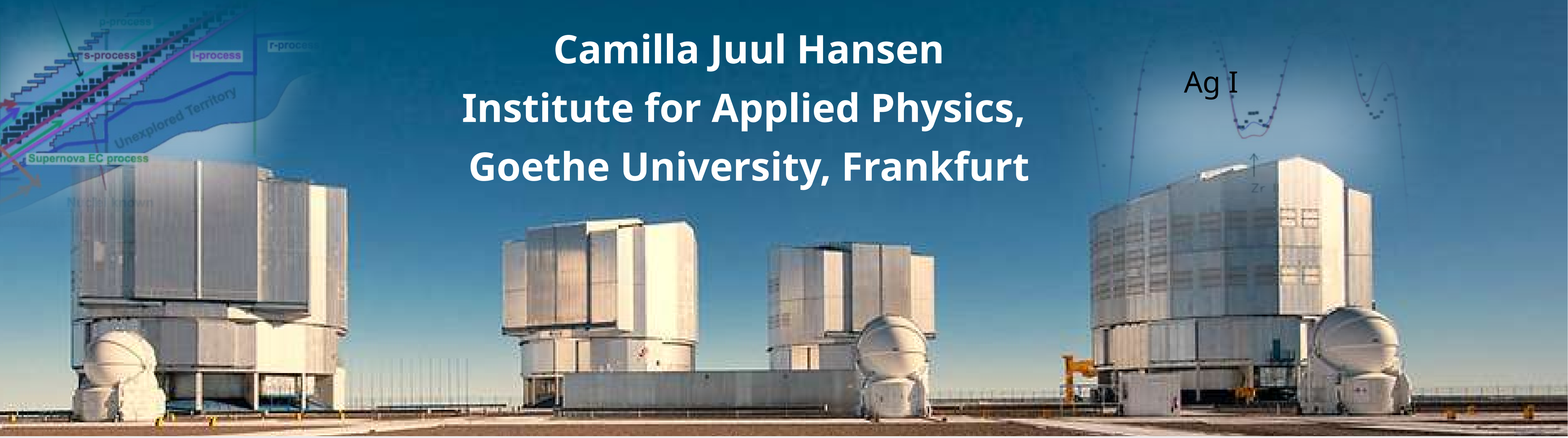
Challenges in Observational Studies of Heavy Elements

Camilla Juul Hansen

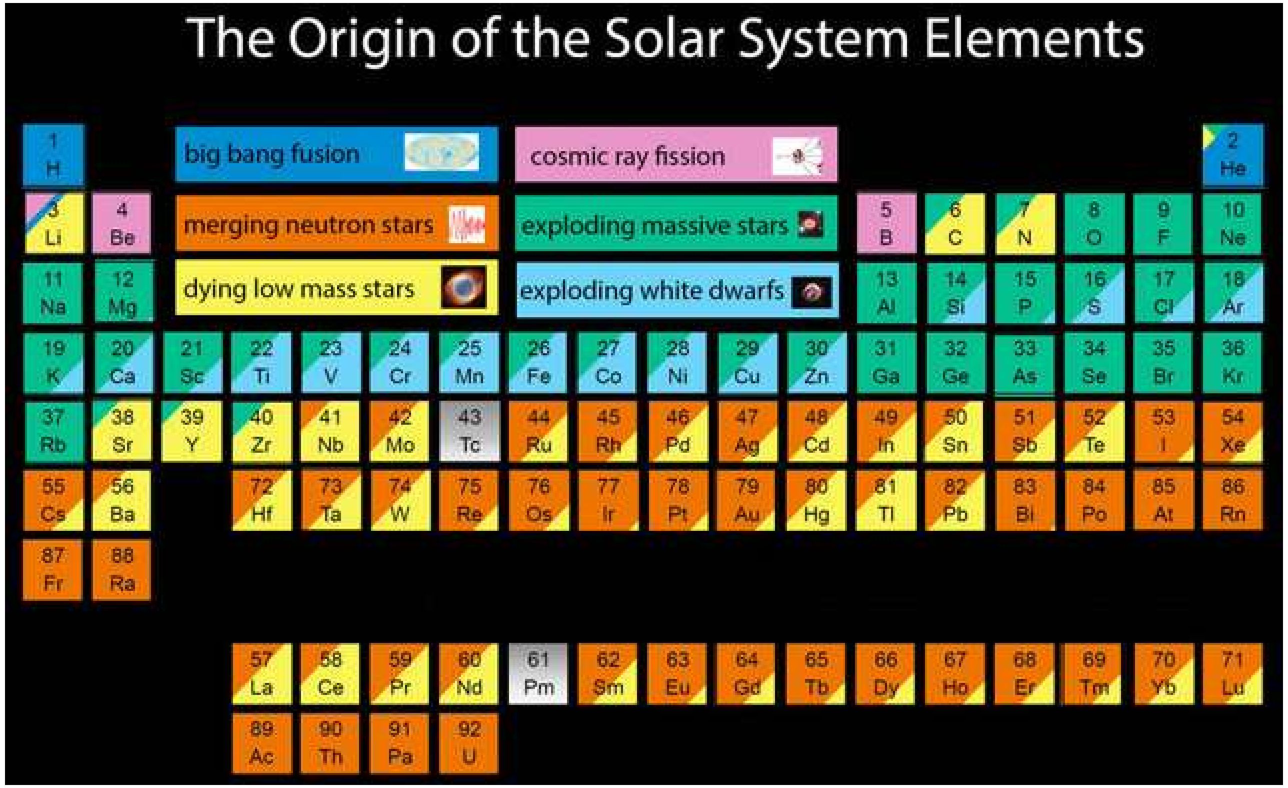
Institute for Applied Physics,

Goethe University, Frankfurt



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

Stellar observations: How and where?



Jennifer Johnson

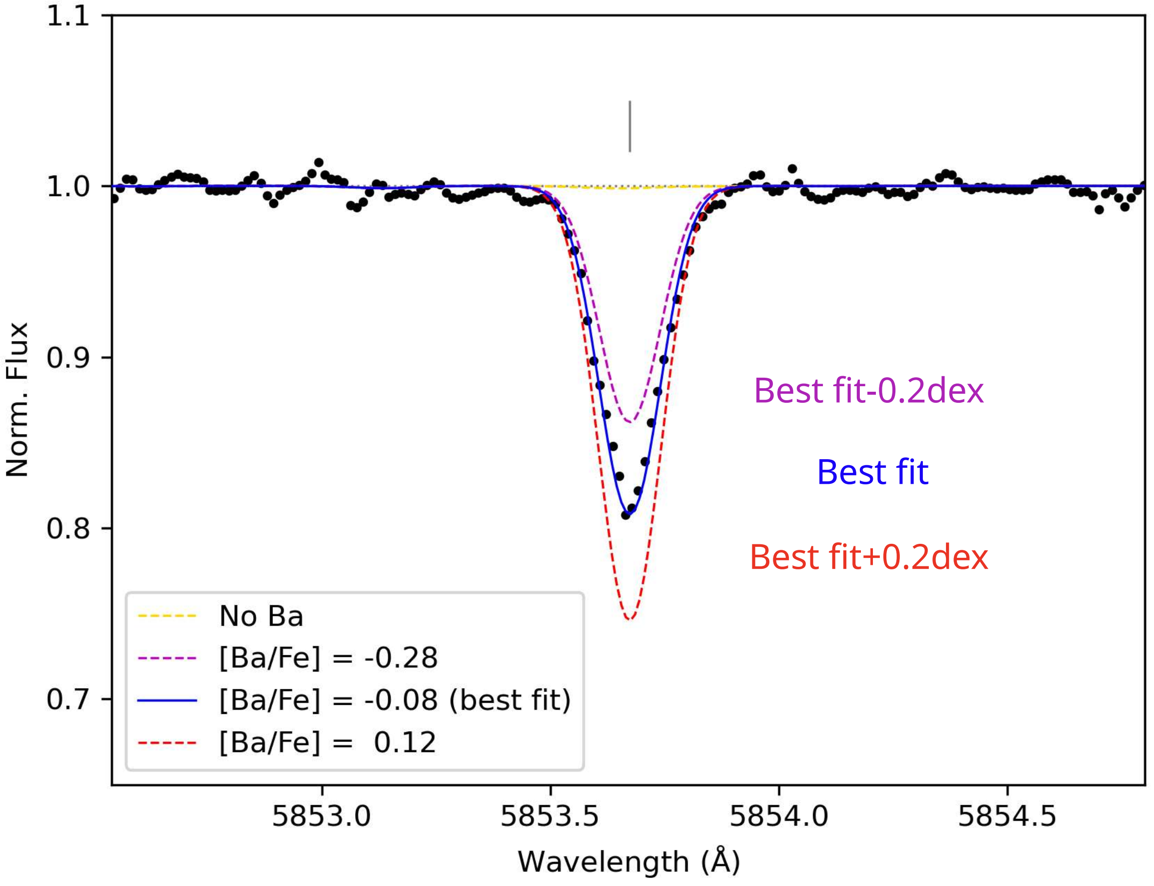
- How are the heavy elements formed?
- Which observables do we have to explore these processes?
- What is the role of stellar spectroscopy?

Where do we observe the heavy elements?

A few heavy elements seen in the visual/red wavelength region – but most in the blue/UV range!

<u>Input needed</u>

- Spectra
- Stellar parameters (Teff, logg, ...)
- Atomic data
- Synthesis code → abundances



L. Lombardo

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

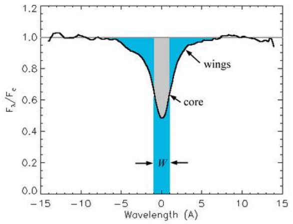
Const.

Abundance

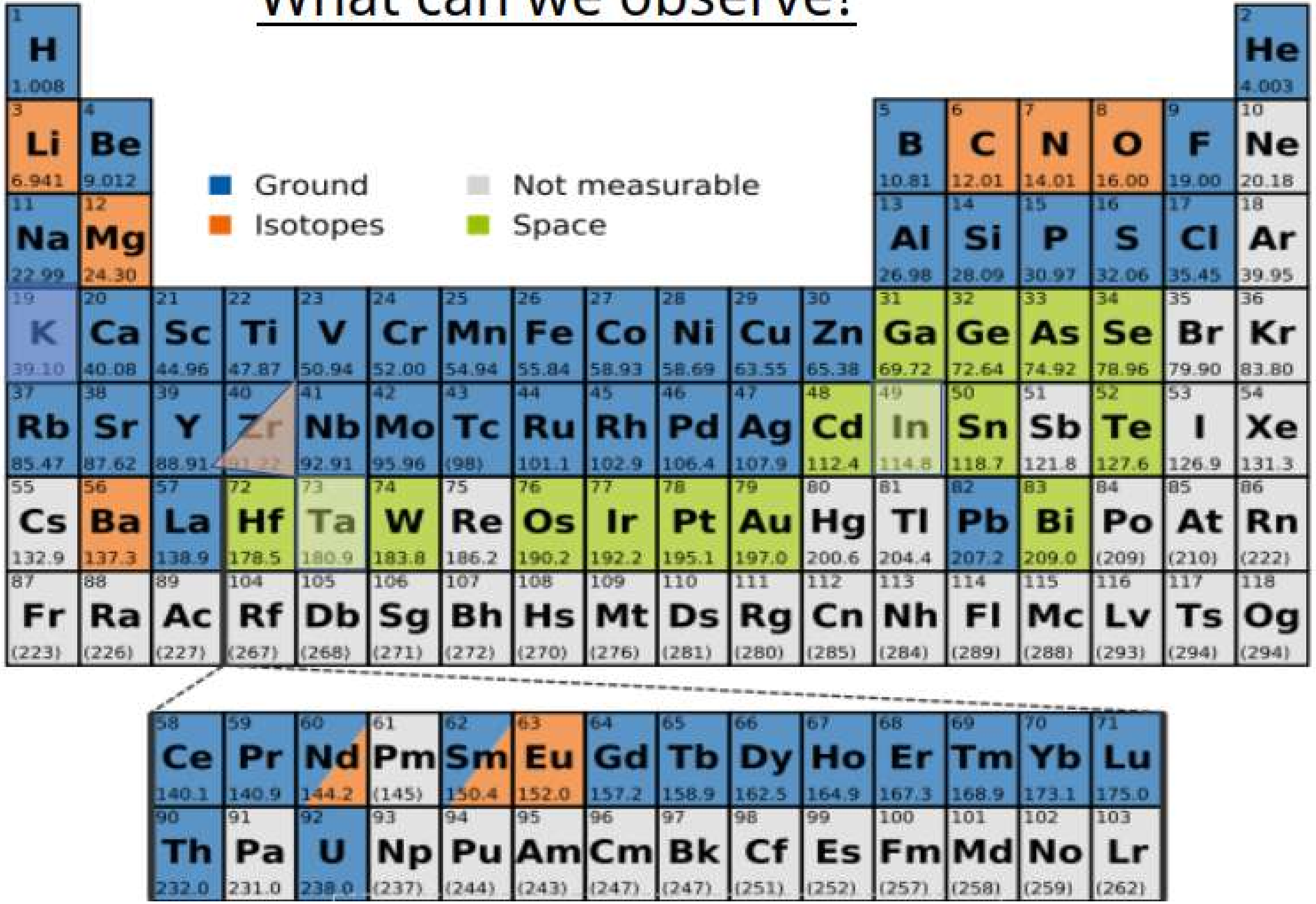
Atomic data (oscillator strength)

Temp.

Absorption coefficient → pressure/logg



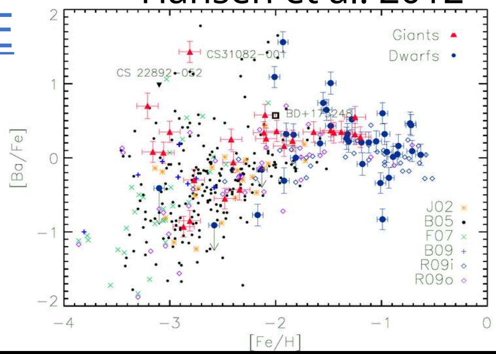
What can we observe?



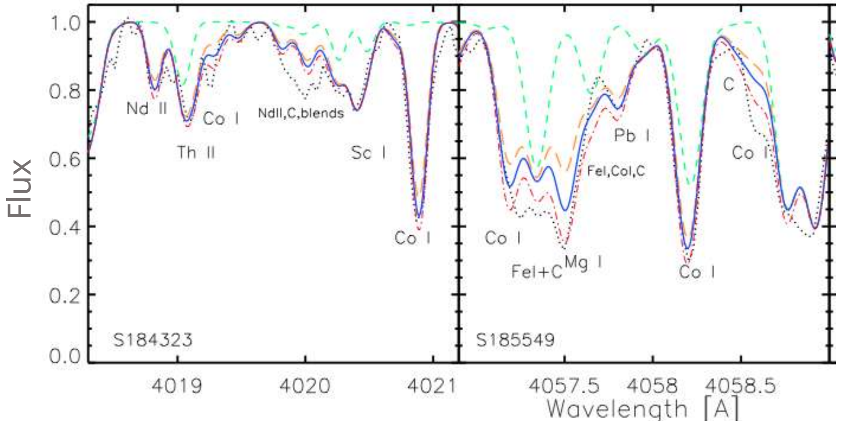
Old Stars

Hansen et al. 2012

[GCE]

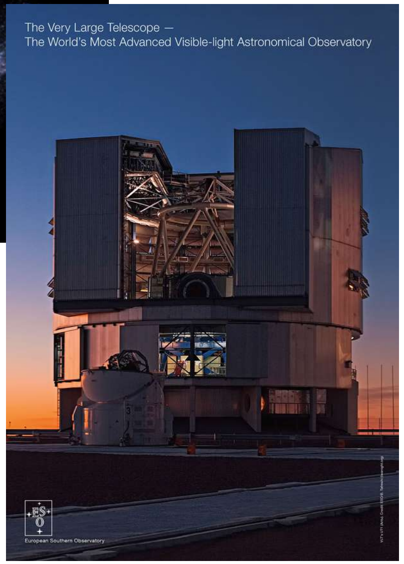


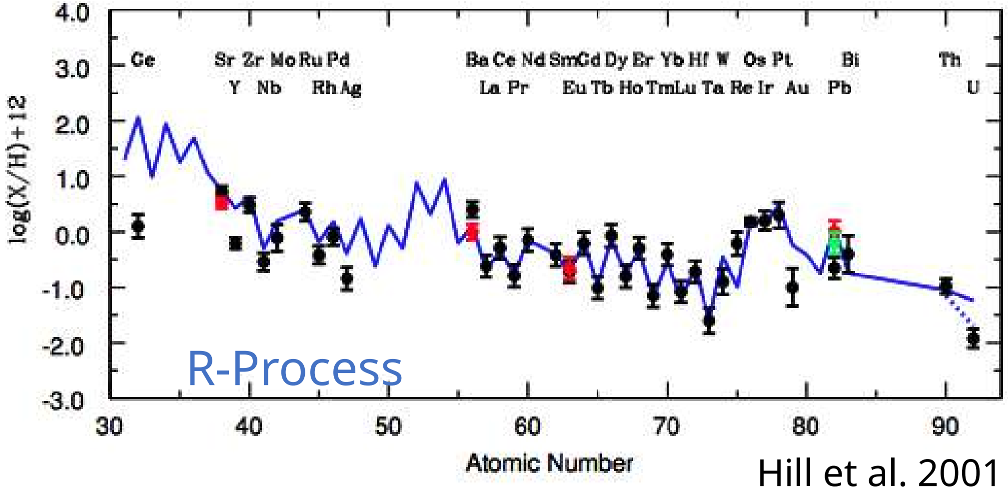
Hansen et al. 2018



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

Th & Eu → [Age]

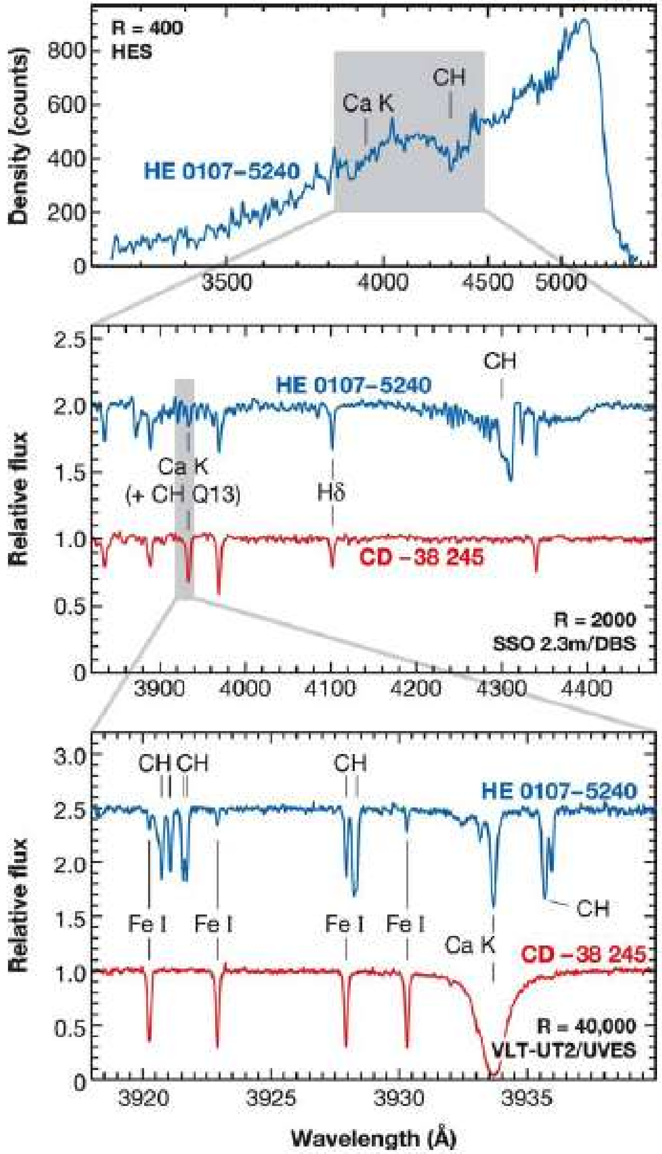


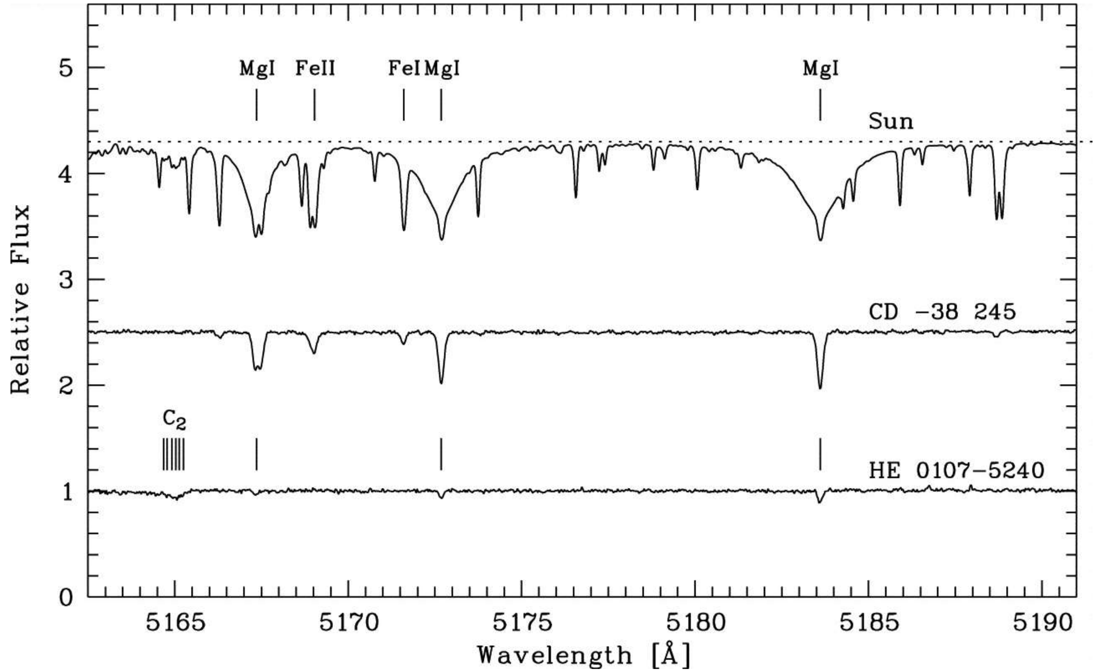


Hill et al. 2001

[Pattern]

Old stars vs the Sun





Beers & Christlieb 2005, ARA&A

[Fe/H]=0

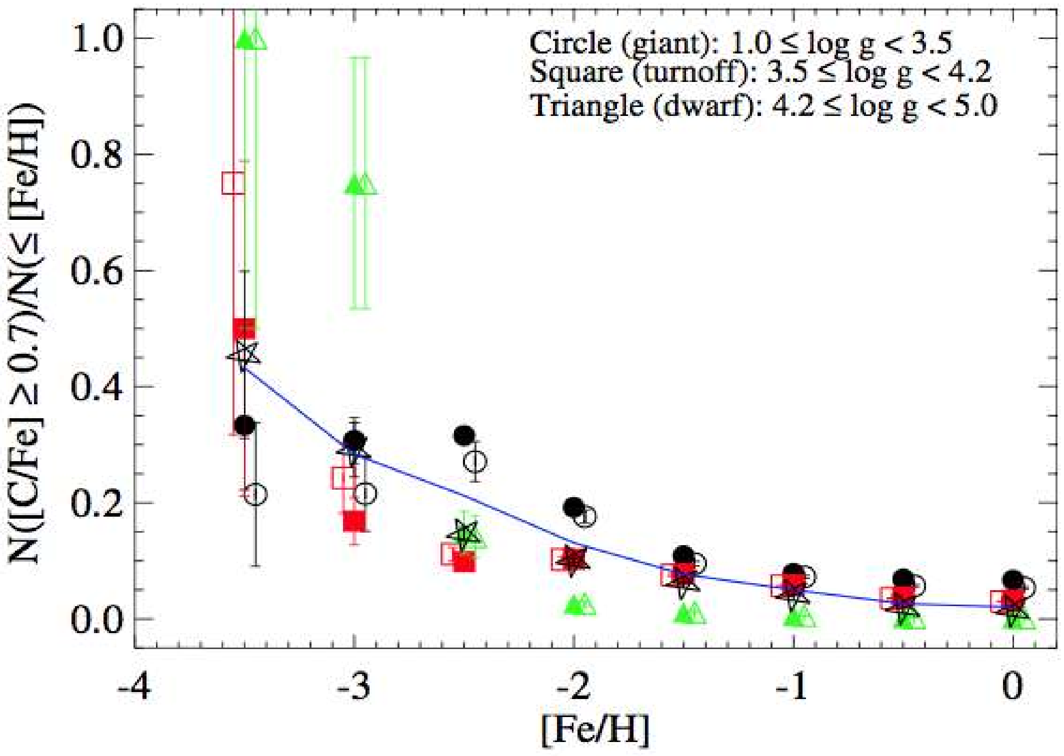
Age: 4.6Gyr

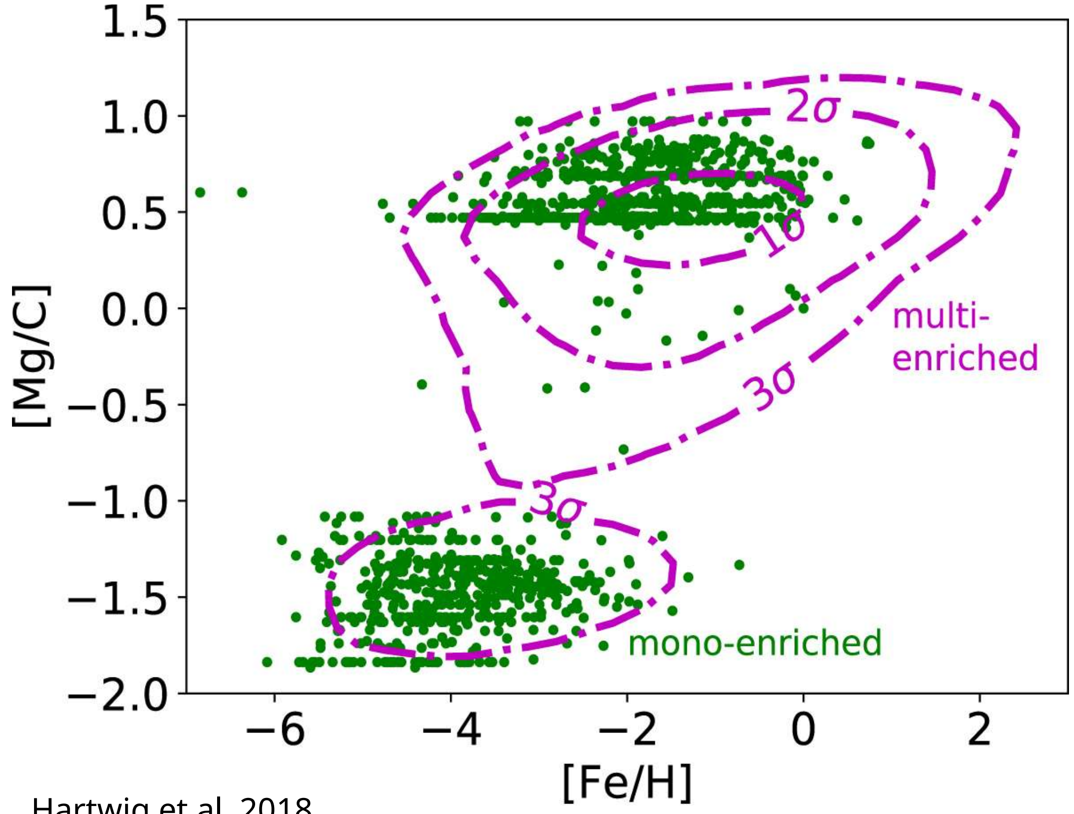
[Fe/H]~ -4
Age: 10 Gyr

[Fe/H]~ -5
Age: 12-13 Gyr

Early chemical enrichment

Lee et al. 2013



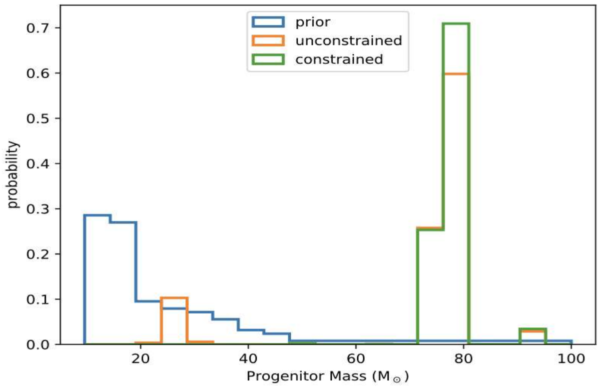


Hartwig et al. 2018

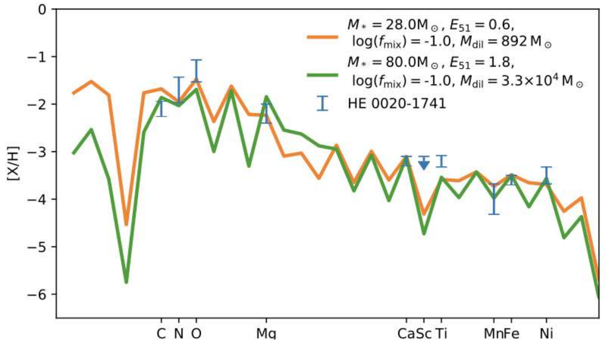
Dilution processes

- 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:
  - $M_{dil,min}=4/3\pi n_o \mu m_H R^3_{fade}$

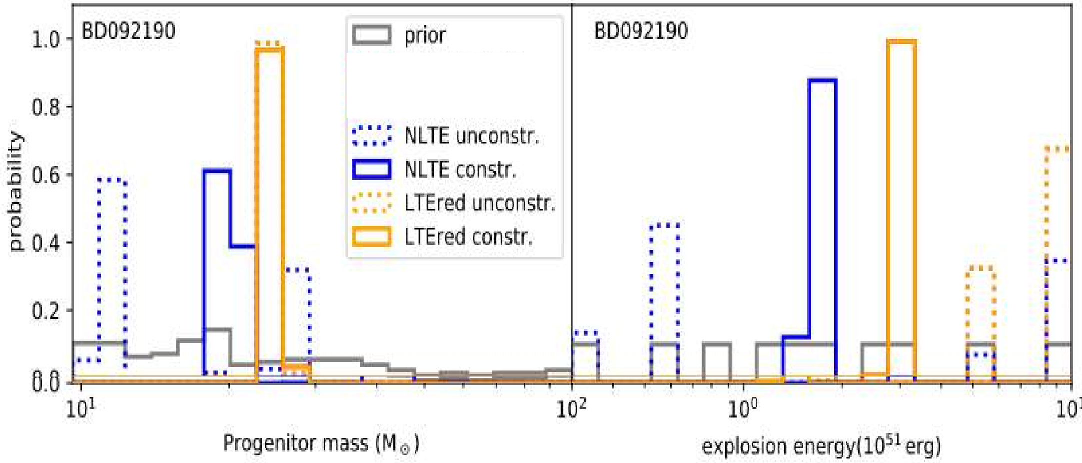
    $=1.9\ 10^4 M_\odot E^{0.96}_{51} n^{-0.11}_o$
  - Abundance: $\log(M_i/(\mu X_H M_{dil}))-\log(N_i/N_H)_\odot$



Magg et al. 2020



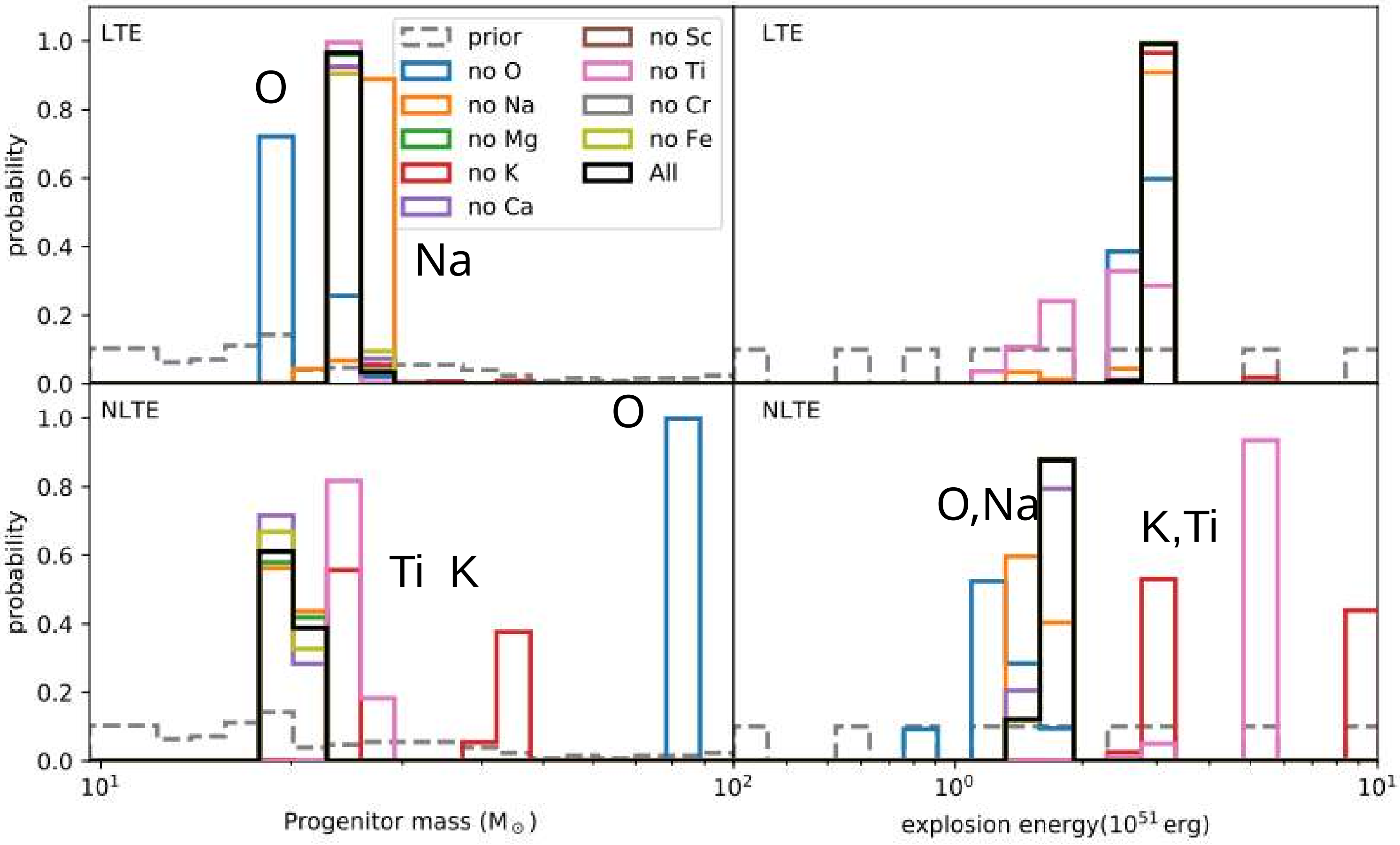
Hansen et al.2020



<u>**Best fit model**</u>	
LTE	NLTE
25.5M, E_{51}=3	19.2M, E_{51}=1.5
Constrained	Constrained

Predictive power of lighter elements

Hansen et al. 2020



Test: Removed shown element from fit

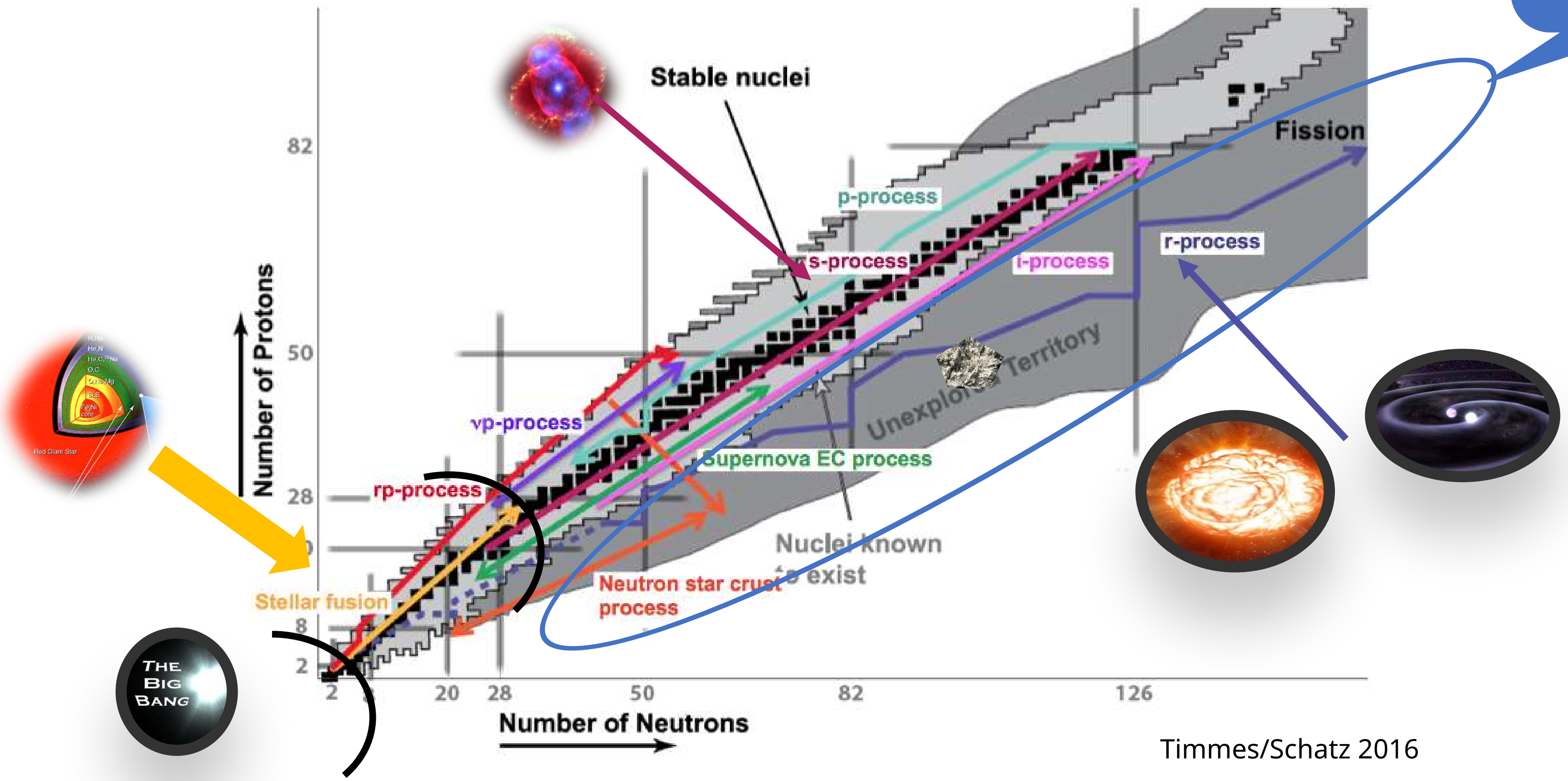
- Key elements:

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

- **Need odd/even!**

Nuclear reactions

Unknown Reactions!



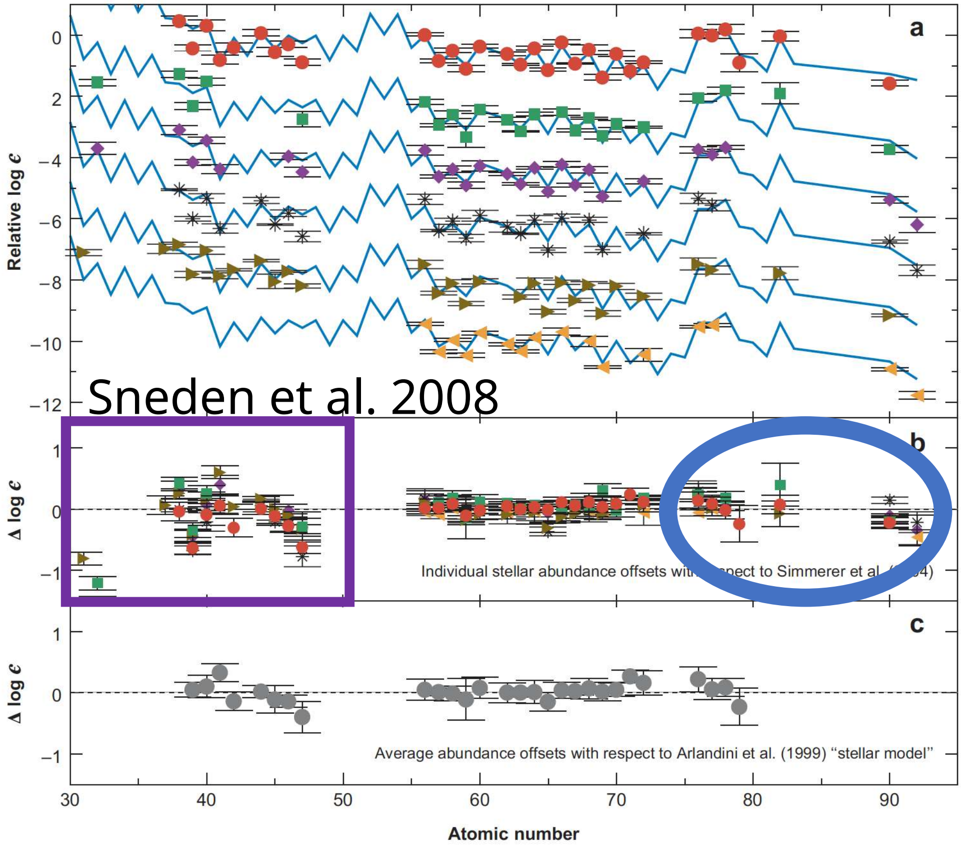
Timmes/Schatz 2016

Heavy element abundances

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

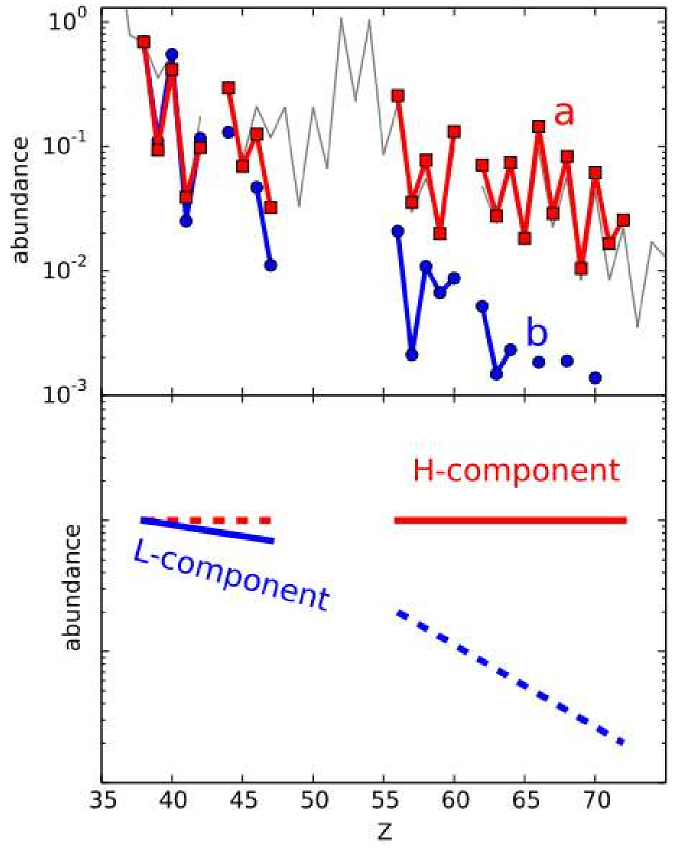
No site – just observations
H represented by r-rich stars
L represented by r-poor stars

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



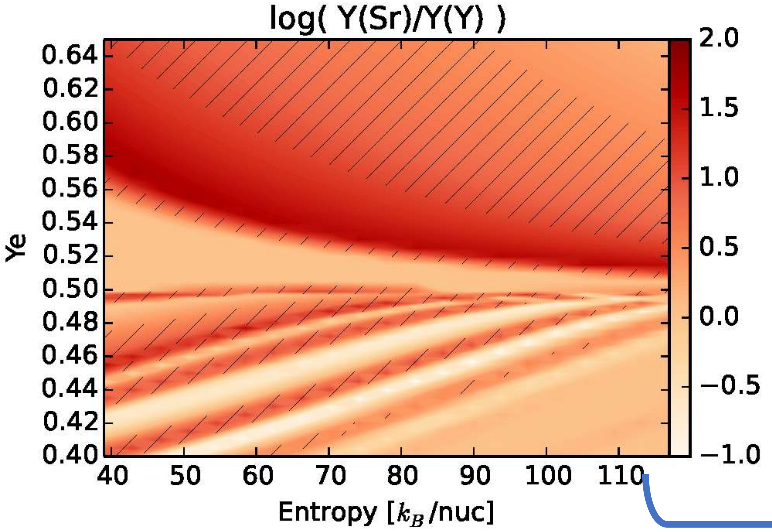
Sneden et al. 2008

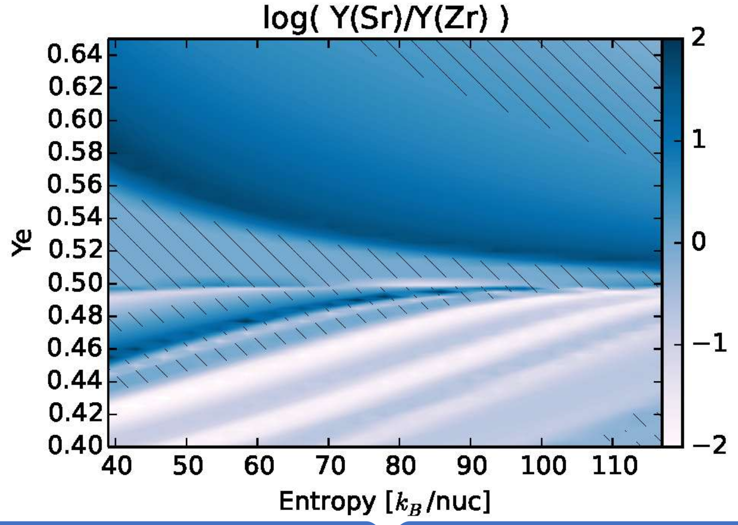
Large residuals for Z=30-50 → Solar-s=r not sufficient!

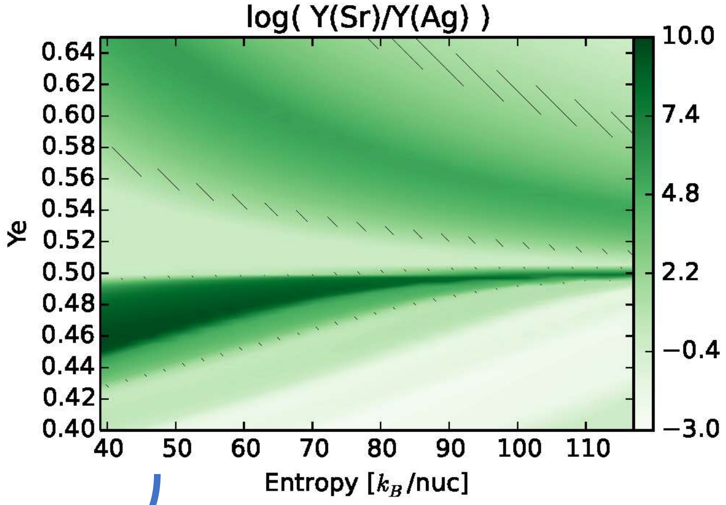


CJH et al. 2014

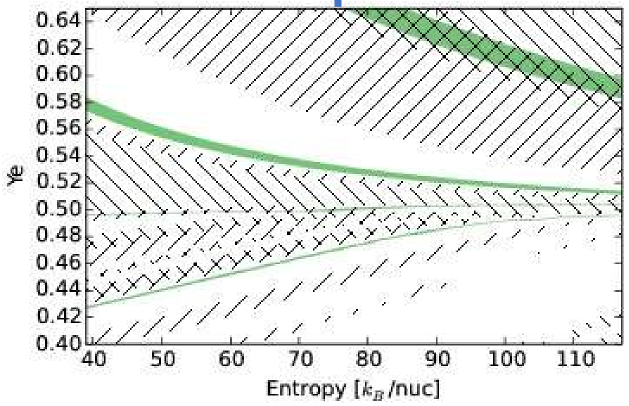
Exploring the nature of the weak r-process







Combined conditions – forming Sr to Ag →
Slightly proton rich (as shown by Martinez-Pinedo et al. 2012) or slightly r-rich and maybe not robust…

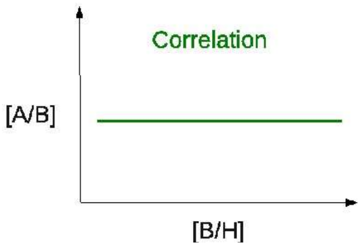


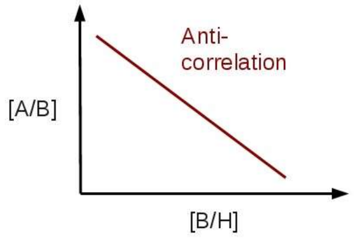
Models:
Arcones et al. 2007;
Arcones & Montes 2011

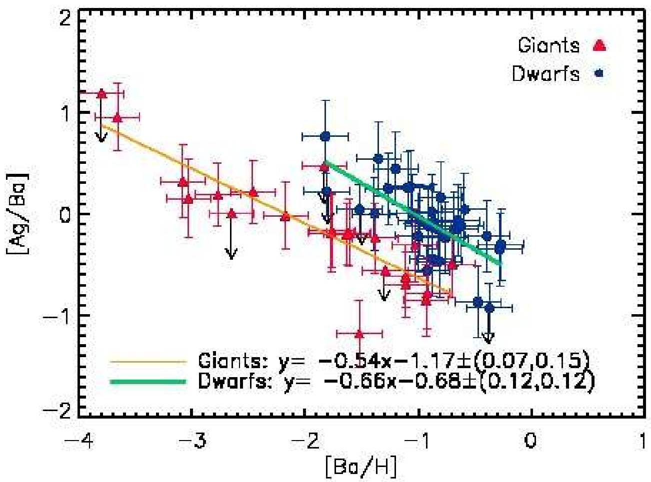
Observations:
Hansen et al. 2014b

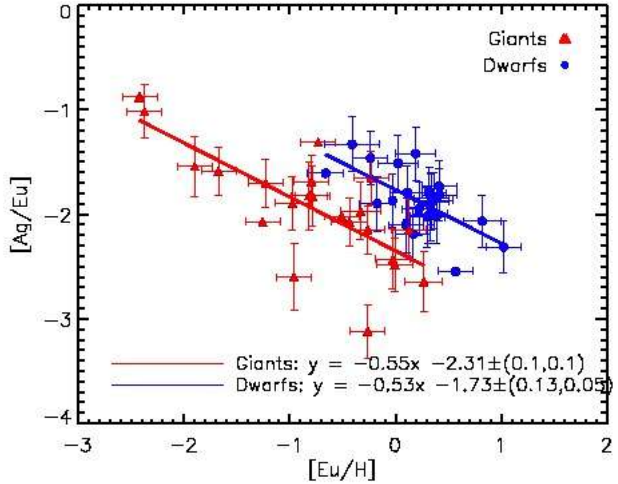
Weak r and 3D-NLTE Ag

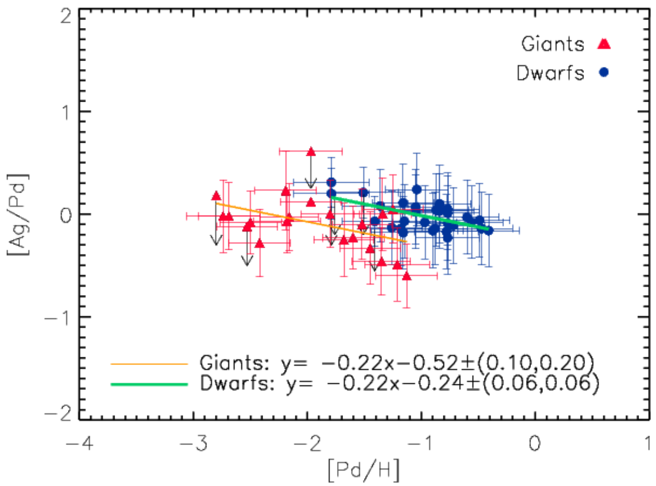
Hansen et al. 2012

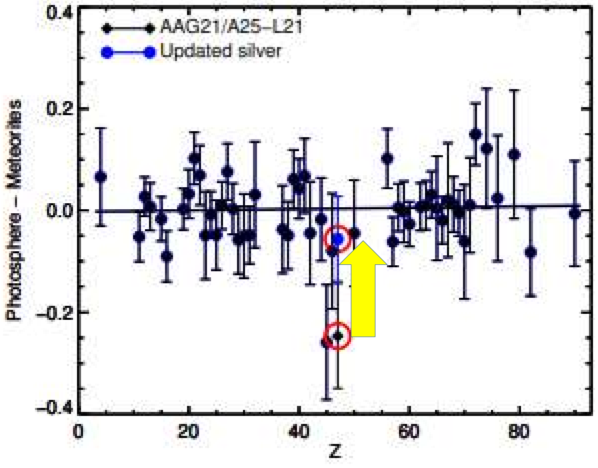


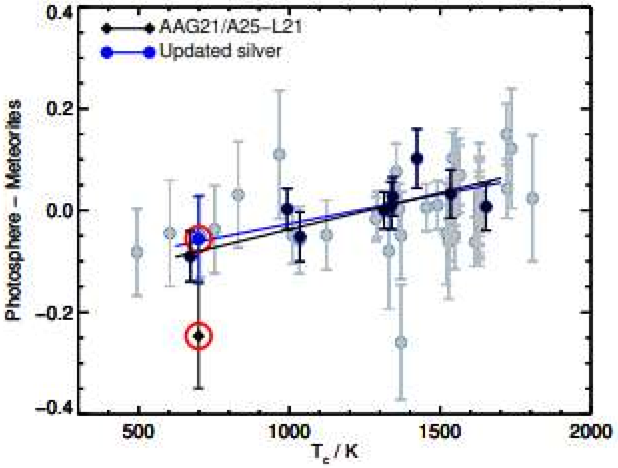








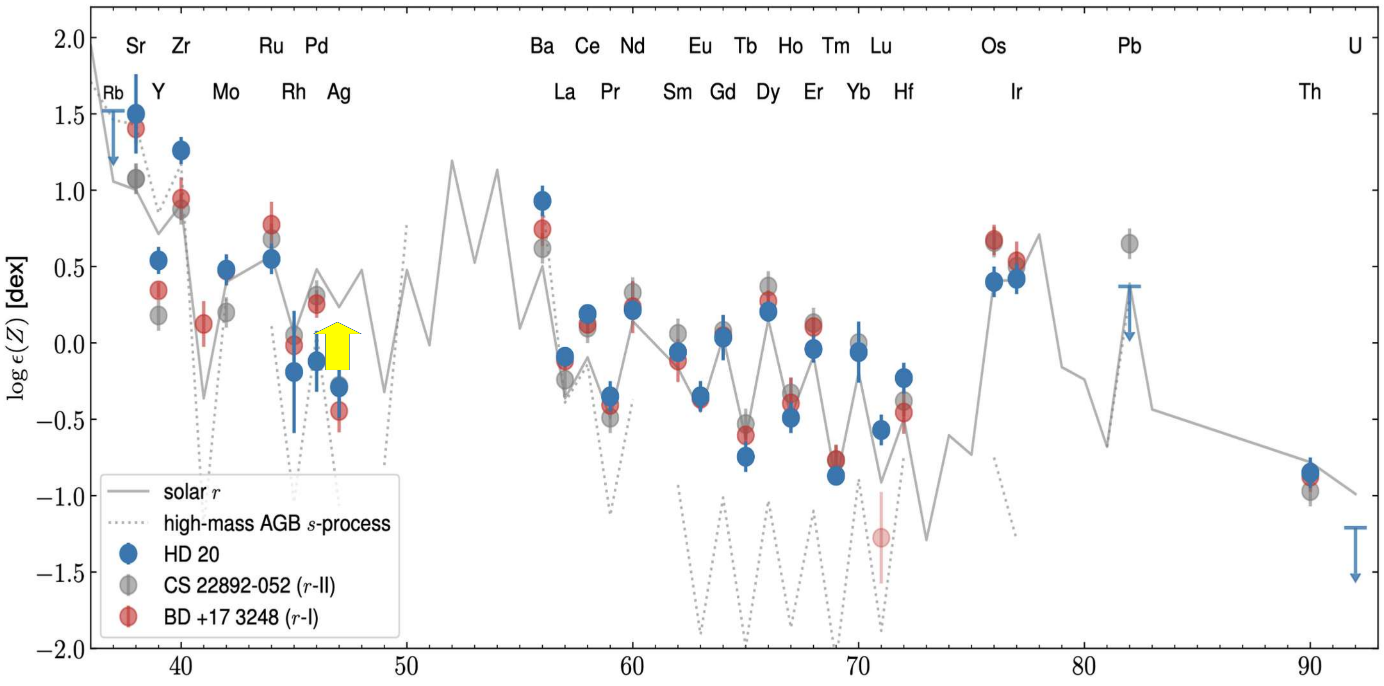


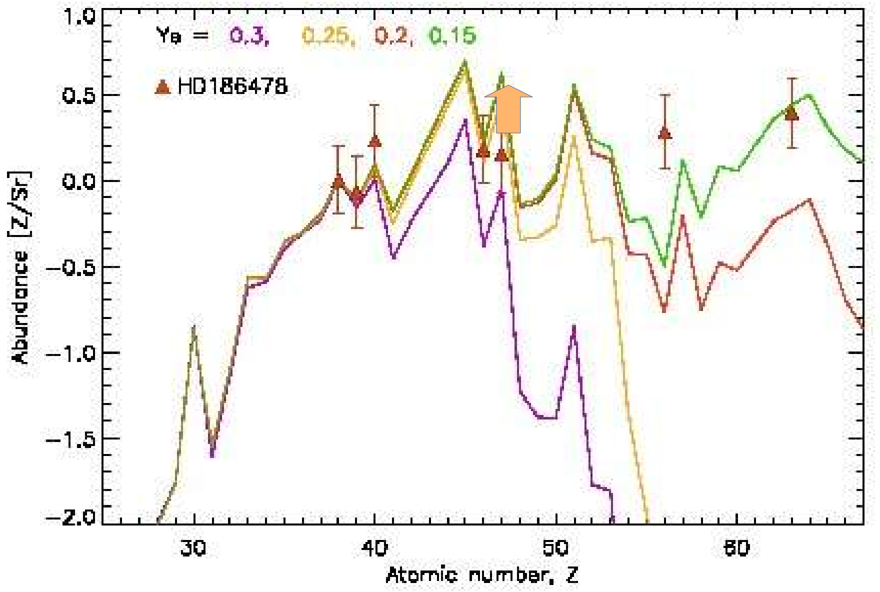


Caliskan et al. 2026

Ag 3D, NLTE
correction ~ +0.3dex

Corrections to Ag – do they matter?





Hanke, CJH et al. 2020

Large separation between s and r

Hansen et al. 2012

0.3dex in Ag could change the weak r conditions or the impact of fission cycling

Chemical Evolution of R-process Elements in Stars – CERES

CERES: PI C. J. Hansen

Goal: Improve 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 (>100h observing time)

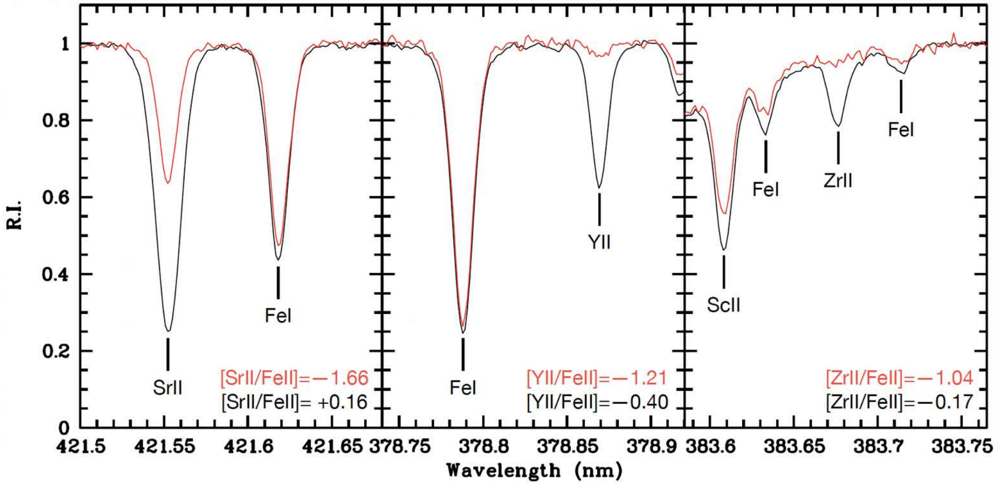
Sample: 52 giant stars with few known heavy element abundances

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

Status: Li, C, N, O, Na – Zr, [Zr-Ag], Ba – Eu, Hf, Os, Ir, Pt, [Th,U]

CERES I - IV

CERES I

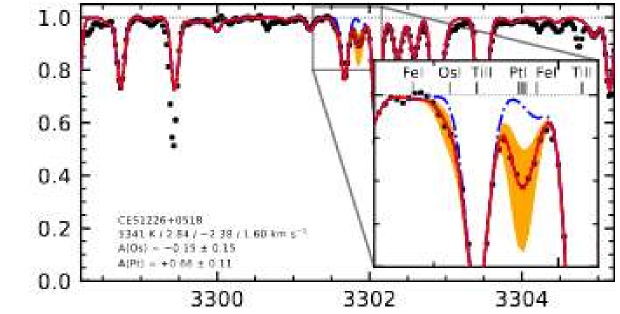


Lombardo et al. 2022

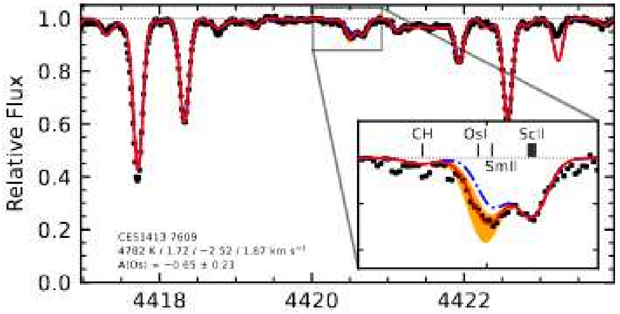
R-process in old, metal-poor stars

Arthur Alencastro Puls
Postdoc

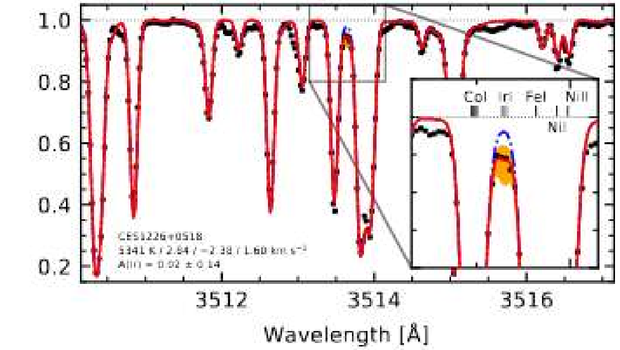
Pt



Os

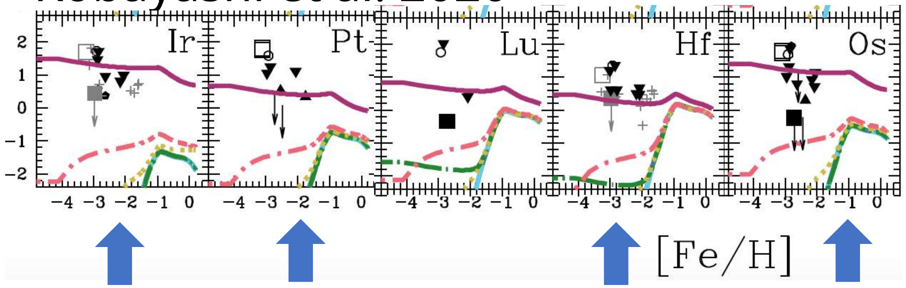


Ir

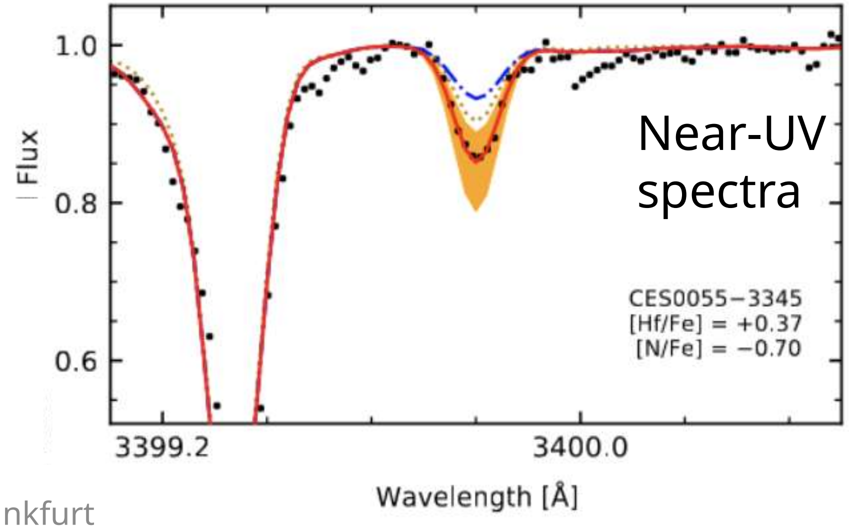


Alencastro Puls et al. 2025; CERES IV

Kobayashi et al. 2020



Poorly studied heavy elements!



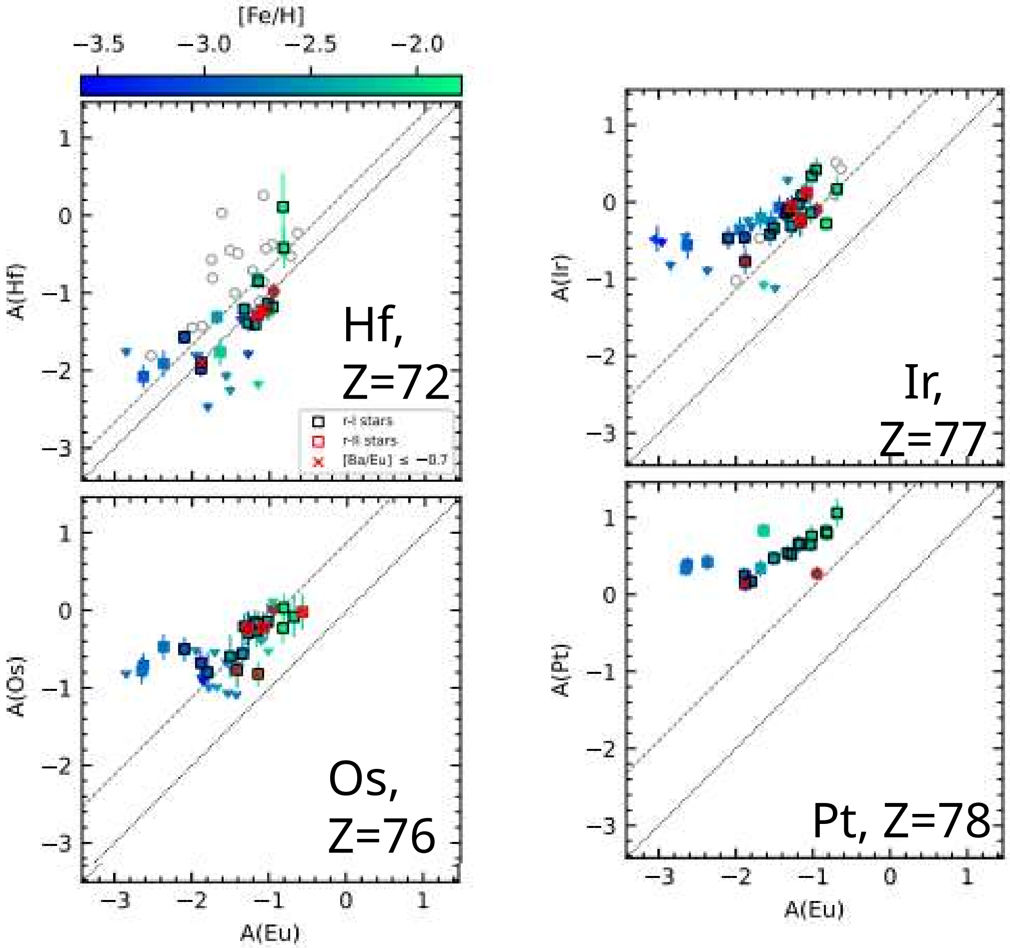
Near-UV spectra

Hf

R-process in old, metal-poor stars

Arthur
Alencastro
Puls
Postdoc

Alencastro Puls et al. 2025; CERES IV



A possible shift in the 3rd peak!

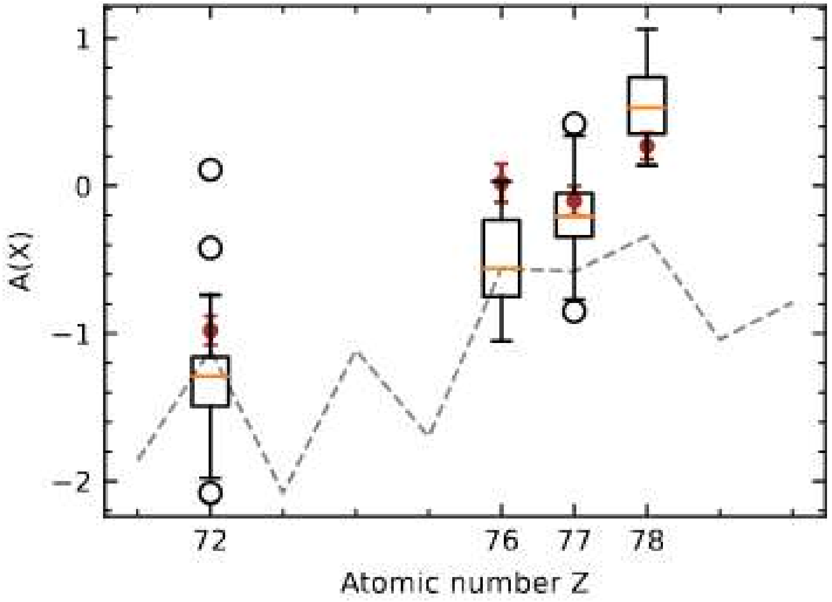
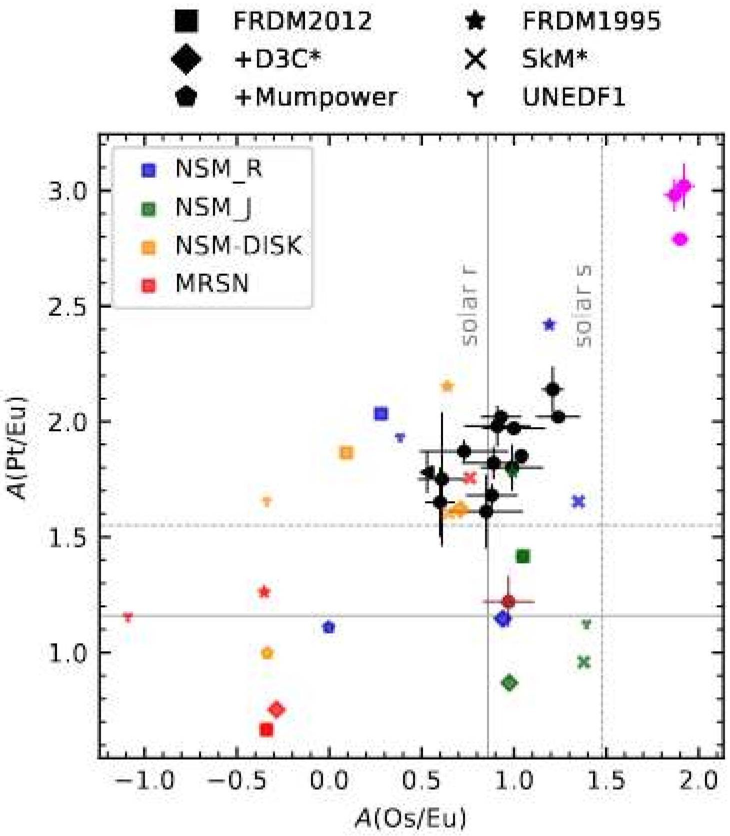


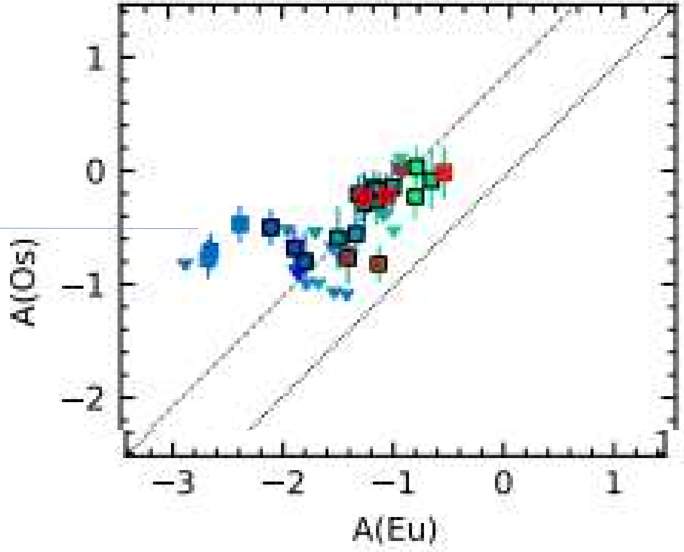
Fig. 9. Box plots representing the distributions of A(Hf, Os, Ir, Pt) in our sample. The orange lines represent the medians. The grey dashed line is the solar-scaled abundance normalised to the median of the Os abundances from this work. Open black circles are the outliers in our sample. The filled brown circles are the abundances for Sneden's star as

No good match!? A new process?



Tail

Alencastro Puls et al. 2025, CERES IV



NSM_R – Rosswog et al. 2013
NSM_J – Jacobi et al. 2023
NSM-DISK – Wu et al. 2016
MRSN – Reichert et al. 2021

Heavy radioactive clocks

$$\Delta t = 46.7[\log(\mathrm{Th/Eu})_0 - \log(\mathrm{Th/Eu})_{\mathrm{obs}}],$$

Hansen et al. 2018,

log(Th/Eu)o = -0.295 (Cowan et al. 2002)

τ_{232Th} = 14.05Gyr, τ_{238U} =4.5Gyr (half life)

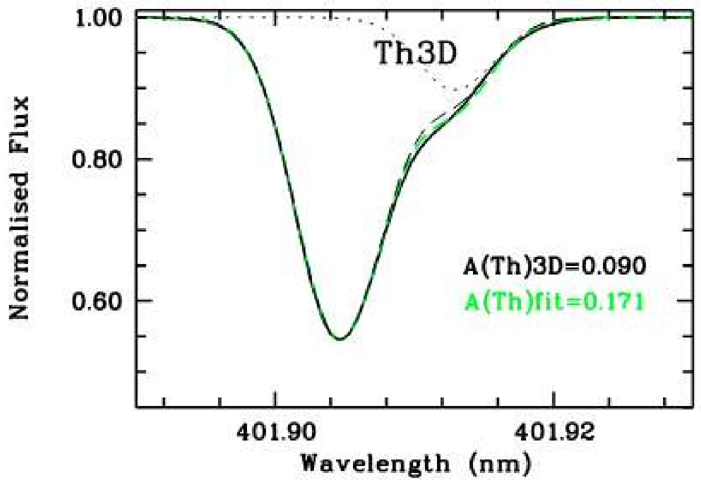


Fig. 3. The 3D profile of (Fe I+Ni I) + (Th II+Co I+V II) blend in solid black is over-imposed on the $1D_{LHD}$ fit (green/grey dashed line). In the

Caffau et al. 2008

Th/Eu and Th/U – useful for field stars with unknown distances

Accuracy of ages depends on:

Stellar spectra,

nuclear production rates,

atomic physics

Ludwig et al. 2010

Th and U

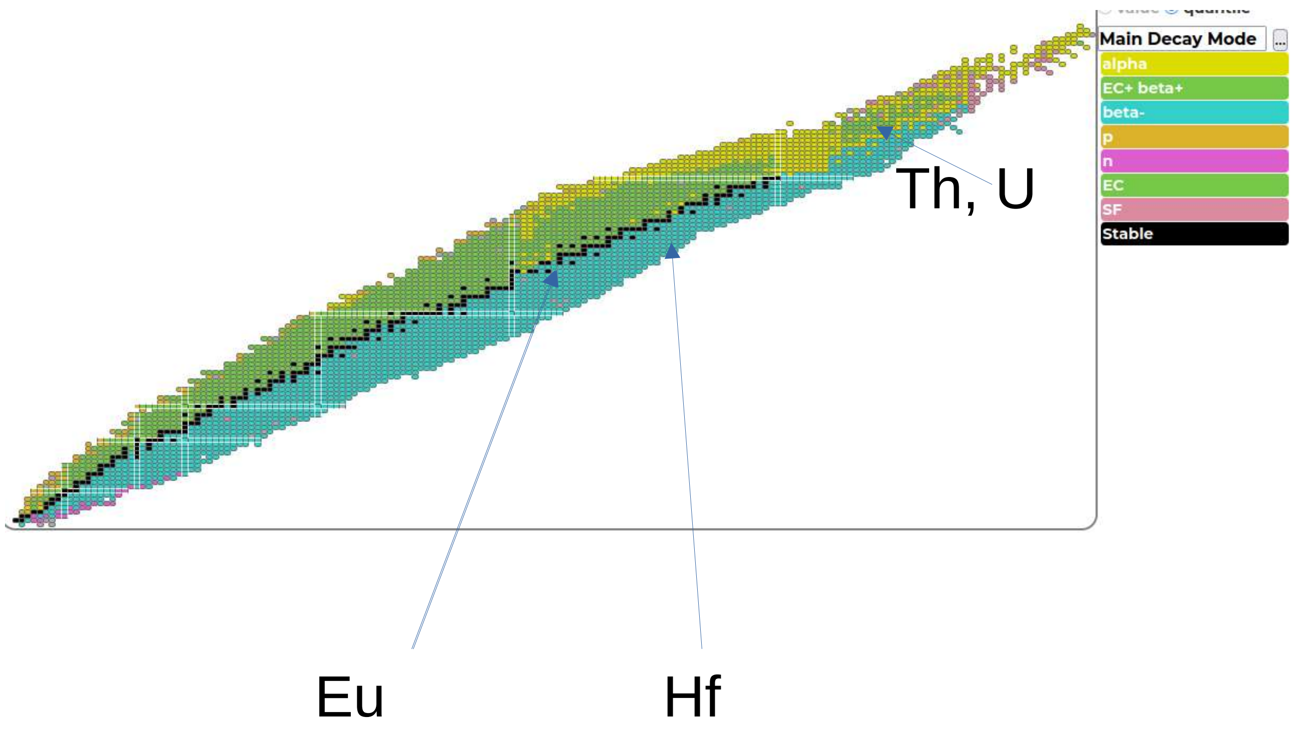
<u>Nuclear limitations:</u>

The clocks work best for two elements close in atomic number that are co-produced by the same nuclear process

Th – U pair has less uncertainties & common production, but Eu is easier to measure than U

Alternative Hf

(Kratz et al. 2007)



The closer the elements – the more likely they are co-produced
– but Hf has challenging NH blend

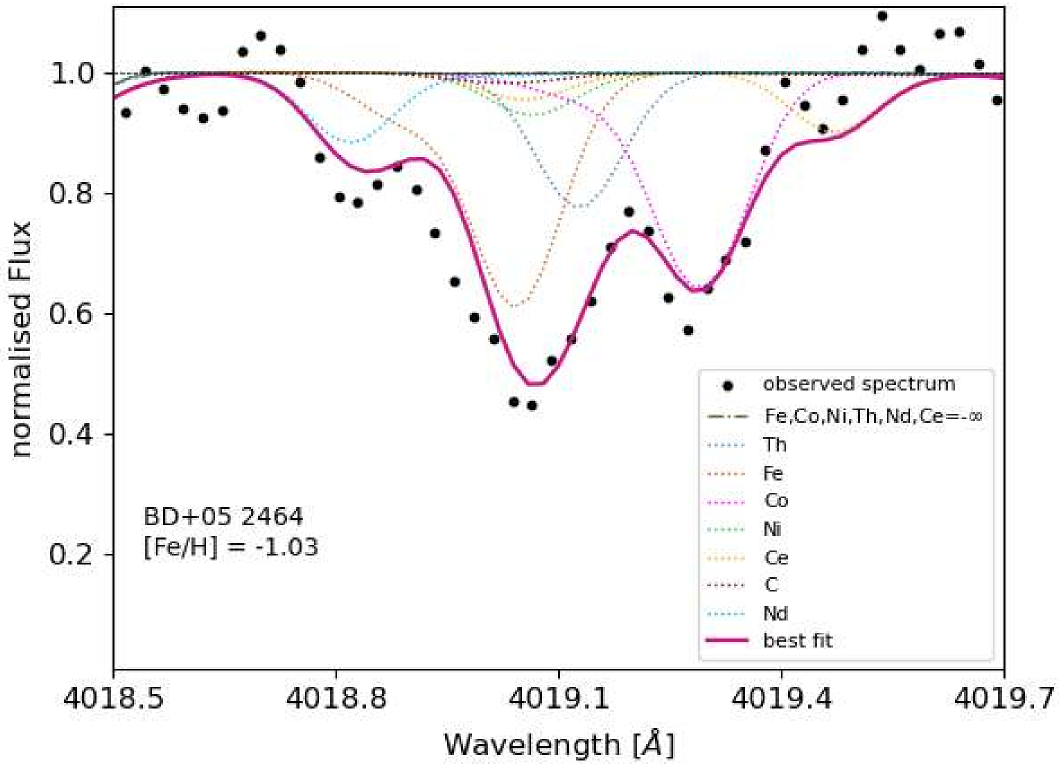
Features around Th and U

<u>Atomic physics</u>

→ blends – saturation effects

Despite showing weak lines, any of the blending components or Th itself can be saturated leading to the wrong abundance/equivalent width, W (Ludwig et al. 2010)

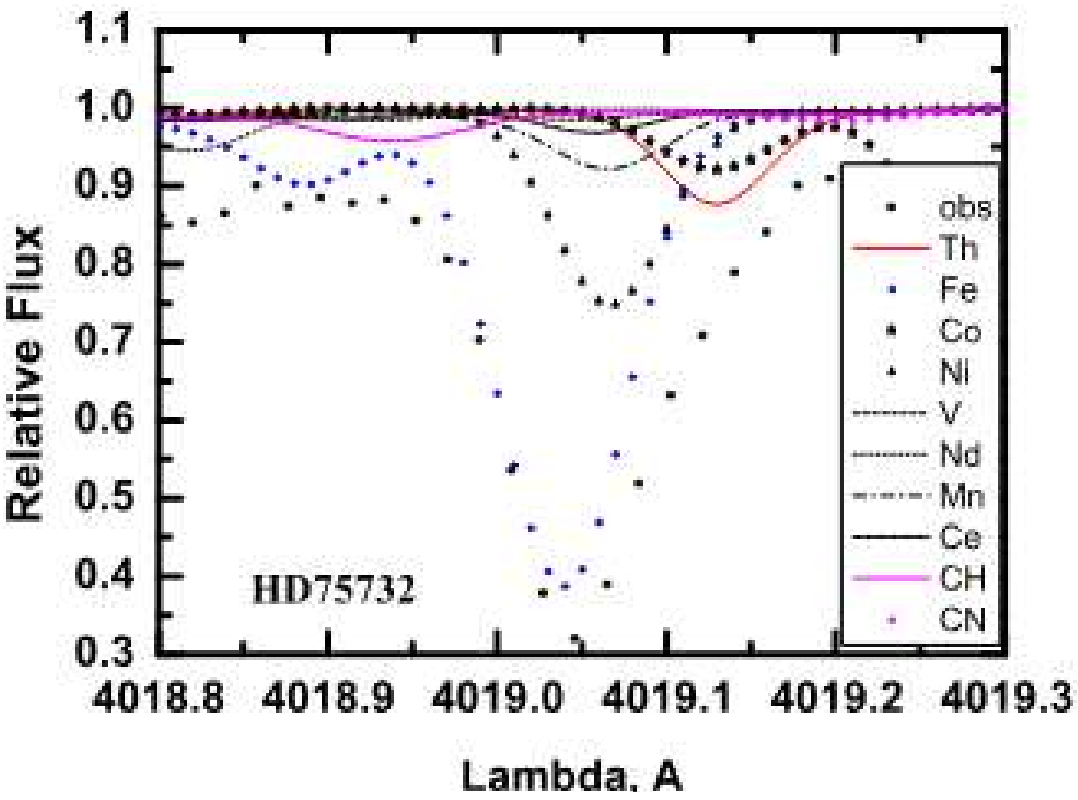
The precision is limited to the precision in production, W, and atomic physics (ex.pot & loggf)



Alencastro Puls, CJH, et al. In prep. CERES V

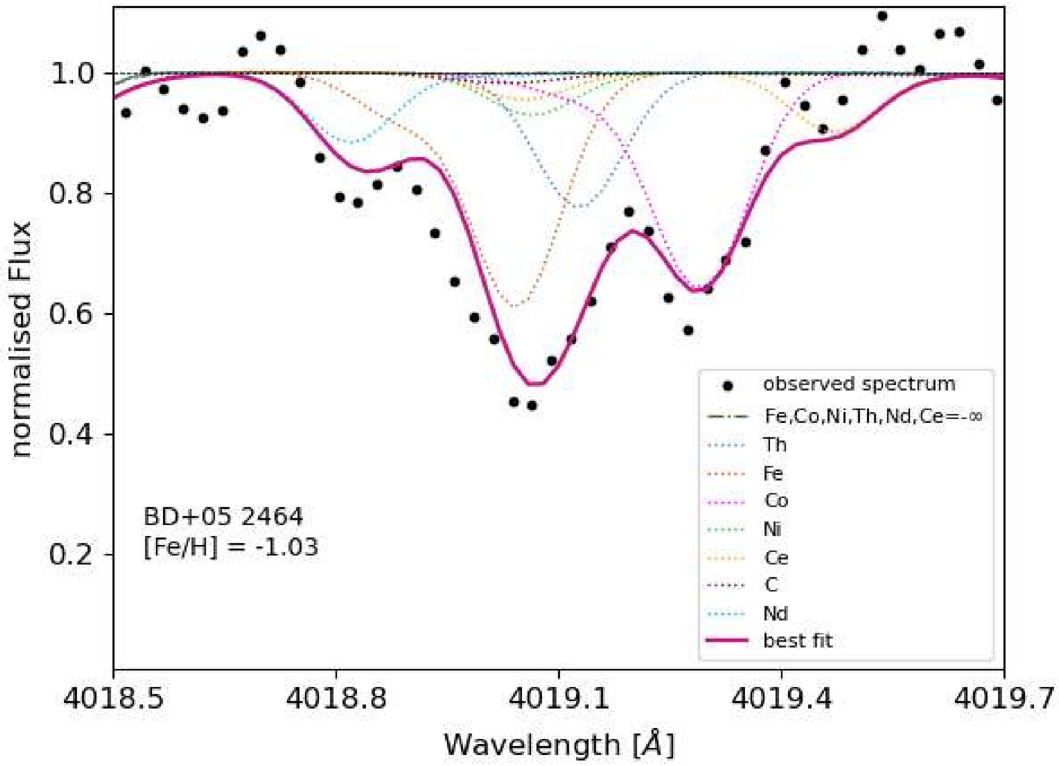
Atomic physics comparison

Scaled loggf of blends (blue Fe line)

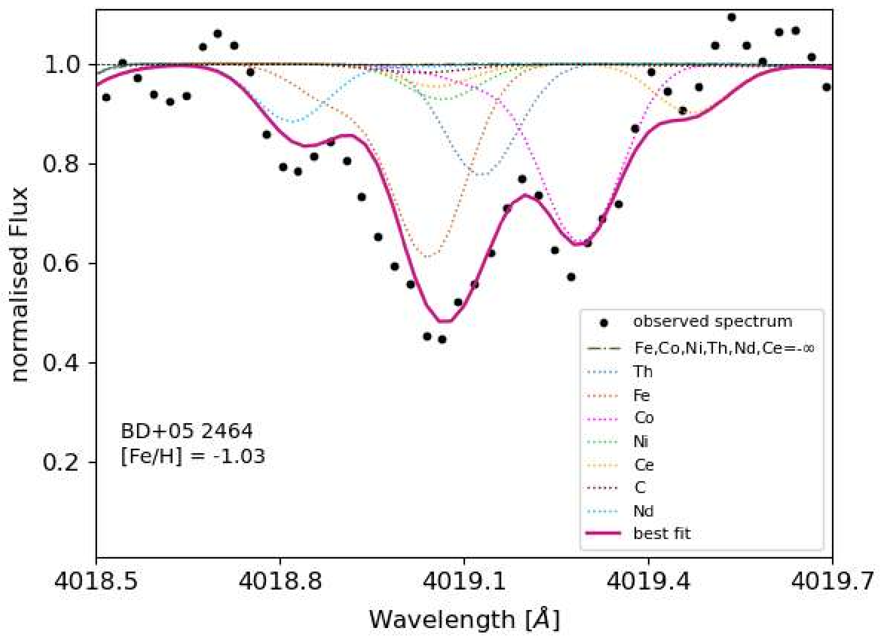


Mishenina et al. 2022

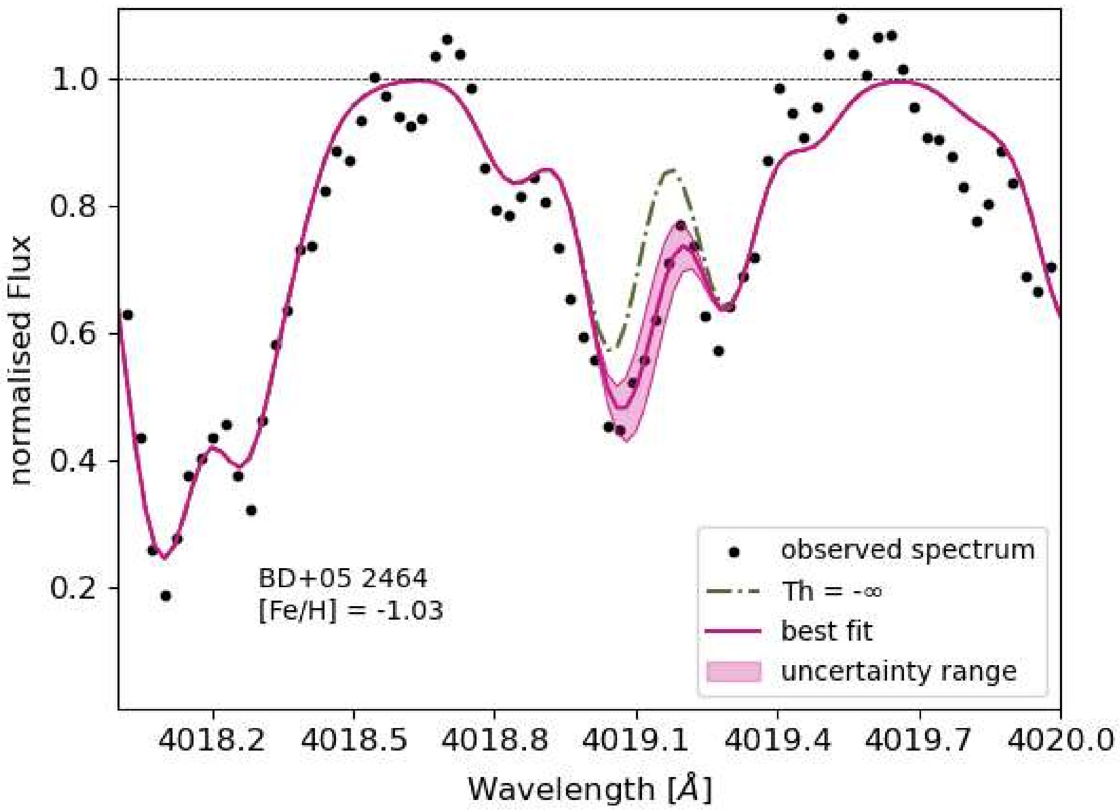
Blending lines - have NLTE corr. (Co)



The heaviest elements – Th



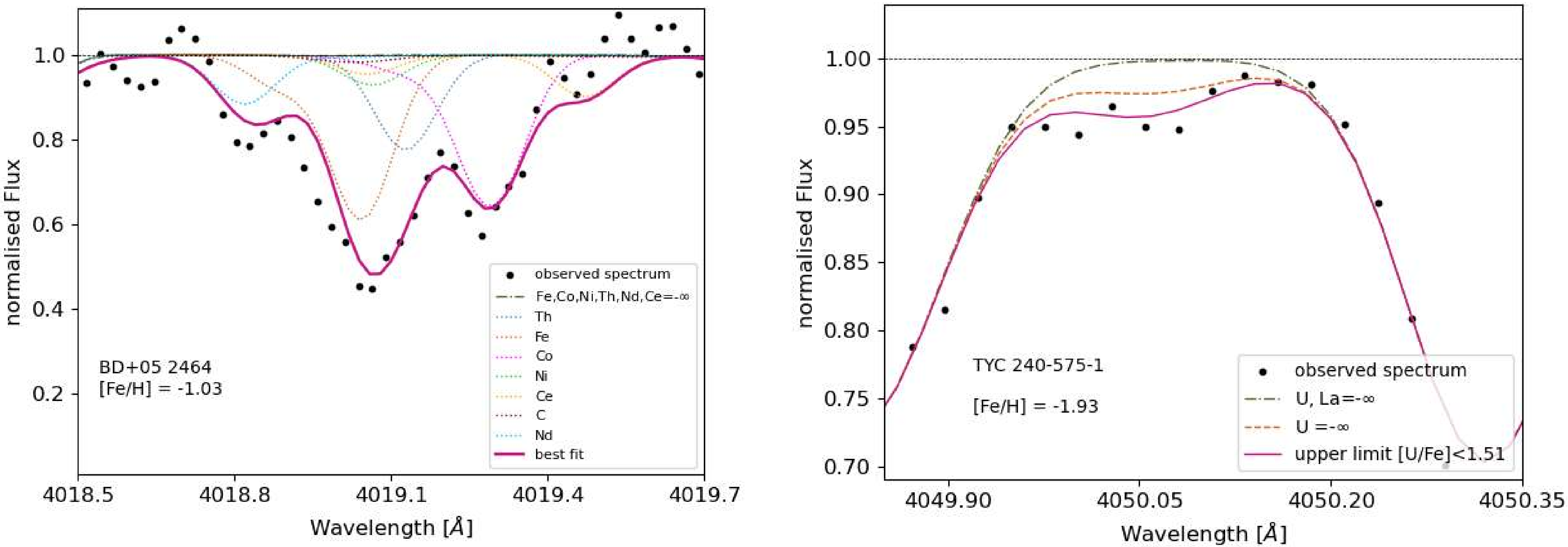
We need accurate atomic data in addition to good stellar spectra and parameters!



Clara Peter

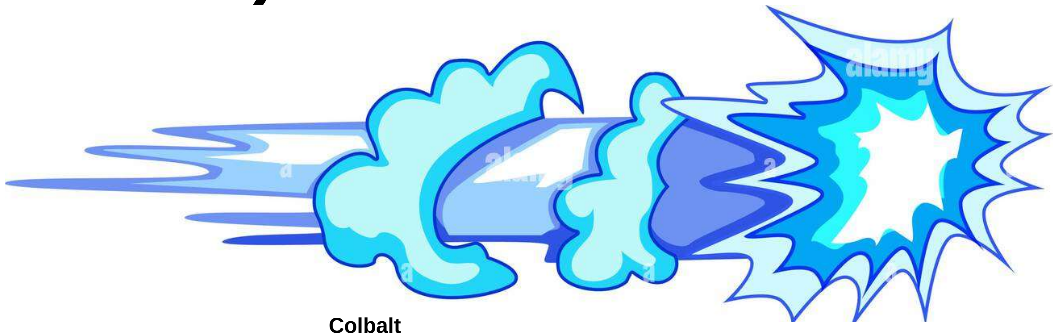
Th and U – blue spectra

Plonka, Peter, CJH, et al. In prep



Better SNR, resolution, and sampling needed to improve spectra

But there is Hope (& Jason) – blue laser



- **Atomic Physics collaboration:**

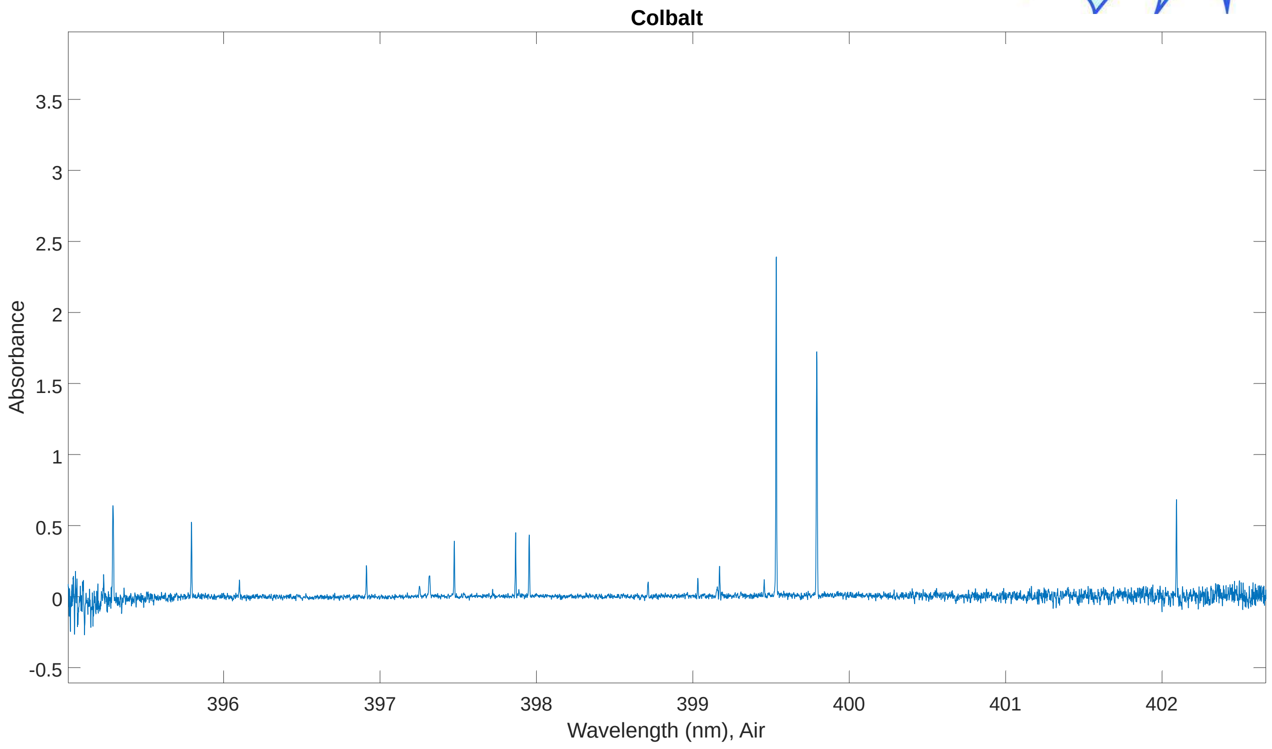
  Hope and Jason Univ. of Arizona

  Dual-combs for spectroscopy

- Explore loggf of Fe and Co blends in wavelength range 395.5- 403nm (can be expanded) →

- To Do:

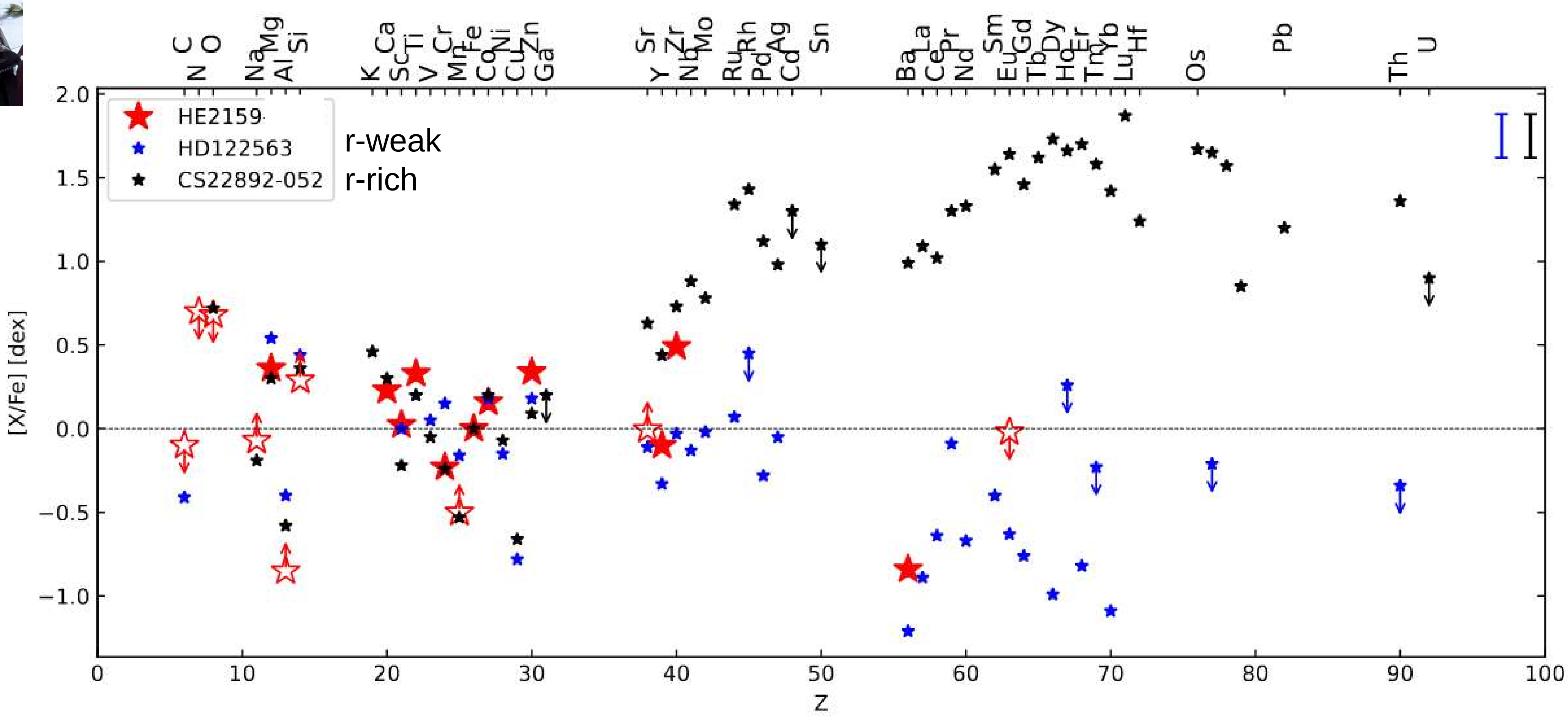
  Higher SNR, and test Ni, Fe



A peculiar star

Schichtel et al. 2025

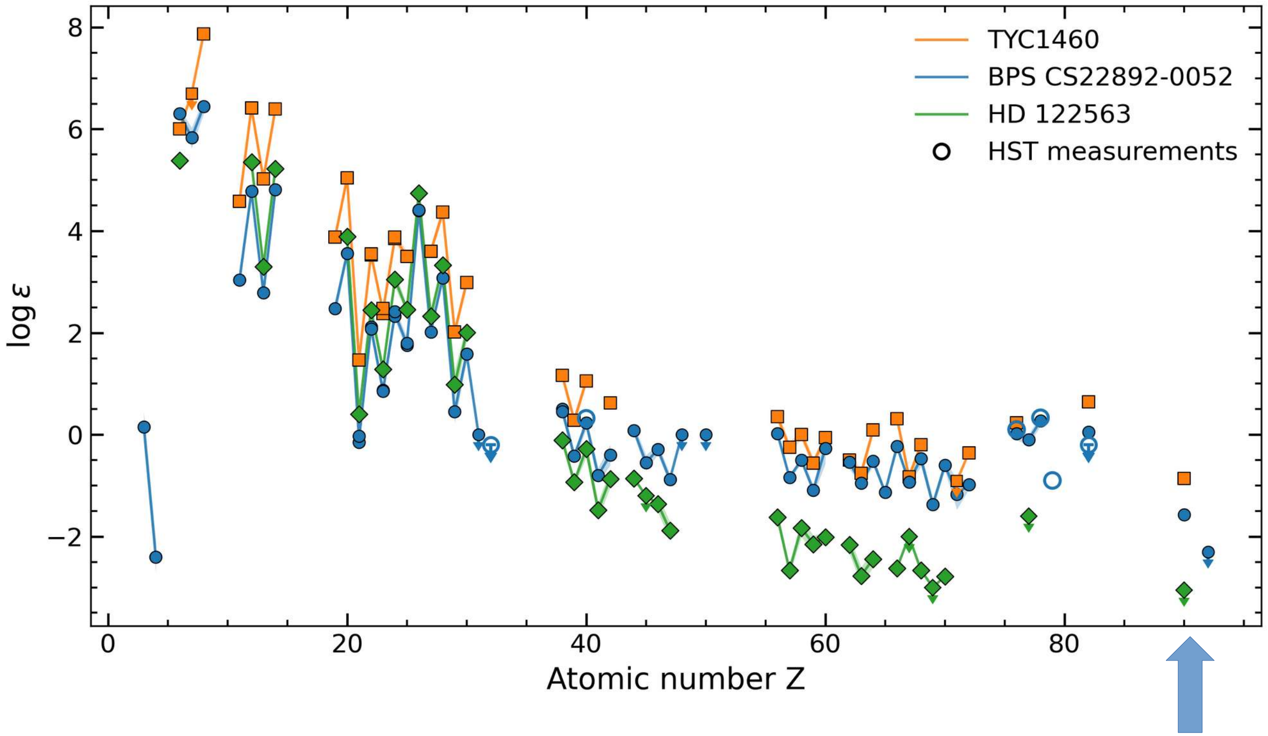
Annika
Schichtel
PhD student



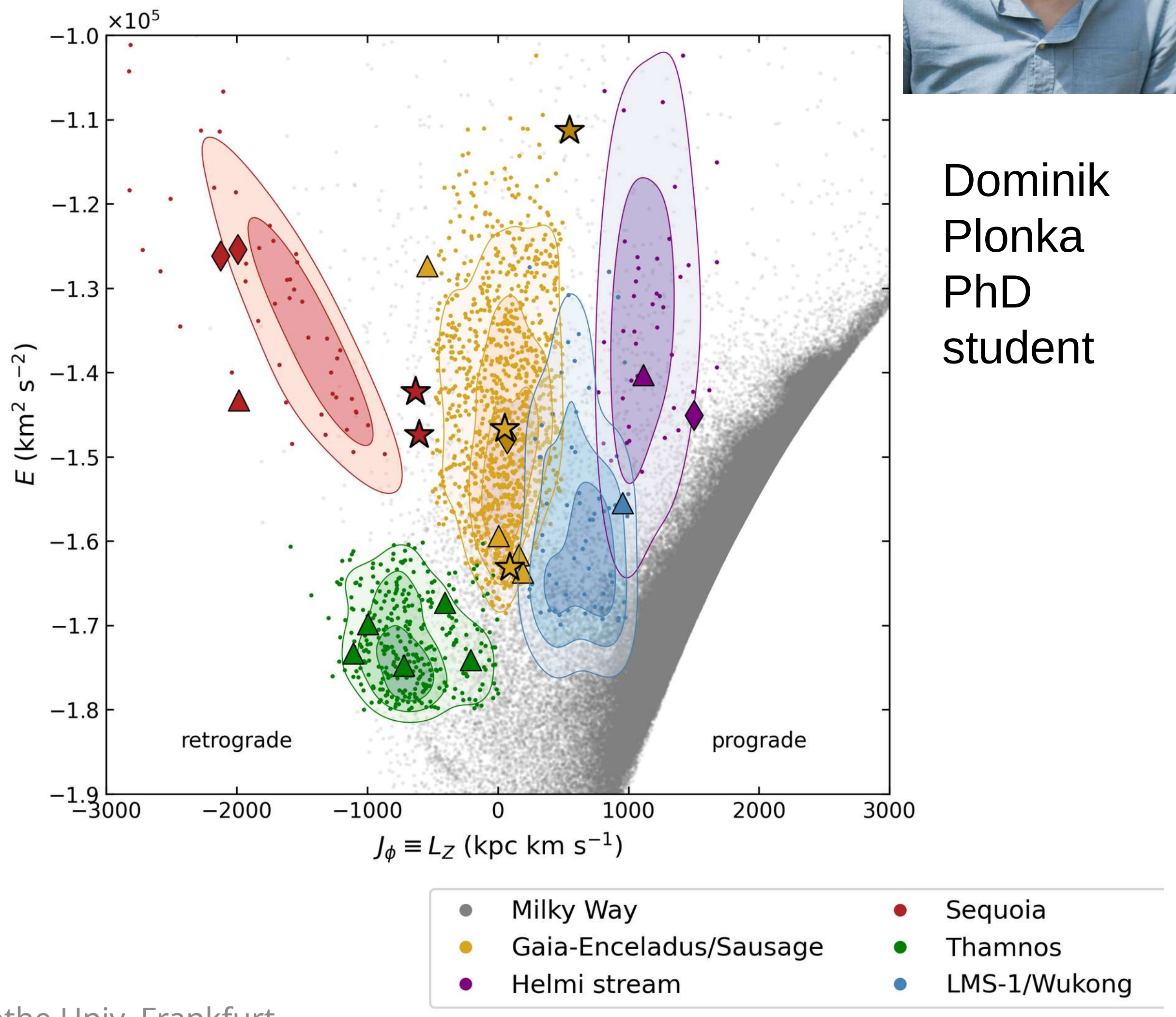
Kinematics & Peculiar stars

Plonka in prep. (CERES VI)

CERES sample compared to GALAH data



Actinide boost stars – but what about Th???



Dominik Plonka PhD student

Future spectrographs

CUBES (VLT)

R ~20.000
Sampling: 2.35
λ ~ 305-4(2)0nm

Limiting mag~17.5

(Hansen et al. 2022, Corvino et al. 2023, Geroni et al. 2024...)

HRMOS (VLT)

R ~60 – 80.000
4 arms
Sampling: 2.5
λ ~ 380-420nm → Th
SNR ~50 @ 15.5mag

(Magrini et al. 2023, ...)

ANDES (ELT)

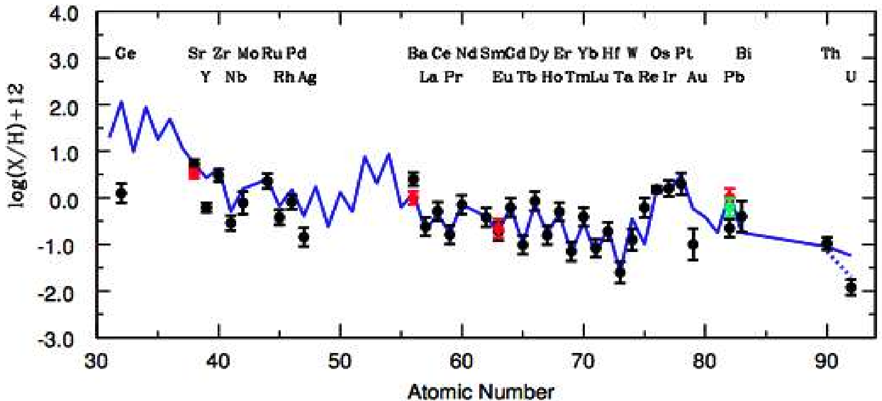
R ~100.000
λ~400-1800nm (350-2400nm) → Th
Magnitude: 17-18
For SNR ~50

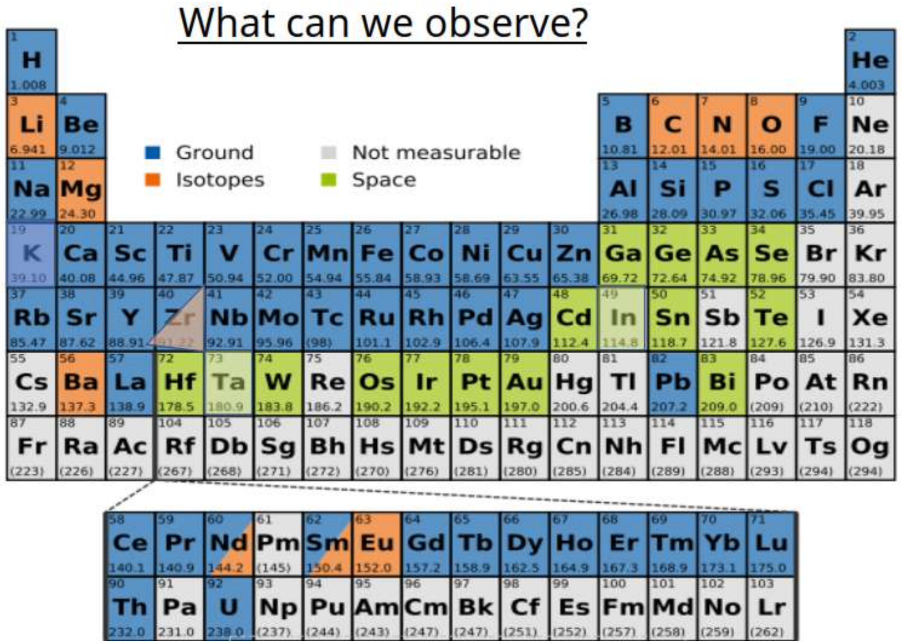
(Marconi et al. 2024, Roederer et al. 2024, ...)

Summary

Through high-resolution (HR) spectroscopy we can explore:

- Stellar evolution and self-enrichment
- Early GCE
- Nuclear formation processes
- Need for atomic physics
- Heavy elements for stellar ages – need elements close together – and accurate abundances (+/-0.1dex → +/-2 Gyr)
- Need more blue (HR) spectrographs





Goals and limitations:

- More complete patterns
- Missing atomic data (1D)
- 3D, NLTE (atomic data)
- 4MOST/4DWARFS
- ELT, CUBES, HST + smaller follow-up surveys needed…