Constraining neutron-capture nucleosynthesis from surface chemical composition of chemically peculiar cool stars

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Chemically Peculiar Stars

- Chemically peculiar stars are common among hot MS (hydrogen-burning) stars : Am Cp1, Ap Cp2, HgMn Cp3, He-weak Cp4

- Chemically peculiar cool stars - spectral type G or later -- two categories -

➔ Many of the cooler chemically peculiar stars are the result of the mixing of the nuclear fusion products from the interior of the star to its surface: Carbon stars, S-type stars

➔ Others are results of mass transfer in a binary star system: Ba stars, CN, CH, metal-poor counter parts of CH stars, i.e., the carbon-enhanced metal-poor (CEMP)-s and CEMP-r/s stars

Metal-poor stars

- Long-lived low-mass Pop II stars
- Formed from the ejecta of massive Pop III stars
- Fossil records of the early universe
- A fraction of them exhibit enhanced carbon (CEMP stars)

  - carbon abundance increases with decreasing metallicity

CEMP-s and CEMP-r/s stars are powerful tracers of -

a) slow (s) and intermediate (i) n-capture nucleosynthesis

b) evolution of binary systems - binary interactions at very low-metallicity

c) mechanisms of mass transfer

e) production sites & production mechanisms of i-process nucleosythesis

d) epoch of the earliest s-process nucleosynthesis that influenced the chemical enrichment

Current Issues

- Large uncertainties remain in estimates of the contribution of low to intermediate-mass stars to the chemical enrichment of the Galaxy.

- AGB phase of evolution of low-mass stars are short-lived, obscured by circumstellar envelope due to mass-loss

Several factors limit accurate estimates of contribution of AGB nucleosynthesis:

a) sparse data
b) analysis limited by low resolution, wavelength regions,
c) poor understanding of the key physical and chemical processes that govern evolution of these stars
d) inadequate understanding of model predictions
e) lack of high resolution abundance data for validation

Stars in binary systems with now invisible white dwarf companions (Ba, CH, CEMP-s, CEMP-r/s) provide opportunity to understand AGB nucleosynthesis –providing observational constraints for n-capture nucleosynthesis.

Ba, CH, CEMP stars as probes

– Characterizing the companion AGB stars

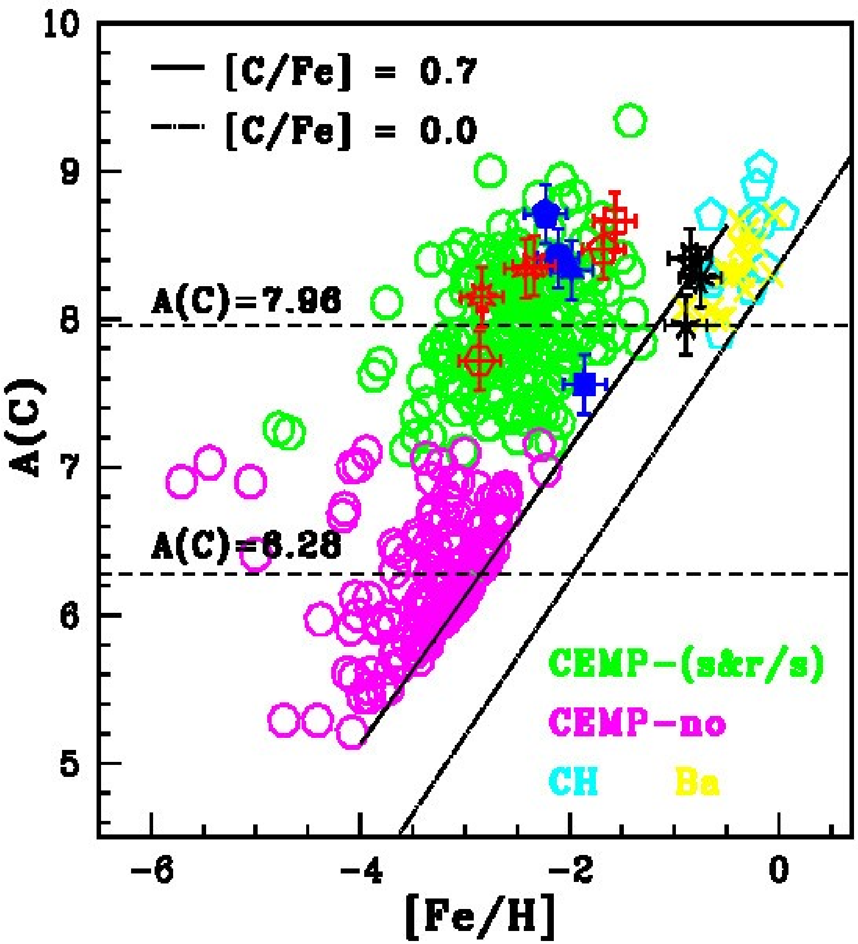
Stellar samples : potential Ba, CH, CEMP-s and CEMP-r/s stars

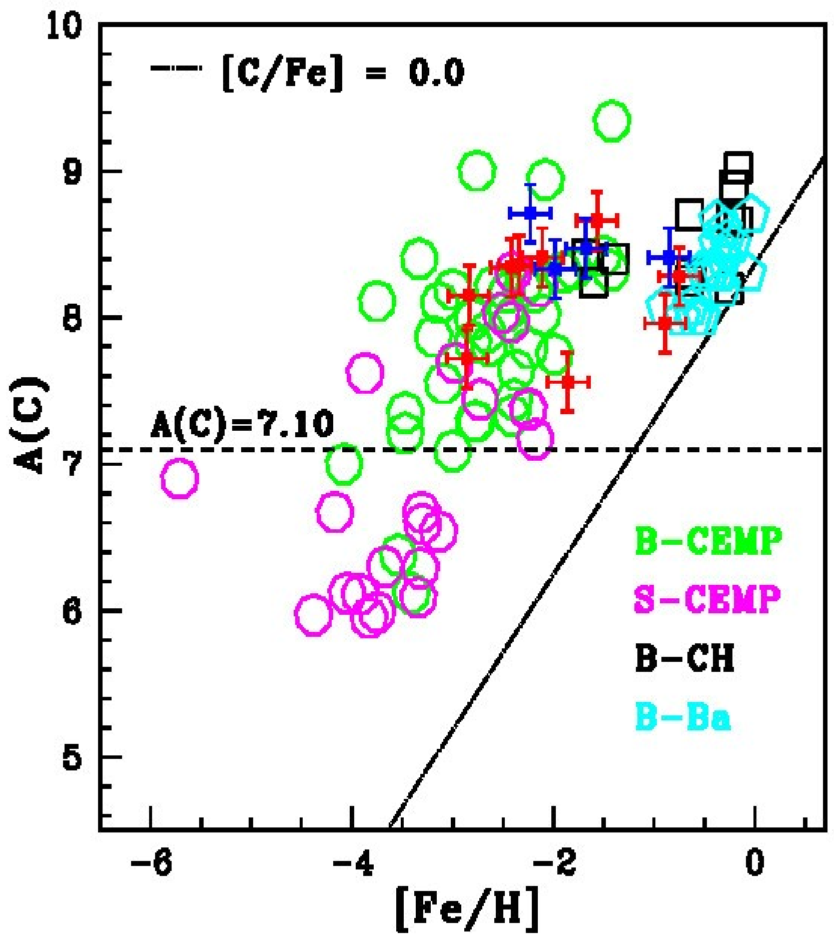
Data Acquisition/Data resource

Instrument	wavelength coverage (Å)	Resolution
HCT/HESP	3530 - 9970	30,000 & 60,000
MERCATOR/HERMES	3800 - 9000	86,000
VLT/UVES (Archive)	3290 - 6650	48,000
ESO-MPG/FEROS (Archive)	3520 - 9200	48,000
SUBARU/HDS (Archive)	4100 - 6850	50,000

Goswami et al. (2021), Goswami & Goswami (2022, 2024), Purandardas & Goswami (2019, 2022, 2025), Shejeelammal et al. (2021), Shejeelammal & Goswami (2021, 2022, 2024)

Binary status of the program stars

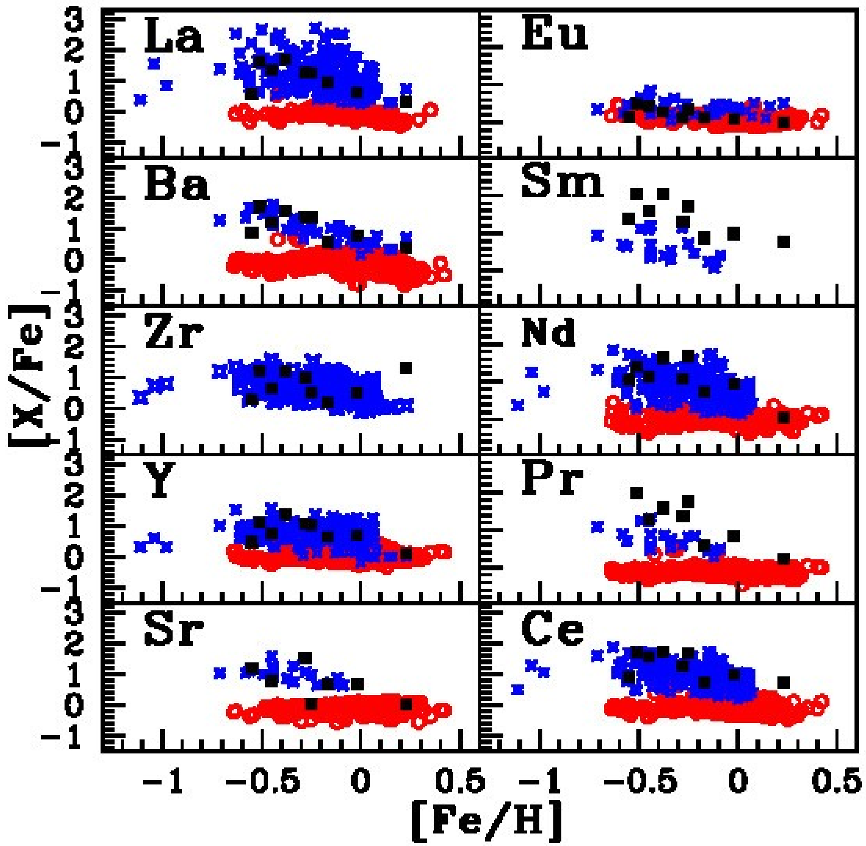




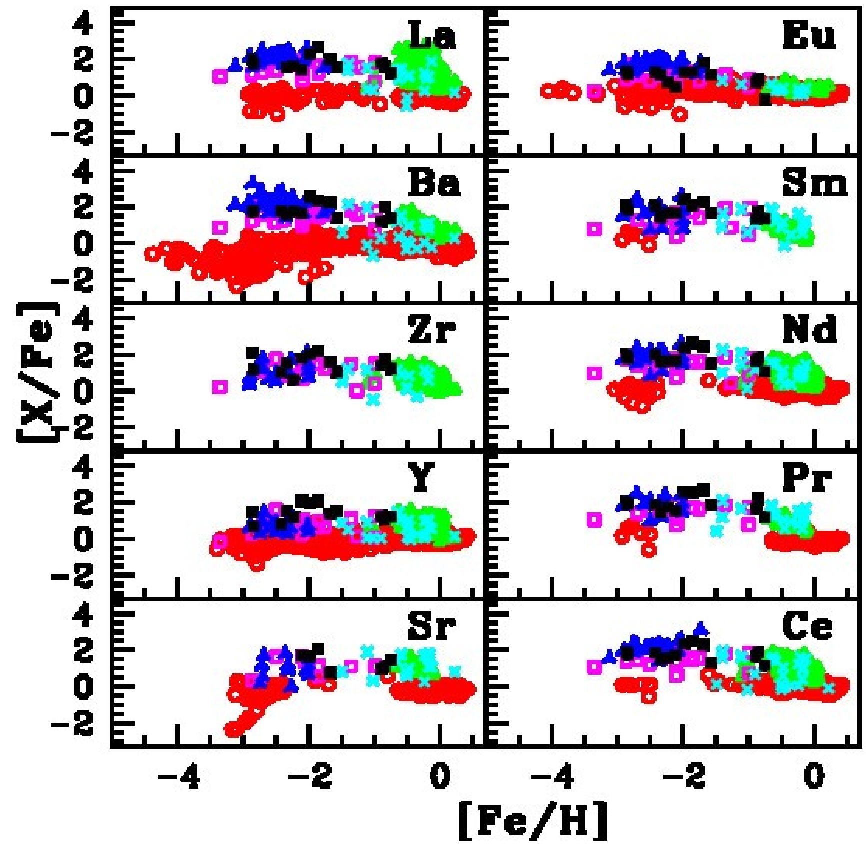
Carbon bimodality : Yoon et al. (2016)
Majority of binary stars lie above A(C) ~7.1

Program stars lie in the region occupied by the binary stars. The binary and single stars are separated by a line at A(C) = 7.1

Observed abundances



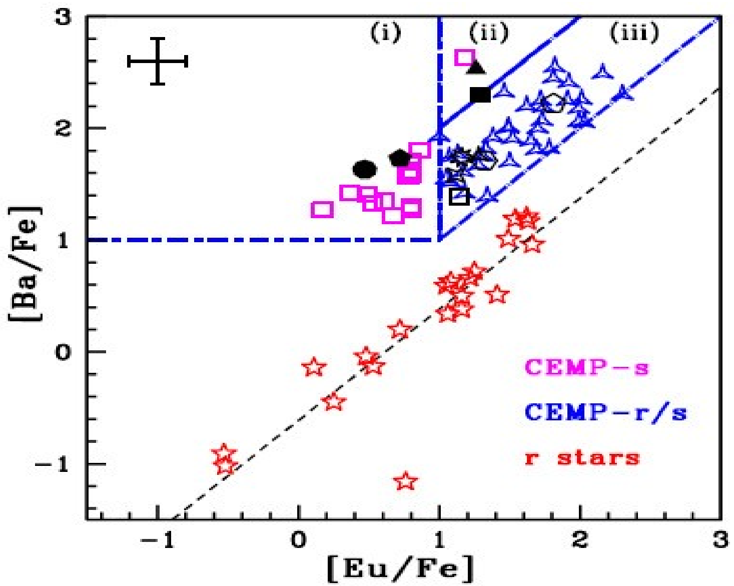
Sample Ba stars (black), literature Ba stars (blue) and normal giants (red)

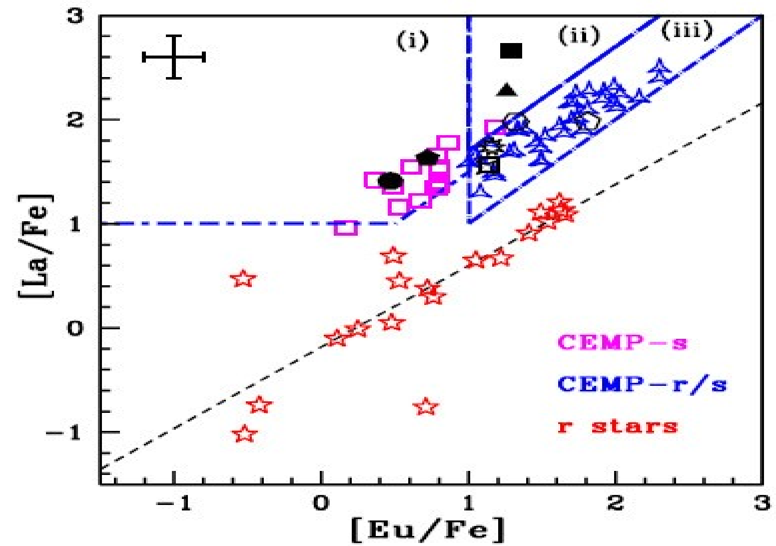


Sample CEMP stars (black), normal giants (red), Ba stars (green), CH stars (Cyan), CEMP-s (magenta), CEMP-r/s (blue)

T_eff: 4005 – 5380 K; log g: 0.61 – 2.65 (giants); [Fe/H]: -2.86 to -0.75

Classification of program stars -





CEMP-s: occupy regions (i) and (ii),

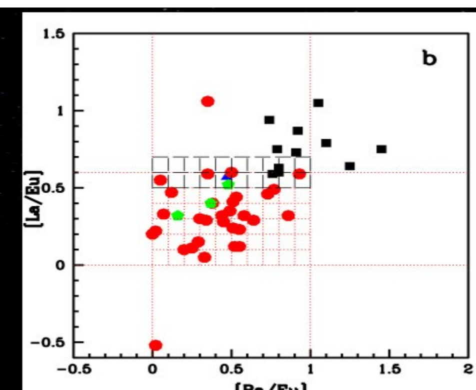
CEMP-r/s: occupy region (iii)

Program stars are indicated with different symbols in black.

CH (3), CEMP-s (4), CEMP-r/s (6)

Classification scheme (Ba, La, Eu)

- **CEMP**: [C/Fe] ≥ 0.7
- **CEMP-r/s**: [Ba/Fe] ≥ 1.0, [Eu/Fe] ≥ 1.0
  (i) 0.0 ≤ [Ba/Eu] **≤ 1.0** and/or
  0.0 ≤ [La/Eu] ≤ 0.7;
- **CEMP-s**: [Ba/Fe] ≥ 1.0
  (i) [Eu/Fe] < 1.0, [Ba/Eu] > 0.0 and/or
  [La/Eu] > 0.5;
  (ii) [Eu/Fe] ≥ 1.0, [Ba/Eu] > 1.0 and/or
  [La/Eu] > 0.7.

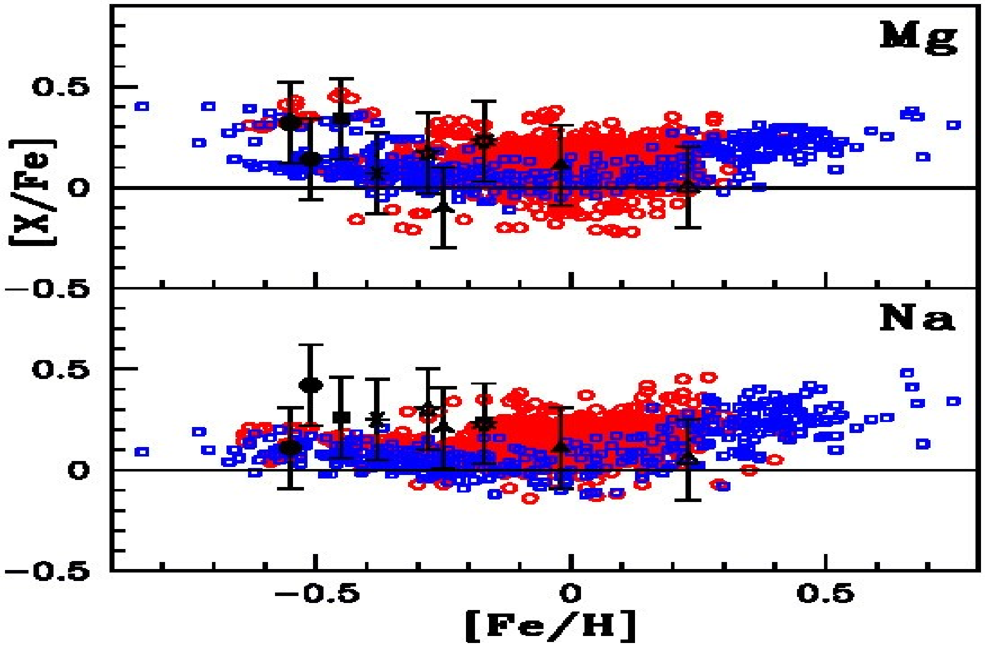


Goswami, P P et al. (2021)

Characterizing the companions -

low-mass nature of companion AGBs

Na & Magnesium (Ba stars)



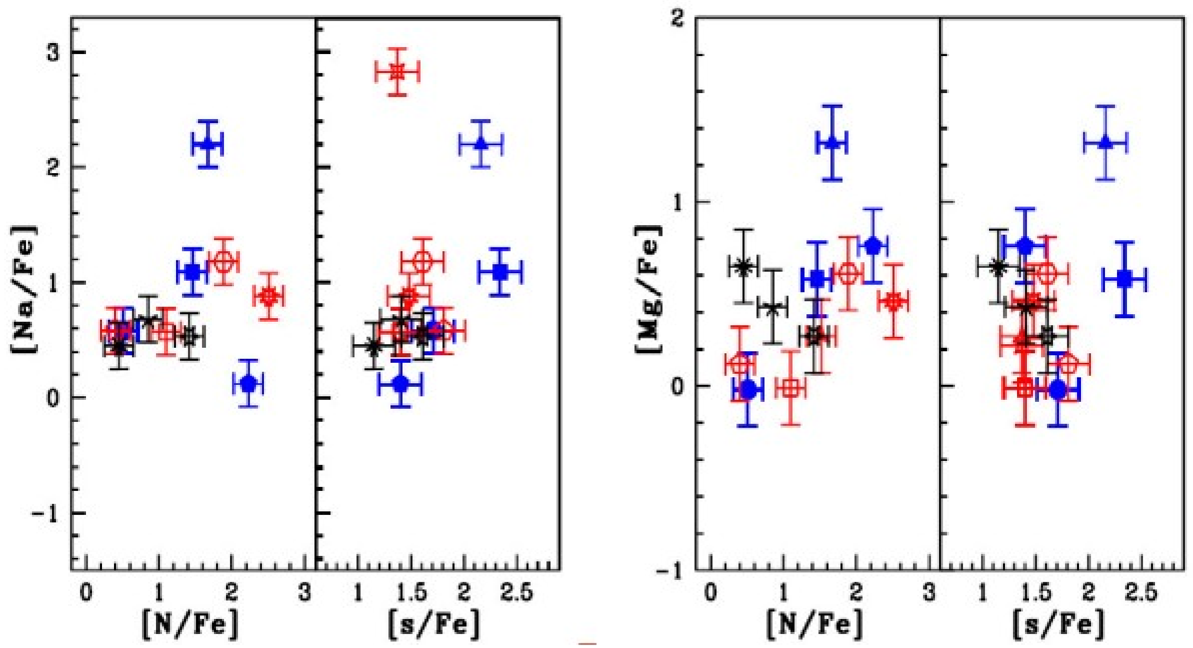
Red open circles- normal field giants
Blue squares – disk dwarfs
Black – program Ba stars

- Na and Mg enhancement is expected if the s-process pattern results from $^{22}Ne(\alpha,n)^{25}Mg$ neutron source in massive AGB stars.
  Such enhancement is not observed when compared with disk and normal giants. Discards massive AGB companion for the program stars.

- The observed Na and Mg abundances confirm low-mass for the former AGB companions of the program stars.

Low-mass nature of companion AGBs

Na & Magnesium (CH, CEMP-s, CEMP-r/s stars)



- Na – N correlation

  Ne - Na chain

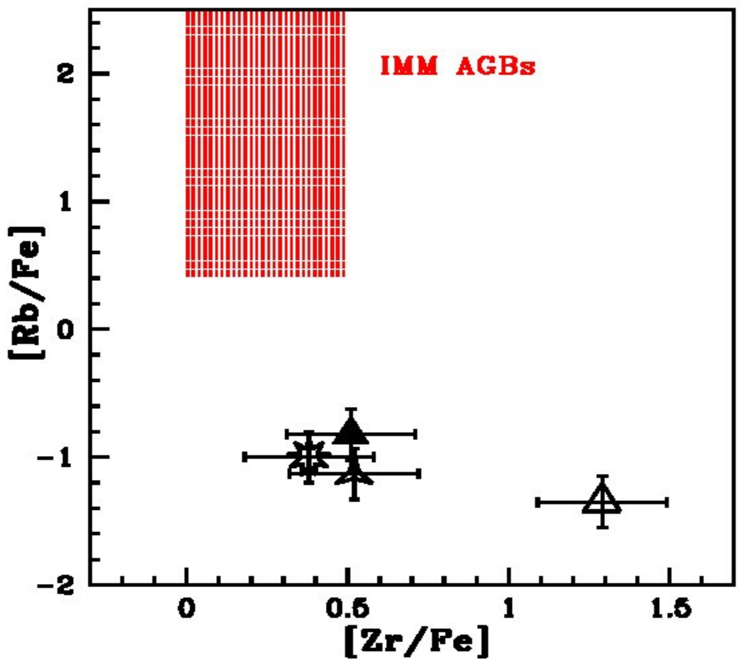
  CN – ON cycles

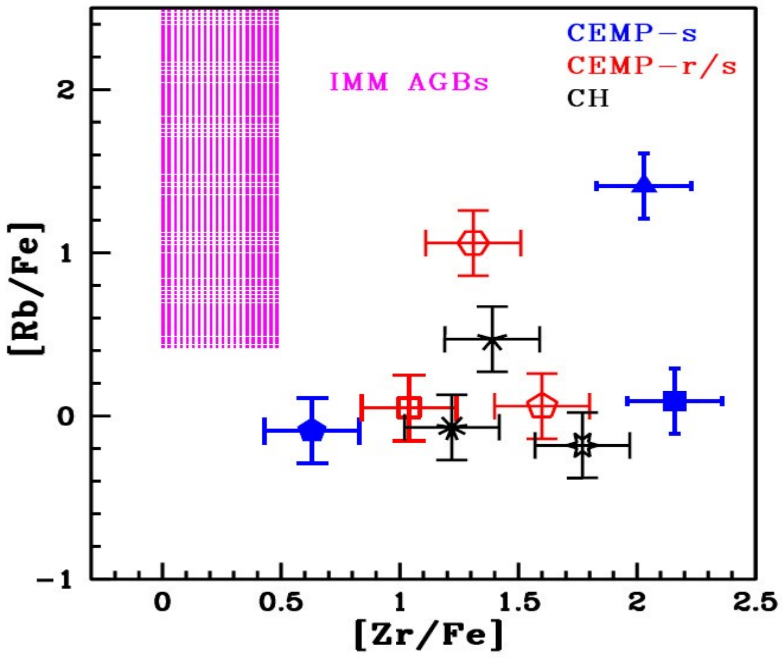
- Na – s anti-correlation

- Na enhancement through the Ne-Na cycle is expected in massive AGB stars where HBB operates. HBB also results in an increased surface abundance of N through CN cycle. N and Na should therefore be correlated. No such trend is observed.

- The diffusive mixing and H-burning in massive AGB stars can reduce the s-process efficiency, and it should be anti-correlated with the products of HBB. Such a trend is not noticed - rules out pollution from massive AGBs.
  Black – CH, Blue – CEMP-s, Red - CEMP-r/s

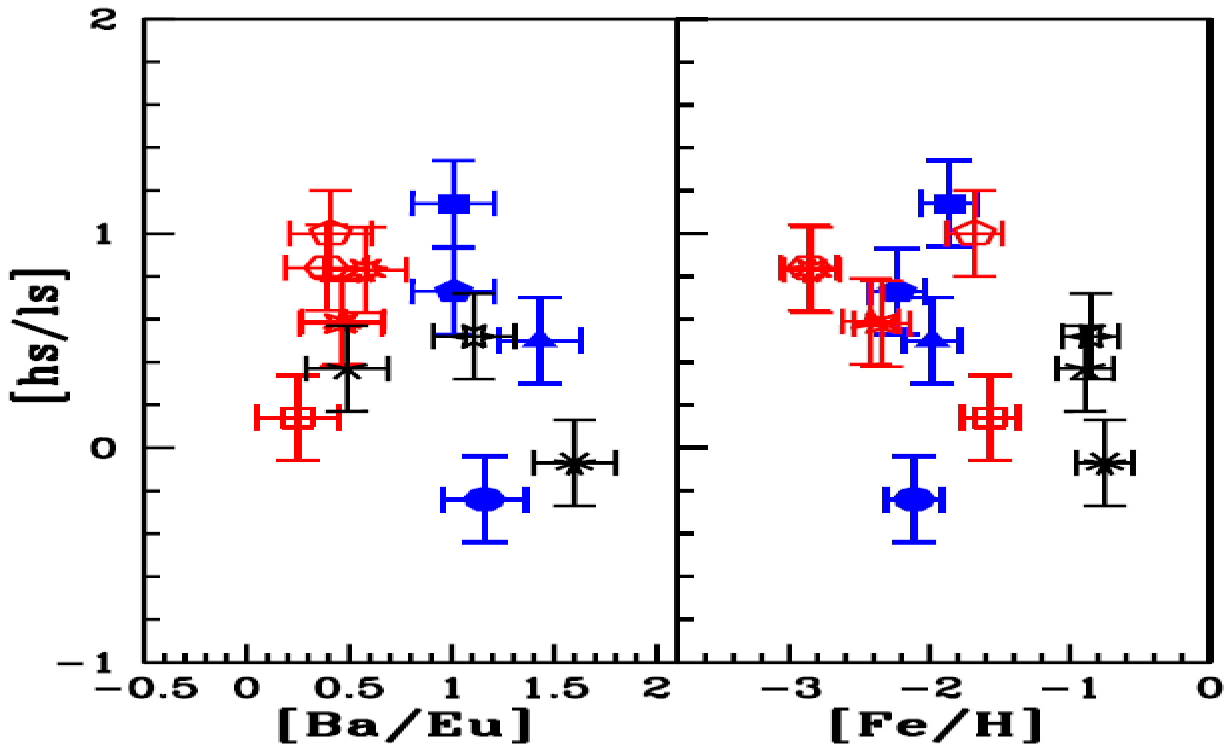
[Rb/Fe] vs [Zr/Fe] – Progenitor Mass from Neutron Densitometer





- Shaded regions - observed ranges of [Rb/Fe] and [Zr/Fe] in intermediate-mass AGB stars in the Galaxy and the Magellanic clouds (van Raai et al. 2012).
- [Rb/Zr] estimates ranges from -1.33 to -2.64 (4 Ba stars), and -0.25 to -2.07 (9 C-stars)
- [Rb/Zr] = -ve –> low-mass AGB stars (M < 3 M_sun)
- [Rb/Zr] = +ve --> Massive AGB stars (M > 4 M_sun)

[hs/ls] ratio as indicator of neutron source



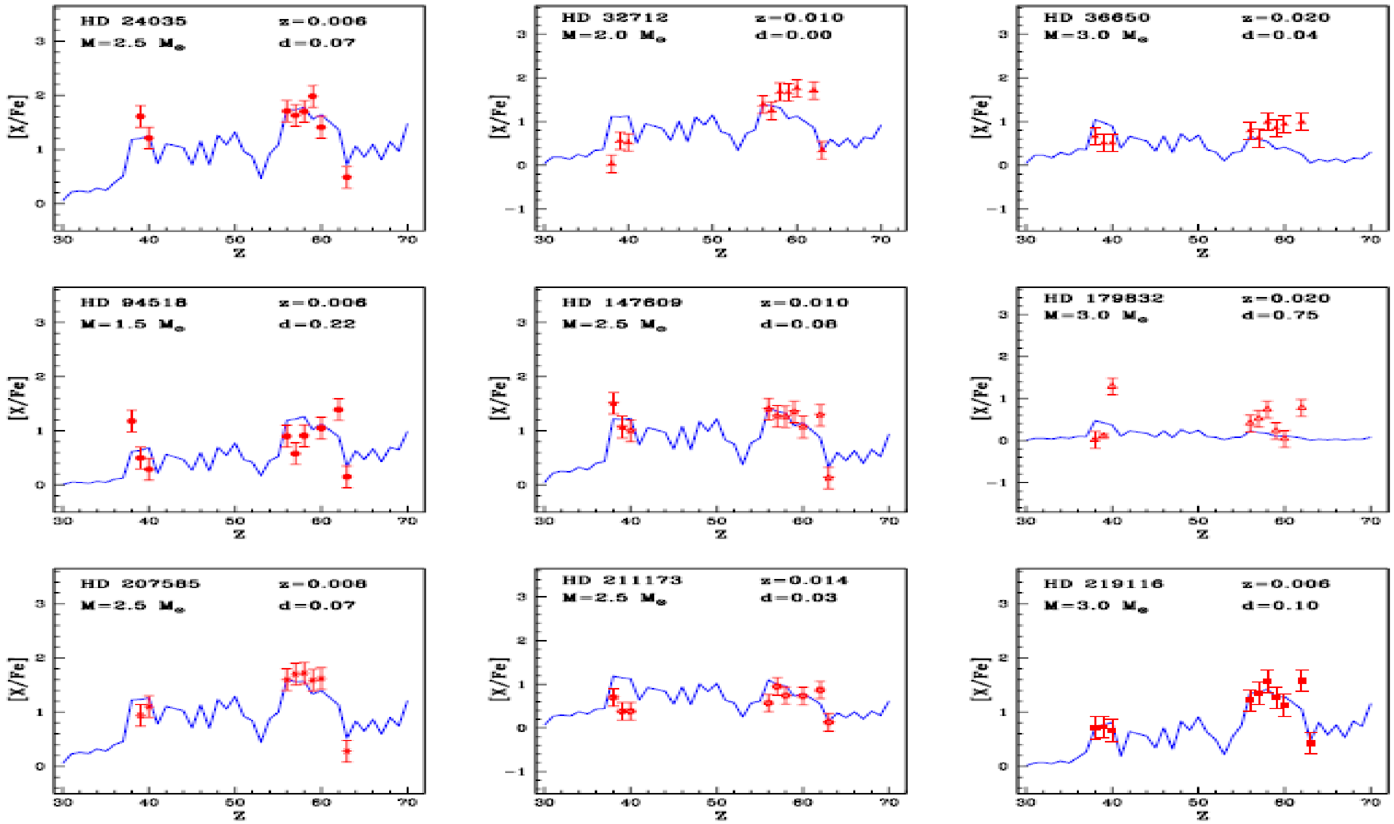
CEMP-s,

CEMP-r/s

CH stars

- Low-mass, low-metallicity stars with neutron source $^{13}C(\alpha,n)^{16}O$ show +ve values for [hs/ls]
- Massive AGB stars with neutron source $^{22}Ne(\alpha,n)^{25}Mg$ show -ve values for [hs/ls]
- HE 0920-0506 & HE 1354-2257 show -ve [hs/ls]; but N, Na, Mg are not enhanced indicating low-mass for the companion AGBs.

Parametric model-based analysis of Ba stars



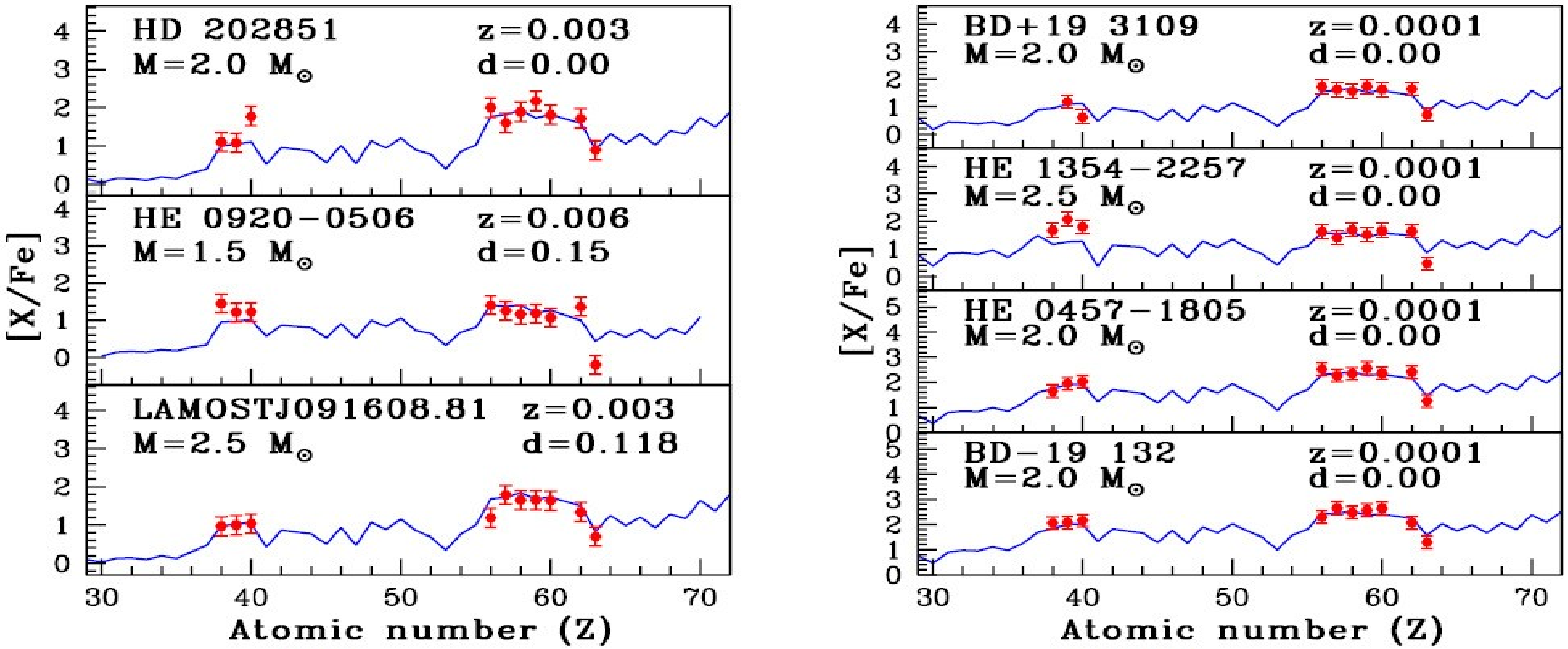
Solid curves – Best fits for the parametric model function obtained from the comparison of the observed abundances in the Ba stars and predicted abundances from the FRUITY models by minimizing the chi square.

Points with error bars – observed abundances

Shejeelammal & Goswami (2022)

Parametric model based analysis for CH & CEMP-s stars

- Same procedure as in the case of Ba stars

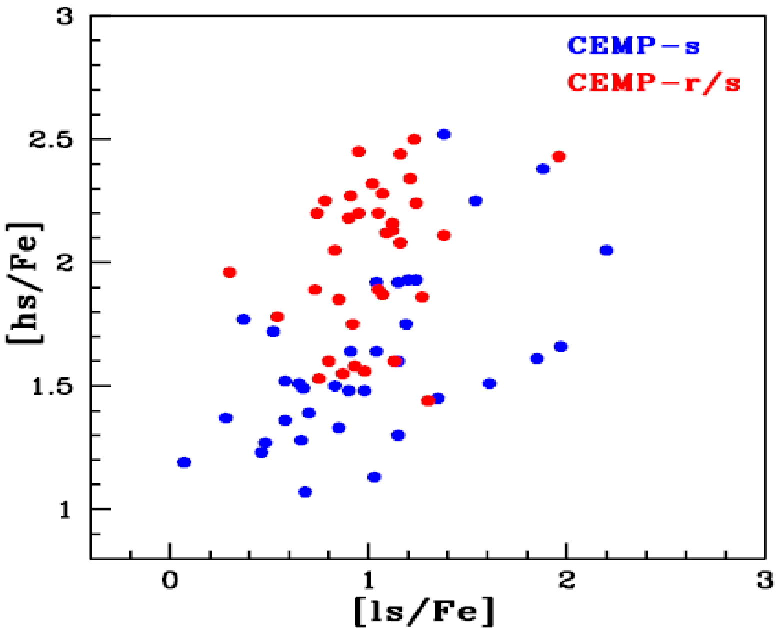


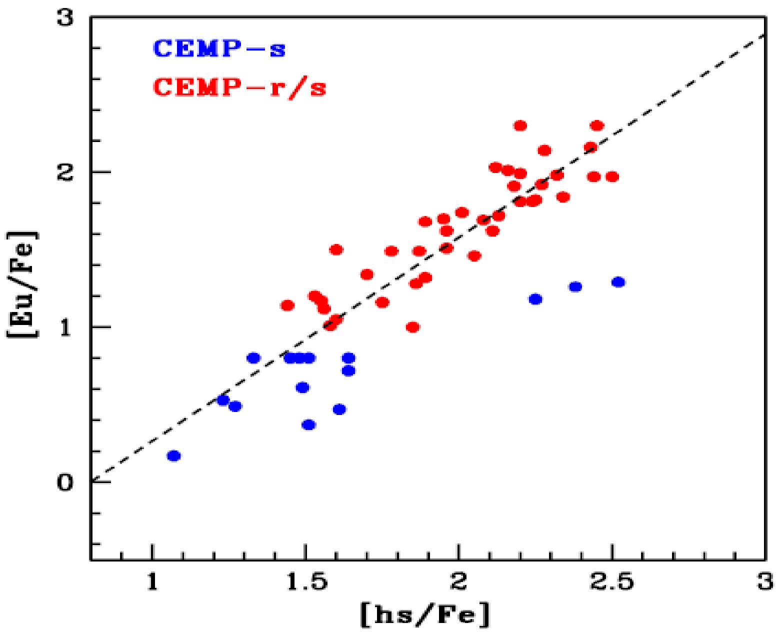
CH CEMP-s

$M_{AGB} < 3\ M_\odot$

Shejeelammal & Goswami (2022)

Clues to the origin of CEMP-r/s stars

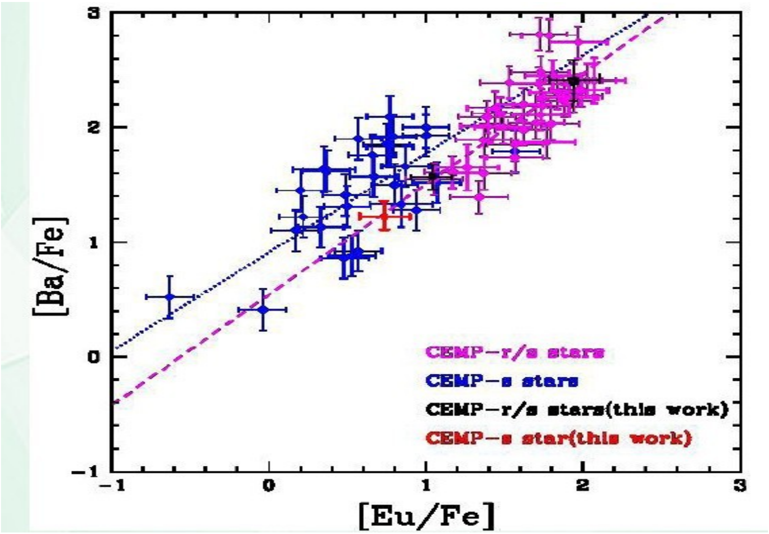




- Similar [ls/Fe] for both the classes

- Higher [hs/Fe] for CEMP-r/s stars

➔ Higher neutron exposure than classical s-process.



- Tight correlation between [Ba/Fe] & [Eu/Fe]

➔ Both s- and r-process elements produced at single stellar site

- Tight correlation between [Eu/Fe] & [hs/Fe]

➔ Higher neutron density than classical s-process

Production of heavy elements in CEMP-r/s stars

Heavy elements observed in the CEMP-r/s stars could not be reproduced by s-process or r-process nucleosynthesis alone.

s-process

- $\tau_n >> \tau_\beta$
- $N_n \sim 10^{7-10}/cm^3$
- site → LM & IMM AGB stars

i-process

- $\tau_n < \tau_\beta$
- $N_n \sim 10^{12-15}/cm^3$
- site → several proposed sites

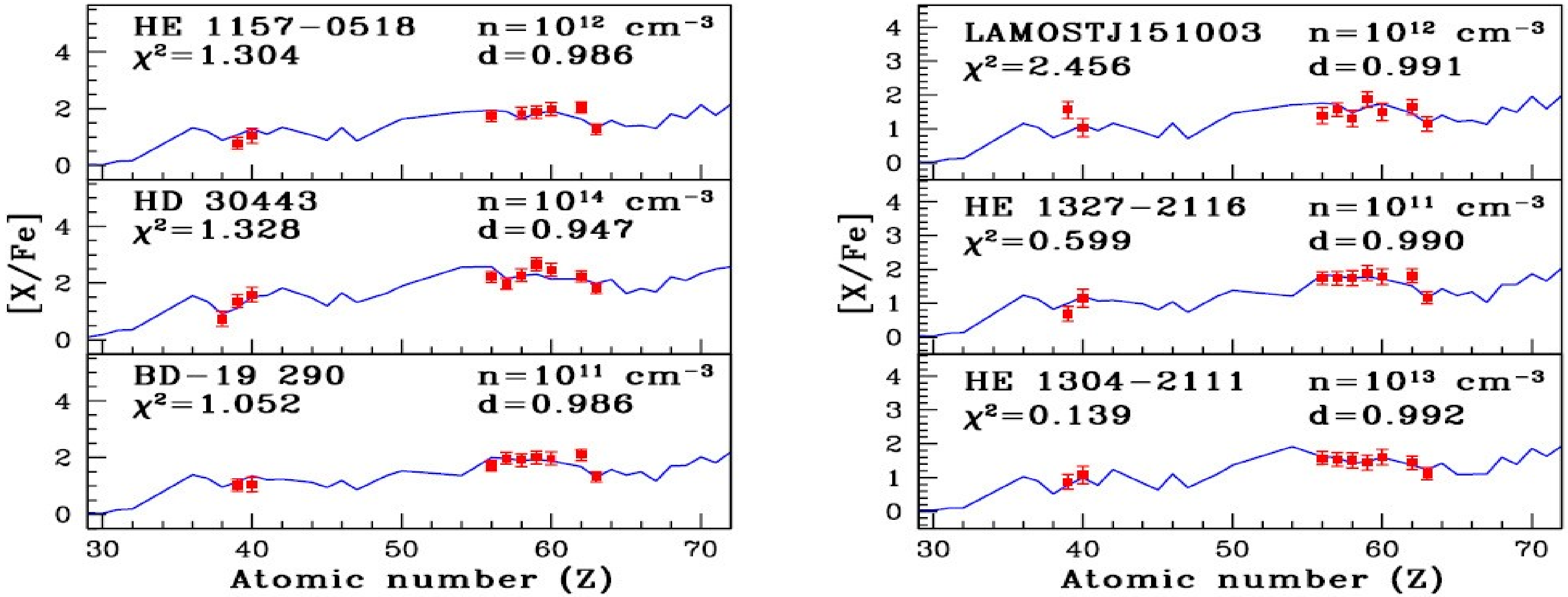
r-process

- $\tau_n << \tau_\beta$
- $N_n \sim 10^{20-25}/cm^3$
- site → CCSNe, NSM

Modified neutron-capture process called intermediate neutron-capture process (i-process) (Dardelet et al. 2014, Hampel et al 2016, 2019, Hansen et al. 2016c)

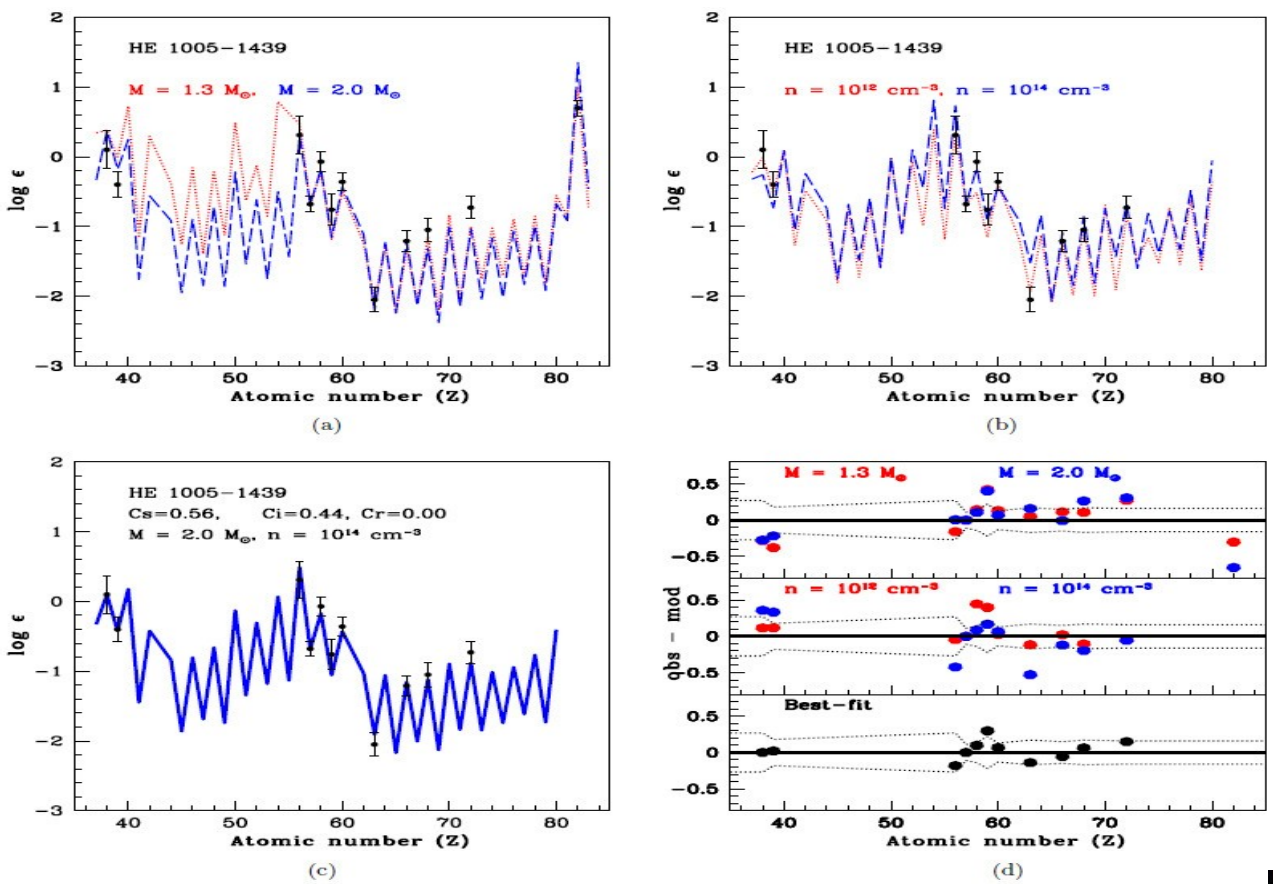
- Originally proposed by Cowan & Rose (1977)

The i-process in low-mass low-metallicity AGB stars: parametric model based analysis



low-metallicity, low-mass AGB stars are the progenitors

HE 1005-1439: Evidence of dual nucleosynthesis – i-process followed by s-process



a) s-process: Cristallo et al. (2009, 2011, 2015)
b) i-proocess: Hampel et al. (2016)
c) Parametric model best fit
d) Residual plot

[Fe/H] = – 3.03,

Estimated abundance of 12 heavy elements : Sr, Y, Ba, La, Ce, Pr, Nd, Eu, Dy, Er, Hf, Pb

Classification – CEMP-s sub-class

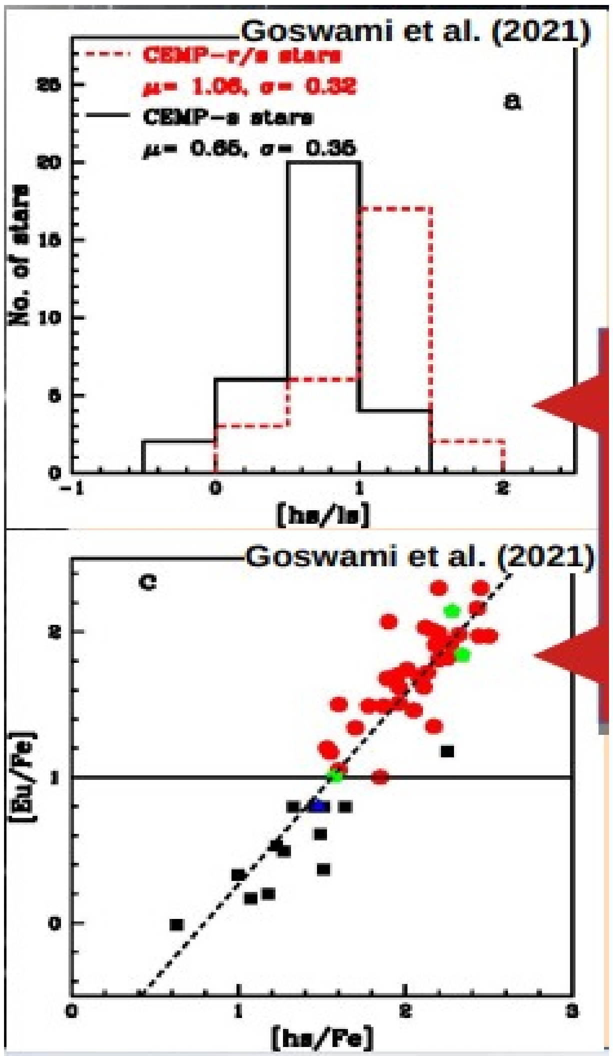
[hs/ls] = 0.92 , close to the CEMP-r/s peak

$$\log(\epsilon_j) = C_s N_{sj} + C_i N_{ij} + C_r N_{rj}$$

Goswami & Goswami (2022)

HE 1005-1439 – proposed formation scenario

A formation scenario involving a binary picture is proposed.



- A model involving PIEs during the beginning of the AGB phase followed by a limited number of TPs is likely to explain the abundance pattern.

- It would be interesting to see if such a scenario could help in explaining -

➔ the overlap of [hs/ls] ratios in CEMP-s and CEMP-r/s stars and also the smooth transition of elemental abundances from CEMP-s to CEMP-r/s regime.

➔ the interplay between PIEs and partial mixing of protons in the intershell region of AGB stars.

Summary

- Classification scheme of Goswami et al. (2021) involving Ba, La, Eu clearly distinguishes CEMP-s and CEMP-r/s stars.

- Abundance ratio of key elements such as [Na/Fe], [Mg/Fe], [Rb/Zr], [hs/ls] etc. provide robust diagnostics for the characteristic properties of the companion AGB stars, mass, neutron densities and nucleosynthesis sites.

- Abundance analyses, and parametric model based analyses of Ba, CH, CEMP-s and CEMP-r/s stars, confirm low-mass for their former companion AGB stars.

- i-process models could successfully reproduce the observed abundance in CEMP-r/s stars.

- Abundances of HE 1005-1439 provided observational evidence of the occurrence of dual nucleosynthesis in the companion AGB star.

Future perspective

- To understand the full potential of CEMP stars for Galactic Archaeology the knowledge of the fraction of CEMP stars relative to carbon normal stars is important for our interpretation of populations of metal-poor stars.

Open questions -

- What exactly is the fraction of CEMP stars as a function of metallicity?
- How it changes with the different classes of CEMP stars and different stellar evolutionary phases?
- How it may be different in different Galactic environments, such as -
  - Different regions of the halo
  - Dwarf galaxies
  - Globular clusters
  - Stellar streams
  - The Galactic bulge

The next-generation observatories with future large telescopes are expected to offer unprecedented precision in spectroscopy, astrometry, and imaging, enabling detailed studies of stellar populations, chemical abundances, and dynamics. This will greatly advance our understanding of Galactic archaeology.

Thank you