

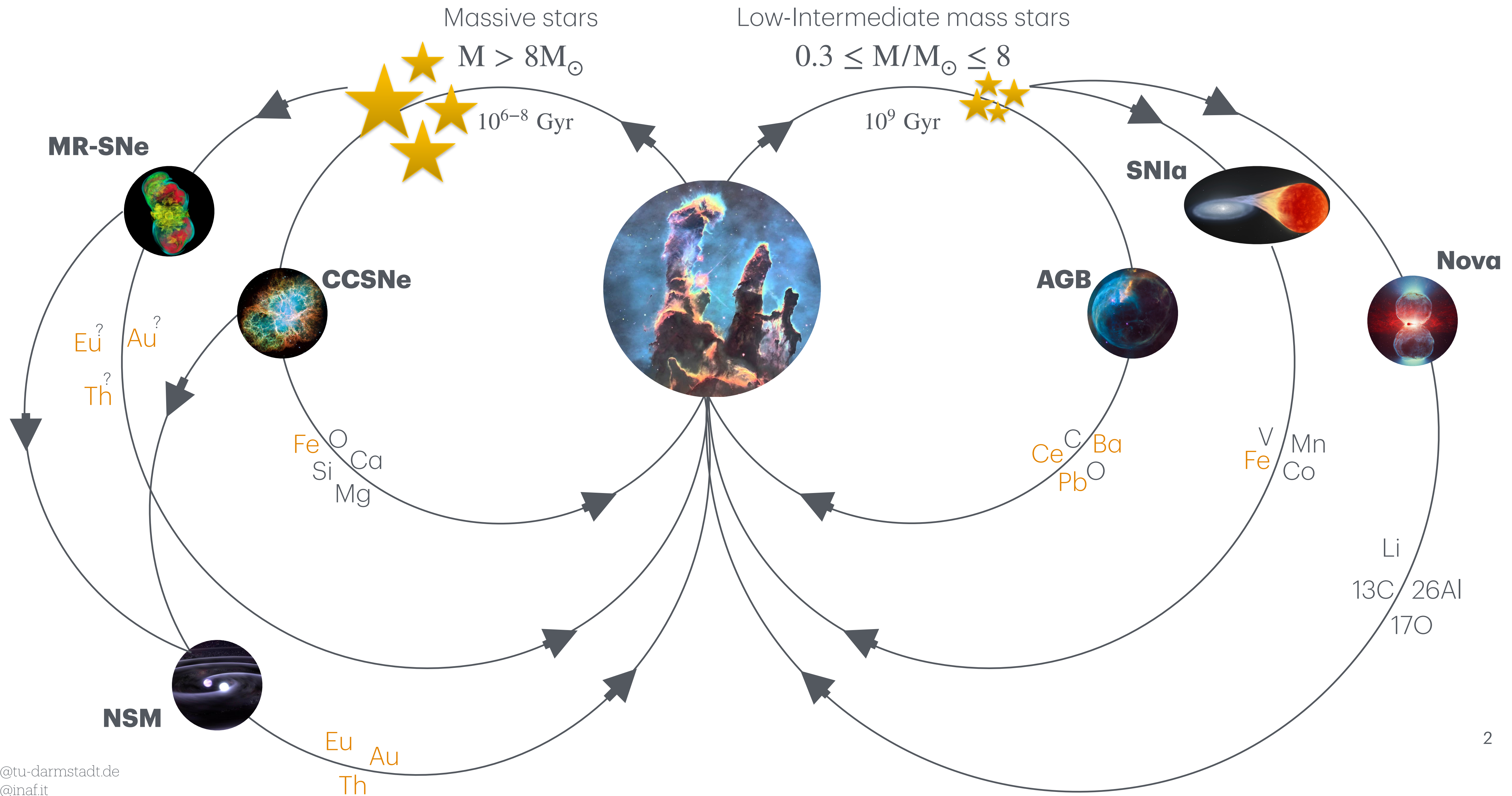
Chemical evolution of NC-elements: a homogeneous approach



Marta Molero

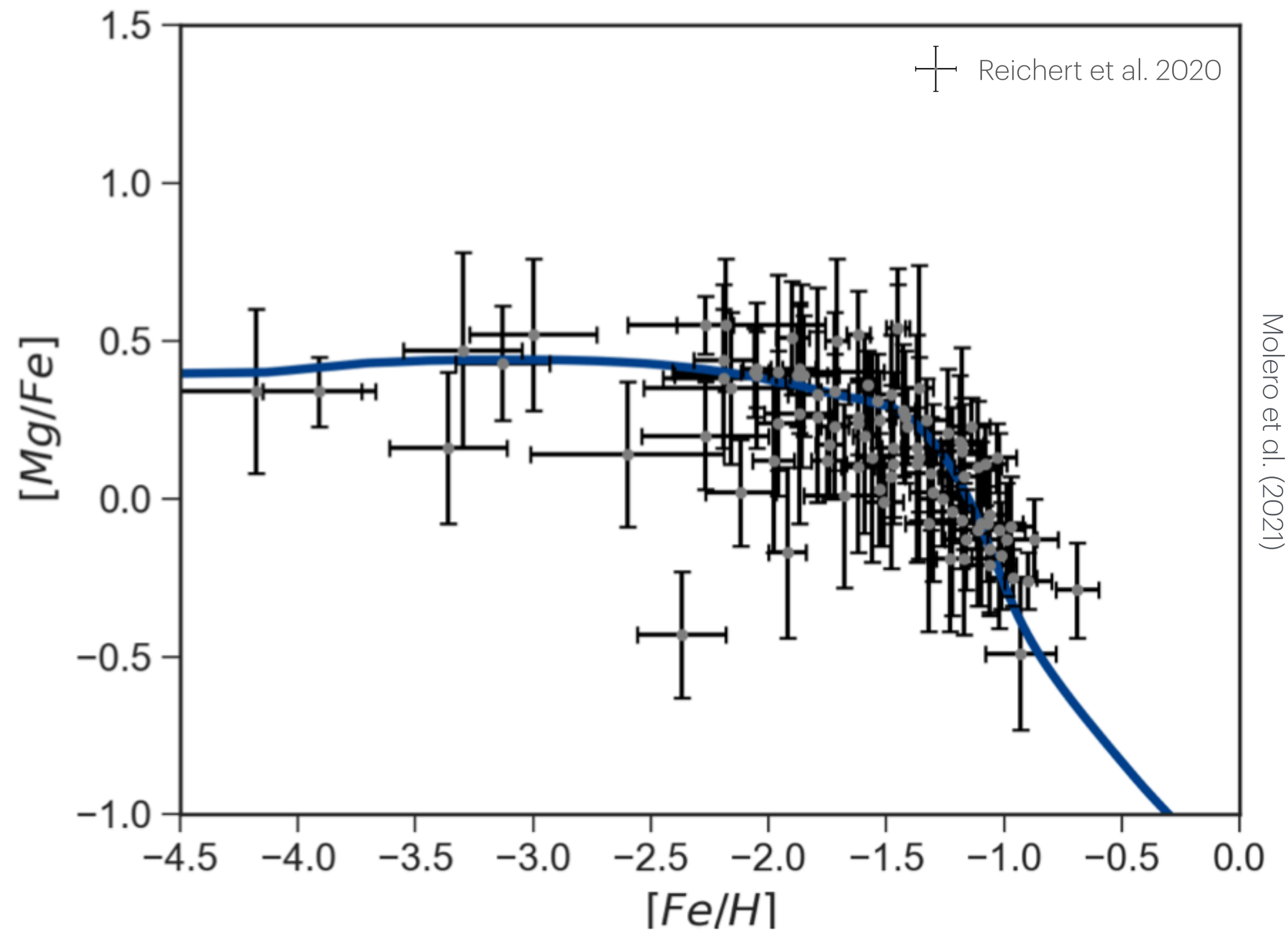
Hirscheegg 2025 - nucleosynthesis of Heavy Elements: r-process

Introduction: chemical evolution



Introduction: chemical evolution

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



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

Introduction: chemical evolution

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

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

Introduction: chemical evolution

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

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

accretion of
gas through
infall

lost of gas galactic
winds

Introduction: chemical evolution

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

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

accretion of
gas through
infall

lost of gas galactic
winds

lost of gas by feeding the
central BH

Introduction: chemical evolution

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

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

lost of gas because of
SF processes

accretion of
gas through
infall

lost of gas galactic
winds

lost of gas by feeding the
central BH

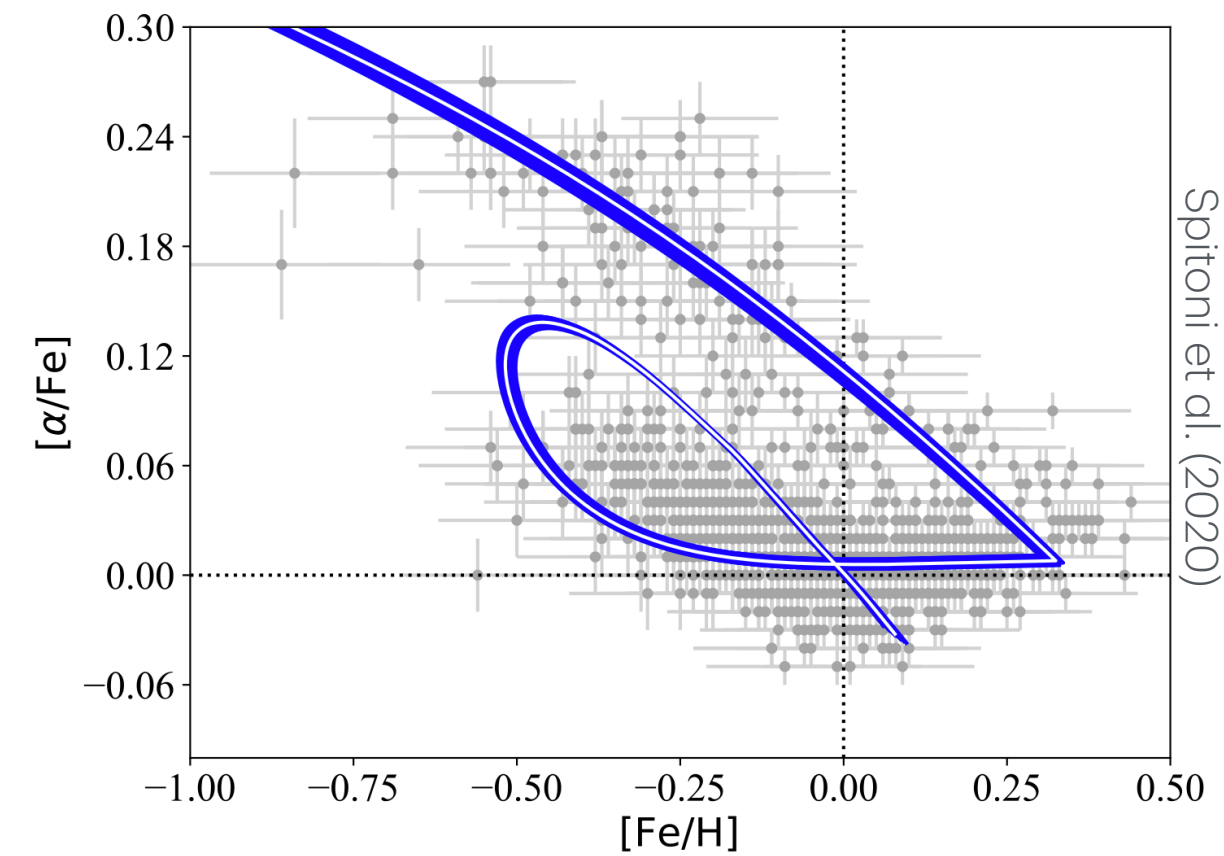
Introduction: chemical evolution

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

$$\dot{M}_{\text{gas},i}(R, \theta, t) = \underbrace{-\psi(R, \theta, t)X_i(R, \theta, t)}_{\substack{\downarrow \\ \text{lost of gas because of} \\ \text{SF processes}}} + \underbrace{X_{i,A}A(R, \theta, t)}_{\substack{\downarrow \\ \text{accretion of} \\ \text{gas through} \\ \text{infall}}} - \underbrace{X_i(R, \theta, t)W(R, \theta, t)}_{\substack{\downarrow \\ \text{lost of gas galactic} \\ \text{winds}}} - \underbrace{X_i(R, \theta, t)\dot{M}_{BH}(R, \theta, t)}_{\substack{\downarrow \\ \text{lost of gas by feeding the} \\ \text{central BH}}} + \underbrace{\dot{R}_i(R, \theta, t)}_{\substack{\downarrow \\ \text{restitution of} \\ \text{gas from stars}}}$$

Homogeneous models:

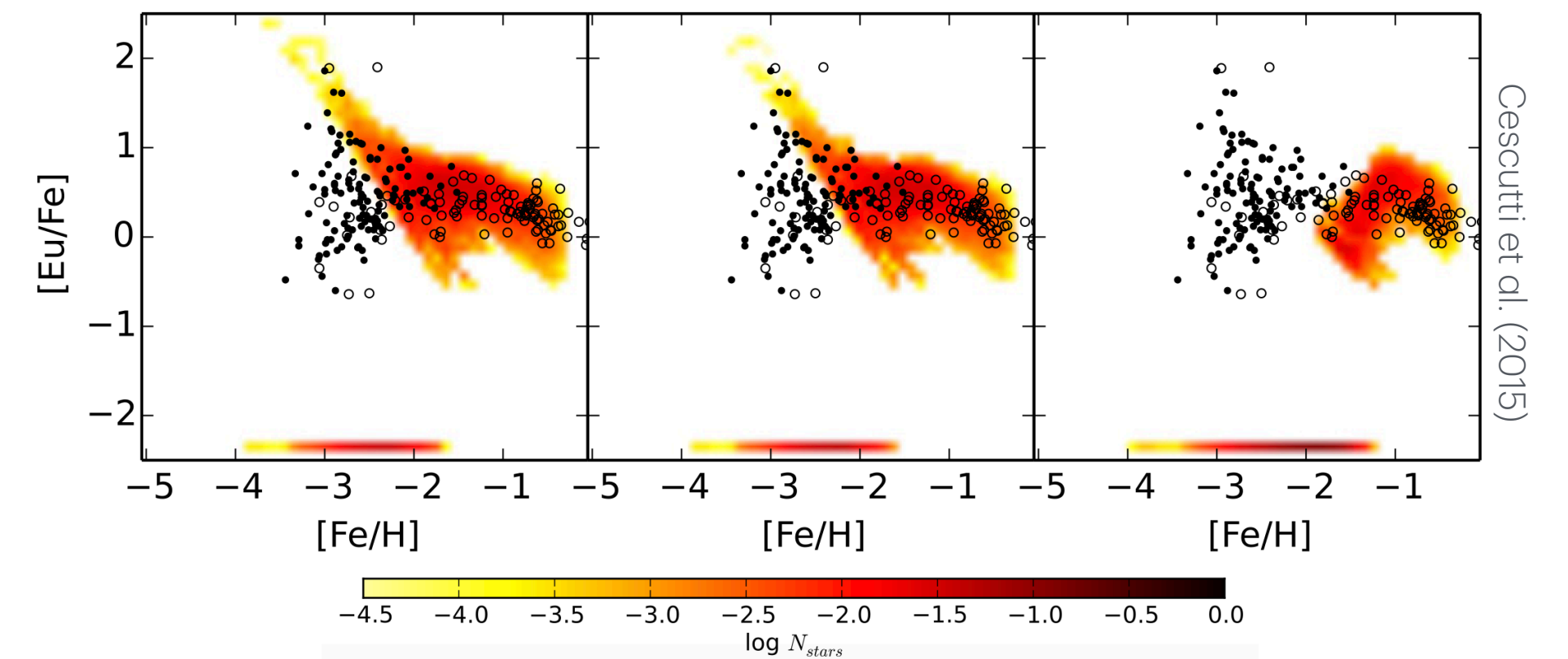
- One or multi-Zone system treated as a single homogeneous zone



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

Stochastic models:

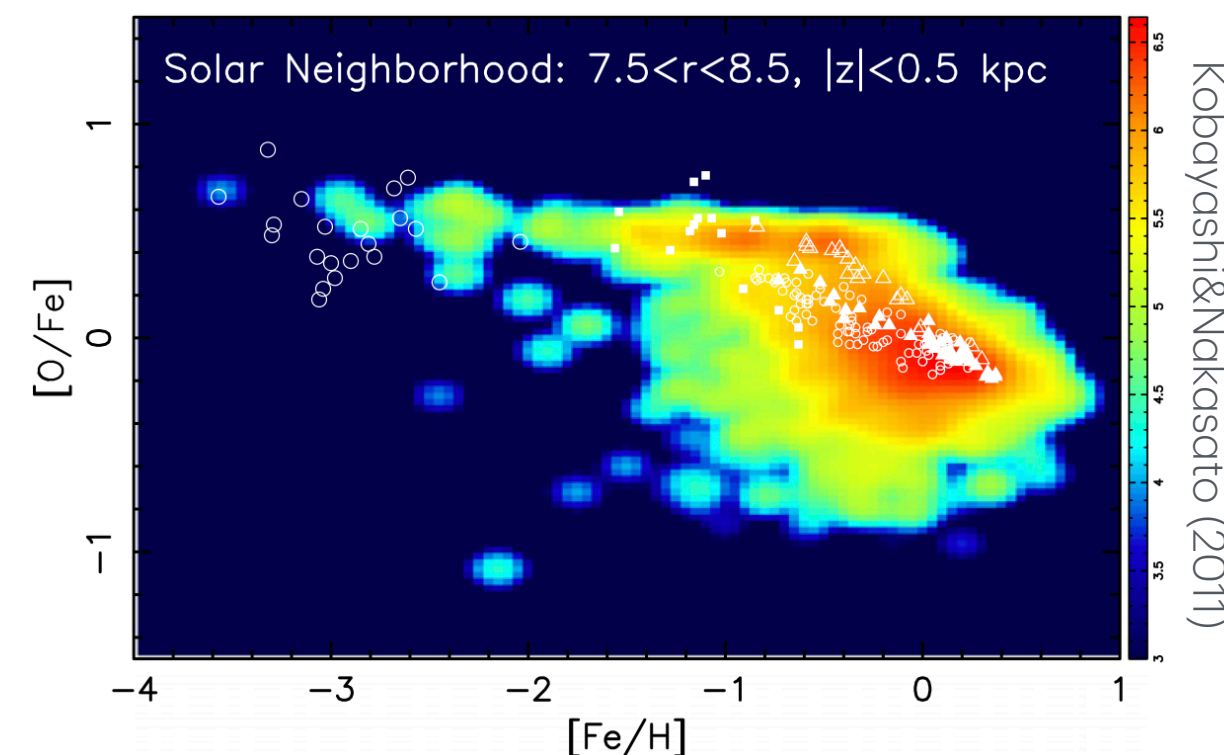
- System divided into multiple zones: each evolves independently with stochastic sampling of stellar mass distribution



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

Chemodynamical simulations:

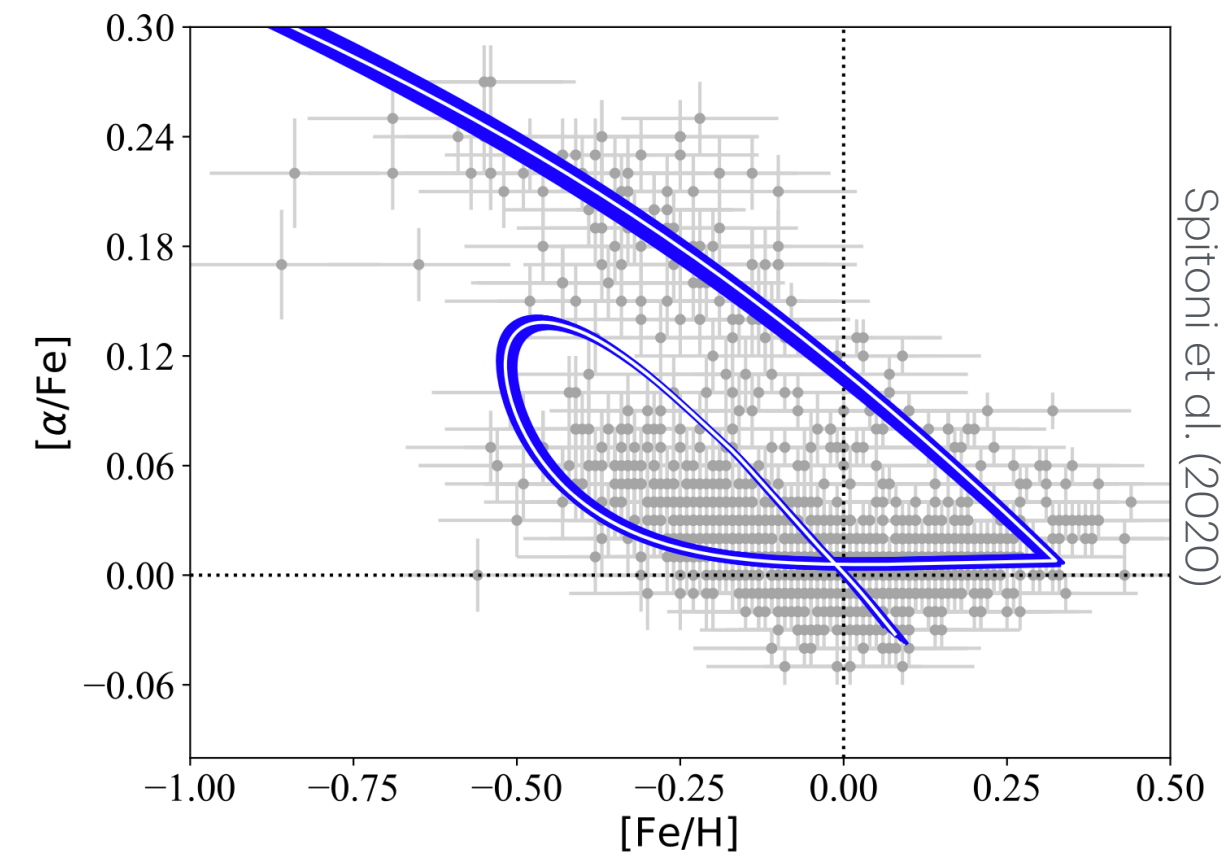
- Integrate chemical evolution + dynamical processes in a cosmological framework



Kobayashi 2004; Scannapieco+22

Homogeneous models:

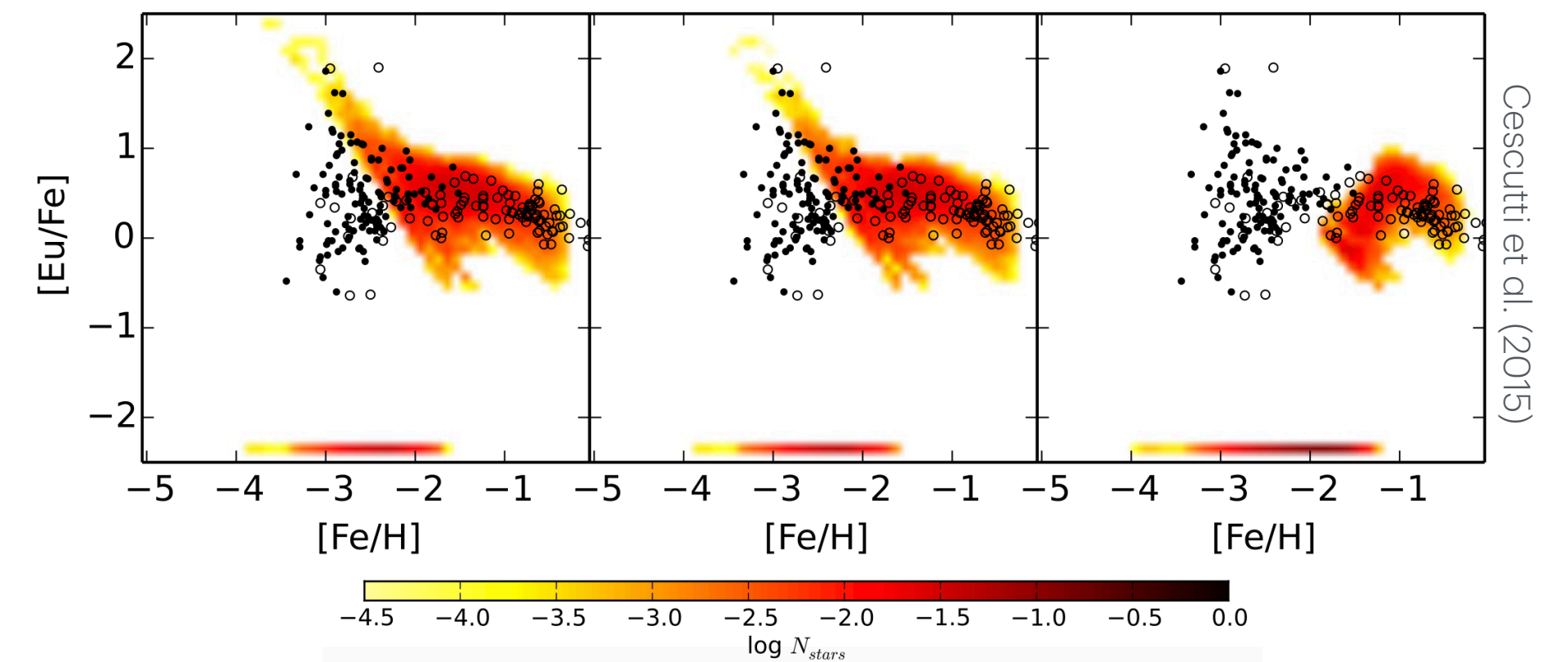
- One or multi-Zone system treated as a single homogeneous zone



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

Stochastic models:

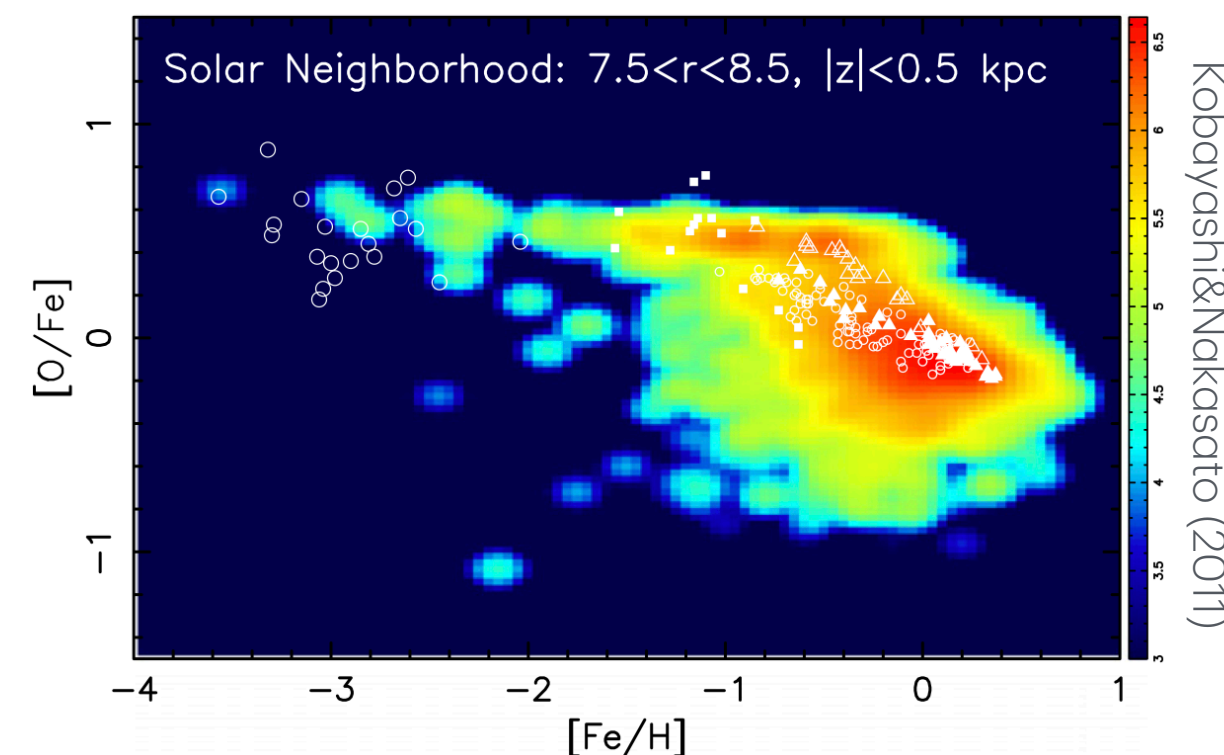
- System divided into multiple zones: each evolves independently with stochastic sampling of stellar mass distribution



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

Chemodynamical simulations:

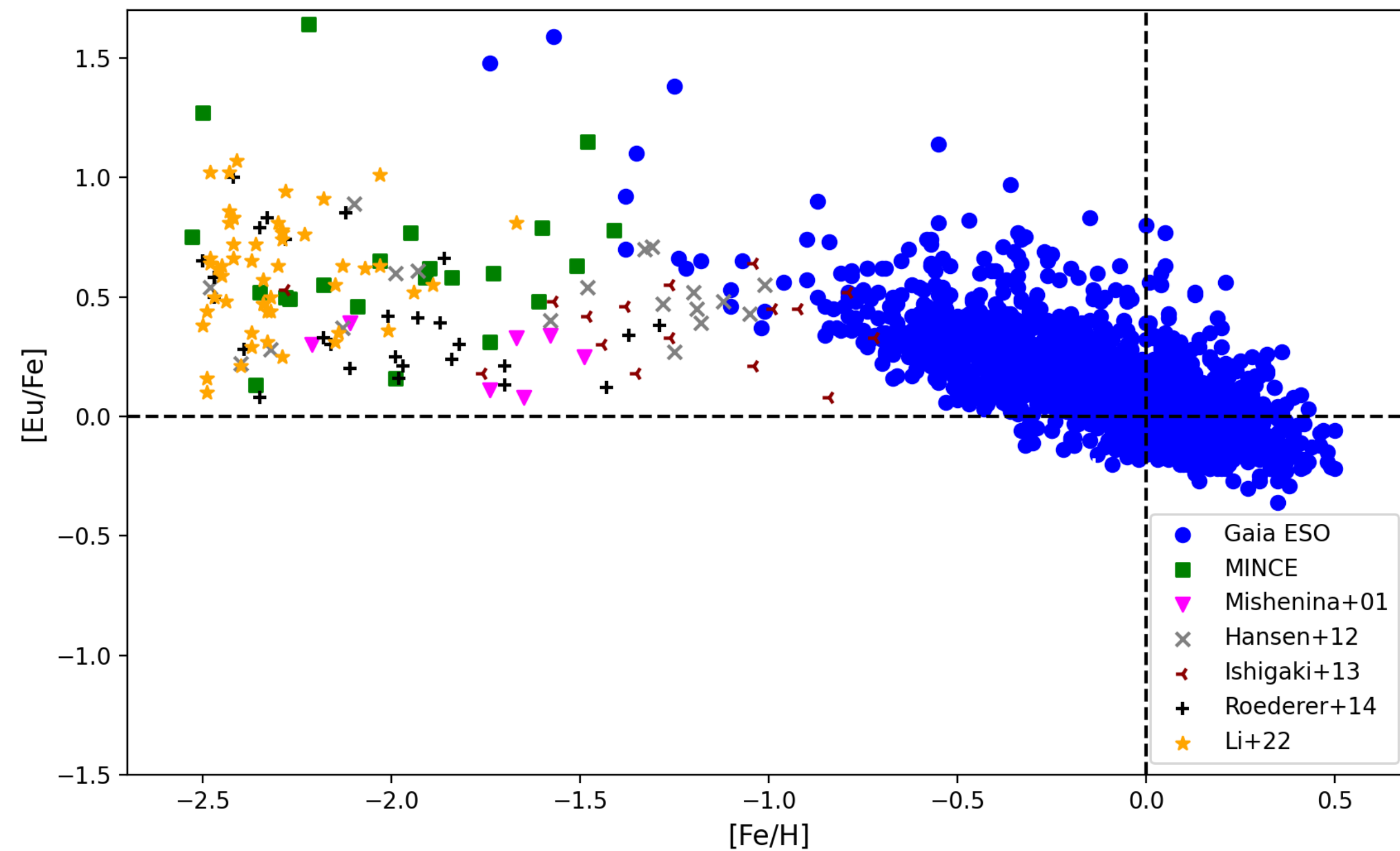
- Integrate chemical evolution + dynamical processes in a cosmological framework



Kobayashi 2004; Scannapieco+22

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

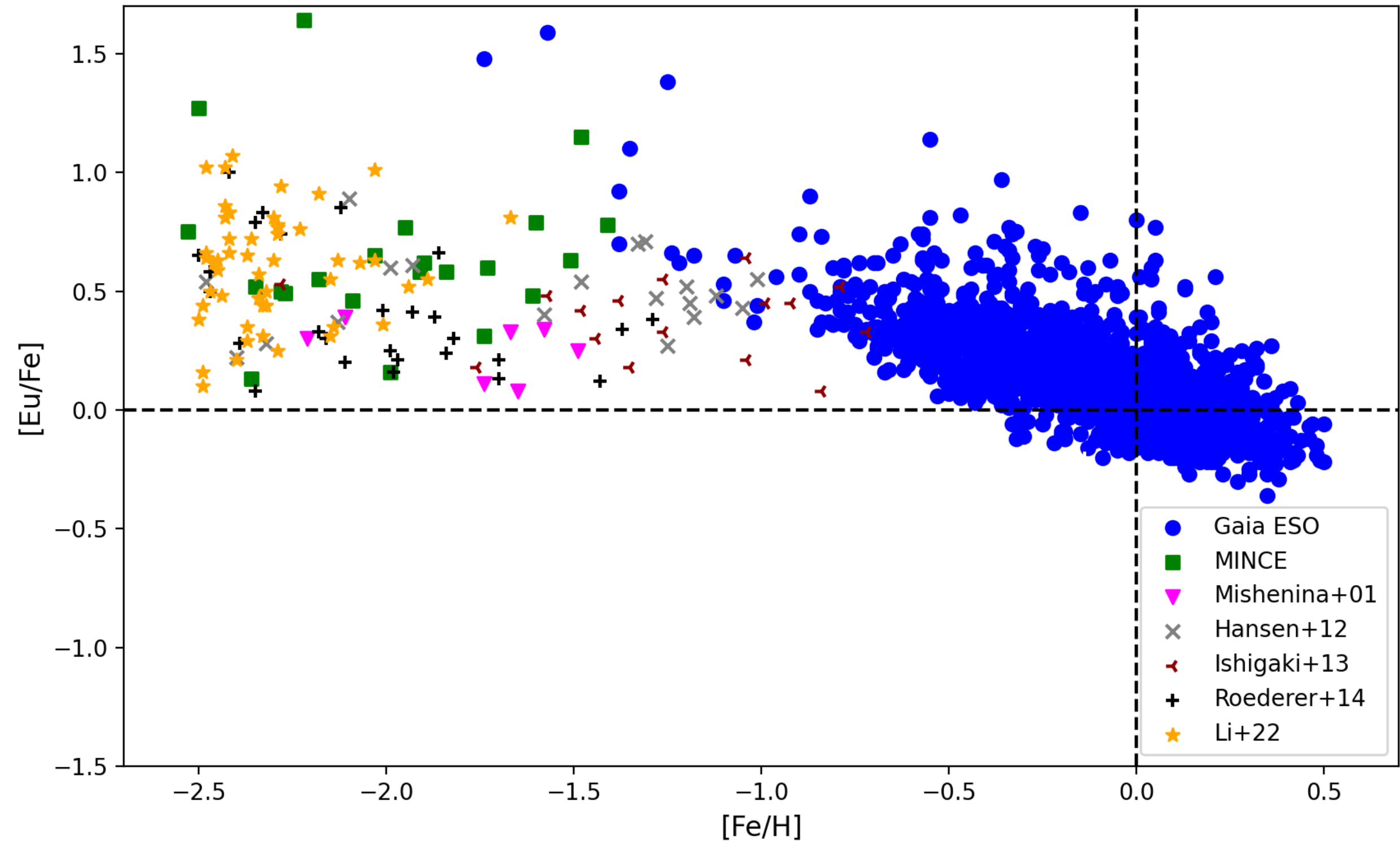
$$[\text{Eu}/\text{Fe}] = \log(\text{Eu}/\text{Fe}) - \log(\text{Eu}/\text{Fe})_{\odot}$$



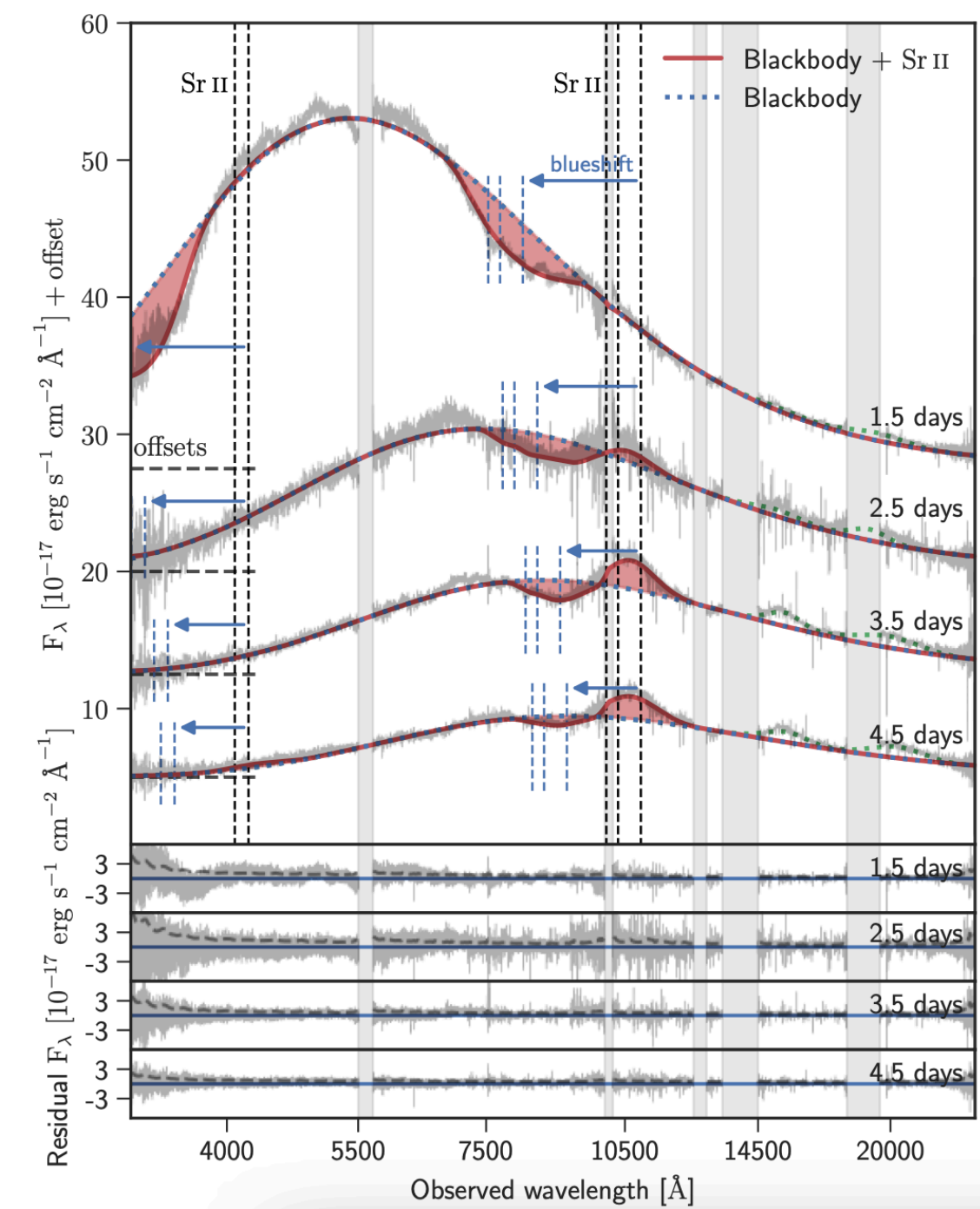
Type Ia SNe
long lifetimes main Fe producers

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

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

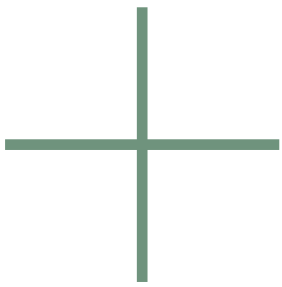


$$Y_{\text{Sr}} \propto 10^{-5} M_{\odot}$$
$$Y_{\text{Eu}} \propto 10^{-6} M_{\odot}$$



Watson et al. (2019)

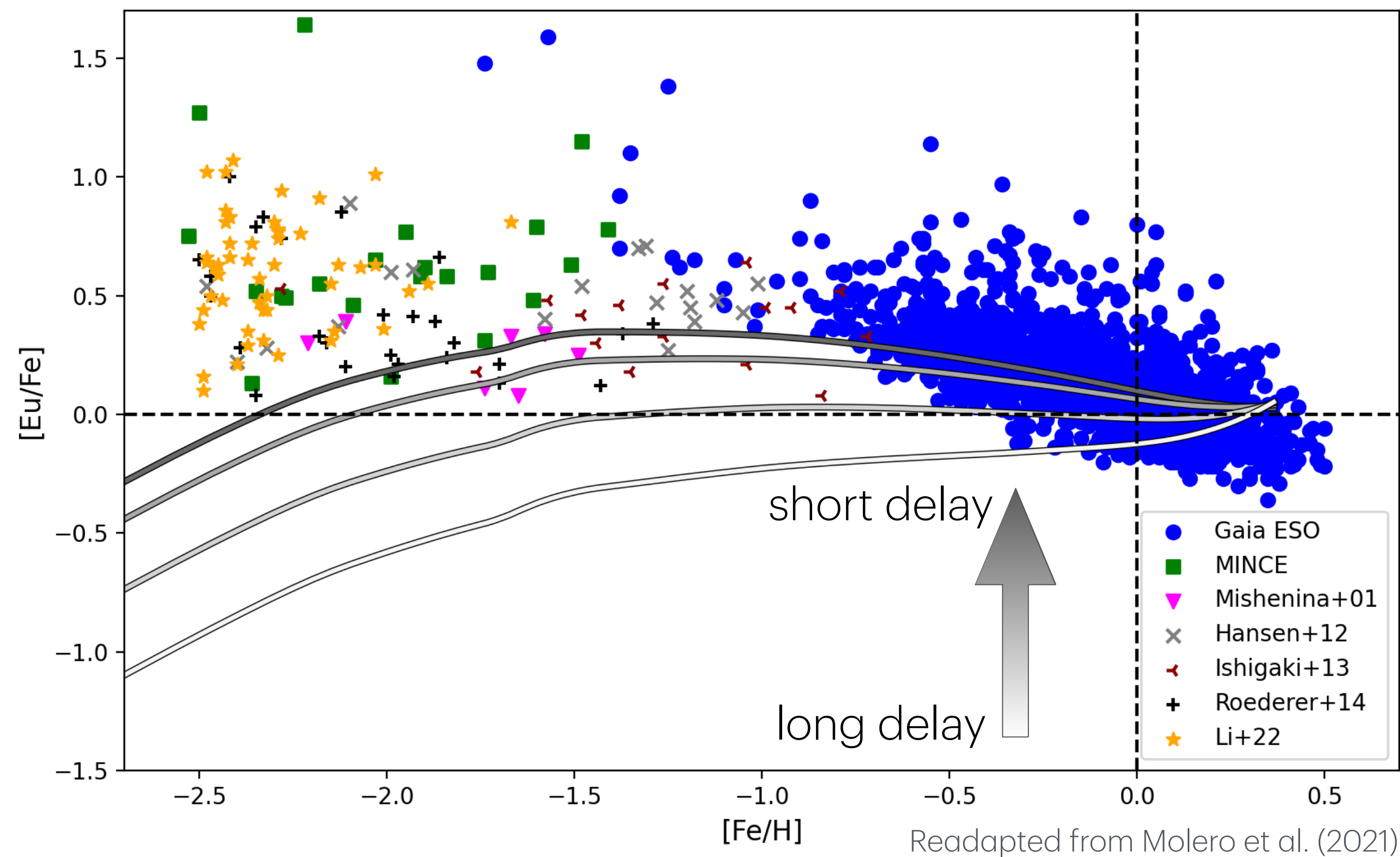
Type Ia SNe
long lifetimes main Fe producers



Neutron star mergers

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

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



lifetime of secondary component

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

gravitational radiation delay

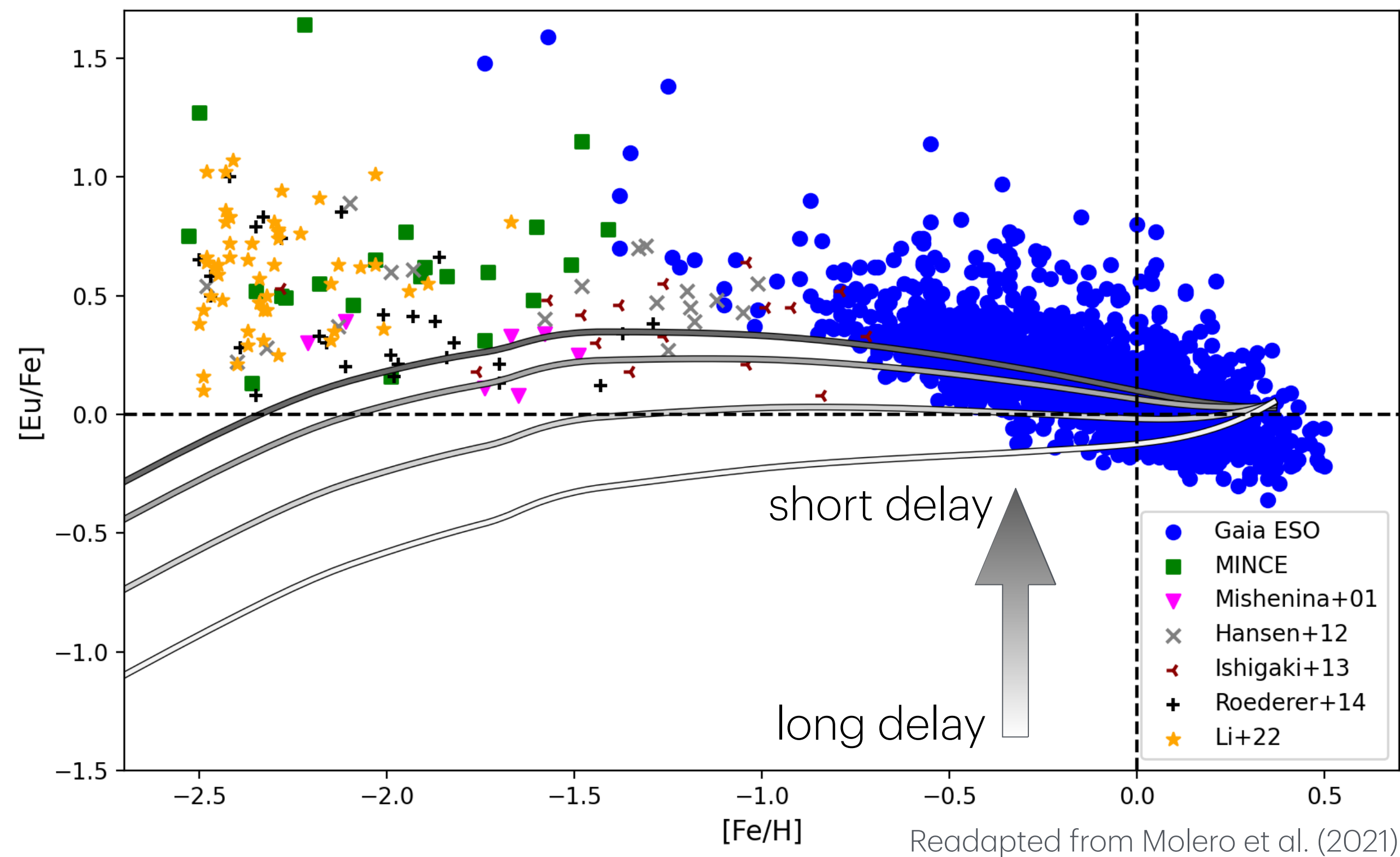
$$\tau_{gw} = \tau_{gw}(m_1, m_2, A, e)$$

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, ...

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

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



lifetime of secondary
component

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

gravitational radiation
delay

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

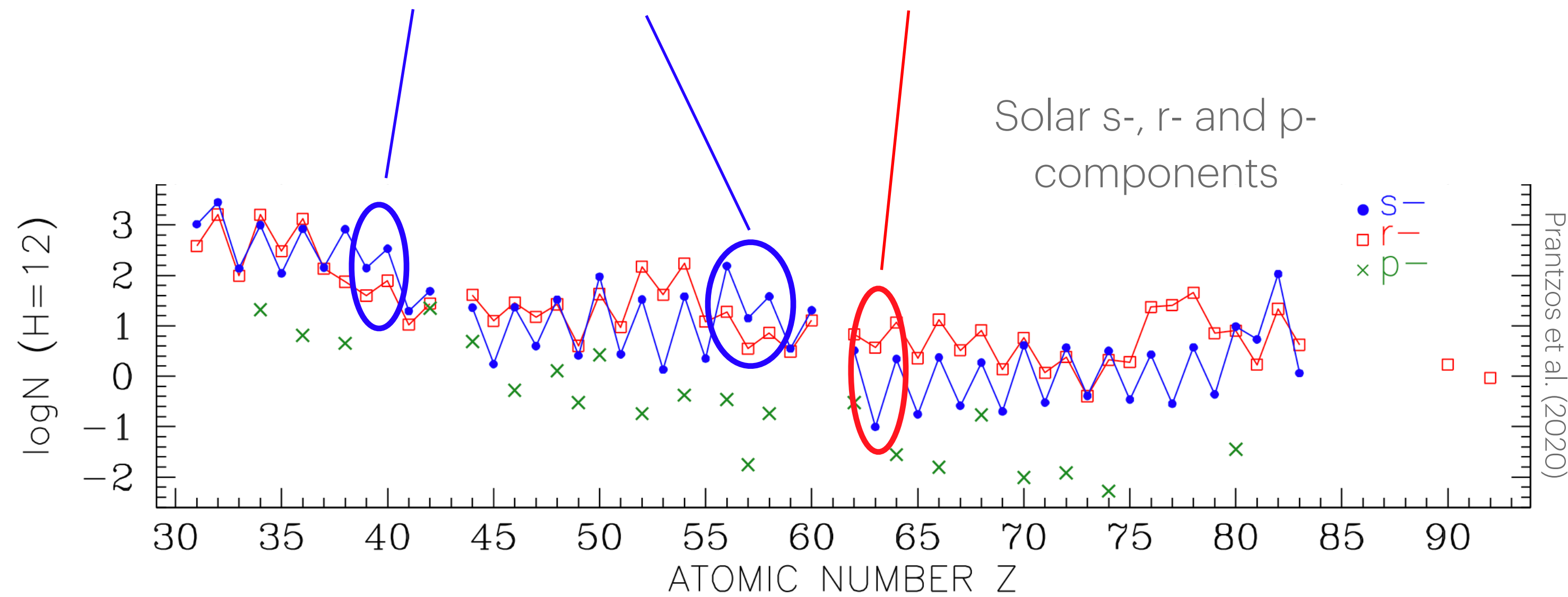
Either NS all merge on short timescales or
they cannot be the major producers of Eu

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

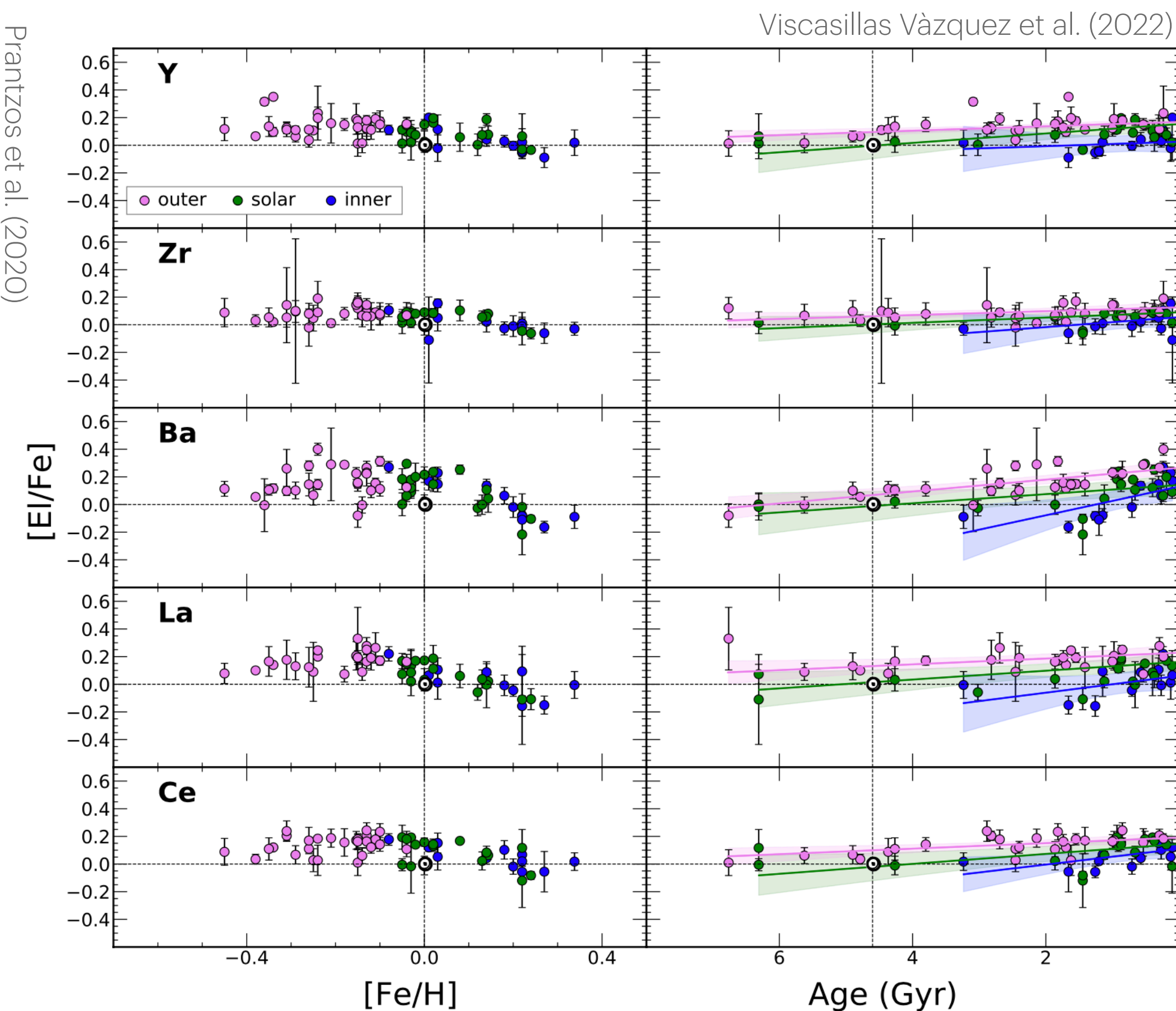
Massive stars... MR-SNe, collapsars... something quick

Homogeneous model for the disk

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



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



Abundance patterns

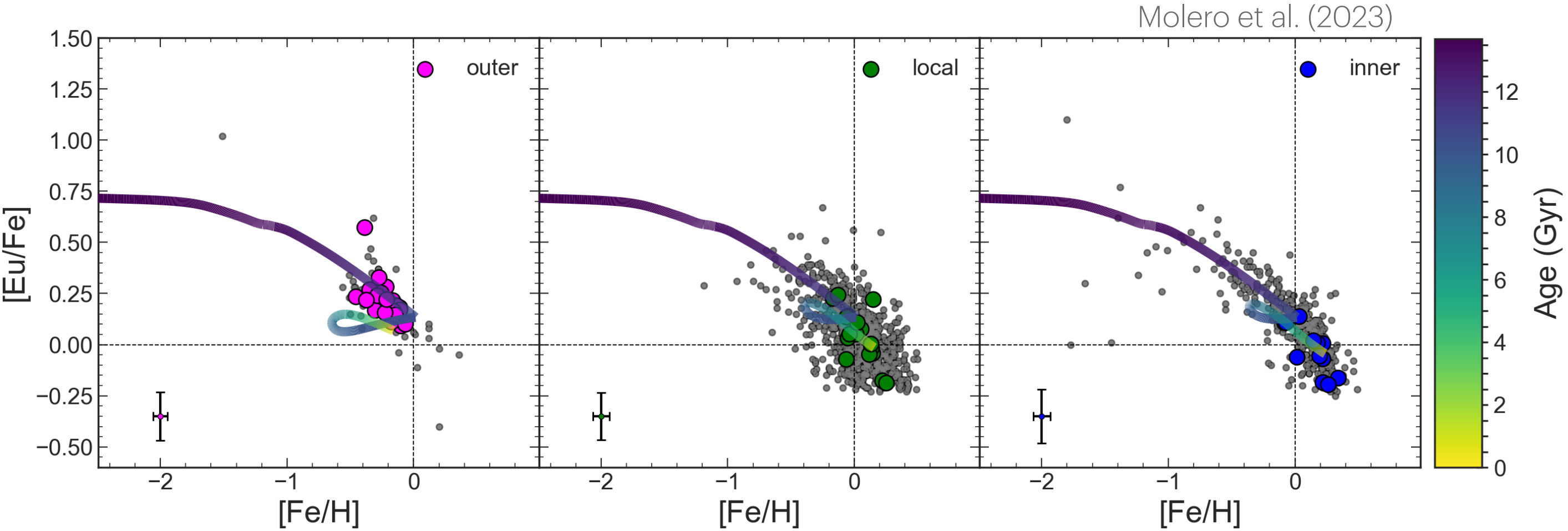
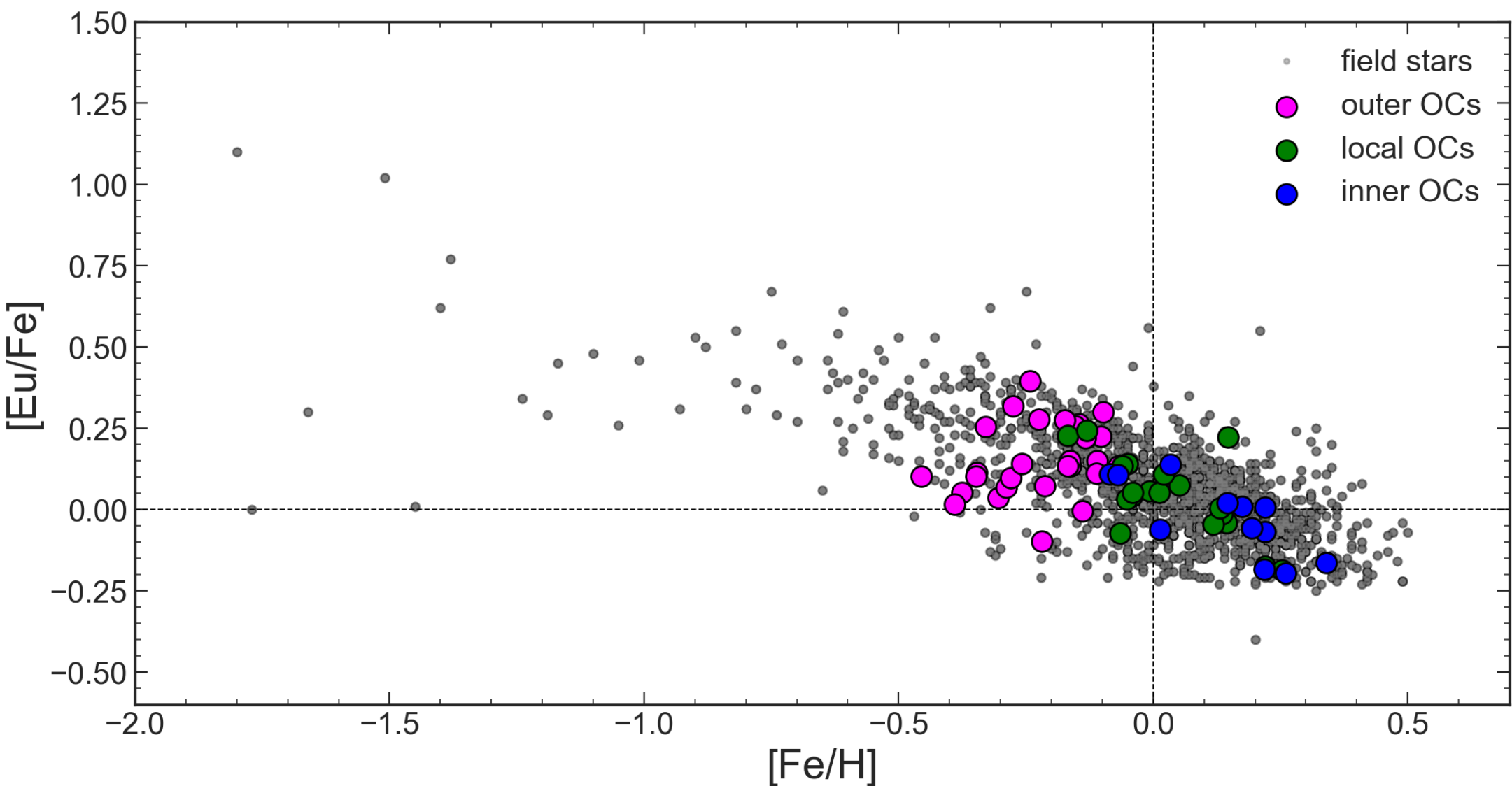
R-process

QUICK

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

DELAYED

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



Abundance patterns

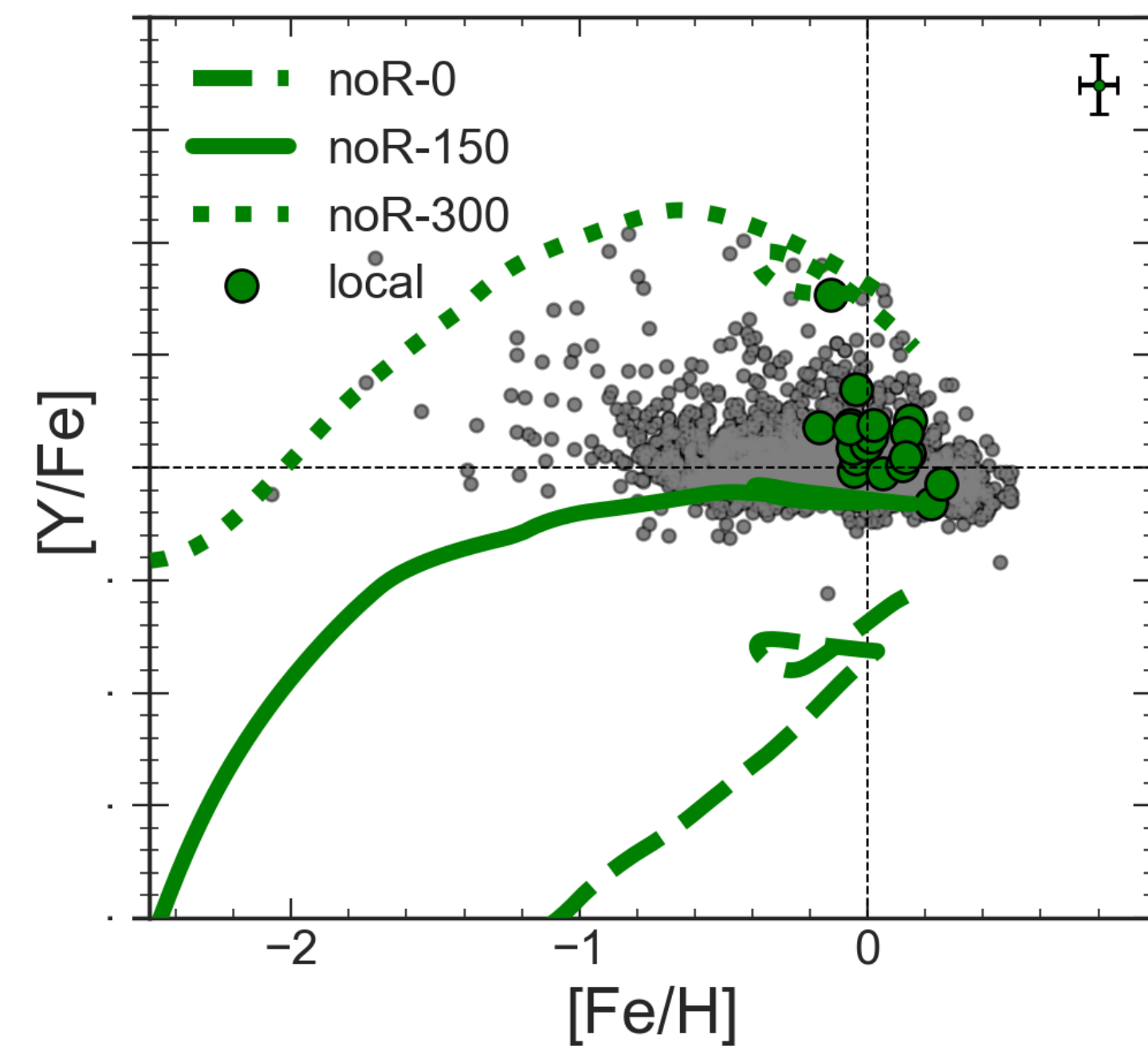
S-process

QUICK

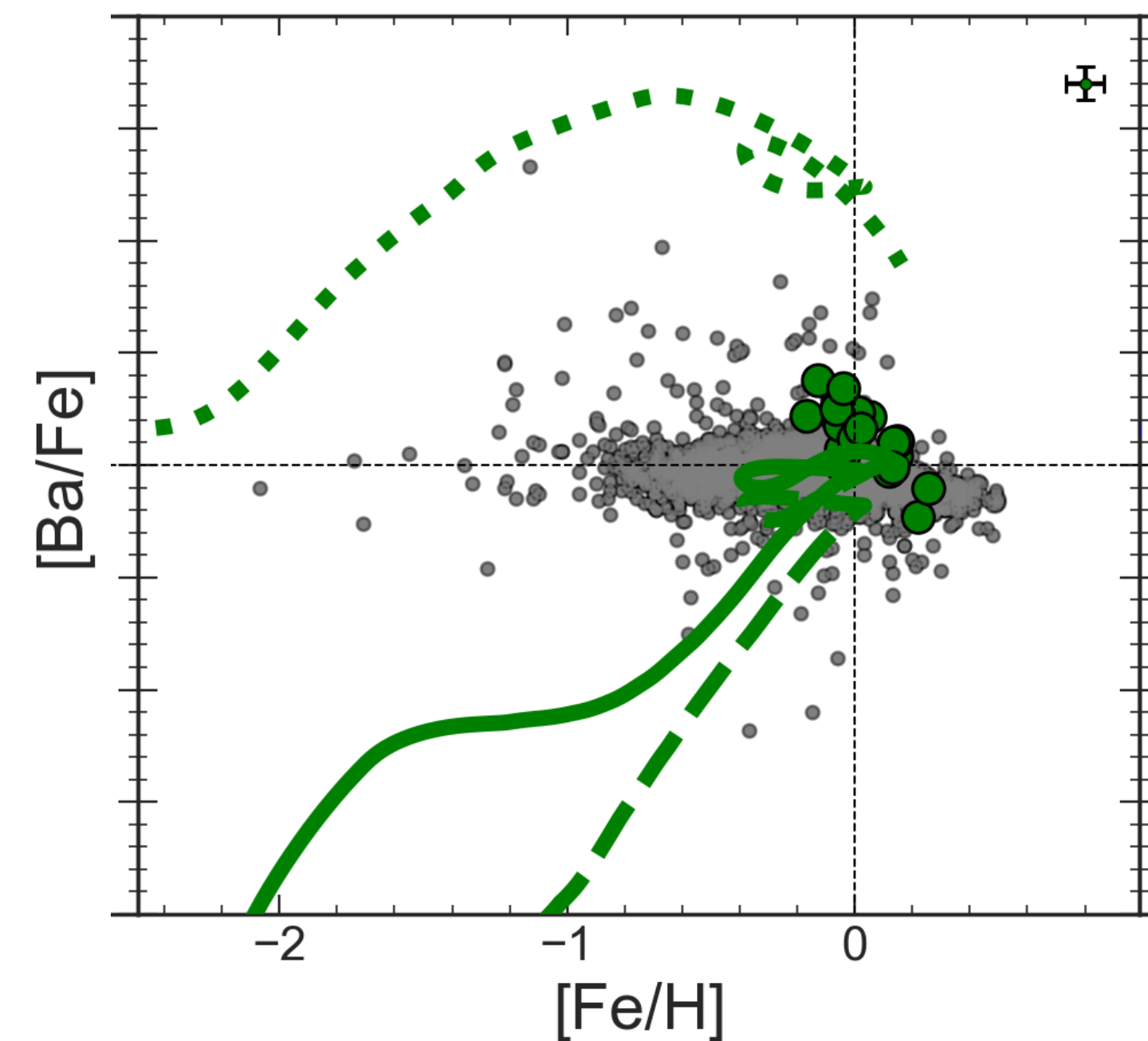
- Rotating massive stars : i) 36 progenitors yield grid (Limongi&Chieffi 2018)
ii) rate fine-tuned with observations

DELAYED

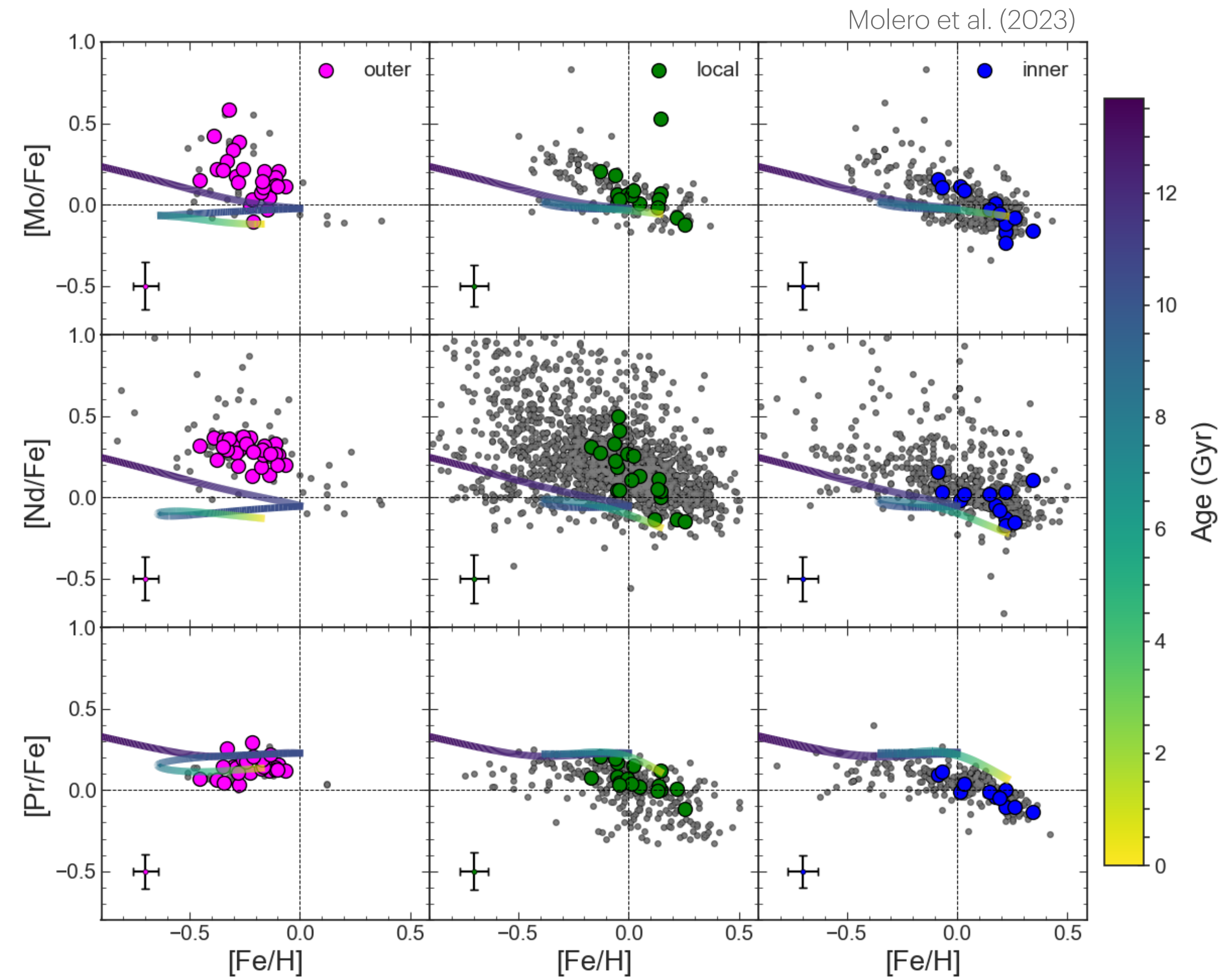
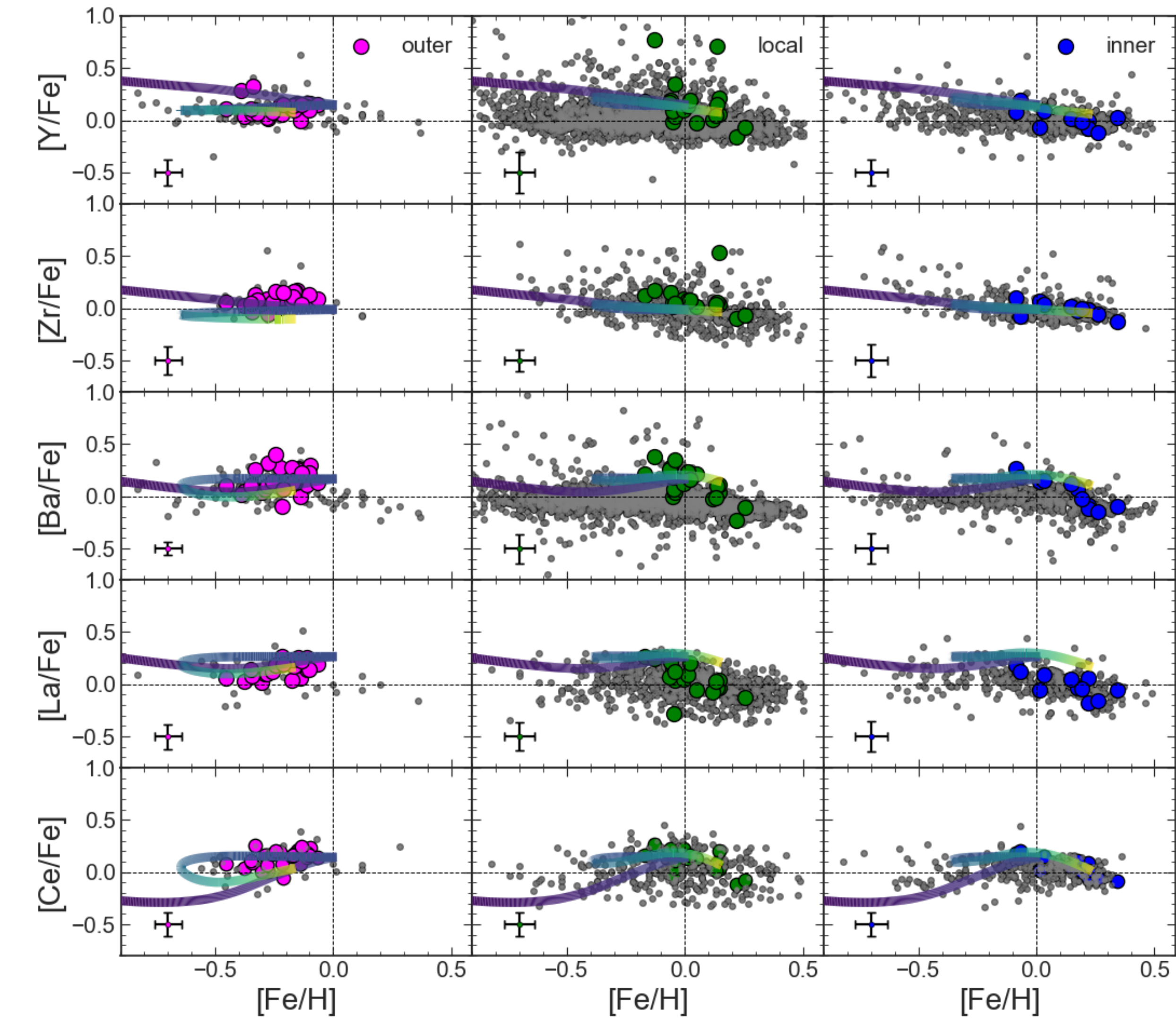
- AGB stars : i) large (108 progenitors) yield grid from FRUITY



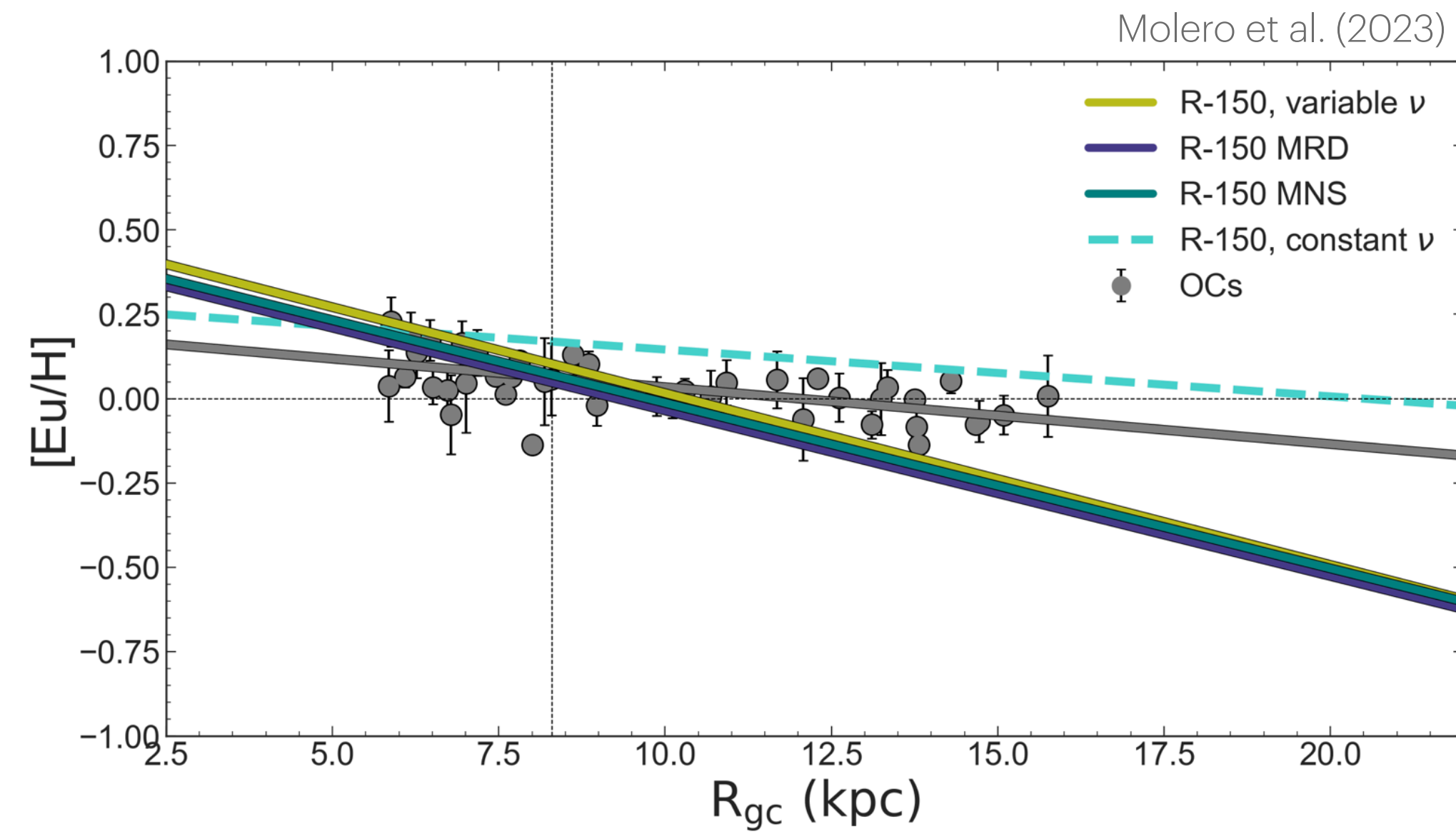
--- 0 km/s
— 150 km/s
... 300 km/s



Abundance patterns



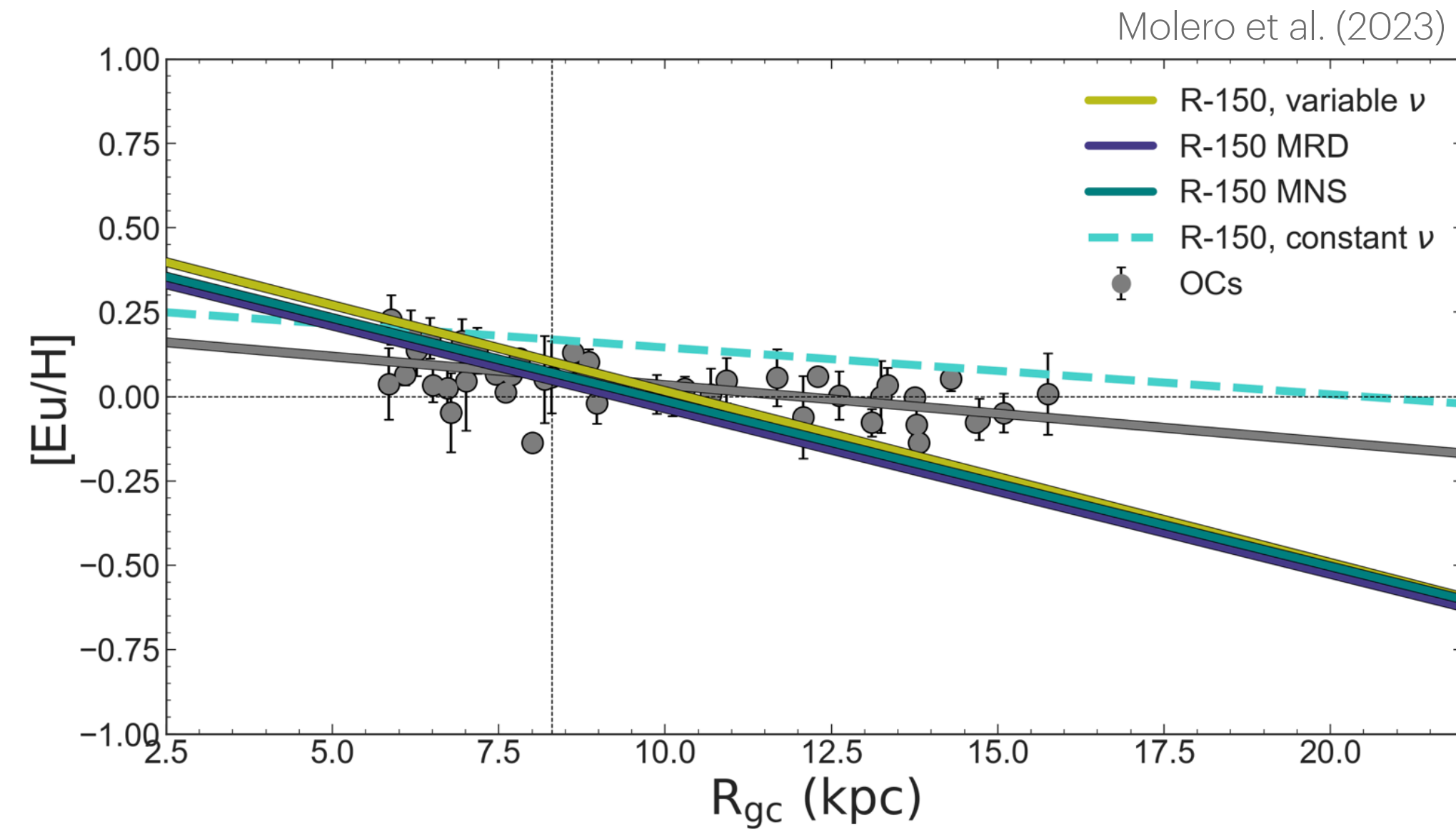
Abundance gradients



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

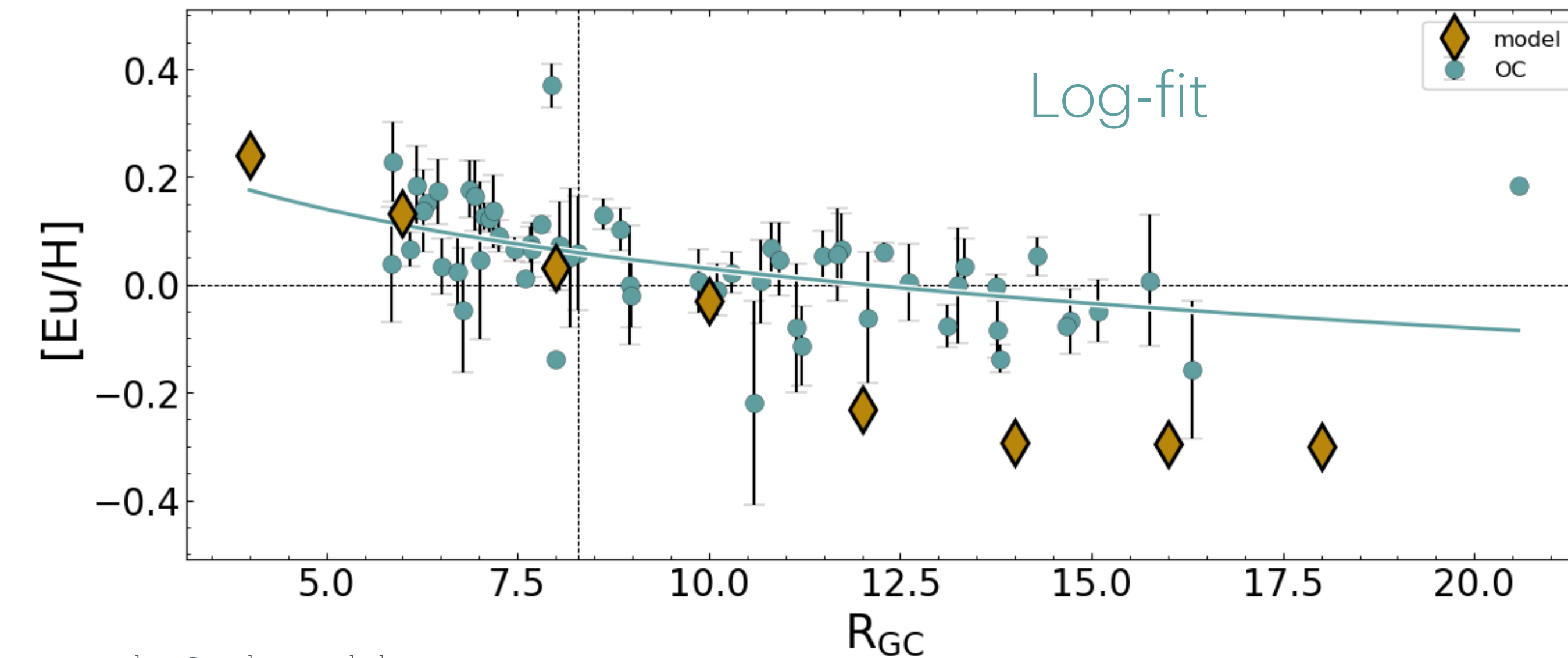
Model: $-0.050(\pm 0.003) \text{ dex kpc}^{-1}$

Abundance gradients

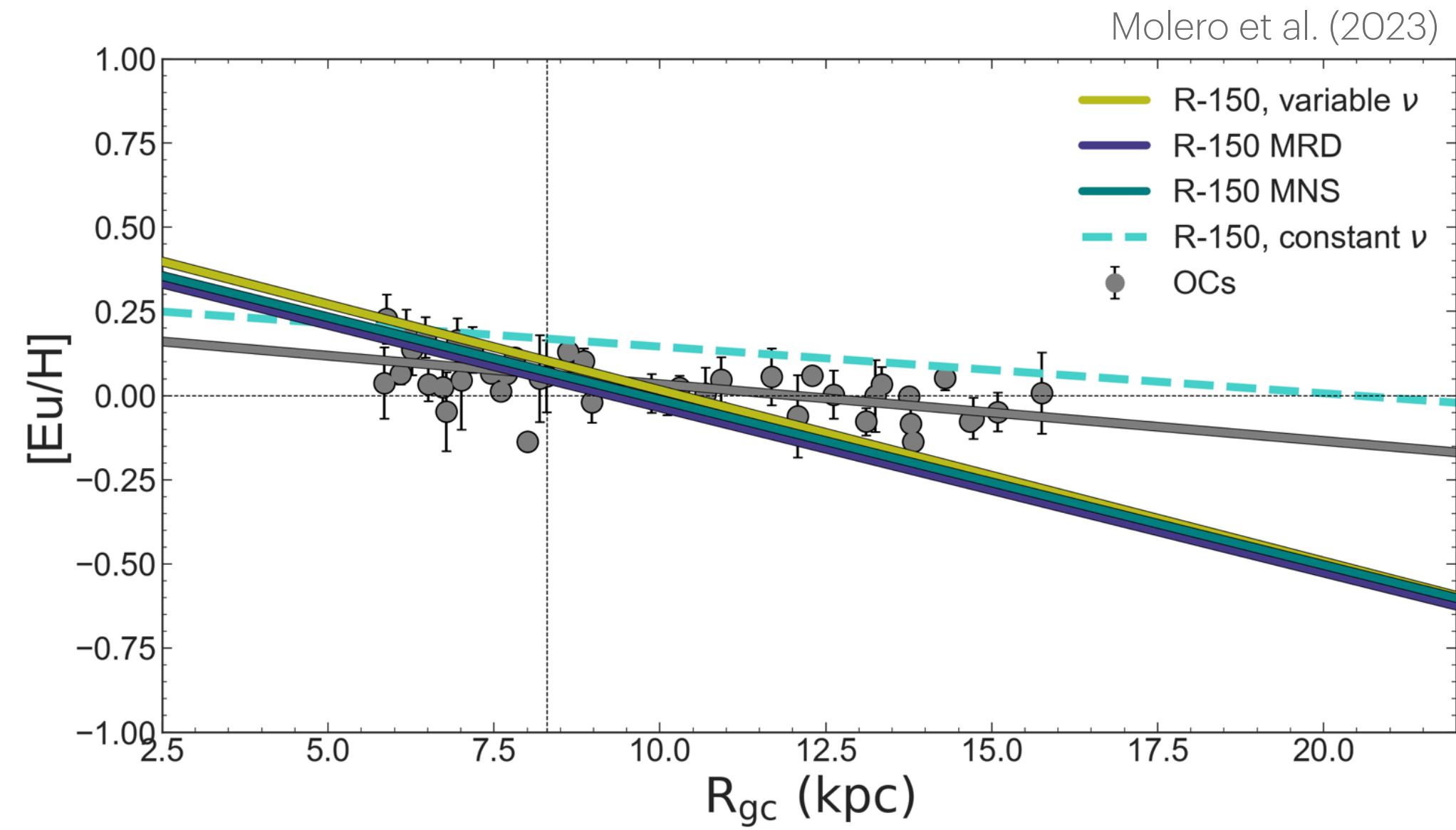


Observed: $[\text{Eu}/\text{H}] = -0.019(\pm 0.003) \times R_{GC} + 0.245(\pm 0.030)$

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

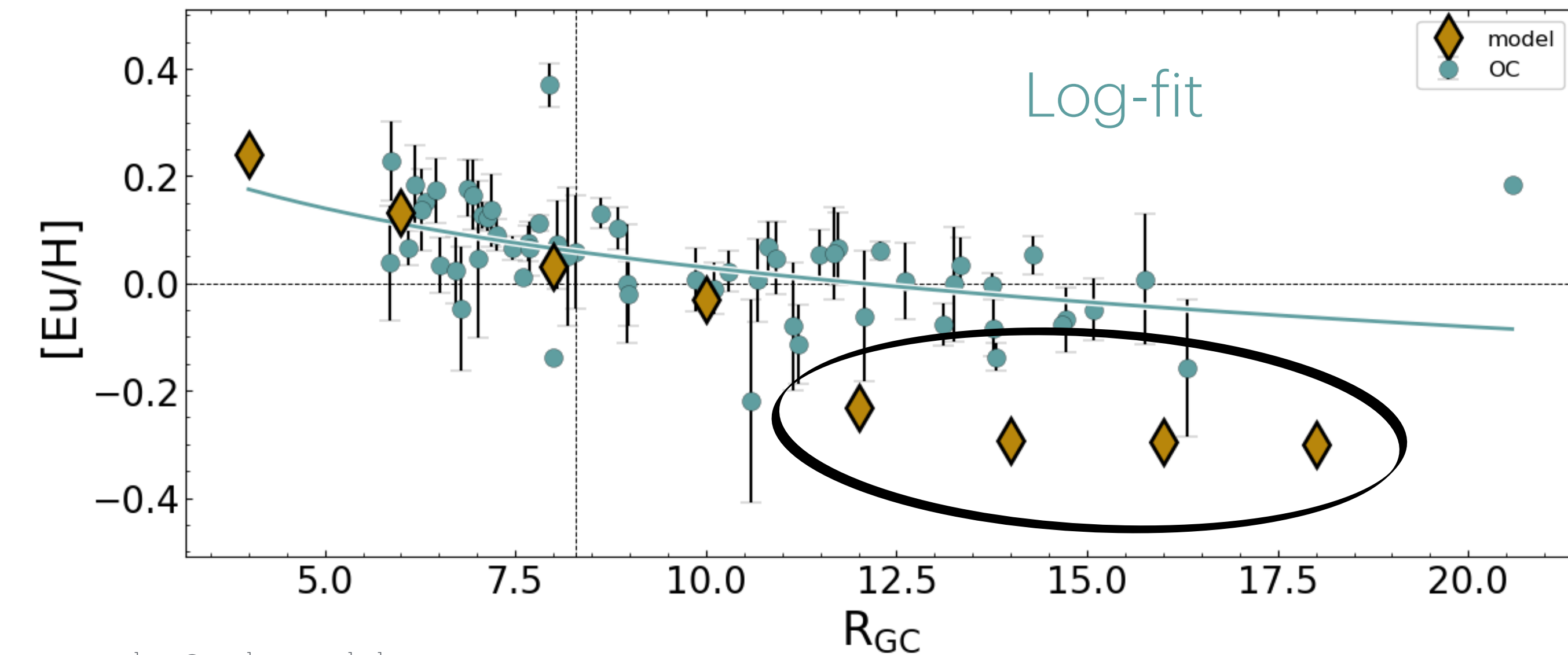


Abundance gradients

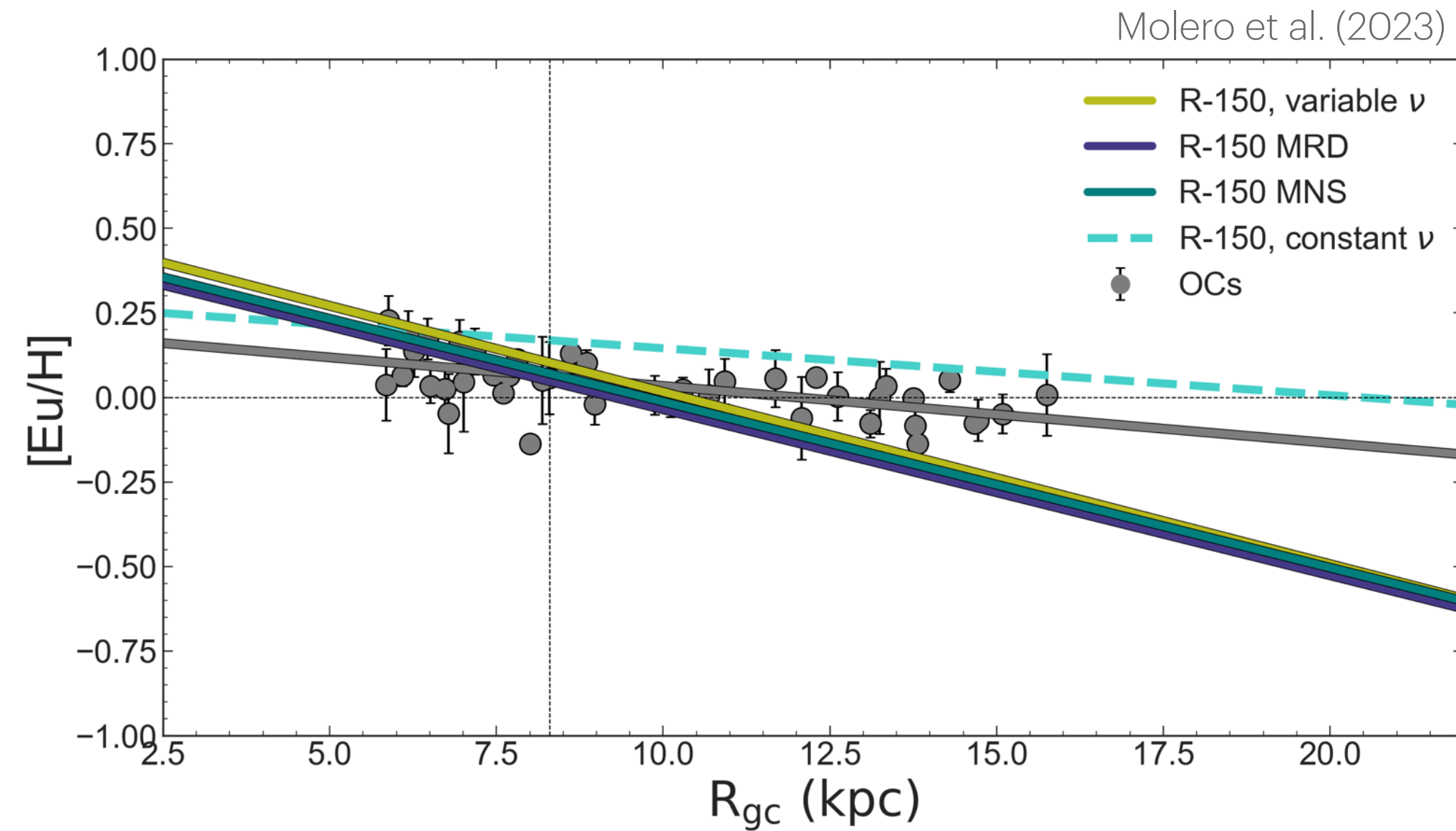


Observed: $[Eu/H] = -0.019(\pm 0.003) \times R_{GC} + 0.245(\pm 0.030)$

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



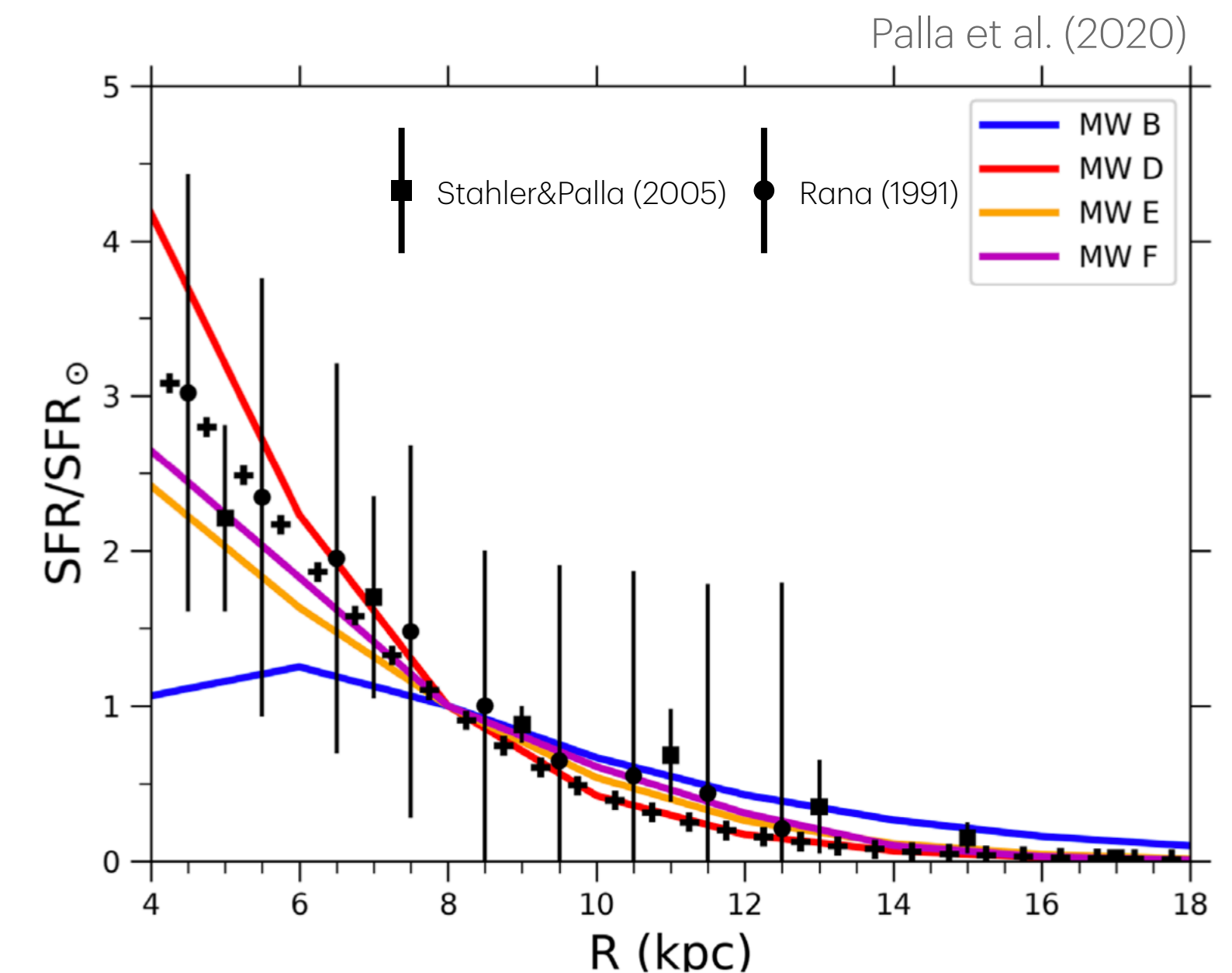
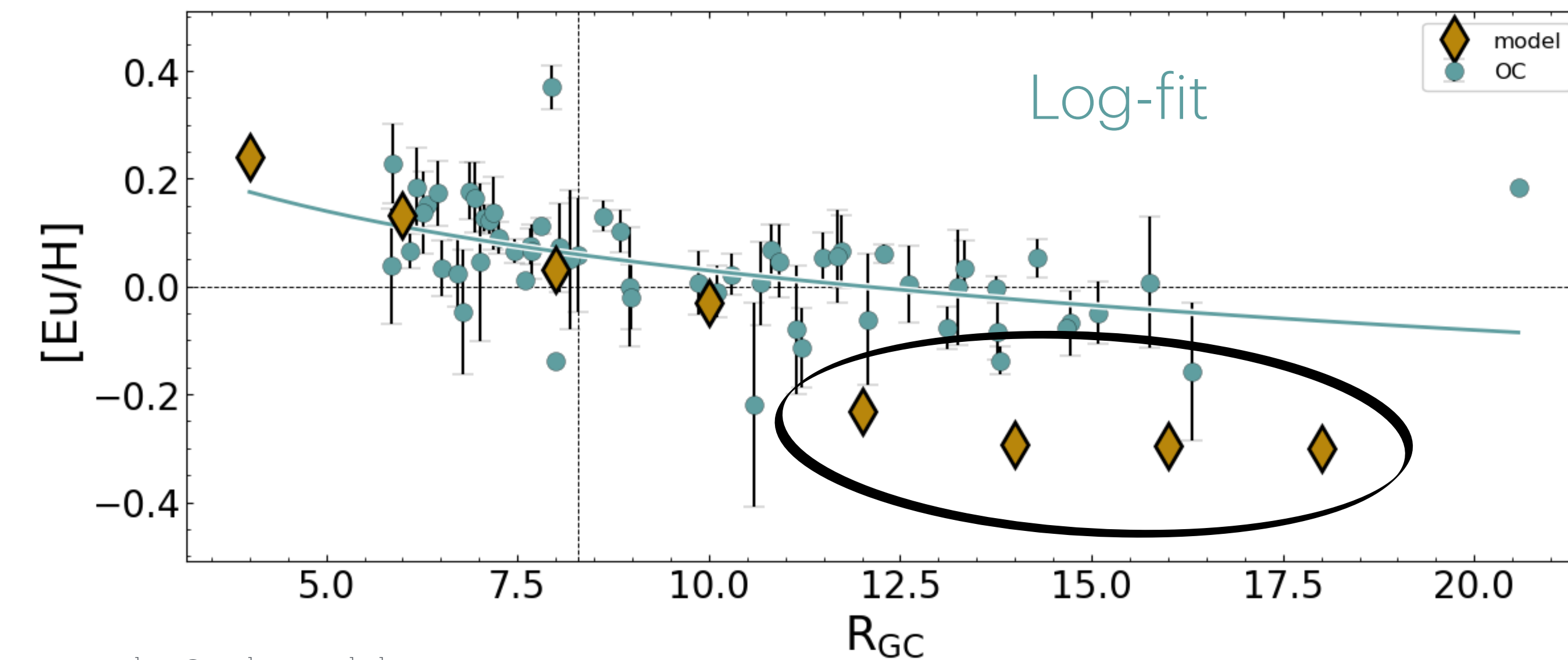
Abundance gradients



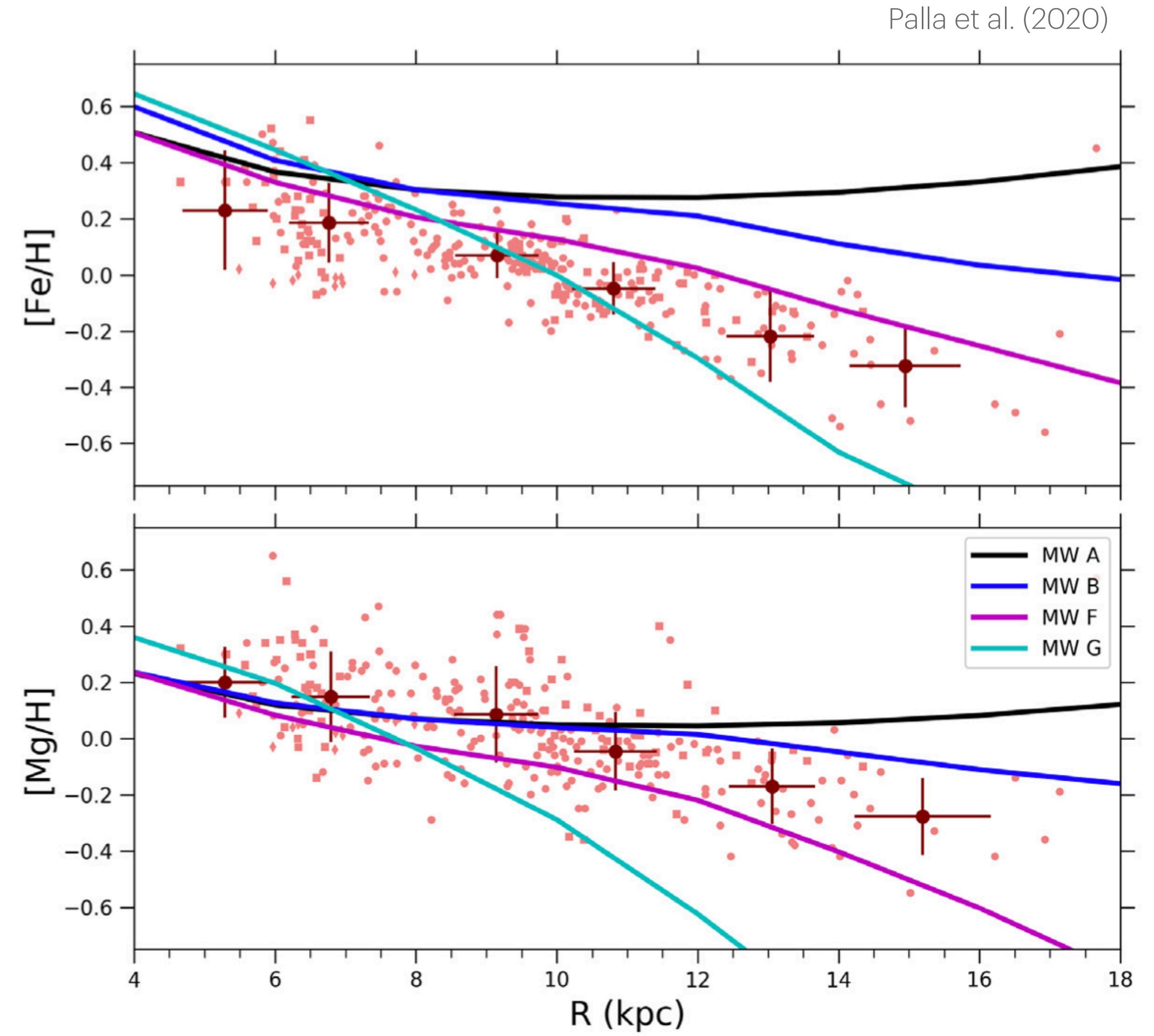
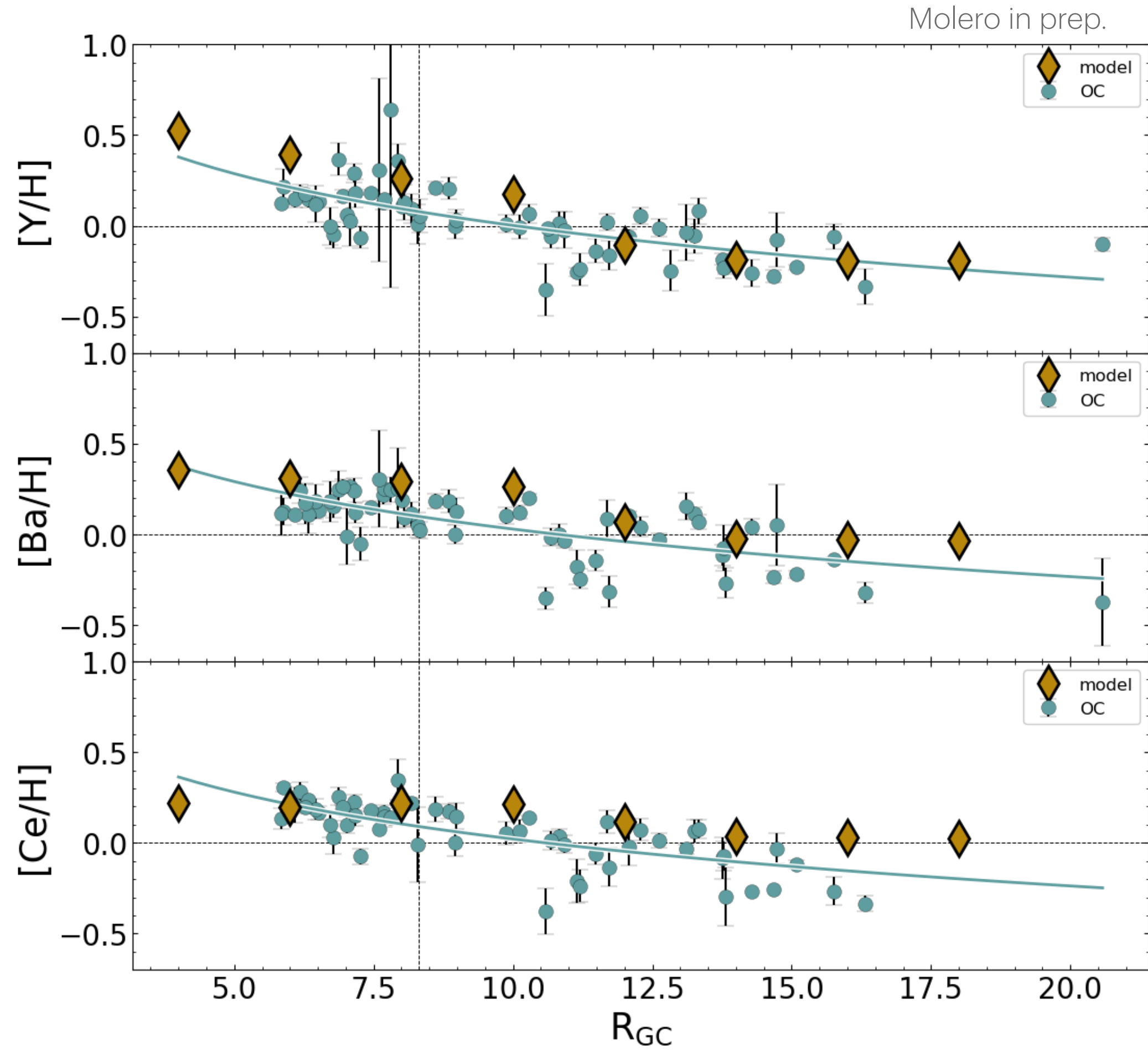
Observed: $[\text{Eu}/\text{H}] = -0.019(\pm 0.003) \times R_{GC} + 0.245(\pm 0.030)$

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

Inside out Galaxy formation

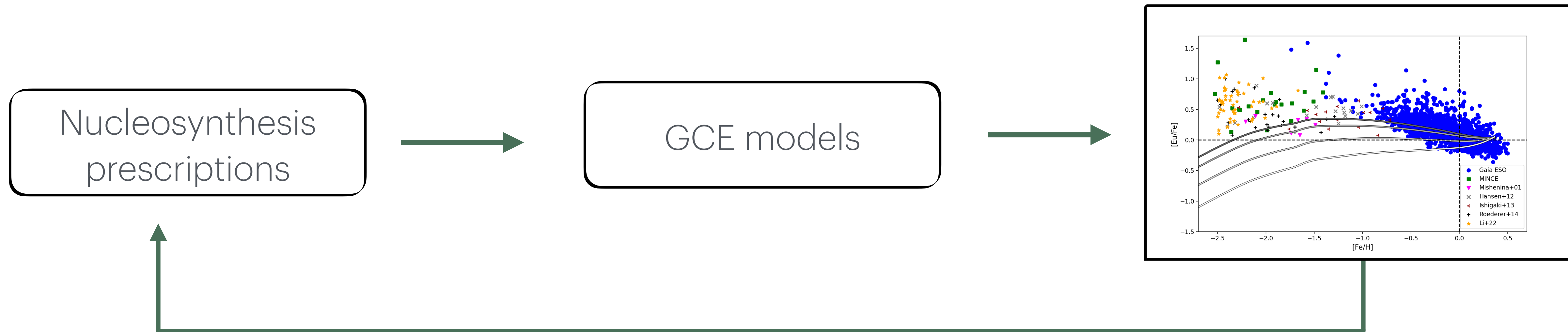


Abundance gradients



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?
- Homogenous models can explain the average trend neutron-capture elements? Gradients?
- Open questions still remain...