GALACTIC CHEMICAL EVOLUTION

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INTRODUCTION

- Galactic chemical evolution (GCE) models describe how the chemical composition of the interstellar medium (ISM) in galaxies changes with time and position, owing to several processes, such as accretion of gas and/or stars, star-formation activity, stellar feedback (mass and energy injection), radial motions of gas and stars, galactic fountains and/or outflows
- GCE has not (yet) the status of a full astrophysical theory: it provides a framework in which the observed chemical composition of stars and gas in galaxies can be interpreted. The reason for this is our poor knowledge of the main drivers of galaxy evolution

INVESTIGATION TOPICS

ORIGIN OF ELEMENTS

"The following question can be asked: What has been the history of the matter, on which we can make observations, which produced the elements and isotopes of that matter in the abundance distribution which observation yields? This history is hidden in the abundance distribution of the elements. To attempt to understand the sequence of events leading to the formation of the elements it is necessary to study the so-called universal or cosmic abundance curve.
Whether or not this abundance curve is universal is not the point here under discussion. It is the distribution for matter on which we have been able to make observations."

(Burbidge, Burbidge, Fowler & Hoyle 1957, Reviews of Modern Physics, 29, 547)

EVOLUTION OF GALAXIES

"… it should be clear that attempts to understand the evolution of stars and gas in galaxies inevitably get involved in very diverse aspects of astronomical theory and observation. This is not a field in which one can hope to develop a complete theory from a simple set of assumptions, because many relevant data are unavailable or ambiguous, and because galactic evolution depends on many complicated dynamical, atomic, and nuclear processes which themselves are incompletely understood…"

(Tinsley, 1980, Fundamentals of Cosmic Physics, 5, 287)

USEFUL NOTATION

In stellar astrophysics, it is customary to define abundance ratios and element abundances as follows:

$$[X/Y] = \log(N_X/N_Y)_{star} - \log(N_X/N_Y)_{sun}$$

$$A(X) = \log \epsilon\ (X) = \log(N_X/N_H)_{star} + 12$$

Here, N_X, N_Y, and N_H are the abundances by number

BASIC EQUATIONS AND ASSUMPTIONS

First attempts to model the chemical evolution of galaxies:

The Simple Model

Basic (unrealistic) assumptions:

- Closed-box system
- Instantaneous recycling approximation (IRA): all stars with $m \geq 1\ M_\odot$ die instantaneously, while all stars with $m < 1\ M_\odot$ live forever

Analytical solution possible!

Basic relation between global metallicity *(Z)* and gas fraction in the studied system

BASIC EQUATIONS AND ASSUMPTIONS

Classic, numerical GCE models relax the instantaneous recycling approximation (IRA, i.e., take the stellar lifetimes into account) and solve a set of integro-differential equations:

$$\frac{d\Sigma_i(r,t)}{dt} = -\psi(r,t)X_i(r,t) + R_i(r,t) + \frac{d\Sigma_{i,inf}(r,t)}{dt} - \frac{d\Sigma_{i,out}(r,t)}{dt}$$

$\Sigma_i(r,t) = \Sigma_{\rm gas}(r,t)\,X_i(r,t)$	surface mass density of element *i* at time *t*
$\Sigma_{\rm gas}(r,t)$	surface mass density of the ISM at time *t*
$X_i(r,t)$	abundance by mass of element *i* at time *t*
$\psi(r,t) = \nu(r)\Sigma^k_{\rm gas}(r,t)$	star formation rate (SFR) at time *t*
$R_i(r,t) = \int_{m(t)}^{m_U} \psi(r,t-\tau_m)Q_{mi}(t-\tau_m)\varphi(m)\,dm$	rate of restitution of element *i* by dying stars
$\varphi(m)$	stellar initial mass function (IMF, often assumed time and position invariant)
τ_m	lifetime of stars of initial mass *m*
$Q_{mi}(t-\tau_m)$	element production matrix

See e.g. Matteucci (2012, 2021)

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$$\frac{d\Sigma_{i,inf}(r,t)}{dt} = \Lambda \exp^{-t/\tau_{inf}(r)} X_{i,inf}$$

infall rate (usually, $X_{i,inf} = X_{i,P}$)

$$\Lambda = \frac{\Sigma_{inf}(r, t_{\rm now})}{\tau_{inf}(r)[1 - \exp^{-t_{\rm now}/\tau_{inf}(r)}]}$$

infall rate normalisation constant ($t_{\rm now}$ = 13.7 Gyr)

$$\frac{d\Sigma_{i,out}(r,t)}{dt} = w_i\,\psi(r,t)\,X_i(r,t)$$

outflow rate

w_i

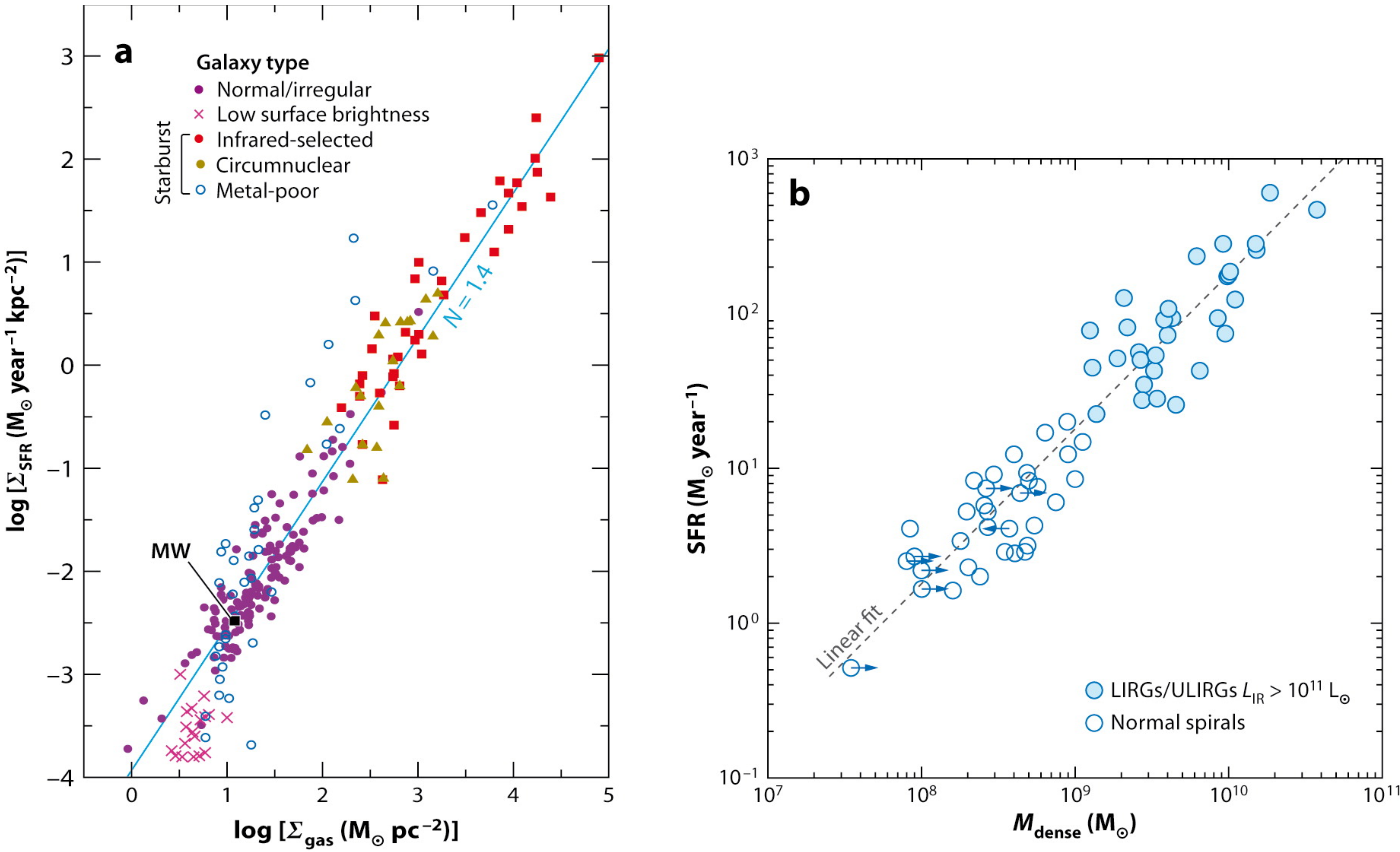
mass loading factor for element *i*

See e.g. Matteucci (2012, 2021)

BASIC EQUATIONS AND ASSUMPTIONS

STAR FORMATION RATE

- Schmidt (1959): $\Sigma_{\rm SFR} \propto \Sigma^n_{\rm H\,I}$
  $n = 1$—3 (2–3 in the ISM of the MW)
- Kennicutt (1989): $\Sigma_{\rm SFR} \propto \Sigma^n_{\rm H\,I+H_2}$
  $n = 1$—3
- Kennicutt (1998): $\Sigma_{\rm SFR} \propto \Sigma^n_{\rm H\,I+H_2}$
  $n = 1.4$
- Gao & Solomon (2004): $\Sigma_{\rm SFR} \propto \Sigma^n_{\rm H\,I+H_2}$
  $n = 1$ in dense gas



Kennicutt & Evans (2012)

BASIC EQUATIONS AND ASSUMPTIONS

GAS INFALL/ACCRETION

- Larson (1976), Matteucci & Francois (1989): inside-out formation of galactic discs, namely, $\tau_{inf}(r_{in}) < \tau_{inf}(r_{out})$

- Merger history from cosmological simulations (e.g., Kruijssen et al. 2020)

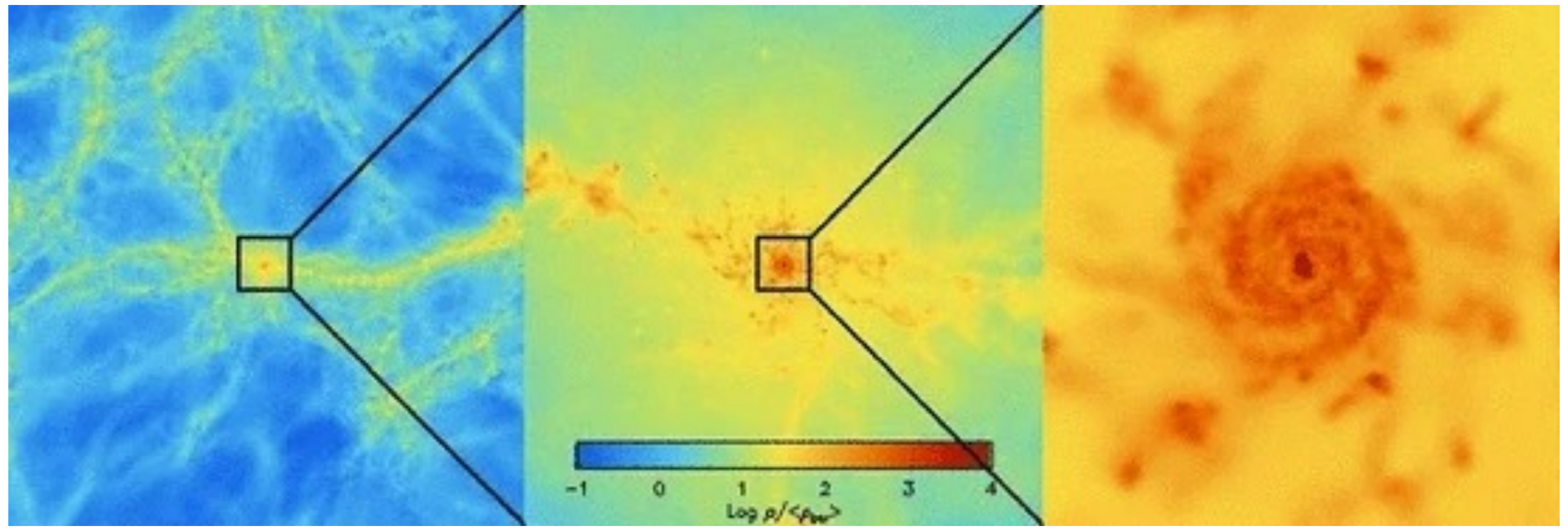


Figure from Schaye et al. (2010)

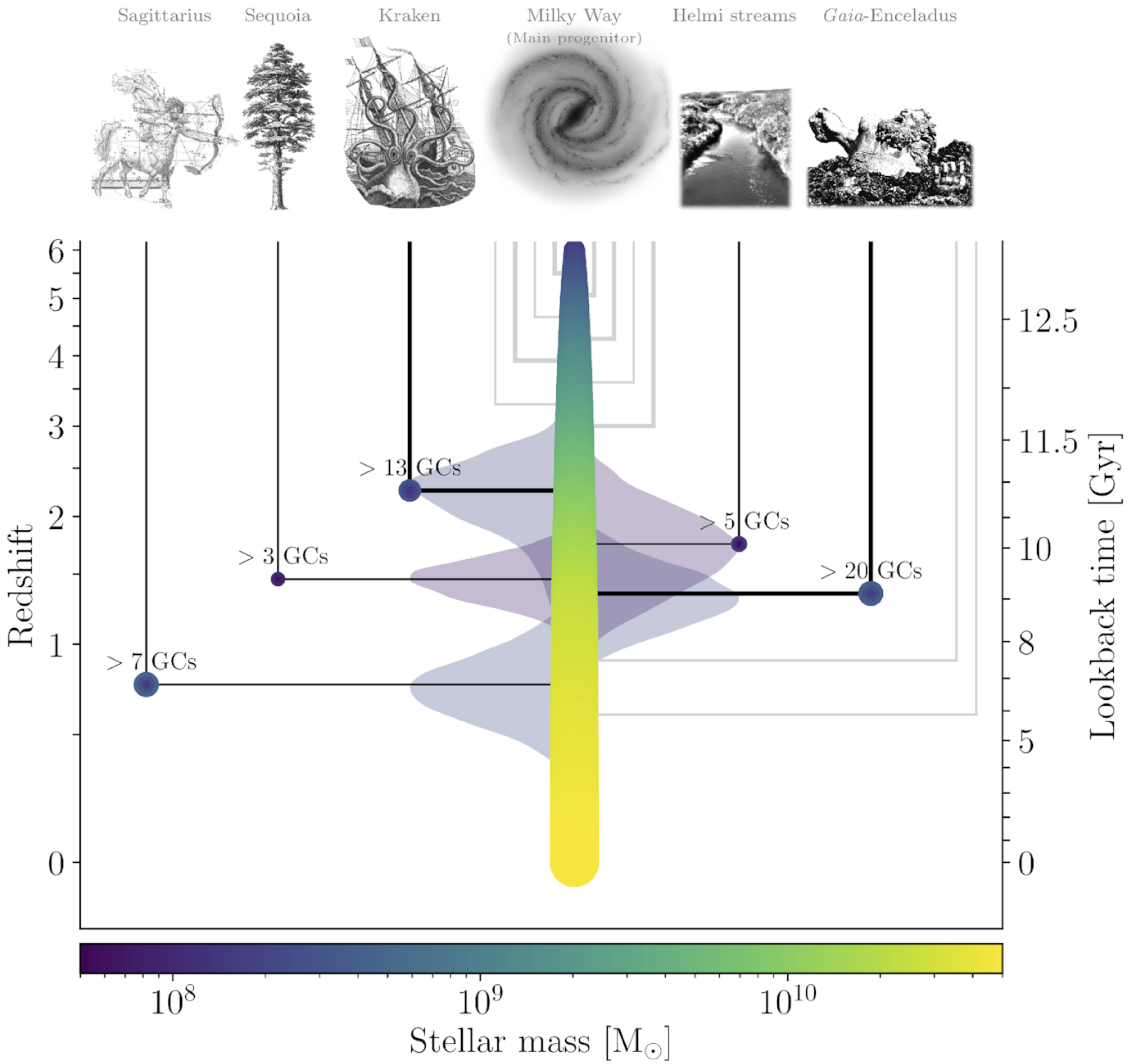


Figure from Kruijssen et al. (2020)

ELEMENT PRODUCTION SITES

- Big Bang nucleosynthesis: H, D, ^{3}He, ^{4}He, ^{6}Li, ^{7}Li (e.g., Pitrou et al. 2021)
- Cosmic ray spallation processes in the ISM: Li, Be, B (e.g., Meneguzzi et al. 1971; Lemoine et al. 1998)
- Single low- and intermediate-mass stars (1–8 $M_\odot$): ^{3}He, ^{4}He, ^{12}C, ^{13}C, ^{14}N, ^{17}O, F, s-process elements (Sr, Y, Zr, Ba, Pb, …)
  (e.g., Cristallo et al. 2009, 2011, 2015; Lagarde et al. 2012; Ventura et al. 2013, 2018, 2020, 2021; Karakas & Lugaro 2016; Cinquegrana & Karakas 2022)
- Binary low- and intermediate-mass stars: novae: ^{7}Li, ^{13}C, ^{15}N, ^{17}O (+ ^{26}Al, ^{60}Fe) (e.g., José & Hernanz 1998; José et al. 2020; Starrfield et al. 2020)
- Binary low- and intermediate-mass stars: SNeIa: Si, S, Ca, Ti, V, Cr, Mn, Fe, Ni, Co, Cu, Zn (e.g., Iwamoto et al. 1999; Leung & Nomoto 2018, 2020; Seitenzahl et al. 2013)
- Electron-capture supernovae (8–10 $M_\odot$): 1st peak s-process elements (Sr, Y, Zr, …) (e.g., Poelarends et al. 2008; Doherty et al. 2015; Jones et al. 2019)
- Massive stars ($M > 10\ M_\odot$): ^{4}He, ^{7}Li (?), ^{12}C, ^{13}C, ^{14}N, ^{15}N (?), ^{17}O, ^{18}O, F, Na, Al, α, Fe-peak, s- and r-process elements (e.g., Heger & Woosley 2010; Nomoto et al. 2013; Pignatari et al. 2015; Nishimura et al. 2017; Limongi & Chieffi 2018)
- Compact binary mergers: r-process elements (e.g., Lattimer & Schramm 1974, 1976; Hotokezaka et al. 2013; Rosswog 2013)

STELLAR YIELD GRIDS

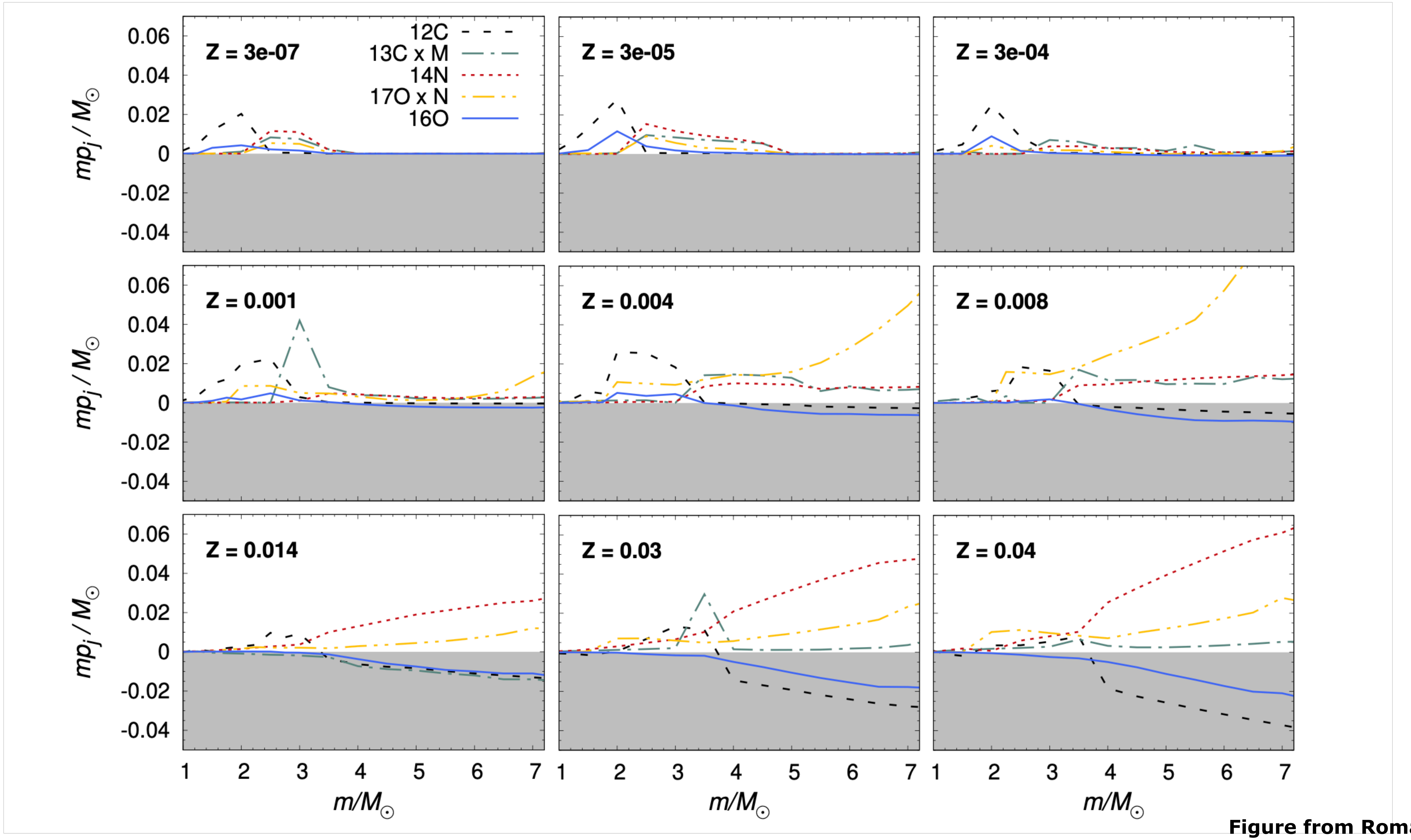


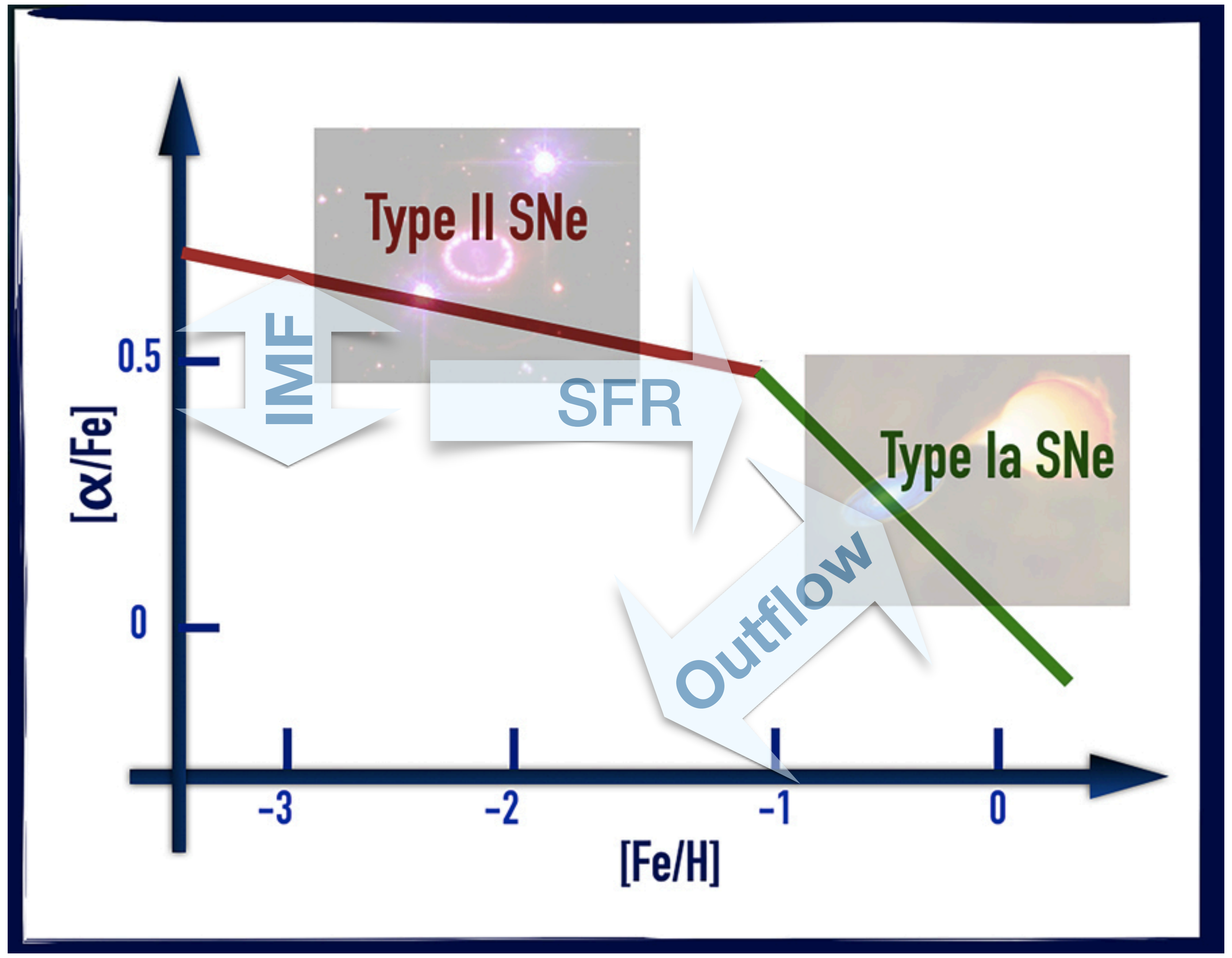
Figure from Romano (2022, A&ARv)

BARYON CYCLING AND CHEMICAL ENRICHMENT

SO WHAT CAN I DO WITH A GCE MODEL?

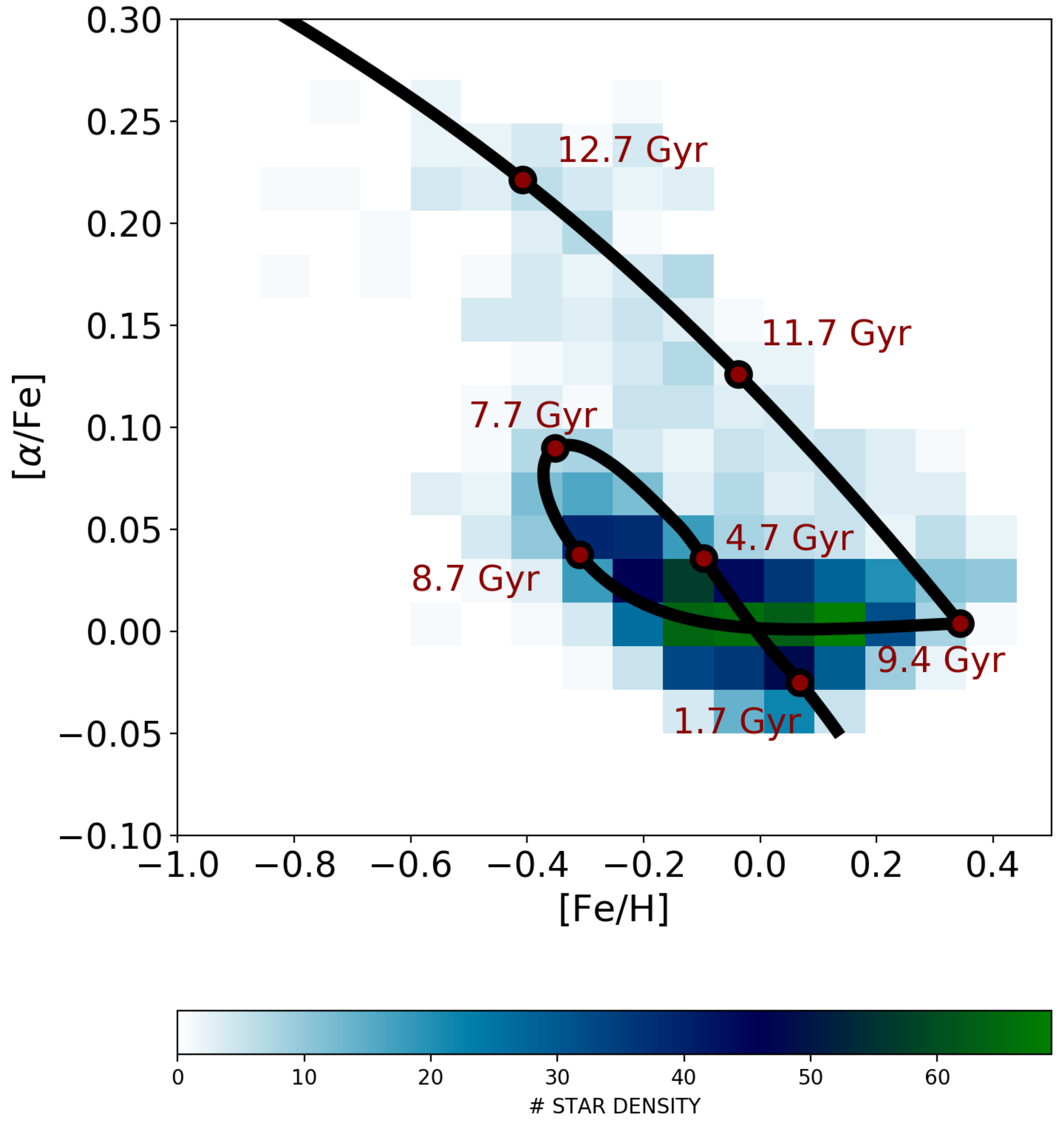
A GCE model allow you to:

- constrain stellar evolution and nucleosynthesis theory in a statistical way, by comparing the predictions obtained using different stellar yields to the average abundance trends observed in different galaxies/galactic components
- establish a chronology of events (basing on when a given stellar source is expected to contribute significantly to a given element)
- infer how a system was formed, by constraining the roles of any gas infall/outflow



MILKY WAY MODELS

Benchmark GCE model: two-infall model. The Galaxy forms out of two main sequential accretion episodes: the first forms the inner halo and thick disc, the second forms the thin disc on much longer timescales.



On the left: the observed density of stars in the [α/Fe]—[Fe/H] space for the APOKASC stars by Silva Aguirre et al. (2018), compared with the latest version of the two-infall **GCE model for the solar neighbourhood**. Filled red circles indicate the abundance ratios of the chemical evolution model at the given age. The area of each bin is fixed at the value of (0.083 dex)×(0.02 dex).

NB1: the updated APOKASC (APOGEE + *Kepler* Asteroseismology Science Consortium) sample presented by Silva Aguirre et al. (2018) is composed by 1989 red giant stars with stellar properties from a combination of spectroscopic, photometric, and asteroseismic observables.

NB2: the adopted stellar yields are *empirical* yields based on the fit of a set of observed stellar abundances (François et al. 2004).

Figure from Spitoni et al. (2019)

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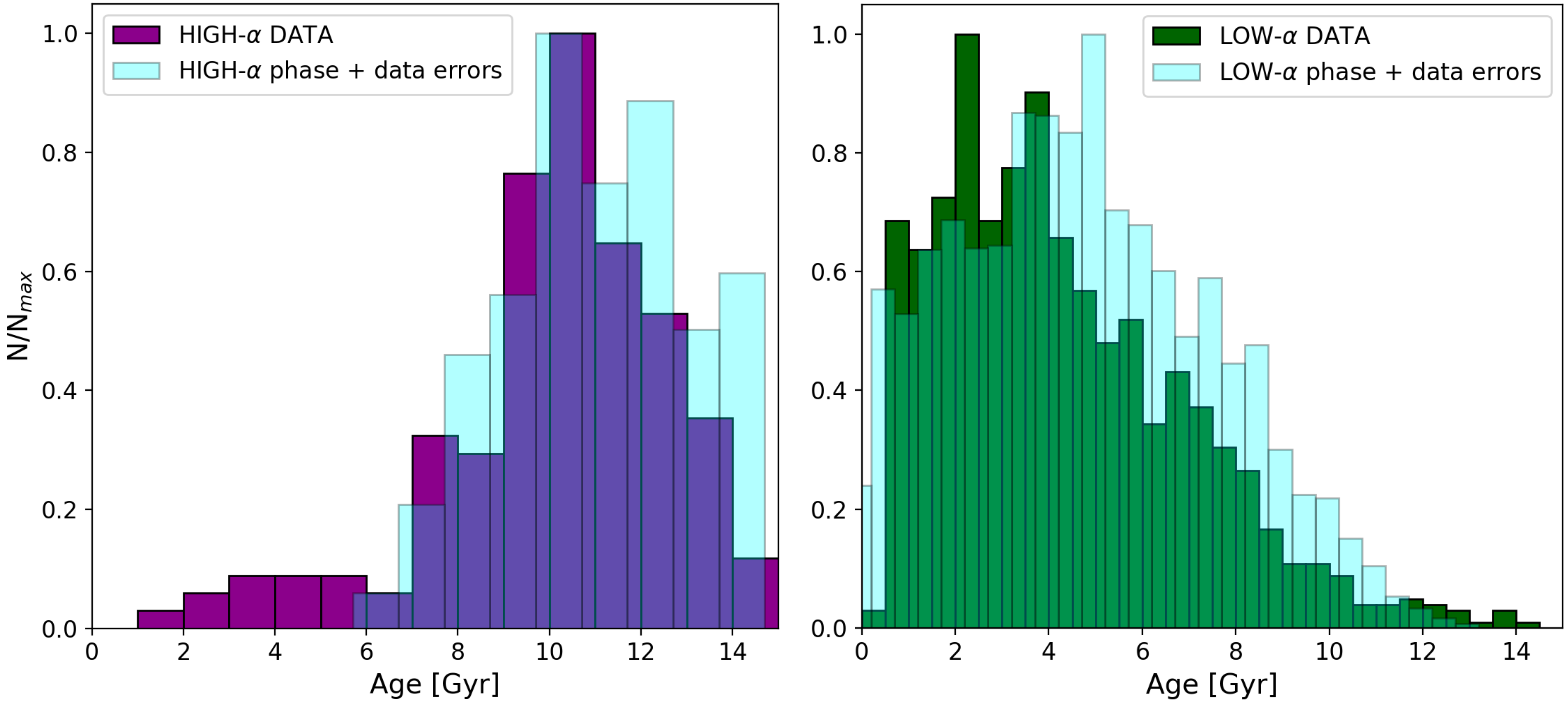

Model predicted age distributions (cyan histograms) for the high-α and low-α components, compared to the APOKASC data (left and right panels, respectively).

Figure from Spitoni et al. (2019)

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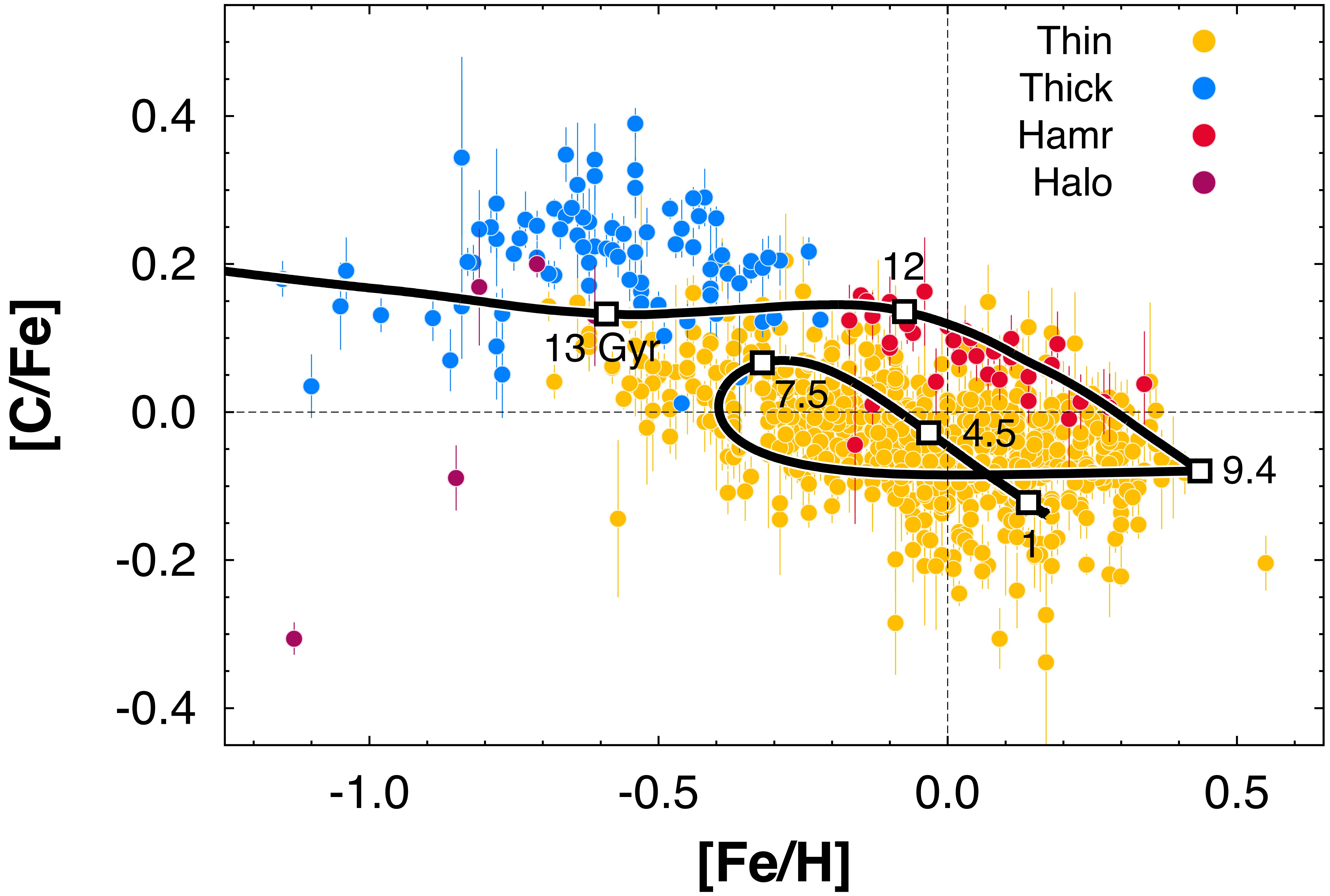
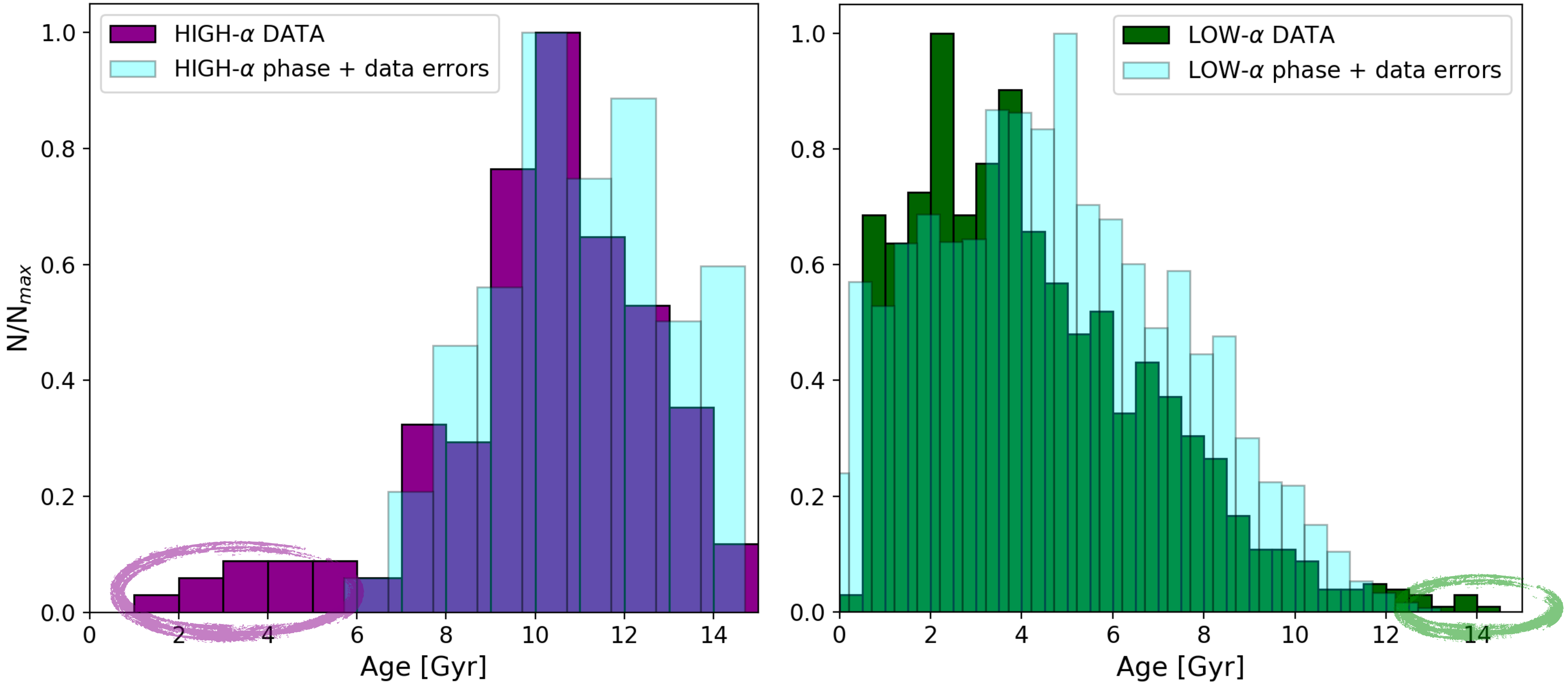


On the left: [C/Fe] vs [Fe/H] trend predicted by the two-infall model with nucleosynthesis prescriptions from full stellar evolution and nucleosynthesis theory compared to data for 757 nearby dwarf stars (Delgado-Mena et al. 2021). The stellar yields are from Ventura et al. (2013, 2014, 2018, 2020, 2021) for low- and intermediate-mass stars and from Limongi & Chieffi (2018) for massive stars.

Figure from Romano (2022, A&ARv)

MILKY WAY MODELS

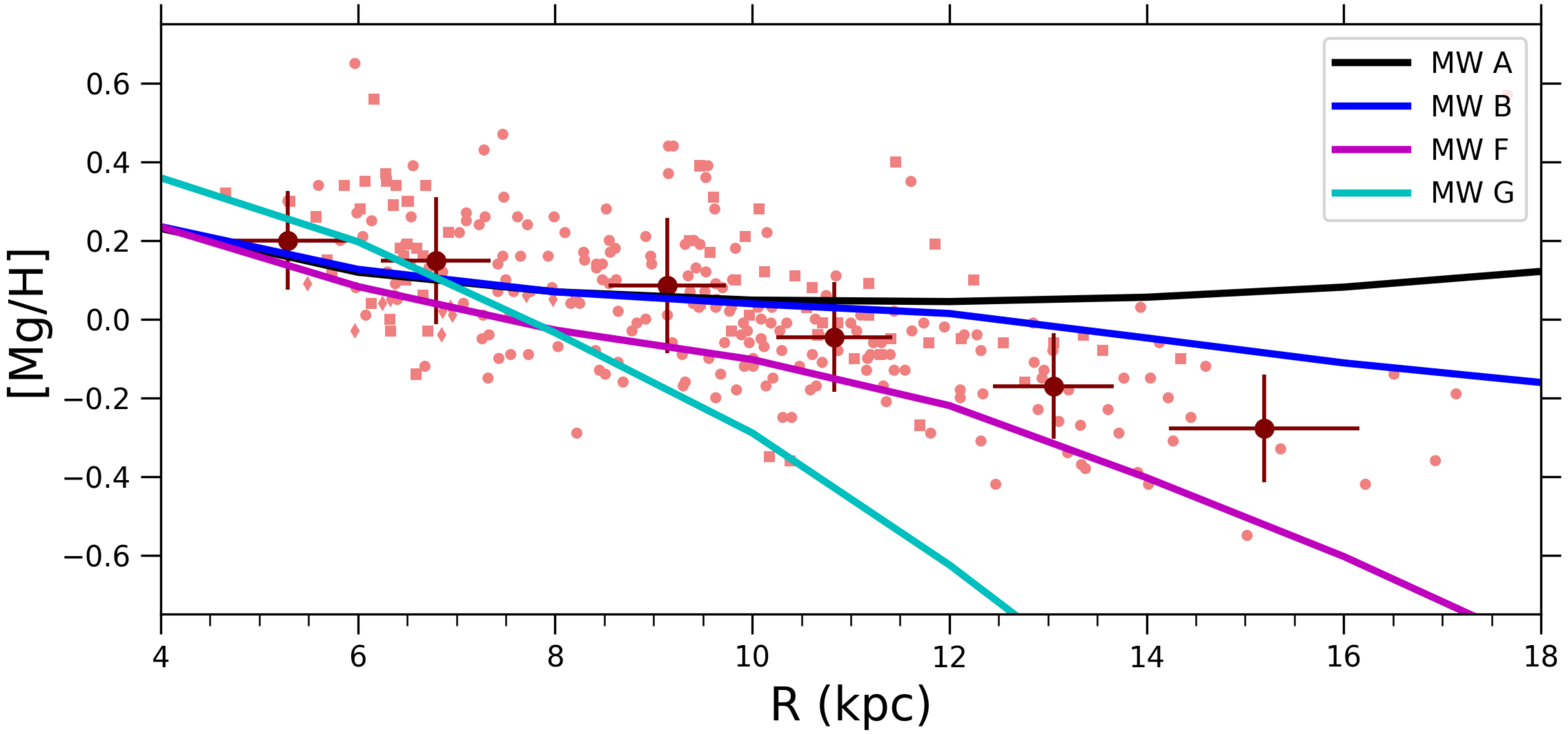
Problem: temporal overlap of thick- and thin-disc components?



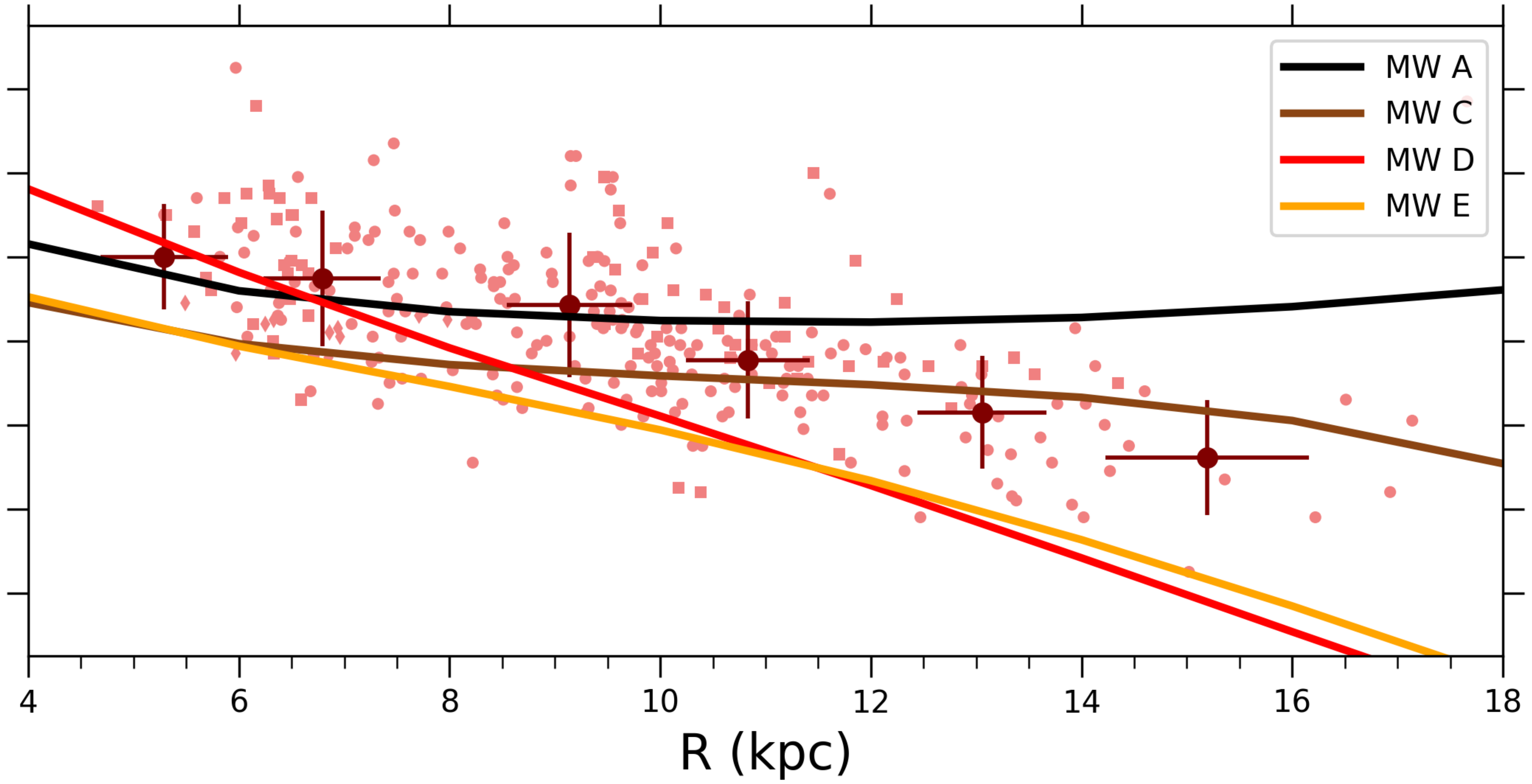
MILKY WAY MODELS

Abundance gradients: inside-out disc formation (Larson 1976; Matteucci & François 1989) is not enough!

VARIABLE STAR FORMATION EFFICIENCY



RADIAL GAS FLOWS

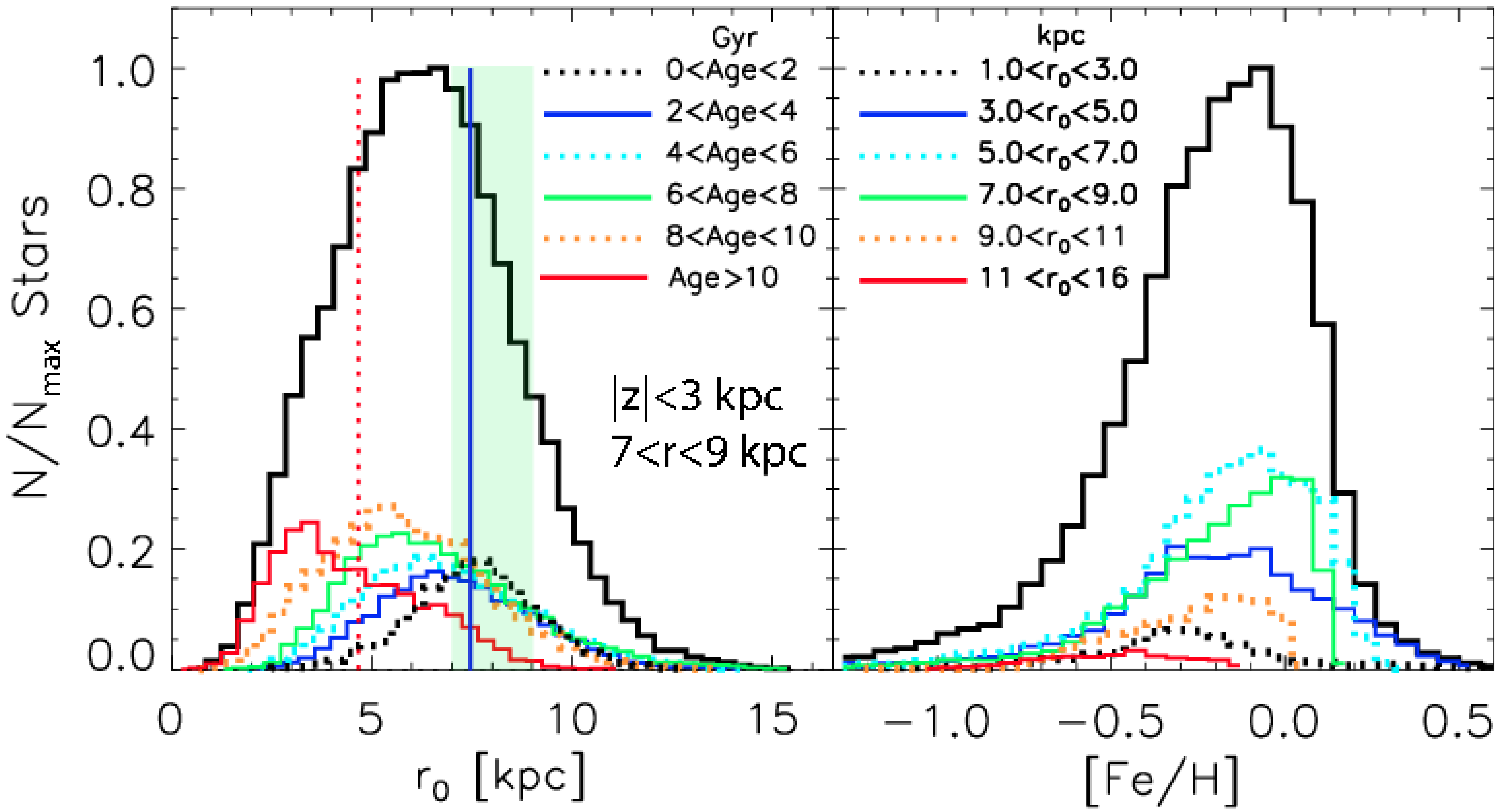


Observed (dots) and predicted (lines) **radial abundance gradients** for magnesium. Model MW A considers inside-out formation only. Models MW B, F, G consider also a variable star formation efficiency. Models MW C, D, E consider also radial gas flows.

Figure from Palla et al. (2020)

MILKY WAY MODELS

… and stars may move: Schoenrich & Binney (2009); Minchev et al. (2013); Kubryk et al. (2015a,b); Spitoni et al. (2015); Vincenzo & Kobayashi (2020)…

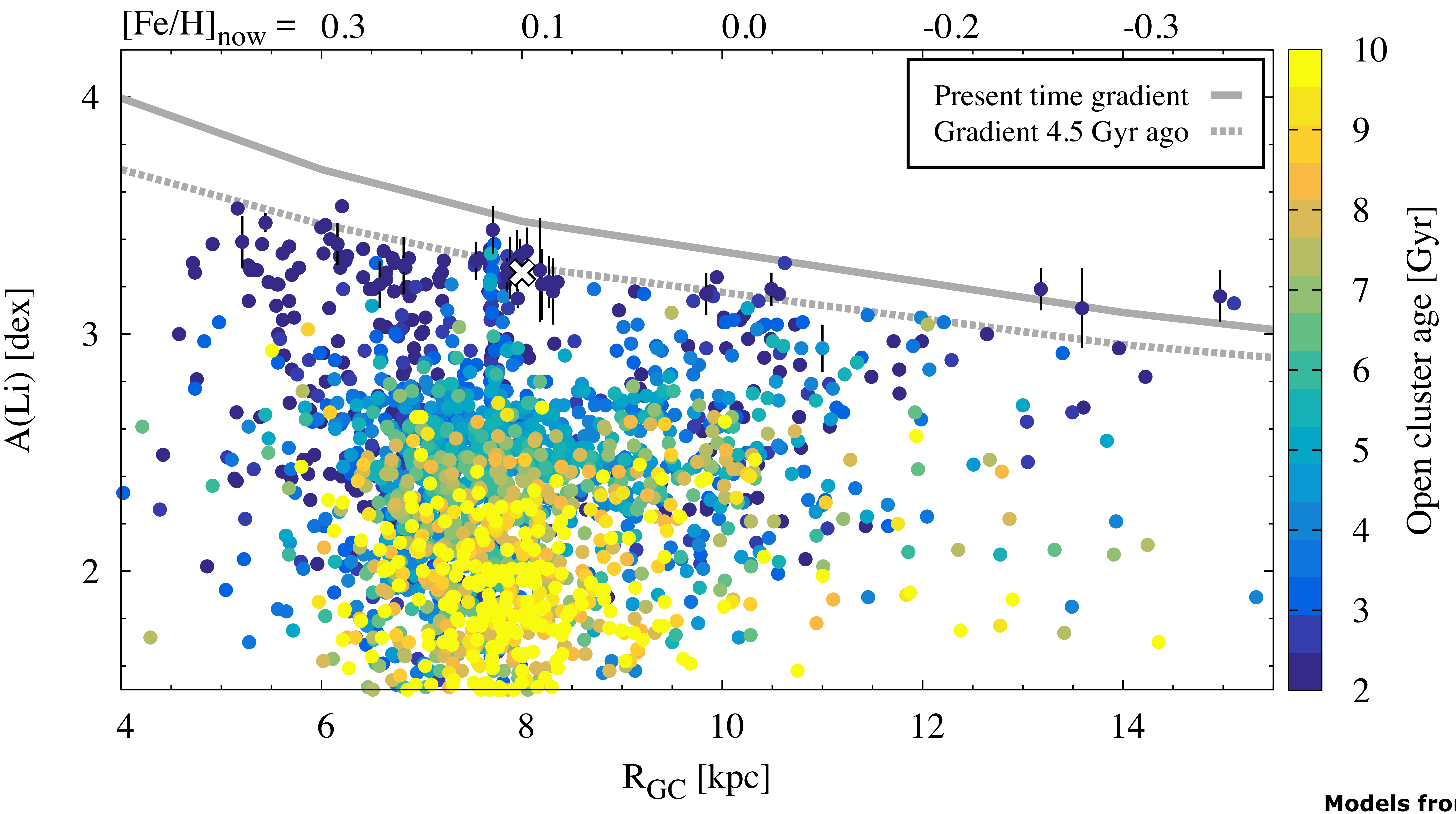


Left: birth radii of stars now found in the solar vicinity (green shaded strip). The solid black curve plots the total distribution, while the colour-coded curves show the distributions in six different age groups. The dotted-red and solid-blue vertical lines indicate the positions of the bar's corotation resonance (CR) and outer Lindblad resonance at the final simulation time. Middle: [Fe/H] distributions for stars ending up in the solar vicinity. The importance of the bar's CR is seen in the large fraction of stars with 3 < r0 < 5 kpc (blue line).

Figure from Minchev et al. (2013)

MILKY WAY MODELS

… and stars age: their atmospheric composition can change



Models from Romano et al. (2021)

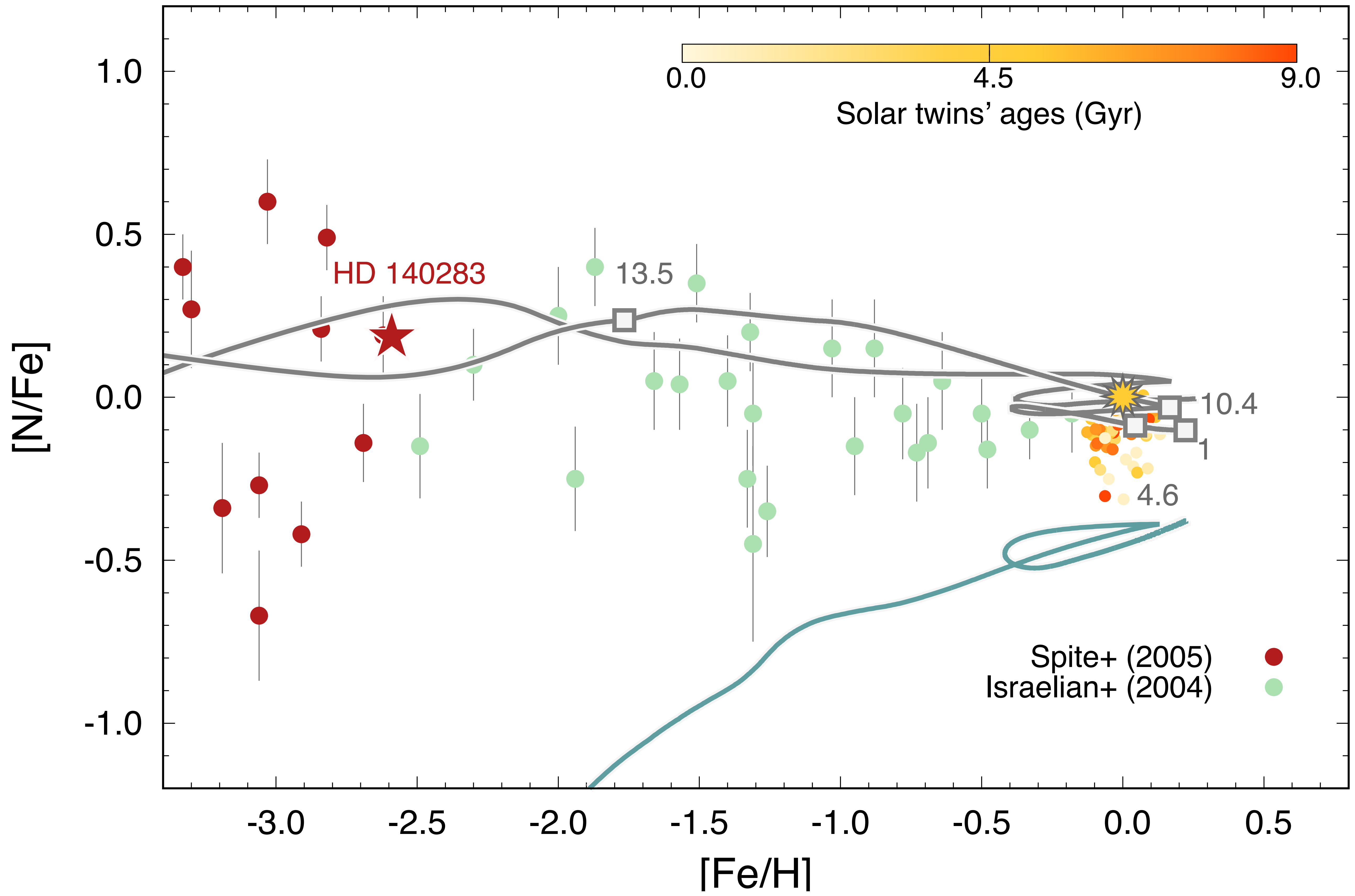
WHAT'S NEXT?

A golden era for GCE studies:

Precise stellar astrometry (Gaia) & stellar ages (Kepler, TESS, PLATO...)
Large spectroscopic surveys (Gaia-ESO Survey, APOGEE, GALAH, WEAVE, 4MOST...)
New instrumentation (MOONS, ANDES, CUBES, HRMOS...)

Chemical abundances measured in high-redshift galaxies (JWST, ALMA): a new window on the earliest phases of chemical enrichment!

IMPROVED MODELS



— Large scatter in N abundances of unevolved stars (which shouldn't be affected by stellar evolution…)

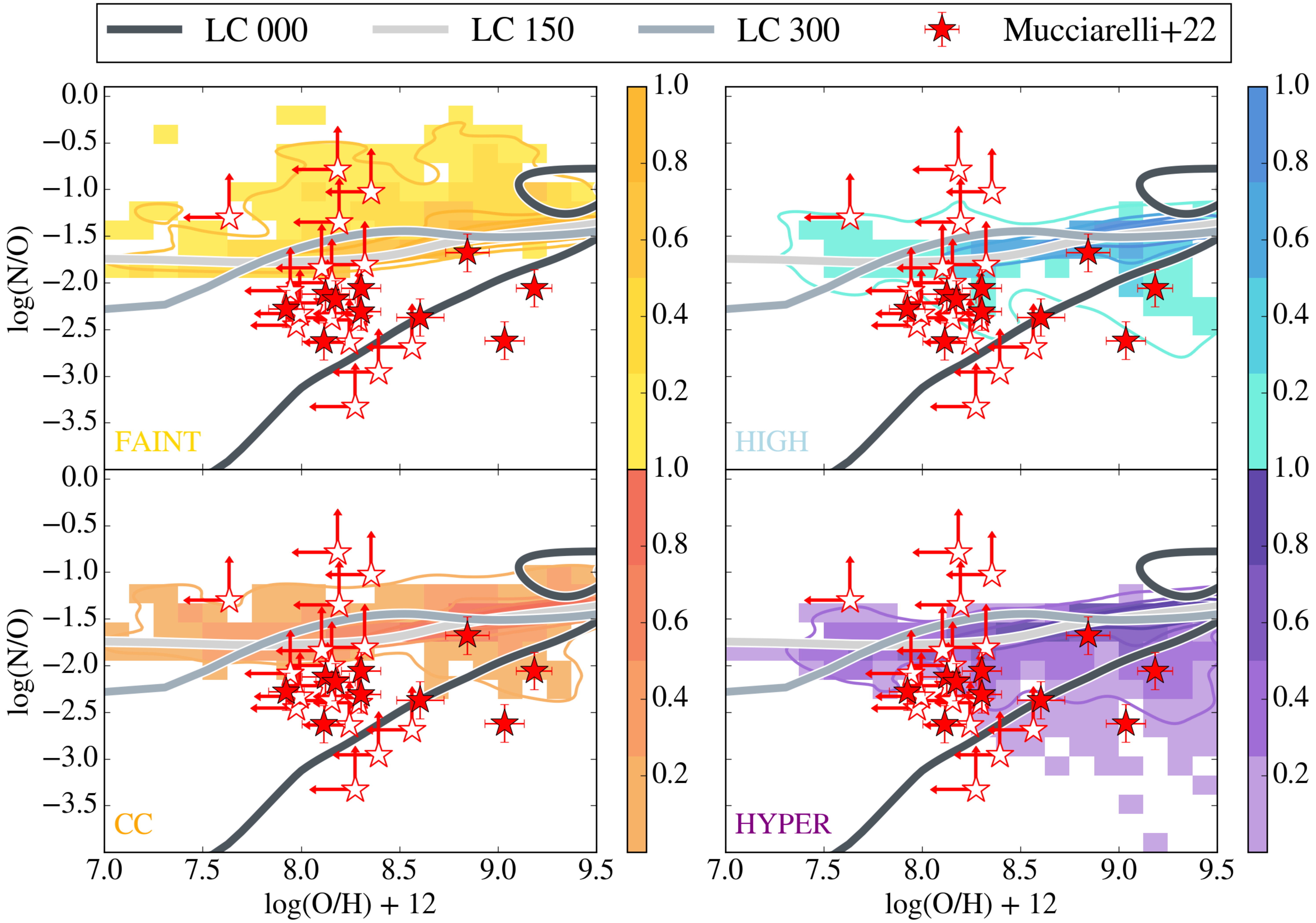
— Is the dispersion real?

— Is the dispersion due to pollution from stars rotating with different initial rotational velocities?

Inhomogeneous chemical evolution

(Martina Rossi, postdoc @ INAF-OAS)

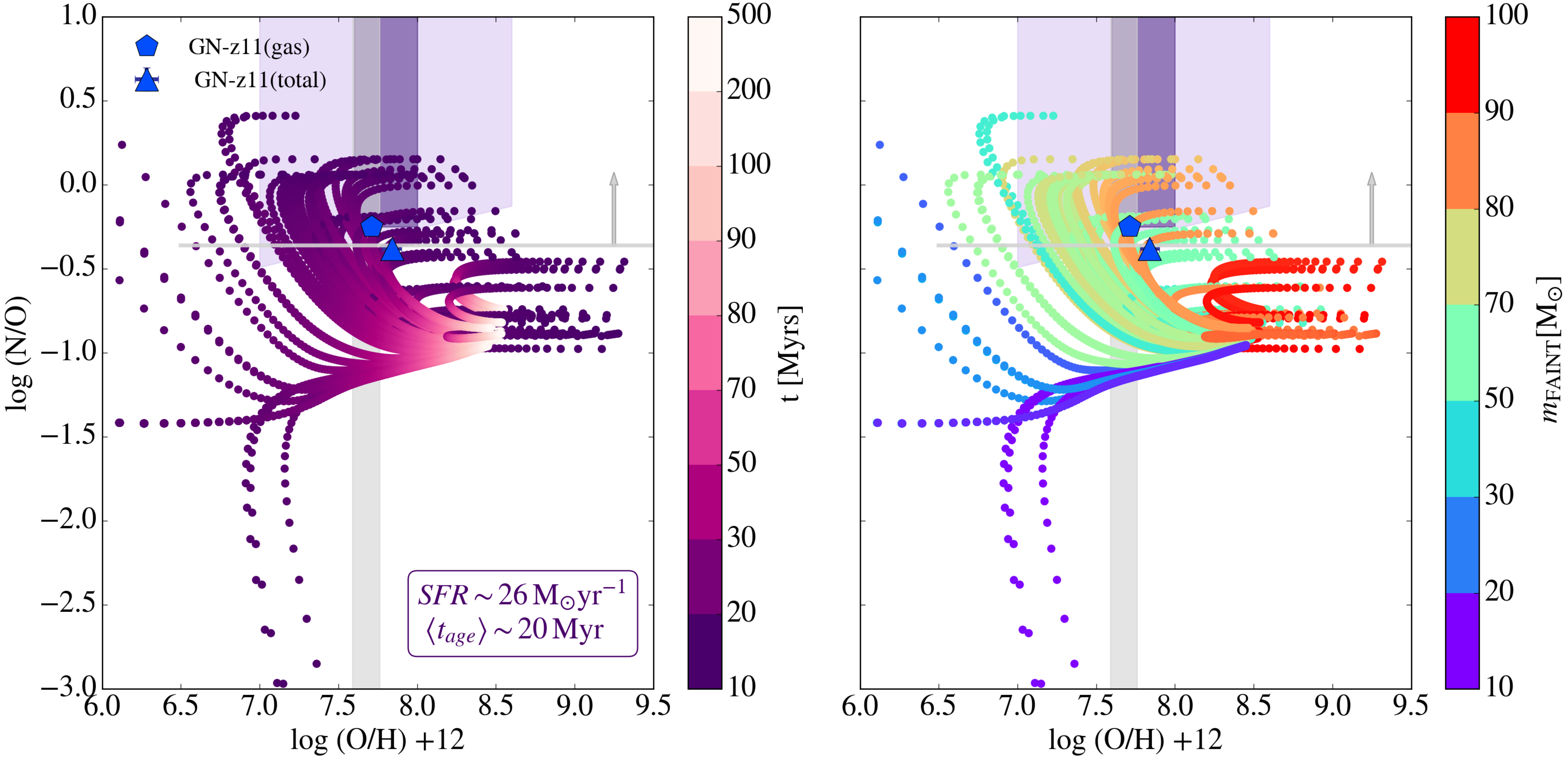
IMPROVED MODELS



IMPORTANT: model calibrated with local data

Figures from Rossi, DR et al. (2024, submitted)

EXTENSION TO HIGH REDSHIFT UNIVERSE



Figures from Rossi, DR et al. (2024, submitted)

SOME READINGS

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