Observational evidence of r-process enrichment in the Galaxy

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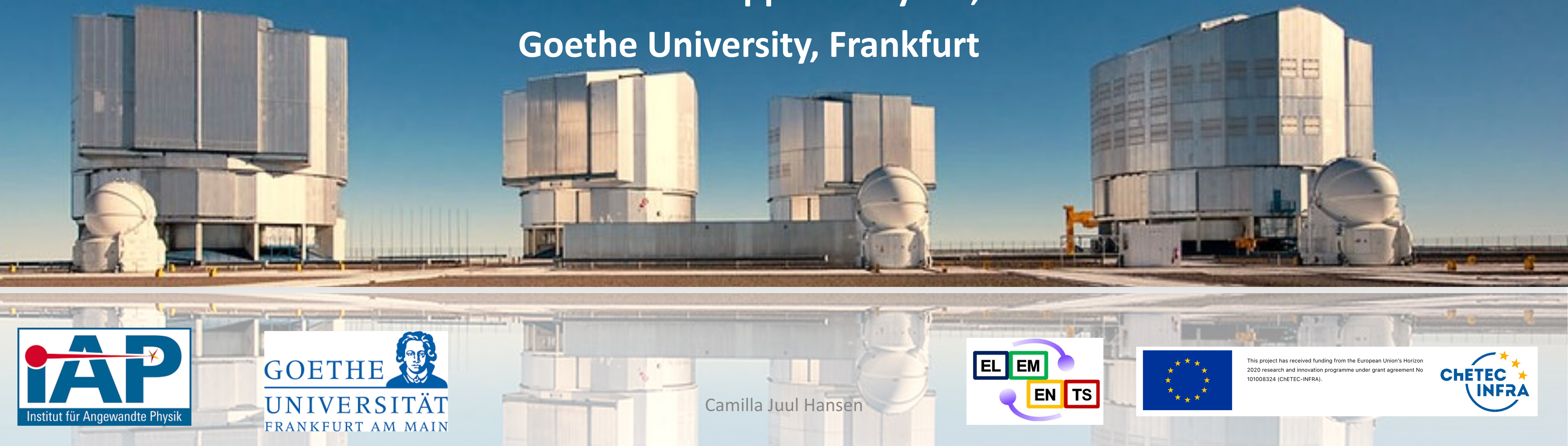


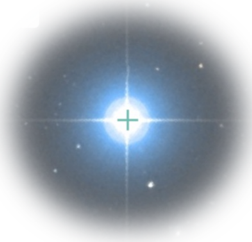
This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101008324 (ChETEC-INFRA).

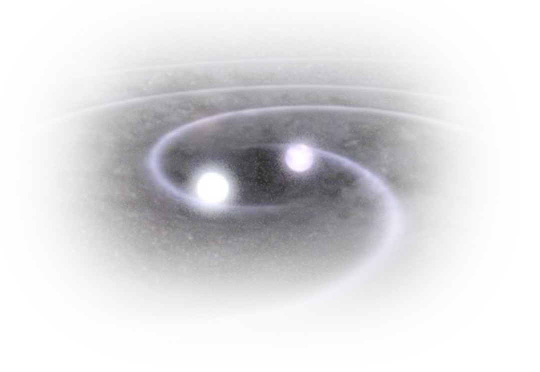
How do we trace the formation of elements?

- The elements can be traced in a number of astrophysical events:
  - Low-mass stars
  - Meteoritic grains

  - Massive stars
  - Transient events (GBRs, kilonovae)

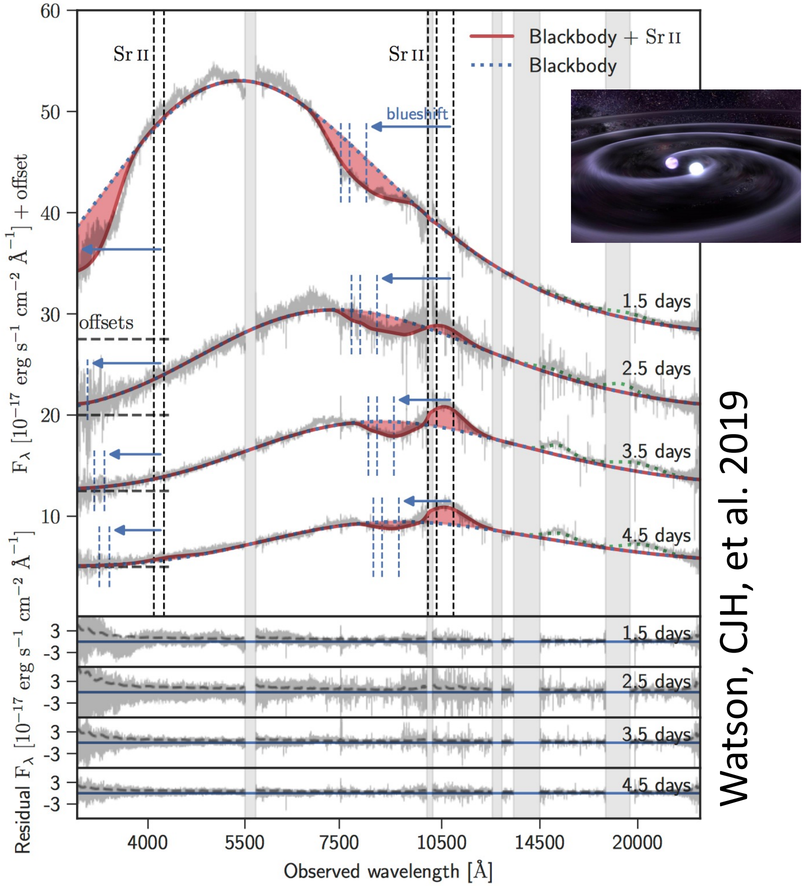
  - …..





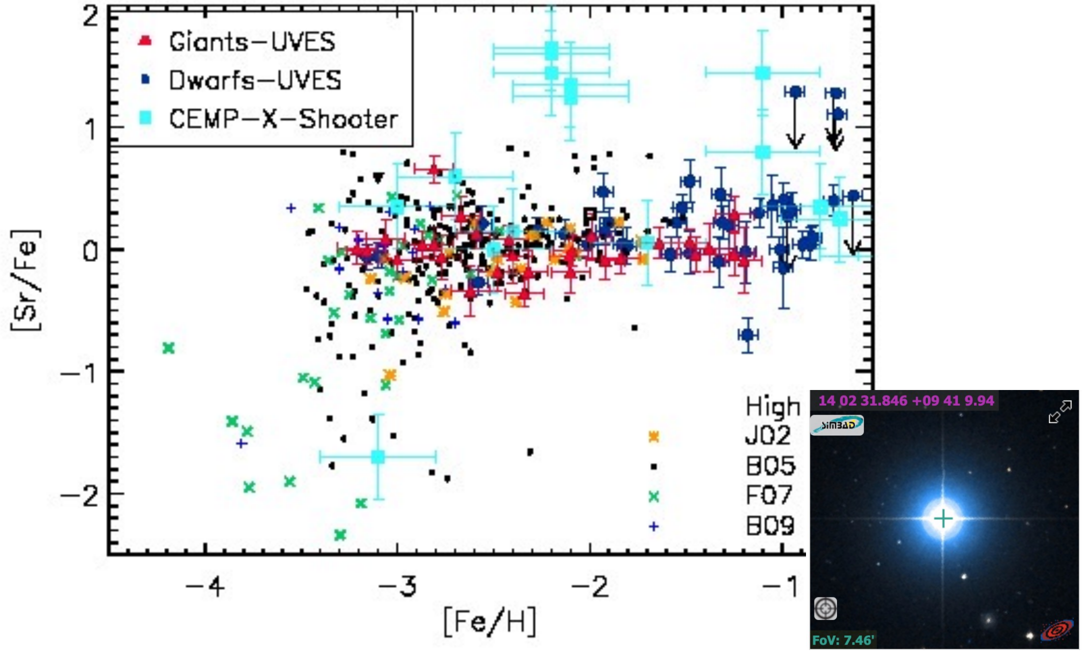
How do we trace the origin of the elements?

- Direct tracers → Kilonovae (Sr)
- Indirect tracers → old stars (Sr)



Watson, CJH, et al. 2019

Adapted from CJH+12



Sr in the merger event vs Sr in old Milky Way Stars

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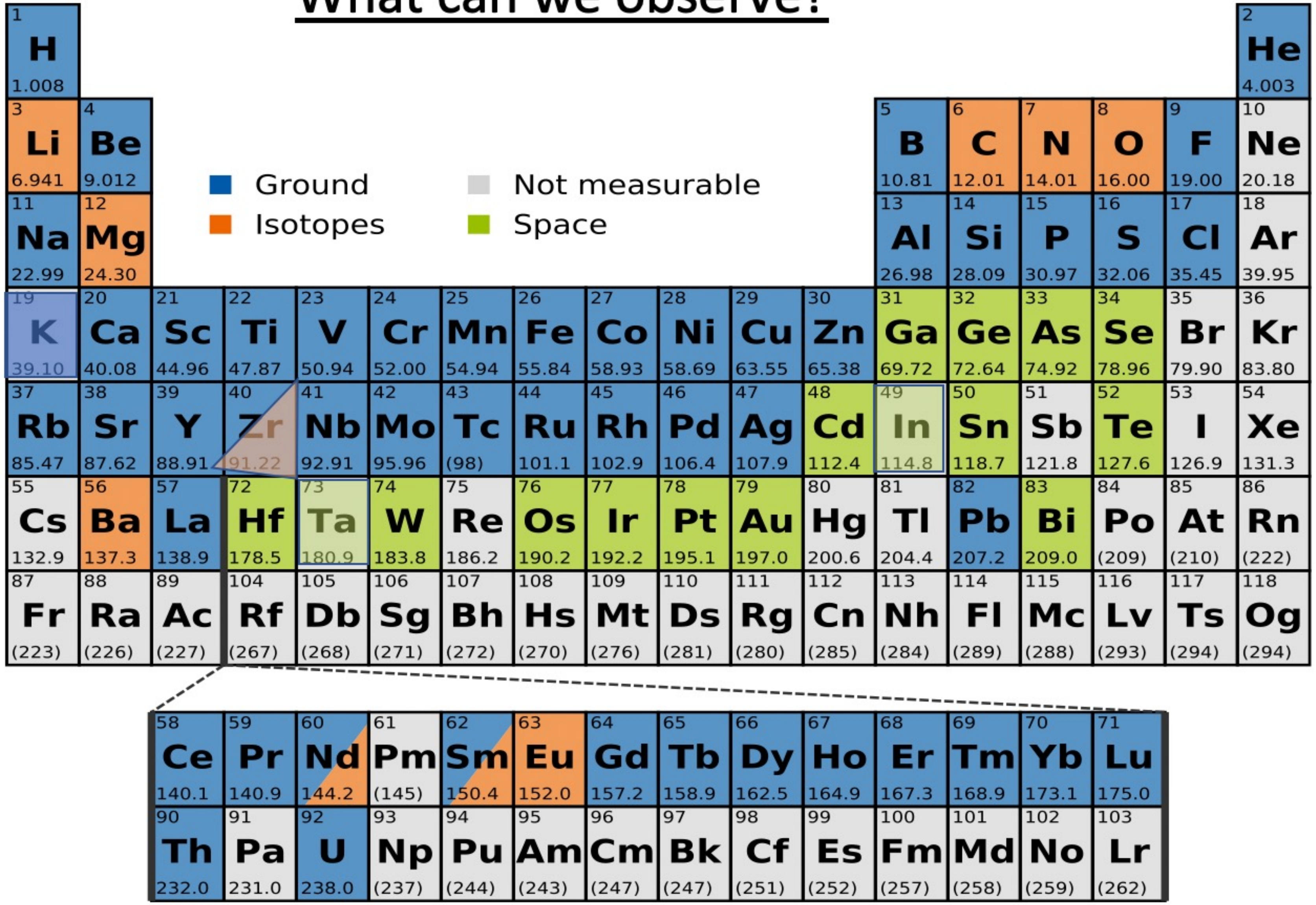
What can we observe?



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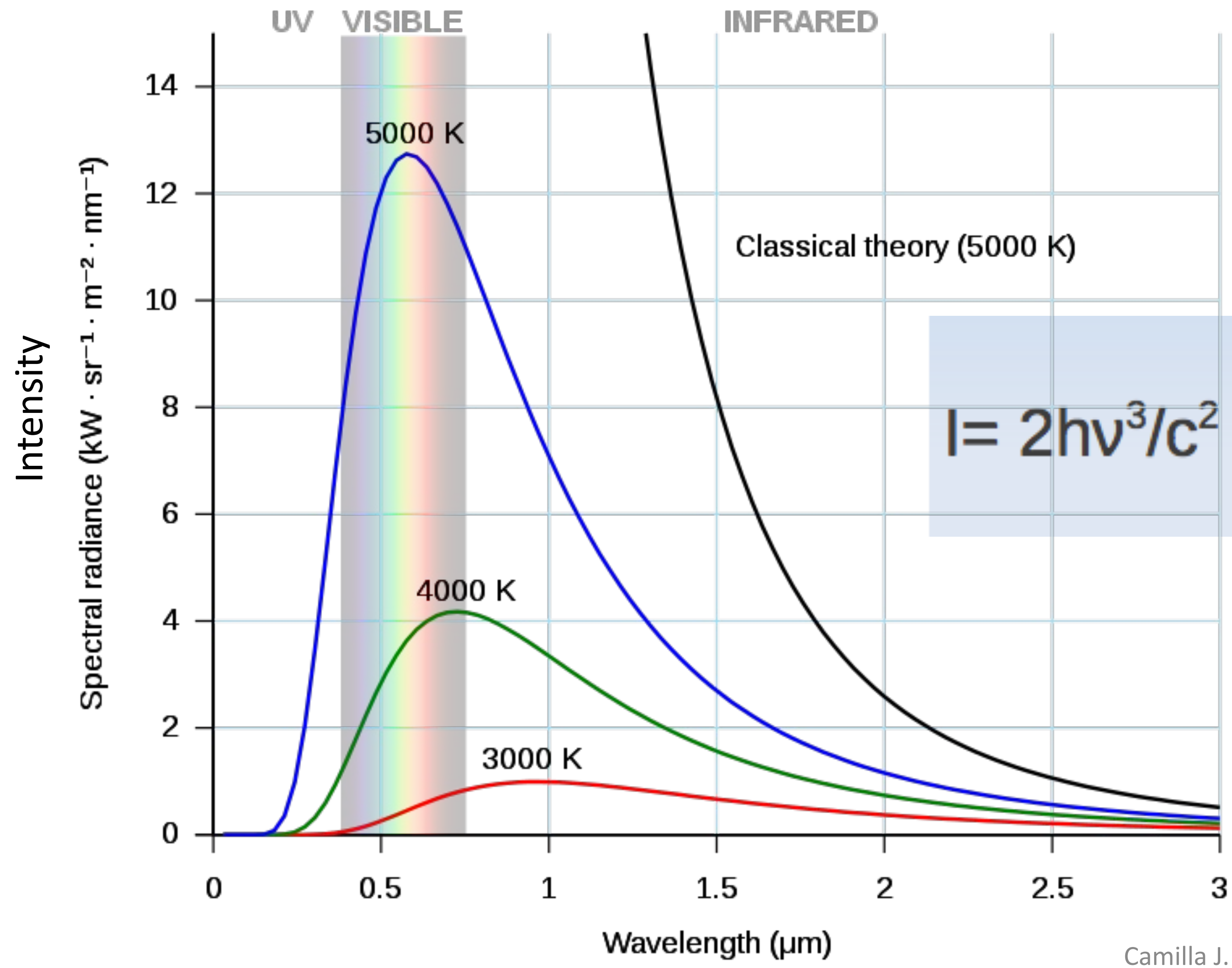
Temperature in Stars

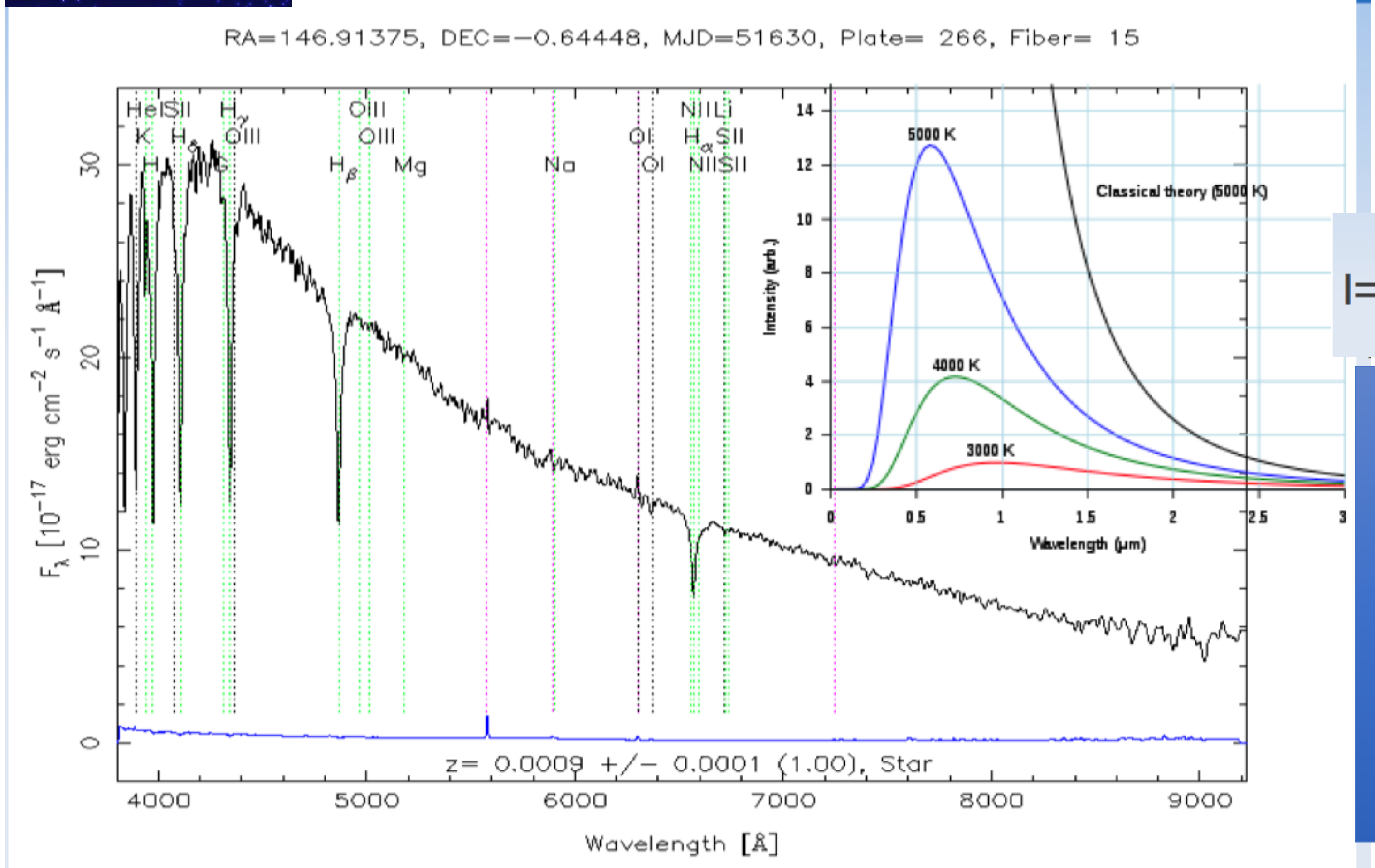


$$I = 2h\nu^3/c^2 \; 1/(e^{h\nu/k\mathbf{T}}-1)$$

Max Planck
(1858-1947)

Image:
https://en.wikipedia.org/wiki/
Black_body

Information from Stars



http://skyserver.sdss.org/dr1/en/get/specById.asp?ID=75094093029441536

$I = 2h\nu^3/c^2 \; 1/(e^{h\nu/kT}-1)$

Spectra:

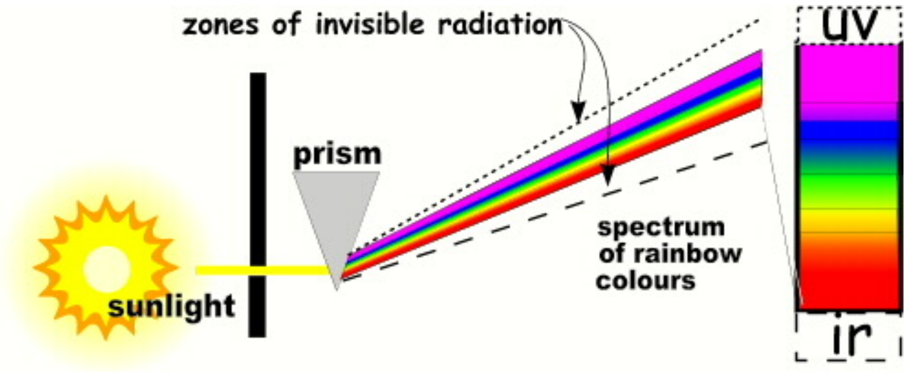
Temperature

Pressure

'Metallicity'

Chemistry

Spectral analysis
&
Data reduction



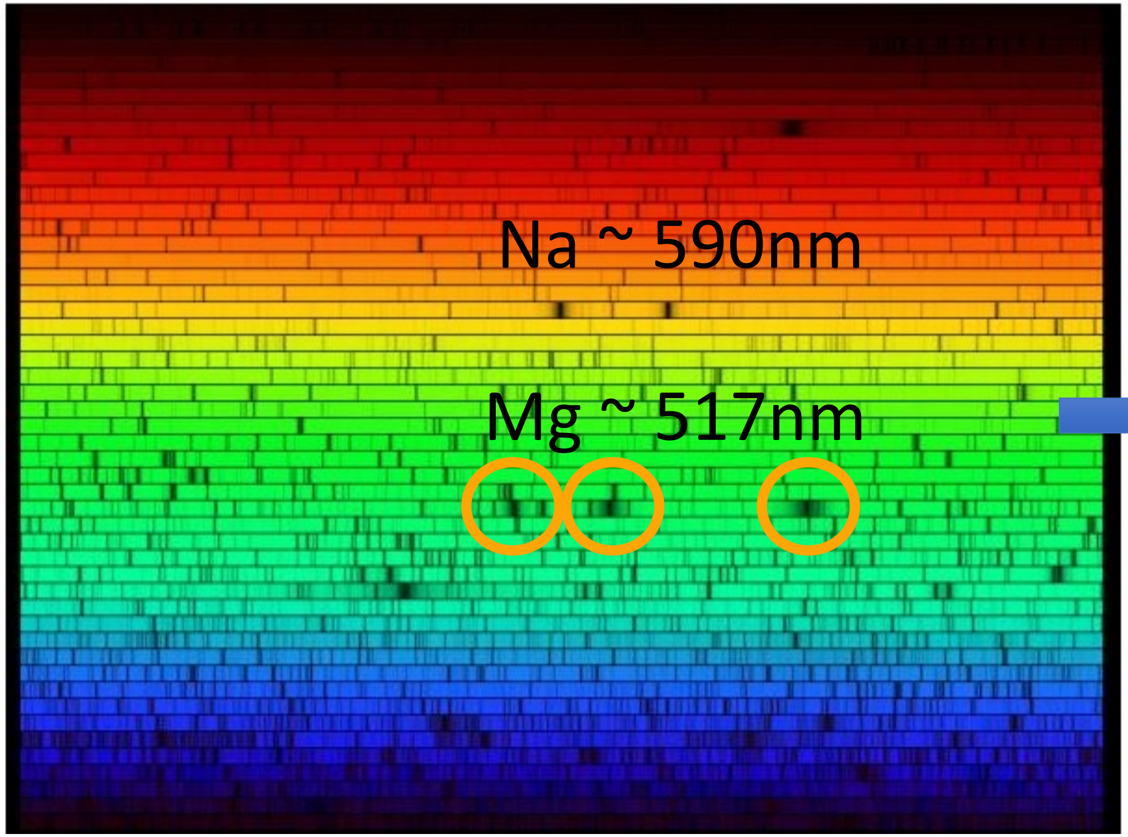
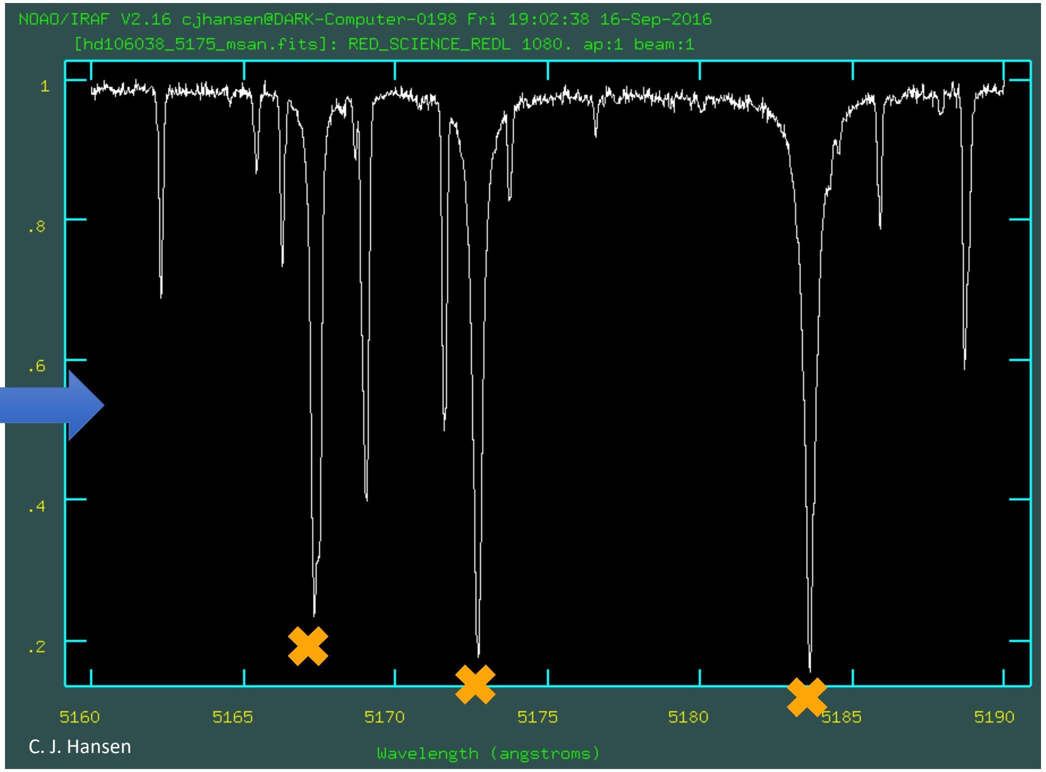


Image: https://apod.nasa.gov/apod/ap180926.html



C. J. Hansen

Spectral analysis

$$W_\lambda = \int_{\text{line}} \frac{\mathcal{F}_c - \mathcal{F}^l_\lambda}{\mathcal{F}_c} \, d\lambda.$$

Equivalent Width (EW or W)

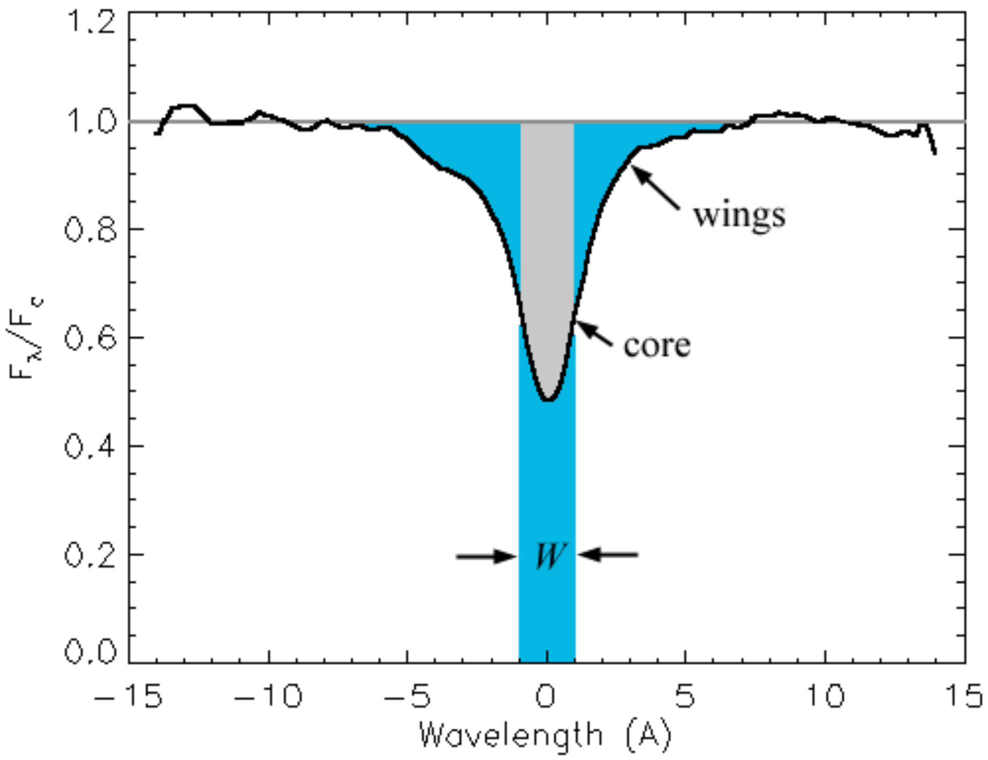
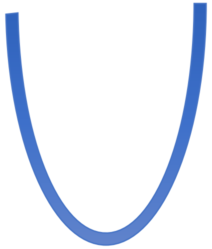


Image: http://www.bdnyc.org/2012/03/spectral-line-measurements-visualized/



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Abundances (A)

$$\log\left(\frac{w}{\lambda}\right) = \log\left[\text{constant}\,\frac{\pi e^2}{mc^2}\,\frac{N_j/N_\mathrm{E}}{u(T)}N_\mathrm{H}\right] + \log A + \log g_n f\lambda - \theta_\mathrm{ex}\chi - \log\kappa_\nu$$

$$= \log C + \log A + \log g_n f\lambda - \theta_\mathrm{ex}\chi - \log\kappa_\nu.$$

EW
Equivalent
width

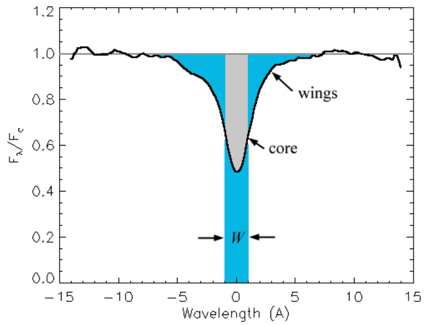
Const.

Abundance

Atomic
data
(oscillator
strength)

Temp.

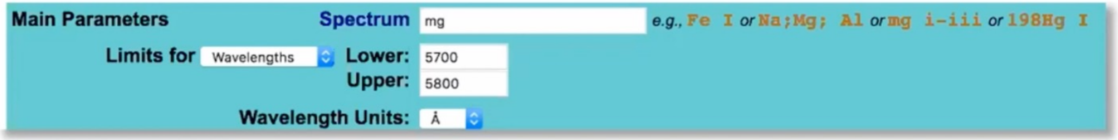
Absorption
coefficient →
pressure/logg



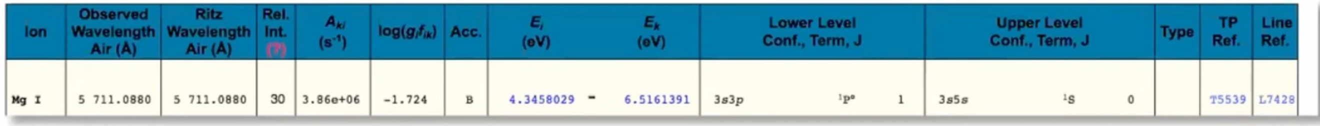
Impact and assumptions

Line lists:

→ **VALD** (http://vald.astro.uu.se/)
→ **NIST** (https://physics.nist.gov/PhysRefData/ASD/lines_form.html)



Main Parameters
Spectrum: mg — e.g., Fe I or Na;Mg; Al or mg i-iii or 198Hg I
Limits for: Wavelengths — Lower: 5700 — Upper: 5800
Wavelength Units: Å



Ion	Observed Wavelength Air (Å)	Ritz Wavelength Air (Å)	Rel. Int. (?)	A_{ki} (s^{-1})	$\log(g_i f_{ik})$	Acc.	E_i (eV)		E_k (eV)	Lower Level Conf., Term, J	Upper Level Conf., Term, J	Type	TP Ref.	Line Ref.
Mg I	5 711.0880	5 711.0880	30	3.86e+06	-1.724	B	4.3458029	-	6.5161391	3s3p $^1P^o$ 1	3s5s ^1S 0		T5539	L7428

- Atomic physics

- 1D, LTE vs 3D, NLTE

Assumptions – Excitations → Boltzmann Eq.,

$$\frac{N_b}{N_a} = \frac{g_b\, e^{-E_b/kT}}{g_a\, e^{-E_a/kT}} = \frac{g_b}{g_a}\, e^{-(E_b-E_a)/kT}.$$

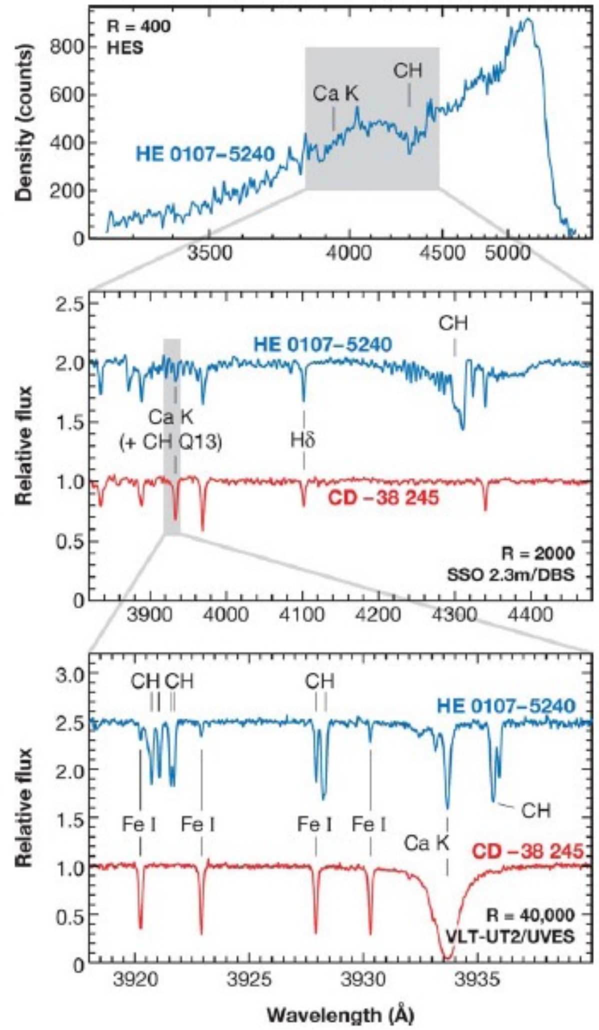
Ionisation → Saha Eq., and

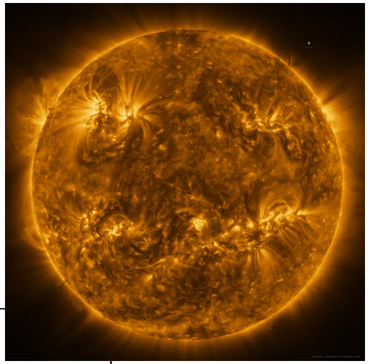
$$\frac{N_{i+1}}{N_i} = \frac{2Z_{i+1}}{n_e Z_i}\left(\frac{2\pi m_e kT}{h^2}\right)^{3/2} e^{-\chi_i/kT}.$$

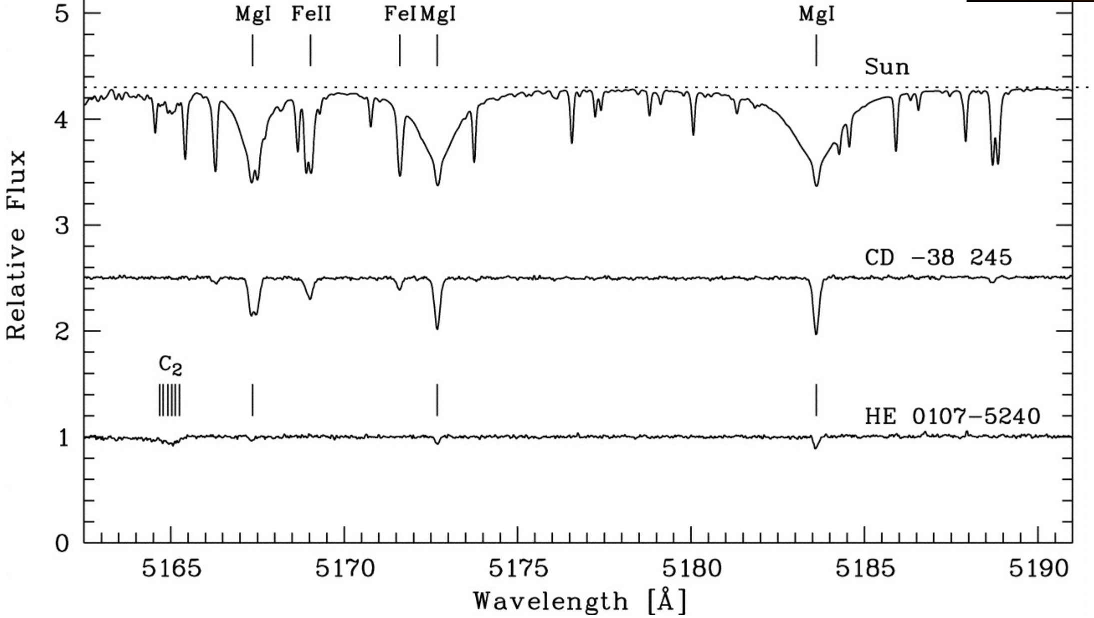
$$Z = \sum_{j=1}^{\infty} g_j\, e^{-(E_j-E_1)/kT}.$$

I = B (Planck Function)

Old stars vs the Sun







~ 5 bil. years

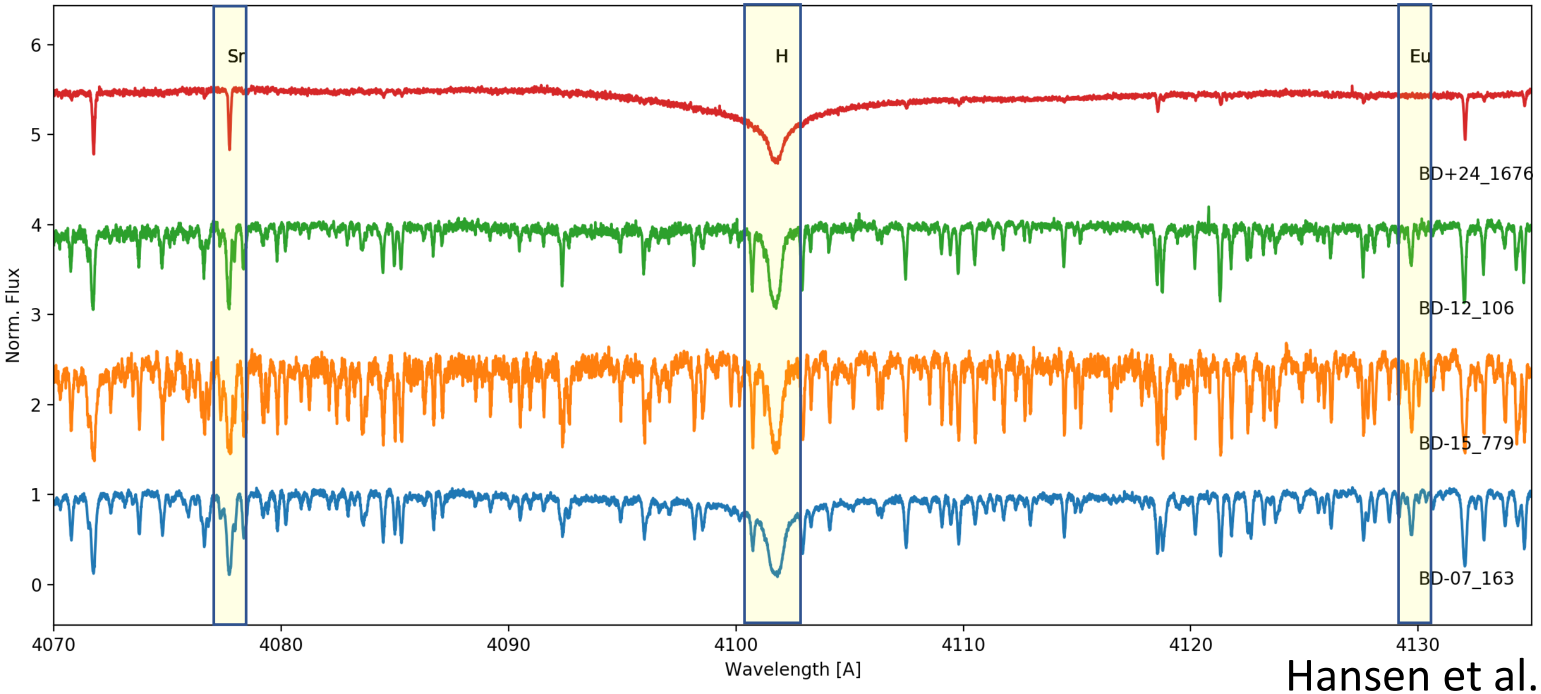
12-13 bil. years

Beers & Christlieb 2005, ARA&A

Camilla Juul Hansen, IAP

Metal-poor, old stars

Looking back in time



[Fe/H]

-2.53

-2.11

-1.48

-1.44

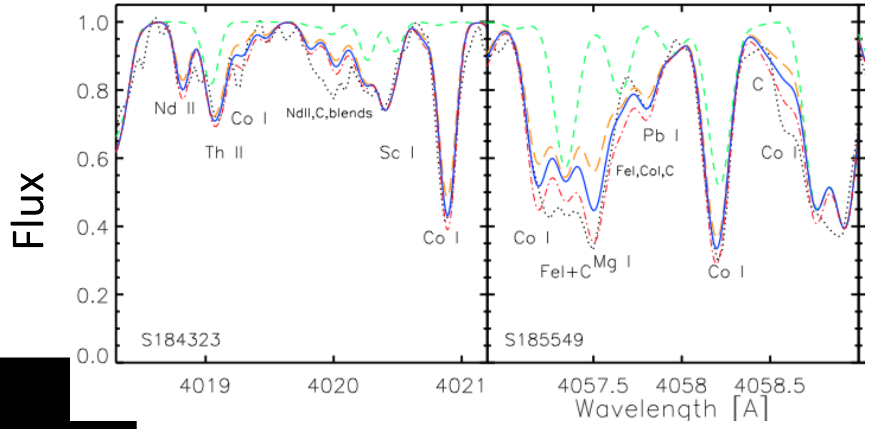
Lines weaken!

Hansen et al. 2020

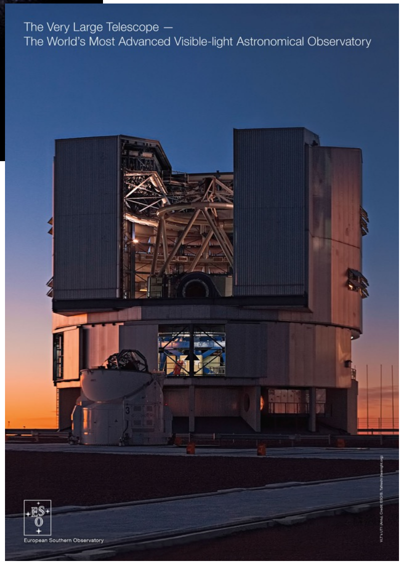
- Sample of 14 stars: -2.8 < [Fe/H] < -0.9, photometric temperatures and gravities from Gaia parallaxes.
- Abundances of 34 elements

Old Stars

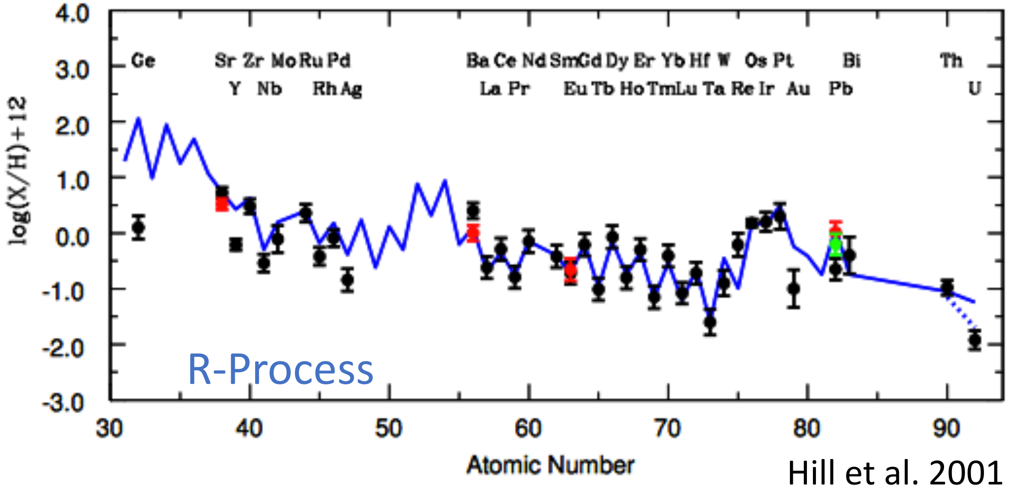
Hansen et al. 2018



Old stars provide the first insight into how heavy elements were created. These are ‘frozen’ in the stellar surfaces and today allow for studies of nucleosynthetic events that occurred 13 billion years ago.



Th & Eu → Age



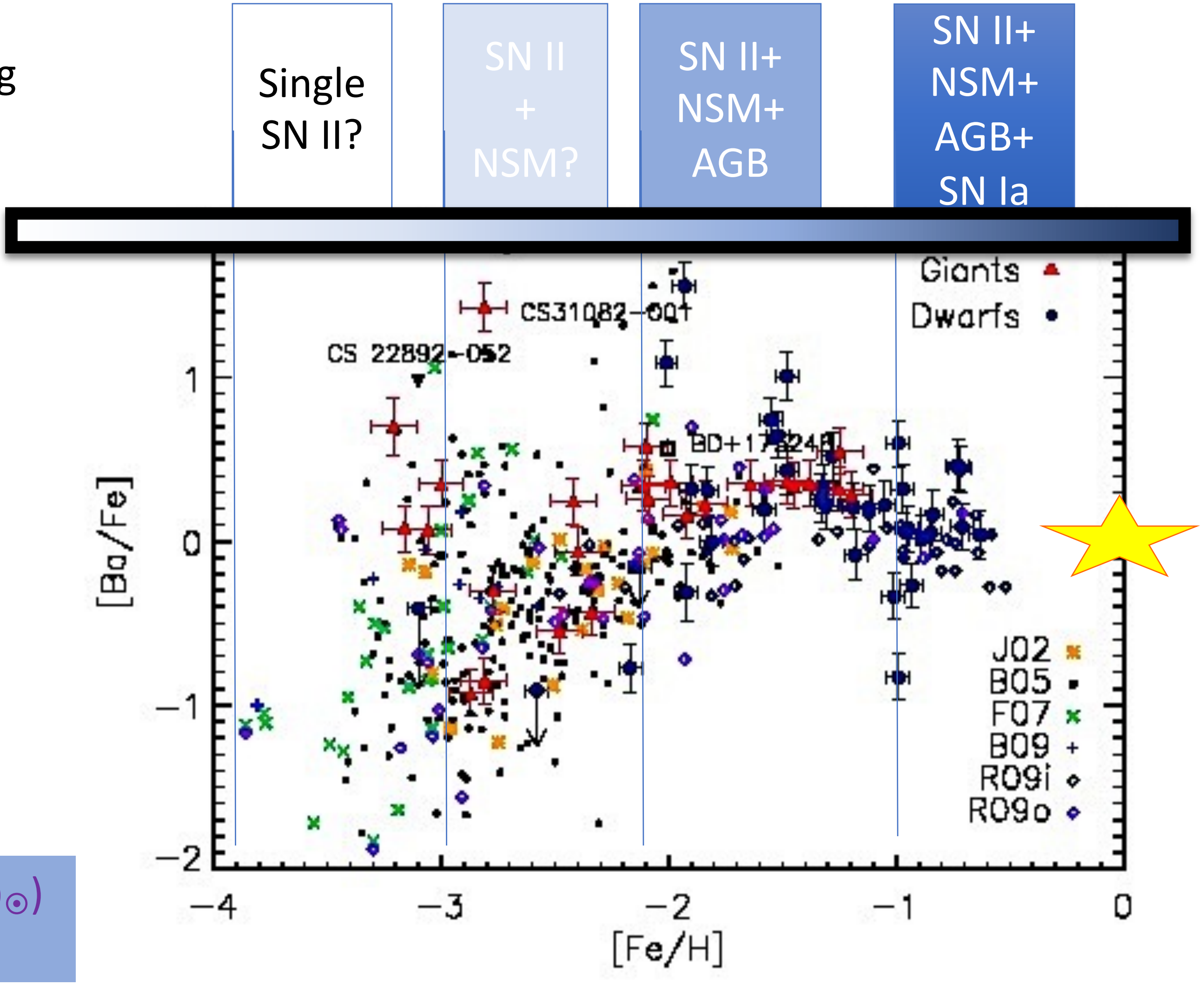
Hill et al. 2001

Chemical Evolution of the Milky Way

Big Bang

- The Sun ([Fe/H]=0)
- Traces of SN Ia ([Fe/H] > ~ -1)
- AGB stars ([Fe/H] > ~ -2.5?)
- NSM (NS-NS merger)
- Core-collapse supernovae

$[\mathrm{Ba/Fe}] = \log(\mathrm{Ba})*-\log(\mathrm{Ba})_\odot-(\log(\mathrm{Fe})*-\log(\mathrm{Fe})_\odot)$



Single SN II?

SN II + NSM?

SN II+ NSM+ AGB

SN II+ NSM+ AGB+ SN Ia

Looking back

Chemical concentration

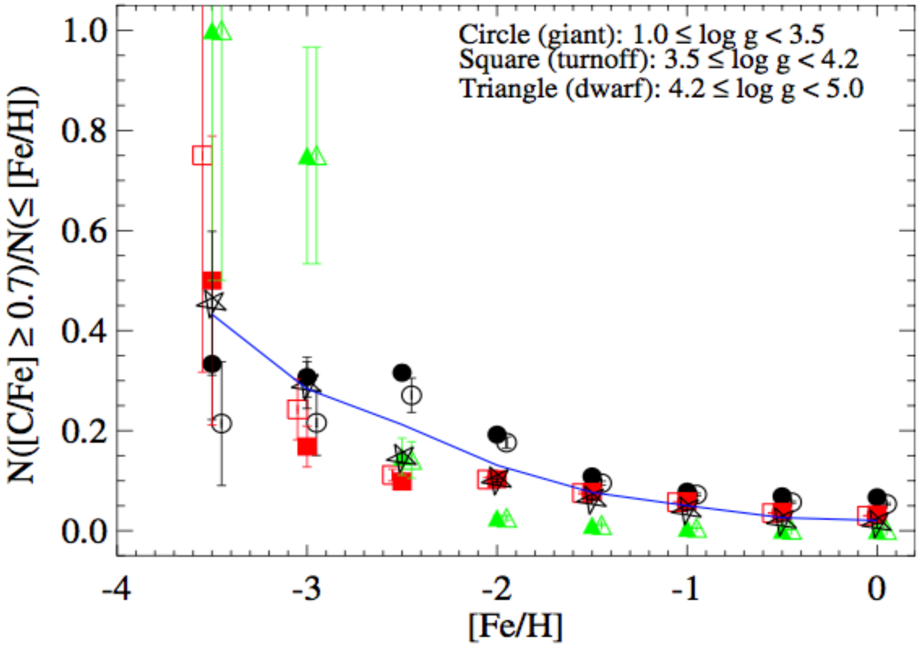
The Sun as reference: [X/Fe]=0

Hansen et al. 2012

Looking back – metal-poor Stars

- Metal-poor stars, chemically more simple
- Lower [Fe/H]
- Often high [C/Fe] → these stars are carbon enhanced metal-poor stars – CEMP stars

Lee et al. 2013

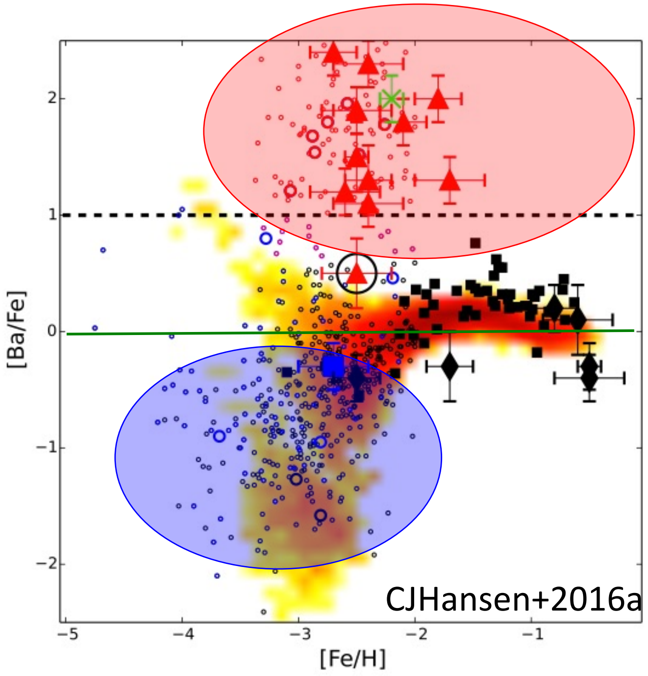


The First Stars – the cleanest nucleosynthesis traces

- The oldest, most metal-poor stars → C-rich!
- Cleanest fingerprints = mono-enrichment

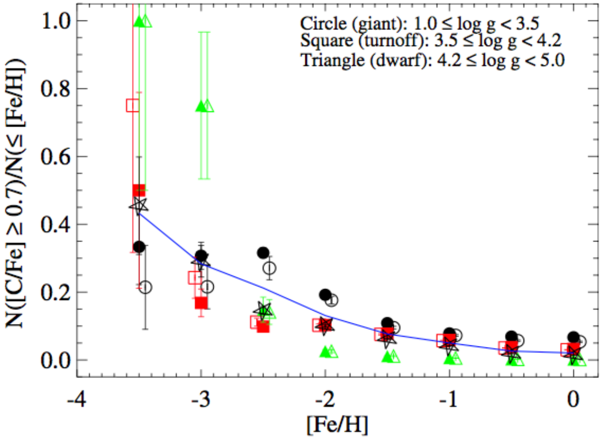
CEMP-s stars are typically binaries
(Lucatello et al. 2005; Starkenburg et al. 2014)
Mass transfer of s-process from an AGB star to a low-mass secondary – NOT primordal composition

CEMP-no – no heavy element enrichment – true 2nd generation – primordial composition!
Possible event: Faint fall-back SN
(Tominaga et al. 2014; Bonifacio et al. 2015)



CJHansen+2016a

Lee et al. 2013

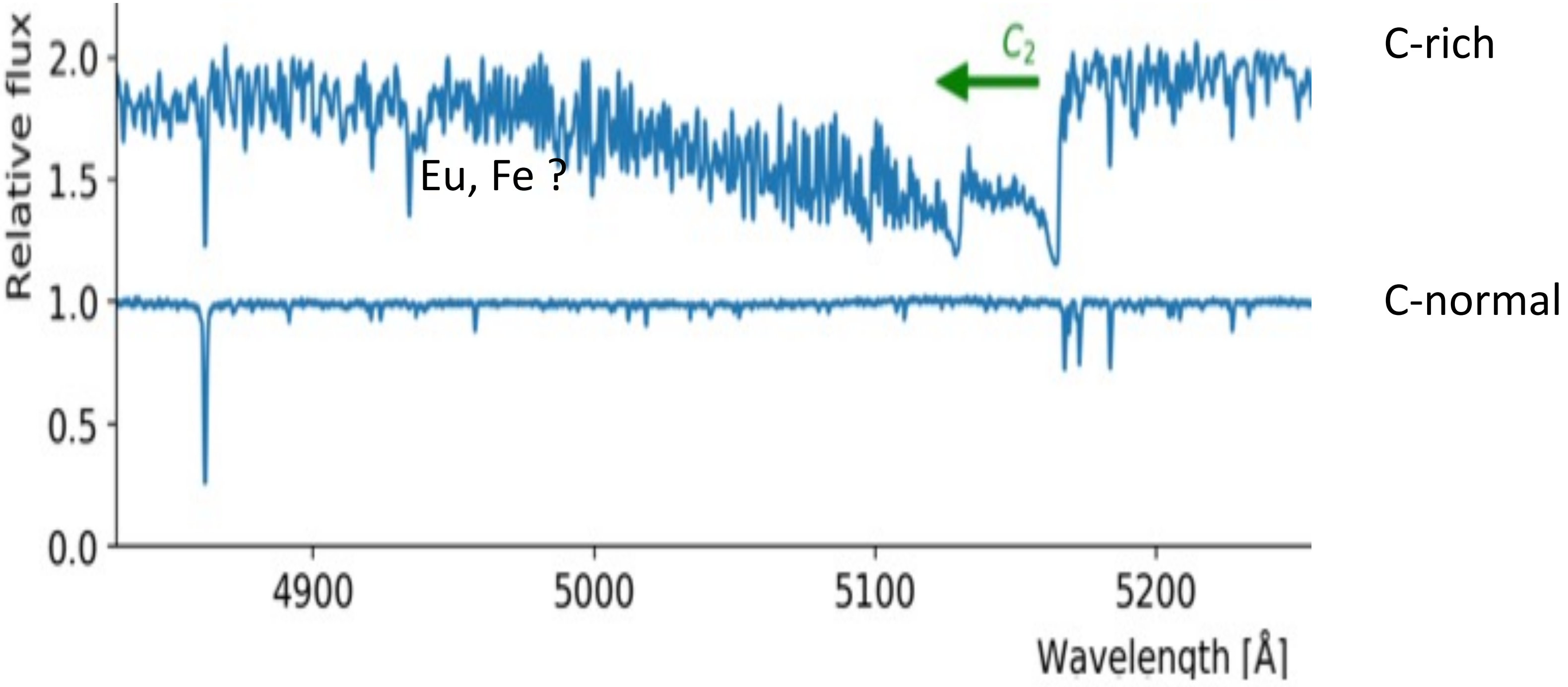


CEMP – Carbon Enhanced Metal-Poor Stars
(Spite et al. 2013)

Models: Gabriele Cescutti

What does a C-rich star look like?

- Strong C bands (CH, C_2, CN, CO..)
- Some bands are also sensitive to the stellar parameters



Classifying CEMP stars

- High C (A(C) ~8.25) CEMP-s/ CEMP-i
- Low C (A(C) ~6.5): CEMP-no (Spite et al. 2013, Bonifacio et al. 2015)
- Solar A(C) = 8.5

  (Lodders et al. 2009)

- The majority of CEMP stars above [Fe/H] = -3 are CEMP-s/i (formed in situ – inner halo)
- Below -3 CEMP-no (outer halo?, accreted?) – often remote/faint

Spite et al. 2013

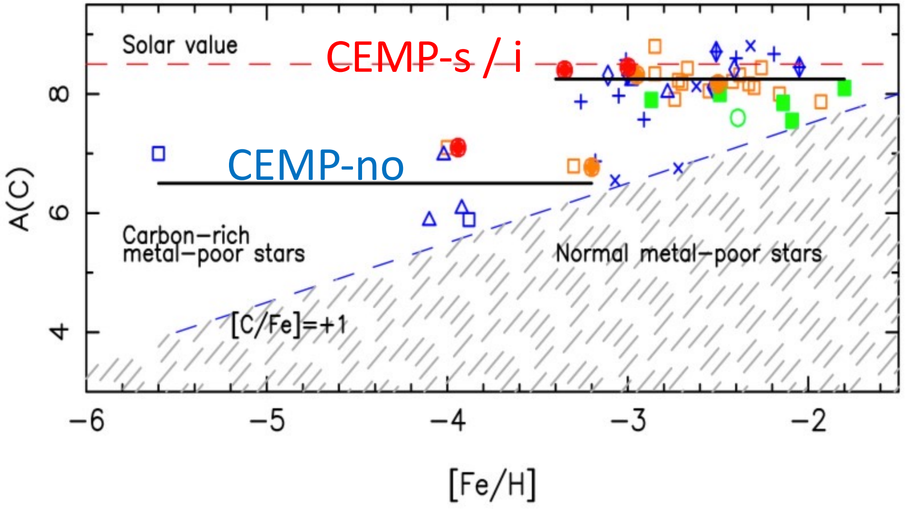
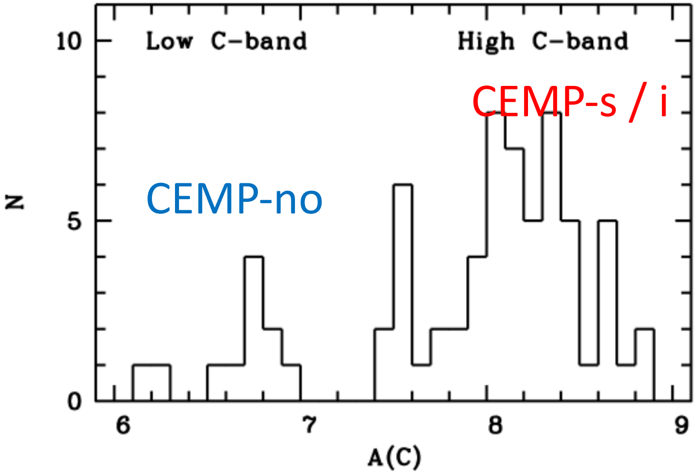


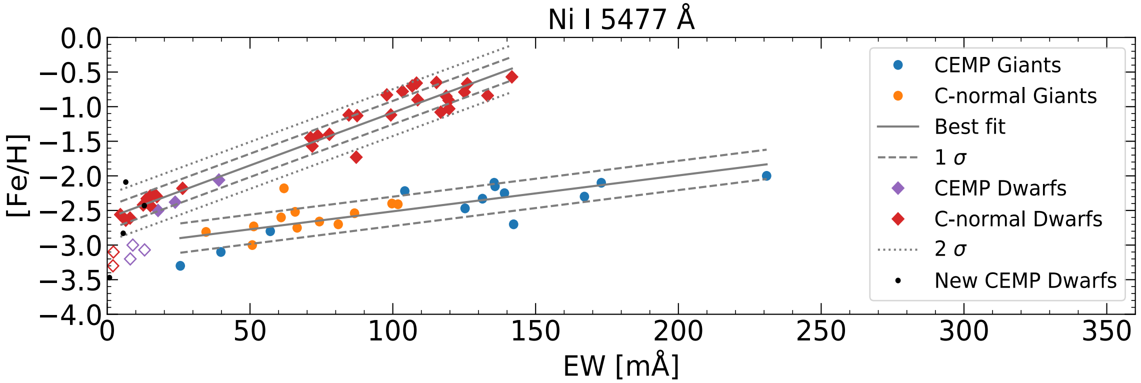
Fig. 14. Abundance of carbon A(C) vs. [Fe/H] in dwarfs and turnoff

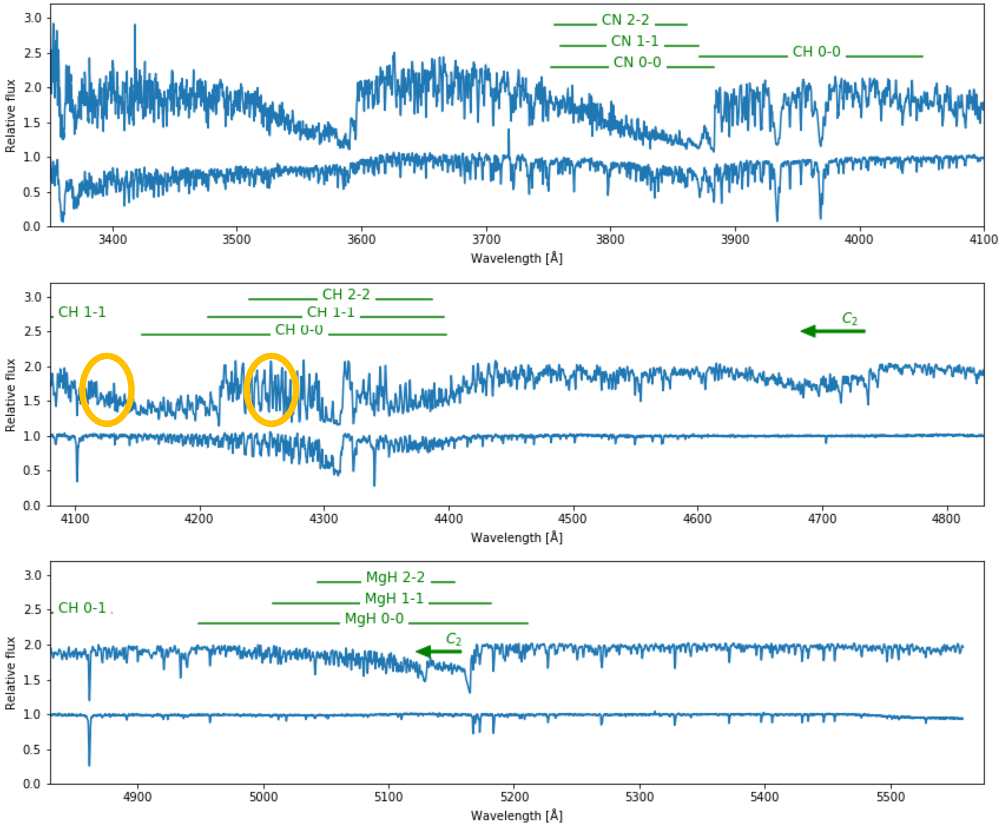


Bonifacio et al. 2015

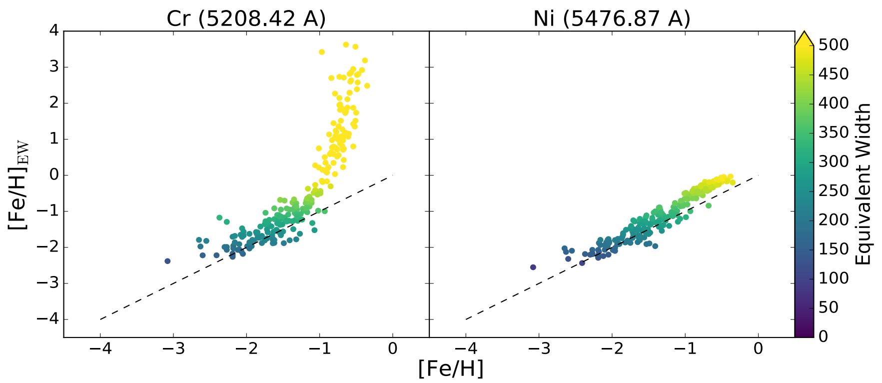
Metallicities in CEMP stars

- CEMP stars are often faint and therefore we need to observe them with larger telescopes – often lower resolution is used to save costs
- Differences in e.g., [Fe/H] >0.3dex has been seen between LR and HR (e.g. Hansen et al. 2019, Arentsen et al. 2022)
- An empirical [Fe/H] tracer can help solve this
- 10 (7) elements were tested → best tracer = Ni (also useful in C-normal stars)



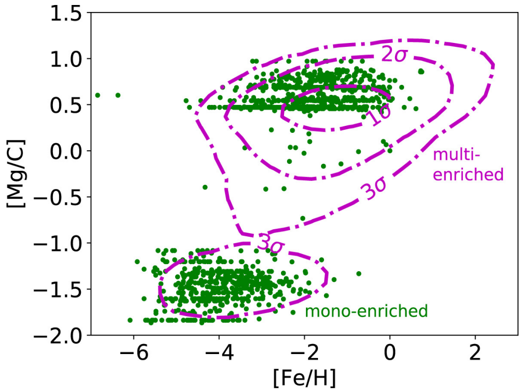


Singh et al. 2020

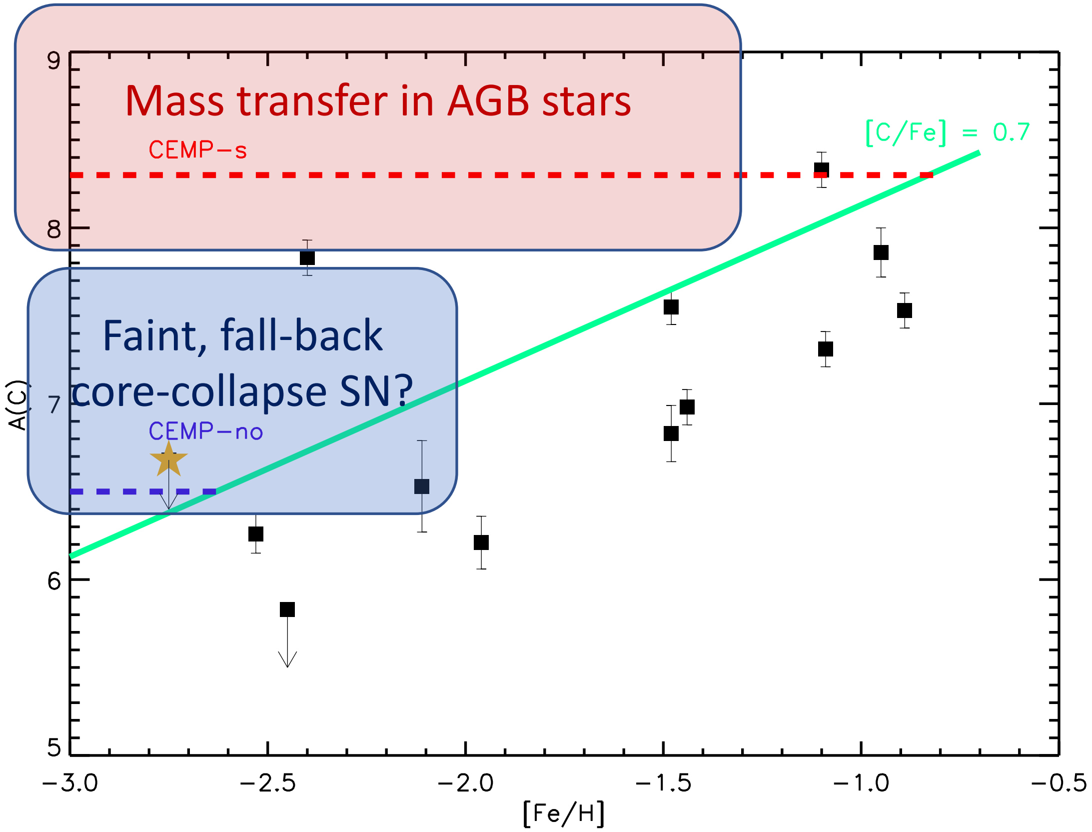


Early chemical enrichment

- Bona fide 2nd generation stars
- Carbon Enhanced Metal-Poor stars → CEMP-no stars
- Stars with low [Mg/C]



Hartwig et al. 2018



Mass transfer in AGB stars

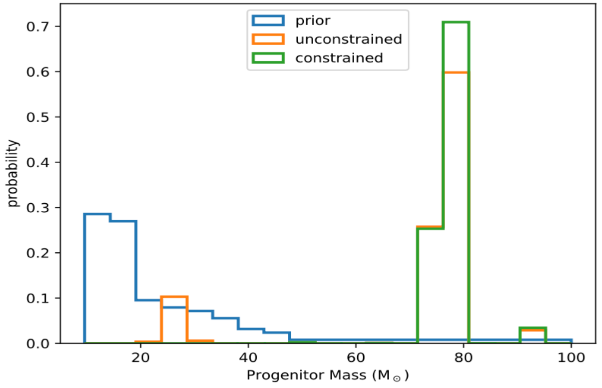
Faint, fall-back core-collapse SN?

Dilution processes

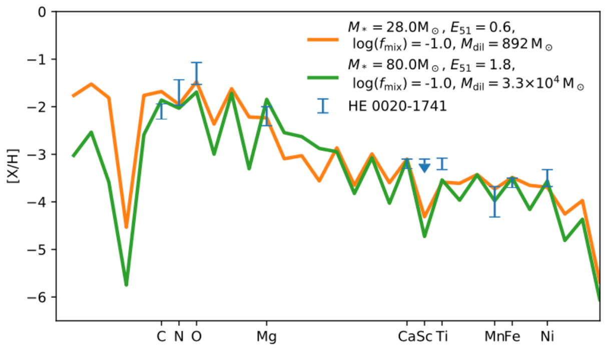
- All material detected in abundances has been mixed or diluted
- Tested this for Pop III SN using a realistic mixing and improved abundance including a Bayesian fitting:
  - $M_{dil,min}=4/3\pi n_o \mu m_H R^3_{fade}$
    $=1.9\ 10^4 M_\odot E^{0.96}_{51} n^{-0.11}_o$
  - Abundance: $\log(M_i/(\mu X_H M_{dil}))-\log(N_i/N_H)_\odot$

Best fit model

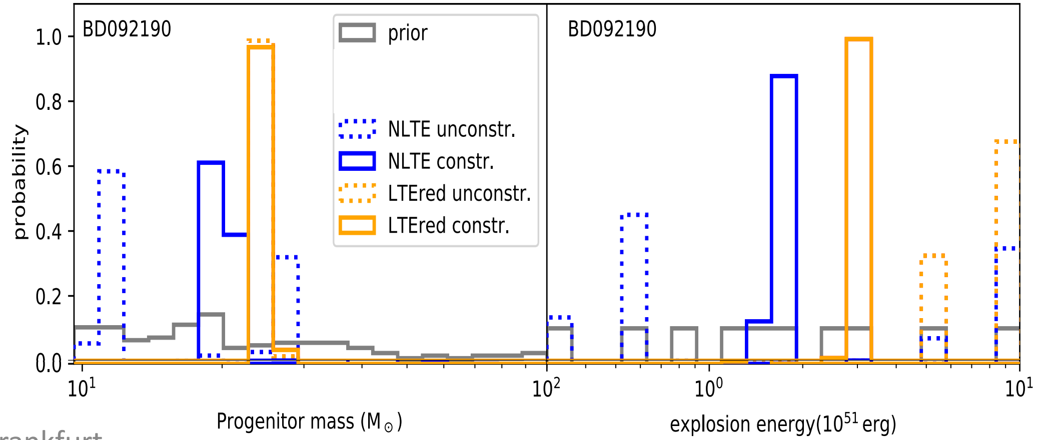
LTE	NLTE
25.5M, E_{51}=3	19.2M, E_{51}=1.5
Constrained	Constrained



Magg et al. 2020

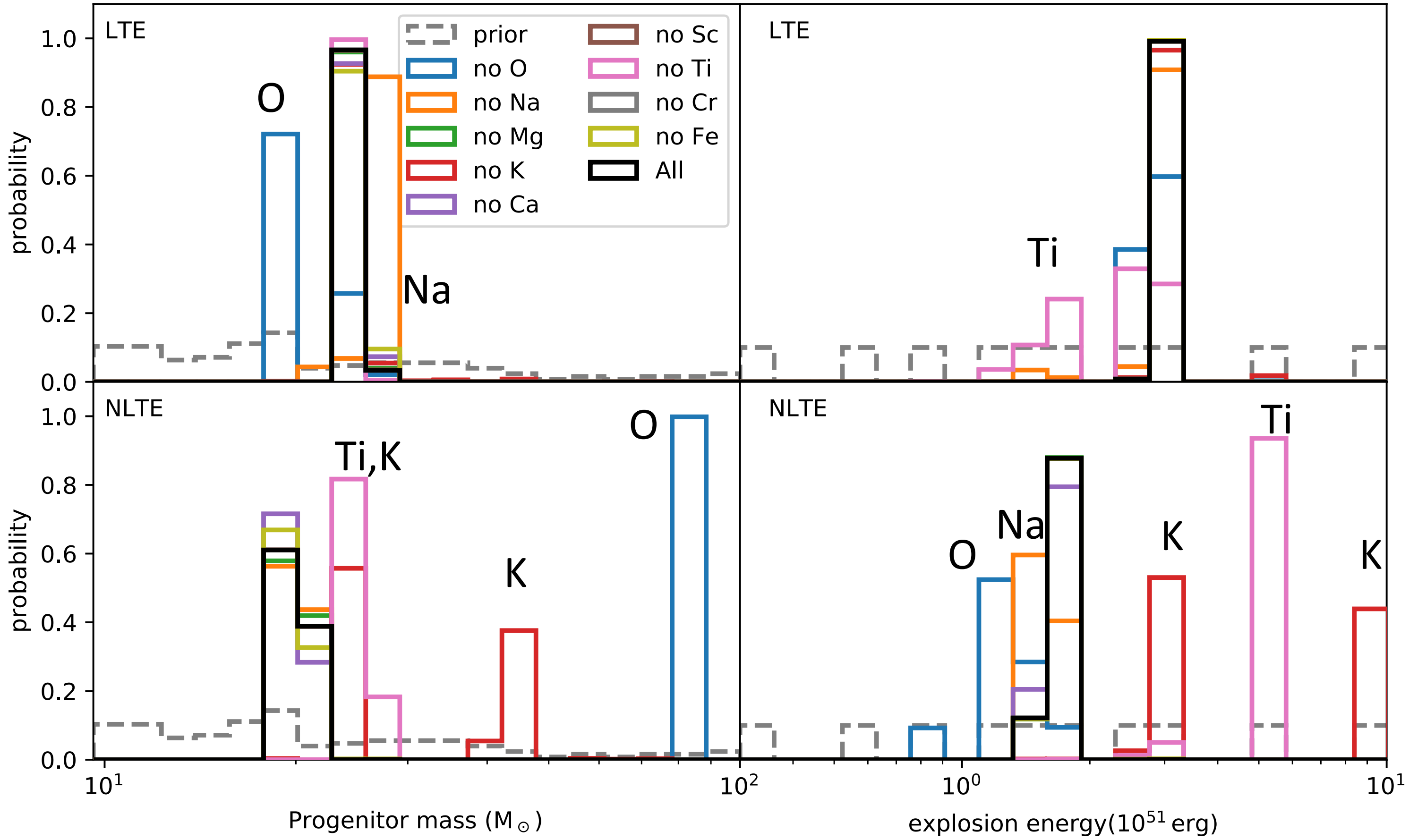


Hansen et al.2020



Predictive power of elements - patterns

Hansen et al. 2020



<u>Test:</u> Removed shown element from fit

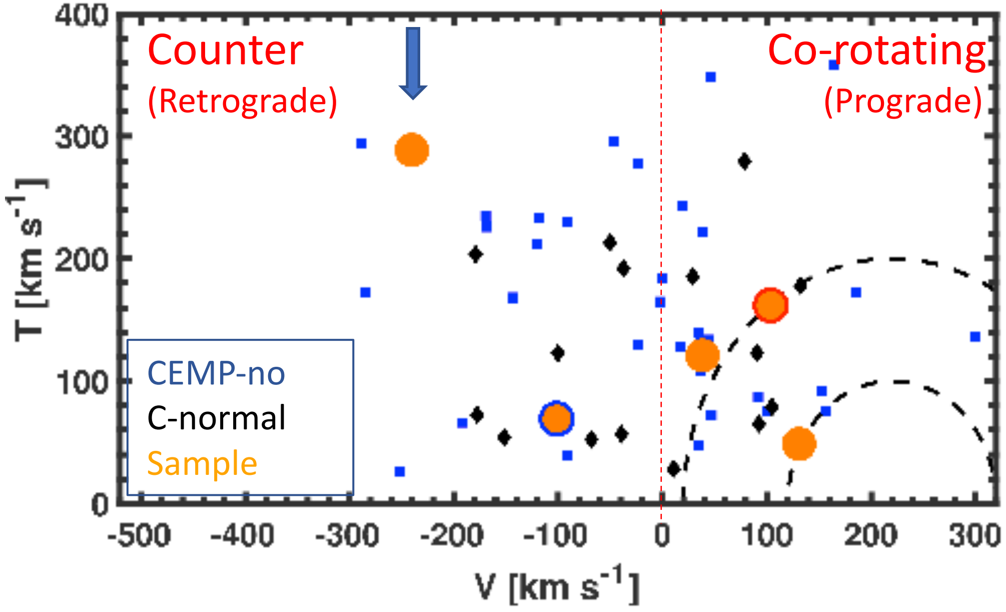
- <u>Key elements:</u>

C, O, Na, K, Ti + Co or Mn & Mg or Ca

- **Need odd/even!**

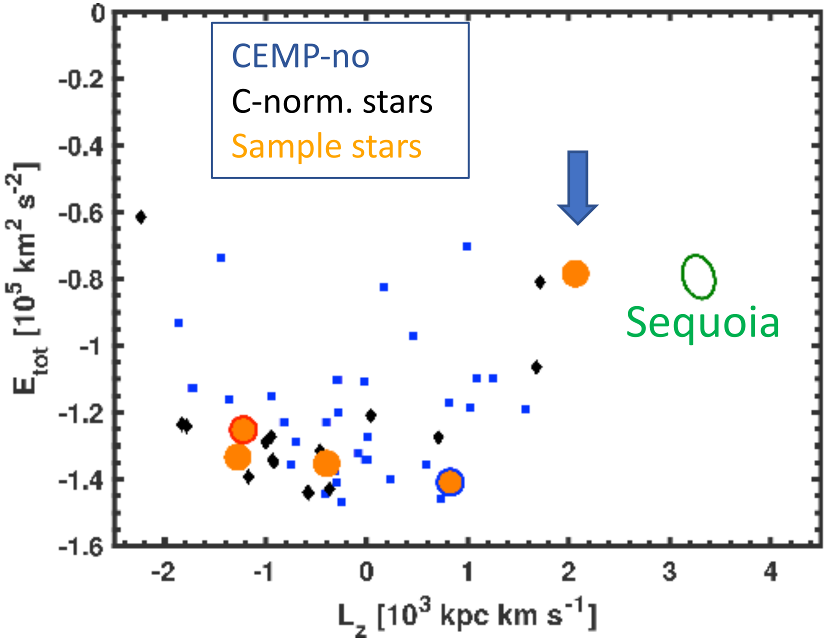
Origin of BD+09 2190

Hansen et al. 2020



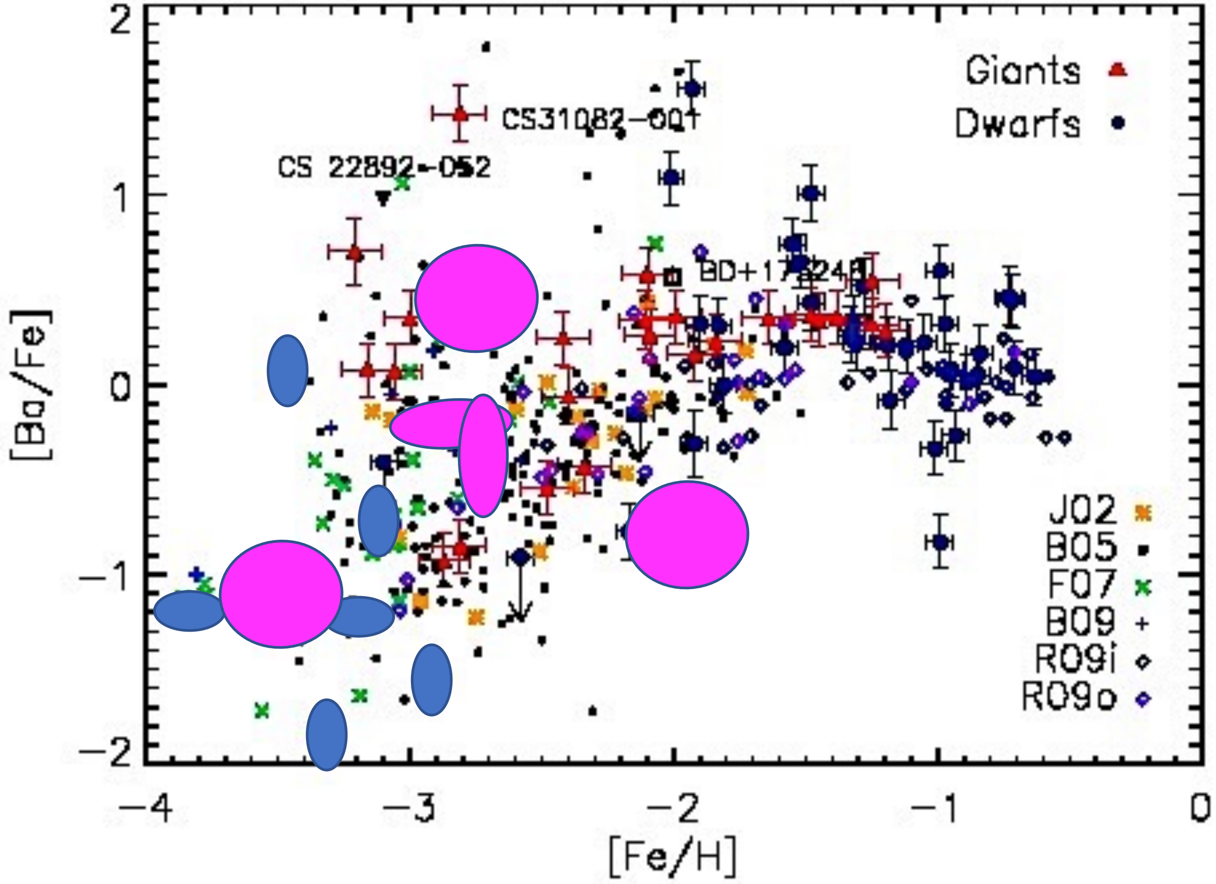
Kinematics

- 12 Gyr backwards integr. in a simple potential, logarithmic halo, spherical bulge
  (Fellhauer et al. 2008, Dehnen & Binney 1998)
- Fast retrograde orbit → outer halo origin
- Possibly accreted from dwarf galaxy – maybe the Sequoia event (Myeong et al. 2019)



Interpreting abundances…

- What affects abundances?



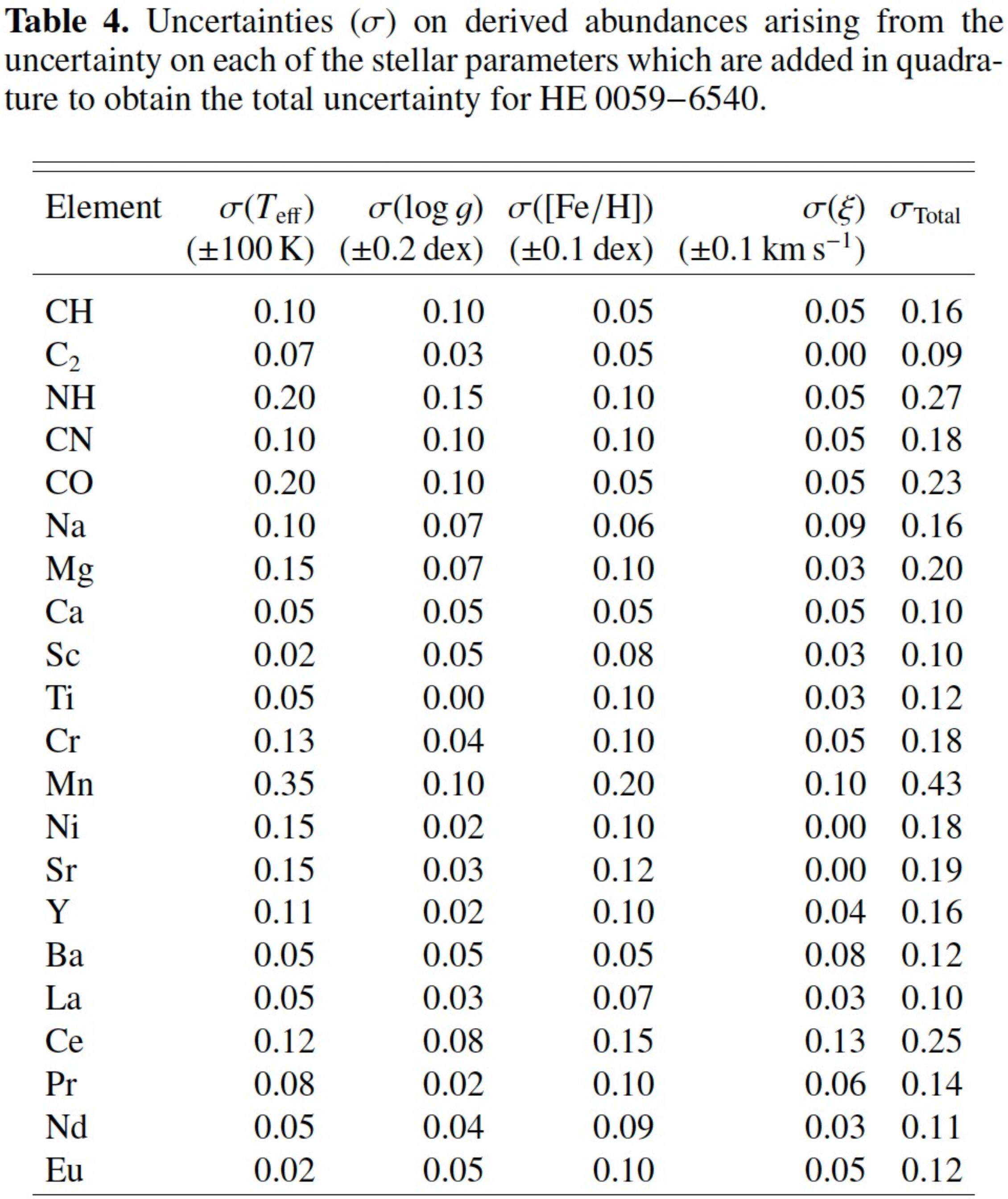
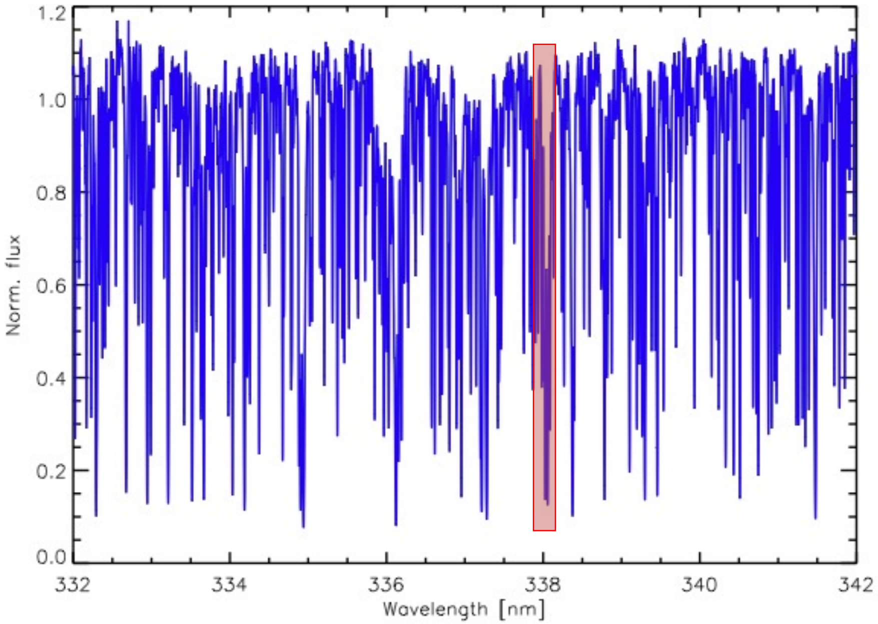


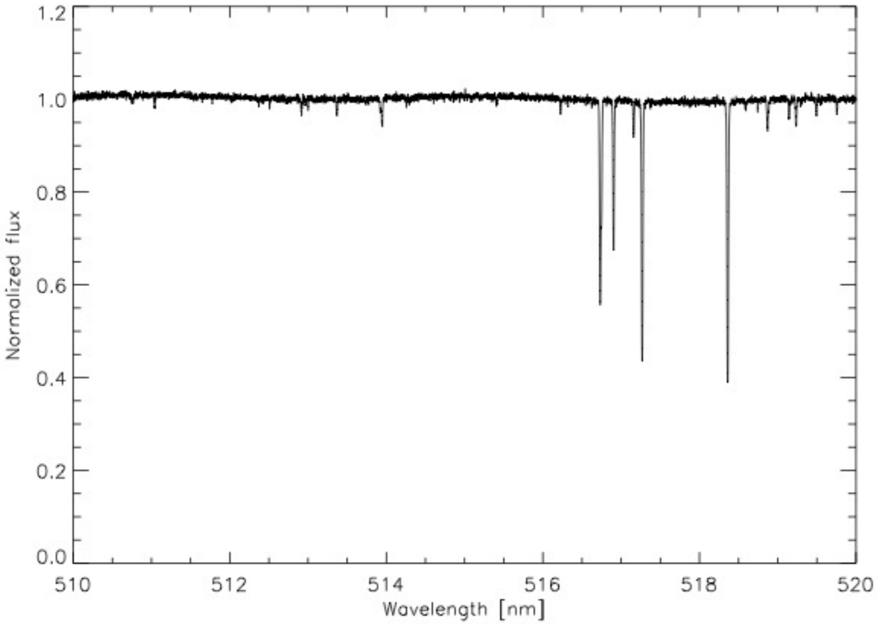
Table 4. Uncertainties (σ) on derived abundances arising from the uncertainty on each of the stellar parameters which are added in quadrature to obtain the total uncertainty for HE 0059−6540.

Element	$\sigma(T_{\rm eff})$ (±100 K)	$\sigma(\log g)$ (±0.2 dex)	σ([Fe/H]) (±0.1 dex)	$\sigma(\xi)$ (±0.1 km s^{-1})	$\sigma_{\rm Total}$
CH	0.10	0.10	0.05	0.05	0.16
C_2	0.07	0.03	0.05	0.00	0.09
NH	0.20	0.15	0.10	0.05	0.27
CN	0.10	0.10	0.10	0.05	0.18
CO	0.20	0.10	0.05	0.05	0.23
Na	0.10	0.07	0.06	0.09	0.16
Mg	0.15	0.07	0.10	0.03	0.20
Ca	0.05	0.05	0.05	0.05	0.10
Sc	0.02	0.05	0.08	0.03	0.10
Ti	0.05	0.00	0.10	0.03	0.12
Cr	0.13	0.04	0.10	0.05	0.18
Mn	0.35	0.10	0.20	0.10	0.43
Ni	0.15	0.02	0.10	0.00	0.18
Sr	0.15	0.03	0.12	0.00	0.19
Y	0.11	0.02	0.10	0.04	0.16
Ba	0.05	0.05	0.05	0.08	0.12
La	0.05	0.03	0.07	0.03	0.10
Ce	0.12	0.08	0.15	0.13	0.25
Pr	0.08	0.02	0.10	0.06	0.14
Nd	0.05	0.04	0.09	0.03	0.11
Eu	0.02	0.05	0.10	0.05	0.12

Spectral analysis

Blue vs visual spectra

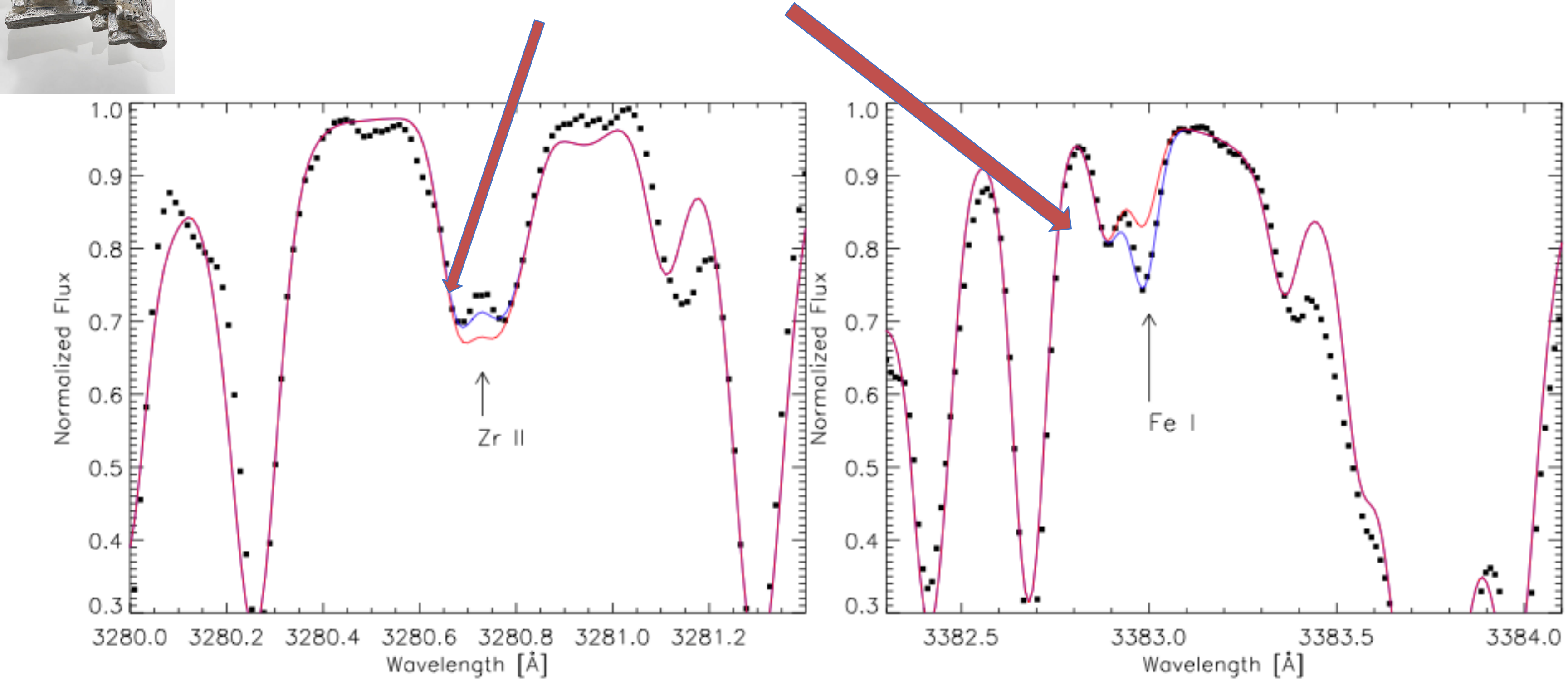




Analysing Near UV-Lines

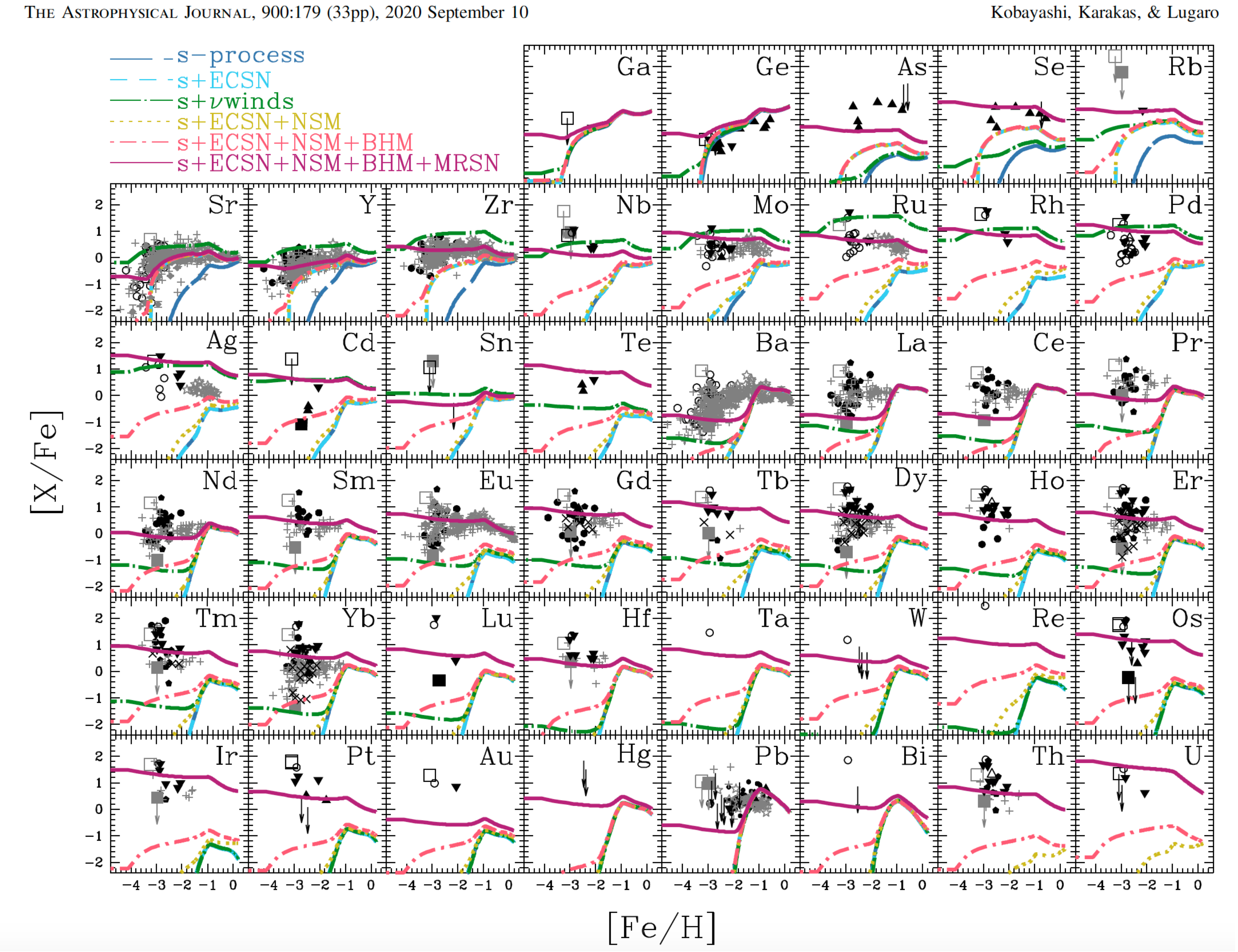

Wikipedia

Silver (Ag, Nr. 47)



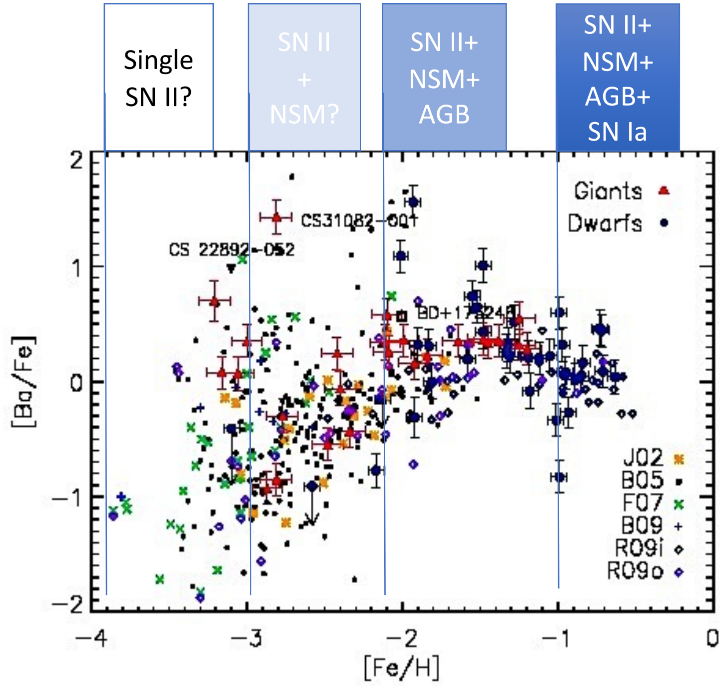
Hansen et al. 2012

Galactic chemical evolution



THE ASTROPHYSICAL JOURNAL, 900:179 (33pp), 2020 September 10 Kobayashi, Karakas, & Lugaro

What do you notice here??



Single SN II?

SN II + NSM?

SN II+ NSM+ AGB

SN II+ NSM+ AGB+ SN Ia

Isotopes

- Isotopes – typically need high-resolution, high SNR spectra of **atomic lines** (Li, Ba, [Nd, Sm], Eu)
- For some **molecules** low-res can be used – but high SNR typically needed (C, N, O, Mg)

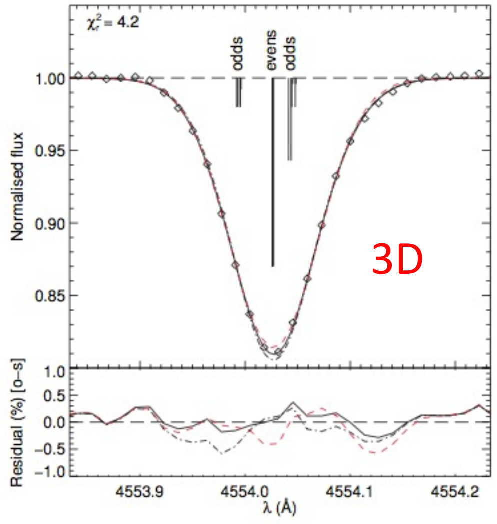


Fig. 10. Best fit 3D (solid black line – f_{odd} = 0.38) and 1D (dashed red line – f_{odd} = 0.02 from Paper I) fits to the observed Ba II 4554 Å profile (black diamonds). A residual plot is presented in the *bottom panel*.

Gallagher et al. 2015

A. J. Gallagher et al.: 3D non-LTE Ba in the Sun

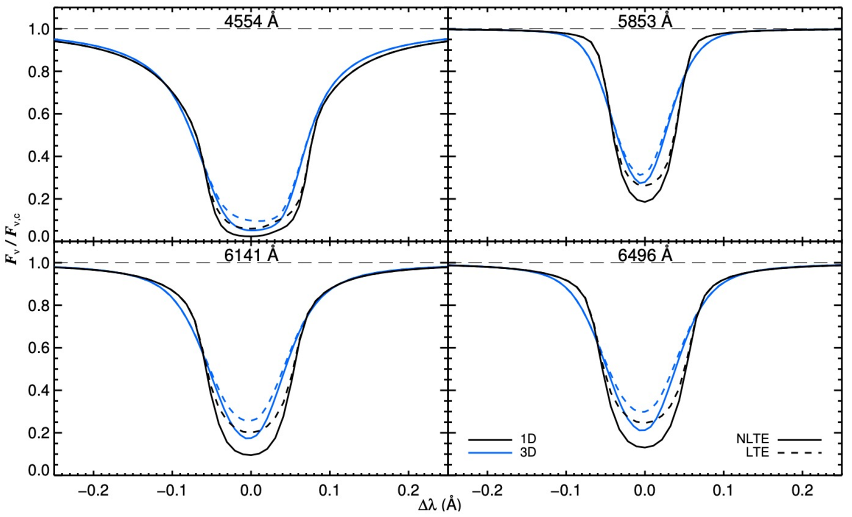
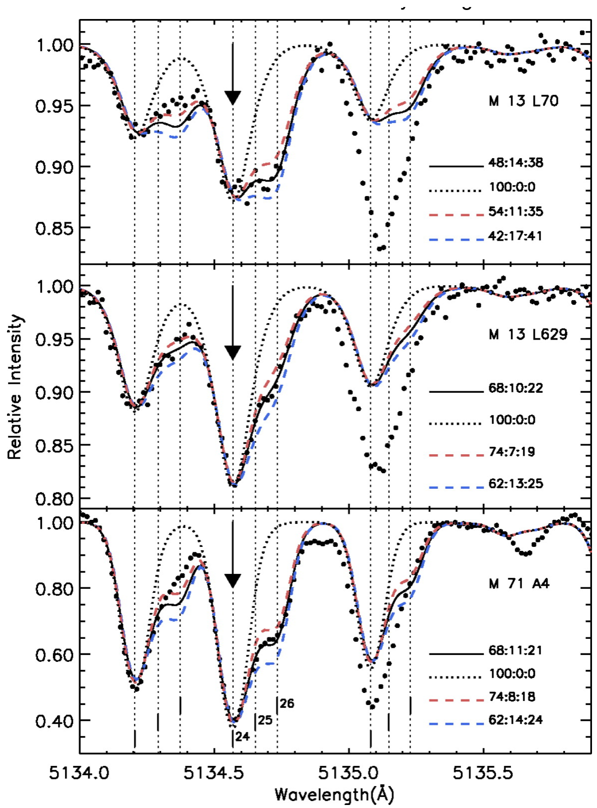


Fig. 4. 1D (black) and 3D (blue) LTE (dashed-lines) and non-LTE (solid-lines) Ba II line profiles at A(Ba) = 2.26 dex. No extra broadening was added to any of the depicted lines. The 3D profiles are shown to be shifted relative to the 1D profiles. This is a natural consequence of the convective shifts indicative to a dynamic model atmosphere.



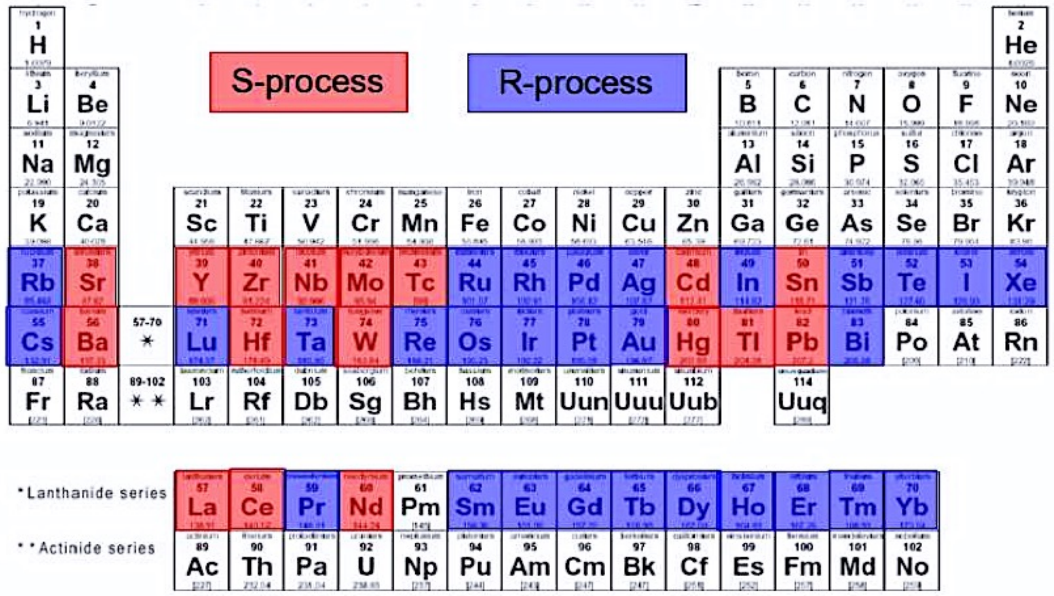
Top: MgH – Yong et al. 2006, Thygesen et al;

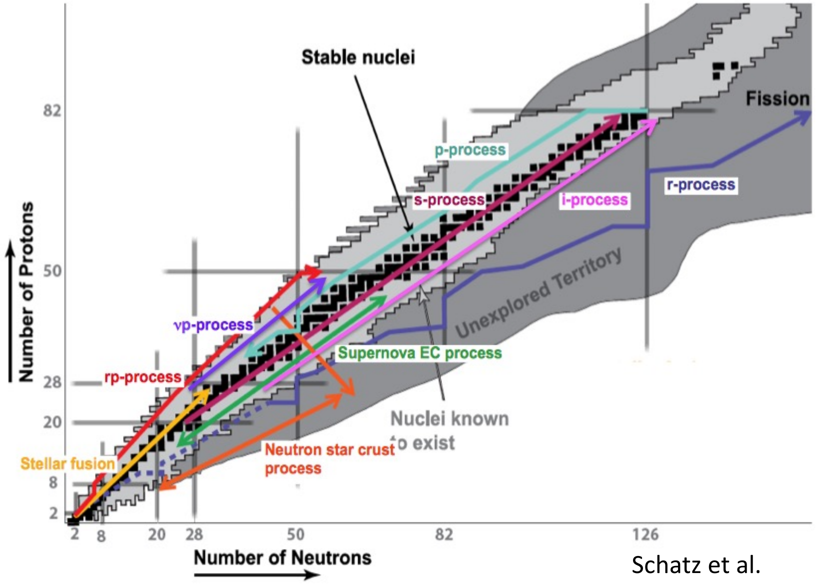
Middle: Sm – Roederer et al. 2008

Ba profiles – Gallagher et al. 2020

The Periodic Table – n-capture processes

r- and s-process elements (Arlandini+1999)





Schatz et al.

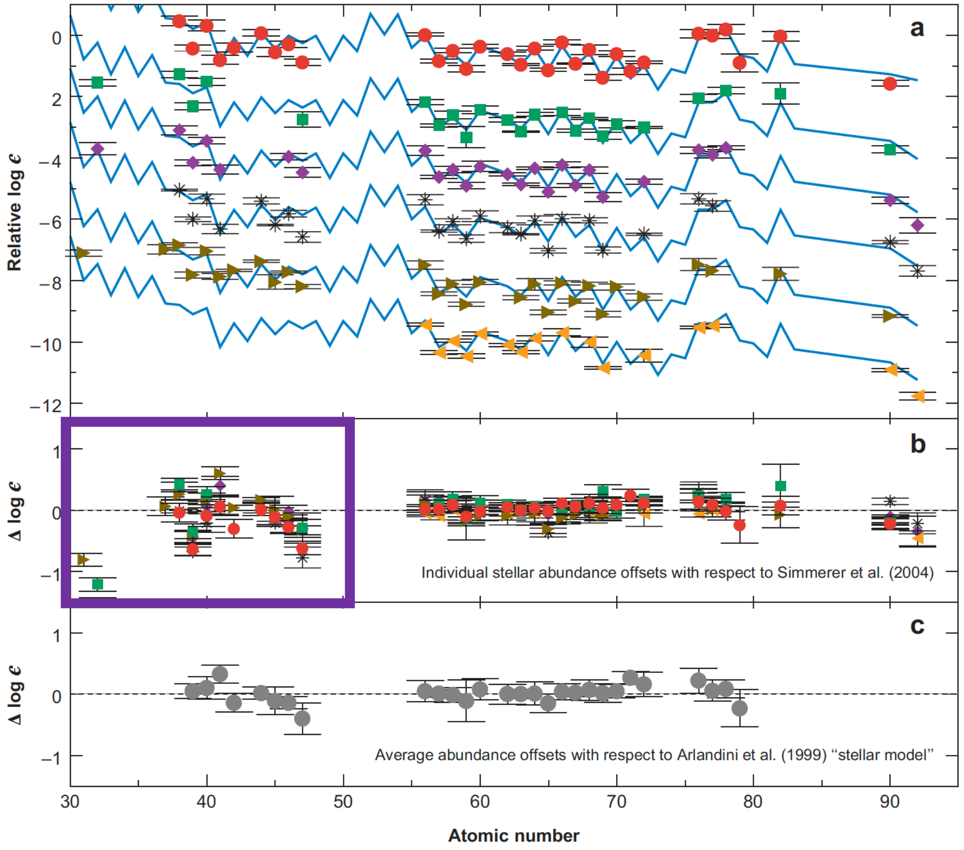
Figure 1. Schematic overview of the nuclear processes in the universe on the chart of nuclides (adapted from figure by F. Timmes).

Heavy element abundances

- Different stars show different patterns
- Some elements differ more than others

No site – just observations
H represented by r-rich stars
L represented by r-poor stars

$$\mathrm{Abun}(Z) = (C_H A_H(Z) + C_L A_L(Z))*10^{[\mathrm{Fe/H}]}$$

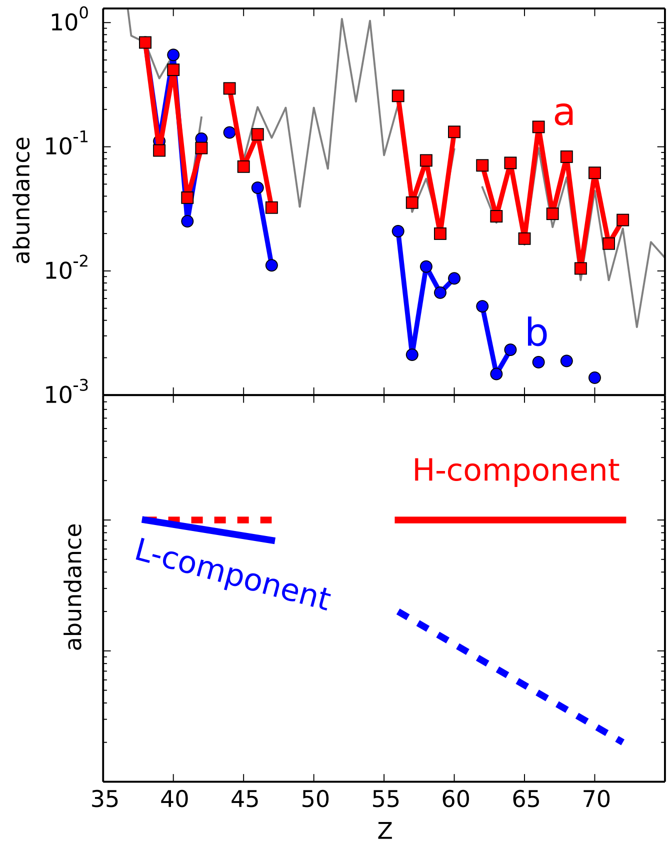


Individual stellar abundance offsets with respect to Simmerer et al. (2004)

Average abundance offsets with respect to Arlandini et al. (1999) "stellar model"

Sneden et al. 2008

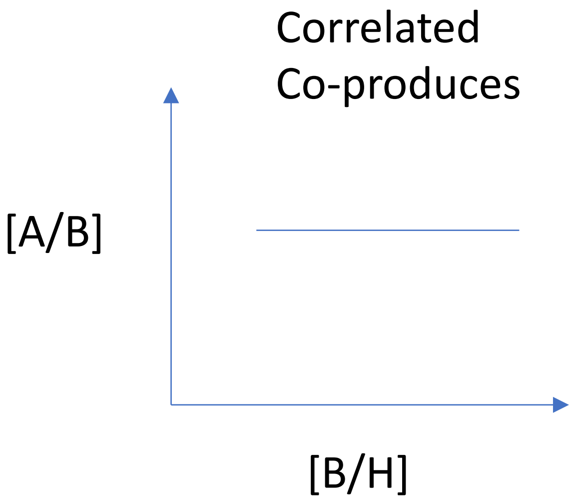
Large residuals for Z=30-50 → Solar-s=r not sufficient!

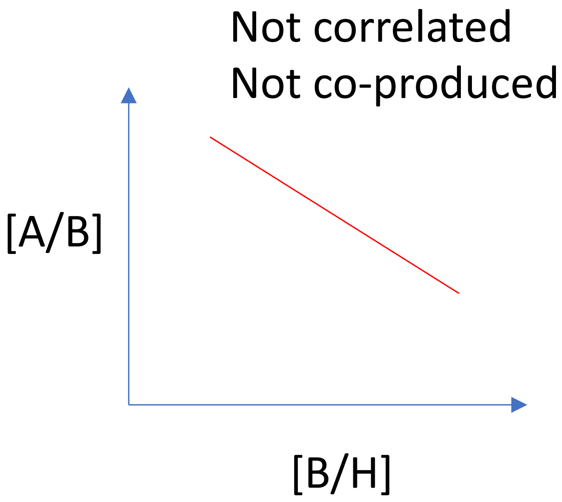


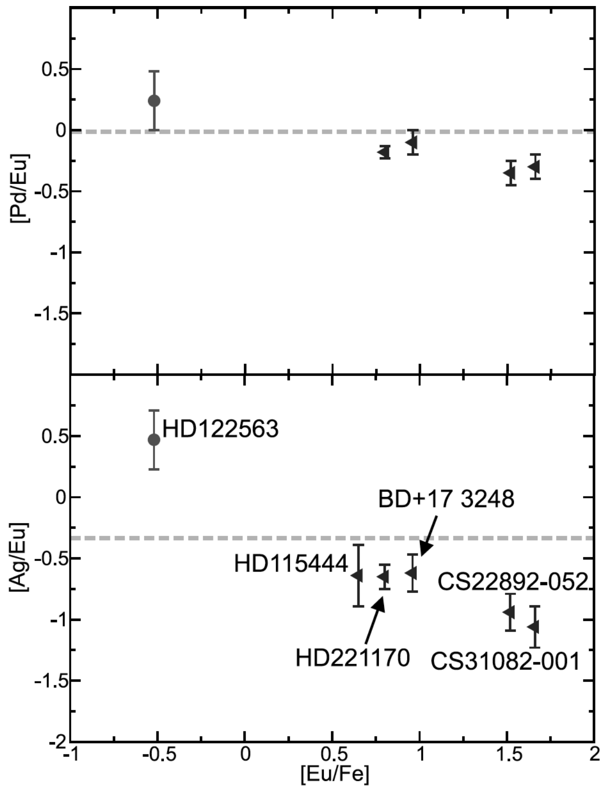
CJH+14

Formation of silver

- Well-known r- (Eu) and s- (Ba) tracers – but how are the poorly studied elements with 40<Z<50 formed?





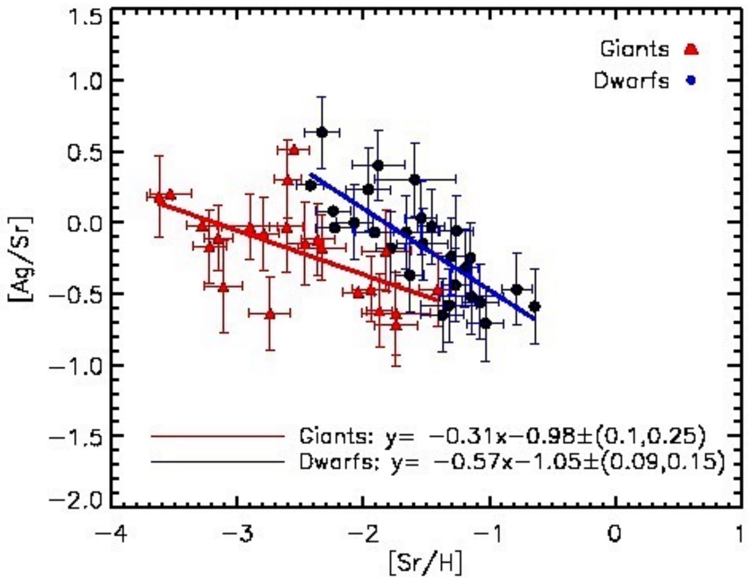


Montes et al. 2007

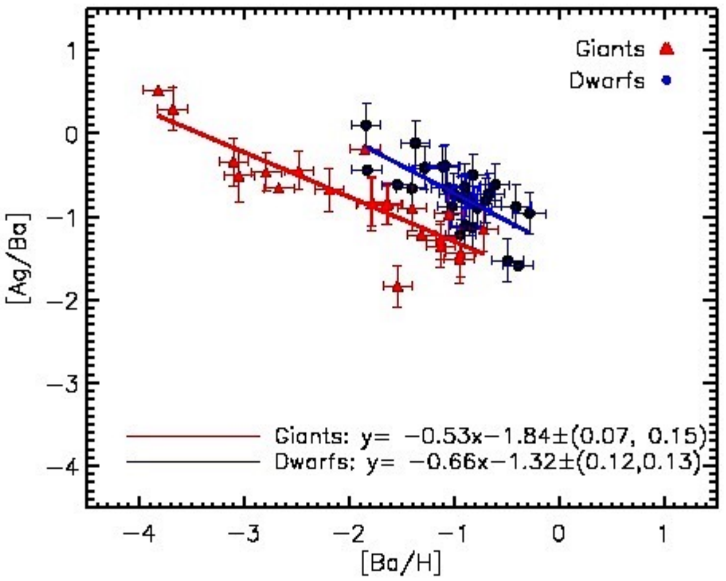
Note the axes – no Fe in the ratio!

First large sample of Ag – how is it formed?

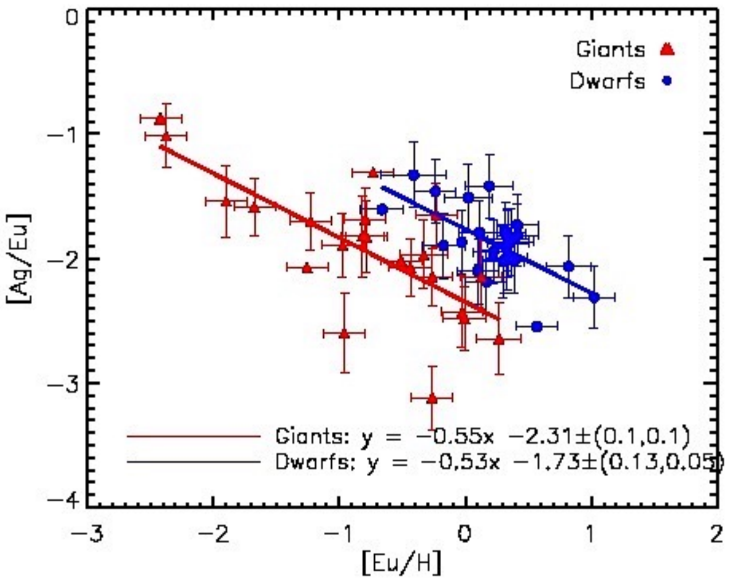
Sr – weak s (FRMS)



Ba – main s (AGB)



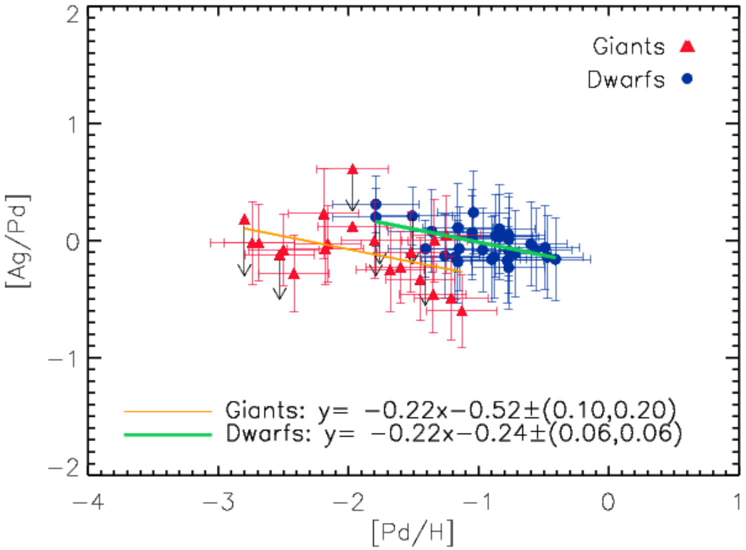
Eu – main r (rare SN/NSM)

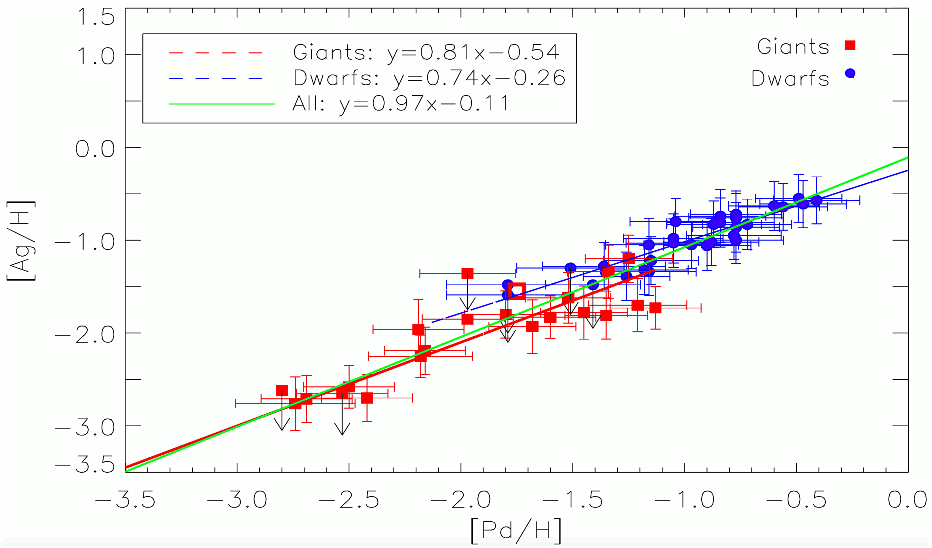


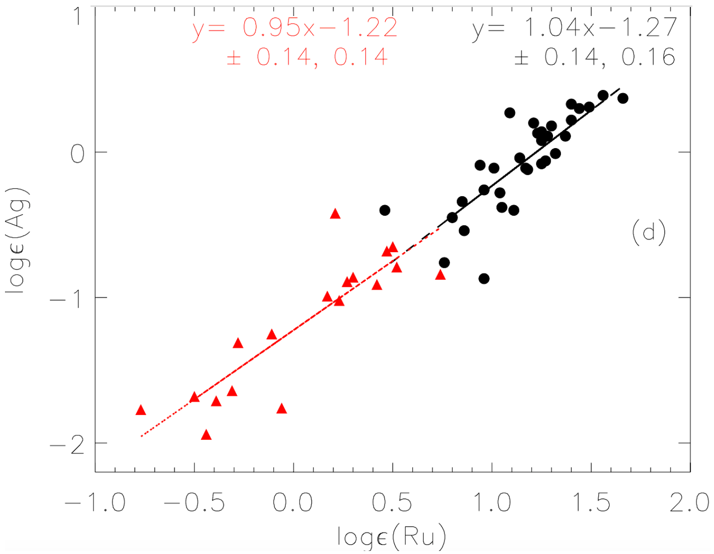
Ag not co-produced with Sr, Ba, or Eu!

Silver, Ruthenium & Palladium

Almost a perfect 1:1 correlation of Ag (Z=47) & Pd (Z=46) and Ag (Z=47) & Ru (Z=44)







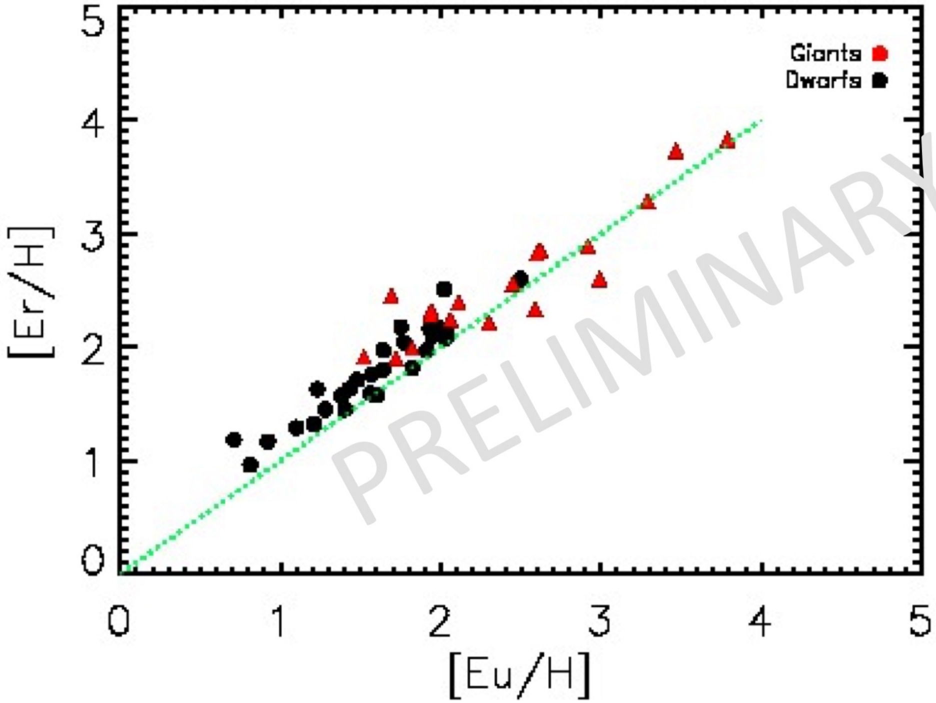
→ Ru, Pd, and Ag formed in a weak r-process!

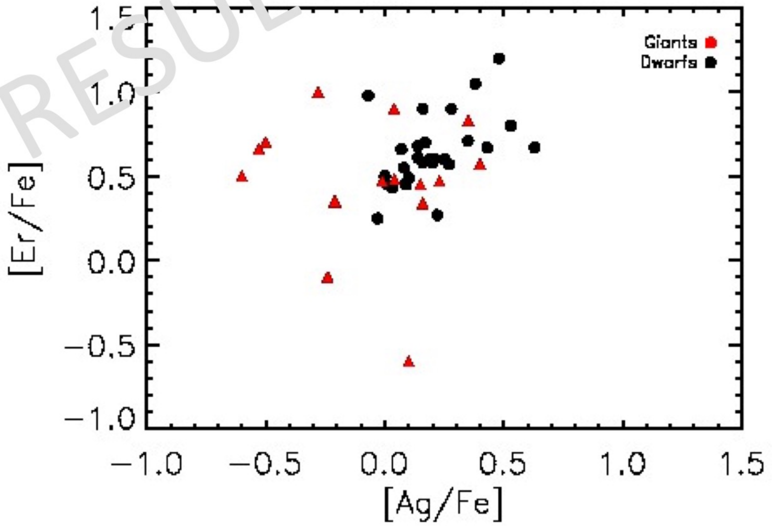
→ This may be hosted in a different astrophysical environment from the main r and the amount/efficiency may vary among different events

New Er data

- Tight correlation → similar formation mechanism
- Difference in origin → Scatter!

Eu – Er are co-produced they require a low Ye → compact merger event (NSM)





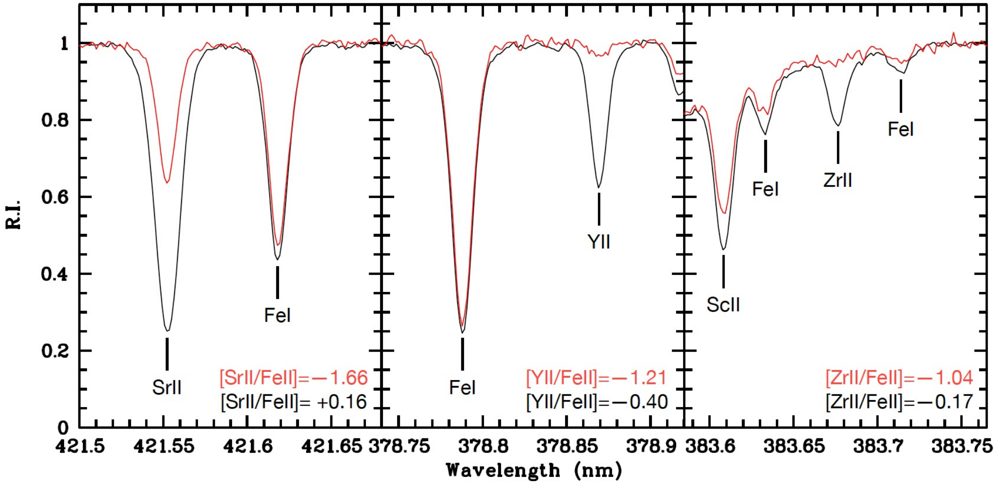
CJH et al. in prep

CERES

- **CERES**: Chemical Evolution of R-process Enriched Stars (PI Hansen)
  - Observations made with UVES/VLT in Chile – high-resolution spectrograph, high signal-to-noise (50-200)
  - Sample size: 52 stars
  - Stars selected with < 5 known heavy elements
  - Homogeneous analysis
    - Line list (atomic data), stellar models, synthetic spectrum code

Goal: More than triple the heavy element information

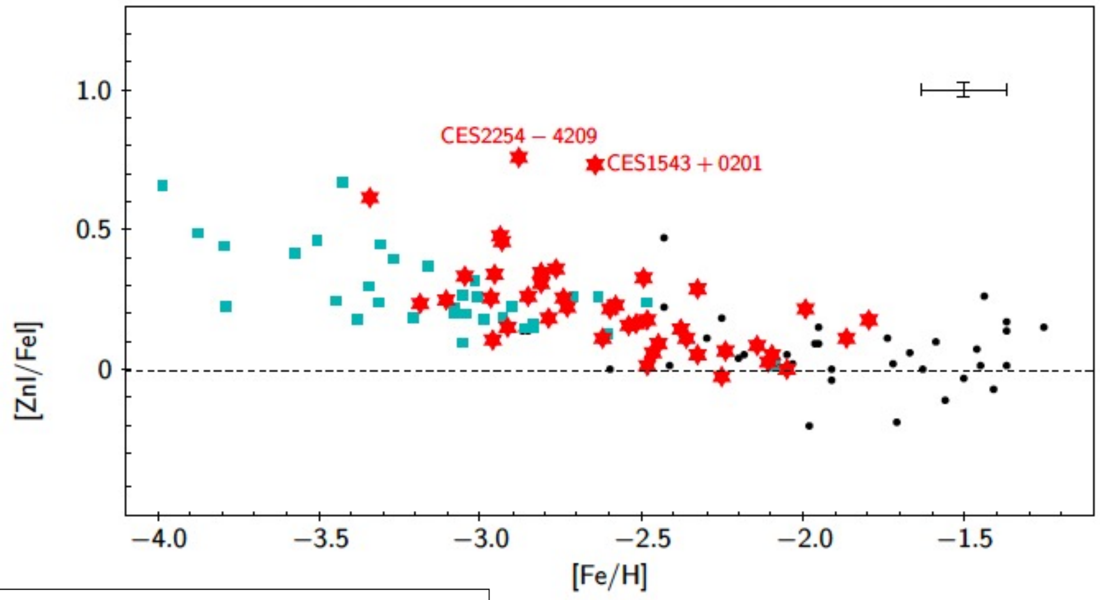
Sr, Y, Zr, Ru, Pd, Ag, Ba, La, Ce, Pr, Nd, Sm, Eu, Hf, Os, Ir, Th and U

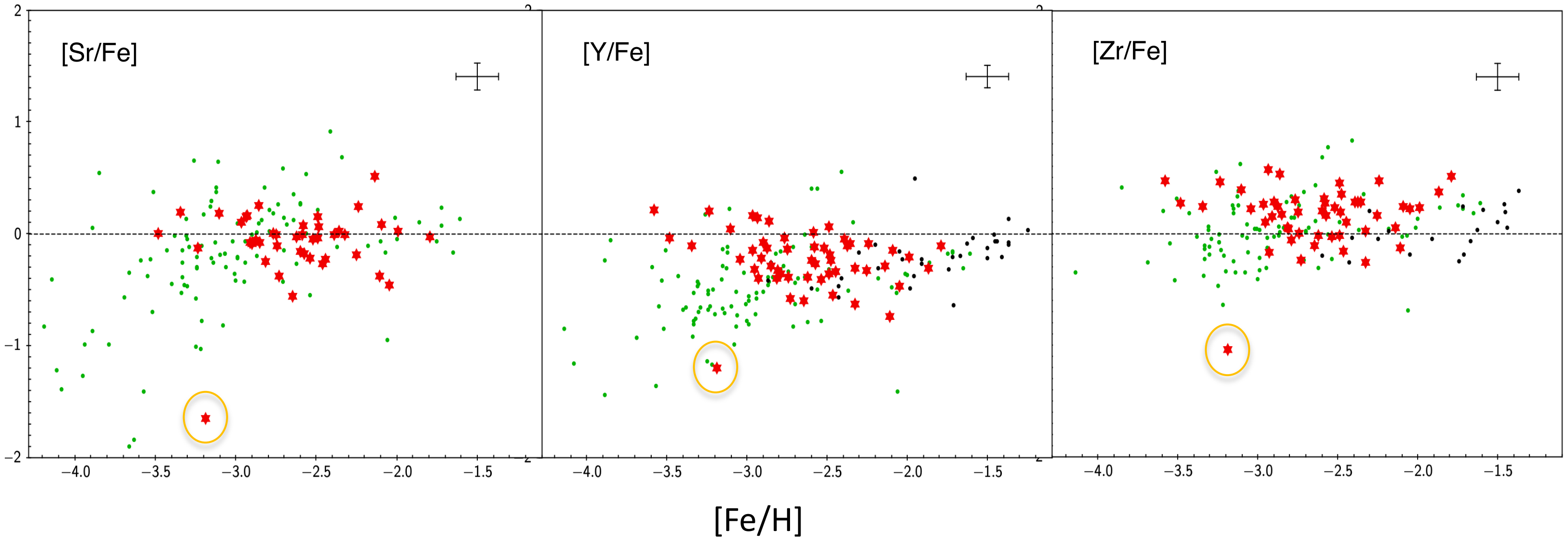


Lombardo et al. 2022

Combining light and heavy elements

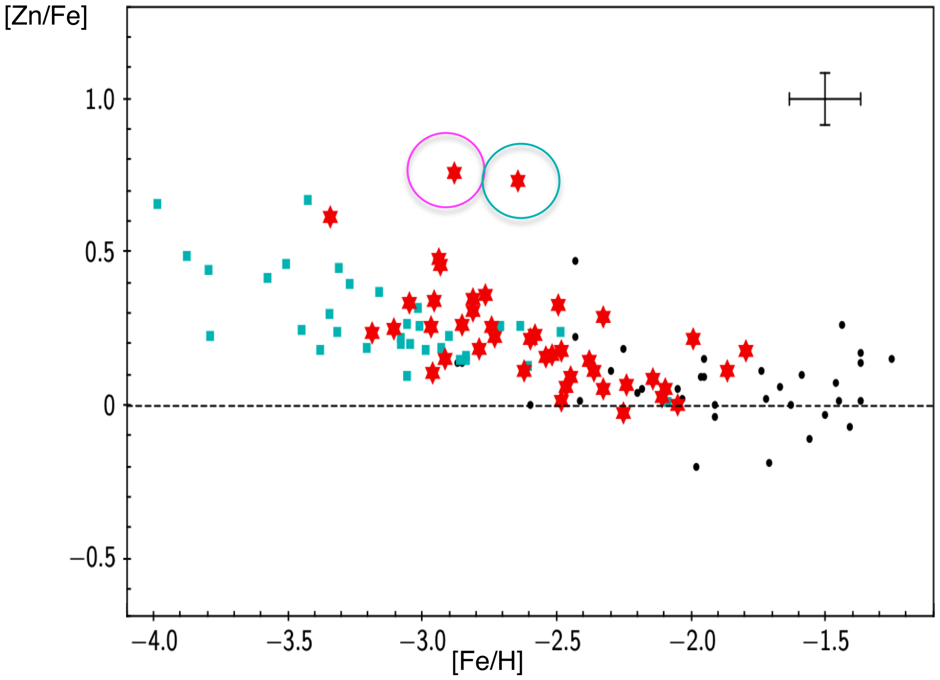
- Lombardo et al. 2022 – Na to Zr
  - Zn-rich stars
  - Sr – Y – Zr poor stars

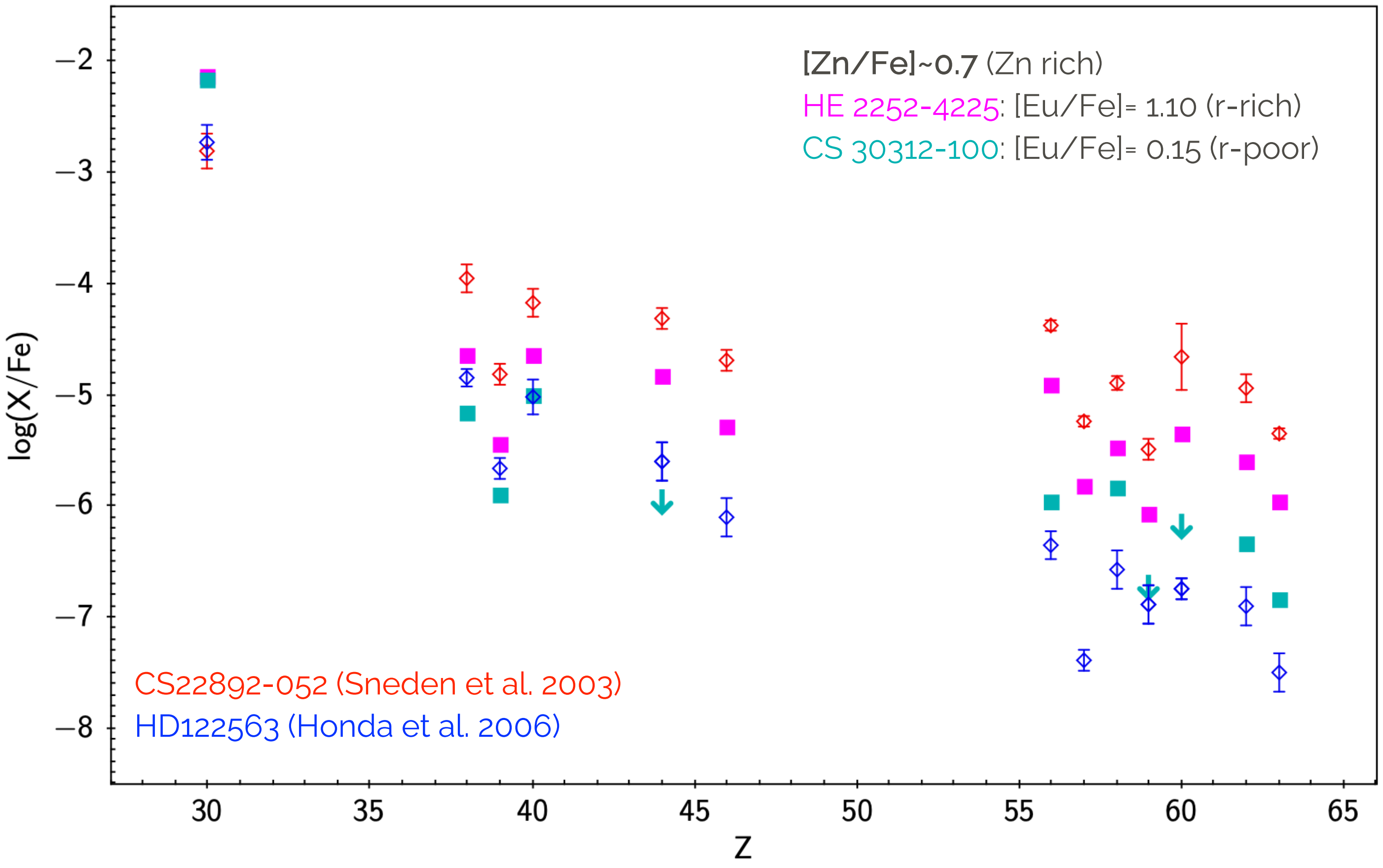




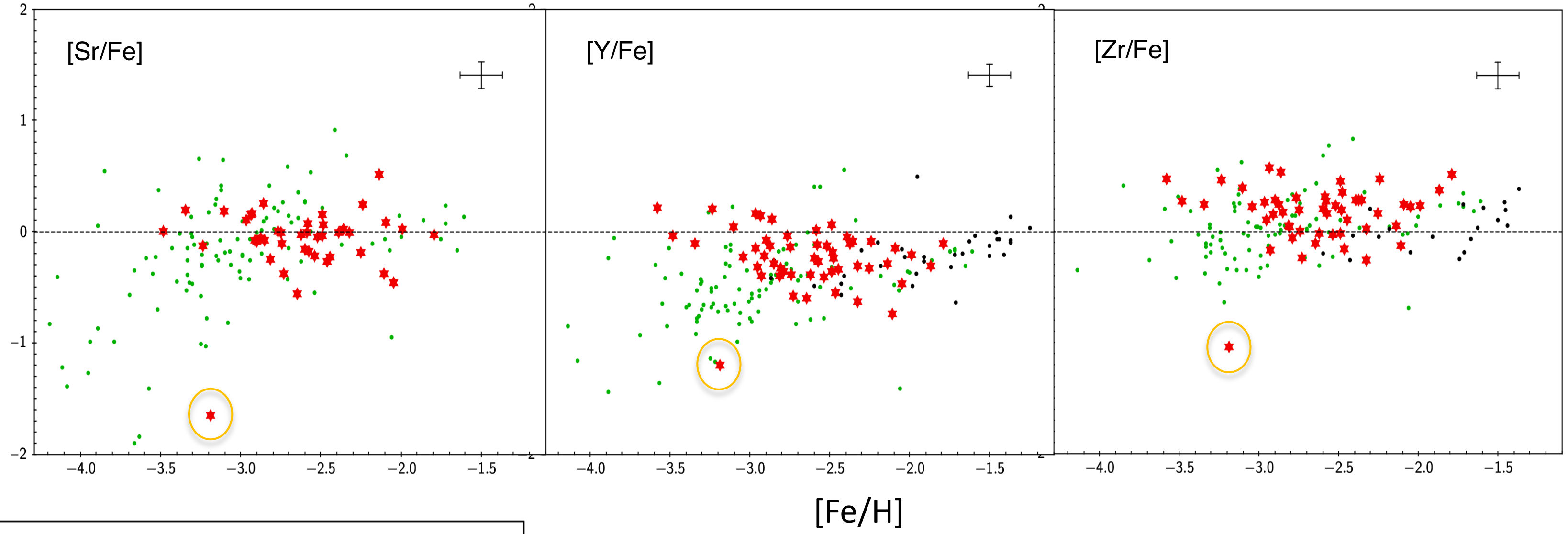
Zn-rich stars

Lombardo et al. in prep.

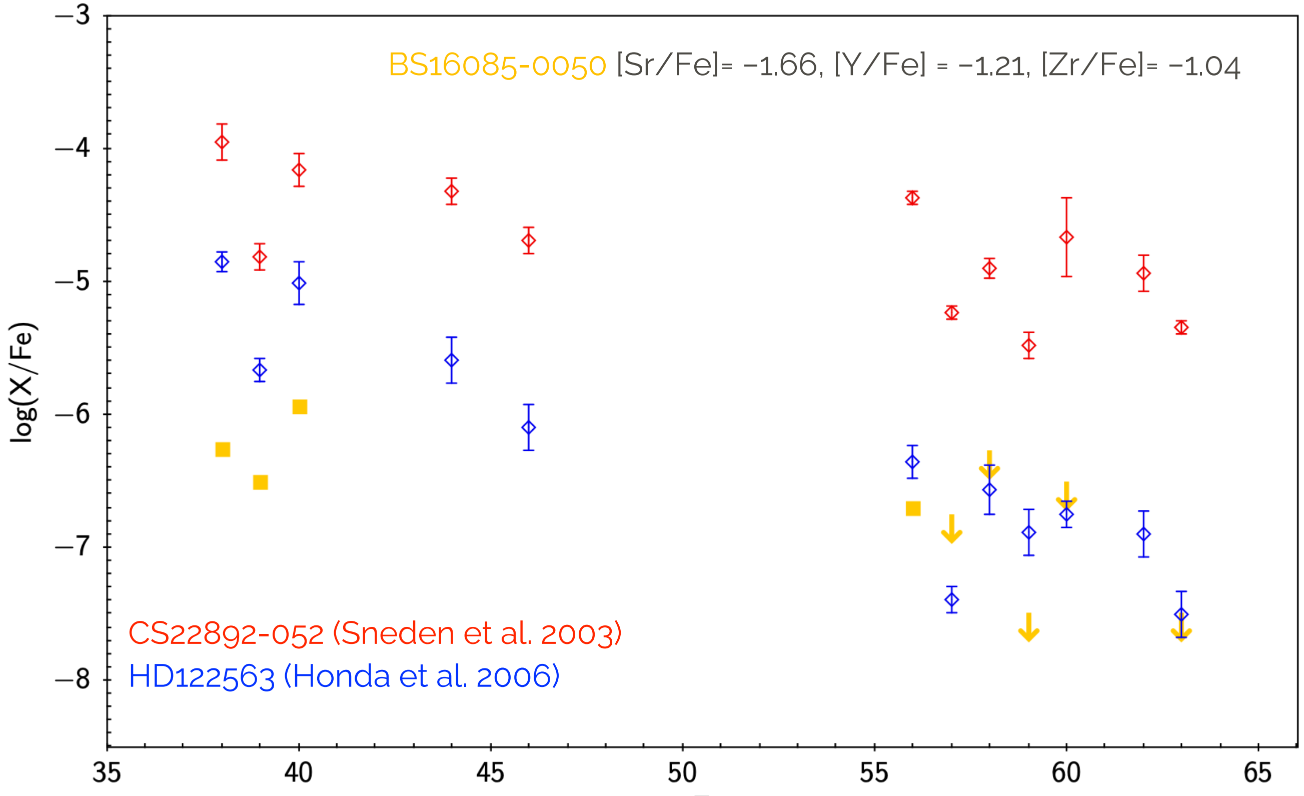




Sr-Y-Zr – poor stars



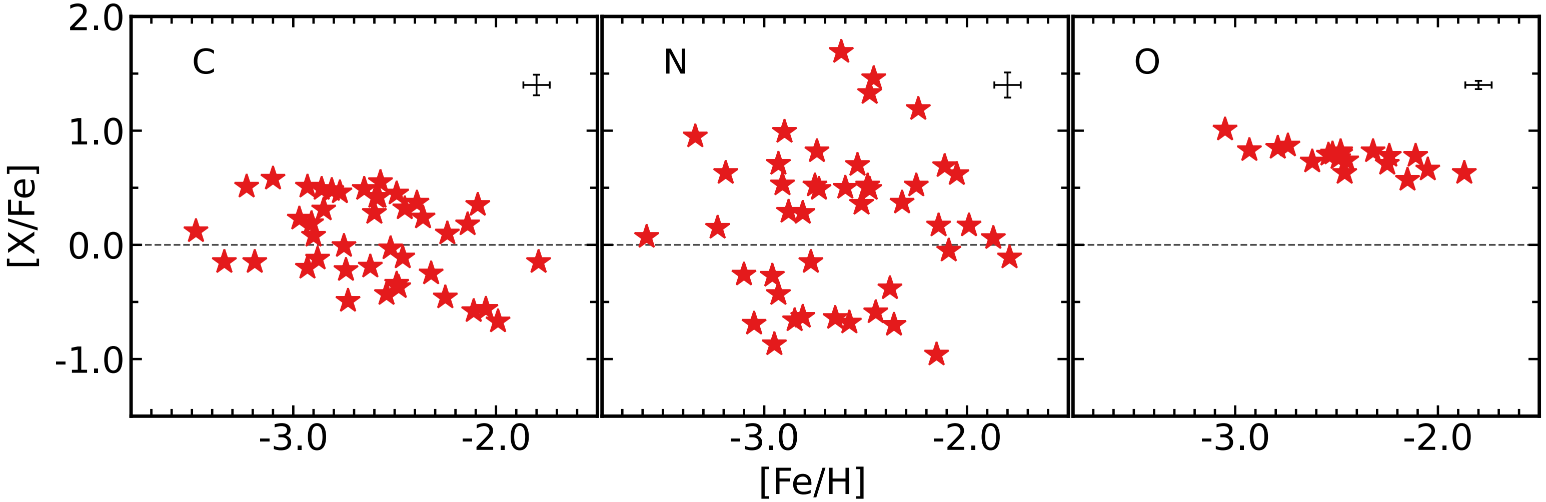
Lombardo et al. in prep.



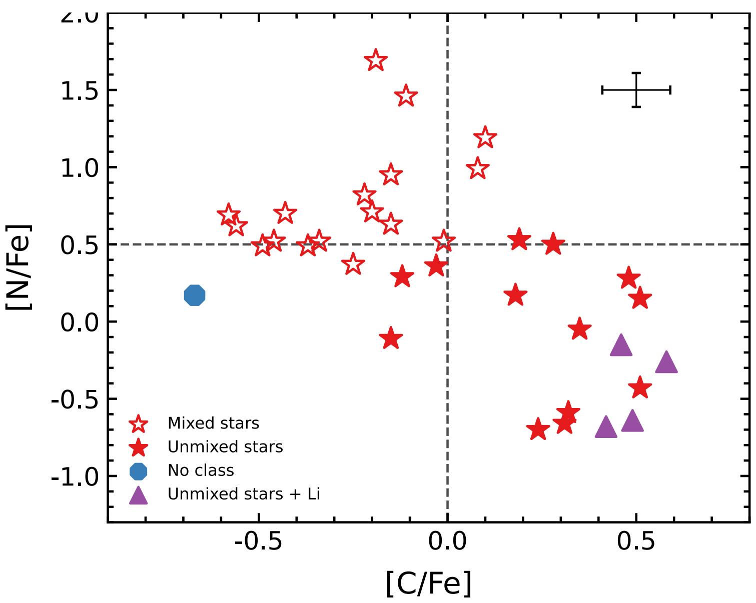
The star in yellow ([Fe/H]=-3.19, [Mg/Fe]=+0.77), is more extreme than the 'Honda' star!
A(SrII) = -1.78dex
Only 7 stars known with similarly low Sr – Zr.

Compare to high A(SrII)=+1.55

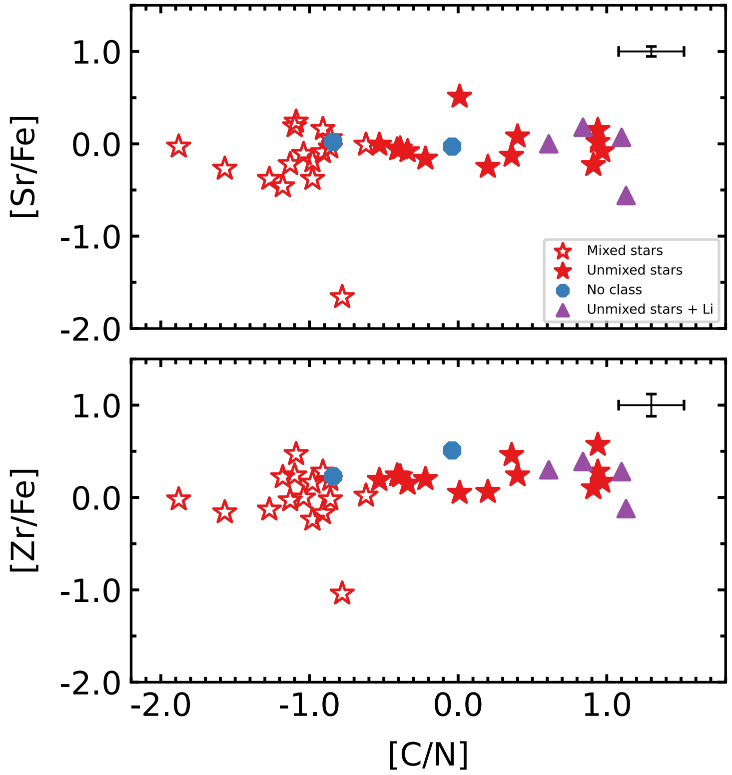
Combining light and heavy elements



Raphaela Fernandes de Melo
PhD Student

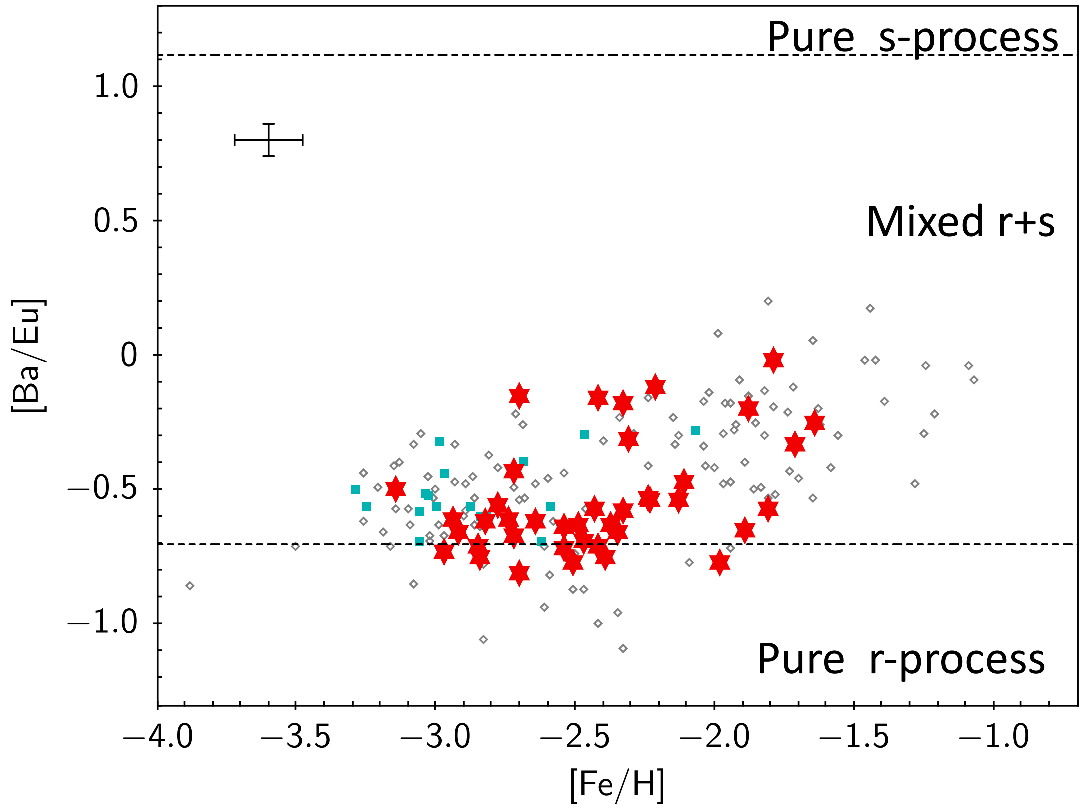


Fernandes de Melo et al.
2024 in prep



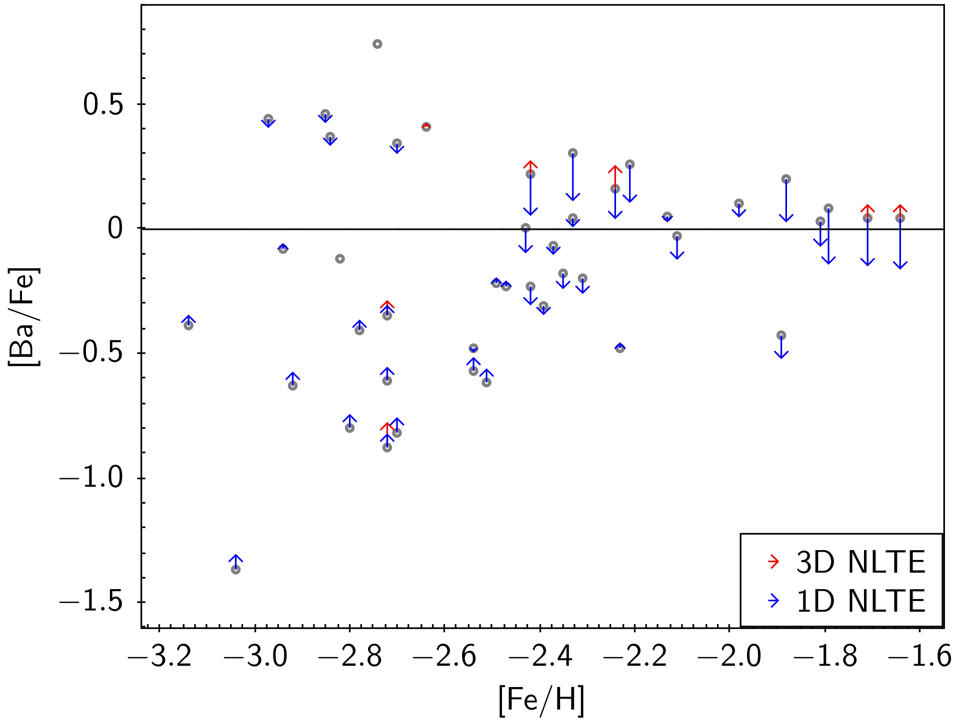
Rare earth elements as nuclear tracers

Linda Lombardo
Postdoc



Ba, La, Ce, Pr, Nd, Sm, Eu

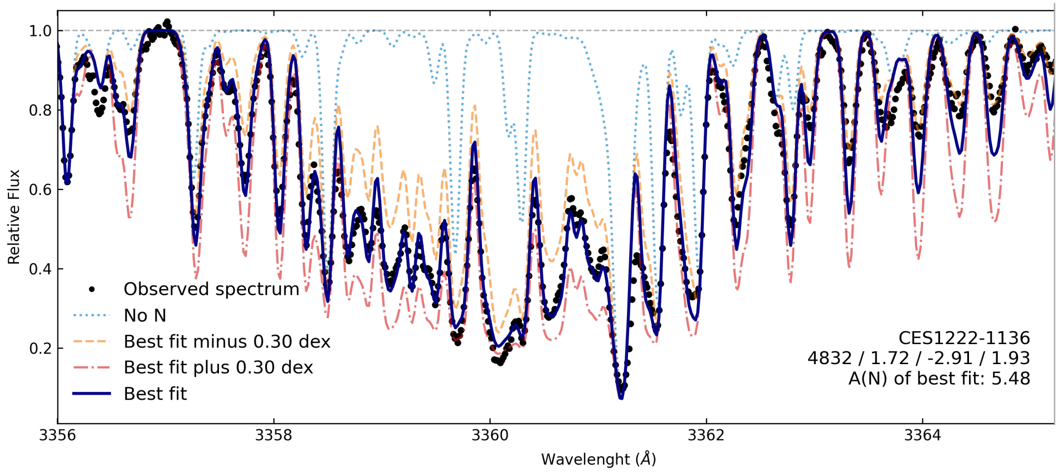
Lombardo et al. 2024
in prep.



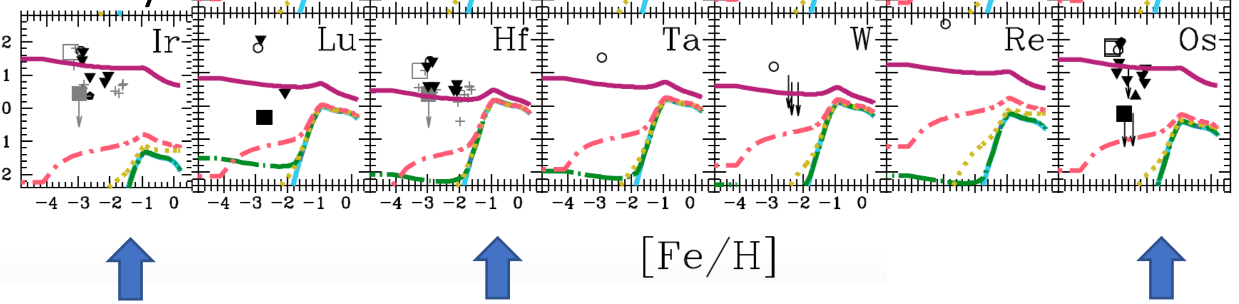
R-process in old, metal-poor stars

Arthur
Alencastro
Puls
Postdoc

In cool stars, many heavy element features suffer from molecular blends (CH or NH)

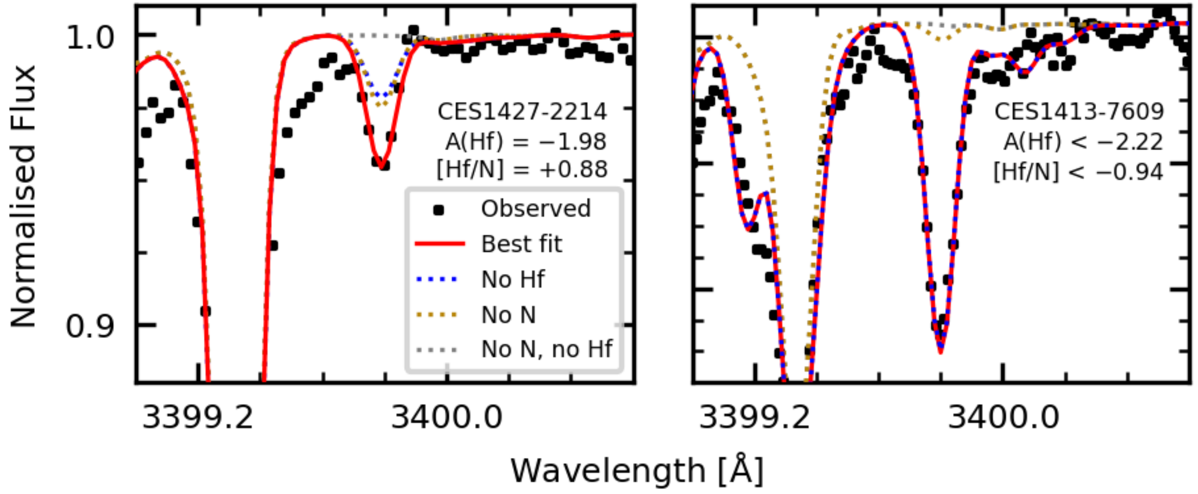


Kobayashi et al. 2020



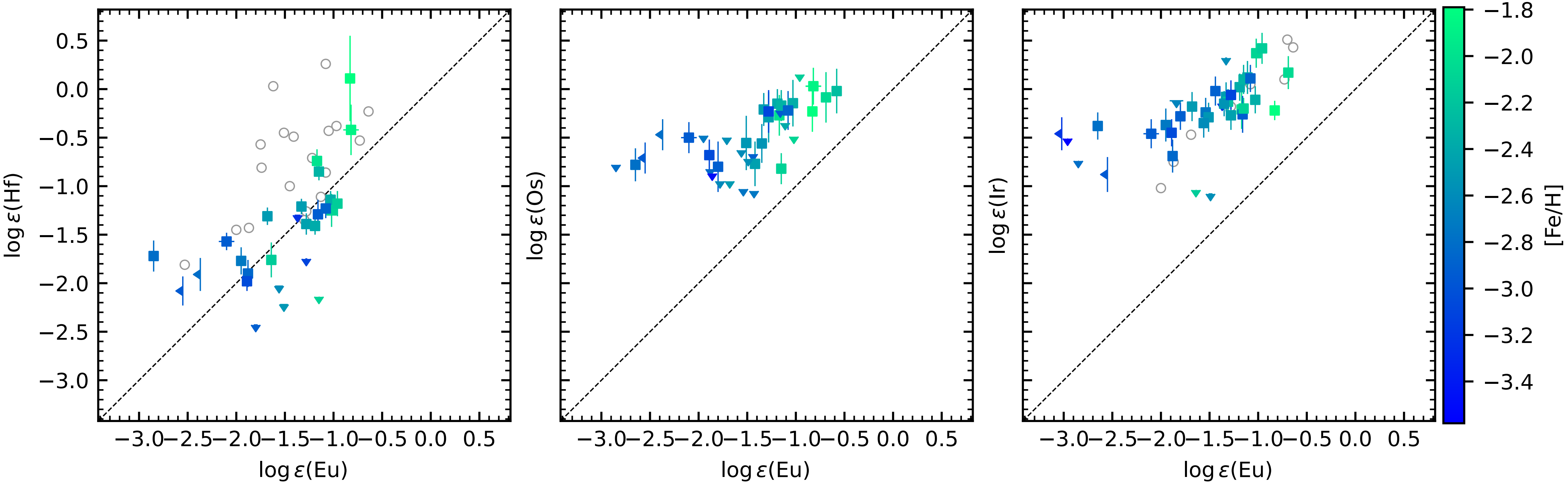
Poorly studied heavy elements!

Alencastro Puls et al. 2024 in prep.



Ir, Hf, and Os

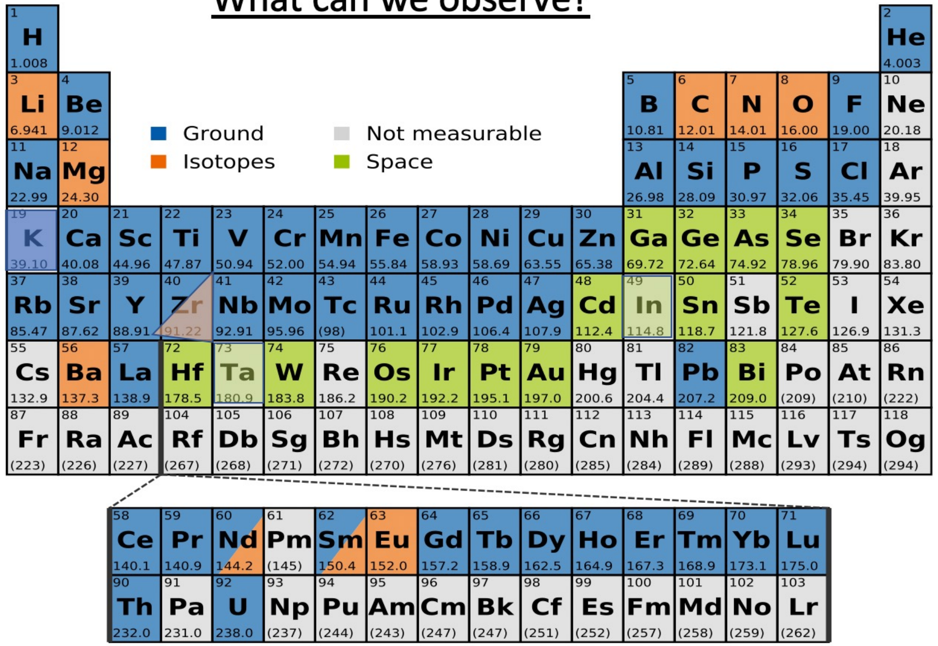
- Alencastro Puls et al. 2024 in prep.



Summary

- With stellar abundances of ~70 elements we can explore:
  - Stellar evolution and self-enrichment
  - Early chemical enrichment and nuclear processes
  - High-resolution spectra allow for accurate elemental abundances, which we can use to explore nuclear formation processes
  - Metal-poor stars with pure r-process traces
    - Abundance correlations
    - Chemical peculiarities & abundance patterns
    - Insight into formation sites

What can we observe?



Camilla J. Hansen, IAP, Frankfurt

Goals and limitations:

- Elemental abundances – not isotopic (only ~7 elements)
- 3D, NLTE
- Outlook: ELT, CUBES,…

THANK YOU