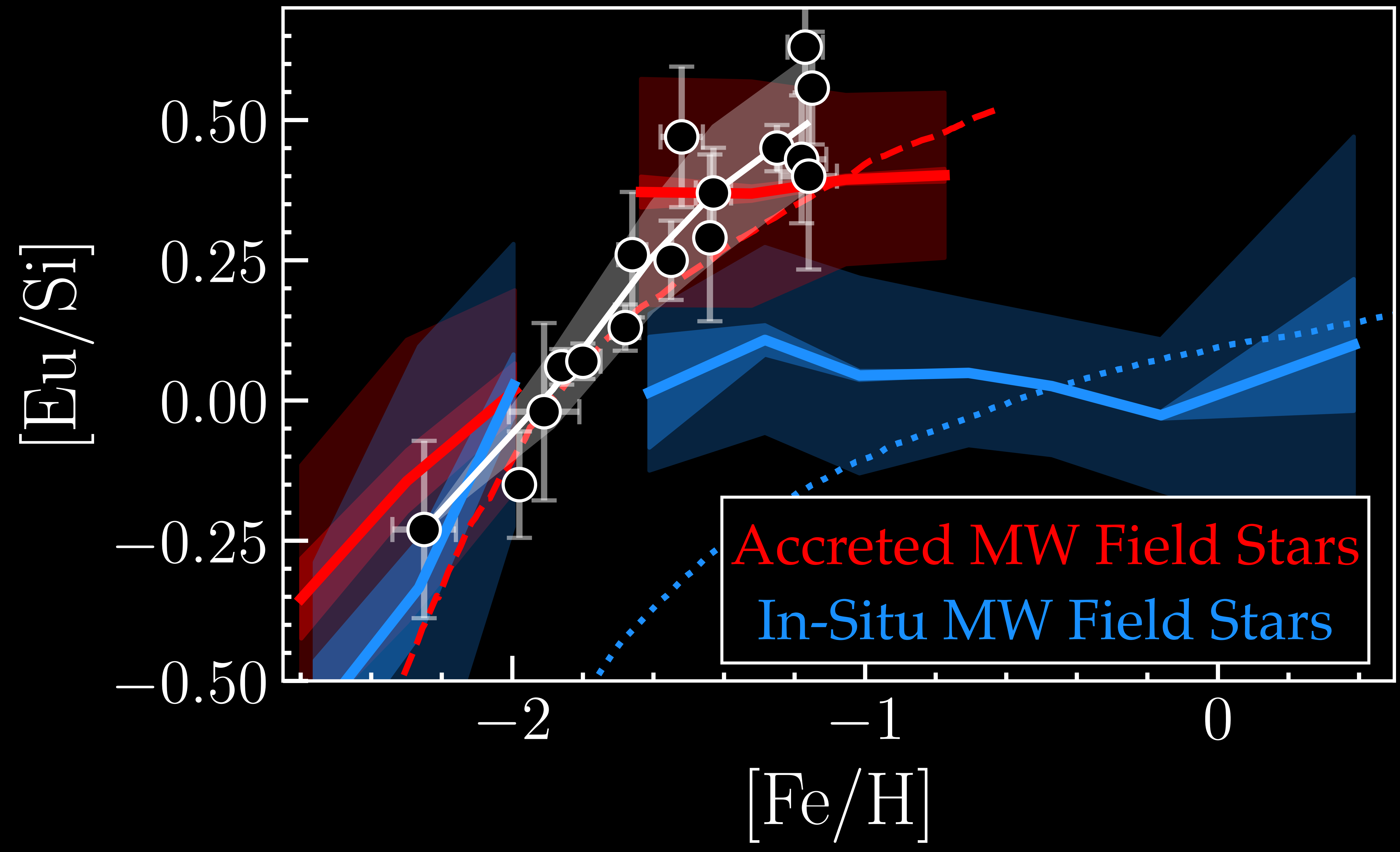

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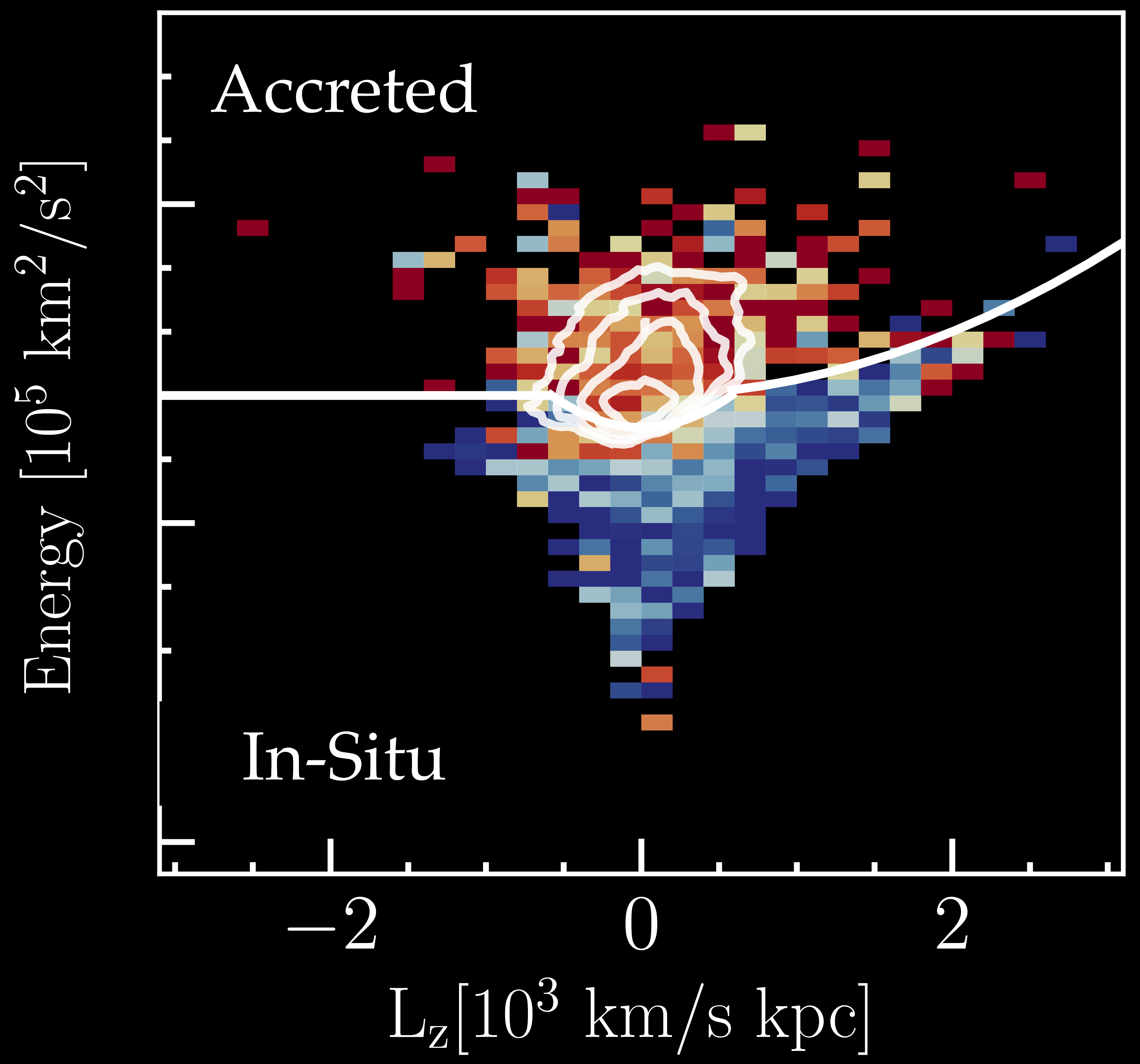

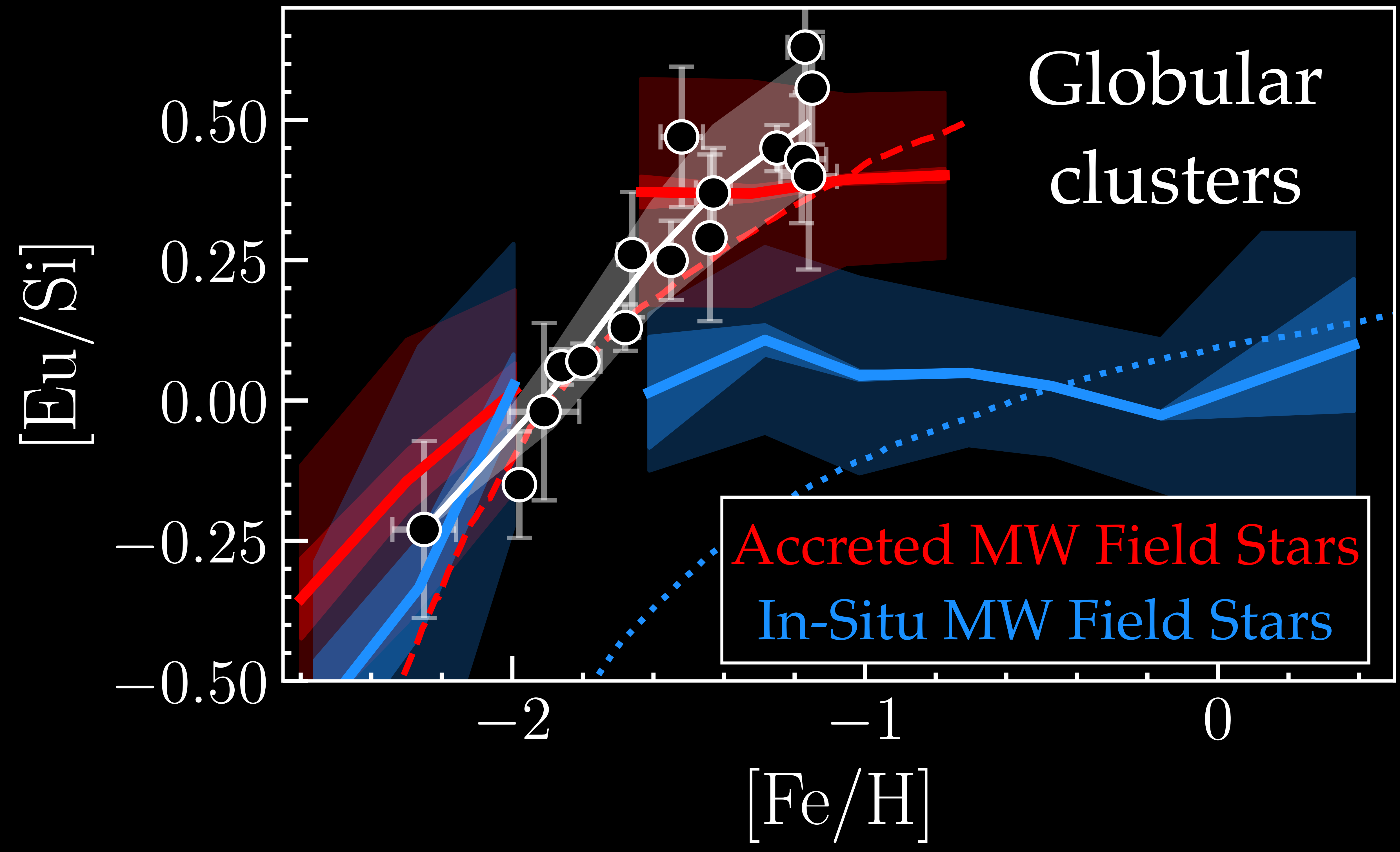

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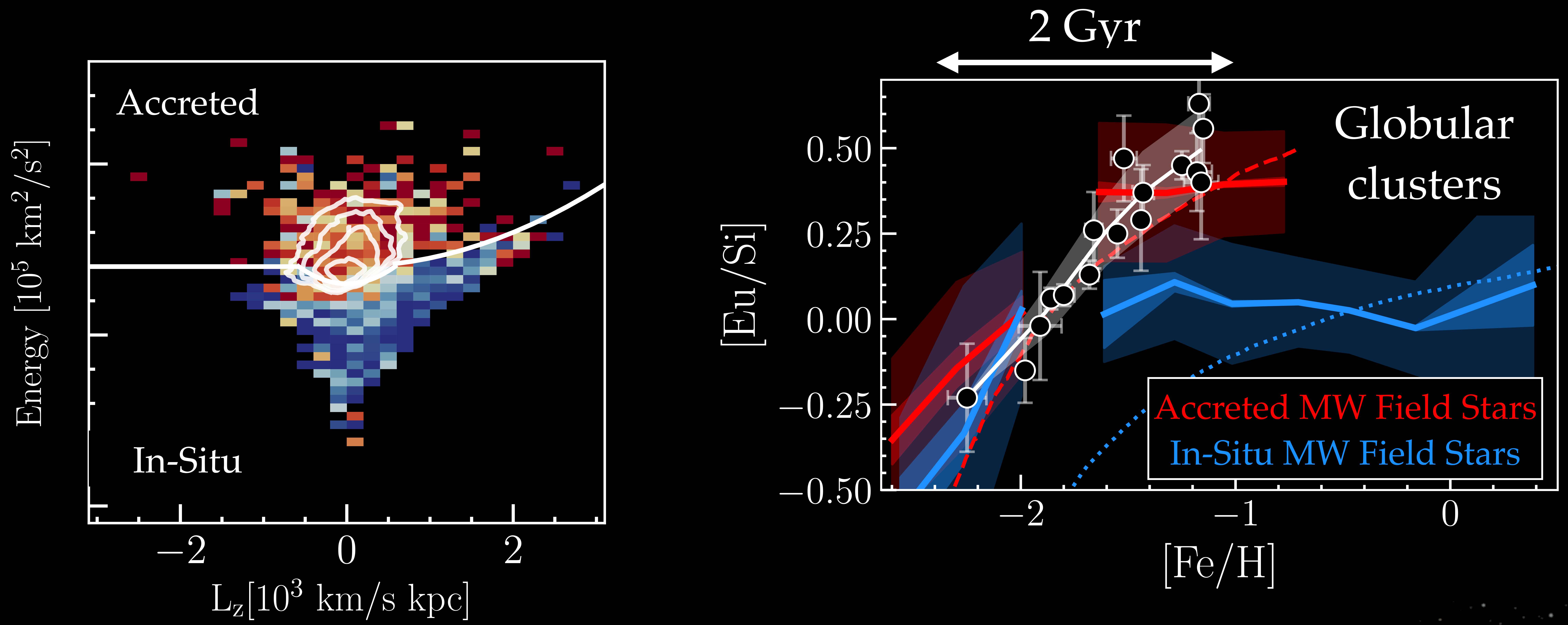

Monty et al. 2024

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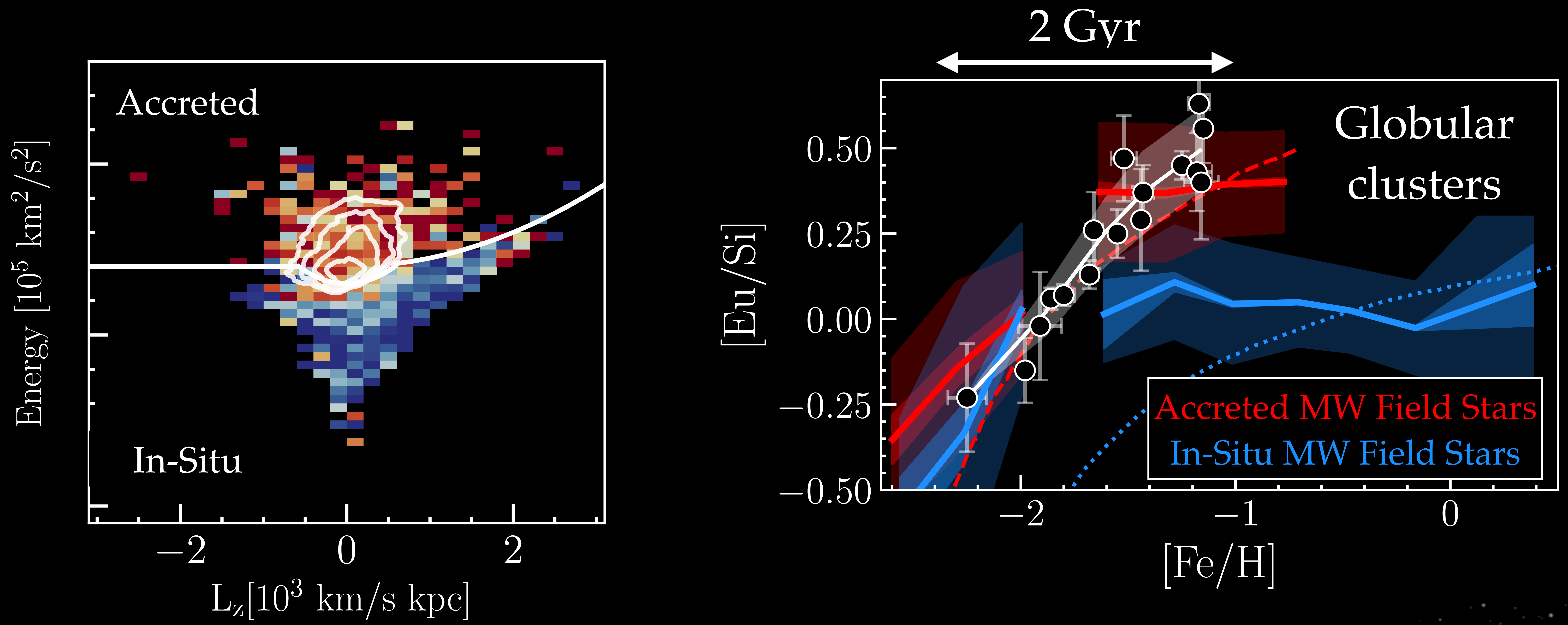
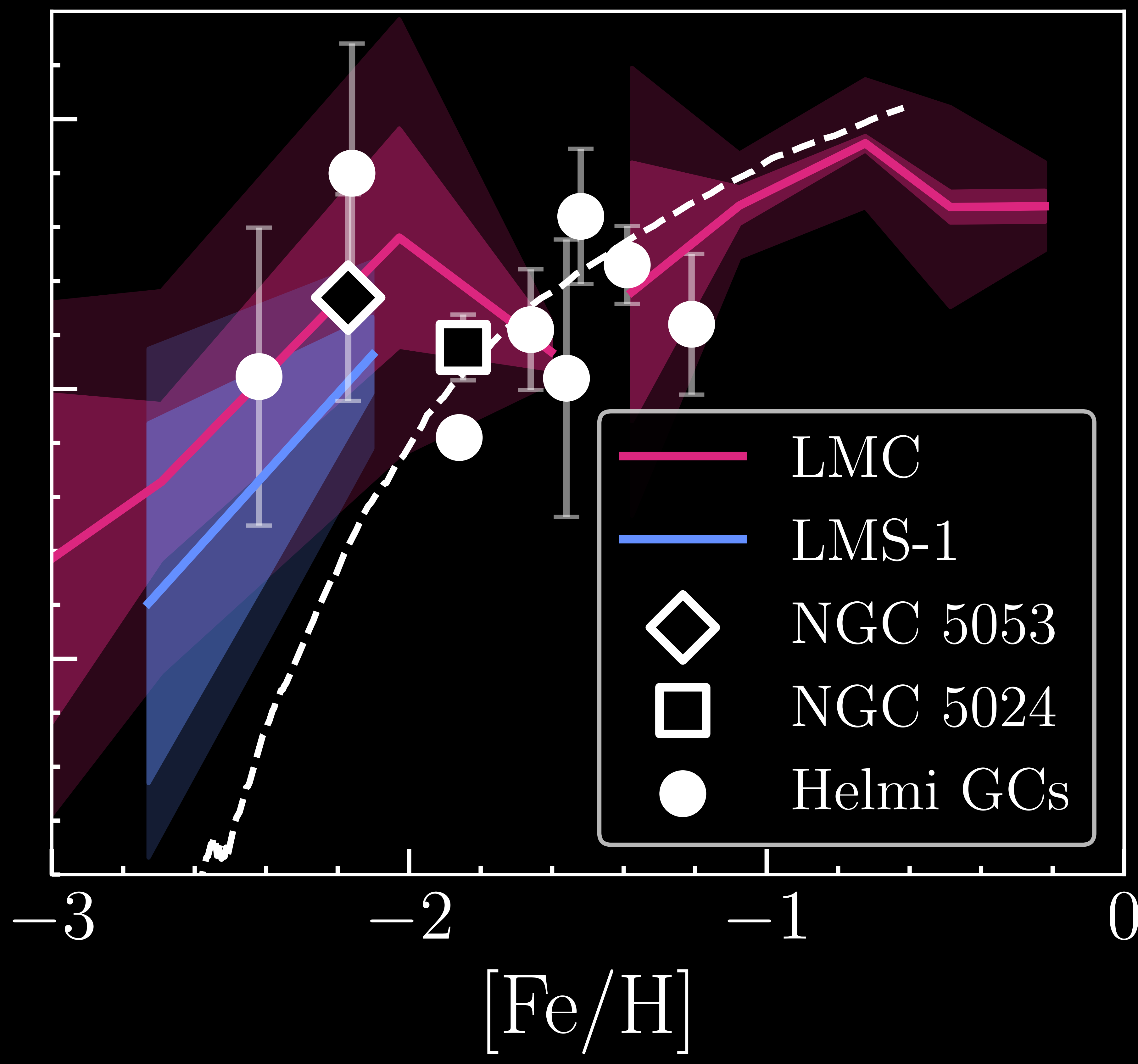
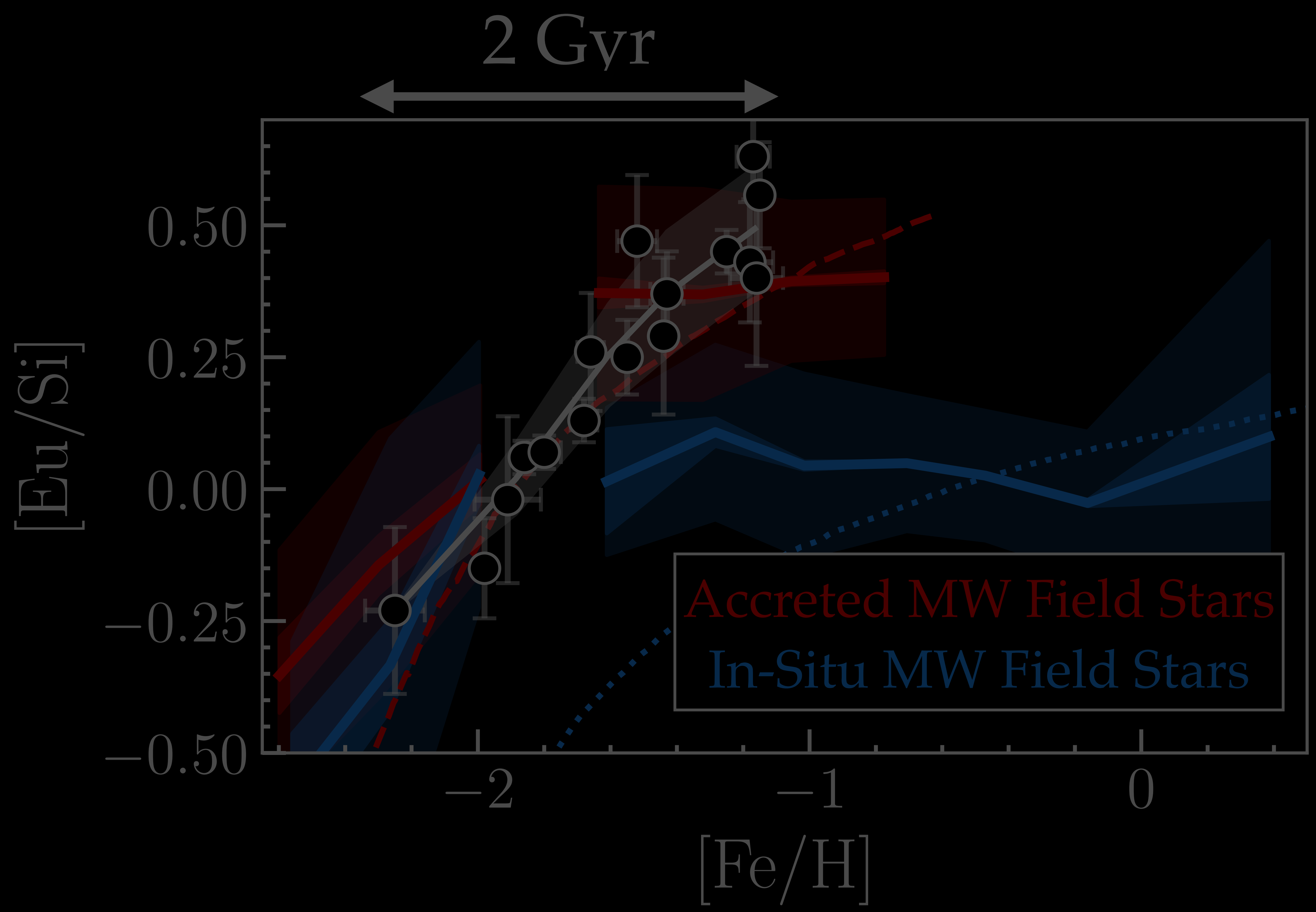


[Eu/α] is a sensitive probe of star formation histories
Globular clusters can time the chemical enrichment history

Monty et al. 2024

Globular clusters *time* the r-process evolution of their hosts





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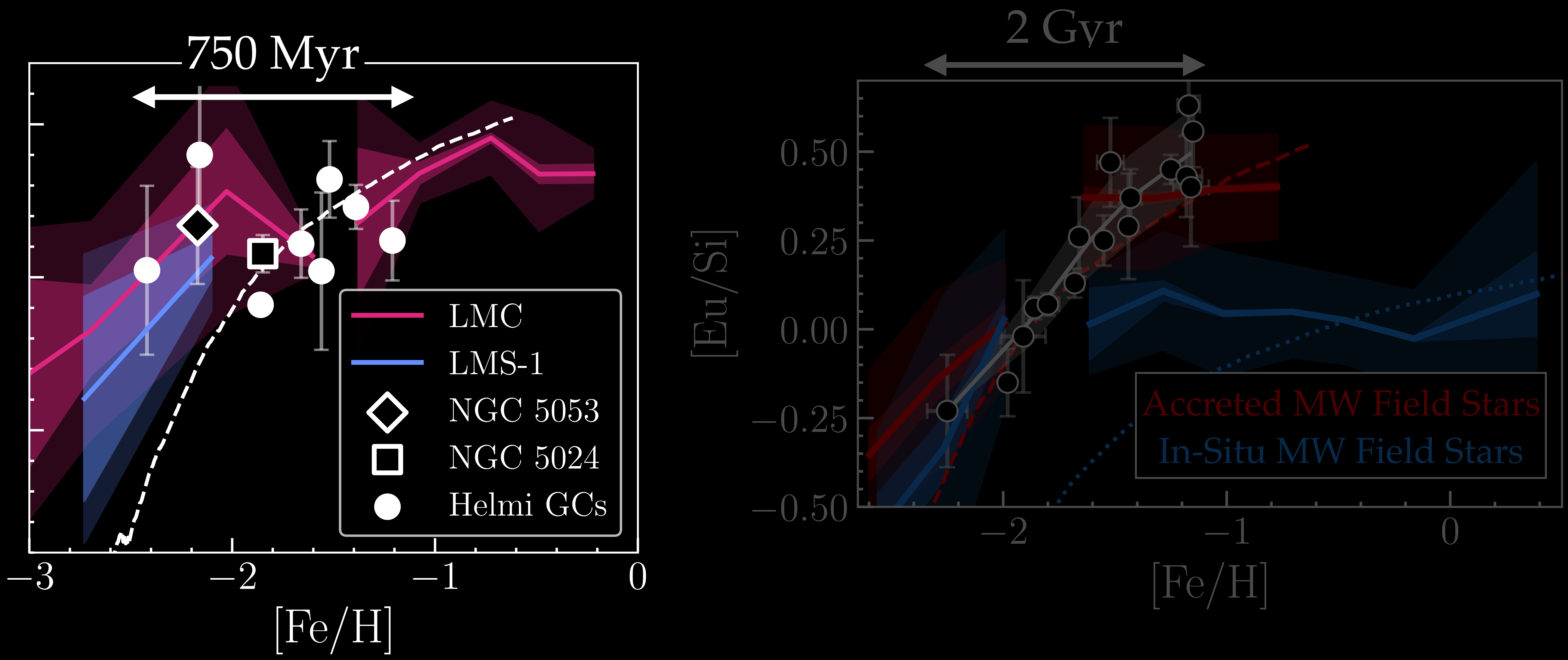

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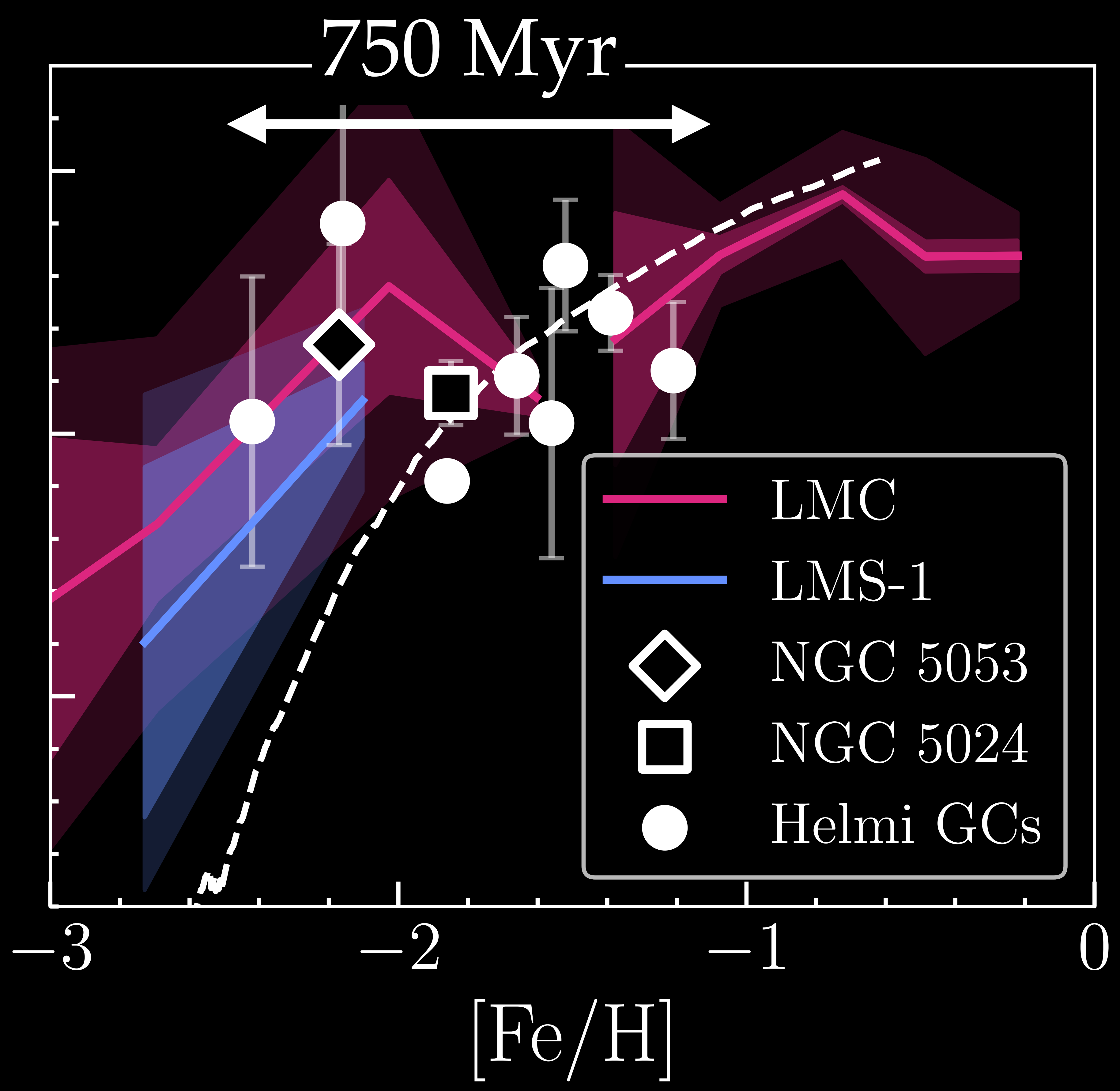

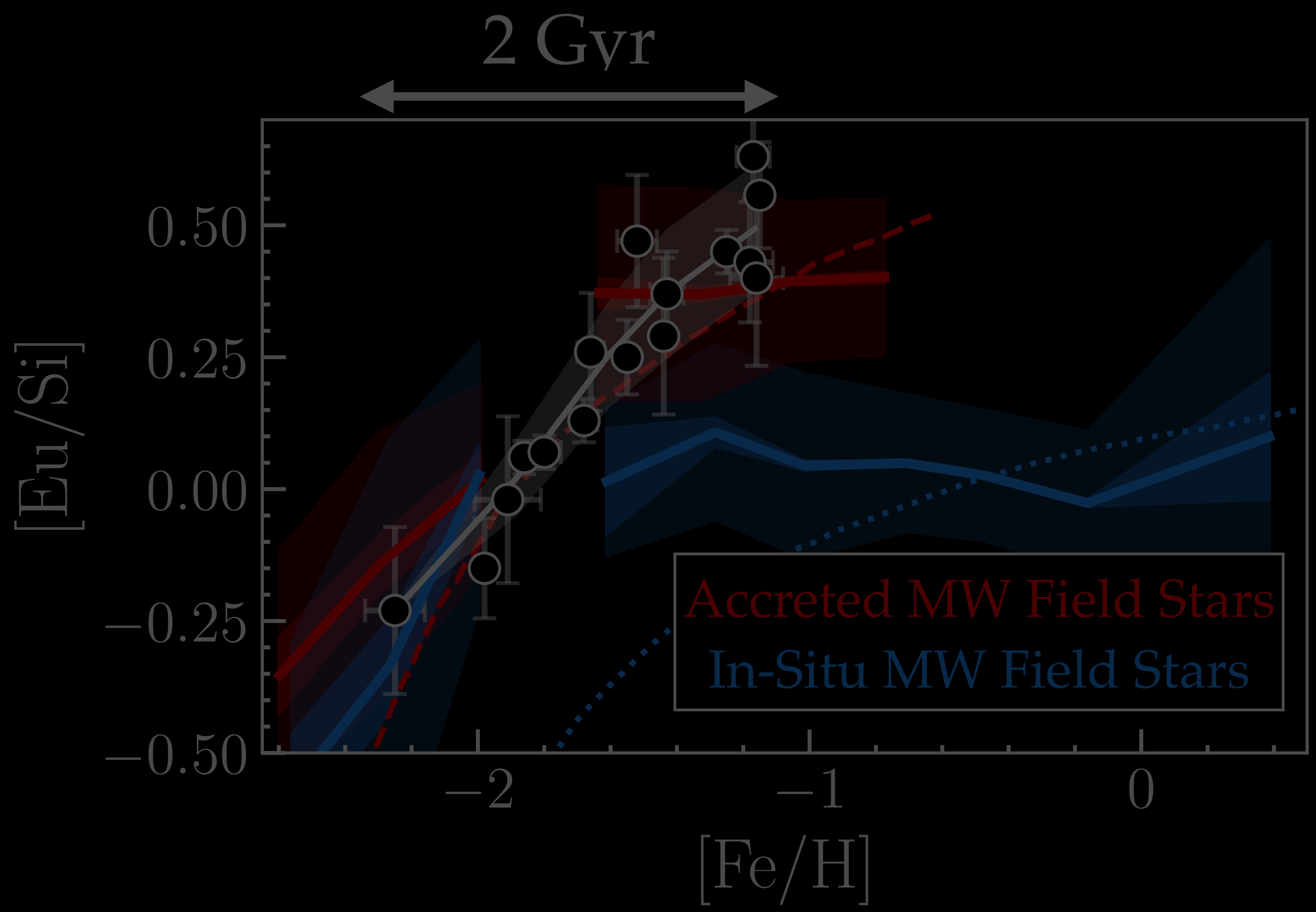

LMS-1 reaches a plateau in [Eu/α], maintained for 750 Myr
if LMS-1 and the Helmi Streams are the same system

Monty et al. 2024

Searching for system similarities, is LMS-1 a unique system?

$$\chi^2 = \sum_i \frac{(\mu_{\mathrm{LMS}}^2 - \mu_{\mathrm{gal}}^2)}{\sigma_{\mathrm{LMS}}^2 + \sigma_{\mathrm{gal}}^2 + \sigma_{\mathrm{LMS,ave.err}}^2 + \sigma_{\mathrm{gal,ave.err}}^2}$$

Data from:
Hill+2019 (Sculptor)
Norris+2017 (Carina)
Ji+2020 (Indus)
Limberg+2024 (Wukong)
Li+2022 (Helmi Streams)

ESO/L. Calçada

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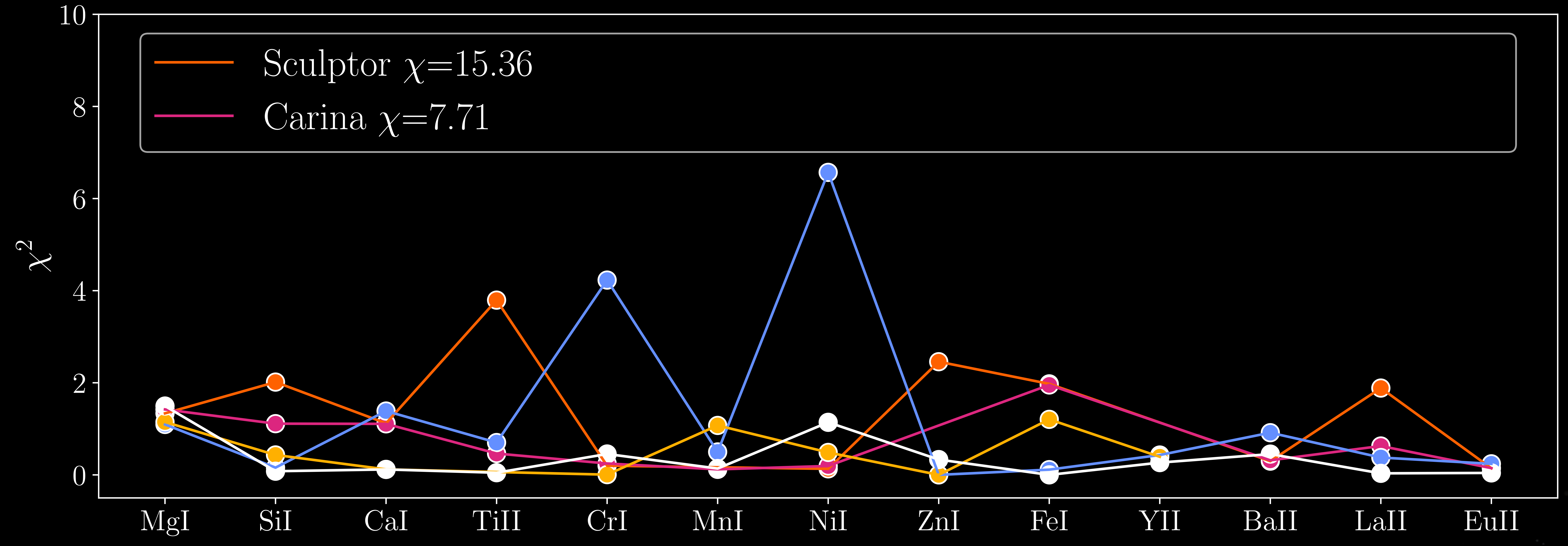

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ESO/L. Calçada

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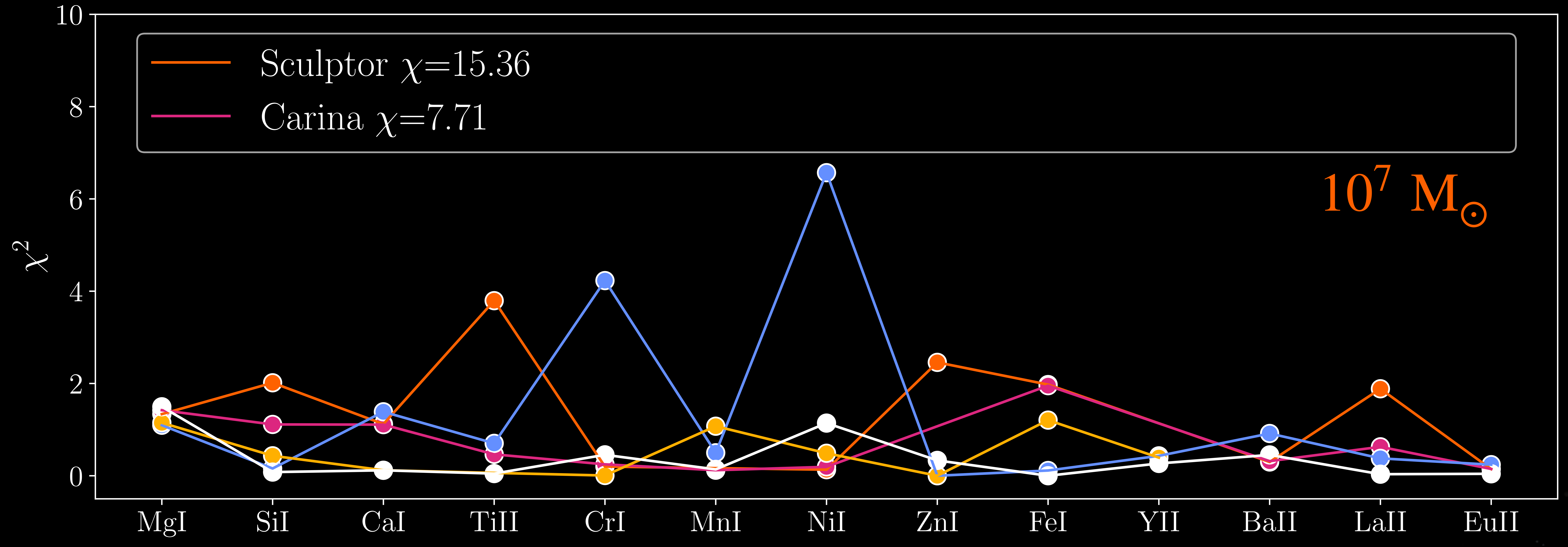

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ESO/L. Calçada

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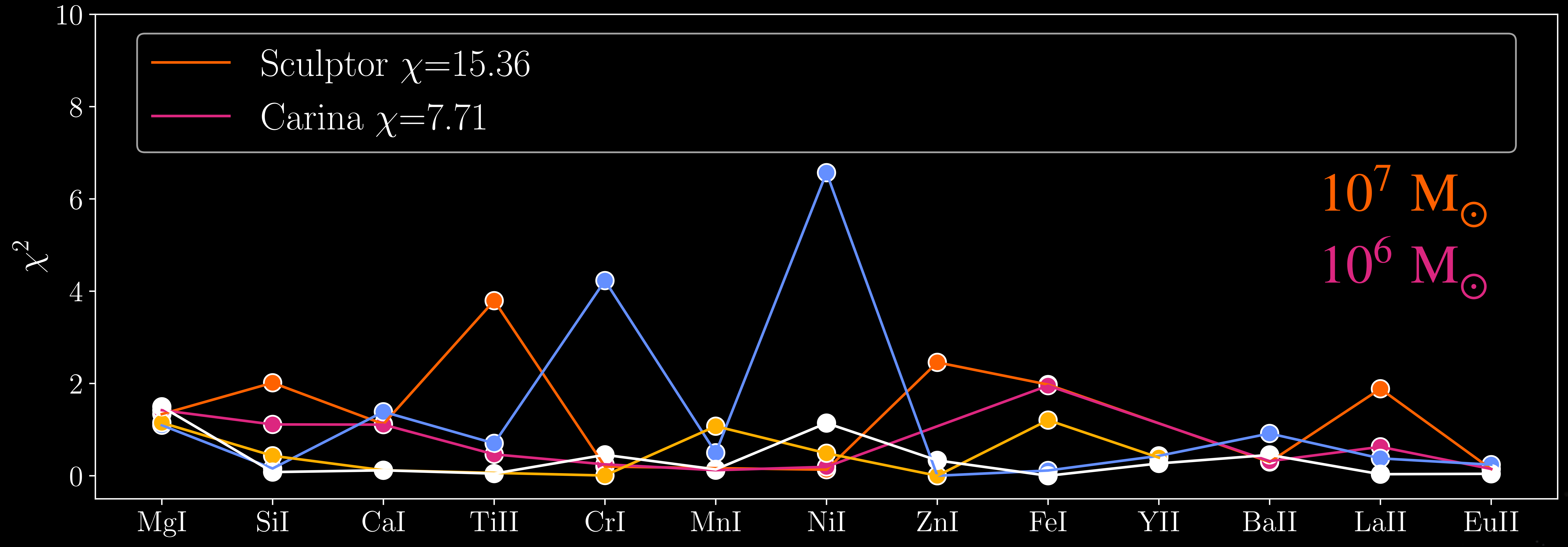

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ESO/L. Calçada

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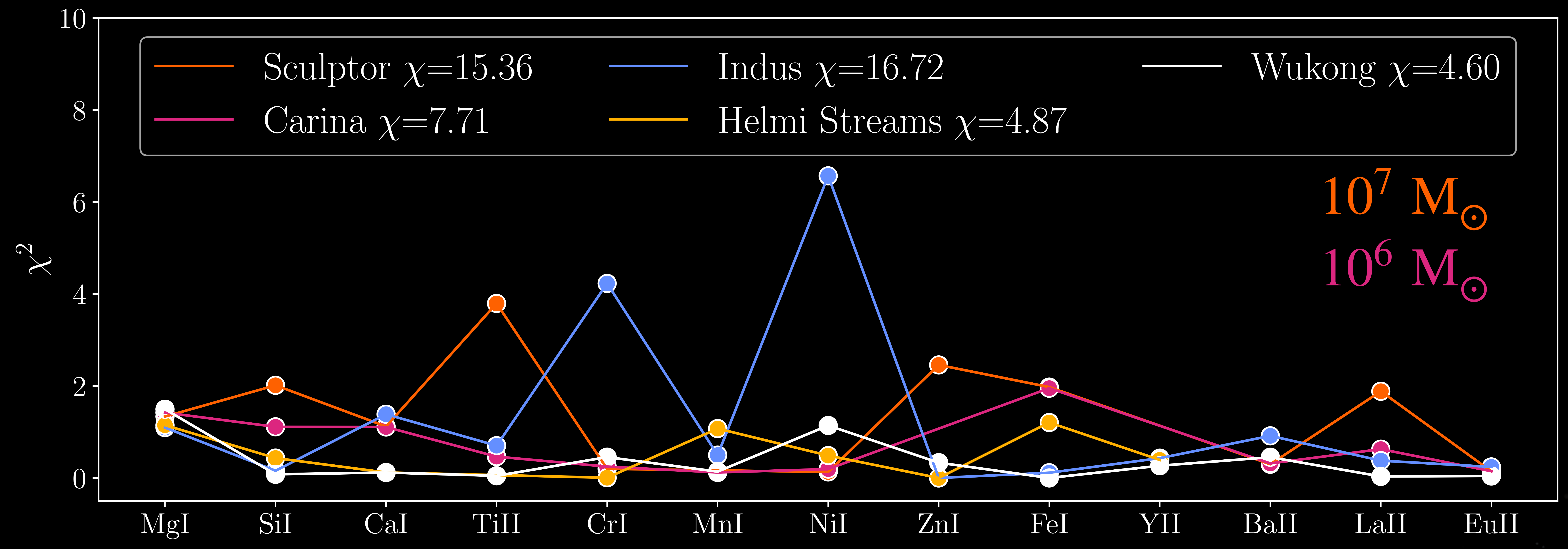

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ESO/L. Calçada

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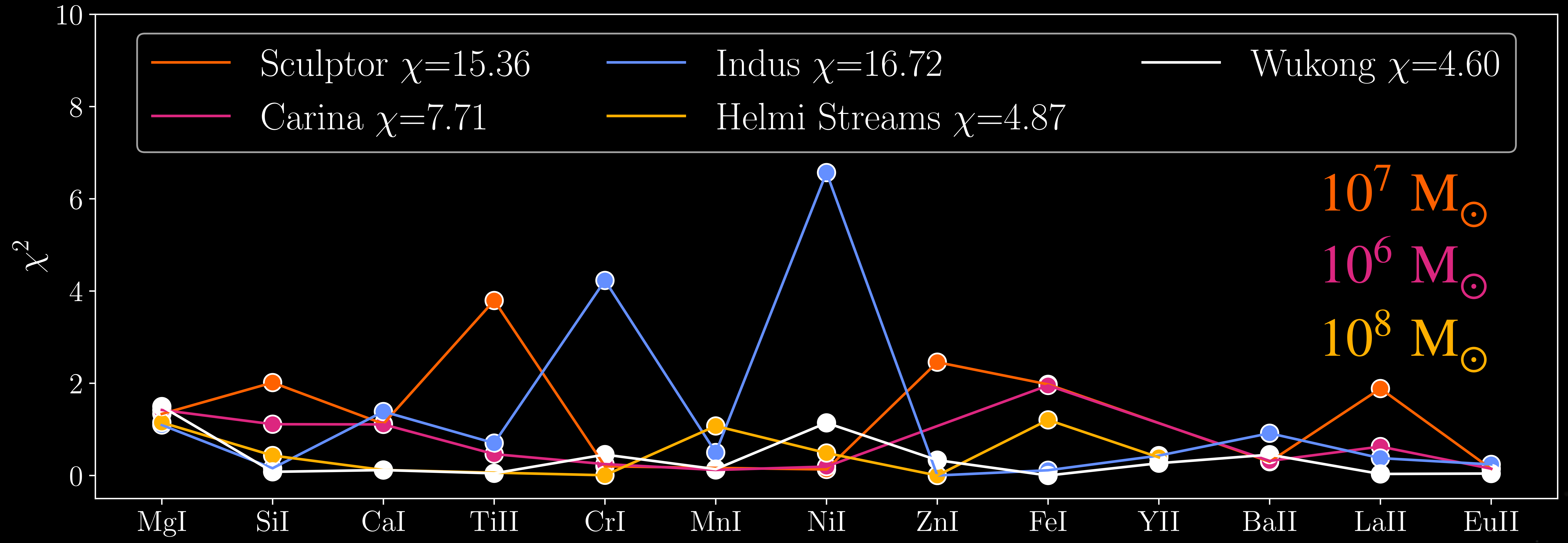

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ESO/L. Calçada

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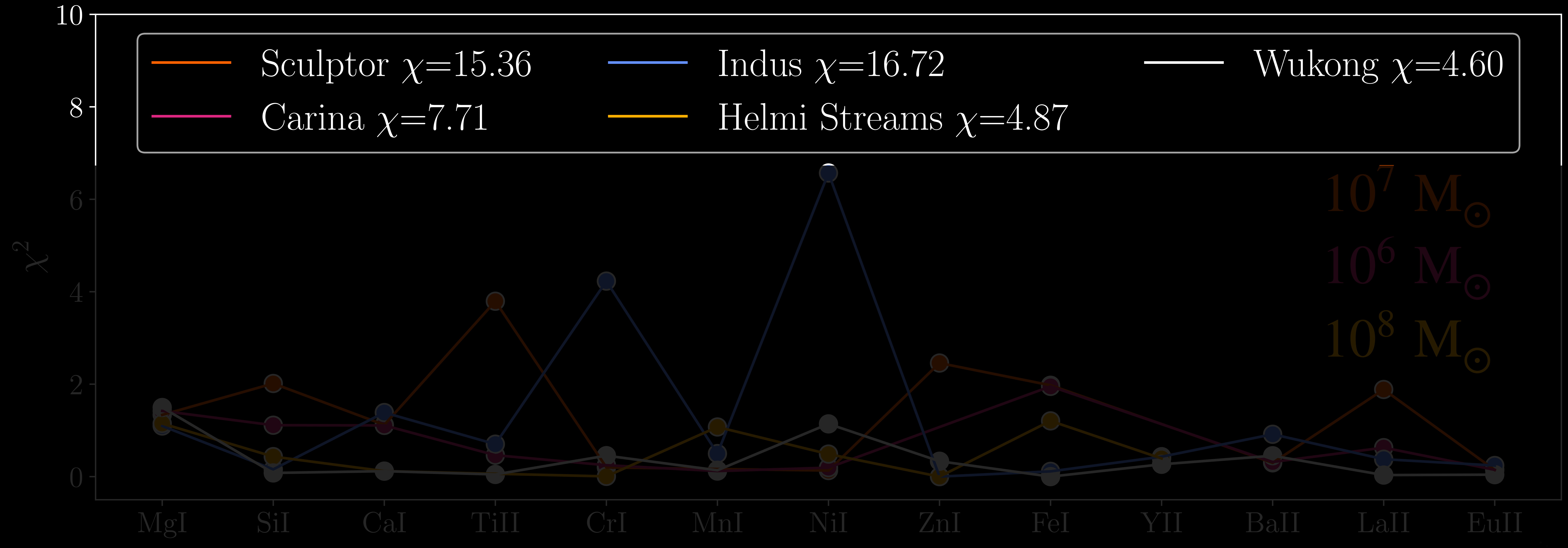

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ESO/L. Calçada

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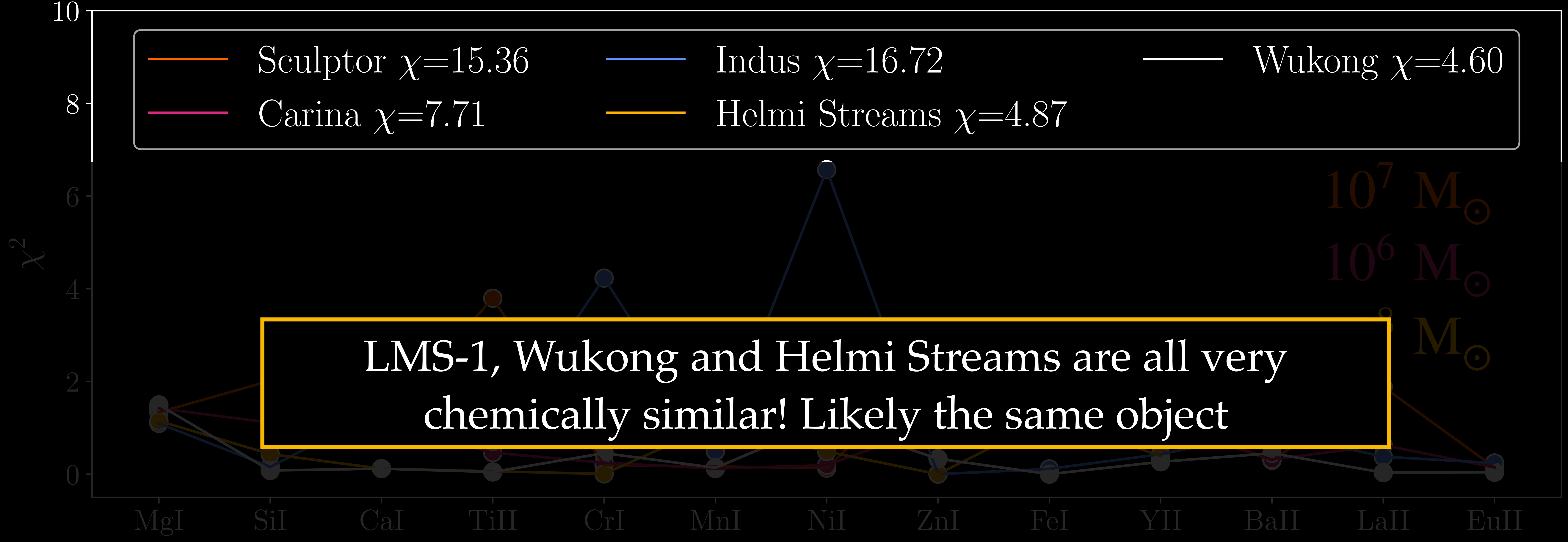


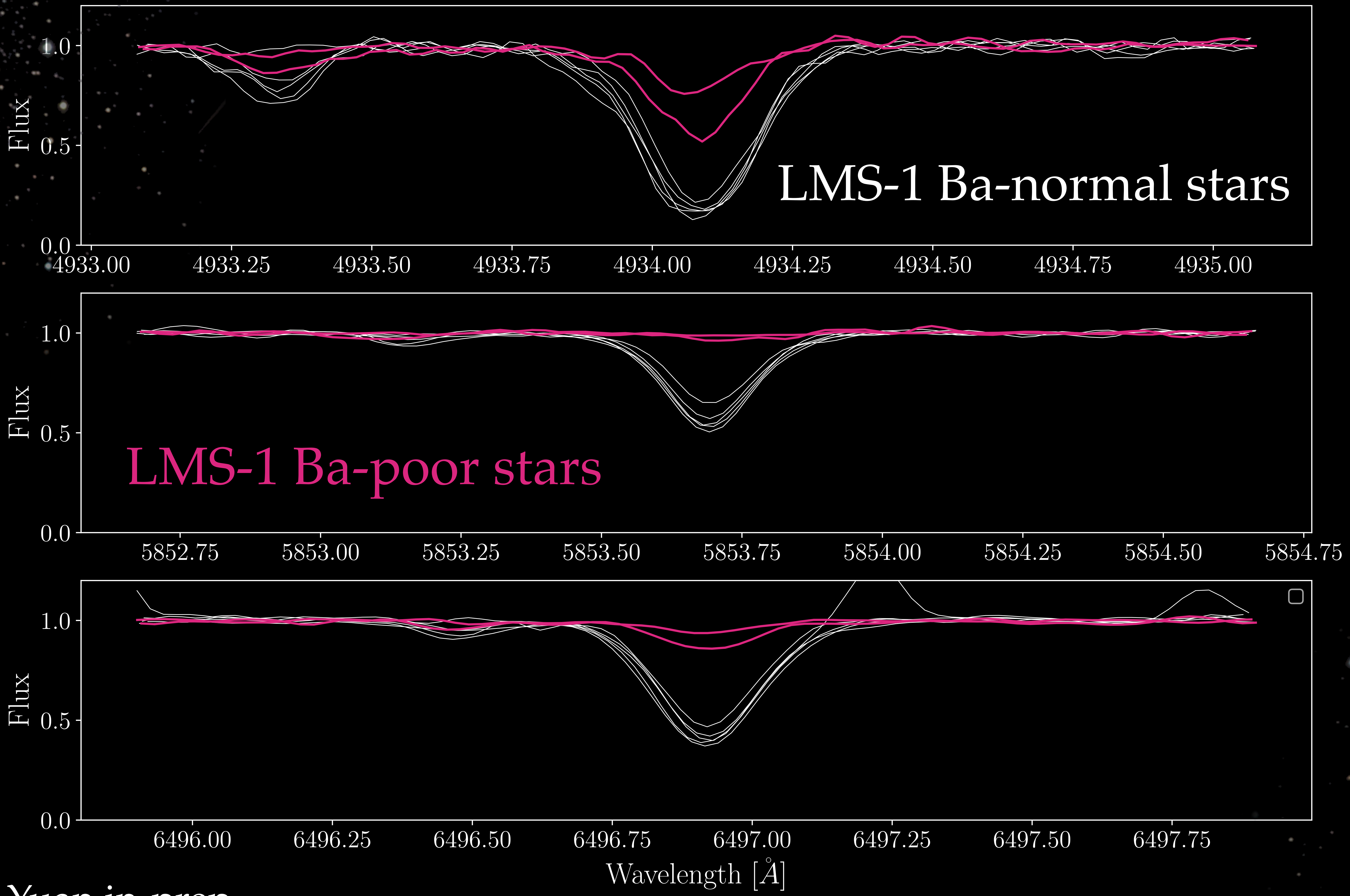
LMS-1, Wukong and Helmi Streams are all very chemically similar! Likely the same object

Data from:
Hill+2019 (Sculptor)
Norris+2017 (Carina)
Ji+2020 (Indus)
Limberg+2024 (Wukong)
Li+2022 (Helmi Streams)

$$\chi^2 = \sum_i \frac{(\mu_{\mathrm{LMS}}^2 - \mu_{\mathrm{gal}}^2)}{\sigma_{\mathrm{LMS}}^2 + \sigma_{\mathrm{gal}}^2 + \sigma_{\mathrm{LMS,ave.err}}^2 + \sigma_{\mathrm{gal,ave.err}}^2}$$

ESO/L. Calçada

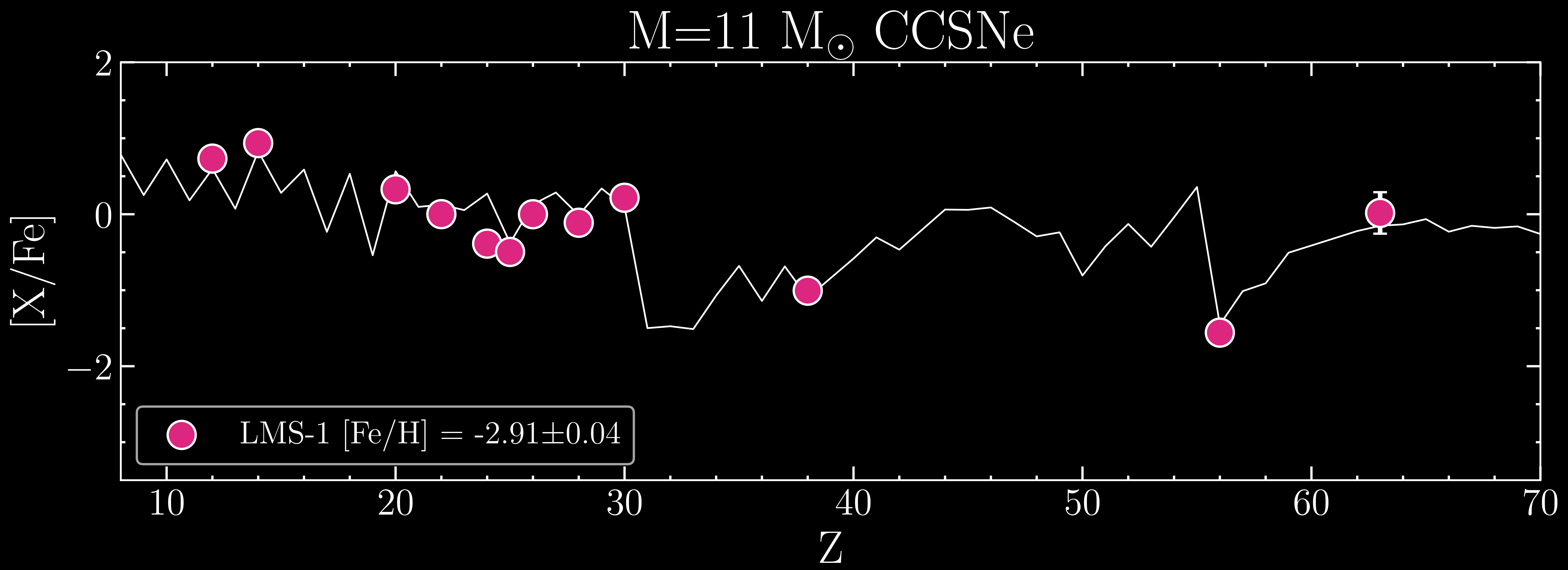
Chemical abundance results: a visibly large spread in Ba



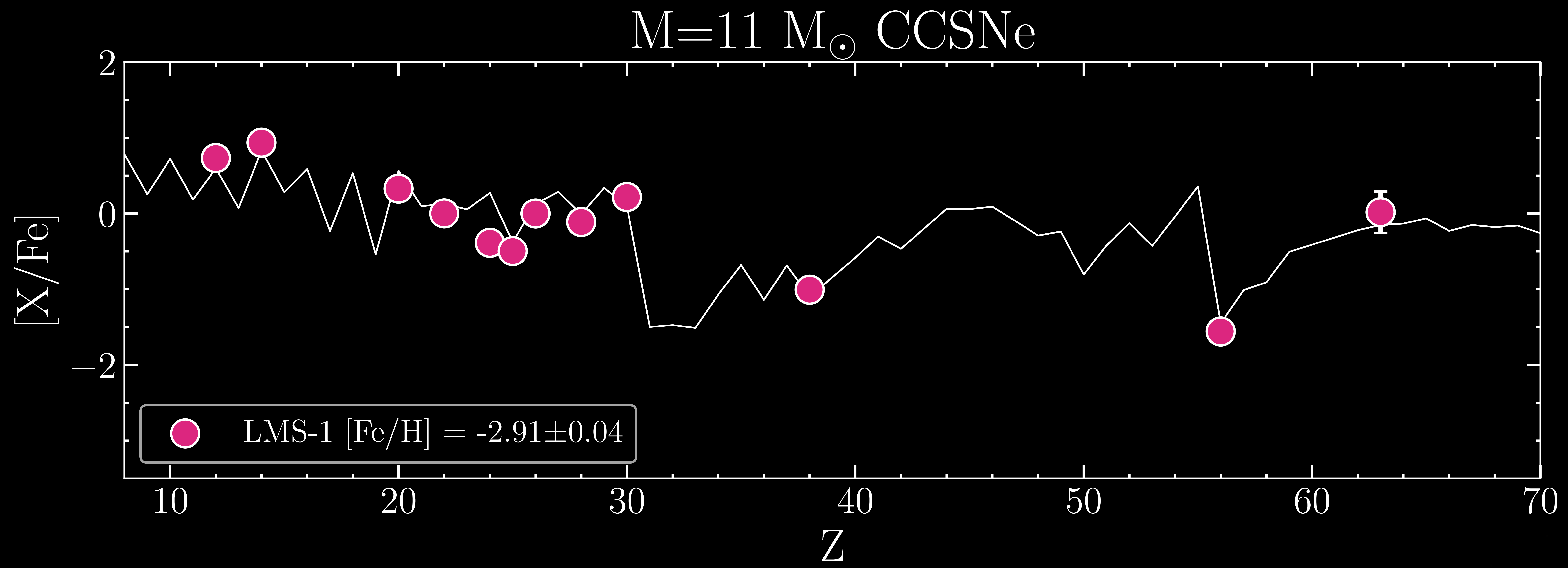
Monty, Matsuno & Yuan in-prep

ESO/L. Calçada

Single Pop III progenitor fit to the most metal-poor LMS-1 star



Single Pop III progenitor fit to the most metal-poor LMS-1 star



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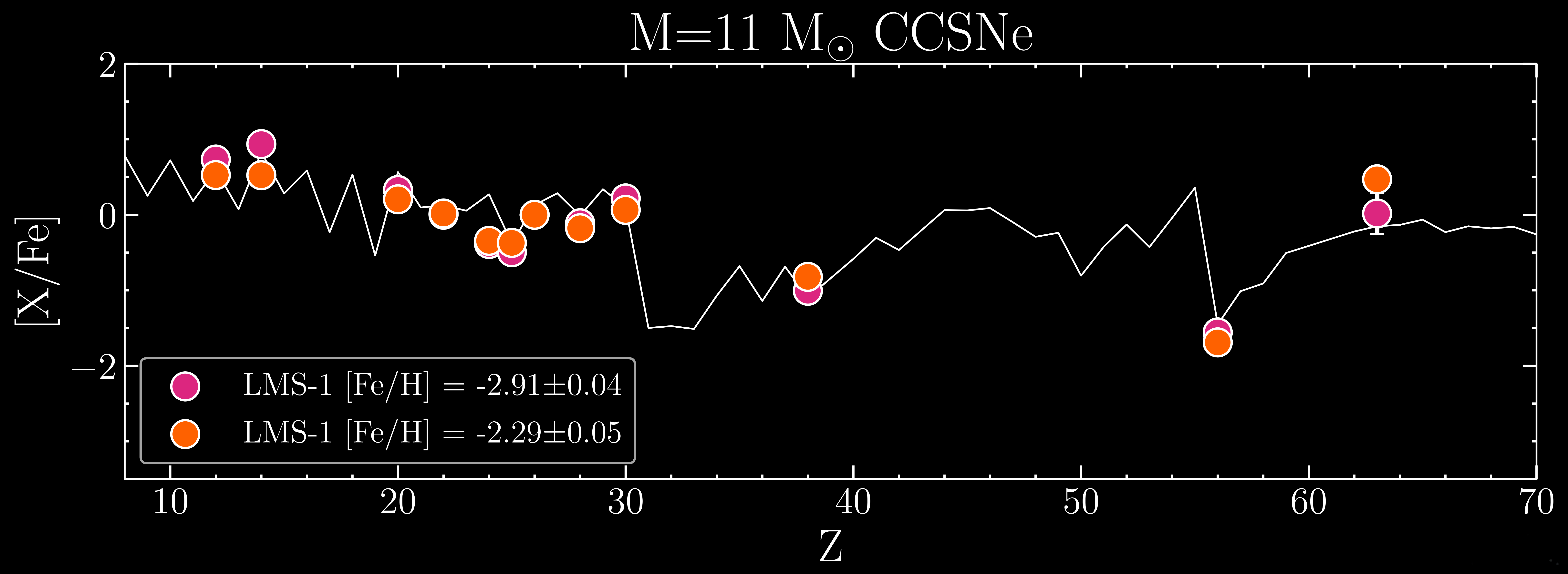

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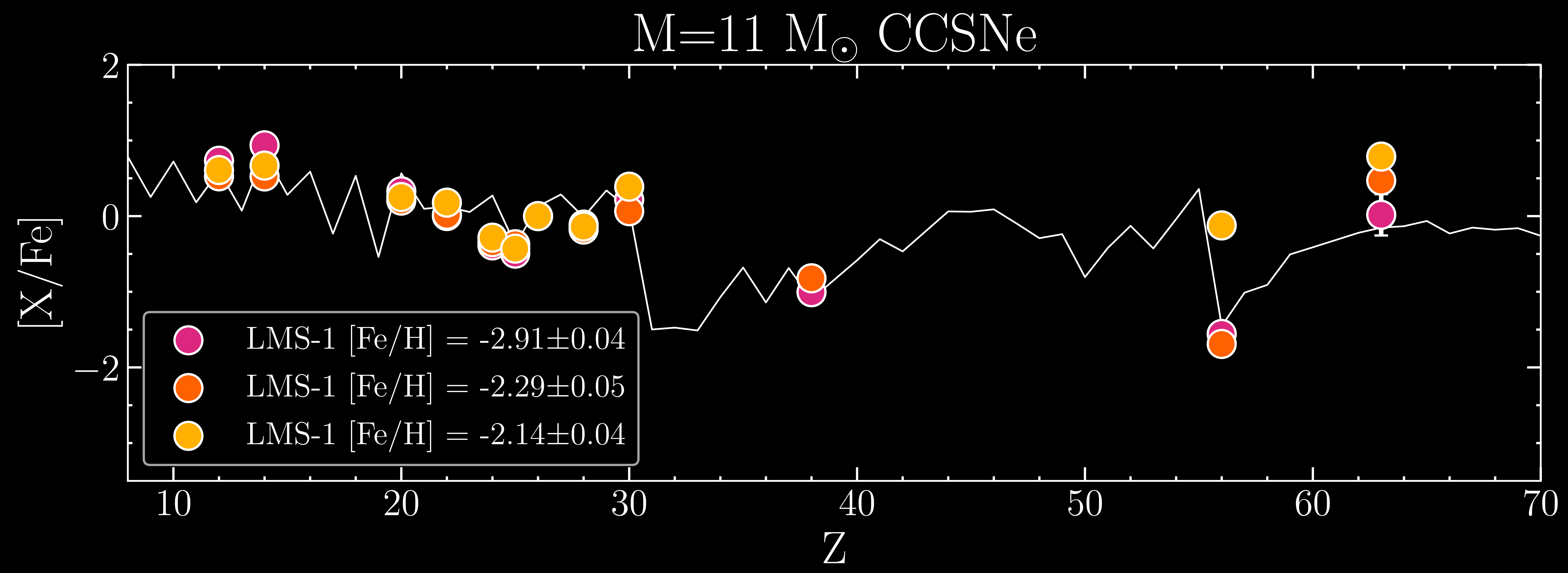

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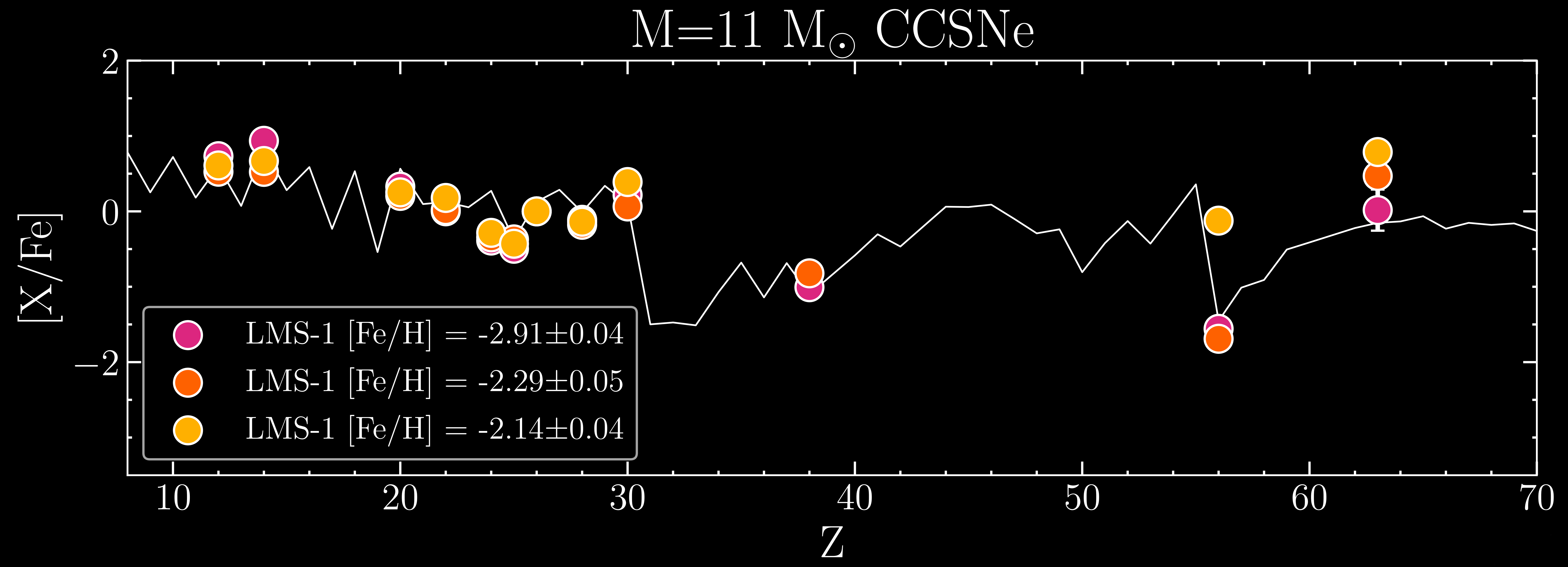

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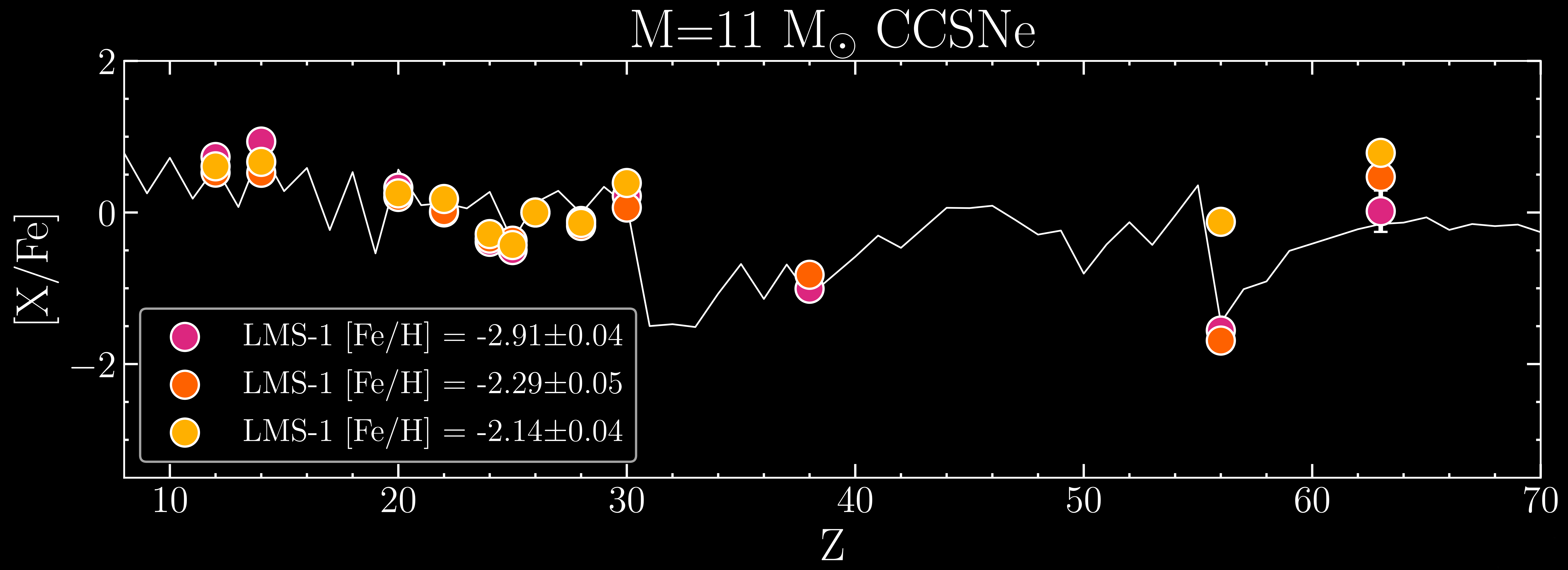

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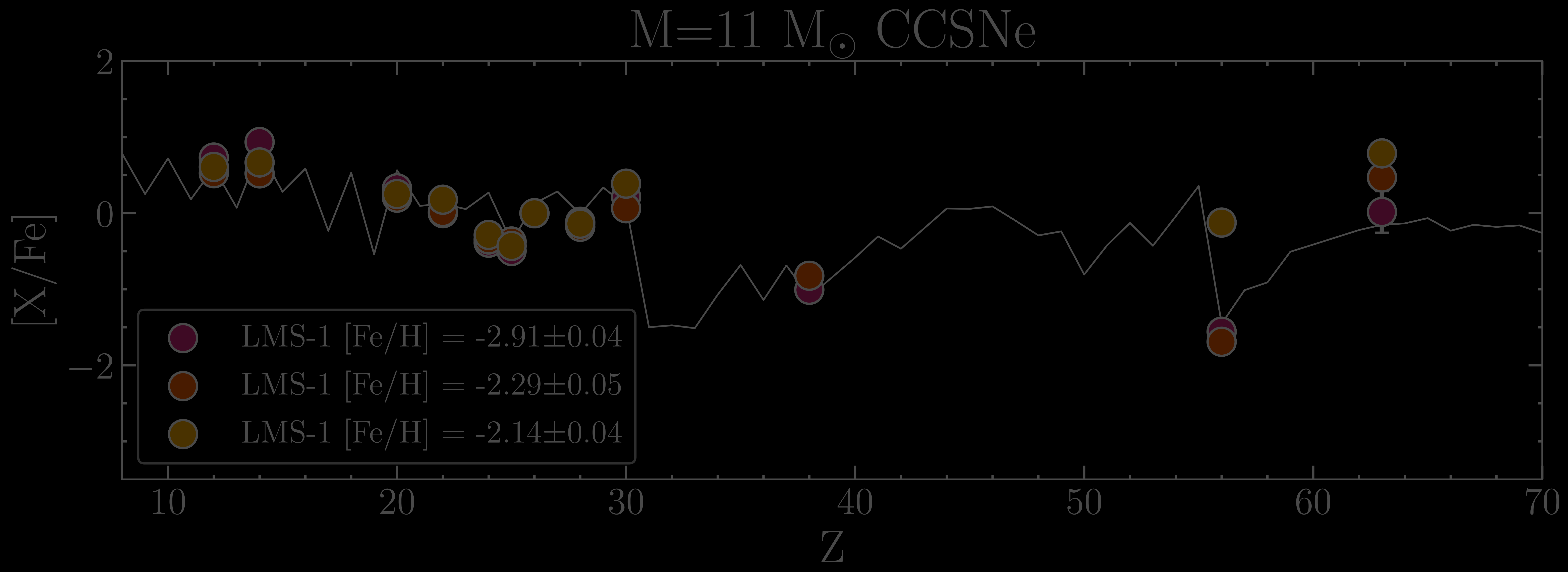

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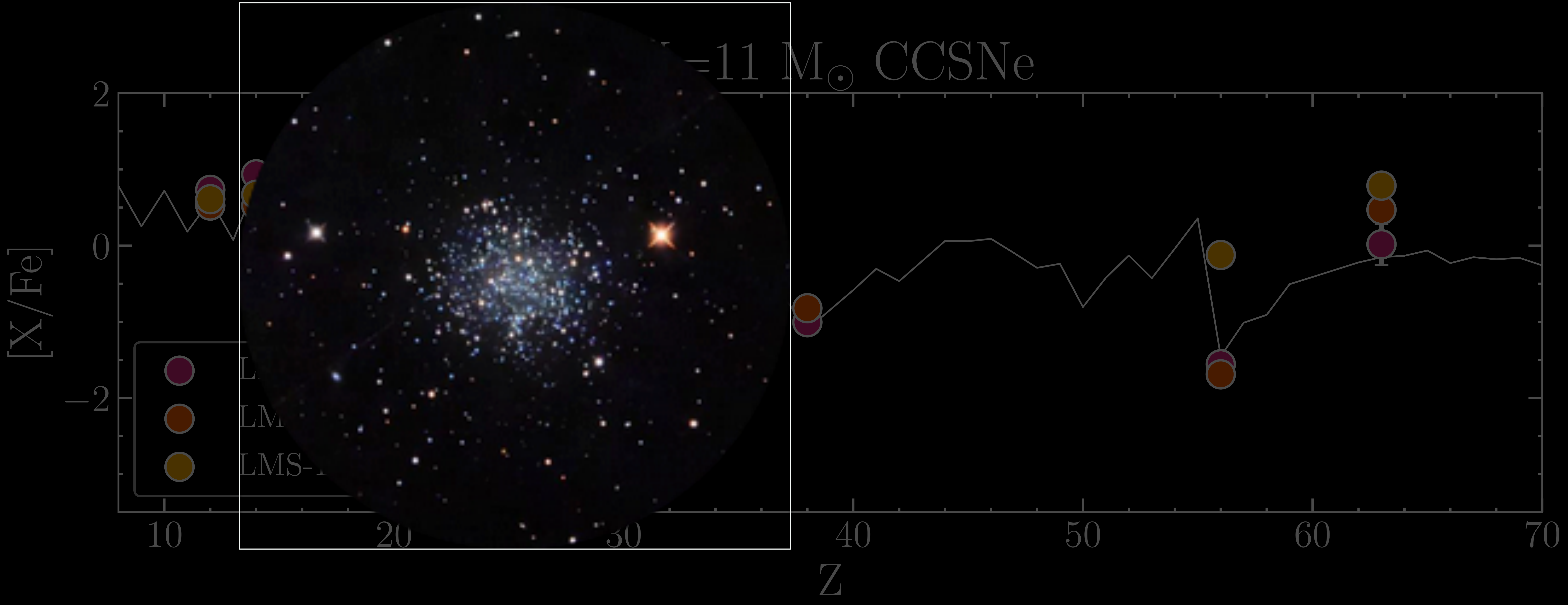

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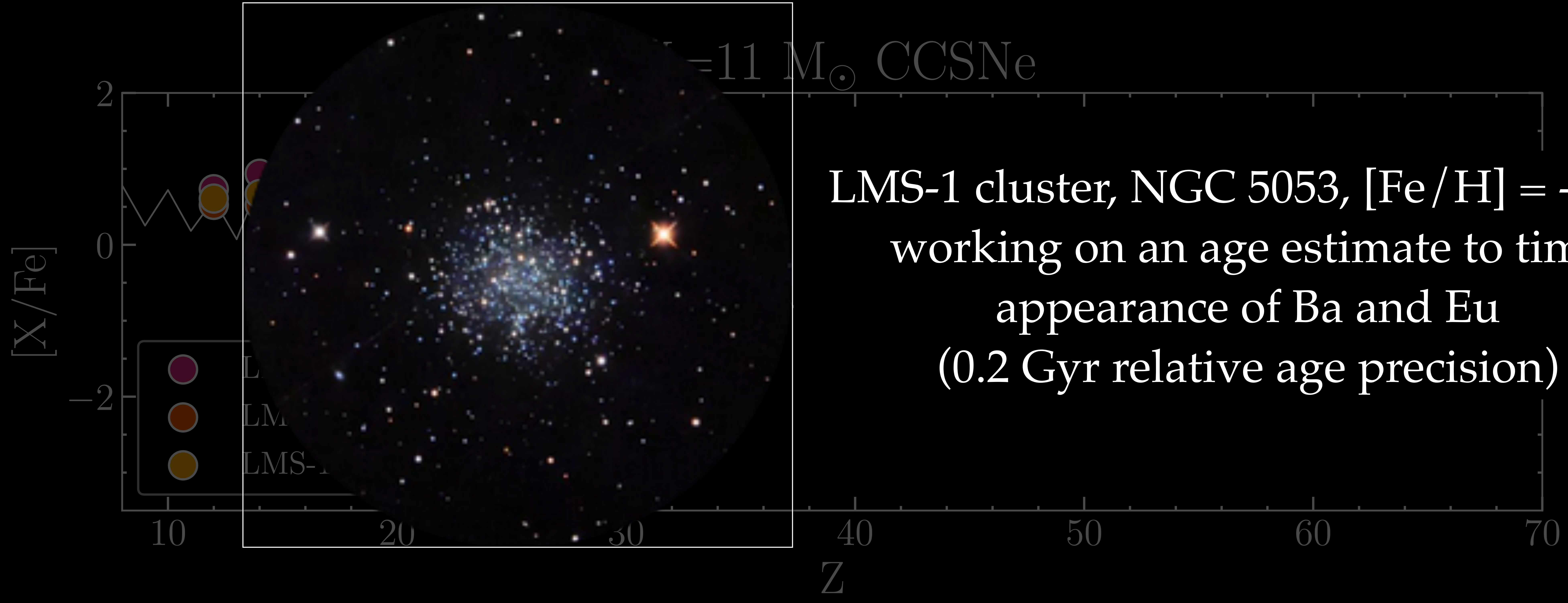

LMS-1 cluster, NGC 5053, [Fe/H] = -2.17!
working on an age estimate to time appearance of Ba and Eu
(0.2 Gyr relative age precision)

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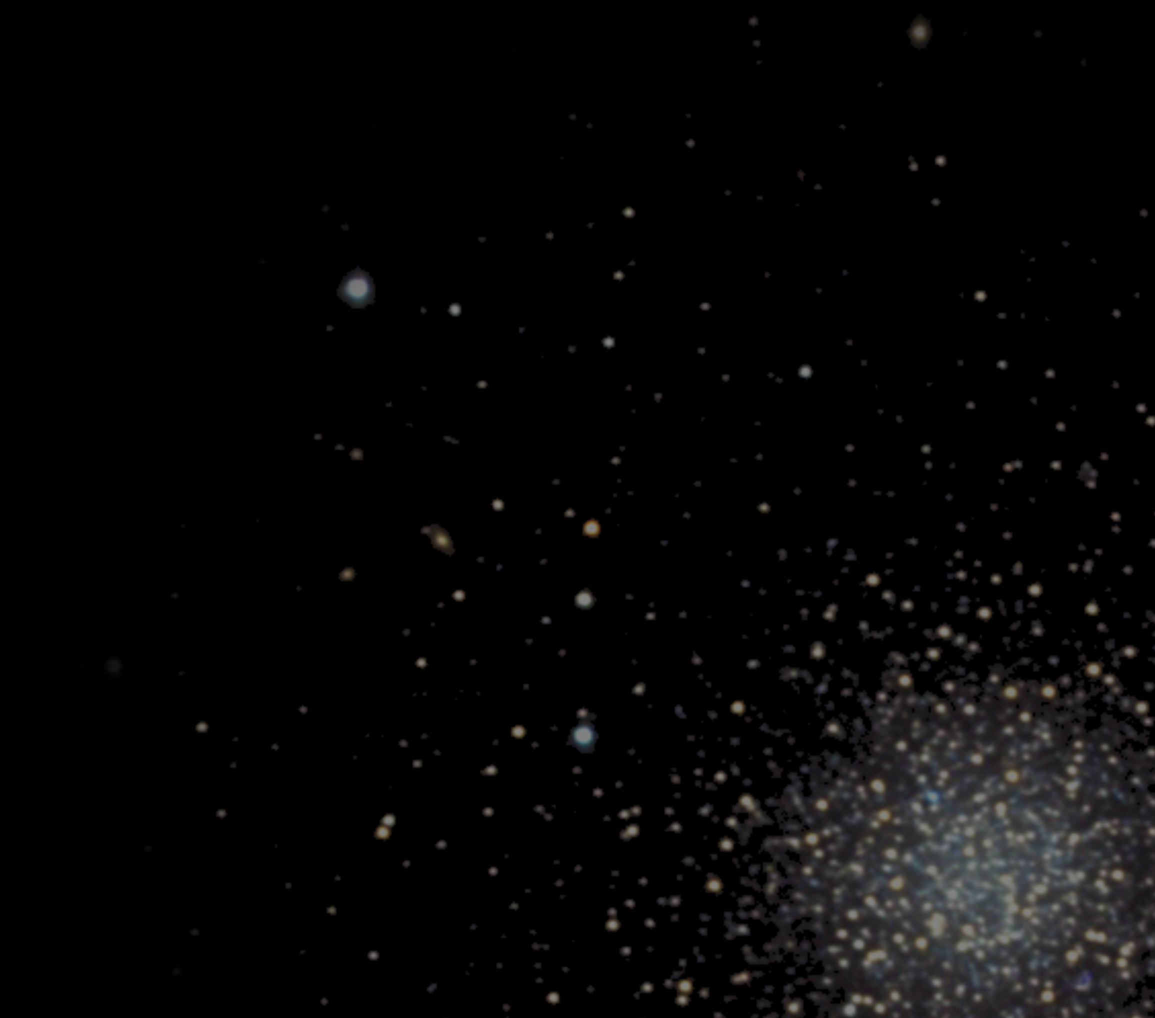

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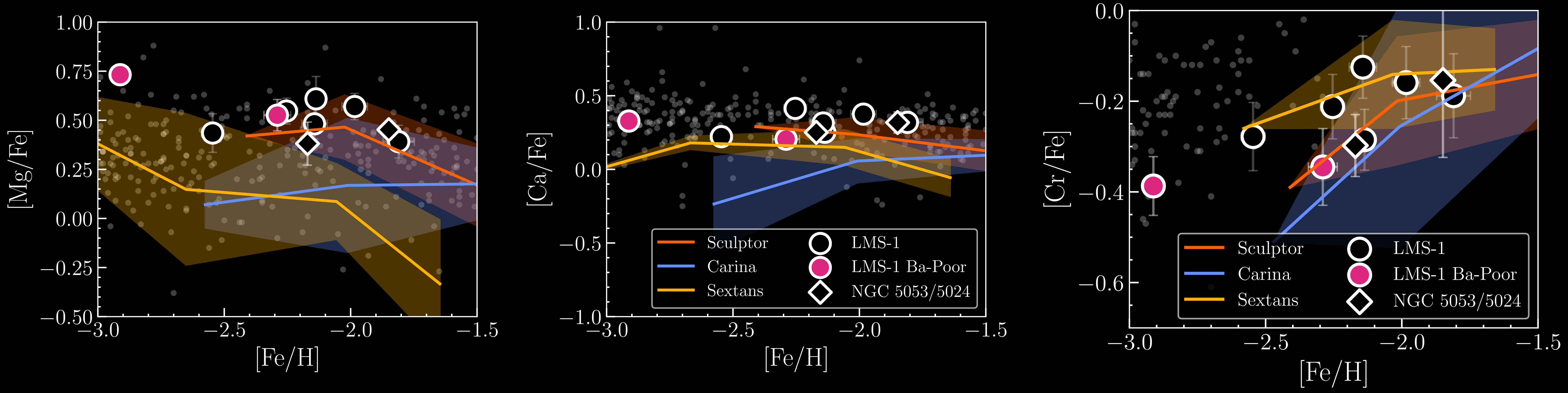
Extra Slides

Chemical Abundance Results: dGal vs. Others



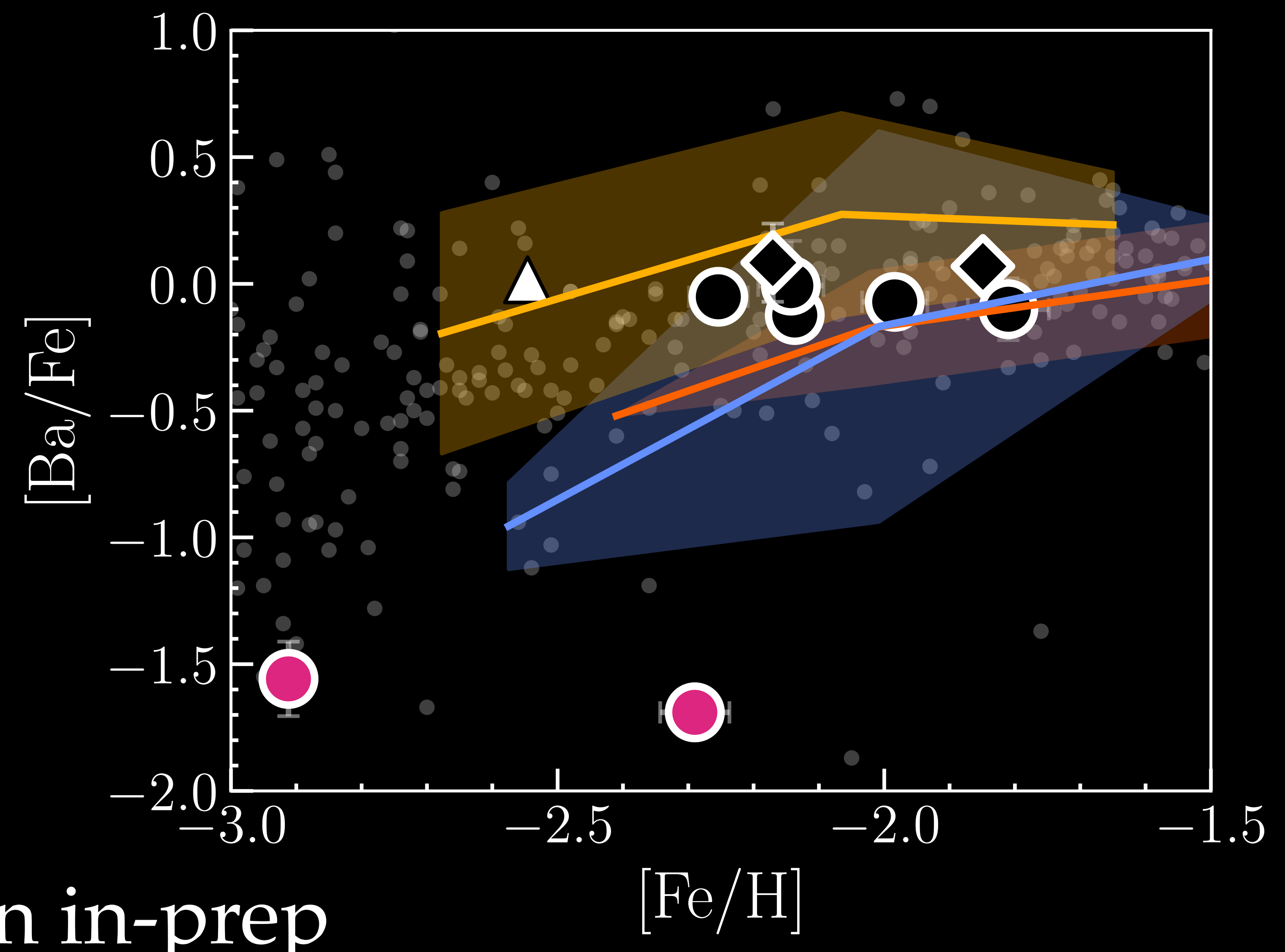
Sculptor (Hill+ 2019)

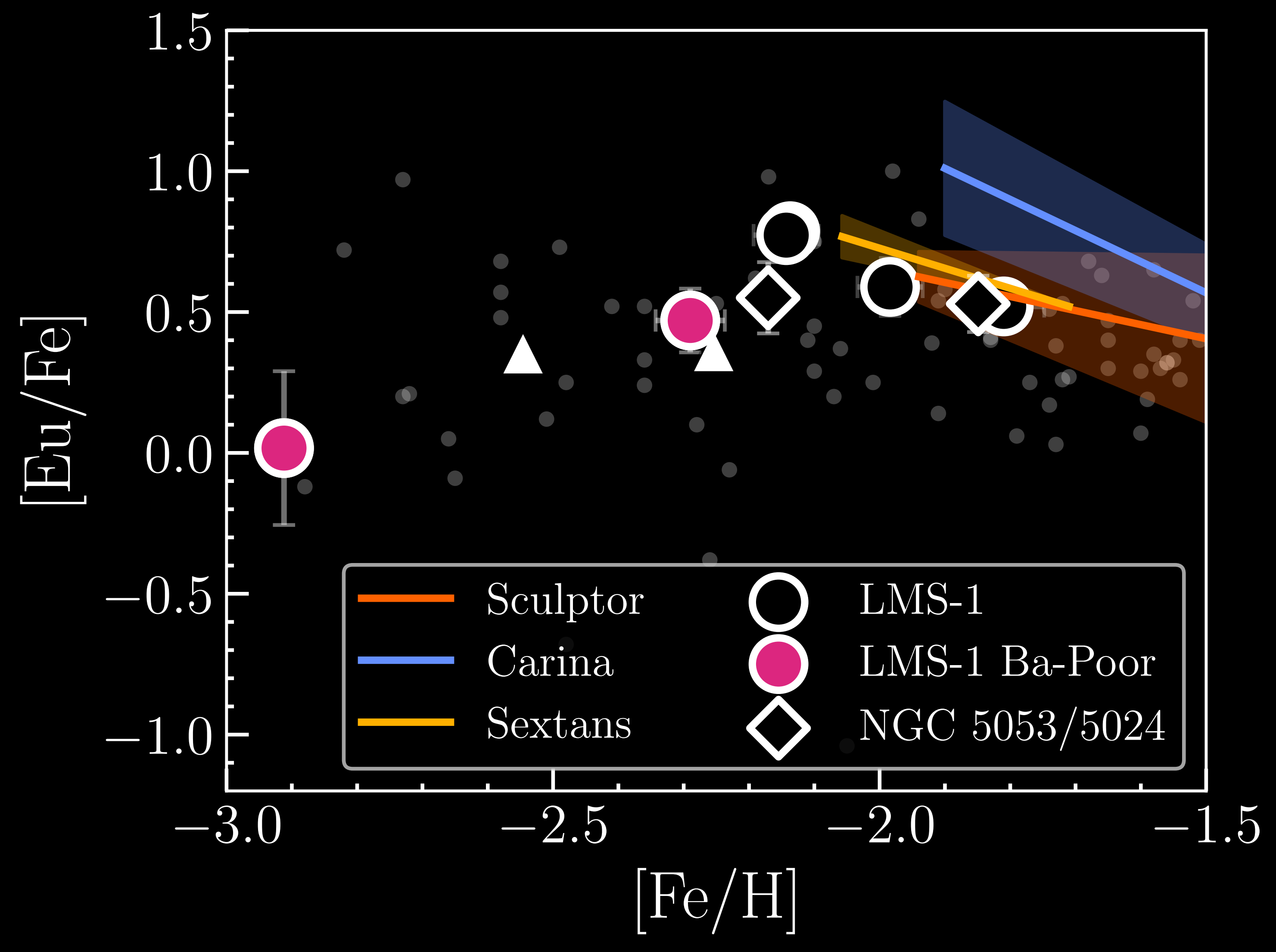
Carina (Norris+ 2017)

Sextans (Theler+ 2020)

LMS-1 Ba-poor stars

LMS-1 Stars





Monty, Matsuno & Yuan in-prep

ESO/L. Calçada

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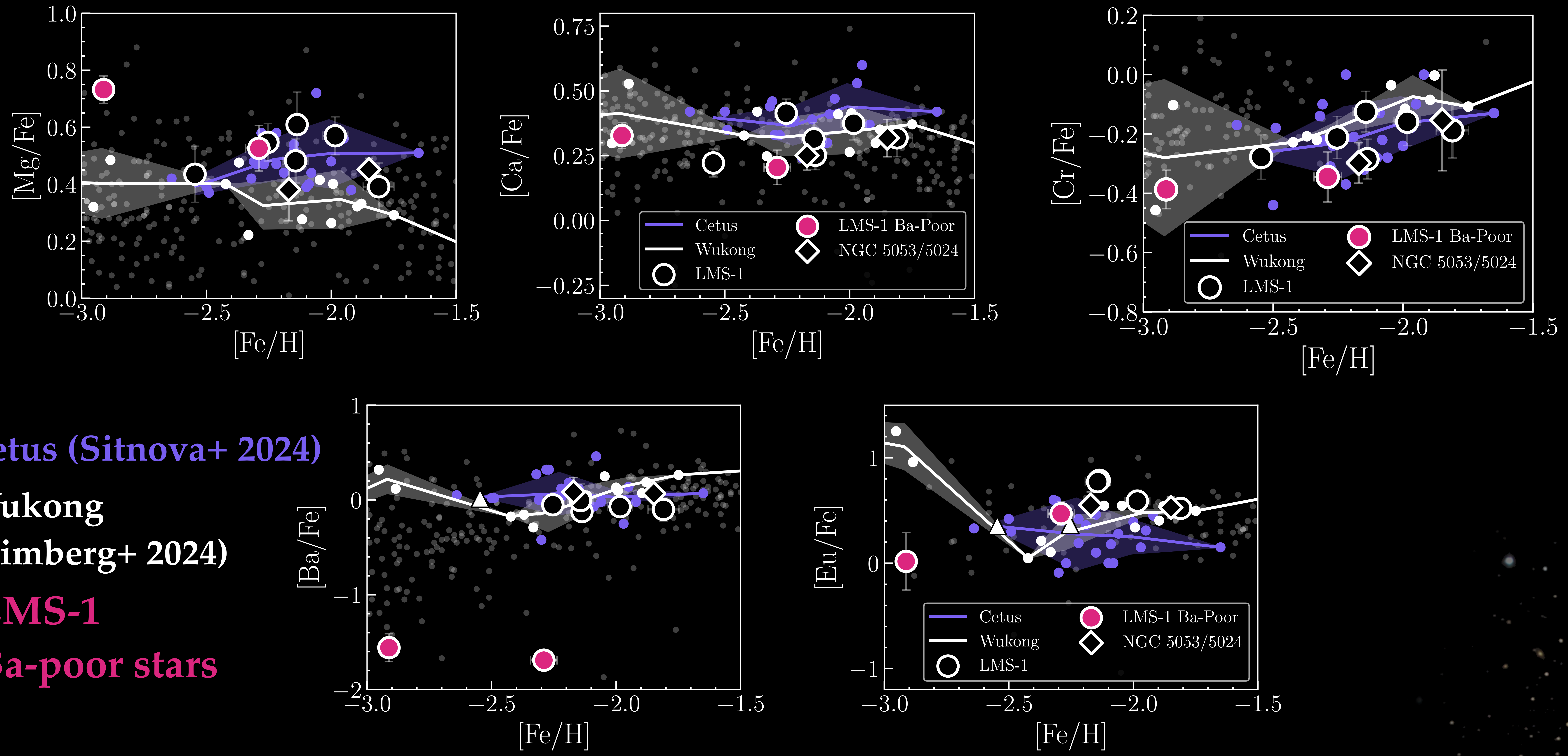

Cetus (Sitnova+ 2024)

Wukong (Limberg+ 2024)

LMS-1

Ba-poor stars

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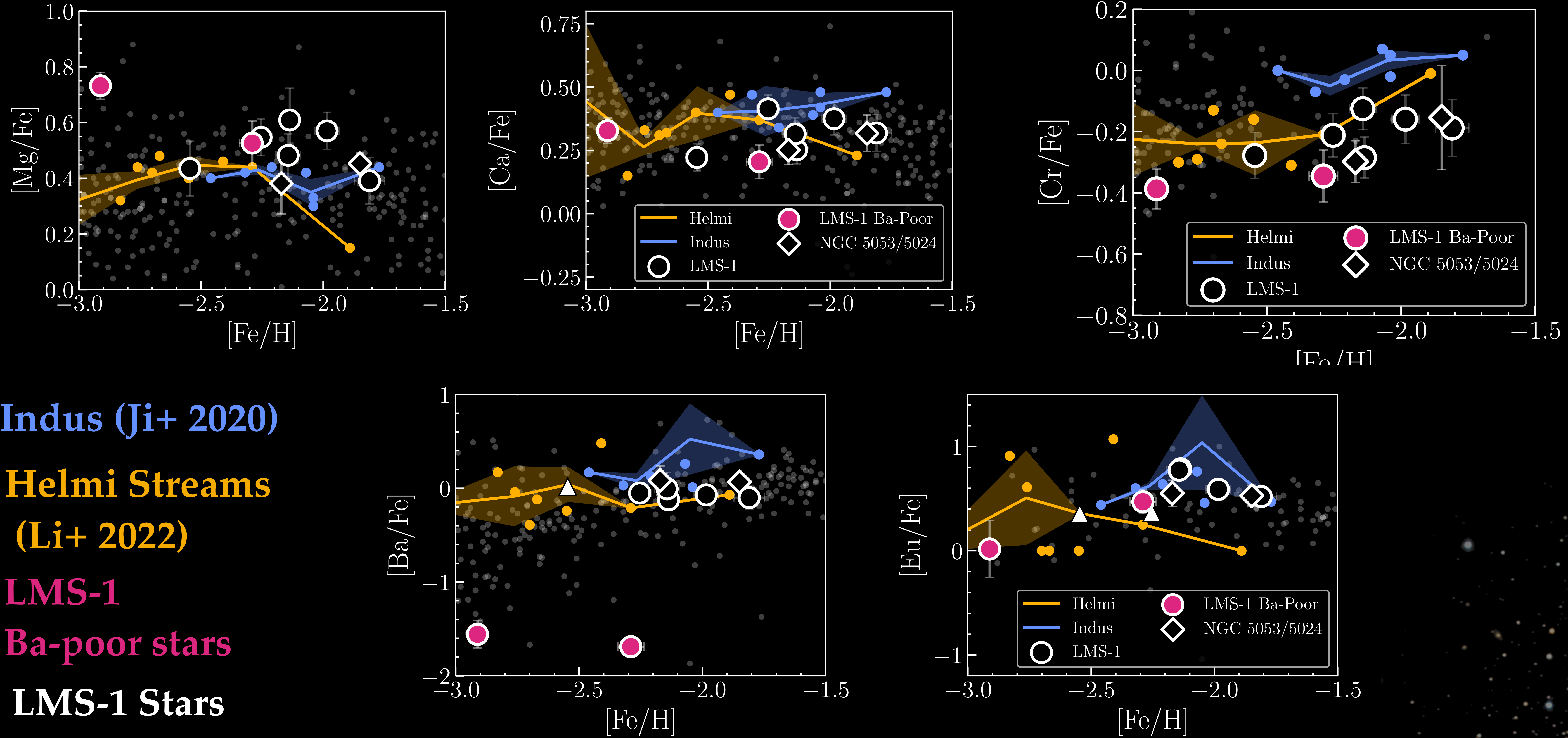

Indus (Ji+ 2020)

Helmi Streams (Li+ 2022)

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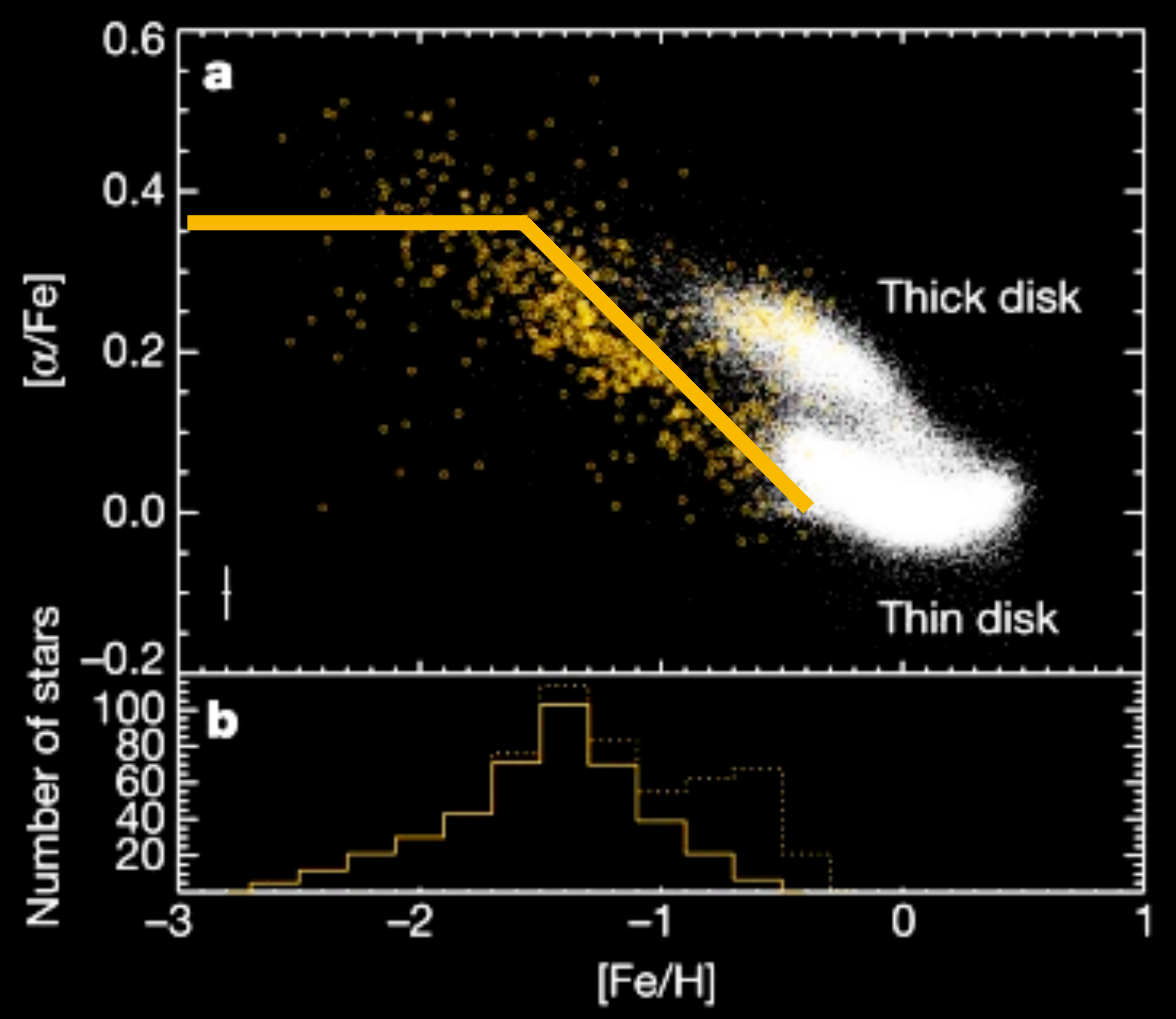
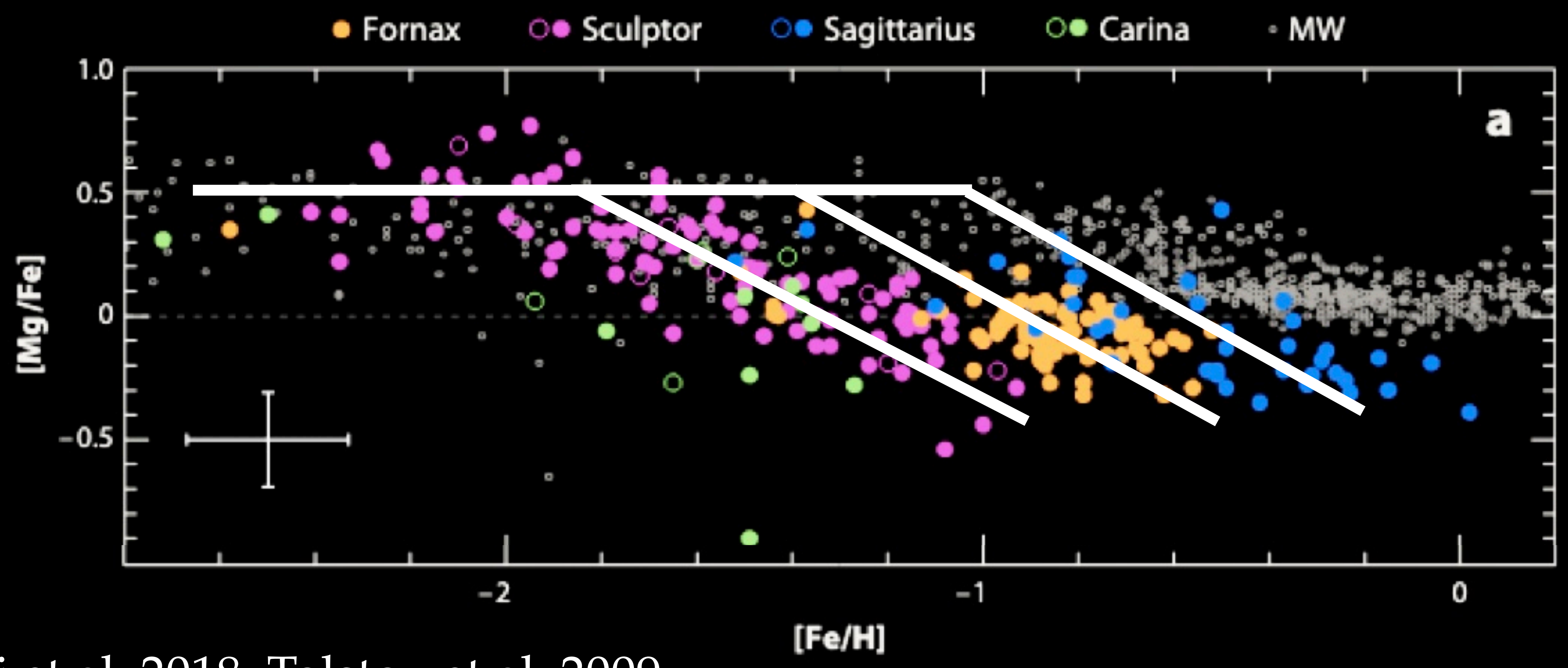
Gaia-Sausage-Enceladus has a unique signature in [Eu/α]





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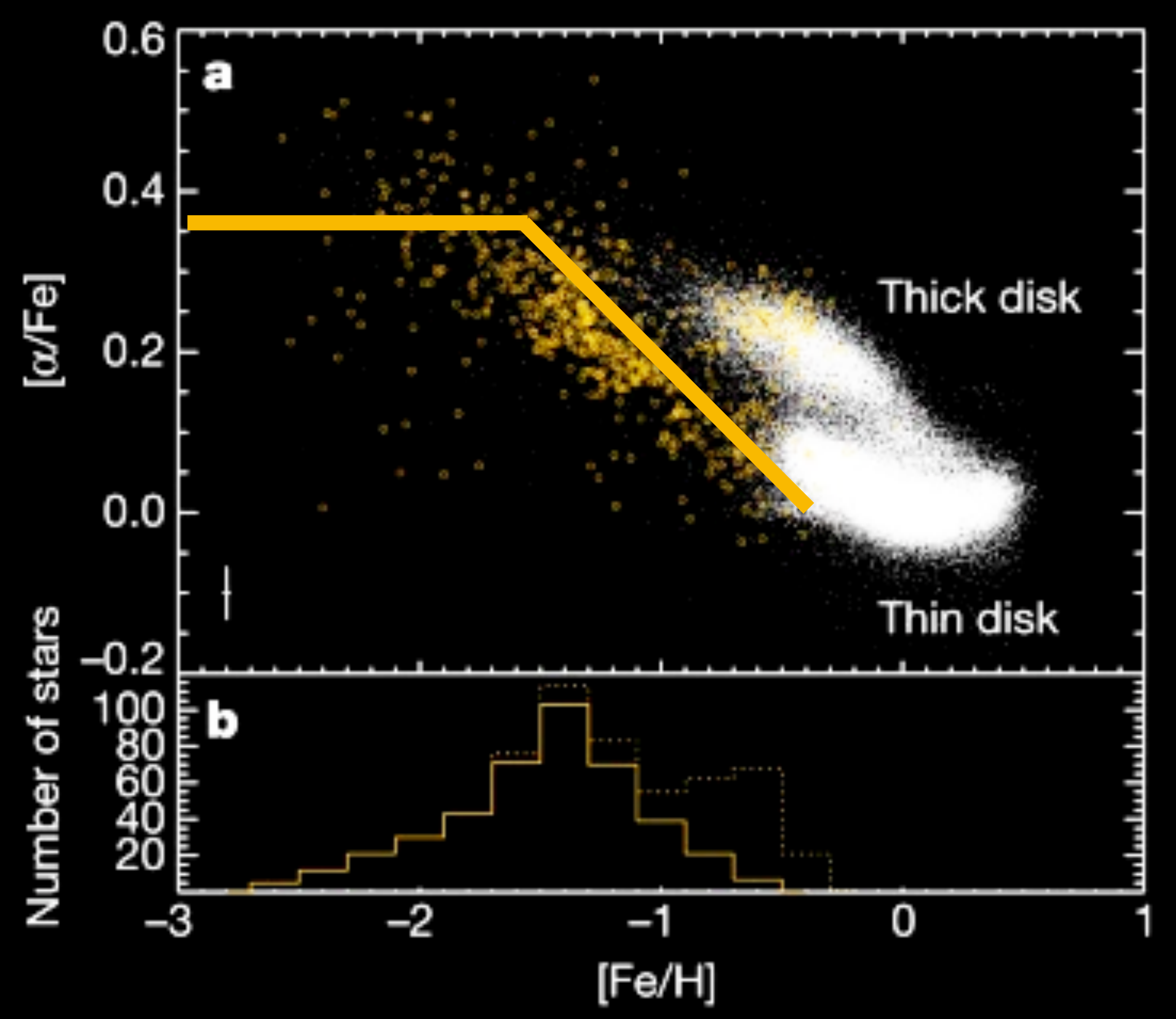
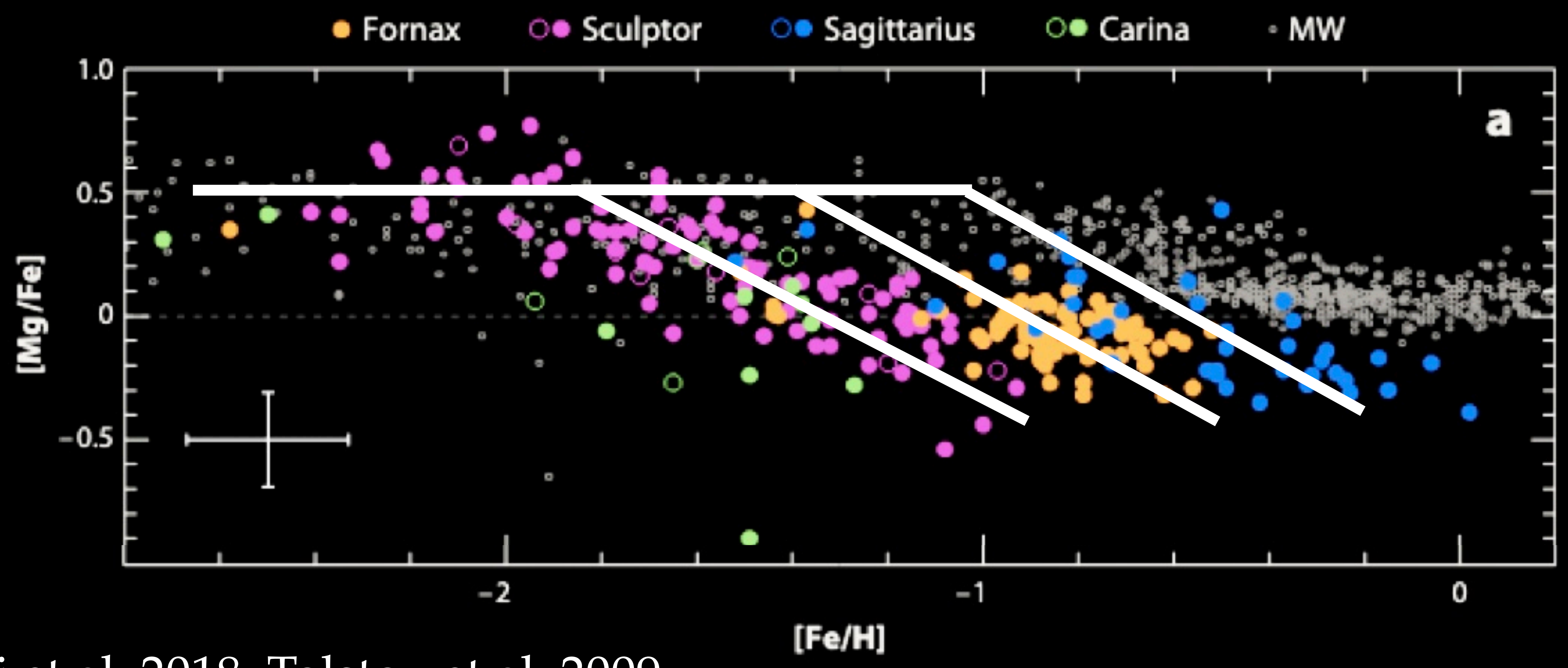


[α/Fe] encodes star formation history



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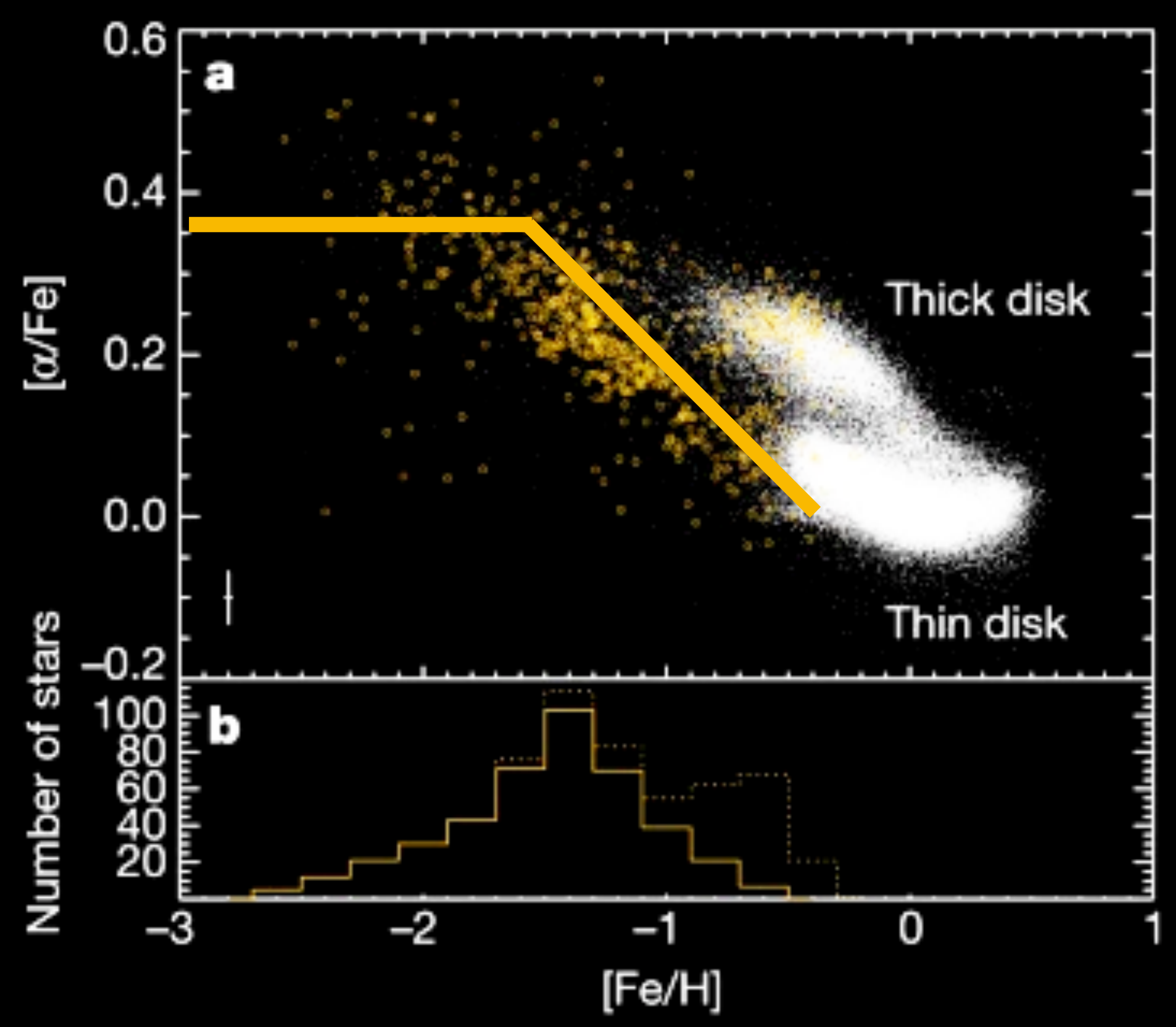

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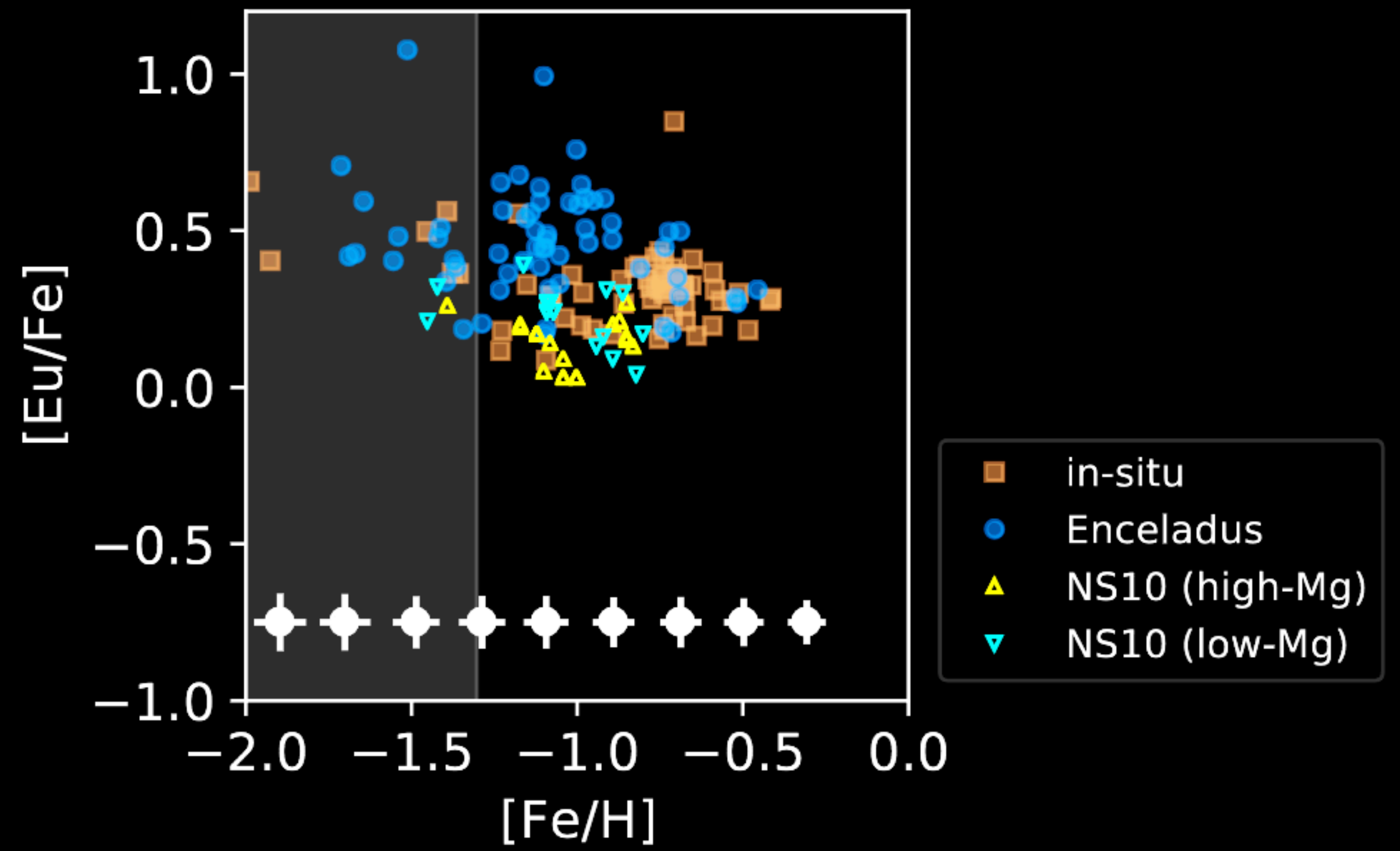

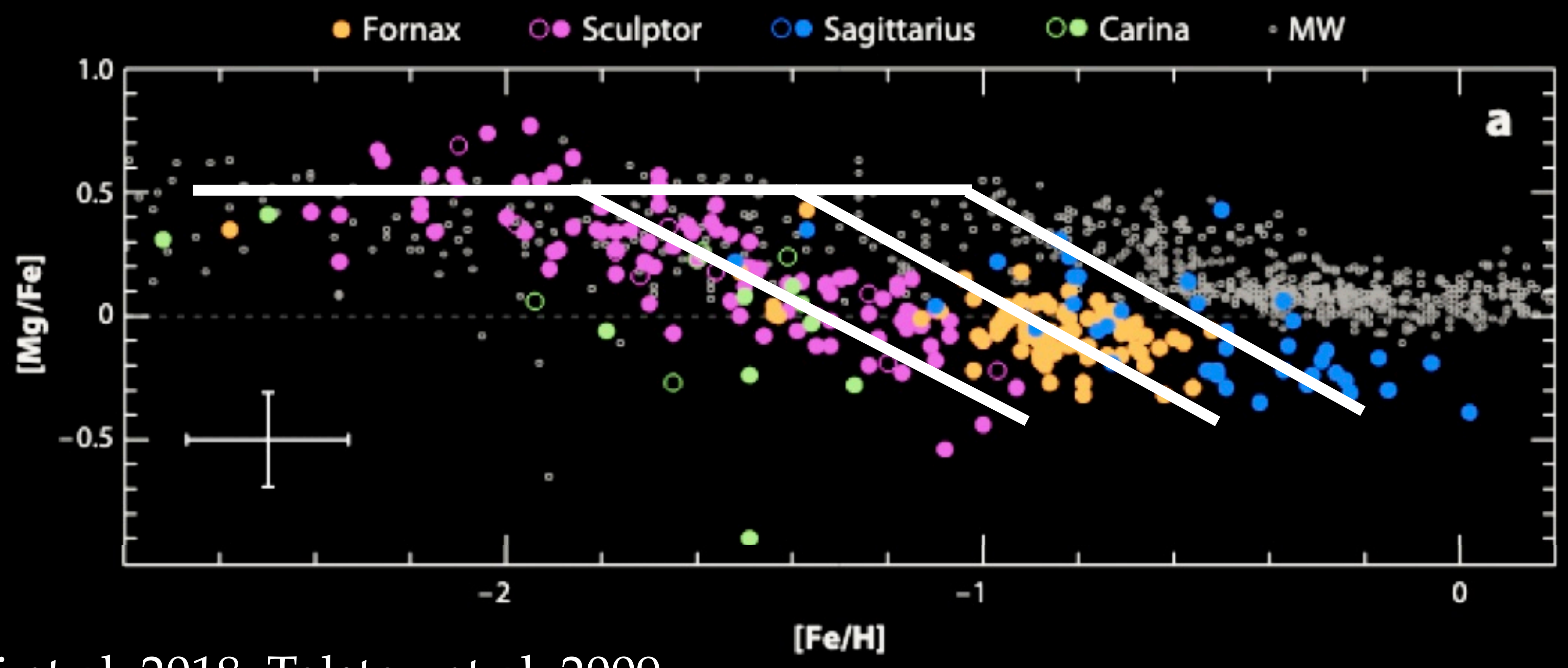

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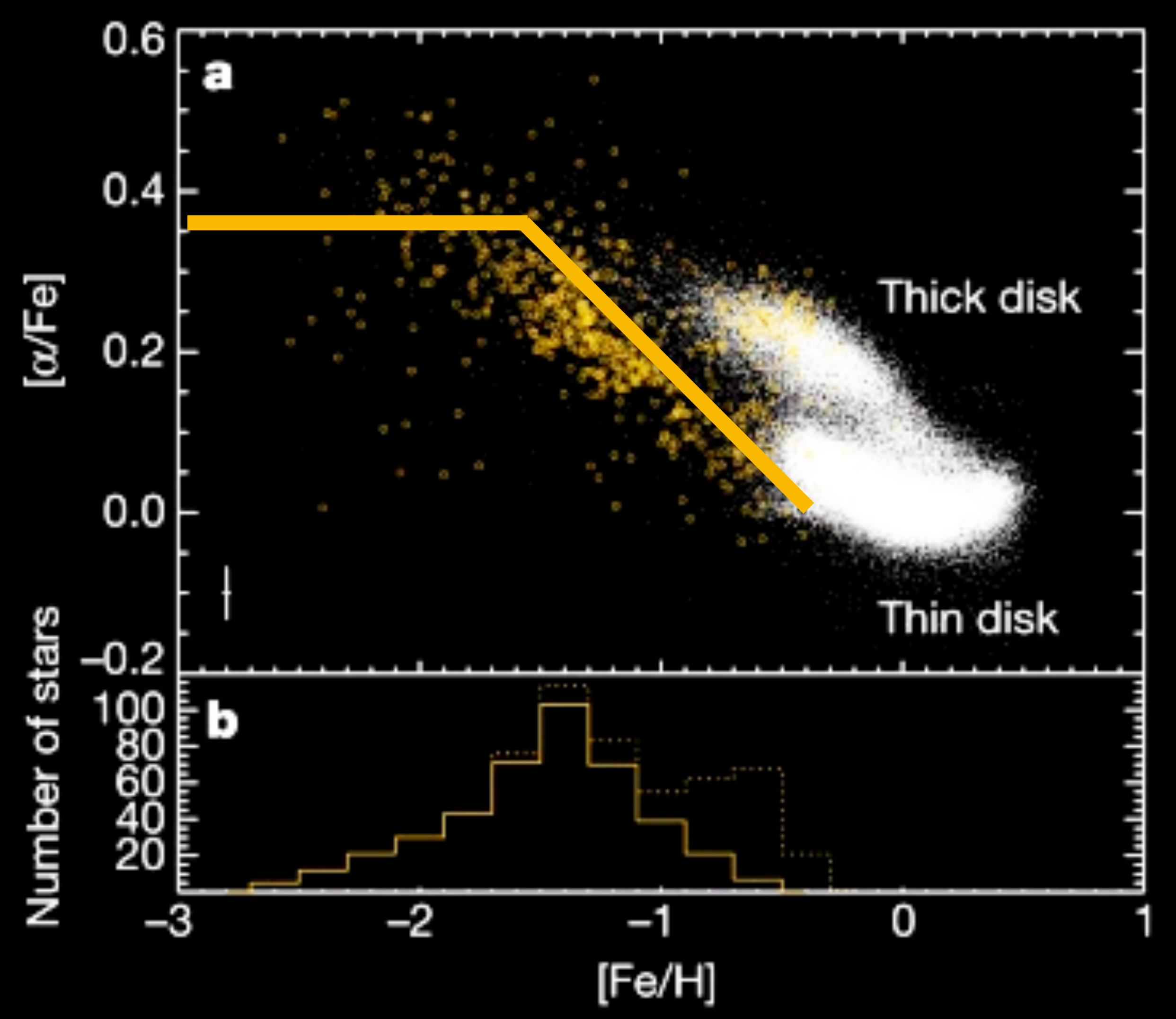

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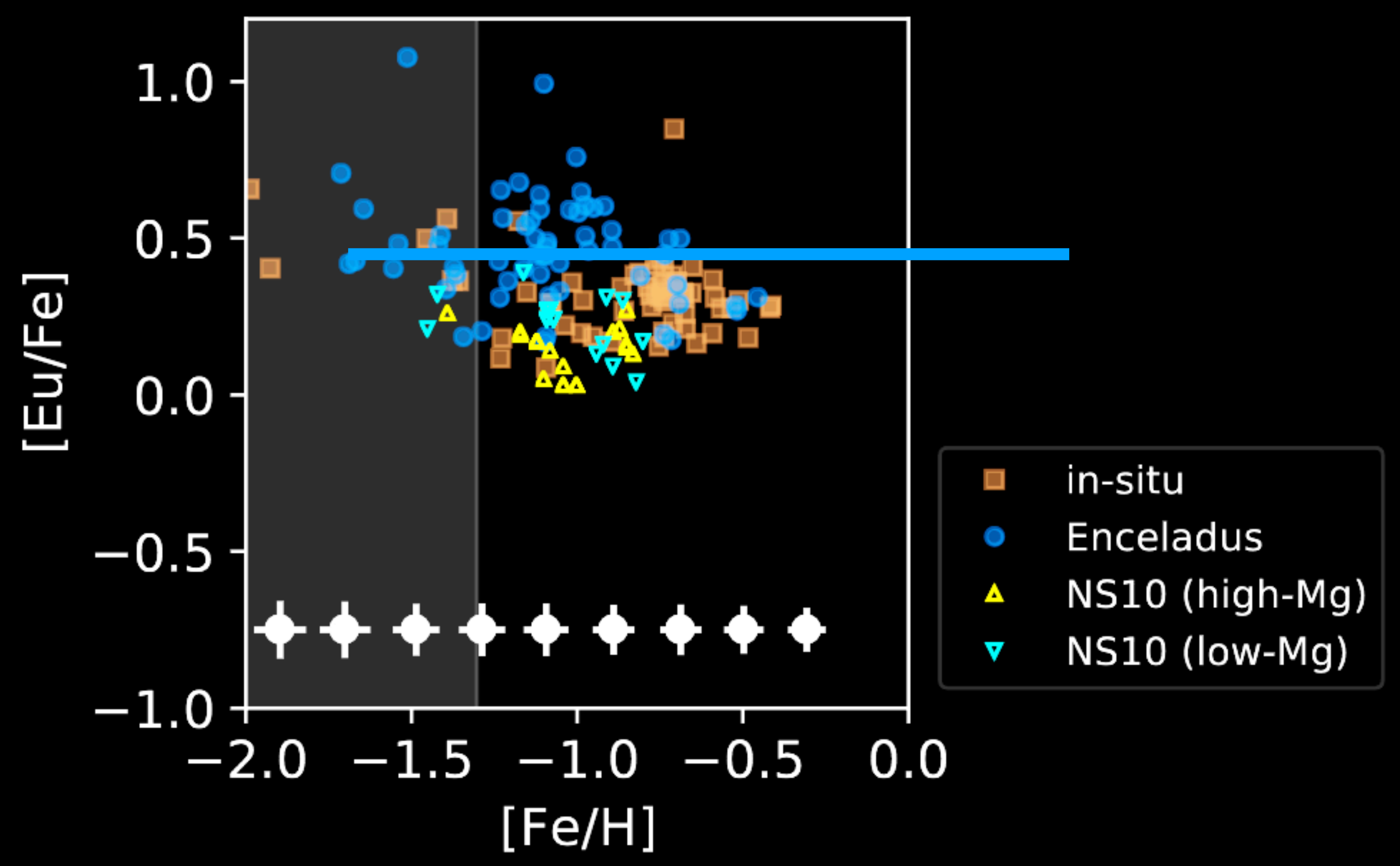

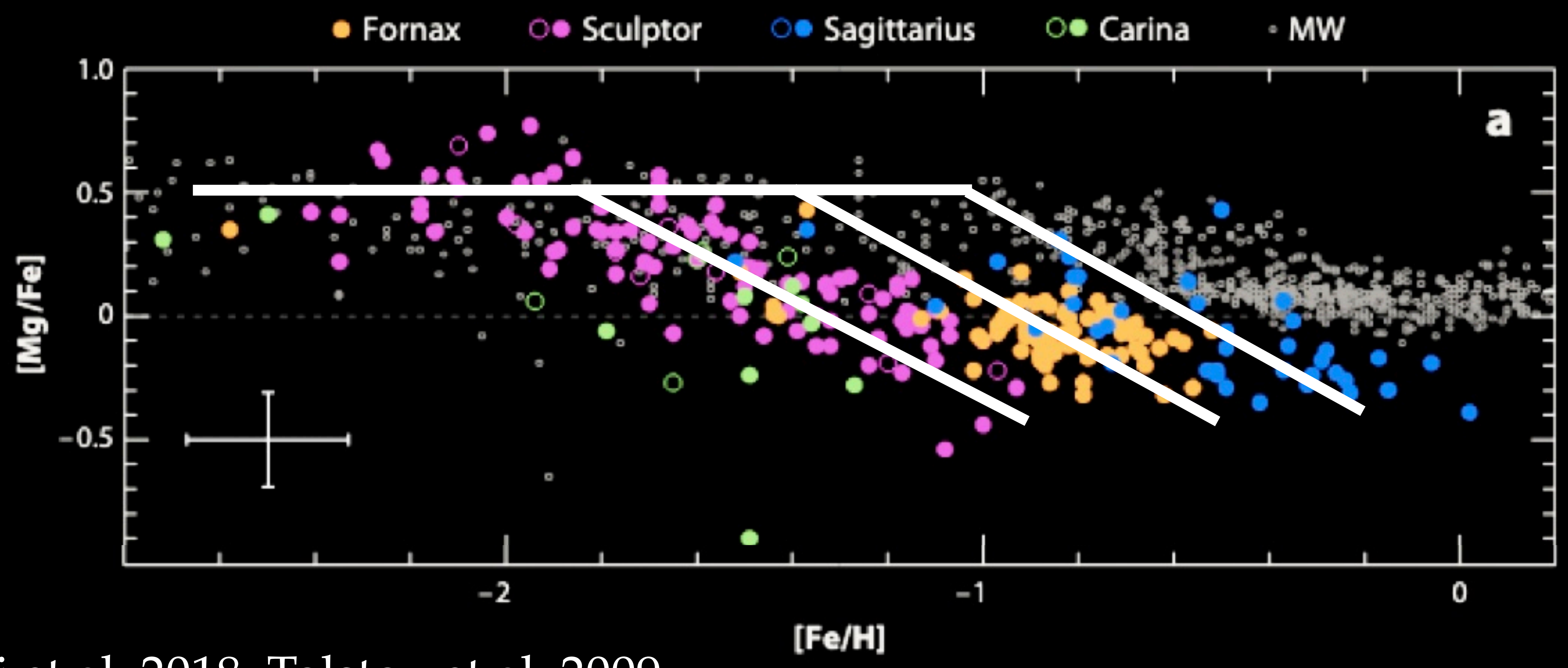

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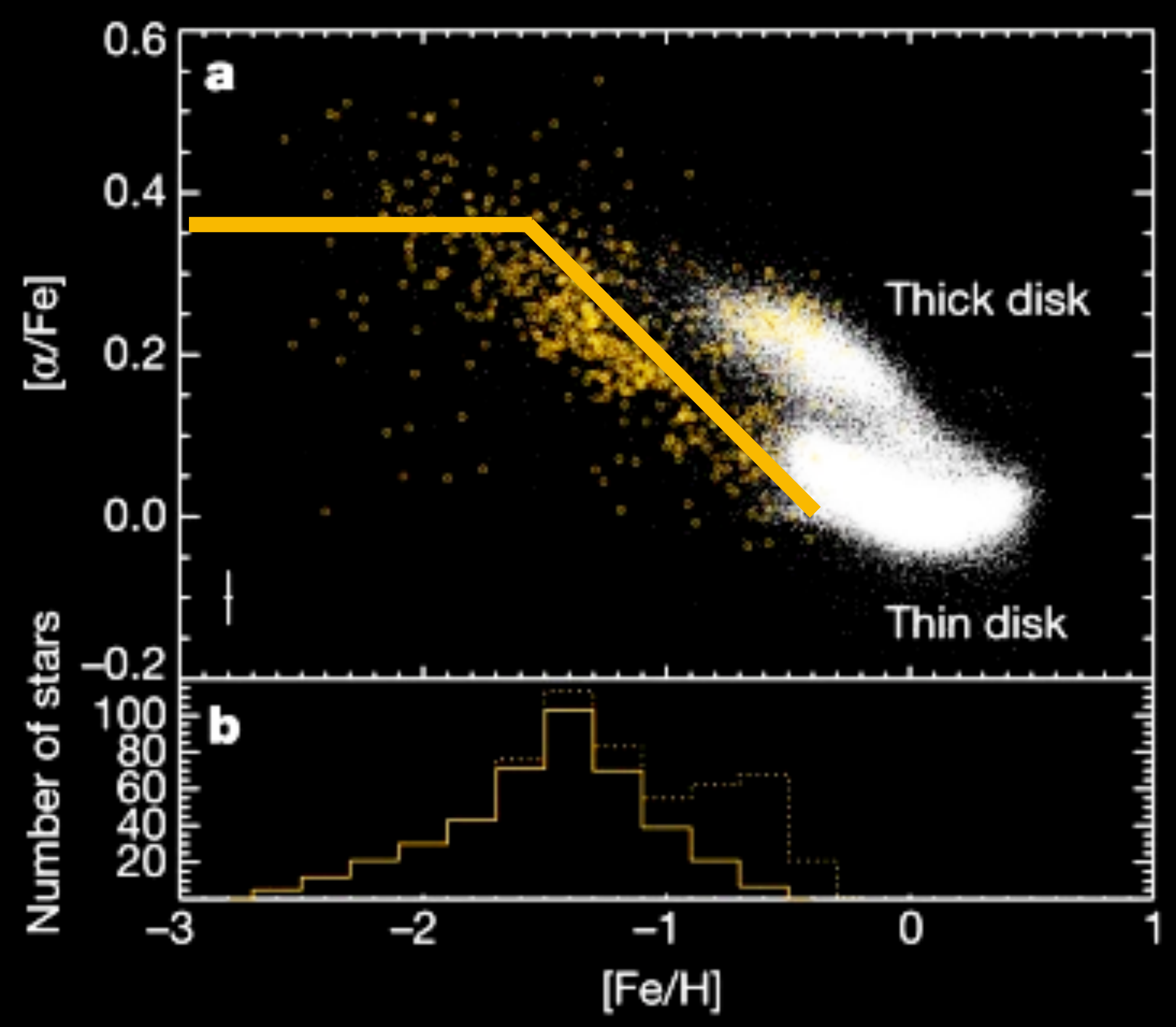

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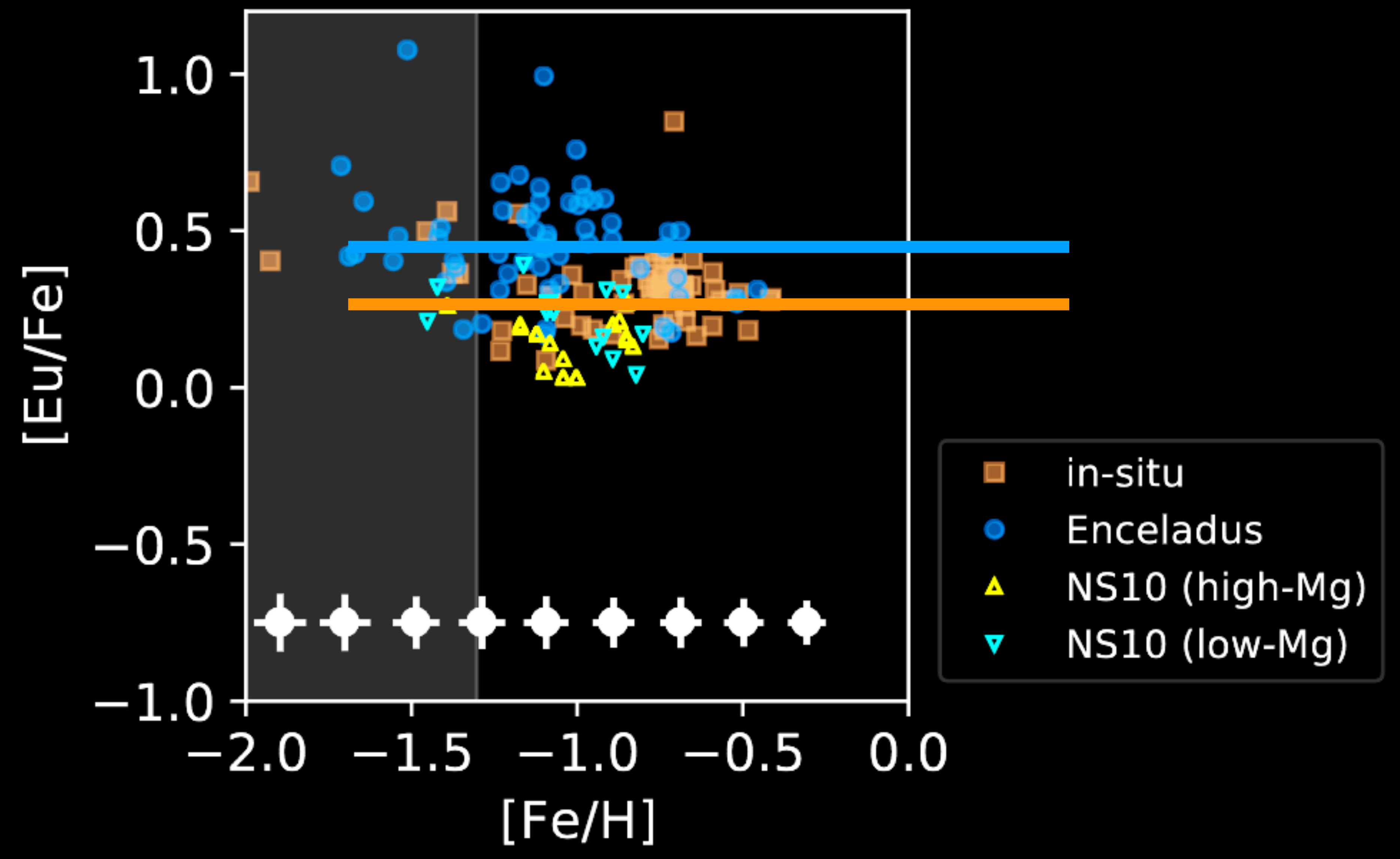

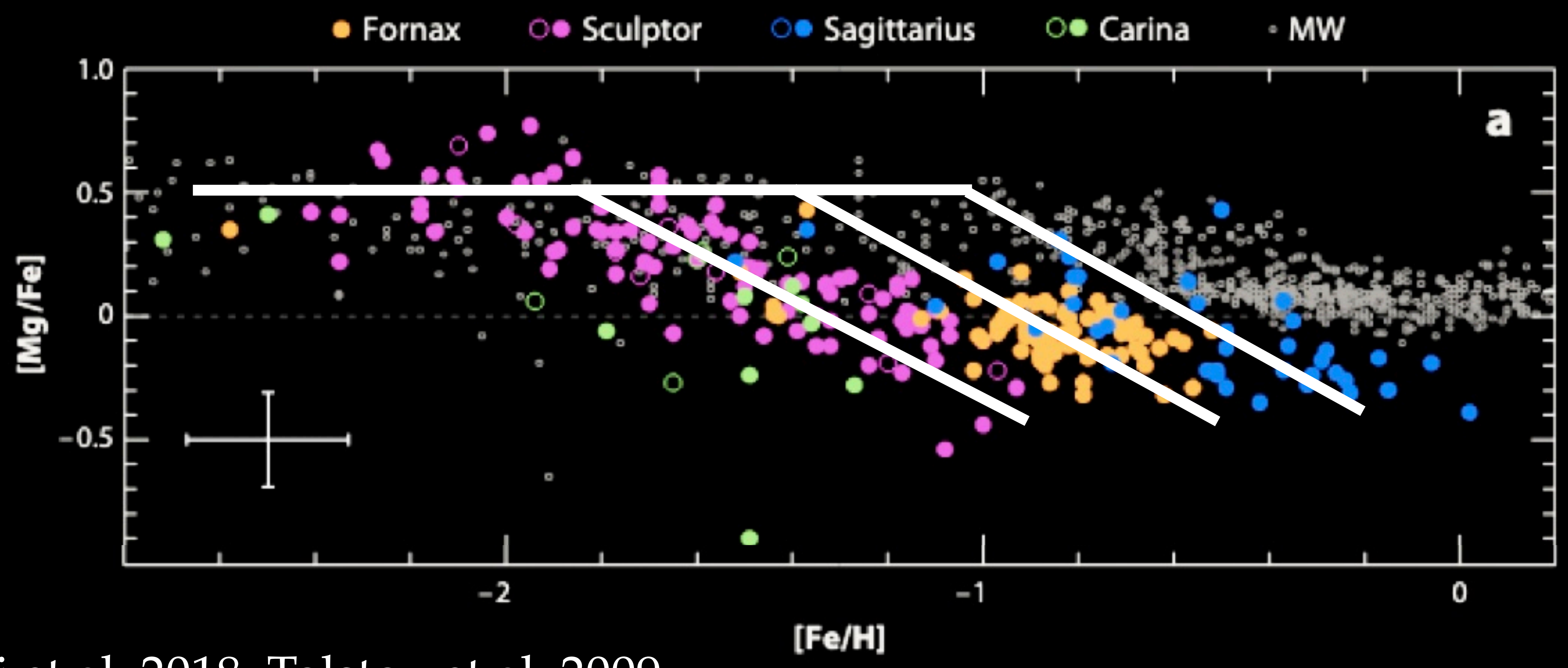

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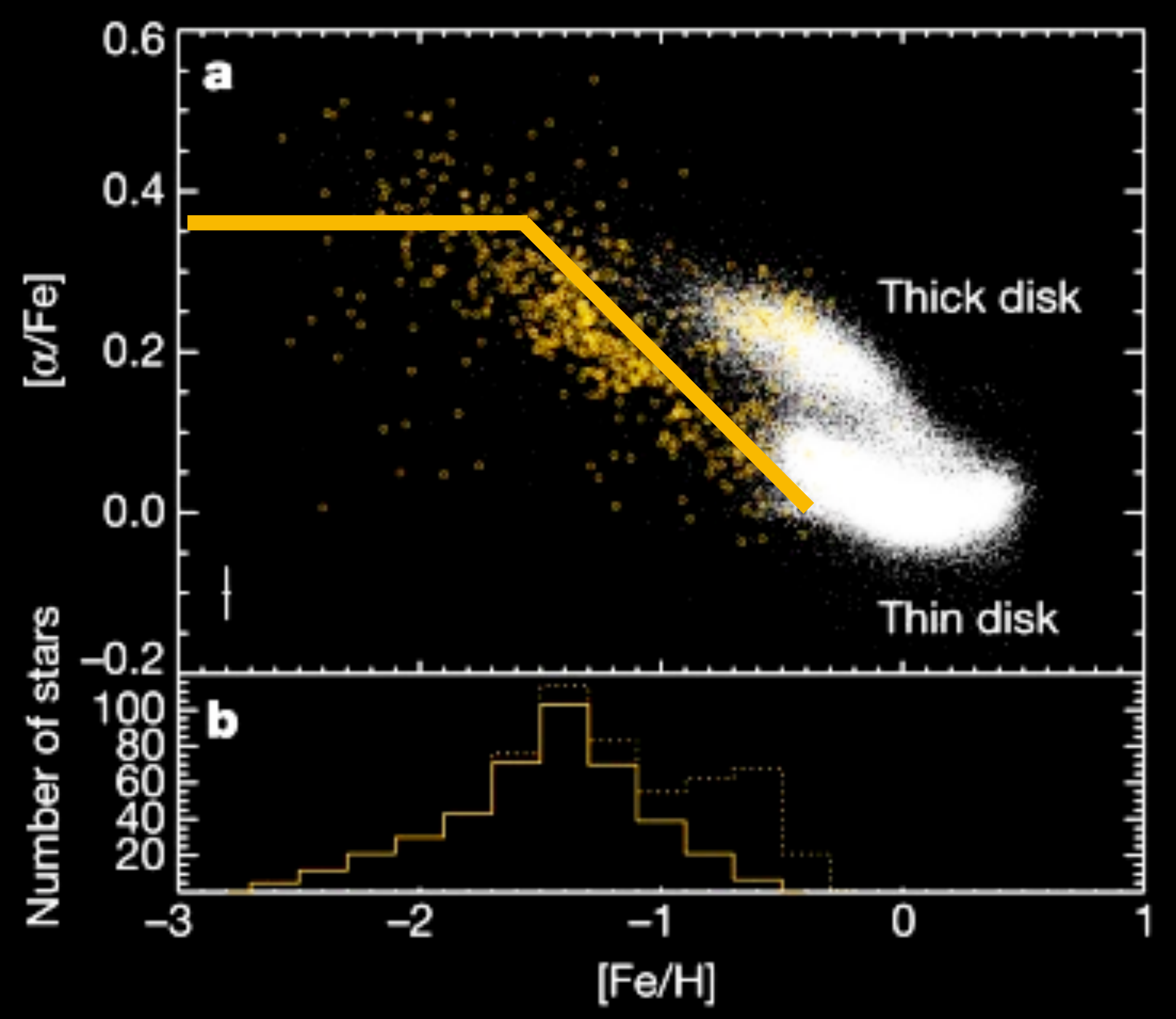

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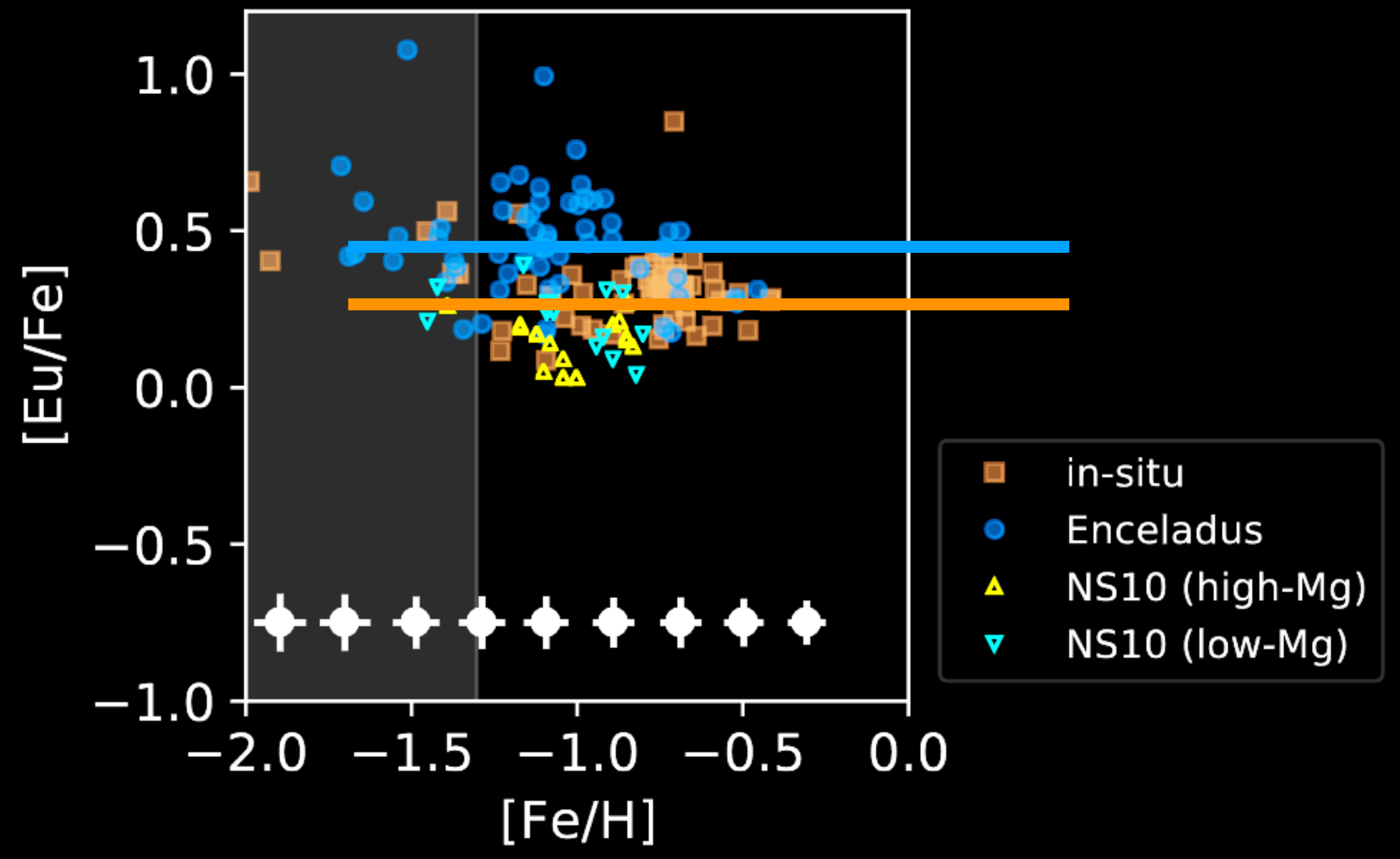

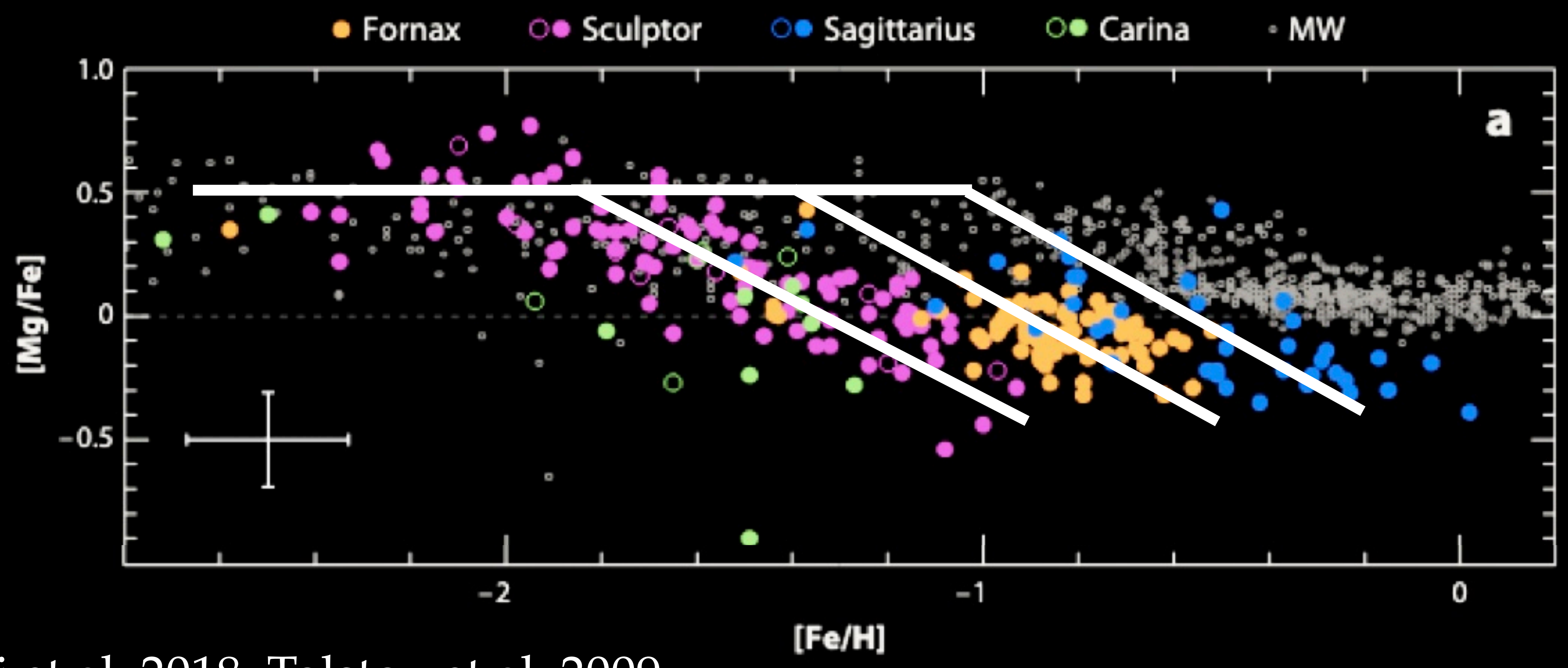

[Eu/Fe] encodes information on rare channels and mixing timescales

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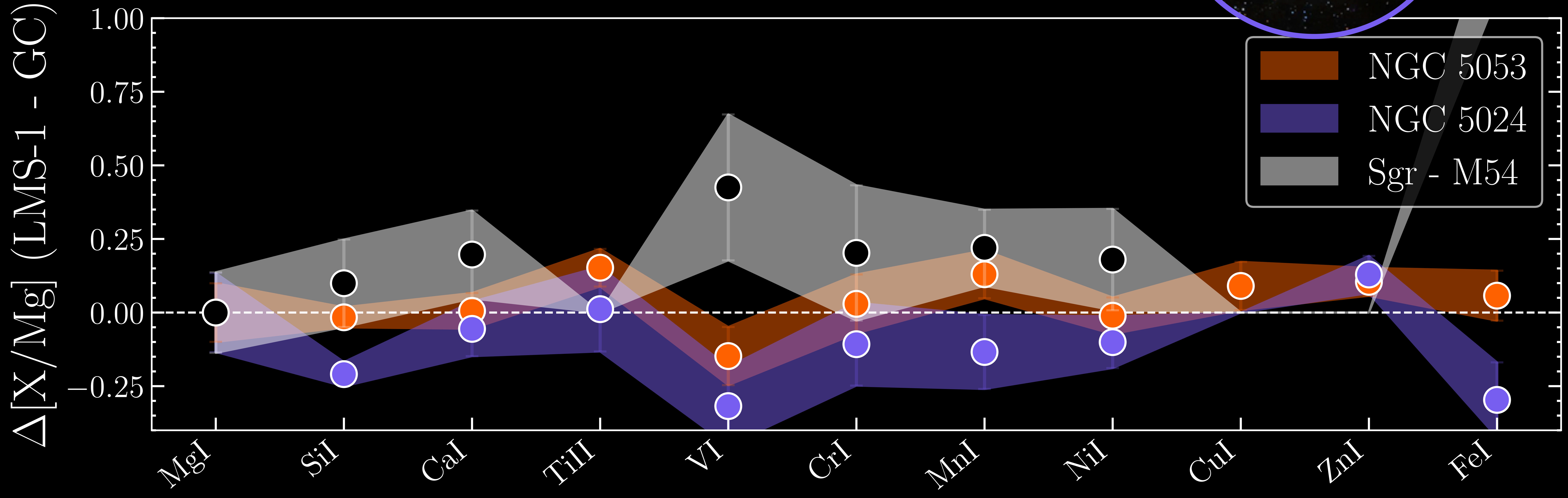
Chemical Abundance Results: GCs vs. dGal

Difference between LMS-1 and the two GCs, considering first generation stars only, [X/Mg]



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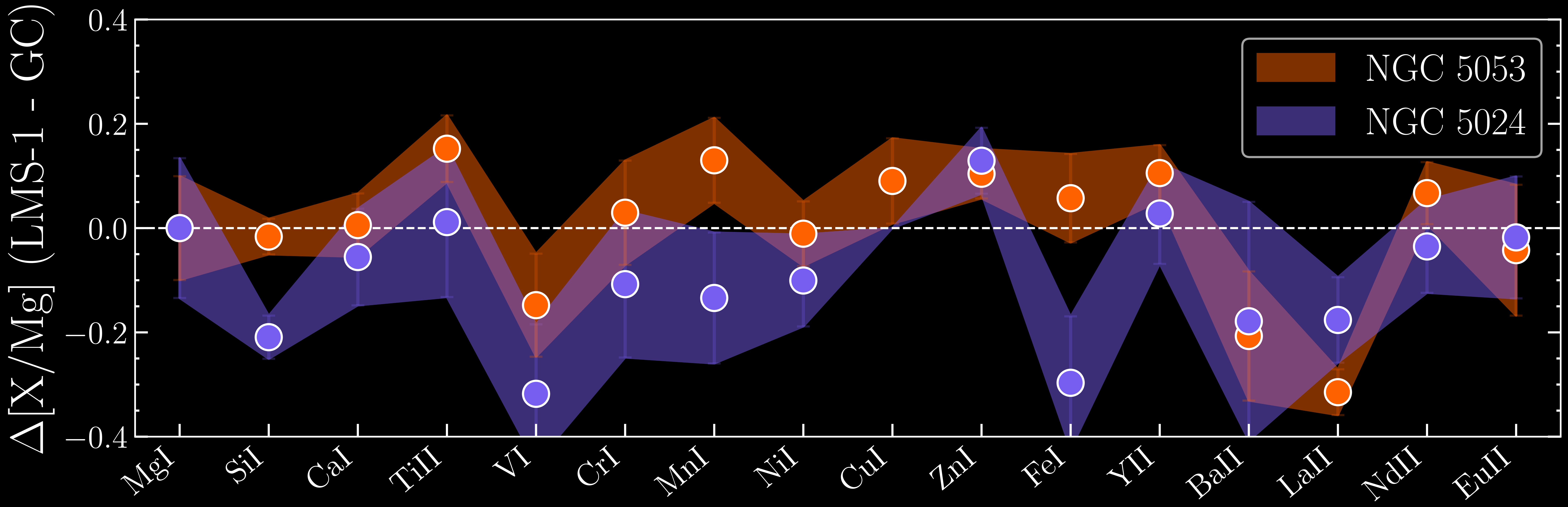

ESO/L. Calçada

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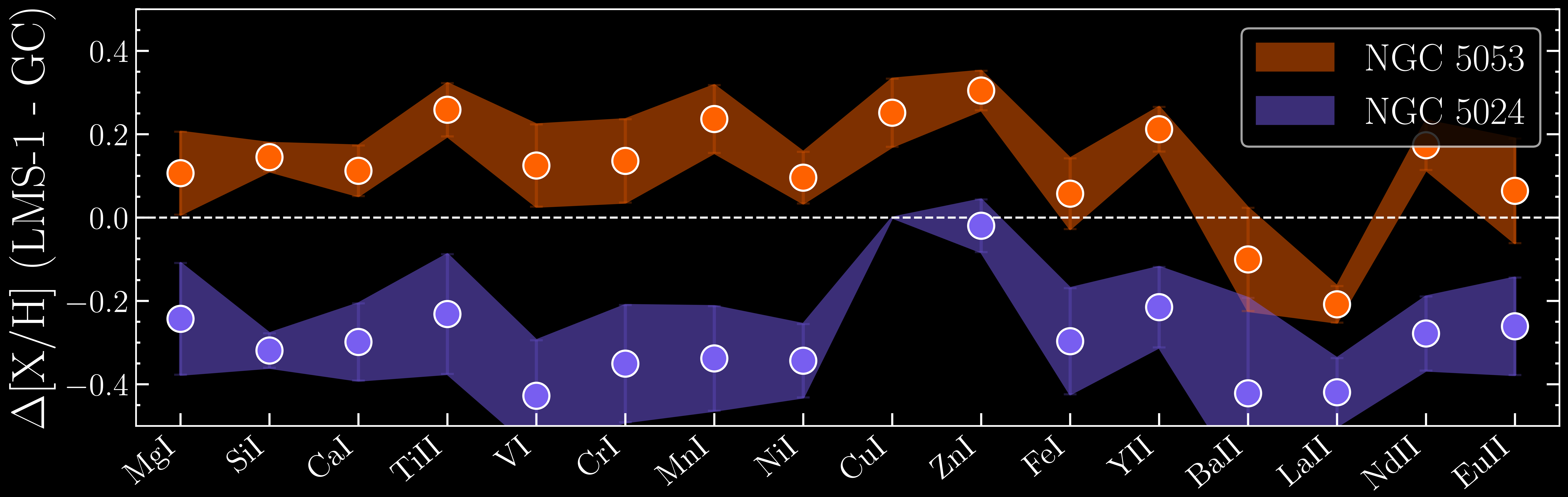

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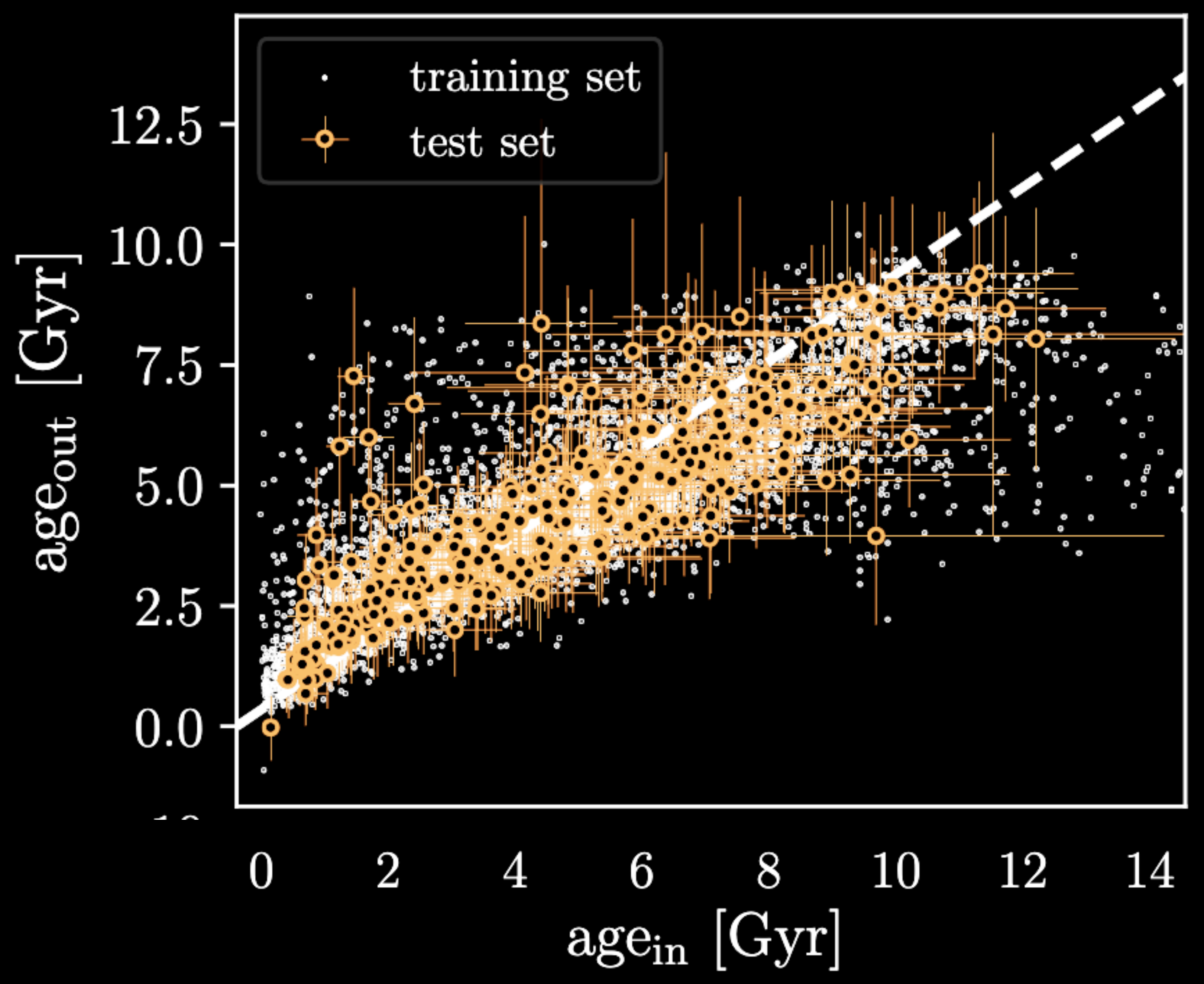
What do GCs provide that field stars do not?



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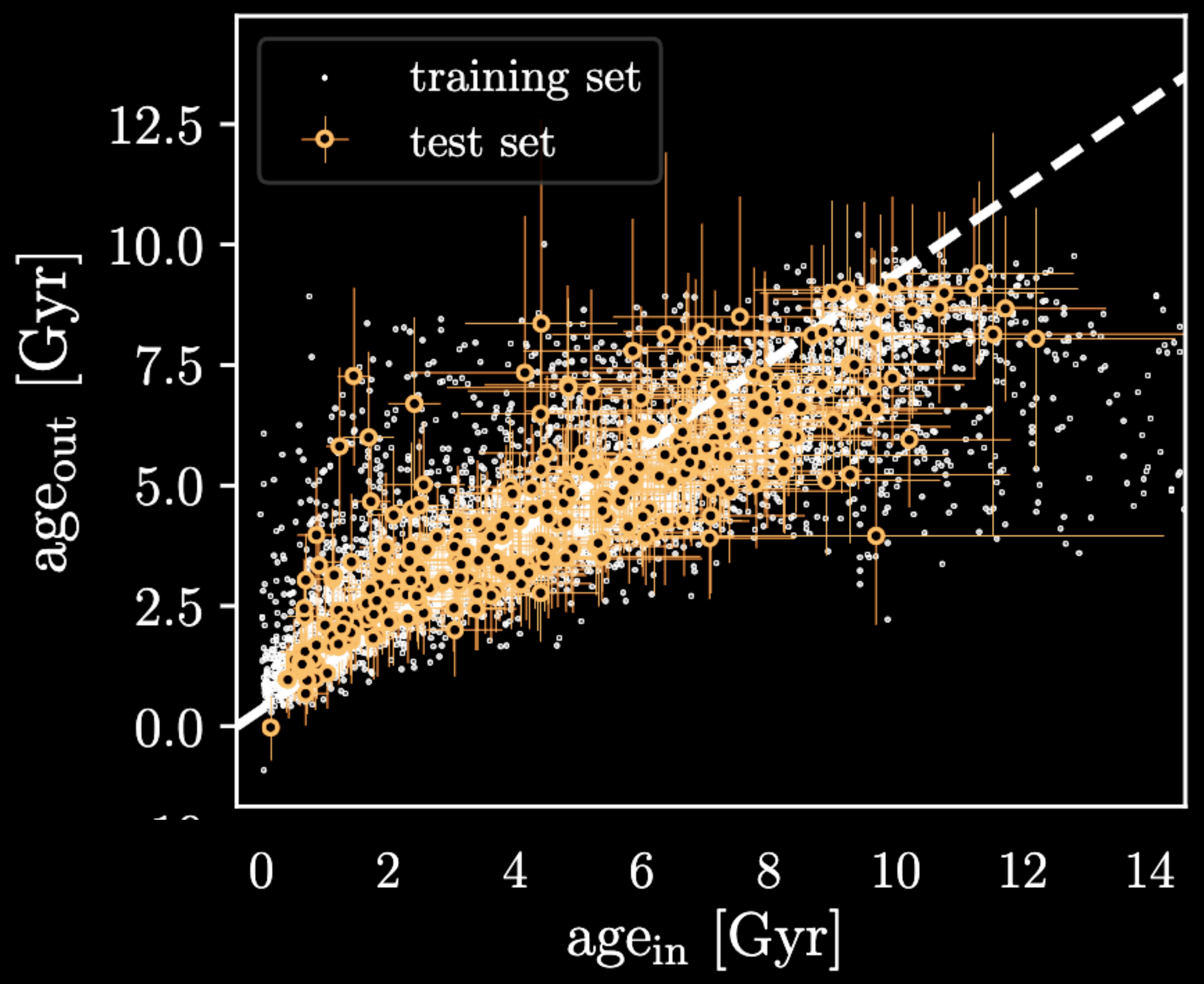

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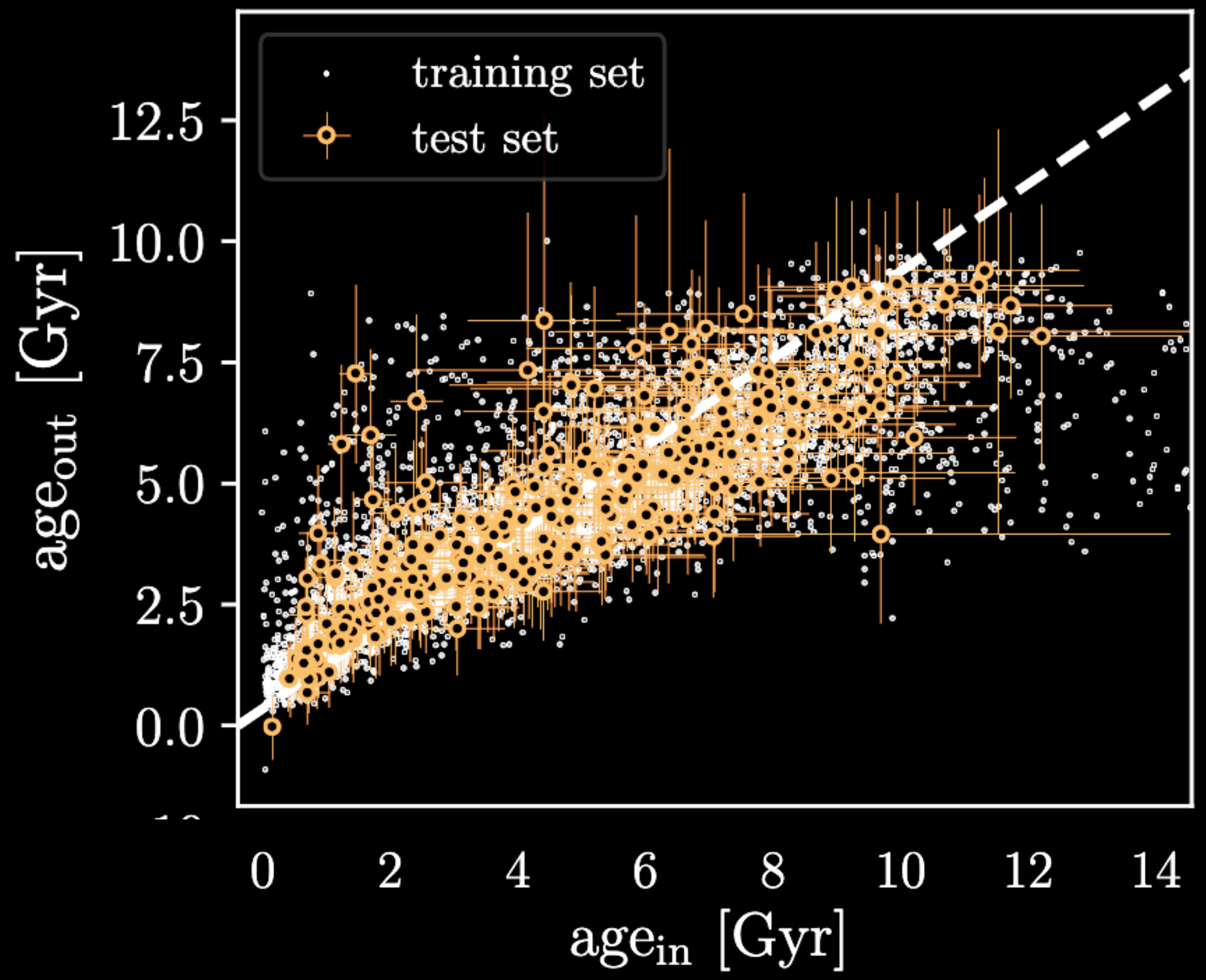

-0.5 < [Fe/H] < 0.5

10 +/- 3 Gyr

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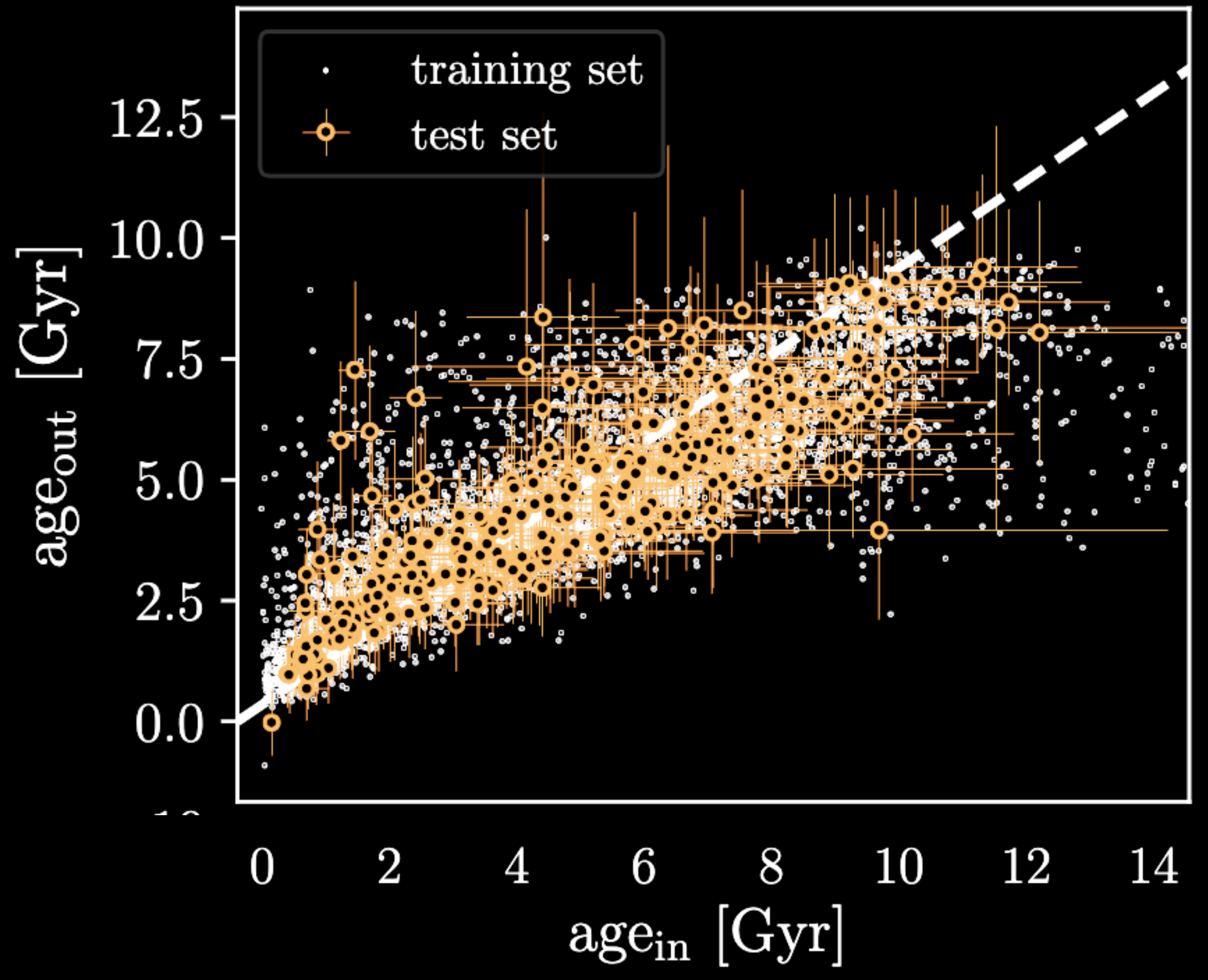

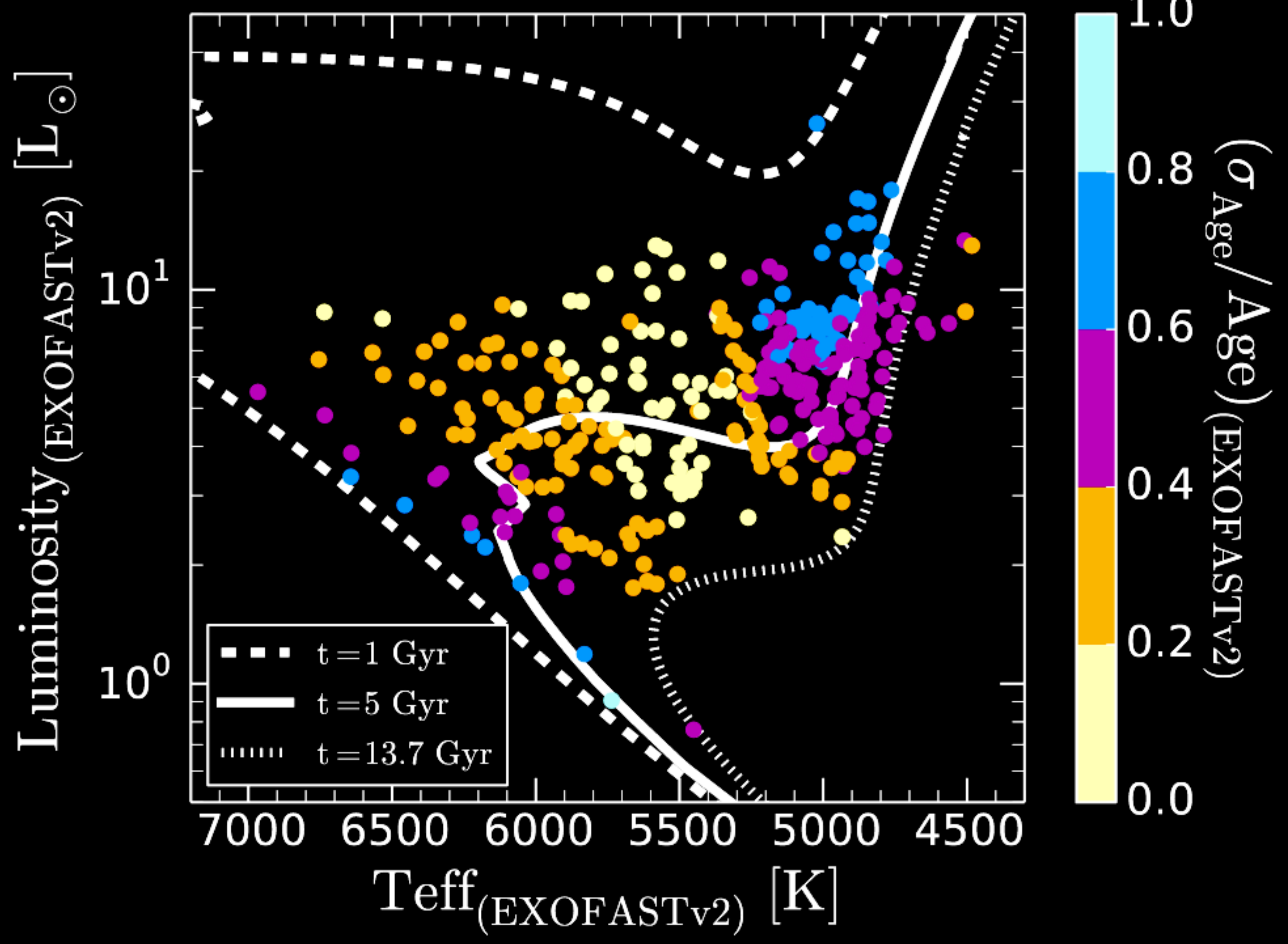

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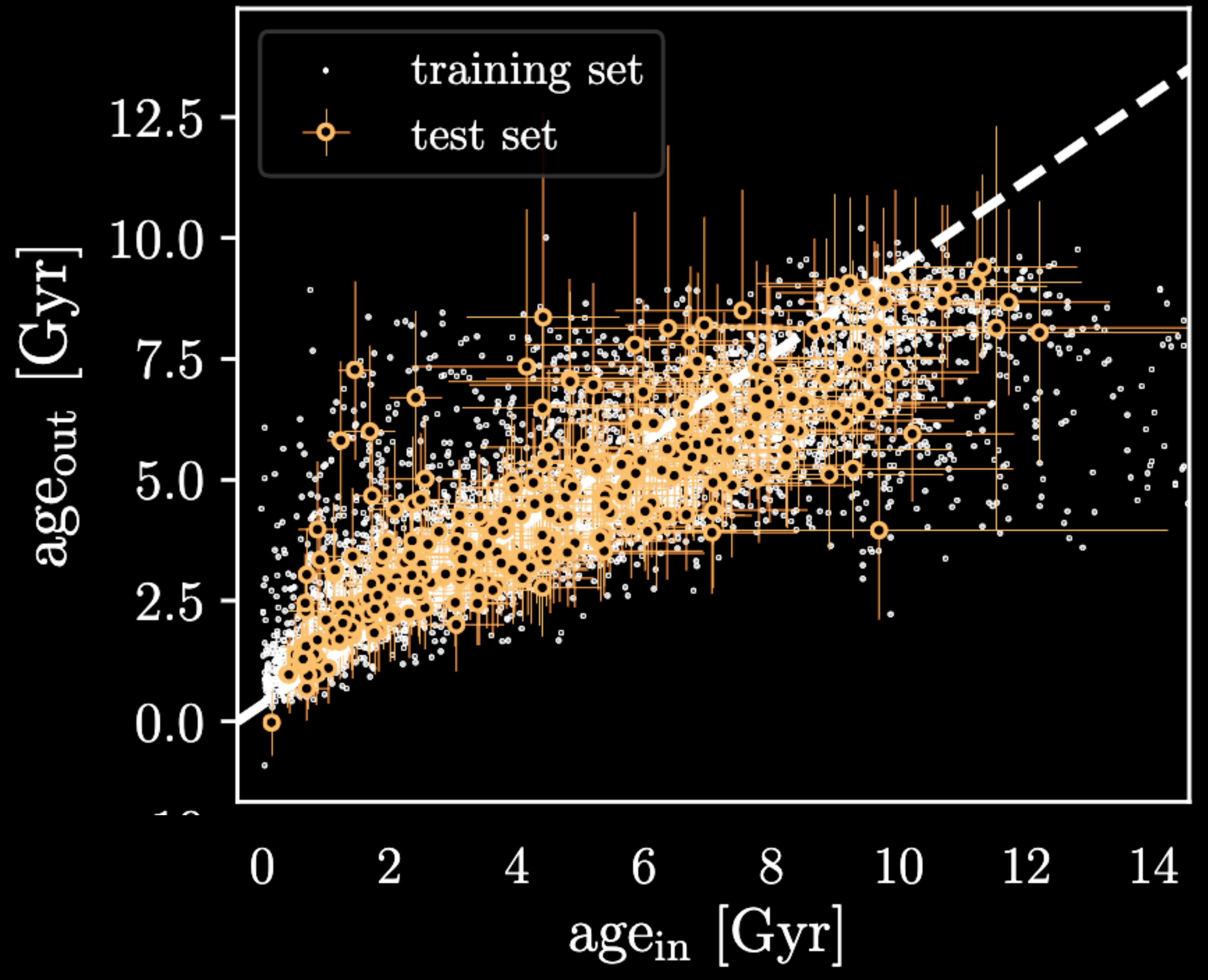
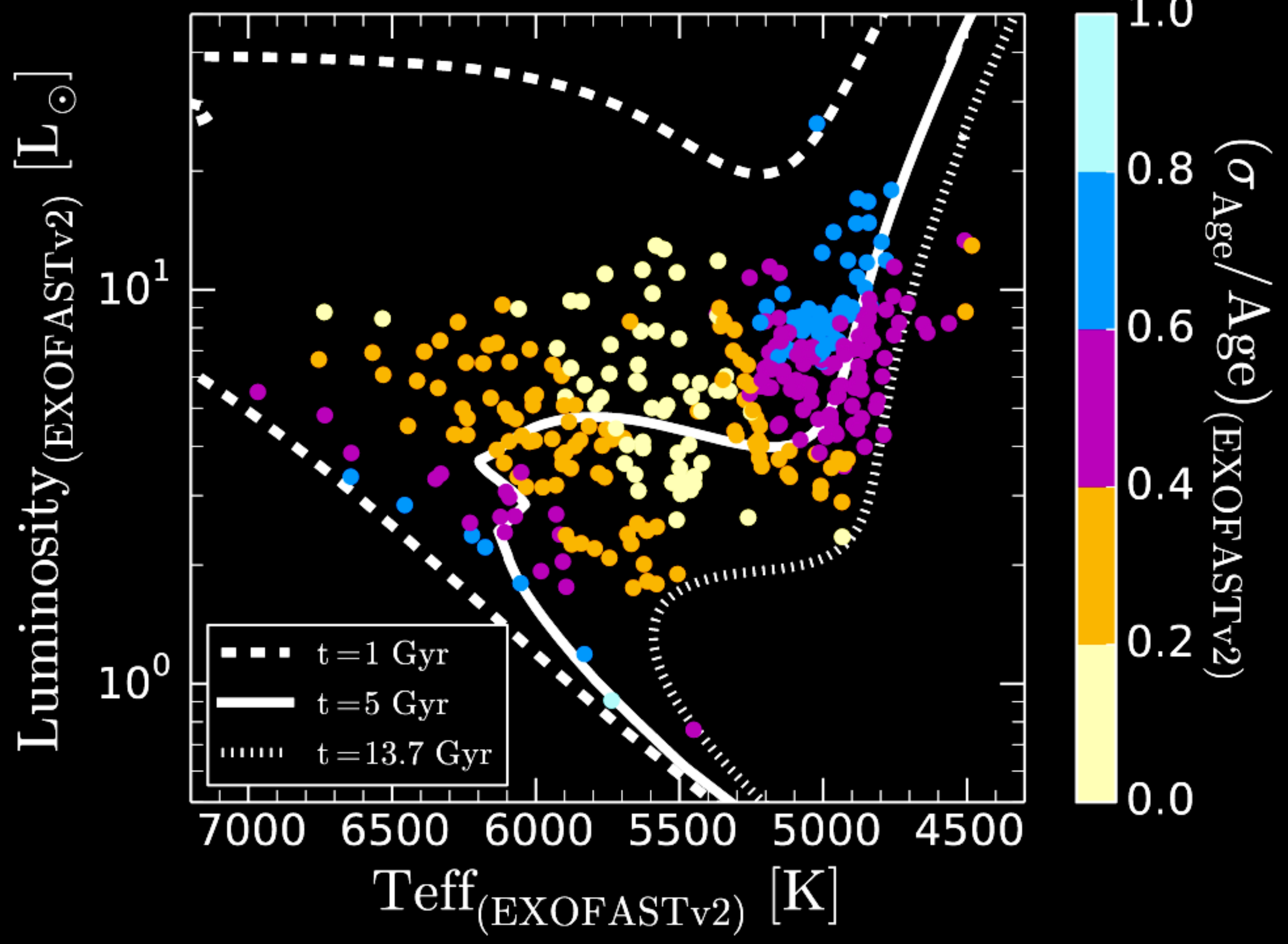


SED Fitting (Godoy Rivera et al. 2021)
See D. Horta's talk



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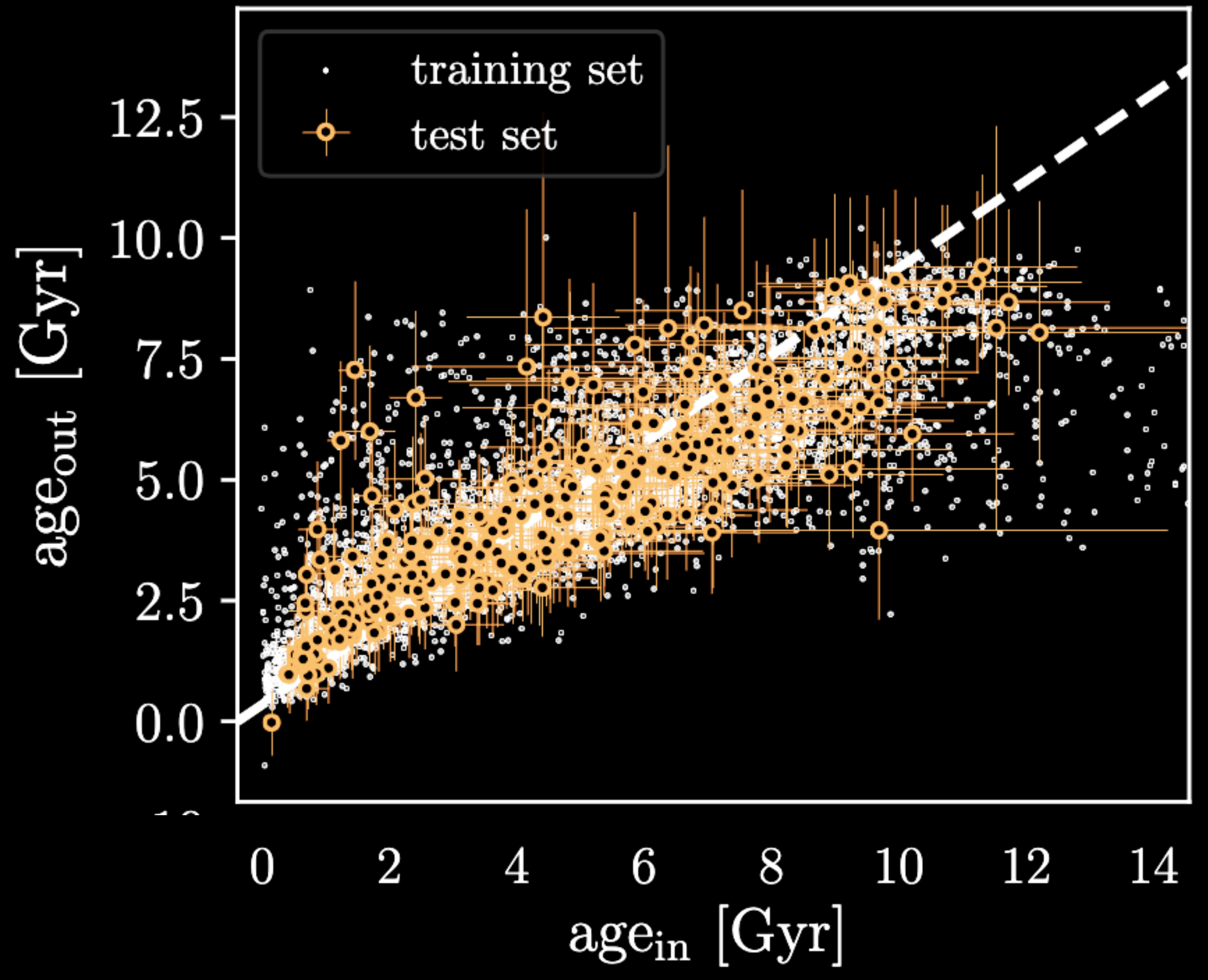

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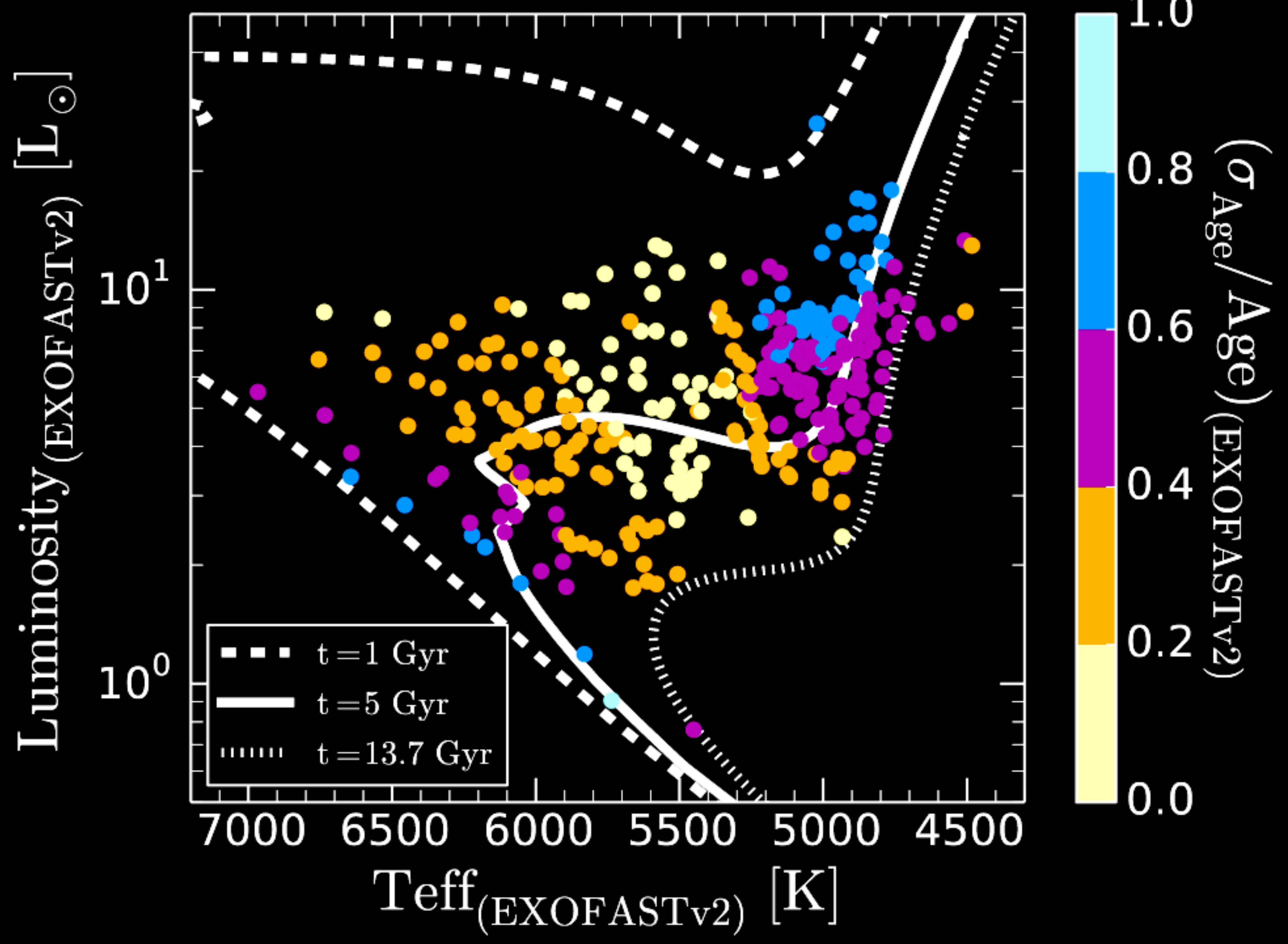

[Fe/H] ~ 0

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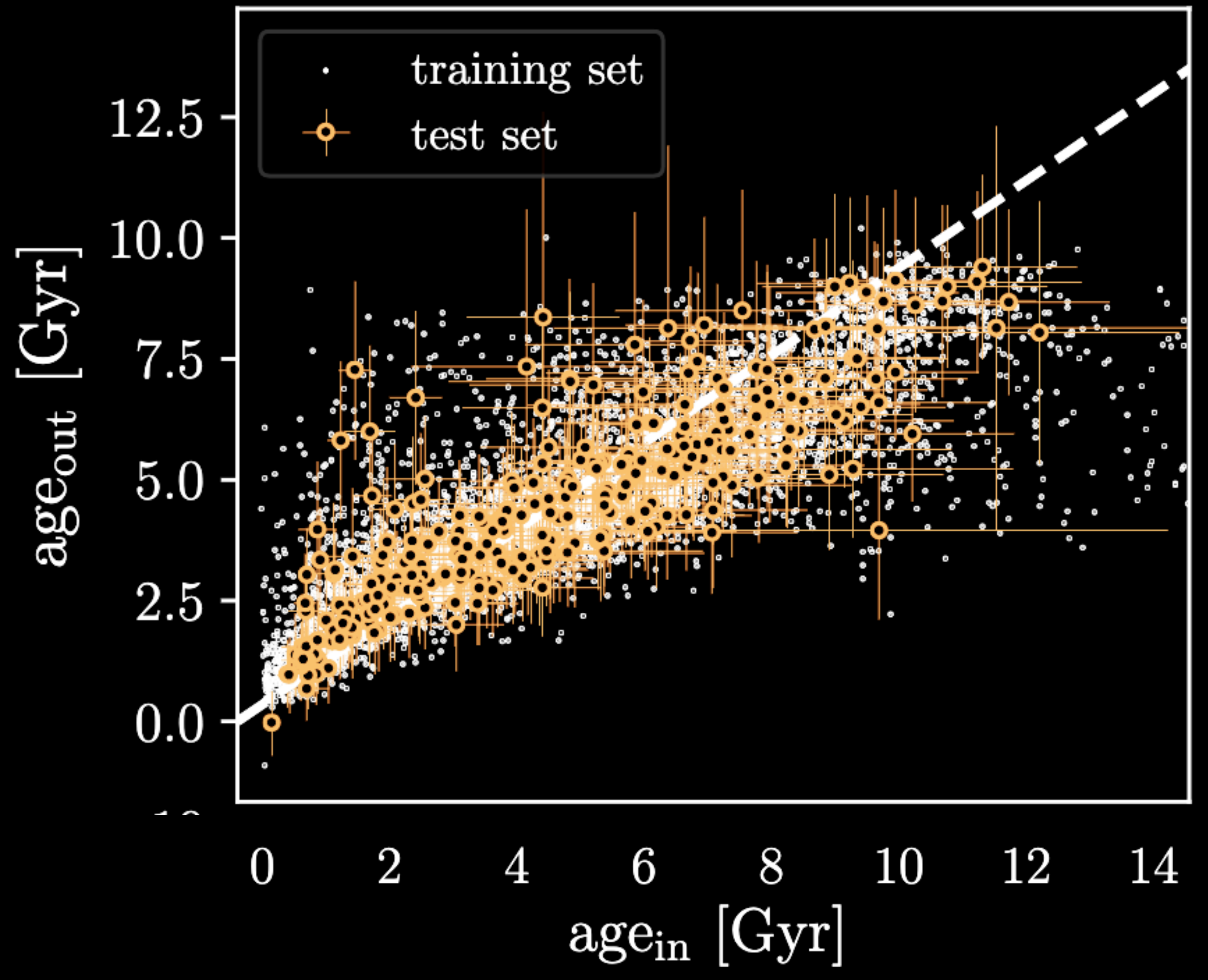

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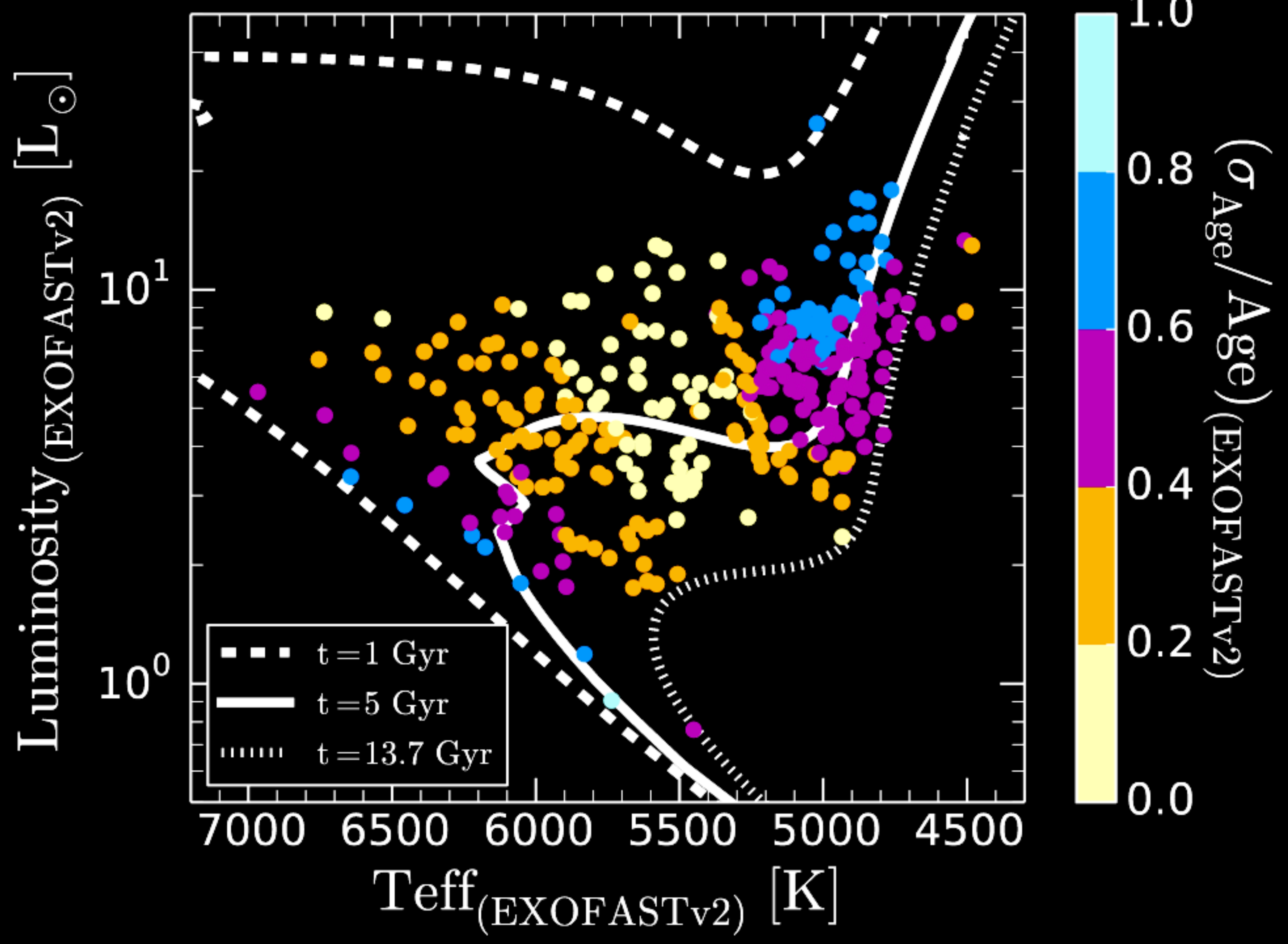

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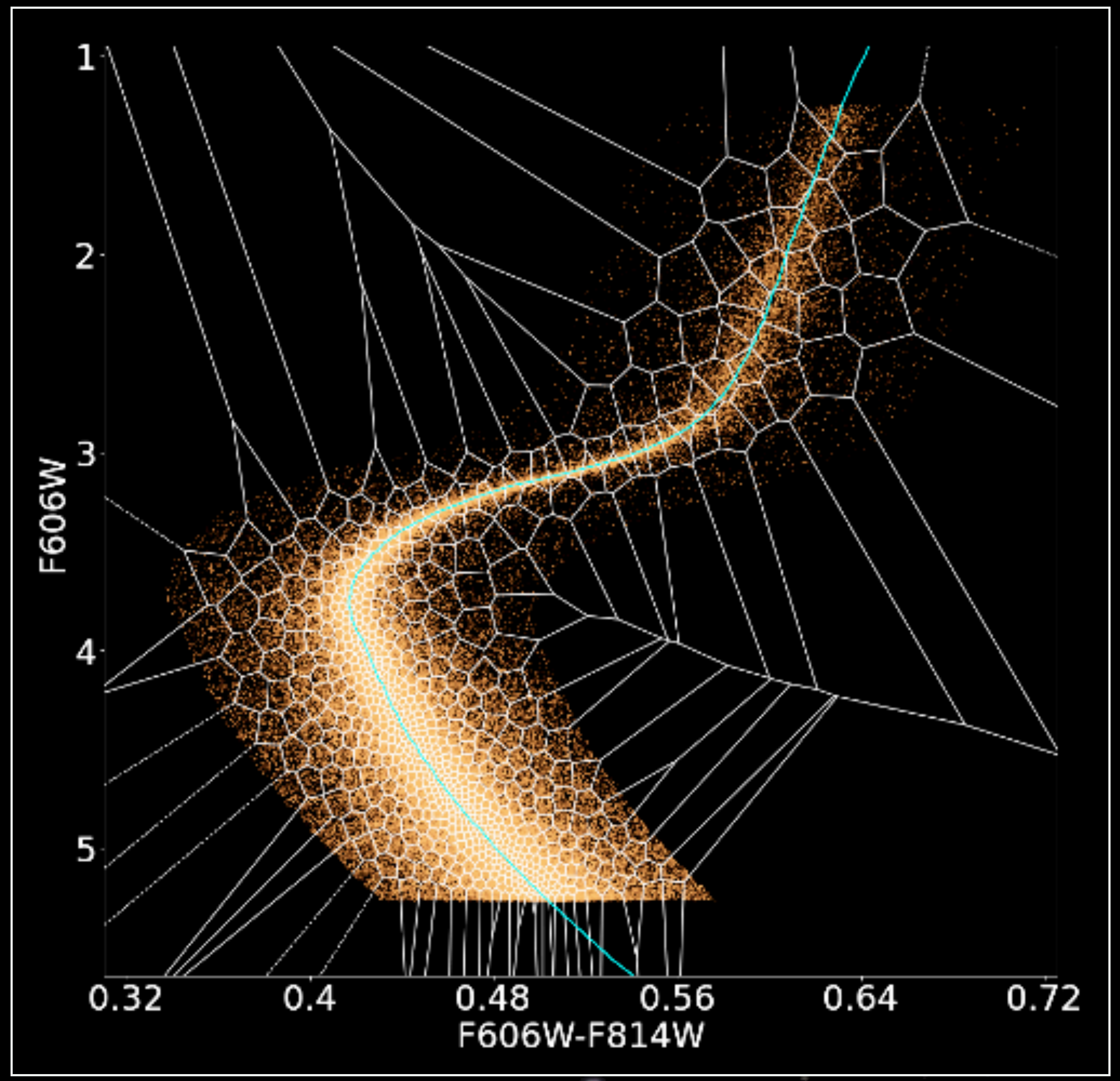

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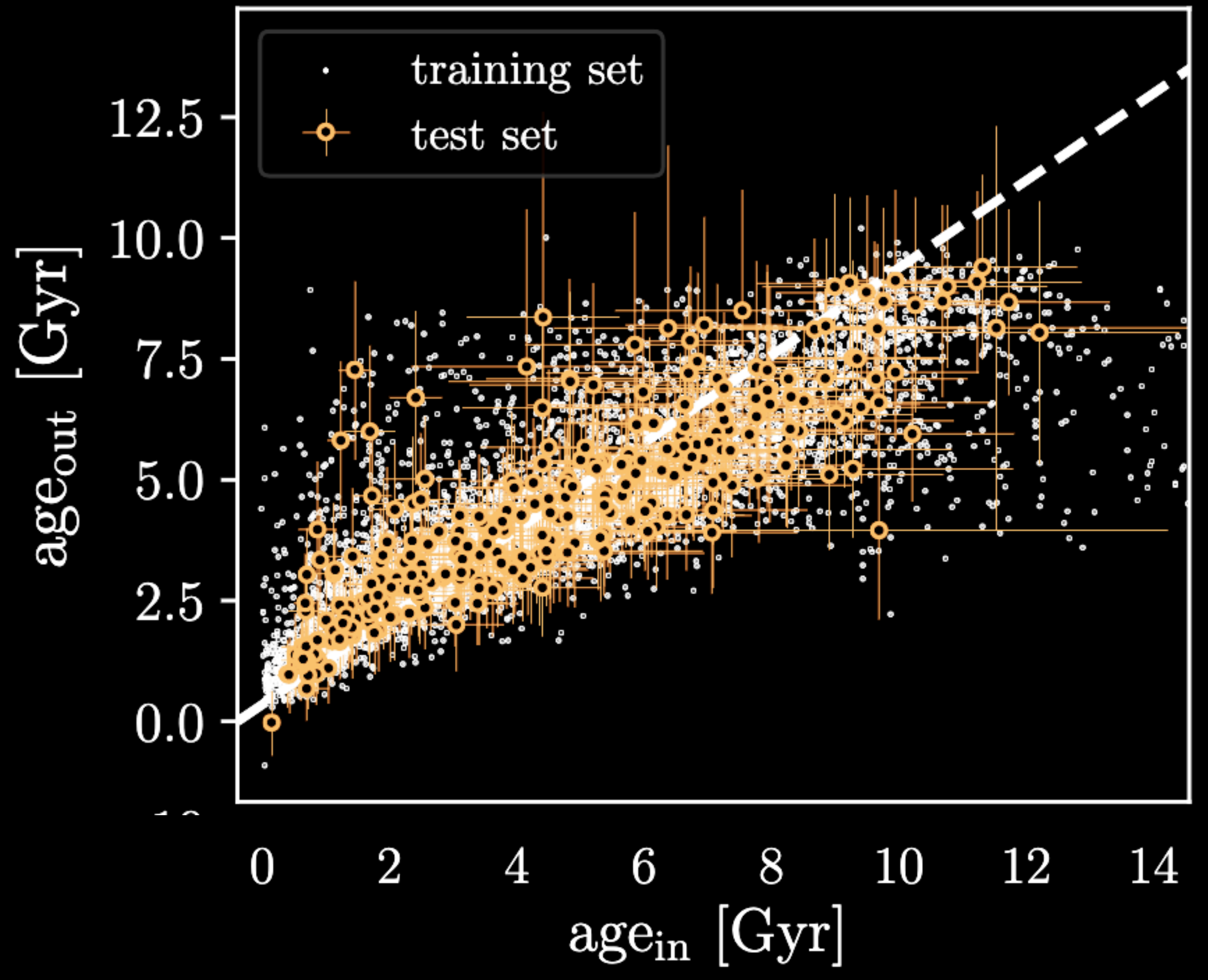

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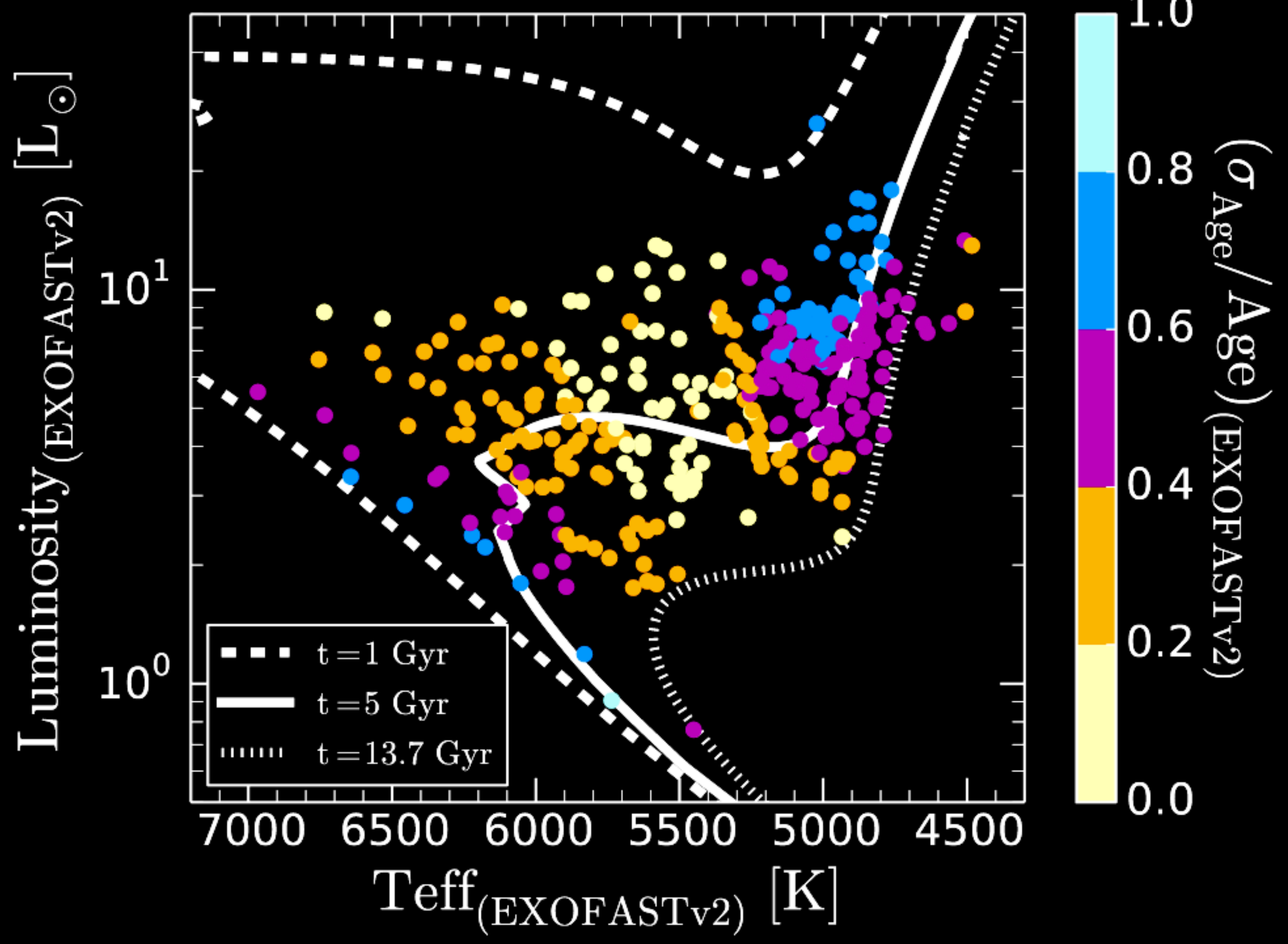

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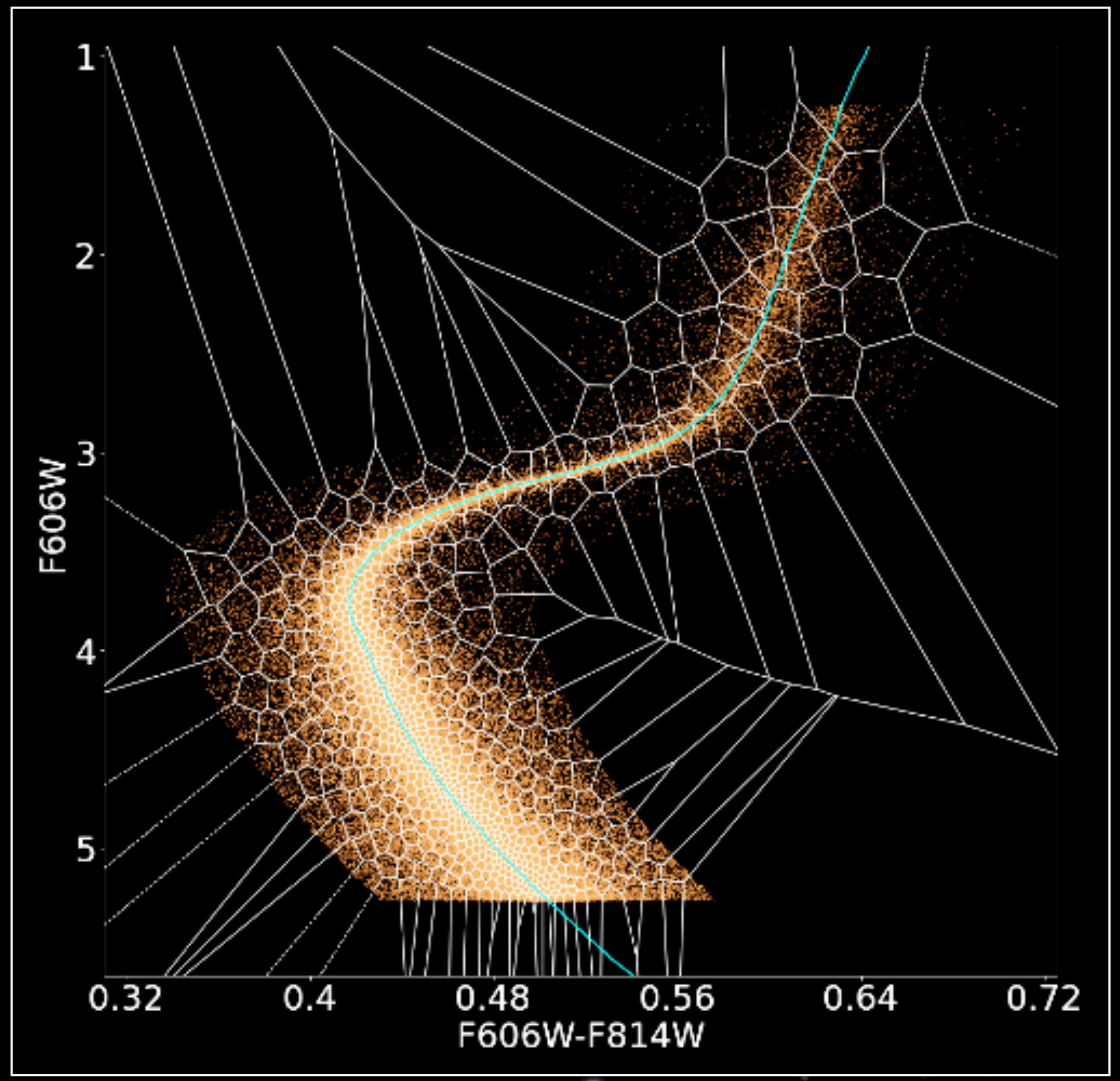
6 +/- 1 Gyr

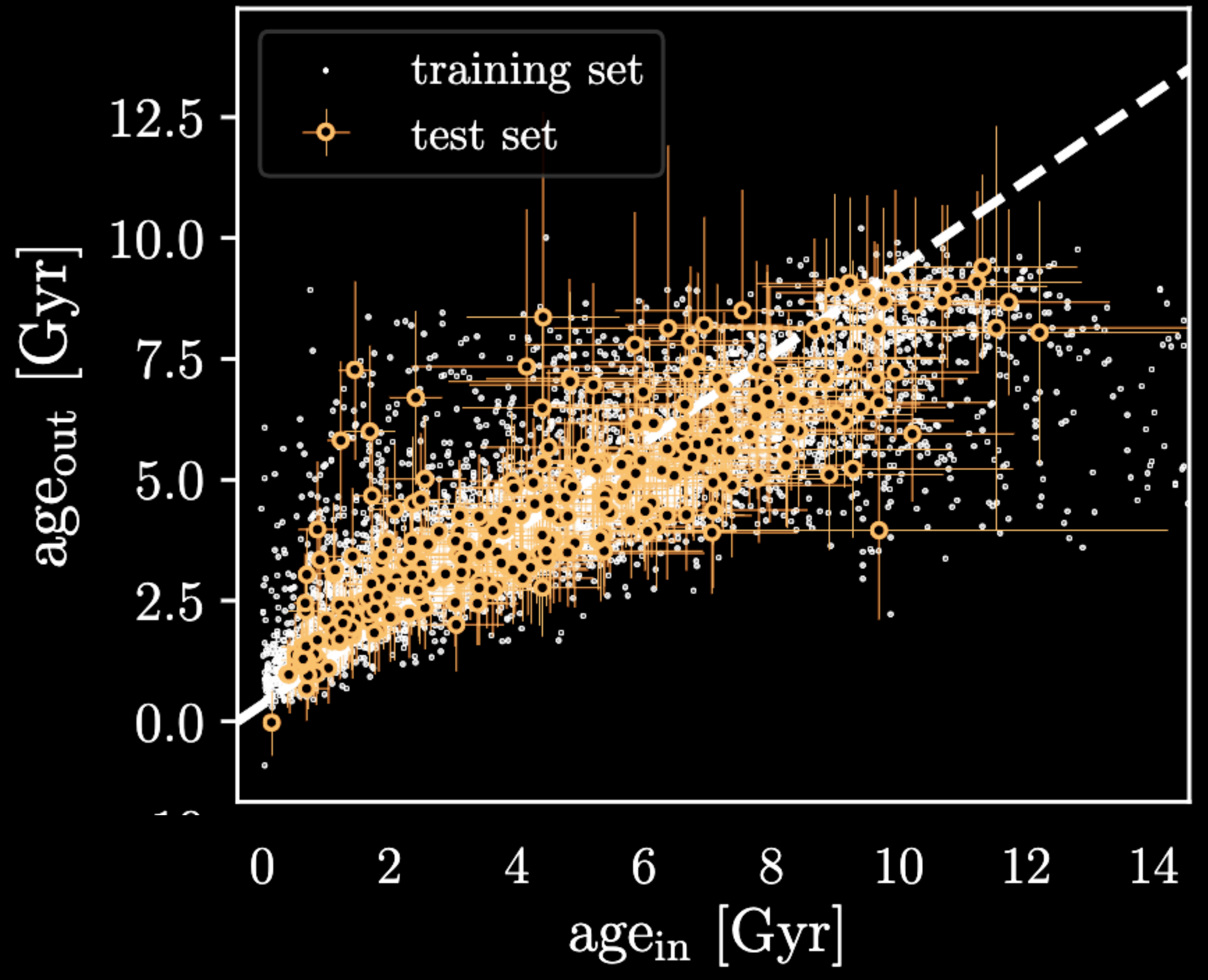
Isochrone Fitting (Ying et al. 2023)

See also, CARMA (Massari et al. 2024)



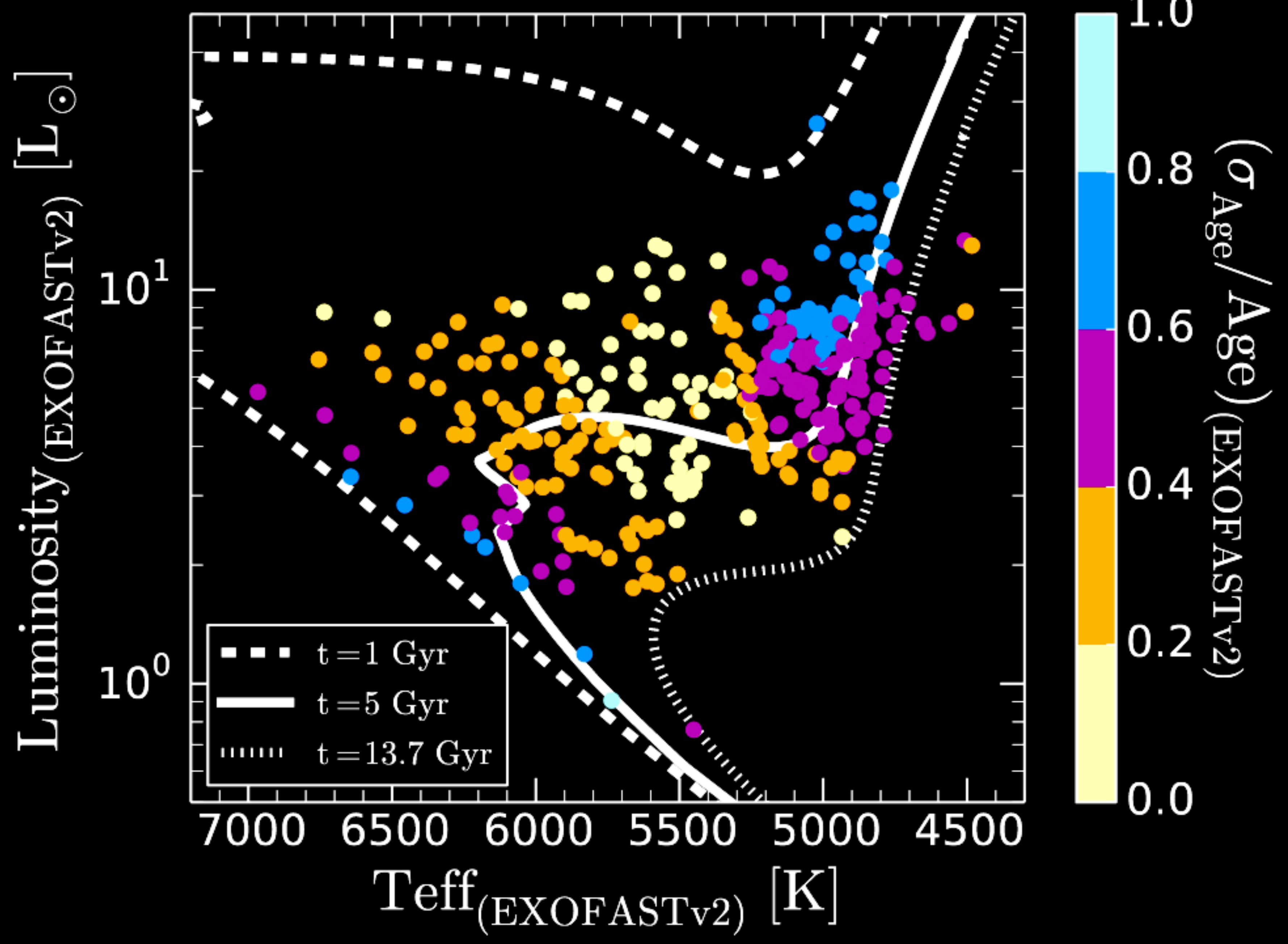
What do GCs provide that field stars do not?

Label Transfer (Mackereth et al. 2019)



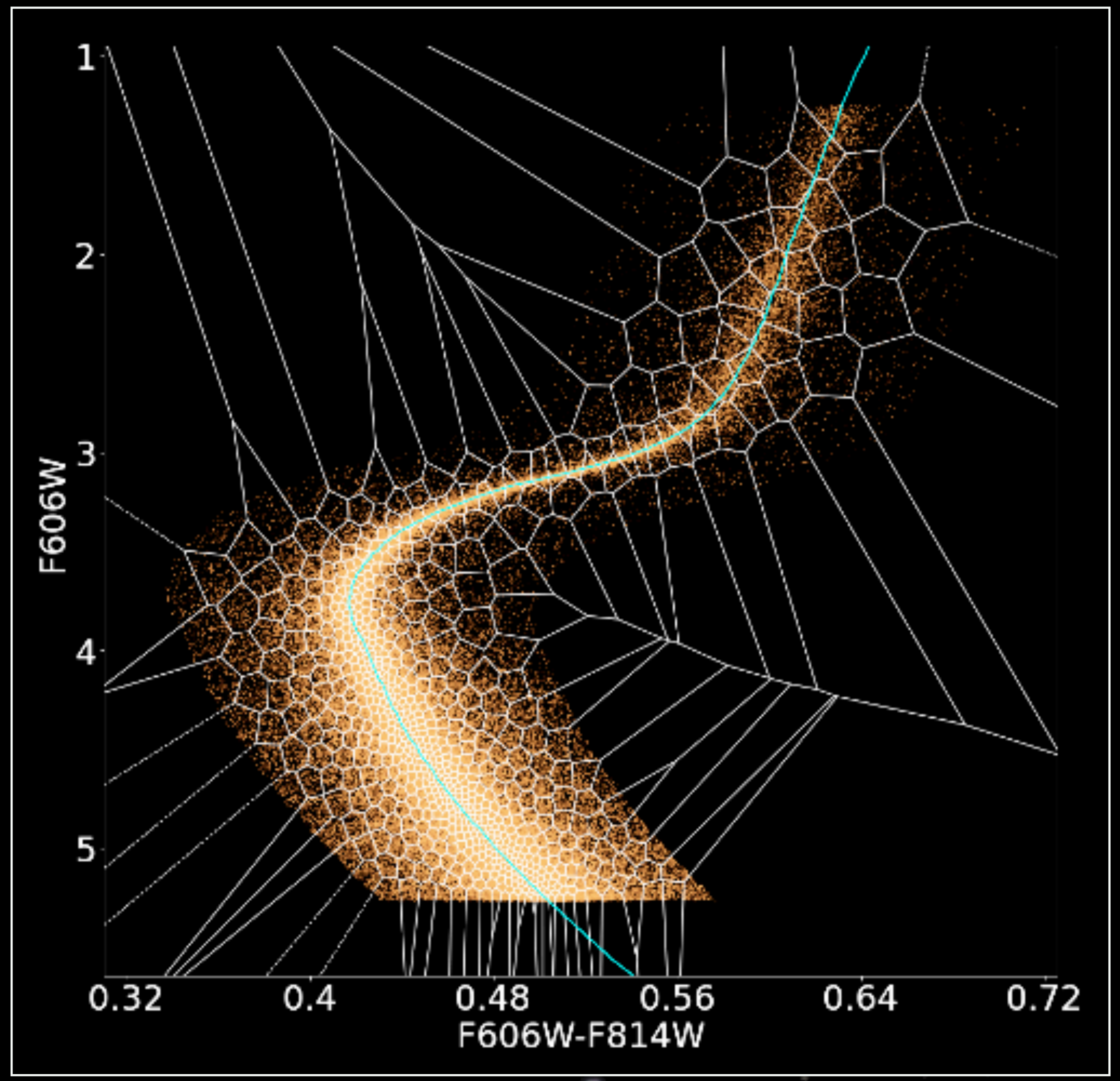
-0.5 < [Fe/H] < 0.5
10 +/- 3 Gyr

SED Fitting (Godoy Rivera et al. 2021)
See D. Horta's talk



[Fe/H] ~ 0
6 +/- 1 Gyr

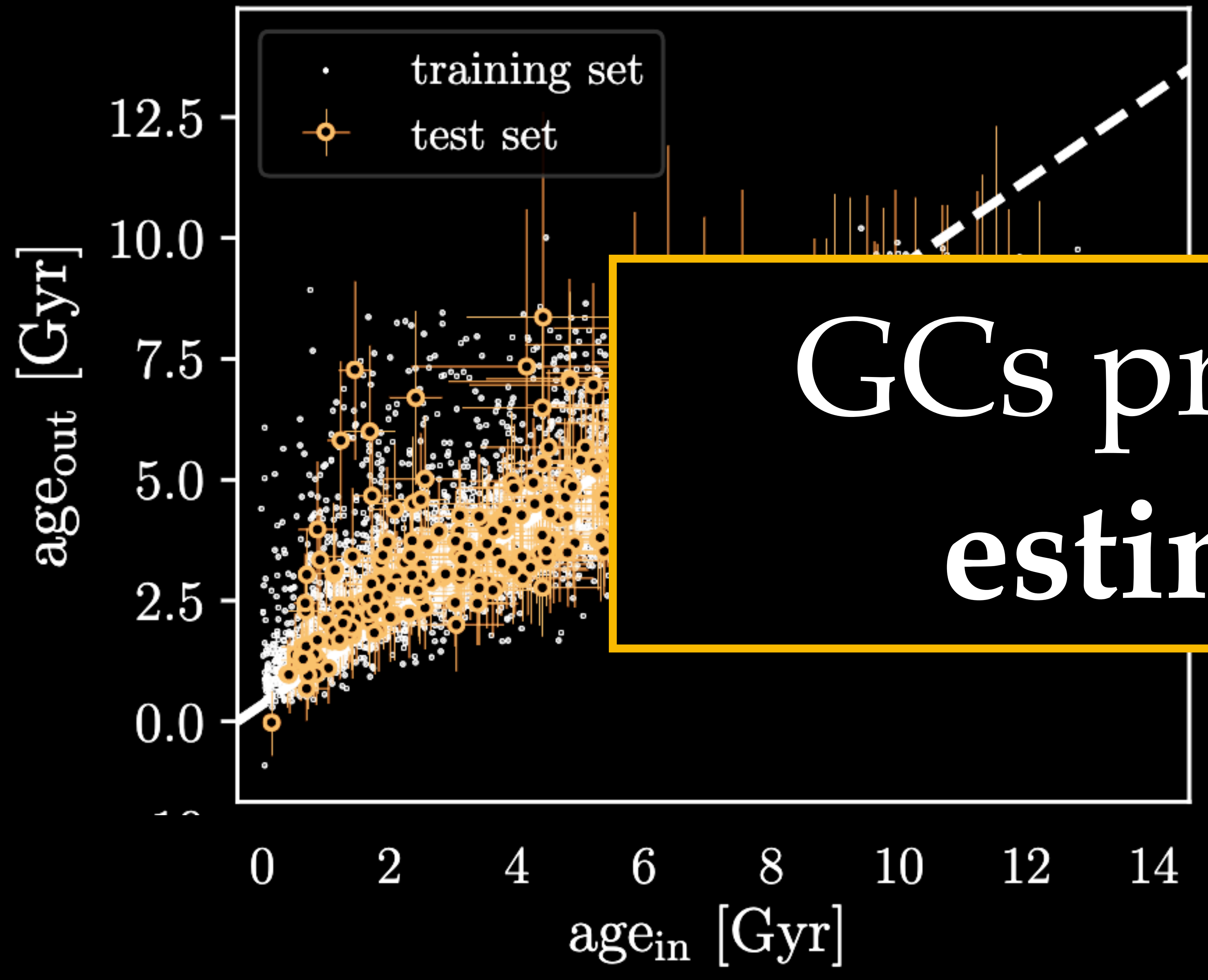
Isochrone Fitting (Ying et al. 2023)
See also, CARMA (Massari et al. 2024)



[Fe/H] < -2.5
13.8 +/- 0.75 Gyr

What do GCs provide that field stars do not?

Label Transfer (Mackereth et al. 2019)



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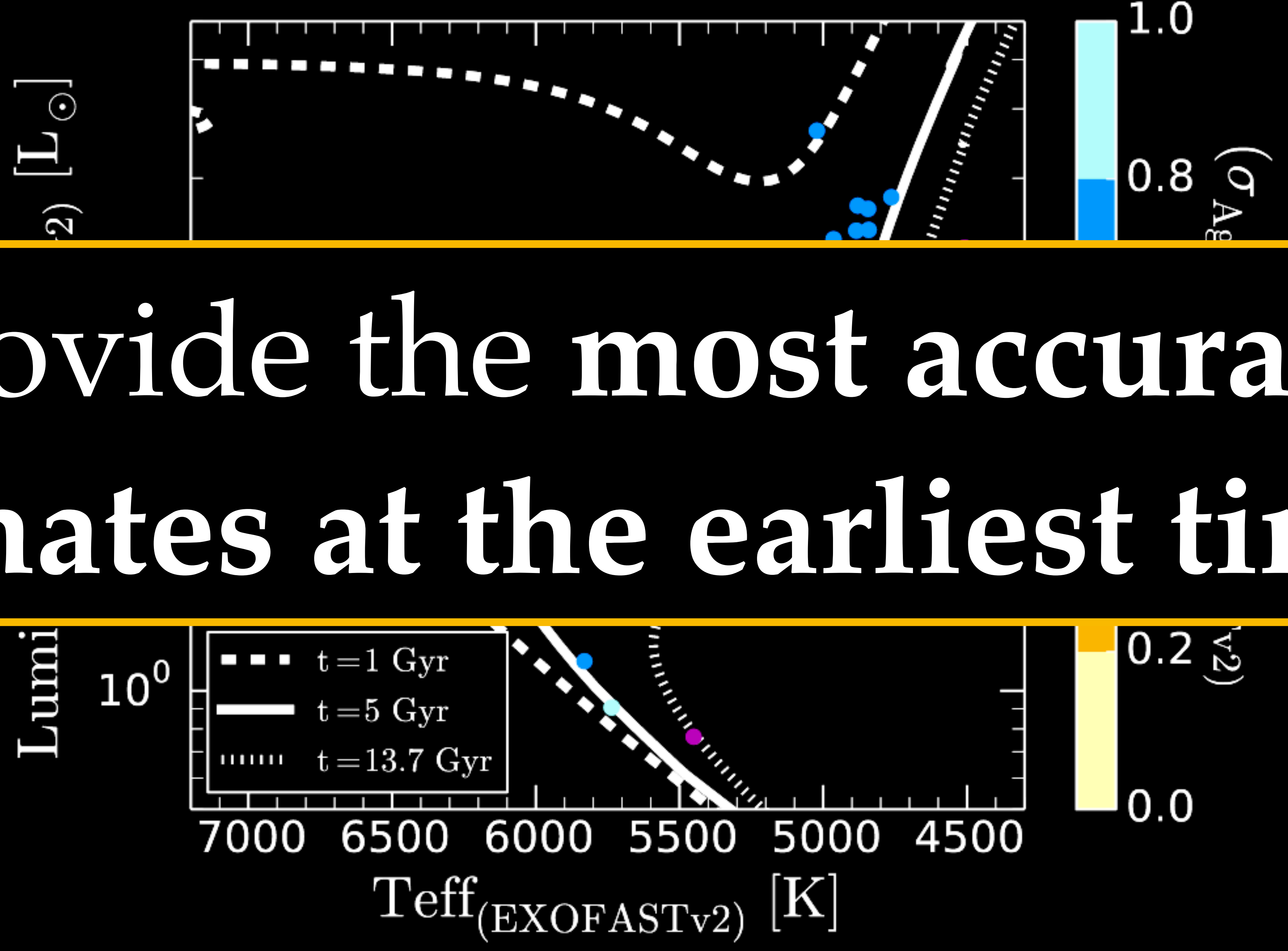

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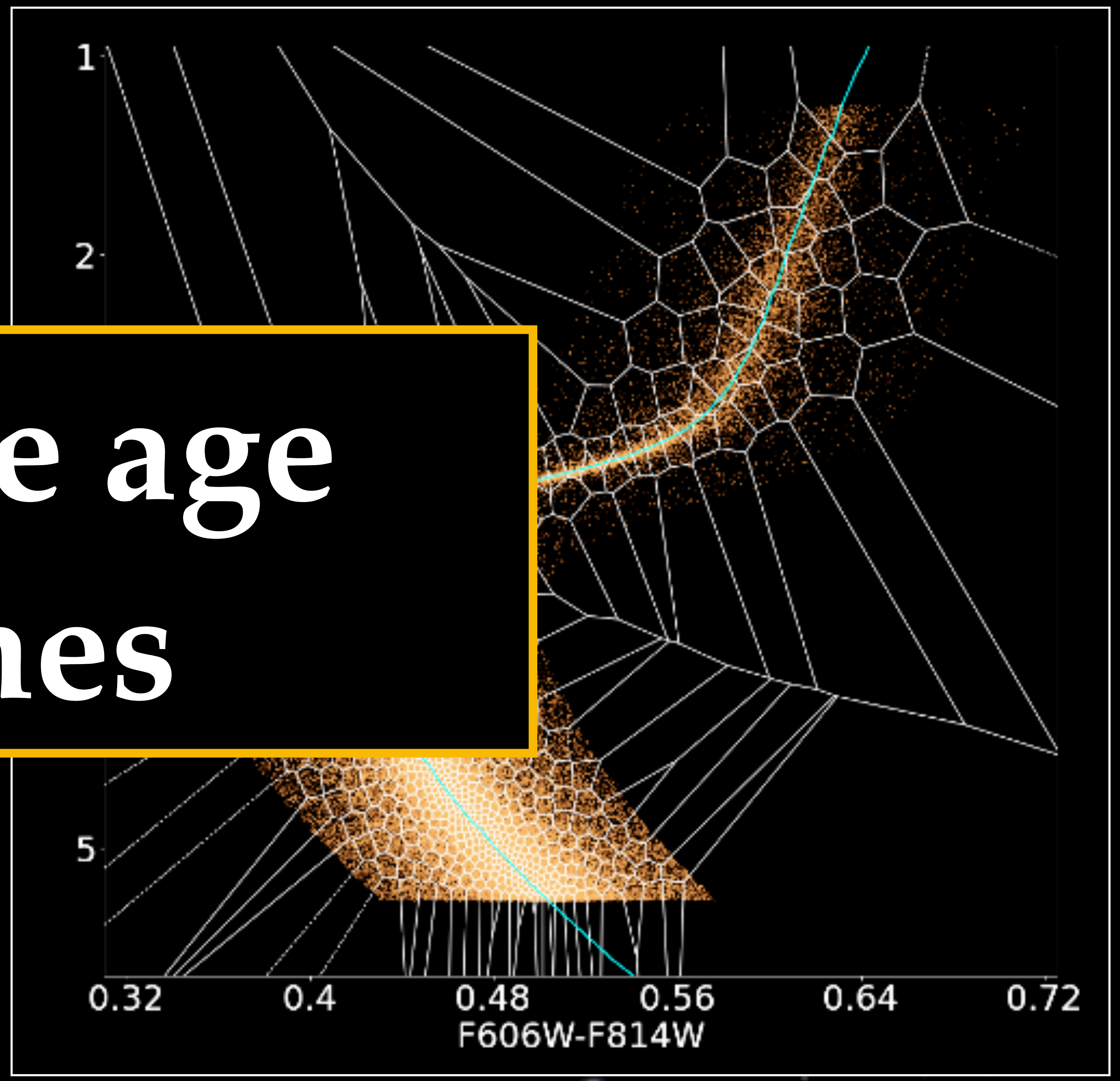


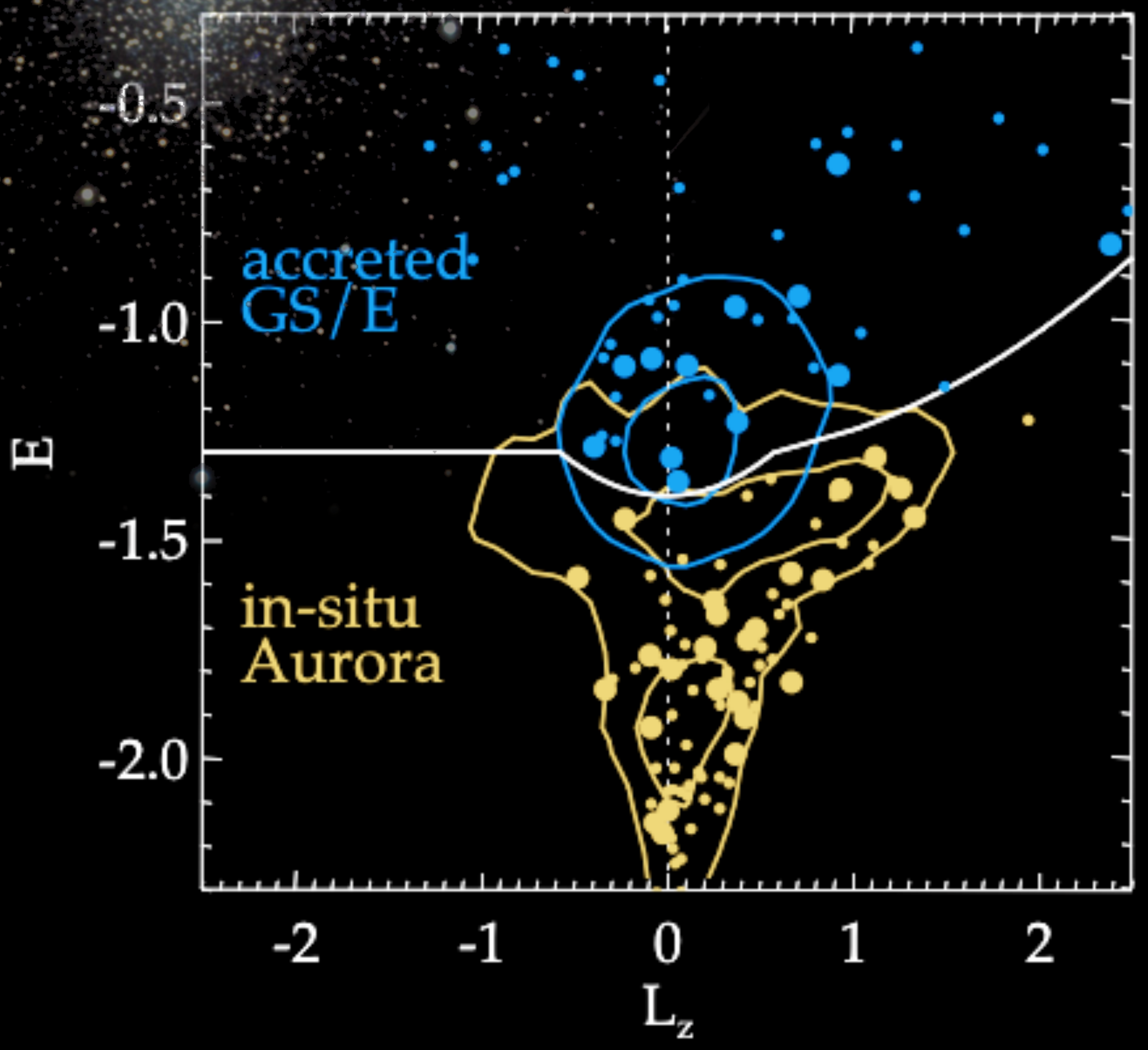
GCs provide the **most accurate age estimates at the earliest times**

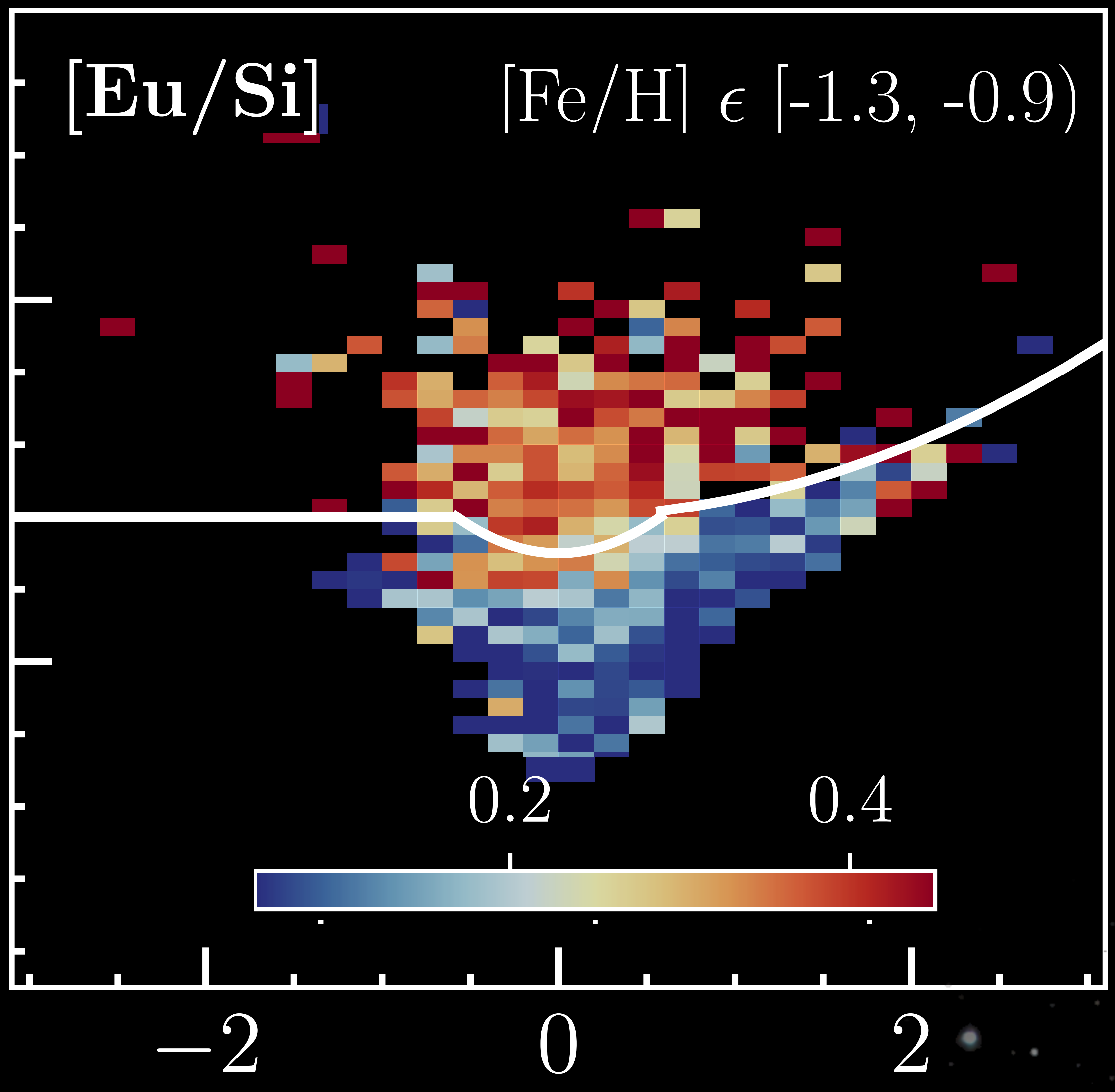
-0.5 < [Fe/H] < 0.5
10 +/- 3 Gyr

[Fe/H] ~ 0
6 +/- 1 Gyr

[Fe/H] < -2.5
13.8 +/- 0.75 Gyr

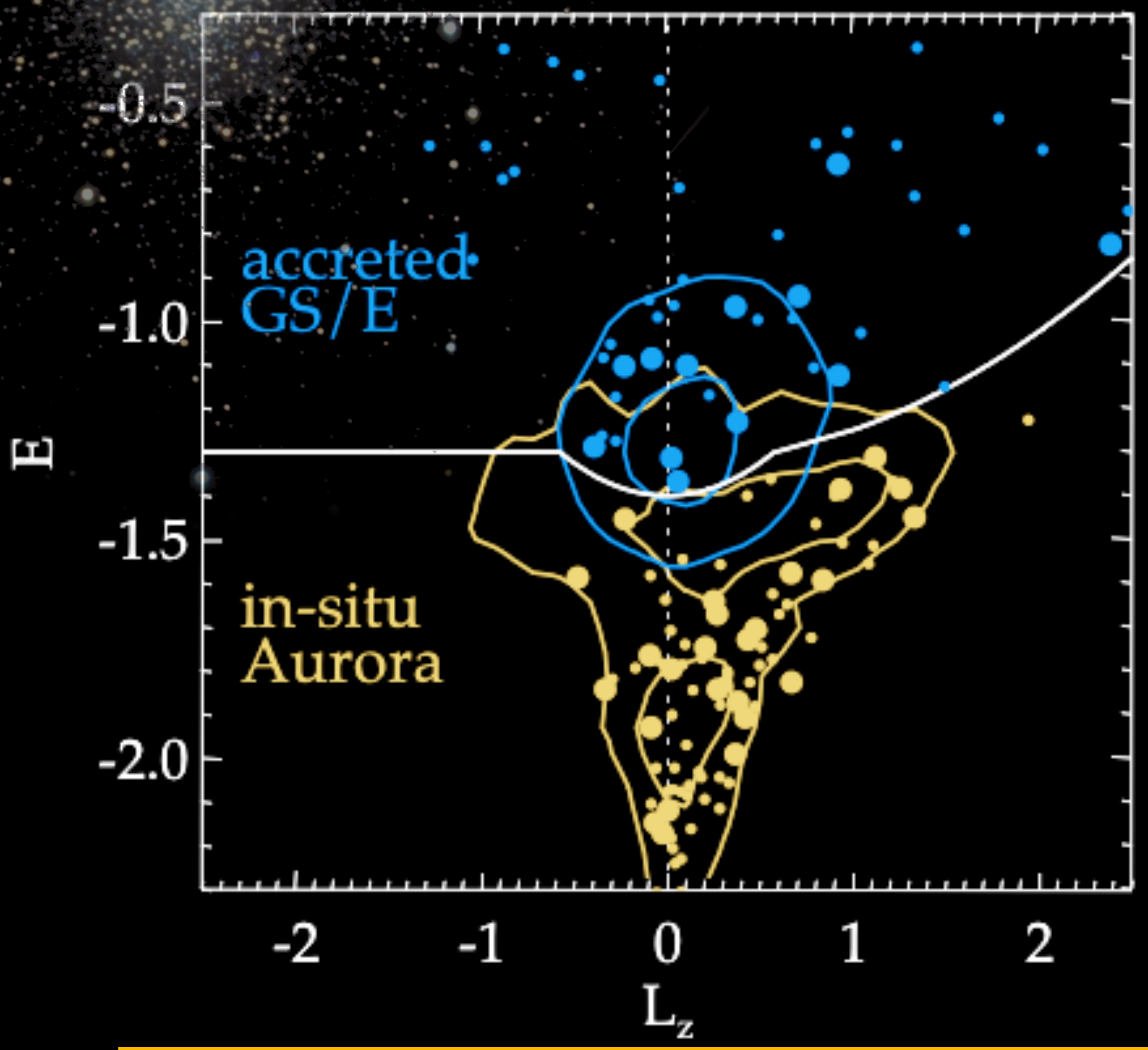
Gaia-Sausage/Enceladus in Chemical & Dynamical Space

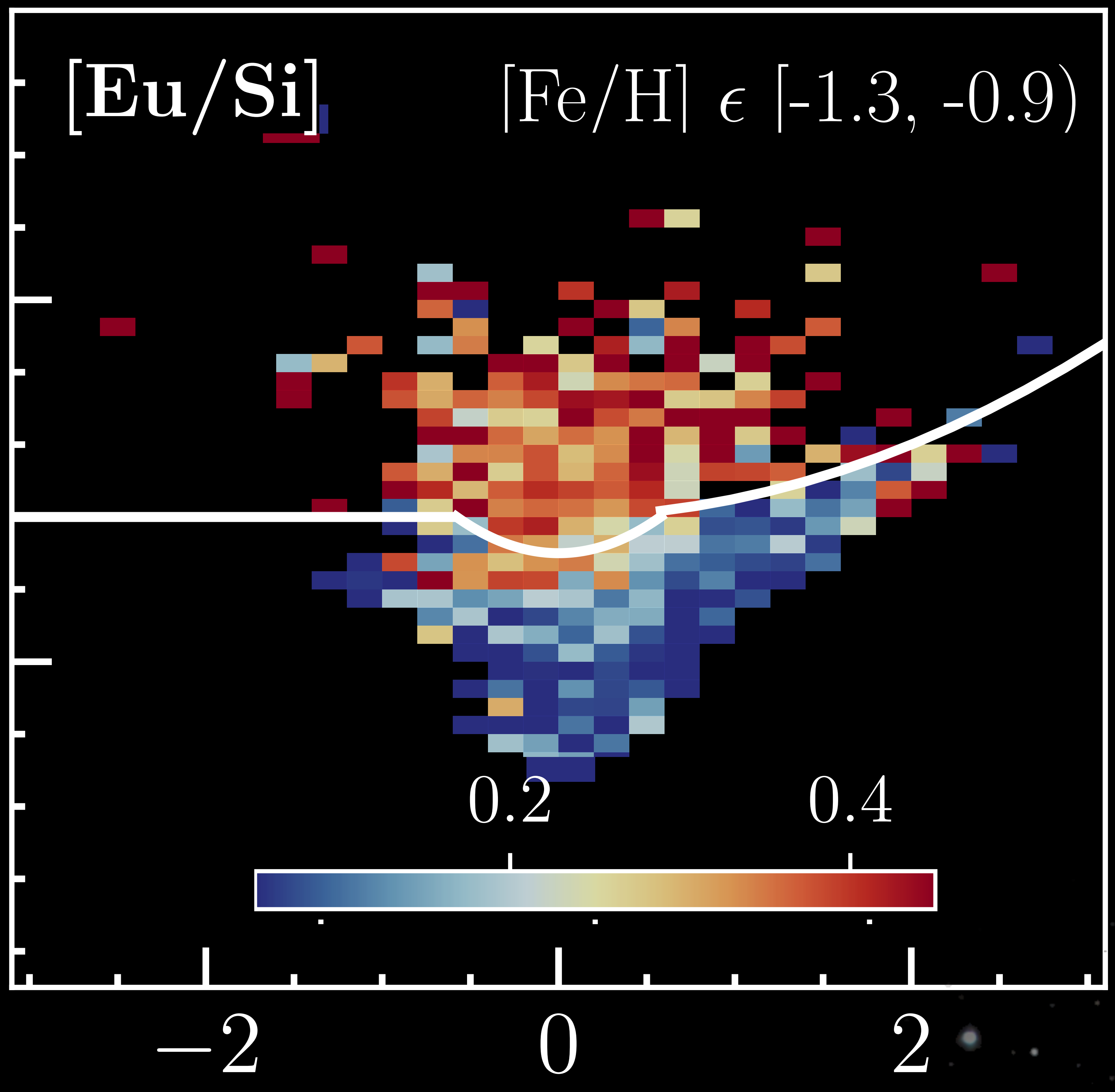




Belokurov et al. 2022

Gaia-Sausage/Enceladus in Chemical & Dynamical Space

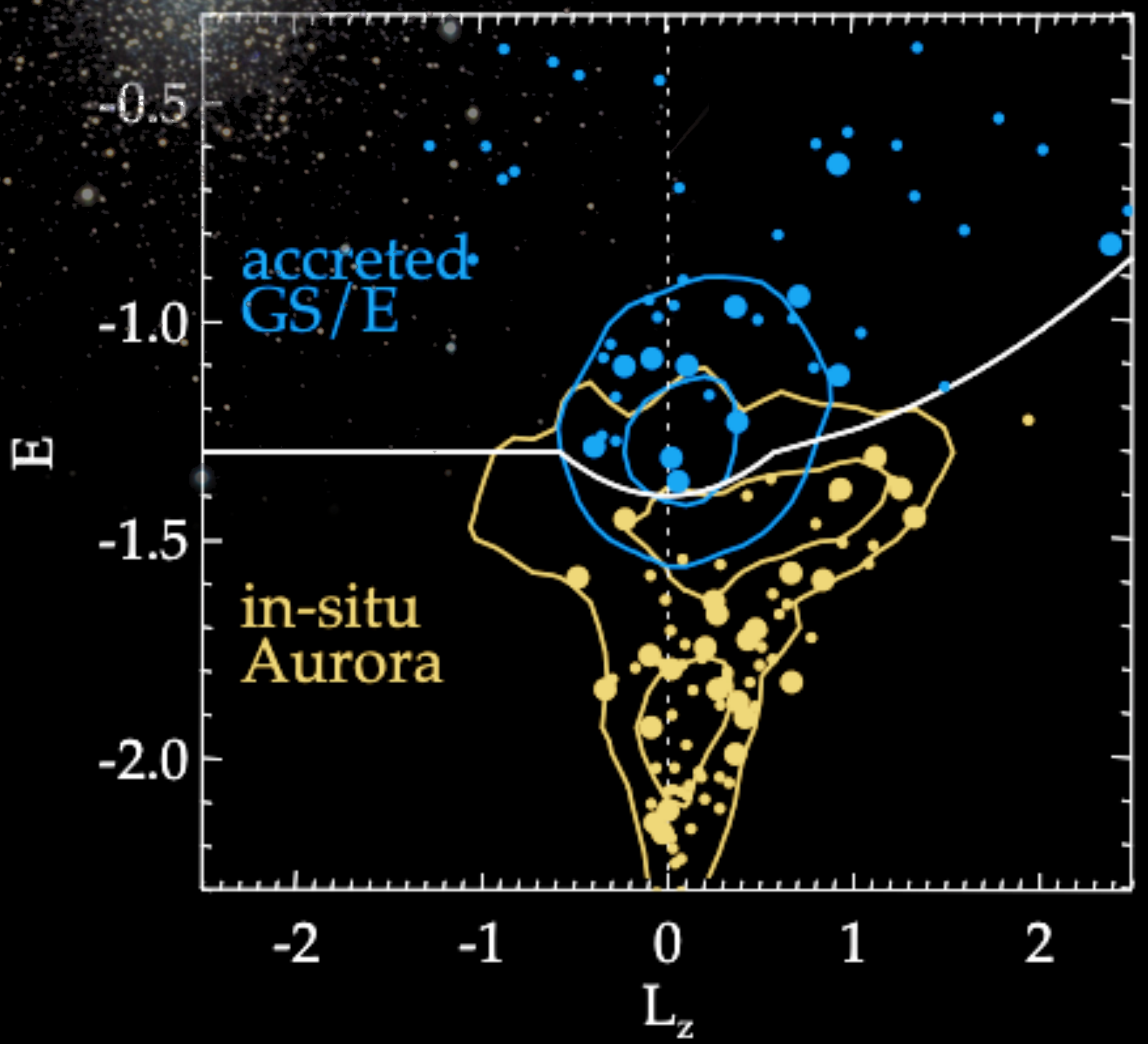


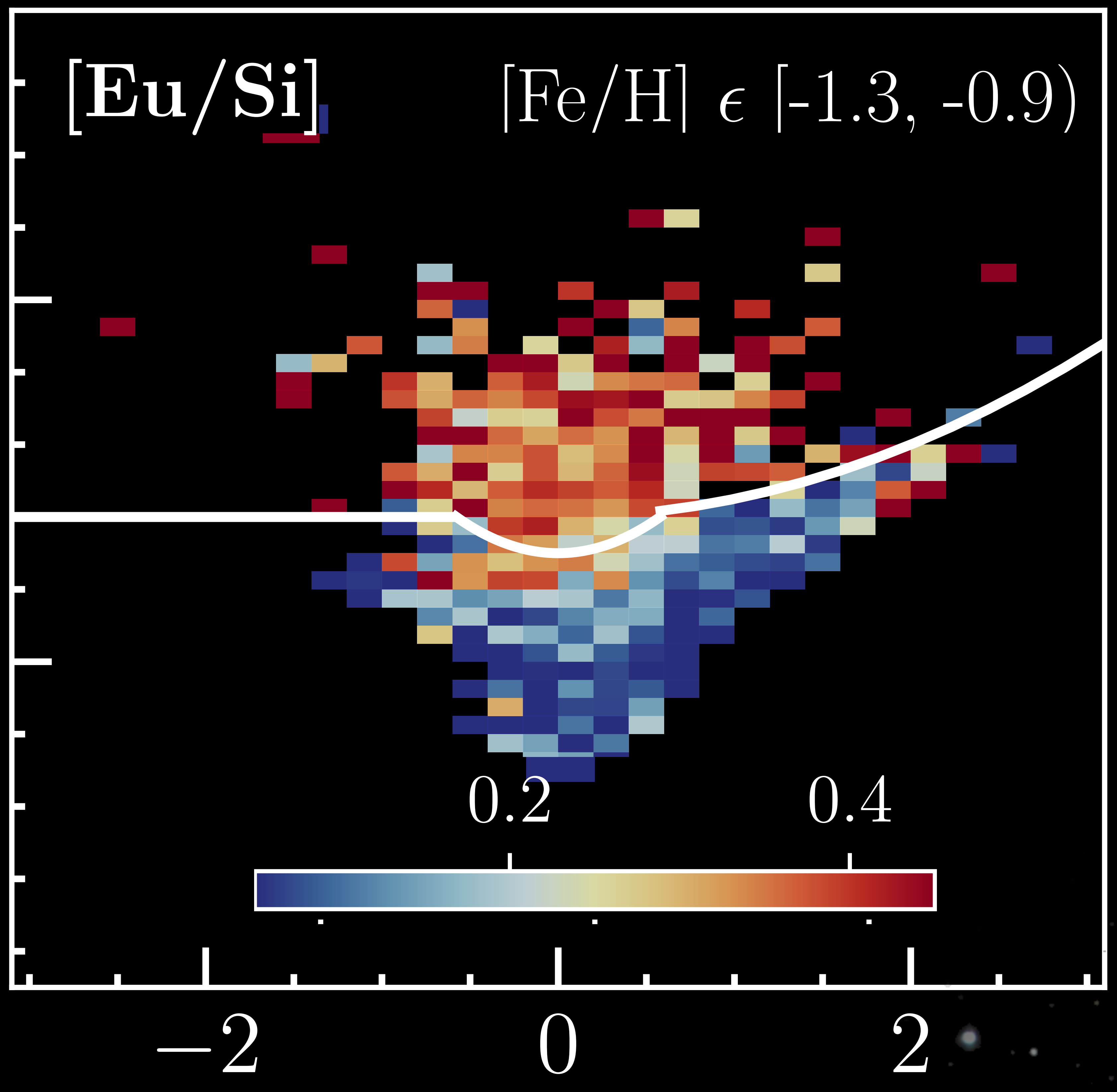


Highly radial, plunging orbits —>
little net angular momentum

Belokurov et al. 2022

Gaia-Sausage/Enceladus in Chemical & Dynamical Space



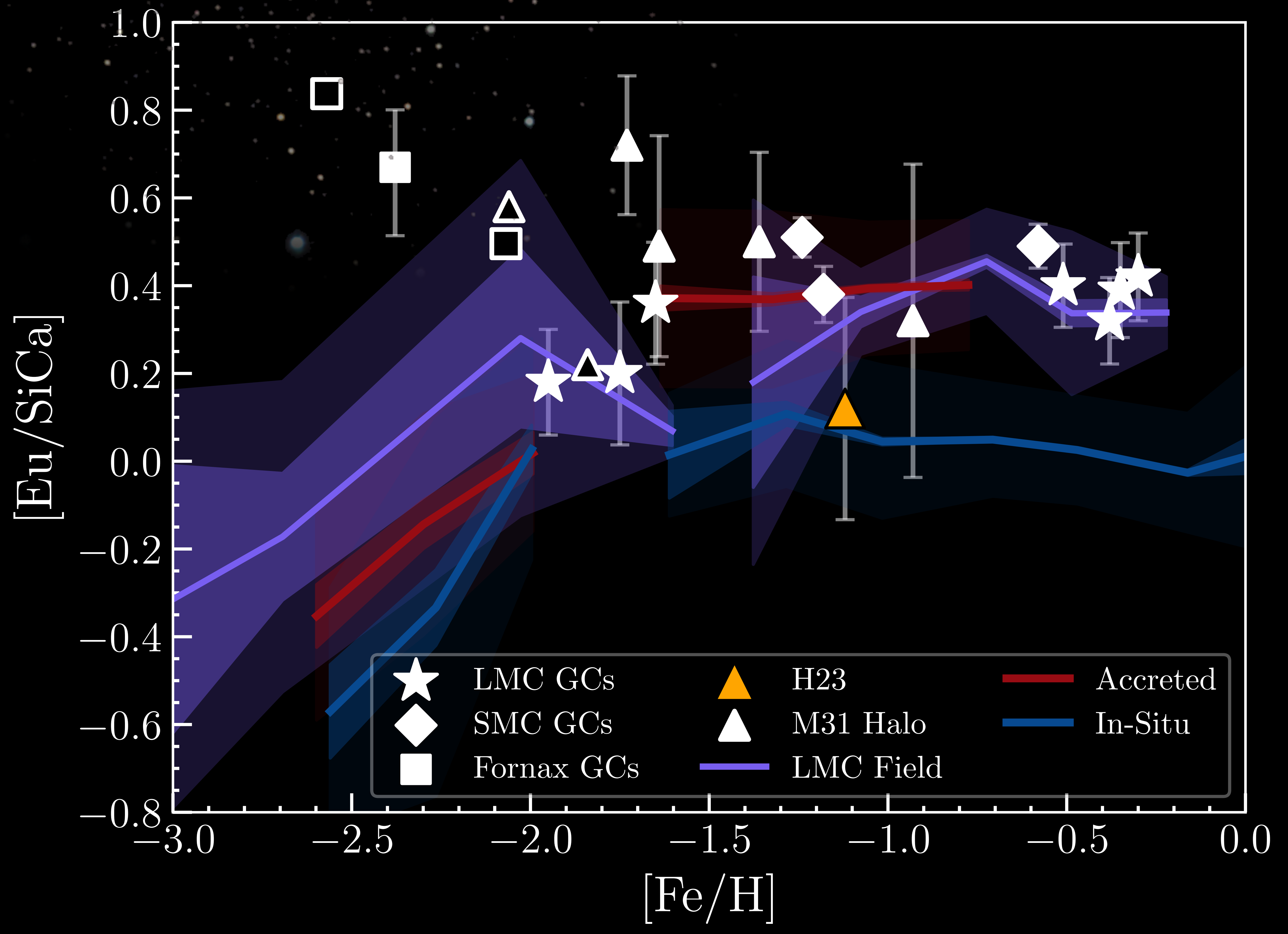


Highly radial, plunging orbits —> little net angular momentum

[Si/Fe] depletion, [Eu/Fe] enhancement

Belokurov et al. 2022

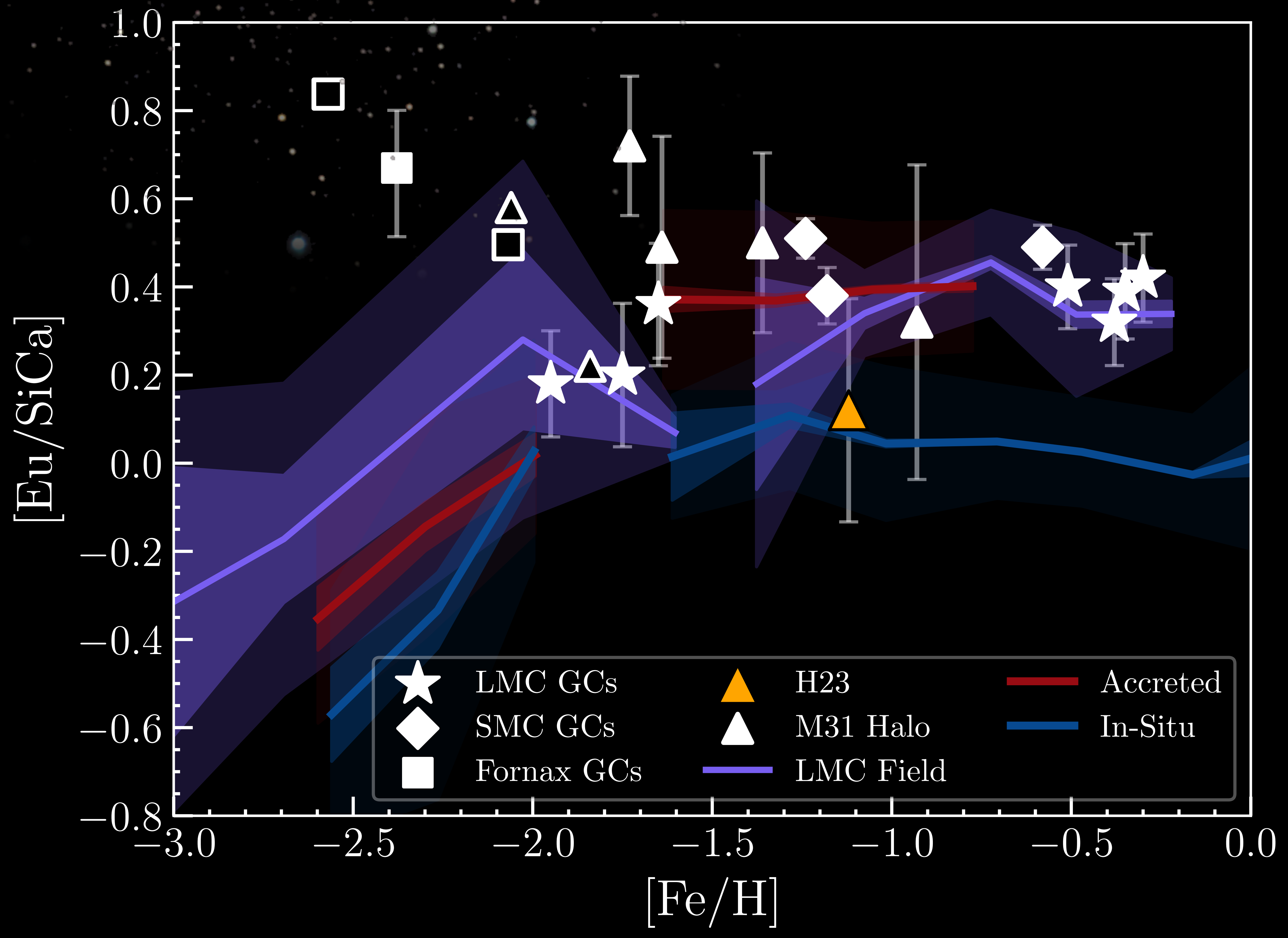
Bonus: [Eu/Si] could be used to perform Extra-galactic Archaeology



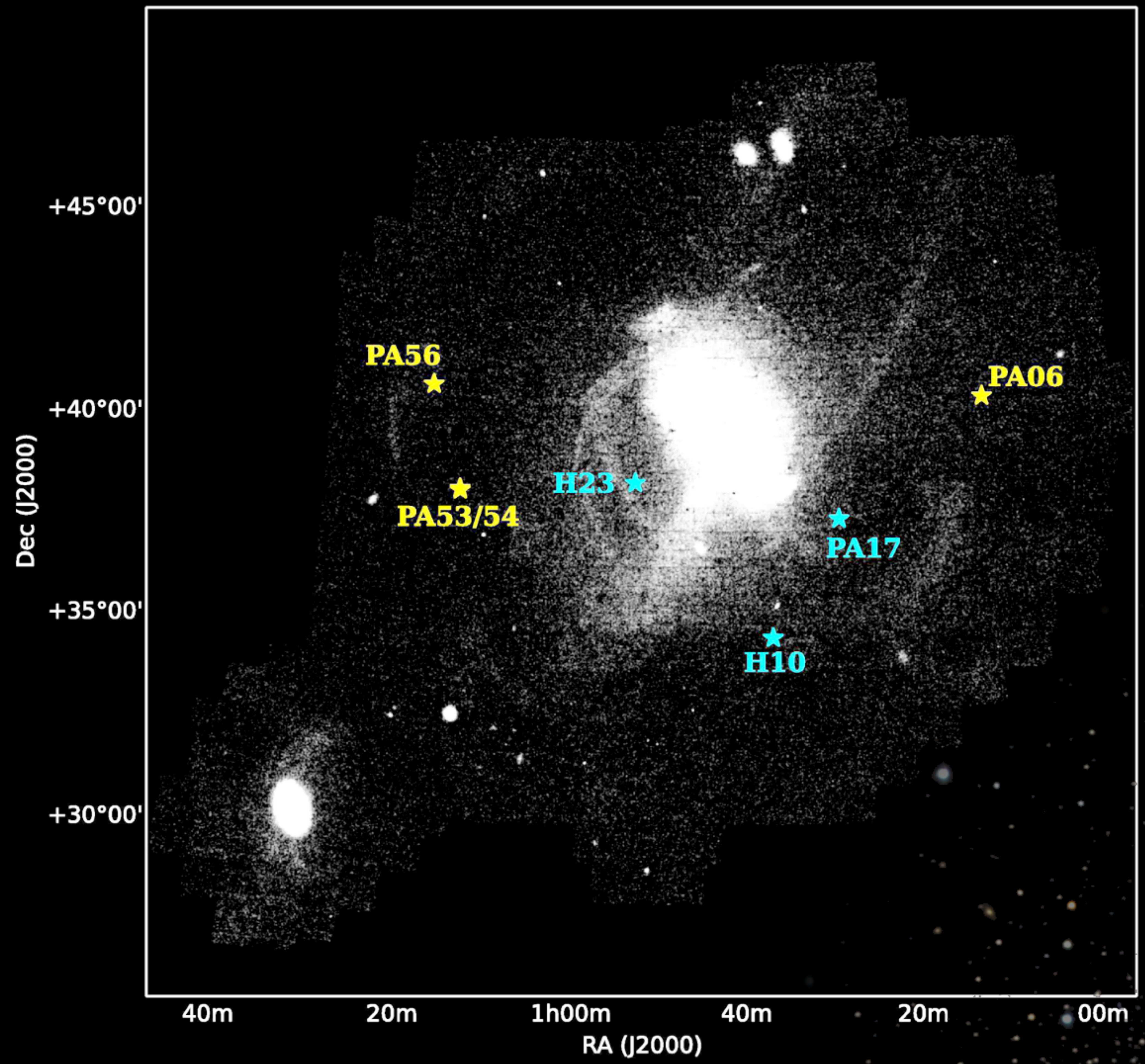
Monty+ 2024

Sakari et al. 2015

Bonus: [Eu/Si] could be used to perform Extra-galactic Archaeology



Monty+ 2024



Sakari et al. 2015

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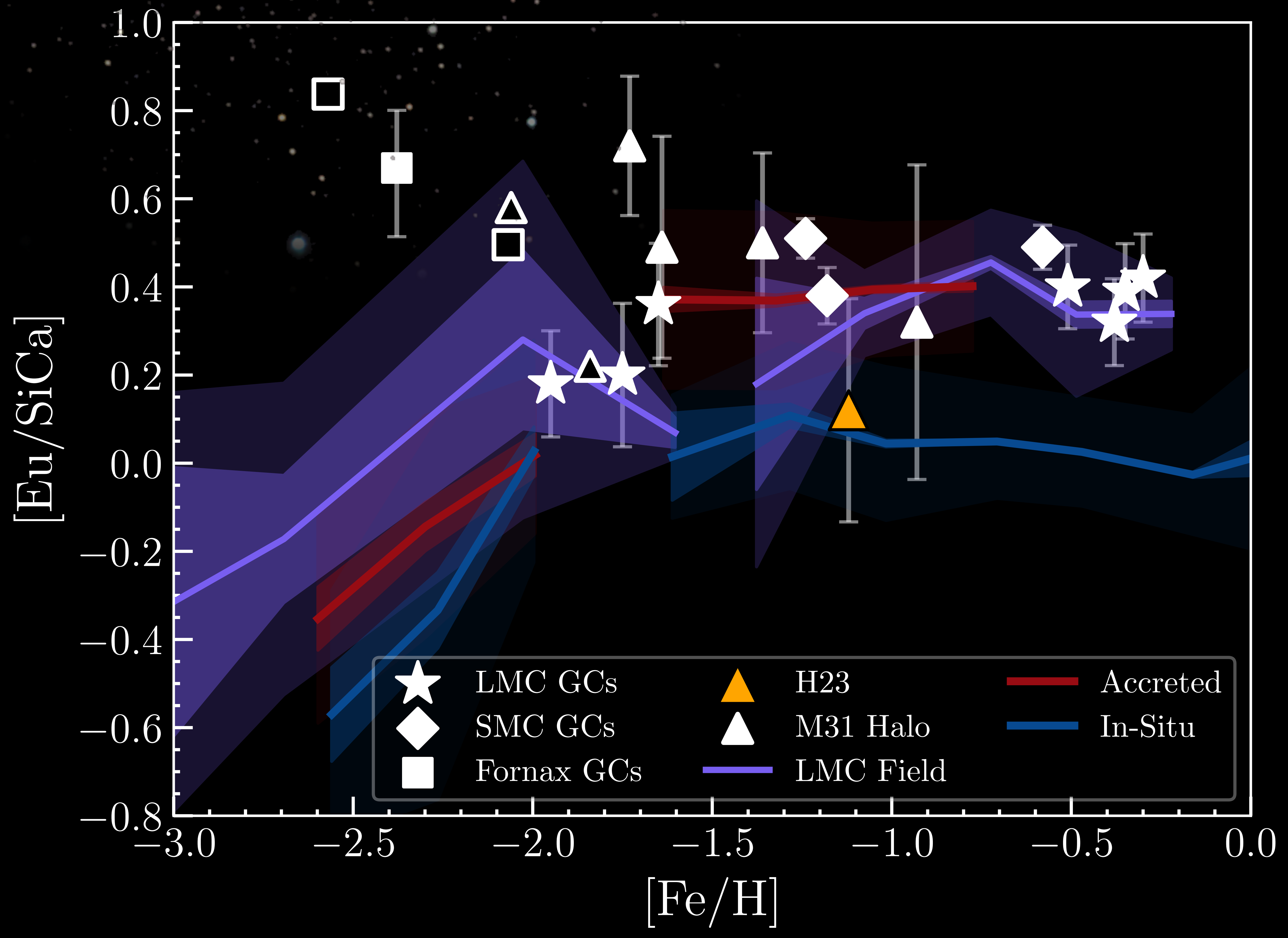

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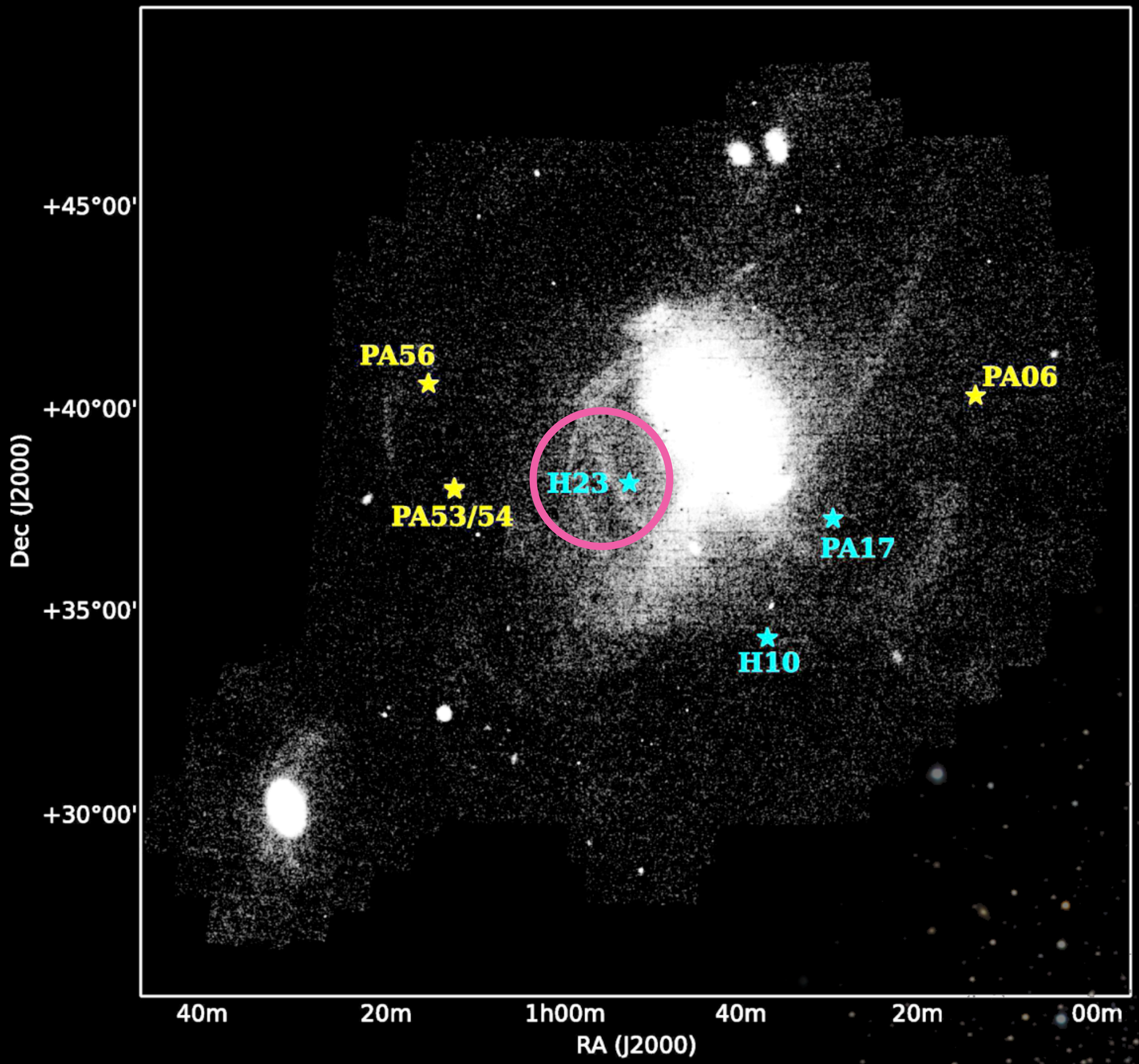

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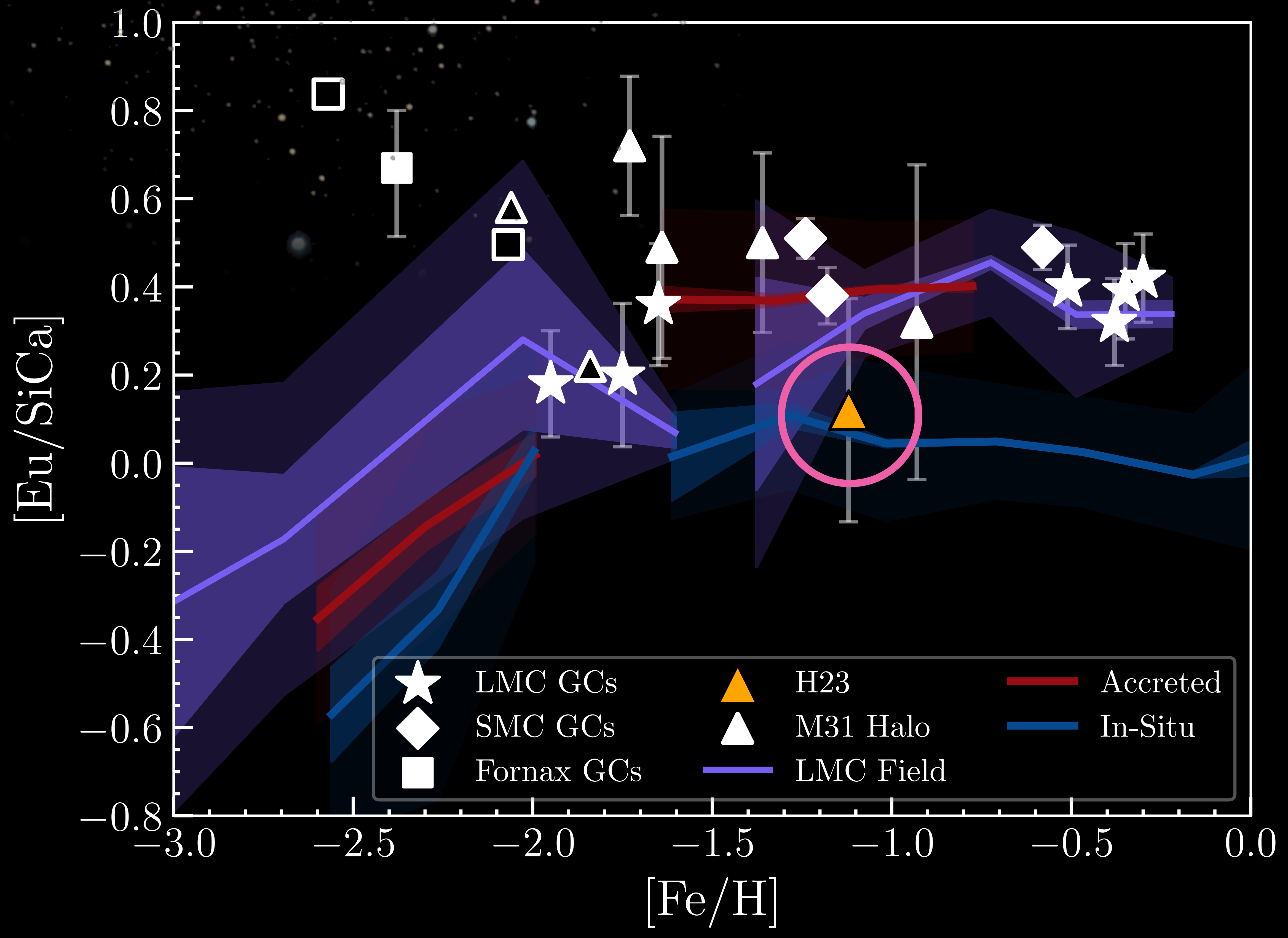

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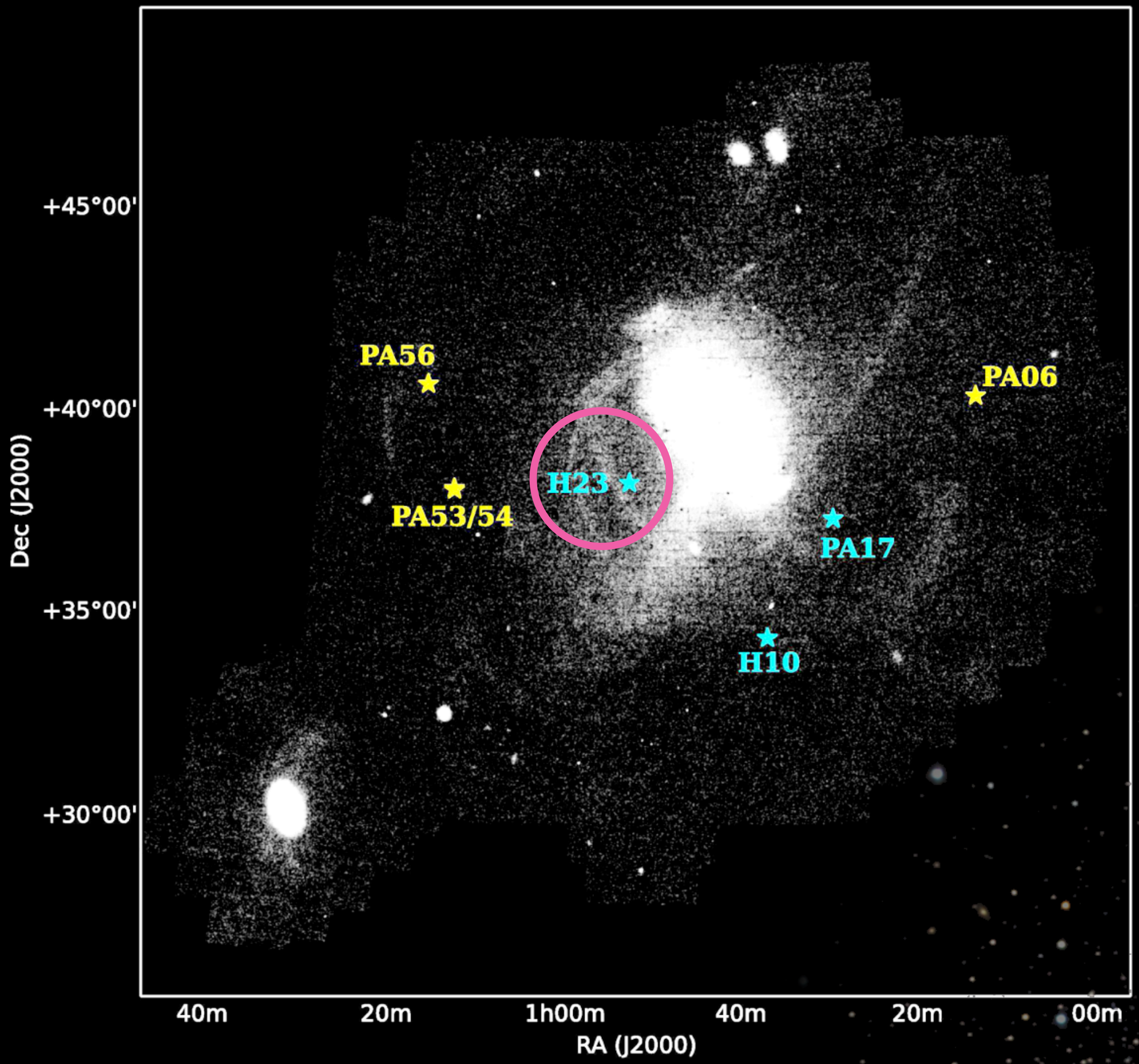
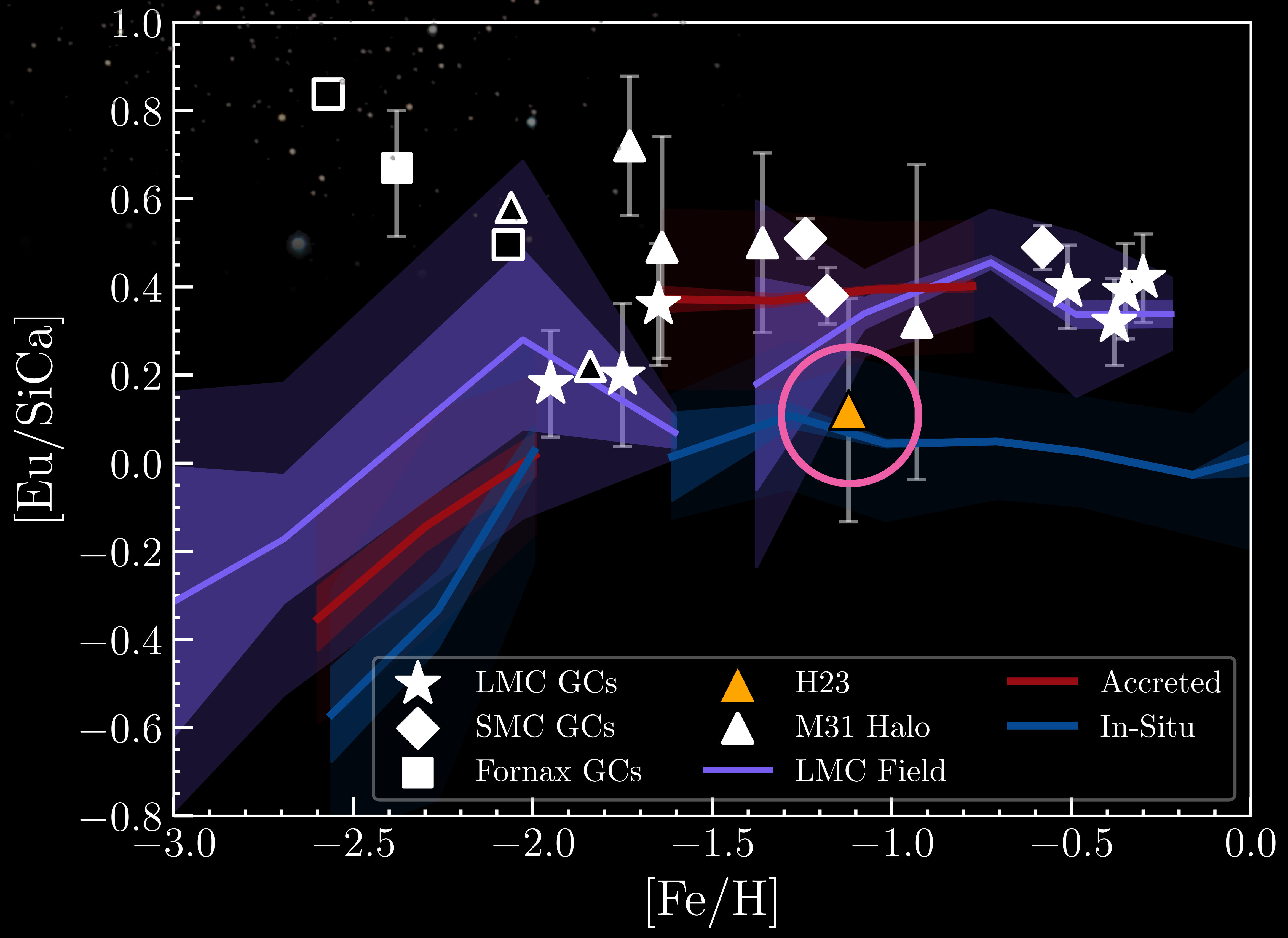


Sakari et al. 2015

Bonus: [Eu/Si] could be used to perform Extra-galactic Archaeology

Most likely in-situ GC which formed alongside M31



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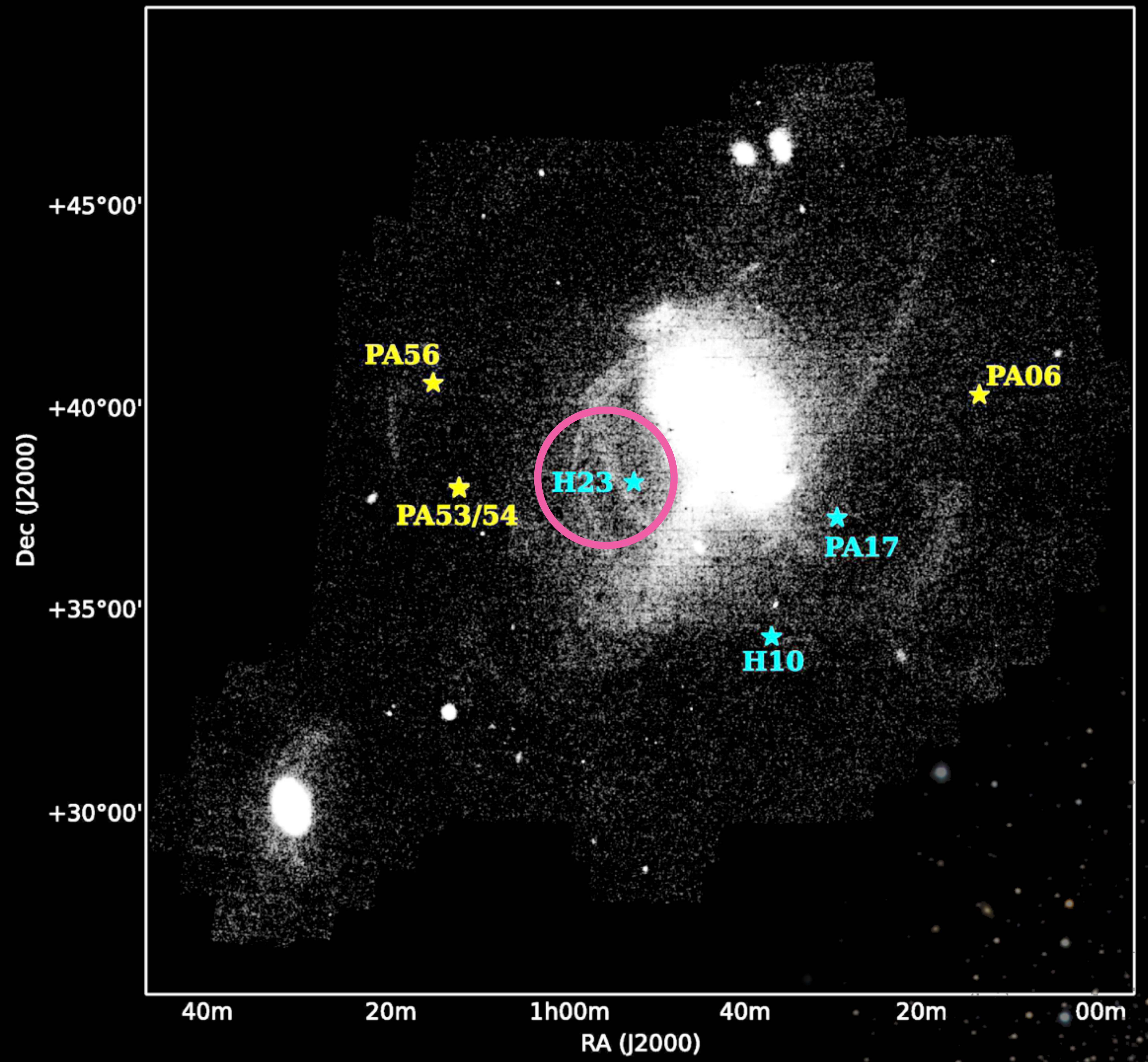

Sakari et al. 2015