Leibniz-Institut für Astrophysik Potsdam
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OSSERVATORIO ASTRONOMICO DI PADOVA

The complex behaviour of the s-process element abundances at young ages

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and Maria Lugaro, Marco Pignatari, Laura Magrini, Lorenzo Spina et al.

THE 13TH TORINO WORKSHOP ON AGB STARS
PERUGIA, 19TH-24TH JUNE 2022

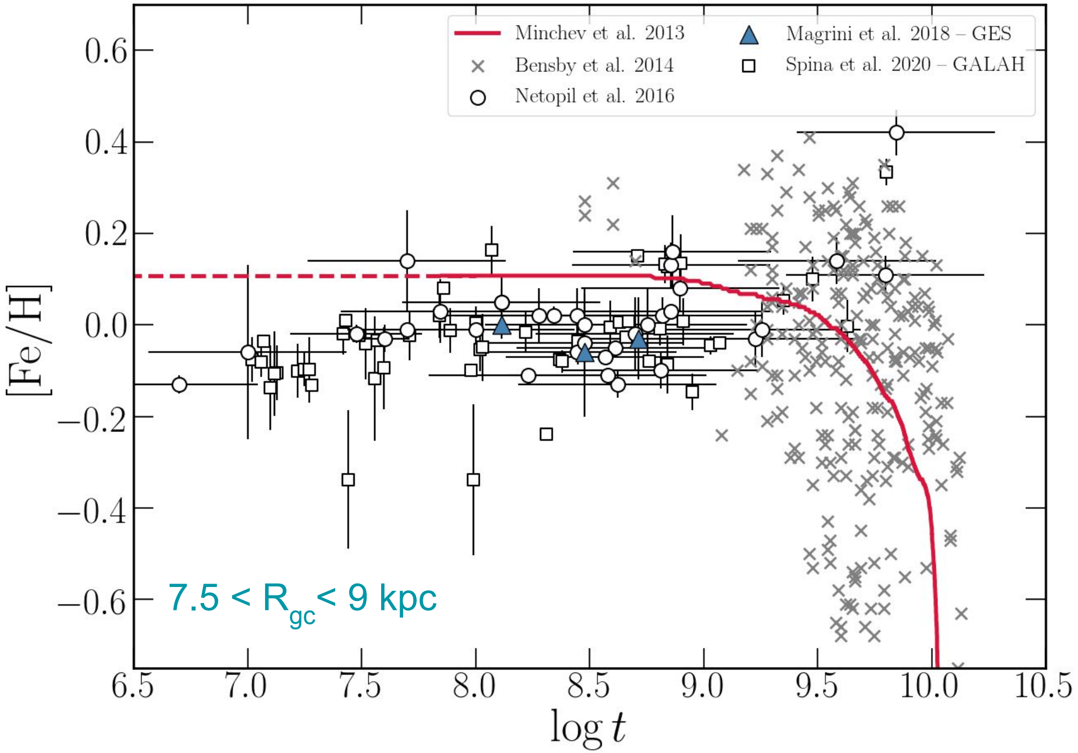
What we (really) know about the chemical composition of young open clusters?

- ★ Open clusters (OCs) : simple stellar population (coeval stars, same initial chemical composition)
- ★ Large range of ages (few Myr to several Gyr)
- ★ Ubiquitous in the disc
- ★ -0.4 < [Fe/H] < +0.4 dex, solar-scaled abundance ratios

- ★ What we actually measure in YOUNG (< 200 Myr) systems is different (James+2006; Santos+2008; D'Orazi+2011, 2012, Biazzo+2012, Spina+2017, and references therein) → **SUBSOLAR [Fe/H] and THE Ba PUZZLE**

Young OCs/stars: Issue #1

The local anaemia of the interstellar medium



THERE ARE NO METAL-ENRICHED SYSTEMS AT log *t*<200 Myr IN THE SOLAR NEIGHBOURHOOD

Model predict an enrichment of ~0.15 dex in the last 4-5 Gyr

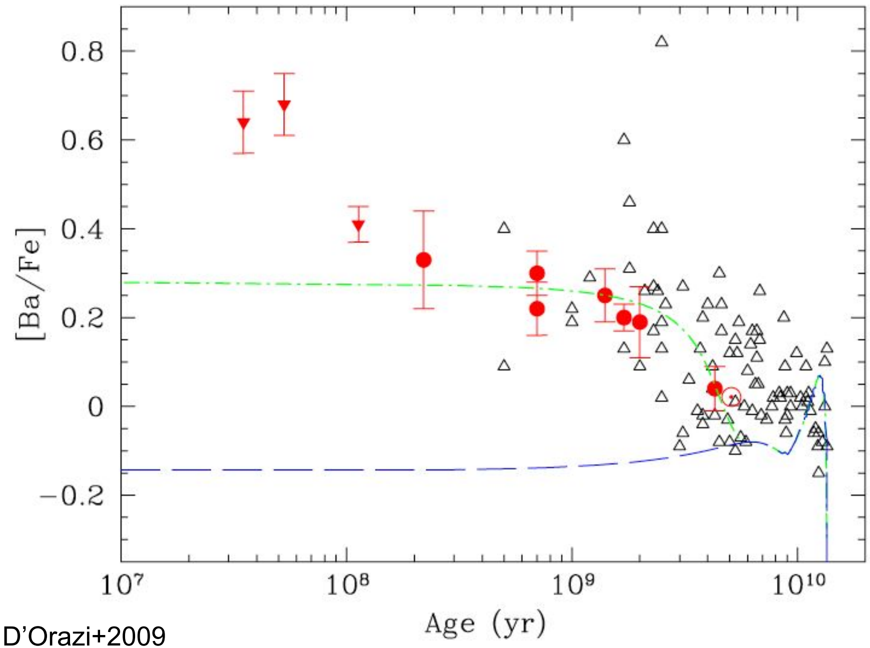
Complex combination of parental molecular cloud? No chemical evolution?

Young OCs/stars: Issue #2

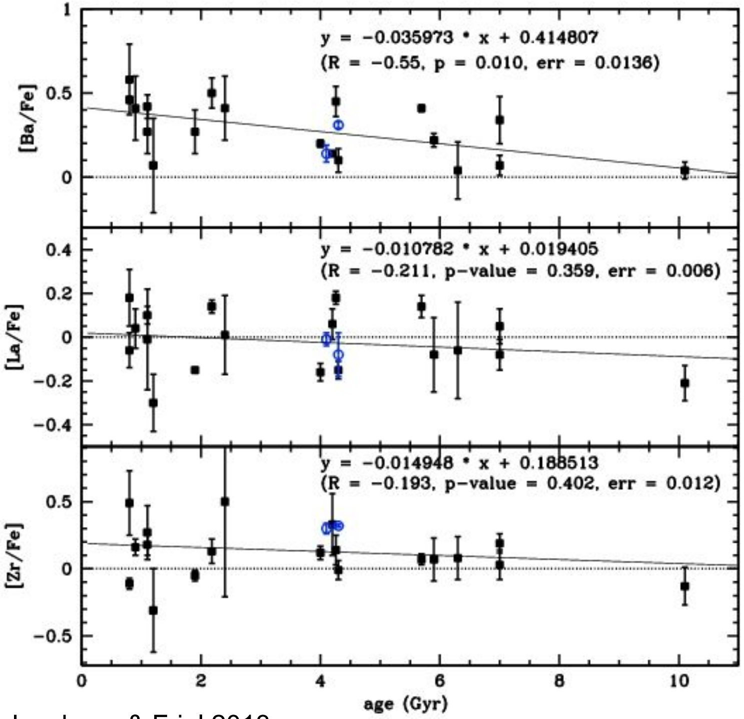
The Barium Puzzle

Young stars (log *t*<200 Myr): INCREASED [Ba/Fe] (~+0.6 - 0.7 dex, expected solar abundance ratios)

Models with increased stellar yields FAIL!!!



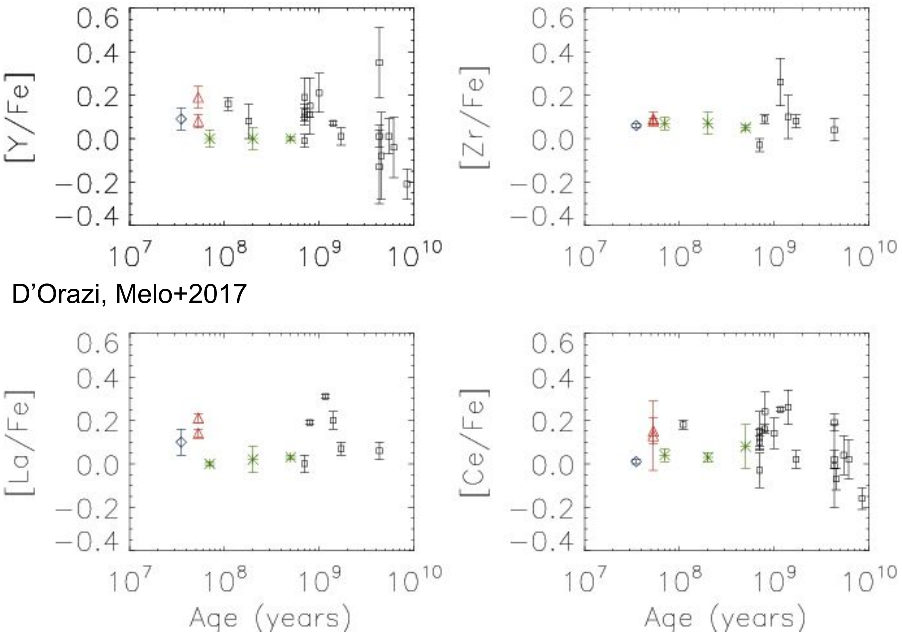
D'Orazi+2009



Jacobson & Friel 2013

Young OCs/stars: Issue #2

The Barium Puzzle

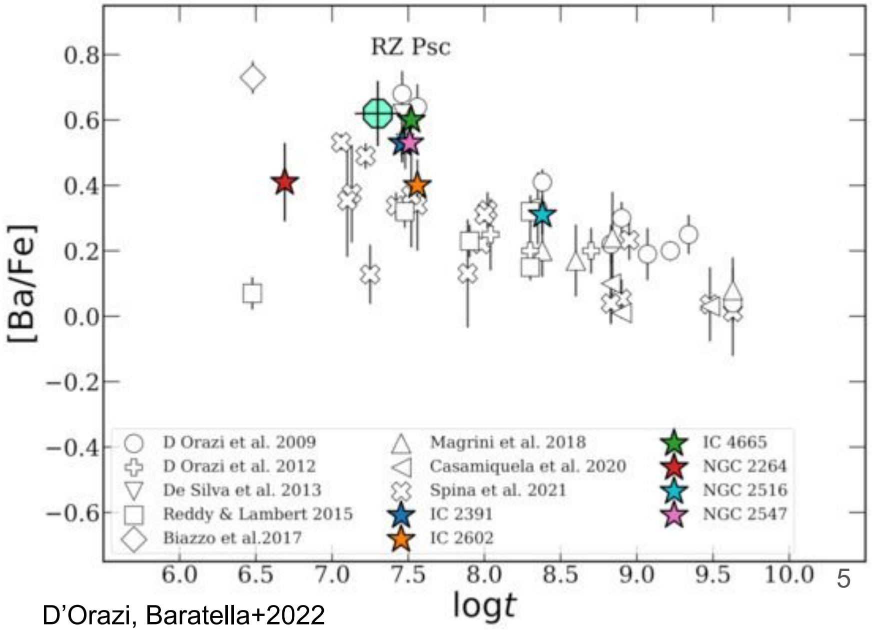


D'Orazi, Melo+2017

No similar enrichments in other s-process elements are observed (both 1st and 2nd peak)
(D'Orazi+2012, 2017; Yong+2012; Reddy & Lambert 2017)

Different solutions investigated:

- non-LTE effects (?)
- activation of intermediate (*i*-) process (?)
- influence of hot chromosphere (?)



D'Orazi, Baratella+2022

Our hypothesis

Not intrinsic properties of young stars, but issues in spectroscopic analysis

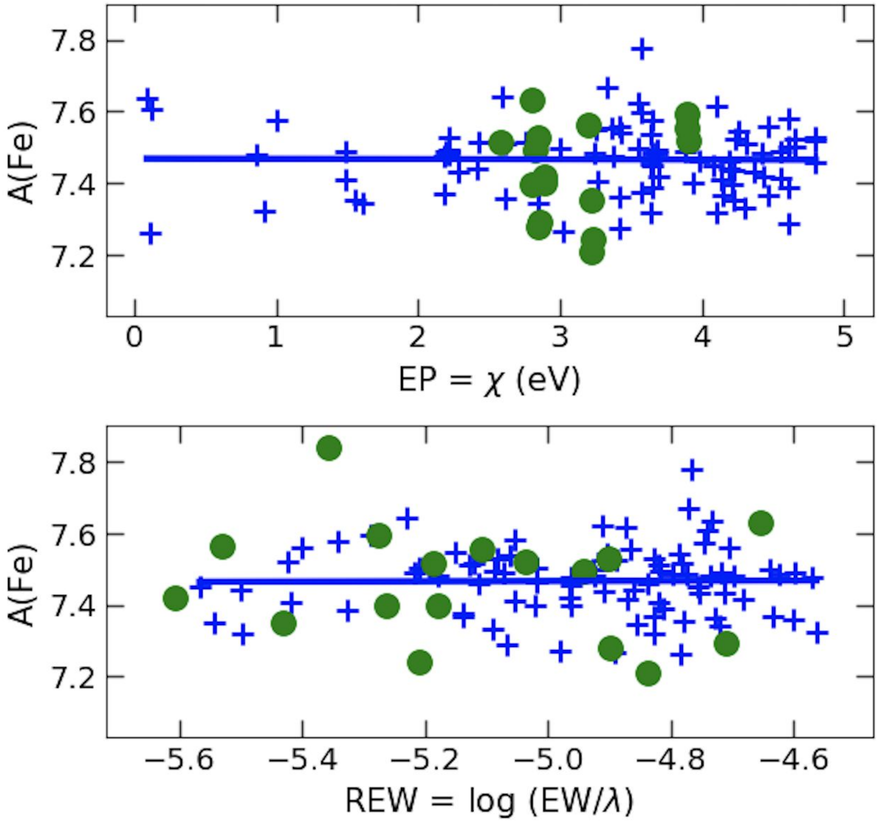
The younger the star, the higher the levels of its stellar activity

Influence on formation of spectral lines
(especially in upper layers of photosphere)

→ "standard" spectroscopic analysis (i.e. using iron lines, formed at different optical depths, to determine T_{eff}, log*g* and V_t) COULD FAIL at such young ages

→ stellar parameters and element abundances are strictly related (stellar model atmosphere)

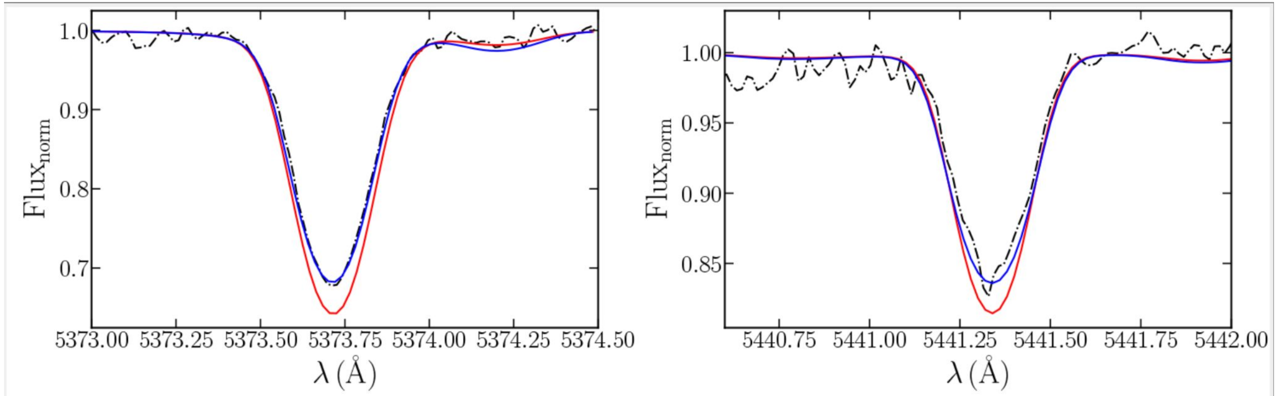
The standard spectroscopic approach (EW method)



Equivalent width (EW) of IRON lines (neutral and ionised) + model atmosphere (MARCS or KURUCZ) + dedicated code (MOOG, q2, Turbospectrum, pymoogi…)

- T_{eff}: no trends between $A(Fe)_i$ and EP_i (excitation equilibrium)
- log*g*: same abundance of neutral and ionised Fe (ionisation equilibrium)
- V_t: strong and weak Fe lines have same abundance

The effect of overestimated microturbulence V_t



Baratella, D'Orazi+2020a

Young stars (<200 Myr), V_t is overestimated by 1-1.5 km/s

Results: poor fit (red line) of the observed spectral line

Blue line: with expected values

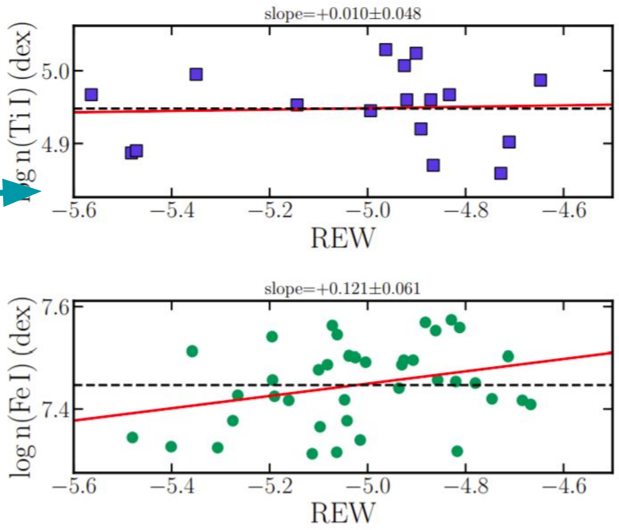
Large V_t → artificially LOW abundances (low values of [Fe/H] and [X/Fe] that rescale accordingly)

Yana-Galarza+2019; Spina+2020; Baratella, D'Orazi+2020a demonstrated that line profiles are altered by the increased stellar activity, and stellar parameters vary along the activity cycle

The new spectroscopic approach: titanium lines

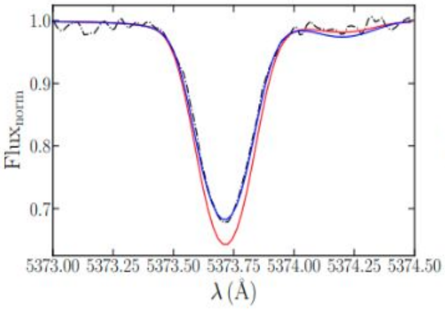
Titanium lines form deeper in photosphere and accurate atomic data from laboratory measurements (Lawler+2013)

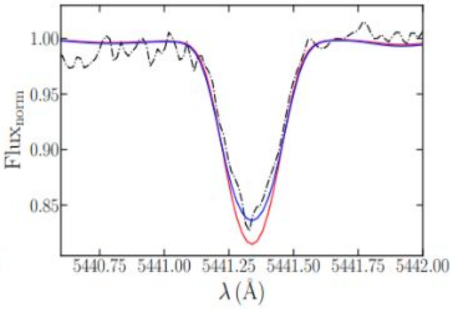
- T_{eff} from Ti + Fe (large coverage of EP)
- log*g* from TiI and TiII
- V_t from Ti only



V_t (Ti)= 0.85±0.10 km/s

V_t (Fe)= 1.75±0.15 km/s



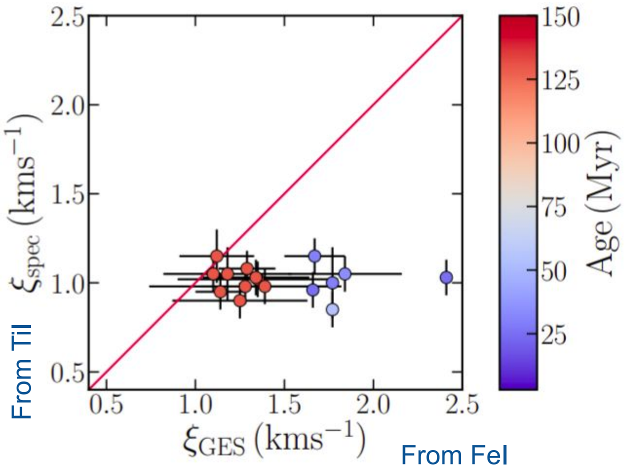


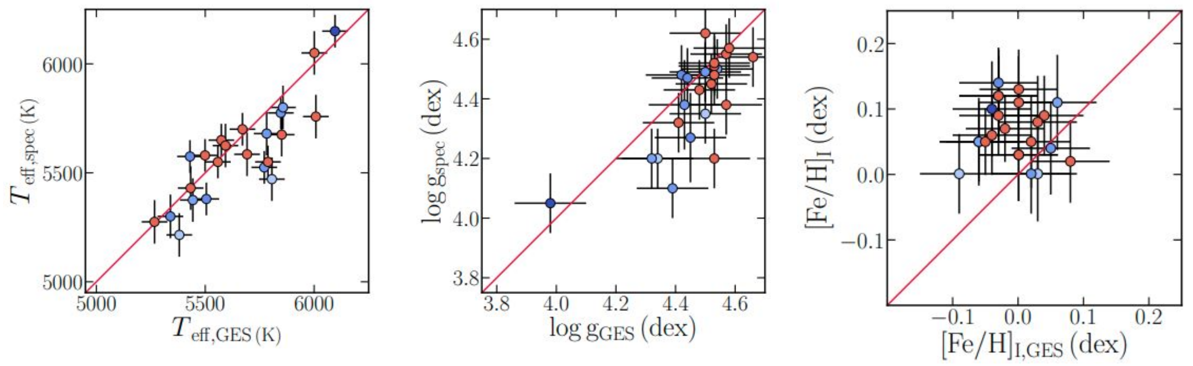
Star:
T_{eff}= 5215±100 K
log*g* = 4.35±0.10
age = 50 Myr

New values of V_t reproduce well the observed profiles

Baratella, D'Orazi+2020a

The new spectroscopic approach: titanium lines

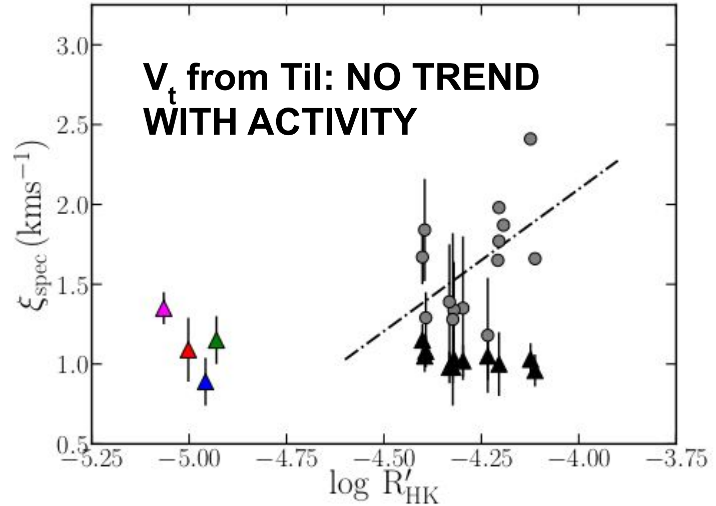




23 dwarf stars in 6 OCs

Clusters t > 100 Myr: **$\Delta(V_{t,\,TiI} - V_{t,\,FeI})$= -0.23±0.13 km/s**

Clusters t < 100 Myr: **$\Delta(V_{t,\,TiI} - V_{t,\,FeI})$= -0.85±0.27 km/s**

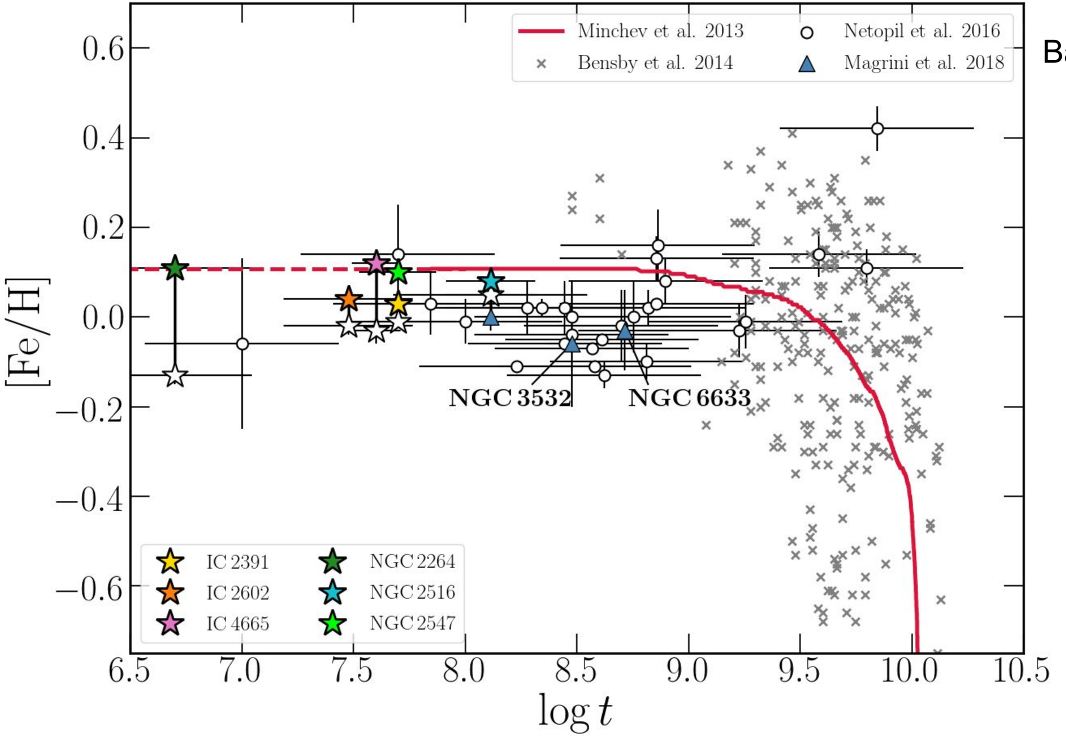


Baratella, D'Orazi+2020a

The Galactic metallicity trend at young ages

No sub-solar [Fe/H] at log*t* < 8.5 !!!

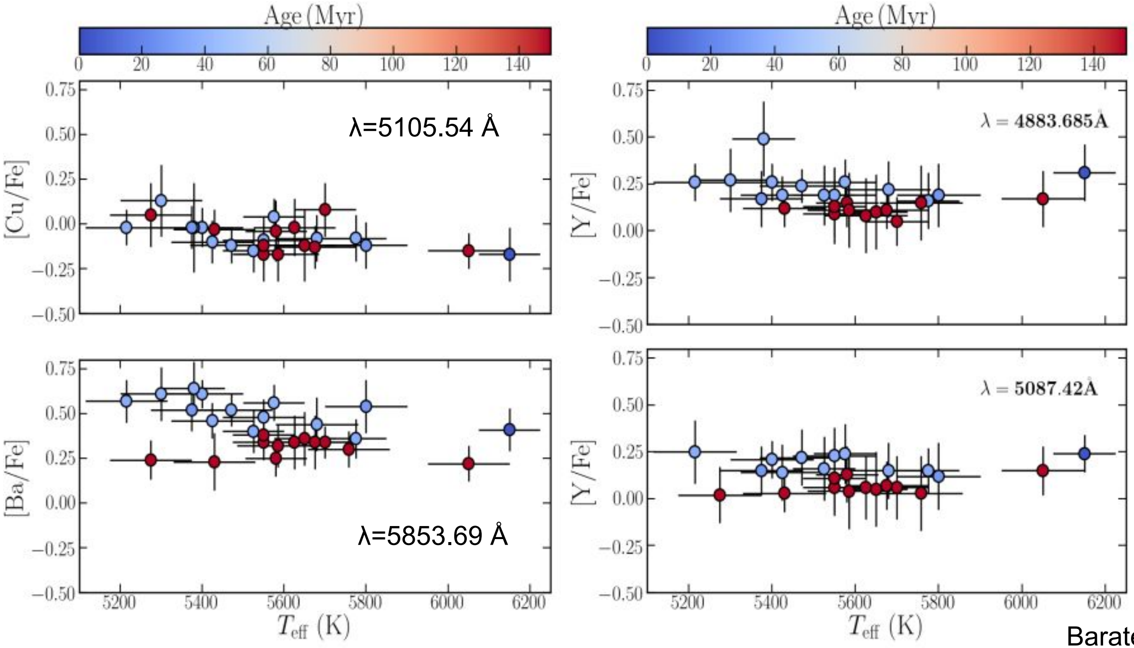
NO peculiar chemical evolution needed



Baratella, D'Orazi+2020a

Apparent sub-solar metallicity: fundamental issues in the spectroscopic analysis of young stars, related to stronger stellar activity.

Heavy elements abundances: Cu, Sr, Y, Zr, Ba, La and Ce



Baratella, D'Orazi+2021

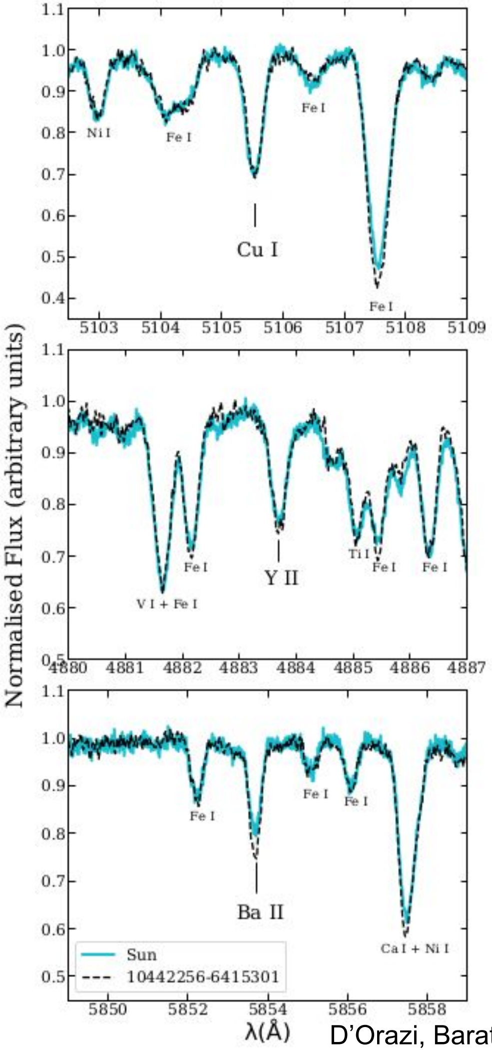
- ➔ Sharp separation with age for Y and Ba
- ➔ [Ba/Fe] between +0.25 and +0.65 dex
- ➔ [Y/Fe] between 0 and +0.30 dex
- ➔ [Cu/Fe] ~solar

Abundances of Y, Sr, Zr, La and Ce = from bluer wavelengths (3800 < λ < 4800Å)

$[Y/Fe]_{blue} = [Y/Fe]_{red}$

[Sr/Fe], [Zr/Fe], [La/Fe] and [Ce/Fe] = SOLAR

NLTE corrections of Cu (+0.02 dex) and Ba (~ -0.10) dex not able to explain the enhancements

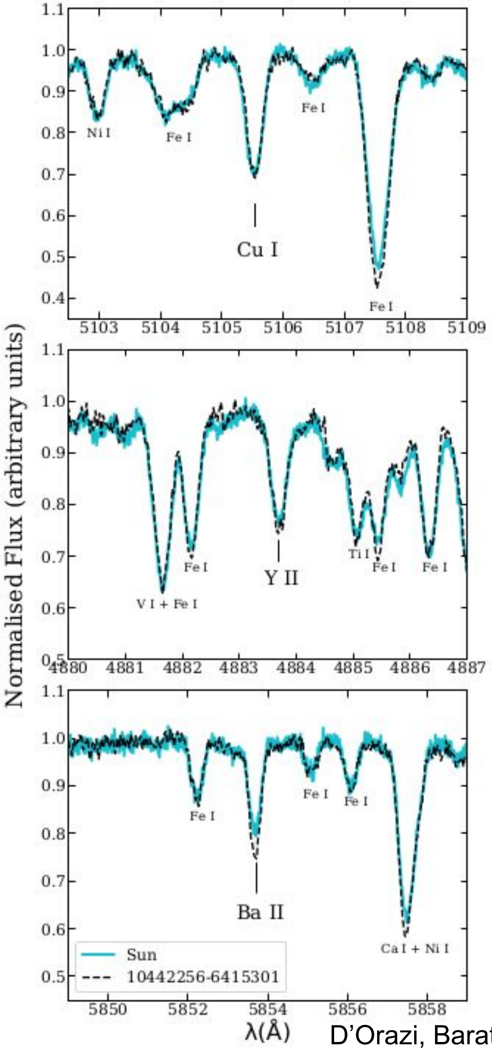


Behaviour of spectral lines in solar-analog of 35 Myr

Cu: Fe-peak + weak s-process; Y: 1° peak s-process; Ba: 2° peak s-process

[Cu/Fe]= -0.08±0.13 [Y/Fe]= +0.16±0.15 [Ba/Fe]=+0.36±0.11

D'Orazi, Baratella+2022



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- Optical depth of line formation: logτ (Cu)= -3.4; logτ(Y)= -2.6; logτ (Ba)= -3.2 → similar effect expected

D'Orazi, Baratella+2022

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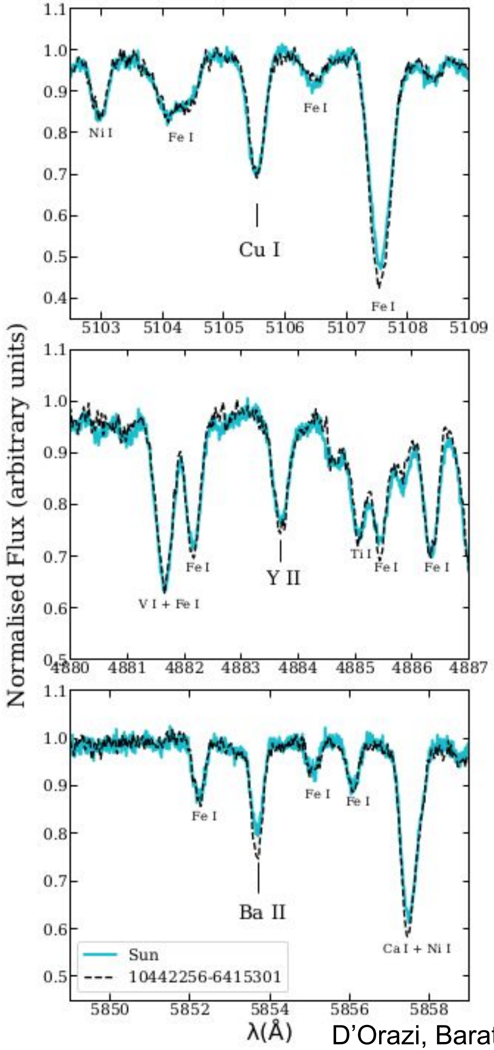

D'Orazi, Baratella+2022

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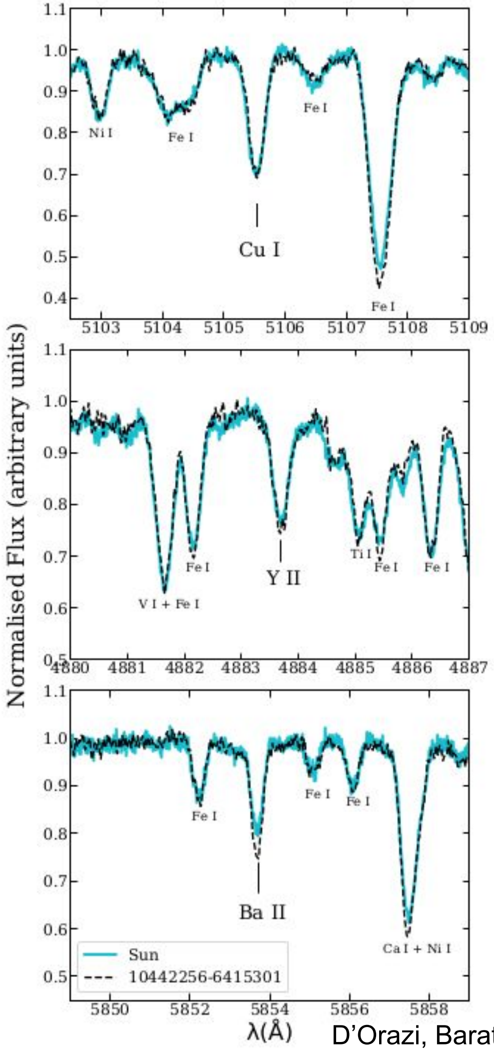

D’Orazi, Baratella+2022

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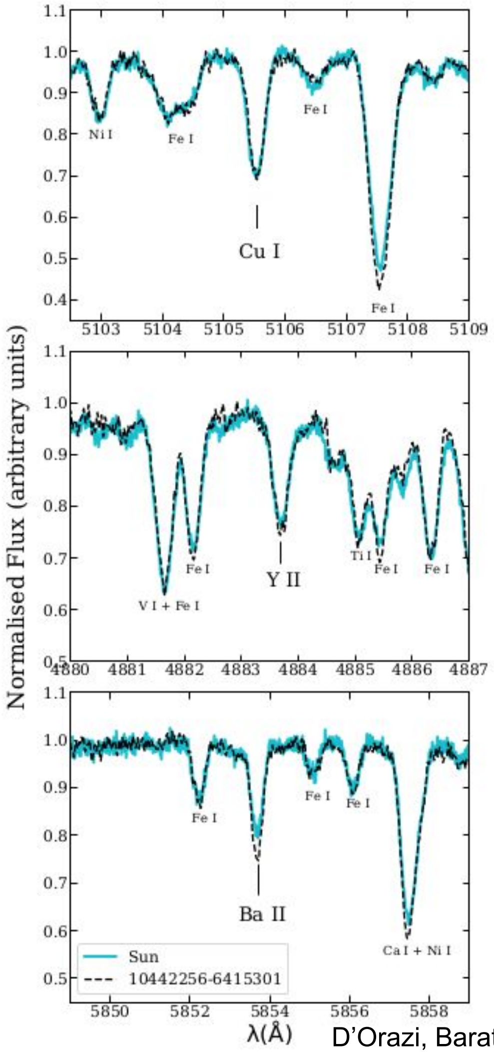
- Ionisation status: Cu=neutral; Y=ionised; Ba=ionised → over-ionisation effect (Tsantaki+2019)



D'Orazi, Baratella+2022

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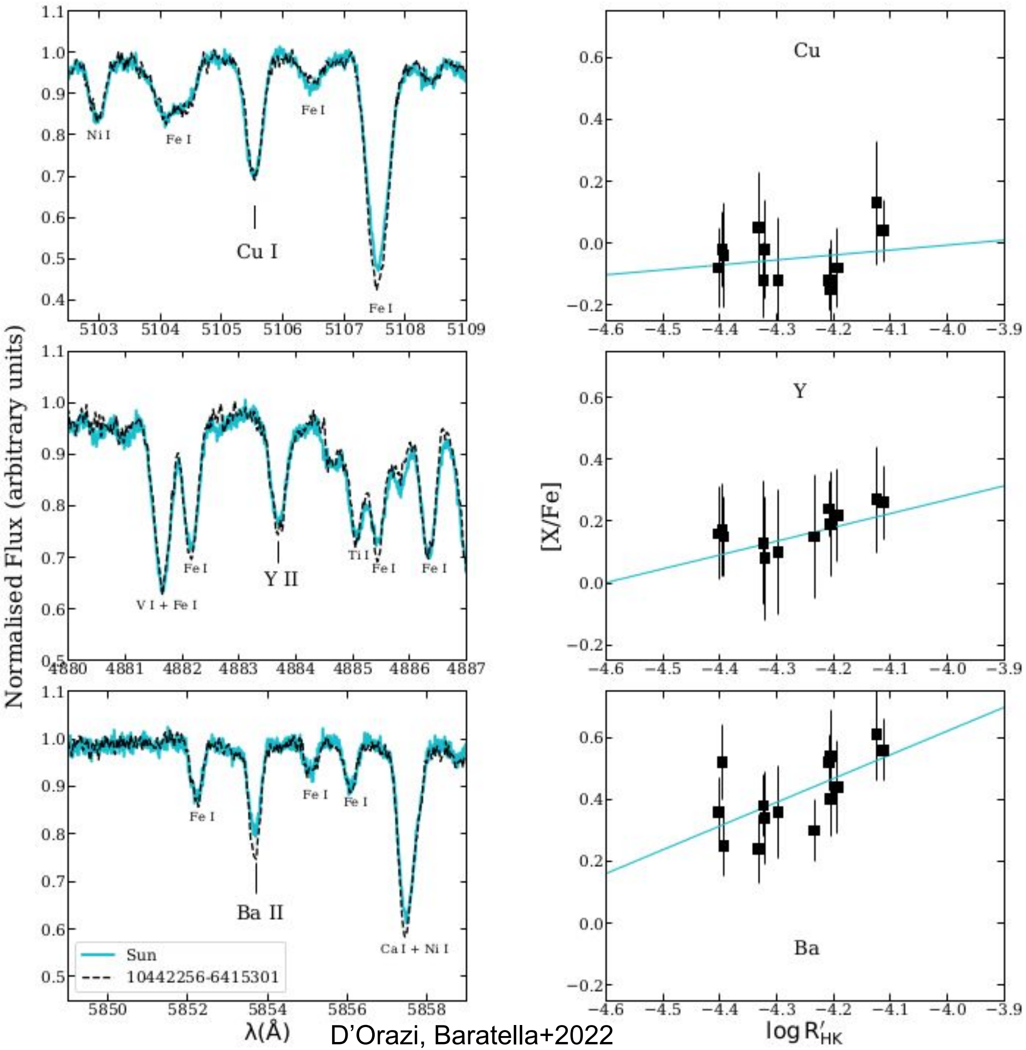
- Ionisation status: Cu=neutral; Y=ionised; Ba=ionised → over-ionisation effect (Tsantaki+2019)
- First Ionisation Potential (FIP): FIP (Cu)= 7.72 eV; FIP(Y)=6.38 eV; FIP (Ba)=5.21 eV



D'Orazi, Baratella+2022

- Ba (overabundant) and Sr (solar) have similar physical and chemical properties
- Sr and Y both 1° peak s-process elements
- Y (enhanced) and La (solar) both ionised, same depth and nucleosynthesis channel
- Ba and La produced in same way

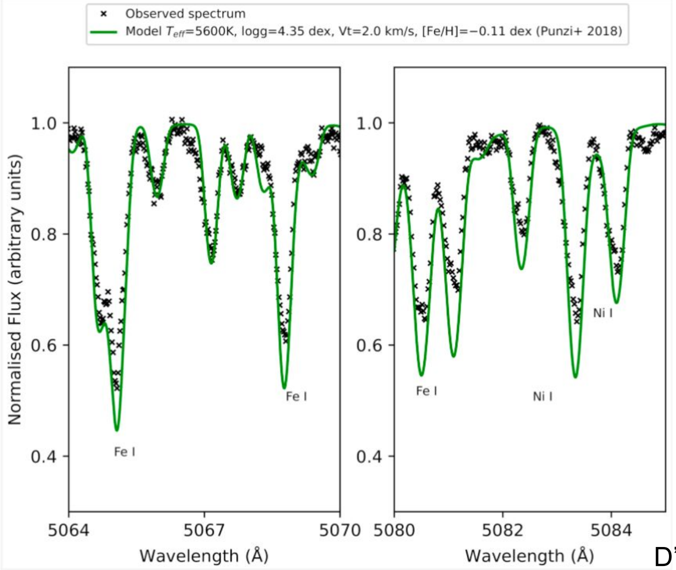
Indication of possible correlation with stellar activity $\log R'_{HK}$

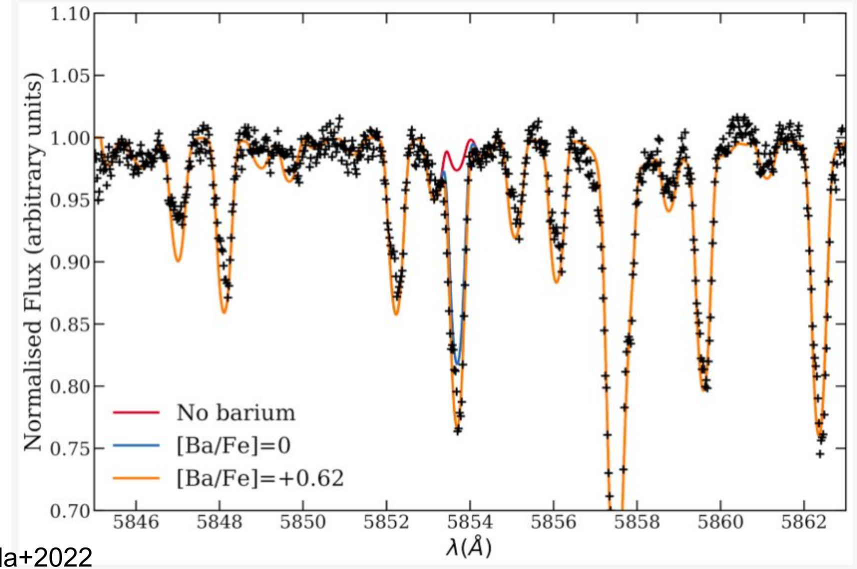
(measurements are not synchronous)

The case of RZ Piscium (*t* = 20±5 Myr, Potravnov+19)

T_{eff}(J-K) = 5300 ± 90 K; T_{eff}(Bp-Rp) = 5492 ± 73 K

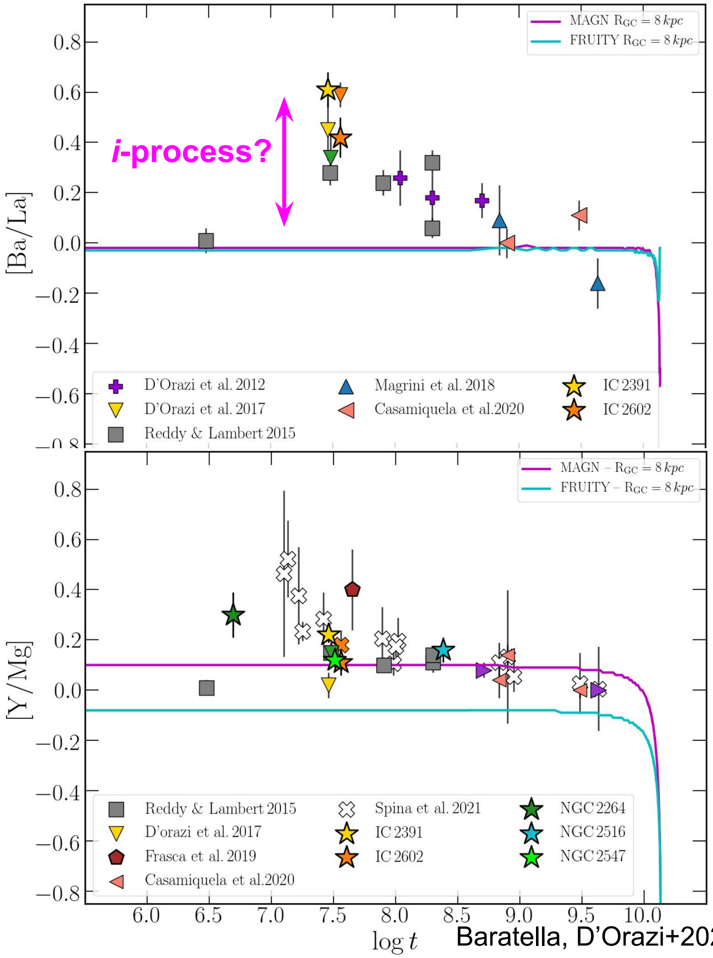
	T_{eff}	log*g*	V_t	[Fe/H]	[Ba/Fe]
Punzi+18 + Shen+19	5600±75 K	4.35±0.10	**2.0±1.0 km/s**	-0.11±0.03	**+0.18±0.15**
D'Orazi, Baratella+22	5350±75 K	4.05±0.05	**0.85±0.15 km/s**	-0.01±0.02	**+0.62±0.14**





D'Orazi, Baratella+2022

The Galactic chemical evolution of s-process elements

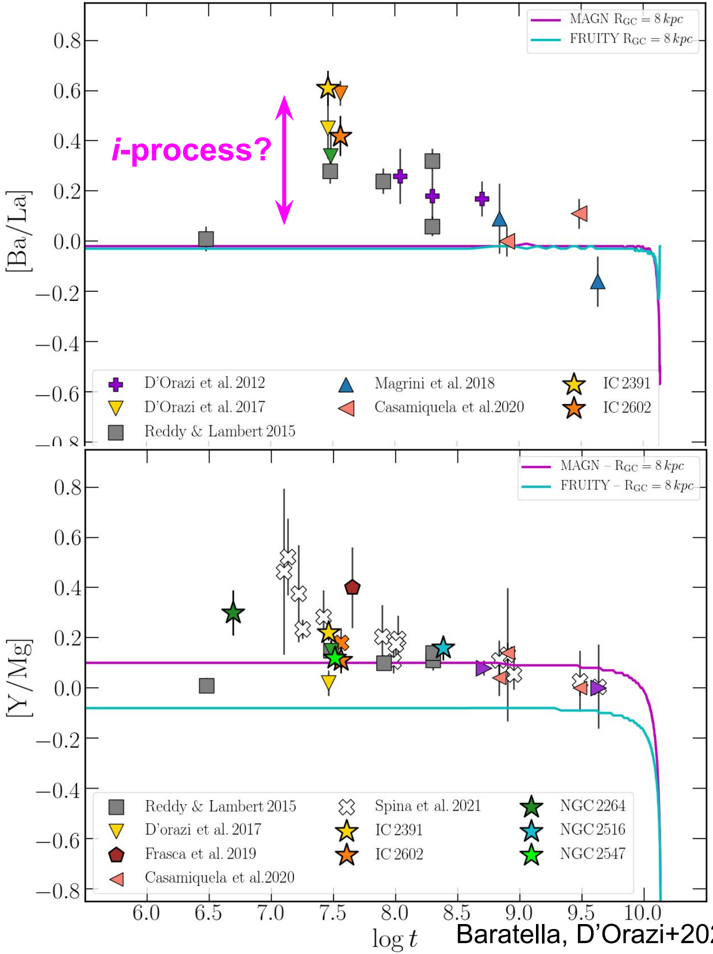


Baratella, D'Orazi+2021

Y (1° peak) and Ba and La (2° peak): low-mass AGB stars (small % from massive stars in early Galactic epoch) from ^{13}C pocket during 3-DU

Models: FRUITY (Cristallo+2009) and MAGN (Magrini et al.2021) – recent FRUITY with magnetic fields

The Galactic chemical evolution of s-process elements



Baratella, D'Orazi+2021

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➔ Ba and La are produced in the same way = FAIL at reproducing observed [Ba/La]

➔ ***i*-process?? Firstly proposed by Cowan & Rose 1977, Mishenina+2015 → additional source of Ba (La untouched)....but which site of production?**

➔ Mild enrichment of Y wrt Zr and Sr = mainly explained with observational issues (lower V_t), but large variety of processes could contribute

Conclusions

From spectral POV

- Over-ionisation effect
- Optical depth of line formation
- FIP effect
- Microturbulence
- Fundamental issues due to activity

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From nucleosynthesis POV

Models fail at reproducing the [Ba/La] time evolution

i-process is an interesting solution, but large uncertainties

Conclusions

From spectral POV

- Over-ionisation effect
- Optical depth of line formation
- FIP effect
- Microturbulence
- Fundamental issues due to activity

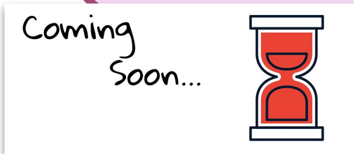
Nordlander+, *in prep*:

Including magnetic fields (dark/bright spots and surface coverage fraction) in 1D stellar atmosphere models

New tool to analyse active stars (4MOST)!

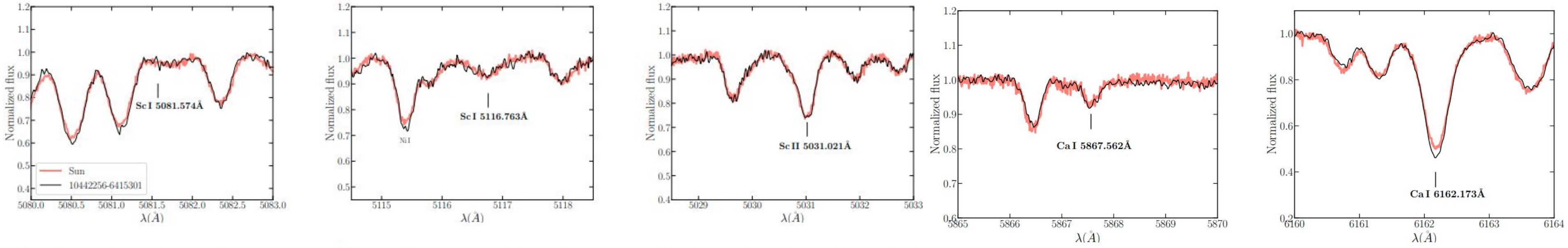
l at reproducing the [Ba/La] time evolution

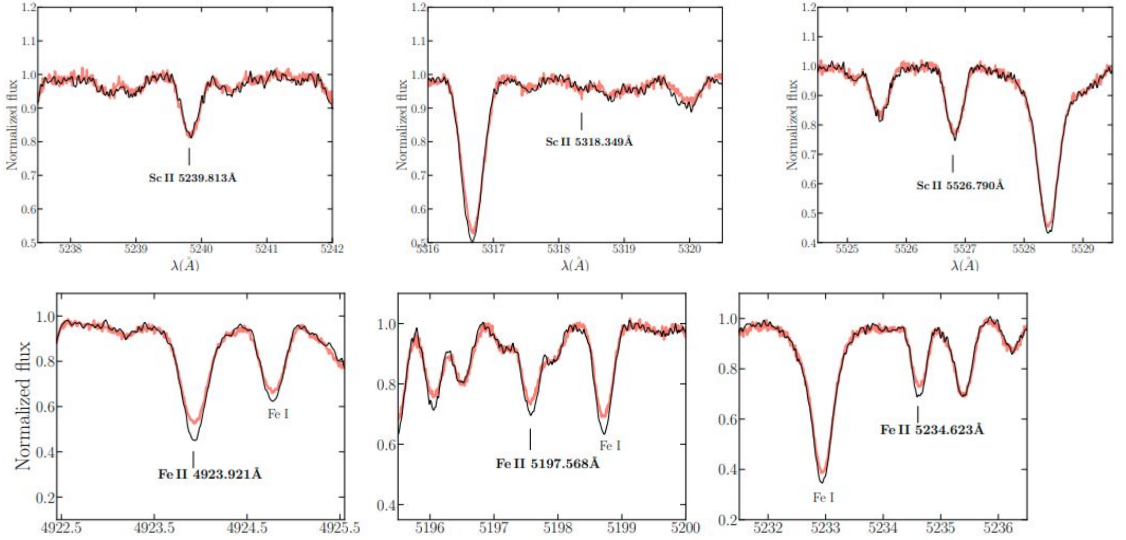
s an interesting solution, but large uncertainties



Going beyond …

Behaviour of spectral lines: other elements …





STRONG lines (forming in upper layers of photosphere) are stronger in the young star than in the Sun

Sc: same electronic configuration as Y and similar to La

Ionisation stage and line formation depth are not able ALONE to explain enhancements

Baratella, D'Orazi+2021

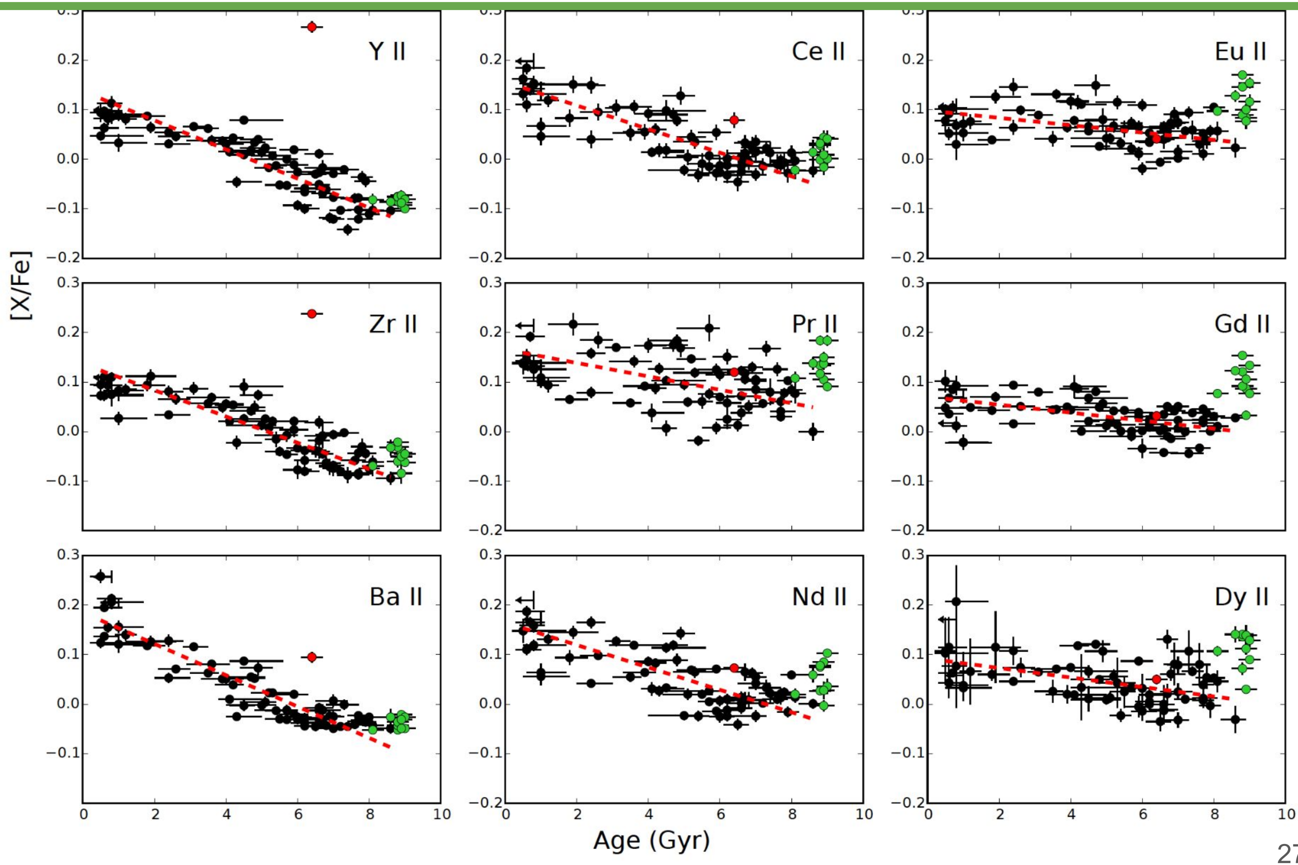
Chemical clocks: [Y/Mg] or [Ba/Mg]

Ba and Y: useful for chemical clocks (relations between abundance ratios and age, e.g., Nissen+2016, Spina+2018, Casali+2020)

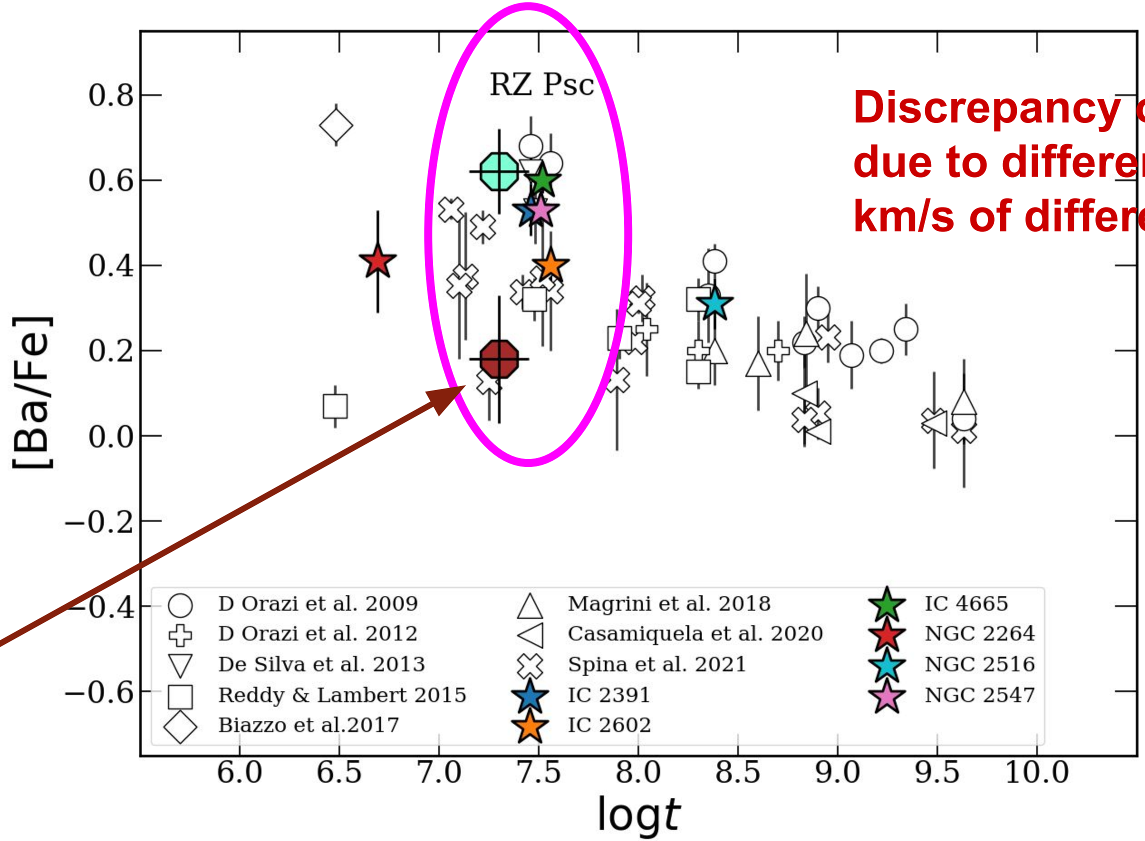
Extreme caution below 200Myr (relations not well constrained)

La or Zr might be valid substitute

Spina+2018



The case of RZ Piscium (t = 20±5 Myr, Potravnov+19)



Discrepancy of RZ Psc: mainly due to difference in V_t (1.15 km/s of difference)!!!

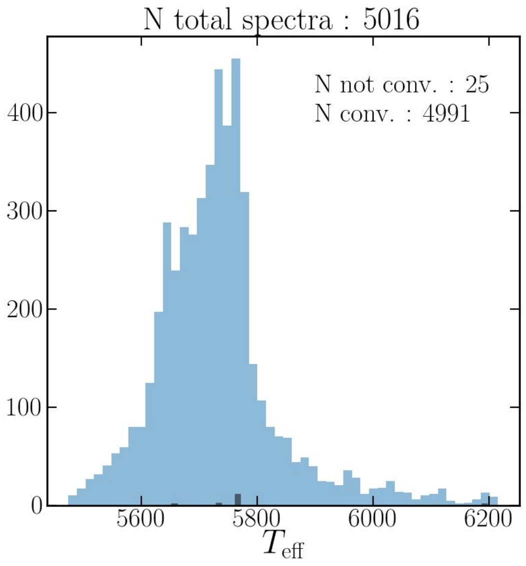
Large scatter at young ages: not only microturbulence!!!

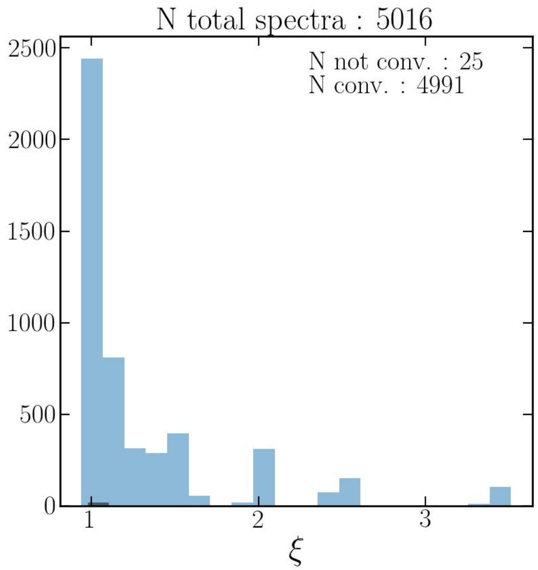
Work in progress: including magnetic fields in stellar atmospheric models (Nordlander et al., *in prep*)

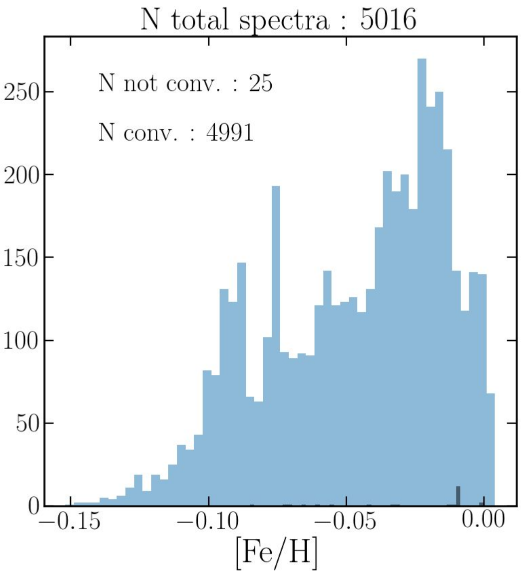
From initial 5000 spectra, set of ~600 synthetic spectra of the Sun:

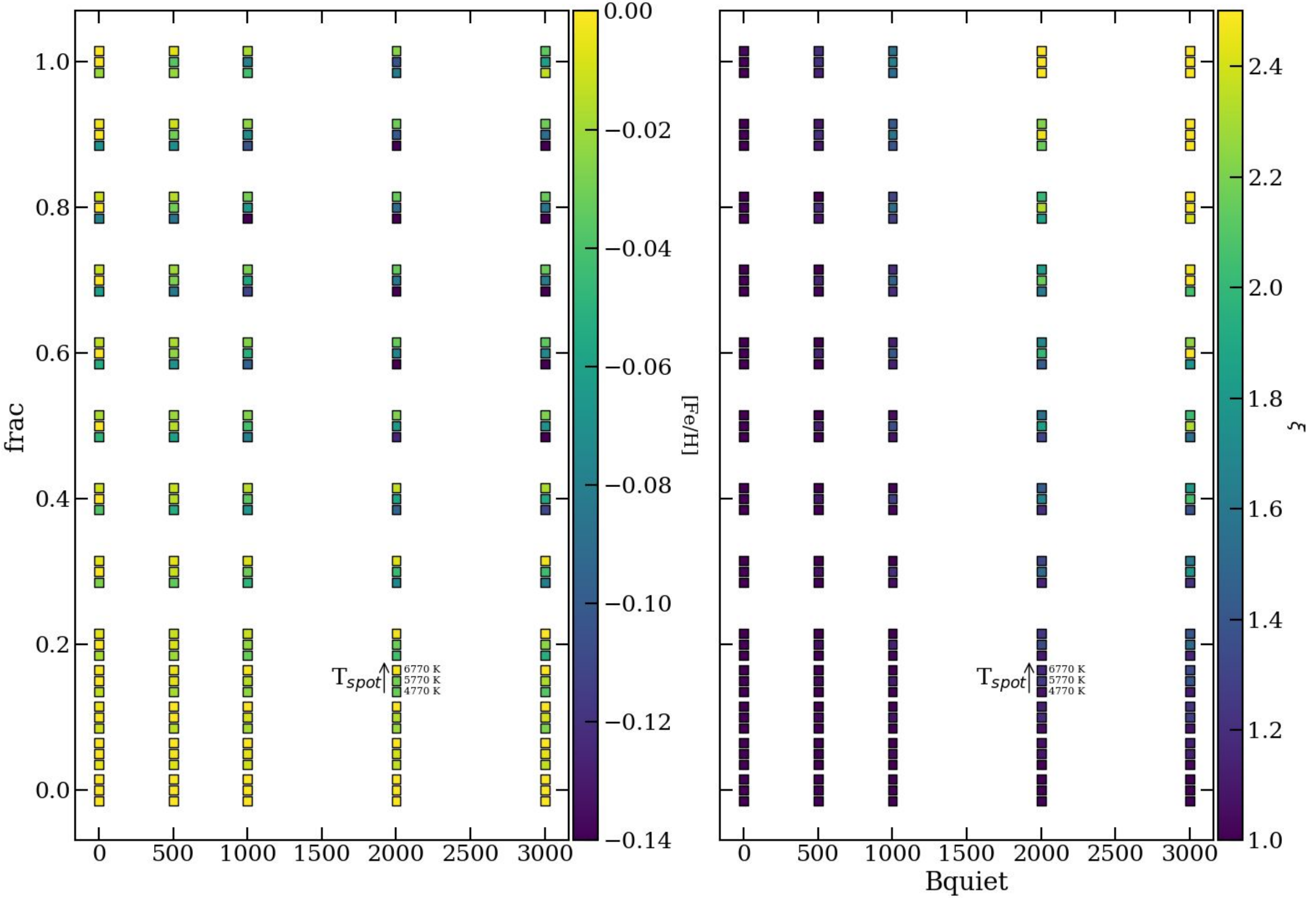
- quiet: T_{eff}=5771 K, log$g$=4.44, [Fe/H]=0.0, V_t=1.00 km/s, B=0 G
- spots fraction: f= 0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0
- bright and dark spots: Tspots= Teff ± 0, 100, 250, 500, 1000
- spots magnetic fields: Bspots= 0, 500, 1000, 2000, 3000 G (see discussion Kochukov+2020)

Preliminary results…









Presence of spots is important.

Still investigating how the EW of different elements are altered

Our goal: corrections for EW as a function of activity index (i.e., filling factor) ….
NOT AN EASY TASK

Sample of young active stars (not too much fast rotators, not too active): 4MOST