# Early Chemical Tracers in the Milky Way

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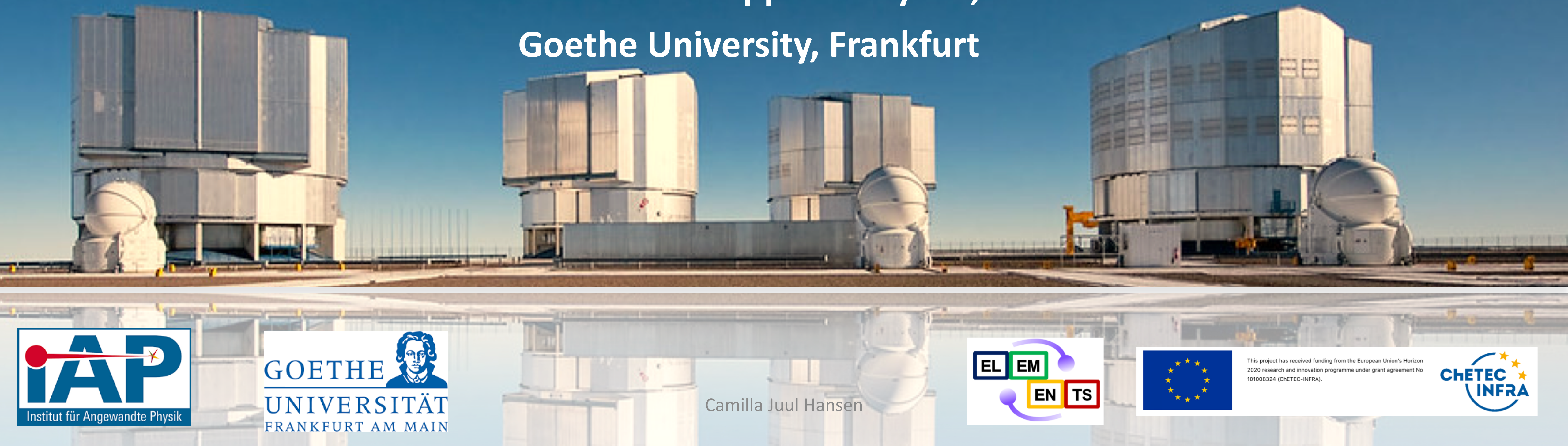


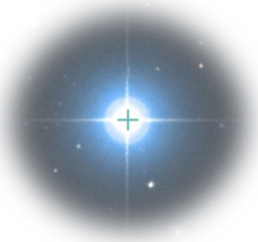
This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101008324 (ChETEC-INFRA).

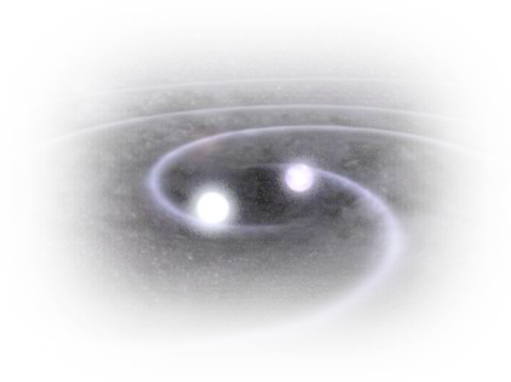
# How do we trace the formation of elements?

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

    - Massive stars
    - Transient events (GBRs, kilonovae)

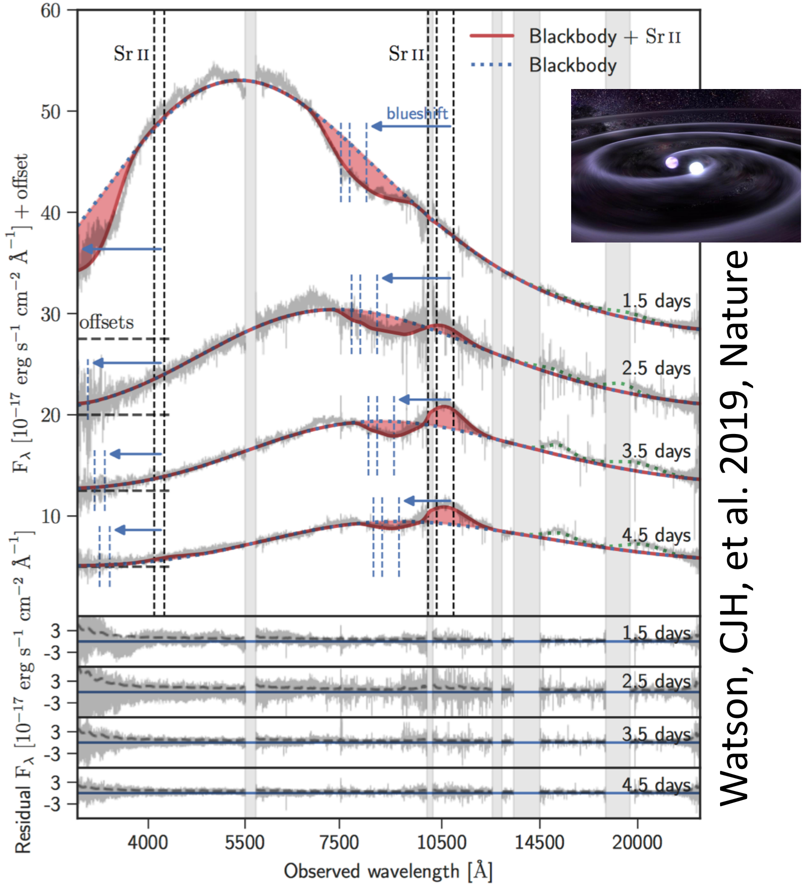
    - …..





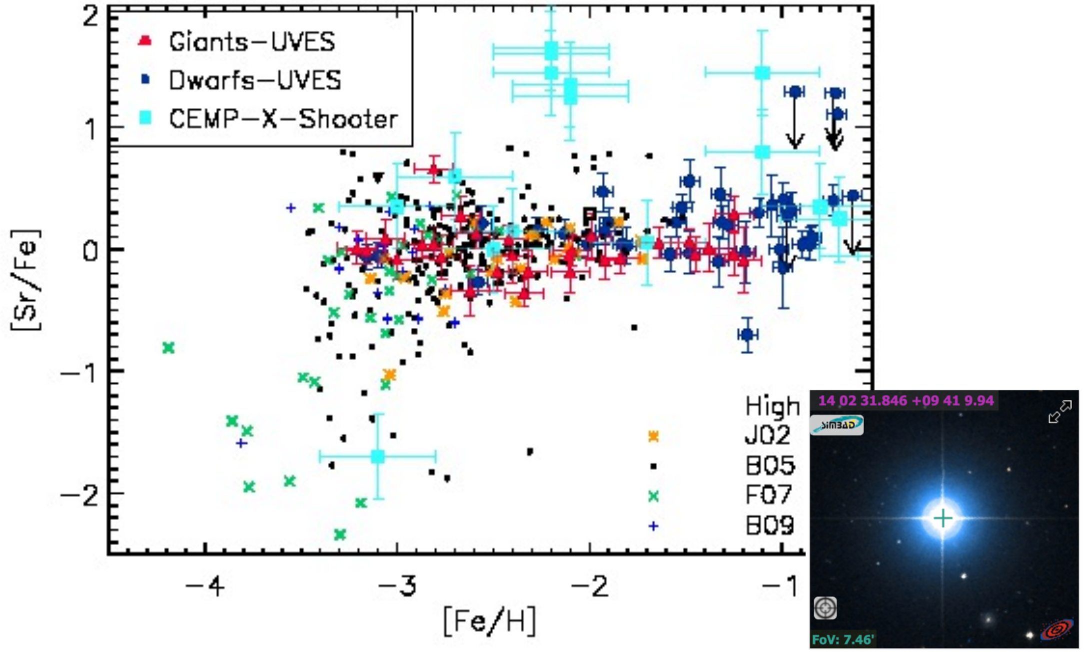
# How do we trace the origin of the elements?

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



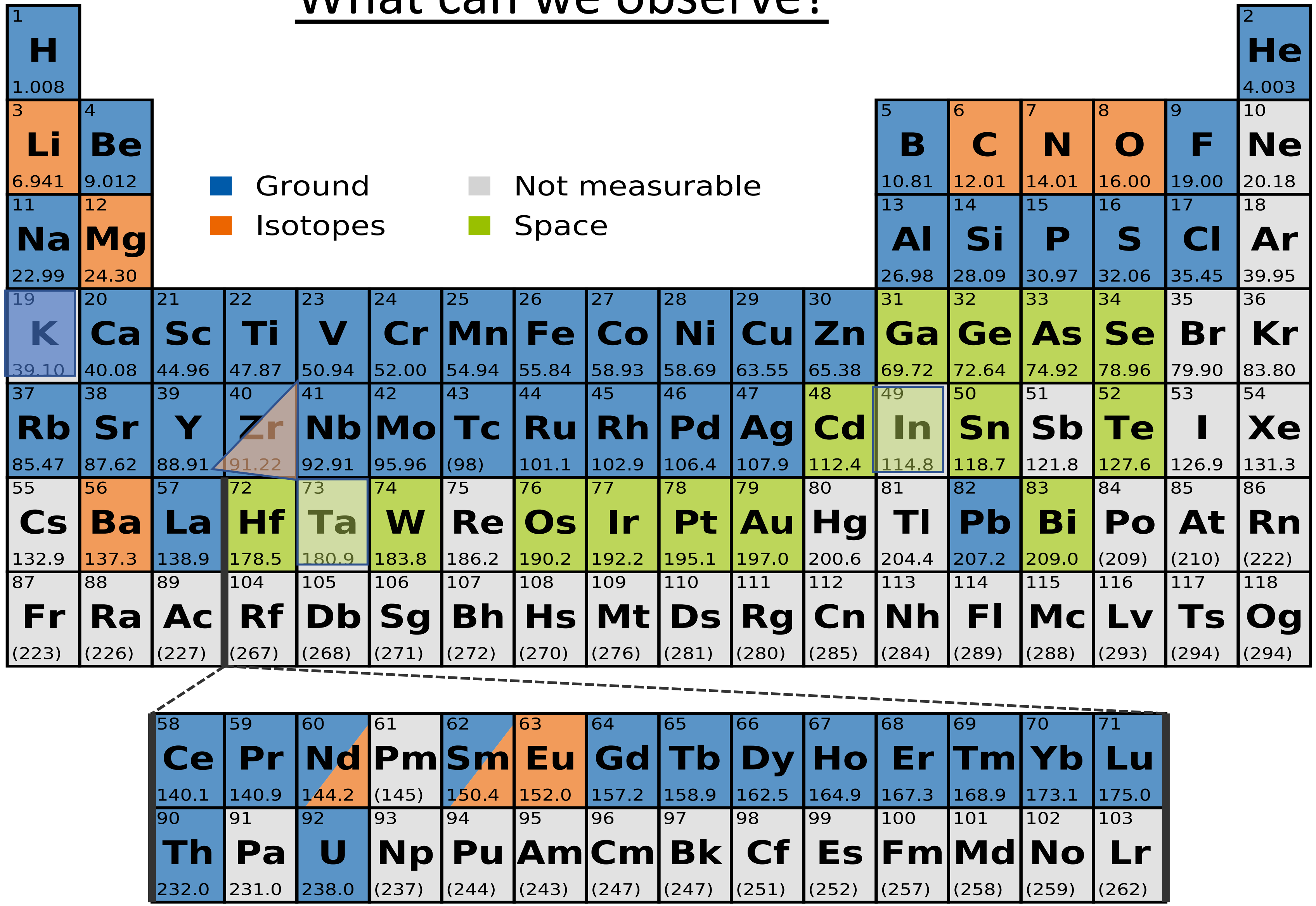
Watson, CJH, et al. 2019, Nature

Adapted from CJH+12



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

# What can we observe?



🟦 Ground
🟧 Isotopes
⬜ Not measurable
🟩 Space

| | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 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) |

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 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) |

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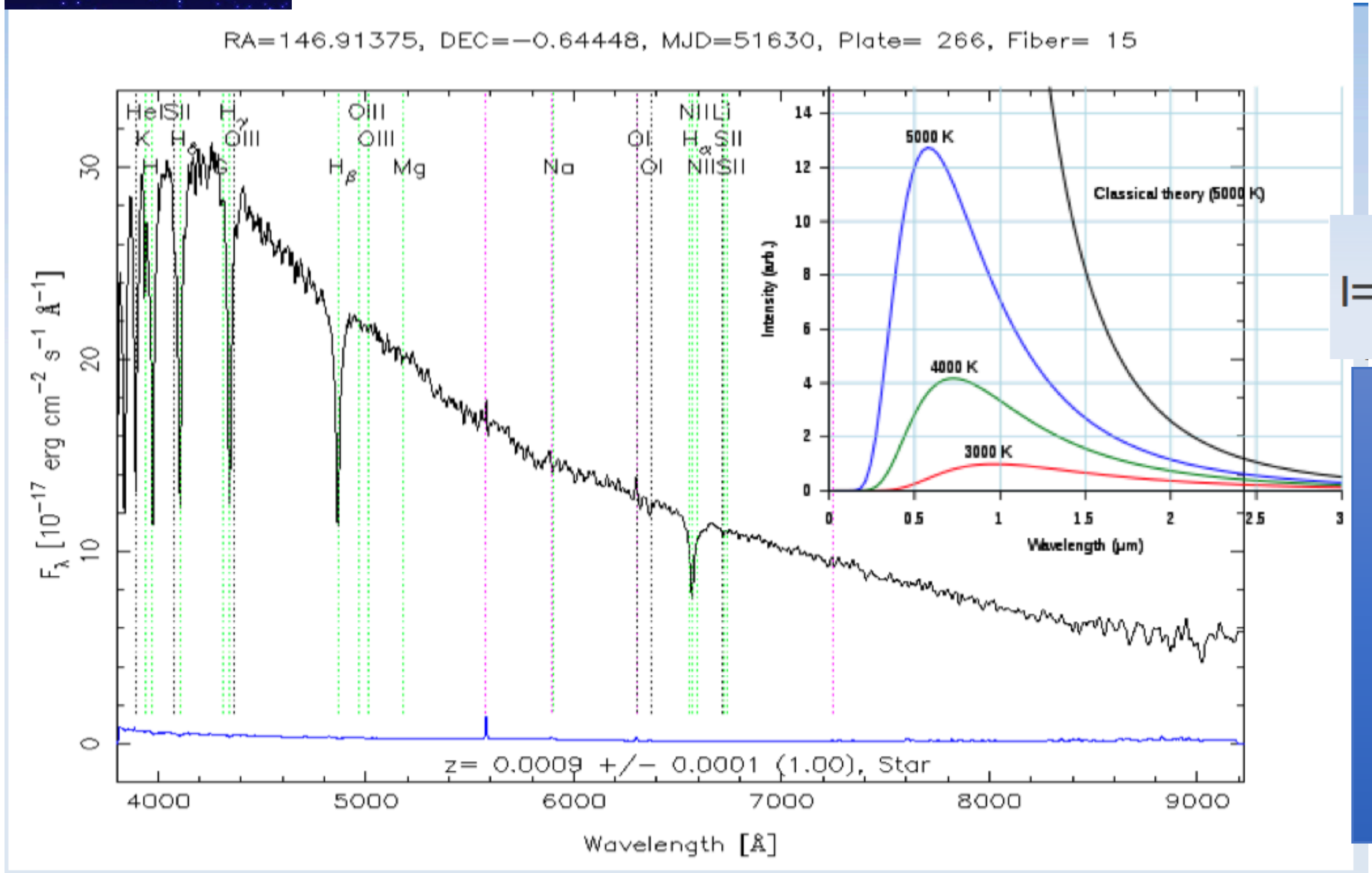
# Information from Stars



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

**Spectra:**

Temperature

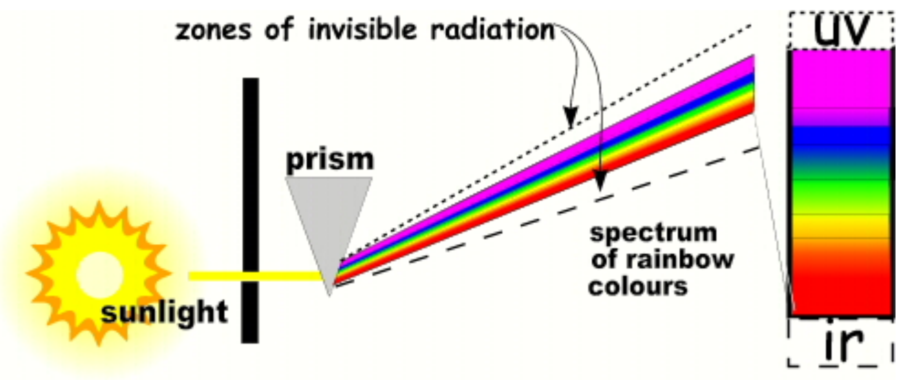
Pressure

'Metallicity'

Chemistry

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

# Spectral analysis
# &
# Data reduction



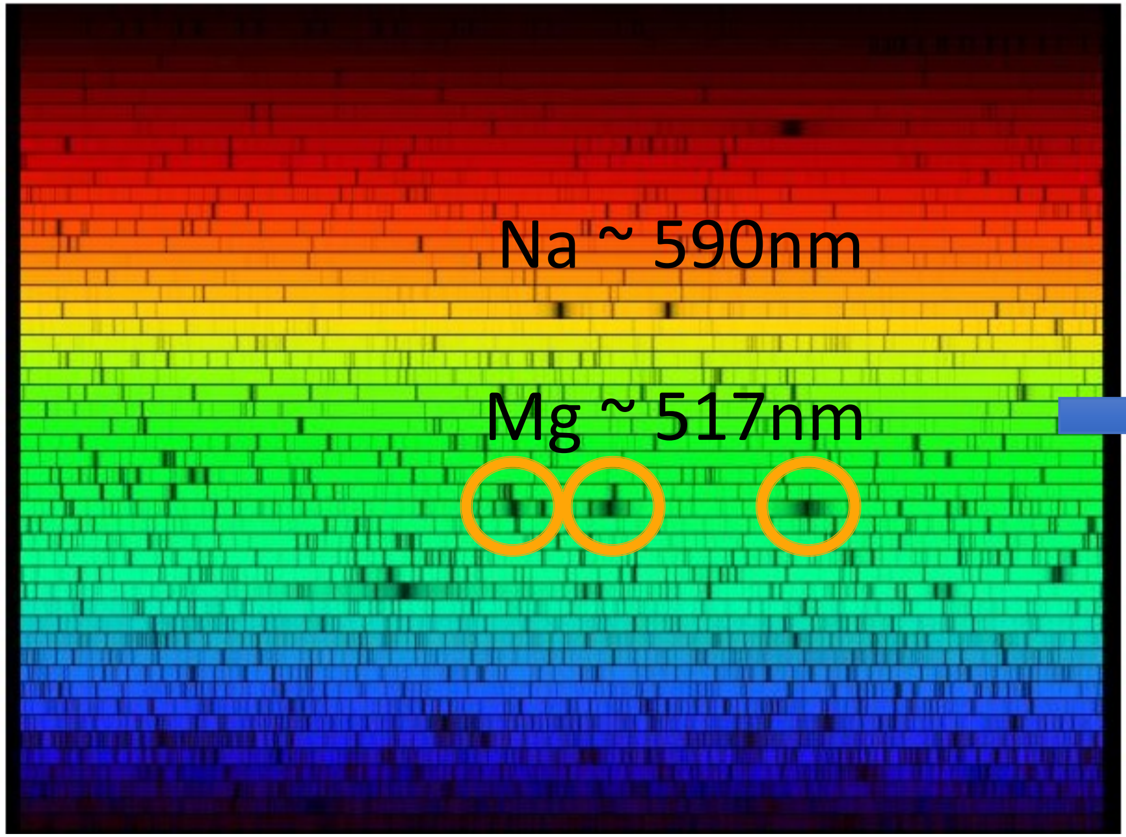
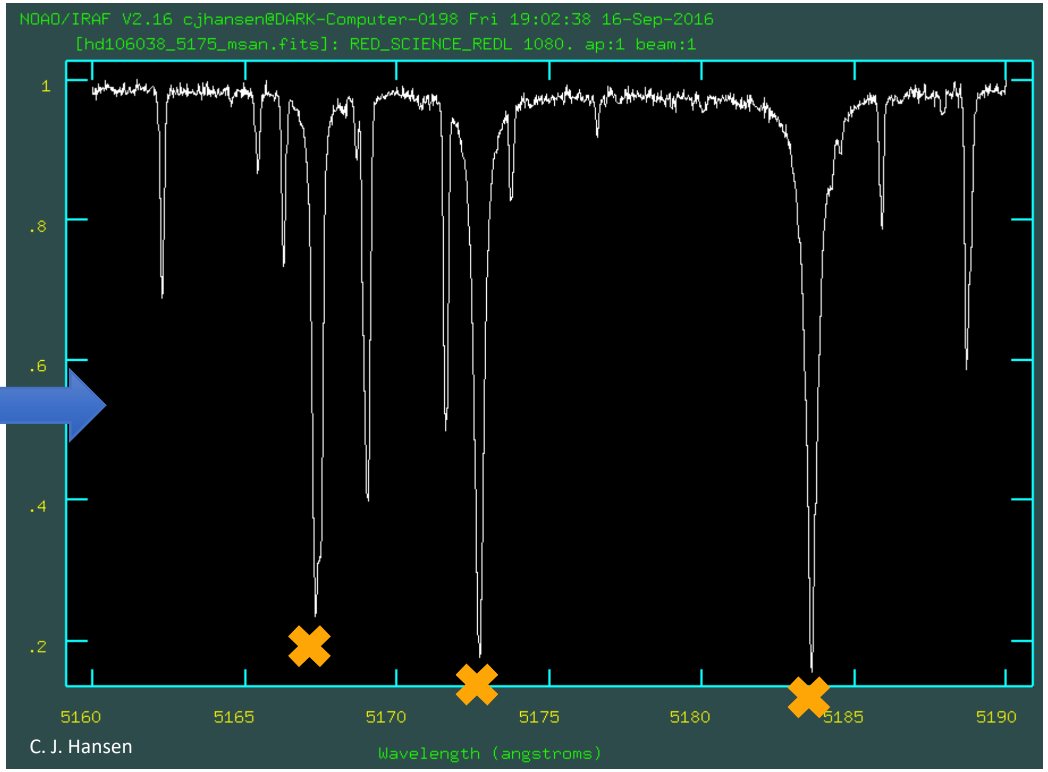


Image: https://apod.nasa.gov/apod/ap180926.html



C. J. Hansen

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# Spectral analysis

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

Equivalent Width (EW or W)

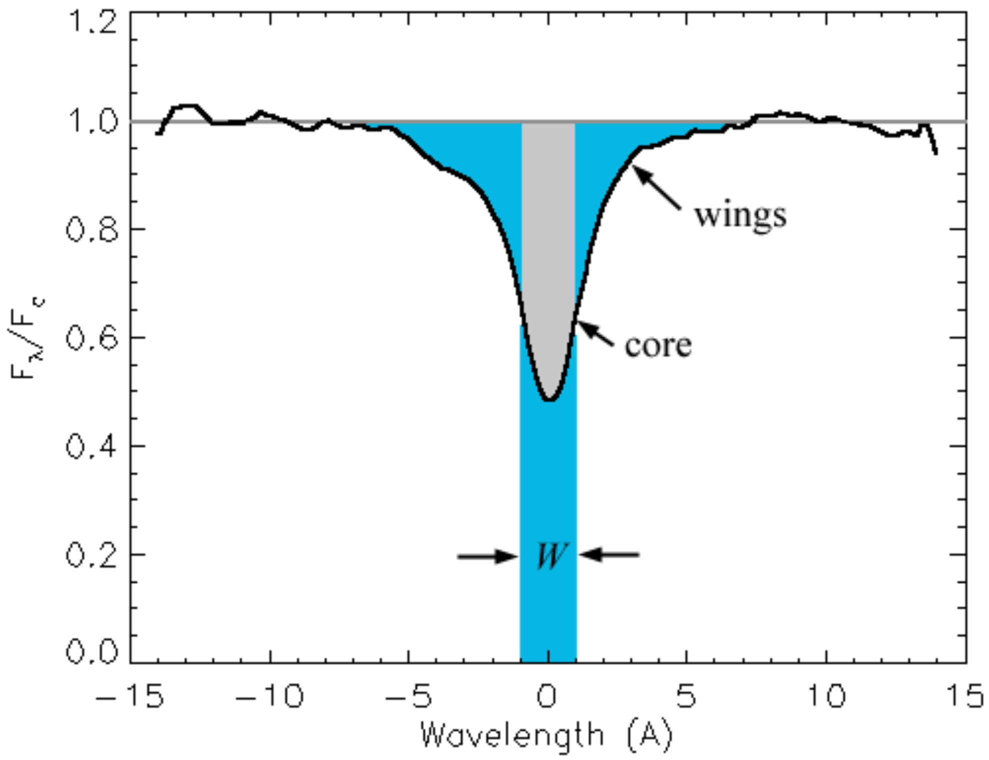


Image: http://www.bdnyc.org/2012/03/spectral-line-measurements-visualized/

# Abundances (A)

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

$$= \log C + \log A + \log g_n f\lambda - \theta_{ex}\chi - \log\kappa_\nu. \qquad (16.4)$$

EW
Equivalent
width

Const.

Abundance

Atomic
data
(oscillator
strength)

Temp.

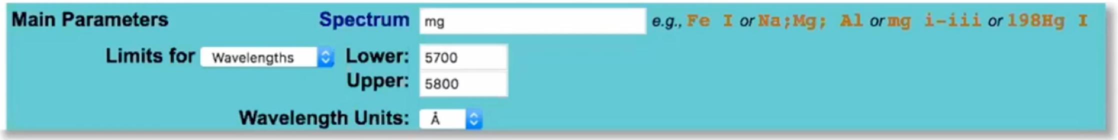
Absorption
coefficient →
pressure/logg

# Impact and assumptions

**Line lists:**

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

- Atomic physics

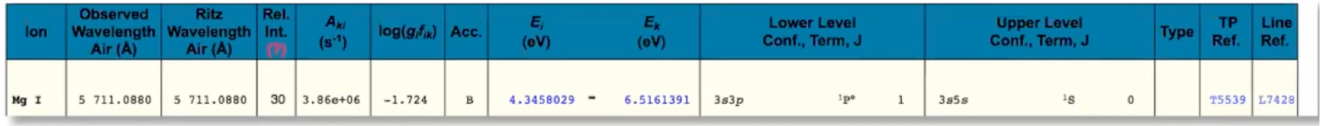


**Main Parameters**

**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 |

- 1D, LTE vs 3D, NLTE

Assumptions – Excitations → Boltzmann Eq.,

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

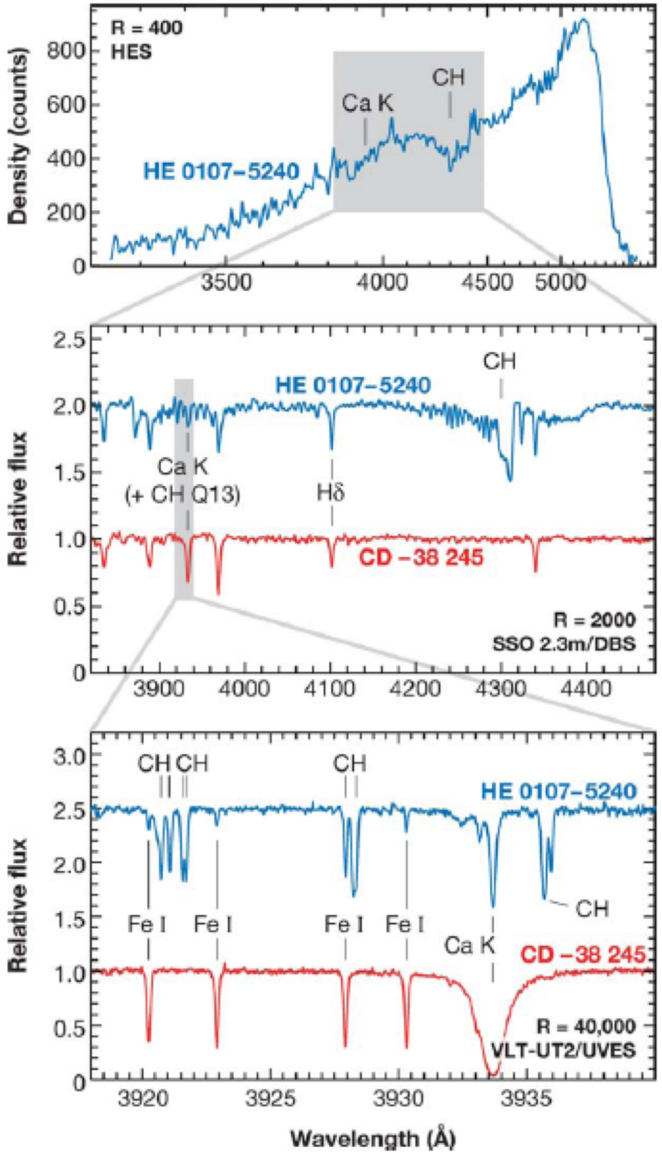
Ionisation → Saha Eq., and

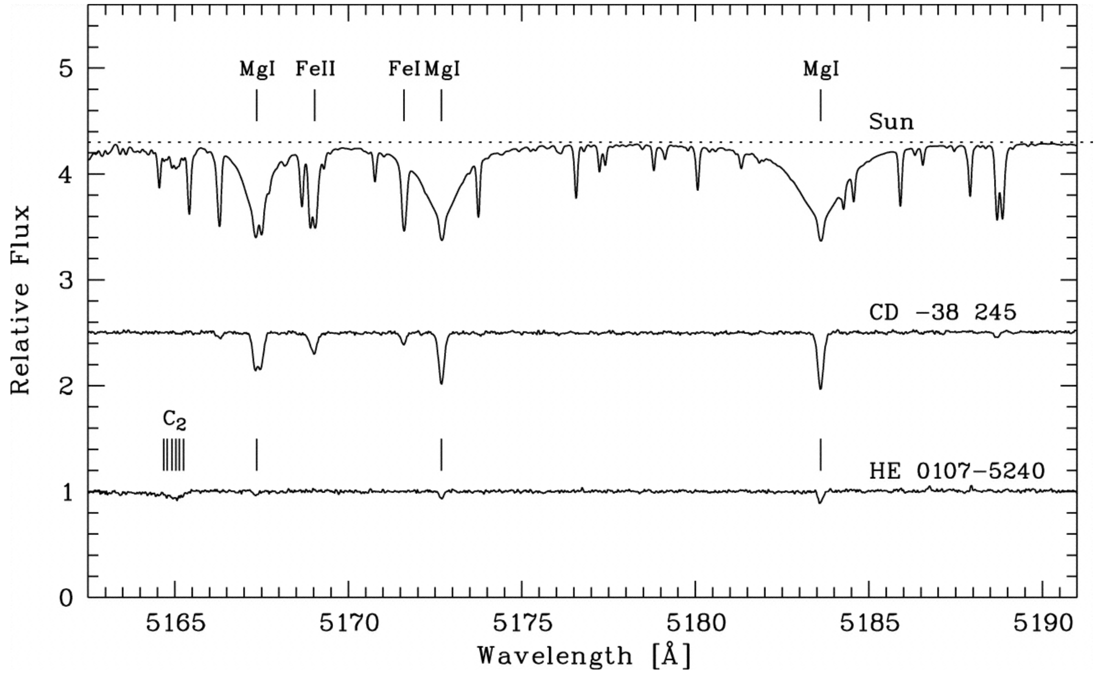
$$\frac{N_{i+1}}{N_i} = \frac{2Z_{i+1}}{n_e Z_i}\left(\frac{2\pi m_e kT}{h^2}\right)^{3/2} e^{-\chi_i/kT}\,.$$

I = B (Planck Function)

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

# Old stars vs the Sun

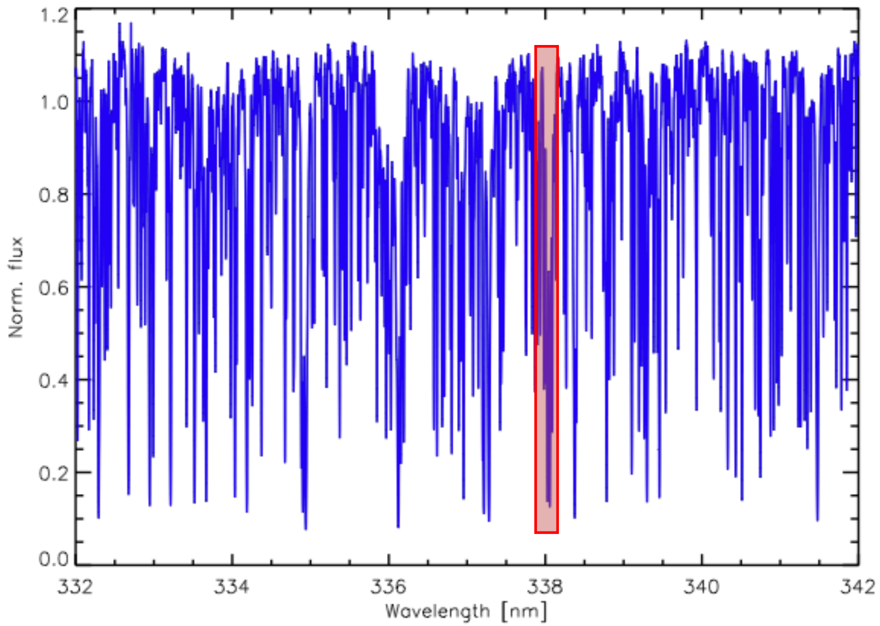


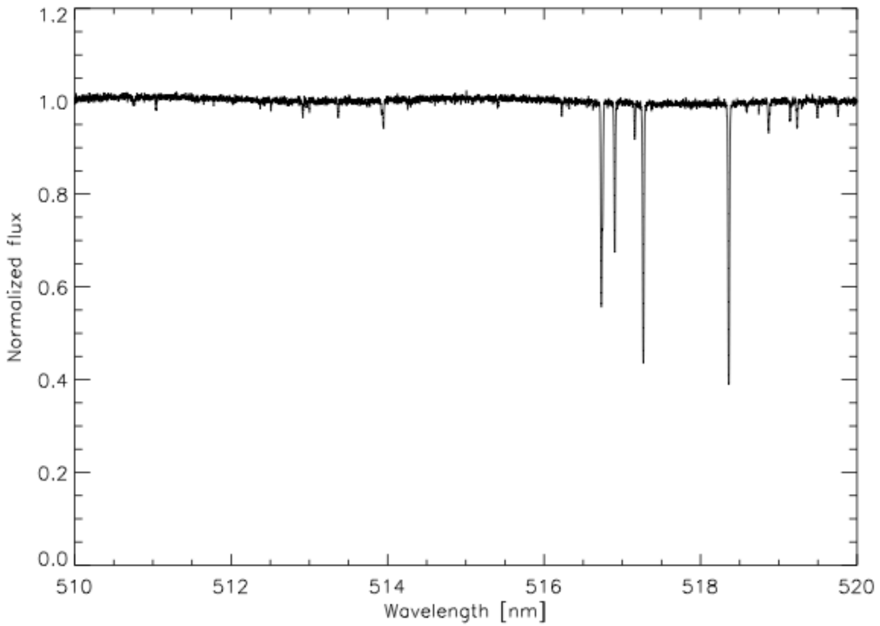


Beers & Christlieb 2005, ARA&A

# Spectral analysis

## Blue vs visual spectra



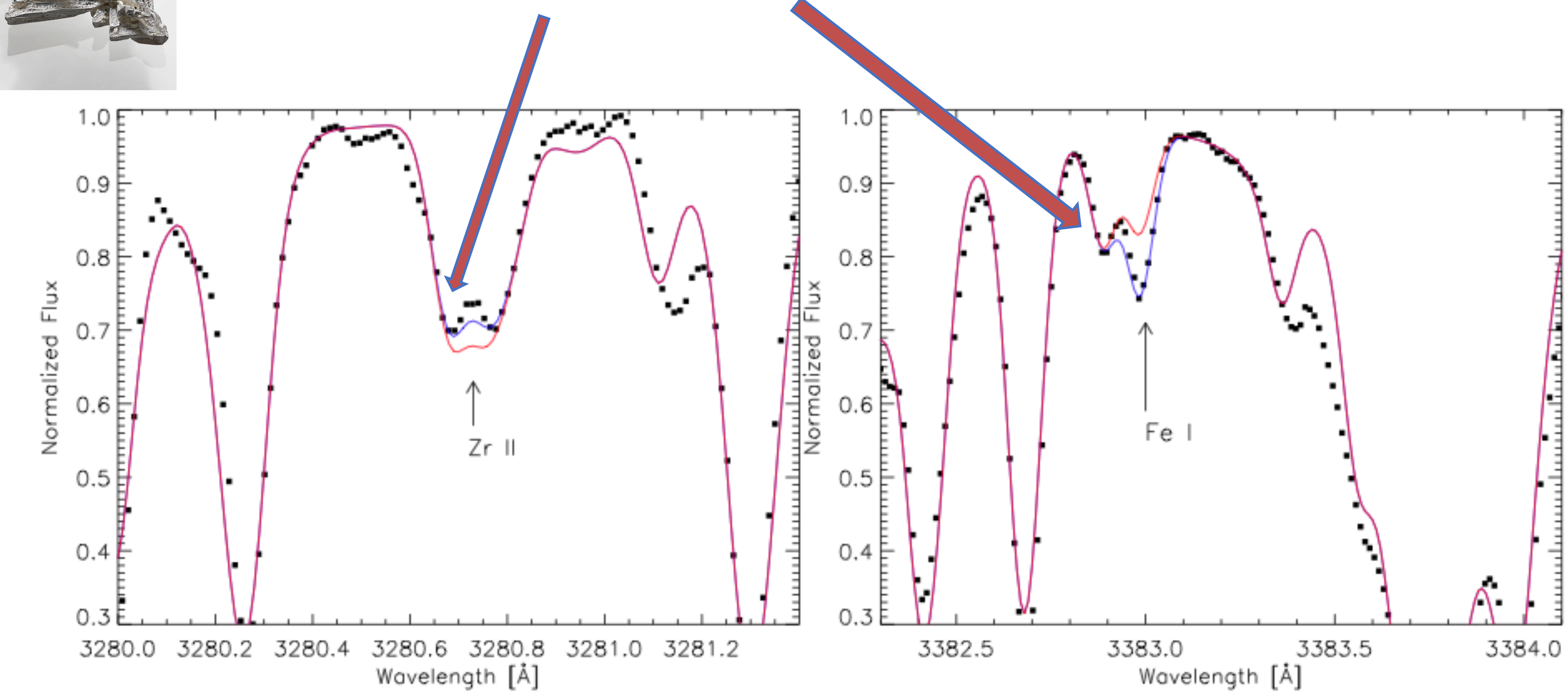


Images: C. J. Hansen

# Analysing UV-Linies

Wikipedia

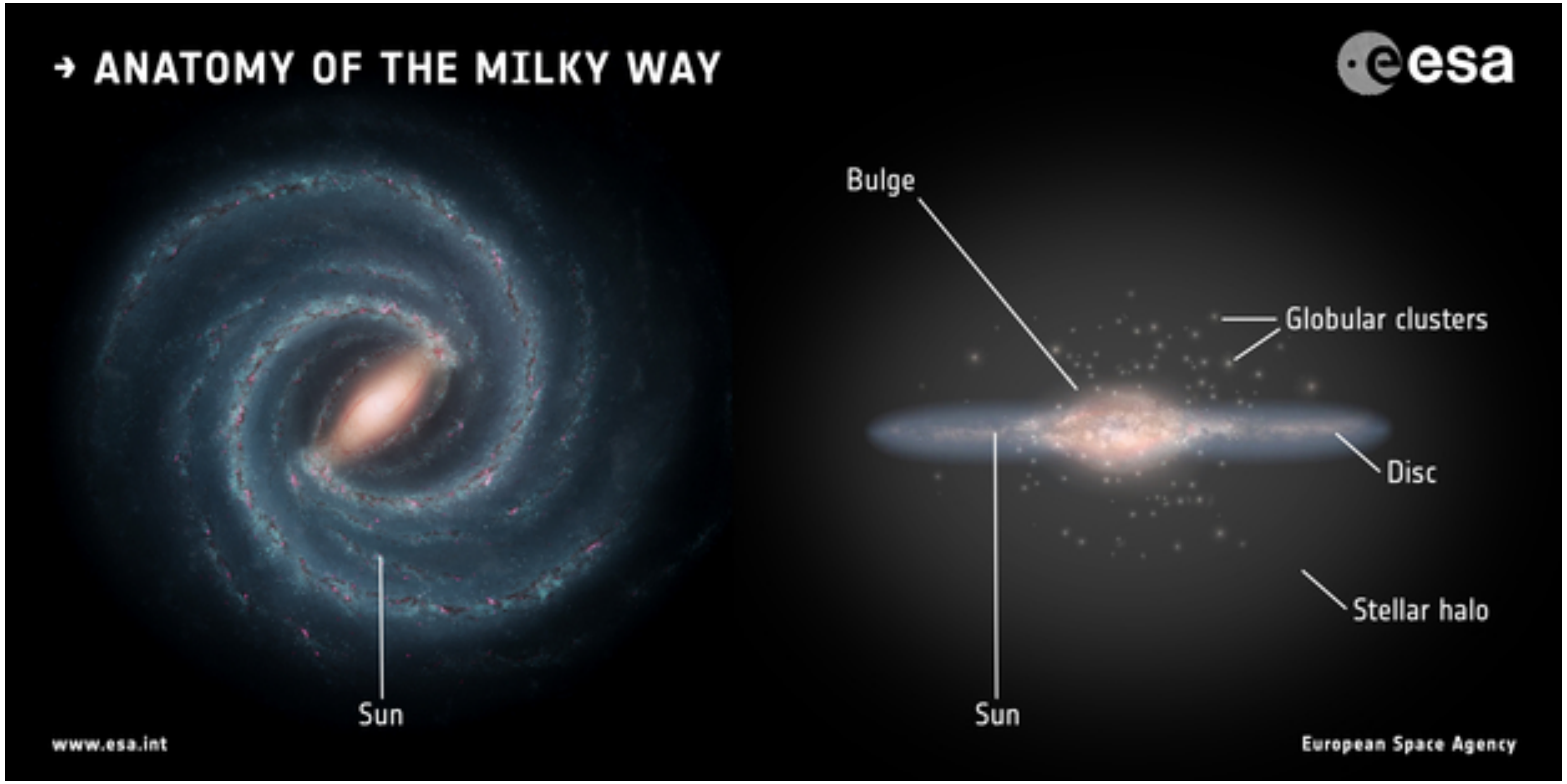
Silver (Ag, Nr. 47)



Hansen et al. 2012

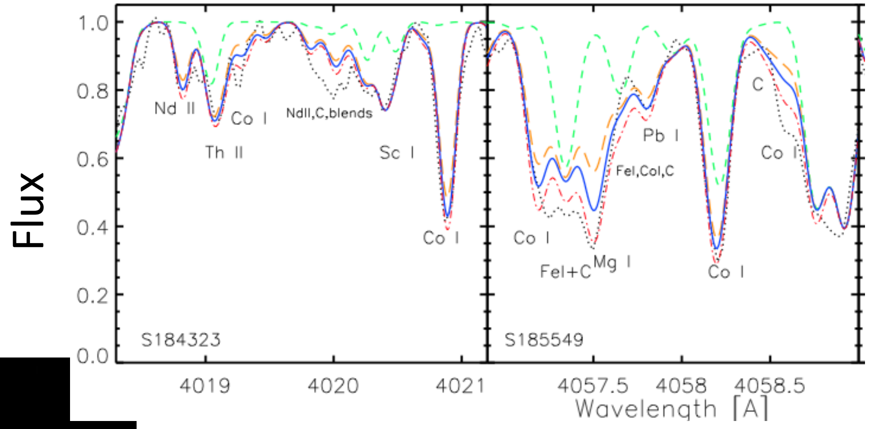
# The Milky Way and its stars

- Tracing nuclear processes is easiest in old metal-poor stars → chemically speaking simpler
- Major components: Halo, disks, bulge
- Old stars in halo & bulge
- Observational pros/cons



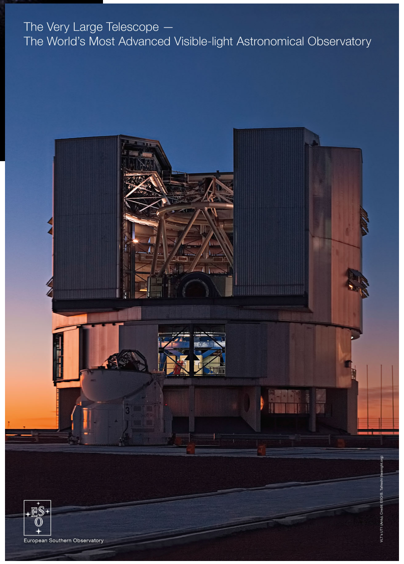
# Old Stars

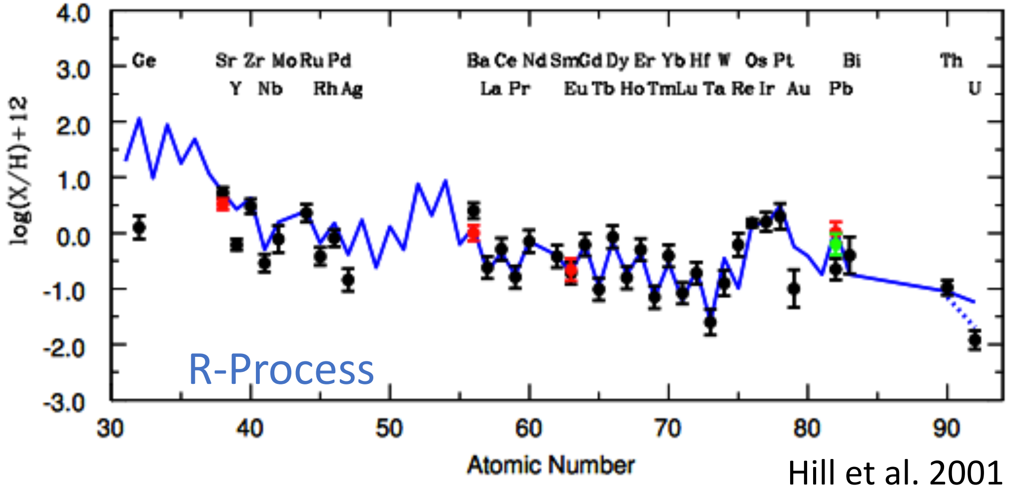
Hansen et al. 2018



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

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# Spectral analysis

Tools of the astronomer/ spectroscopist:

- Spectra (observations)
- Stellar models: Temperature, pressure, etc.
- Atomic data
- Programs

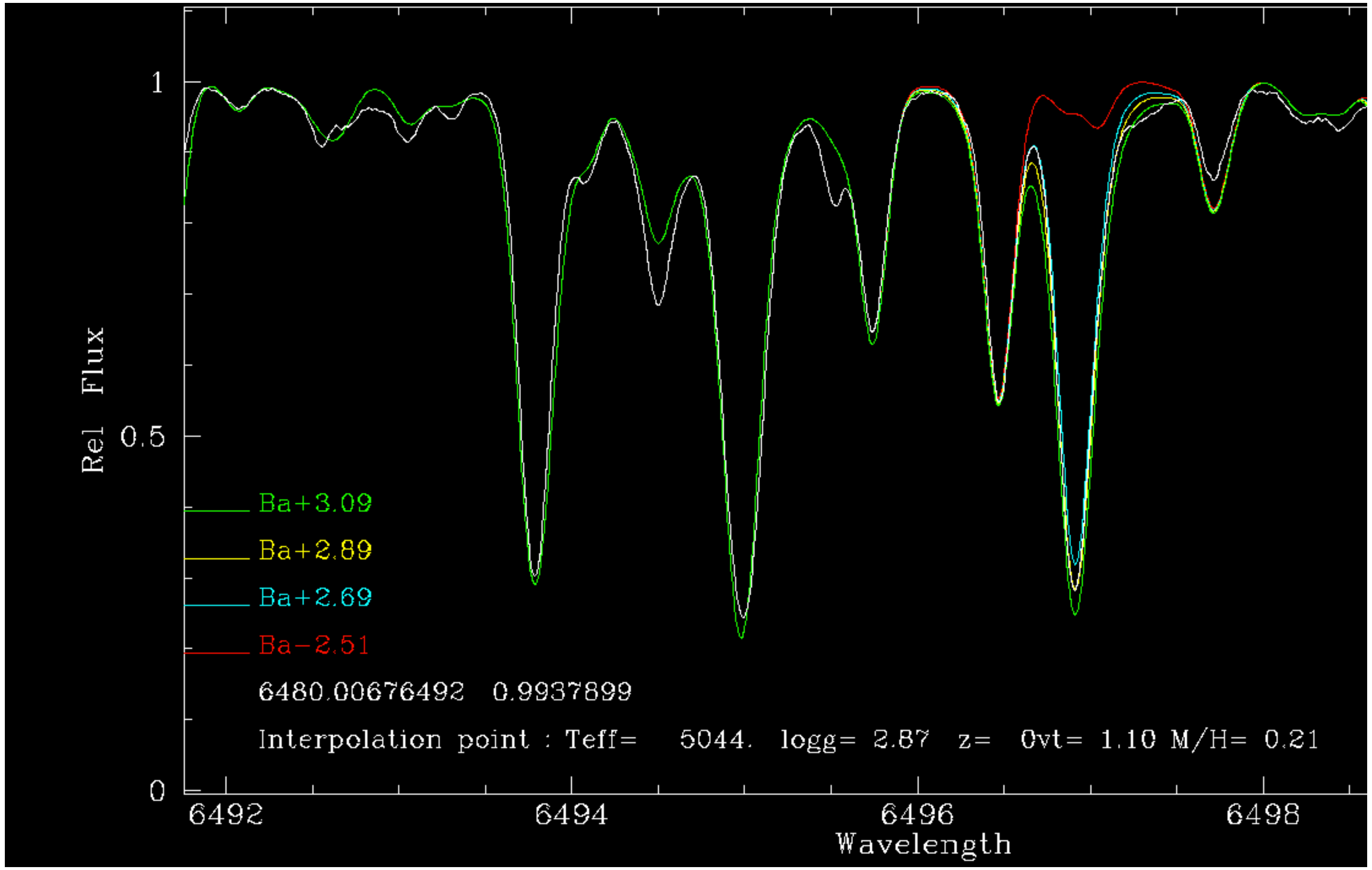


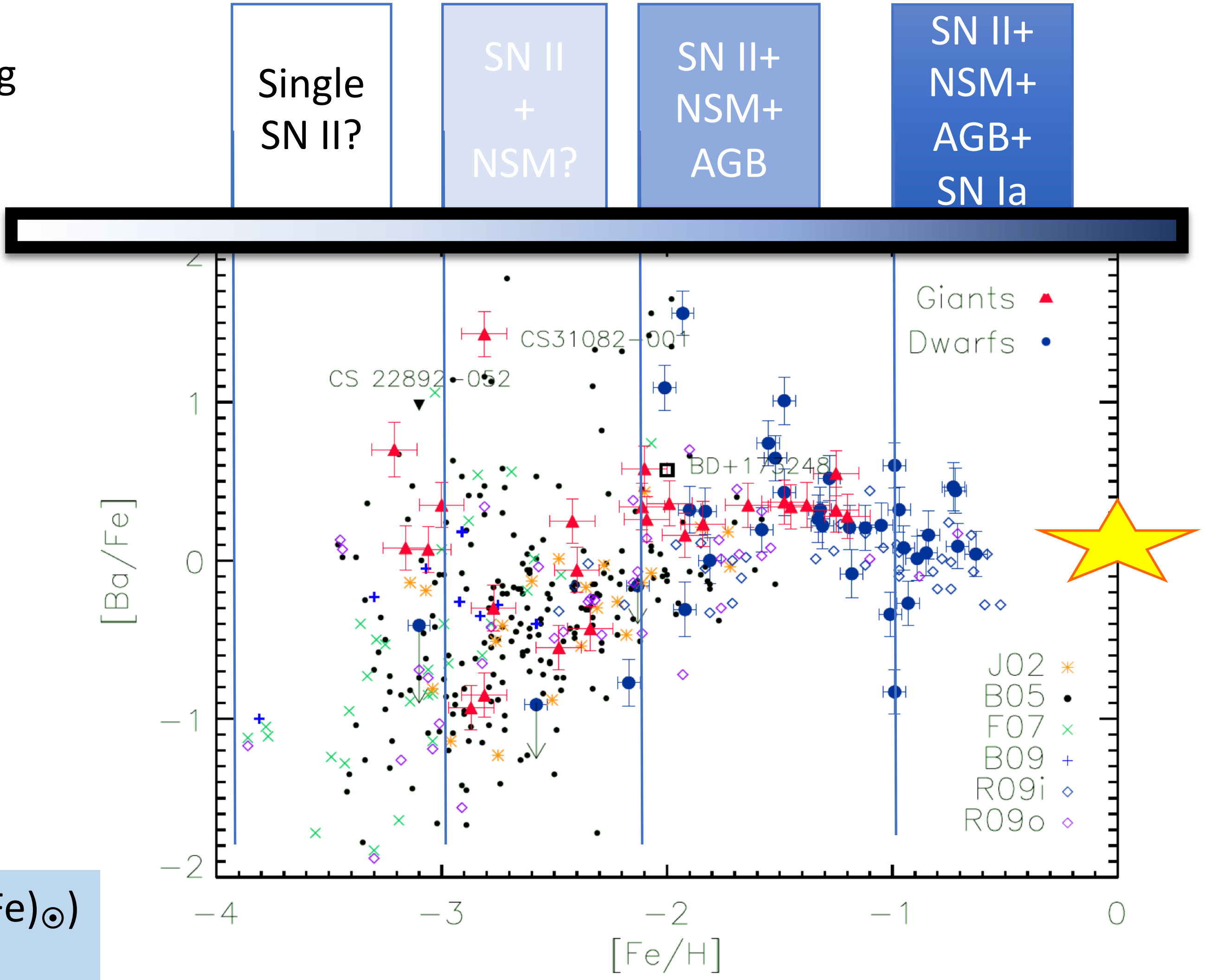
Image: C. J. Hansen

# 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

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



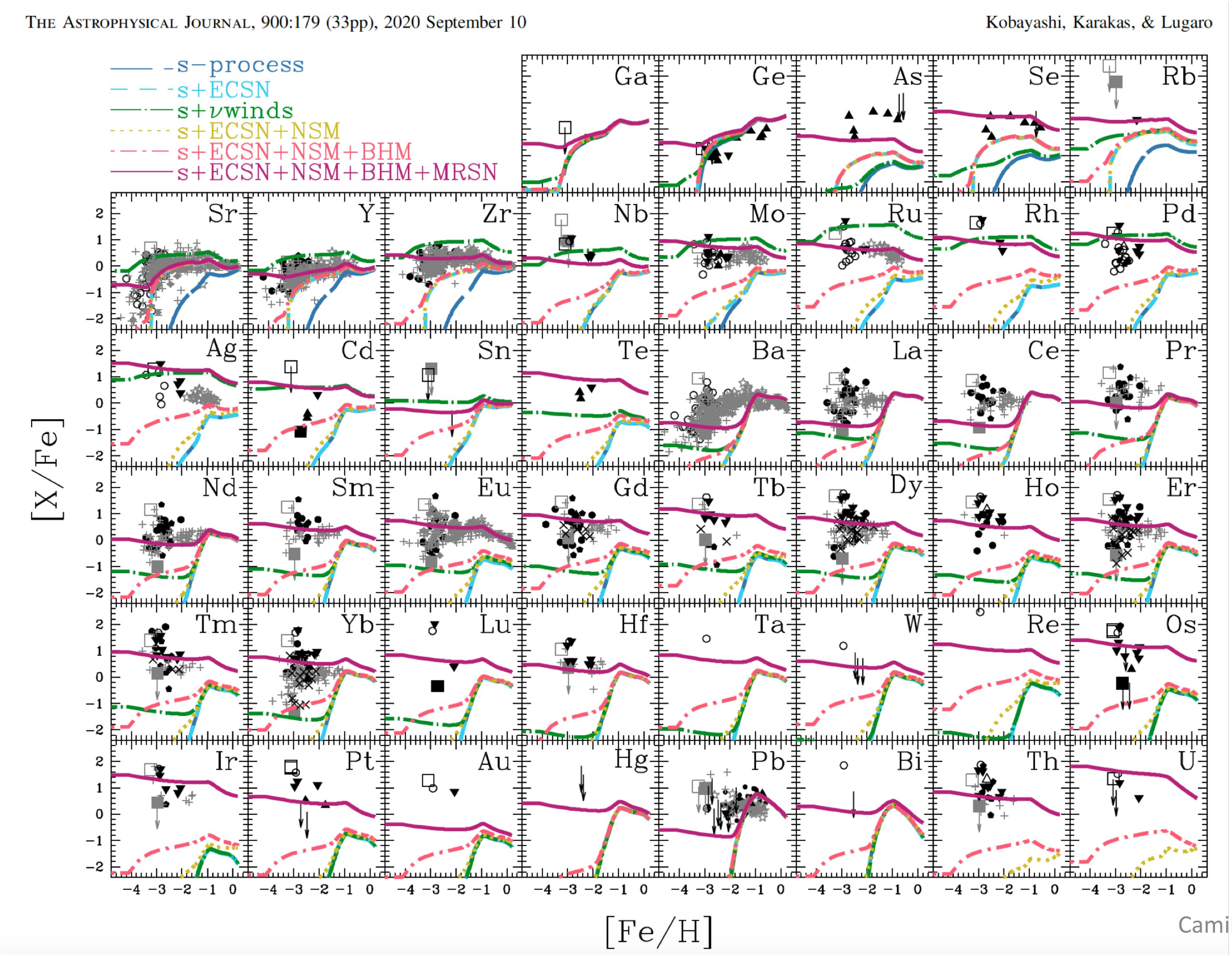
Looking back

Chemical concentration

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

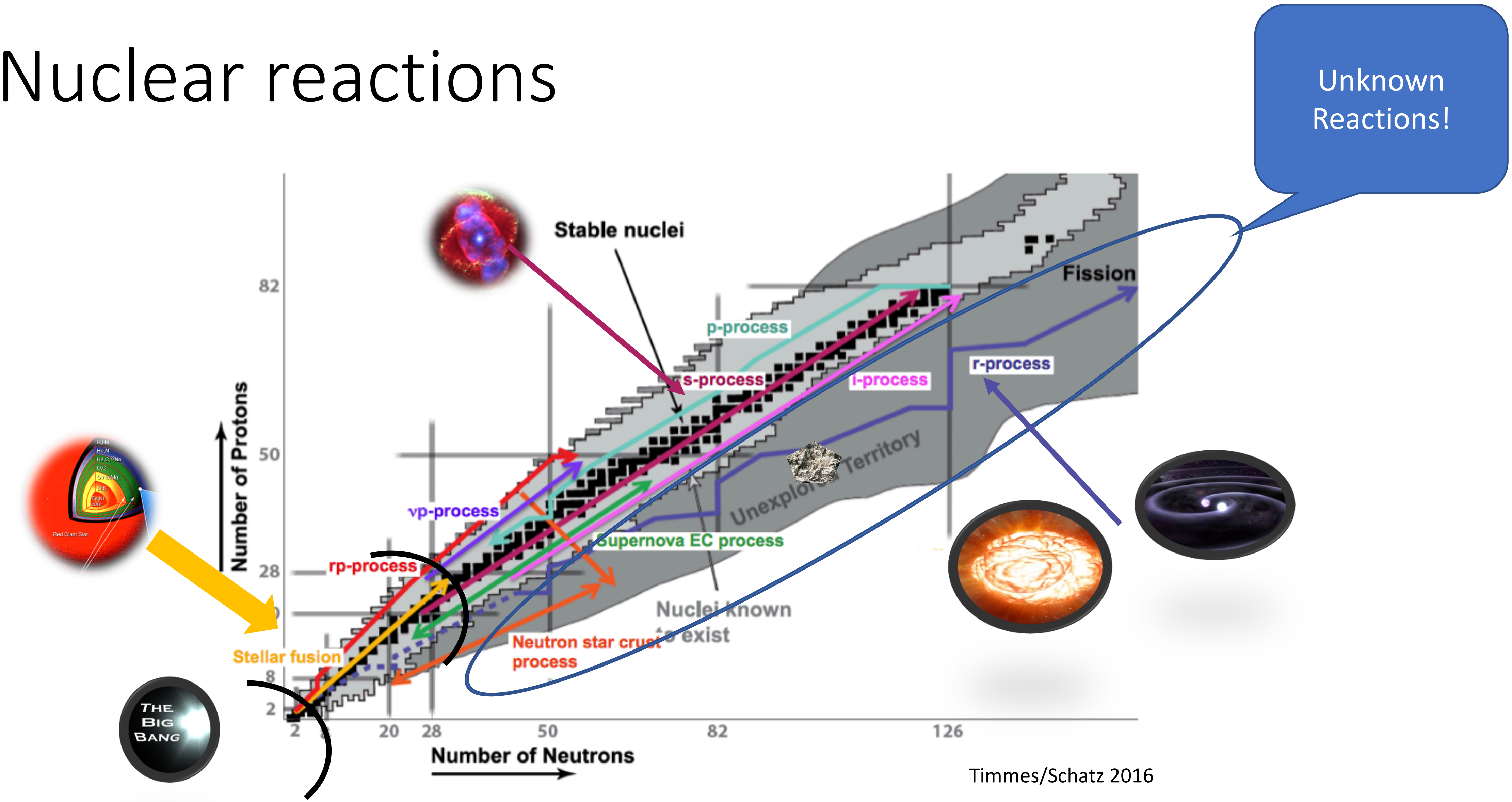
Hansen et al. 2012

# Galactic chemical evolution



The Astrophysical Journal, 900:179 (33pp), 2020 September 10 Kobayashi, Karakas, & Lugaro

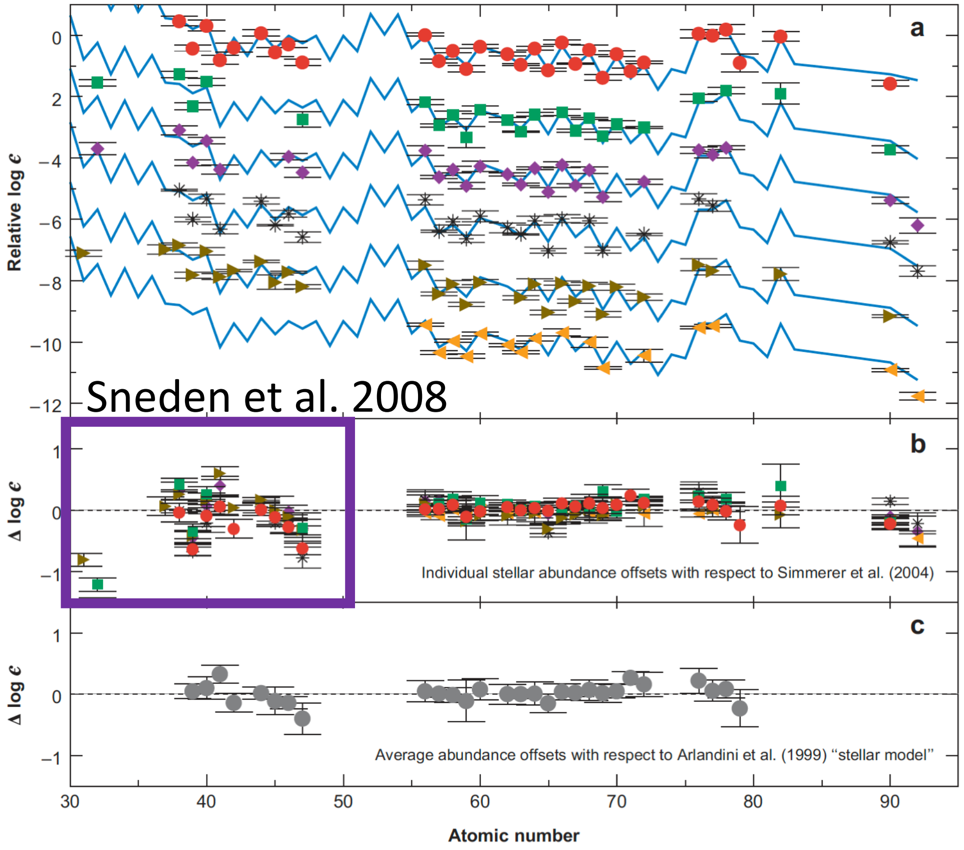
# Nuclear reactions



Timmes/Schatz 2016

# Heavy element abundances

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

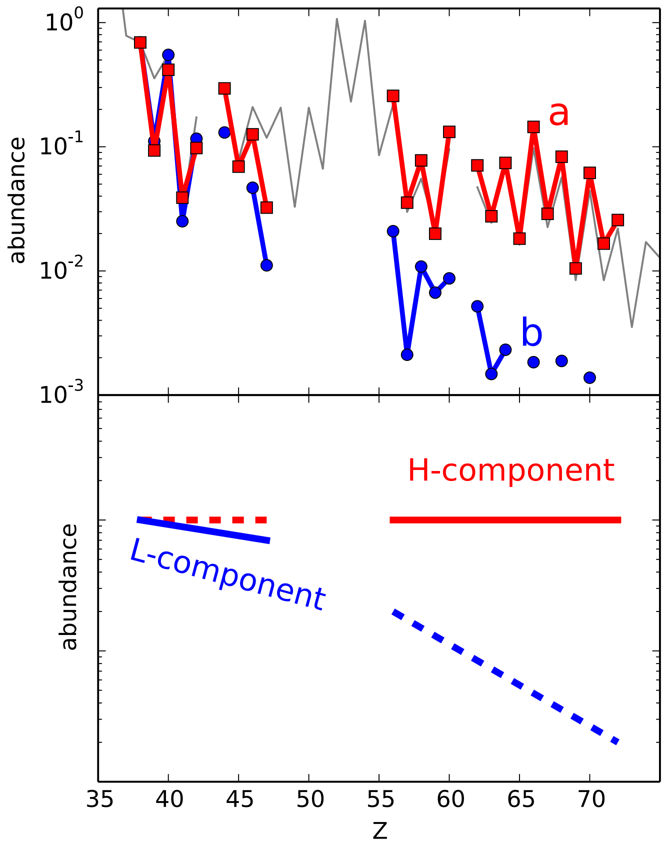


Sneden et al. 2008

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

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

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

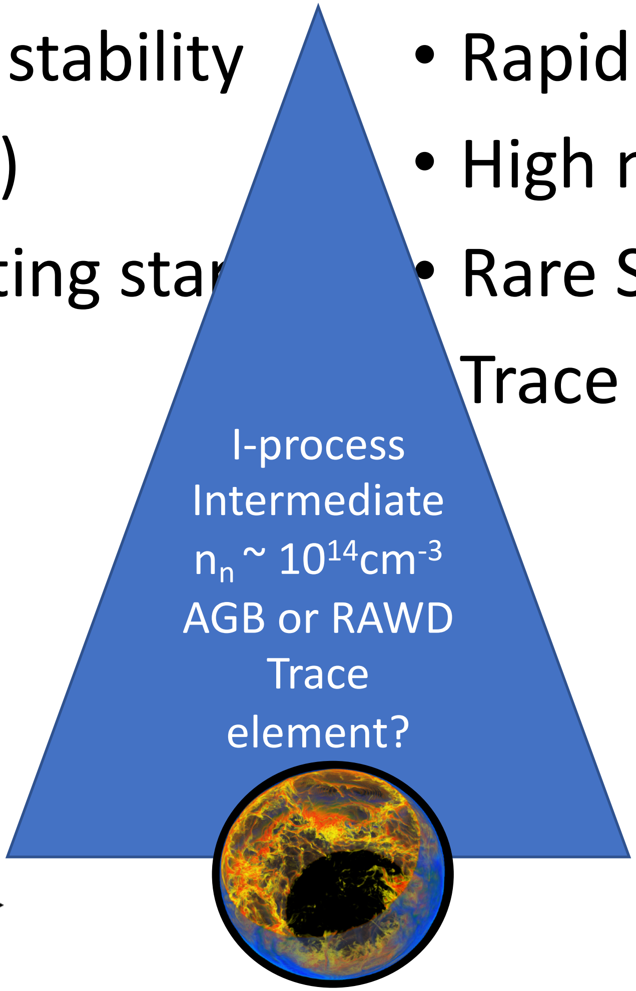


Hansen+14

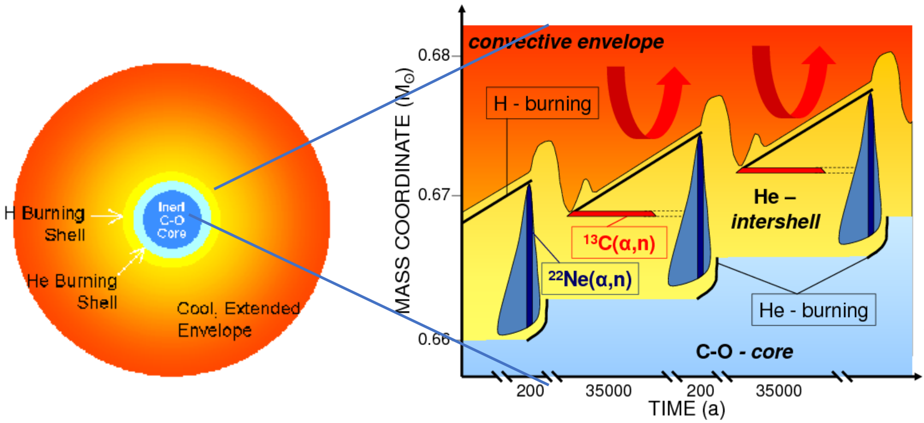
# Indirect tracers of n-capture processes

- S-process
- Slow ($t_{cap} \sim t_{\beta}$) & close to stability
- Low n-density ($\sim 10^{8}$ cm$^{-3}$)
- AGB or massive fast rotating star
- Trace element: Ba

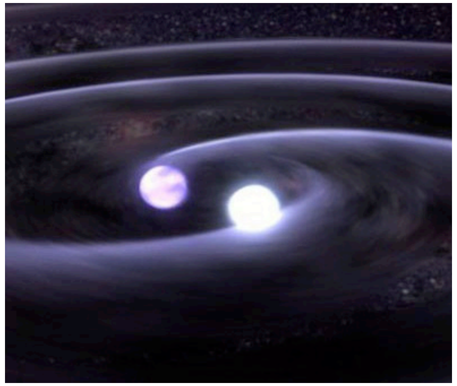
- R-process
- Rapid ($t_{cap} < t_{\beta}$) & far from stability
- High n-density ($> 10^{23}$ cm$^{-3}$)
- Rare SN or NS mergers
- Trace element: Eu



I-process
Intermediate
$n_n \sim 10^{14}$cm$^{-3}$
AGB or RAWD
Trace
element?



M. Heil, 2005,
https://doi.org/10.1063/1.1945255

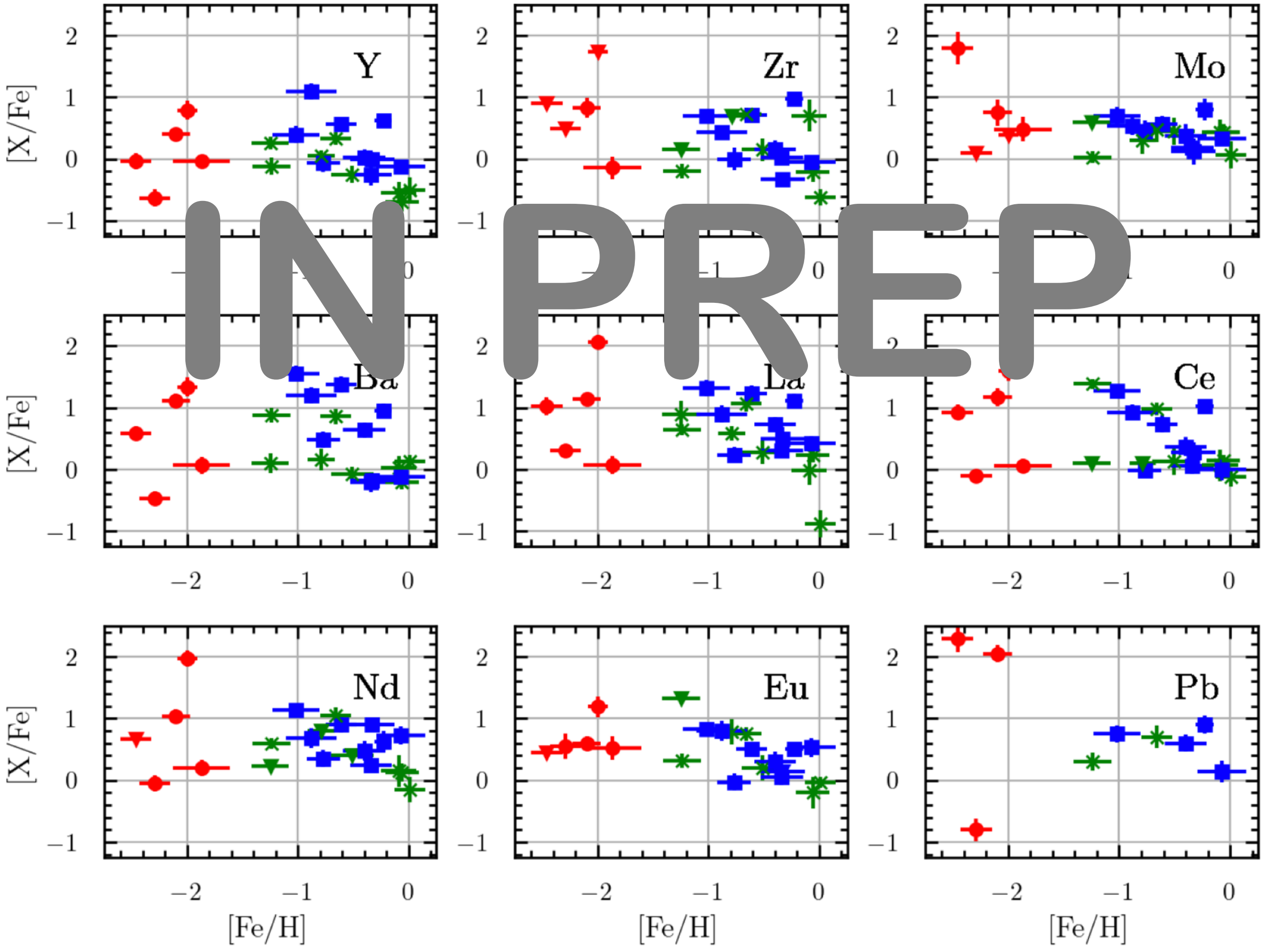


http://public.virgo-gw.eu/the-gravitational-wave-universe/

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

Alexander Dimoff
(PhD student)

# S-process in metal-poor stars



IN PREP

CEMP/CH
Ba (binaries)
Other (incl AGB)

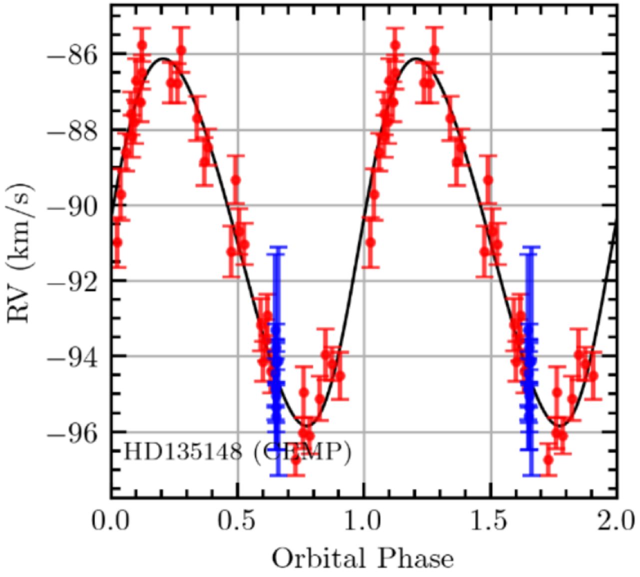


**Fig. 7.** Phase-folded RV curves for the stars HR CMa, HD 50264, and HD 135148. Red data points are literature data, and blue data points are our contributions. HD 50264 has few literature data points, but with our additions we have enough to characterize the orbit and constrain

# S-process in metal-poor stars

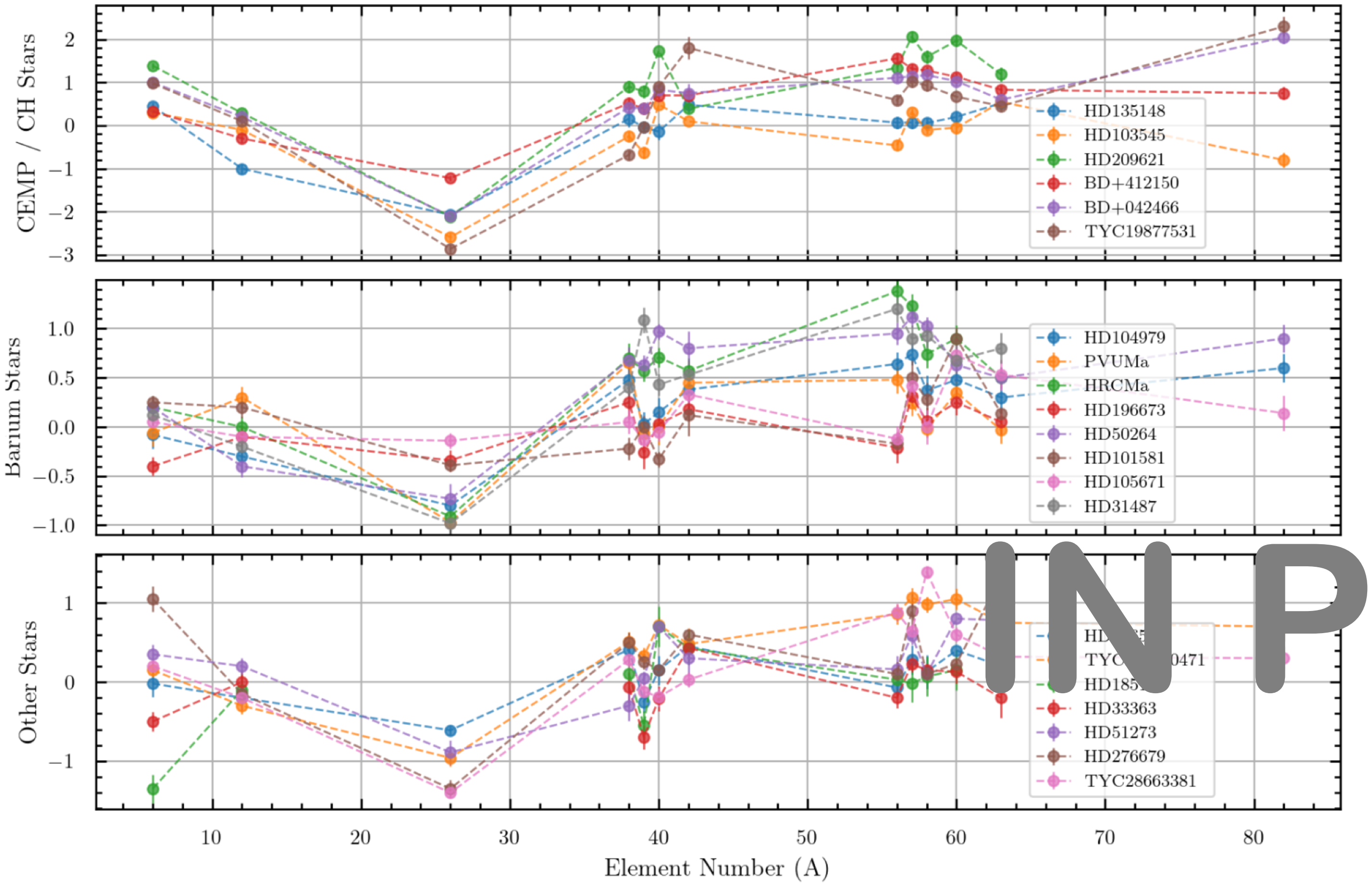
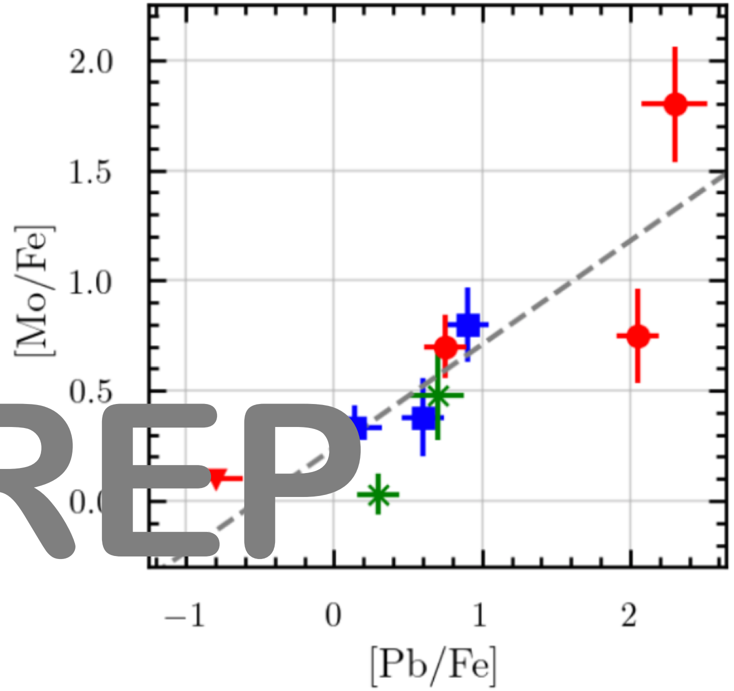


**Fig. 6.** Abundance patterns for our sample of stars separated by stellar classification; Ba and CH stars ([hs/Fe] > +0.25 and [Fe/H] > -1.0), CEMP stars ([C/Fe] ≳ 0.6 and [Fe/H] < -1.0), and others.

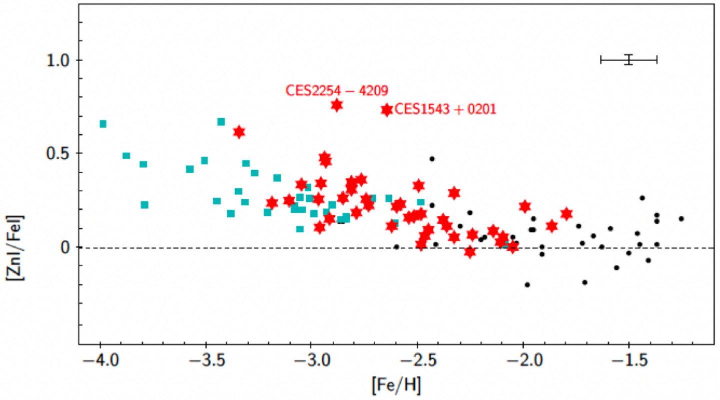
Dimoff et al. 2024 in prep

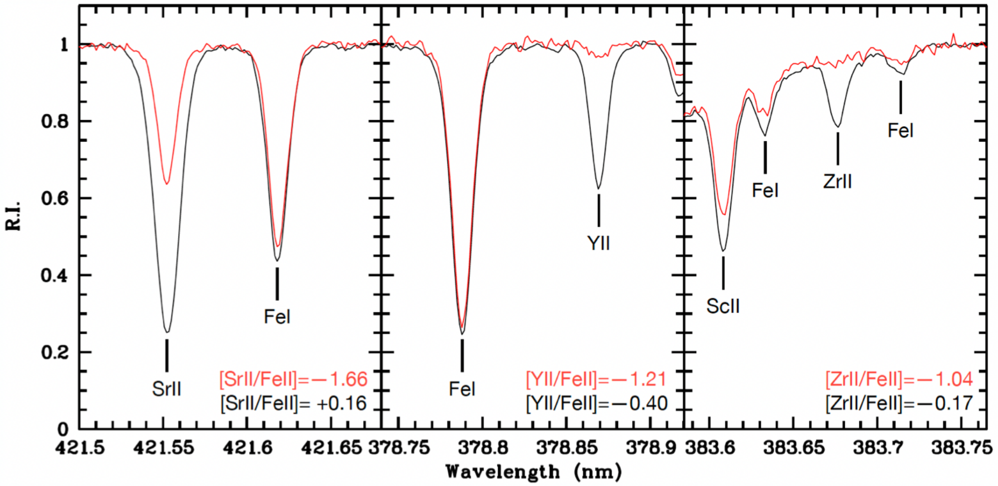


IN PREP

# CERES

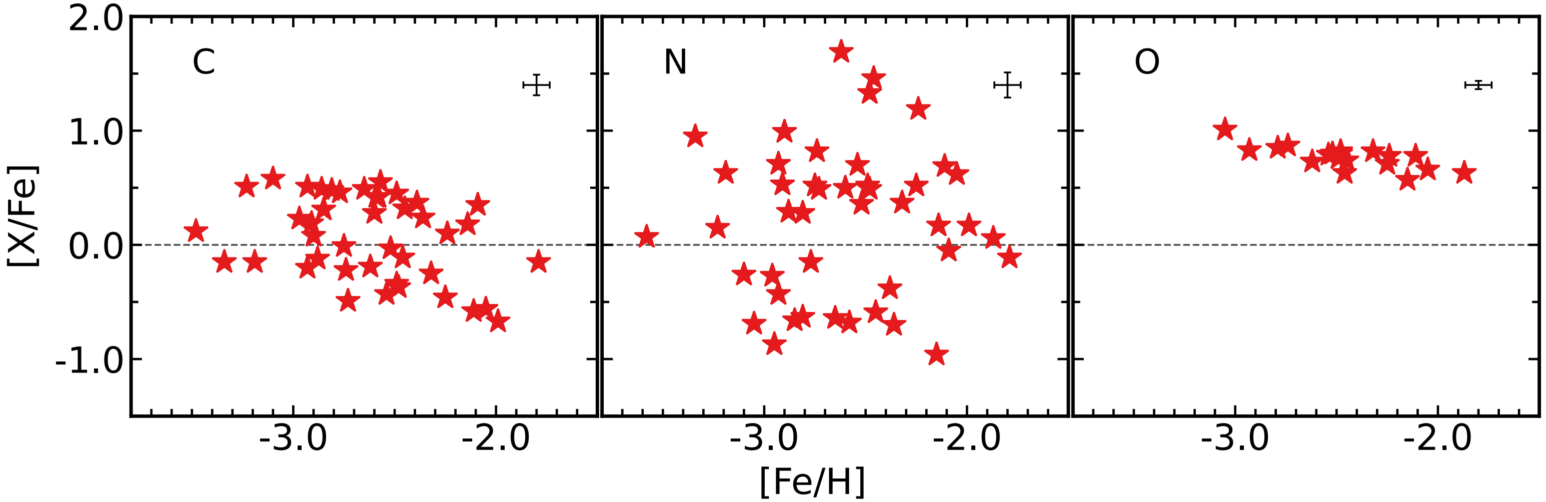
- **CERES**: Chemical Evolution of R-process Enhanced Stars (PI Hansen)
  - Observations made with UVES/VLT in Chile – high-resolution spectrograph, high signal-to-noise (50-200)
  - Sample size: 52 stars
  - Homogeneous analysis
    - Line list (atomic data), stellar models, synthetic spectrum code



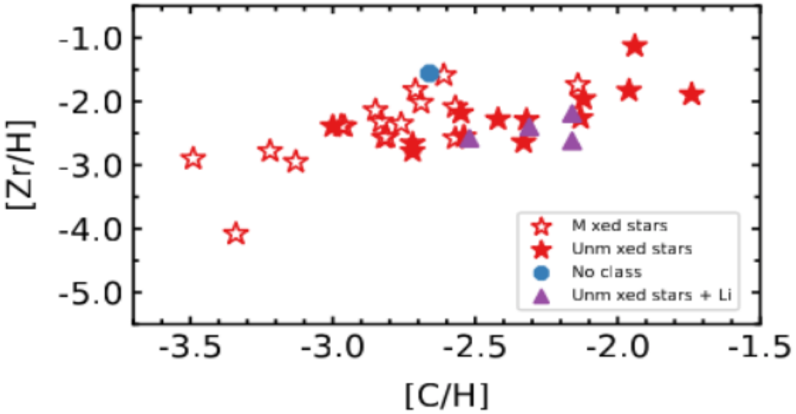


Lombardo et al. 2022

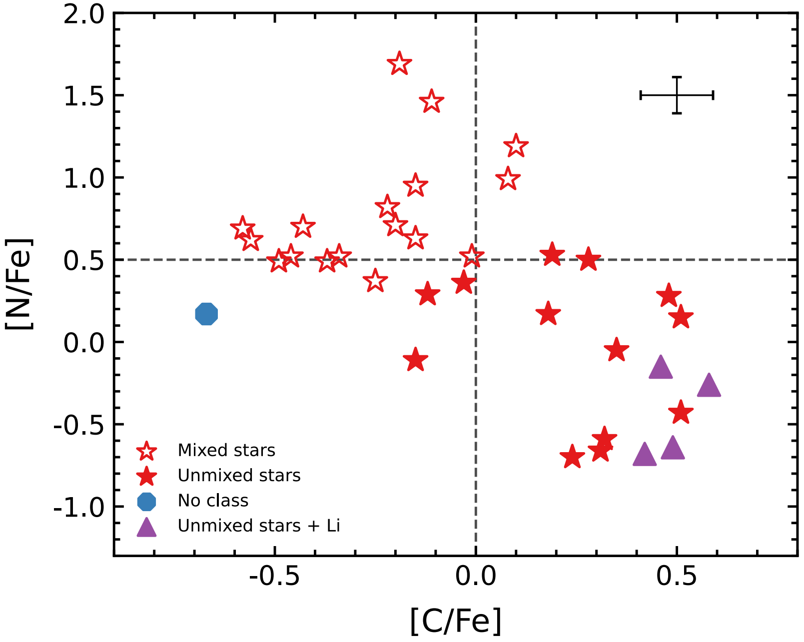
# Combining light and heavy elements



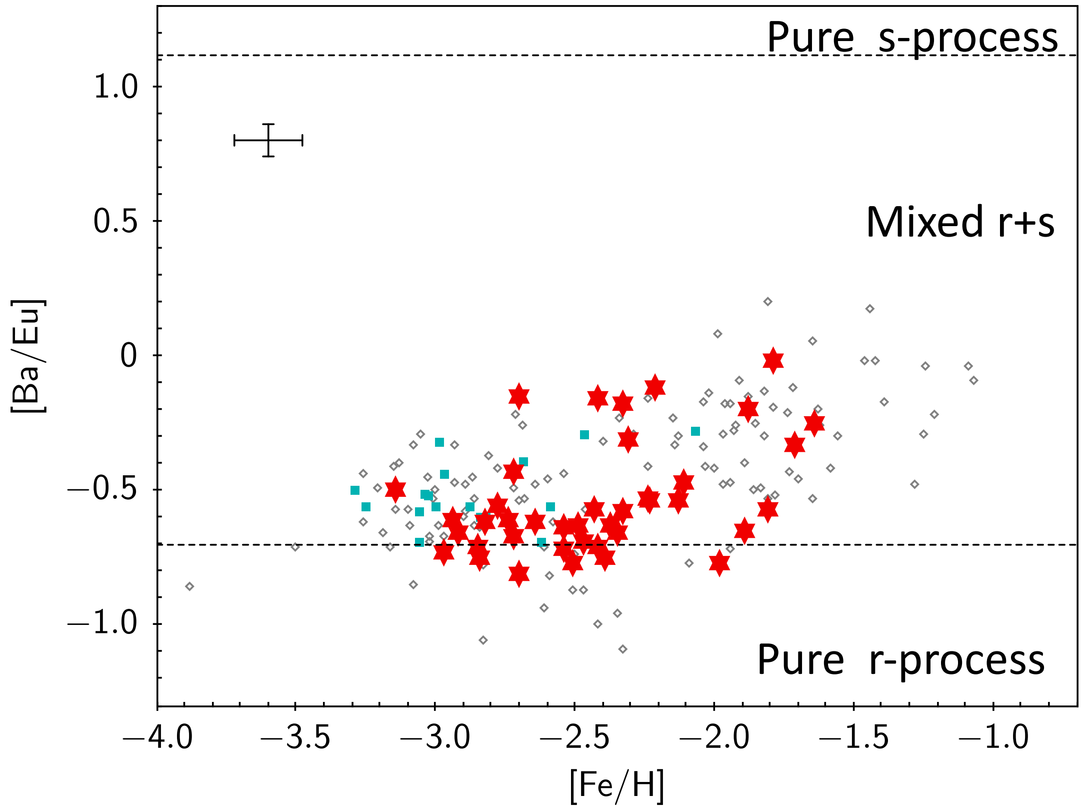
Raphaela Fernandes de Melo
PhD Student



Fernandes de Melo et al.
2024 in prep

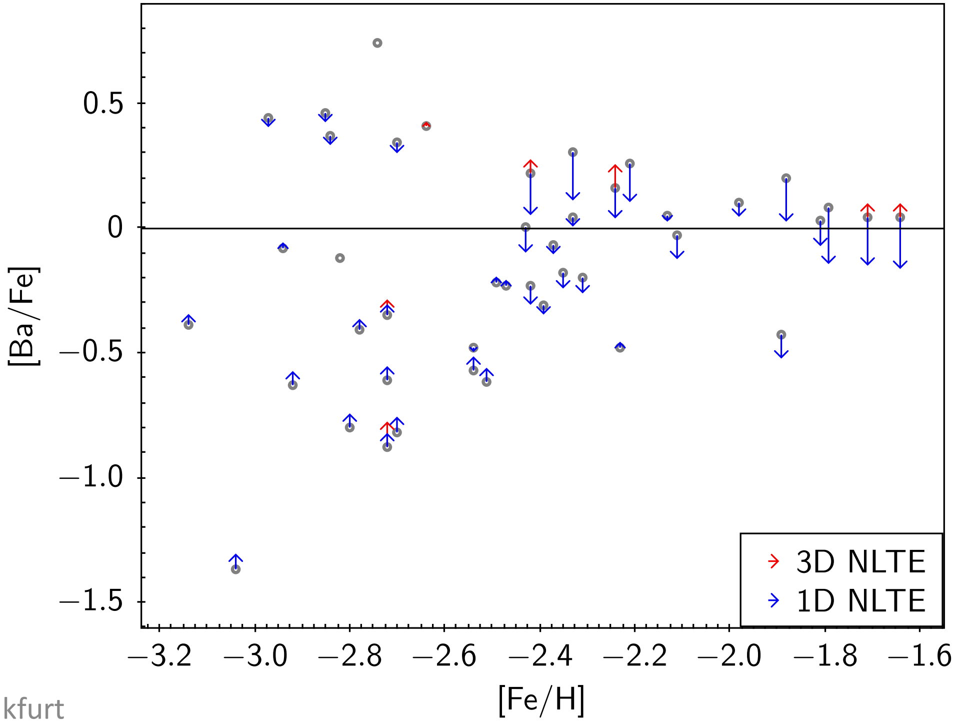


# Rare earth elements as nuclear tracers



Lombardo et al. 2024
in prep.

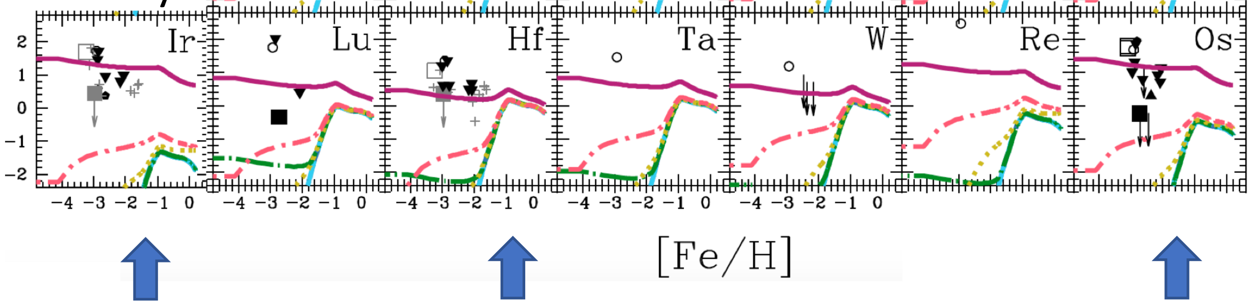
*Linda Lombardo*
*Postdoc*



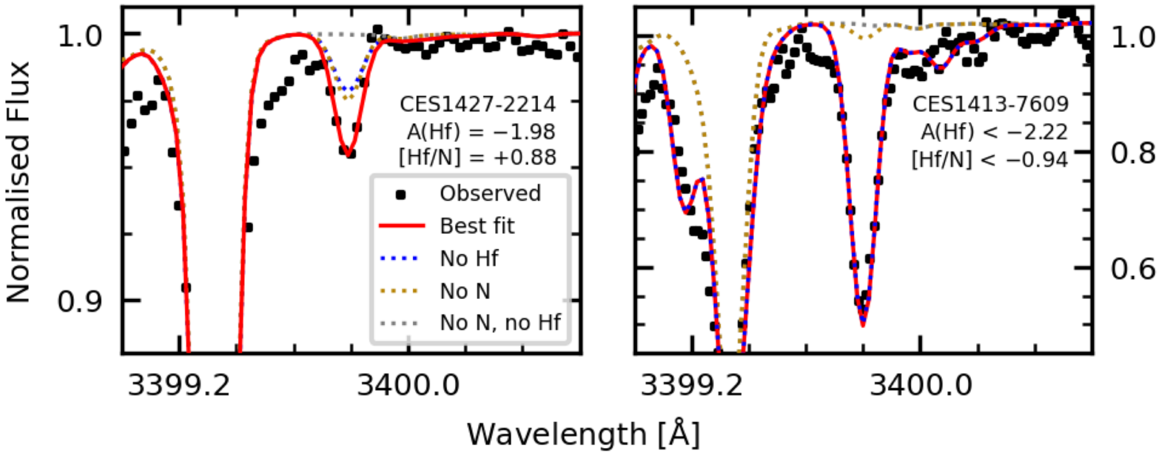
# R-process in old, metal-poor stars

Arthur
Alencastro
Puls
Postdoc

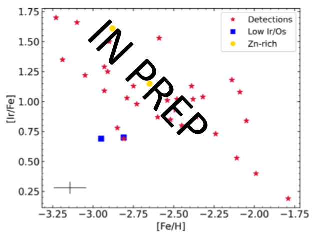
Kobayashi et al. 2020



Alencastro Puls et al. 2024 in prep.

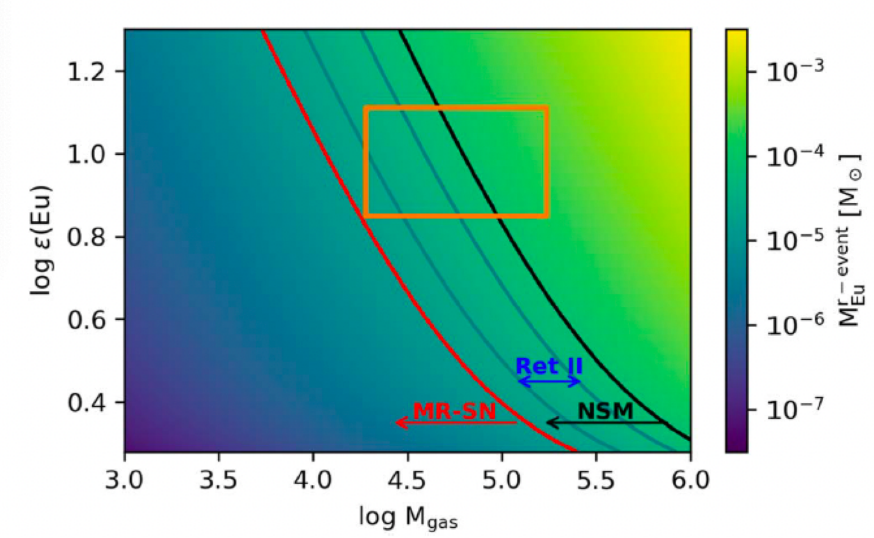


Poorly studied heavy elements!



# Heavy elements in dwarf galaxies

- Extreme Eu enhancement in Fornax



Reichert et al . 2021

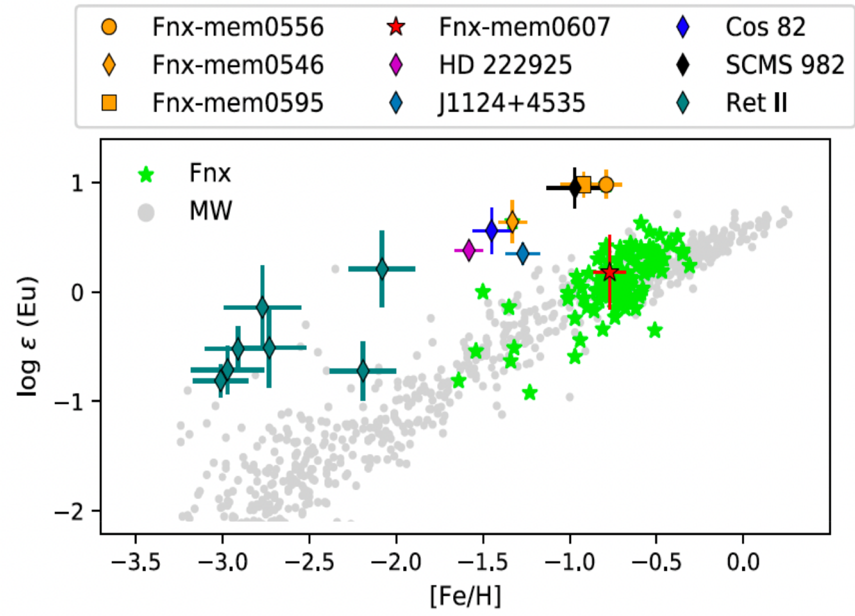


**Figure 5.** Absolute Eu (upper panel) and relative [Eu/Fe] abundances (lower panel) vs. metallicity following the same notation and references as in Figure 2.

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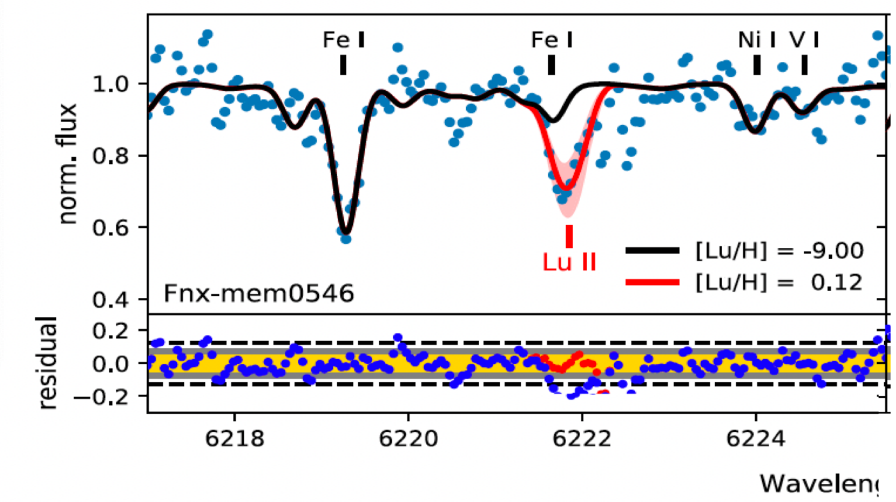
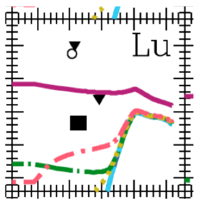




Little known!

Hansen et al. 2020

# Tracing nuclear processes in metal-poor stars

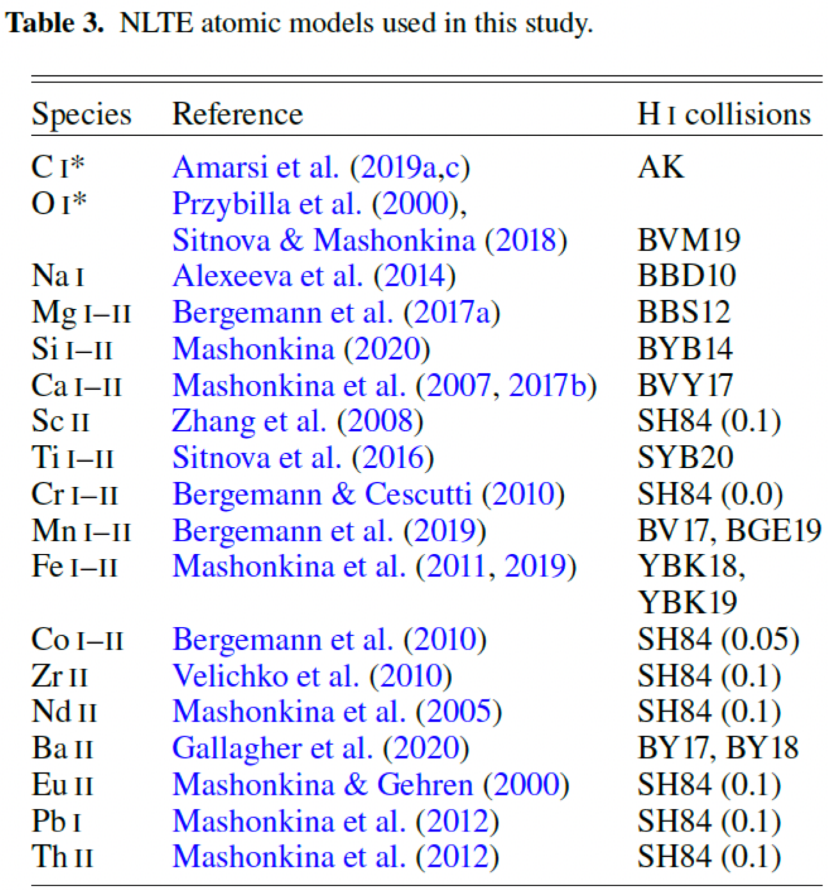
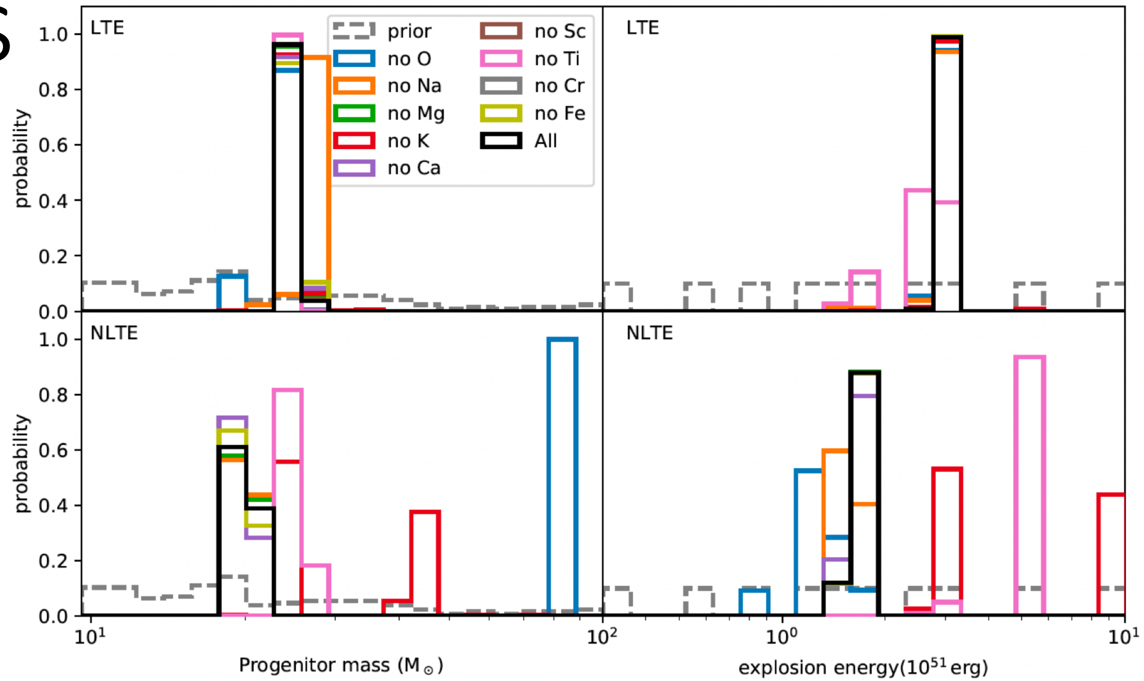


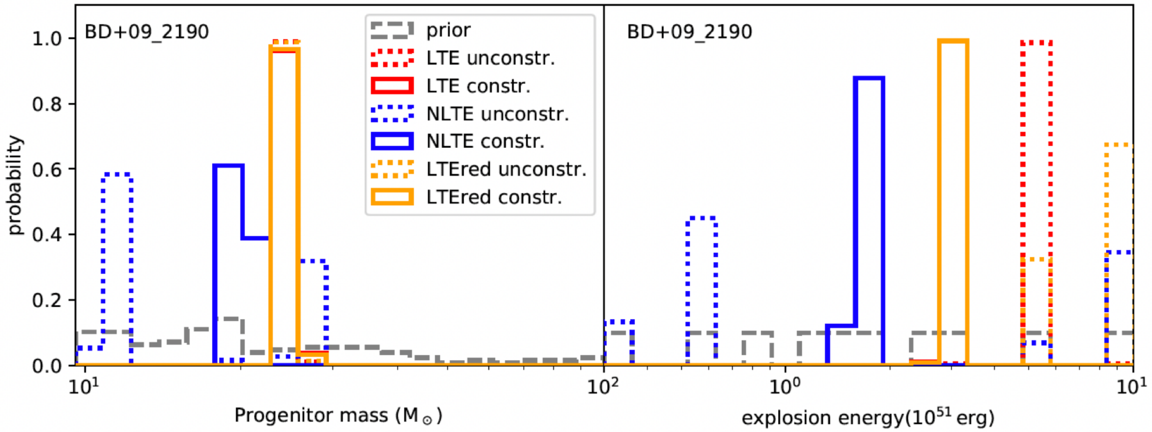
**Table 3.** NLTE atomic models used in this study.

| Species | Reference | H I collisions |
|---|---|---|
| C I* | Amarsi et al. (2019a,c) | AK |
| O I* | Przybilla et al. (2000),<br>Sitnova & Mashonkina (2018) | BVM19 |
| Na I | Alexeeva et al. (2014) | BBD10 |
| Mg I–II | Bergemann et al. (2017a) | BBS12 |
| Si I–II | Mashonkina (2020) | BYB14 |
| Ca I–II | Mashonkina et al. (2007, 2017b) | BVY17 |
| Sc II | Zhang et al. (2008) | SH84 (0.1) |
| Ti I–II | Sitnova et al. (2016) | SYB20 |
| Cr I–II | Bergemann & Cescutti (2010) | SH84 (0.0) |
| Mn I–II | Bergemann et al. (2019) | BV17, BGE19 |
| Fe I–II | Mashonkina et al. (2011, 2019) | YBK18,<br>YBK19 |
| Co I–II | Bergemann et al. (2010) | SH84 (0.05) |
| Zr II | Velichko et al. (2010) | SH84 (0.1) |
| Nd II | Mashonkina et al. (2005) | SH84 (0.1) |
| Ba II | Gallagher et al. (2020) | BY17, BY18 |
| Eu II | Mashonkina & Gehren (2000) | SH84 (0.1) |
| Pb I | Mashonkina et al. (2012) | SH84 (0.1) |
| Th II | Mashonkina et al. (2012) | SH84 (0.1) |

## Key elements

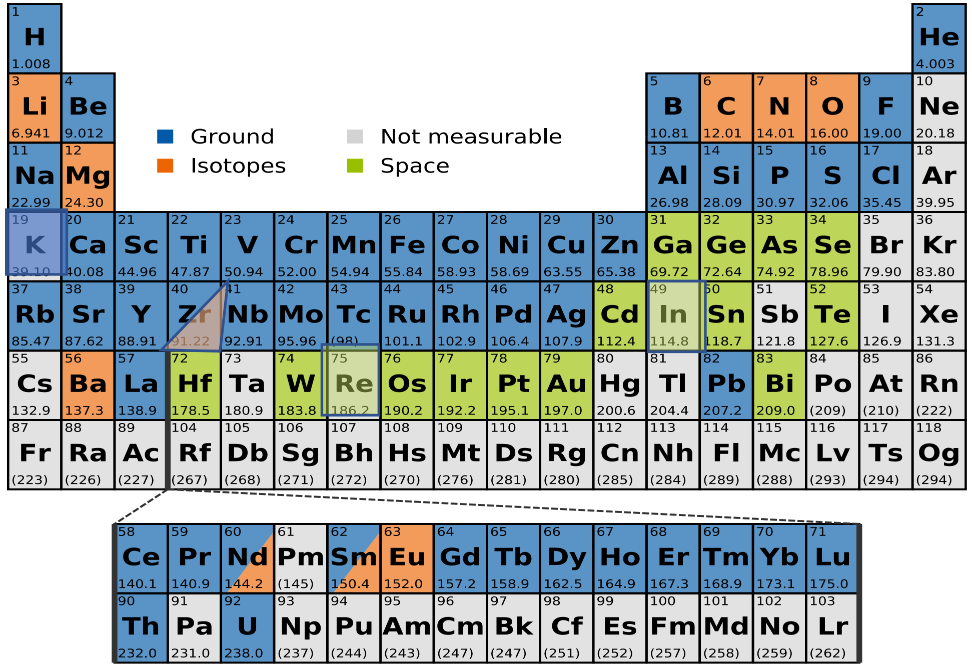
- C, O, Na, K, Ti + Co or Mn & Mg or Ca
- Need odd/even!





# Summary

- With stellar abundances of ~70 elements we can explore:
  - Stellar evolution and self-enrichment
  - Binarity and fundamental parameters (M)
  - Early chemical enrichment and nuclear processes
  - High-resolution spectra allow for accurate elemental abundances, which we can use to place constraints on e.g. nuclear formation processes
  - We need >8 abundances and odd+even elements for a good trace



<u>Goals and limitations:</u>

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