GALACTIC CHEMICAL EVOLUTION

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OAS
BOLOGNA

ESO
BETWEEN THE LINES
A Stellar Spectroscopy Workshop

AIMS OF THIS INTRODUCTORY LECTURE

- Get to know the ingredients and main assumptions of galactic chemical evolution (GCE) models
- Learn about their I. successes (and failures) in reproducing the data and II. predictive power
- Current challenges
- Get inspired!

MY CAREER IN A NUTSHELL

- 1998: Master's degree in Physics, University of Trieste, Italy
- 2002: PhD in Astrophysics, International School for Advanced Studies, Trieste, Italy
- Moved to Bologna, postdoc positions from 2003 to 2010
- Now senior research scientist at INAF-OAS, Bologna
- Most of my time, I develop simulations of galaxy formation and evolution to interpret data from current and future state-of-the-art telescopes

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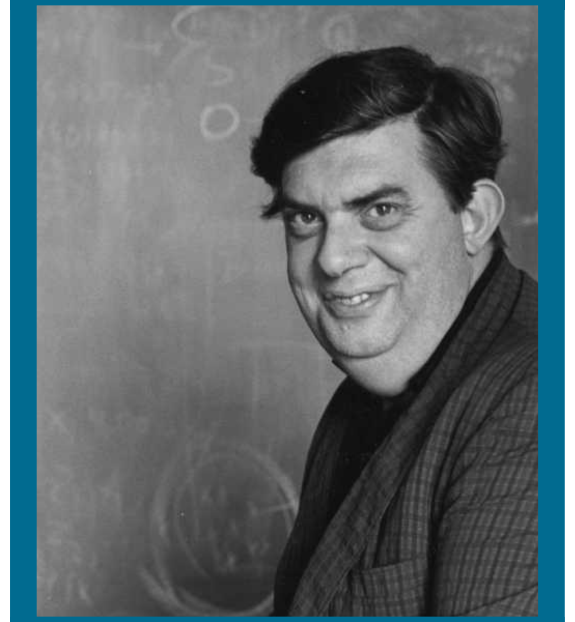
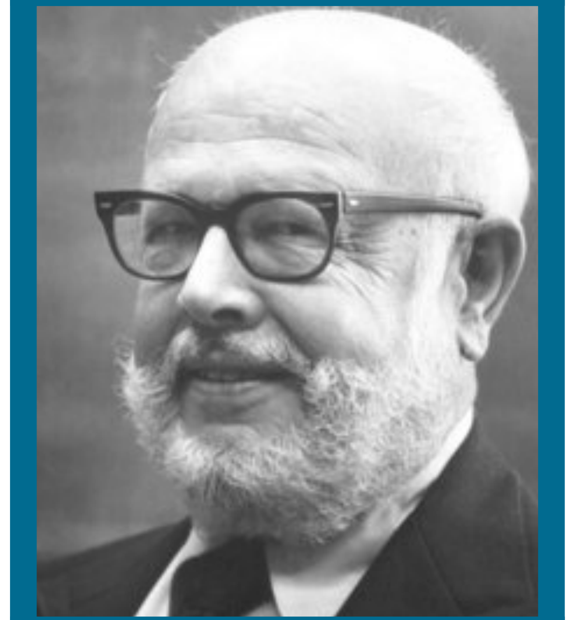
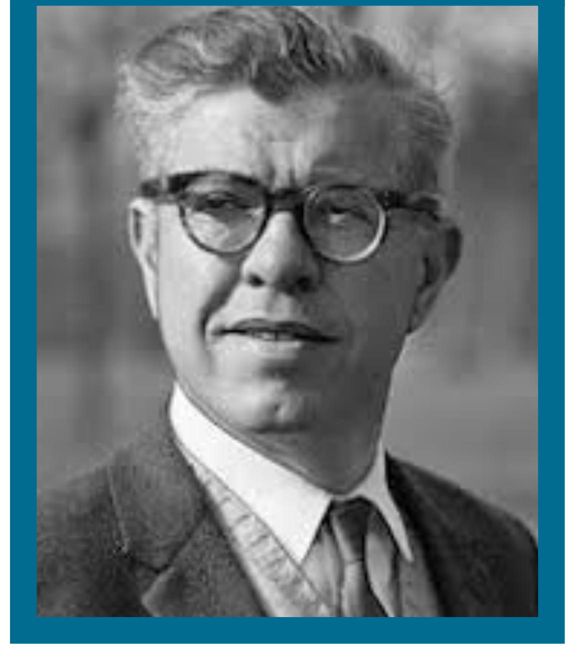


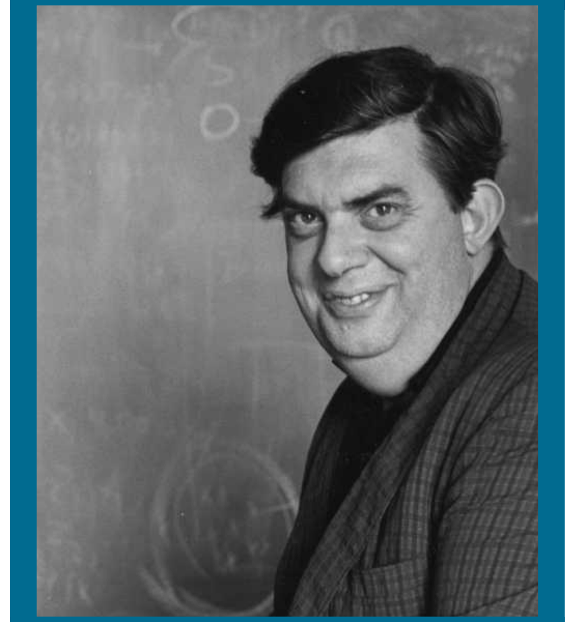
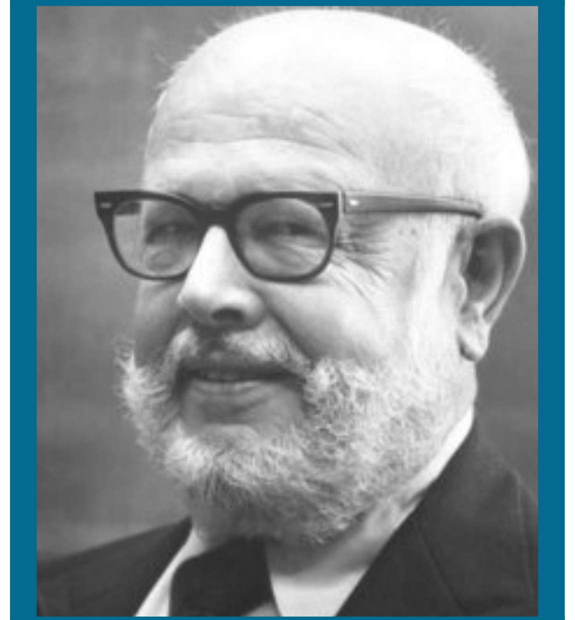
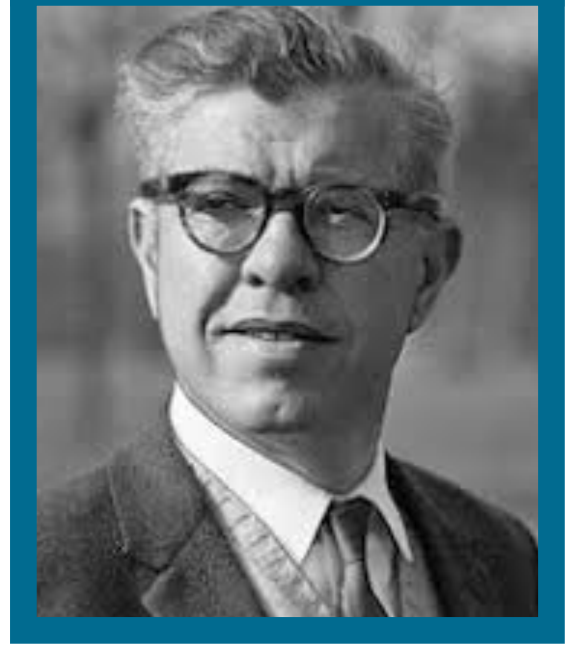




GCE: BASIC CONCEPTS

“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)

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“… 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)

GCE is not a full astrophysical theory: it merely provides a framework in which the observed chemical composition of stars and gas in galaxies can be interpreted

THE SIMPLE MODEL

- First attempt to model the chemical evolution of galaxies
- Assumptions:
  - Closed-box system
  - Instantaneous recycling approximation (IRA): all stars with $m \geq 1\ M_{\odot}$ die instantaneously, all stars with $m < 1\ M_{\odot}$ live forever
  - Initial mass function not dependent on time
  - Gas well mixed at any time (instantaneous mixing approximation)
- Analytical solution possible
- Basic relation between global metallicity *(Z)* and gas fraction in the studied system

MODERN WORK TOOLS

- (Fortran) code that solves numerically a set of integro-differential equations:

Star formation | Stellar feedback | Gas accretion | Galactic-scale outflow

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

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- Adding complexity: radial motions of gas and stars, recycling of matter through hot halos..

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- The model follows how the chemical composition of the ISM changes in time and space in galaxies owing to different physical processes

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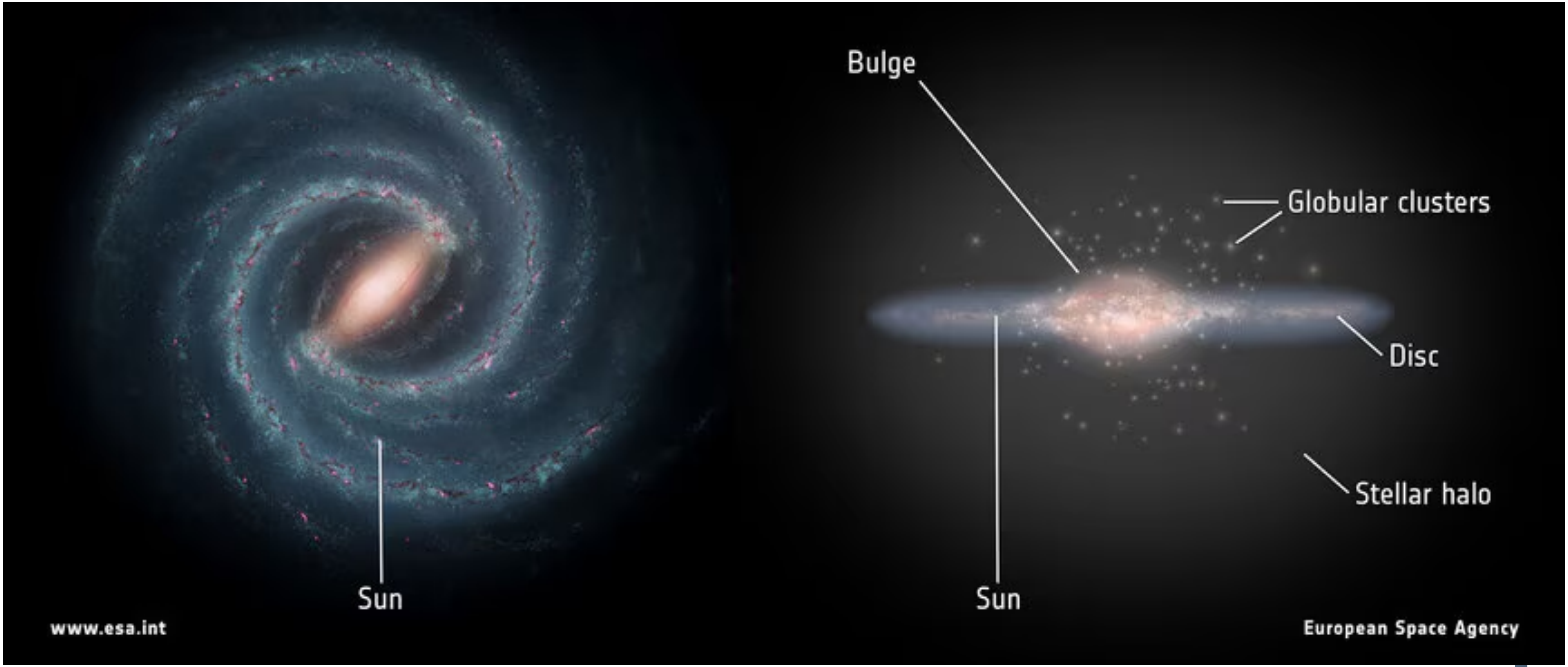
Star formation — Stellar feedback — Gas accretion — Galactic-scale outflow

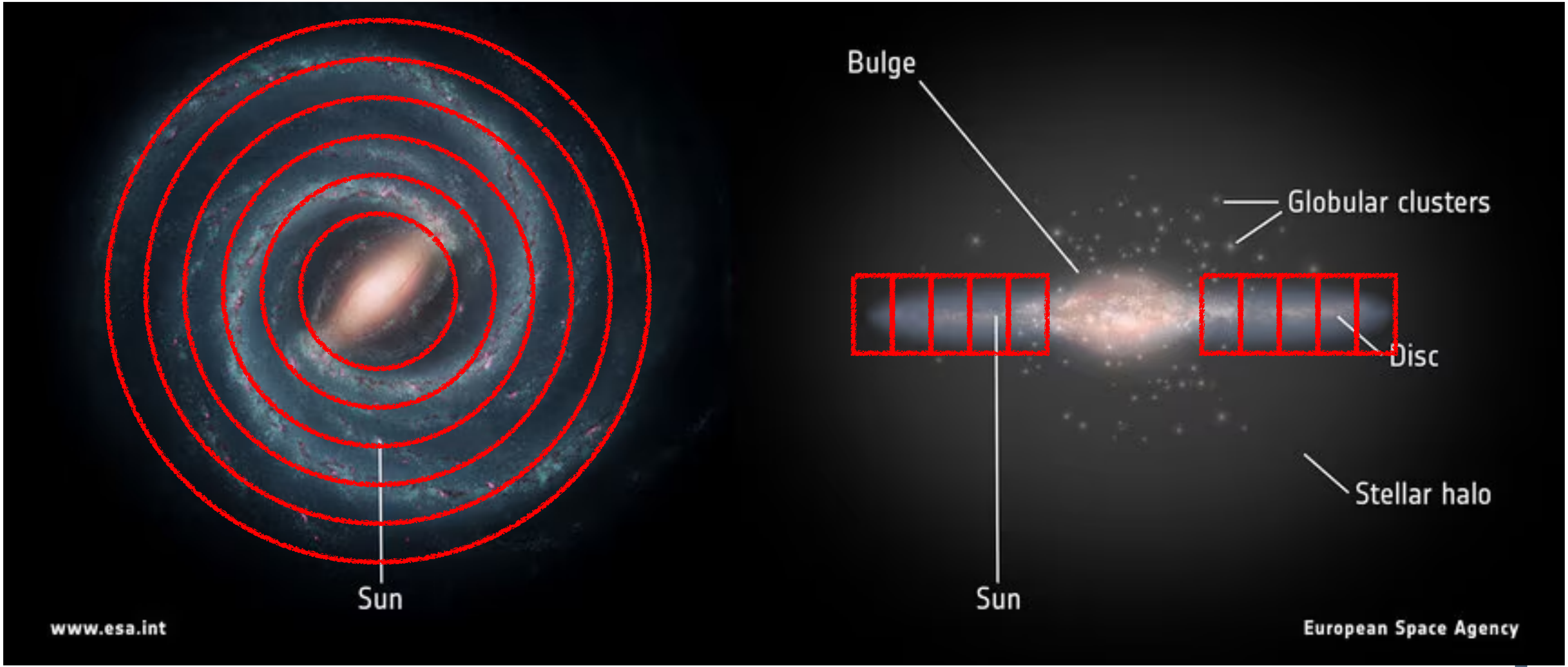
$$\frac{d\Sigma_i(r,t)}{dt} = -\psi(r,t)X_i(r,t) + R_i(r,t) + \frac{d\Sigma_{i,inf}(r,t)}{dt} - \frac{d\Sigma_{i,out}(r,t)}{dt}$$

- Adding complexity: radial motions of gas and stars, recycling of matter through hot halos..
- The model follows how the chemical composition of the ISM changes in time and space in galaxies owing to different physical processes
- Homogeneous/inhomogeneous models

MODERN WORK TOOLS



MODERN WORK TOOLS



GCE MODEL INGREDIENTS

Recommended readings:
Gao & Solomon (2004)
Kennicutt & Evans (2012)
Bolatto et al. (2013)
Schinnerer & Leroy (2024)

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): $\Sigma_{\rm SFR} \propto \Sigma^n_{\rm H\,I+H_2}$

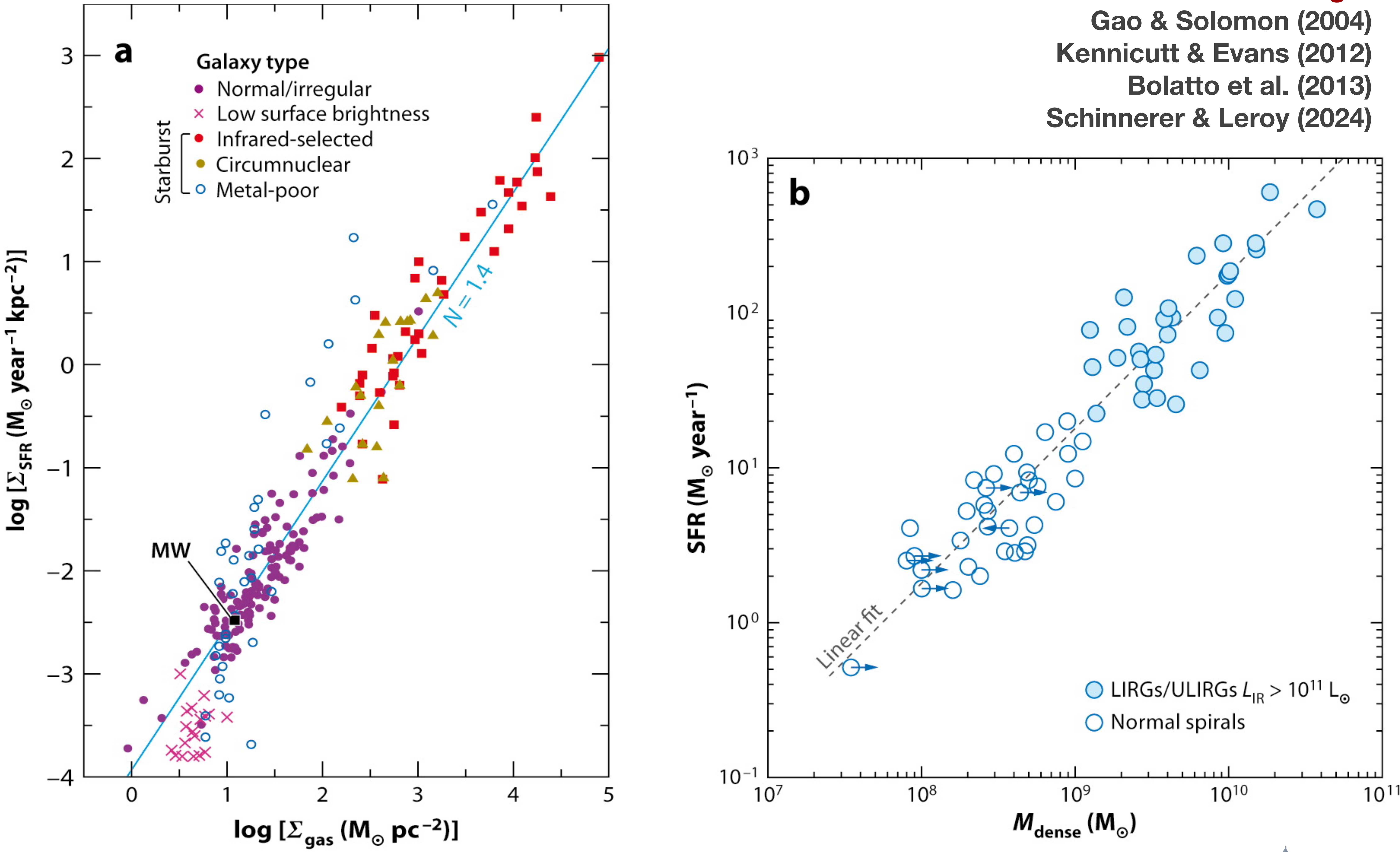
  $n = 1 - 3$

- 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



GCE MODEL INGREDIENTS

$$\Sigma_{\mathrm{SFR}} = \nu \, \Sigma_{\mathrm{gas}}^{n}$$

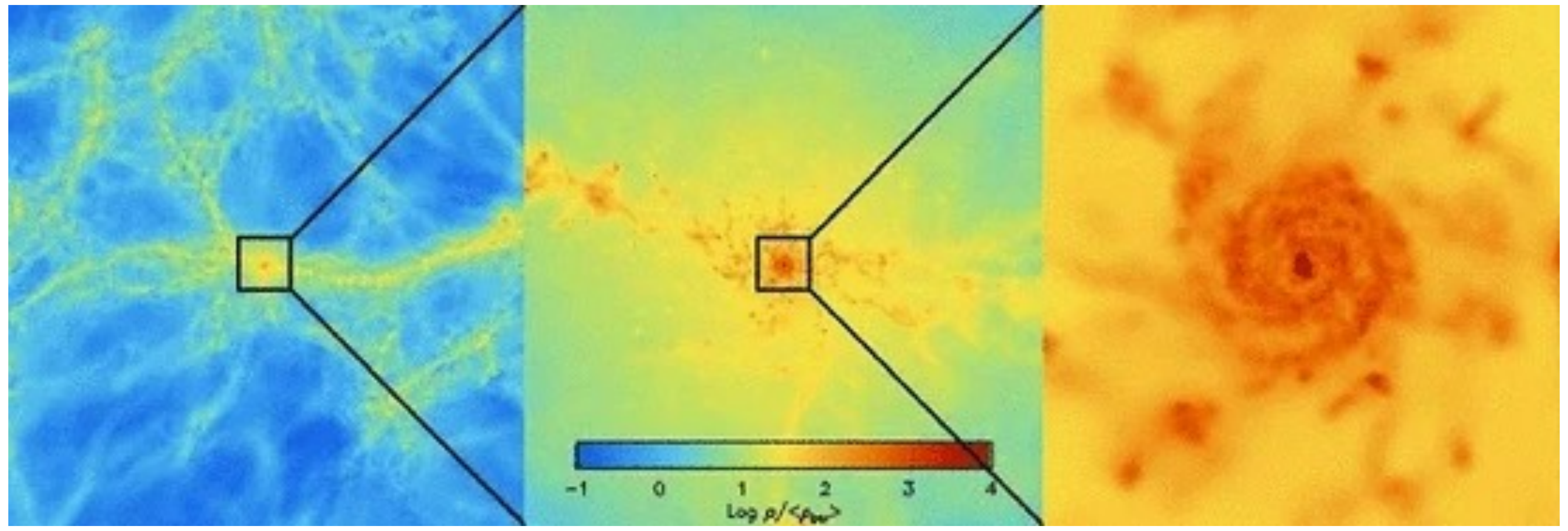
From a few % (ultrafaint dwarfs) to >50% (bulges of spirals, massive ellipticals)

GCE MODEL INGREDIENTS

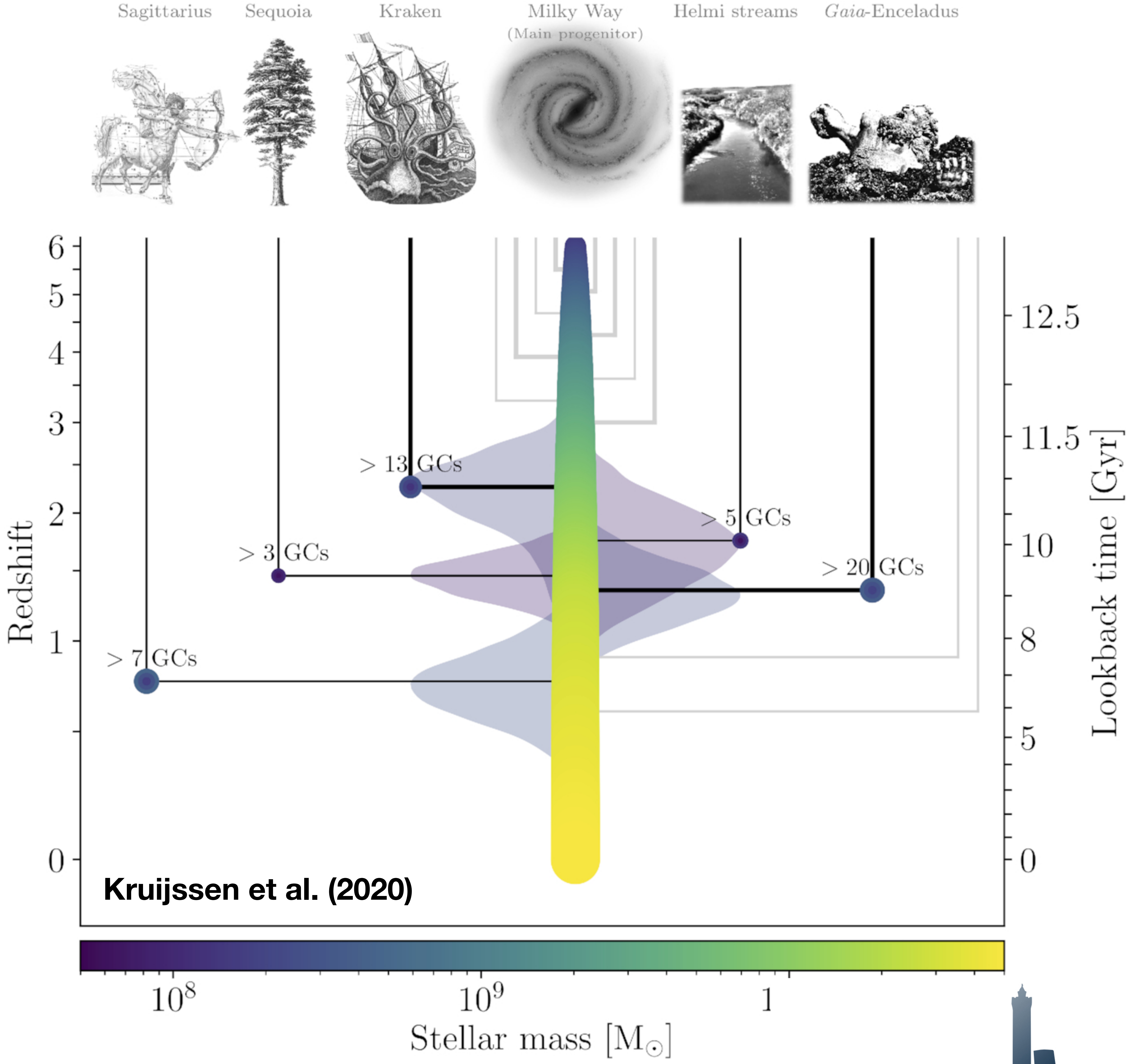
GAS INFALL/ACCRETION:

- 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)



Schaye et al. (2010)



Kruijssen et al. (2020)

GCE MODEL INGREDIENTS

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

Varies from hundreds of Myr to ~a Hubble time

Fixed by the request of reproducing the current density of matter

GCE MODEL INGREDIENTS

GALACTIC OUTFLOWS:

- Emission and absorption line measurements of cool/warm gas provide the best physical diagnostics of galactic outflows
- Hydrodynamical simulations study how mass, energy, and momentum injected by SNe are mixed with the ISM and entrained into an outflow
- This remains a principal topic of research

M82 as seen by Hubble (left) and JWST (right)

Recommended reading:
Thompson & Heckman (2024)

GCE MODEL INGREDIENTS

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

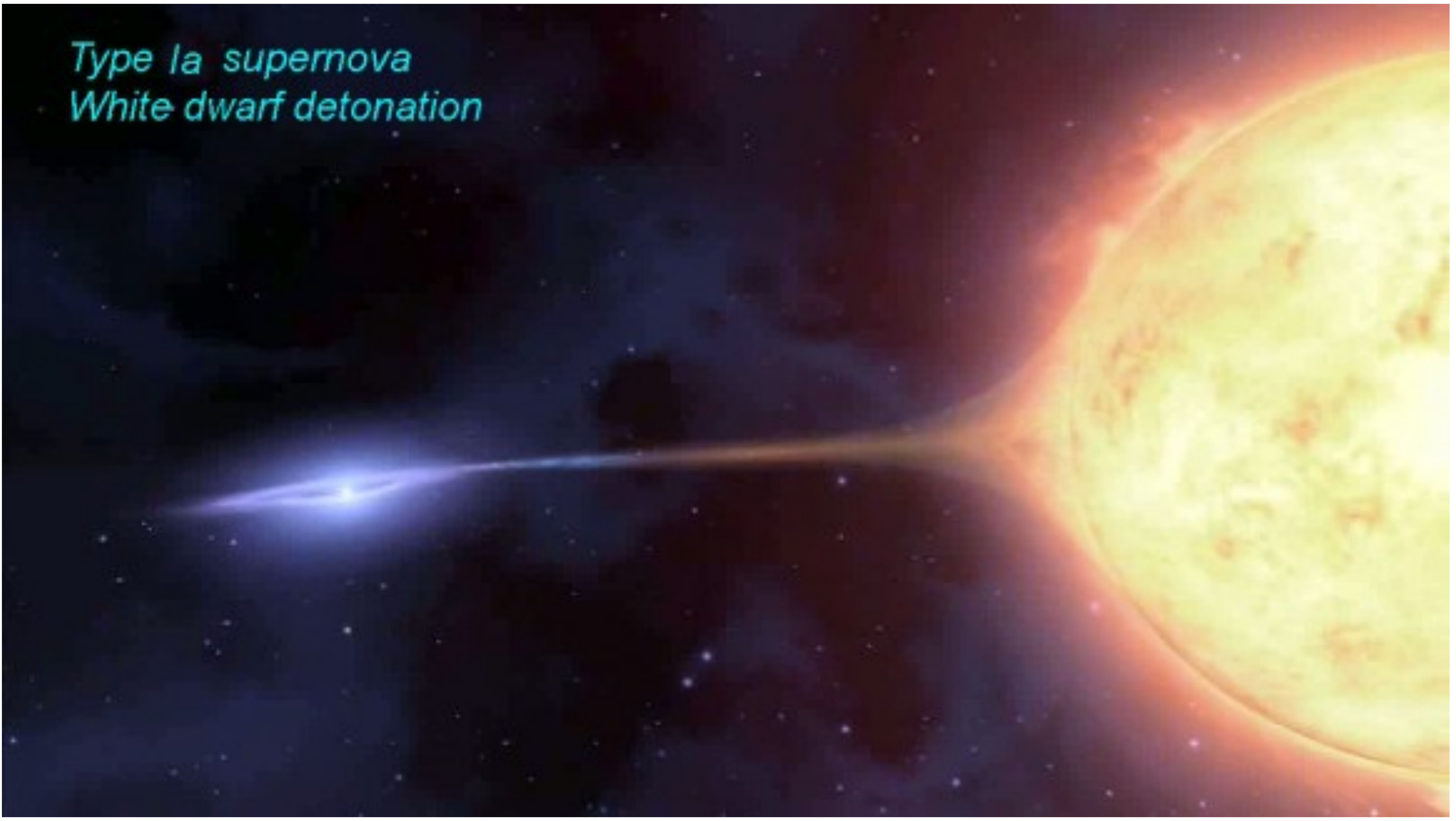
Very ill-constrained, may vary from element to element (differential wind)

ELEMENT PRODUCTION SITES

Lecture by Chiaki Kobayashi

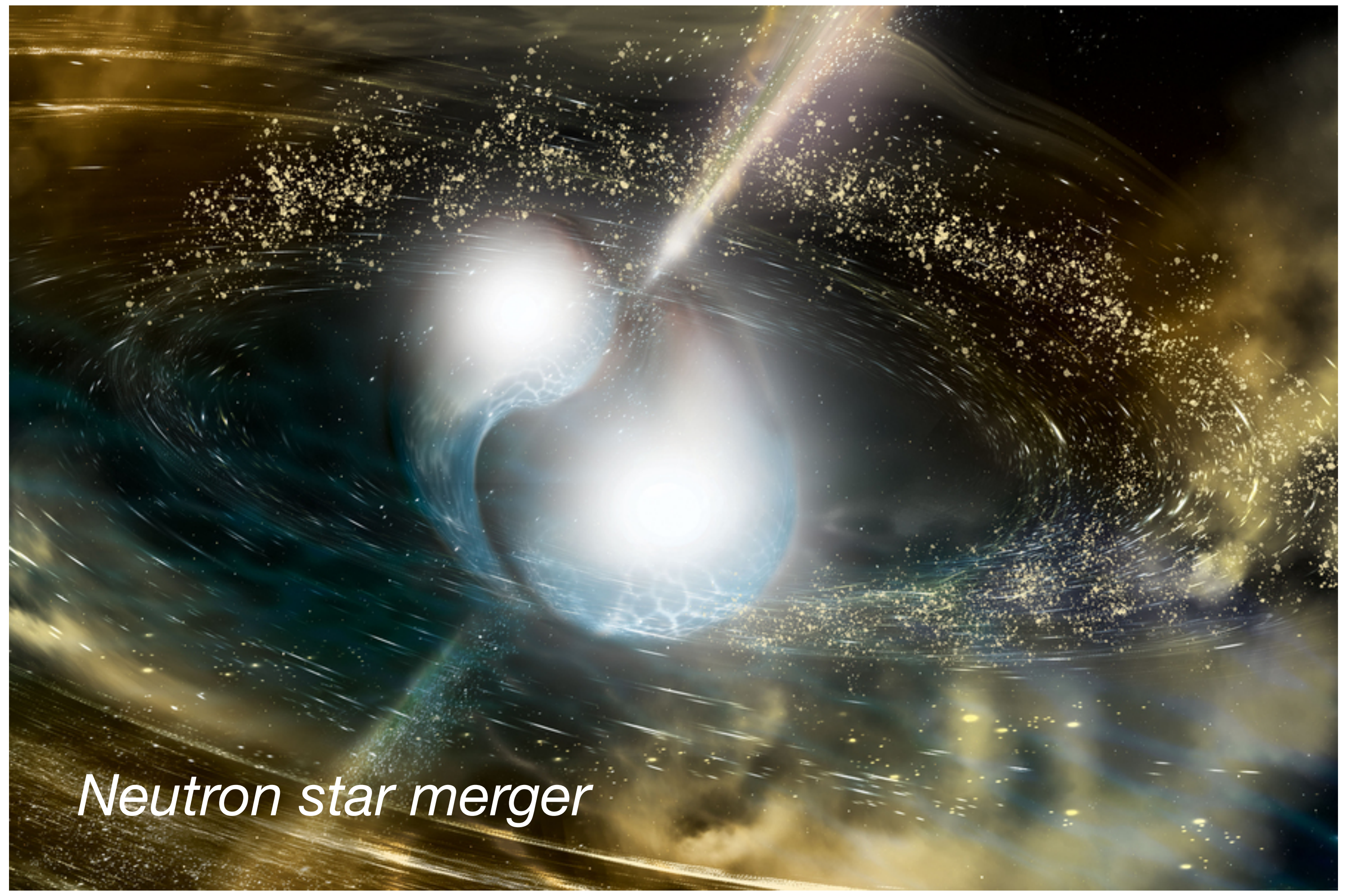
- Big Bang nucleosynthesis: H, D, ^{3}He, ^{4}He, ^{6}Li, ^{7}Li
  (e.g., Pitrou et al. 2021)
- Cosmic ray spallation processes in the ISM: Li, Be, B
  (e.g., Meneguzzi et al. 1971; Lemoine et al. 1998)
- Single low- and intermediate-mass stars (1–8 $M_\odot$): ^{3}He, ^{4}He, ^{12}C, ^{13}C, ^{14}N, ^{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)

BINARY SYSTEMS



Lecture by Chiaki Kobayashi

FE-PEAK ELEMENTS



NEUTRON-CAPTURE ELEMENTS

RARE ISOTOPES (^{7}LI, ^{13}C, ^{15}N, ^{17}O)

STELLAR YIELDS

Lecture by Chiaki Kobayashi

Fraction of initial stellar mass expelled as newly-produced element *j* during the full stellar lifetime:

$$m_j^{new} = mp_j = mp_j^{wind} + mp_j^{SN} = \int_0^{\tau(m)} \left[X_j(t) - X_j^{init}\right] \dot{M}(t)\, dt + \int_{m_{remn}}^{\tilde{m}(\tau)} \left[X_j(m') - X_j^{init}\right] dm'$$

- Stellar yield: p_j
- Stellar lifetime: $\tau(m)$
- Surface abundance: $X_j(t)$
- Initial abundance: X_j^{init}
- Mass loss rate: $\dot{M}(t)$
- Remaining mass at age τ: $\tilde{m}(\tau)$
- Stellar remnant mass: m_{remn}
- Abundance at Lagrangian mass coordinate m′: $X_j(m')$
- Initial abundance: X_j^{init}

$$m_j^{eje} = m_j^{old} + m_j^{new} = (m - m_{remn})\, X_j^{init} + mp_j$$

STELLAR LIFETIMES

gwIMF

STELLAR YIELDS

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Stellar yield: p_j

Stellar lifetime: $\tau(m)$

Surface abundance: $X_j(t)$

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Mass loss rate: $\dot{M}(t)$

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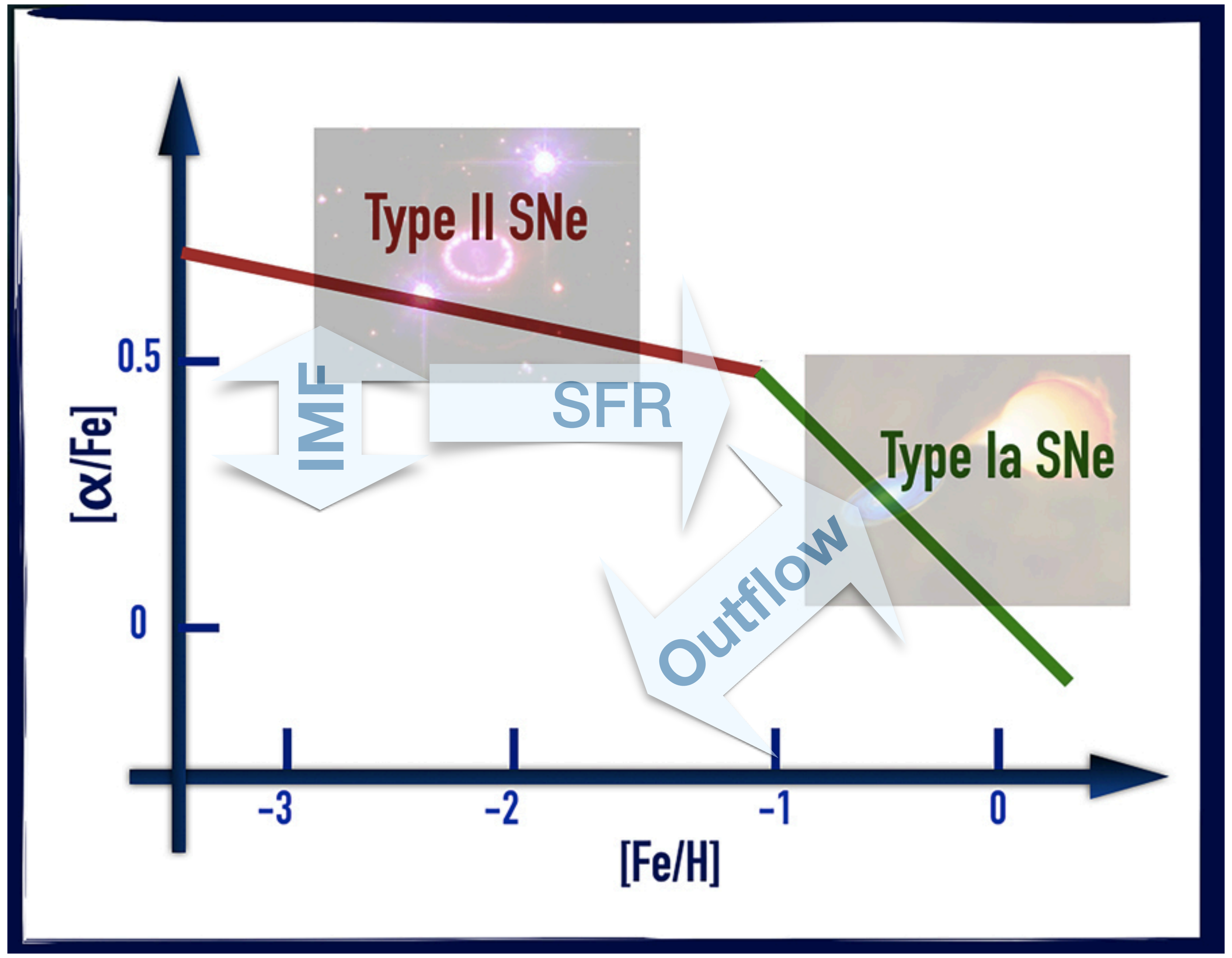
A GCE MODEL ALLOWS TO:

- 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

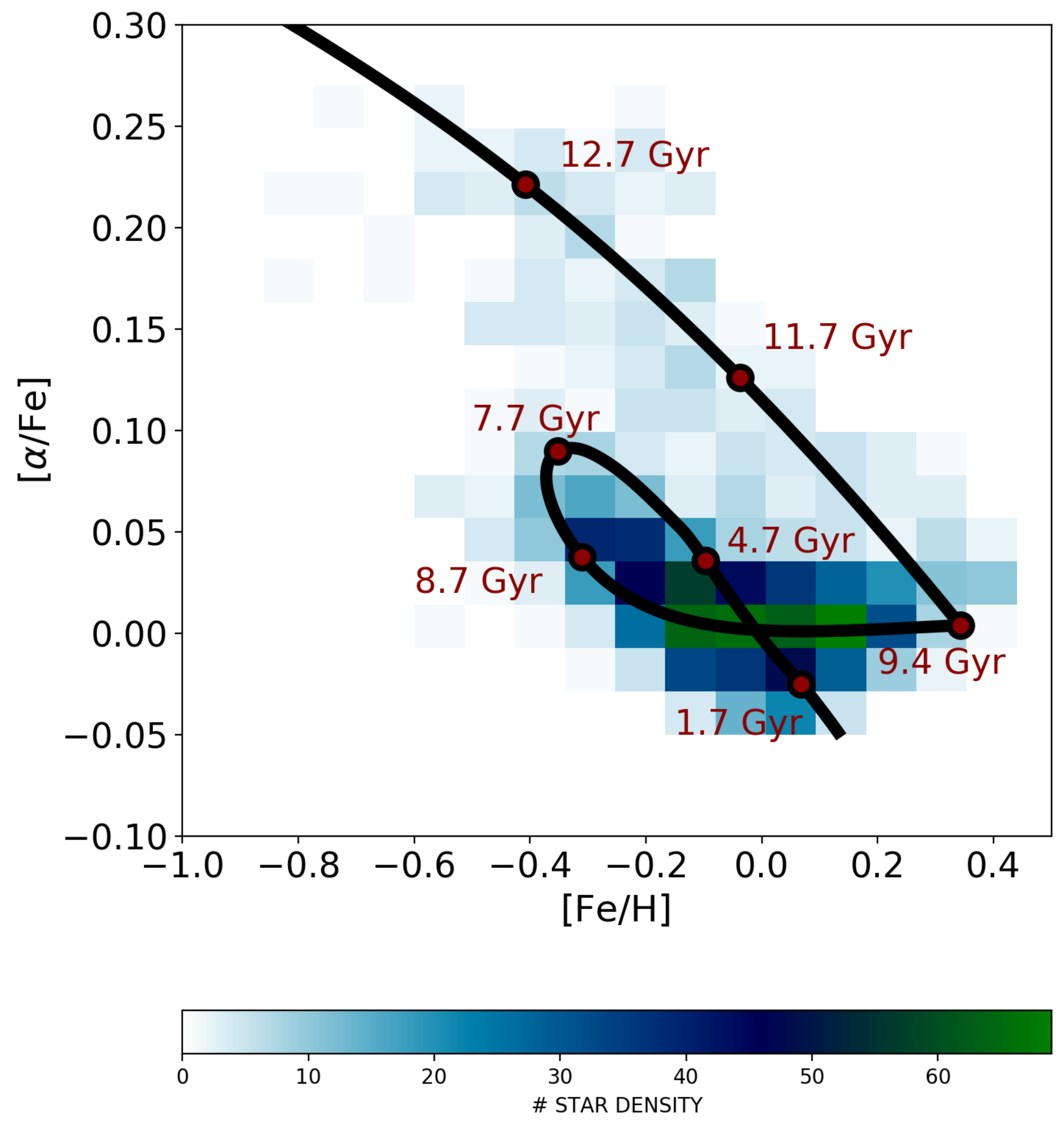
- Establish a chronology of events (basing on when a given stellar source is expected to contribute significantly to a given element)

- Infer how a system was formed, by constraining the roles of any gas infall/outflow and the shape of the gwIMF



GCE MODEL RESULTS (A SELECTION OF)

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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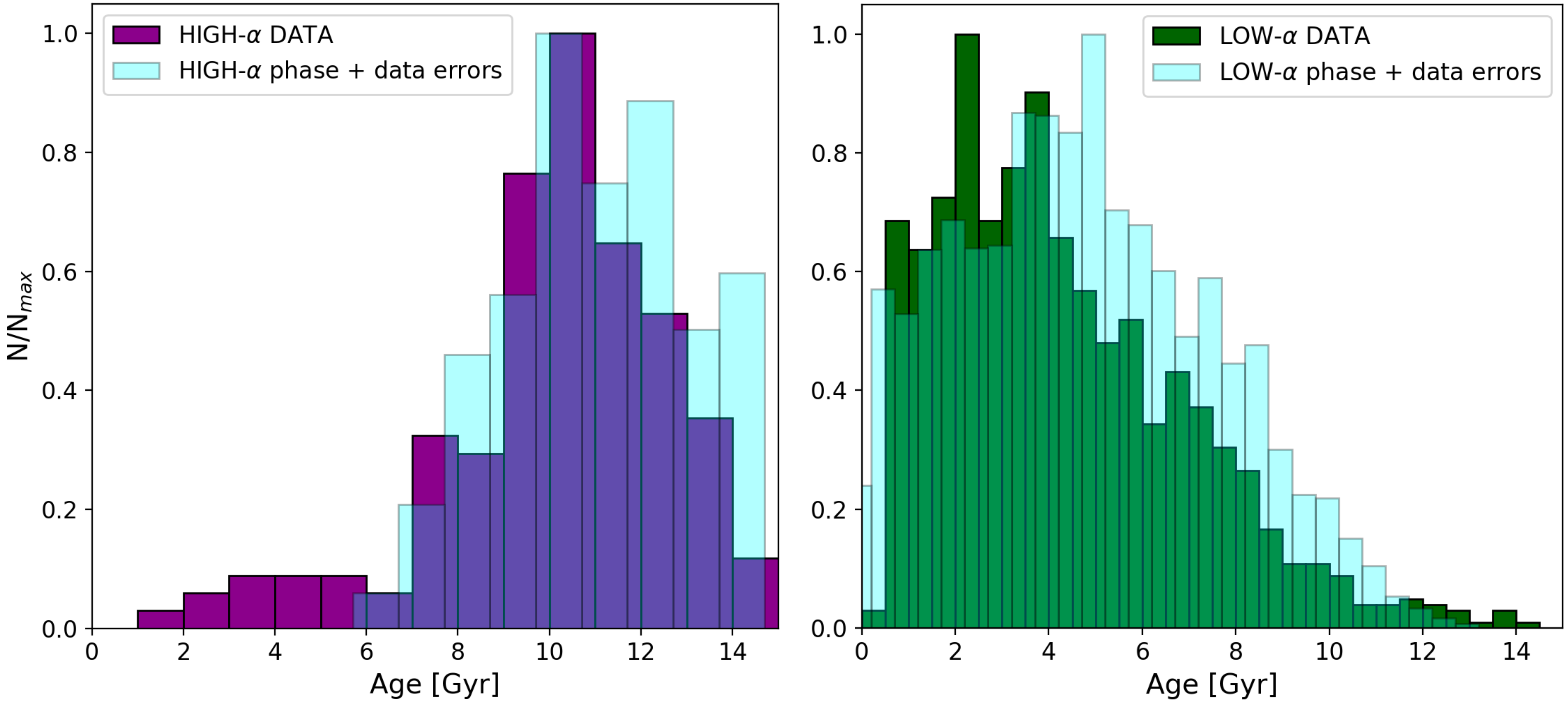
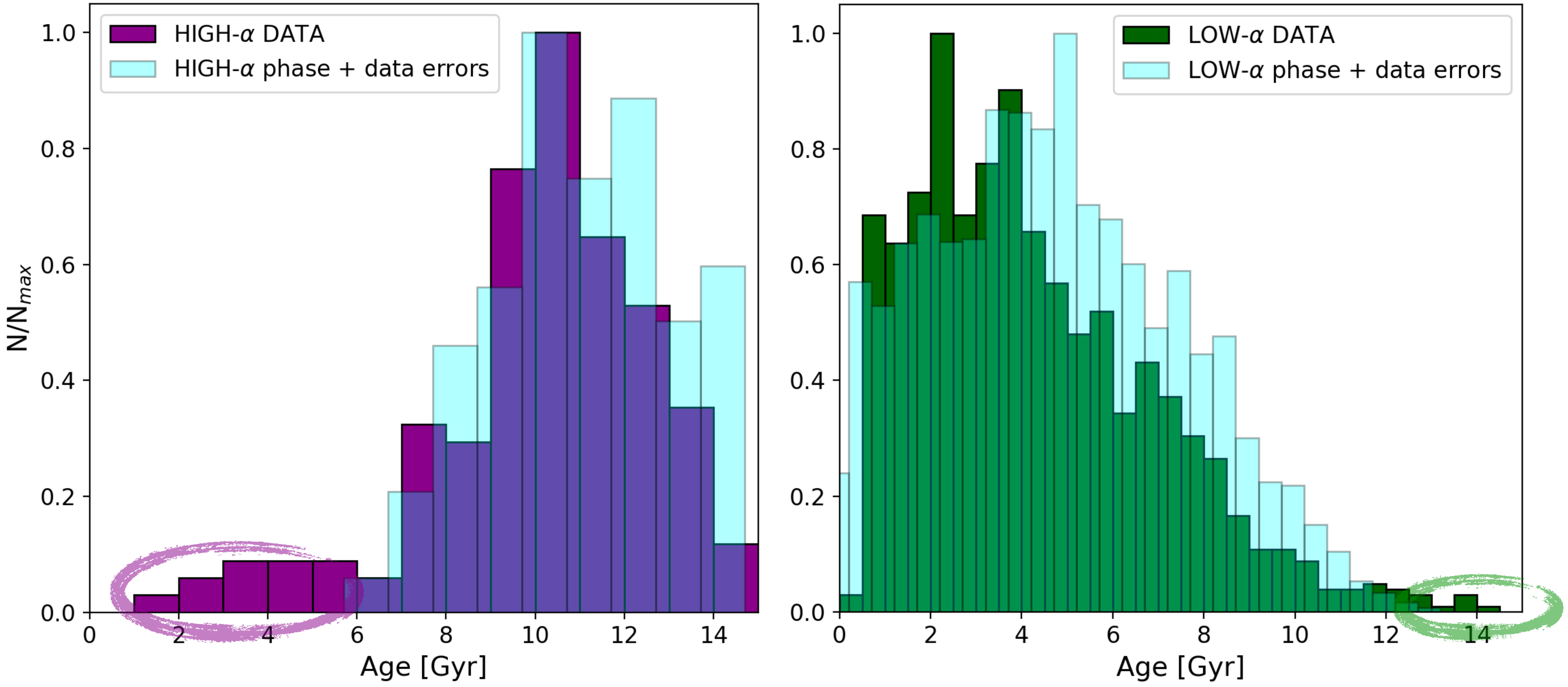


Model predicted age distributions (cyan histograms) for the high-α and low-α components, compared to the APOKASC data (left and right panels, respectively).

Figure from Spitoni et al. (2019)

GCE MODEL RESULTS (A SELECTION OF)

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



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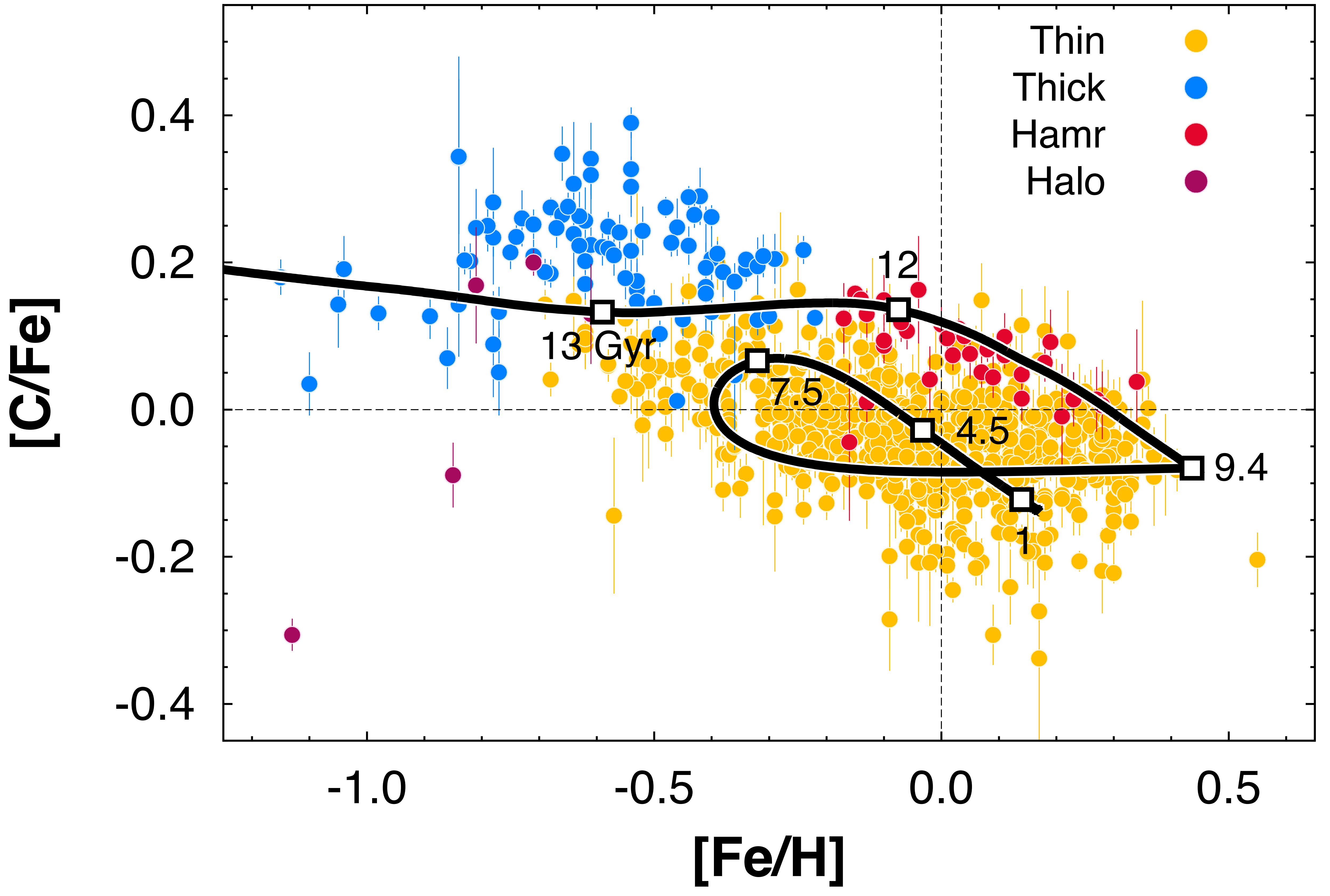


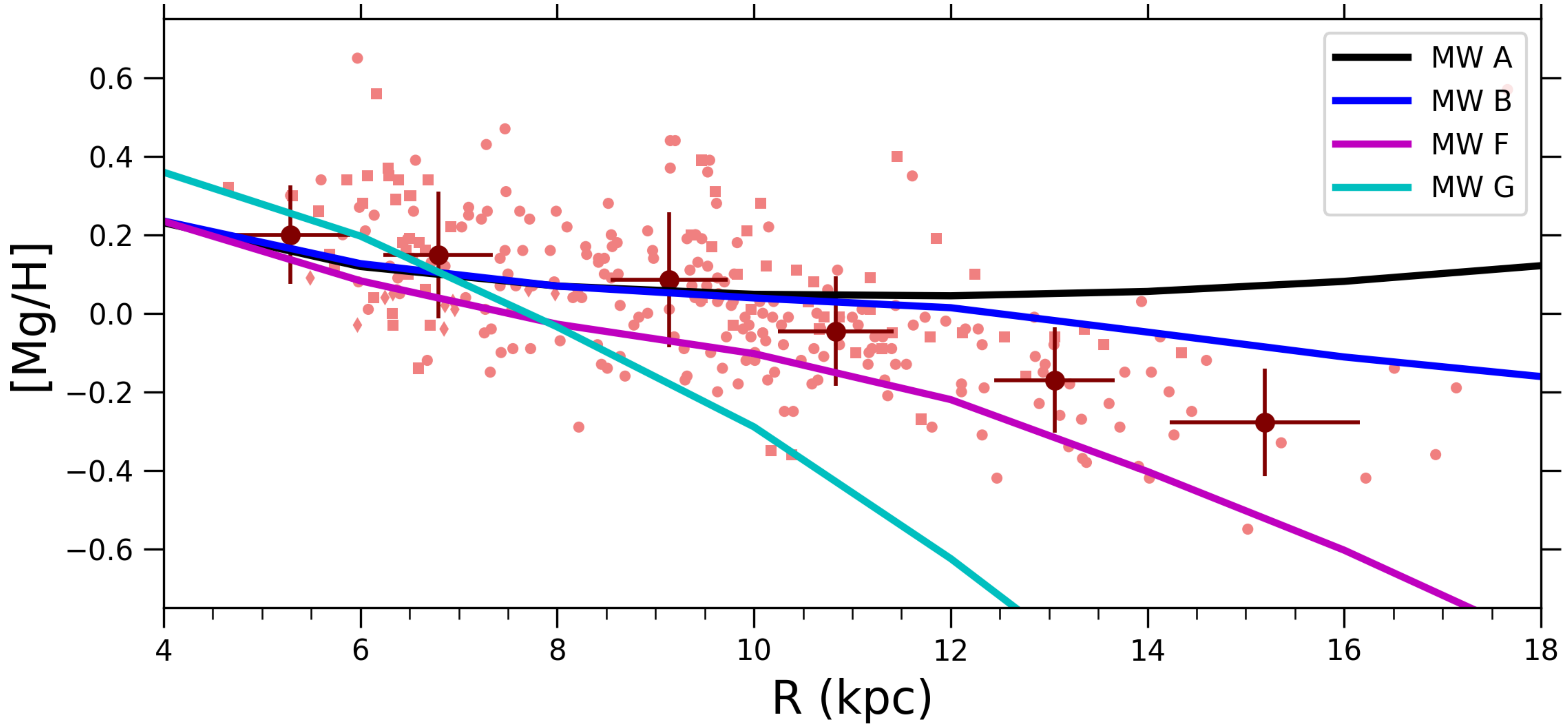
On the left: [C/Fe] vs [Fe/H] trend predicted by the two-infall model with nucleosynthesis prescriptions from full stellar evolution and nucleosynthesis theory compared to data for 757 nearby dwarf stars (Delgado-Mena et al. 2021). The stellar yields are from Ventura et al. (2013, 2014, 2018, 2020, 2021)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

Figure from Romano (2022, A&ARv)

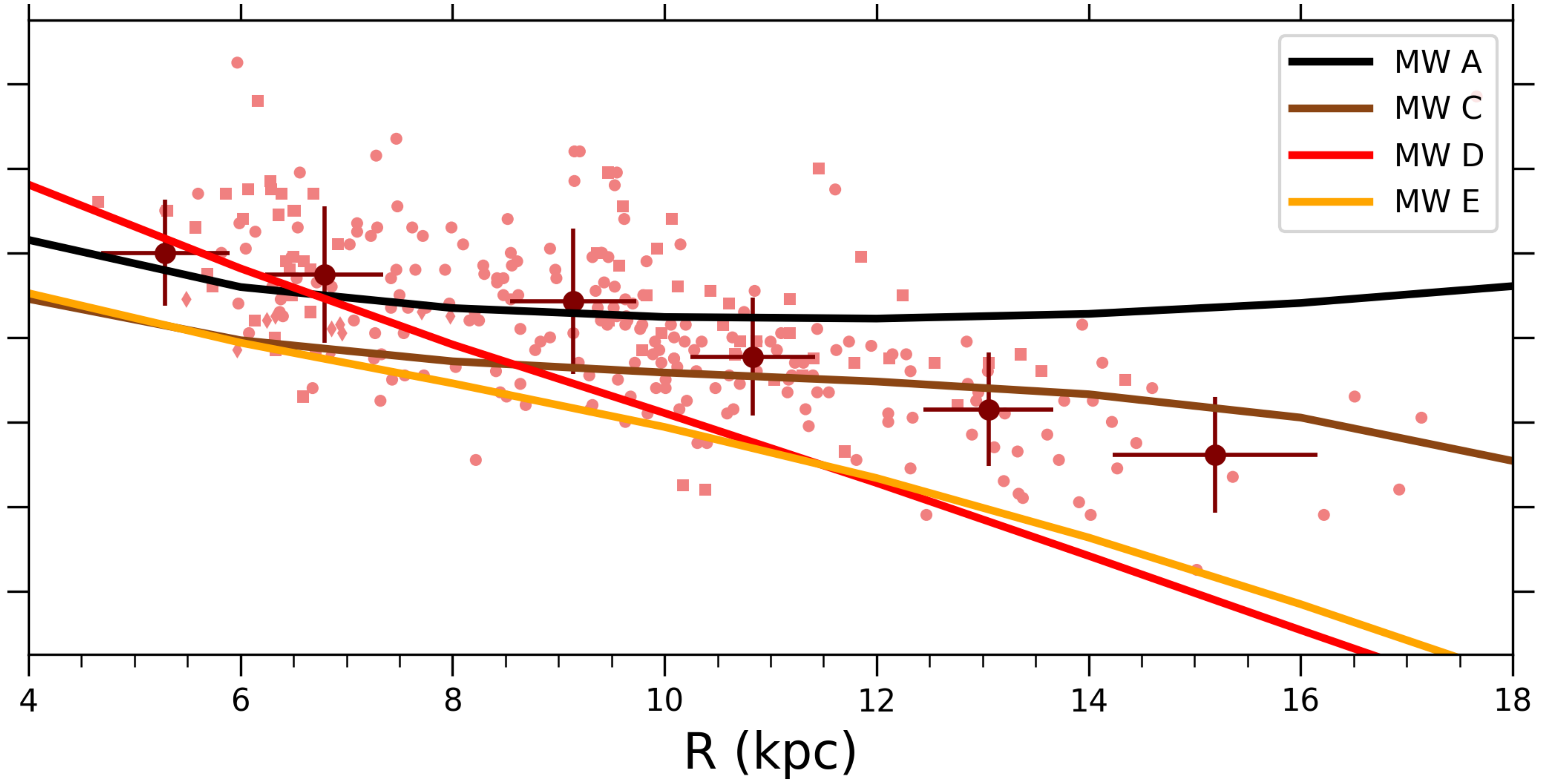
GCE MODEL RESULTS (A SELECTION OF)

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

VARIABLE STAR FORMATION EFFICIENCY



RADIAL GAS FLOWS

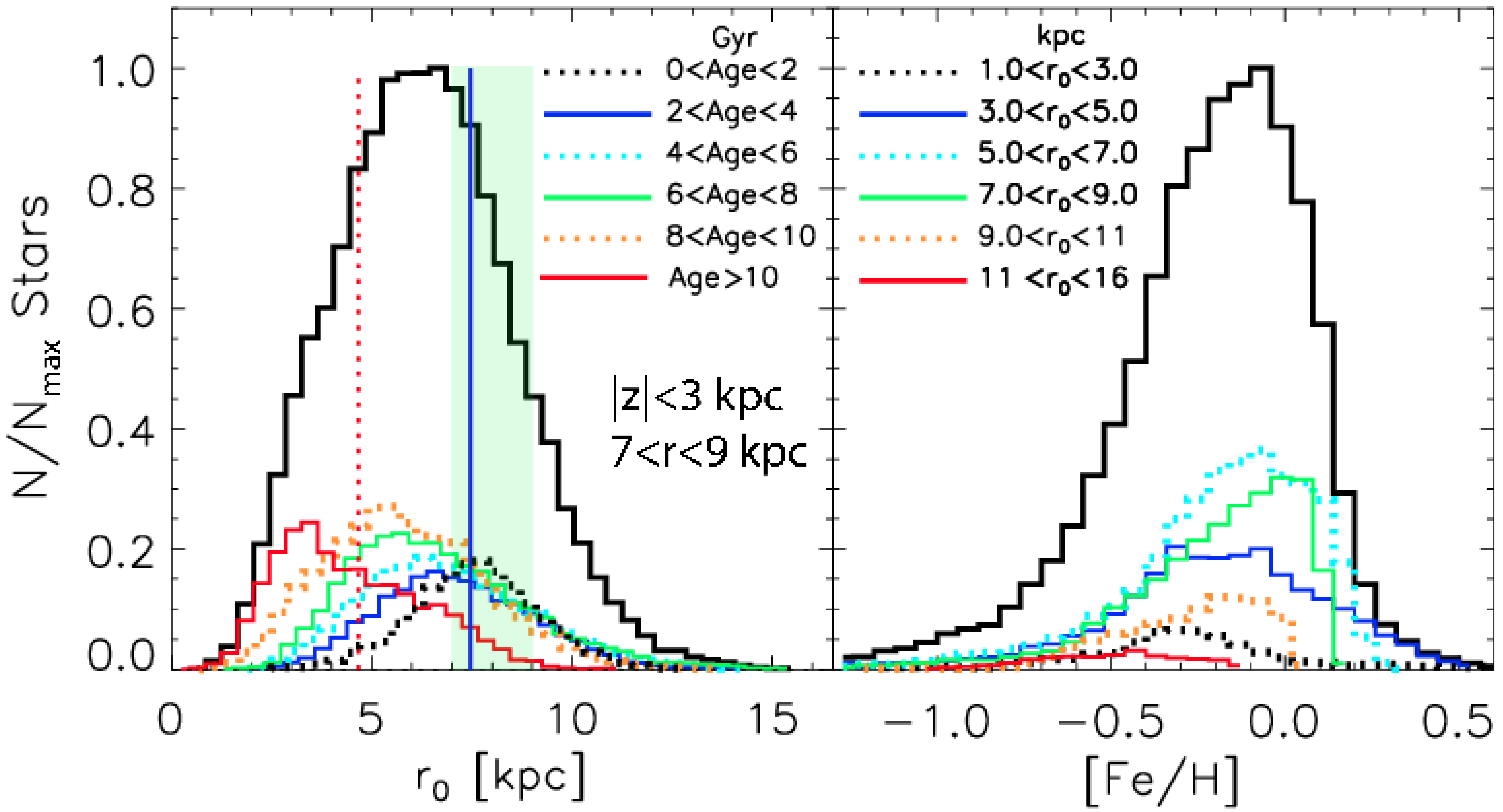


Palla et al. (2020)

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.

GCE MODEL RESULTS (A SELECTION OF)

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

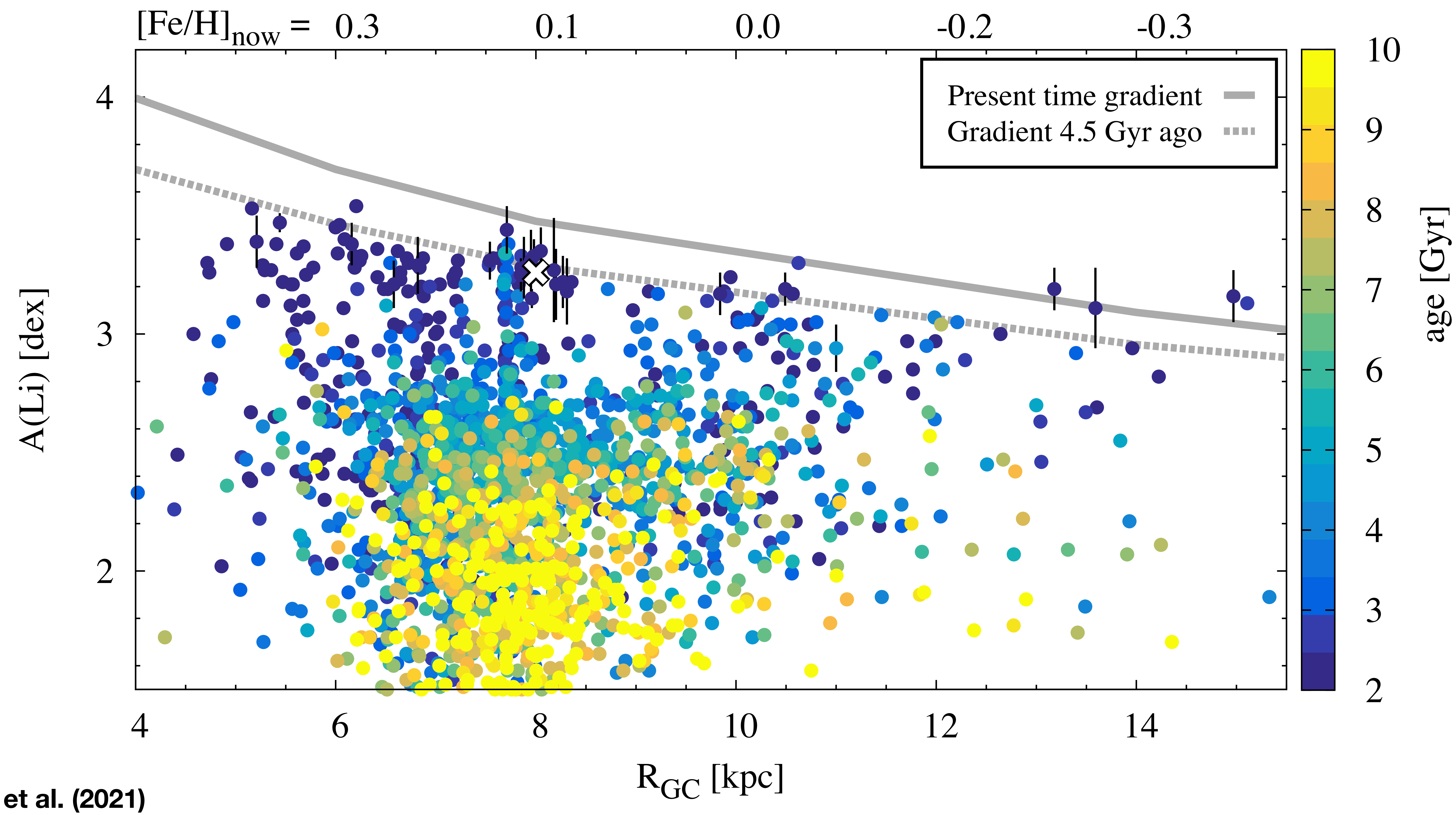


Minchev et al. (2013)

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).

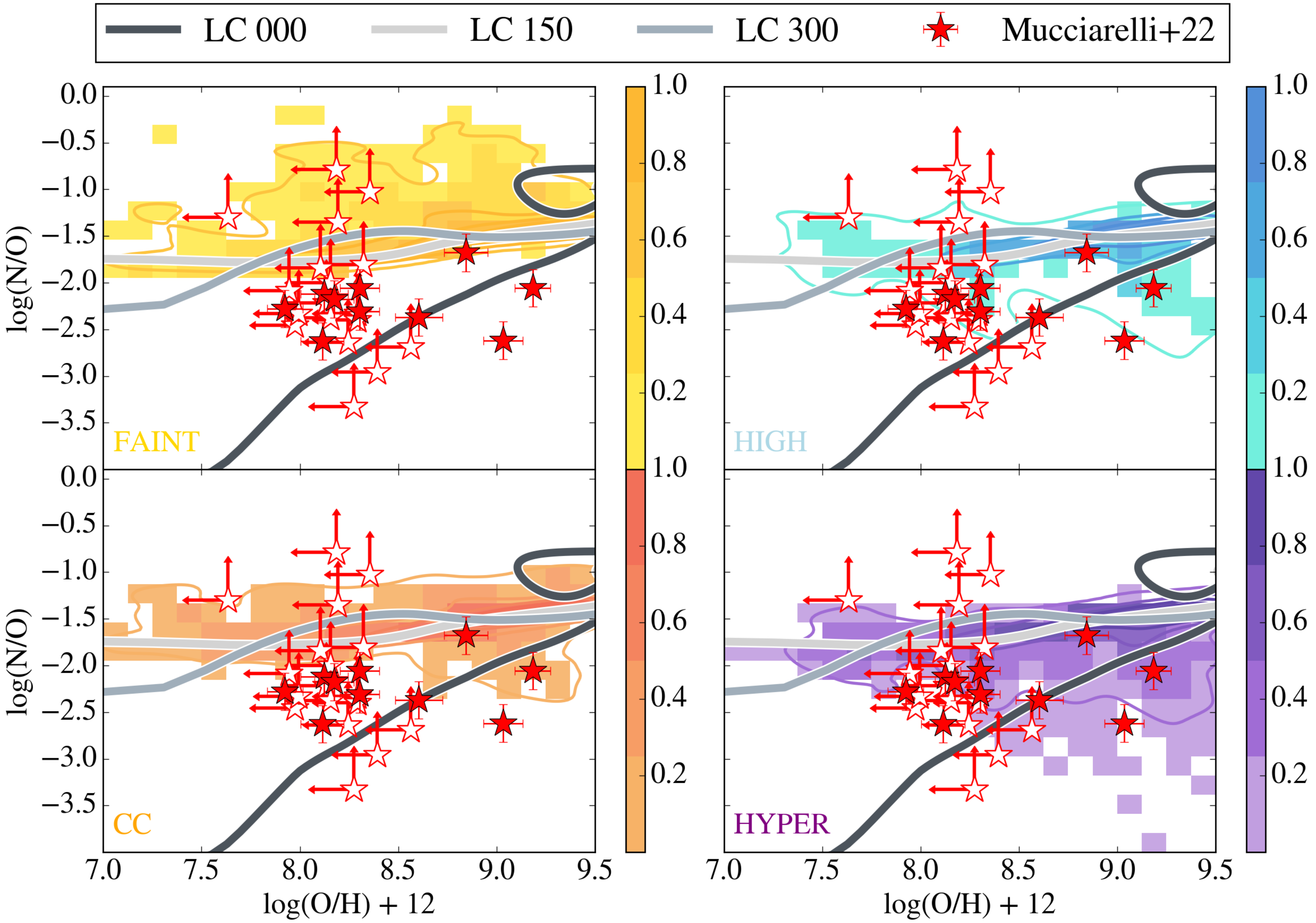
GCE MODEL RESULTS (A SELECTION OF)

… and stars age: their atmospheric composition can change



Adapted from Romano et al. (2021)

GCE MODEL RESULTS (A SELECTION OF)



Considering early inhomogeneous evolution deeply affects model predictions for CNO elements

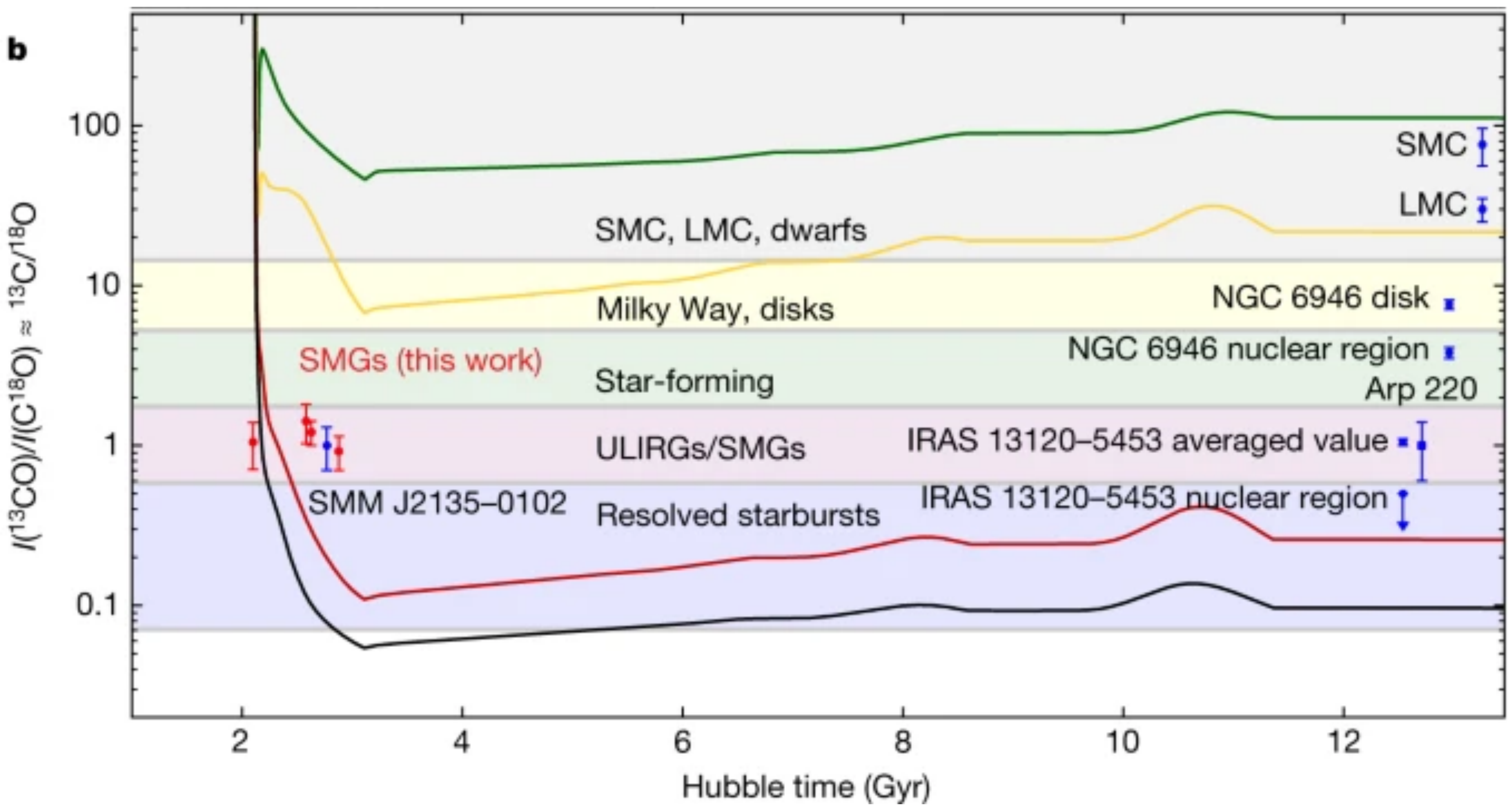
Inhomogeneous GCE model with yields of Pop III stars from Heger & Woosley (2010) with different initial masses, level of internal mixing, and explosion energies

Figures from Rossi, DR et al. (2024)

GCE MODELS AS PROBES OF gwIMF

Emission in both ^{13}CO and $C^{18}O$ is optically thin for the bulk of the molecular gas in the four SMGs. The systematically low $I(^{13}CO)/I(C^{18}O)$ ratios reflect intrinsic isotopologue abundance ratios over galaxy-sized molecular hydrogen reservoirs

gwIMF skewed towards massive stars in the starbursts!



IMF	$\alpha_{0.1\text{-}0.5}$	$\alpha_{0.5\text{-}1}$	$\alpha_{1\text{-}100}$
Bottom-heavy	-1.7	-1.7	-1.7
Kroupa	-0.3	-1.2	-1.7
Top-heavy	-0.3	-1.1	-1.1
Ballero	-0.3	-0.95	-0.95

Zhang, DR et al. (2018)

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!

FURTHER READINGS

- Schmidt M. (1963) The Rate of Star Formation. II. The Rate of Formation of Stars of Different Mass. ApJ, 137, 758
- Talbot R. J. Jr., Arnett W. D. (1971) The Evolution of Galaxies. I. Formulation and Mathematical Behavior of the One-Zone Model. ApJ, 170, 409
- Talbot R. J. Jr., Arnett W. D. (1973) The Evolution of Galaxies. II. Chemical Evolution Coefficients. ApJ, 186, 51
- Tinsley B. M. (1980) Evolution of the Stars and Gas in Galaxies. FCPh, 5, 287
- Pagel B. E. J. (1997) Nucleosynthesis and Chemical Evolution of Galaxies. Cambridge Univ. Press
- Matteucci F. (2012) Chemical Evolution of Galaxies. Astronomy & Astrophysics Library, Springer-Verlag Berlin
- Matteucci F. (2021) Modelling the chemical evolution of the Milky Way. A&ARv, 29, 5
- Romano D. (2022) The evolution of CNO elements in galaxies. A&ARv, 30, 7