Chemical evolution of NC-elements

Marta Molero

s, i, & r Element Nucleosynthesis (sirEN) Conference

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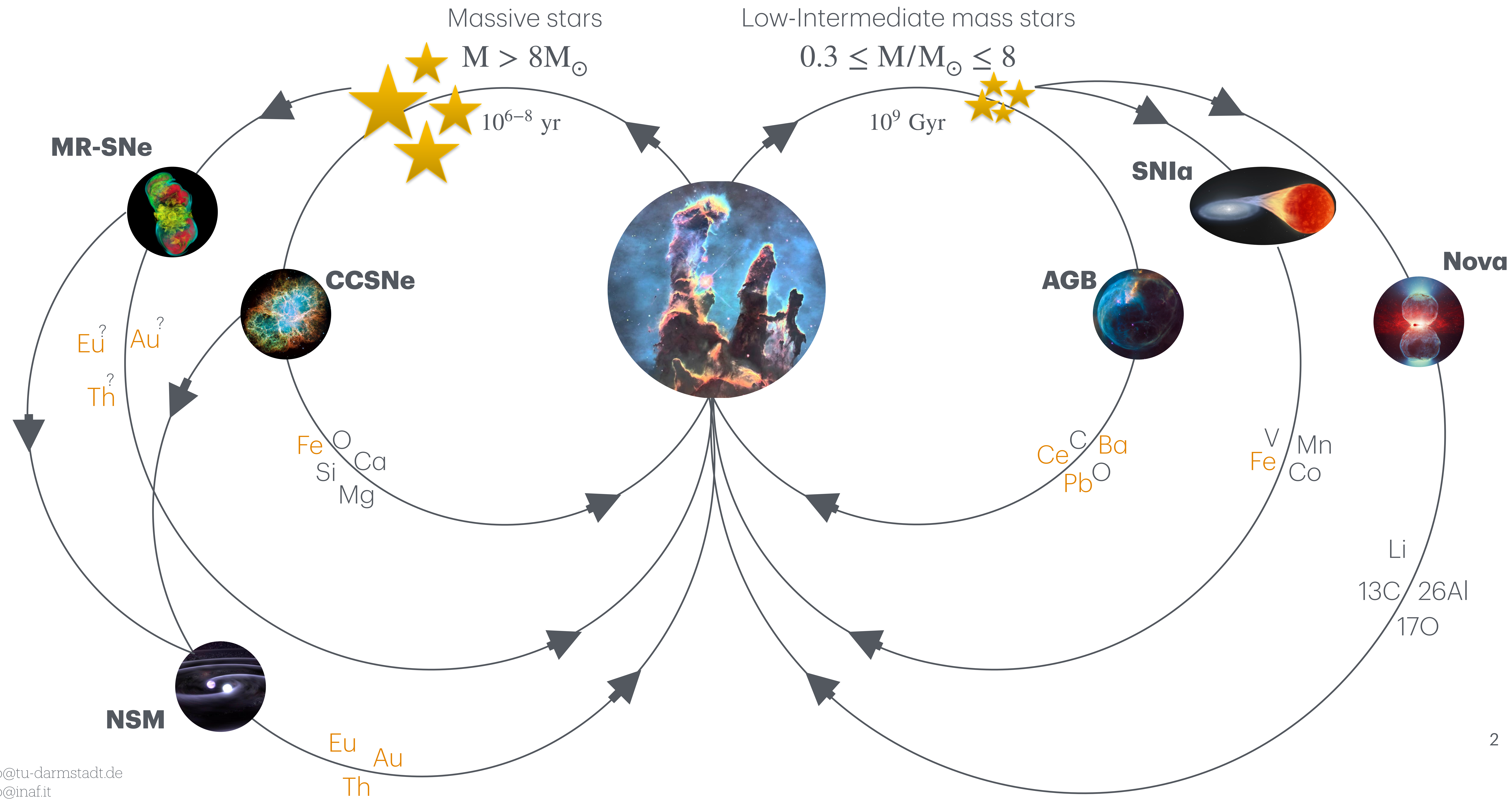
Introduction: chemical evolution



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Introduction: chemical evolution

- The evolution of the mass of gas in the form of the chemical element i

$$\dot{M}_{\mathrm{gas},i}(R,\theta,t) = -\psi(R,\theta,t)X_i(R,\theta,t) + X_{i,A}A(R,\theta,t) - X_i(R,\theta,t)W(R,\theta,t) - X_i(R,\theta,t)\dot{M}_{BH}(R,\theta,t) + \dot{R}_i(R,\theta,t)$$

Emanuele's talk for 2D (Spitoni et al. 2019,2023; Vasini et al. 2025)
Benjamin's talk for 3D (Wehmeyer et al. 2023)

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$$\dot{M}_{\mathrm{gas},i}(R,\theta,t) = -\psi(R,\theta,t)X_i(R,\theta,t) + \underbrace{X_{i,A}A(R,\theta,t)}_{\text{accretion of gas through infall}} - \underbrace{X_i(R,\theta,t)W(R,\theta,t)}_{\text{lost of gas galactic winds}} - X_i(R,\theta,t)\dot{M}_{BH}(R,\theta,t) + \dot{R}_i(R,\theta,t)$$

accretion of gas through infall

lost of gas galactic winds

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accretion of gas through infall

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lost of gas by feeding the central BH

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lost of gas because of SF processes

accretion of gas through infall

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lost of gas because of SF processes

accretion of gas through infall

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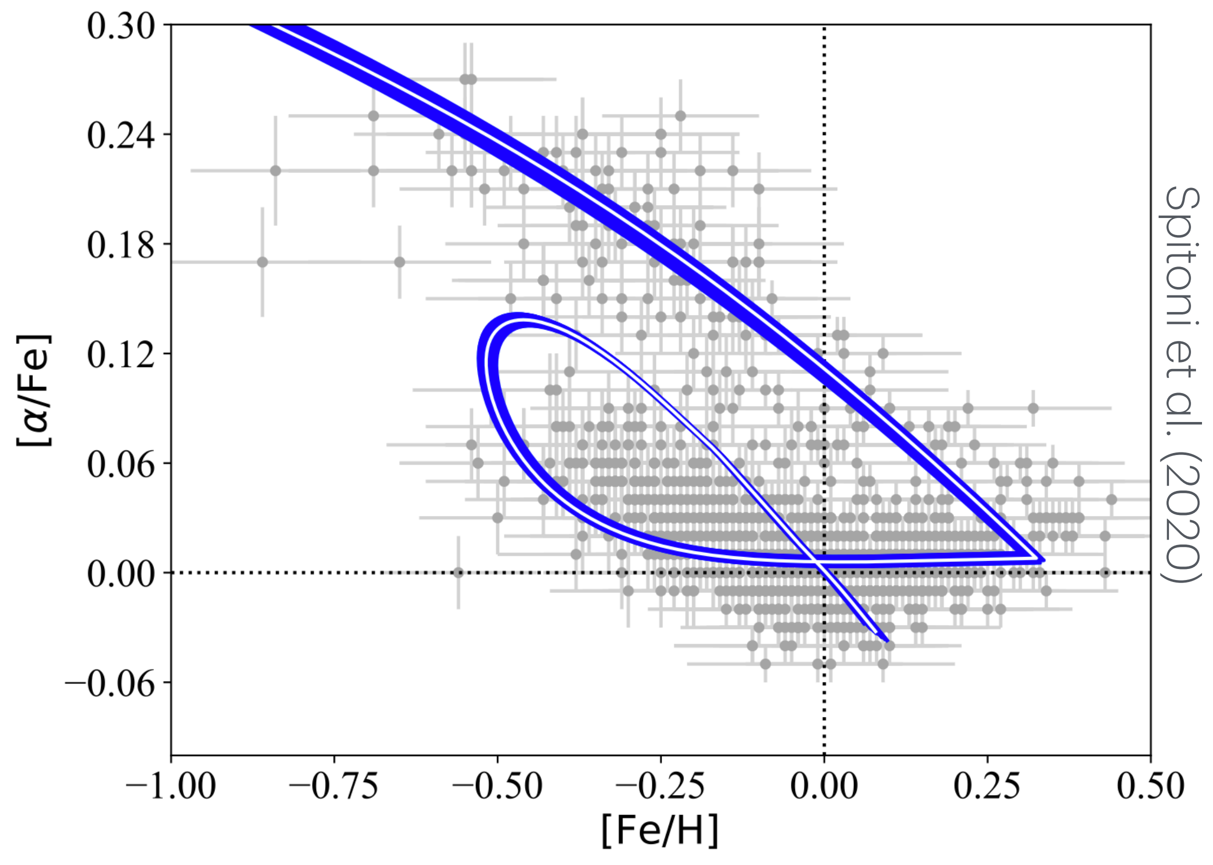
Homogeneous models:

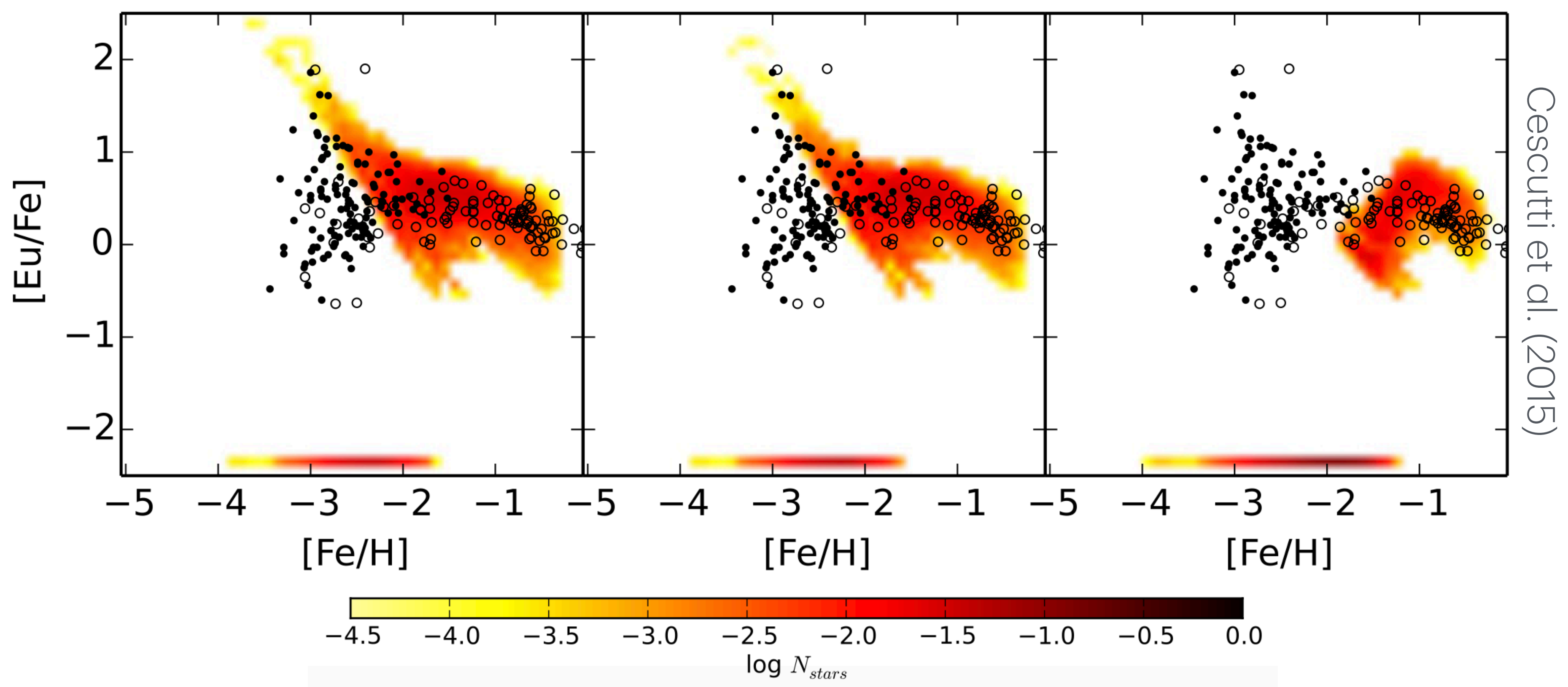
- One or multi-Zone system treated as a single homogeneous zone



Matteucci&Greggio 1986; Chiappini+97; Mollà+15; Côté+17; Spitoni+23;...

Stochastic models:

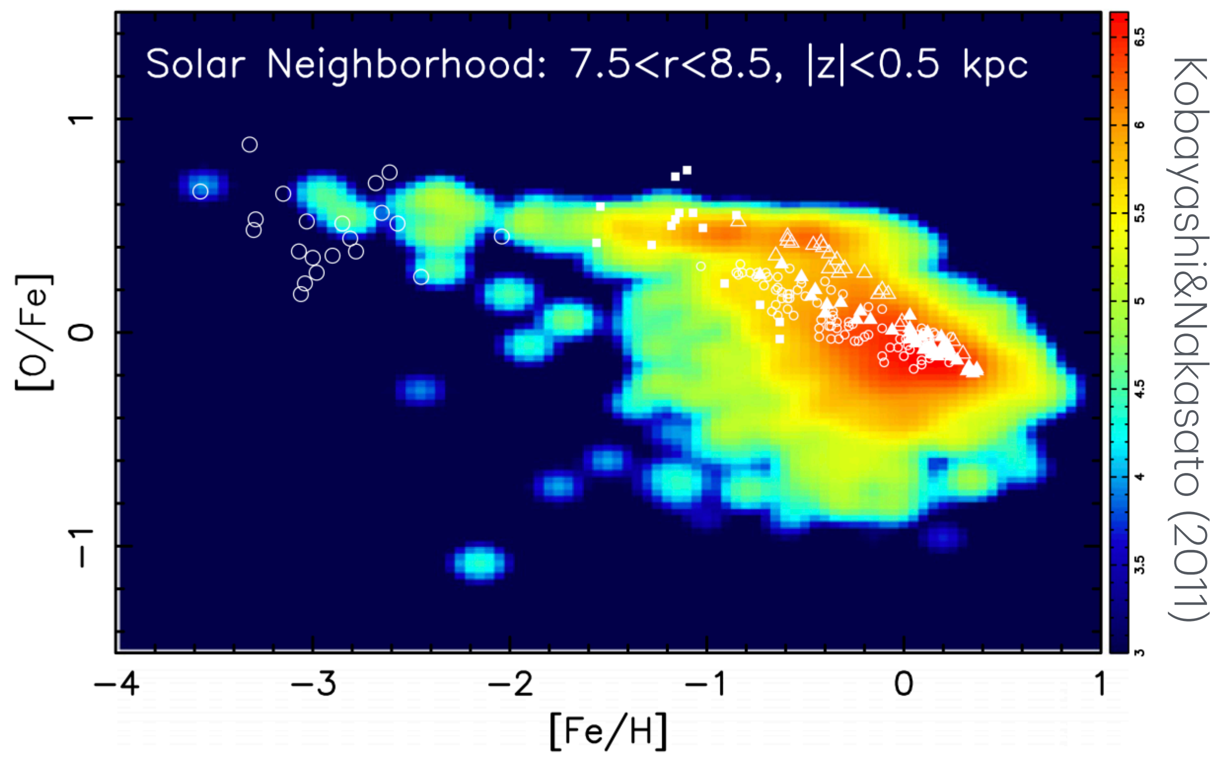
- System divided into multiple zones: each evolves independently with stochastic sampling of stellar mass distribution



Argast+00; Cescutti 2008; Hishimaru+15;...

Chemodynamical simulations:

- Integrate chemical evolution + dynamical processes in a cosmological framework



Kobayashi 2004; Scannapieco+22

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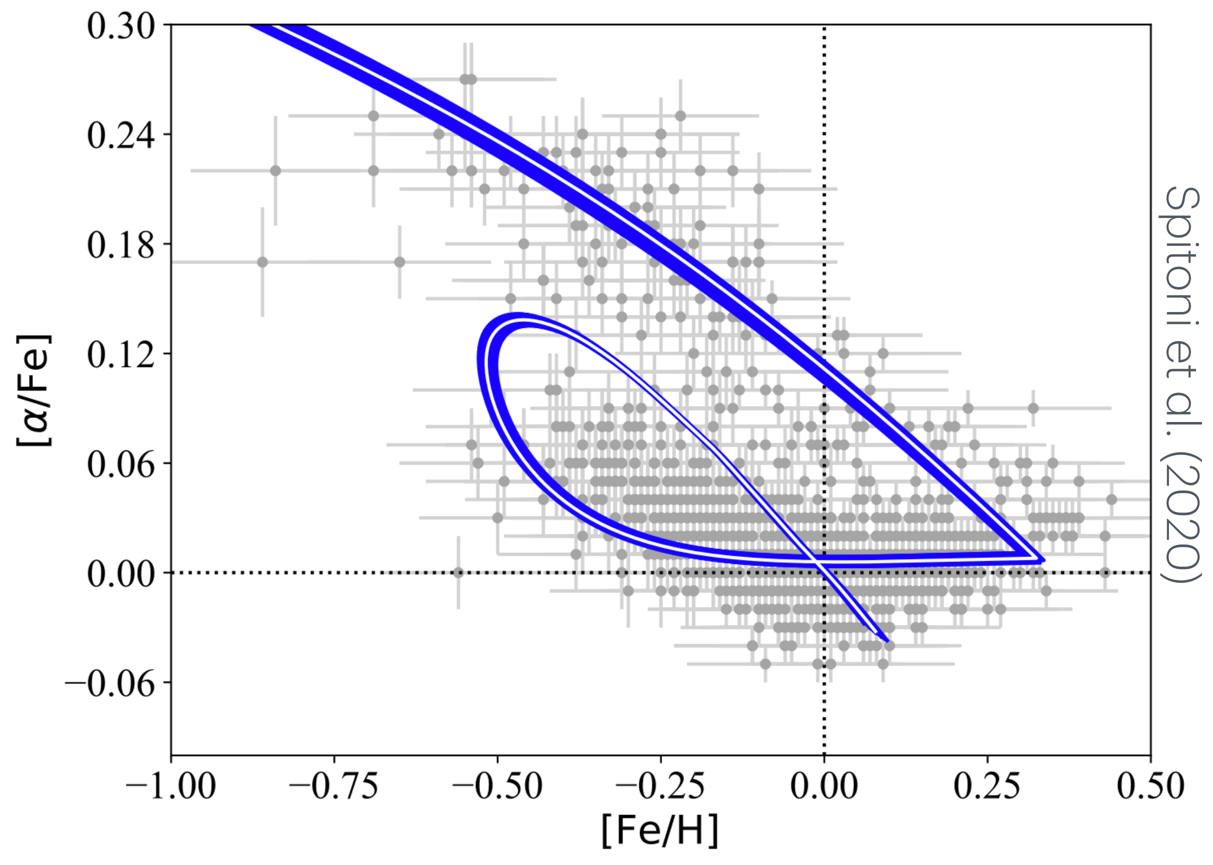

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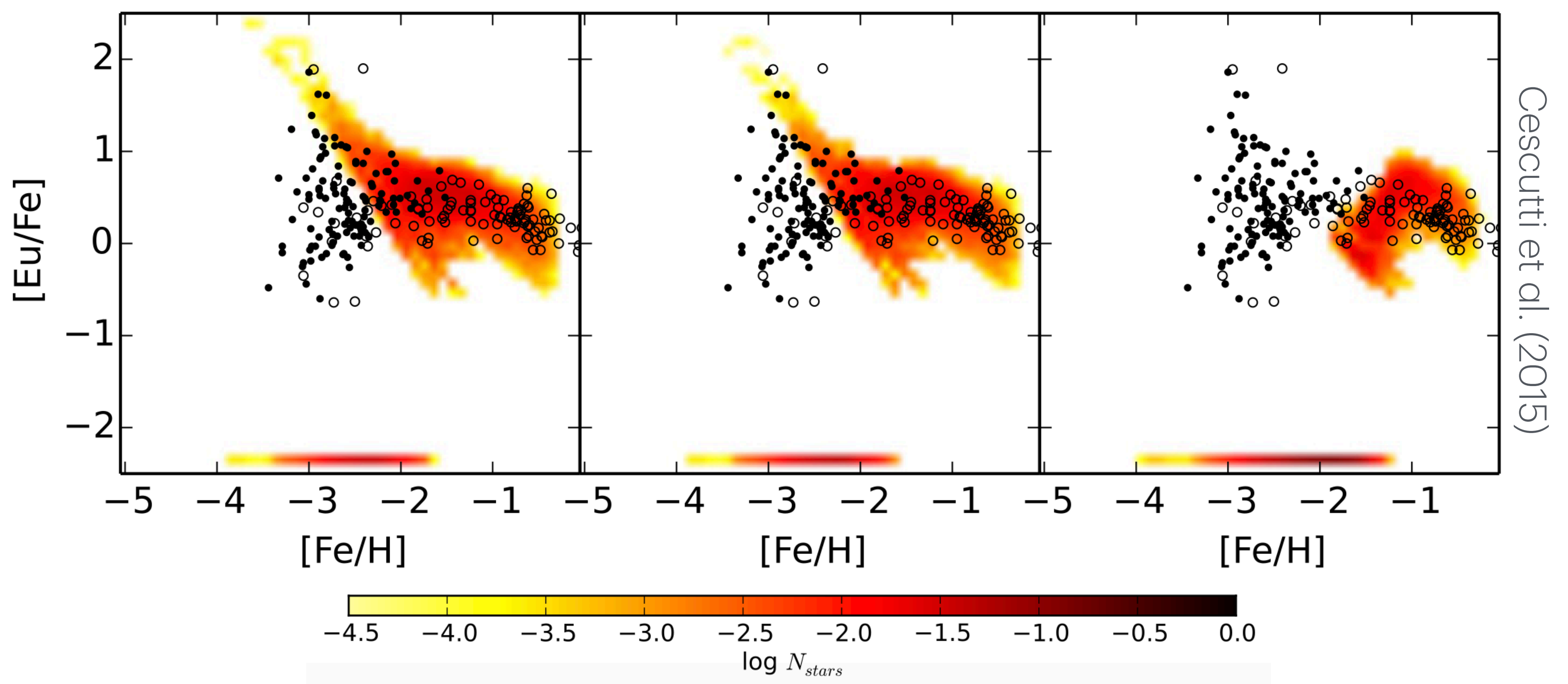

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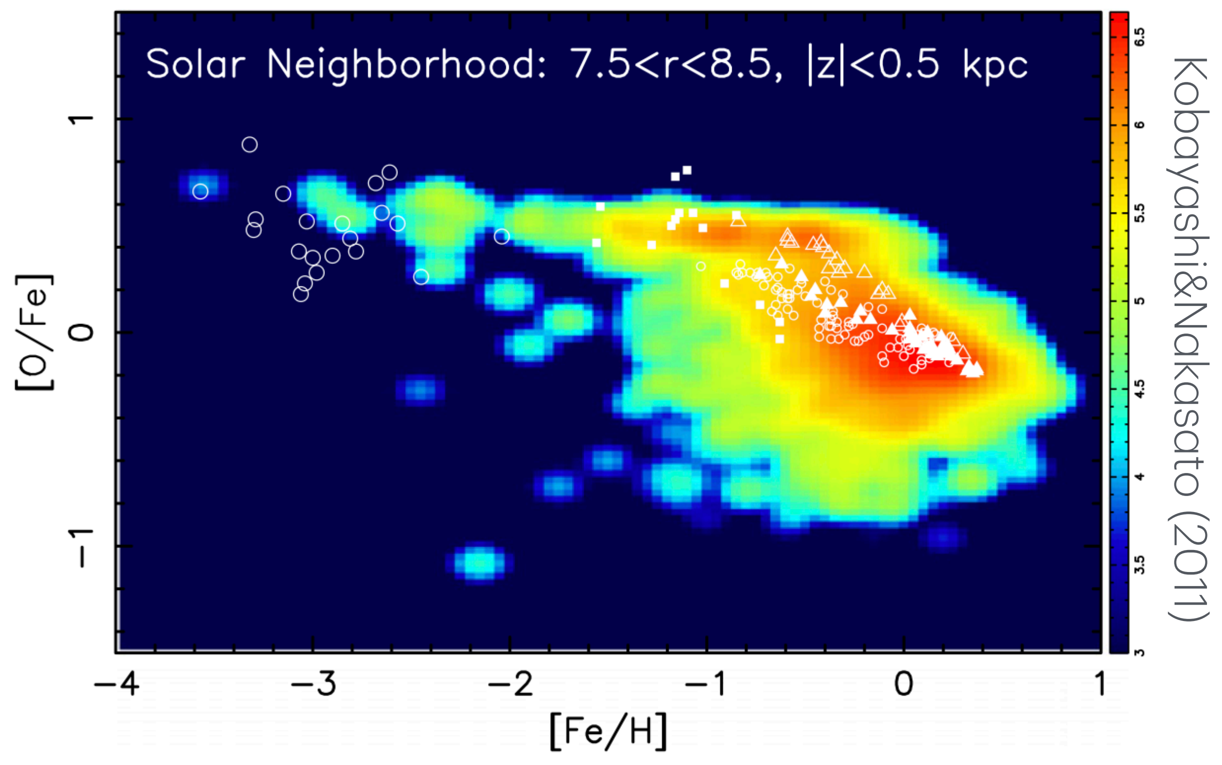

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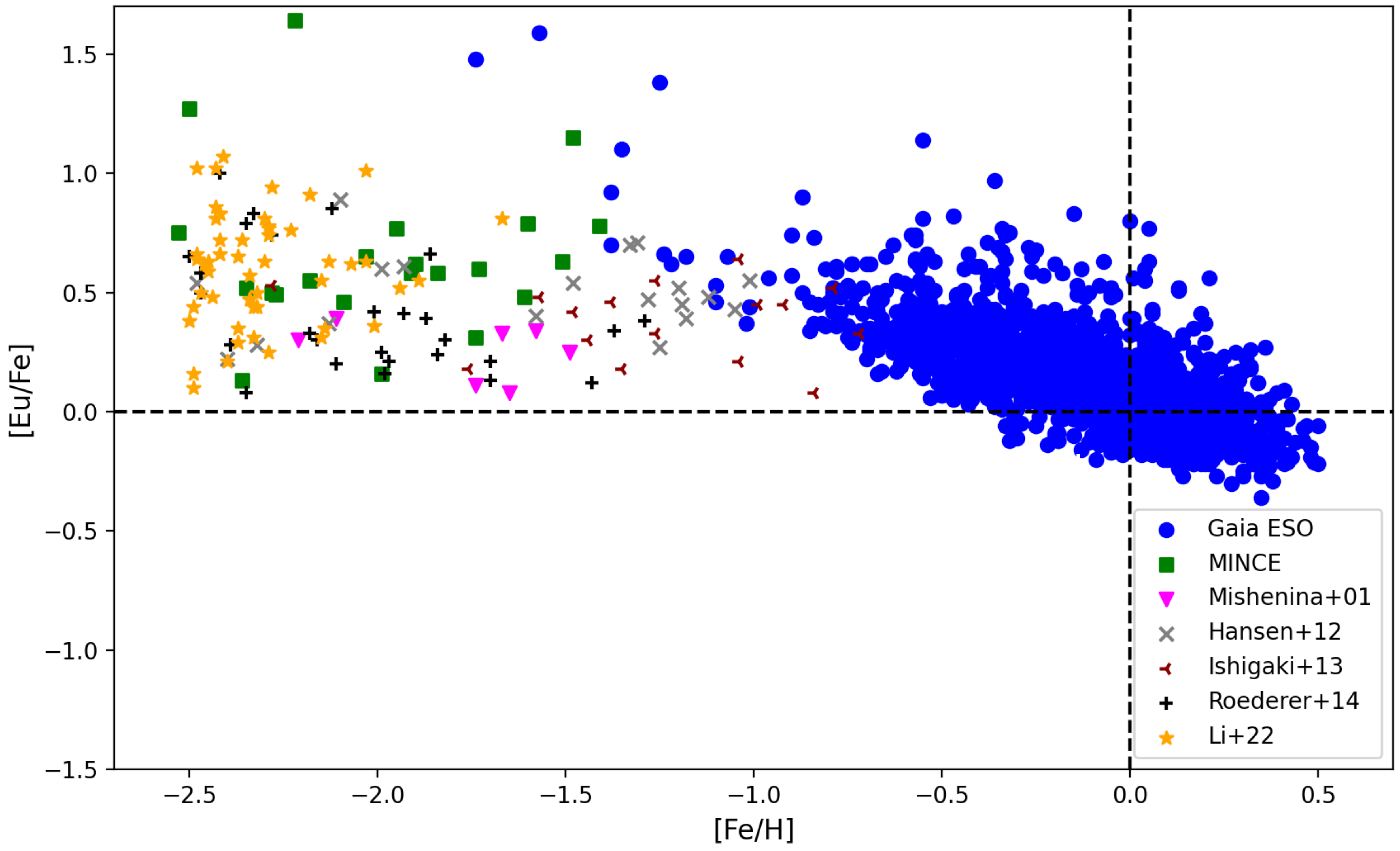
The [Eu/Fe] vs. [Fe/H]

$$[\mathrm{Eu/Fe}] = \log(\mathrm{Eu/Fe}) - \log(\mathrm{Eu/Fe})_{\odot}$$



the observed metal abundances of stars today measures the composition of the ISM when the star was formed

Stars are the *fossil records* of past events:

Galactic Archeology

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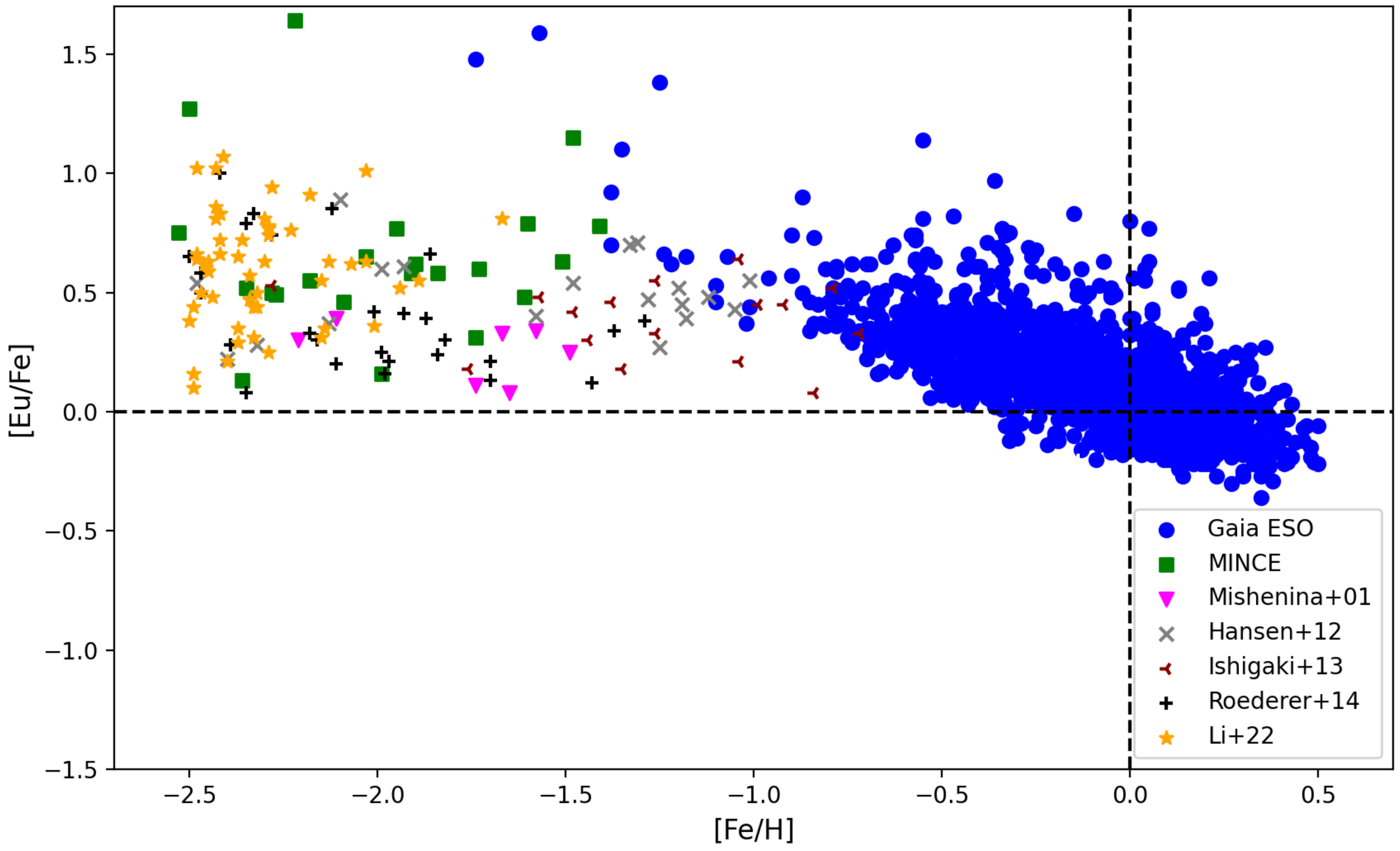

Type Ia SNe

long lifetimes main Fe producers

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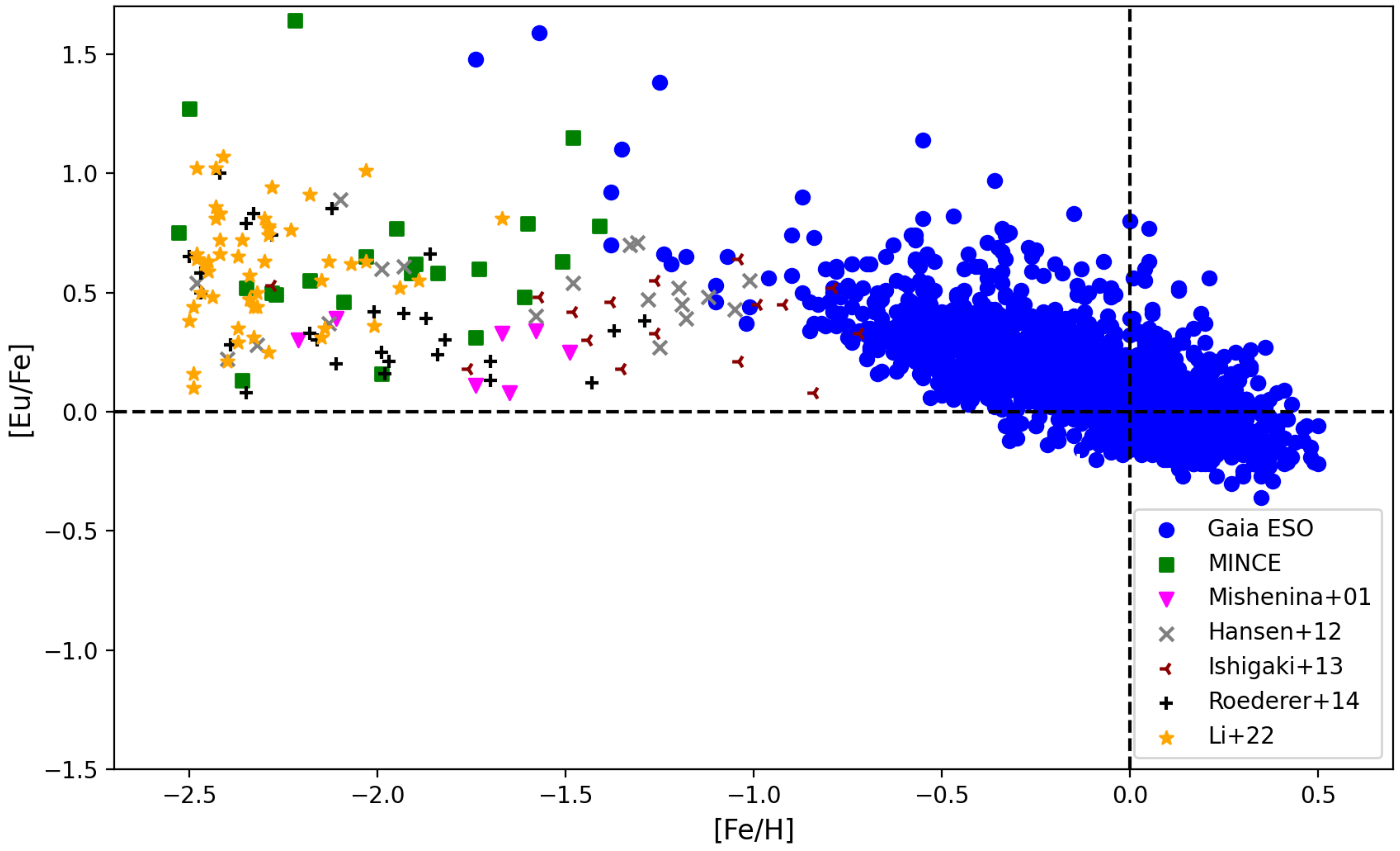
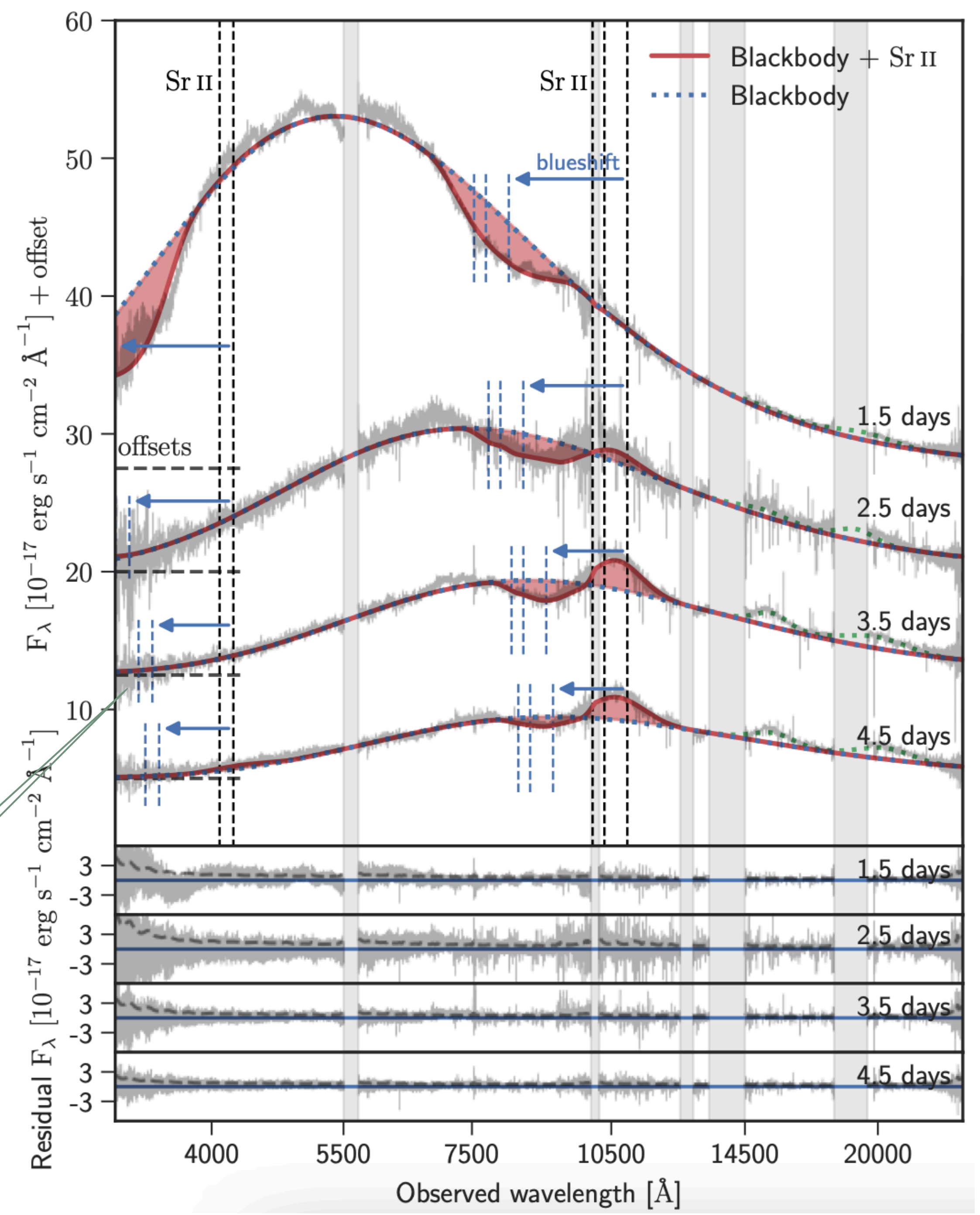


$$Y_{Sr} \propto 10^{-5}\ M_{\odot}$$
$$Y_{Eu} \propto 10^{-6}\ M_{\odot}$$



Watson et al. (2019)

Type Ia SNe

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+

Neutron star mergers

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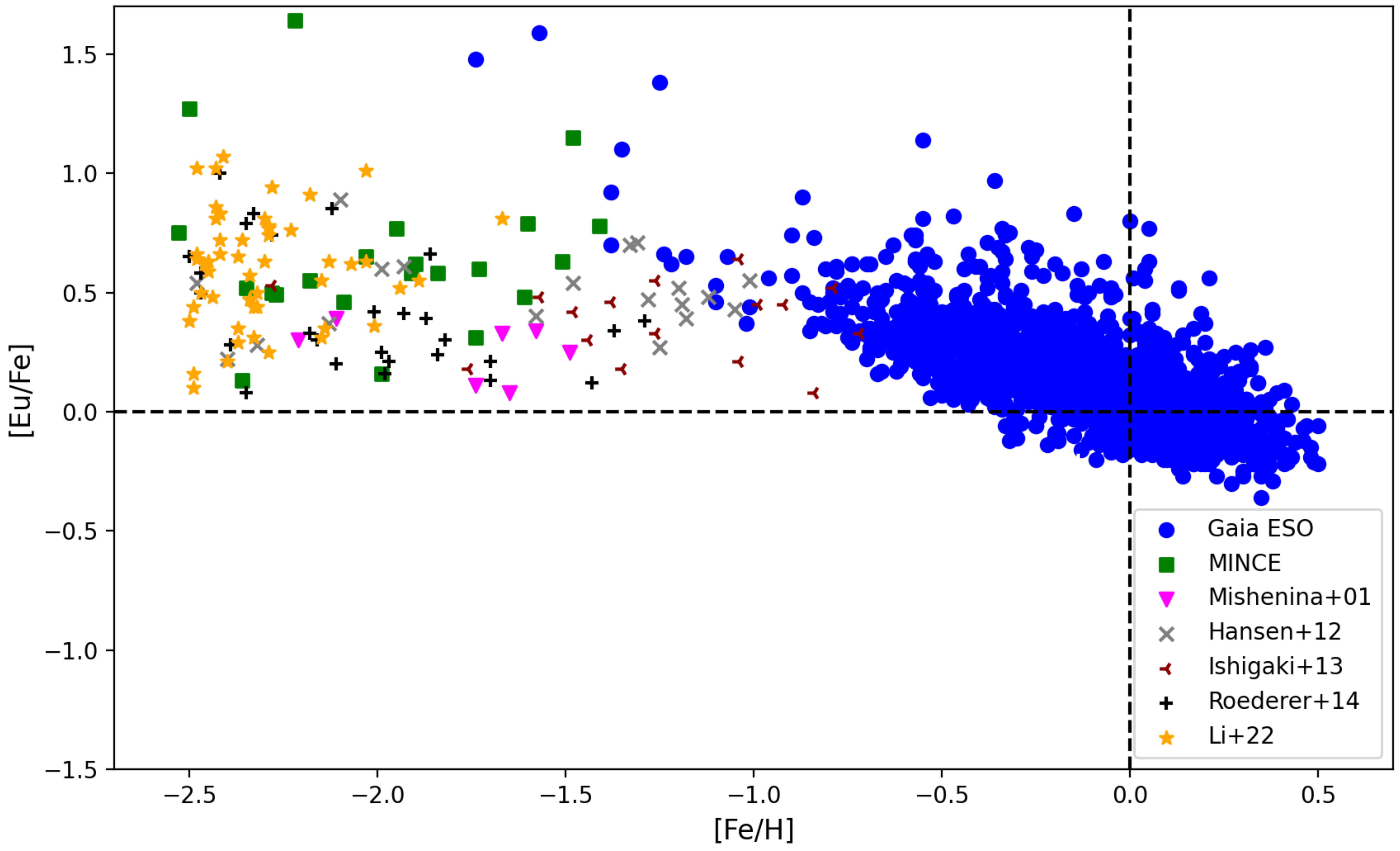

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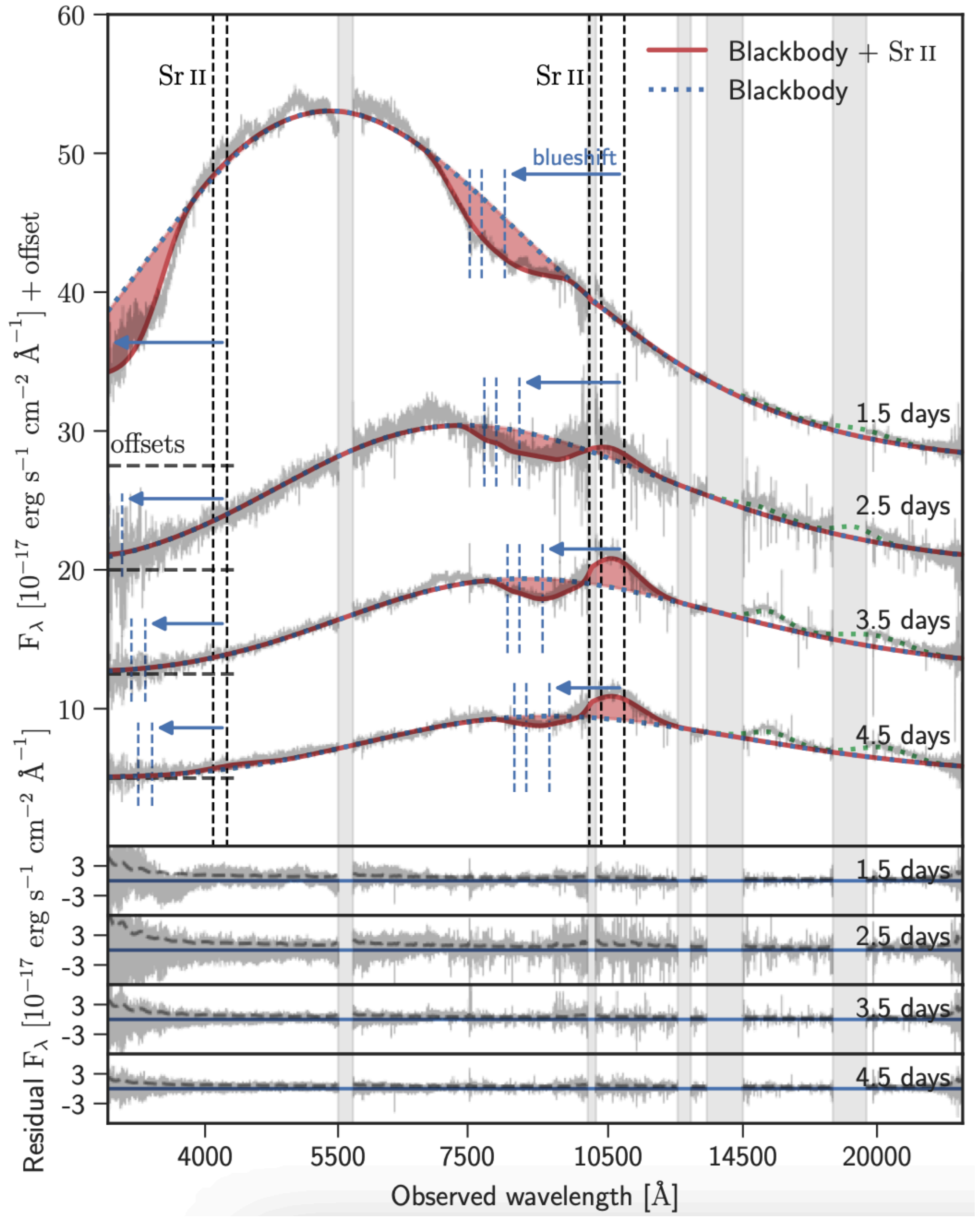

Watson et al. (2019)

lifetime of secondary component

Delay time for MNS: $\tau = \tau_s + \tau_{gw}$

gravitational radiation delay

$$\tau_{gw} = \tau_{gw}(m_1, m_2, A, e)$$

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The rate of neutron star mergers

More DTDs

Fong et al. (2017)
Chruslinska et al. (2018)
Cotè et al. (2019)
Greggio et al. (2021)

When? + How much? + How many?

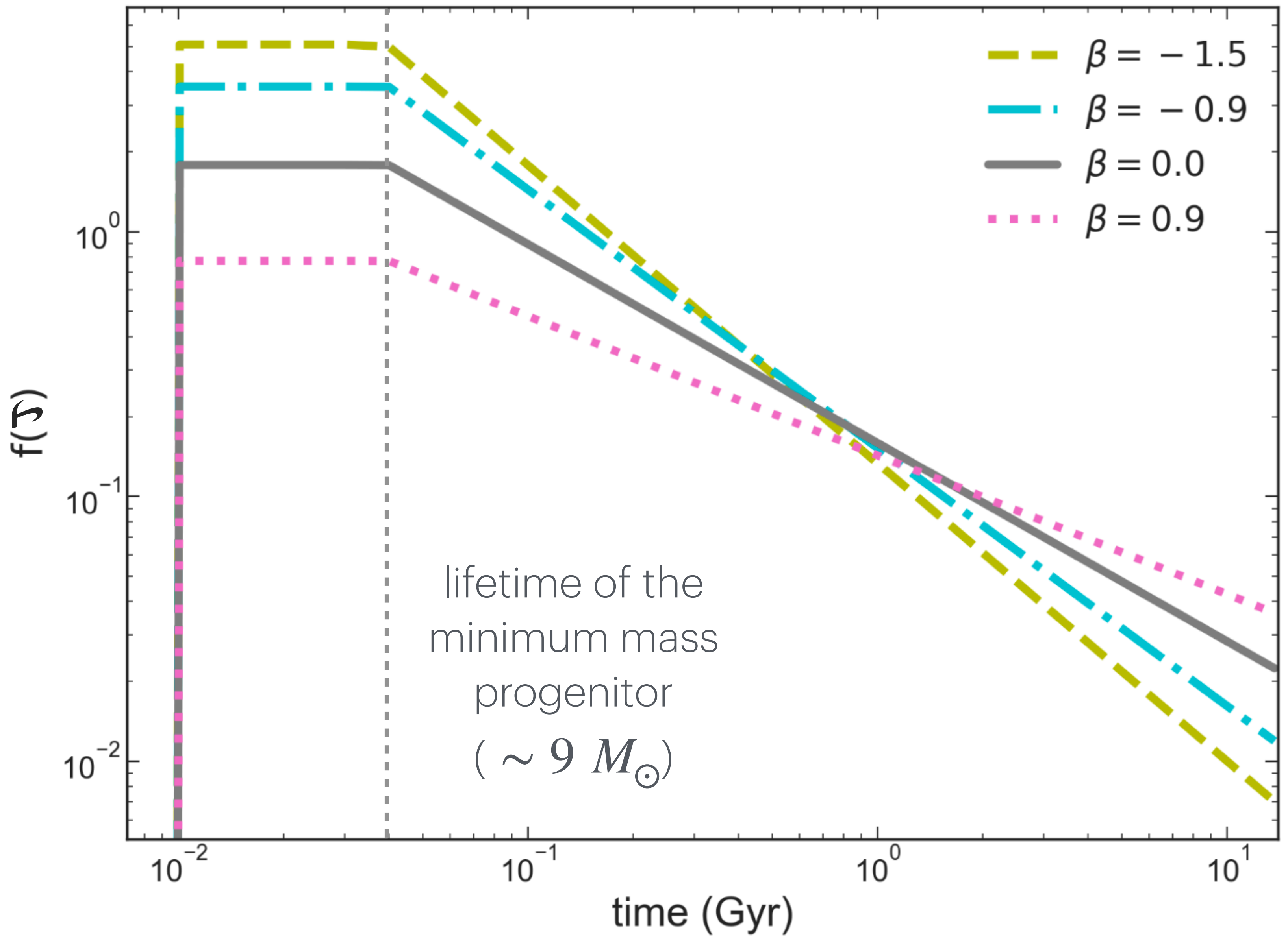
Star Formation

$$R_{MNS}(t) = k_\alpha \int_{\tau_i}^{min(t,\tau_x)} \alpha_{MNS}(\tau)\psi(t-\tau)f_{MNS}(\tau)\,\mathrm{d}\tau$$

Initial Mass Function

Delay Time Distribution

Simonetti et al. (2019)



Readapted from Molero et al. (2021)b

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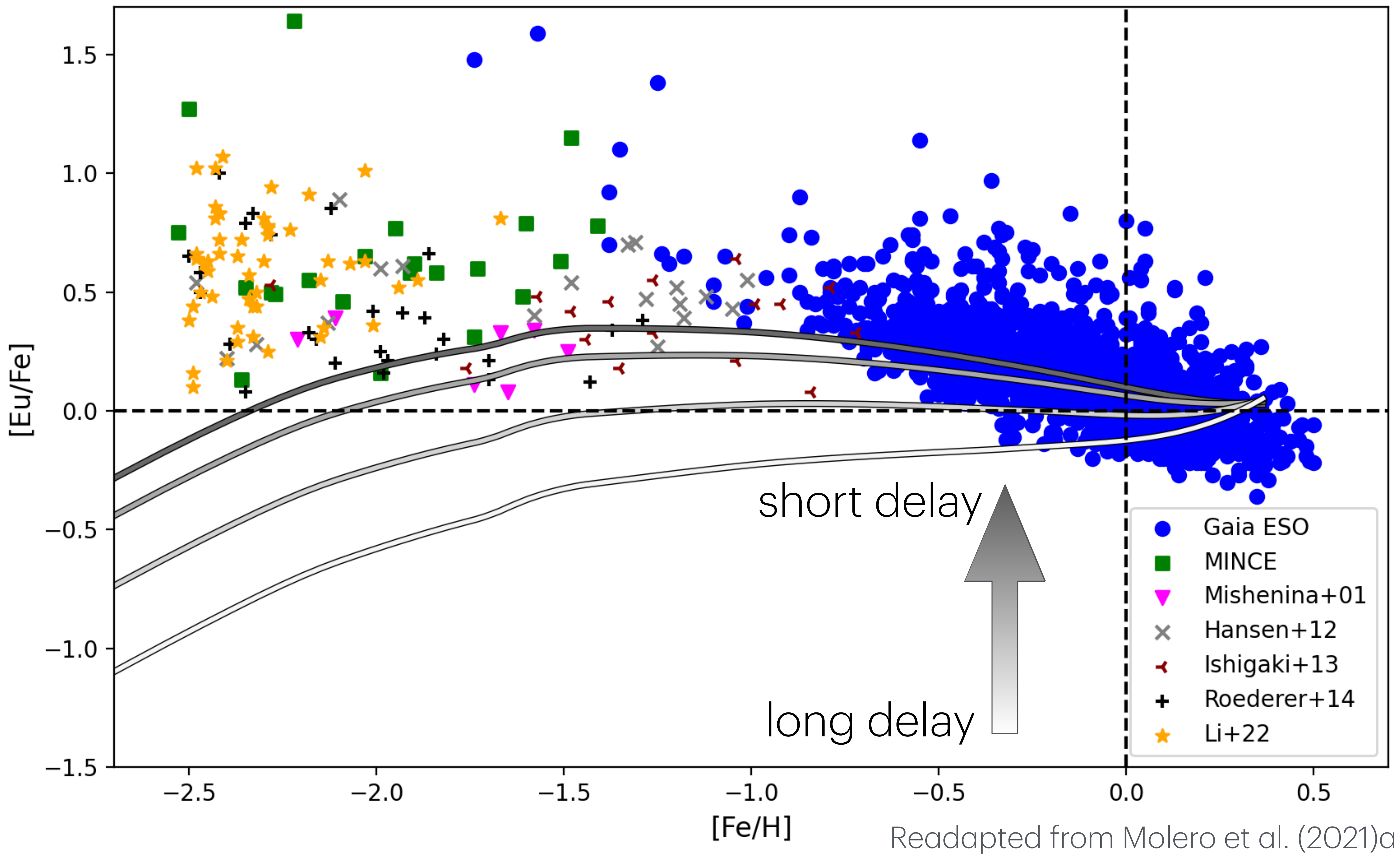

Readapted from Molero et al. (2021)a

Either NS all merge on short timescales or they cannot be the major producers of Eu

Argast+04, Matteucci+14, Cescutti+15, Wehmeyer+15, Cotè+19, Simonetti+19, Kobayashi+20, Cavallo+21, Molero+21a,b, Van der Swaelmen+23, ...

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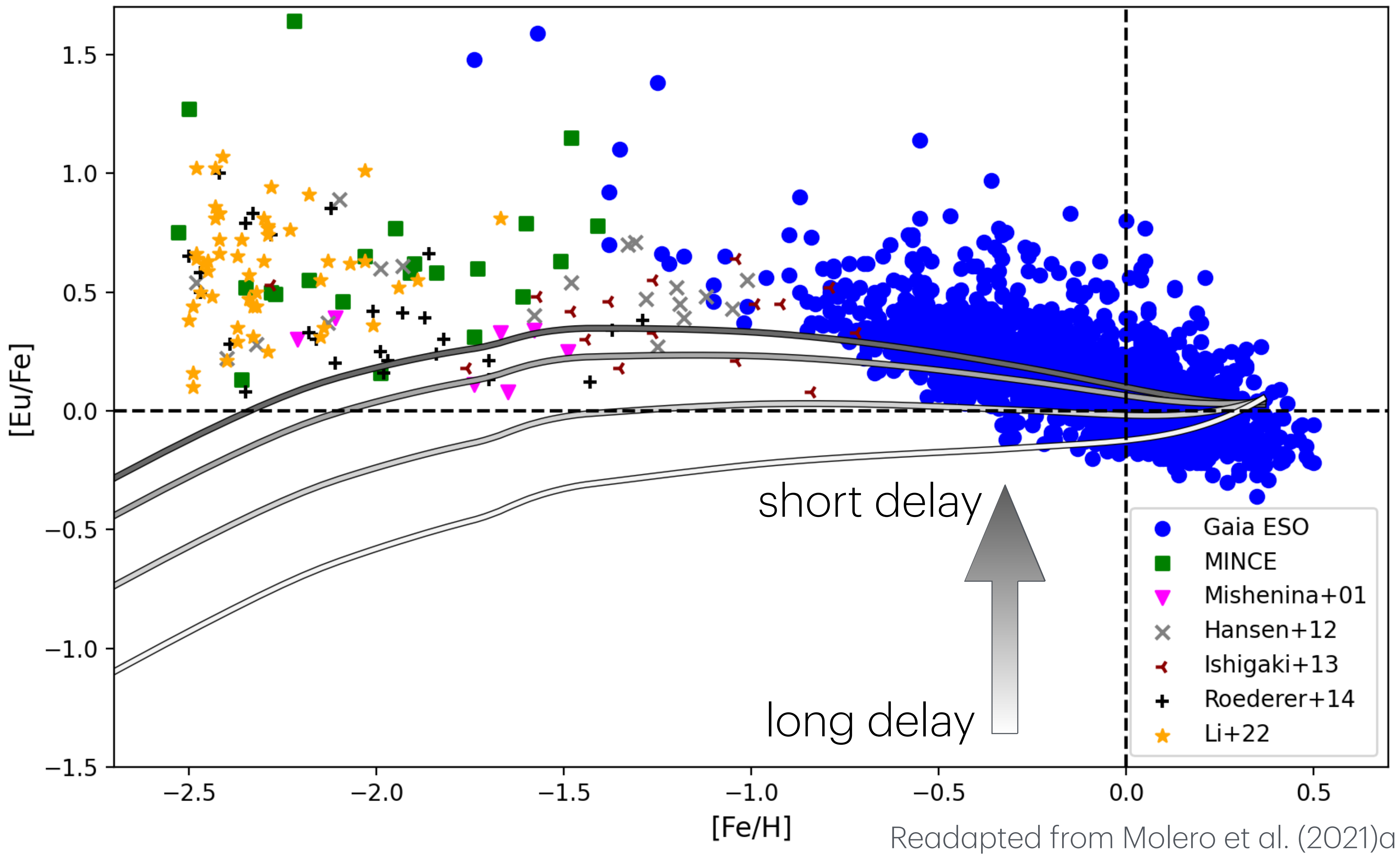

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Massive stars... MR-SNe, collapsars... something quick

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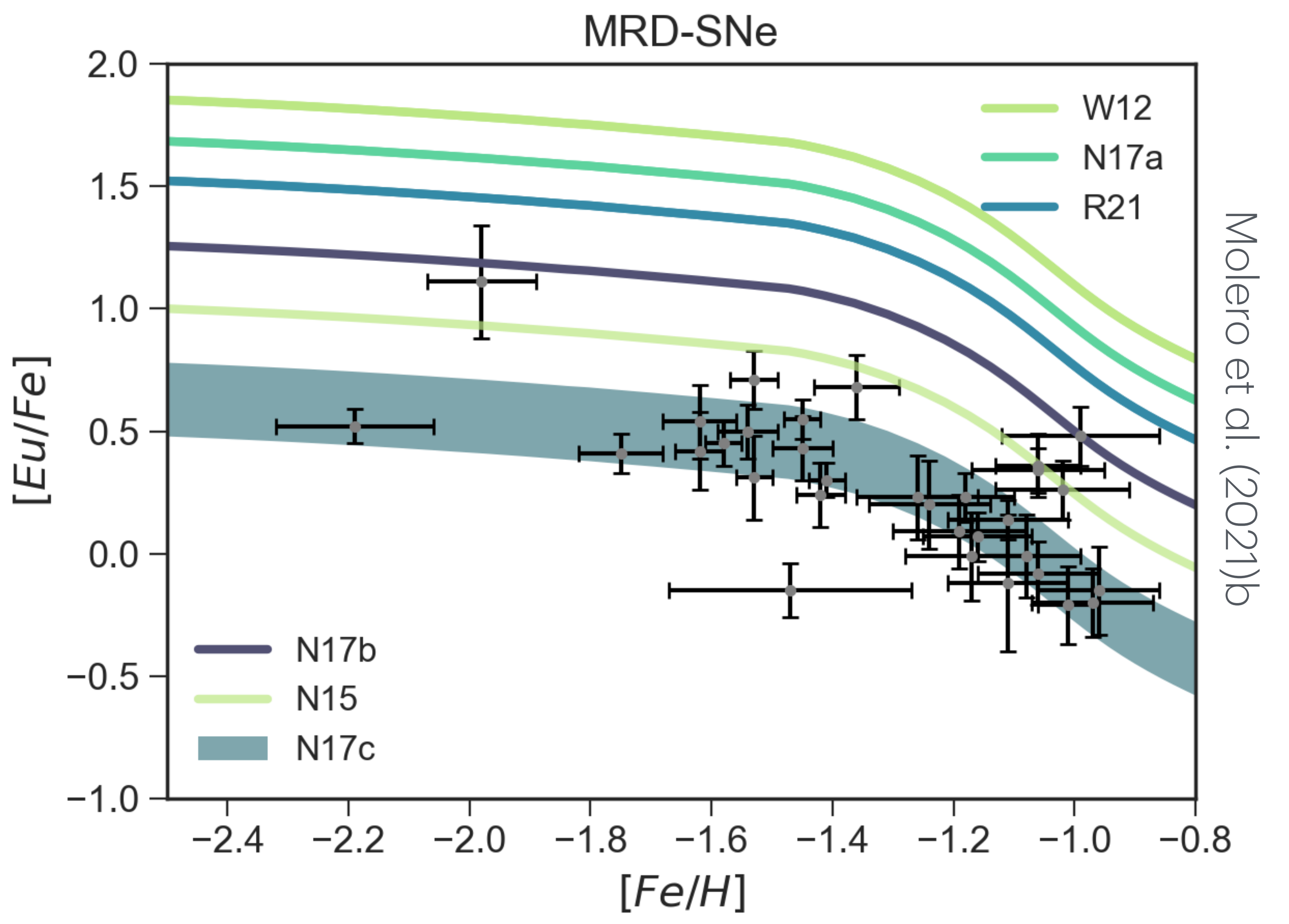
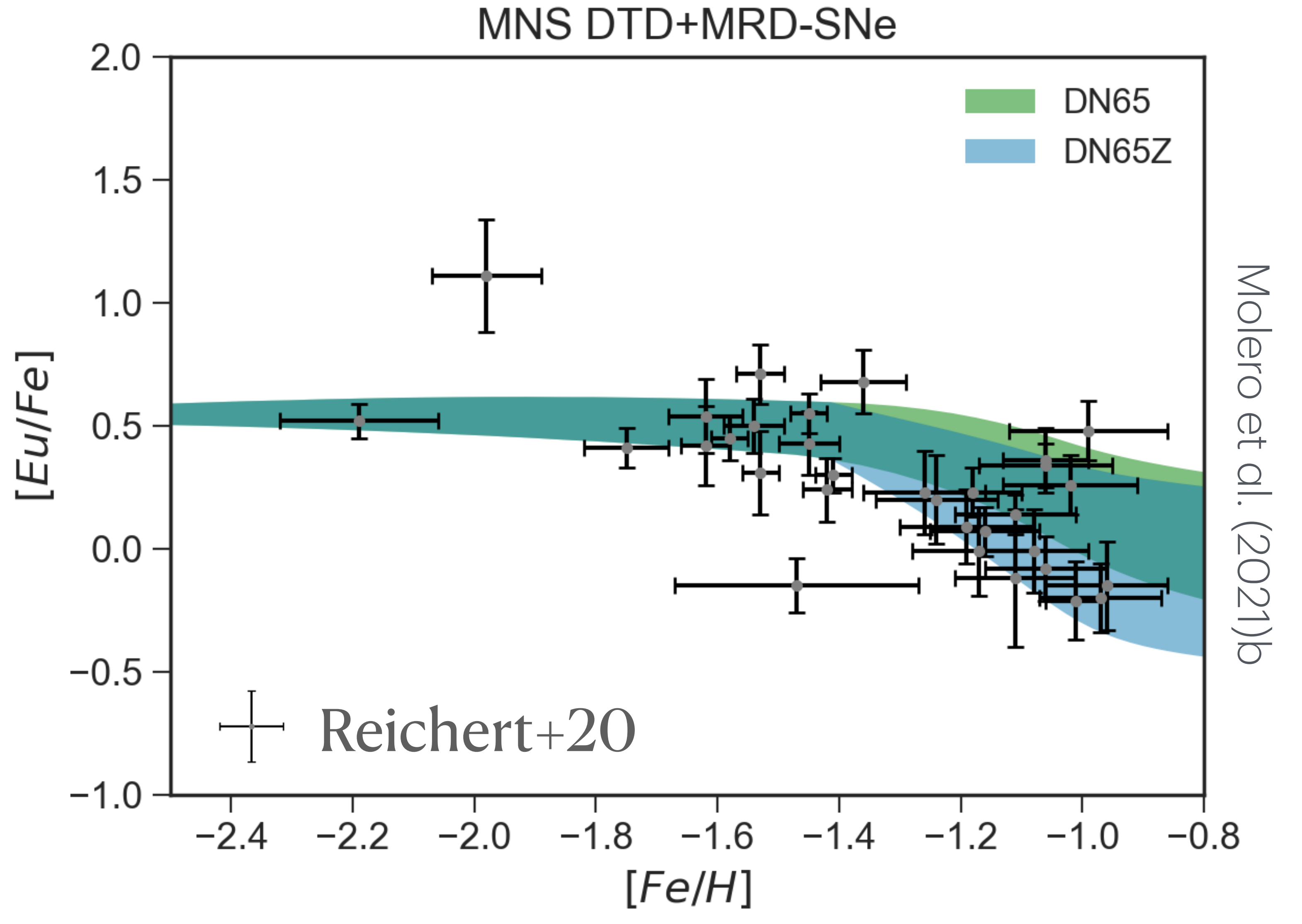
The [Eu/Fe] vs. [Fe/H] - Local Group galaxies

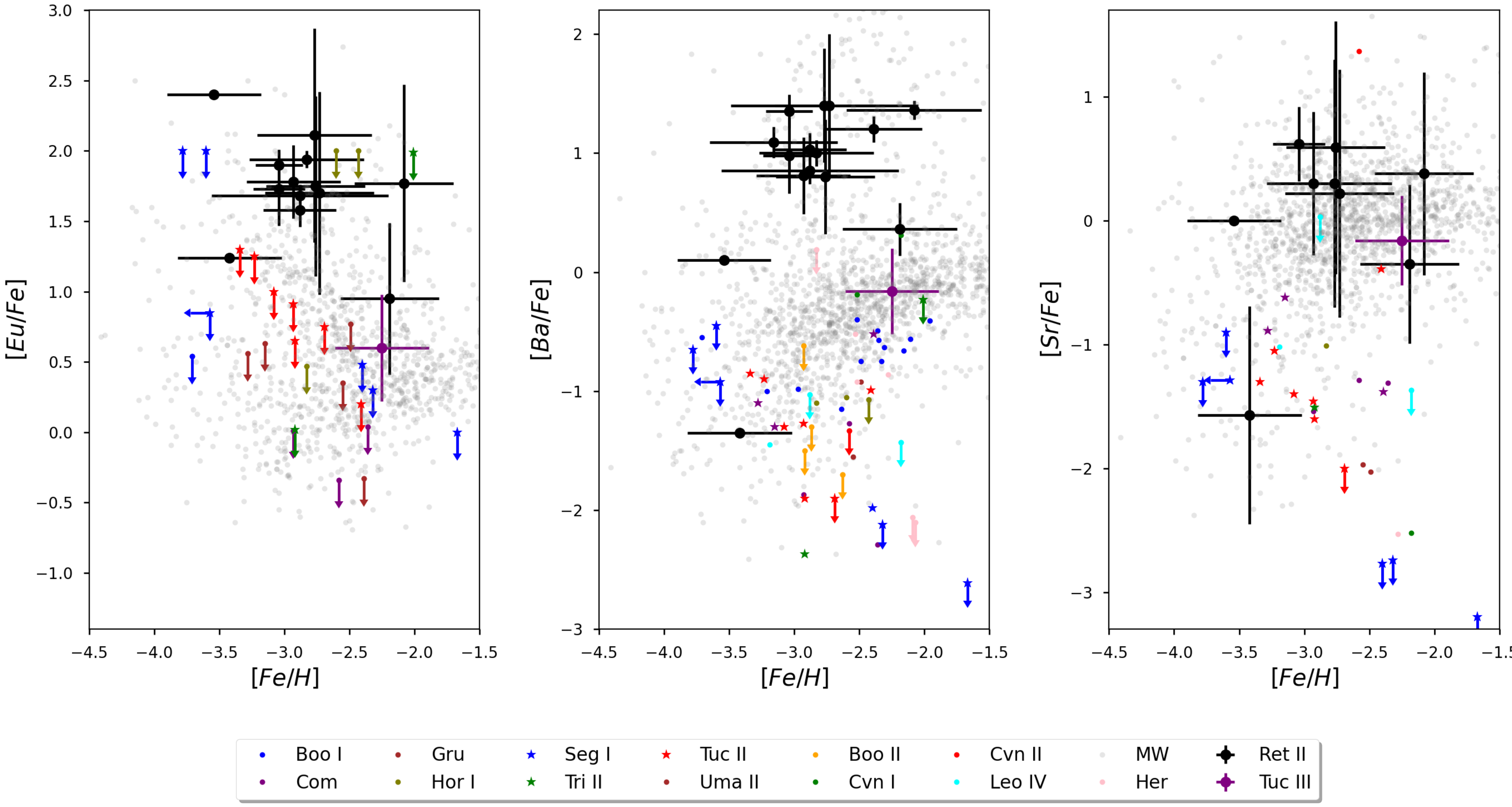


Molero et al. (2021)b



Molero et al. (2021)b

$Y_{Eu} \propto 10^{-6}\ M_\odot$



Readapted from Ji et al. (2016)

Data collection from SAGA database + Reichert et al. (2020)

Cescutti&Chiappini (2014) for MR-SNe in GCE

For more dwarf galaxies model of nc-elements: Lanfranchi et al. (2008), Hirai et al. (2015), Vincenzo et al. (2015), Palla, Molero, et al. (2025)

see also Skúladóttir & Salvadori (2020)

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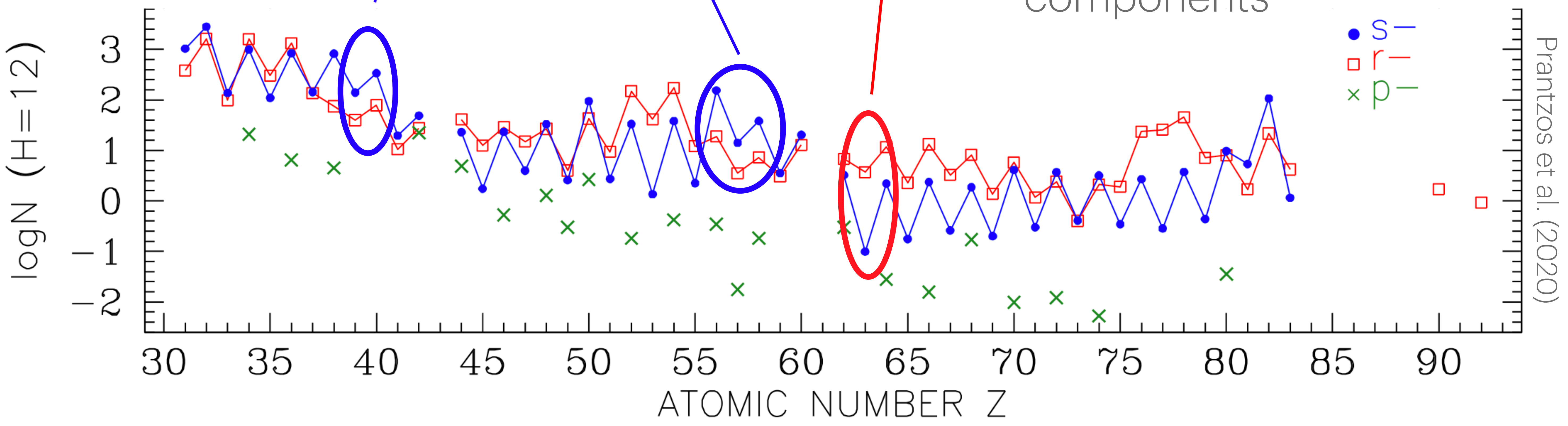
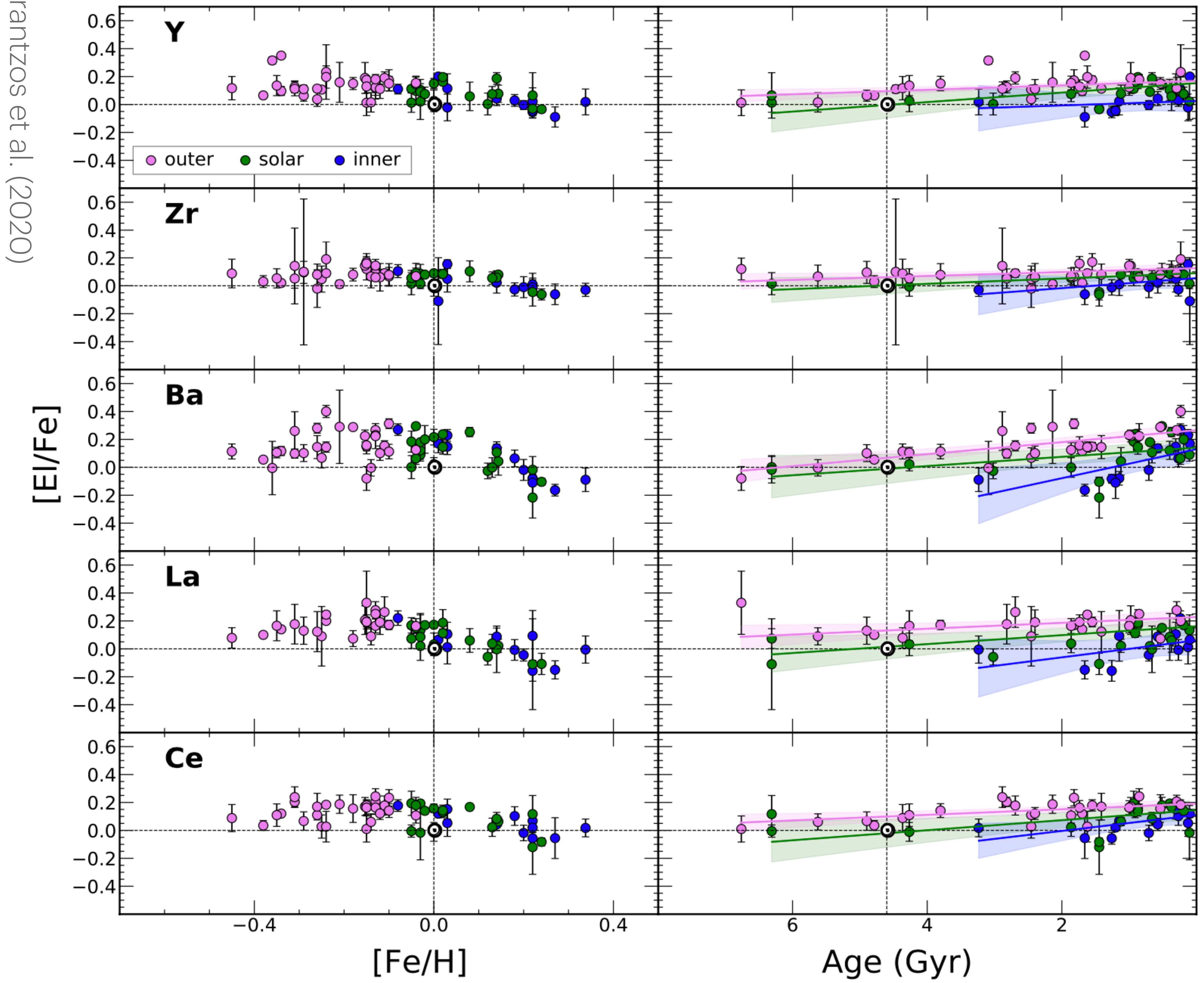
Homogeneous model for the disk

- NC elements: Y, Zr, Mo, Ba, La, Ce, Pr, Nd, Eu

Solar s-, r- and p-components



Viscasillas Vàzquez et al. (2022)



- Gaia-ESO survey data from the 6th data release:
  1. field stars (3975)
  2. Open clusters (OCs, 62)

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Abundance patterns

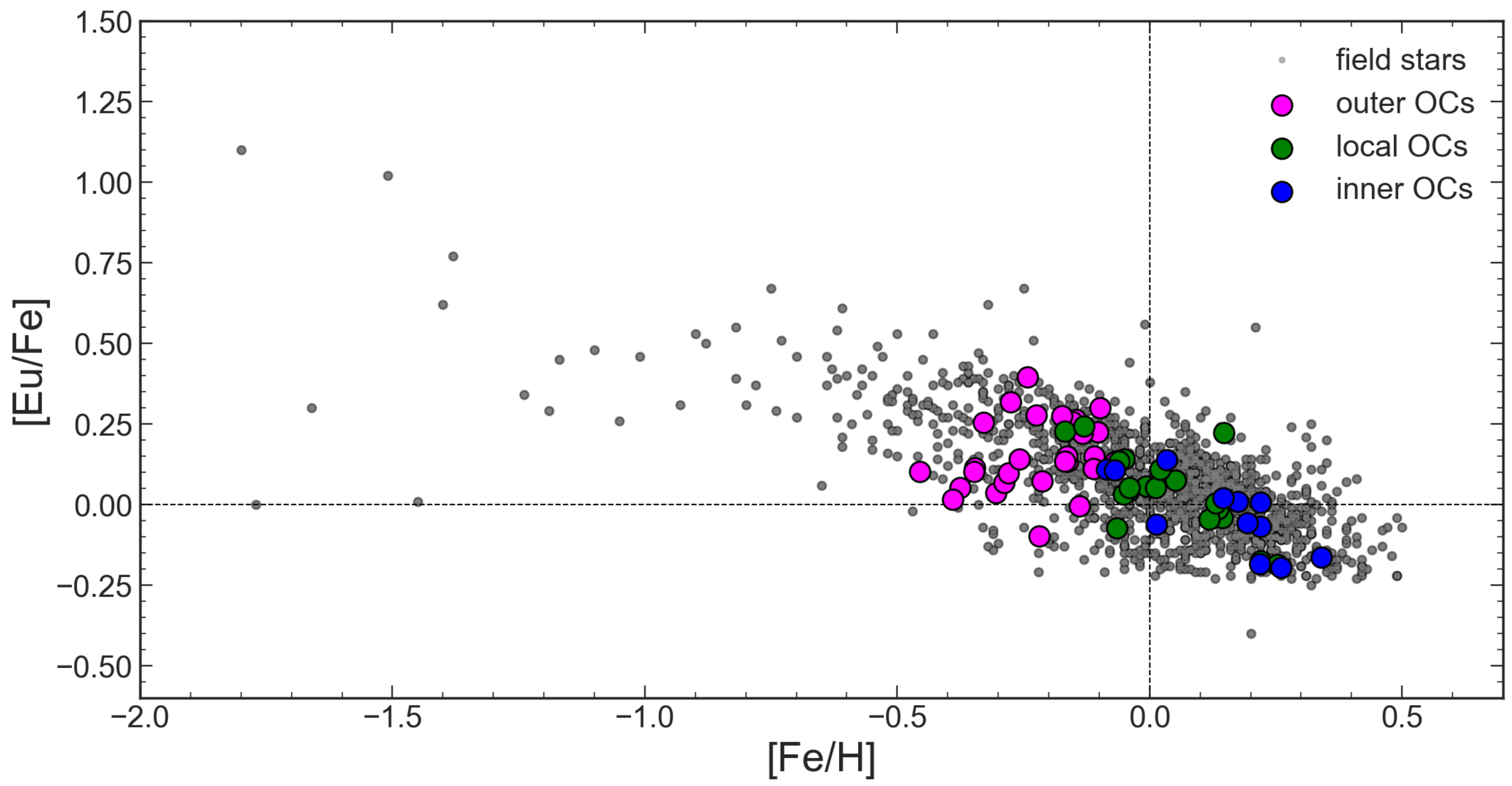
R-process

QUICK

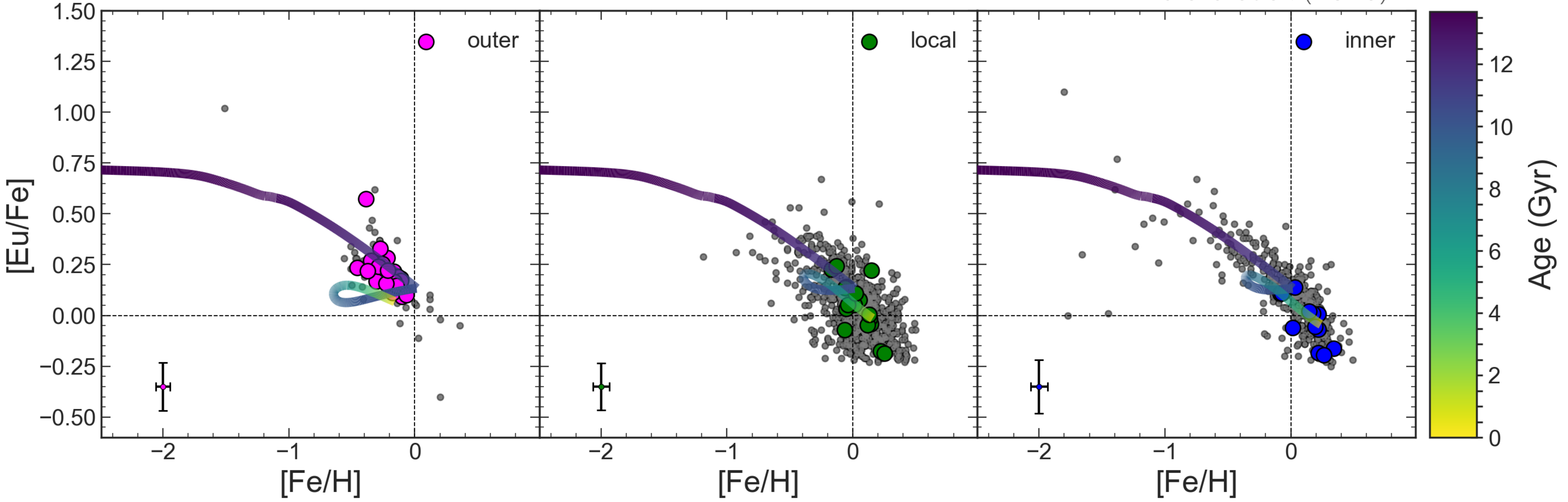
- MR-SNe : i) with yield from Nishimura et al. (2017)
  ii) low fraction of normal CC-SNe

DELAYED

- NSM : i) yield $Y_{Eu} \propto 10^{-6}\ M_{\odot}$
  ii) rate from LIGO/Virgo



Molero et al. (2023)



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Abundance patterns

S-process

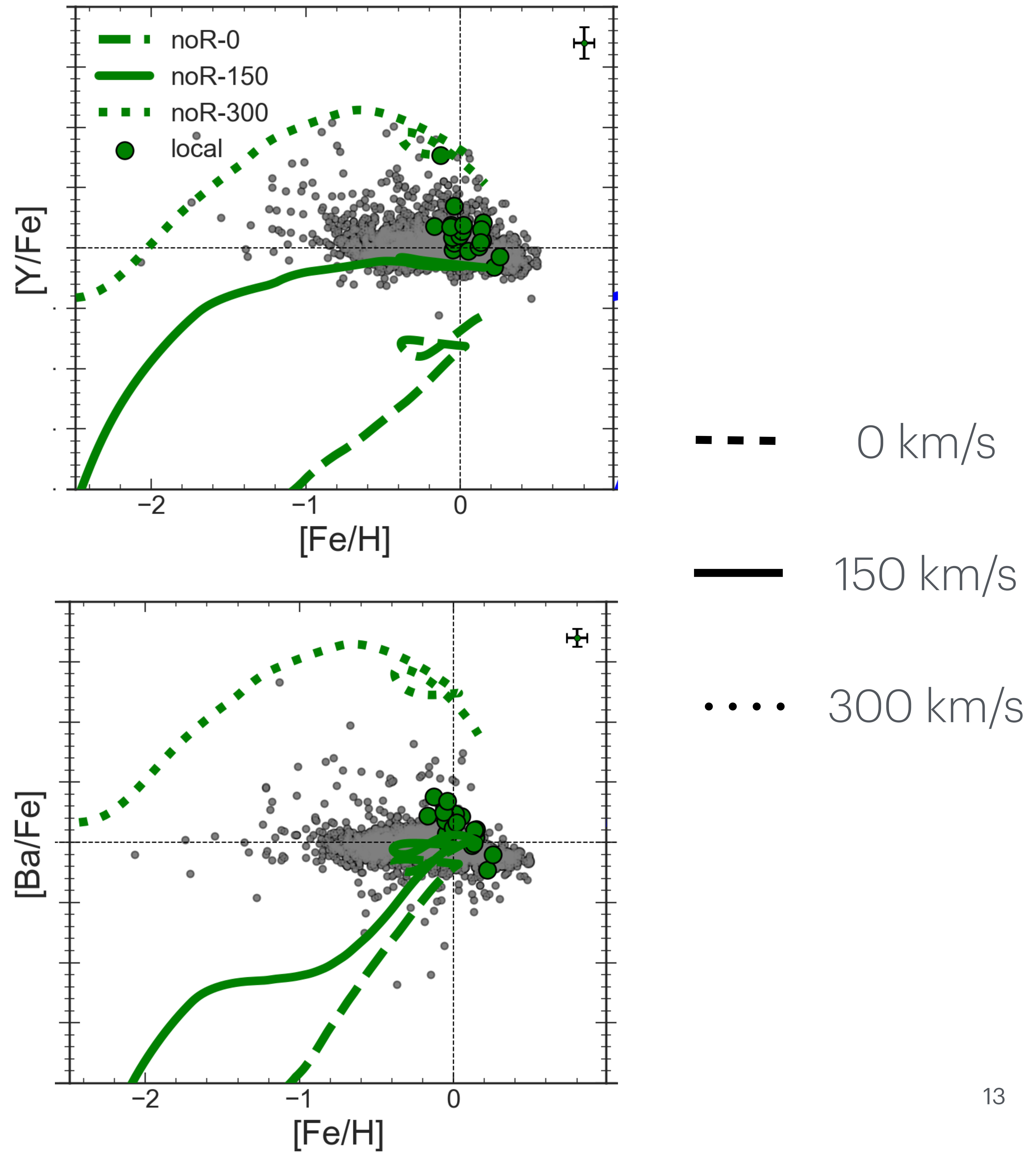
QUICK

- Rotating massive stars : i) 36 progenitors (x3) yield grid (Limongi&Chieffi 2018)
  ii) rate fine-tuned with observations

DELAYED

- AGB stars : i) large (108 progenitors) yield grid from FRUITY

Molero et al. (2023)



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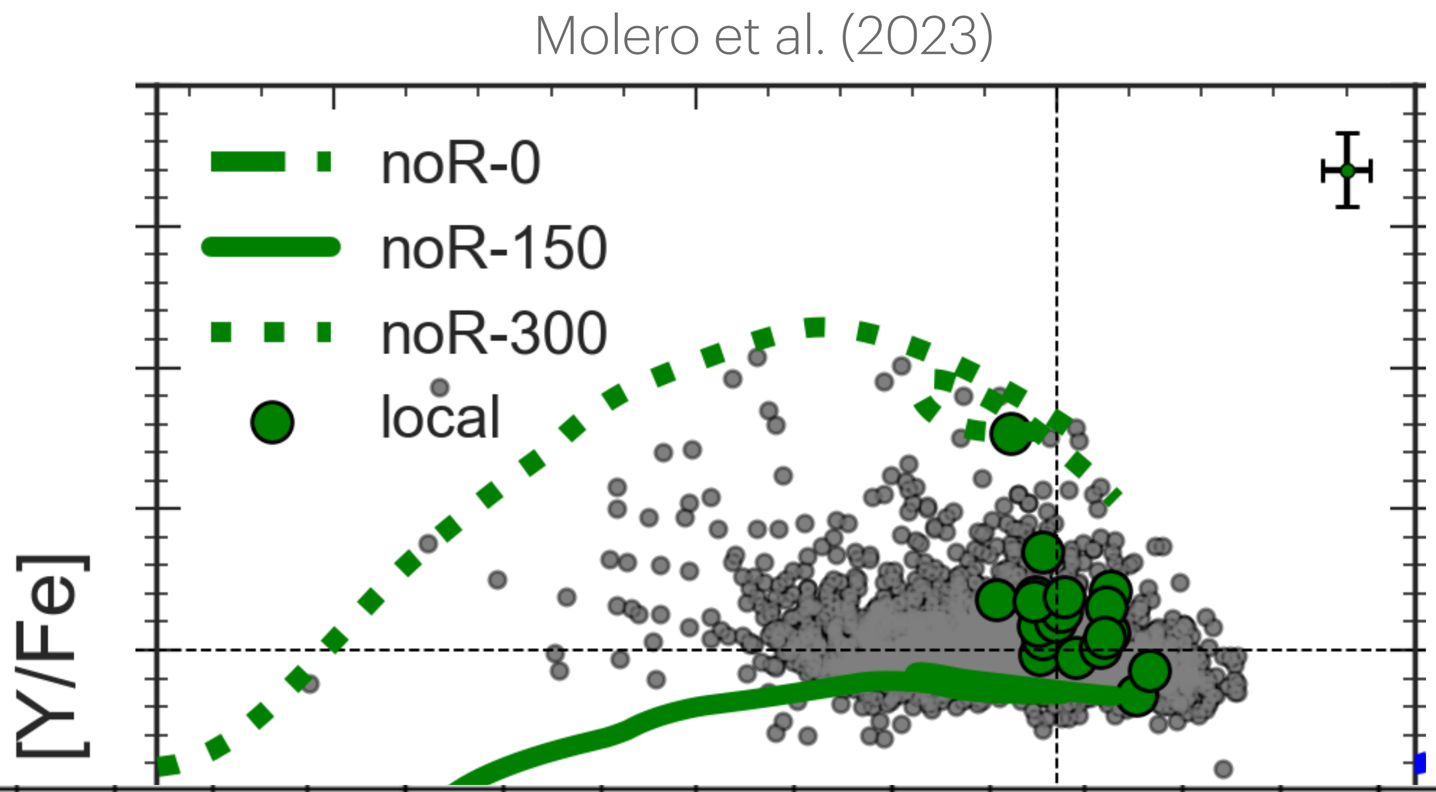
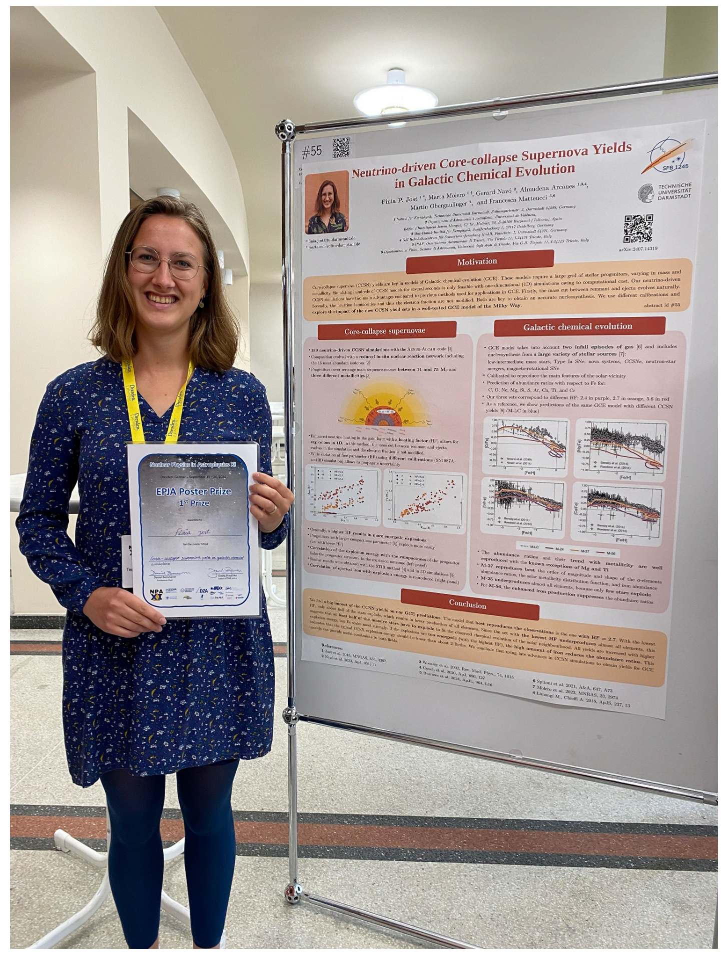
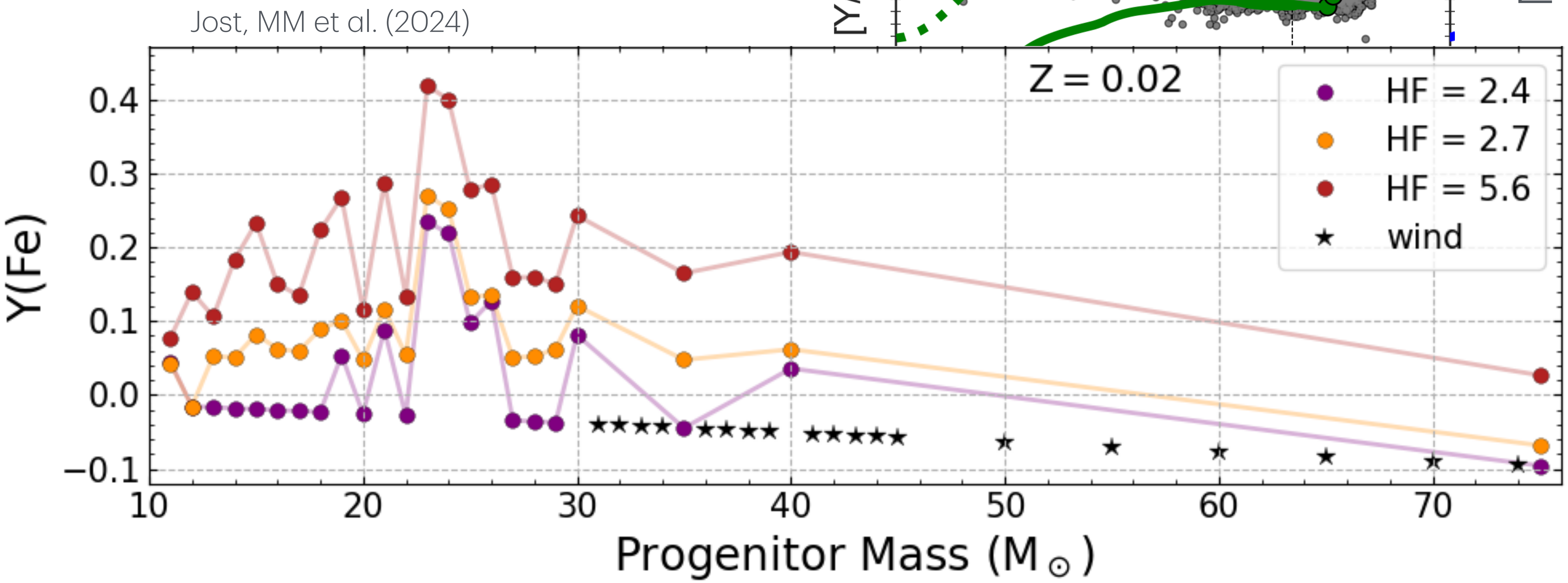
Abundance patterns



NPA 2024



S-process



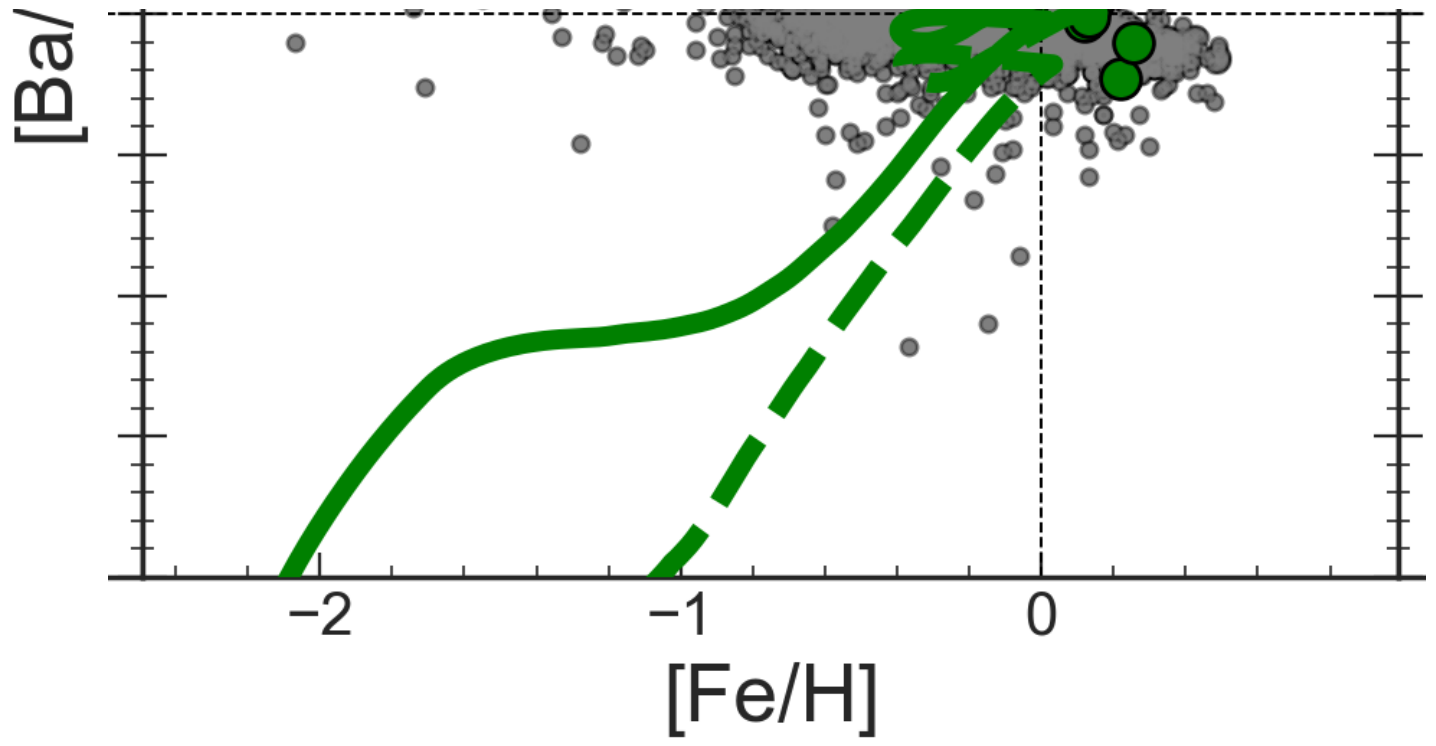
0 km/s

150 km/s

300 km/s

- Rotating massive st

- AGB stars : i) large



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Abundance patterns

S-process nucleosynthesis

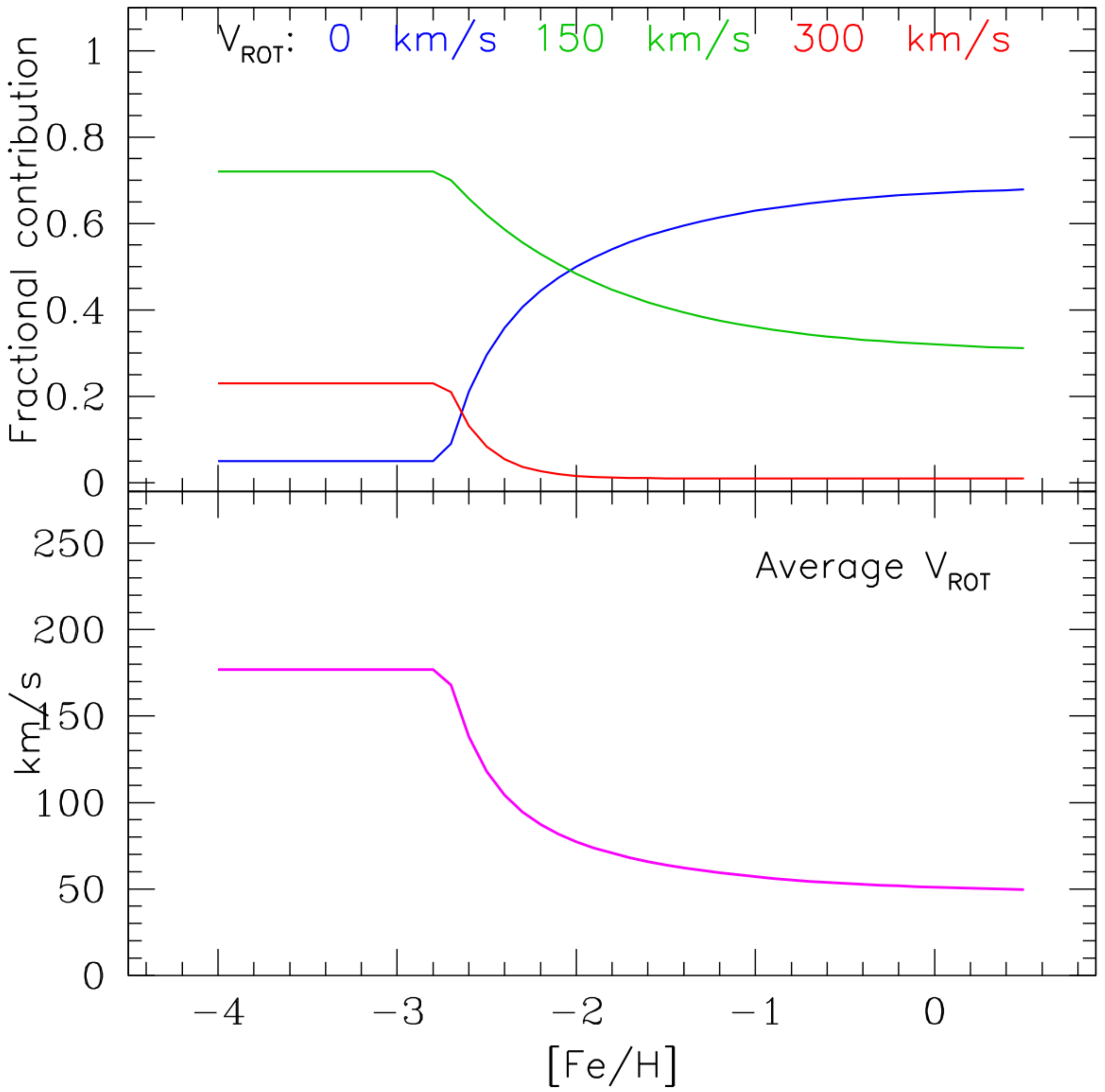
MDF of the bulge

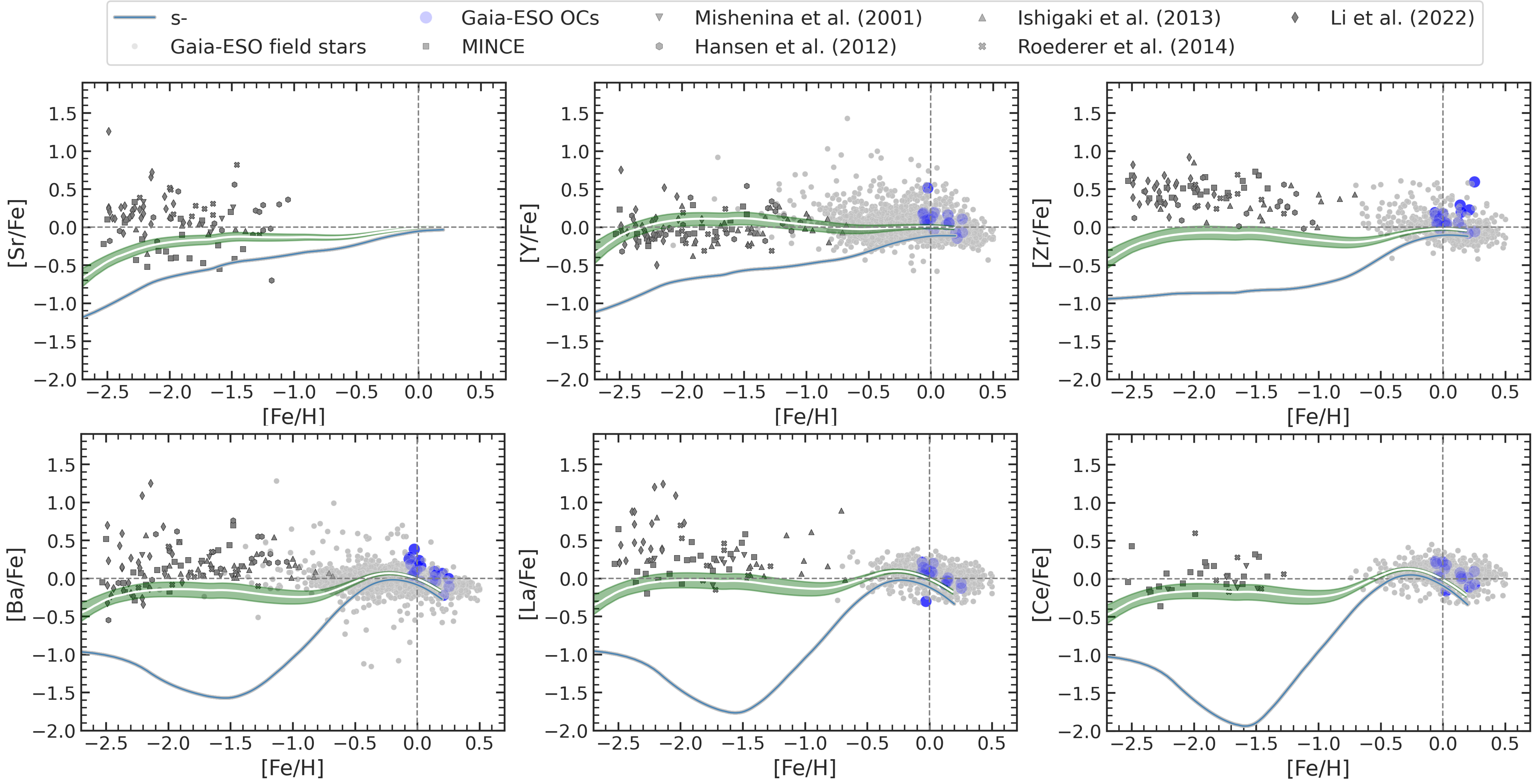
Rizzuti et al. (2021), Romano et al. (2019), Molero et al. (2024,2025)

CNO isotopes

Chemical clocks

Prantzos et al. (2018)





S- + r-

S-

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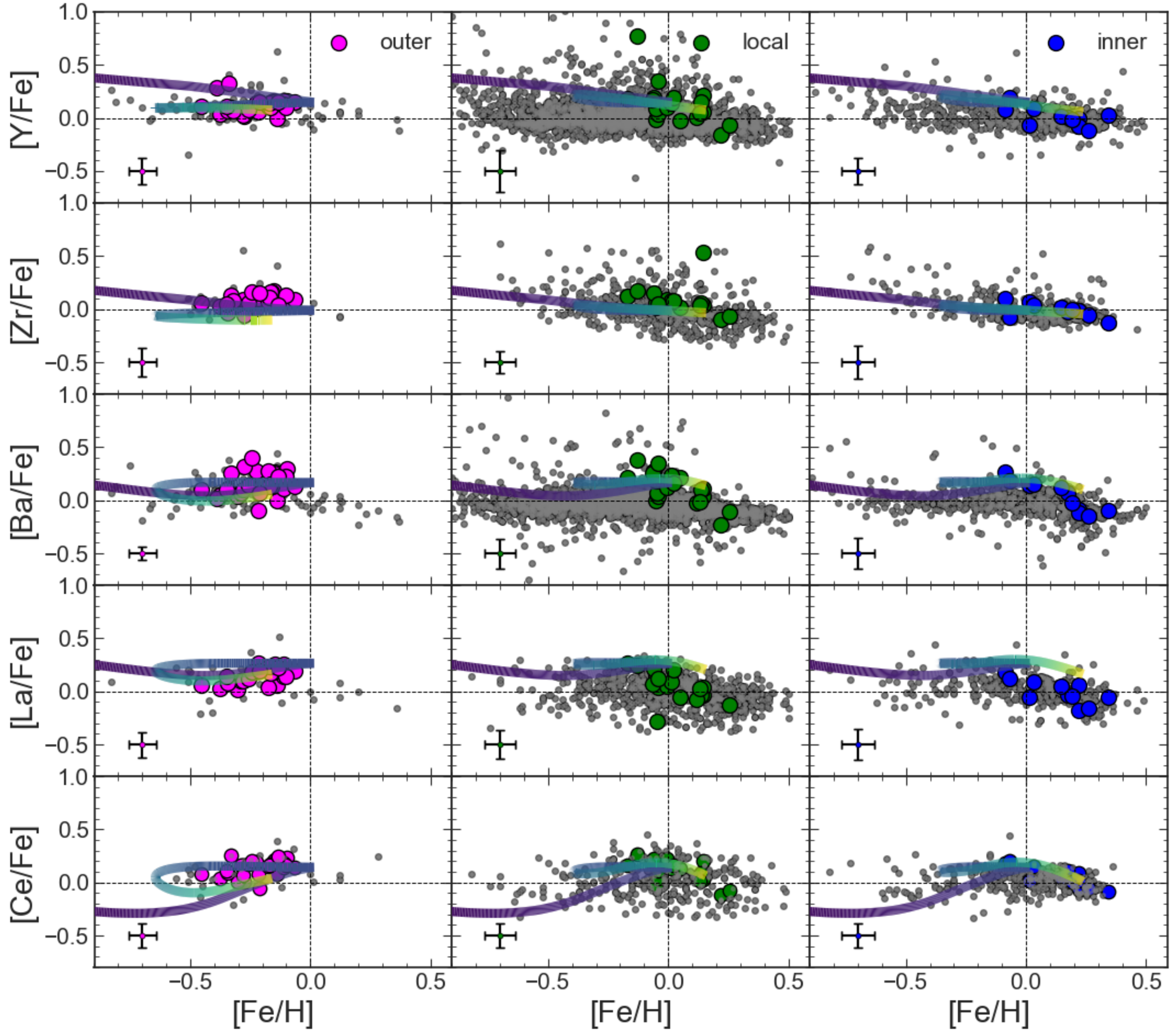
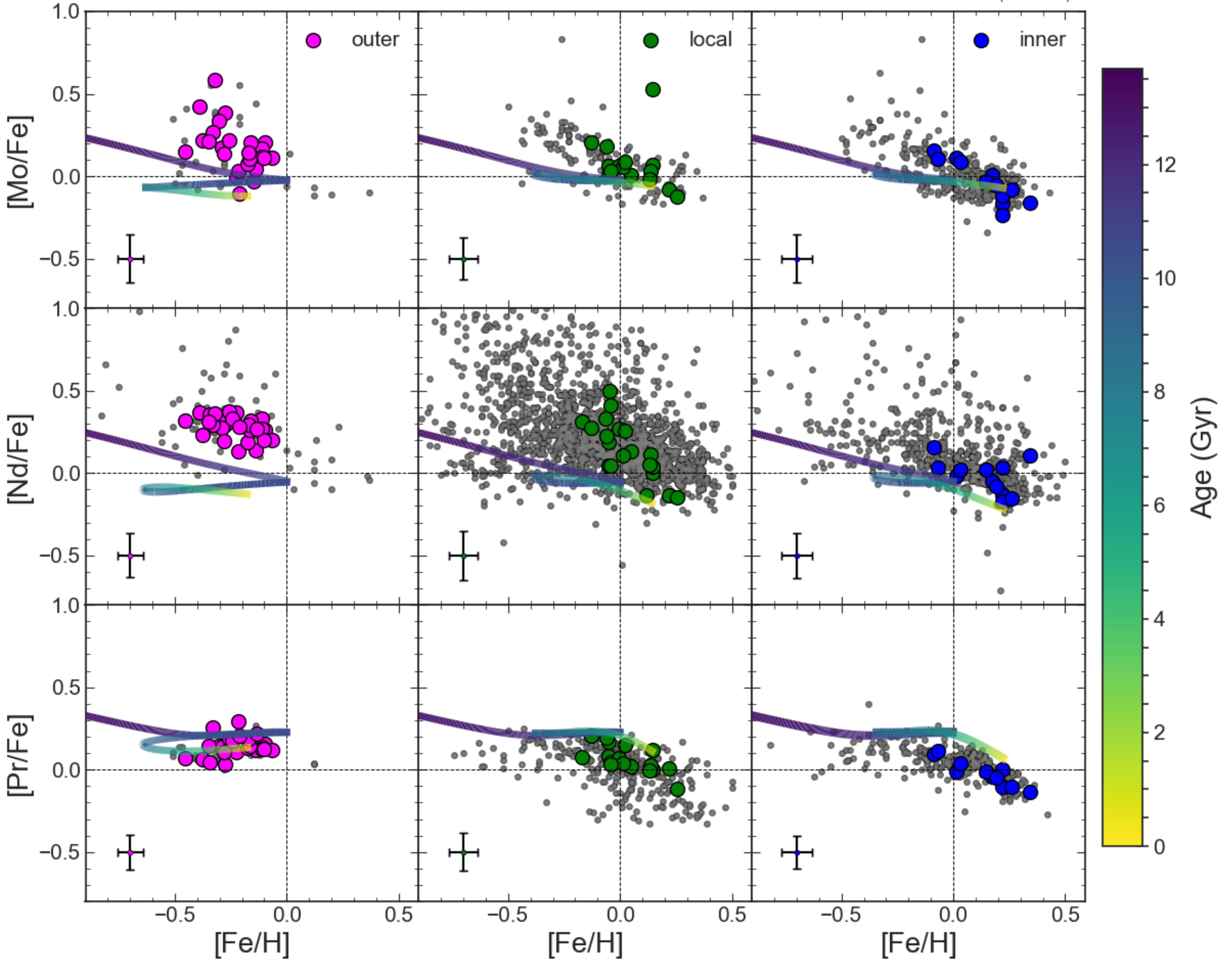
Abundance patterns



Molero et al. (2023)



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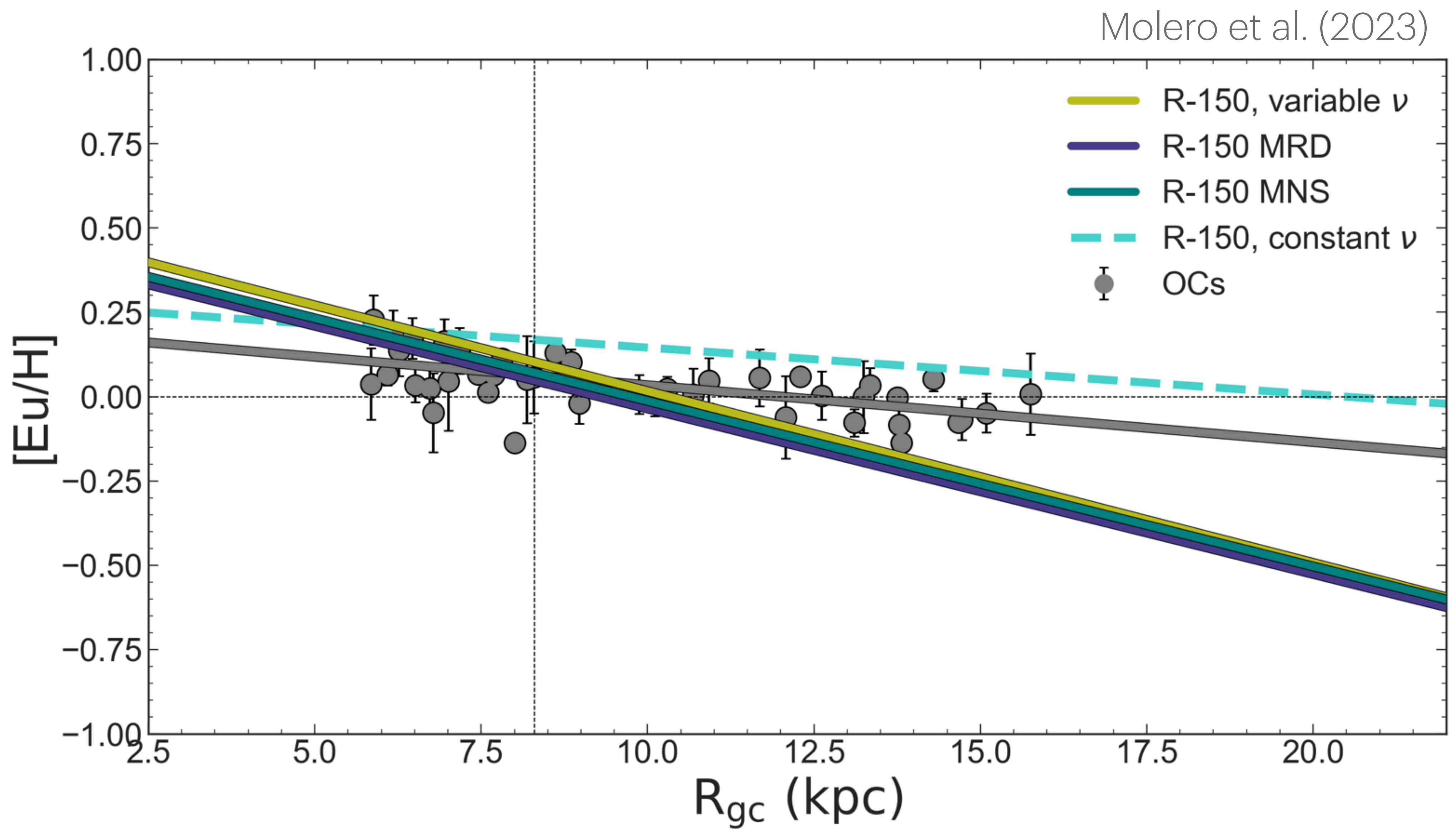
Abundance gradients



Observed: $[Eu/H] = -0.019(\pm 0.003) \times R_{GC} + 0.245(\pm 0.030)$

Model: $-0.050(\pm 0.003)$ dex kpc^{-1}

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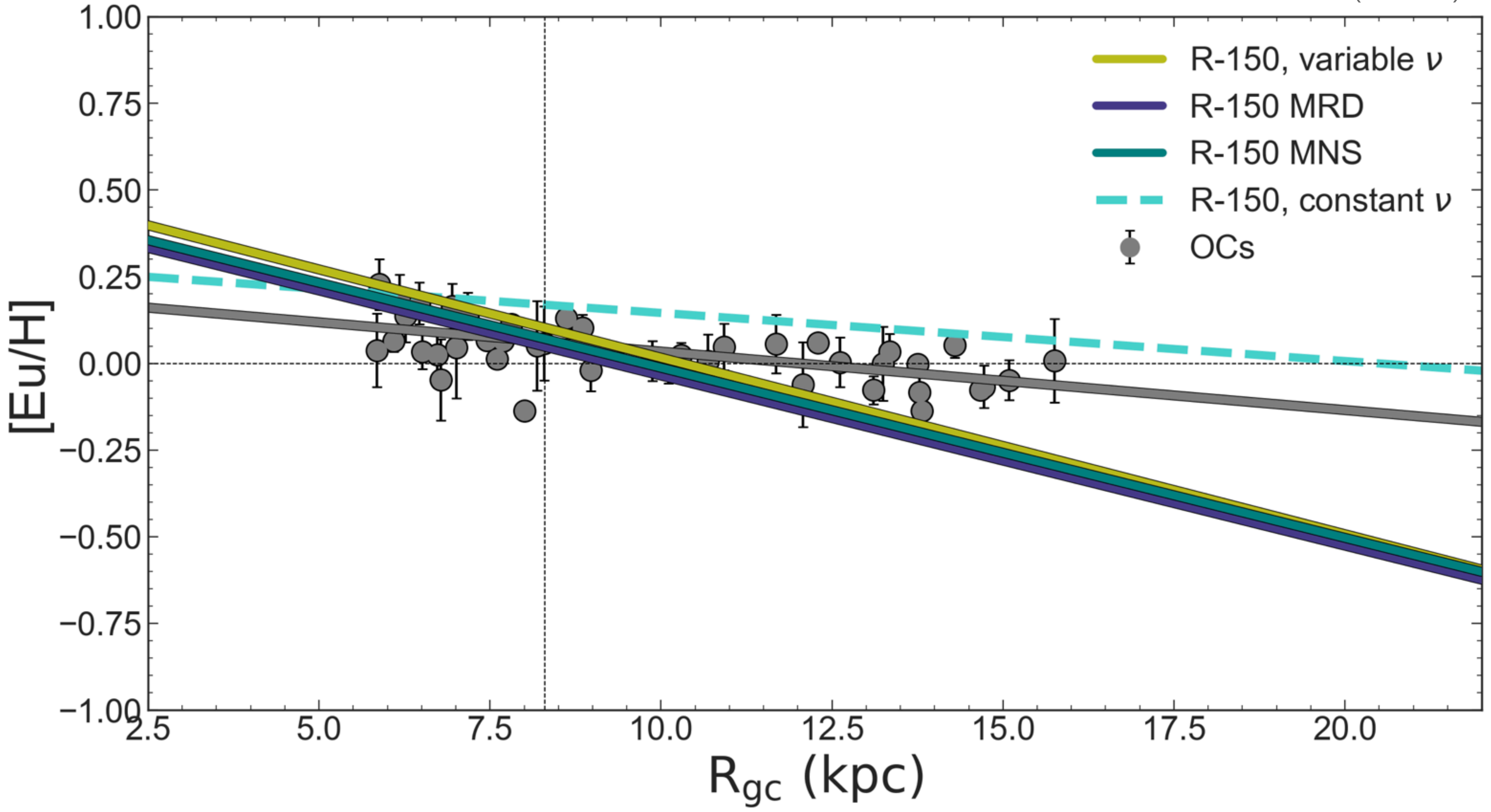
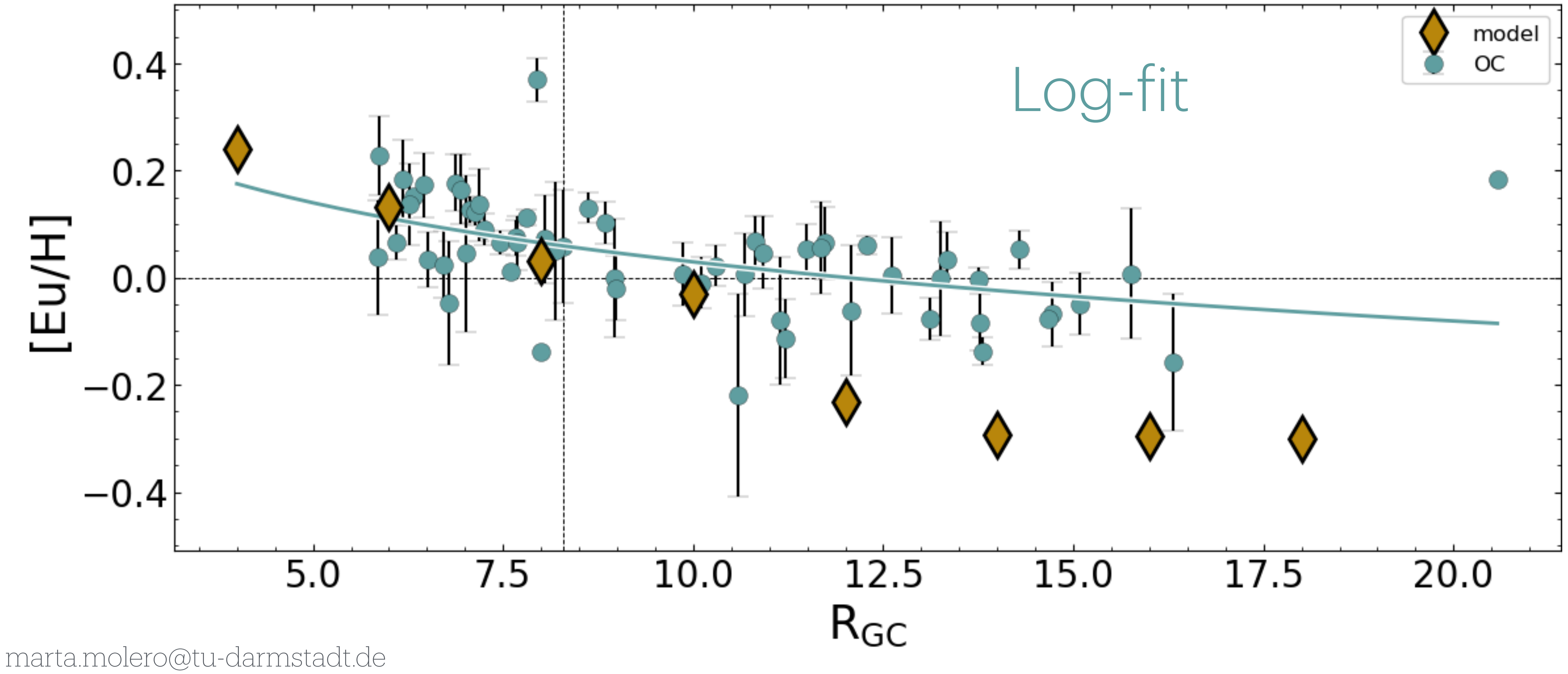
Abundance gradients

Molero et al. (2023)





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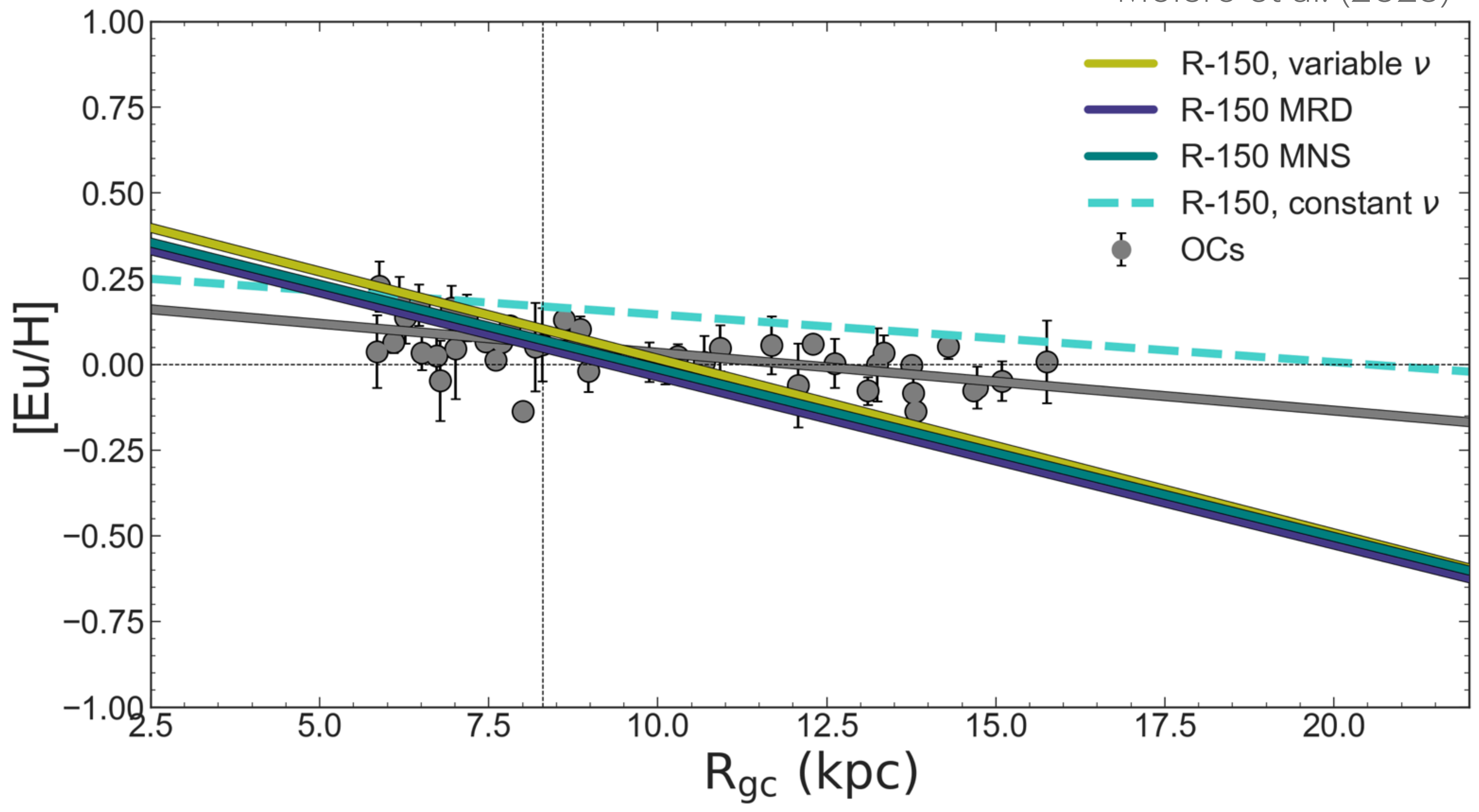

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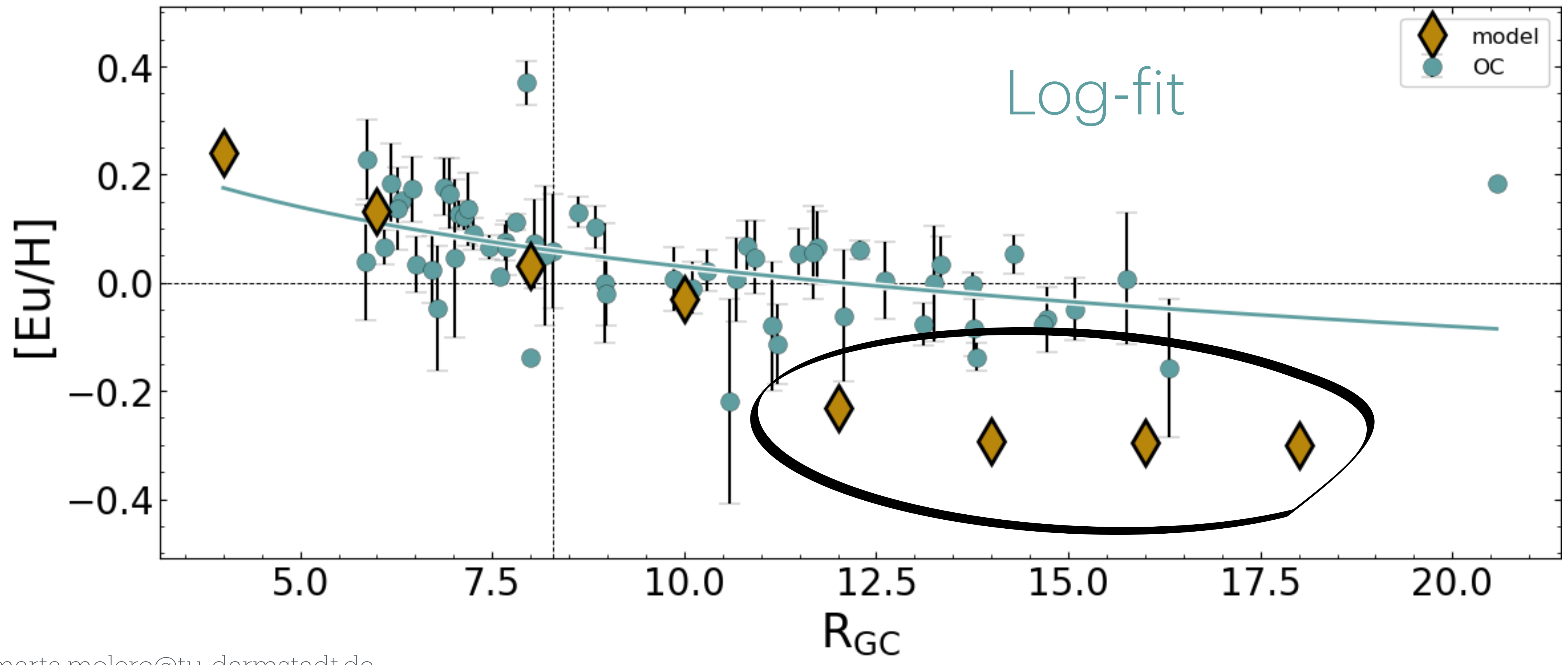

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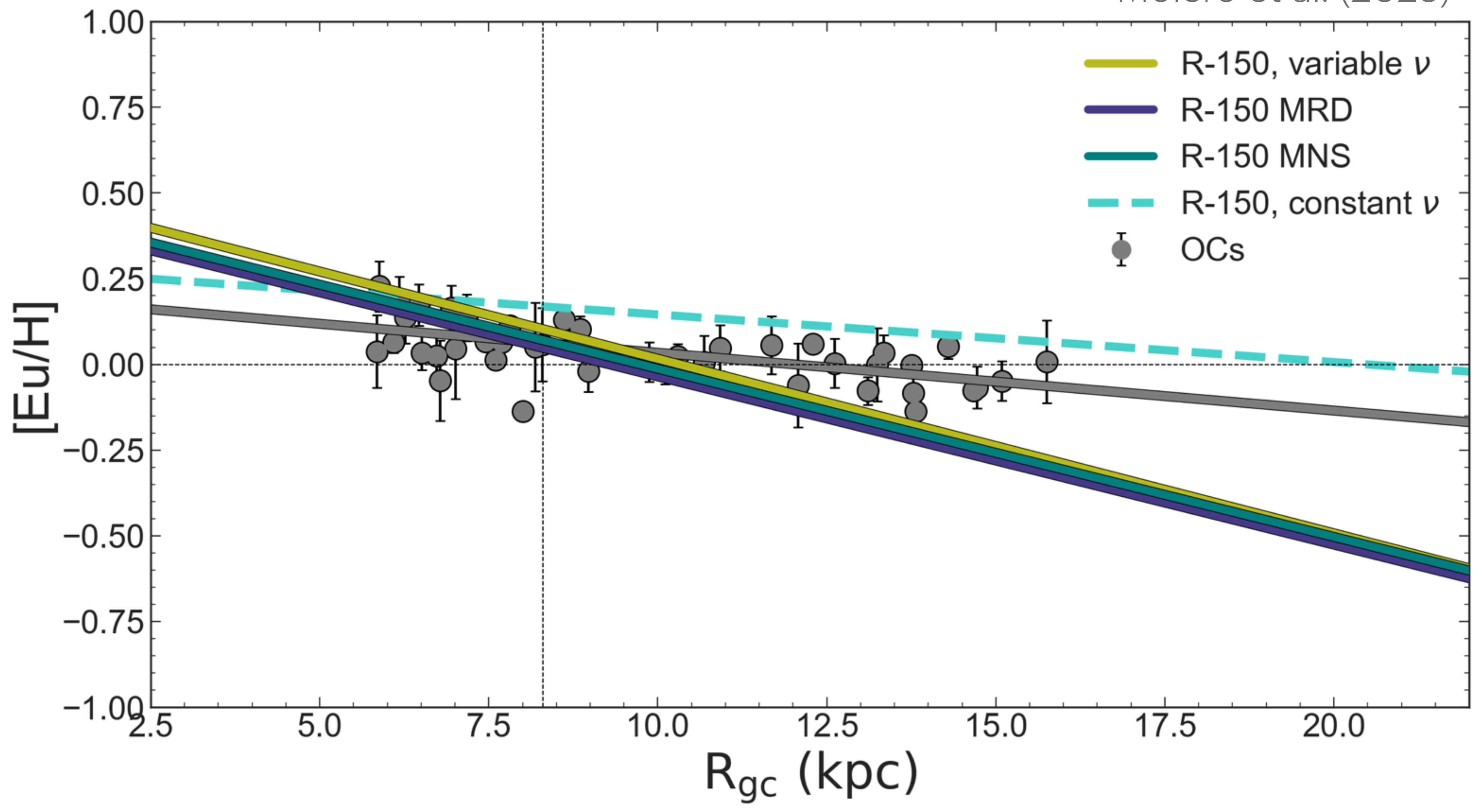

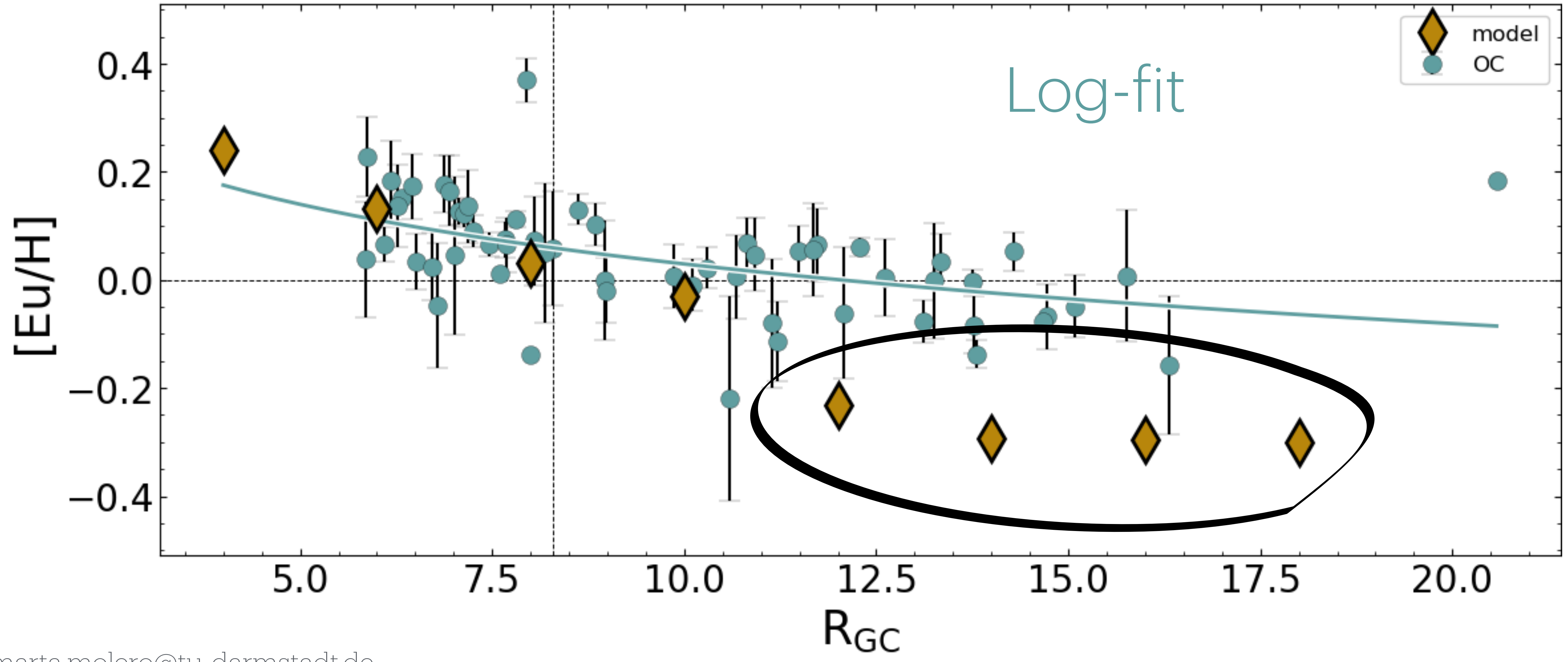

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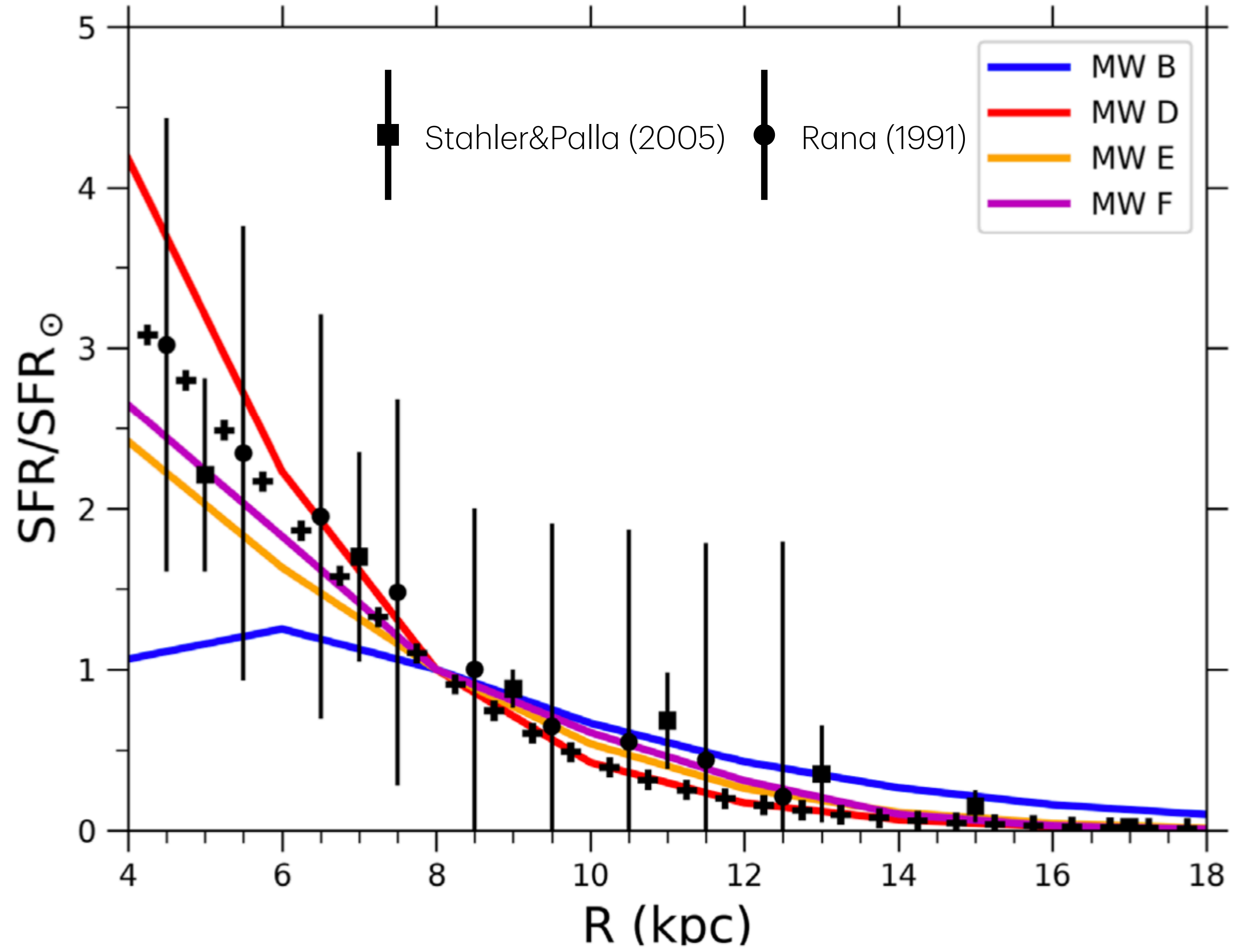
Inside out Galaxy formation

Palla et al. (2020)



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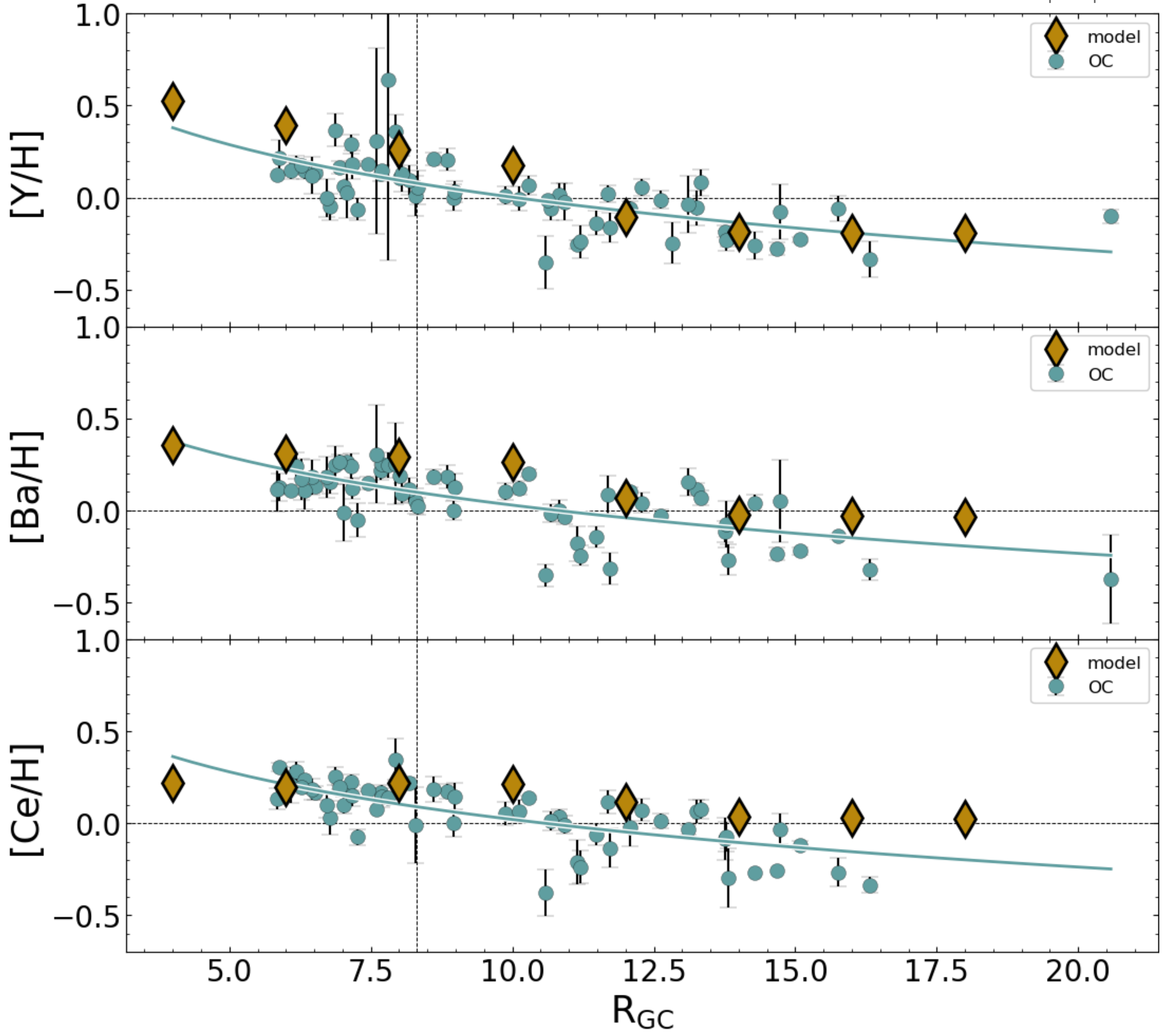
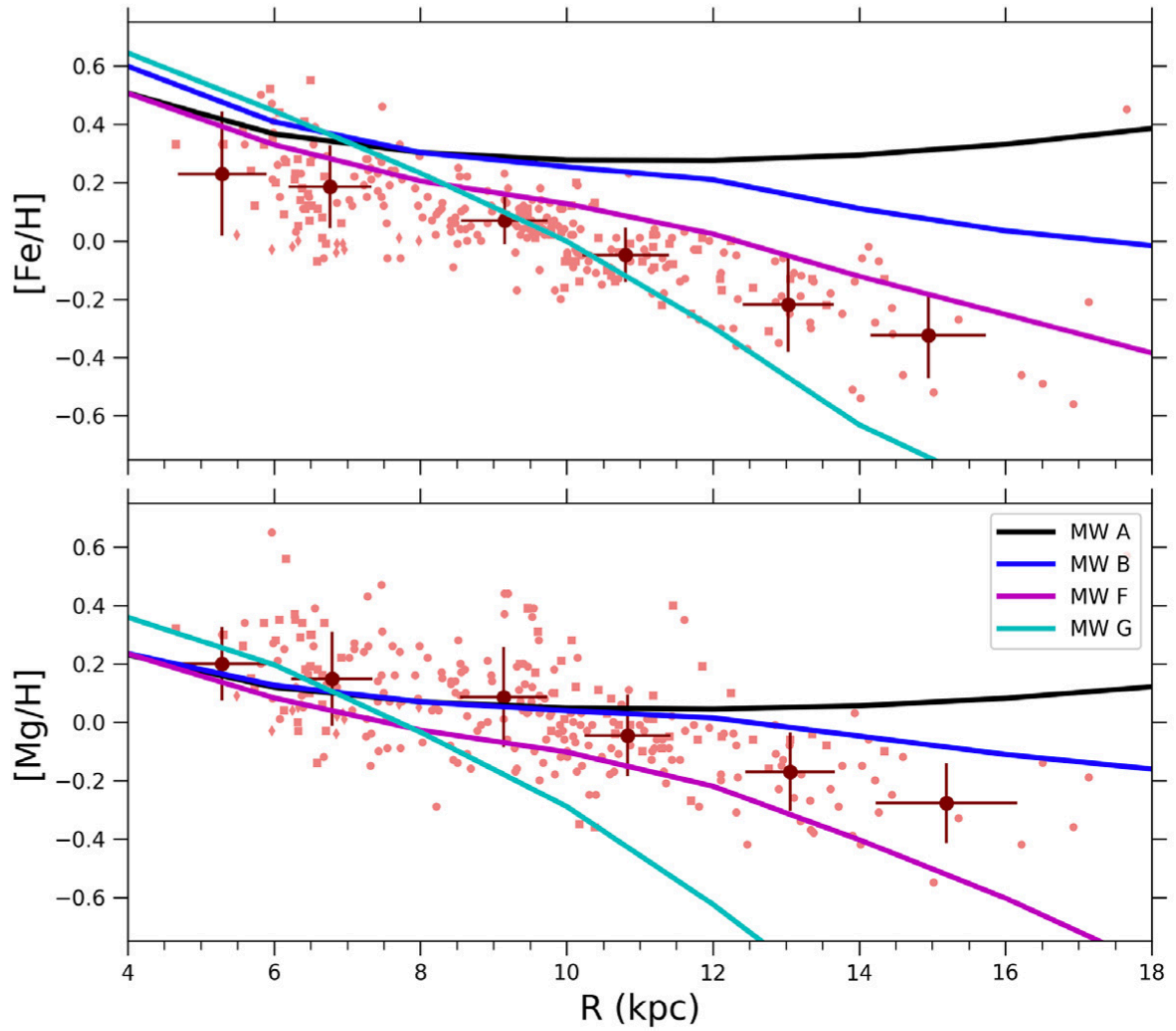
Abundance gradients

Molero in prep.



Palla et al. (2020)



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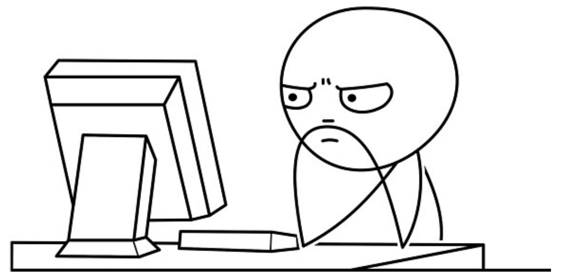
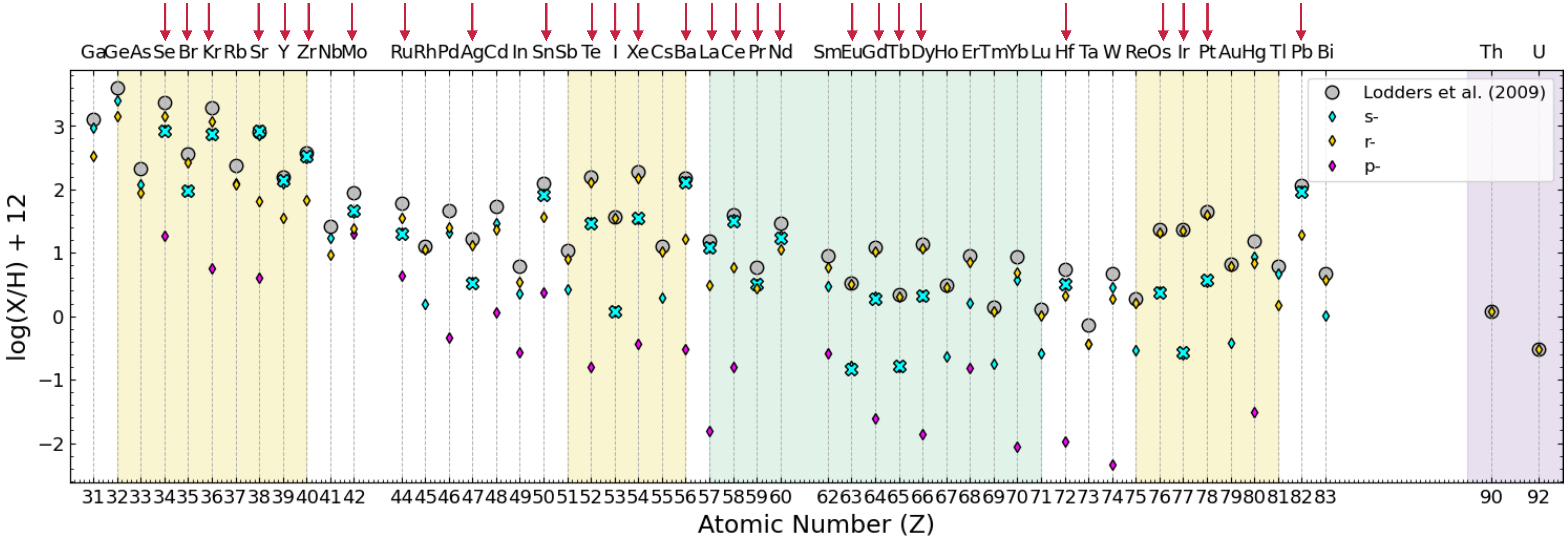
Parameter space exploration

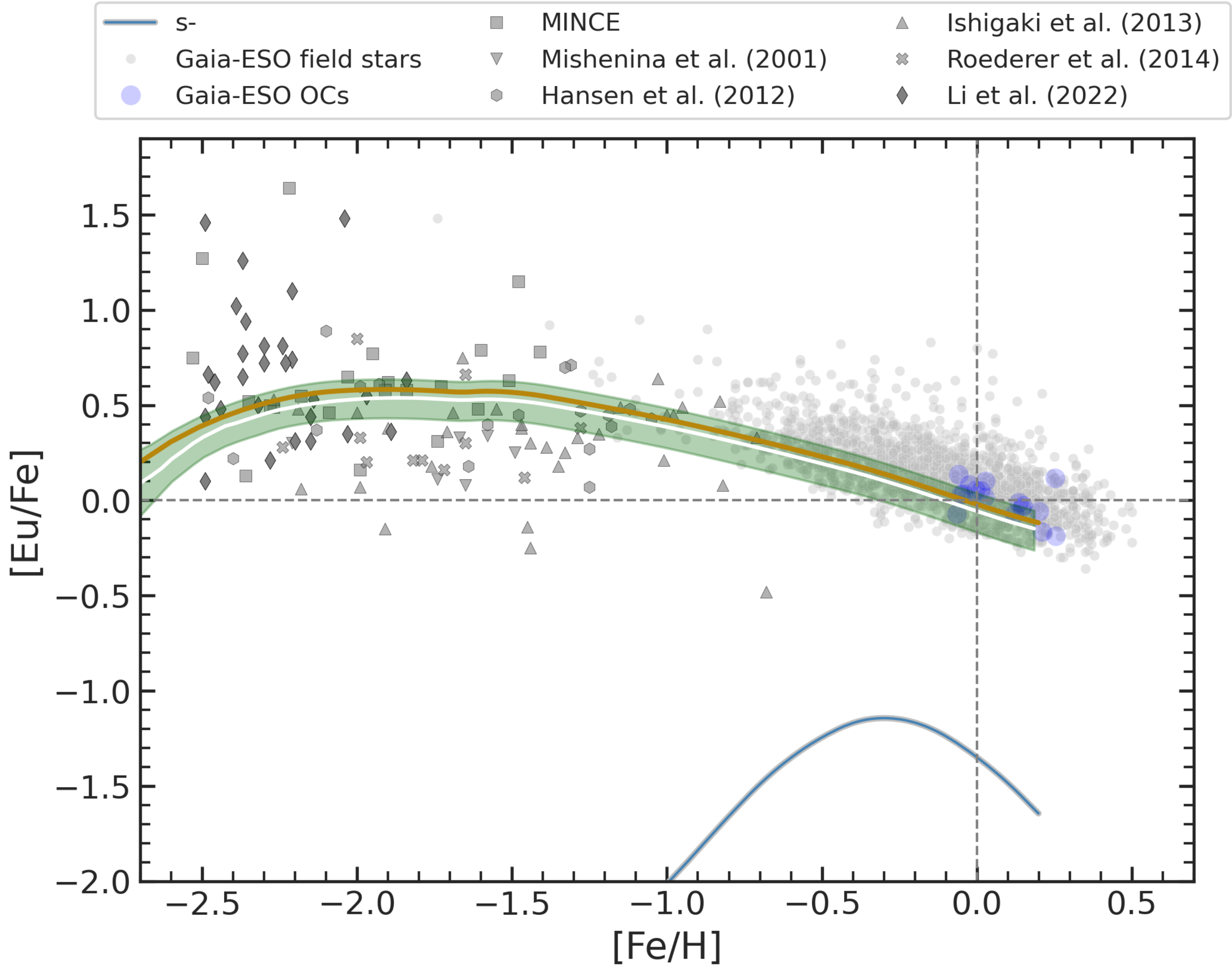




e.g., Matteucci et al. (2014)

$$Y_{Eu} \times \alpha \int_{M_{min}}^{M_{max}} \psi(t - \tau_m - \tau)\phi(m)dm$$

$\sim 1 \times 10^5$ runs



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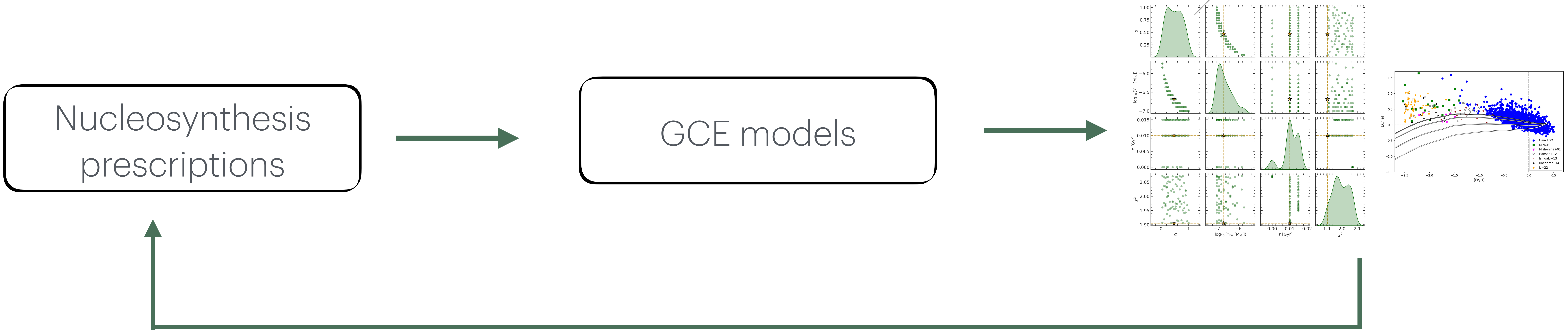
Conclusions

- GCE models are powerful tools to understand the formation and distribution of chemical species
- Homogenous models are useful for parameter exploration (**nucleosynthesis**) and sensitivity analysis



- Are NSM the dominant source of r-process in the Galaxy? Frequency? Delay?
- Do we need a second source? How can we calibrate it? Is the r-process still robust?
- Homogenous models can explain the average trend neutron-capture elements? Gradients?
- Open questions still remain…

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Backup slides

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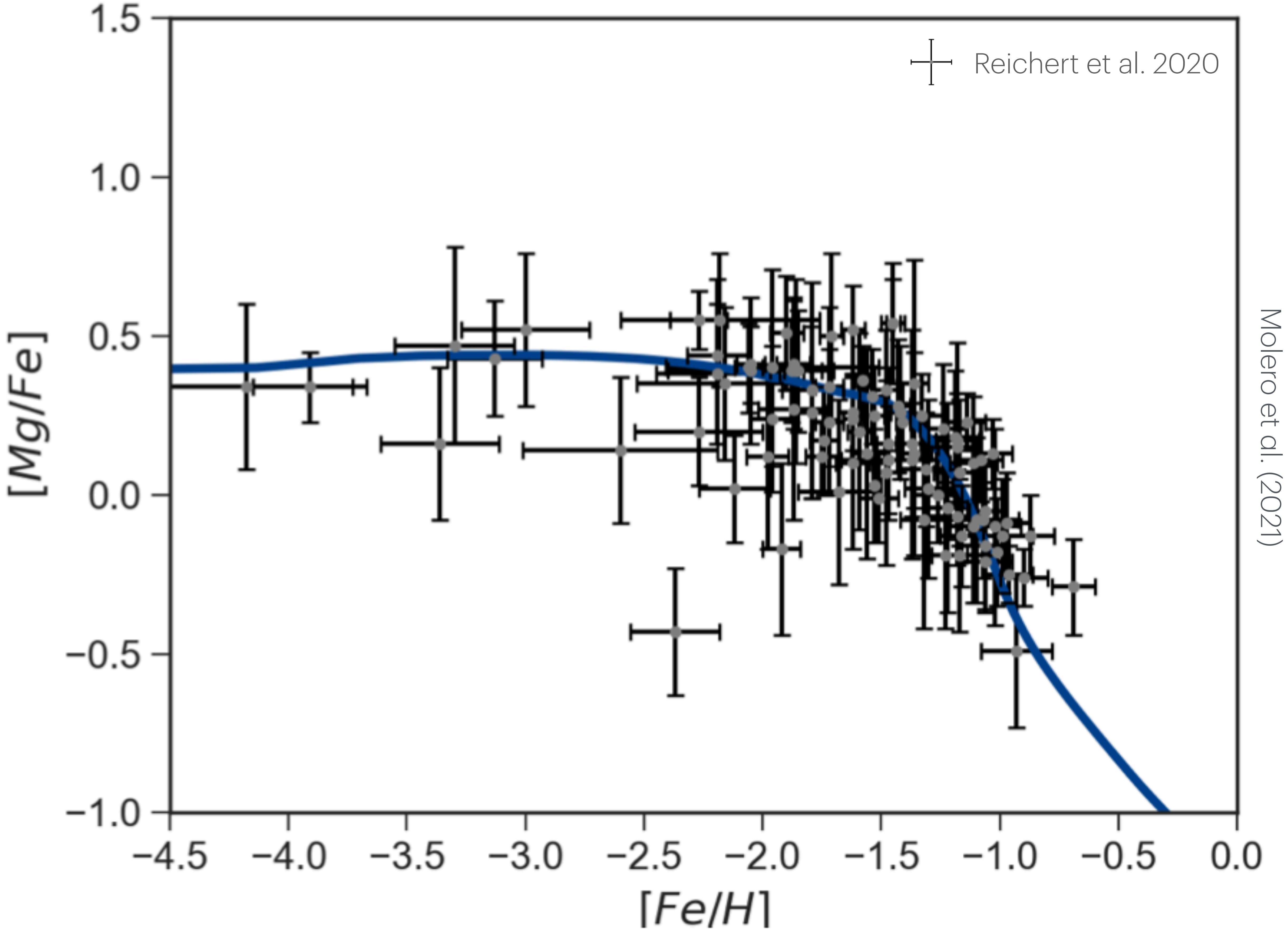
Introduction: chemical evolution

$$[Mg/Fe] = \log(Mg/Fe) - \log(Mg/Fe)_\odot$$



Molero et al. (2021)

the observed metal abundances of stars today measures the composition of the ISM when the star was formed

Stars are the *fossil records* of past events:

Galactic Archeology

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DTD for neutron star mergers

Delay time for MNS: $\tau = \tau_s + \tau_{gw}$

τ_s: lifetime of the secondary component

τ_{gw}: gravitational radiation delay

$$\tau_{gw} = \frac{5c^5 A^4}{156 G^3 m_1 m_2 (m_1 + m_2)} Gyr$$

Landau&Lifshitz (1966)

$$\tau_{gw} \propto \frac{0.15 A^4}{m_1 m_2 (m_1 + m_2)} Gyr$$

Simonetti et al. (2019)

$$\tau_{gw} \propto \frac{0.6 A^4}{M^3} Gyr$$

$$df(\tau_{gw}) = df(A, M) = g(A) h(M) dA dM$$

$$\begin{cases} g(A) \propto A^{\beta} \\ h(M) \propto const. \end{cases}$$

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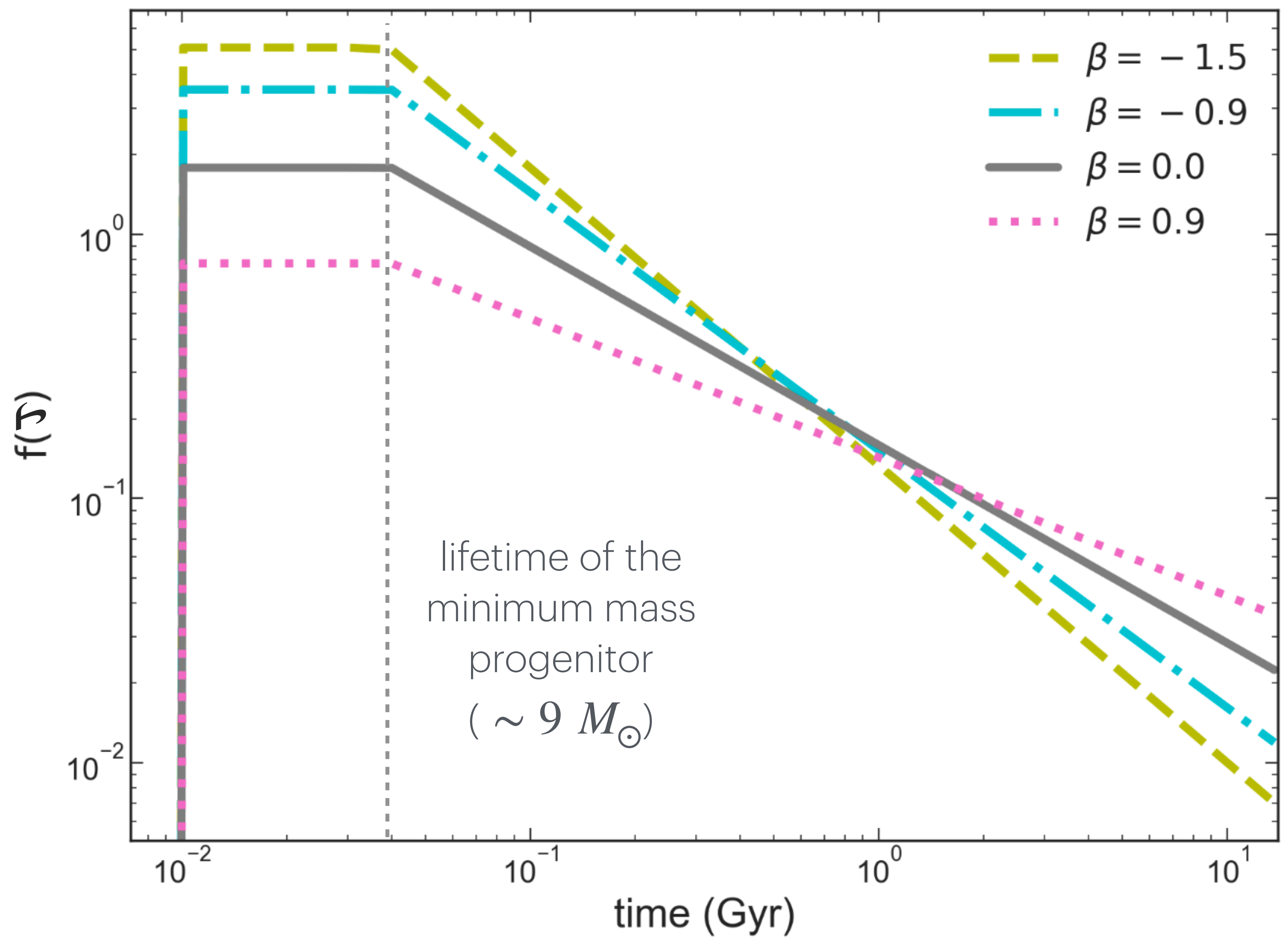
For a complete derivation see Simonetti et al. (2019); Greggio et al. (2021)

DTD for neutron star mergers

$$f(\tau) \propto \begin{cases} 0 & if \quad \tau < 10\ Myr \\ p_1 & if \quad 10 < \tau < 40\ Myr \\ p_2 \tau^{0.25\beta - 0.75} (M_s^{0.75(\beta+2.33)} - M_l^{0.75(\beta+2.33)}) & if \quad 40\ Myr < \tau < 13.7\ Gyr \end{cases}$$



- First portion: formation of the first DNS system.
- Second portion: systems which merge soon after formation of DNS system.
- Third portion: distribution of gravitational delay times.

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For a complete derivation see Simonetti et al. (2019); Greggio et al. (2021)

Rate of neutron star mergers

When? + How much? + How many?

→ The rate, $R_{event}(t)$

$$R_{MNS}(t) = k_\alpha \int_{\tau_i}^{min(t,\tau_x)} \alpha_{MNS}(\tau)\psi(t-\tau)f_{MNS}(\tau)\,\mathrm{d}\tau$$

Initial Mass Function

Star Formation

Delay Time Distribution

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Two-infall model for the disk

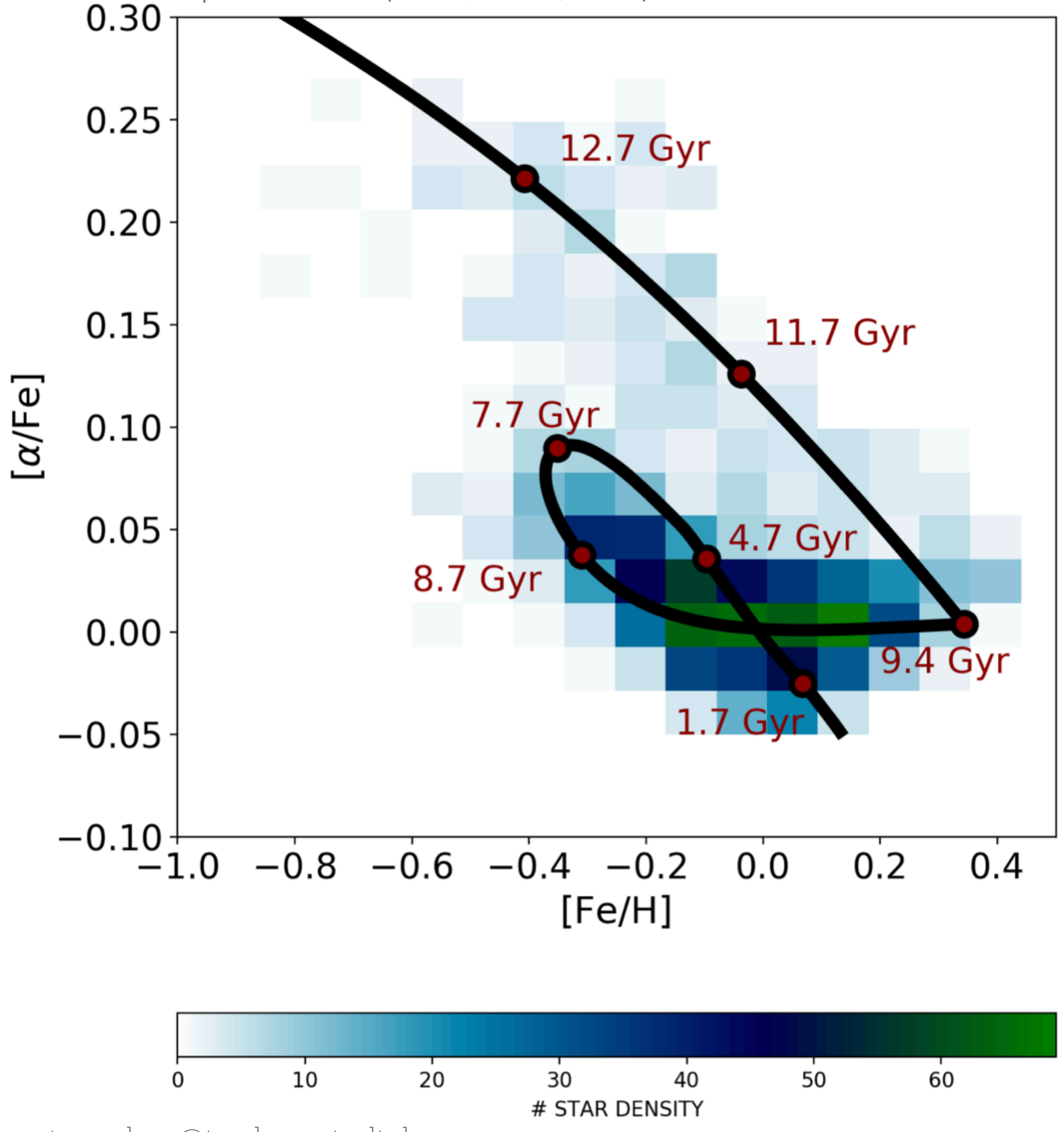
$$\dot{M}_{\mathrm{gas},i}(t,R) = -\psi(t,R)X_i(t,R) + X_{i,A}A(t,R) + \dot{R}_i(t,R)$$

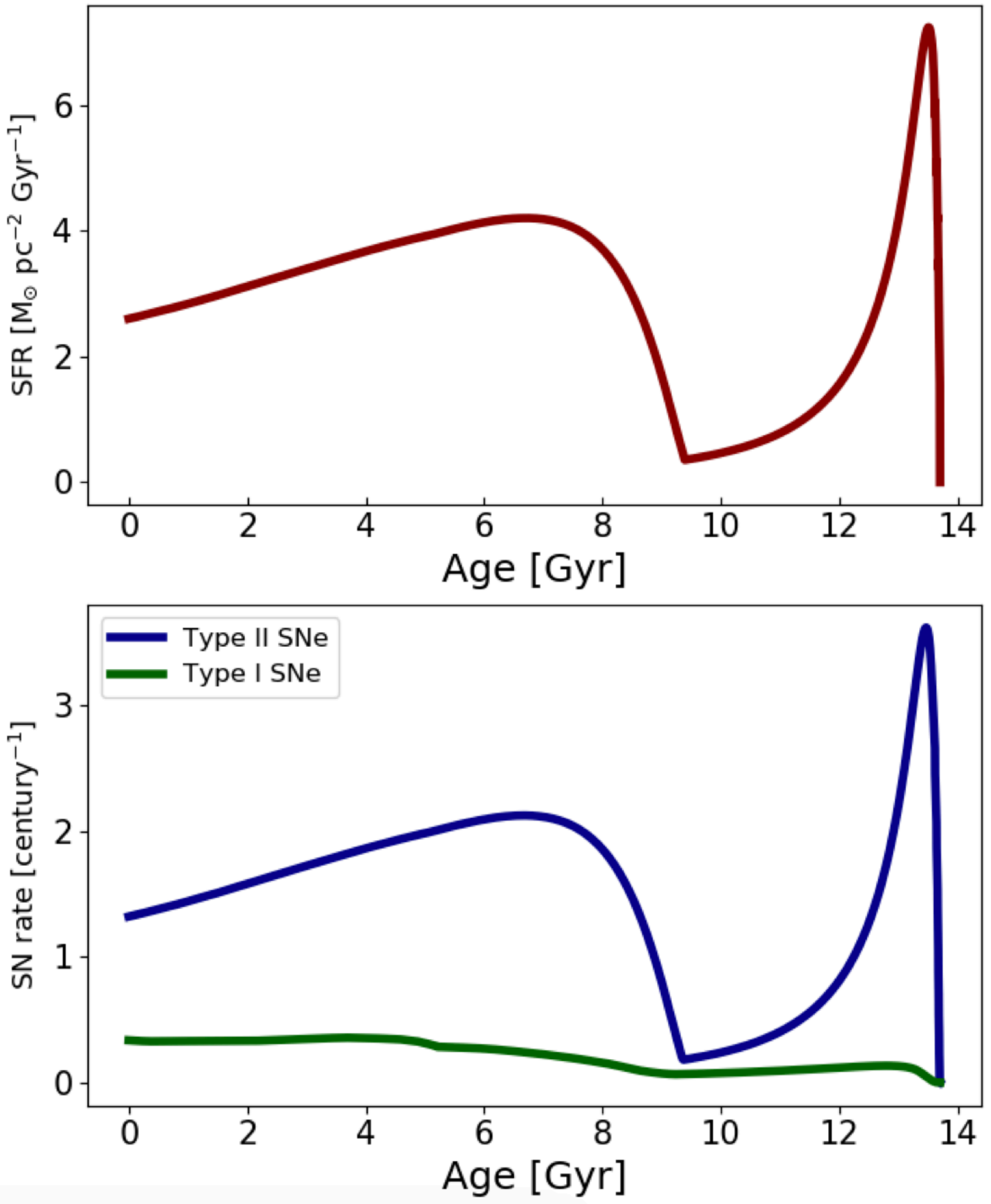
$$\downarrow$$

$$A(t,R) = c_1 e^{-t/\tau_{D_1}} + \theta(t - t_{max})c_2 e^{-(t-t_{max})/\tau_{D_2}}, \; t_{max} = 3.25 \; Gyr$$

Palla et al. (2020)

Spitoni et al. (2019;2020;2021)





- The late accretion of pristine gas has the effect of decreasing the metallicity of each stellar population born immediately after the infall event while it has little effect on the [α/Fe] ratio

- When the SF resumes, Type II SNe produce a rise in the [α/Fe] ratio, which is then decreased and shifted towards higher metallicities due to pollution from Type Ia SNe

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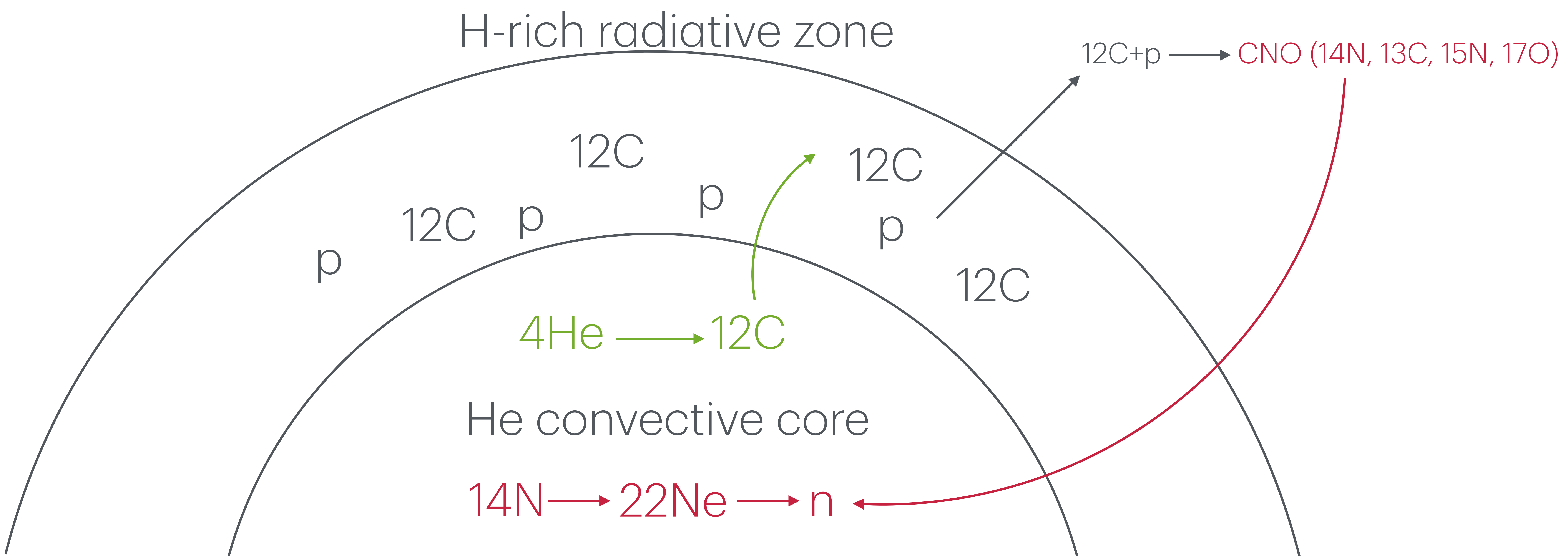
The effect of rotation

1. 12C synthesized in the He core diffuses up to the base of the H-burning shell
2. 12C is converted into CNO nuclei, enhancing their abundance (14N in particular)
3. CNO and some He are brought back to the centre
4. 14N in the centre is converted into 22Ne first and then into 25,26Mg

primary neutron source

22Ne(α,n)25Mg



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