

Observationally constraining the physical nature of the r-process

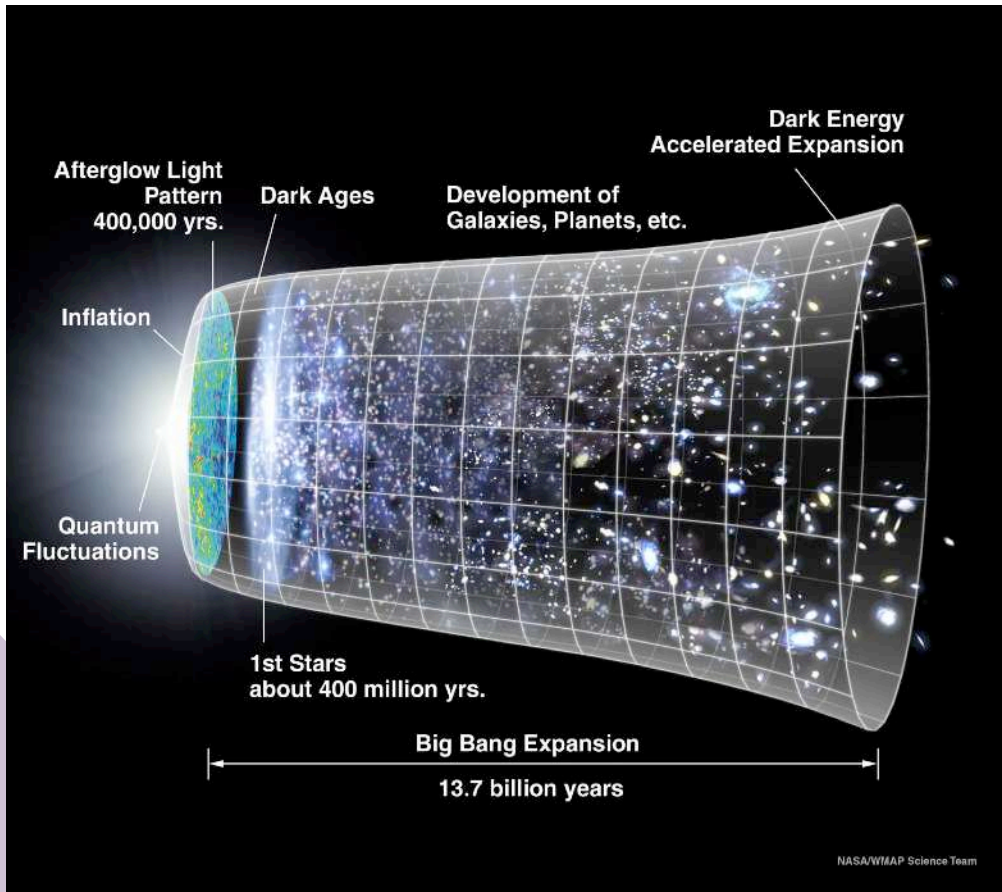
Linda Lombardo

Postdoc at IAP - Goethe University Frankfurt



How do the elements form?

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



Origin of the elements

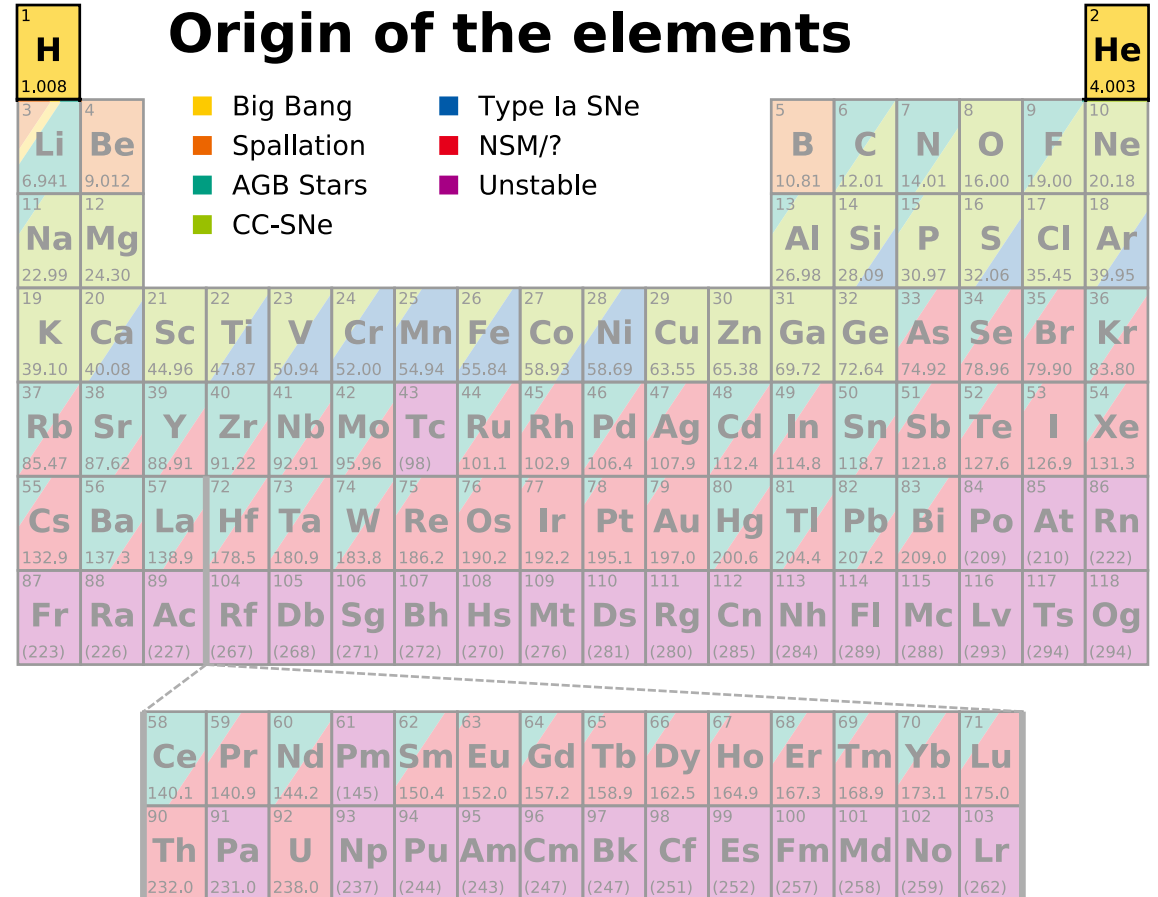
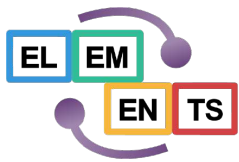
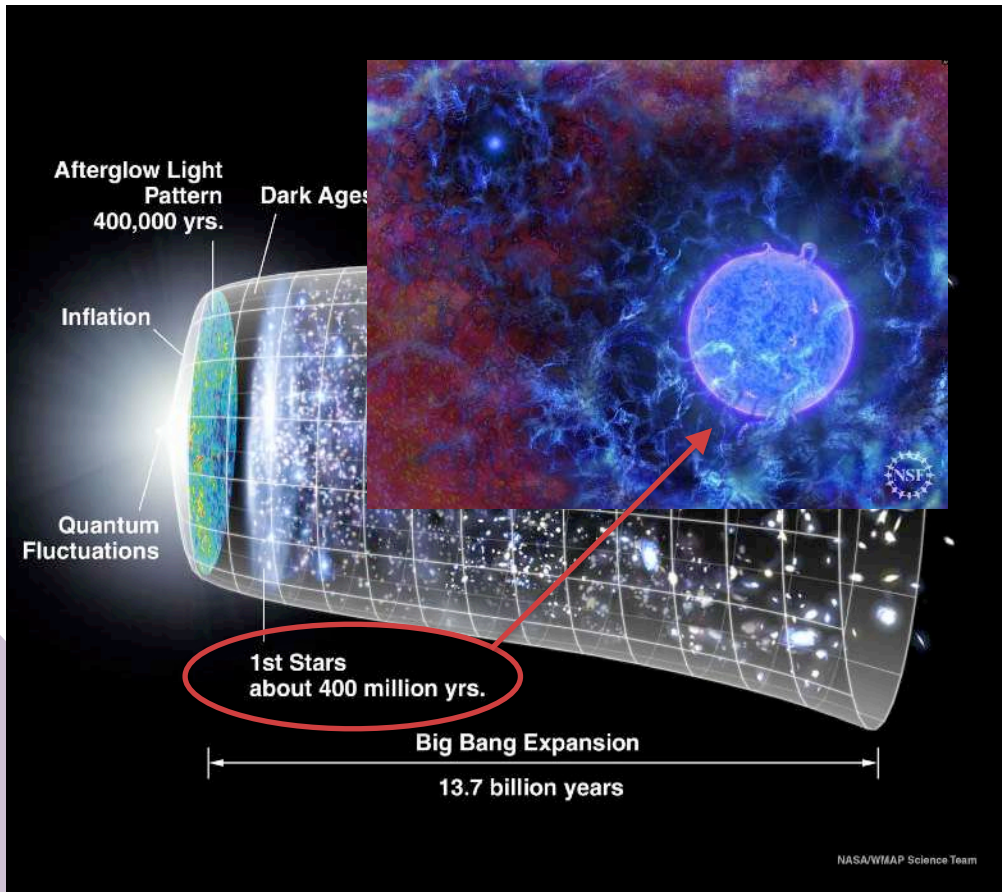


Image courtesy of M. Reichert

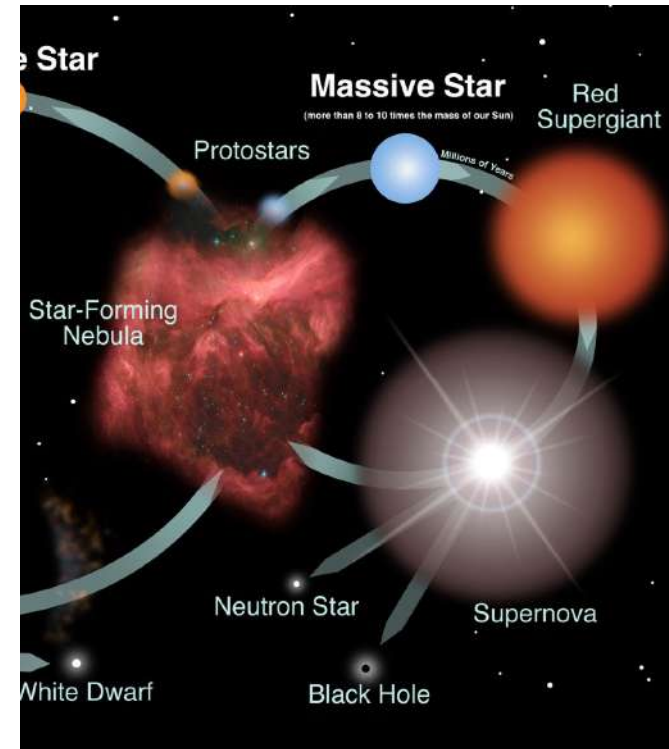


How do the elements form?

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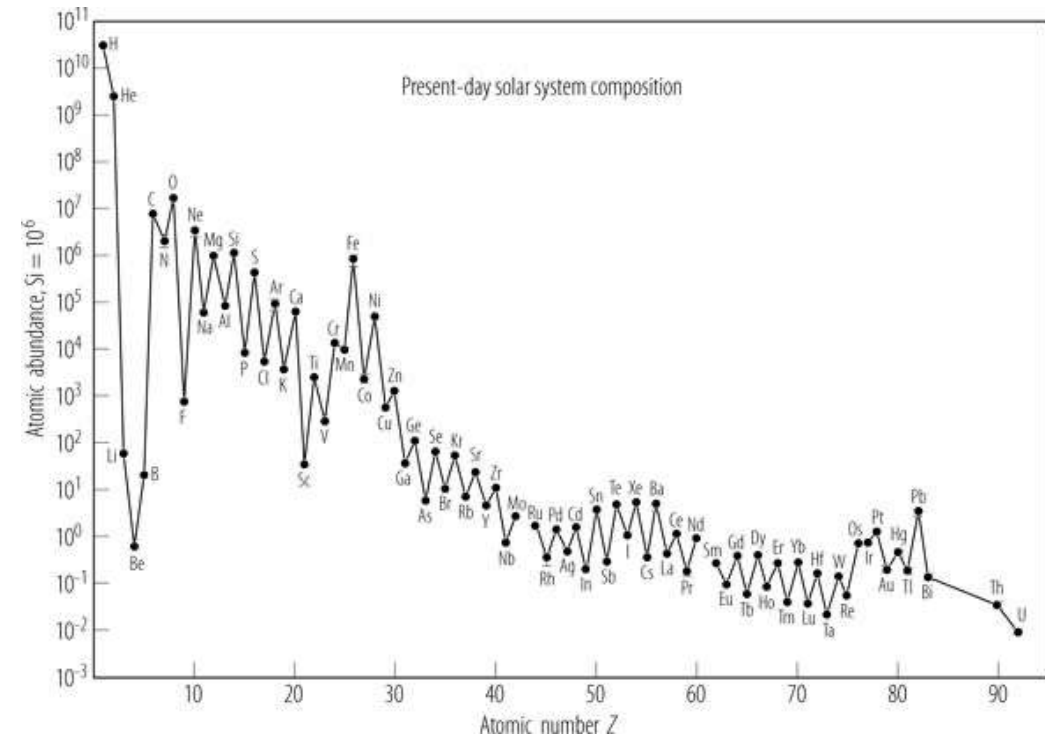
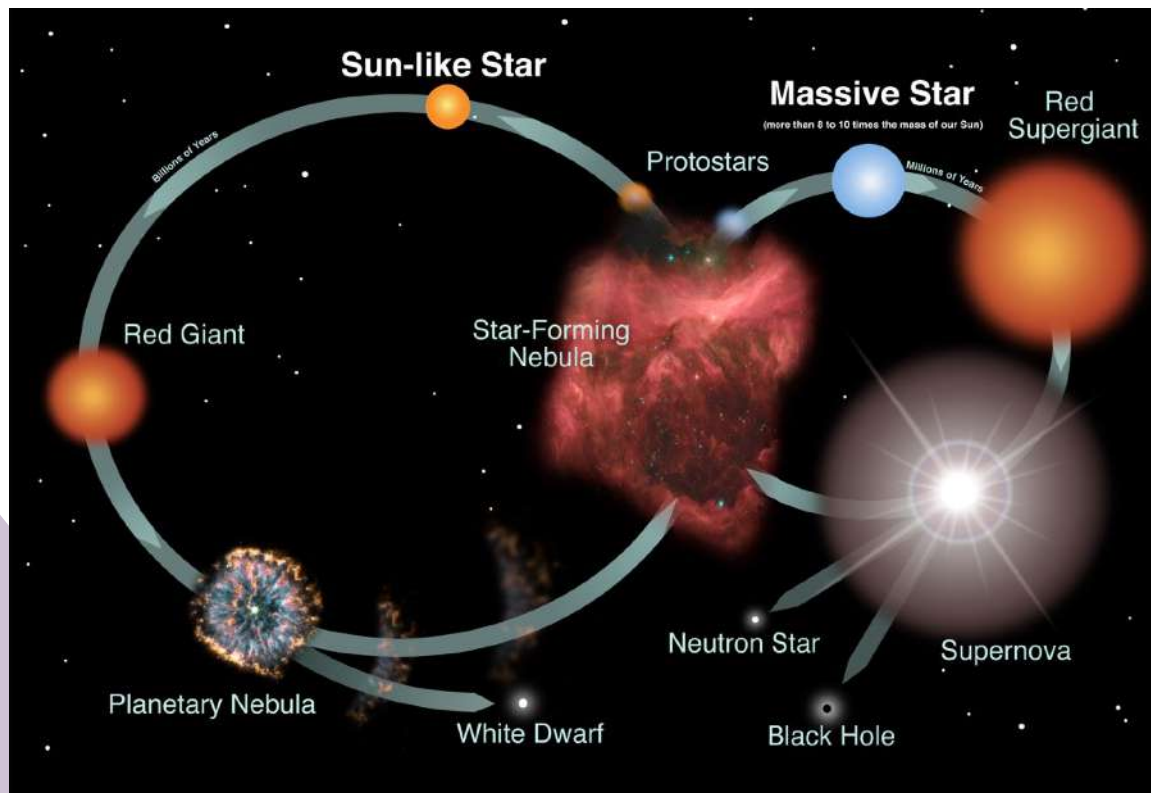
Credit: N.R.Fuller, National Science Foundation



First stars formed -> very high masses -> short lived -> SN explosions -> **elements heavier than He can be formed and injected into the interstellar medium**

How do the elements form?

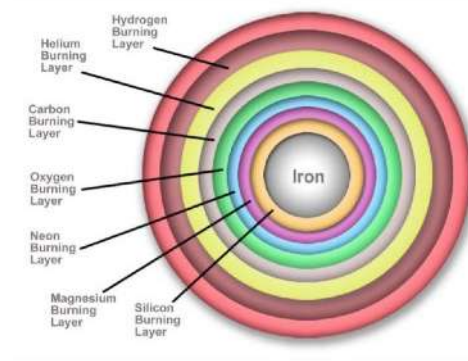
Second (and subsequent) generation of stars continued to create elements heavier than He (metals) and release them into the interstellar medium -> **newer stars have a more complex chemistry**



Solar system abundances (Lodders 2009)

How do the elements form?

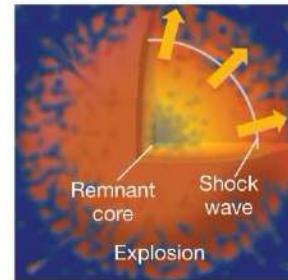
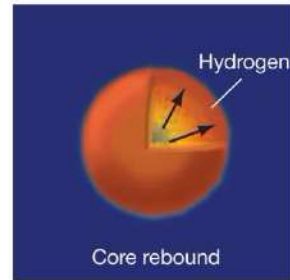
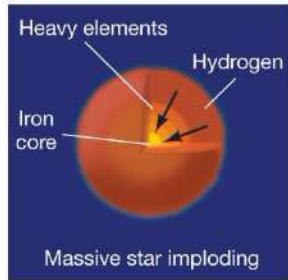
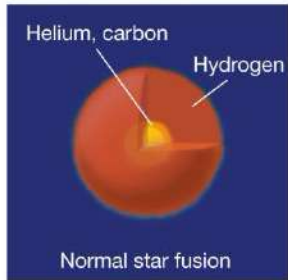
Light elements ($Z < 30$) : formed through nuclear fusion in stellar interiors of massive stars and supernovae explosion



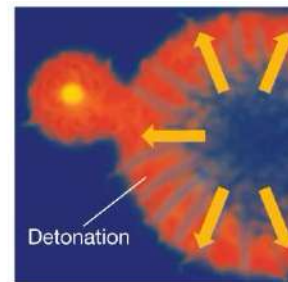
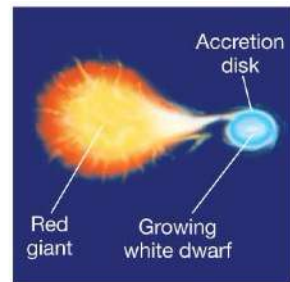
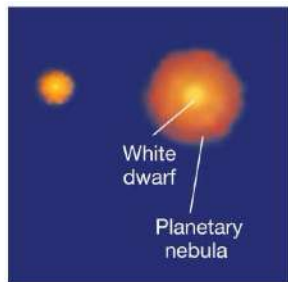
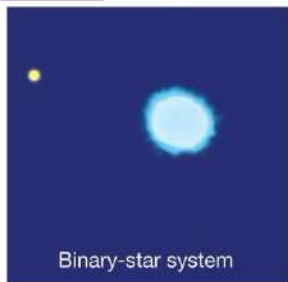
Origin of the elements

- Big Bang
- Spallation
- AGB Stars
- CC-SNe
- Type Ia SNe
- NSM/?
- Unstable

1 H 1.008																	2 He 4.003						
3 Li 6.941	4 Be 9.012																	5 B 10.81	6 C 12.01	7 N 14.01	8 O 16.00	9 F 19.00	10 Ne 20.18
11 Na 22.99	12 Mg 24.30																	13 Al 26.98	14 Si 28.09	15 P 30.97	16 S 32.06	17 Cl 35.45	18 Ar 39.95
19 K 39.10	20 Ca 40.08	21 Sc 44.96	22 Ti 47.87	23 V 50.94	24 Cr 52.00	25 Mn 54.94	26 Fe 55.84	27 Co 58.93	28 Ni 58.69	29 Cu 63.55	30 Zn 65.38	31 Ga 69.72	32 Ge 72.64	33 As 74.92	34 Se 78.96	35 Br 79.90	36 Kr 83.80						
37 Rb 85.47	38 Sr 87.62	39 Y 88.91	40 Zr 91.22	41 Nb 92.91	42 Mo 95.96	43 Tc (98)	44 Ru 101.1	45 Rh 102.9	46 Pd 106.4	47 Ag 107.9	48 Cd 112.4	49 In 114.8	50 Sn 118.7	51 Sb 121.8	52 Te 127.6	53 I 126.9	54 Xe 131.3						
55 Cs 132.9	56 Ba 137.3	57 La 138.9	72 Hf 178.5	73 Ta 180.9	74 W 183.8	75 Re 186.2	76 Os 190.2	77 Ir 192.2	78 Pt 195.1	79 Au 197.0	80 Hg 200.6	81 Tl 204.4	82 Pb 207.2	83 Bi 209.0	84 Po (209)	85 At (210)	86 Rn (222)						
87 Fr (223)	88 Ra (226)	89 Ac (227)	104 Rf (267)	105 Db (268)	106 Sg (271)	107 Bh (272)	108 Hs (270)	109 Mt (276)	110 Ds (281)	111 Rg (280)	112 Cn (285)	113 Nh (284)	114 Fl (289)	115 Mc (288)	116 Lv (293)	117 Ts (294)	118 Og (294)						



Type II SNe

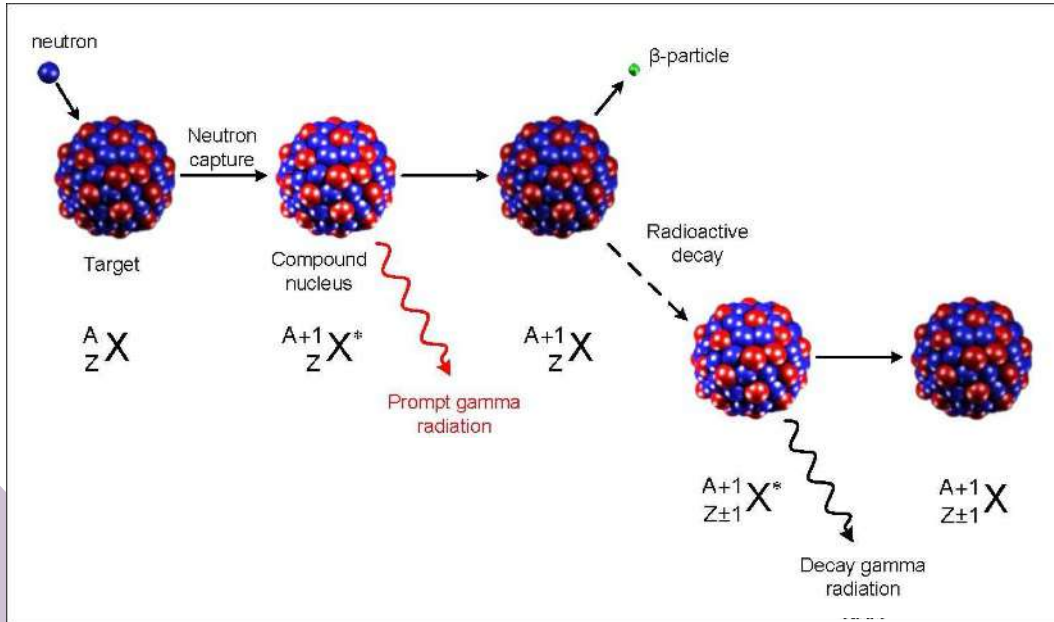


Type Ia SNe

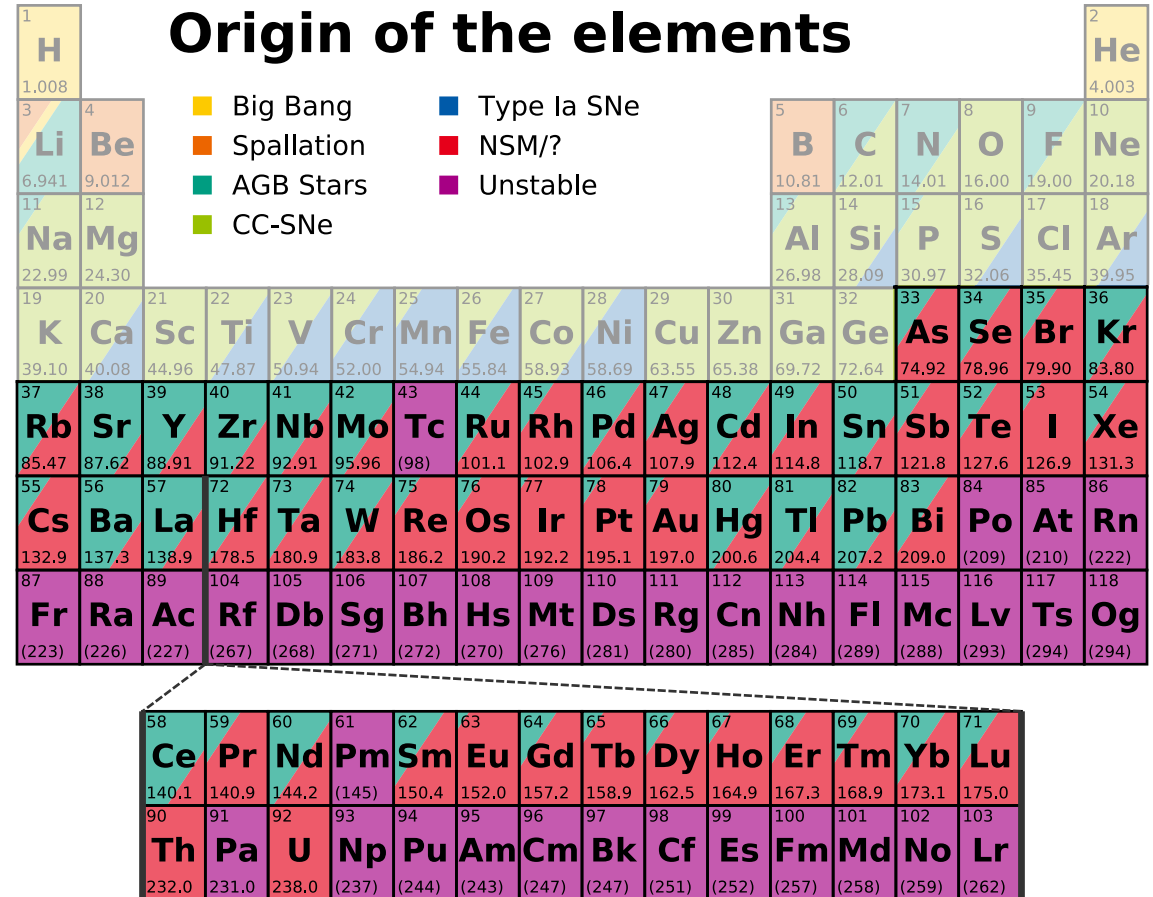
58 Ce 140.1	59 Pr 140.9	60 Nd 144.2	61 Pm (145)	62 Sm 150.4	63 Eu 152.0	64 Gd 157.2	65 Tb 158.9	66 Dy 162.5	67 Ho 164.9	68 Er 167.3	69 Tm 168.9	70 Yb 173.1	71 Lu 175.0
90 Th 232.0	91 Pa 231.0	92 U 238.0	93 Np (237)	94 Pu (244)	95 Am (243)	96 Cm (247)	97 Bk (247)	98 Cf (251)	99 Es (252)	100 Fm (257)	101 Md (258)	102 No (259)	103 Lr (262)

How do the elements form?

Heavy elements (Z>30) : formed through neutron captures on a seed nucleus -> creation of unstable isotope followed by a beta decay



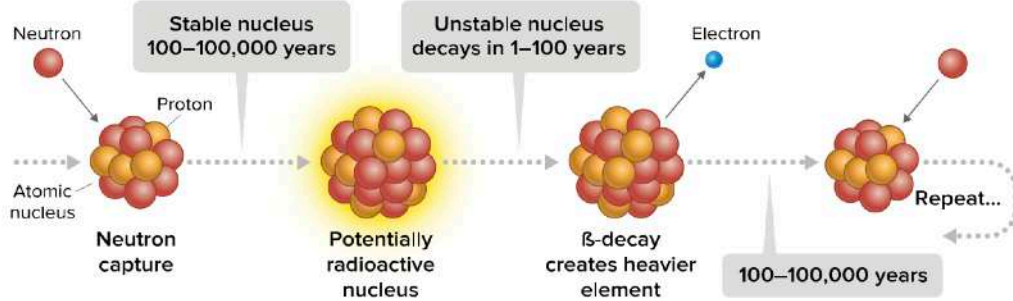
Origin of the elements



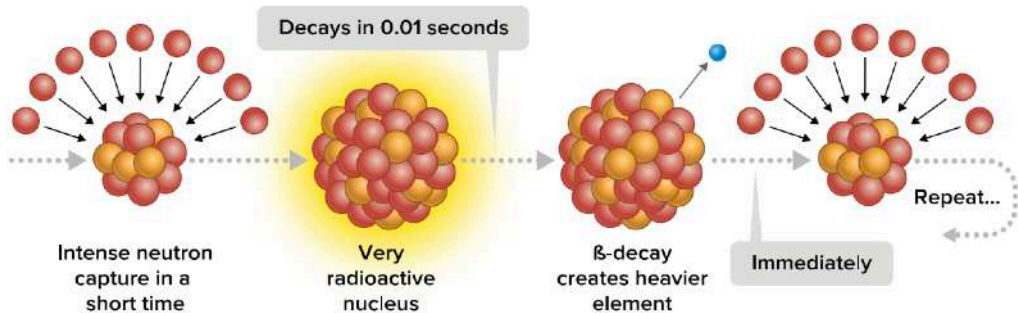
How do the elements form?

Depending on the neutron flux :

- If n -density $\approx 10^8 \text{ cm}^{-3}$ ($\tau_n \gg \tau_\beta$): slow neutron capture process (**s-process**)



- If n -density $\approx 10^{24} \text{ cm}^{-3}$ ($\tau_n \ll \tau_\beta$): rapid neutron capture process (**r-process**)



Credits: Jonas Lippuner / Los Alamos National Laboratory

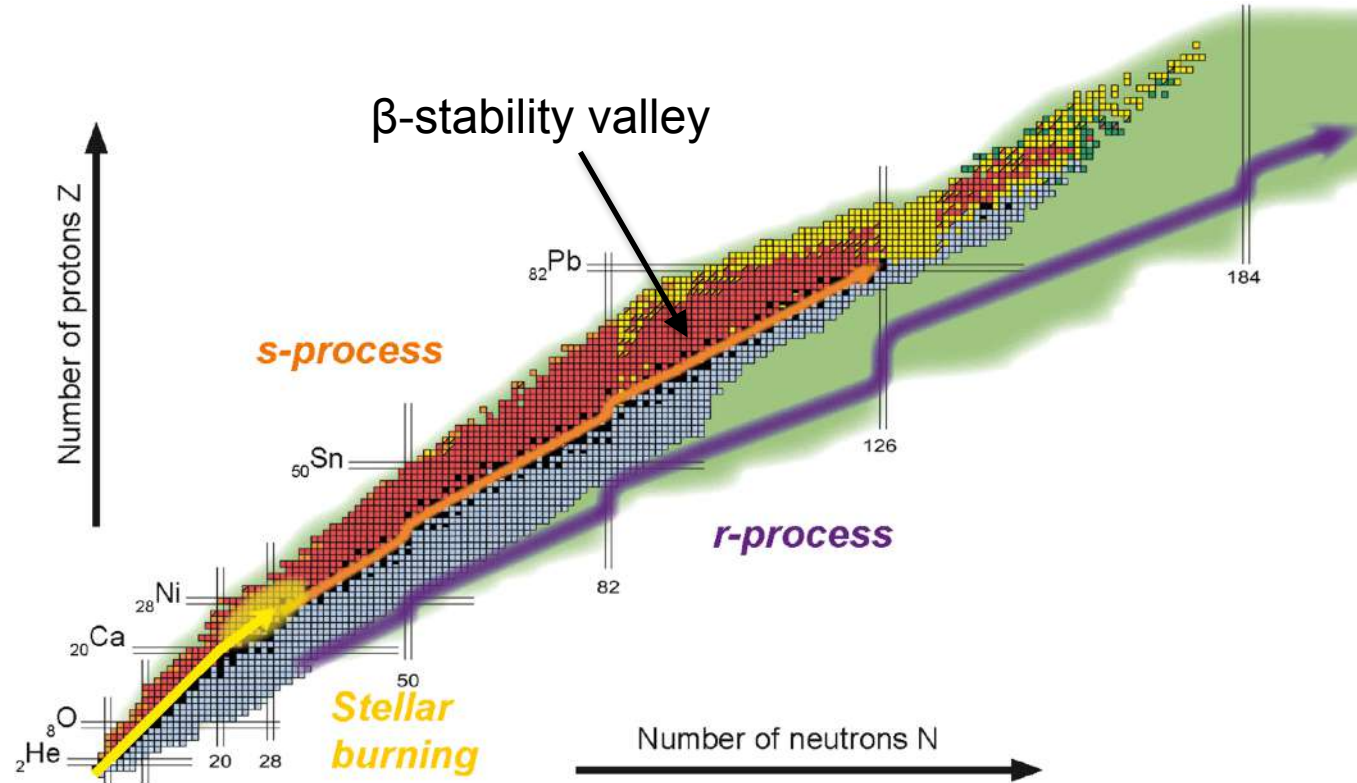
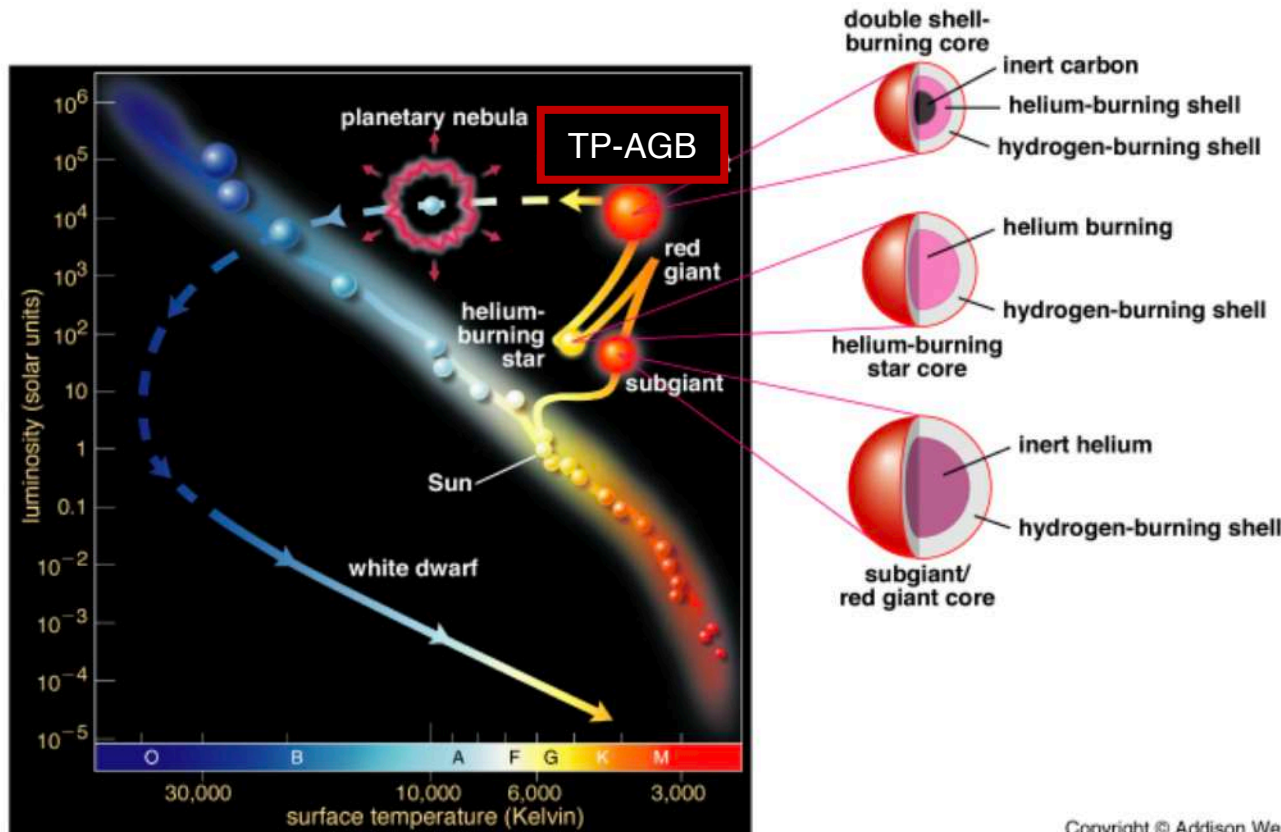


Figure from Thielemann, FK. *Eur. Phys. J. A* 59, 12 (2023)

How do the elements form?

- **s-process**: asymptotic giant branch (AGB) stars during thermal pulses phase (TP-AGB)

- **r-process**: neutron star mergers (NSM) -> confirmed by observations of r-process signature in the kilonova following the GW170817 event (Abbott et al 2017)



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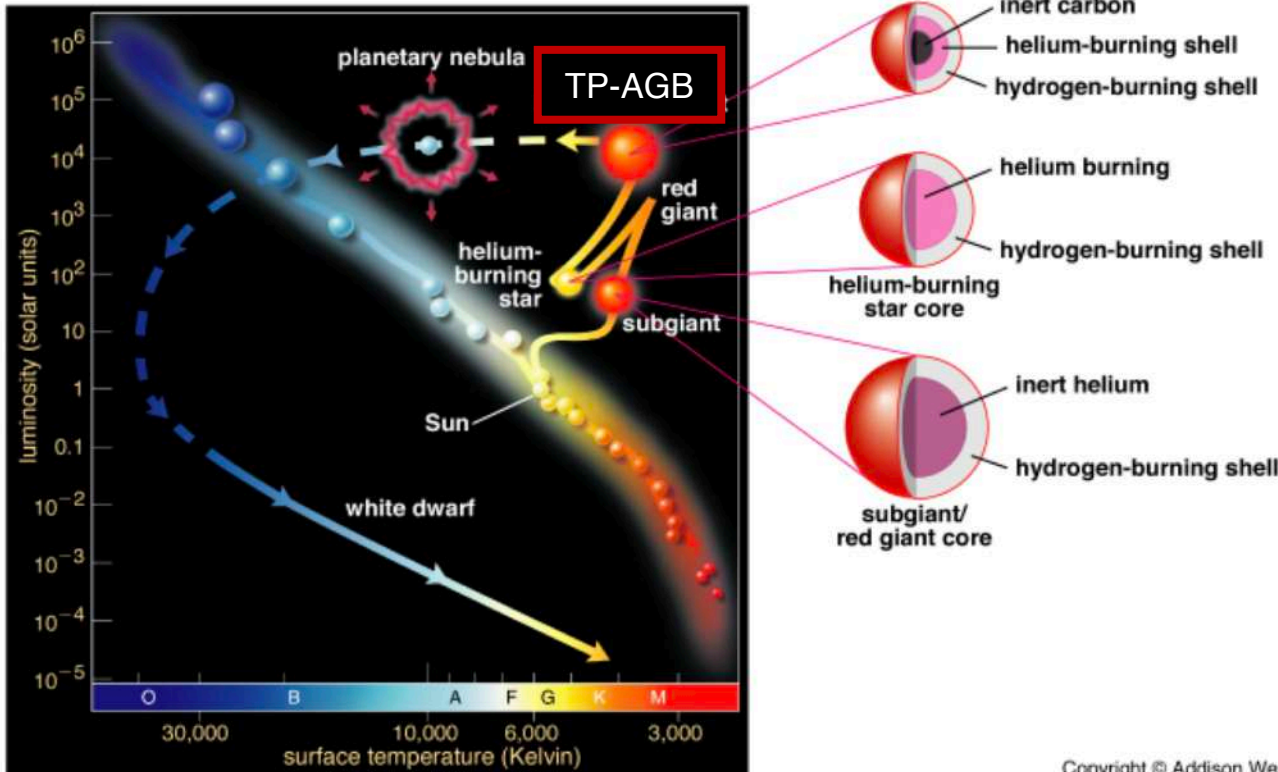


<http://public.virgo-gw.eu/the-gravitational-wave-universe/>

How do the elements form?

- **s-process**: asymptotic giant branch (AGB) stars during thermal pulses phase (TP-AGB)

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<http://public.virgo-gw.eu/the-gravitational-wave-universe/>

However AGB and NSMs alone cannot explain the entire production of heavy elements in the Galaxy!

Metal-poor stars: descendants of the first generations of stars

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

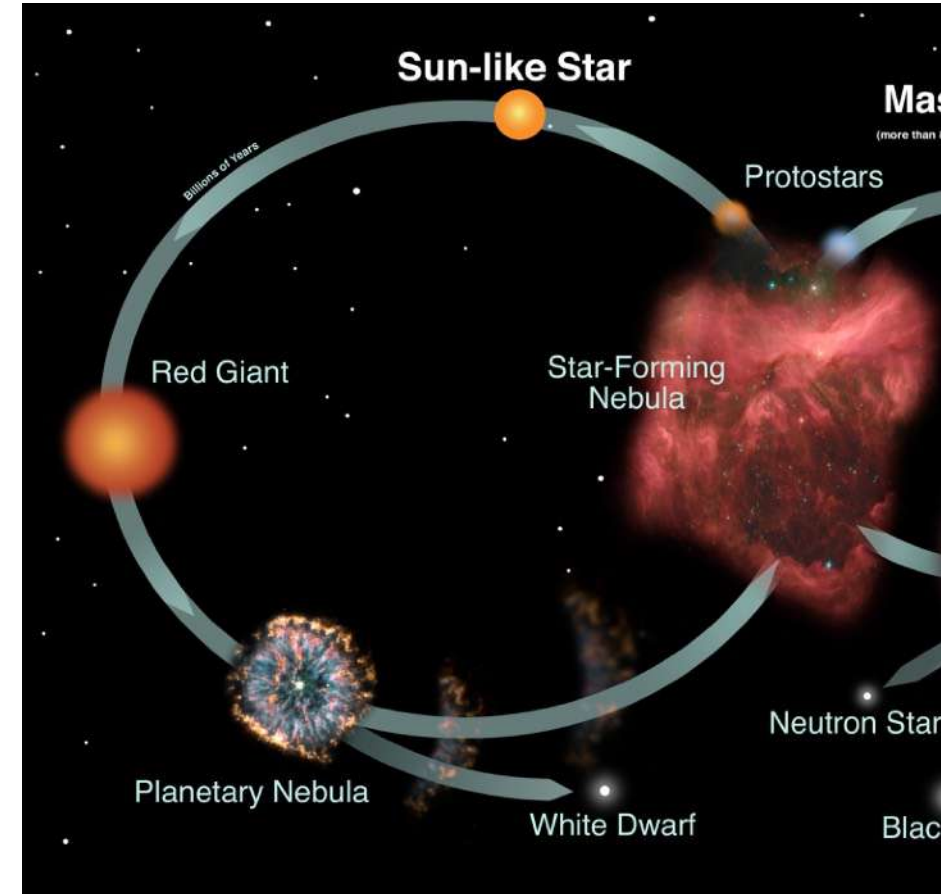
First stars formed -> elements heavier than He can be formed and injected into the interstellar medium

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

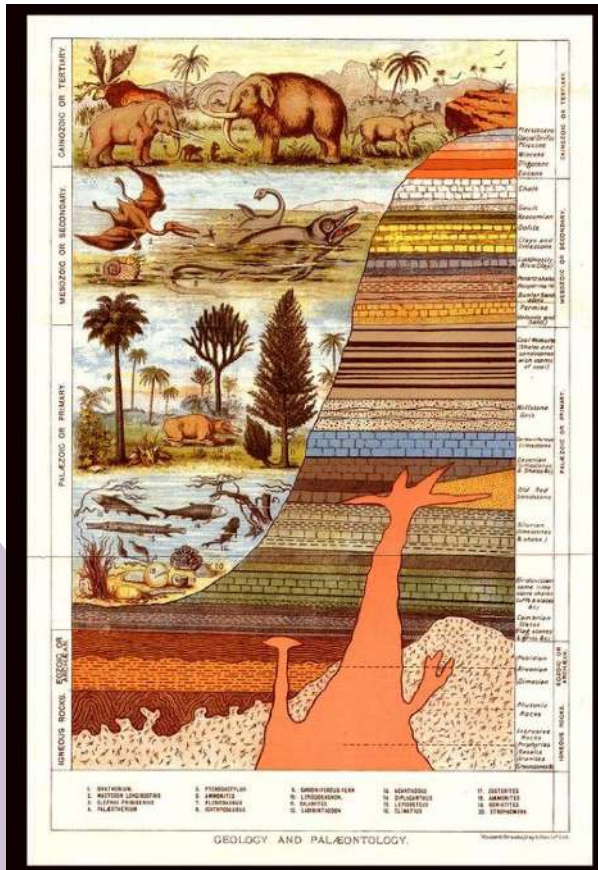
Nucleosynthesis in the early Universe

Chemical evolution of the early Universe

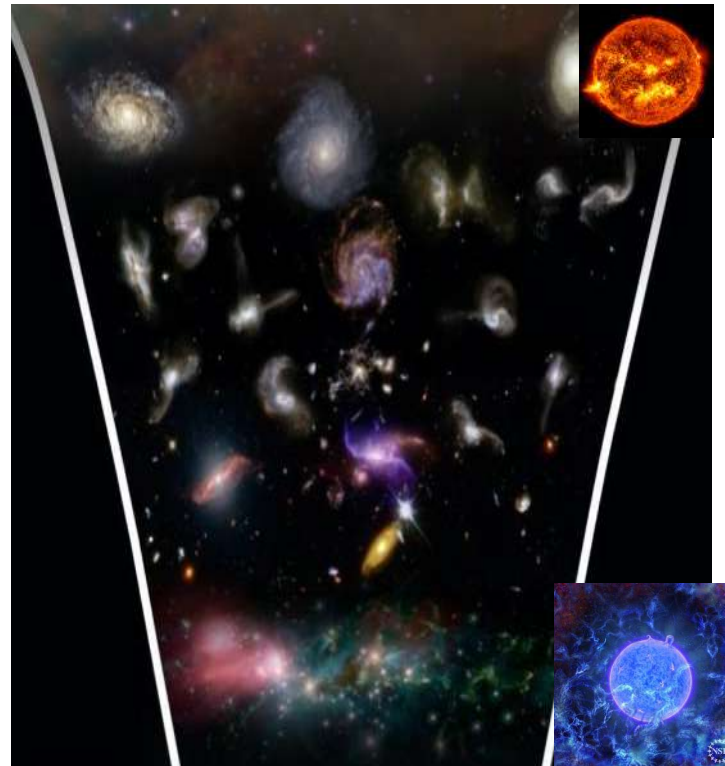


Metal-poor stars: descendants of the first generations of stars

Stellar chemistry : fossil record of the gas out of which the star formed (**Stellar archaeology**)



↑
Time



Timeline of the Universe. Image credit: Rhys Taylor

SUN

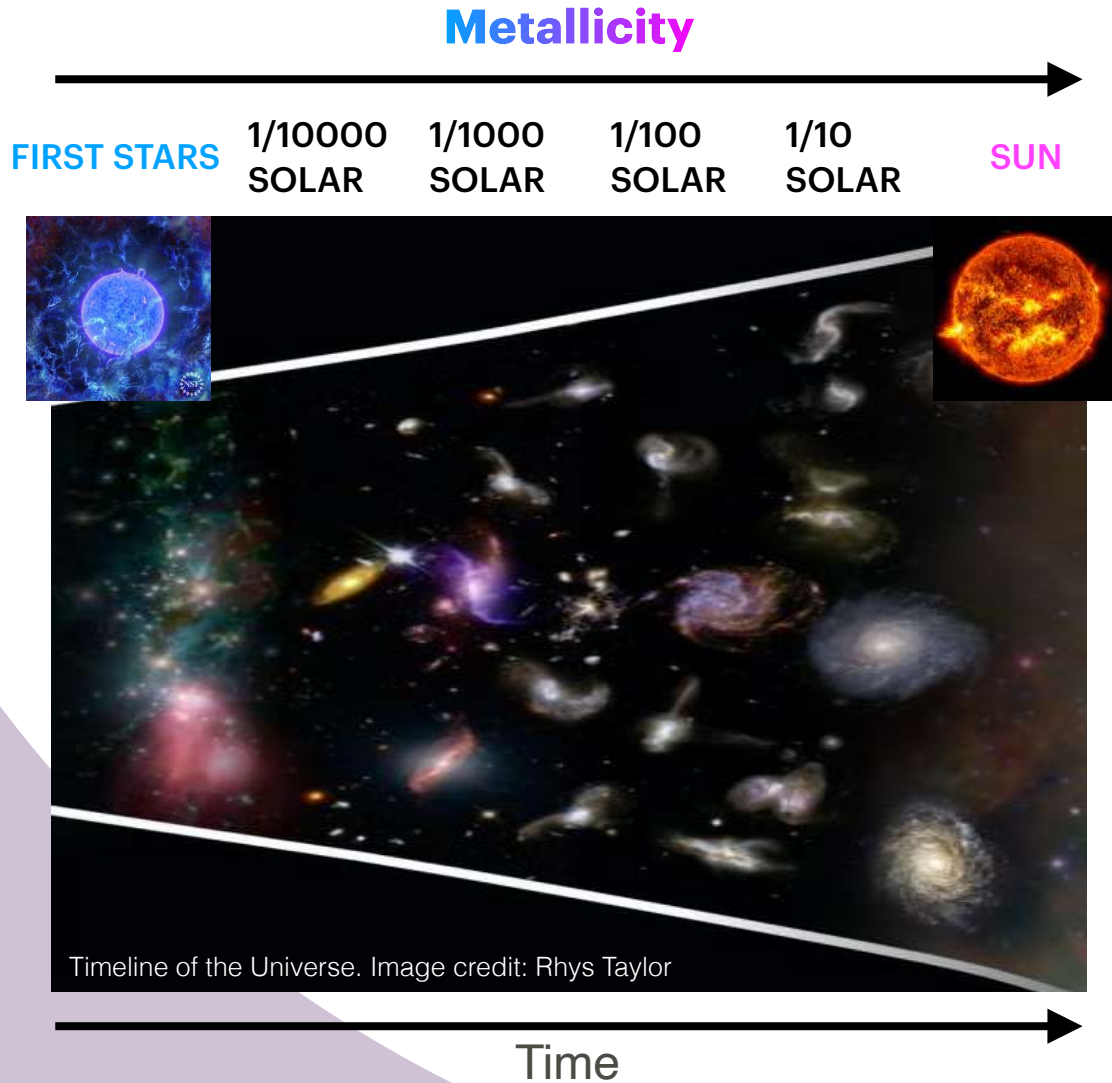
How do we know if a star is old?



We use the *metallicity* as a proxy of the age of the star

FIRST STARS

Metal-poor stars: descendants of the first generations of stars



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

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

Sun's abundances are used as the reference abundances

Abundance: $A(X) = \log \epsilon(X) = \log_{10}(N_{Fe} / N_H) + 12$

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

- Metal-poor* : $[Fe/H] < -1$ (1/10 of the Sun)
- Very metal-poor* : $[Fe/H] < -2$ (1/100 of the Sun)
- Extremely metal-poor* : $[Fe/H] < -3$ (1/1000 of the Sun)
- Ultra metal-poor* : $[Fe/H] < -4$ (1/10000 of the Sun)

How do we measure stellar abundances?

From stellar spectra to chemical abundances

Input needed:

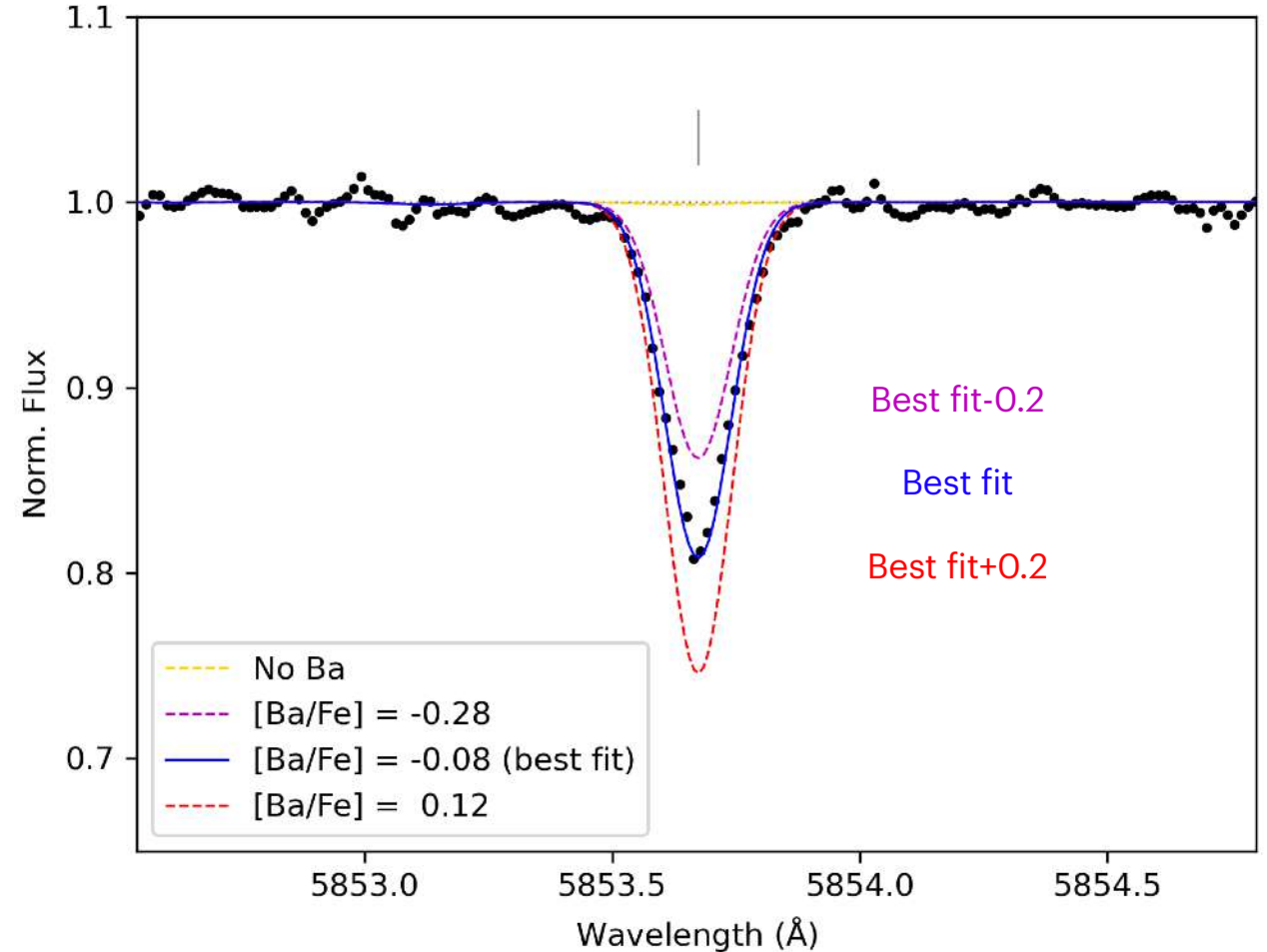
- Observed stellar spectra
- Stellar parameters (effective temperature, surface gravity, ...)
- Atomic data (energy levels, transition strengths, ionisation stage, ...)
- Spectrum synthesis code

Absolute abundance: $\log_{10}\varepsilon(X)_{\star} = \log_{10}(N_X/N_H)_{\star} + 12$

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

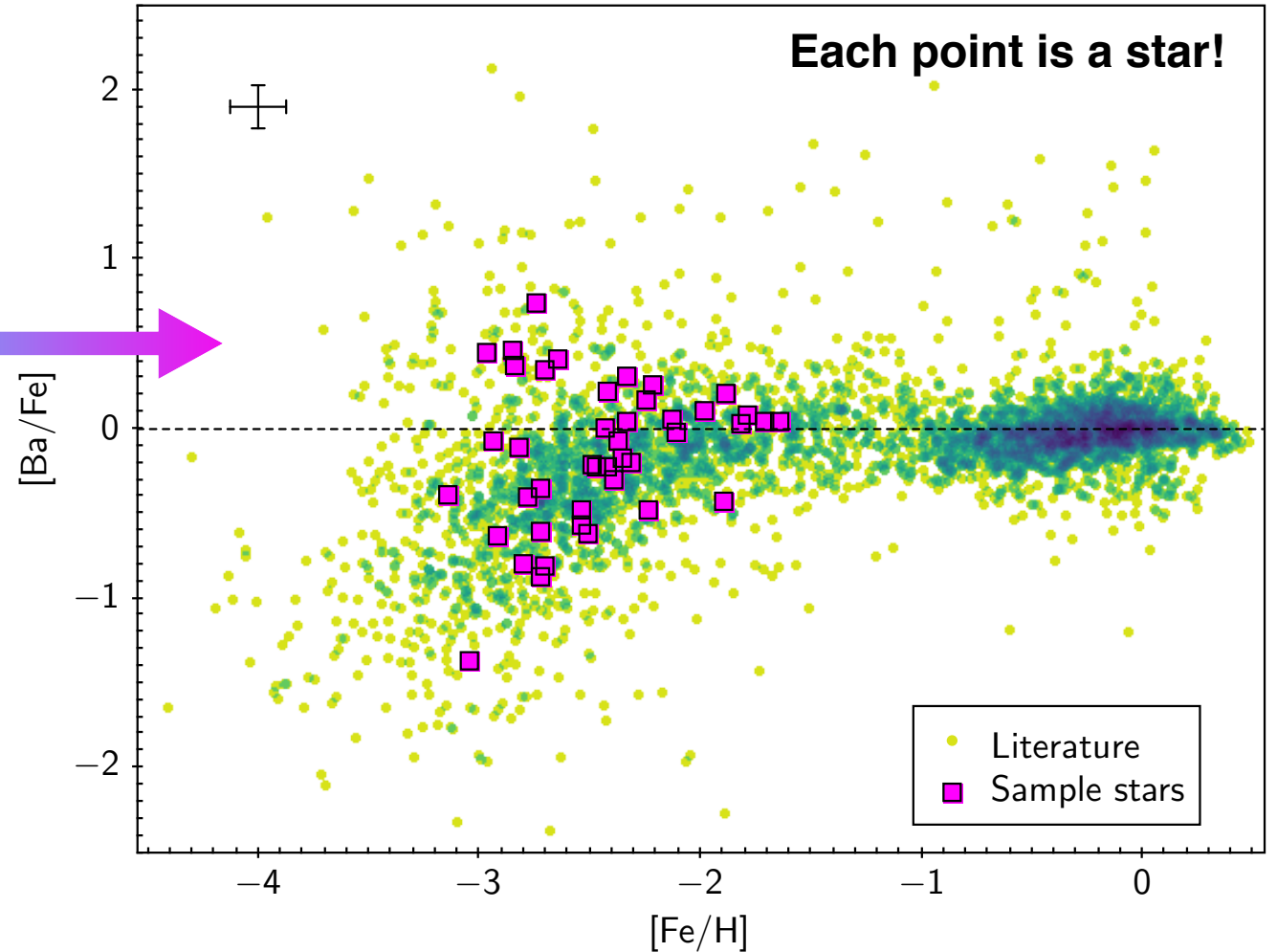
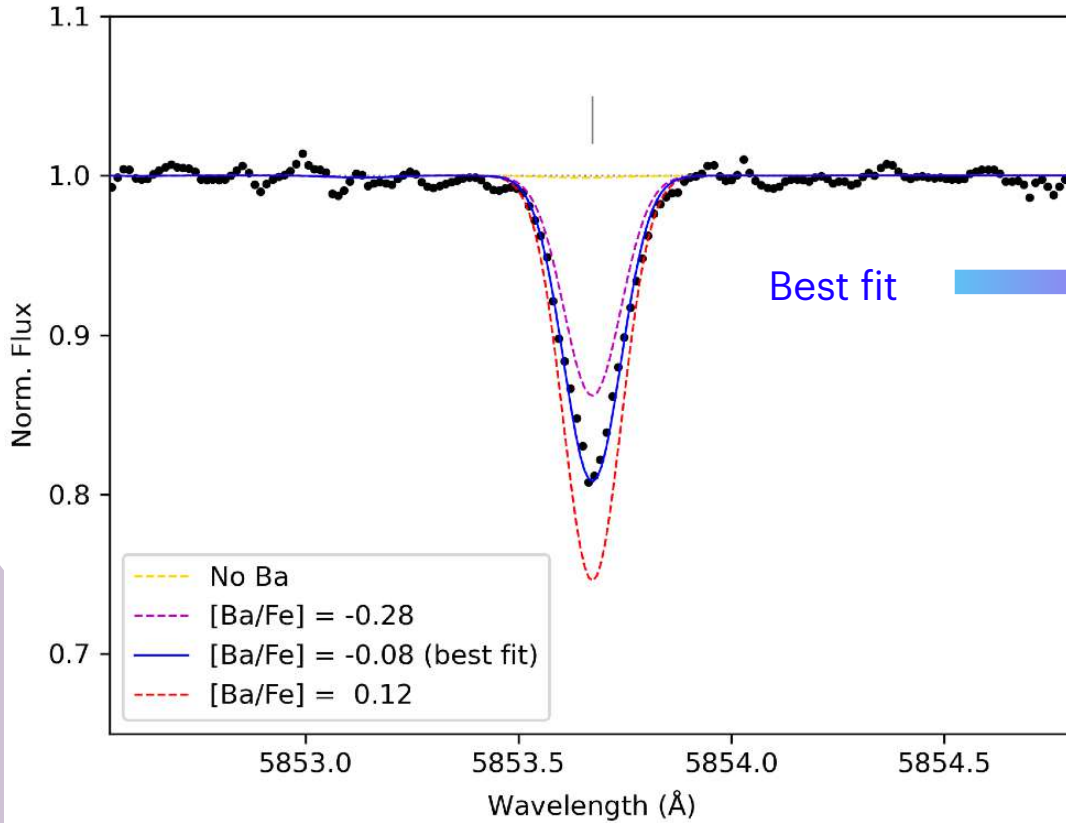
Abundance ratio: $[X/Y] = \log_{10}(N_X/N_Y)_{\star} - \log_{10}(N_X/N_Y)_{\odot}$

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



From stellar spectra to chemical abundances

For each star:

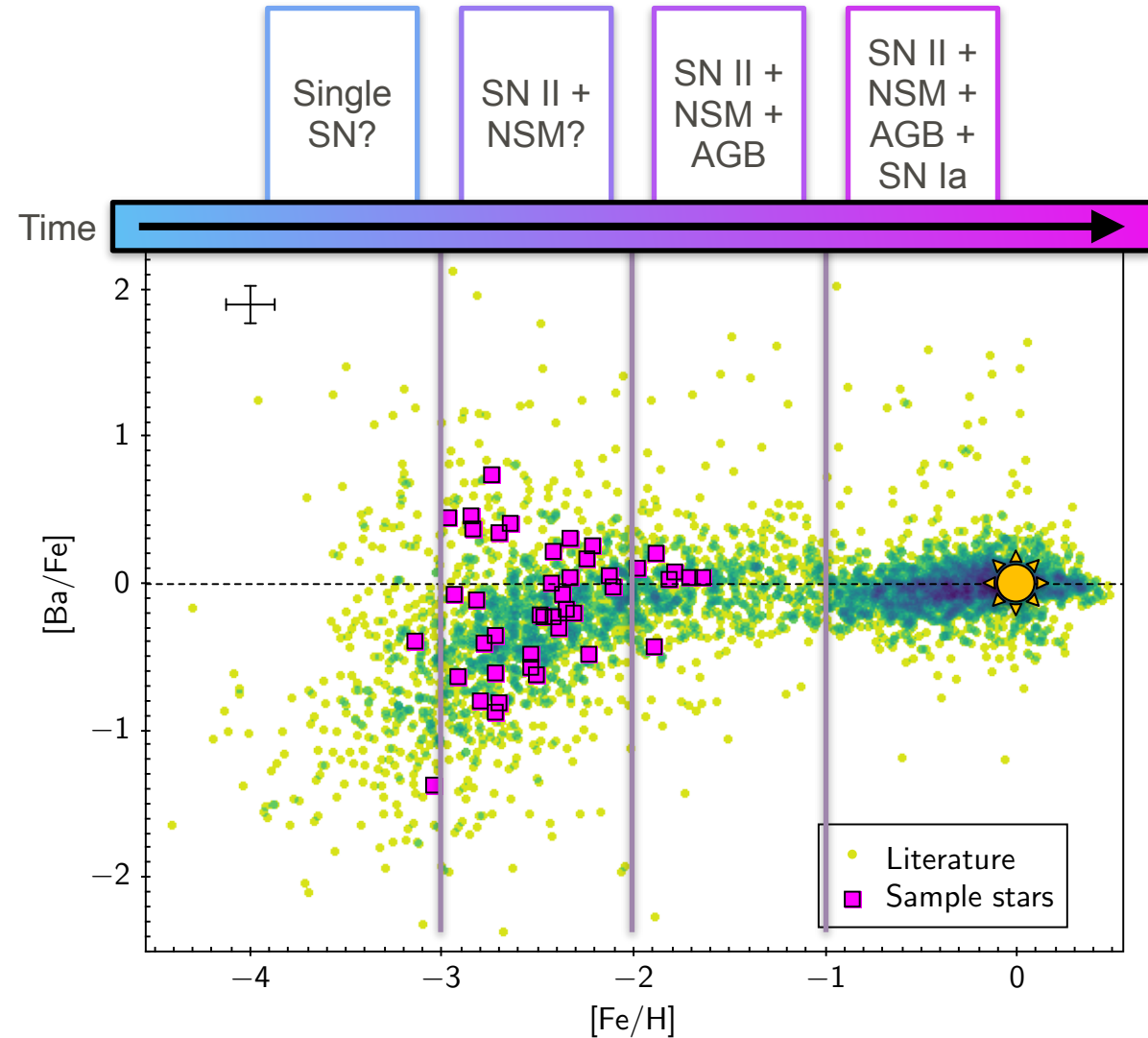


Why chemical abundances are important?

Different sites (SNe II, SNe Ia, NSM, AGB stars...)
produce different elements in various amounts

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?

Different sites (SNe II, SNe Ia, NSM, AGB stars...) produce different elements in various amounts

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

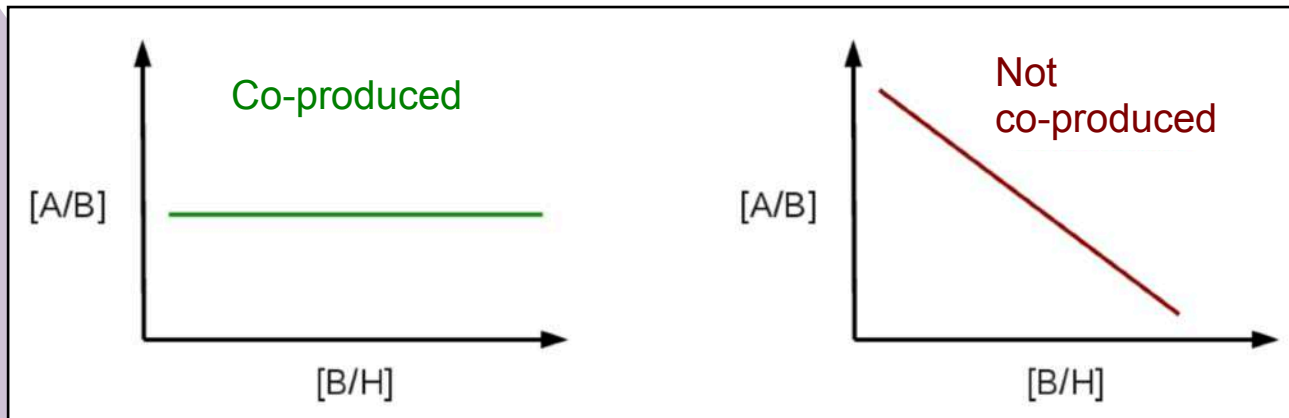
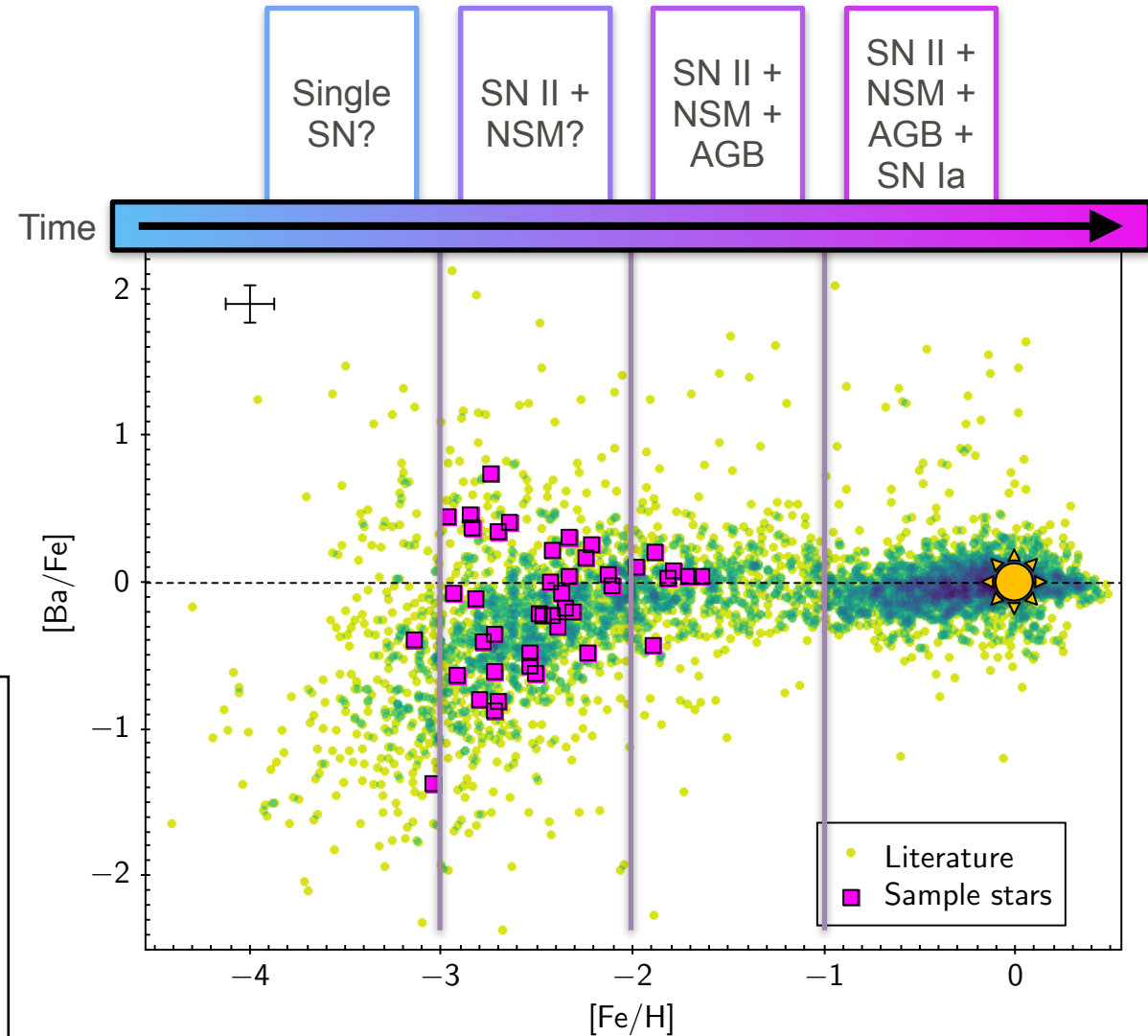
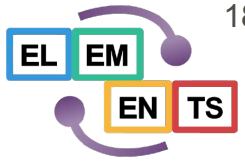


Figure from Hansen 2012





Chemical Evolution of R-process Elements in Stars

(PI: Prof. C.J.Hansen)



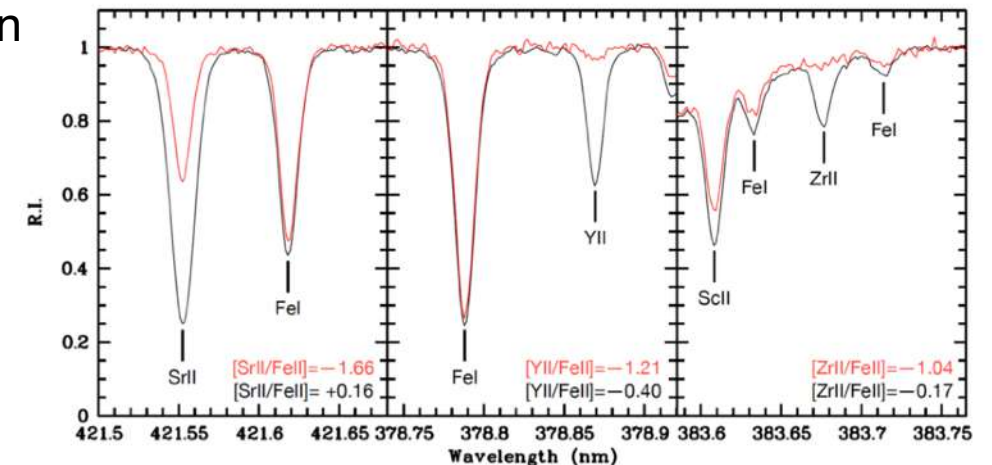
Stellar observations focused on measuring heavy elements in a sample of metal-poor stars ($[Fe/H] \leq 1.8$)

Goal: increase our knowledge of the physical conditions and formation sites of r-process elements

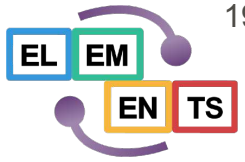
Data: High-resolution ($R > 40000$), high signal-to-noise ratio ($SNR > 50$ @ 390 nm) spectra obtained with ESO VLT/UVES

Sample: 52 giant stars with < 5 heavy element abundances known in the literature

Method: Fully homogeneous analysis (1D, LTE models, codes, data, line lists...)



Lombardo et al. 2022



Chemical Evolution of R-process Elements in Stars

(PI: Prof. C.J.Hansen)



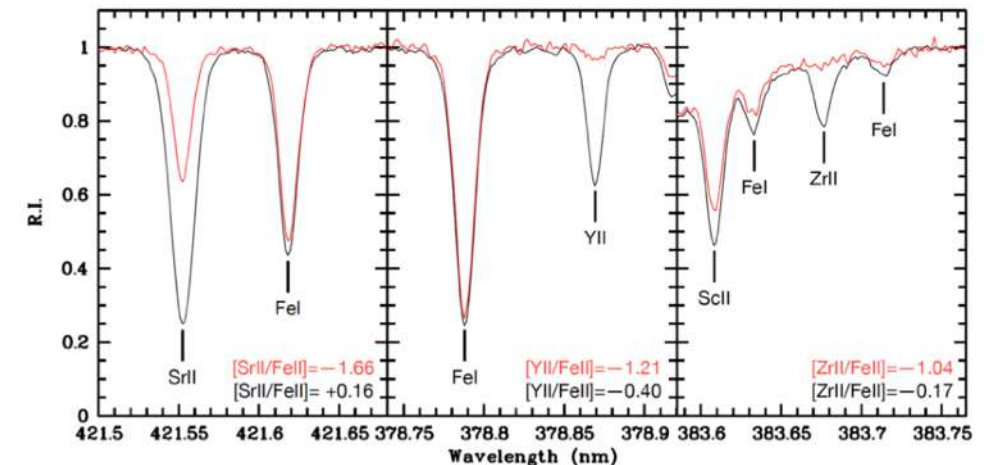
Status: Li, C, N, O, Na to Zr, Ba to Eu, Hf, Os, Ir, Pt

CERES I (Lombardo et al. 2022): Perform a homogeneous determination of stellar parameters and measure chemical abundances of elements from Na to Zr

CERES II (Fernandes de Melo et al. 2024, accepted): chemical abundances of C, N, O and Li and comparison with stellar evolution models

CERES III (Lombardo et al, submitted): chemical abundances for heavy elements from Ba to Eu

CERES IV (Alencastro Puls et al., submitted): chemical abundances of Hf, Os, Ir, and Pt



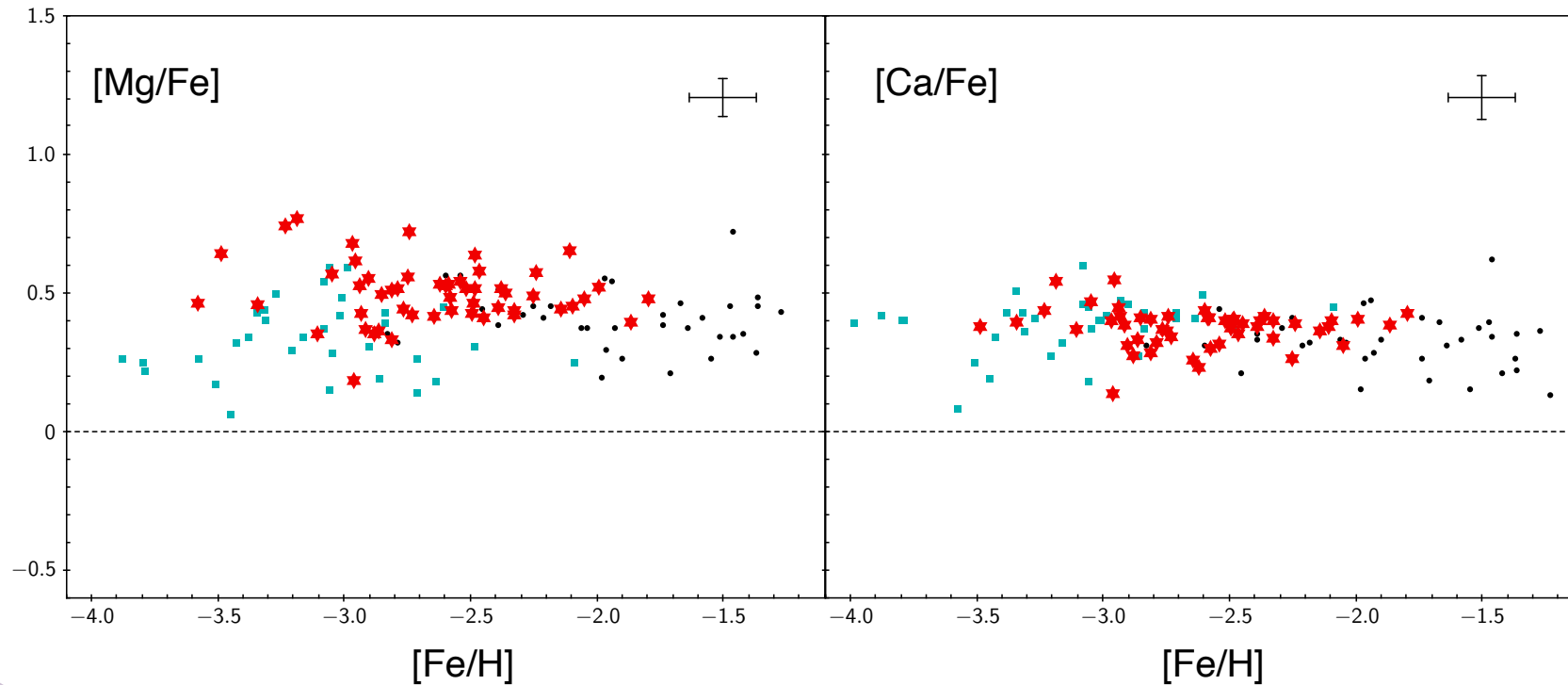
Lombardo et al. 2022

CERES I (Lombardo et al. 2022)

Homogeneous determination of stellar parameters and chemical abundances for 26 species of 18 elements (Na, Mg, Al, Si, Ca, Sc, Ti, V, Cr, Mn, Fe, Co, Ni, Zn, Sr, Y and Zr)

α -elements

Cayrel et al. (2004)
Ishigaki et al. (2012)



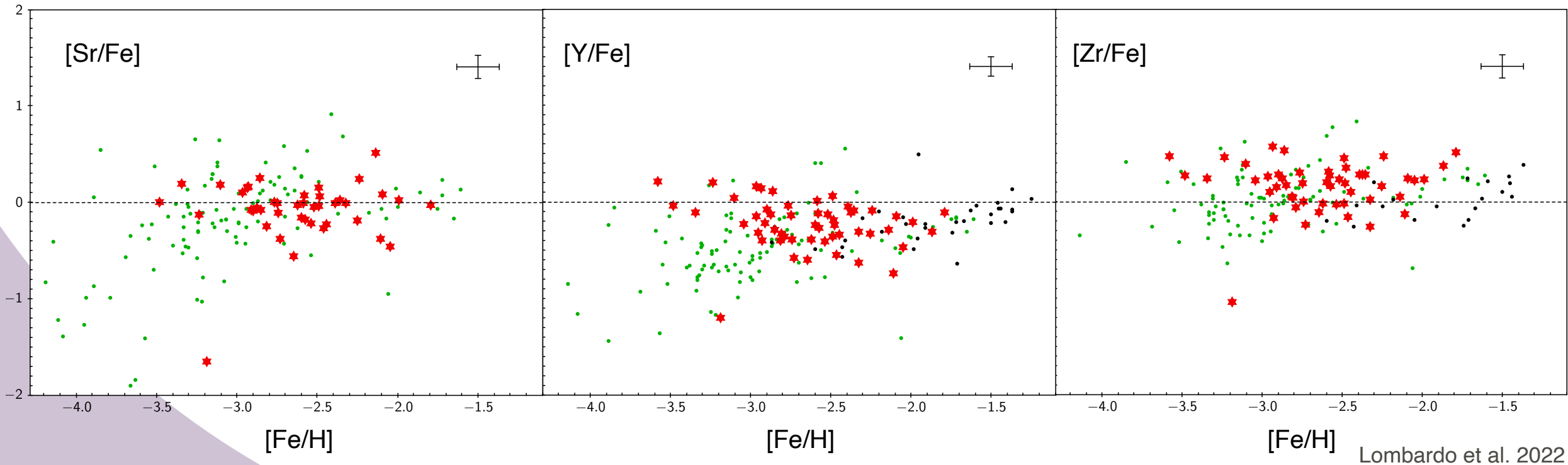
Lombardo et al. 2022

CERES I (Lombardo et al. 2022)

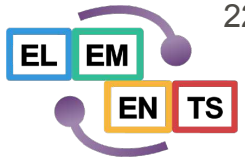
Homogeneous determination of stellar parameters and chemical abundances for 26 species of 18 elements (Na, Mg, Al, Si, Ca, Sc, Ti, V, Cr, Mn, Fe, Co, Ni, Zn, Sr, Y and Zr)

Light neutron-capture elements

Roederer et al. (2014)
Ishigaki et al. (2012)

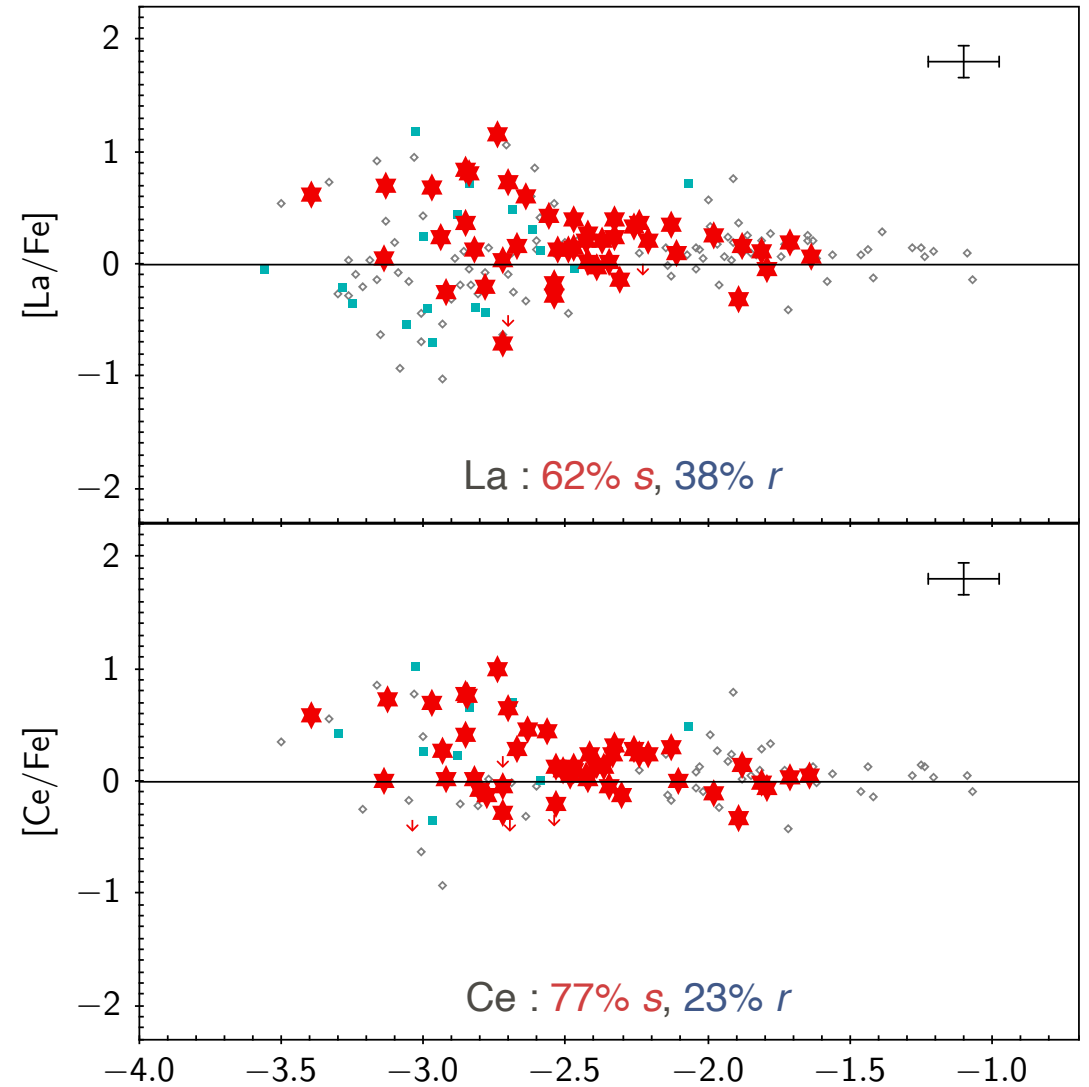
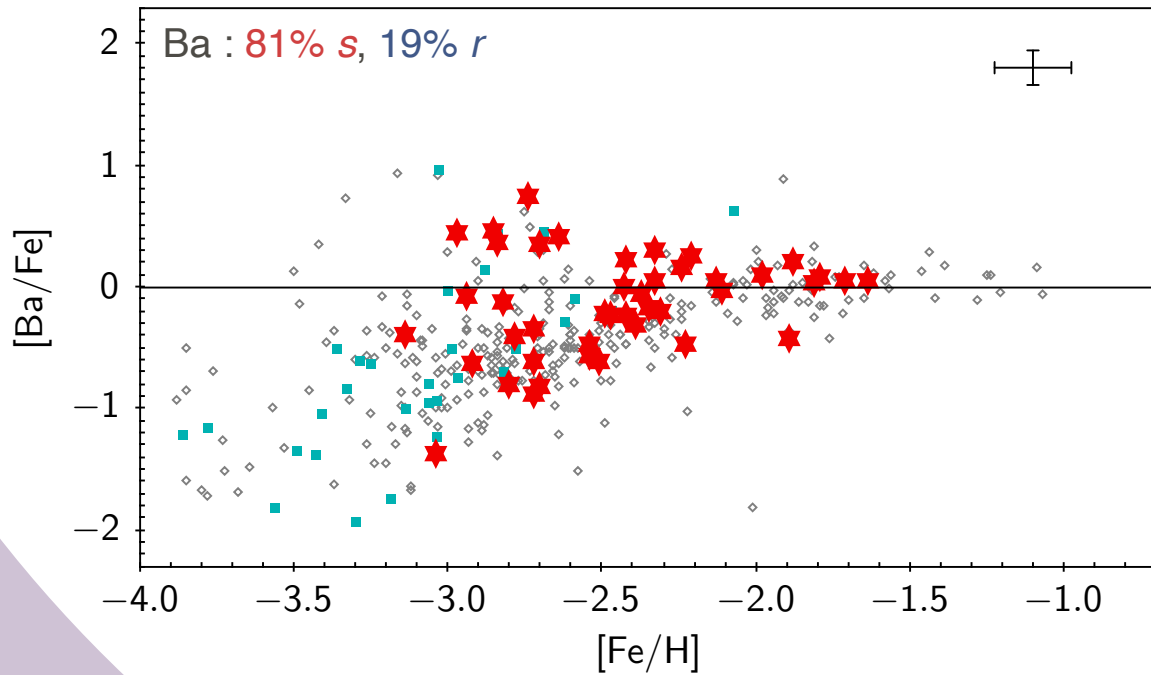


Lombardo et al. 2022

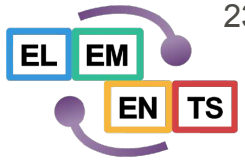


CERES III: [Ba/Fe], [La/Fe], [Ce/Fe] vs [Fe/H]

Solar system composition (Arlandini+99)

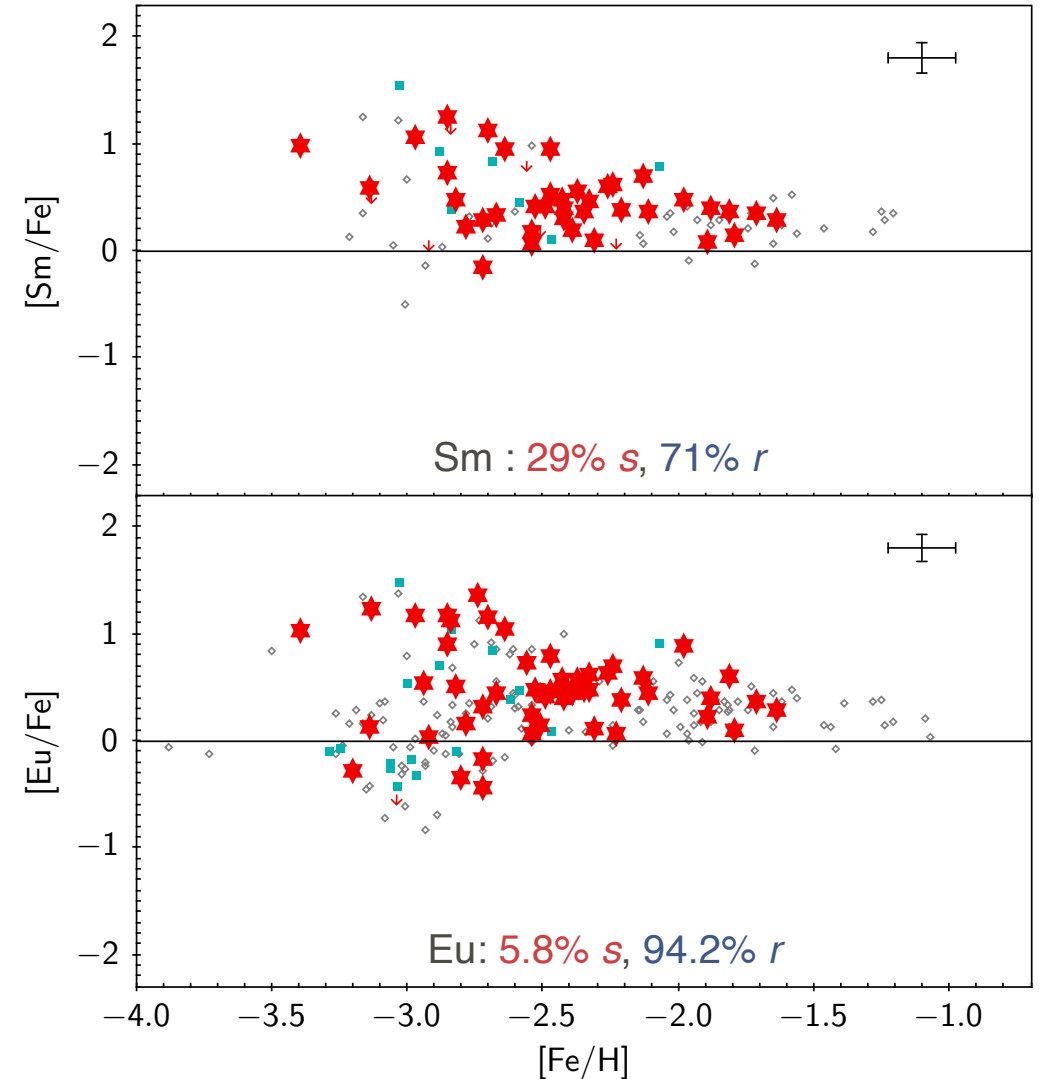
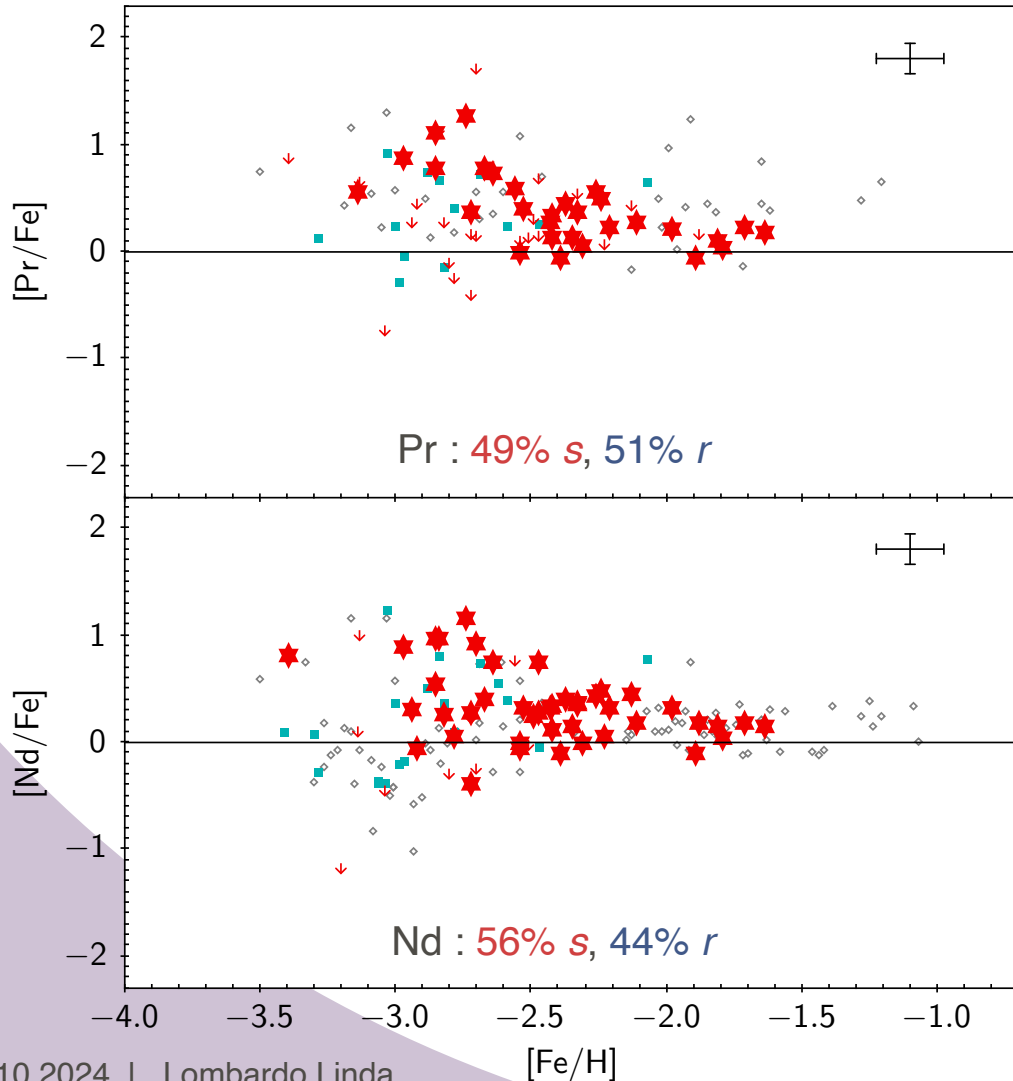


Francois et al. (2007)
Roederer et al. (2014)



CERES III: [Pr/Fe], [Nd/Fe], [Sm/Fe], [Eu/Fe] vs [Fe/H]

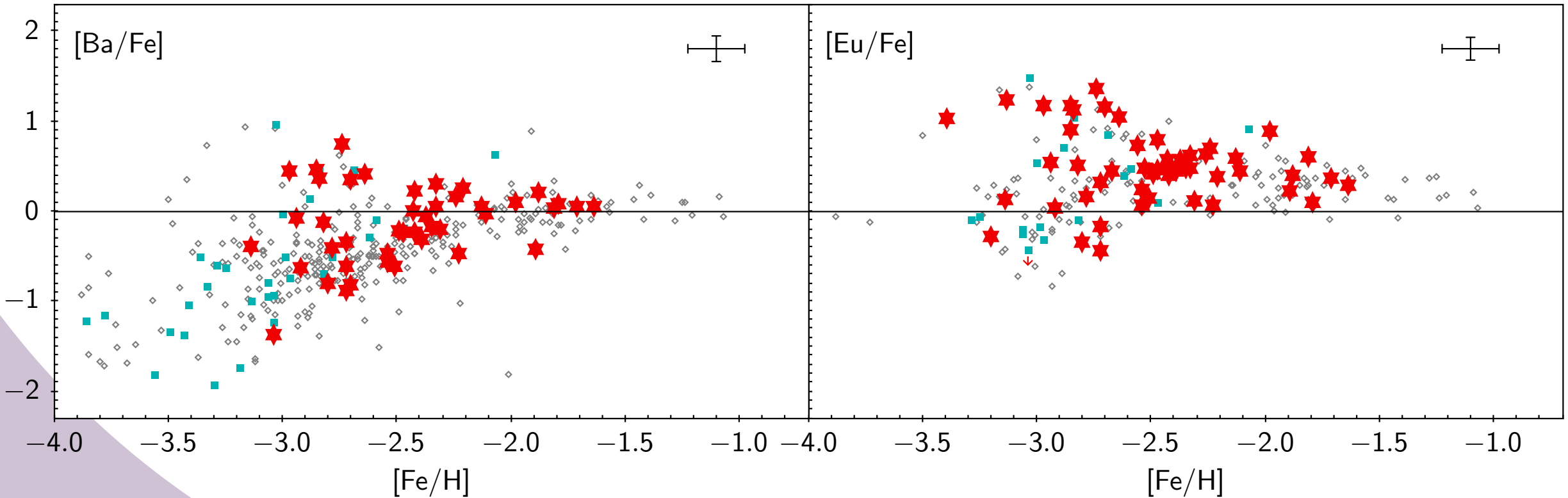
Solar system composition (Arlandini+99)



CERES III: $[\text{Ba}/\text{Fe}]$ vs $[\text{Fe}/\text{H}]$ and $[\text{Eu}/\text{Fe}]$ vs $[\text{Fe}/\text{H}]$

Large scatter of heavy elements with decreasing metallicity -> **single events polluted the gas in different amounts**

Lombardo et al. 2024



CERES III: [Ba/Eu] vs [Fe/H]

In solar system material : (Arlandini+99)

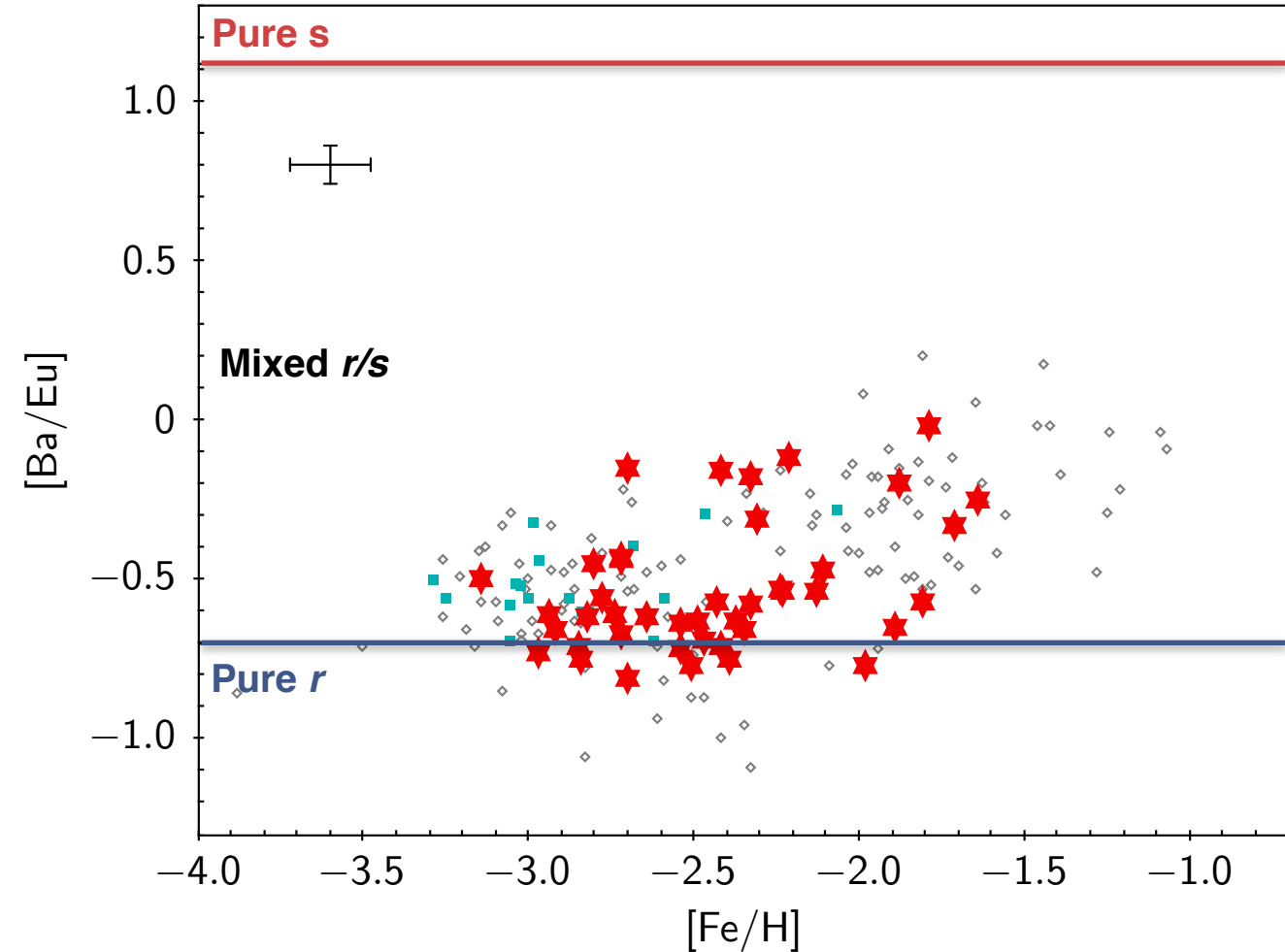
Ba : 81% *s*, 19% *r* → mainly *s*

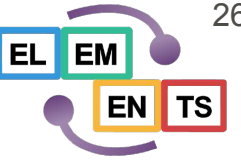
Eu: 5.8% *s*, 94.2% *r* → mainly *r*

[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**





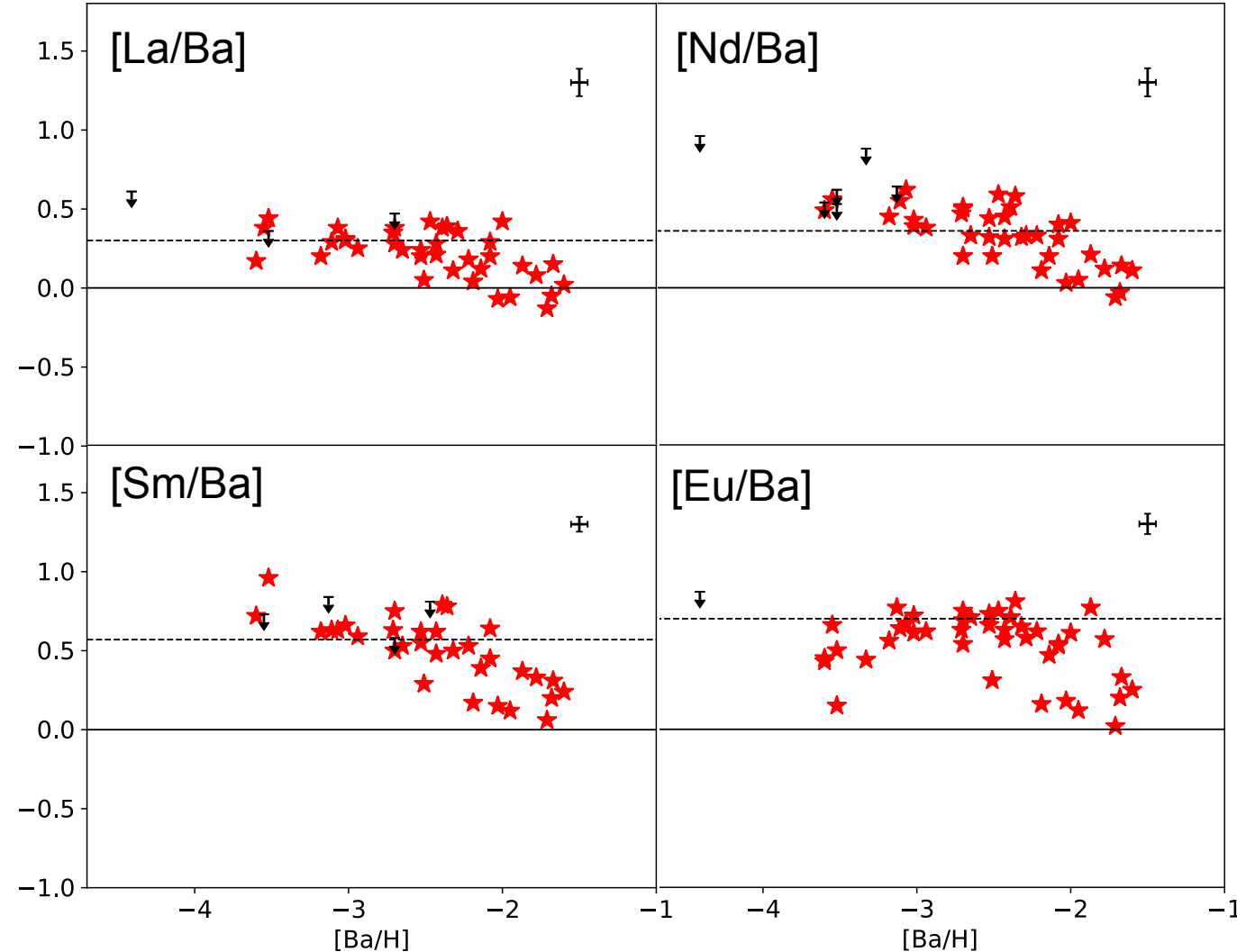
CERES III: estimating the onset of the s-process in the MW halo

At which values of $[\text{Ba}/\text{H}]$ and $[\text{Fe}/\text{H}]$ the onset of the s-process occurs?

We observe a change in the trends at $[\text{Ba}/\text{H}] = -2.4$, which corresponds to $[\text{Fe}/\text{H}] = -2.4$

For $[\text{Ba}/\text{H}] < -2.4$: flat trend + clustering around the solar pure r-process values \rightarrow r-process as primary production mechanism

For $[\text{Ba}/\text{H}] > -2.4$: large scatter \rightarrow onset of s-process in heavy elements nucleosynthesis



CERES III: [Sr/Ba] vs [Ba/Fe]

In solar system material : (Arlandini+99)

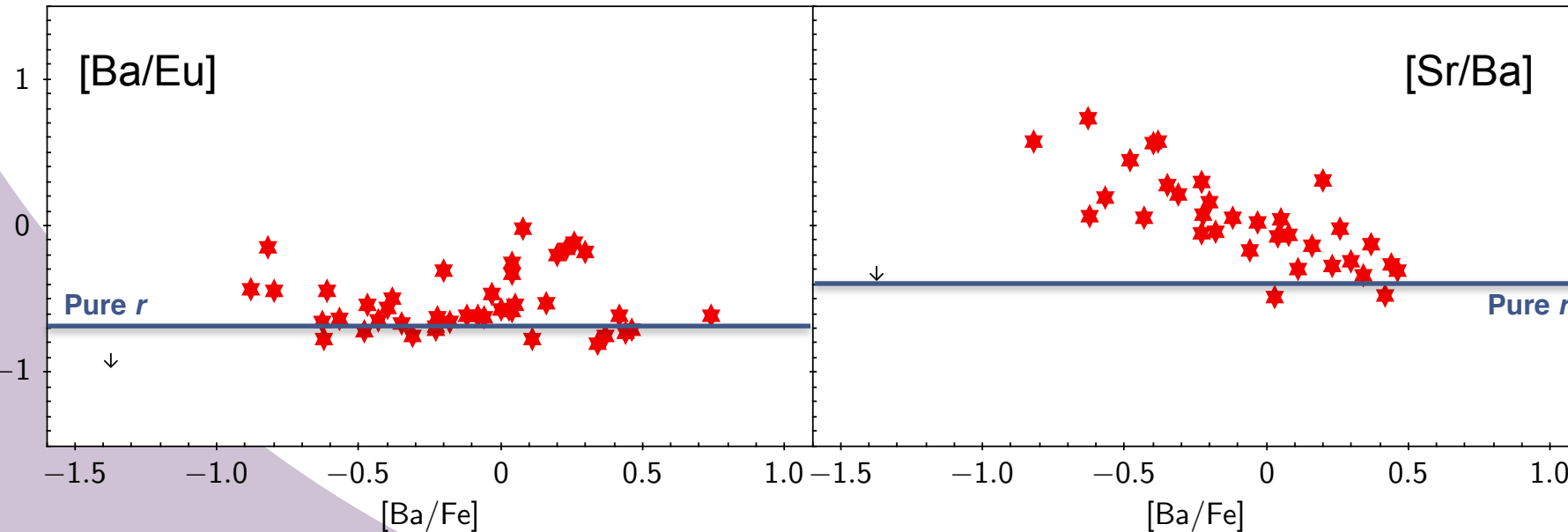
Sr: 85% *s*, 15% *r* → mainly *s*

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**



Several hypothesis:

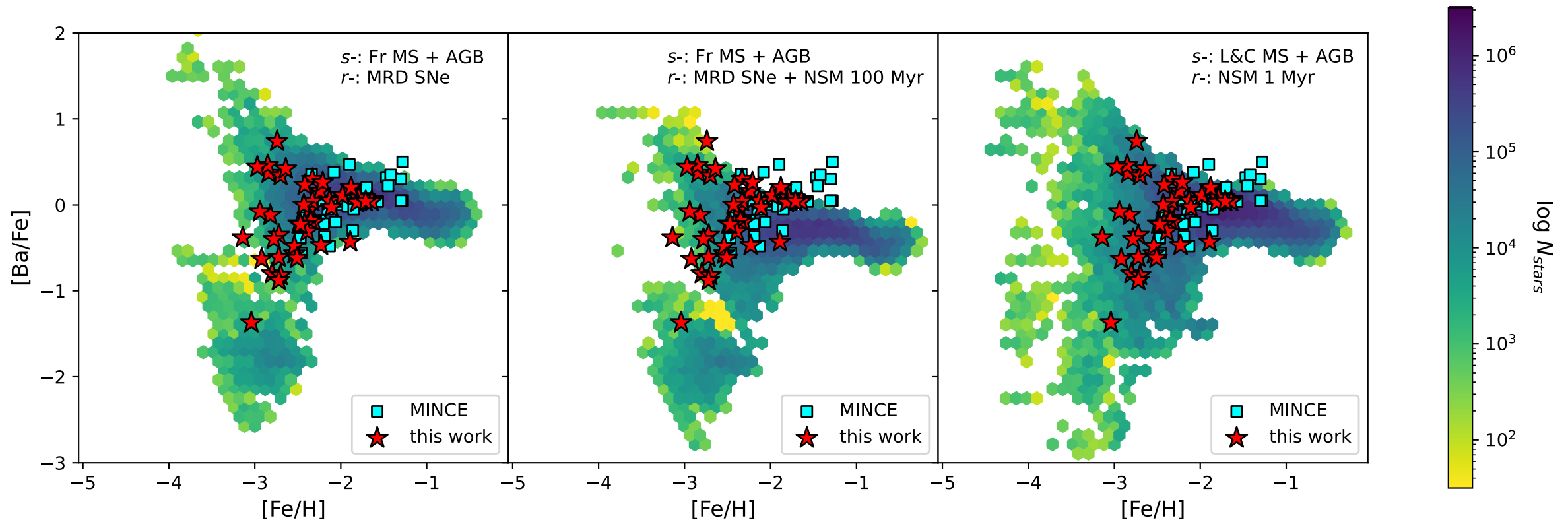
- Weak r-process
- Weak s-process
- Lighter element primary process (LEPP)...

Comparison with GCE models: [Ba/Fe] vs [Fe/H]

Cescutti & Chiappini 2014: Fast rotating massive stars + AGB stars (s-process), magneto rotational SNe (r-process)

Cescutti et al. 2015: Fast rotating massive stars + AGB stars (s-process), magneto rotational SNe + neutron star mergers with 100 Myr delay (r-process)

Rizzuti et al 2021: Fast rotating massive stars + AGB stars (s-process), neutron star mergers with 1 Myr delay (r-process)

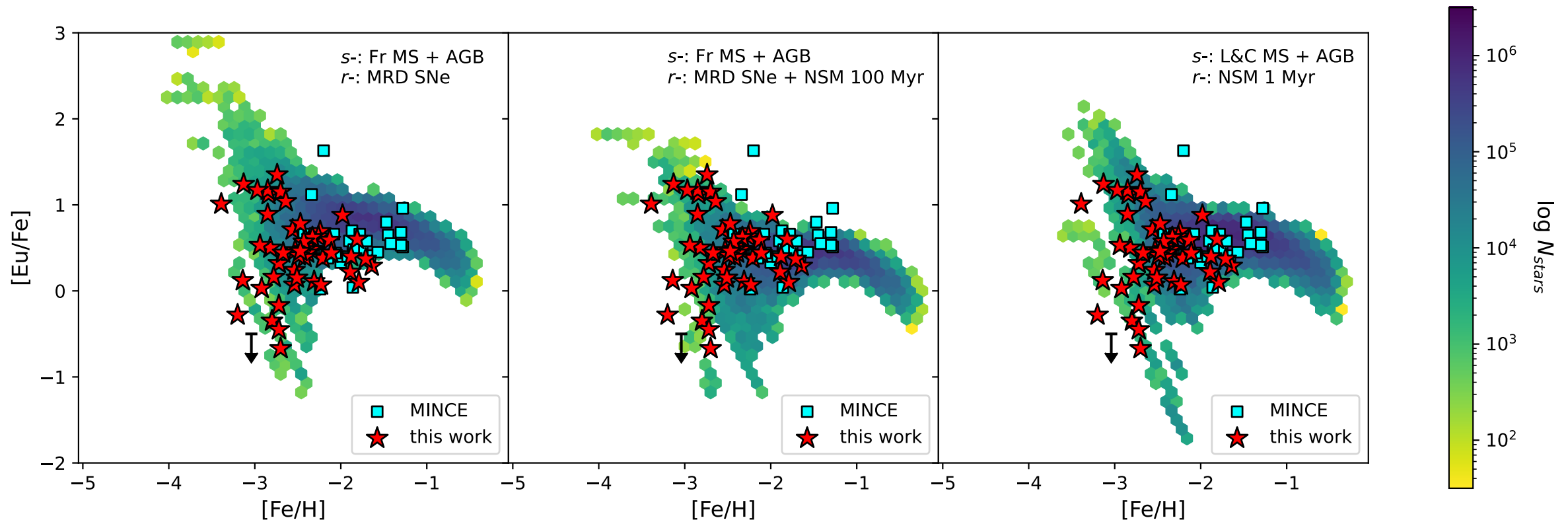


Comparison with GCE models: [Eu/Fe] vs [Fe/H]

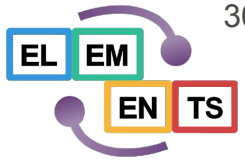
Cescutti & Chiappini 2014: Fast rotating massive stars + AGB stars (s-process), magneto rotational SNe (r-process)

Cescutti et al. 2015: Fast rotating massive stars + AGB stars (s-process), magneto rotational SNe + neutron star mergers with 100 Myr delay (r-process)

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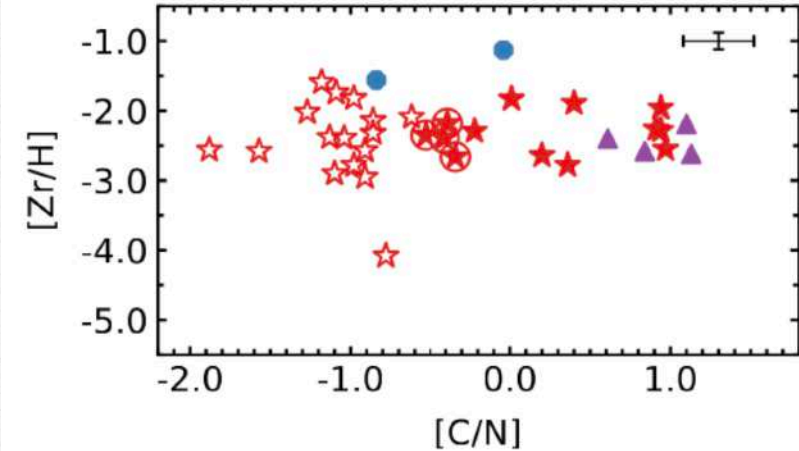
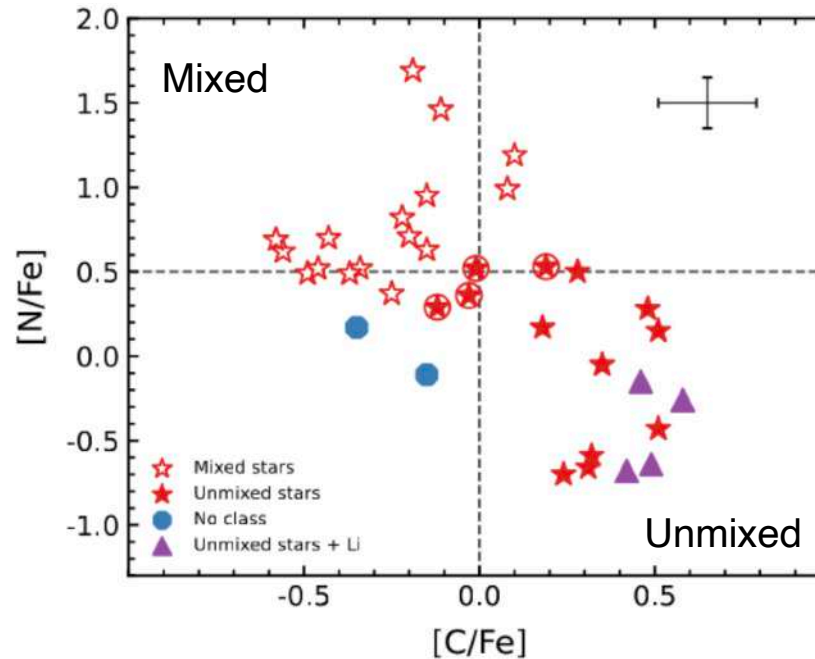
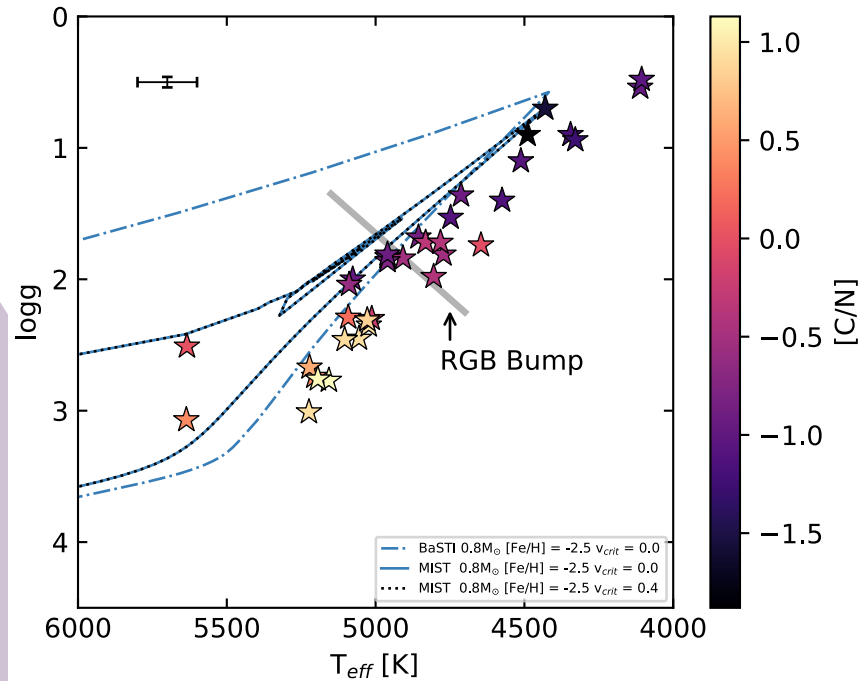
Combining light and heavy elements



Raphaella Fernandes de Melo
PhD Student

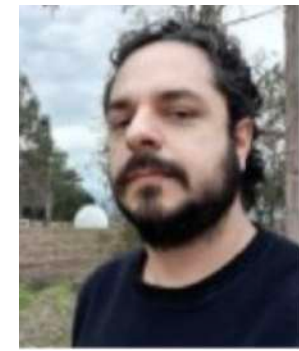
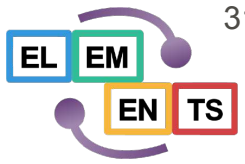
CERES II (Fernandes de Melo et al. 2024, accepted): chemical abundances of C, N, O and Li and comparison with stellar evolution models

Fernandes de Melo et al. 2024



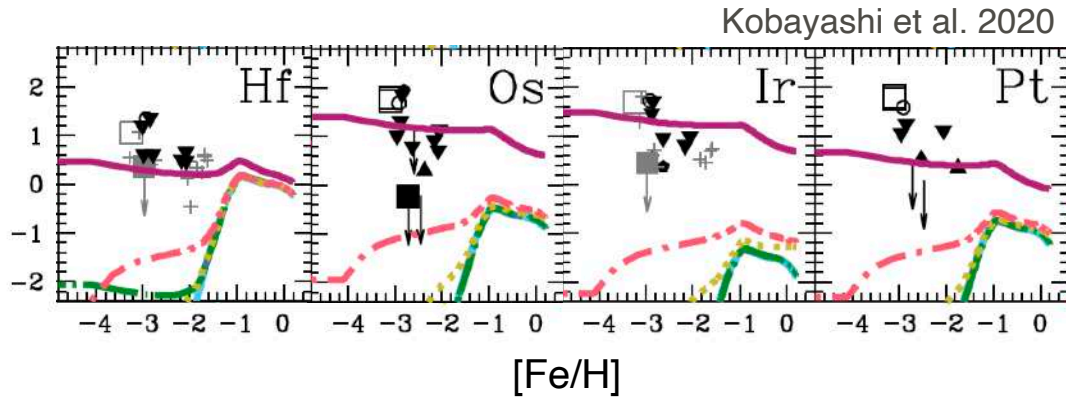
Extra-mixing occurring after the RGB bump affects C,N but not heavy elements abundances

R-process in old, metal-poor stars

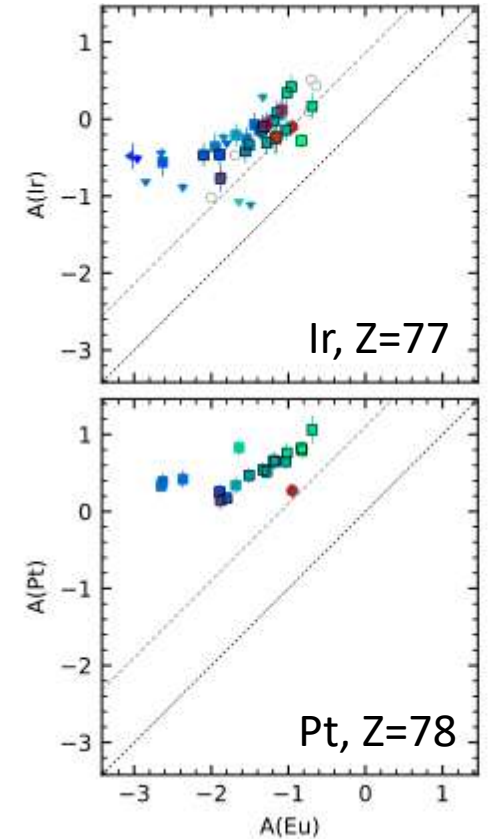
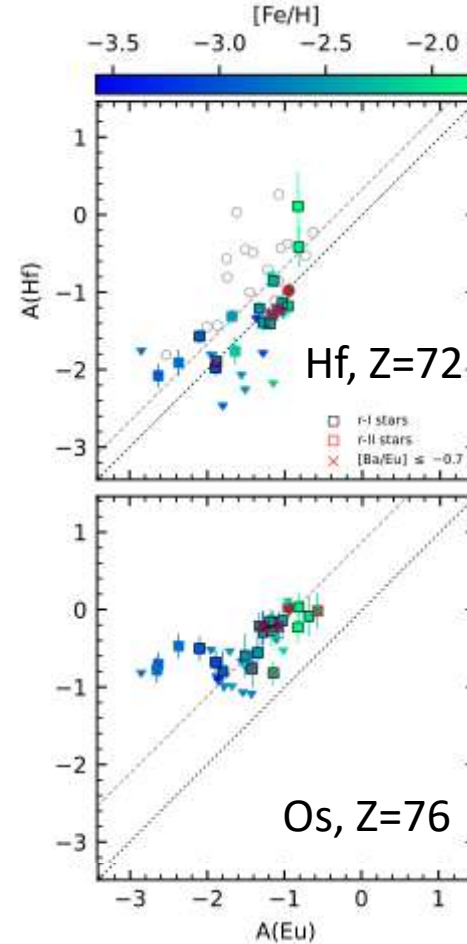
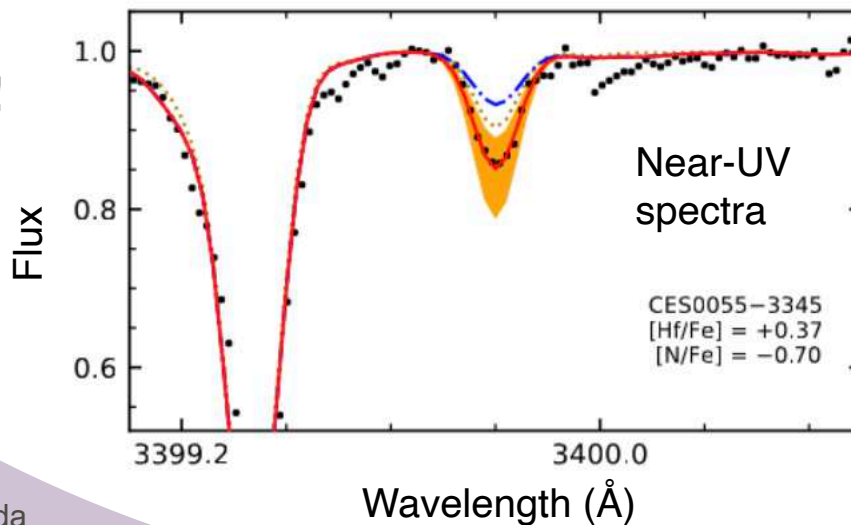


Arthur Alencastro Puls
Postdoc

CERES IV (Alencastro Puls et al., submitted): chemical abundances of Hf, Os, Ir, and Pt



Poorly studied heavy elements!

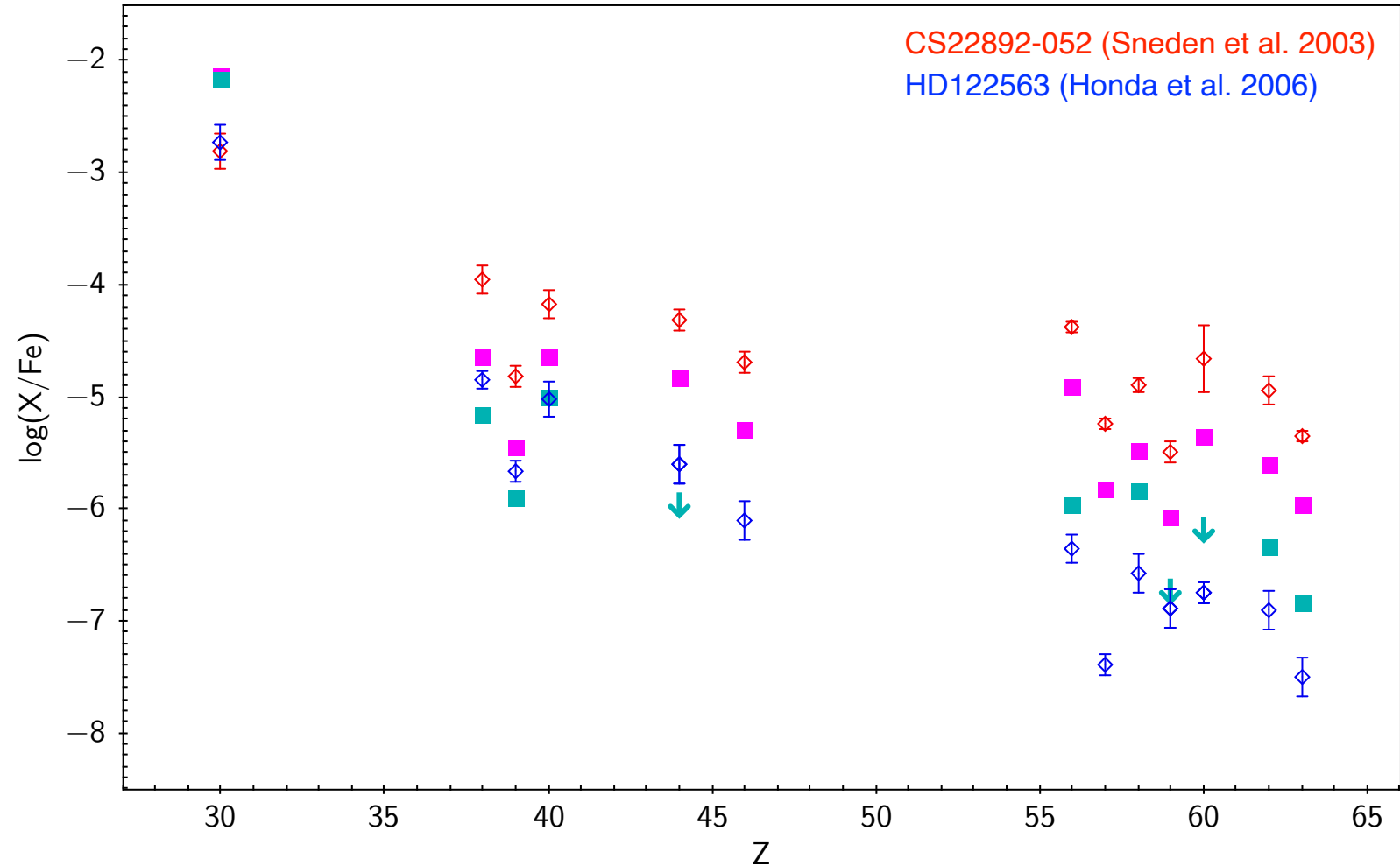
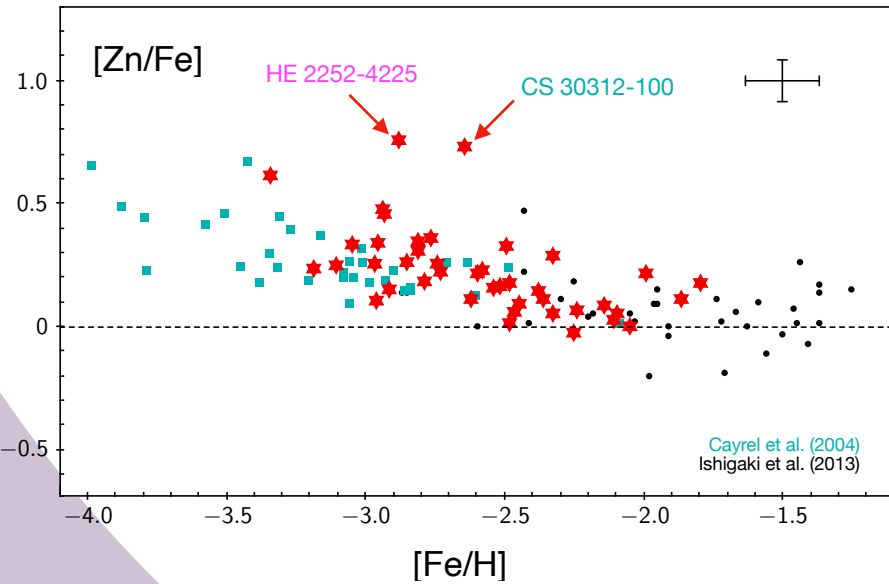


Next steps: stars with peculiar abundance patterns

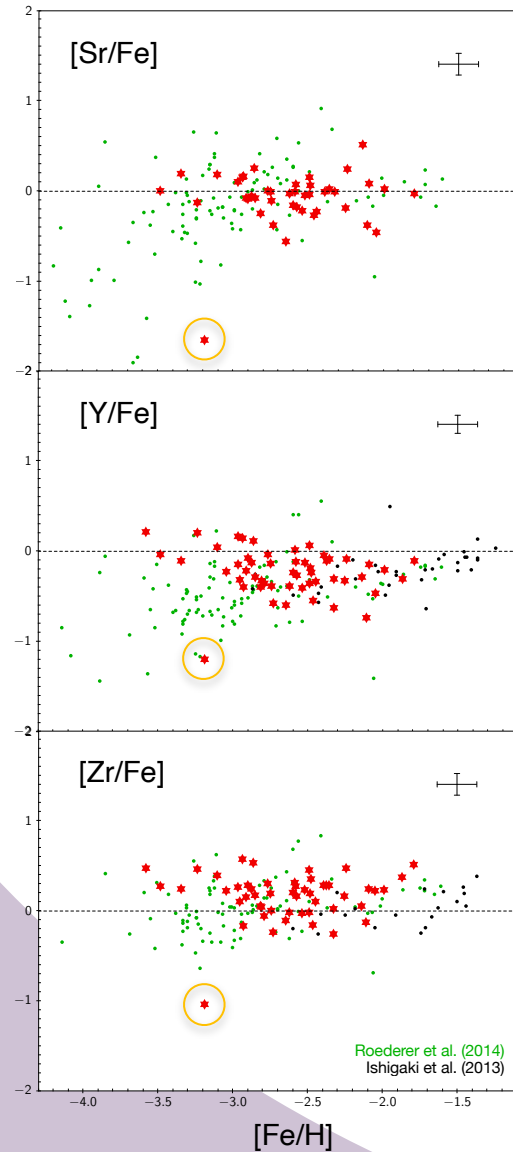
$[Zn/Fe] \sim 0.7$ (Zn rich)

HE 2252-4225: $[Eu/Fe] = 1.10$ (r-rich)

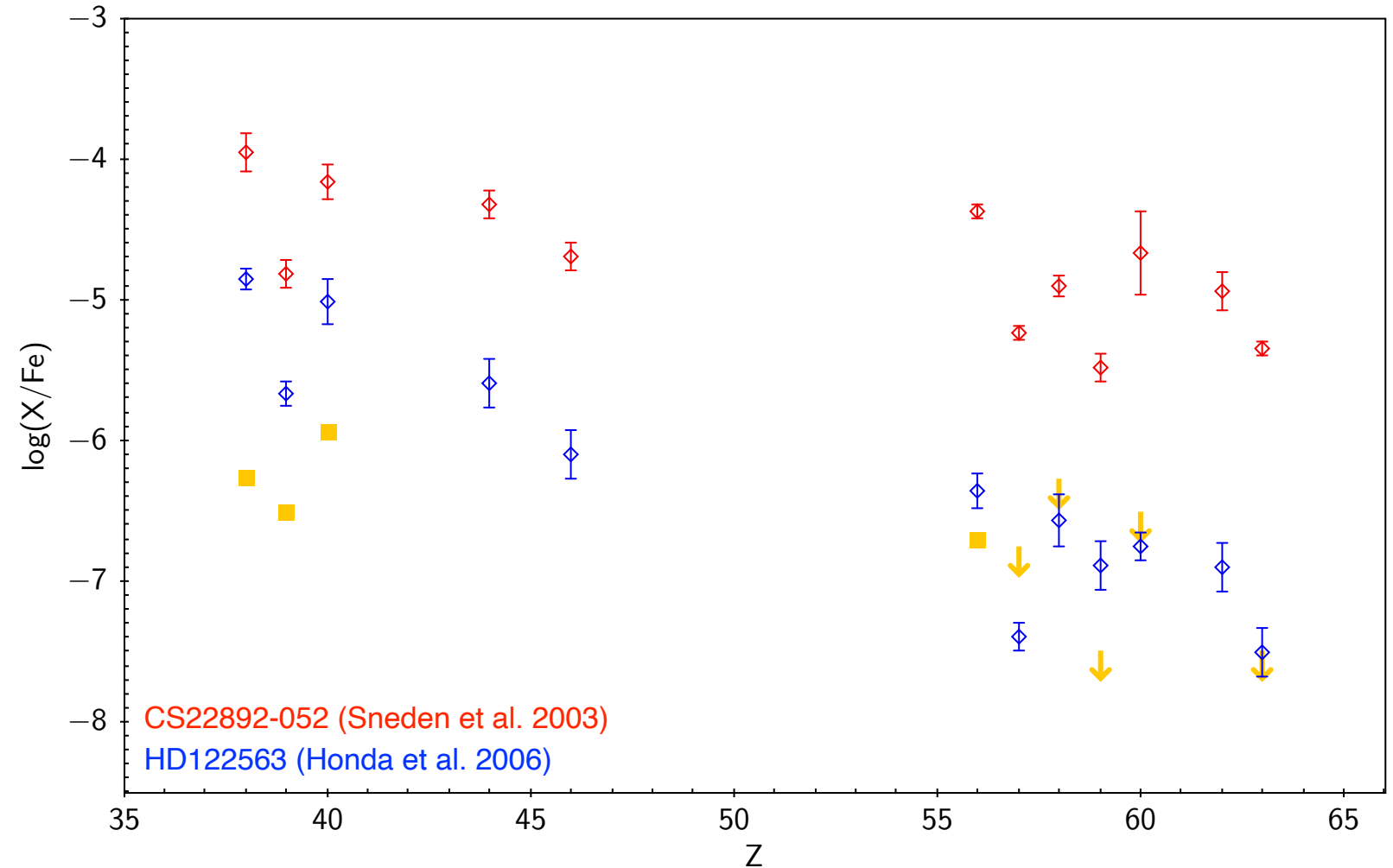
CS 30312-100: $[Eu/Fe] = 0.15$ (r-poor)



Next steps: stars with peculiar abundance patterns

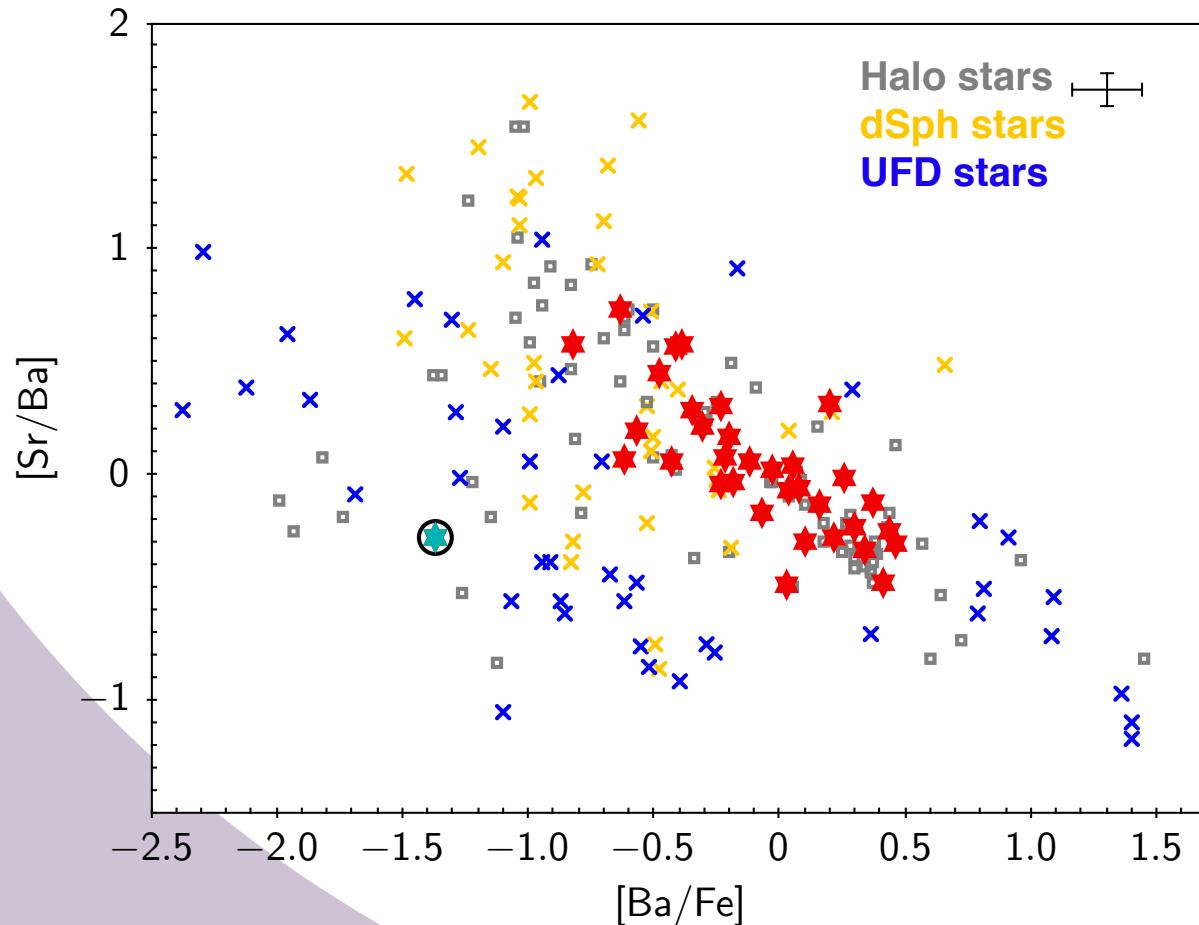


BS16085-0050 $[\text{Sr}/\text{Fe}] = -1.66$, $[\text{Y}/\text{Fe}] = -1.21$, $[\text{Zr}/\text{Fe}] = -1.04$



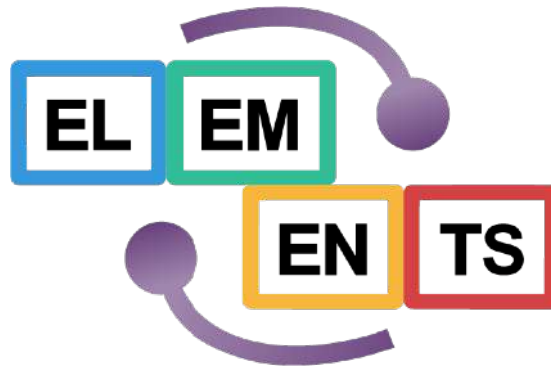
Next steps: stars with peculiar abundance patterns

BS16085-0050 $[\text{Sr}/\text{Fe}] = -1.66$, $[\text{Y}/\text{Fe}] = -1.21$, $[\text{Zr}/\text{Fe}] = -1.04$



The star lie in the region of the $[\text{Sr}/\text{Ba}]$ versus $[\text{Ba}/\text{Fe}]$ diagram mainly occupied by UFD stars
 —> It could be formed in UFDs later accreted by the Milky Way, or formed in situ

The complete abundance pattern + kinematics will tell us if the stars is accreted or not!



Thank you for your attention!