

The Heavies in CEMP stars

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DE BRUXELLES

CEMP classification (Carbon-Enriched Metal-Poor)

Classification based on carbon...

Different definitions:

- $[C/Fe] > 1$ (Beers & Christlieb 2005)
- $[C/Fe] > 0.7$ if $\log L/L_{\text{sun}} < 2.3$
 $[C/Fe] = 3 - \log(L/L_{\text{sun}})$
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- <i>r</i>	$[C/Fe] > +0.7, [Eu/Fe] > +0.7, [Ba/Eu] < 0.0$
CEMP- <i>s</i>	$[C/Fe] > +0.7, [Ba/Fe] > +1.0, [Ba/Eu] > +0.5$
CEMP- <i>i</i> (<i>r/s</i>)	$[C/Fe] > +0.7, 0.0 < [Ba/Eu] < +0.5$ or $[C/Fe] > +0.7, 0.0 \leq [La/Eu] \leq +0.6$
CEMP-no	$[C/Fe] > +0.7, [Ba/Fe] < 0.0$

Zepeda+ 2023

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

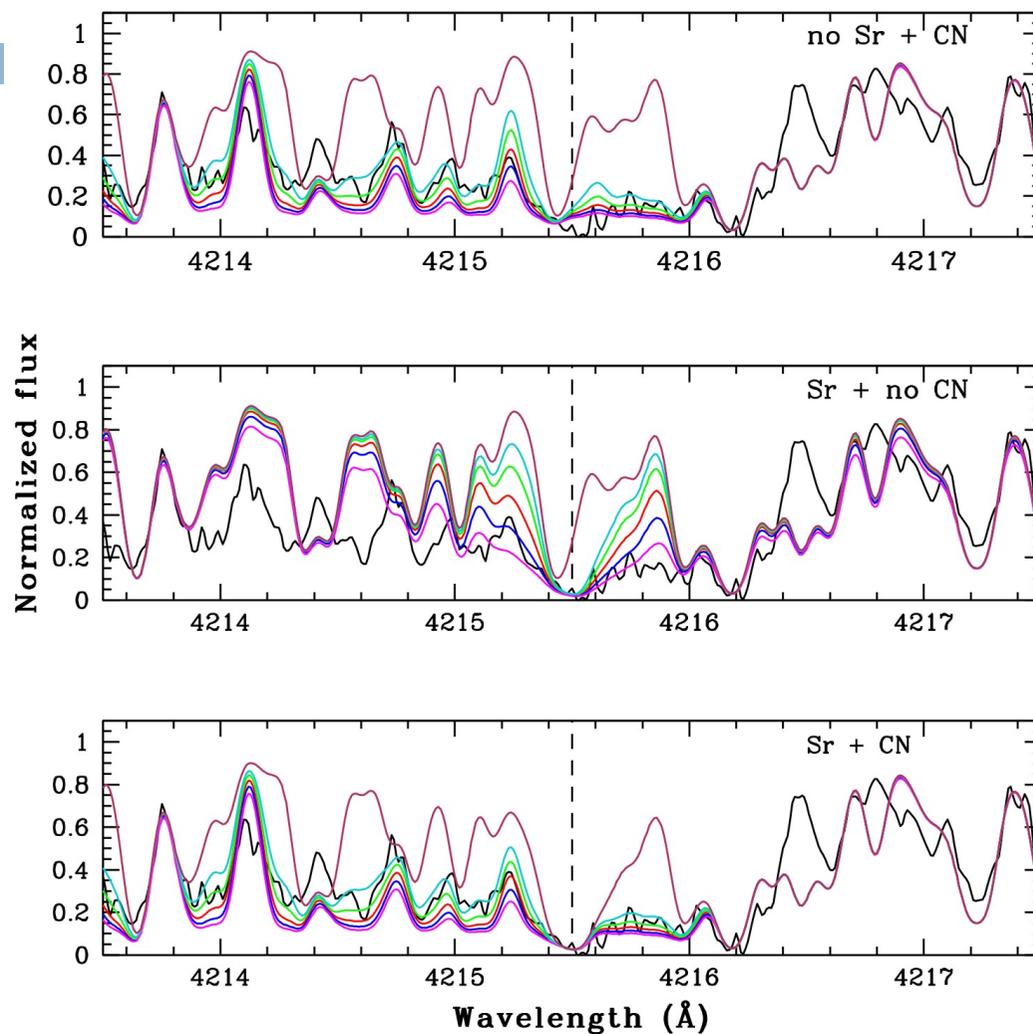
Christlieb et al. 2004; Beers & Christlieb 2005; Holmbeck et al. 2020

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

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- Binary frequency $32 \pm 10\%$
Arentsen+ 2019
See also Starkeburg 2014; Hansen 2016b

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CEMP-s

- Compatible with 100% binaries
Lucatello+ 2005, Starkenburg+ 2014,
Hansen+ 2016, Jorissen, Van Eck+ 2016, Arentsen+ 2019

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CEMP-s

- Compatible with 100% binaries
Lucatello+ 2005, Starkenburg+ 2014,
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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

□ Double event (r+s):

ISM (r)

or

Kilonova (r)



Kilonova

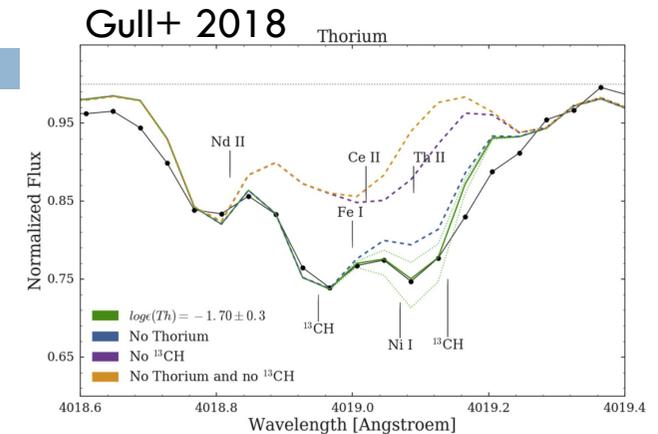


AGB

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

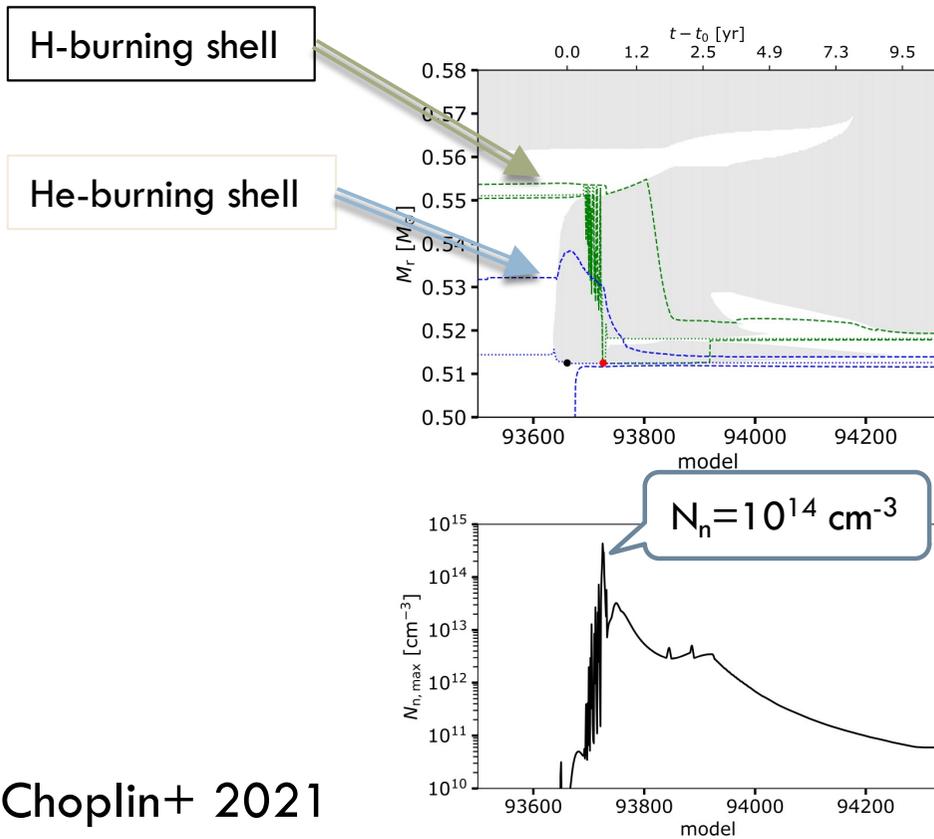
□ i-process in a single astrophysical site:

- Proton injection event (Hampel+ 2019; Karinkuzhi+ 2021; Choplin+ 2021)
Favoured in Mashonkina+ 2023, Karinkuzhi+ 2023
- He shell flash of rapidly accreting WD (Denissenkov+ 2016)

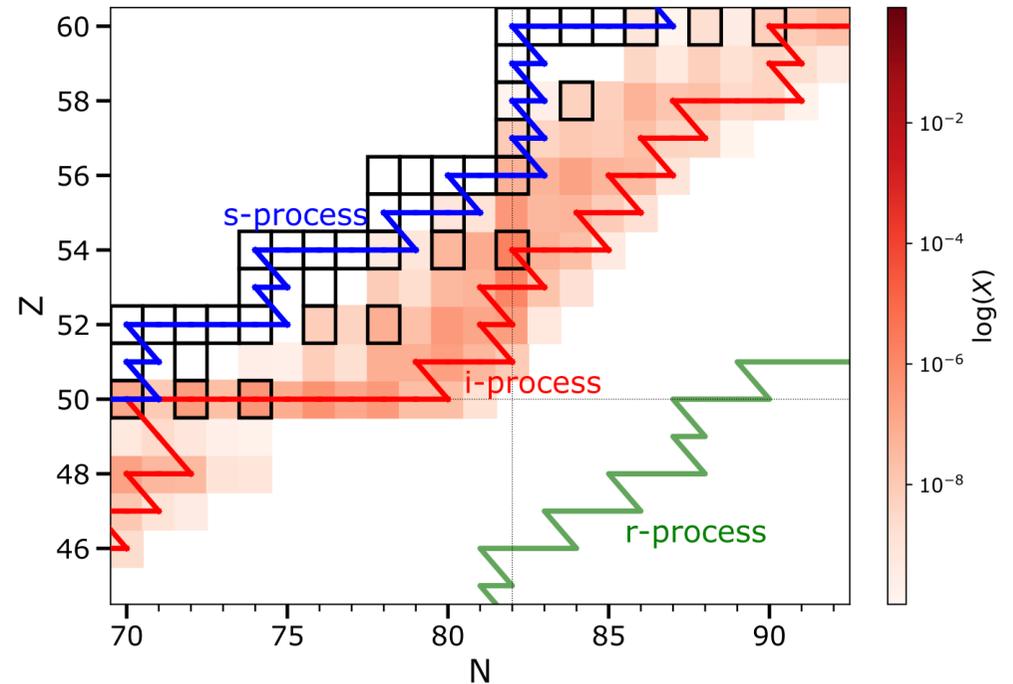


Intermediate (i-) process: theory

Proton injection event in a low-Z AGB model

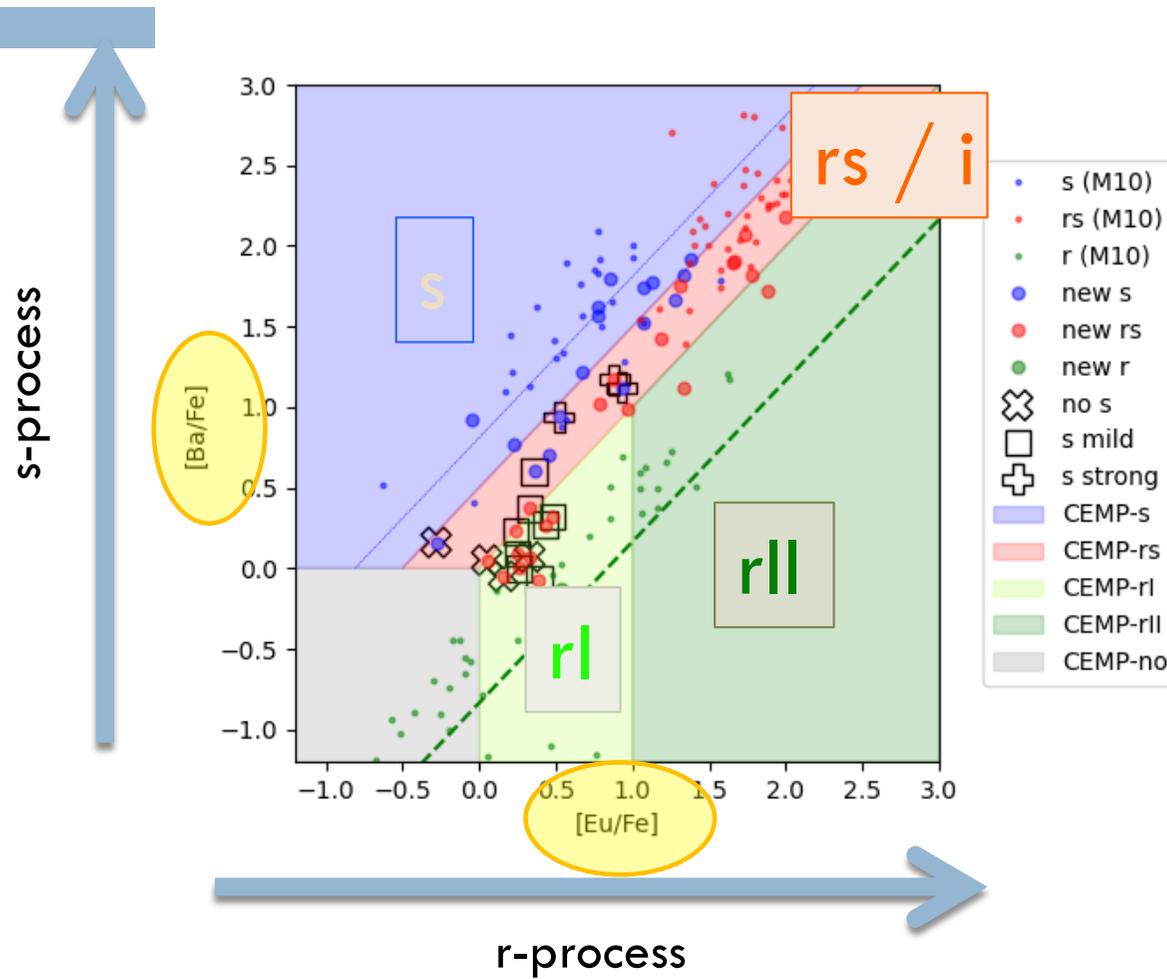


Choplin+ 2021



Choplin+ 2023

CEMP-rs classification attempts: [s/r]

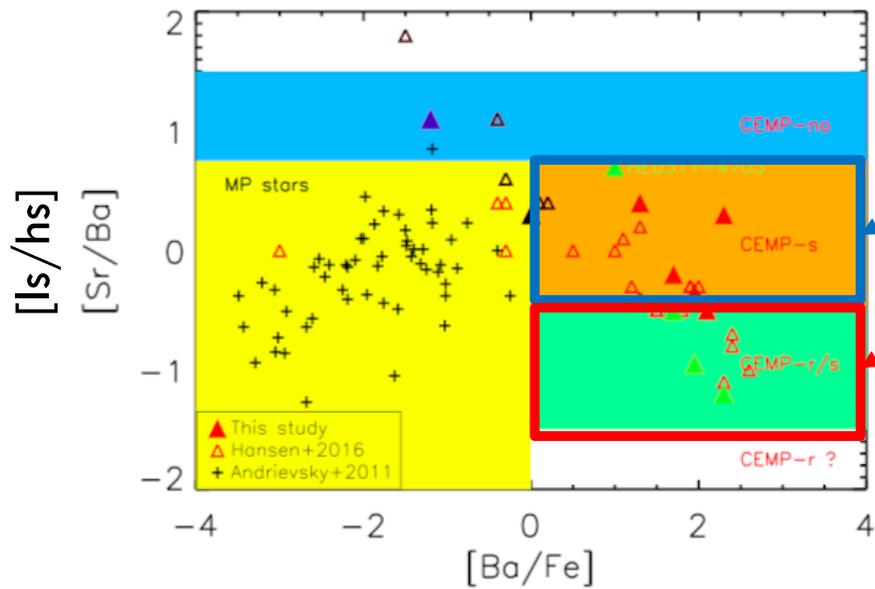


→ [s/r]

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

Hansen+ 2019

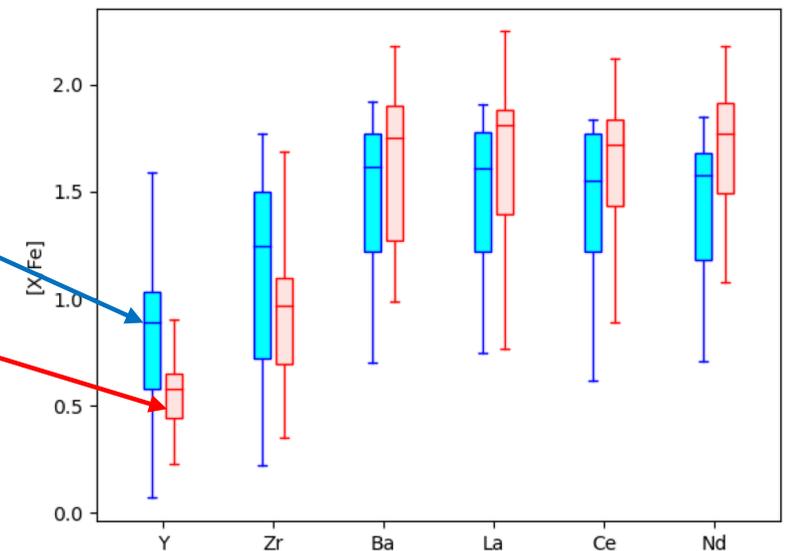
Karrinkuzhi+ 2021



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

Light s

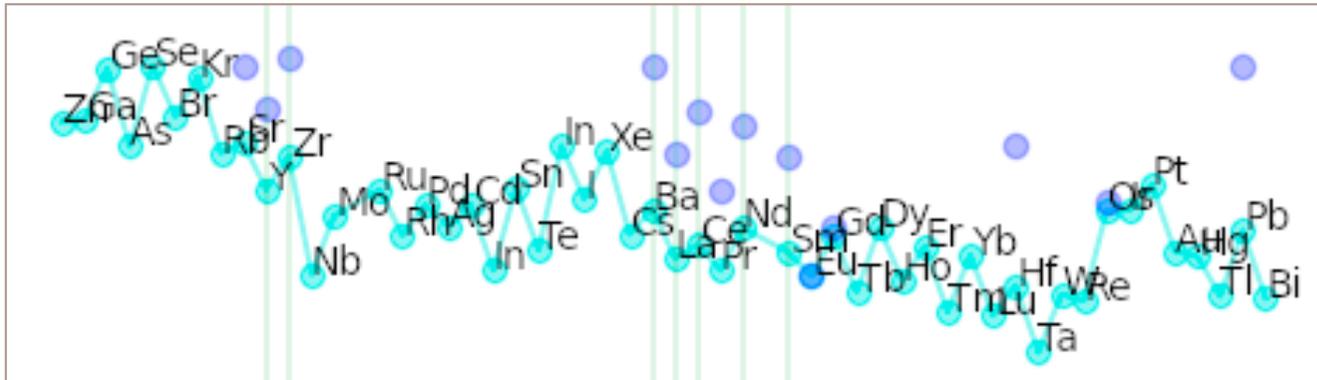
Heavy s



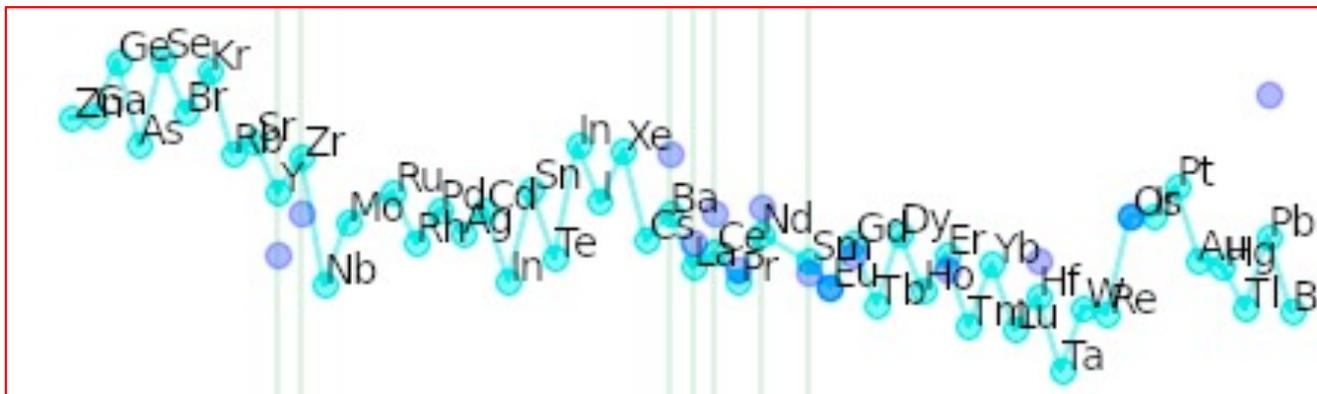
CEMP-rs classification attempts: Distance to r-process

Signed distance to the r-process
Karinkuzhi+ 2023

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



→ CEMP-s



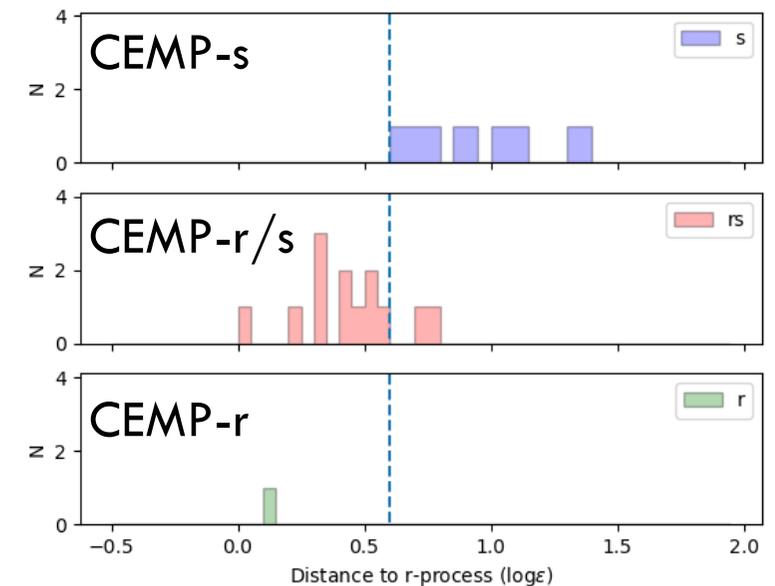
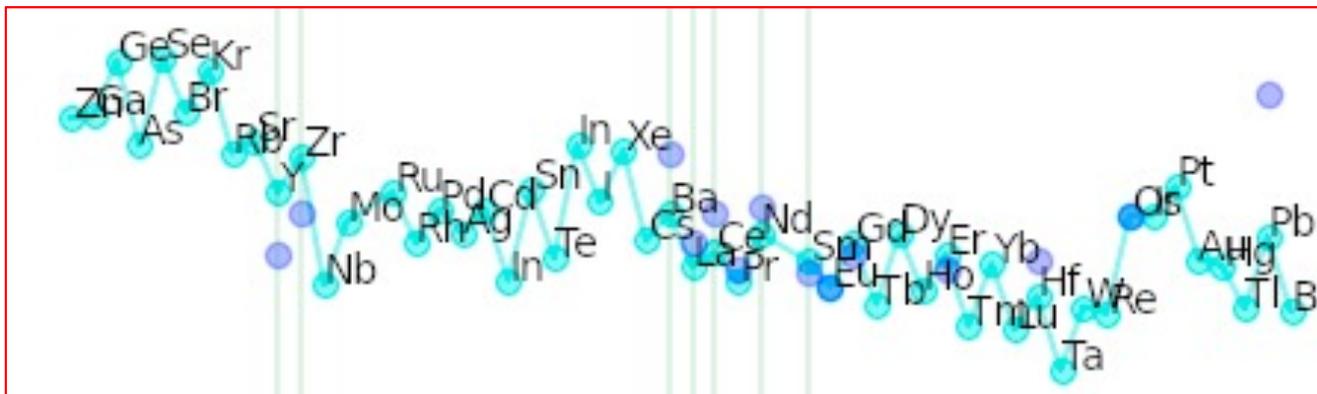
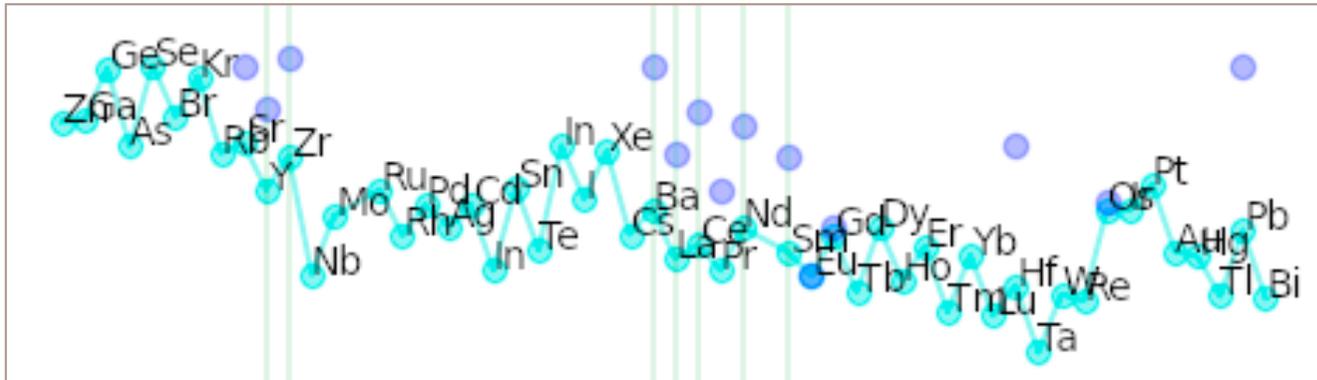
→ CEMP-r

→ Distance to solar r abundance distribution

CEMP-rs classification attempts: Distance to r-process

Signed distance to the r-process
Karinkuzhi+ 2023

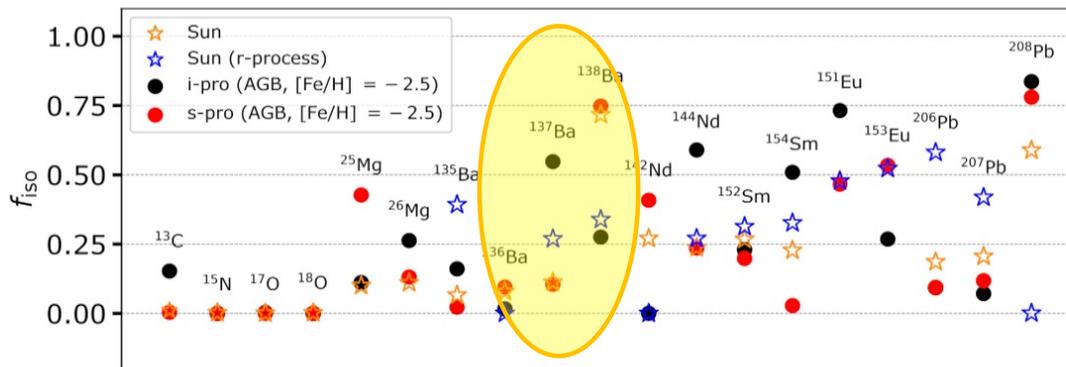
$$d_s = \frac{1}{N} \sum_{x_i} (\log_{10} \epsilon_{x_i,*} - \log_{10} \epsilon_{x_i,\text{norm}(r,*)})$$



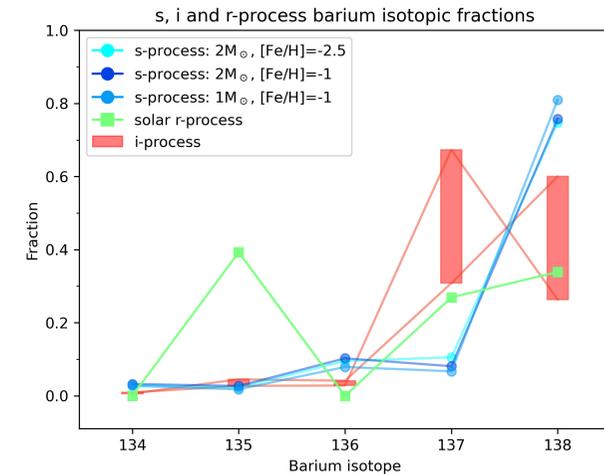
CEMP-rs classification attempts: Isotopic ratio

r,i and s-processes predict distinct isotopic mixtures

Choplin, Siess & Goriely 2021



Martinet,
Choplin+ 2024

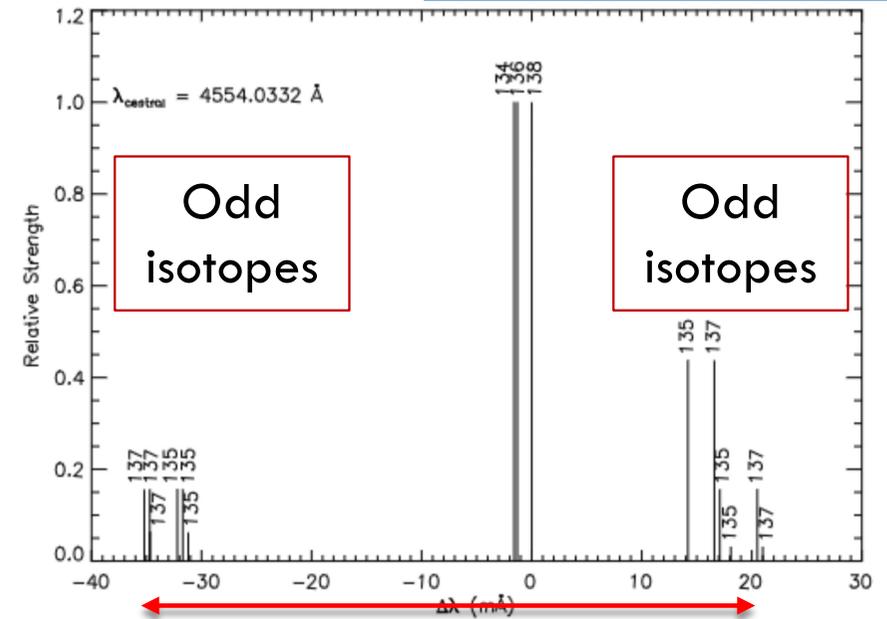


CEMP-rs classification attempts: Isotopic ratio

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

Gallagher+ 1996

Maximum isotopic shift: 2mÅ

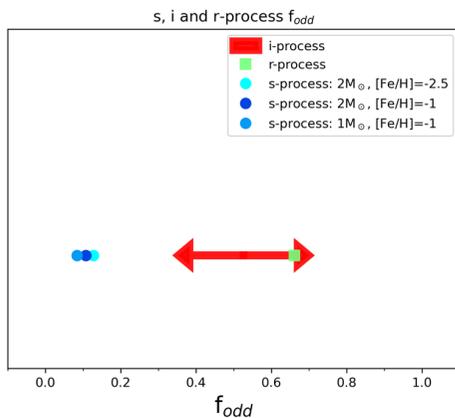


Hyperfine splitting of odd isotopes: $\sim 55\text{m\AA}$

CEMP-rs classification attempts: Isotopic ratio

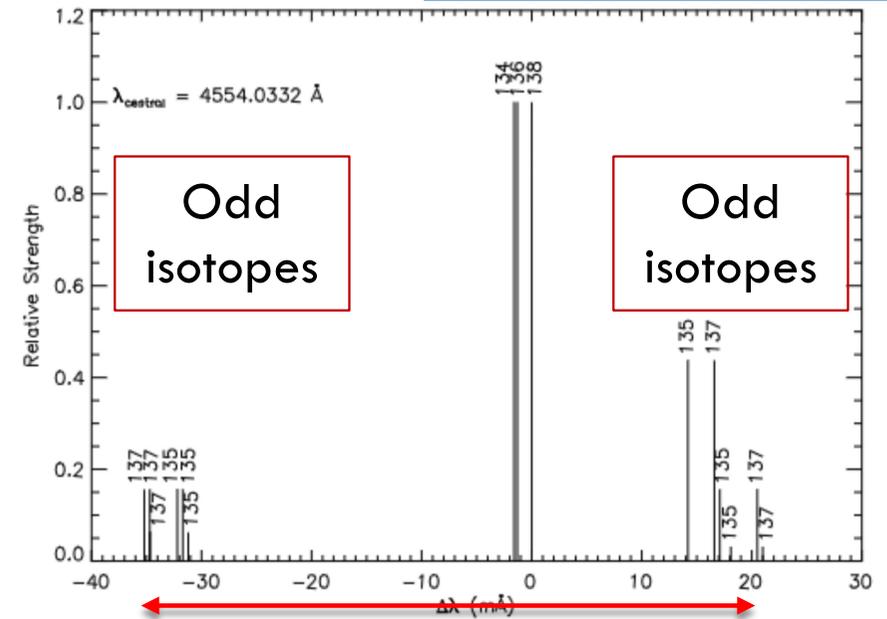
- Isotopic shifts are too tiny to be detected
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$$f_{\text{Ba,odd}} = \frac{N(^{135}\text{Ba}) + N(^{137}\text{Ba})}{N(\text{Ba})}$$



Gallagher+ 1996

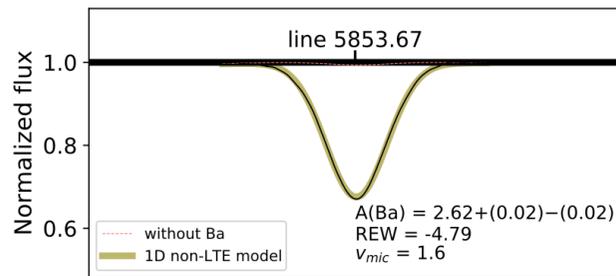
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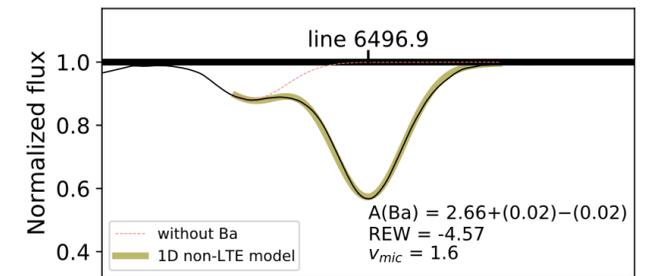
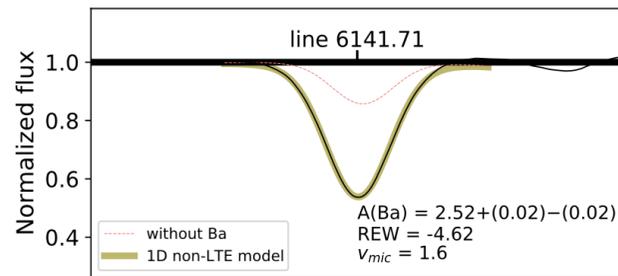
Hyperfine splitting of odd isotopes: $\sim 55\text{m\AA}$

CEMP-rs classification attempts: Isotopic ratio

Subordinate lines:



Giribaldi+, in prep.



Riano
Giribaldi

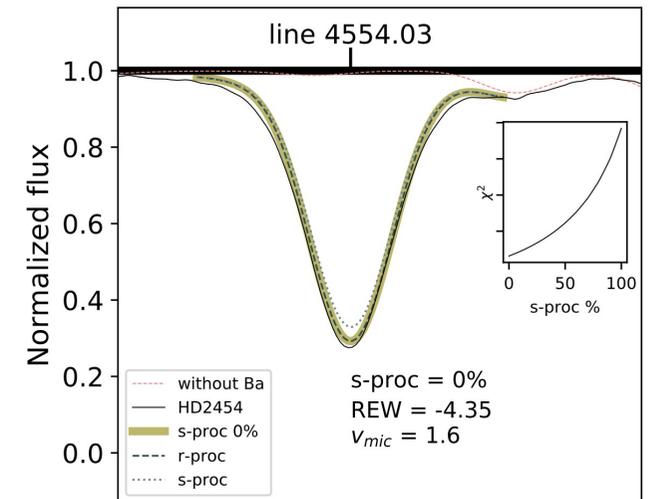
Resonance lines:

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

Hypothesis: $A(\text{Ba}) = A(\text{Ce})$

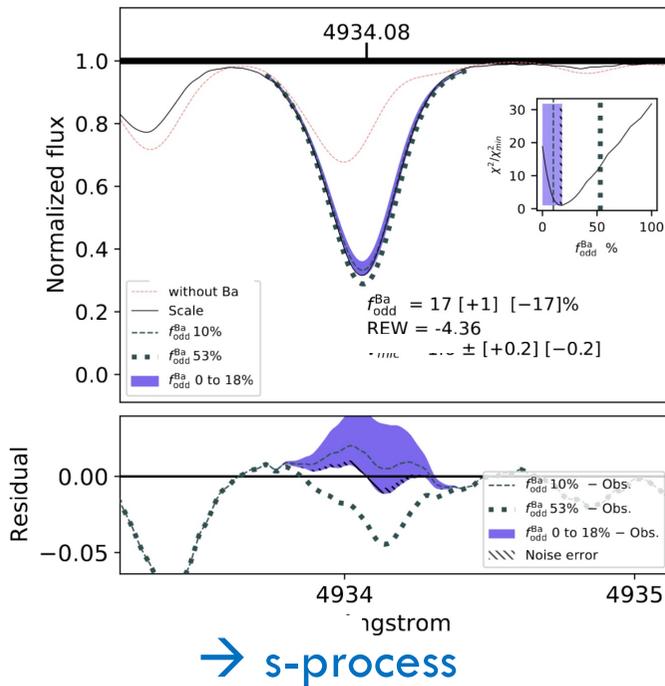


Thibault Merle

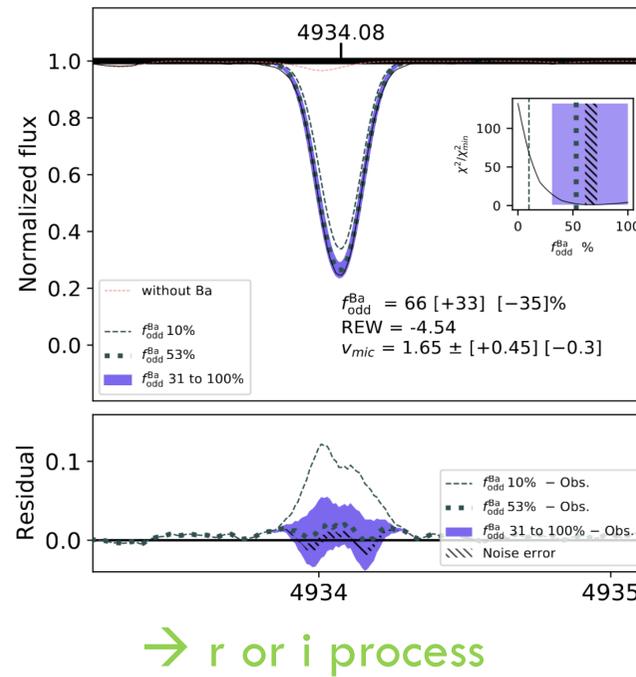


CEMP-rs classification attempts: Isotopic ratio

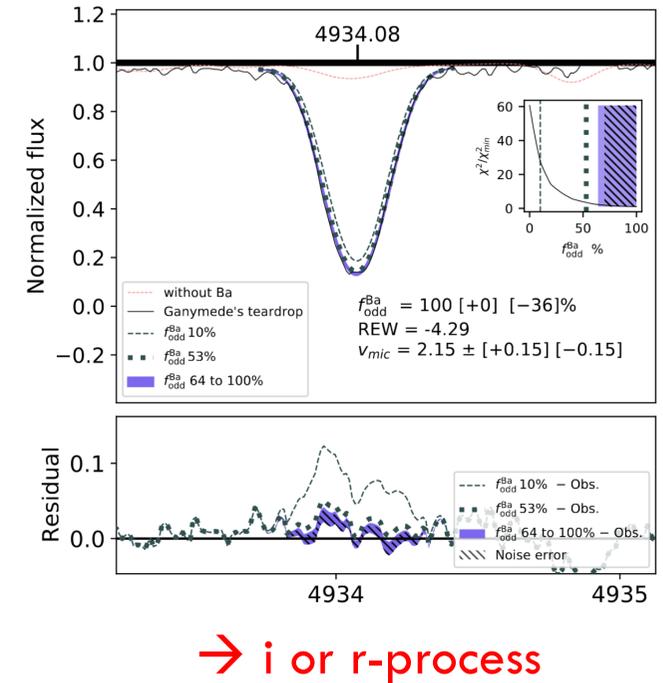
HD 2454
s-process (Tomkin+89)



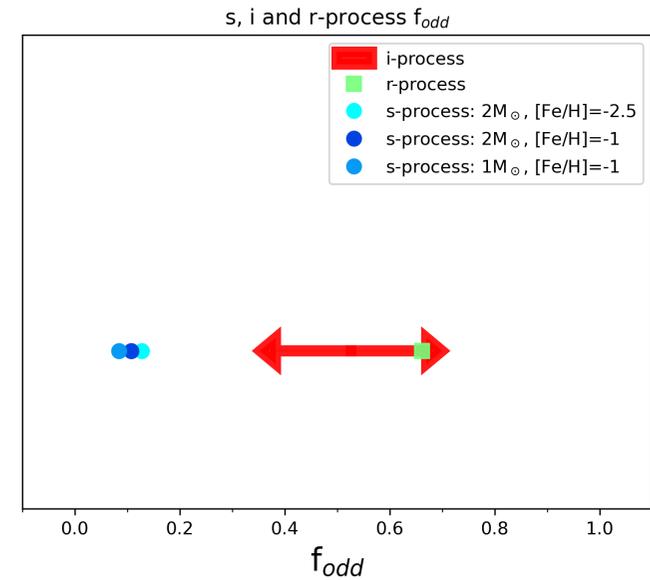
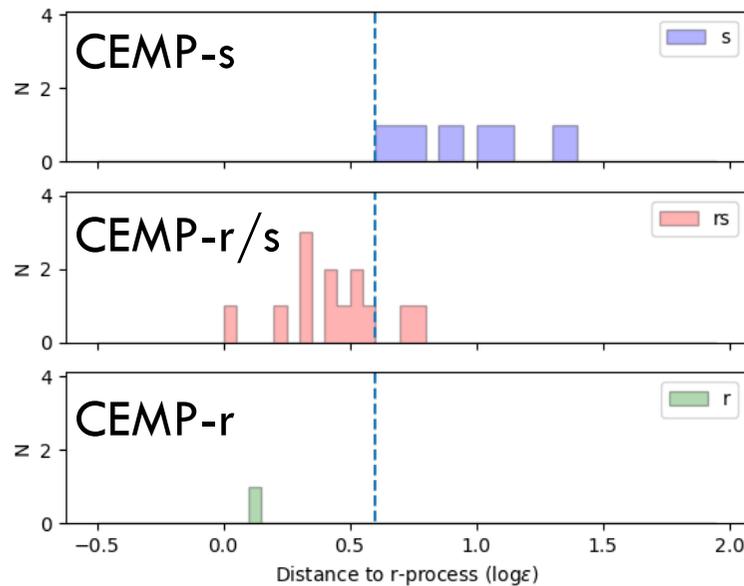
HD 115444
r-process (Snedden+2009)



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



CEMP-rs classification attempts: Isotopic ratio

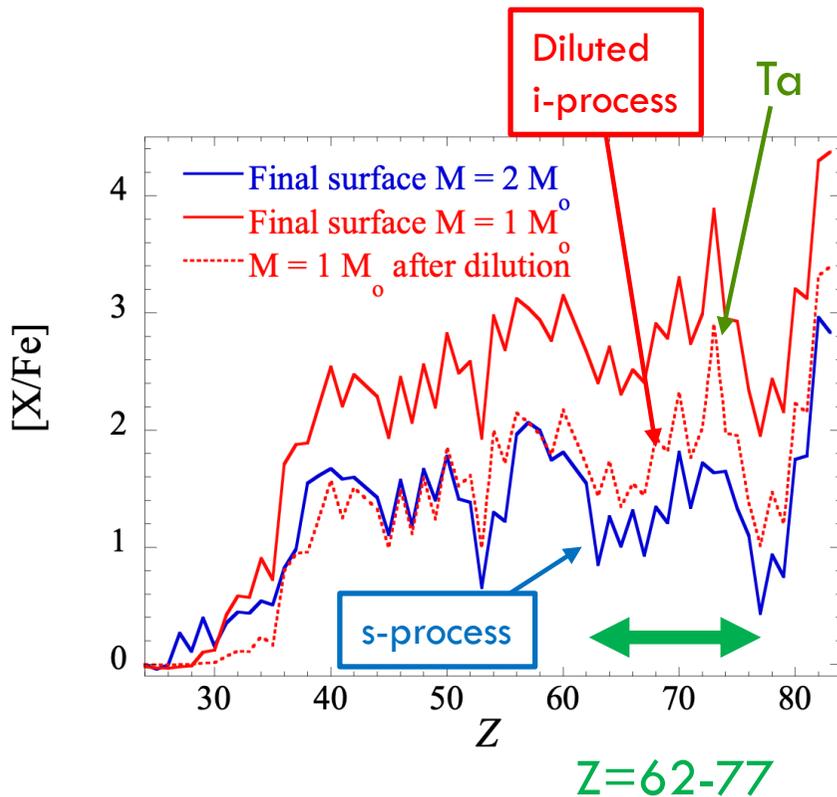


s-process (Tomkin+89)
 r-process (Snedden+2009)
 CEMP-rs (Hansen+2015)

Star	Signed distance	χ^2_{s-pro}	χ^2_{i-pro}	χ^2_{r-pro}	f_{odd}^{Ba} 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
 r or i-process
 i or r-process

CEMP-rs classification attempts: heavy r



Periodic Table of the Elements

1 1A H Hydrogen 1.008	2 2A He Helium 4.003																
3 Li Lithium 6.941	4 Be Beryllium 9.012											5 3A B Boron 10.811	6 4A C Carbon 12.011	7 5A N Nitrogen 14.007	8 6A O Oxygen 15.999	9 7A F Fluorine 18.998	10 8A Ne Neon 20.180
11 Na Sodium 22.990	12 Mg Magnesium 24.305	3 3B Sc Scandium 44.956	4 4B Ti Titanium 47.867	5 5B V Vanadium 50.942	6 6B Cr Chromium 51.996	7 7B Mn Manganese 54.938	8 8 Fe Iron 55.845	9 VIII 8 Co Cobalt 58.933	10 VIII 8 Ni Nickel 58.693	11 1B Cu Copper 63.546	12 2B Zn Zinc 65.38	13 3A Al Aluminum 26.982	14 4A Si Silicon 28.086	15 5A P Phosphorus 30.974	16 6A S Sulfur 32.066	17 7A Cl Chlorine 35.453	18 8A Ar Argon 39.948
19 K Potassium 39.098	20 Ca Calcium 40.078	21 Sc Scandium 44.956	22 4B Ti Titanium 47.867	23 5B V Vanadium 50.942	24 6B Cr Chromium 51.996	25 7B Mn Manganese 54.938	26 8 Fe Iron 55.845	27 VIII 8 Co Cobalt 58.933	28 VIII 8 Ni Nickel 58.693	29 1B Cu Copper 63.546	30 2B Zn Zinc 65.38	31 3A Ga Gallium 69.723	32 4A Ge Germanium 72.631	33 5A As Arsenic 74.922	34 6A Se Selenium 78.971	35 7A Br Bromine 79.904	36 8A Kr Krypton 83.798
37 Rb Rubidium 85.468	38 Sr Strontium 87.62	39 Y Yttrium 88.906	40 Zr Zirconium 91.224	41 Nb Niobium 92.906	42 Mo Molybdenum 95.95	43 Tc Technetium 98.907	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.906	46 Pd Palladium 106.42	47 Ag Silver 107.868	48 Cd Cadmium 112.414	49 In Indium 114.818	50 Sn Tin 118.711	51 Sb Antimony 121.760	52 Te Tellurium 127.6	53 I Iodine 126.904	54 Xe Xenon 131.294
55 Cs Cesium 132.905	56 Ba Barium 137.328	57-71 Lanthanide Series La Ce Pr Nd Pm Sm Eu Gd Tb Dy Ho Er Tm Yb Lu	72 Hf Hafnium 178.49	73 Ta Tantalum 180.948	74 W Tungsten 183.84	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.227	78 Pt Platinum 195.085	79 Au Gold 196.967	80 Hg Mercury 200.592	81 Tl Thallium 204.383	82 Pb Lead 207.2	83 Bi Bismuth 208.980	84 Po Polonium [209]	85 At Astatine [209]	86 Rn Radon 222.018
87 Fr Francium 223.020	88 Ra Radium 226.025	89-103 Actinide Series Ac Th Pa U Np Pu Am Cm Bk Cf Es Fm Md No Lr	104 Rf Rutherfordium [261]	105 Db Dubnium [262]	106 Sg Seaborgium [266]	107 Bh Bohrium [264]	108 Hs Hassium [269]	109 Mt Meitnerium [278]	110 Ds Darmstadtium [281]	111 Rg Roentgenium [280]	112 Cn Copernicium [285]	113 Nh Nihonium [286]	114 Fl Flerovium [289]	115 Mc Moscovium [289]	116 Lv Livermorium [293]	117 Ts Tennessine [294]	118 Og Oganesson [294]

Often measured

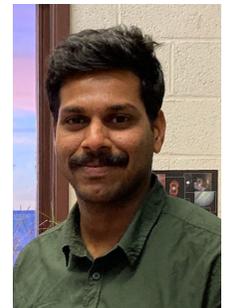
Not so often measured

Stellar sample

Name	T_{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
- 3280-6835Å



HERMES@Mercator

- R=85000
- 3800-8000Å

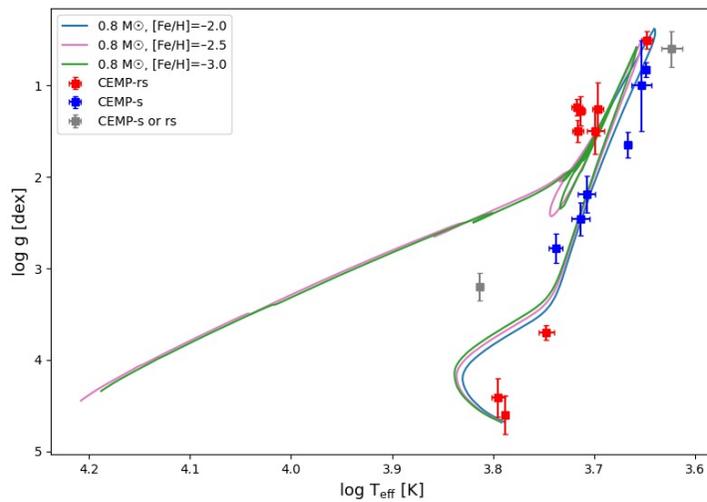


MARCS model atmosphere (Gustafsson+ 2008)
Turbospectrum radiative transfer code (Plez 2012)
Bacchus (Masseron + 2016)
Non-LTE corrections when available in the literature

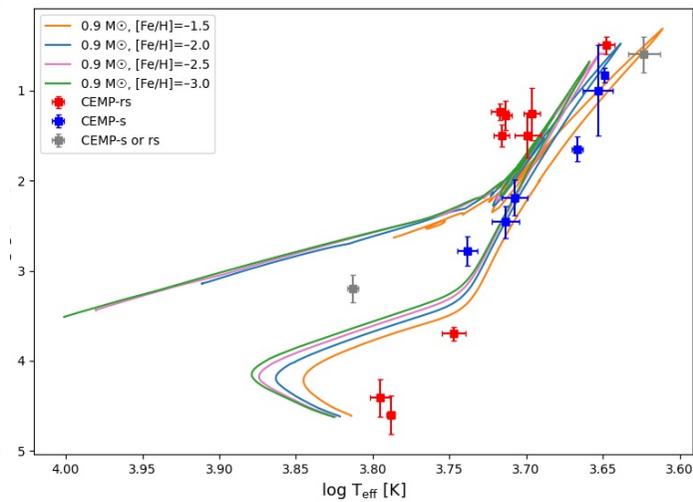
Kiel diagrams

Starevol evolutionary tracks
 $-3 < [\text{Fe}/\text{H}] < -1.5$

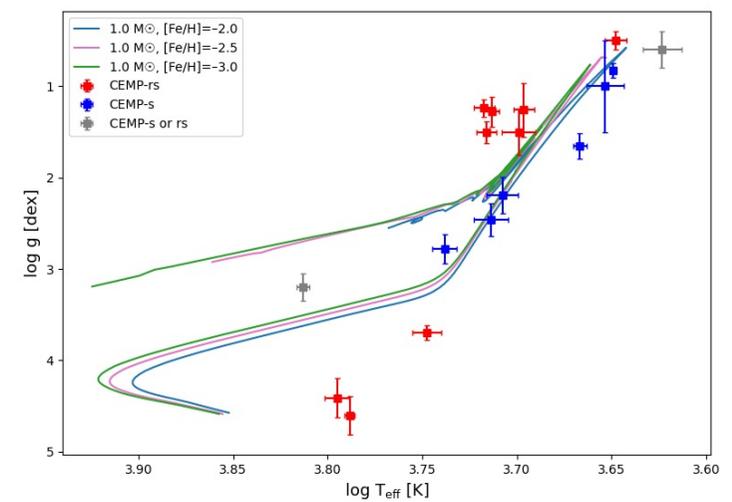
0.8M



0.9M

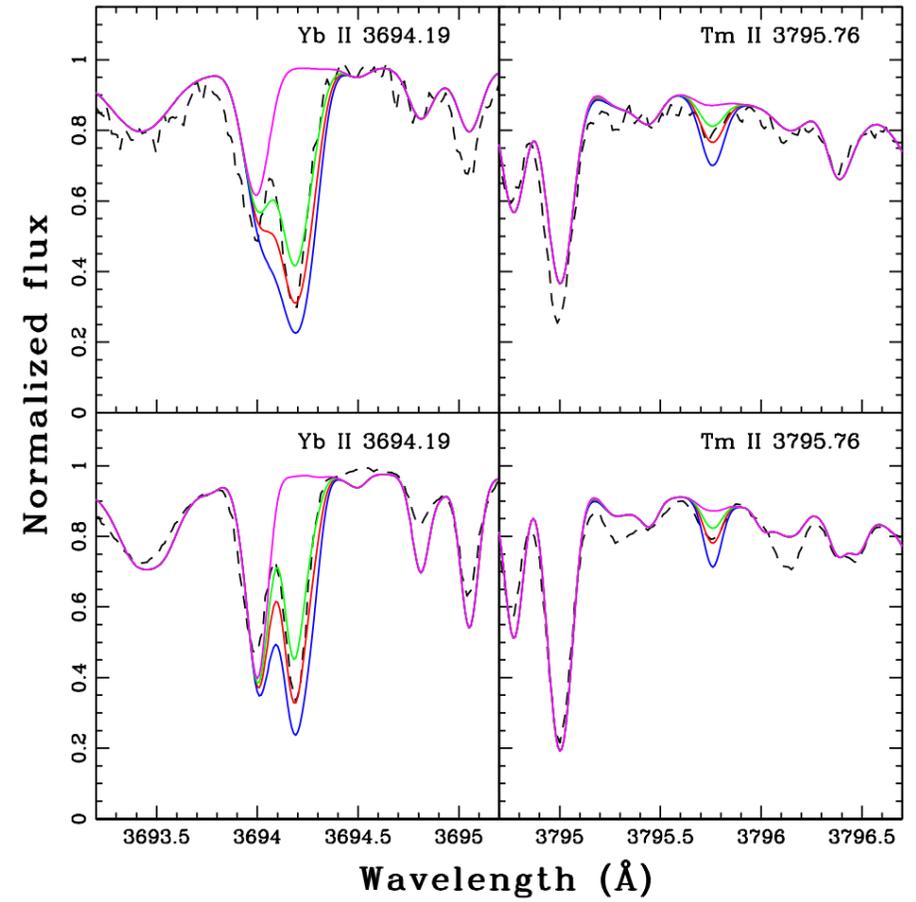
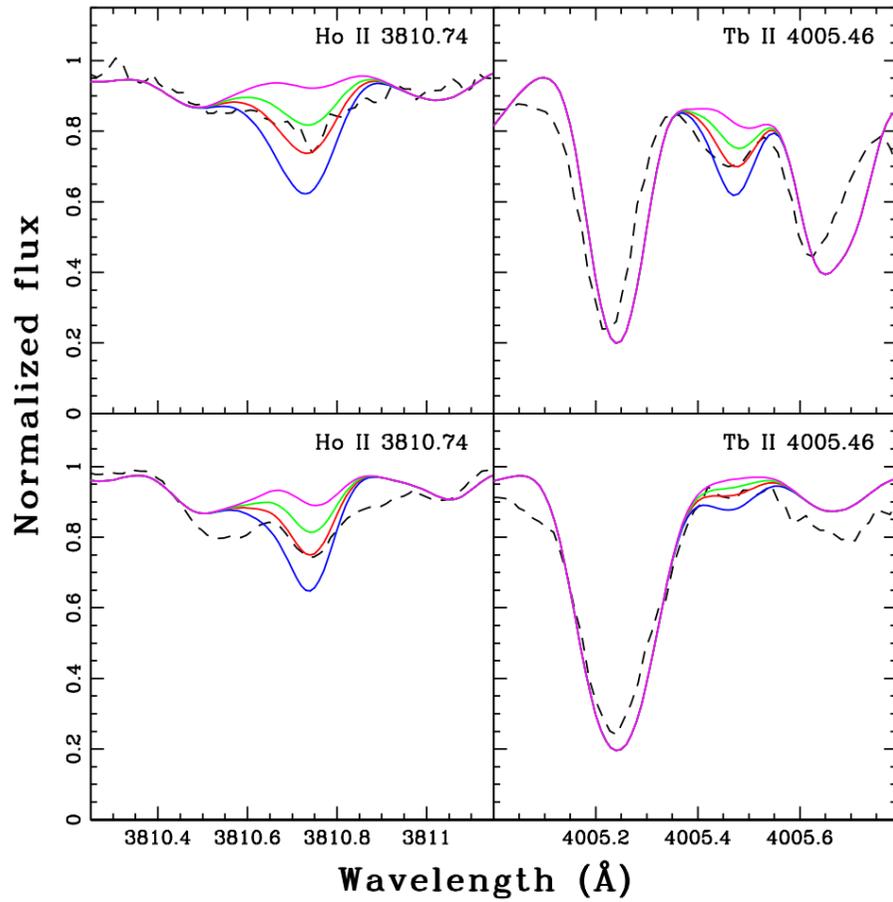


1.0M



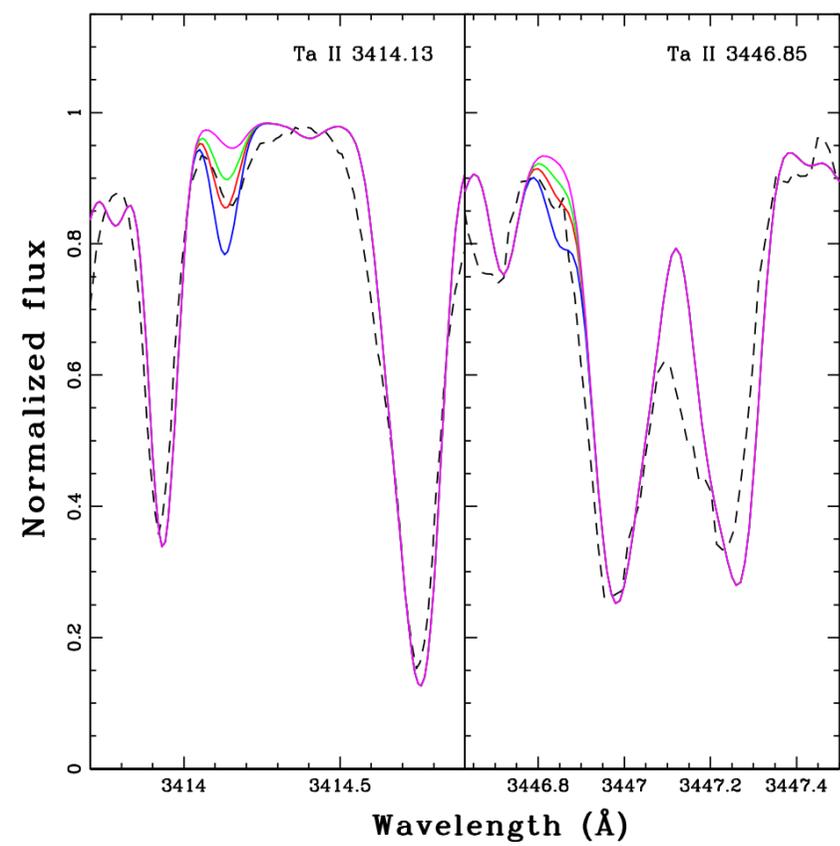
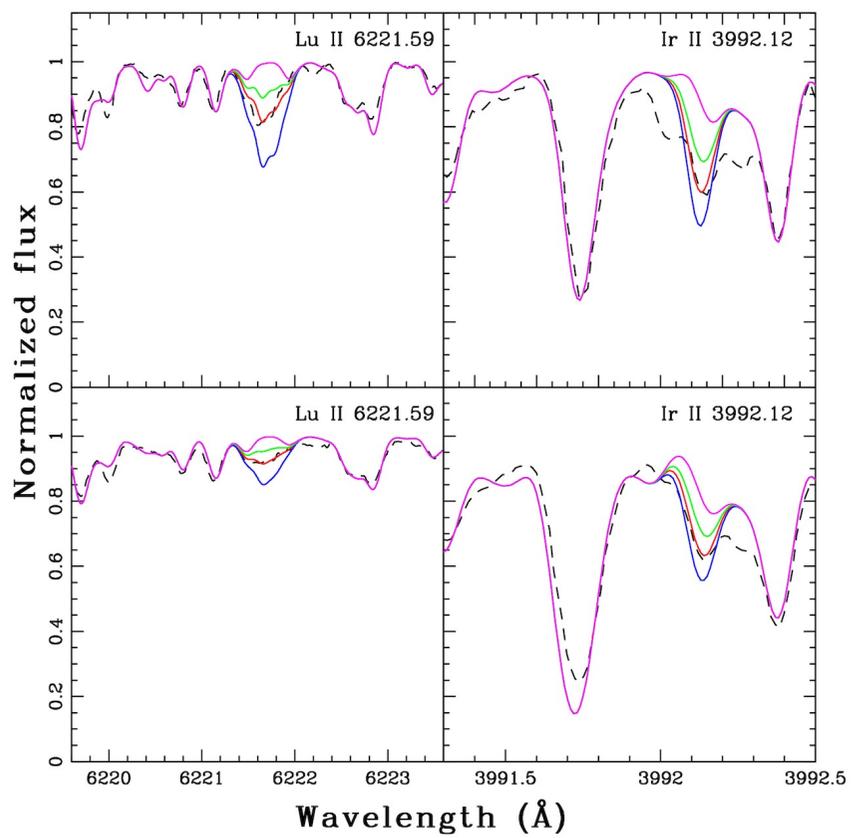
Ho II, Tb II

Yb II, Tm II



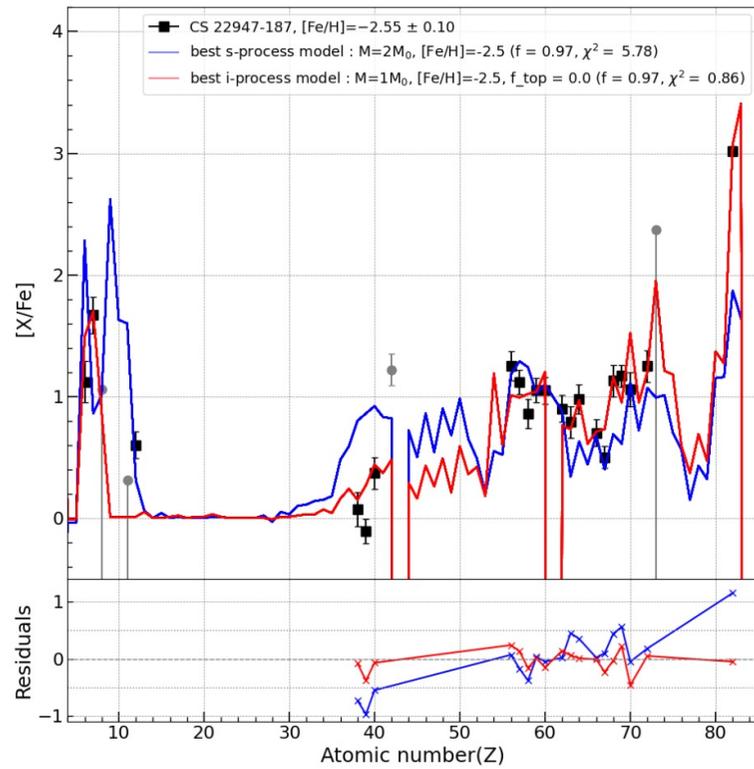
Lu II, Ir II

Ta II

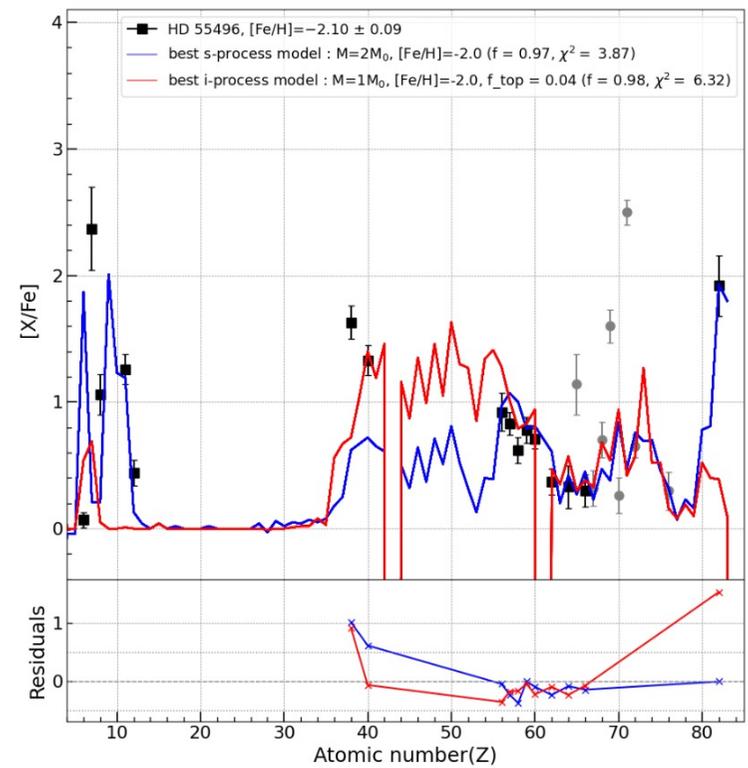


Abundance profiles

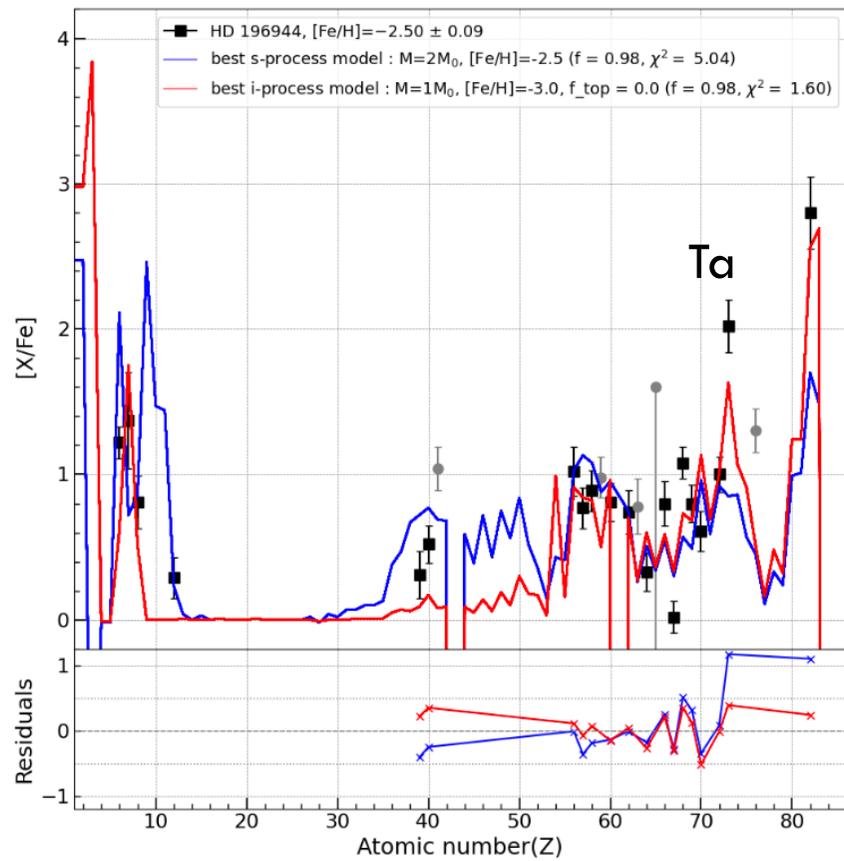
CEMP-rs



CEMP-s



Abundance profiles



Classification result

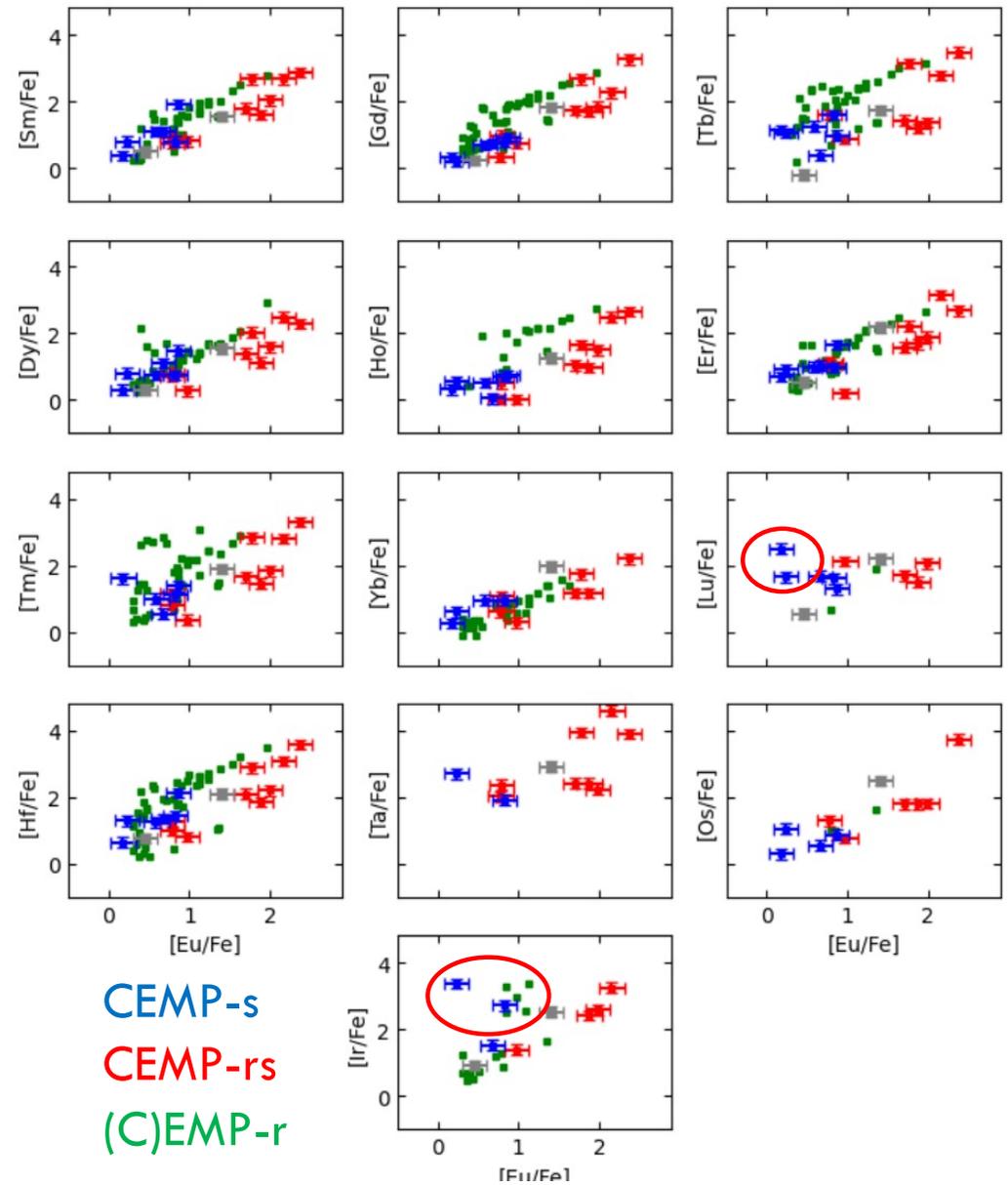
Object	[s/r]			Distance to r				Chi2 with models			Final Class
	[s/r]			Distance				χ^2			
	[La/Eu]	[Ba/Eu]	Class _{sr}	d_s	Class _{d_s}	d_{rms}	Class _{d_{rms}}	χ_s^2	χ_i^2	Class χ^2	
CS 22891-171	0.55	0.37	s/rs	0.48	rs	0.73	s/rs	3.81	1.66	rs	rs
CS 22947-187	0.33	0.46	rs	0.43	rs	0.64	rs	5.78	0.86	rs	
HD 145777	0.10	0.02	rs	0.47	rs	0.57	rs	2.01	2.58	s/rs	
HD 187861	-0.05	-0.16	r/rs	0.04	r	0.48	rs	6.54	1.78	rs	
HD 196944	-0.01	0.24	rs	0.39	rs	0.52	rs	5.04	1.60	rs	
HD 224959	0.17	0.19	rs	0.35	rs	0.56	rs	3.29	1.61	rs	
SDSS J0912-0216	0.24	-0.27	rs	0.52	rs	0.68	s/rs	19.87	8.29	rs?	
SDSS J1036+1212	0.17	-0.98	rs	0.38	rs	0.72	s/rs	27.79	8.17	rs?	
SDSS J1349-0229	0.01	-0.29	rs	0.40	rs	0.59	rs	25.81	13.63	rs?	
CS 22887-048	0.50	0.42	s	0.63	s/rs	0.75	s	3.69	1.30	rs	
CS 22942-019	0.51	0.79	s	0.91	s	1.07	s	2.41	1.08	rs	
CS 29512-073	0.58	0.68	s	0.77	s	0.90	s	3.38	0.88	rs	
CS 30322-023	0.82	0.64	s	0.83	s	0.97	s	2.60	1.87	rs	
HD 26	0.92	0.94	s	1.18	s	1.28	s	2.09	1.88	s/rs	
HD 55496	-	-	-	1.00	s	1.22	s	3.87	6.32	s	
HD 198269	0.55	0.55	s	0.83	s	0.95	s	1.10	1.17	s/rs	
HD 206983	0.30	0.27	rs	0.60	s/rs	0.70	s/rs	1.24	0.87	s/rs	

Classification result

Object	[s/r]			Distance to r				Chi2 with models			Final Class
	[s/r]			Distance				χ^2			
	[La/Eu]	[Ba/Eu]	Class _{sr}	d_s	Class _{d_s}	d_{rms}	Class _{d_{rms}}	χ_s^2	χ_i^2	Class χ^2	
CS 22891-171	0.55	0.37	s/rs	0.48	rs	0.73	s/rs	3.81	1.66	rs	rs
CS 22947-187	0.33	0.46	rs	0.43	rs	0.64	rs	5.78	0.86	rs	
HD 145777	0.10	0.02	rs	0.47	rs	0.57	rs	2.01	2.58	s/rs	
HD 187861	-0.05	-0.16	r/rs	0.04	r	0.48	rs	6.54	1.78	rs	
HD 196944	-0.01	0.24	rs	0.39	rs	0.52	rs	5.04	1.60	rs	
HD 224959	0.17	0.19	rs	0.35	rs	0.56	rs	3.29	1.61	rs	
SDSS J0912-0216	0.24	-0.27	rs	0.52	rs	0.68	s/rs	19.87	8.29	rs?	
SDSS J1036+1212	0.17	-0.98	rs	0.38	rs	0.72	s/rs	27.79	8.17	rs?	
SDSS J1349-0229	0.01	-0.29	rs	0.40	rs	0.59	rs	25.81	13.63	rs?	
CS 22887-048	0.50	0.42	s	0.63	s/rs	0.75	s	3.69	1.30	rs	
CS 22942-019	0.51	0.79	s	0.91	s	1.07	s	2.41	1.08	rs	
CS 29512-073	0.58	0.68	s	0.77	s	0.90	s	3.38	0.88	rs	
CS 30322-023	0.82	0.64	s	0.83	s	0.97	s	2.60	1.87	rs	
HD 26	0.92	0.94	s	1.18	s	1.28	s	2.09	1.88	s/rs	
HD 55496	-	-	-	1.00	s	1.22	s	3.87	6.32	s	
HD 198269	0.55	0.55	s	0.83	s	0.95	s	1.10	1.17	s/rs	
HD 206983	0.30	0.27	rs	0.60	s/rs	0.70	s/rs	1.24	0.87	s/rs	

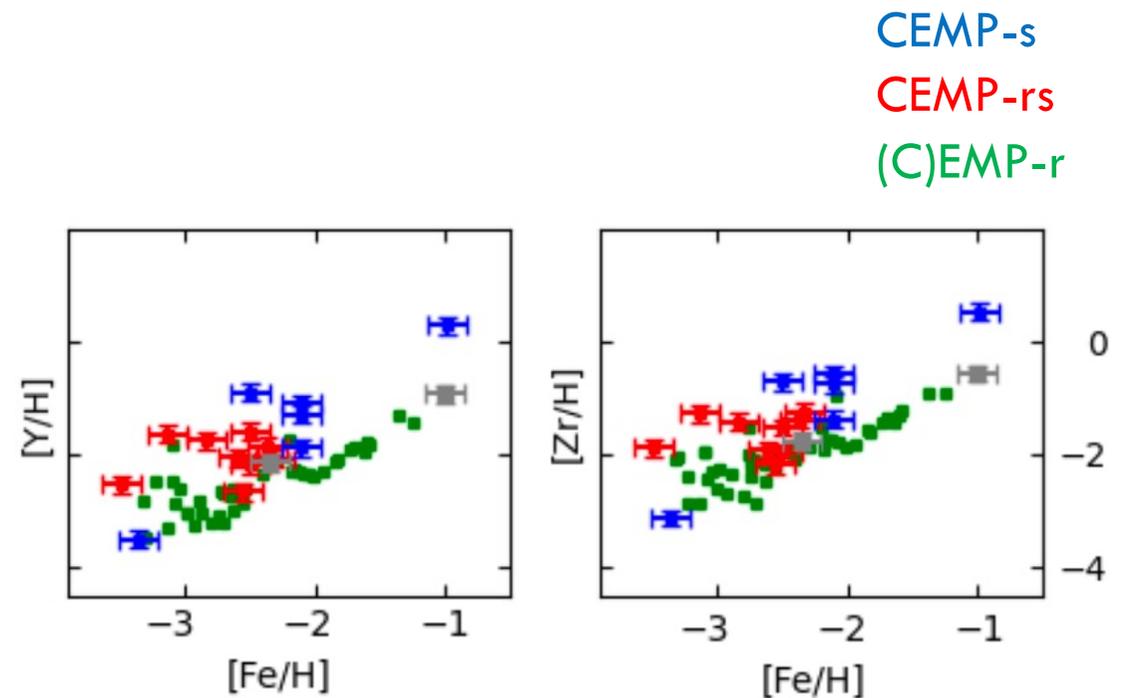
r-r correlation

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

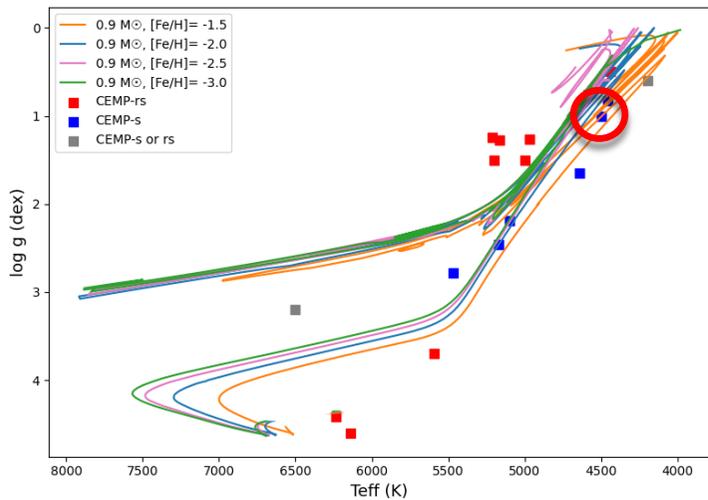
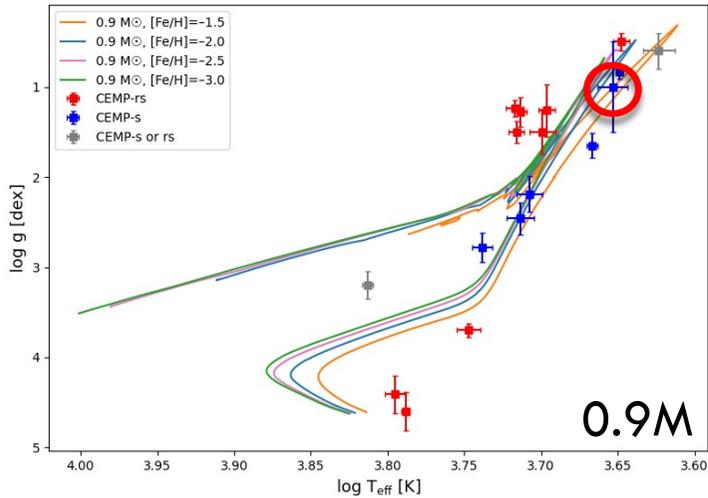


Mainly-s elements with $[\text{Fe}/\text{H}]$

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



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



Masseron+ 2006

$[Fe/H] = -3.35$

Not-constraining limit on T_c :

$\log N_{T_c} < -1.4$

↑ TP-AGB ↓

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
 - ($^{12}\text{C}/^{13}\text{C}$)

- Interpretation challenges:
 - The scenario (**r+s** versus **i-process**): still uncertain
(especially since Thorium does provide a definitive test for the r+s scenario)