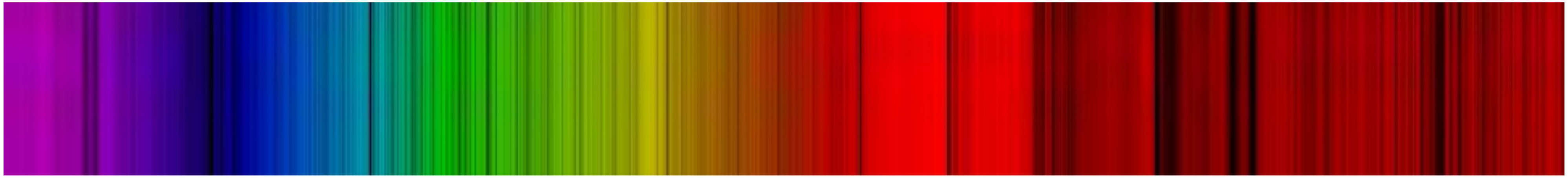


Mapping the r-process using stellar observations

Camilla Juul Hansen

Dark Cosmology Centre,

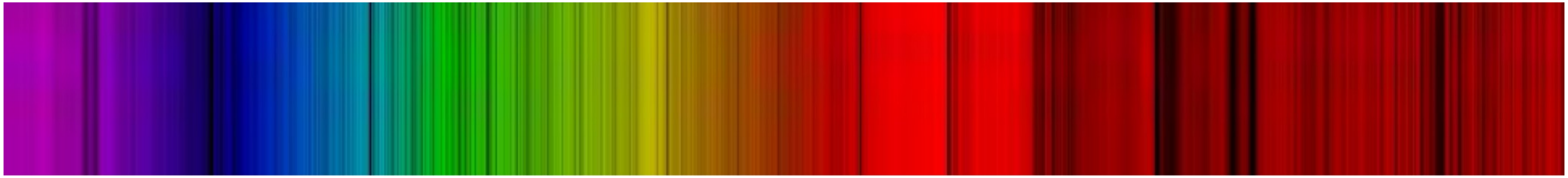
University of Copenhagen

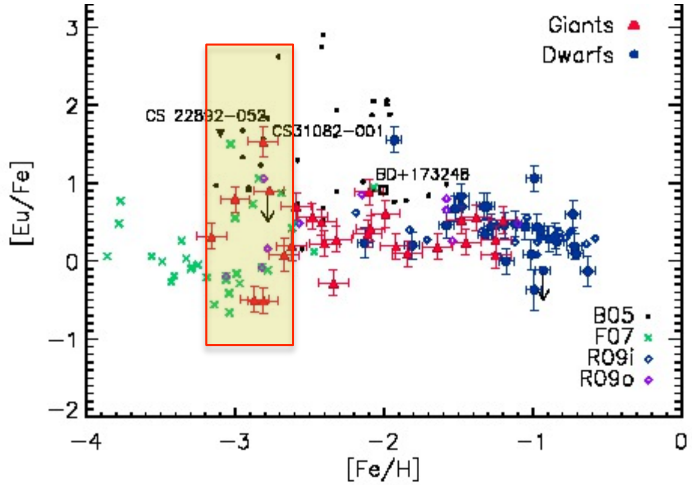
Outlook

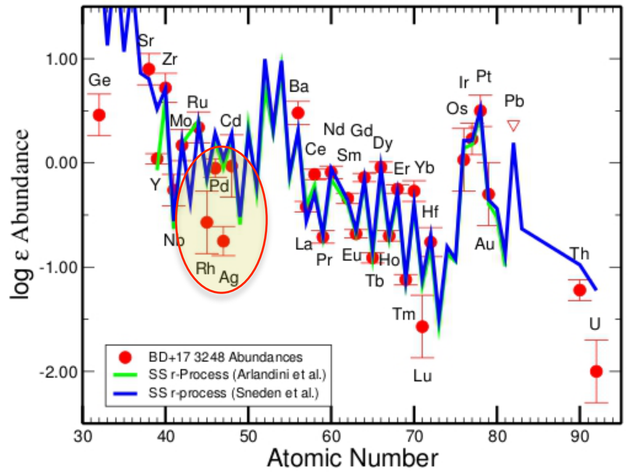
Cool, low-mass stars are the only astrophysical objects in which we can conduct a detailed and precise abundance study of up to ~70 elements

- Stellar abundances & parameters (observations of M_{low} stars)
- Old stars (RR Lyrae) – limitations in abundance patterns…
- Tracing astrophysical formation sites using stellar abundances
- Galactic Chemical Evolution
- How many processes* are needed in the early Universe?

*or "contributions"







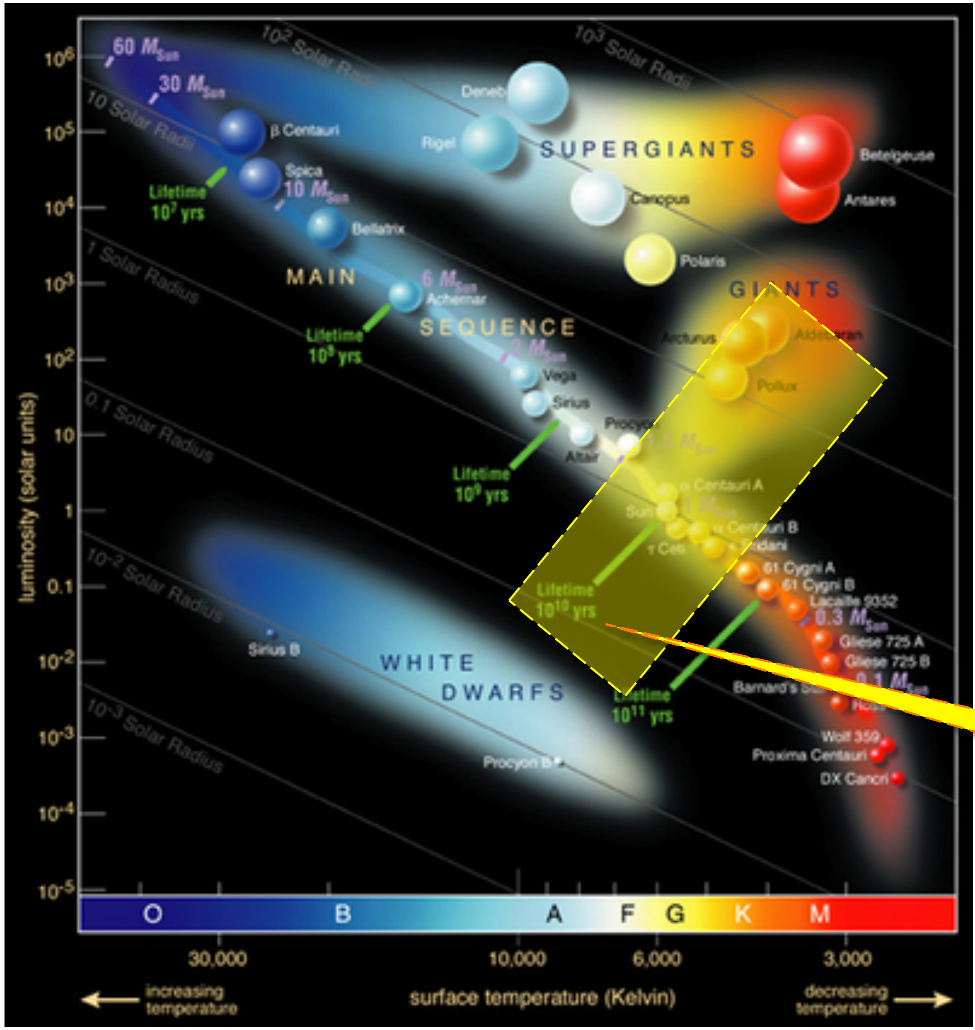
Multiple formation sites/mechan. may need to co-exist to explain

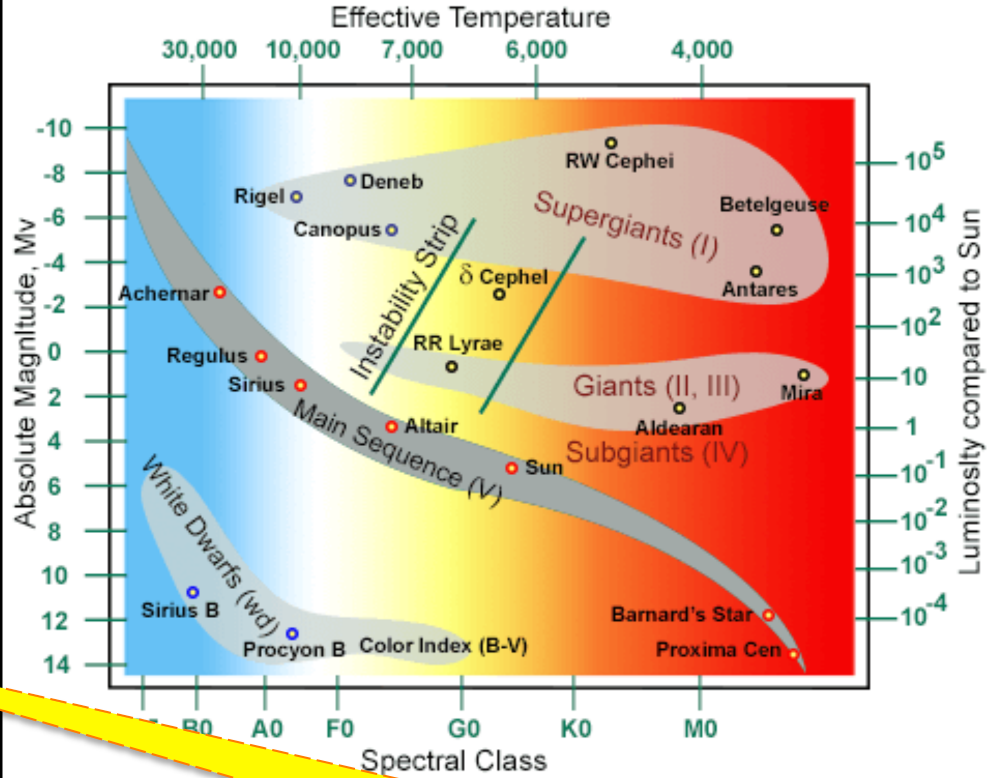
→the broad range of abundance patterns and

→ the abundance scatter seen at low metallicity

- We need to explain the 3 dex abundance scatter around [Fe/H] = -3
- Deviations from solar r at the light end of the r-process (1st -2nd peak)

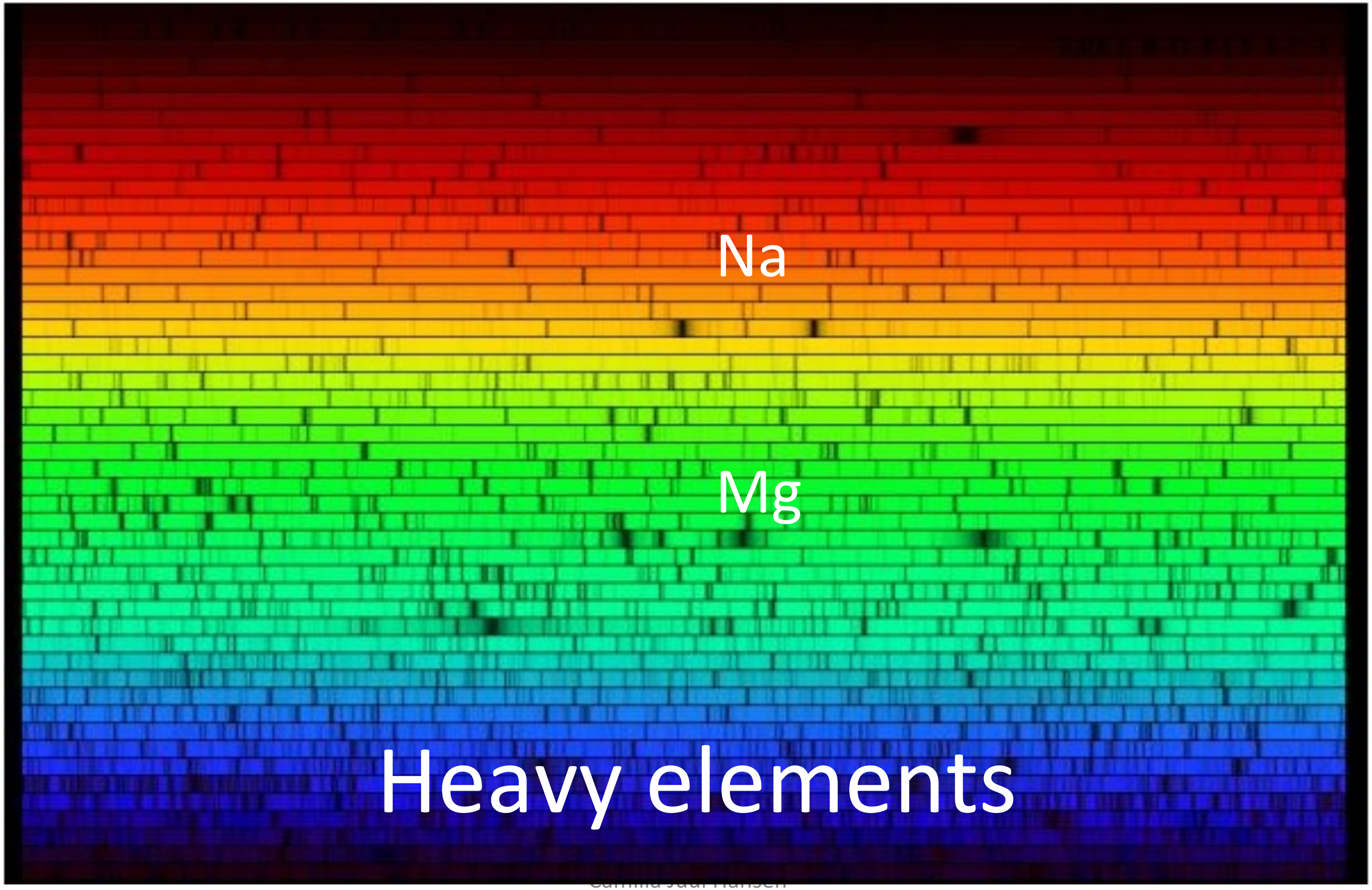
Low-mass, cool stars – why?





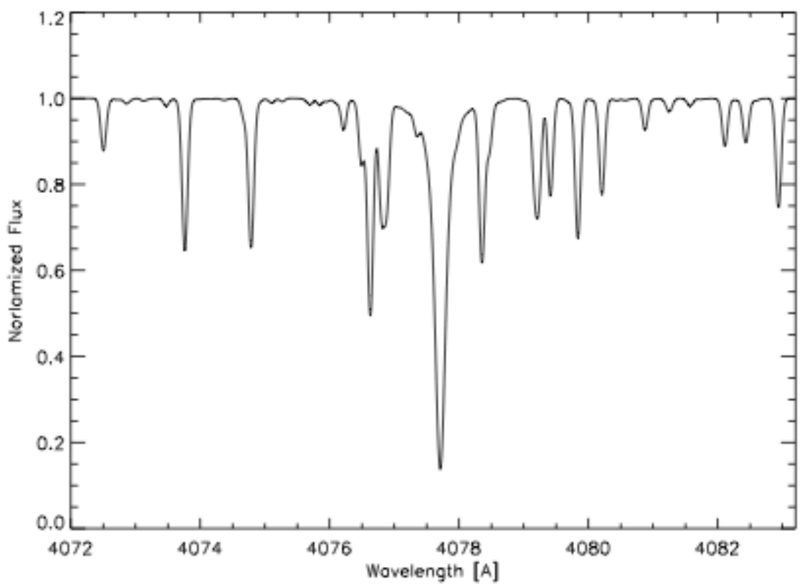
Low-mass (<1M_o) live long.
Stars with M < 0.7M_o are ~ 12 Gyr – typical for RR Lyr stars.

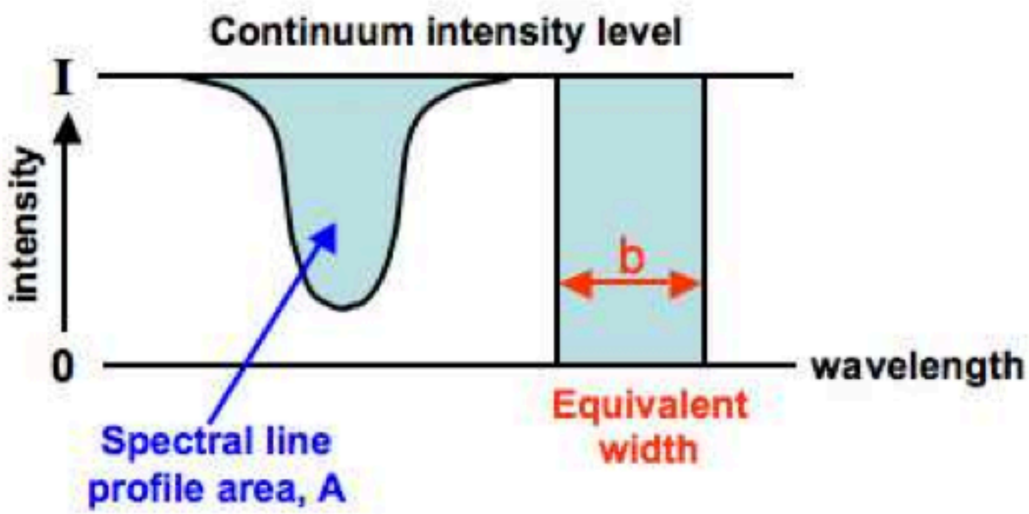
Observations



Stellar abundances

Stellar spectra and equivalent width (W)

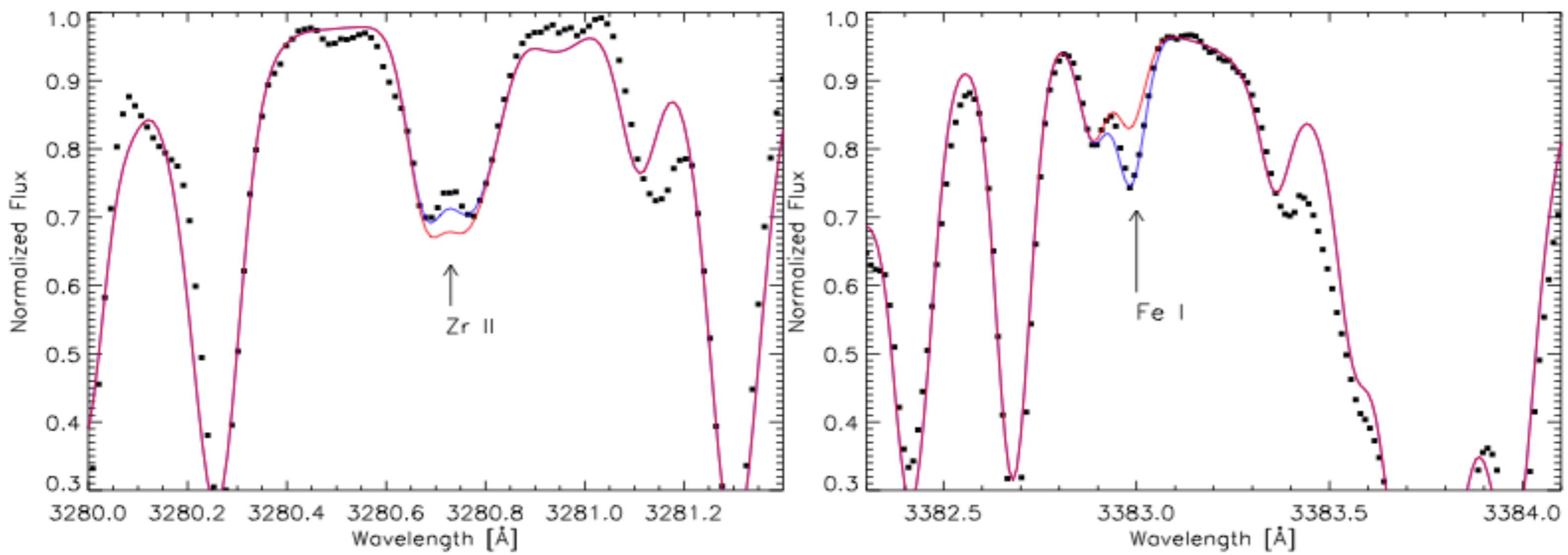




Abundance - W - log gf relation; the impact of stellar parameters and atomic data

$$\log W = \log(const) + \log(A) + \log(gf\lambda) - \theta\chi - \log(\kappa) \qquad (1)$$

Figure: Near-UV Silver lines!

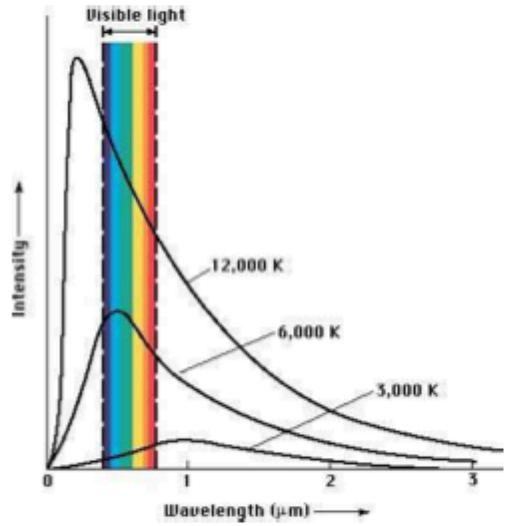


C.J.Hansen et al, 2012

Since the UV-region of the spectra is crowded we have to carry out spectral synthesis on line lists with accurate atomic data.

Two ways of deriving abundances:

- Equivalent width and synthetic spectra
- We need to know the stellar parameters: Temperature, gravity, metallicity and velocity (small scale)
- Model atmosphere (e.g. MARCS) and synthetic spectrum code (e.g. MOOG)
- Assumptions: 1D, LTE – one local temperature, black body radiation (Planck), Maxwellian velocity distribution, Boltzmann and Saha describe excitation and ionisation
- Line lists with atomic and molecular information (excitation potential and log gf)



Stellar parameters

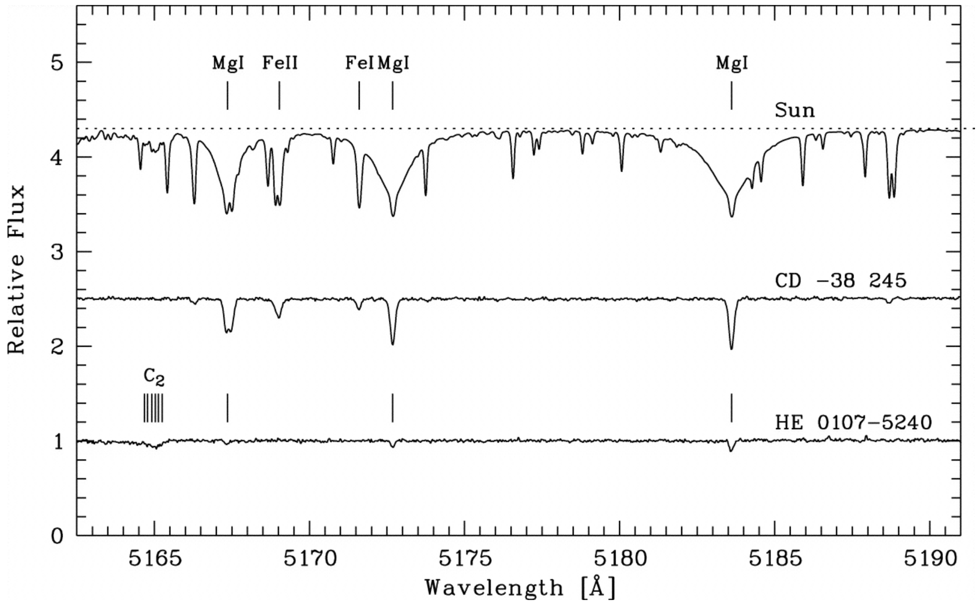
Temperature, gravity and metallicity

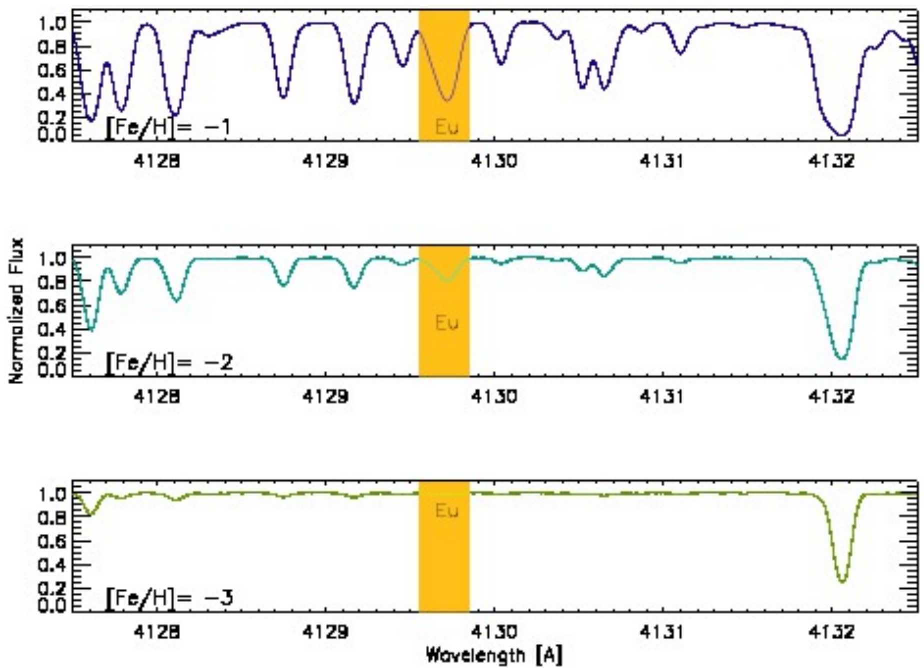
- The color of a star depends on two factors: Temperature and metallicity
- Color (V-K) calibration Alonso et al. 1999, Casagrande et al. 2010:
  $T = a + b(V-K) + c(V-K)^2 + d(V-K)[Fe/H] + ...$
- Excitation potential - based on Fe lines (NLTE sensitive)
- Parallax/distance (π) e.g., Nissen et al. 1997:
  $log\frac{g}{g_{Sun}} = log\frac{M}{M_{Sun}} + 4\frac{T}{T_{Sun}} + 0.4V_o + 2log(\pi) + corrections$
- Ionisation equilibrium from Fe lines (NLTE sensitive)
- Metallicity ([Fe/H]) from equivalent widths of Fe lines

Metallicity – impact on spectra

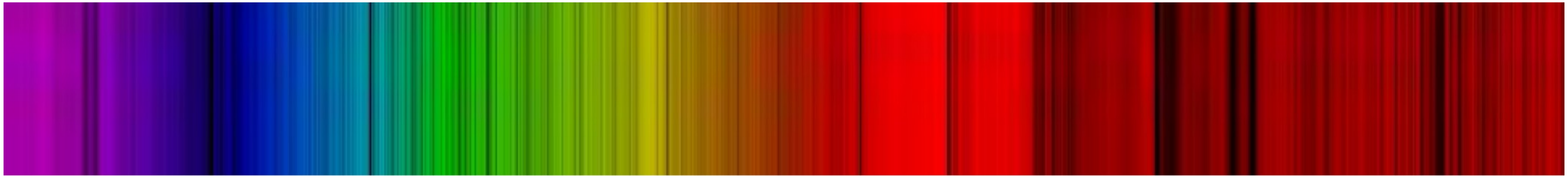
$$[Fe/H] = \log(N_{Fe}/N_H)_\star - \log(N_{Fe}/N_H)_\odot$$

CJH et al. 2014b

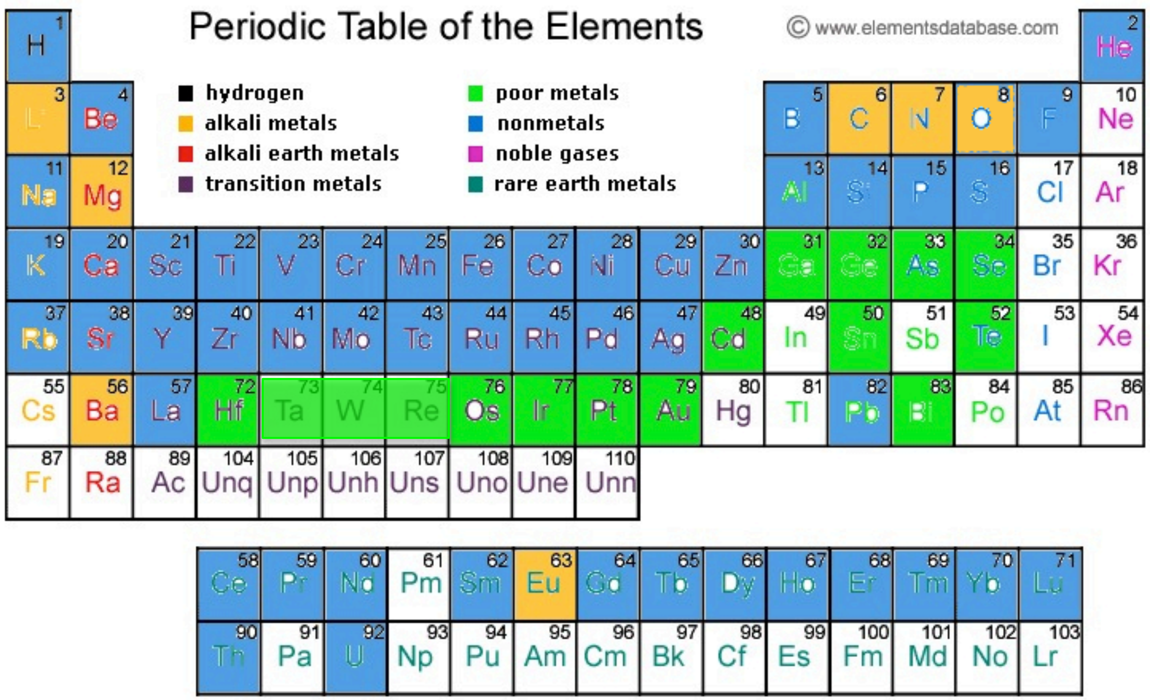




Top: Solar ([Fe/H] = 0) spectrum – Mg triplet.
Bottom: Star with [Fe/H] ~ -5. Christlieb +2004



An observer's periodic table



Record holding star - CS31082-001
Abundances of almost 70 elements, 37 of which are heavy elements.
Siqueira Mello et al. 2013

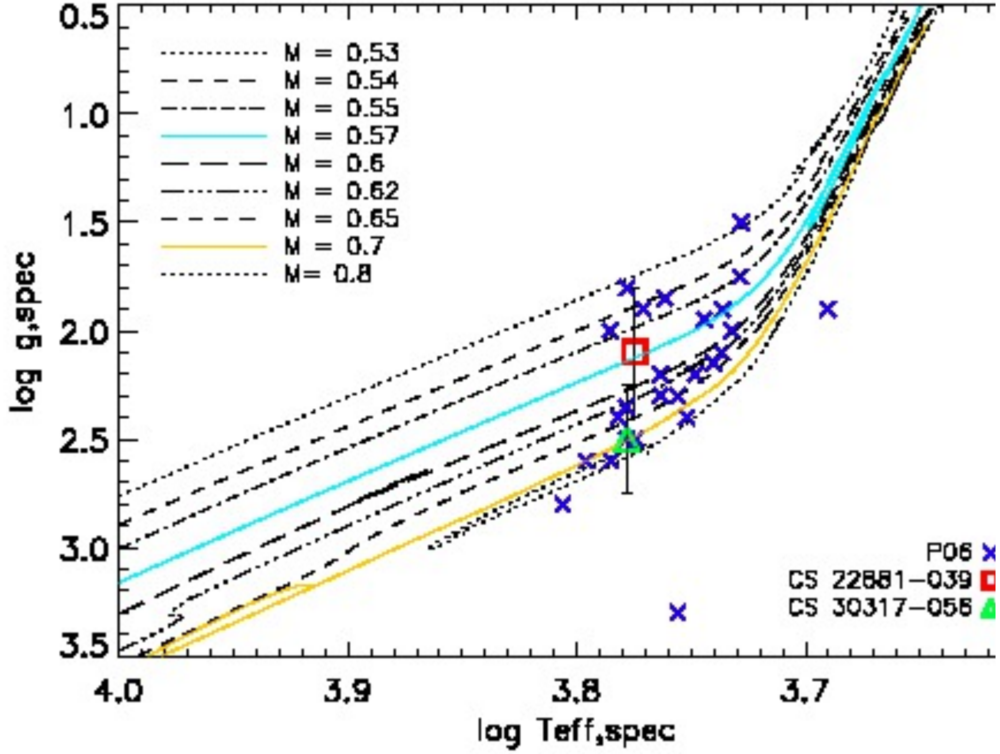
Table 1. LTE abundances in CS 31082-001 as derived from previous works, from the present paper, and our adopted final abundances.

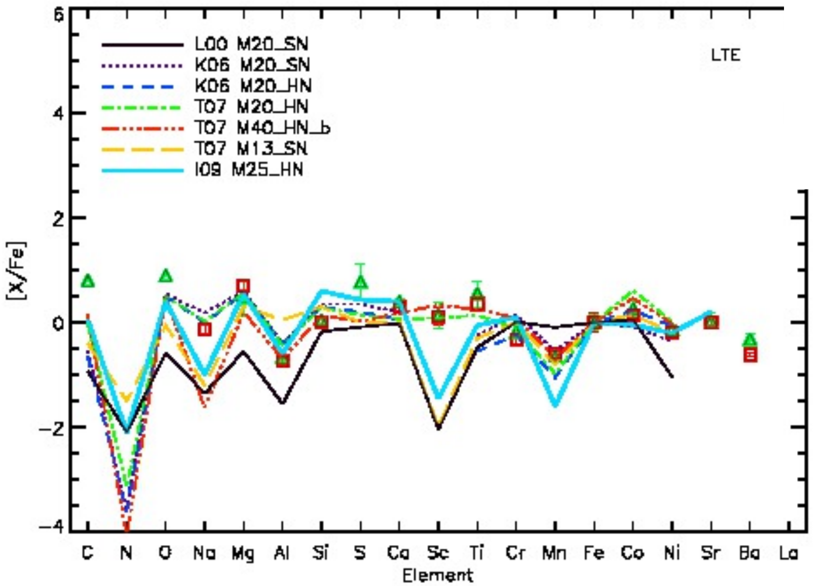
El.	Z	A(X) (1)	A(X) (2)	A(X) (3)	A(X) This Work	A(X) adopted	[X/Fe] adopted
Ge	32	—	—	—	+0.10	+0.10±0.21	-0.55
Sr	38	+0.72	—	—	—	+0.72±0.10	0.73
Y	39	-0.23	—	—	-0.15	-0.19±0.07	0.53
Zr	40	+0.43	—	—	+0.55	+0.49±0.08	0.84
Nb	41	-0.55	—	—	-0.52	-0.54±0.12	0.97
Mo	42	—	—	—	-0.11	-0.11±0.13	0.90
Ru	44	+0.36	—	—	+0.36	+0.36±0.12	1.45
Rh	45	-0.42	—	—	-0.42	-0.42±0.12	1.39
Pd	46	-0.05	—	—	-0.09	-0.09±0.07	1.18
Ag	47	-0.81	—	—	-0.84	-0.84±0.21	1.15
Ba	56	+0.40	—	—	—	+0.40±0.14	1.16
La	57	-0.60	-0.62	—	—	-0.62±0.05	1.17
Ce	58	-0.31	-0.29	—	-0.31	-0.29±0.05	1.03
Pr	59	-0.86	-0.79	—	—	-0.79±0.05	1.38
Nd	60	-0.13	-0.15	—	-0.21	-0.15±0.05	1.33
Sm	62	-0.51	-0.42	—	-0.42	-0.42±0.05	1.51
Eu	63	-0.76	-0.72	—	-0.75	-0.72±0.05	1.69
Gd	64	-0.27	-0.21	—	-0.29	-0.21±0.05	1.61
Tb	65	-1.26	-1.01	—	-1.00	-1.01±0.05	1.64
Dy	66	-0.21	-0.07	—	-0.12	-0.07±0.05	1.73
Ho	67	—	-0.80	—	—	-0.80±0.06	1.62
Er	68	-0.27	-0.30	—	-0.31	-0.30±0.05	1.67
Tm	69	-1.24	-1.15	—	-1.18	-1.15±0.05	1.64
Yb	70	—	-0.41	—	—	-0.41±0.11	1.66
Lu	71	—	—	—	-1.08	-1.08±0.13	1.73
Hf	72	-0.59	-0.72	—	-0.73	-0.72±0.05	1.33
Ta	73	—	—	—	-1.60	-1.60±0.23	1.47
W	74	—	—	—	-0.90	-0.90±0.24	0.92
Re	75	—	—	—	-0.21	-0.21±0.21	2.45
Os	76	+0.43	—	+0.18	—	+0.18±0.07	1.72
Ir	77	+0.20	—	+0.20	—	+0.20±0.07	1.72
Pt	78	—	—	+0.30	—	+0.30±0.23	1.46
Au	79	—	—	-1.00	—	-1.00±0.34	0.89
Pb	82	—	—	-0.65	—	-0.65±0.19	0.25
Bi	83	—	—	-0.40	—	-0.40±0.33	1.83
Th	90	-0.98	—	—	—	-0.98±0.13	1.84
U	92	-1.92	—	—	—	-1.92±0.17	1.68

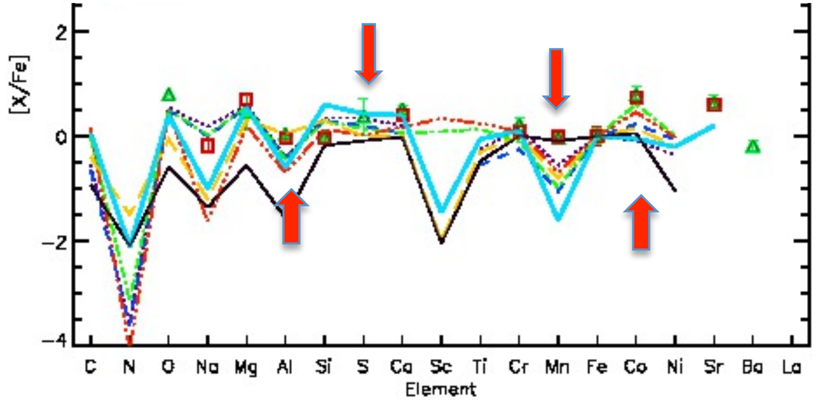
References. (1) Hill et al. (2002), (2) Sneden et al. (2009), (3) Barbuy et al. (2011).

Tracing the yields from the first stars?

- RR lyr vs. Fe-poor stars – Tv
- α-elements → SN Mass (Kob
- α/Z_{odd} & Fe-peak → E_{51}
- Sc, Ti, Zn → Y_e
- In-/complete Si burn → Tpe



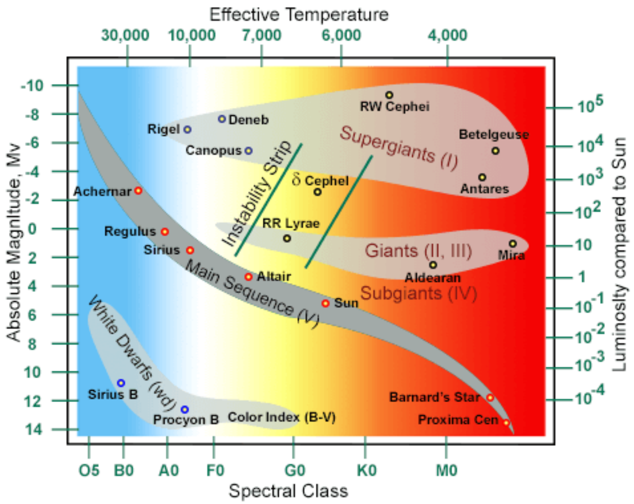




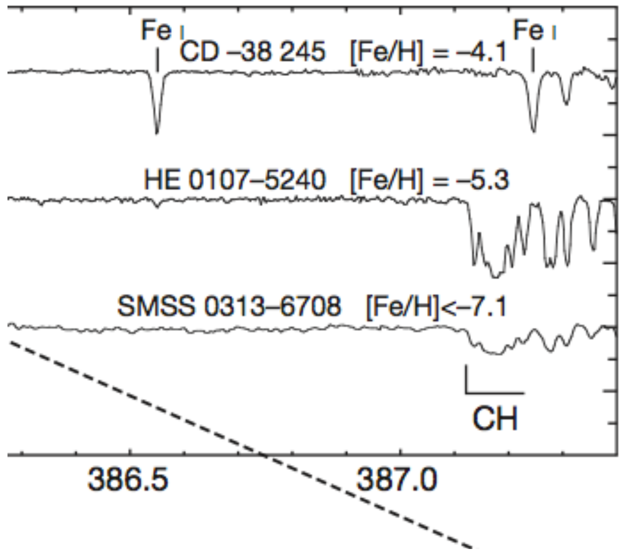
CJH + 2011a

Tracing the yields from the first stars?

- RR lyr vs. Fe-poor stars



Few absorption lines → few abundances! Molecular bands obscure.



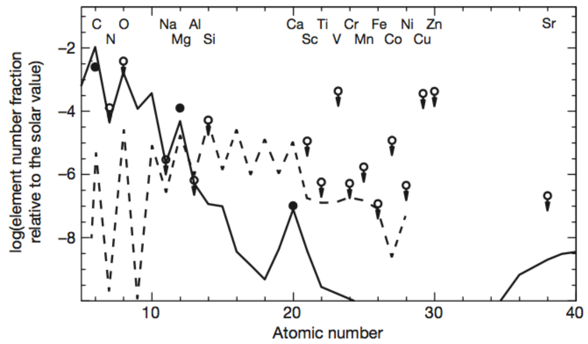


Figure 3 | **The element abundance pattern for SMSS 0313−6708 compared**

Keller + \`14 (1D, LTE): [Fe/H] < -7.1 – SN II: 60M$_\odot$

Bessel + \`15 (3D, NLTE – molec.): [Fe/H] < -7.5 – SNII: 40M$_\odot$

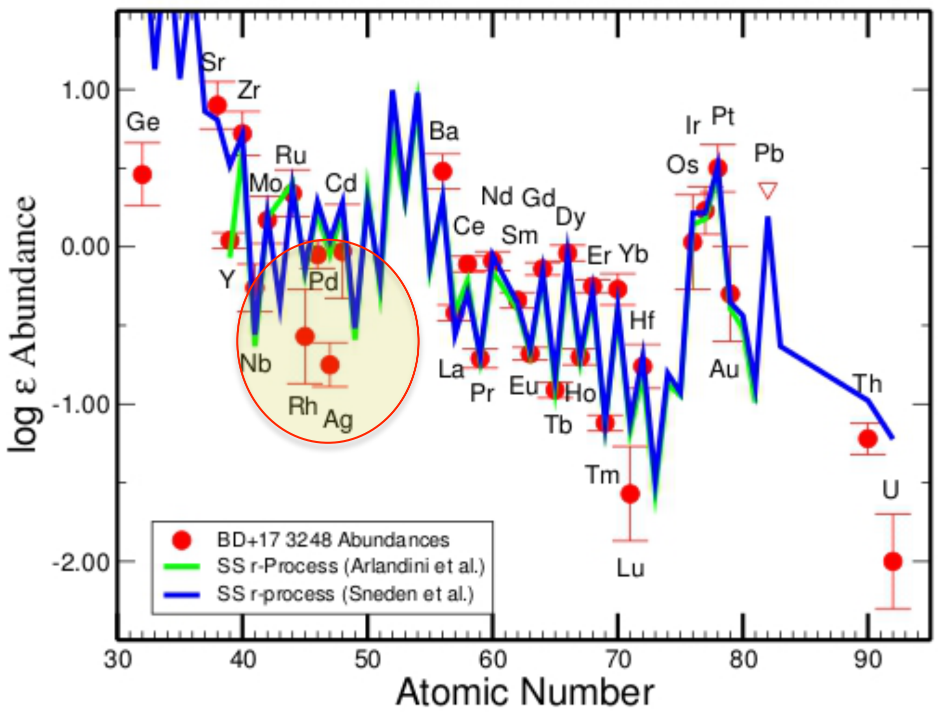
Nordlander + \`17 (3D, NLTE – atom.): [Fe/H] < -6.5 – SNII Faint 10M$_\odot$ or ~2B 20-60M$_\odot$

Keller et al. 2014

Contributions to single EMP stars

2 different contributions are needed!

Seen in star-to-star abundance scatter + deviation from solar r-pattern

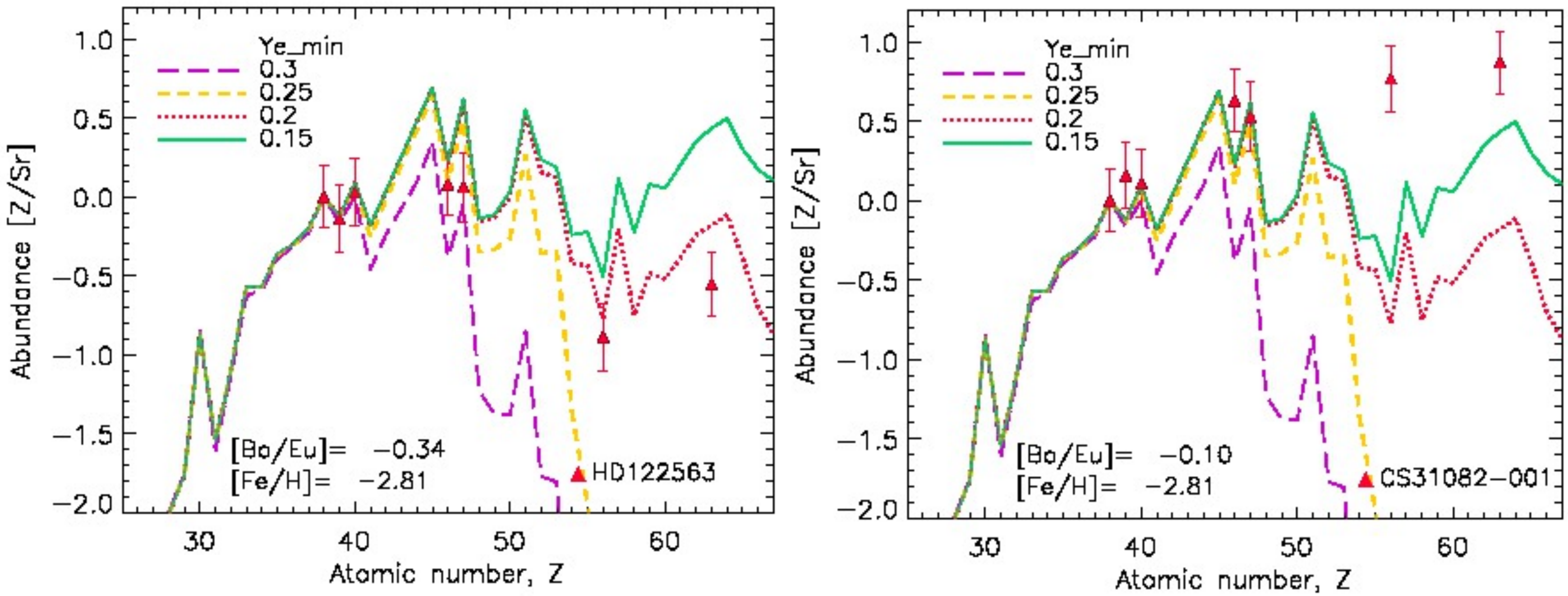


Cowan + 2011

How many processes are needed at low [Fe/H]?

- Stellar patterns: r-poor vs r-rich stars → different environments needed!

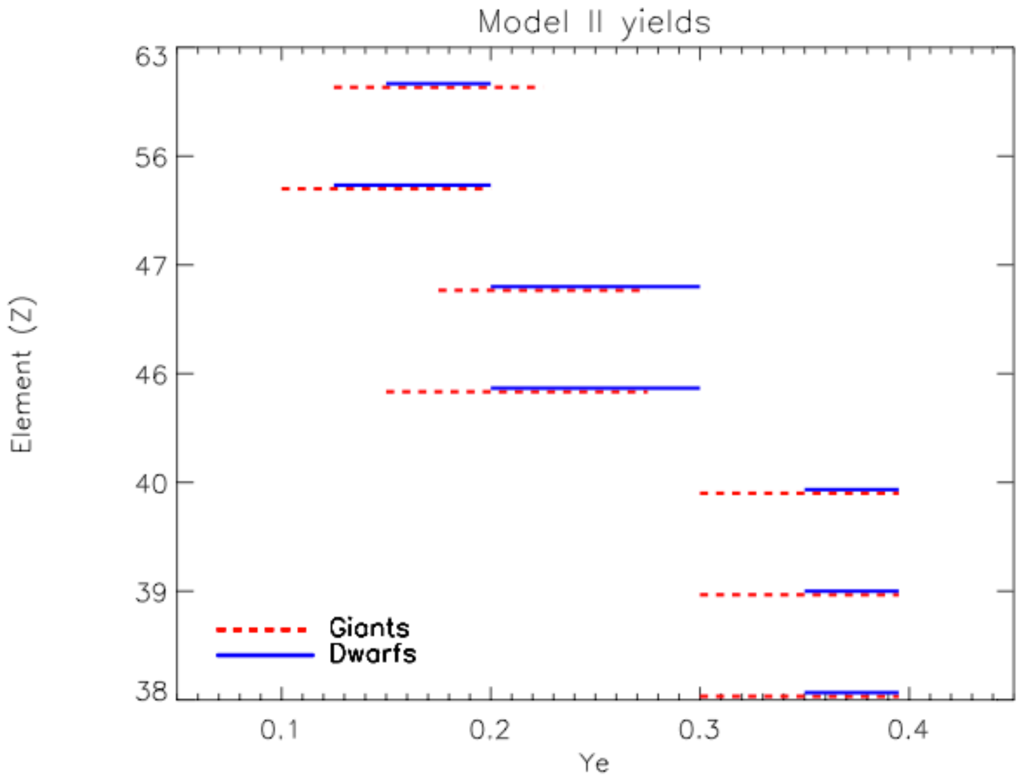
CJH et al. 2012



Observations: Honda et al. 2004, 2007, Hill et al. 2002, Siqueira Mello et al. 2013; Yields: Wanajo et al. 2011

Constraining the physics…

- Stellar abundances vs yield predictions may help constrain Ye

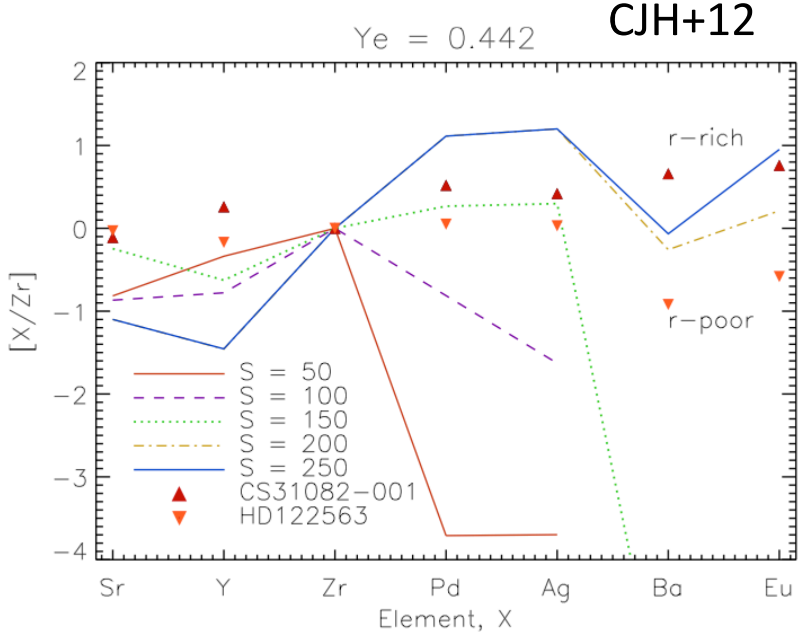


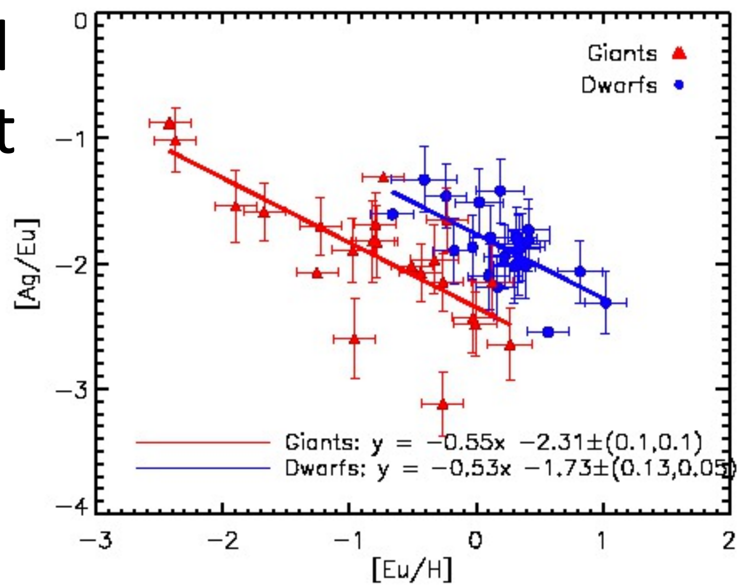
Observations: CJH+2012, Yields: Wanajo et al. 2011

Solar System abundance – Solar-s=r…

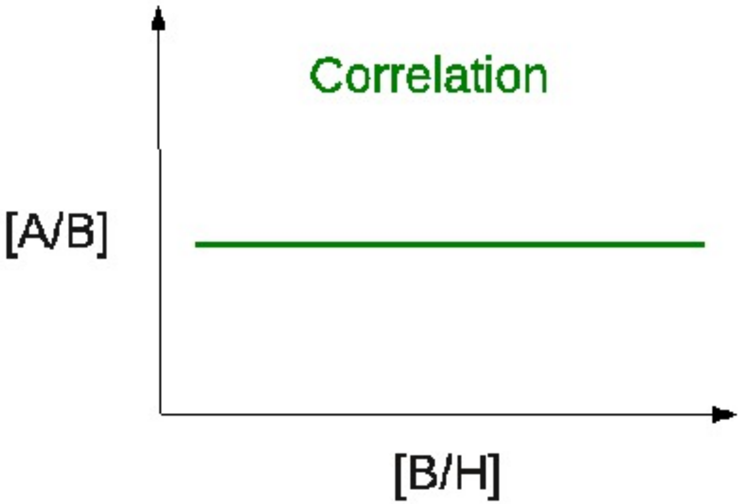
CJH+12

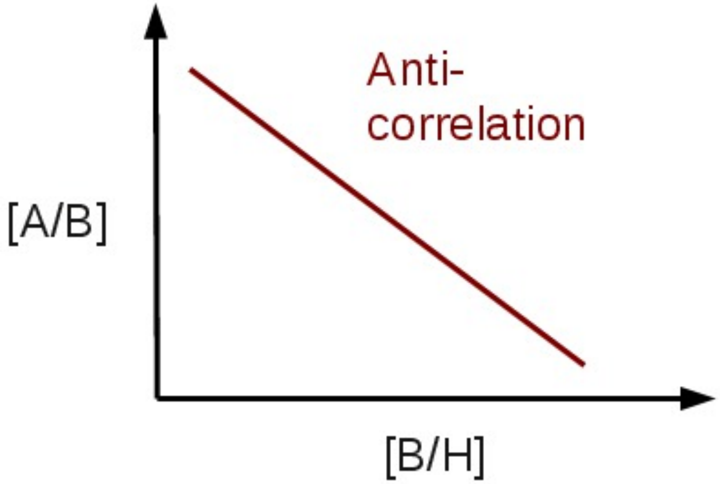
- Once we focus on r-poor stars, different processes like the weak r can be detected.
- The r-poor stars do not agree perfectly with Solar – s = r.
- Solar system abundances are integrated over billions of years and are highly convolved – they may not be the best r-tracers despite their large number and accuracy!





Primary processes: Co-production or not?

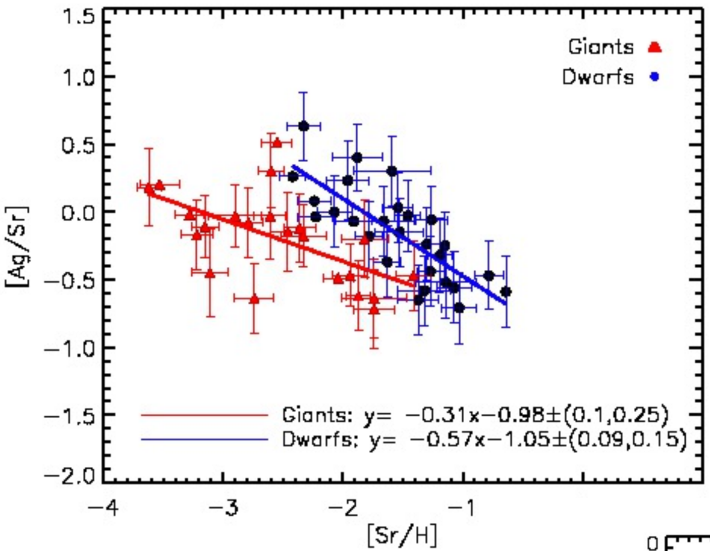




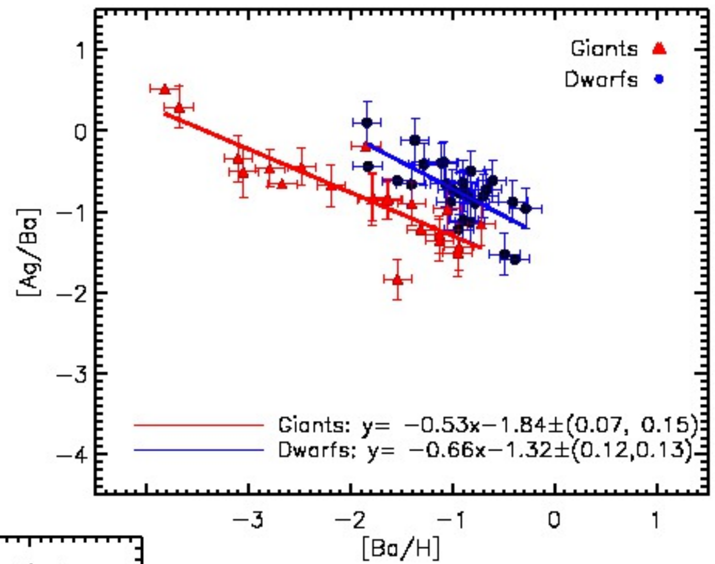
- Two elements produced in the same way, most likely grow at the same rate over time if the process is robust and show a small abundance scatter.
- The lighter 38 < Z < 50 seem not always to be co-produced with the heavy elements (Z > 56)
(Burris et al. 2000, Montes et al. 2007, Francois et al. 2007, CJH et al. 2012, 2014)

Mining for Silver

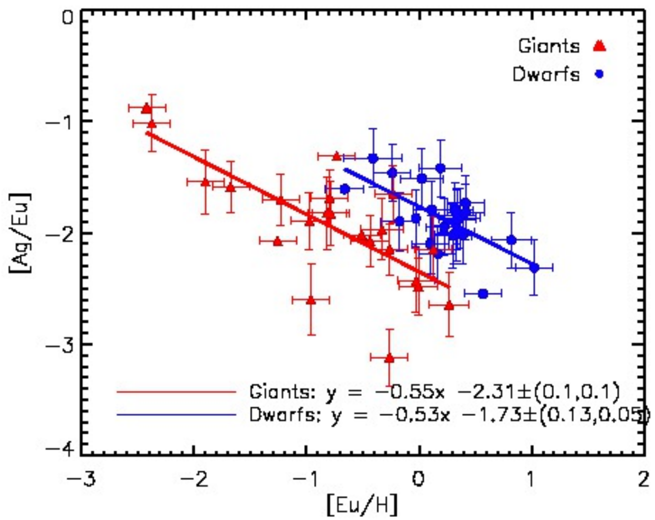
- Sr ~ 85% s, Ba ~ 81%, Eu~94% r vs Ag 79% “r”?
  (Arlandini et al 1999, Bisterzo et al. 2014)



CJH et al. 2012



Ag not weak s/
charged particle or
main r-process!

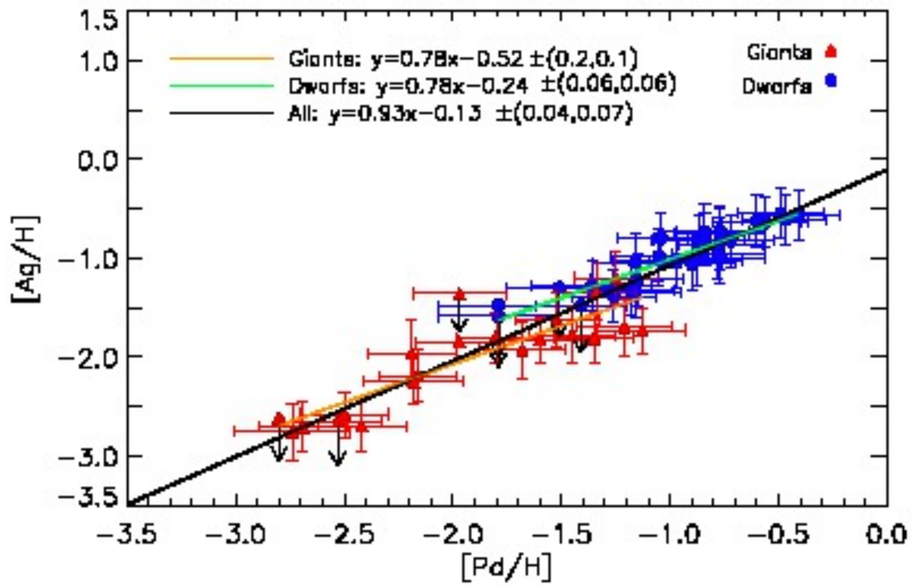


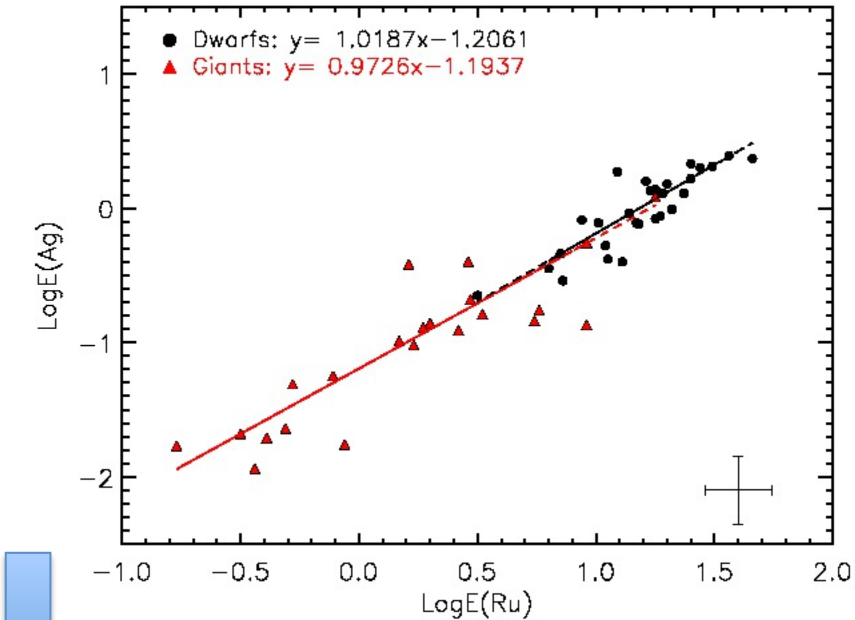
Blue: Higher metallicity dwarf stars [Fe/H] > -2.0

Red: Lower metallicity giants down to [Fe/H] ~ -3.5

Mining for Silver

- Ru, Pd, and Ag co-produced at low metallicity





CJH et al. 2011, 2012

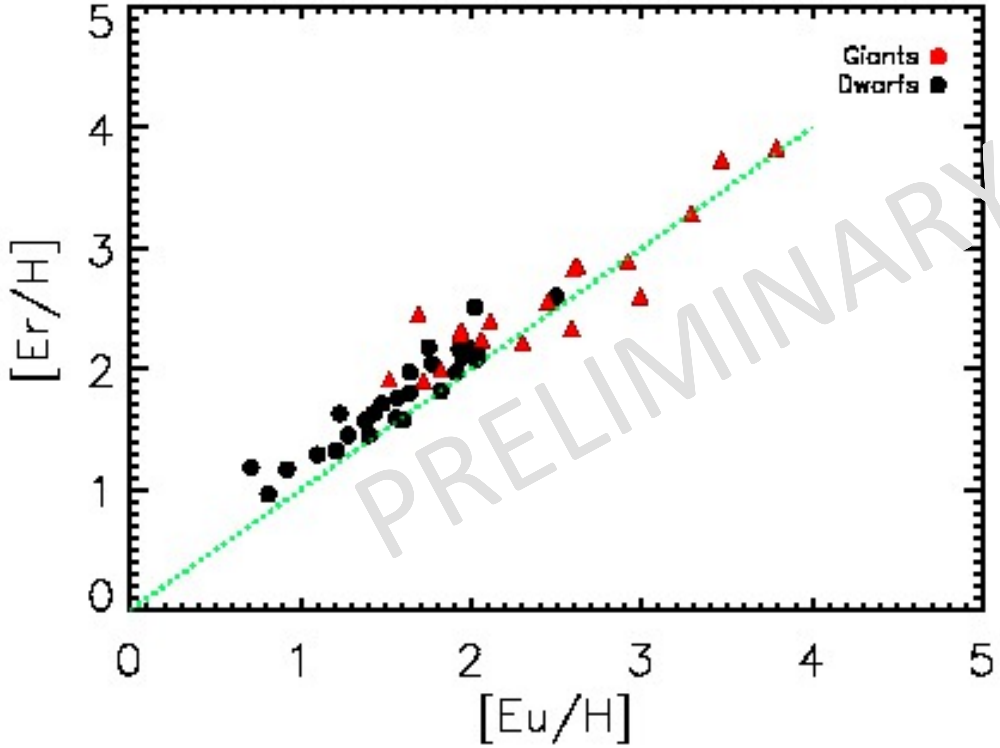
CJH et al. 2014

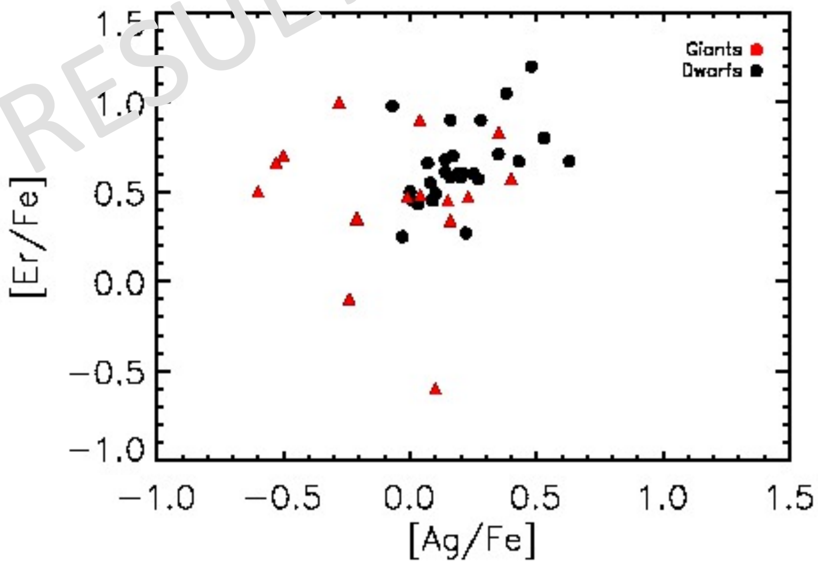
Ru – Ag: Weak r-process – higher Ye, closer to stability than main r – maybe a wind from SN or NSM

New rare earth element observations

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

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



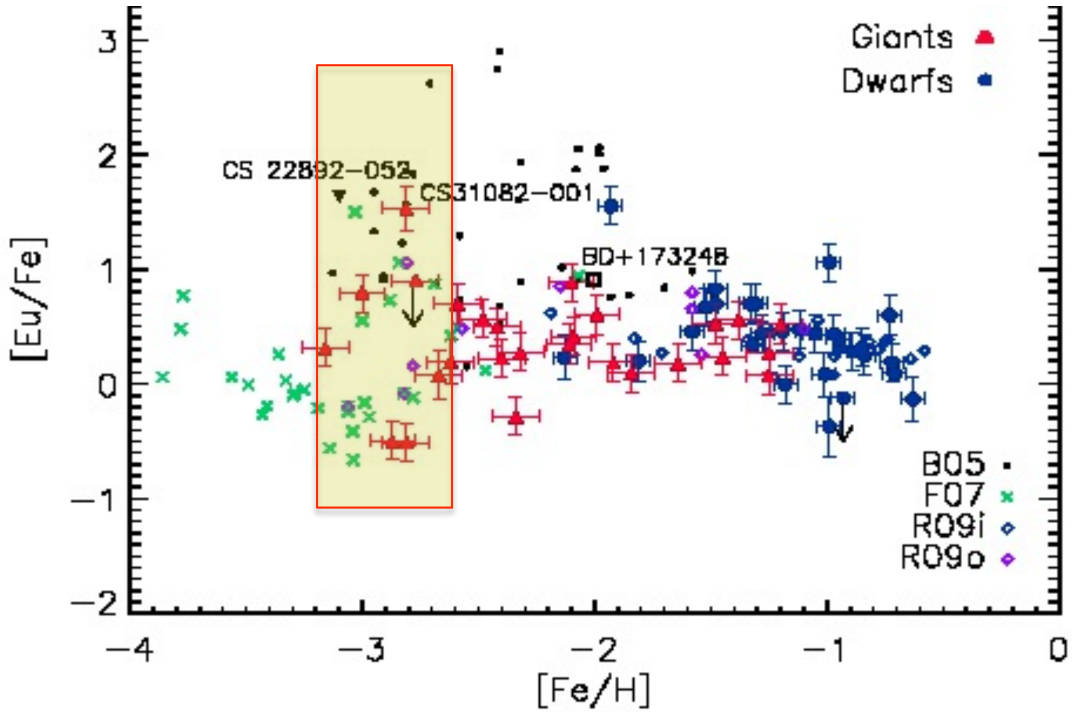


CJH et al. 2017 in prep.

Contributions to many stars (GCE)

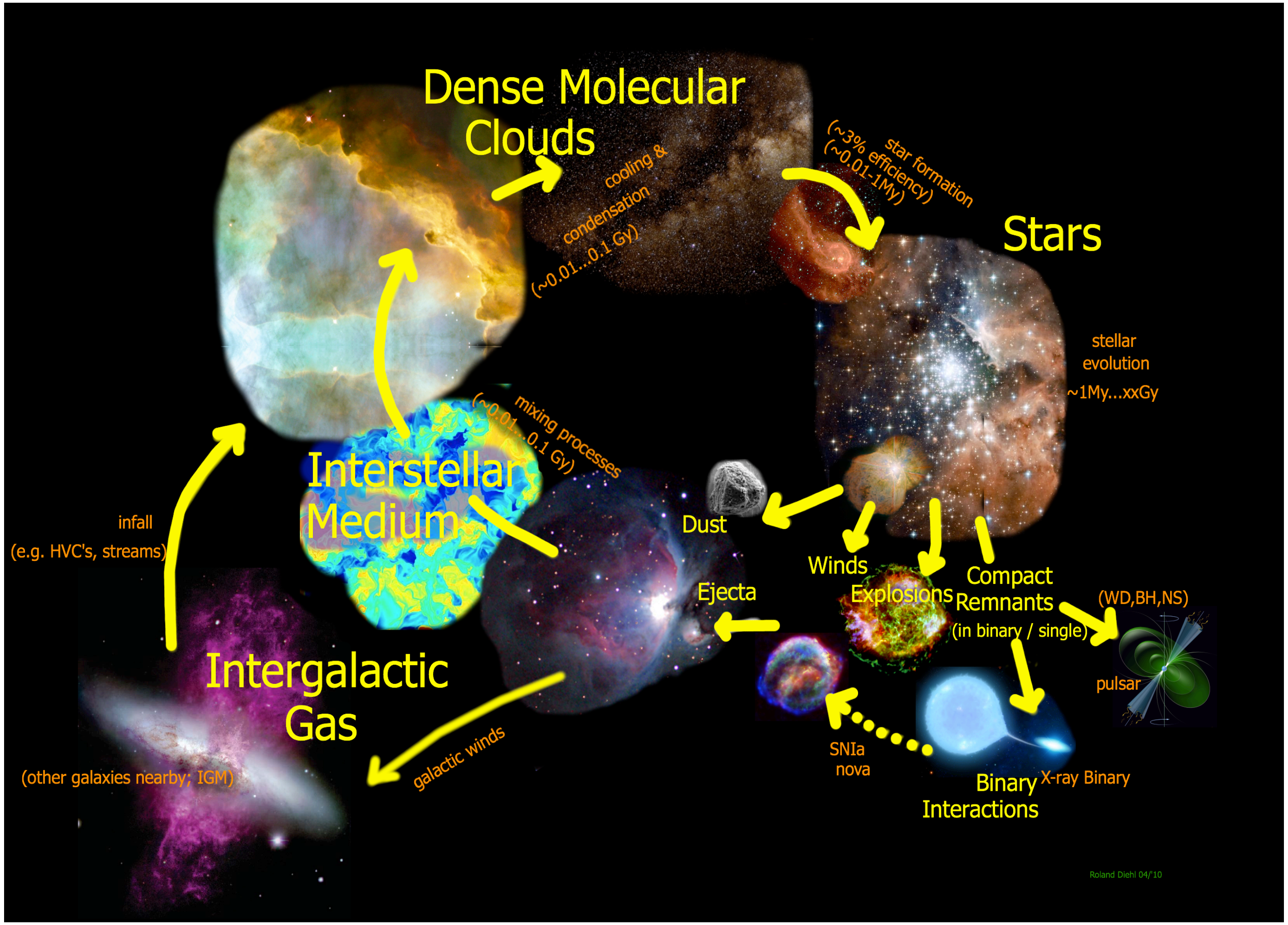
2 different contributions are needed!

Seen in star-to-star abundance scatter + deviation from solar r-pattern



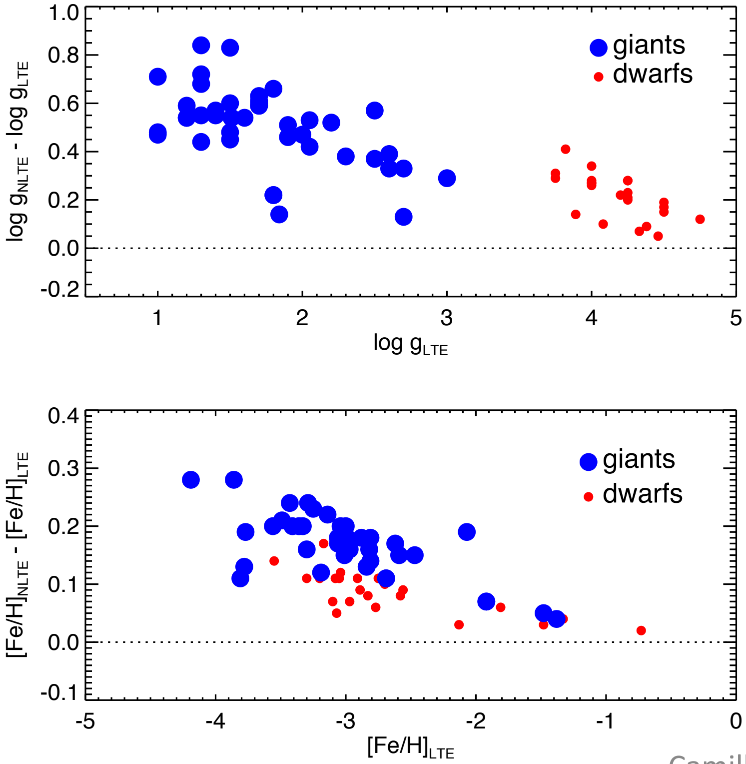
CJH + 2012

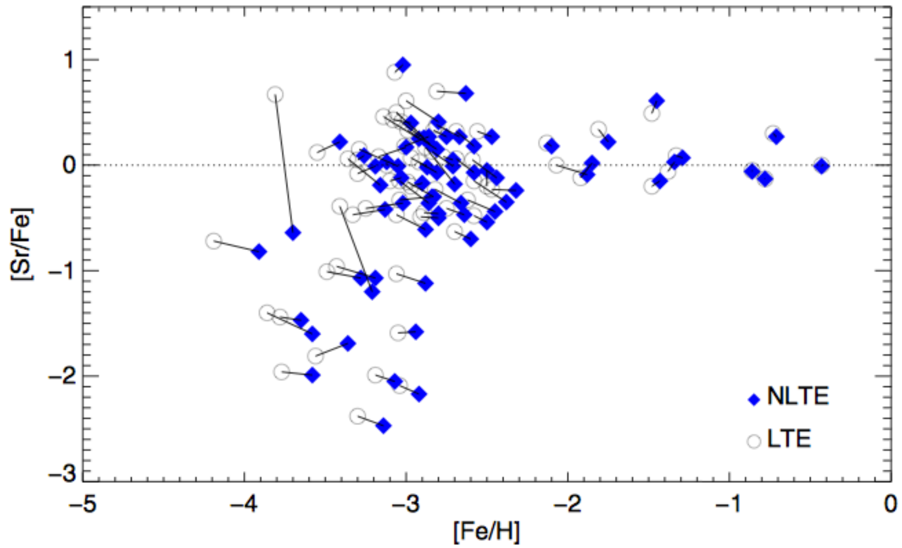
Galactic Chemical Evolution (GCE)



GCE of Sr

- Sr is one of the best heavy element tracers owing to strong lines (CJH et al. 2013)
- We can separate yield contributions and assess star-to-star abundance scatter



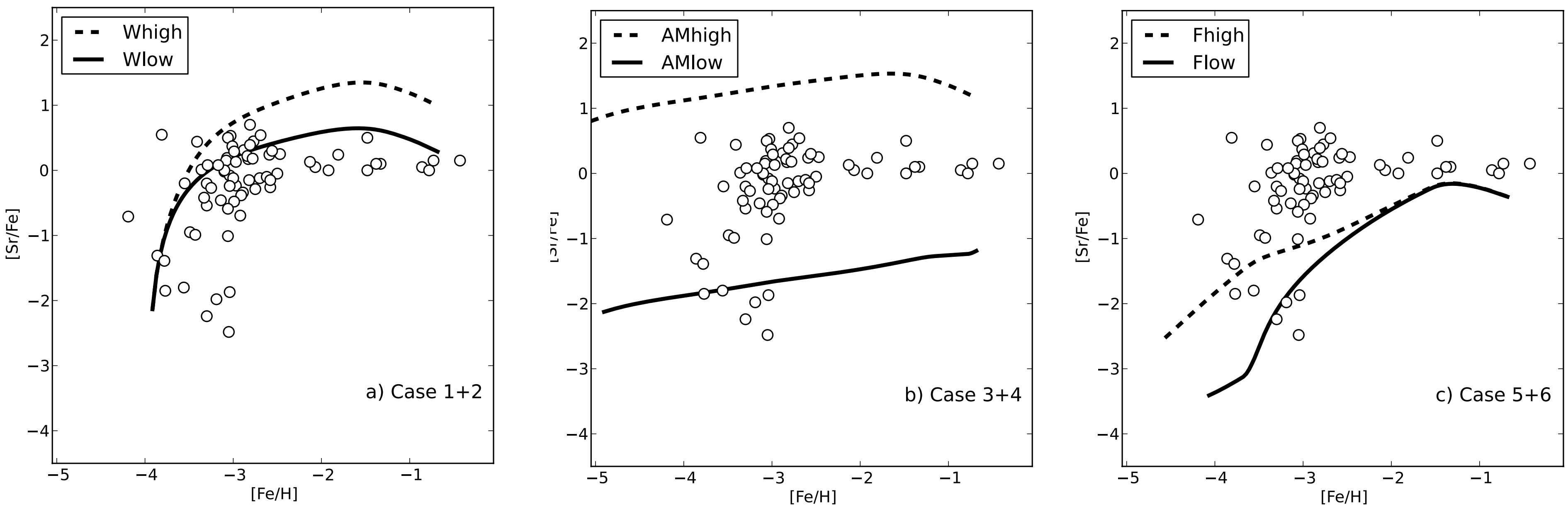


CJH et al. 2013

GCE of Sr

- We can separate yield contributions and assess star-to-star abundance scatter
- NLTE corr. cannot explain scatter → nuclear origin!

CJH et al. 2013



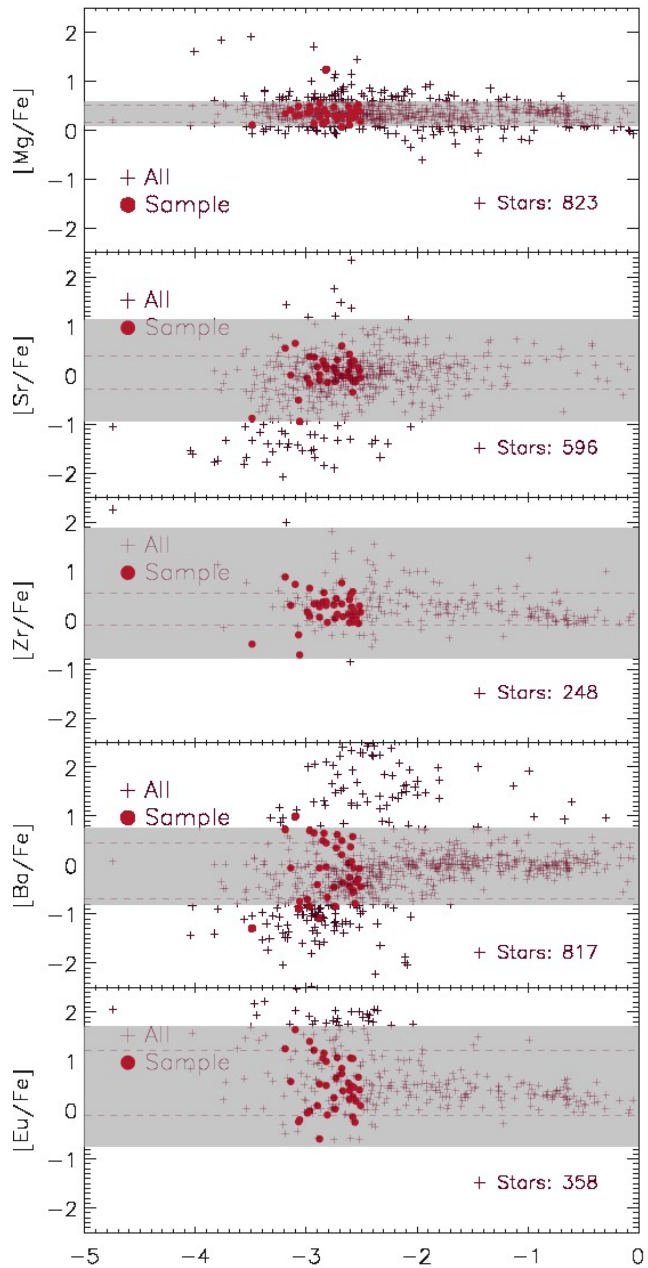
Yields from: Wanajo +`11, Arcones & Montes `11, Frischknecht +`12

Stellar abundances & formation processes

Scatter → Multiple formation sites

- Weak s (Z ≤ 40)
- Main s (broad range, Ba, Z ≥ 50)
- Weak r (~40 < Z < 50)
- Main r (full range, or Z > 50)

(CJH et al. 2014b)

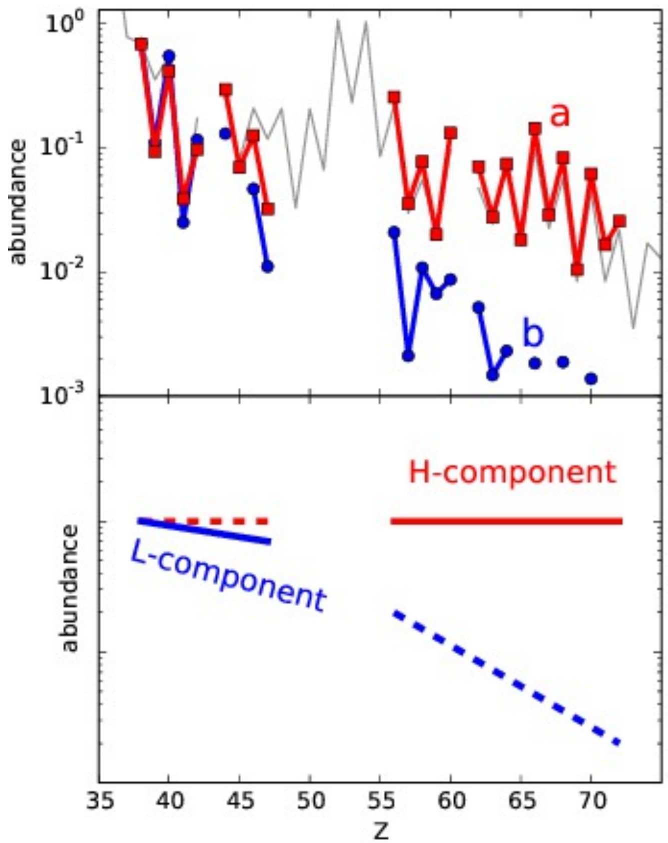


Are 2 “processes” sufficient?

<u>Assumptions (EMP stars):</u>

- There are 2 robust processes: main r (H), weak r (L) (e.g., Qian & Wasserburg 2007)
- M1: H=CS22892-052, L=HD122563
- M2: H=CS22892-052, H+L = HD122563
- M3: H+L=CS22892-052, H+L=HD122563 – all stars are mixed (Li et al. 2013)

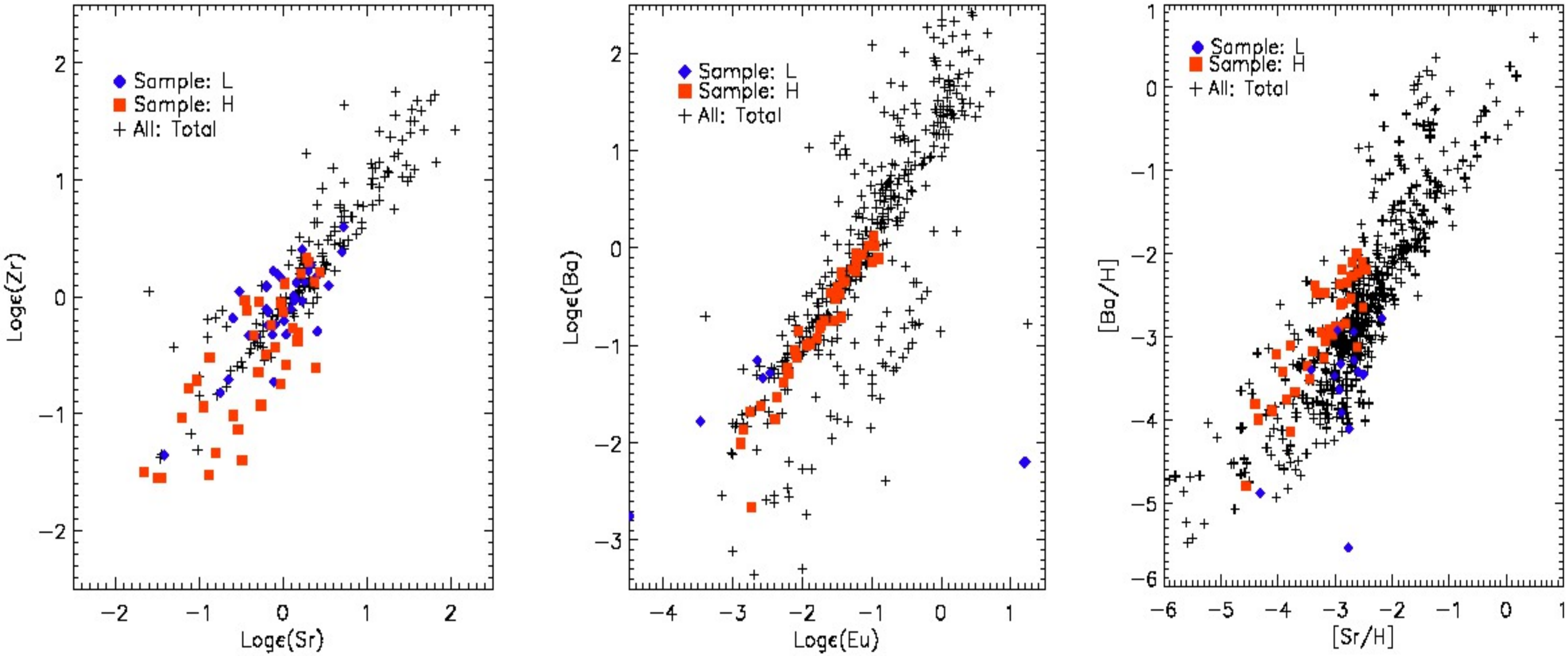
$$Y_{calc}(Z) = (C_H Y_H(Z) + C_L Y_L(Z)) * 10^{[Fe/H]}$$



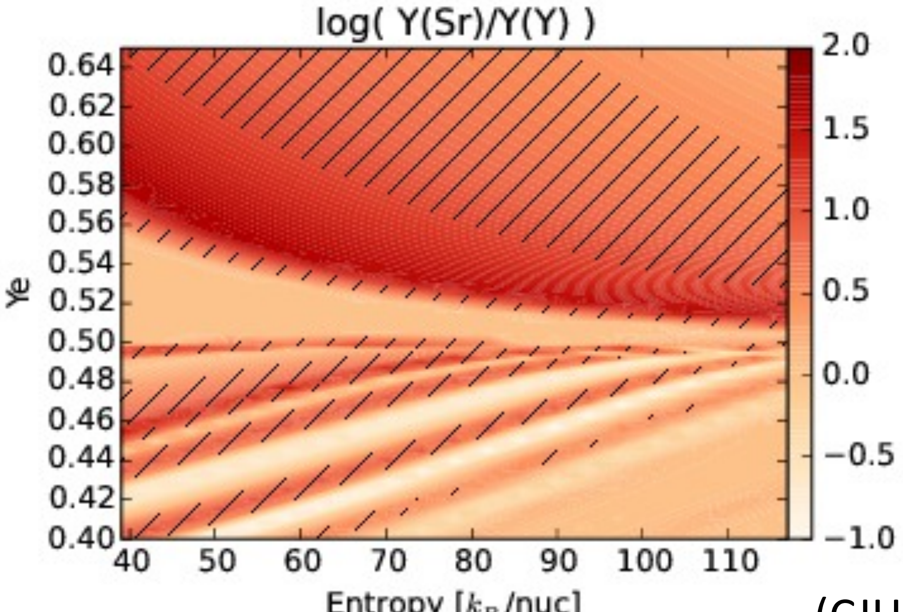
(CJH et al. 2014b)

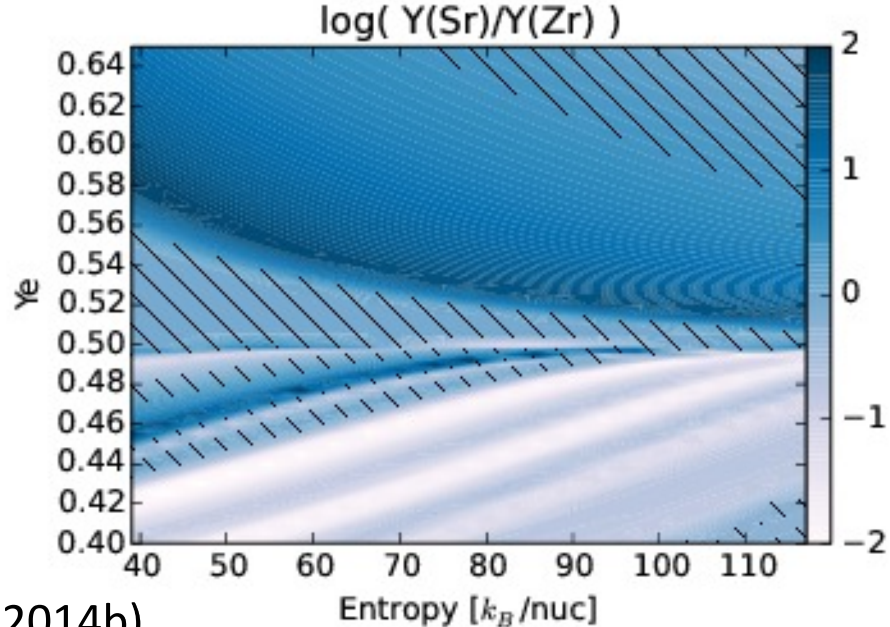
Scatter and robustness of processes

(CJH et al. 2014b)

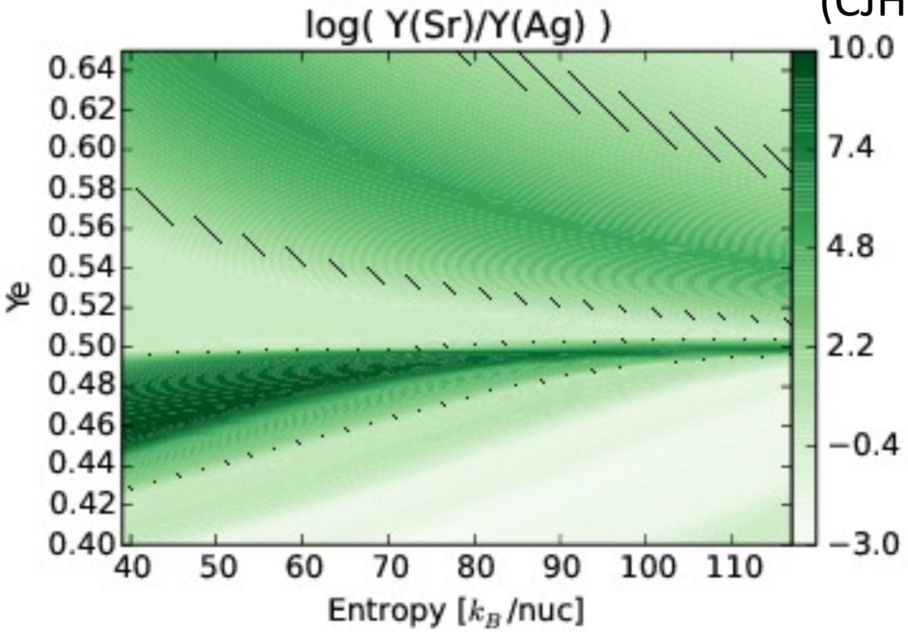


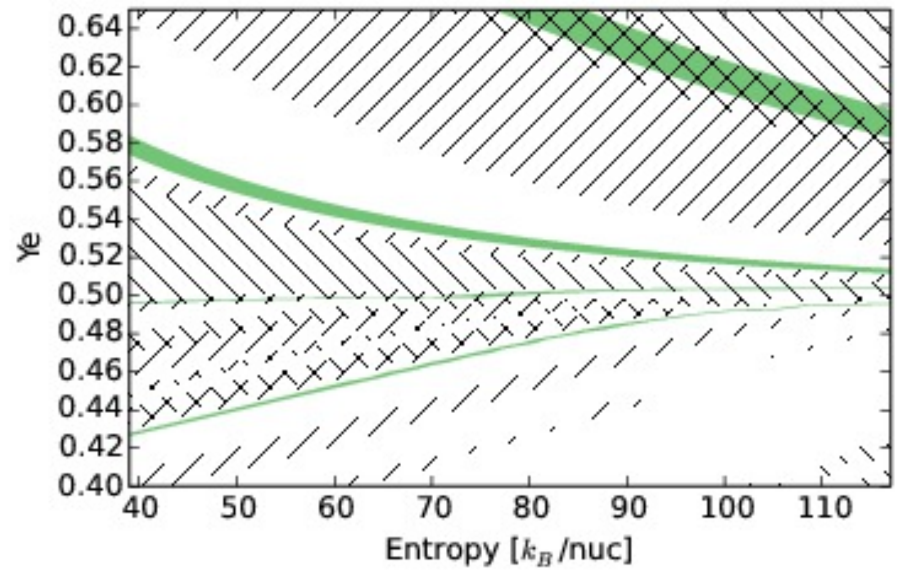
SN ν-winds as L/weak r formation site





(CJH et al. 2014b)



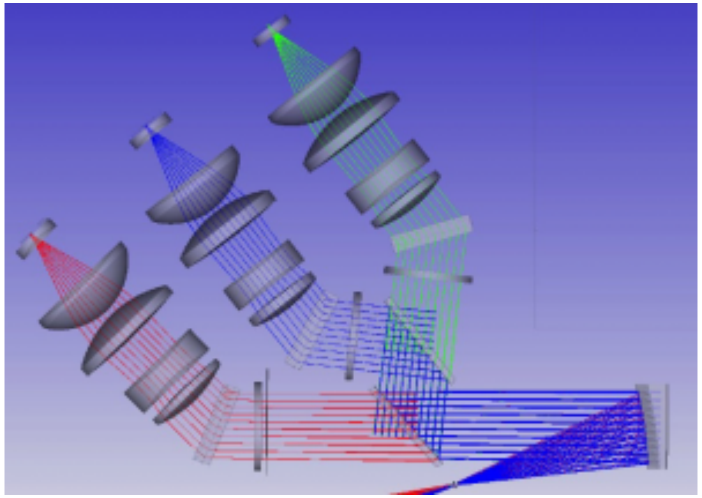


Summary

- A broad variety of stars carry key information on the nature of the r-process
- When looking at stellar abundance patterns and comparing to yields – we need to know how our 1D, LTE assumptions bias the pattern
- A broad parameter range may be needed at the host site (NSM vs SN) to explain Sr – Ag vs Eu – Er – or we have a mixture of both…
  → NSM and SN (ν-driven winds) seem to co-exist and we need to explore how these mix and what that does to the stellar abundance pattern…
- Age – [Fe/H] is not a perfect clock – intrinsically old r-normal stars also carry key information on the first primary processes that produce r-process material:
  We seem to understand the 25 r-II stars – but what about the r-poor halo stars (Honda-like stars)?
- If the r-process is robust and universal – it must be able to explain the abundance patterns we see in both the Galactic halo, disk, as well as UFD / dSph and Globular clusters. This is the challenge.
- Two primary processes/conditions seem to be needed to explain the r-poor as well as the r-rich (rII) stars!
- <u>New challenge: How does the NSM dynamic ejecta mix with the wind/disk?</u>

Future

- Outlook – E-ELT & 4MOST




Thank You!
Camilla Juul Hansen