Nuclei in the Cosmos School
2025

SPECTROSCOPY & STELLAR ABUNDANCES

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This lecture

First half:

A quick introduction to the **N**ordic **O**ptical **T**elescope (NOT) at
Roque de las Muchachos, La Palma, The Canary Islands

and

dito for the **FI**ber-fed **E**chelle **S**pectrograph (FIES)

Second half:

A guided tour of the NOT with our dedicated night assistants
Amanda* and *Shilpa.

Roque de los Muchachos, La Palma

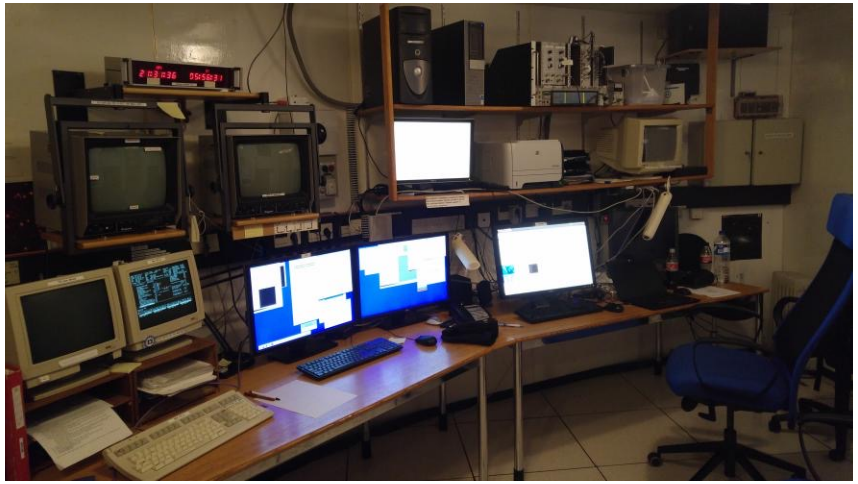
Largest and best observatory in Europe. Home of 15 operational telescopes, including the largest single-aperature optical telescope: the 10.4m **Gran Te**lescopio **Can**arias (GranTeCan).

(Site for the US TMT?)

The Nordic Optical Telescope (NOT)

A 2.56m Nordic Optical Telescope (presently run by Arhus University, DK & University of Turku, FI) just below Roque de los Muchachos.
https://www.not.iac.es/

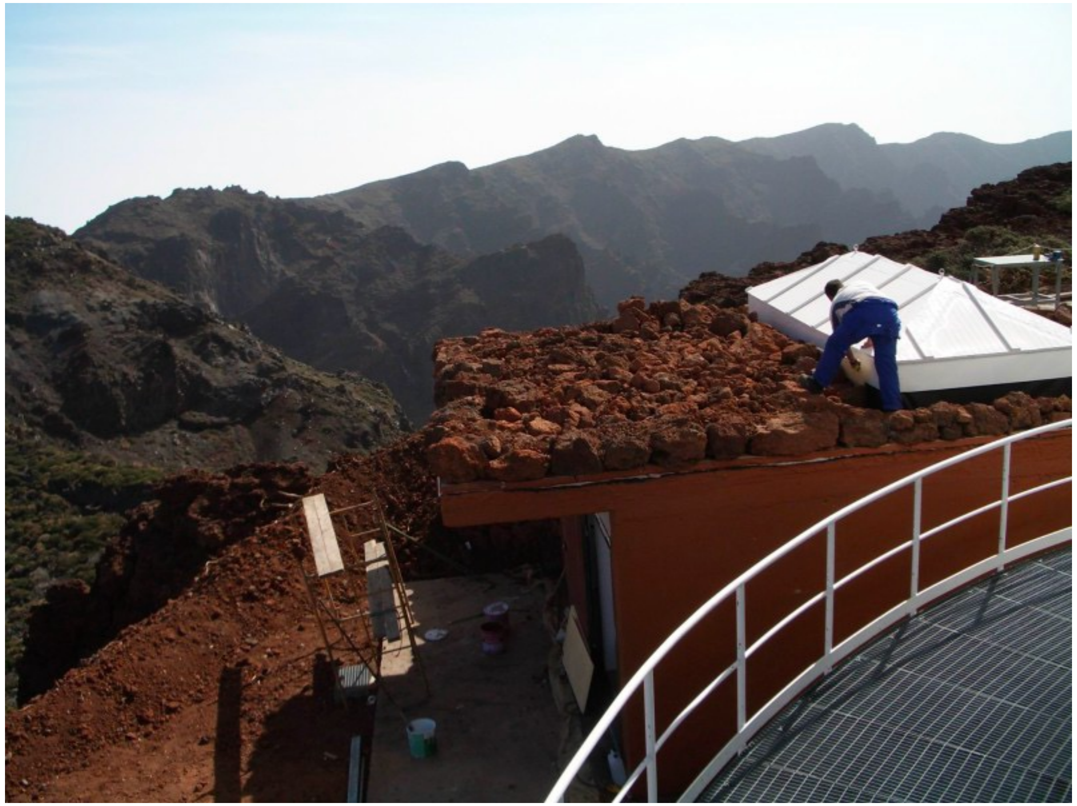
The telescope has been operated since 1989 and is known for its reliability.

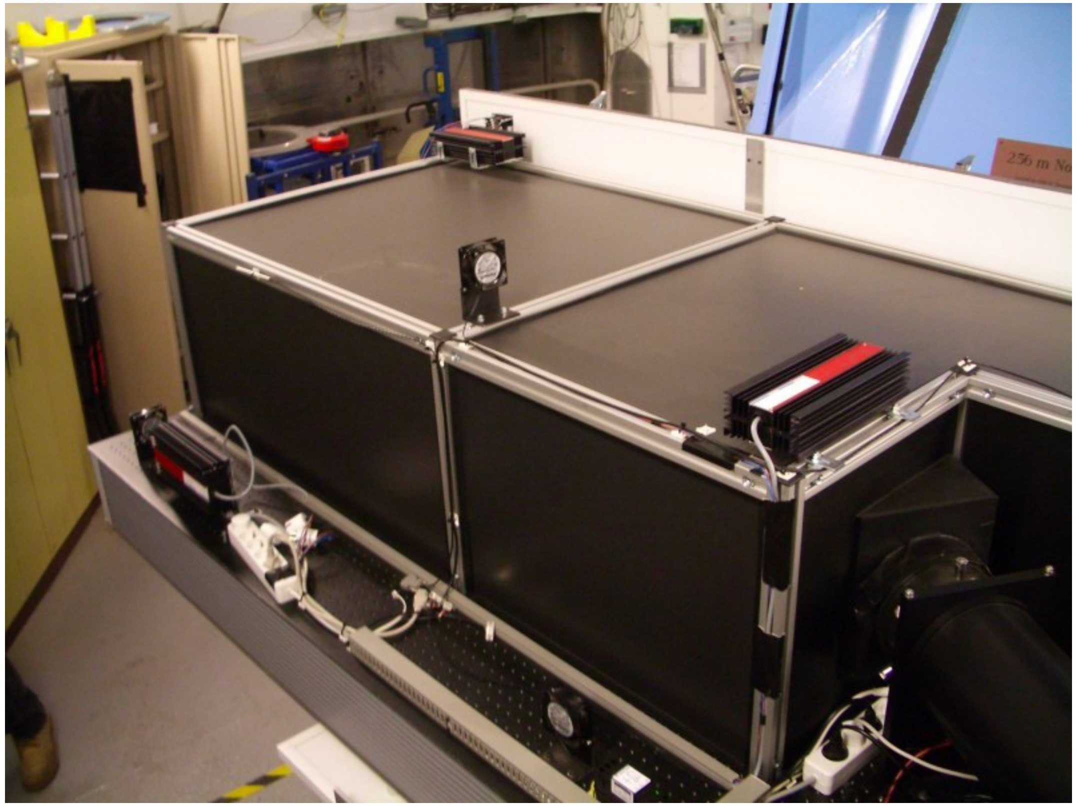


It has a modern spectrograph, FIES, which is the sole instrument we will use this week.

Parque Nacional de la Caldera de Taburiente

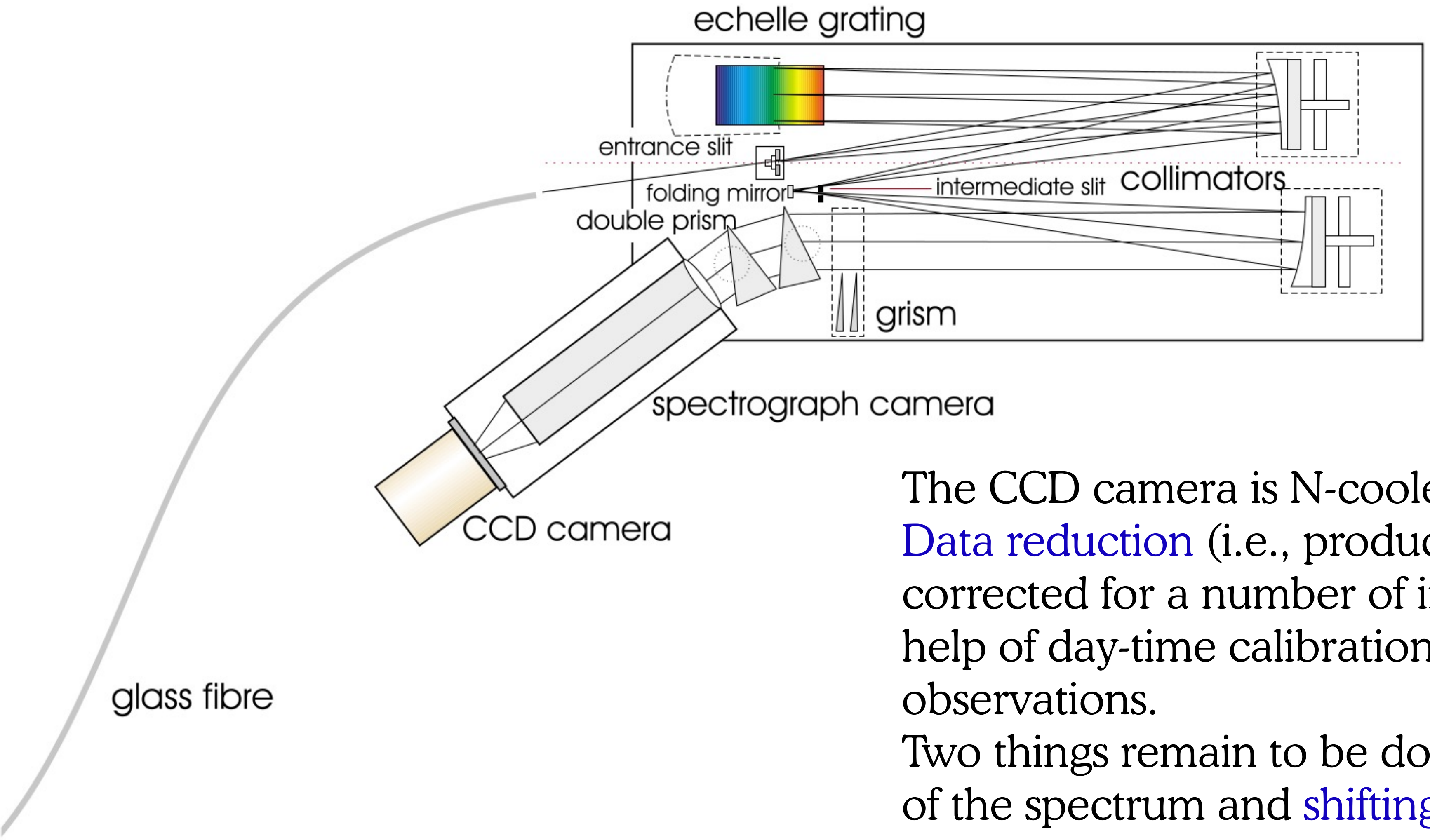

FIES is in a separate building…





…for mechanical and thermal stability. Necessitates a fiber link.

Echelle spectrographs



The CCD camera is N-cooled to minimize dark current.
Data reduction (i.e., producing one long spectrum corrected for a number of instrumental effects with the help of day-time calibration files) is done right after the observations.
Two things remain to be done: continuum normalization of the spectrum and shifting it to laboratory wavelength.

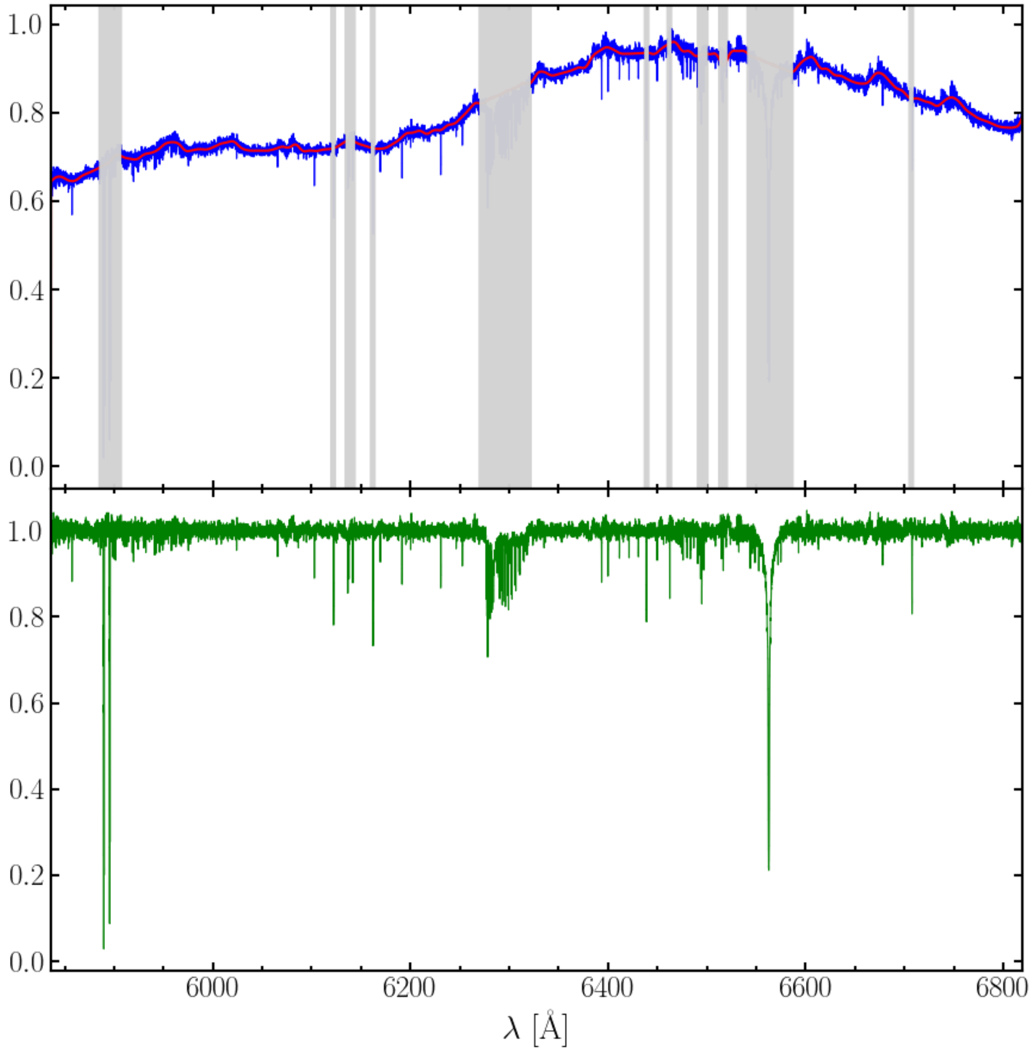
A small helper tool: JP’s normalizer

We need to provide webSME will a normalized spectrum, i.e. continuum level = 1.

Does not have to be perfect, as it will be refined by webSME.

To this end, a normalization tool by ChETEC-INFRA postdoc Johannes Puschnig (UU) is provided: https://github.com/astrojohannes/normalizer

Download it and check it out!



The FIber-fed Echelle Spectrograph (FIES)

FIES is a modern high-resolution fibre-fed echelle spectrograph. Light enters the spectrograph through a fibre with a 1.3 arcsec diameter on the sky. This means that if the seeing at the telescope is 1.3", roughly one third of the light gets lost.

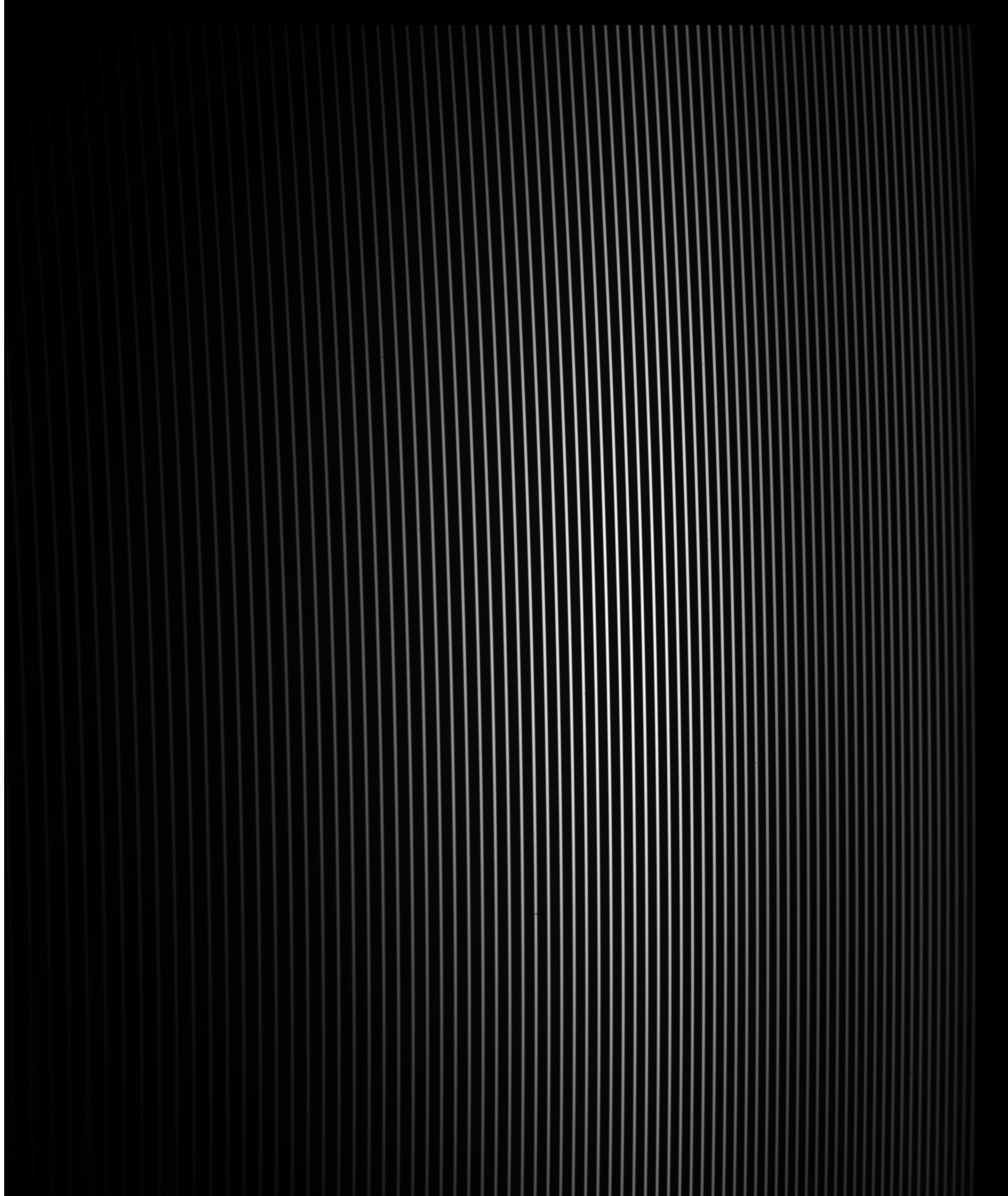
The dispersive element is an echelle grating. Cross-dispersion is provided by yet another grating. The spectral orders are recorded on a CCD. Data reduction is done on-the-fly, i.e. we receive a fits file with the reduced (w/o radial-velocity correction and normalization) spectrum right after the observations.

FIES has several modes with different resolving powers. Since we are dealing with cool stars with intrinsically sharp lines, we go for the highest-*R* setting ($\lambda/\delta\lambda = 67{,}000$). Full optical coverage out to 7300 Å.

See http://www.not.iac.es/instruments/fies/ and

http://www.not.iac.es/instruments/fies/devel/telting2014FIES.pdf

A FIES echellogram



The cross-dispersion places the slightly curved spectral orders on the CCD. Each order contains a portion of the stellar spectrum, typically 100 Å.

There are numerous steps in the data reduction to produce a long spectrum, notably flat-fielding and wavelength calibration. Day-time frames are used for this.

The analysis tool of the day: webSME

Evolution of "Spectroscopy Made Easy" (SME)

Original version published by Valenti & Piskunov (1996)

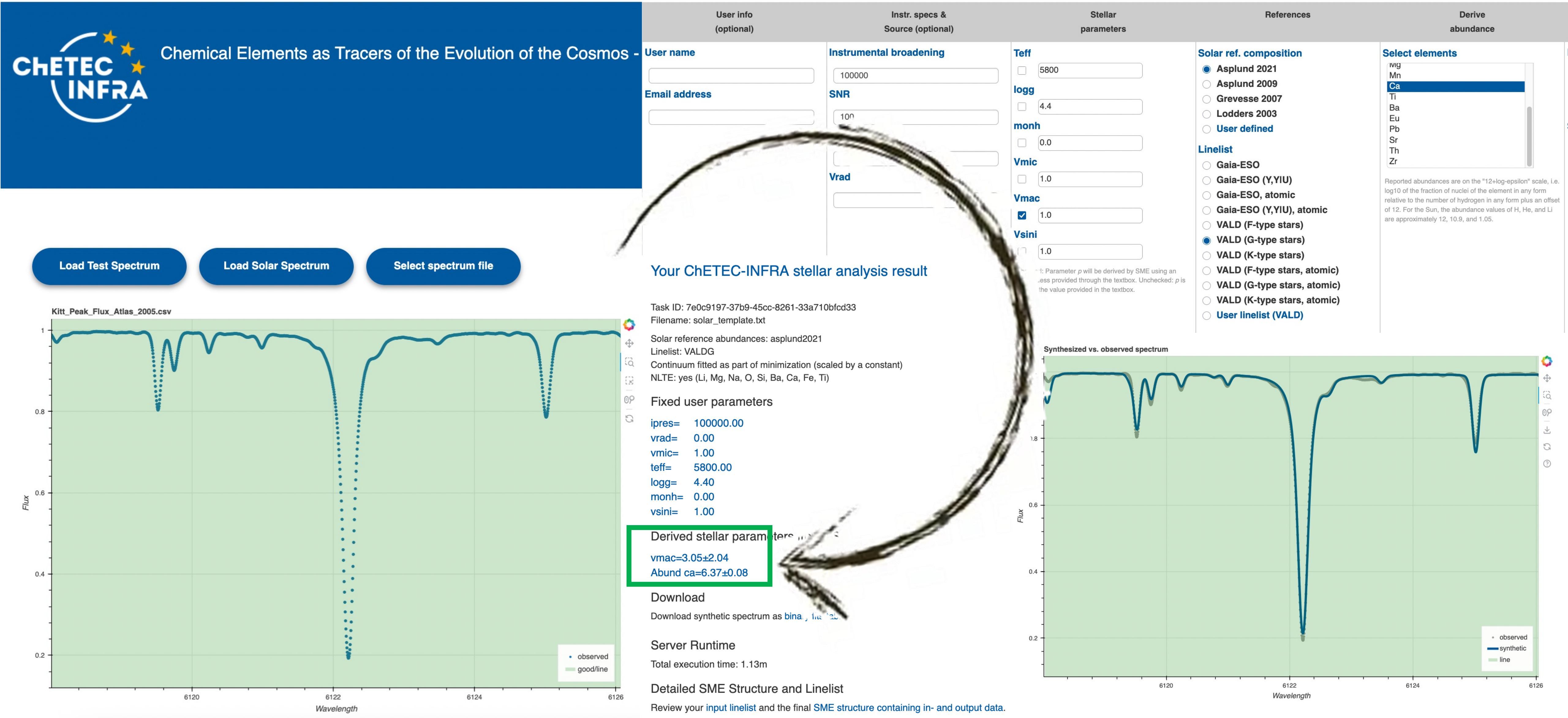
C++ and FORTRAN library complemented by IDL framework

Library has undergone significant development (Piskunov & Valenti 2017)

pySME: Wehrhahn *et al.* (2022) translated IDL part of code to python

webSME: based on pySME, with some cool updates (Puschnig *et al.*, in prep.)

From spectrum to stellar abundances



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SPECTROSCOPIC OBSERVATIONS

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Astronomical observations

First you need to have a science case. You don't need this today, as I bring the science cases to you.

With a viable science case, you can apply for observing time. You don't need this, as we have secured observing time through the European network for nuclear astrophysics ChETEC-INFRA.

Telescopes are usually oversubscribed (by a factor of a few). So you are generally competing for time. Fyi, a NOT night costs some 6000 €.

Observing time at ESO telescopes is free but hard to get.

Preparing observations

You need to know some key properties of the stars you wish to take a spectrum of: the star's position on the sky (RA, DEC, equinox), its brightness in a certain filter (Vega *V* or Gaia *G*), what signal-to-noise ratio (SNR) you wish to achieve.

There are lots of tools to help you prepare the observations:

Simbad for stellar data: https://simbad.cds.unistra.fr/simbad/sim-fid

Exposure time calculator: https://www.not.iac.es/observing/forms/signal/index.php

NOT visibility tool: https://www.not.iac.es/observing/forms/visibility/

Generating Observing Blocks

These are the scripts to be executed at the telescope. I will guide you through the process (which I pre-prepared).

Proposal: 71-704 -> Groups andreaskorn

Front Page
General Info
Instruments
Observer Info
Resources
Weather
Outreach

Search
Text Size: A A A

List Targets | List Proposals | Help | Logout

SUMMARY OF PROPOSAL: 71-704

Proposal	P.I.	Title	Email	
71-704	ChETEC school		andreas.korn@physics.uu.se,tiina.liimets@ut.ee	View

OBSERVING TIME BREAKDOWN

Totals InPrep:10444 | Submitted:11486 | Active:0 | Closed:0 | Expired:0 | Redundant:0

An observing group of type 'Visitor' has been submitted. At the telescope, you now have the option to generate observing scripts of all the blocks in this group by clicking the 'Compile' button or add the observing group to the OB queue interface by clicking the 'Queue it!' button.

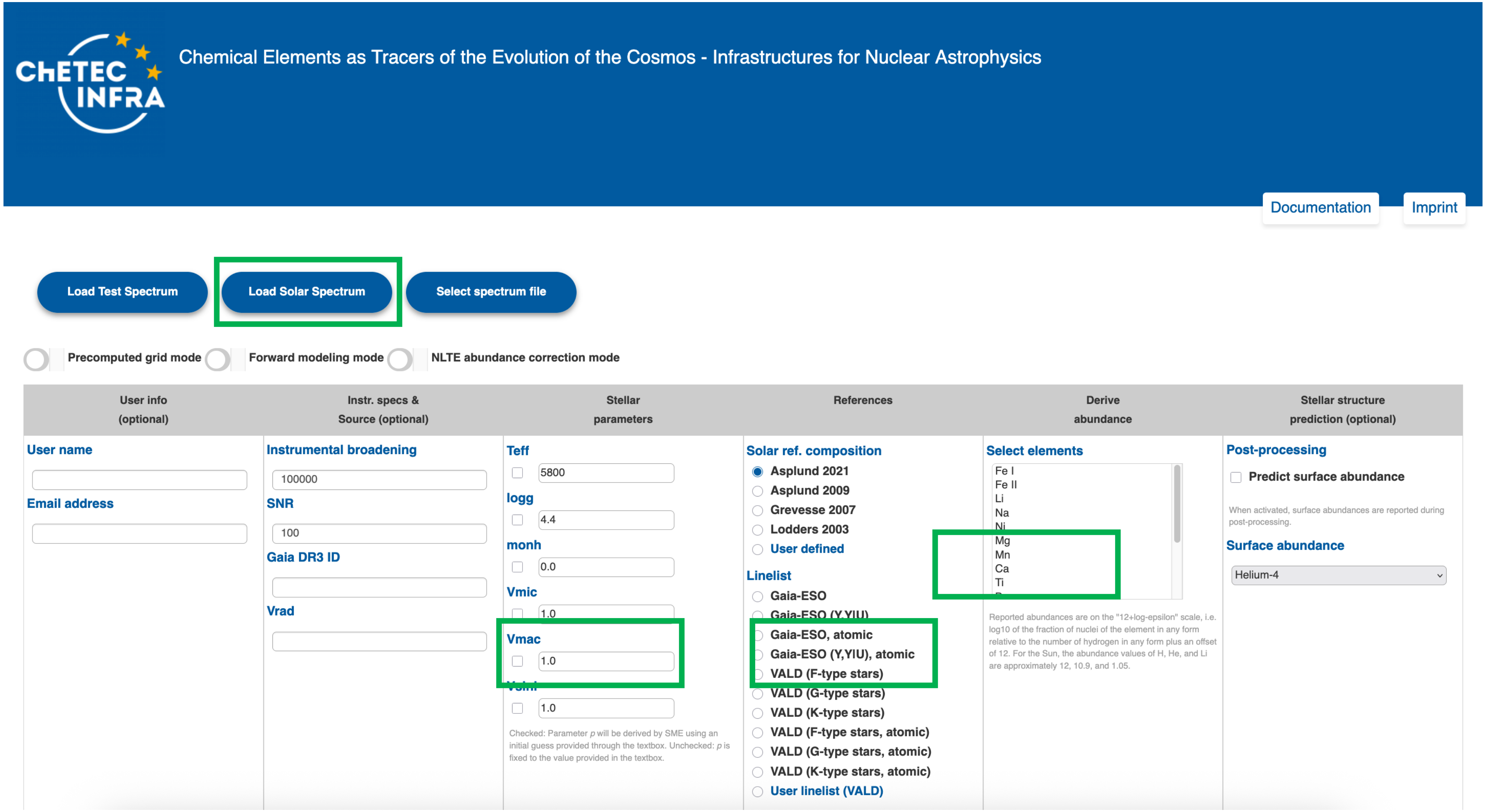
LIST OF OBSERVING GROUPS

Show Closed/Expired

Group Name	Instrument(s)	Mode(s)	Type	Seeing	Weather	Moon	Obs. Time	Comments	Time Critical	Priority	Linked	Blocks	Status	Group Actions
benchmark	FIES	SPEC	Visitor	9.9	Thin Clouds	Any	3046	No	20250612	1	No	List	Submitted	Copy
gr8stars	FIES	SPEC	Visitor	9.9	Thin Clouds	Any	8440	No	20250612	1	No	List	Submitted	Copy
mincebright	FIES	SPEC	Visitor	9.9	Thin Clouds	Any	10444	No	20250612	1	No	List	InPrep	Copy Edit Delete Submit

Add New Group | Import Group | Link Groups | Show All Blocks

Getting to know *webSME*: Ca I 6122



First steps

Determine the solar Ca abundance from the (strong) Ca I 6122 line:

- Load the solar spectrum. Zoom into the region of the line of interest. NB: Restrict the wavelength range to be analysed.
- Choose ◉ *Vmac*, the *Gaia-ESO (Y,Y/U) atomic* line list and *Ca* from the *Select elements* window. In the window which appears below, select Ca I 6122. This tells SME to only fit this line.

You can run LTE or NLTE and choose whether you want to retain the continuum level or whether it should be included in the fitting.

Once you have a first result, you can vary some parameters (wavelength range, *Vmac*, stellar parameters, LTE/NLTE). Get a feel for stellar line formation…

An alternative approach

There is also the *forward-modelling mode* of webSME which you activate by the toggle button at the top.

Here you can load a spectrum (only as background, for comparison; spectrum needs to be normalized) and then produce a spectrum with given input parameters. No fitting is performed, thus no free parameters allowed.

This mode is fast, i.e. you can try to reproduce larger portions of the spectrum. But you have to quantitatively assess the results outside of webSME (e.g by computing a difference spectrum).

Our science targets

Tonight we will observe

- the Sun (how do you observe the Sun at night?)
- some benchmark stars with interferometric radii (from which "fundamental" T_{eff} values can be derived)
- some new stars for the gr8stars sample (see https://arxiv.org/pdf/2505.12945)
- some stars for the MINCE project (see https://ui.adsabs.harvard.edu/abs/2022A%26A...668A.168C/abstract)

So some educational data and some science data.

Spectroscopic techniques

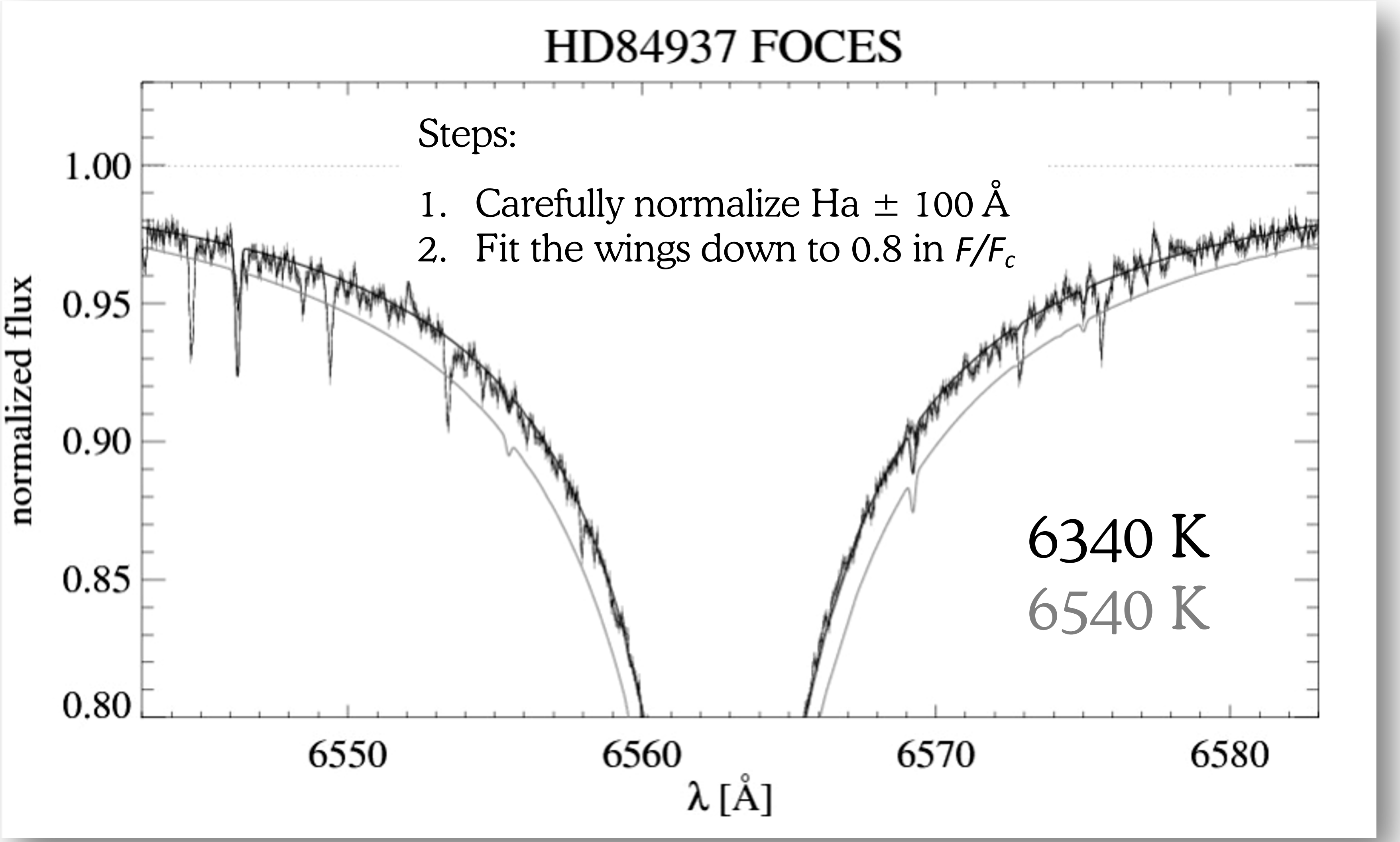
Most spectroscopic techniques rely on many lines.

webSME can synthesize large portions of the spectrum (e.g. 1000 Å) in one go and determine stellar parameters in the process. But this takes time. So tonight we will focus on individual lines with diagnostic power.

The lines of choice are

- Halpha and Hbeta as T_{eff} indicators
- the Mg I b triplet lines as log g indicators
- Fe II lines 6332.6, 6432.6, 6456.4 (and additional ones, if needed) to test the theoretical log g sensitivity

Hα as a function of T_{eff}



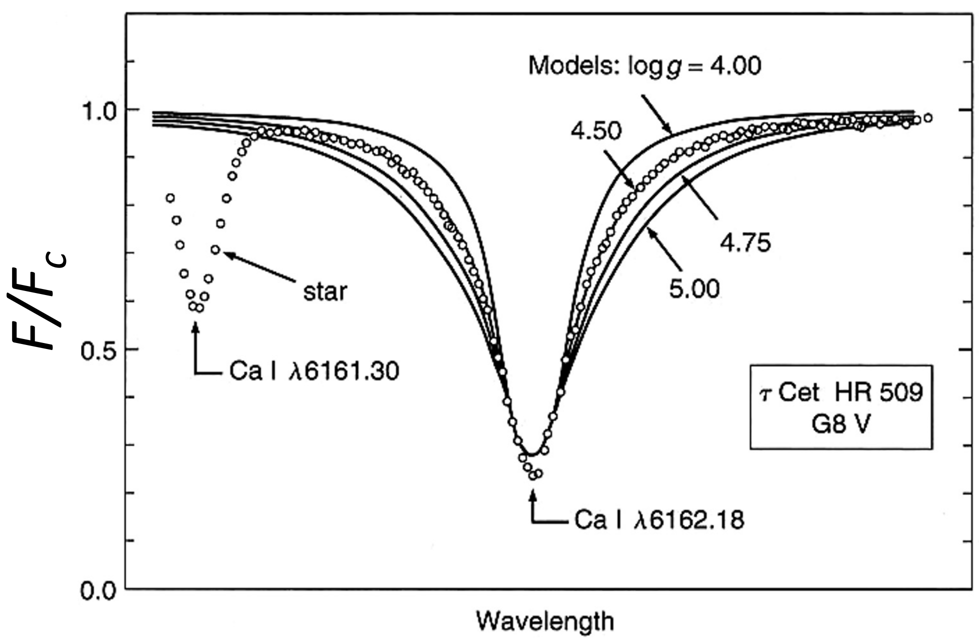
Strong neutral lines as a function of log g

Damped (neutral) lines show a strong gravity sensitivity, because

$$I_\nu \propto \gamma_6 \propto P_g \propto g^{2/3}$$

Like with ionization equilibria, log ε needs to be known. This is to be obtained from weak lines of the same ionization stage, preferably originating from the same lower state (small differential NLTE effects).

Gray, Fig. 15.4



Examples: Ca I 6162 (see above), Fe I 4383, Mg I 5183, Ca I 4226.

Below [Fe/H] ≈–2, there are no optical lines strong enough to serve as a surface-gravity indicator.

Ionized lines as a function of log *g*

Recall that ionized lines of an element that is mainly ionized have a P_e^{-1} sensitivity via the continuous opacity of H^-.

Integrating the hydrostatic equation, we find

$$P_g \propto g^{2/3}$$

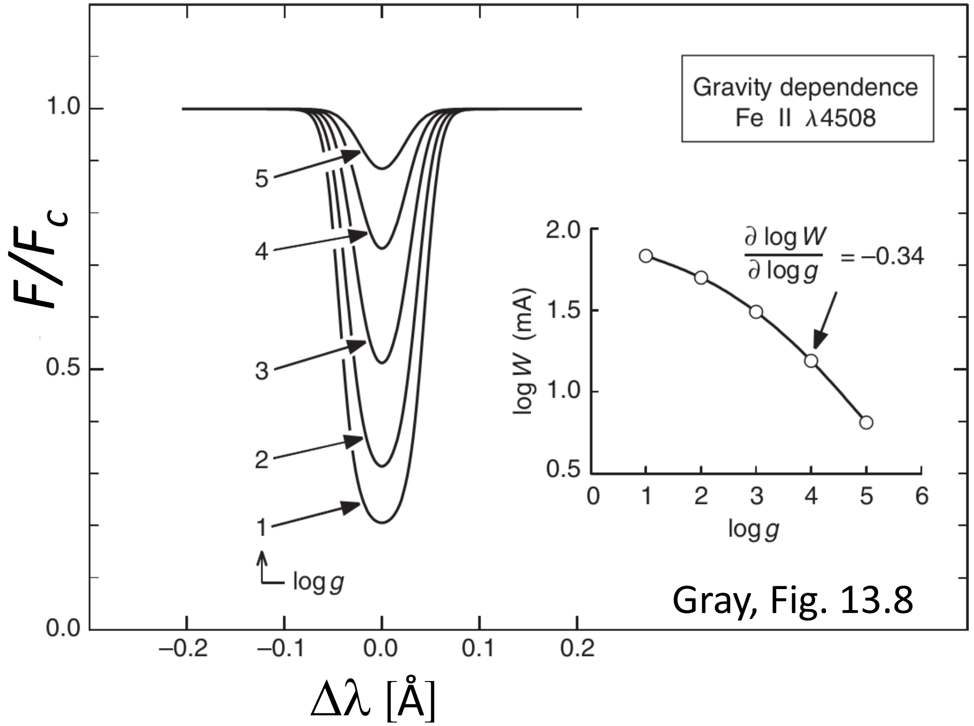
and together with $P_e \propto \mathrm{sqrt}(P_g)$ we expect

$$l_\nu / \kappa_\nu \propto g^{-1/3}.$$

This is borne out by actual calculations (see rhs plot) .

Hydrostatic equilibrium

$$dP / d\tau_\nu = g / \kappa_\nu$$



Gray, Fig. 13.8

Sun and the benchmark stars

Science questions:

- Can you reproduce the known effective temperatures?
- What about the other parameters? How do they influence your result? How could you constrain them?

Generally speaking, you can determine many stellar parameters with webSME at the same time. But some are weak, some strong (in a PCA sense).

My recommendation for tonight: fix Vmic to 1 (dwarfs) and 2 km/s (giants) and determine one external broadening parameter, e.g. Vmac. Leave Vsini (rotation) at 1 km/s (it can not be determined separately).