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Optical Spectroscopy Reveals **Hidden Neutron-capture Elemental Abundance Differences** among **APOGEE-identified Chemical Doppelgängers**

Catherine Manea

NSF Astronomy and Astrophysics Postdoctoral Fellow @ Columbia University

Collaborators: Melissa Ness (ANU), Keith Hawkins (UT Austin), Megan Bedell (CCA), David Hogg (NYU), Kathryn Johnston (Columbia), Carrie Filion (CCA), Emily Griffith (CU-Boulder), Natalie Myers (TCU), Amaya Sinha (Utah), Austin Rothermich (AMNH), Caprice Phillips (OSU), Aida Behmard (CCA), Madeline Lucey (UPenn), Andy Casey (Monash), Zoe Hackshaw (UT Austin), and others

APOGEE

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APOGEE: Apache Point Observatory Galactic Evolution Experiment”

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SDSS

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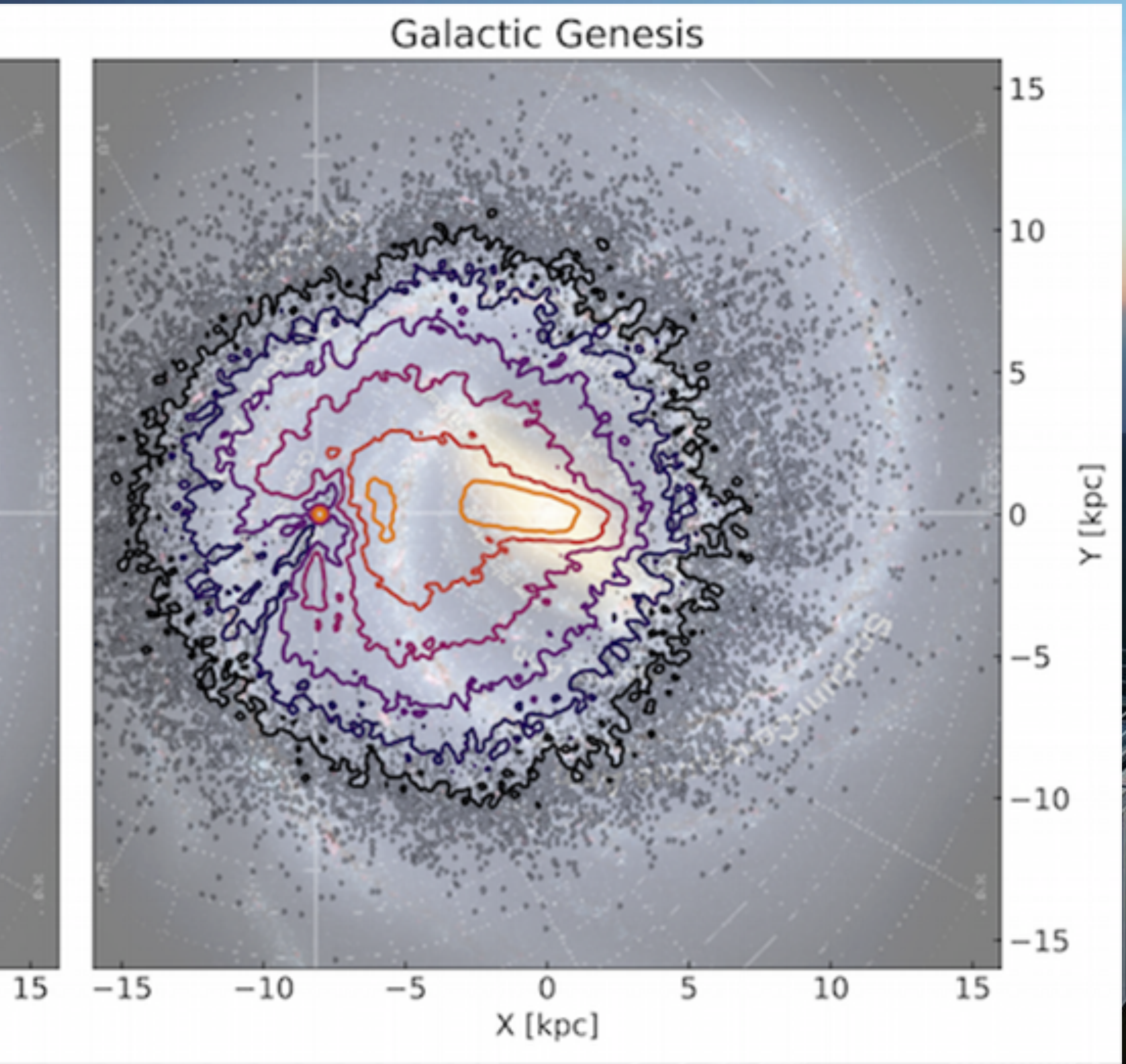

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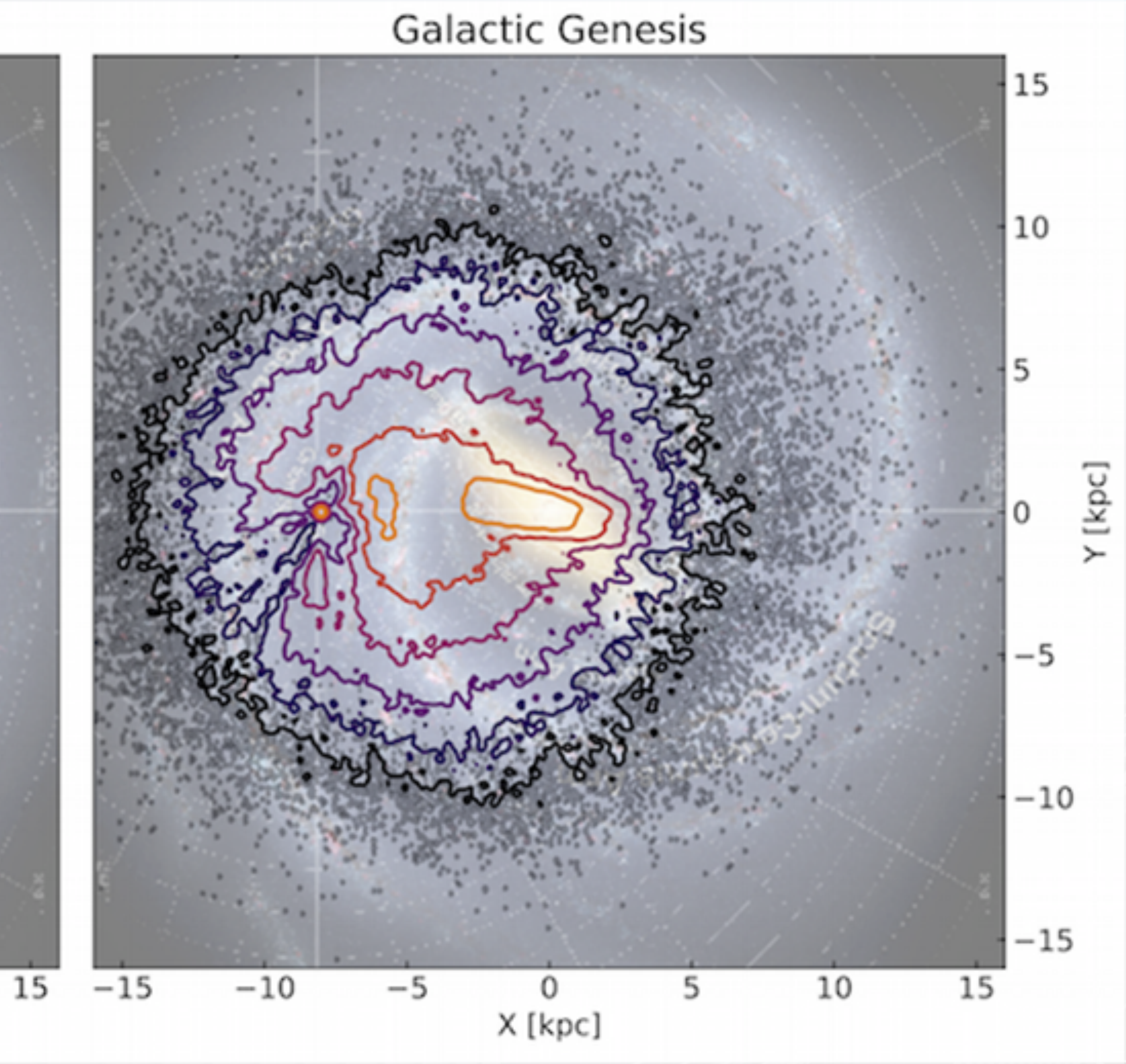

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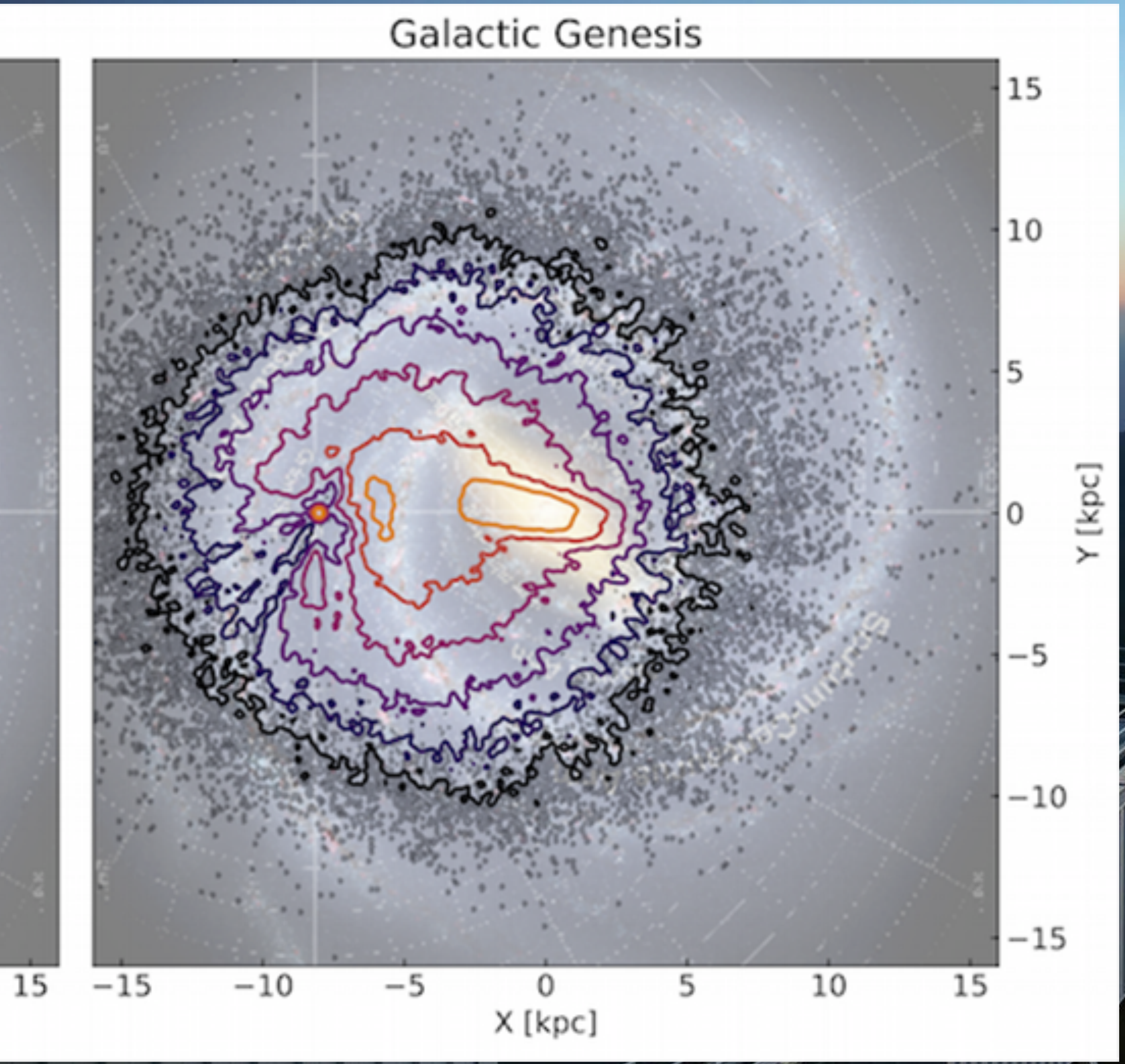

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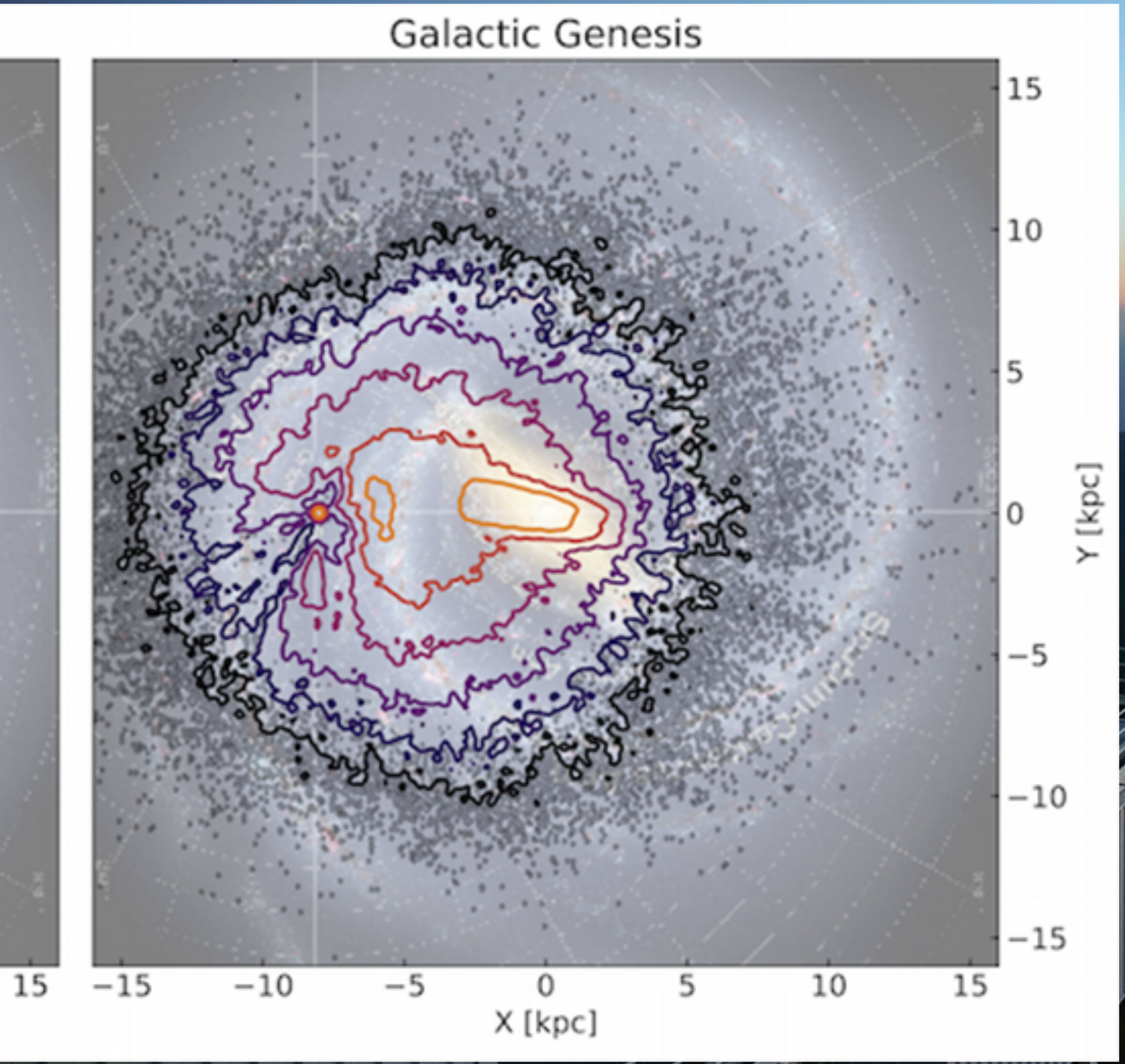

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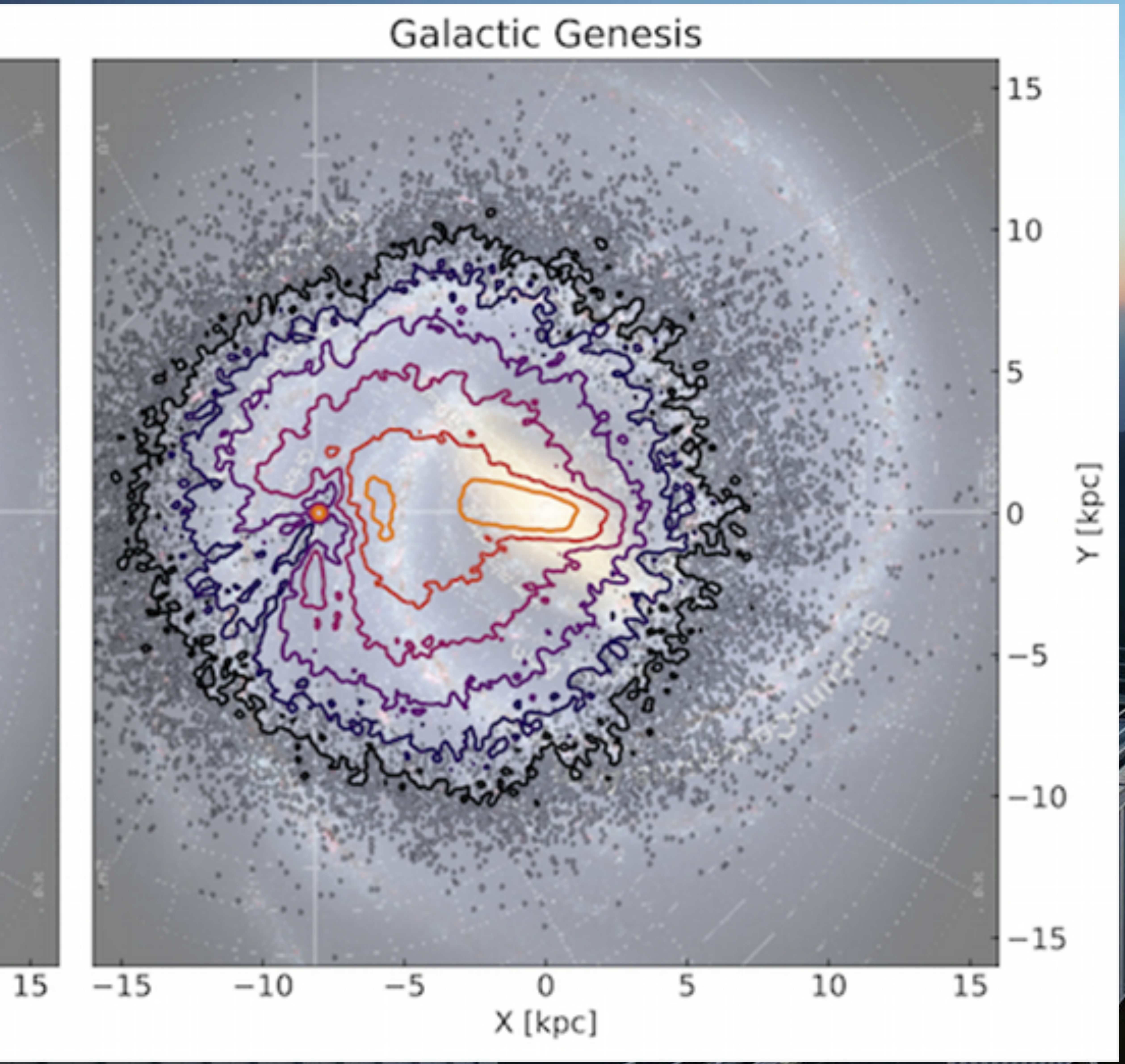

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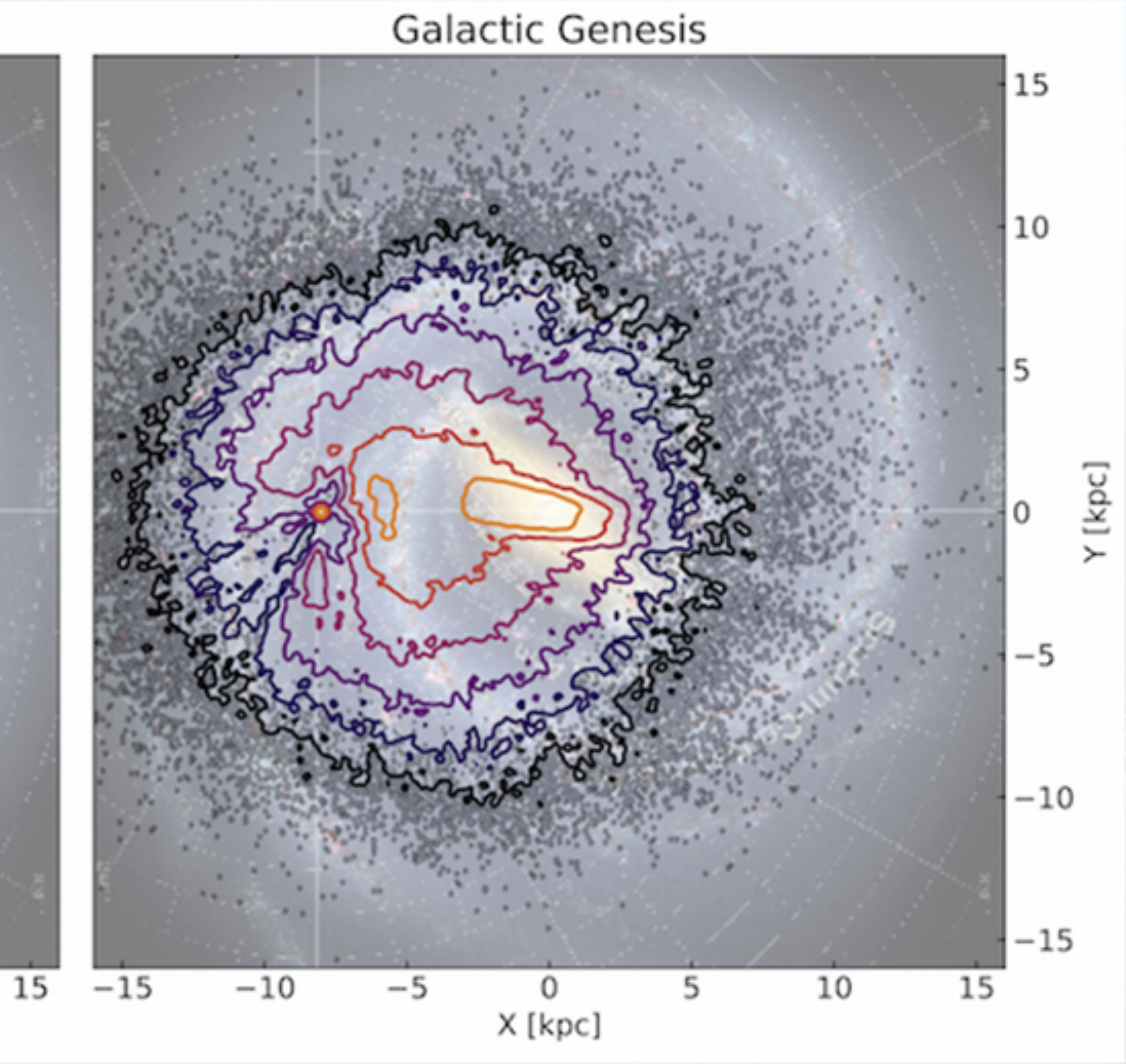

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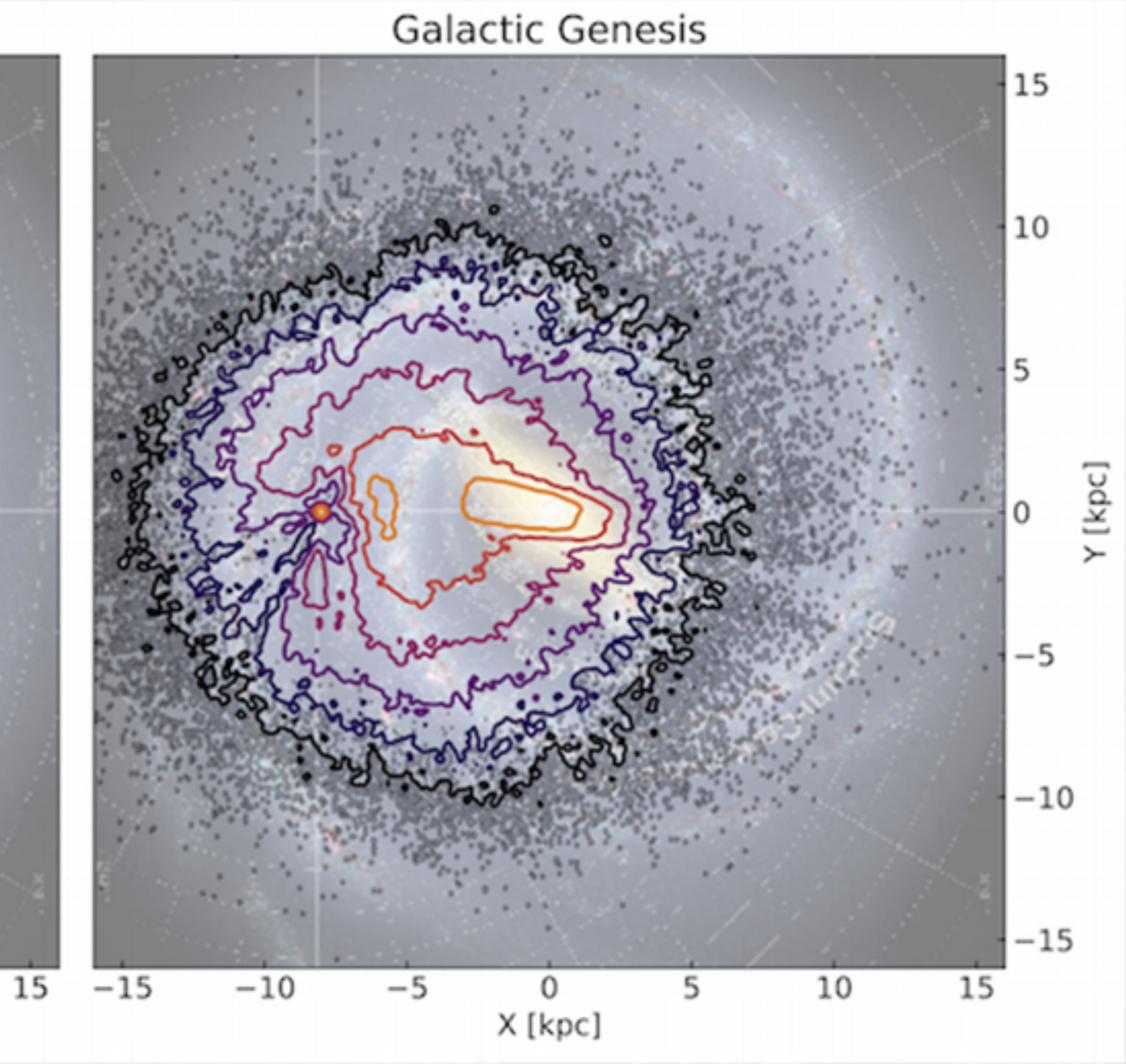

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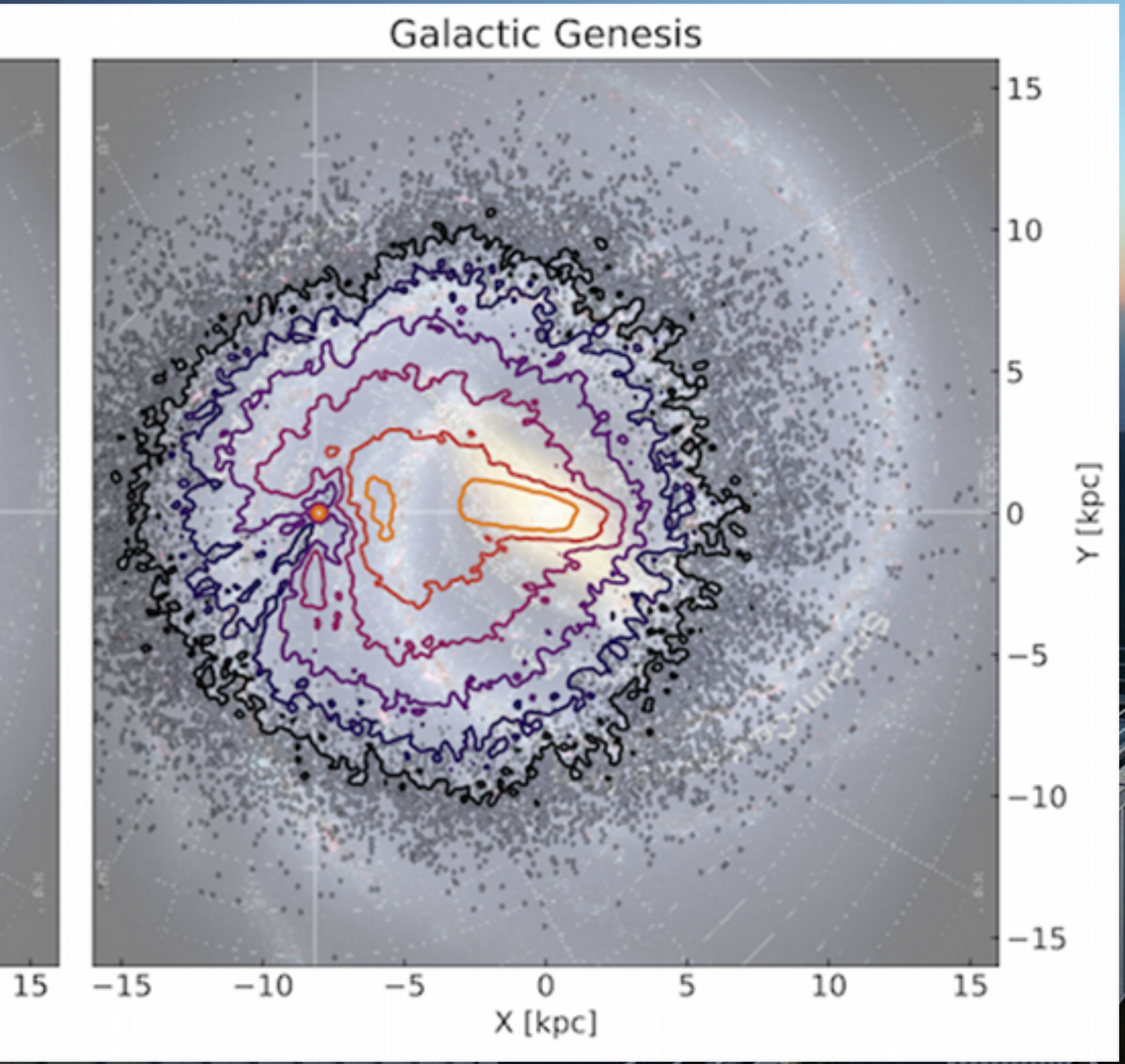

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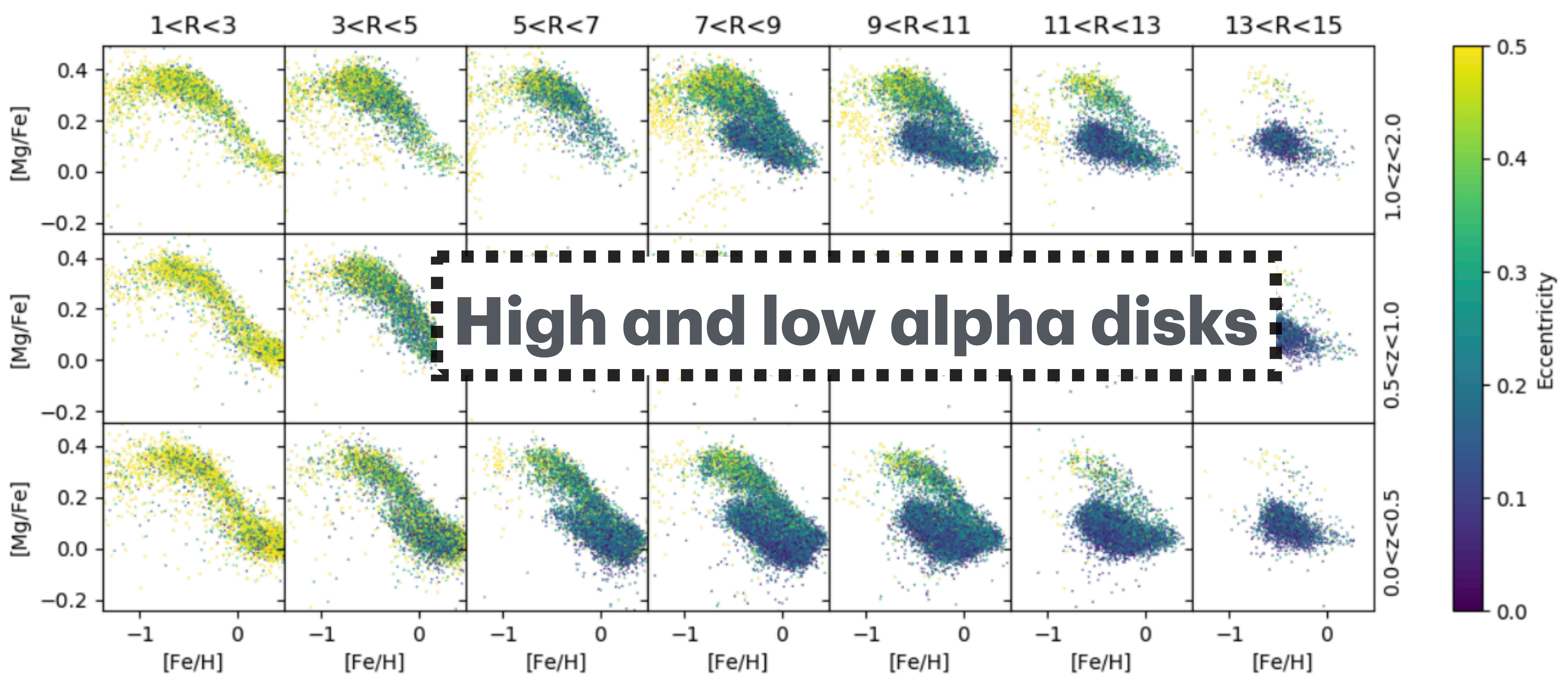
    - Spectral grid matching with FERRE (Allende-Prieto+2017)

APOGEE abundances have revolutionized our understanding of the Milky Way disk



Holtzmann+2018

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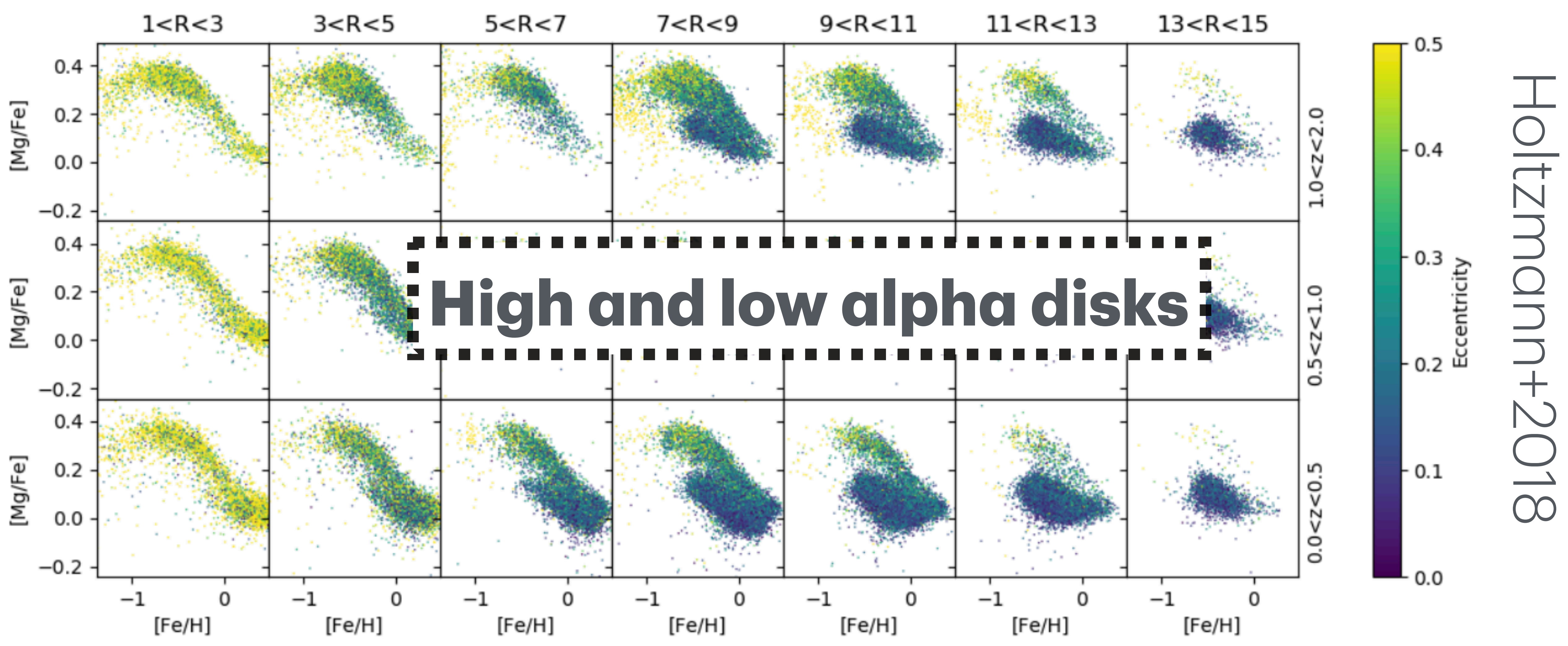

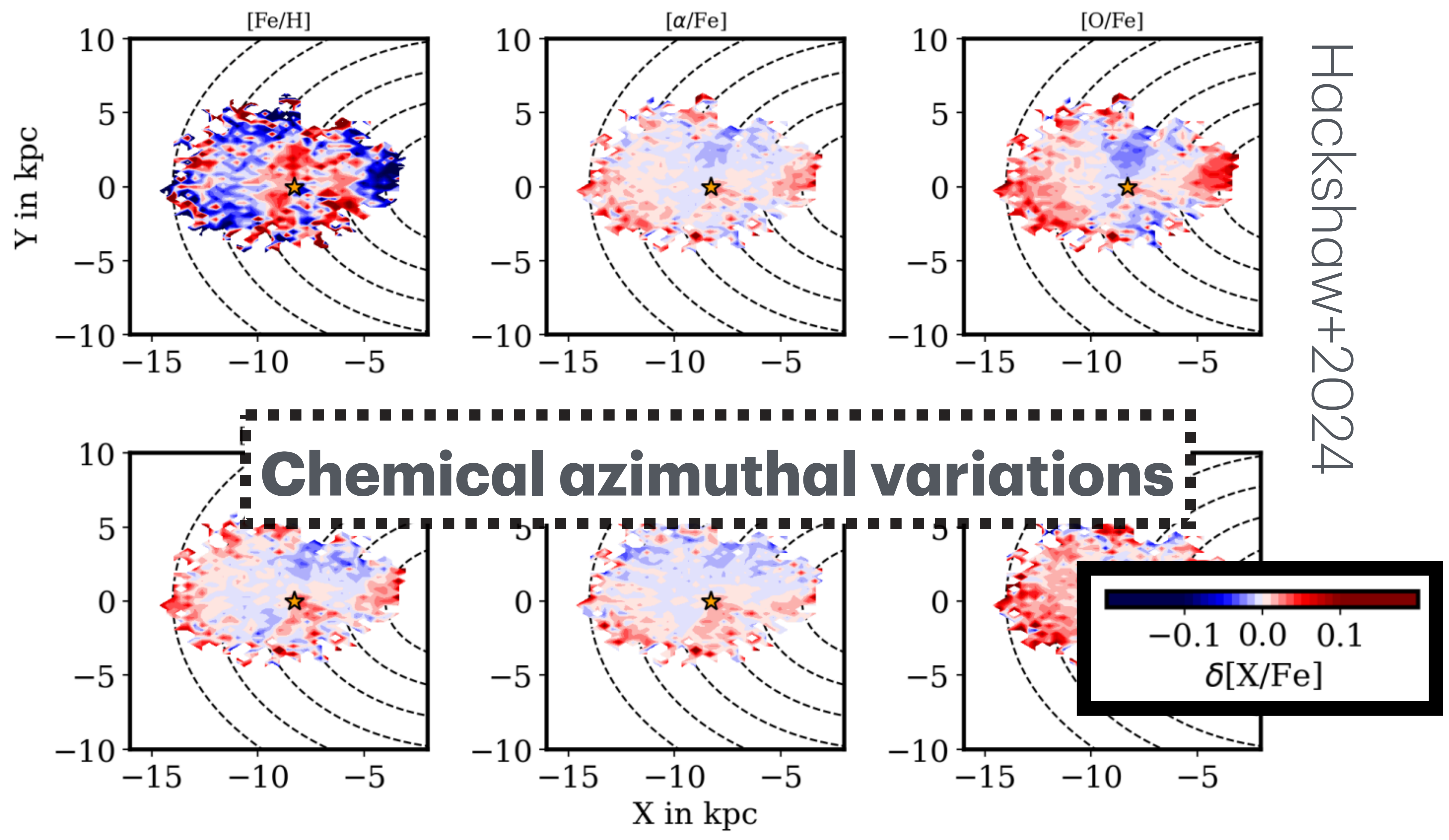

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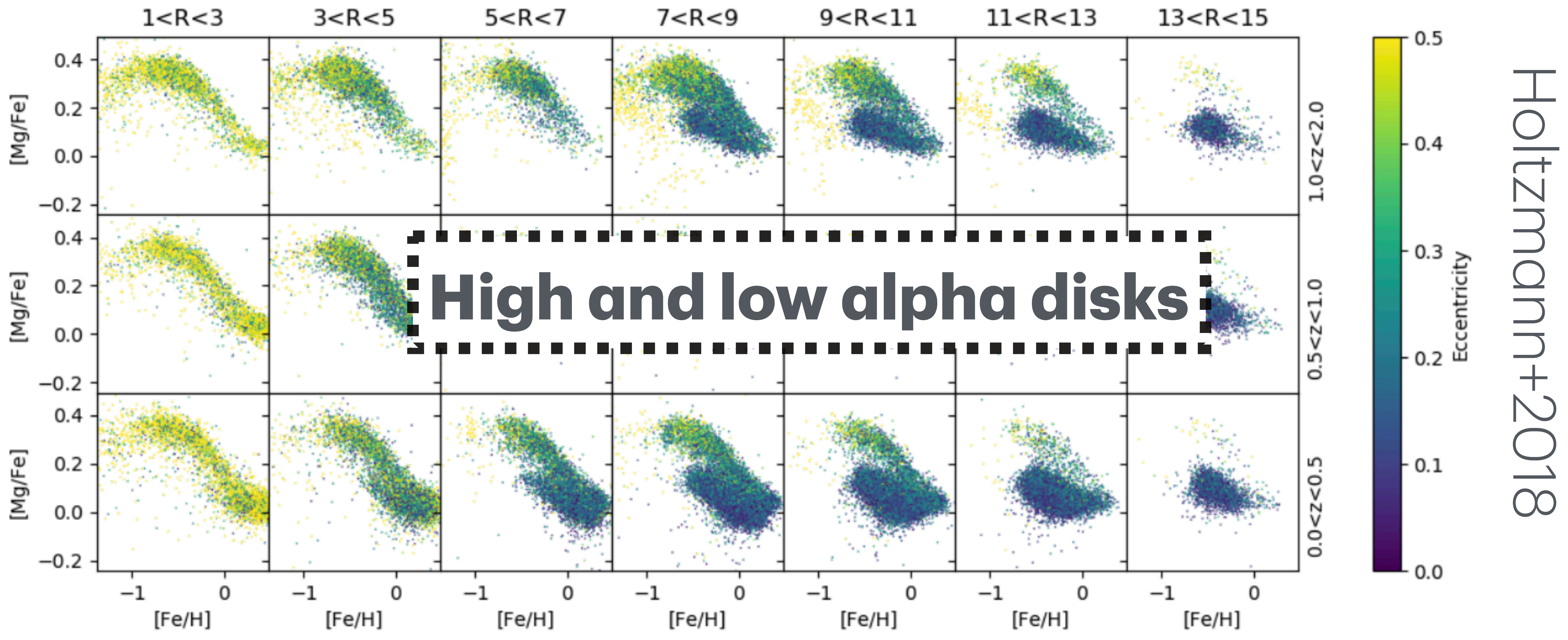

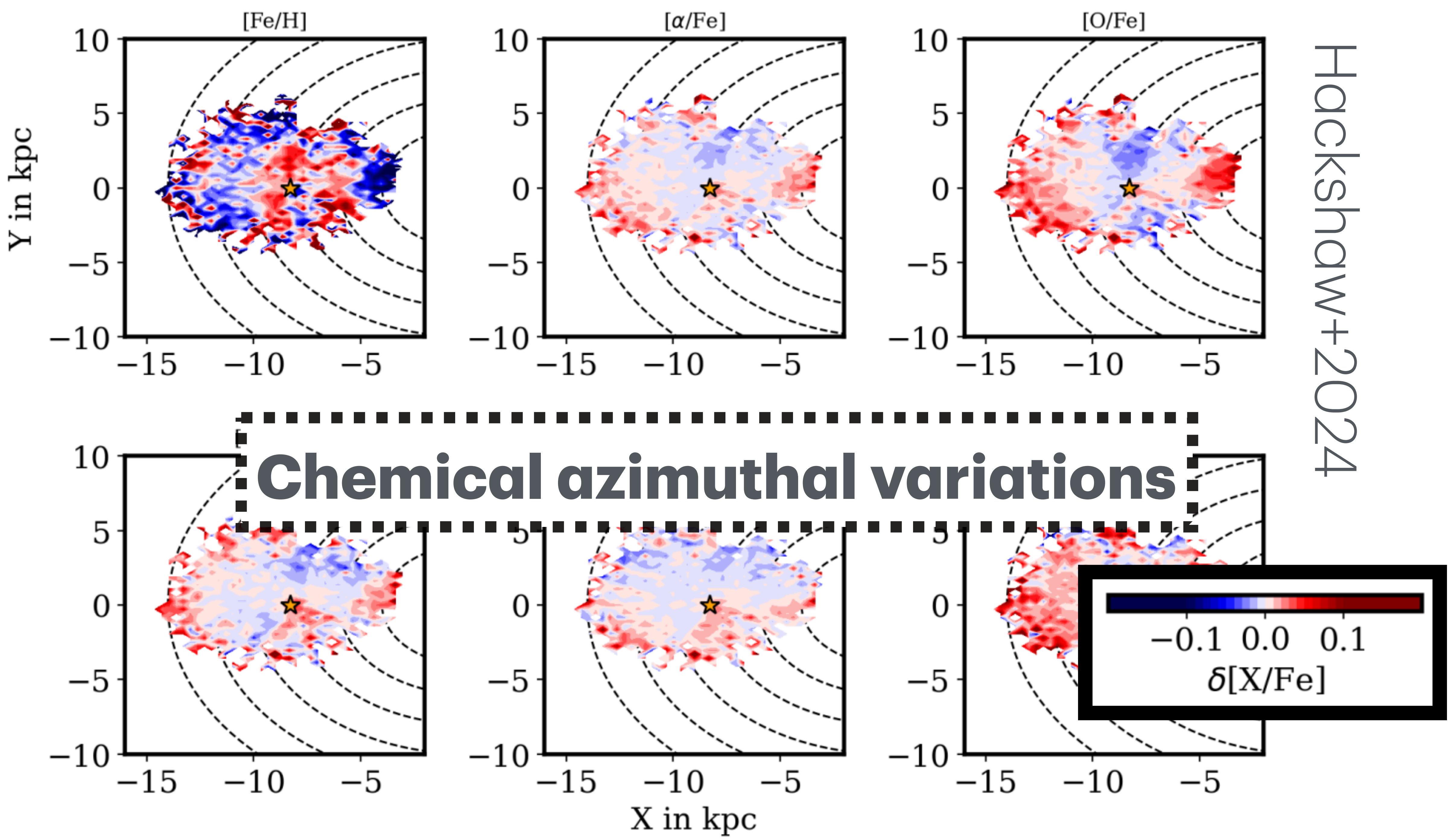

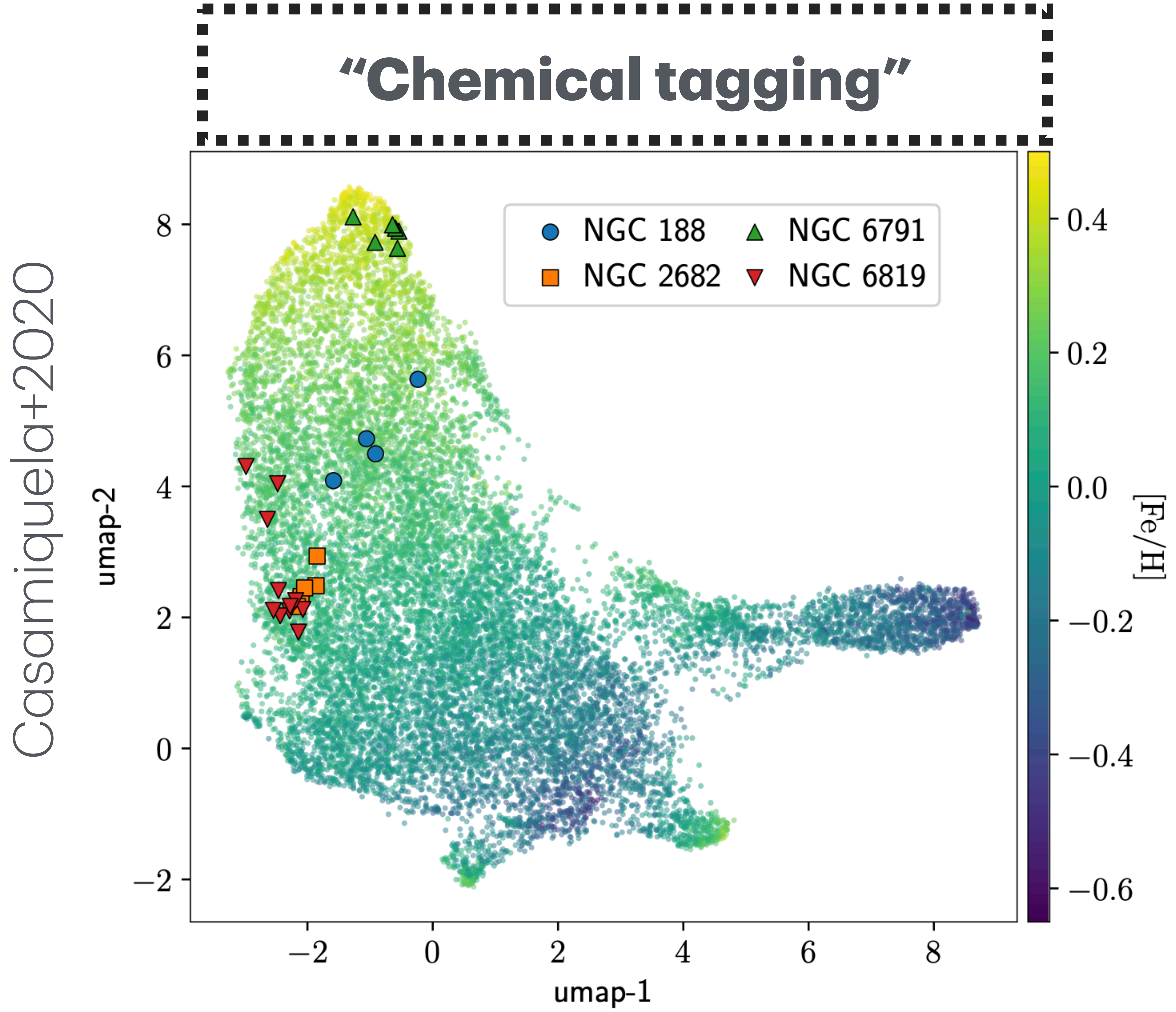

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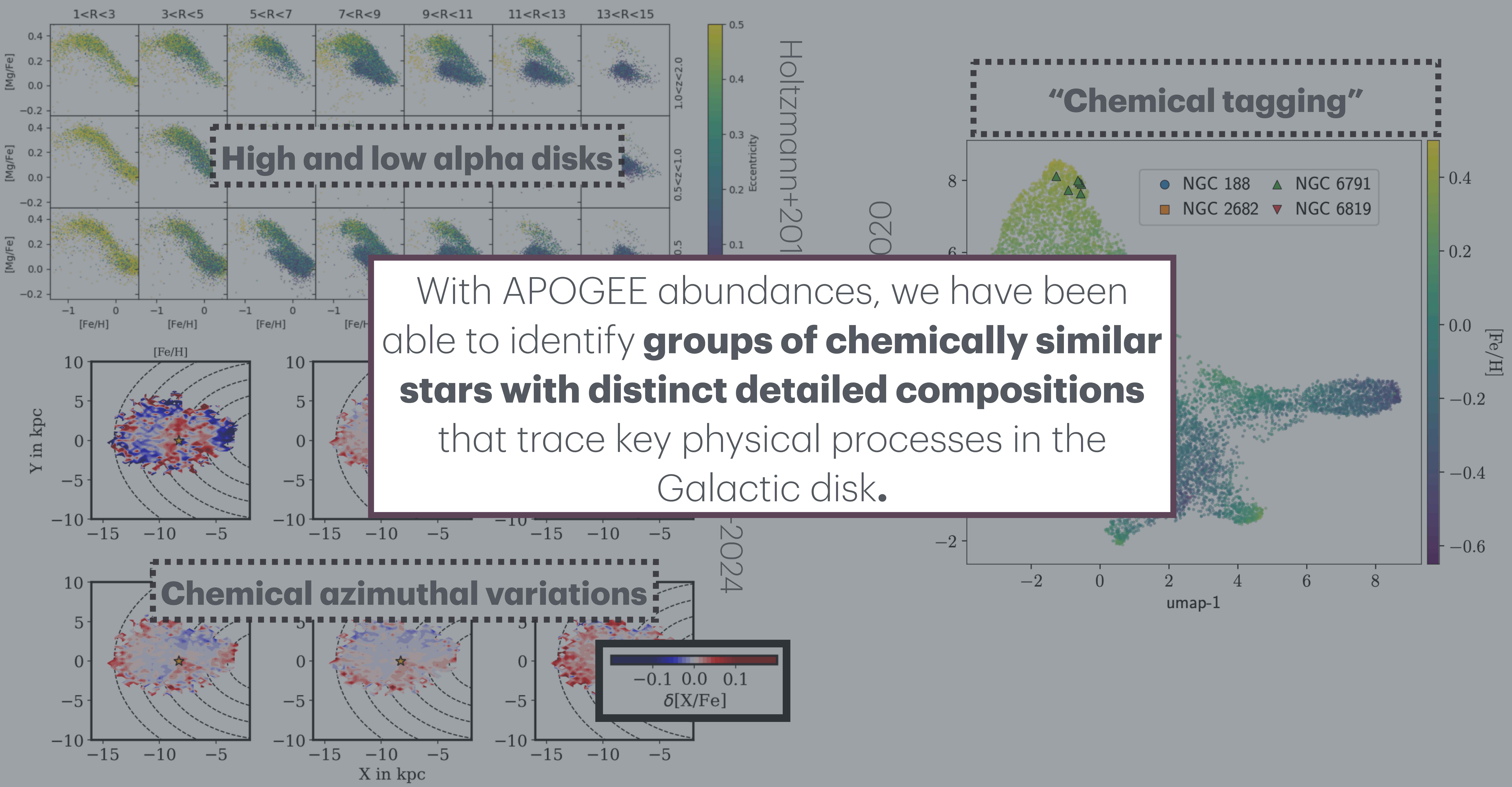
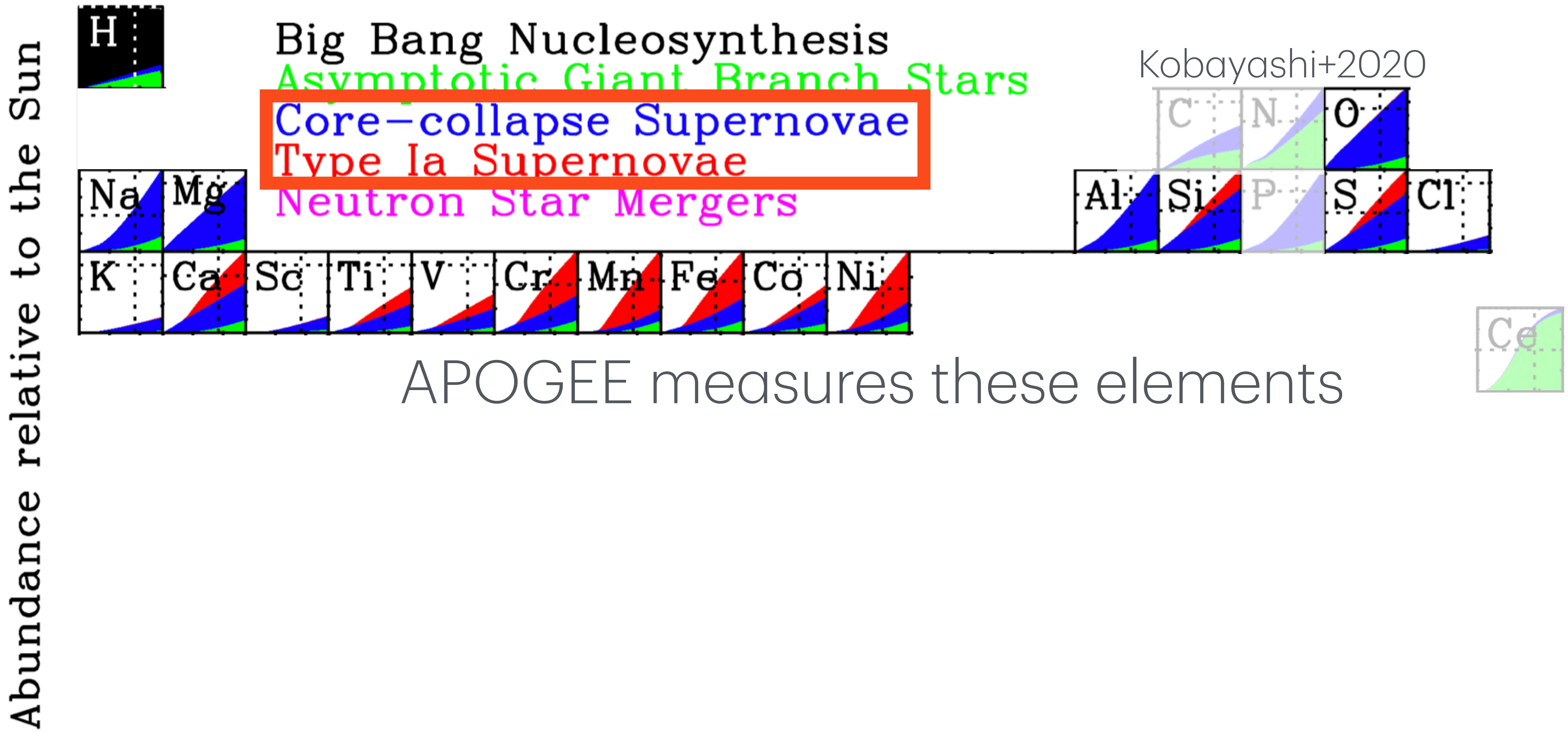


With APOGEE abundances, we have been able to identify **groups of chemically similar stars with distinct detailed compositions** that trace key physical processes in the Galactic disk.

Is APOGEE all we need in the disk? Is it missing anything?



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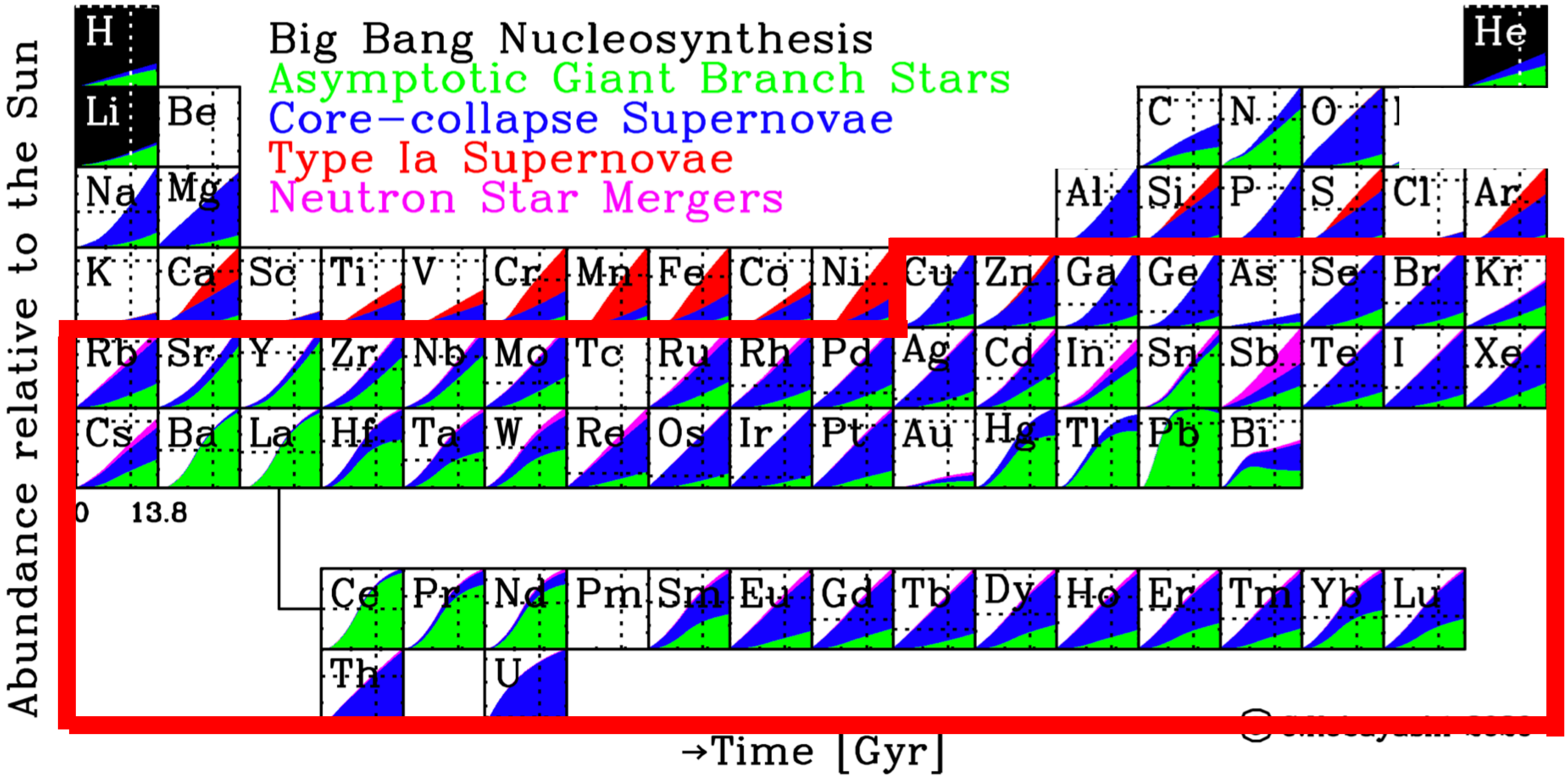
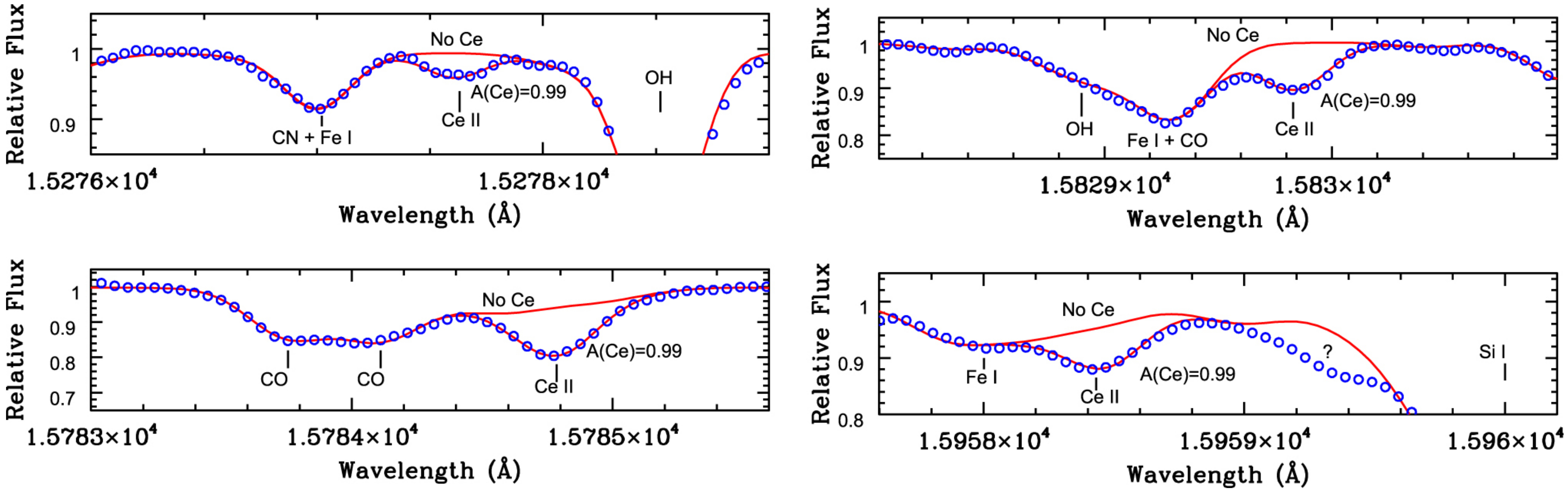


But what about the neutron-capture elements?

Adding the s-Process Element Cerium to the APOGEE Survey: Identification and Characterization of Ce II Lines in the H-band Spectral Window

Katia Cunha, Verne V. Smith, Sten Hasselquist, Diogo Souto, Matthew D. Shetrone,
Carlos Allende Prieto, Dmitry Bizyaev, Peter Frinchaboy, D. Anibal García-Hernández, Jon Holtzman



Ade... OGEE Survey:
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Katia... Shetrone,
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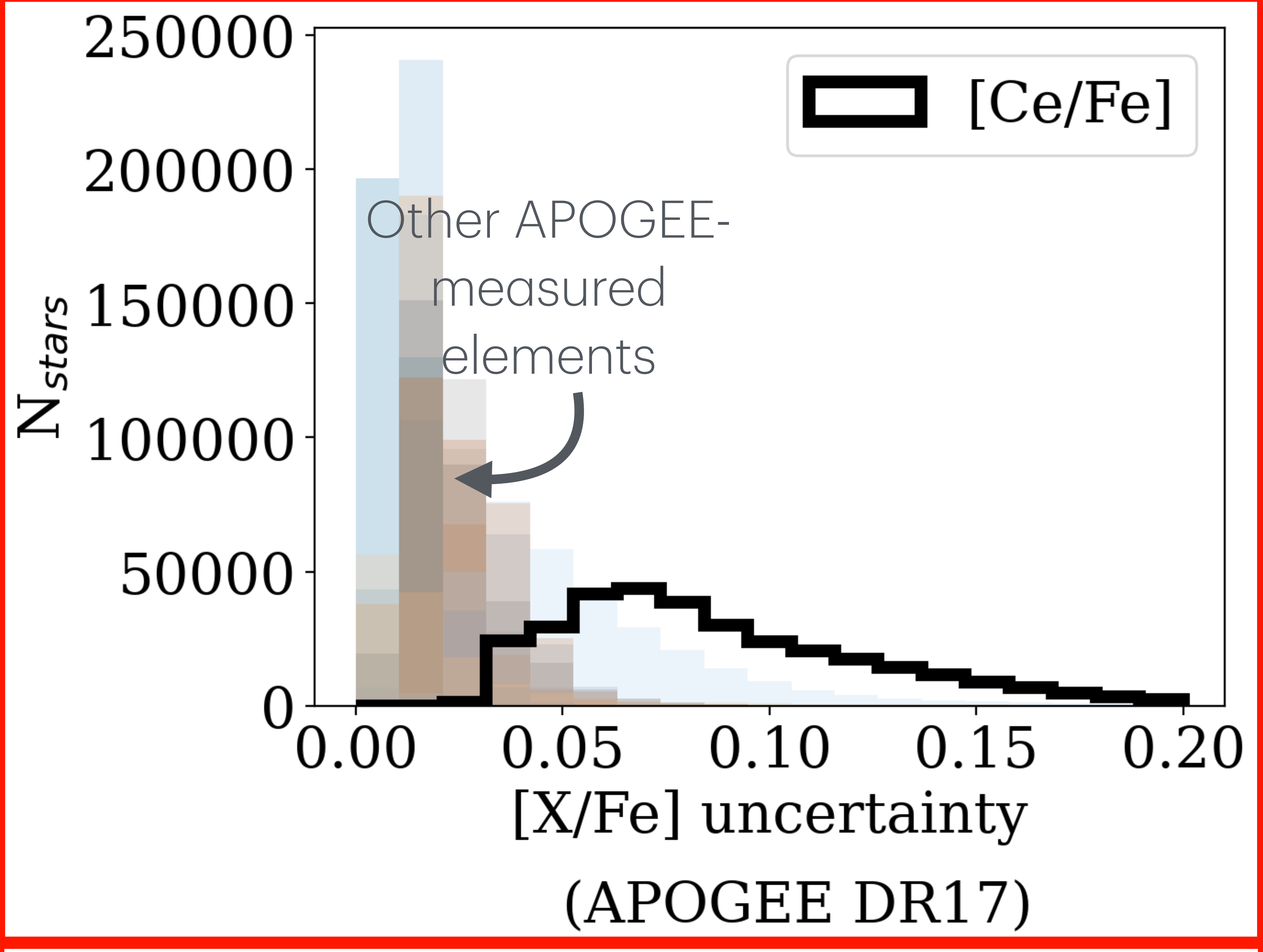

[Ce/Fe] is one of the least precisely measured elements in APOGEE.

s-process elements are unique

- Strong relationship between star’s [s/alpha] abundance and **age**
- Relationship varies across the disk; strongly **metallicity and spatially dependent**
  - (e.g., Casali+2020, Magrini+2021, Viscasillas Vazquez+2022, Ratcliffe+2023, Molero+2024)

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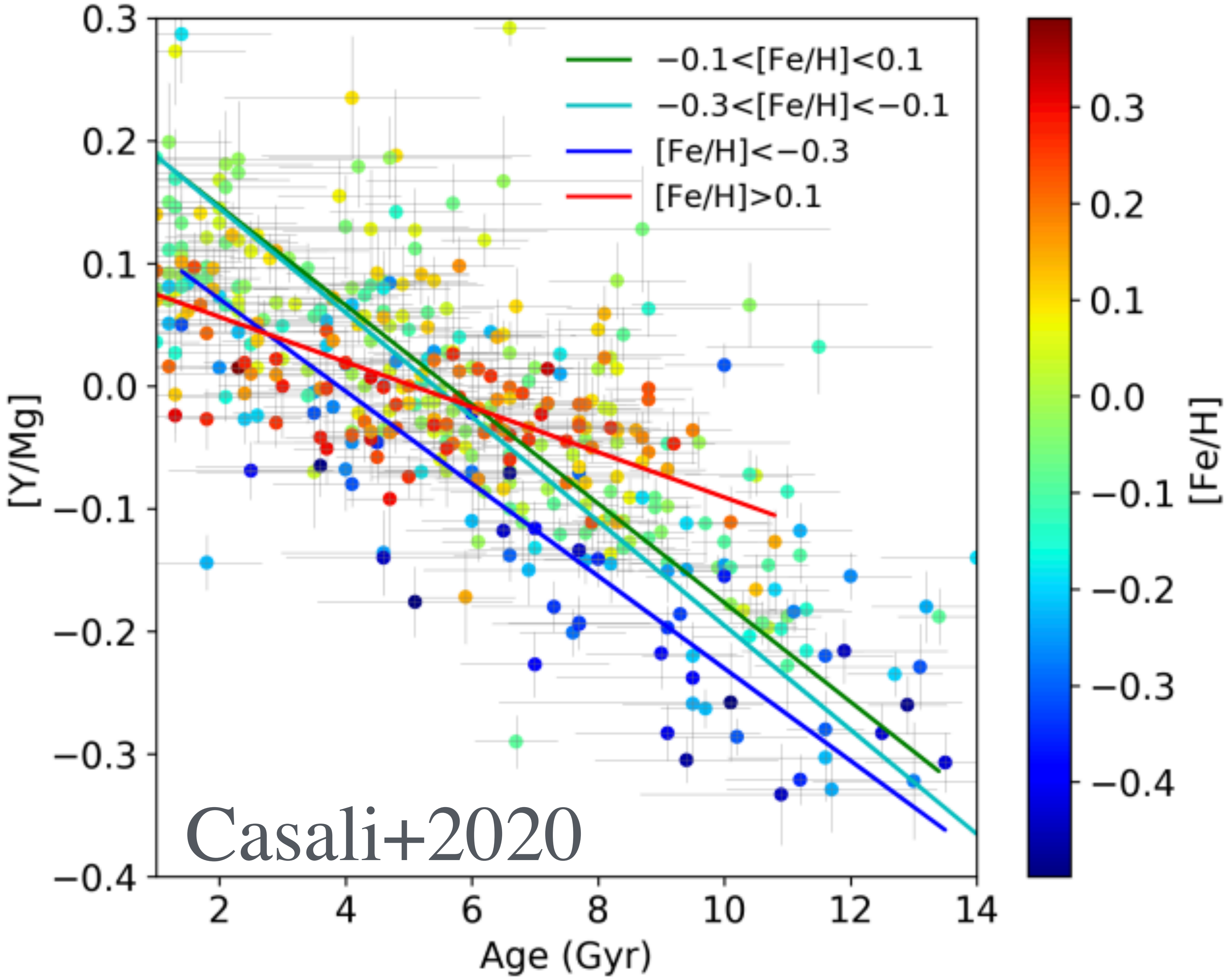

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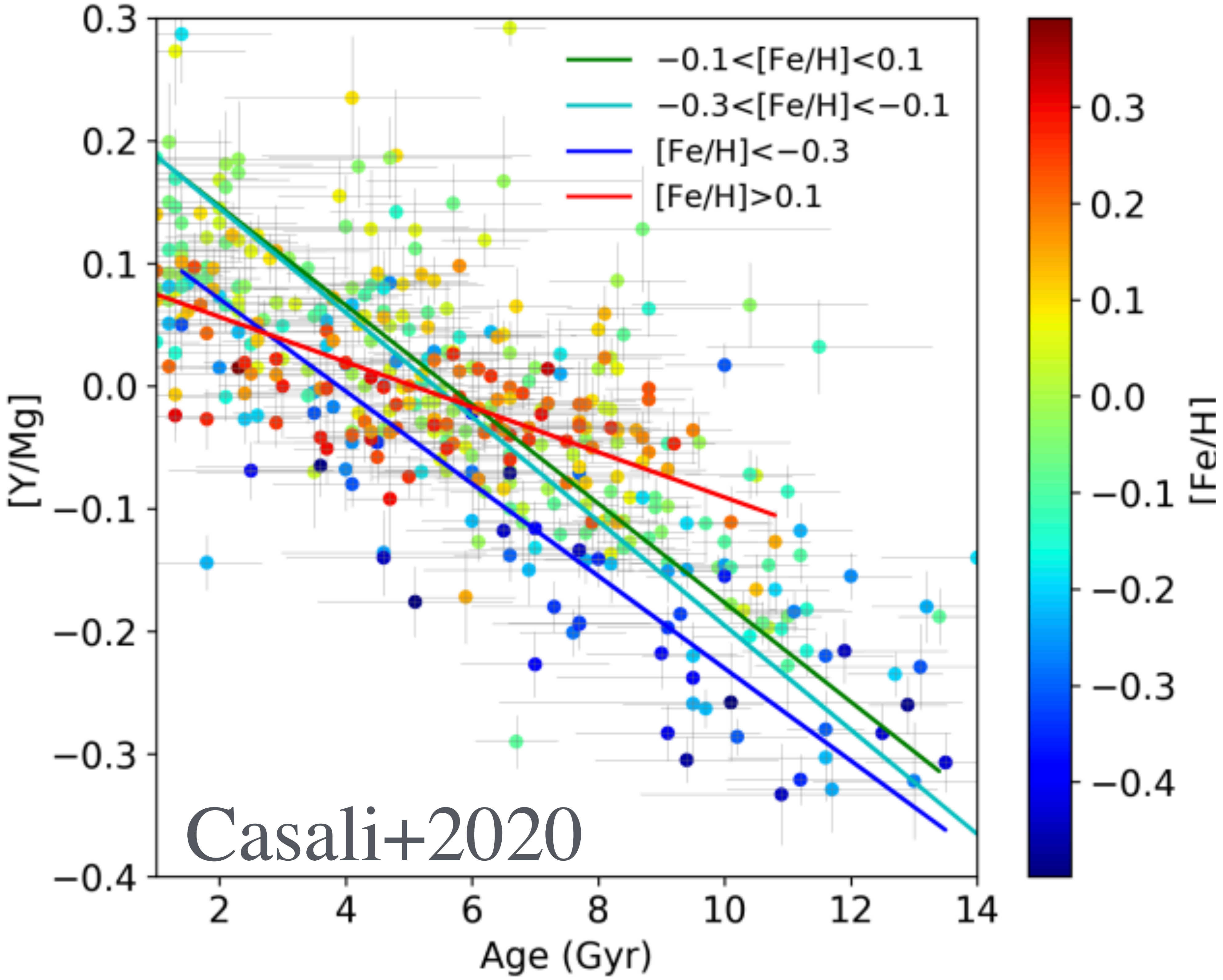

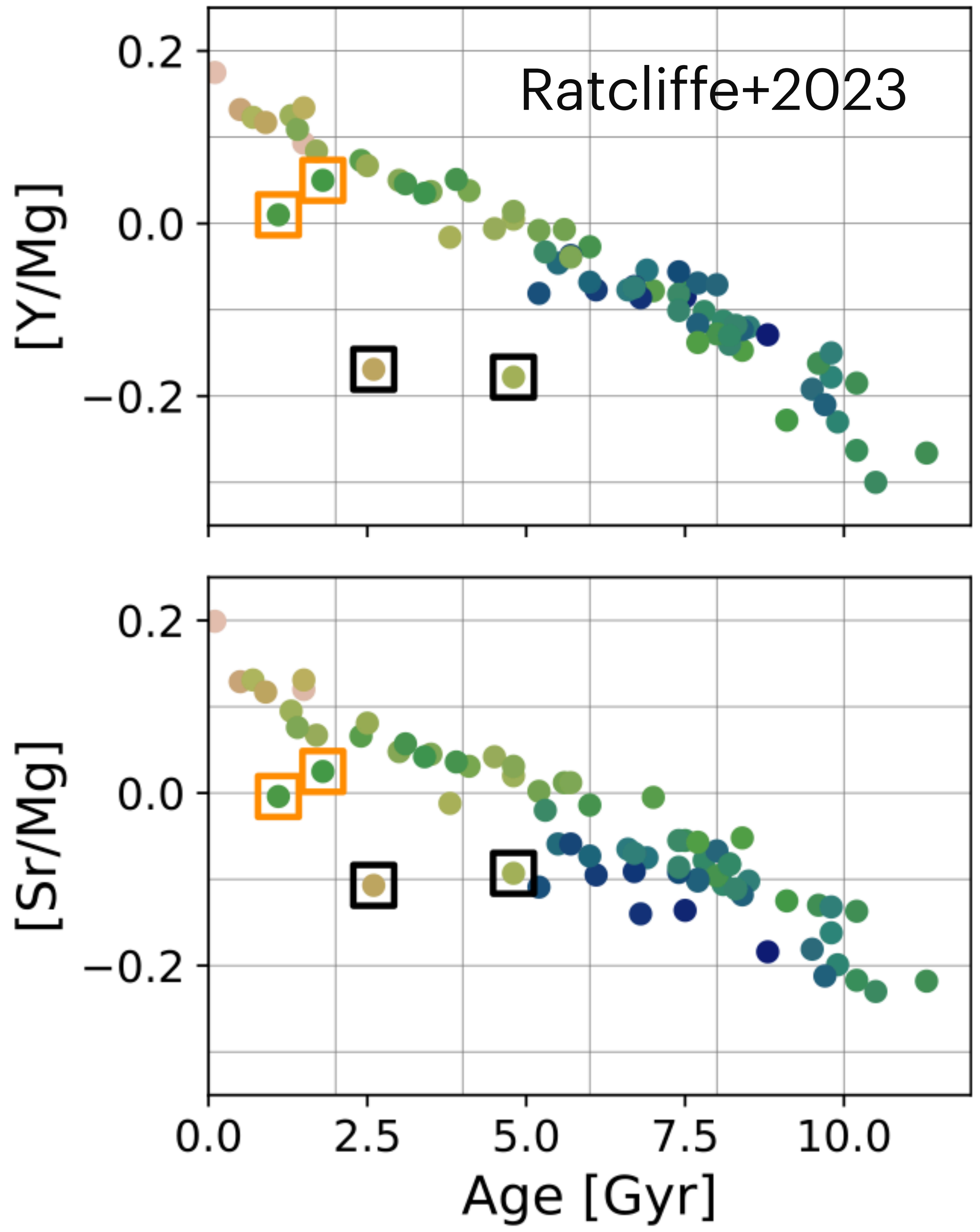

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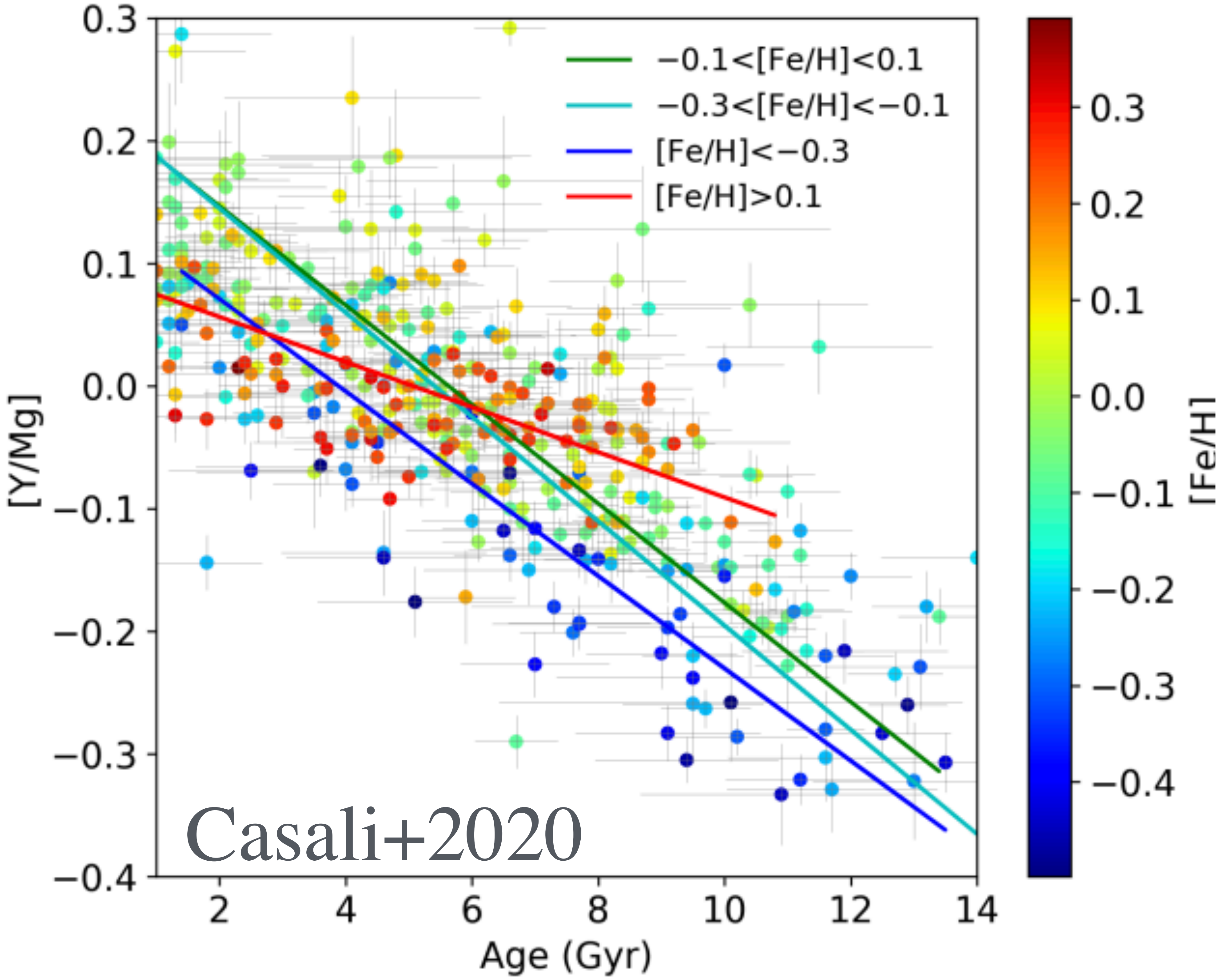

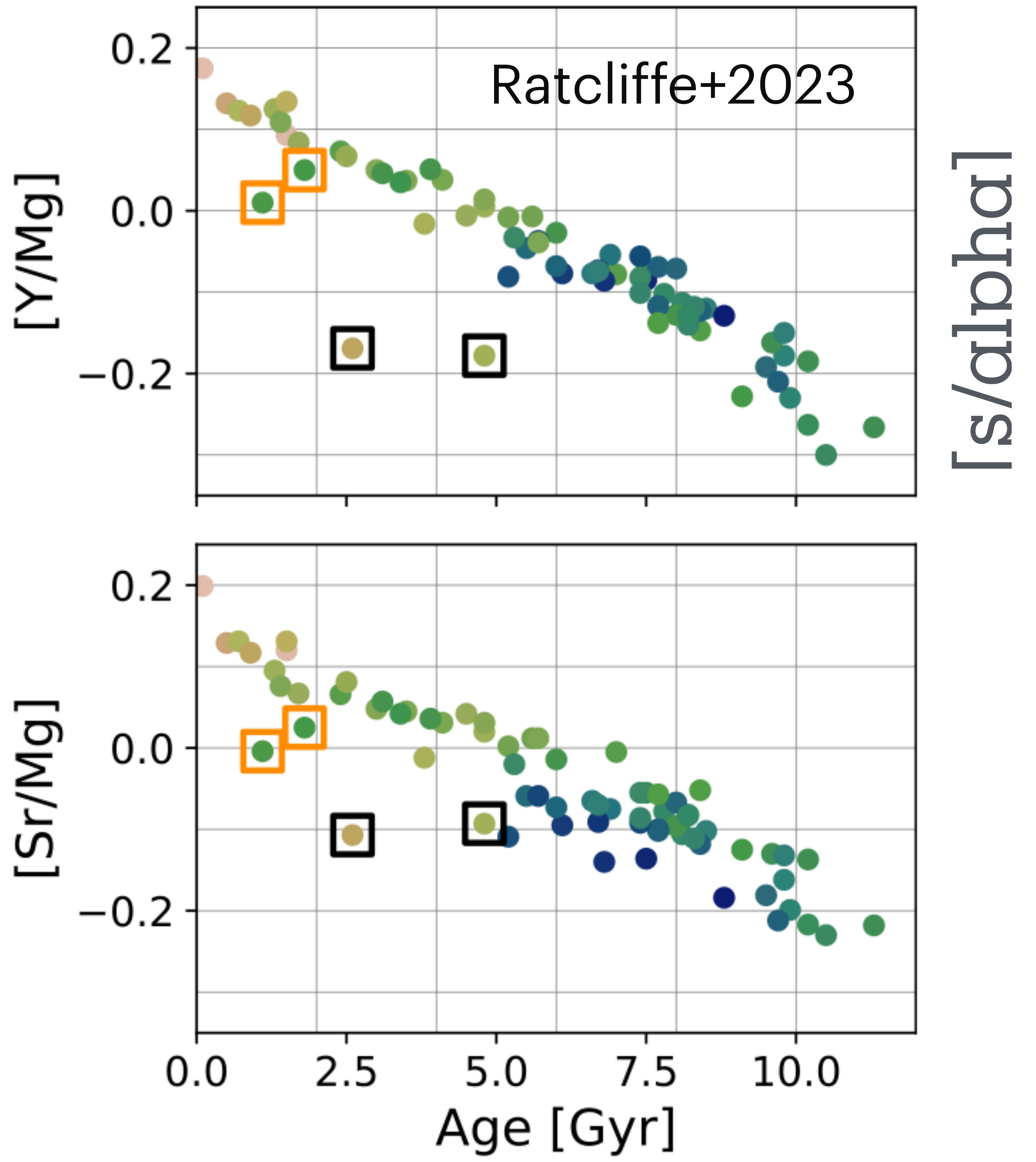

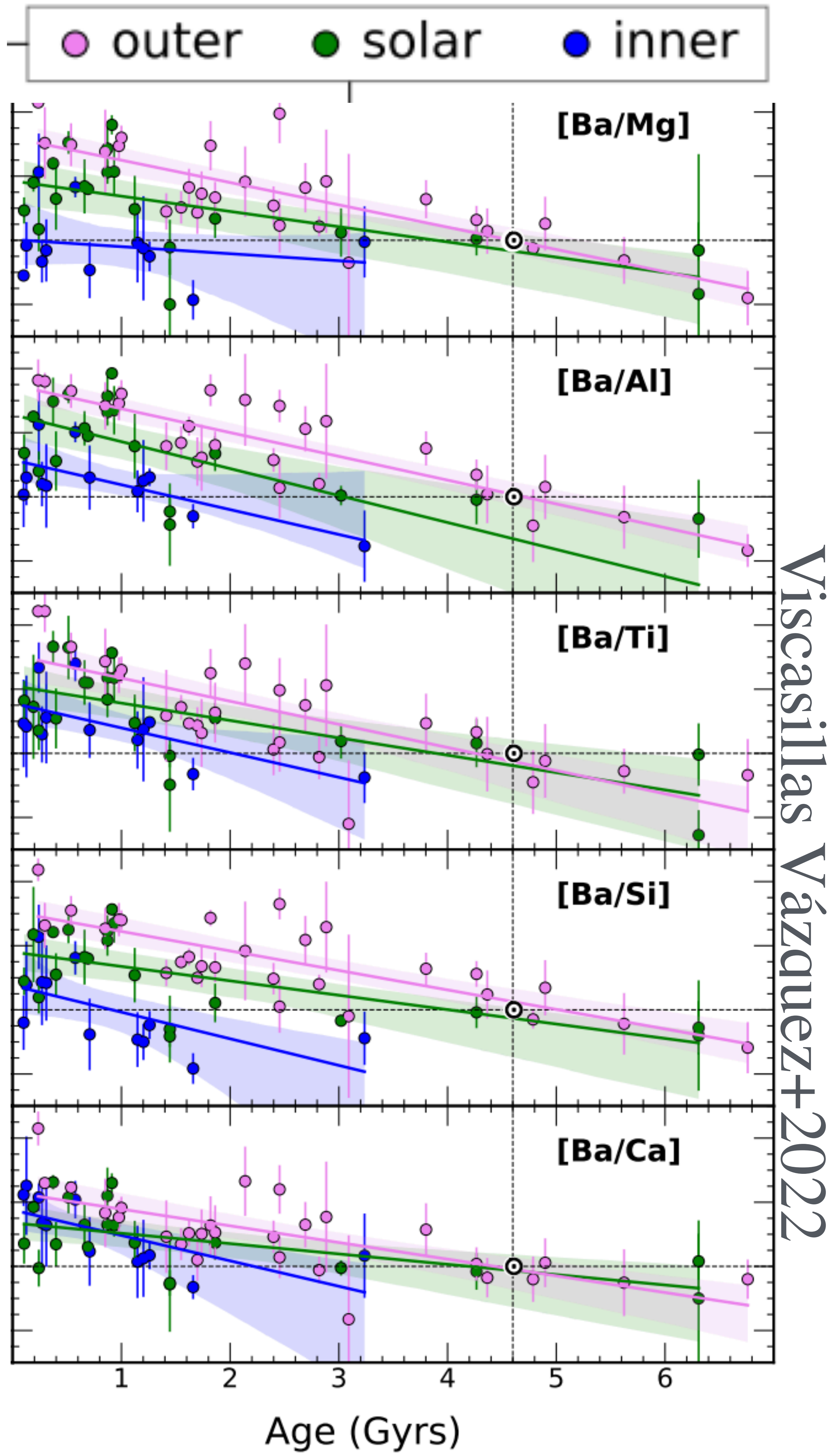

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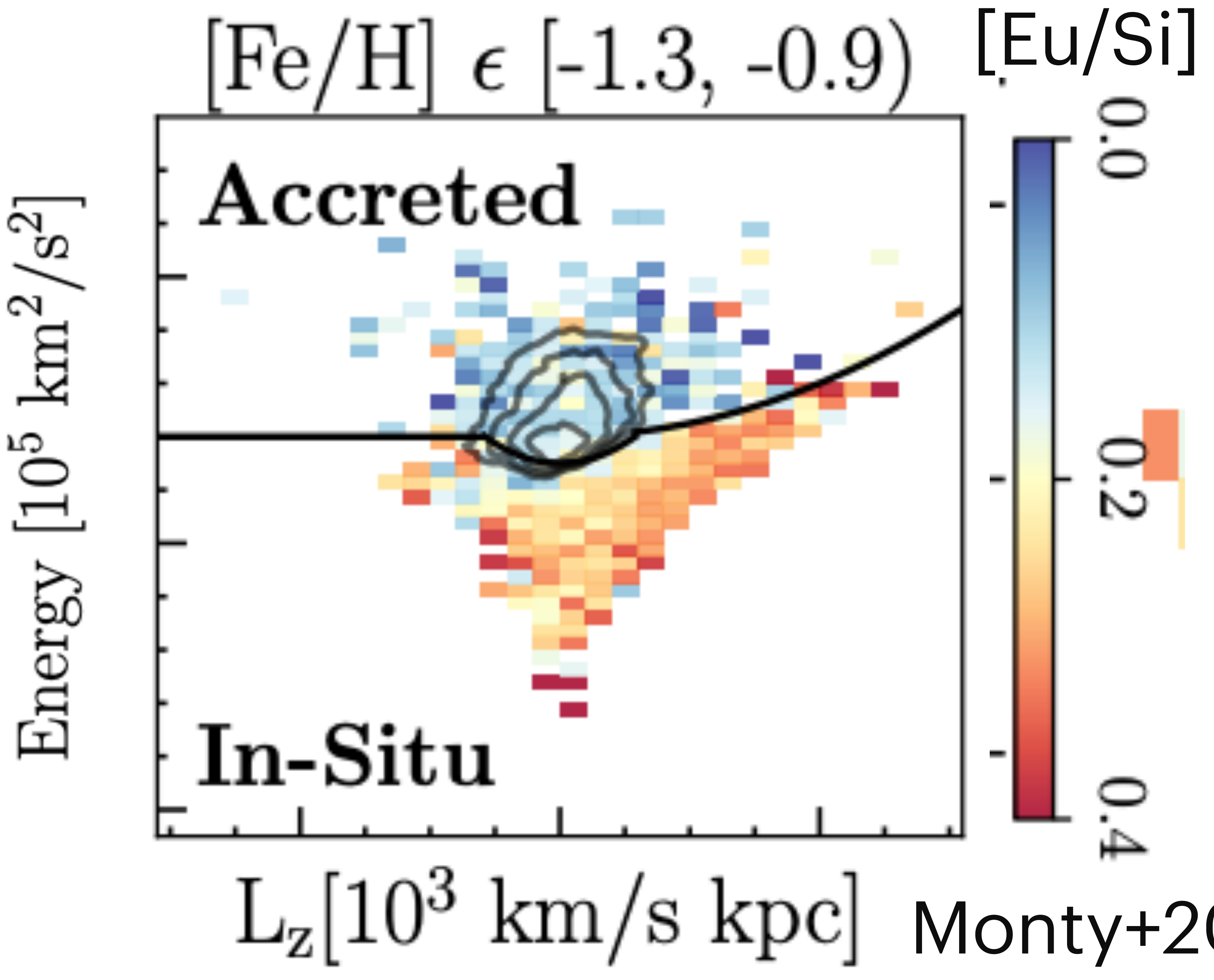
r-process elements are unique

- Events that produce r-process elements are **rare** yet highly productive and energetic
  - e.g., Wehmeyer+2015, 2019, François+2024, Lucertini+2025
- r-process element abundance ratios (e.g., [Eu/alpha]) have **demonstrated discriminating power** (e.g., Monty+2024)



Monty+2024

Is APOGEE all we need in the disk? Is it missing anything?

"What is the observed dimensionality of chemical abundance space in the disk?"

Is APOGEE all we need in the disk? Is it missing anything?

In the Galactic Disk, Stellar [Fe/H] and Age Predict Orbits and Precise [X/Fe]

M. K. Ness, K. V. Johnston, K. Blancato, H-W. Rix, A. Beane, J. C Bird, and K. Hawkins

Published 2019 October 3 •

How Many Elements Matter?

Yuan-Sen Ting (丁源森)[1,2,3,4,5] and David H. Weinberg[6,3]

Many elements matter: Detailed abundance patterns reveal star-formation and enrichment differences among Milky Way structural components

Emily J. Griffith,[1,*] David W. Hogg,[2,3,4] Sten Hasselquist,[5] James W. Johnson,[6] Adrian Price-Whelan,[4] Tawny Sit,[7] Alexander Stone-Martinez,[8] and David H. Weinberg[7]

OPEN ACCESS

Chemical Cartography with APOGEE: Two-process Parameters and Residual Abundances for 288,789 Stars from Data Release 17

Tawny Sit, David H. Weinberg, Adam Wheeler, Christian R. Hayes, Sten Hasselquist, Thomas Masseron, and Jennifer Sobeck

Published 2024 July 30 •

70, Number 2

Four Elements to Rule Them All: Abundances are Rigidly Coupled in the Milky Way Disk

Jennifer Mead,[1] Rebeca De La Garza,[2] and Melissa Ness[3,1]

[1]*Department of Astronomy, Columbia University, New York, NY 10027, USA*
[2]*Columbia College, Columbia University, New York, NY 10027, USA*
[3]*Research School of Astronomy & Astrophysics, Australian National University, Canberra ACT 2611, Australia*

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JENNIFER MEAD,[1] RE... ZA,[2] AND MELISSA NESS[3,1]

[1]Department of Astrono... sity, New York, NY 10027, USA

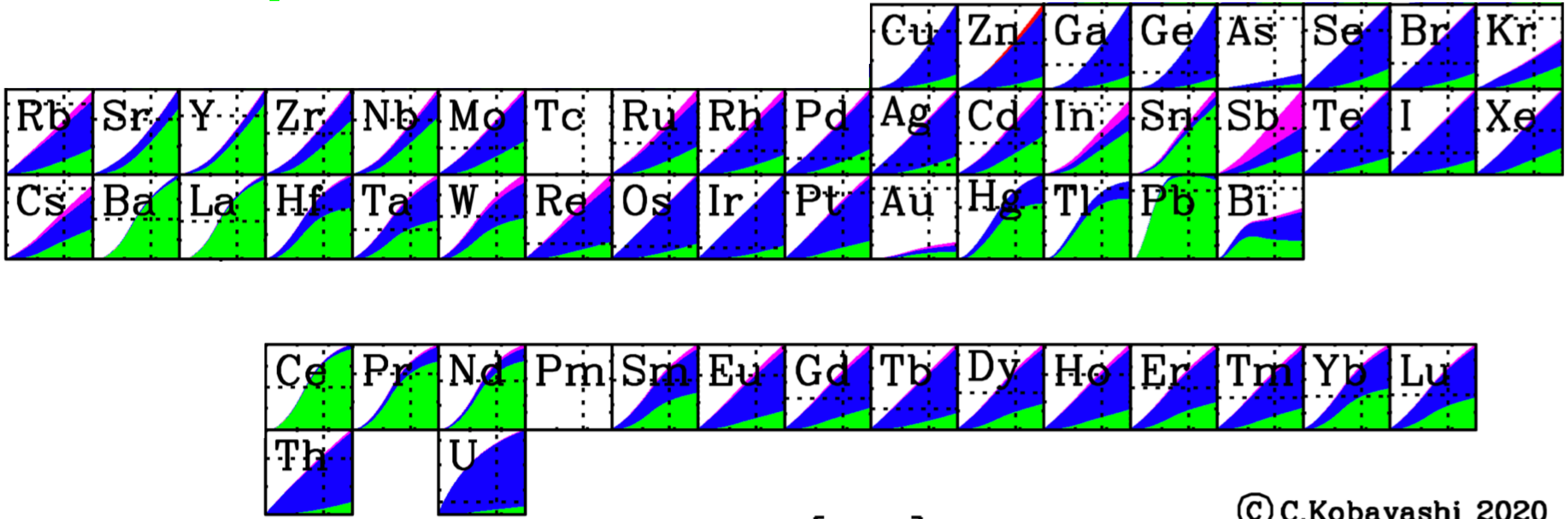
[2]Columbia College, ... New York, NY 10027, USA

[3]Research School of Astronomy & Astrophysics, Australian National University, Canberra ACT 2611, Australia

Is APOGEE all we need? Is it missing anything?

We can directly **test this** by **identifying chemically similar stars in APOGEE** and following them up in the **optical**

where we can access strong **neutron-capture element** lines



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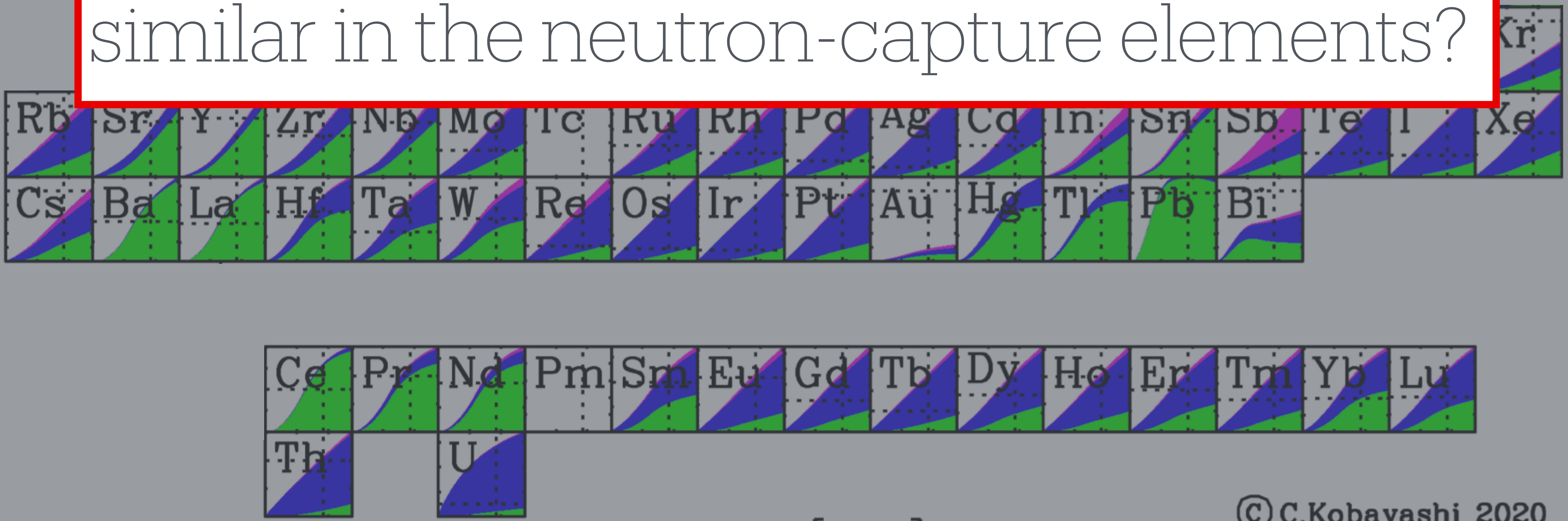
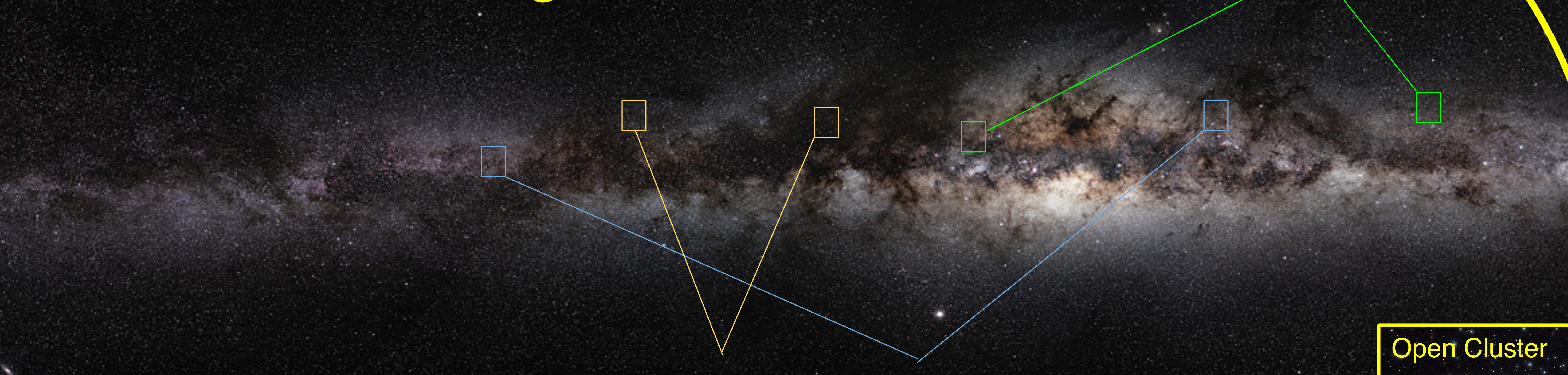
Are stars that APOGEE says are chemically similar also chemically similar in the neutron-capture elements?

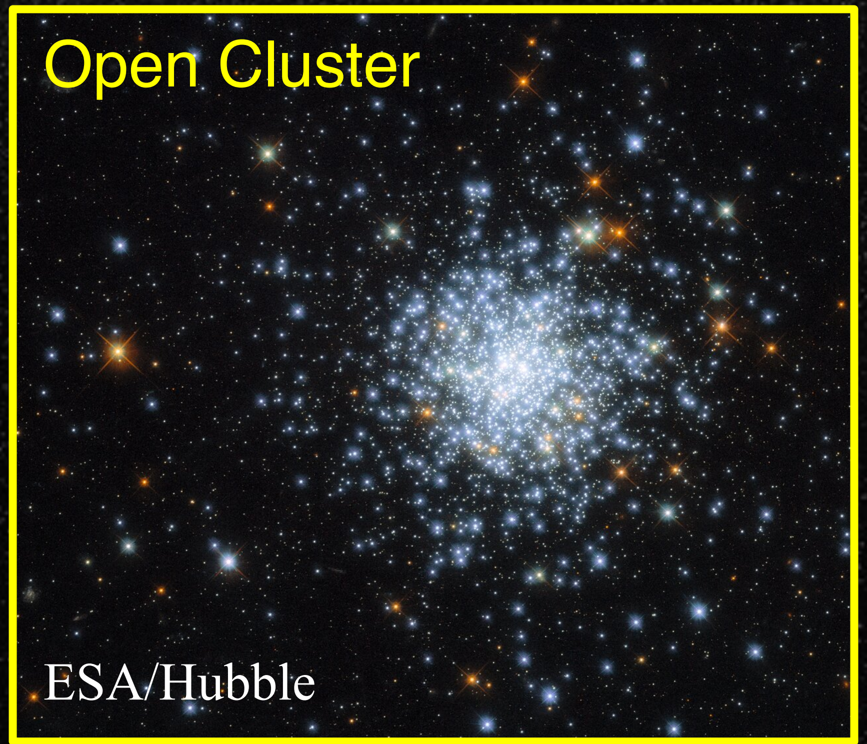


“Galactic Chemical Doppelgängers”

coined by Ness et al. 2018

Apparently unrelated pairs of field stars that appear as chemically similar as stars born together*.



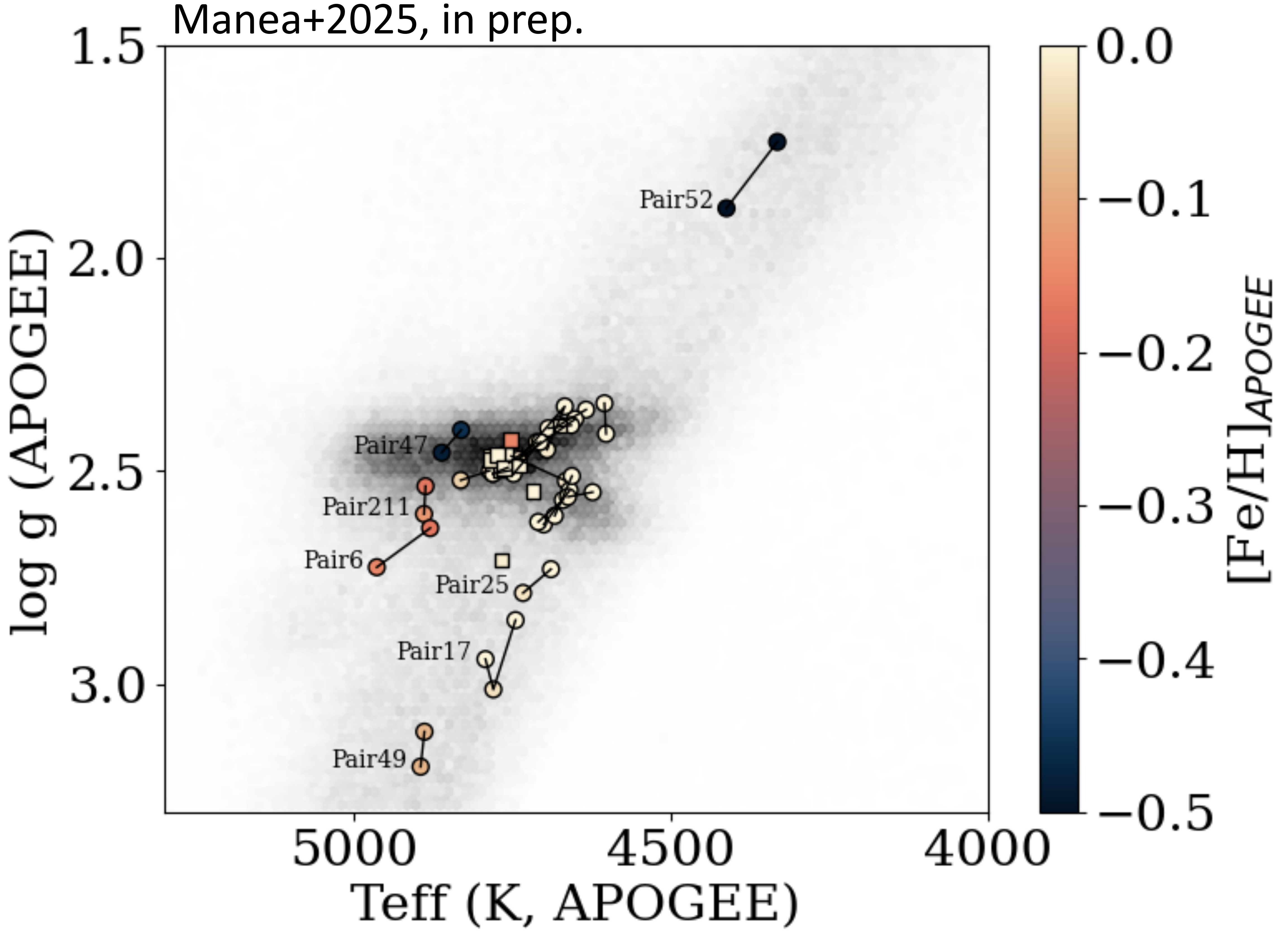


*stars born together are highly chemical similar (e.g., Bovy 2016, Poovelil+2020, Sinha+2024)

Optical investigation of APOGEE-identified chemical doppelgängers

- Sample: **25** pairs of stars that APOGEE DR17 says are **chemical doppelgängers** (including in **Ce**) and 12 open cluster stars for comparison

Manea+2025, in prep.



Harlan J. Smith 2.7m Telescope at McDonald Observatory
Equipped with the Tull high-resolution (R~60,000) optical spectrograph

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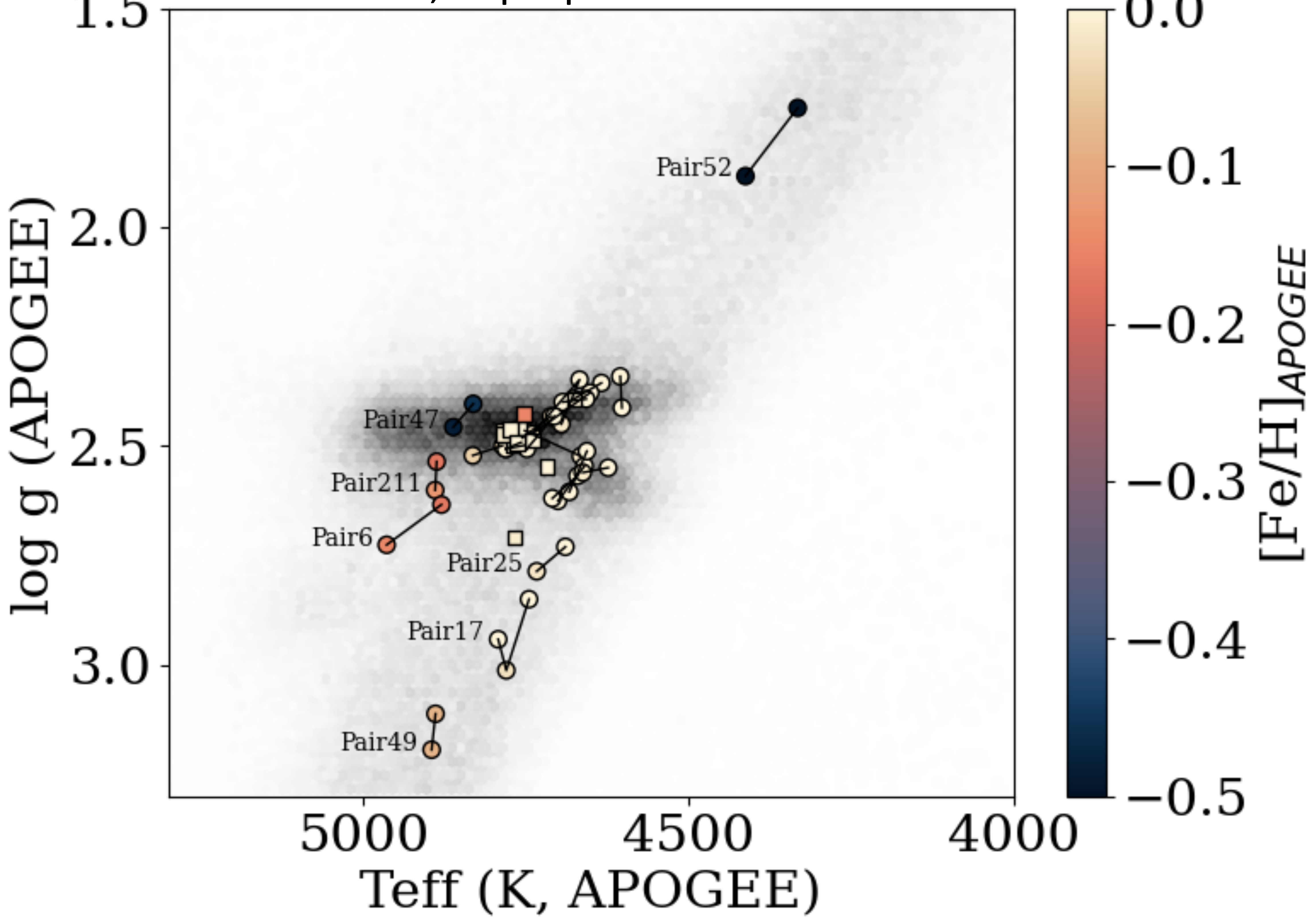

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- Obtain **R~60,000 optical** spectroscopy and analyze their **neutron-capture element similarity**.

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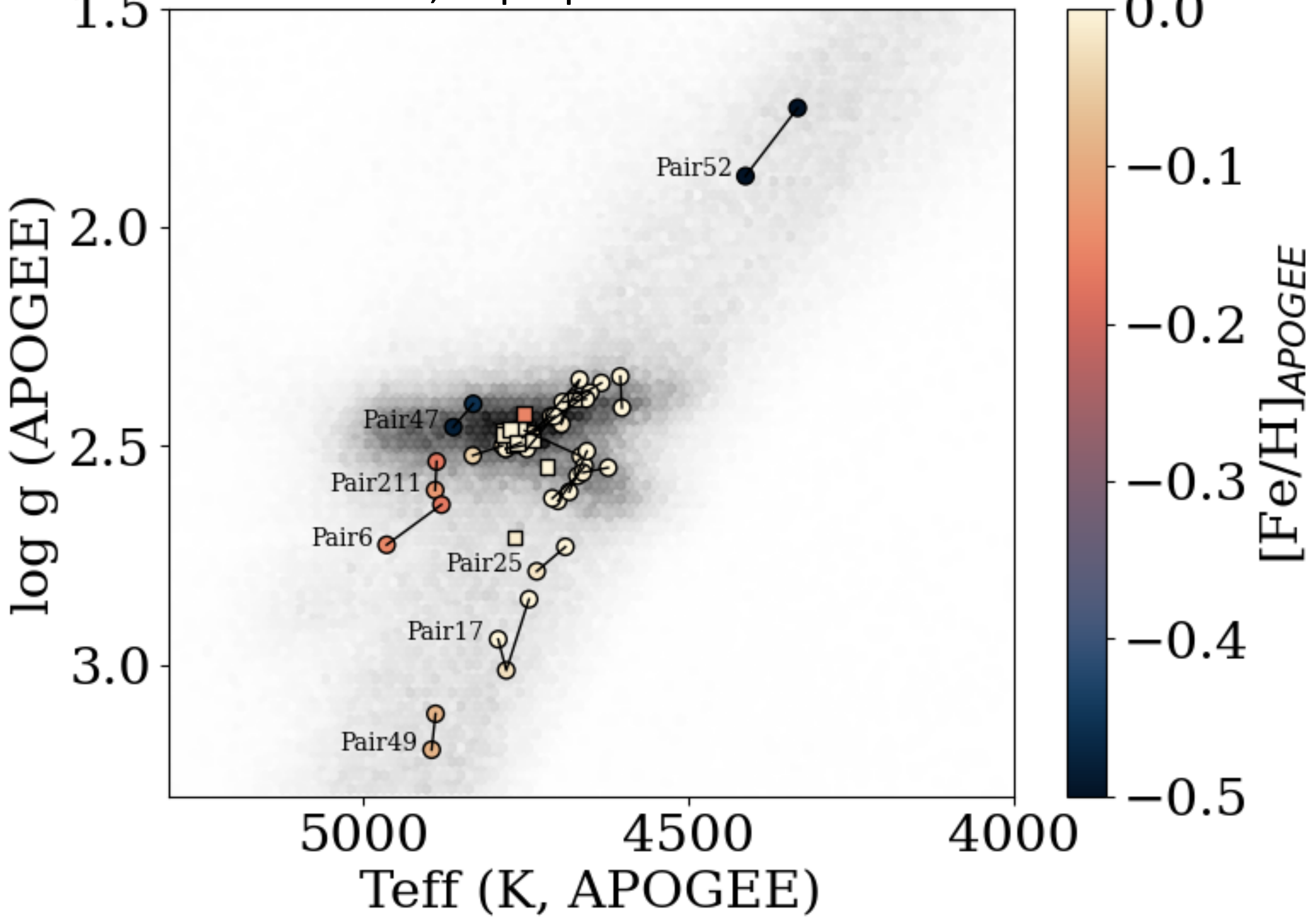

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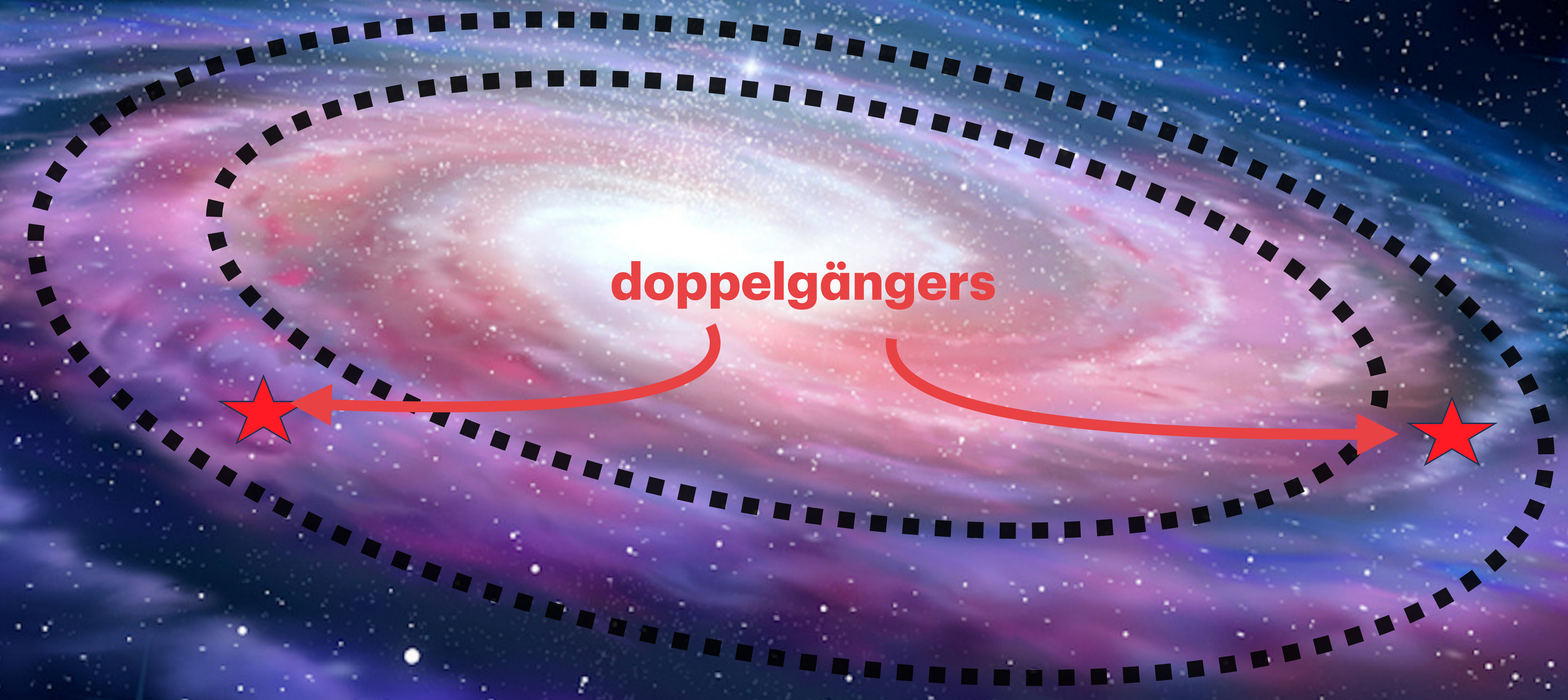
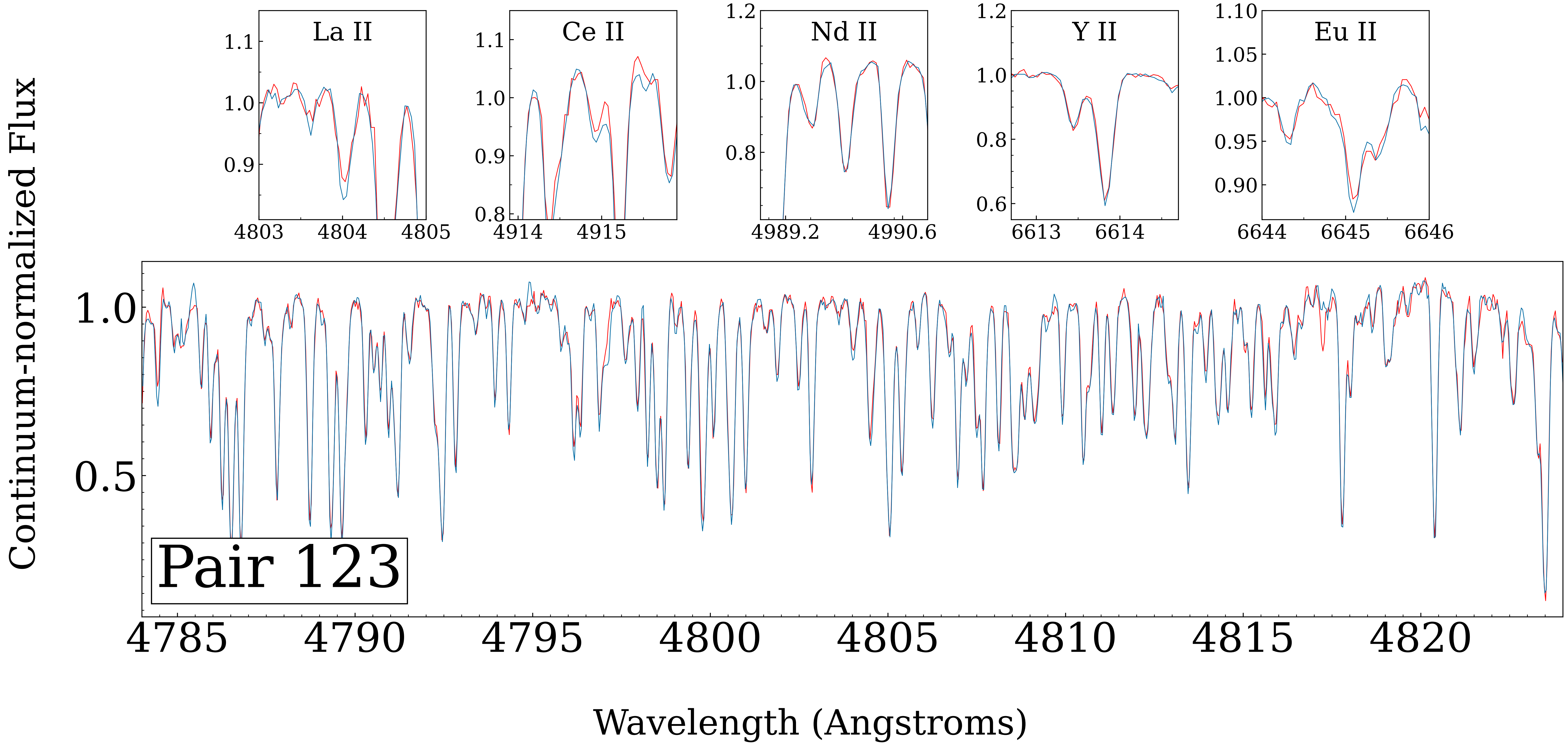


Similar [Fe/H], C/N, and APOGEE-reported compositions indicates **doppelgängers formed at a similar Galactic radius and time (e.g., Minchev+2018, Lu + 2024)**

Our own optical spectra of 2 stars that APOGEE deems to be chemical “doppelgängers”



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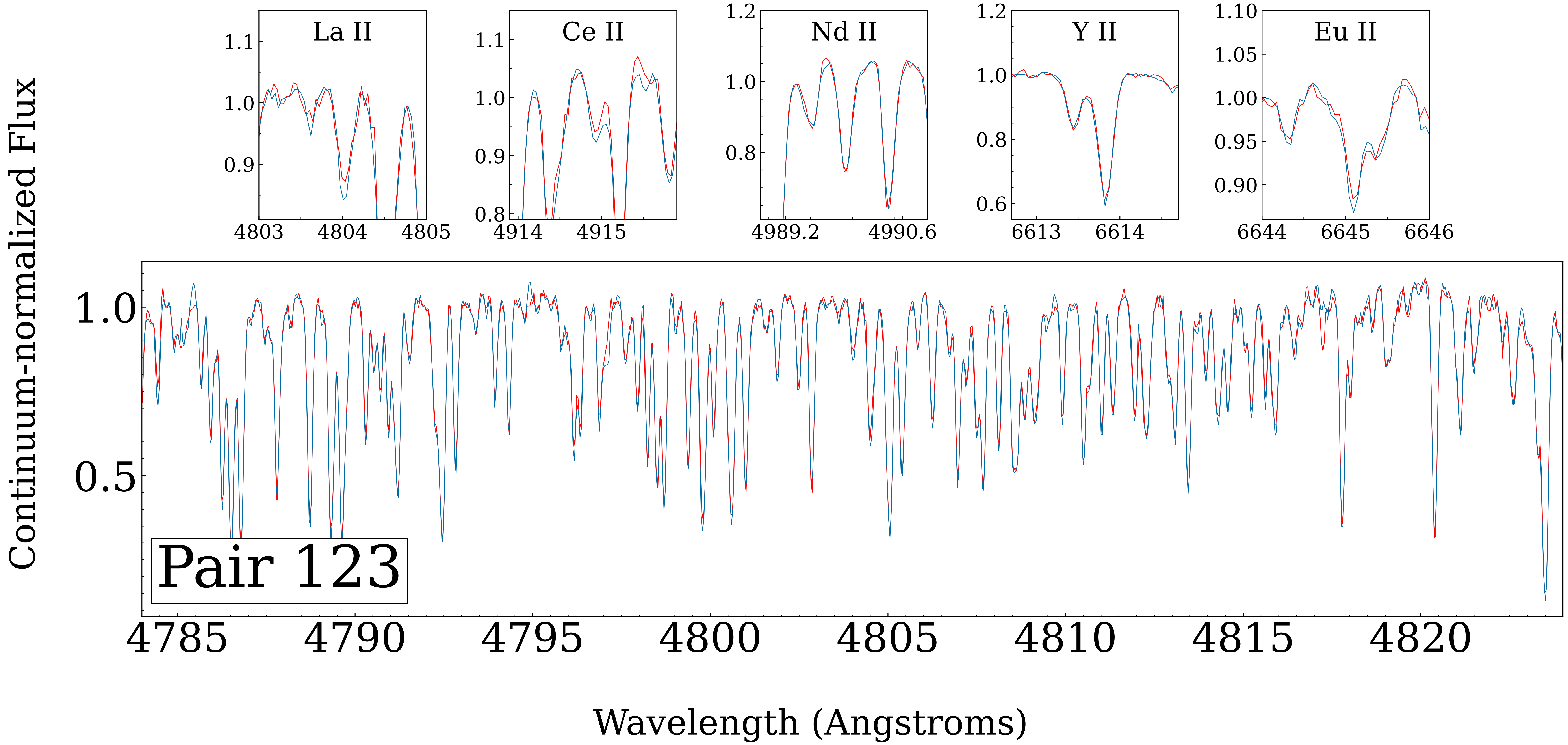
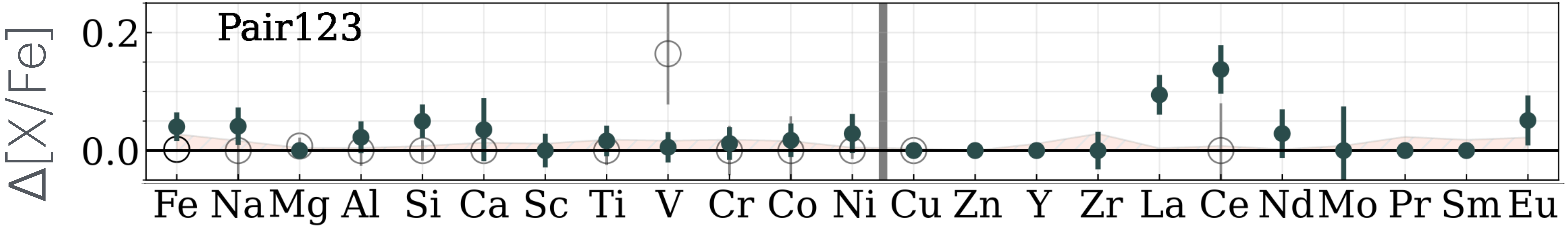


Measure abundance differences from the high res optical spectra:



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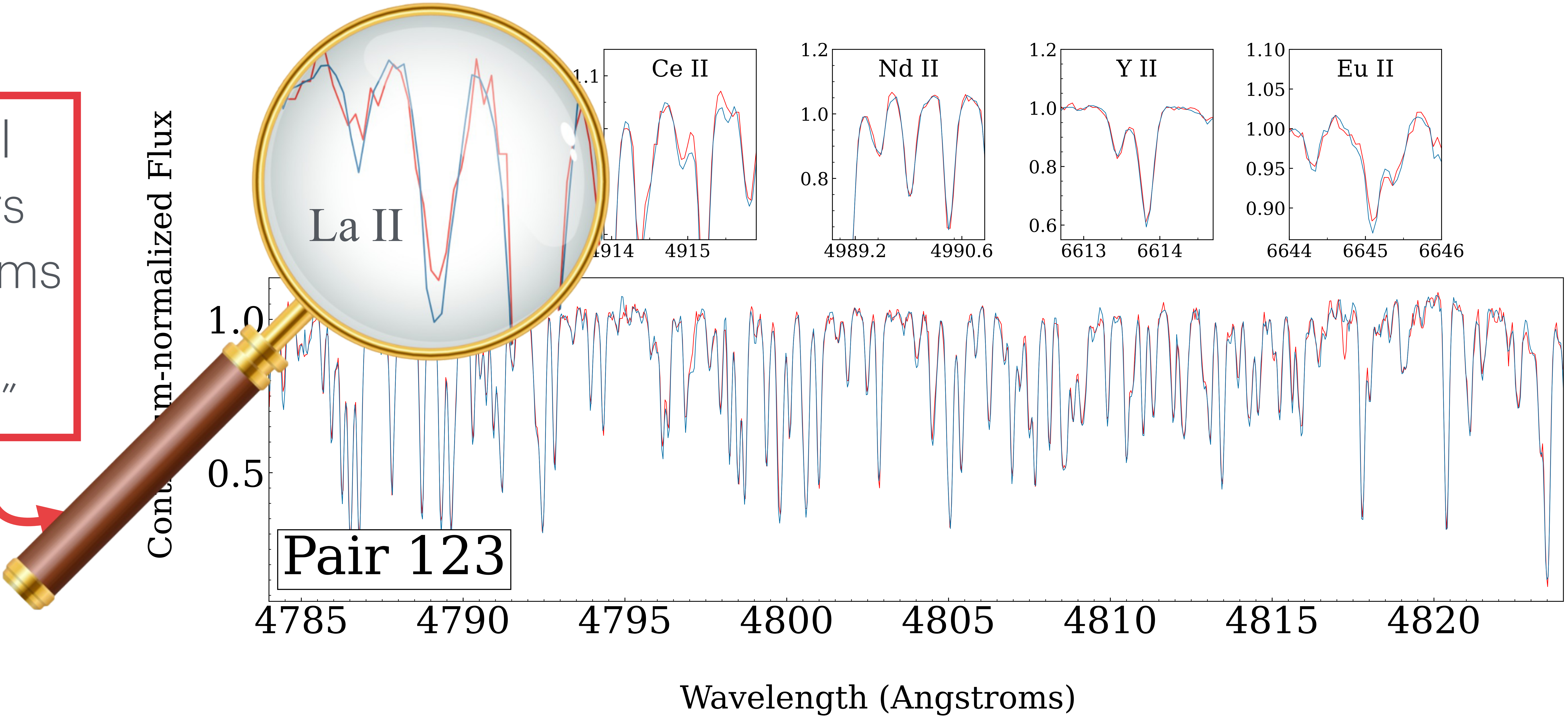

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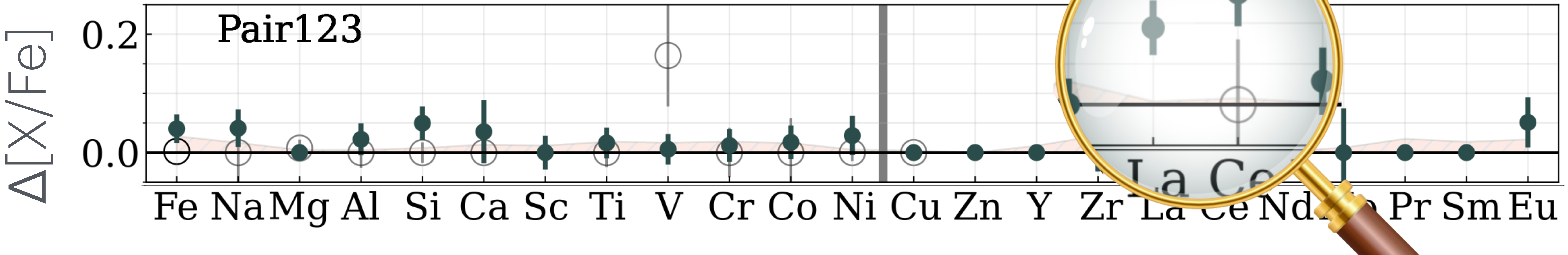

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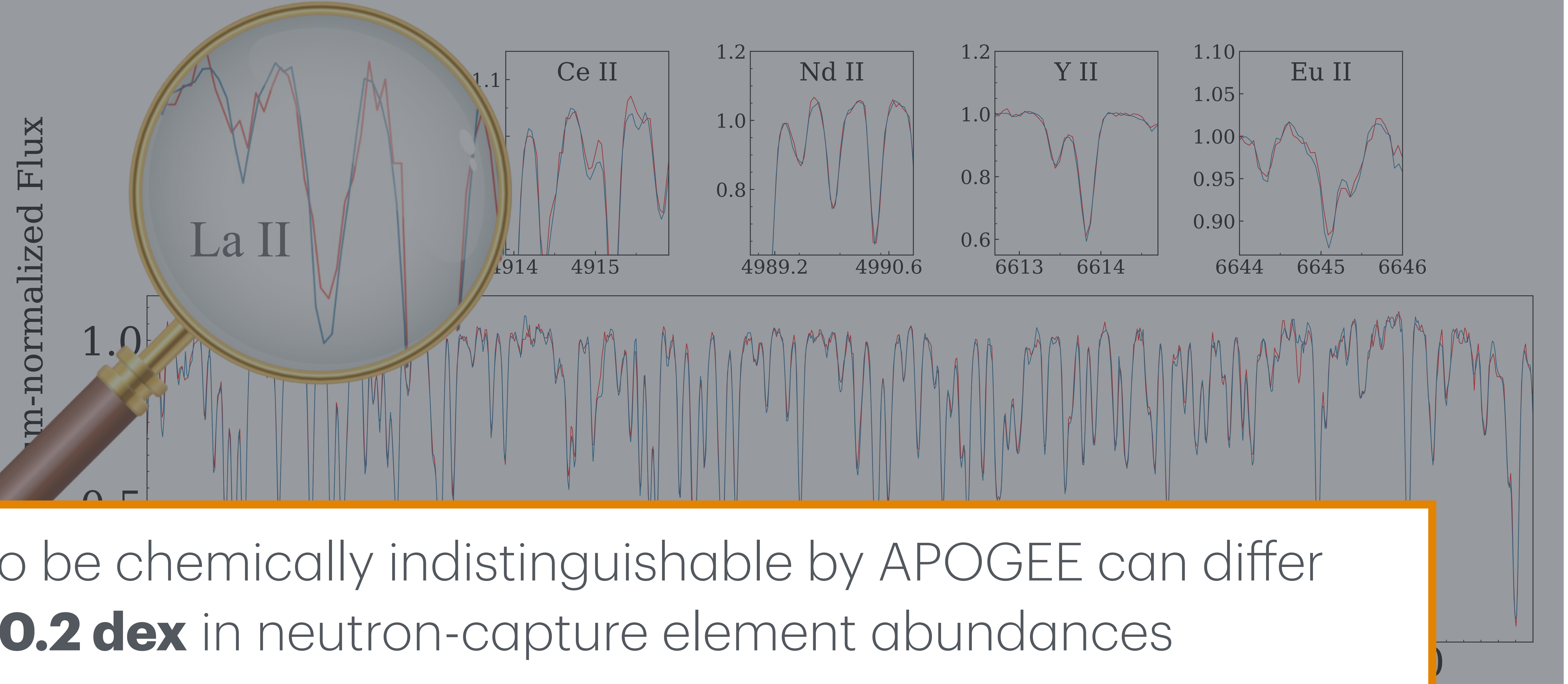

Result

Stars deemed to be chemically indistinguishable by APOGEE can differ **by up to 0.2 dex** in neutron-capture element abundances

Manea+2025, in prep.

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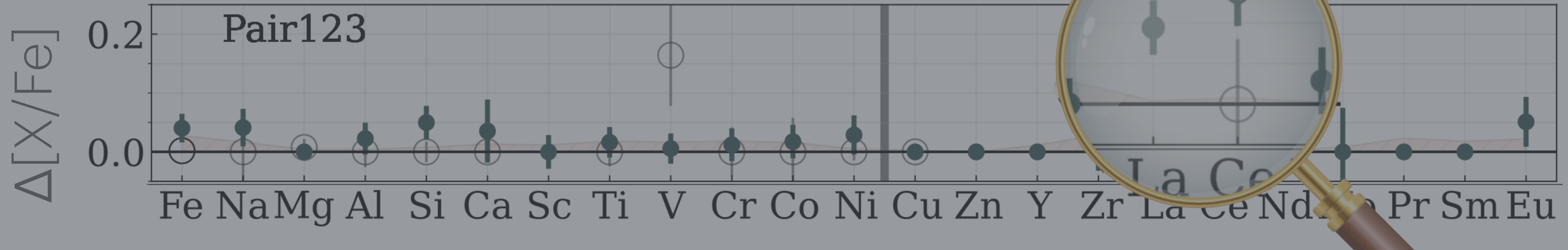

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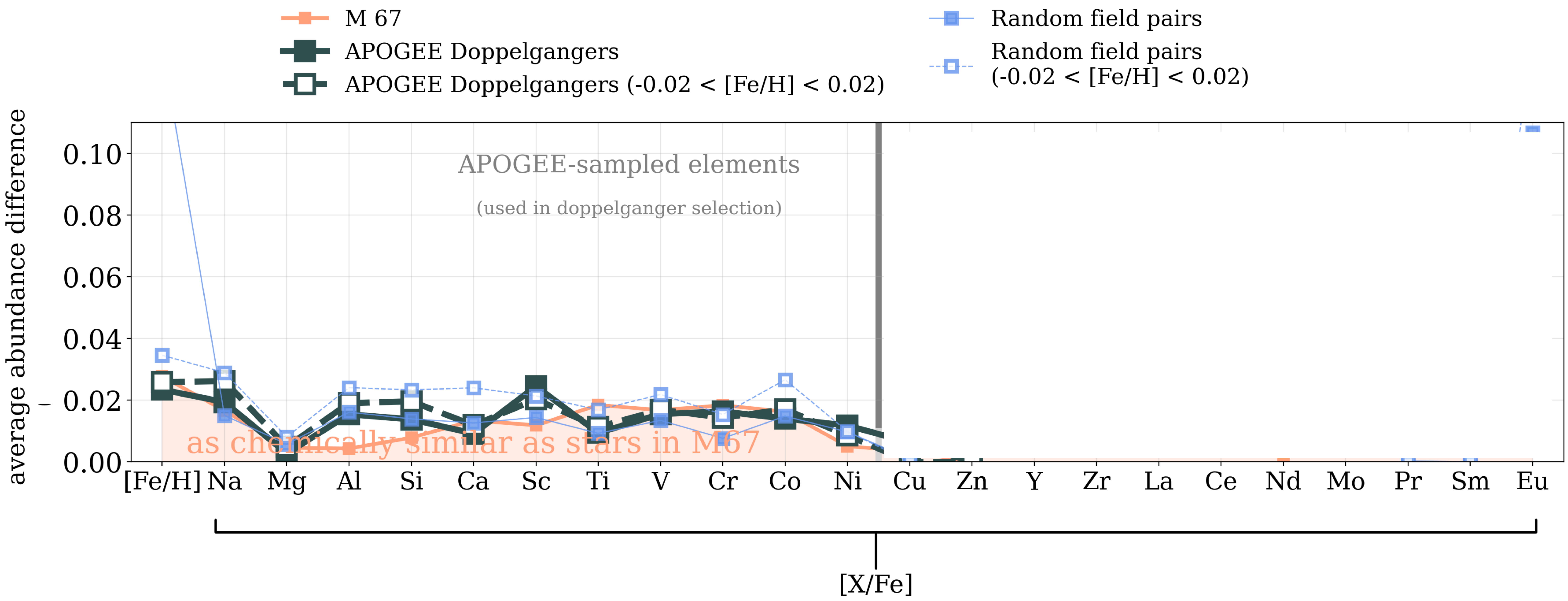

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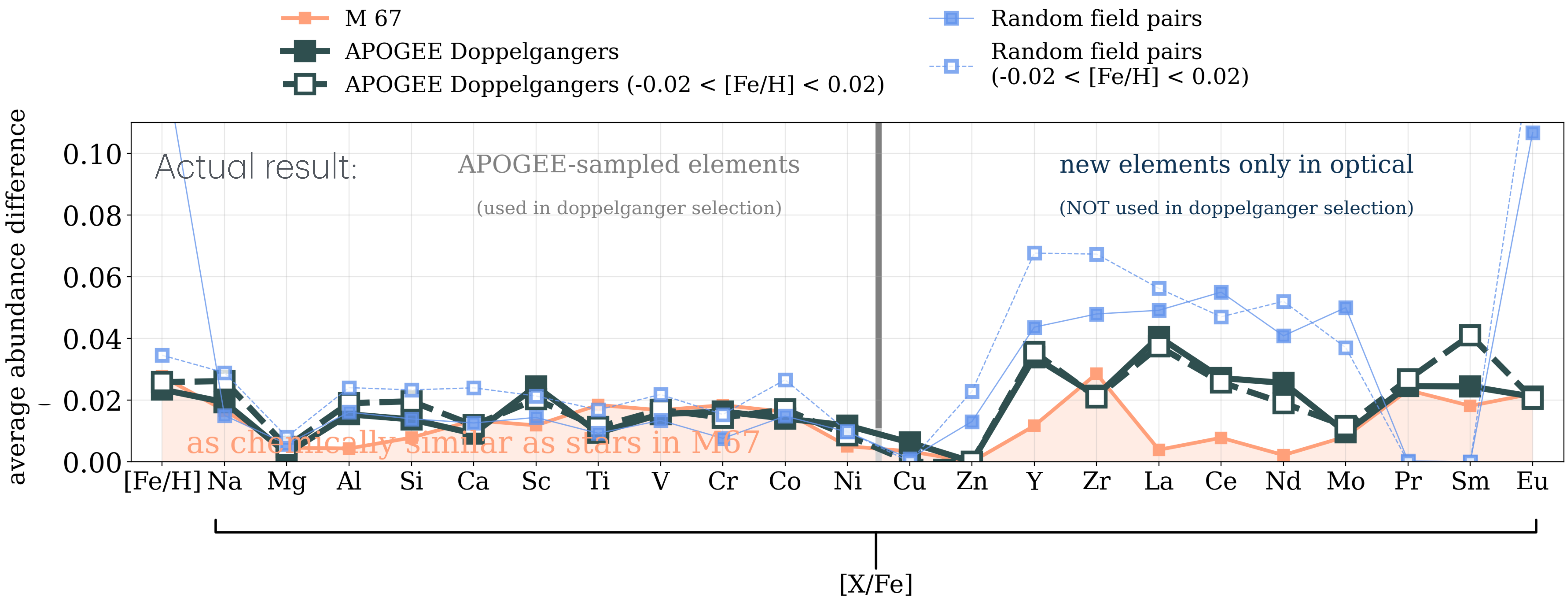

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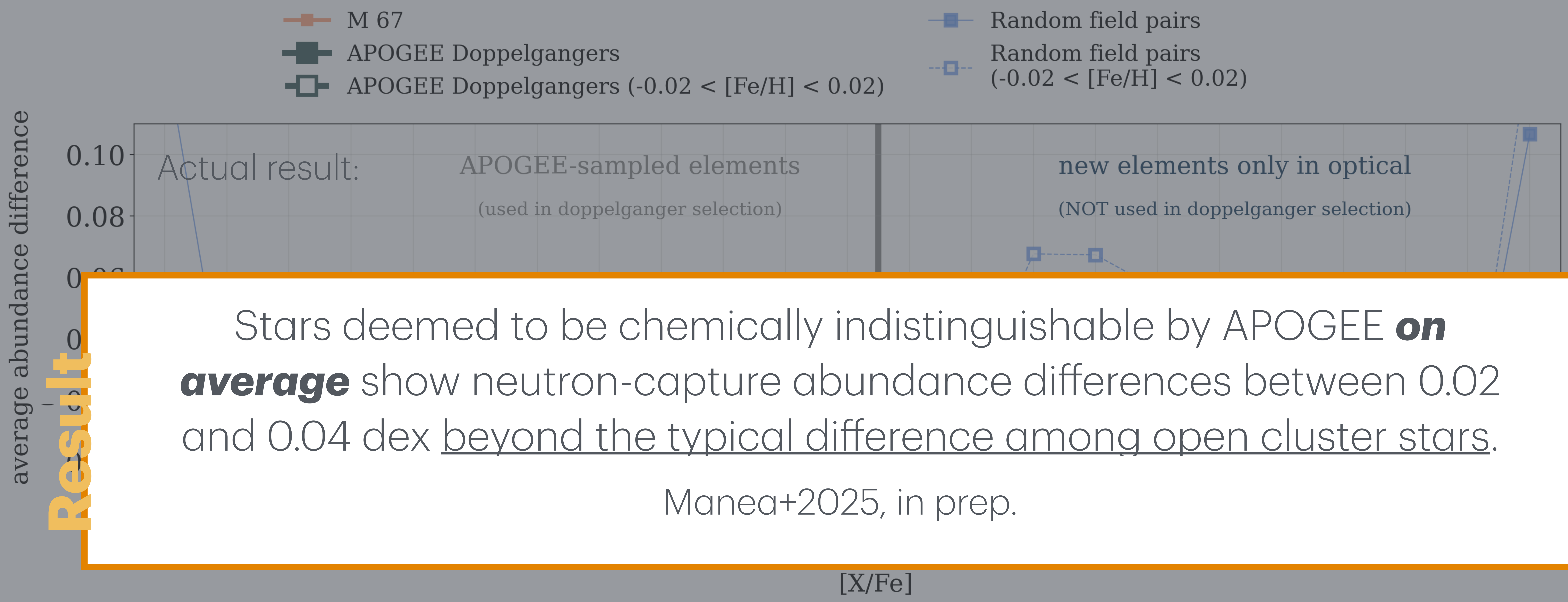

Result

Stars deemed to be chemically indistinguishable by APOGEE ***on average*** show neutron-capture abundance differences between 0.02 and 0.04 dex <u>beyond the typical difference among open cluster stars</u>.

Manea+2025, in prep.

Is APOGEE all we need? Is it missing anything?

Result

APOGEE abundances, even from SNR > 300 spectra, are not necessarily sufficient for identifying chemically similar stars across all elements.

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Implication

What more can we learn more about the Milky Way disk's stellar populations when we also consider the neutron-capture element abundances of APOGEE stars?

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(As demonstrated by high-res optical surveys such as GAIA-ESO and GALAH, a lot.)

Possible Physical Interpretations

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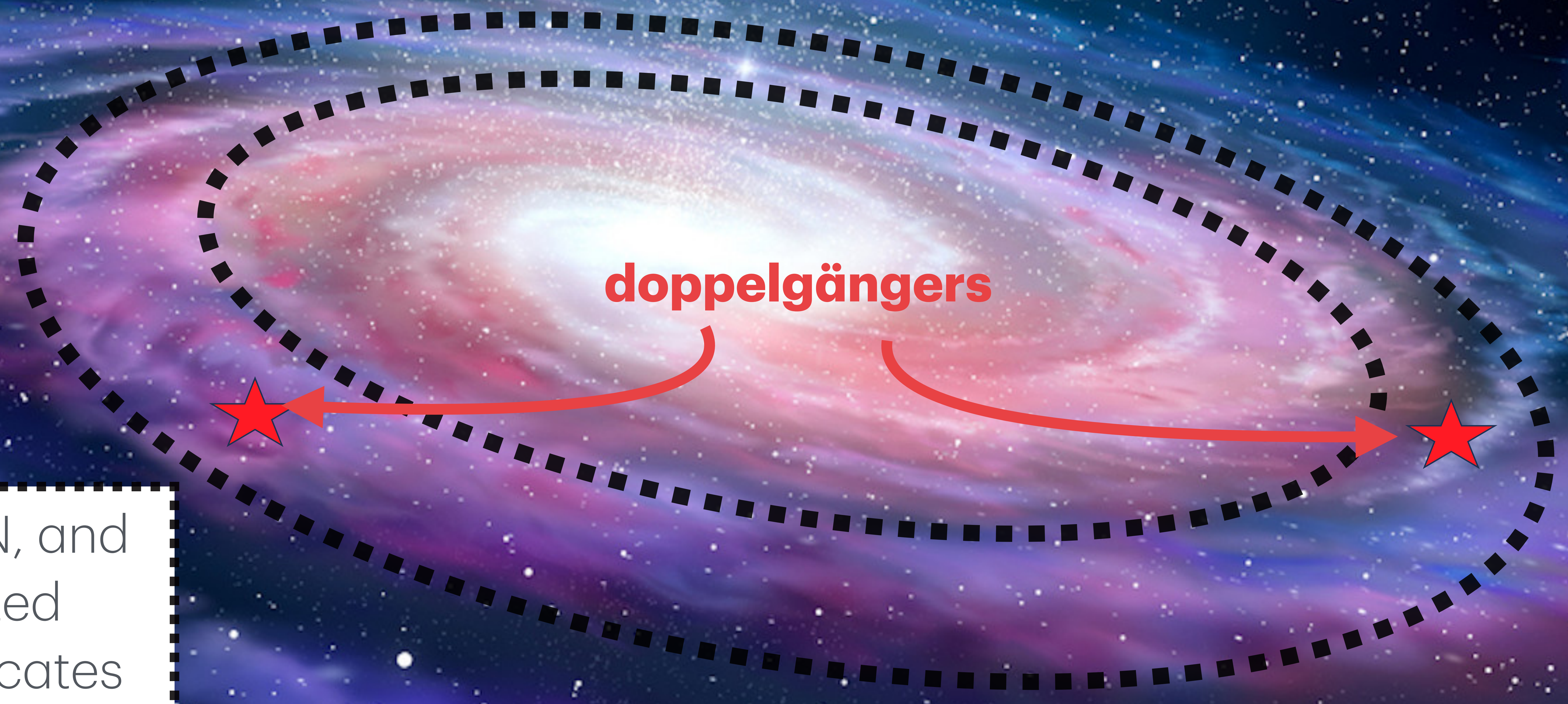

Similar [Fe/H], C/N, and APOGEE-reported compositions indicates **doppelgängers formed at a similar Galactic radius and time**

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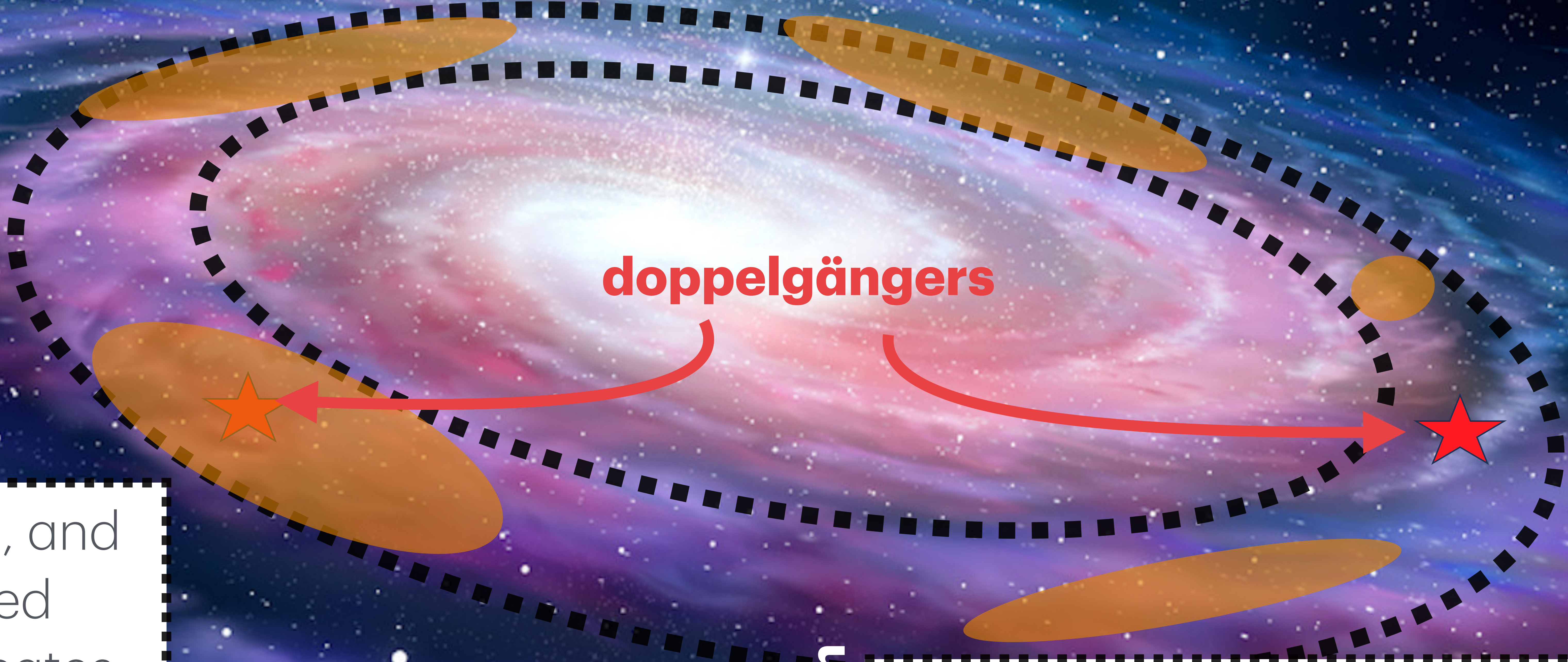

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Thus, neutron-capture element differences could point to **azimuthal variations in neutron-capture element abundances**

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(Analytical)
Emerick+2020
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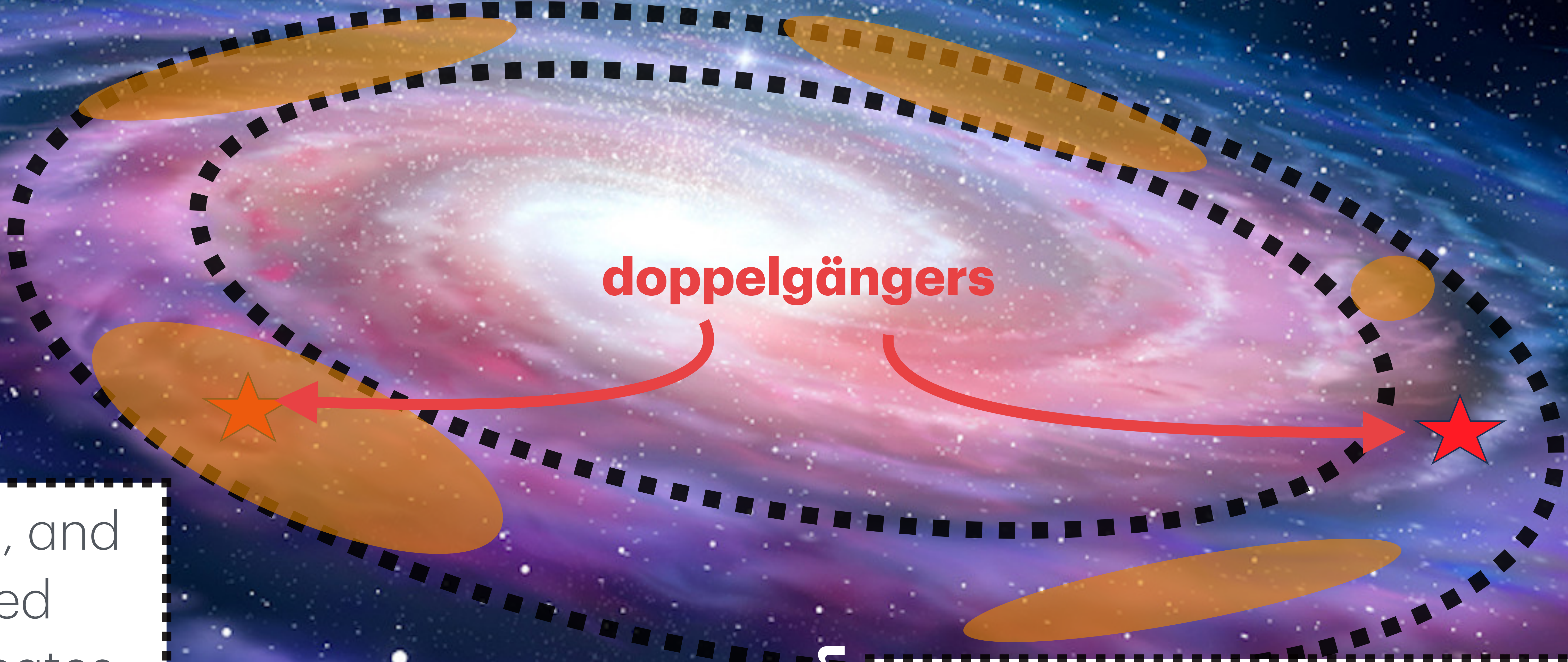

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Implication

Maybe C/N isn't a perfect age indicator (so these stars didn't form at the same time)

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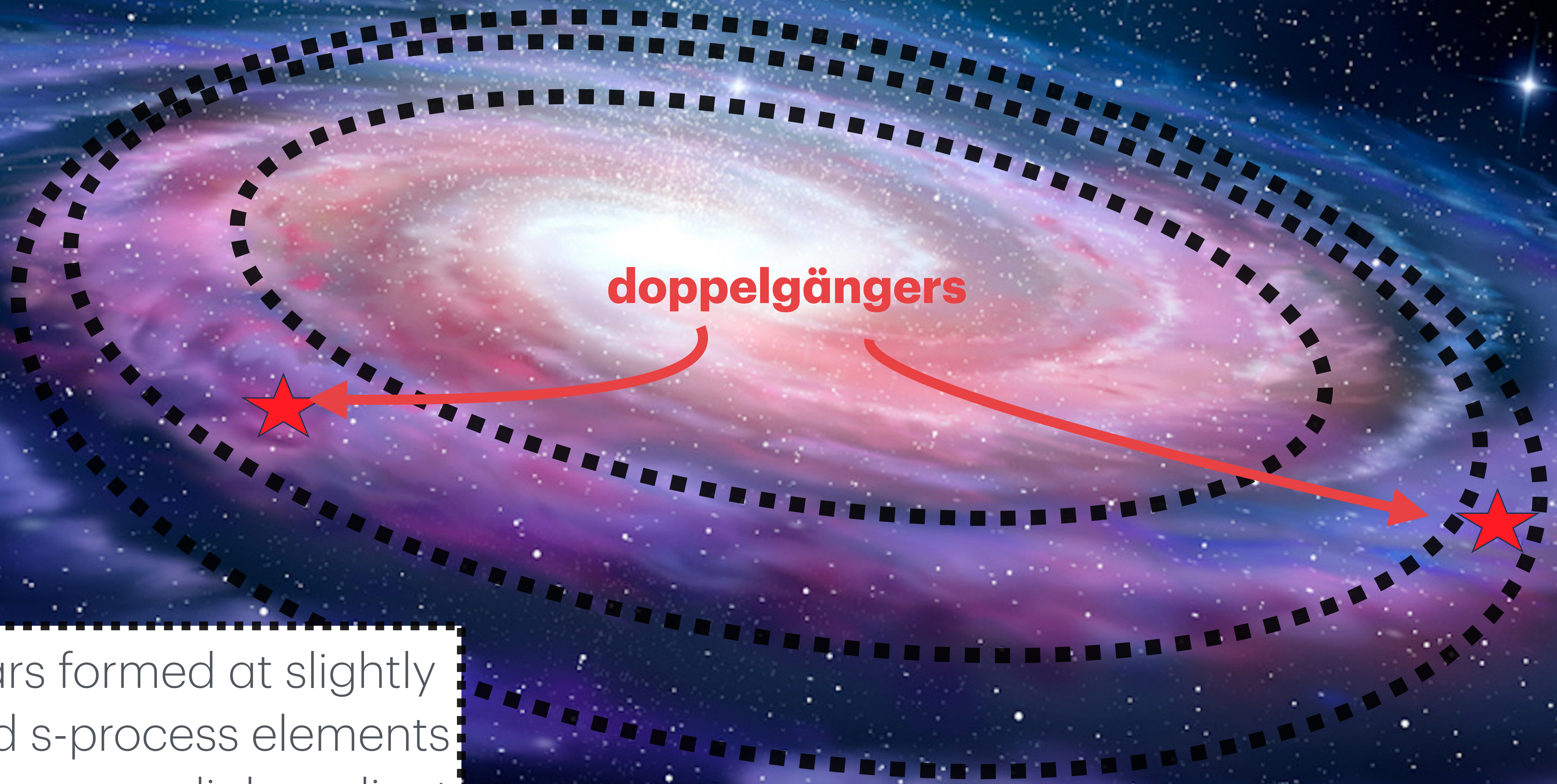

Implication

Maybe these stars formed at slightly different radii and s-process elements have a slightly steeper radial gradient than other elements

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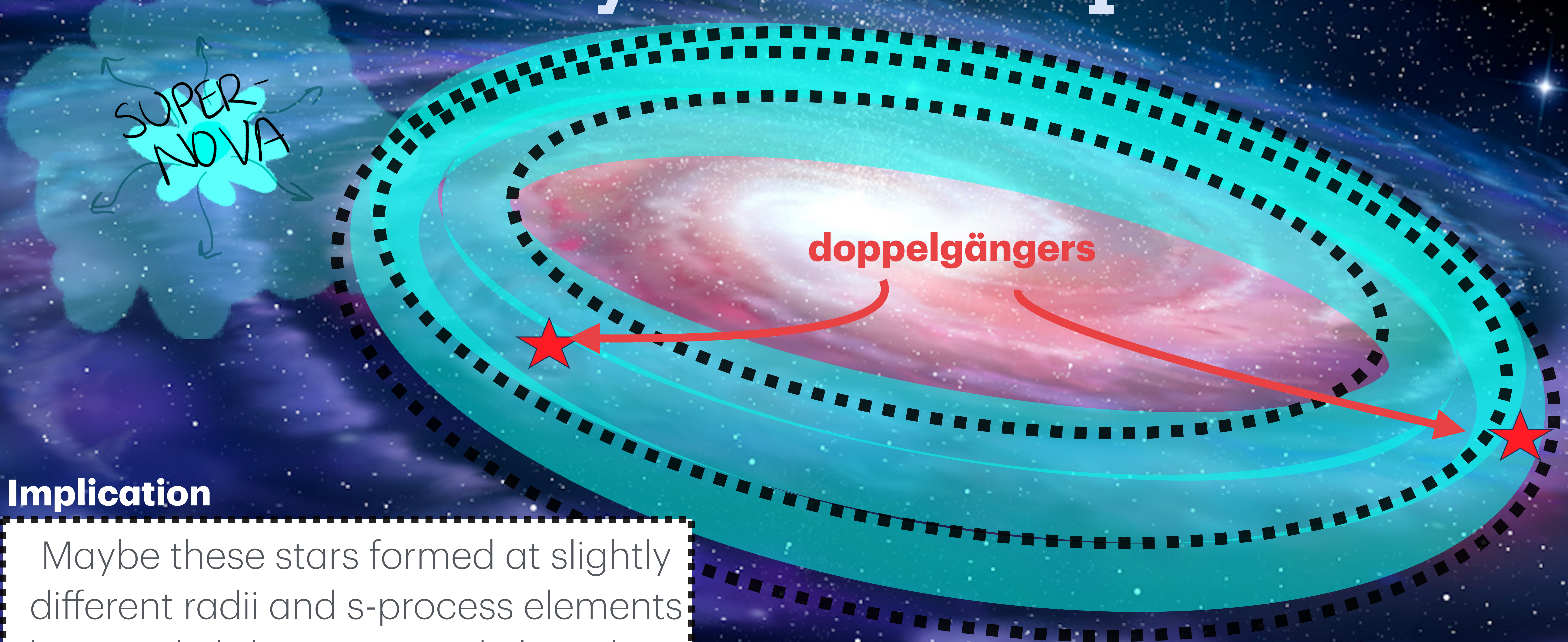

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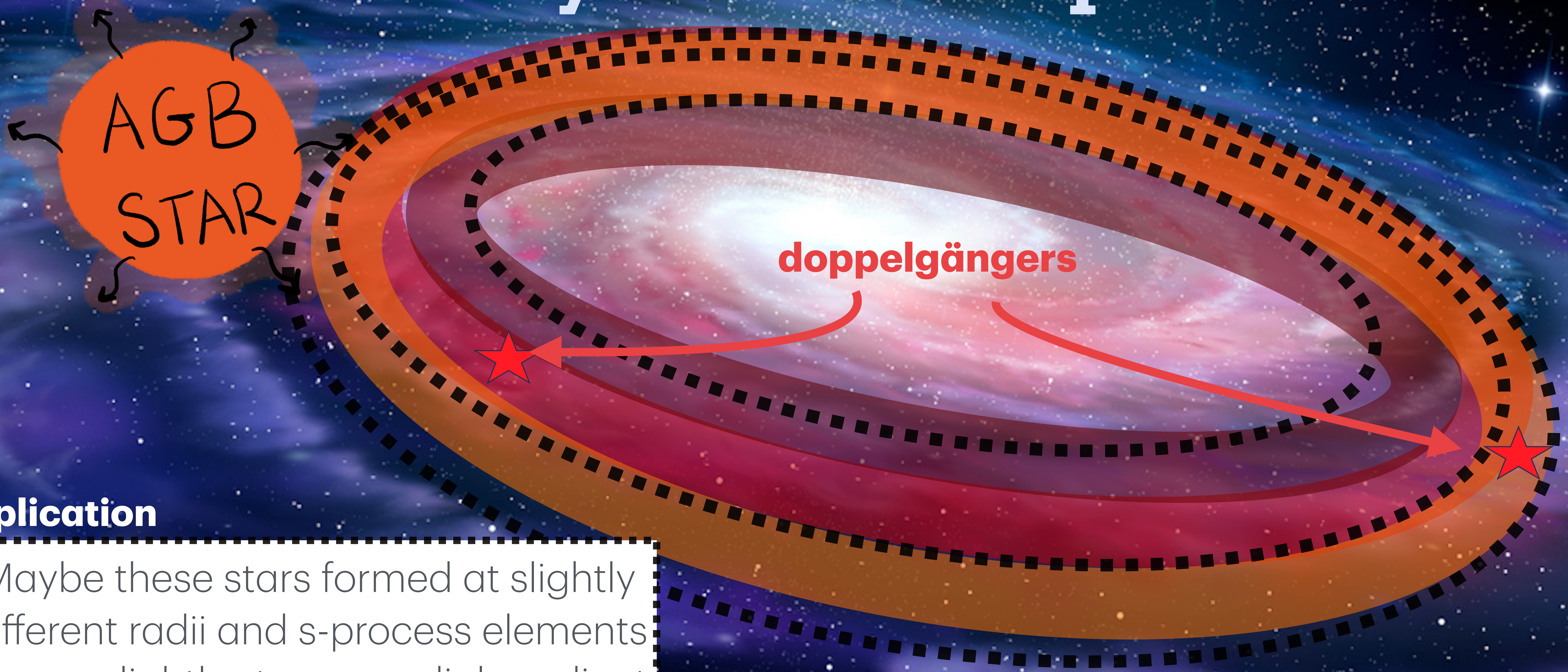

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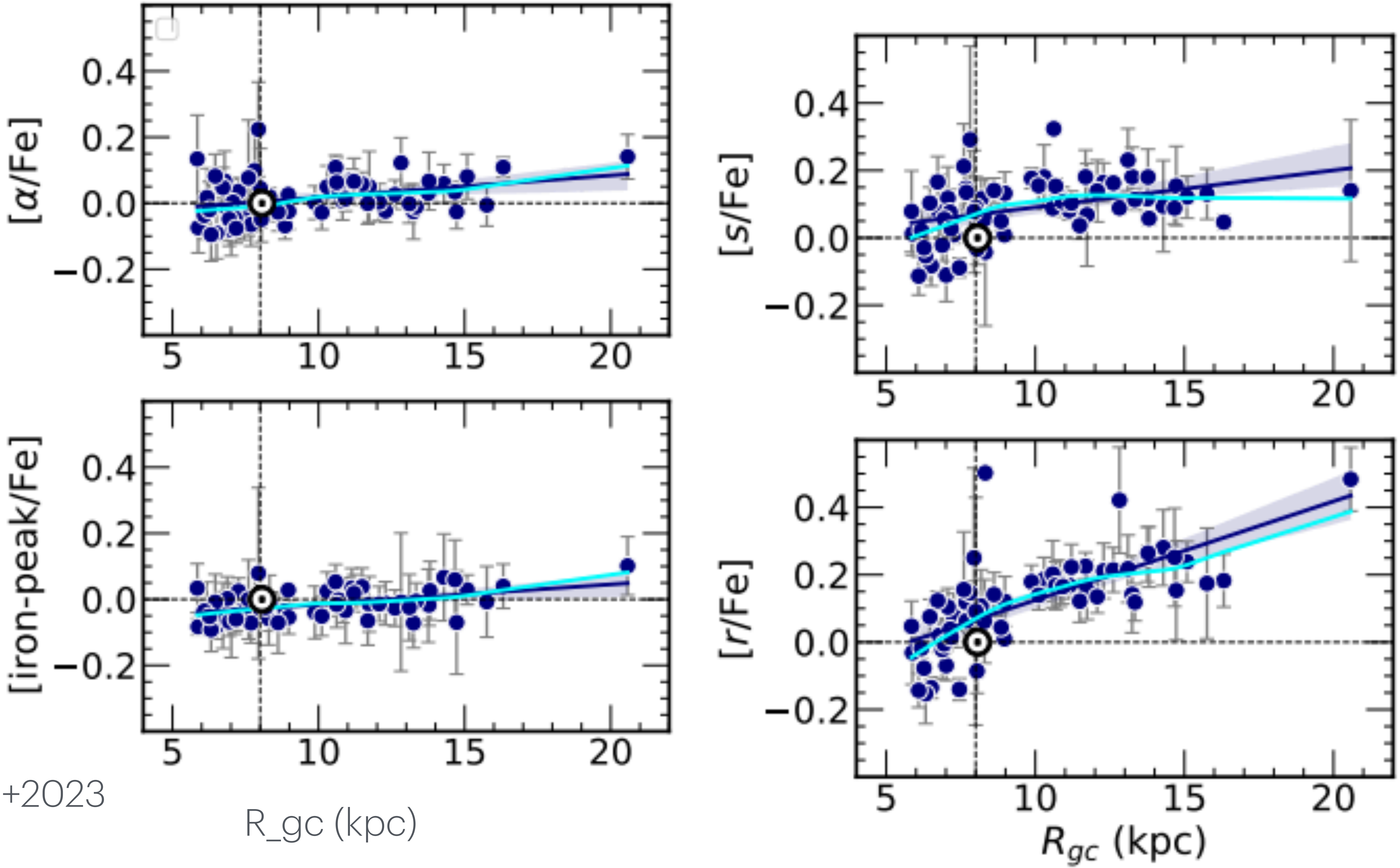
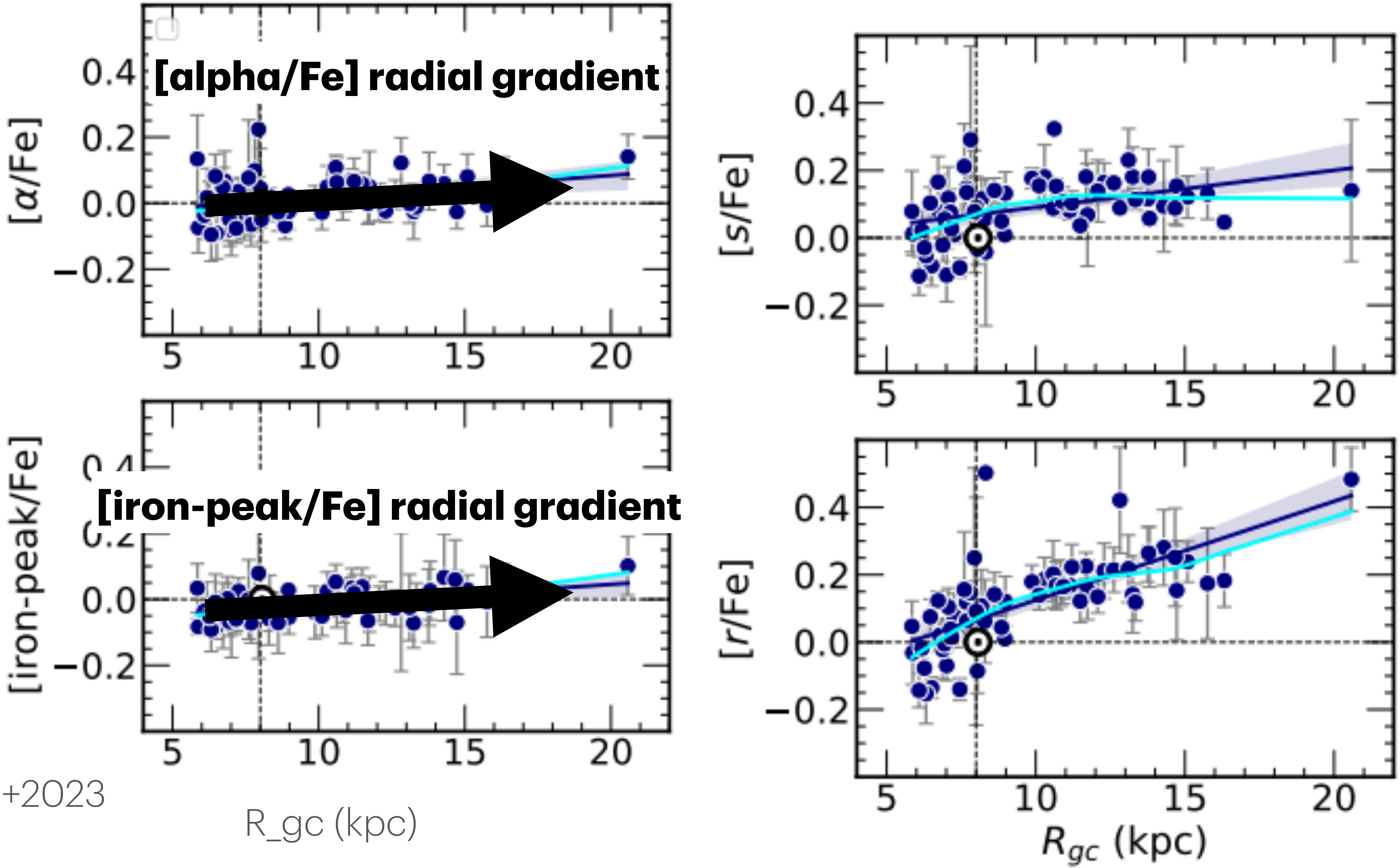


Magrini+2023

R_gc (kpc)



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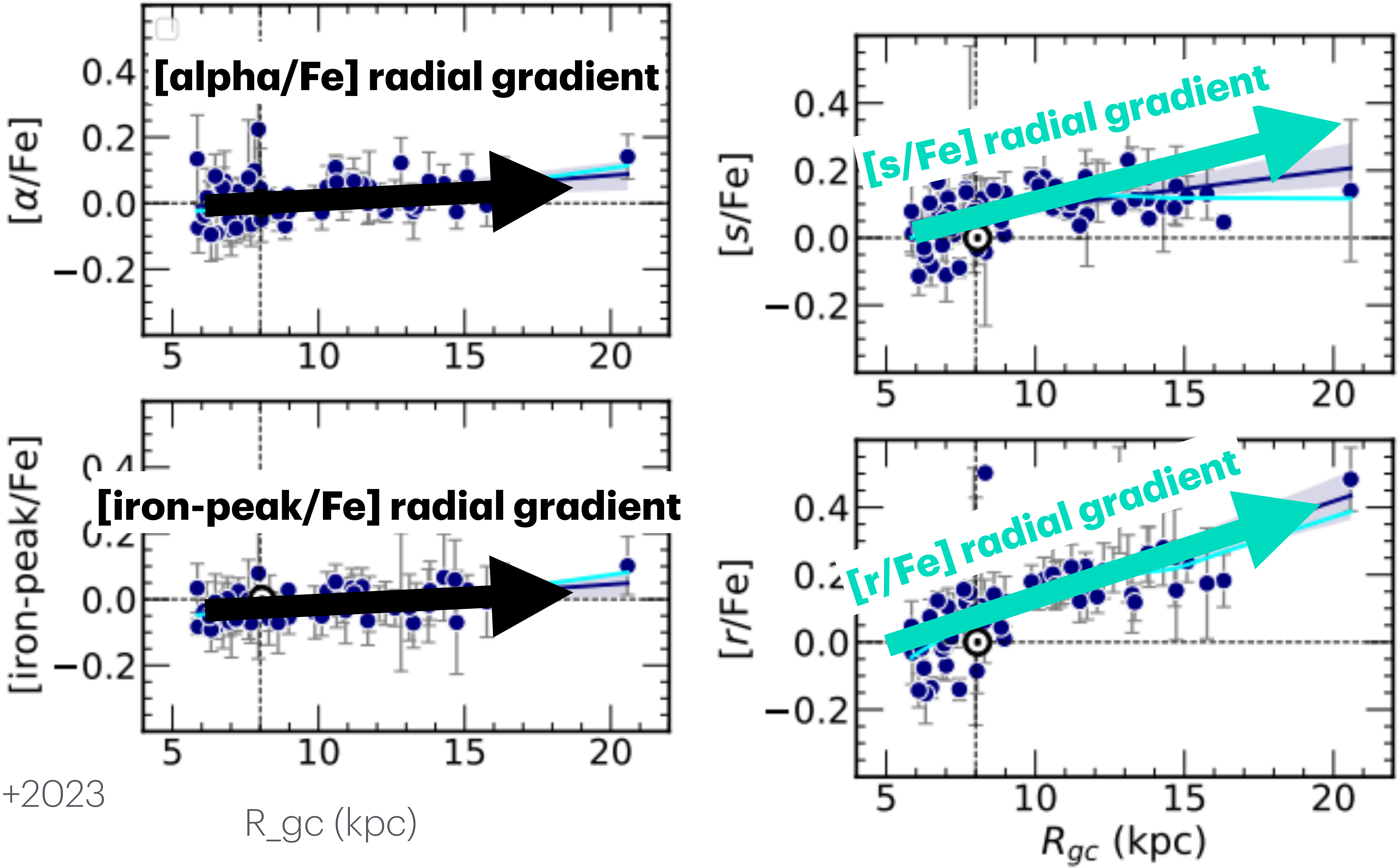


Magrini+2023

R_gc (kpc)

Summary

Stars deemed to be chemically indistinguishable by APOGEE can differ **by up to 0.2 dex** in neutron-capture element abundances.

Stars deemed to be chemically indistinguishable by APOGEE ***on average*** show neutron-capture abundance differences between 0.02 and 0.04 dex beyond the typical difference among open cluster stars.

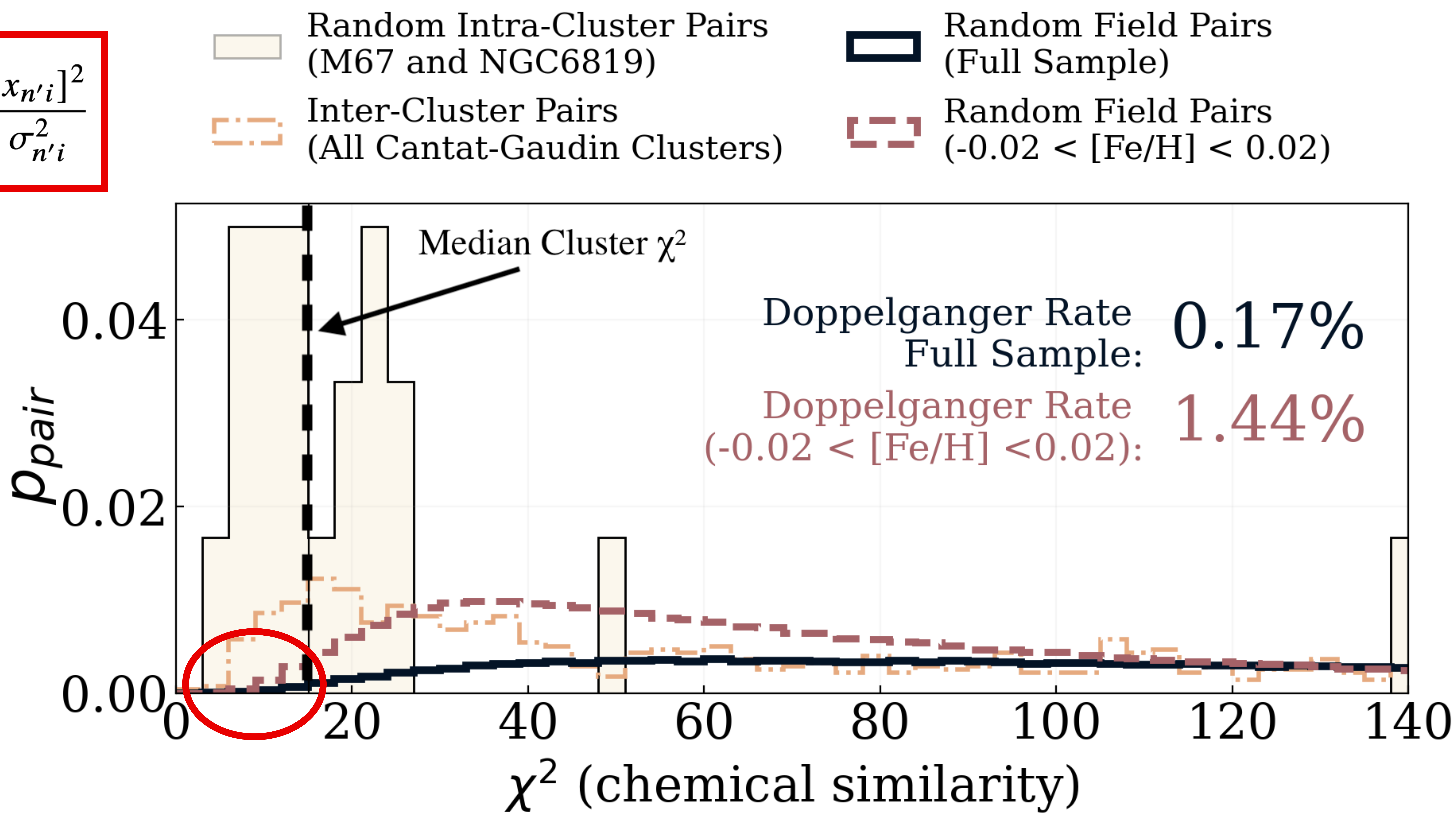
APOGEE abundances, even from SNR > 300 spectra, are not necessarily sufficient for identifying chemically similar stars across all elements.

Also, optical spectroscopy is important

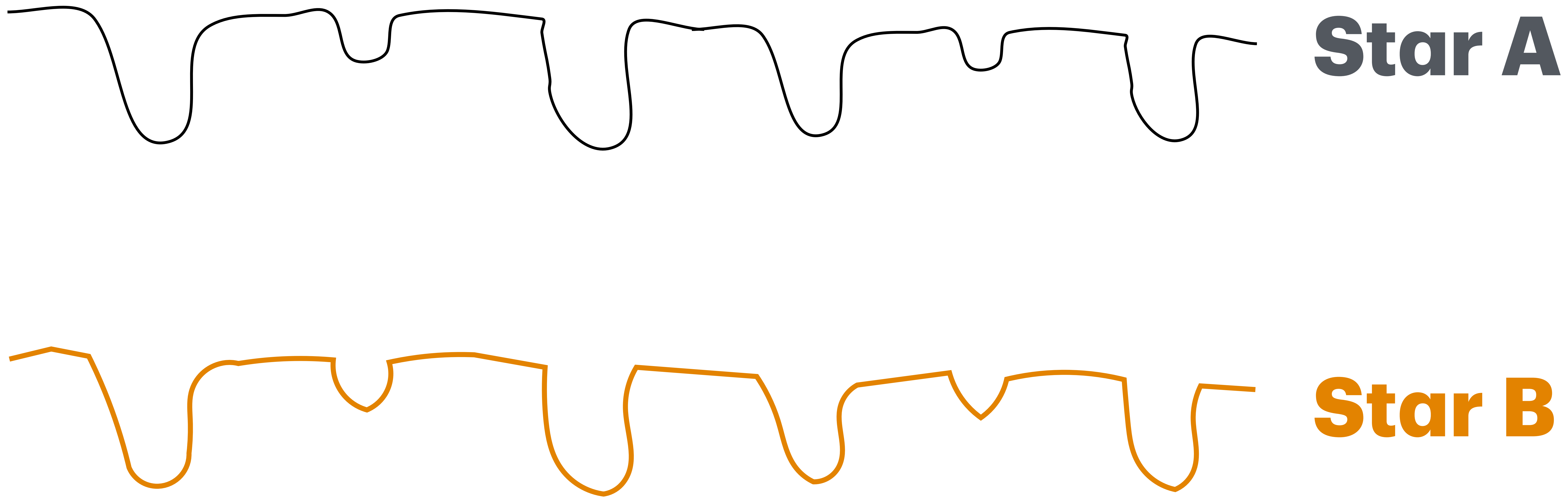
BACKUP

Selecting chemical doppelgängers

$$\boxed{\chi^2_{nn'} = \sum_{i=1}^{I} \frac{[x_{ni} - x_{n'i}]^2}{\sigma^2_{ni} + \sigma^2_{n'i}}}$$



"Regular" abundance analysis



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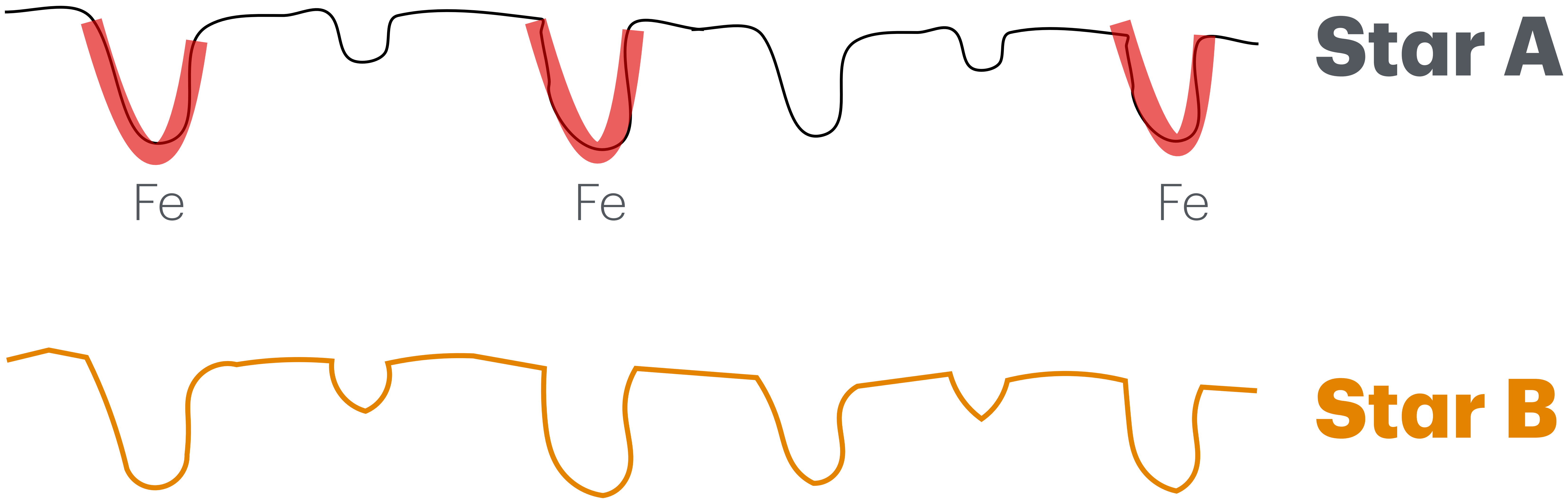

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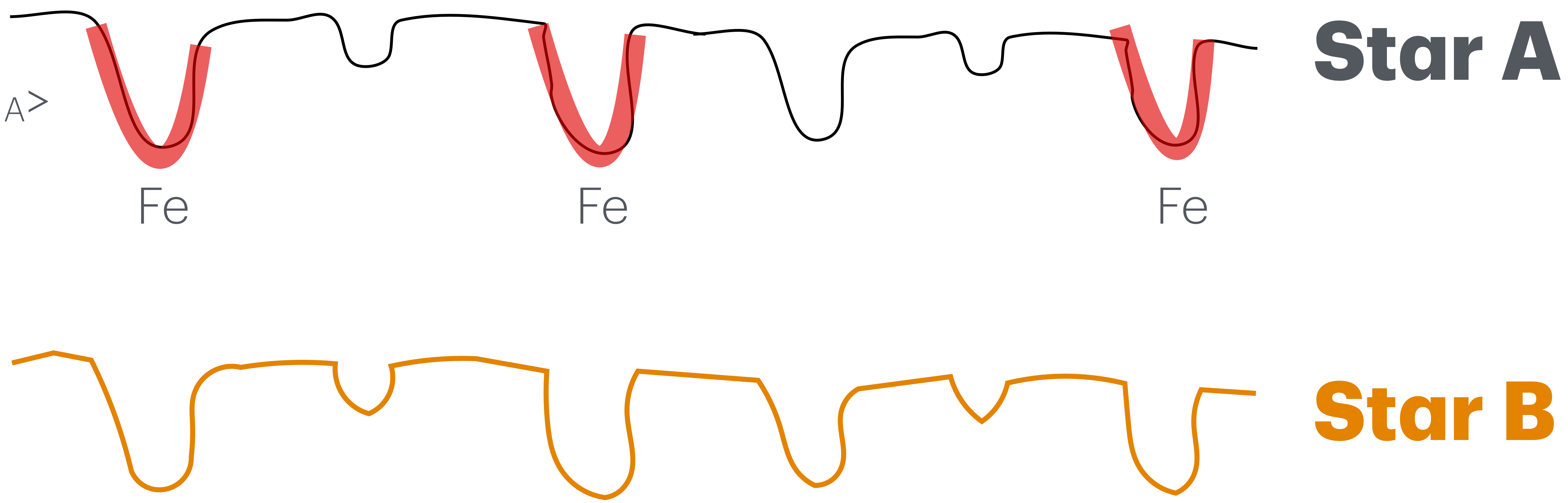
$$\mathrm{Abund(Fe)}_{\mathrm{STAR\ A}} = \langle \mathrm{Abund(Fe}_{\lambda})_{\mathrm{STAR\ A}} \rangle$$



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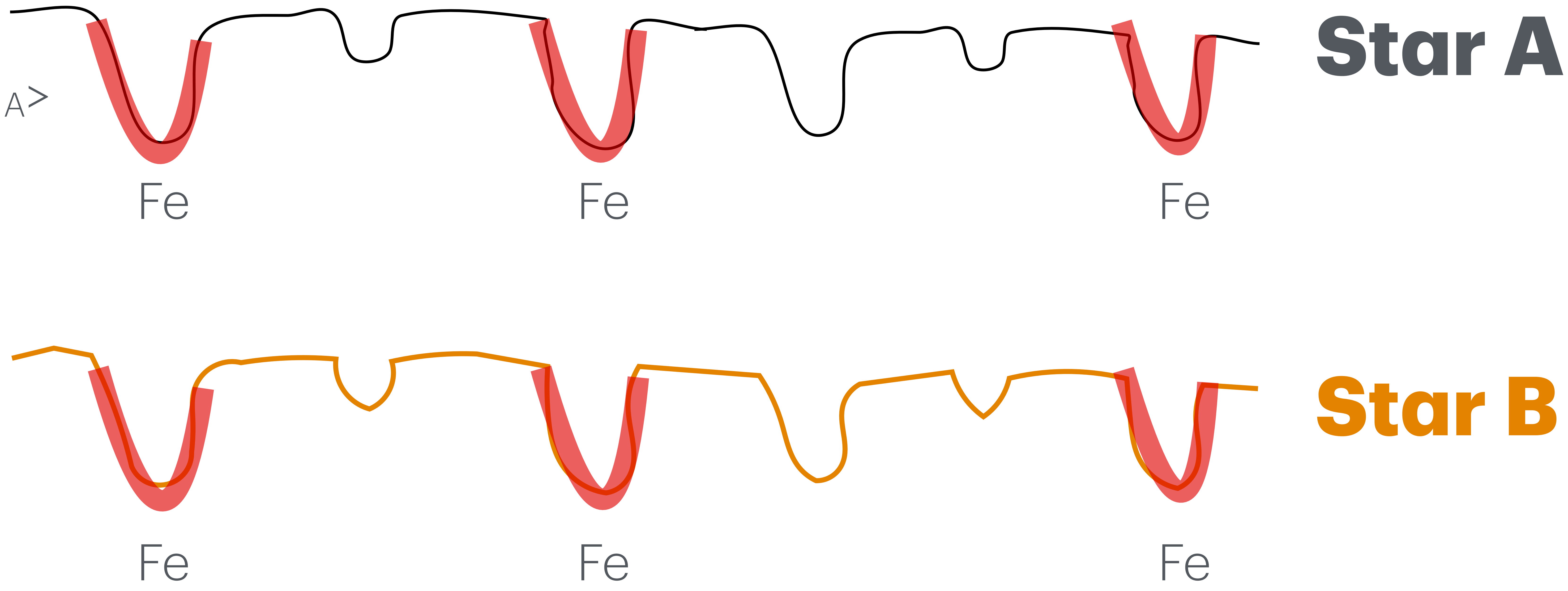

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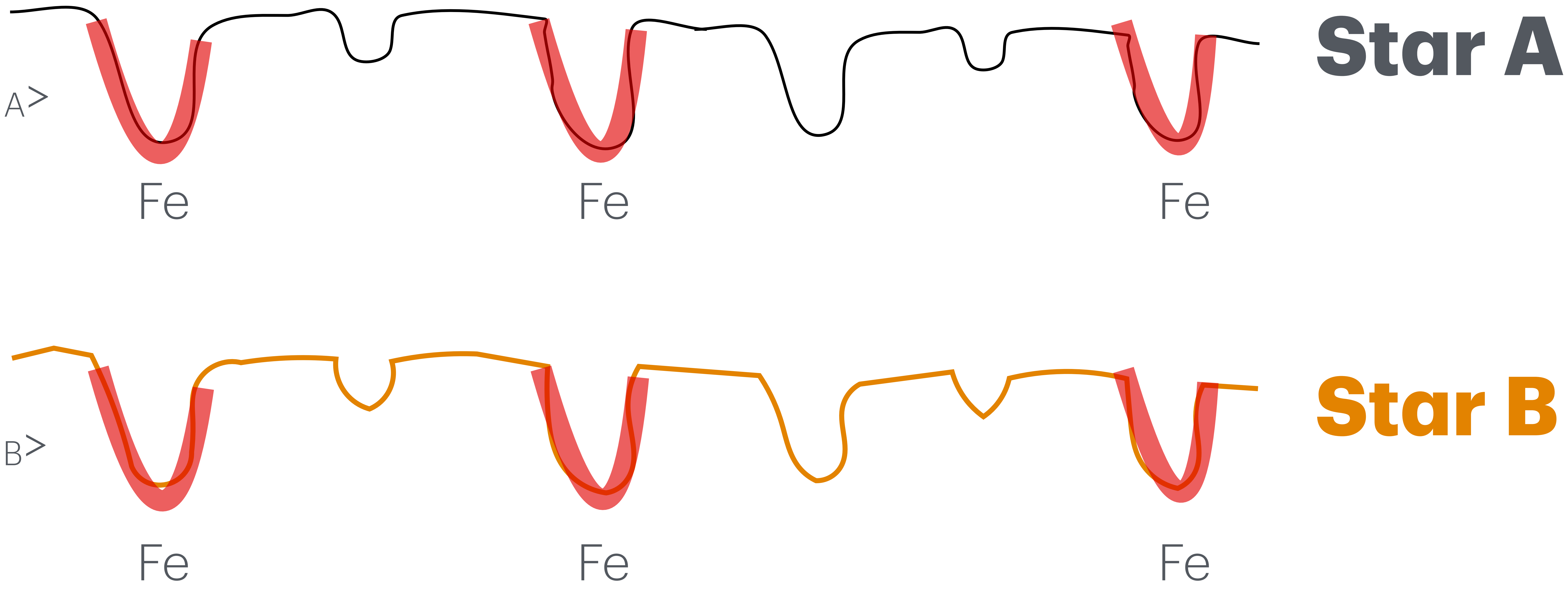

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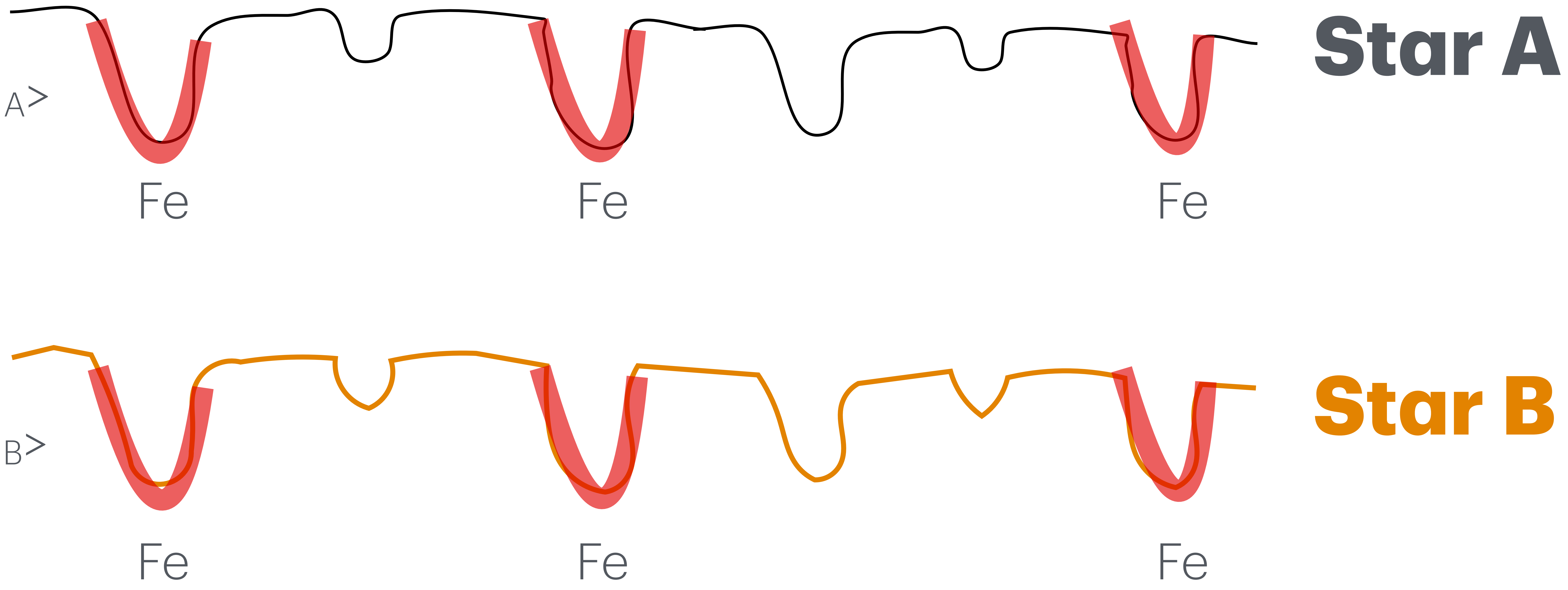

$$\Delta\mathrm{Abund(Fe)} = \langle \mathrm{Abund(Fe}_\lambda)_{\mathrm{STAR\ A}} \rangle - \langle \mathrm{Abund(Fe}_\lambda)_{\mathrm{STAR\ B}} \rangle$$

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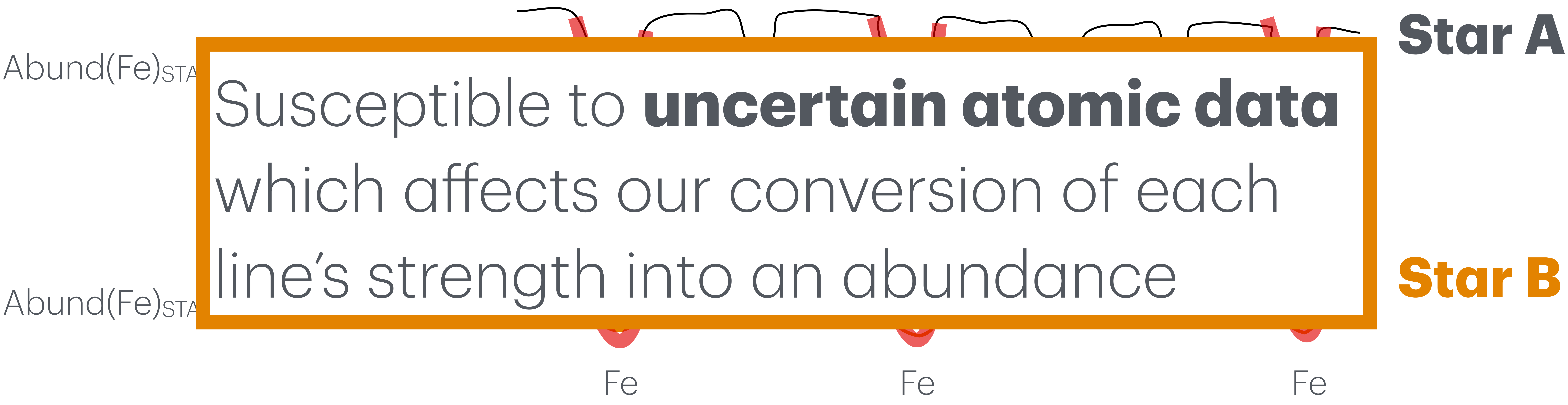
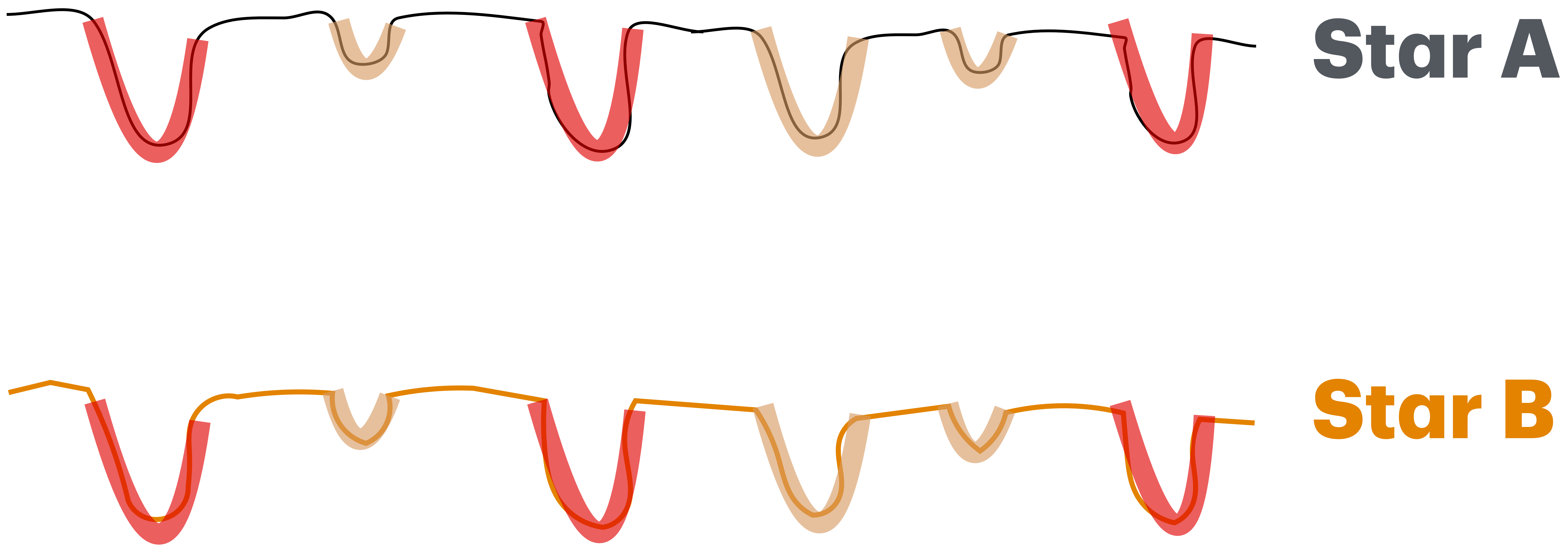


Susceptible to **uncertain atomic data** which affects our conversion of each line's strength into an abundance

$$\Delta \mathrm{Abund(Fe)} = \langle \mathrm{Abund}(\mathrm{Fe}_\lambda)_{\mathrm{STAR\ A}} \rangle - \langle \mathrm{Abund}(\mathrm{Fe}_\lambda)_{\mathrm{STAR\ B}} \rangle$$

Differential abundance analysis



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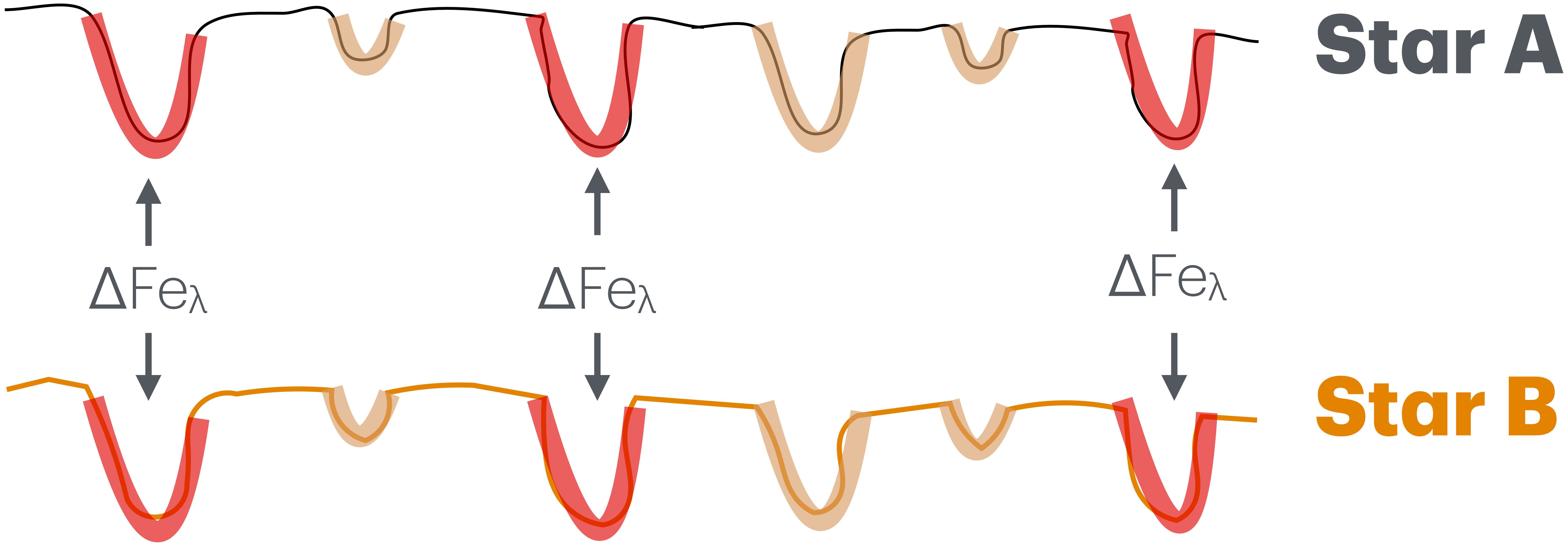

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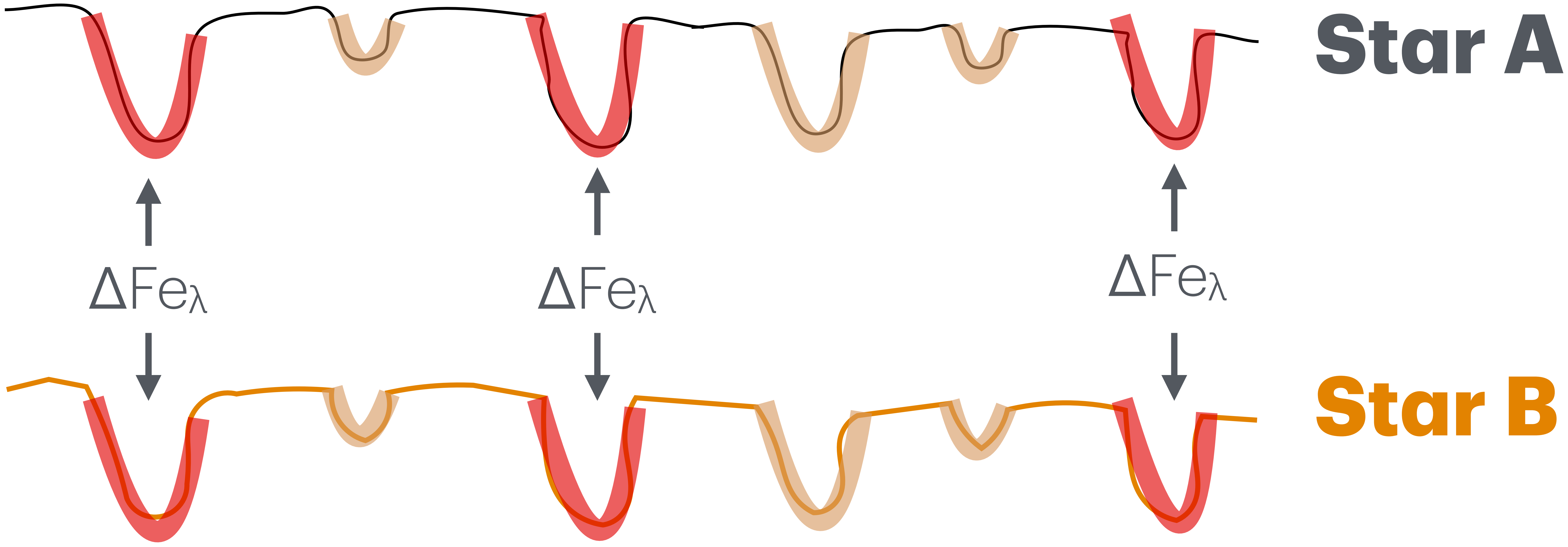

$$\Delta \text{Abund(Fe)} = \langle \Delta \text{Fe}_\lambda \rangle$$

Differential abundance analysis

Bypasses abundance uncertainties due to **uncertain atomic data, systematic wavelength-specific reduction issues, etc.**

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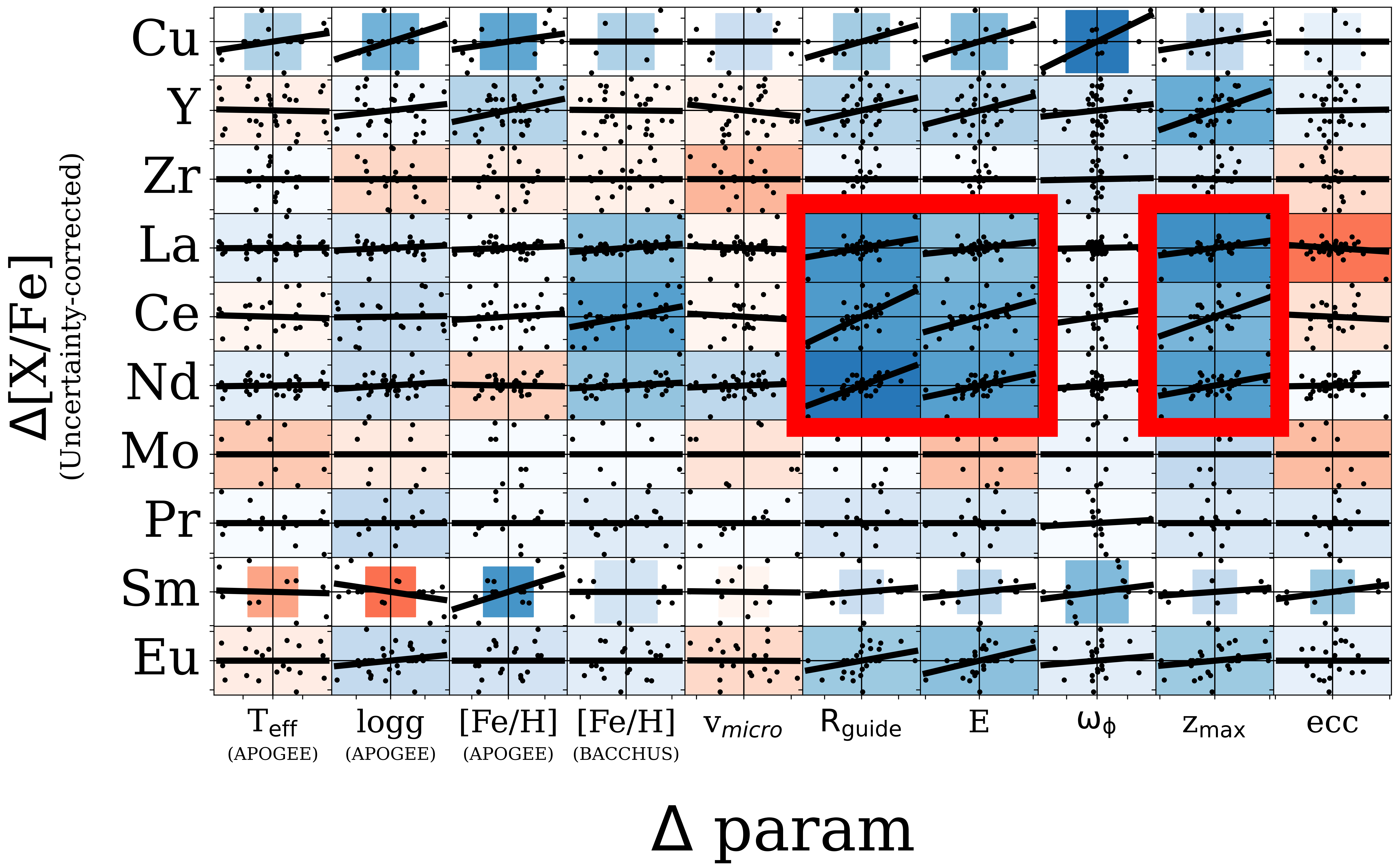
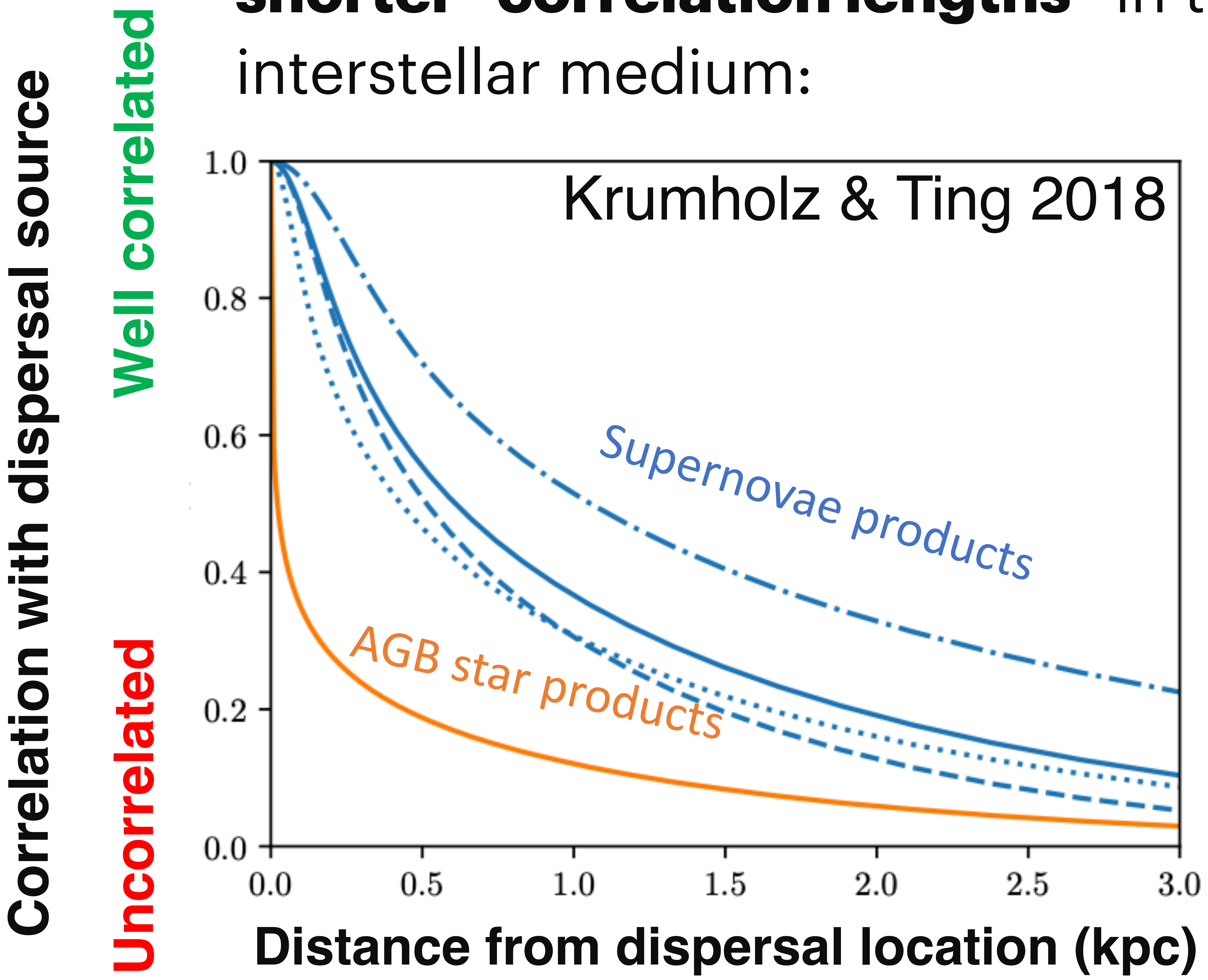
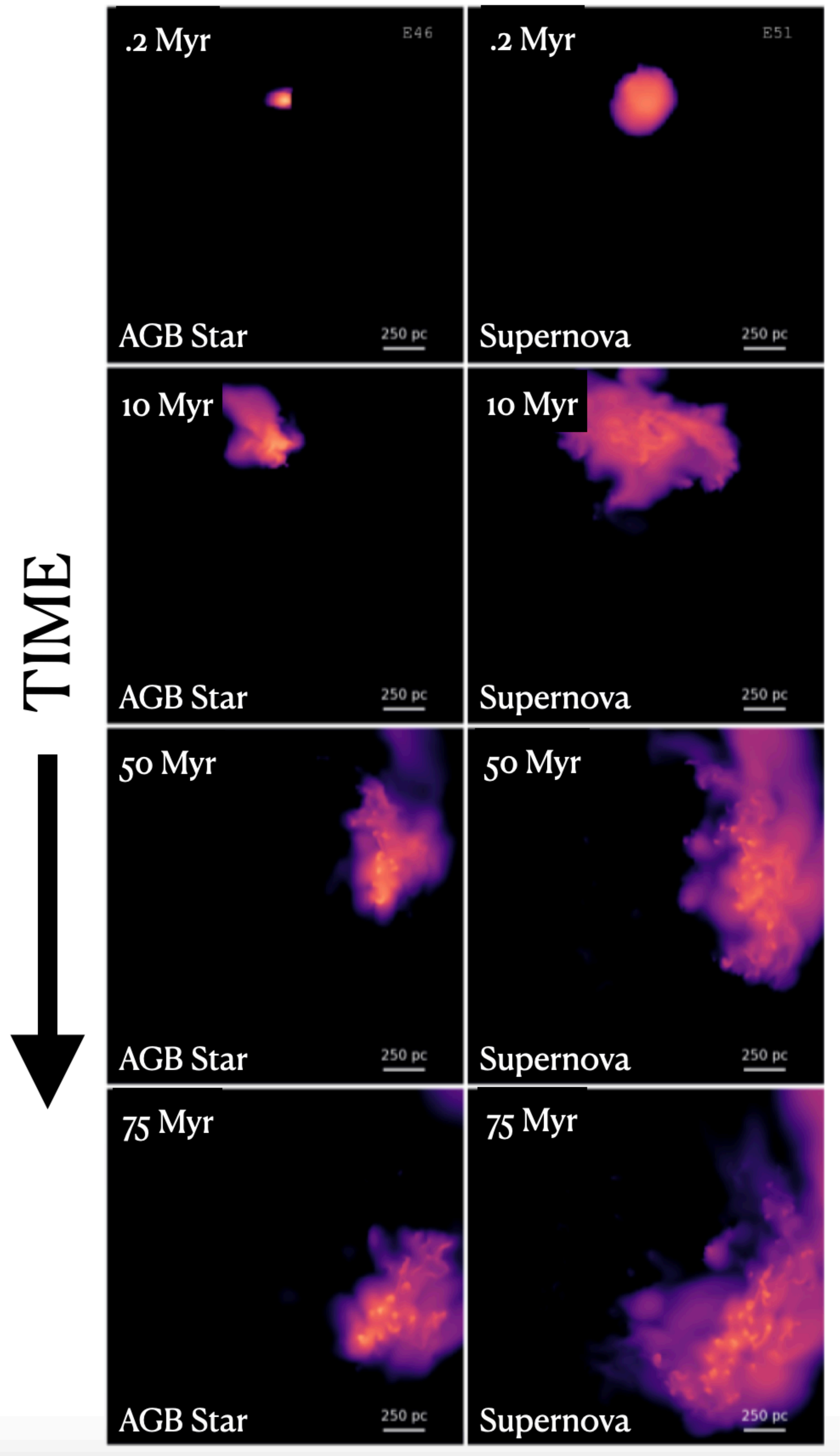


Cu
Y
Zr
La
Ce
Nd
Mo
Pr
Sm
Eu
Δ[X/Fe]
(Uncertainty-corrected)
T_{eff} (APOGEE)
logg (APOGEE)
[Fe/H] (APOGEE)
[Fe/H] (BACCHUS)
v_{micro}
R_{guide}
E
ω_ϕ
z_{max}
ecc
Δ param

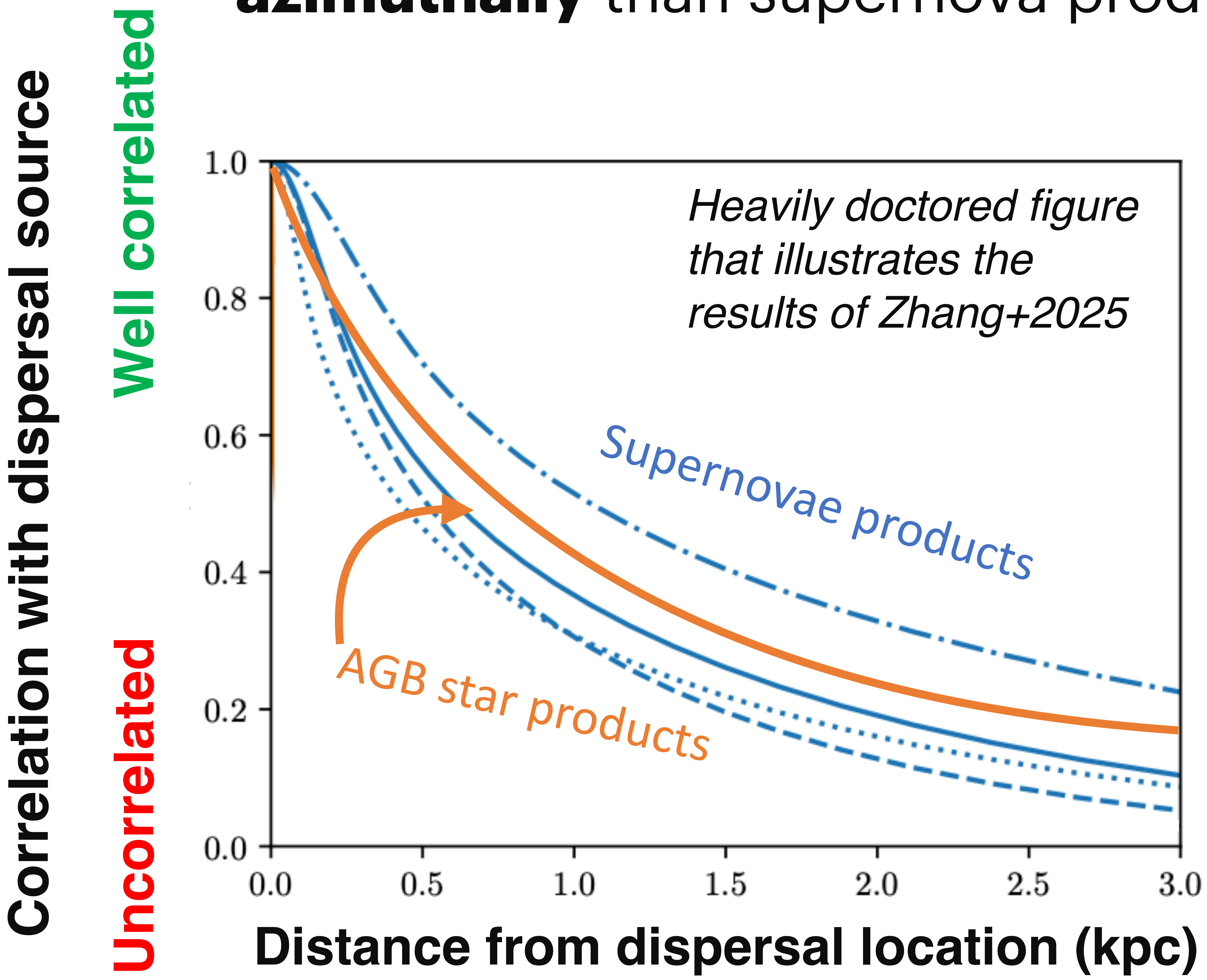
Krumholz&Ting+2018 simulations suggest AGB star nucleosynthetic products have **shorter “correlation lengths”** in the interstellar medium:

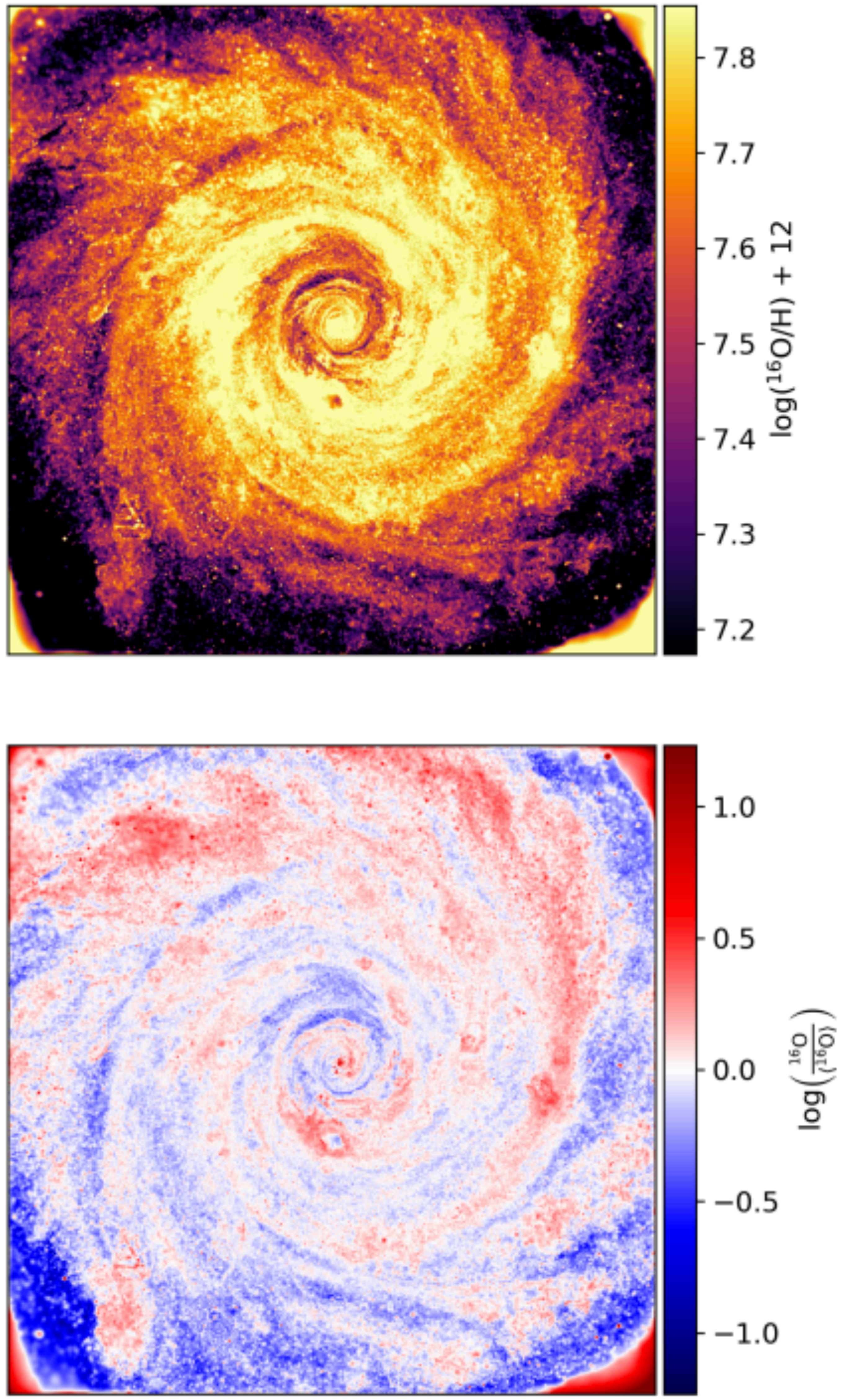


Emerick et al. 2020



Zhang+2025 simulations find that AGB star products are **more well-mixed azimuthally** than supernova products





[C/N] has been demonstrated to be an **effective tracer of giant star age** but can be unreliable in some stars with **extra mixing** (e.g., Shetrone+2018)

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