From the s-process to the i-process: A new perspective on the chemical enrichment of extrinsic stars

Sophie Van Eck; Riano Giribaldi; Thibault Merle; Adrian Lambotte; Drisya Karinkuzhi; Stéphane Goriely; Arthur Choplin; Lionel Siess; Alain Jorissen

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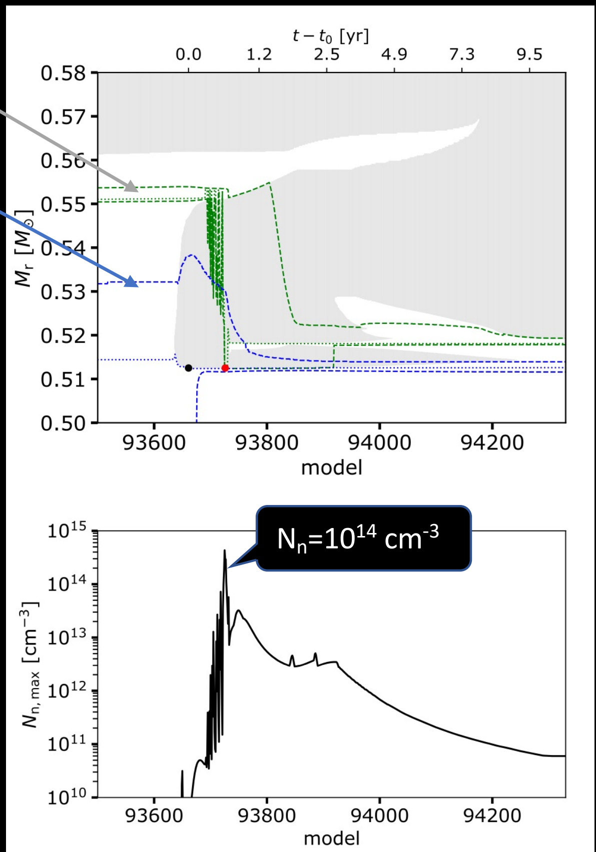
EOS THE EXCELLENCE OF SCIENCE

Intermediate (i-) process: theory

Proton injection event in a low-Z AGB model

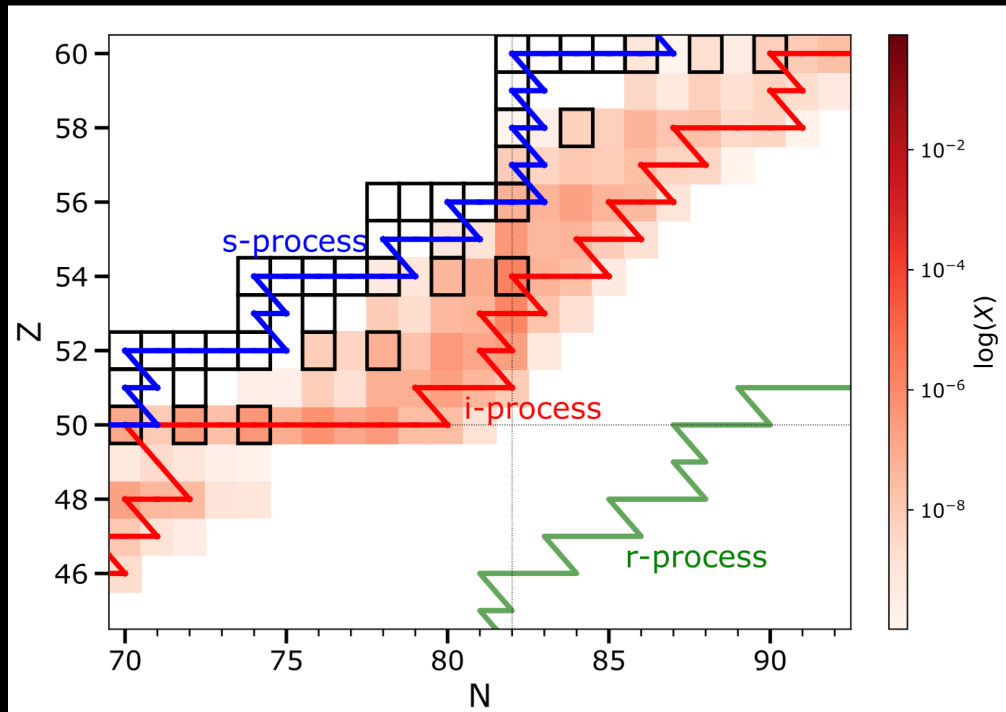
H-burning shell

He-burning shell



Choplin+ 2021

Arthur Choplin
Sébastien Martinet



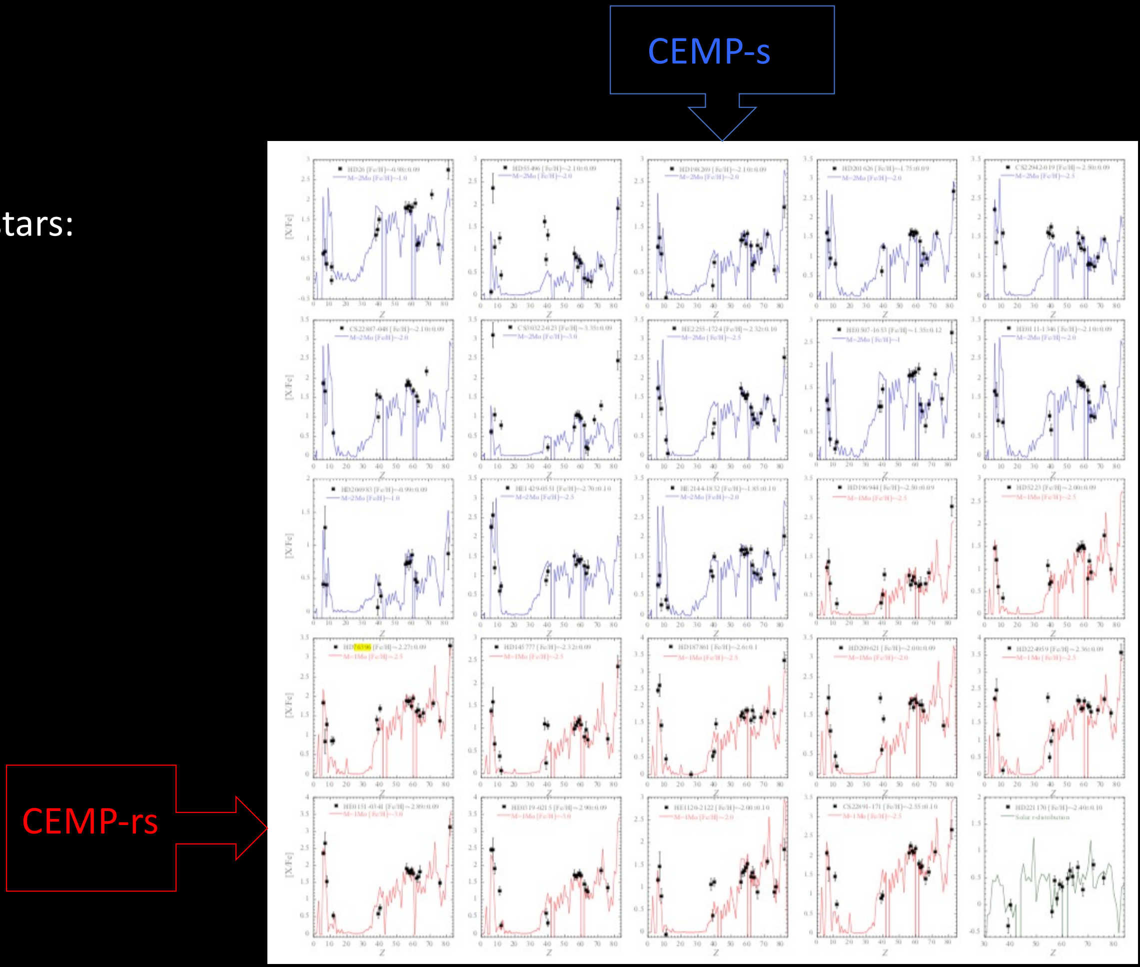
Choplin+ 2023

Intermediate (i-) process: abundance measurements

Observationnally:

Hybrid rs pattern found in:

- CEMP-rs
- Higher metallicity [Fe/H] ~ -0.5 C-enriched stars:
    - Cui+ 2014
    - Karinkuzhi+ 2018: HD 100503
    - den Hartogh+ 2022
    - Karinkuzhi+ 2021
    - Karinkuzhi+ 2023



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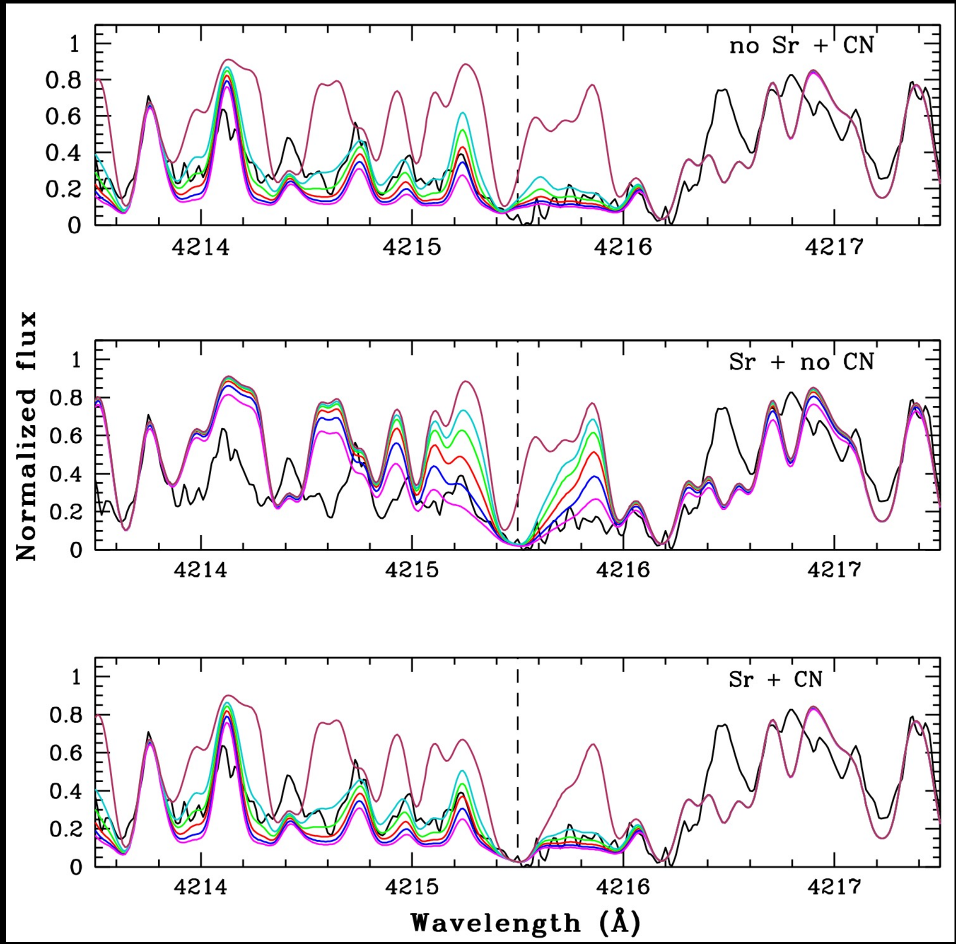
    - Karinkuzhi+ 2023

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

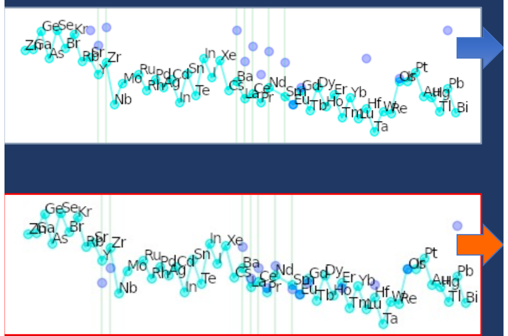
→1/3 not enriched in Sr

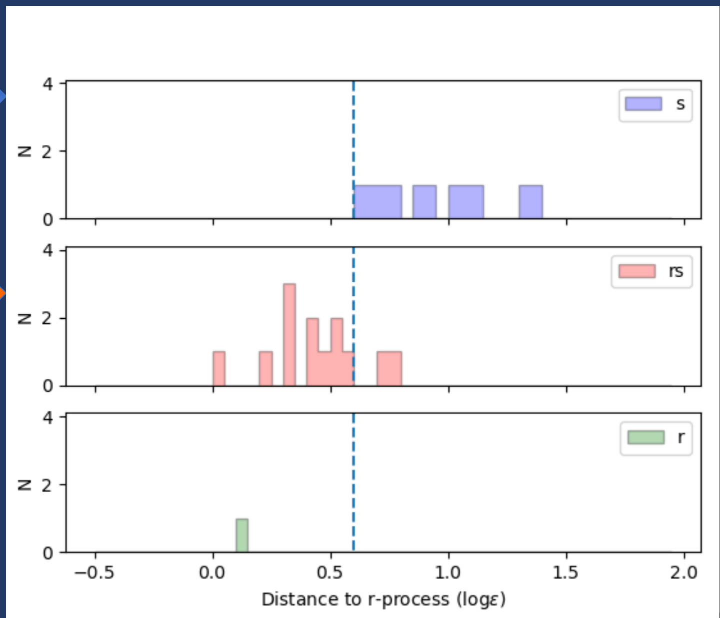


Characterizing the s, r and i nucleosynthetic processes

- Signed distance to the r-process
  Karinkuzhi+ 2023

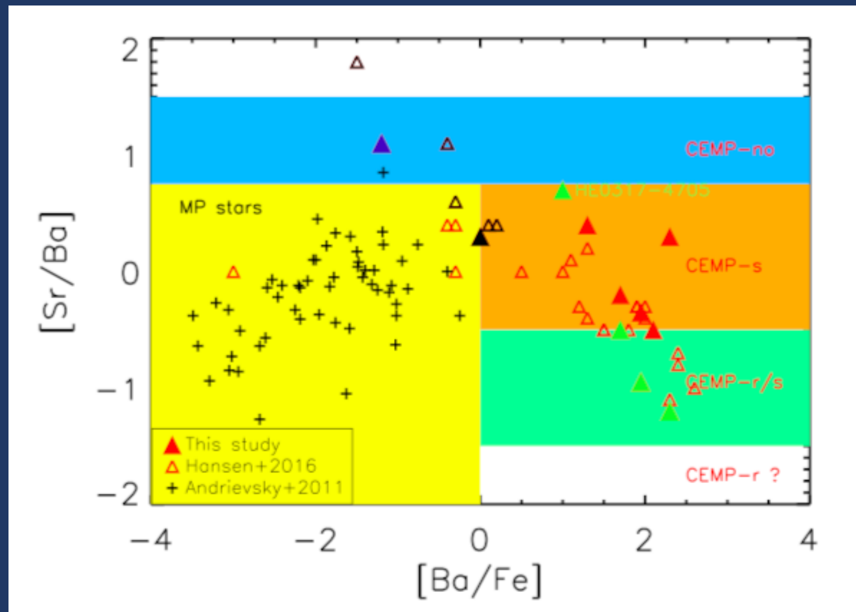
$$d_S = \frac{1}{N}\sum_{x_i}(\log_{10}\epsilon_{x_i,*} - \log_{10}\epsilon_{x_i,\mathrm{norm(r,*)}})$$





- Abundance ratio

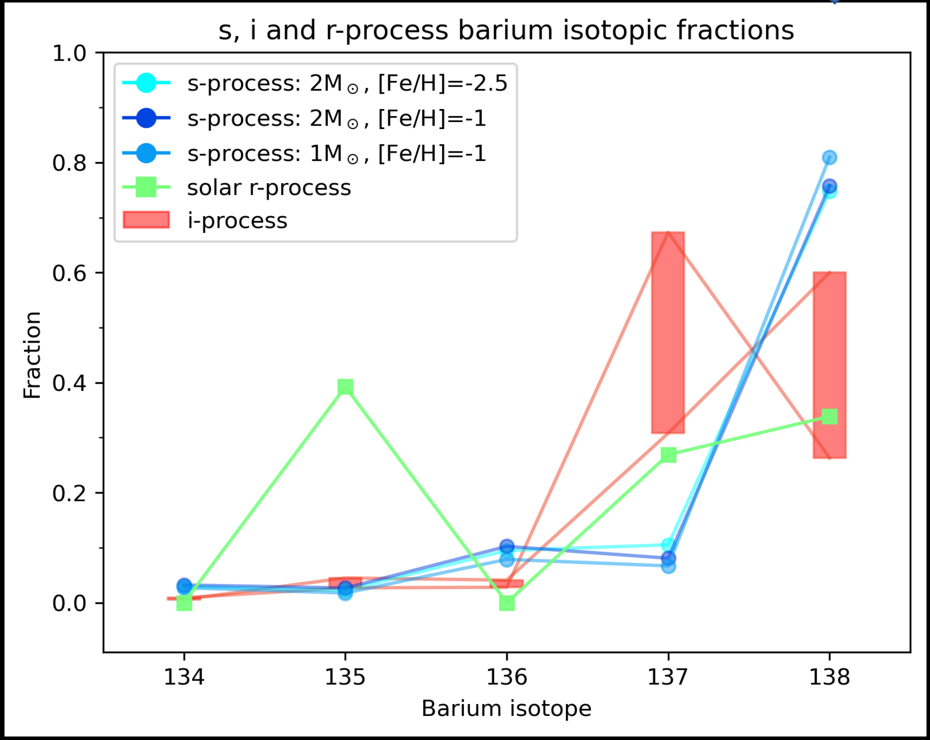
C.J. Hansen et al.
A&A 623, A128 (2019)

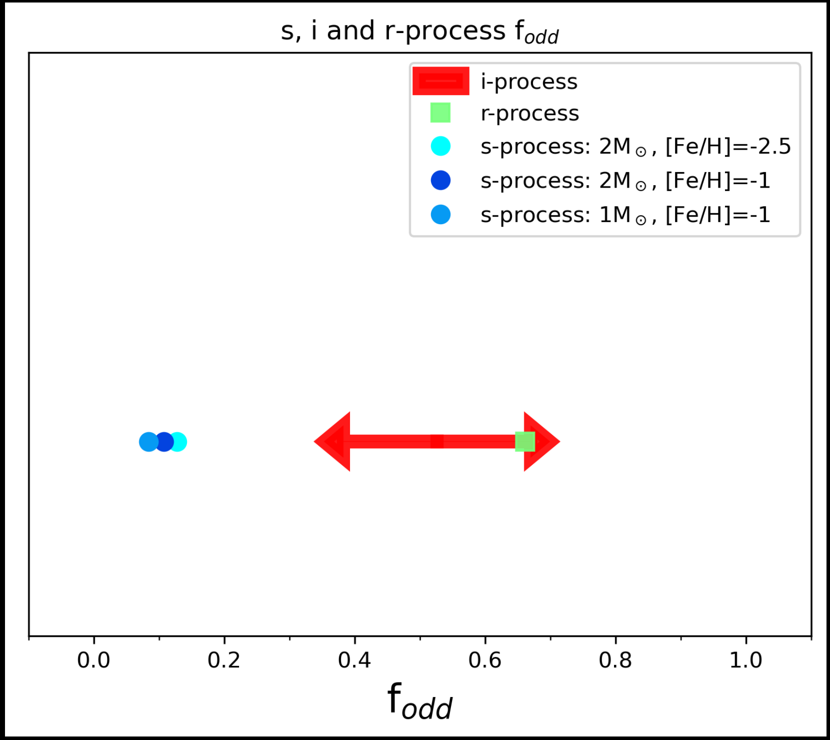


Using isotopes

Example: Barium

Magic nucleus
(N=82)





Adapted from Martinet+ 2024

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

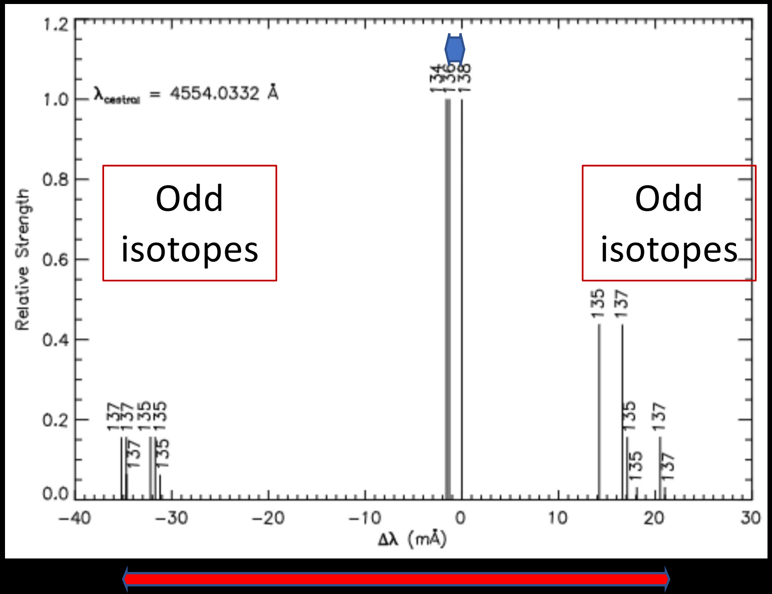
Ba II resonance line at 4554A

Maximum isotopic shift: 2mA

Isotopic shifts are too tiny to be detected

But hyperfine splitting is not!

Even and odd isotopes are affected differently by the s, i and r-processes

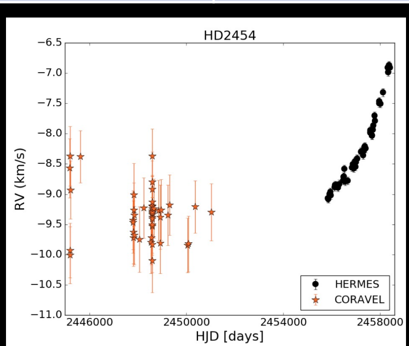


Gallagher+ 1996

Hyperfine splitting of odd isotopes: ~55mA

3 test cases:

Star	Previous classification	Source
HD 2454	Dwarf Barium star	Tomkin+1989
HD 115444	r-process star	Sneden 2009+
HE 2208-1239	CEMP r/s	Hansen+2015



Escorza+2019

Riano Giribaldi

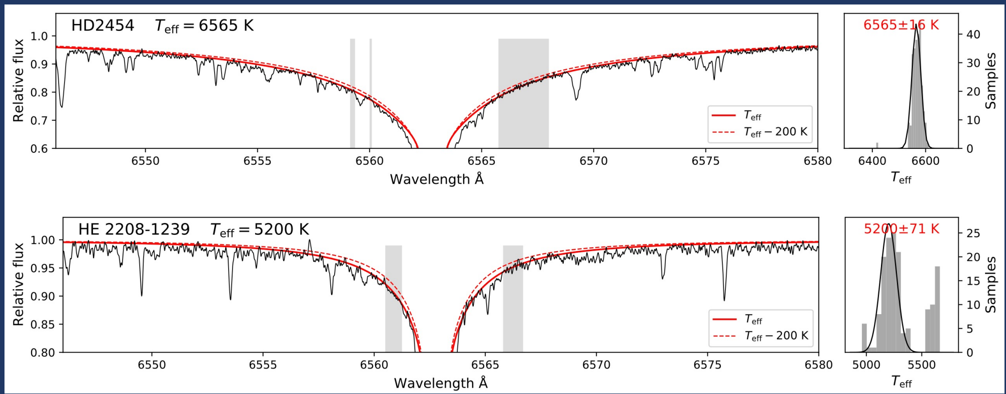
Thibault Merle

Also in collaboration with:
Maria Bergemann
Nick Storm
Richard Hoppe
Jonas Klevas

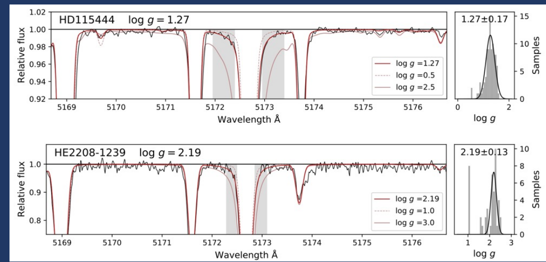
Arthur Choplin

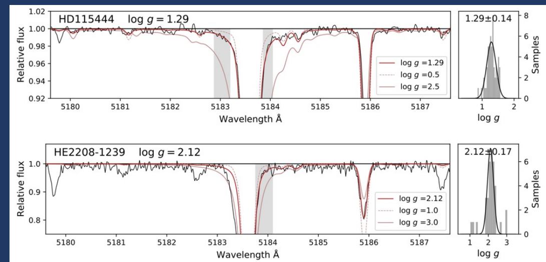
Stellar parameters

- **Teff:** Wings of (3D NLTE) Halpha fitting (Giribaldi+ 2019,2023, Amarsi 2018)



- **Surface gravity:** Mg Ib 5171, 5183 triplet fit (Giribaldi+ 2023)



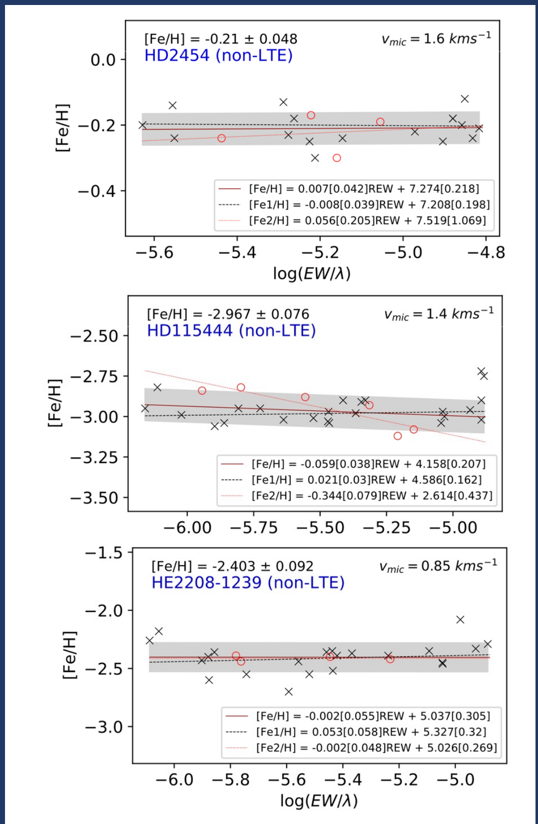


Stellar parameters

- Metallicity, microturbulence:

1D, Non-LTE Turbospectrum

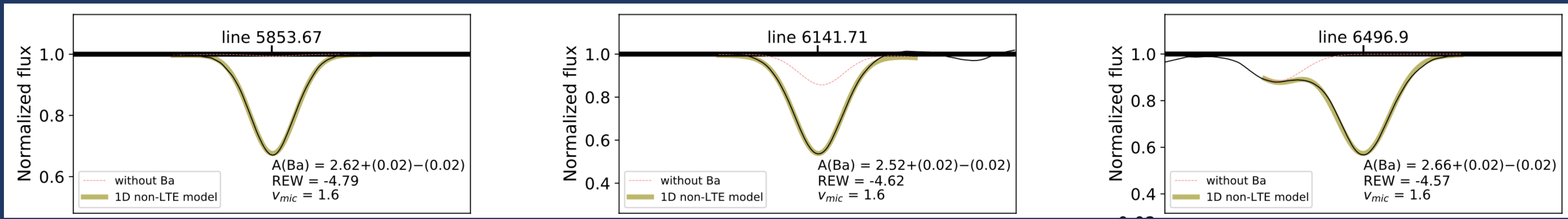
(Gerber+ 2023)



Star	$T_{\rm eff}$ (K)	log g (dex)	[Fe/H]$_{NLTE}$ (dex)	[Fe/H]$_{LTE}$ (dex)	v_{mic}^{NLTE} (km/s)
HD 2454	6565 ± 21	4.11 ± 0.06	−0.21 ± 0.05	−0.27 ± 0.05	1.60 ± 0.20
HD 115444	4667 ± 86	1.28 ± 0.15	−2.97 ± 0.08	−3.11 ± 0.10	1.40 ± 0.15
HE 2208−1239	5200 ± 75	2.14 ± 0.15	−2.40 ± 0.09		0.85 ± 0.20

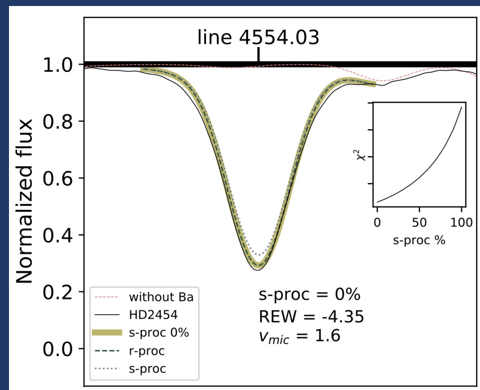
Barium abundance

Subordinate lines:



Resonance lines:

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

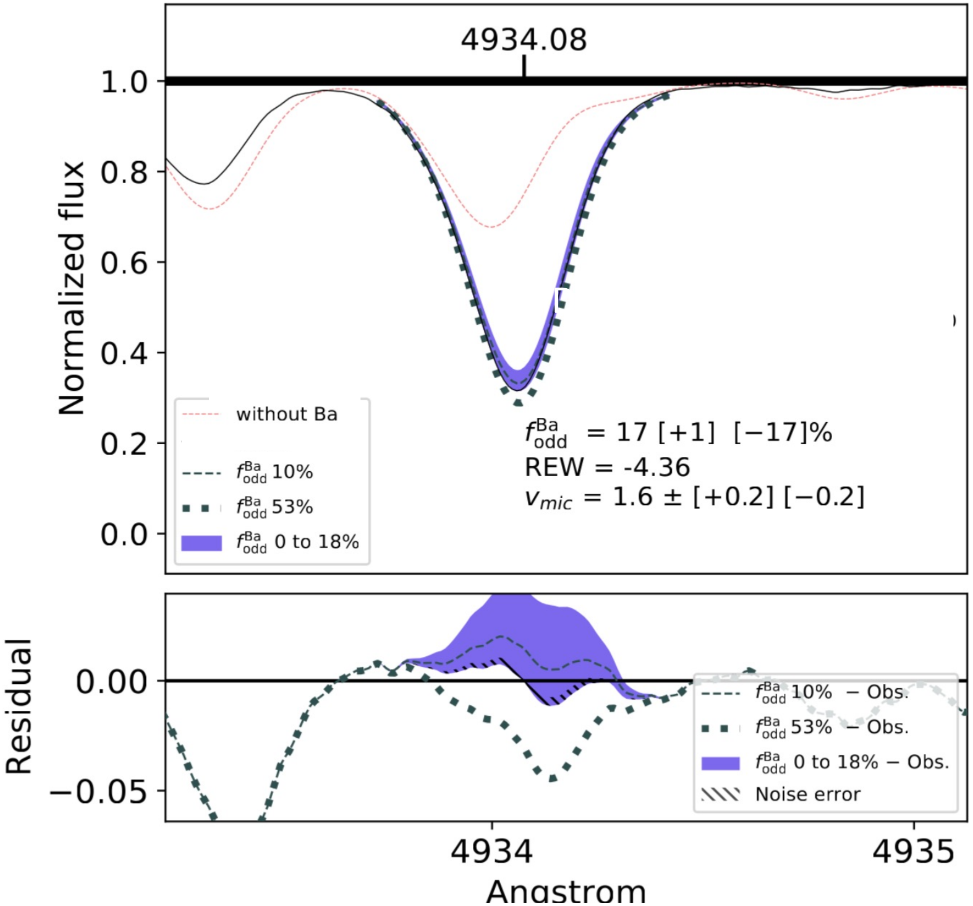


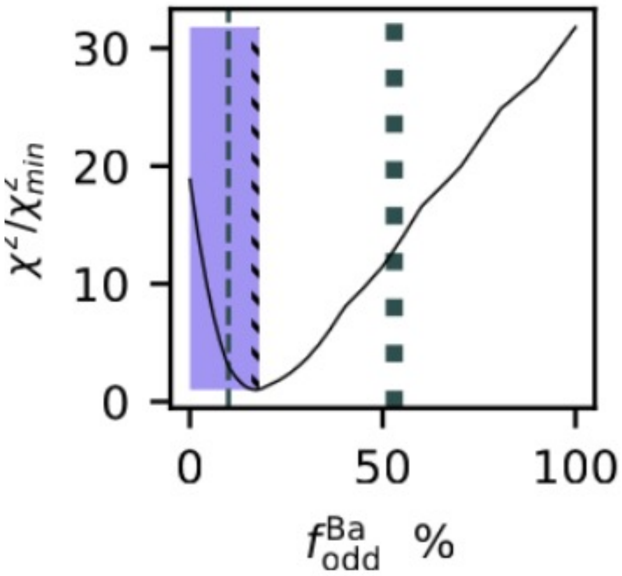
Hypothesis: A(Ba)=A(Ce)

Ba resonance line

HD 2454 (s-process star)

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

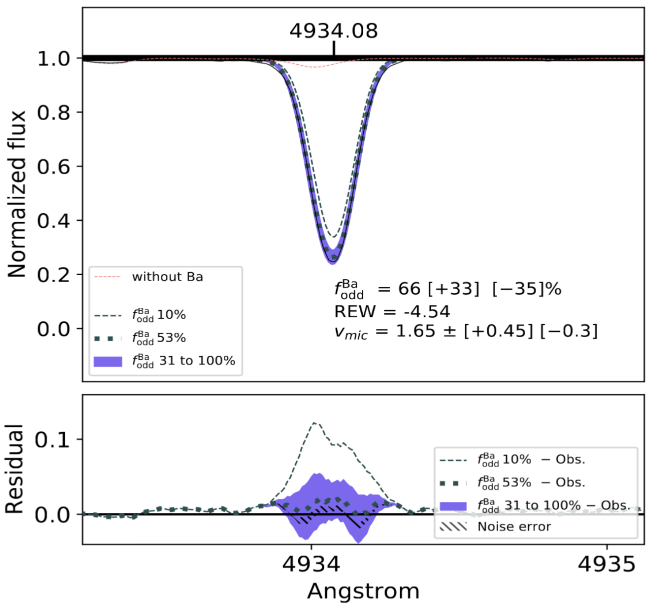


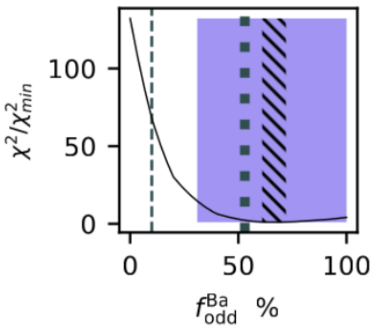


→ s-process

Ba resonance line

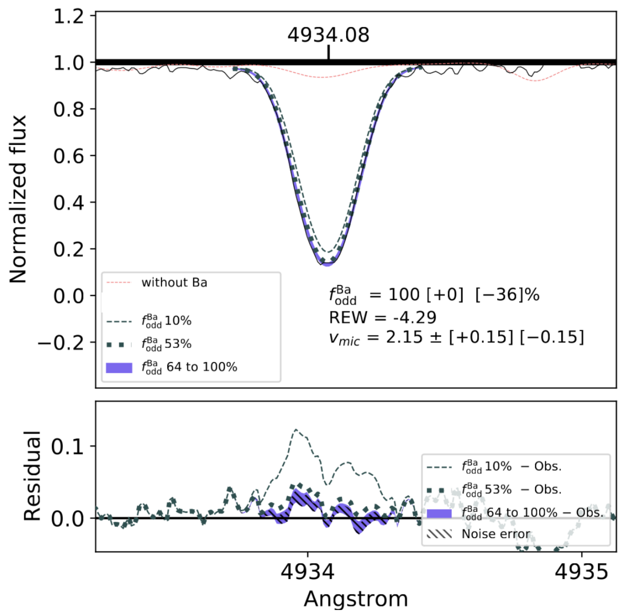
HD 115444
(litt: r-process star)

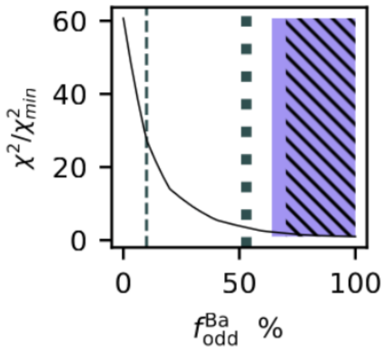




→ r or i process

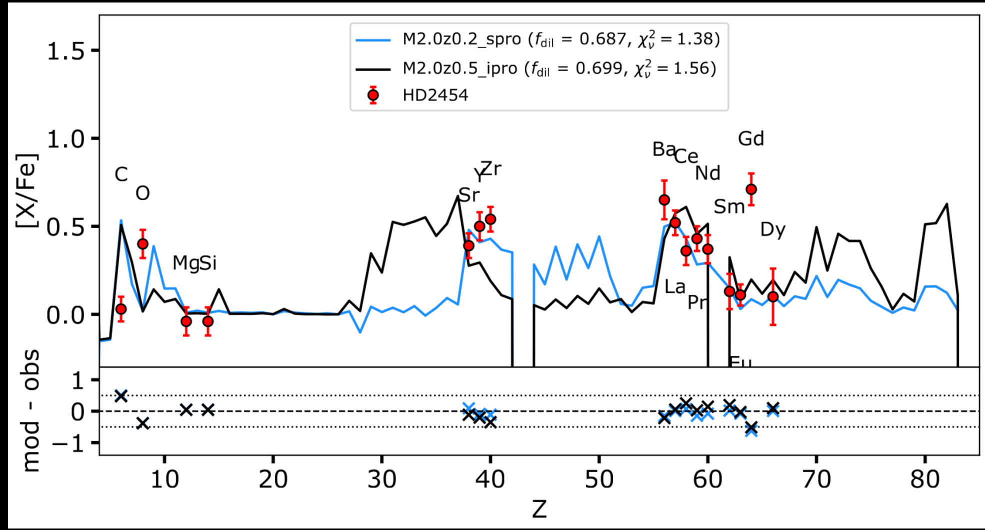
HE 2208-1239:
(litt: CEMP-r/s star)

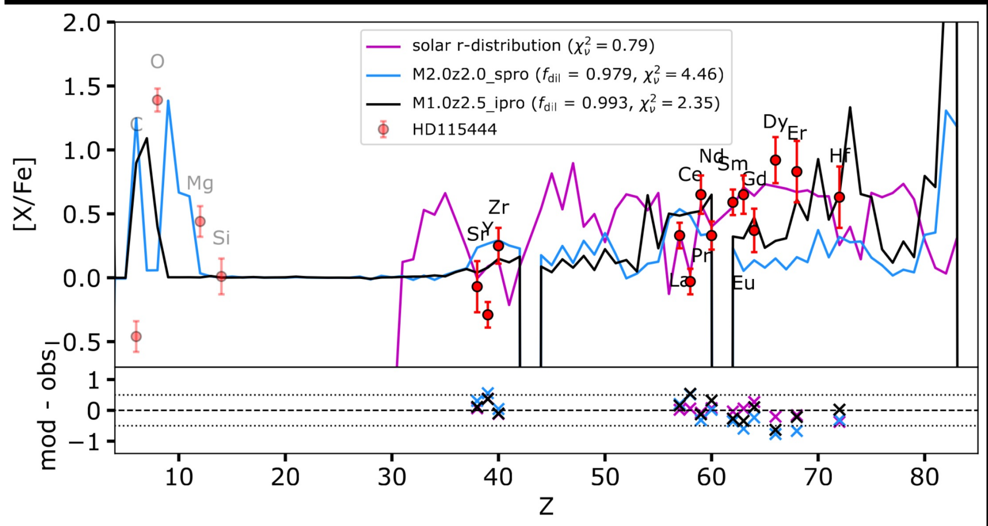


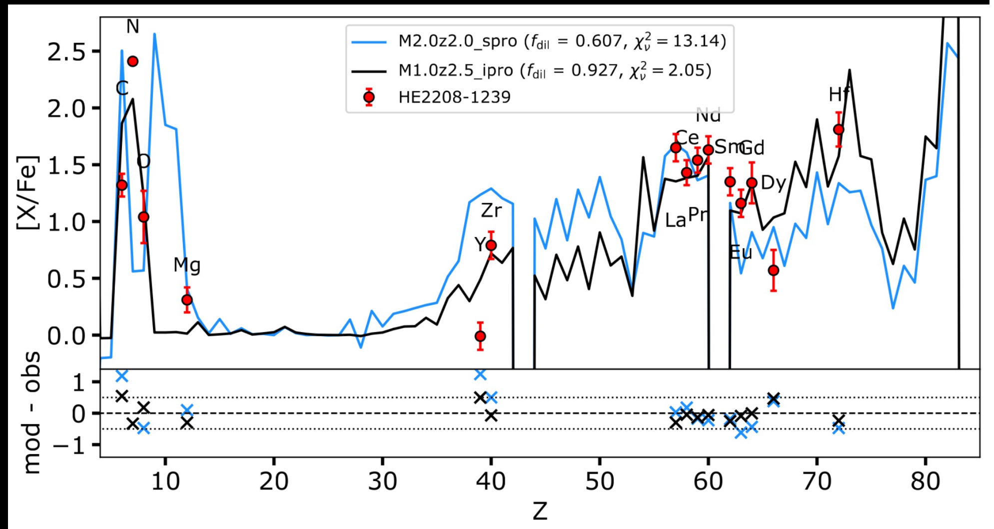


→ i or r-process

Chemical pattern

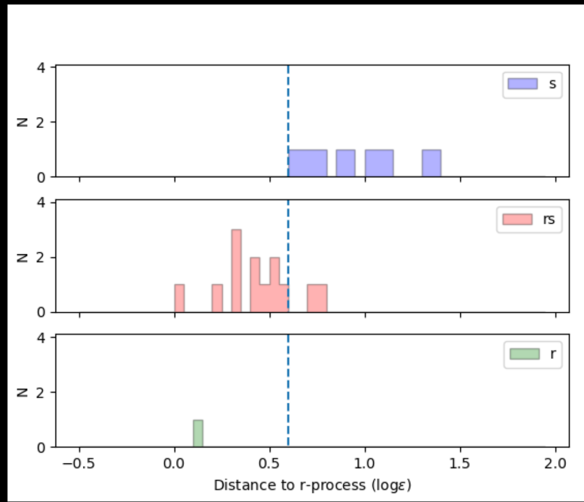


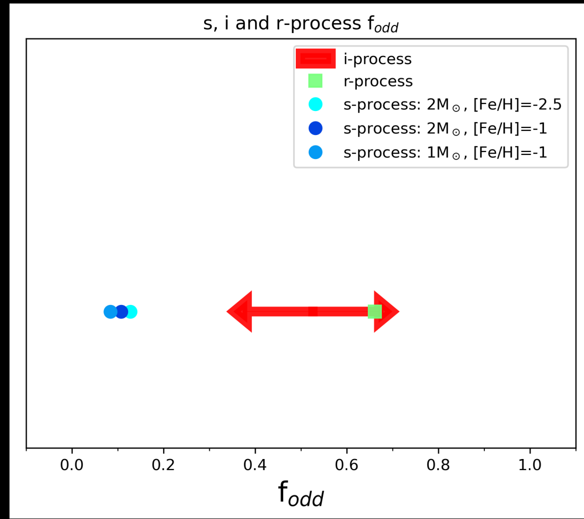




Model predictions from A. Choplin, L. Siess, S. Goriely

Comparing nucleosynthesis diagnostics



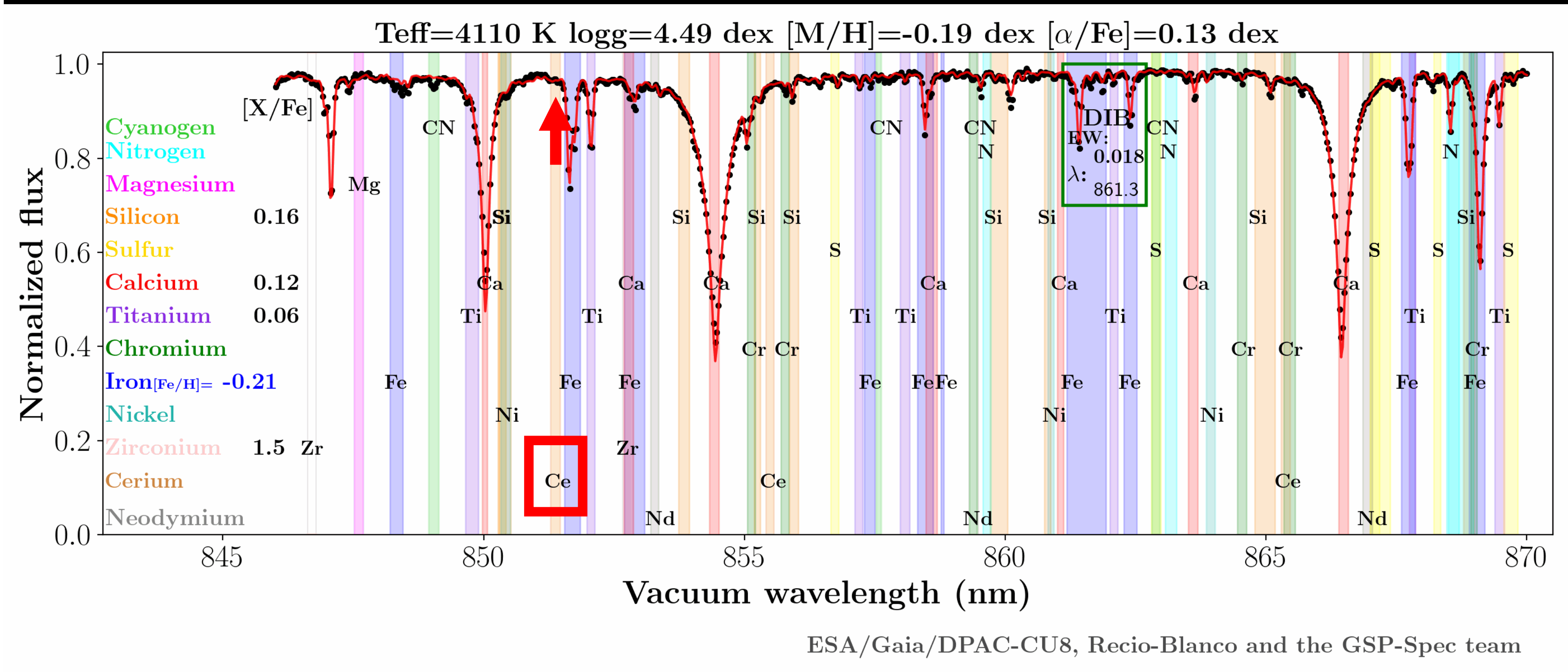


Literature	Star	Signed distance	RMS distance	χ^2_{s-pro}	χ^2_{i-pro}	f^{Ba}_{odd}	
Litt: s-process	HD 2454	0.83	0.90	1.38	1.56	17^{+1-17}	→ s-process
Litt: r-process	HD 115444	0.00	0.14	4.46	2.35	66^{+33-35}	→ r-process
Litt: CEMP-r/s	HE 2208−1239	0.56	0.80	13.14	2.05	100^{+0-36}	→ i-process

Chasing extrinsic stars in large spectroscopic surveys

Alain Jorissen
Patrick de Laverny

Gaia RVS spectra



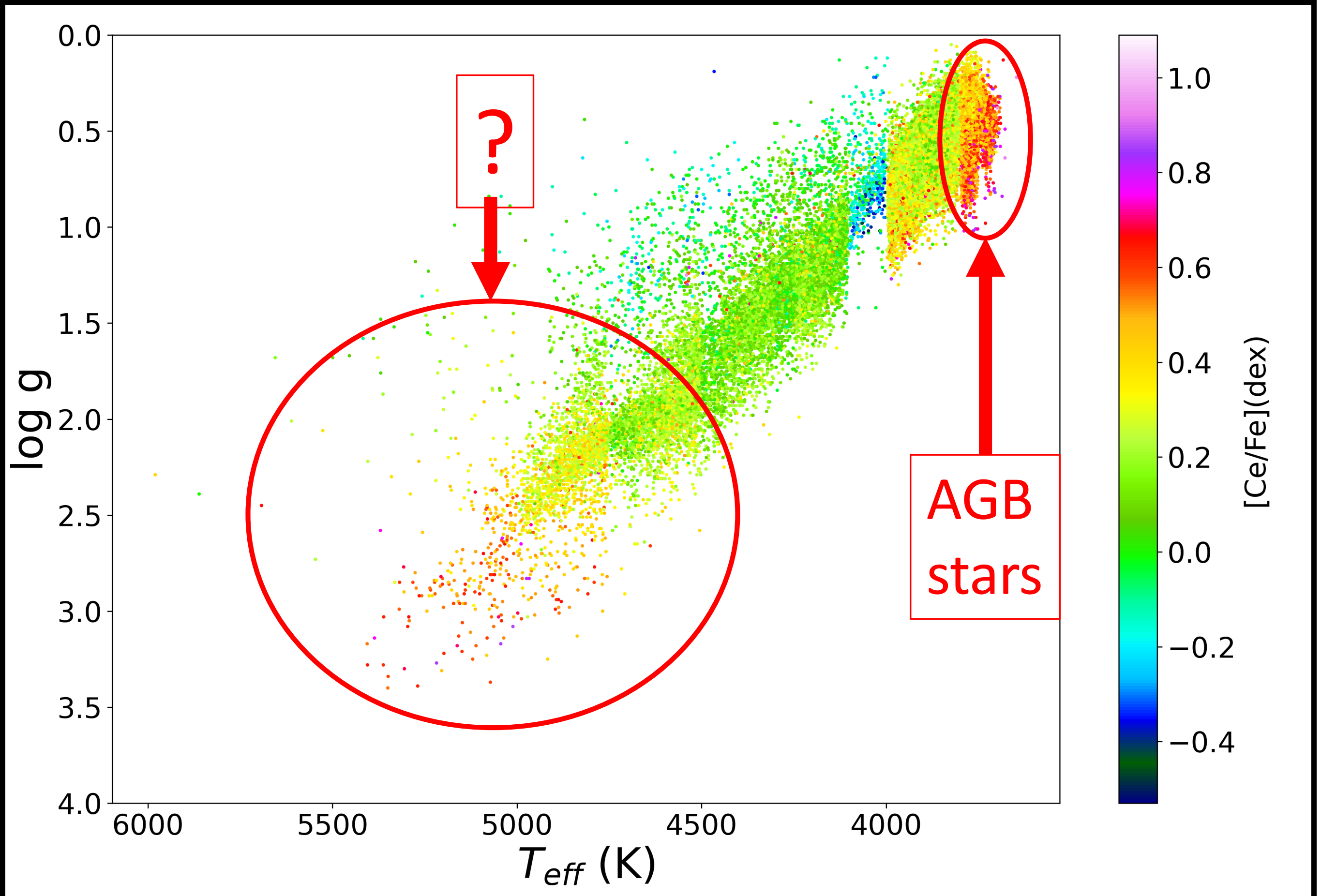
Adrian Lambotte

Extrinsic stars in Gaia?

Contursi+ 2022: Cerium from Gaia RVS

Kiel diagram of the stars with reliable Ce abundance

Kiel diagram for 28 613 stars with the recommended flag selection



Extrinsic stars in Gaia?

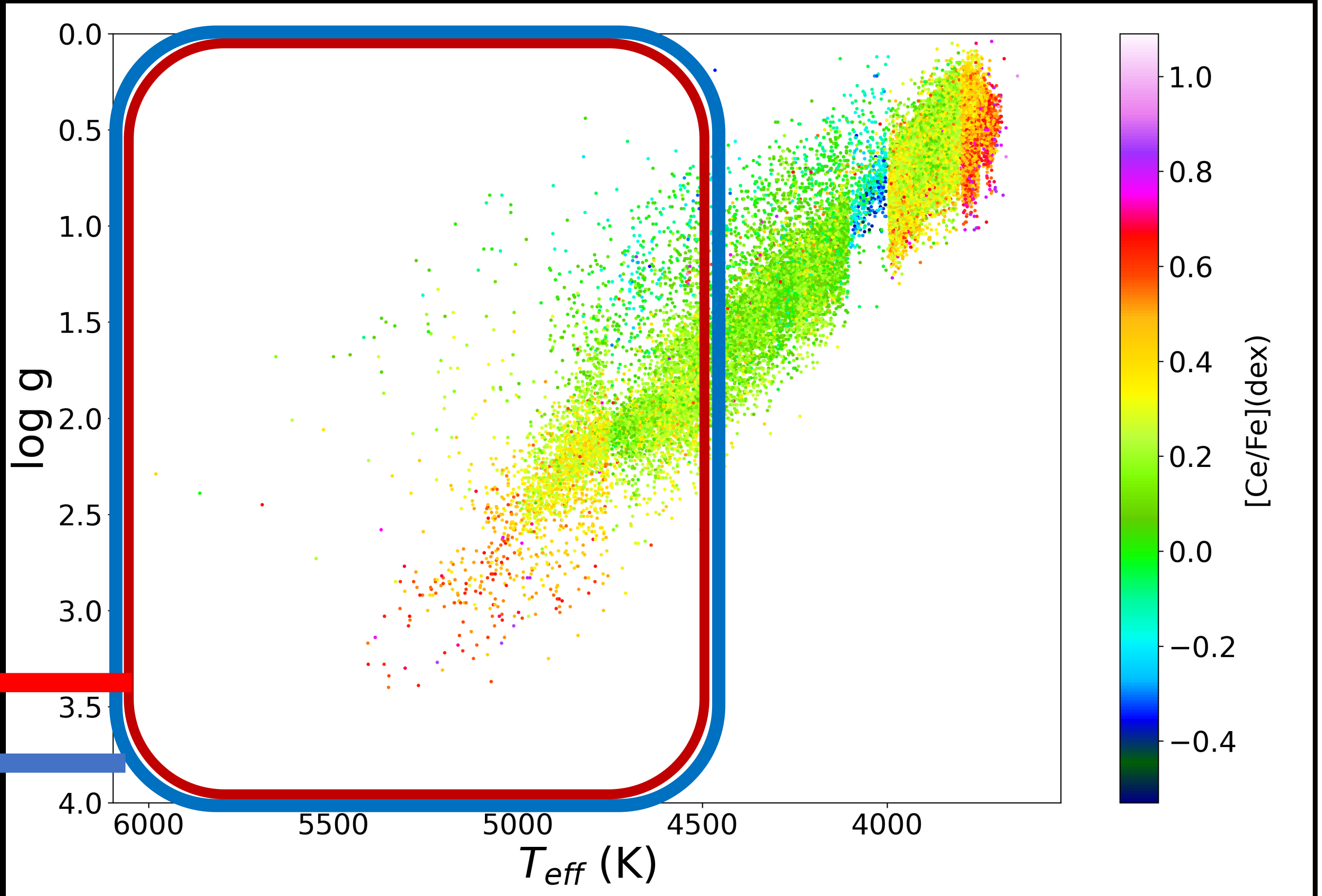
Erroneous abundances

or

Extrinsic stars?

Reliable Cerium (Contursi+22) and 4500K < T_{eff} < 6000K	
« Extrinsic »	Control
[Ce/Fe]>0,6 dex	[Ce/Fe]<0,3 dex
82 stars	4161 stars

Kiel diagram for 28 613 stars with the recommended flag selection

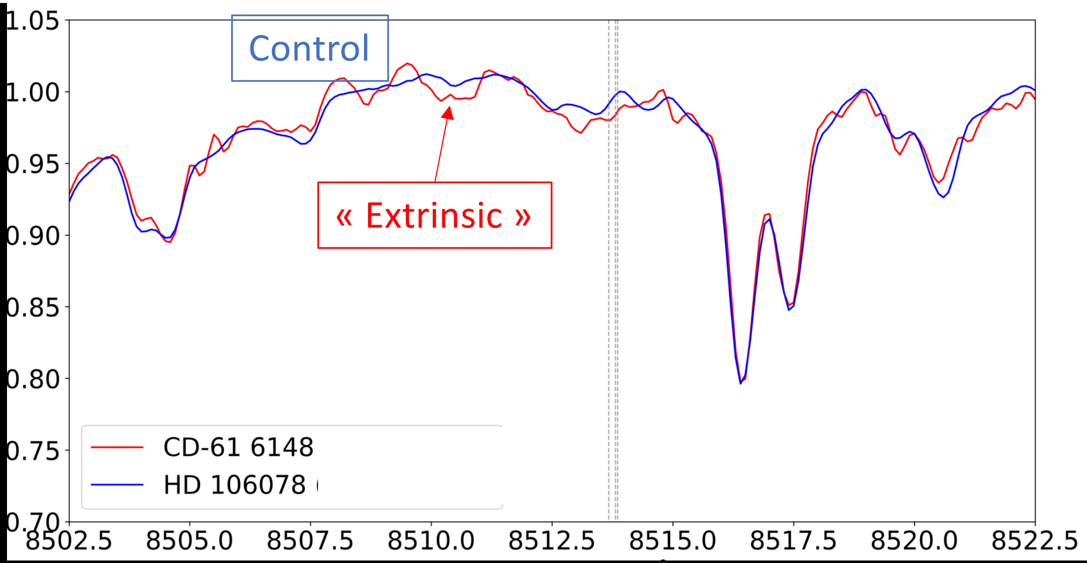


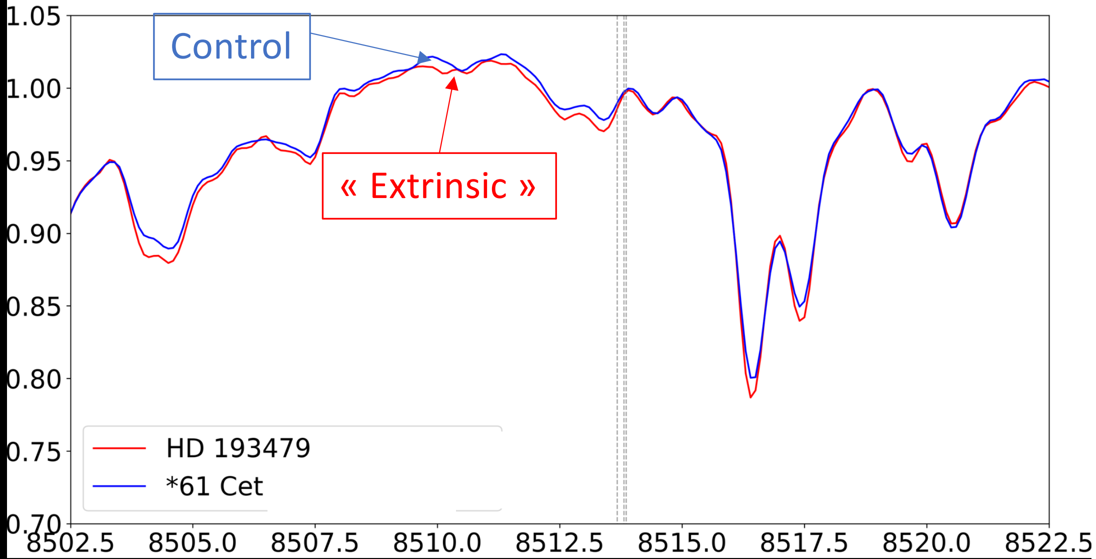
Cerium Abundance check

Gaia RVS spectra

Comparison between extrinsic and control **twins** (similar stellar parameters)

Reliable Cerium (Contursi+22) and 4500K < T_{eff} < 6000K	
« Extrinsic »	Control
[Ce/Fe]>0,6 dex	[Ce/Fe]<0,3 dex
82 stars	4161 stars

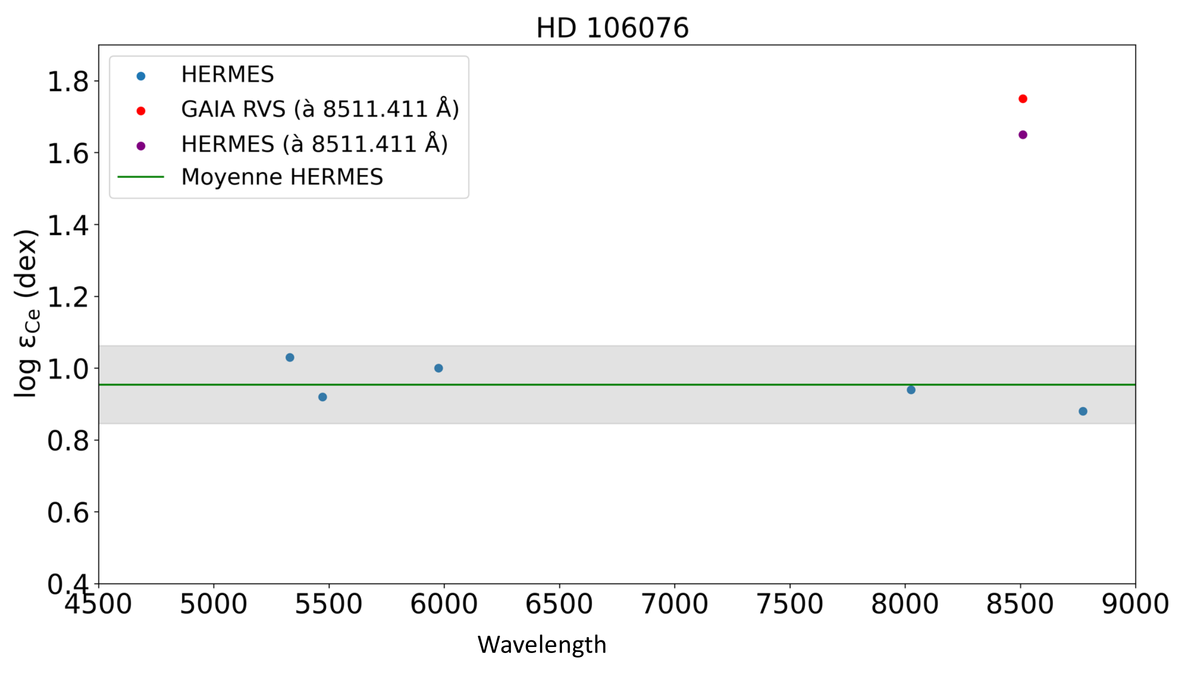




Cerium Abundance check

High-resolution spectra:
14 « extrinsic » stars re-observed at R=86 000

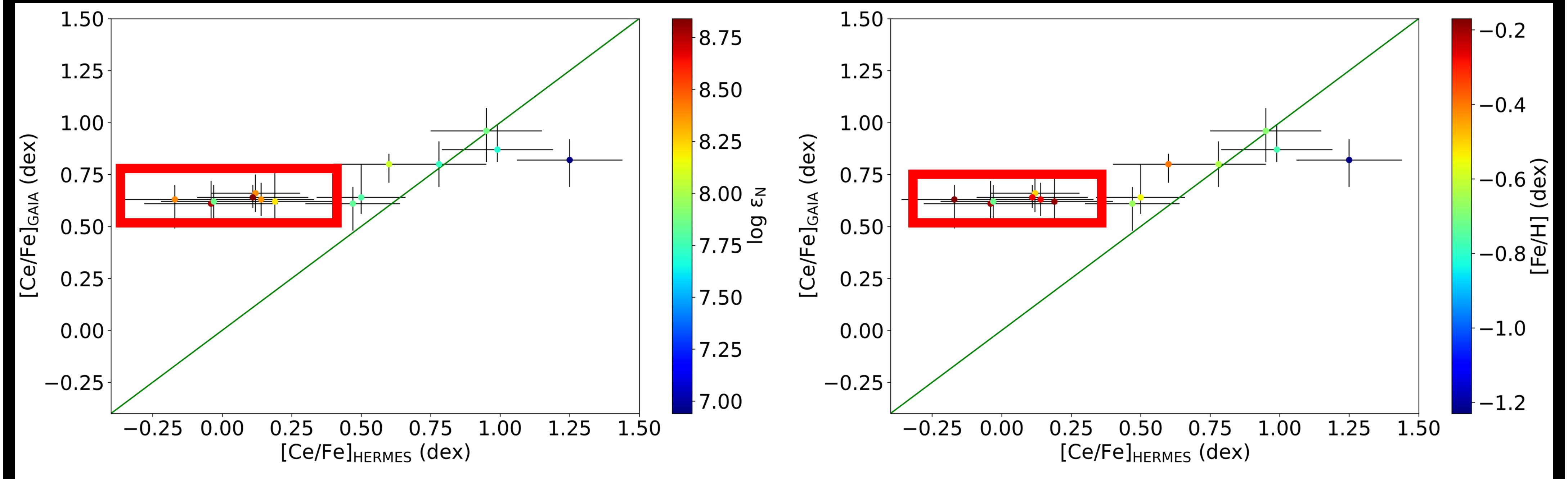
Hans
Van Winckel talk
on Friday



→ Determination (1D, LTE, MARCS model atmospheres, Gaia parameters) C, $^{12}C/^{13}C$, N, Fe Nb, Zr, La, Ba, Ce, Eu

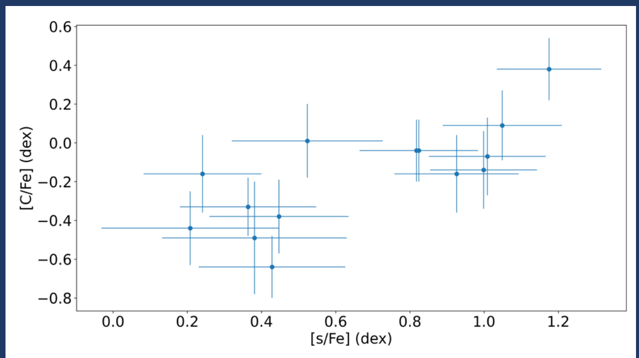
Cerium Abundance check

Too high Cerium abundances when
- high N abundance
- high metallicity

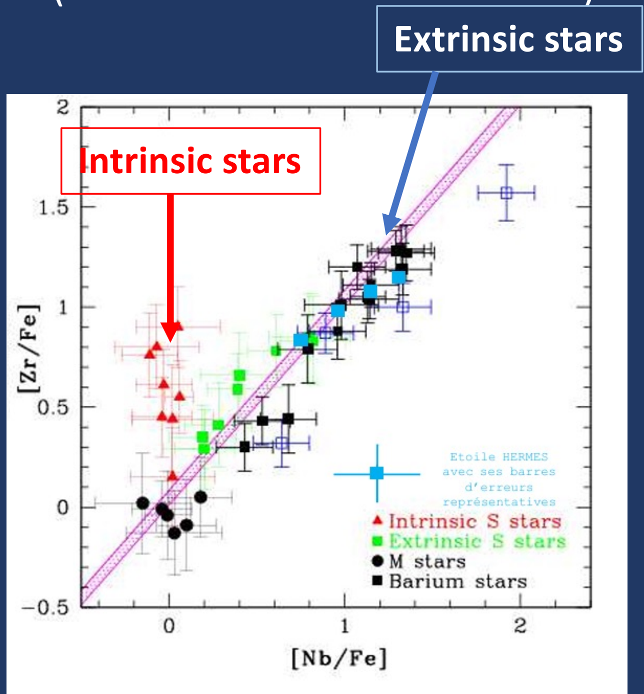


Extrinsicity of the truly enriched objets:

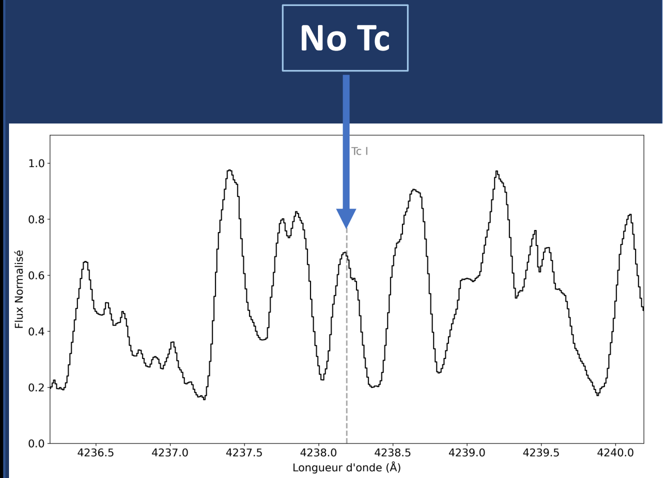
1. Correlation between [C/Fe] and [s/Fe]



2. Nb-enriched
$^{93}Zr \rightarrow$ monoisotopic ^{93}Nb
in extrinsic stars
(Karinkuzhi+ 2018 2021 2023)



3. Tc-poor



More on Tc in Shreeya Sheye's talk (Tuesday)

Extrinsicity of the truly enriched objets:

4. Binarity

		Extrinsic sample proportion (%)	Extrinsic sample number (Total : 82 stars)	Reference sample proportion (%)	Reference sample number (Total : 4161 stars)	Golden sample proportion (%)	Golden sample number (Total : 28 stars)
Variable radial velocity	Yes	45.12 ± 5.49	37 ± 4.51	14.59 ± 0.55	607 ± 22.77	57.14 ± 9.35	16 ± 2.62
	No	51.22 ± 5.52	42 ± 4.53	80.72 ± 0.61	3359 ± 25.45	39.29 ± 9.23	11 ± 2.58
	Undetermined	3.66 ± 0.23	3 ± 0.19	4.69 ± 0.33	195 ± 13.64	3.57 ± 0.68	1 ± 0.19
Gaia binarity flags	Non binary (NSS=0)	69.51 ± 5.08	57 ± 4.17	88.18 ± 0.50	3669 ± 20.83	46.43 ± 9.42	13 ± 2.64
	Astrometric binary (NSS=1)	10.98 ± 3.45	9 ± 2.83	3.58 ± 0.29	149 ± 11.98	17.86 ± 7.23	5 ± 2.02
	Spectroscopic binary (NSS=2)	9.76 ± 3.28	8 ± 2.69	5.19 ± 0.34	216 ± 14.31	17.86 ± 7.23	5 ± 2.02
	Astrometric and spectroscopic binary (NSS=3)	9.76 ± 3.28	8 ± 2.69	3.05 ± 0.27	127 ± 11.09	17.86 ± 7.23	5 ± 2.02
re-normalized v_r error	RUWE$\geq$ 1.4	41.46 ± 5.44	34 ± 4.46	16.46 ± 0.57	685 ± 23.92	50.00 ± 9.45	14 ± 2.65
	RUWE<1.4	58.54 ± 5.44	48 ± 4.46	83.49 ± 0.58	3474 ± 23.95	50.00 ± 9.45	14 ± 2.65
Union of all binarity indicators		52.44 ± 5.51	43 ± 4.52	21.68 ± 0.64	902 ± 26.58	62.50 ± 9.15	18 ± 2.56

Binarity:

Extrinsic 52%

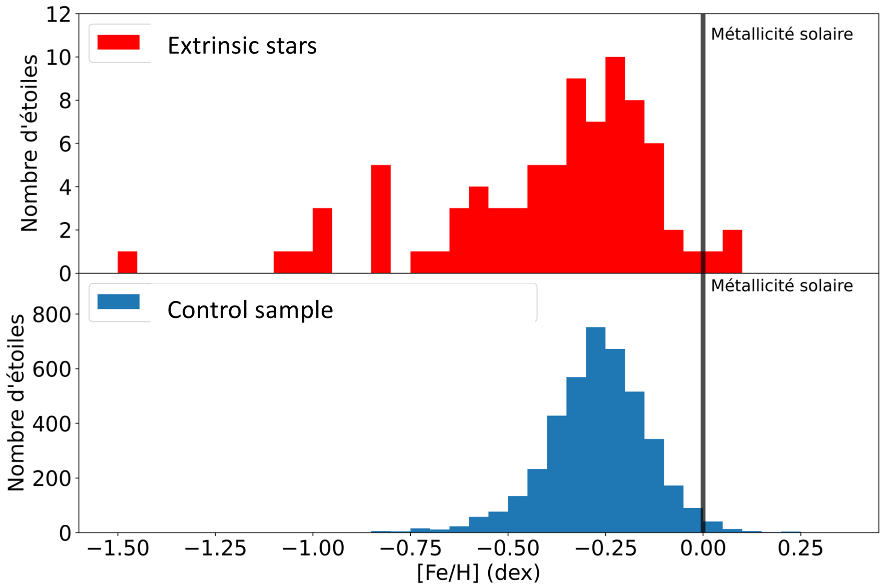
Control: 22%

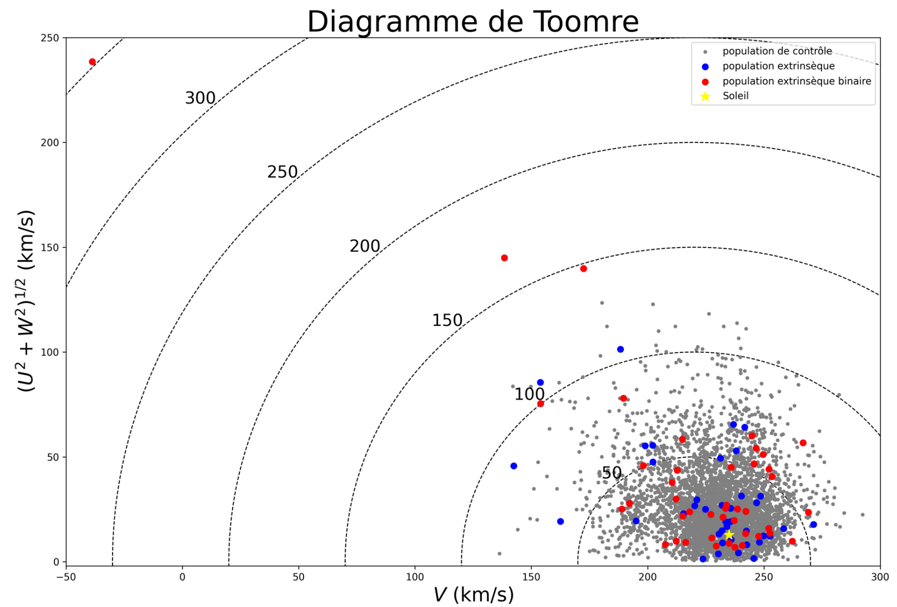
Golden sample: 63%

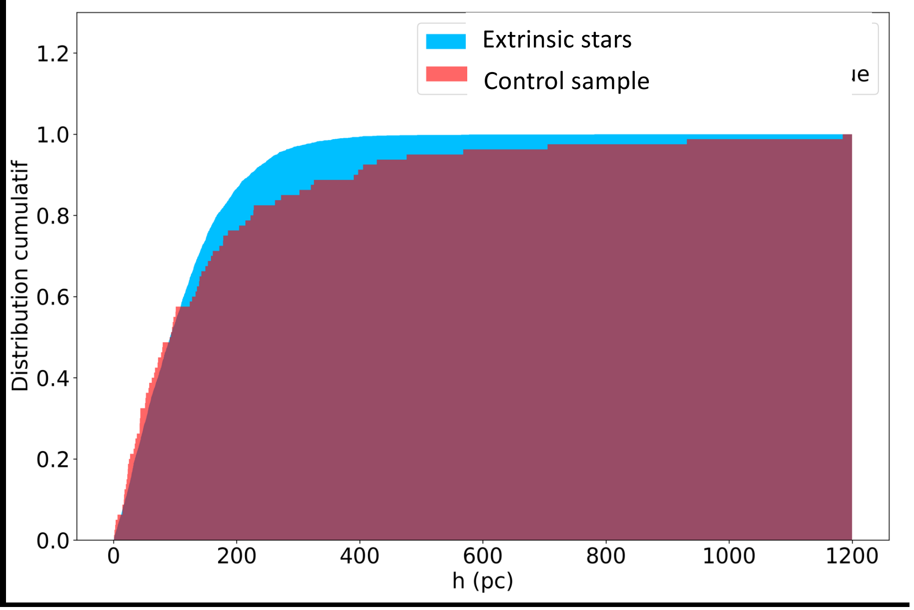
Extrinsicity of the truly enriched objets:

4. Height above the galactic plane

Extrinsic	Control sample
149,64 ± 2,01	82,37±0,89







Conclusions:

- Isotopic diagnostics are feasible but except for some stars with weak lines, 3D NLTE is recommended
- Hidden treasures of extrinsic stars in large surveys

Perspectives:

- Isotopic ratio: comparison 1D/3D NLTE
- Completing existing Ba and CEMP star catalogues with Gaia and other large surveys (use machine learning with precaution)
- Candidate i-process stars from Gaia RVS