From stellar observations to nuclear reactions

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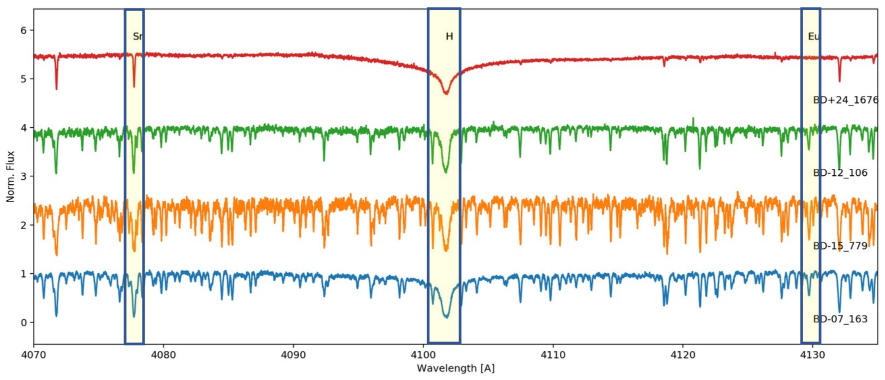
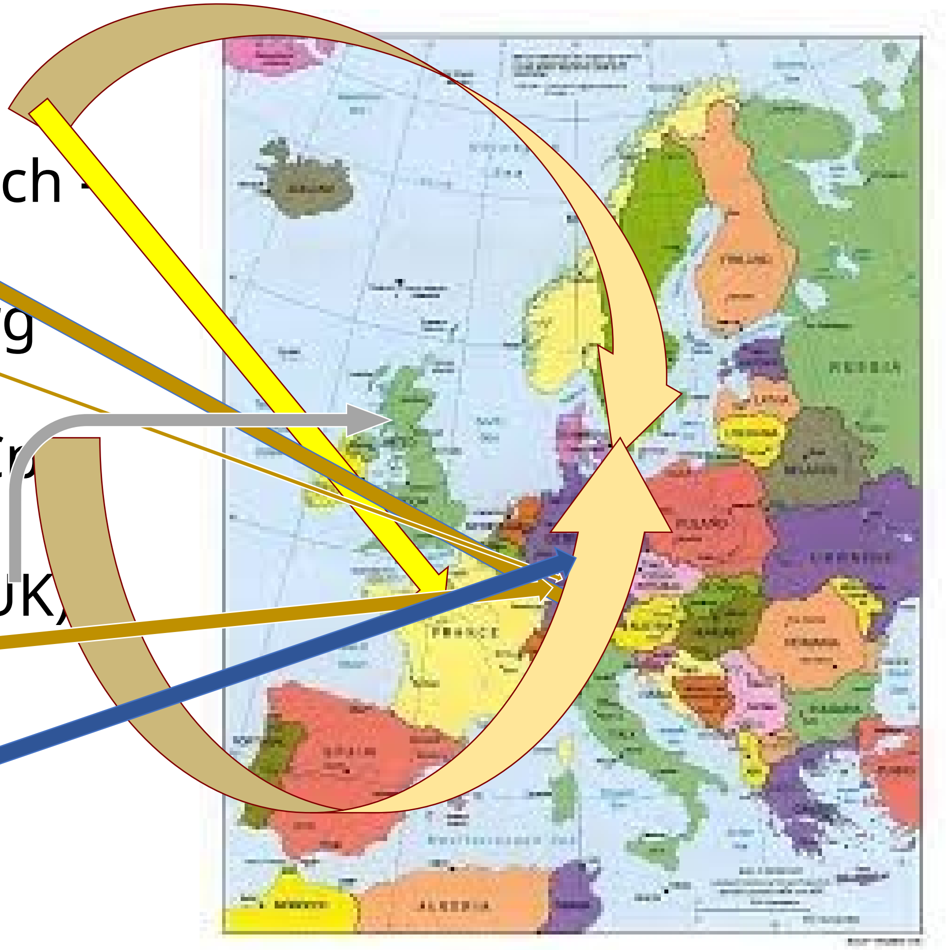
Outline

- Stellar observations
- Stellar parameters and abundan
- Tracing nuclear formation proce
- Chemical evolution



Who am I?

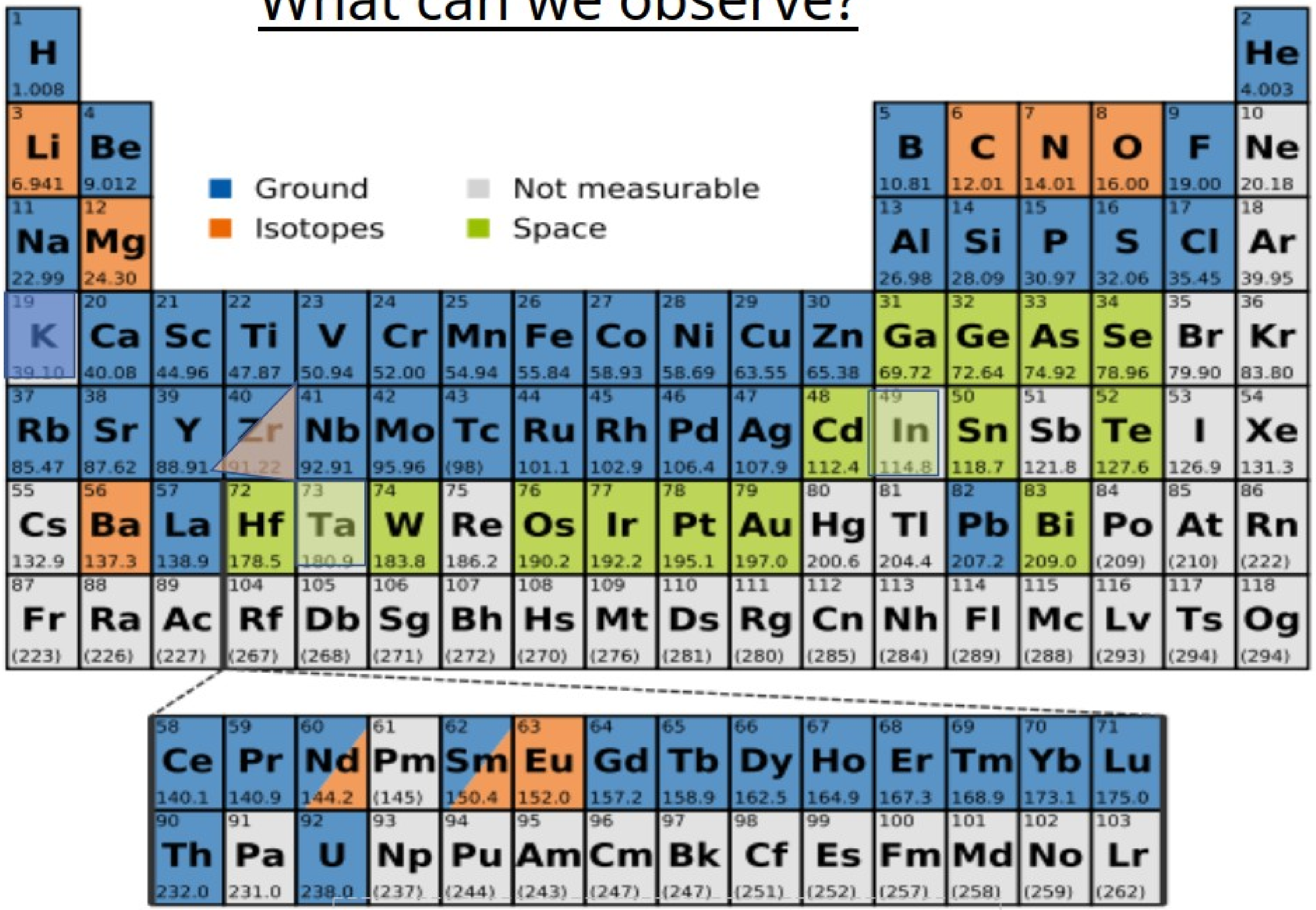
- MSc in Astrophysics (NBI, Cph+Paris)
- PhD in Astrophysics (ESO, Munich - spectroscopy Ag+Pd weak r)
- Postdoc (`Milky Way', Heidelberg Uni)
- Fellow @ Niels Bohr Ins. (NBI, Cph Nucleosynthesis+kilonova)
- Science visitor (Lancaster Uni, UK)
- Postdoc MPIA (Heidelberg)
- Staff Technical Uni. Darmstadt
- Prof. IAP, Frankfurt



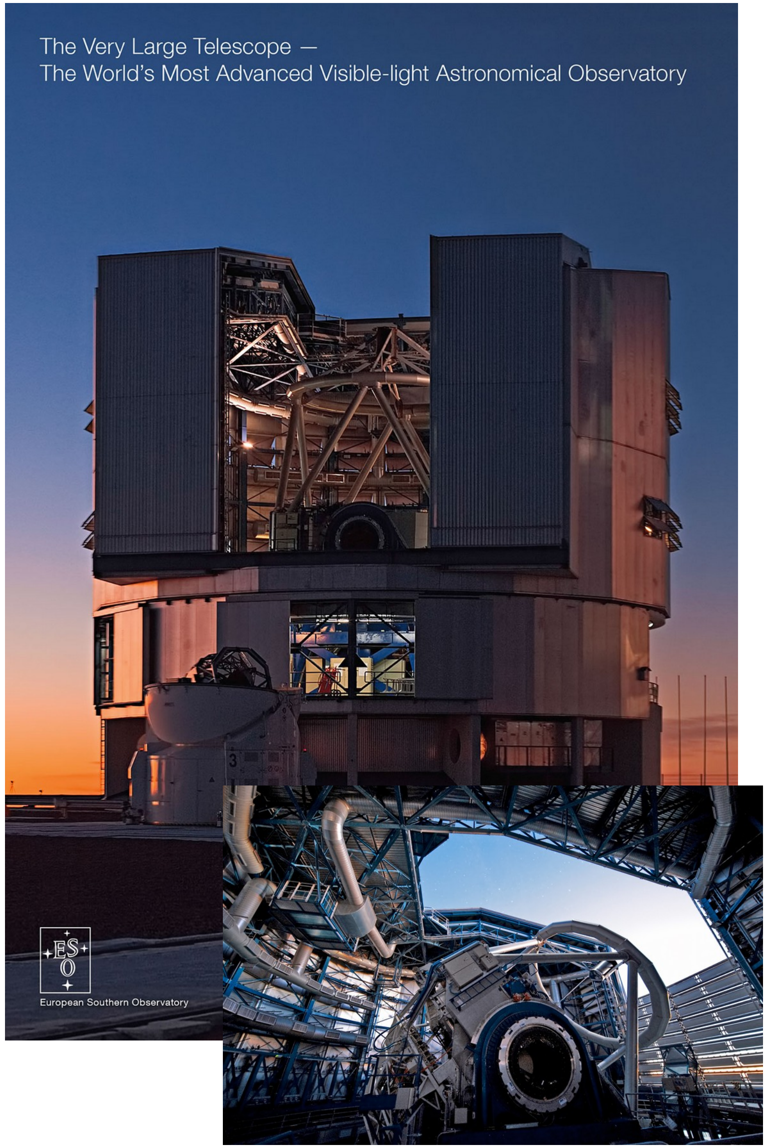
Camilla Juul Hansen

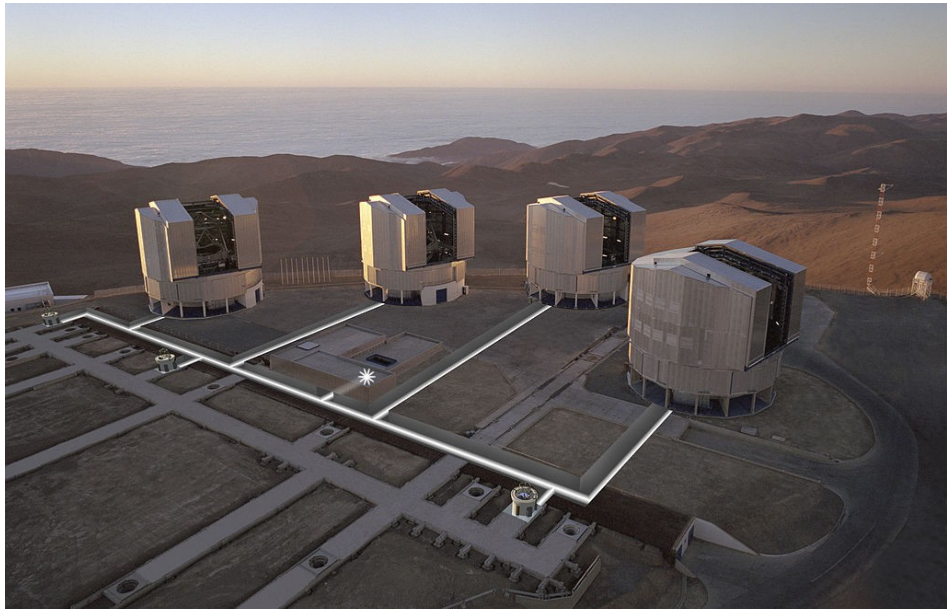
The Night sky

What can we observe?



Observing remote stars…





"Aerial View of the VLTI with Tunnels Superimposed" by ESO - ESO. Licensed under CC BY 4.0 via Commons - https://commons.wikimedia.org/wiki/File:Aerial_View_of_the_VLTI_with_Tunnels_Superimpose

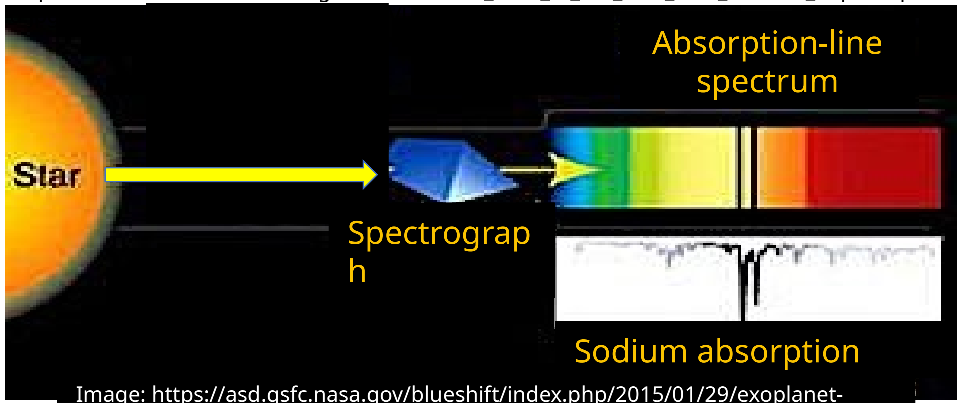


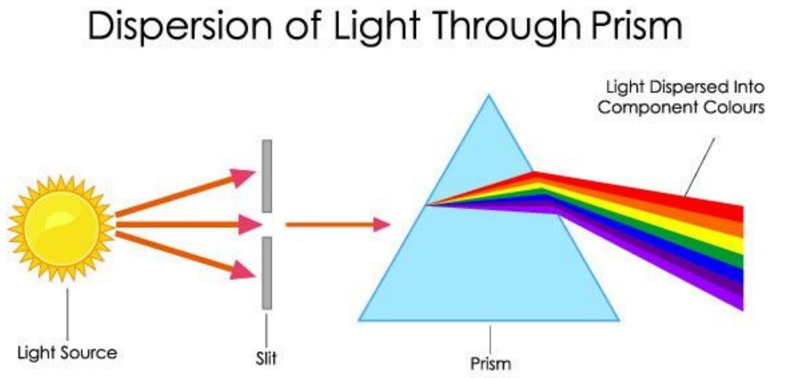
Image: https://asd.gsfc.nasa.gov/blueshift/index.php/2015/01/29/exoplanet-weather/

More on instruments → SNAQs by H. Korhonen https://www.youtube.com/watch?v=IFUNy9TnNz0

Spectral analysis

Kirchhoff & Bunsen ~1860

Image: H. Roscoe; https://www.uni-heidelberg.de/de/newsroom/laboratorien-kirchhoff-und-bunsen-werden-historische-erinnerungsstaette-der-physik



https://lab-training.com/2017/09/26/understanding-of-light-dispersing-elements-in-a-spectrometer/

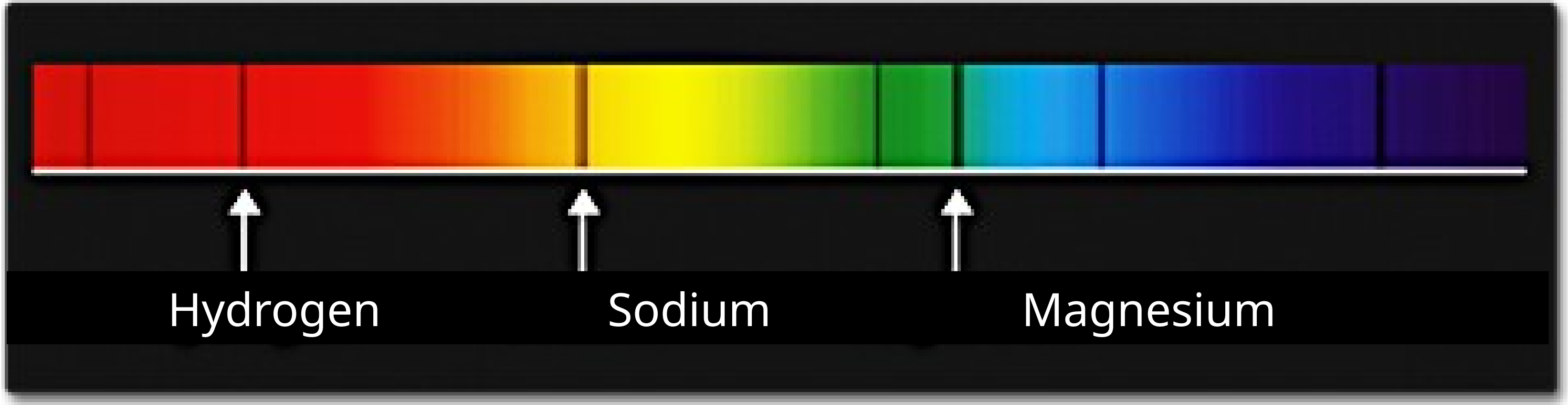


Image: https://science.nasa.gov/ems/09_visiblelight

Our reference star – the Sun

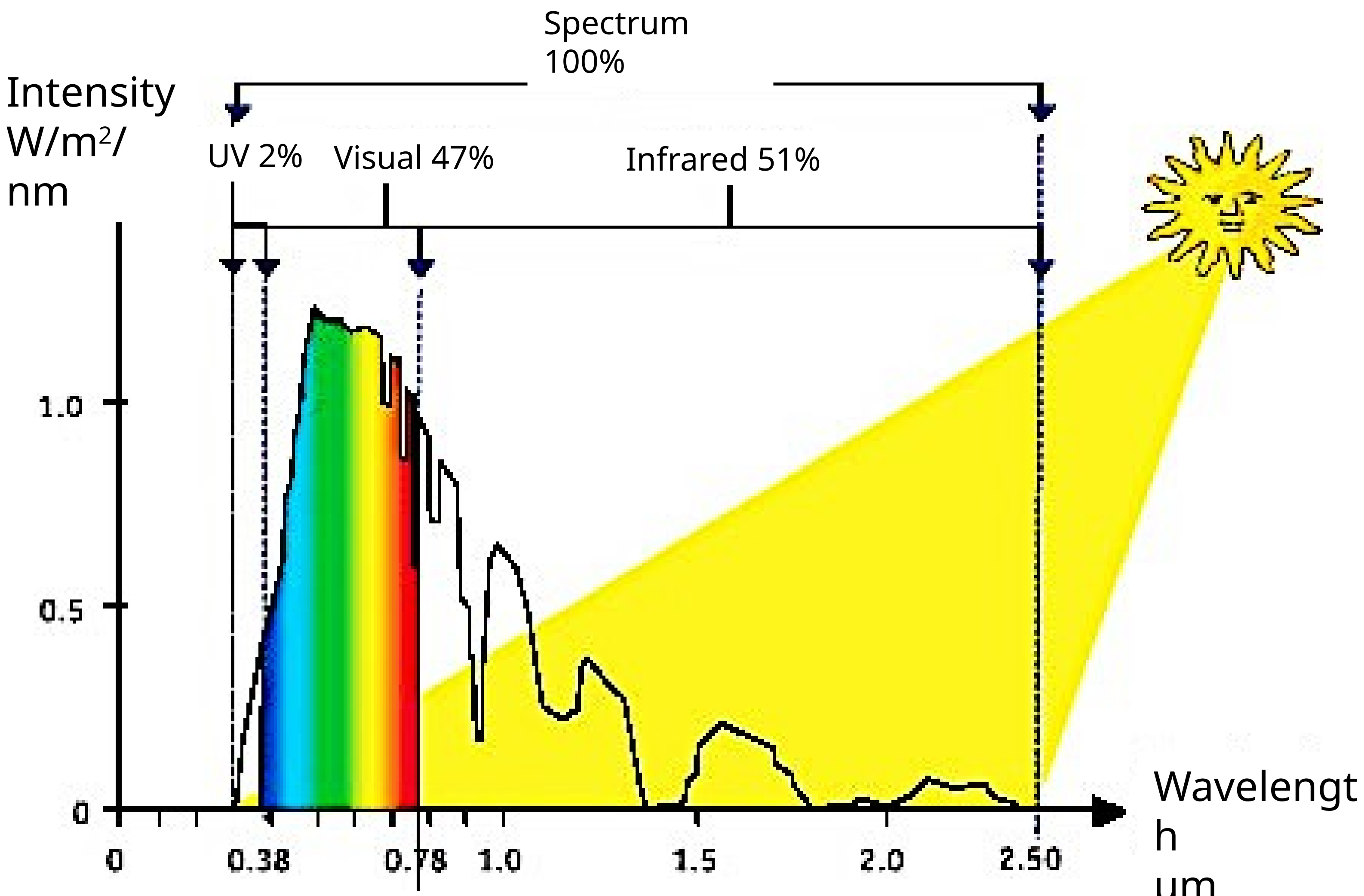
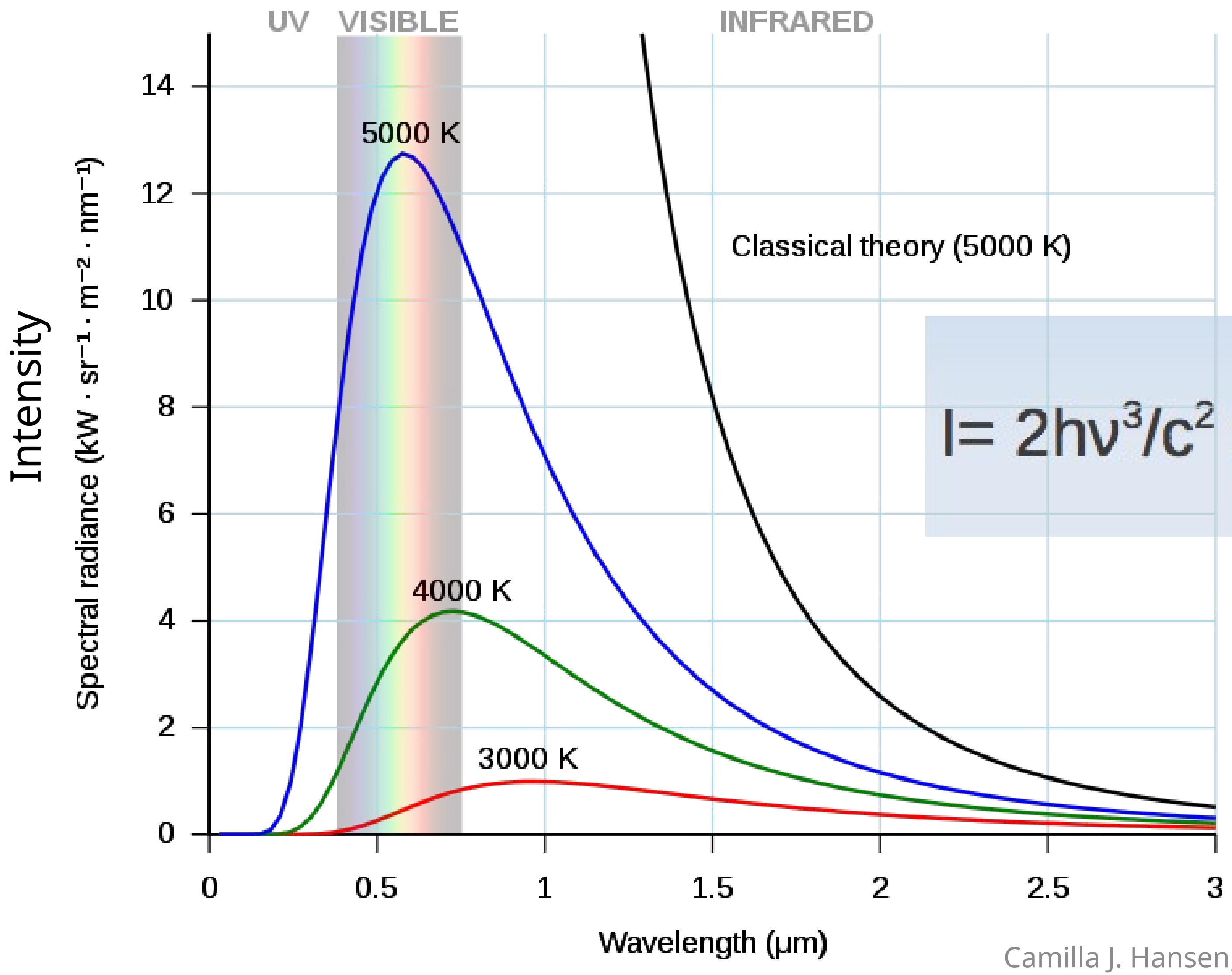


Image: scottamyx.com, https://bestleader-intl.weebly.com/solar-energy-and-solar-window-film.html

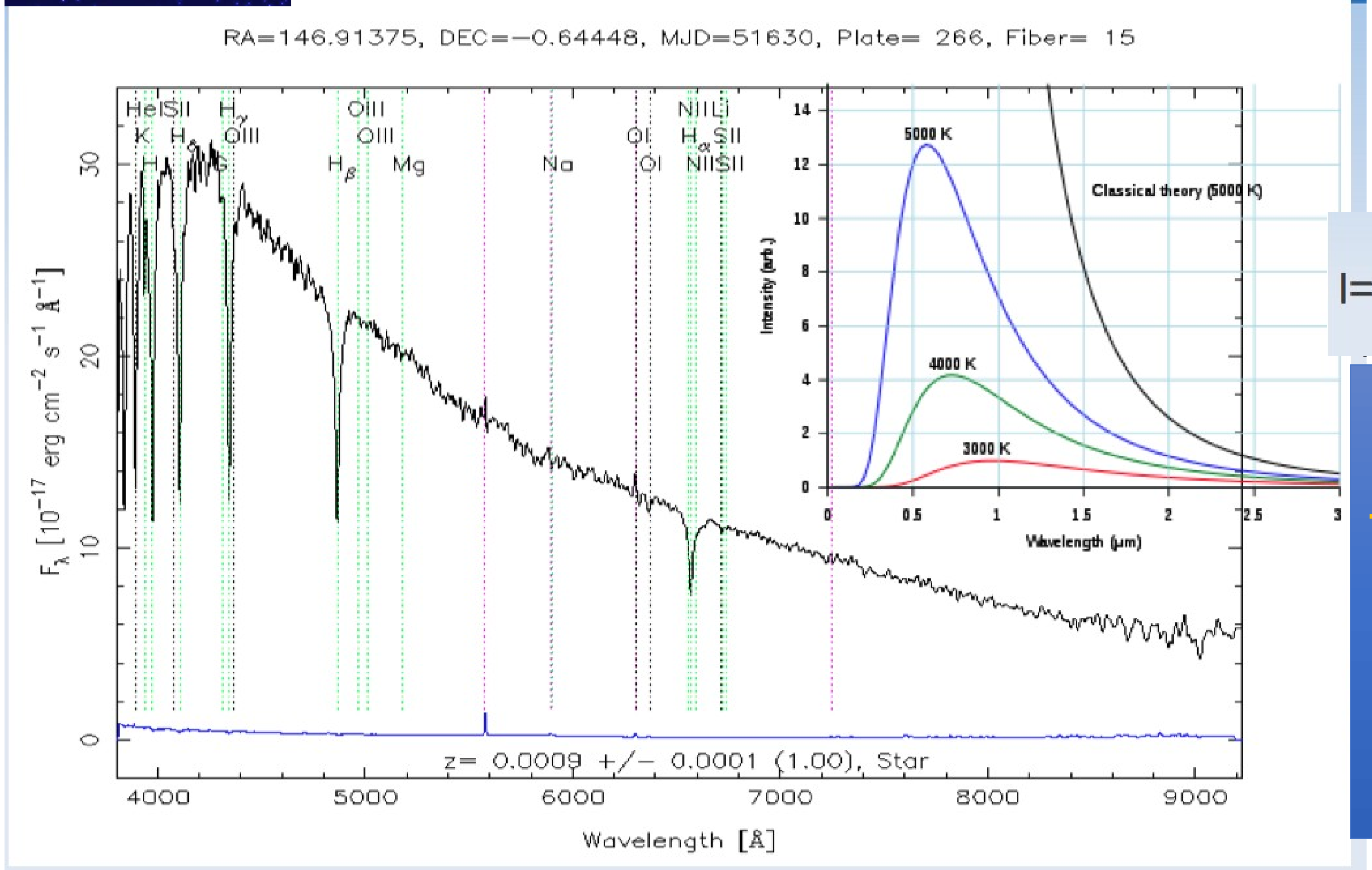
Temperature in Stars



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

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:

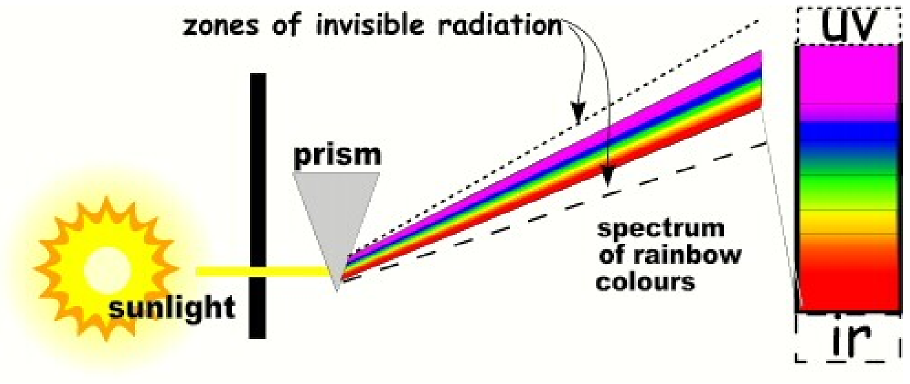
Temperature

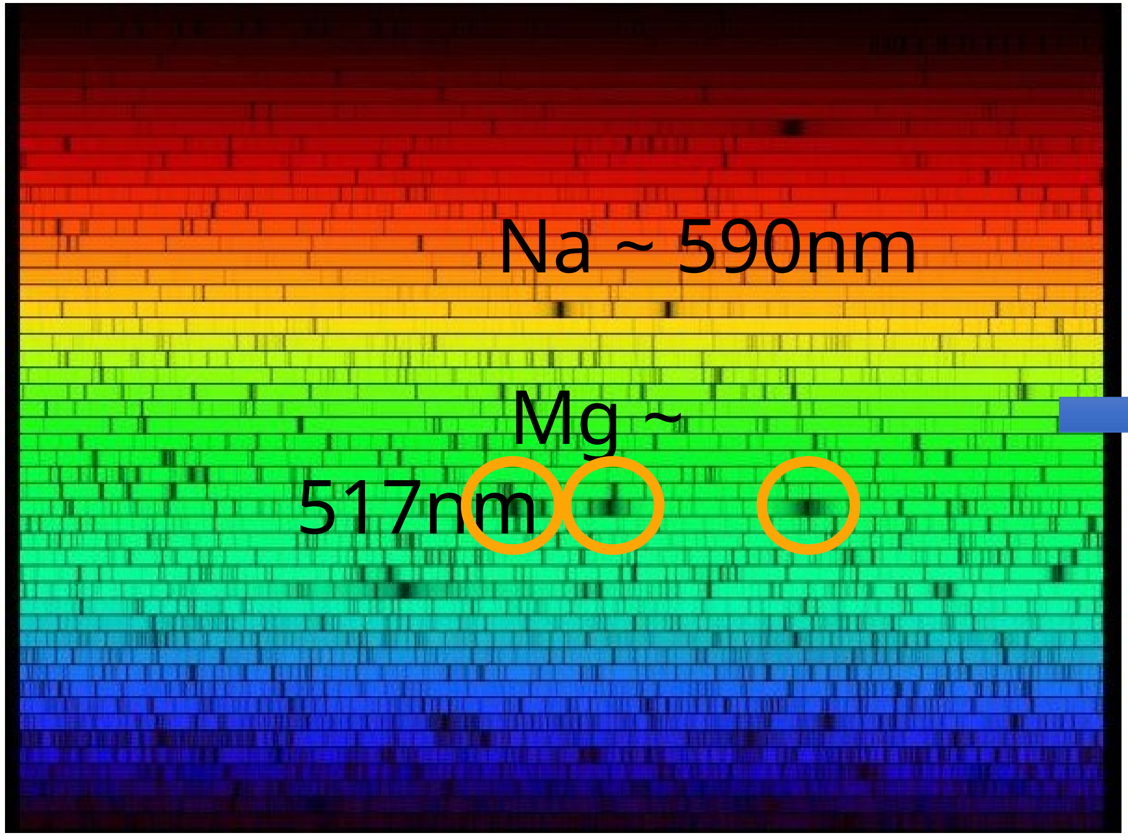
Pressure

'Metallicity'

Chemistry

Spectral analysis
&
Data reduction





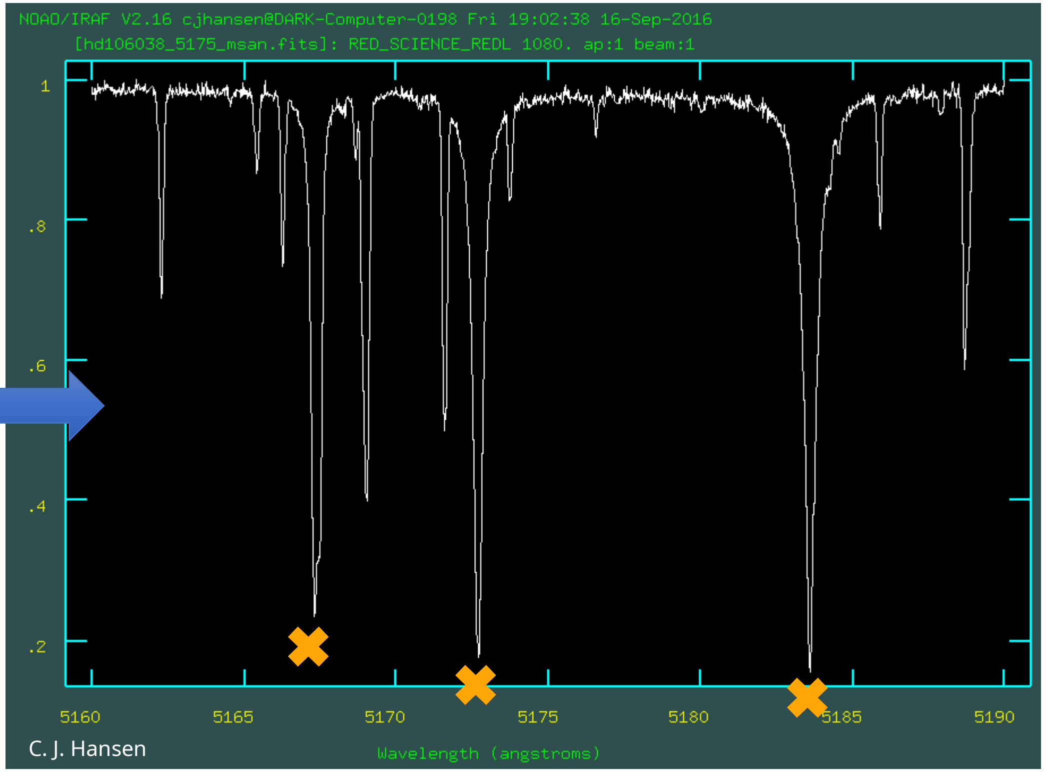
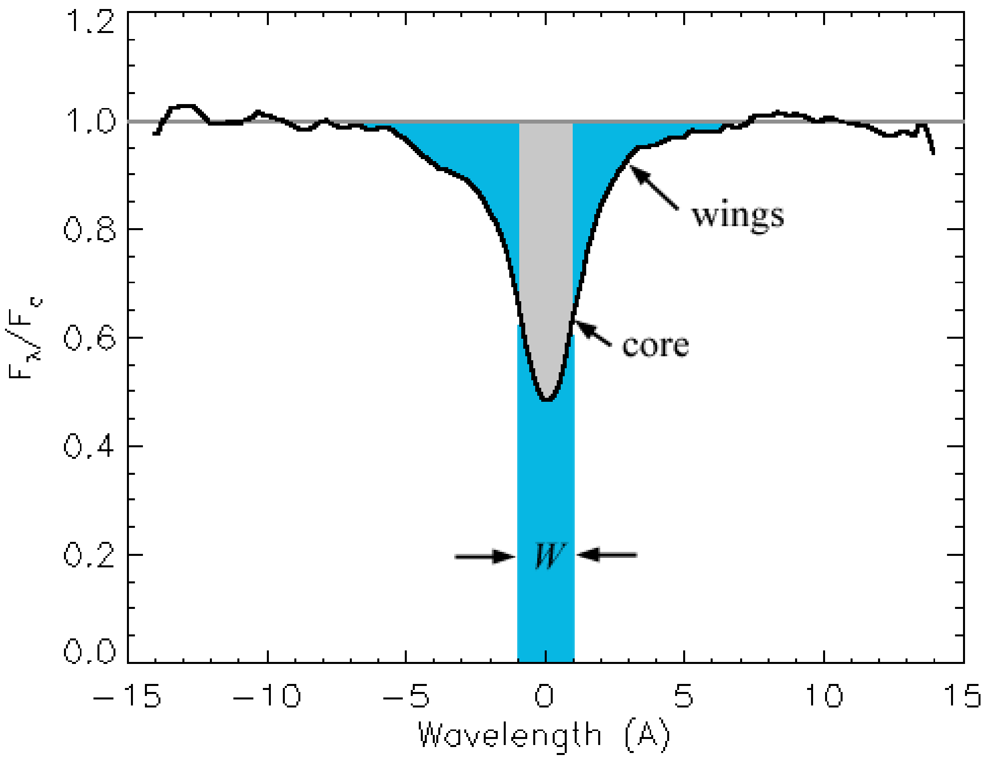


Image:

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)



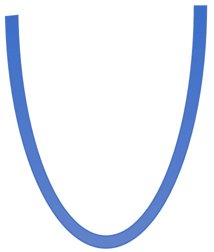
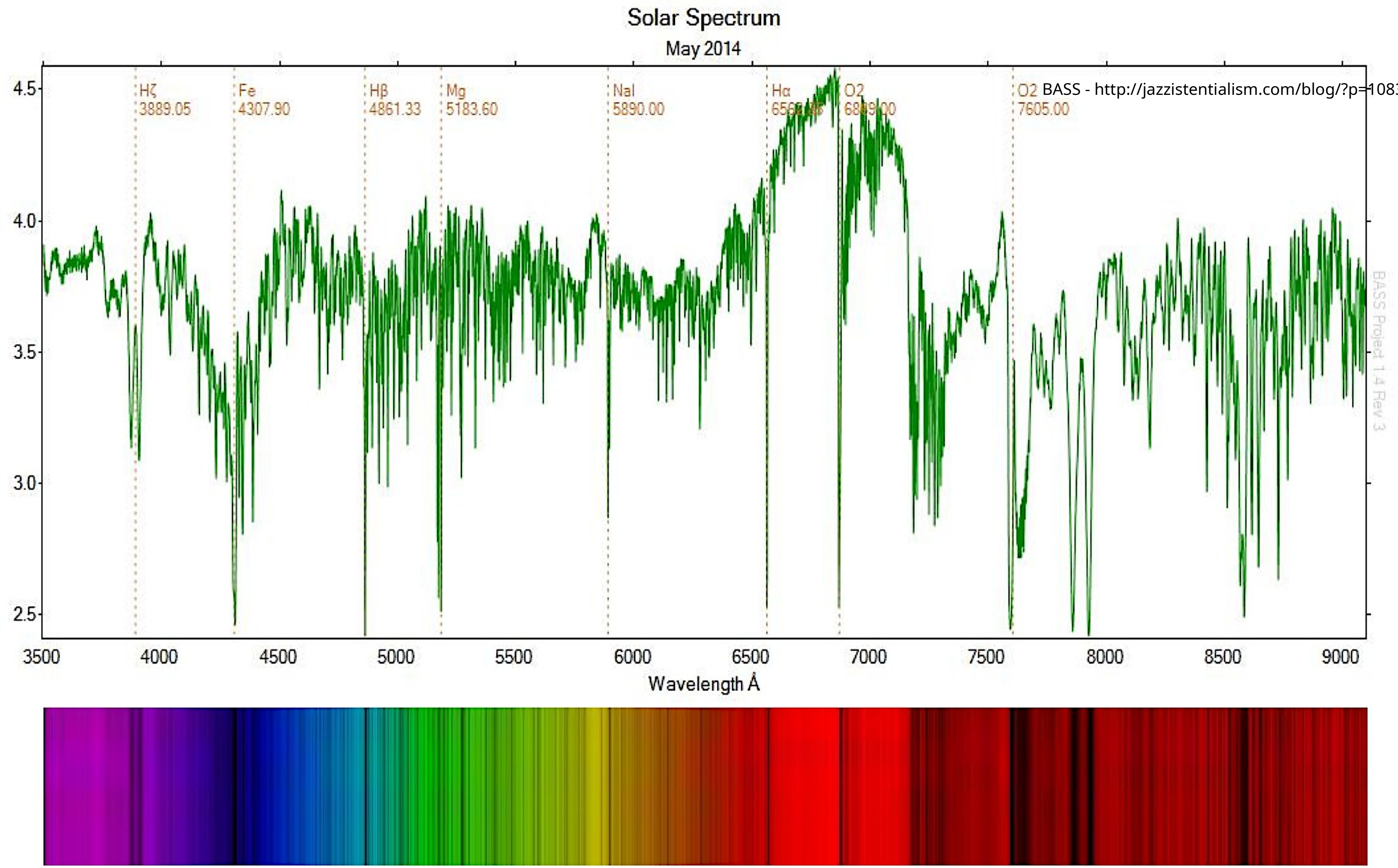


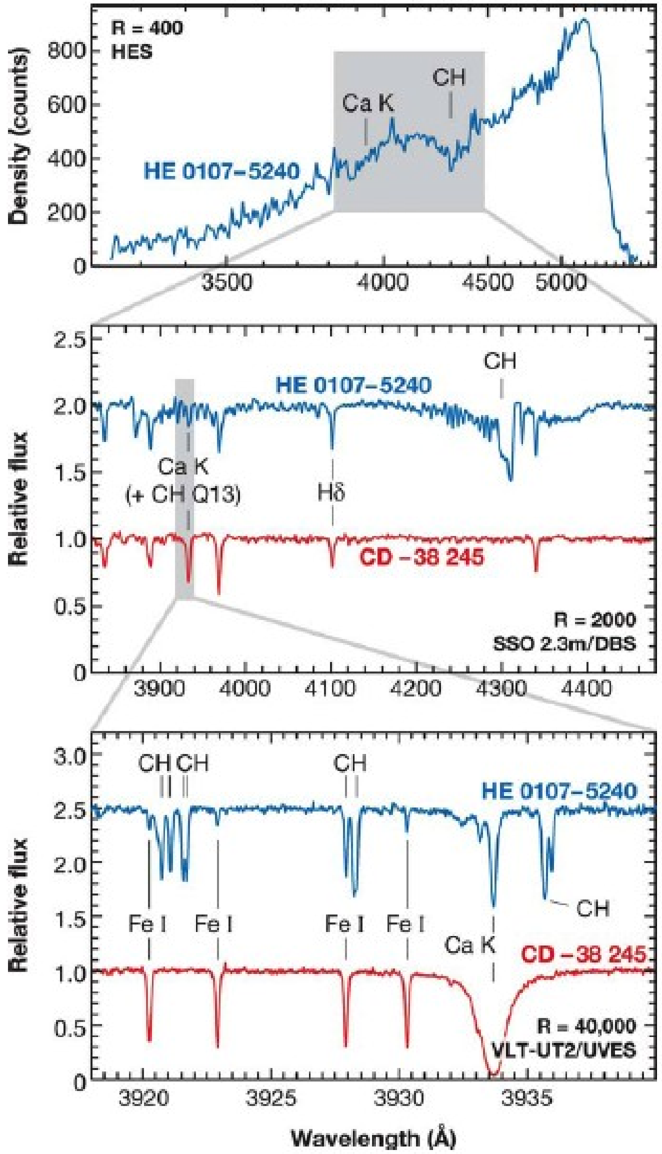
Image: http://www.bdnyc.org/2012/03/spectral-line-measurements-visualized/

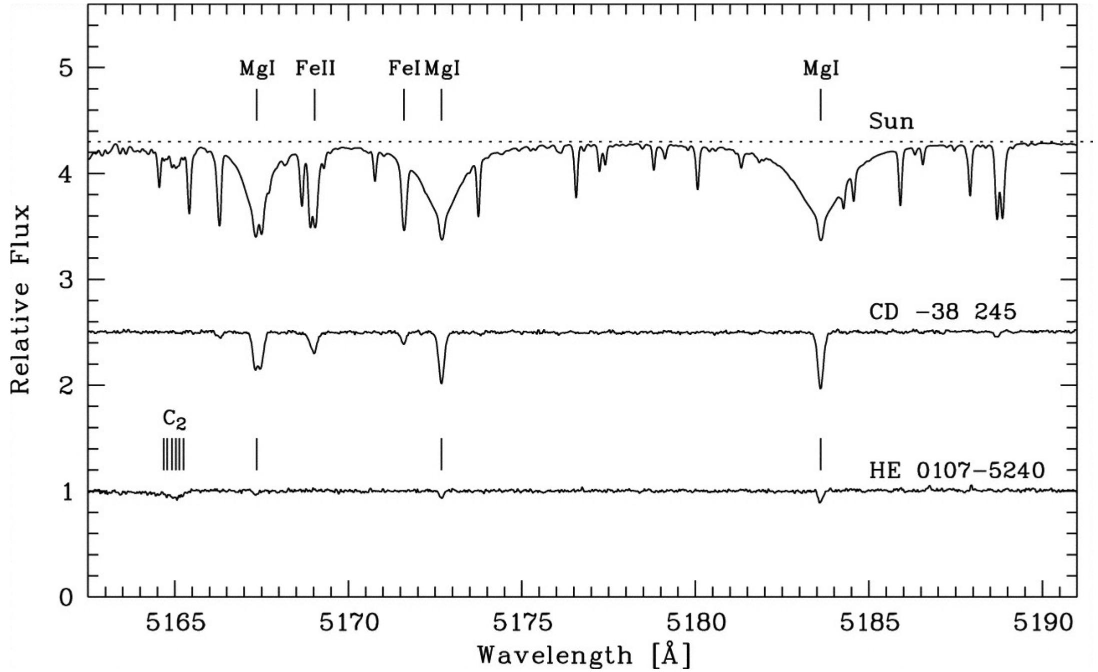
Solar spectrum & Information



BASS - http://jazzistentialism.com/blog/?p=1083

Old stars vs the Sun

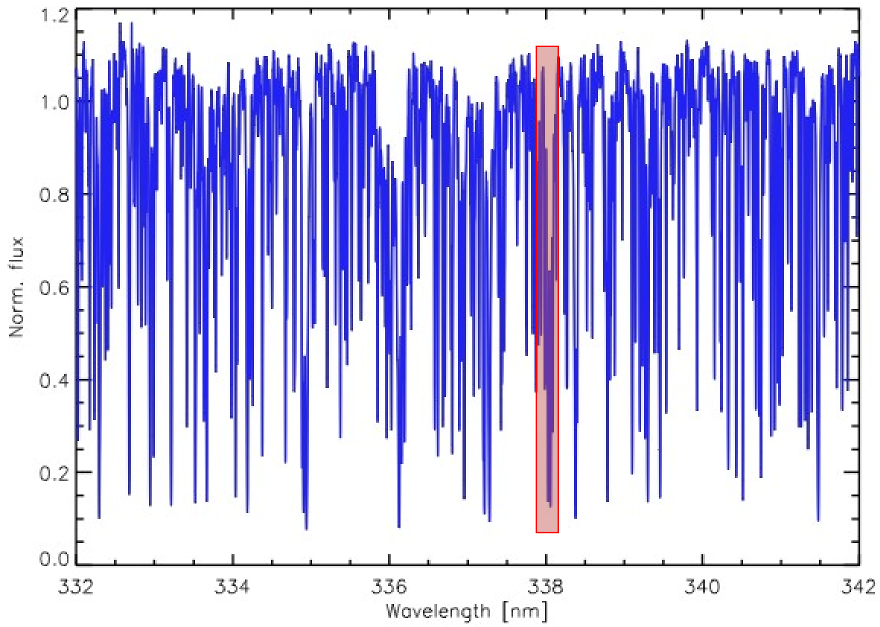


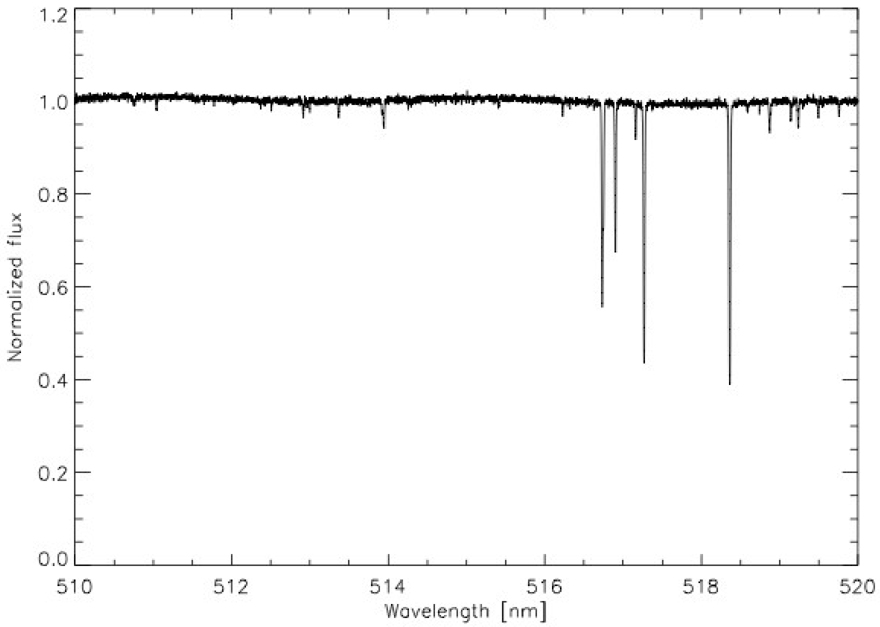


Beers & Christlieb 2005, ARA&A

Spectral analysis

Blue vs visual spectra

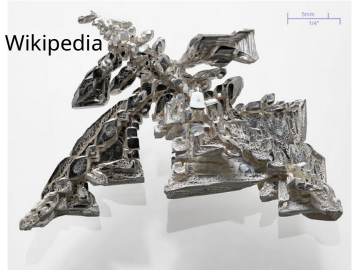




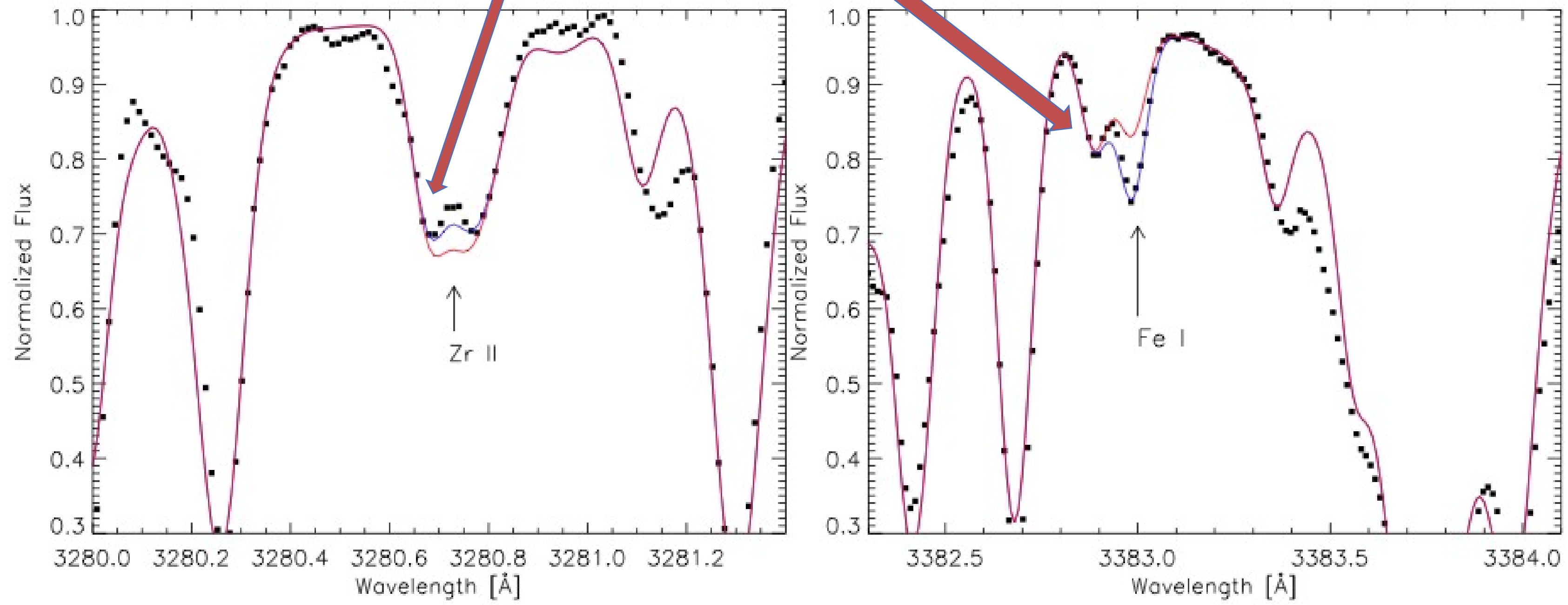
Images: C. J. Hansen

Analysing UV-Linies

Wikipedia



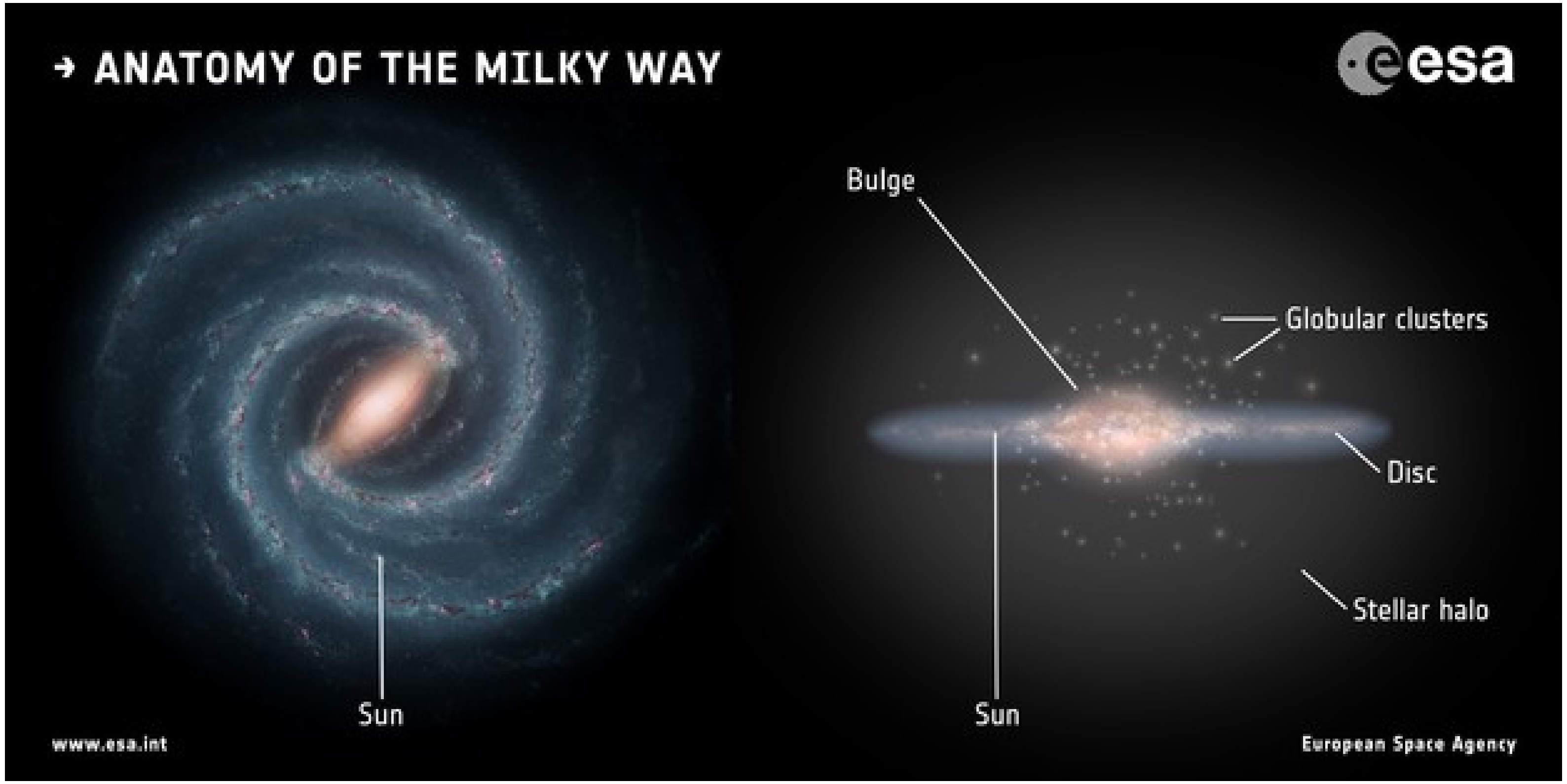
Silver (Ag, Nr. 47)



Hansen et al. 2012

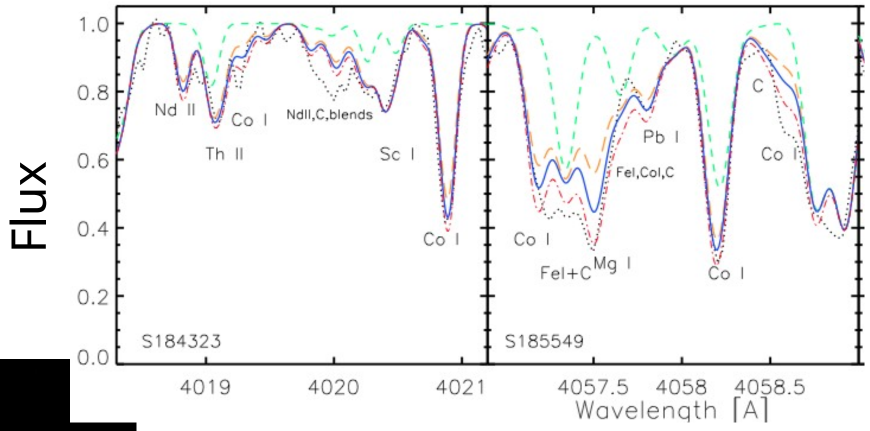
The Milky Way and its stars

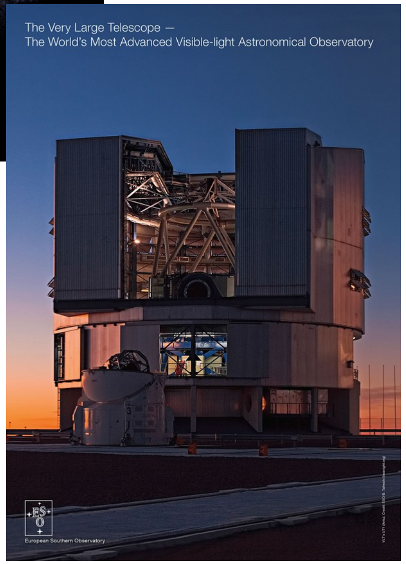
- Tracing the r-process is easiest in old metal-poor stars → chemically speaking simpler
- Major components: Halo, disks, bulge
- Old stars in halo & bulge
- Observational pros/cons



Old Stars

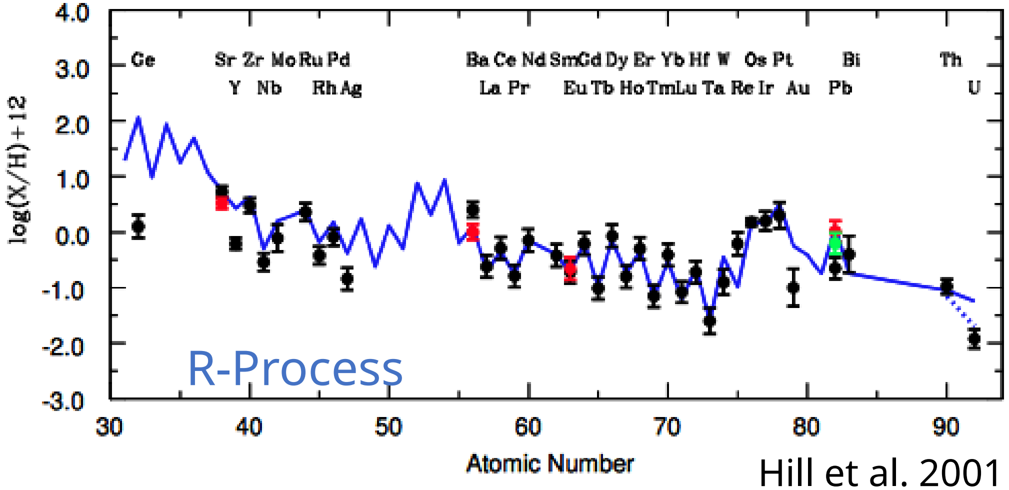
Hansen et al. 2018





Th & Eu → Age

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.



Hill et al. 2001

Spectral analysis

Tools of the astronomer/ spectroscopist:

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

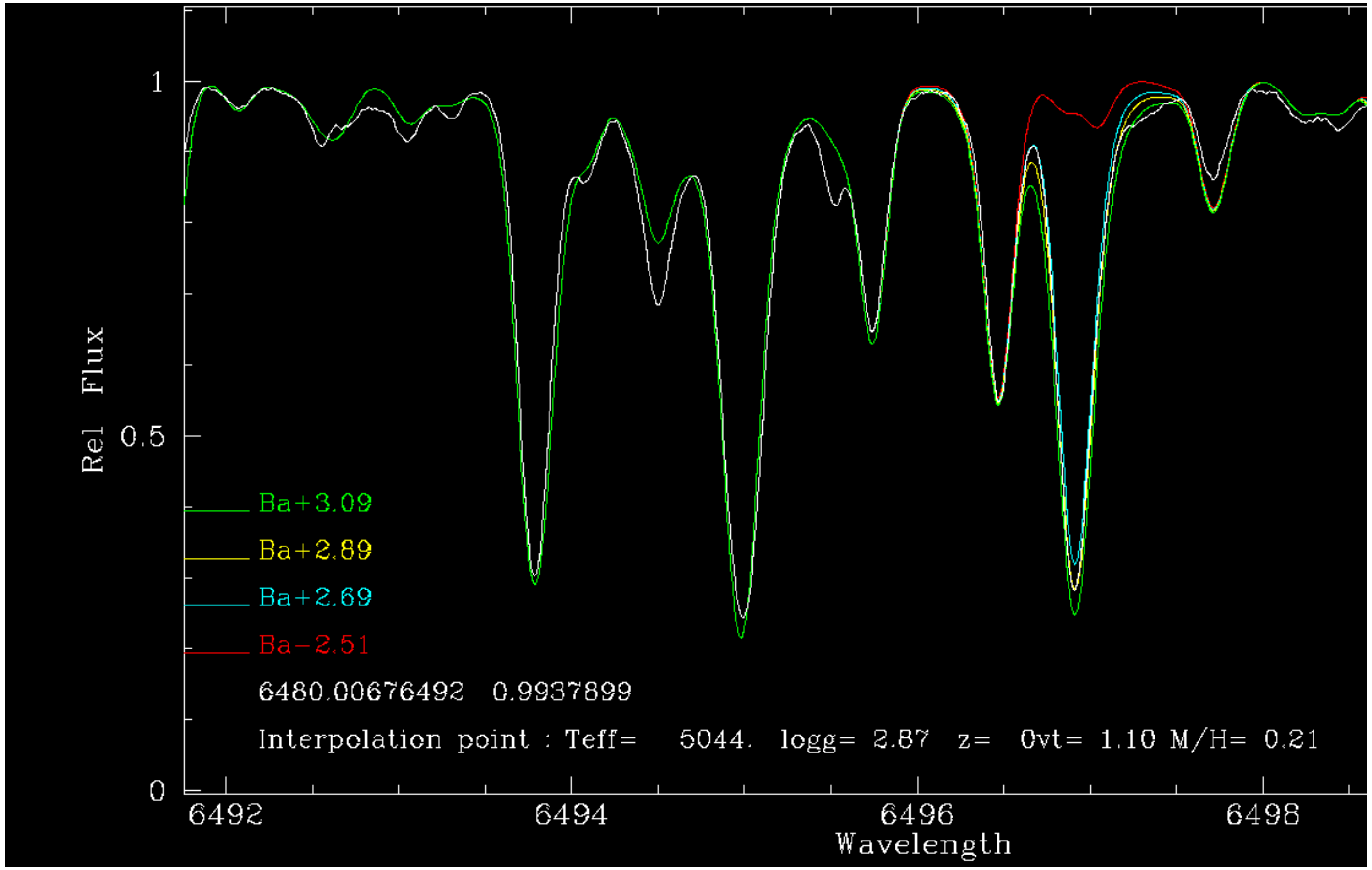


Image: C. J. Hansen

Questions

- How can we derive stellar temperatures from a spectrum?

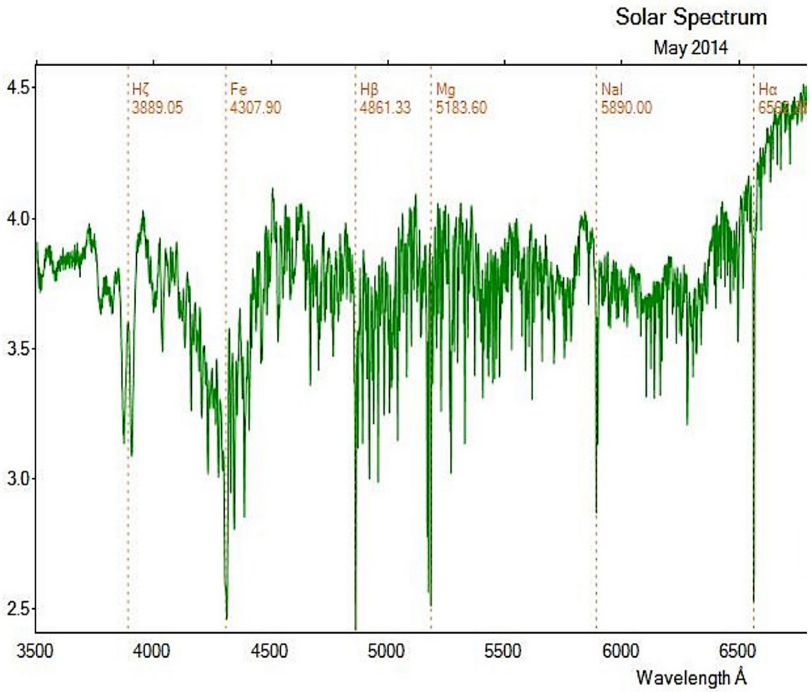
- What can we learn from a stellar spectrum in general?

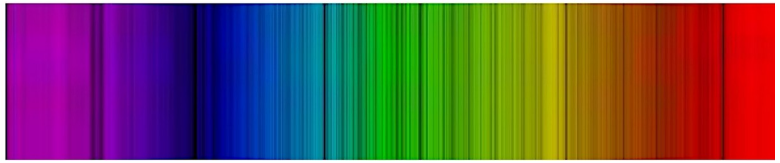
- Where can we easiest observe stars (where is it not easy)? Why?

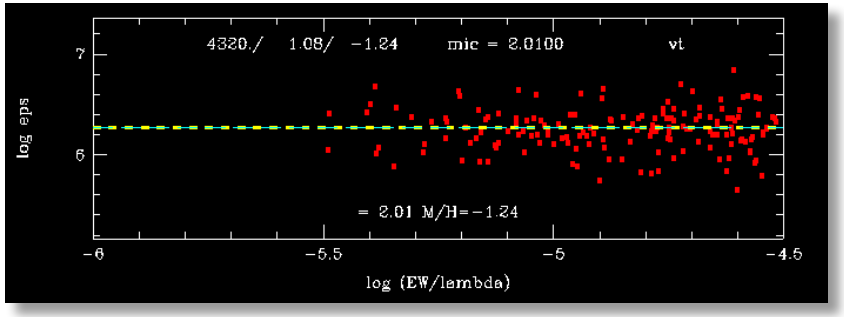
- Which 2-3 things should we always think about before observing?

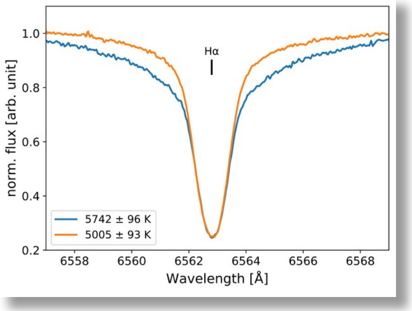
Stellar parameters

- Temperature: T
- Gravity: logg
- Metallicity: [Fe/H]
- Microturbulence: Vt (or ξ)









What does a star's colour tell us?

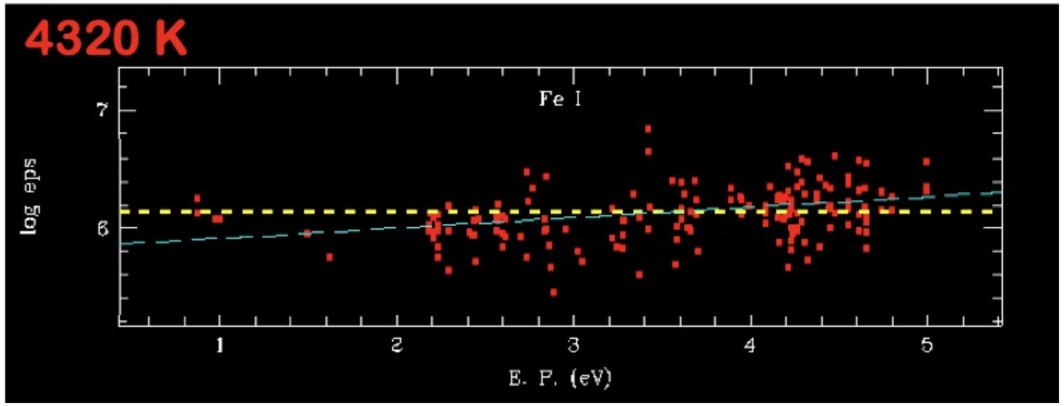
Temperature

- Photometry (InfraRed Flux

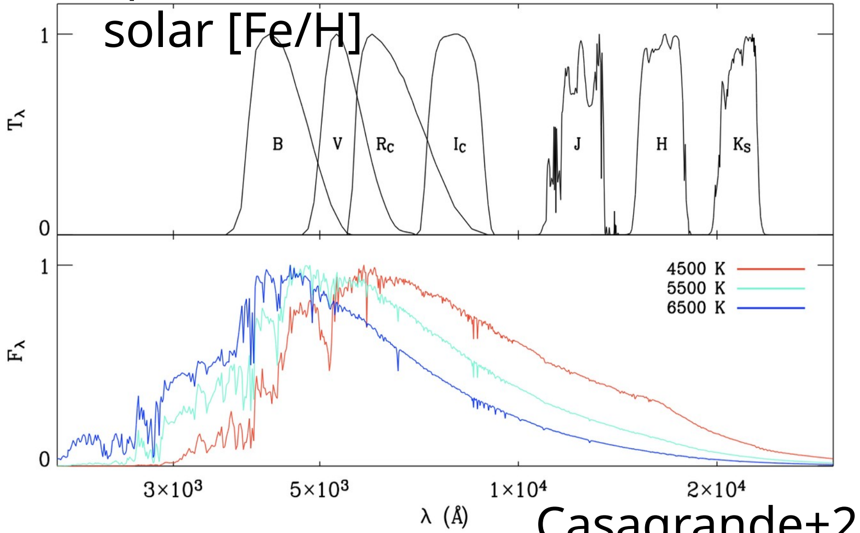
$$\theta_{\rm eff} = a_0 + a_1X + a_2X^2 + a_3X[\mathrm{Fe/H}] + a_4[\mathrm{Fe/H}] + a_5[\mathrm{Fe/H}]^2$$

where $\theta_{\rm eff} = 5040/T_{\rm eff}$, X represents the colour

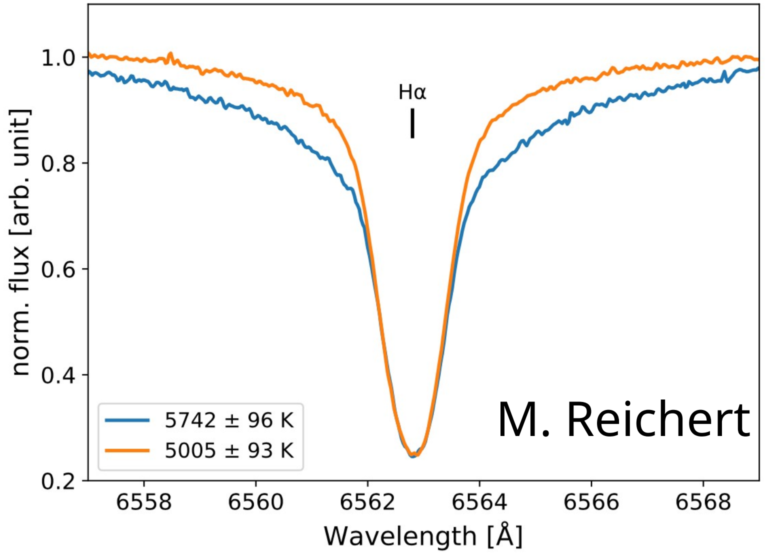
- Spectroscopy: T sensitive lines (Fe, H) – e.g., excitation potential balance wrt abundance.



Filters and black body spectra with different T but solar [Fe/H]



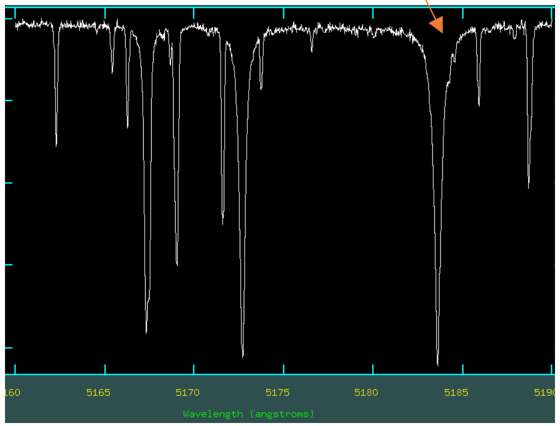
Casagrande+2010



M. Reichert

Gravity

Gravity ∝ pressure
$P_g \sim \text{const } g^{2/3}$



- Spectroscopic (Fe, Mg) – either fit Mg triplet wings or enforce ionisation balance (A(FeI) = A(FeII) - sensitive to Fe abundance assumption, LTE)

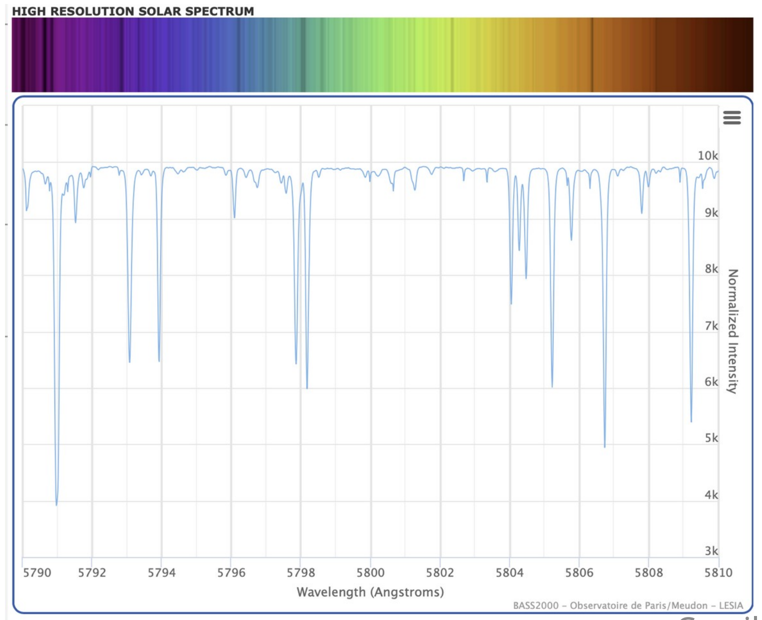
- Astrometry (parallaxes)

  depends on T, and mass, and bolometric correction (BC)

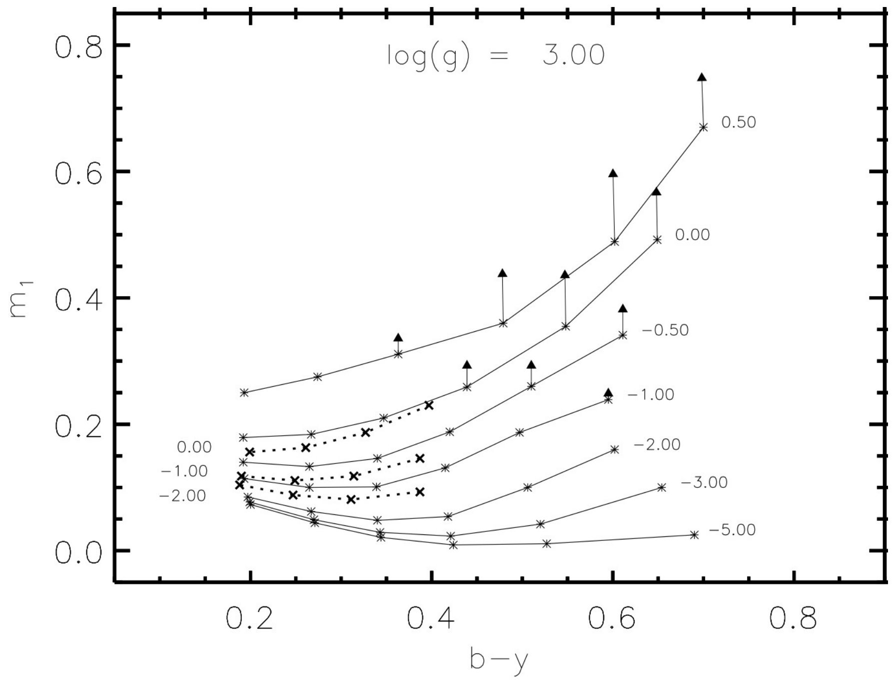
$$\log \frac{g}{g_\odot} = \log \frac{M}{M_\odot} + 4 \log \frac{T_{\rm eff}}{T_{\rm eff\,\odot}} + 0.4V_0 + 0.4BC + 2\log\pi + 0.12$$

Metallicity, [Fe/H]

- Photometry (Strömgren) – m1 vs *(b*
- Spectroscopy – EW of Fe lines – ave



BASS2000 high-res. Spectrum
https://bass2000.obspm.fr/solar_spect.php

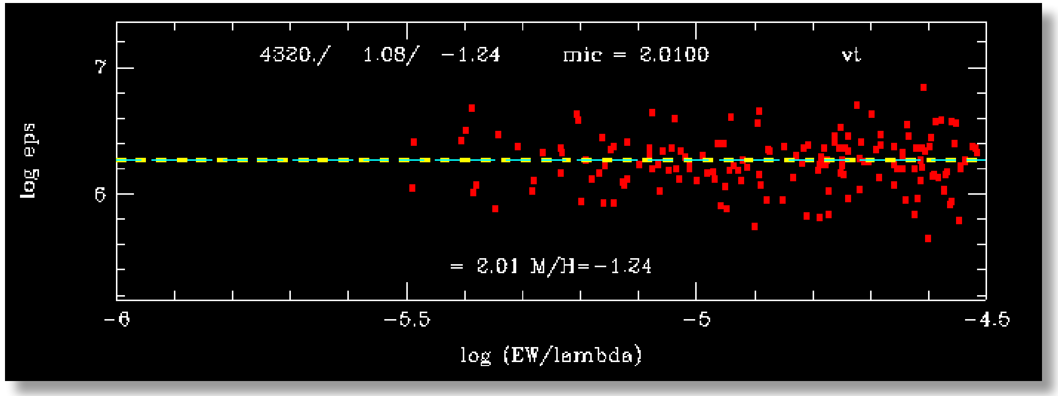


Önehag+2008 – atmosphere models

Microturbulence, Vt (ξ)

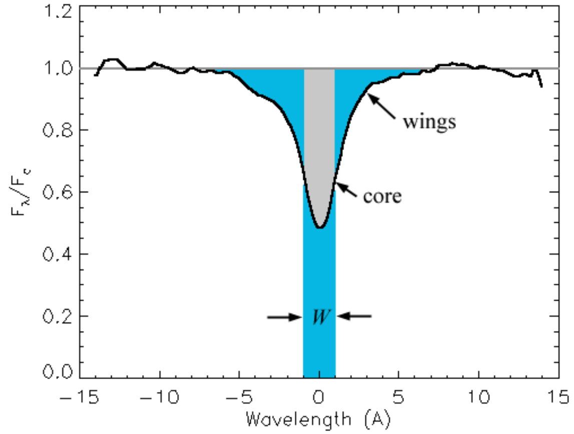
A fudge parameter used in 1D atmospheres to make up for the improper treatment of convection (possible in 3D). Vt can e.g., help desaturate strong lines.

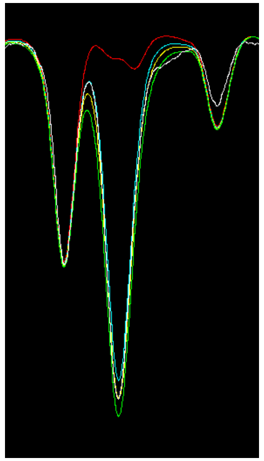
- Typically Fe lines of various strength → Balance of abundances & EW



Stellar abundances

- Two ways of deriving stellar abundances accurately:
  Equivalent widths & spectrum synthesis
- Absolute and relative abundances:





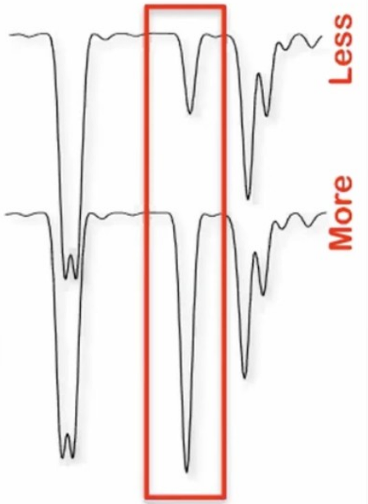
"*Amount" of absorbers* **in a stellar atmosphere, normalized to a reference value. It reflects the atmosphere's *chemical composition*.**

→ ***Absolute abundance*** $\log A(X) = \log_{10}\left(\frac{N_X}{N_H}\right) + 12$

→ ***Abundance ratio*** $[X/Y] = \log_{10}\left(\frac{N_X}{N_Y}\right)_* - \log_{10}\left(\frac{N_X}{N_Y}\right)_\odot$

→ **The Sun: [X/Y] = 0**

A.Koch-Hansen



For more details on stellar parameters and abundances:

https://www.youtube.com/watch?v=M_Mmx9JXymE

SNAQs by A. Koch-Hansen

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/log g

Atomic data

- Excitation potentials
- Oscillator strengths

- Wavelength coverage
- Line selection

→ Li: only at 6707 Å , (6103 Å).
→ Mg: broad range of lines across blue to near-IR (e.g., 4571 Å … 8808 Å) + H-band region of APOGEE.

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

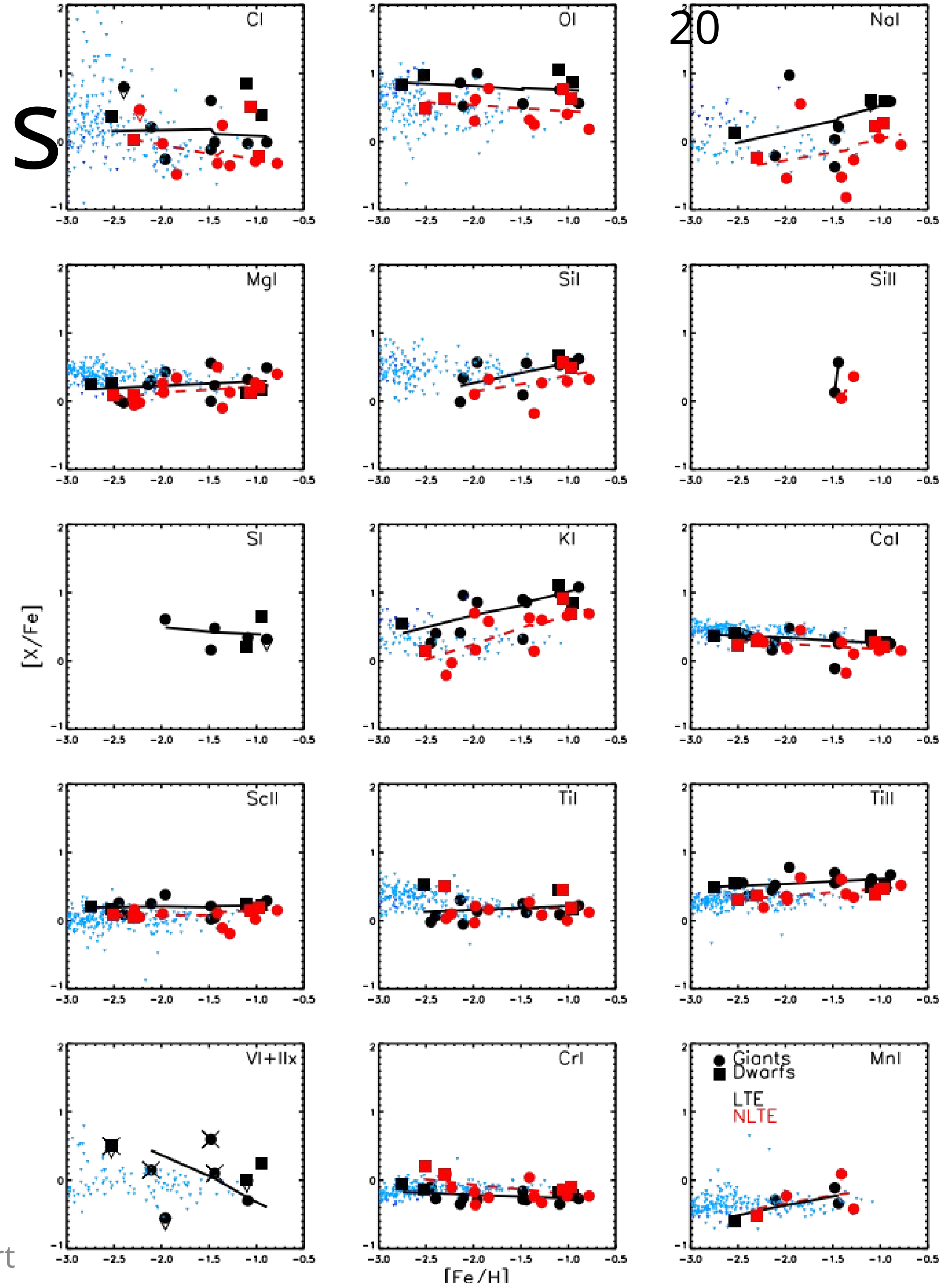
A.Koch-Hansen SNAQs

Hansen+2020

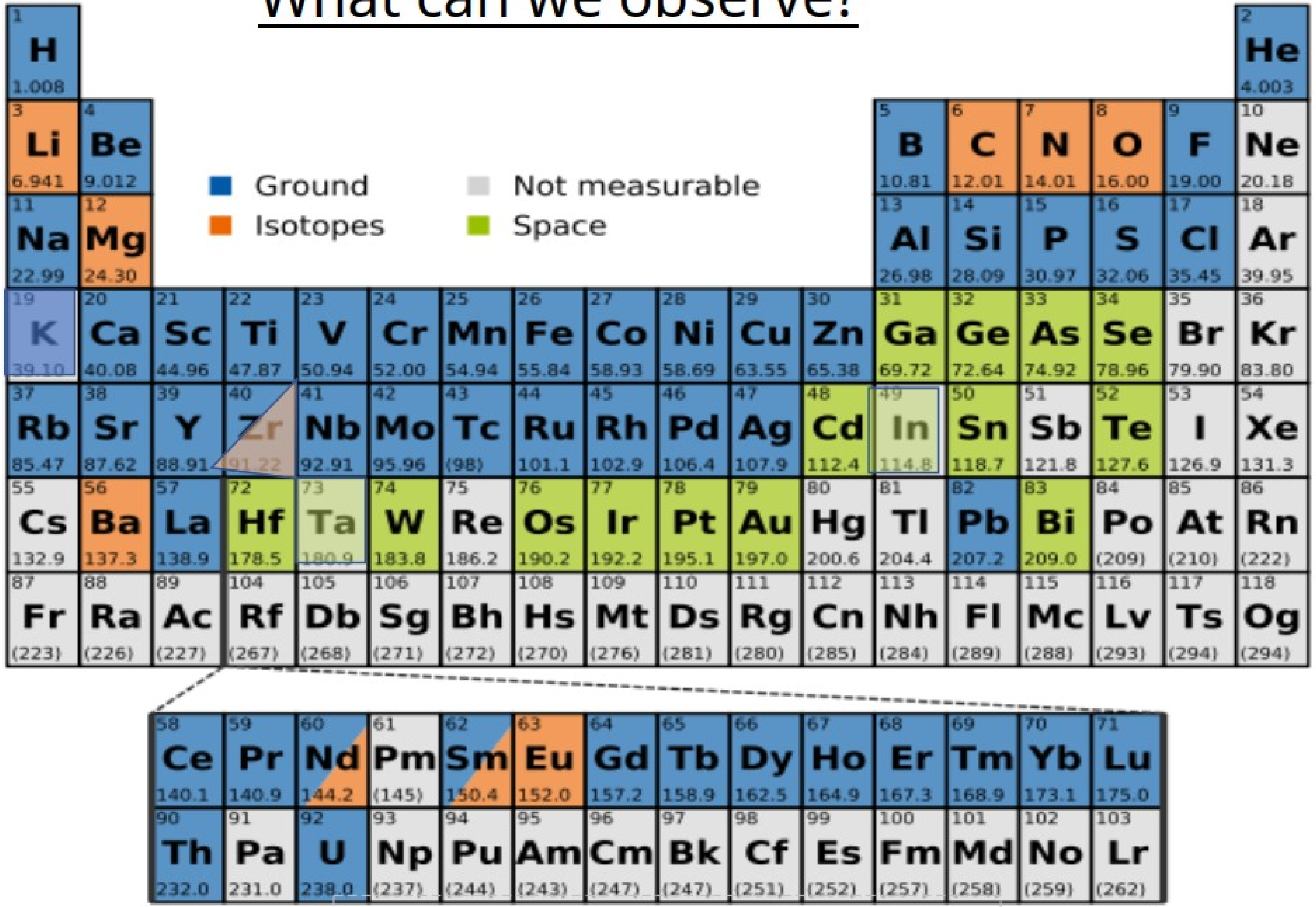
Abundance assumptions

- Stellar atmospheres are assumed to be in Local Thermodynamic Equilibrium (LTE) and 1-D.
    - Velocity distribution Maxwellian, excitations & ionisations described by Bolzmann & Saha equations, and one local T describing the stellar atm. layer

$$[X/Y] = \log_{10}\left(\frac{N_X}{N_Y}\right)_* - \log_{10}\left(\frac{N_X}{N_Y}\right)_\odot$$



What can we observe?

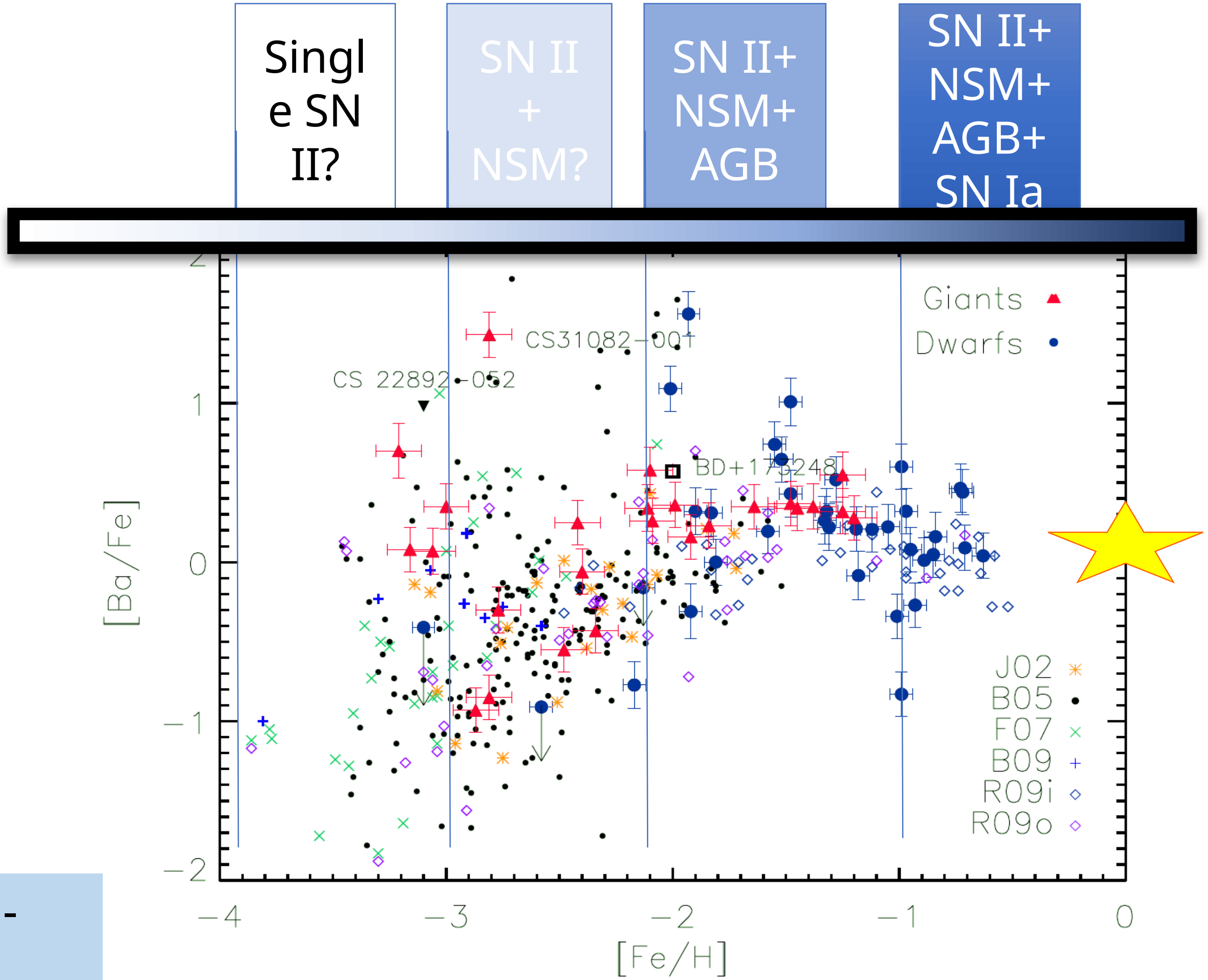


Chemical Evolution of the Milky Way

- The Sun ([Fe/H]=0)

Big Bang

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



Looking back

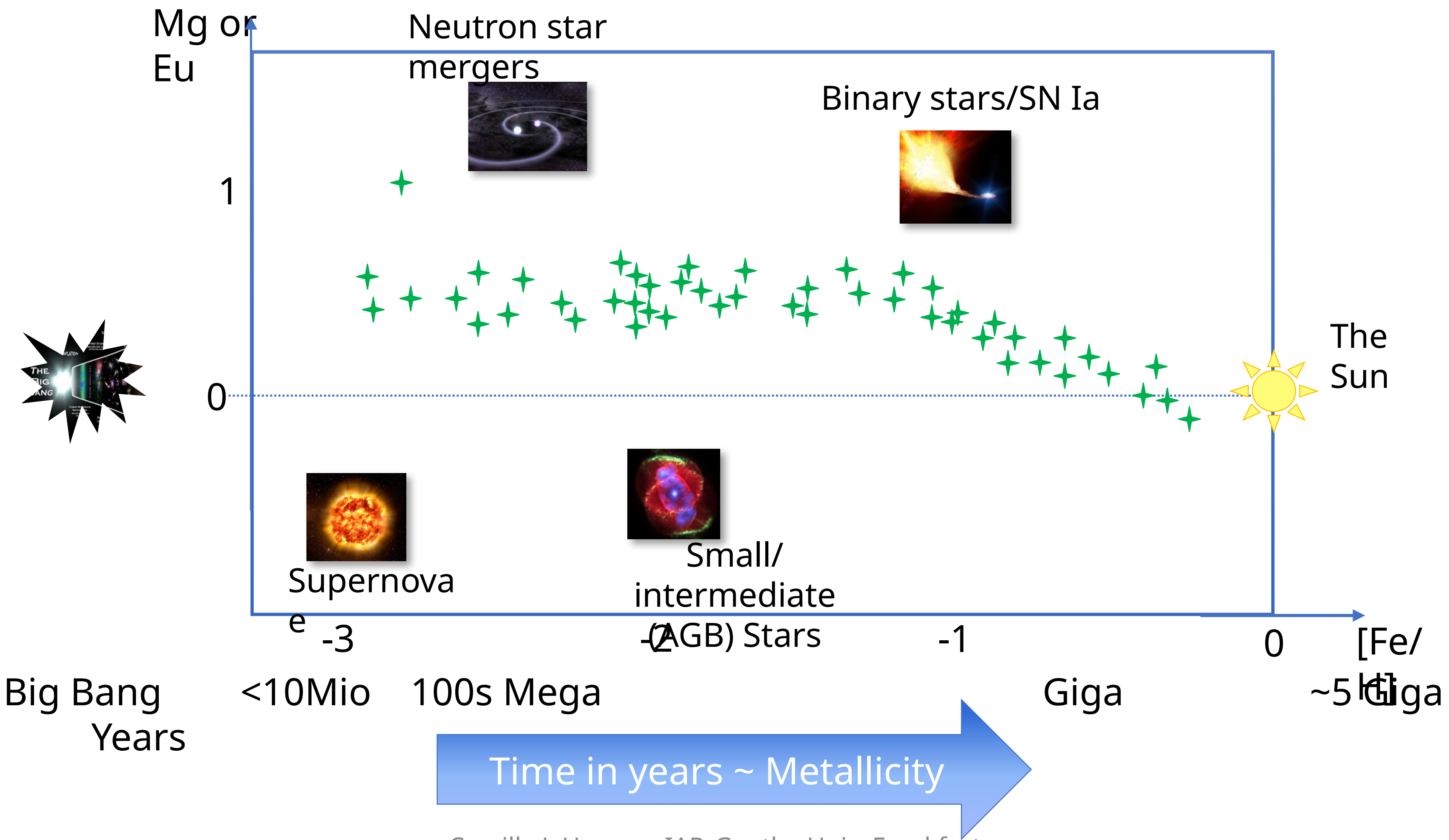
Chemical concentration

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

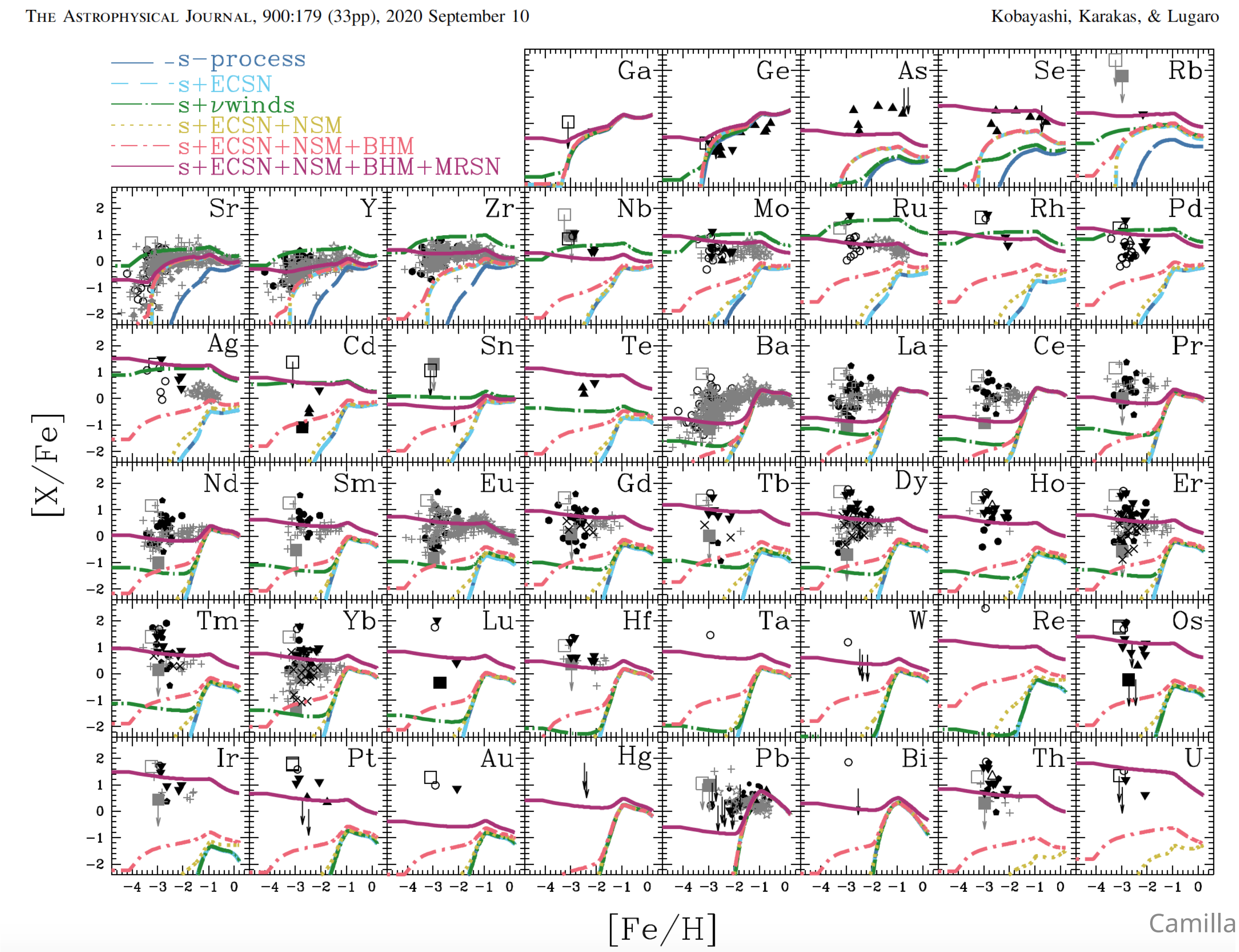
Hansen et al. 2012

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

The Milky Way



Galactic chemical evolution



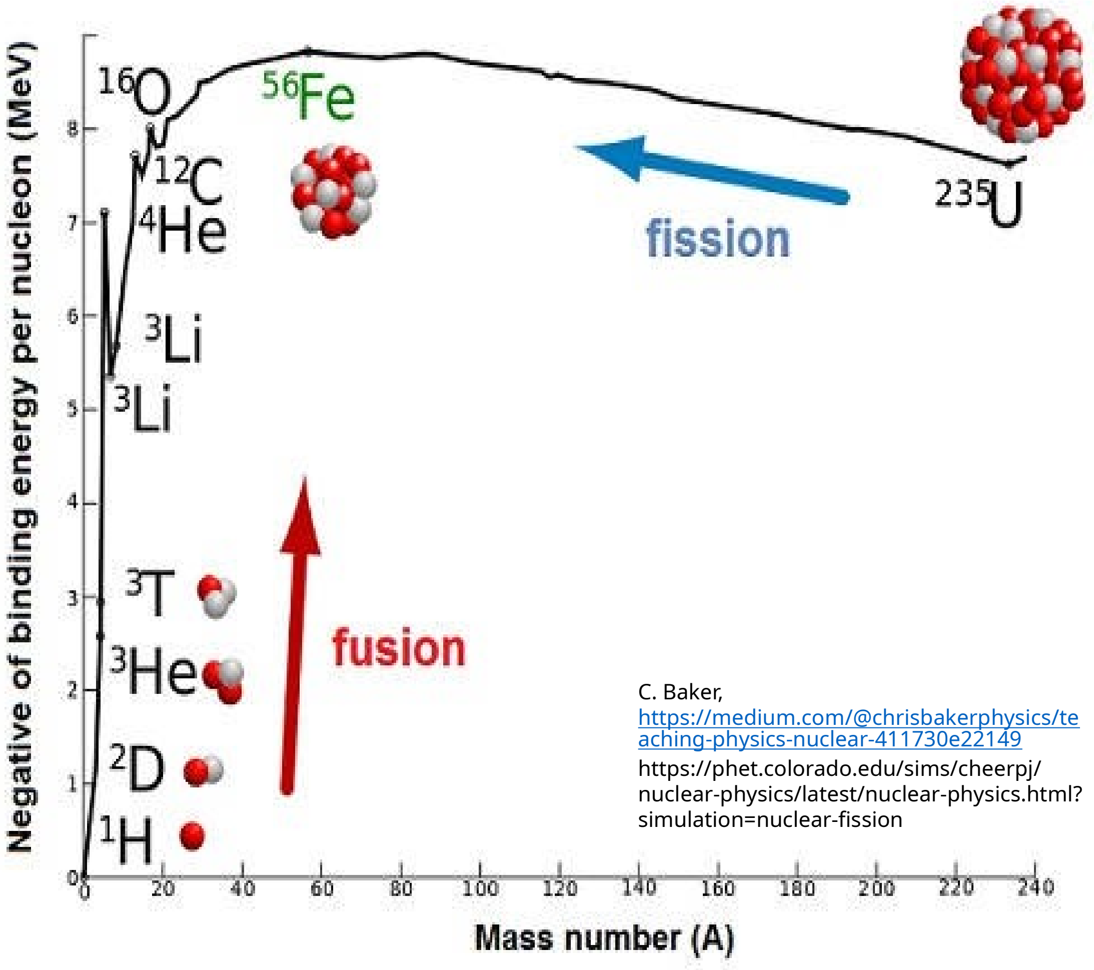
What do you notice here??

Camilla J. Hansen, IAP, Goethe Univ. Frankfurt


2 He Helium 4.002602 2
79 Au Gold 196.966569 2 8 18 32 18 1
23 V Vanadium 50.9415 2 8 11 2
39 Y Yttrium 88.90585 2 8 18 9 2
63 Eu Europium 151.964 2 8 18 25 8 2
116 Lv Livermorium [293] 2 8 18 32 32 18 6
63 Eu Europium 151.964 2 8 18 25 8 2
25 Mn Manganese 54.938045 2 8 13 2
63 Eu Europium 151.964 2 8 18 25 8 2
7 N Nitrogen 14.0067 2 5
69 Tm Thulium 168.93421 2 8 18 31 8 2
16 S Sulfur 32.065 2 8 6

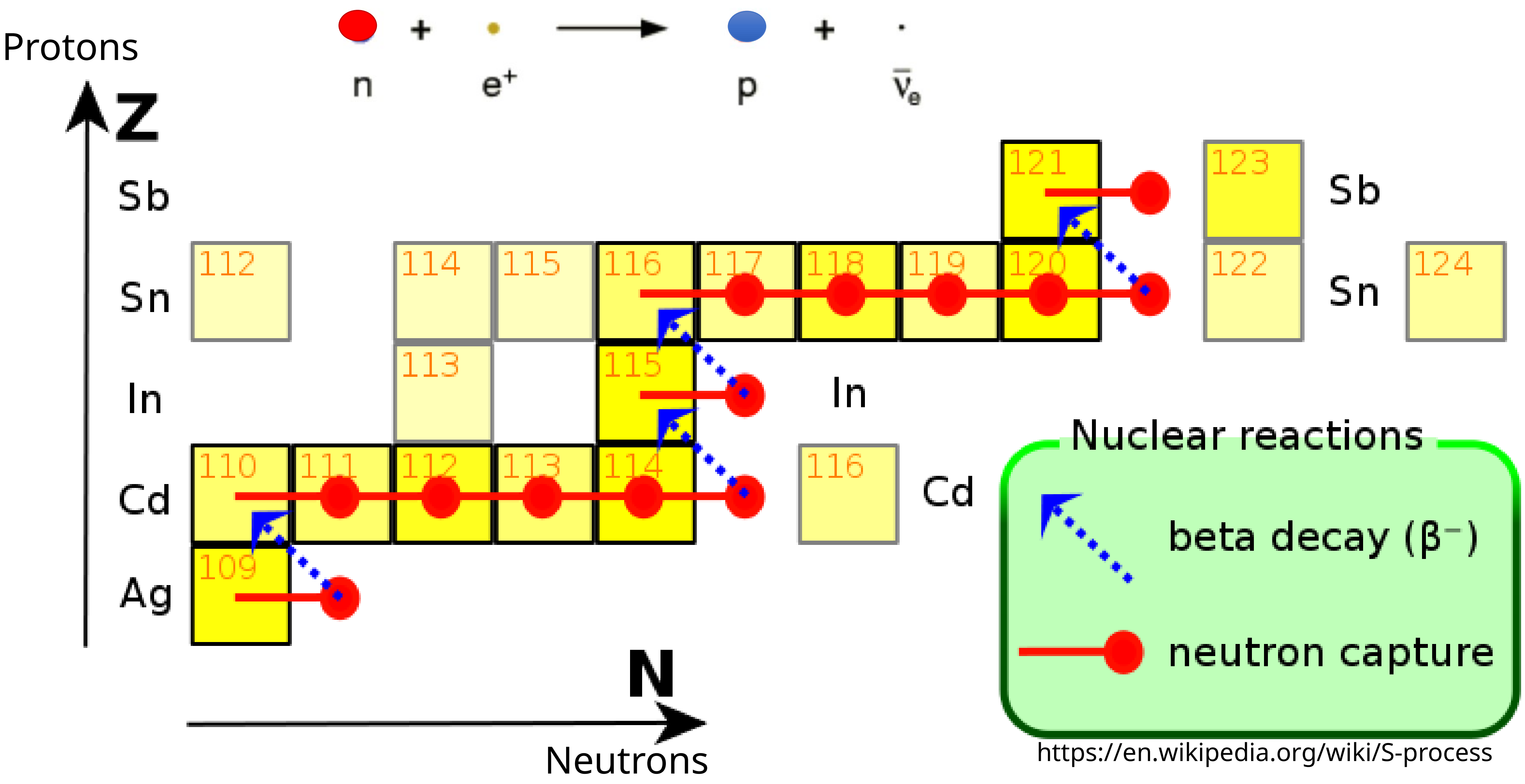
How do heavy elements form?

- ➢Stars form up to Fe during their lives
- ➢Heavier atoms have larger positively charged nuclei that repel protons
- ➢Elements > Fe mostly form via neutron captures



C. Baker, https://medium.com/@chrisbakerphysics/teaching-physics-nuclear-411730e22149
https://phet.colorado.edu/sims/cheerpj/nuclear-physics/latest/nuclear-physics.html?simulation=nuclear-fission

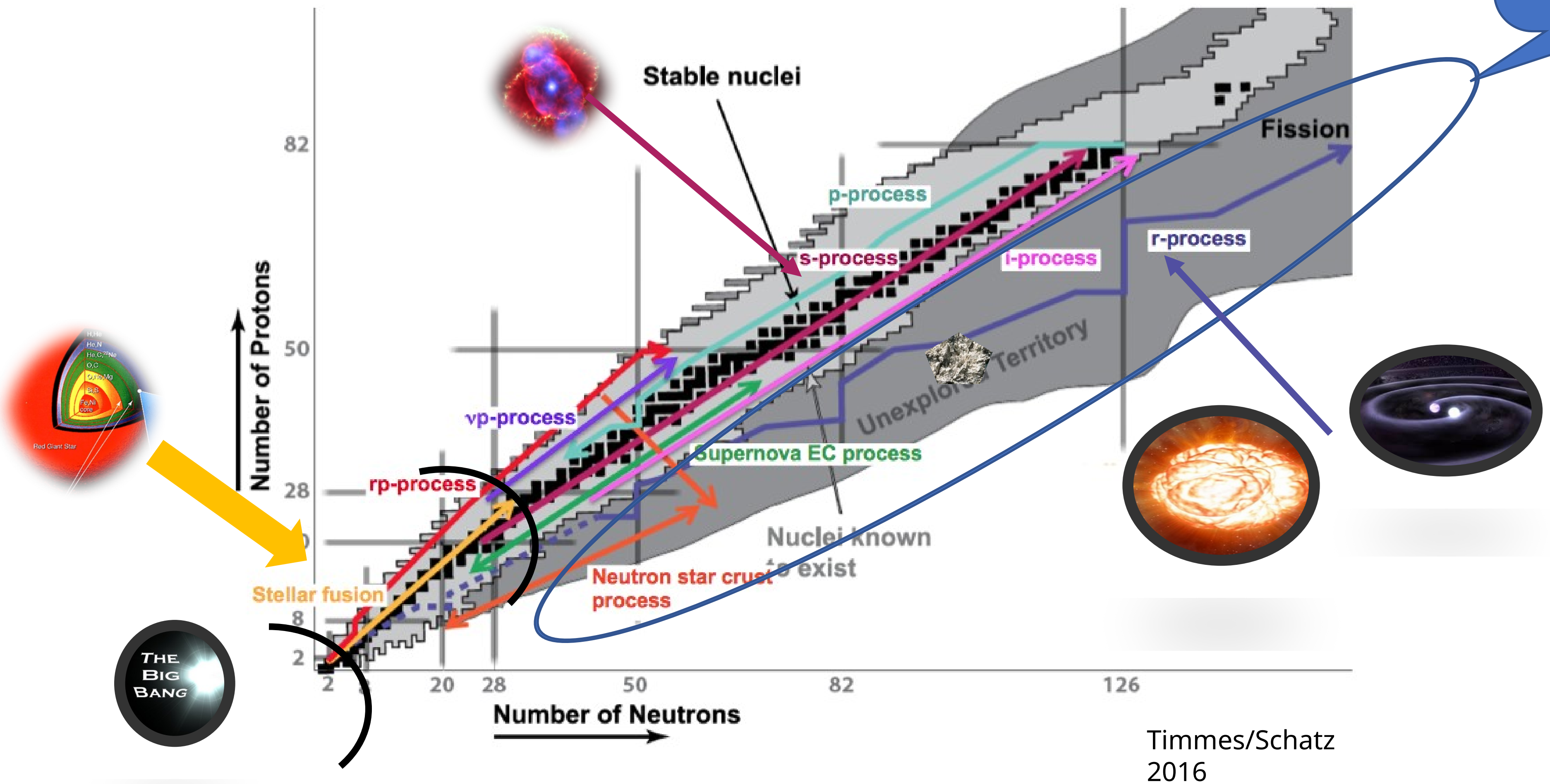
Neutron capture & decay



https://en.wikipedia.org/wiki/S-process

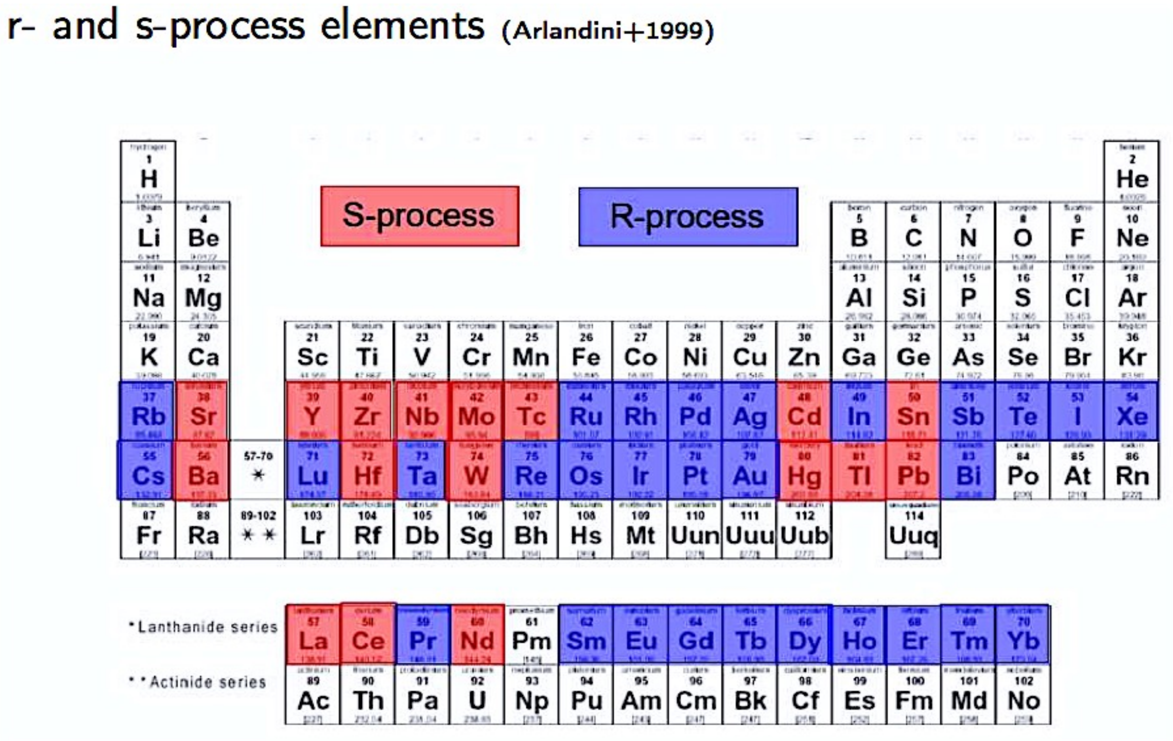
Nuclear reactions

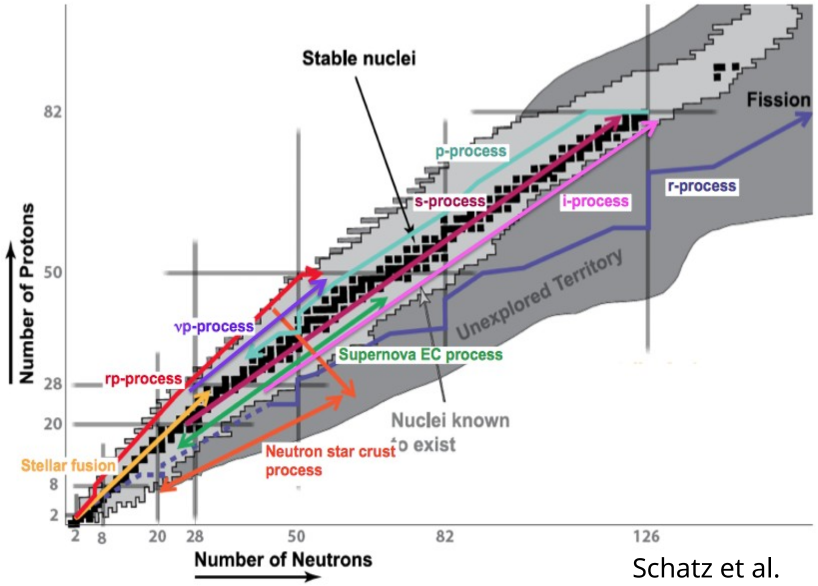
Unknown Reactions!



Timmes/Schatz 2016

The Periodic Table – n-capture processes



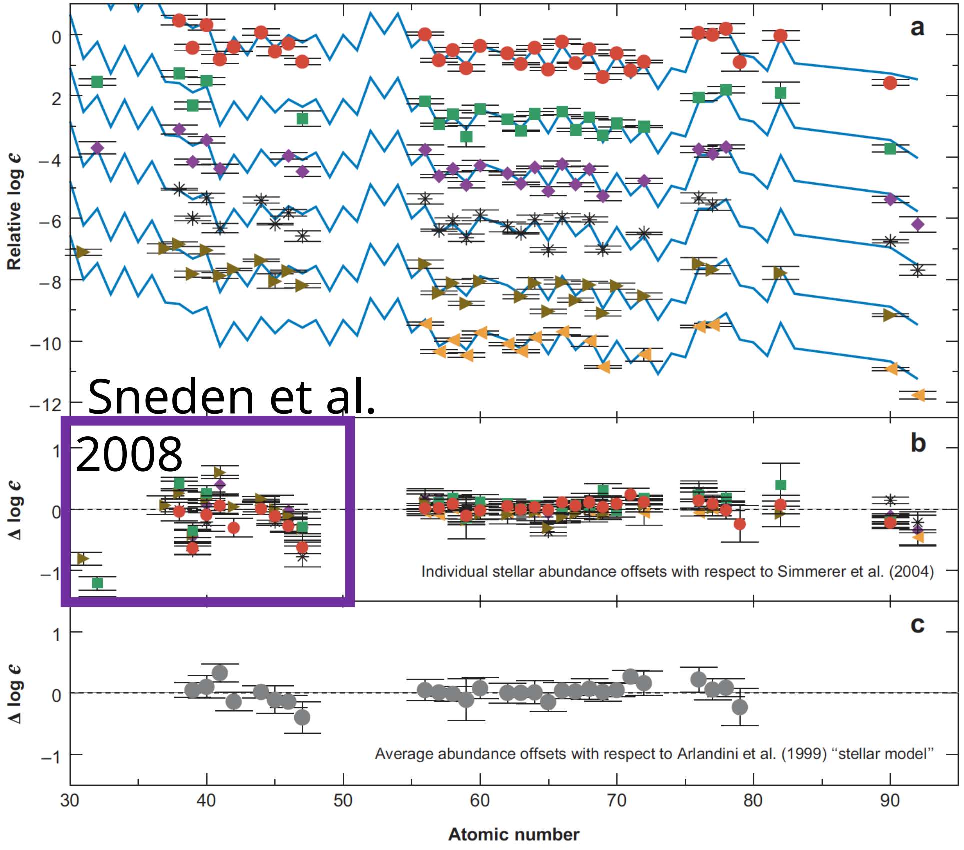


Schatz et al.

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

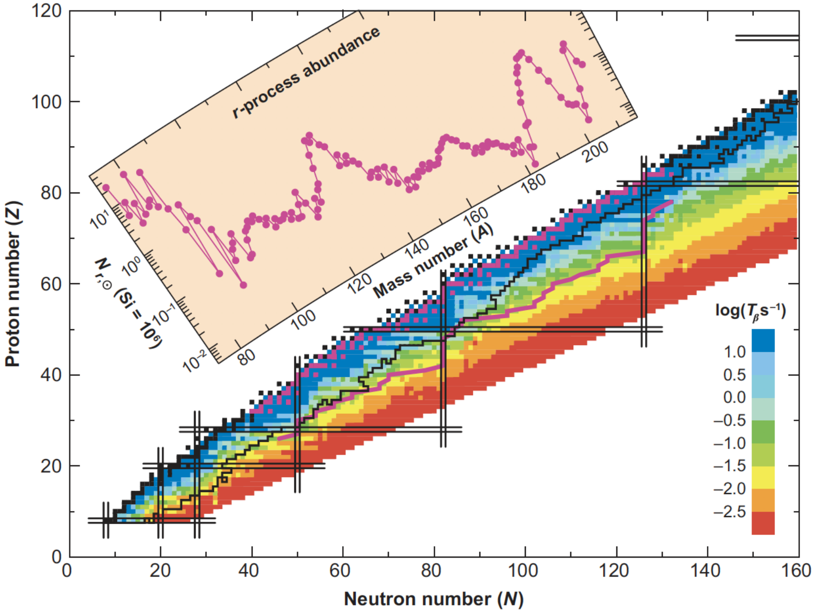
Heavy element abundanc

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

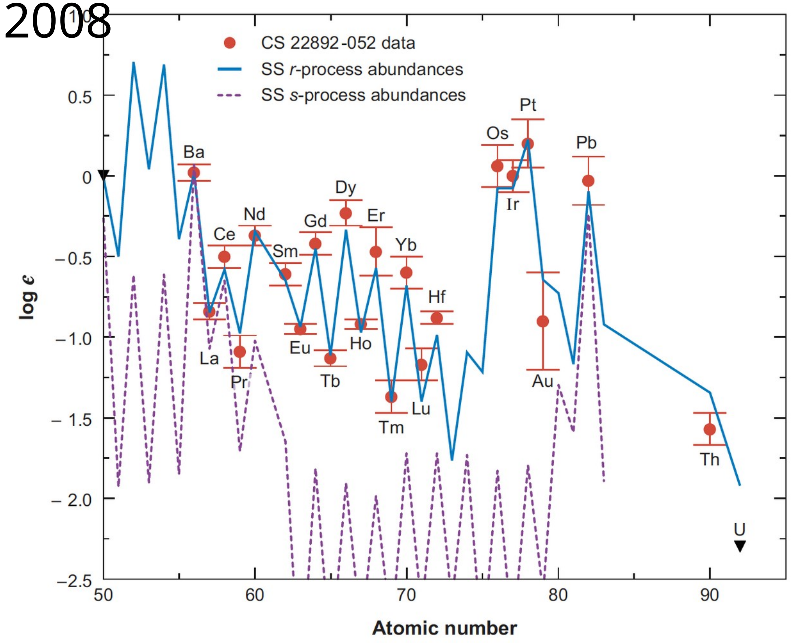


Sneden et al. 2008

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

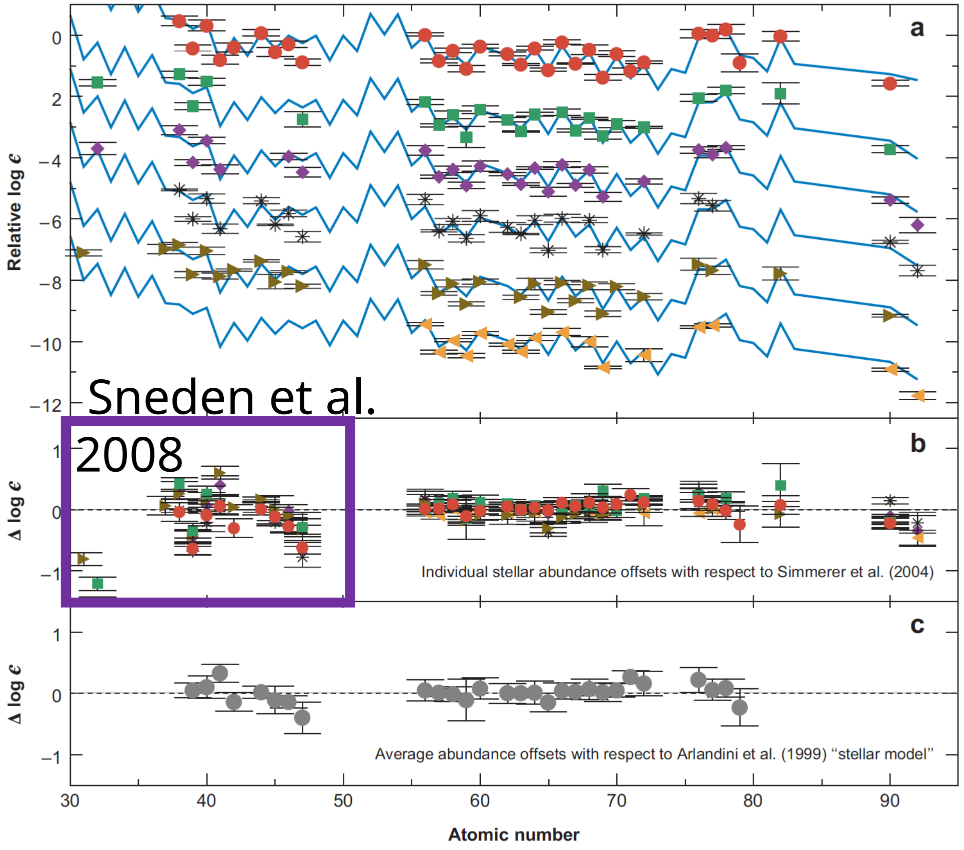


^Møller et al. 1997; v Sneden et al. 2008



Heavy element abundances

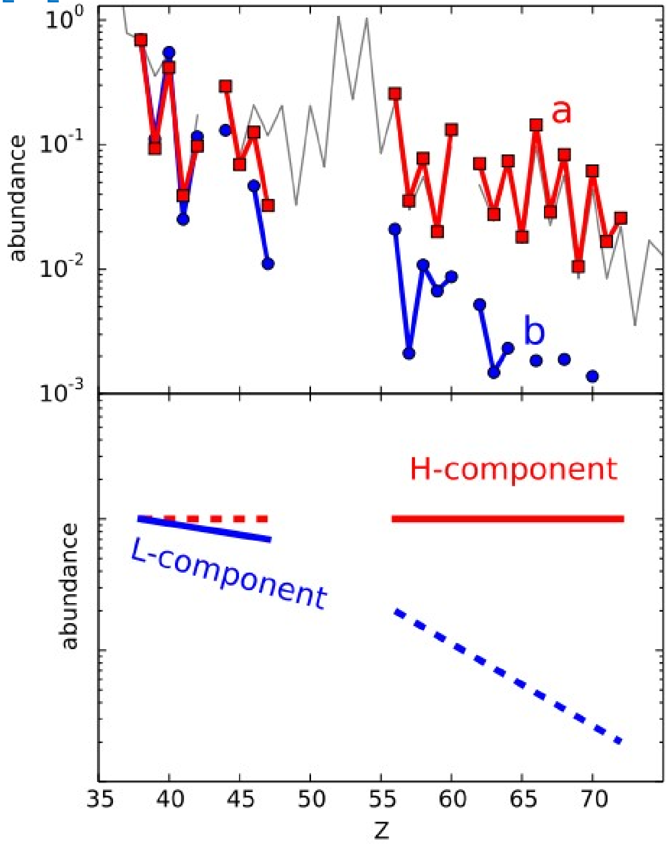
- Different stars show different patterns
- Some elements differ more than



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

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



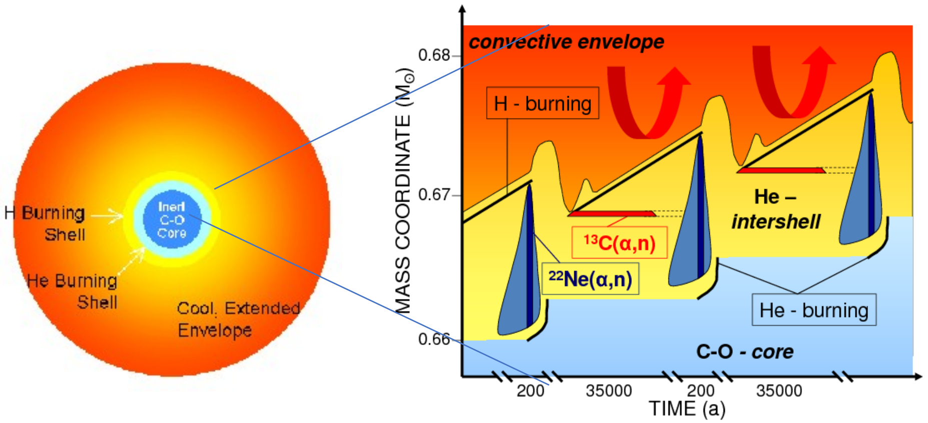
Hansen+1

Indirect tracers of n-capture processes

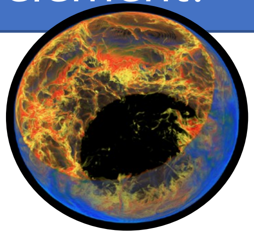
- S-process
- Slow ($t_{cap} \sim t_{\beta}$) & close to stability
- Low n-density (~10^8 cm^{-3})
- AGB or massive fast rotating stars
- Trace element: Ba

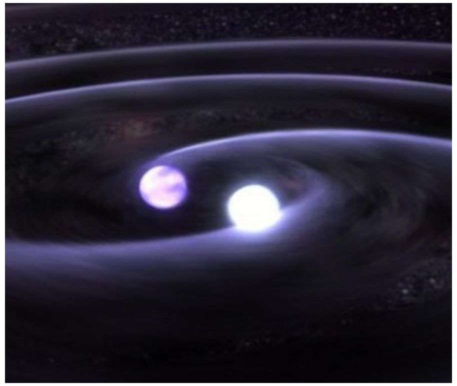
- R-process
- Rapid ($t_{cap} < t_{\beta}$) & far from stability
- High n-density (>10^{23} cm^{-3})
- Rare SN or NS mergers
- Trace element: Eu

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



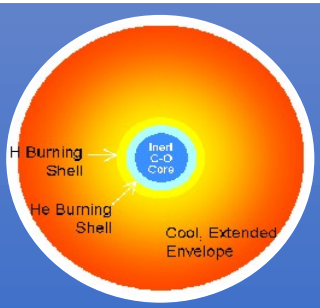


http://public.virgo-gw.eu/the-gravitational-wave-universe/

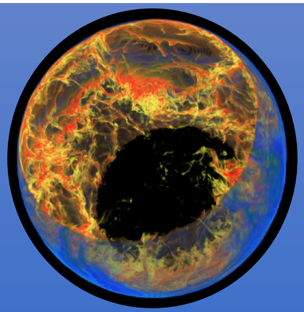
Neutron-capture processes

$\tau_{\text{n-cap}} >> \tau_{\beta\text{-decay}}$

$\tau_{\text{n-cap}} << \tau_{\beta\text{-decay}}$



s-process –
^{13}C pockets or ^{22}Ne reactions,
FRMS or AGB

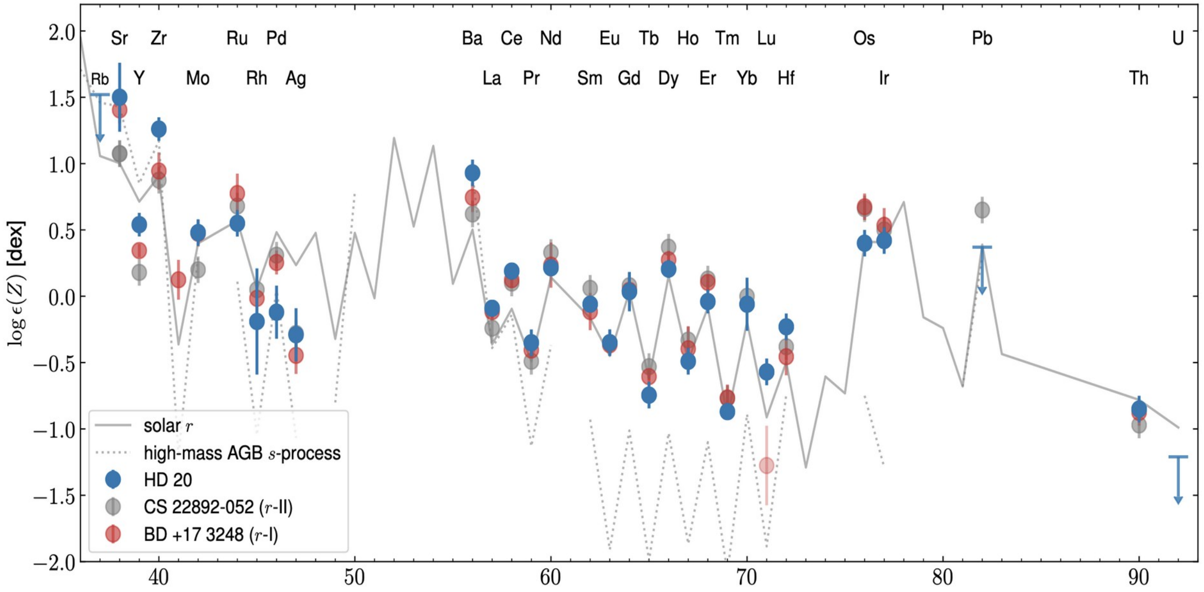


i-process –
H ingestion into hot He-burning region,
AGB, RAWD...?

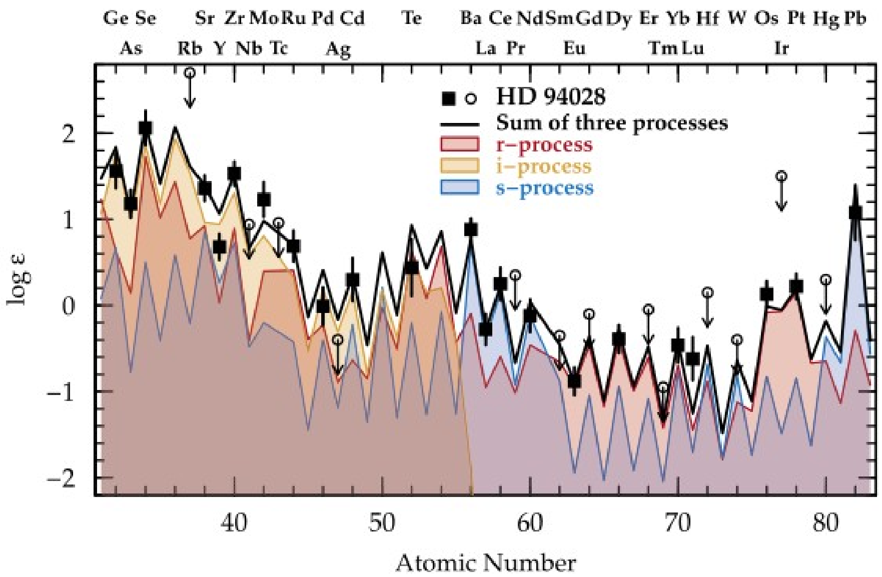
r-process –
rare MRD SN or compact mergers

→ Increasing n-density and exposure
→ Increasing distance from stability
Occurrence with time ←

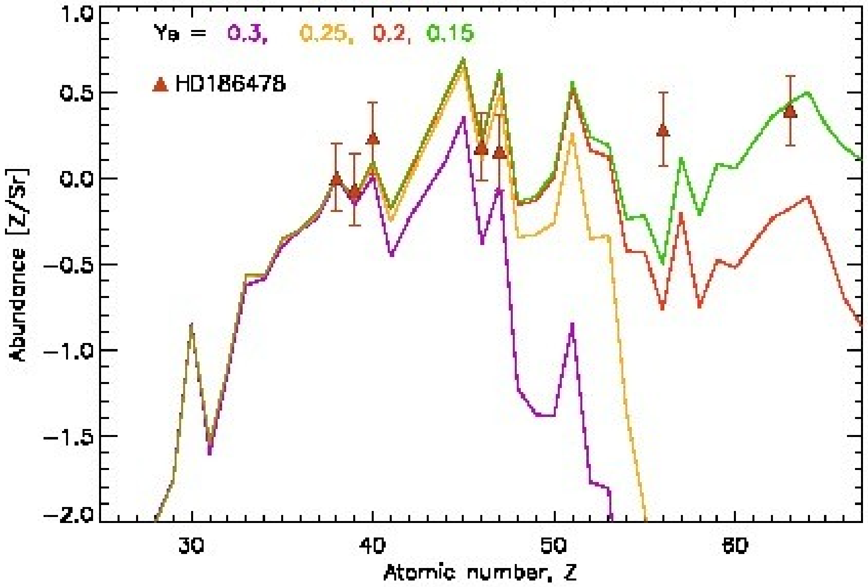
Formation processes



Hanke, CJH et al. 2020



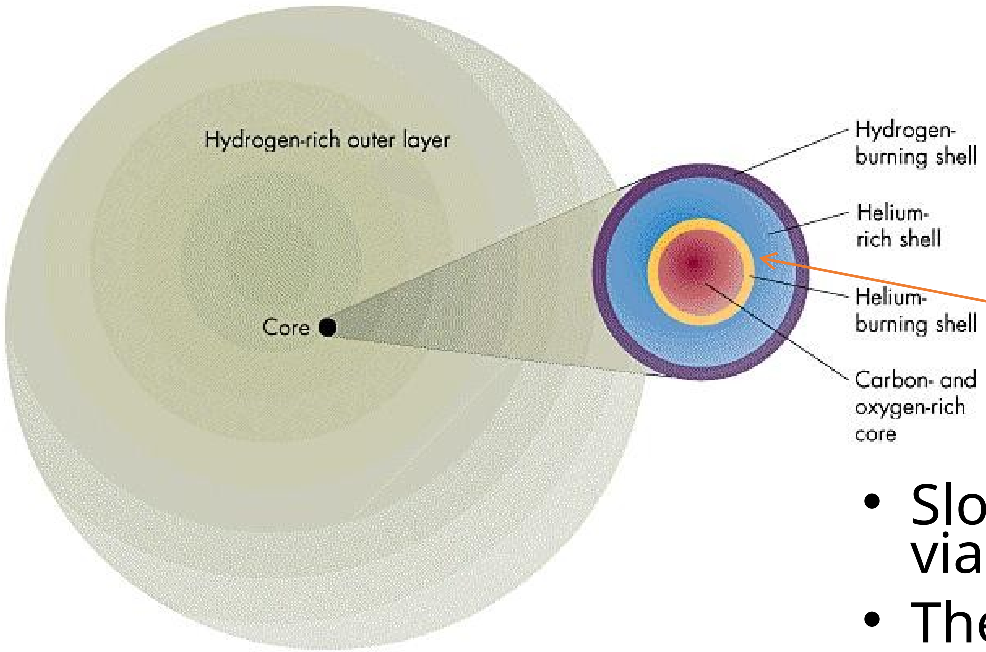
Roederer et al. 2016



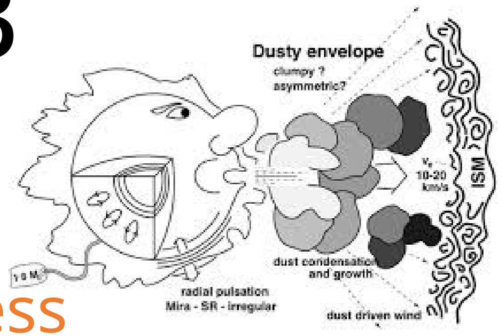
CJH et al. 2012

A generic comparison to the neutron-capture process dominant formation processes
Following we can try to constrain the free parameters/micro-physics of the process

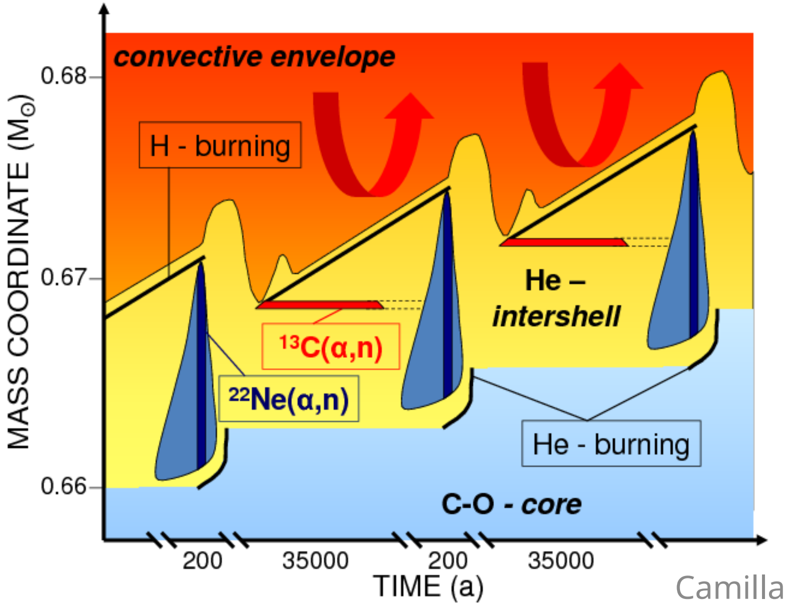
AGB



s-process



- Slow neutron-capture process (*s-process*) via C- or Ne-reactions
- The s-process can only take place after seeds like C atoms have formed and only in evolved stars → time delay
- Lead (Pb), and barium (Ba) are formed in deeper layers of AGB stars (only little Pb forms!)
- Tc is a direct indicator of ongoing s-process

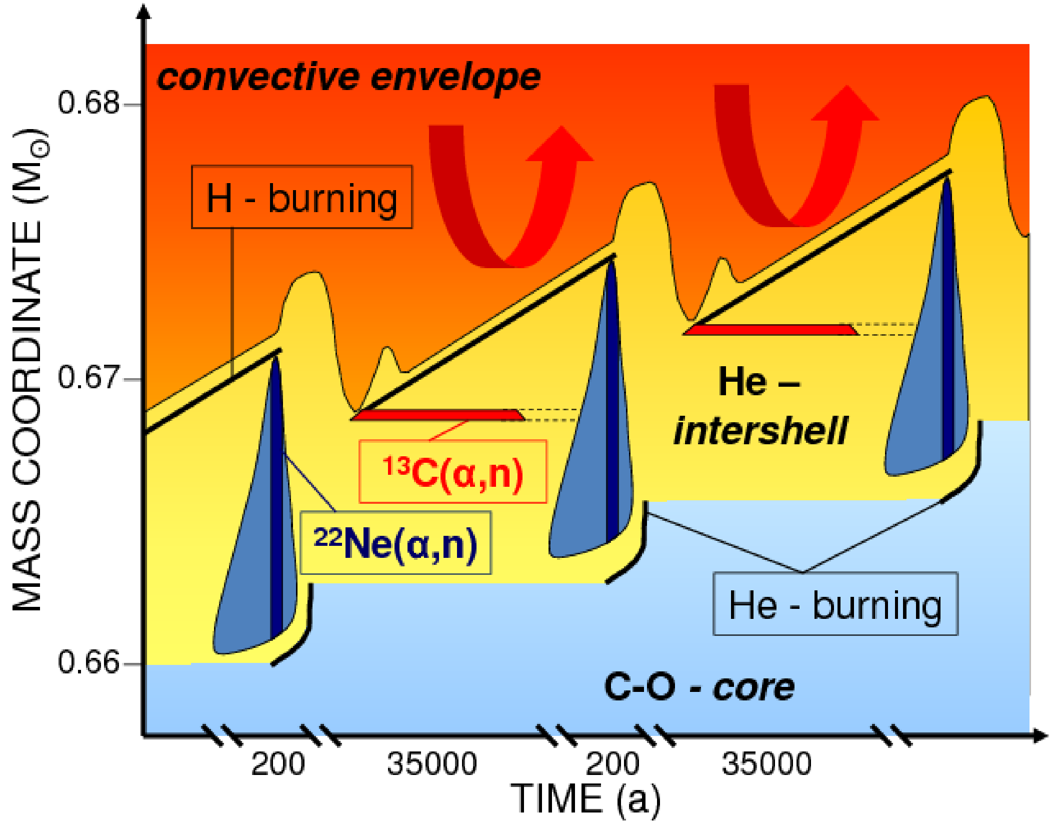


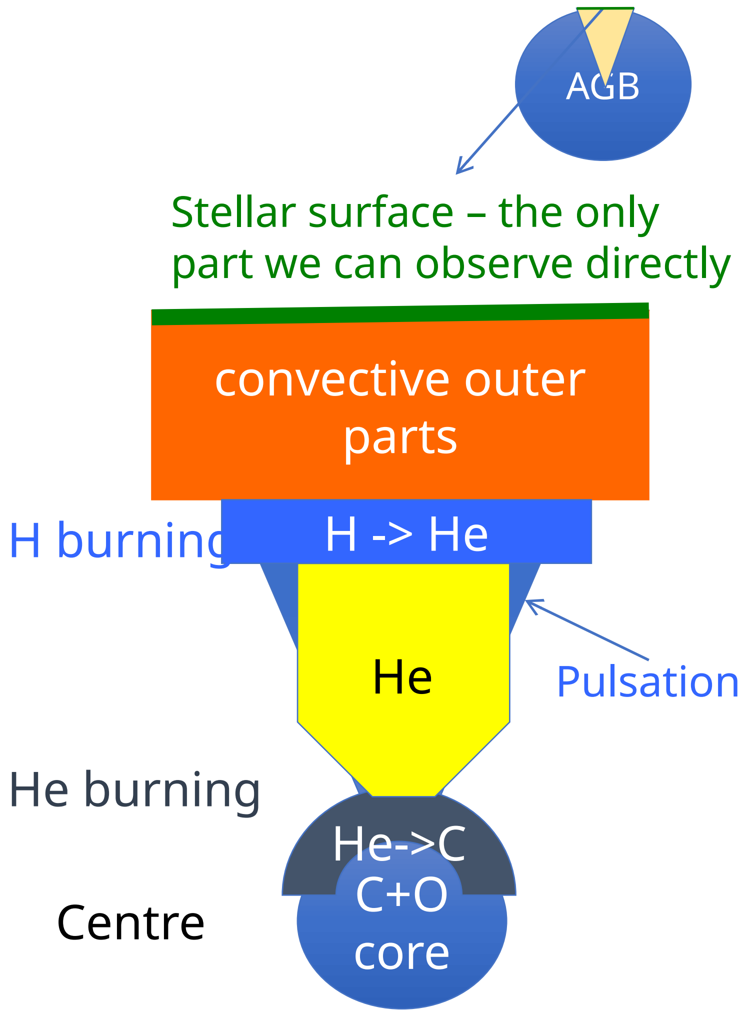
AGB = Asymptotic Giant Branch stars

($M<8M_o$ and they pulsate)

Where does the s-process occur?

- In AGB Stars - ^{4}He, ^{12}C, s-process (Ba, Pb....) between pulsations (1.000-10.000 yrs)





Supernovae

Image: ESO/L. Calçada

- The first stars were massive and exploded as supernovae releasing energy and particles.

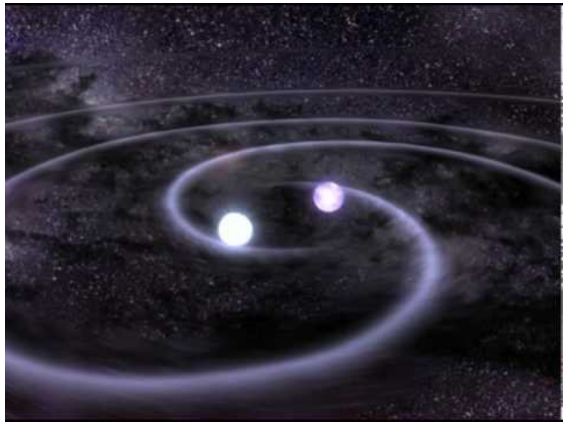
- Newly released particles were captured and formed elements like magnesium and calcium

- A rapid neutron capture process (*r*-process) can take place in the explosion and form elements like Strontium (Sr, Nr. 38) and Silver (Ag, Nr. 47)

Supernova Mass > 8 Solar masses
Typically 10-40 Solar masses

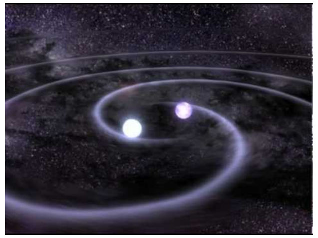
Image: https://scitechdaily.com/supercomputer-simulations-of-core-collapse-supernovae-reveal-complicated-physics-of-exploding-massive-stars/

Neutron star mergers



+

→

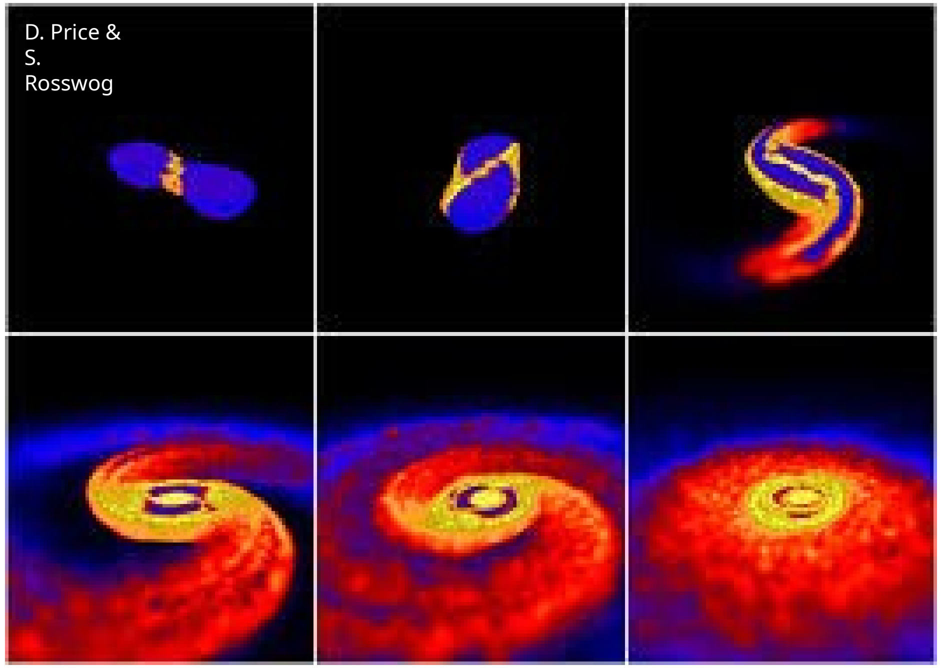


http://public.virgo-gw.eu/the-gravitational-wave-universe/

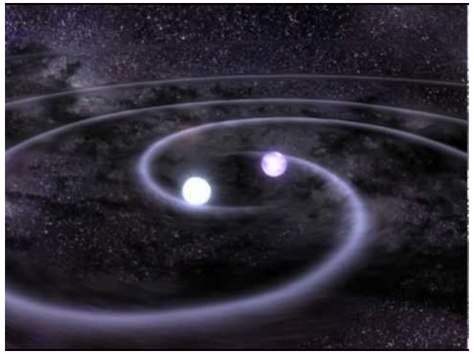
- 2 Supernovae → 2 Neutron stars

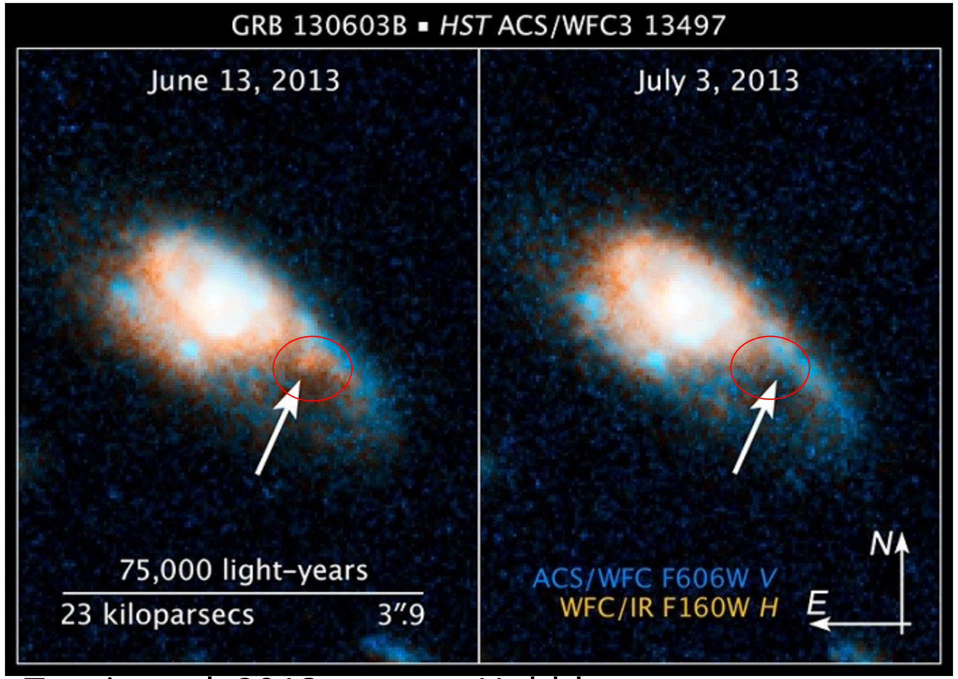
- Neutron stars are full of neutrons that can be captured and via an *r-process* form elements like silver (Ag, No. 47), europium (Eu, No. 63), gold (Au, No. 79) or uranium (U, No. 92)

~10 ms!

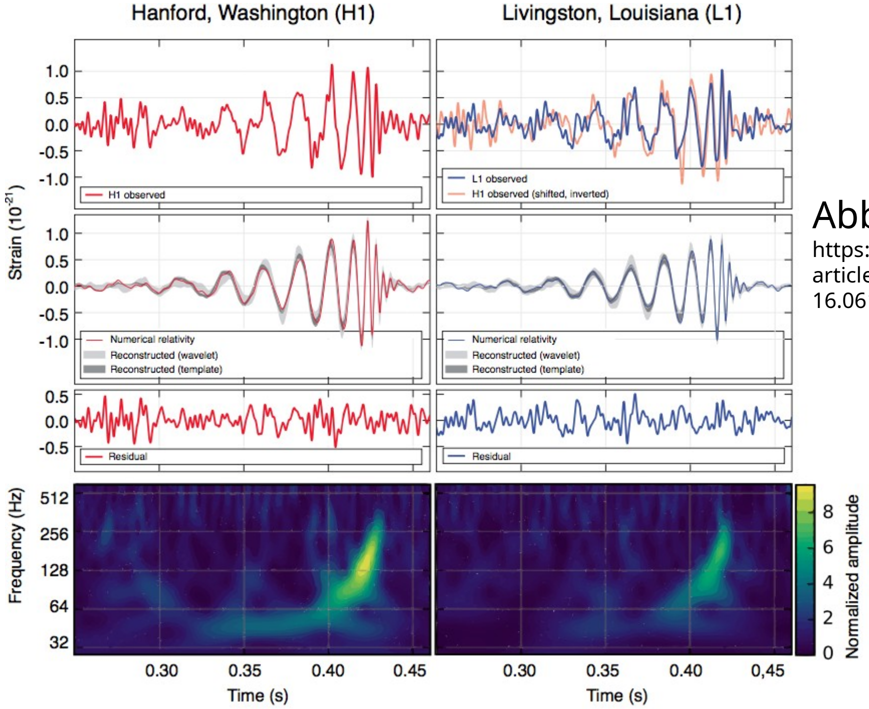


Mergers – black holes and neutron stars





Tanvir et al. 2013, source: Hubble

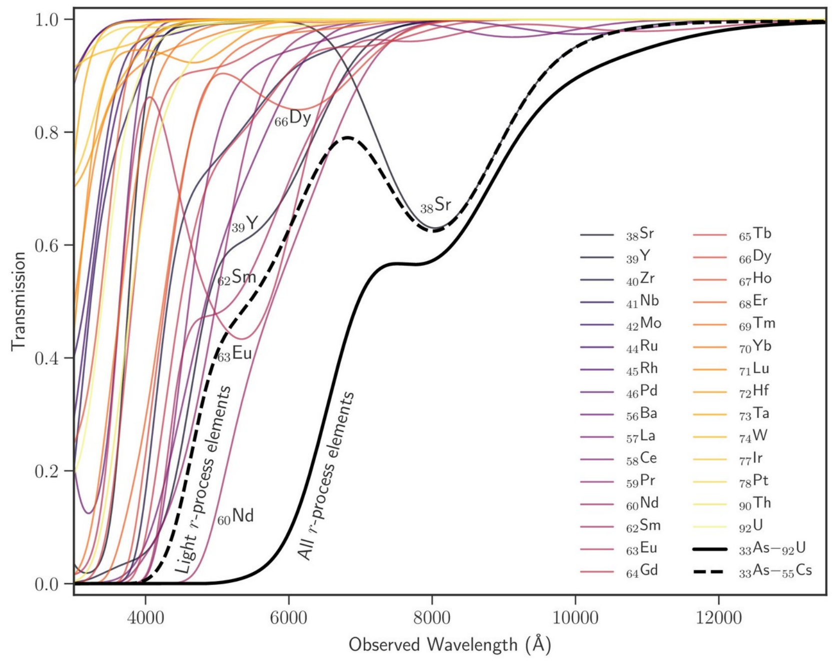


Abbott et al. 2016,
https://physics.aps.org/featured-article-pdf/10.1103/PhysRevLett.116.061102

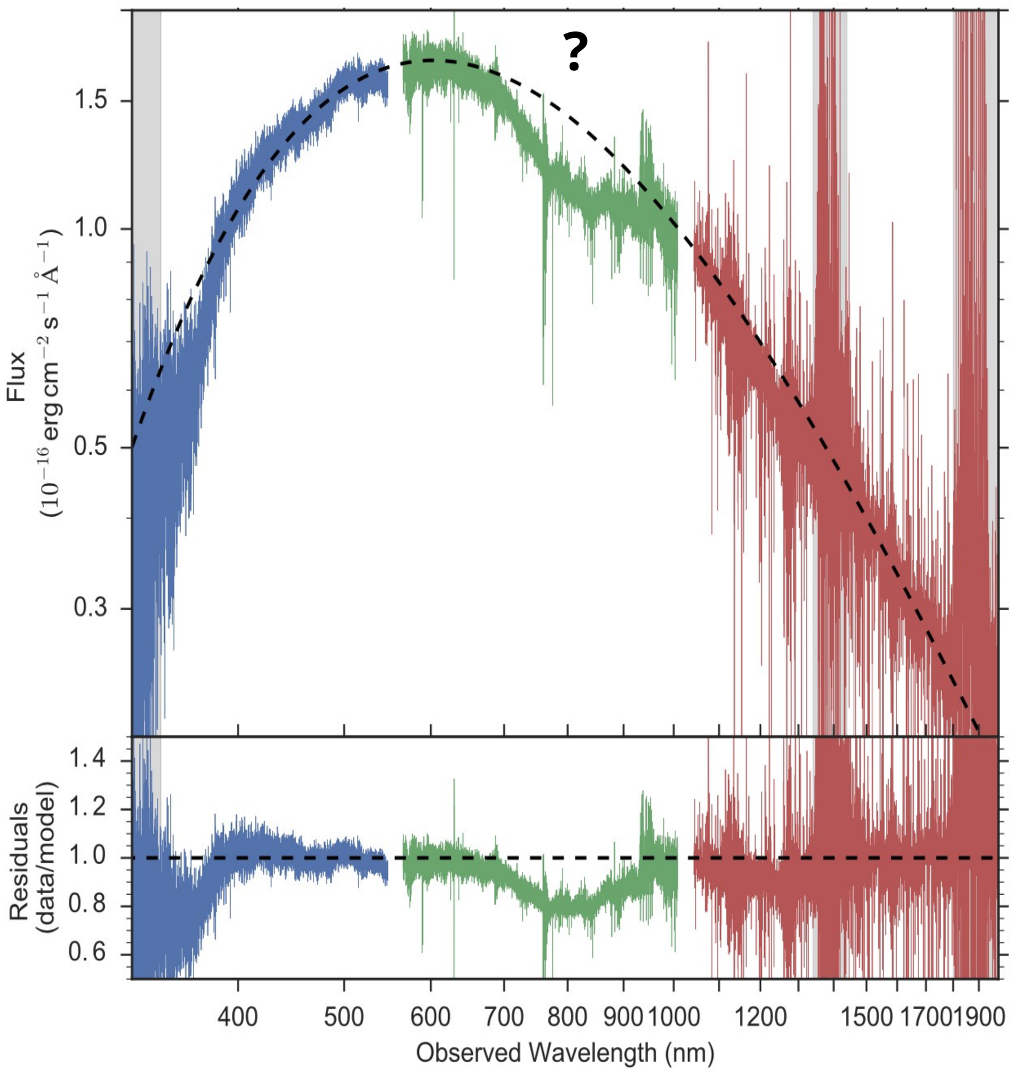
LIGO; https://physicsworld.com/a/ligo-upgrade-to-allow-almost-daily-detection-of-gravitational-waves/

The blue kilonova

- Observations with the Very Large Telescope, Chile
- Modelled all heavy elements between As & U

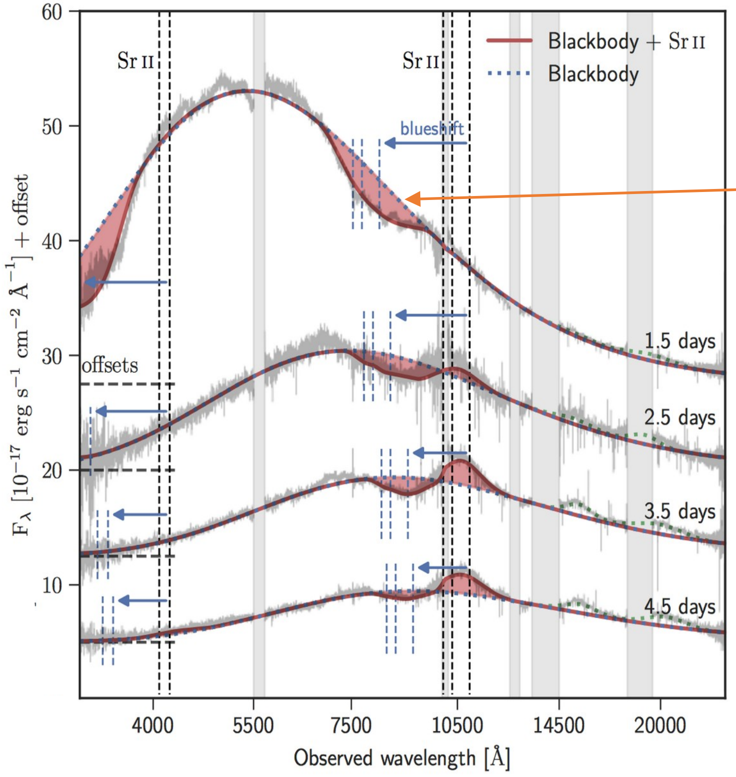


Watson, Hansen, Selsing et al. 2019, Nature



More than lanthanides in mergers! Direct detection of n-captures

- The 2017 kilonova was blue
- This does not agree with lanthanide production
- Expanding gas as is blueshifted by 0.2c
- ~$10^{-5} M_\odot$ Sr produced

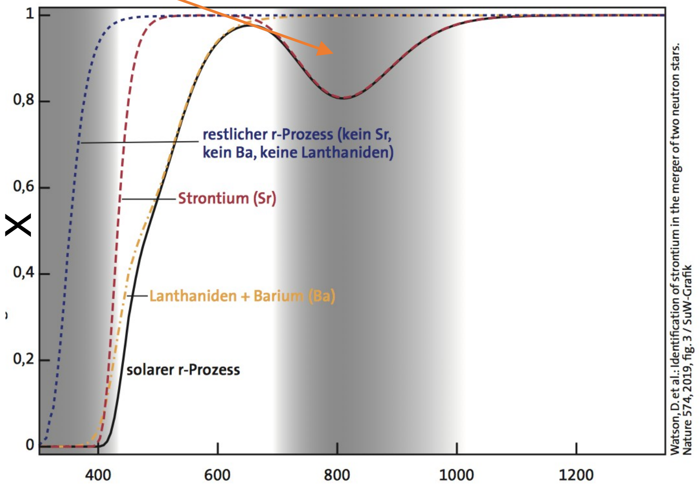


Watson et al. 2019, Nature 574, 479

First **direct** detection of Sr in a merger

Very Large Telescope (VLT), Chile

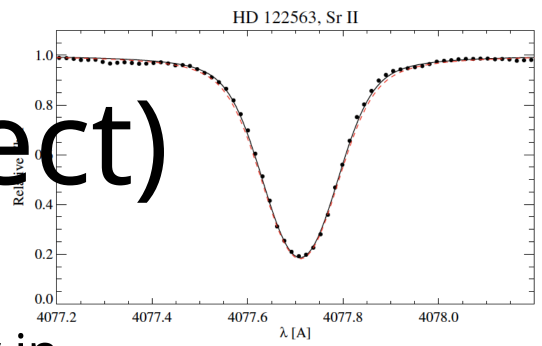
Sterne und Weltraum, März, 2020 s.5



Flux

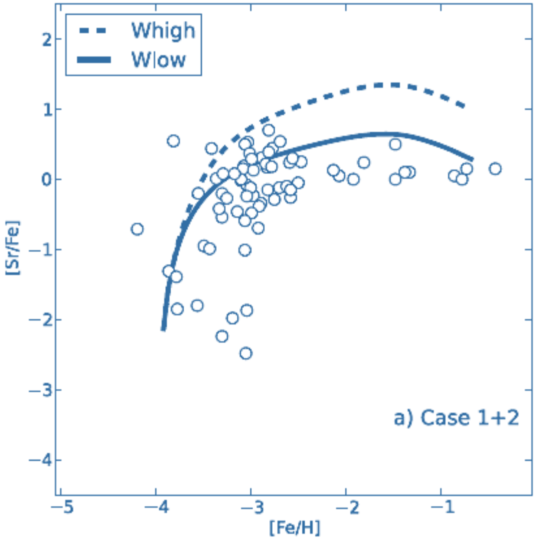
Wavelength (obs) [nm]

Formation of Sr over time (indirect)

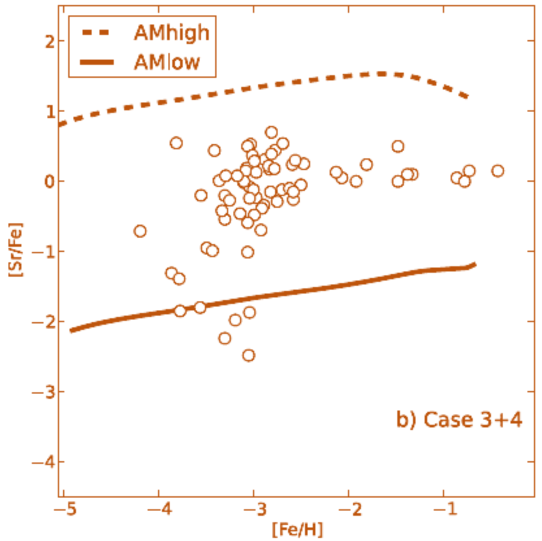


Hansen et al. 2013

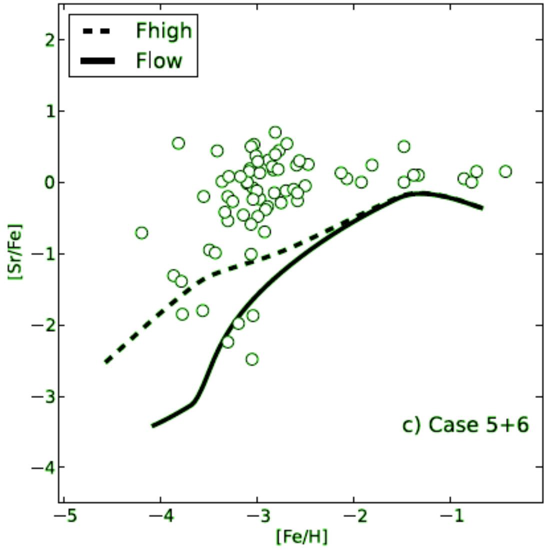
- Sr is the n-capture element that shows the strongest line → good to study in stars
- Sr (Z=38) can be formed in a number of processes and sites
- In the Solar System – Sr is formed mainly via the s-process in AGB stars but at low metallicity the r-process can form Sr – different sites produce different amounts



Electron capture SN – r (Wanajo et al. 2011)



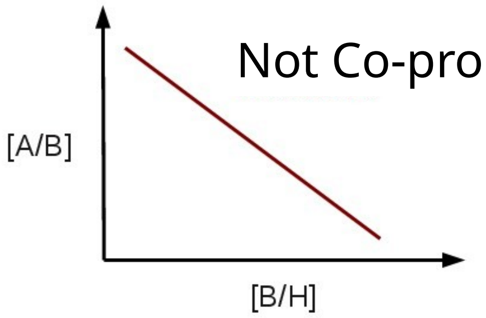
ν-driven winds from SN – r
(Arcones & Montes 2011)

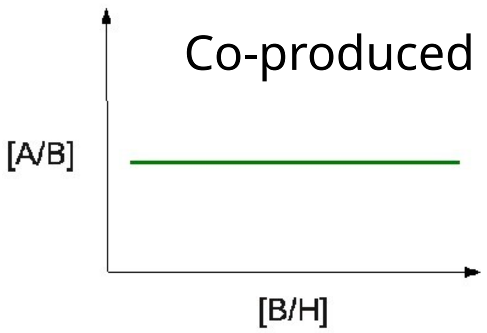


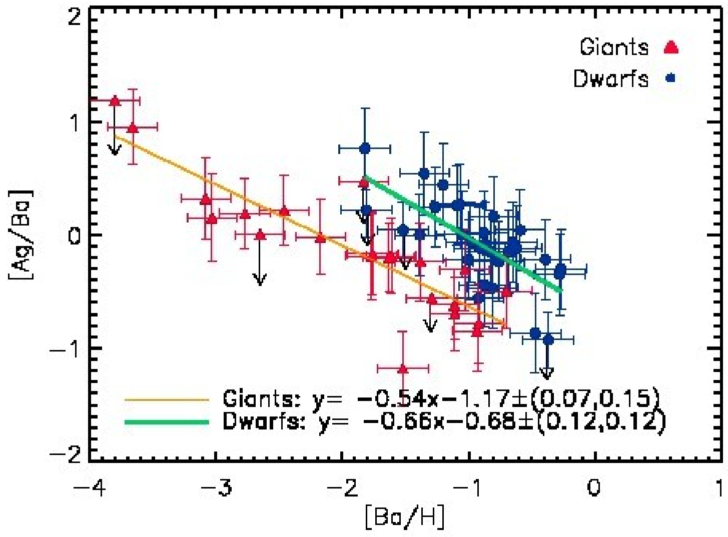
Fast rotating massive stars (early s)
(Frischknecht et al. 2012)

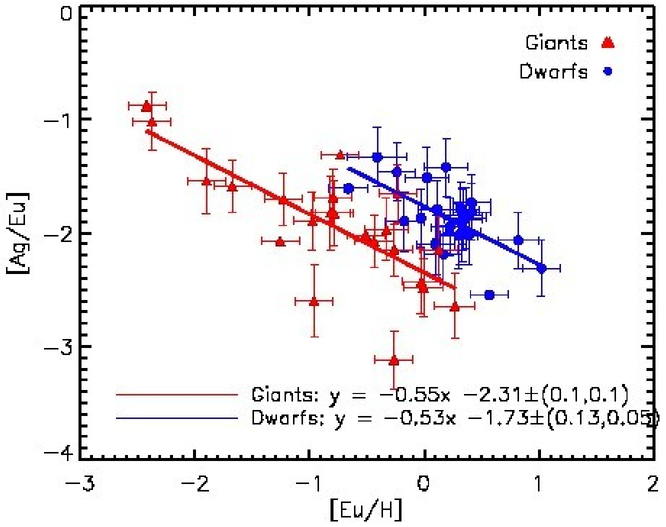
R-process – not universal?!

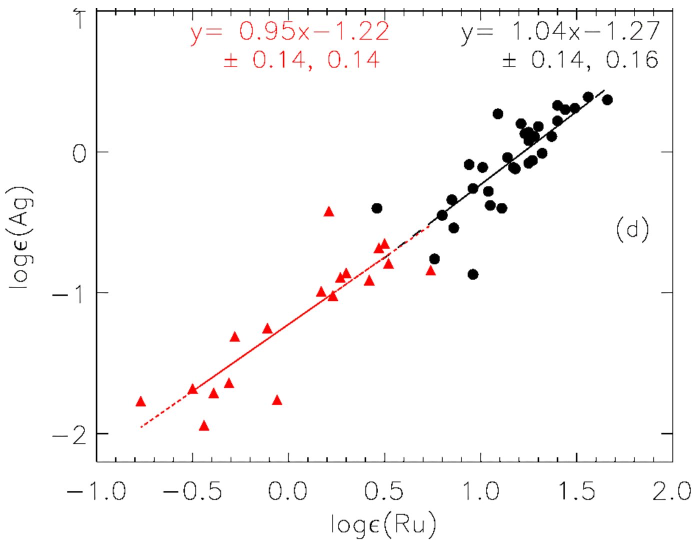
Ag not co-produced with Ba (s) nor Eu (r) A need for a weak r-process/ different conditions/ physics/sites











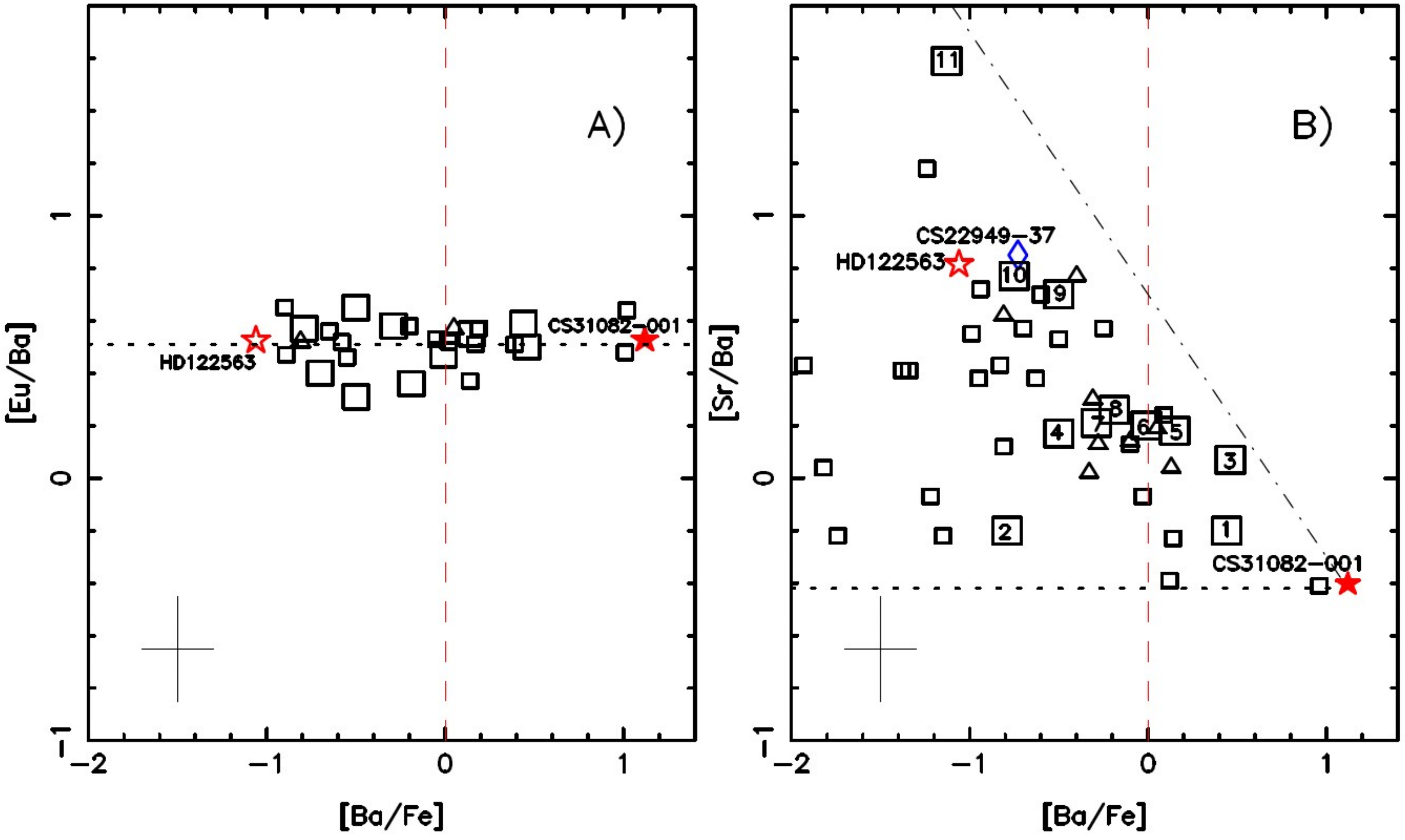
Hansen et al. 2012, 2014

Weak r-process

Spite et al. 2018

- Sr and Ba do not correlate

- Min and max in [Sr/Ba]!



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)

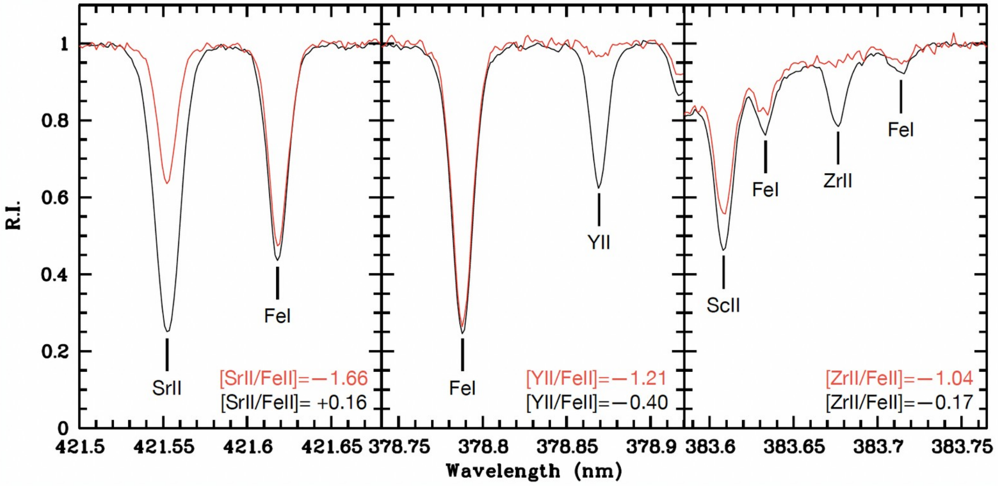
Sample: 52 giant stars with few known heavy element abundances

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

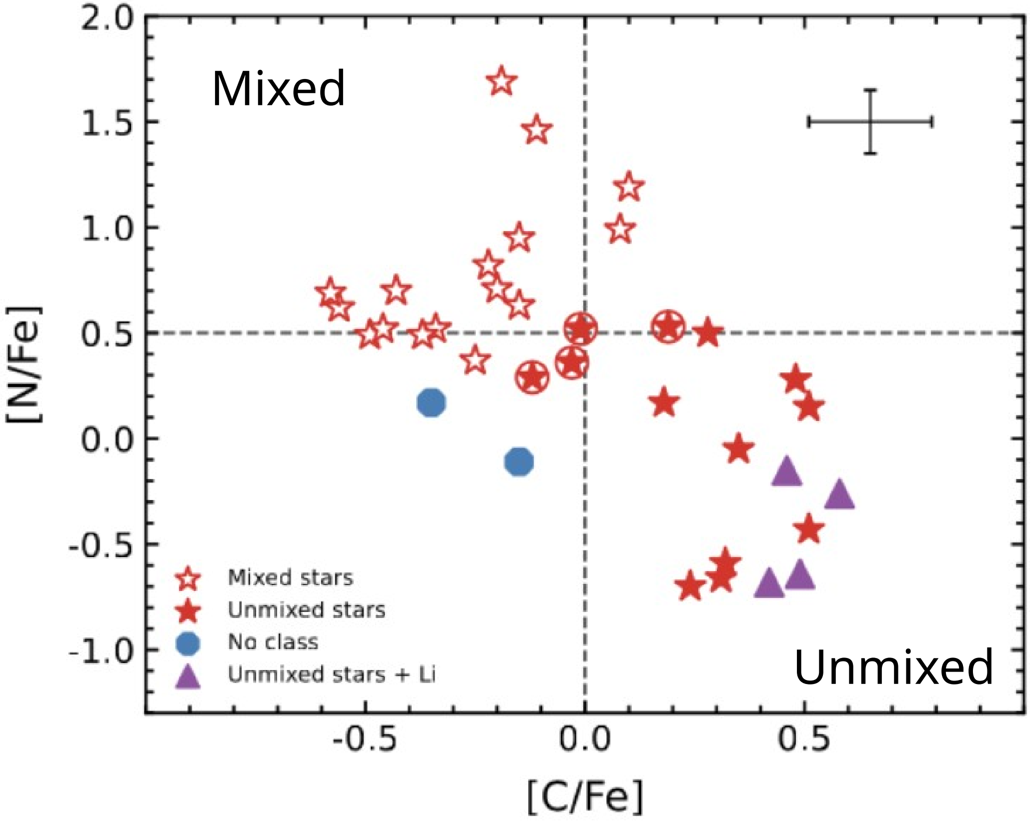
CERES I



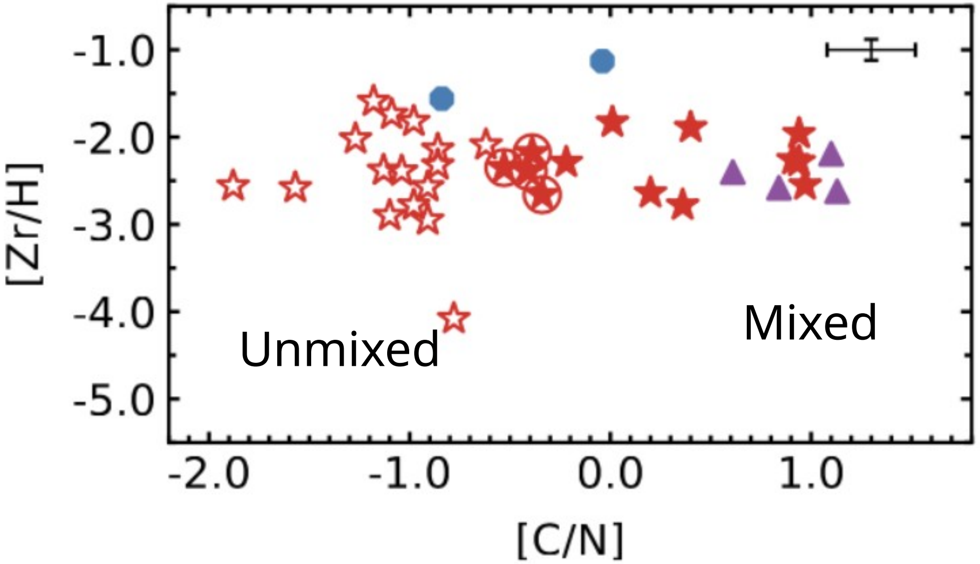
Lombardo et al. 2022

Combining light and heavy elements

Fernandes de Melo et al. 2024
CERES II



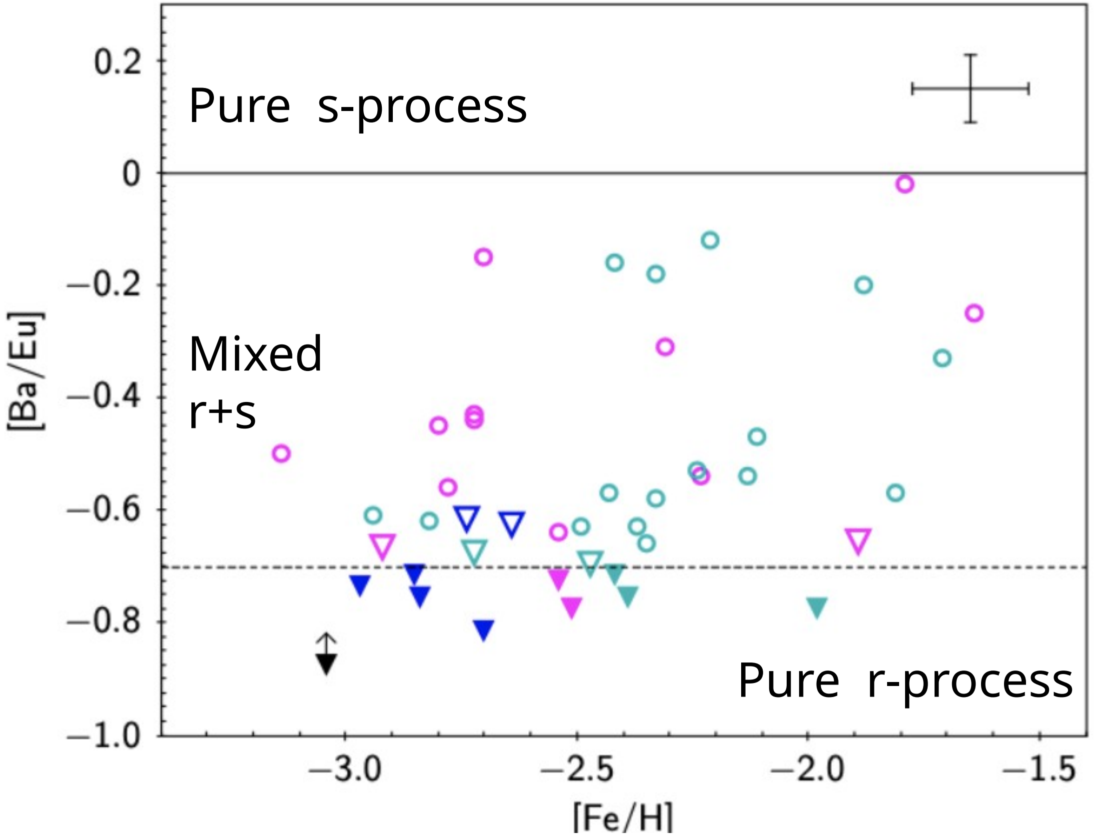
Raphaela Fernandes de Melo
PhD Student

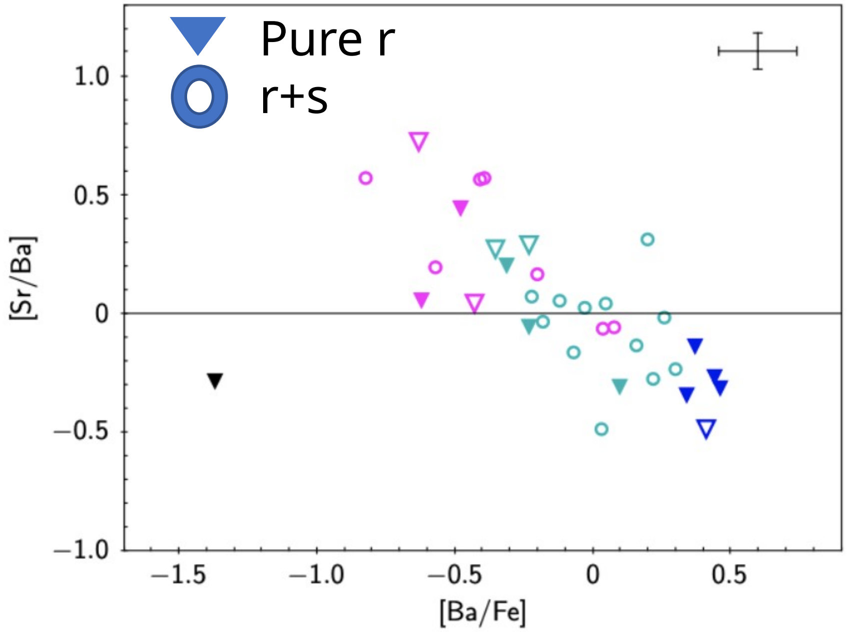


Rare earth elements as nuclear tracers

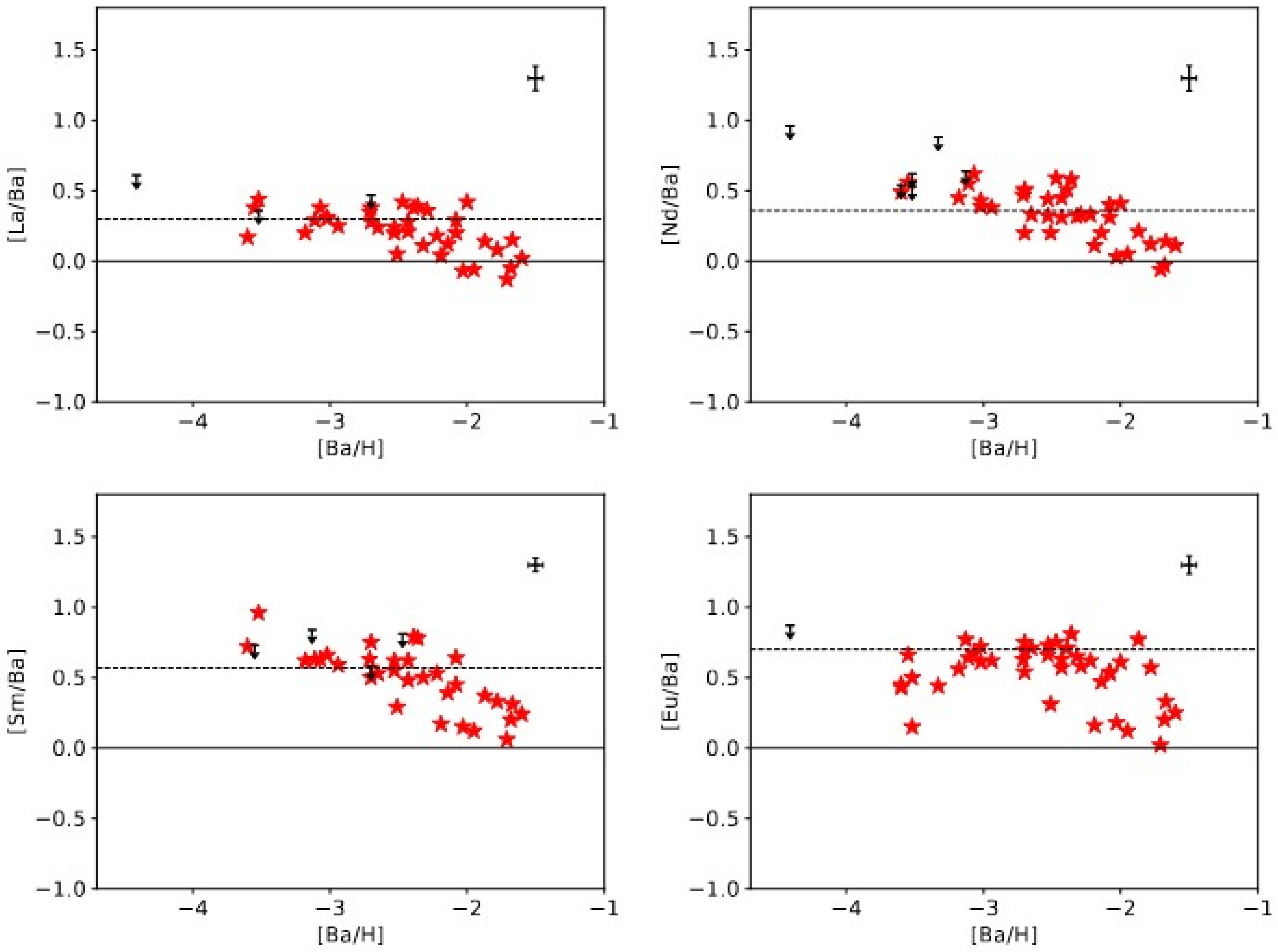
Linda
Lombardo

Lombardo et al. 2025
CERES III



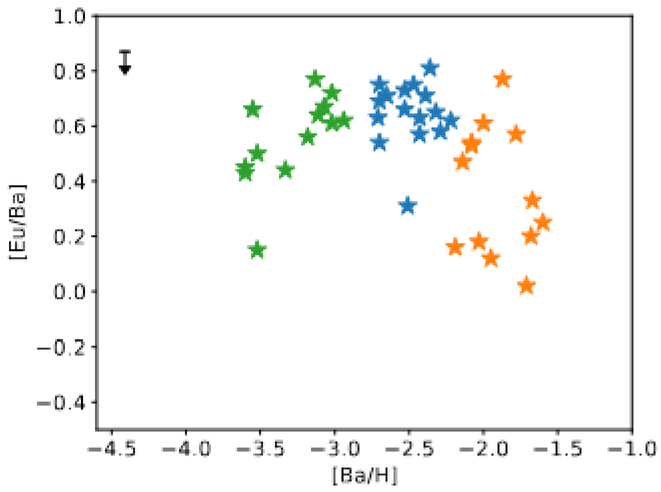


Rare earth elements as nuclear tracers



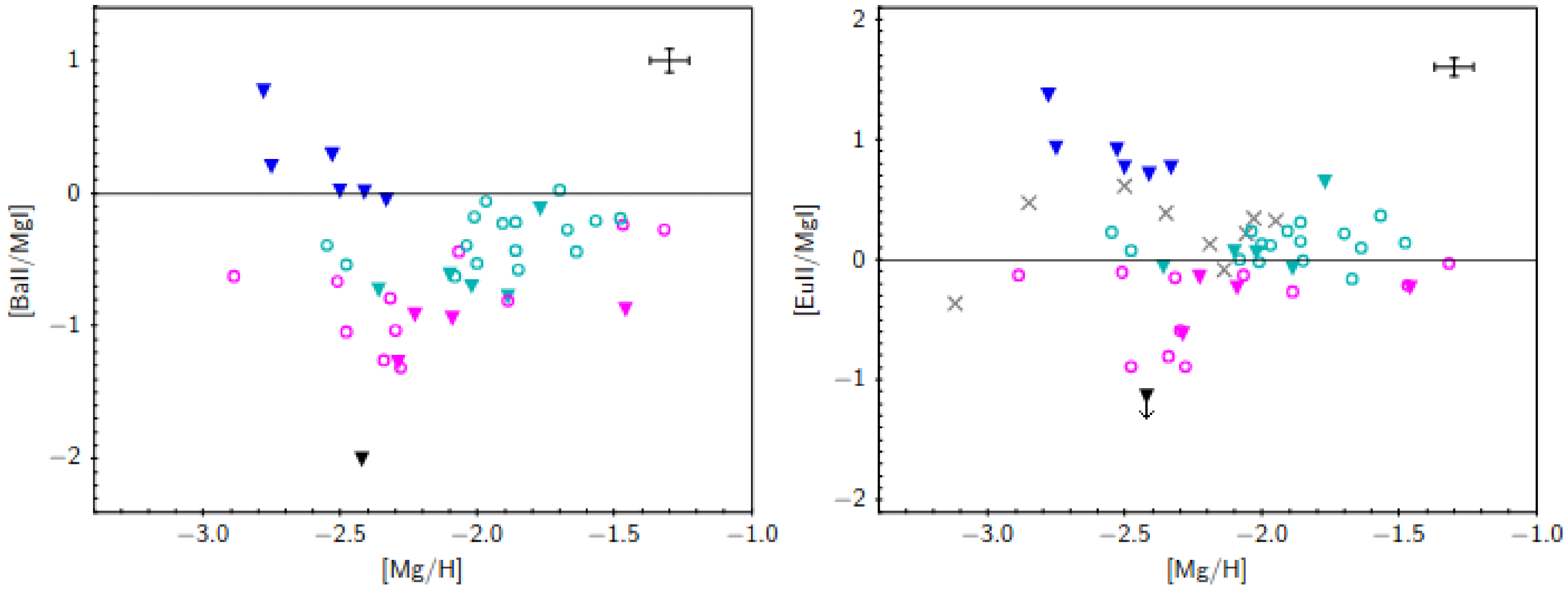
Lombardo et al. 2025
CERES III

Possible s-process onset



REE vs Mg – tracing massive stars (SN)

L. Lombardo et al.: Chemical Evolution of R-process Elements in Stars (CERES)



Legend:

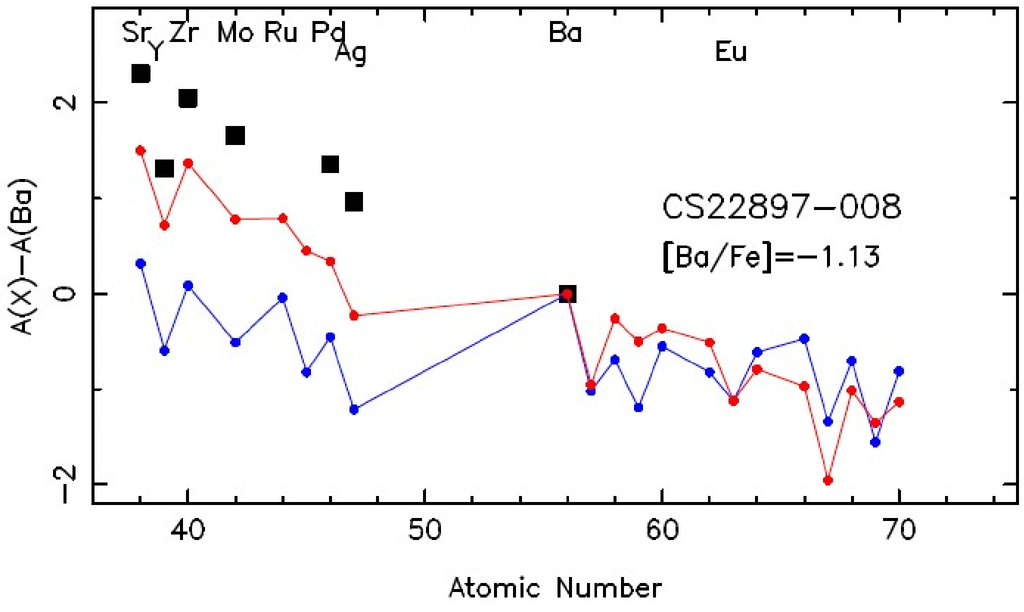
R-II

R-I

R-poor

Peculiar stars

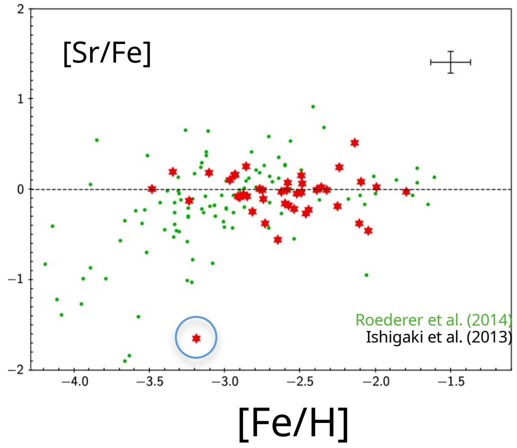
Spite et al. 2018

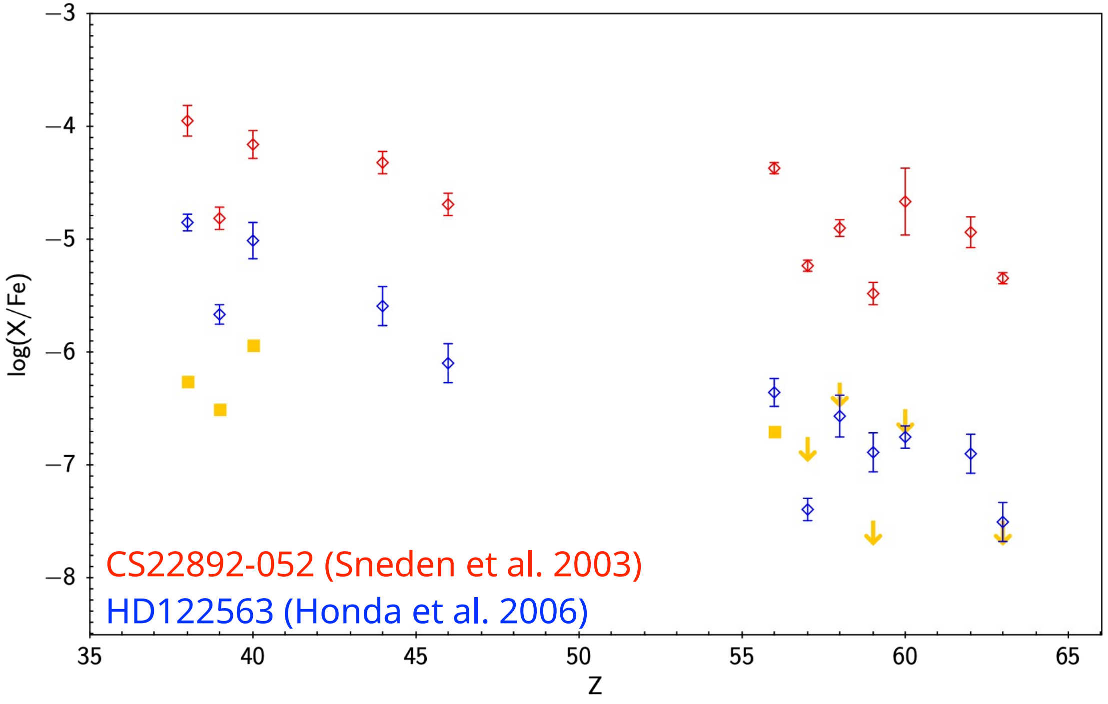


CS22897-008 [Sr/Ba] ~ 1.6
CS22892-052 (Sneden et al. 2003)
HD122563 (Honda et al. 2006)

Lombardo et al, in prep. 2025, 2022

- **BS16085-0050**
- [Sr/Fe]= −1.66,
- [Y/Fe] = −1.21,
- [Zr/Fe]= −1.04





Peculiar stars

Lombardo et al, in prep. 2025,
+ 2022, 2025

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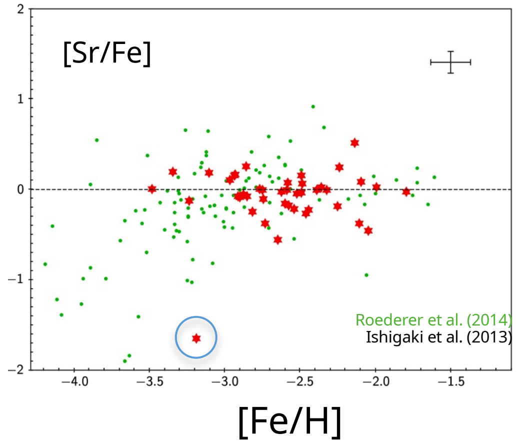
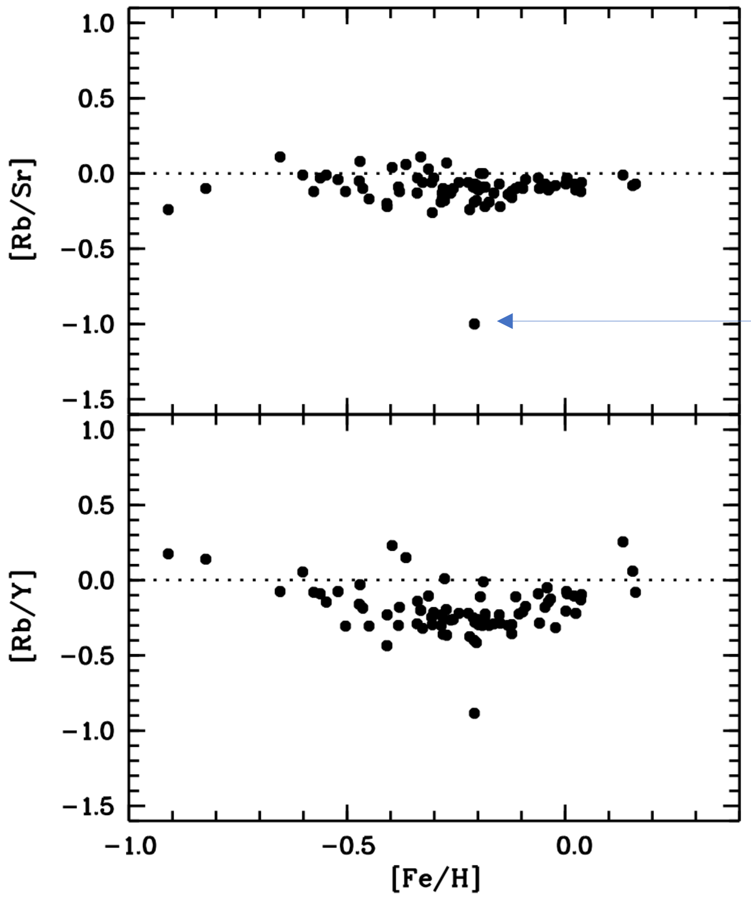
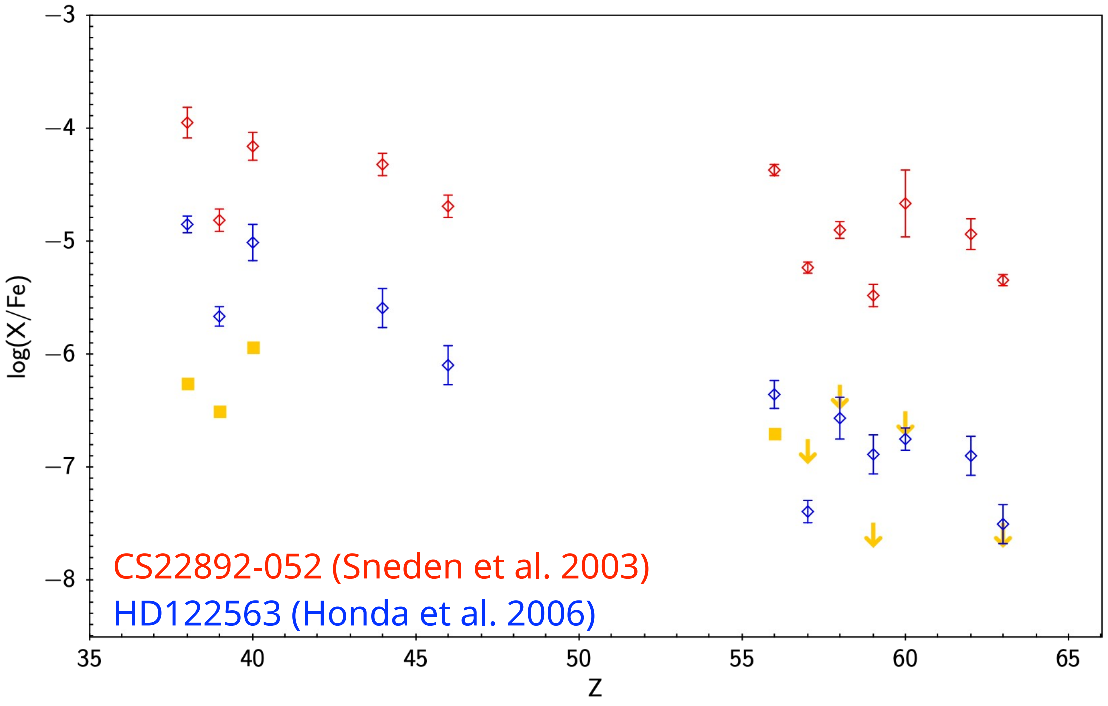


Caffau et al. 2016



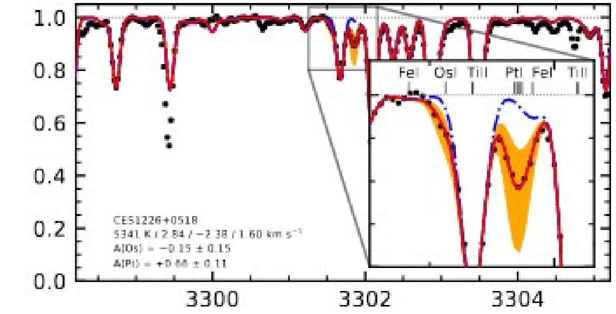
High
Sr!



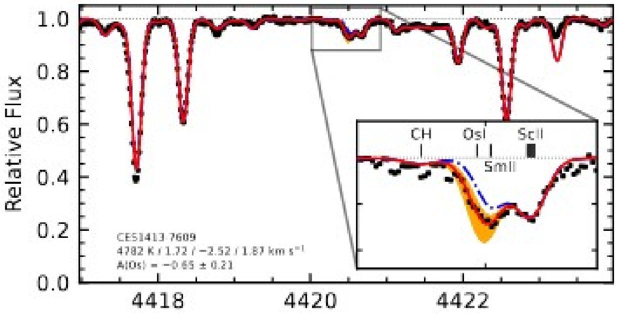
R-process in old, metal-poor stars

Arthur
Alencastro
Puls
Postdoc

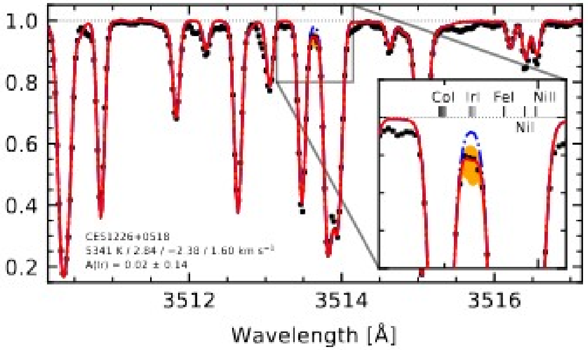
Pt



Os

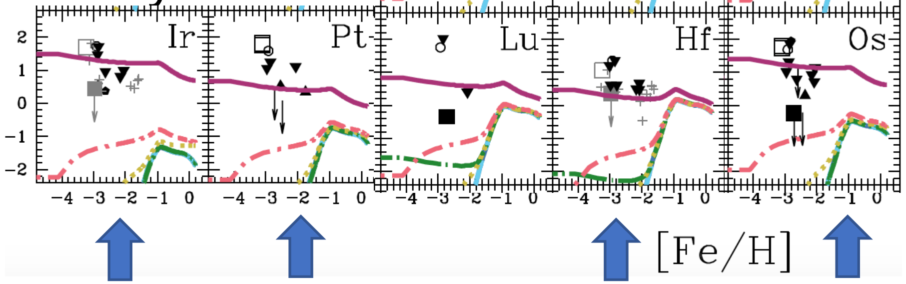


Ir

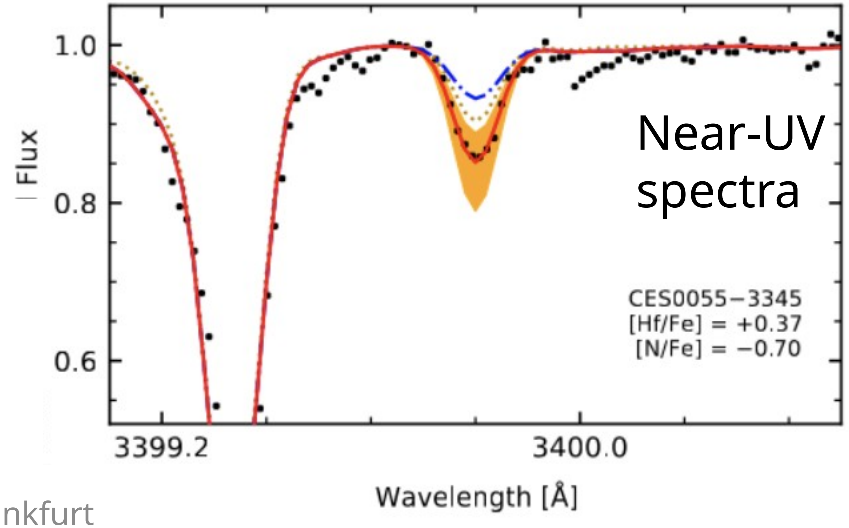


Alencastro Puls et al. 2025; CERES IV

Kobayashi et al.



Poorly studied heavy elements!



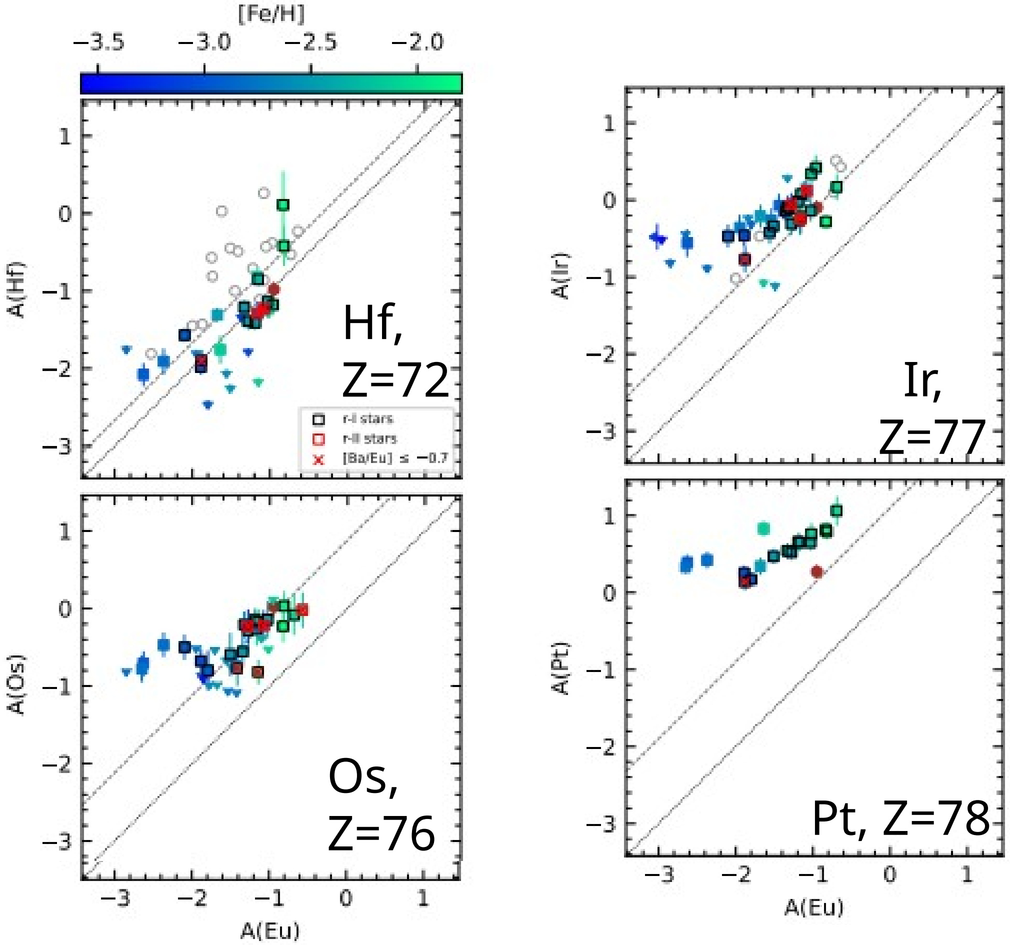
Near-UV spectra

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!

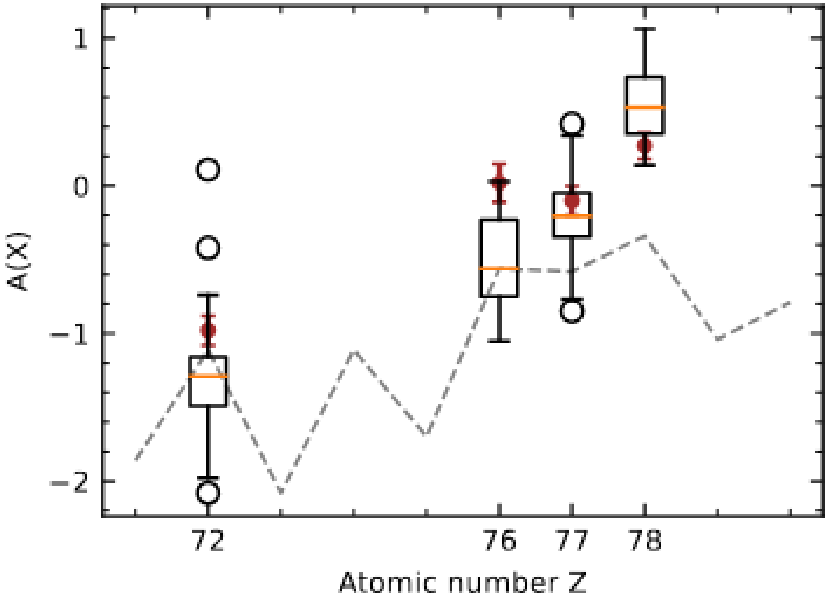
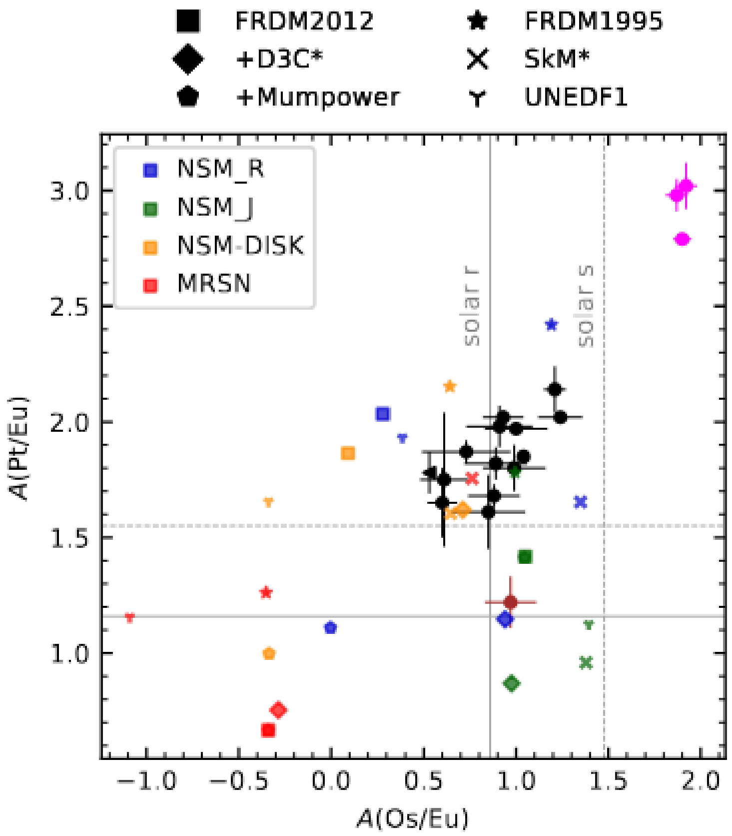
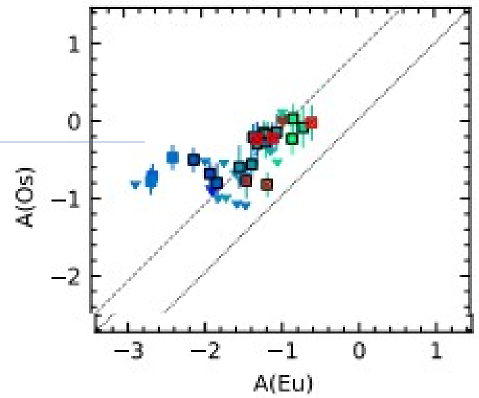


Fig. 9. Box plots representing the distributions of A(Hf, Os, Ir, Pt) in our sample. The orange lines represent the medians. The grey dashed line is the solar-scaled abundance normalised to the median of the Os abundances from this work. Open black circles are the outliers in our sample. The filled brown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

No good match!?



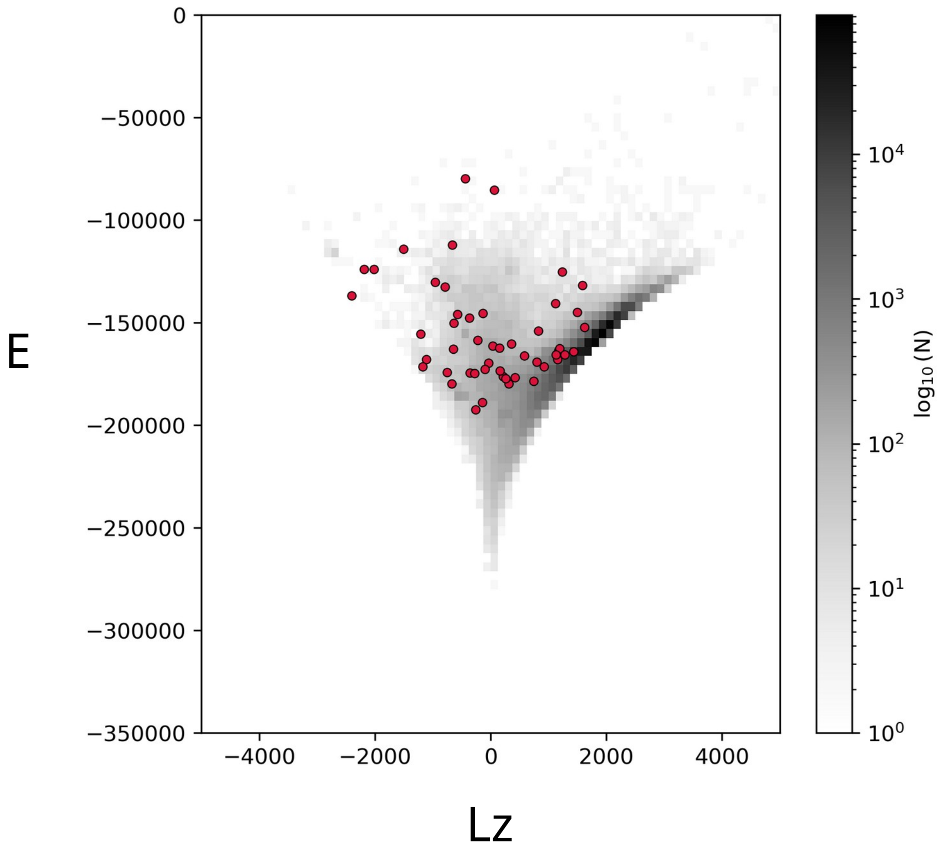
Tail



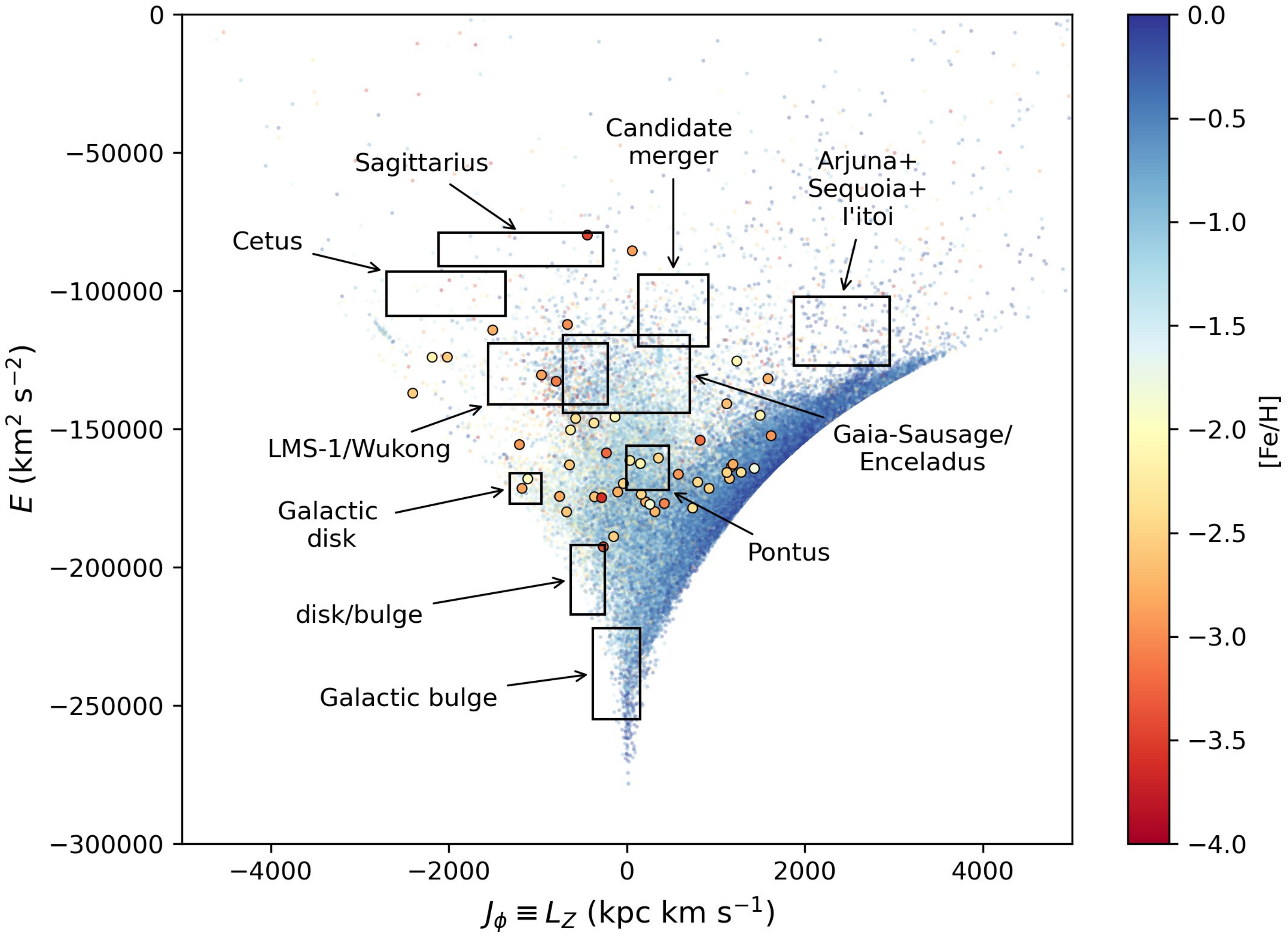
NSM_R – Rosswog et al. 2013
NSM_J – Jacobi et al. 2023
NSM-DISK – Wu et al. 2016
MRSN – Reichert et al. 2021

Kinematics

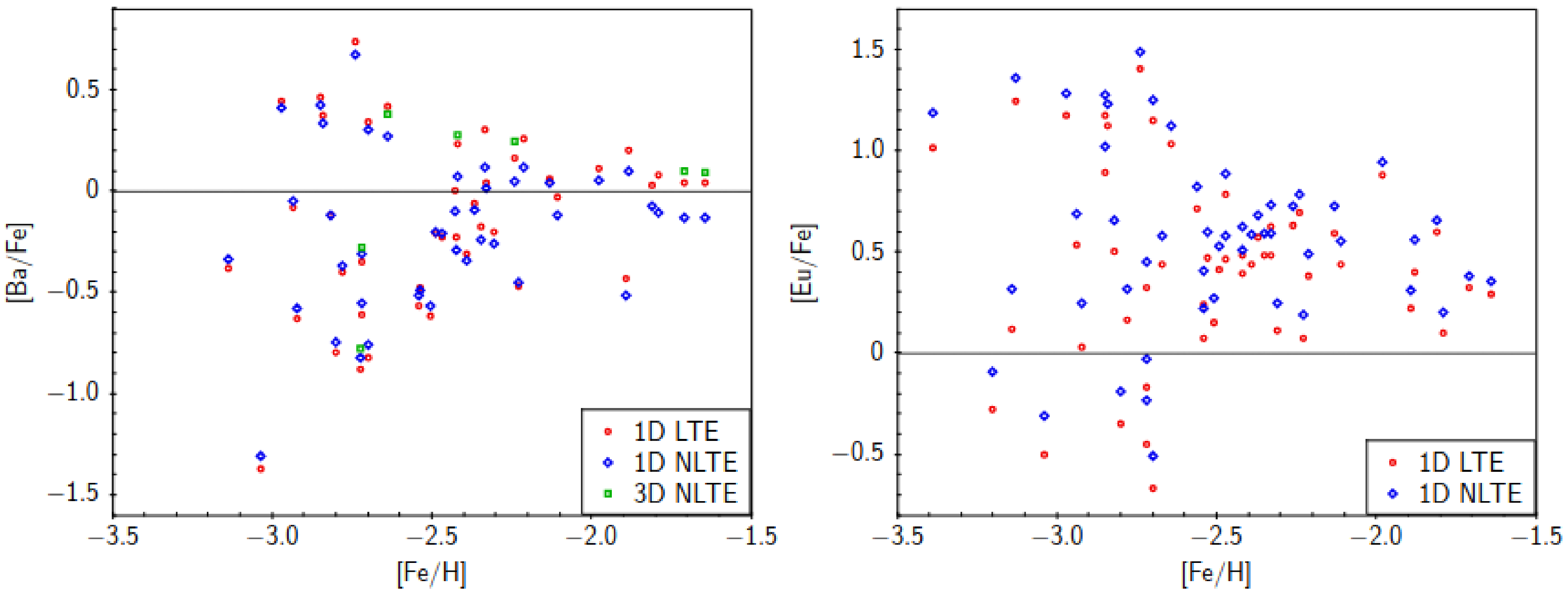
- Plonka in prep. (student)



CERES sample compared to GALAH data (background)

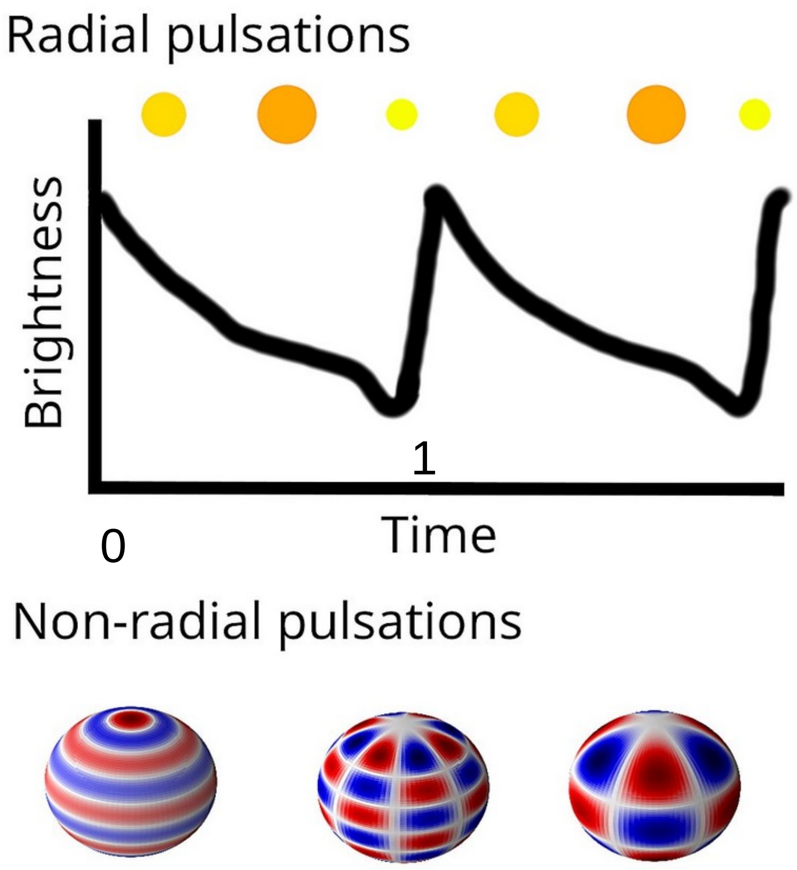


Ba in 1D LTE vs 3D NLTE – and Eu 1D NLTE



Lombardo et al. 2025,
CERES IV

Metal-poor, old, evolved RR Lyrae



The variation in light comes from the pulsations → the size varies → stellar parameters vary:

T by ~ 2000K,
Logg by ~ 1.5 dex
(Pena et al. 2009)

Best phase is close to minimum light
(Kohlenberg et al. 2010)

For spectroscopic analysis, phase 0.9 – 0.1 should be avoided due to the rapid atmosphere changes

Metal-poor, old, evolved RR Lyrae

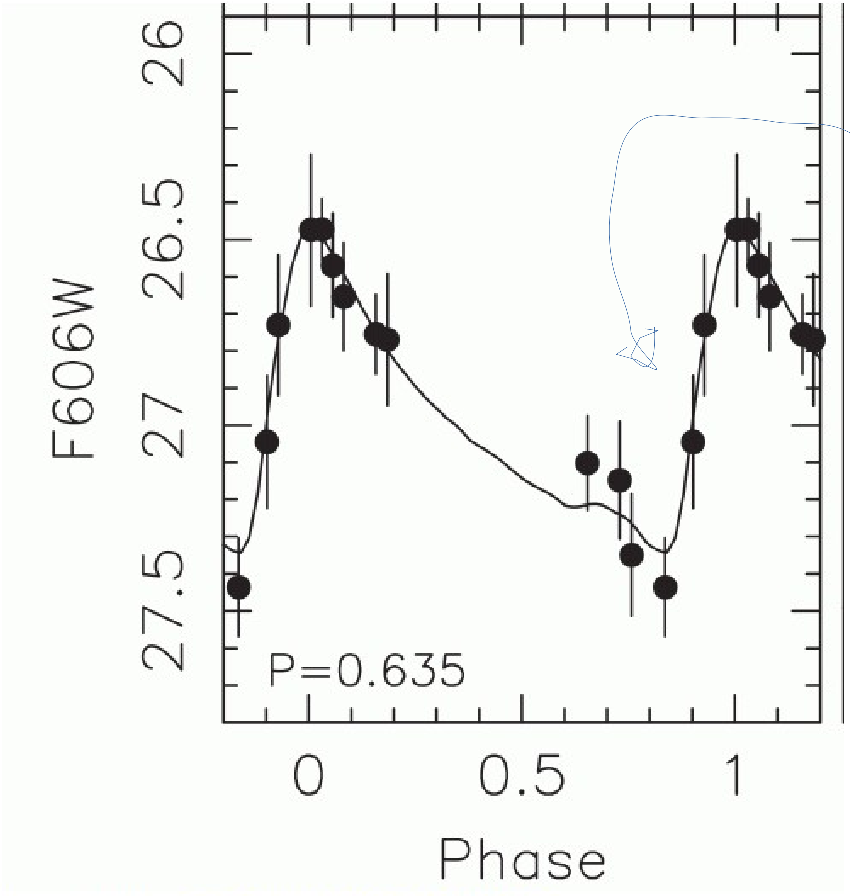
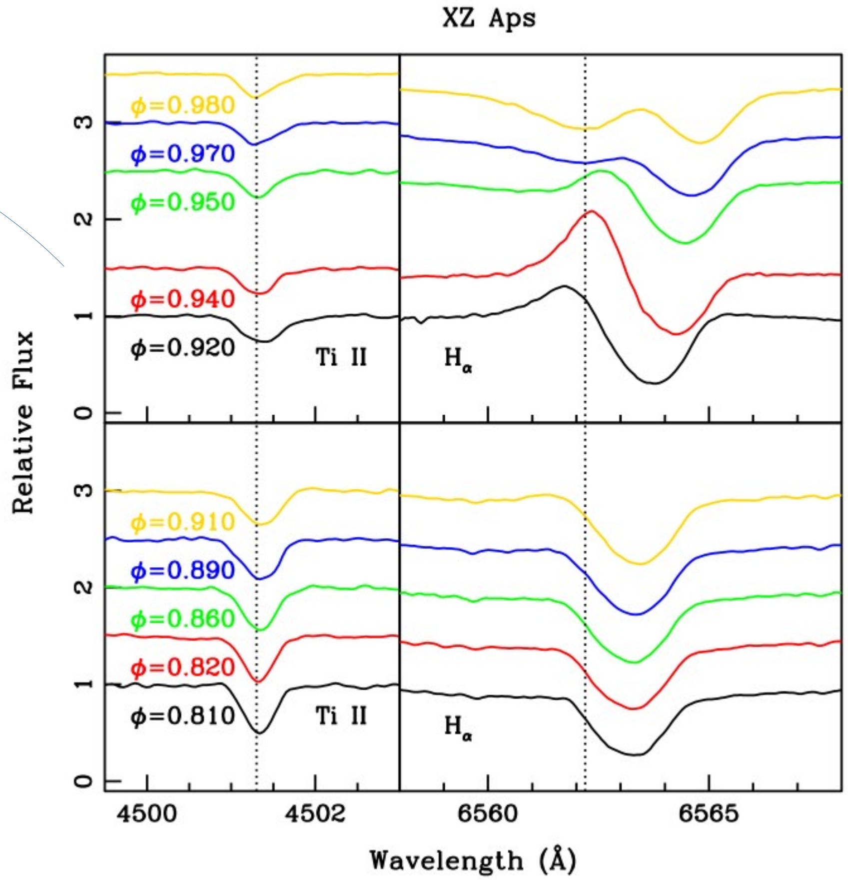
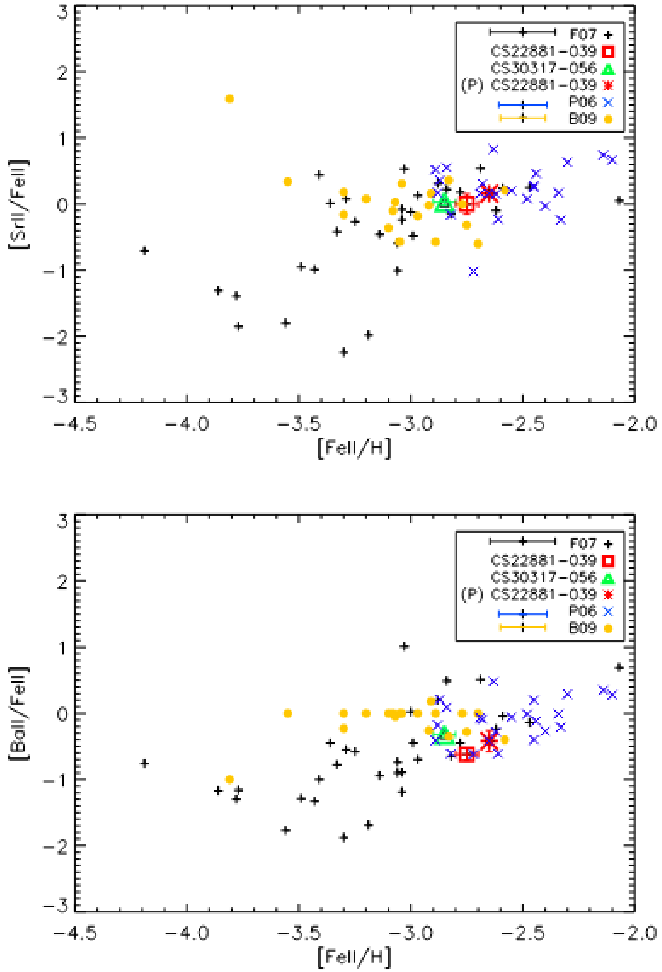


Figure taken from Da Costa et al., ApJ 708, 121 (2010)

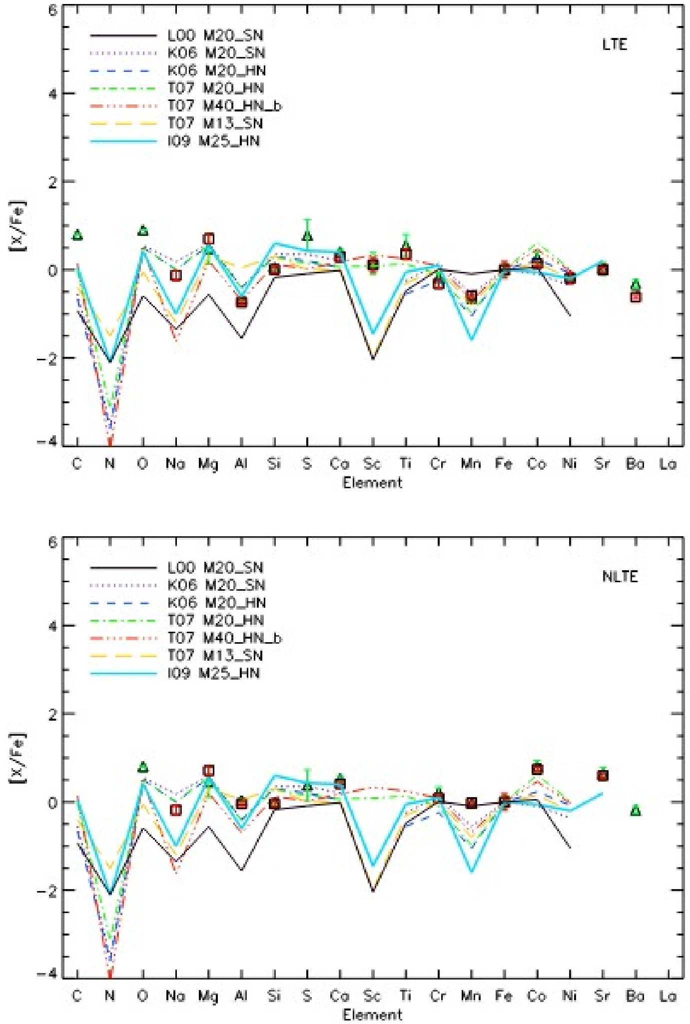


Metal-poor, old, evolved RR Lyrae



In a quiet phase, we can derive abundances from RR Lyr stars and place them in GCE context (left) or if we have a pattern we can look for possible formation sites, since these stars are truly old (right)

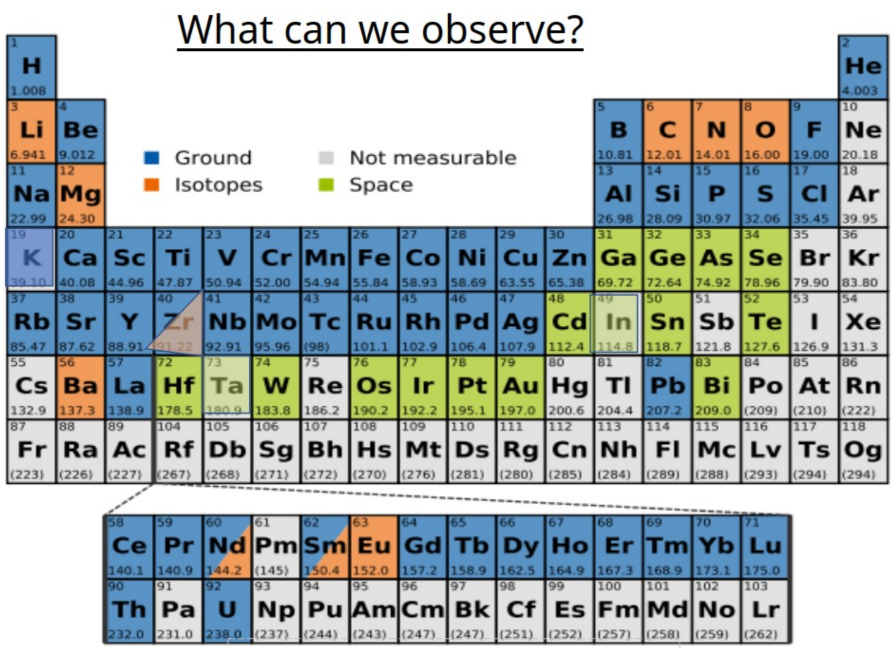
Hansen et al. 2011, see also D'Orazi et al. 2025

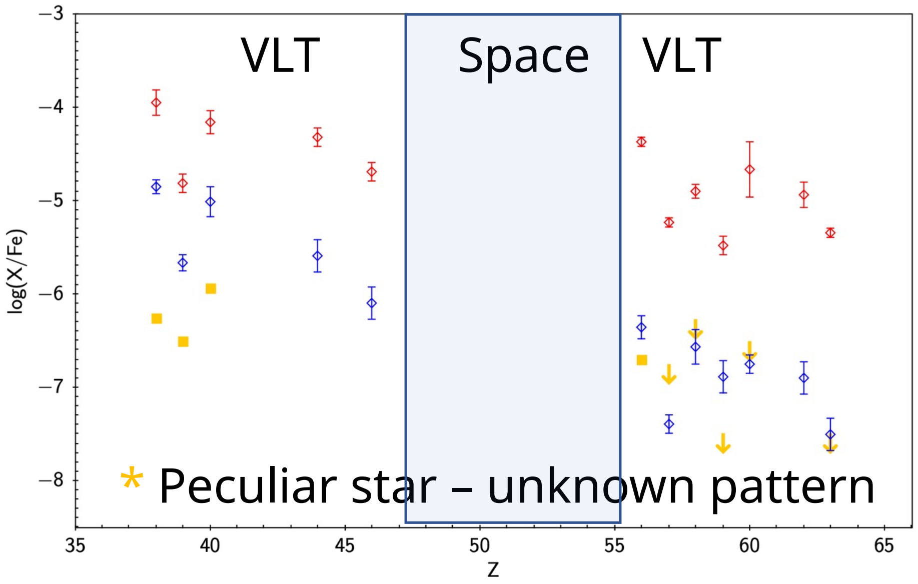


Summary

With almost complete abundance patterns of ~70 elements in old stars we can explore:

- Stellar evolution and self-enrichment
- Early chemical enrichment of the Galaxy
- Nuclear formation processes (physics)



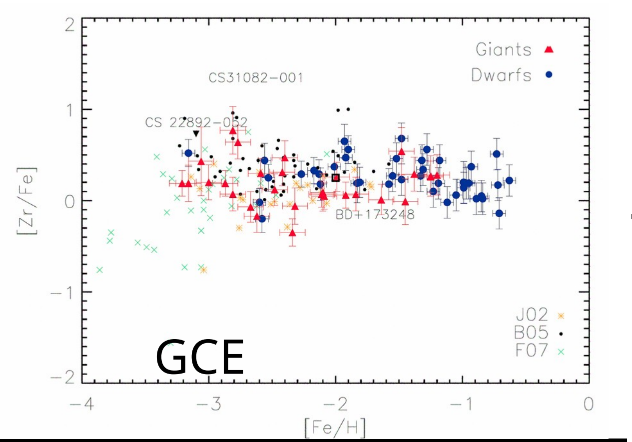


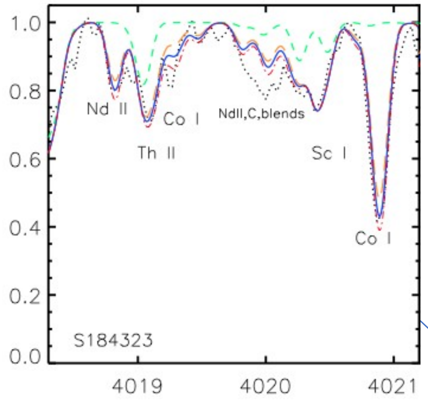
Lombardo et al. in prep.
CERES V

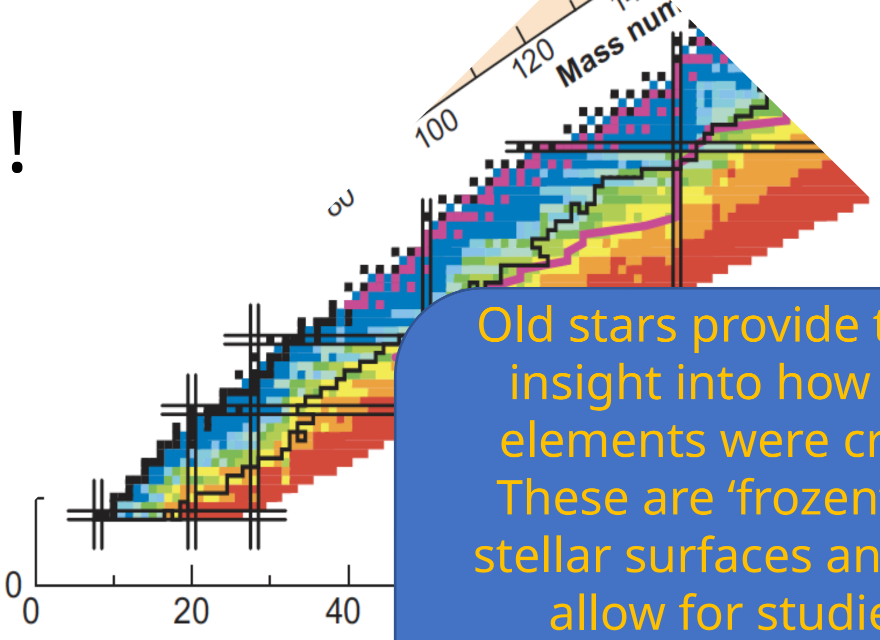
Goals and limitations:

- More complete patterns
- Elemental abundances – not isotopic (only ~7 elements)
- 3D, NLTE (atomic data)
- ELT, CUBES, HST + smaller follow-up surveys needed…

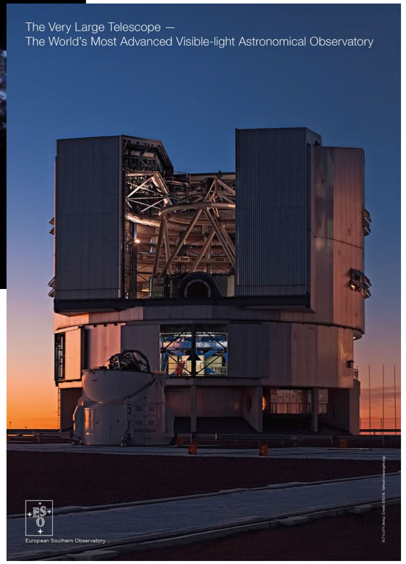
Stars – and why we observe them!



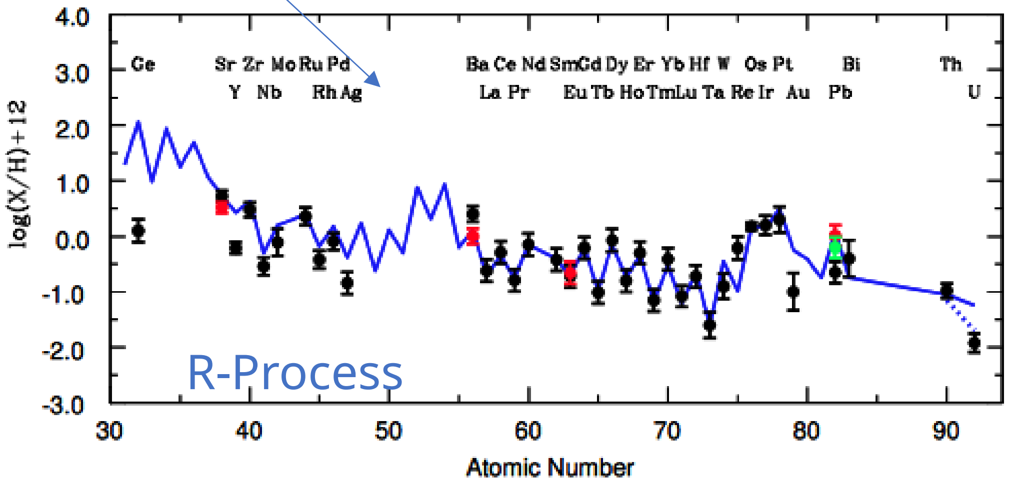




Old stars provide the first insight into how heavy elements were created. These are 'frozen' in the stellar surfaces and today allow for studies of nucleosynthetic events that occurred 13 billion years ago.



Th & Eu → Age



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