SNAQS - Schools on Nuclear Astrophysics QuestionS: How to get from starlight to stellar abundances?
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The chemical composition of very young open clusters

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The open clusters (OCs)

Open clusters (OCs) : **single stellar population**

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

Characteristics:

- **-0.3 < [Fe/H] < 0.4 dex**
- **few Myr** (star forming regions - SFRs -) **to several Gyr**
- **ubiquitous** in the disc (few pc to several kpc from Galactic center)

Extensively studied in large surveys (and small programs):

- APOGEE (Cunha et al. 2016)
- OCCASO (Casamiquela et al. 2019)
- GALAH (Spina et al. 2021)
- **Gaia-ESO Survey** (Gilmore et al. 2012)

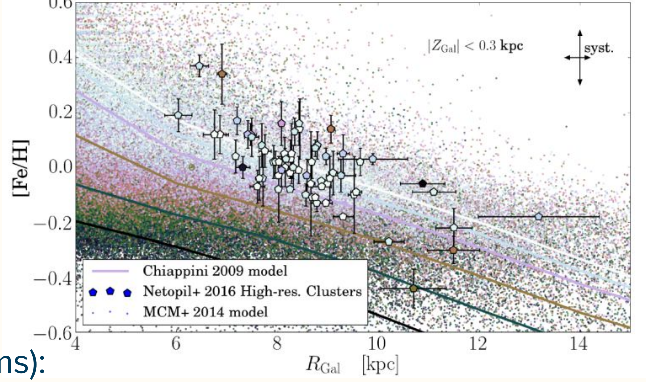
GaiaESO

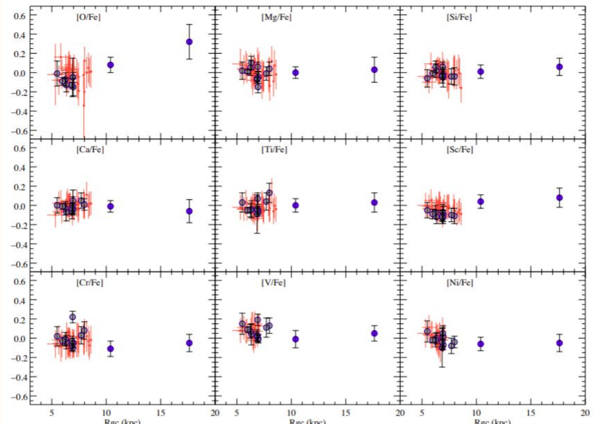
HOWEVER...

Less attention has been payed to <u>young</u> clusters

<u>(t < 200 Myr)</u>

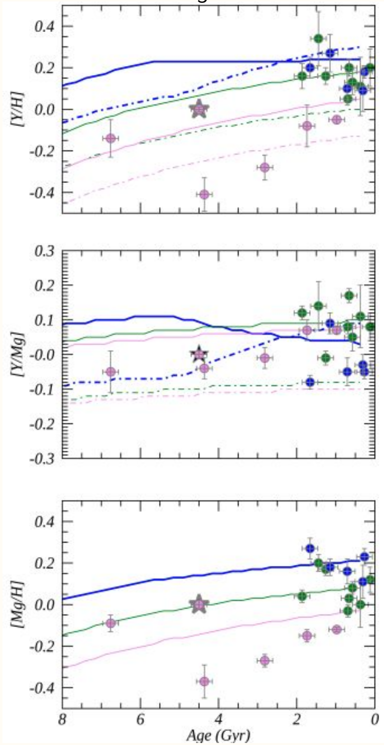
Anders et al. 2017





Magrini et al. 2017

Magrini et al. 2021



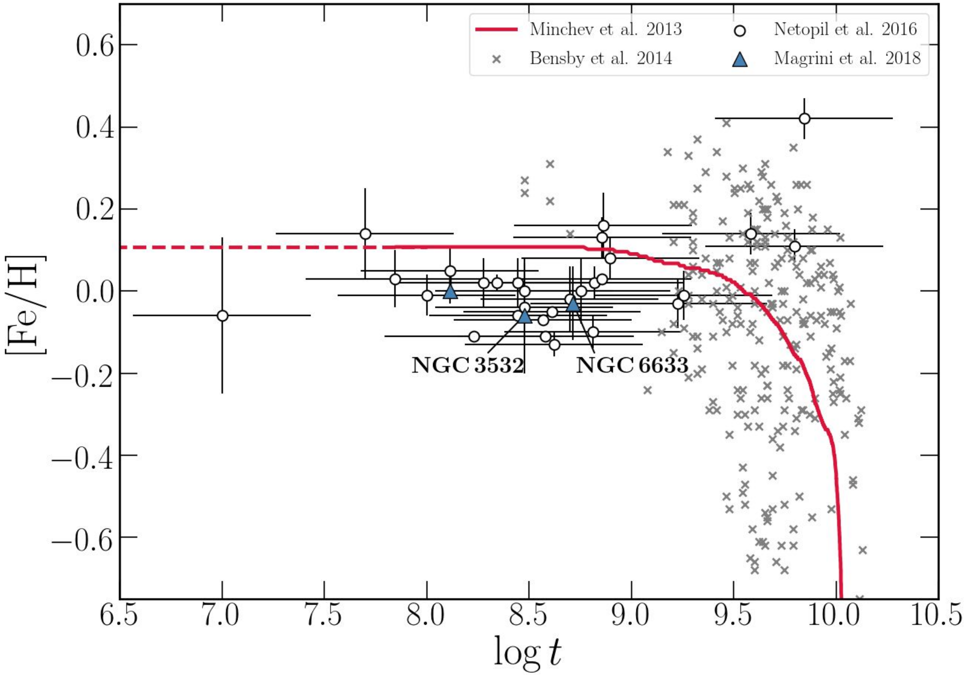
The issues of the young OCs (YOCs, *t* < 200 Myr): #1

Anomalous behaviour of YOCs : **local anaemia of the interstellar medium (IMS)**

7.5 < R_{GC} < 9 kpc
(solar neighborhood)

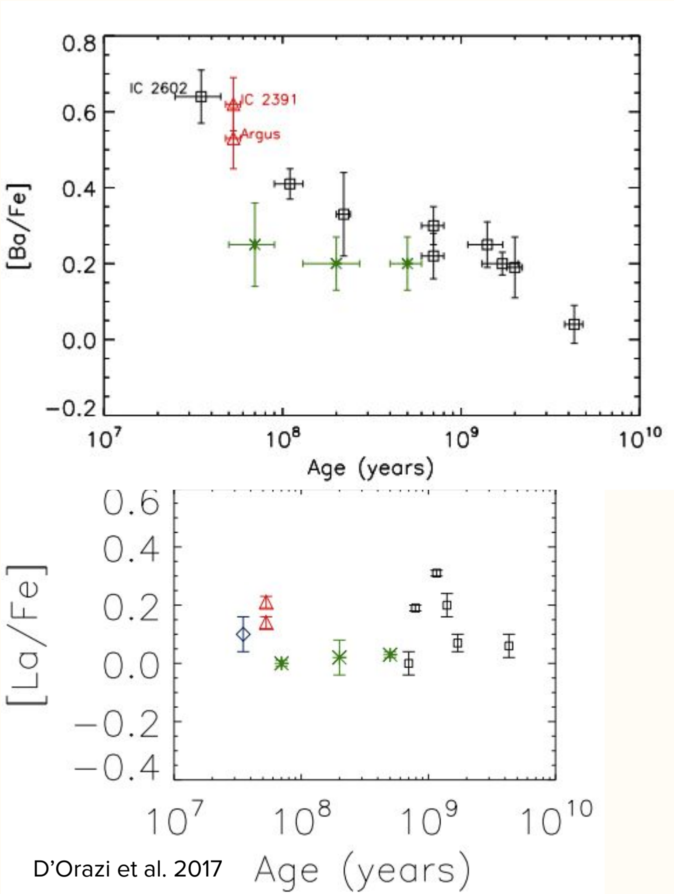
NO METAL-RICH YOCs, star forming regions (SFRs), moving groups or local associations
(e.g., James et al. 2006; Santos et al. 2008; Biazzo et al. 2011; Spina et al. 2014a,b; Spina et al. 2017)

Predictions of the Galactic chemical evolution (GCE) models (Minchev et al. 2013) = **enrichment of [Fe/H] ~ 0.1-0.15 dex in the last 4-5 Gyr**



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 ~+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) = general disagreement in literature (some authors= SOLAR abundances at all ages, other = same behaviour as Ba)

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**

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

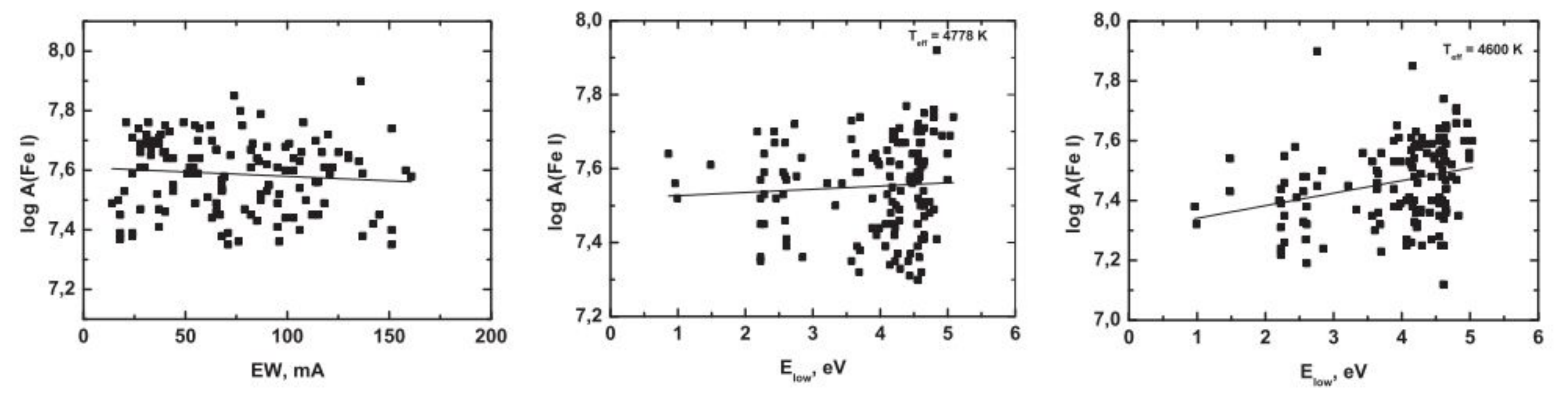
… SPOILER ALERT …

The spectroscopic analysis of YOUNG stars is not straightforward!!!

Different conspiring mechanisms can alter the spectral lines, thus affecting the stellar parameters and abundances

Are the chemical anomalies real or not? The *standard* approach

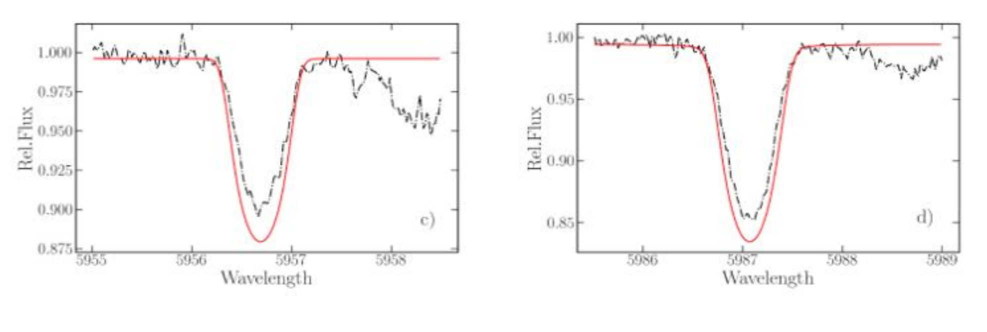
The ***standard*** spectroscopic analysis = EW method with Fe lines



- Measure the **EWs** (i.e., the strength of the line) in the stellar spectrum : typically, Fe lines
- Use model atmosphere (Kurucz or **MARCS)**
- Designated code (**MOOG**)
- **T_{eff}** : zeroing the trend between E.P. of individual lines and the corresponding abundances
- **log *g*** : FeI and FeII give the same abundance
- **microturbulence velocity ξ** : weak and strong lines of FeI give the same abundance (i.e., zeroing the trend between EW and individual abundances)

When all 3 criteria are satisfied = characterised the star and we can derive the chemical composition

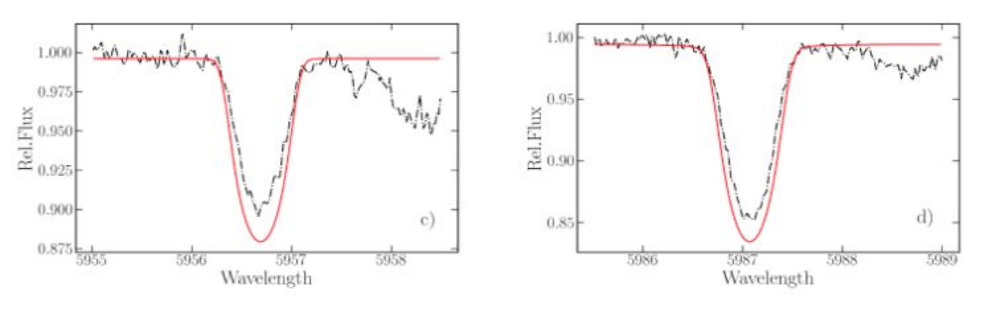
Are the chemical anomalies real or not? The *standard* approach



Young dwarf stars (t < 200 Myr): ξ values are overestimated (+1.0-1.5 km/s wrt the typical values)

Result = poor fit of the observed lines

Are the chemical anomalies real or not? The *standard* approach



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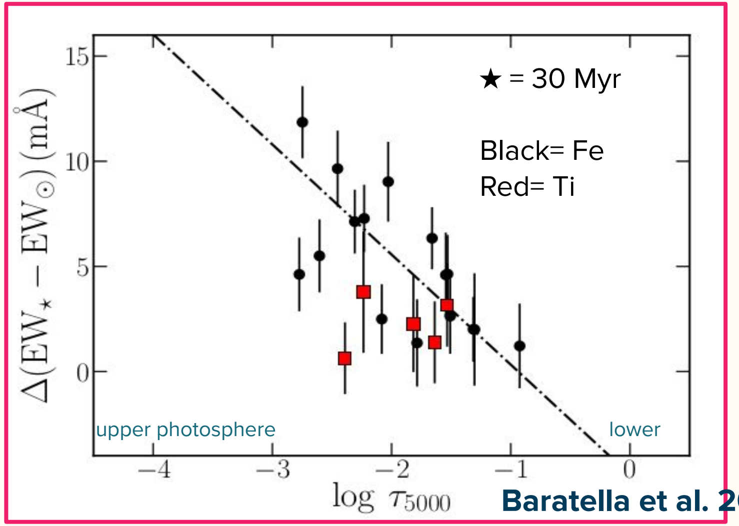


Baratella et al. 2020a

ARTIFICIALLY LOW VALUES OF [Fe/H] and [X/Fe] rescaling accordingly

(for solar-like dwarf stars in OCs we expect solar [X/Fe]**)**

Increased levels of activity could alter the line formation, especially of those lines forming up in the photosphere

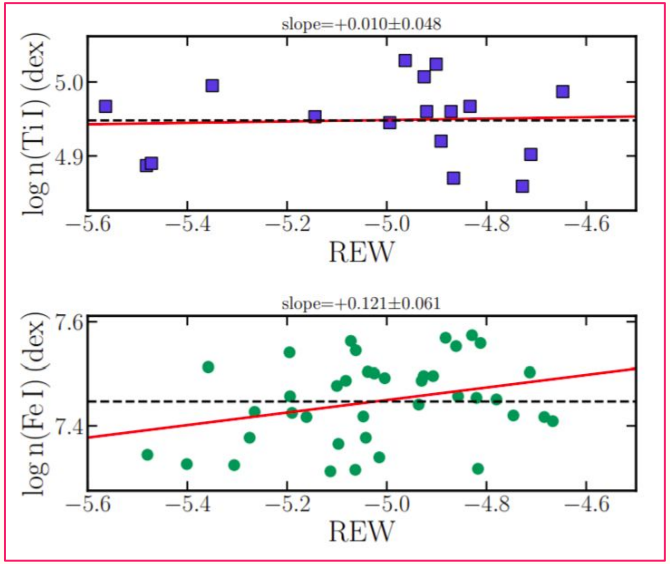
(Yana-Galarza et al. 2019, Baratella et al. 2020a, Spina et al. 2020)

This explains the large values of ξ

The *new* spectroscopic approach

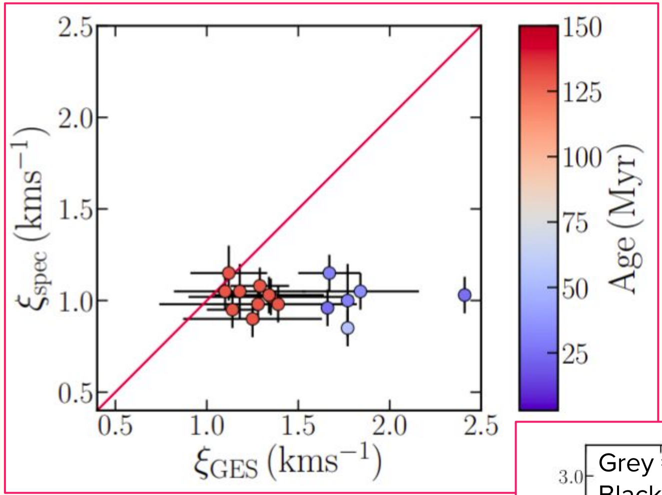
Titanium lines (form deeper in the photosphere and very precise atomic data from laboratory measurements - Lawler et al. 2013)

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



T_{eff}=5215±100 K; log g =4.35±0.10 dex; ξ=0.85±0.10 km/s; age=50 Myr (ξ from FeI = 1.75 km/s)

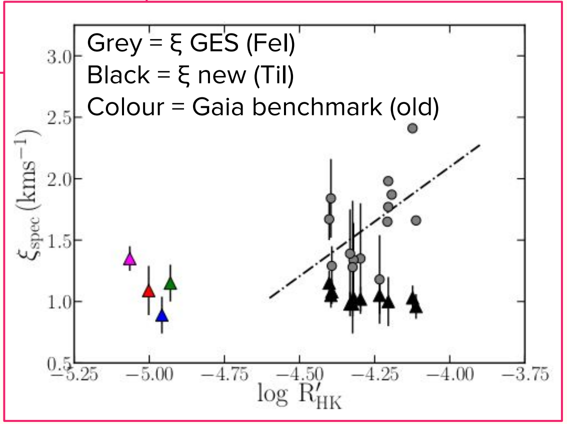
From Ti I



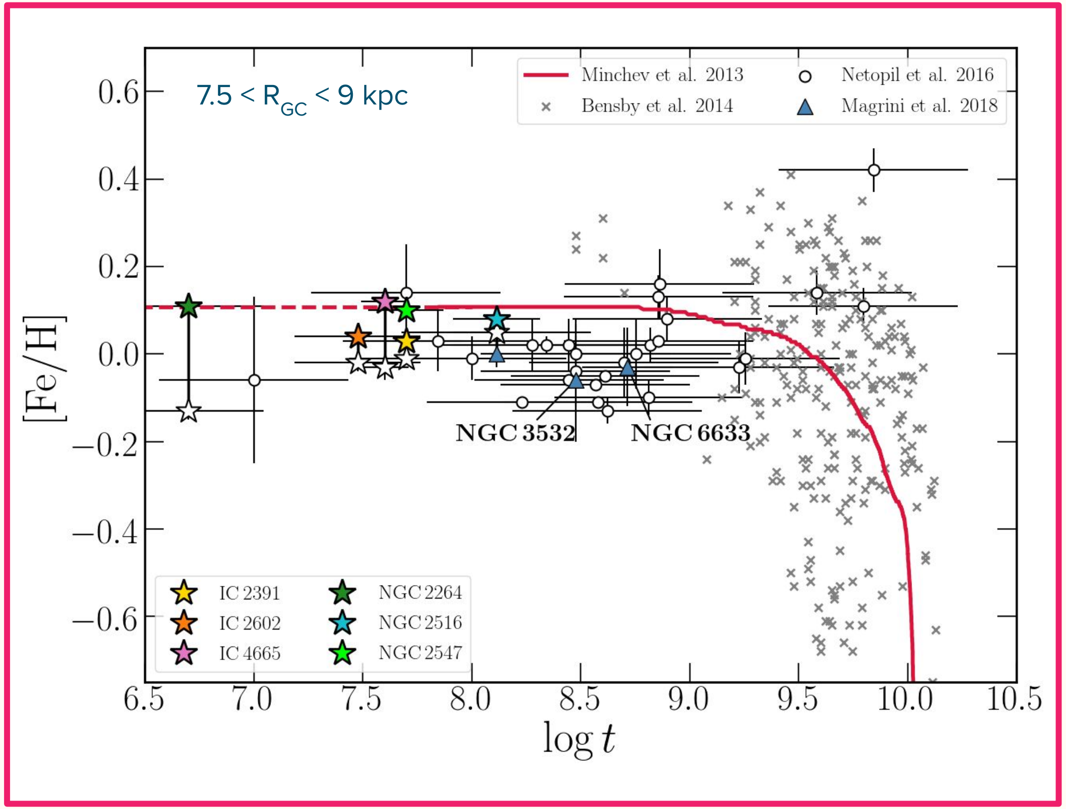
From Fe I

Baratella et al. 2020a
(https://ui.adsabs.harvard.edu/abs/2020A&A...634A..34B/abstract)

Log R'_{HK} = activity index from CaII H&K lines at 3968.47 Å and 3933.66 Å

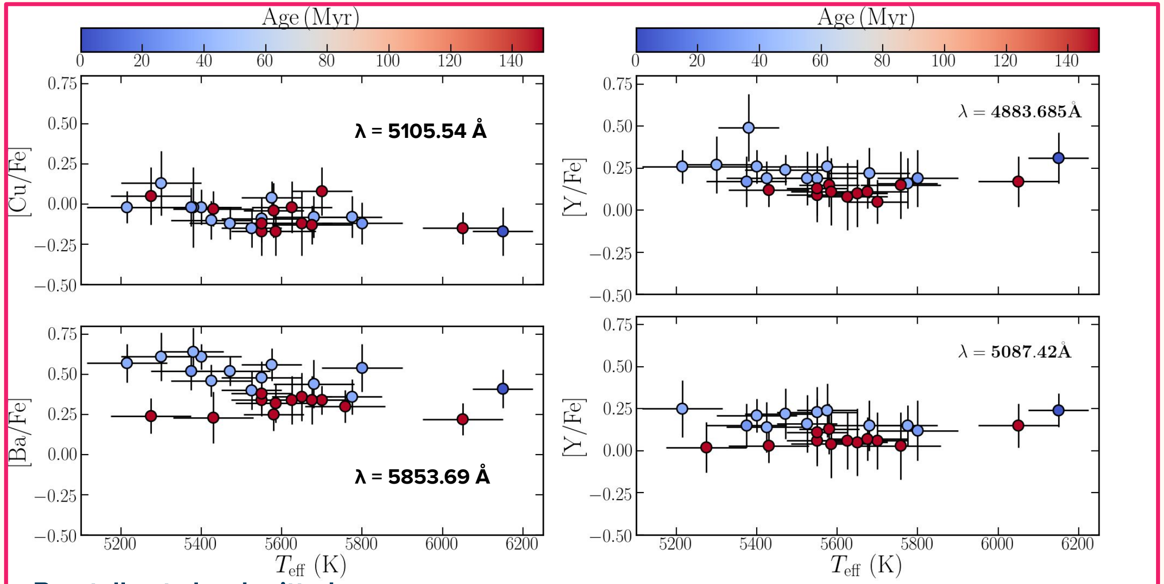


No sub-solar [Fe/H] at all ages !!!



Apparent METAL-POOR nature of YOCs = results of fundamental issues in the spectroscopic analysis of young stars

Abundances of neutron-capture elements Cu, Sr, Y, Zr, Ba, La and Ce



Baratella et al. submitted

- Spectral synthesis technique; very accurate line selection for redder range 480-680 nm (from Gaia-ESO official line list, Heiter et al. 2020)
- **Sharp separation with age for Ba and Y (homogeneous for Cu)**
- **[Cu/Fe] ~ SOLAR**
- **[Ba/Fe] between +0.25 and +0.75 dex**
- **[Y/Fe] between 0 and +0.30 dex**

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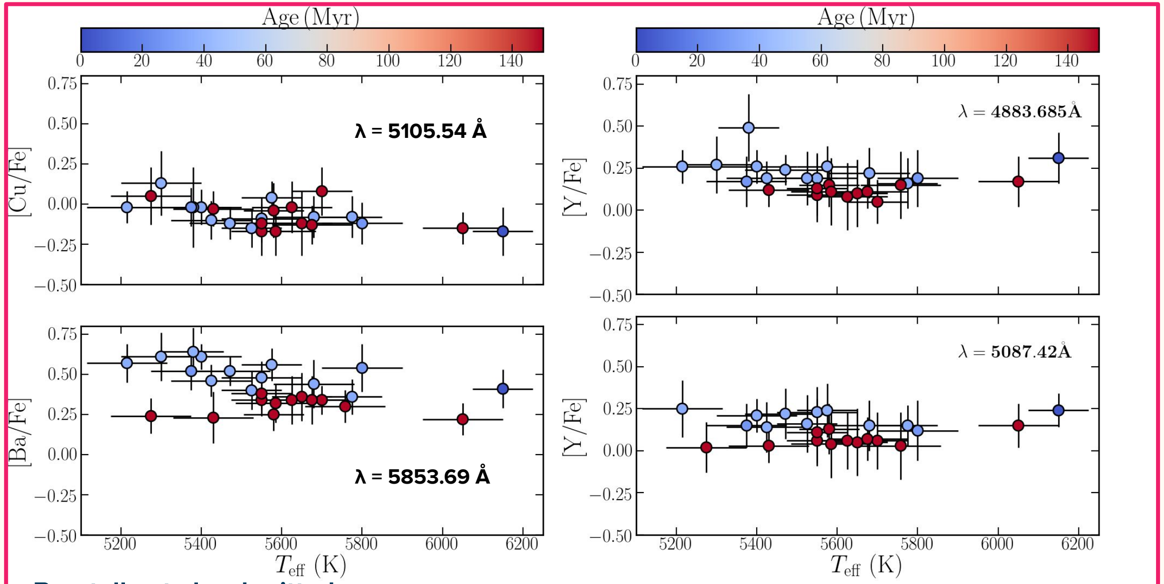

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Abundances of **Sr, Y, Zr, La and Ce** derived in 380-480 nm bluer range from well studied lines (D'Orazi et al. 2017)

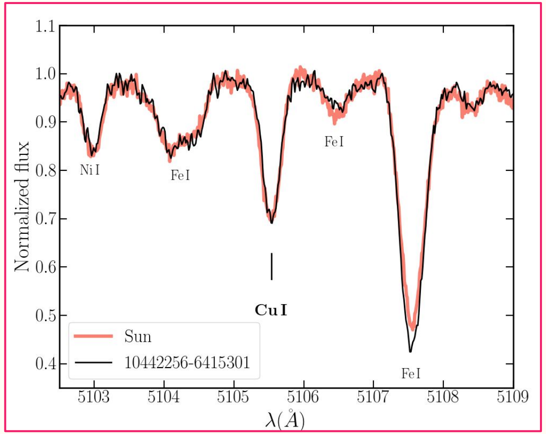
$[Y/Fe]_{blue}$ = $[Y/Fe]_{red}$

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

Δ_{NLTE}(Cu) = +0.02dex
Δ_{NLTE}(Ba) ~ -0.10 dex

Comparison of Sun and a 30 Myr solar-analog (IC 2602) : behaviour of lines

Fe-peak + weak/main s-process

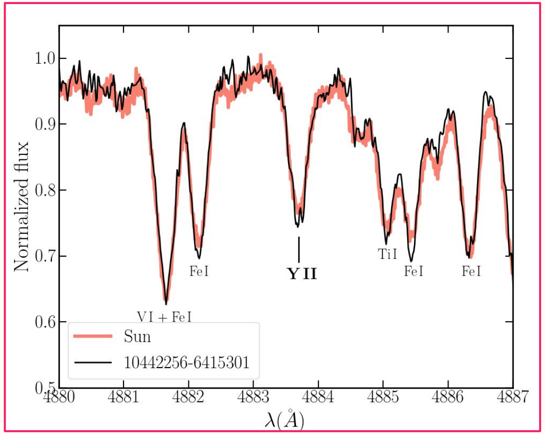


[Cu/Fe]= -0.08±0.13

log τ (Cu_{5105}) = -3.4 g_L=1.10

Neutral FIP=7.72 eV

First-peak main s-process

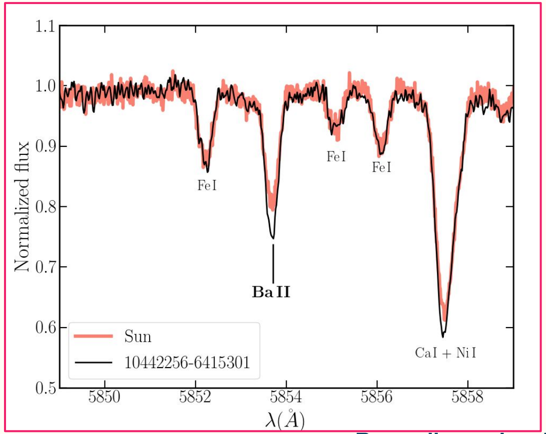


[Y/Fe]= +0.16±0.15

log τ (Y_{4883}) = -2.6 g_L=1.13

Ionised FIP=6.38 eV

Second-peak main s-process



Baratella et al. submitted

[Ba/Fe]= +0.36±0.11

log τ (Ba_{5853}) = -3.2 g_L=1.07

Ionised FIP=5.21 eV

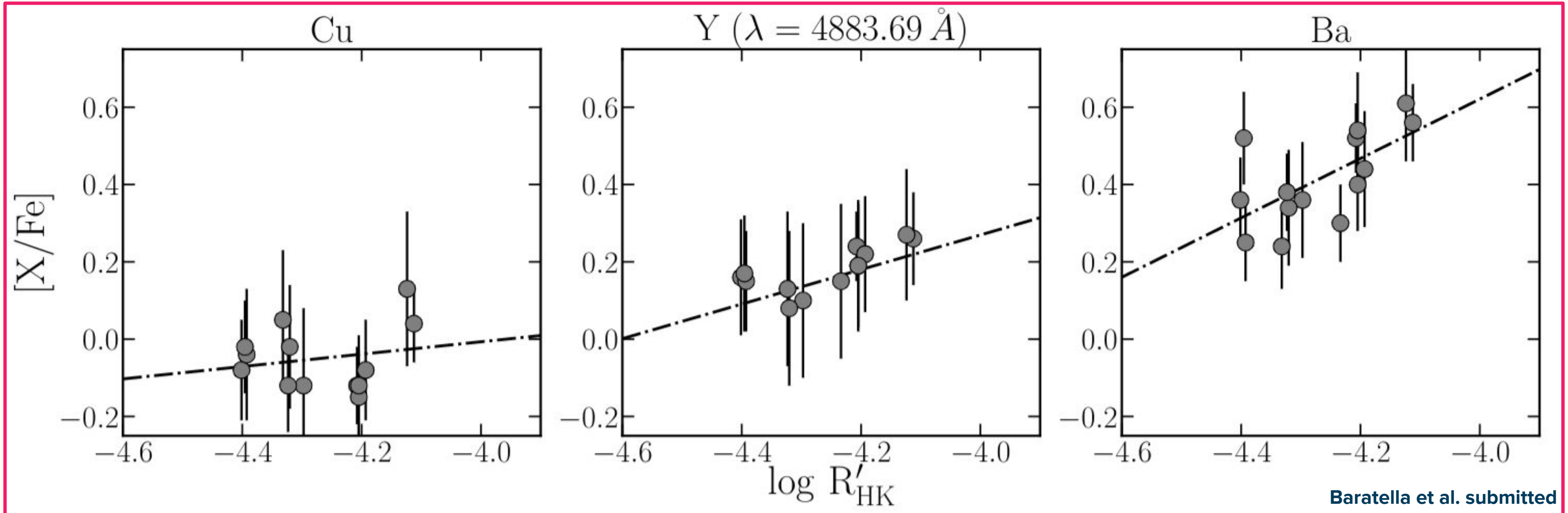
Overionization effect (e.g. Tsantaki et al.2019): ionisation balance problem, abundances from ionised lines >> neutral lines

Ba and Sr = similar physical and chemical properties, however **[Sr/Fe]=solar**

Y and La = both ionised, same depth, nucleosynthesis channel, however **[La/Fe]=solar**

Lines have Landè factor g_L similar (same for FIP)

Dependency on activity

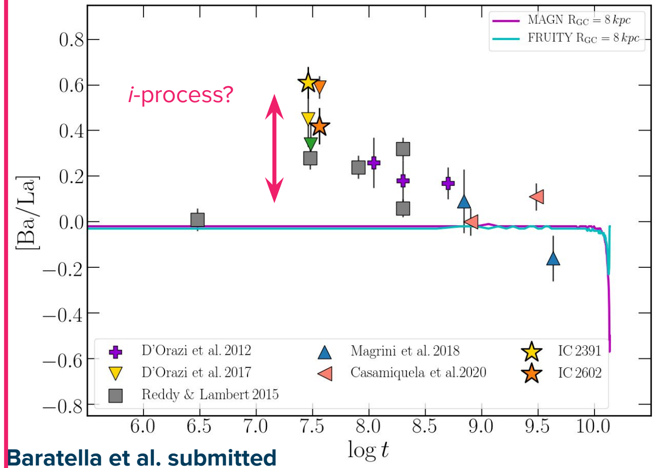


Baratella et al. submitted

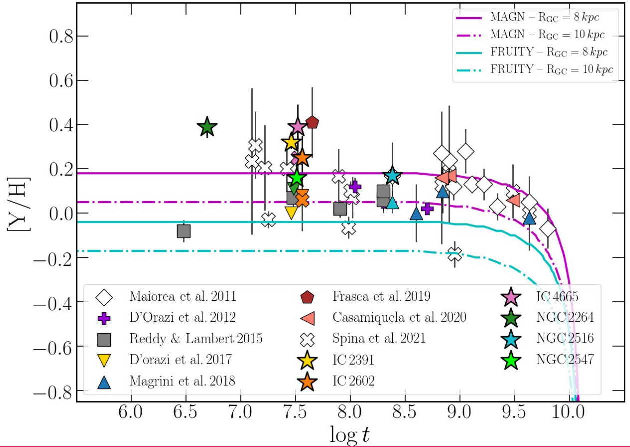
Indication of a possible correlation with activity index log R'_{HK}

(measurements = NOT synchronous, further investigation needed to confirm this)

The Galactic chemical evolution of s-process elements at young ages



Baratella et al. submitted



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 the 3-DU

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

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, but problems with the site of production

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

Extreme caution with chemical clocks [Y/Mg] at ages < 200 Myr !!!

Conclusions

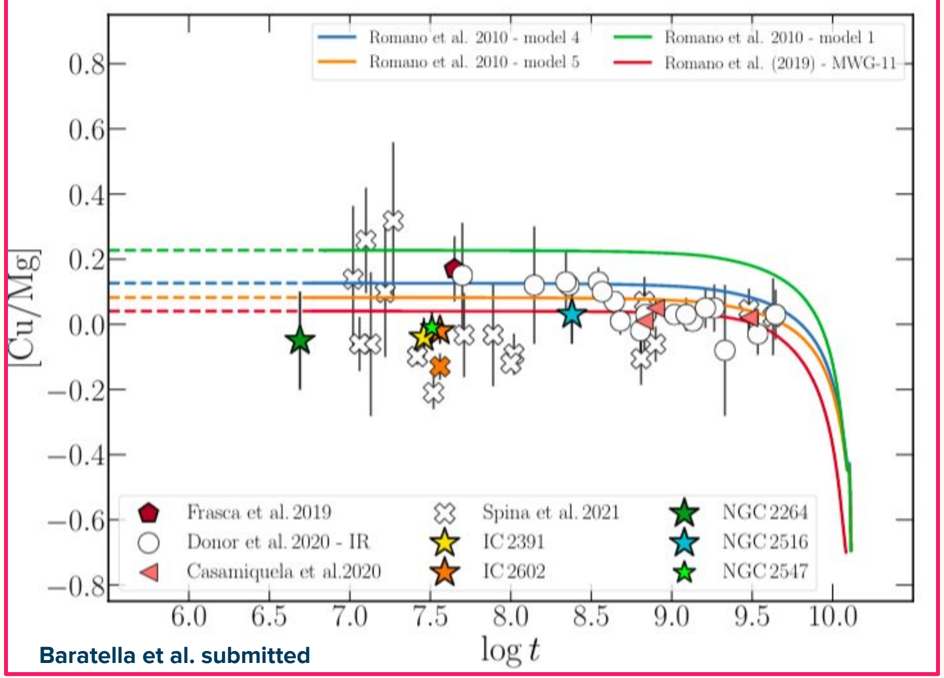
- Recent investigations of YOCs = necessity to revise the spectroscopic analysis techniques **(Yana-Galarza et al. 2019, Baratella et al. 2020a, Spina et al. 2020)**
- **New spectroscopic approach (Ti+Fe)** to overcome issues related to spectral line formation
- Situation more complex when moving to the **peculiar pattern of the s-process elements** abundances
- **[Cu/Fe] is solar, [Y/Fe] is mild enhanced, [Ba/Fe] is over-abundant, [La/Fe] is solar as well as [Sr/Fe], [Zr/Fe] and [Ce/Fe]**
- Lines of some elements (BaII, YII, FeI, NiI…) are stronger in a 30 Myr solar-analog, but relative weak lines of other elements show the same behaviour
- GCE are not able to reproduce the [Ba/La], unless we invoke additional sources (*i*-process ?)
- Extreme caution with [Y/Mg] at ages < 200 Myr

The Ba puzzle is still unsolved…

observational issues or are these real abundances? Further critical observations needed

❇❇❇ Extras ❇❇❇

The Galactic chemical evolution of Cu



Baratella et al. submitted

Cu production on Galactic scales from weak s-process in massive stars from ^{22}Ne(α,n)^{25}Mg (plus small % from explosive nucleosynthesis in CC-SNe and SNIa)

[Cu/Mg] = both from CC-SNe (limited effects due to Galactic evolution)

Solar values confirmed at all ages!!!

Scatter of 0.2 dex = number of possible explanations (different reaction rates of the different yields)