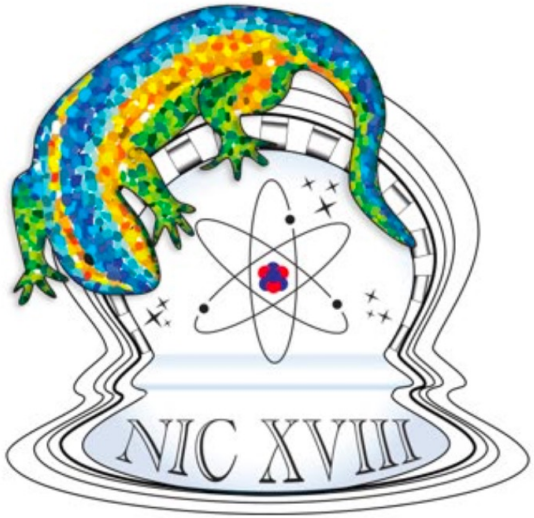
The Heavies in CEMP stars



Sophie Van Eck
Muhammed Riyas Thibault Merle Drisya Karinkuzhi Riano Giribaldi
Stéphane Goriely Arthur Choplin Lionel Siess Alain Jorissen

BLU ULB
BRUSSELS LABORATORY OF THE UNIVERSE

Girona, June 16-20, 2025

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CEMP classification (Carbon-Enriched Metal-Poor)

Classification based on carbon…

Different definitions:

- [C/Fe]>1 (Beers & Christlieb 2005)
- [C/Fe]>0.7 if log L/Lsun<2.3
  [C/Fe]=3-log(L/Lsun)
  if log L>2.3 (Aoki+2007)

N.B. Varying limits for external system.
e.g. Sgr, Dra, Umi, Scl (Sestito+ 2024)

… and on heavy elements : Ba, (La), Eu

Table 1
CEMP Subclass Definitions

Subclasses	Definition
CEMP	[C/Fe] > +0.7
CEMP-*r*	[C/Fe] > +0.7, [Eu/Fe] > +0.7, [Ba/Eu] < 0.0
CEMP-*s*	[C/Fe] > +0.7, [Ba/Fe] > +1.0, [Ba/Eu] > +0.5
CEMP-*i* (*r*/*s*)	[C/Fe] > +0.7, 0.0 < [Ba/Eu] < +0.5 or [C/Fe] > +0.7, 0.0 ⩽ [La/Eu] ⩽ +0.6
CEMP-no	[C/Fe] > +0.7, [Ba/Fe] < 0.0

Zepeda+ 2023

r-I:	0.3 < [Eu/Fe] <= 0.7 and [Ba/Eu]<0
r-II:	[Eu/Fe] > 0.7 and [Ba/Eu]<0
r-III :	[Eu/Fe] >2

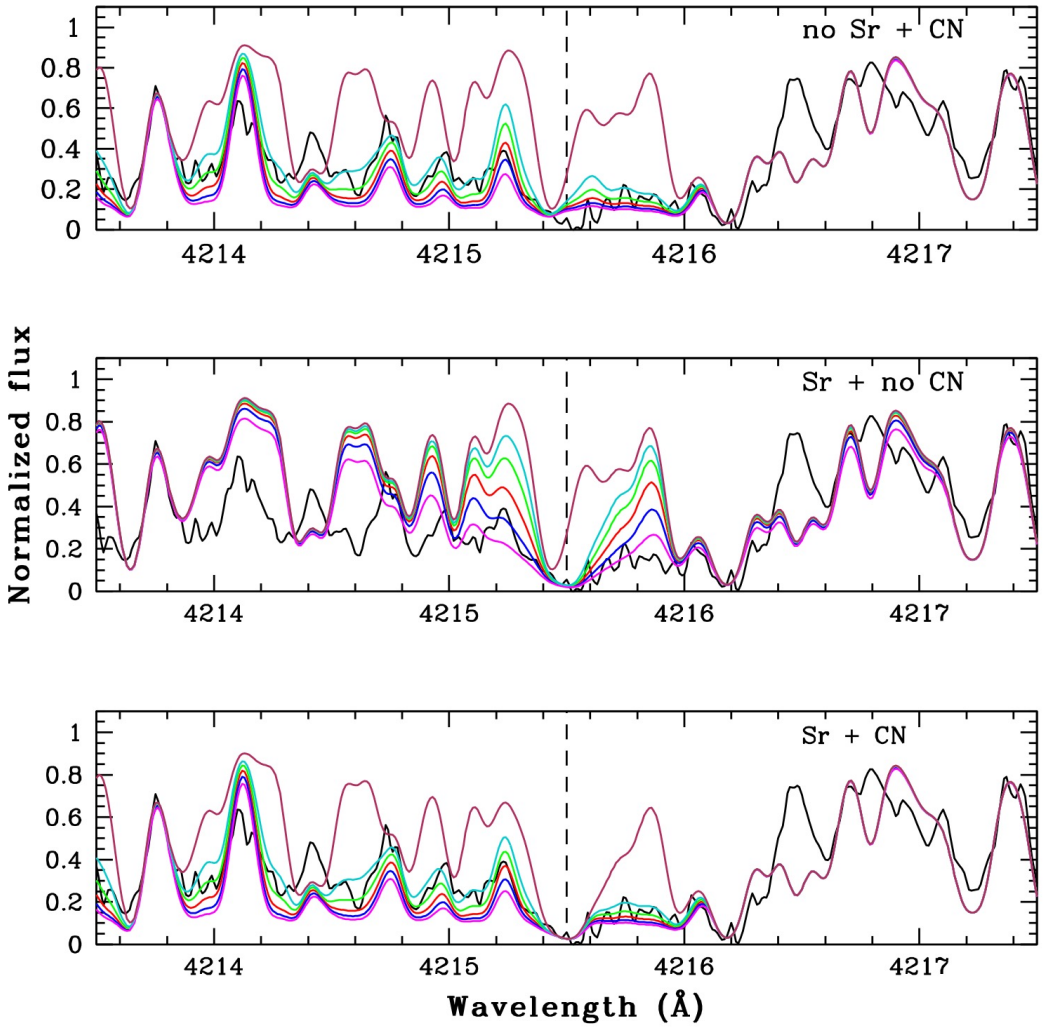
Christlieb et al. 2004; Beers & Christlieb 2005; Holmbeck et al. 2020

Abundance measurements

Beware of blended and saturated lines:

- 454 000+ Lamost stars analysed with **machine learning** (Norfolk+ 2019)
- High-resolution re-analysis of 15 stars in Karinkuzhi+ 2021

→1/3 not enriched in Sr



CEMP stars: binarity & scenarii

CEMP-r

- Binary frequency 18±6% (Hansen+ 2015), similar to the one of normal metal-poor field giants (16±4%, Carney+ 2003)

CEMP stars: binarity & scenarii

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CEMP-no

- Binary frequency 32 ± 10%

Arentsen+ 2019

See also Starkenburg 2014; Hansen 2016b

CEMP stars: binarity & scenarii

CEMP-r

- Binary frequency 18±6% (Hansen+ 2015), similar to the one of normal metal-poor field giants (16±4%, Carney+ 2003)

CEMP-no

- Binary frequency 32 ± 10%

Arentsen+ 2019

See also Starkenburg 2014; Hansen 2016b

CEMP-s

- Compatible with 100% binaries

Lucatello+ 2005, Starkenburg+ 2014,

Hansen+ 2016, Jorissen, Van Eck+ 2016, Arentsen+ 2019

CEMP stars: binarity & scenarii

CEMP-r

- Binary frequency 18±6% (Hansen+ 2015), similar to the one of normal metal-poor field giants (16±4%, Carney+ 2003)

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See also Starkenburg 2014; Hansen 2016b

CEMP-s

- Compatible with 100% binaries

Lucatello+ 2005, Starkenburg+ 2014,

Hansen+ 2016, Jorissen, Van Eck+ 2016, Arentsen+ 2019

CEMP-rs

- More binaries than among CEMP-s

Hansen T.T. + 2016

Karinkuzhi, Van Eck+ 2021

CEMP stars: binarity & scenarii

CEMP-r

→fossile record from a C- and r-enriched ISM
Or
Stars polluted by nearby C and r-process source

CEMP-no

→fossile record from a C-enriched ISM
Or
Stars polluted by nearby C source

CEMP-s

→Polluted by an AGB companion

CEMP-rs

→Polluted by an AGB companion
(+ by a possible other source ?)

Scenarios for CEMP-rs

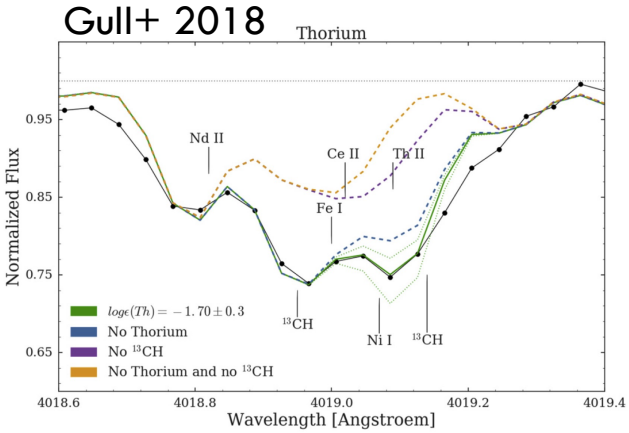
- **<u>Double event (r+s):</u>**

  ISM (r)

  or

  Kilonova (r)

Kilonova AGB



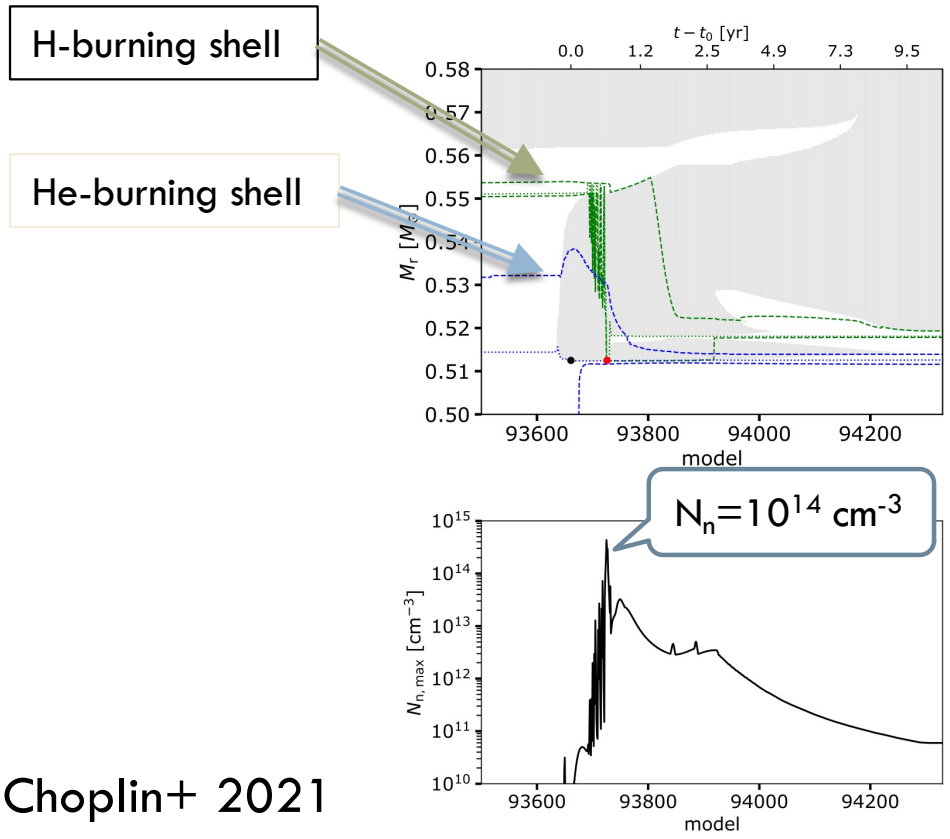
  - Gull+ 2018: detection of Thorium → r+s; see however Choplin+ 2022
  - Koch 2019: 1 bulge CEMP star better fitted by 2i or s+i

- **<u>i-process in a single astrophysical site:</u>**
  - Proton injection event (Hampel+ 2019; Karinkuzhi+ 2021; Choplin+ 2021)

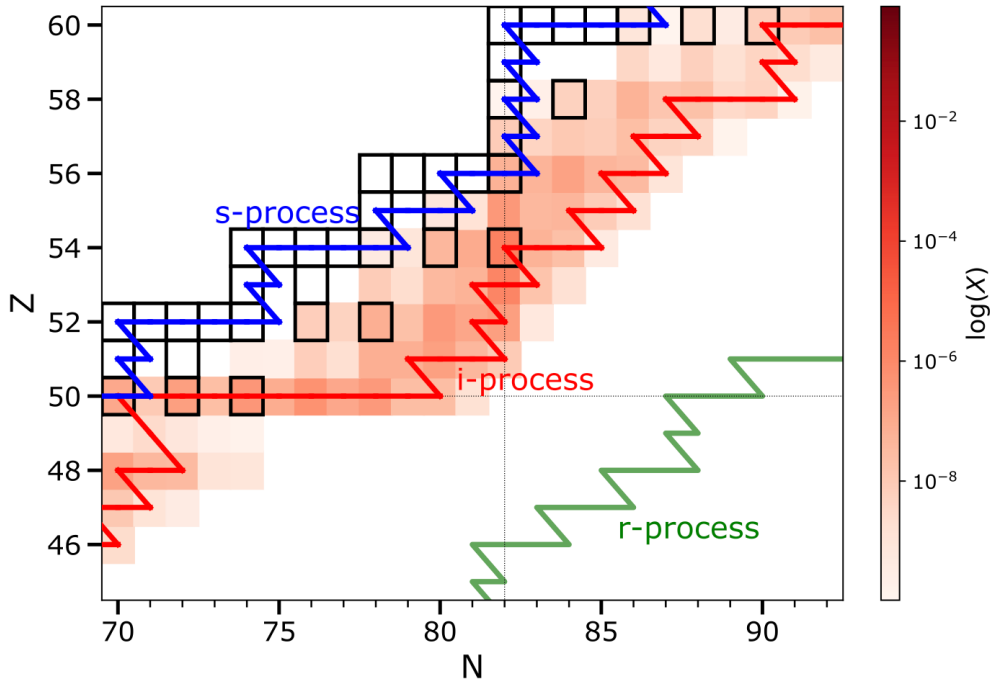
    Favoured in Mashonkina+ 2023, Karinkuzhi+ 2023
  - He shell flash of rapidly accreting WD (Denissenkov+ 2016)

Intermediate (i-) process: theory

Proton injection event in a low-Z AGB model

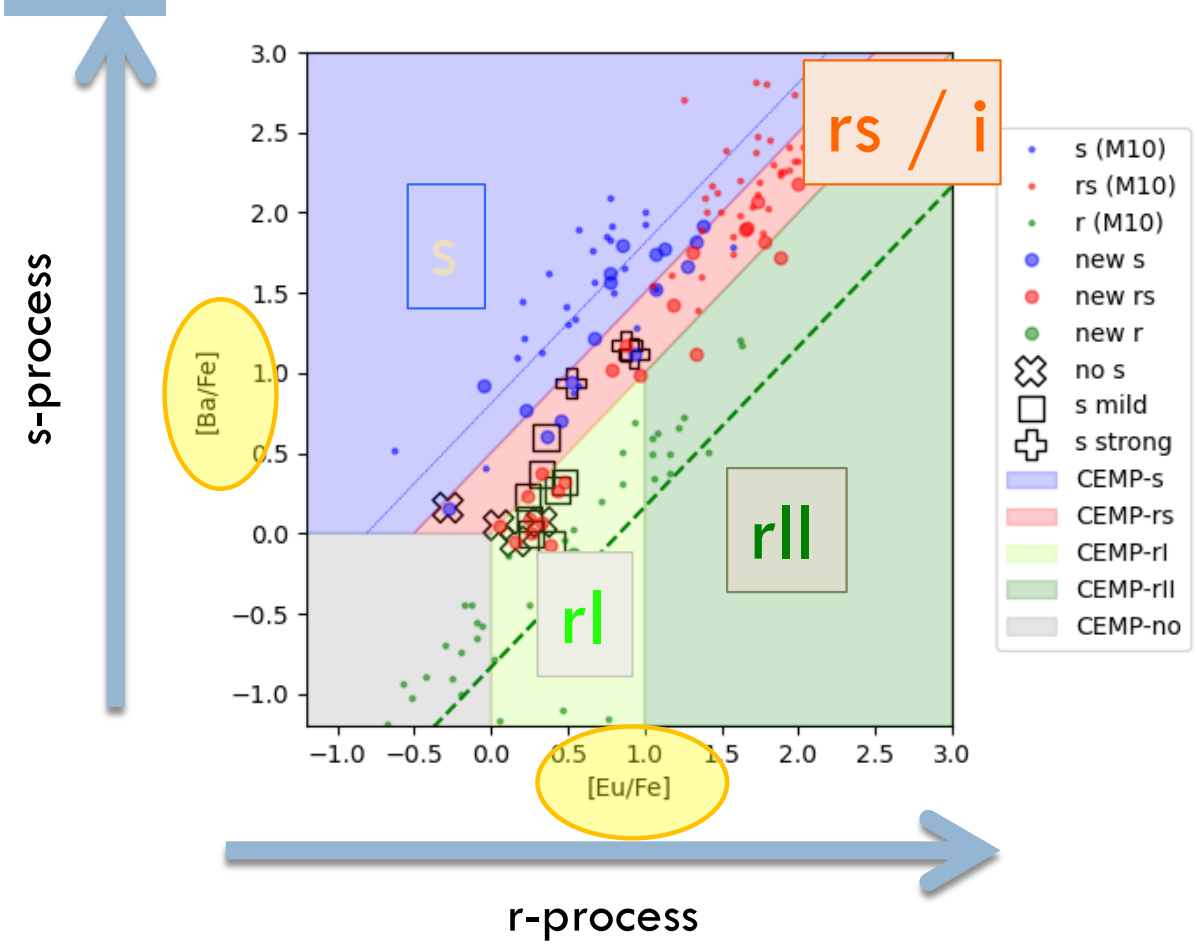


Choplin+ 2021



Choplin+ 2023

CEMP-rs classification attempts: [s/r]

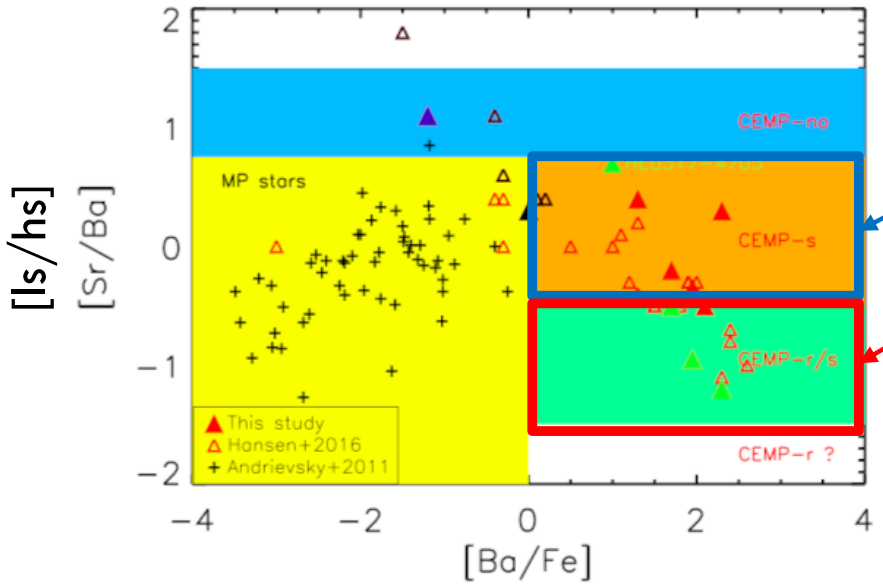


→ [s/r]

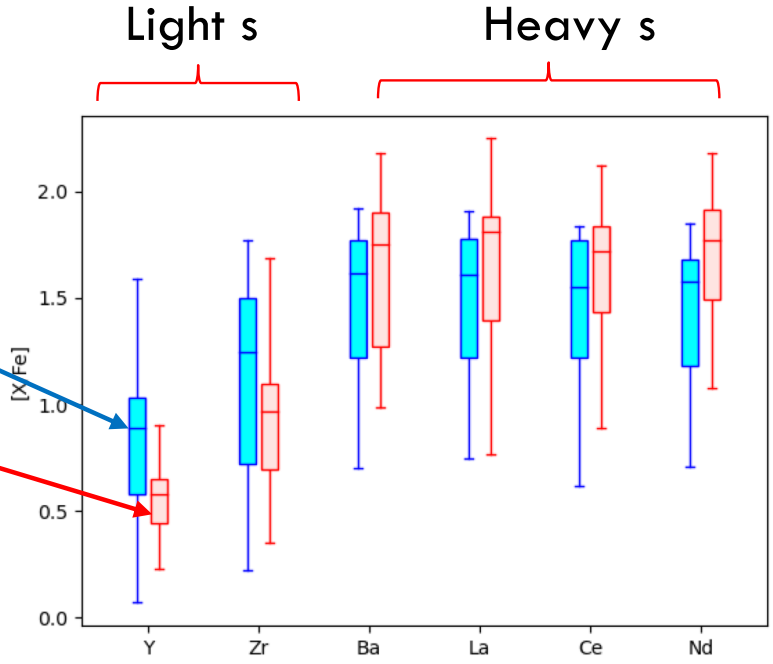
CEMP-rs classification attempts: [light s/heavy s]

Hansen+ 2019

Karrinkuzhi+ 2021



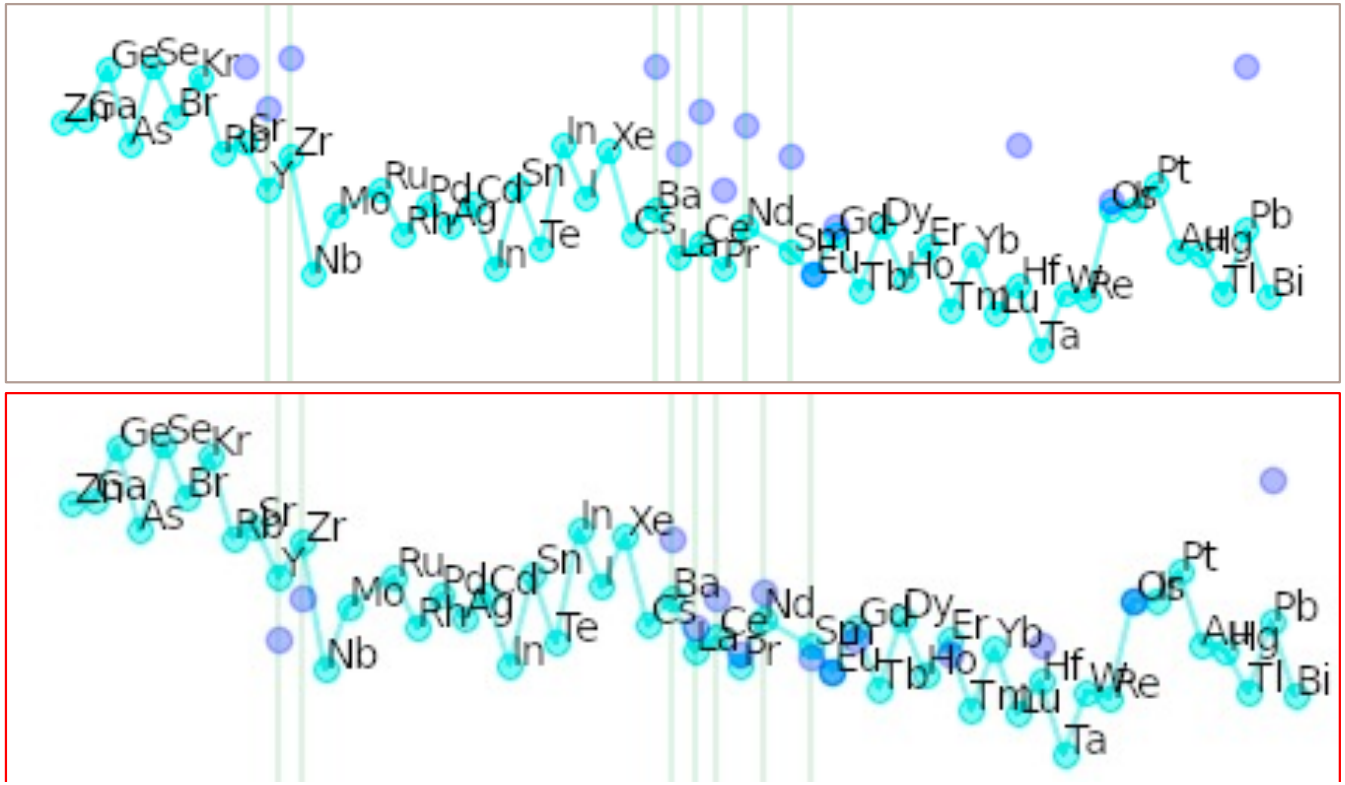
[ls/hs] larger in CEMP-s than in CEMP-rs



CEMP-rs classification attempts: **Distance to r-process**

Signed distance to the r-process
Karinkuzhi+ 2023

$$d_S = \frac{1}{N} \sum_{x_i} (\log_{10} \epsilon_{x_i,*} - \log_{10} \epsilon_{x_i,\mathrm{norm(r,*)}})$$



CEMP-s

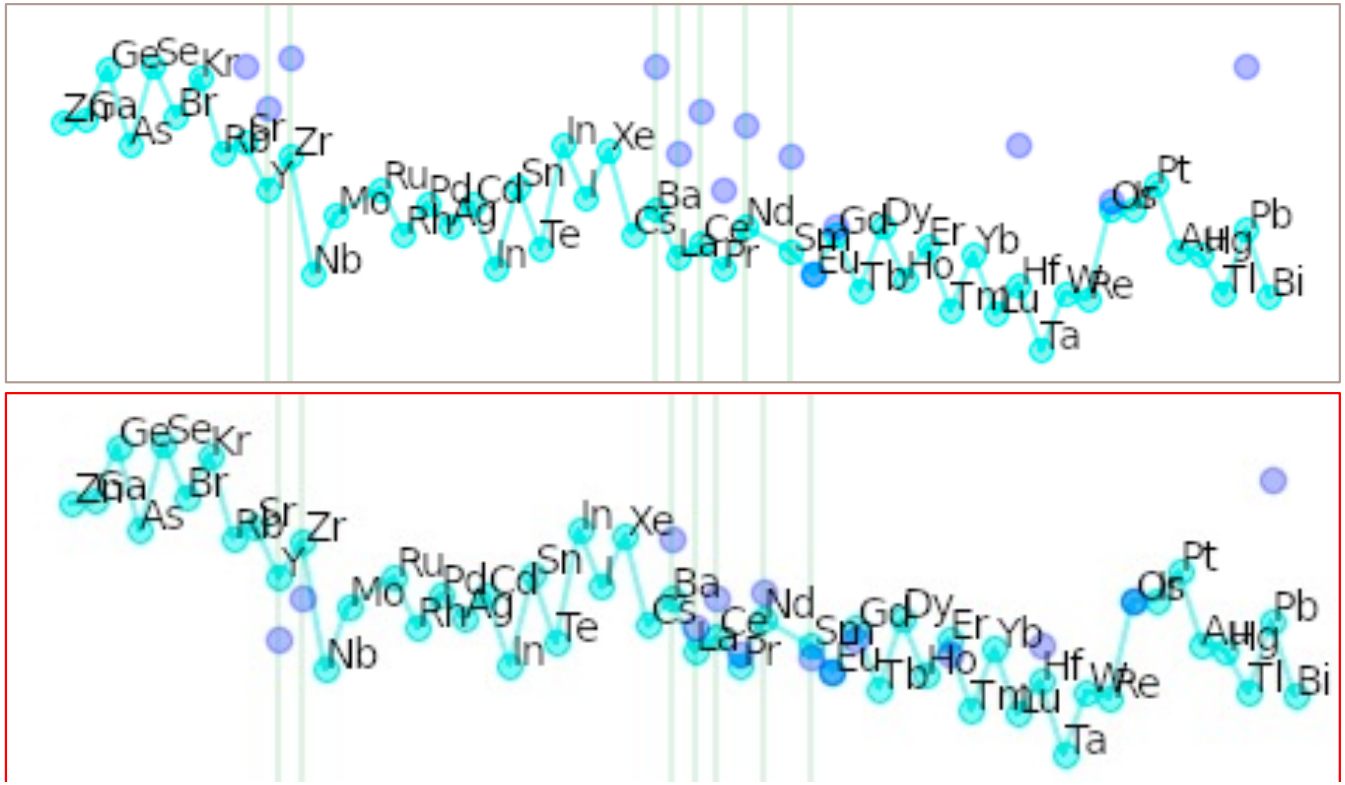
CEMP-r

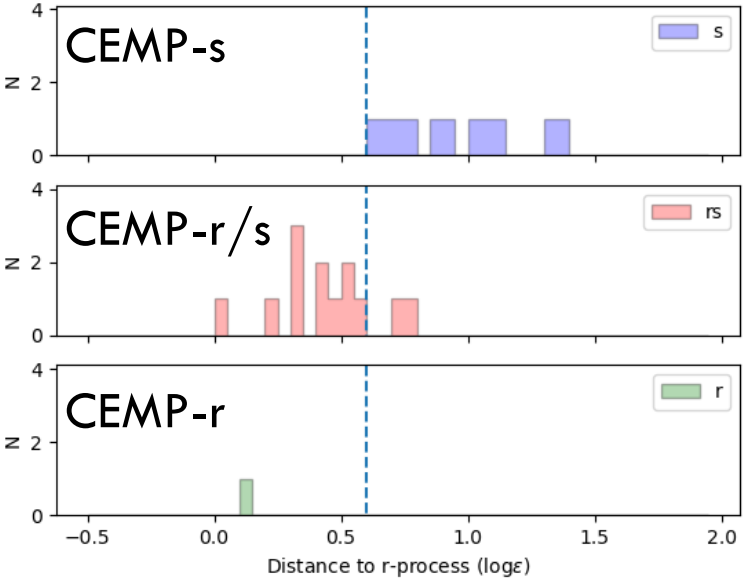
→ Distance to solar r abundance distribution

CEMP-rs classification attempts: **Distance to r-process**

Signed distance to the r-process
Karinkuzhi+ 2023

$$d_S = \frac{1}{N} \sum_{x_i} (\log_{10} \epsilon_{x_i,*} - \log_{10} \epsilon_{x_i,\mathrm{norm(r,*)}})$$

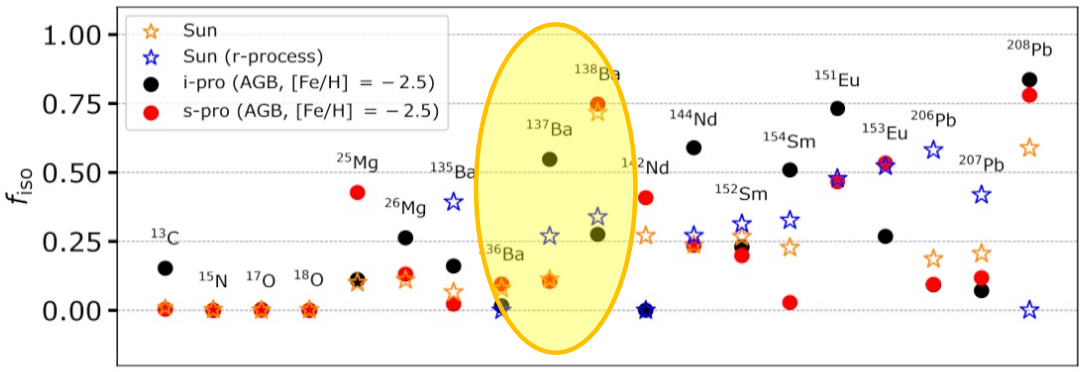




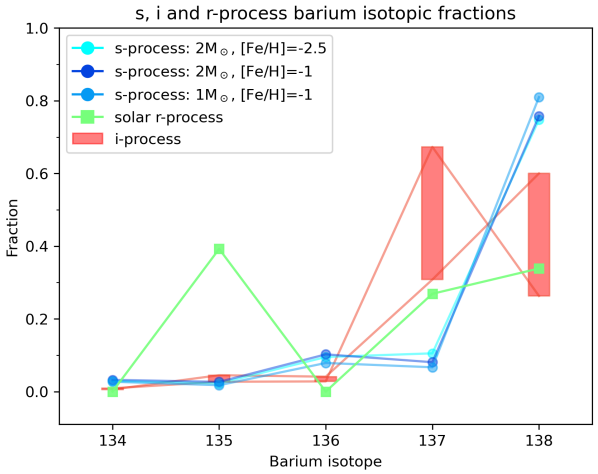
CEMP-rs classification attempts: **Isotopic ratio**

r,i and s-processes predict distinct isotopic mixtures

Choplin, Siess & Goriely 2021



Martinet,
Choplin+ 2024

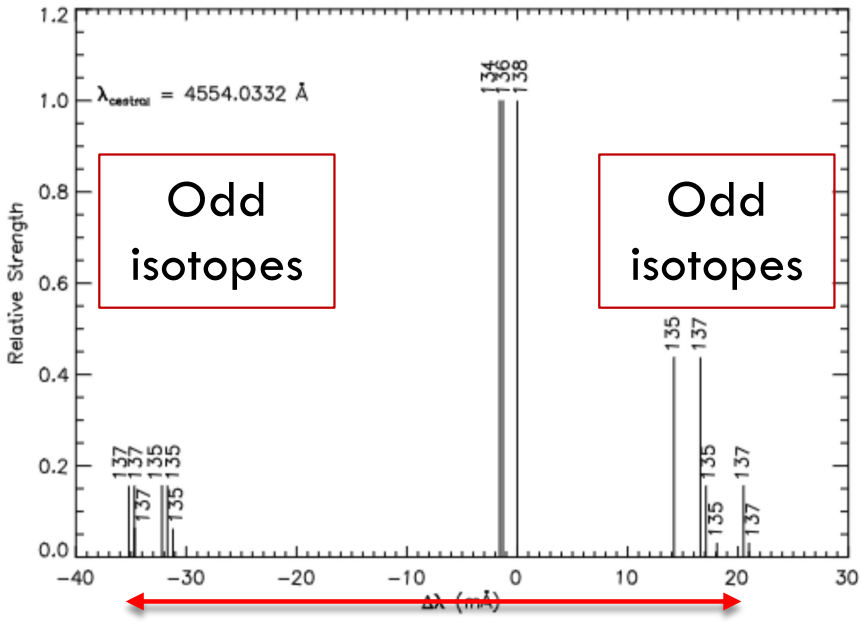


CEMP-rs classification attempts: **Isotopic ratio**

- Isotopic shifts are too tiny to be detected
- But hyperfine splitting is not!

Gallagher+ 1996

Maximum isotopic shift: 2mA

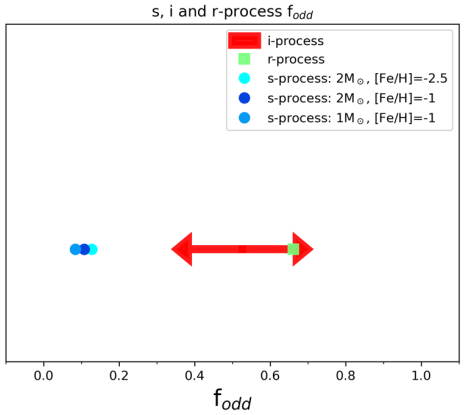


Hyperfine splitting of odd isotopes: ~55mA

CEMP-rs classification attempts: **Isotopic ratio**

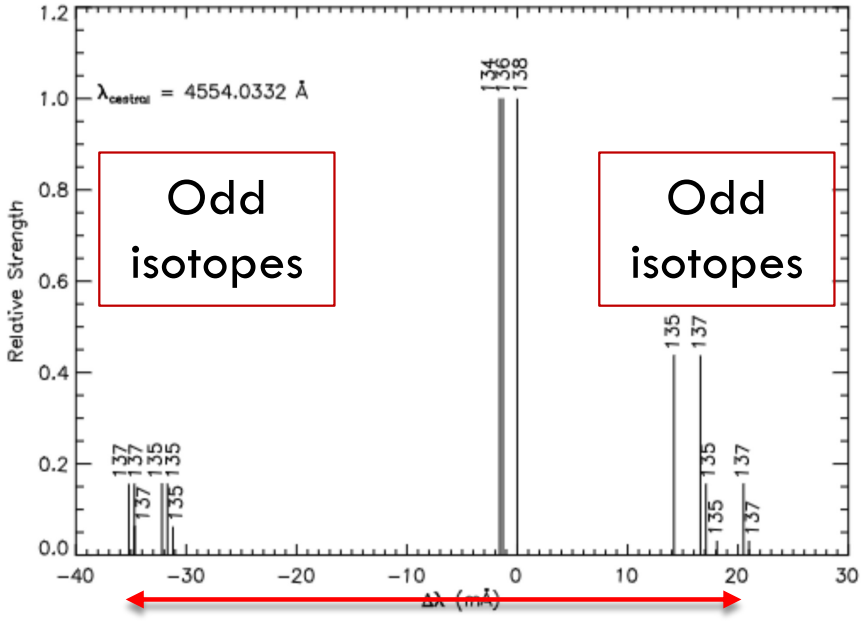
- Isotopic shifts are too tiny to be detected
- But hyperfine splitting is not!

$$f_{Ba,odd} = \frac{N(^{135}Ba) + N(^{137}Ba)}{N(Ba)}$$



Gallagher+ 1996

Maximum isotopic shift: 2mA

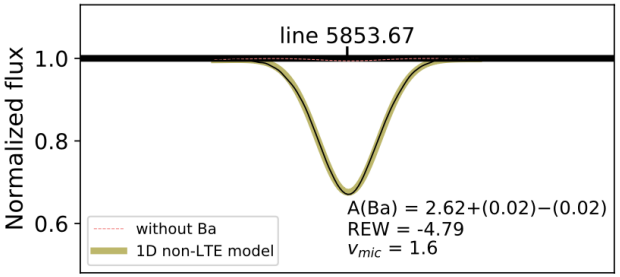


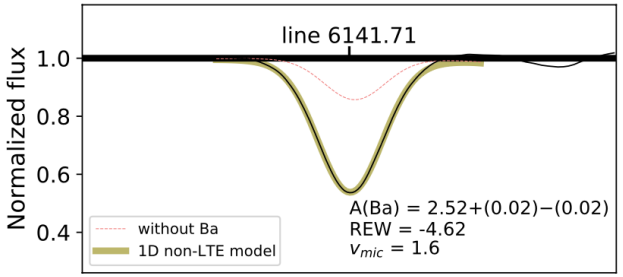
Hyperfine splitting of odd isotopes: ~55mA

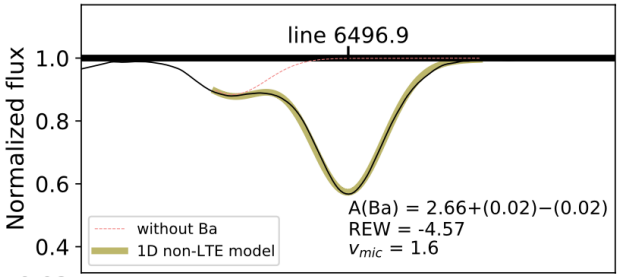
CEMP-rs classification attempts: **Isotopic ratio**

Subordinate lines:

Giribaldi+, in prep.







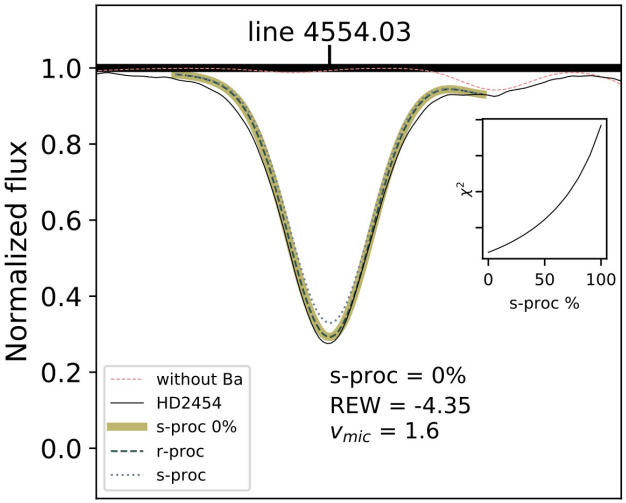
Riano Giribaldi

Thibault Merle

Resonance lines:

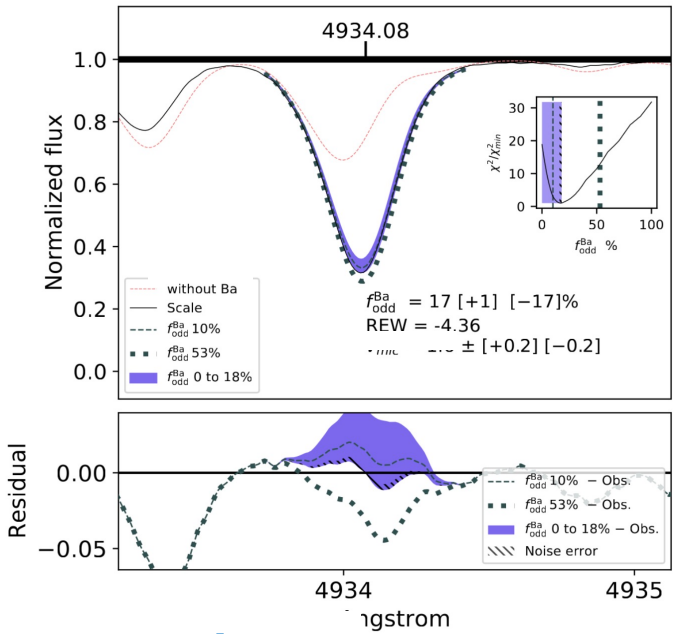
Problem: Abundance offset between resonance and subordinate lines (0.7 dex higher)

Hypothesis: A(Ba)=A(Ce)



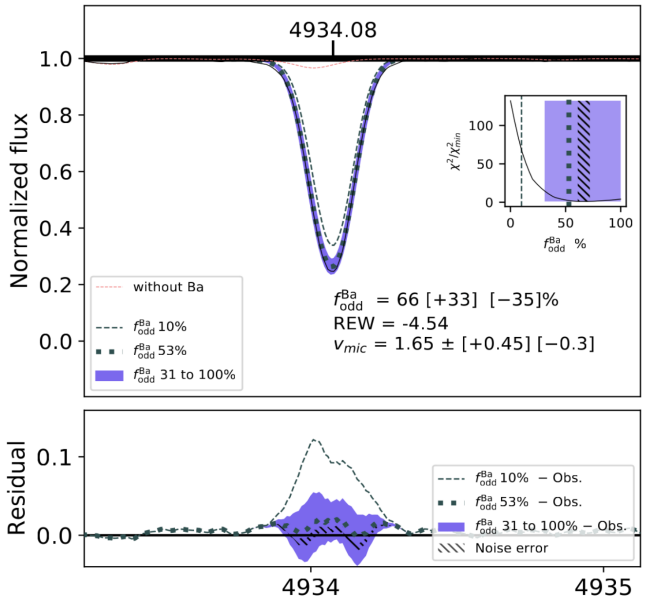
CEMP-rs classification attempts: **Isotopic ratio**

HD 2454
s-process (Tomkin+89)



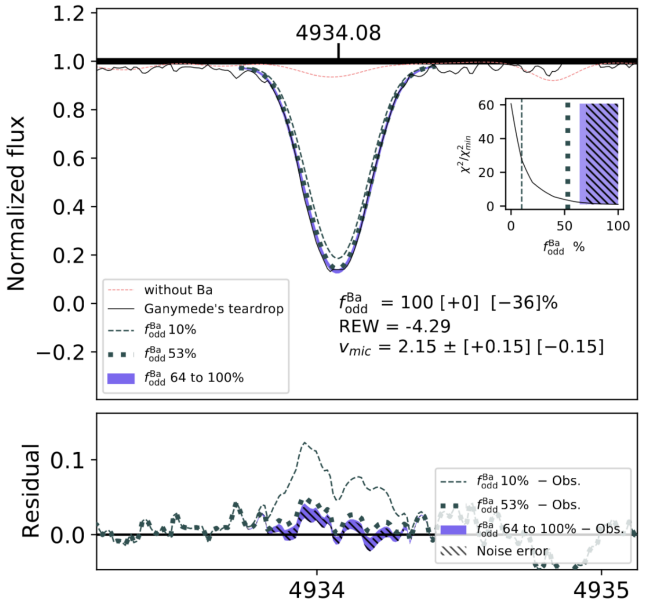
→ s-process

HD 115444
r-process (Sneden+2009)



→ r or i process

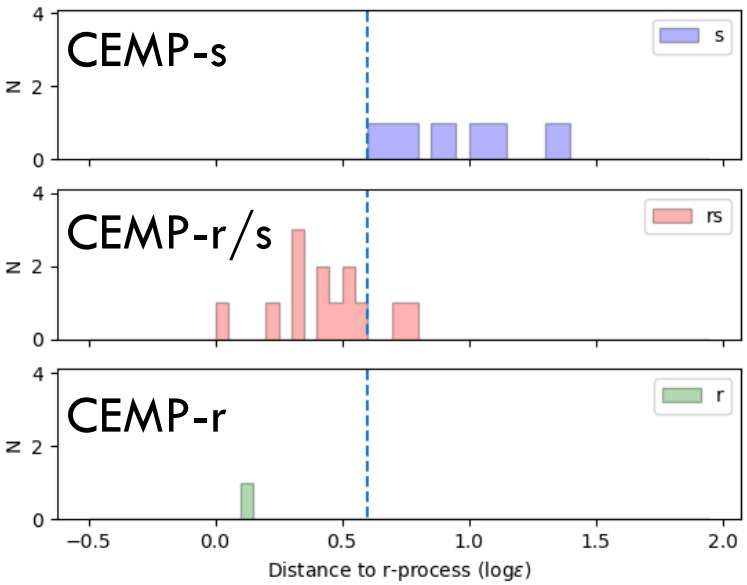
HE 2208-1239
CEMP-rs (Hansen+2015)

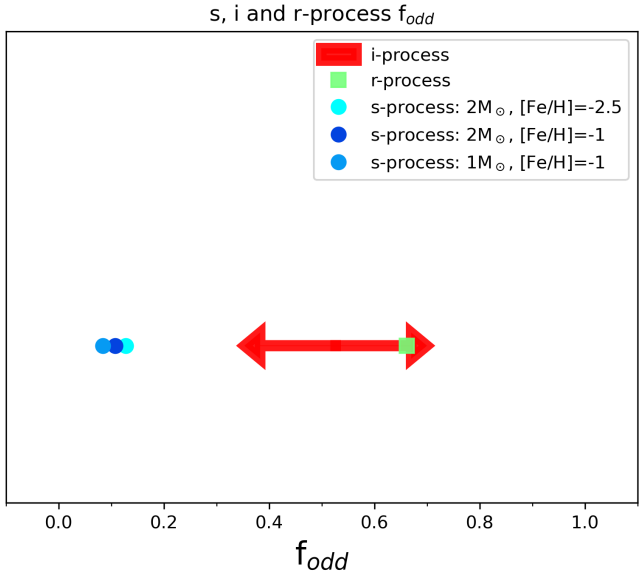


→ i or r-process

Giribaldi+, in prep.

CEMP-rs classification attempts: **Isotopic ratio**



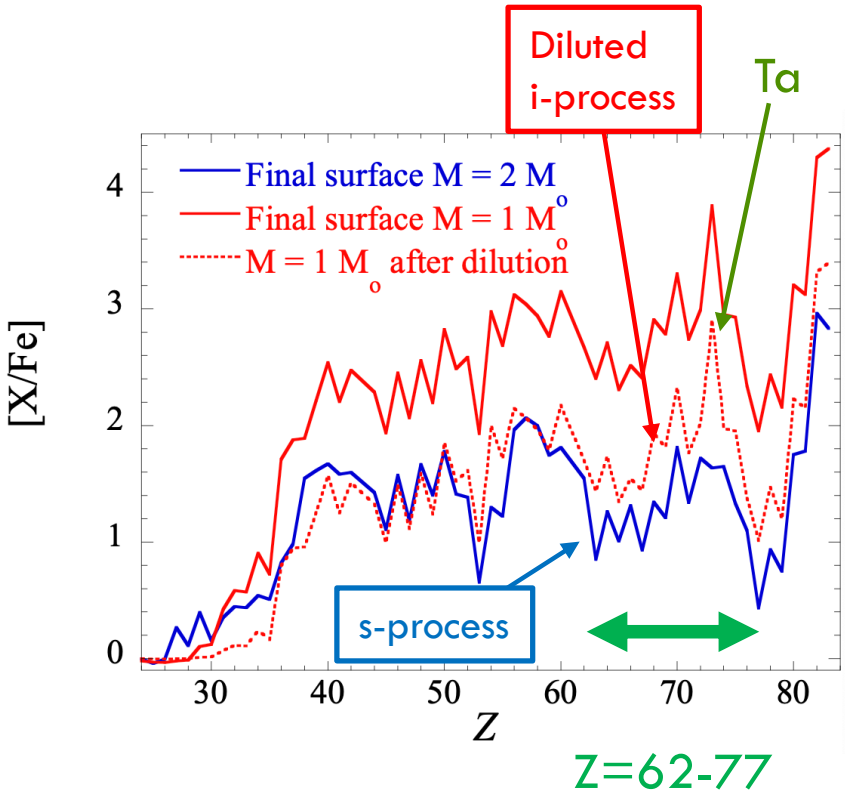


Star	Signed distance	$\chi^2_{\mathrm{s-pro}}$	$\chi^2_{\mathrm{i-pro}}$	$\chi^2_{\mathrm{r-pro}}$	f^{Ba}_{odd} x100
HD 2454	0.83	1.38	1.56	4.47	17^{+1}_{-17}
HD 115444	0.00	4.46	2.35	0.79	66^{+33}_{-35}
HE 2208-1239	0.56	13.14	2.05	7.37	100^{+0}_{-36}

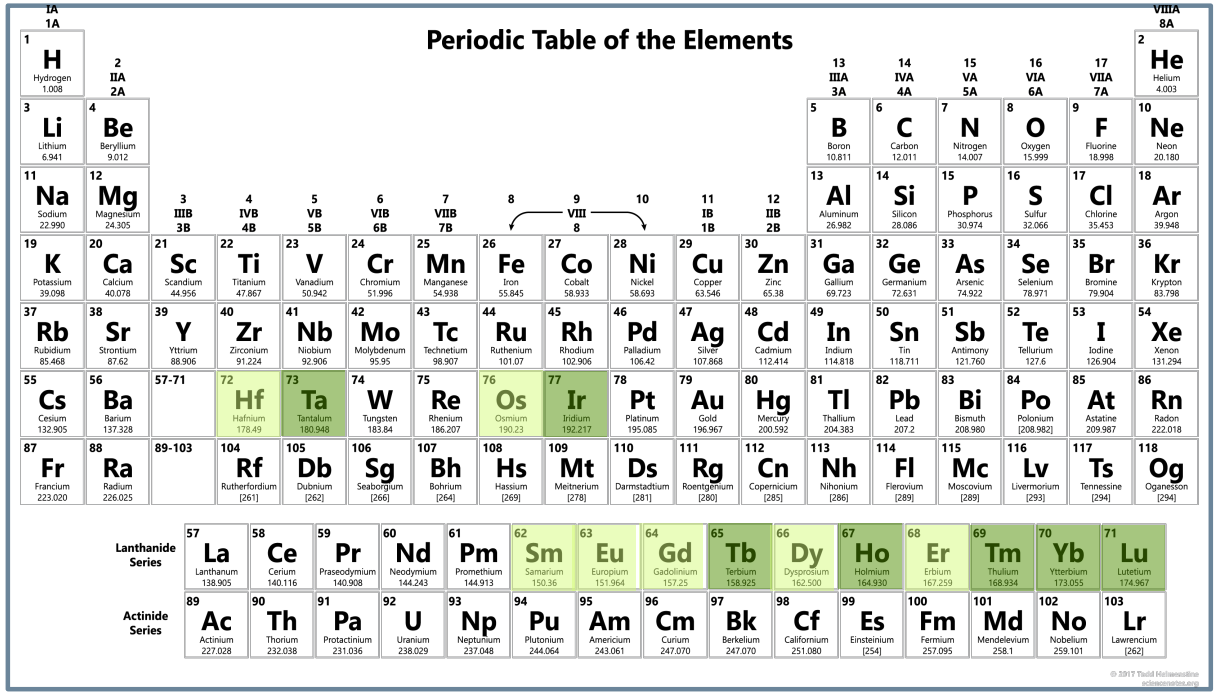
s-process (Tomkin+89)
r-process (Sneden+2009)
CEMP-rs (Hansen+2015)

s-process
r or i-process
i or r-process

CEMP-rs classification attempts: **heavy r**



Z=62-77



Often measured

Not so often measured

Stellar sample

Name	$T_{\rm eff}$ (K)	$\log g$ (cms^{-2})	ξ (km s^{-1})	[Fe/H]
CEMP-rs stars				
CS 22891−171	5215 ± 68	1.24 ± 0.09	2.14 ± 0.14	−2.50 ± 0.10
CS 22947-187	5200 ± 62	1.50 ± 0.12	1.70 ± 0.08	−2.55 ± 0.10
HD 145777	4443 ± 57	0.50 ± 0.10	2.63 ± 0.10	−2.32 ± 0.10
HD 187861	5000 ± 100	1.50 ± 0.25	2.00 ± 0.20	−2.60 ± 0.10
HD 196944	5168 ± 48	1.28 ± 0.16	1.68 ± 0.11	−2.50 ± 0.09
HD 224959	4969 ± 64	1.26 ± 0.29	1.63 ± 0.14	−2.36 ± 0.09
SDSS J0912+0216	6140 ± 37	4.60 ± 0.21	1.19 ± 0.07	−2.83 ± 0.07
SDSS J1349−0229	6238 ± 95	4.41 ± 0.21	1.45 ± 0.08	−3.13 ± 0.07
CEMP-s stars				
CS 22887−048	6500 ± 50	3.20 ± 0.15	1.00 ± 0.05	−2.10 ±0.09
CS 22942−019	5100 ± 98	2.19 ± 0.20	1.73 ± 0.10	−2.50 ± 0.09
CS 29512−073	5471 ± 82	2.78 ± 0.16	1.28 ± 0.08	−2.35 ± 0.09
CS 30322−023	4500 ± 100	1.00 ± 0.50	2.80 ± 0.10	−3.35 ± 0.09
HD 26	5169 ± 108	2.46 ± 0.18	1.46 ± 0.08	−0.98 ± 0.09
HD 55496	4642 ± 39	1.65 ± 0.14	1.33 ± 0.08	−2.10 ± 0.09
HD 198269	4458 ± 15	0.83 ± 0.08	1.64 ± 0.09	−2.10 ± 0.10
HD 206983	4200 ± 100	0.60 ± 0.20	1.50 ± 0.10	−1.00 ± 0.10
SDSS J1036+1212	5591 ± 99	3.70 ± 0.08	0.87 ± 0.10	−3.48 ± 0.09

D. Karinkuzhi

M. Riyas

Observations

UVES @ VLT

- R= 47000
- 3280-6835A

HERMES@Mercator

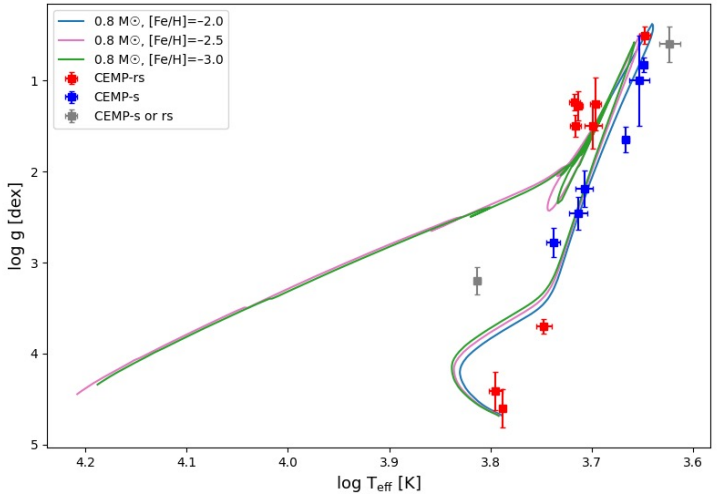
- R=85000
- 3800-8000A

MARCS model atmosphere (Gustafsson+ 2008)
Turbospectrum radiative transfer code (Plez 2012)
Bacchus (Masseron + 2016)
Non-LTE corrections when available in the litterature

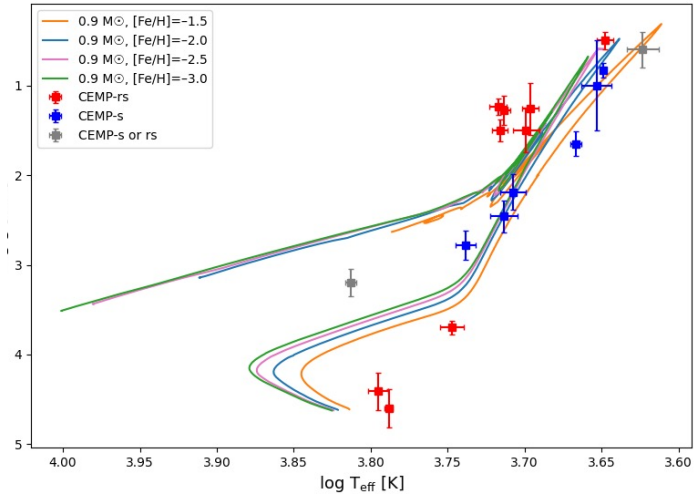
Kiel diagrams

Starevol evolutionary tracks
-3 < [Fe/H] < -1.5

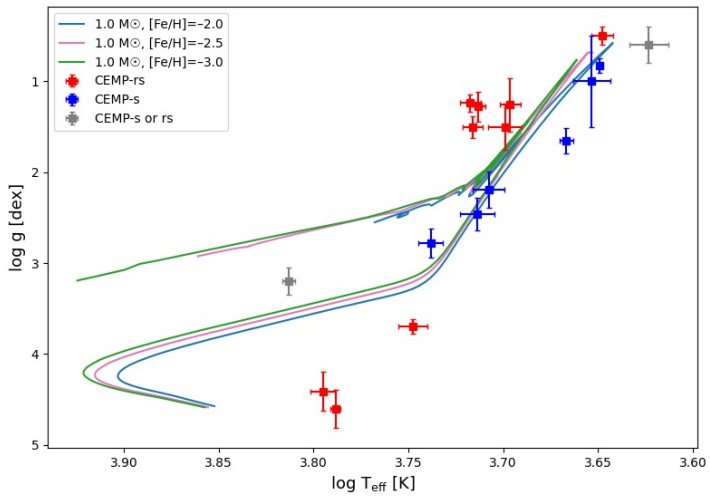
0.8M



0.9M

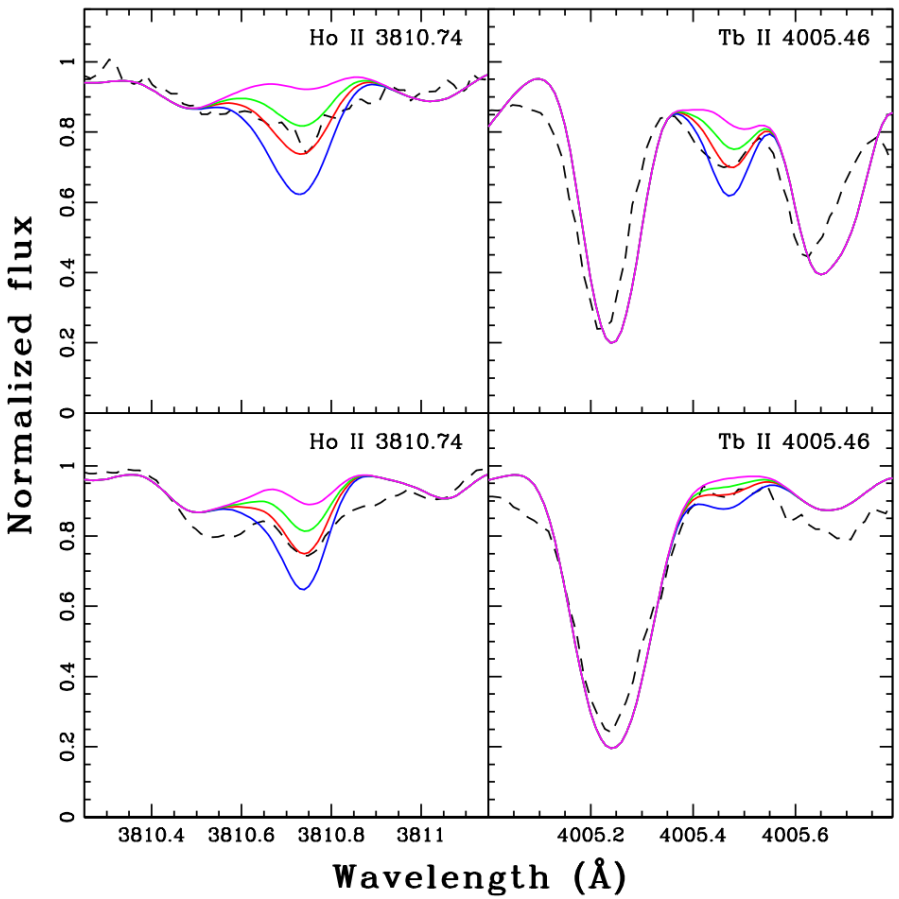


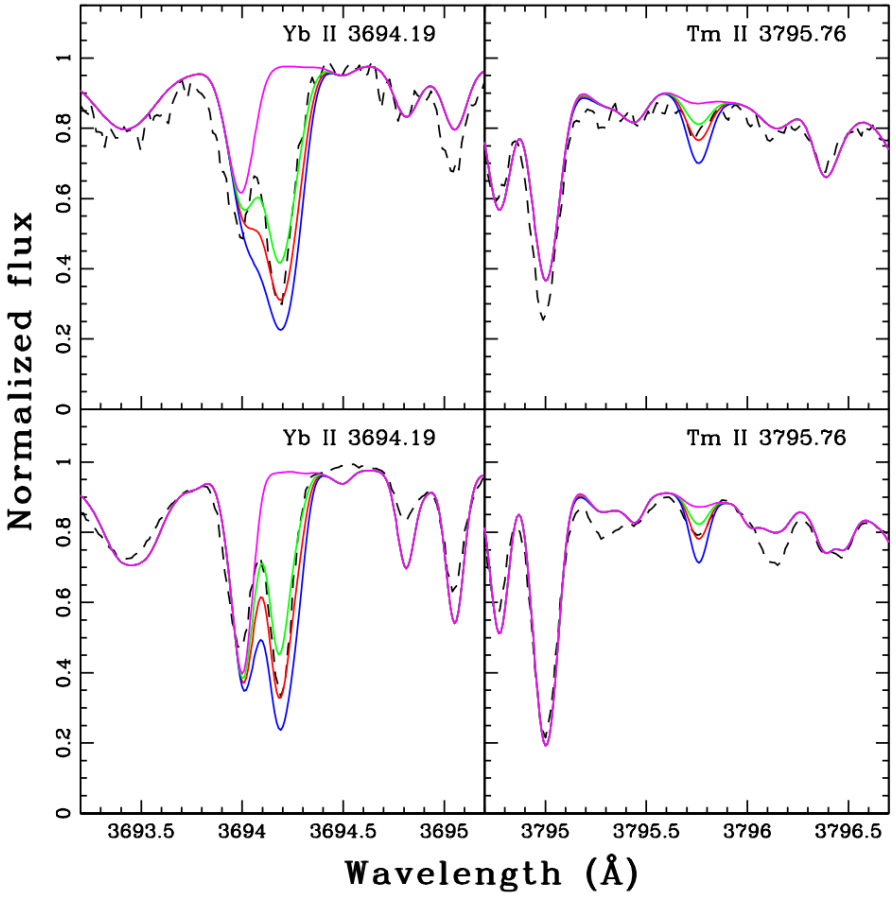
1.0M



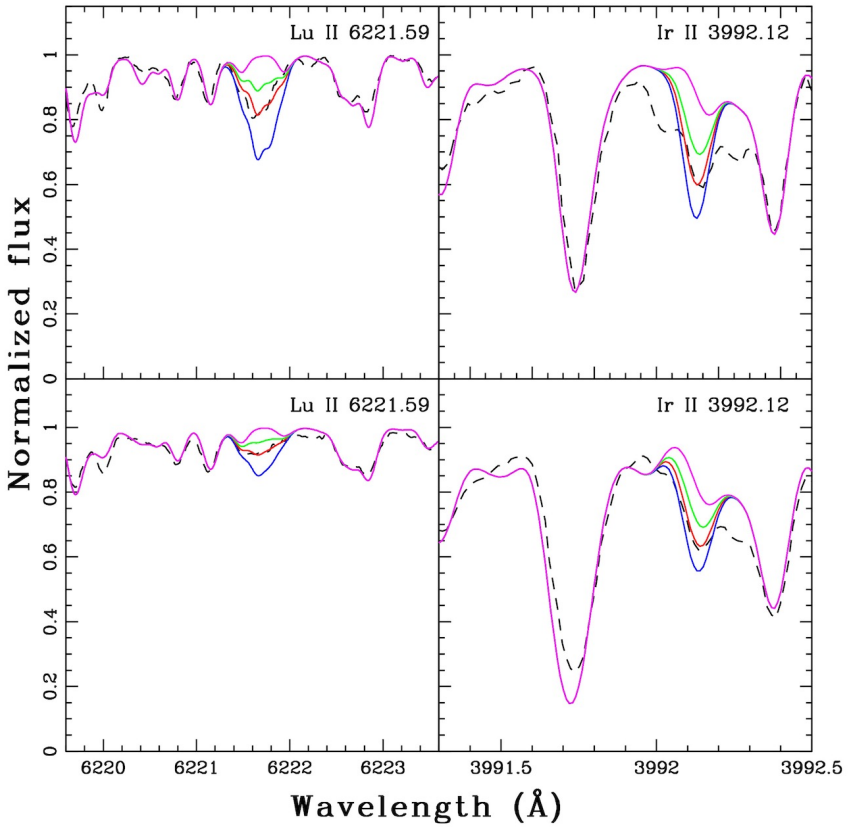
Ho II, Tb II

Yb II, Tm II

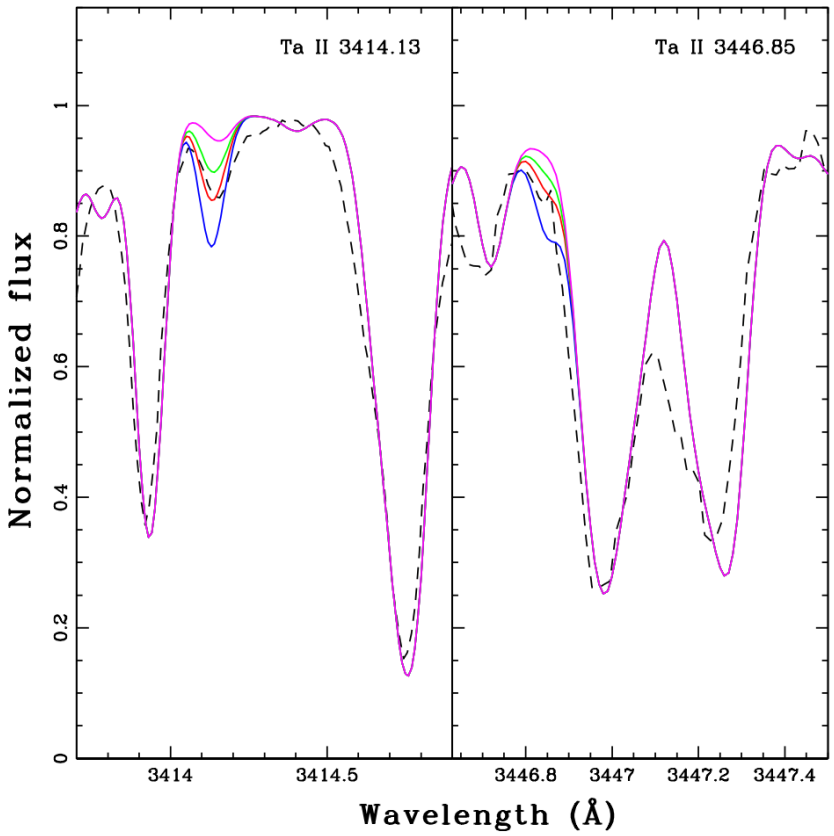




Lu II, Ir II

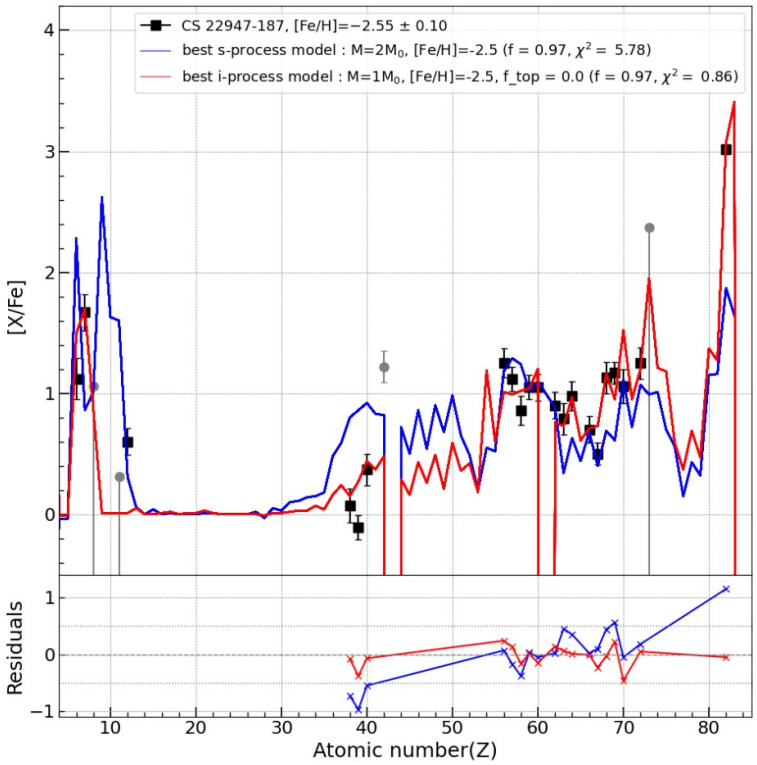


Ta II

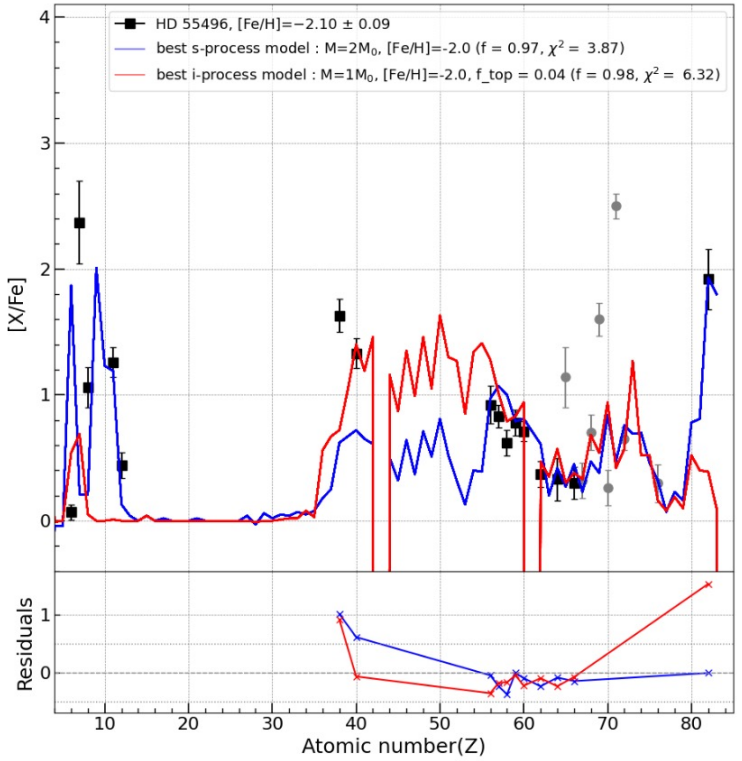


Abundance profiles

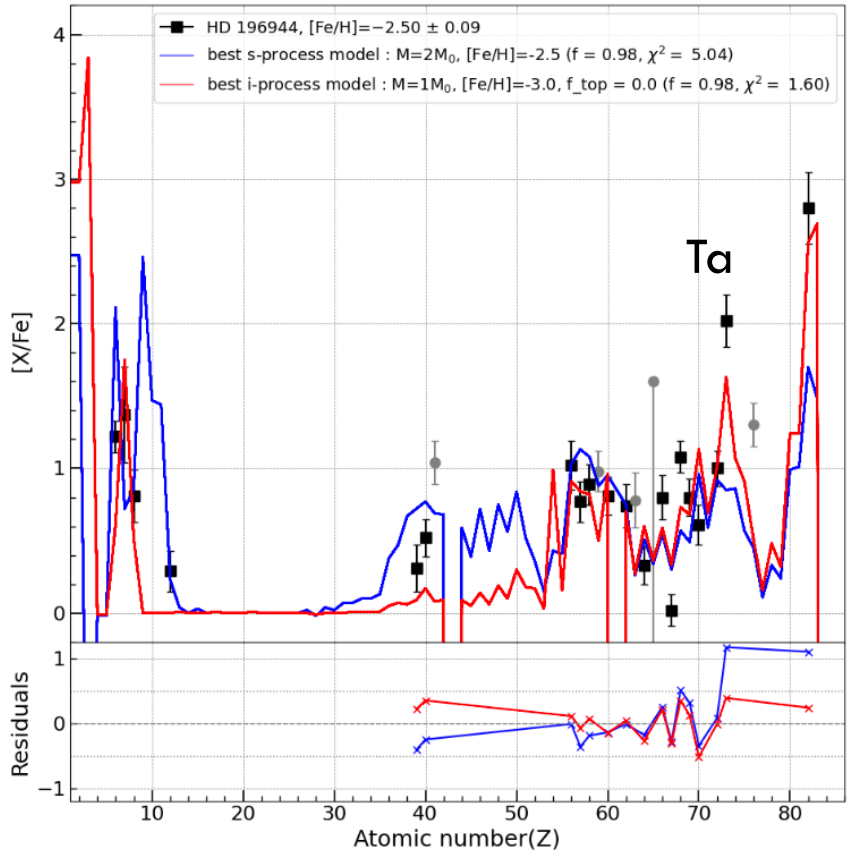
CEMP-rs



CEMP-s



Abundance profiles



Classification result

[s/r] | Distance to r | Chi2 with models

Object	[s/r]			Distance				χ^2			Final Class	
	[La/Eu]	[Ba/Eu]	Class$_{sr}$	d_s	Class$_{d_s}$	d_{rms}	Class$_{d_{rms}}$	χ^2_s	χ^2_i	Class$_{\chi^2}$		
CS 22891−171	0.55	0.37	s/rs	0.48	rs	0.73	s/rs	3.81	1.66	rs	rs	rs
CS 22947−187	0.33	0.46	rs	0.43	rs	0.64	rs	5.78	0.86	rs	rs	
HD 145777	0.10	0.02	rs	0.47	rs	0.57	rs	2.01	2.58	s/rs	rs	
HD 187861	−0.05	−0.16	r/rs	0.04	r	0.48	rs	6.54	1.78	rs	rs	
HD 196944	−0.01	0.24	rs	0.39	rs	0.52	rs	5.04	1.60	rs	rs	
HD 224959	0.17	0.19	rs	0.35	rs	0.56	rs	3.29	1.61	rs	rs	
SDSS J0912−0216	0.24	−0.27	rs	0.52	rs	0.68	s/rs	19.87	8.29	rs?	rs	
SDSS J1036+1212	0.17	−0.98	rs	0.38	rs	0.72	s/rs	27.79	8.17	rs?	rs	
SDSS J1349−0229	0.01	−0.29	rs	0.40	rs	0.59	rs	25.81	13.63	rs?	rs	
CS 22887−048	0.50	0.42	s	0.63	s/rs	0.75	s	3.69	1.30	rs	s or rs	
CS 22942−019	0.51	0.79	s	0.91	s	1.07	s	2.41	1.08	rs	s	s
CS 29512−073	0.58	0.68	s	0.77	s	0.90	s	3.38	0.88	rs	s	
CS 30322−023	0.82	0.64	s	0.83	s	0.97	s	2.60	1.87	rs	s	
HD 26	0.92	0.94	s	1.18	s	1.28	s	2.09	1.88	s/rs	s	
HD 55496	-	-	-	1.00	s	1.22	s	3.87	6.32	s	s	
HD 198269	0.55	0.55	s	0.83	s	0.95	s	1.10	1.17	s/rs	s	
HD 206983	0.30	0.27	rs	0.60	s/rs	0.70	s/rs	1.24	0.87	s/rs	s or rs	

Classification result

[s/r] | Distance to r | Chi2 with models

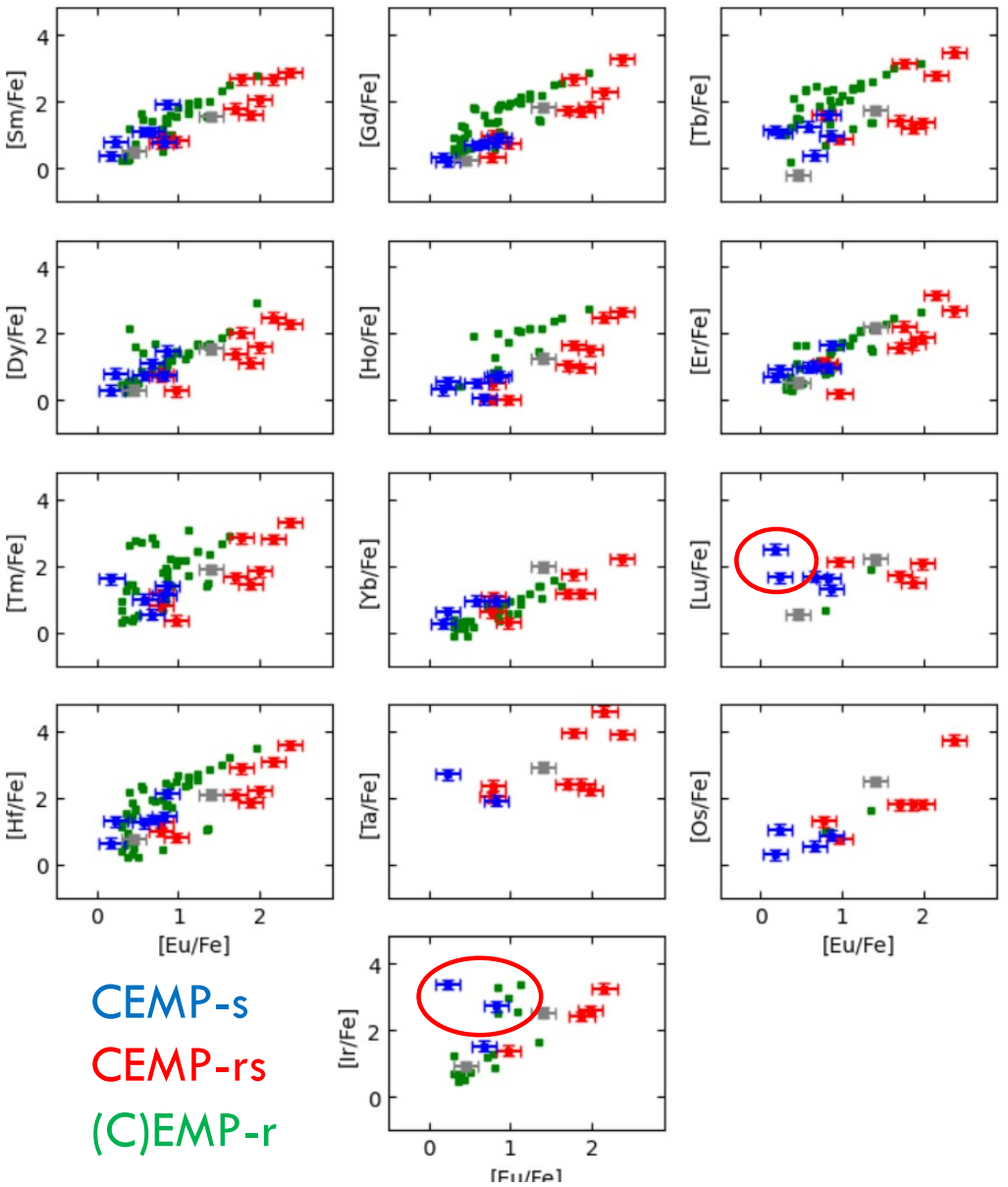
Object	[s/r]			Distance				χ^2			Final Class	
	[La/Eu]	[Ba/Eu]	Class$_{sr}$	d_s	Class$_{d_s}$	d_{rms}	Class$_{d_{rms}}$	χ^2_s	χ^2_i	Class$_{\chi^2}$		
CS 22891−171	0.55	0.37	s/rs	0.48	rs	0.73	s/rs	3.81	1.66	rs	rs	rs
CS 22947−187	0.33	0.46	rs	0.43	rs	0.64	rs	5.78	0.86	rs	rs	
HD 145777	0.10	0.02	rs	0.47	rs	0.57	rs	2.01	2.58	s/rs	rs	
HD 187861	−0.05	−0.16	r/rs	0.04	r	0.48	rs	6.54	1.78	rs	rs	
HD 196944	−0.01	0.24	rs	0.39	rs	0.52	rs	5.04	1.60	rs	rs	
HD 224959	0.17	0.19	rs	0.35	rs	0.56	rs	3.29	1.61	rs	rs	
SDSS J0912−0216	0.24	−0.27	rs	0.52	rs	0.68	s/rs	19.87	8.29	rs?	rs	
SDSS J1036+1212	0.17	−0.98	rs	0.38	rs	0.72	s/rs	27.79	8.17	rs?	rs	
SDSS J1349−0229	0.01	−0.29	rs	0.40	rs	0.59	rs	25.81	13.63	rs?	rs	
CS 22887−048	0.50	0.42	s	0.63	s/rs	0.75	s	3.69	1.30	rs	s or rs	
CS 22942−019	0.51	0.79	s	0.91	s	1.07	s	2.41	1.08	rs	s	s
CS 29512−073	0.58	0.68	s	0.77	s	0.90	s	3.38	0.88	rs	s	
CS 30322−023	0.82	0.64	s	0.83	s	0.97	s	2.60	1.87	rs	s	
HD 26	0.92	0.94	s	1.18	s	1.28	s	2.09	1.88	s/rs	s	
HD 55496	-	-	-	1.00	s	1.22	s	3.87	6.32	s	s	
HD 198269	0.55	0.55	s	0.83	s	0.95	s	1.10	1.17	s/rs	s	
HD 206983	0.30	0.27	rs	0.60	s/rs	0.70	s/rs	1.24	0.87	s/rs	s or rs	

rs

s

r-r correlation

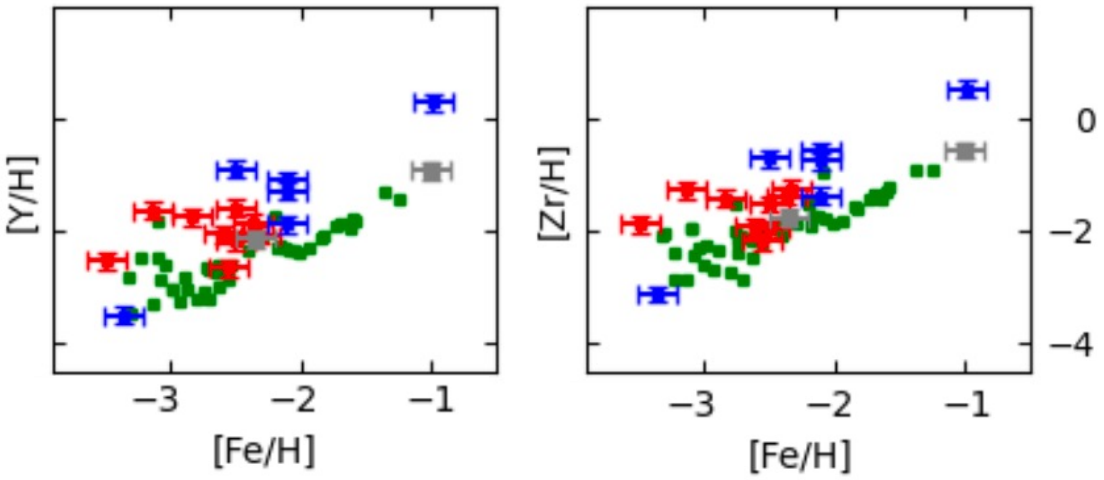
- Consistency of the heavy-r
- Potentially problematic: Ir, Lu
- Overlap between CEMP-rs and CEMP-s stars.



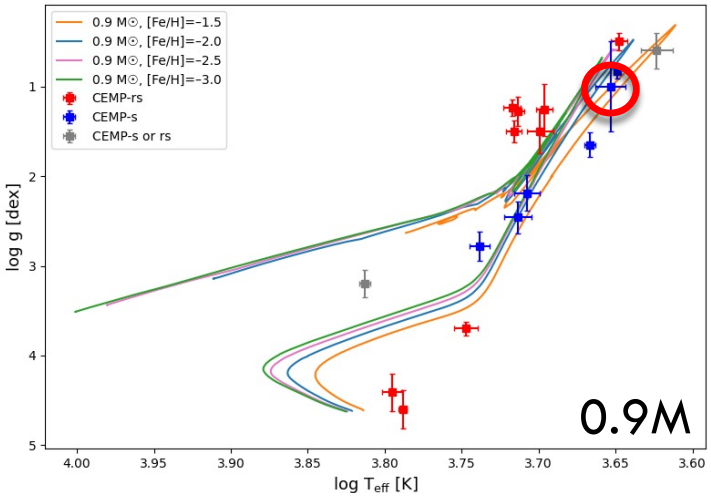
Mainly-s elements with [Fe/H]

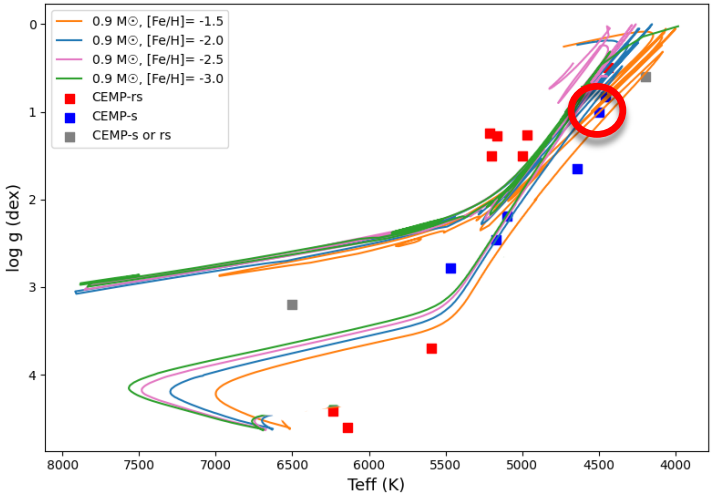
- r stars: GCE
- s stars: larger [s/H] than r-stars
  - AGB polluting star
  - Smaller dilution
  - CS 30322-23: NEMP-s at very low [Fe/H]=-3.35
    - Low-Z AGB star? Or s-process pollution starts at much lower [Fe/H] than usually assumed

CEMP-s
CEMP-rs
(C)EMP-r



CS 30322-23: NEMP-s or the lowest-metallicity TPAGB?





TP-AGB

Masseron+ 2006

[Fe/H]=-3.35

Not-constrainful limit on Tc:

log N_{Tc}<-1.4

Take-home message

- Key-Diagnostics to isolate CEMP-rs:
  - [s/r]
  - [light s/heavy s]
  - Isotopic ratio (Ba)
  - Abundance pattern deviation from pure r-process distribution (« r-distance »)
    - $62 < Z < 77$ elements are crucial for distinguishing CEMP-s from CEMP-rs
  - (Dis-)agreement with s and i-process nucleosynthesis predictions
  - ($^{12}C/^{13}C$)

- Interpretation challenges:
  - The scenario (**r+s** versus **i-process**): still uncertain

(especially since Thorium does provide a definitive test for the r+s scenario)