UNIVERSITÀ DEGLI STUDI DI TRIESTE

Ministero dell'Università e della Ricerca

Nuclear Physics in Astrophysics – Dresden 2024

The contribution of massive stars to the chemical evolution of the Galaxy

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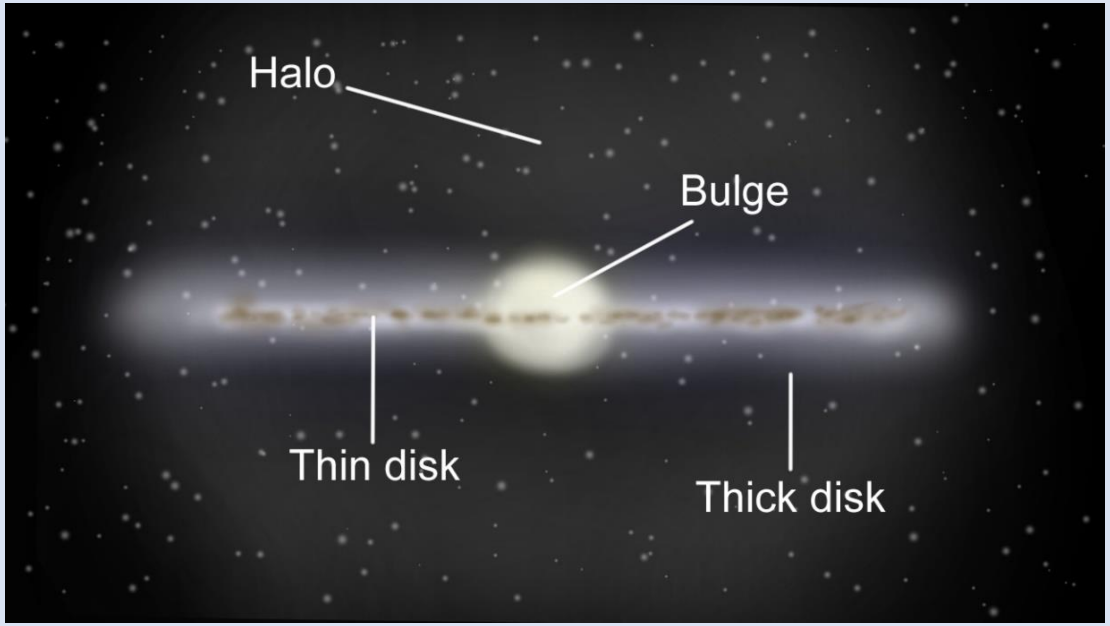
Galactic chemical evolution (GCE)

GCE studies the formation and evolution of chemical abundances in the interstellar gas

Ingredients for gas evolution:

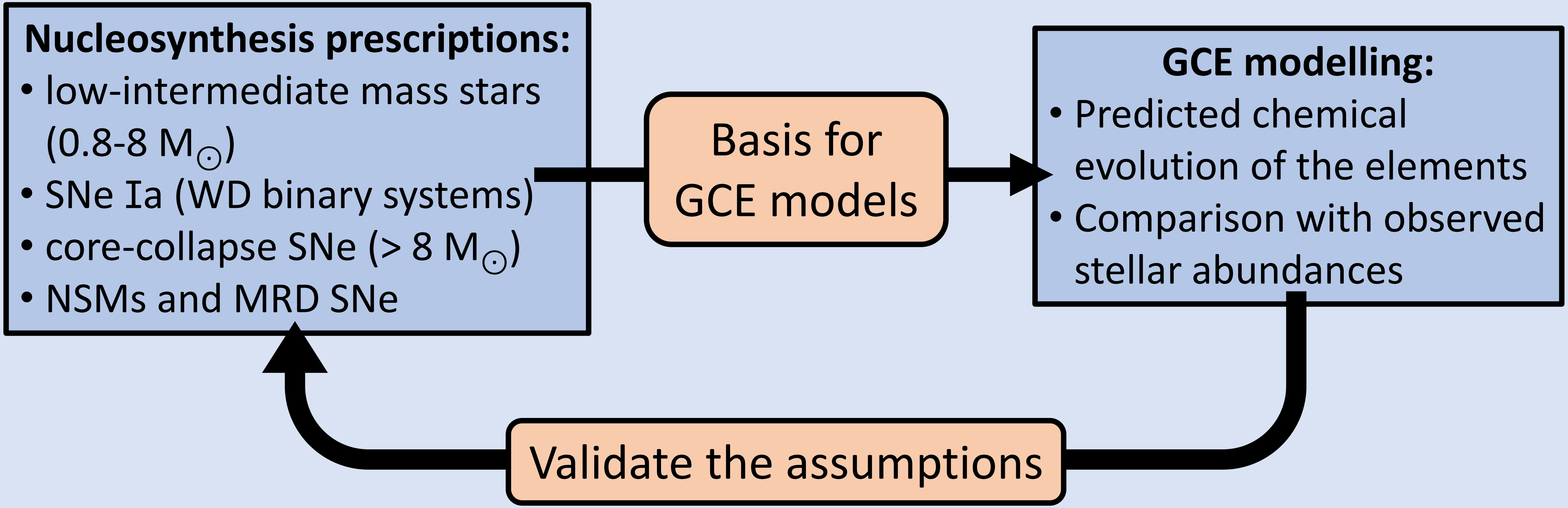
- gas converted into stars (initial mass function, star formation rate)
- gas restored (stellar yields, wind, SNe)
- infall, outflow…



Different parts of the Milky Way underwent a different evolution:

- Halo: very eccentric orbits, low metallicity, globular clusters
  → most ancient part of the Milky Way

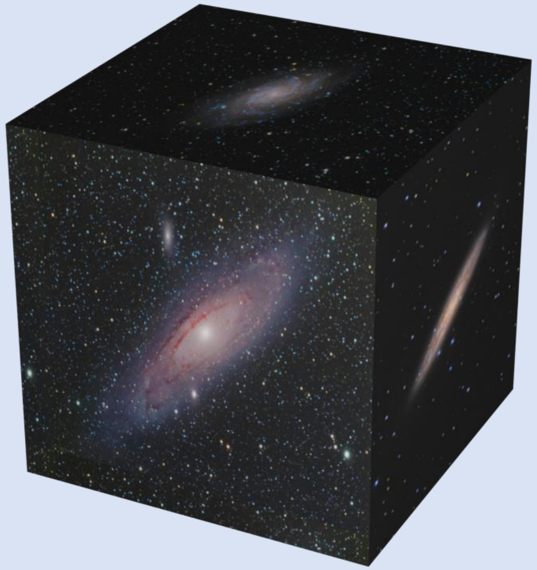
How can we use GCE models?



Different types of chemical evolution models

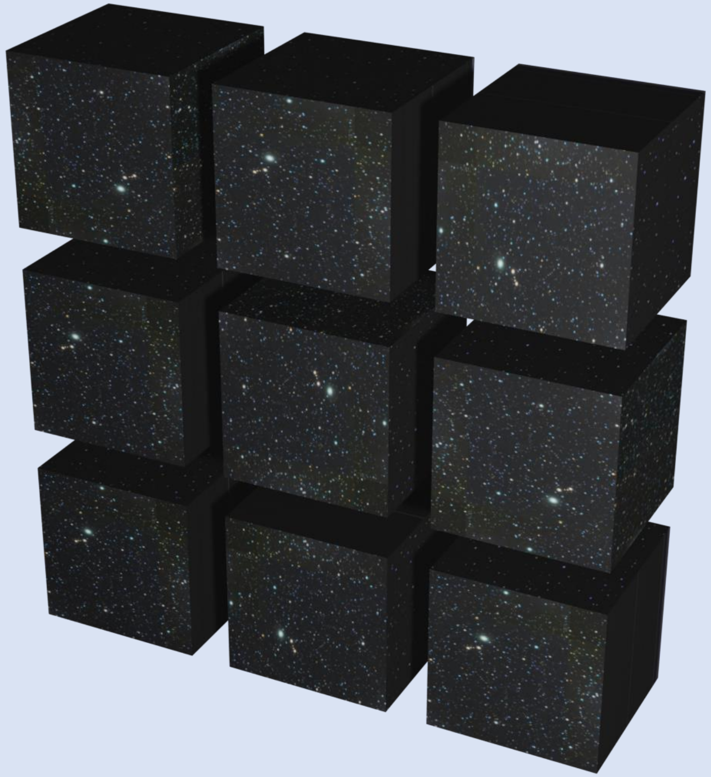
One-zone (homogeneous) model

- Matteucci & Greggio 1986, Chiappini et al. 1997, Goswami & Prantzos 2000, Côté et al. 2017



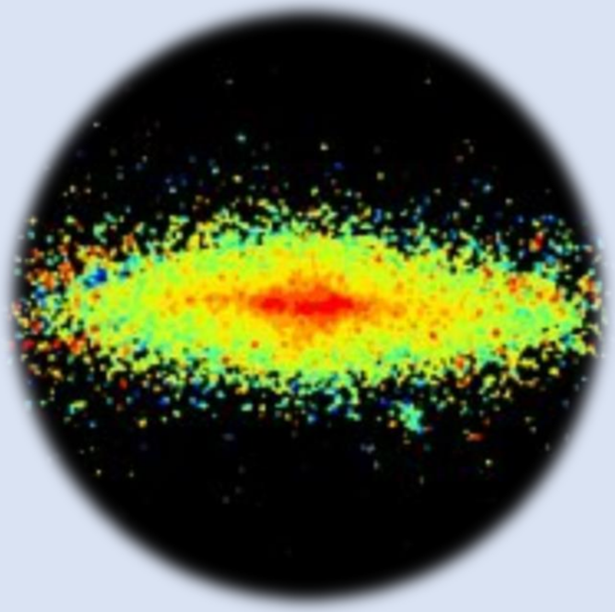
Multi-zone (inhomogeneous) model

- Argast et al. 2000, Cescutti 2008, Hishimaru et a. 2015



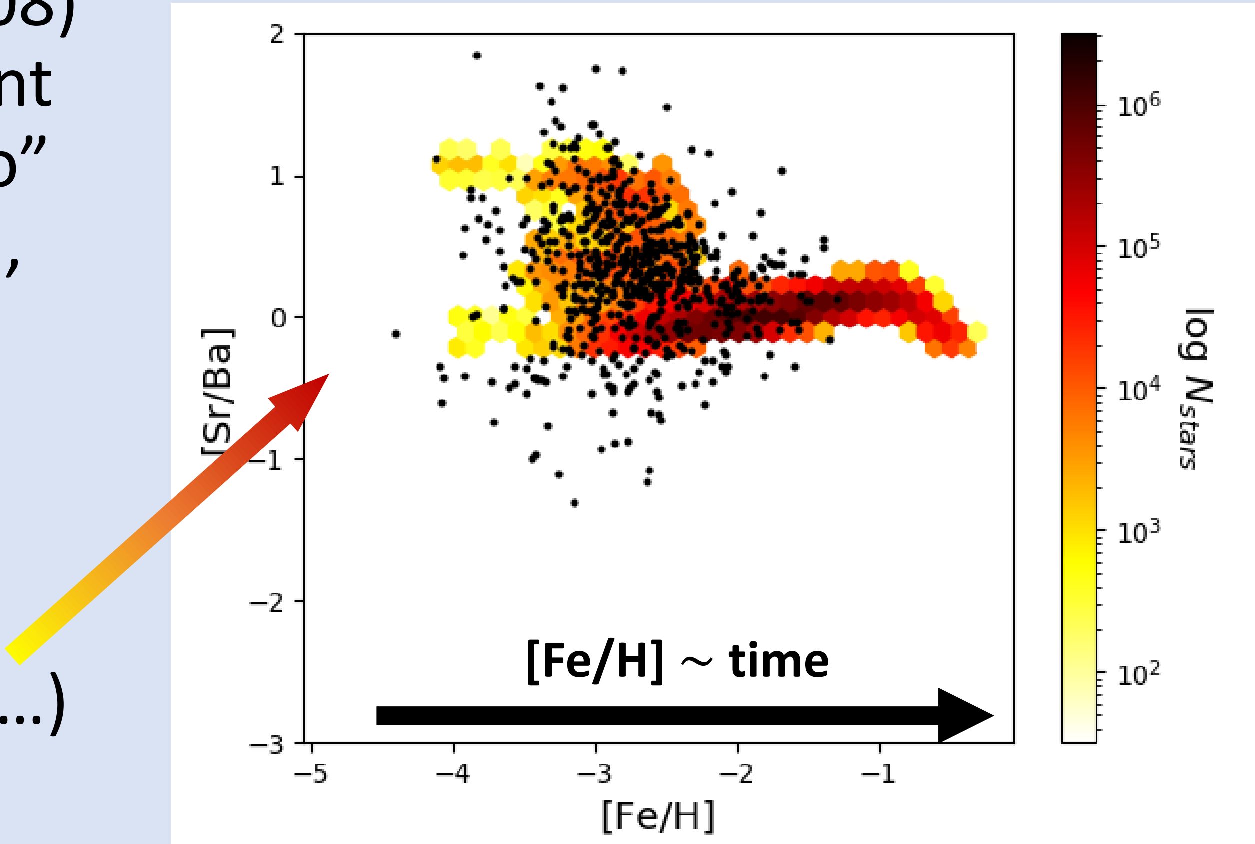
Multi-dimensional model

- Kobayashi 2004 (SPH), Spitoni et al. 2019 (2D), Scannapieco et al. 2022 (SPH)



Stochastic GCE model of Cescutti (2008)

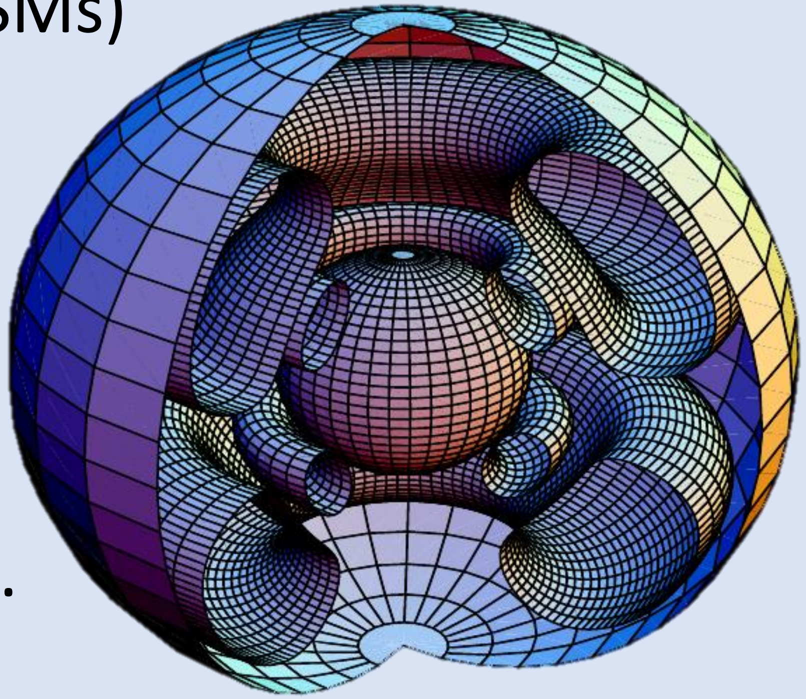
- Multi-zone simulations (Cescutti 2008) of the Galactic halo with independent realizations, stochastic "Monte Carlo" sampling of stellar mass distribution, weighted on the IMF
- Parameters fixed to reproduce the metallicity distribution function
- Introduced to explain the spread observed for heavy elements (Sr, Ba…)



Cescutti et al. (2014)

The nucleosynthesis from massive stars

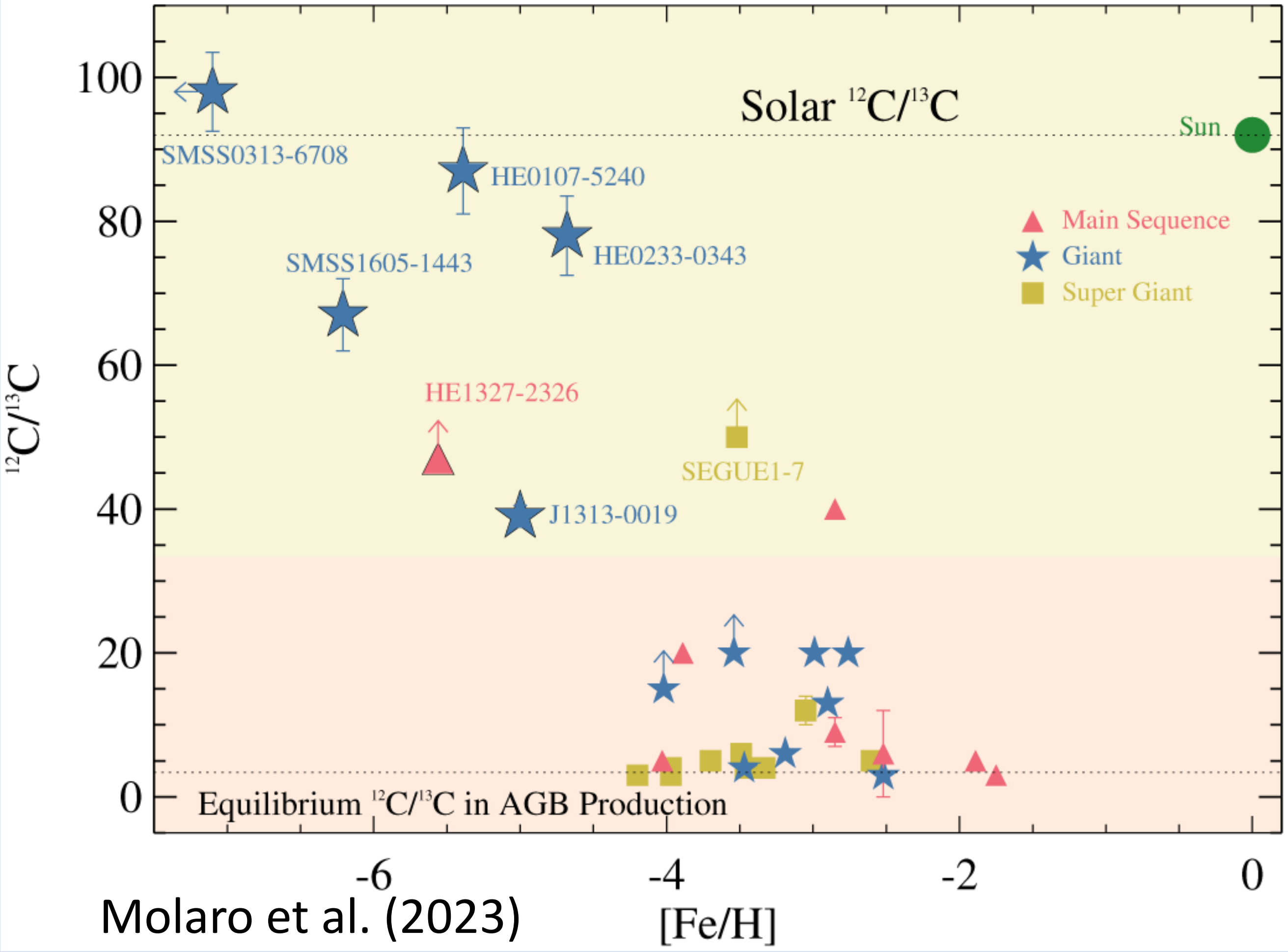
- Massive stars (> 8 $M_{\odot}$): important production of α-elements (C, O, Ne, ...), iron, neutron-capture elements (s-process, r-process as MRD SNe or NSMs)
- Beneficial effect of rotation: rotation-induced mixing, larger cores, longer lifetimes, …
- Even more evident at lower metallicity, where stars are more compact and rotate faster
- Great progress thanks to the stellar modelling studies of Meynet & Maeder (2002), Hirschi et al. (2004); Chieffi & Limongi (2012), …



Meynet & Maeder (2002)

The problem of carbon isotopes

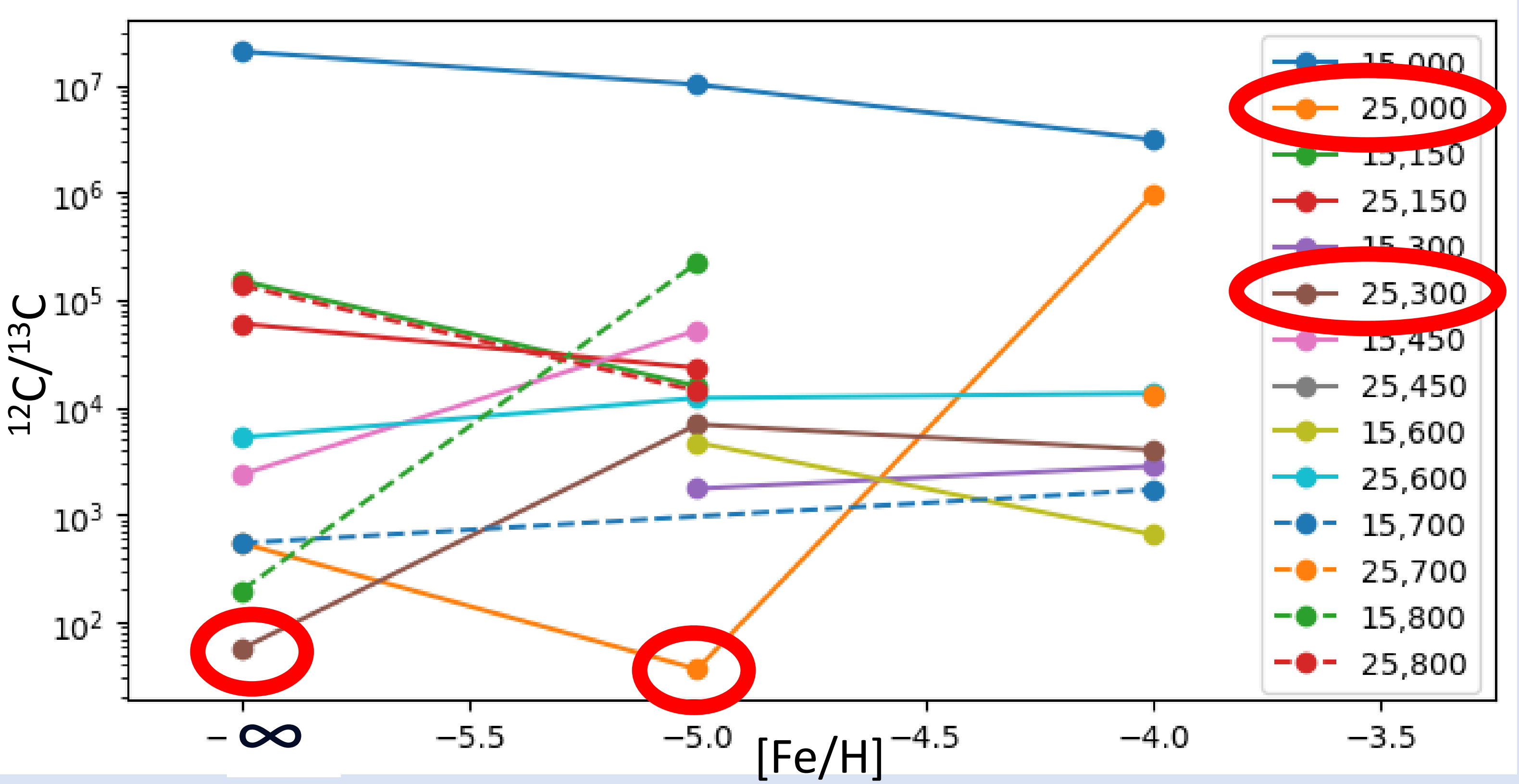
- Observations of extremely metal poor halo stars show high [C/Fe] > - 1 and $^{12}C/^{13}C$ between 30-100
- At [Fe/H] < - 3, only massive stars had the time to enrich: pollution by Pop III stars
- First explained by Chiappini+06, 08 with rotating massive stars
- We need stellar yields of zero-metal massive stars with low Fe and high ^{13}C



Molaro et al. (2023)

Zero metal rotating massive stars

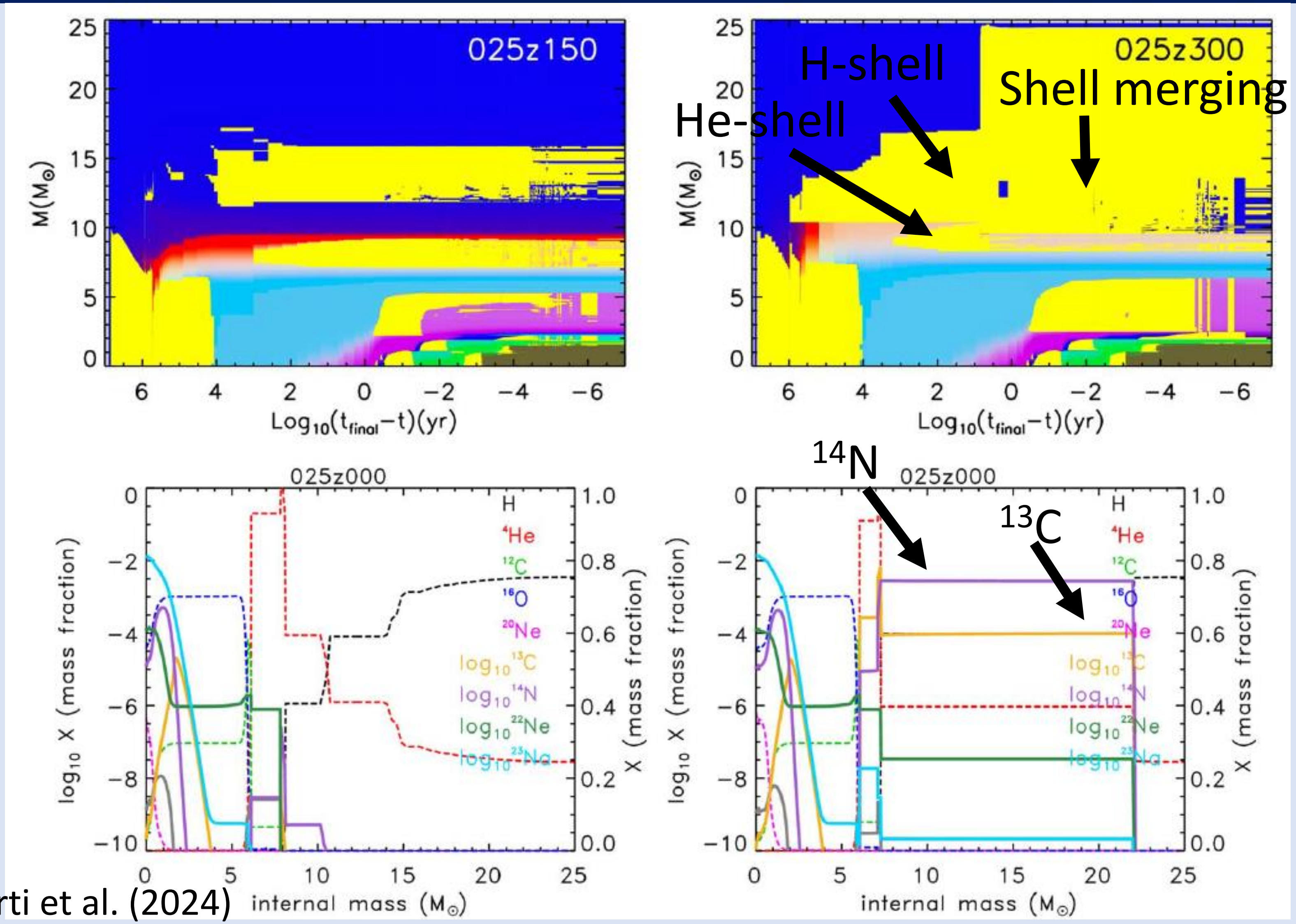
- Roberti et al. (2024) models of zero-metal 15 - 25 $M_\odot$, different rotation velocities
- Most models have $^{12}C/^{13}C > 100$, but a few have $^{12}C/^{13}C < 100$
- Why? What has changed?



Data from Roberti et al. (2024)

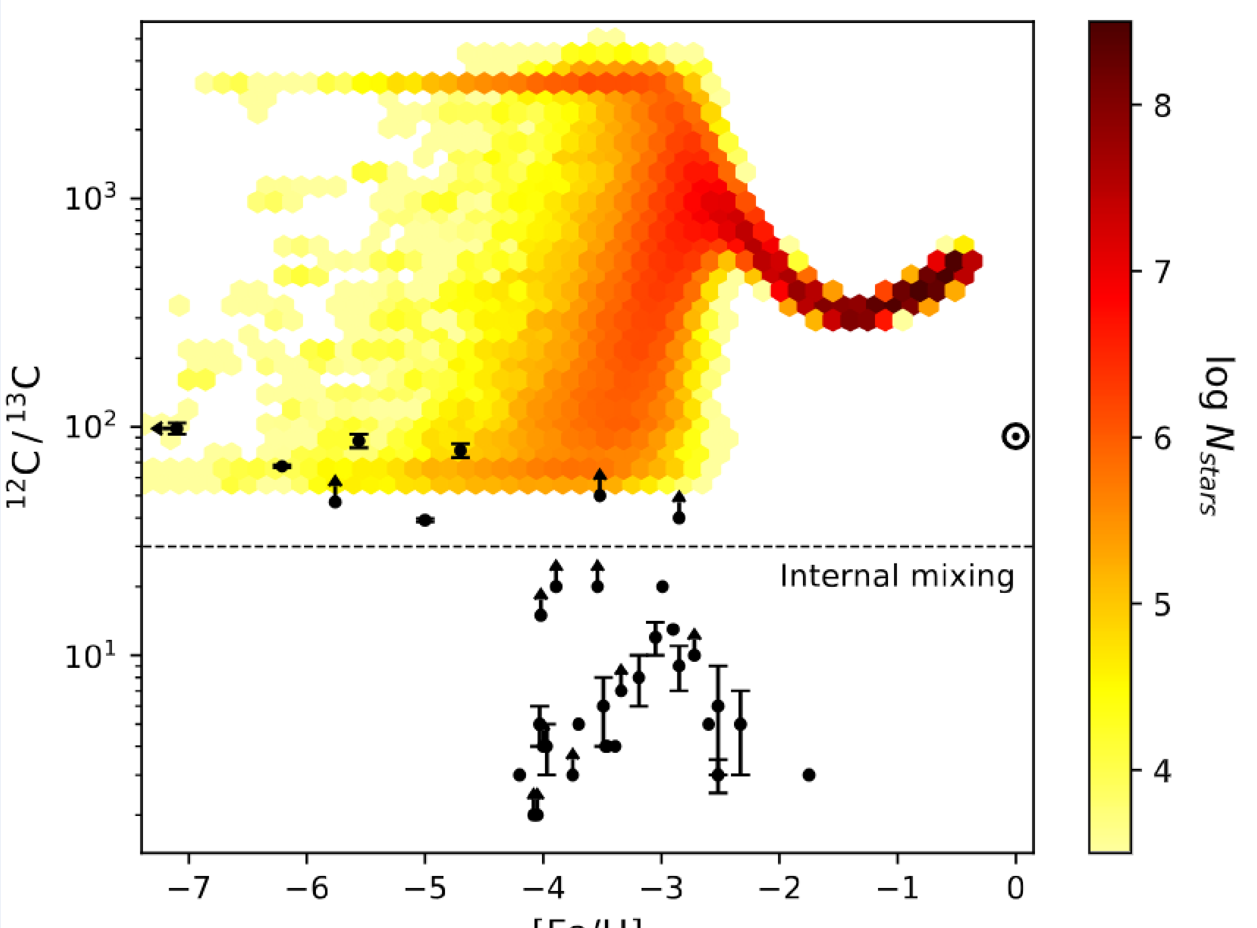
H - He shell merging and ^{13}C production

- Occurrence of merging between H-envelope and He-shell
- Proton ingestion into He-burning, synthesis of ^{13}C, transported outside
- Efficient synthesis of primary ^{13}C and ^{14}N
- How common? We don't know, but indications from 1D & 3D models (Rizzuti et al. 2024)



Roberti et al. (2024)

The stochastic model for $^{12}C/^{13}C$

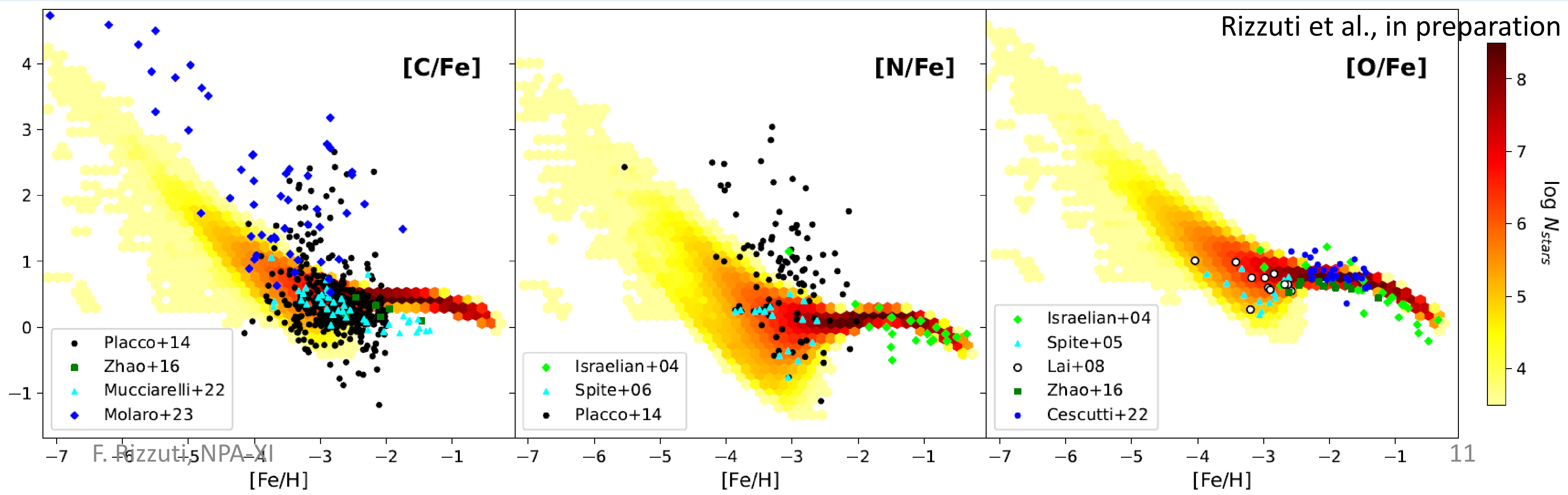


Rizzuti et al., in preparation

- The contribution from Roberti et al. (2024) zero-metal model 25 $M_{\odot}$, 300 km/s reproduces the data
- Shell mergers are an excellent way of explaining metal-poor $^{12}C/^{13}C$
- $^{12}C/^{13}C < 30$ cannot be explained: internal mixing in LIMS? Pollution?

CNO abundances in halo stars

- The stochastic model predicts high [CNO/Fe] for low [Fe/H], due to large CNO production and low Fe: same production from RMS
- C from stellar models underproduced at low [Fe/H], overproduced at high [Fe/H]
- Valid for CEMP-no stars, but CEMP-s are a different story



Conclusions

- GCE models are powerful tools for learning how elements are produced
- Rotation in massive stars is necessary, and stars need to rotate faster at lower metallicity
- Observations of C isotopes in metal-poor stars raise questions on the production of the $^{12}C/^{13}C$ ratio
- H-He shell mergers in primordial massive stars are an excellent candidate

→ The model-data comparison can be used to estimate free parameters, related to stellar physics: rotation distribution, frequency of shell mergers…

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