UNIVERSITÀ DEGLI STUDI DI TRIESTE

Ministero dell'Università e della Ricerca

HITS

Alexander von HUMBOLDT STIFTUNG

s, i & r Element Nucleosynthesis (sirEN) - Giulianova 2025

The production of heavy elements from rotating massive stars in the Galaxy

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Galactic Chemical Evolution models

See Marta's review

One-zone (homogeneous) model

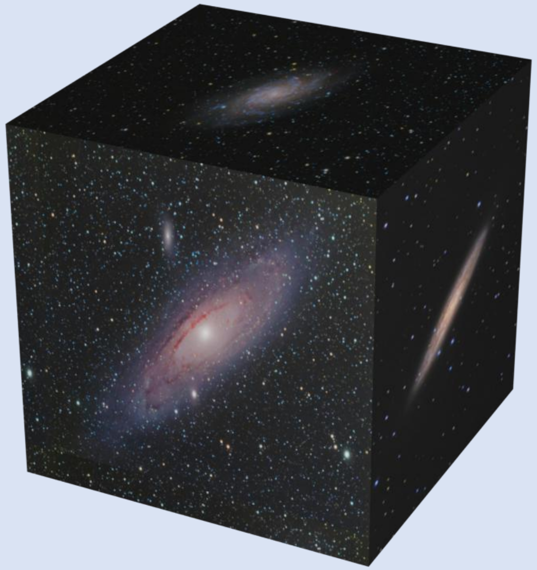
- Matteucci & Greggio 1986, Chiappini et al. 1997, Goswami & Prantzos 2000, Côté et al. 2017

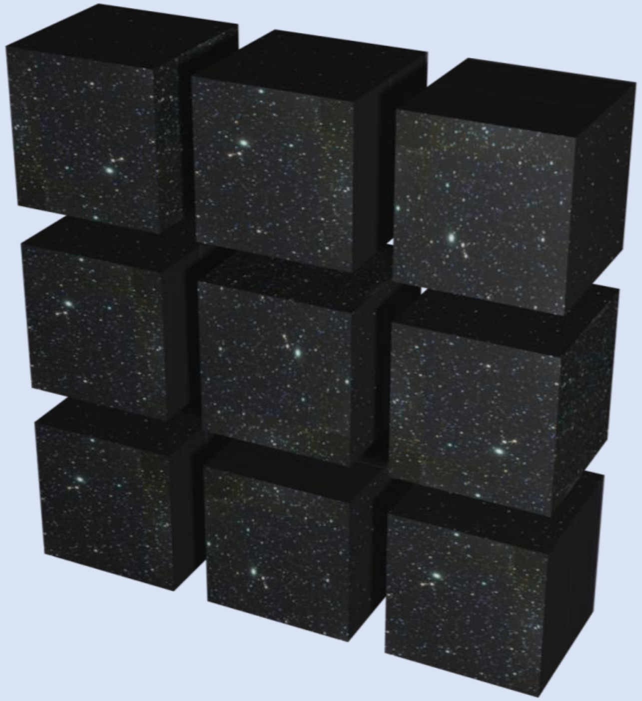
Multi-zone (inhomogeneous) model

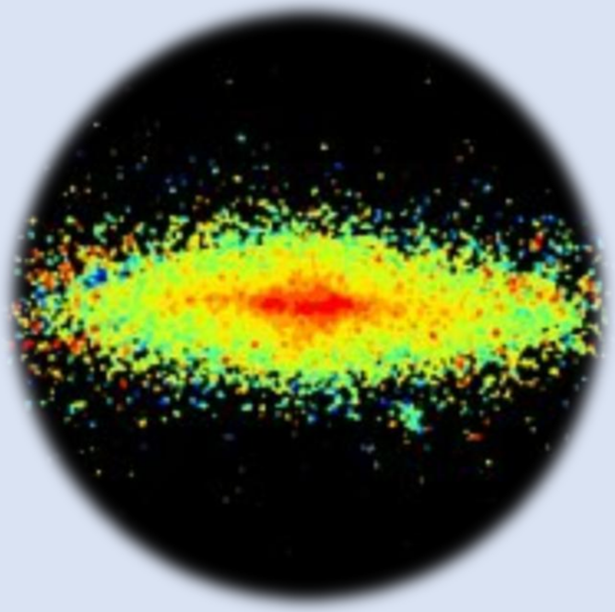
- Argast et al. 2000, Cescutti 2008, Hishimaru et al. 2015, Wehmeyer et al. 2015

Multi-dimensional model

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







How to use Galactic Chemical Evolution models

Nucleosynthesis prescriptions:
- low-intermediate mass stars (0.8-8 $M_\odot$)
- SNe Ia (WD binary systems)
- core-collapse SNe (> 8 $M_\odot$)
- NSMs and MRD SNe

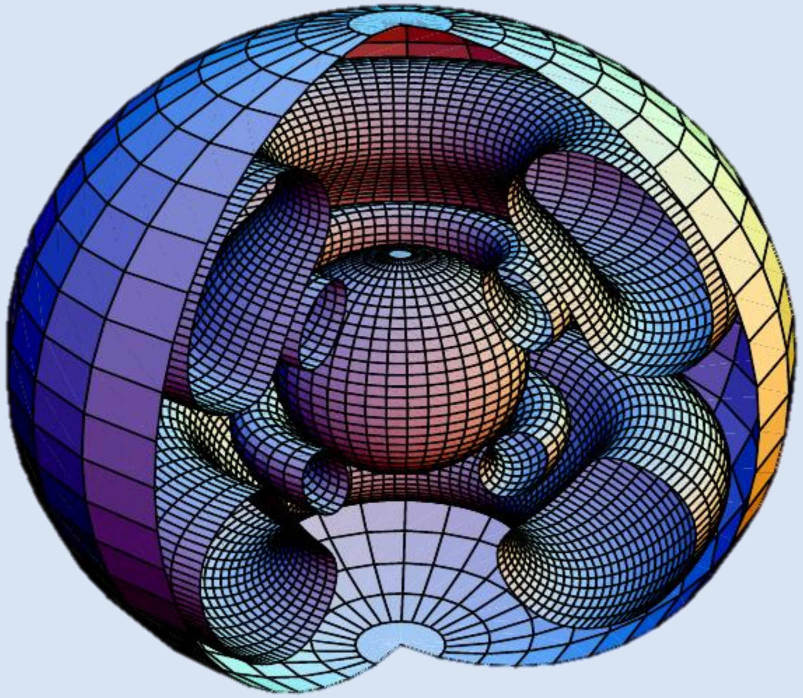
Basis for GCE models

GCE modelling:
- Predicted chemical evolution of the elements
- Comparison with observed stellar abundances

Validate the assumptions

The nucleosynthesis from massive stars

- Massive stars (> 8 $M_\odot$) have short lifetimes: the first to die and enrich
- Important producers of both light (C, α-elements, iron) and heavy elements (**s-process**, r-process as MRD SNe, 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)

Models of rotating massive stars (RMS)

Models of RMS that provide complete nucleosynthesis for different mass range, metallicity, rotation velocity:

See Lorenzo's talk

Frischknecht et al. (2016):
- GENEC code
- 15 - 40 $M_\odot$
- [Fe/H]: 0, -1.8, -3.8, -5.8
- Initial rotation velocity: 1 set with different velocities

Limongi & Chieffi (2018):
- FRANEC code
- 13 - 120 $M_\odot$
- [Fe/H]: 0, -1, -2, -3
- Initial rotation velocity: 3 sets (0, 150, 300 km/s)

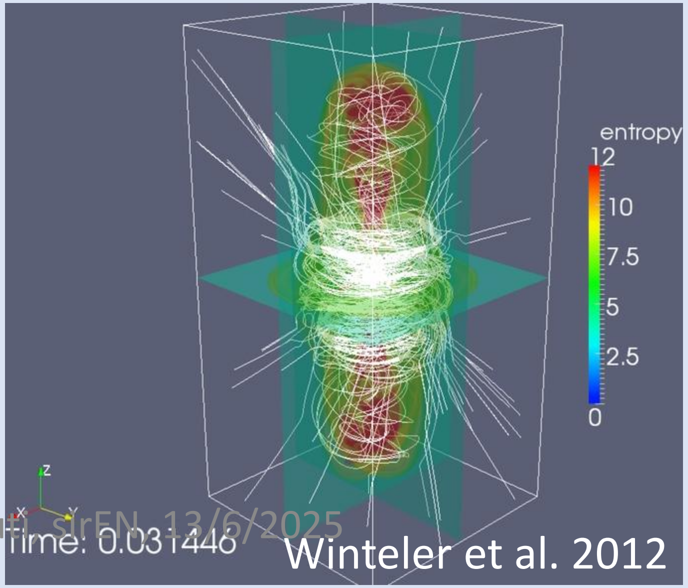
Roberti et al. (2024):
- FRANEC code
- 15 - 25 $M_\odot$
- [Fe/H]: -4, -5, -∞
- Initial rotation velocity: 7 sets (0 to 700 km/s)

Successfully used for GCE by Cescutti et al. (2013), Prantzos et al. (2018), Rizzuti et al. (2019), Romano et al. (2019), Molero et al. (2023) etc…

Prescriptions for r-process

Magneto-rotationally driven SNe

- Winteler et al. (2012) →
  GCE by Cescutti et al. (2014)
- 10%, 10-80 $M_\odot$



Winteler et al. 2012

Neutron star mergers

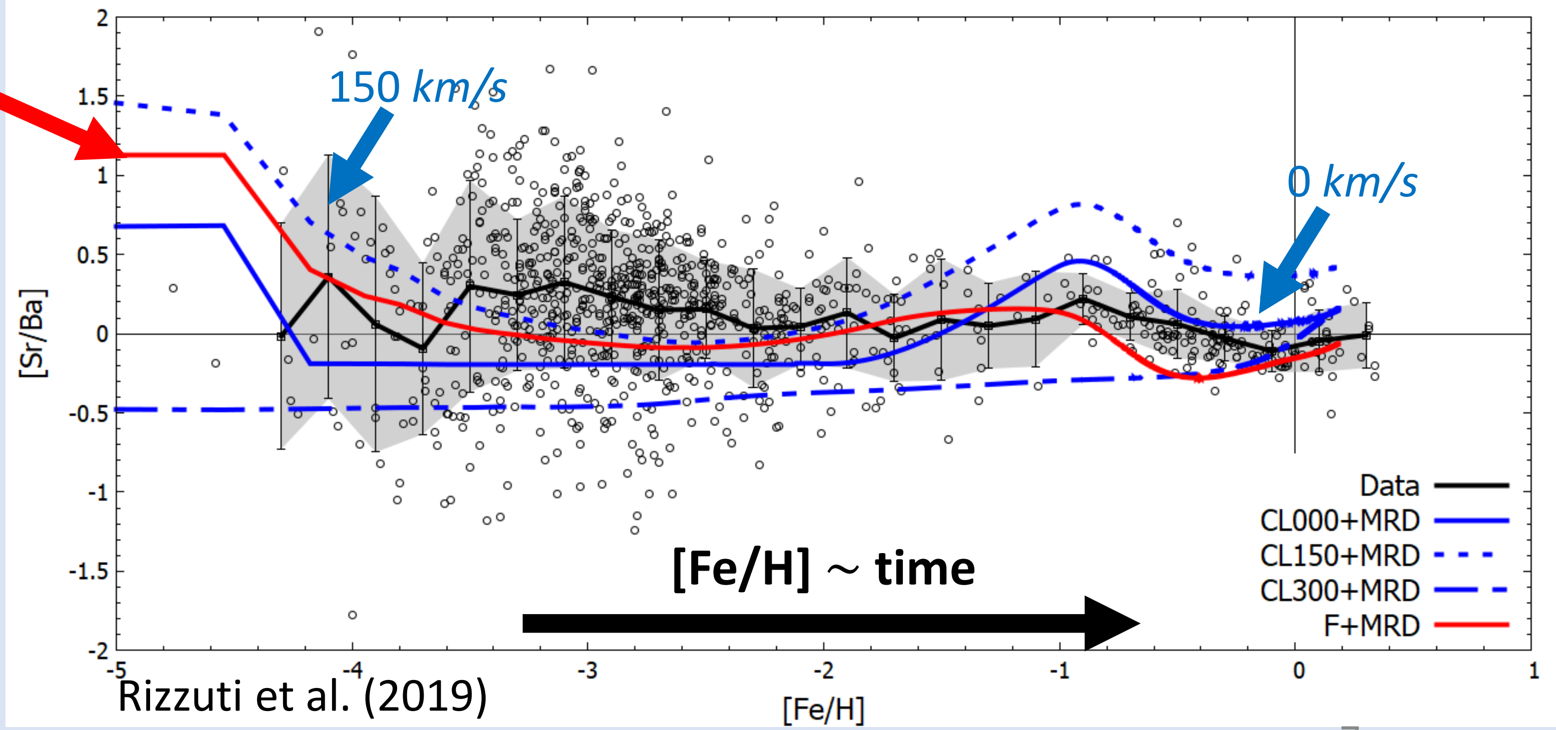
- Rosswog et al. (1999) →
  GCE by Matteucci et al. (2014), Cescutti et al. (2015)
- 2%, 9-50 $M_\odot$ + delay time distribution
  (Simonetti+19, Cavallo+21, Molero+23)


svs.gsfc.nasa.gov

Homogeneous GCE models

- One-zone simulations (Chiappini et al. 1997): reproducing the mean trend of the data
- Assuming that all stars have the same rotation velocity (blue lines) cannot explain the observations at all metallicities
- Mixed rotation velocities (red line) are preferred, but can be improved
- Need higher rotation velocities (150 km/s) at lower metallicities, and non rotating (0 km/s) a higher ones

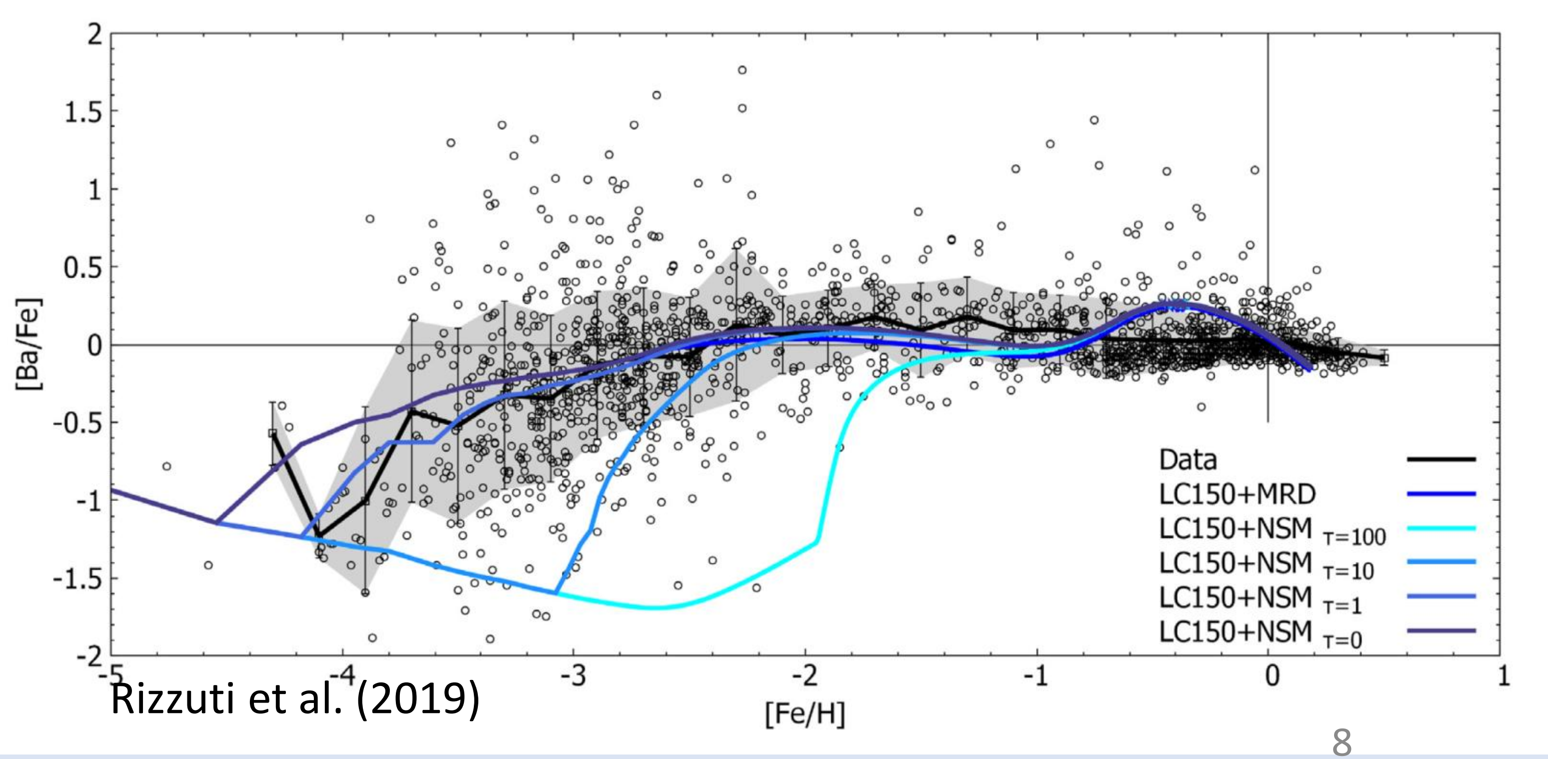
But: homogeneous models don't reproduce the dispersion in data



Homogeneous GCE models

- We run tests changing the r-process production sites (MRD SNe vs NSM)
- Assumed a simplified fixed time delay for NSMs: 0, 1, 10, 100 Myr

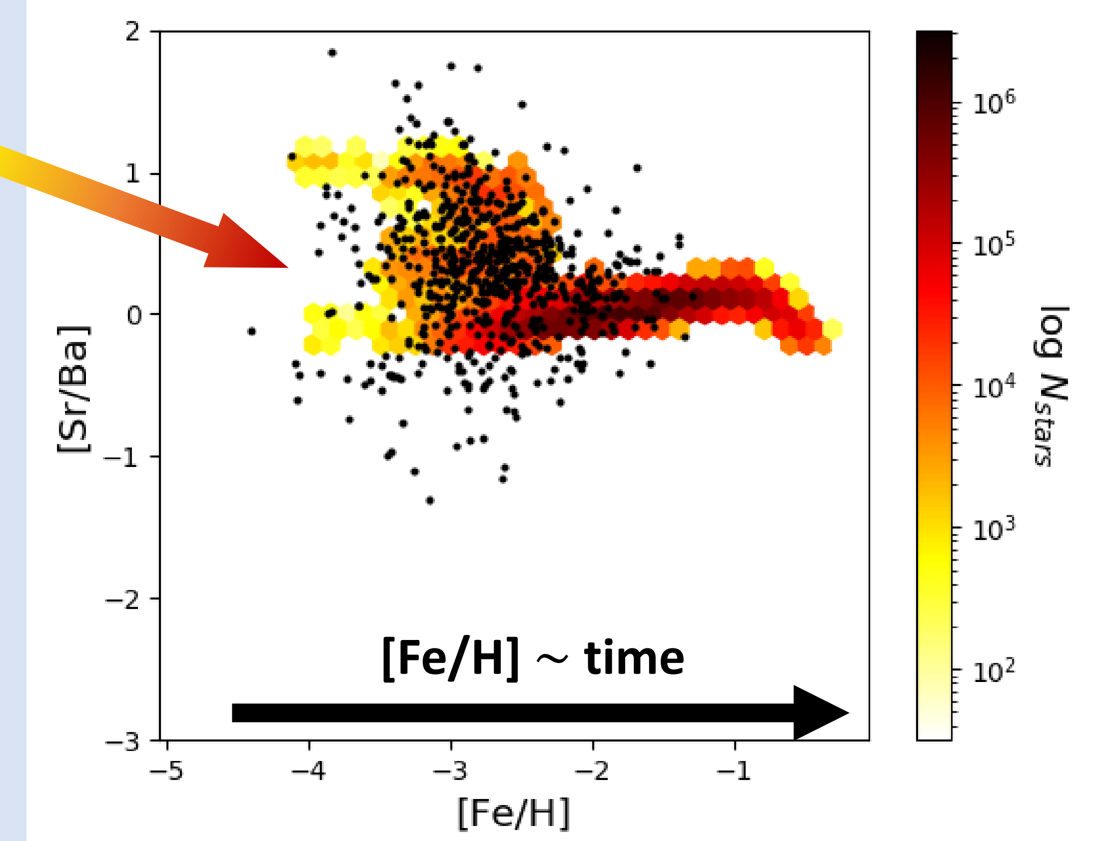
- We need a fast source of r-process at low metallicity:
- either short-delayed NSMs (0 or 1 Myr, as in Matteucci et al. 2014)
- or MRD SNe, which originate from short-lived massive stars



Rizzuti et al. (2019)

The stochastic GCE model

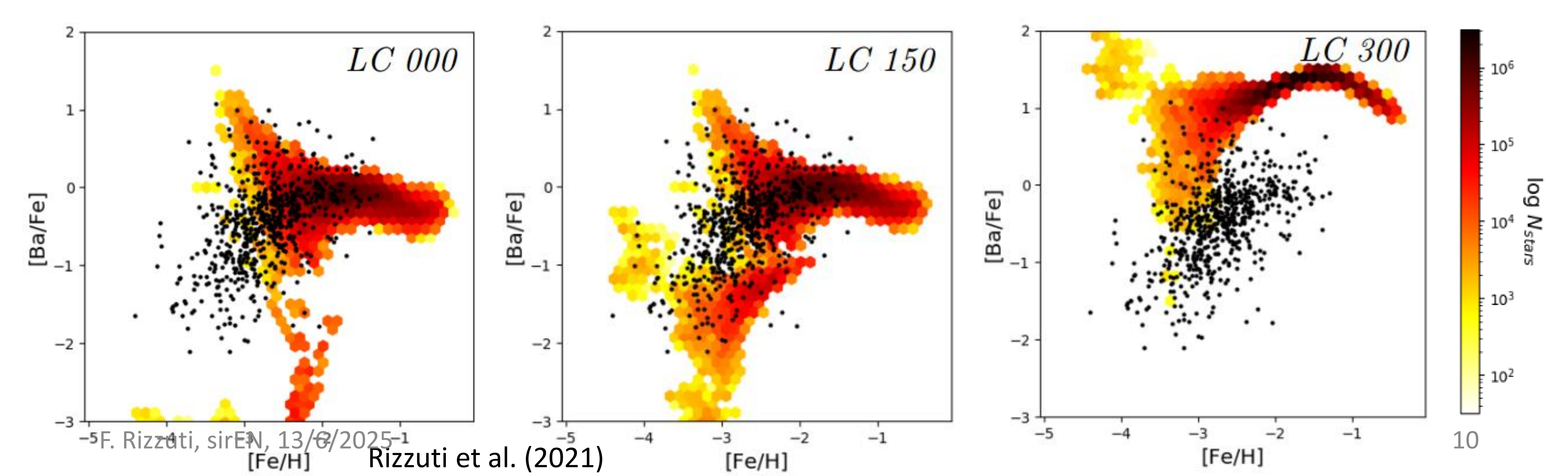
- **GEMS**: **G**alaxy **E**volution via **M**ontecarlo **S**ampling (Rizzuti et al. 2025b)
- Multi-zone simulations (Cescutti 2008) of the Galactic halo with independent realizations, stochastic “Monte Carlo” sampling of stellar mass distribution, weighted on the IMF
- Parameters fixed to reproduce the metallicity distribution function
- Introduced to explain the spread observed for heavy elements (Sr, Ba…)



Cescutti et al. (2014)

Rotation velocity in the stochastic model

- The yields from Limongi & Chieffi (2018) allow us to choose the massive star rotation velocity
- Assuming the same rotation velocity for all stars (0, 150, 300 km/s) cannot explain the data at all metallicities

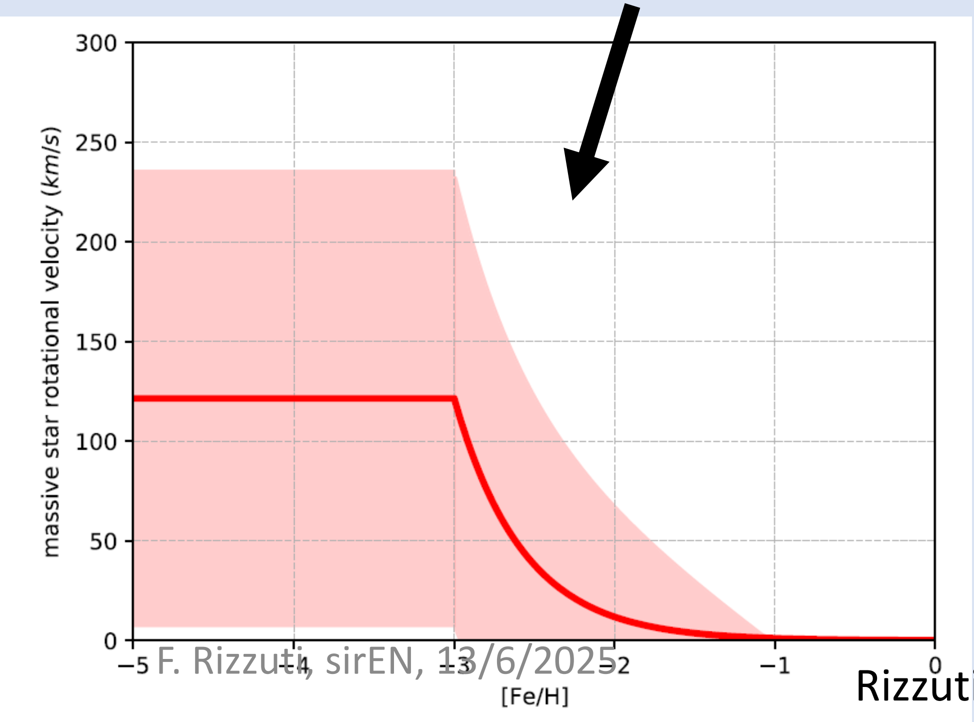


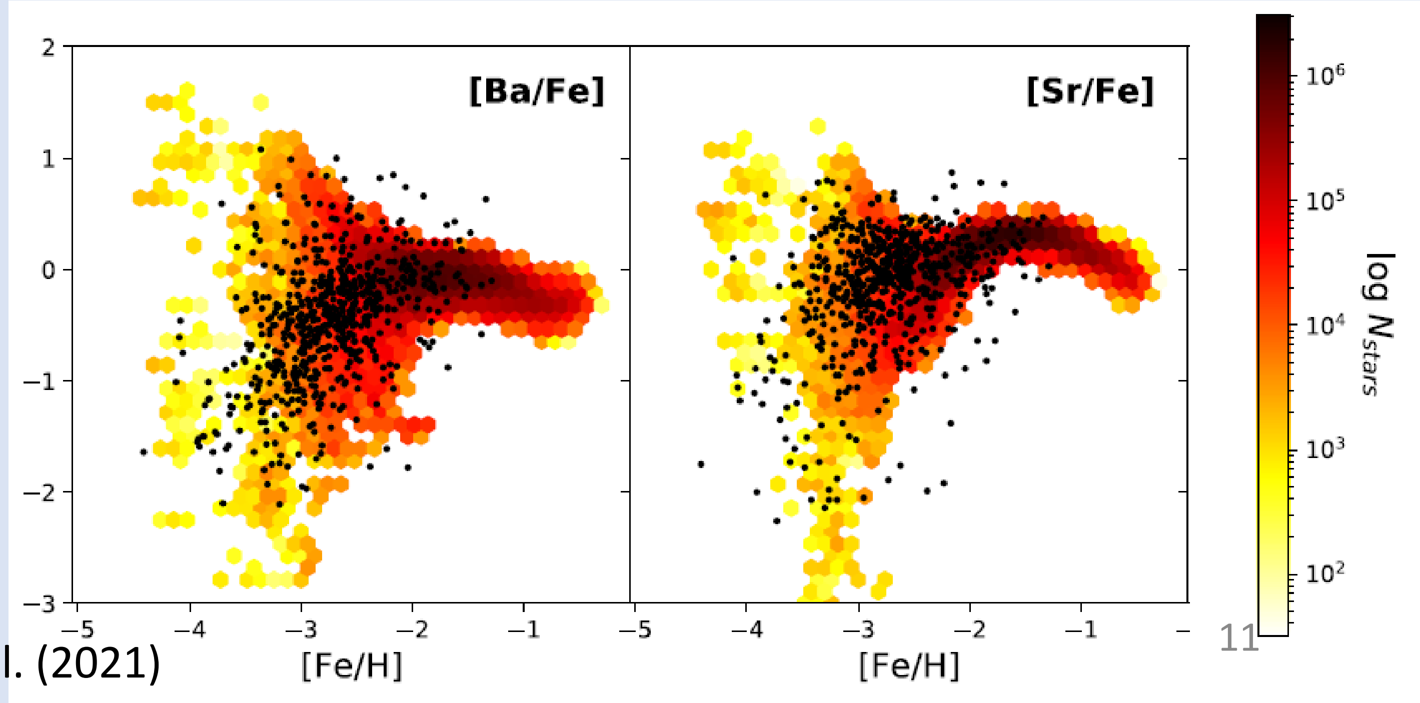
Rizzuti et al. (2021)

Constraints to rotation in massive stars

- We used the yields from Limongi & Chieffi (2018) in the stochastic model
- Selecting a distribution of velocities, Sr and Ba can be reproduced at all metallicities: faster rotation at lower metallicity (Rizzuti et al. 2021)

A way of calibrating rotation: many uncertainties, but a strong indication!

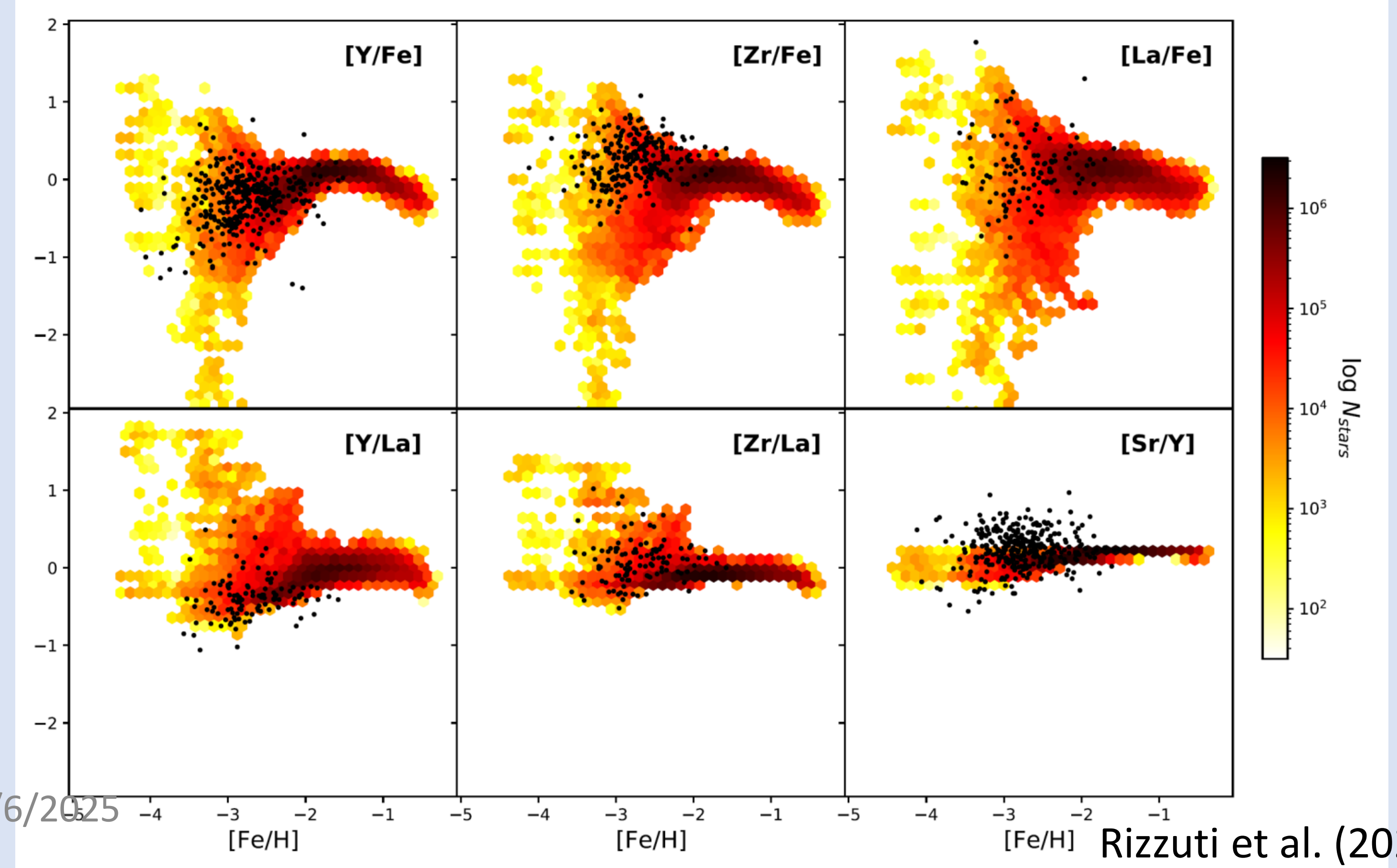




Rizzuti et al. (2021)

Predictions for other heavy elements

- Using the same model, we can make predictions for other heavy elements (Y, Zr, La)
- Those were not used for the calibration, but still reproduced

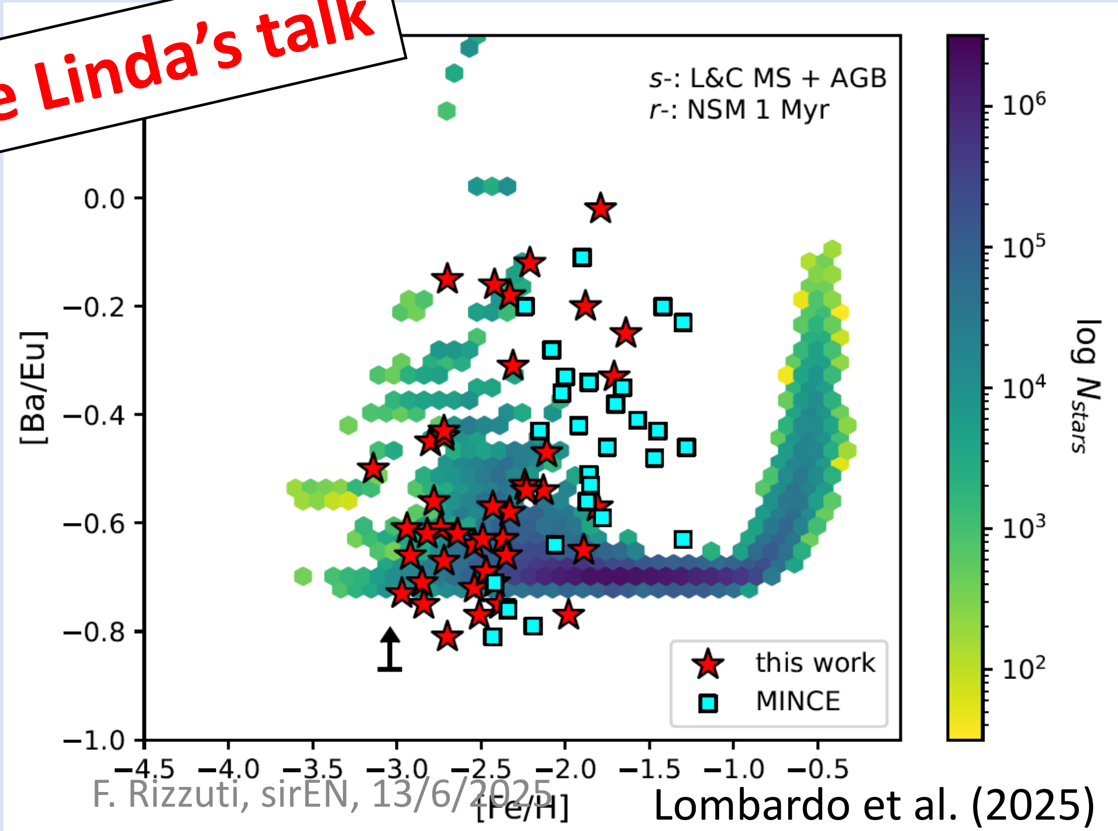


Rizzuti et al. (2021)

Abundances in EMP halo stars

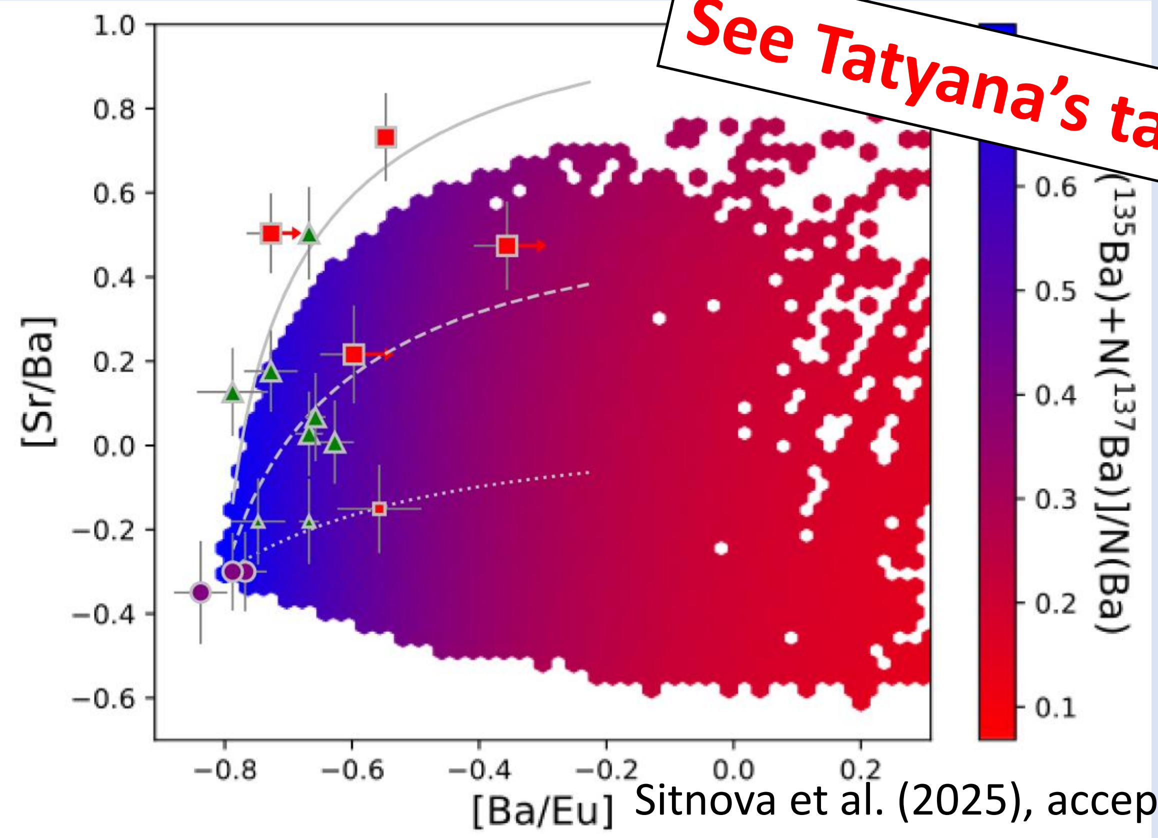
- Recent interest in observations of increasingly metal-poor stars
- Information on the s- and r- production of the very first generations

See Linda’s talk



Lombardo et al. (2025)

See Tatyana’s talk

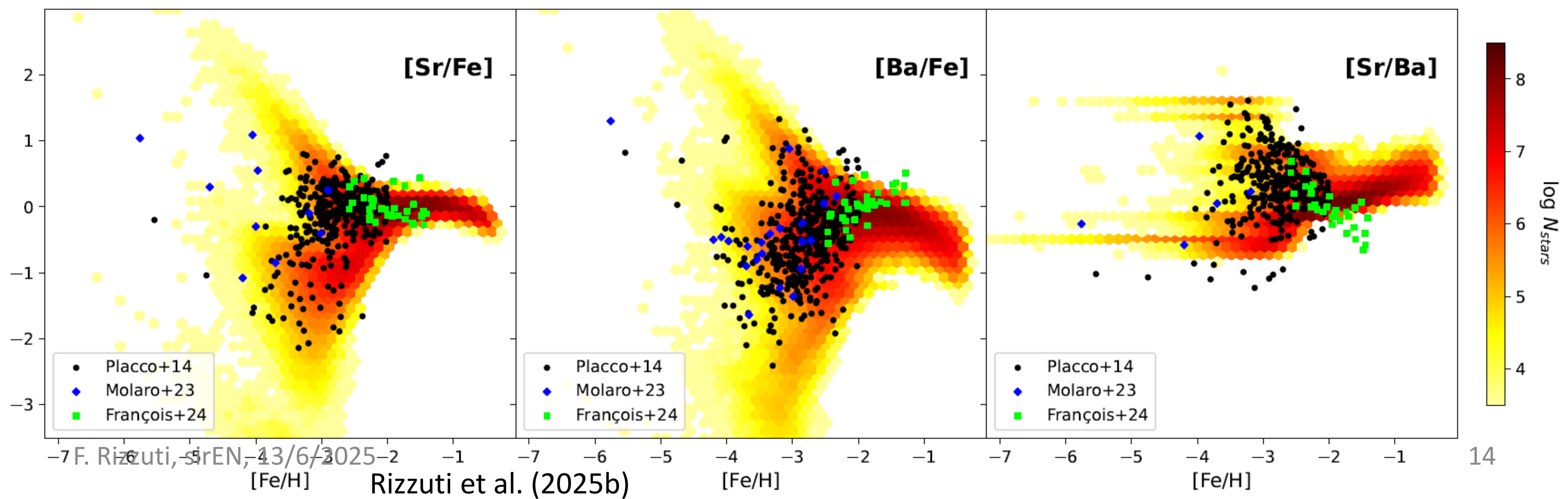


Sitnova et al. (2025), accepted

Abundances in EMP halo stars

More in Schiappacasse-Ulloa talk/paper

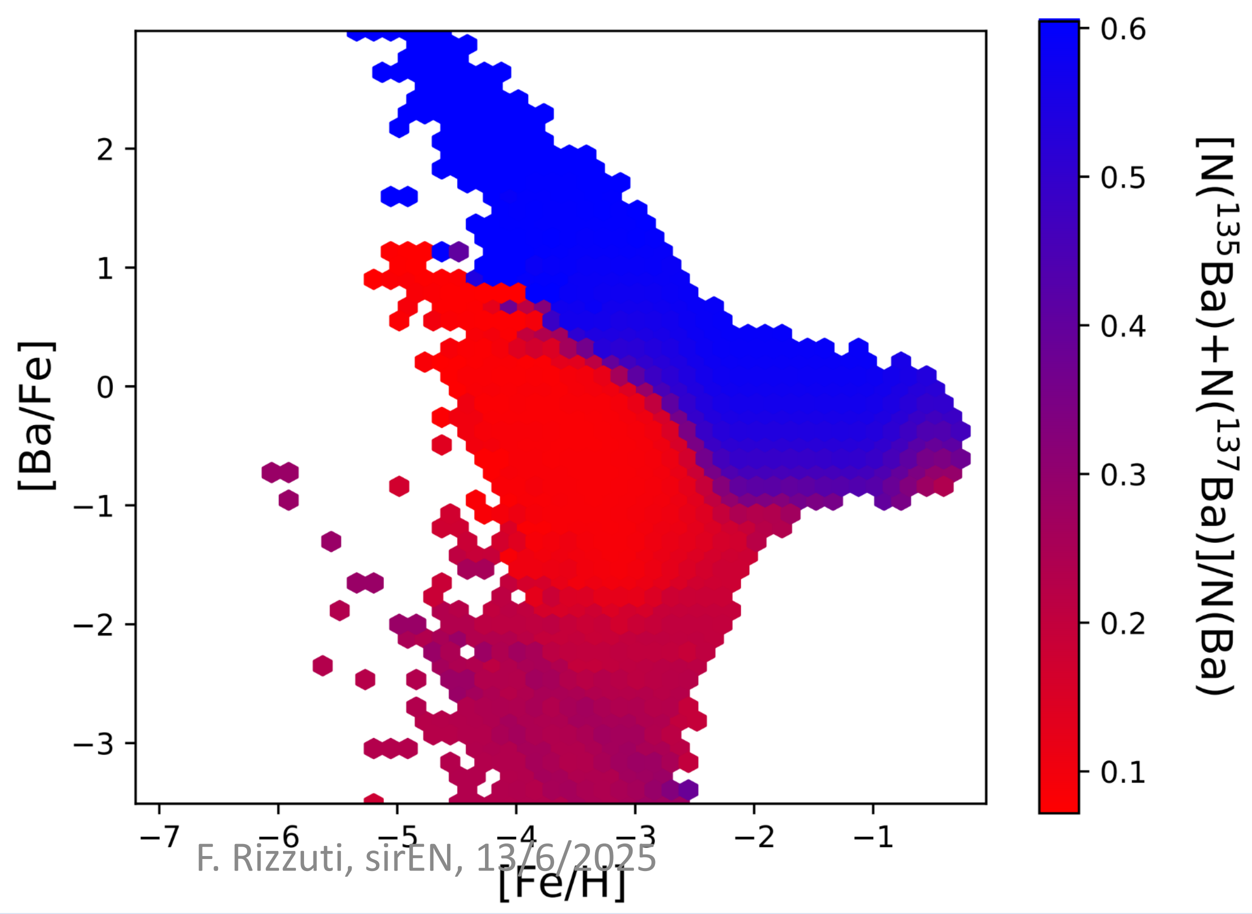
- Rizzuti+25b: we extend the model by including pop III yields from Roberti et al. (2024) (fixing the rotation at 300 km/s at low metallicity)
- Free-metal stars can't produce n-capture, but the next generation does
- EMP stars can be explained by the stochastic model as rare events

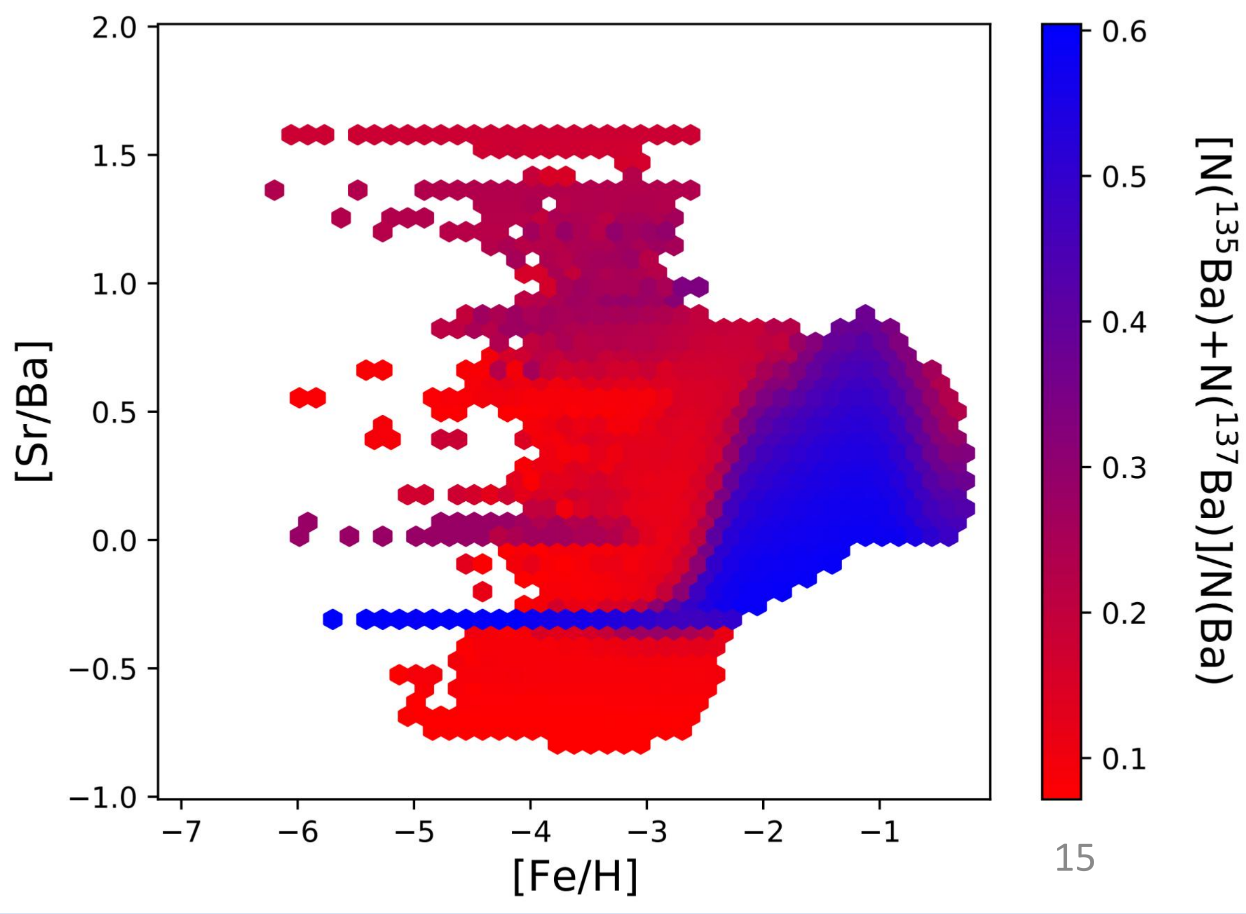


Rizzuti et al. (2025b)

Abundances in EMP halo stars

- The breakdown into even/odd Ba isotopes help us isolate the s-/r- component (as first done in Cescutti et al. 2014)





Conclusions

- GCE models are powerful tools for learning how elements are produced
- Different assumptions can be compared using GCE models: results are checked against observational stellar abundances
- Observations of s- and r-process production for Sr, Ba can be used to constrain the rotation of massive stars
- Information from metal-poor star observations helps put constraints on the early sources of s- and r-process.

→ The model-data comparison can be used to estimate free parameters, related to stellar physics: rotation distribution, dependency on metallicity, early r- vs s-…

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