CosmoVerse School@Sofia 2026

Measuring stellar abundaces

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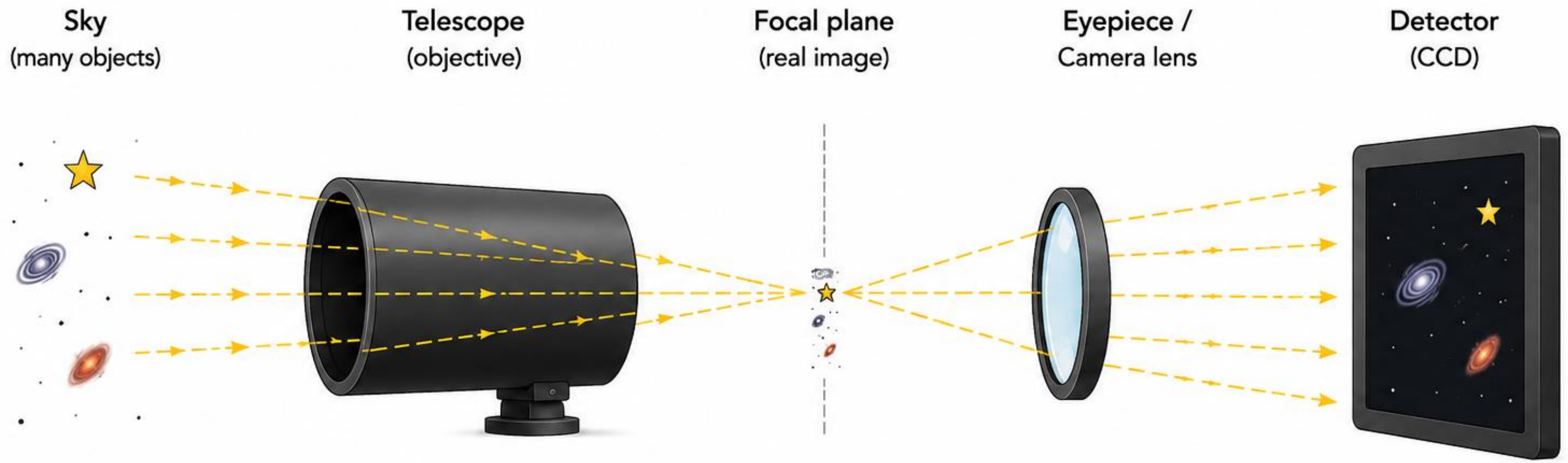
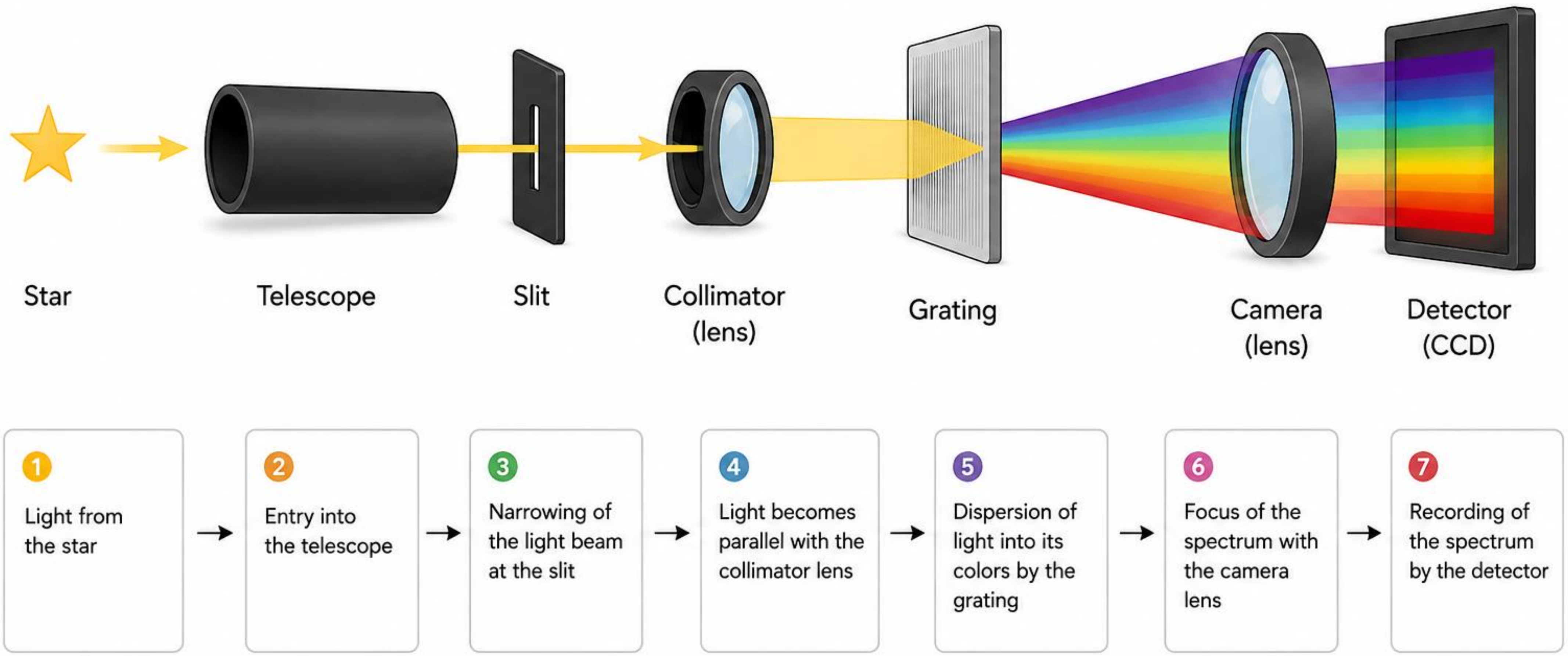
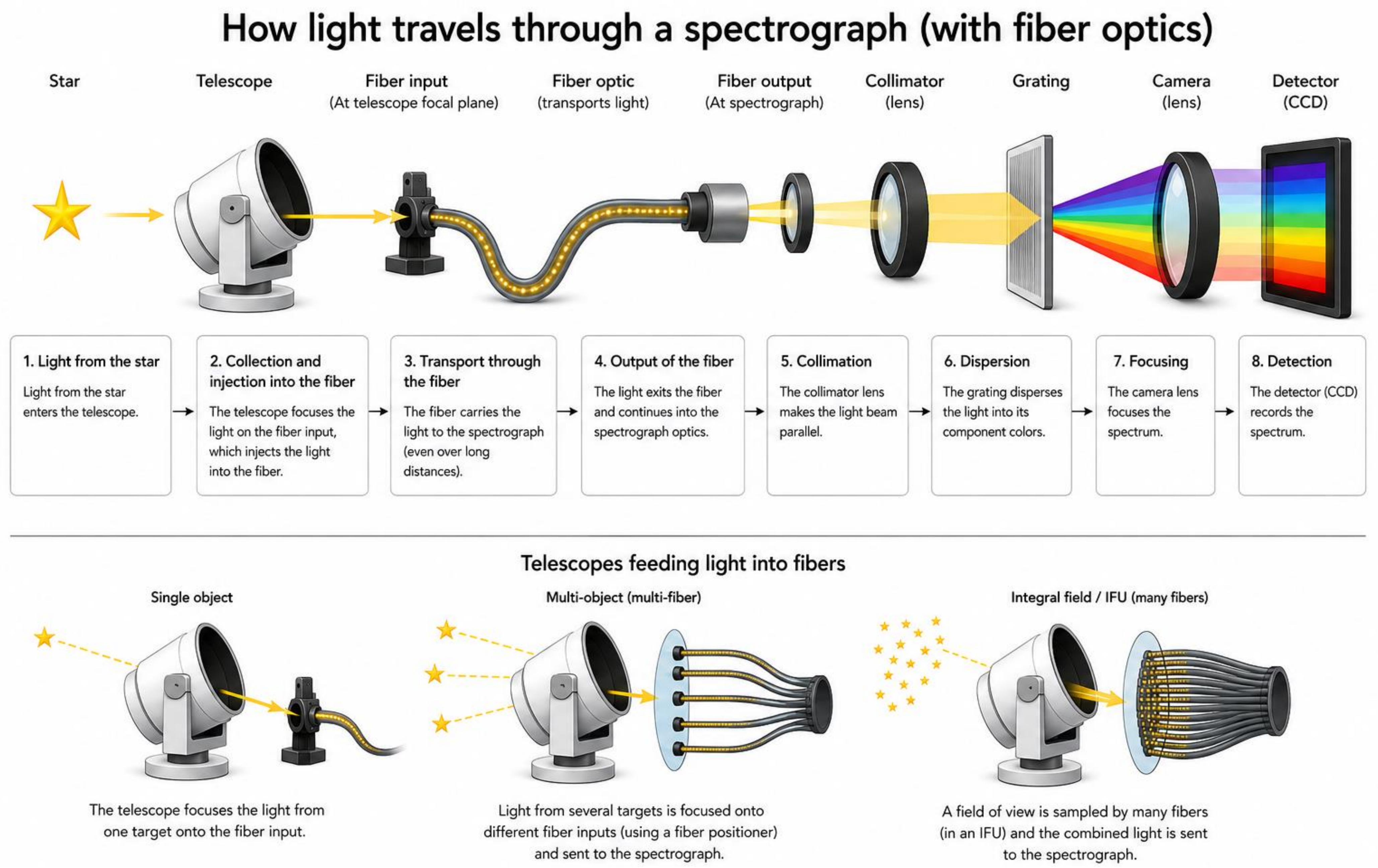
How light travels through a telescope to form an image



1. Light from many objects in the sky arrives at the telescope as parallel rays. →
2. The objective lens (or mirror) collects the light and converges it toward the focal plane. →
3. A real, inverted image of the sky is formed at the focal plane. →
4. The eyepiece or camera lens re-images the focal plane. →
5. The light is focused onto the detector. →
6. The detector (CCD) records the image: brightness at each position forms a picture.

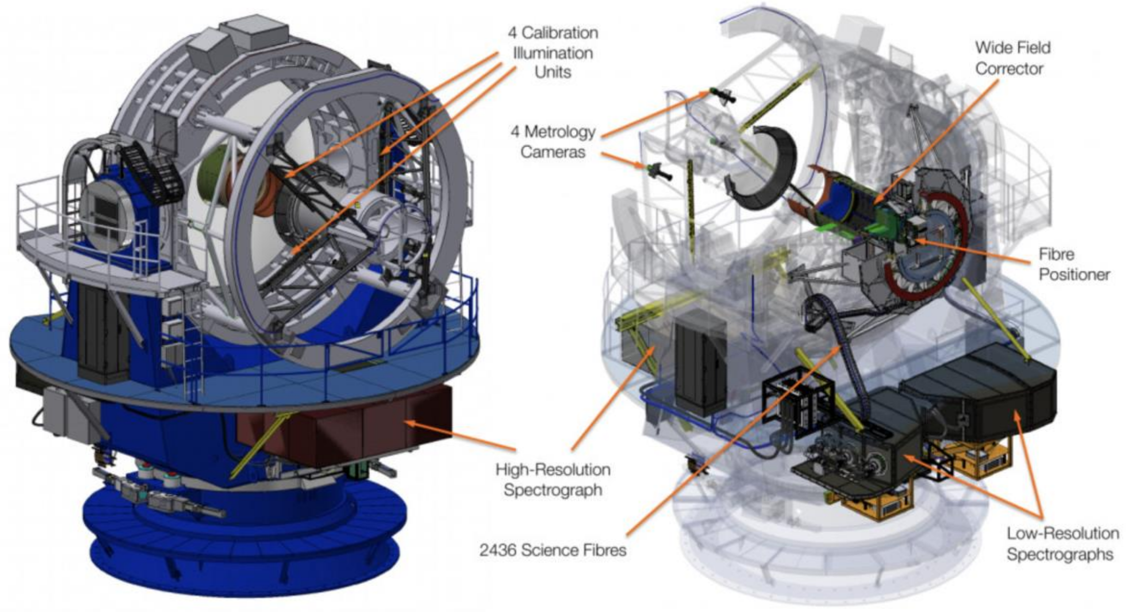
How light travels through a spectrograph

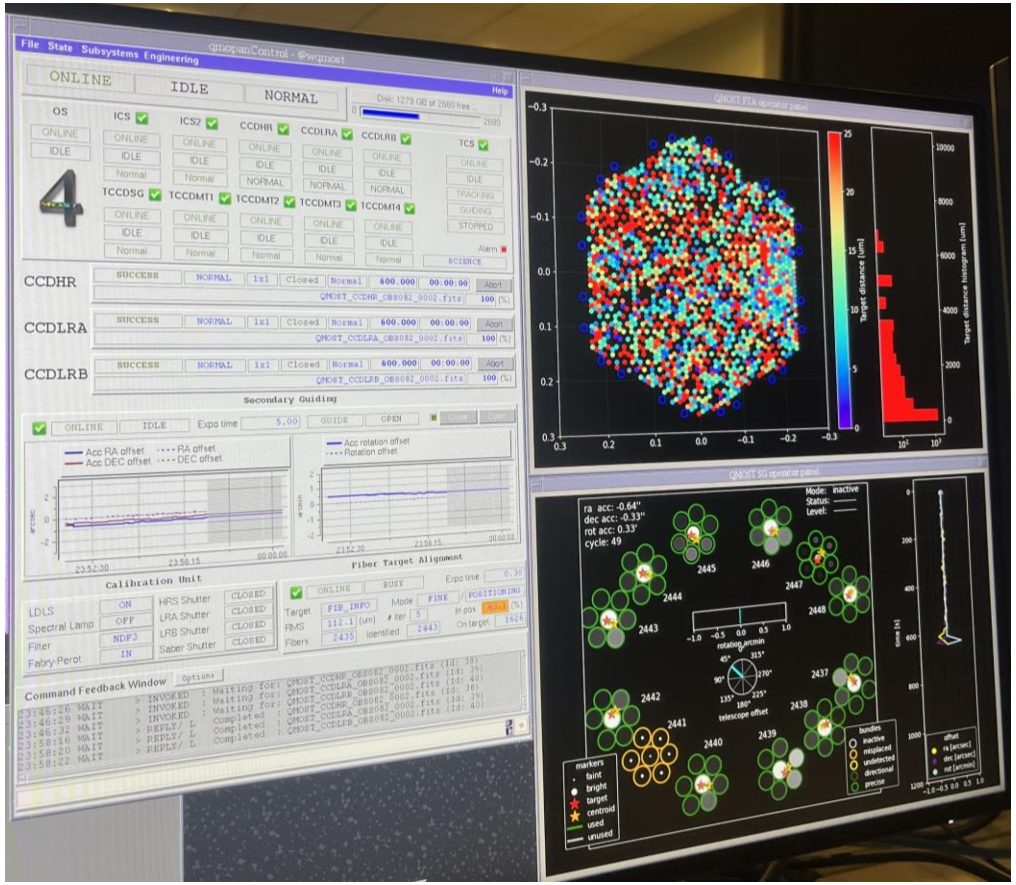



How light travels through a spectrograph (with fiber optics)
Star
Telescope
Fiber input
(At telescope focal plane)
Fiber optic
(transports light)
Fiber output
(At spectrograph)
Collimator
(lens)
Grating
Camera
(lens)
Detector
(CCD)
1. Light from the star
Light from the star enters the telescope.
2. Collection and injection into the fiber
The telescope focuses the light on the fiber input, which injects the light into the fiber.
3. Transport through the fiber
The fiber carries the light to the spectrograph (even over long distances).
4. Output of the fiber
The light exits the fiber and continues into the spectrograph optics.
5. Collimation
The collimator lens makes the light beam parallel.
6. Dispersion
The grating disperses the light into its component colors.
7. Focusing
The camera lens focuses the spectrum.
8. Detection
The detector (CCD) records the spectrum.
Telescopes feeding light into fibers
Single object
The telescope focuses the light from one target onto the fiber input.
Multi-object (multi-fiber)
Light from several targets is focused onto different fiber inputs (using a fiber positioner) and sent to the spectrograph.
Integral field / IFU (many fibers)
A field of view is sampled by many fibers (in an IFU) and the combined light is sent to the spectrograph.

4MOST

Optical spectroscopic survey facility mounted on ESO's 4-m-class telescope VISTA.
2.5-degree diameter field-of-view with 2436 science fibres in the focal plane.





How spectral lines form and which regions they probe

1 Light from the star

Continuum photons are generated in the deep, hot layers of the star and travel outward through cooler layers.

2 Atoms and ions can absorb or emit photons

When a photon's energy matches the difference between two energy levels, it can be absorbed (up) or emitted (down).

3 Different elements have unique wavelengths

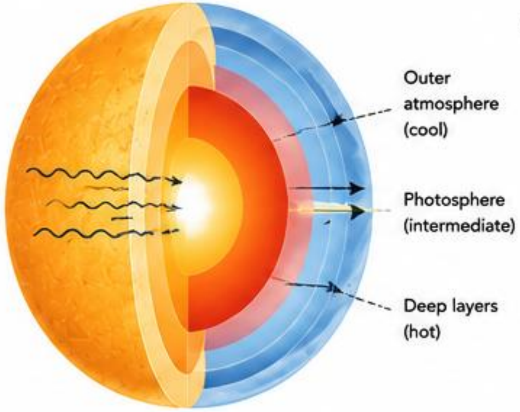
Each transition occurs at a specific wavelength, producing absorption or emission lines characteristic of that element.

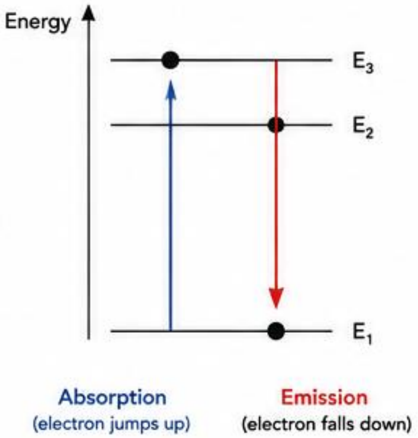
4 Lines are imprinted in the emerging spectrum

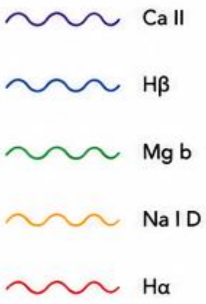
As light passes through the atmosphere, certain wavelengths are absorbed (dark lines) or emitted (bright lines) on top of the continuum.

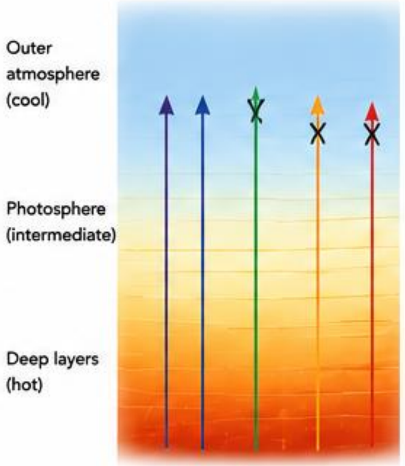
5 We observe the spectrum

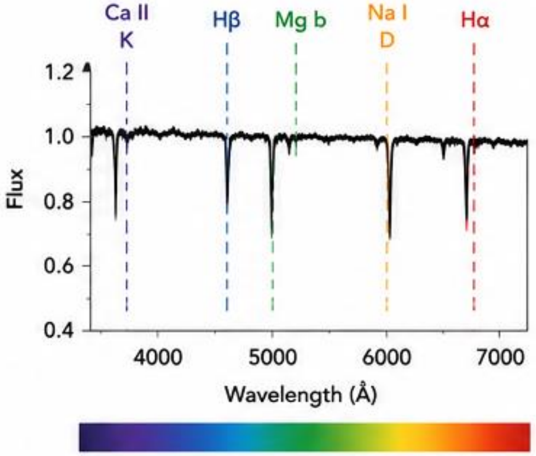
A spectrograph disperses the light by wavelength. Absorption (or emission) lines appear at the characteristic wavelengths of each element.



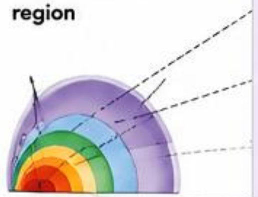






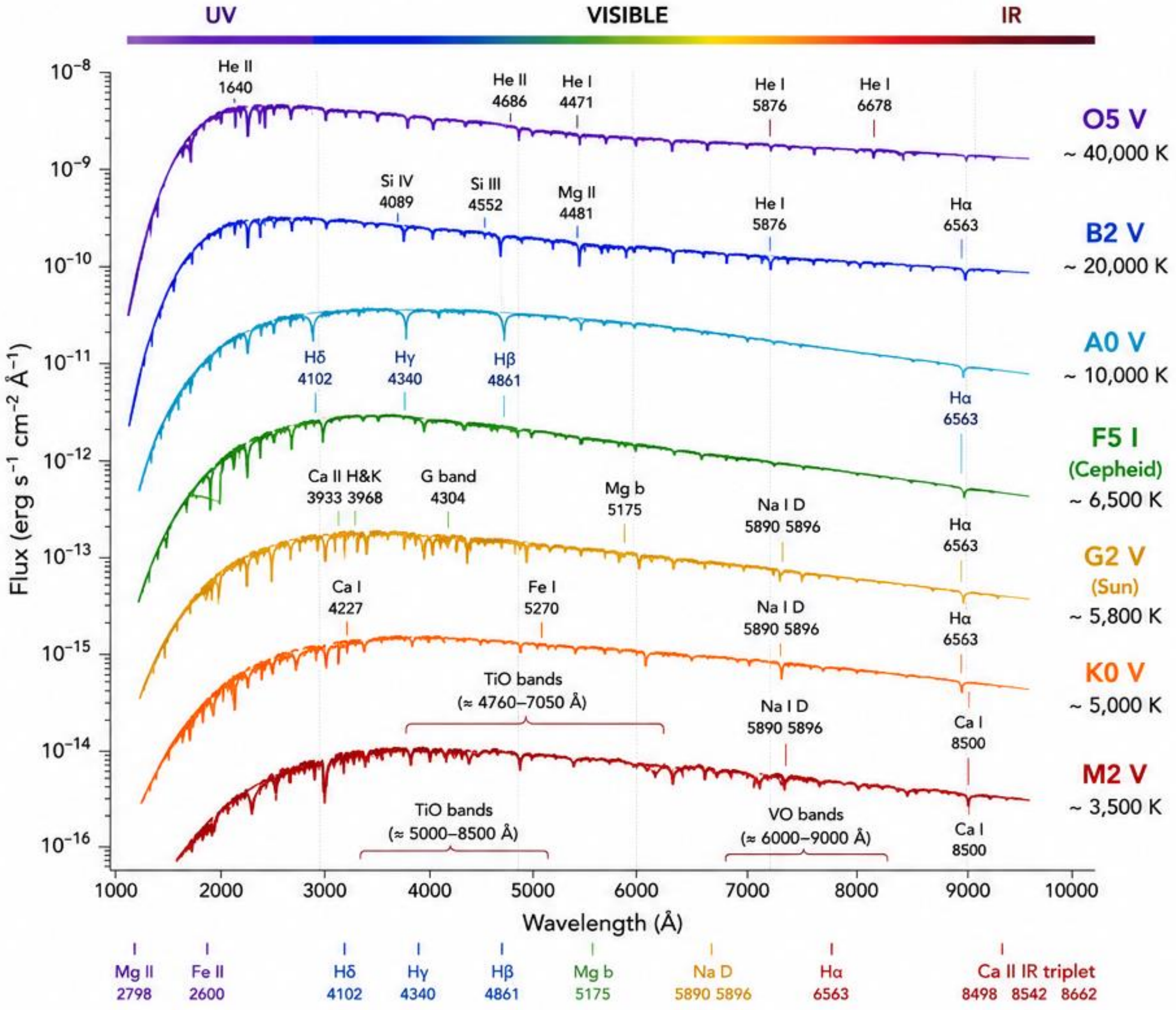


Which regions probe which part of the star?

Line formation region	Very high in the atmosphere (chromosphere / wind)	Upper atmosphere (low density)	Photosphere (line forming region)	Deep photosphere	Very deep layers (continuum forming)
	e.g. Ca II H&K cores, Hα emission Traces: activity, winds, chromospheric structure	e.g. strong resonance lines, some ionized species Traces: temperature, ionization, low-density gas	e.g. Mg b triplet, Fe I lines, most metal lines Traces: chemical composition, temperature, gravity, microturbulence	e.g. broad wings of strong lines Traces: temperature, surface gravity	Continuum light comes from the deepest, hottest layers
Typical lines	Ca II H&K, Hα emission, He I 10830 Å	Ca II IR triplet (wings), Na I D (upper parts)	Fe I, Fe II, Mg I/II, Si I/II, Ti I/II, Na I D (core), many metal lines	Strong lines (e.g. Balmer wings, Mg b wings)	Continuum

Stellar Spectra Across Spectral Types

Stellar spectra are shaped by the temperature of the photosphere (blackbody continuum) and modified by absorption lines from different elements and ions.



Type	Star (example)	T_{eff} (K)	Key spectral features
O5 V	ζ Puppis	~40,000	• Very hot, blue continuum (UV-peaked) • He II lines very strong • Metals highly ionized (weak in optical)
B2 V	Rigel	~20,000	• He I lines strong • Some Si IV, Si III visible • Balmer lines present
A0 V	Vega	~10,000	• Balmer lines strongest • He I lines weak • Metals weak
F5 I (Cepheid)	δ Cephei	~6,500	• Balmer lines weaker • Metals (e.g., Ca II, Fe I) become stronger • Used for distance measurements (Period–Luminosity relation)
G2 V (Sun)	Sun	~5,800	• Many metal lines • Ca II H&K lines prominent • Hα in absorption
K0 V	Arcturus	~5,000	• Metal lines strong • Molecular bands begin (e.g., MgH) • Continuum redder
M2 V	Proxima Cen	~3,500	• Cool, red continuum (IR-peaked) • Strong molecular bands (TiO, VO) • Atomic lines fewer and weaker

1. [X/H] measures an abundance

Use [X/H] when you want to know whether one specific element is more or less abundant than in the Sun.

$$[X/H] = \log_{10}(N_X/N_H)_\star - \log_{10}(N_X/N_H)_\odot$$

- $[X/H] = 0$ → same abundance as the Sun
- $[X/H] > 0$ → X is enhanced
- $[X/H] < 0$ → X is depleted

Examples:

- $[Si/H] = +0.3$ → about 2 times more Si than the Sun
- $[Mg/H] = 0.0$ → solar magnesium abundance
- $[Fe/H] = -2.0$ → 100 times less Fe than the Sun

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2. [Fe/H] is a metallicity proxy

Use [Fe/H] when you need a compact description of the overall metal content of a star, using iron as a reference.

$$[Fe/H] = \log_{10}(N_{Fe}/N_H)_\star - \log_{10}(N_{Fe}/N_H)_\odot$$

[Fe/H]	Interpretation
+0.5	≈ 3× solar Fe
0.0	solar Fe
−1.0	10× less Fe
−2.0	100× less Fe

Caveat: [Fe/H] is not exactly the same as the total metal mass fraction Z.

[X/H] = abundance | [Fe/H] = metallicity proxy |

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Caveat: [Fe/H] is not exactly the same as the total metal mass fraction Z.

3. [X/Fe] reveals the chemical pattern

Use [X/Fe] when you want to study nucleosynthesis, enrichment history, and abundance ratios relative to iron.

$$[X/Fe] = [X/H] - [Fe/H]$$

- **Positive [X/Fe]** → element X is enhanced relative to iron
- **Negative [X/Fe]** → element X is depleted relative to iron
- Helps identify the origin of the material (e.g., supernovae type II vs Ia, AGB stars, etc.)

Examples:

- [α/Fe] → α-elements (O, Mg, Si, Ca, Ti)
- [Ba/Fe] → s-process enrichment
- [Eu/Fe] → r-process enrichment

[X/H] = abundance | [Fe/H] = metallicity proxy | [X/Fe] = relative abundance pattern

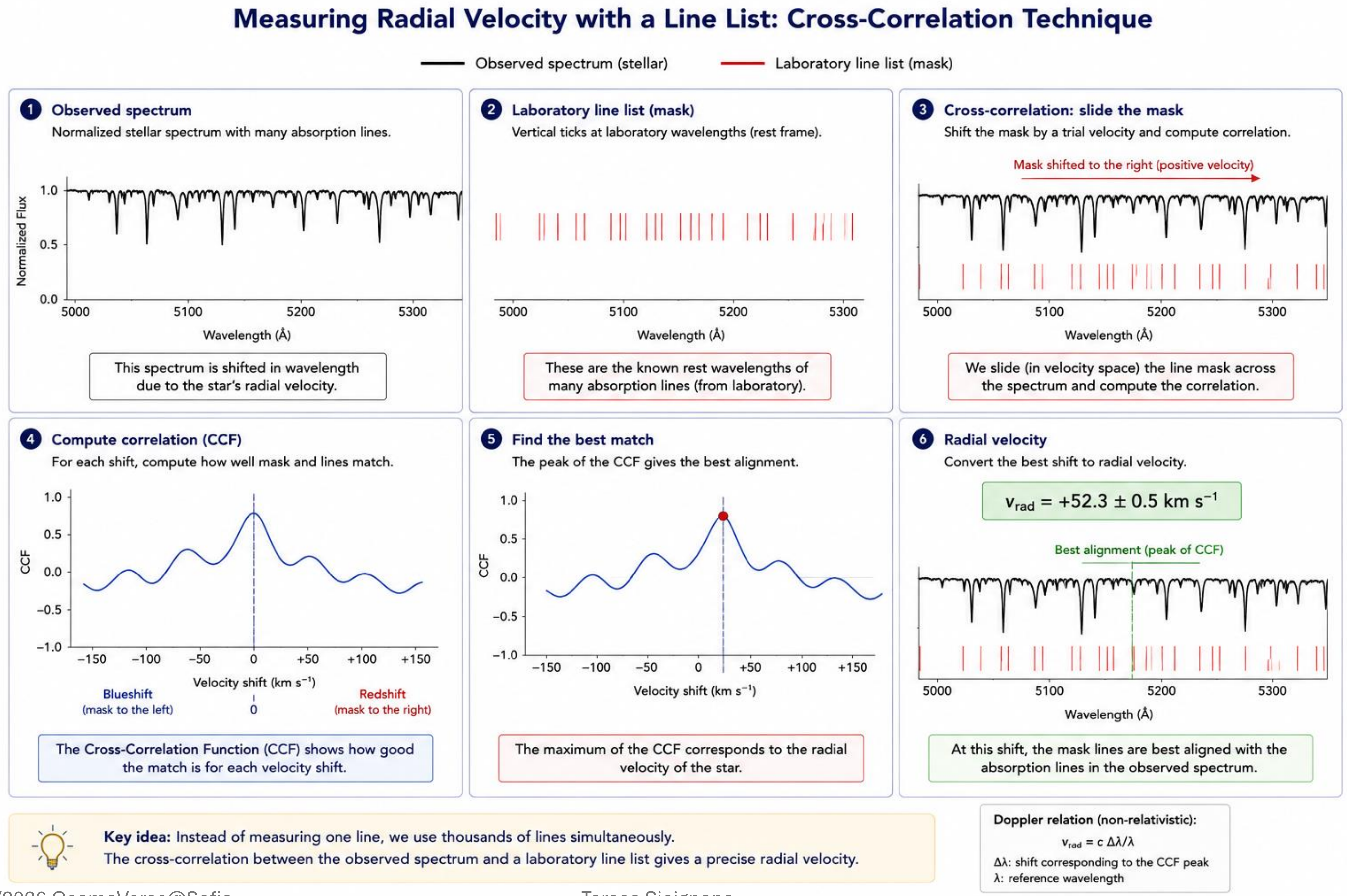
HOW TO DERIVE INFORMATION?

- NORMALIZATION OF THE SPECTRUM

HOW TO DERIVE INFORMATION?

- NORMALITATION OF THE SPECTRUM

- RADIAL VELOCITY CORRECTION

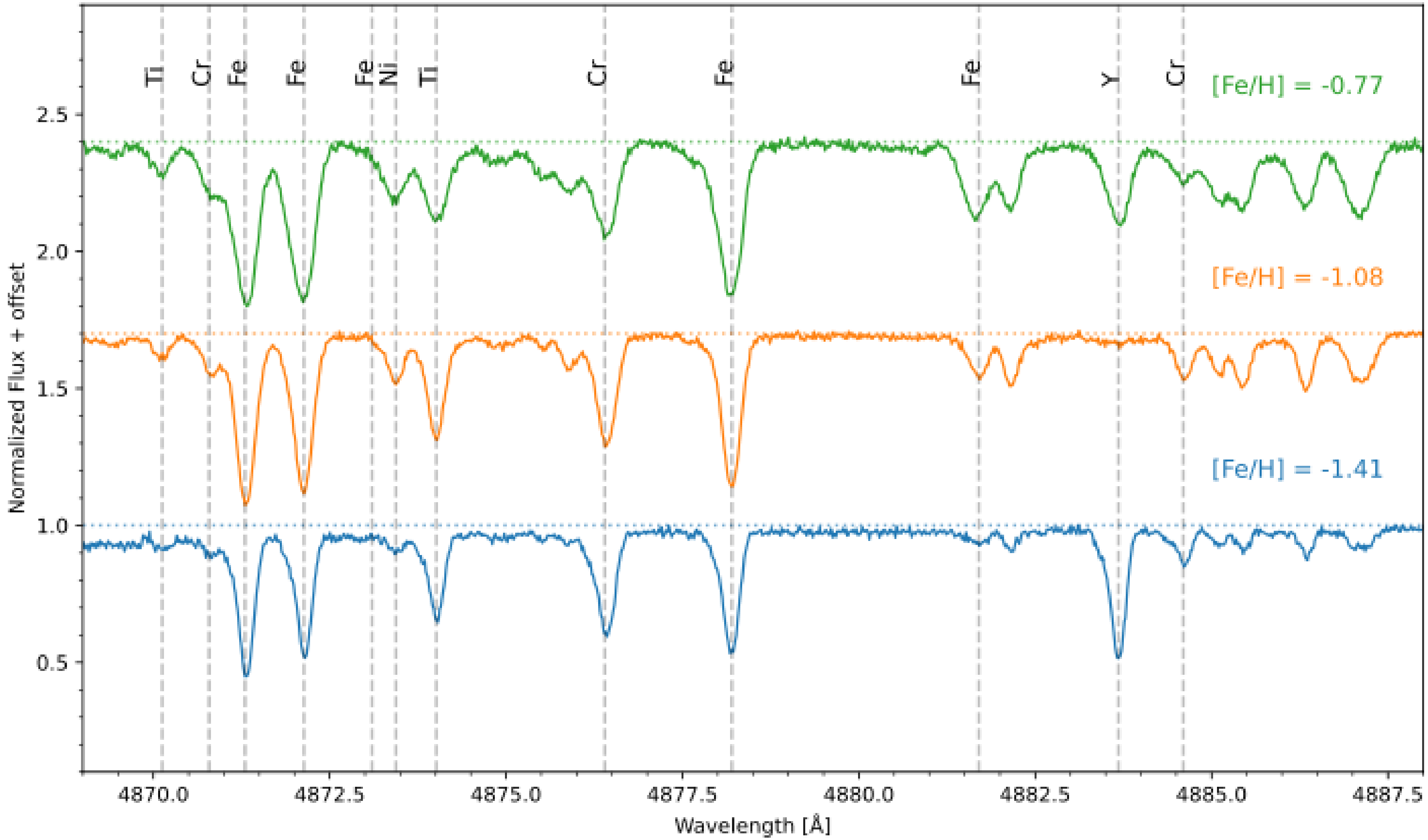

Measuring Radial Velocity with a Line List: Cross-Correlation Technique
Observed spectrum (stellar)
Laboratory line list (mask)
1 Observed spectrum
Normalized stellar spectrum with many absorption lines.
Normalized Flux
1.0
0.5
0.0
5000
5100
5200
5300
Wavelength (Å)
This spectrum is shifted in wavelength due to the star's radial velocity.
2 Laboratory line list (mask)
Vertical ticks at laboratory wavelengths (rest frame).
5000
5100
5200
5300
Wavelength (Å)
These are the known rest wavelengths of many absorption lines (from laboratory).
3 Cross-correlation: slide the mask
Shift the mask by a trial velocity and compute correlation.
Mask shifted to the right (positive velocity)
5000
5100
5200
5300
Wavelength (Å)
We slide (in velocity space) the line mask across the spectrum and compute the correlation.
4 Compute correlation (CCF)
For each shift, compute how well mask and lines match.
CCF
1.0
0.5
0.0
−0.5
−1.0
−150
−100
−50
0
+50
+100
+150
Velocity shift (km s⁻¹)
Blueshift
(mask to the left)
0
Redshift
(mask to the right)
The Cross-Correlation Function (CCF) shows how good the match is for each velocity shift.
5 Find the best match
The peak of the CCF gives the best alignment.
CCF
1.0
0.5
0.0
−0.5
−1.0
−150
−100
−50
0
+50
+100
+150
Velocity shift (km s⁻¹)
The maximum of the CCF corresponds to the radial velocity of the star.
6 Radial velocity
Convert the best shift to radial velocity.
$v_{rad} = +52.3 \pm 0.5$ km s^{-1}
Best alignment (peak of CCF)
5000
5100
5200
5300
Wavelength (Å)
At this shift, the mask lines are best aligned with the absorption lines in the observed spectrum.
Key idea: Instead of measuring one line, we use thousands of lines simultaneously.
The cross-correlation between the observed spectrum and a laboratory line list gives a precise radial velocity.
Doppler relation (non-relativistic):
$v_{rad} = c\,\Delta\lambda/\lambda$
Δλ: shift corresponding to the CCF peak
λ: reference wavelength

EXAMPLES OF UVES (VLT) SPECTRA

Red Mode Central Wlgt	580 nm
Red Slit Width	1
Red Readout Mode	225kHz,1x1,low

PI A. Bhardwaj

SNR>40@587nm



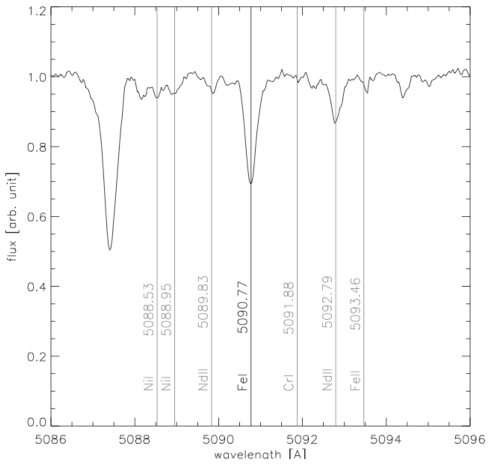
DIFFERENT TECNIQUES

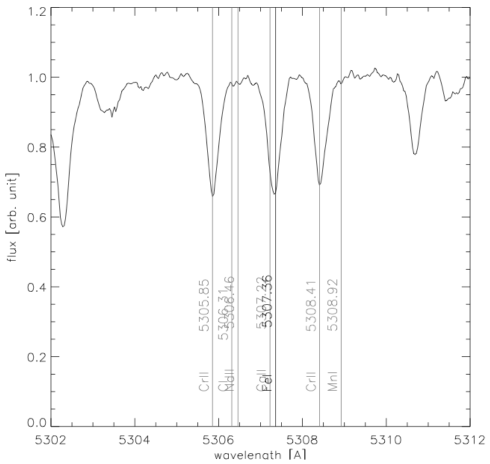
- Curve of growth
- Spectral synthesis
- Artificial Intelligence/ Neural Networks..

WHAT TO TAKE INTO ACCOUNT:

- Model atmospheres: LTE, NLTE, plane parallel, multi-dimensional geometry, …
  - Caveat: static models applied to dynamic Cepheid atmospheres
- Atomic physics: oscillator strength, excitation potential, damping constants
- Line list / spectral inclusion regions
- Continuum estimation
- Zero point: abundances usually expressed wrt solar value
- The details of the analysis
  - What/how to reject/keep, fitting techniques, ML training, …

☑ Clean line





✕ Blended line

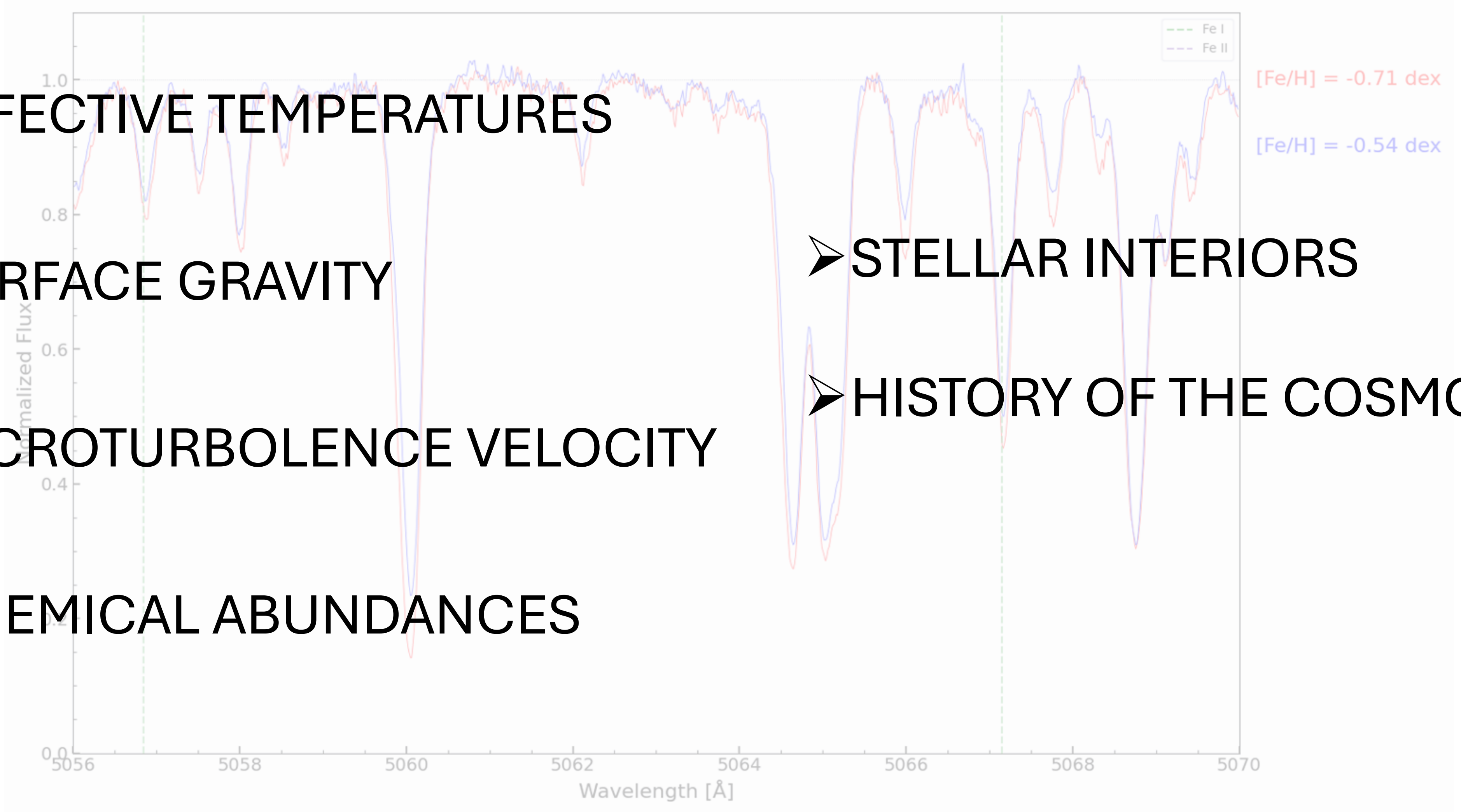
Courtesy of M. Romaniello

INFORMATIONS FROM A SPECTRUM

- EFFECTIVE TEMPERATURES
- SURFACE GRAVITY
- MICROTURBOLENCE VELOCITY
- CHEMICAL ABUNDANCES

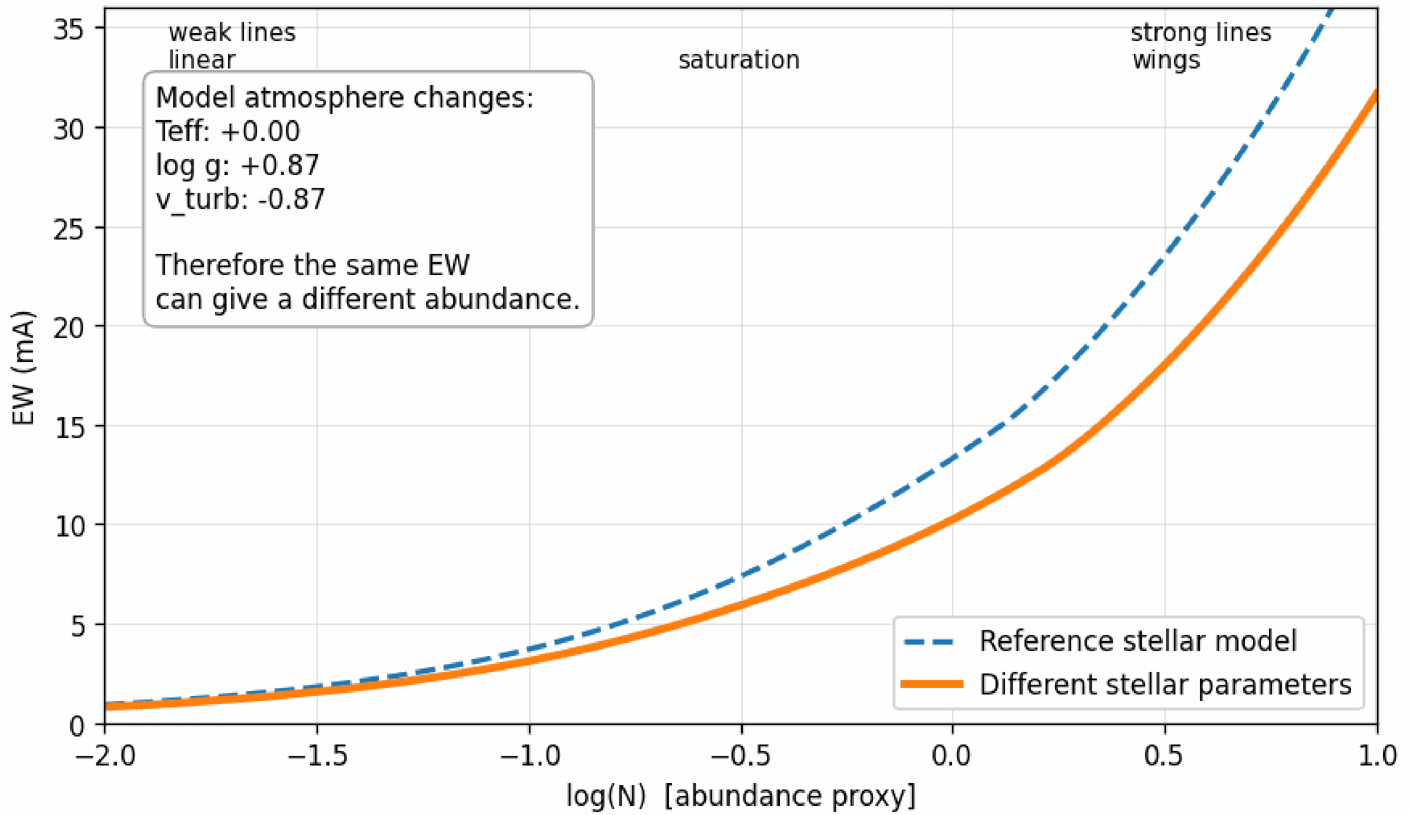
➢ STELLAR INTERIORS

➢ HISTORY OF THE COSMOS



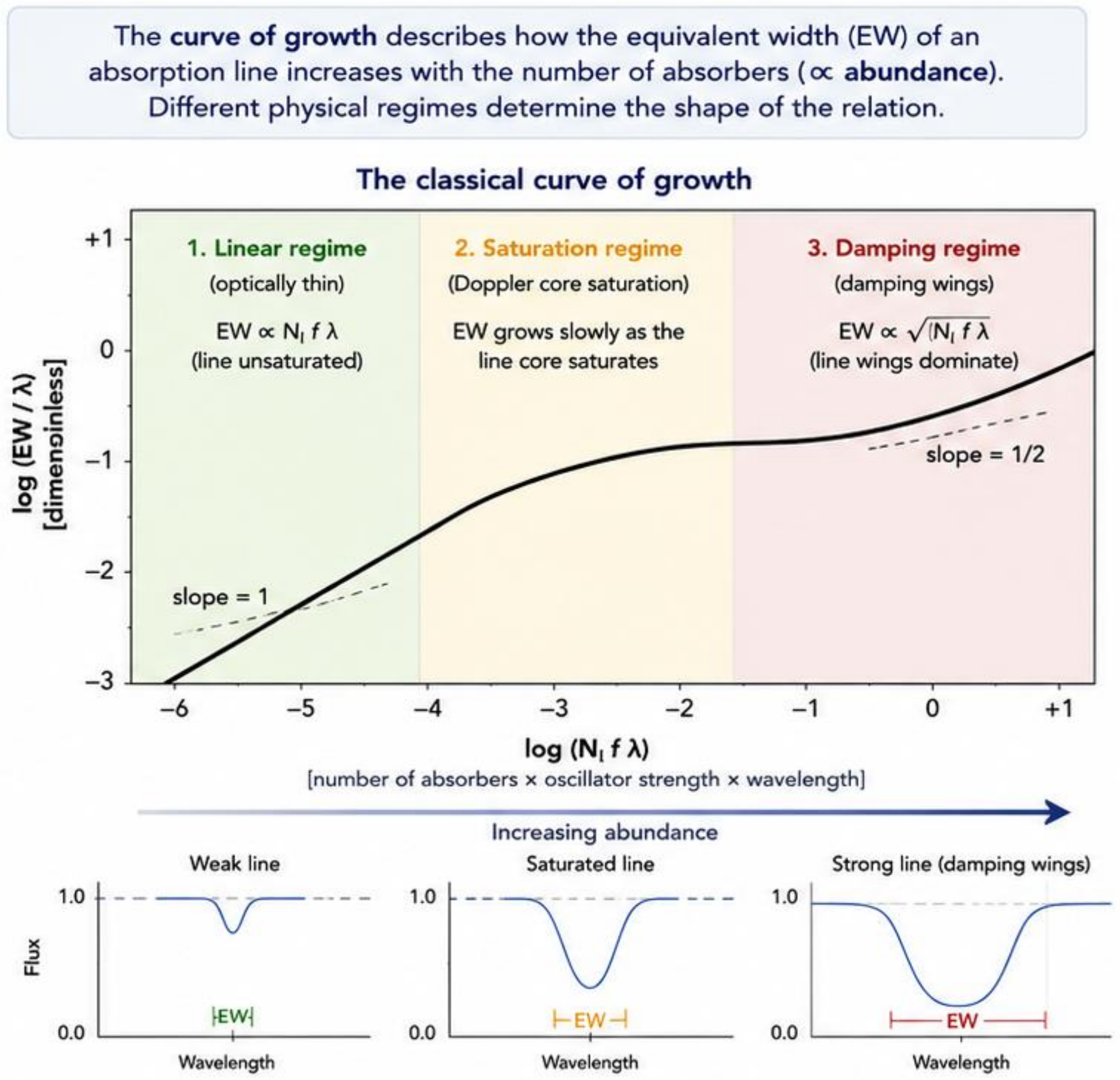
THE CURVE OF GROWTH METHOD

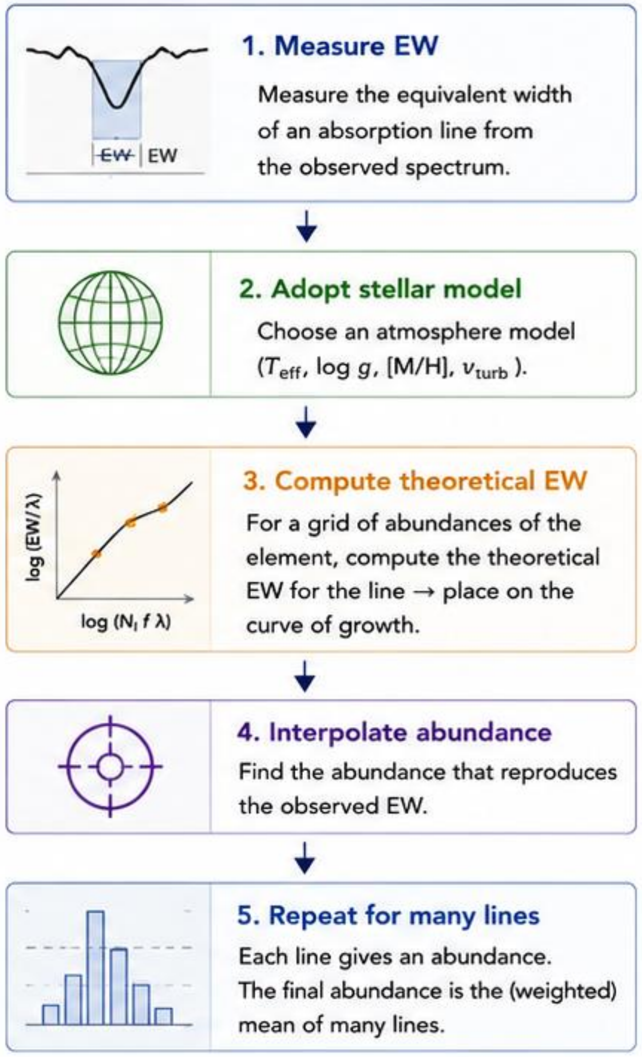
- Solving the radiative transfer in stellar atmospheres yields a relation between the Equivalent Width of a line of an element and its abundance: that's the Curve of Growth



- The physics of the particular transition: oscillator strength, excitation potential, damping constants
- The stellar parameters: T_{eff}, log(g), v_{turb}

THE CURVE OF GROWTH METHOD





THE CURVE OF GROWTH METHOD

- **T_{eff}** by excitation equilibrium: no residual correlation between the iron abundance and the excitation potential of neutral iron lines

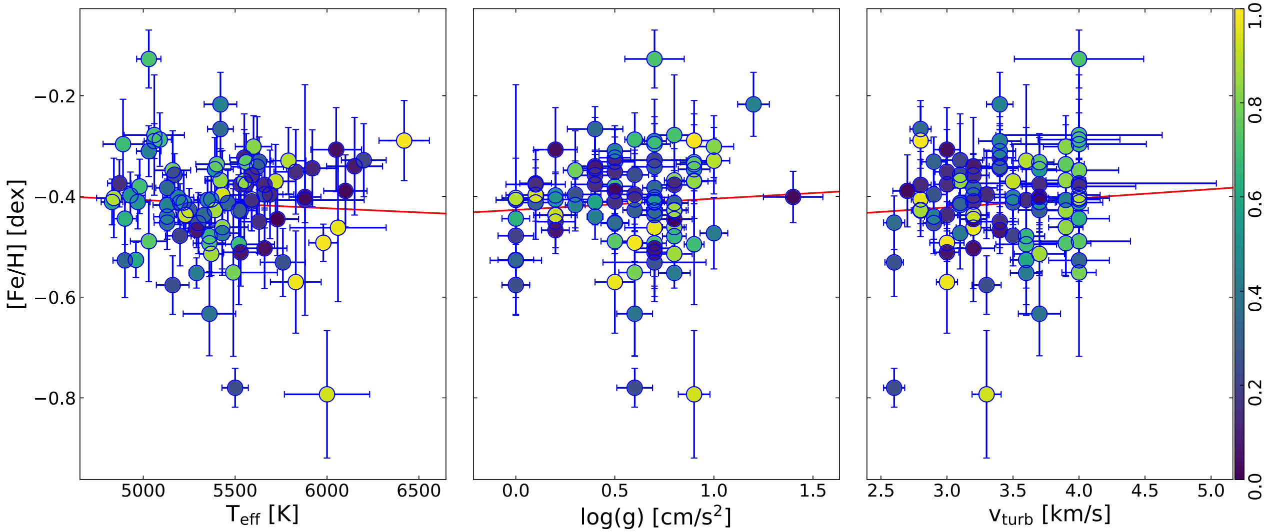
- **Surface gravity** by ionization equilibrium: same abundance within the uncertainties FeI and FeII

- **Microturbulent velocity:** no residual correlation between the iron abundance and EW

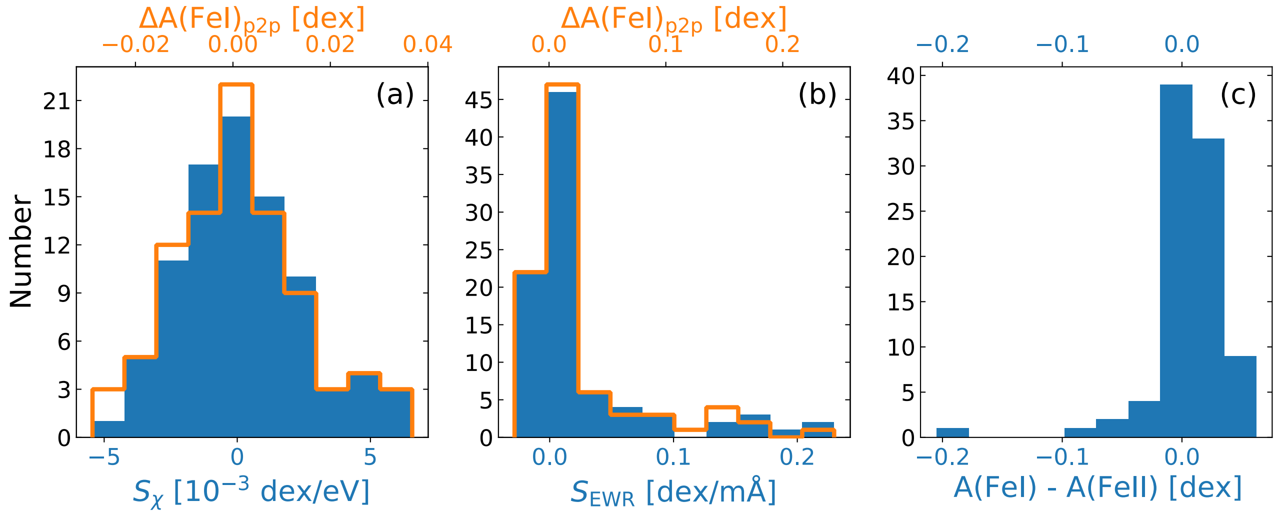
- **Iron abundance** is the mean of the ones from the individual lines in the convergence iteration

THE CURVE OF GROWTH METHOD

Method consistency checks



☑ No dependence of the abundance on the parameters



☑ T_{eff}

☑ v_{turb}

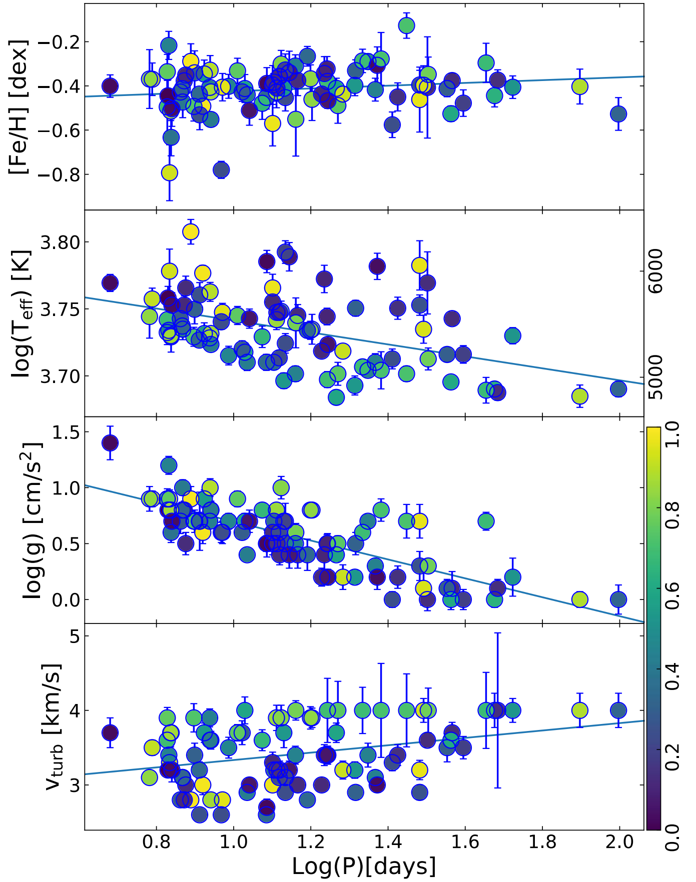
☑ log(g)

Courtesy of M. Romaniello

THE CURVE OF GROWTH METHOD

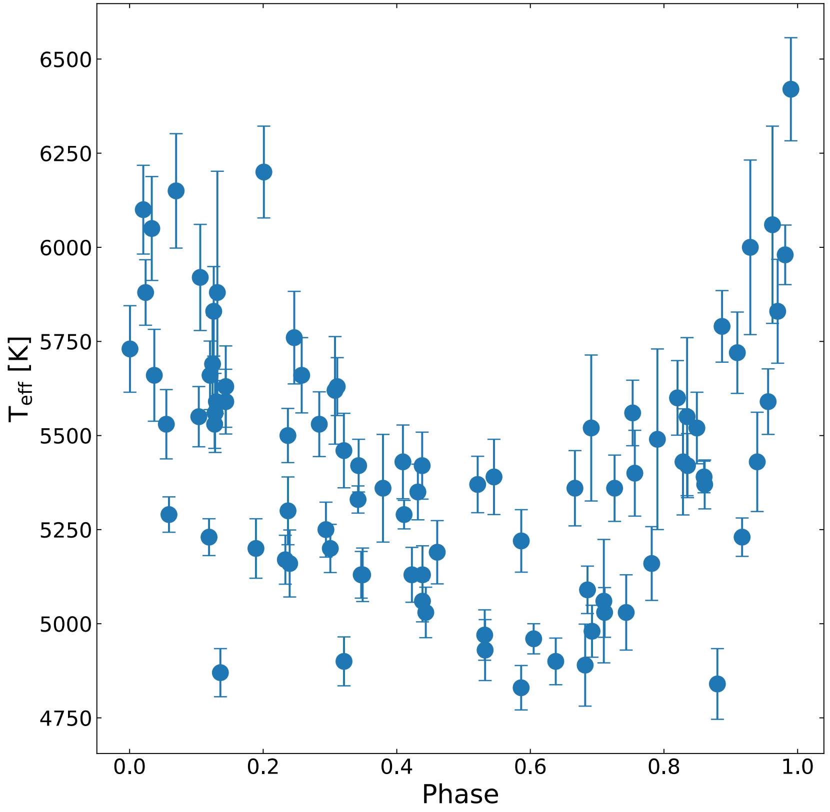
Cepheid-specific consistency checks

✓ Iron independent of period



✓ Parameters depend on period

✓ The temperature follows the phase



Courtesy of M. Romaniello

THE SPECTRAL SYNTHESIS

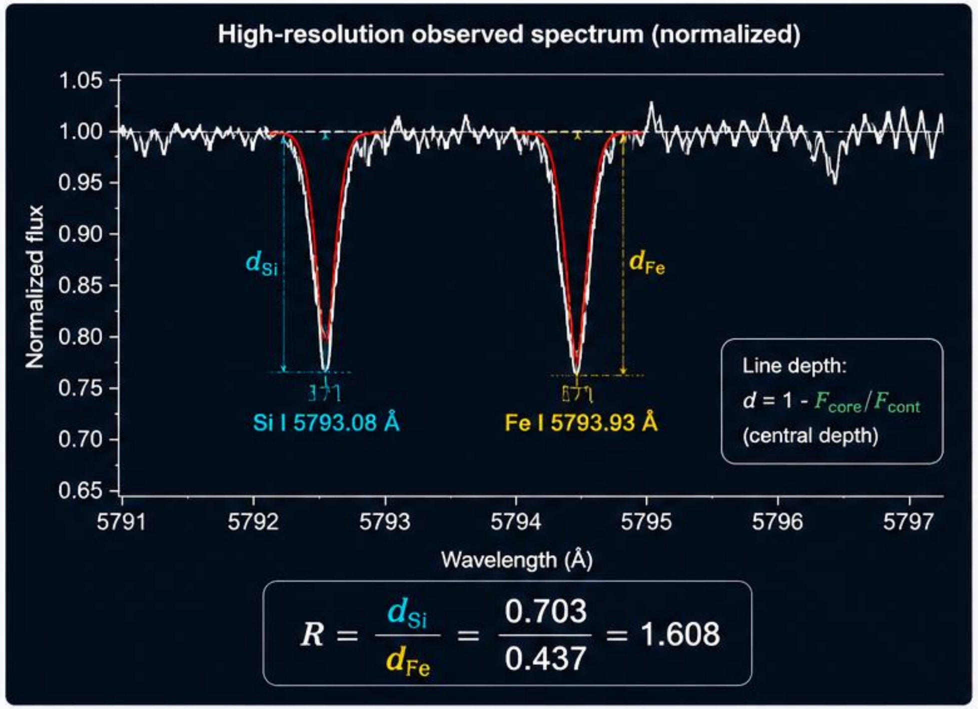
The curve of growth is still implicitly present in spectral synthesis, but the full spectral profile is modeled instead of only the equivalent width.

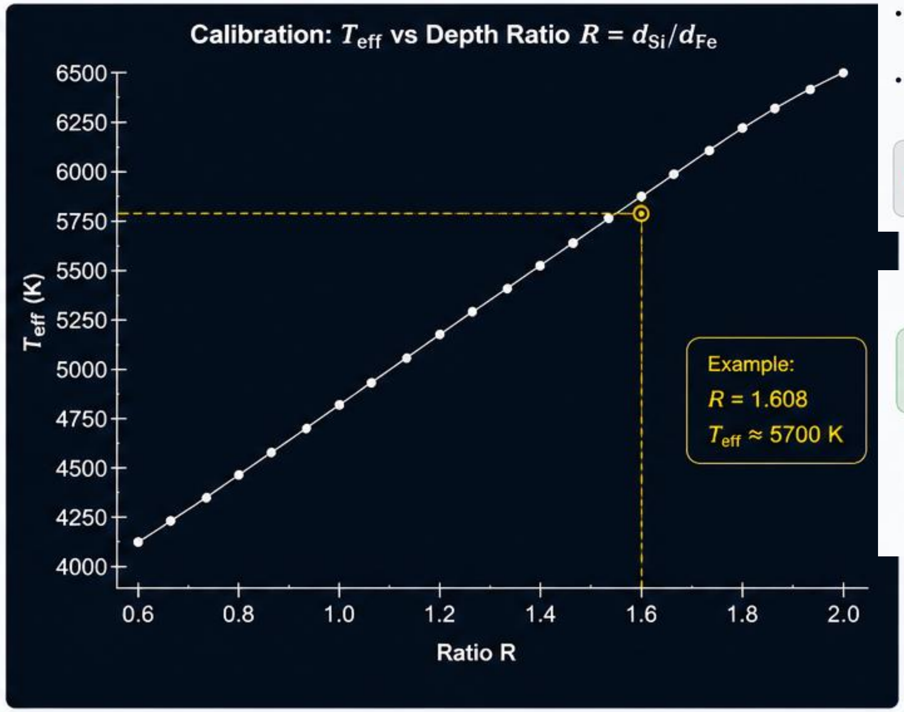
- Synthetic spectrum ,T_{eff} , microturbulence, log g, V_{broad}

  → chemical abundances

THE SPECTRAL SYNTHESIS

- T_{eff} from Line Deep Ratio method (Kovtyukh + 2006)





Physical meaning

- Fe I 5793.93 Å is a temperature-sensitive line: its depth decreases as T_{eff} increases.
- Si I 5793.08 Å is nearly temperature-independent: it serves as an internal reference.

➡ The ratio R increases monotonically with T_{eff}, making it a robust temperature indicator.

Calibration function

- $T_{eff} = c_1 + c_2 R + c_3 R^2 + c_4 R^3$

Coefficients c_1–c_4 are determined from a large sample of stars with known T_{eff} (from interferometry or the InfraRed Flux Method).

Why this method works

- Using a ratio cancels out many systematic effects (e.g., continuum placement, reddening).
- Lines are close in wavelength → minimizes differential effects.
- Applicable to FGK stars (~4000–6500 K).

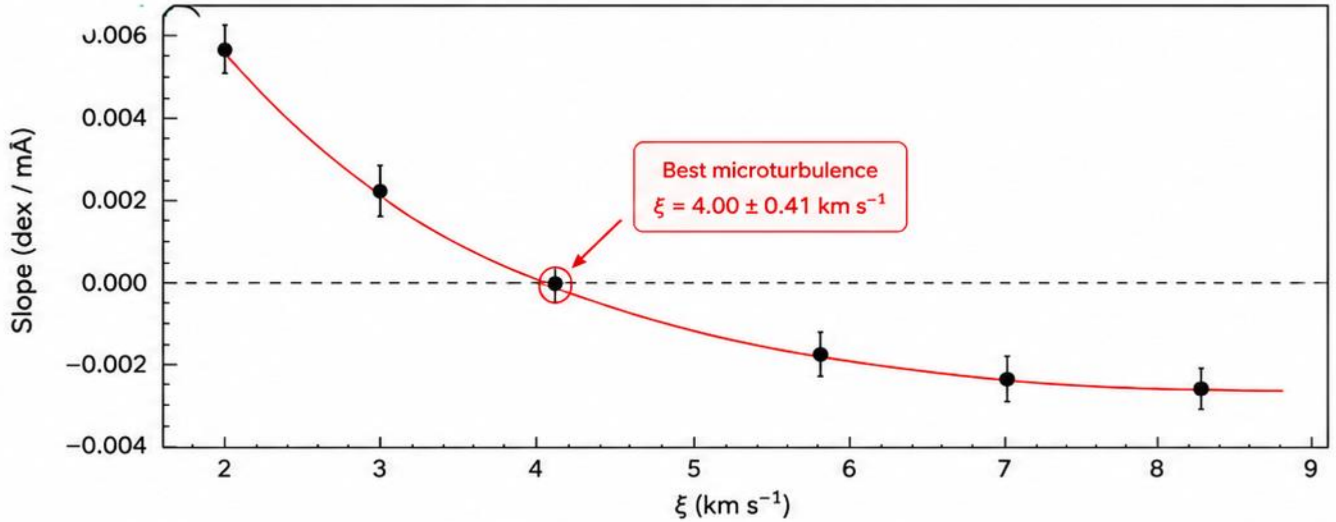
THE SPECTRAL SYNTHESIS

Microturbulence (ξ) from Fe I lines

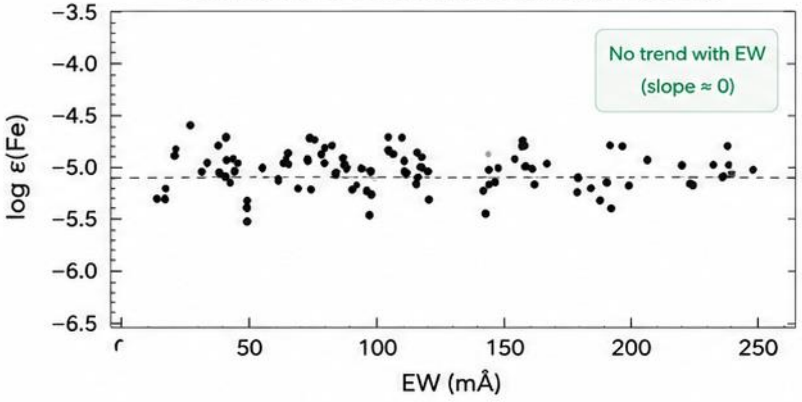
Adjust the microturbulent velocity (ξ) until the iron abundances show no trend with line strength (equivalent width, EW).

1. Measure EW of many unblended Fe I lines
2. Derive Fe abundance for a grid of ξ values (log *g* fixed)
3. Plot abundance vs. EW for each ξ
4. Best ξ gives zero slope (no trend with EW)

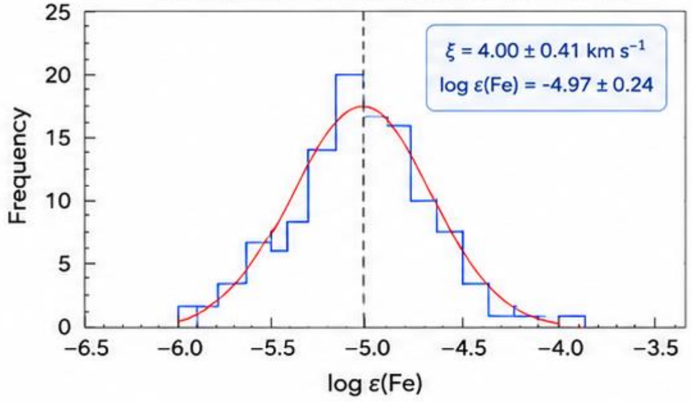
Slope of log ε(Fe) vs. Equivalent Width as a function of ξ



Fe abundance vs. Equivalent Width (for best ξ)



Histogram of Fe abundances (for best ξ)



Key idea

The correct microturbulence removes any dependence of abundance on line strength.

Assumption

Fe I lines are assumed to be largely insensitive to log *g* in this step.

→ **Takeaway:** Choose ξ such that the slope of log ε(Fe) vs. EW is zero. This yields the most reliable iron abundance.

THE SPECTRAL SYNTHESIS

Deriving surface gravity from Fe II lines

Adjust the surface gravity until the iron abundances show no trend with equivalent width (EW).

1. Select Fe II lines

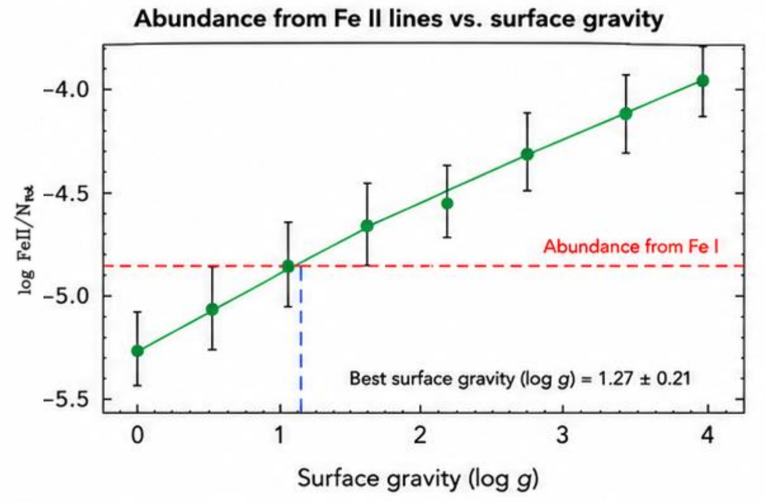
Choose a list of clean, unblended Fe II lines.

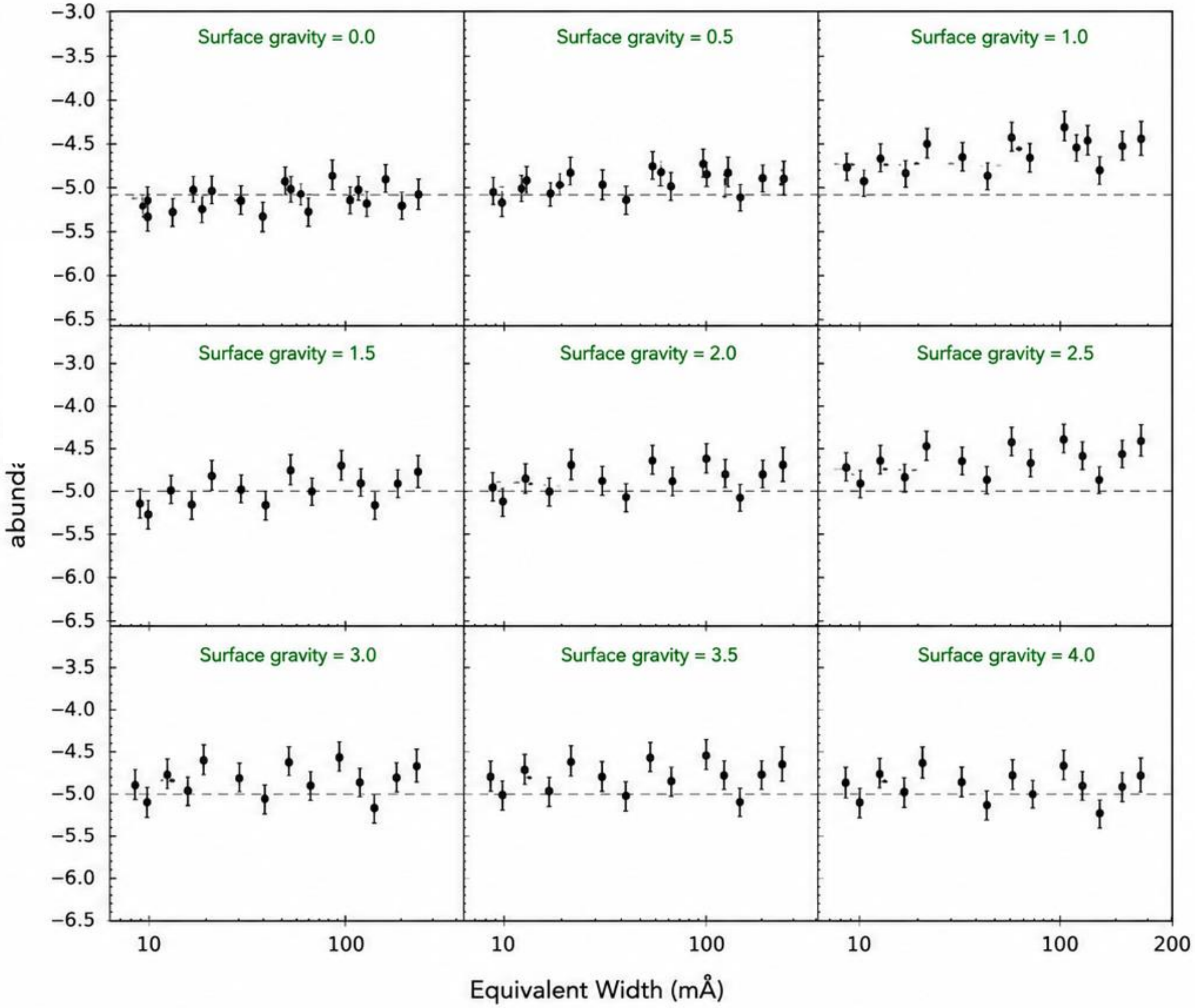
2. Measure the EW

Measure the equivalent width of each line.

3. Derive abundances for different surface gravity

Derive the iron abundance from each line for a grid of surface gravity values.

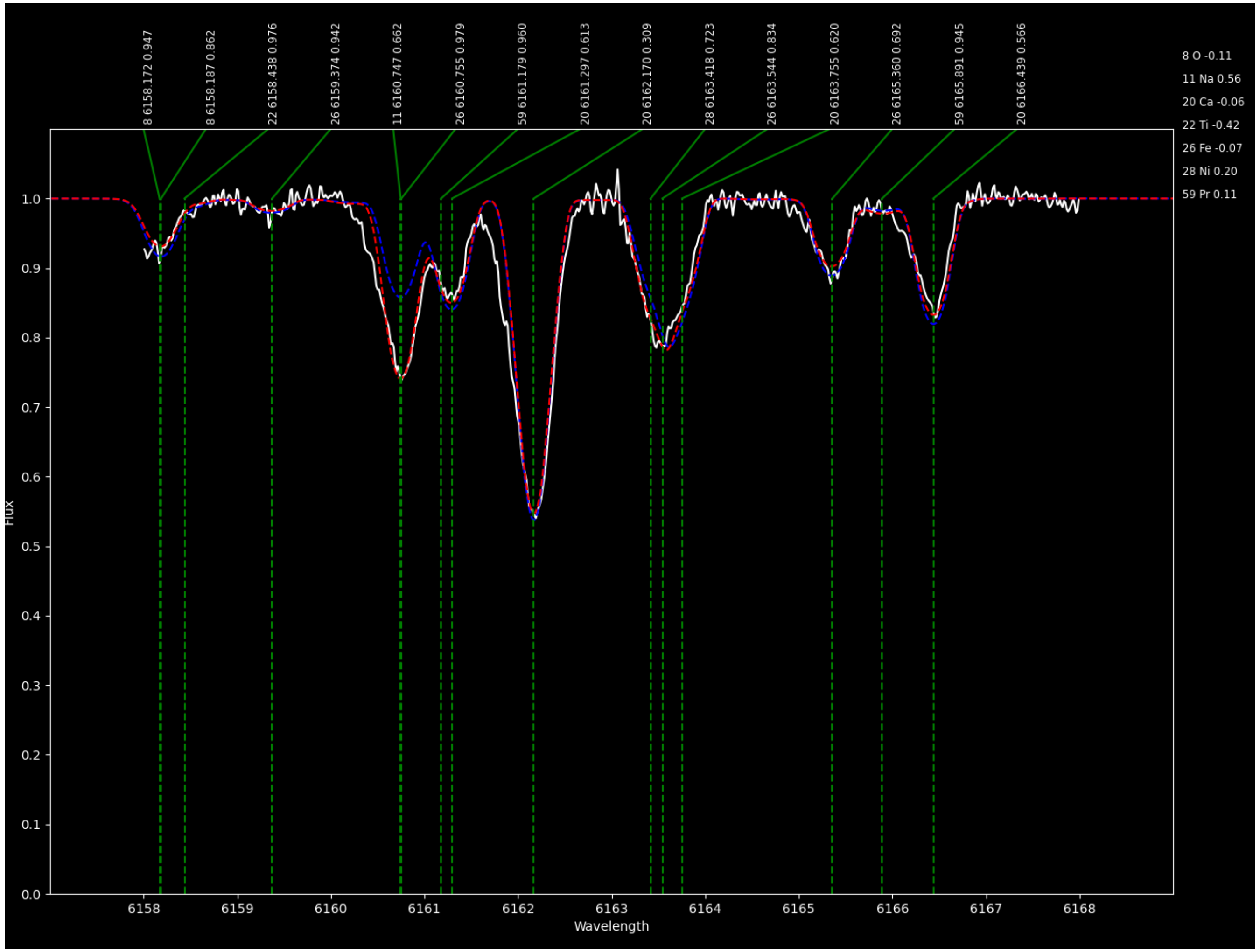




THE SPECTRAL SYNTHESIS

Chemical pattern through spectral synthesis

1. Compare the observed spectrum with synthetic spectra
2. Adjust elemental abundances until the line profiles match*

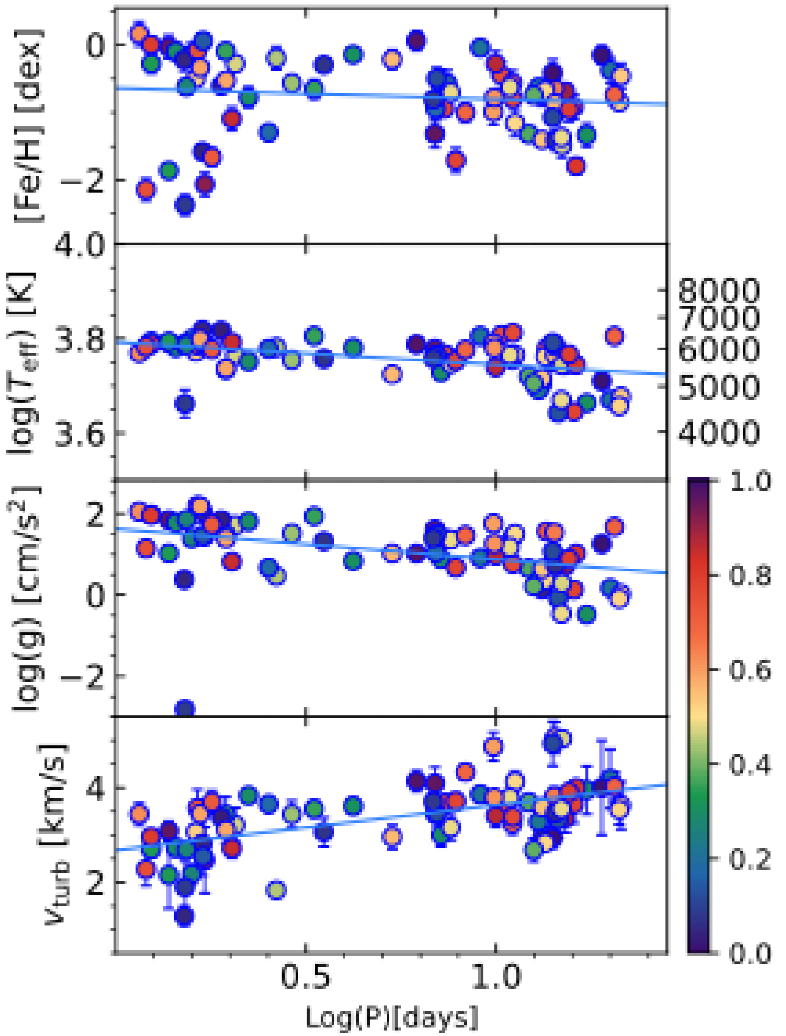


THE SPECTRAL SYNTHESIS

- Type II Cepheid-specific consistency checks

☑ Iron independent of period

☑ Parameters depend on period

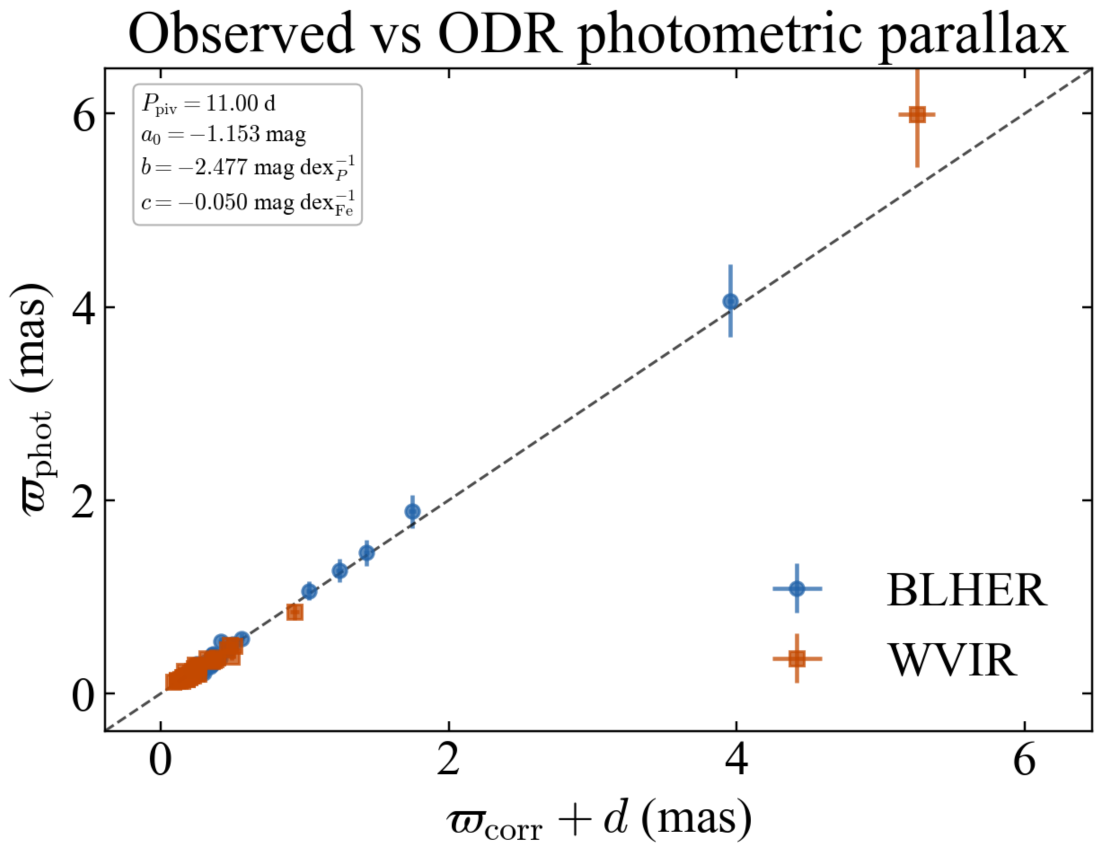


PRELIMINARY RESULTS ON TYPE II CEPHEIDS

$$\varpi_{phot} = 10^{-0.2(w-W-10)}$$

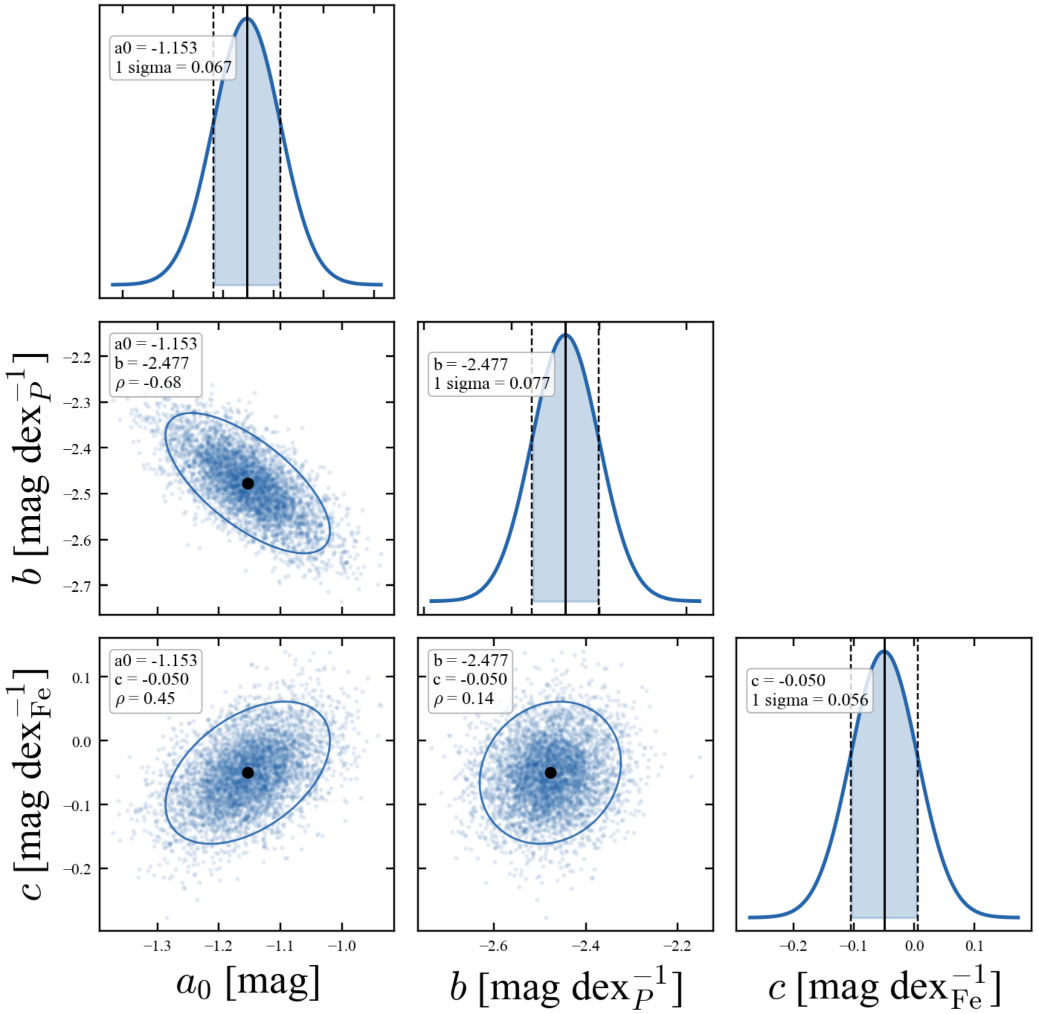
$$W = a + b \cdot \log P + c \cdot [Fe/H]$$

$$\chi = \sum \frac{\left((\varpi_{DR3} + d) - \varpi_{phot}\right)^2}{\sigma^2}$$



PRELIMINARY RESULTS ON TYPE II CEPHEIDS

γ= -0.050 $\pm$ 0.056 mag/dex



TAKE HOME MESSAGES

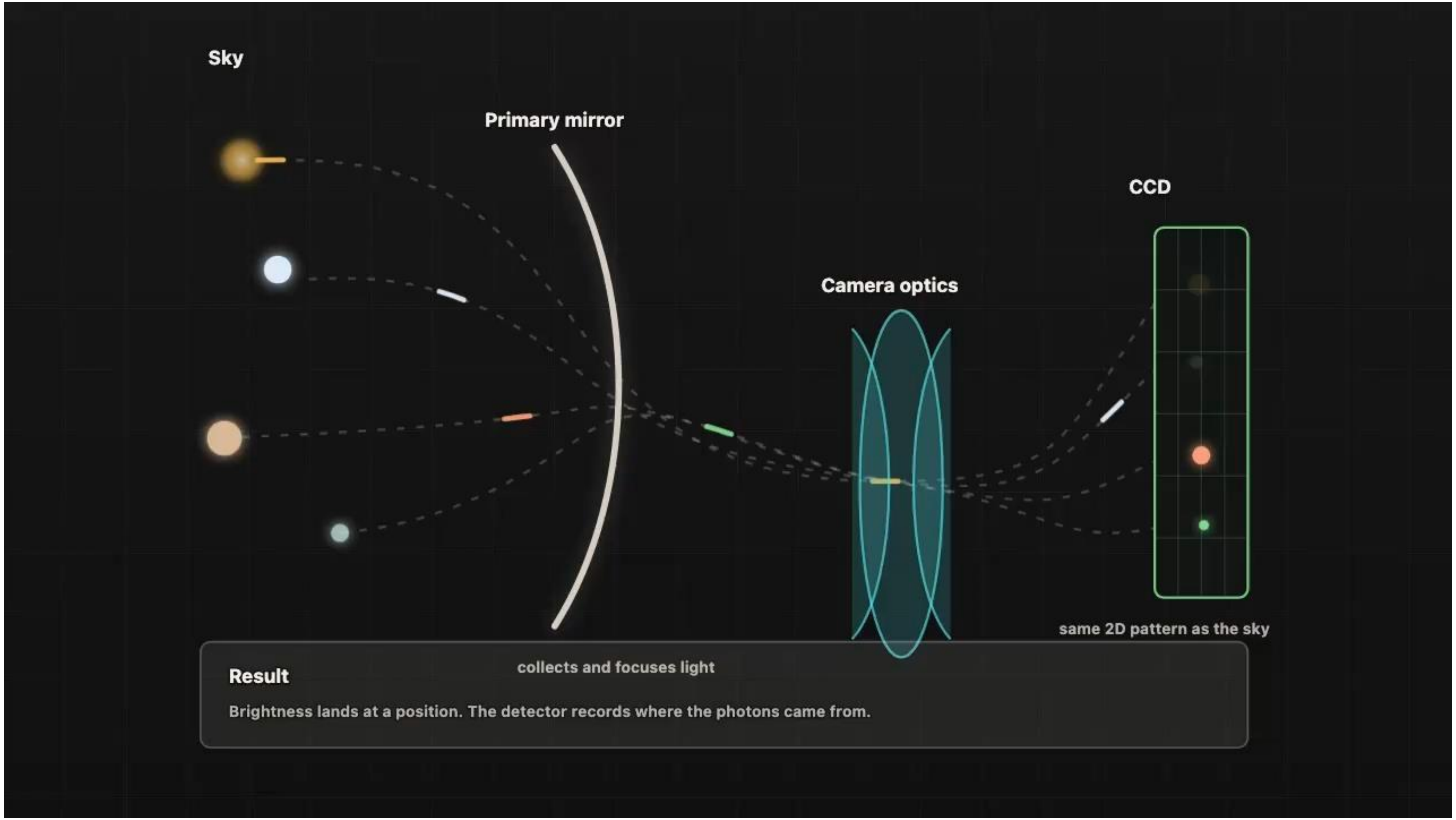
- Spectra contain information about the stellar atmospheric composition.
- Every choice made during the analysis process can introduce systematic effects.
- The curve of growth links stellar parameters to the EW.
- Spectral synthesis fits the entire line profile.
- A good standard candle should be affected by as few systematics as possible.

Thank you for your attention!

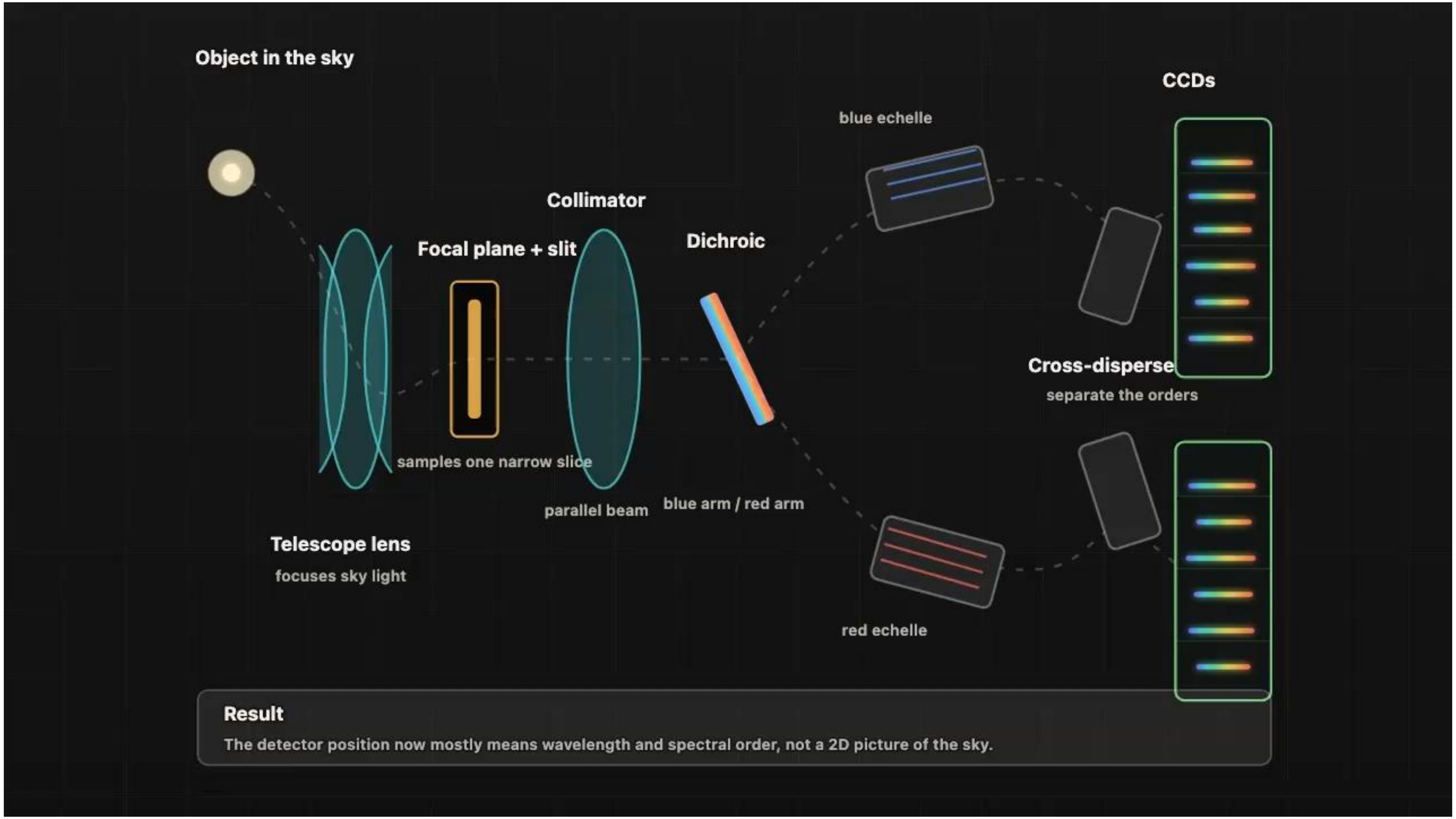
teresa.sicignano@inaf.it

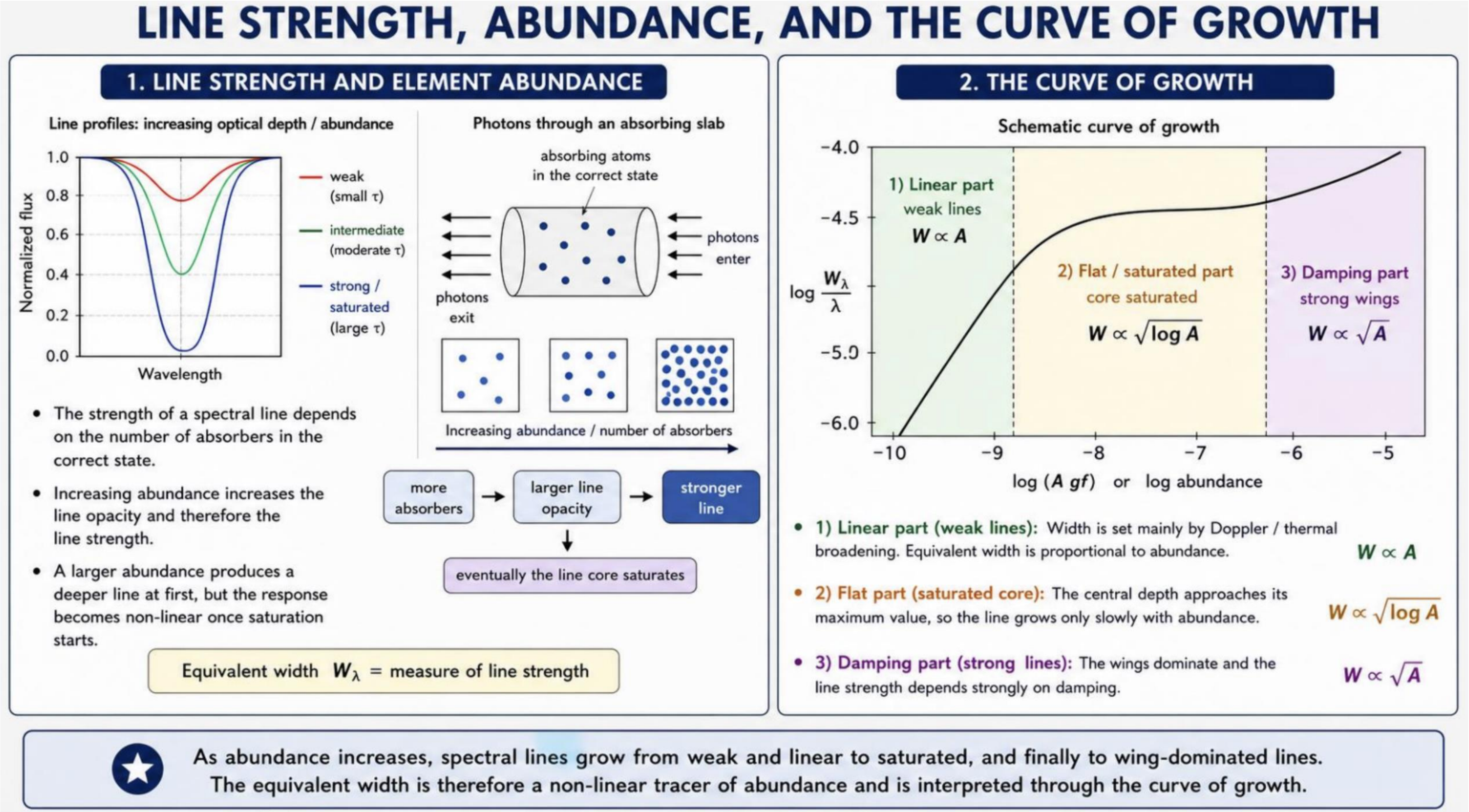
BACKUP SLIDES

SPECTRUM VS IMAGE



SPECTRUM VS IMAGE

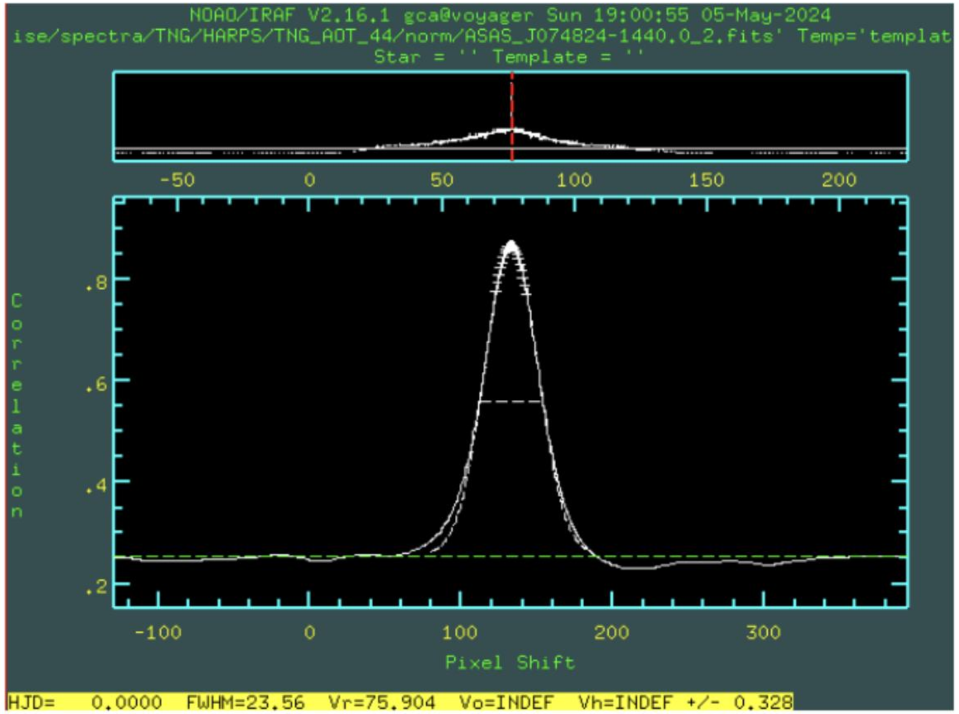



LINE STRENGTH, ABUNDANCE, AND THE CURVE OF GROWTH
1. LINE STRENGTH AND ELEMENT ABUNDANCE
Line profiles: increasing optical depth / abundance
Normalized flux
1.0
0.8
0.6
0.4
0.2
0.0
Wavelength
weak (small τ)
intermediate (moderate τ)
strong / saturated (large τ)
Photons through an absorbing slab
absorbing atoms in the correct state
photons enter
photons exit
Increasing abundance / number of absorbers
more absorbers
larger line opacity
stronger line
eventually the line core saturates
• The strength of a spectral line depends on the number of absorbers in the correct state.
• Increasing abundance increases the line opacity and therefore the line strength.
• A larger abundance produces a deeper line at first, but the response becomes non-linear once saturation starts.
Equivalent width W_λ = measure of line strength
2. THE CURVE OF GROWTH
Schematic curve of growth
$\log \frac{W_\lambda}{\lambda}$
-4.0
-4.5
-5.0
-6.0
-10
-9
-8
-7
-6
-5
log (A gf) or log abundance
1) Linear part
weak lines
$W \propto A$
2) Flat / saturated part
core saturated
$W \propto \sqrt{\log A}$
3) Damping part
strong wings
$W \propto \sqrt{A}$
• 1) Linear part (weak lines): Width is set mainly by Doppler / thermal broadening. Equivalent width is proportional to abundance. $W \propto A$
• 2) Flat part (saturated core): The central depth approaches its maximum value, so the line grows only slowly with abundance. $W \propto \sqrt{\log A}$
• 3) Damping part (strong lines): The wings dominate and the line strength depends strongly on damping. $W \propto \sqrt{A}$
As abundance increases, spectral lines grow from weak and linear to saturated, and finally to wing-dominated lines.
The equivalent width is therefore a non-linear tracer of abundance and is interpreted through the curve of growth.

Radial velocity from cross correlation function

The radial velocity is obtained from the position of the maximum of the cross-correlation function. The peak marks the velocity shift that gives the best match between the observed spectrum and the template. A fit to the peak allows a more precise estimate of the Doppler shift and its uncertainty.

$$CCF(v) = \Sigma_i F_{obs}(\lambda_i) F_{templ}\left(\lambda_i (1 + v/c)\right)$$



The cross-correlation function reaches its maximum when the template best matches the observed spectrum.