Nuclei in the Cosmos School
2025

SPECTROSCOPY & STELLAR ABUNDANCES

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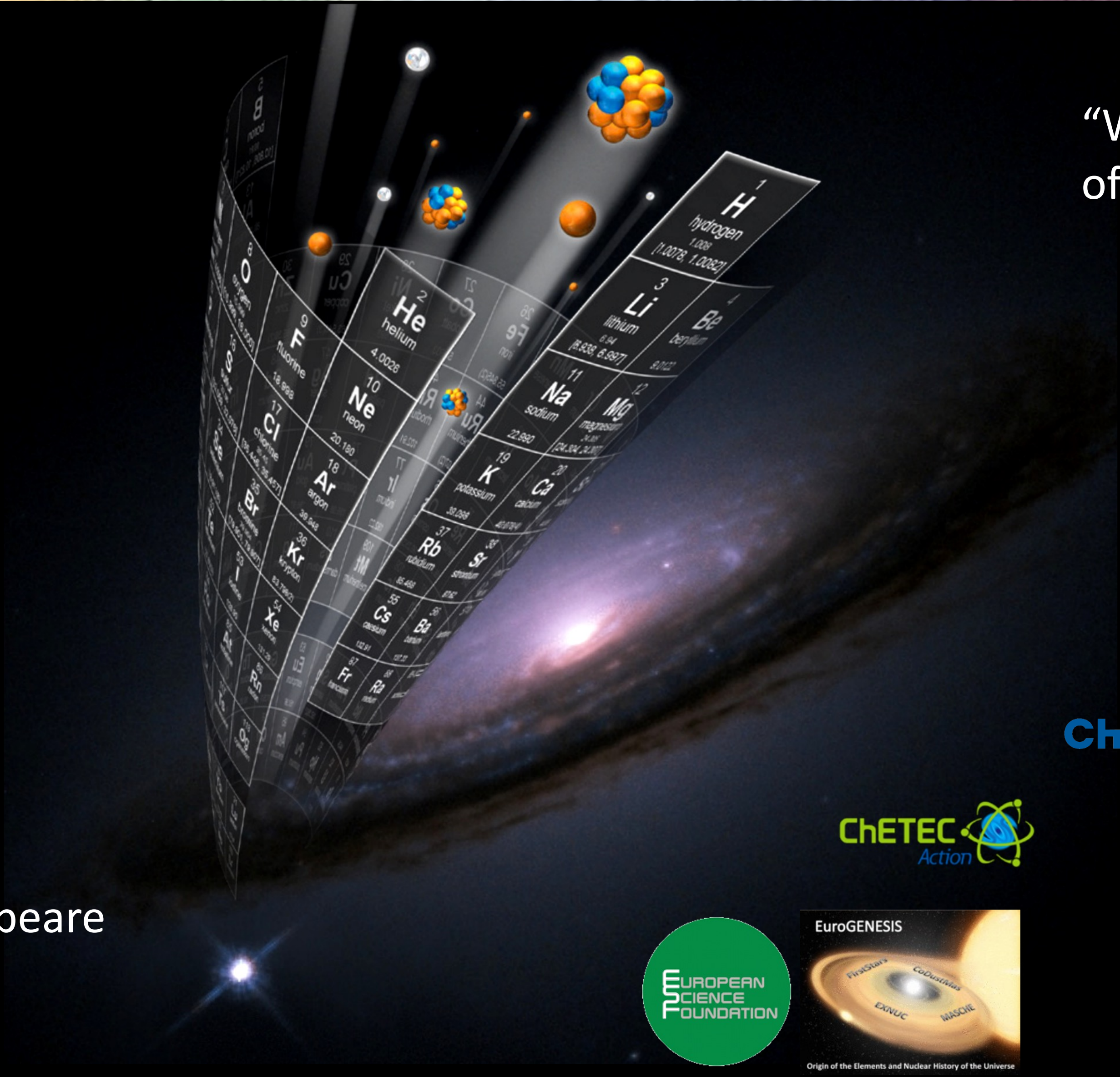
Where do the elements come from?



“We are made
of star stuff.”
Carl Sagan

“It is the stars,
the stars above us,
govern our conditions.”
William Shakespeare

ChETEC INFRA

ChETEC Action

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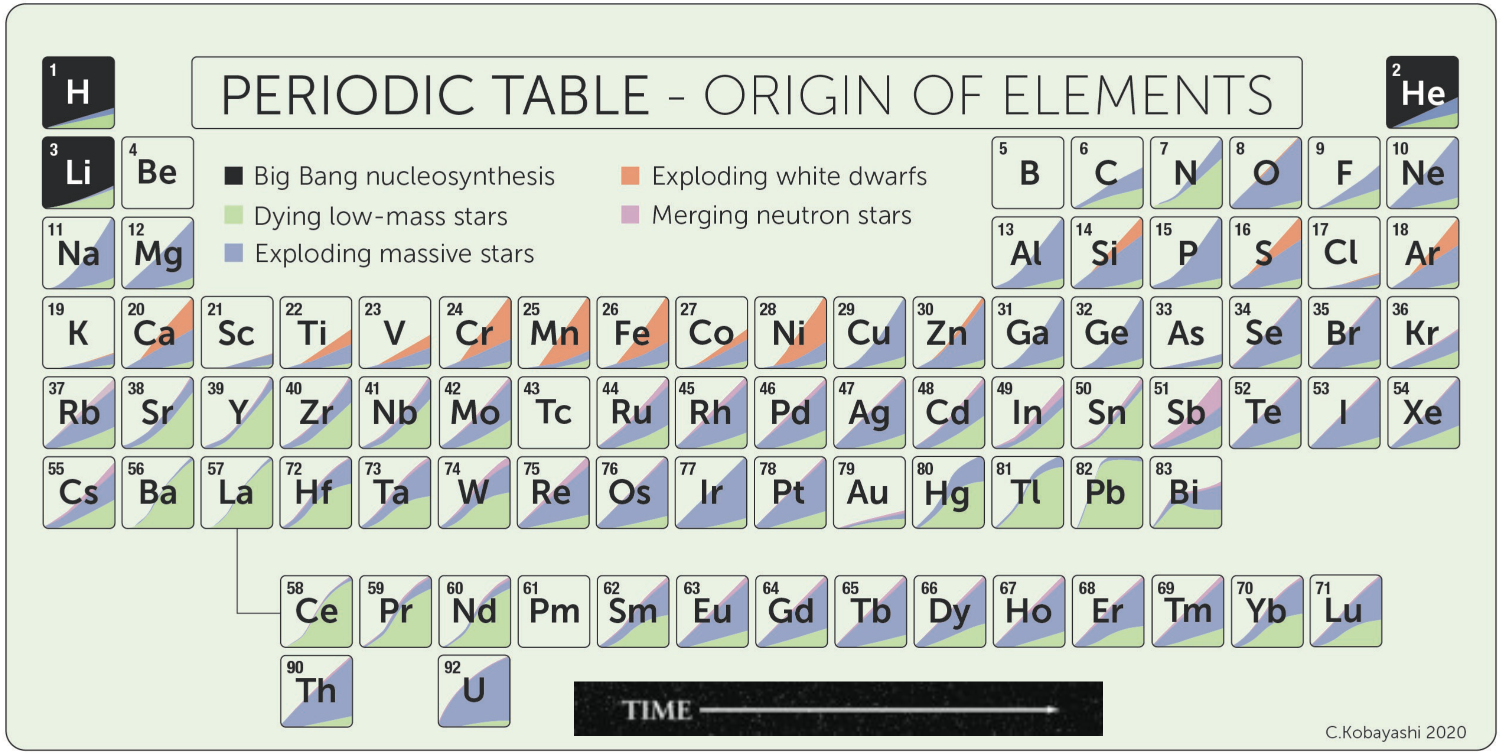
Origin of the Elements and Nuclear History of the Universe

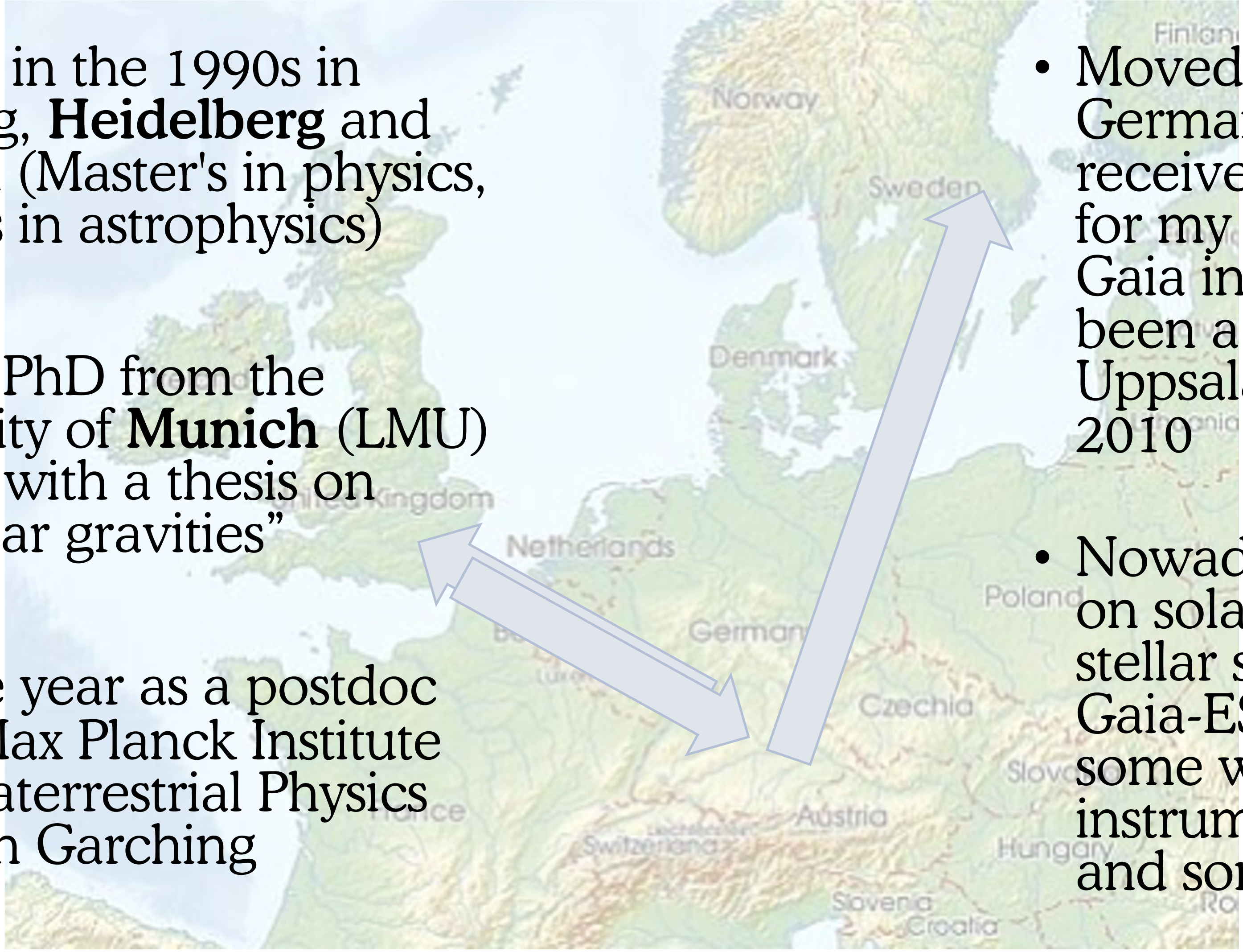
Nuclear astrophysics 101

Observing the ~90 stable elements, inferring their abundances throughout the cosmos and unravelling their origin.



Observing isotopes in stellar spectra is only possible when the isotopic shift is large: this is the case in the lightest elements (e.g. Li) and when the element of interest is visible in molecular form (e.g. C2, MgH), mostly in cool (giant) stars.
Hfs splitting of strong lines works in some cases (Gallagher et al. 2015).

Who am I / my career on one slide



- Studied in the 1990s in Marburg, **Heidelberg** and London (Master's in physics, Master's in astrophysics)
- Got my PhD from the University of **Munich** (LMU) in 2002 with a thesis on "Cool-star gravities"
- Did one year as a postdoc at the Max Planck Institute for Extraterrestrial Physics (MPE) in Garching
- Moved to **Uppsala** on a German scholarship, received Swedish funding for my research, joined Gaia in 2008 and have been a lecturer at Uppsala University since 2010
- Nowadays, I mostly work on solar-type stars and stellar surveys (Gaia, Gaia-ESO, 4MOST), plus some work for ELT instruments like ANDES, and some SETI…

stars

10s

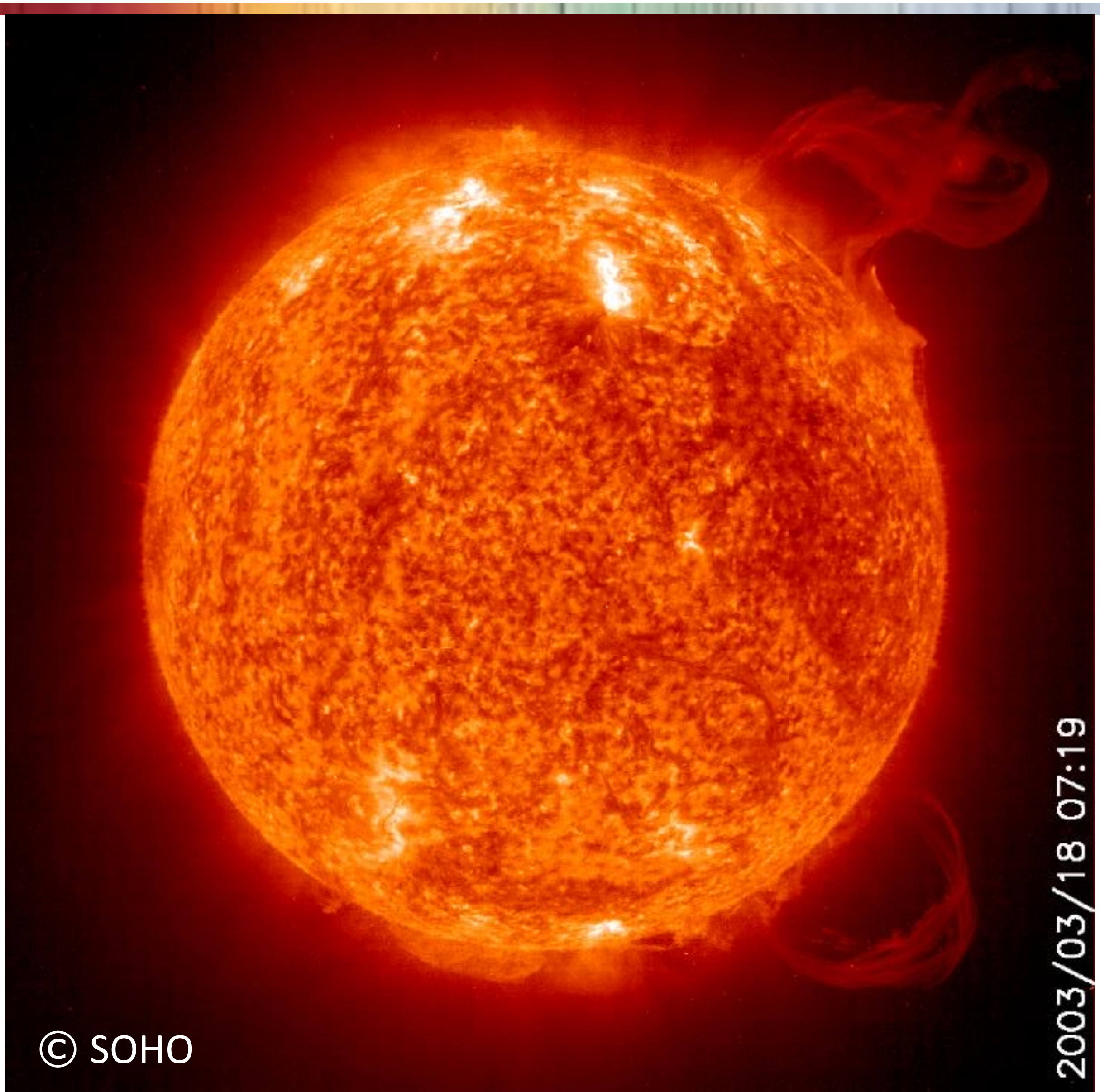
…

1000s

…

$5 \cdot 10^8$

Observables: stellar photons



Photons mainly originate from the stellar surface,a fairly thin (a few hundred km in the case of the Sun, R=600,000 km) layer which we call the **stellar photosphere**.

Unless there is significant exchange between the stellar interior and the atmosphere, the latter is a decent representation of the stellar material at birth. This is mostly the case.
This is the foundation of **chemical tagging** and **Galactic archaeology**.

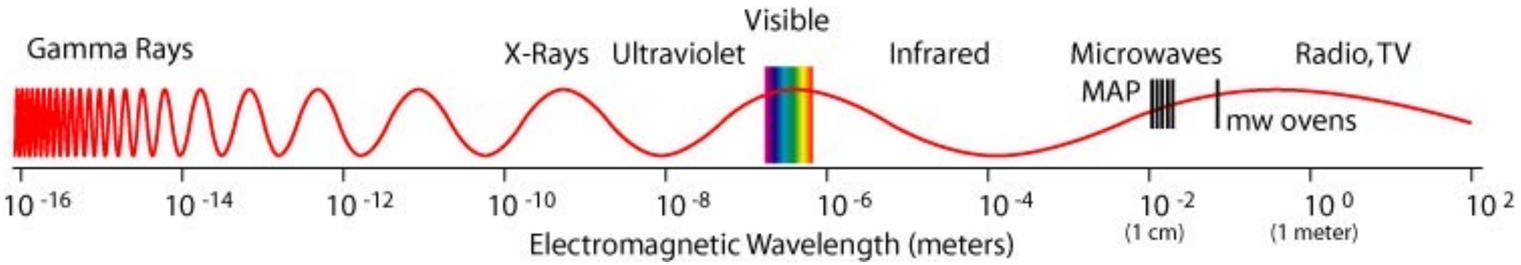
The big picture: stars

astro-physics = **physics of stars** (and other objects out there)

stellar interiors

stellar photospheres

(the regions of stars we receive (most of the) light from)

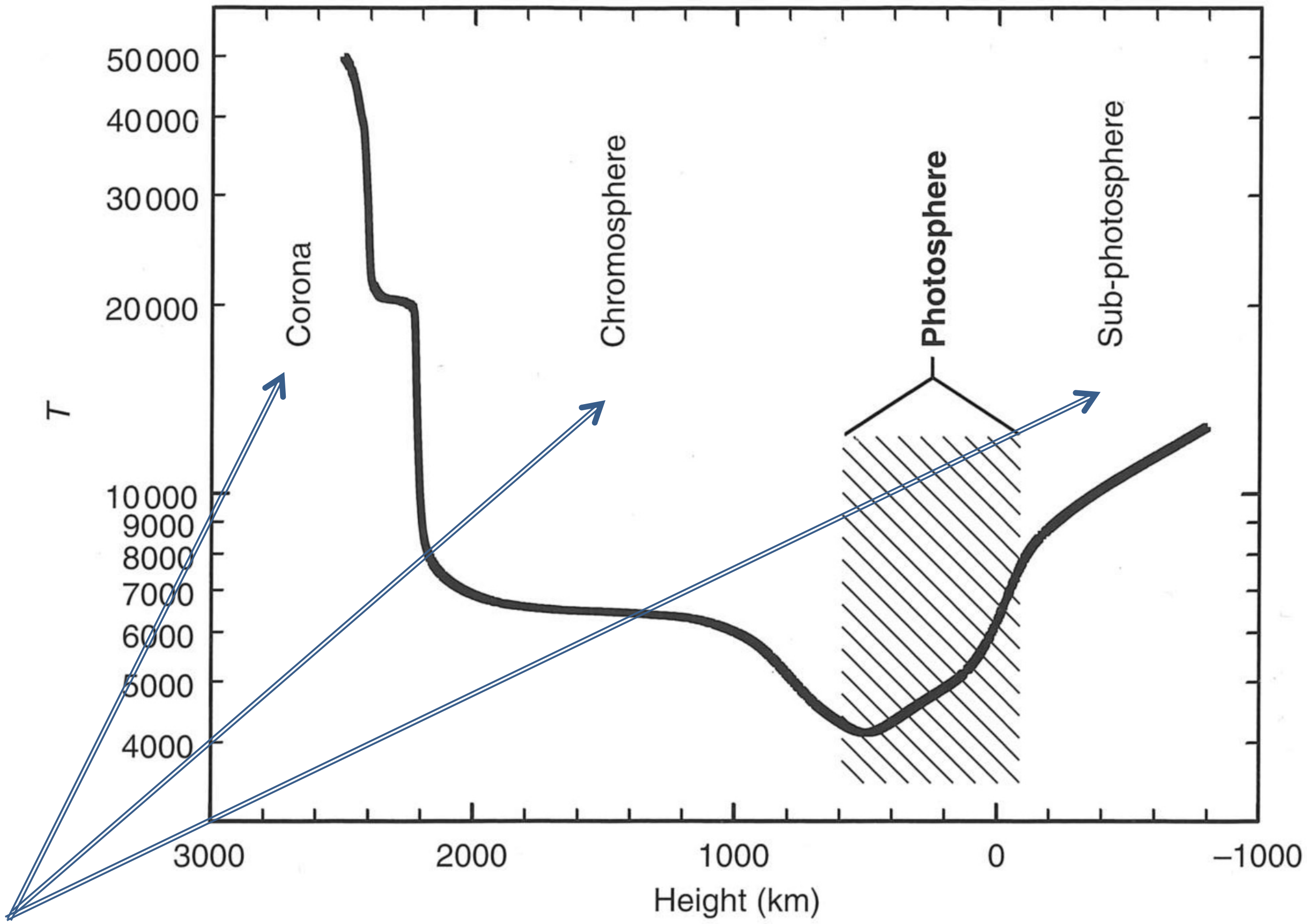


1 Å(ngström) = 0.1 nm = 10^{-10} m

Anders Ångström (1814–1874)

practically all light we receive originates in stellar photospheres
main exception: the cosmic microwave background (CMB)

Why only model the photosphere?



Why can't we see these hotter sub-photospheric and outer layers?

Anything else?

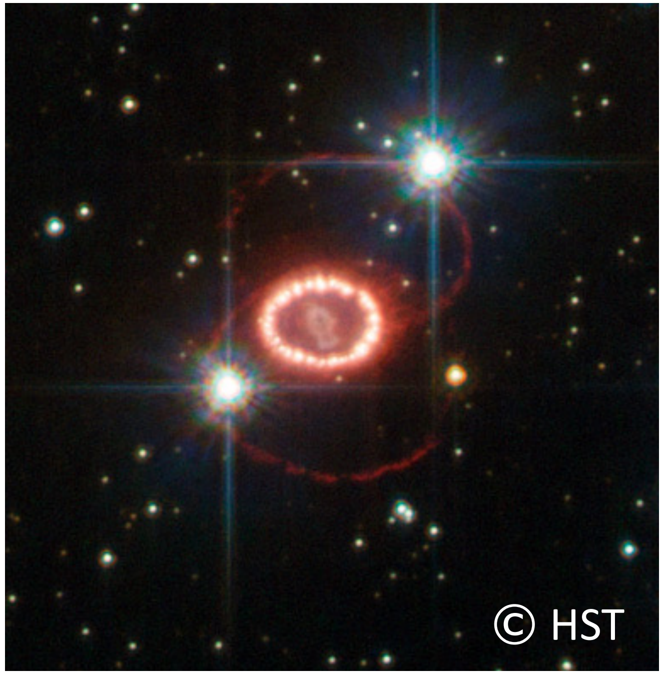
Yes, we have received other *messenger* particles:

neutrinos, the second most abundant particle known (1965+, NP 1988, 1995, 2002 & 2015)

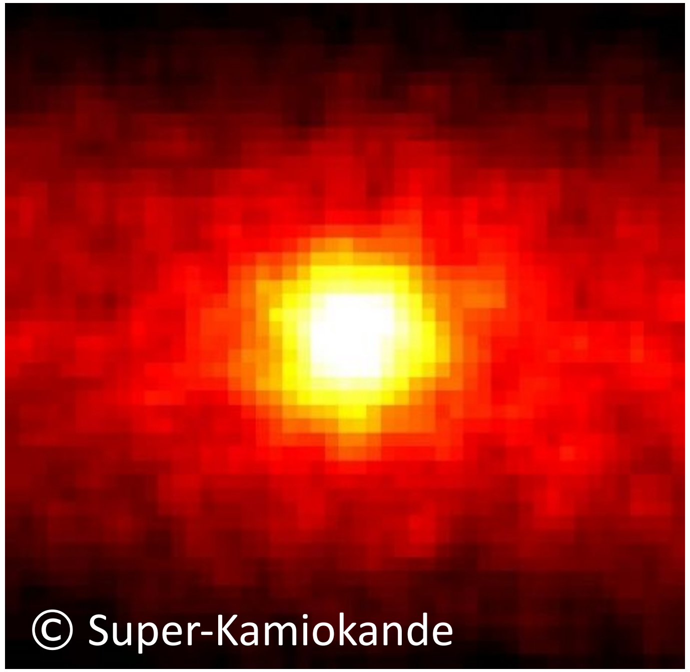
and ***gravitational waves*** (2015+, NP 2017)

and **cosmic rays** (1912+).

SN1987A in the Large Magellanic Cloud



The Sun in neutrino light



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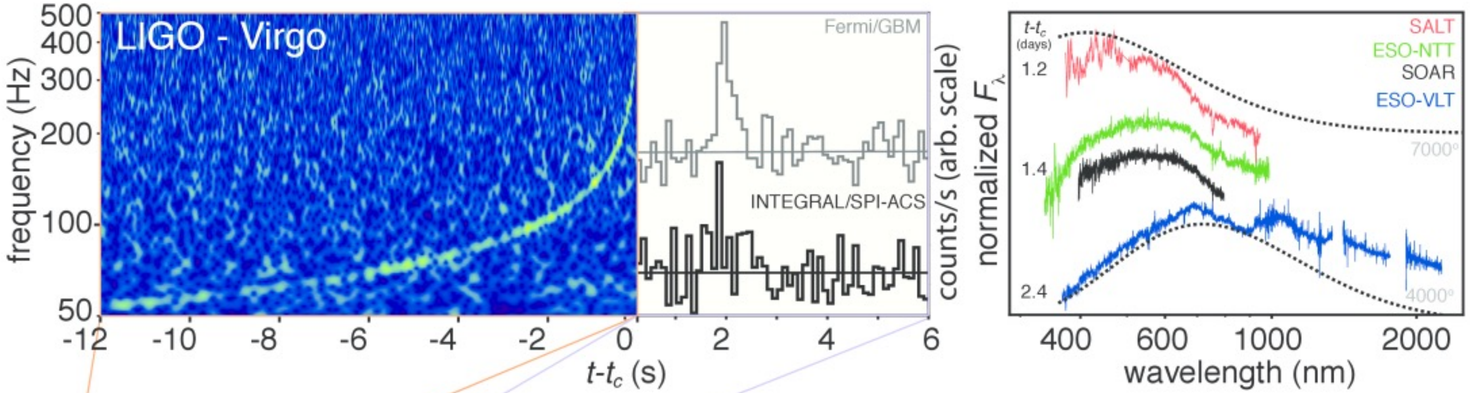


Morgan-Keenan(-Kellman) classification

(1940s/50s)

“early type”

O

B

A

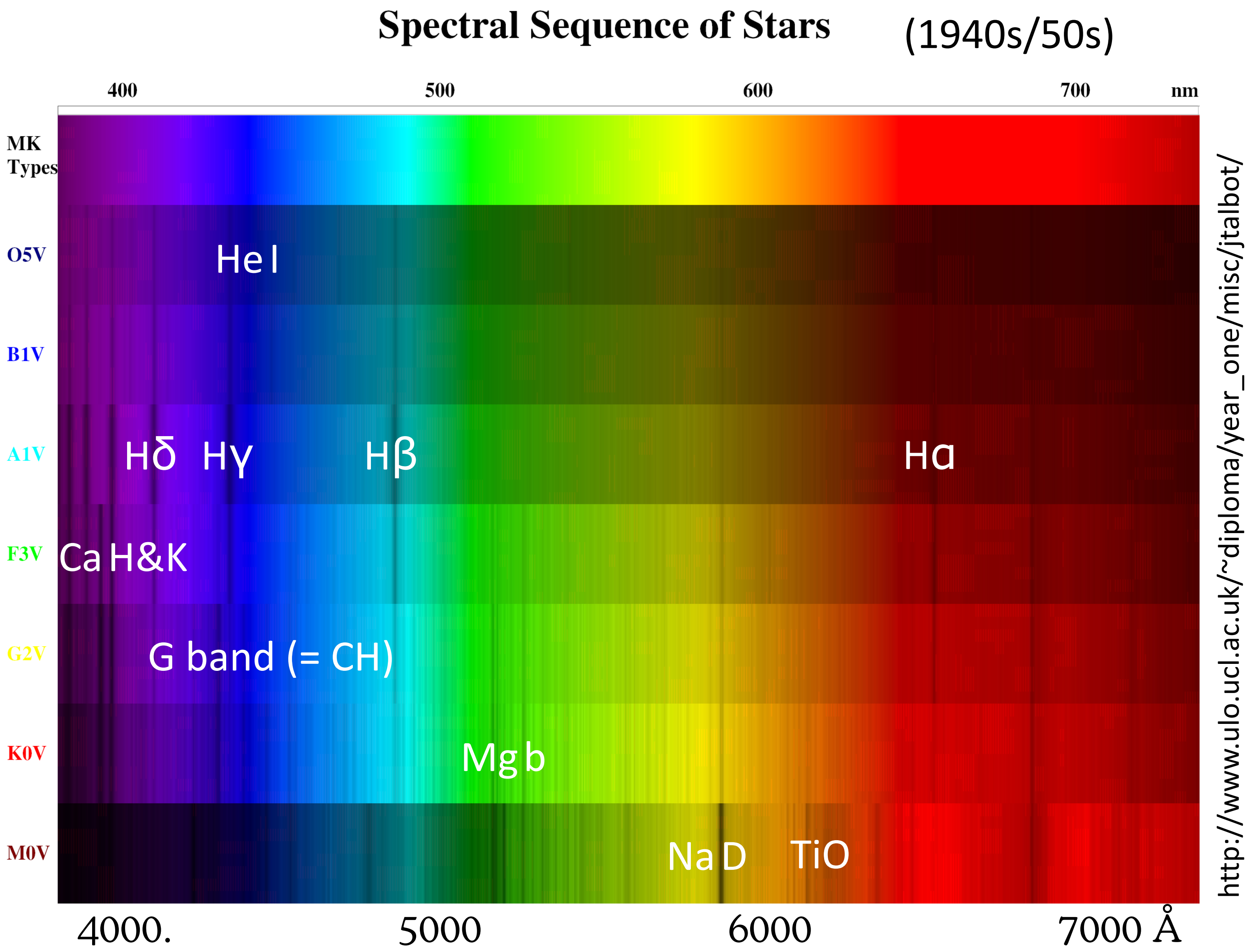
F

G

K

M

” late type”



Mnemonic:

Oh,

be

a

fine

girl/guy,

kiss

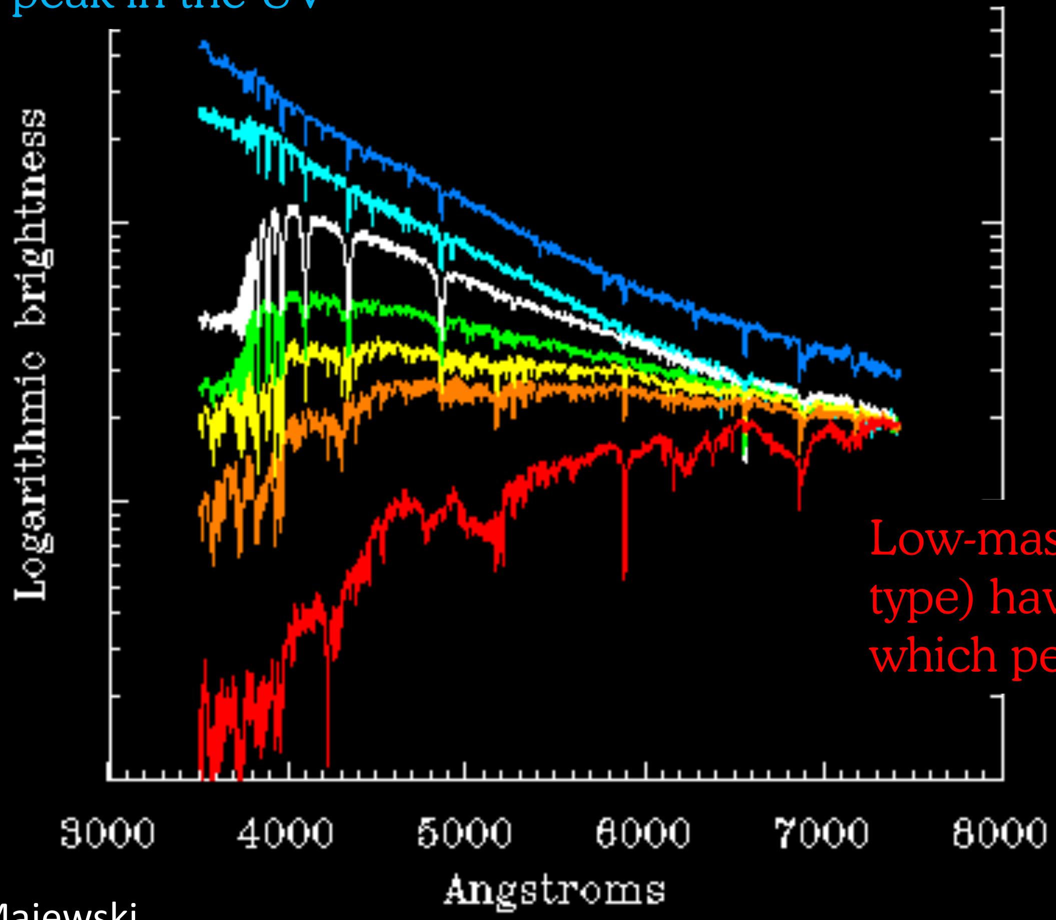
me!

(NB: not complete!)

Flux spectra as graphs

High-mass stars (OB-type) have blue SEDs which peak in the UV

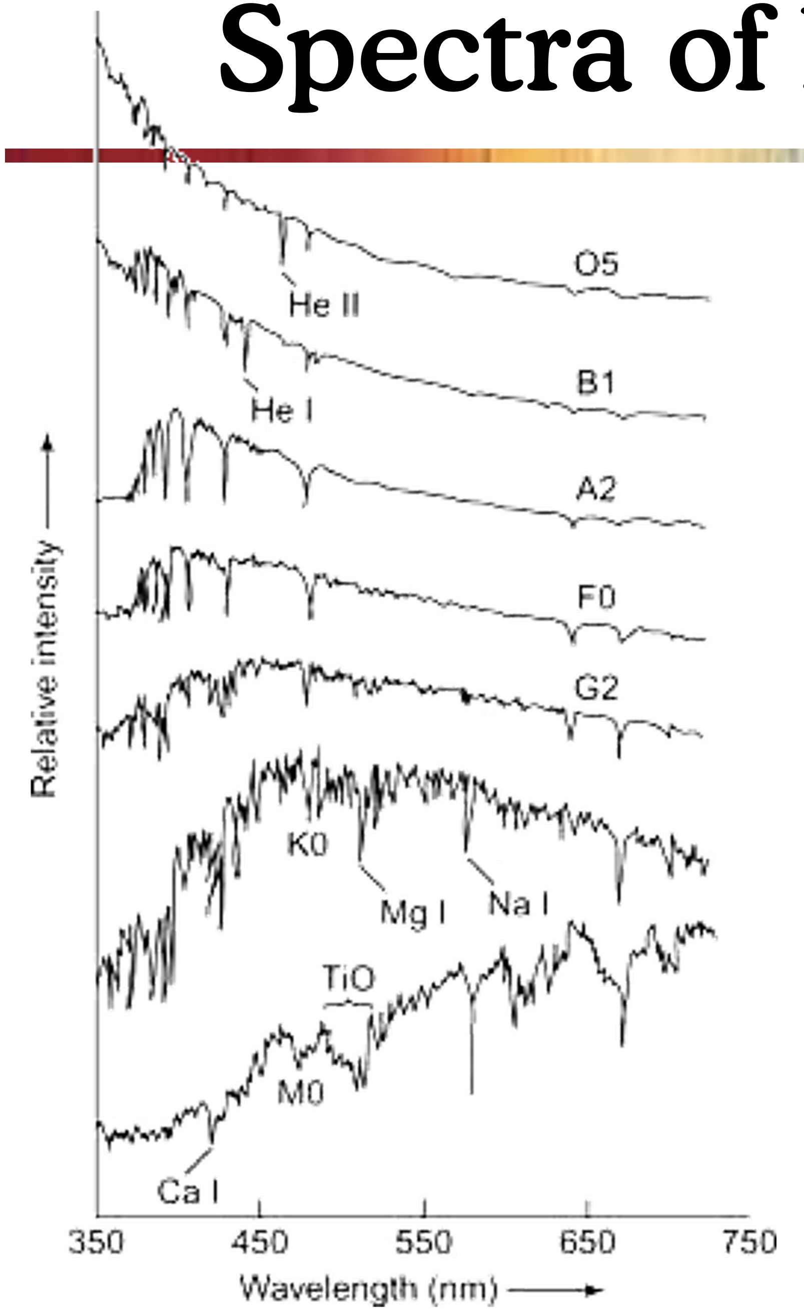
Wien's law:
$\lambda_{max} = 2.9 \times 10^{7}\,\text{Å} / T_{surface}\,[\text{K}]$

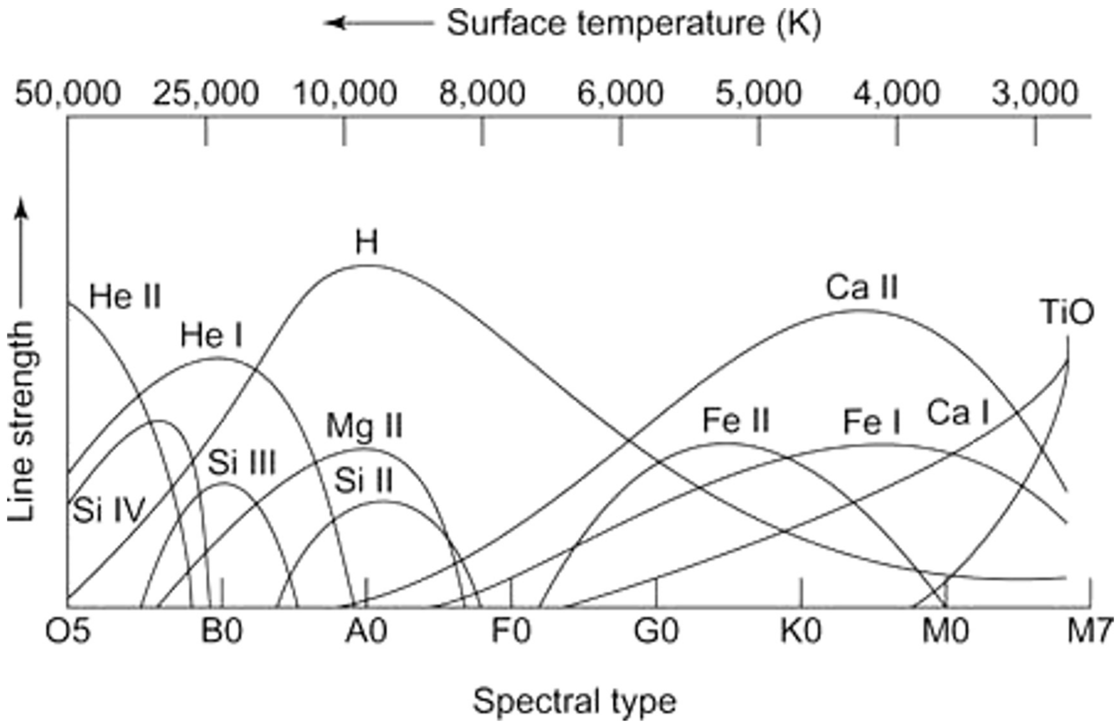


Low-mass stars (KM-type) have red SEDs which peak in the IR

Such 1-dimensional spectra at high resolution we will observe and analyse tomorrow night!

Spectra of late-type stars are complex

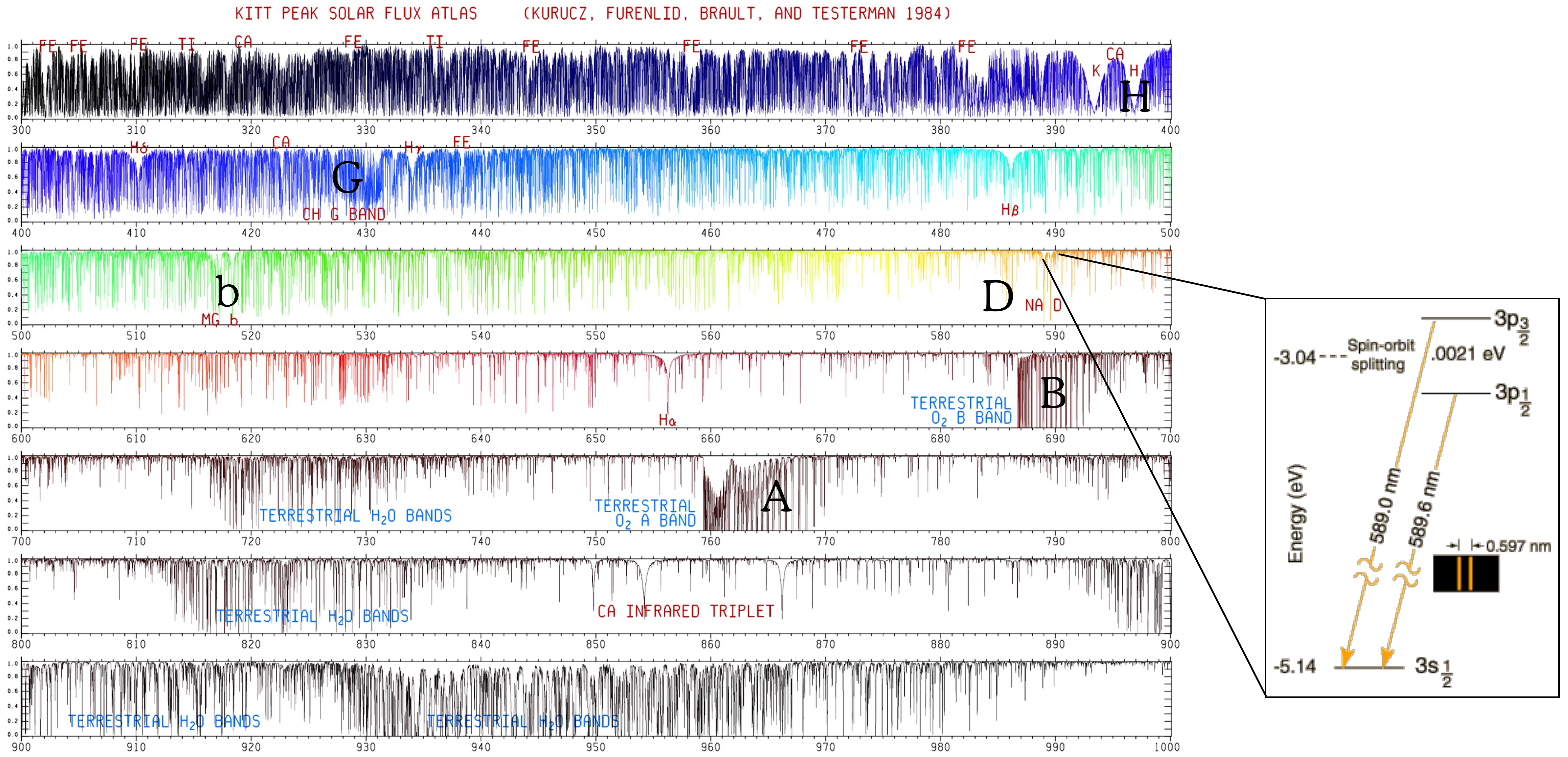




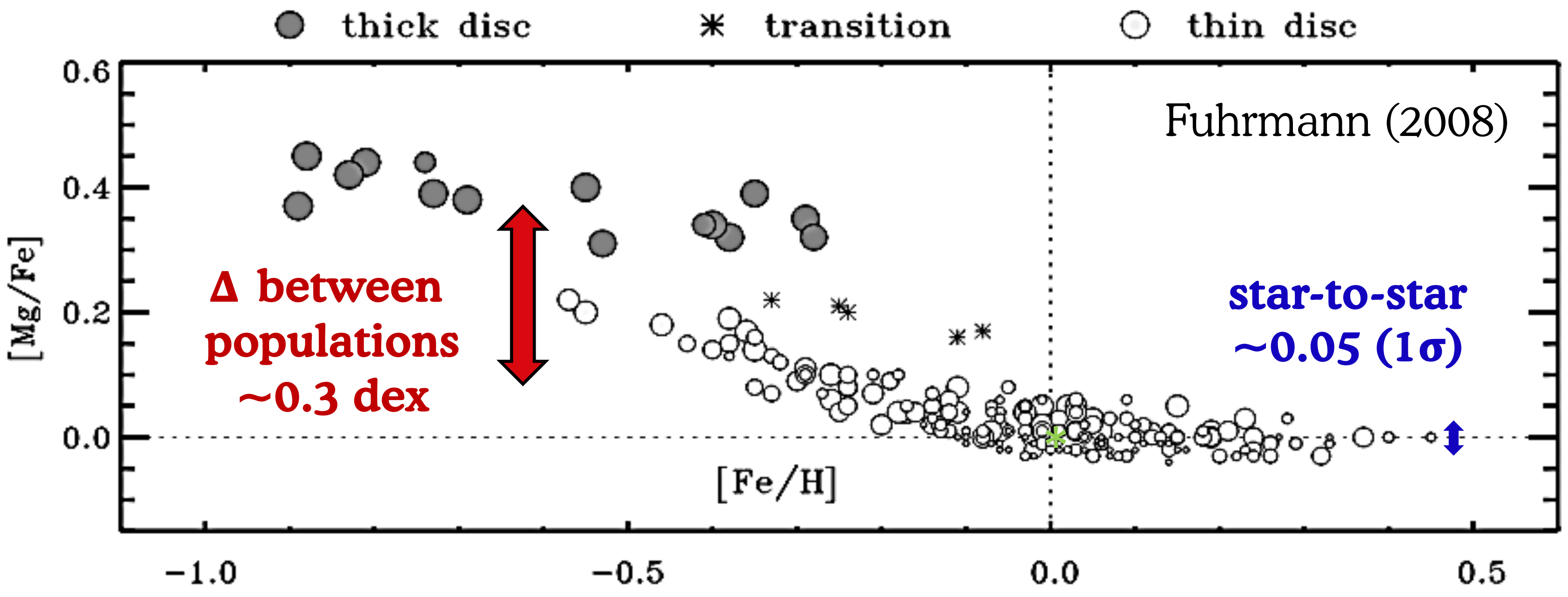
In most cases, one can only observe one ionization stage of an element. If you see 2+, you can use them as a diagnostic.

Spectra of low-mass stars (K/M) allow to probe some isotopic ratios, e.g. ^{24,25,26}Mg via molecules (Yong *et al.* 2003)

The solar spectrum: a beautiful mess!



Achievable abundance accuracies



The figure shows the solar neighbourhood (25 pc) as seen in F- & G-type stars.

The Sun (*) is found to be a normal, albeit fairly high-mass, thin-disk star.

(No bulge and very few halo stars (not shown here) within 25 pc of the Sun.)

Model photospheres 101

The cool tenuous layer we call stellar photospheres absorb and emit photons. We model this by solving the **radiative transfer equation**:

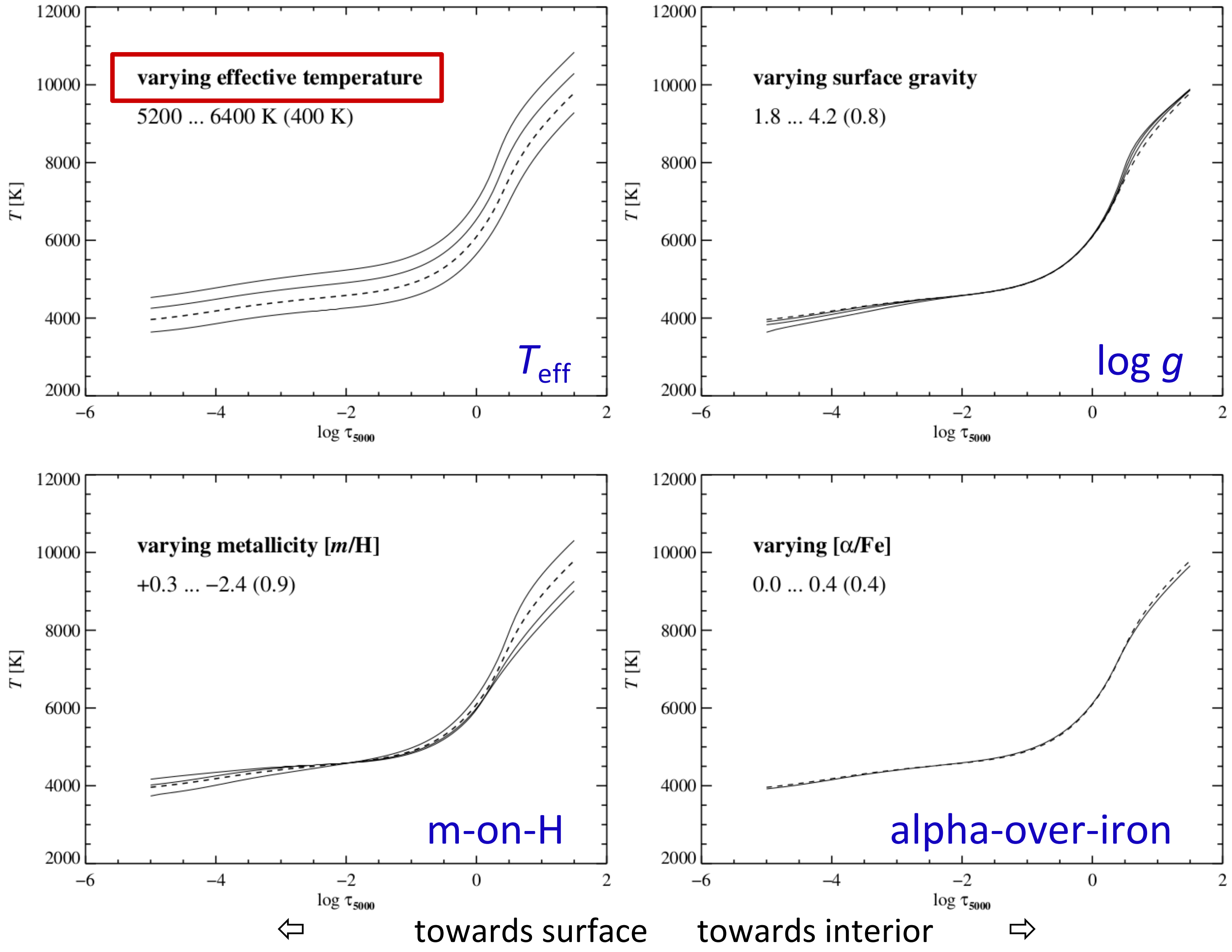
$$\frac{\mathrm{d}I_\nu}{\mathrm{d}\tau_\nu} = -I_\nu + S_\nu$$

A central goal is to find the temperature gradient that establishes itself in order to conserve the total flux (flux-constancy models).

A model photosphere tabulates two or more thermodynamic variables as a function of (optical) depth. It is one of the main inputs to calculations of synthetic stellar spectra.

In order to derive reasonably realistic models, one needs to consider 100s of 1000s of opacity sources from atoms and molecules. See e.g. Gustafsson *et al*. (2008) for one set of such 1D models ("MARCS").

A grid of model photospheres: T vs τ



When analysing stellar spectra with webSME, we will use a pre-computed grid of MARCS model photospheres, interpolate in it and perform on-the-fly line-formation calculation for specific combinations of stellar parameters.

Line formation 101

The flux coming from subphotospheric layers (which are *optically thick* at all wavelengths) is Planckian, i.e. a blackbody.

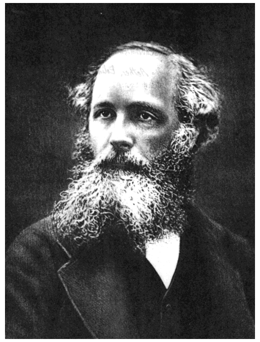
Based on the run of temperature and pressure as a function of (optical) depth, you can study how the electronic transitions in atoms and molecules lead to absorption lines at characteristic wavelengths.

The strength of a spectral line is proportional to the ratio of the line vs the continuous absorption coefficient. It also depends on the gradient of the source function throughout the depths of line formation.

In the classical LTE approximation, the formation of every lines is taken as an isolated process following *local* equilibrium (Saha-Boltzmann) statistics.

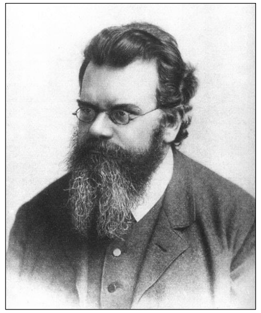
Equilibrium statistics

Particle velocities are assumed to be Maxwellian:



$$\frac{n(v)}{n_{\rm tot}}\mathrm{d}v = \left(\frac{m}{2\pi kT}\right)^{\frac{3}{2}} e^{-\frac{mv^2}{2kT}}\,\mathrm{d}v$$

Excitation follows the Boltzmann distribution:



$$\frac{n_u}{n_{\rm tot}} = \frac{g_u}{u(T)} e^{-\frac{\chi_u}{kT}}$$

χ: excitation energy

Ionization can be computed via the Saha equation:

$$\frac{n_{\rm II}}{n_{\rm I}} P_e = \frac{(2\pi m_e)^{3/2} kT^{5/2}}{h^3} \frac{2u_{\rm II}(T)}{u_{\rm I}(T)} e^{-\frac{I}{kT}}$$

I: ionization energy

In local thermodynamic equilibrium (LTE) often used in line-formation calculations, these are applied *locally*.

Spectral-line dependencies

$$\frac{\mathfrak{F}_\mathrm{c} - \mathfrak{F}_\nu}{\mathfrak{F}_\mathrm{c}} \approx \tau_1 \frac{\mathrm{d}\ln S_\nu}{\mathrm{d}\tau_\mathrm{c}}\bigg|_{\tau_1} \frac{\ell_\nu}{\kappa_\nu}$$

governed by the line formation (LTE vs. NLTE)

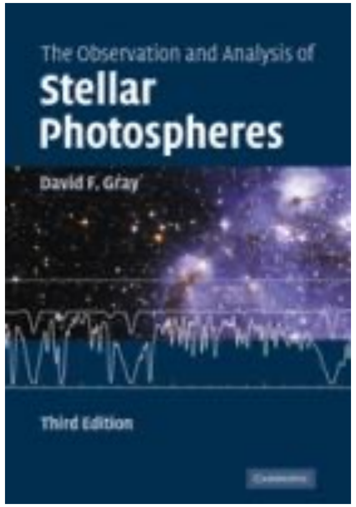
governed by the model atmosphere (1D vs. 3D)

The left-hand side of the above equation is a measure of the monochromatic line flux (subscript ν) eaten out of the continuum (subscript c). Integrate this and you get the line strength.

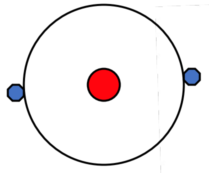
The right-hand side shows important dependencies:

* gradient of the source function with optical depth and
* the ratio of line to continuous absorption coefficient.

With this, one can basically understand how different lines. (transitions) behave. See Gray's excellent book.



Opacities



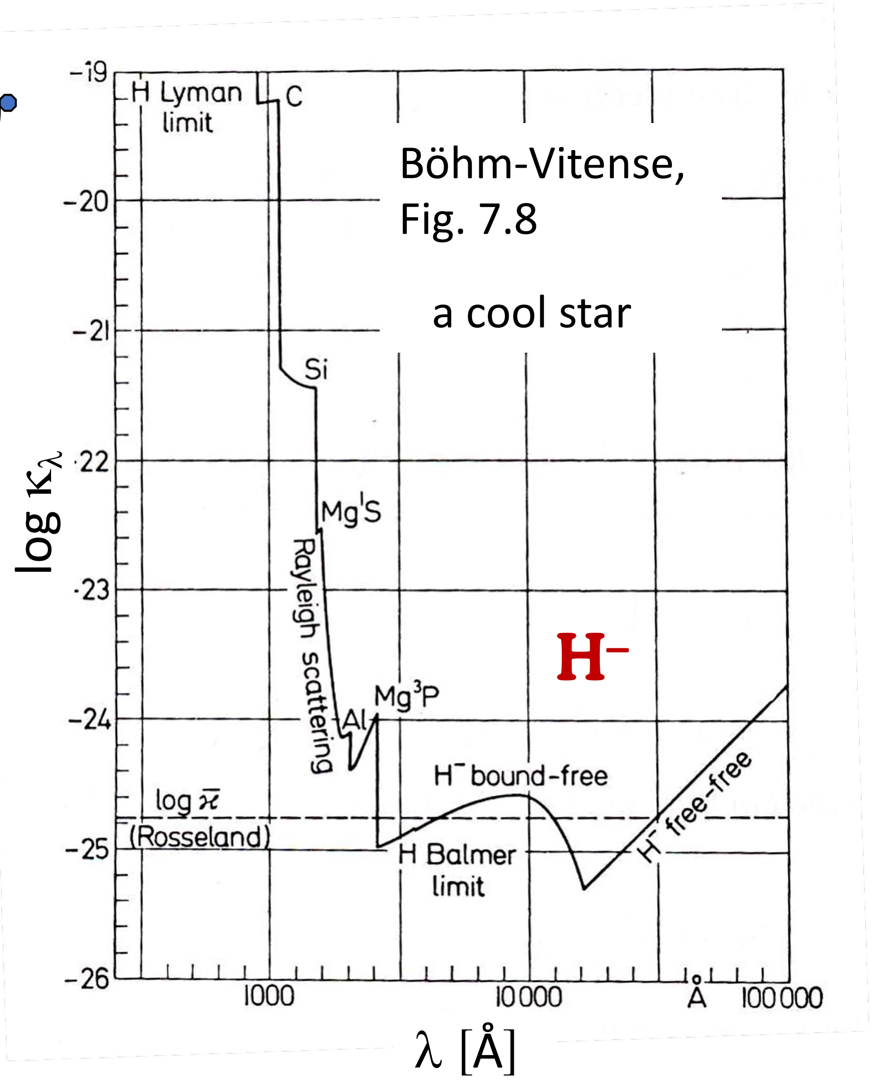
Continuous opacity

Caused by *bf* or *ff* transitions

In the optical and near-IR of cool stars, H^- (I = 0.75 eV) dominates:

$$\kappa_\nu(H^-_{bf}) = \text{const.}\ T^{-5/2}\, P_e \exp(0.75/kT)$$

NB: There is only 1 H^- per 10^8 H atoms in the Solar photosphere. Why can H^- compete with H?



Line opacity *(all the lines you see!)*

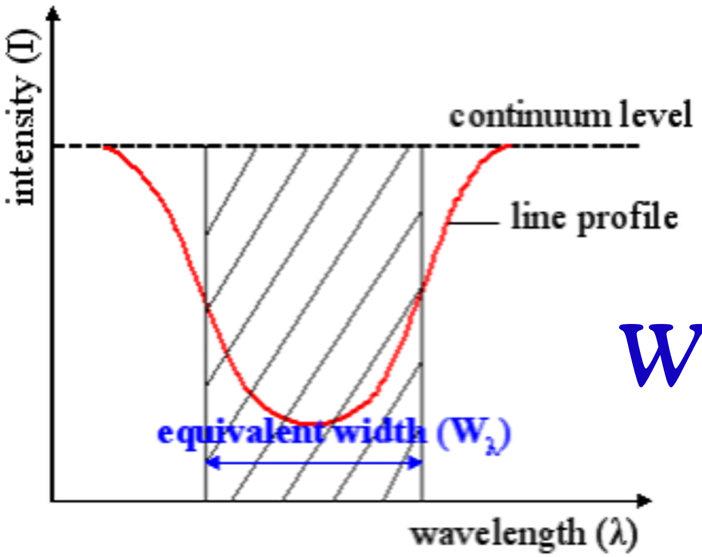
Caused by *bb* transitions

Need to know log *gf*, damping and assume an abundance

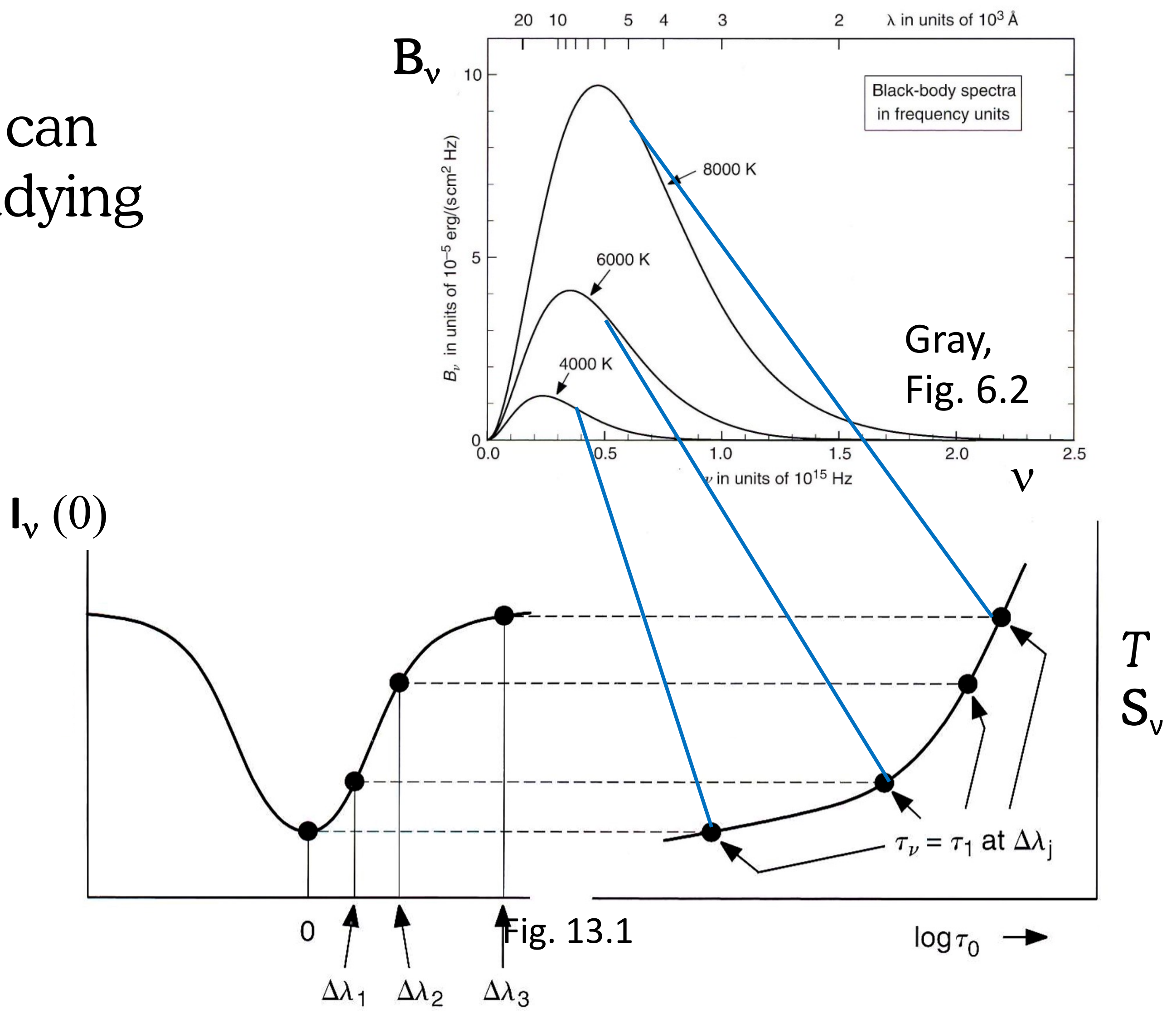
How spectral lines form

The formation of absorption lines can be qualitatively understood by studying how S_ν changes with depth:

$$W_\lambda \propto d\ln S_\nu / d\tau_\nu$$



W_λ



Spectral lines as a function of abundance

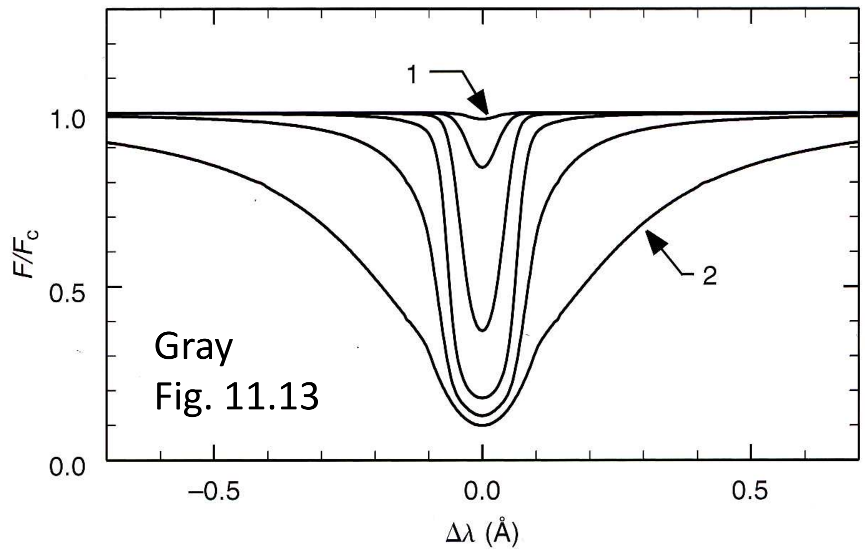
Starting from low log ε (low log *gf*), the line strength is directly proportional to *f* and n_X:

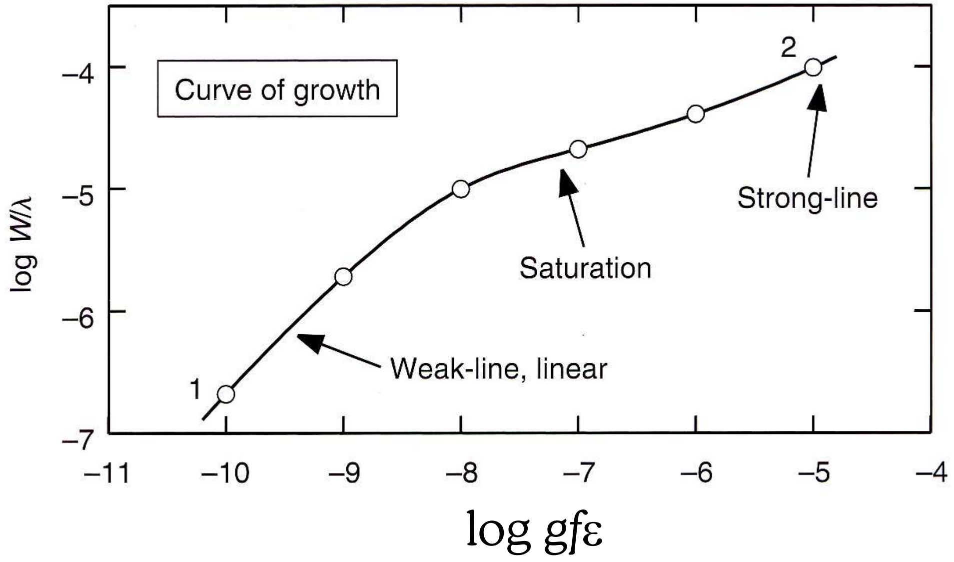
$$W_\lambda \propto gf\, n_X$$

When the line centre becomes optically thick, the line begins to saturate. The dependence on abundance lessens. Only when damping wings develop, the line can grow again in a more rapid fashion:

$$W_\lambda \propto \mathrm{sqrt}(gf\, n_X)$$

Weak lines are thus best suited to derive the stellar composition, given that they are well-observed (high SNR, little or known blending contributions)



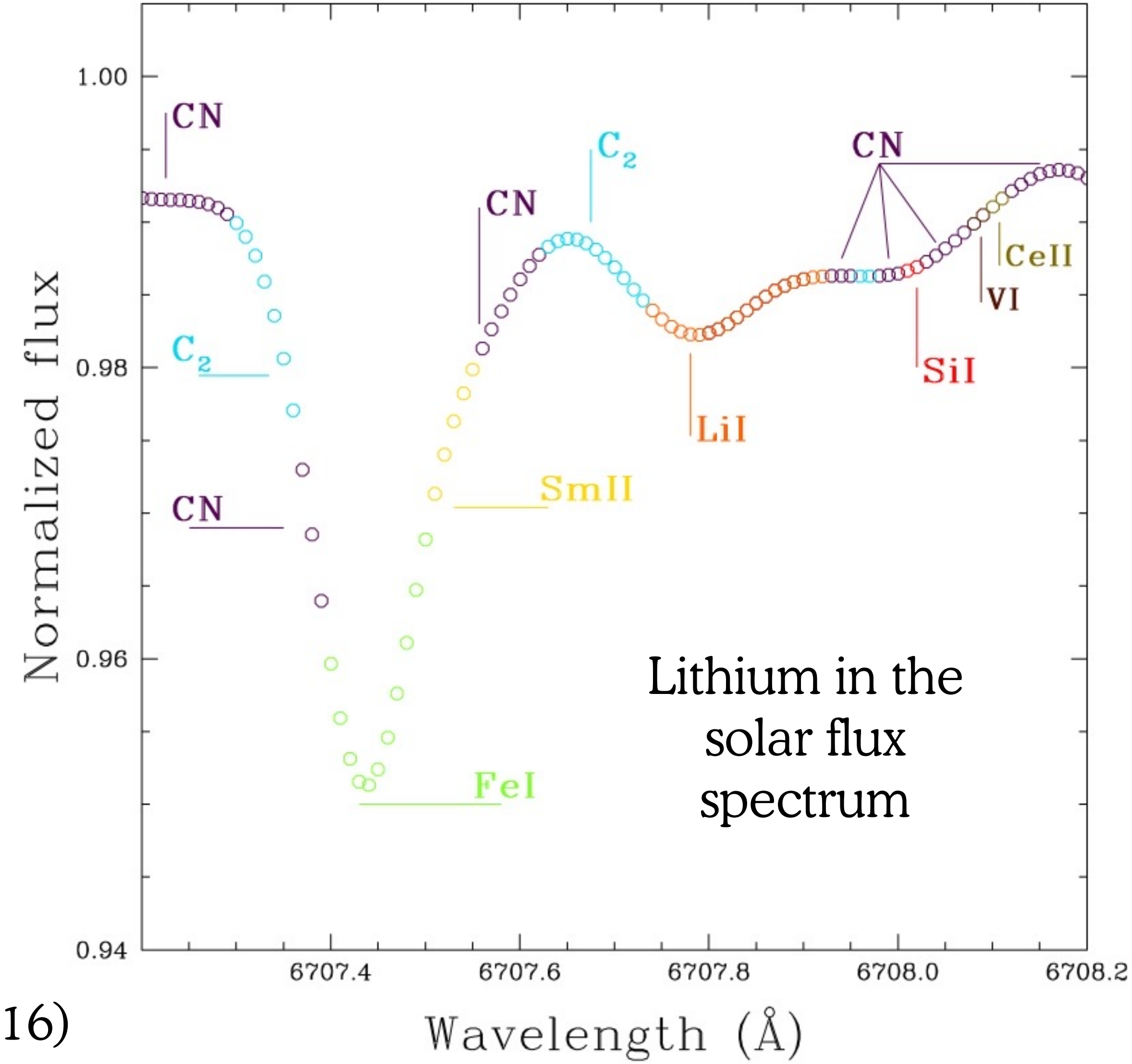


Line blending

If you do not know your blending contributions, you will always overestimate your elemental abundances.

This means that the choice of line list can matter a lot (exception: differential analyses).

There are few established standard line lists.



Carlos *et al.* (2016)

Understanding abundance nomenclature

Mass fractions let X, Y, Z denote the mass-weighted abundances of H, He and all other elements ("metals"), respectively, normalized to unity ($X + Y + Z = 1$).

example: $X = 0.744$, $Y = 0.242$, $Z = 0.014$ for the *present* Sun (Asplund *et al.* 2021)

The 12 scale. $\log \varepsilon(\mathrm{X}) = \log (n_\mathrm{X} / n_\mathrm{H}) + 12$

example: $\log \varepsilon(\mathrm{O})_\odot \approxeq 8.7$ dex, i.e., oxygen is 2000 times less abundant than H in the Sun (the exact value is still debated!) ($\log \varepsilon(\mathrm{H}) \equiv 12$)

Square-bracket scale $[\mathrm{X/H}] = \log (n_\mathrm{X} / n_\mathrm{H})_\star - \log (n_\mathrm{X} / n_\mathrm{H})_\odot$

example: $[\mathrm{Fe/H}]_{\mathrm{HE0107-5240}} = -5.3$ dex, i.e., this star has an iron abundance (metallicity) a factor of 200 000 below the Sun (Christlieb *et al.* 2002)

($[\mathrm{X/H}]_\odot \equiv 0$)

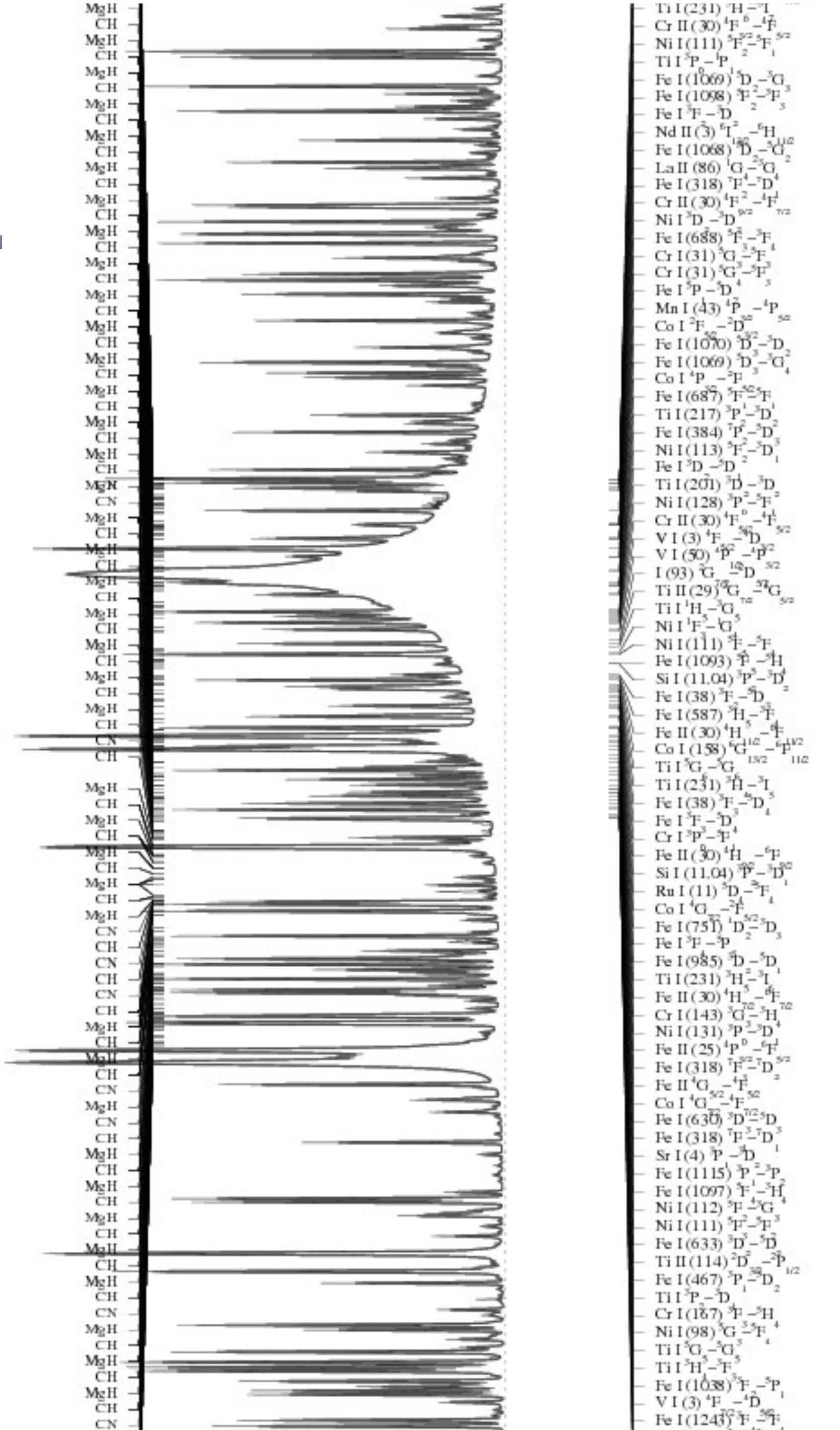
Abundances from H to U

Assuming that the stellar parameters are not biased, it is relatively easy to determine chemical abundances for your favourite element(s).

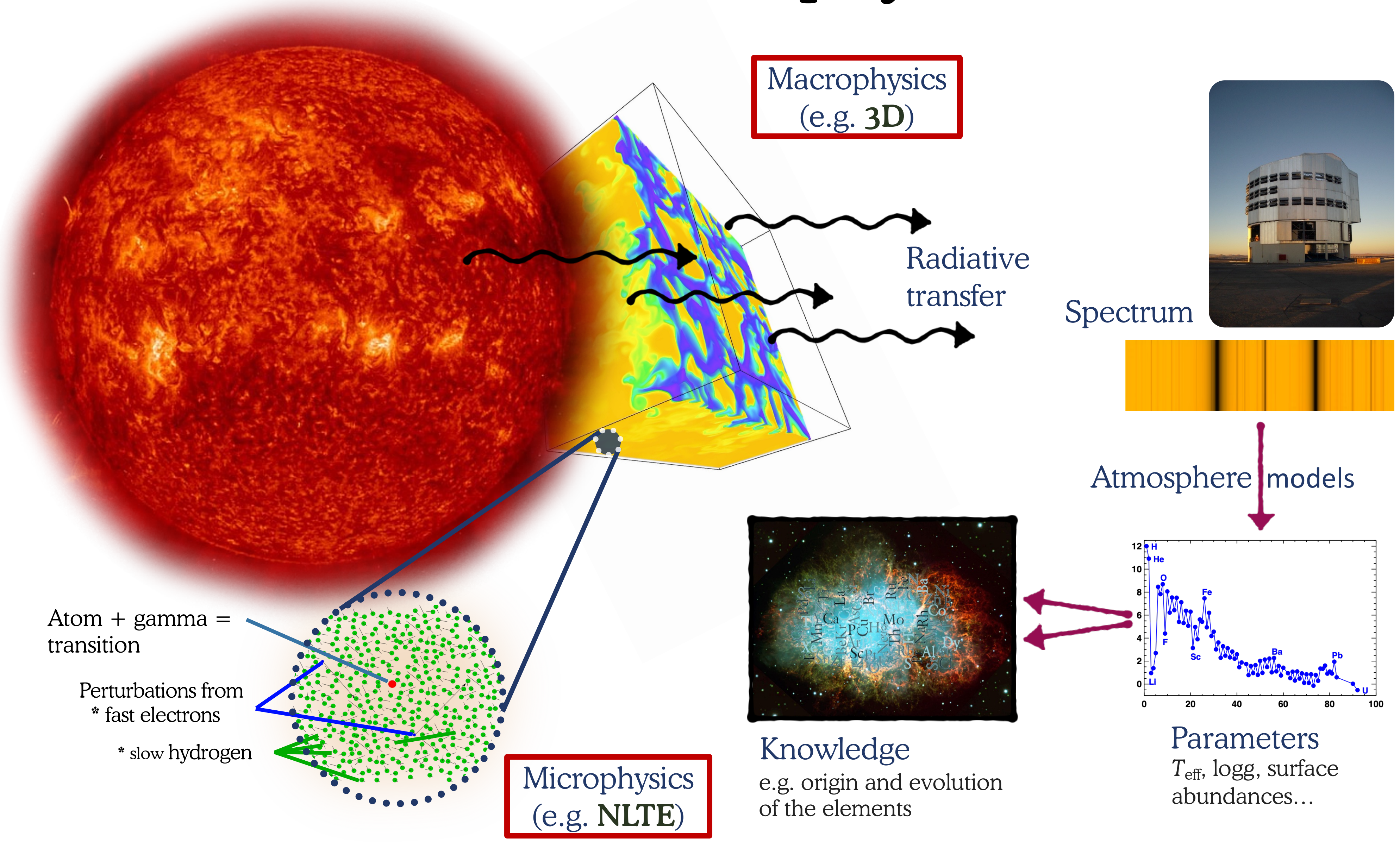
Caveats

- some elements are not visible, e.g. noble gases in cool stars
- lines may lack or have inaccurate atomic data (differential abundances can help)
- lines can be subject to unmodelled effect, e.g. blending, **3D** and **NLTE**, hfs, isotopic and Zeeman splitting

When in doubt, look for the most trustworthy 1D-NLTE or 3D-NLTE abundances.

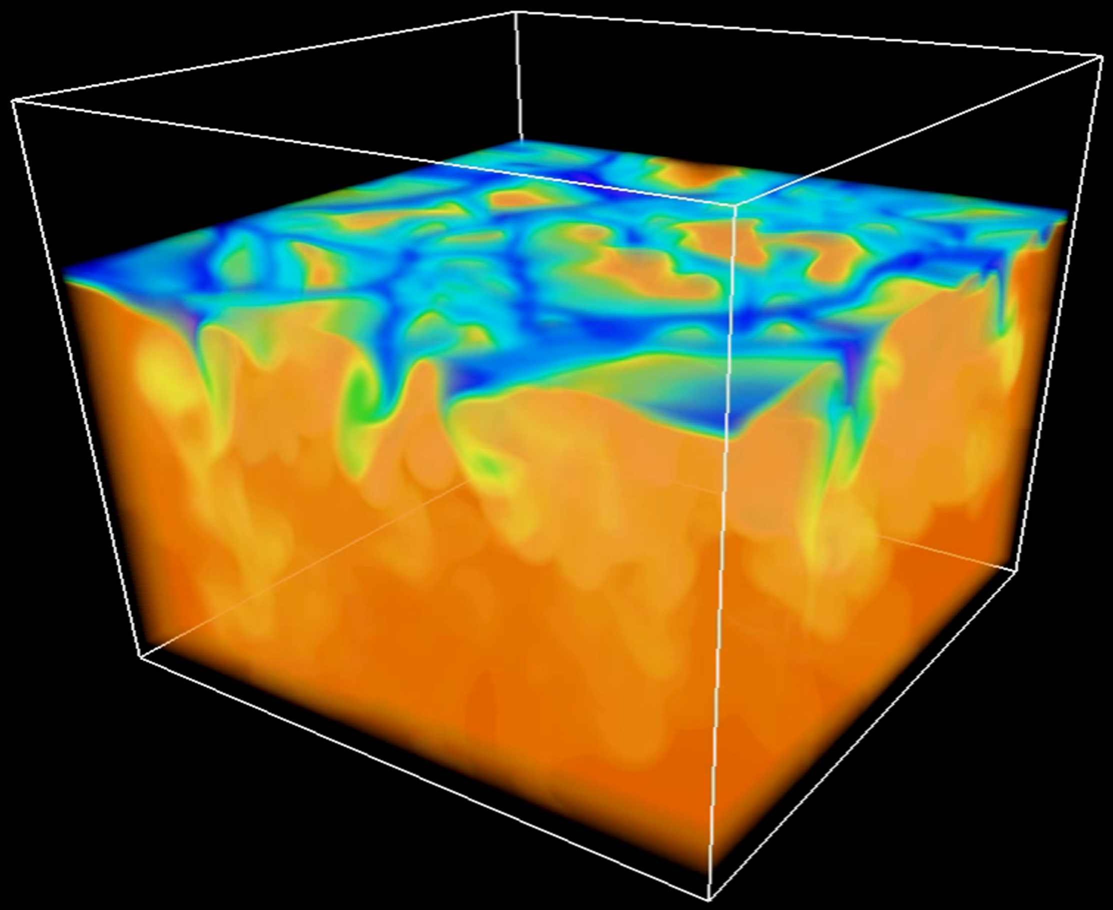


Where micro- and macrophysics meet…



adapted from A. Amarsi,
see Lind & Amarsi (2024)

State-of-the-art RHD simulations



Highly realistic, as analyses of solar data has shown.

Entropy fluctuations in STAGGER-code simulations (Collet *et al.* 2018)

LTE *vs.* NLTE

Occupation, excitation & ionization are assumed to be local gas properties

⇨ **Saha-Boltzmann statistics**

Assuming the T-P-τ relation to be known, all you need to to calculate a line strength is

(a) the level energies and statistical weights involved

(b) the transition probability

(c) broadening mechanisms (microturbulence, van-der-Waals damping)

Photons carry non-local information!

Occupation, excitation & ionization depend on the microphysics (radiation field, collisions etc.)

One needs to know (and master!) a whole lot of atomic physics.

One also needs to solve the involved numerical problem of radiative transfer plus **rate equations**:

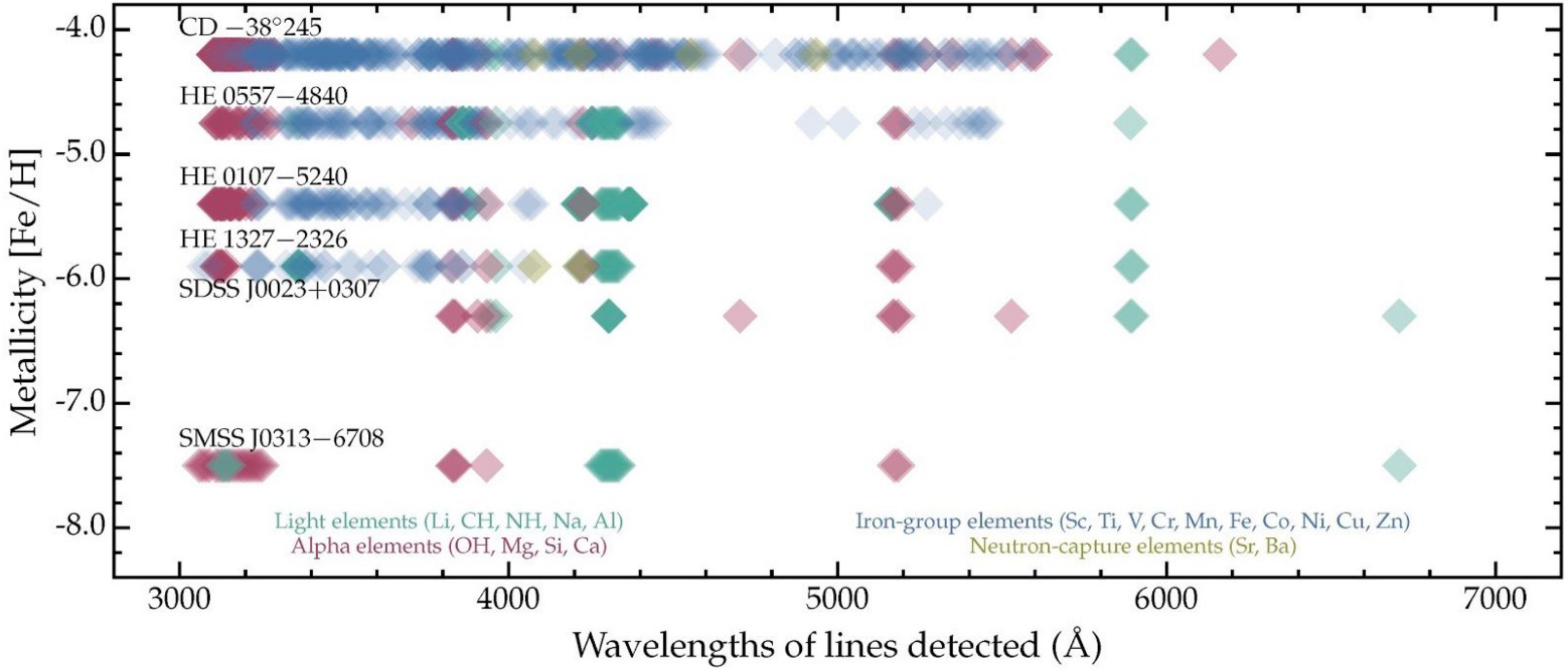
$$n_\mathrm{i} \sum_{\mathrm{j} \neq \mathrm{i}} (R_\mathrm{ij} + C_\mathrm{ij}) = \sum_{\mathrm{j} \neq \mathrm{i}} n_\mathrm{j} (R_\mathrm{ji} + C_\mathrm{ji})$$

While LTE may be an acceptable approximation for a cool-star photosphere on the whole, it can be very wrong for specific lines.

Where stars have their spectral lines

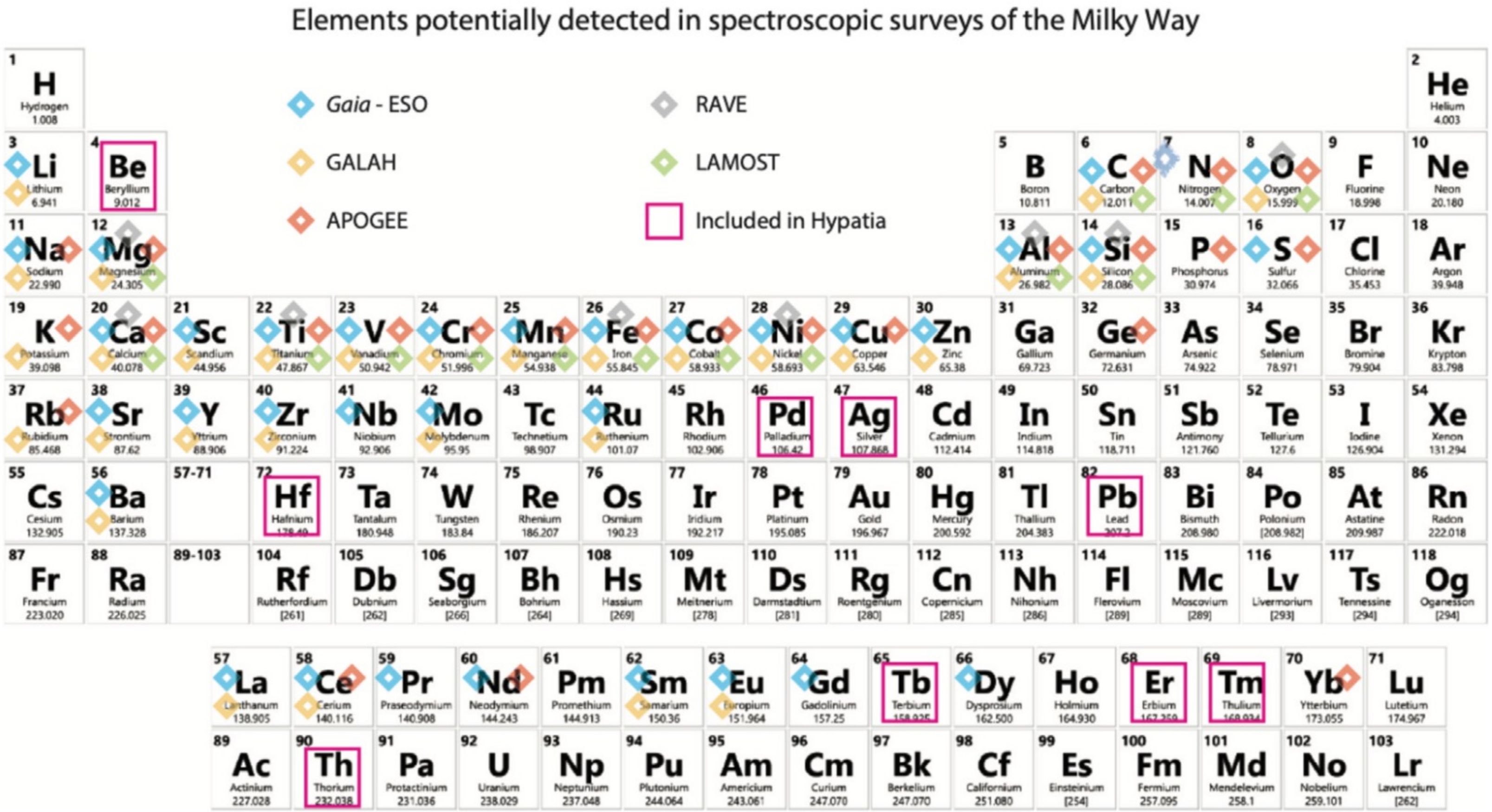
Metal-rich stars (like the Sun) have so many lines that observations in the blue or UV spectral region can be difficult. Tomorrow, you can take a look yourself.

Metal-poor stars have significantly reduced line densities which makes observations in the blue/UV a necessity, especially for rare species.



Roederer *et al.* (2019)

Deep and wide stellar surveys



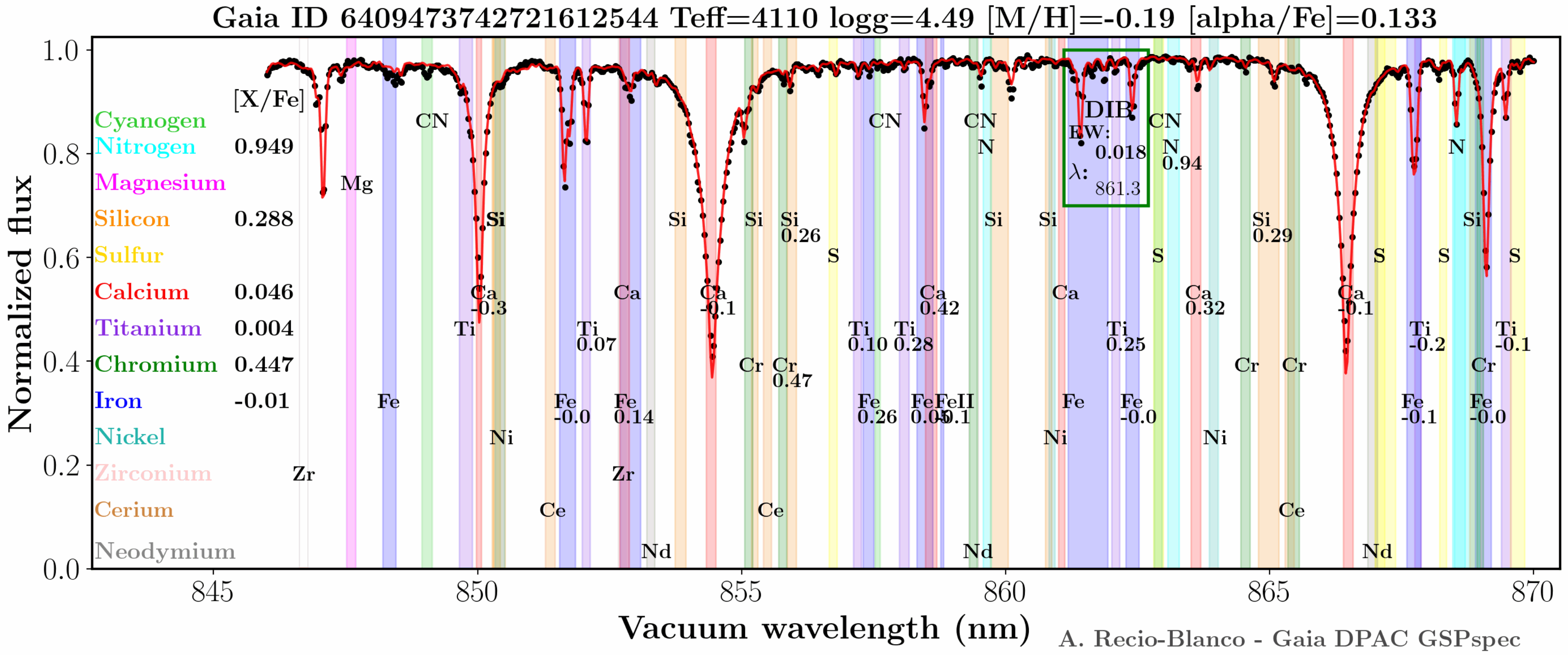
Jofré *et al.* (2019)

The near future will see surveys with *tens of millions* of spectra:
WEAVE (N, La Palma) and 4MOST (S, Paranal). Plus Gaia-RVS!

Gaia RVS: spectra by the million

With Data Release 3 (June 2022), the Gaia archive contains individual chemical abundances for a few million stars. Up to a ~dozen elements are derived from the RVS spectra (R=11500, see below).

Gaia RVS is a growing treasure trove of stellar surface abundances!



Many more spectra in Gaia DR4 in late-2026!

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