Osservatorio Astronomico di Trieste
Astronomical Observatory of Trieste

Chemical abundances of light neutron-capture elements in metal-poor stars

Linda Lombardo

Post-doc at INAF - OATs

s, i & r Element Nucleosynthesis (sirEN) Conference
Giulianova, 8-13 June 2025

Metal-poor stars: tracers of the early Universe

Chemical composition of the early Universe: H, He and traces of Li

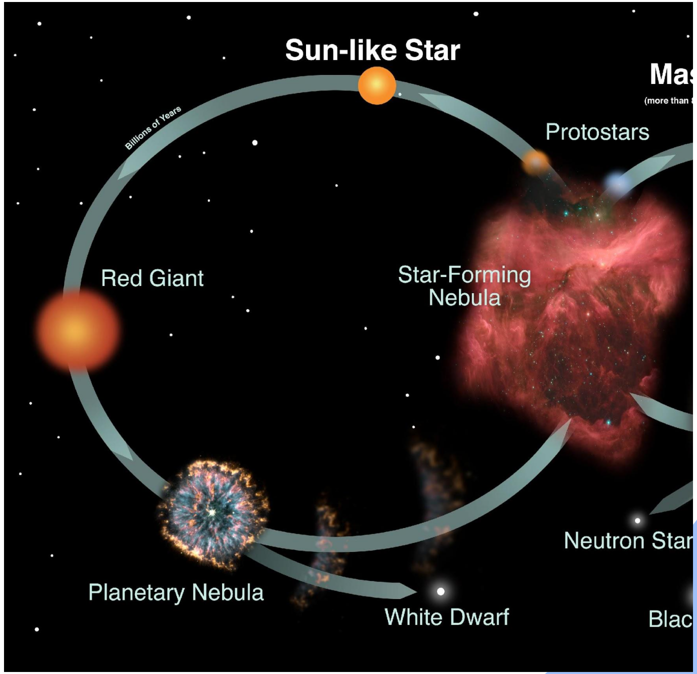
First stars formed -> elements heavier than He can be formed and injected into the interstellar medium

Second (and subsequent) generation of stars with low mass are long lived and are still visible today -> we can study their chemistry

Chemistry of old low-mass stars

Nucleosynthesis in the early Universe

Chemical evolution of the early Universe



Metal-poor stars: tracers of the early Universe

$[Fe/H] = \log_{10}(N_{Fe}/N_{H})_{\star} - \log_{10}(N_{Fe}/N_{H})_{\odot}$

Timeline of the Universe. Image credit: Rhys Taylor

SUN

$[Fe/H]_{\odot} = 0$

FIRST STARS

Metallicity: abundance of elements in a star that are heavier than H and He

Metal-poor : [Fe/H]< –1 (1/10 of the Sun)

Very metal-poor : [Fe/H]< –2 (1/100 of the Sun)

Very metal-poor : [Fe/H]< –3 (1/1000 of the Sun)

Extremely metal-poor : [Fe/H]< –4 (1/10000 of the Sun)

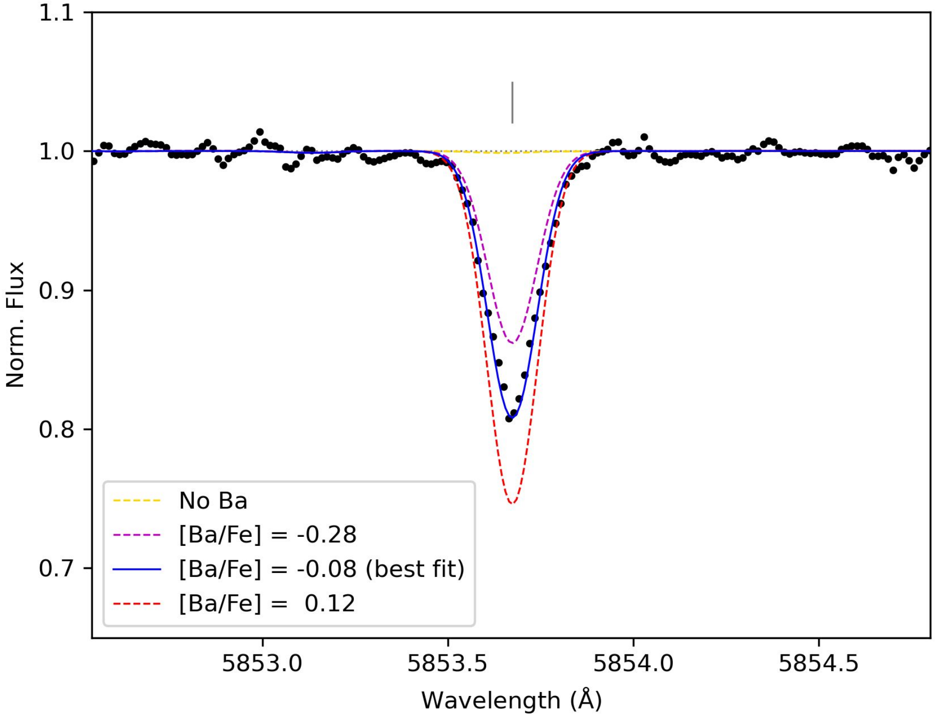
How do we measure stellar abundances?

From stellar spectra to chemical abundances

Abundance: number of absorbers in a stellar atmosphere, normalised to a reference value. It reflects the atmosphere's chemical composition

Abundance ratio: $[X/Y] = \log_{10}(N_X/N_Y)_{\star} - \log_{10}(N_X/N_Y)_{\odot}$

For the Sun: $[X/Y]_{\odot} = 0$

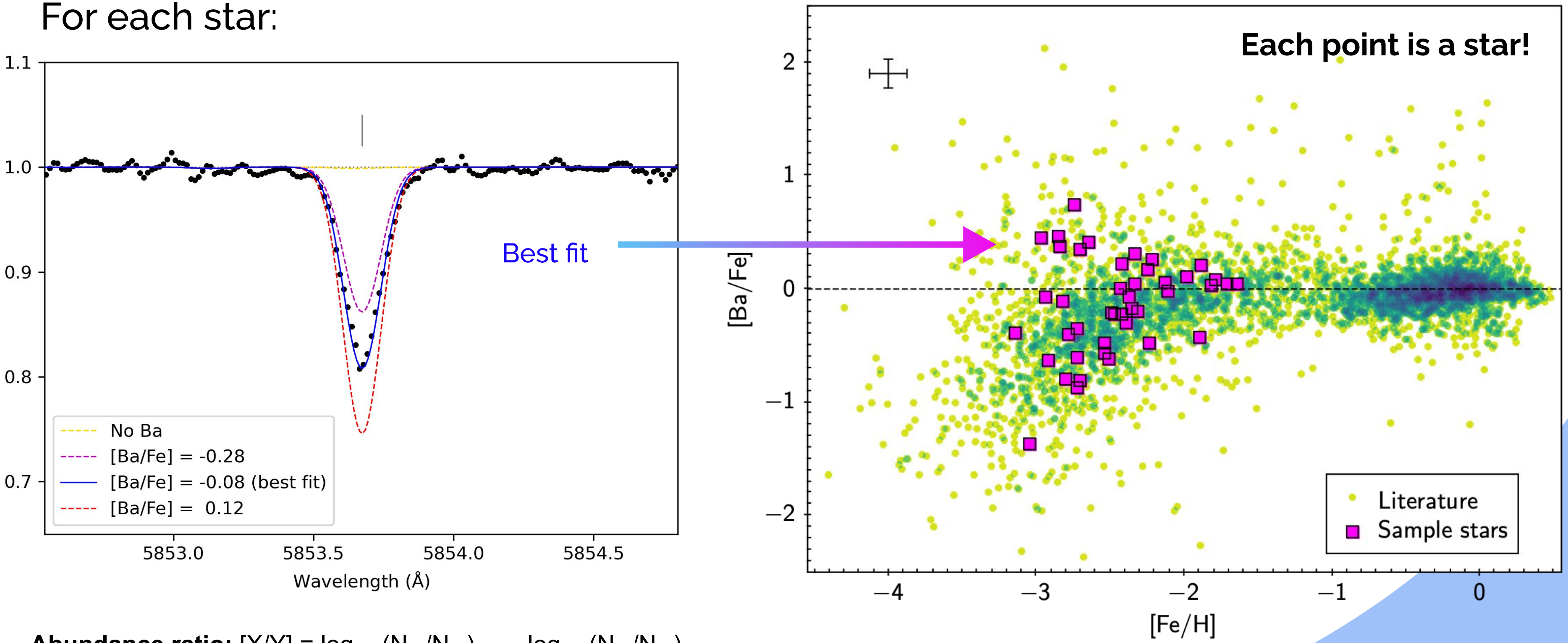


Input needed:

- Observed stellar spectra
- Stellar parameters (effective temperature, surface gravity, …)
- Atomic data (energy levels, transition strengths, ionisation stage, …)
- Spectrum synthesis code

From stellar spectra to chemical abundances

For each star:



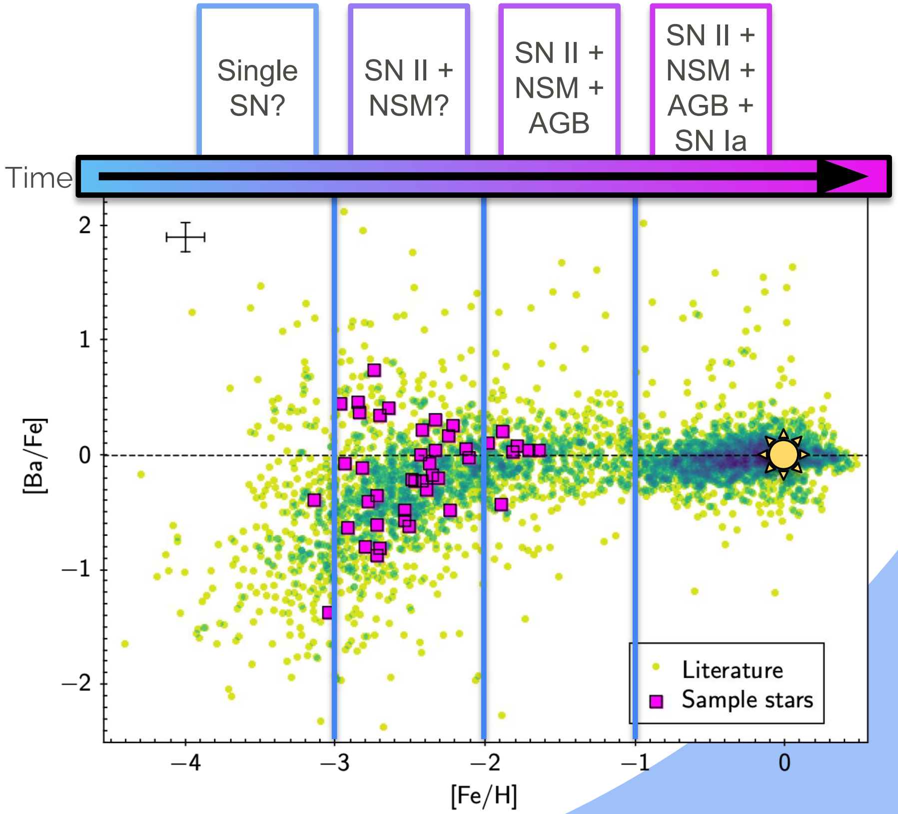
Abundance ratio: $[X/Y] = \log_{10}(N_X/N_Y)_{\star} - \log_{10}(N_X/N_Y)_{\odot}$

For the Sun: $[X/Y]_{\odot} = 0$

Why chemical abundances are important?

Abundance ratios diagrams can tell us

- the different contributions of those sites on their respective time scales -> **we can study the Galactic Chemical Evolution (GCE)**



Why chemical abundances are important?

Abundance ratios diagrams can tell us

- the different contributions of those sites on their respective time scales -> **we can study the Galactic Chemical Evolution (GCE)**
- **if the elements are co-produced or not** through correlations between elements pairs

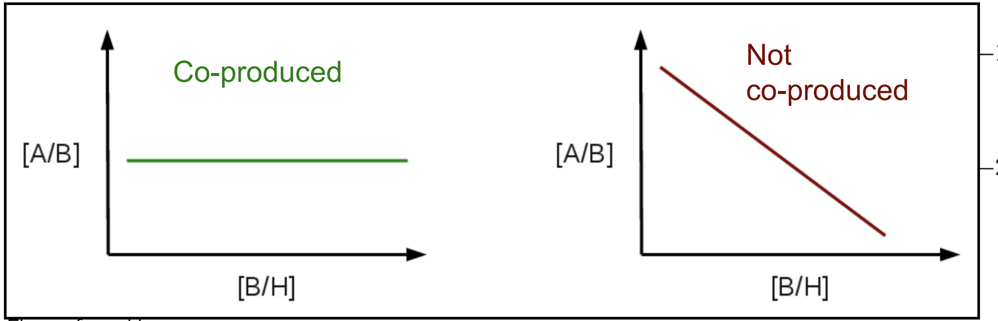
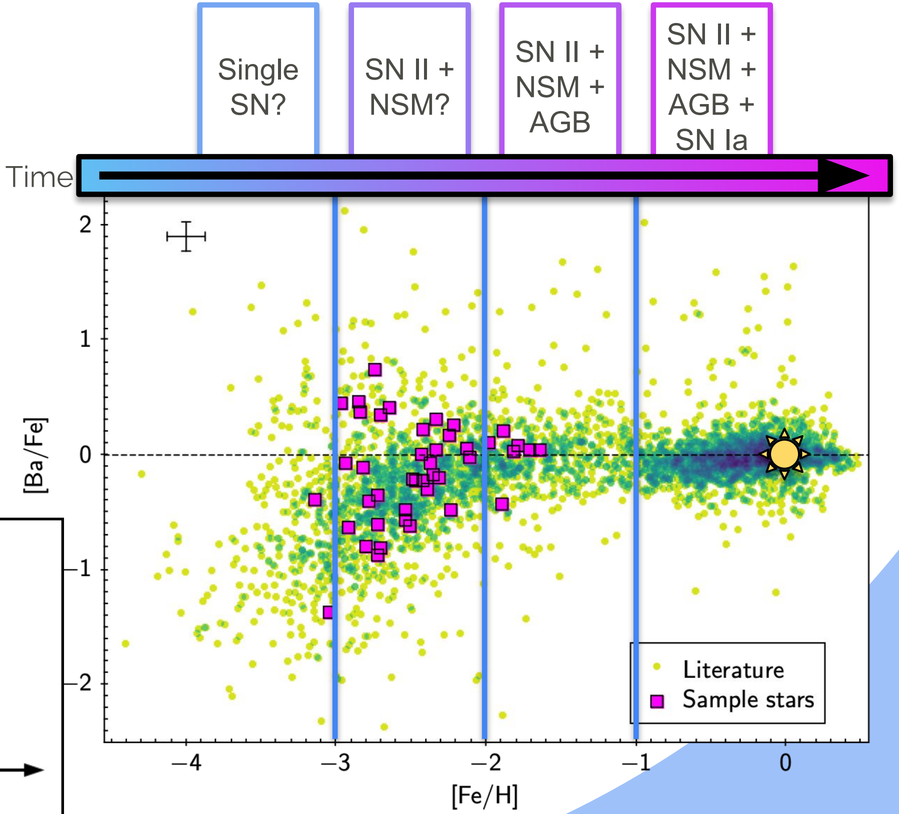


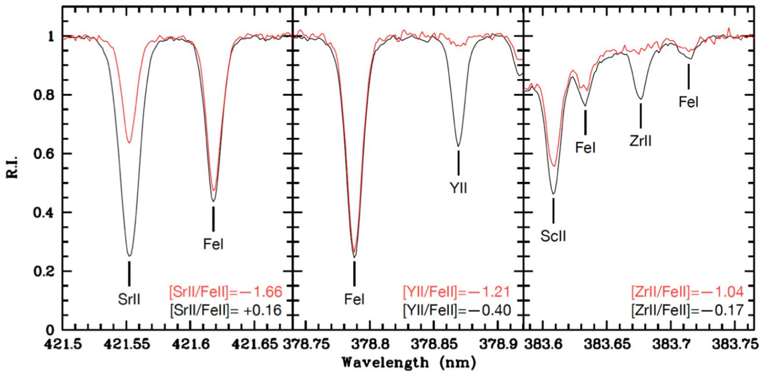
Figure from Hansen 2012



Chemical Evolution of R-process Elements in Stars

PI: Prof. C.J. Hansen

- **Goal**: measuring heavy elements in metal-poor stars ([Fe/H]≤−1.8) to increase our knowledge of the physical conditions and formation sites of r-process elements
- **Sample**: 52 giant stars with <5 heavy element abundances known in the literature
- **Data**: High-resolution (R>40000), high signal-to-noise ratio (SNR>50 @390nm) spectra obtained with ESO VLT/UVES
- **Method**: Fully homogeneous analysis (1D LTE models, codes, data, line lists…)
- **Status**: Li, C, N, O, Na to Zn, Sr, Y, Zr, Ba, La, Ce, Pr, Nd, Sm, Eu, Hf, Os, Ir, Pt



Lombardo et al. 2022

Results: [Ba/Eu] vs [Fe/H]

In solar system material : (Arlandini+99)

Ba : 81% *s*, 19% *r* —> mainly s

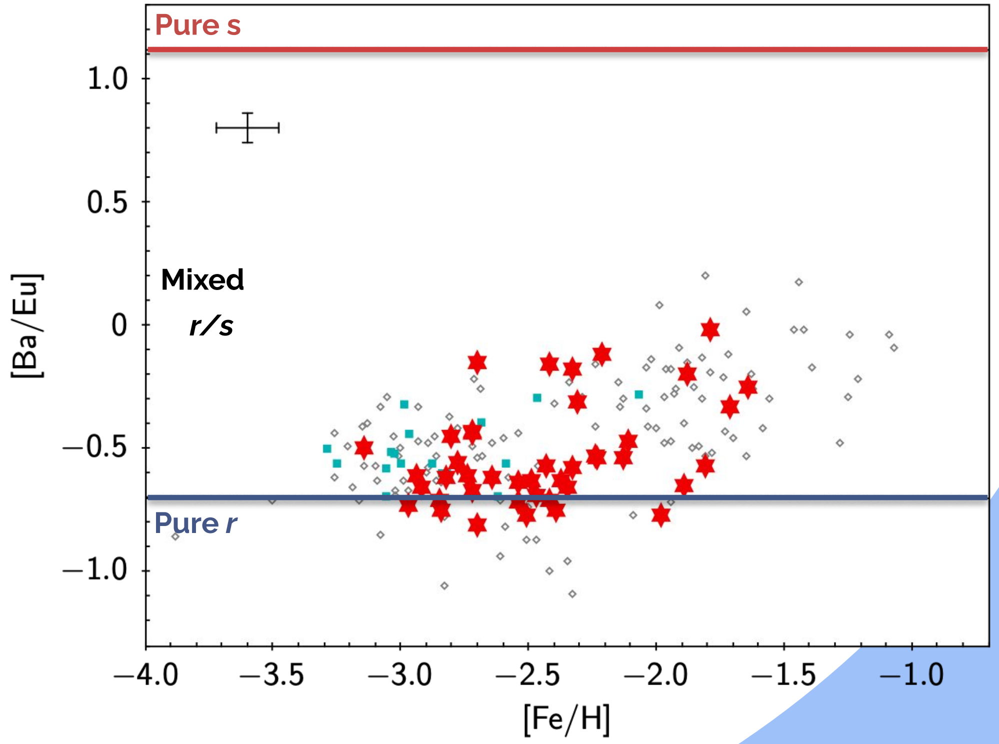
Eu: 5.8% *s*, 94.2% *r* —> mainly r

[Ba/Eu] allow us to investigate the relative contribution of *s*- and *r*- processes

At low metallicities, stars tend to clump around the pure r-process solar system value [Ba/Eu]=−0.7 (Arlandini+99)

→ at low metallicities, **Ba is likely produced by *r*-process instead of *s*-process**

Lombardo et al. 2025



Francois et al. (2007)
Roederer et al. (2014)

Results: onset of s-process in the MW halo

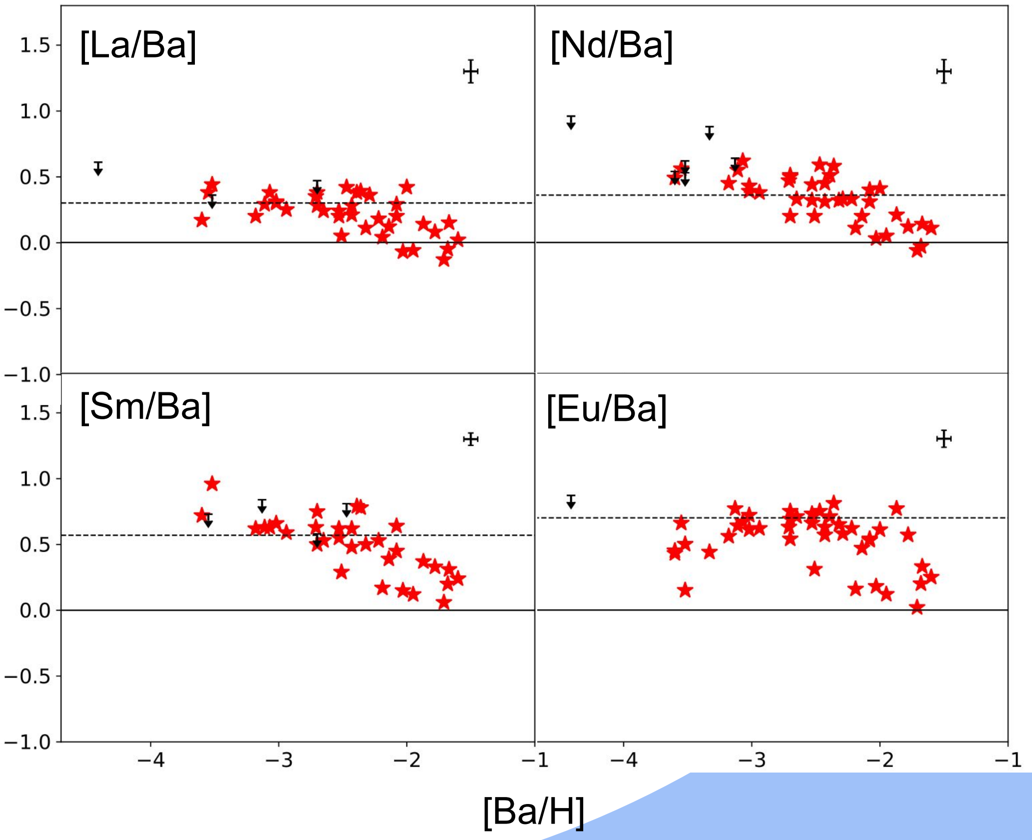
At which values of [Ba/H] and [Fe/H] the onset of the *s*-process occurs?

We observe a change in the trends at [Ba/H]=−2.4 (~ [Fe/H]=−2.4):

For [Ba/H]<−2.4: flat trend + clustering around the solar pure r-process values **→*r*-process as primary production mechanism**

For [Ba/H]>−2.4: large scatter →**onset of *s*-process in heavy elements nucleosynthesis**

Lombardo et al. 2025



Results: [Sr/Ba] vs [Ba/Fe]

In solar system material : (Arlandini+99)

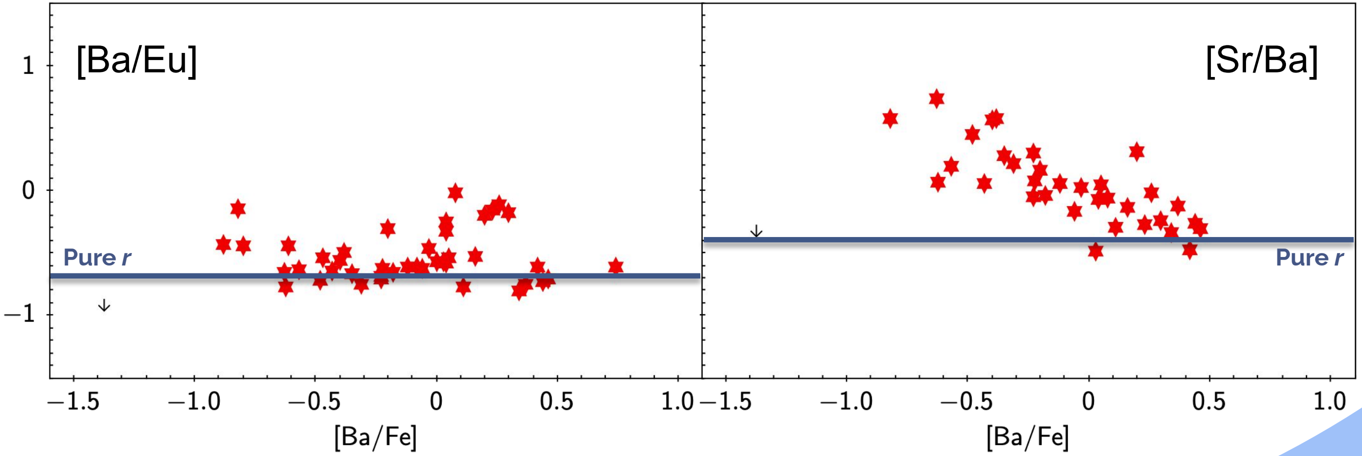
Sr : 85% *s*, 15% *r* —> mainly s

Ba : 81% *s*, 19% *r* —> mainly s

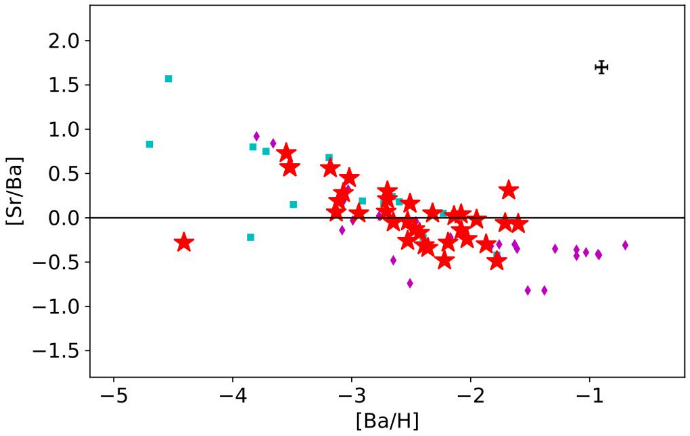
Eu: 5.8% *s*, 94.2% *r* —> mainly r

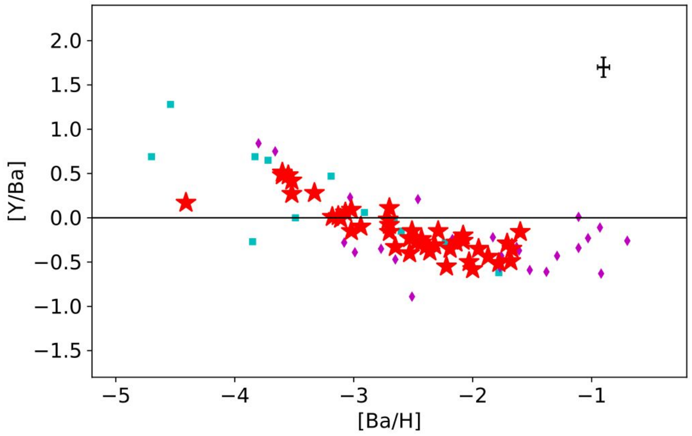
Similarly to Ba, at low metallicity we would expect Sr to be produced by the r-process

At low [Ba/Fe], the scatter in [Sr/Ba] becomes larger → **another process is involved for the formation of Sr at low metallicities**



Results: [Sr/Ba], [Y/Ba], [Zr/Ba] vs [Ba/H]



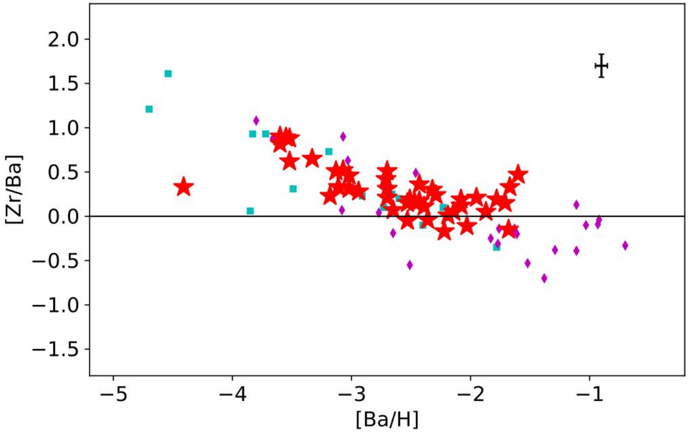


In solar system material :
(Arlandini+99)

Sr : 85% *s*, 15% *r* —> mainly s

Y : 92% *s*, 8% *r* —> mainly s

Zr : 83% *s*, 17% *r* —> mainly s



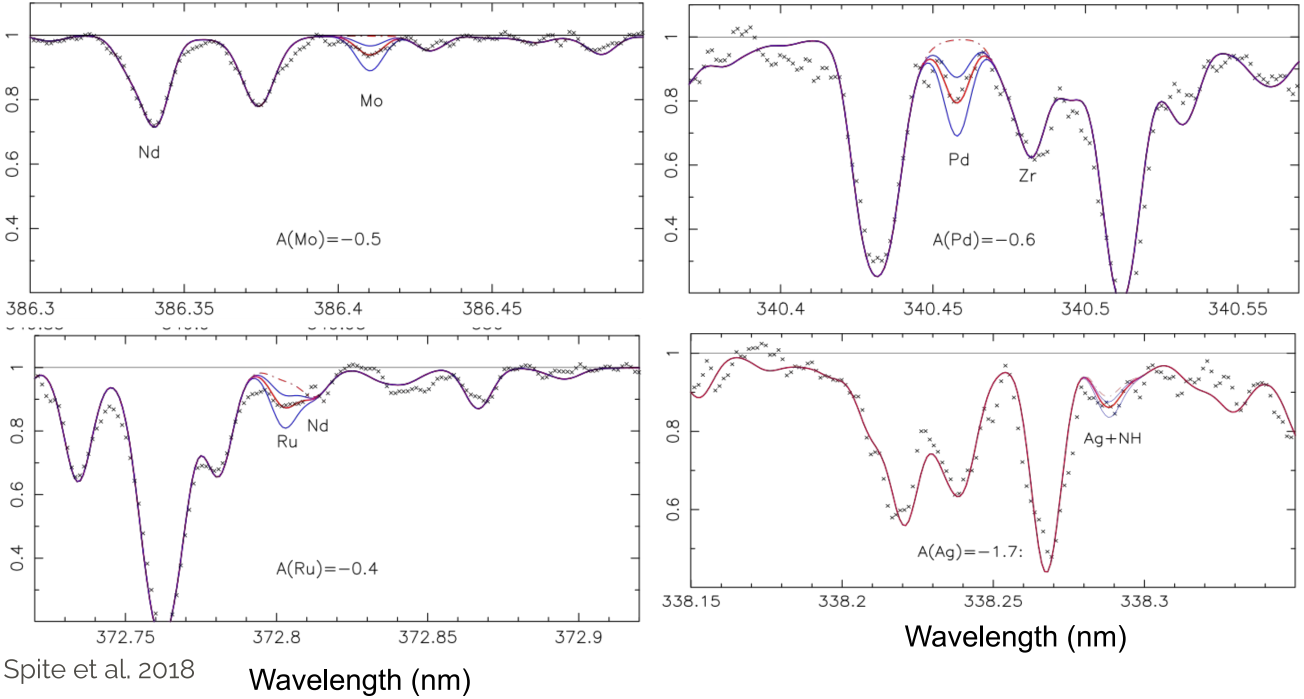
At low [Ba/H], the scatter in [Sr/Ba], [Y/Ba], [Zr/Ba] increases→ **another process is involved for the formation of Sr, Y, Zr at low metallicities**

Possible processes:

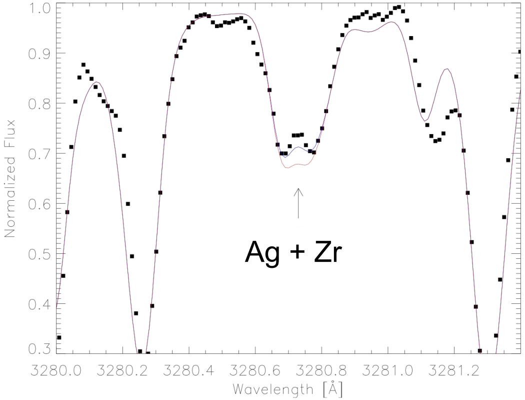
- Weak r-process (Bliss+17, Hansen+12)
- Weak s-process (Pignatari+10, Cescutti+13)
- …

Light n-capture elements: Mo, Ru, Pd, Ag

Light neutron capture elements with strong lines in the UV → difficult to measure due to severe blends with other atomic and molecular lines



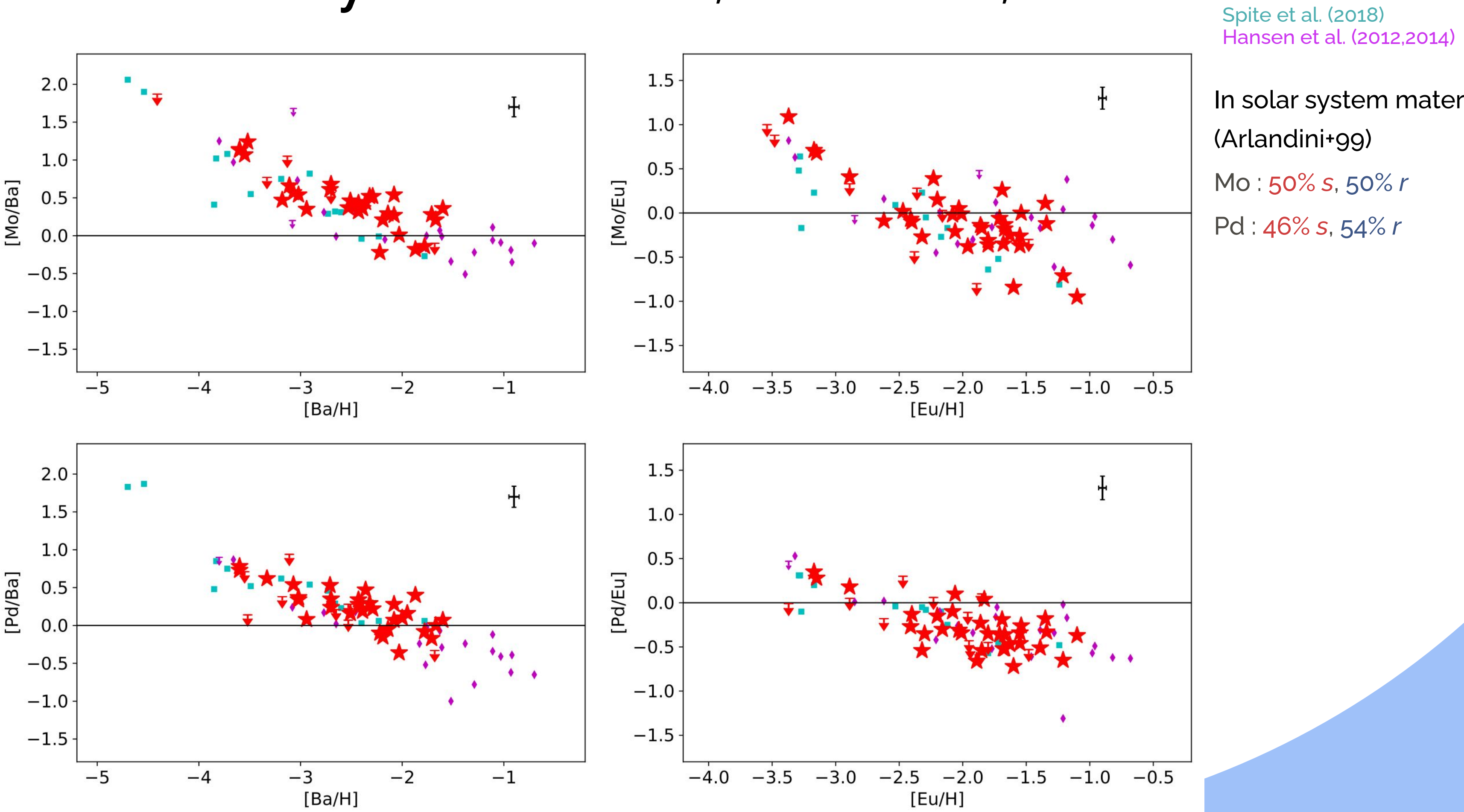
Spite et al. 2018



Hansen et al. 2012

Observations require high resolution and high SNR spectra → long exposure times even for bright stars

Preliminary results: Mo, Pd vs Ba, Eu



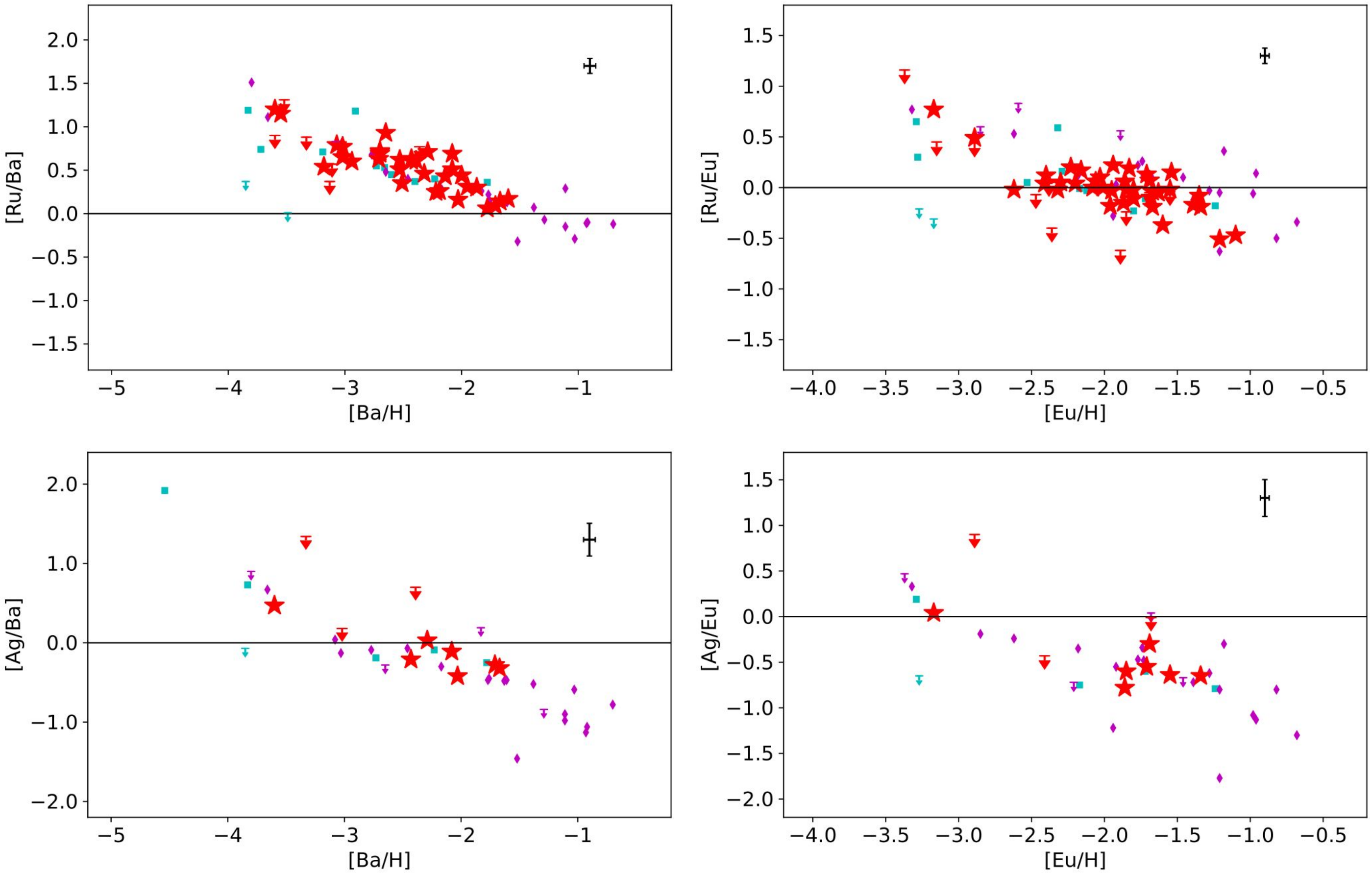
In solar system material :

(Arlandini+99)

Mo : 50% *s*, 50% *r*

Pd : 46% *s*, 54% *r*

Preliminary results: Ru, Ag vs Ba, Eu



Spite et al. (2018)
Hansen et al. (2012,2014)

In solar system material :
(Arlandini+99)

Ru : 32% *s*, 68% *r*

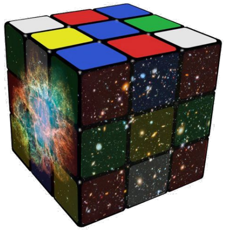
Ag : 20% *s*, 80% *r*

Summary and future perspectives

The onset of s-process seems to occurs at [Ba/H]=−2.4 and [Fe/H]=−2.4 for our sample of star → for [Ba/H]<−2.4 the *r*-process is likely the primary production mechanism of Ba

Strong indications of contributions from different formation processes at low metallicities are found, where at least four **different neutron capture processes are required to explain the observed abundances** (main s-, main r-, weak s-, weak r-)

High quality spectra in the UV are difficult to obtain, so new instruments with a high efficiency in the UV like CUBES (Cassegrain U-Band Efficient Spectrograph) are required

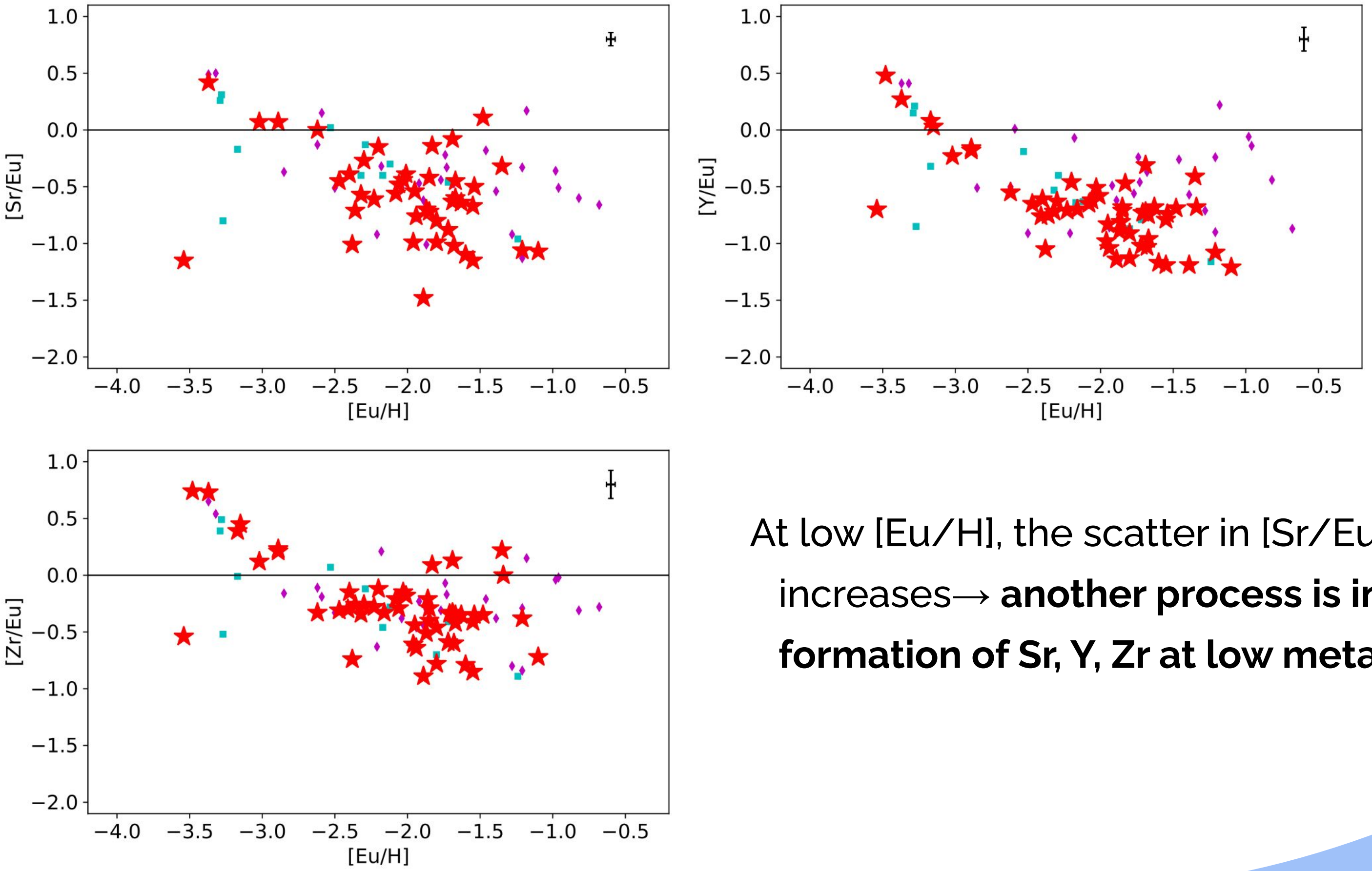


CUBES

R~20000
Range: 305 - 400nm
Efficiency:>40%
Sensitivity: SNR>20 for U=18 mag at 313 nm

Thank you for your attention!

Results: [Sr/Eu], [Y/Eu], [Zr/Eu] vs [Eu/H]



In solar system material : (Arlandini+99)

Sr : 85% *s*, 15% *r* —> mainly s

Y : 92% *s*, 8% *r* —> mainly s

Zr : 83% *s*, 17% *r* —> mainly s

At low [Eu/H], the scatter in [Sr/Eu], [Y/Ba], [Zr/Ba] increases→ **another process is involved for the formation of Sr, Y, Zr at low metallicities**