Time evolution of s-process elements as traced by Galactic Open Clusters

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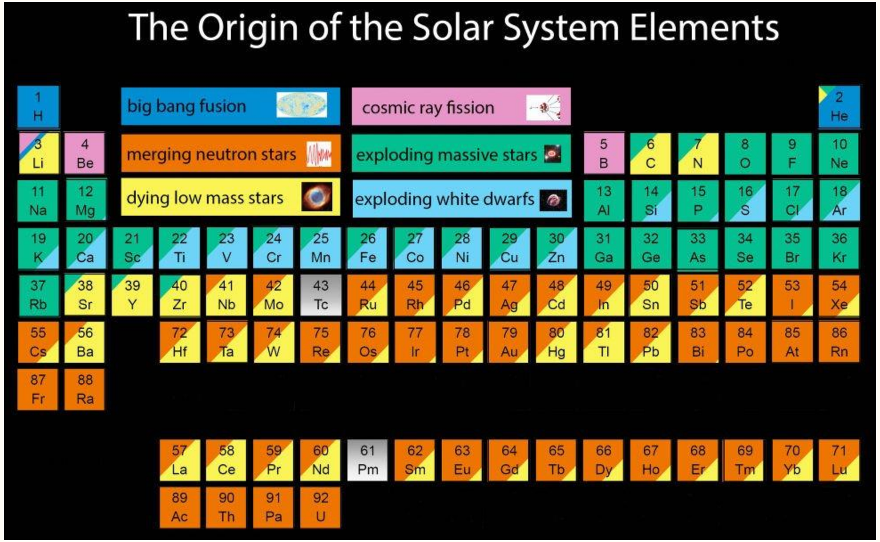
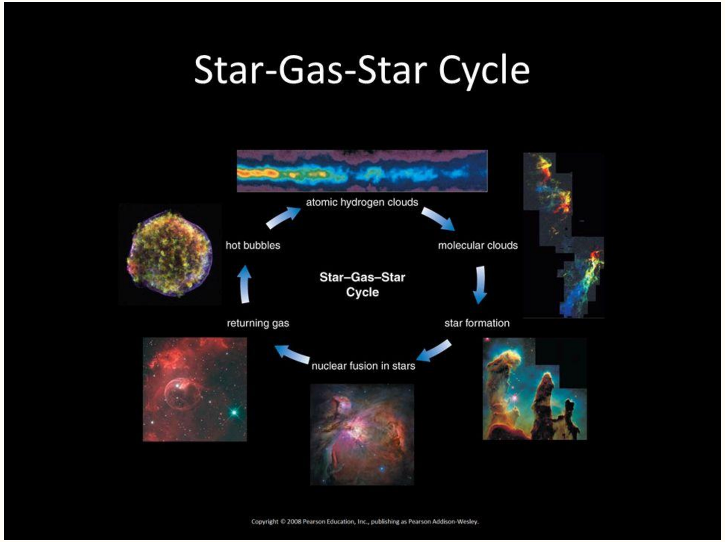
Why determining the chemical composition of stars?

<u>Spectroscopic characterisation</u> (parameters and chemical composition) + dynamics + age + position:

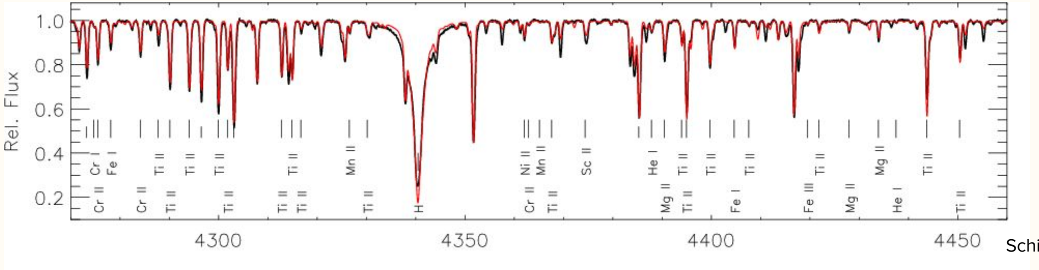
1. Prove the stellar nucleosynthesis theories
2. Investigate Galaxy formation and chemical evolution
3. Study the observed correlations between planets and host stars





Why determining the chemical composition of stars?

HOW: High-resolution spectroscopy ➜ decodification of stellar light into temperature (T_{eff}), gravity (log g) and **chemical composition**



Schiller & Przybilla 2008

Why determining the chemical composition of stars?

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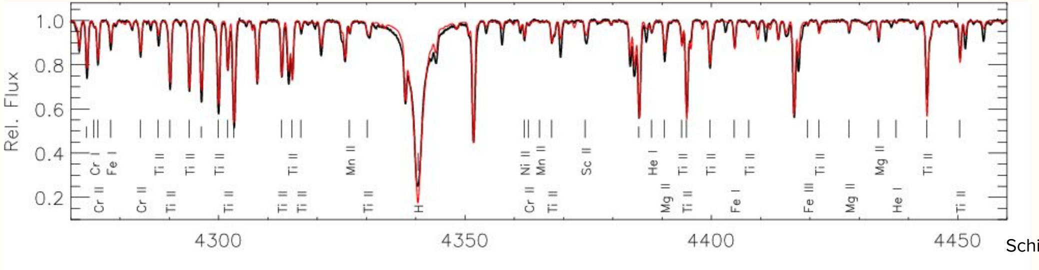
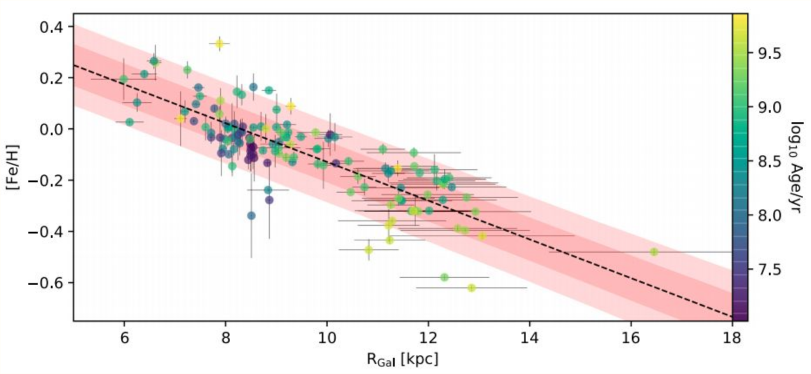


Schiller & Przybilla 2008

WHERE: Stars in clusters ➔ collections of 100-1000 stars that share age, distance, kinematics and initial chemical composition (born from the same molecular cloud)



Spina+ 2021

Open Clusters (OCs) features:

1. ubiquitous in the disc (Cantat-Gaudin et al. 2020)
2. -0.5 < [Fe/H] < +0.5 dex (Netopil et al.2016, Donor et al. 2020)
3. few Myr - several Gyr, more precise age than field stars (Bossini et al. 2019)
4. (initially) homogeneous in chemical composition (0.02-0.03 dex - Bovy 2016)

Gilmore et al. 2012,
Magrini et al. 2017

Casamiquela et al. 2017,2019

Majewski et al. 2015,
Donor et al. 2020

de Silva et al. 2015,
Spina et al. 2021

Dalton et al. 2020

de Jong et al. 2019

OCCAM
Frinchaboy et al. 2013, Donor et al. 2020

Large spectroscopic surveys (and large programs):

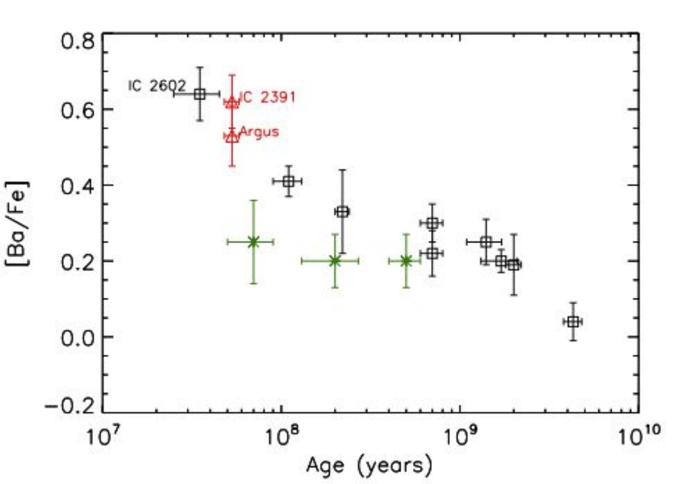
1. Programs dedicated to observe OCs
2. Multi-object, high-resolution (R>20000-40000) spectroscopy
3. Thousands of stars in hundreds of OCs
4. Homogeneous data reduction, analysis and characterisation

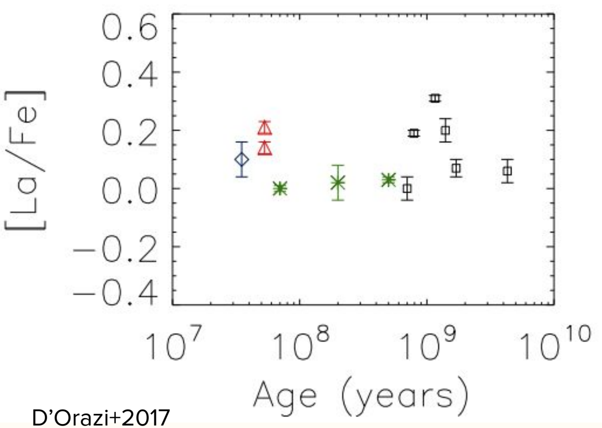
↓

Less attention payed to young OCs (YOCs, $t \leq 200$ Myr) and star forming regions (SFRs, $t \lesssim 10$ Myr) (few exceptions, James et al. 2006; Biazzo et al. 2011a,b; Spina et al. 2014a,b,2017)

Spectroscopic analysis of young stars is challenging !!!

The issues of the young OCs (YOCs, *t* < 200 Myr)





D'Orazi+2017

The Ba puzzle (named by Reddy & Lambert 2015, 2017)

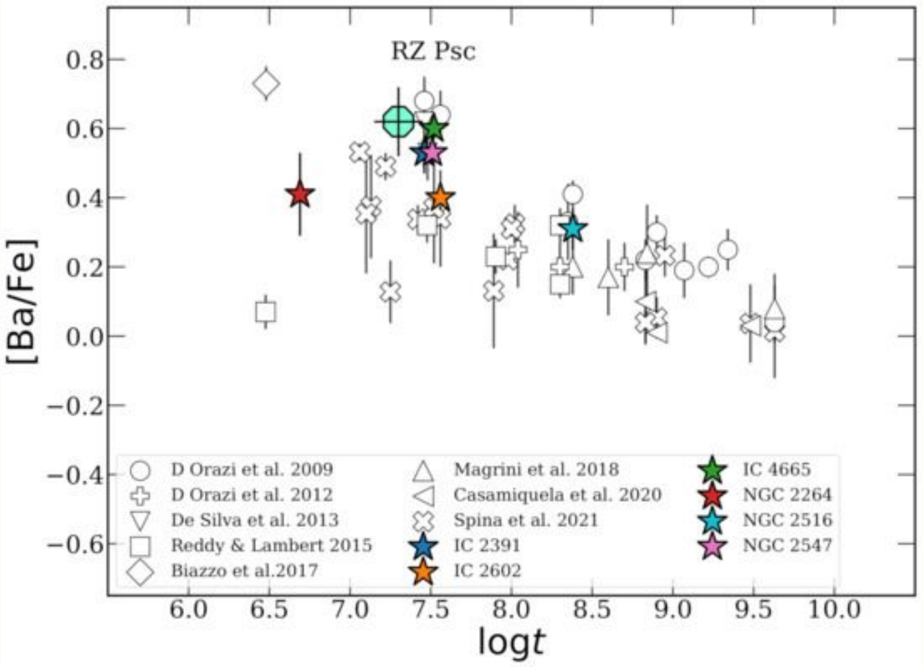
Increasing [Ba/Fe] at decreasing ages (values ~+0.6 dex at *t* < 50 Myr)
(D'Orazi et al. 2009; Maiorca et al. 2011; D'Orazi et al. 2012,2017; Mishenina et al. 2015; Magrini et al. 2018)

For other s-process elements (Y, Zr, La and Ce) = solar or enhanced?

From nucleosynthesis p.o.v. the most puzzling signature to explain is not the enrichment of Ba,
but the **production of Ba DISENTANGLED from La**

$[Ba/Fe] = [Ba/H]_{\star} - [Fe/H]_{\star}$, where $[Fe/H]_{\star} = \log(Fe)_{\star} - \log(Fe)_{\odot}$ and $\log(Fe)_{\star} = \log(N_{Fe}/N_H) + 12$

The Ba puzzle: what we know so far



D'Orazi, Baratella+2022

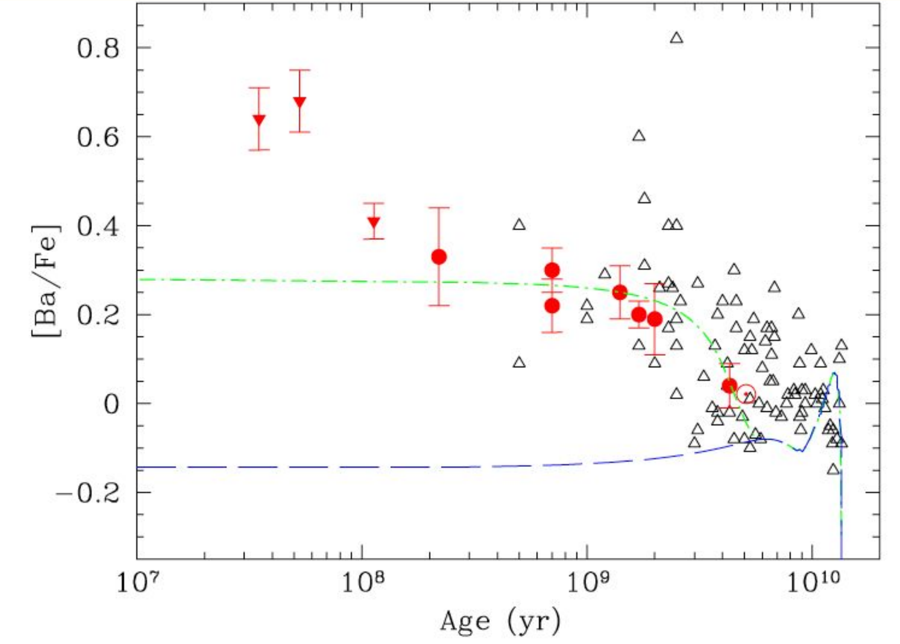
From observations of stars in clusters:

- *Large scatter* at young ages
- Individual measurements also have *large uncertainties*
- Typically, different studies ➜ *different techniques*

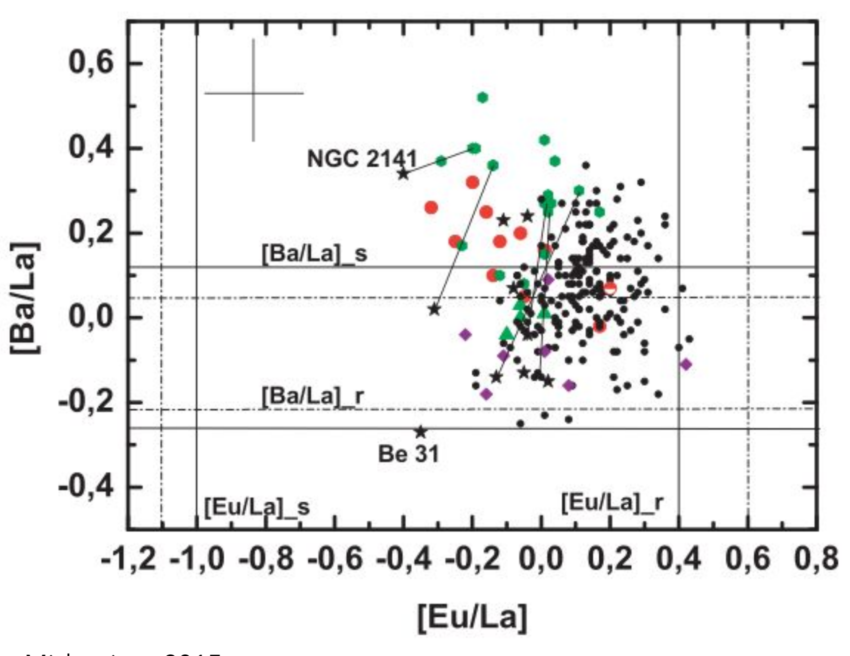
From spectral synthesis pov:

- include hyperfine structure (HFS)
- isotopic splitting
- good S/N (better continuum fitting)
- stellar parameters ➜ accurate
- NLTE corrections ➜ small (~-0.1 dex)

From nucleosynthesis pov



D'Orazi+2009



Mishenina+2015

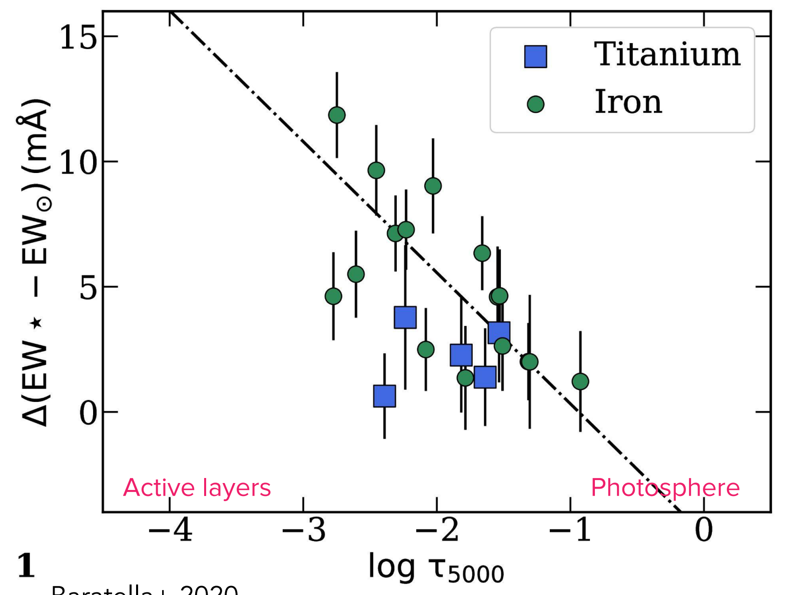
Not explained with pure *s*- or *r*-process (GCE with standard *s*- stellar yields ➔ no recent enrichment)

Additional source of Ba ➔ i-process?

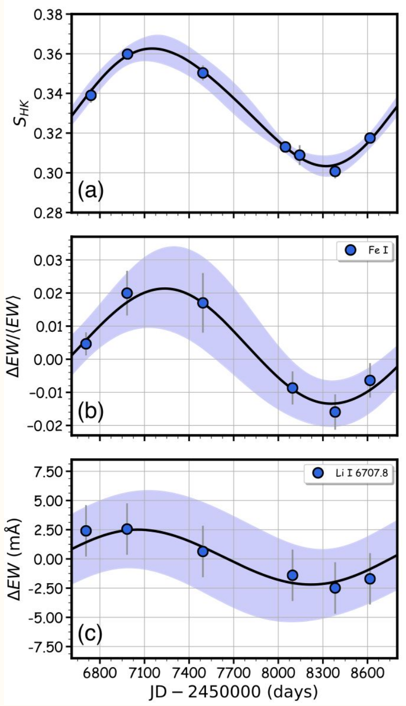
From spectra pov

★ Star in IC2602 (~30 Myr) with 5775±75 K, 4.49±0.10, 1.15±0.10km/s, [Fe/H]=0.05

☉ Sun with 5777K, 4.44, 1.0, [Fe/H]=0

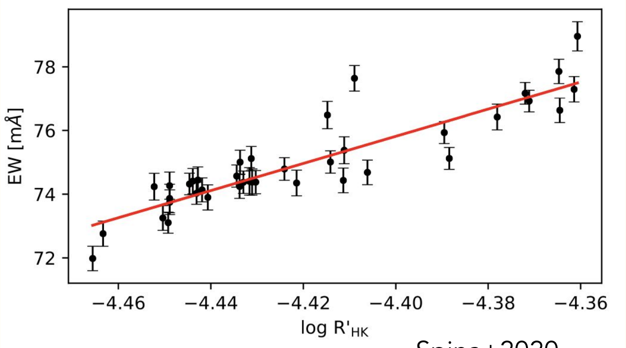


Baratella+ 2020



Yana-Galarza+2019

Barium 5853 Å



Spina+2020

Activity ➔ altering EW ➔ affecting parameters & abundances

From spectra po

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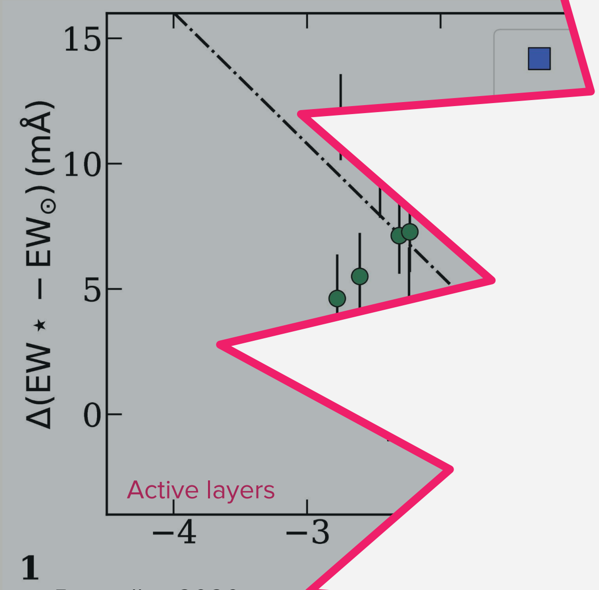
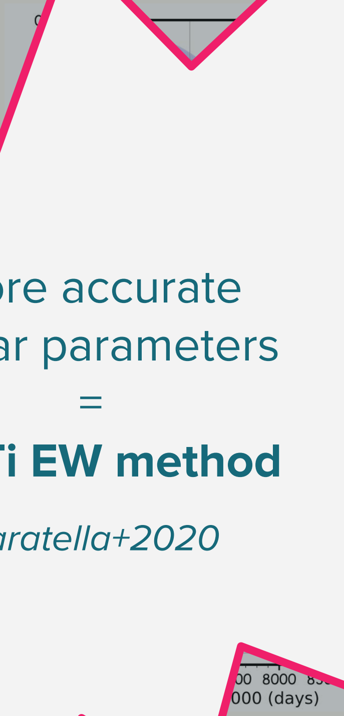
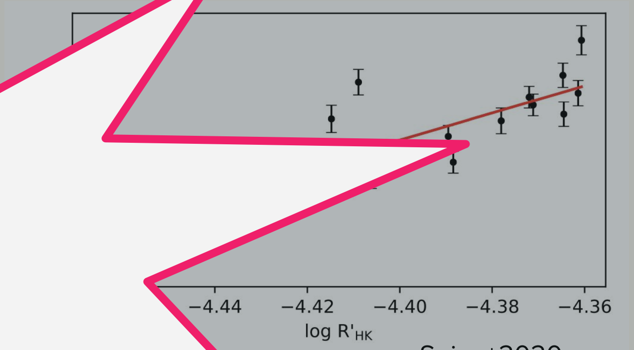


Baratella+ 2020



G 019

Barium 5853 Å



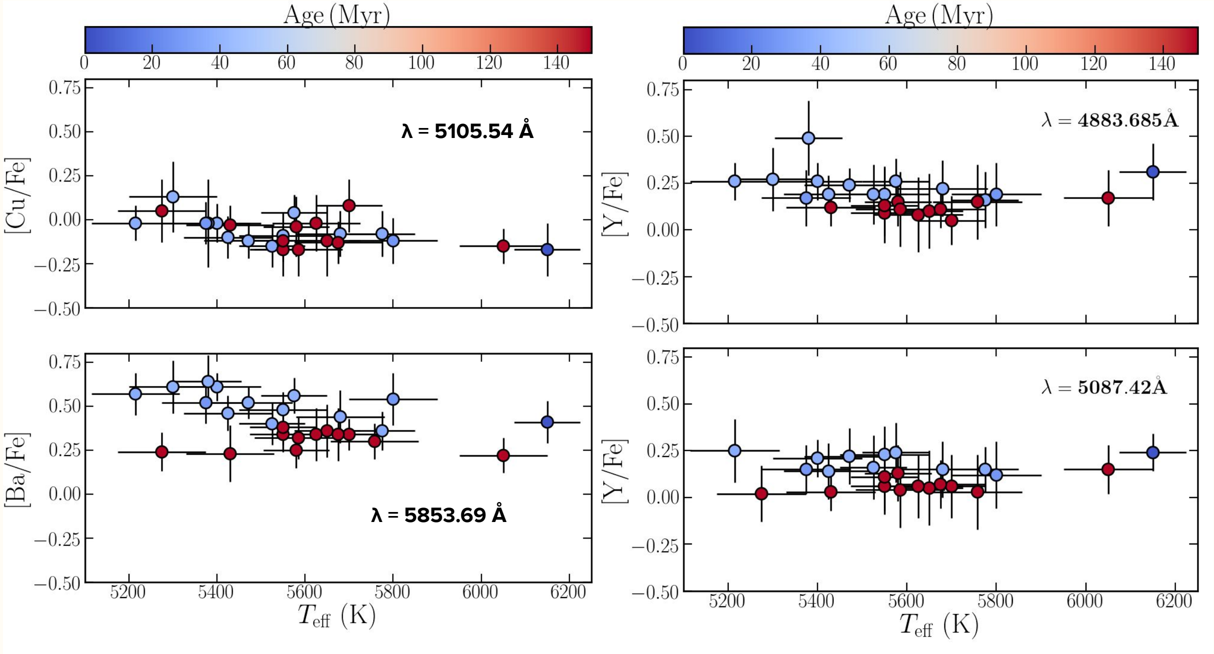
Spina+2020

More accurate
stellar parameters
=
Fe+Ti EW method

Baratella+2020

Activity → ng EW → affecting parameters & abundances

Abundances of Cu, Sr, Y, Zr, Ba, La, and Ce



Spectral synthesis (HFS + isotopic splitting)

1. **[Cu/Fe]** = solar at all ages
2. **[Ba/Fe]** = larger enhancement in younger stars
3. **[Y/Fe]** = mild enhancement detected

NLTE corrections for Ba ~-0.1 dex

Abundances of **Sr, Y, Zr, La and Ce** derived in 380-480 nm bluer range from well studied lines (D'Orazi et al. 2017)

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

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

Baratella+2021

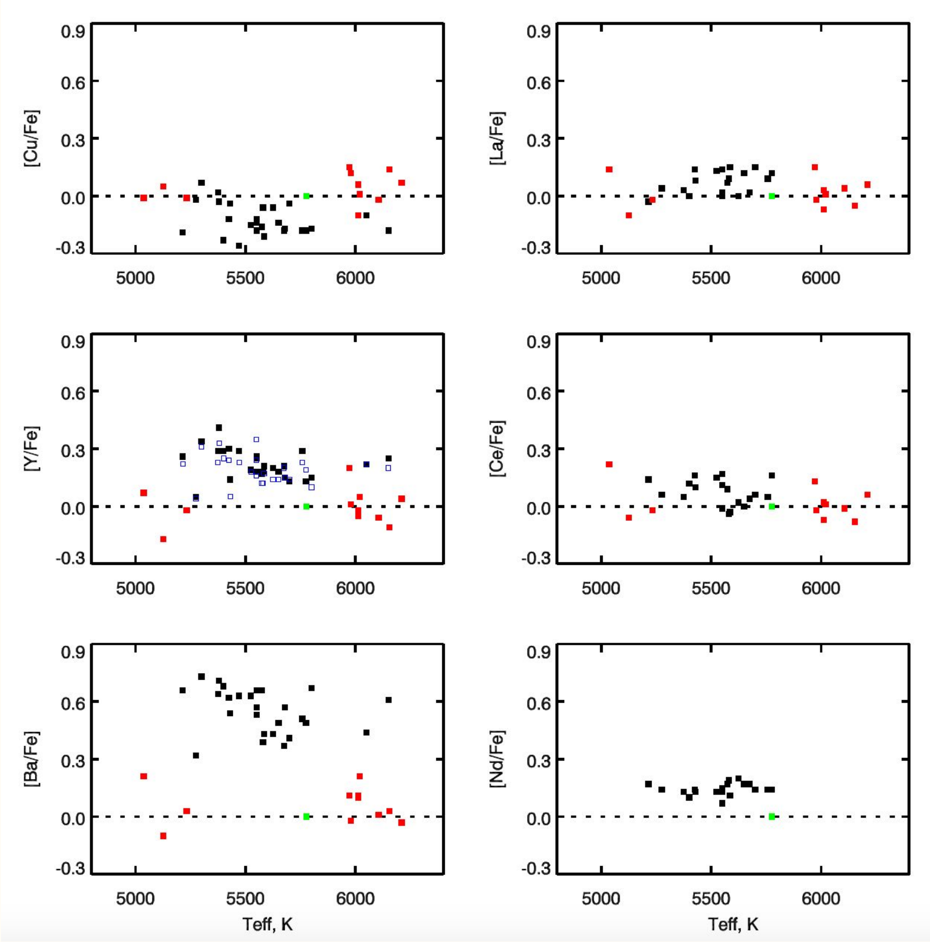
Abundances of Cu, Sr, Y, Zr, Ba, La, and Ce

Old stars → > 2 Gyr

Young stars → < 200 Myr

Sun

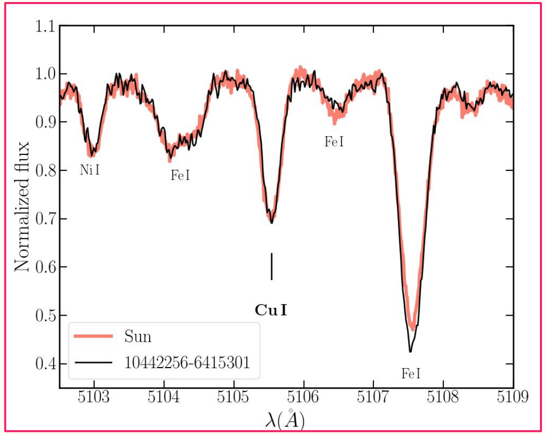
Fitting A(X), vmic and vmac



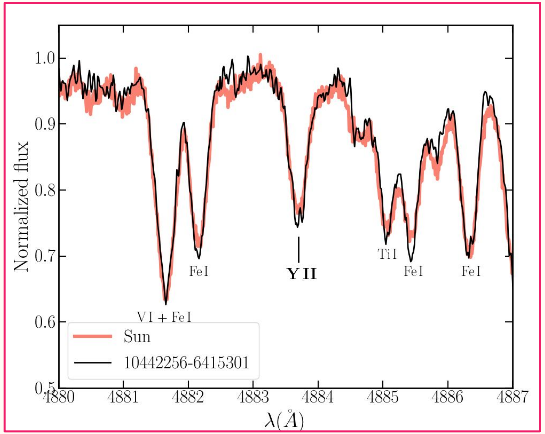
Sheminova, Baratella & D'Orazi 2024 and in prep.

Behaviour of spectral lines: comparison of Sun and a 35 Myr solar-analog (IC 2602)

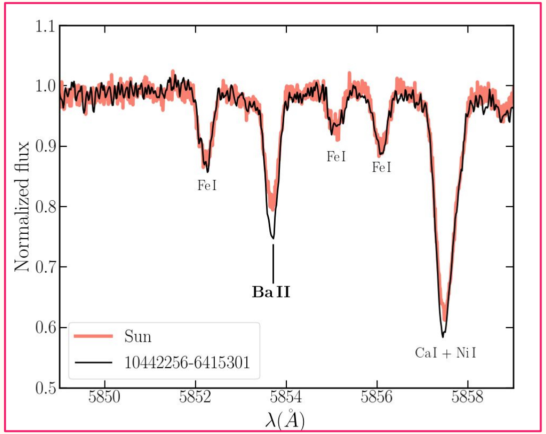
Fe-peak + weak/main s-process



First-peak main s-process



Second-peak main s-process



[Cu/Fe]= -0.08±0.13

log τ *(Cu*$_{5105}$*) = -3.4*

g_L=1.10

FIP=7.72 eV **Neutral**

[Y/Fe]= +0.16±0.15

log τ *(Y*$_{4883}$*) = -2.6*

g_L=1.13

FIP=6.38 eV **Ionised**

but Sr and Zr are solar

[Ba/Fe]= +0.36±0.11

log τ *(Ba*$_{5853}$*) = -3.2*

g_L=1.07

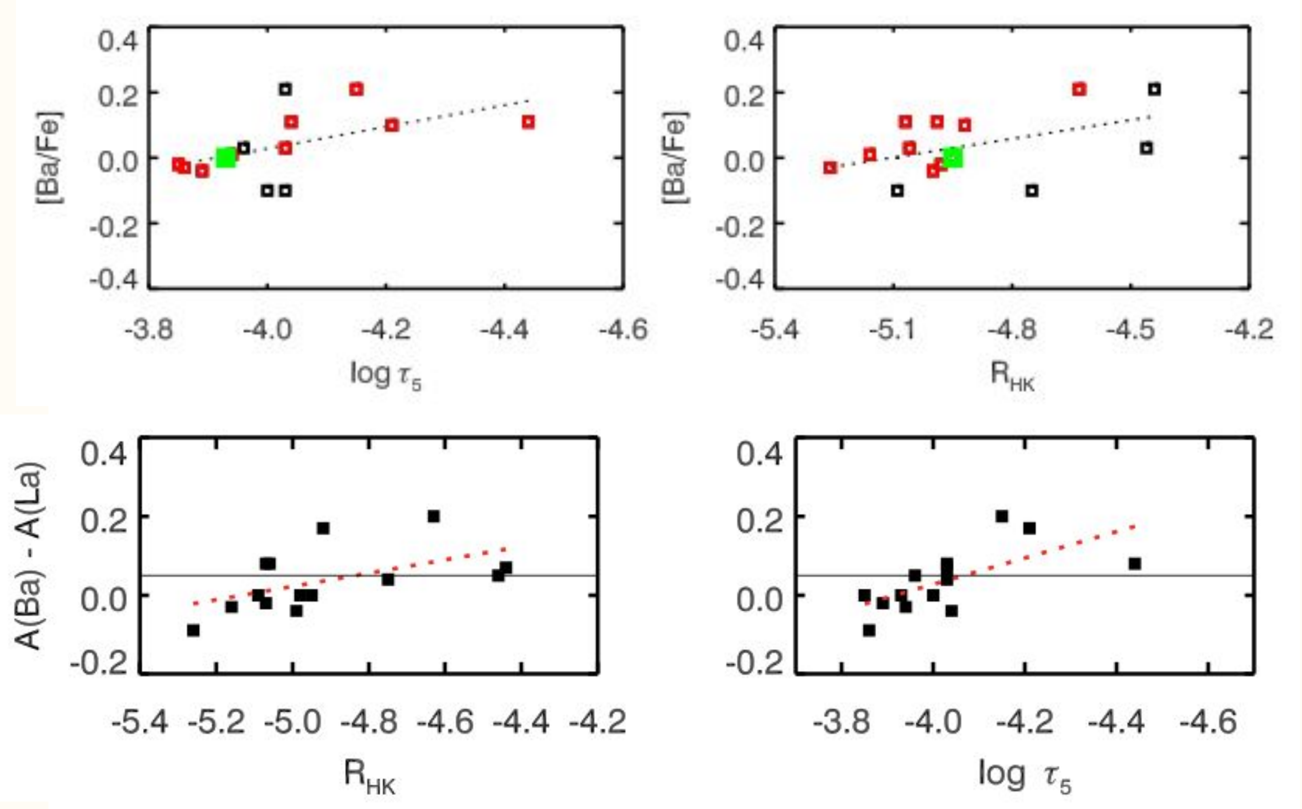
FIP=5.21 eV **Ionised**

but La and Ce are solar

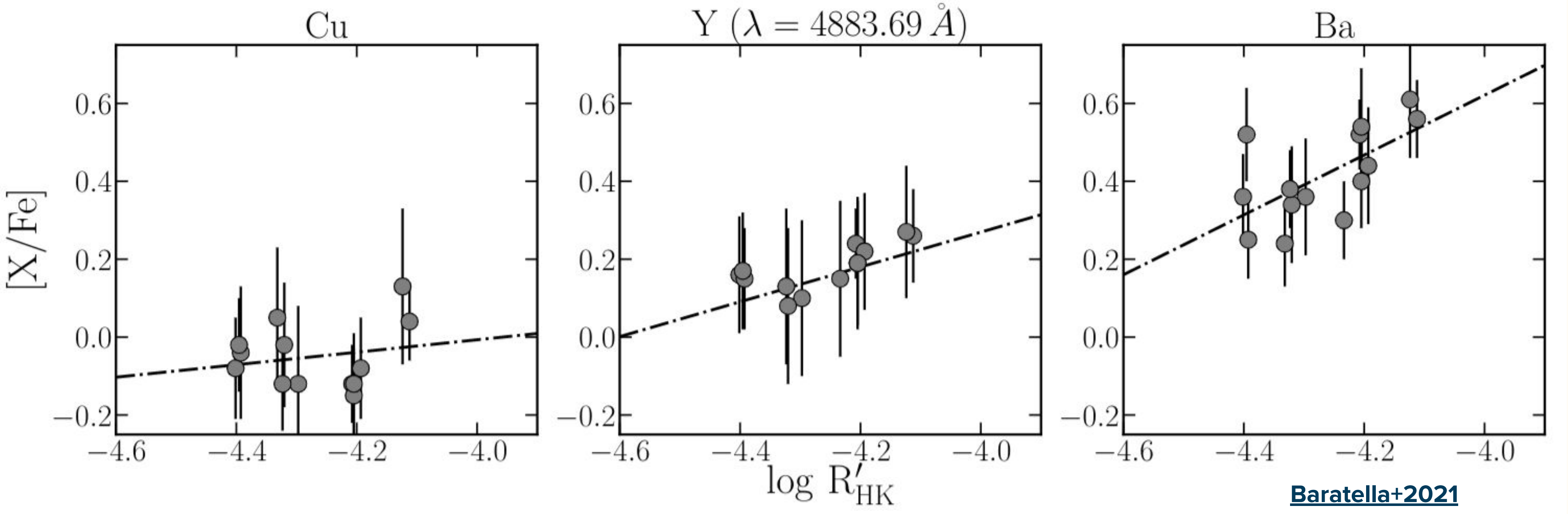
Over-ionization effect (e.g. Tsantaki+2019) ➔ ionised species are over-estimated with respect to neutral ➔ La, Ce, Sr and Zr are all ionised and no such effect

Baratella+2021

Dependency on stellar activity



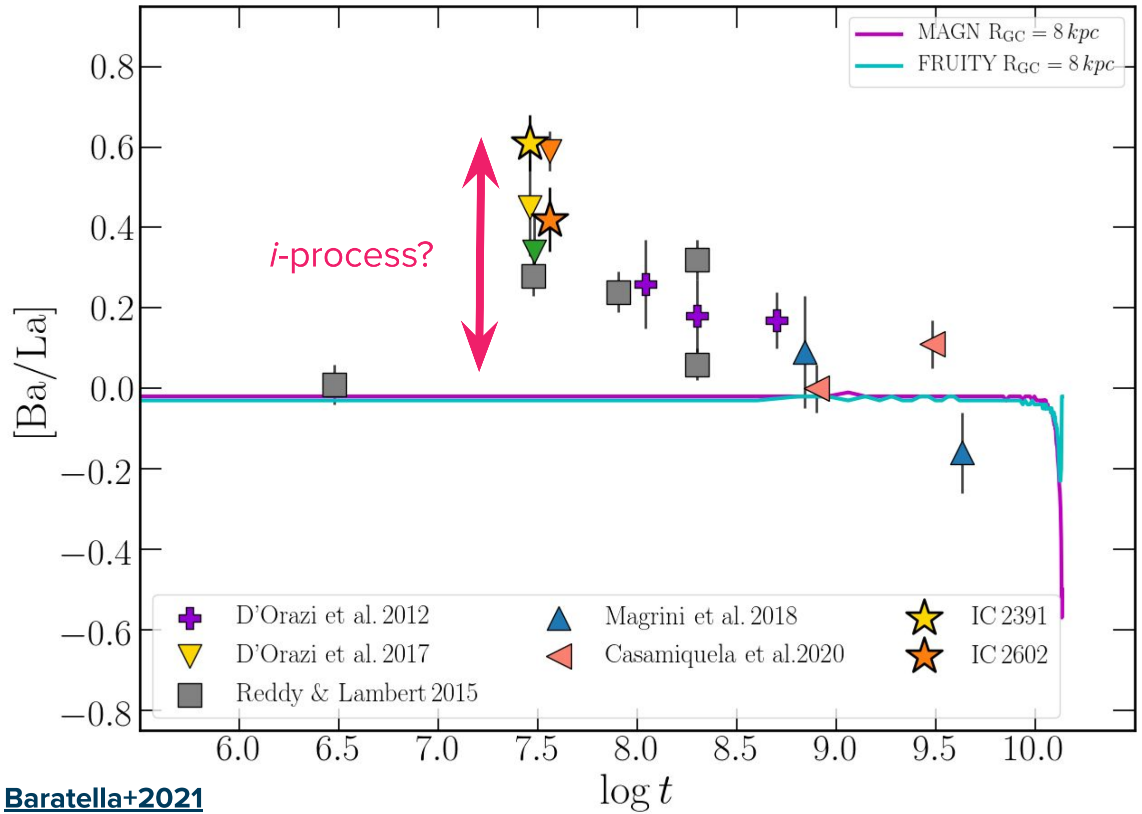
Dependency on stellar activity



Baratella+2021

Indication of a possible correlation with activity index log R'_{HK}

The Galactic chemical evolution at young ages



Baratella+2021

FRUITY (Cristallo et al. 2009)
MAGN (Magrini et al. 2021) = recent FRUITY with mixing by magnetic fields

***i*-process** (Cowan & Rose 1977, Mishenina et al. 2015) = **ADDITIONAL source of Ba (La untouched)**,
but site of production (low mass, massive stars or rapidly accreting WD)?!?

Conclusions

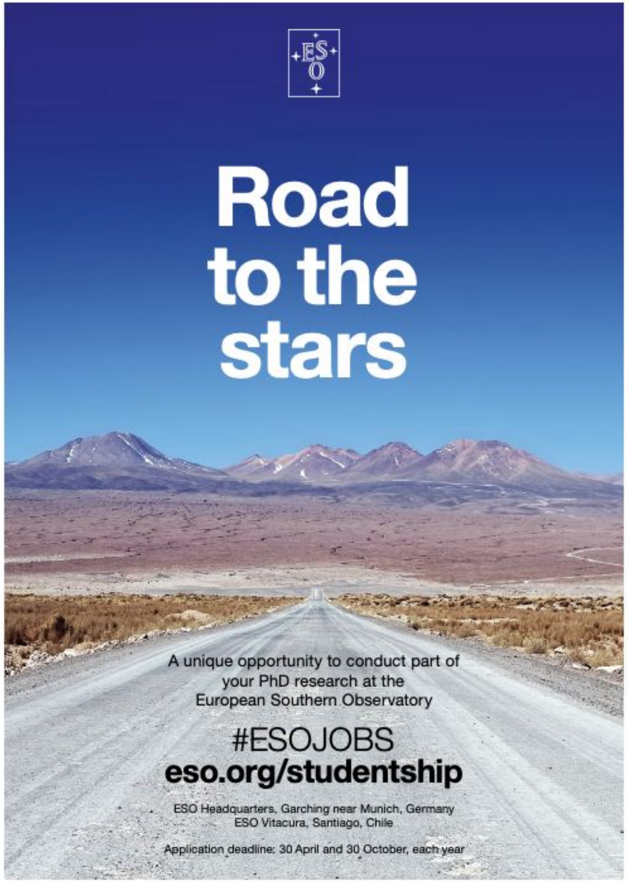
From spectral POV

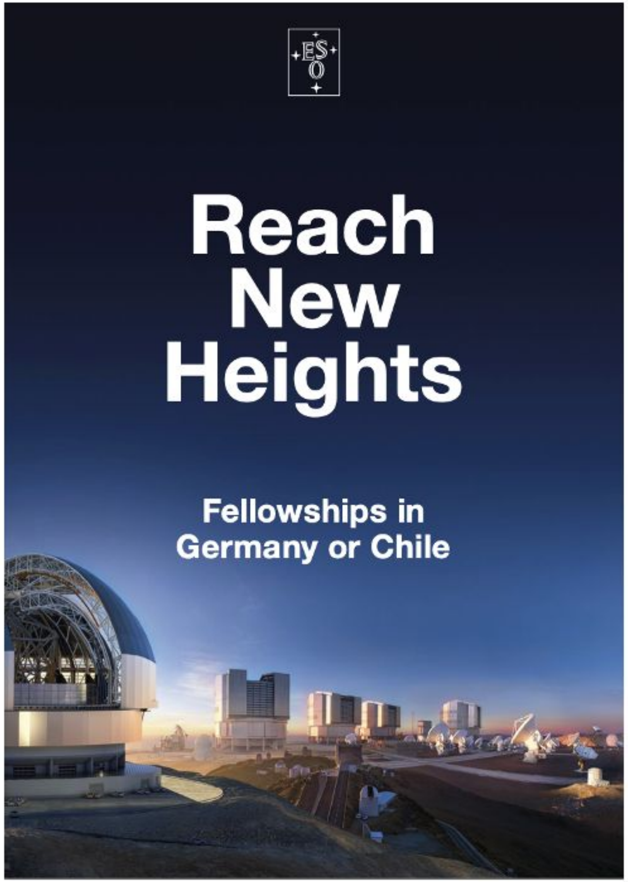
- Over-ionisation effect
- Optical depth of line formation
- FIP effect
- Micro-turbulence velocity
- Fundamental issues due to activity (missing in model atmospheres)

From nucleosynthesis POV

GCE models fail at reproducing the [Ba/La] time evolution

i-process is an interesting solution, but large uncertainties



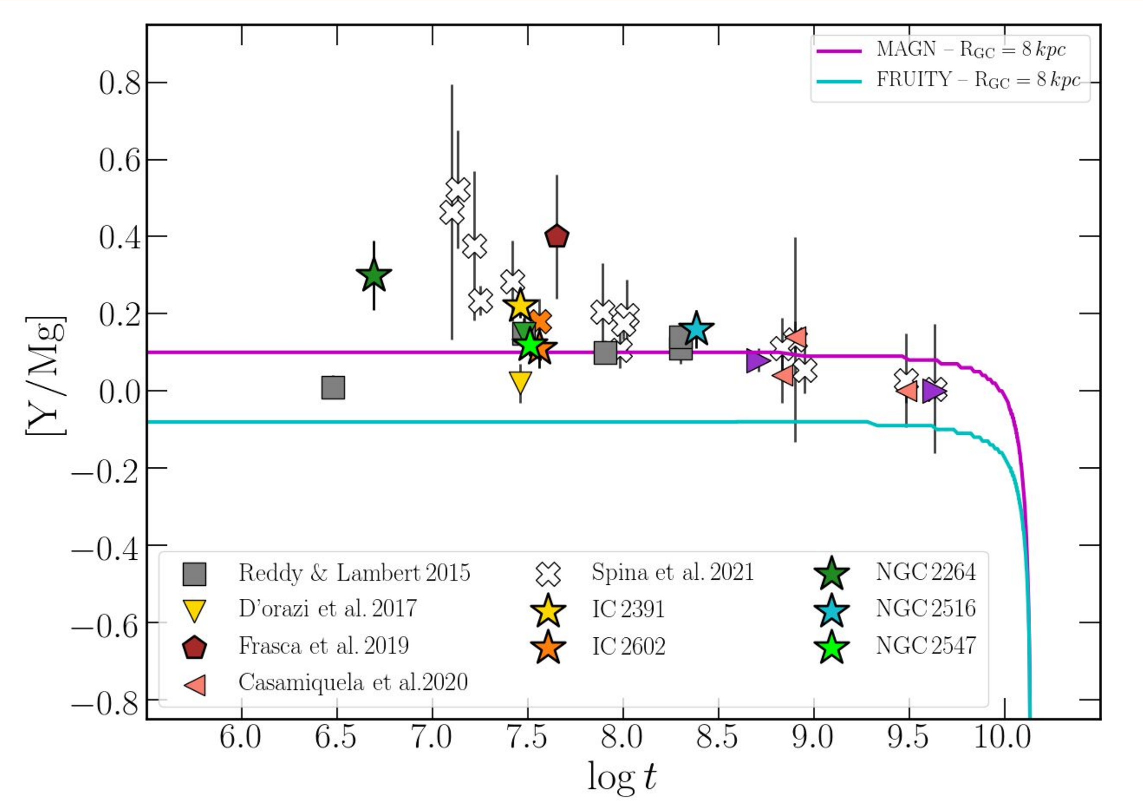


Visitor Program
(PhD, Fellow, Senior,
any time of the year)

Internship
(Master students, up to
3 months, deadline
second half of year)

Office for Science funds
(contact staff from the
ESO webpage)

The Galactic chemical evolution at young ages



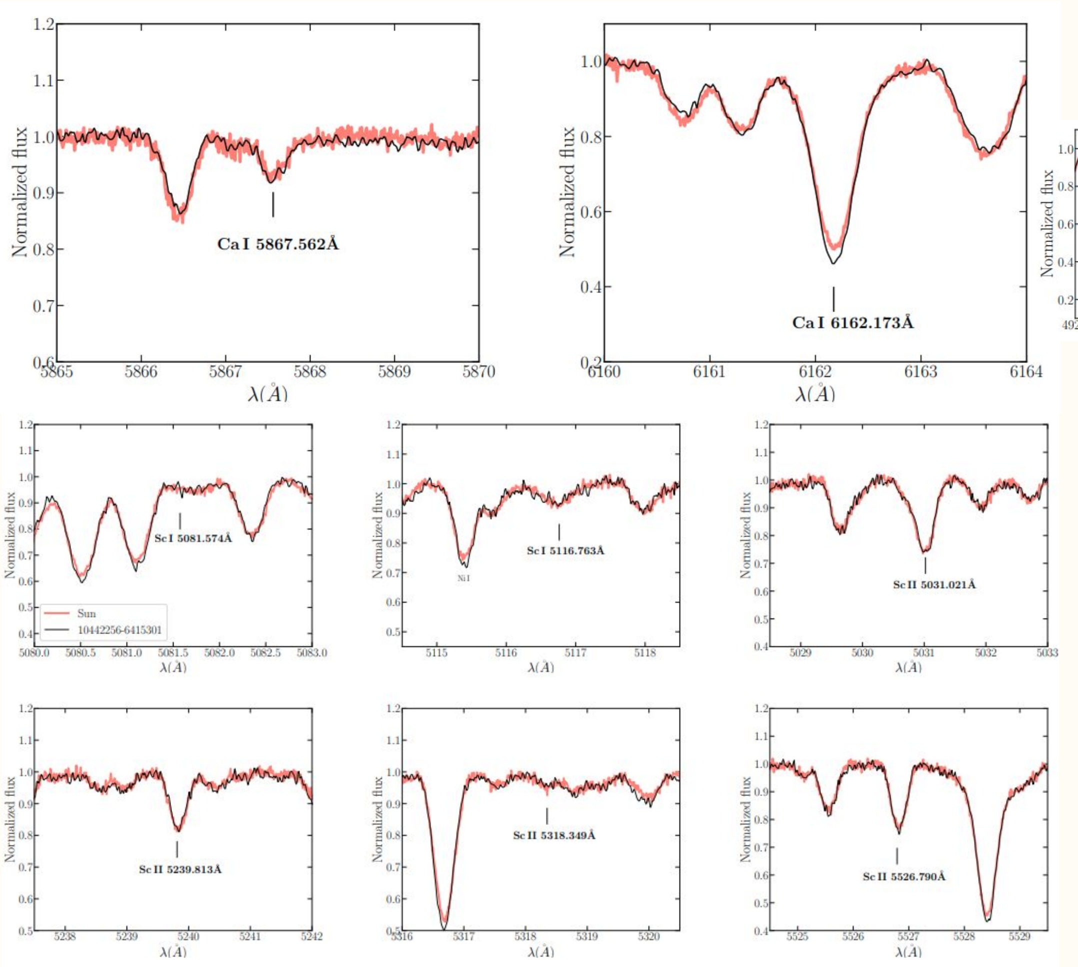
Baratella+2021

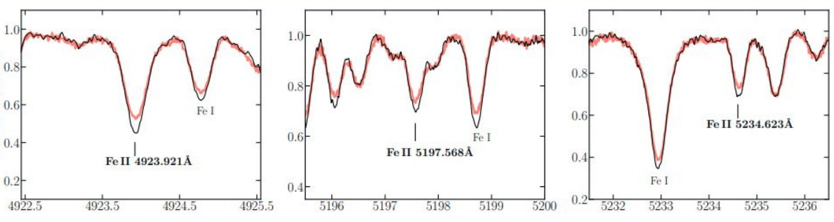
FRUITY (Cristallo et al. 2009)
MAGN (Magrini et al. 2021) = recent FRUITY with mixing by magnetic fields

Mild enrichment of Y wrt Sr and Zr = mainly observational issues, but large variety of processes could contribute

Extreme caution with chemical clocks (e.g., [Y/Mg] or [Ba/Mg]) at ages < 200 Myr !!!

Behaviour of spectral lines: comparison of Sun and a 35 Myr solar-analog (IC 2602)



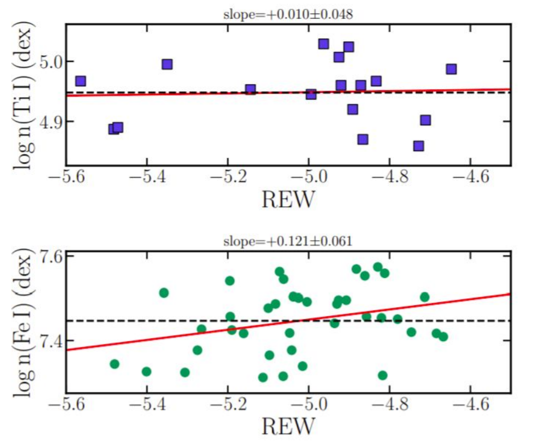


Line formation depth and over-ionisation effects are not able alone to fully solve the Ba puzzle

The *new* spectroscopic approach: titanium lines

Titanium lines (form deeper in the photosphere and very precise atomic data from laboratory measurements - Lawler et al. 2013)

- **T_{eff} from Ti + Fe** (larger coverage of E.P.)
- **log *g* from TiI and TiII**
- **ξ from TiI ONLY**



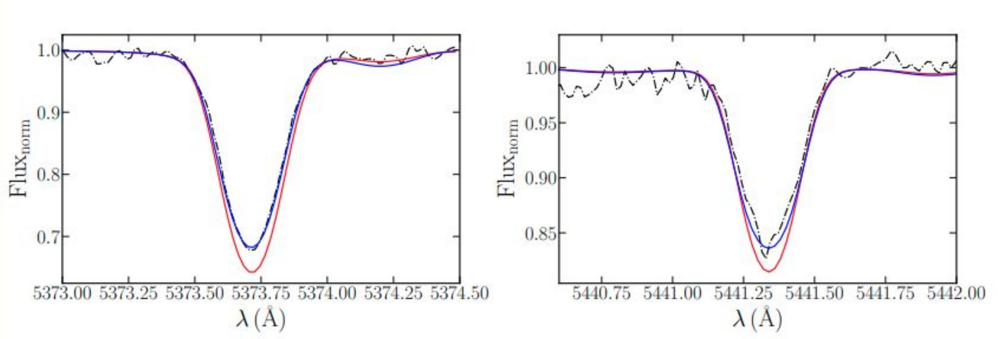
ξ=0.85±0.10 km/s

ξ_{exp}=0.70±0.05 km/s

ξ (from FeI) = 1.75 km/s

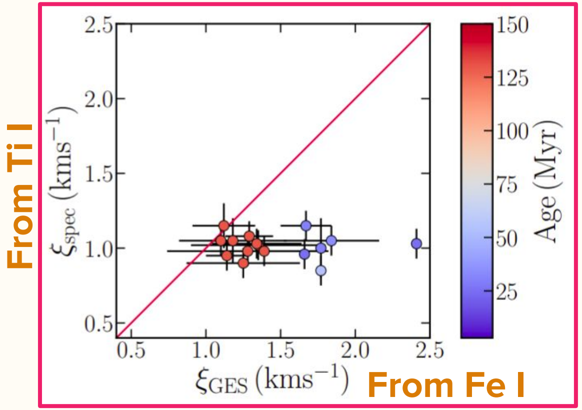
With new ξ, synthetic profiles reproduce well the observed lines

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



Baratella et al. 2020a

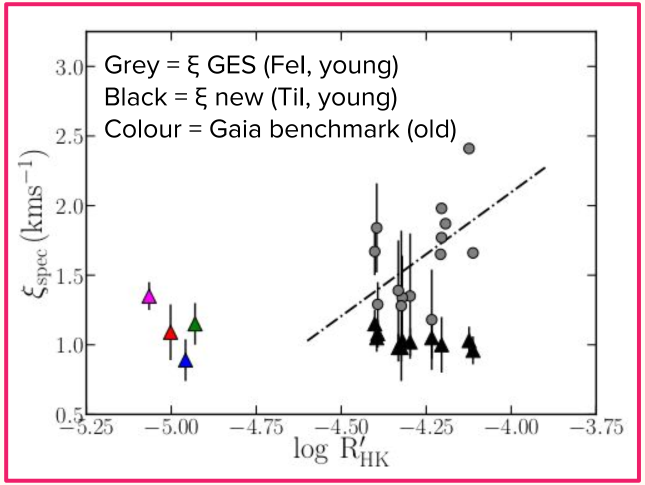
The *new* spectroscopic approach: titanium lines

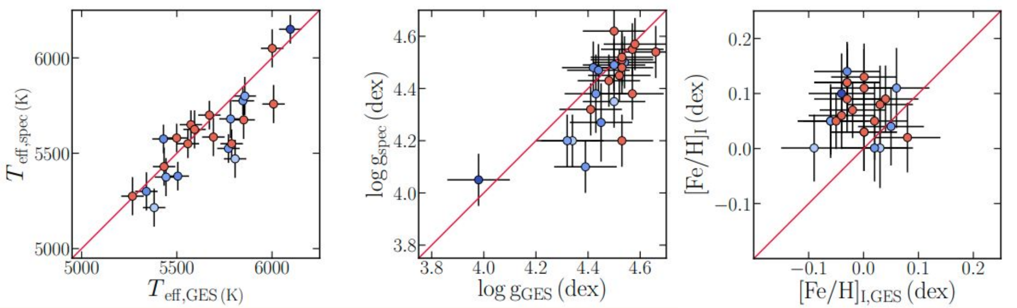


Clusters *t* < 100 Myr: $\Delta(\xi_{Ti}\text{-}\xi_{Fe,\ GES})$ = **-0.85±0.27** kms^{-1}

Clusters *t* ~150 Myr (NGC 2516): $\Delta(\xi_{Ti}\text{-}\xi_{Fe,\ GES})$ = **-0.23±0.13** kms^{-1}

HYPOTHESIS CONFIRMED!!!





Baratella et al. 2020a

Log R'$_{HK}$ = activity index from CaII H&K lines