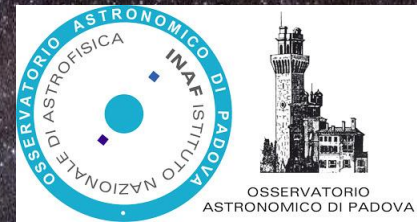


The chemical composition of very young open clusters: is it real or not?

Martina Baratella (INAF-OAPD)

with Valentina d'Orazi (INAF-OAPD), Lorenzo Spina (INAF-OAPD), Angela Bragaglia (INAF-OAS), Laura Magrini (INAF- OAA), Sofia Randich (INAF- OAA) and all from the Gaia-ESO survey



The open clusters (OCs) in large surveys

Excellent tracers of the chemical properties of Galactic disc and time evolution!!!

Characteristics:

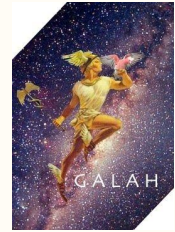
- $-0.3 < [\text{Fe}/\text{H}] < 0.4$ dex
- few Myr (star forming regions - SFRs) to several Gyr (high precision)
- ubiquitous in the disc
- chemical homogeneous (initially)



Gilmore et al. 2012,
Magrini et al. 2017



Casamiquela et al. 2017,2019



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

In large spectroscopic surveys:

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



Majewski et al. 2015,
Donor et al. 2020

OCCAM

Frinchaboy et al. 2013, Donor et al. 2020

Clusters ages >1 Gyr are extensively studied, YOUNG ($t < 600$ Myr) not:

Spectroscopic analysis of young stars is challenging!!!!



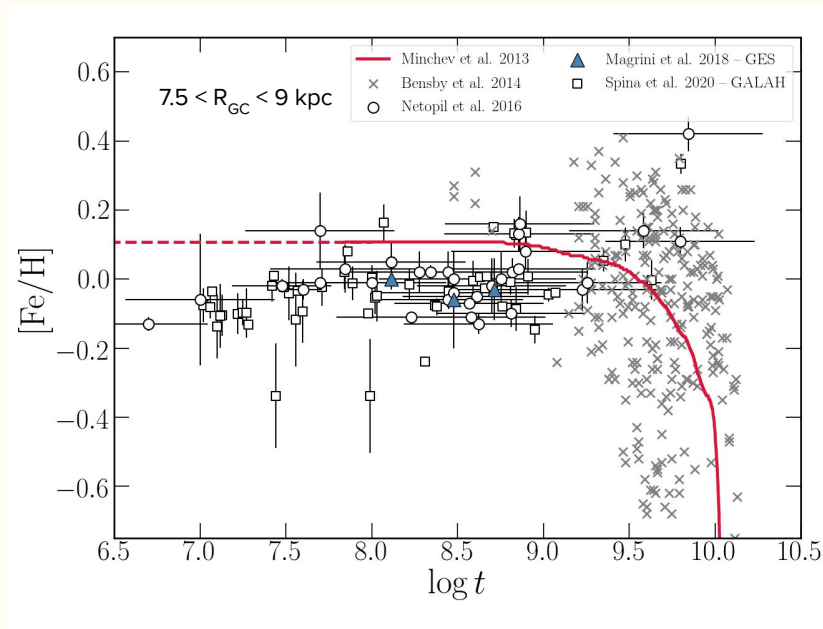
Dalton et al. 2020



de Jong et al. 2019

The issues of the young OCs (YOCs, $t < 200$ Myr): #1

Local anaemia of the interstellar medium (ISM)



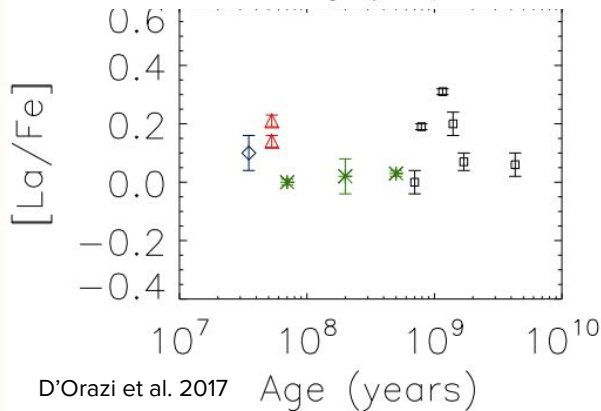
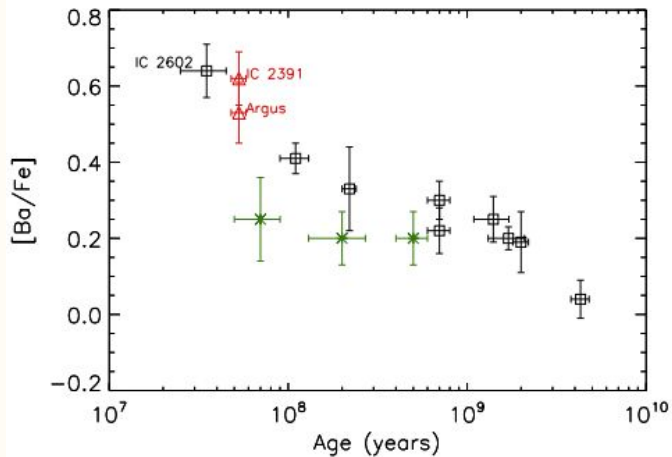
NO METAL-RICH YOCs, star forming regions (SFRs), moving groups or local associations

(e.g., James et al. 2006; Santos et al. 2008; Biazzo et al. 2011; Spina et al. 2014a,b; Spina et al. 2017)

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

The issues of the young OCs (YOCs, $t < 200$ Myr): #2

The behaviour of neutron-capture elements



D'Orazi et al. 2017

Increasing $[Ba/Fe]$ at decreasing ages (values $\sim +0.6$ 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; and others)

For other s-process elements (Y, Zr, La and Ce) = solar or not solar?

Y and Zr = first peak s-process elements (main component)

Ba, La, and Ce = second peak s-process elements (main component)

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**

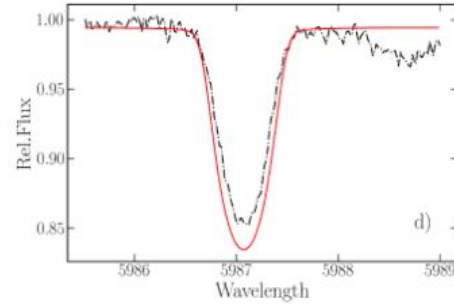
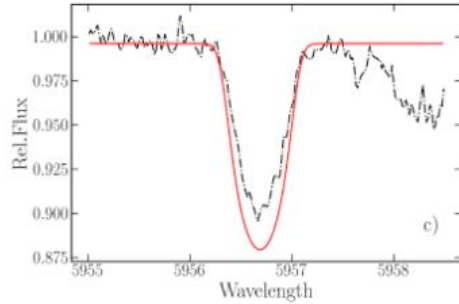
$$[Ba/Fe] = [Ba/H]_{\star} - [Fe/H]_{\star}$$



**Are these peculiarities real
(intrinsic) or not?**

Spoiler Maybe NOT!

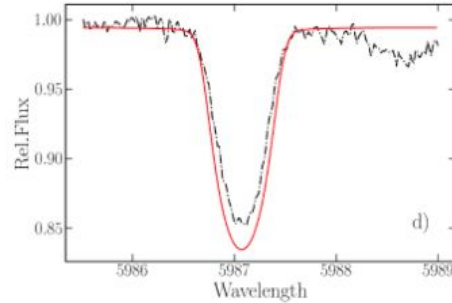
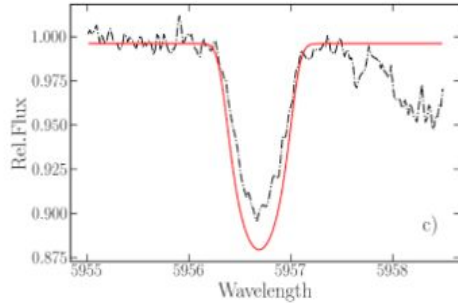
The effects of stellar activity



Standard analysis of young **dwarf** stars
($t < 200$ Myr): **ξ values are overestimated**
(2.0-2.5 km/s wrt the typical values of 1.0 km/s, e.g., James et al 2006, Santos et al. 2008)

Result = poor fit of the observed lines

The effects of stellar activity



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ARTIFICIALLY LOW VALUES OF [Fe/H] and [X/Fe] rescaling accordingly
(for solar-like dwarf stars in OCs we expect solar [X/Fe])

How to explain the large values of ξ :

Increased levels of activity could alter lines forming in the upper layers of the photosphere
(systematically stronger in young solar analog than in the Sun)

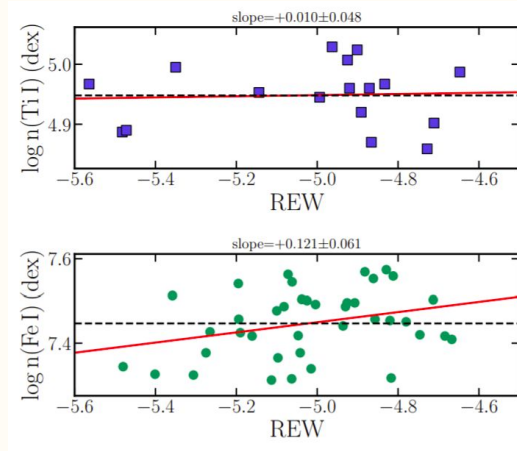
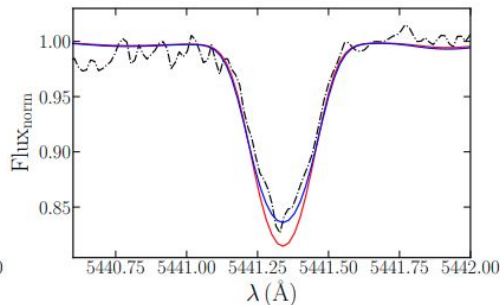
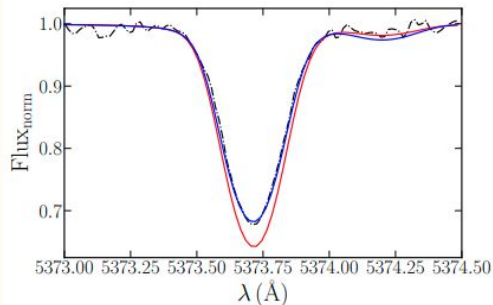
(confirmed independently by Yana-Galarza et al. 2019, Spina et al. 2020, Baratella et al. 2020a)

The *new spectroscopic approach*: Ti(+Fe) 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**

With new ξ , synthetic profiles reproduce well the observed lines



$$\xi = 0.85 \pm 0.10 \text{ km/s}$$

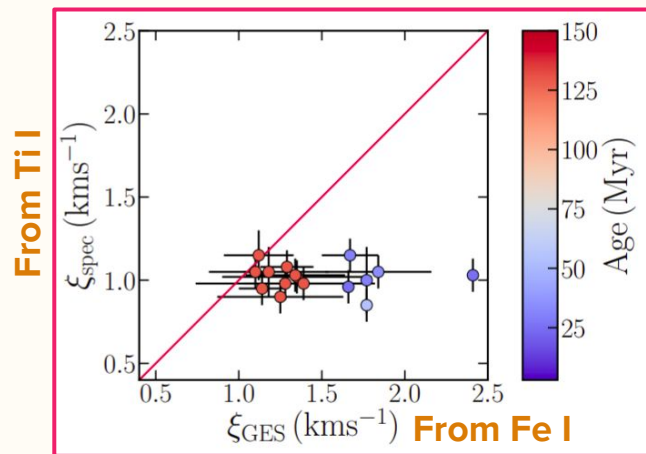
$$\xi_{\text{exp}} = 0.70 \pm 0.05 \text{ km/s}$$

$$\xi \text{ (from Fe I)} = 1.75 \text{ km/s}$$

Star:

$$T_{\text{eff}} = 5215 \pm 100 \text{ K};$$
$$\log g = 4.35 \pm 0.10 \text{ dex};$$
$$\text{age} = 50 \text{ Myr}$$

The new spectroscopic approach: results



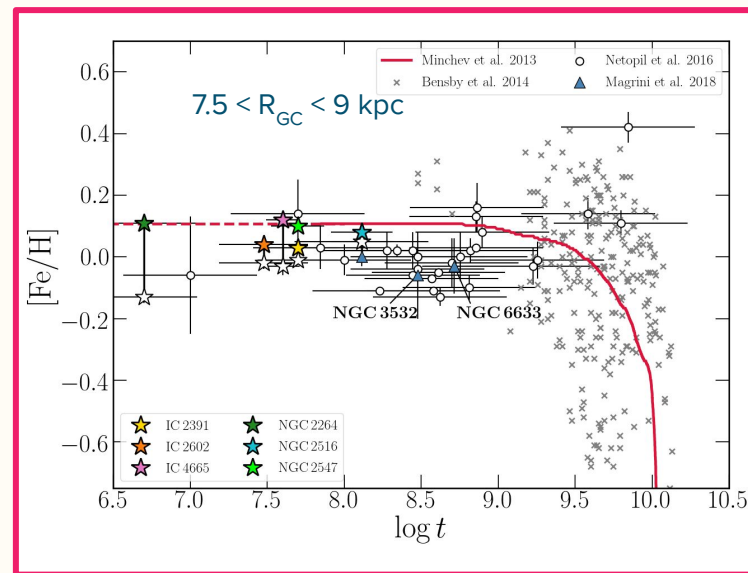
Clusters $t < 100$ Myr: $\Delta(\xi_{\text{Ti}} - \xi_{\text{Fe, GES}}) = -0.85 \pm 0.27 \text{ kms}^{-1}$

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

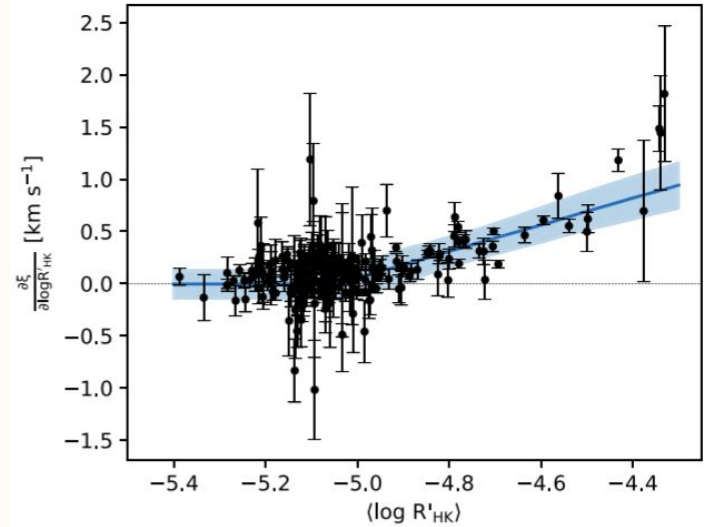
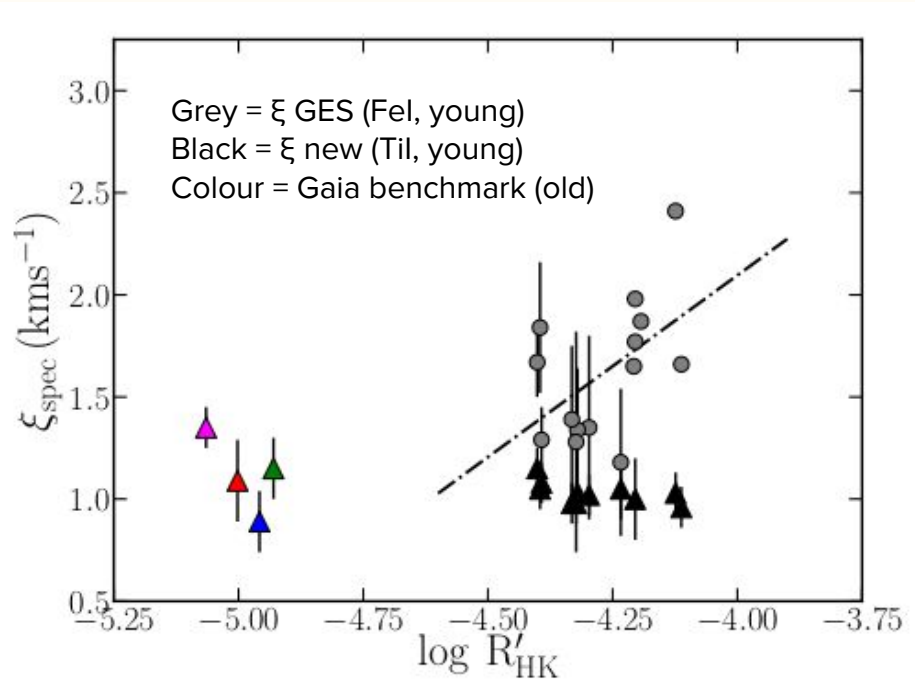
No ad-hoc explanations for the apparent local anaemia !!!

FGK stars ($5200 < T_{\text{eff}} < 6000$ K) in the cluster sample:

- IC2391 (~50 Myr)
- IC2602 (~30 Myr)
- IC4665 (~40 Myr)
- NGC2264 (~5 Myr)
- NGC2516 (~130 Myr)
- NGC2547 (~50 Myr)



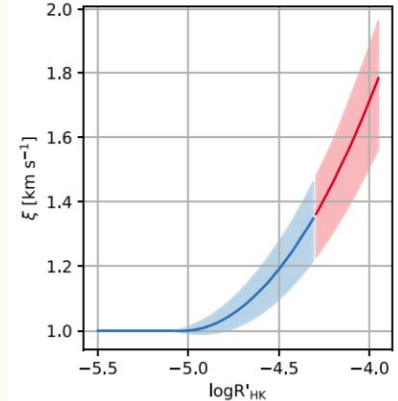
The new spectroscopic approach: results



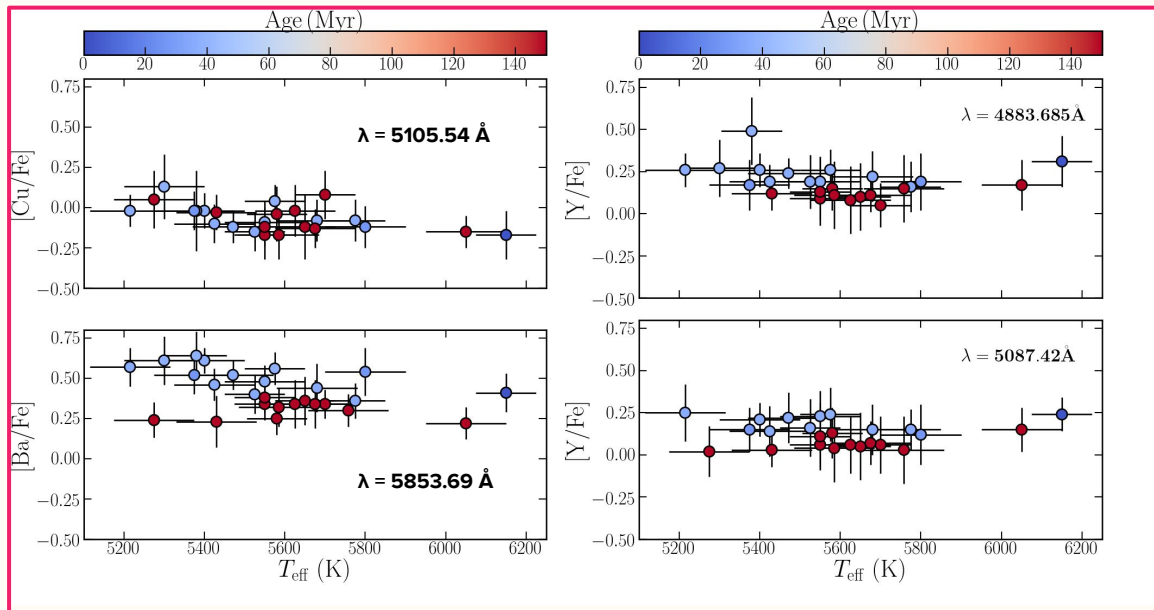
ξ increases with stellar activity (magnetic fields, dark spots, faculae ...

Baratella et al. 2020)

Magnetic intensification of spectral lines (Spina et al. 2020)



Abundances of n-capture elements: the Ba puzzle



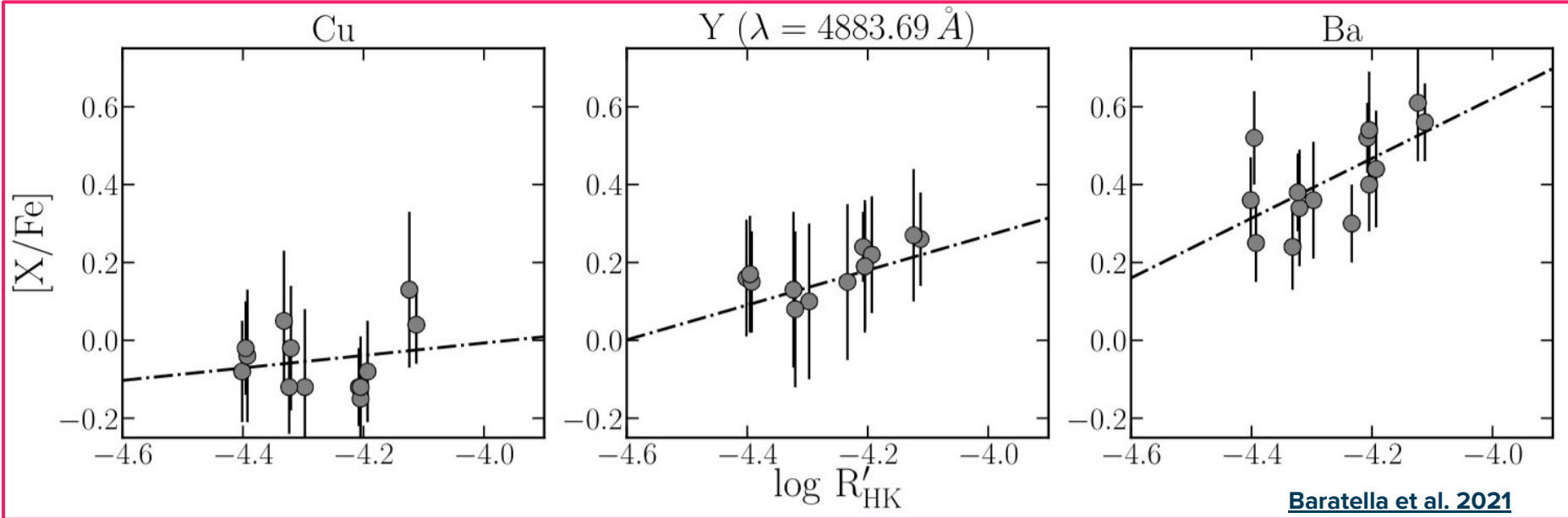
- Sharp separation with age for Ba and Y (homogeneous for Cu)
- [Ba/Fe] between +0.25 and +0.65 dex
- [Y/Fe] between 0 and +0.30 dex

$$\Delta_{\text{NLTE}}(\text{Ba}) \sim -0.10 \text{ dex}$$

Not sufficient to explain the observed enhancements!

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

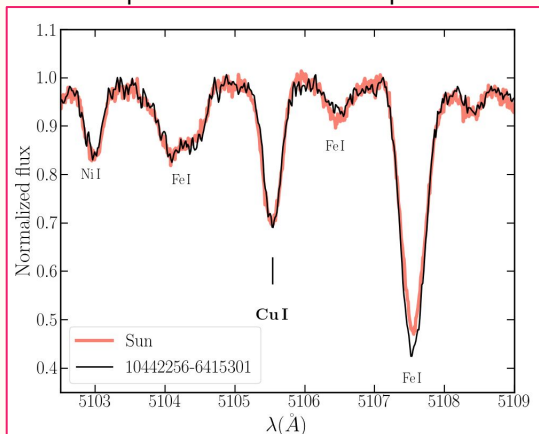
Indication of dependency on activity



Hypothesis: Y and Ba lines form at small optical depth, more sensitive to alteration due to activity

Behaviour of spectral lines: comparison of Sun and a 30 Myr solar-analog (IC 2602)

Fe-peak + weak/main s-process

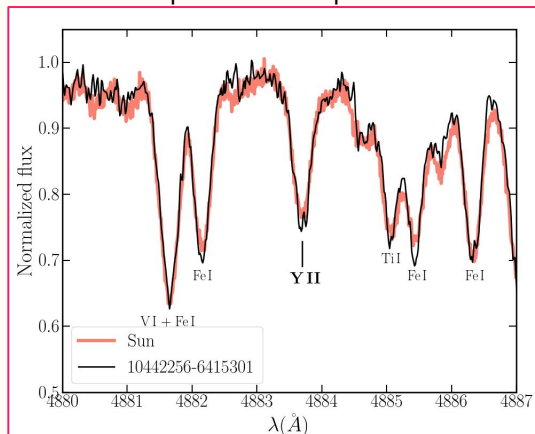


$[Cu/Fe] = -0.08 \pm 0.13$

$\log \tau (Cu_{5105}) = -3.4 \quad g_L = 1.10$

FIP=7.72 eV **Neutral**

First-peak main s-process

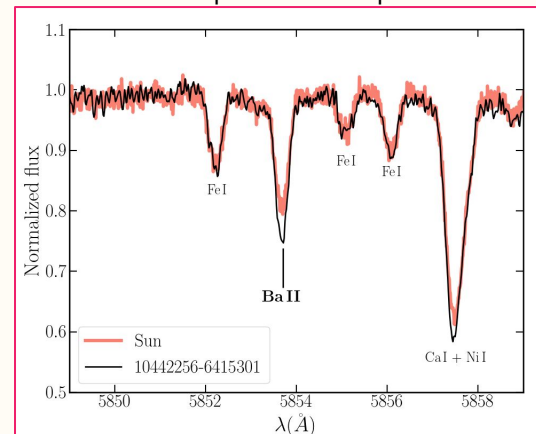


$[Y/Fe] = +0.16 \pm 0.15$

$\log \tau (Y_{4883}) = -2.6 \quad g_L = 1.13$

FIP=6.38 eV **Ionised**

Second-peak main s-process



$[Ba/Fe] = +0.36 \pm 0.11$

$\log \tau (Ba_{5853}) = -3.2 \quad g_L = 1.07$

FIP=5.21 eV **Ionised**

Overionization effect (e.g. Tsantaki et al.2019)

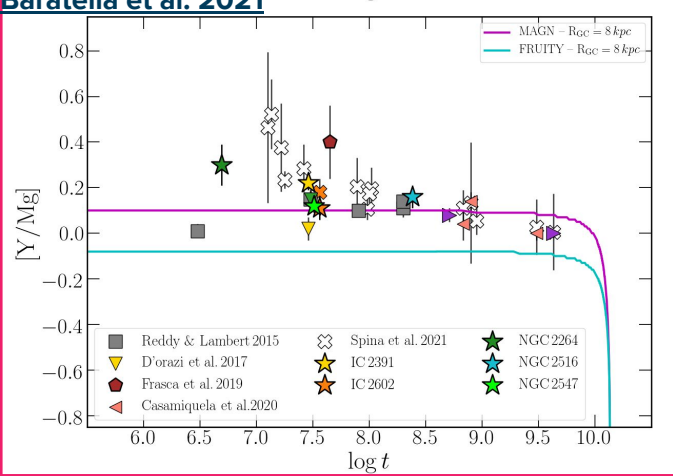
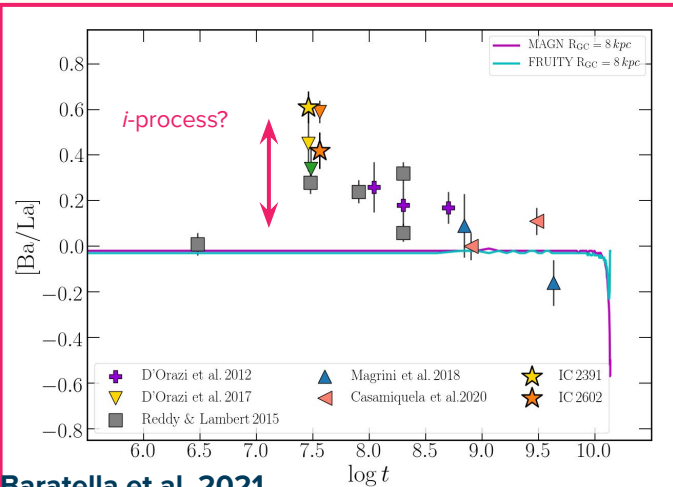
Ba and Sr = similar physical and chemical properties, however $[Sr/Fe] = \text{solar}$ (Y and Sr = 1^o peak, but Y is enhanced)

Y and La = both ionised, same depth, nucleosynthesis channel, however $[La/Fe] = \text{solar}$

Ba and La produced in the same way, but Ba is enhanced while La is solar: WHY?

Baratella et al. 2021

The Galactic chemical evolution at young ages



FRUITY (Cristallo et al. 2009)

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

Ba and Y enhancements at young ages: NOT PREDICTED by models!

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

i-process (Cowan & Rose 1977, Mishenina et al. 2015) =
ADDITIONAL source of Ba (La untouched),
 but site of production ??

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 !!!**

Summary and conclusions

1. **Standard analysis fails** = new spectroscopic approach (Galactic [Fe/H] vs. age in solar vicinity is restored)
2. **n-capture elements** = La (Ce and Zr) are better tracers of the Galactic time evolution of s-process
3. Strong lines (forming up in the photosphere) = more affected
4. Magnetic fields, spots, faculae: not included in model atmosphere, but they shape the spectra of young stars
5. Mechanism(s) behind alteration of spectral lines = still unknown
6. Possible solutions, both from spectral and from nucleosynthesis p.o.v., are still under investigation
7. HRMOS will give big contributions (see also **Lorenzo Spina's talk**)



Take home message: revise the classical chemical abundance analysis techniques applied to young stars!!!