Nucleosynthesis and galactic chemical evolution

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MUR Ministero dell'Università e della Ricerca

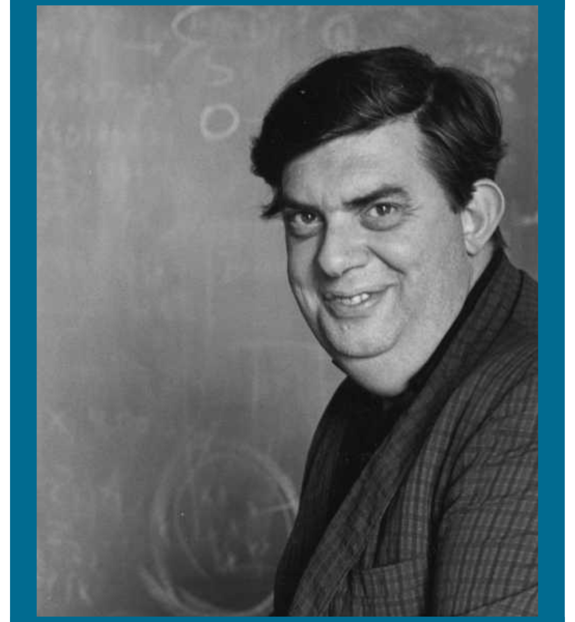
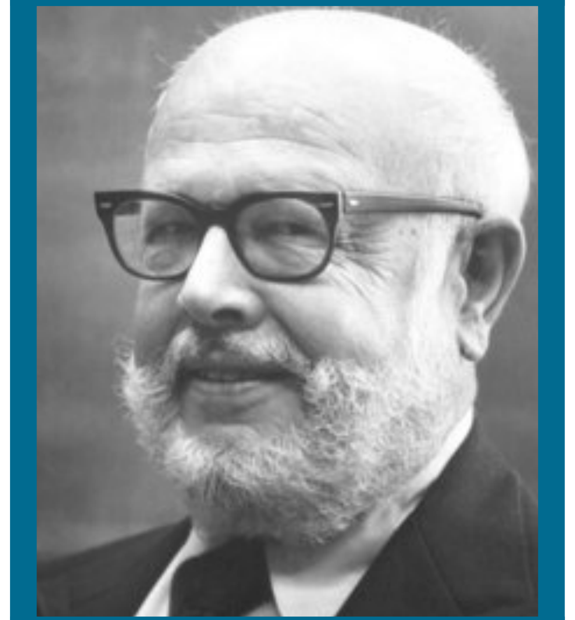
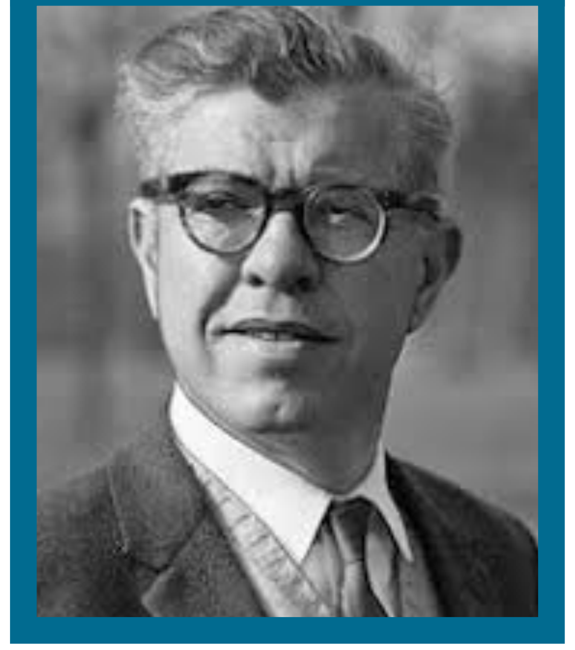
INAF ISTITUTO NAZIONALE DI ASTROFISICA OAS BOLOGNA

GISM3

Galactic chemical evolution models follow the evolution of the chemical composition of the ISM out of which stars form in different galaxies/galactic components

AIMS OF THIS LECTURE

- Get acquainted with the ingredients and main assumptions of GCE models
- Learn about their successes (and failures) in reproducing the data
- Be aware of current challenges
- Get inspired !

GCE BASICS

“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)

“… 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)

GALACTIC ARCHAEOLOGY

Map the composition of stars in all evolutionary stages (possible only in the MW) —> stellar evolution and nucleosynthesis

Get detailed positions and motions —> probe dynamics, mergers

Jointly to stellar ages —> full characterisation of the MW components chemical history

EARLY LARGE-SCALE SPECTROSCOPIC SURVEY

- RAVE | Timeline: 2003-2013 | ~500,000 bright, nearby stars ($9 < I < 12$) | R ~ 7500 | Wavelength: 8410-8800 A (Ca II triplet)
- SDSS | Timeline: 2005-2011 | ~250,000 faint stars ($14 < g < 20.3$) | R ~ 2000 | Wavelength: 3800-9200 A (optical)
- Gaia-ESO Survey | Timeline: 2011-2018 | ~115,000 (mostly disc) stars & OCs | R ~ 17000 (GIRAFFE) 47000 (UVES) | Wavelength: 4000-9000 A
- APOGEE | Timeline: 2011-2021 | ~600,000 red giant stars ($H < 14$), OCs, some GCs | R ~ 22500 | Wavelength: 1.51-1.70 μm
- GALAH | Timeline: 2014-2023 | ~600,000 FGK dwarfs and giants ($V < 14$), OCs, some GCs | R ~ 28000 | Wavelength: 471-789 nm

NOW

- LAMOST | Timeline: 2012-present | >1e6 (LR), > 5e6 (MR) | R ~ 1800 (LR) 7500 (MR) | Wavelength: 3700-9000 A
- Gaia DR3 (2022) | ~5e6 FGK nearby stars | R ~ 11500 | Wavelength: 845-872 nm

… AND MORE IS COMING:

(Courtesy S. Lucatello)

GALACTIC ARCHAEOLOGY

SOME ACHIEVEMENTS:

Hayden et al. (2015)

Galactic abundance gradient

No α-enhanced stars

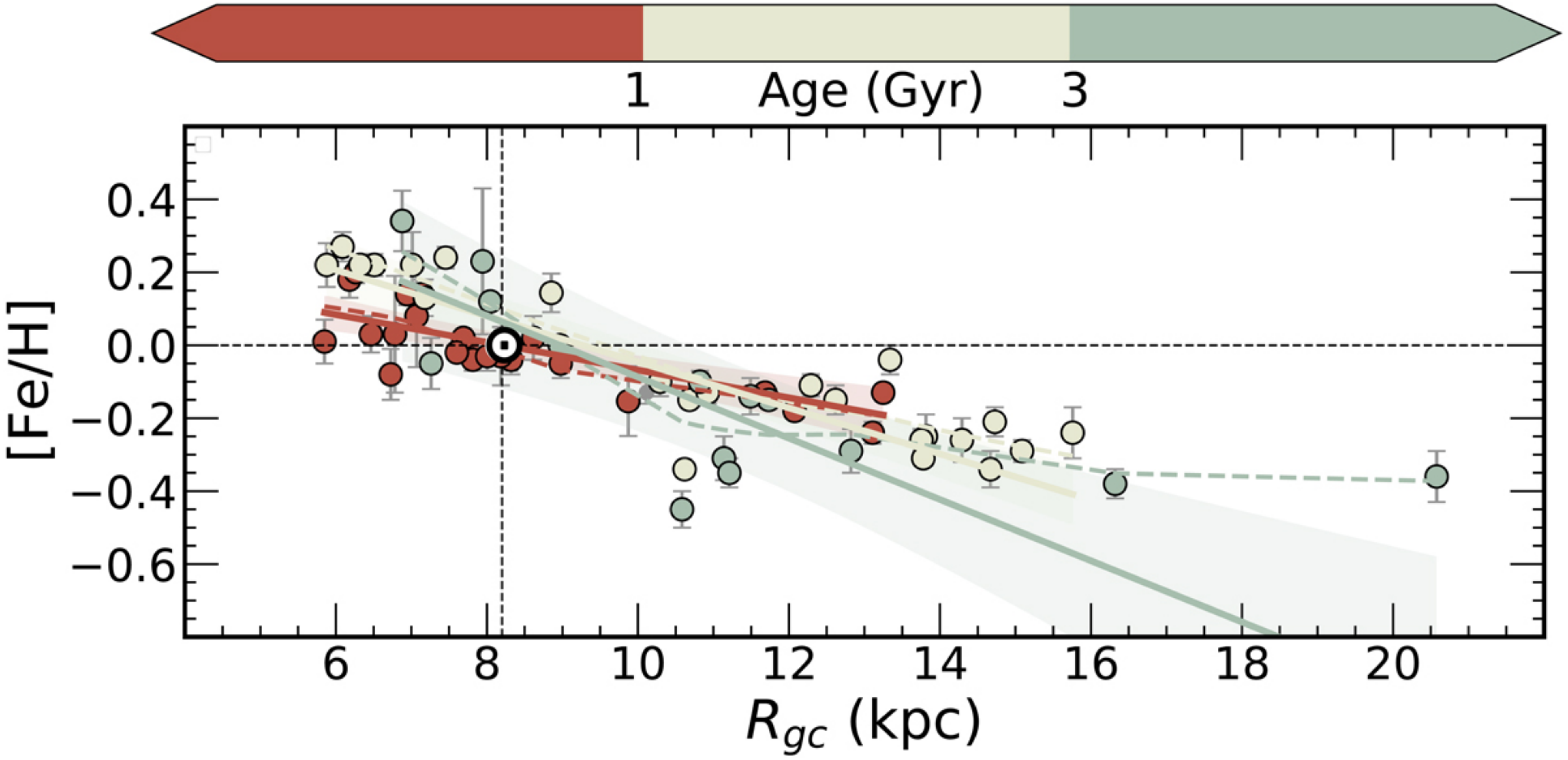
GALACTIC ARCHAEOLOGY

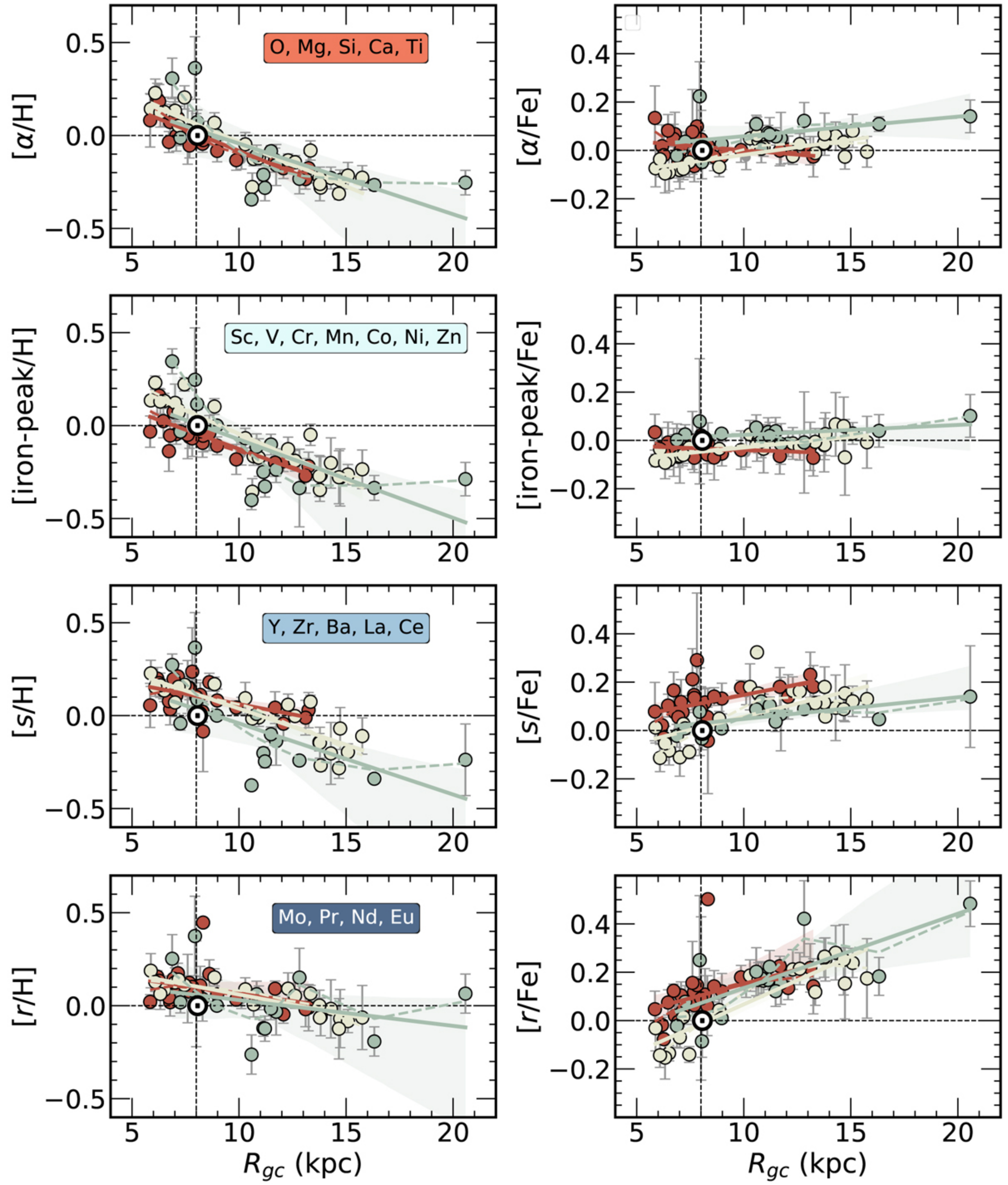
SOME ACHIEVEMENTS:

Magrini et al. (2023)

GaiaESO

Temporal evolution of the Galactic abundance gradients with OCs



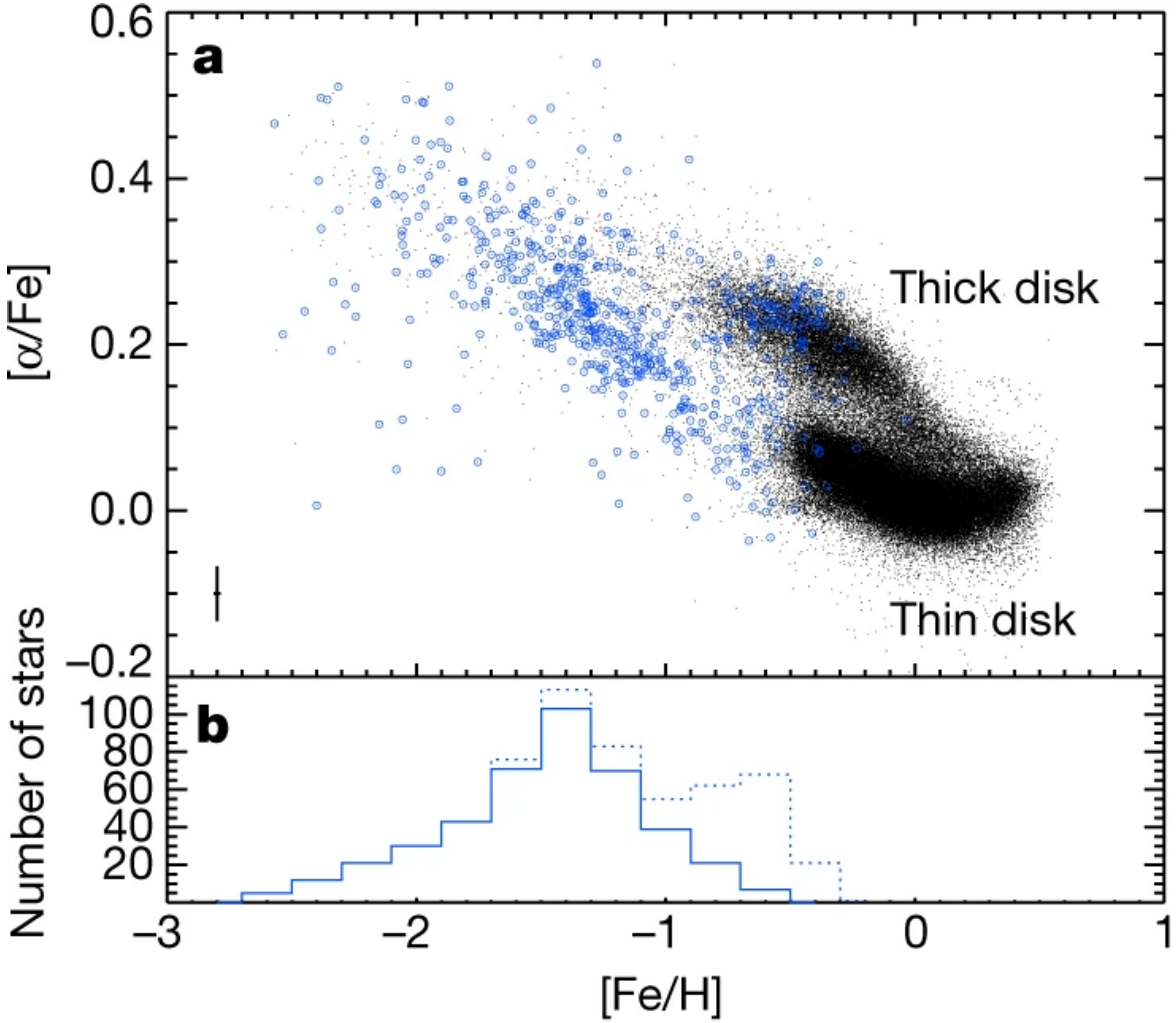


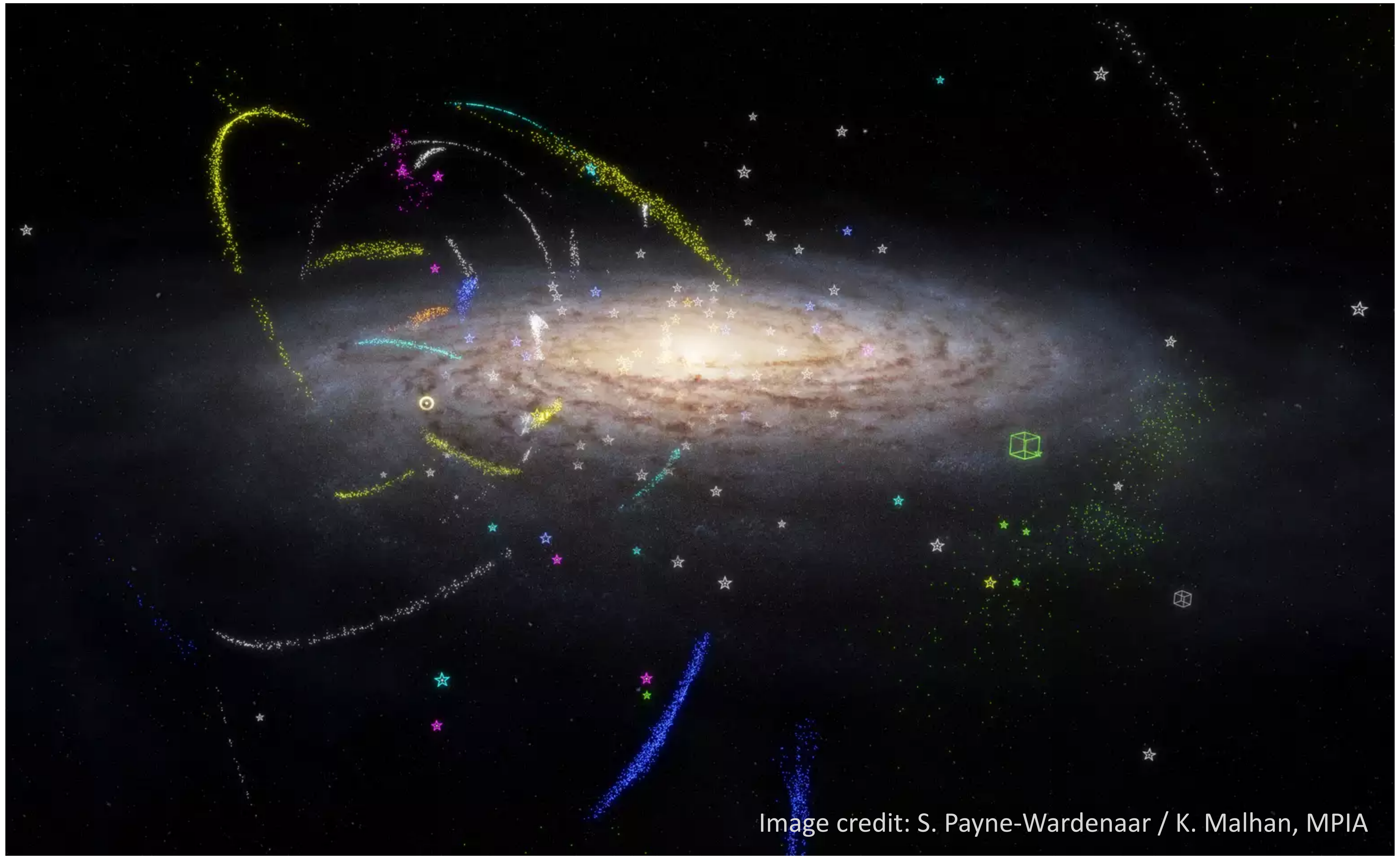
GALACTIC ARCHAEOLOGY

SOME ACHIEVEMENTS:

Mapping ancient mergers with Gaia DR3

Helmi et al. (2018)





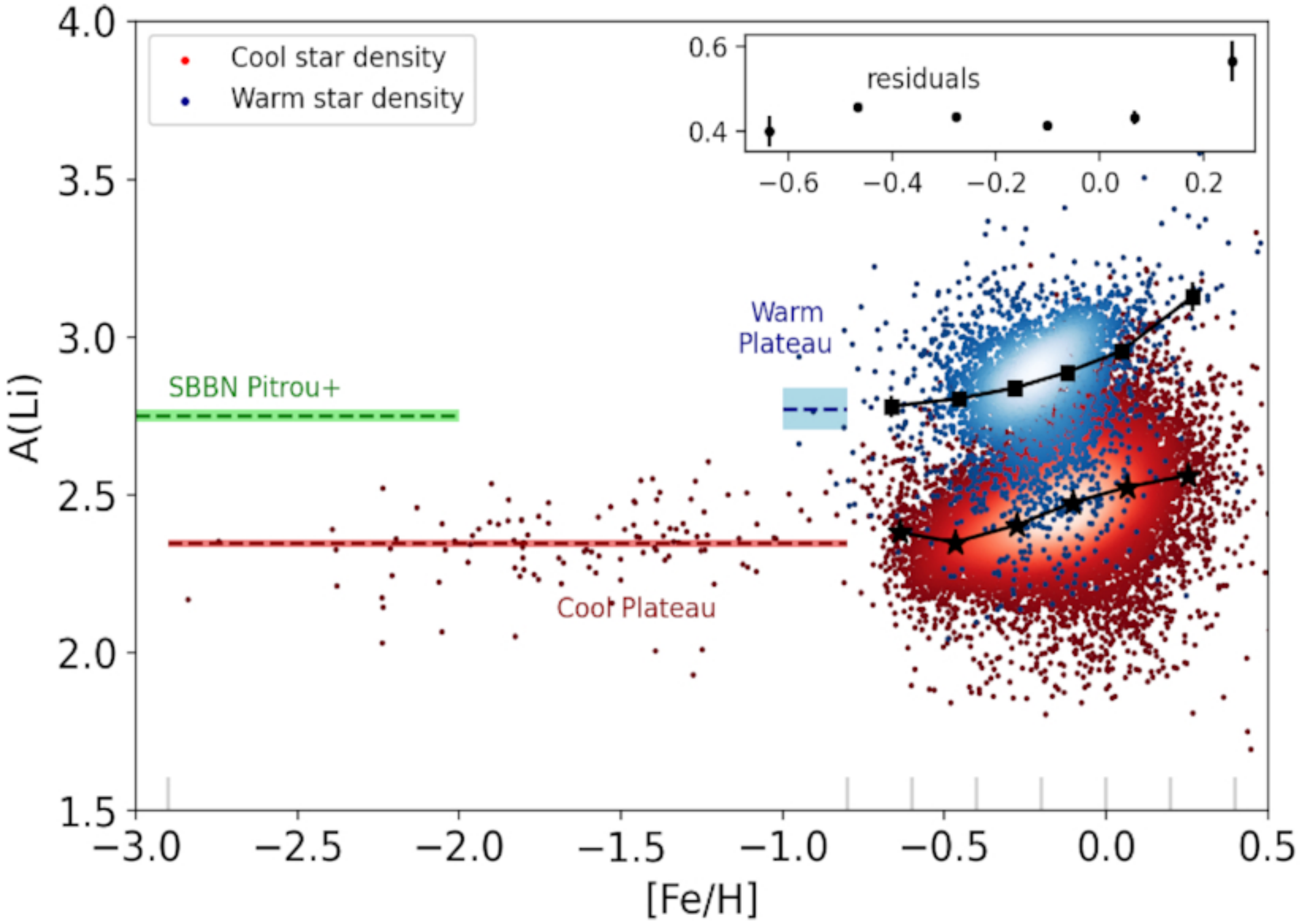
Malhan et al. (2022)

GALACTIC ARCHAEOLOGY

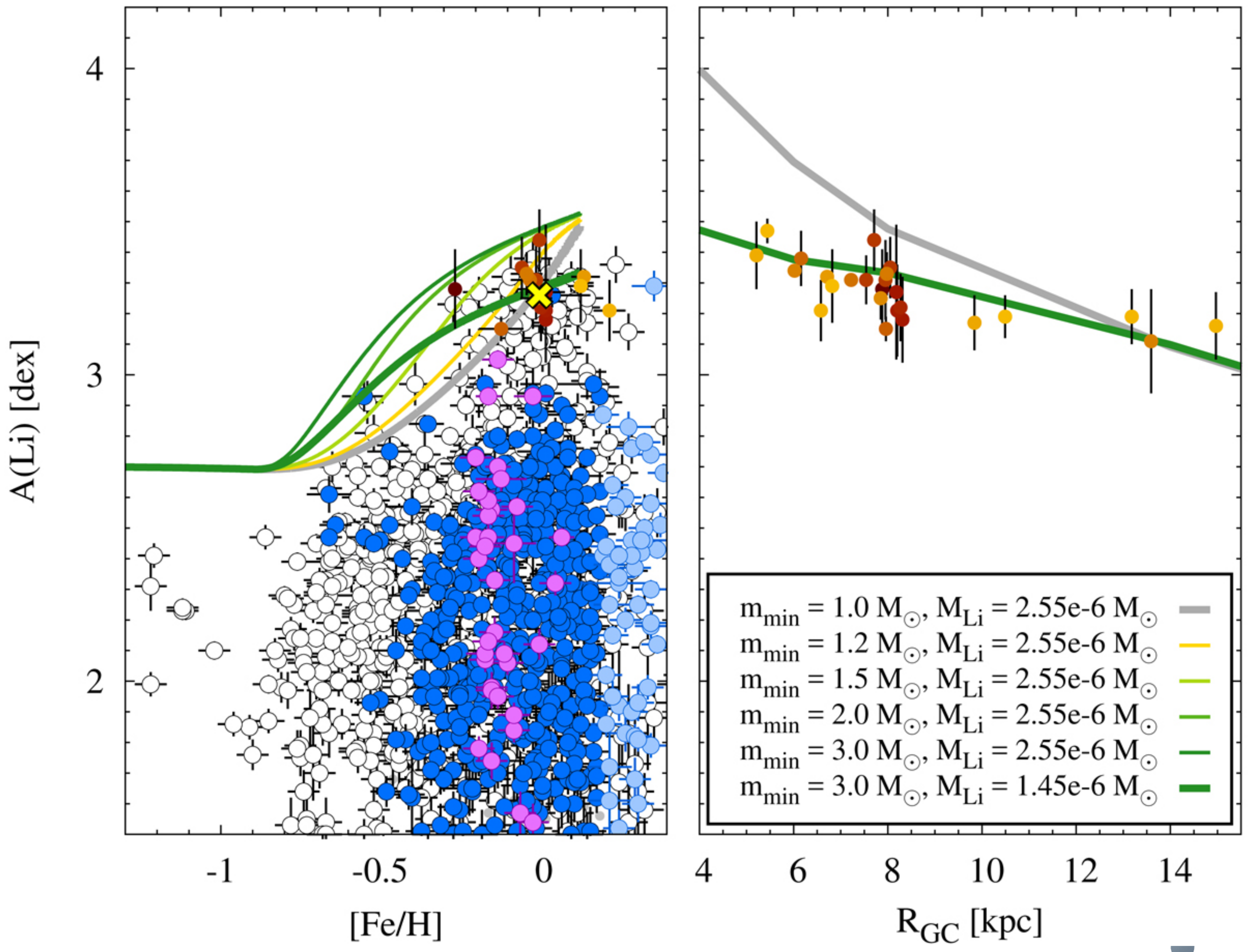
SOME ACHIEVEMENTS:

New constraints on cosmological Li and Galactic Li evolution

GALAH



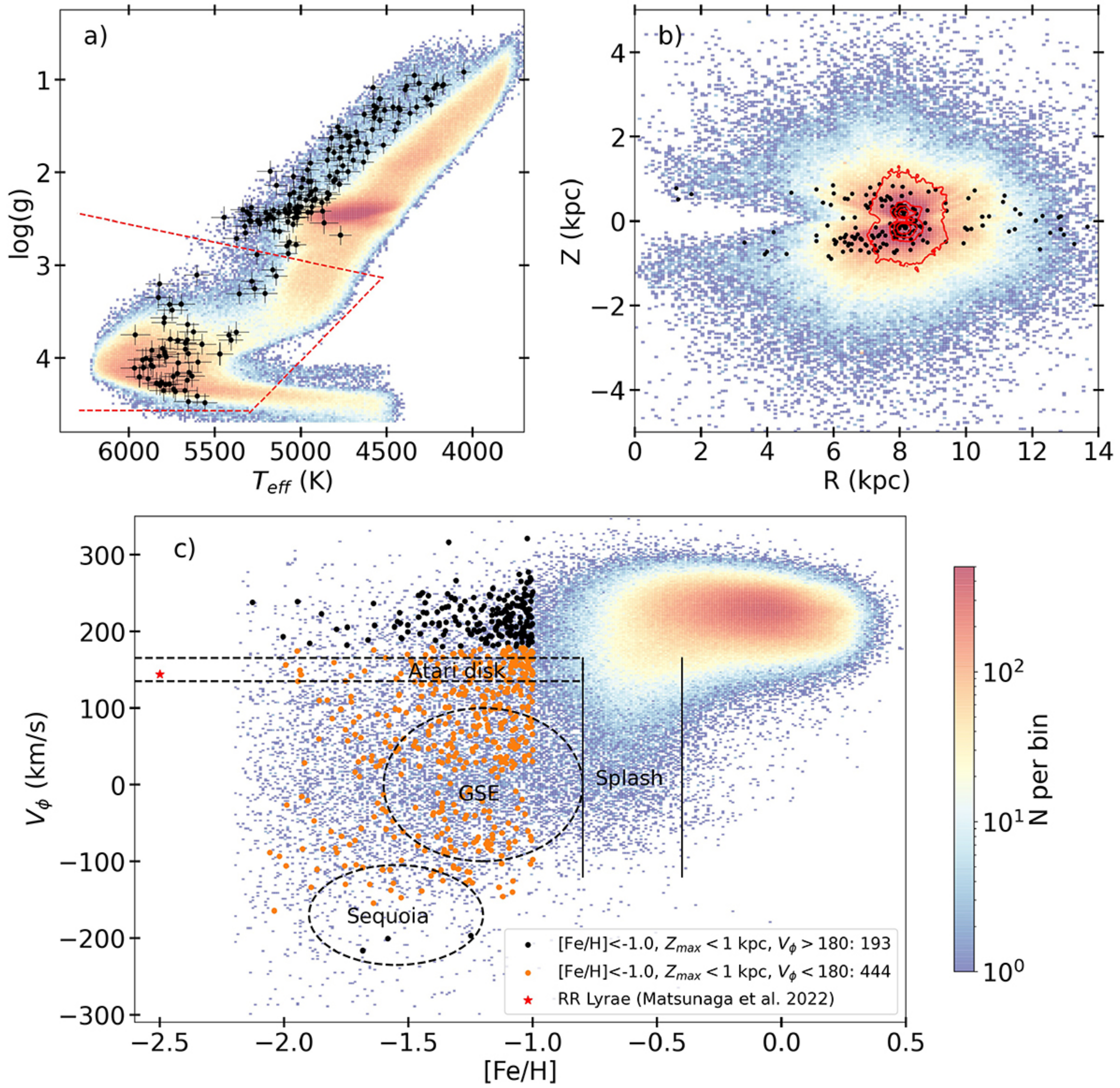
Gao et al. (2020)

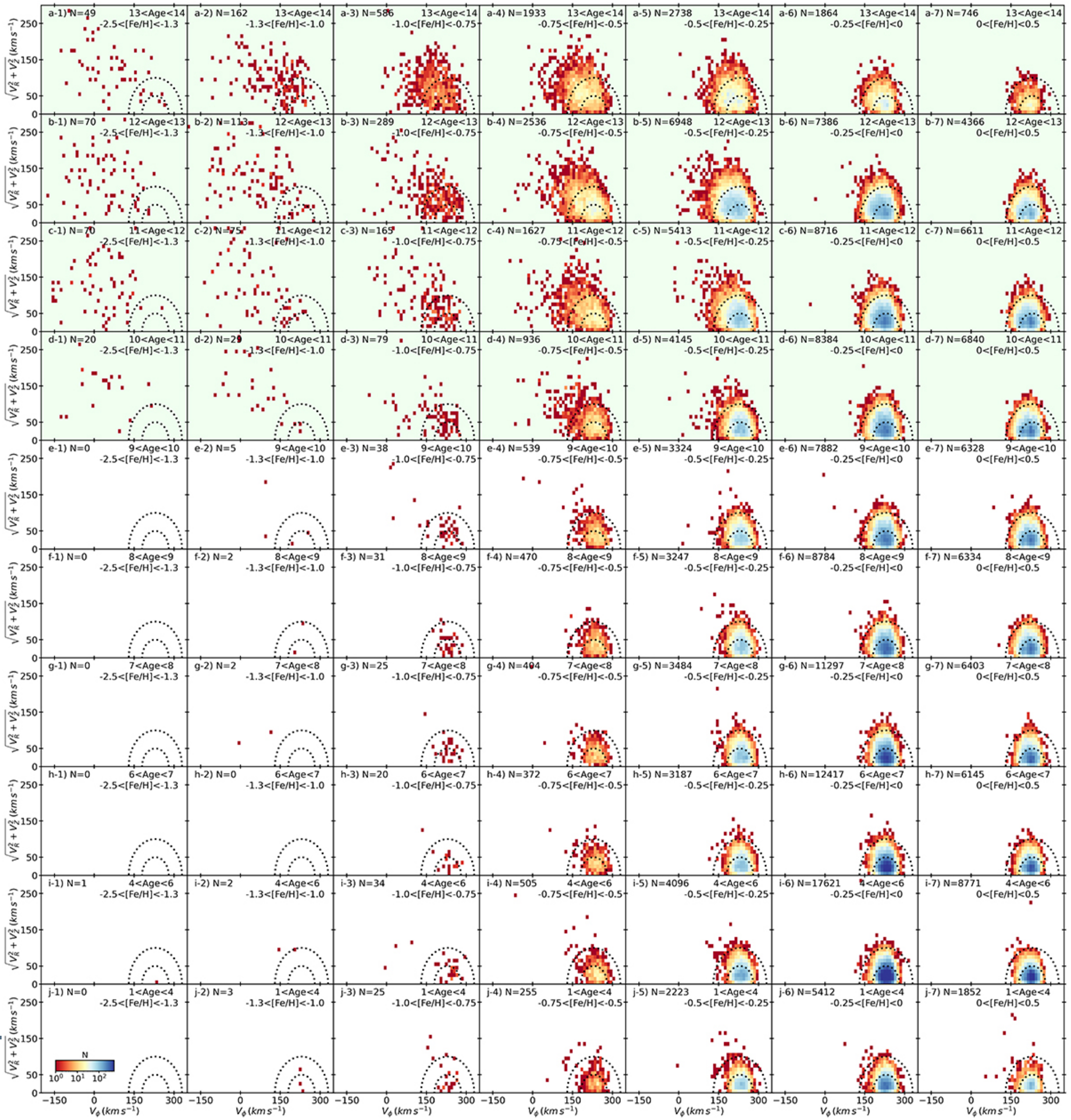


Romano et al. (2021)

GALACTIC ARCHAEOLOGY

SOME ACHIEVEMENTS:





About 200,000 MS and subgiant stars with 6D phase space information from Gaia DR3 + StarHorse ages

—> Discovery of the oldest thin disc of the Milky Way, extending from metal-poor to super-solar metallicities (Nepal+ 2024)

GALACTIC ARCHAEOLOGY

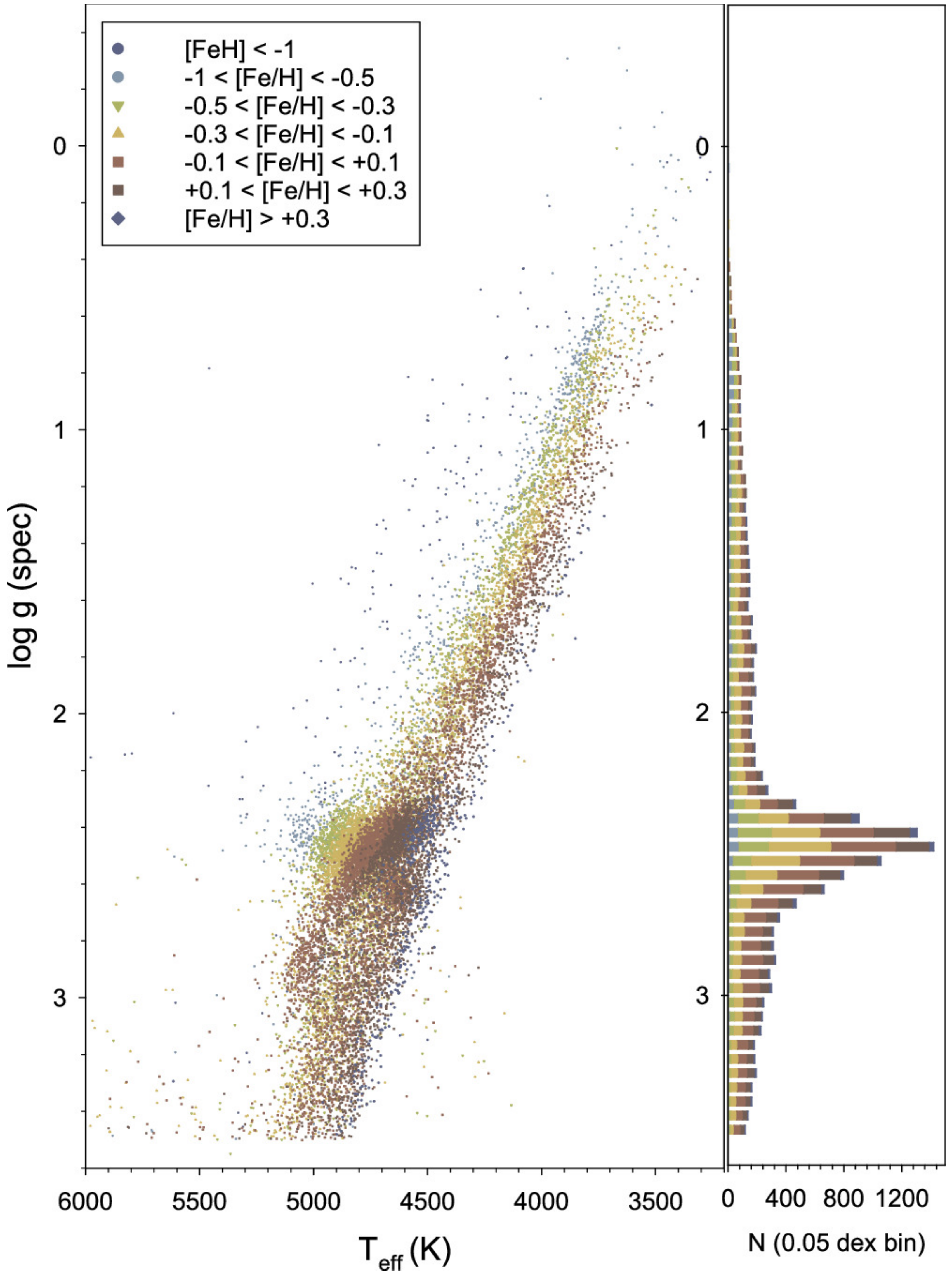
SOME ACHIEVEMENTS:

APOKASC-3 catalogue:

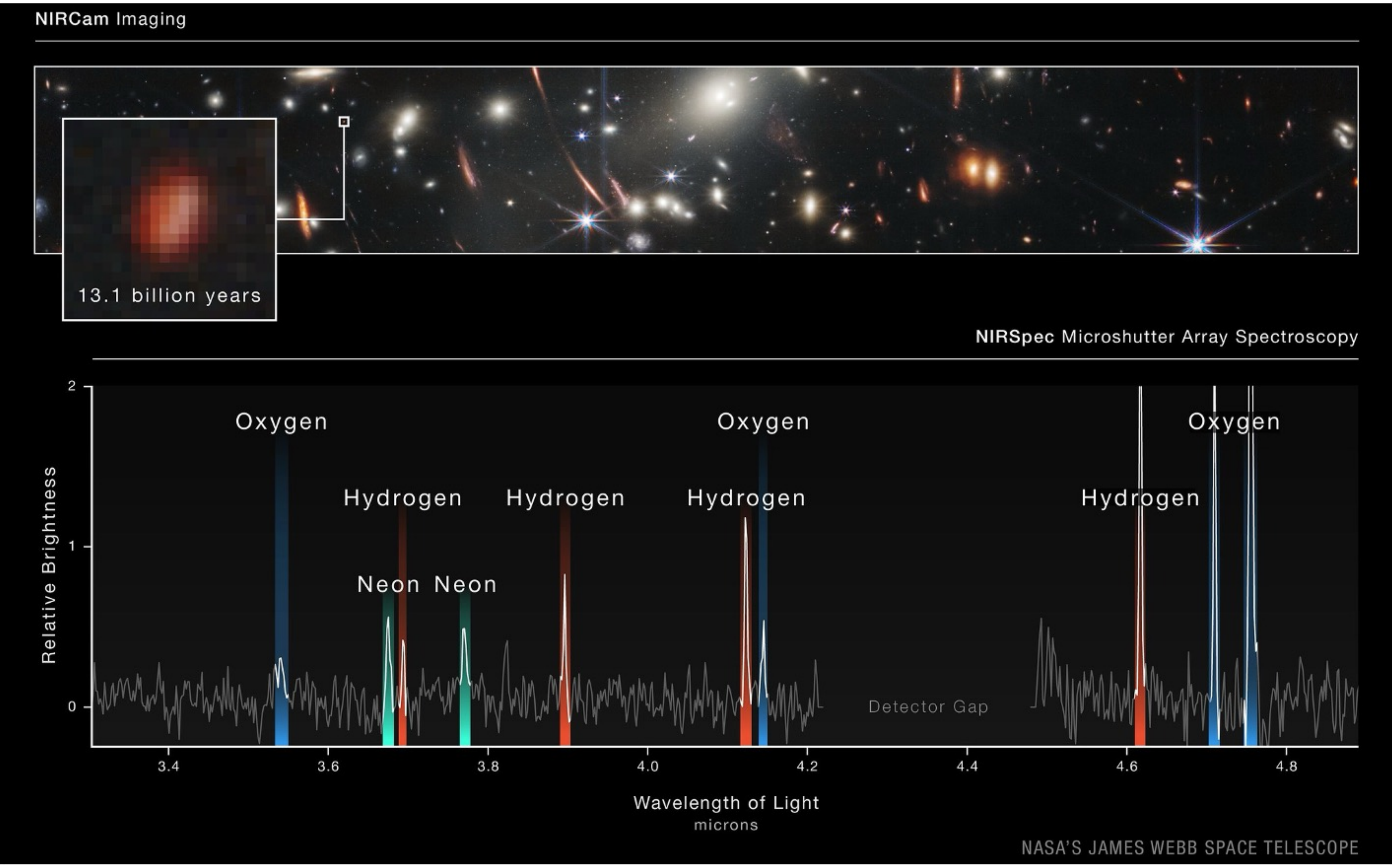
>12000 evolved stars with APOGEE spectroscopic parameters and Kepler asteroseismology

→ **Exceptionally precise measurements of masses, radii, and ages of stars**

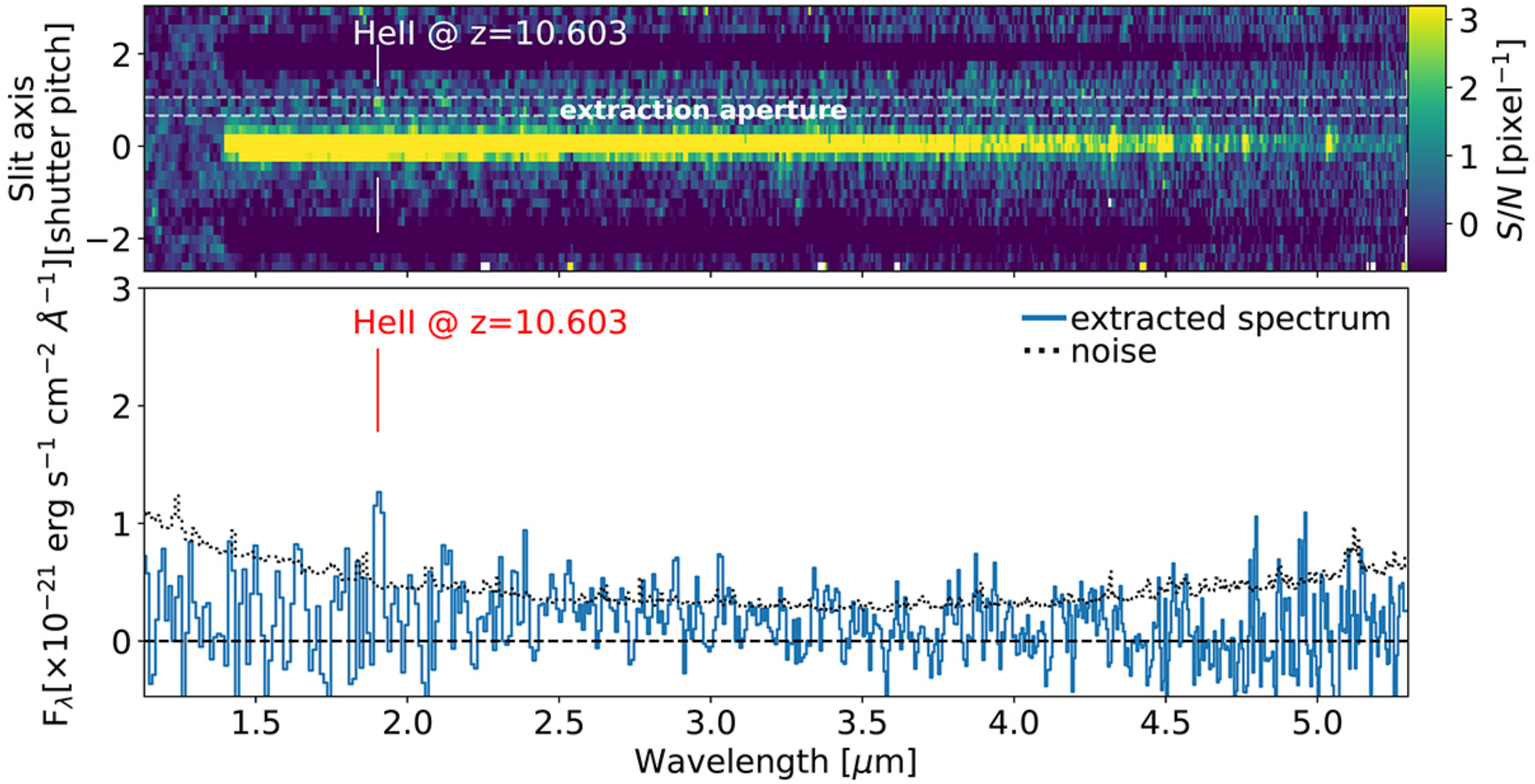
(Pinsonneault+ 2025)

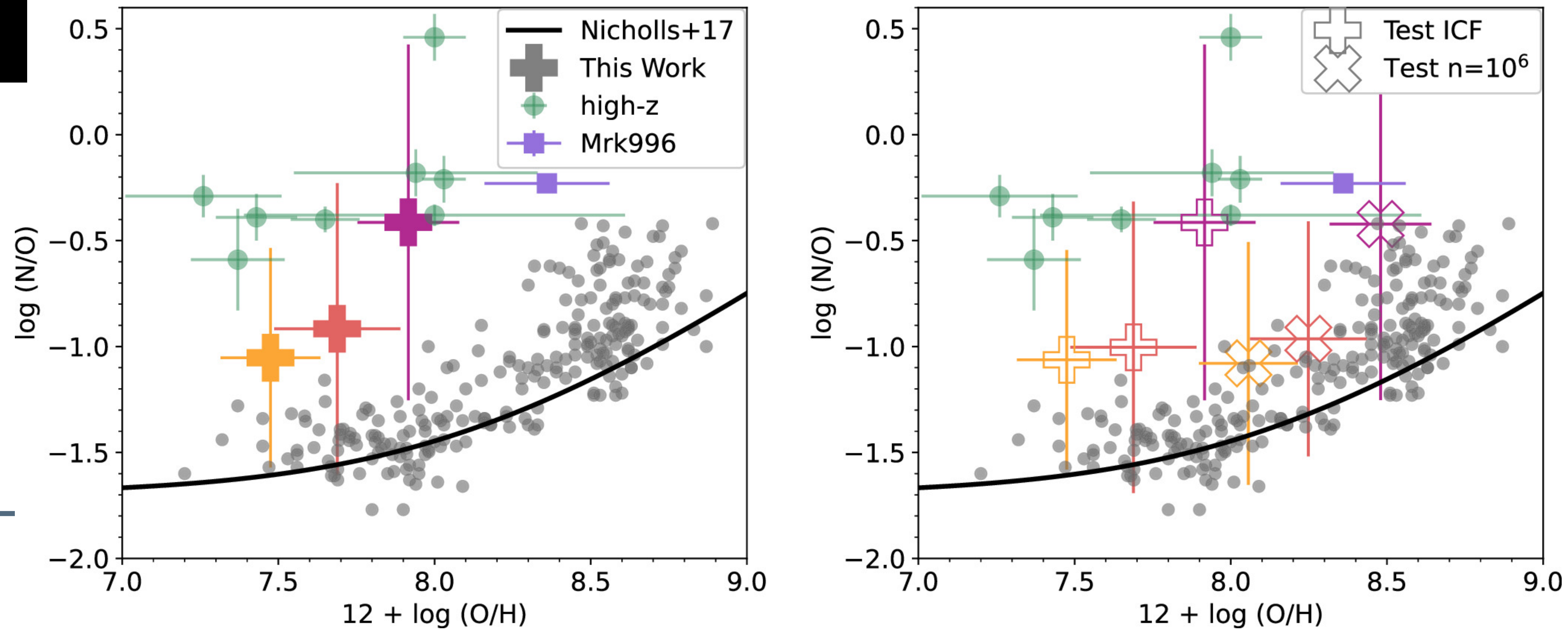


EXTRAGALACTIC ARCHAEOLOGY



Maiolino et al. (2024)





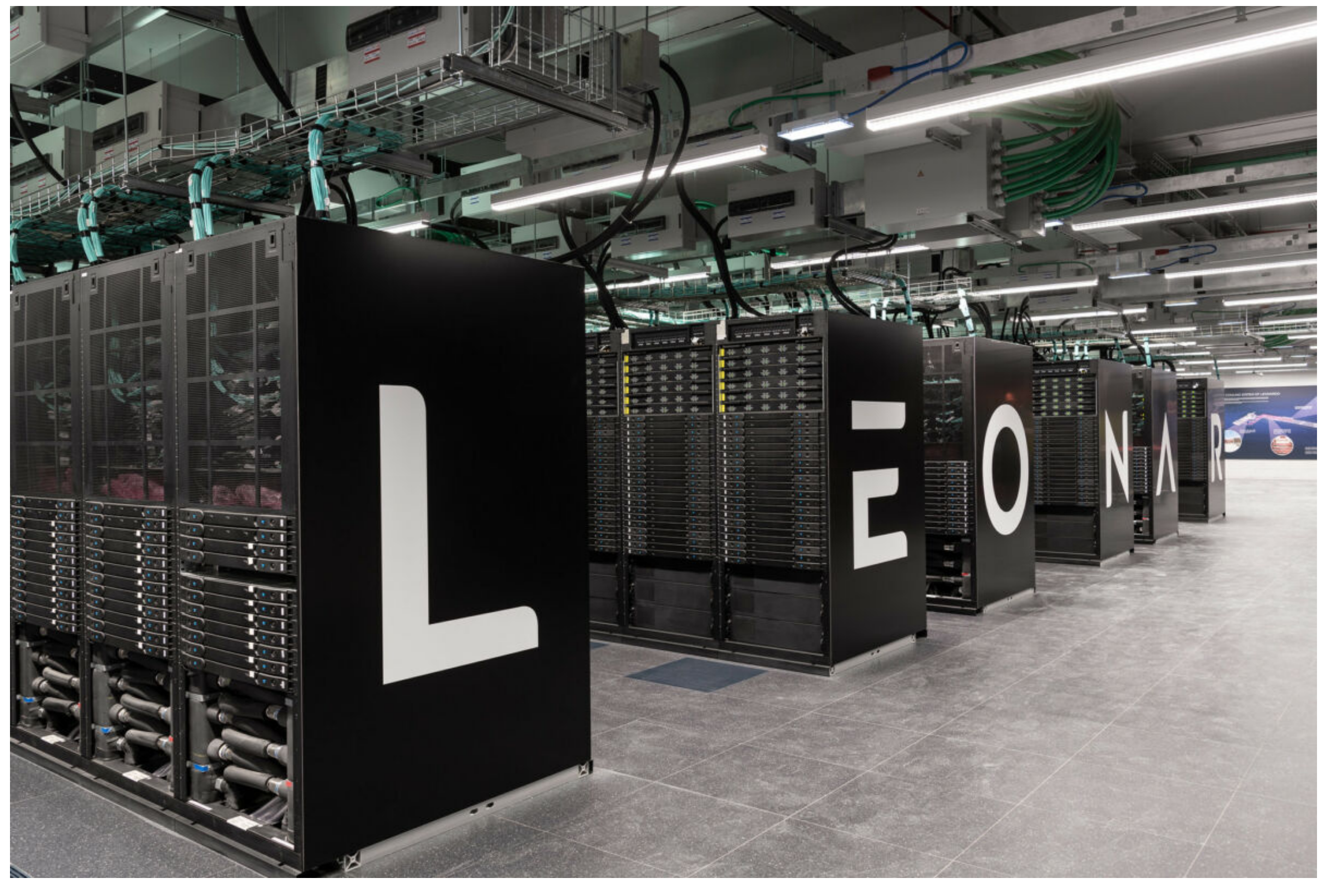
He, CNO, Ne abundance determinations at high redshift thanks to JWST/NIRSpec

Pay attention to gas densities… **(Hayes+ 2025)**

HOW DO WE EXPLOIT THESE DATA?

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

GCE codes are either stand-alone bundles or modules embedded in more complex (cosmological) hydrodynamical simulations

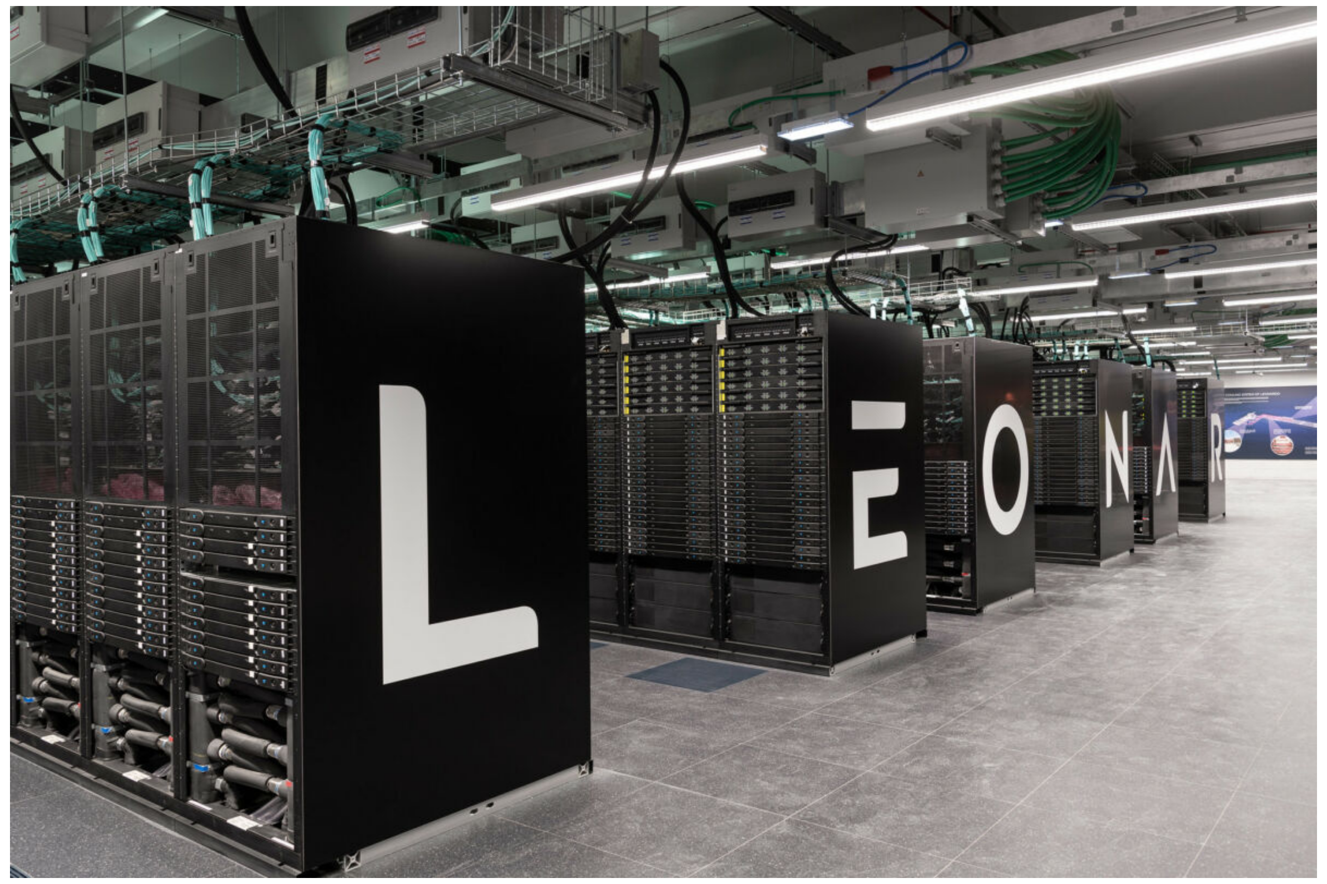


```
      wpad=0.
      do 3001 k1=1,nmax
3001  wpad=wpad+wi1(k1)
      write(6,3002)t(i),wpad
3002  format(1x,1e12.5,1x,'wpad=',1e12.5)
      iter=1
200   continue
      gg1=gpre**(ck-1.)
      gg2=gasp**(ck-1.)
      gg=(gg1+gg2)*0.5
      ra=rap*gg
      derlog=ck-1.
cccccccccccccccccc
      if(ra.eq.0.) go to 658
      po=ra*dtem
      p1=1./exp(po)
      ivo=0
      iper=0
      do 100 j=1,nmax
      p2=wi(j)/ra
      ai=p1*(g(i,j)-p2)+p2
      bi=0.5*derlog*((p
      delta=(gp(j)-ai)/(bi-gp(j))
      gp(j)=gp(j)*(1.+delta)
      if(abs(delta)-epsi) 120,120,110
120   ind(j)=1
110   continue
100   continue
cccccccccccccccccccccccccccccccccccccccccccccccccccccccc
      go to 111
658   continue
      gasp=0.
```

- Follow all stable/ unstable elements produced by stars
- Computationally cheaper

GCE codes are either stand-alone bundles or modules embedded in more complex (cosmological) hydrodynamical simulations

- Follow a subset of elements
- Massive use of HPC resources



GCE MODEL INGREDIENTS

INITIAL CONDITIONS

GCE MODEL INGREDIENTS

INITIAL CONDITIONS

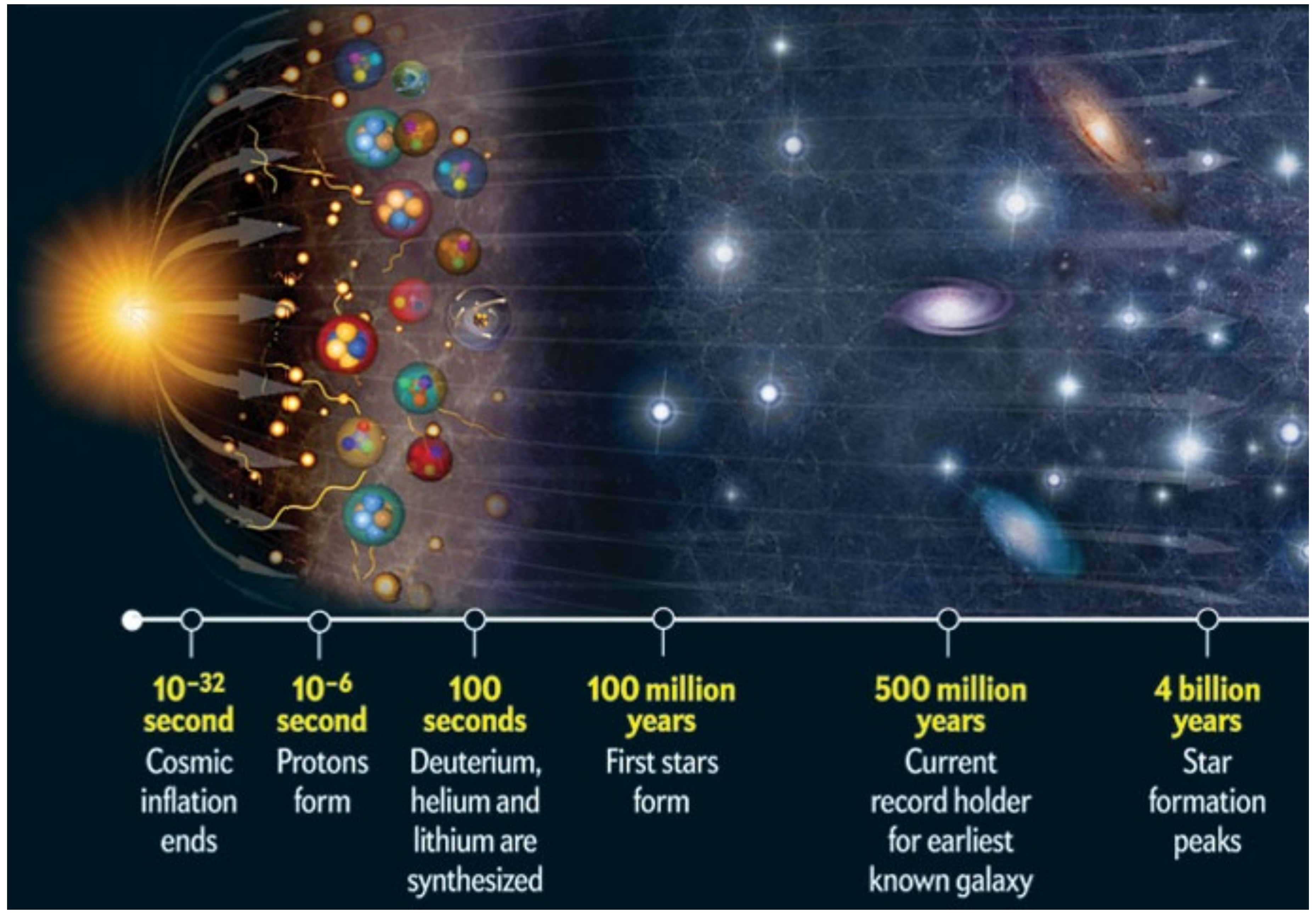
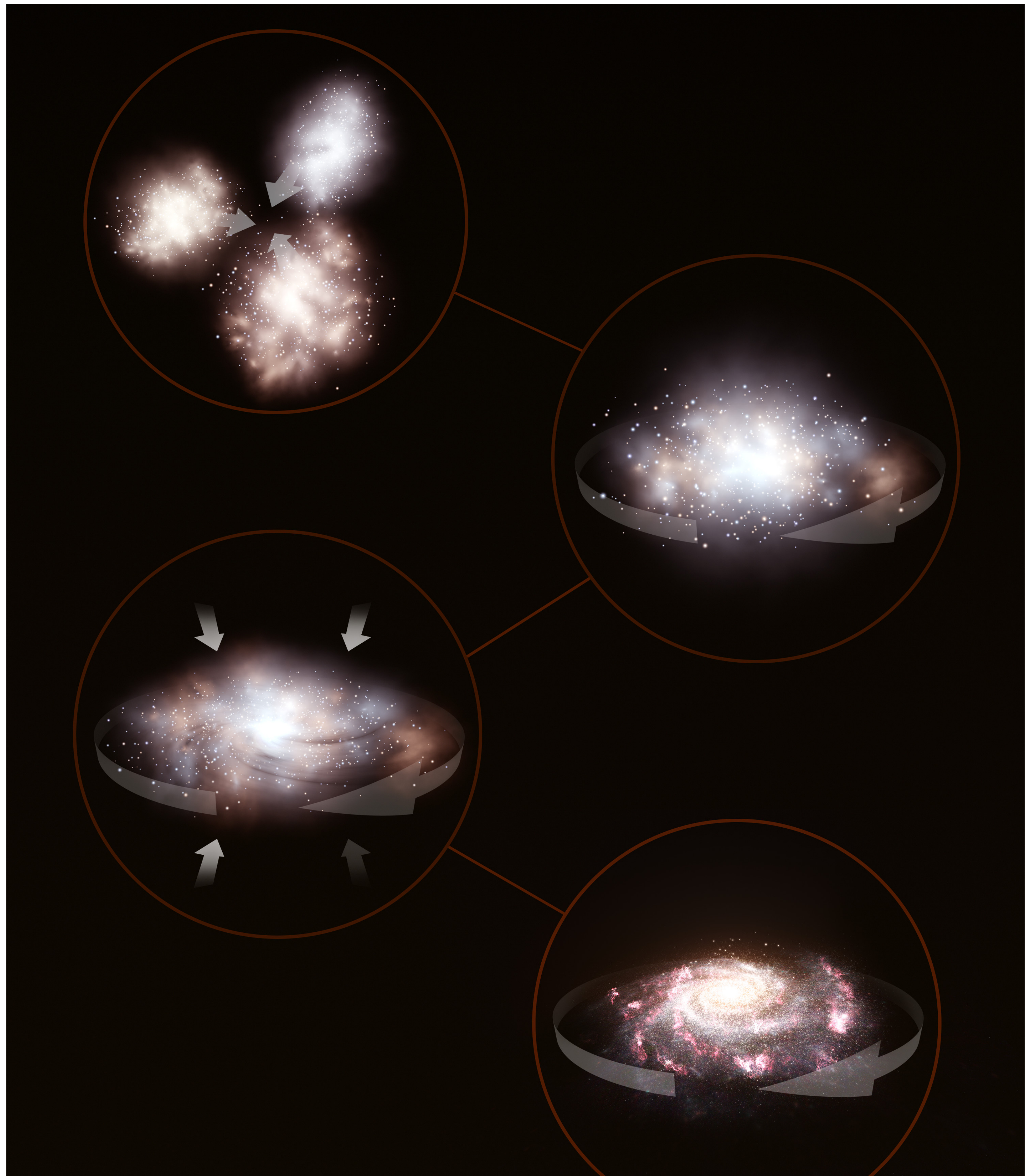


Image credit: Scientific American/Malcolm Godwin

Hierarchical formation (White & Rees 1978)
Image credit: ESO/L. Calçada



Monolithic collapse (Eggen et al. 1962)
Image credit: ESO/L. Calçada

From pristine gas [e.g., Y_P = 0.24721; $(D/H)_P$ = 2.439e-5; $(^3He/H)_P$ = 1.039e-5; $(^7Li/H)_P$ = 5.464e-10; Pitrou et al. 2021] to present-day galaxies !

GCE MODEL INGREDIENTS

- INITIAL CONDITIONS
- STAR FORMATION RATE

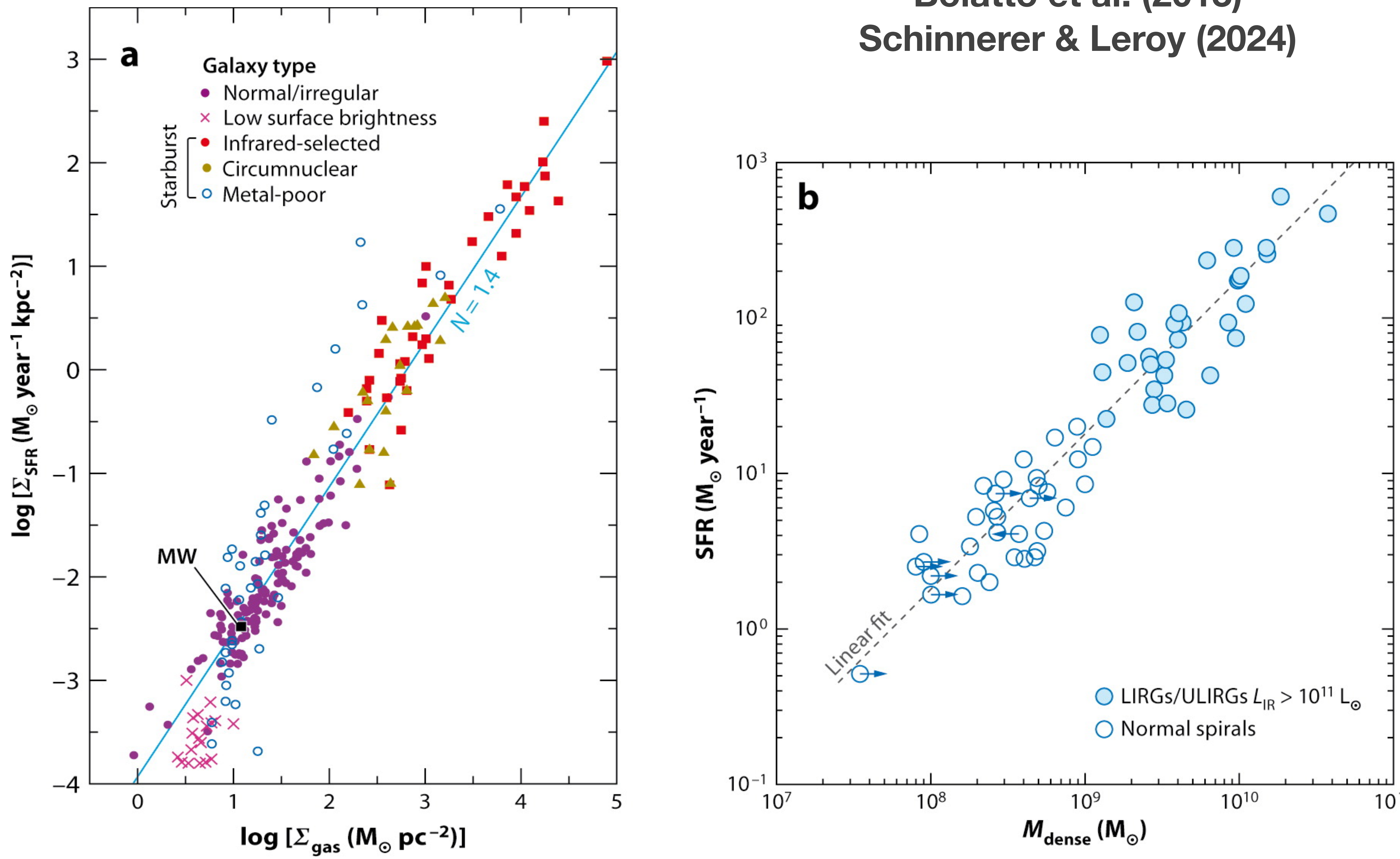
GCE MODEL INGREDIENTS

Recommended readings:

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

- INITIAL CONDITIONS
- **STAR FORMATION RATE**

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



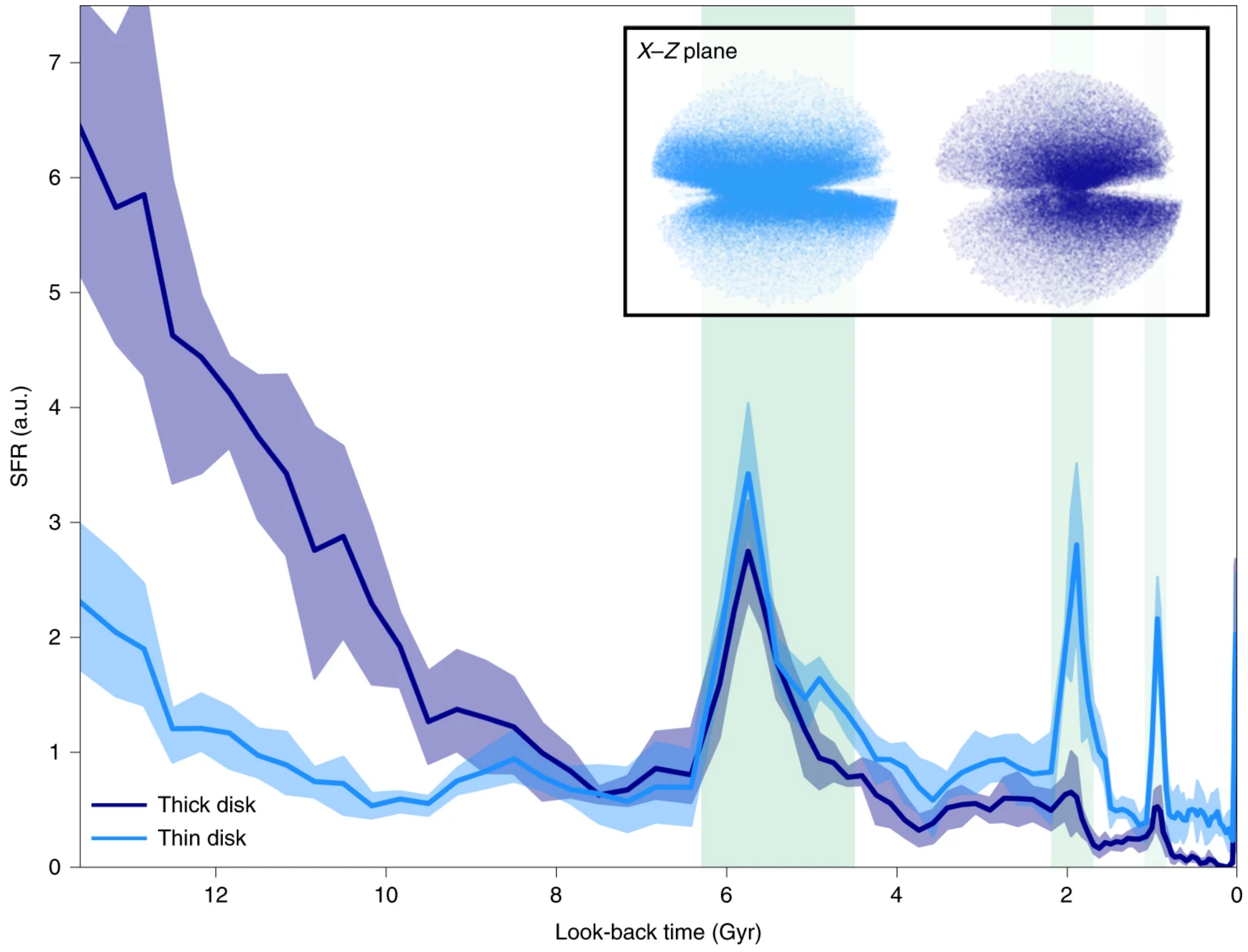
Kennicutt & Evans (2012)

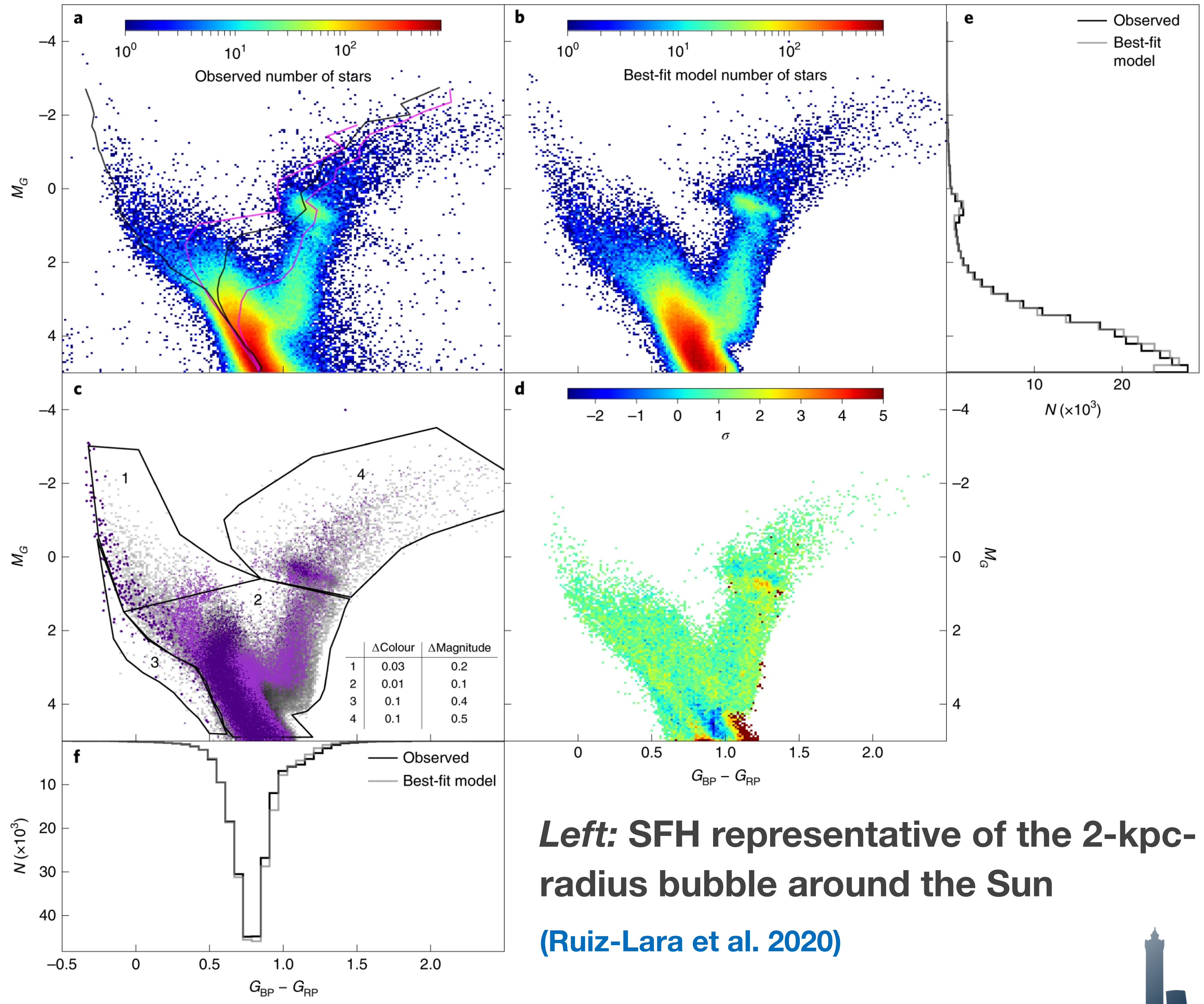
GCE MODEL INGREDIENTS

Gaia distances + dust maps
SFH from deep CMDs
for large MW volumes

(Lallement+2018, Casagrande+2018, Babusiaux+2018)

- INITIAL CONDITIONS
- STAR FORMATION RATE





Left: **SFH representative of the 2-kpc-radius bubble around the Sun**

(Ruiz-Lara et al. 2020)

GCE MODEL INGREDIENTS

- INITIAL CONDITIONS
- STAR FORMATION RATE

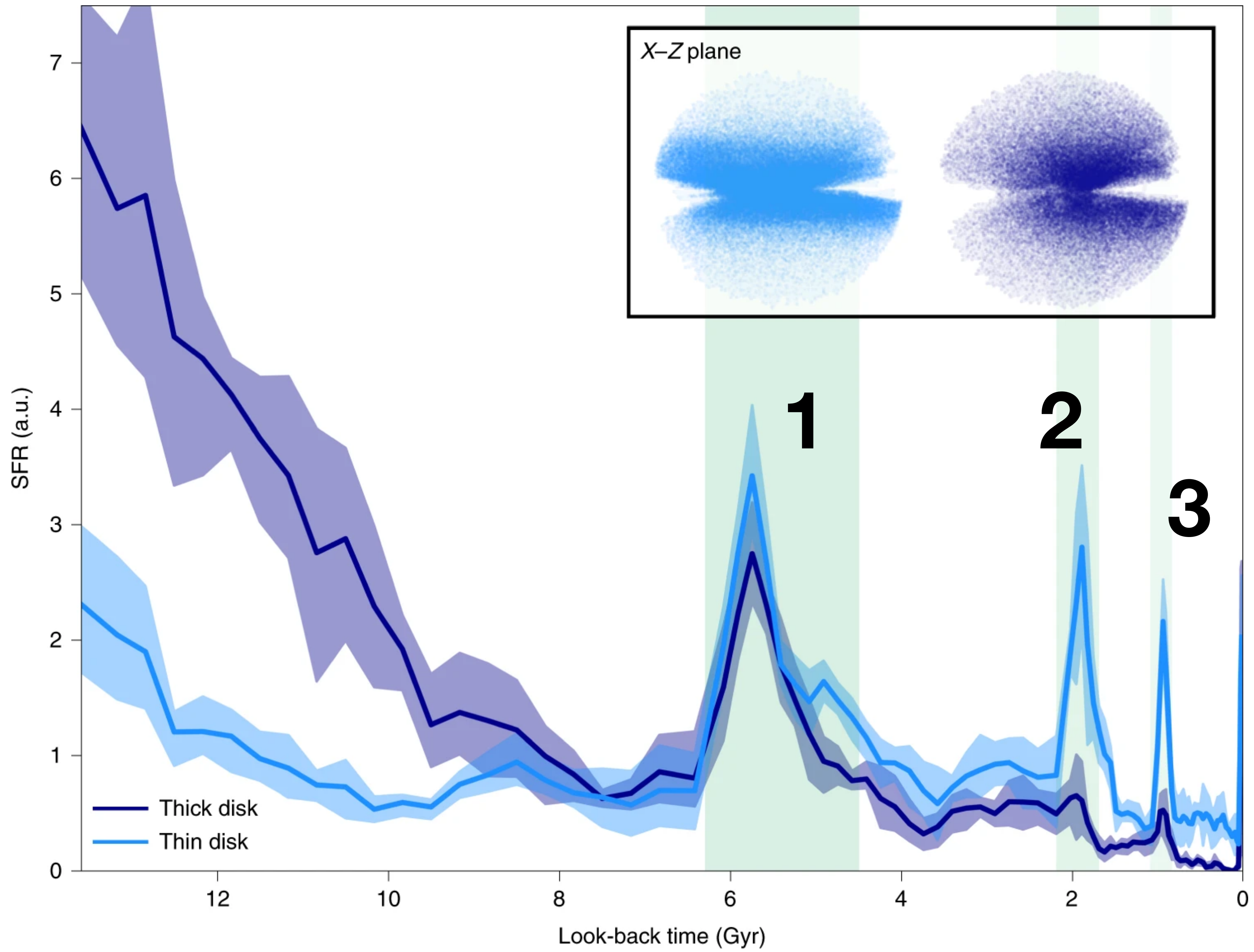
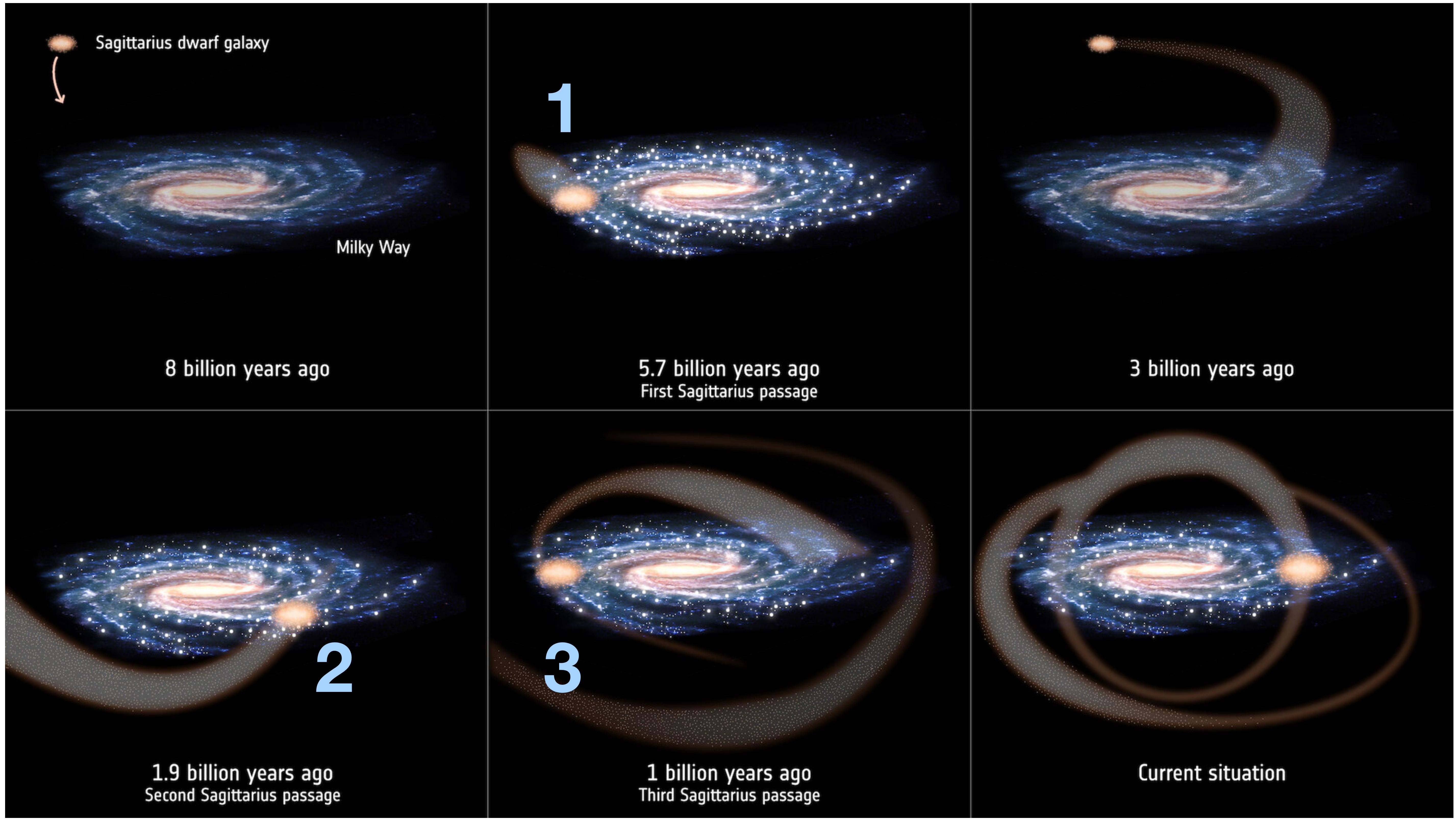


Image credit: ESA



Three collisions between the Sgr dwarf spheroidal galaxy and the Milky Way might have triggered major star formation episodes in the MW disc

(Purcell+ 2011; Laporte+ 2018; Antoja+ 2020)

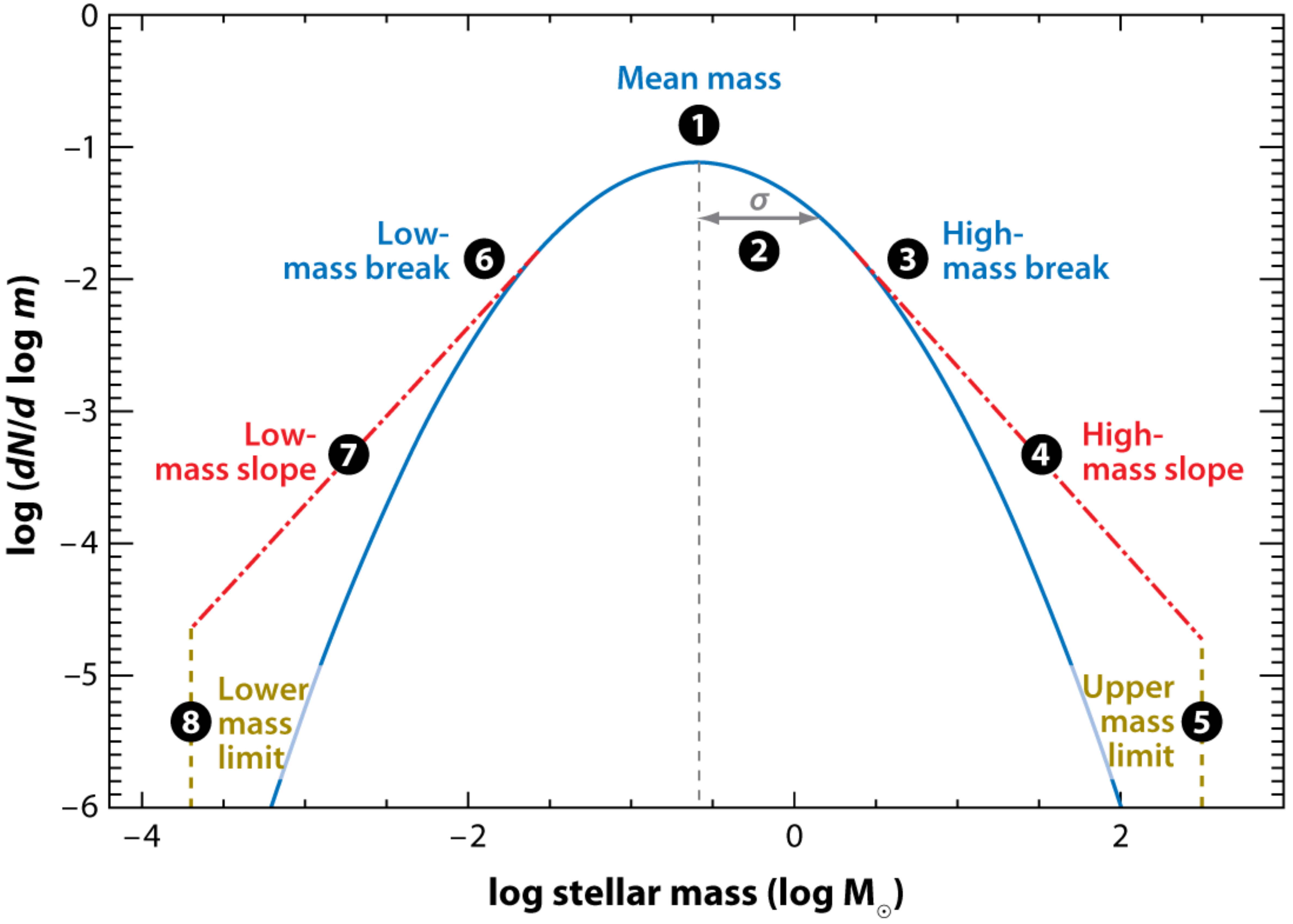
GCE MODEL INGREDIENTS

- INITIAL CONDITIONS
- STAR FORMATION RATE
- STELLAR IMF

GCE MODEL INGREDIENTS

Bastian et al. (2010)

- INITIAL CONDITIONS
- STAR FORMATION RATE
- STELLAR IMF

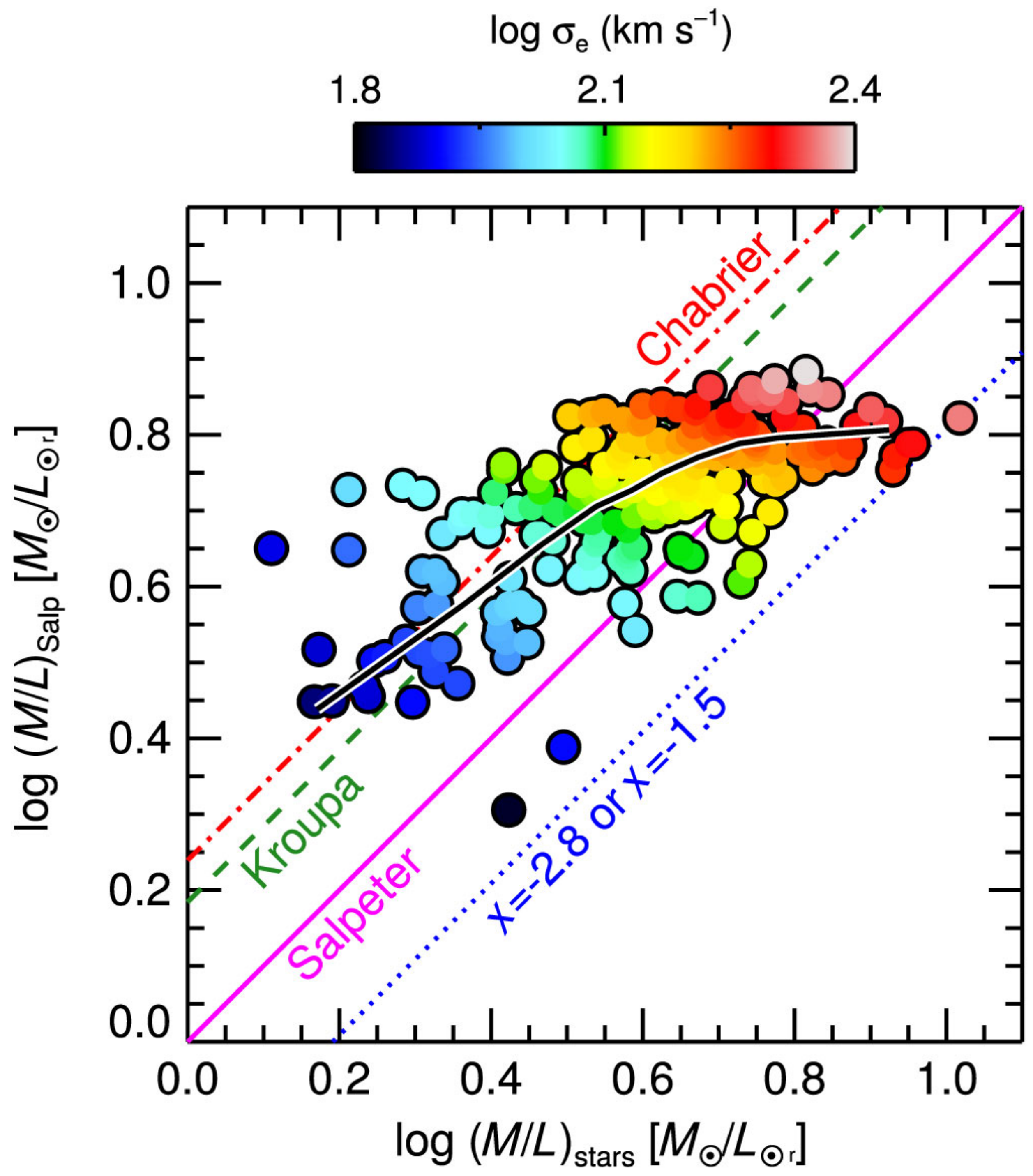


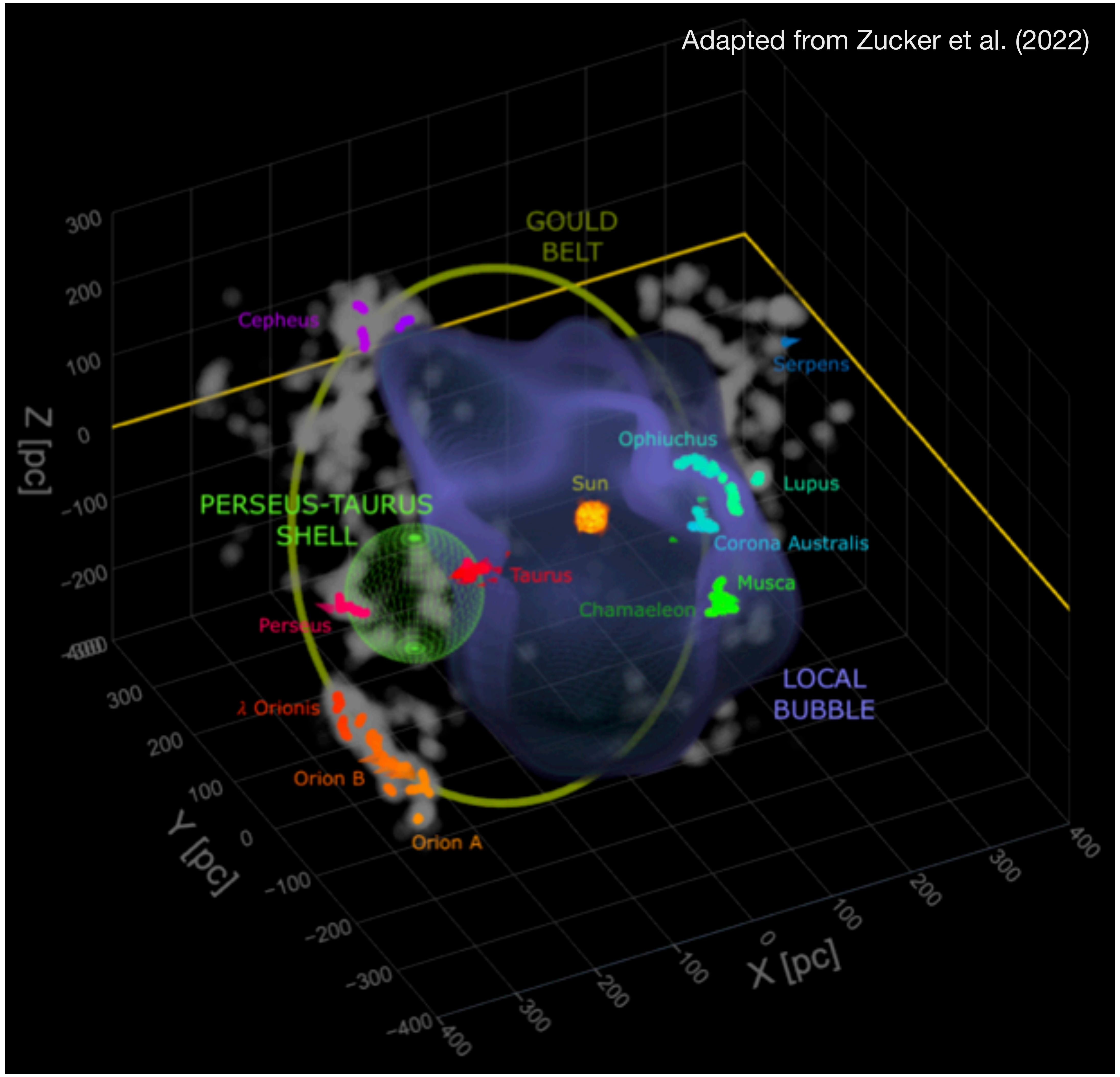
- The IMF describes the distribution of stellar masses formed in a single star formation event (Salpeter 1955)
- Moving from star counts to an IMF is not trivial!
- Needs corrections for stellar multiplicity and evolutionary effects, making assumptions about the age and structure of the Galactic disc, some knowledge of the star formation rate and its evolution with time, considering the diffusion of stellar orbits, and more (Scalo 1986; Kroupa 2002; Chabrier 2003; Kroupa et al. 2013; Hopkins 2018)

GCE MODEL INGREDIENTS

- INITIAL CONDITIONS
- STAR FORMATION RATE
- STELLAR IMF

- Direct estimate of the IMF (star counts) possible only in the solar vicinity ***(right-hand figure)***
- Is the IMF universal or does it vary in space/time? **(e.g., Cappellari+ 2012; *left-hand figure)***



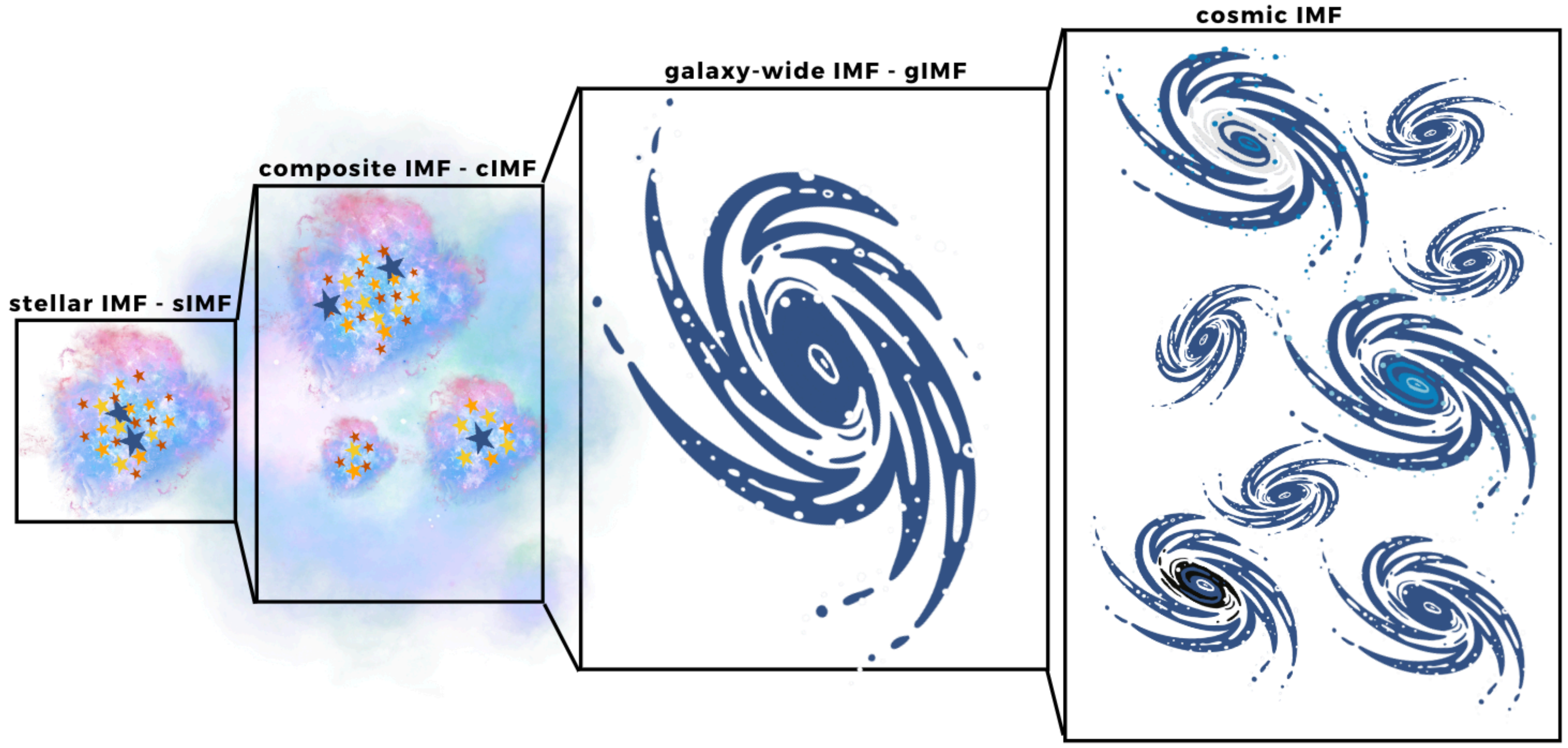


GCE MODEL INGREDIENTS

Recommended readings:

Bastian et al. (2010)
Hopkins (2018)
Smith (2020)
Hennebelle & Grudic (2024)

- **INITIAL CONDITIONS**
- **STAR FORMATION RATE**
- **STELLAR IMF**



- Many IMFs! Stellar IMF, composite IMF, cumulative composite IMF, galaxy-wide IMF, cosmic IMF…
- Moreover: is the stellar IMF an invariant probability density distribution function or it is an optimally sampled distribution function?

(Recent review: Jerabkova, DR, Kroupa+ submitted)

Credits: Tereza Jerabkova

GCE MODEL INGREDIENTS

- INITIAL CONDITIONS
- STAR FORMATION RATE
- STELLAR IMF
- GAS ACCRETION

GCE MODEL INGREDIENTS

INITIAL CONDITIONS

STAR FORMATION RATE

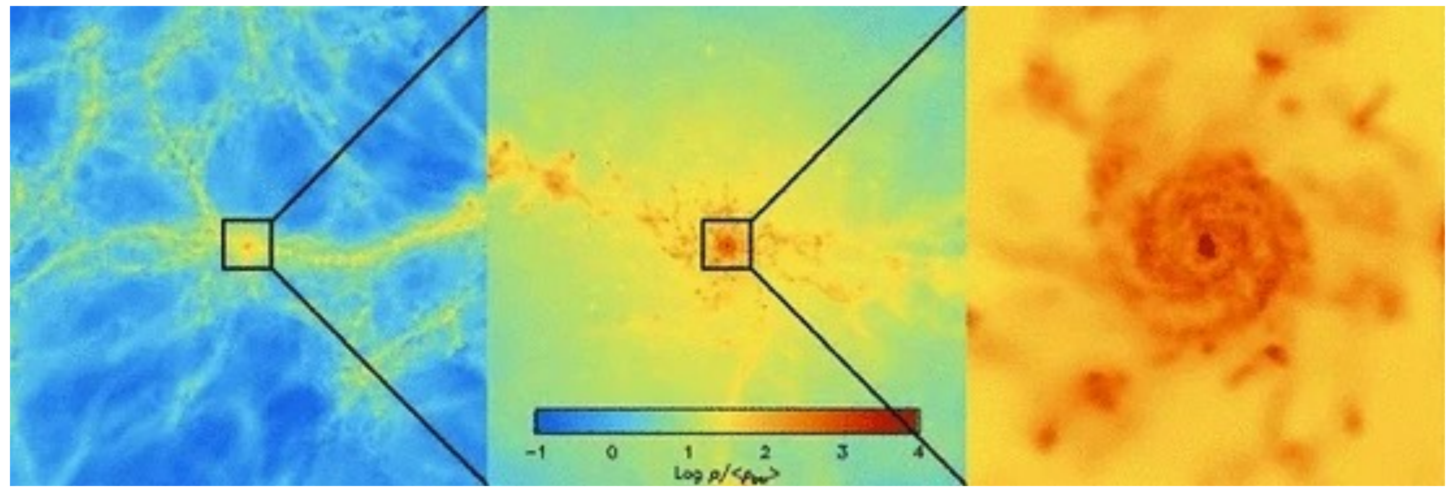
STELLAR IMF

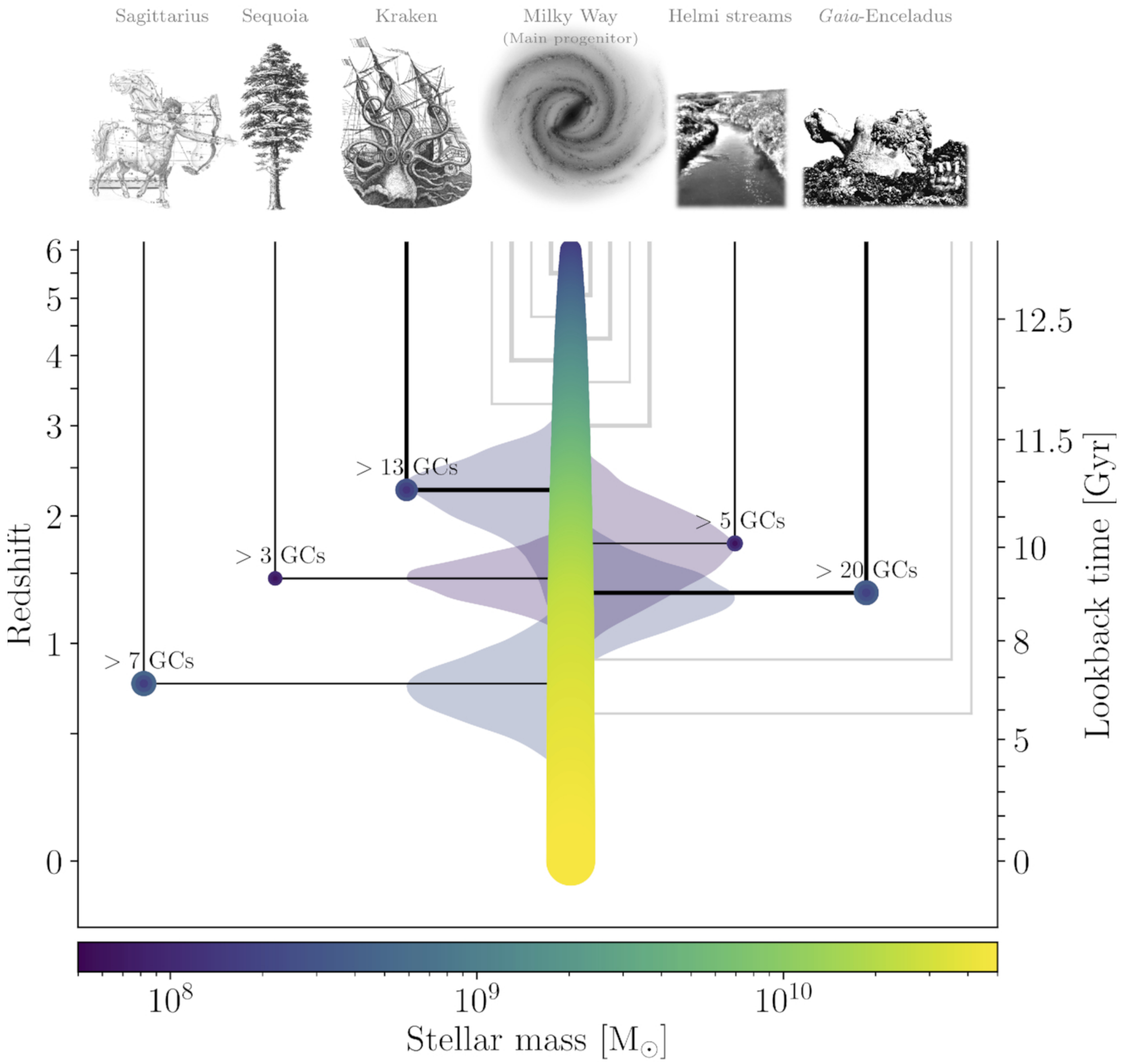
GAS ACCRETION

- Larson (1976), Matteucci & Francois (1989), Chiappini et al. (2001)… inside-out formation of galactic discs:

$$\tau_{inf}(r_{in}) < \tau_{inf}(r_{out})$$

- Merger history from cosmological simulations, e.g., Schaye et al. 2010 *(below)*; Kruijssen et al. 2020 *(right)*… and many others





GCE MODEL INGREDIENTS

- INITIAL CONDITIONS
- STAR FORMATION RATE
- STELLAR IMF
- GAS ACCRETION
- GAS (OUT)FLOWS

GCE MODEL INGREDIENTS

- INITIAL CONDITIONS
- STAR FORMATION RATE
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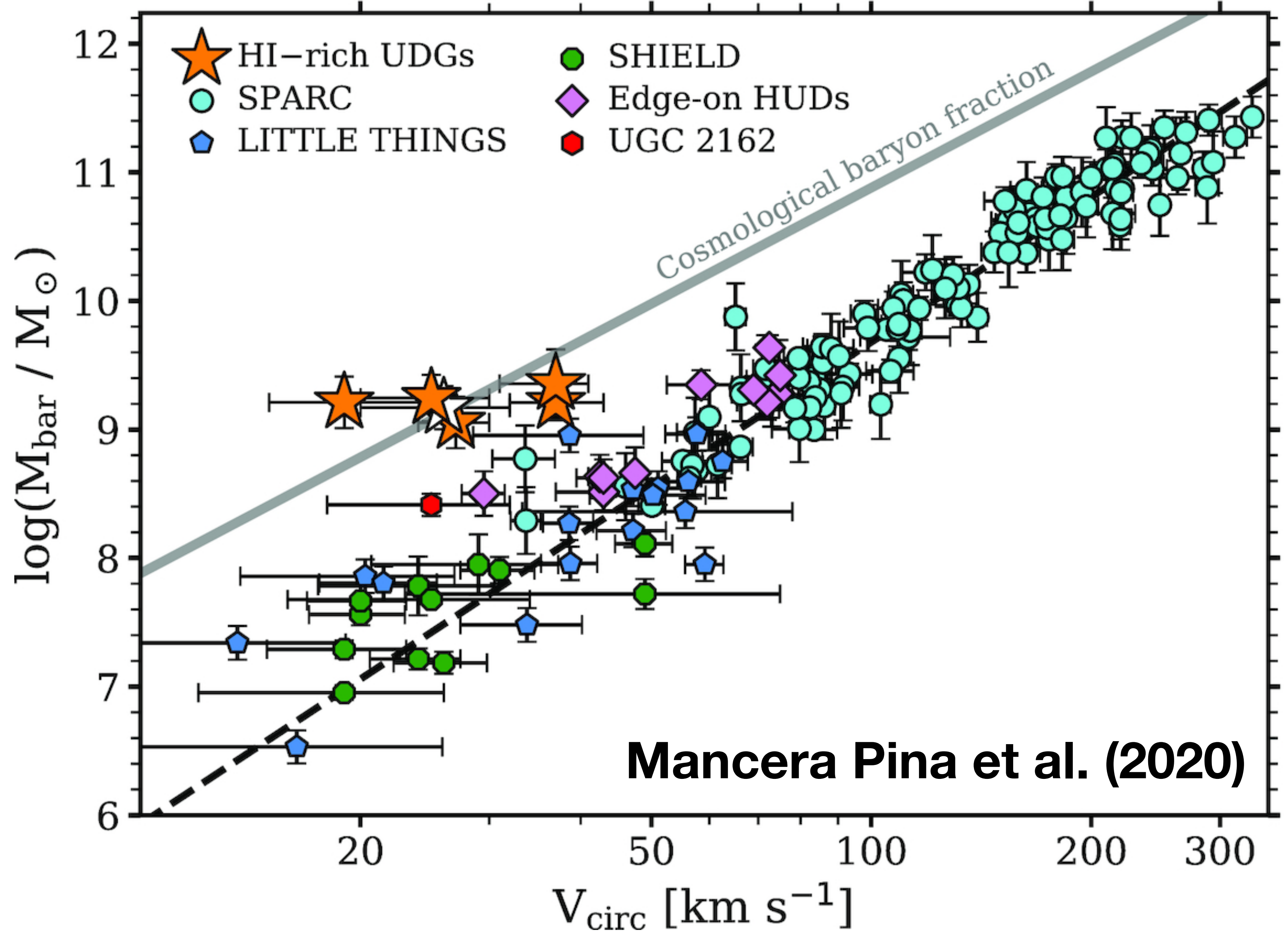
- GAS ACCRETION
- GAS (OUT)FLOWS

Recommended reading:
Thompson & Heckman (2024)



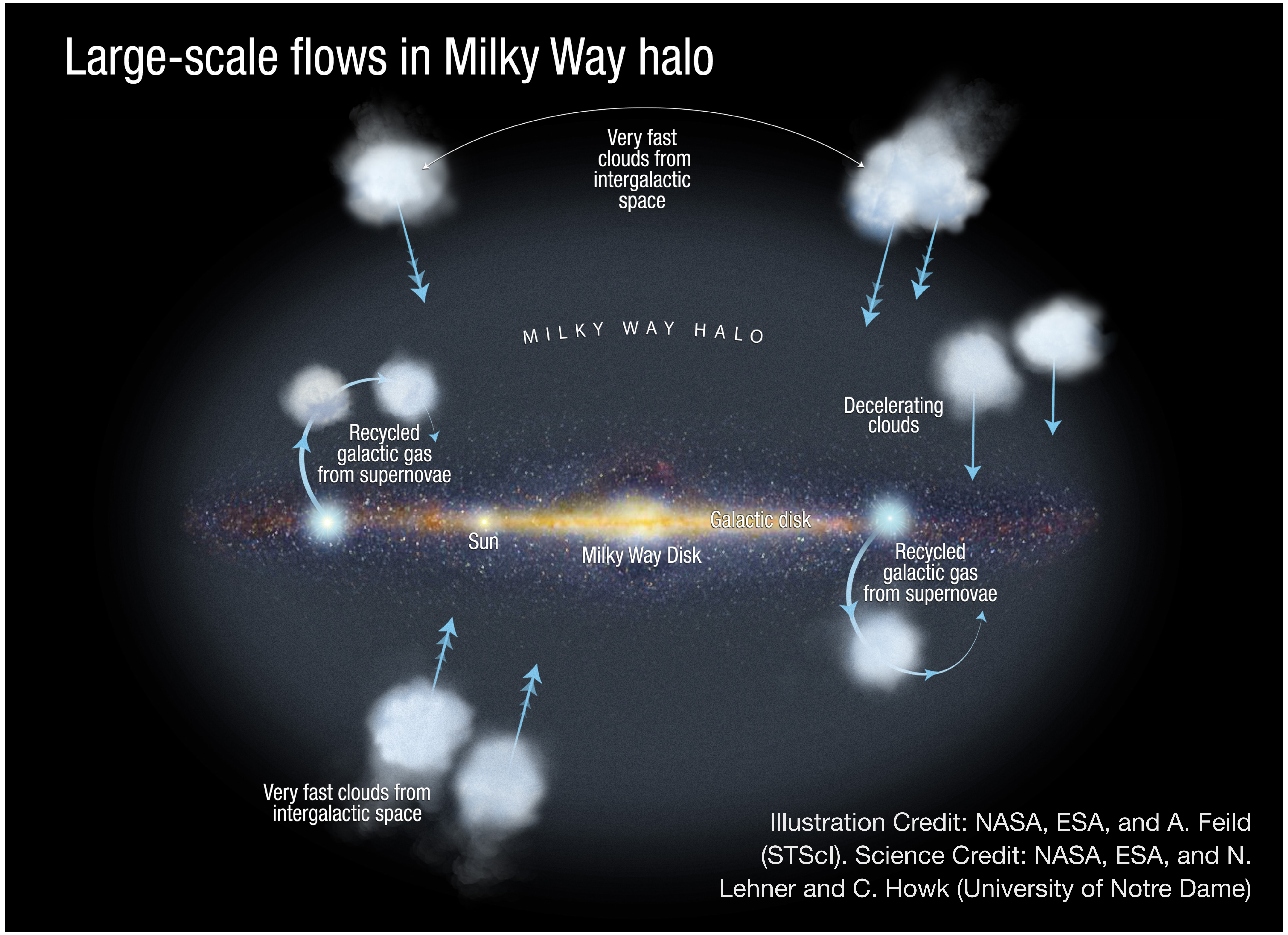
- Emission and absorption line measurements of cool/warm gas provide the best physical diagnostics of galactic outflows
- Hydrodynamical simulations study how mass, energy, and momentum injected by SNe are mixed with the ISM and entrained into an outflow
- This remains a principal topic of research

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

GCE MODEL INGREDIENTS

- INITIAL CONDITIONS
- STAR FORMATION RATE
- STELLAR IMF
- GAS ACCRETION
- GAS (OUT)FLOWS

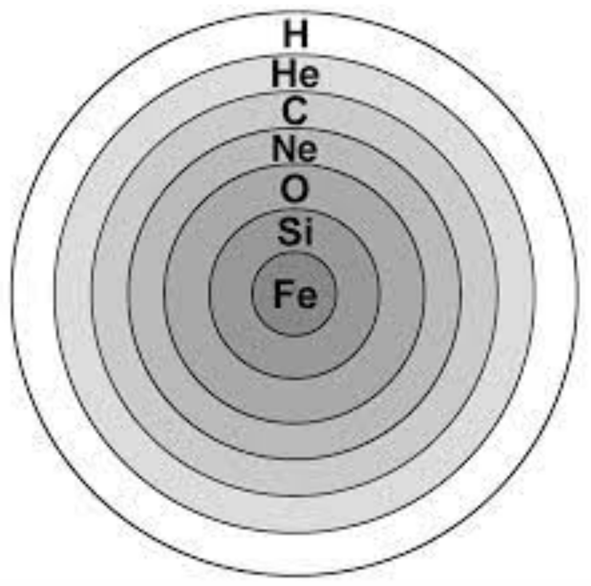
Galactic fountains (Shapiro & Field 1976; Bregman 1980; Kahn 1981; Melioli et al. 2008; Spitoni et al. 2009) and **radial gas flows** (Lacey & Fall 1985; Portinari & Chiosi 2000; Spitoni et al. 2015) also impact the chemical evolution of galaxies

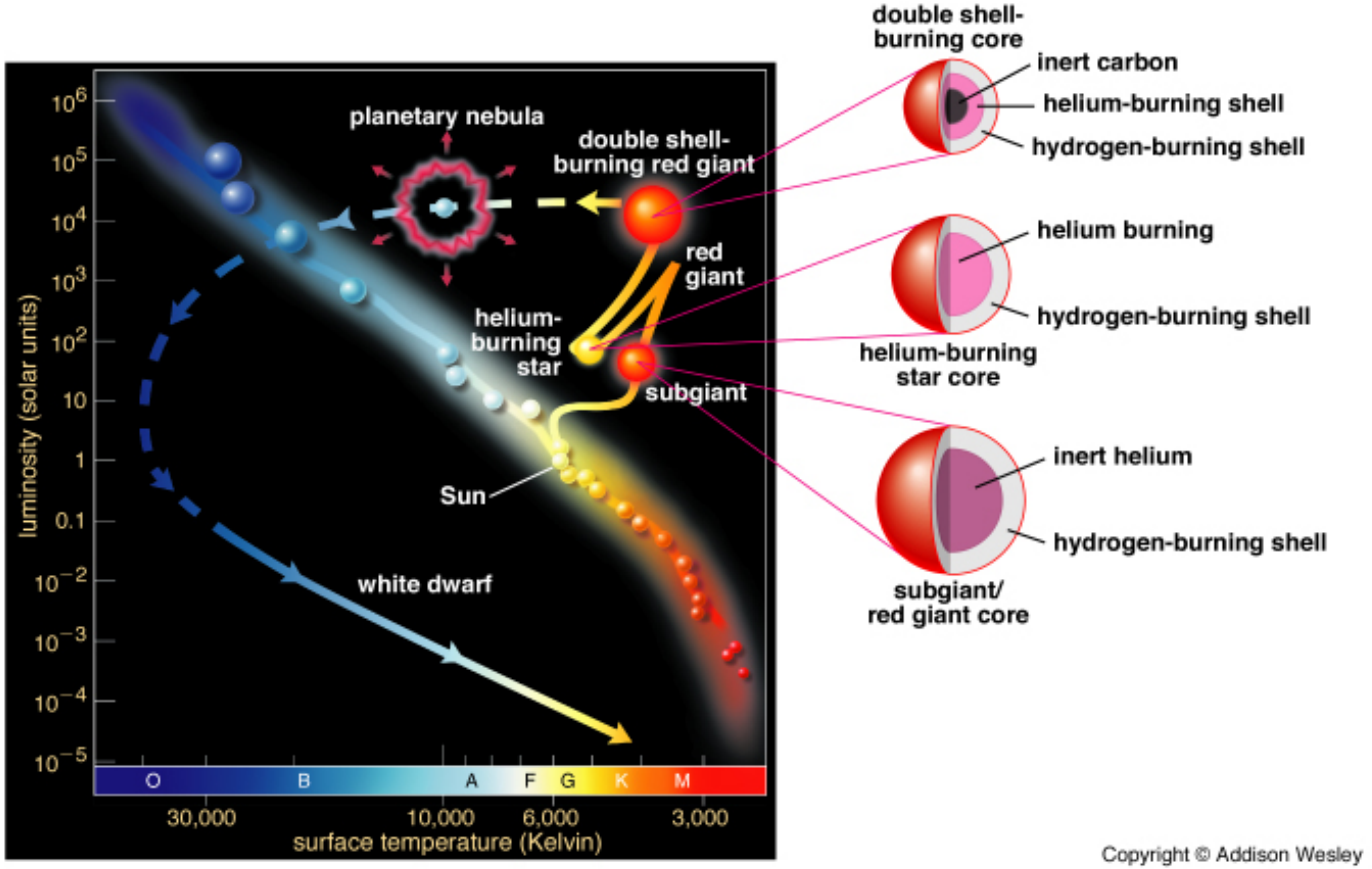


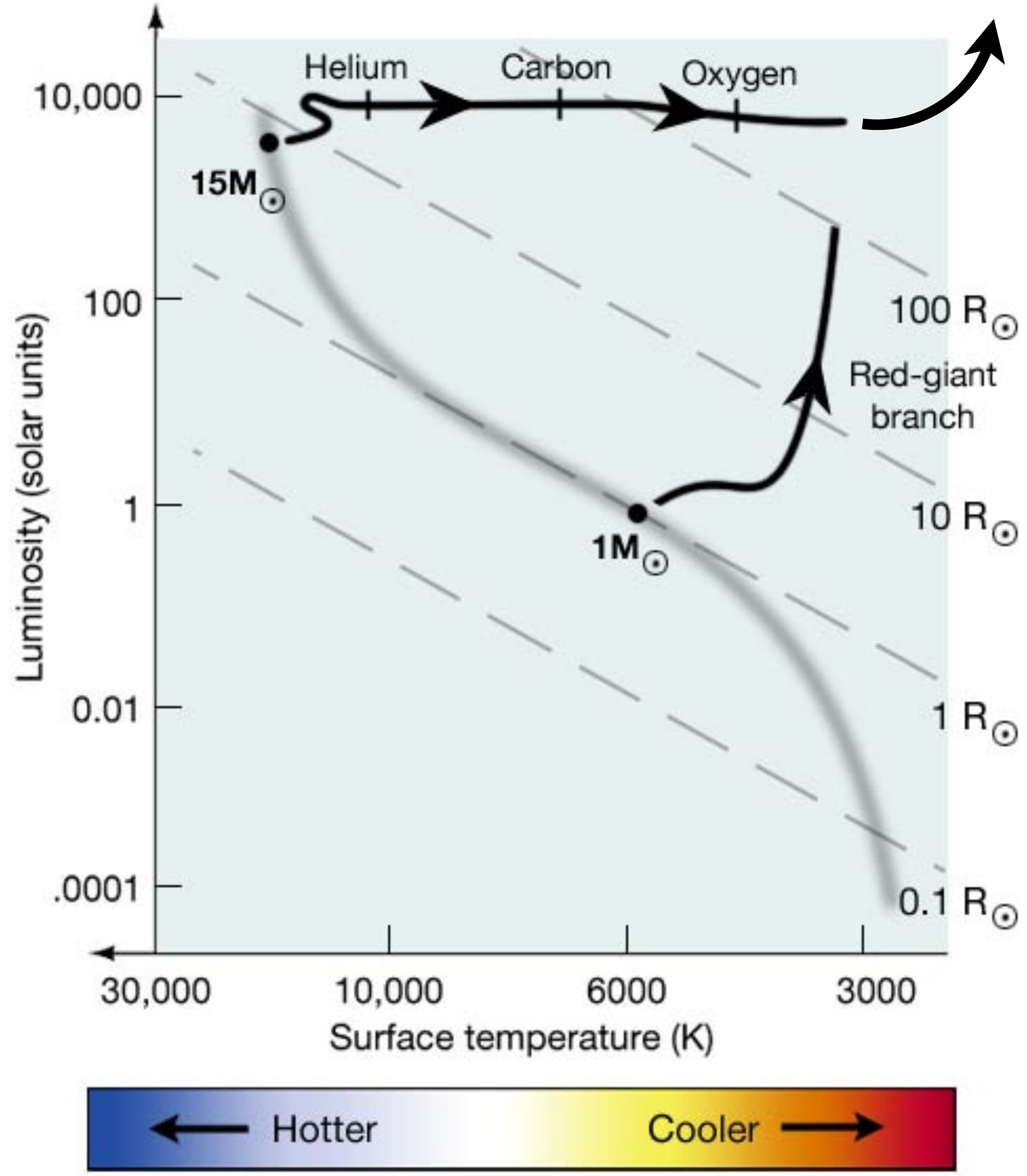
GCE MODEL INGREDIENTS

- INITIAL CONDITIONS
- STAR FORMATION RATE
- STELLAR IMF
- GAS ACCRETION
- GAS (OUT)FLOWS
- STELLAR EVOLUTION AND NUCLEOSYNTHESIS

STELLAR EVOLUTION IN 1 SLIDE







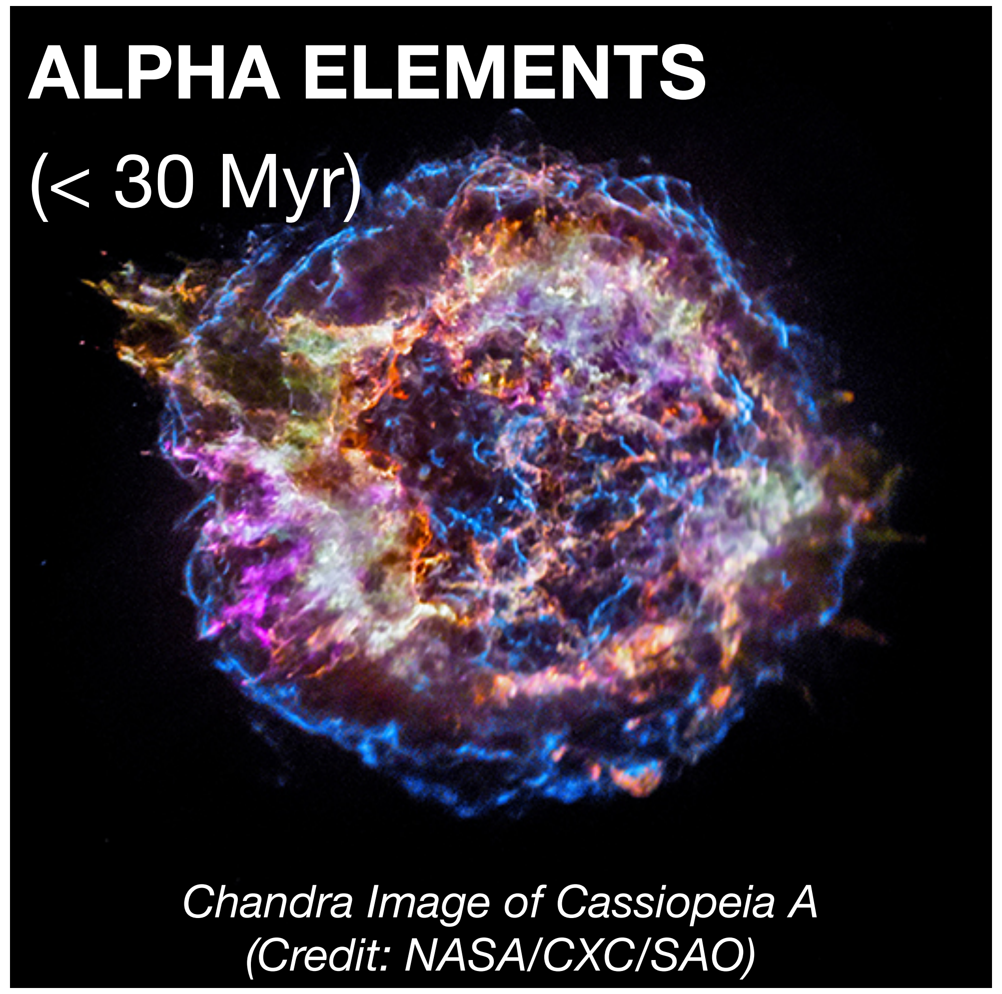
Credit: Penn State Astronomy & Astrophysics

GCE MODEL INGREDIENTS

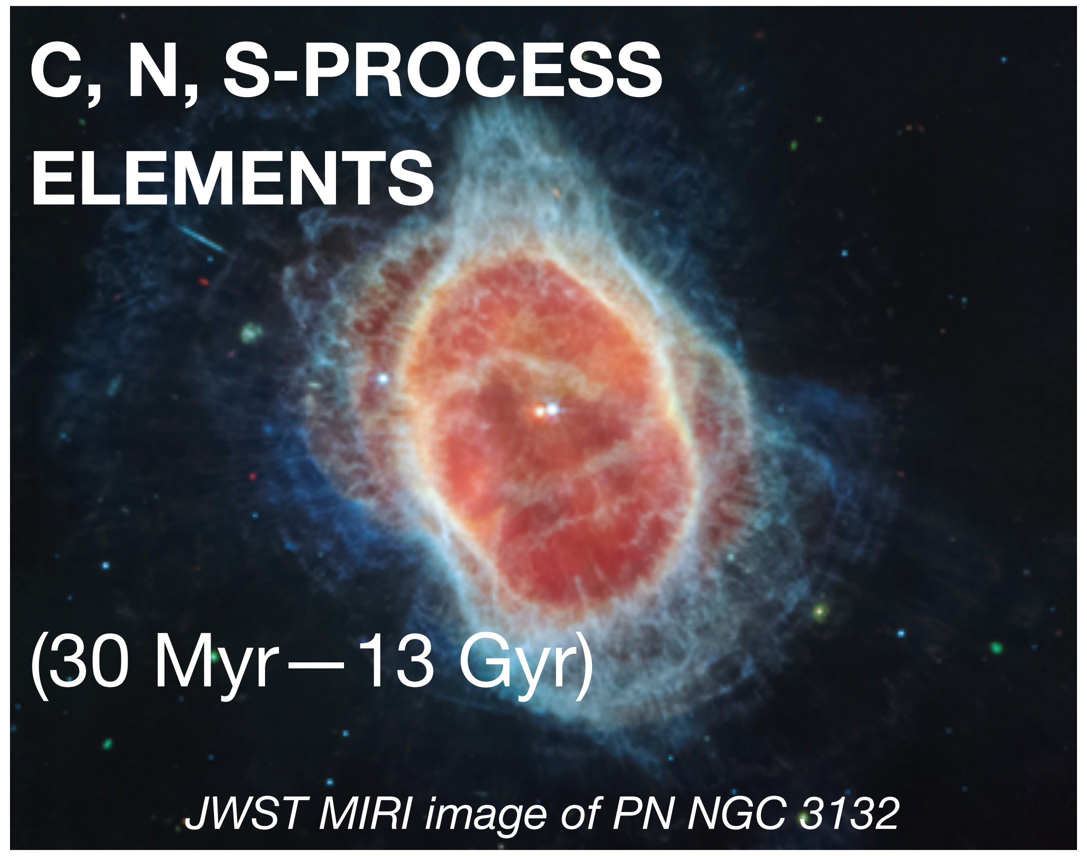
- INITIAL CONDITIONS
- STAR FORMATION RATE
- STELLAR IMF
- GAS ACCRETION
- GAS (OUT)FLOWS
- STELLAR EVOLUTION AND NUCLEOSYNTHESIS

Recommended readings:

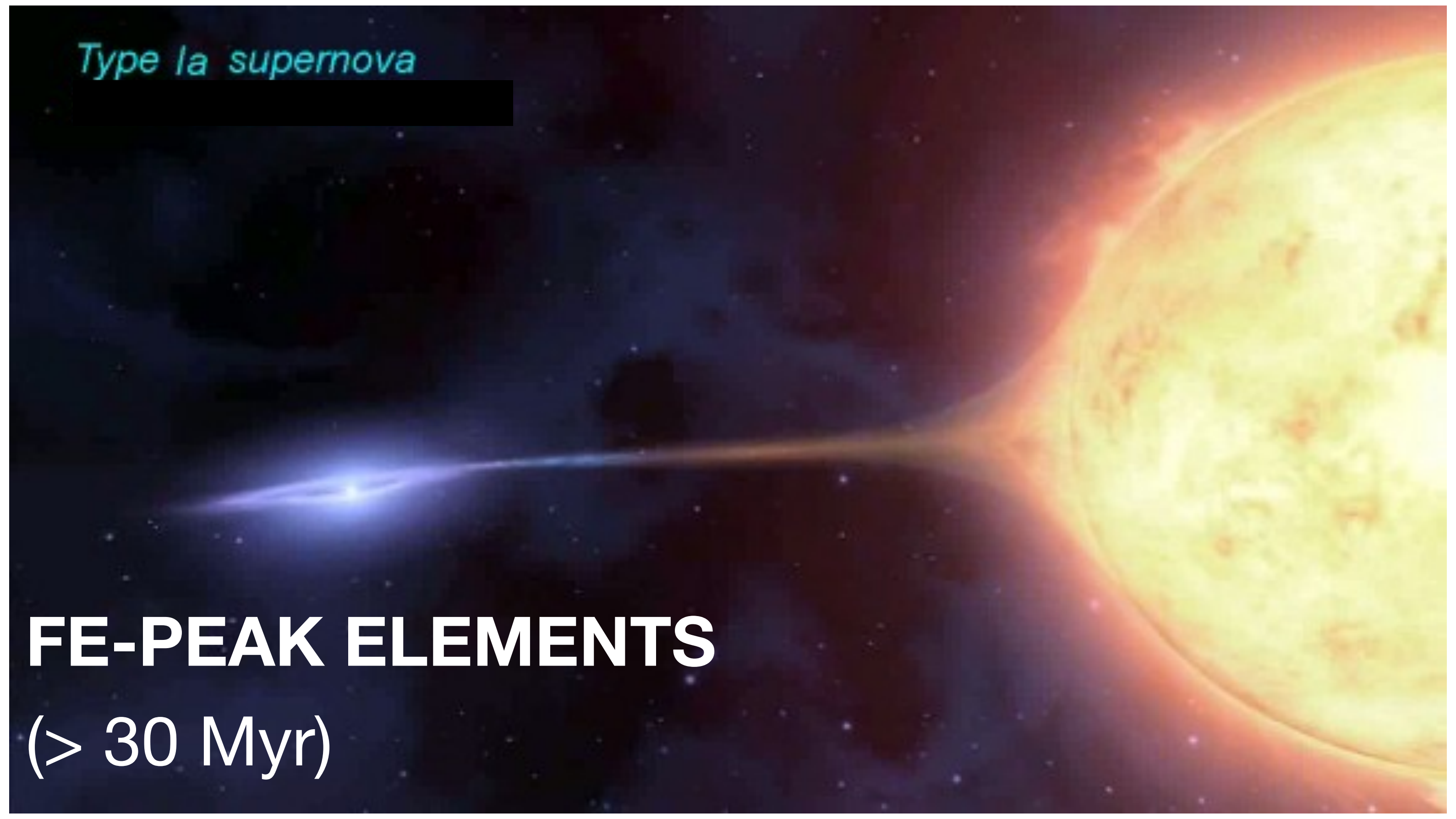
Nomoto et al. (2013)
Karakas & Lattanzio (2014)
Kobayashi et al. (2020)
Burrows & Vartanyan (2021)
Romano (2022)
Arcones & Thielemann (2023)



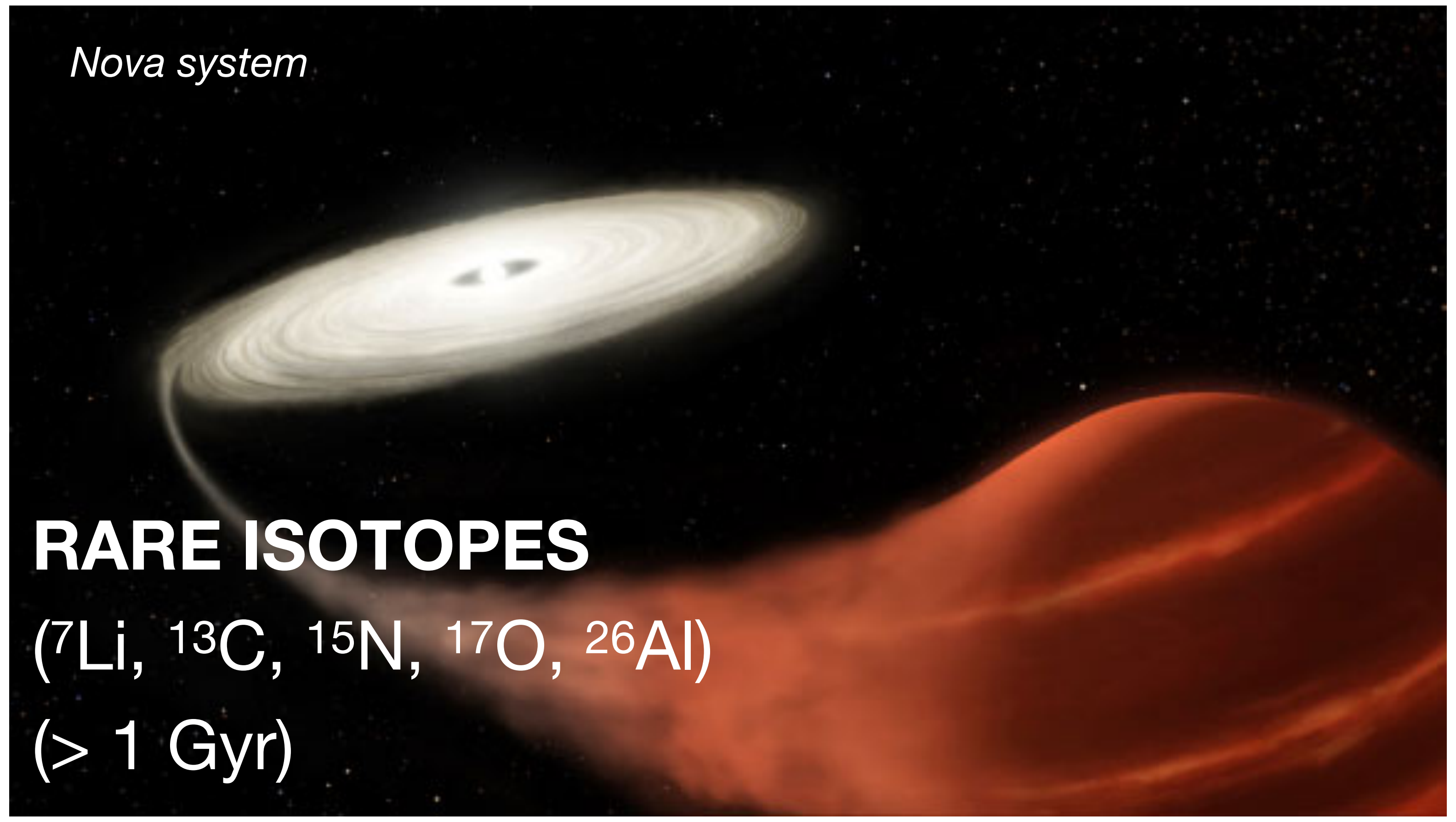
Chandra Image of Cassiopeia A (Credit: NASA/CXC/SAO)



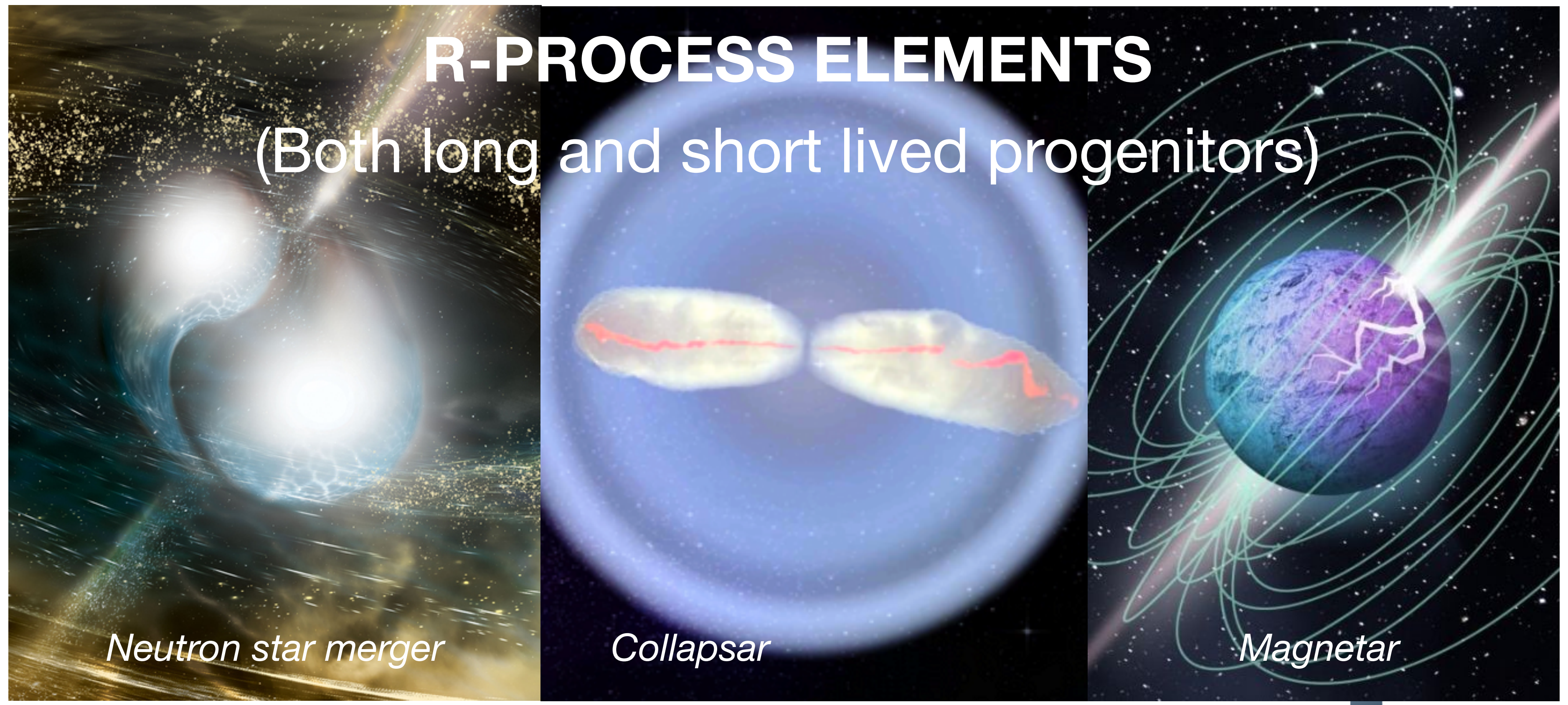
JWST MIRI image of PN NGC 3132



Type Ia supernova



Nova system



Neutron star merger *Collapsar* *Magnetar*

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)
- Novae (binary low- and intermediate-mass stars): ^{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)
- SNeIa (binary low- and intermediate-mass stars): 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; Roberti et al. 2024; Limongi et al. 2025)
- Compact binary mergers: r-process elements
  (e.g., Lattimer & Schramm 1974, 1976; Hotokezaka et al. 2013; Rosswog 2013)

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

GCE BASIC EQUATIONS

- Set of integro-differential equations, where *i* refers to any generic element

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

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

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

- Add complexity: inhomogeneous models

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

GCE BASIC EQUATIONS

Recommended reading:

Matteucci (2021)

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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↓

$$\psi(r,t) = \nu\,\Sigma^n_{\rm gas}(r,t)$$

↓

Star formation efficiency: from a few % (ultrafaint dwarfs) to >50% (bulges of spirals, massive ellipticals)

GCE BASIC EQUATIONS

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Matteucci (2021)

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

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

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

$\tau_{inf}(r)$: Varies from hundreds of Myr to ~a Hubble time

Λ: Fixed by the request of reproducing the current density of matter

GCE BASIC EQUATIONS

Recommended reading:

Matteucci (2021)

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

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

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

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

GCE BASIC EQUATIONS

Recommended reading:

Matteucci (2021)

Gas accretion   Galactic-scale outflow

Star formation   Stellar feedback

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

$$R_i(r,t) = R_i^{\mathrm{LIMS}}(r,t) + R_i^{\mathrm{SNII}}(r,t) + R_i^{\mathrm{SNIa}}(r,t) + R_i^{\mathrm{novae}}(r,t) + R_i^{\mathrm{NSM}}(r,t)$$





GCE BASIC EQUATIONS

Recommended reading:

Matteucci (2021)

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

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

$$R_i(r,t) = R_i^{\rm LIMS}(r,t) + R_i^{\rm SNII}(r,t) + R_i^{\rm SNIa}(r,t) + R_i^{\rm novae}(r,t) + R_i^{\rm NSM}(r,t)$$

$$R_i^{\rm SNII}(r,t) = \int_{m(t)}^{m_U} \psi(r, t-\tau_m) Q_{mi}(t-\tau_m) \varphi(m)\, dm$$

Stellar lifetimes (τ_m)

Production matrix (Talbot & Arnett 1973; Portinari et al. 1998) (Q_{mi})

Stellar IMF: $\varphi(m) \propto (m/M_\odot)^{-x}$

IMF slope (x)

STELLAR YIELDS

gIMF

STELLAR LIFETIMES

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

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

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})

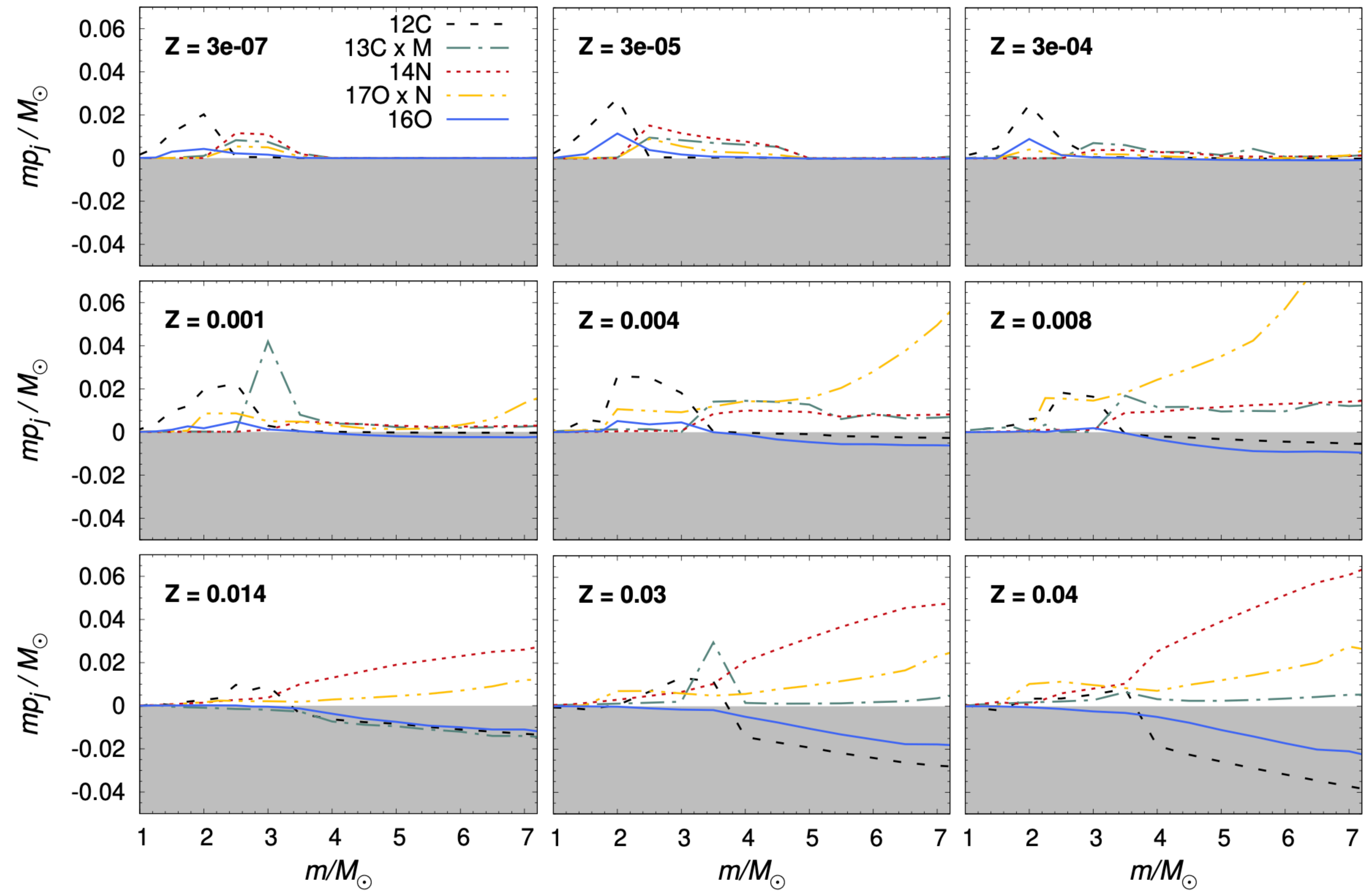
Abundance at Lagrangian mass coordinate m′ ($X_j(m')$)

Initial abundance (X_j^{init})

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

This term can be < 0 !

STELLAR YIELDS



- Grids of yields: need to be dense enough
- Dependence on initial stellar mass, metallicity and, sometimes, stellar rotation
- Need magnetic fields included

STELLAR YIELDS

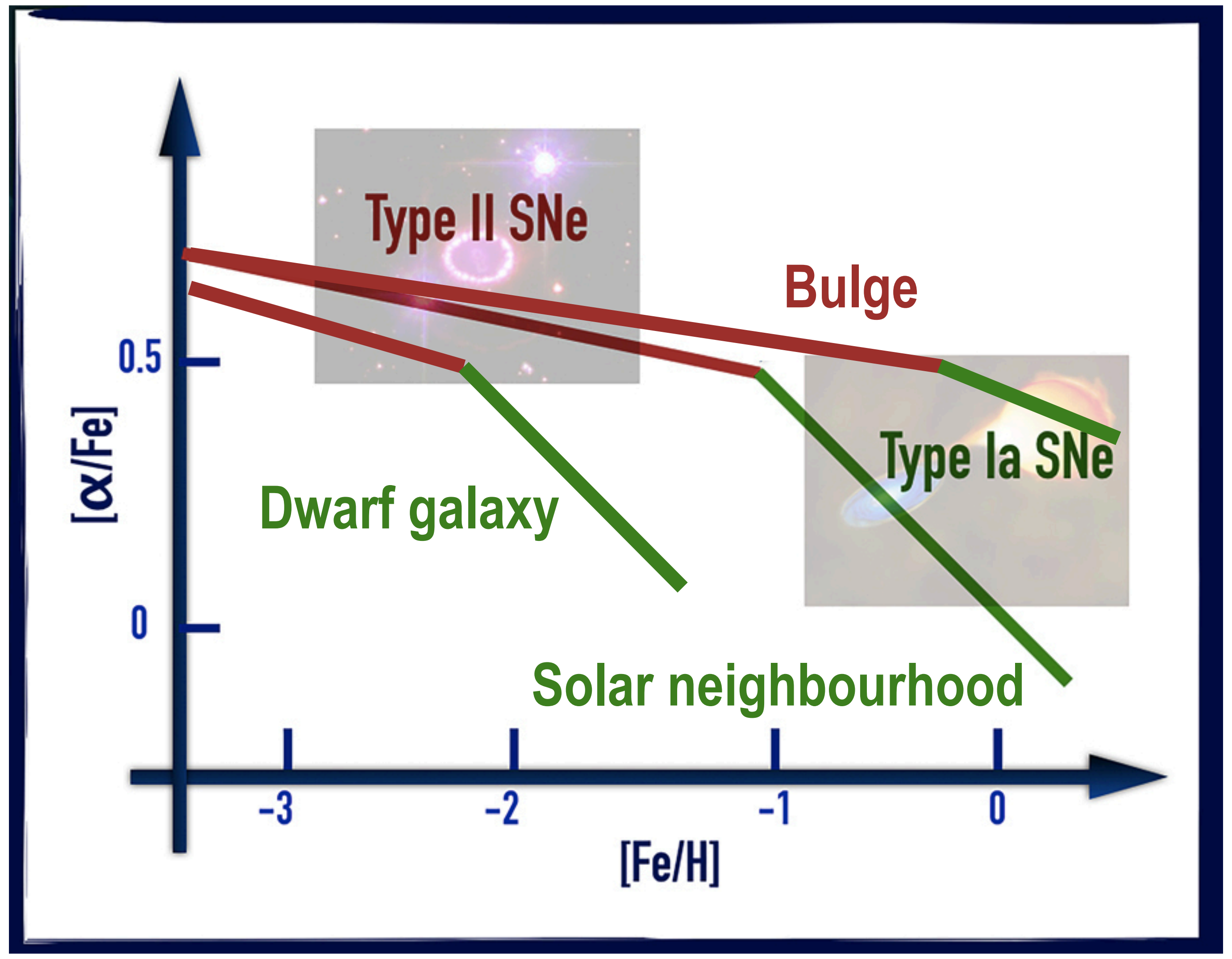
- Stellar yields are uncertain

- Uncertainties are related to:

  - still poorly known nuclear reaction rates, $^{12}C(\alpha, \gamma)^{16}O$
  - convection
  - extra-mixing (rotation, thermohaline, magnetic field)
  - coupling between them
  - mass loss rates (bursting vs continuous)
  - mass cut location
  - possible binary interactions
  - 1D —> 3D

PURE GCE MODELS ALLOW A QUICK SCAN OF THE PARAMETER SPACE !

- 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 flows and the shape of the gIMF



Adapted from figure 4 of Matteucci & Brocato (1990)

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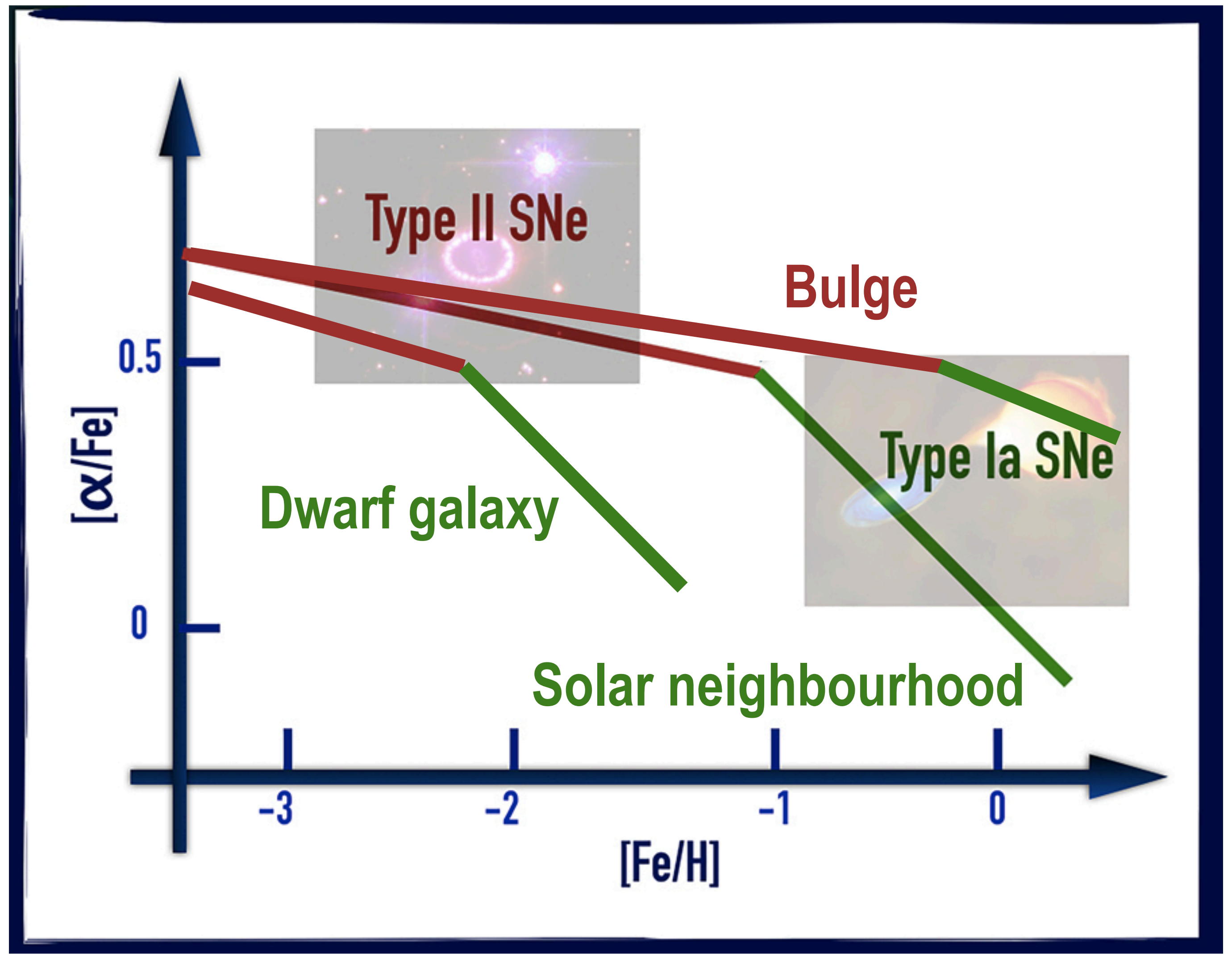

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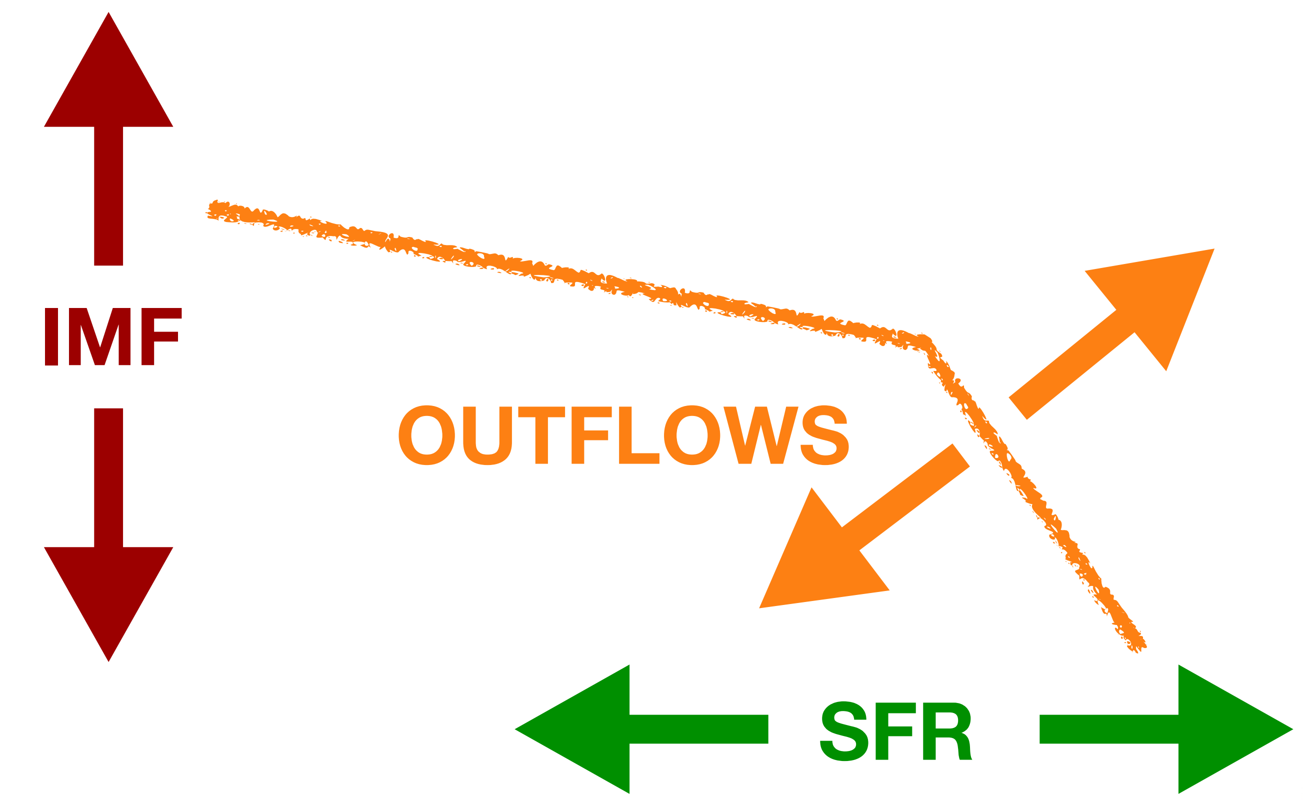


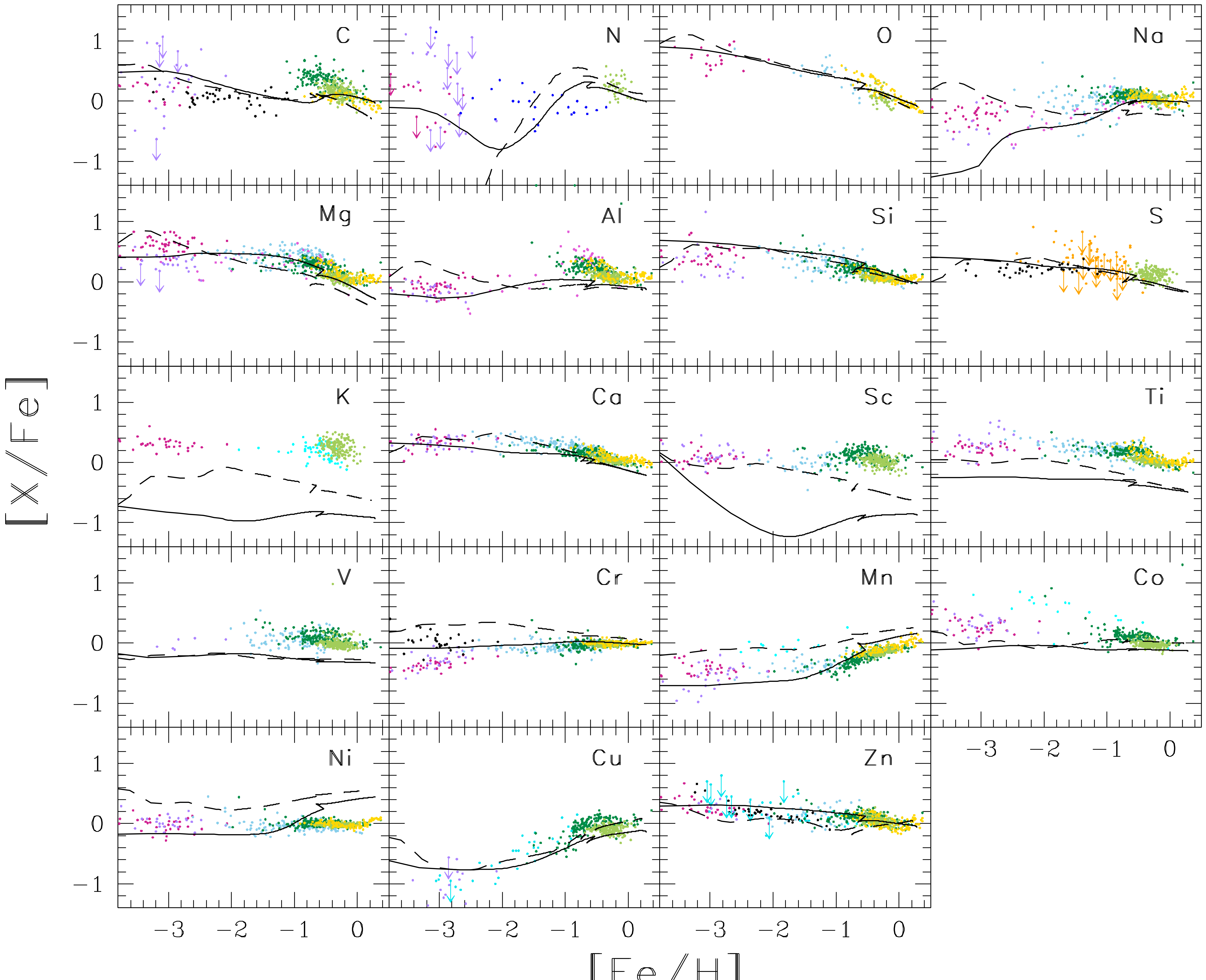
PURE GCE MODELS ALLOW A QUICK SCAN OF THE PARAMETER SPACE !

- 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 flows and the shape of the gIMF

- 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

MILKY WAY (solar neighborhood)



Stellar rotation is necessary to explain primary ^{14}N (and ^{13}C) production at low Z (also Chiappini et al. 2006, 2008)

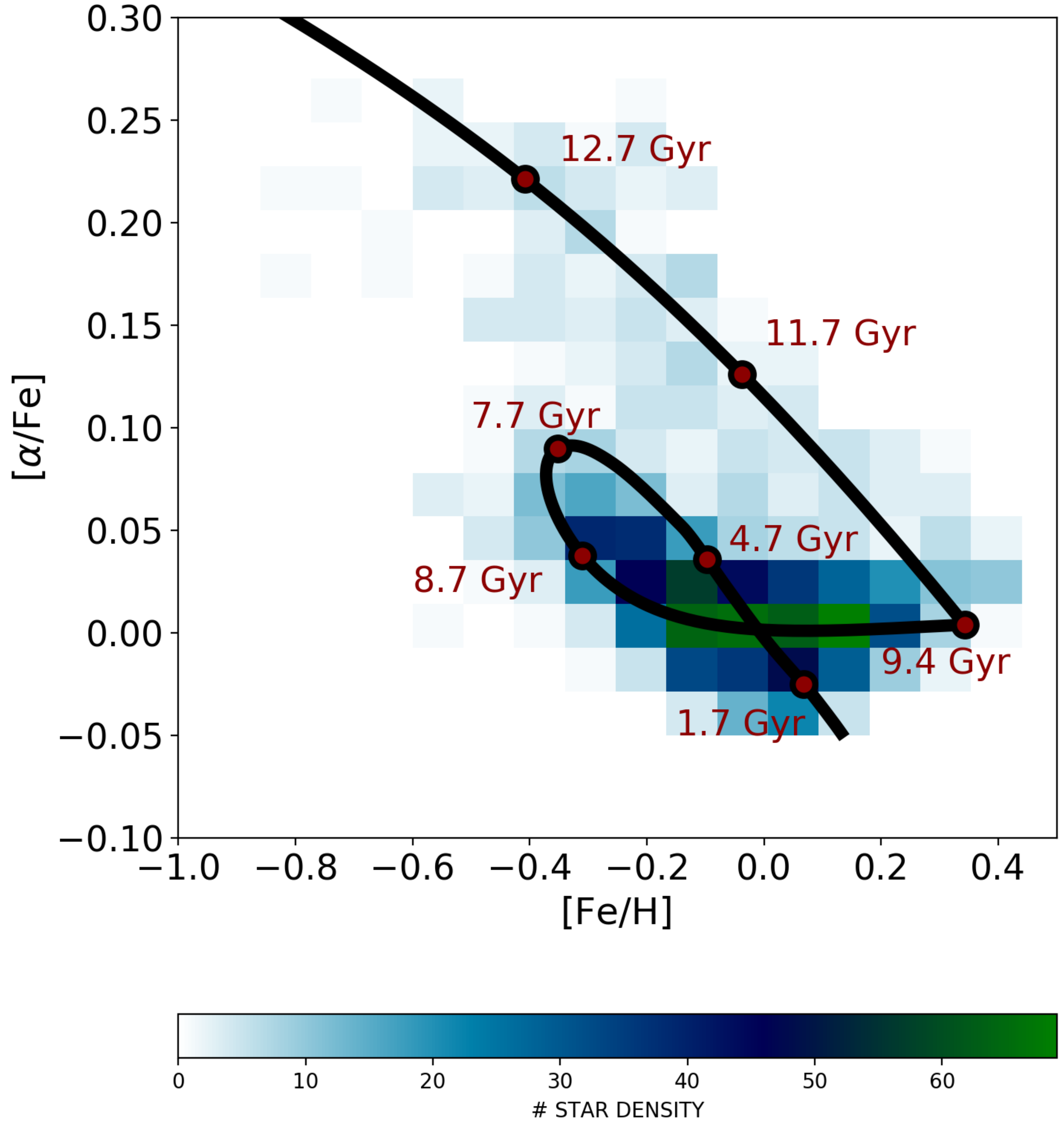
Hypernovae are needed to explain Zn abundances in halo stars (also Kobayashi+ 2006)

K, Sc, Ti, V remain critical elements (also Kobayashi+ 2020)

Romano et al. (2010)

MILKY WAY (solar neighborhood)

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 (first presented by Chiappini+ 1997, 2001).



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).

Note: the 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.

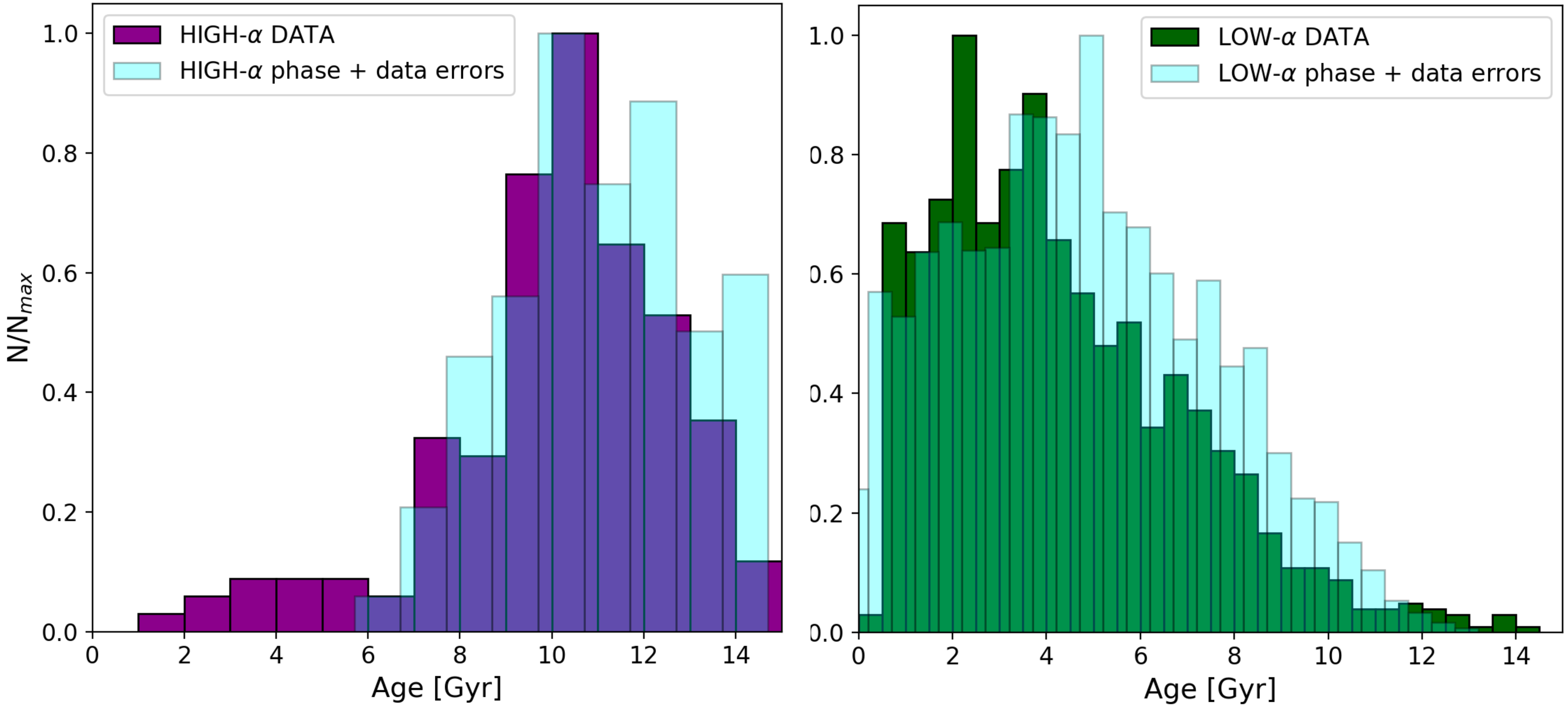
Note: the adopted stellar yields are *empirical* yields based on the fit of a set of observed stellar abundances (François et al. 2004).

Figure from Spitoni et al. (2019)

MILKY WAY (solar neighborhood)

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 (first presented by Chiappini+ 1997, 2001).

~ THICK DISC

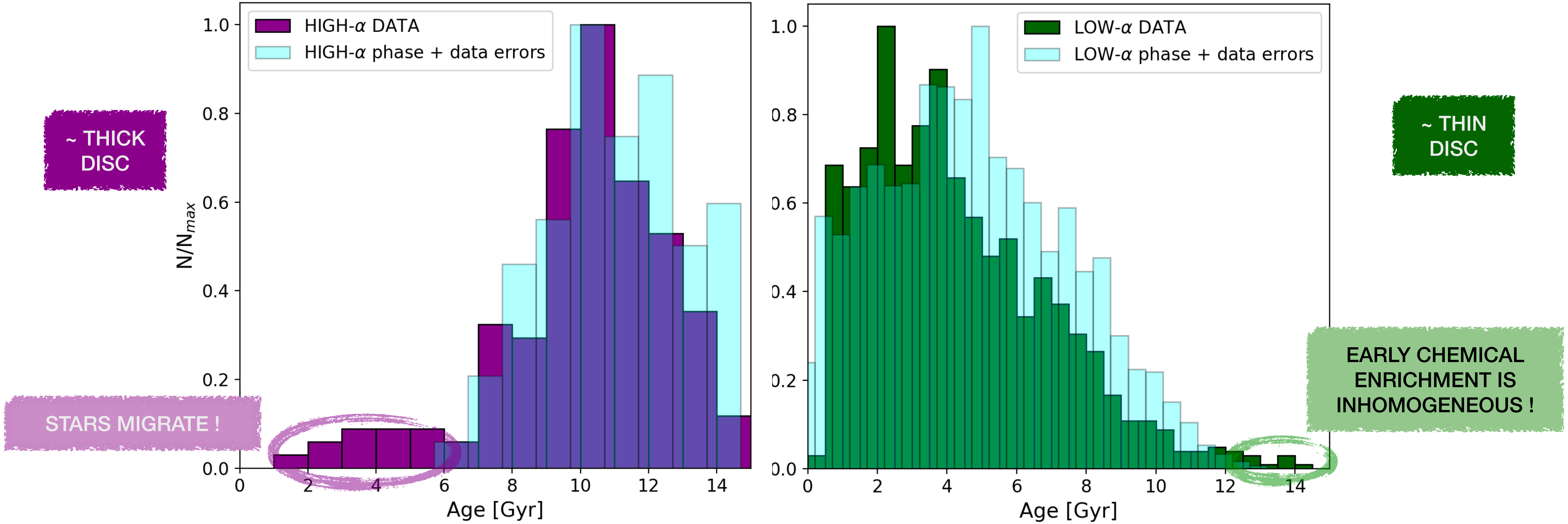


~ THIN DISC

Model predicted age distributions (cyan histograms) for the high-α and low-α components, compared to the APOKASC data (left and right panels, respectively; Spitoni et al. 2019).

MILKY WAY (solar neighborhood)

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 (first presented by Chiappini+ 1997, 2001).



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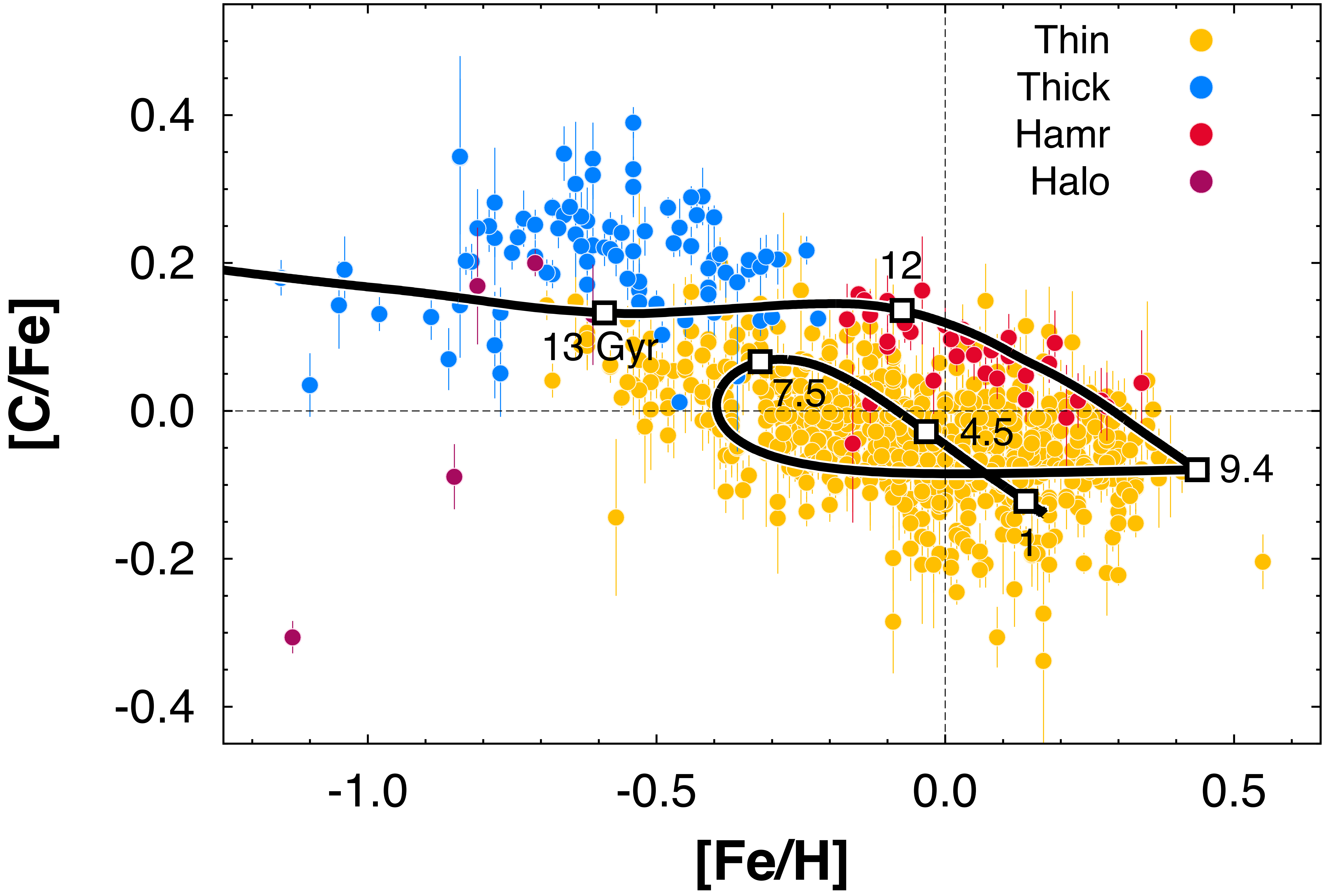


On the left: [C/Fe] vs [Fe/H] trend predicted by the two-infall model compared to data for 757 nearby dwarf stars (Delgado-Mena et al. 2021). The stellar yields are from Ventura et al. (2013, 2014, 2018, 2020, 2021) for low- and intermediate-mass stars and from Limongi & Chieffi (2018) for massive stars.

Romano (2022)

MILKY WAY (solar neighborhood)

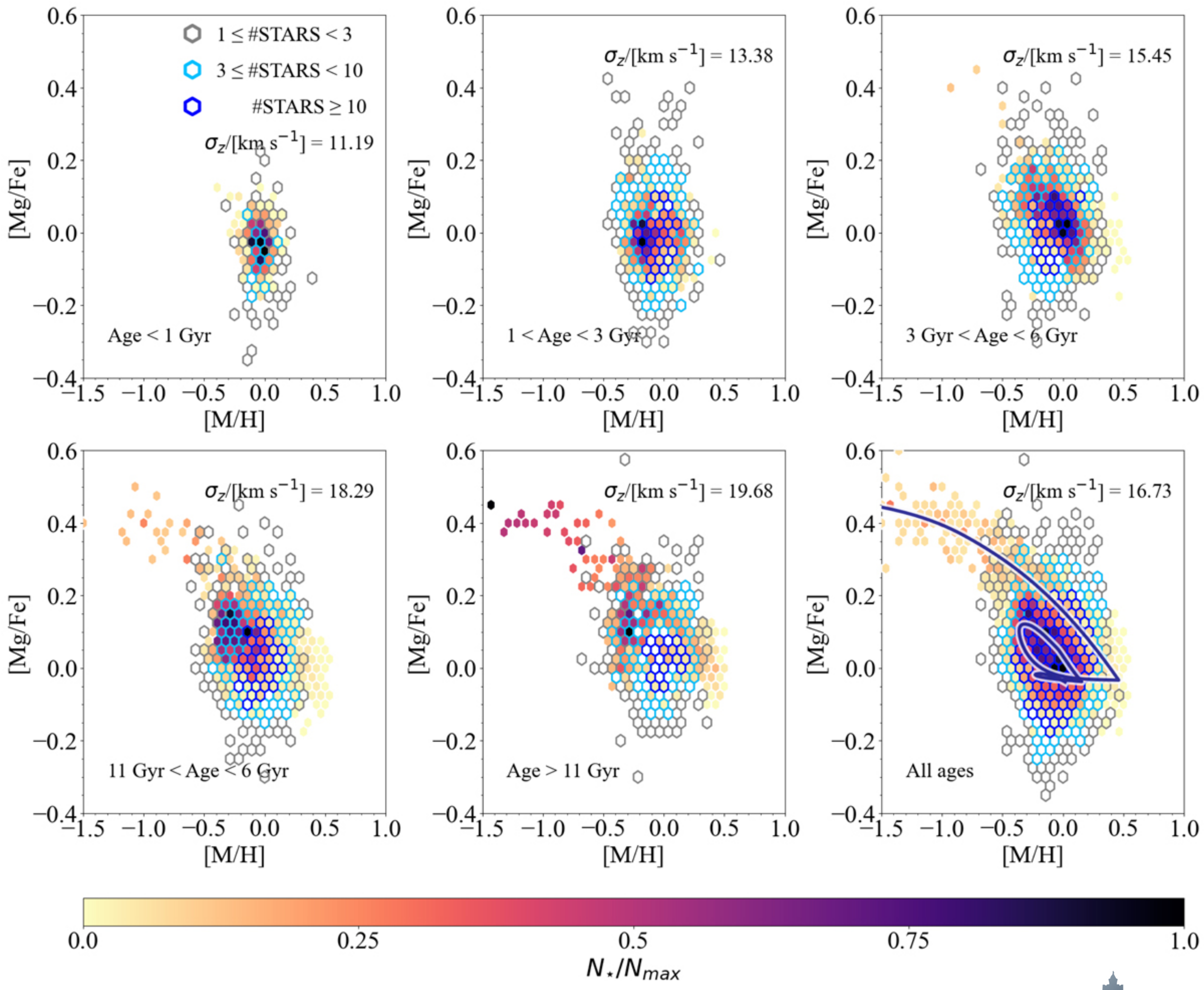
A&A 670, A109 (2023)
https://doi.org/10.1051/0004-6361/202244349

Astronomy & Astrophysics

Beyond the two-infall model

I. Indications for a recent gas infall with *Gaia* DR3 chemical abundances

E. Spitoni[1], A. Recio-Blanco[1], P. de Laverny[1], P. A. Palicio[1], G. Kordopatis[1], M. Schultheis[1], G. Contursi[1], E. Poggio[1,2], D. Romano[3], and F. Matteucci[4,5,6]



Gaia DR3 GSP-Spec: radial velocities and abundance for millions of stars (all sky coverage; Recio-Blanco+ 2023)

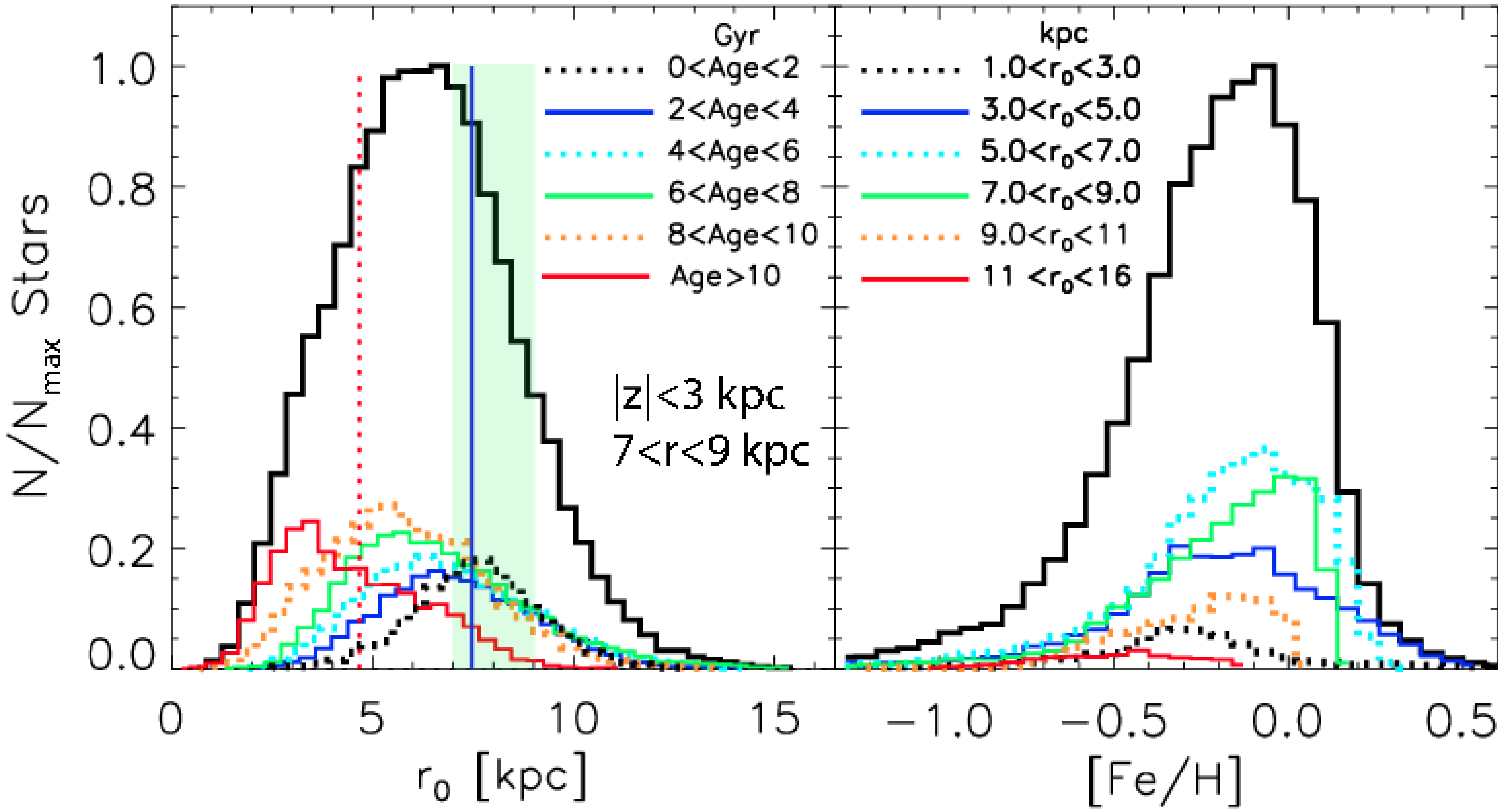
Young disc stars are metal-poor → recent metal impoverishment? (metal-poor stars cannot all be inward migrators…)

A third major infall episode? (See Ruiz-Lara+ 2010)

(Spitoni+ 2023)

MILKY WAY (disc)

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. Right: [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).

MILKY WAY (disc)

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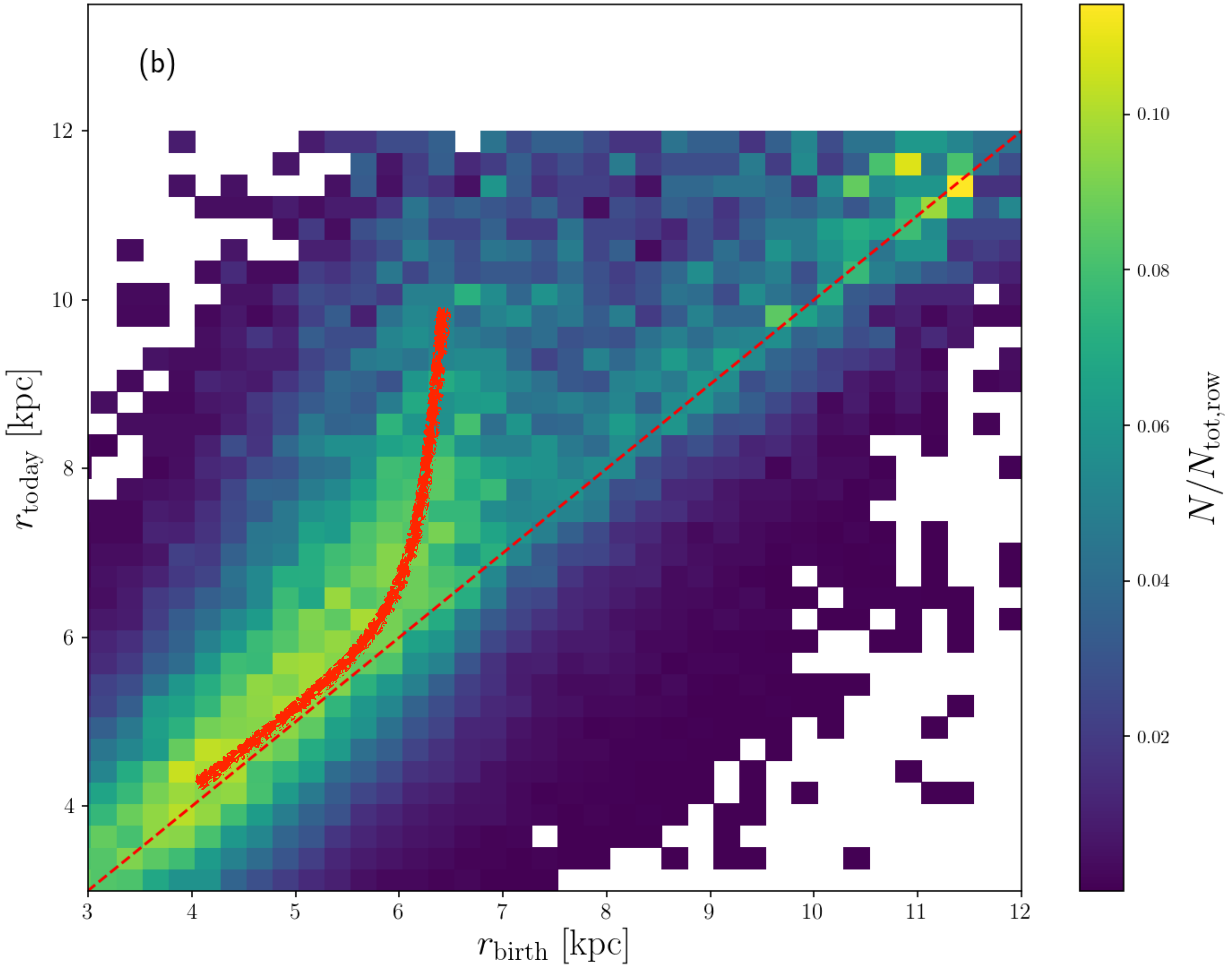
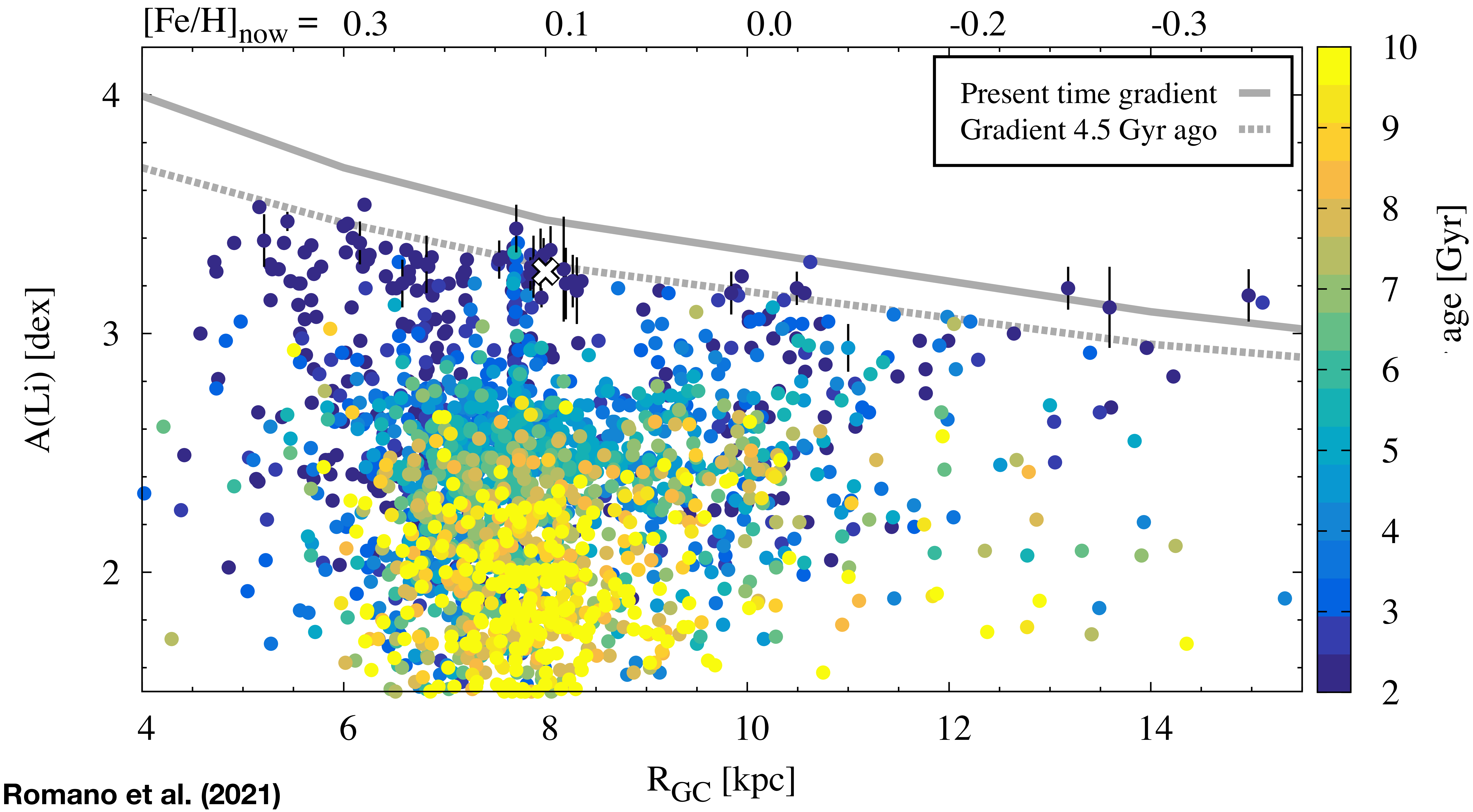


Vincenzo & Kobayashi (2020)

MILKY WAY (disc)

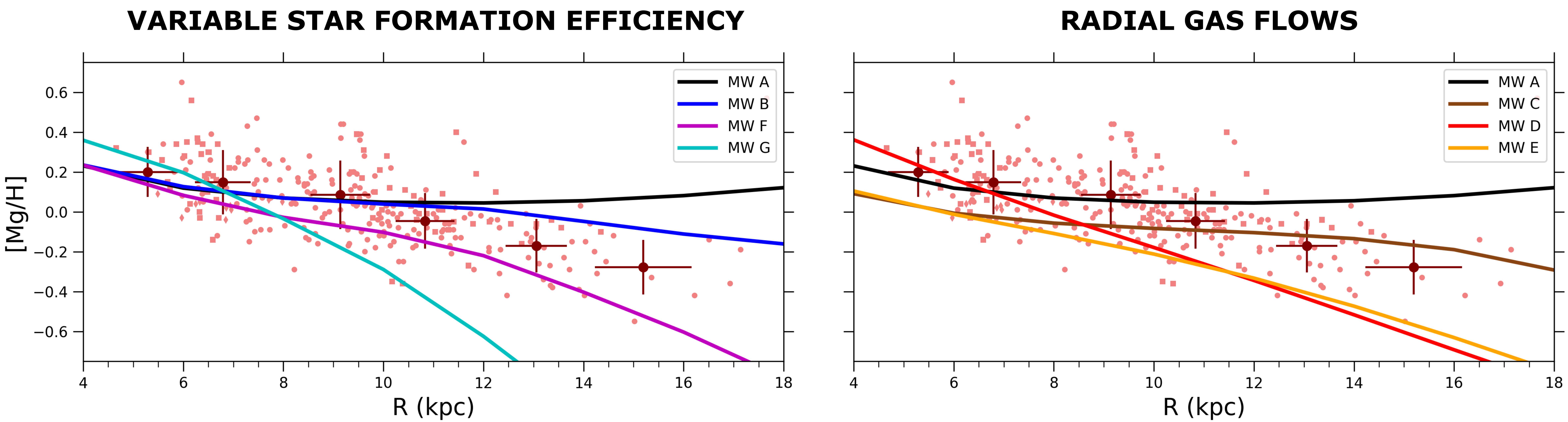
Stars age: their atmospheric composition changes



Adapted from Romano et al. (2021)

MILKY WAY (disc)

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

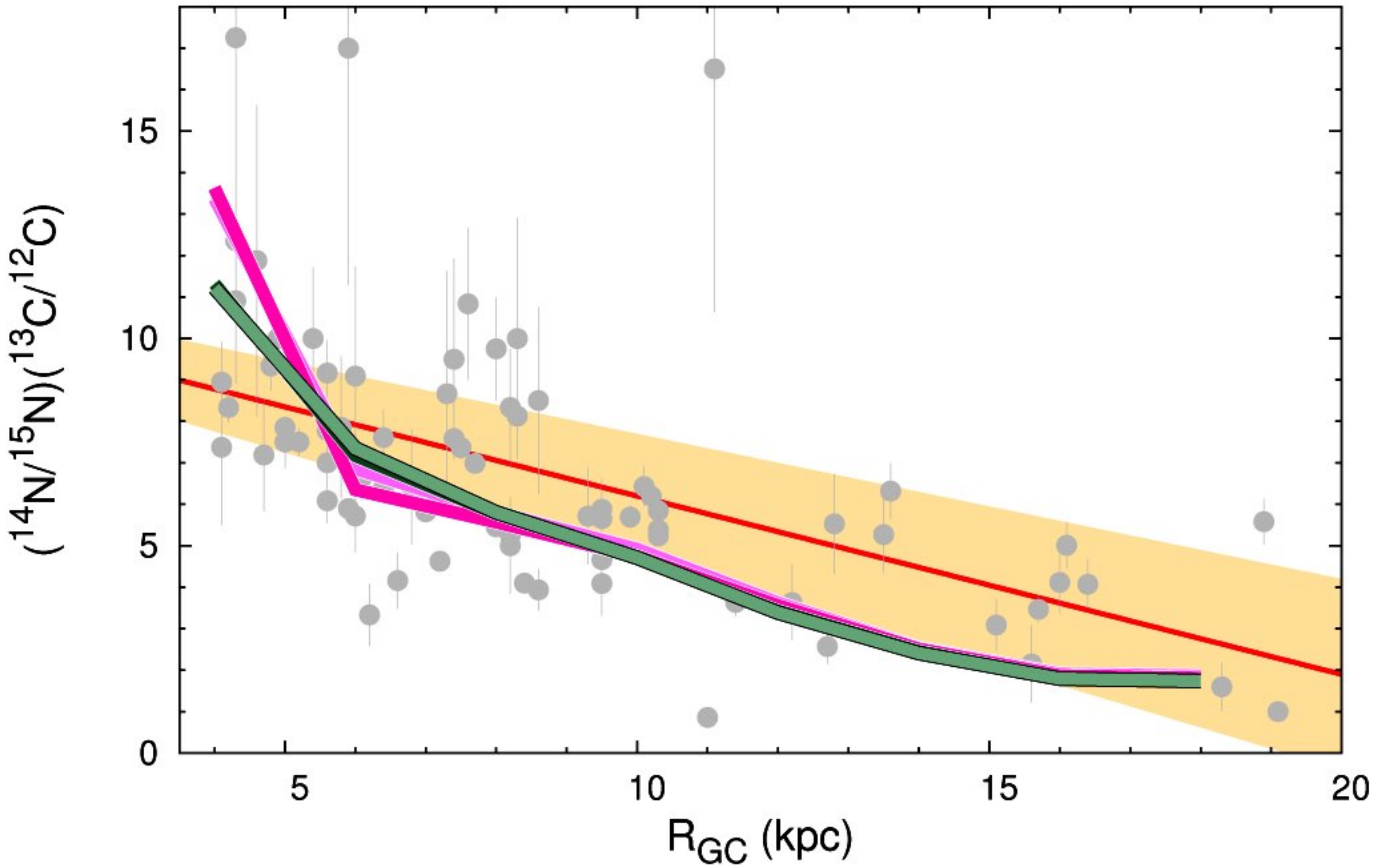


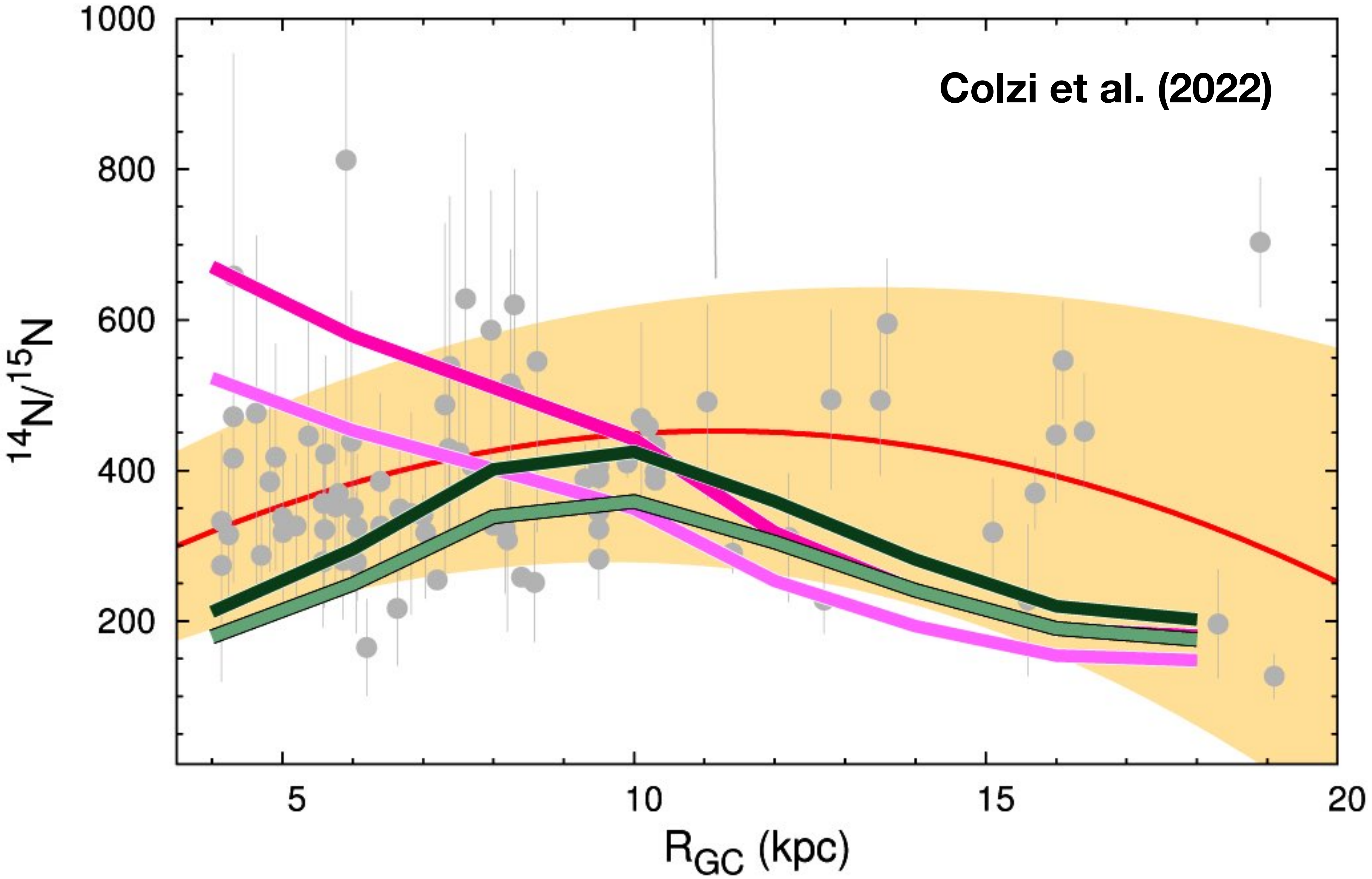
Palla et al. (2020)

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

MILKY WAY (disc)

Molecular cloud data: physical processes/systematics might perturb isotopologue abundance ratios from isotopic ones..

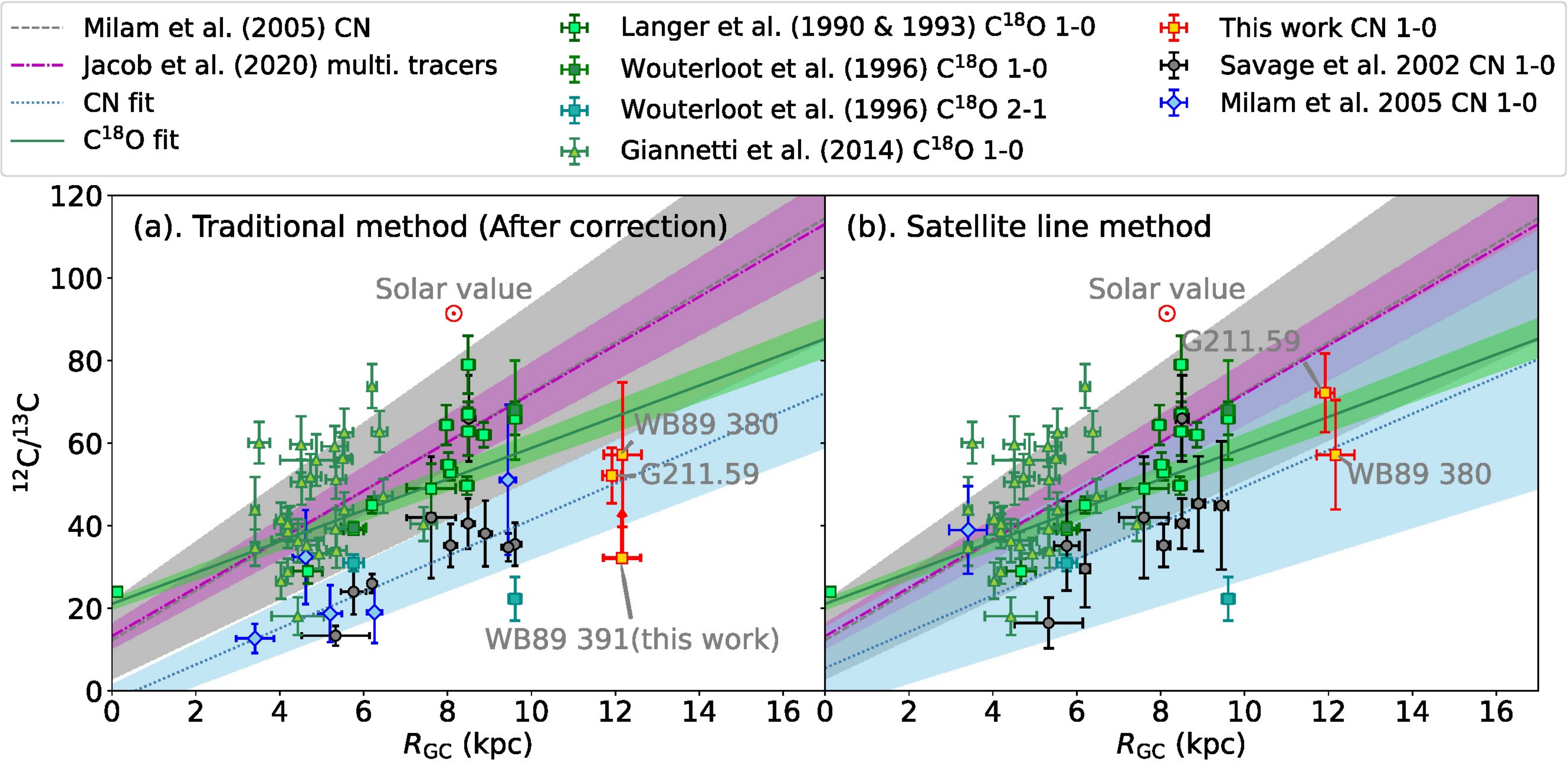




$^{14}N/^{15}N$ ratios from HCN and HNC for sources in the outer (Colzi+ 2022) and inner disc (Colzi+ 2018), using the J = 1–0 rotational transitions of $HN^{13}C$, $H^{15}NC$, $H^{13}CN$, $HC^{15}N$

MILKY WAY (disc)

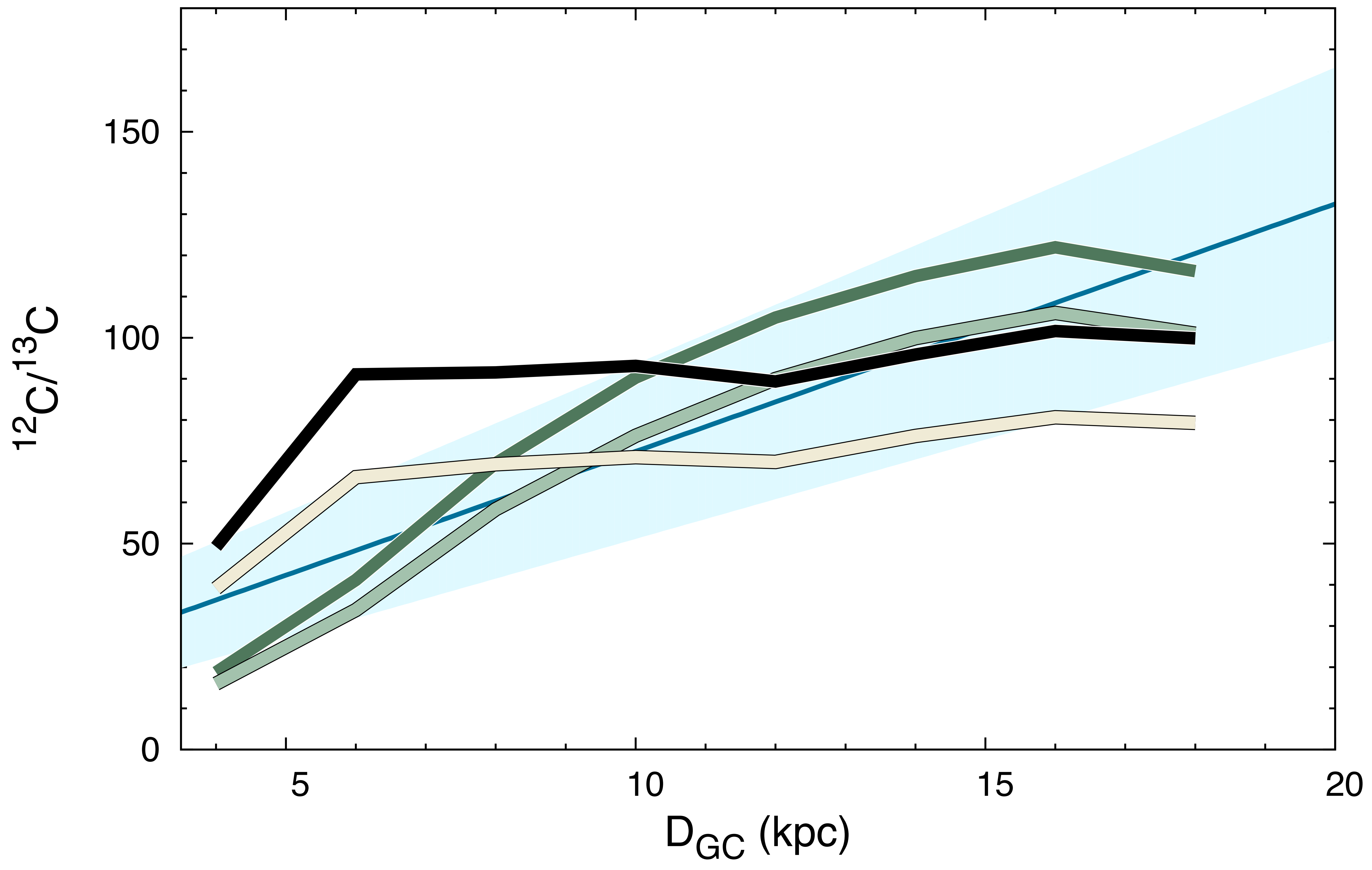
Molecular cloud data: physical processes/systematics might perturb isotopologue abundance ratios from isotopic ones..



Sun et al. (2024)

MILKY WAY (disc)

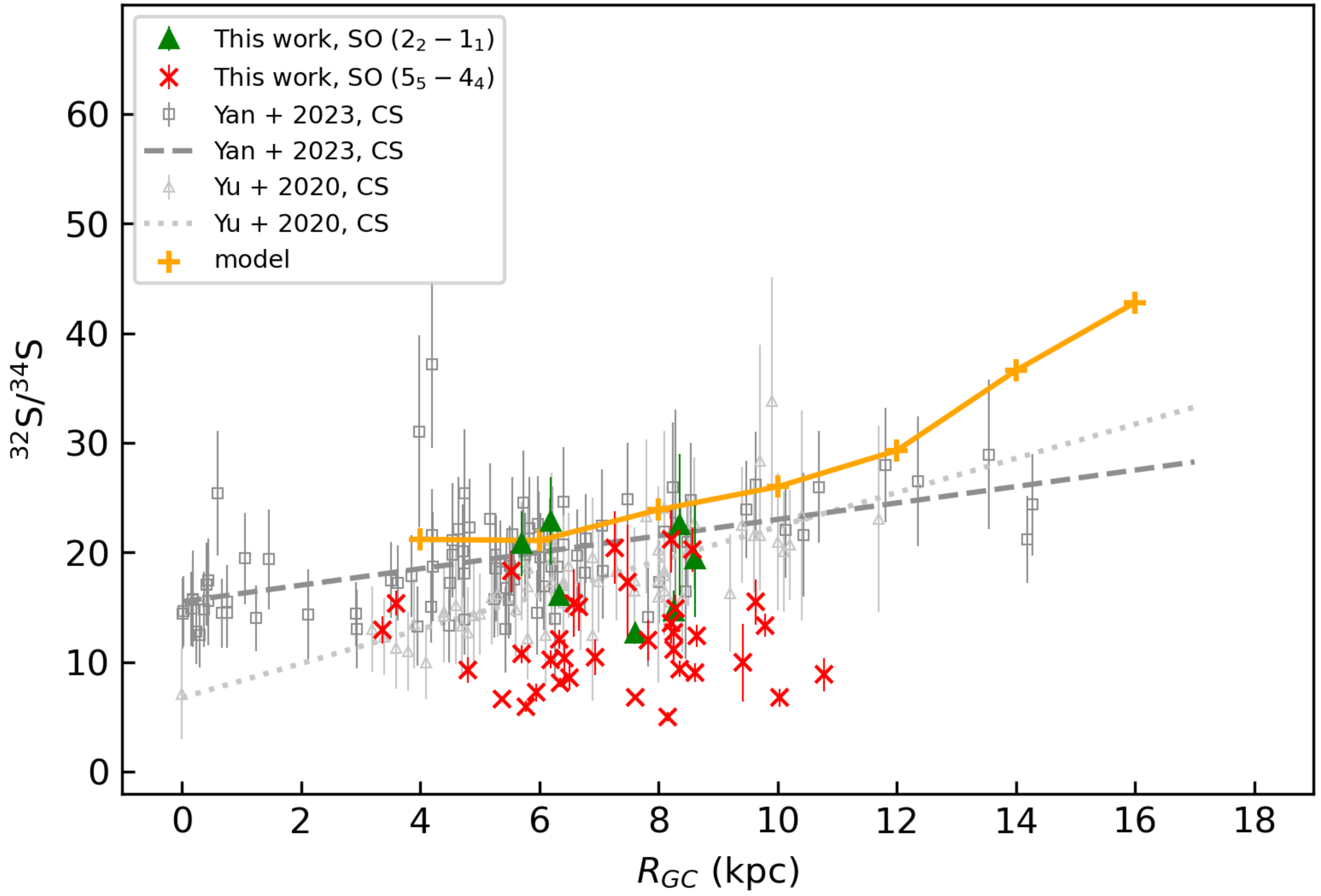
Molecular cloud data: physical processes/systematics might perturb isotopologue abundance ratios from isotopic ones..



Colzi et al. (2022)

MILKY WAY (disc)

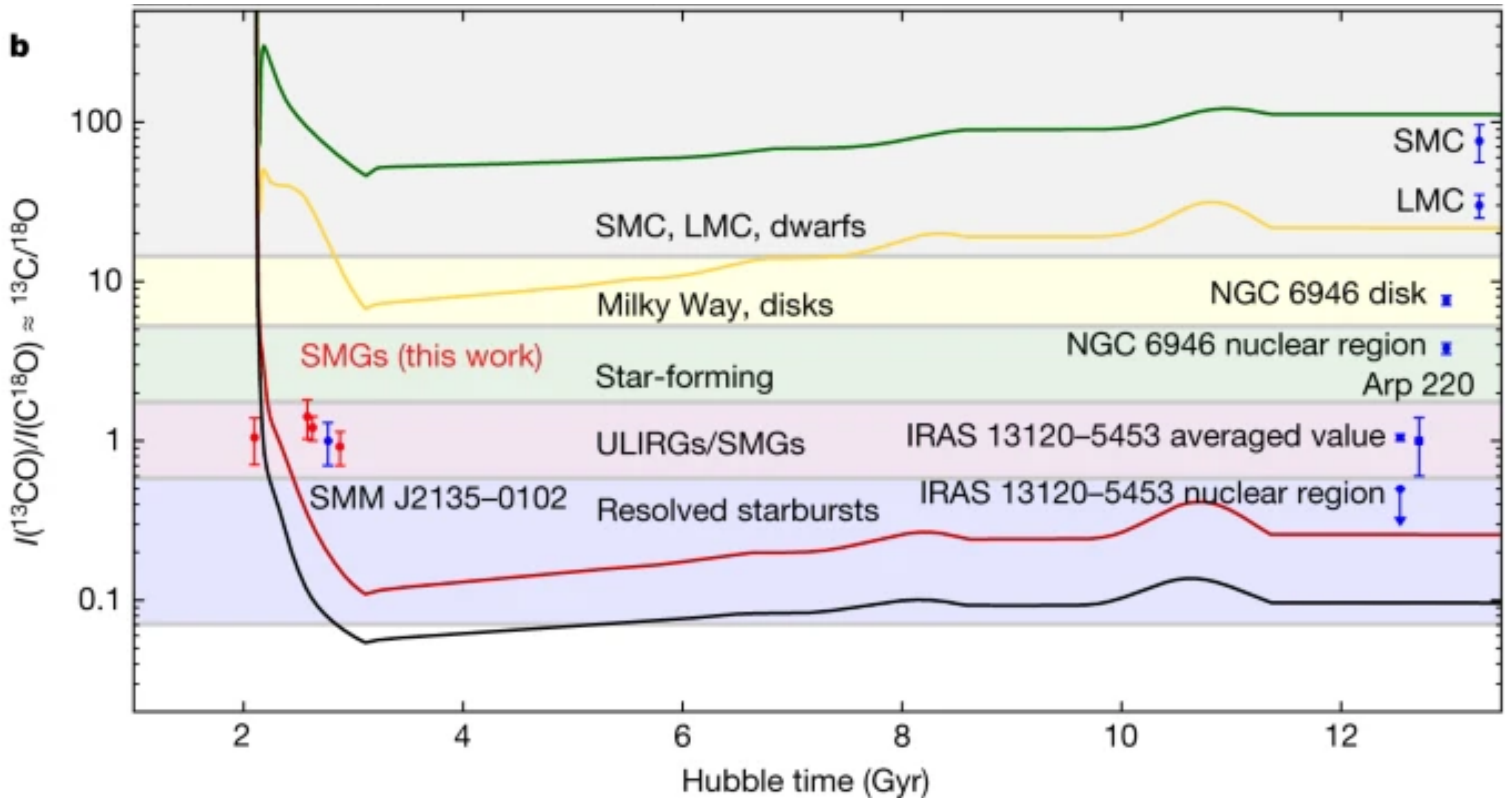
Molecular cloud data: physical processes/systematics might perturb isotopologue abundance ratios from isotopic ones..



Zou et al. (submitted)

EXTERNAL GALAXIES

GCE models as probes of the gIMF



Emission in both ^{13}CO and $C^{18}O$ optically thin for the bulk of the molecular gas in four SMGs at *z* ~ 2—3. The systematically low $I(^{13}CO)/I(C^{18}O)$ ratios reflect intrinsic isotopologue abundance ratios over galaxy-sized molecular hydrogen reservoirs —> gIMF skewed towards massive stars in the starbursts (Zhang et al. 2018, Nat)

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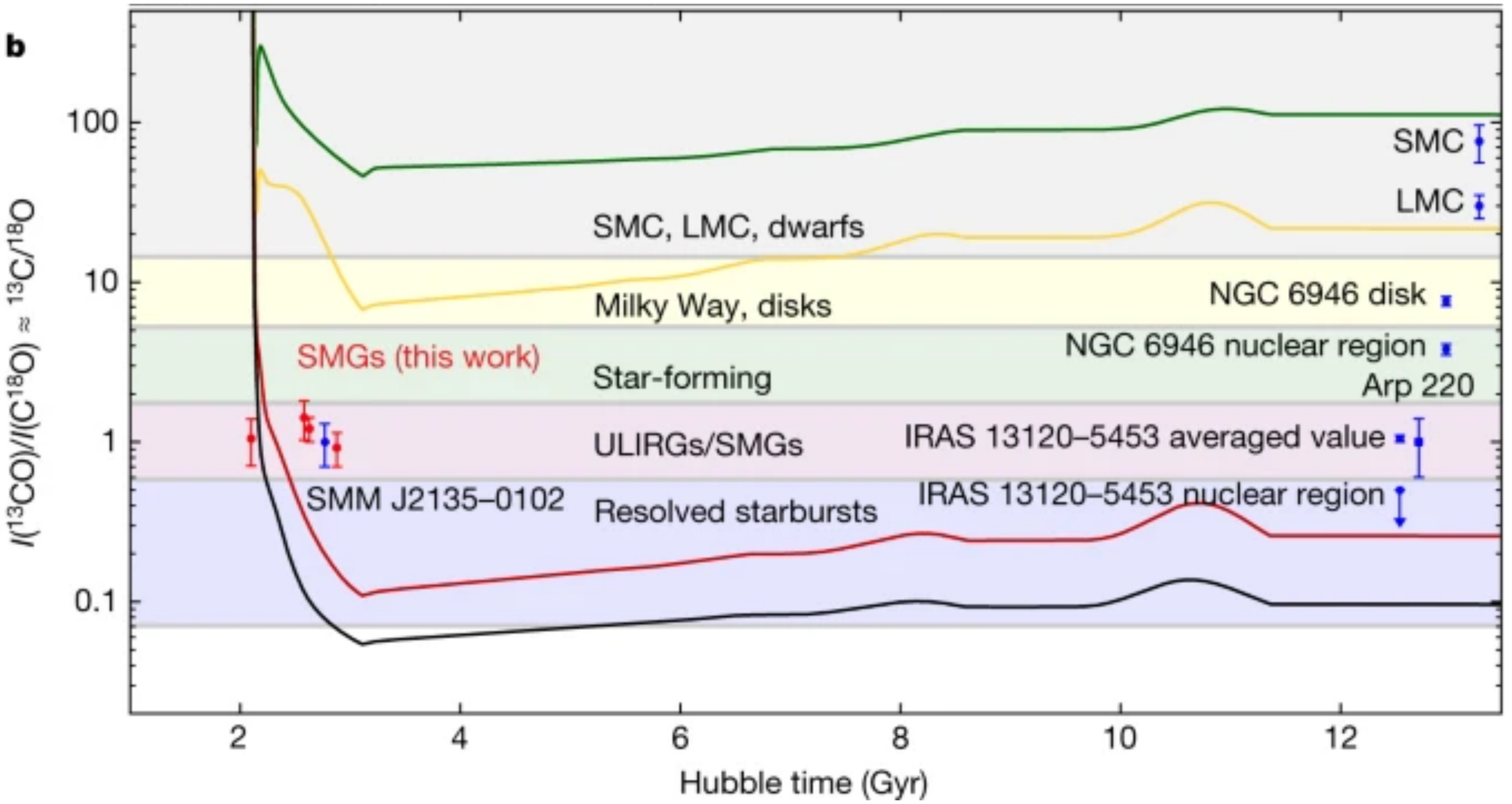

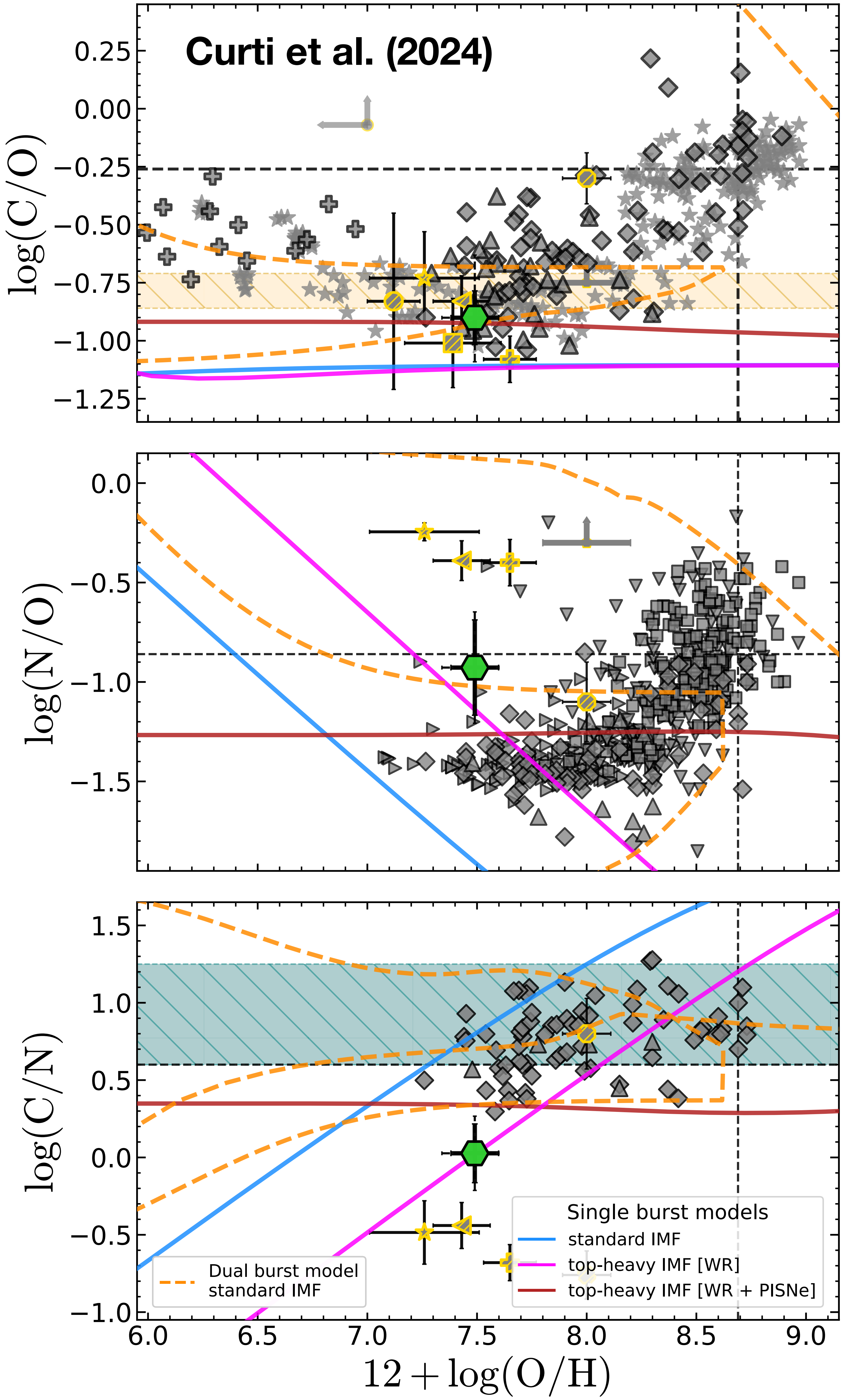

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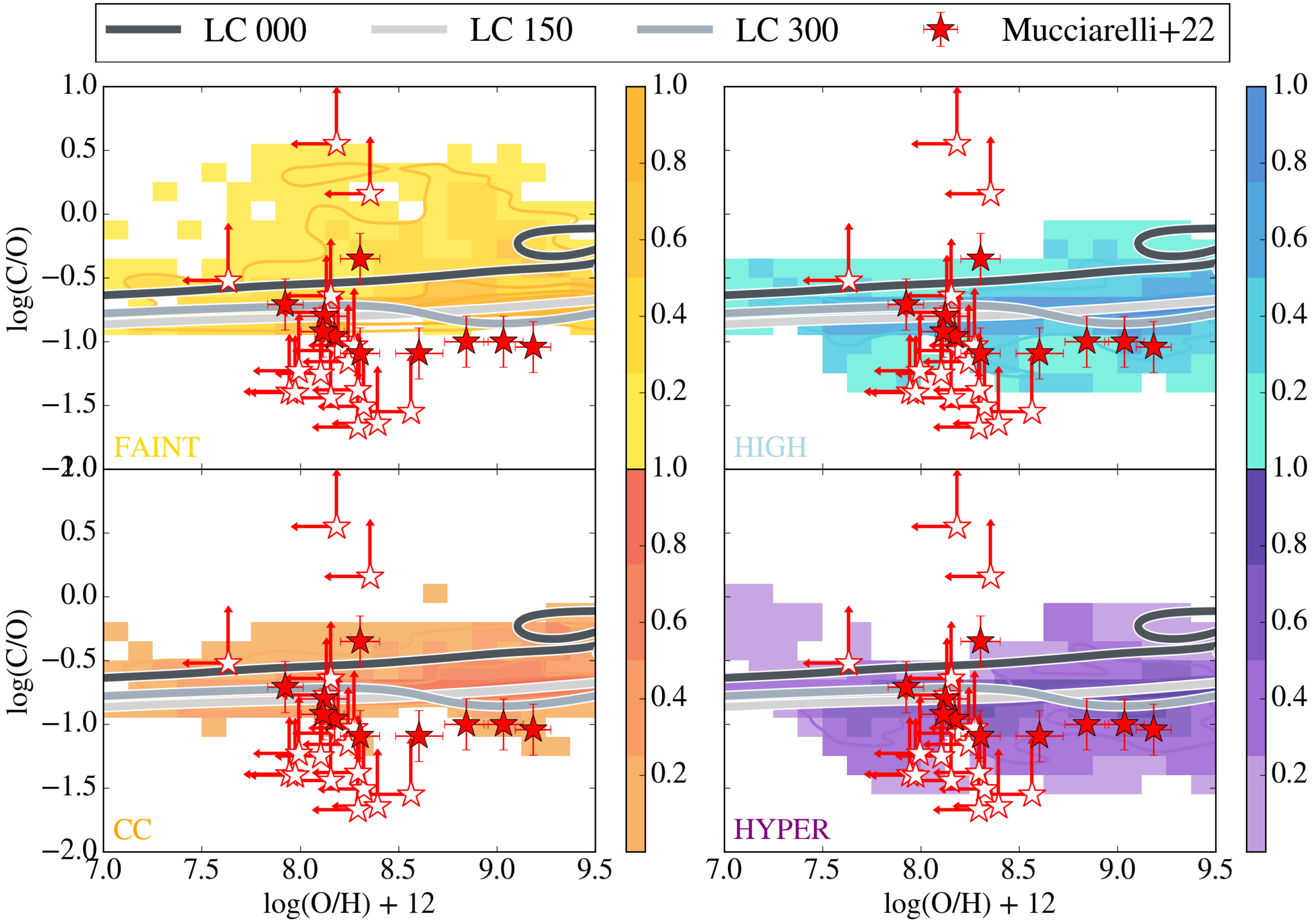
STOCHASTIC ENRICHMENT AND THE HIGH-Z UNIVERSE

STOCHASTIC ENRICHMENT



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

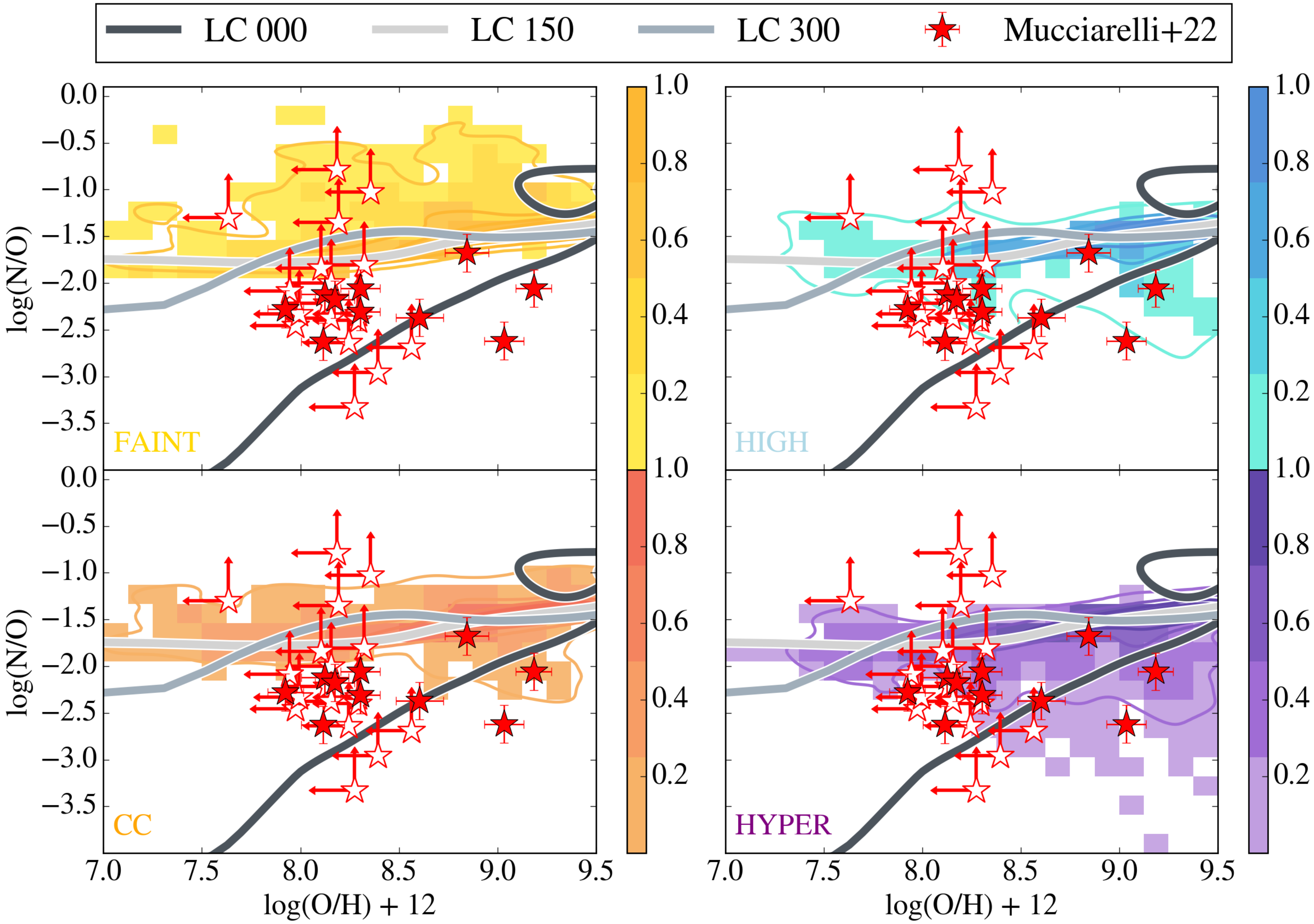
Lines: classical GCE models

Considering early inhomogeneous evolution deeply affects model predictions

Stars: homogeneous sample of subgiant stars from Mucciarelli et al. (2022)

Rossi et al. (2024); also Argast et al. (2004), Cescutti (2008) for n-capture elements

STOCHASTIC ENRICHMENT



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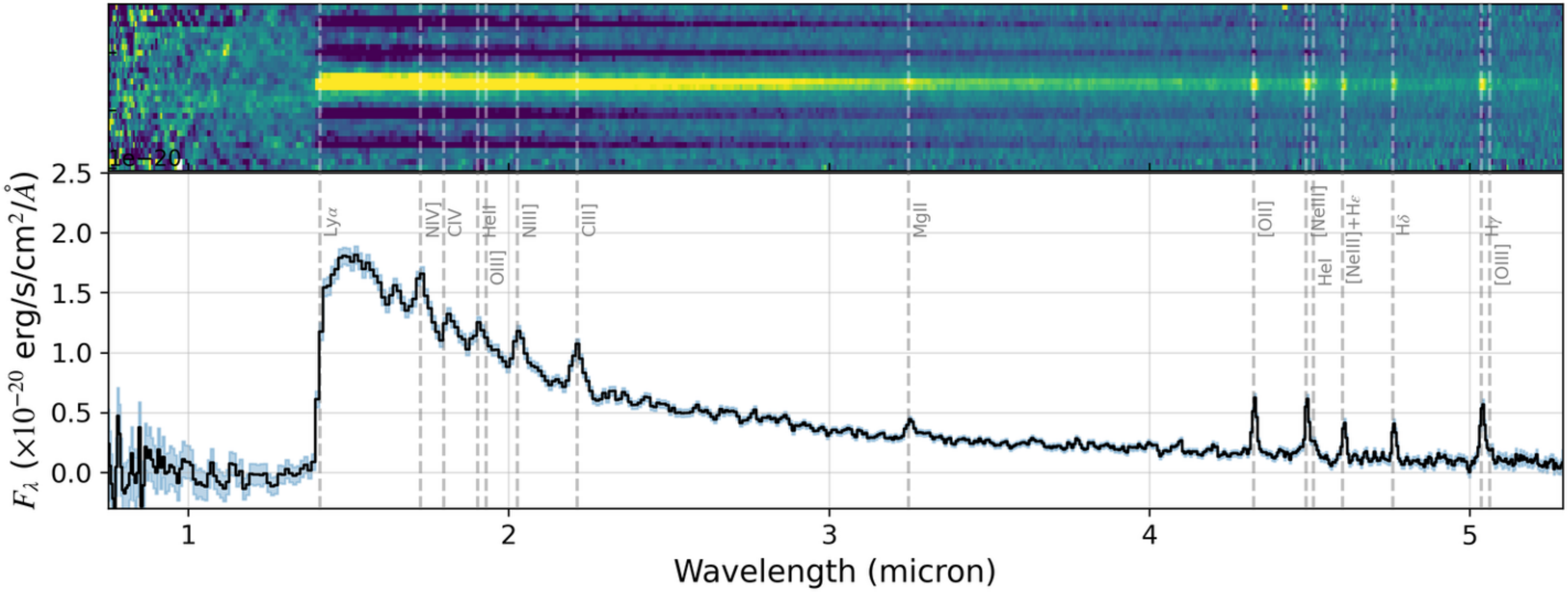
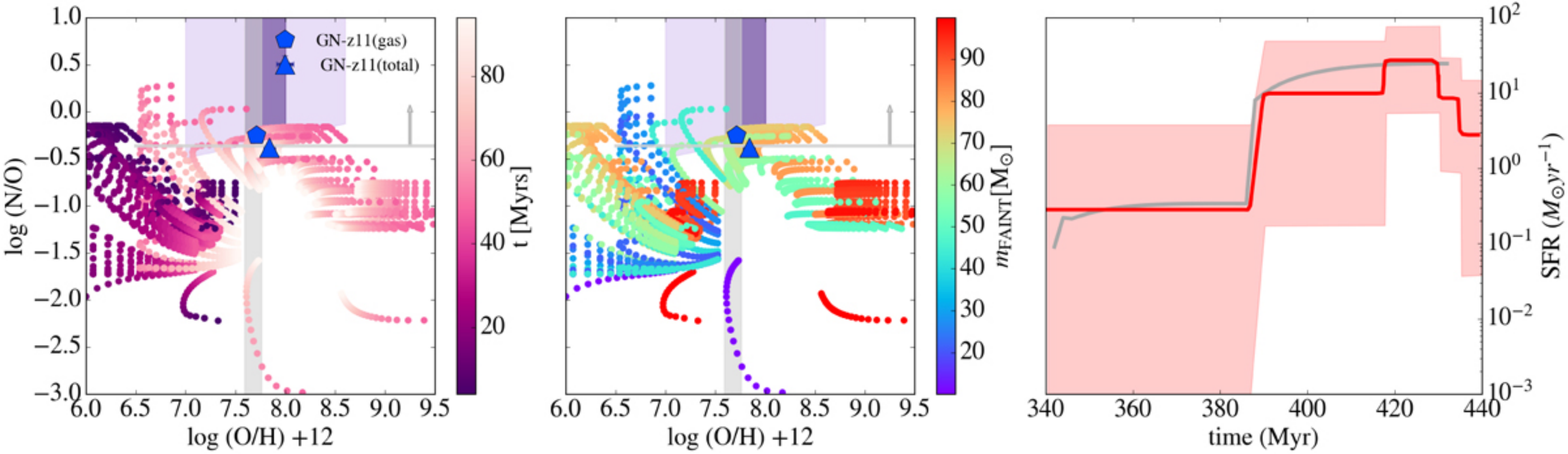
EXTREME-N EMITTERS AT HIGH Z



GN-z11 @ z=10.6 (430 Myr after the Big Bang), $M_\star$~10^9 $M_\odot$, R_e~200pc,

Bunker et al. (2023)

STOCHASTIC ENRICHMENT

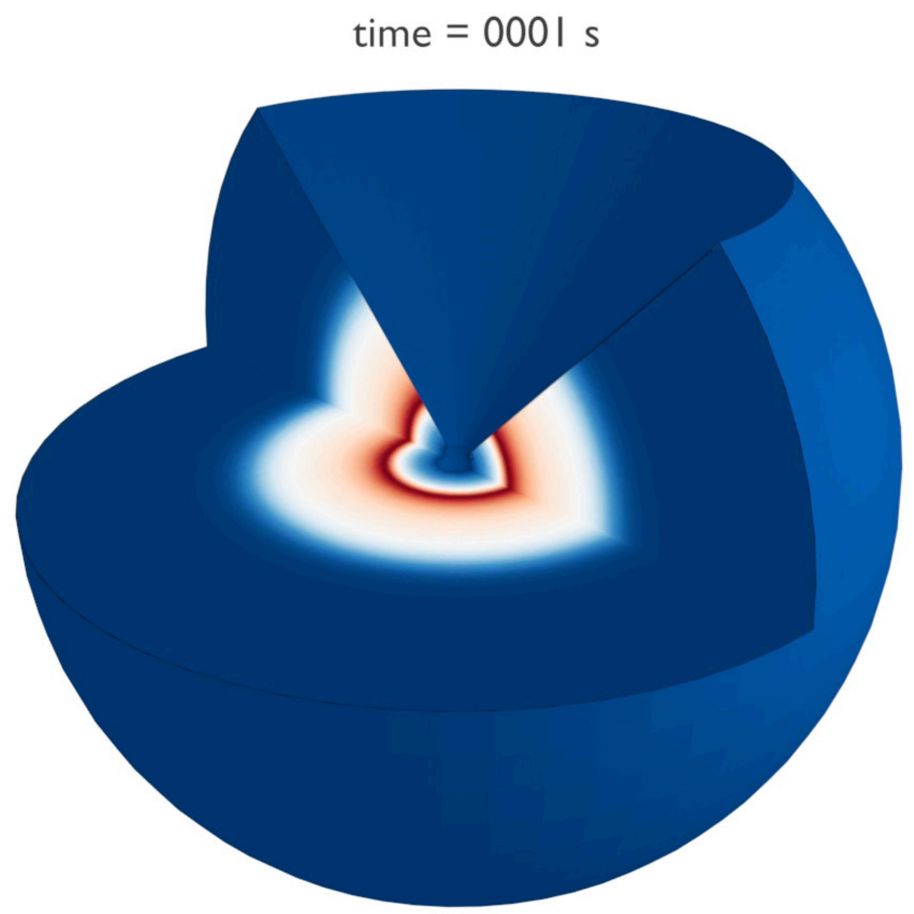


Chemical enrichment of GN-z11. Different evolutionary tracks represent different Pop III star-forming clumps, which merge into the main branch of the galaxy. The tracks are color coded according to time elapsed since the beginning of star formation (left) and stellar mass (middle). Abundance data are from Cameron et al. (2023) and Senchyna et al. (2024); the adopted SFH is from Tacchella et al. (2023). Figure from Rossi et al. (2024)

See also Charbonnel et al. (2023), D'Antona et al. (2023), Nagele & Umeda (2023), Kobayashi & Ferrara (2024), Nandal et al. (2024), Rizzuti et al. (2025)… for alternative explanations

IN THE (NEAR) FUTURE...

Shell mergers in late evolutionary phases of massive stars? (Rizzuti et al. 2024)



C and O isotopic ratios in unevolved stars with age determinations (also for comparison with molecular cloud data...)