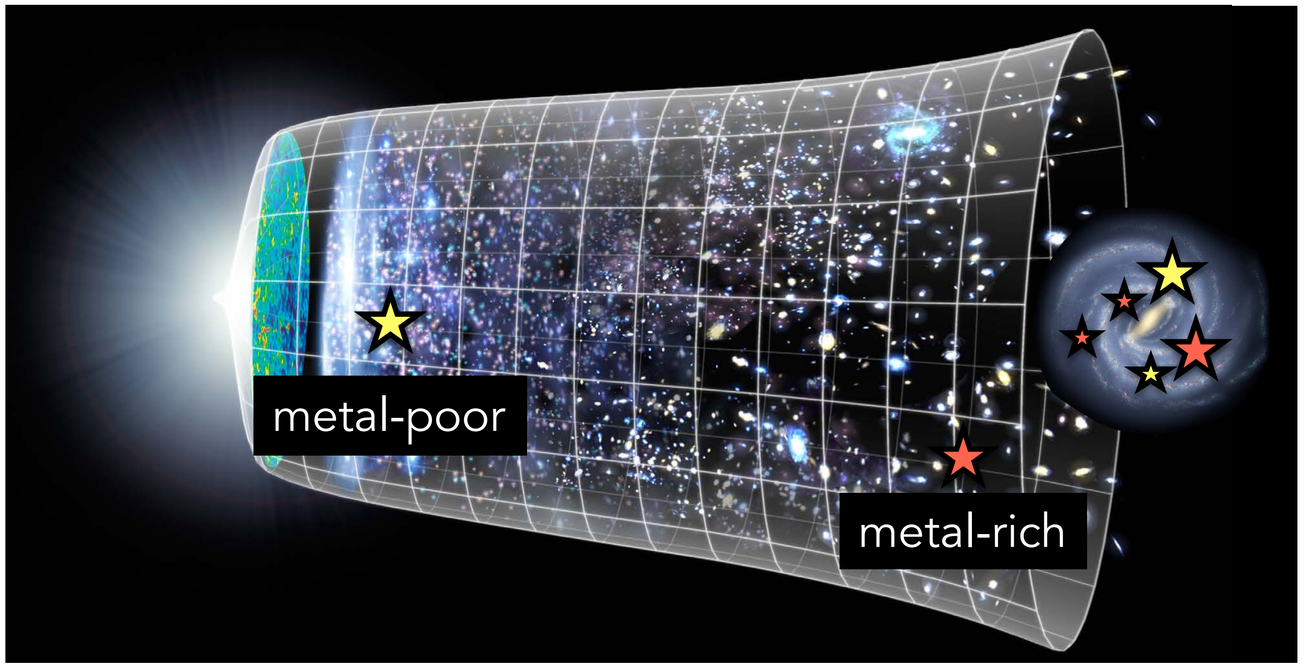
DIS Galactic Archaeology minor module

Lecture 4: Stars as probes of Galactic Archaeology II

Dr Anke Ardern-Arentsen

Recap from previous lecture



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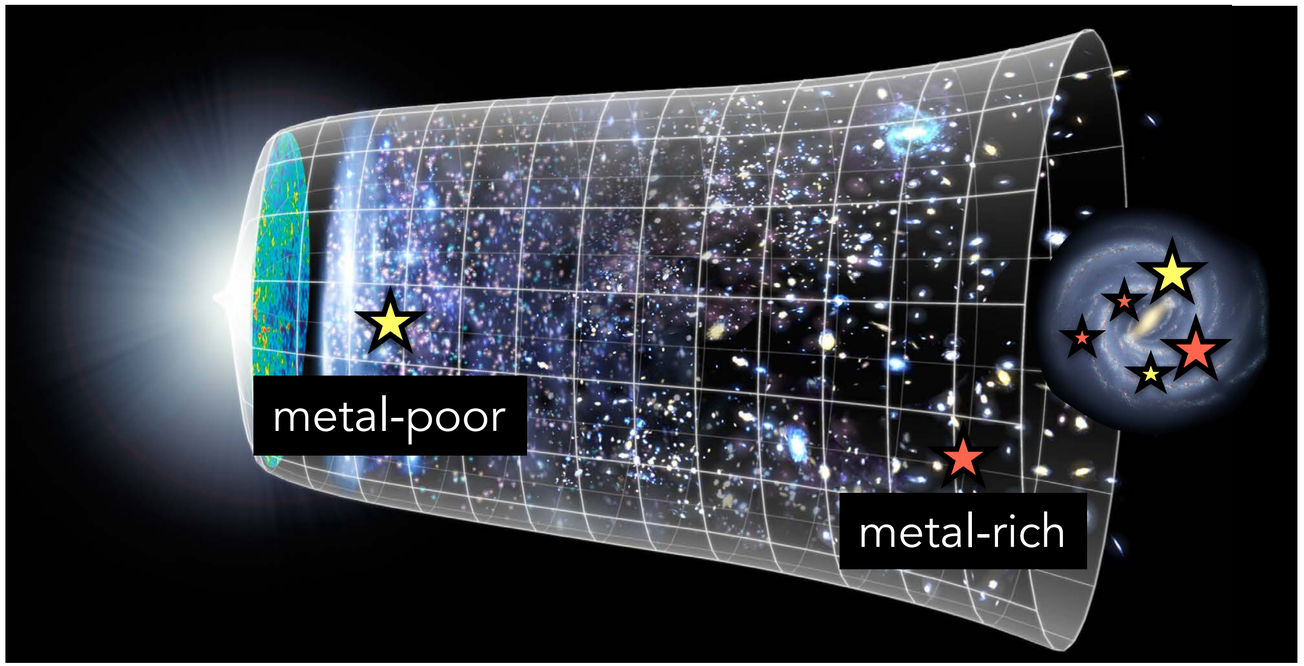

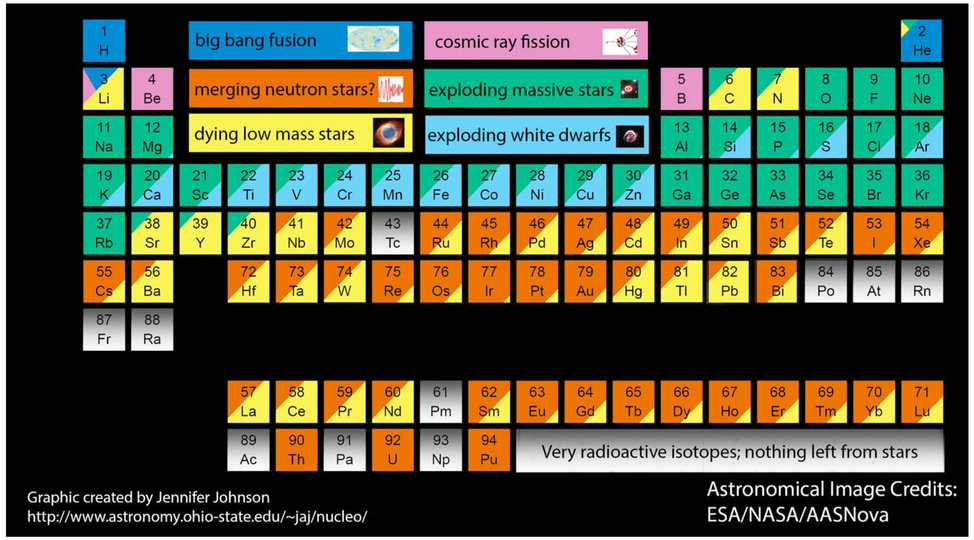

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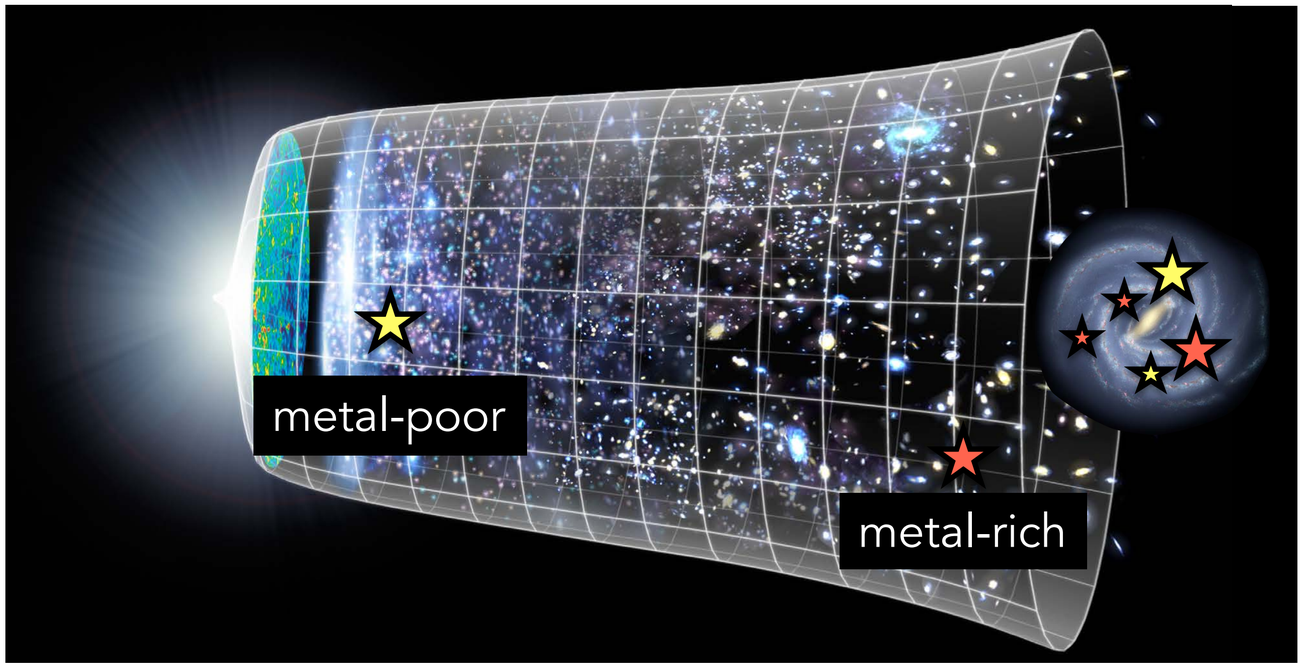

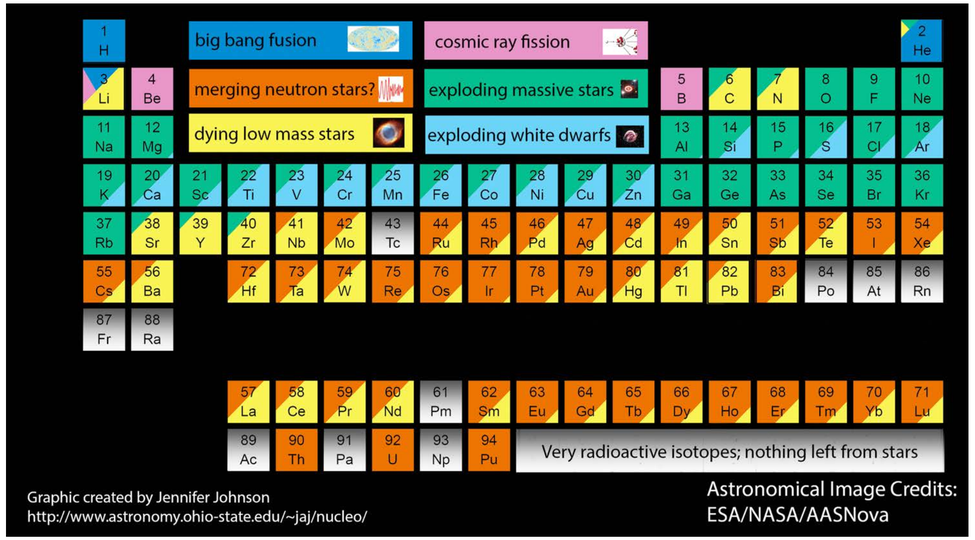

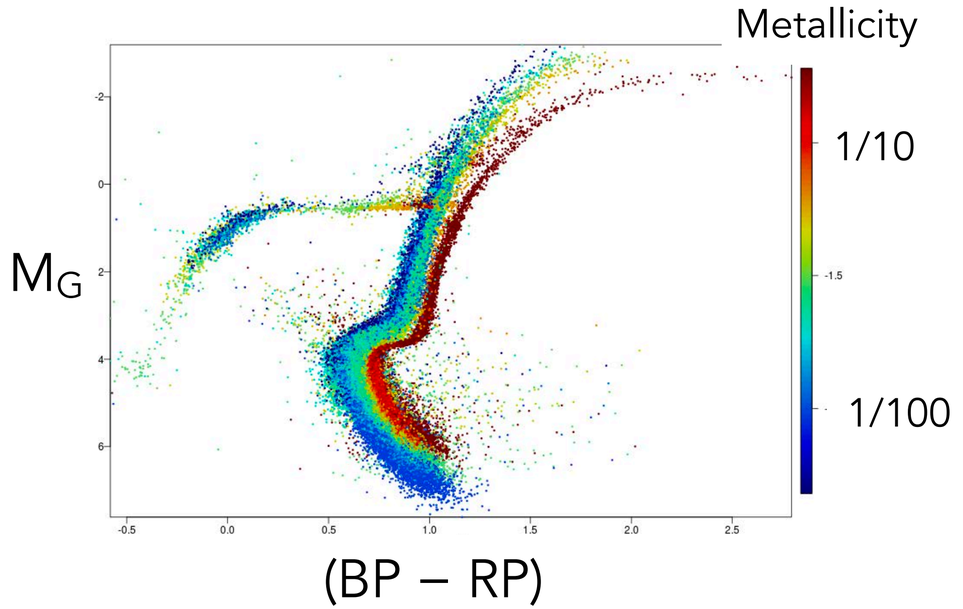

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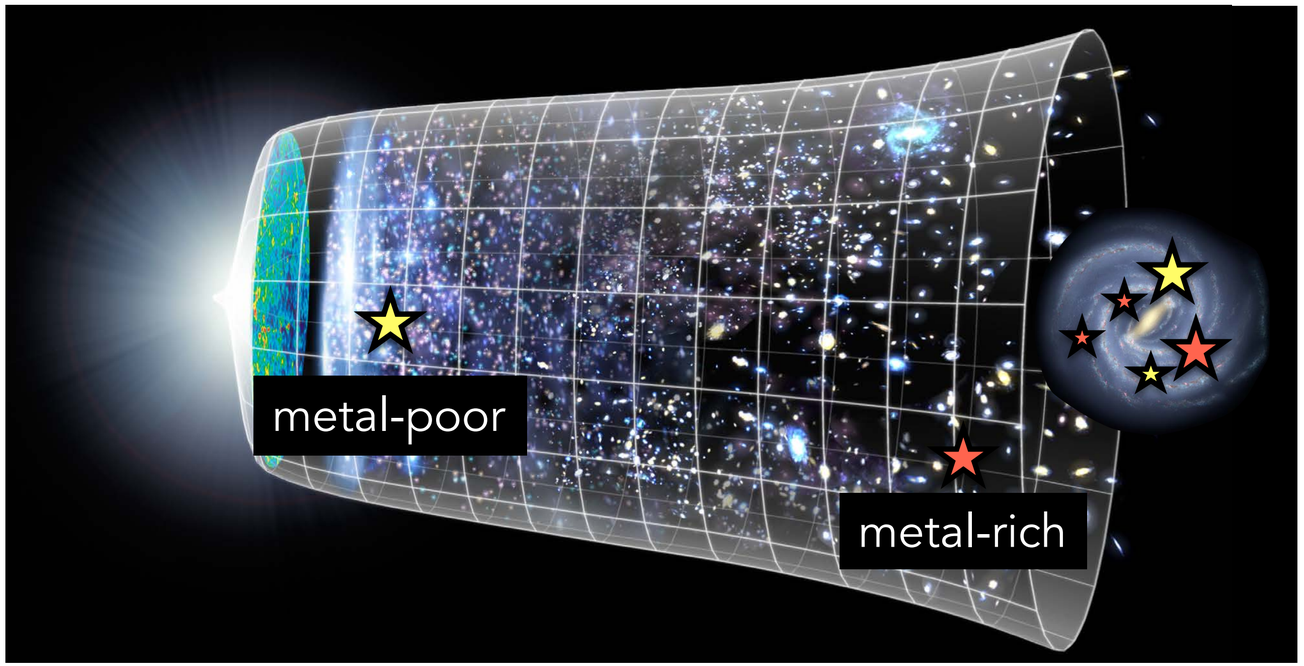
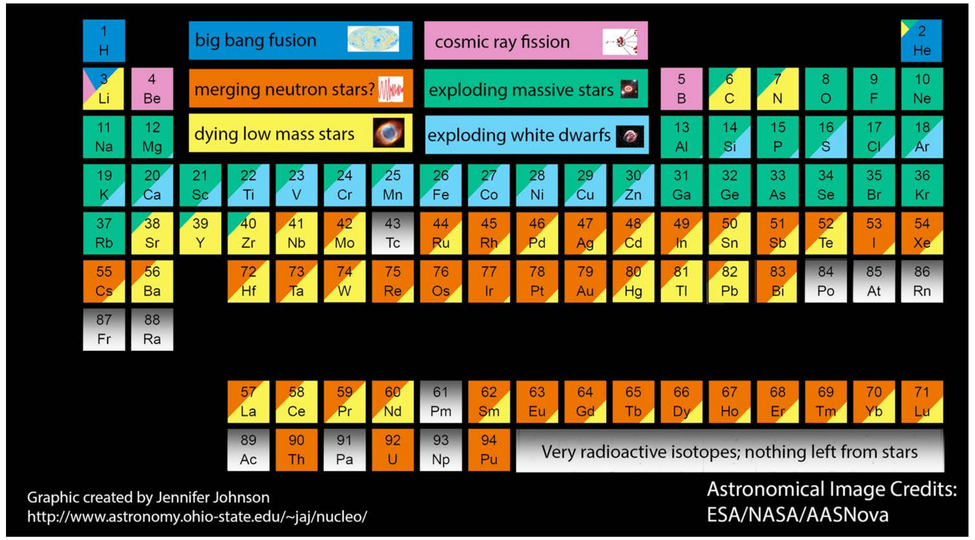
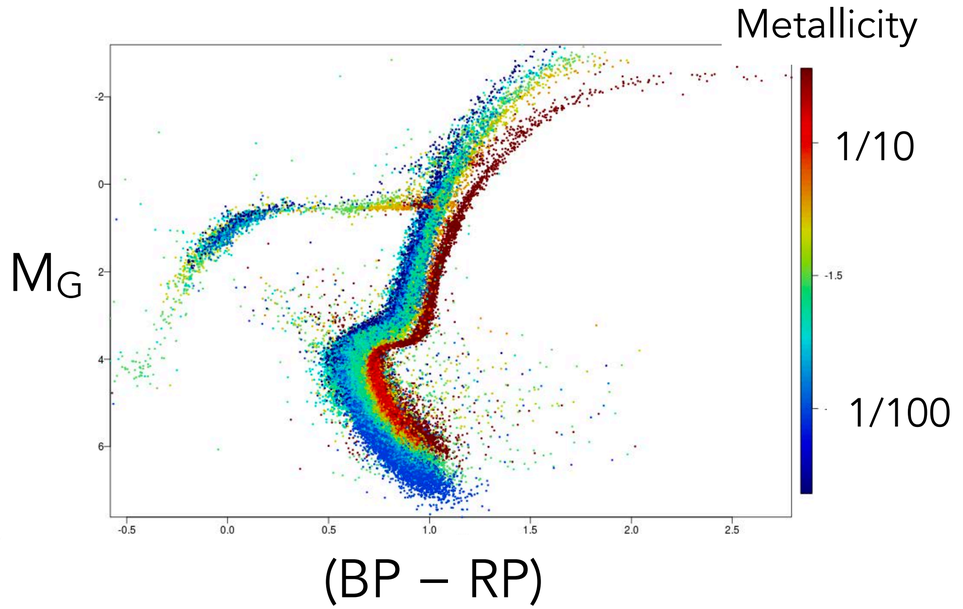






- Uploaded a notebook with instructions how to make the apparent, absolute and extinction-corrected colour-magnitude diagrams (CMDs)
- Also one there to reproduce a couple of the APOGEE figures I will show today

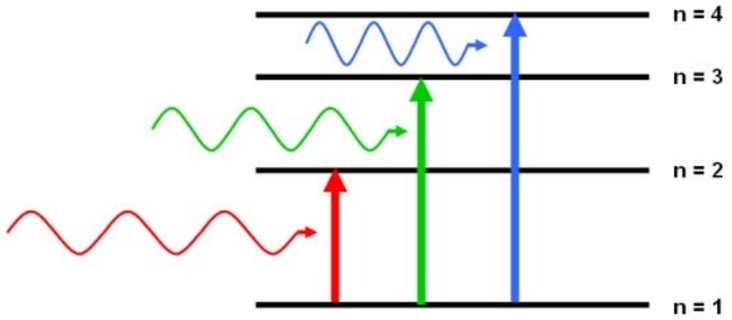
This lecture

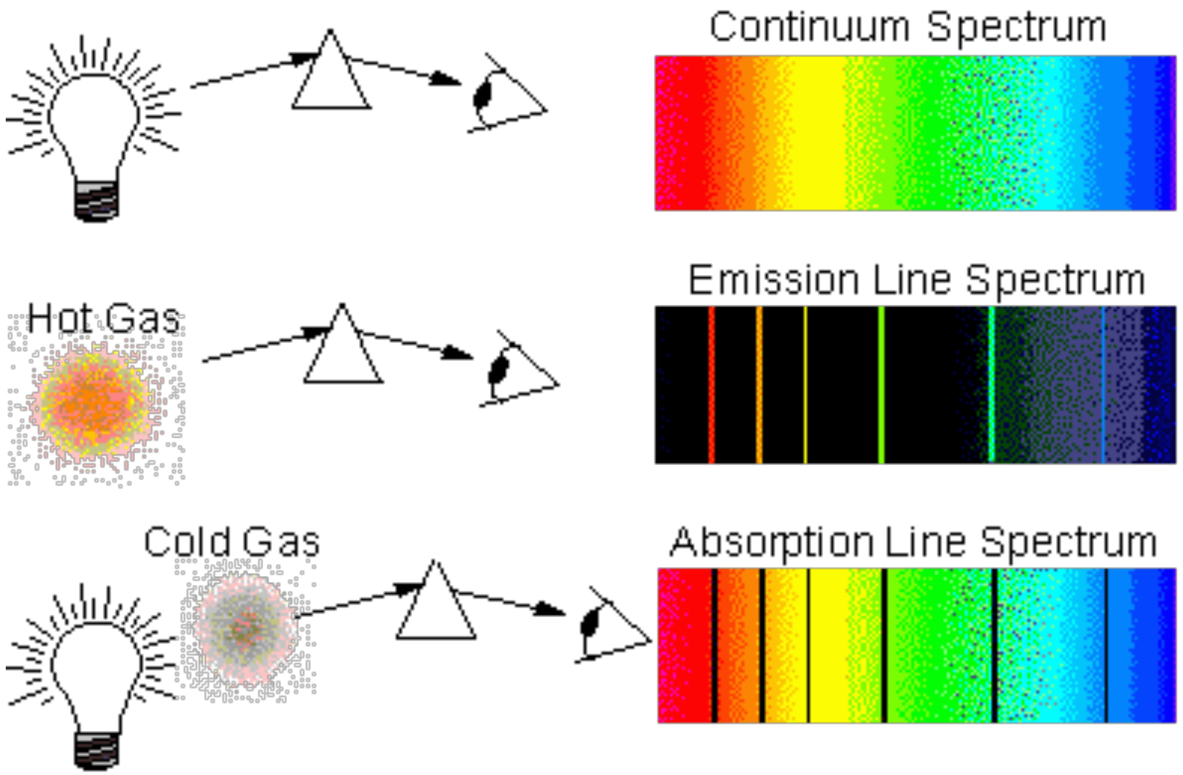
- How to get metallicity and chemical abundances for stars?
  - Spectroscopy (background & techniques)
  - Some recent examples from the literature
- How to use chemical abundances to trace chemical evolution in galaxies?

Measuring abundances

Spectral lines

- The composition of stars is encoded in **stellar spectra, thanks to absorption line features**
  - Spectrum = energy (light) across different frequencies (wavelengths)
  - Absorption = atoms and molecules absorb energy at specific frequencies (wavelengths)





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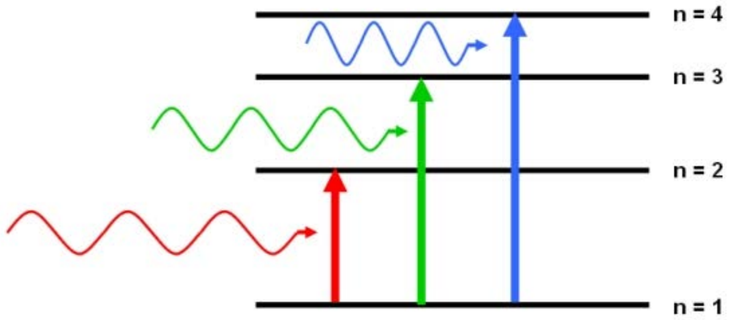
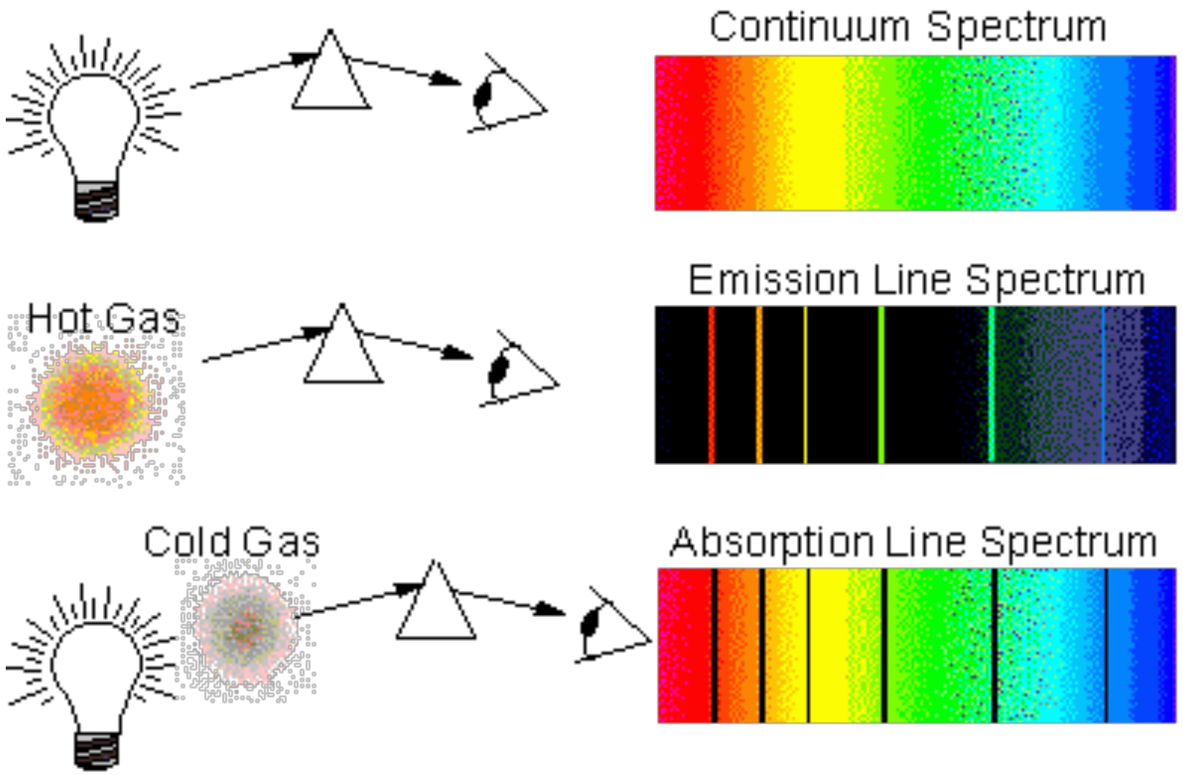
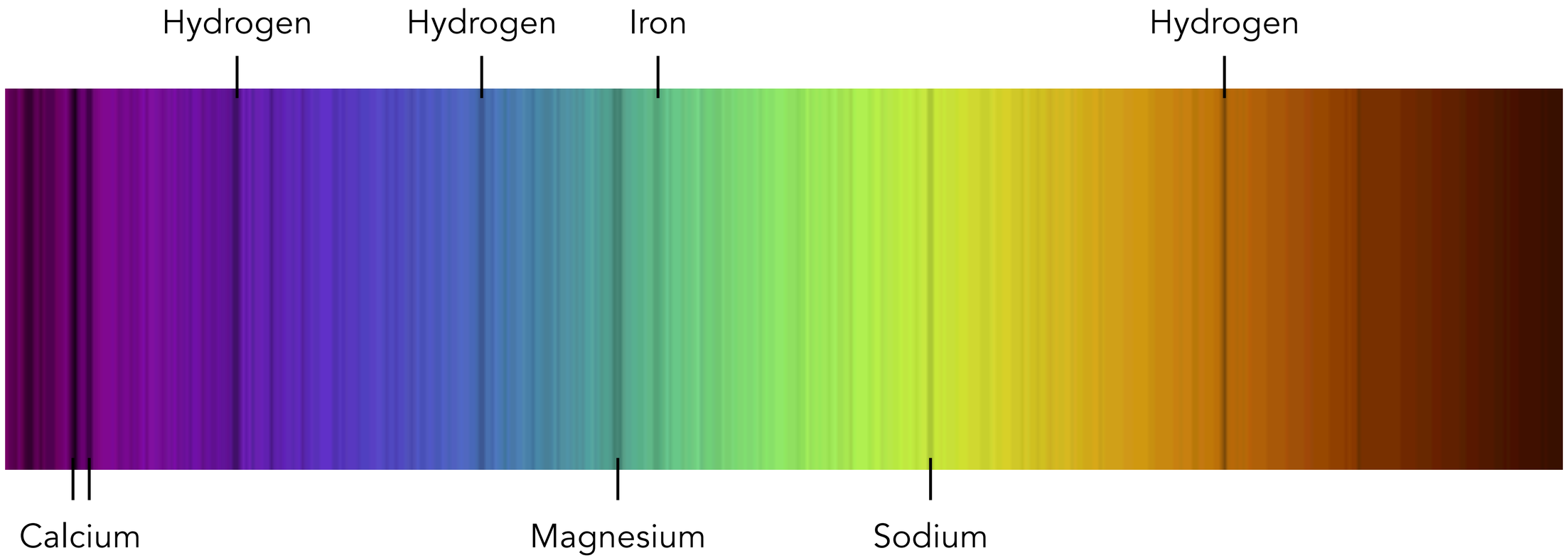
- Absorption lines are the result of light generated in the hot inside of a star **moving out through the cooler atmosphere**



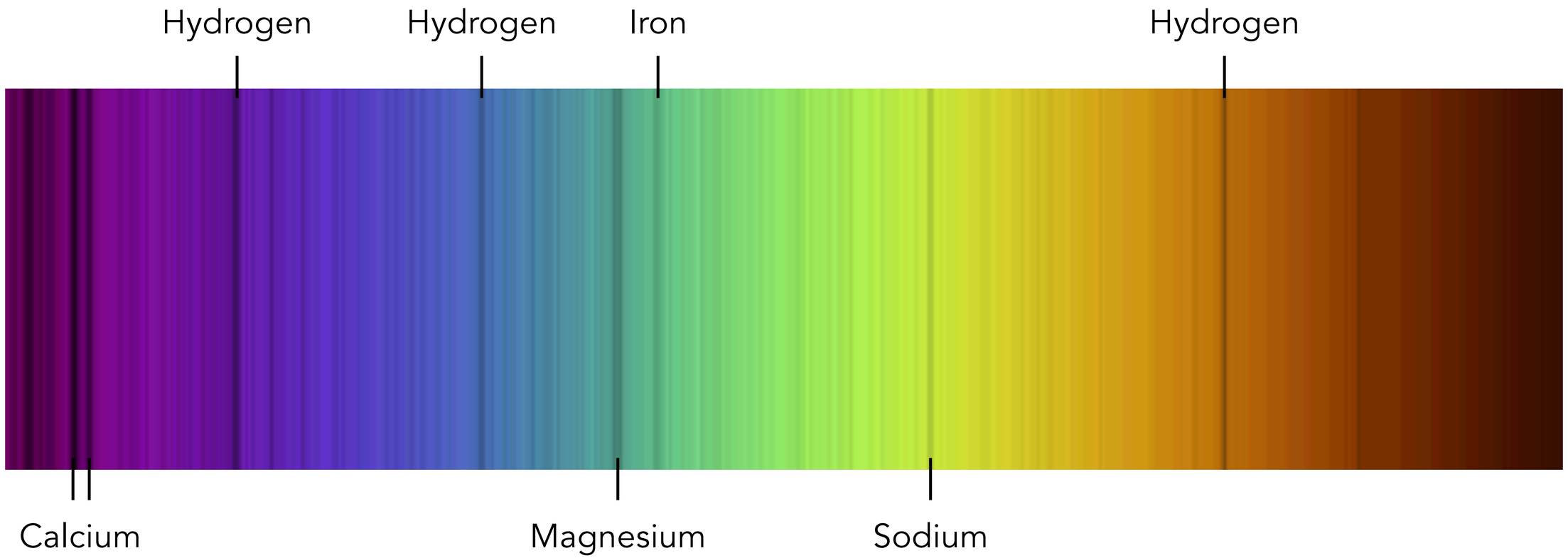


Solar spectrum



Solar spectrum

Q **From this spectrum, can you tell which element is most abundant in the Sun?**

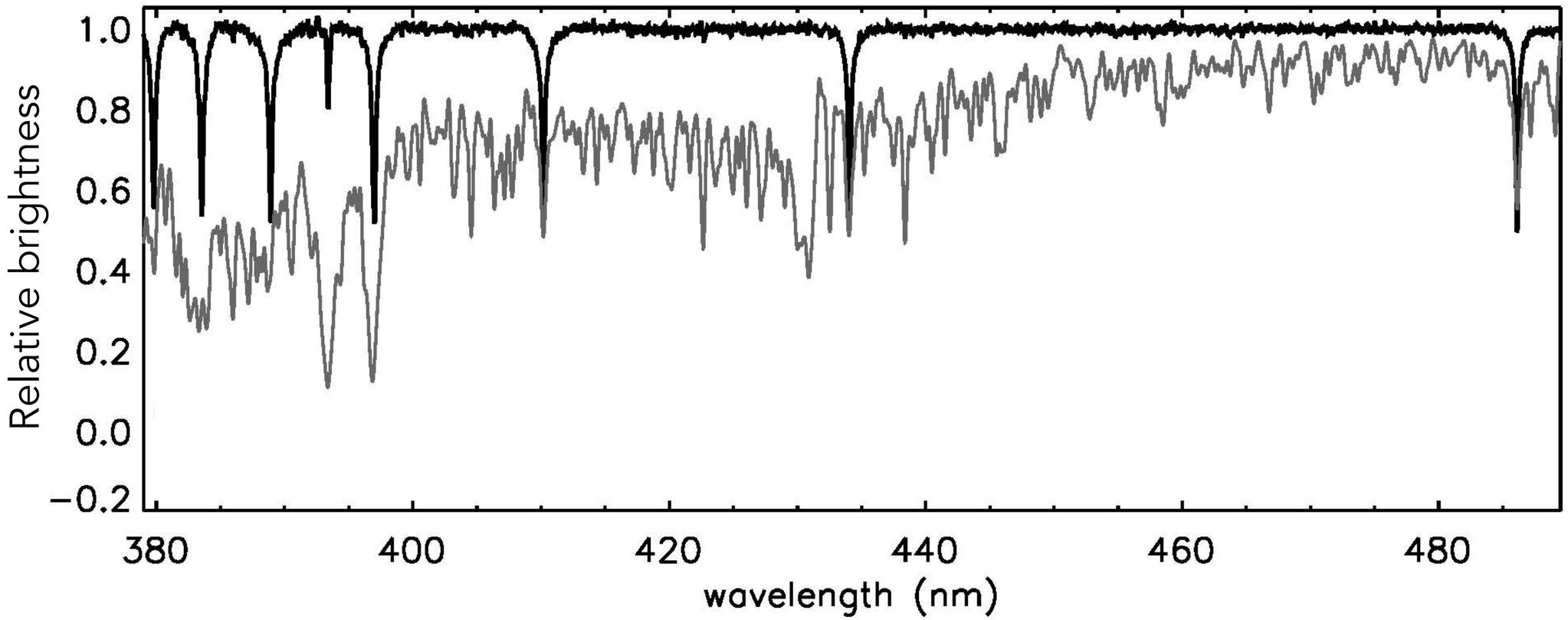


Stellar spectra: metal-poor & metal-rich

*only 1 Fe atom per 10^9 atoms of H!

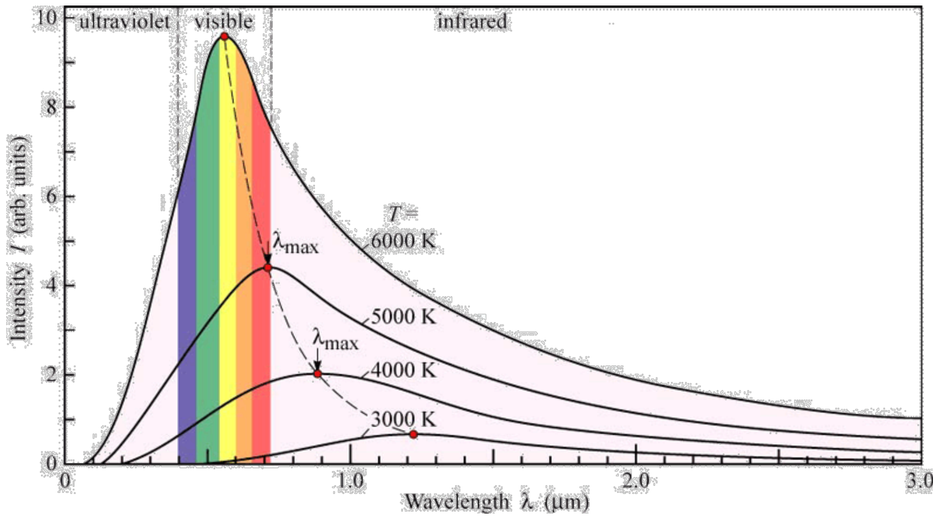
Ultra metal-poor star*: only H lines and a tiny Ca line

Sun (metal-rich): absorption features everywhere (not noise!)



Stellar spectra

- Spectra are the result of a combination of **black body radiation + absorption lines**



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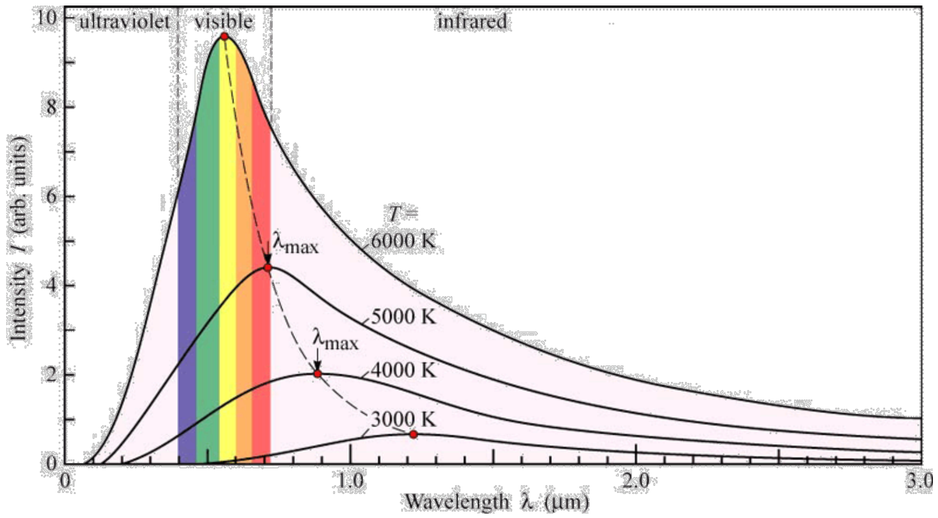
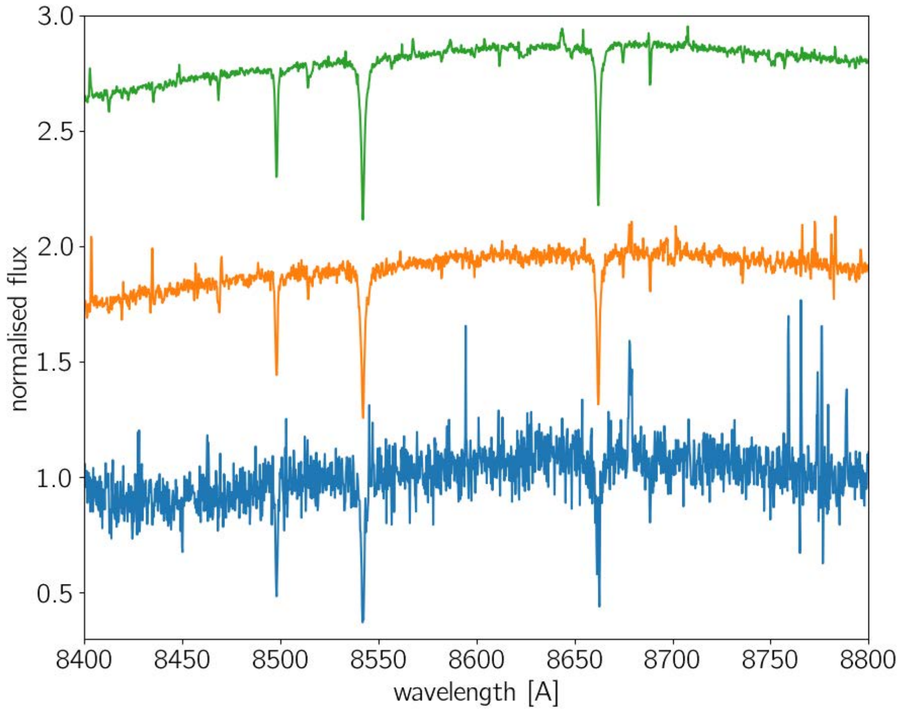
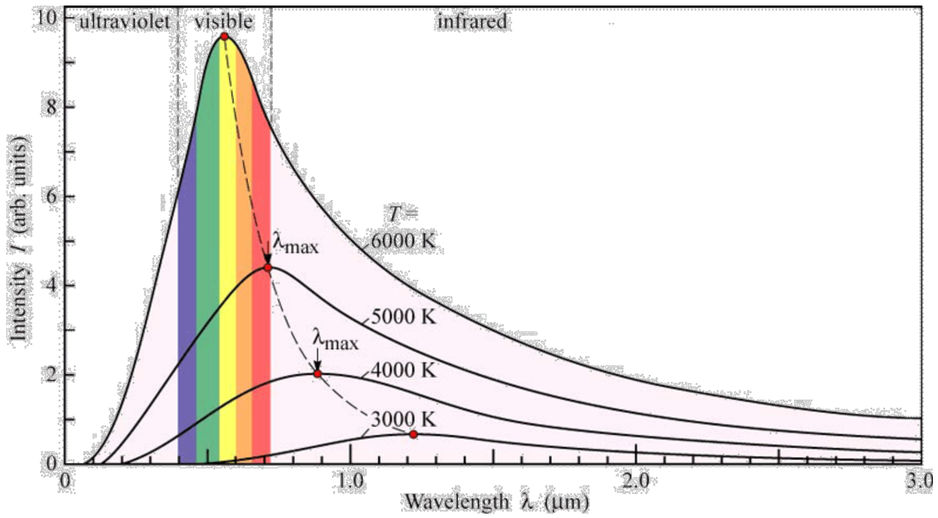


S/N of 120, 50 and 13 (top to bottom)



Stellar spectra

- Spectra are the result of a combination of **black body radiation + absorption lines**
- In practice also:
  - the the instrument profile
  - noise (S/N = signal to noise)
  - spurious features (e.g. cosmic rays or sky)



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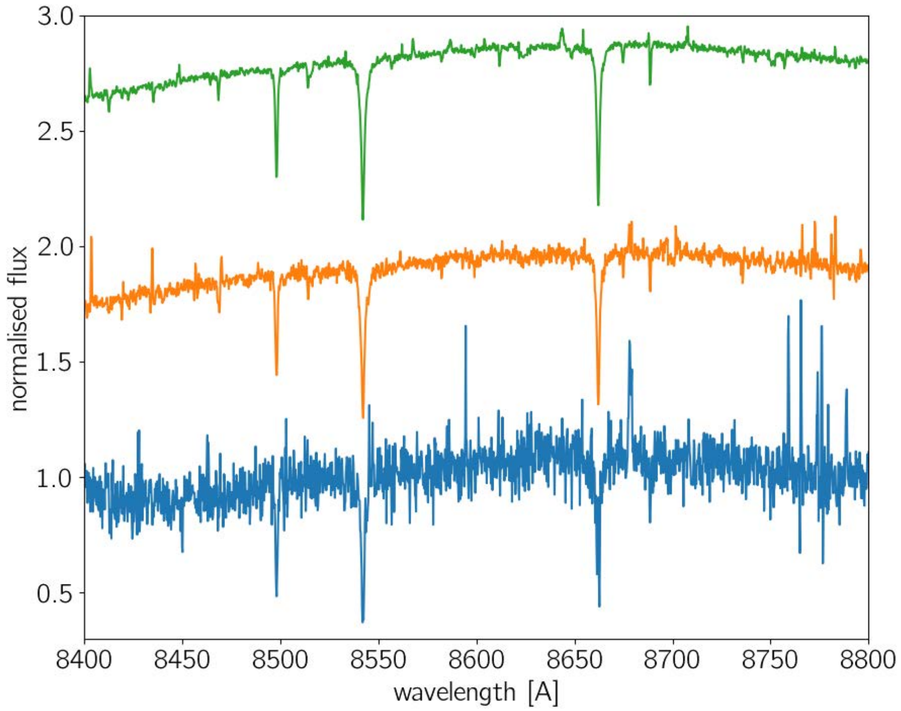

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- **wavelength coverage**
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  (affecting the *quality* of abundance measurements)

$$R = \frac{\lambda}{\Delta\lambda}$$

(and more of each is more expensive)

Christlieb 2003

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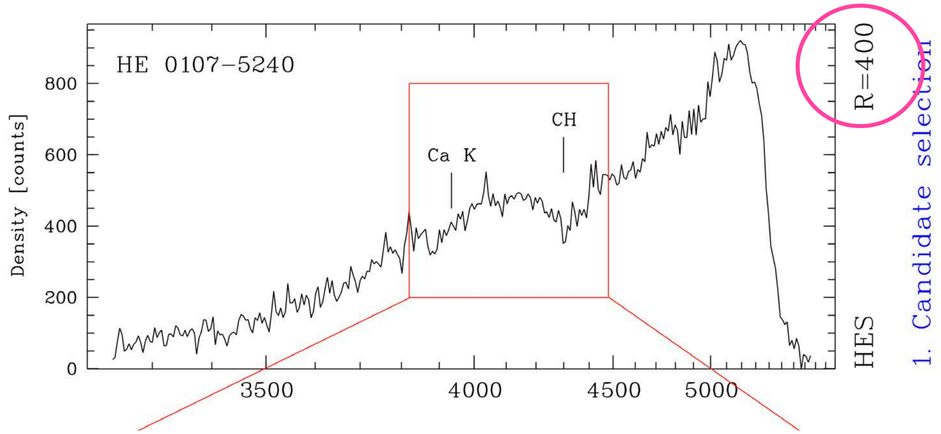

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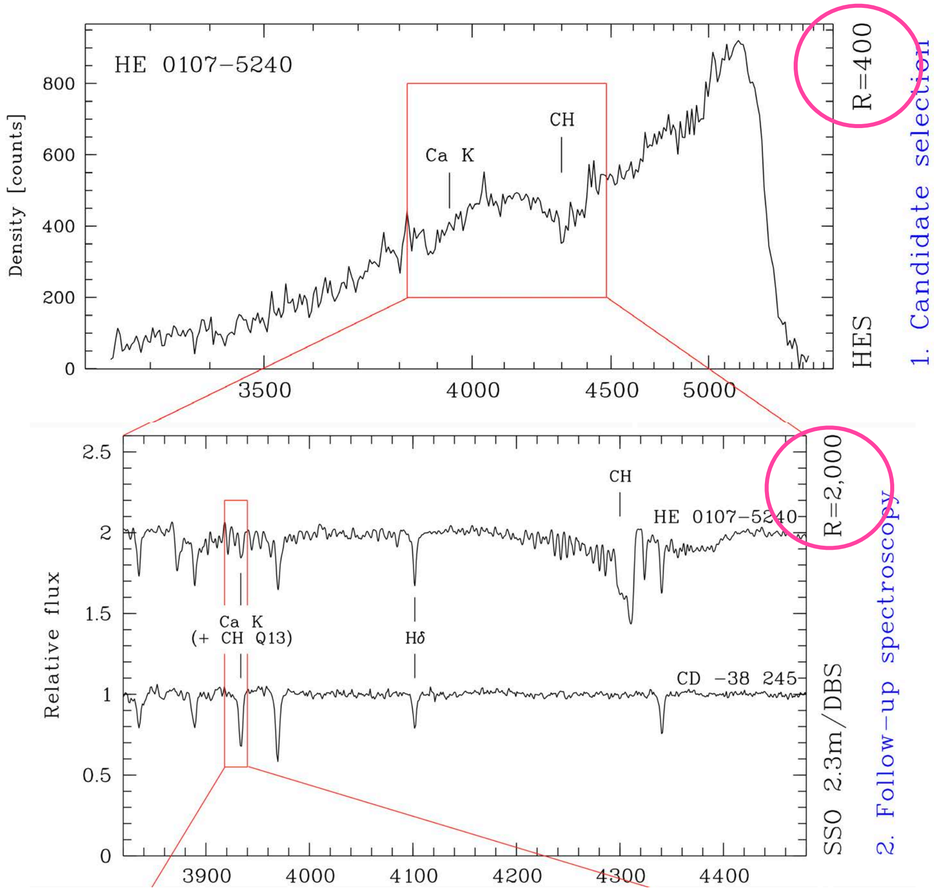

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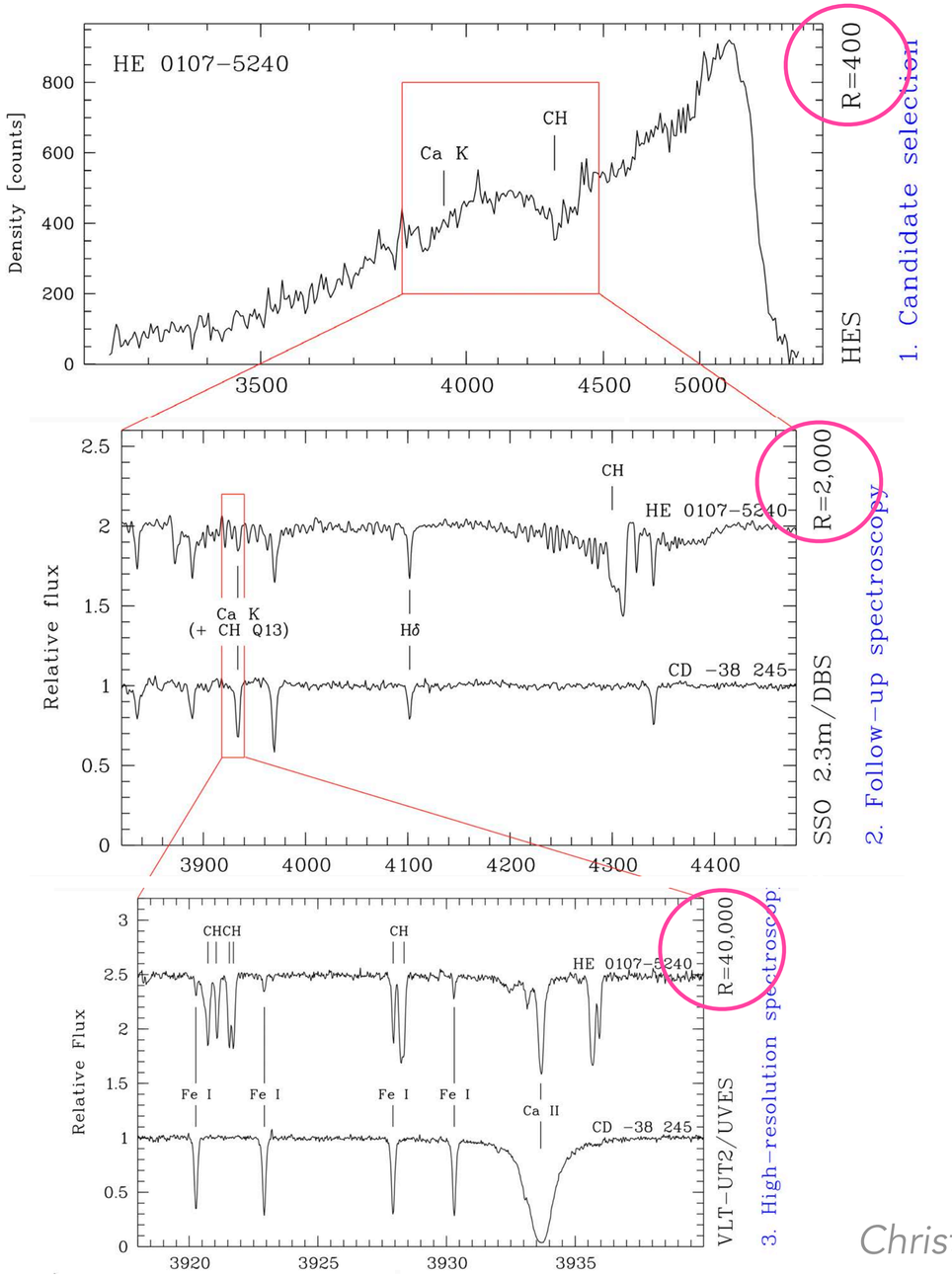

Christlieb 2003

How many elements can we derive from spectra?

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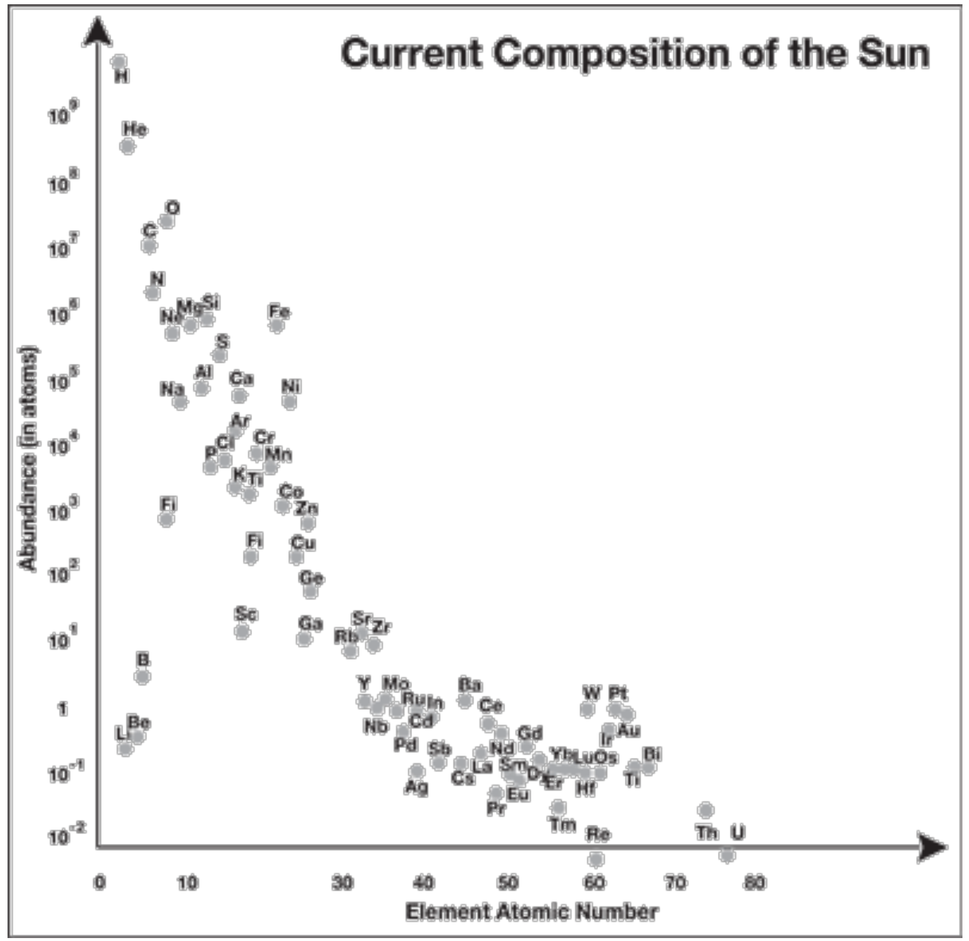

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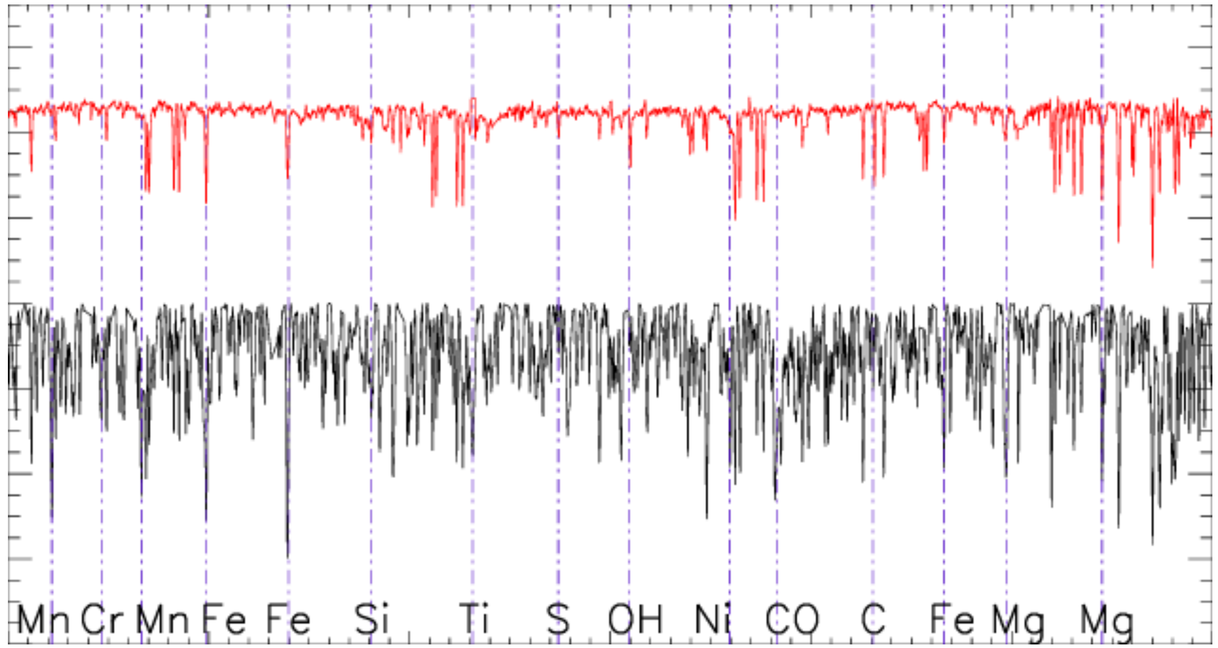

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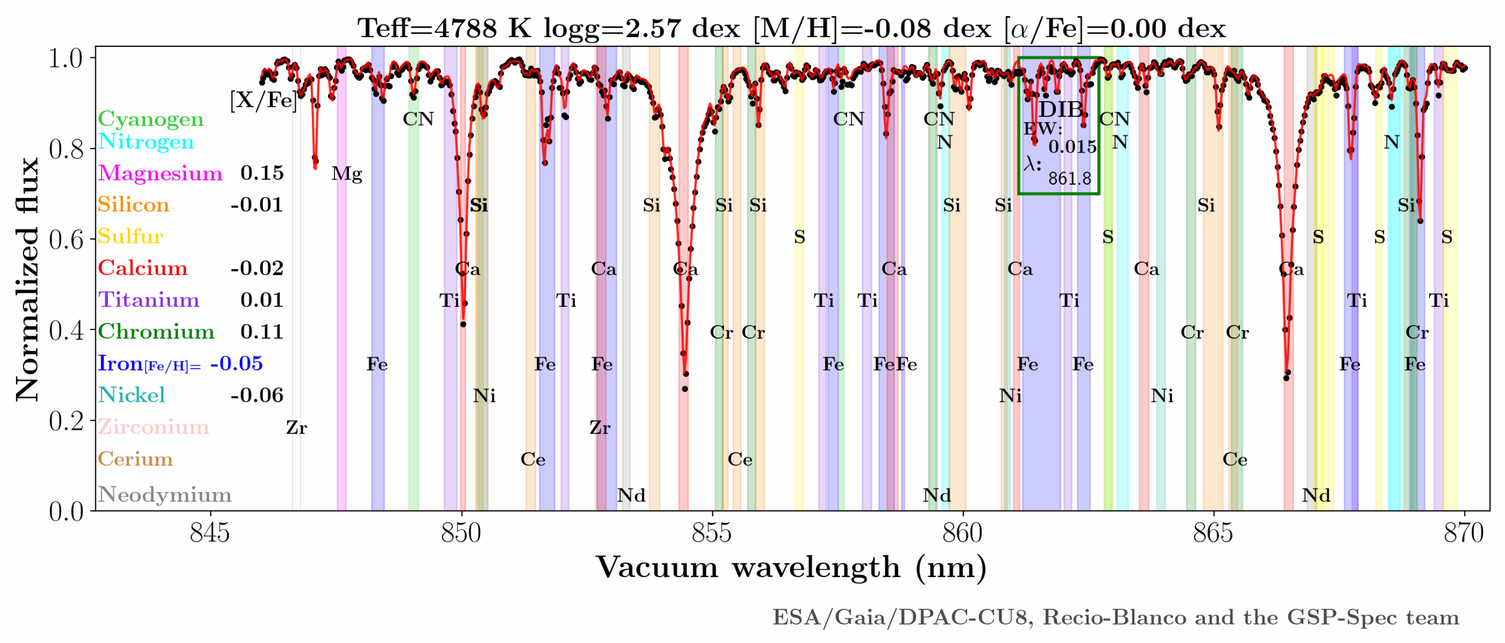

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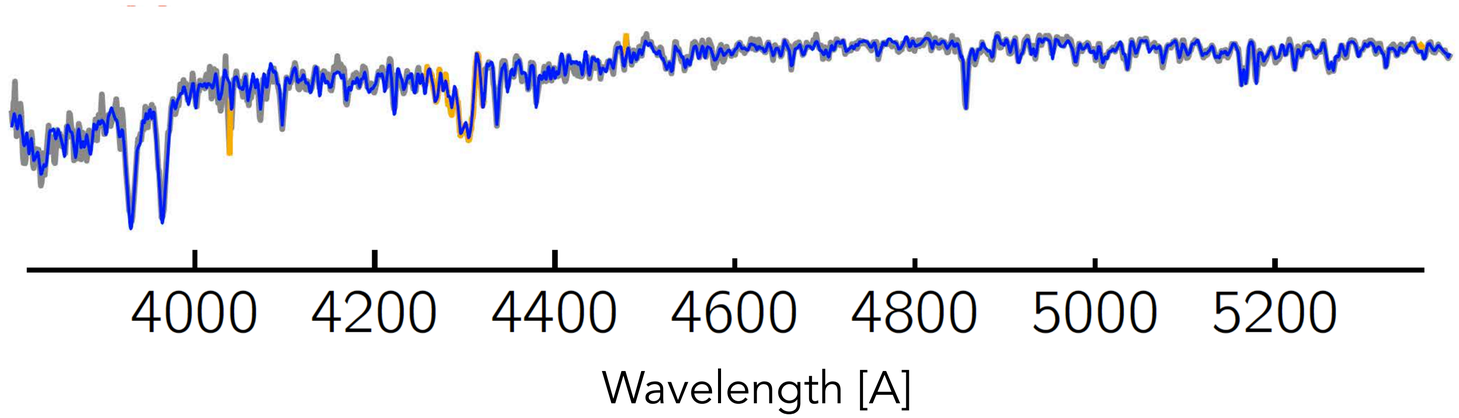

R~1300 (AAT)

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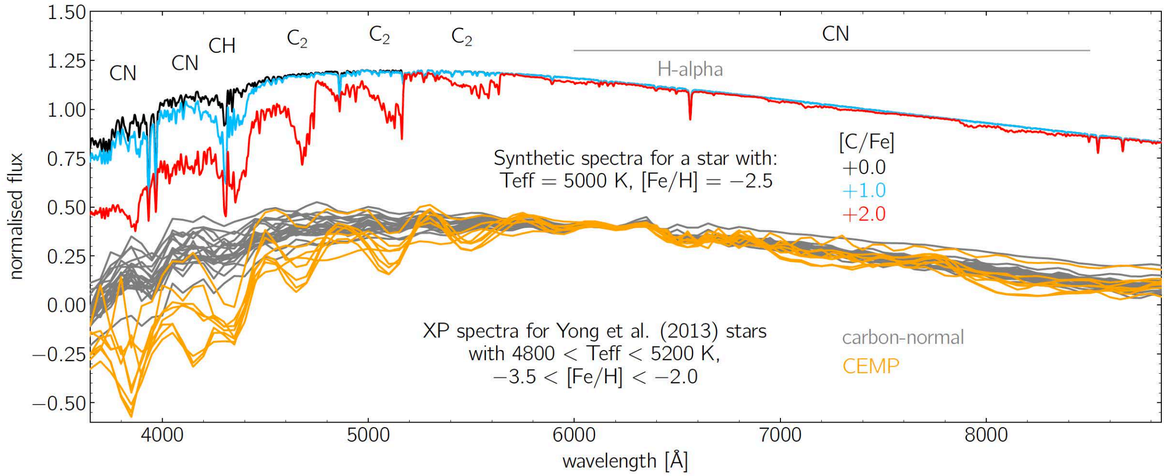

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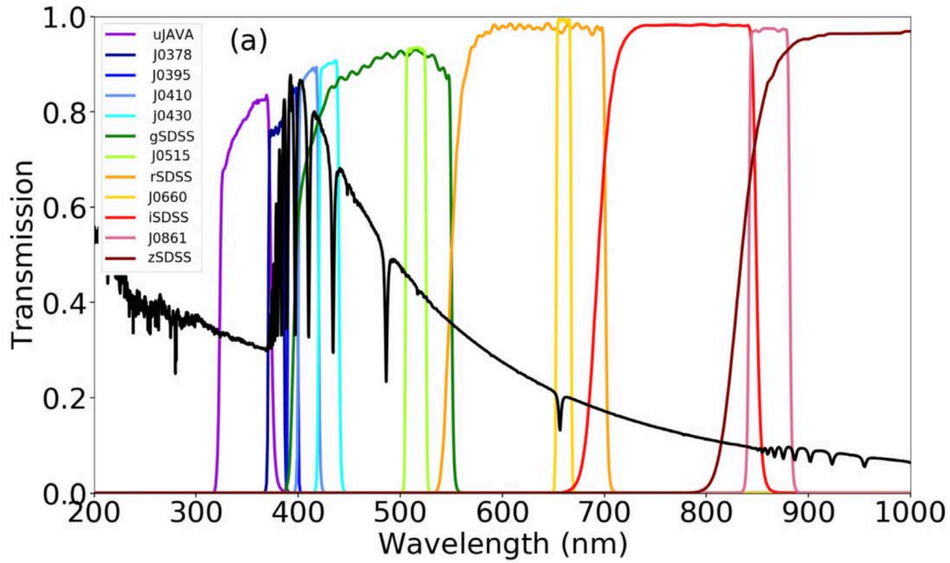
- Photometry: combine multiple (narrow) bands, **2-3 (?) elements** (Fe, "alpha", C)



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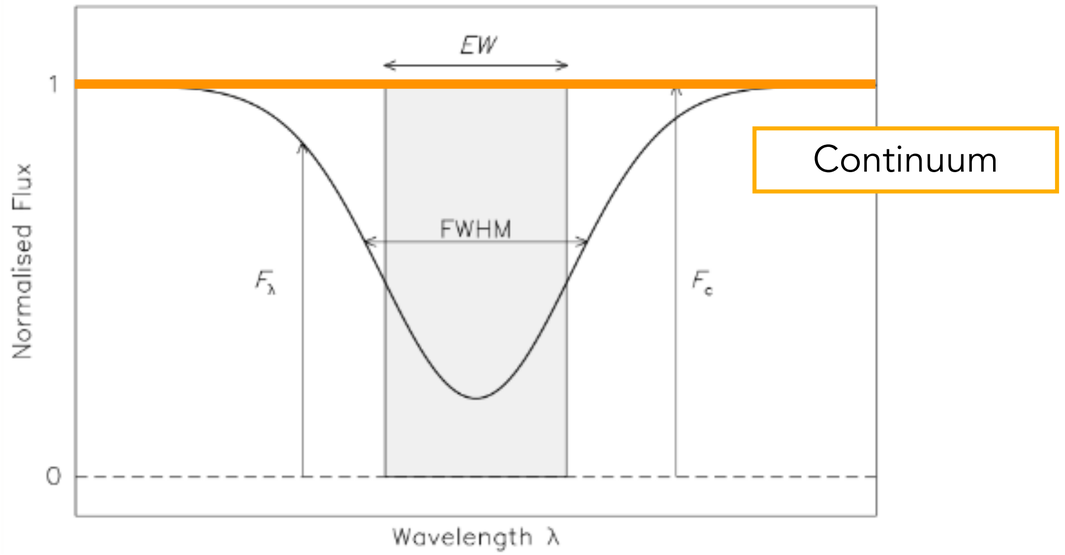
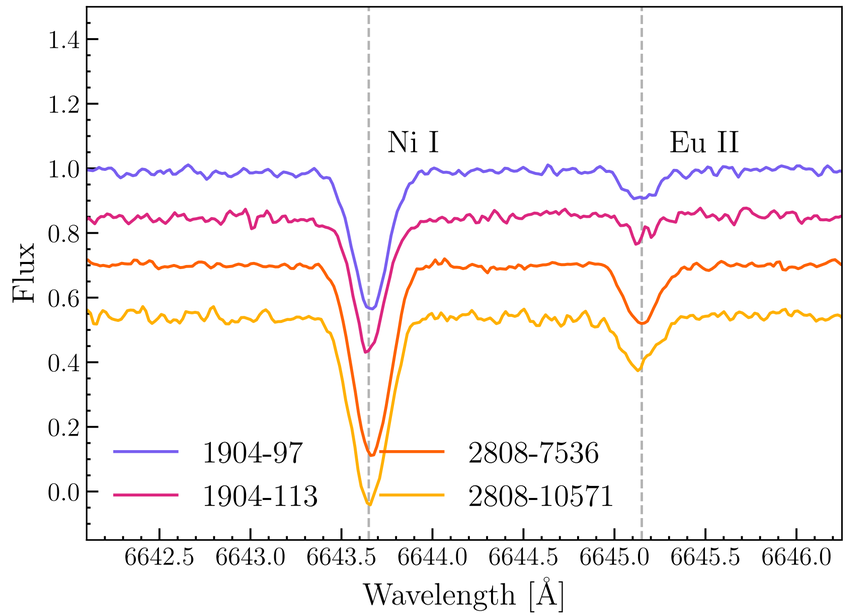
depends very much on S/N & the effective temperature and metallicity of stars

Analysis of absorption features

- Prior to analysis, spectra are usually **“continuum-fit”** and processed into “1D” spectra, into **normalised flux vs. wavelength**
- Absorption features are well-fit with **Gaussian profiles** (*most of the time*)





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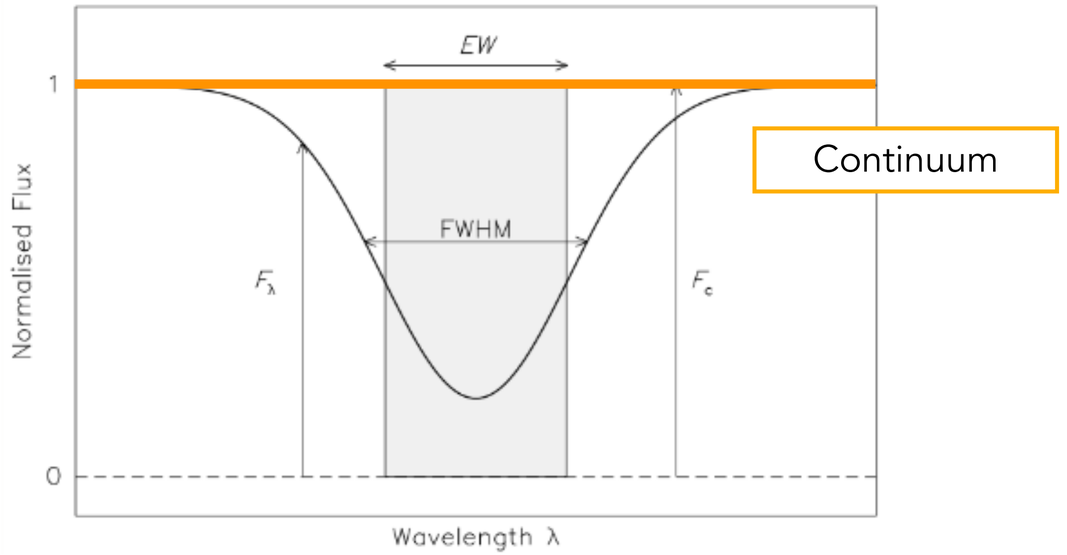
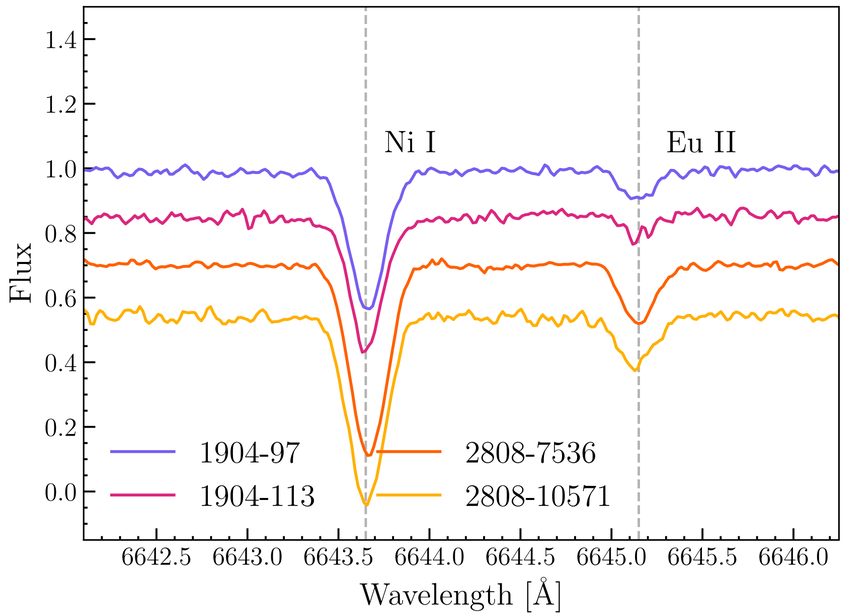
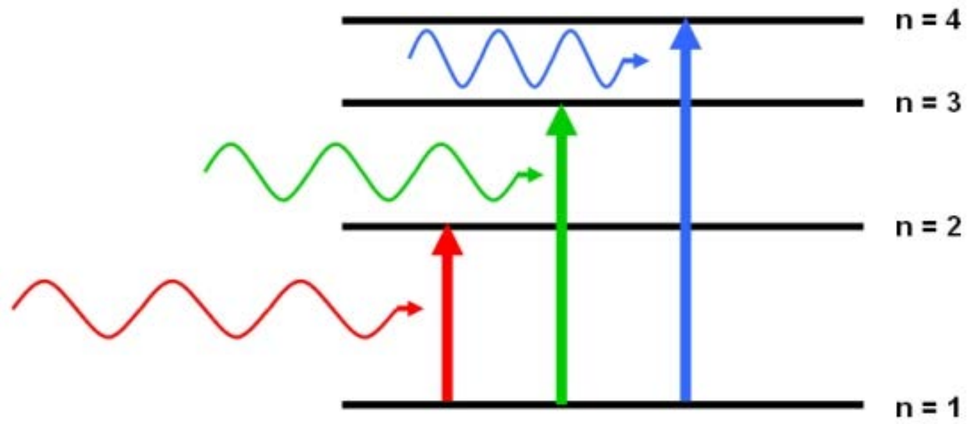
- The **depth of lines relate to the total abundance** of that element
- Often used: **Equivalent Width** (EW)
- Also **full-spectrum fitting**

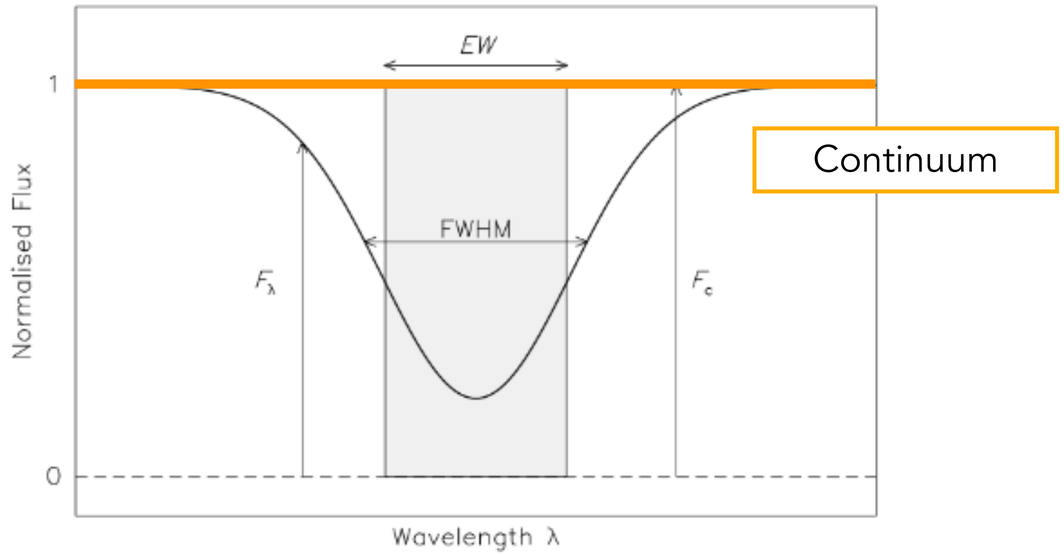


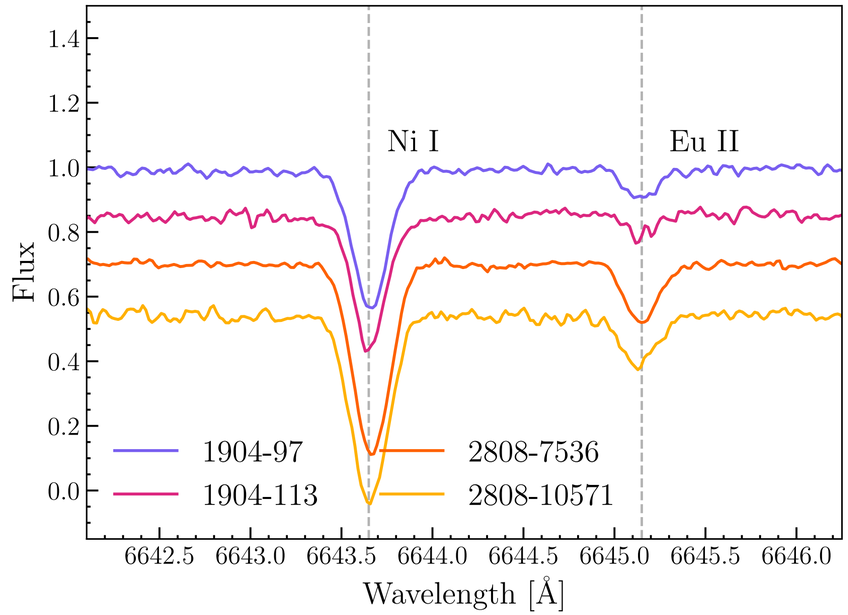


Shape of absorption lines

Q **Why are these spectral lines not delta functions?**







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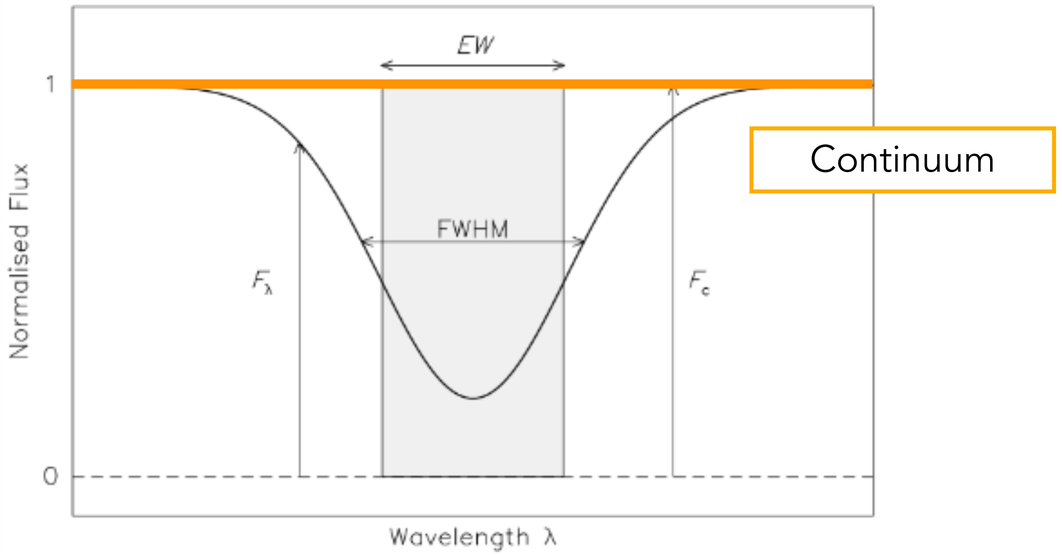

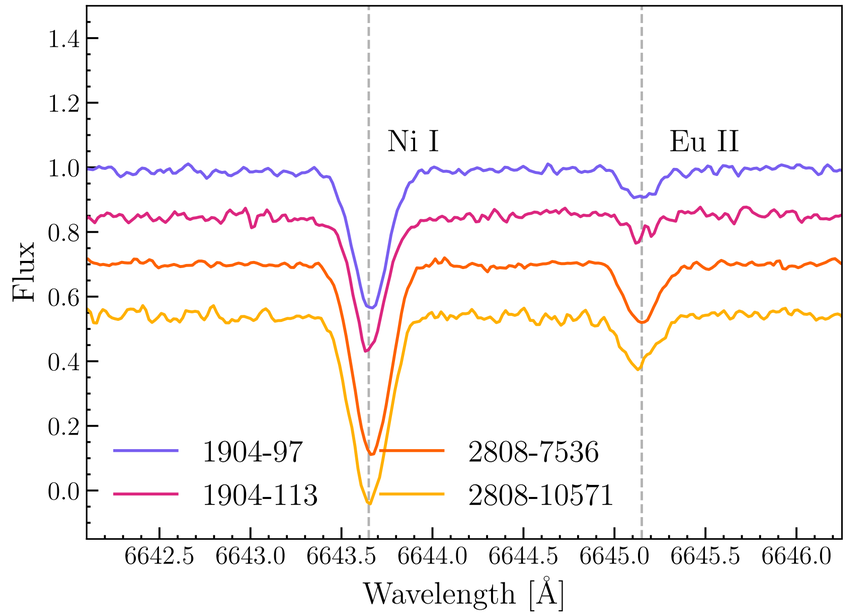

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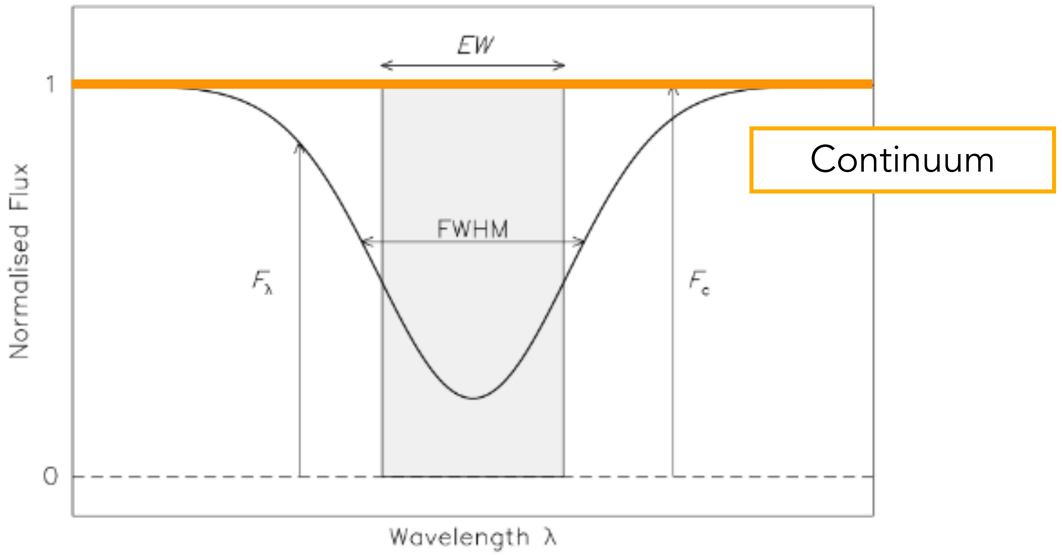
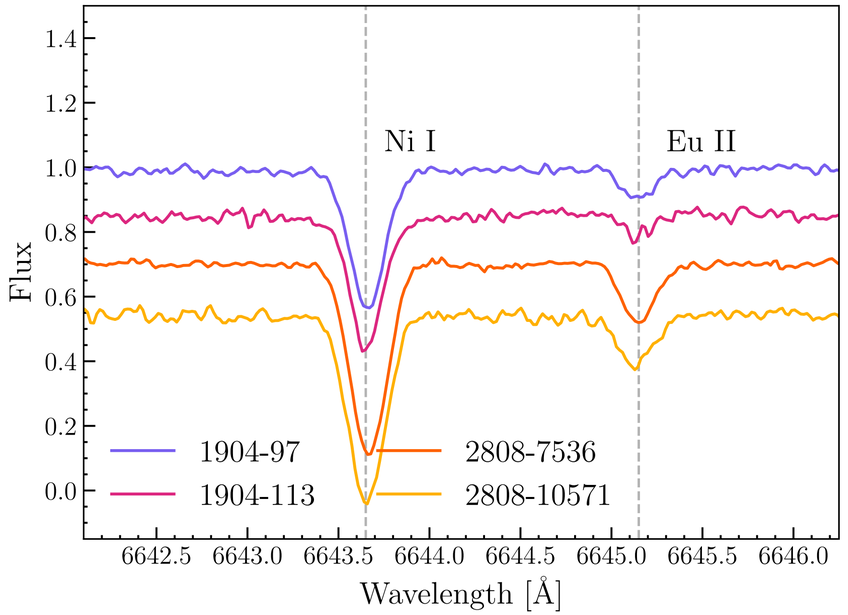
- "Natural broadening": quantum physics





Shape of absorption lines

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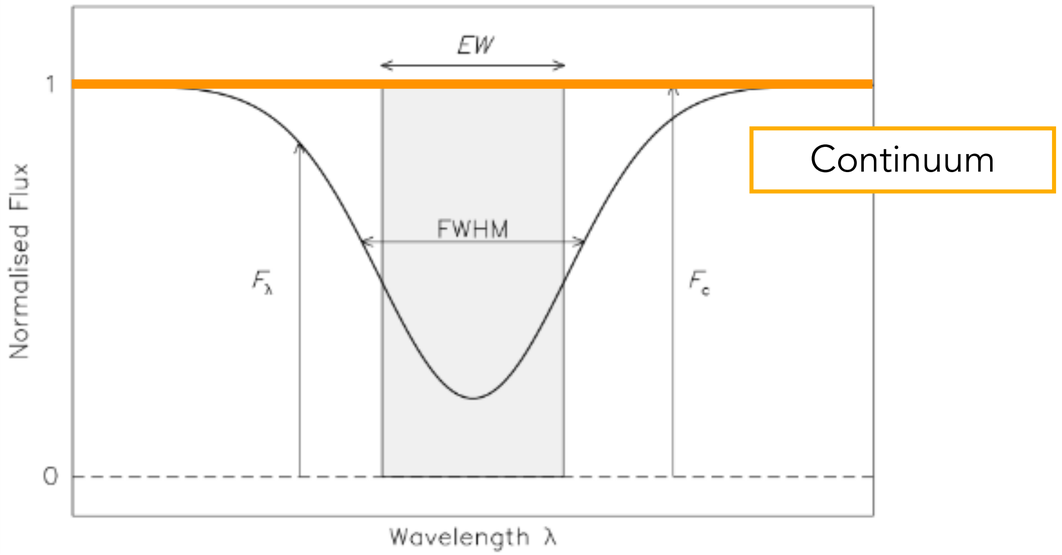
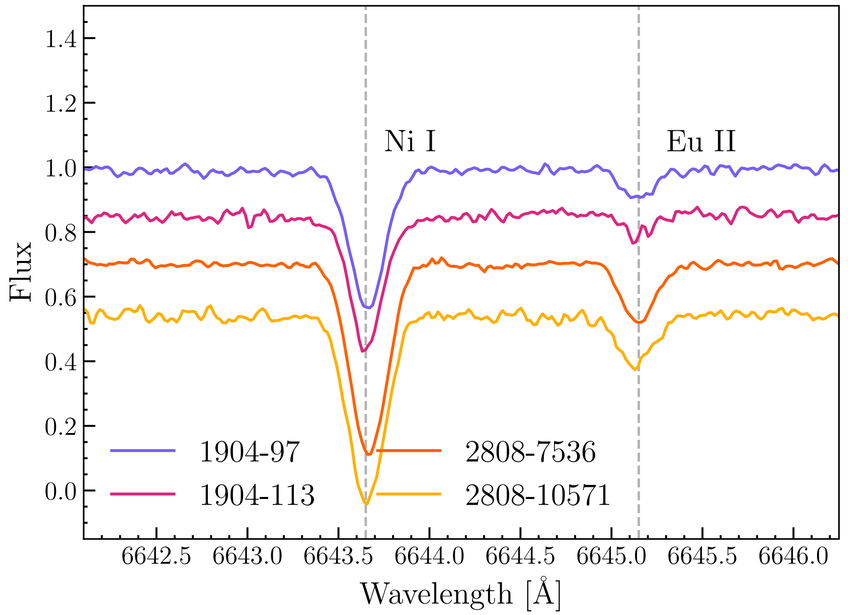
- Instrumental resolution
- “Natural broadening”: quantum physics
- “Pressure broadening”: perturbed energy levels

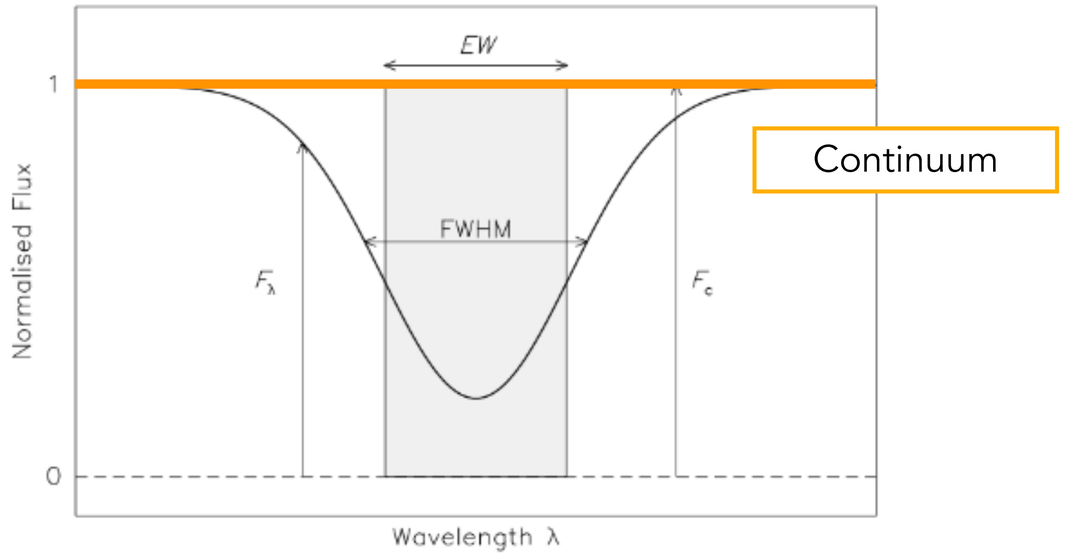


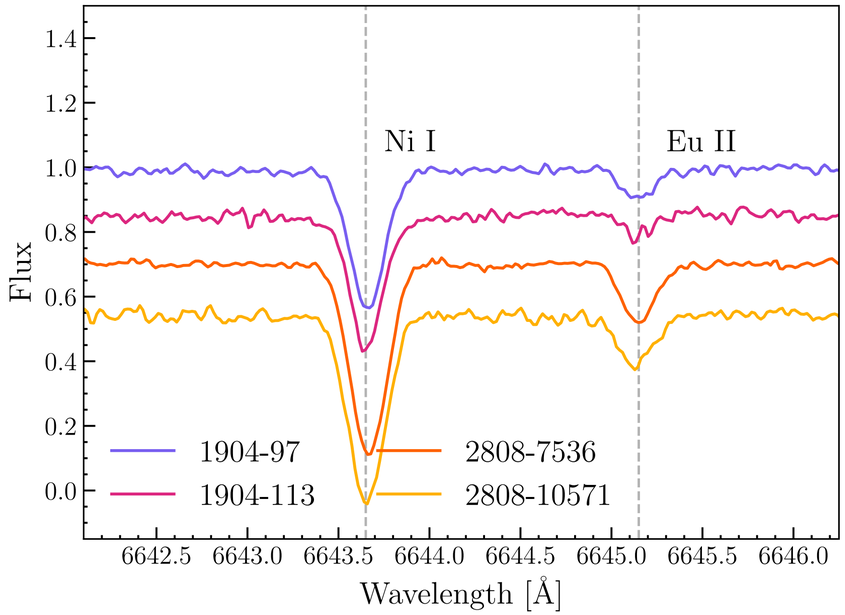


Shape of absorption lines

Q **Why are these spectral lines not delta functions?**

- Instrumental resolution
- “Natural broadening”: quantum physics
- “Pressure broadening”: perturbed energy levels
- “Doppler broadening”: motions of atoms





Abundances and equivalent widths: background

$$\log\left(\frac{W}{\lambda}\right) = \log\left(\frac{\pi e^2}{m_e c^2}\frac{N_k/N_E}{U_k(T)}N_H\right) + \log A + \log(g_{kl} f\lambda) - \chi_{kl}\theta_{exc} + const$$

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Astrophysics

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Stellar Atmosphere

Astrophysics

Abundances and equivalent widths: background

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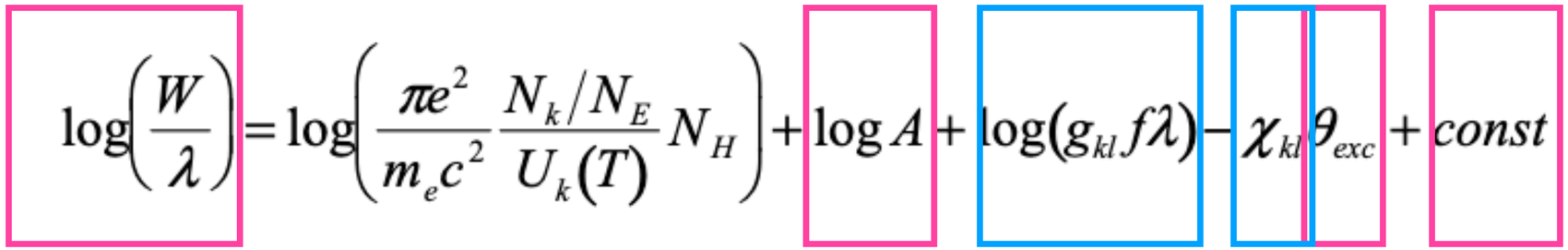

Stellar Atmosphere

Oscillator strength (transition probability)

Excitation potential (energy required for transition)

Astrophysics

Quantum Chemistry (Line list)

Abundances and equivalent widths: in practice

- To relate EWs (line depth) to abundances in practice, requires:
  - A line list of known ionisation states, transition probabilities and excitation energies
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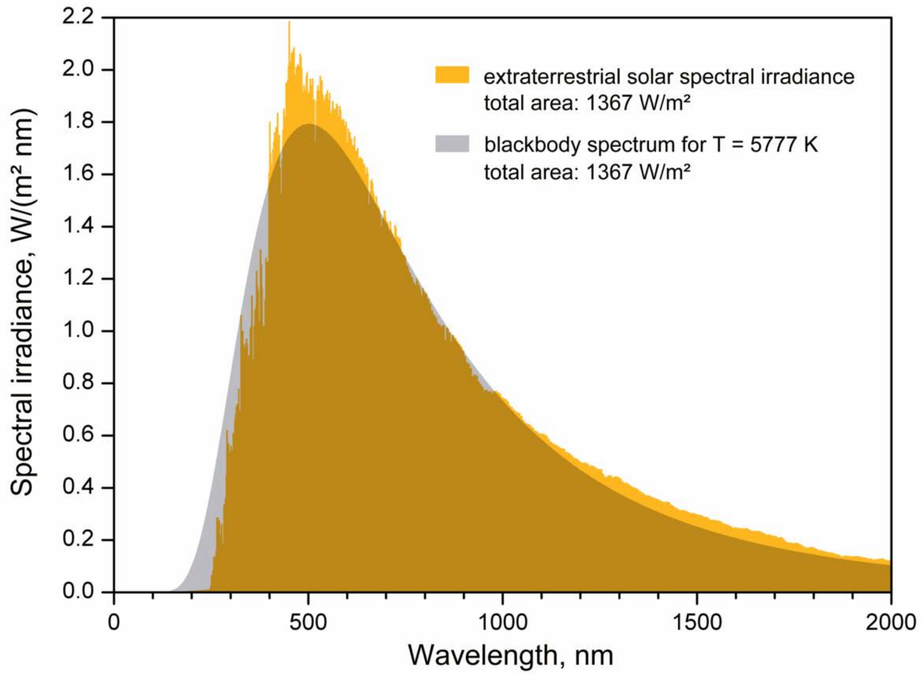

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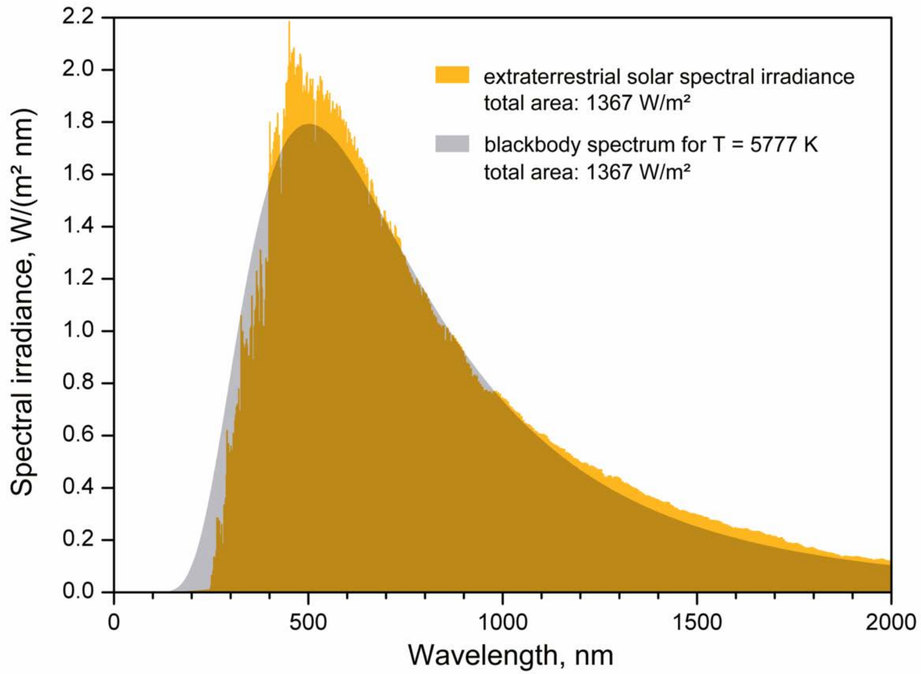
$$g = \frac{GM}{R^2}$$



Spectra changing with temperature

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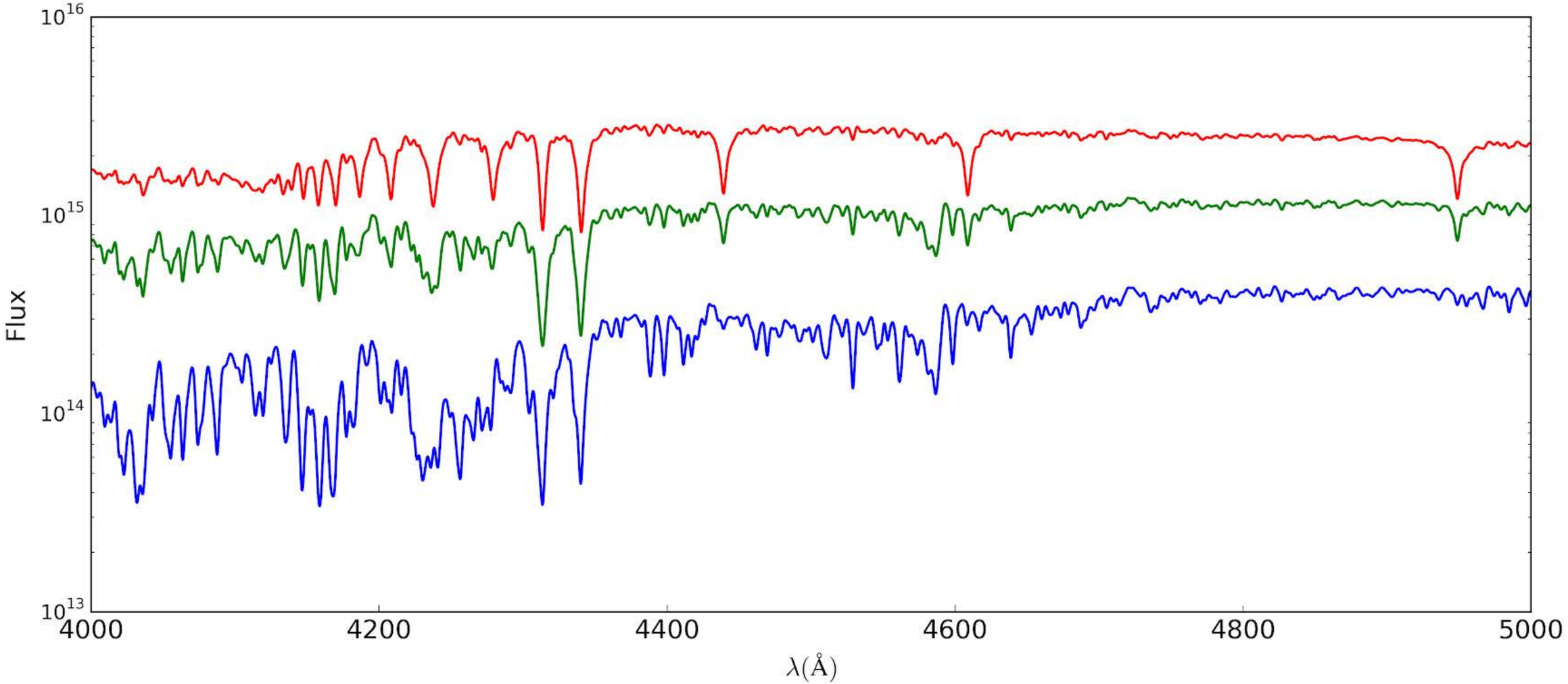

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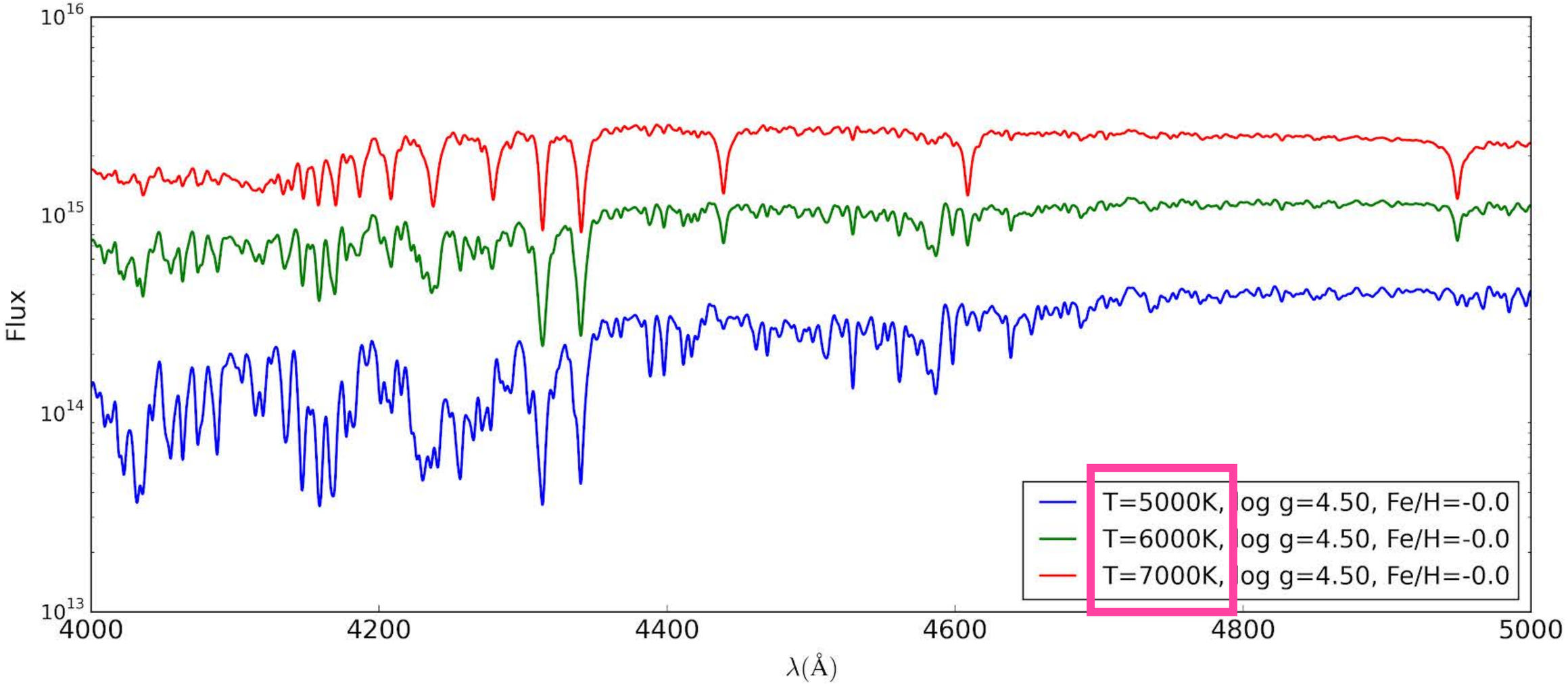
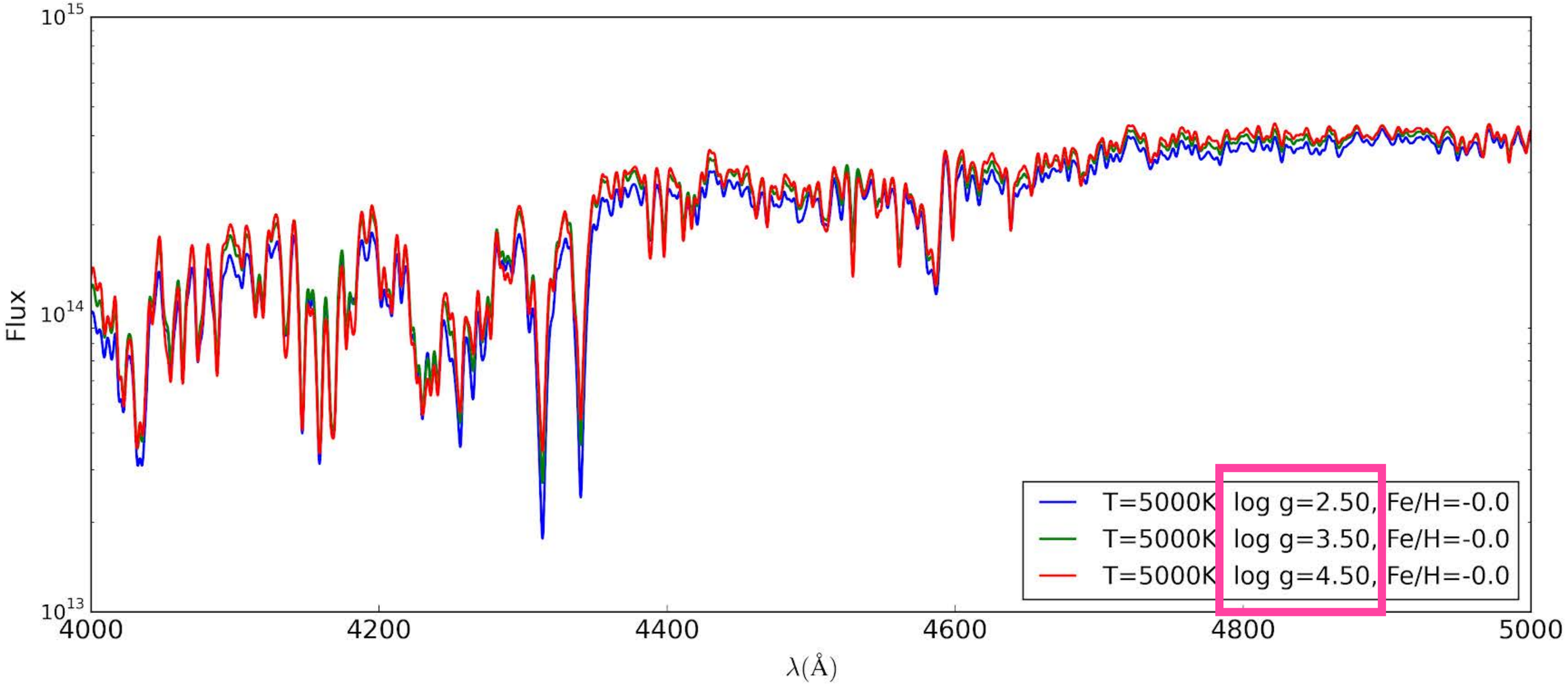
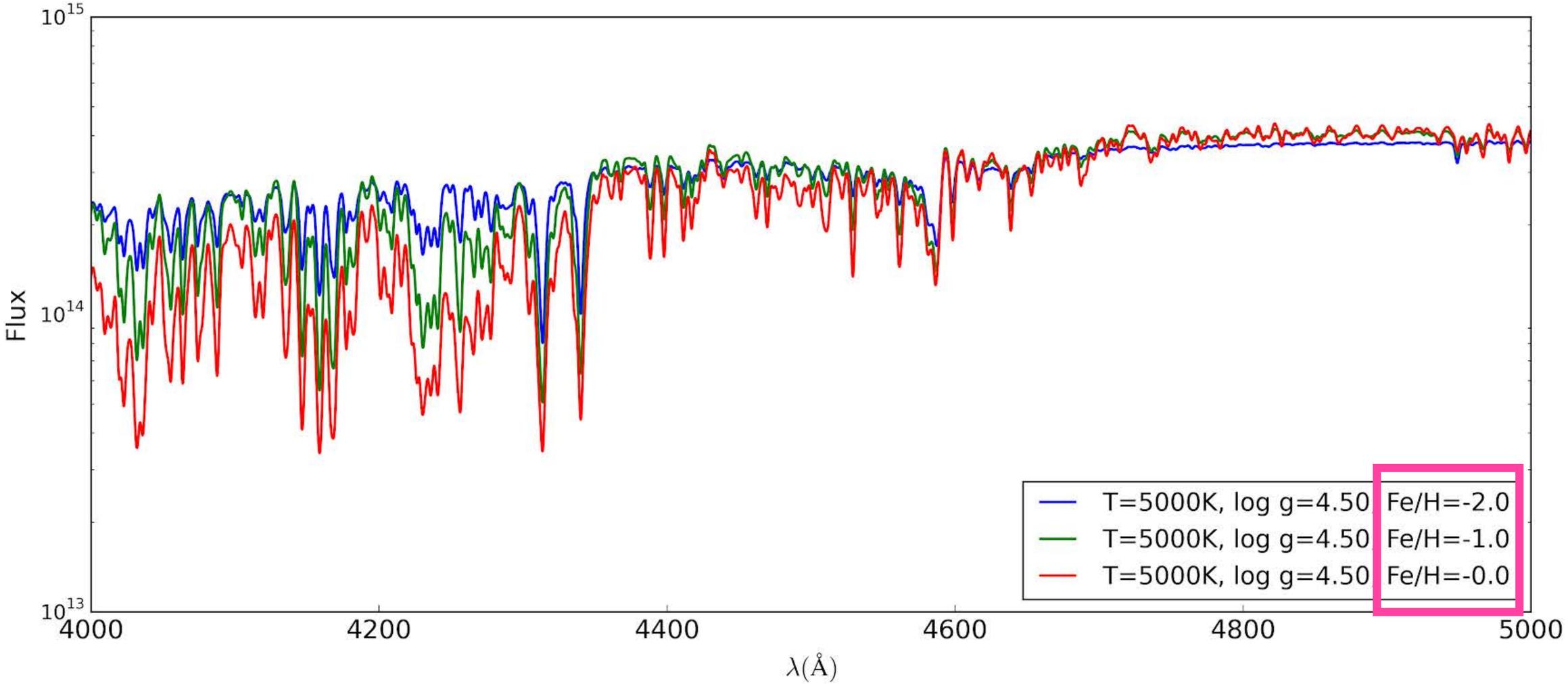


Spectra changing with surface gravity



Spectra changing with metallicity



Spectra changing with stellar velocity

redshift/blueshift due to movement of a star through space with respect to us

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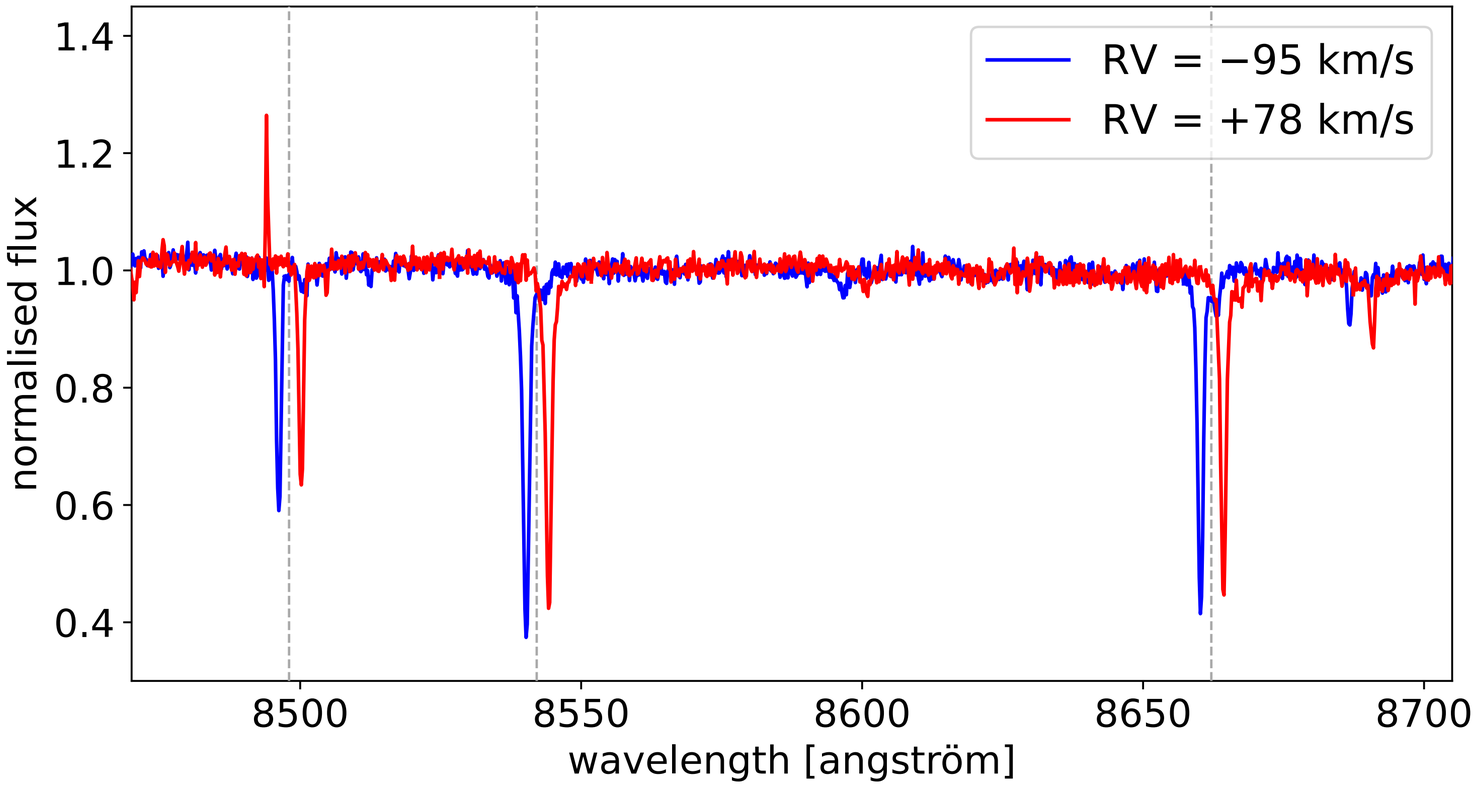
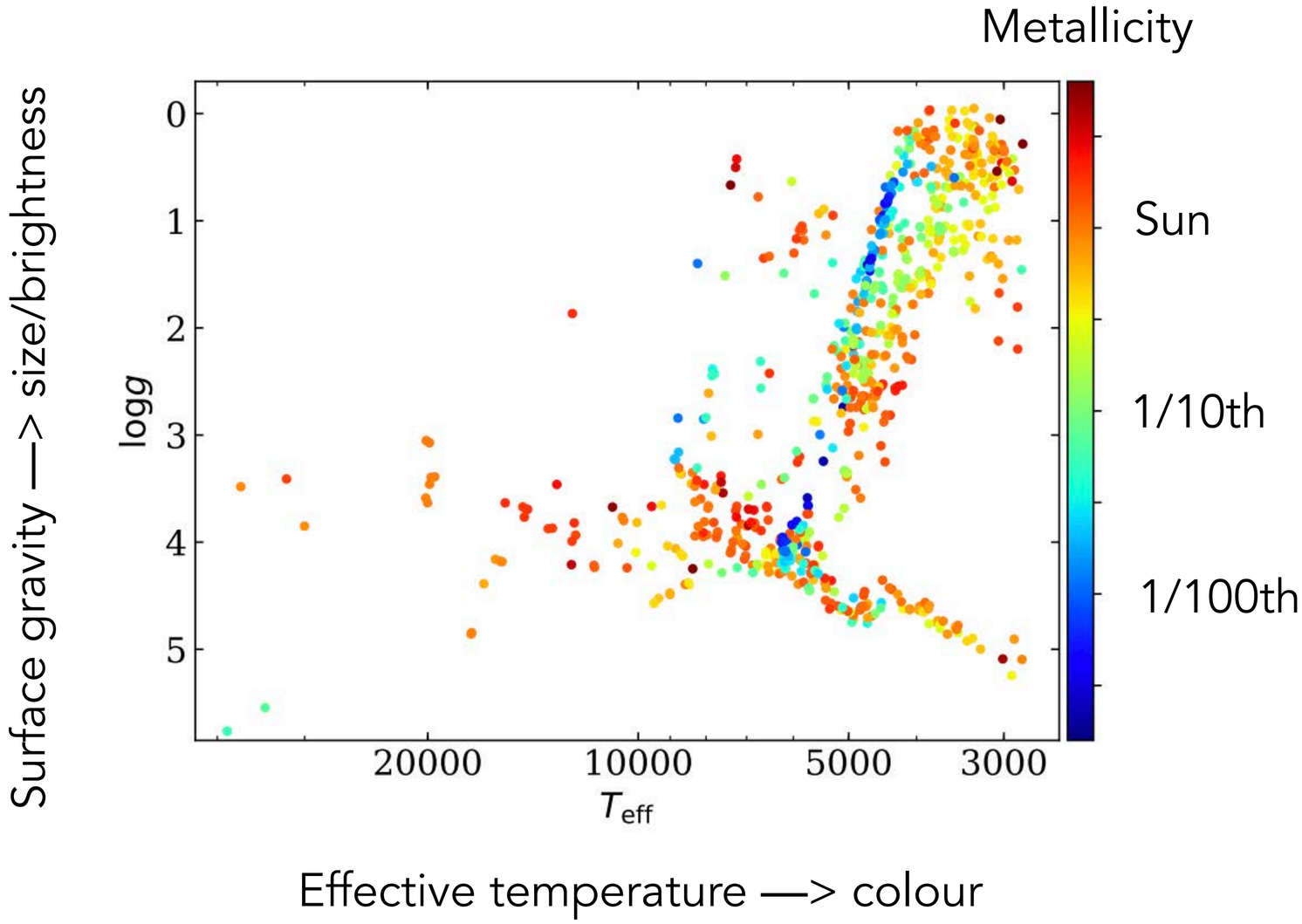


Figure from the X-shooter Spectral Library (Arentsen+19)

Kiel diagram (HR diagram analogue)



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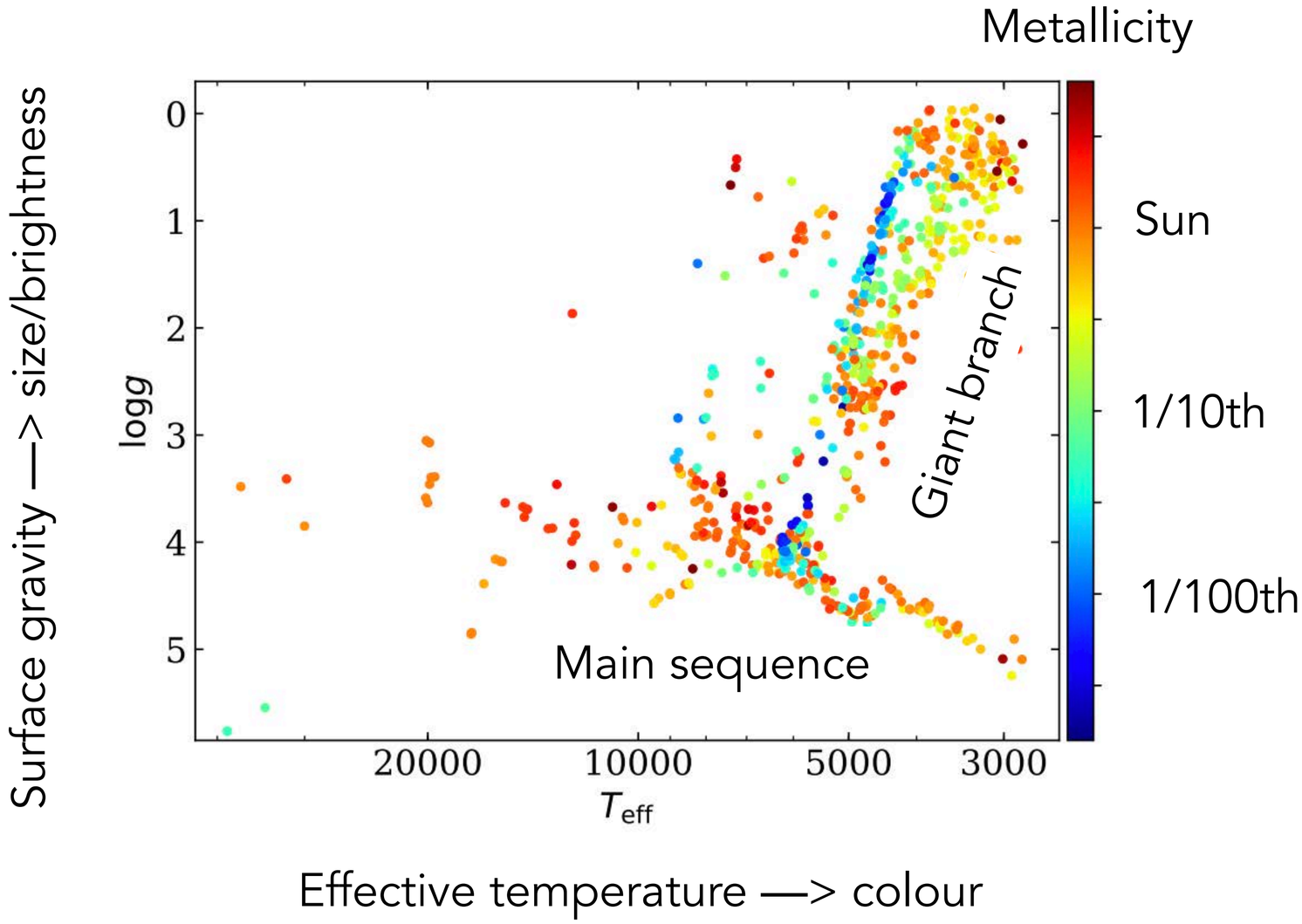
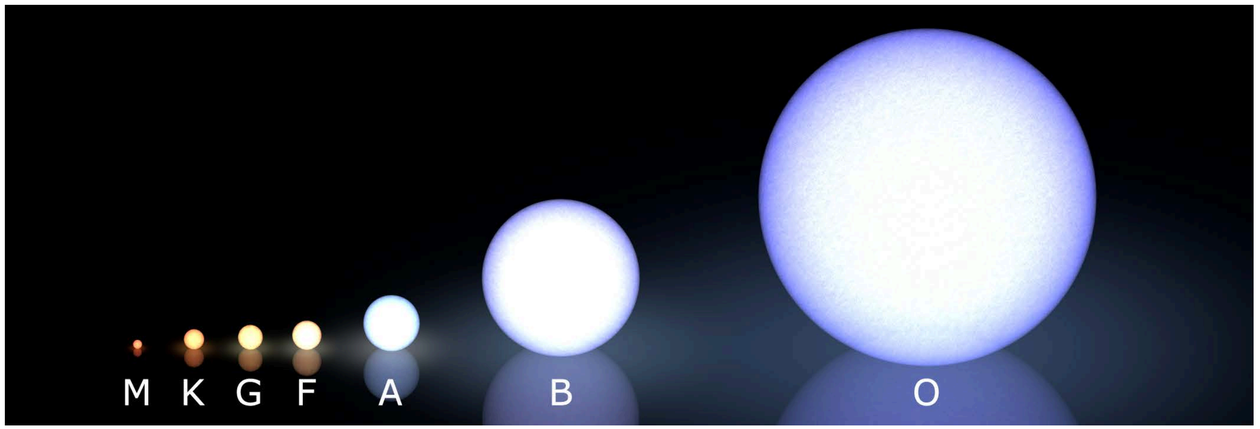
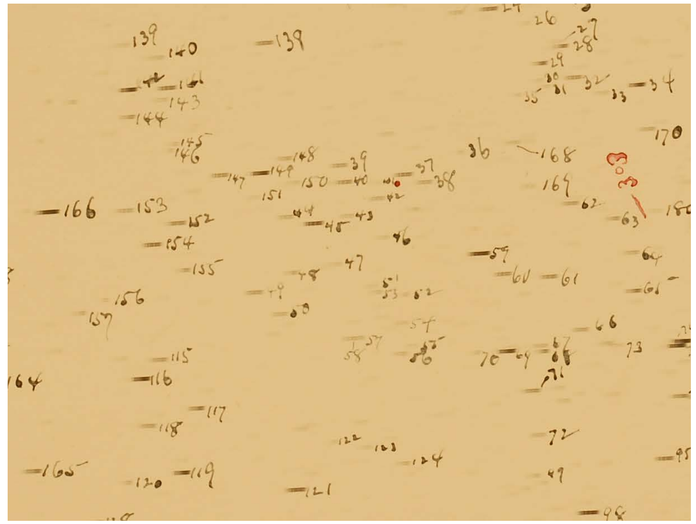


Historical note: stellar classification based on spectra



Cooler stars Hotter stars



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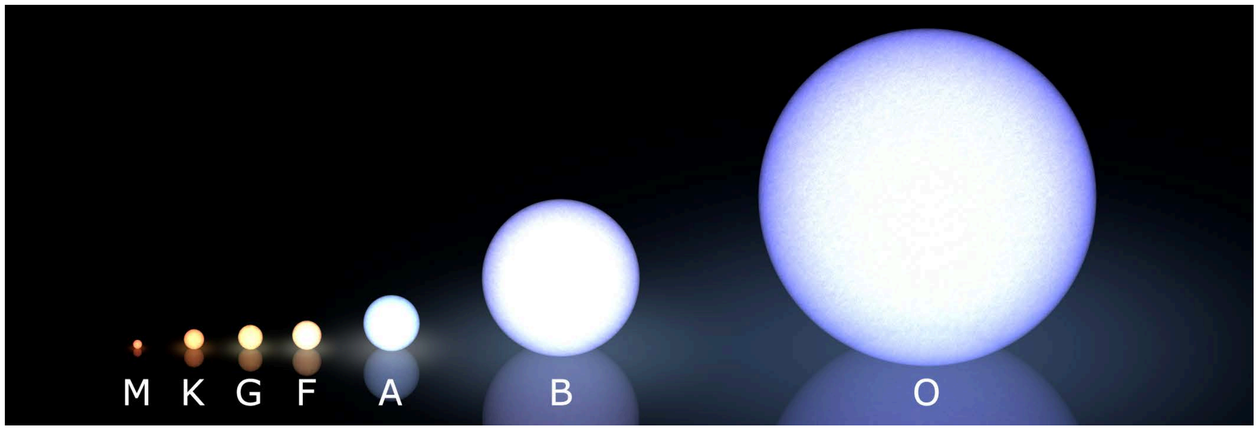

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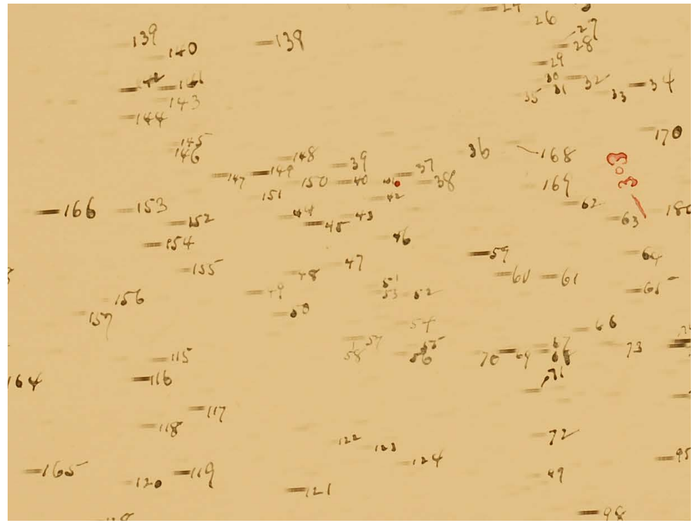

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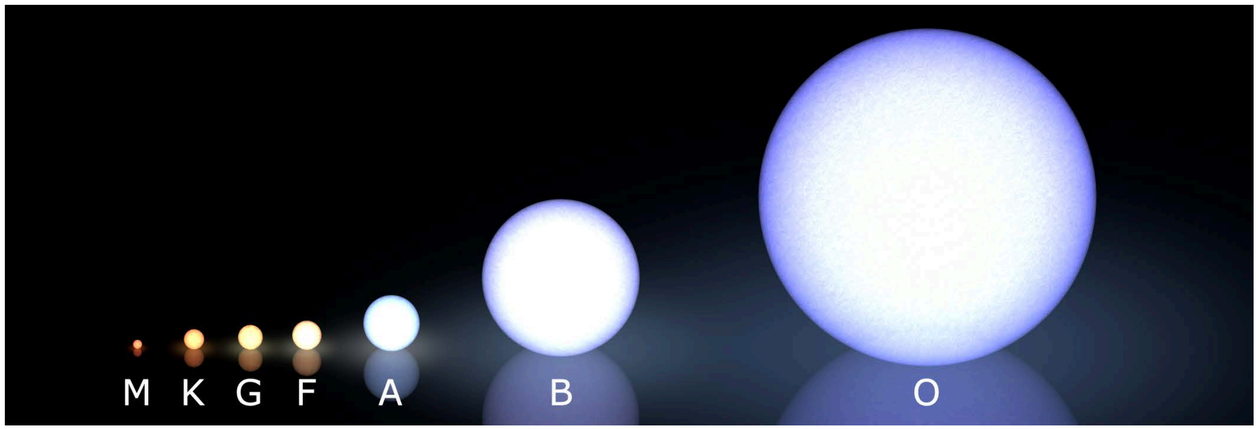

Cooler stars Hotter stars

System still used, e.g. astronomers might refer to FGK stars (which can be giants or dwarfs)

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Elemental abundances

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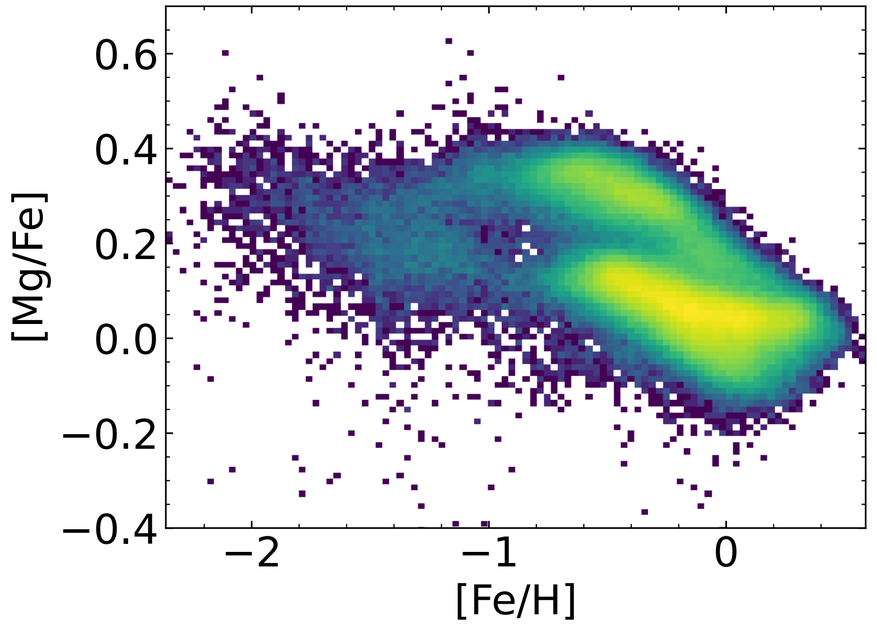

APOGEE data (high- resolution infrared spectra, R~22 500)

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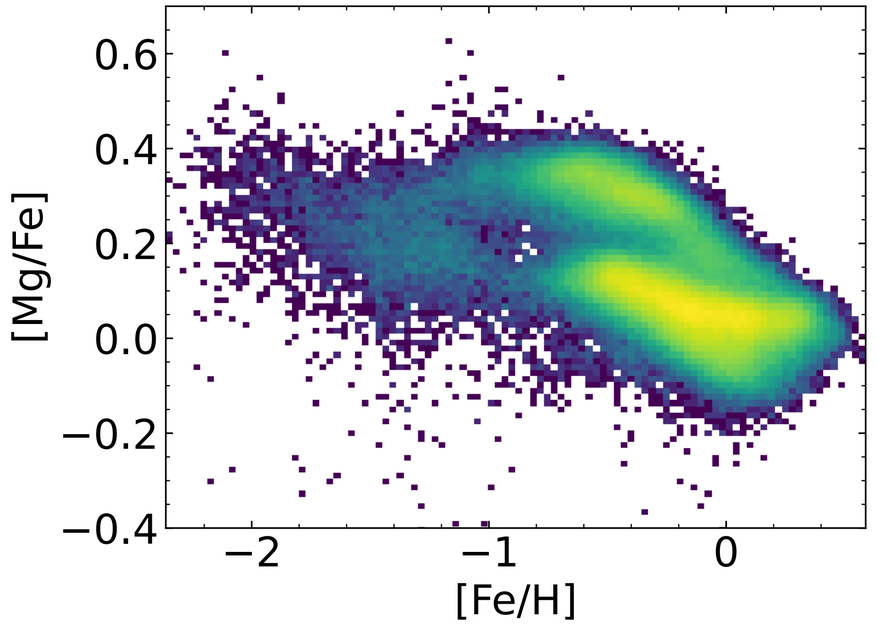

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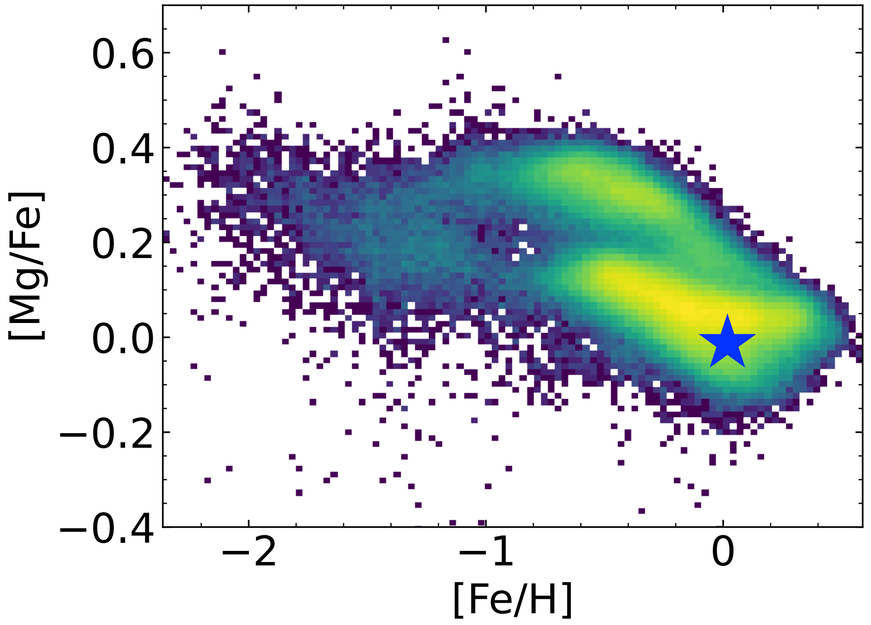

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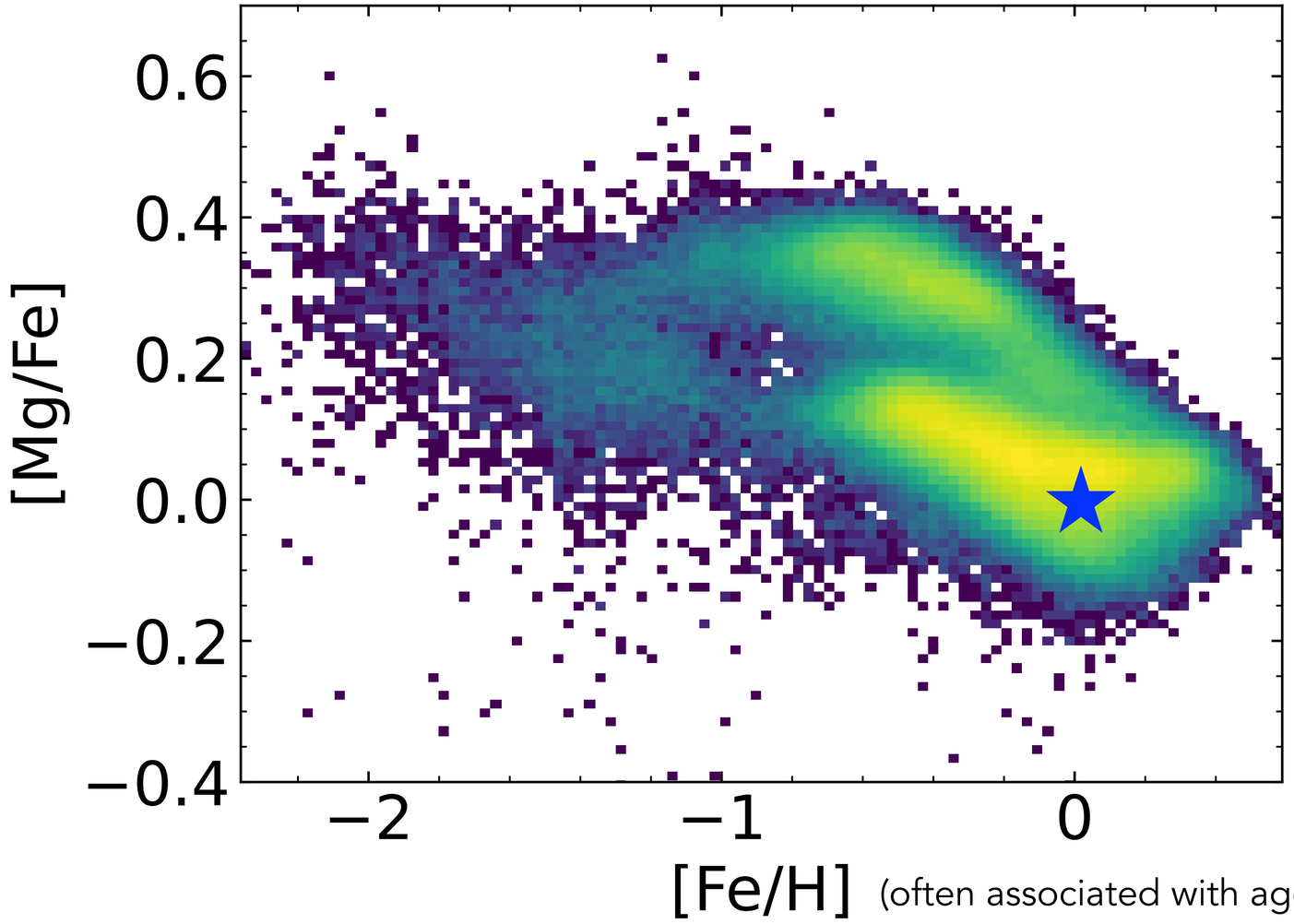

(often associated with age)

~270 000 stars from APOGEE (high-resolution infrared spectra, R~22 500)

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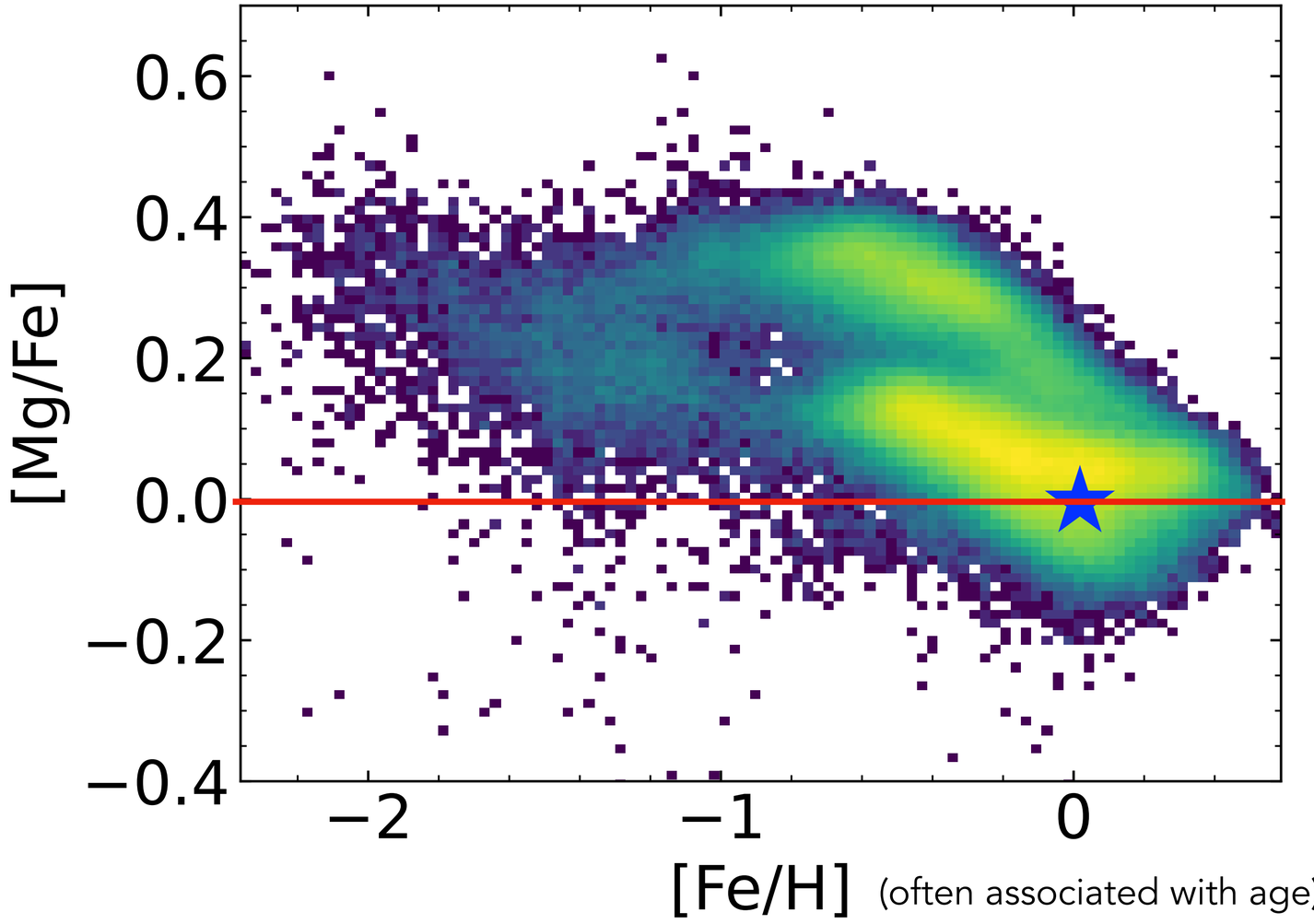

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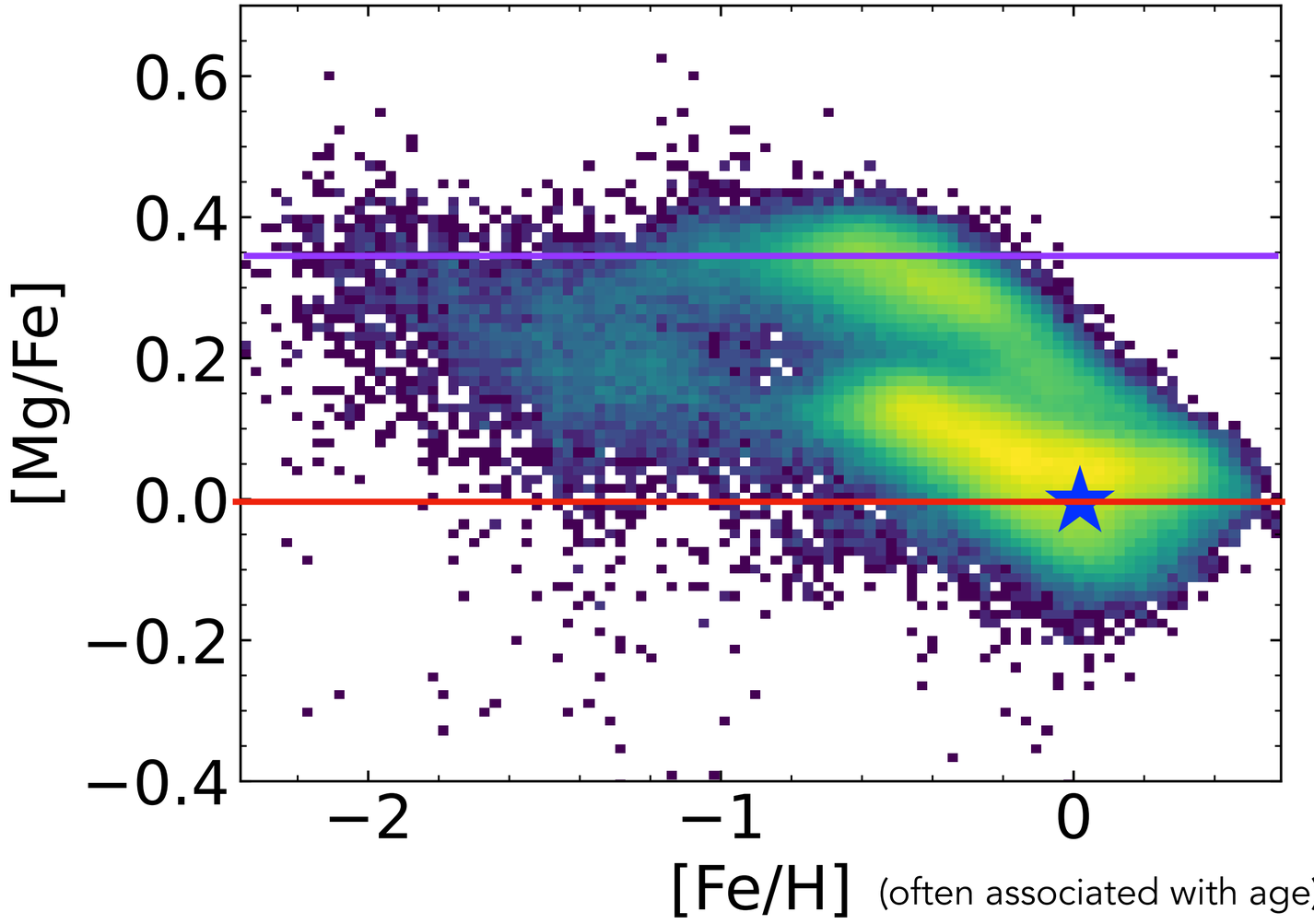

High-alpha plateau
mostly type II supernovae

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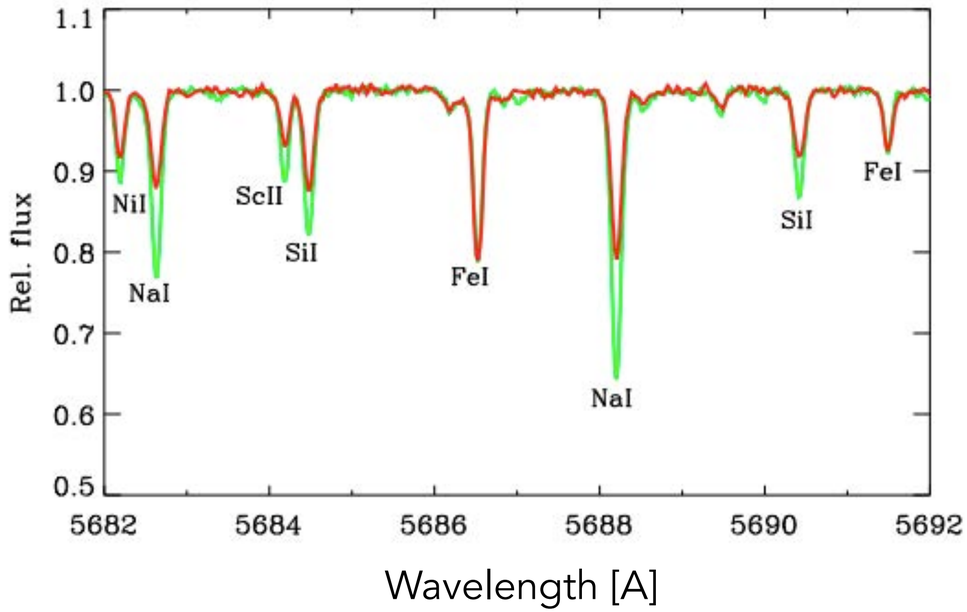
- Purely spectroscopic or include external data?

Line-by-line measurements

Nissen & Schuster (2010)



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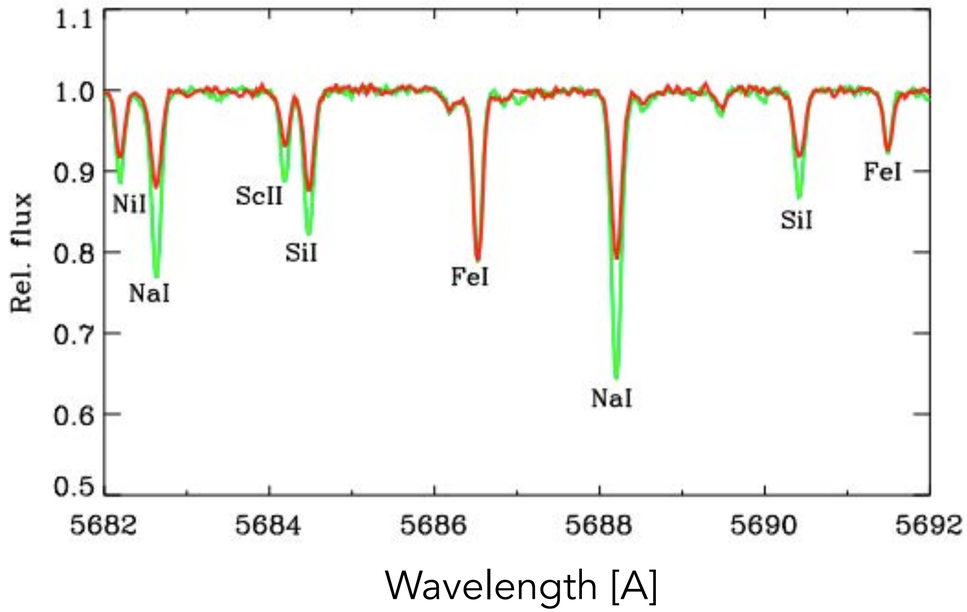

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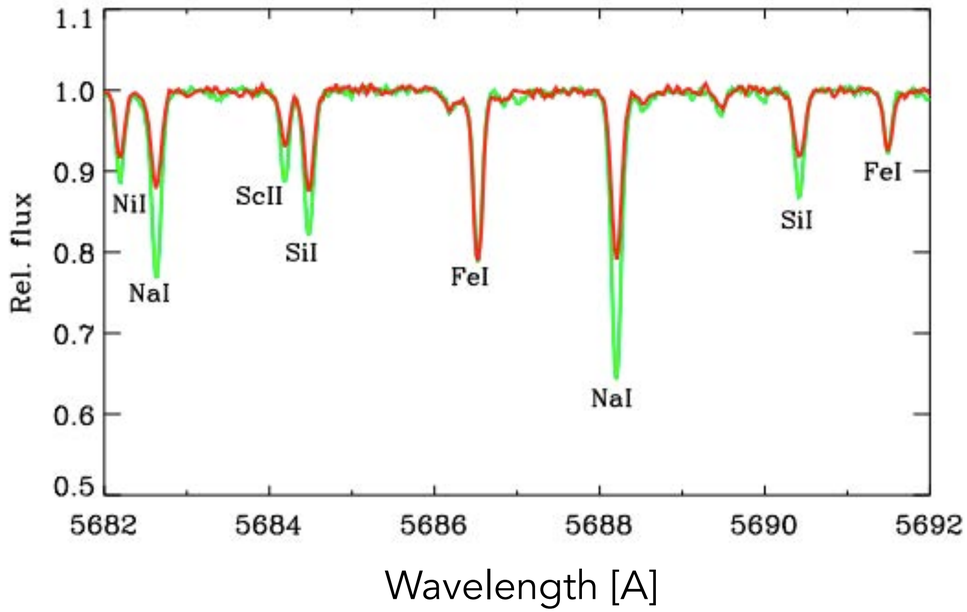

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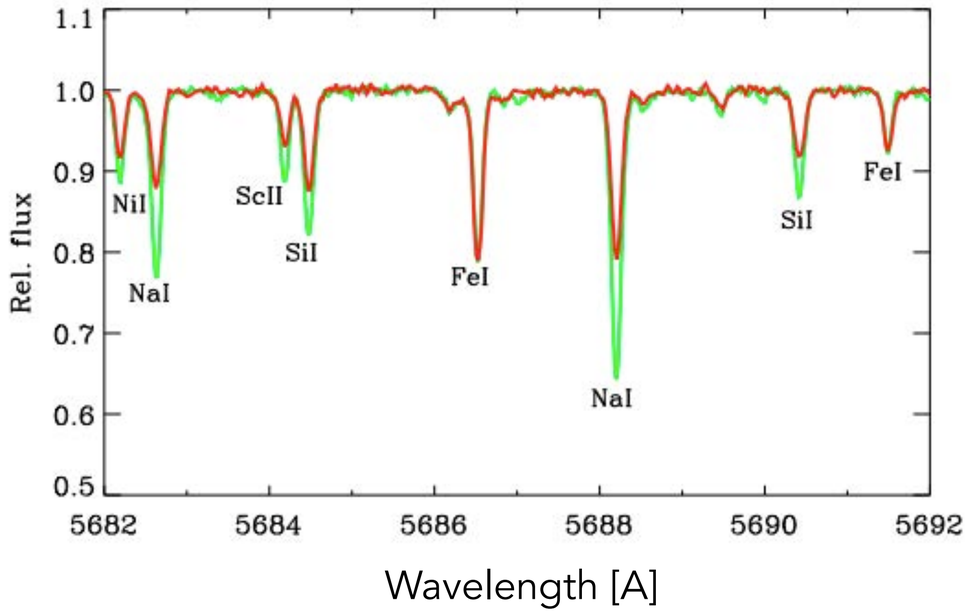

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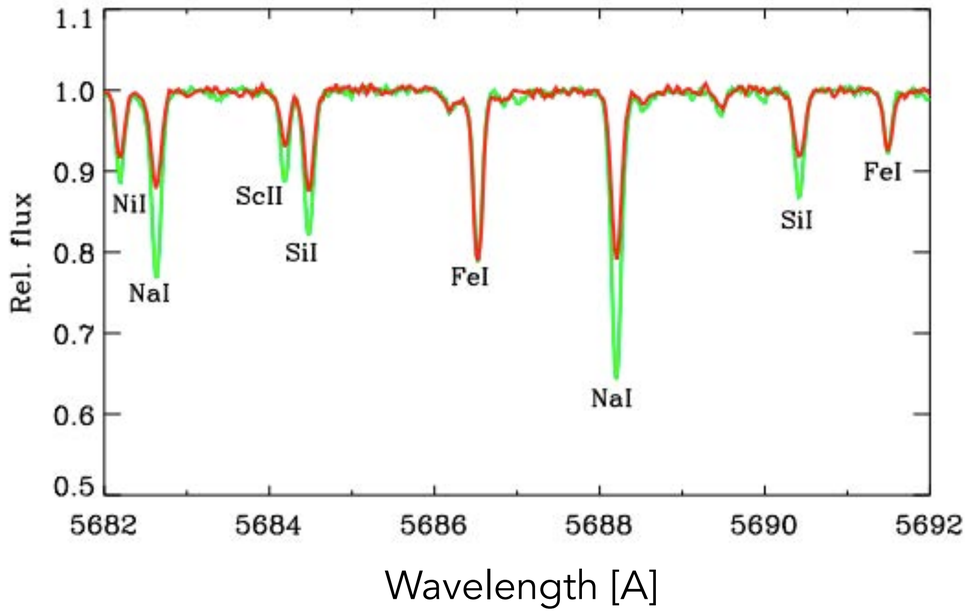

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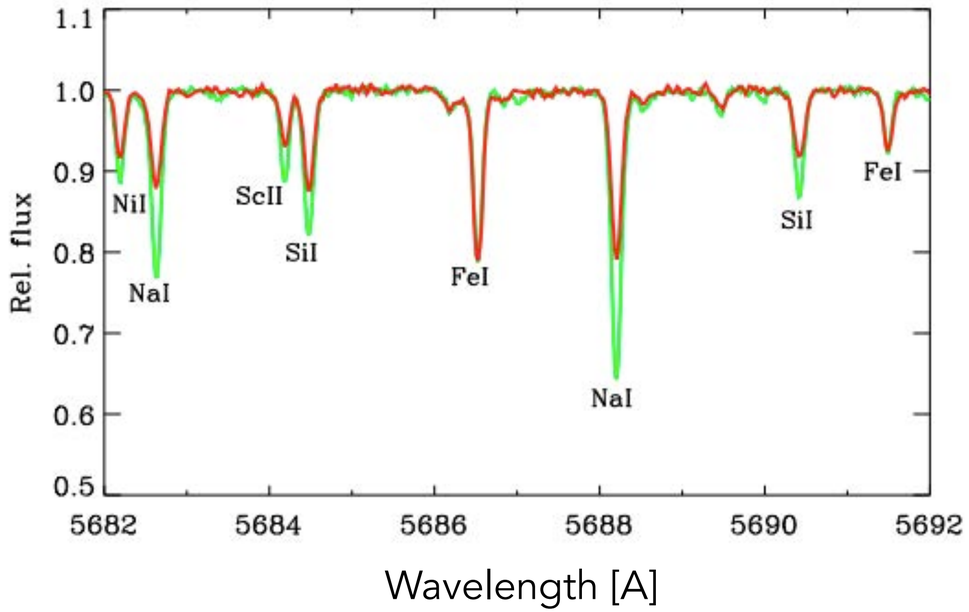

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At the same metallicity: a group of stars formed in an **efficient star-forming environment** and a group from an **inefficient star-forming environment**

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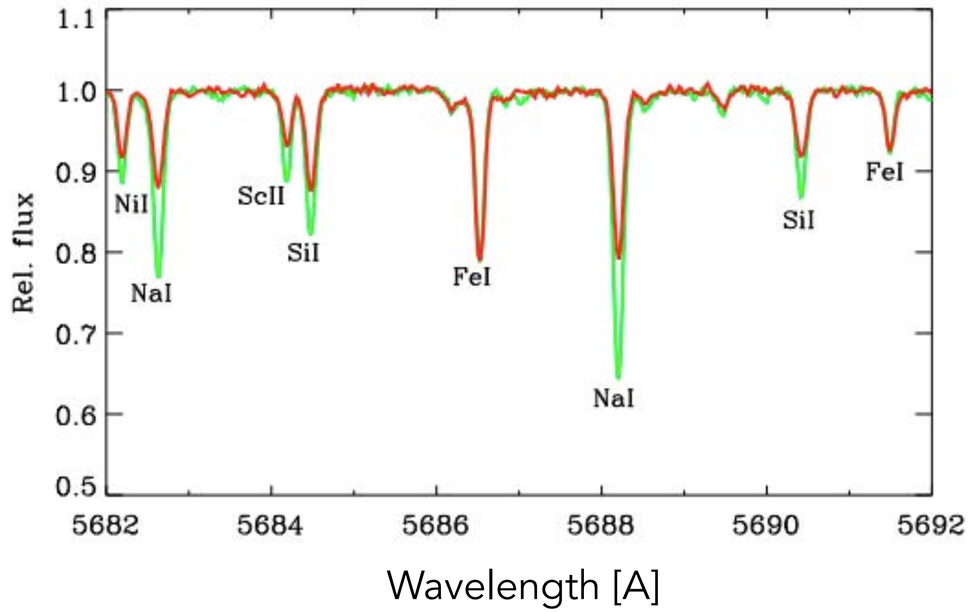
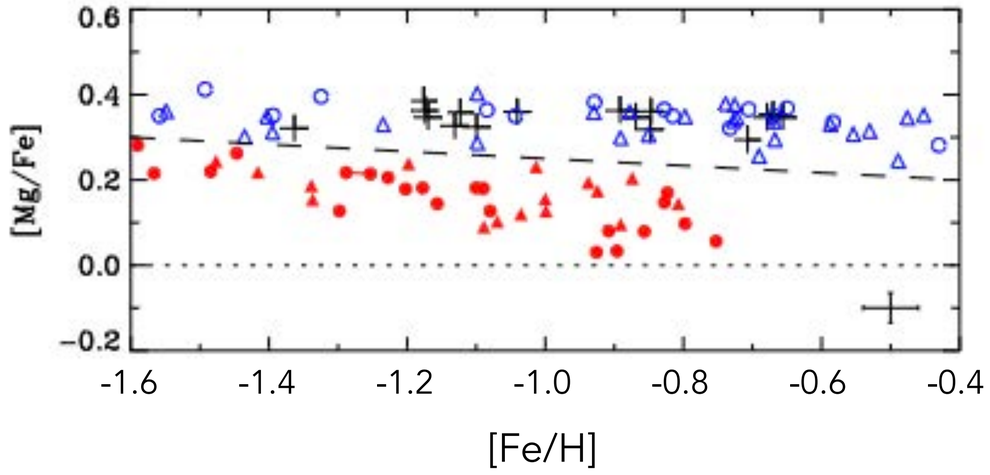
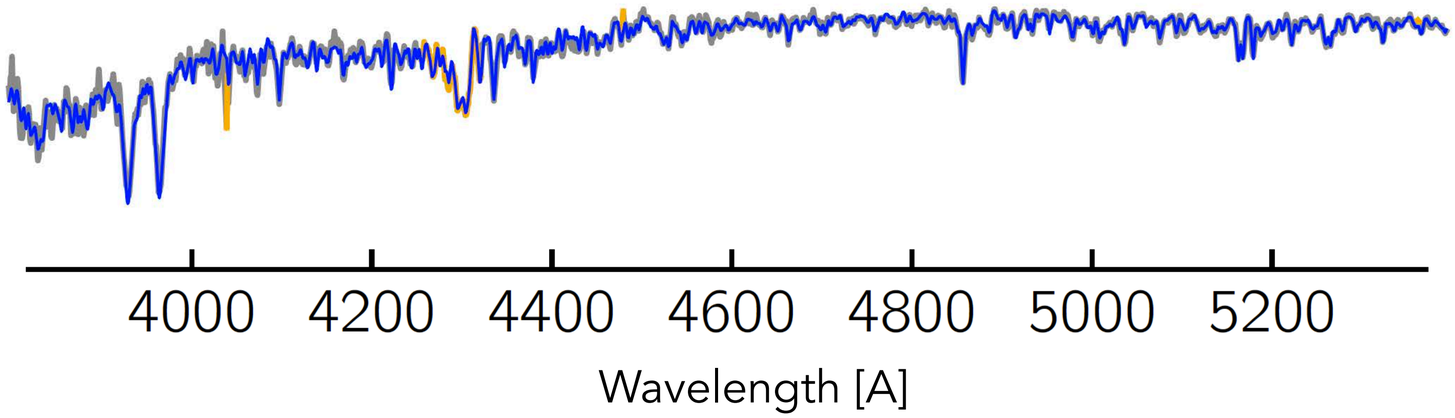




Full-spectrum fitting



Fit of a low-resolution (R~1300) spectrum with an empirical library (Arentsen+20)

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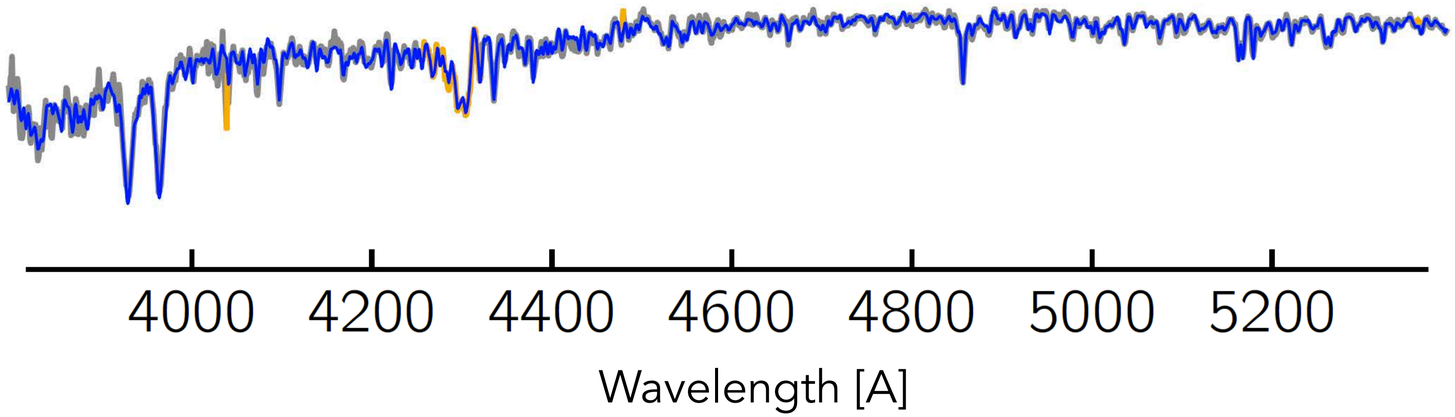

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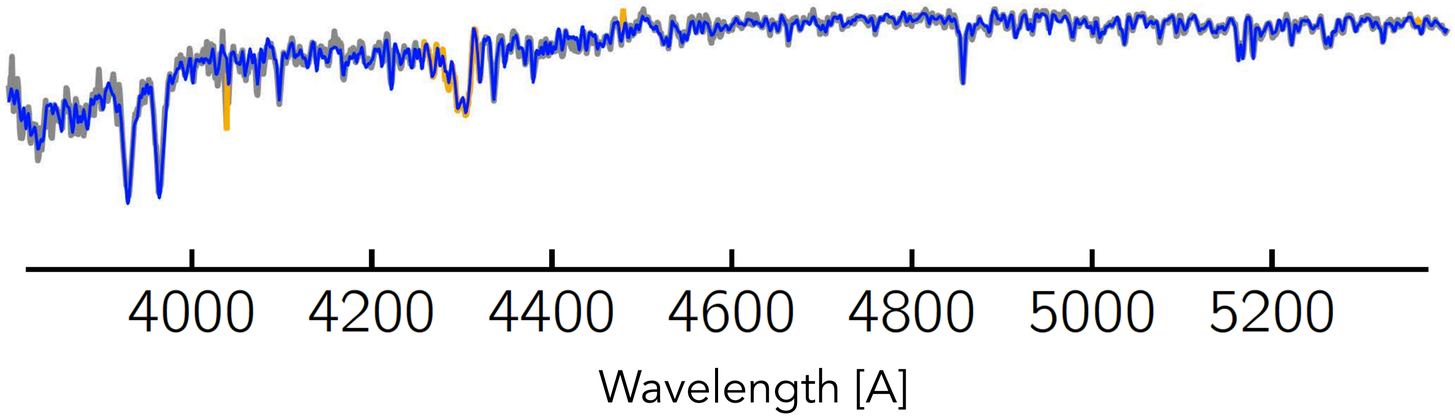

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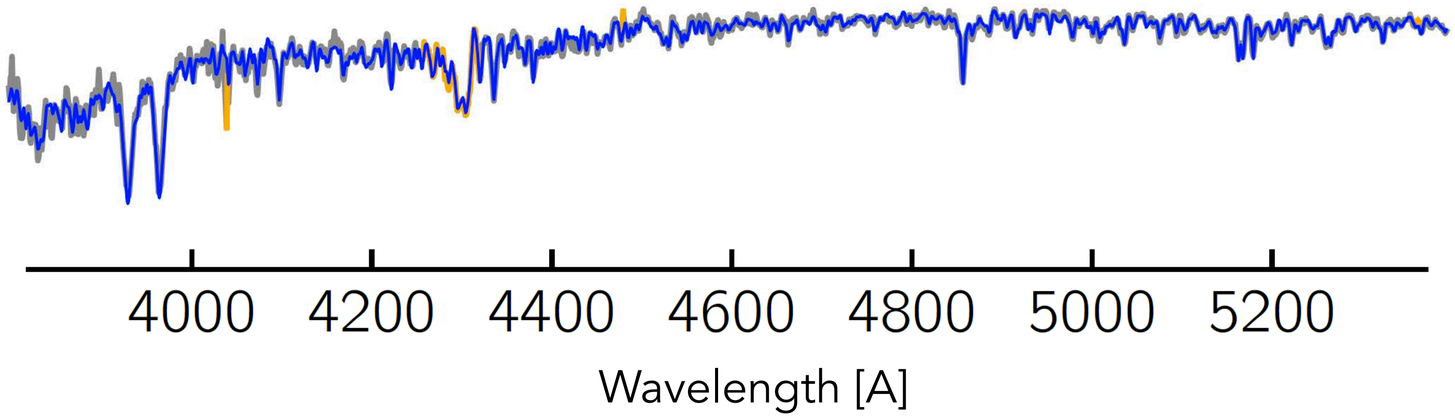

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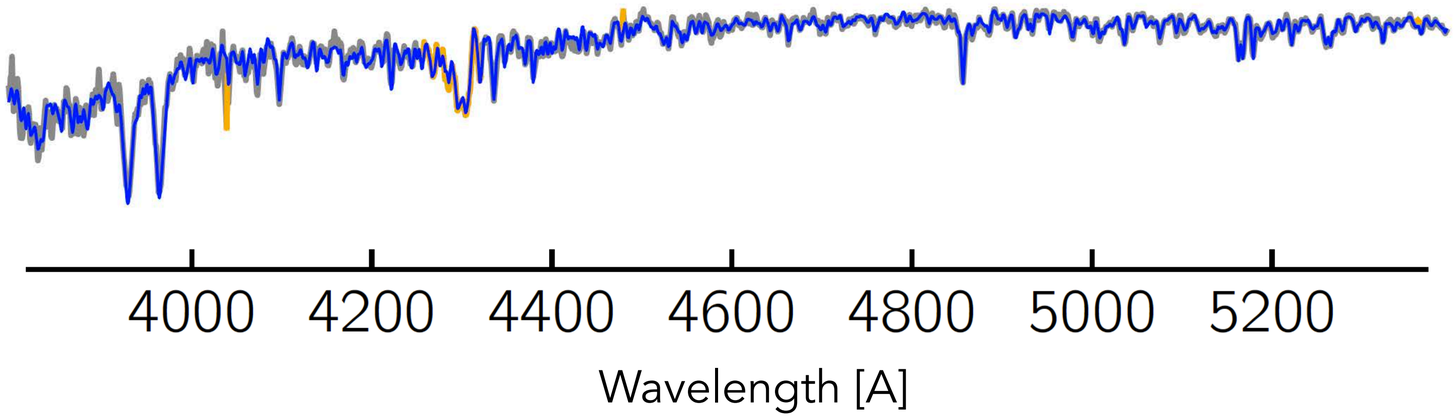
- Tractable for large spectroscopic surveys (e.g. used in APOGEE, GALAH, LAMOST, Gaia RVS)



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Ness et al. 2015, Fabbro et al. 2018, Thomas et al. 2024

Label-transfer

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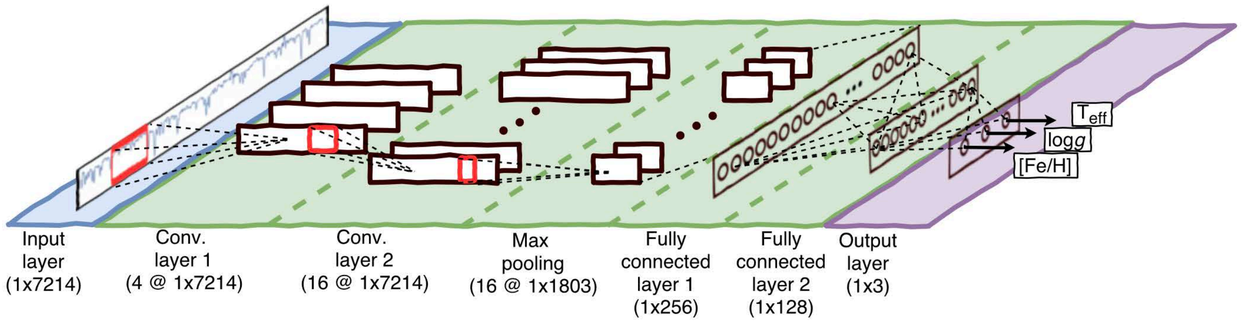

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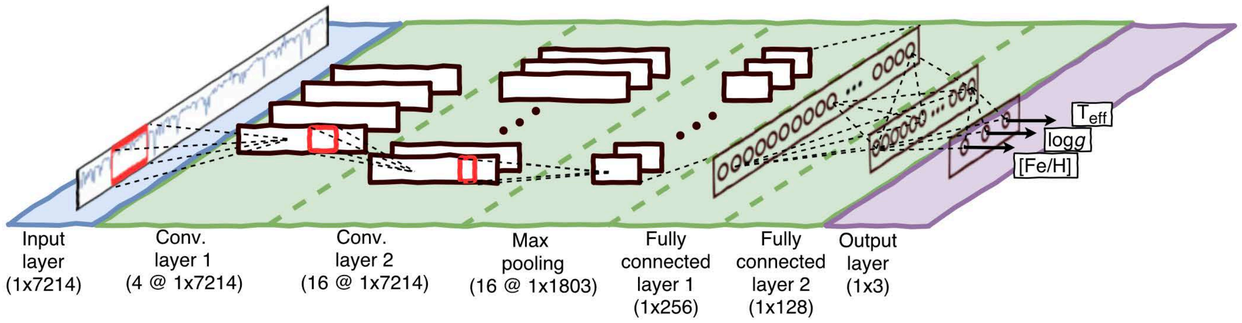
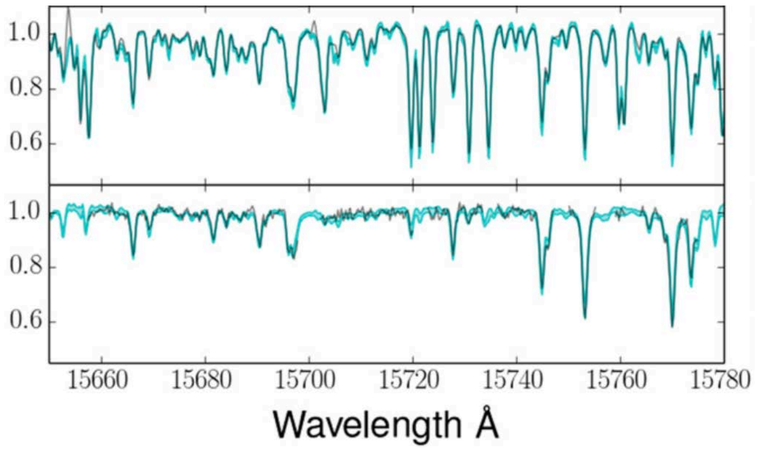
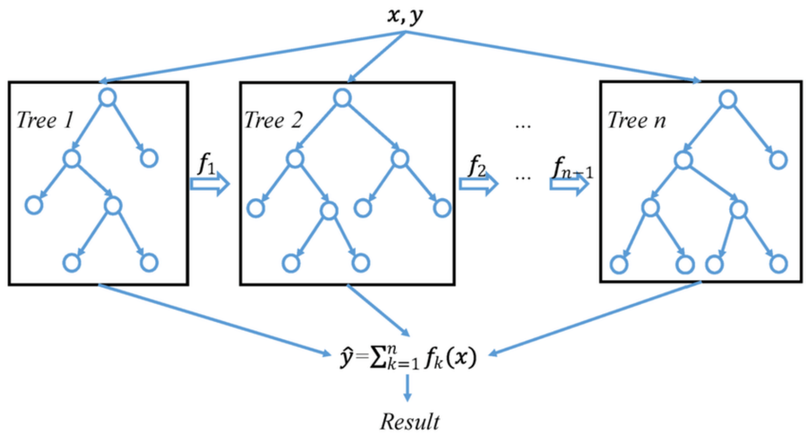


Generative



Label-transfer example

- Method: **XGBoost**, gradient boosted decision trees (similar to random forest)



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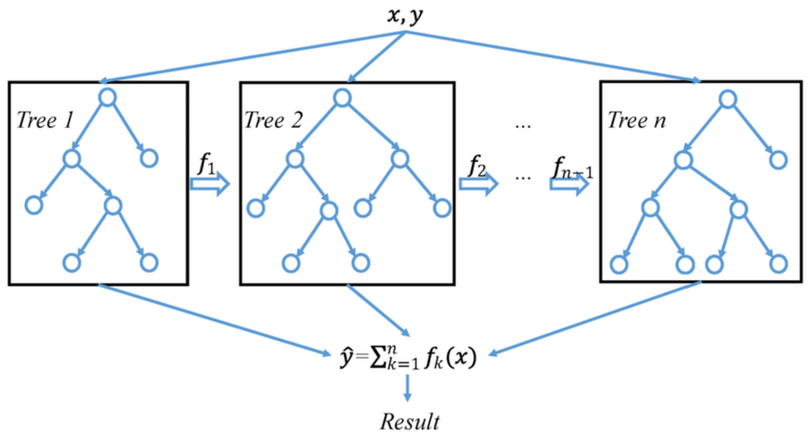

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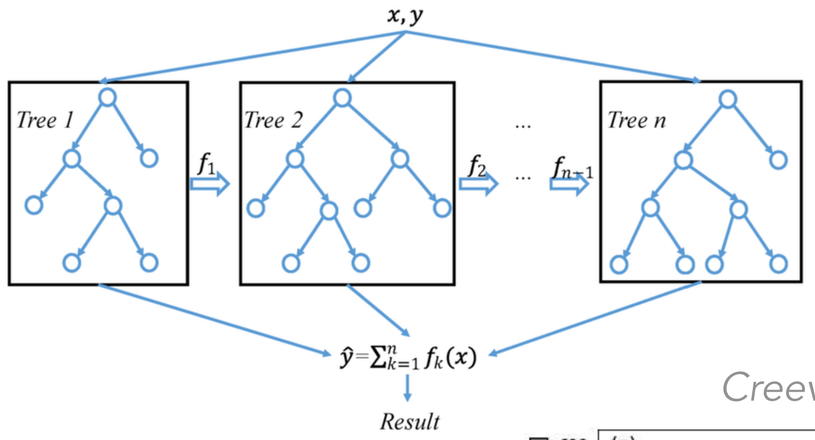
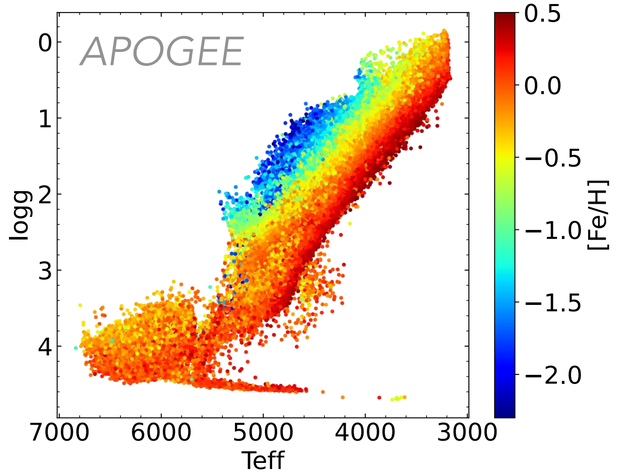
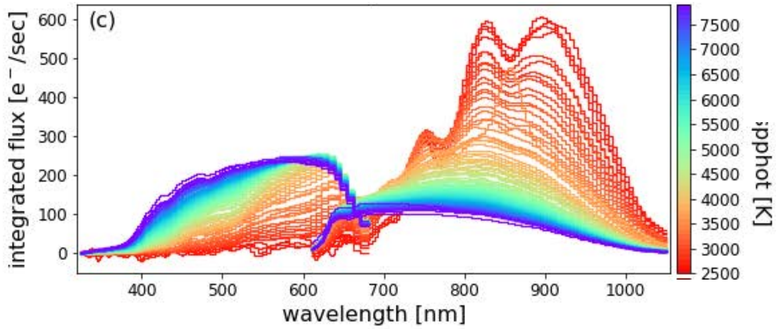




Creevey et al. (2022)



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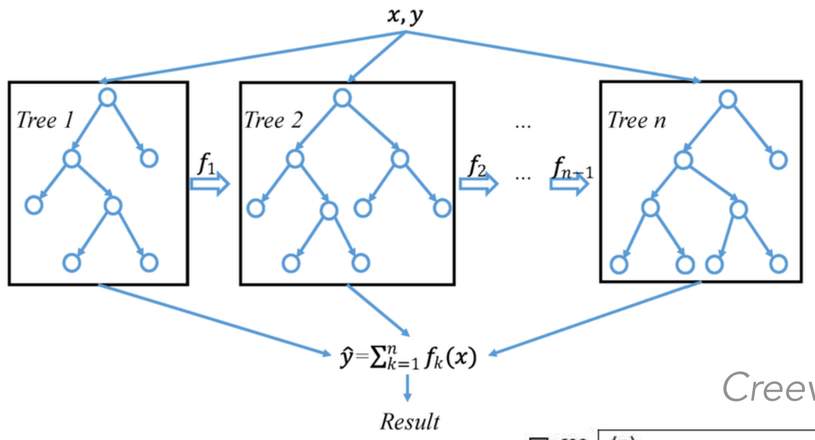

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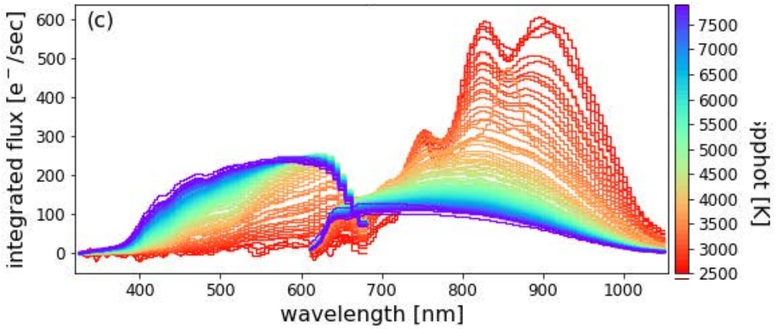
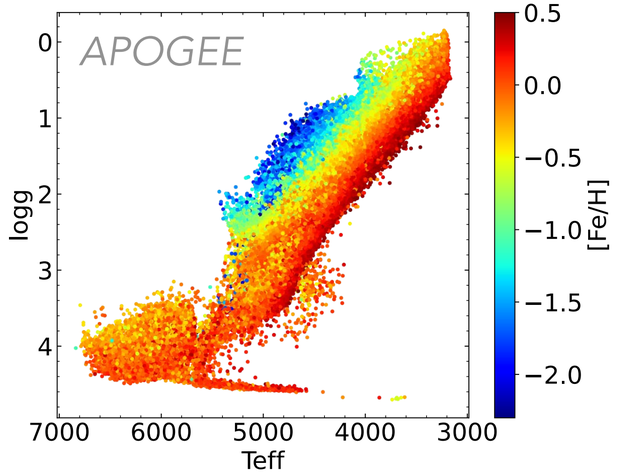
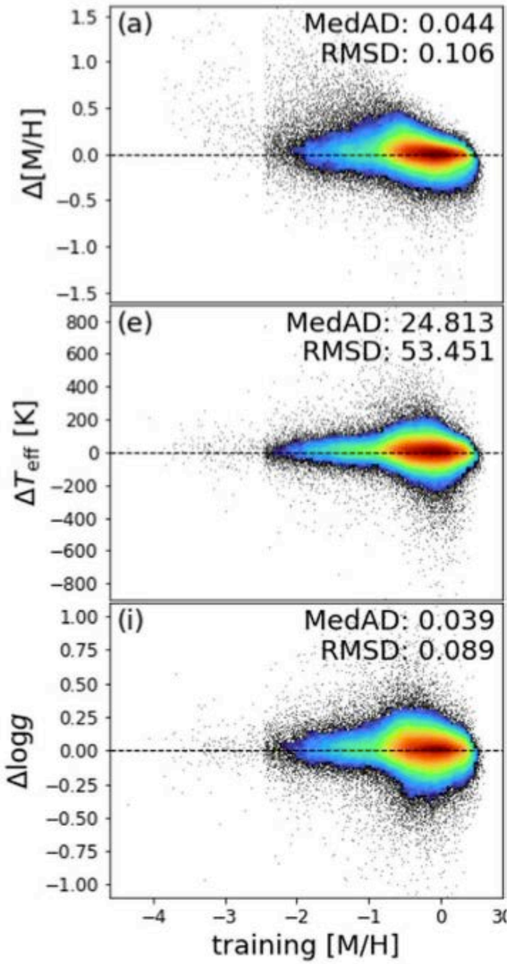


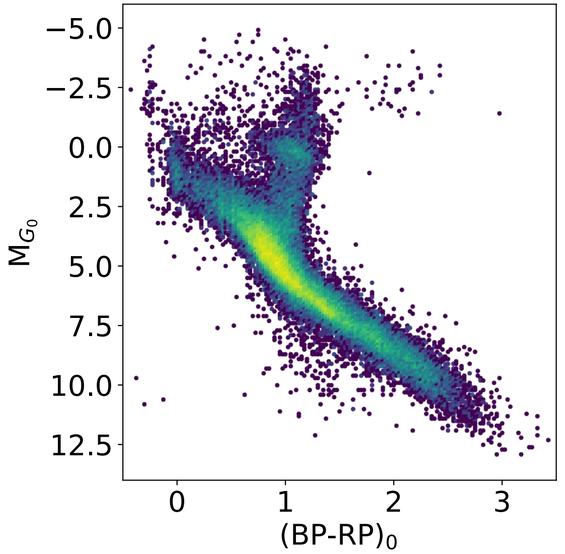




Using additional data?

For example:

- **Photometry (colours and magnitudes):** constrain spectral energy distribution —> Teff)



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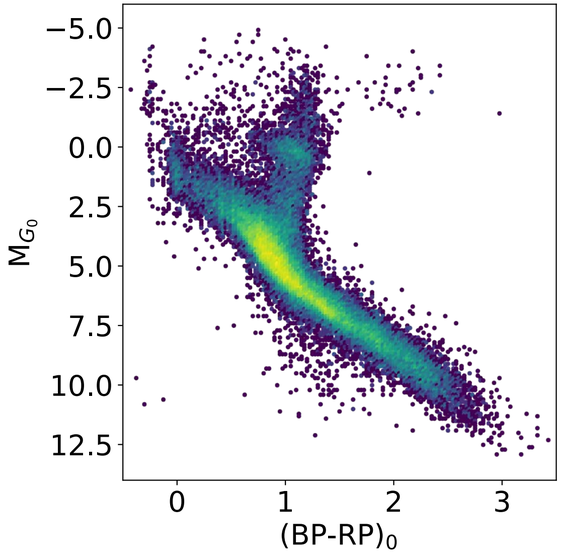

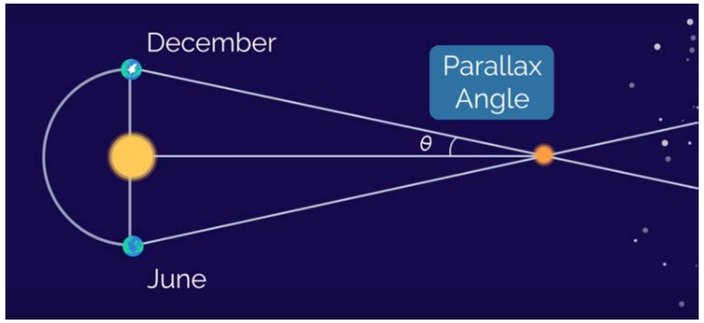

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For example:

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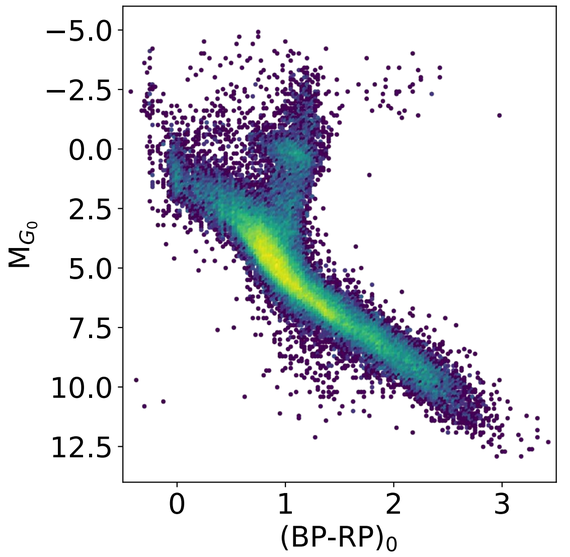
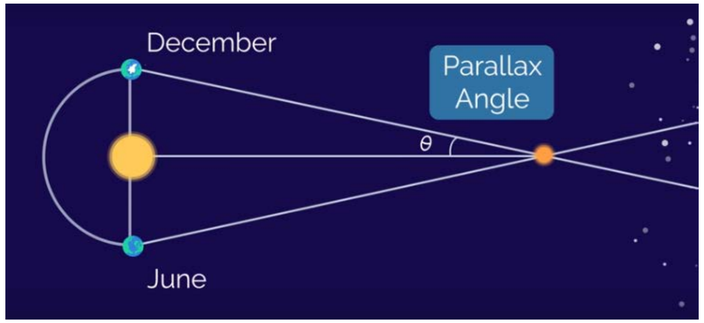
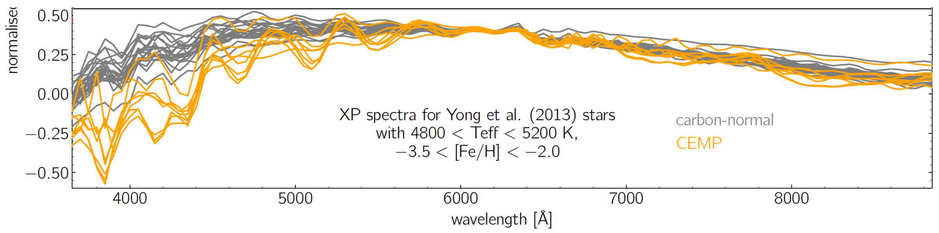
- **Parallax:** constrain the distance and absolute magnitude —> logg
- **Two types of spectra** at the same time: e.g. Gaia XP (R~30-100 but covering the full optical) and Gaia RVS (R~7000 but only a small range in the infrared)

for example Guiglion et al. (2024), who use a convolutional neural network







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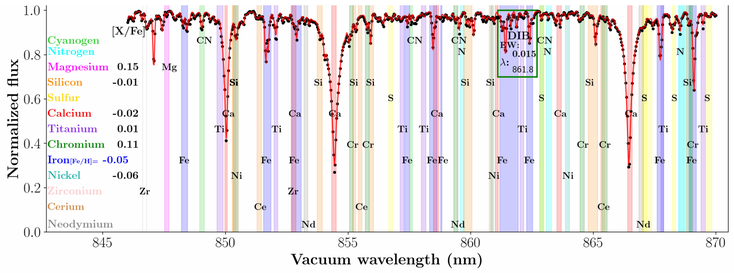

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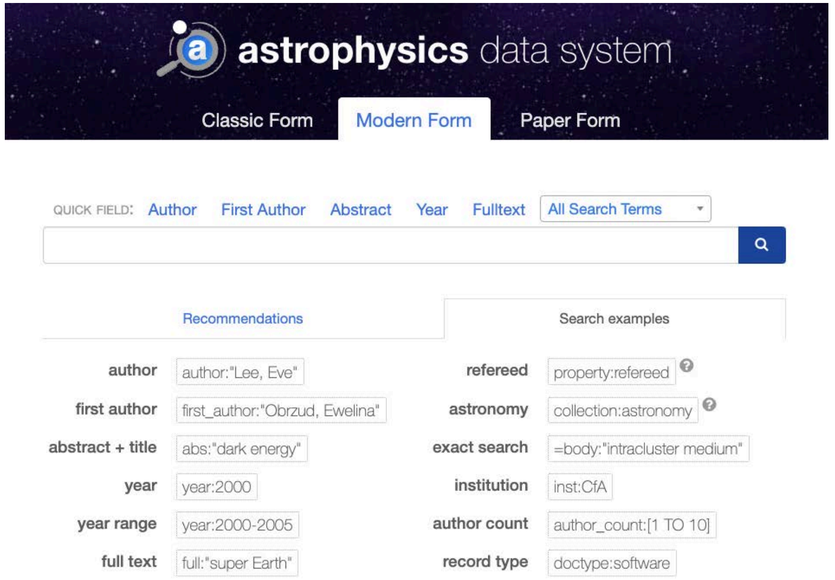
If you want to follow up some of the references, in astronomy we typically use the Astrophysics Data System (ADS) to search for publications:
https://ui.adsabs.harvard.edu/
(e.g. searching for author name & year)



Next lectures

- Friday: How to design and obtain astronomical observations?
- Next Tuesday: part chemical evolution & recent results, and part hands-on
  - bring your laptop if you can