Observations of heavy elements in metal-poor stars

Linda Lombardo

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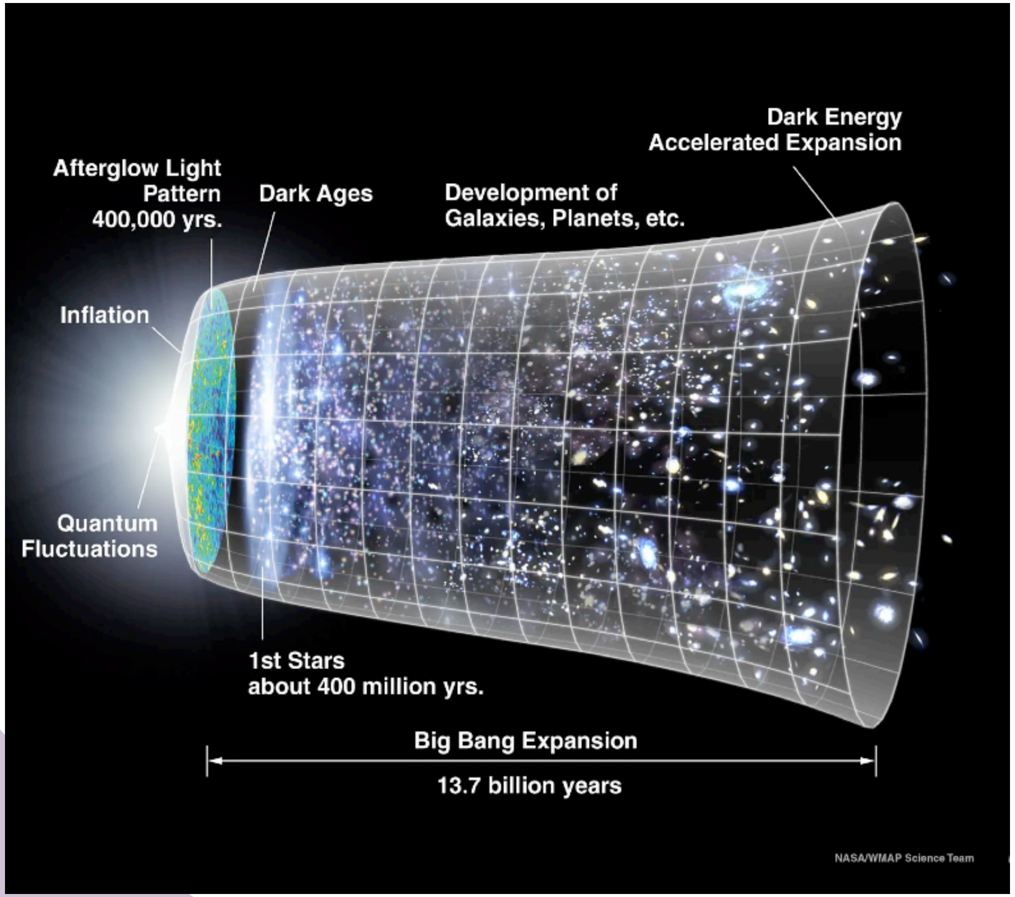
How do the elements form?

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



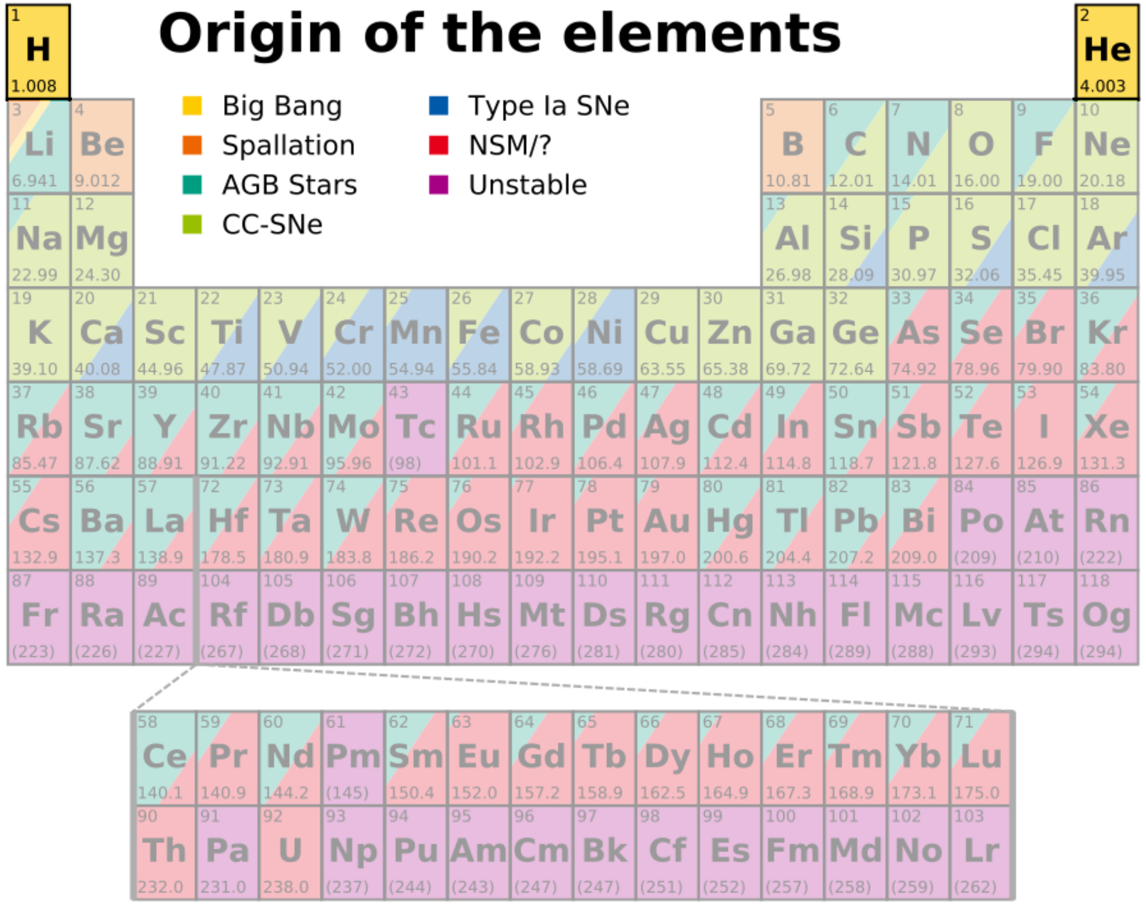


Image courtesy of M. Reichert

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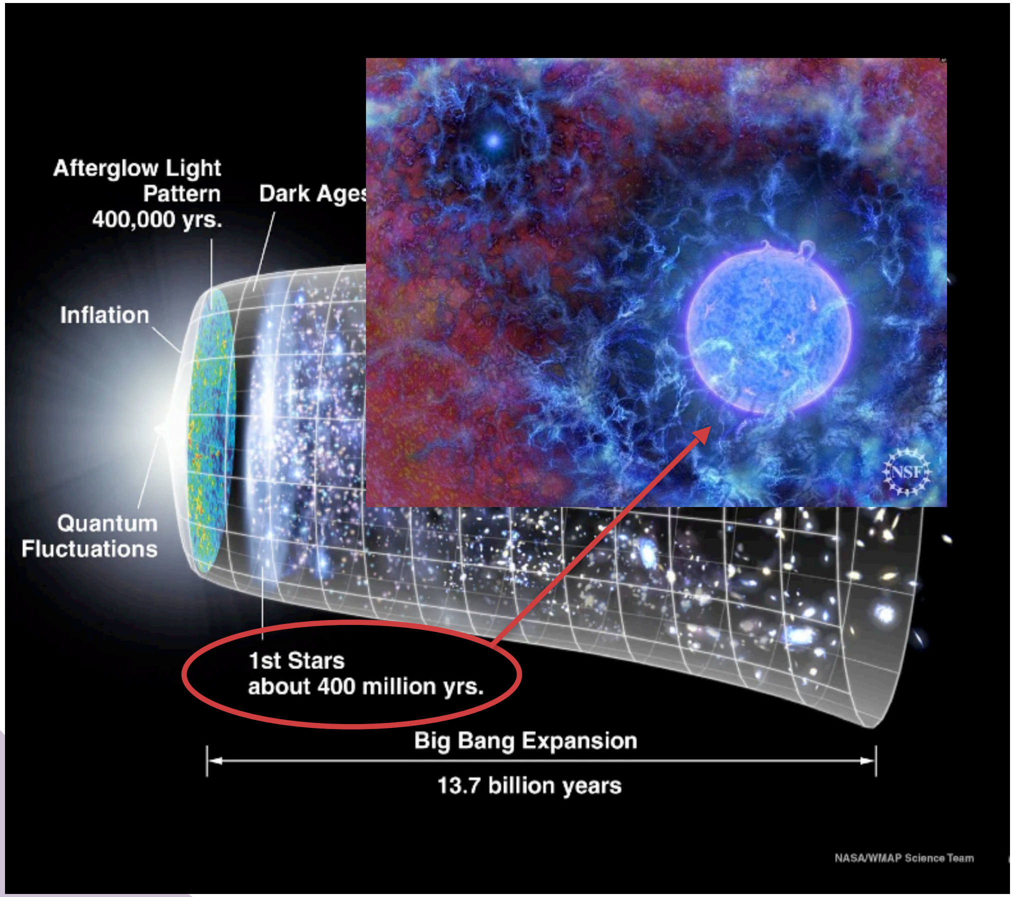
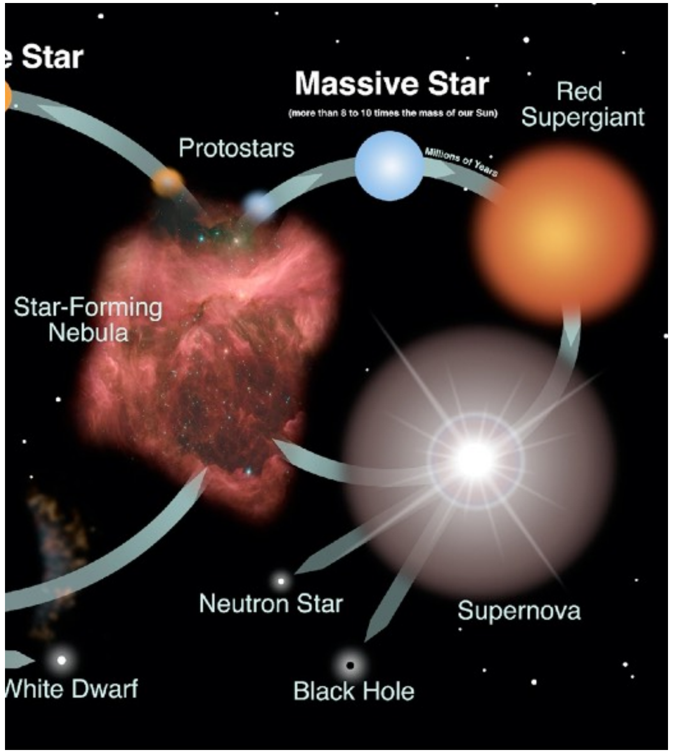


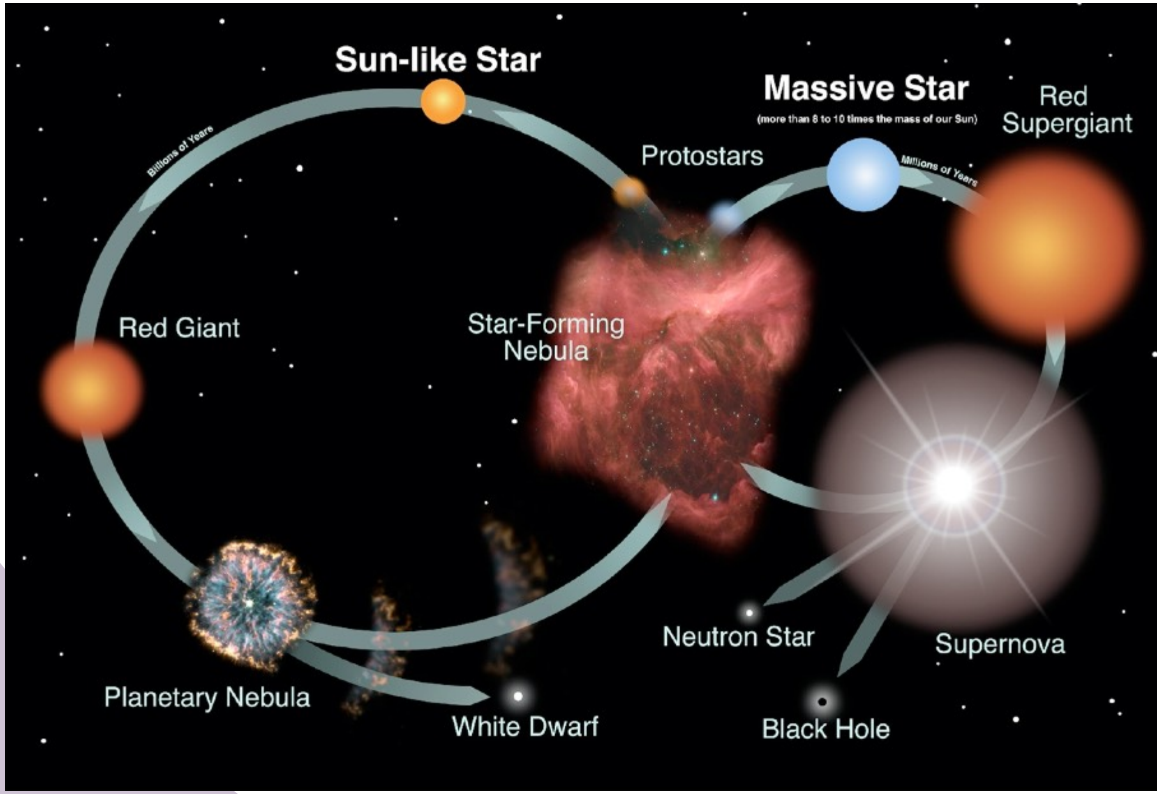
Credit: N.R.Fuller, National Science Foundation

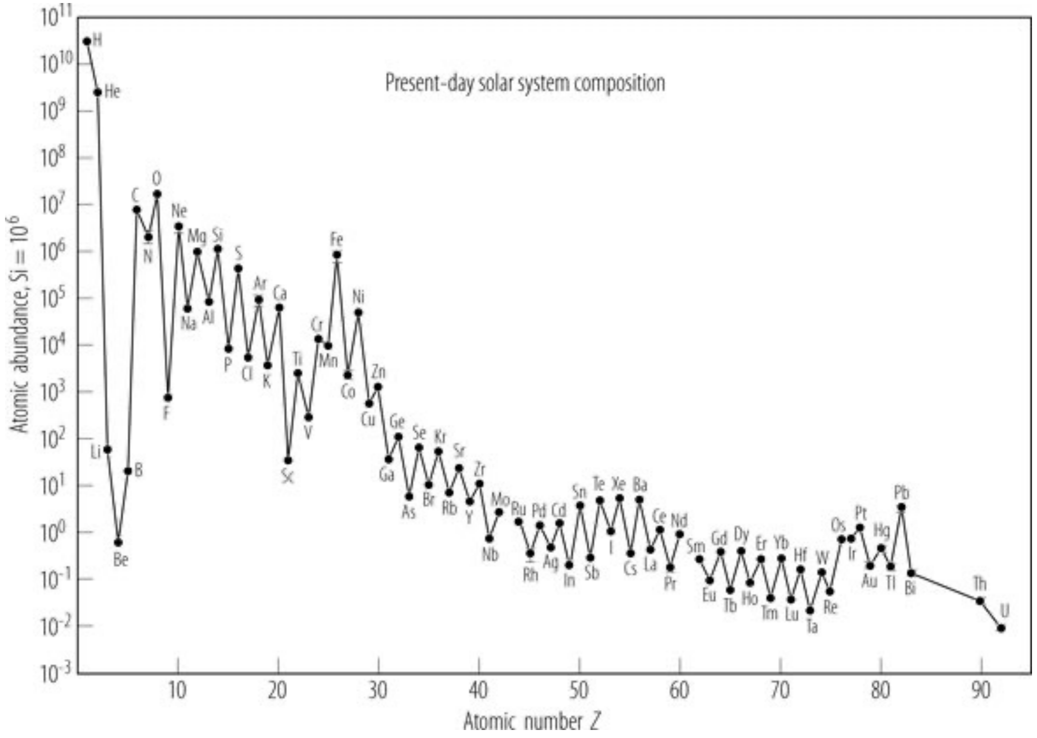


First stars formed -> very high masses -> short lived -> SN explosions -> **elements heavier than He can be formed and injected into the interstellar medium**

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**

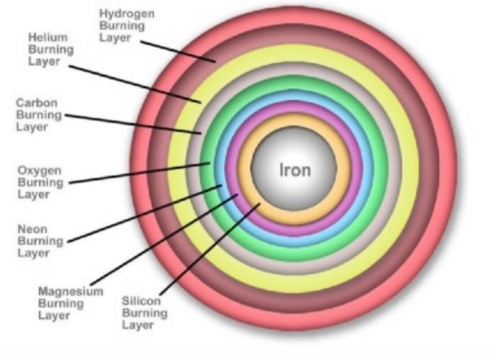


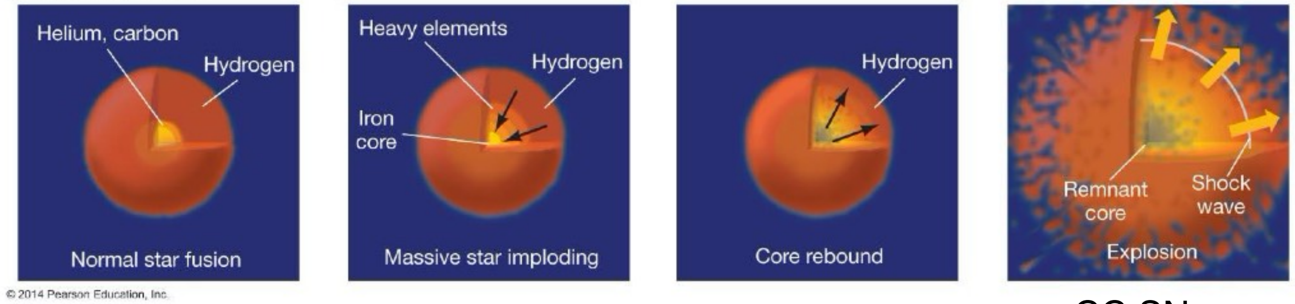


Solar system abundances (Lodders 2009)

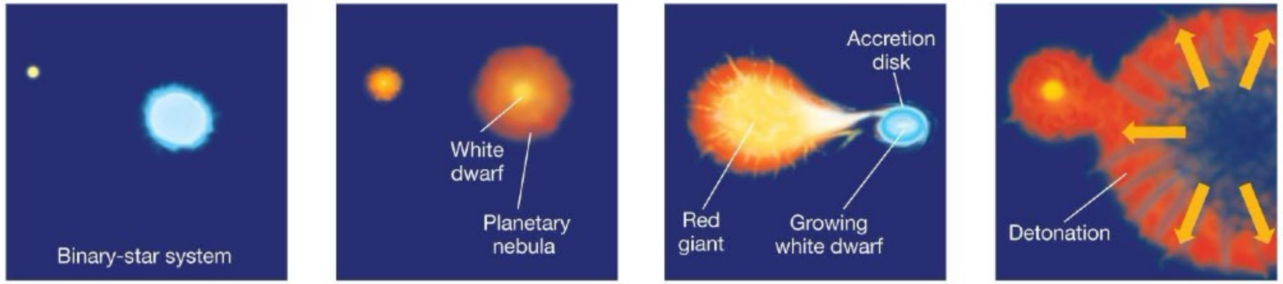
How do the elements form?

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

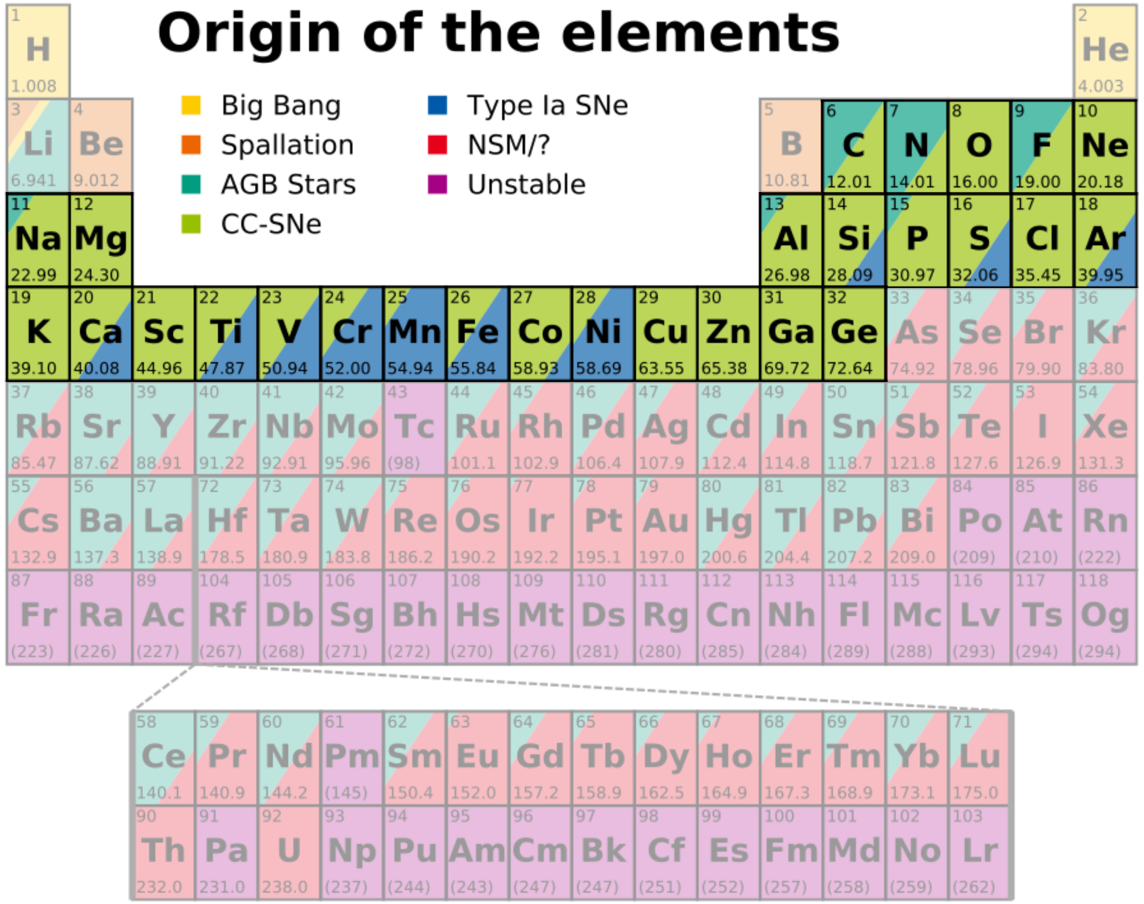




CC SNe

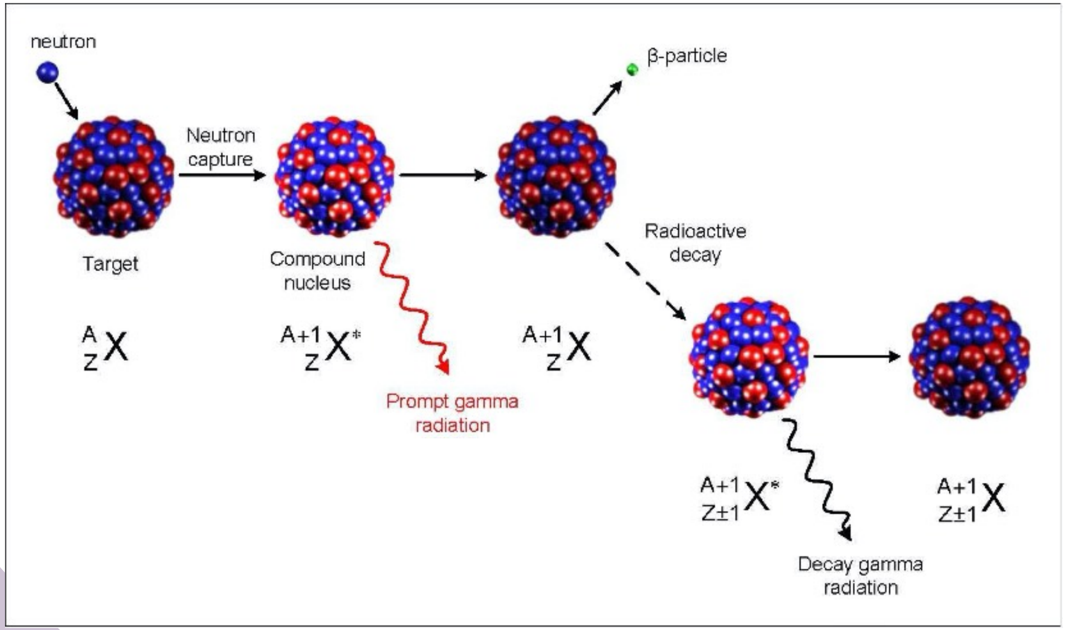


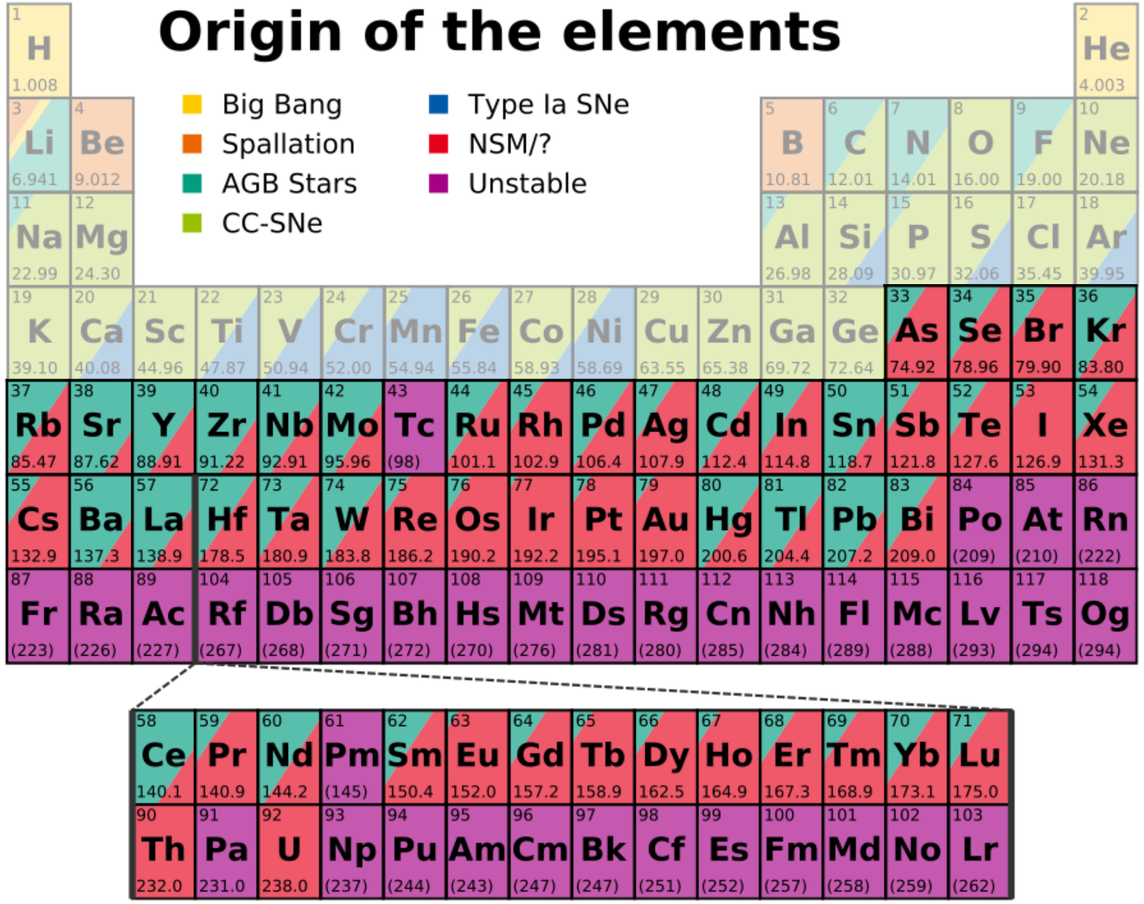
Type Ia SNe



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

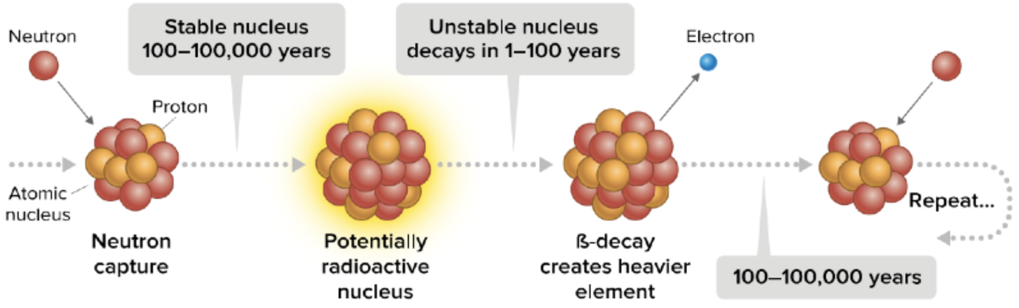




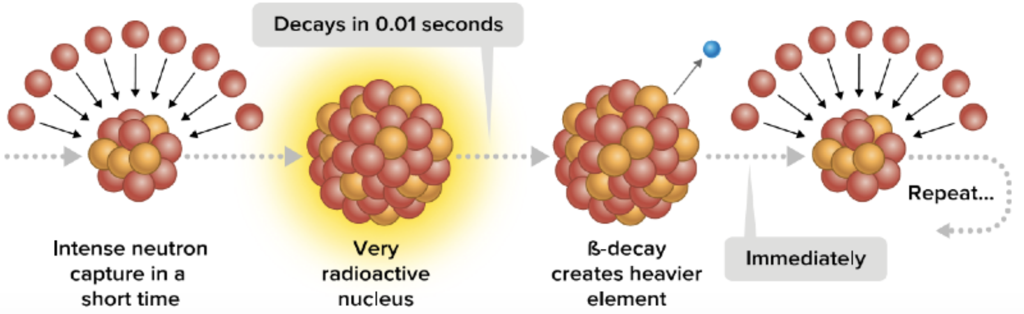
How do the elements form?

Depending on the neutron flux :

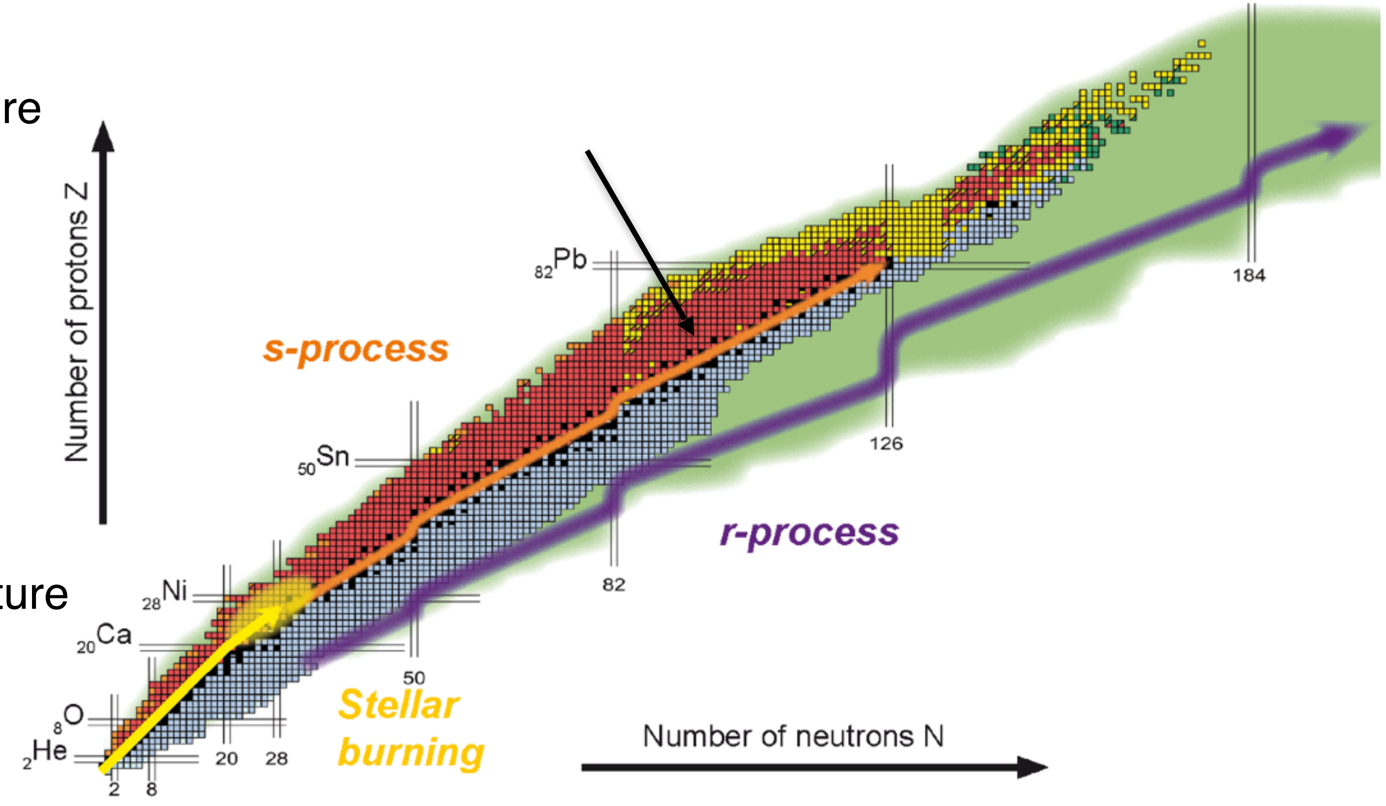
- If n-density$\lesssim 10^8$ cm^{-3} ($\tau_n >> \tau_\beta$): slow neutron capture process (***s*-process**)



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

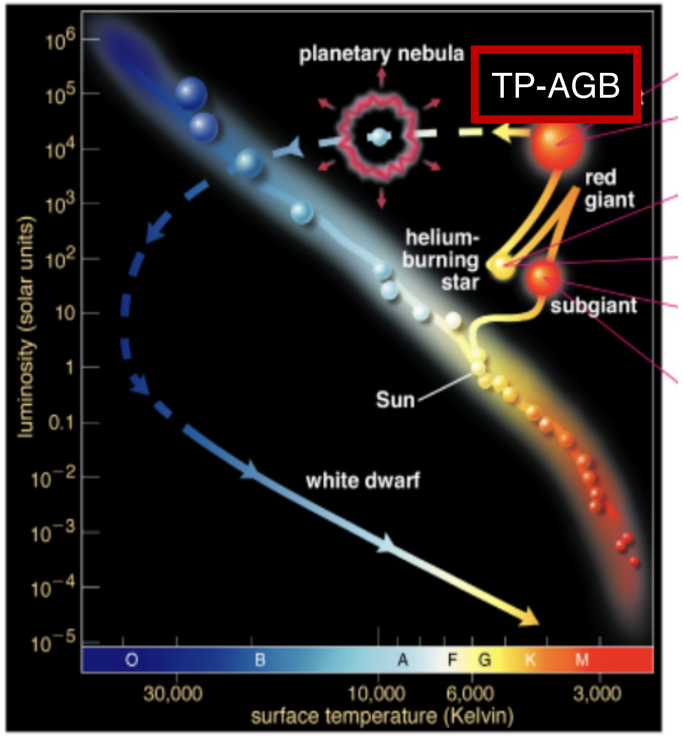


Credits: Jonas Lippuner / Los Alamos National Laboratory

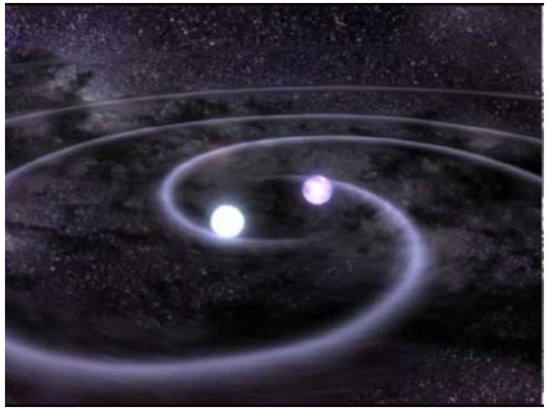


How do the elements form?

s-process:
- asymptotic giant branch (AGB) stars



r-process:
- neutron star mergers (NSM)



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!

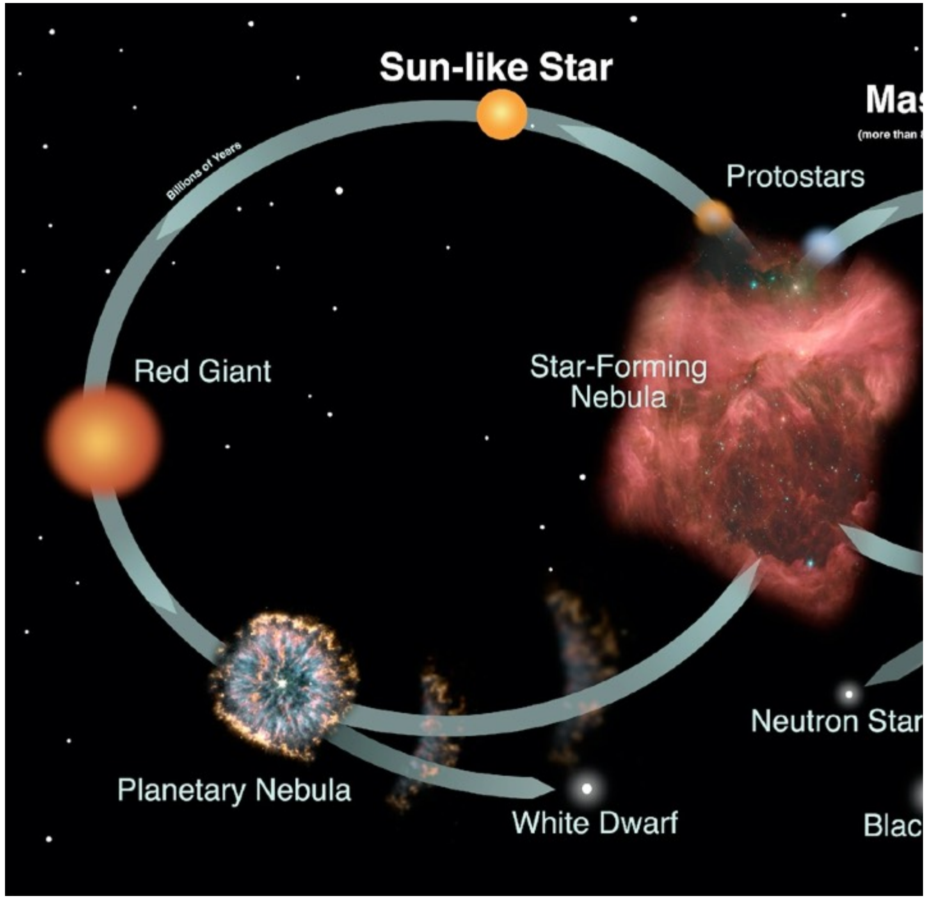
Alternative scenarios:
- Rare SNe (MR-SNe)
- Fast rotating massive stars (FRMS)
- Collapsars
- BH-NS mergers
- …?

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**



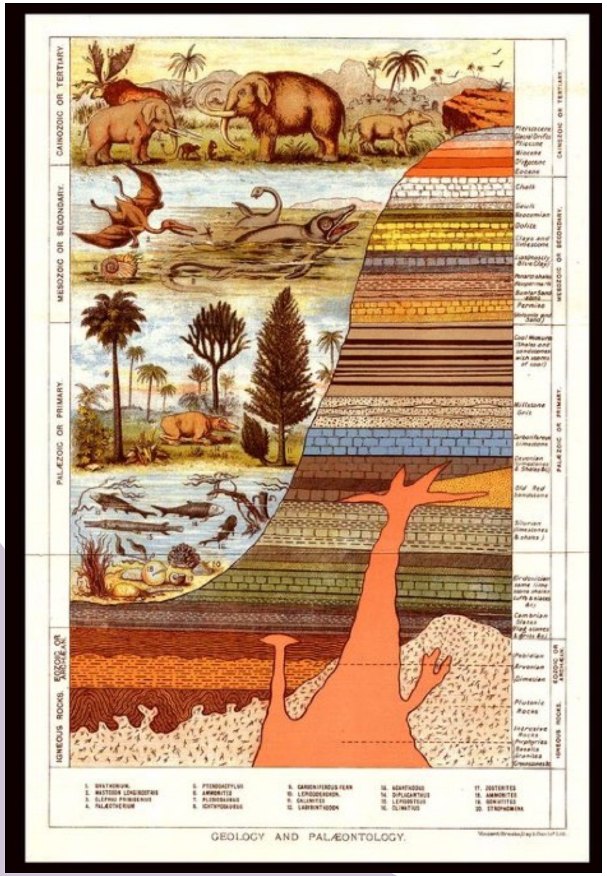
Chemistry of old low-mass stars

Nucleosynthesis in the early Universe

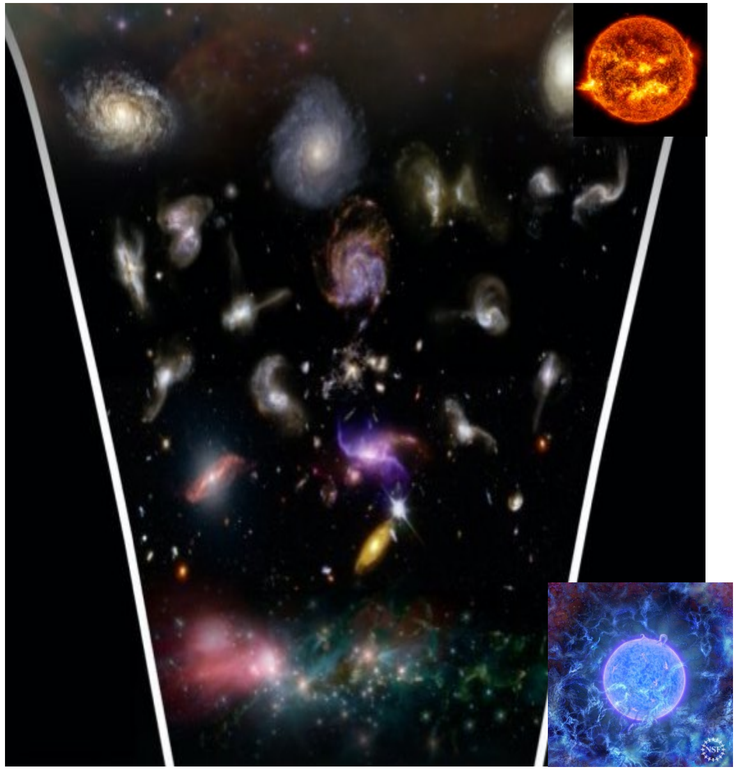
Chemical evolution of the early Universe

Metal-poor stars

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



Time



Timeline of the Universe. Image credit: Rhys Taylor

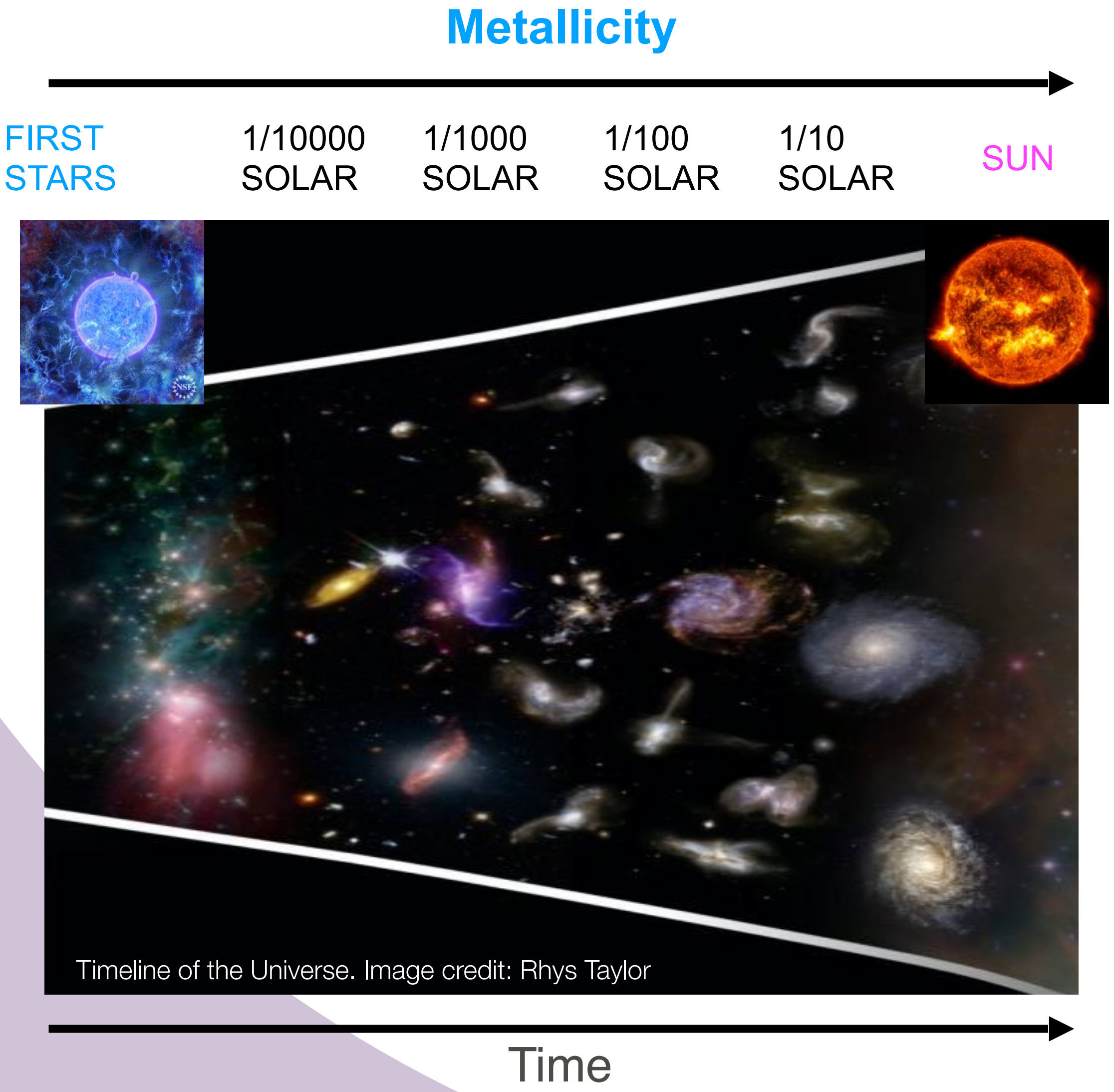
SUN

FIRST STARS

How do we know if a star is **old?**

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

Metal-poor stars



Timeline of the Universe. Image credit: Rhys Taylor

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: For the Sun: $[Fe/H]_{\odot} = 0$

Abundance: $A(X) = \log \varepsilon(X) = \log_{10}(N_X / N_H) + 12$

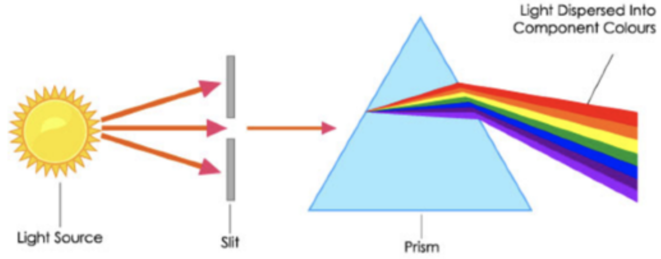
Metallicity: $[Fe/H] = \log_{10}(N_{Fe} / N_H)_{\star} - \log_{10}(N_{Fe} / N_H)_{\odot}$

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)

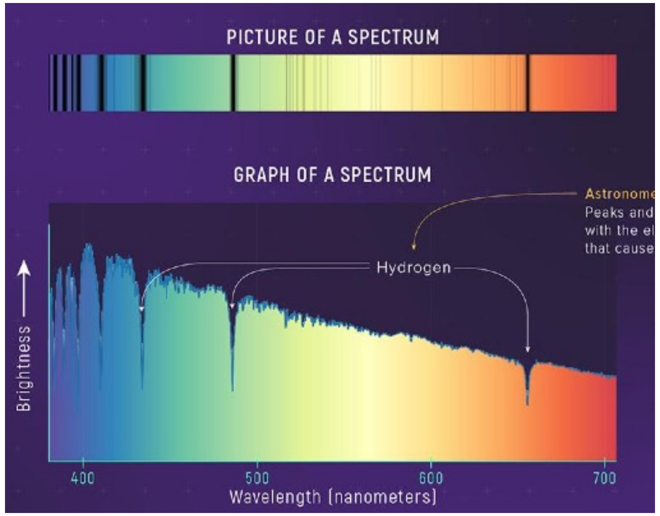
How do we measure stellar abundances?

Stellar spectroscopy

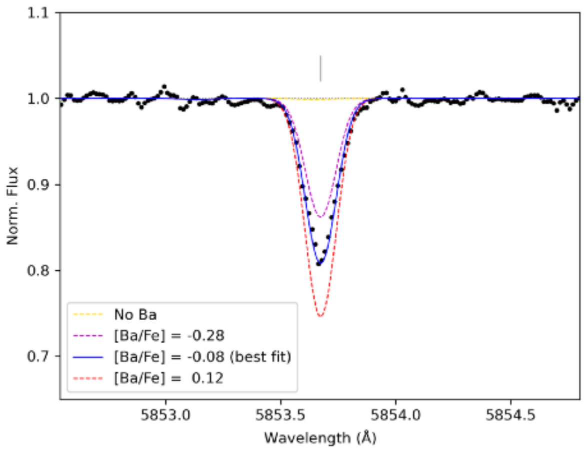
1) Observe the star with a spectrograph



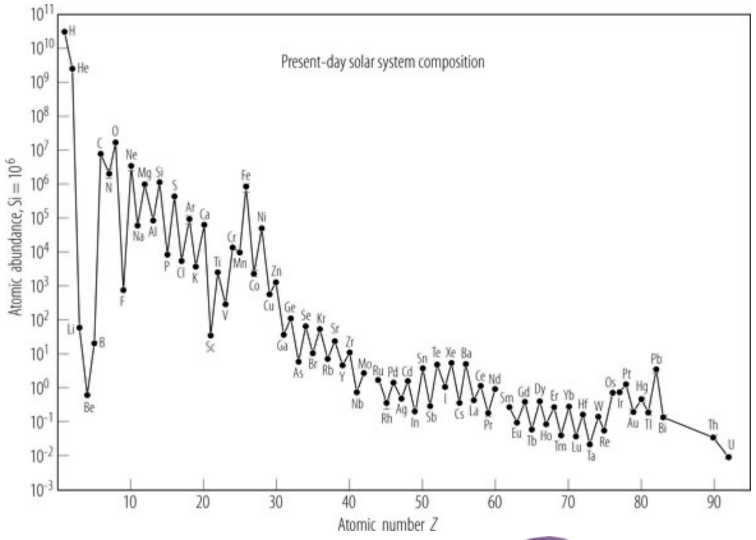
2) Reduce the data to obtain a spectrum of the star



3) Measure the absorption lines



4) Obtain the chemical composition of the star



From stellar spectra to chemical abundances

Input needed:

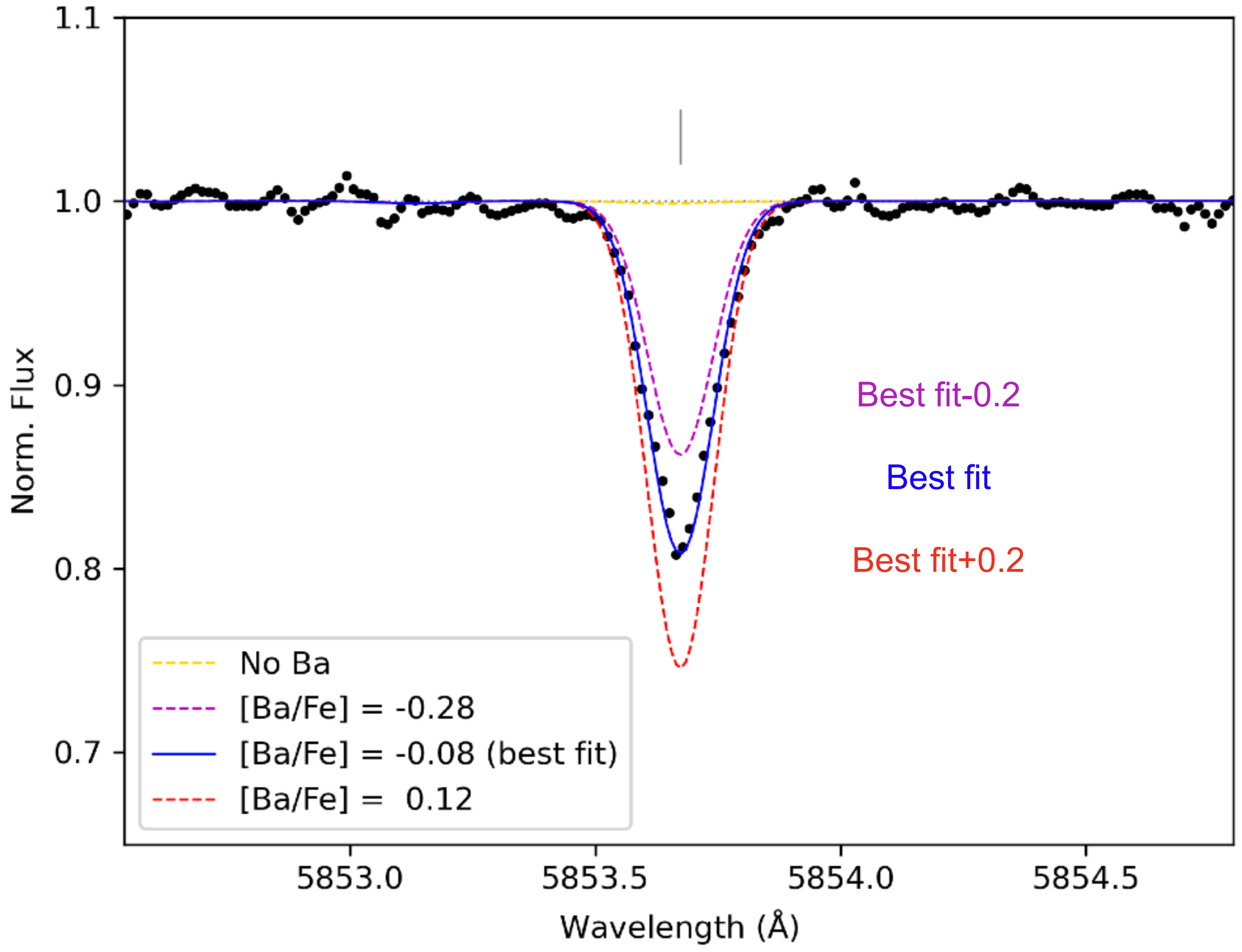
- Observed stellar spectra
- Stellar parameters (effective temperature, surface gravity, …)
- Atomic data (energy levels, transition strengths, ionisation stage, …)
- Spectrum synthesis code

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

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

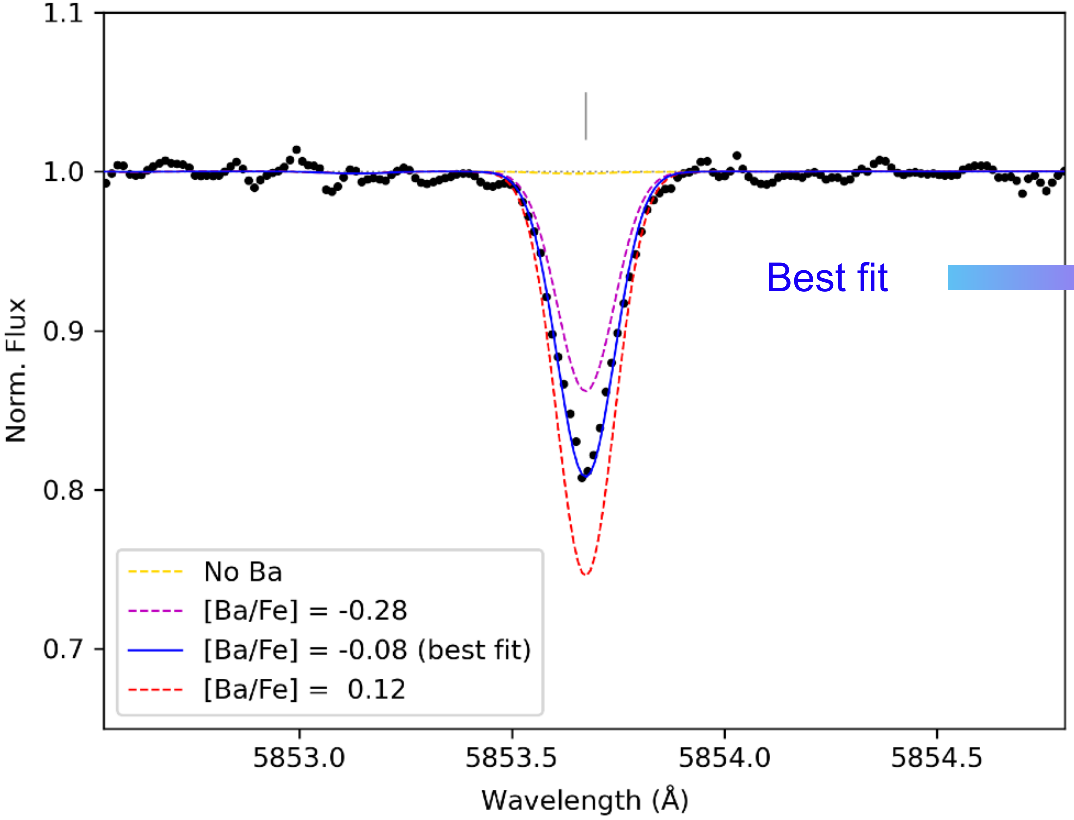
Abundance ratio: $[X/Y] = \log_{10}(N_X/N_Y)_{☆} - \log_{10}(N_X/N_Y)_{\odot}$

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

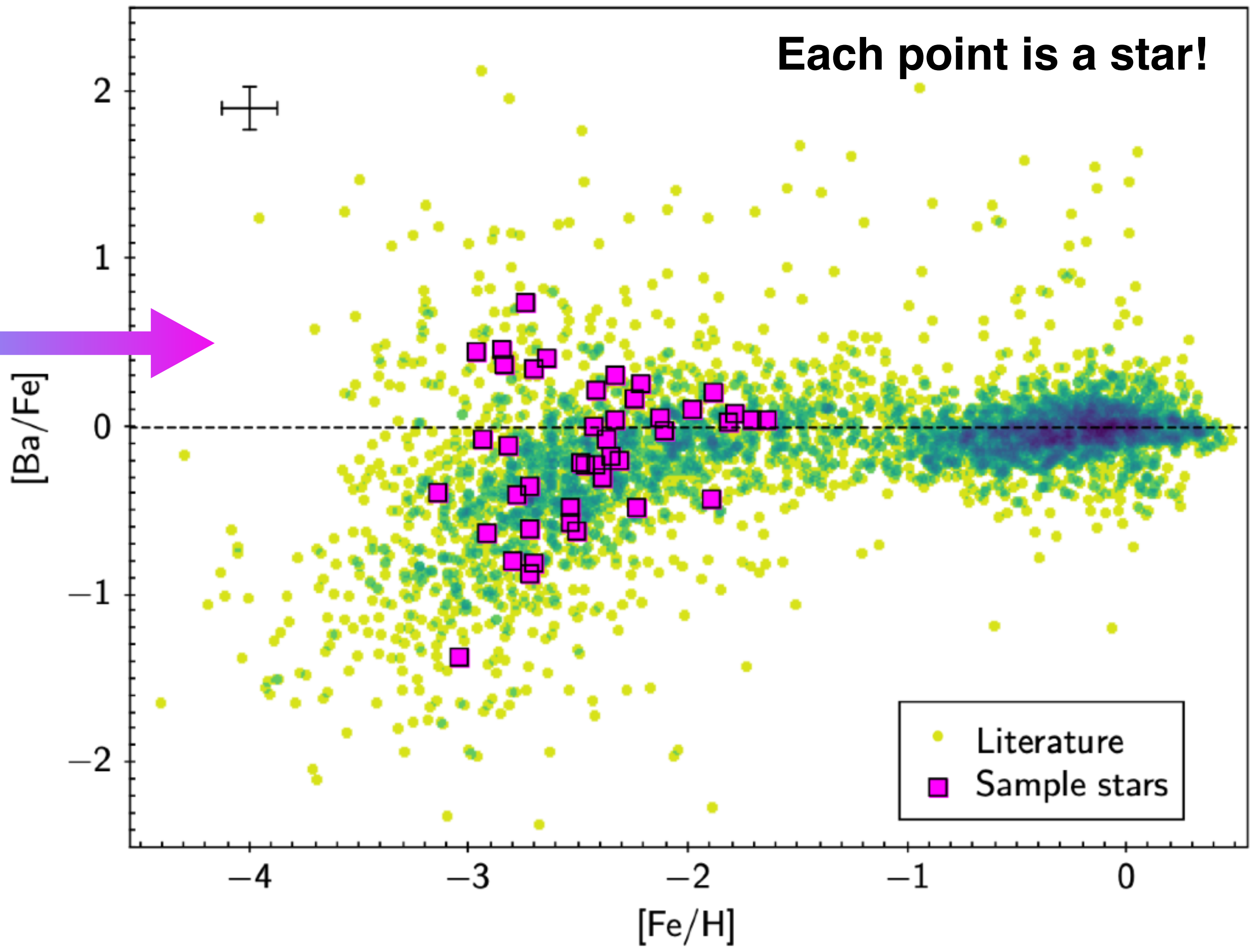


From stellar spectra to chemical abundances

For each star:



Best fit

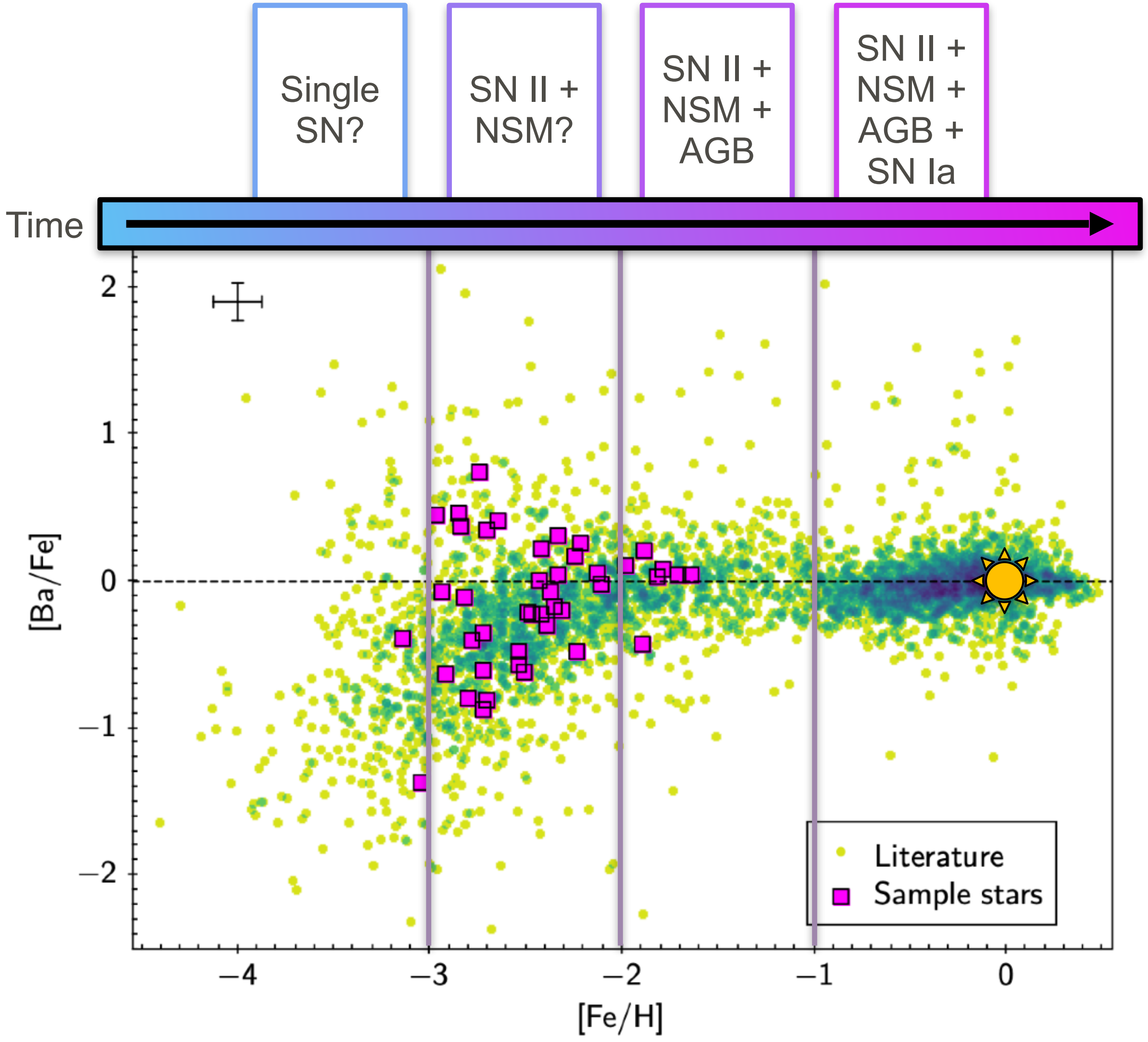


Why chemical abundances are important?

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)**



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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

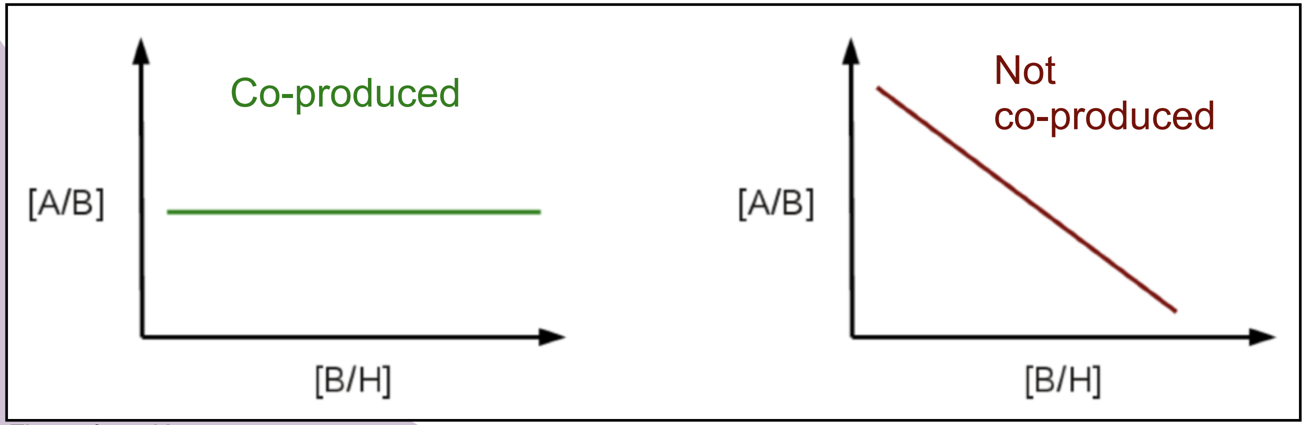
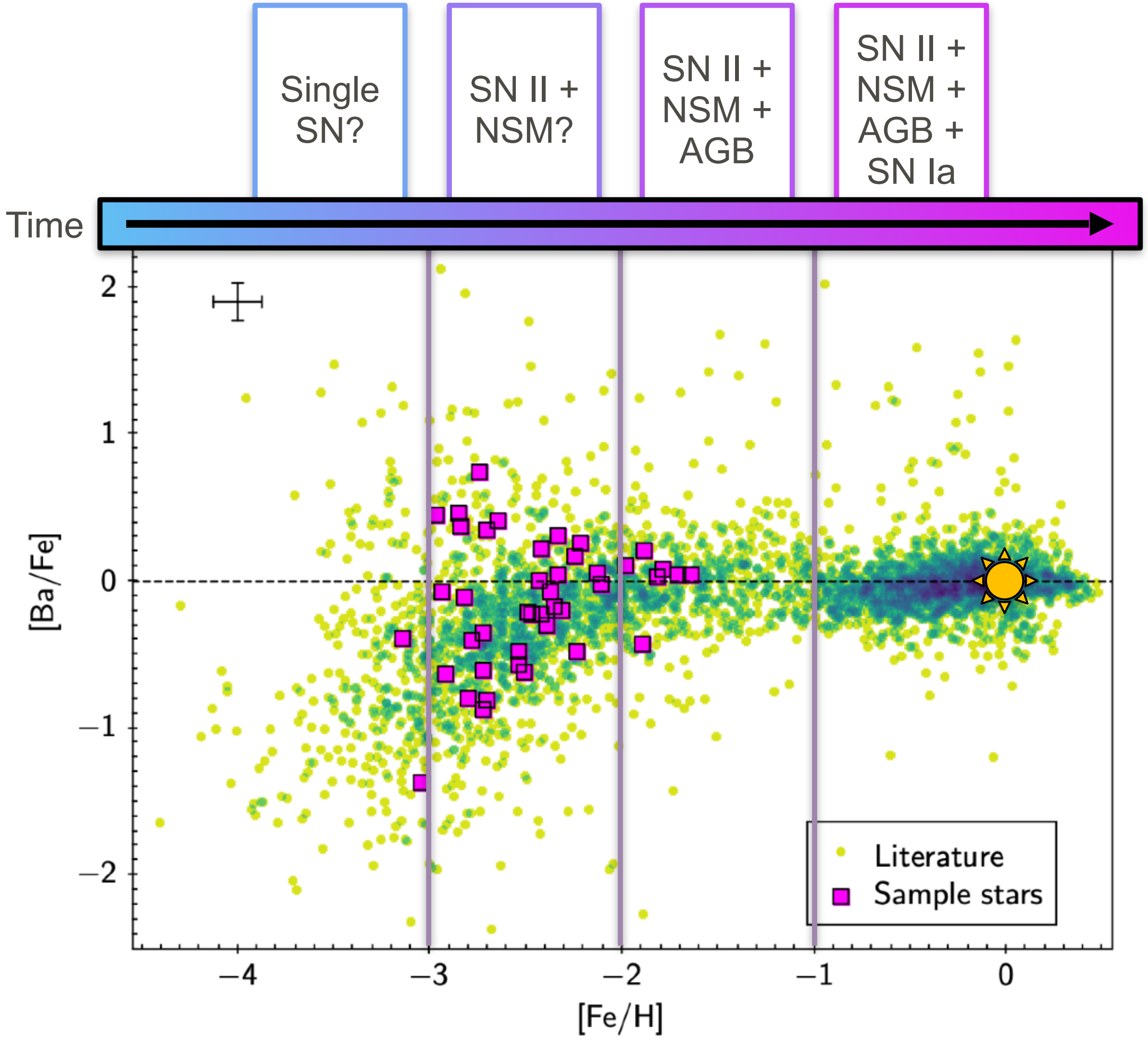


Figure from Hansen 2012



Chemical **E**volution of **R**-process **E**lements in **S**tars

(PI: Prof. C.J.Hansen)

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

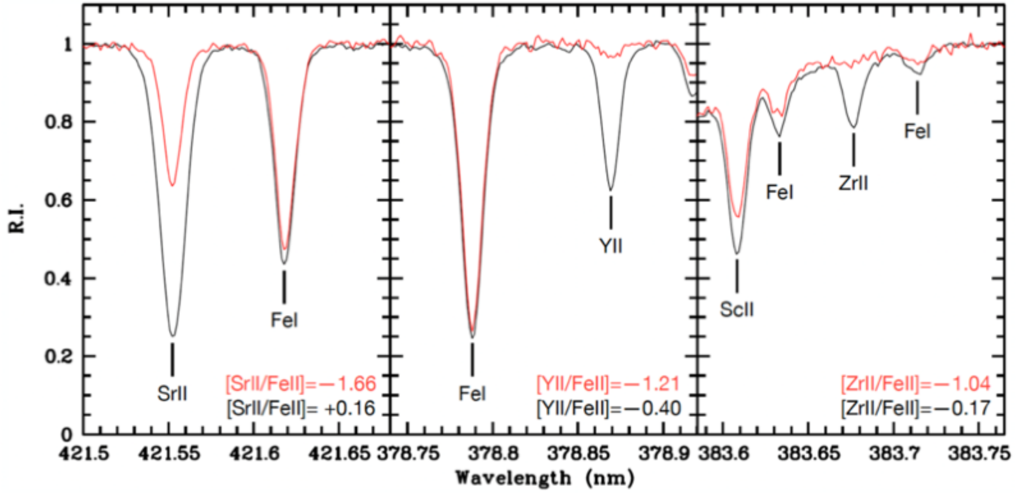
Goal: increase our knowledge of the physical conditions and formation sites of r-process elements

Data: High-resolution (R>40000), high signal-to-noise ratio (SNR>50 @390nm) 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…)

Status: Li, C, N, O, Na to Zn, Sr, Y, Zr, Ba, La, Ce, Pr, Nd, Sm, Eu, Hf, Os, Ir, Pt

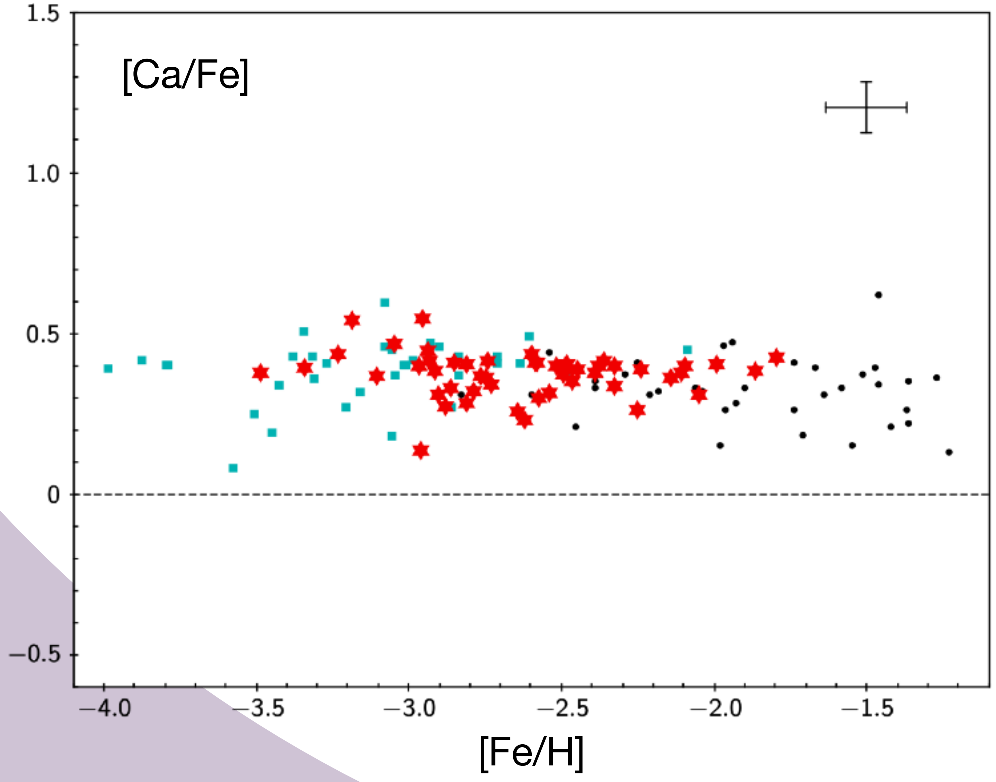


Lombardo et al. 2022

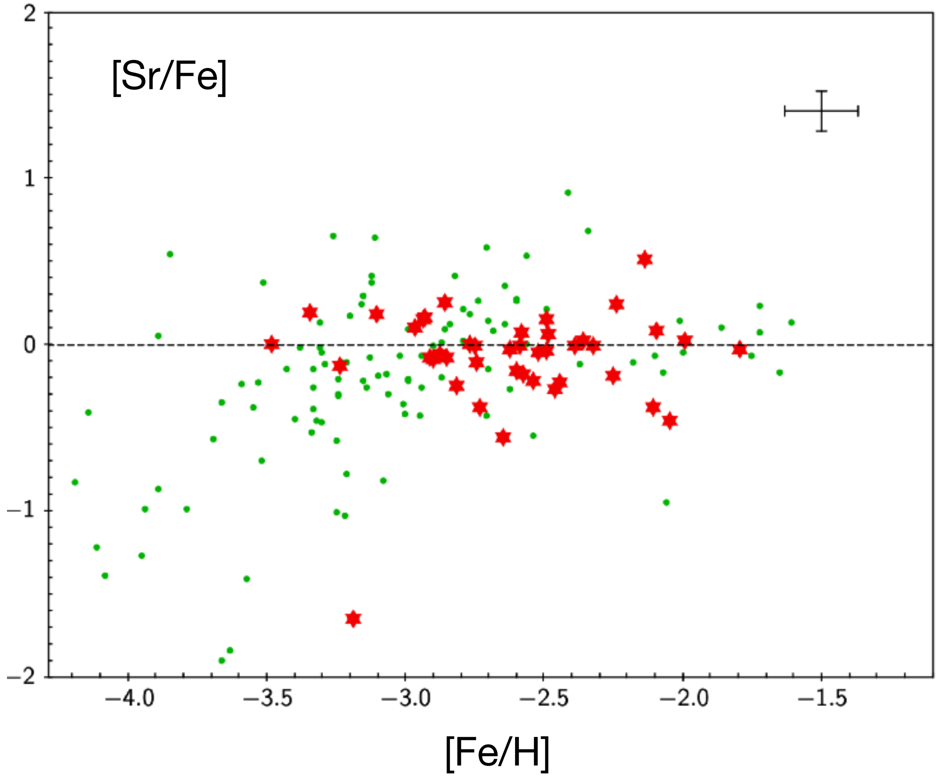
CERES I

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



Light n-capture elements



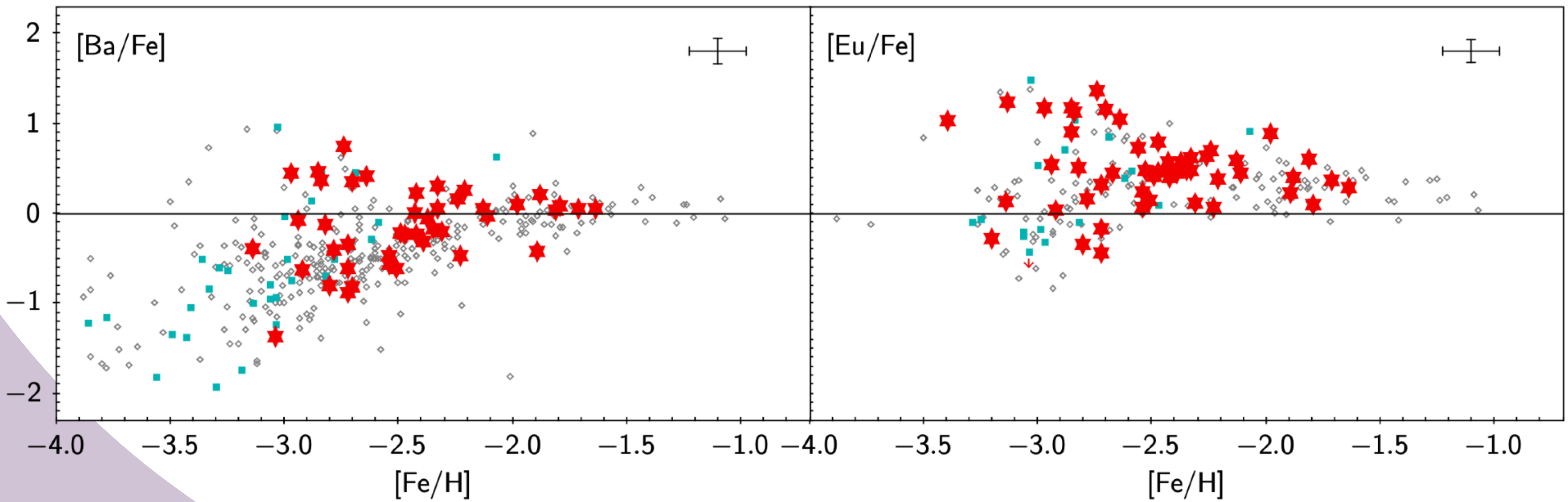
Cayrel et al. (2004)
Ishigaki et al. (2012)
Roederer et al. (2014)

Lombardo et al. 2022

CERES III

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

Lombardo et al. 2025



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

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

Lombardo et al. 2025

In solar system material : (Arlandini+99)

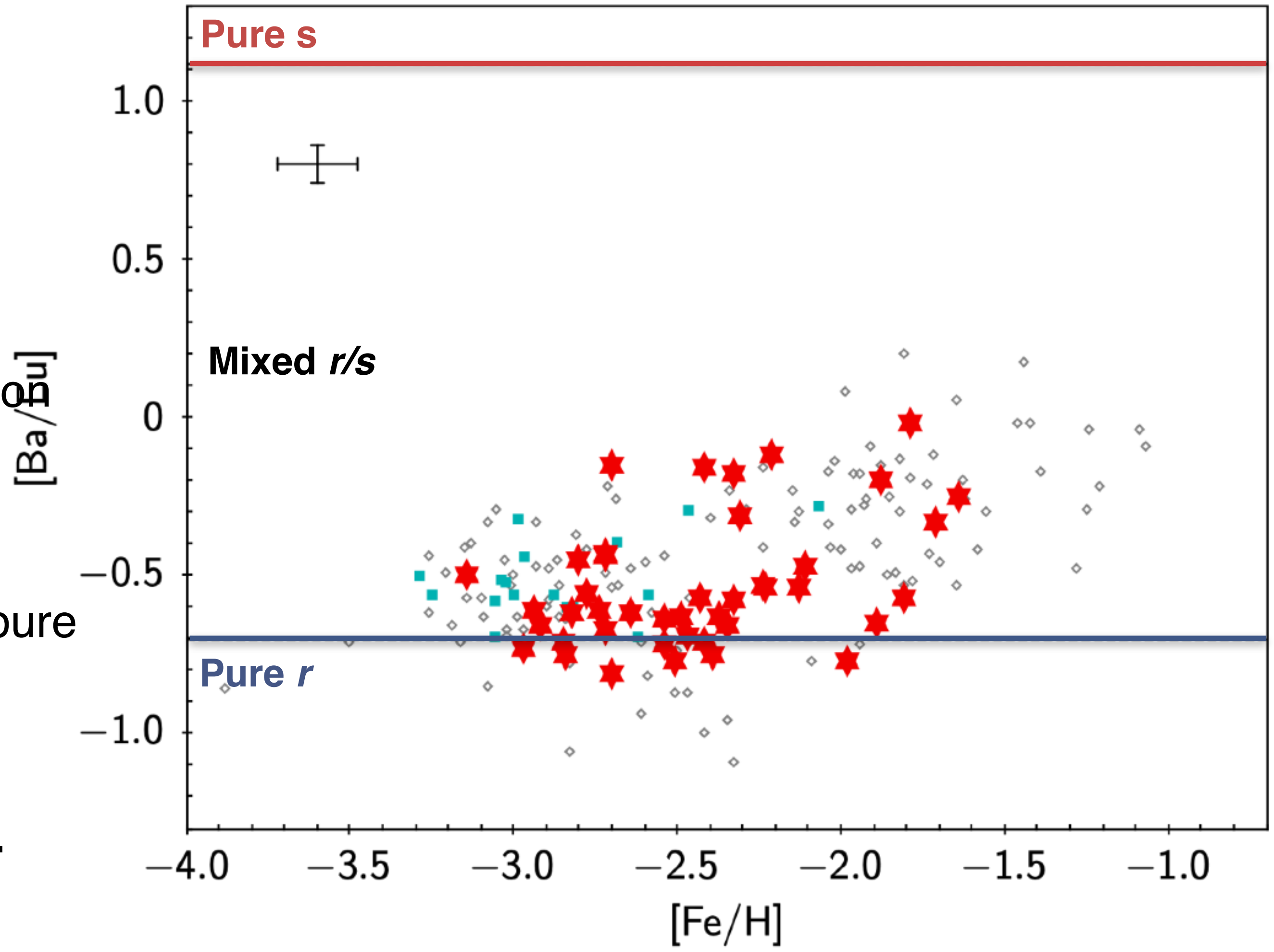
Ba : 81% *s*, 19% *r* —> mainly s

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**



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

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

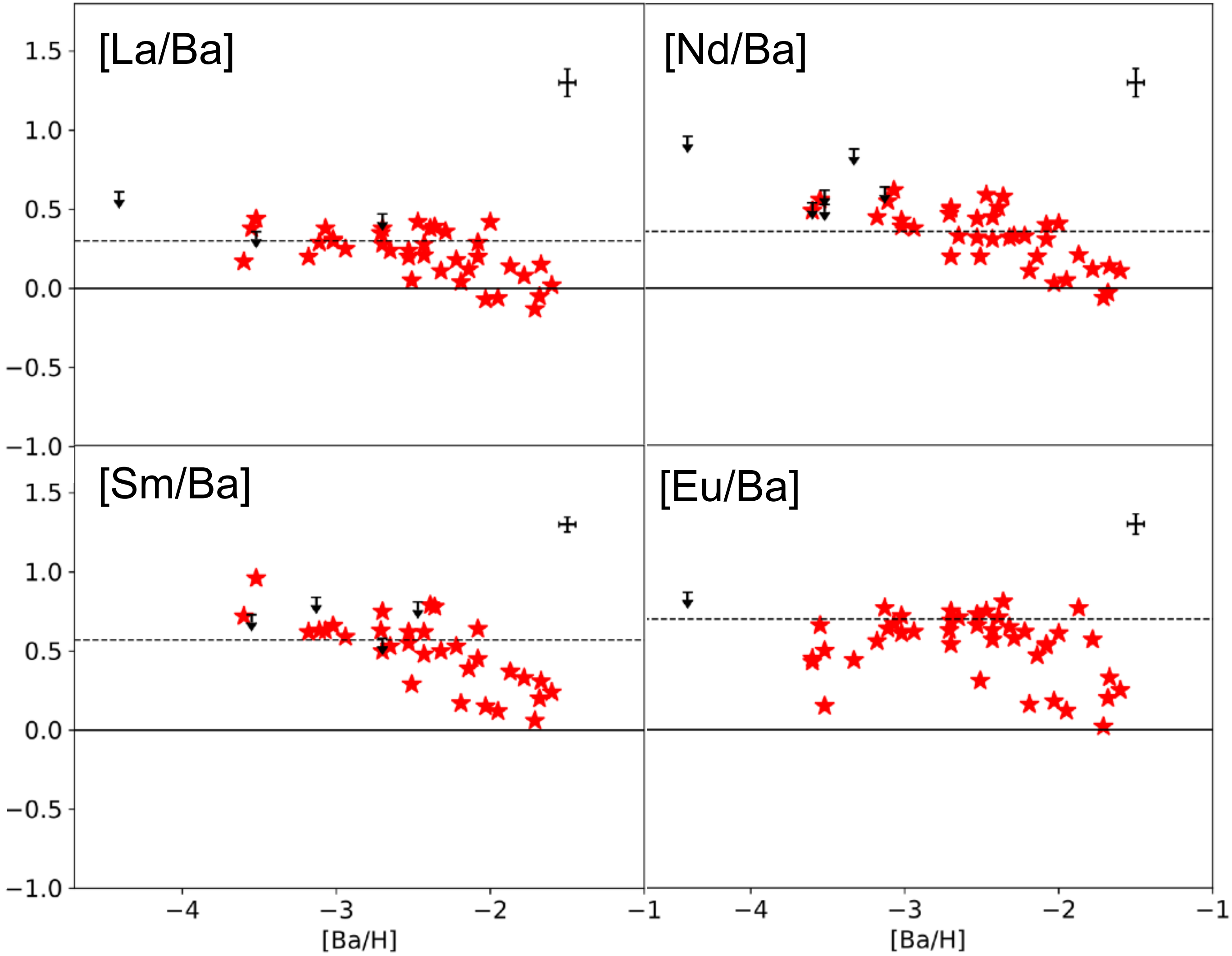
Lombardo et al. 2025

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, which corresponds to [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



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

In solar system material : (Arlandini+99)

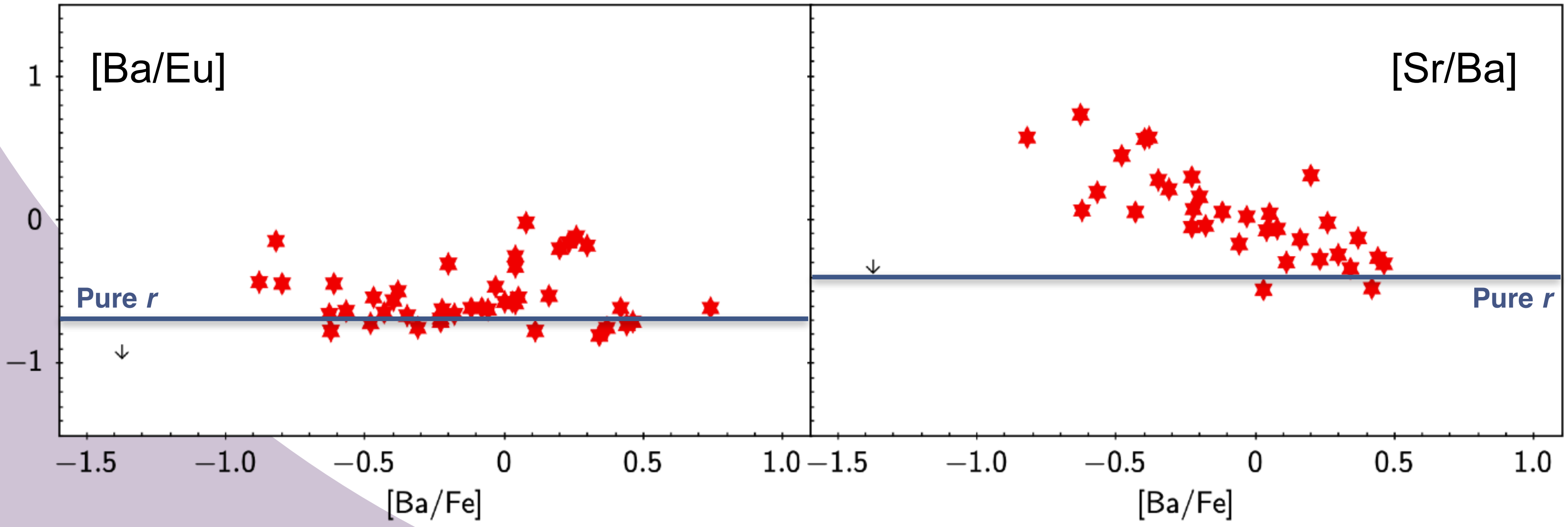
Sr: 85% *s*, 15% *r* —> mainly s

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**

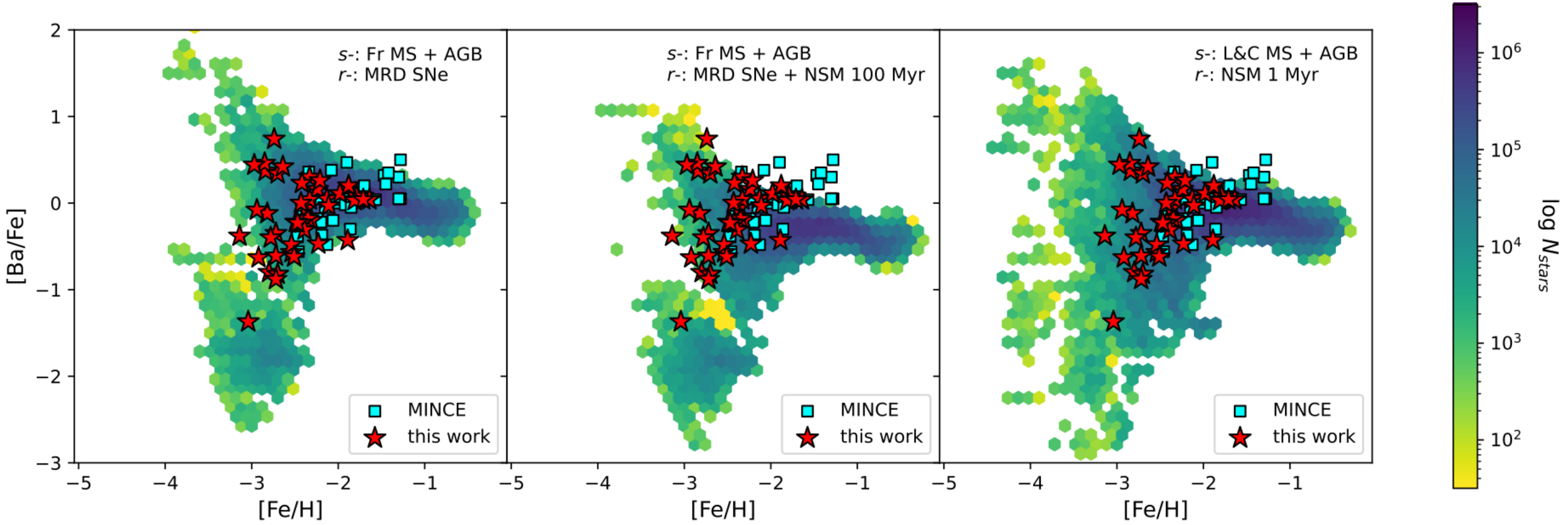


Several hypothesis:

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



Lombardo et al. 2025

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 My delay (r-process)
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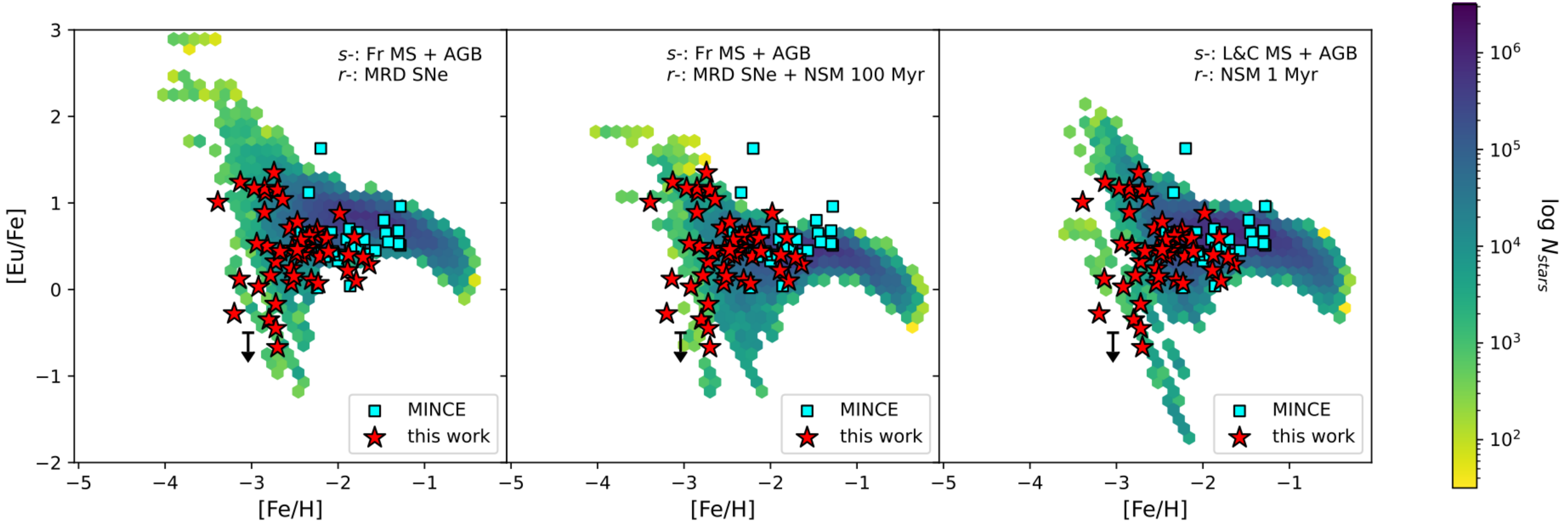


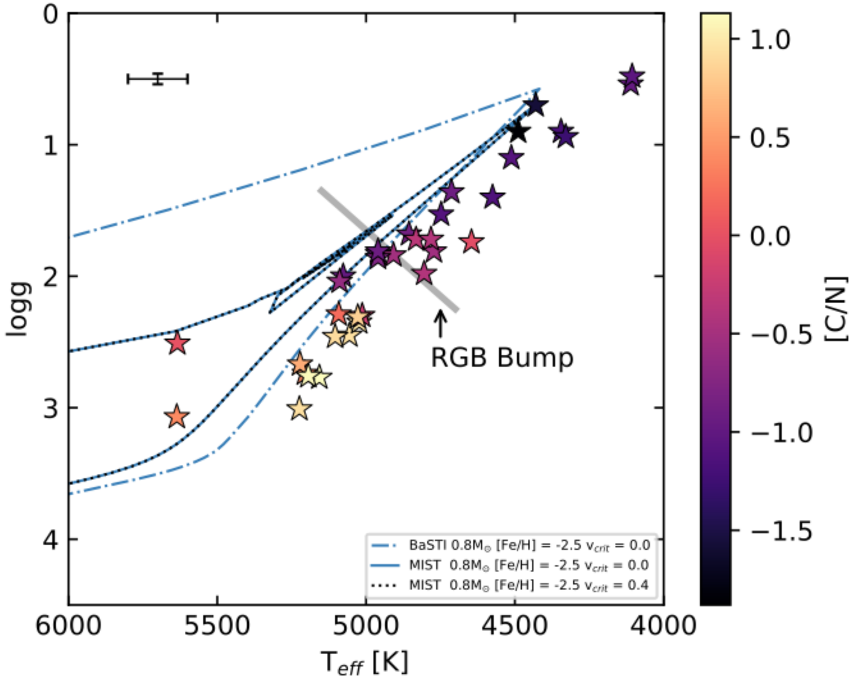
Lombardo et al. 2025

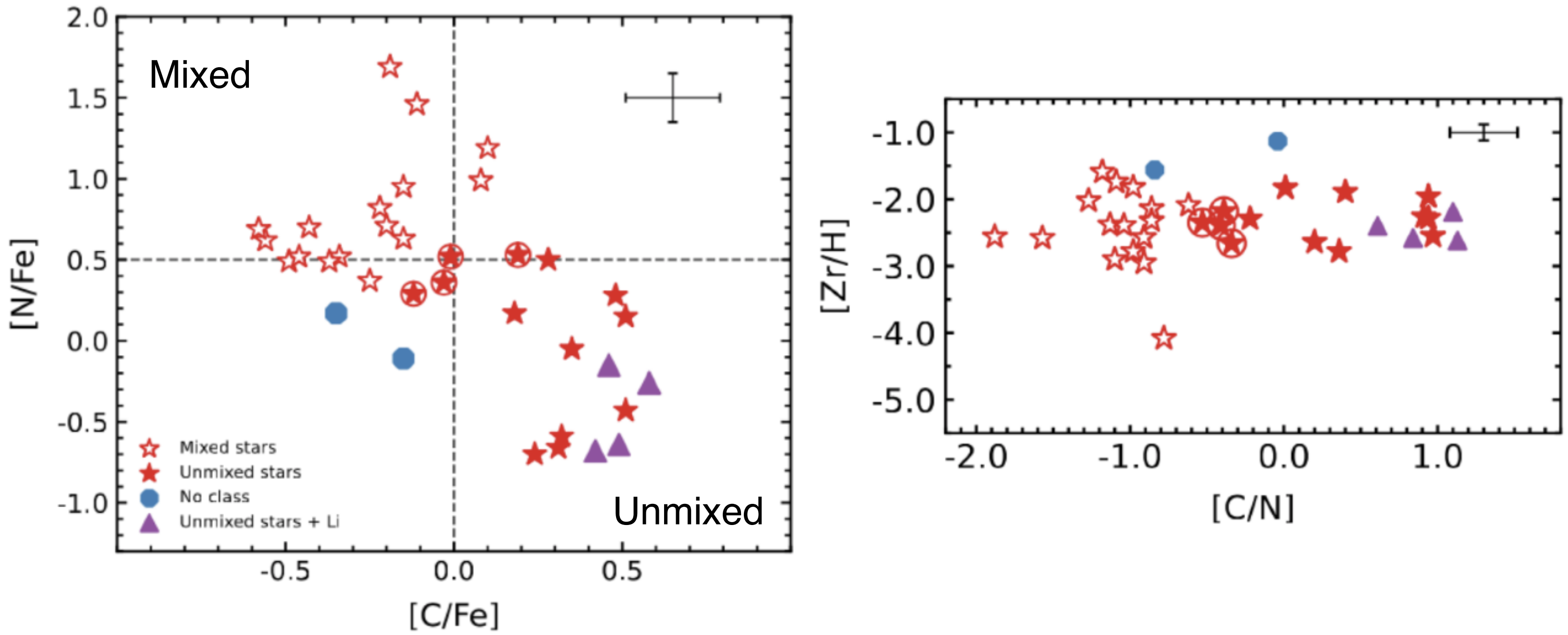
Combining light and heavy elements

Raphaela Fernandes de Melo
PhD Student

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

Fernandes de Melo et al. 2024





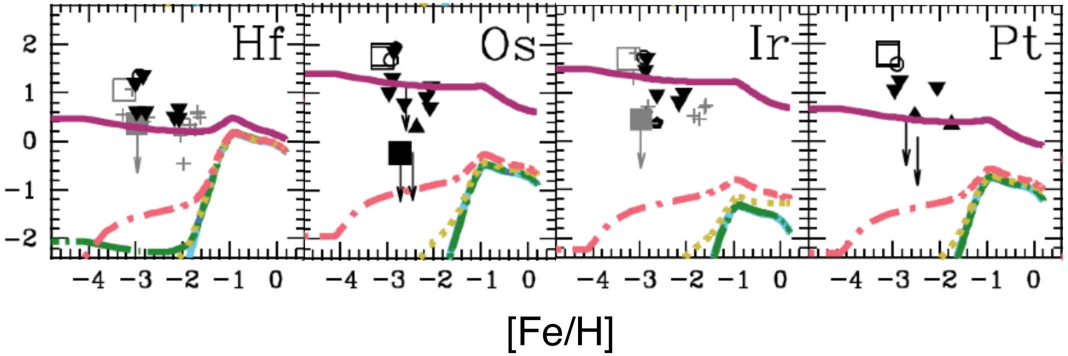
Extra-mixing occurring after the RGB bump affects C,N but not heavy elements abundances

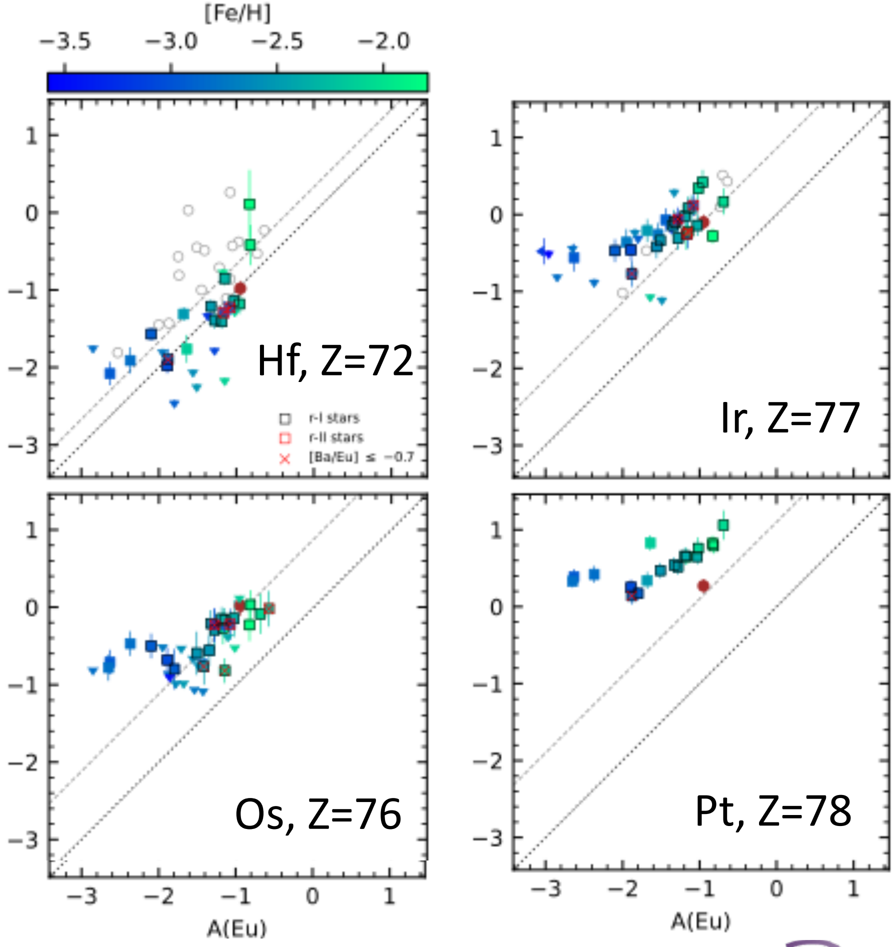
Third r-process peak elements

Arthur Alencastro Puls
Postdoc

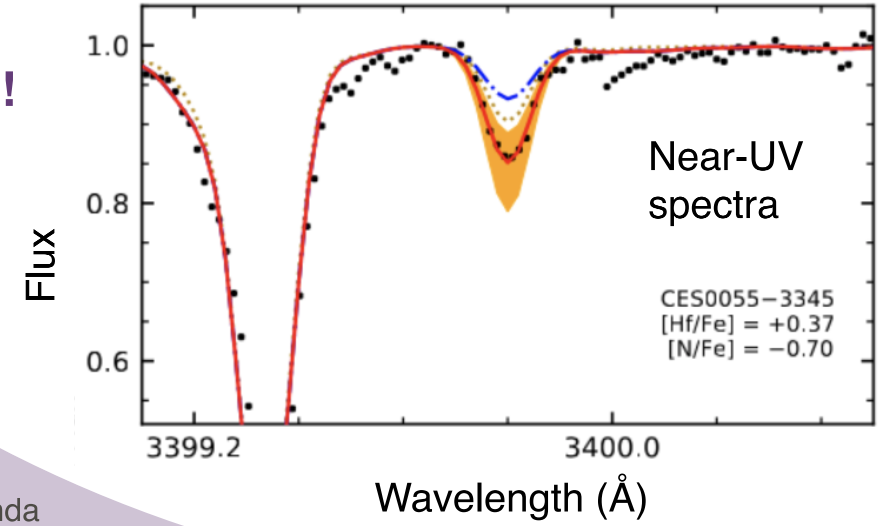
CERES IV (Alencastro Puls et al., 2025): chemical abundances of Hf, Os, Ir, and Pt

Kobayashi et al. 2020





Poorly studied heavy elements!



Thank you for your attention!