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Ministero dell'Università e della Ricerca

Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA

New and precise data of the possible i-process star TYC 6044-714-1

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Osservatorio di Arcetri - INAF

Giulianova 13 June - 2025

Arthur Choplin

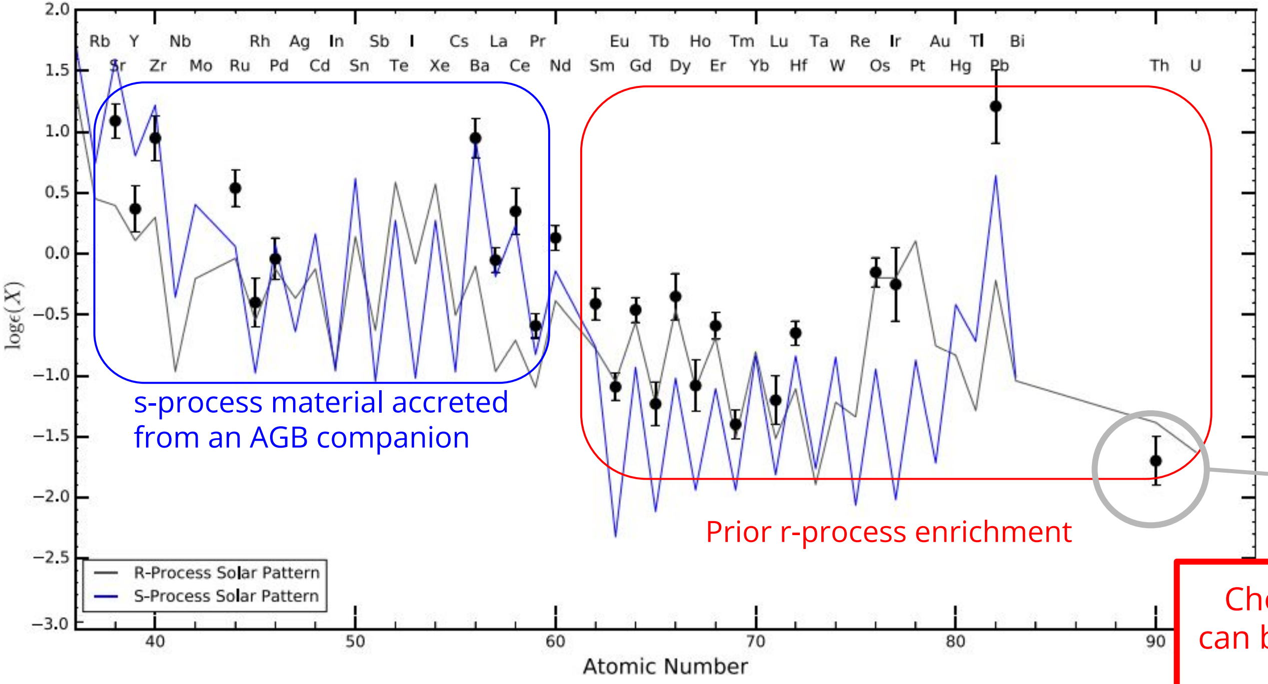
Laura Magrini

Jose Schiappacasse

Sunset at the Arcetri Observatory

s, i & r Element nucleosynthesis (sirEN) conference

The star TYC 6044-714-1



Gull et al. (2018)

A Carbon Enhanced Metal-Poor star (CEMP):

[Fe/H] = -2.1 dex
[C/Fe] = 1.35 dex

With both s- and r-process element enhanced

with a relatively precise Th abundance:

A(Th) = -1.70 ± 0.2 dex
[Th/Fe] = 0.50 ± 0.24 dex

Choplin et al. (2022) support that Th can be produced in significant amounts by the i-process

Objectives

1. To capture the signatures of the i-process

'A goal is not always meant to be reached, it often serves simply as something to aim at.'

Methods

To submit the star to as many tests as possible to have a comprehensive criterion at judging the presence of i-process signatures

1. Isotopic ratio measurements of Ba and Eu

2. Comparison of observationally-based element abundances with those from nucleosynthesis models

Abundances from observation depend on line formation models, therefore **they can be biased**, especially those from the most intense lines

New quality data of TYC 6044-714-1

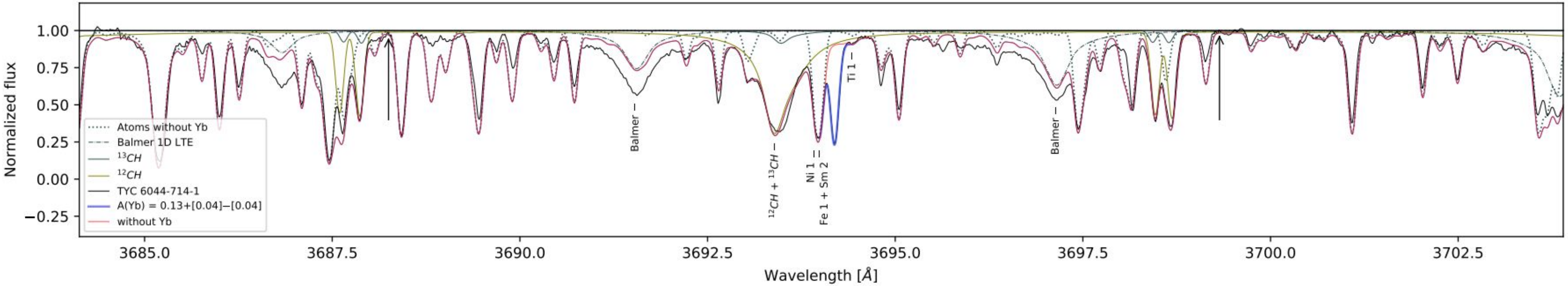
PRELIMINARY

ESO UVES spectra acquired in January 2025 addressed to:

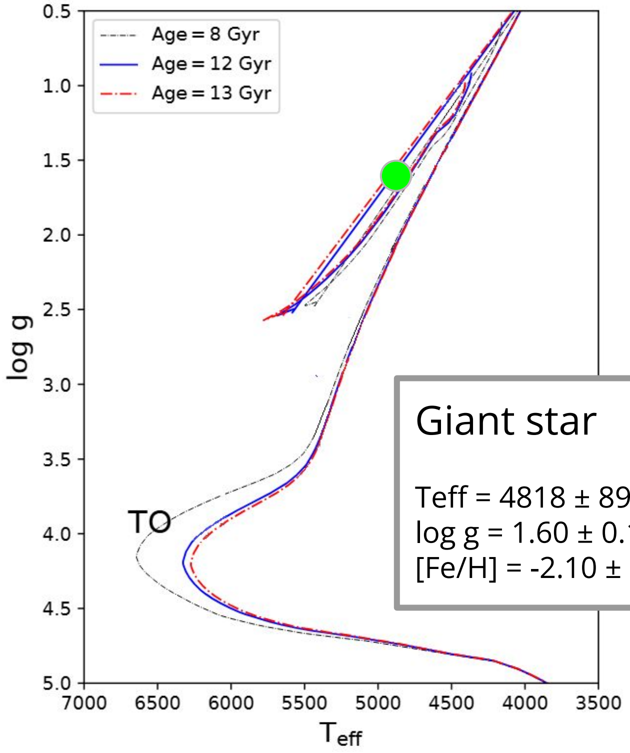
- Derive element abundances of precision A(X) ± 0.02
- A(Th) abundance of precision ± 0.15, whose detection exceeds 3σ
- Enough precision to distinguish between s-, r-, and i-process line profiles, i.e. ΔFlux < 2%

Wavelength range [Å]	Obs. date	$R \equiv \lambda/\Delta\lambda$	S/N nominal
3282-4563	03/01/2025	65030	80
3282-4563	05/01/2025	65030	70
3282-4563	27/01/2025	65030	40
4726-6834	03/01/2025	74450	270
4726-6834	05/01/2025	74450	248
4726-6834	27/01/2025	74450	184

blue: S/N = 185
red: S/N = 480

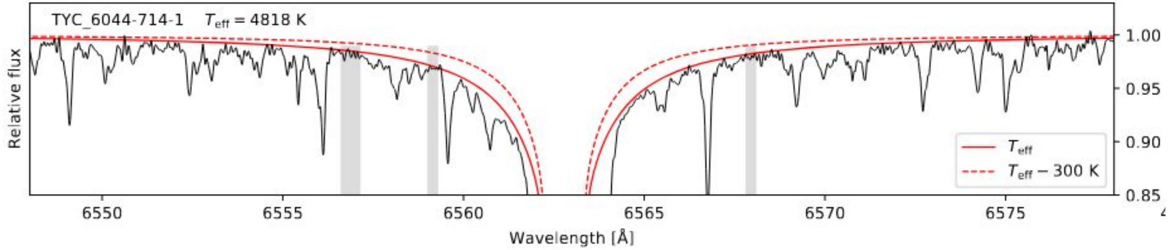


Atmospheric parameters



Giant star

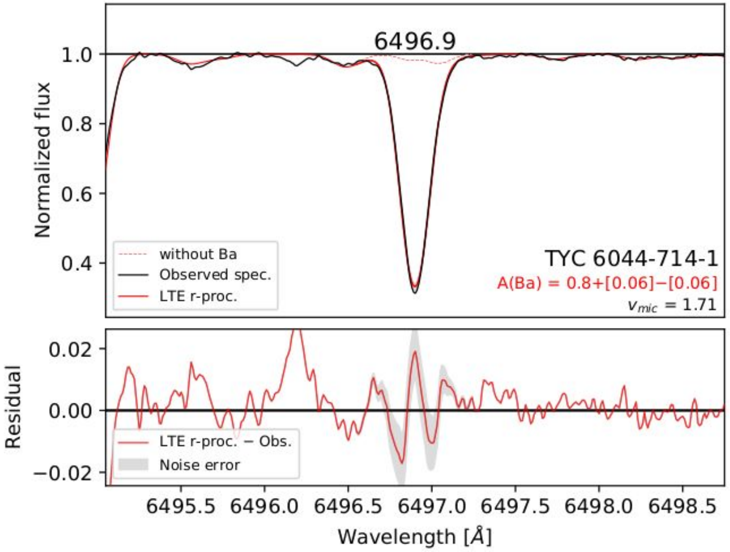
Teff = 4818 ± 89 K
log g = 1.60 ± 0.15 dex
[Fe/H] = -2.10 ± 0.09 dex

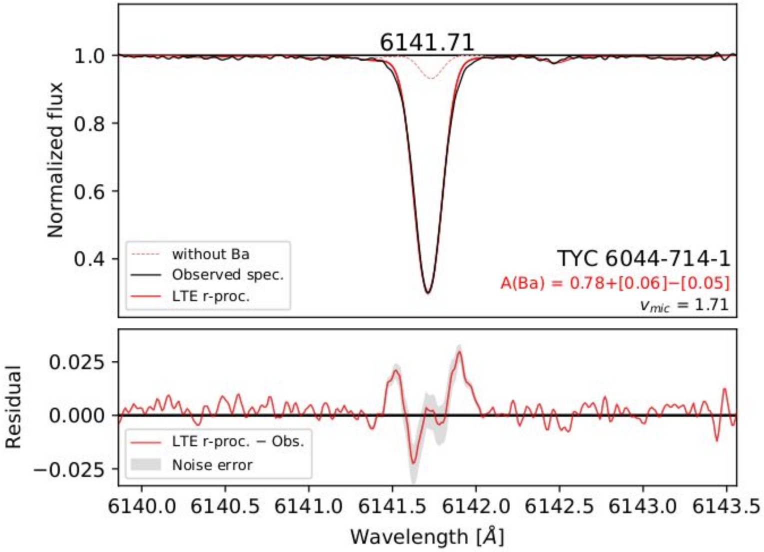


- Hα profile fitting method calibrated in Giribaldi et al . (2019, 2021, 2023)
- 3D NLTE models of Amarsi et al. (2018)
- **Metallicity ([Fe/H]) and surface gravity (log g)** determined under **NLTE** using line synthesis. Method tested in Giribaldi et al. A&A 779, 110 (2023).
- Microturbulence MUST by determined by LTE (Giribaldi et al. in prep. 2025).

Barium isotopic ratios

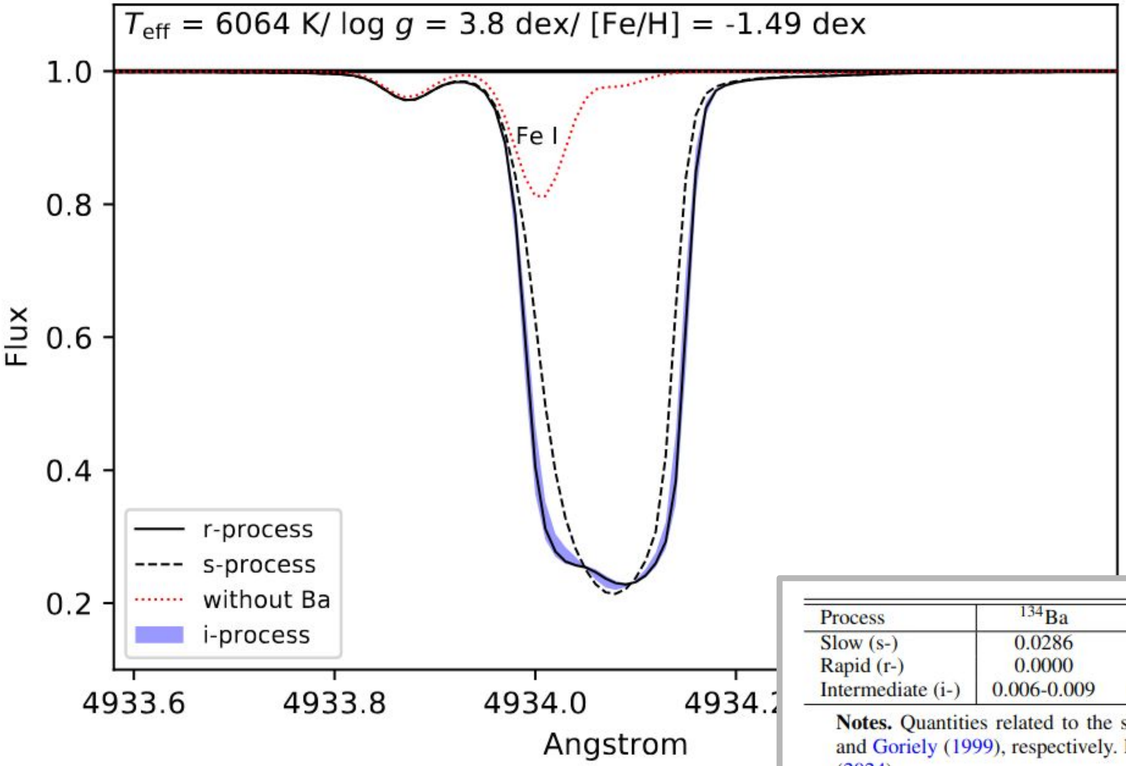
Ba subordinate lines





Ba line at 4934 $\AA$ sensitive to isotopic ratios

Ba line at 4934 $\AA$ sensitive to isotopic ratios



R = 490 000
Infinite S/N

Process	^{134}Ba	^{135}Ba	^{136}Ba	^{137}Ba	^{138}Ba
Slow (s-)	0.0286	0.0222	0.0939	0.1048	0.7505
Rapid (r-)	0.0000	0.3924	0.0000	0.2690	0.3386
Intermediate (i-)	0.006-0.009	0.045-0.027	0.041-0.028	0.308-0.673	0.600-0.263

Notes. Quantities related to the s- and r-processes are inferred from Goriely & Siess (2018) and Goriely (1999), respectively. Isotopic related to the i-process are taken from Martinet et al. (2024).

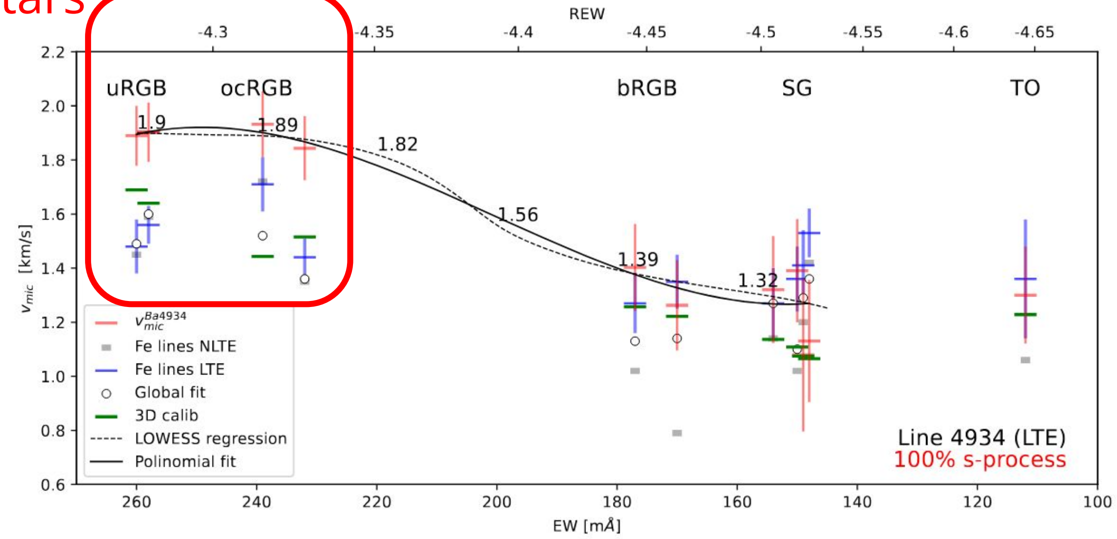
Ba line at 4934 $\AA$ sensitive to isotopic ratios

Barium isotopic ratios in metal-poor stars: calibrating the method with globular clusters ⋆

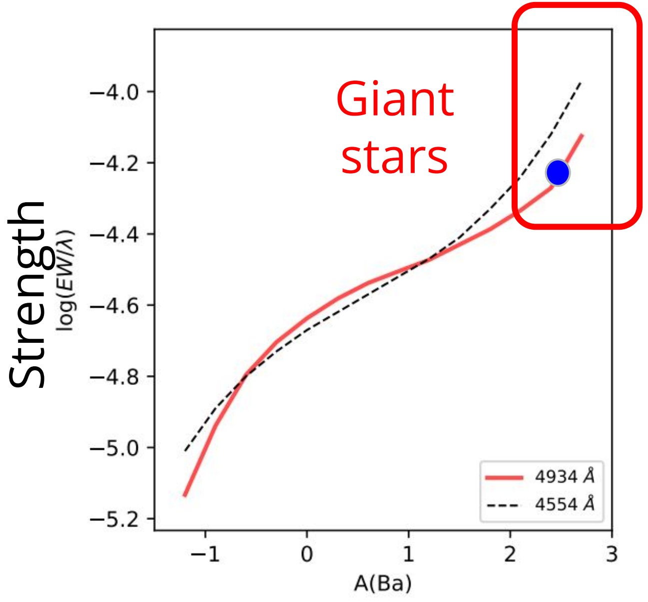
Paper I: Dwarf and giant stars in NGC 6752

R. E. Giribaldi[1], L. Magrini[1], J. Schiappacasse-Ulloa[1]

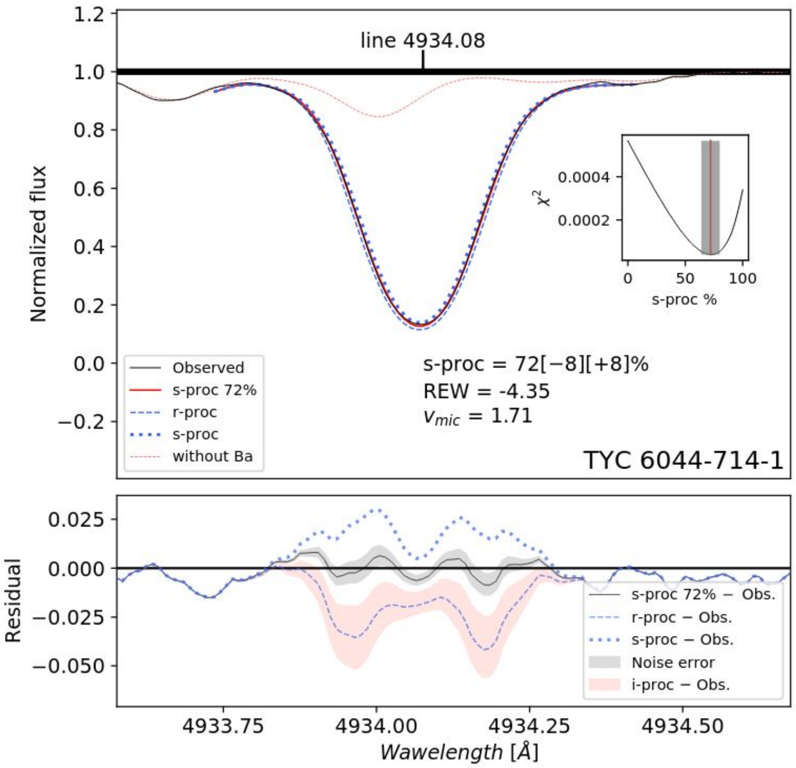
Giant stars



Strength



Ba line at 4934 Å sensitive to isotopic ratios



- Interpretation 1:
  Ba produced by both the r- and s-processes, with 28 and 72% contributions

- Interpretation 2:
  The contribution of 28% may be shared between the r- and i-processes. Considering the abundance due to Galactic evolution A(Ba) ≈ −0.3 ± 0.07 dex (measured in field stars; Giribaldi et al. in prep), it would represent the 8% of the total. Thus, a maximum of 20% is expected for the i-process nucleosynthesis.

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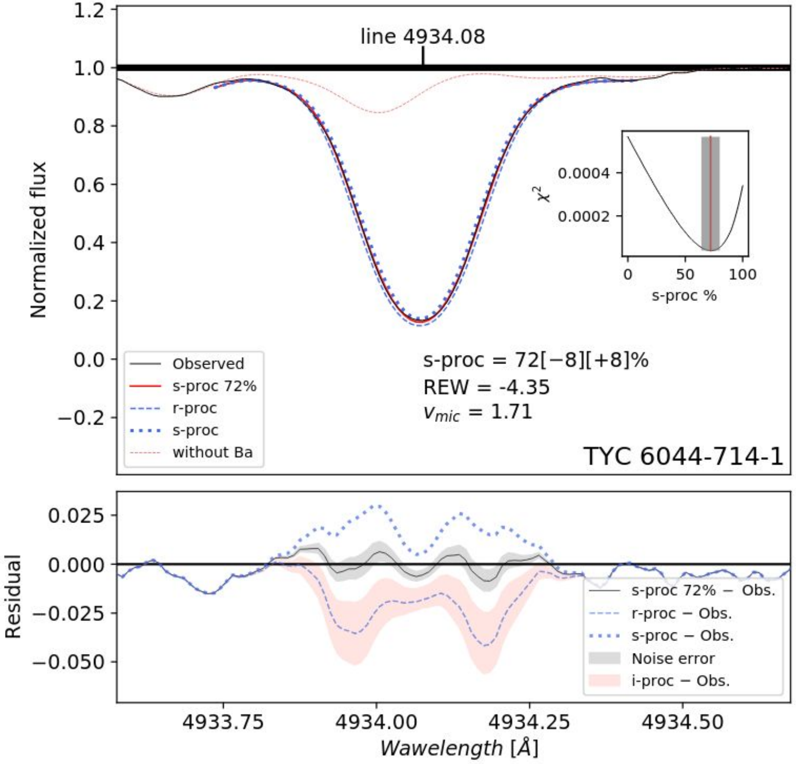

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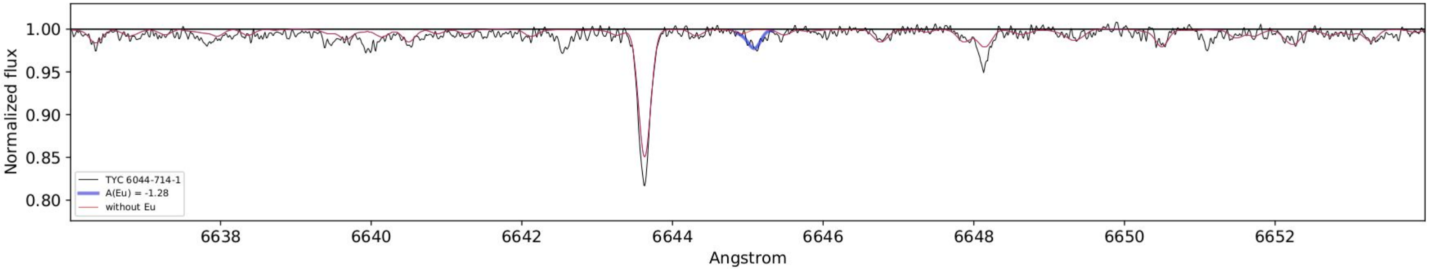
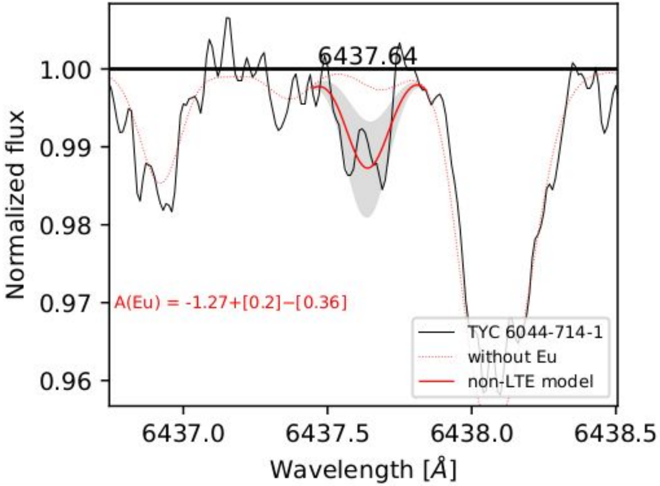
Parameter	TO	SG	bRGB	ocRGB	uRGB
A(Ba)	σ(A(Ba)) / 0.0035				
$T_{\rm eff}$	+12/−16	+15/−25	+16/−27	+16/−28	+16/−29
v_{mic}	±12	±12	±12	±23	±23
[Fe/H]	∓7	∓5	∓3	∓3	∓4

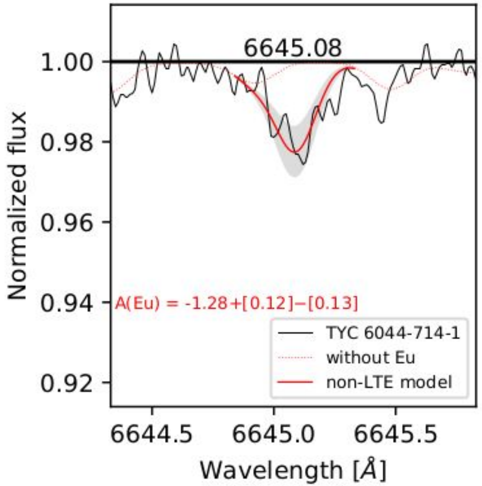
Notes. Unities are expressed in terms of percentage of s-process contribution. Errors related to those of $T_{\rm eff}$ are computed by deviating the true value by ±50 K. Errors related to those of v_{mic} correspond to variations of ±0.1 km s^{-1}. Errors related to those of [Fe/H] are computed by deviating the true value by ±0.1 dex.

Eu isotopic ratios

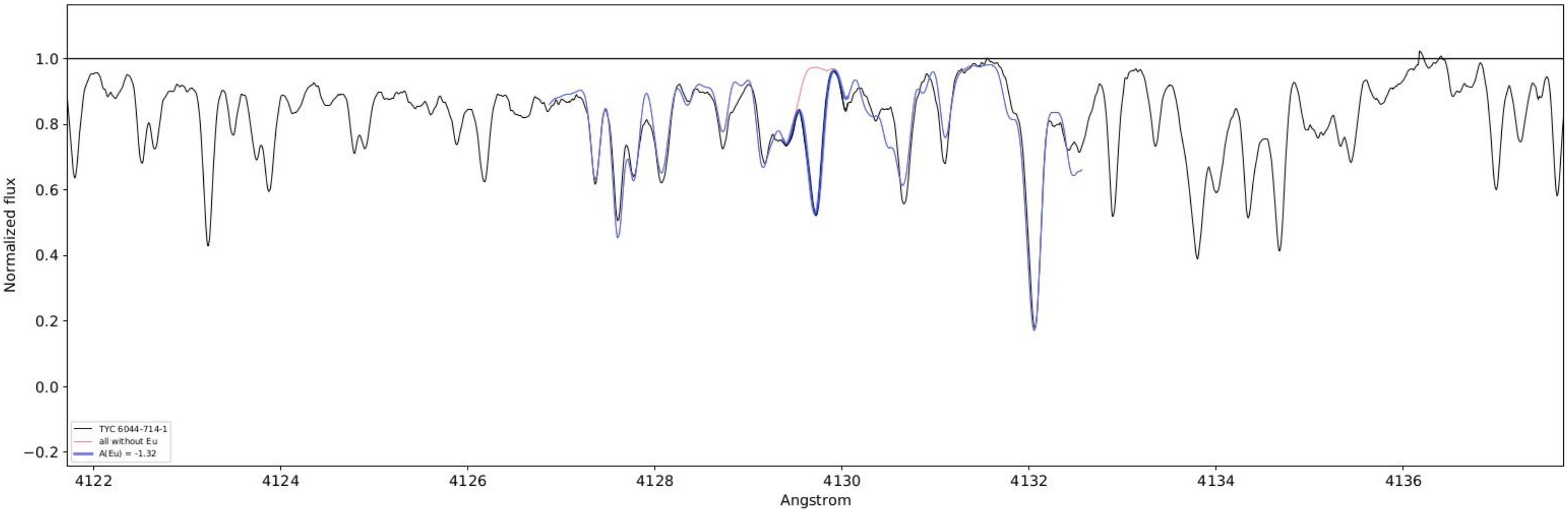
Eu lines insensitive to isotopic ratios







Eu lines sensitive to ratios of the isotopes 151 and 153



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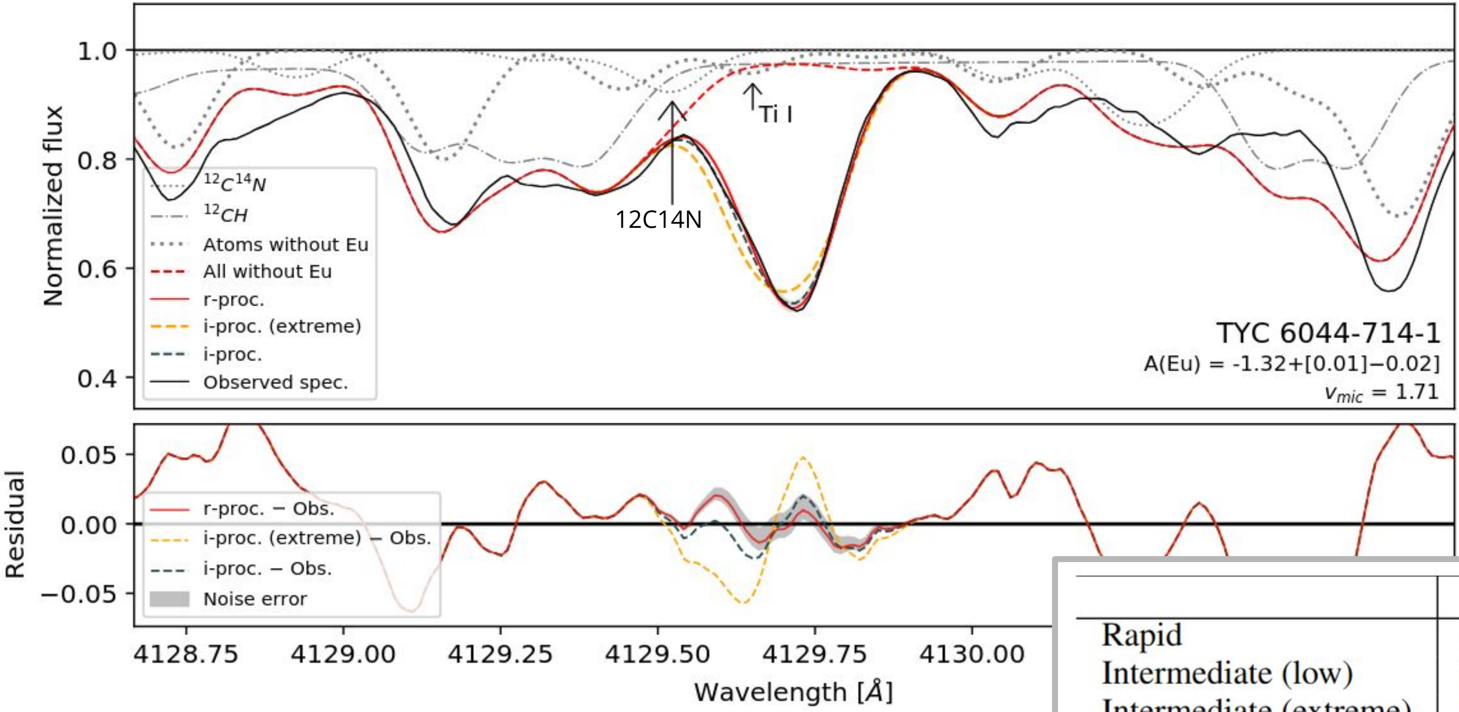
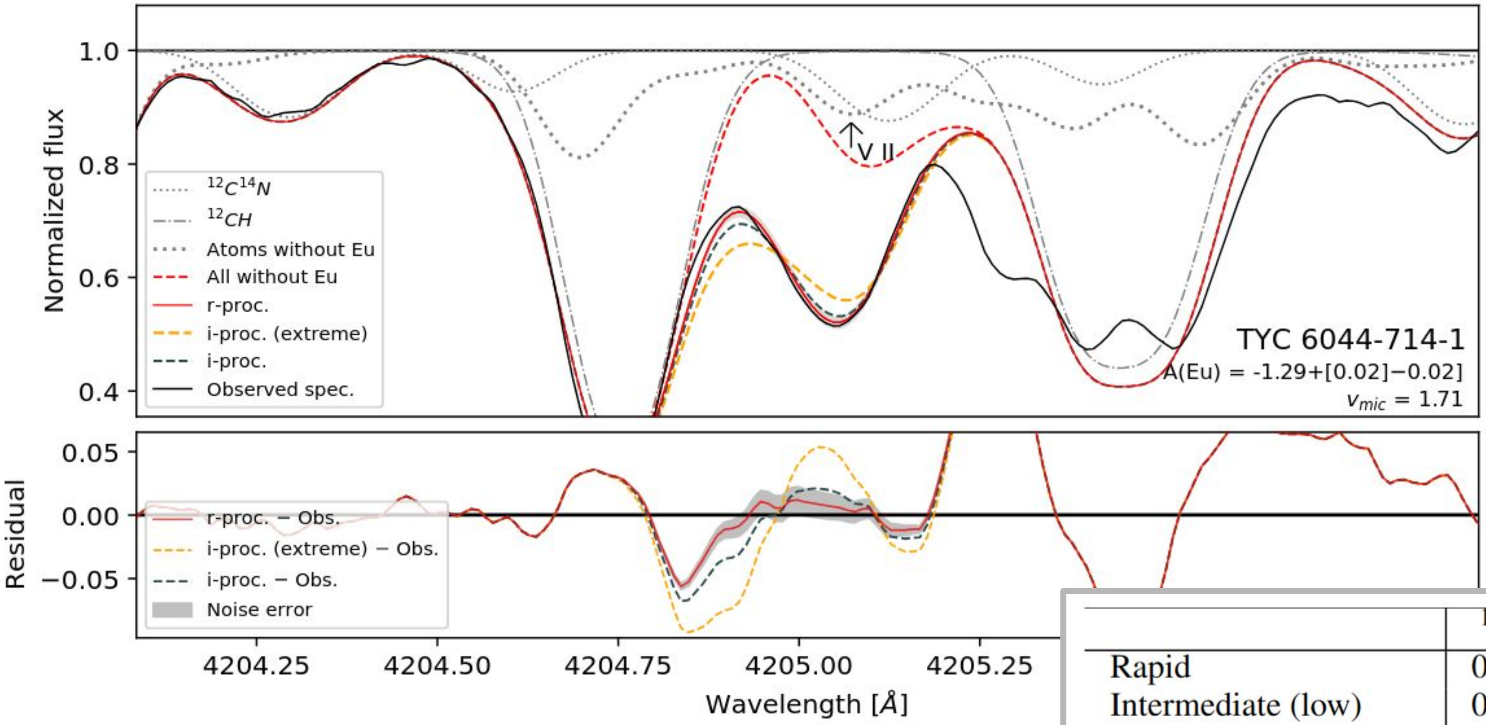


	^{151}Eu	^{153}Eu
Rapid	0.4773	0.5227
Intermediate (low)	0.6175	0.3857
Intermediate (extreme)	8.900	0.1100

Martinet et al. (2024)

- HFS from da Silva & Smiljanic (2025)
- NLTE departure coefficients of Storm et al. (2024)
- log gf of a Ti I and a 12C14N features were modified

Eu lines sensitive to ratios of the isotopes 151 and 153



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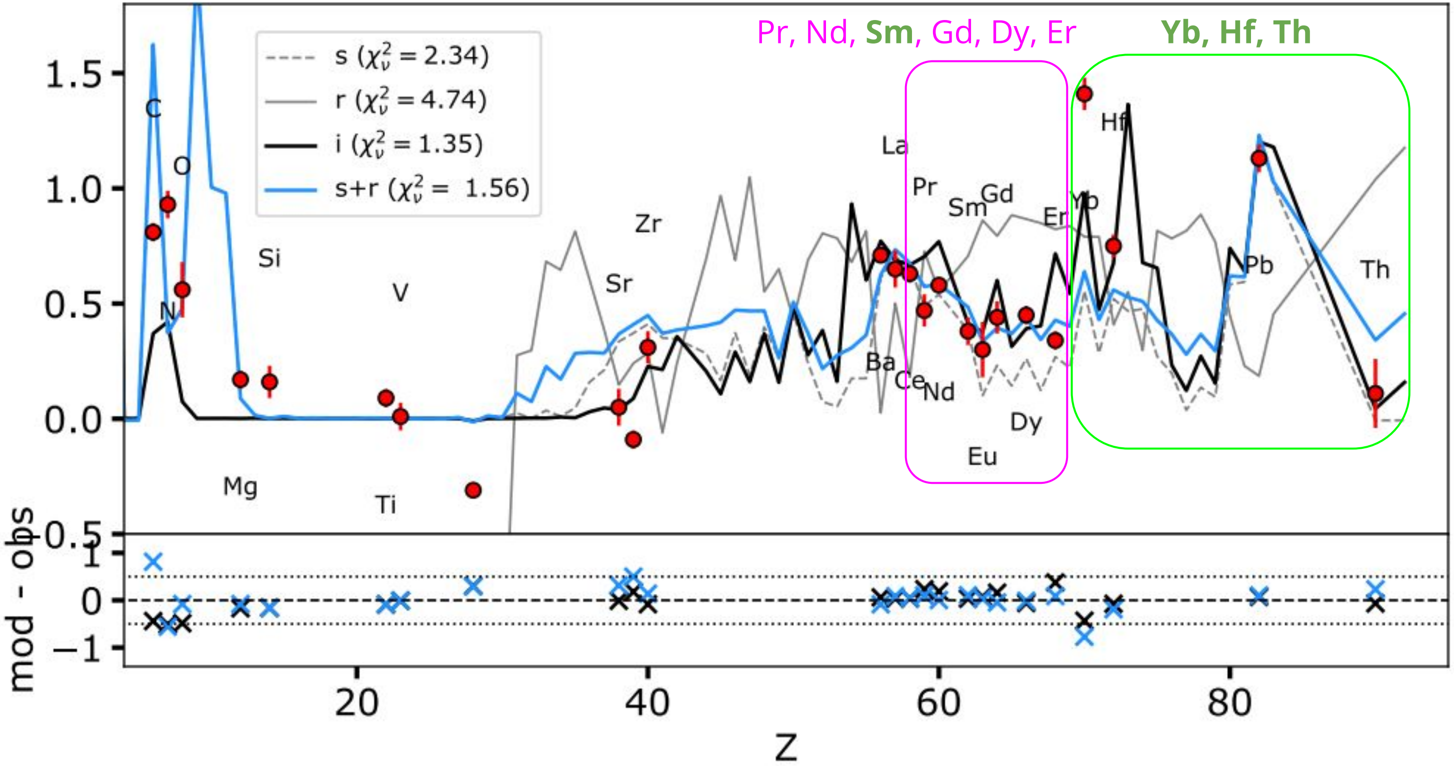
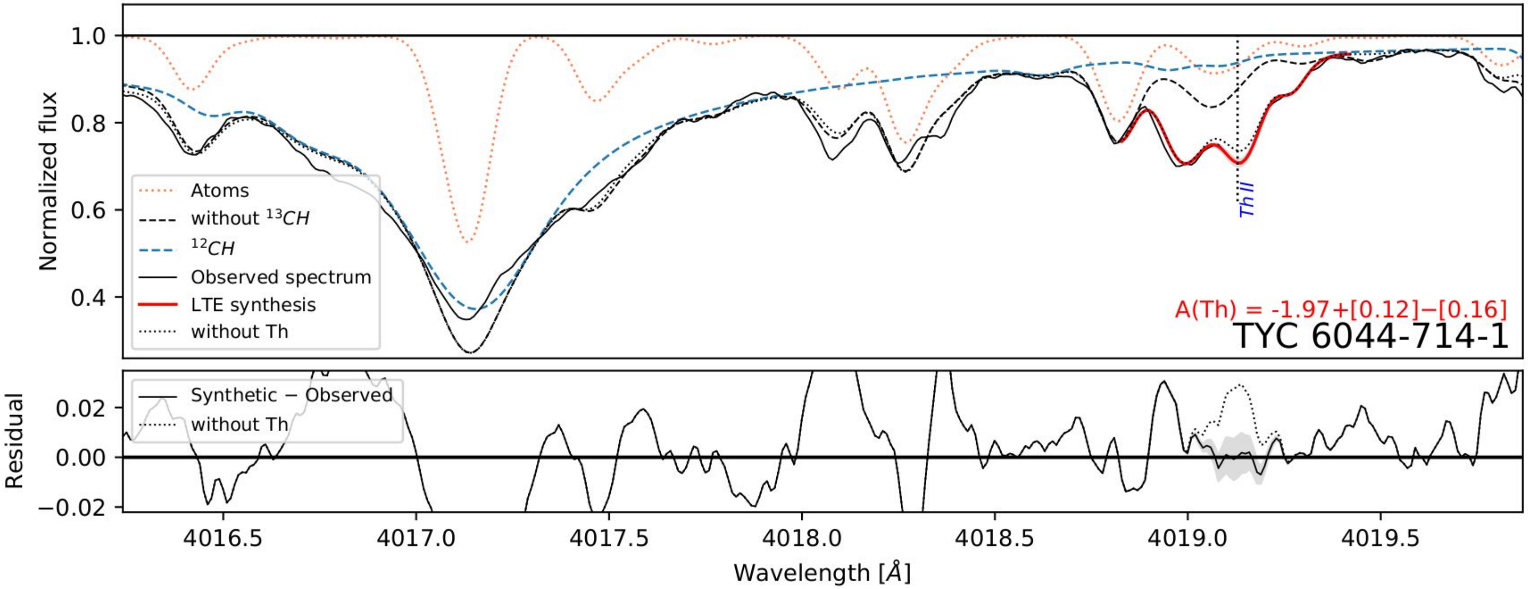
Nucleosynthesis models

- s-process : 2 Mo AGB (STAREVOL, Goriely & Siess 2018)
- r-process : solar (Arnould+2007)
- i-process : 1 Mo AGB (STAREVOL, Choplin+2022)

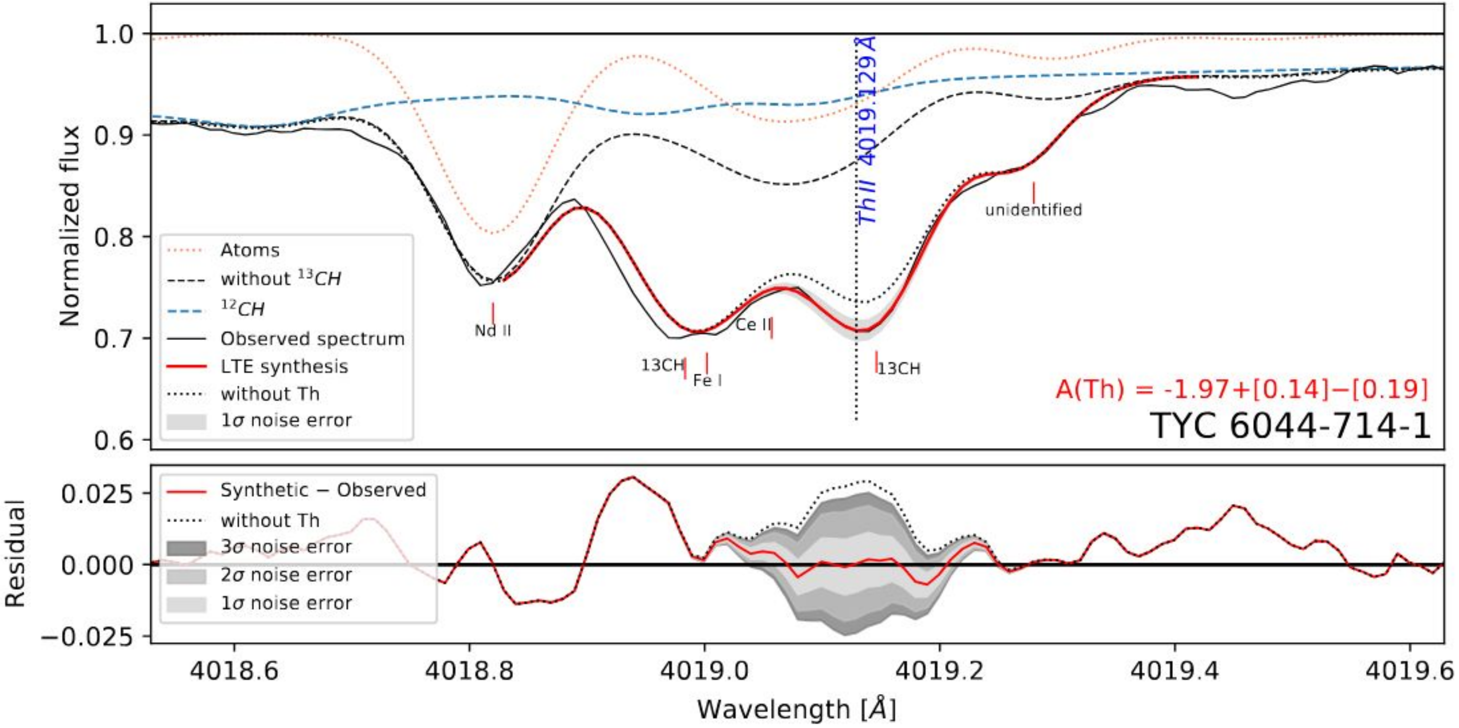


Thorium abundance

Thorium abundance



Thorium abundance



Take home messages

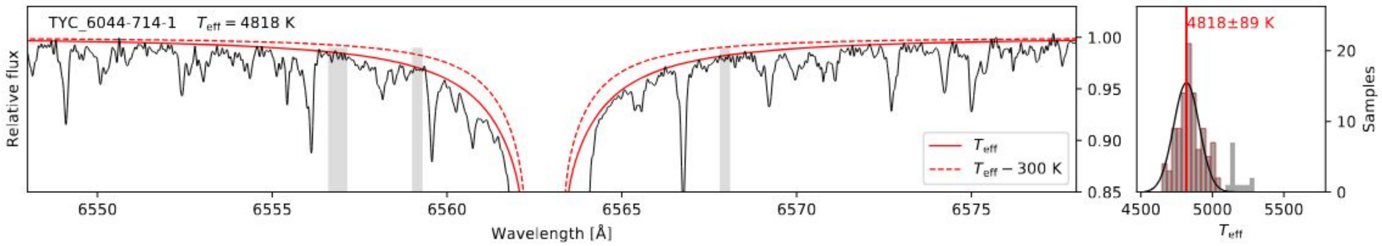
1. *If the products of the i-process are present in TYC 6044-714-1*, its Ba and Eu line profiles are very similar to those of the r-process.

2. In the attempt to capture the signatures of the nucleosynthesis processes, it is paramount to calibrate the methods of stellar parameter determination, line fitting, and abundance measurement.

Thanks!

Backup slides

Atmospheric parameters



- Method scrutinised in Giribaldi et al . (2019, 2021, 2023)
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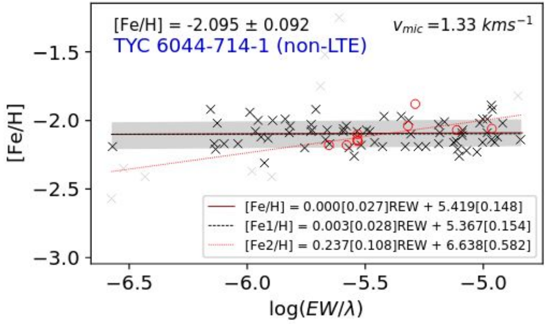

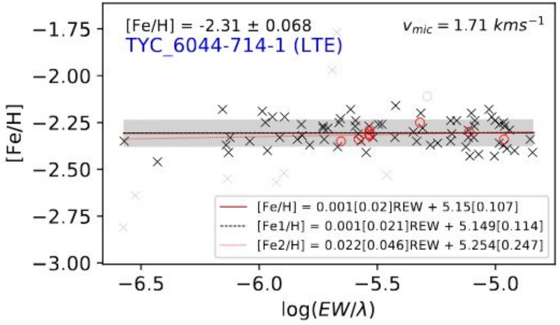

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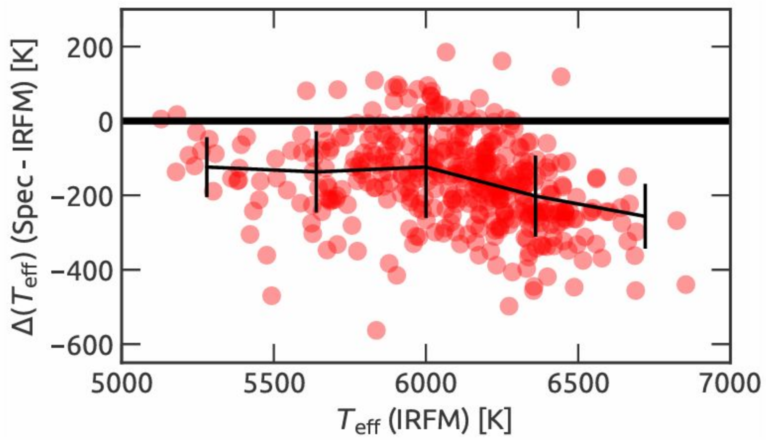
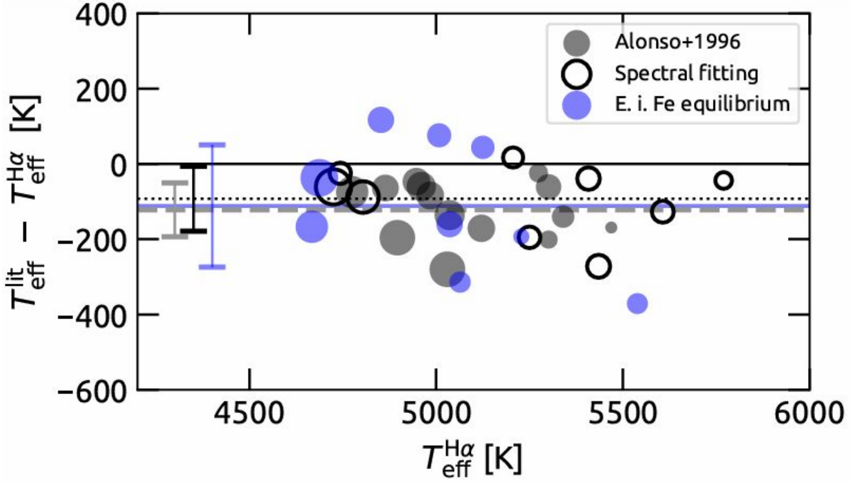
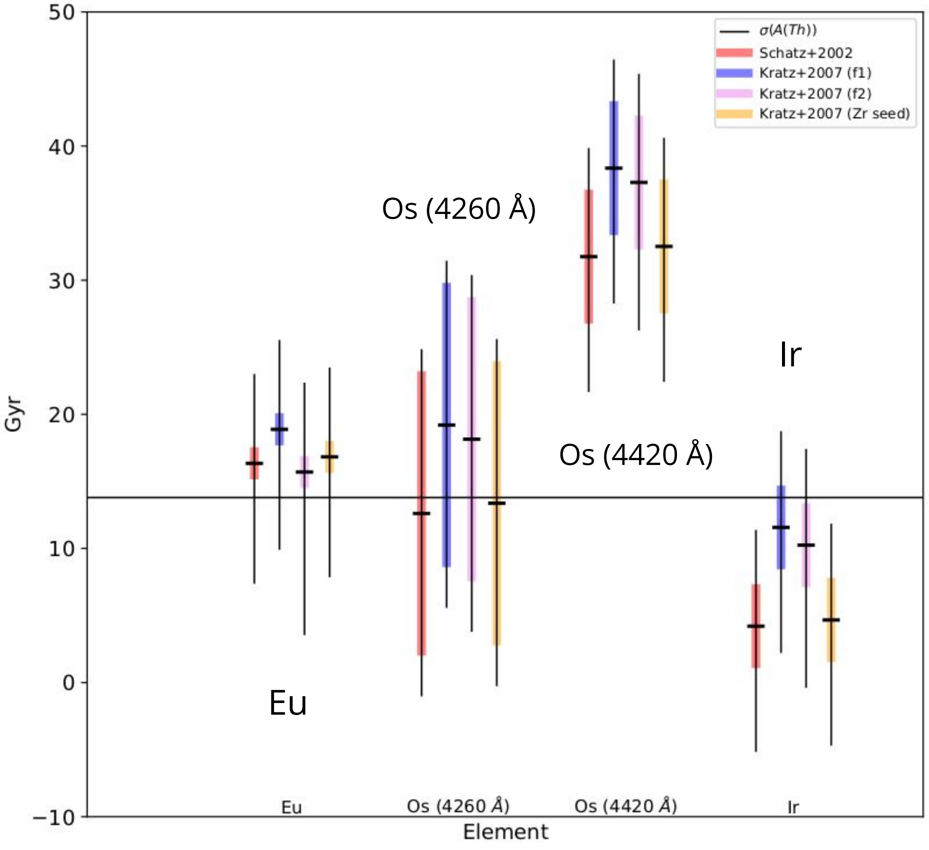




Giribaldi et al. A&A, 673A, 18 (2023)

Giribaldi et al. A&A, 679A, 110 (2023)



Nucleo-cosmo-chronology

$$\Delta t = 46.7\left[\log(\mathrm{Th}/r)_0 - \log(\mathrm{Th}/r)_{obs}\right]$$

where *r* is a stable third-peak r-process element (here Eu, Os, and Ir) (e.g. Cayrel et al. 2001)

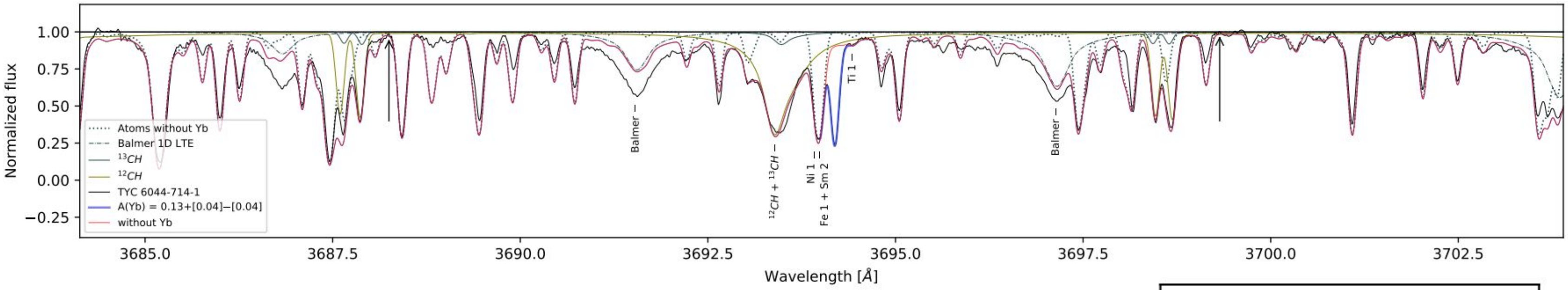
For Th/Eu we obtain between a star age of 8-20 Gyr

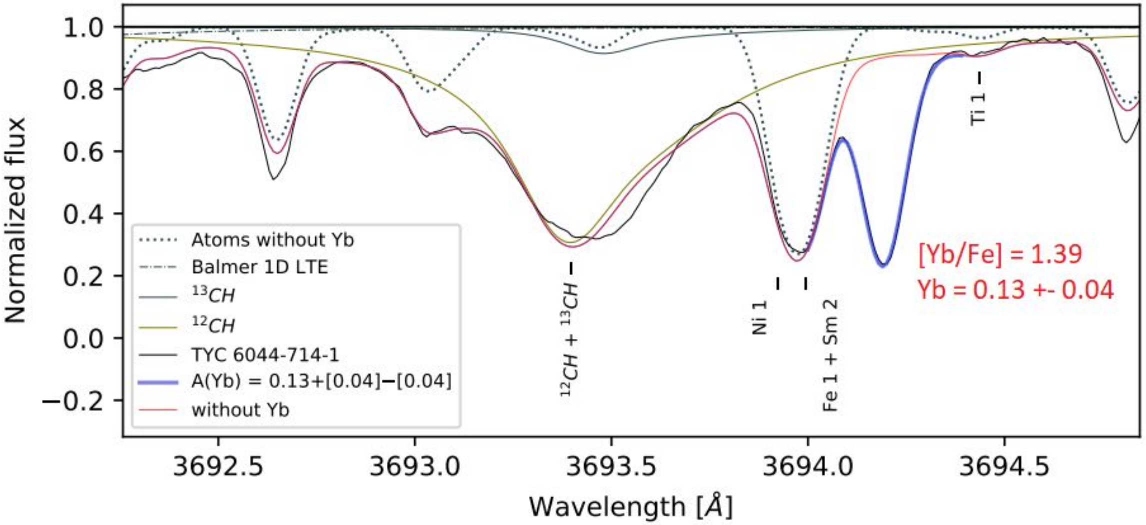
Using the coefficients of Schatz et al. (2002)

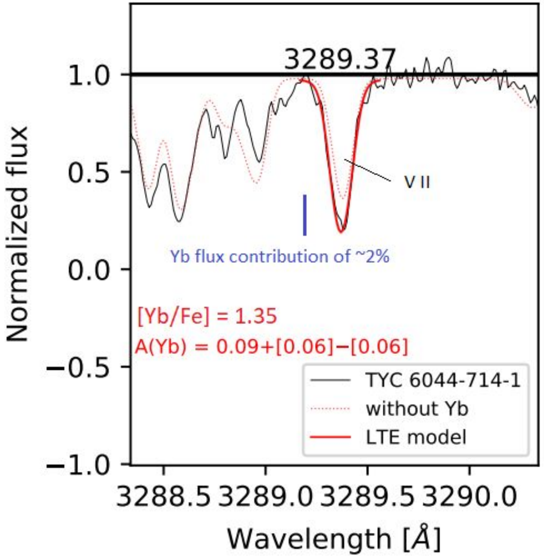
A(Eu) = -1.29 ± 0.20 and A(Th) = $-1.97\pm^{0.14}_{0.19}$

We obtain an age of $15.47 \pm 0.87 \pm {}^{9.74}_{5.66} \pm {}^{6.48}_{4.73}$ Gyr, where the errors are related to those of A(Eu), A(Th), and $\log(\mathrm{Th/Eu})_0$, respectively. The errors of A(Th) are an important source of uncertainty in the age determination, as pointed by Cayrel et al. (2001); Hill et al. (2002). It would be required a spectrum with S/N $\sim$ 750, at the same resolution, to determine A(Th) with an internal precision of 0.04 dex, and thus an associated age error of 1.9 Gyr, for example.

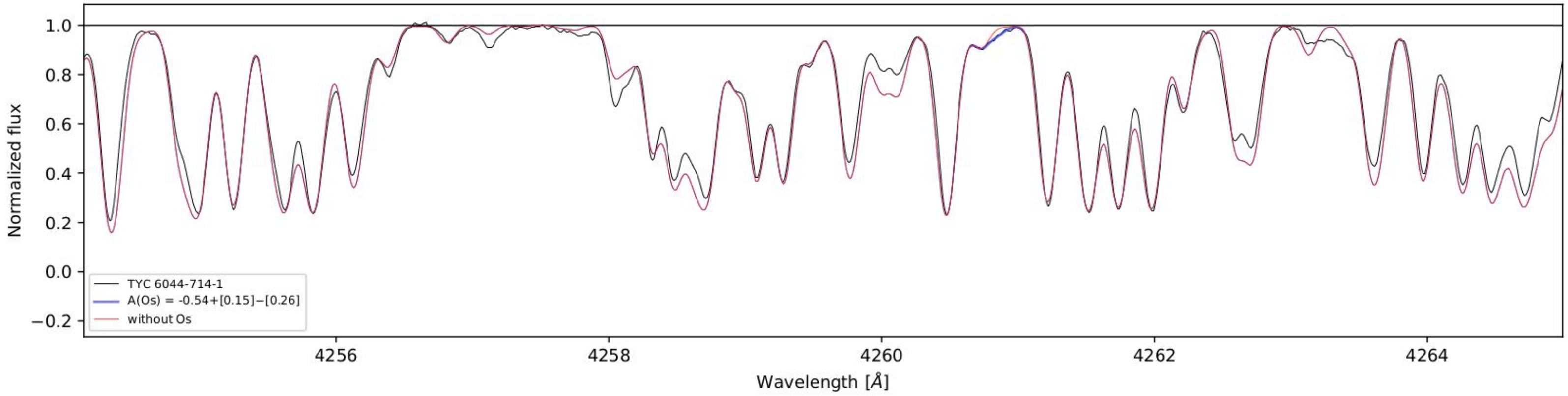
Ytterbium (Yb)



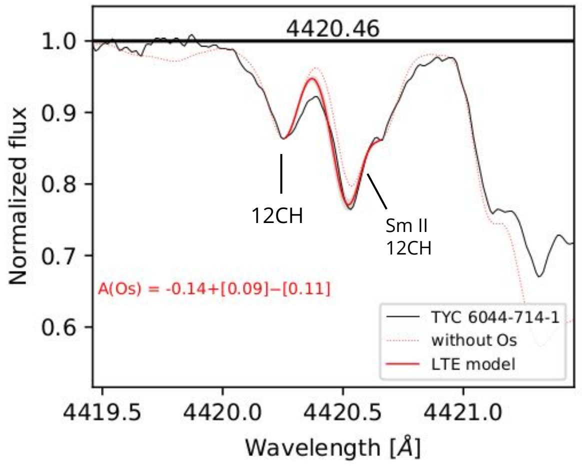




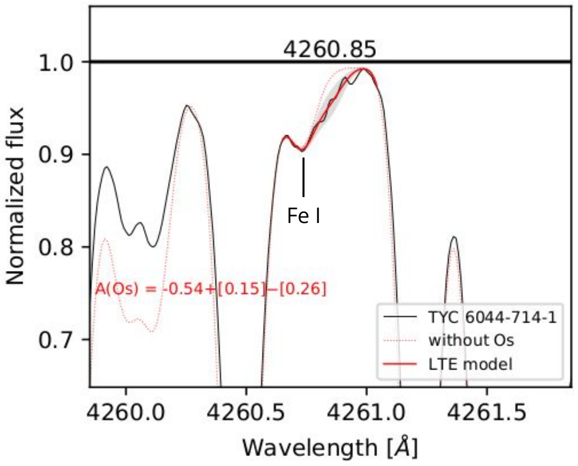
Osmium abundance



Normalized flux
Wavelength [Å]
TYC 6044-714-1
A(Os) = -0.54+[0.15]−[0.26]
without Os

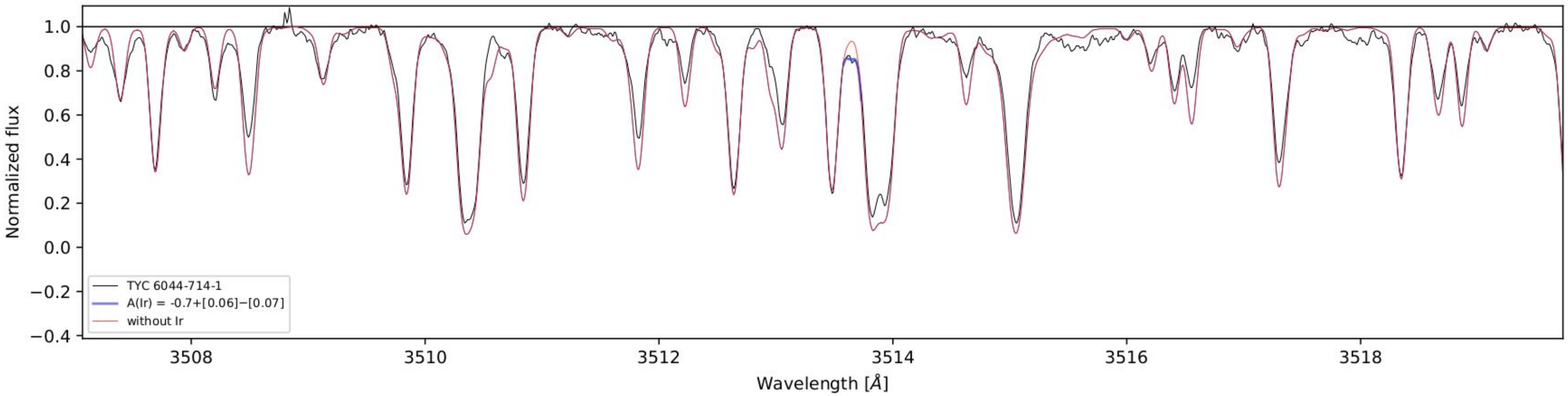


4420.46
12CH
Sm II
12CH
A(Os) = -0.14+[0.09]−[0.11]
TYC 6044-714-1
without Os
LTE model
Normalized flux
Wavelength [Å]

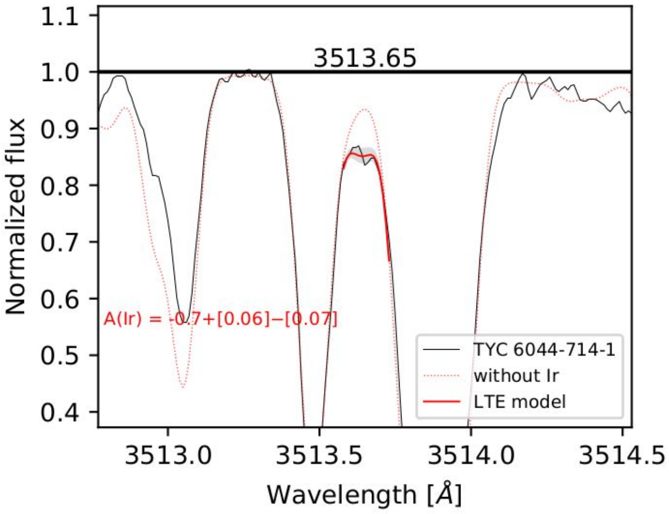


4260.85
Fe I
A(Os) = -0.54+[0.15]−[0.26]
TYC 6044-714-1
without Os
LTE model
Normalized flux
Wavelength [Å]

Iridium abundance



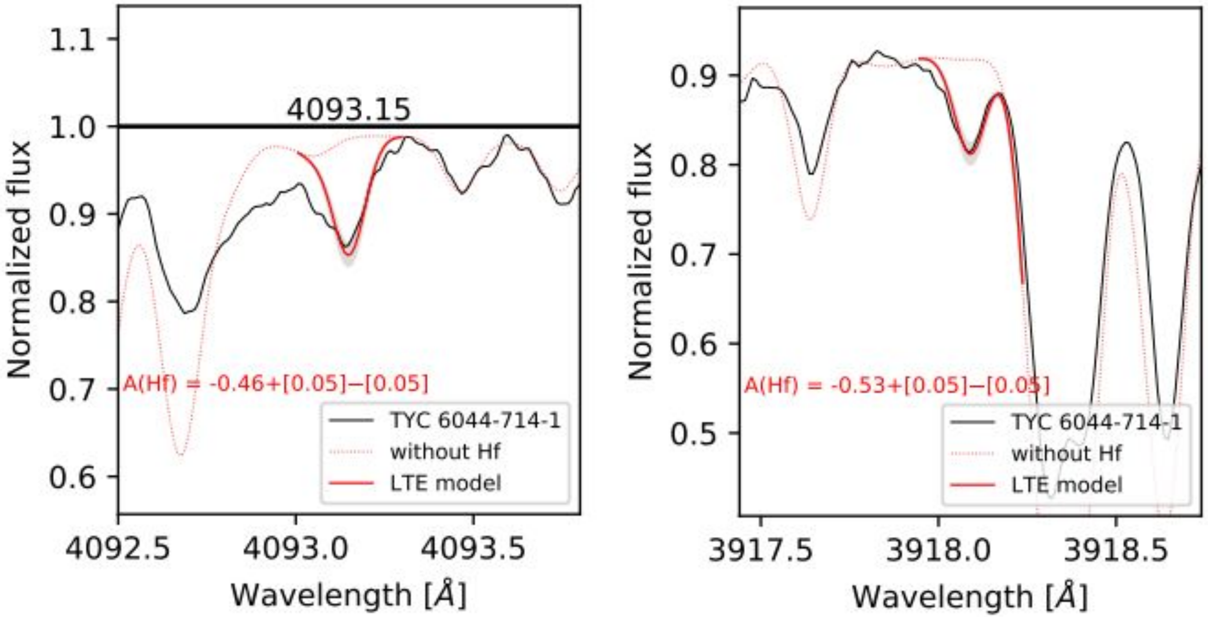
Normalized flux
Wavelength [Å]
TYC 6044-714-1
A(Ir) = -0.7+[0.06]−[0.07]
without Ir



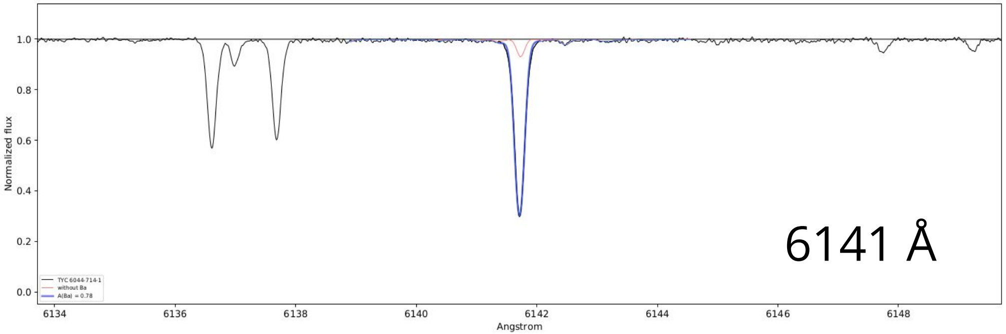
3513.65
Normalized flux
Wavelength [Å]
A(Ir) = -0.7+[0.06]−[0.07]
TYC 6044-714-1
without Ir
LTE model

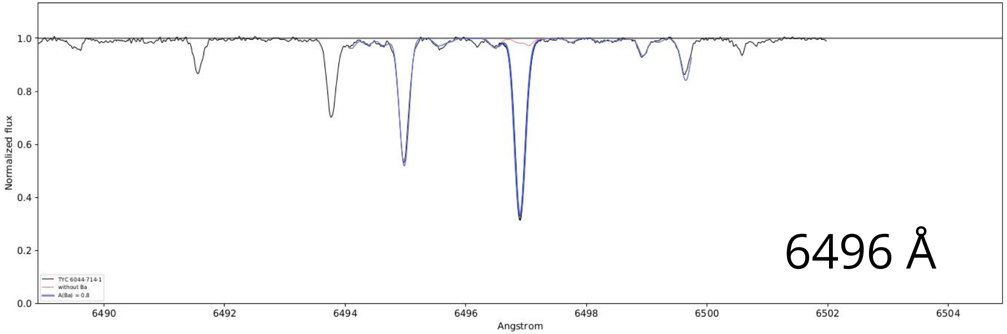
Hafnium abundance

Hafnium (Hf)


4093.15
A(Hf) = -0.46+[0.05]−[0.05]
TYC 6044-714-1
without Hf
LTE model
Normalized flux
Wavelength [Å]
A(Hf) = -0.53+[0.05]−[0.05]
TYC 6044-714-1
without Hf
LTE model
Normalized flux
Wavelength [Å]

Ba subordinate lines

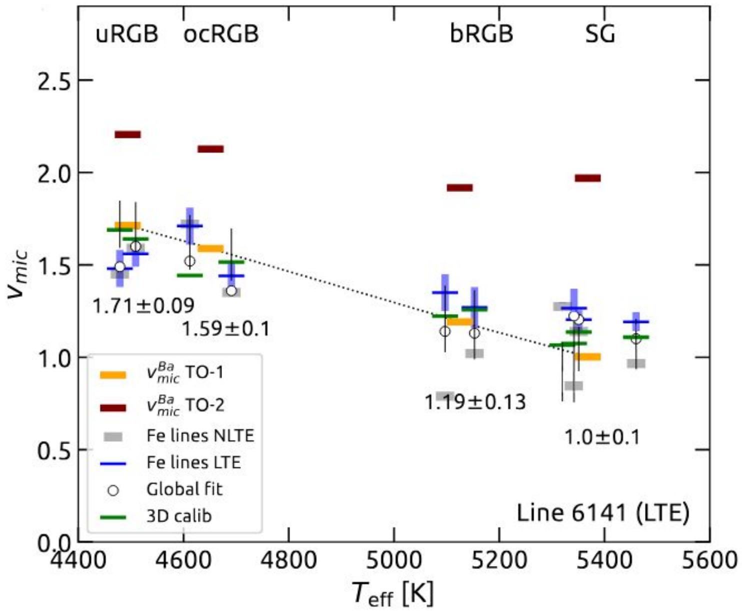




- Abundances from subordinate lines may show erratic results likely due to chromospheric effects, specially affecting intense lines.

- Barium anomalies are frequent in chromopherically active stars, younger than ~8 Gyr (*The Barium Puzzle,* e.g. D'Orazzi et al. 2009, 2012; Reddy & Lambert 2017; Baratella et al. 2020).

Microturbulence adapted to Ba lines

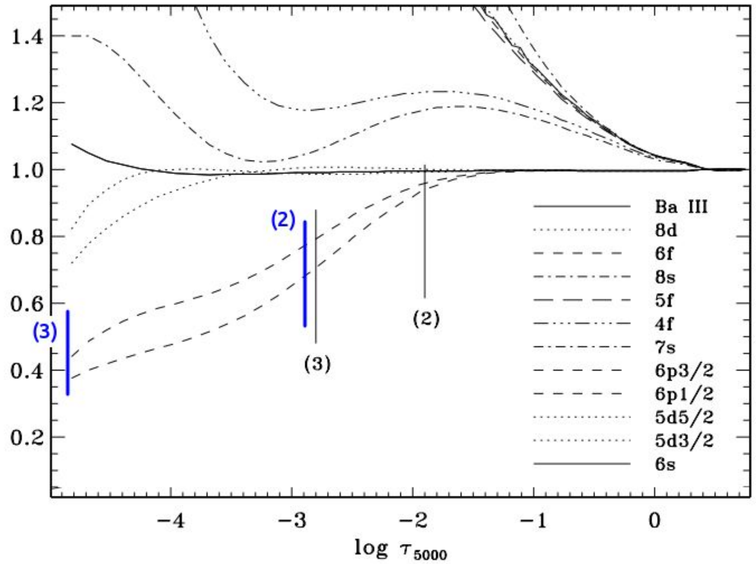


- Fe lines under 1D LTE
- Fe lines under NLTE
- based on **3D LTE modeling** (Dutra-Ferreira et al. 2016)

$$\xi\ \left(\mathrm{km\,s^{-1}}\right) = 0.998 + 3.16\times10^{-4}\,X - 0.253\,Y - 2.86\times10^{-4}\,X\,Y + 0.165\,Y^2,$$

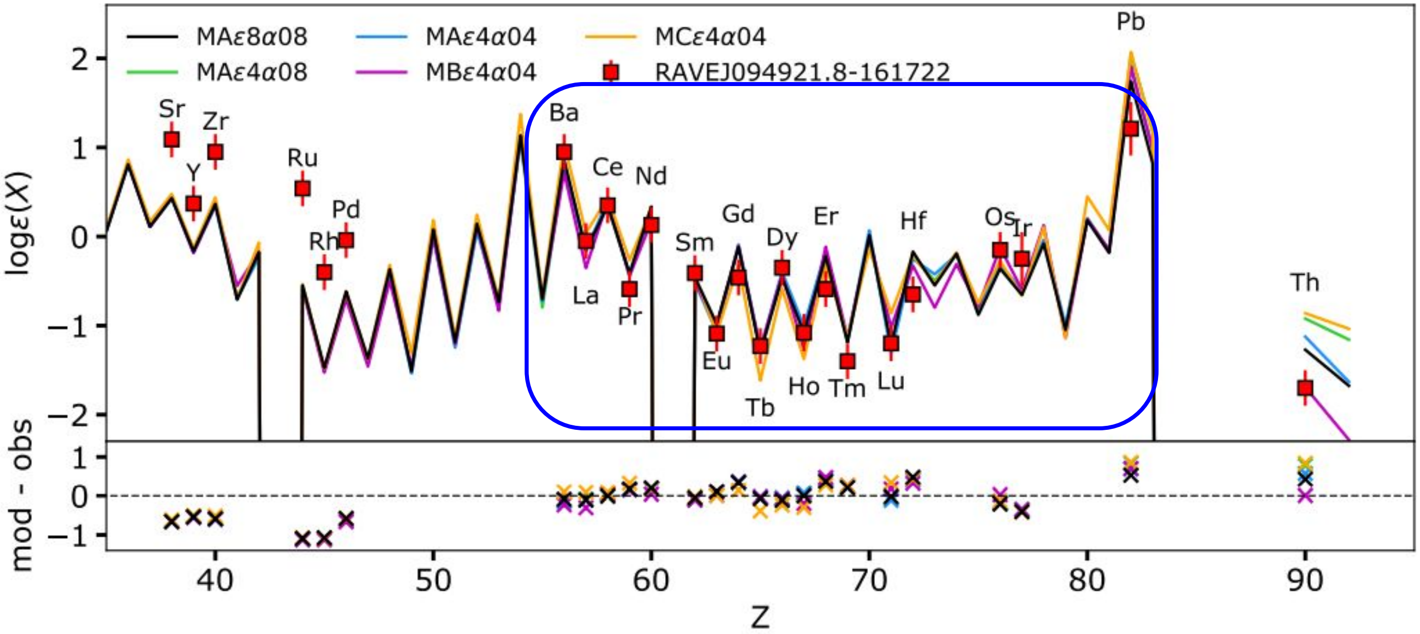
where $X \equiv T_{\rm eff} - 5500$ [K] and $Y \equiv \log g - 4.0$.

- Calibration using a star cluster (Giribaldi et al. in prep.)



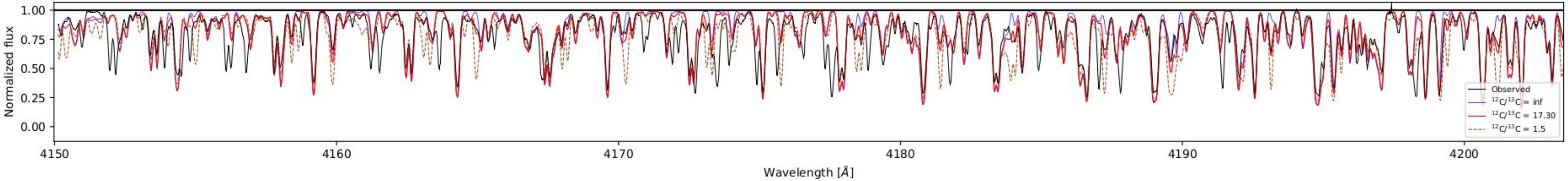
Mashonkina et al. (1999)

The star TYC 6044-714-1

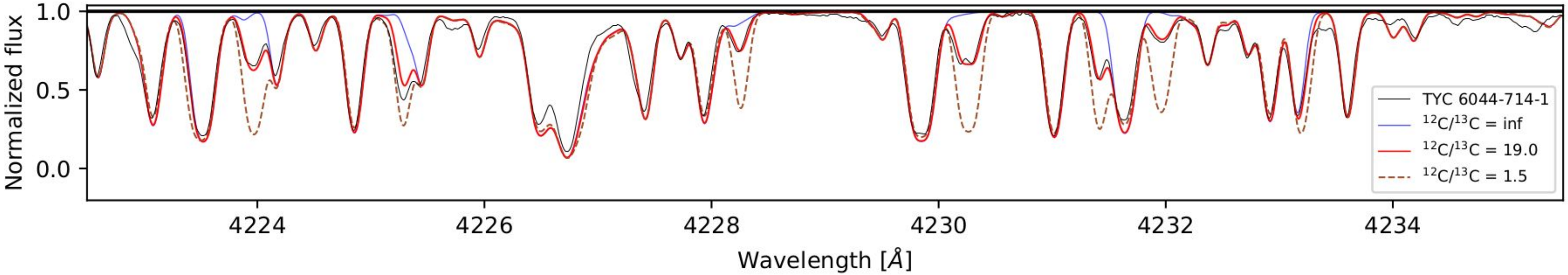


Choplin et al. (2022)

12C/13C



Observed
$^{12}C/^{13}C$ = inf
$^{12}C/^{13}C$ = 17.30
$^{12}C/^{13}C$ = 1.5
Normalized flux
Wavelength [Å]



TYC 6044-714-1
$^{12}C/^{13}C$ = inf
$^{12}C/^{13}C$ = 19.0
$^{12}C/^{13}C$ = 1.5
Normalized flux
Wavelength [Å]