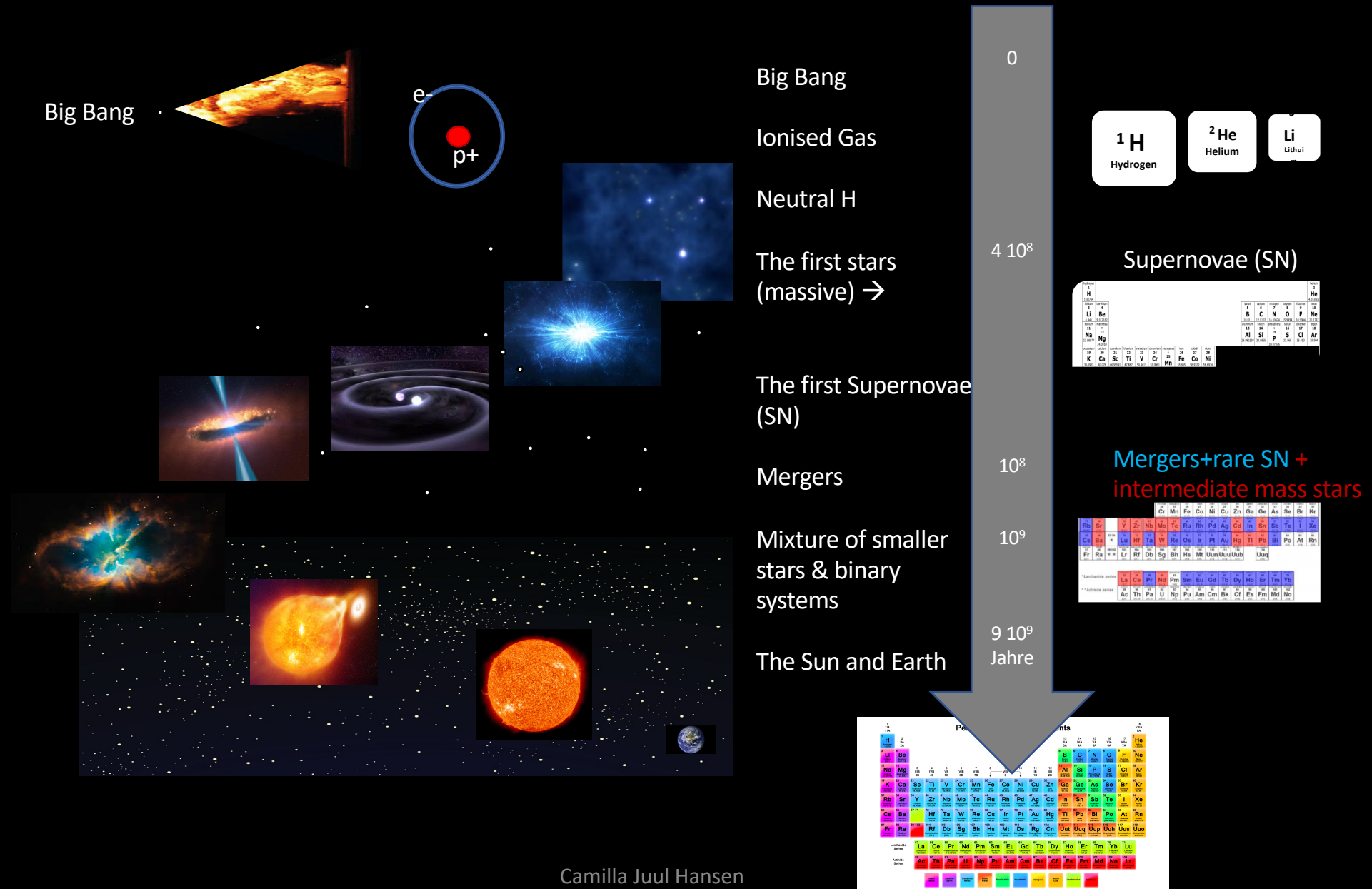


From observations to nuclear reactions and Galactic evolution

Camilla Juul Hansen
Institute for Applied Physics,
Goethe University, Frankfurt

EASE School 2024

Evolution of the Universe in 1 slide



The Night sky



What can we observe?

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)
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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)

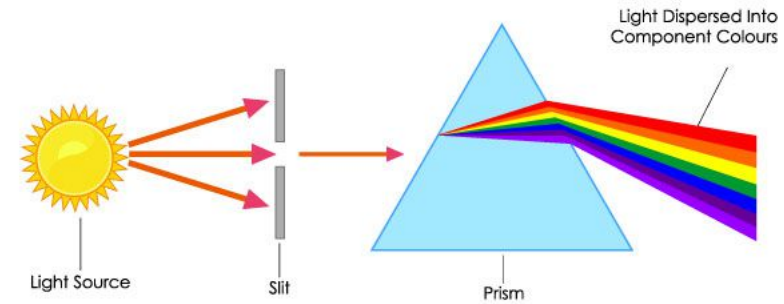
Spectral analysis



Kirchhoff
&
Bunsen
~1860

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

Dispersion of Light Through Prism



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

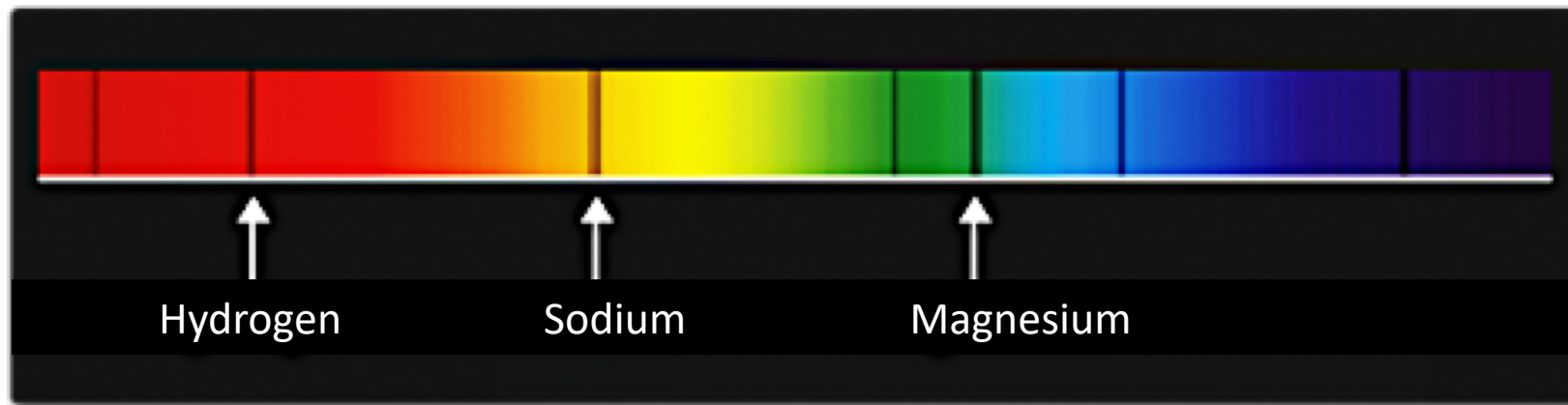


Image: https://science.nasa.gov/ems/09_visiblelight

Our reference star – the Sun

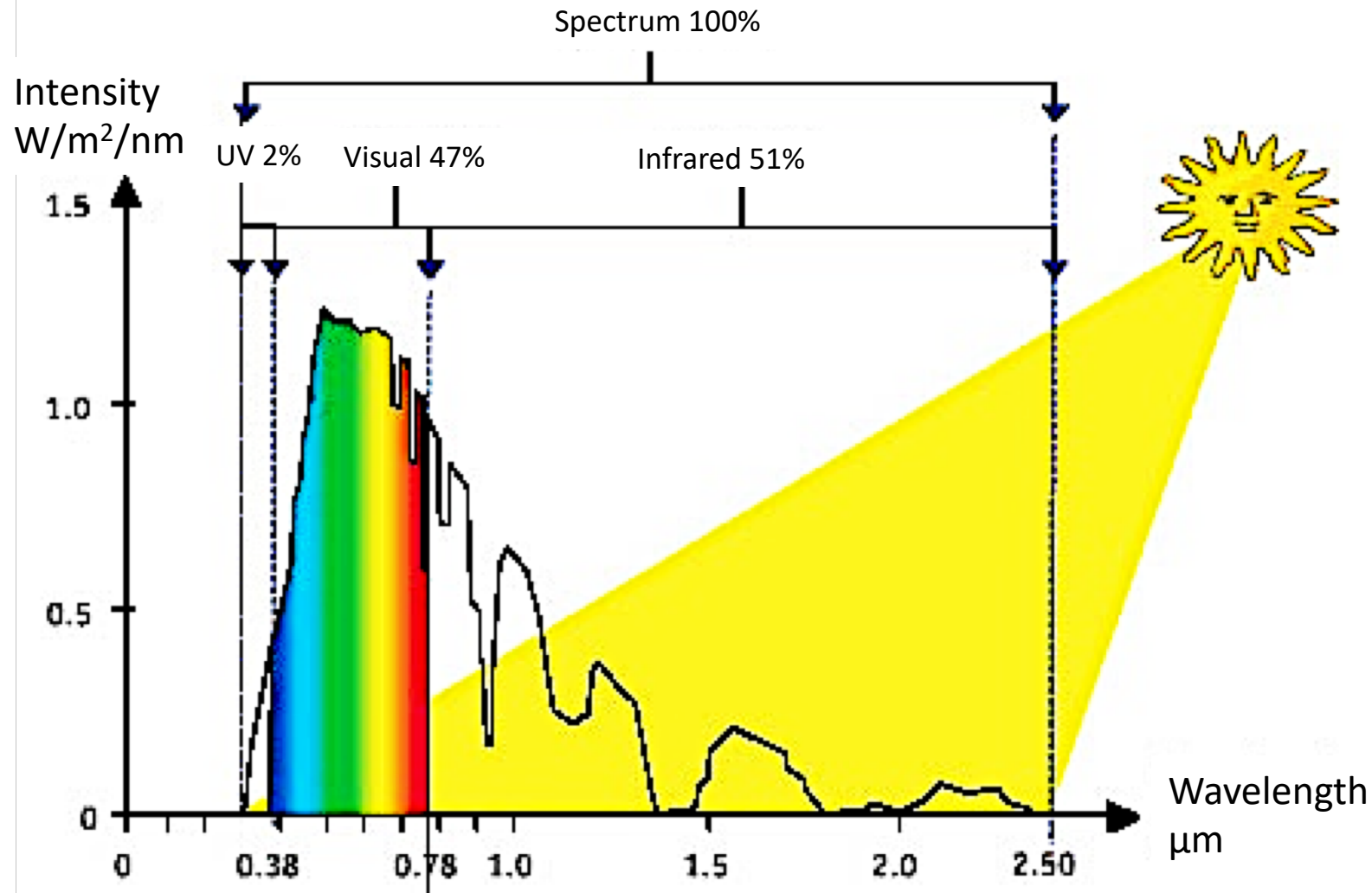
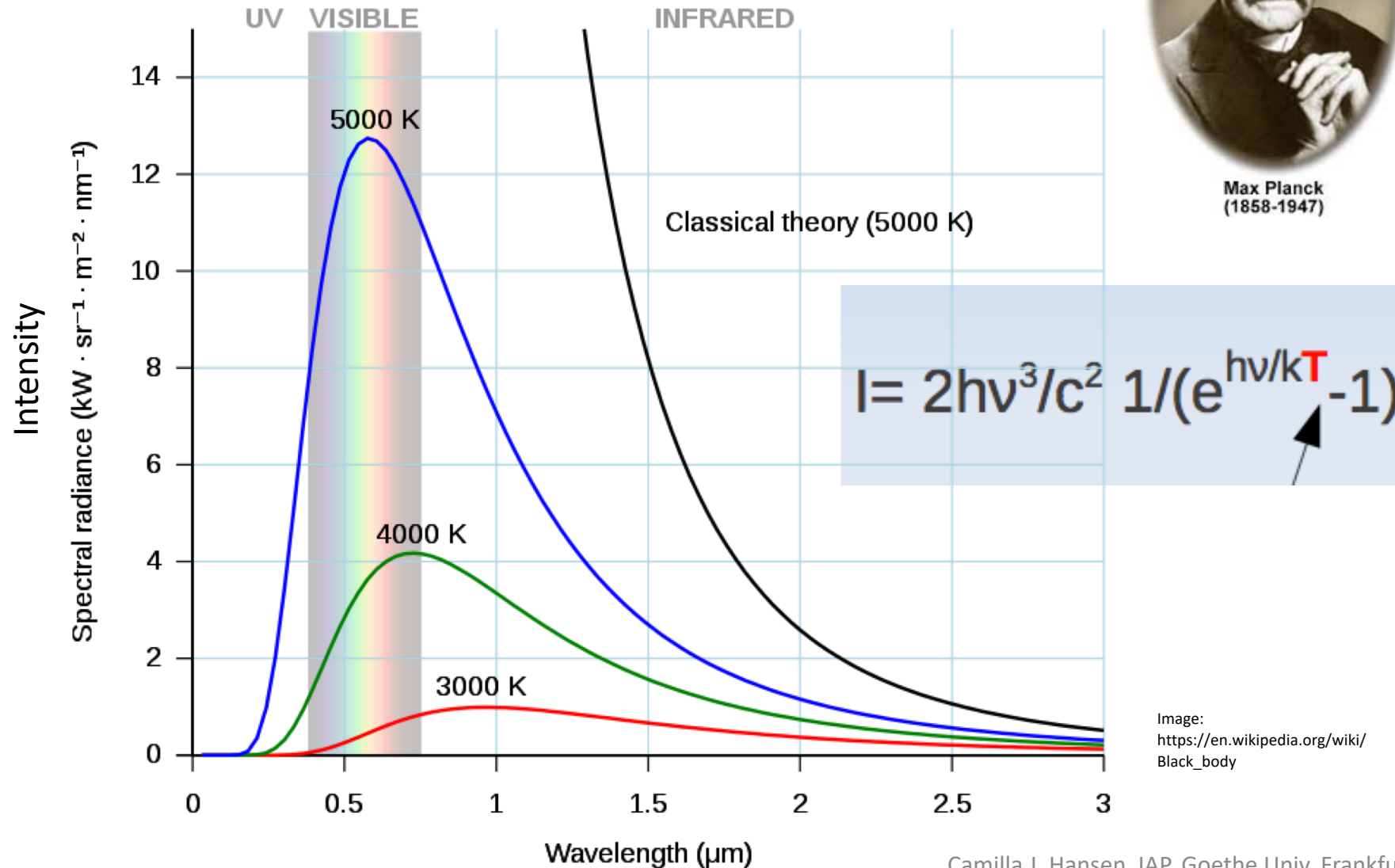


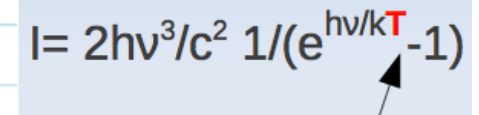
Image: scottamyx.com, <https://bestleader-intl.weebly.com/solar-energy-and-solar-window-film.html>

Temperature in Stars



Max Planck
(1858-1947)

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



Spectra:
Temperature
Pressure
'Metallicity'
Chemistry

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

Spectral analysis & Data reduction

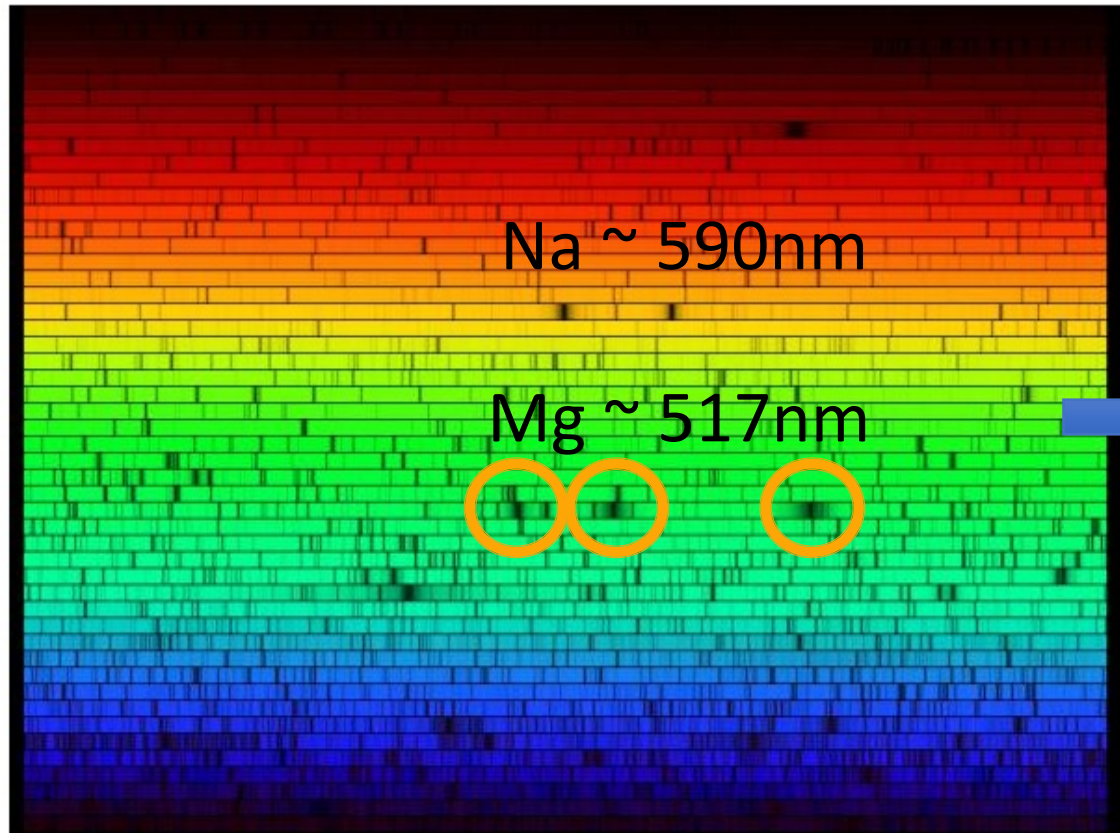
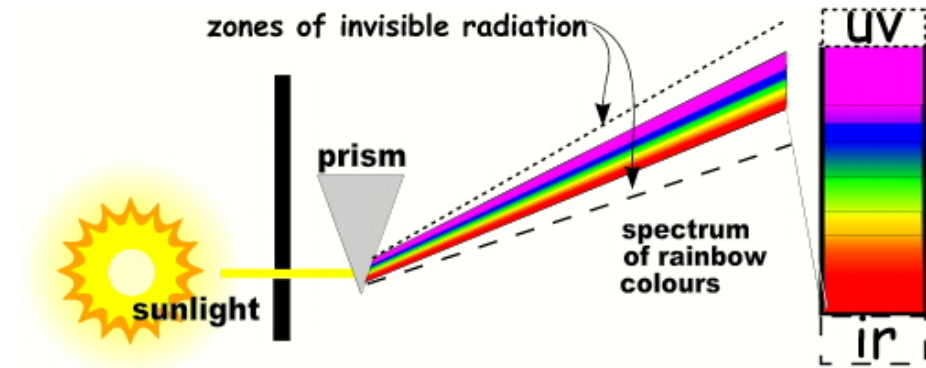
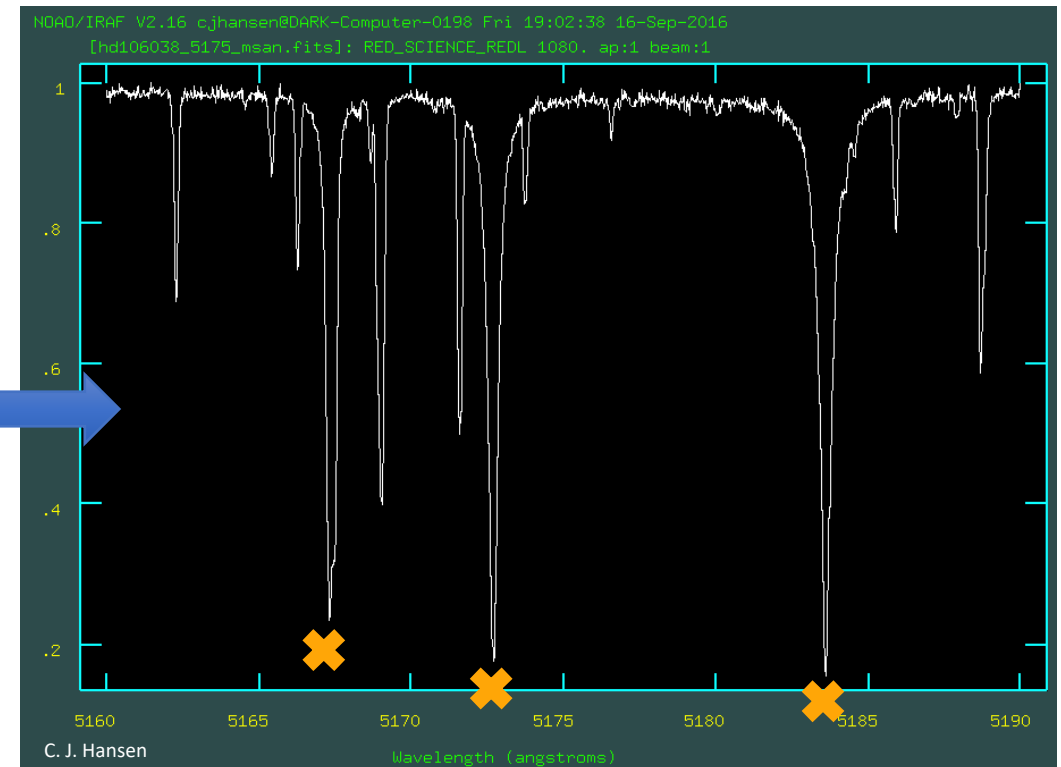
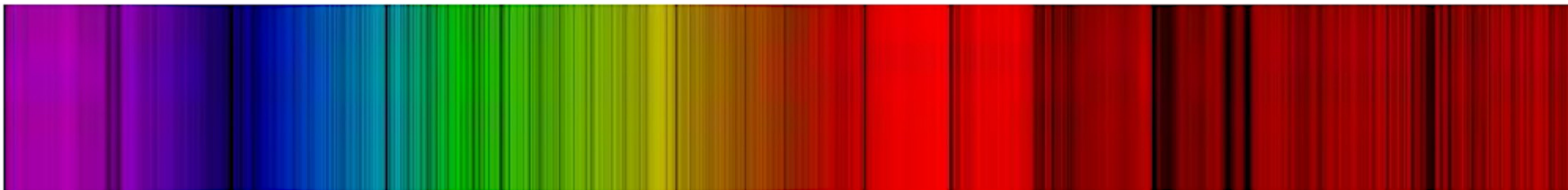
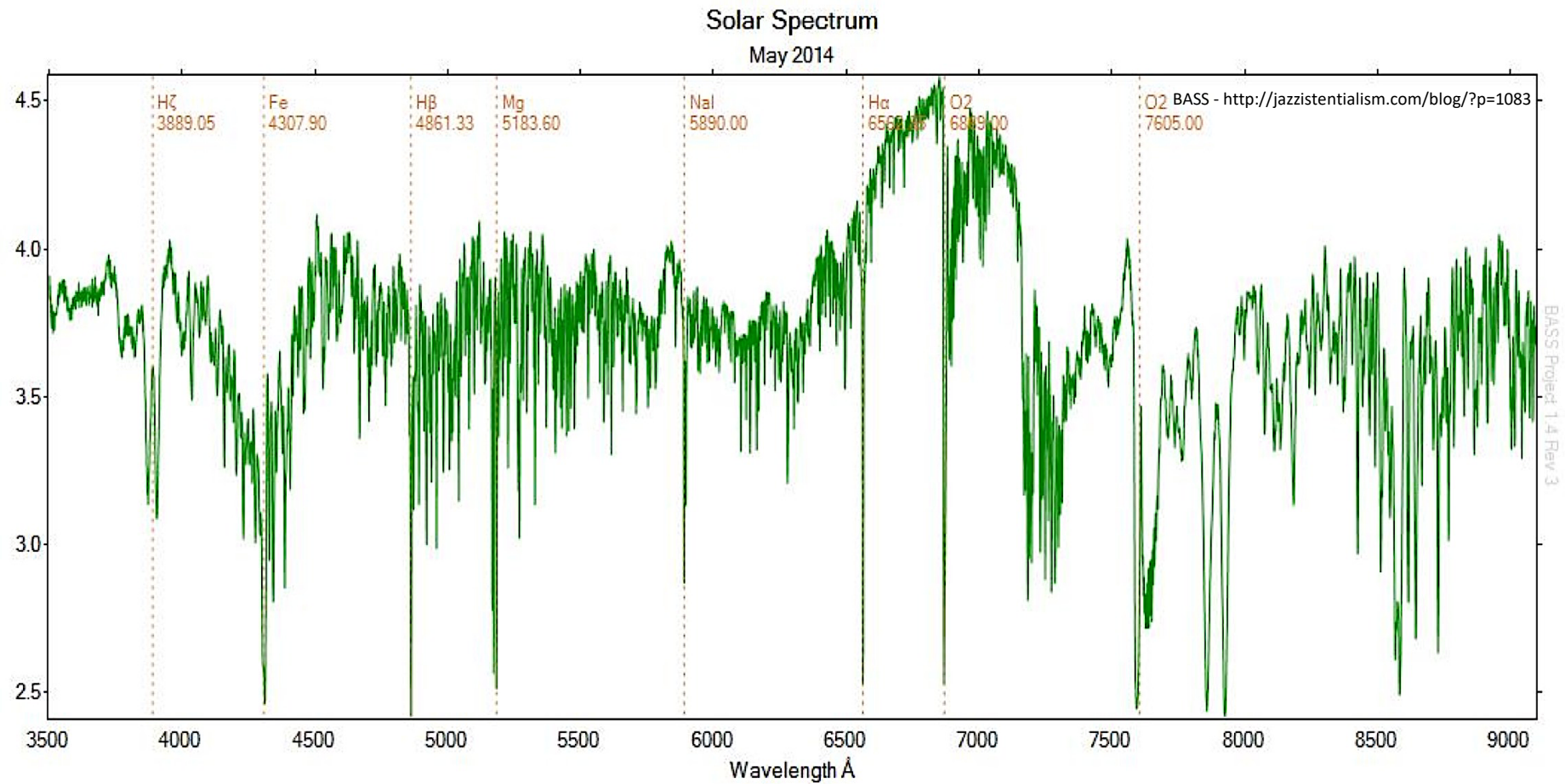


Image: <https://apod.nasa.gov/apod/ap180926.html>



Camilla J. Hansen, IAP, Goethe Univ. Frankfurt

Solar spectrum & Information



Spectral analysis

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

Equivalent Width (EW or W)

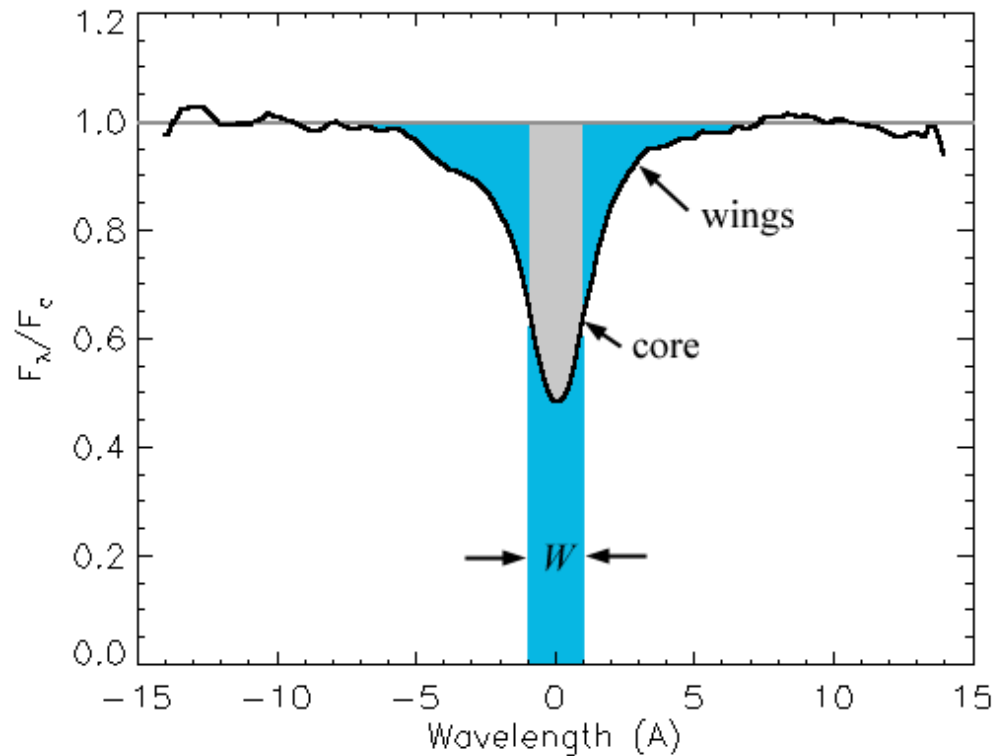
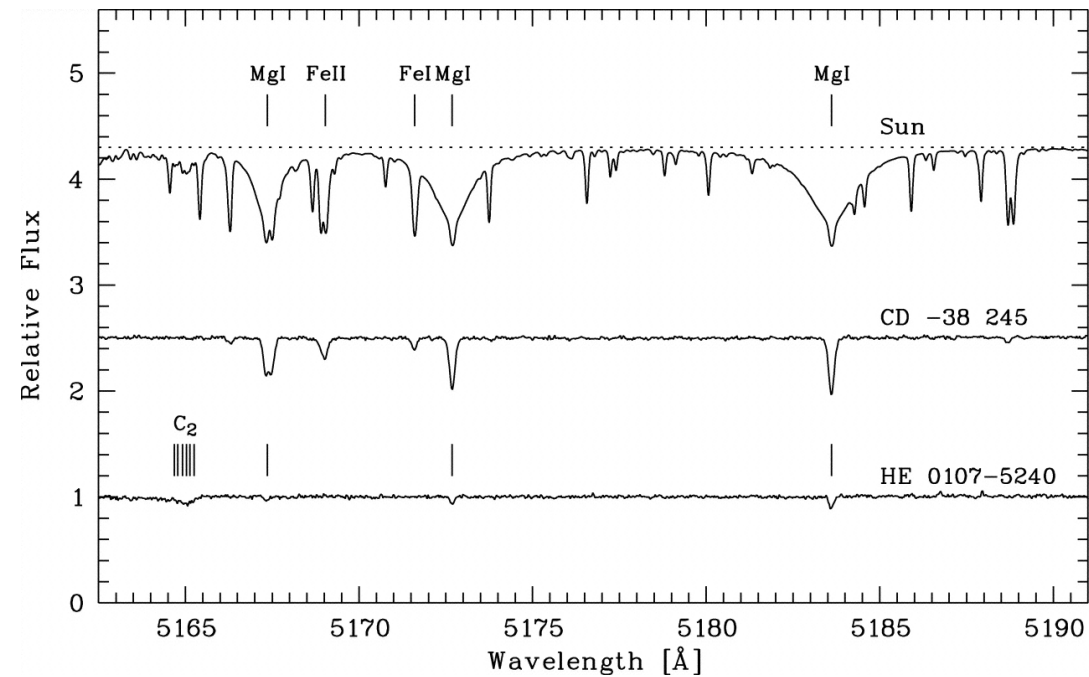
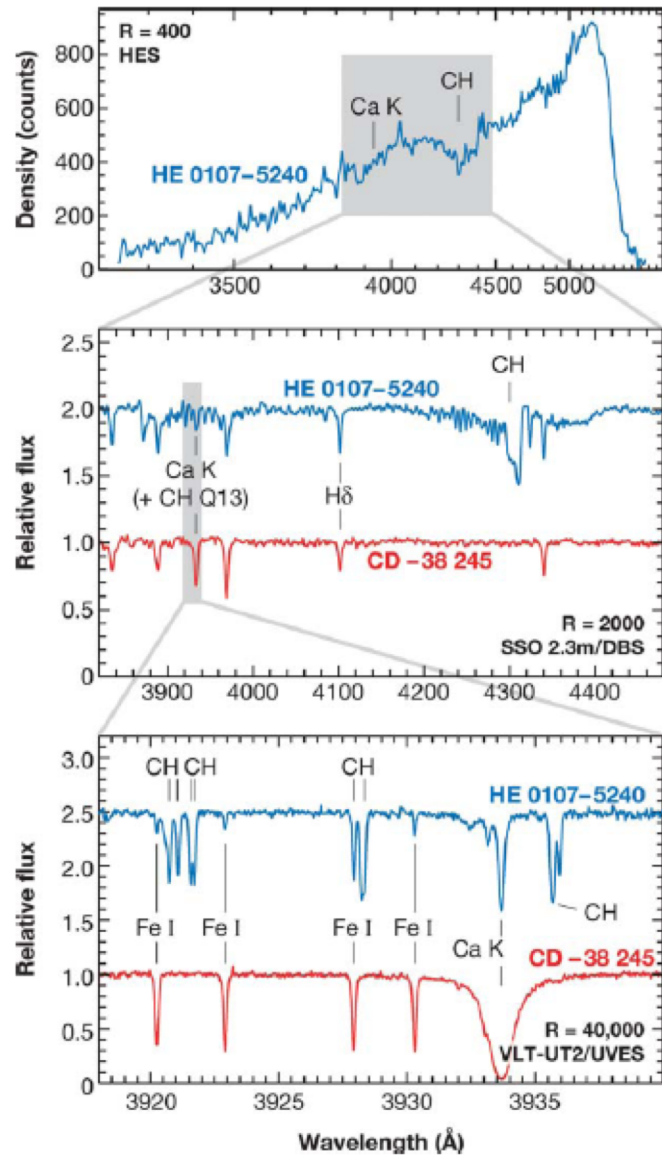


Image: <http://www.bdnyc.org/2012/03/spectral-line-measurements-visualized/>



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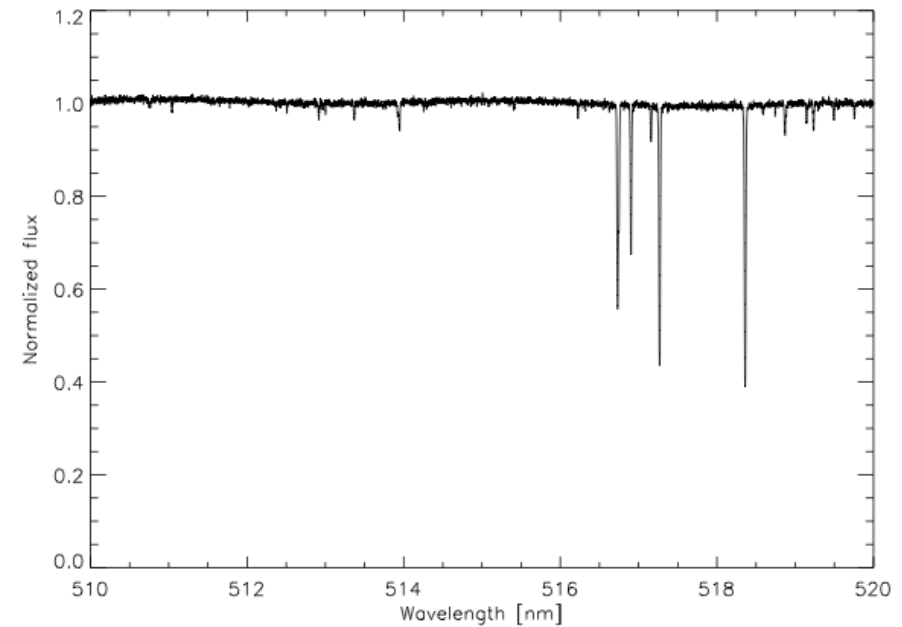
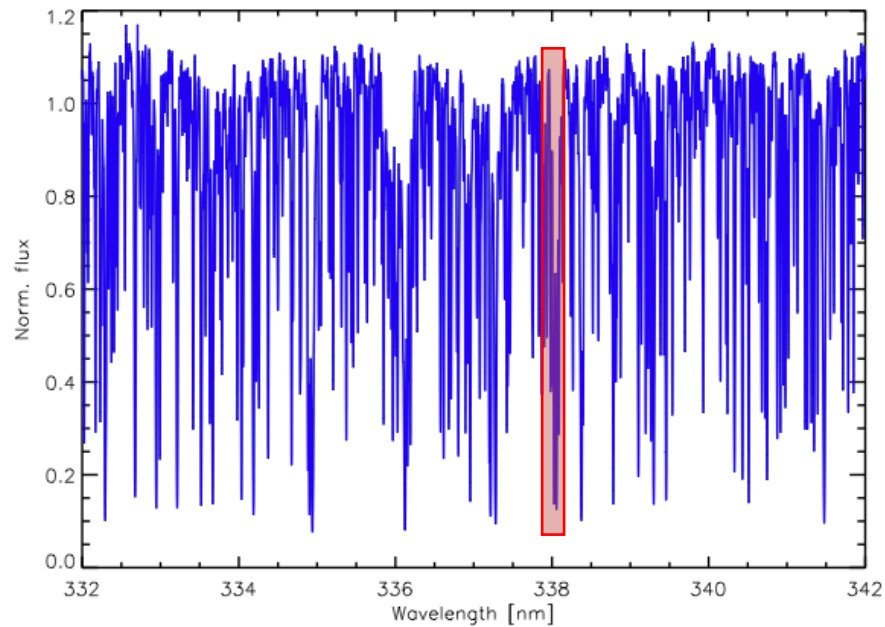
Old stars vs the Sun



Beers & Christlieb 2005, ARA&A

Spectral analysis

Blue vs visual spectra

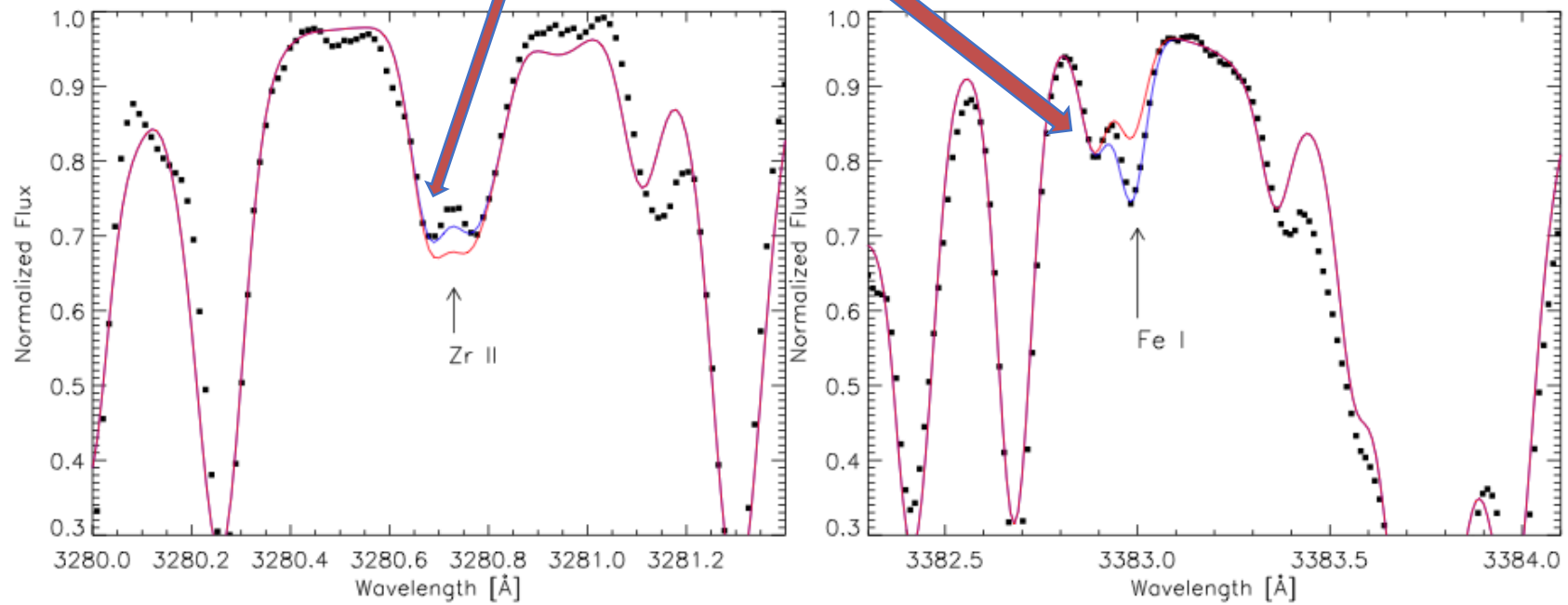


Images: C. J. Hansen

Analysing UV-Linies



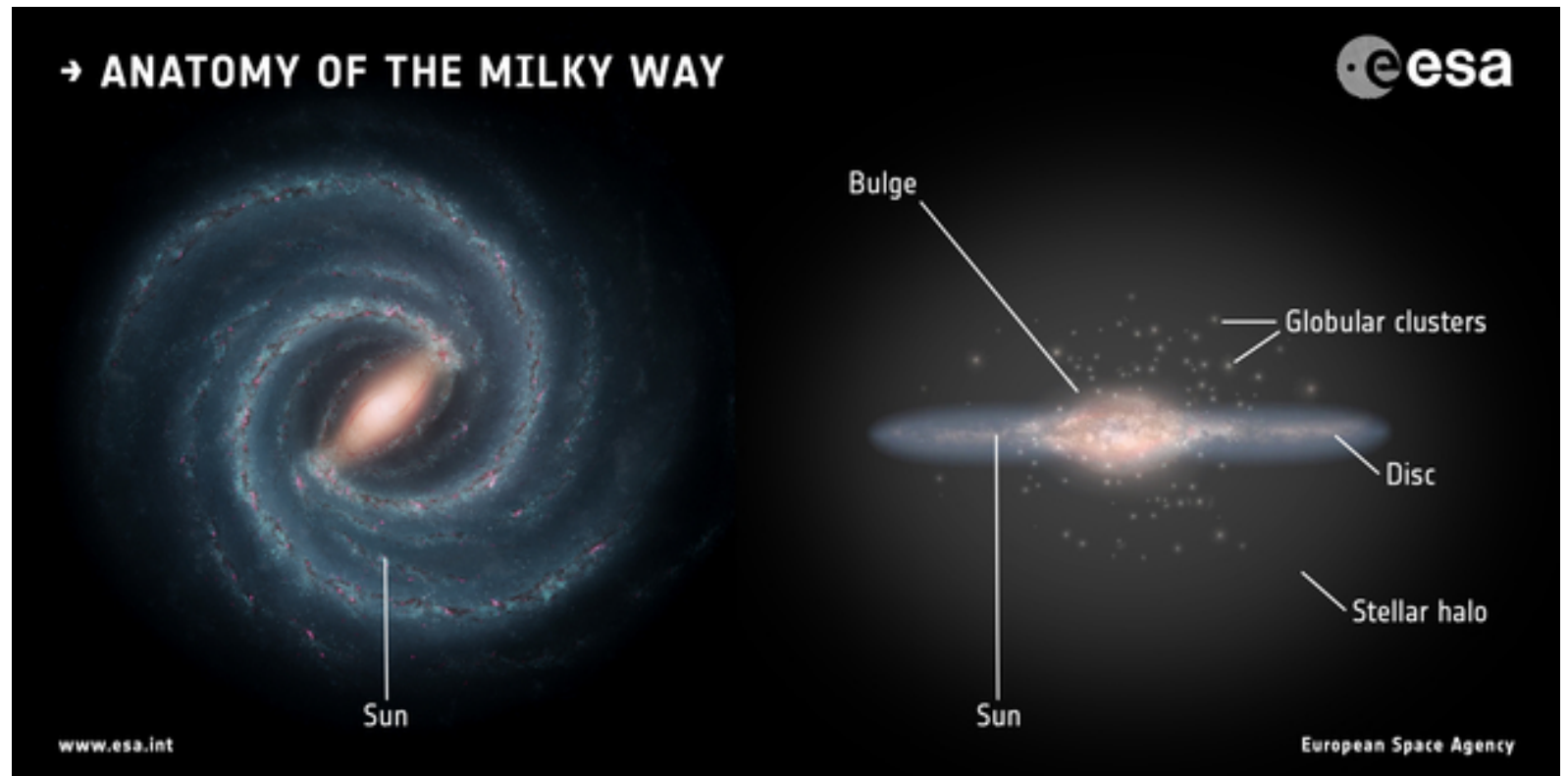
Silver (Ag, Nr. 47)



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



Spectral analysis

Tools of the astronomer/spectroscopist:

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

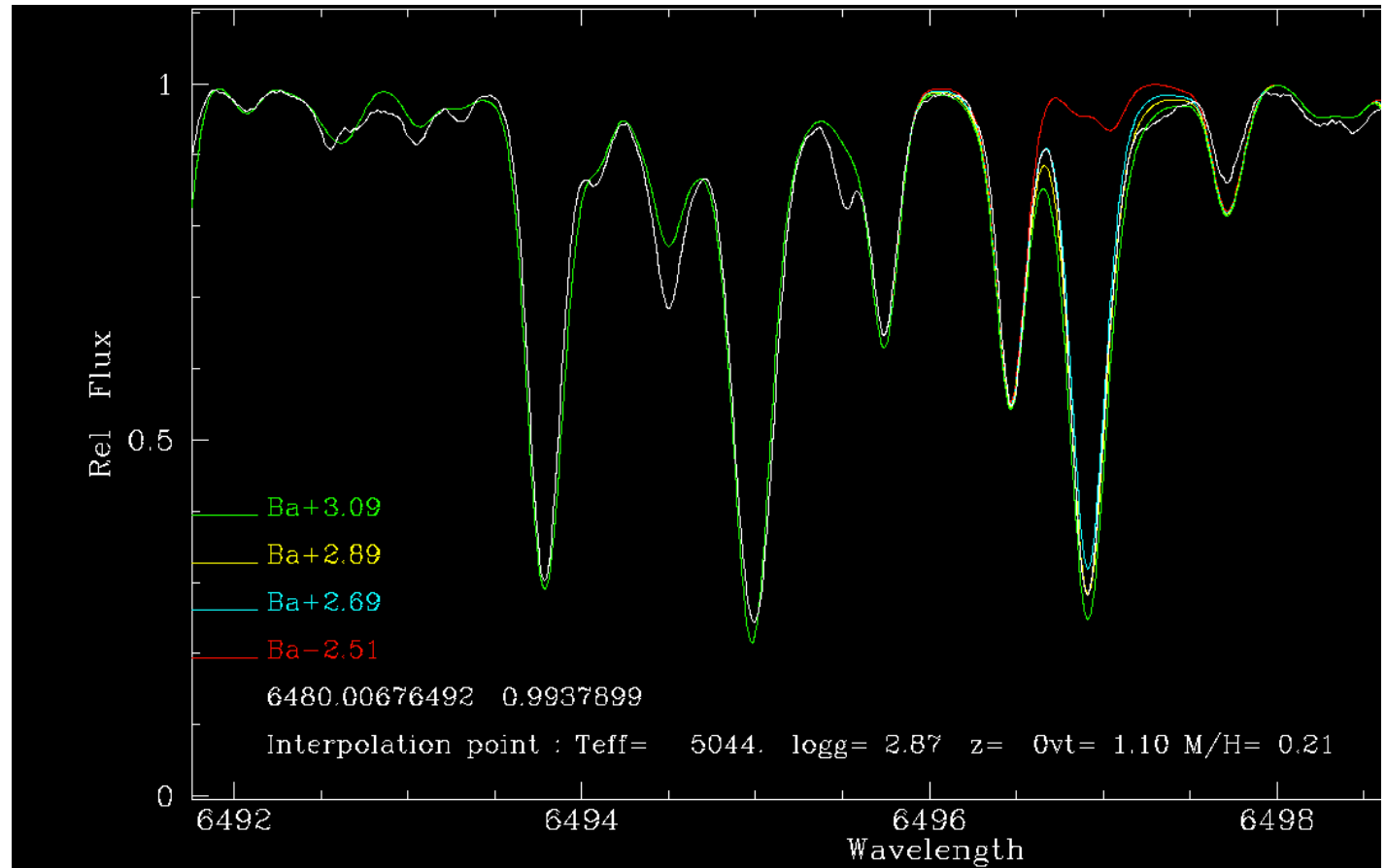
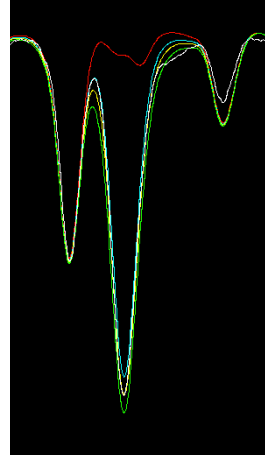
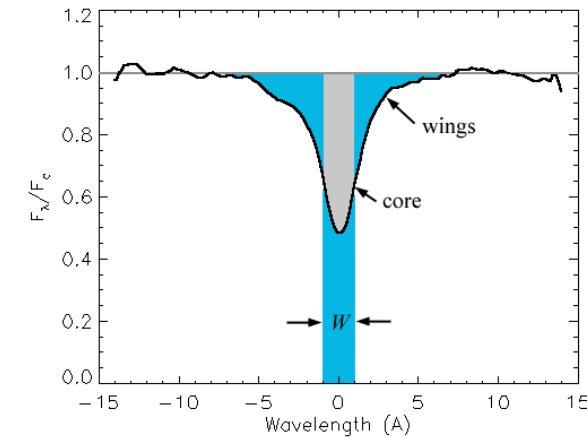


Image: C. J. Hansen

Stellar abundances

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



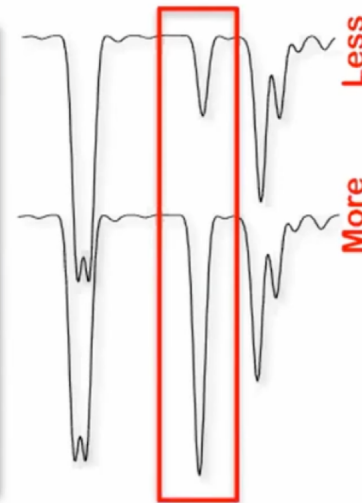
"Amount" of absorbers in a stellar atmosphere, normalized to a reference value. It reflects the atmosphere's *chemical composition*.

→ **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)

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

$$= \log C + \log A + \log g_n f \lambda - \theta_{\text{ex}} \chi - \log \kappa_v. \quad (16.4)$$

Diagram illustrating the components of the abundance equation (16.4):

- EW Equivalent width** (blue arrow pointing to $\log(w/\lambda)$)
- Const.** (black arrow pointing to $\log C$)
- Abundance** (orange arrow pointing to $\log A$)
- Atomic data (oscillator strength)** (yellow arrow pointing to $\log g_n f$)
- Temp.** (green arrow pointing to $\log u(T)$)
- Absorption coefficient $\rightarrow$ pressure/logg** (red arrow pointing to $\log \kappa_v$)

See Linda's and Arthur's talks

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 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)	$\log(g/f_{ik})$	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 ¹ P° 1	3s5s ¹ S 0		T5539	L7428

A.Koch-Hansen SNAQs

Abundance assumptions

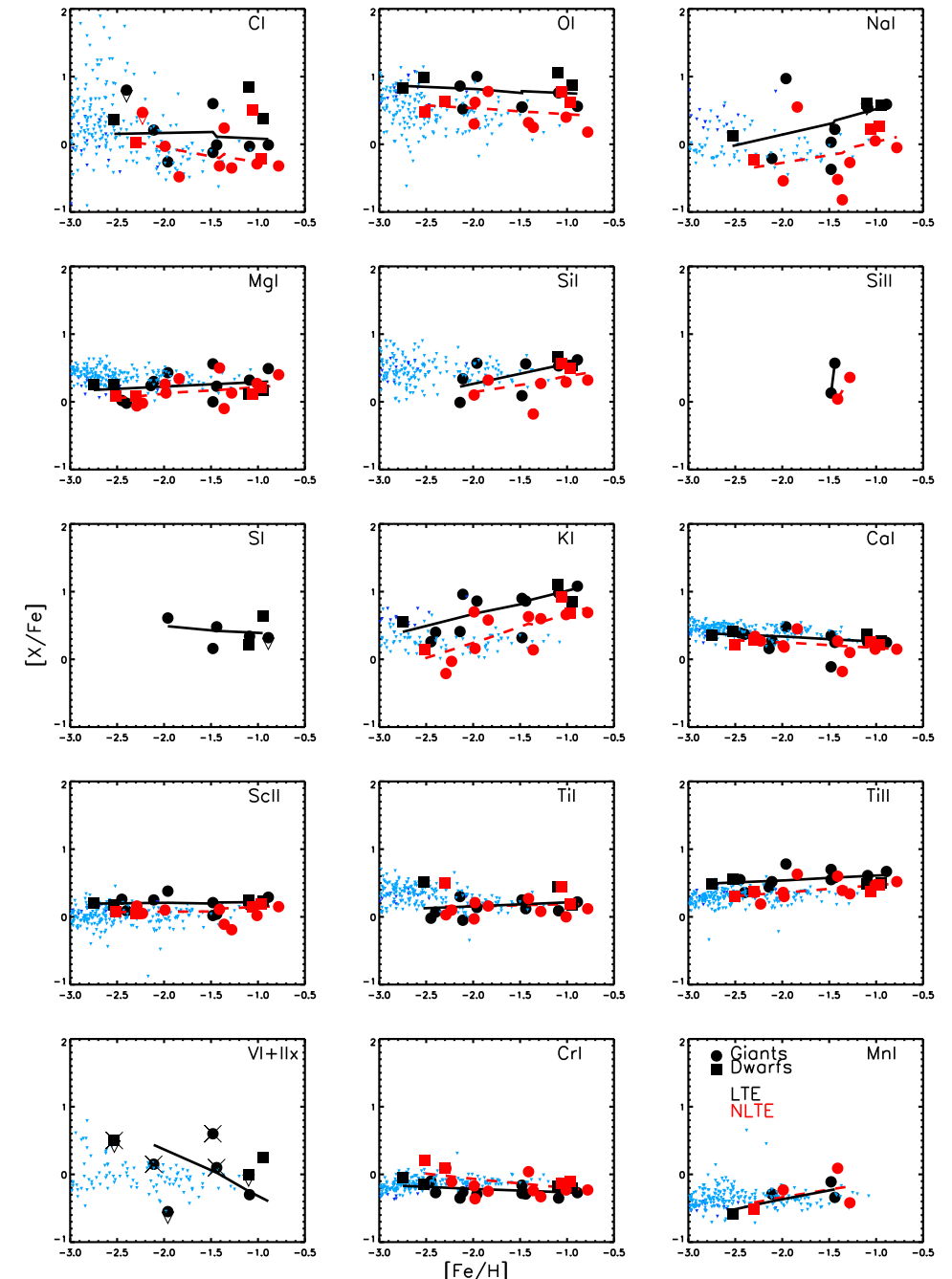
- Stellar atmospheres are assumed to be in Local Thermodynamic Equilibrium (LTE) and 1-D.
 - Velocity distribution Maxwellian, excitations & ionisations described by Boltzmann & Saha equations, and one local T describing the stellar atm. layer

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

Beyond 1D, LTE → A. Gallagher's talk & SNAQs

https://events.hifis.net/event/214/contributions/1041/attachments/234/676/SNAQ_2021_11_4_Andrew_Gallagher.pdf

Hansen+2020



Recall – What can we observe?

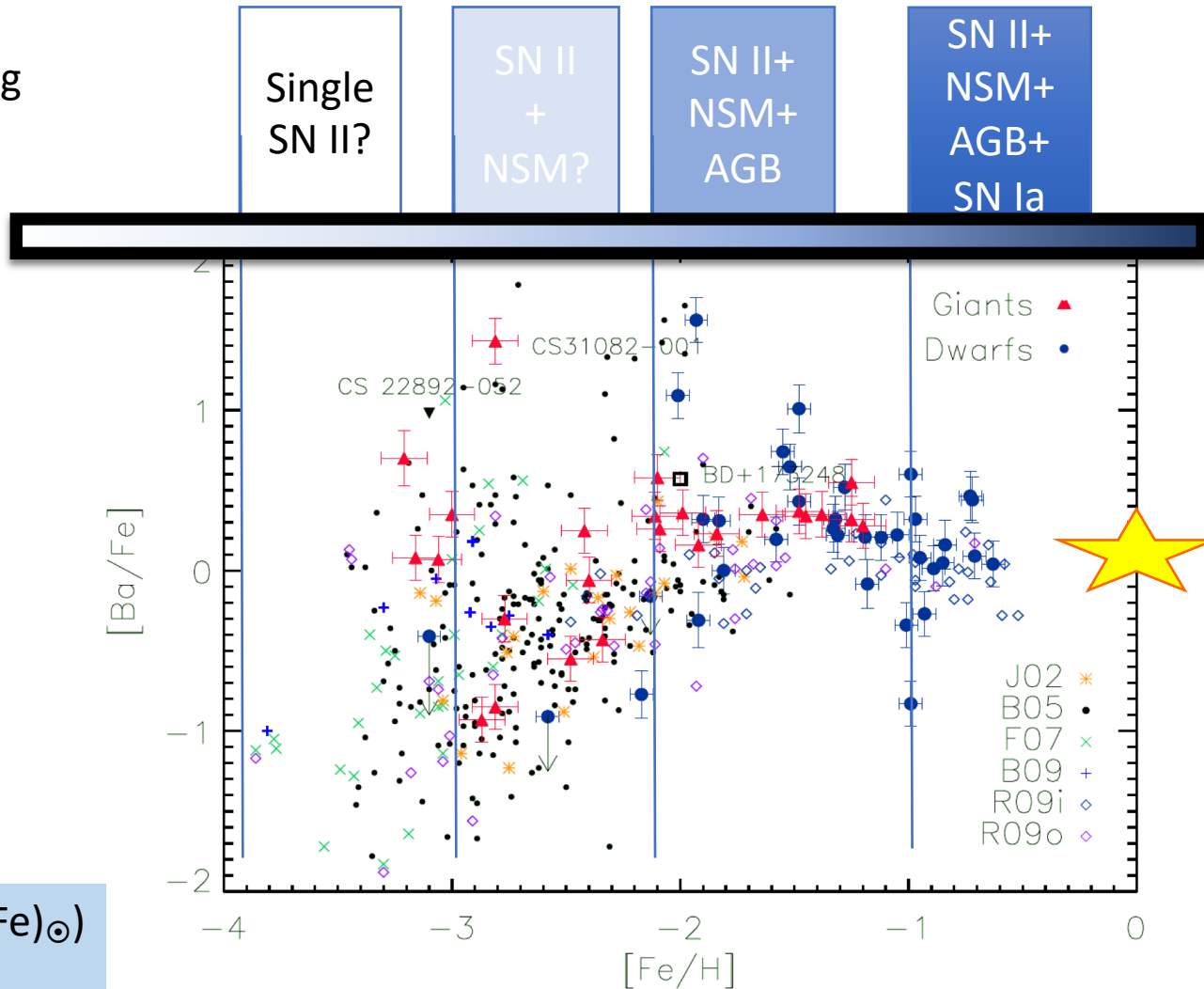
Recall: What can we observe?																														
1 H 1.008																	2 He 4.003													
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Ground Isotopes Not measurable Space																														
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Chemical Evolution of the Milky Way

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

☀ Big Bang

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



Looking back

Chemical concentration

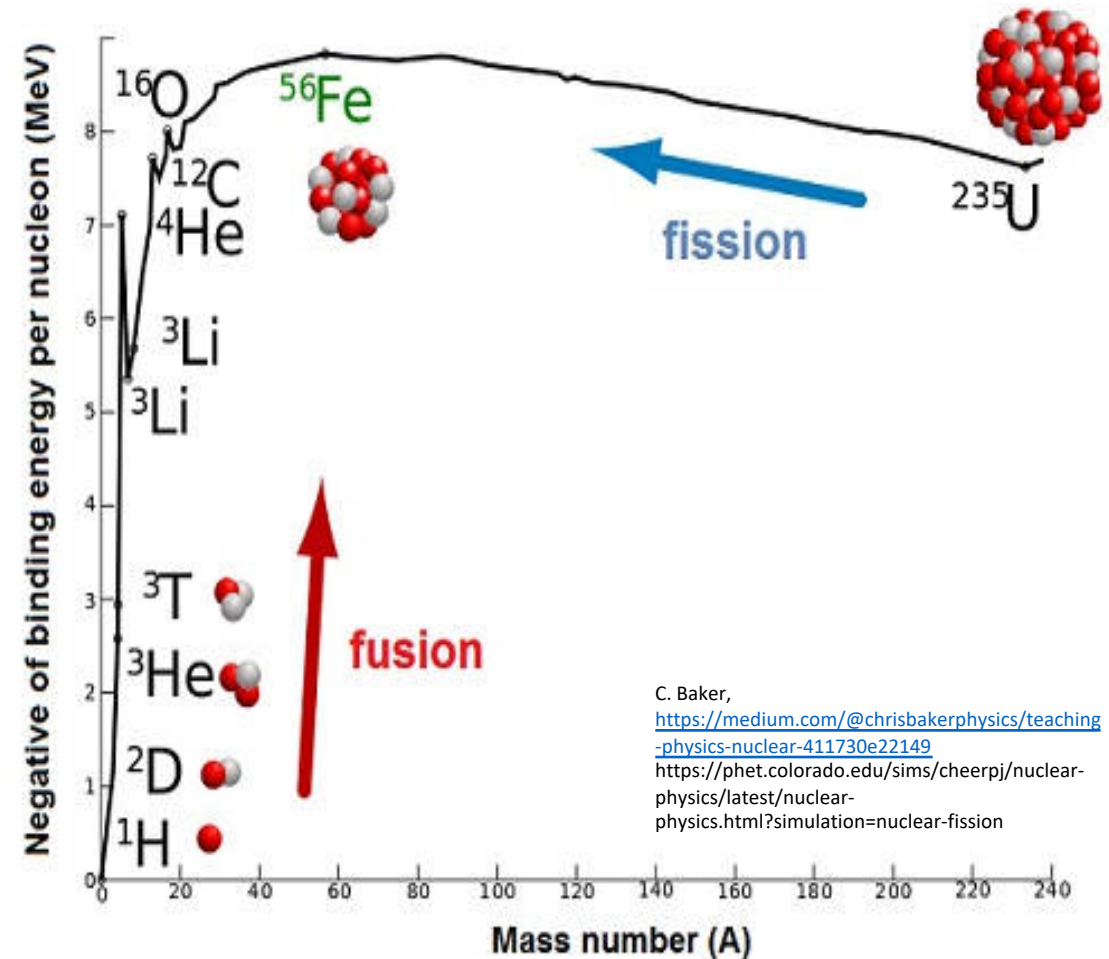
The Sun as reference: $[\text{X}/\text{Fe}]=0$

Hansen et al. 2012

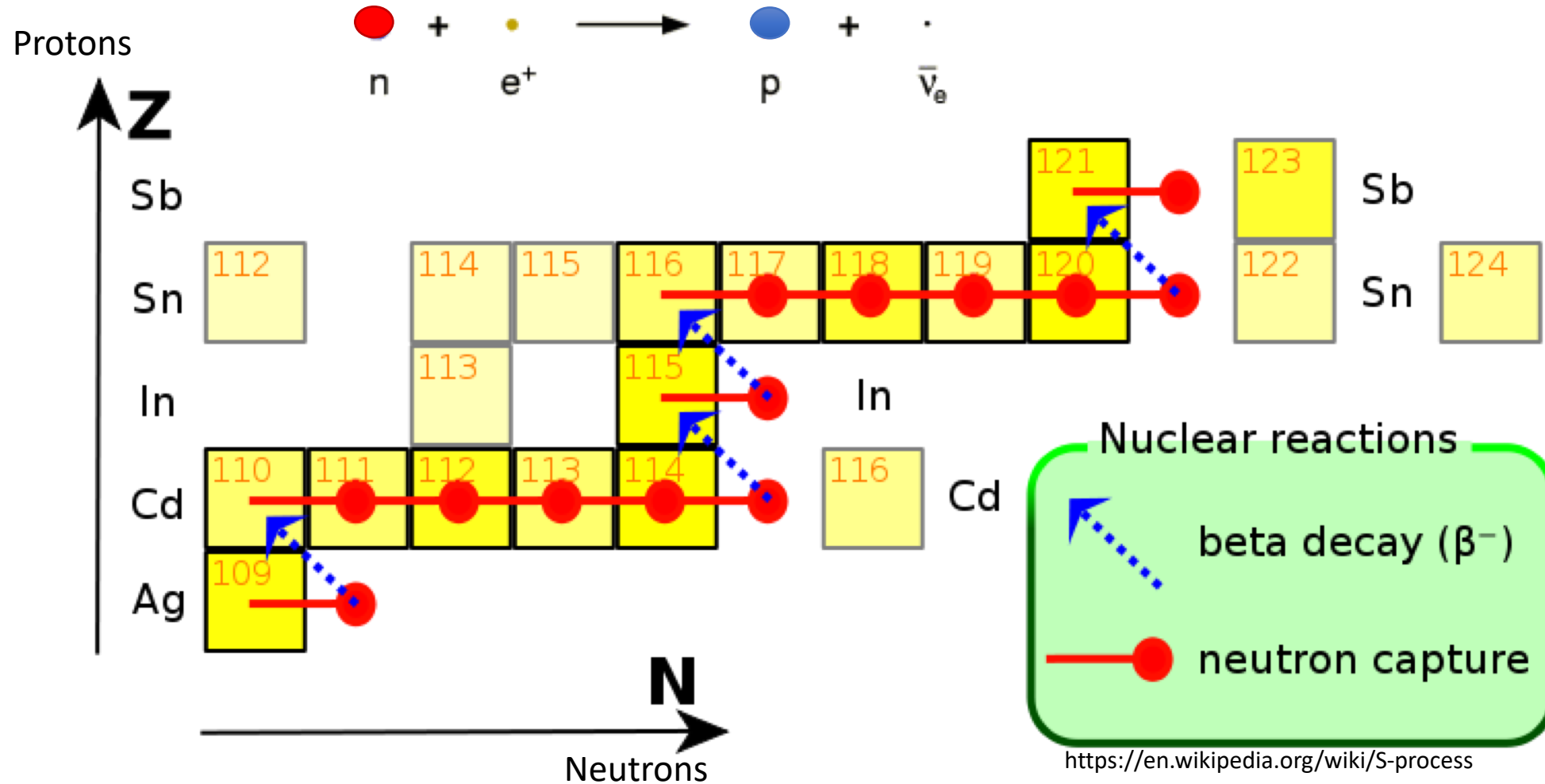
See Marta's talk

How do heavy elements form?

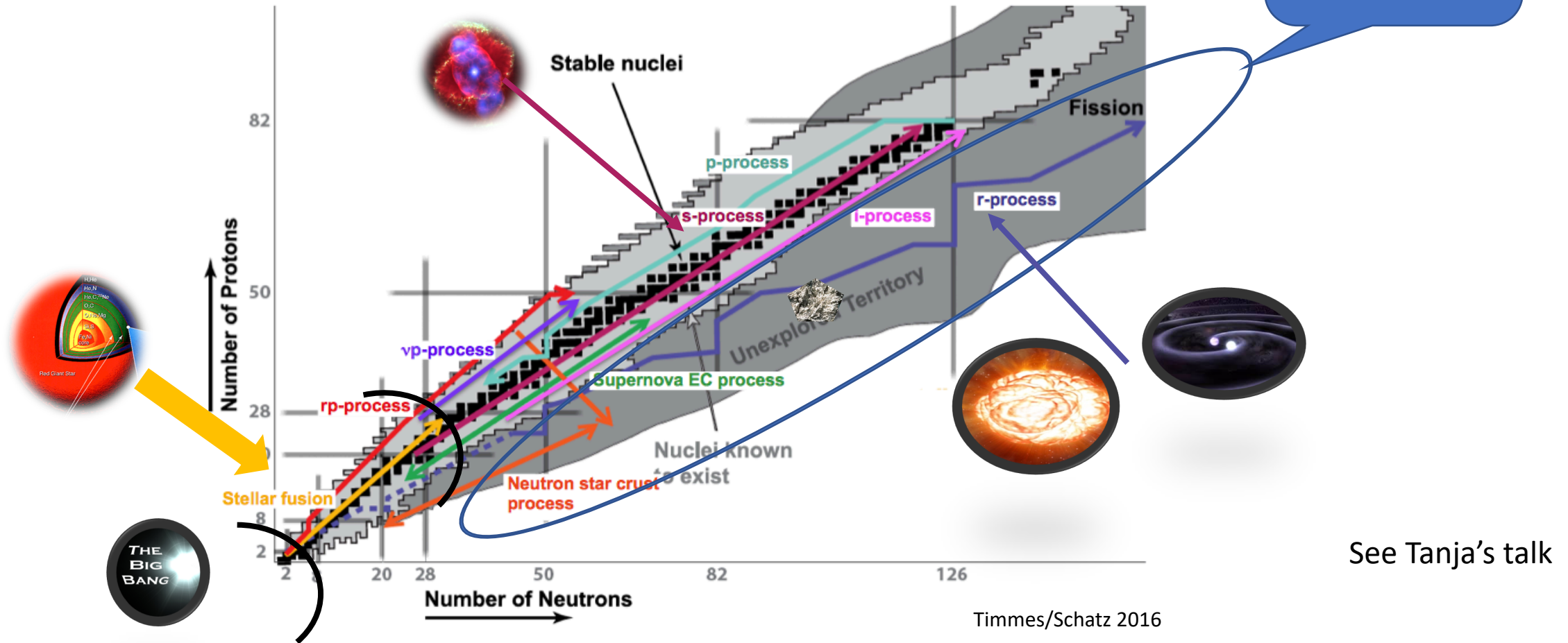
- Stars form up to Fe during their lives
- Heavier atoms have larger positively charged nuclei that repel protons
- Elements $> \text{Fe}$ mostly form via neutron captures



Neutron capture & decay



Nuclear reactions



See Tanja's talk

The Periodic Table – n-capture processes

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

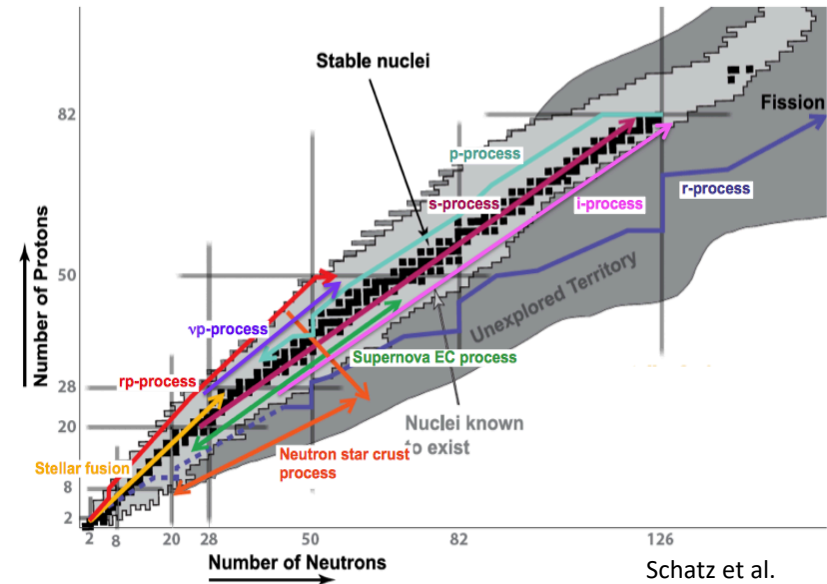
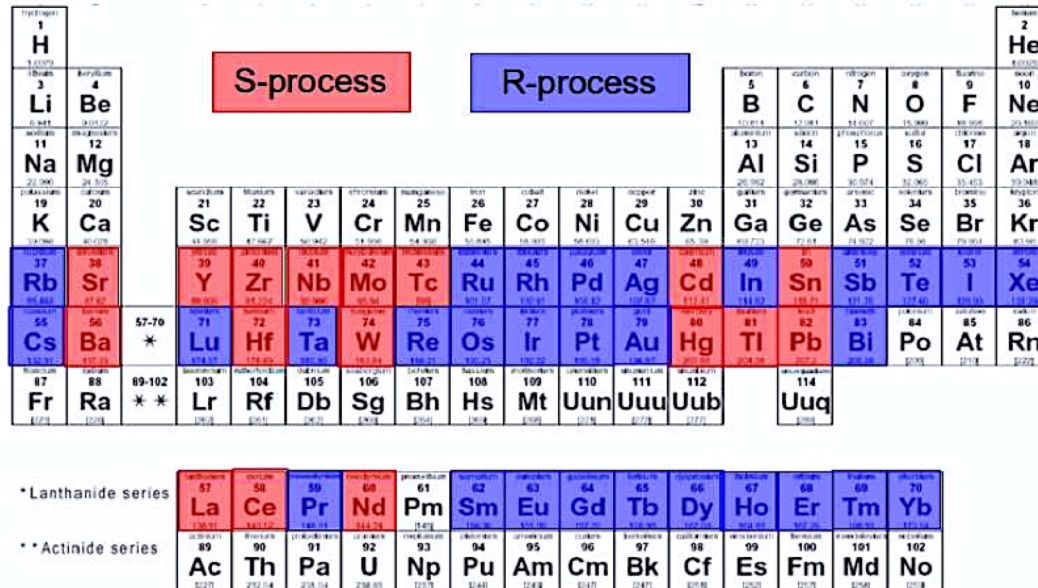
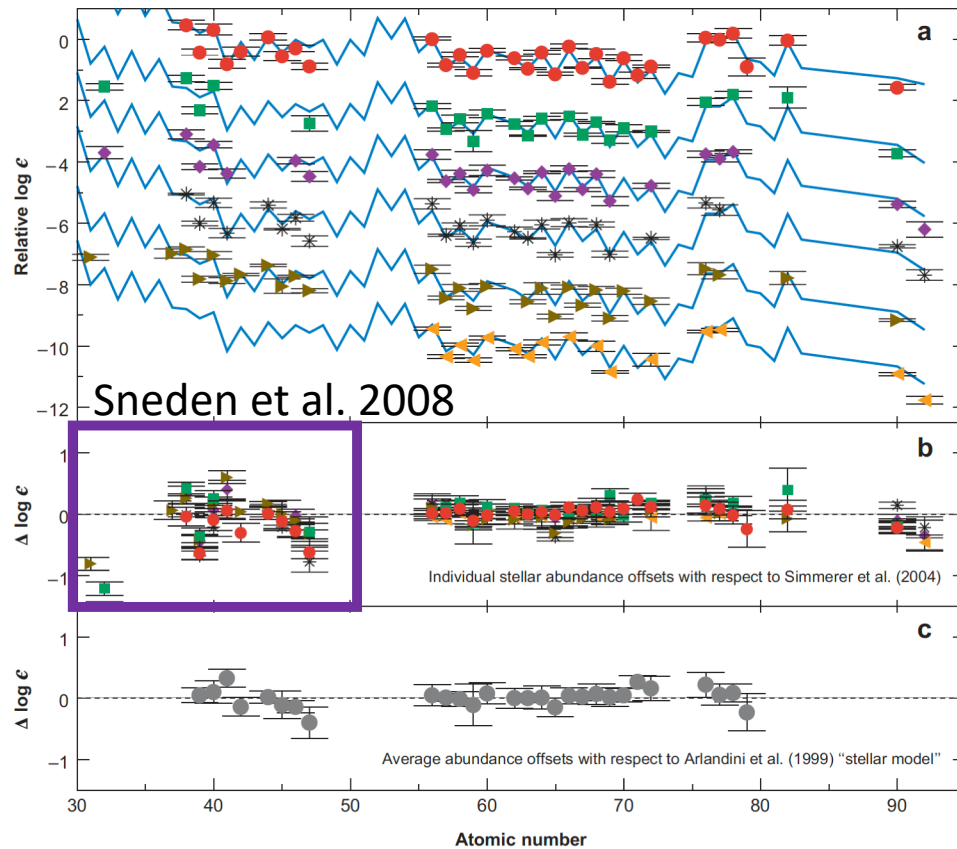


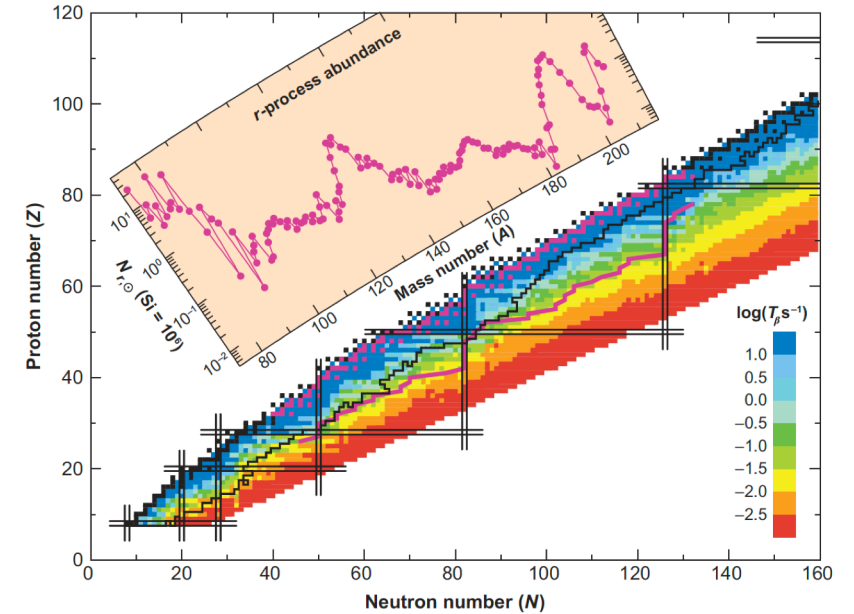
Figure 1. Schematic overview of the nuclear processes in the universe on the chart of nuclides (adapted from figure by F. Timmes).

Heavy element abundances

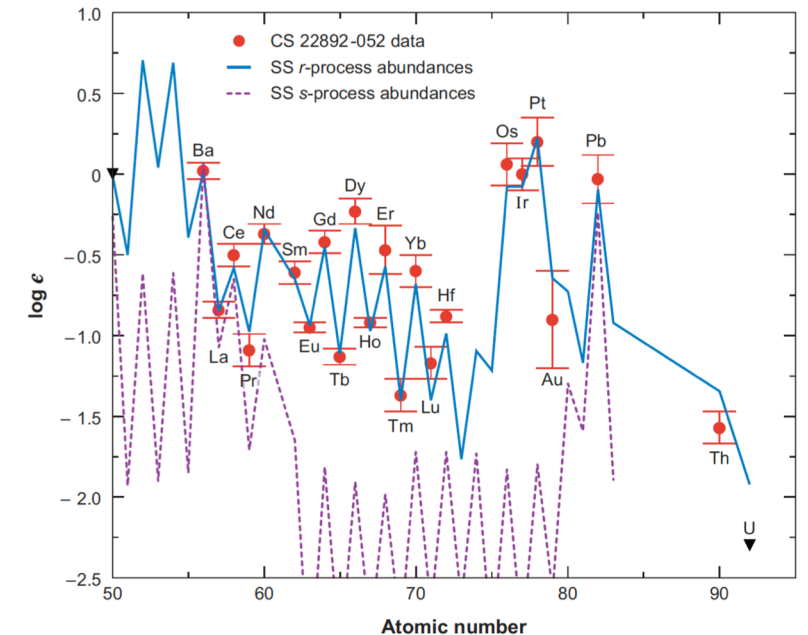
- Different stars show different patterns
- Some elements differ more than others



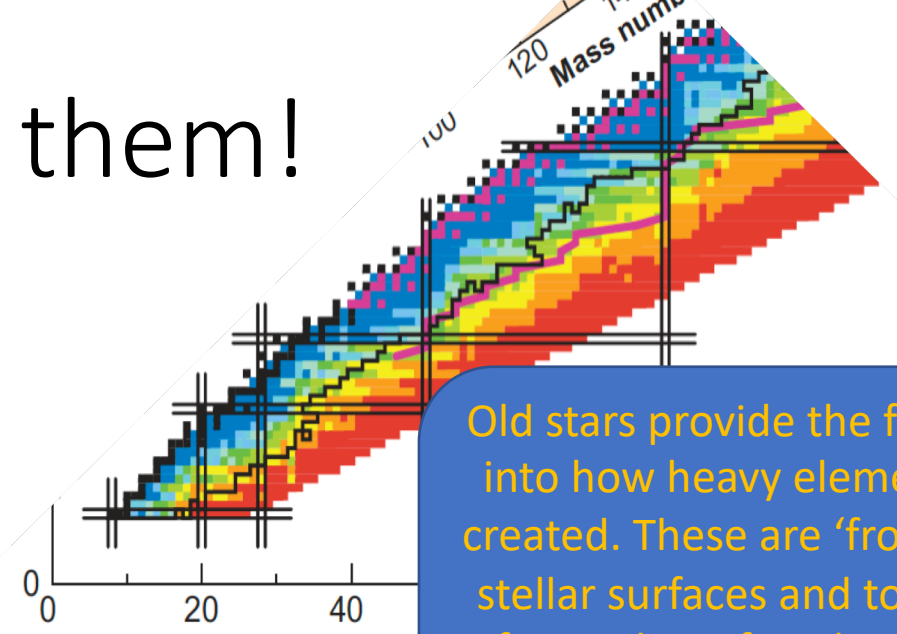
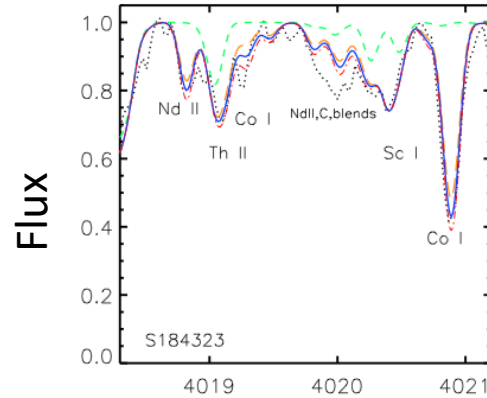
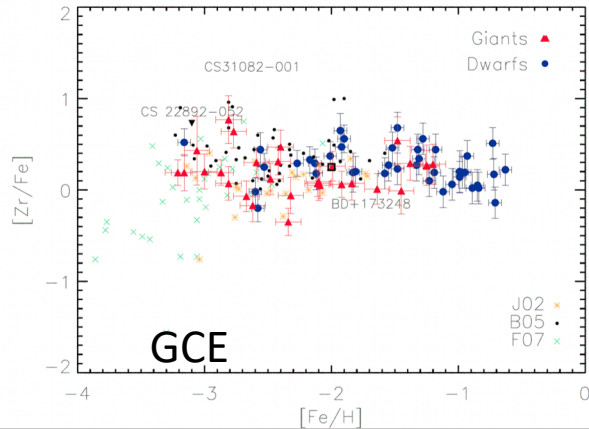
Large residuals for $Z=30-50 \rightarrow$ Solar-s=r not sufficient!



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



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 $\rightarrow$ Age

