spectroscopy of stars and stellar populations: from spectra to chemical abundances

Livia Origlia - INAF - Bologna, Italy

International PhD School "F. Lucchin" - XIV Cycle II Course

Science and Technology with E-ELT

Erice, Sicily, 8-20 October 2015

School Directors:
G. Bono (Univ. of Rome Tor Vergata)
I. Hook (Lancaster University)
S. Ramsay (European Southern Observatory)

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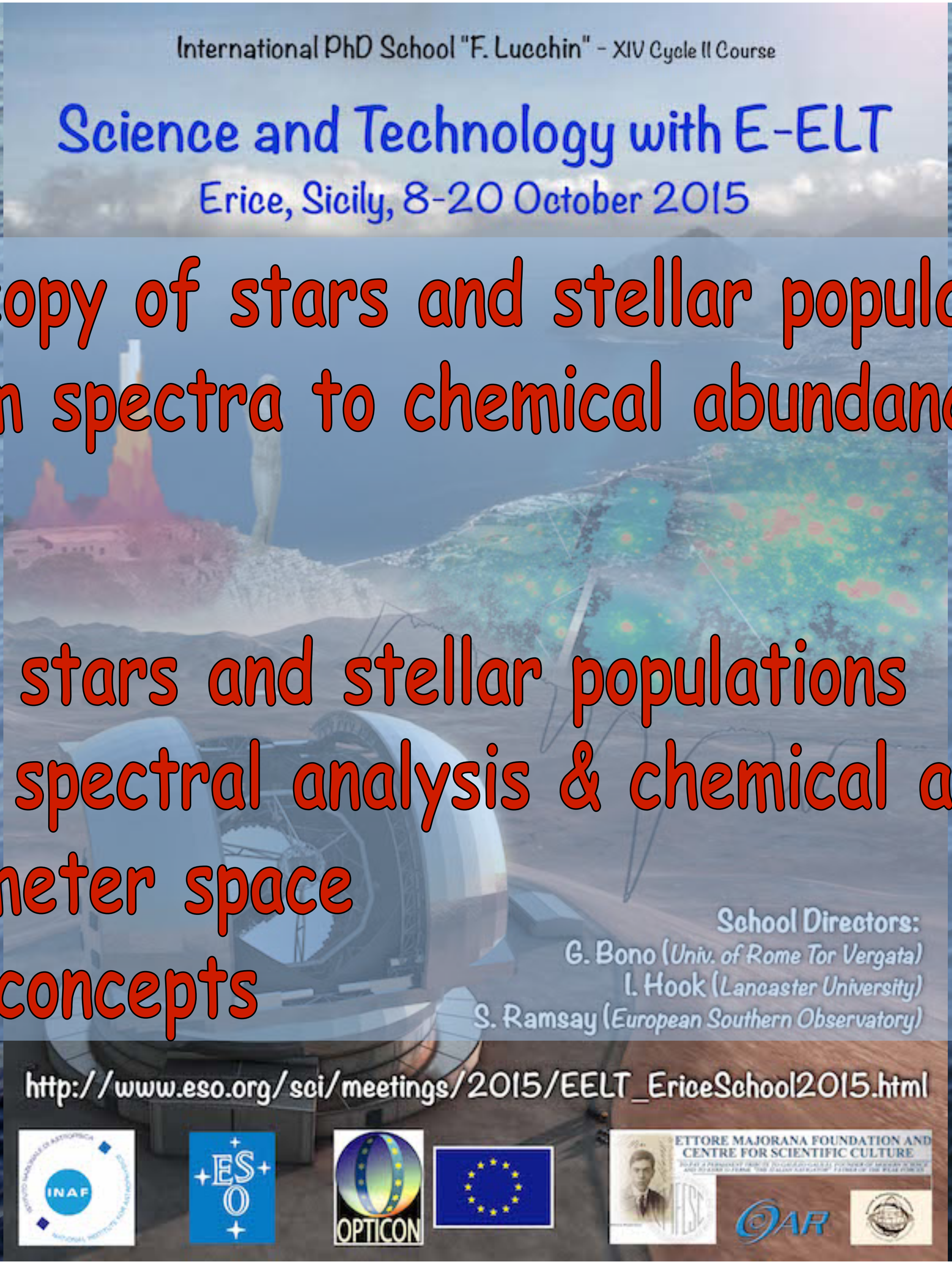

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spectroscopy of stars and stellar populations: from spectra to chemical abundances

Outline

- observing stars and stellar populations
- basics of spectral analysis & chemical abundances
- the parameter space
- modeling concepts

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observing stars and stellar populations

basic question: why ?

basic constituent of complex stellar systems as galaxies

observations needed to

- characterize their structural, chemical, evolutionary and environmental properties
- constrain input parameters & physics of stellar evolution, chemical and dynamical models

stars: point sources when resolved → individually observable

stars: diffuse stellar background when unresolved → observable in integrated light

observing stars and stellar populations

basic question: where in the e.m spectrum ?

a multi-wavelength approach very effective

- each star/sequence in the most suitable range

  blue/hot in the **UV-optical**, **red/cool** in the **infrared**

- each environment in the most suitable range

  metal poor, **low reddening** (e.g. halos) in the **UV-optical**

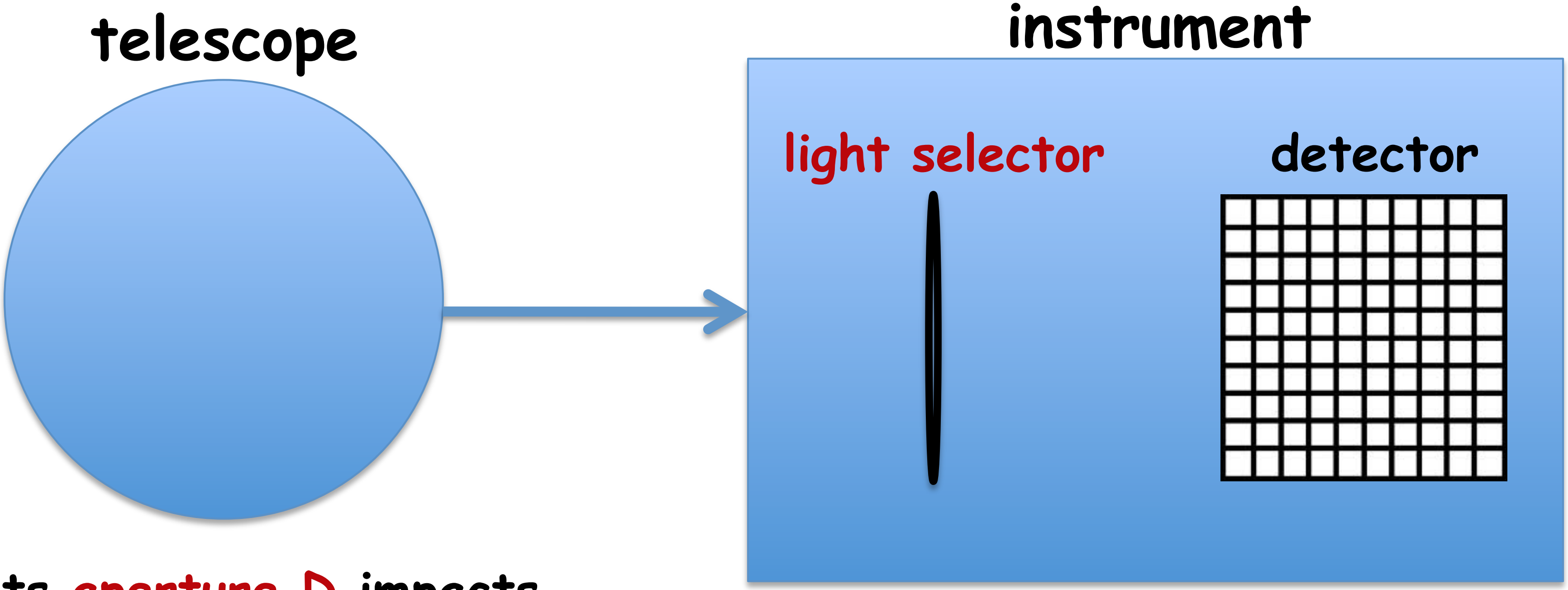
  metal rich, **high reddening** (e.g bulges) in the **infrared**

a larger **baseline/spectral coverage** →
more accurate stellar & population parameters
temperature, gravity, metallicity, mass, age, IMF, reddening etc.
nebular *vs* stellar contributions, mass loss, SF rates etc.

observing stars and stellar populations

basic question: how ?

telescopes & instruments: complex opto-mechanical systems with finite sizes and limited efficiencies



telescope

instrument

light selector

detector

its aperture D impacts

sensitivity ($\sim D^2$)

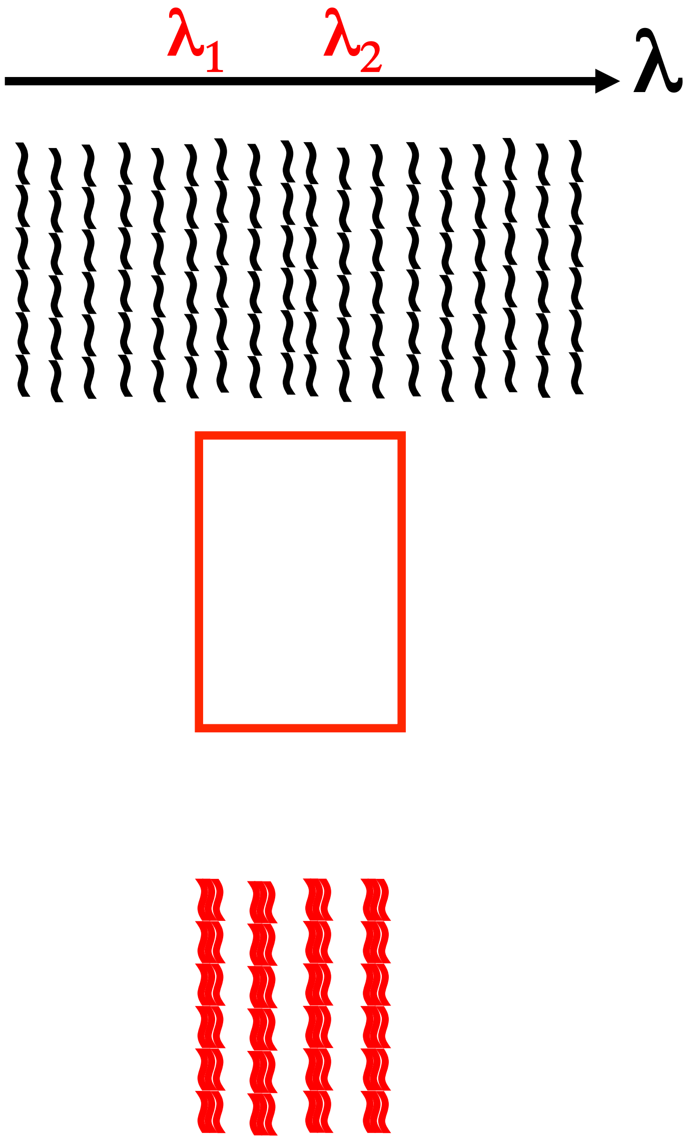
spatial resolution ($\sim 1/D$)

filter ➔ imager

disperser (prism, grating etc.) ➔ spectrograph

observing stars and stellar populations

basic question: how ?



light selector

imaging *vs* spectroscopy

filter ➔ transmits integrated light between λ_1 and λ_2

$$F(\lambda) = \int_{\lambda_1}^{\lambda_2} \Phi(\lambda) \times \Delta\lambda$$

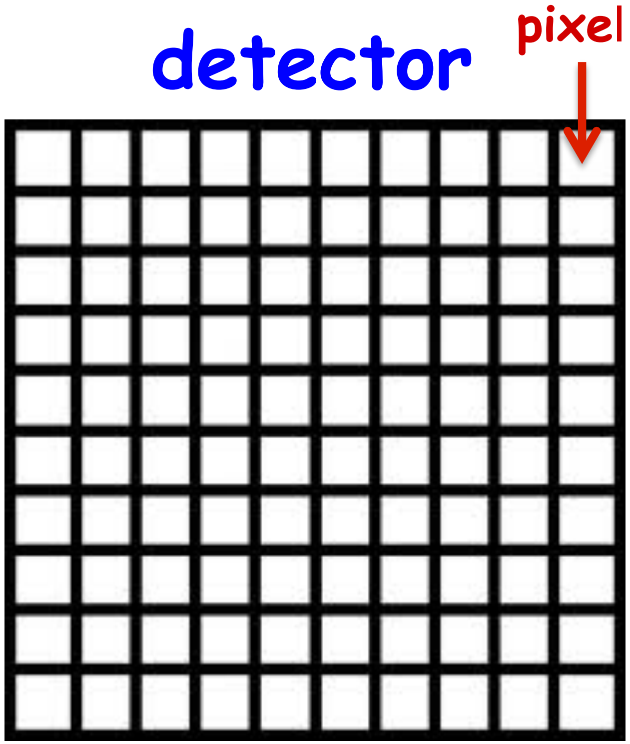
$\Phi(\lambda)$ = filter profile

disperser ➔ decomposes light between λ_1 and λ_2 in steps of $\Delta\lambda$

observing stars and stellar populations

basic question: how ?

observations are recorded on digital array detectors with a finite number of discrete elements (pixels)



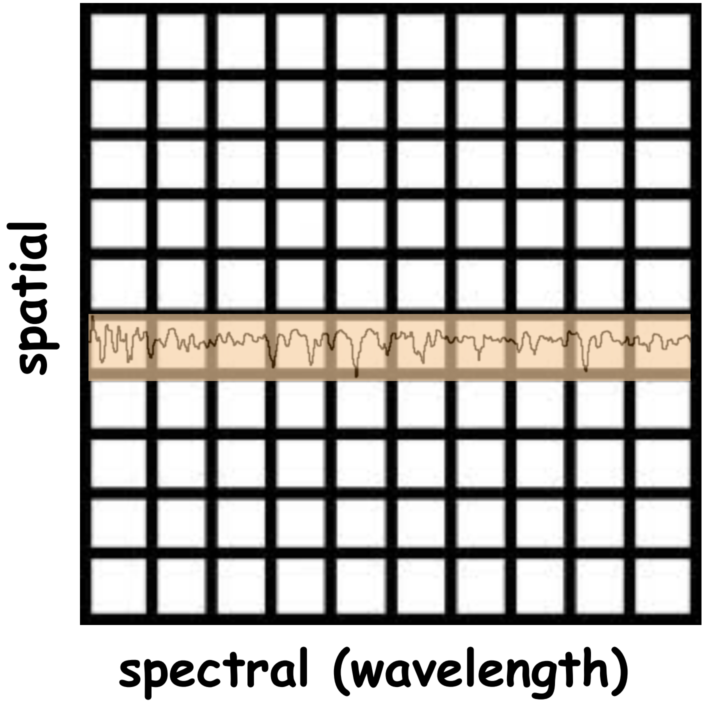
the current generation of UV-optical (CCDs) & IR (CMOS) detectors have
2-4,000 x 2-4,000 pixels

pixel physical size: 15-18 micron

observing stars and stellar populations

observing technique: spectroscopy

1D spatial sampling, resolved spectral information

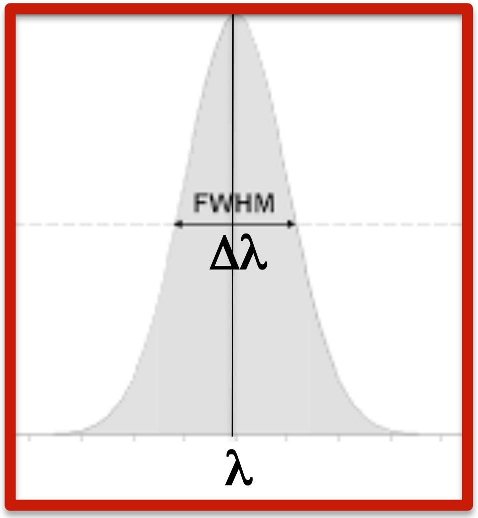


parameters

- spectral resolution
- spectral coverage
- configuration
  - long slit
  - multi-object
  - integral field
  - cross-dispersed

observing stars and stellar populations

spectral resolution ➔ instrumental profile



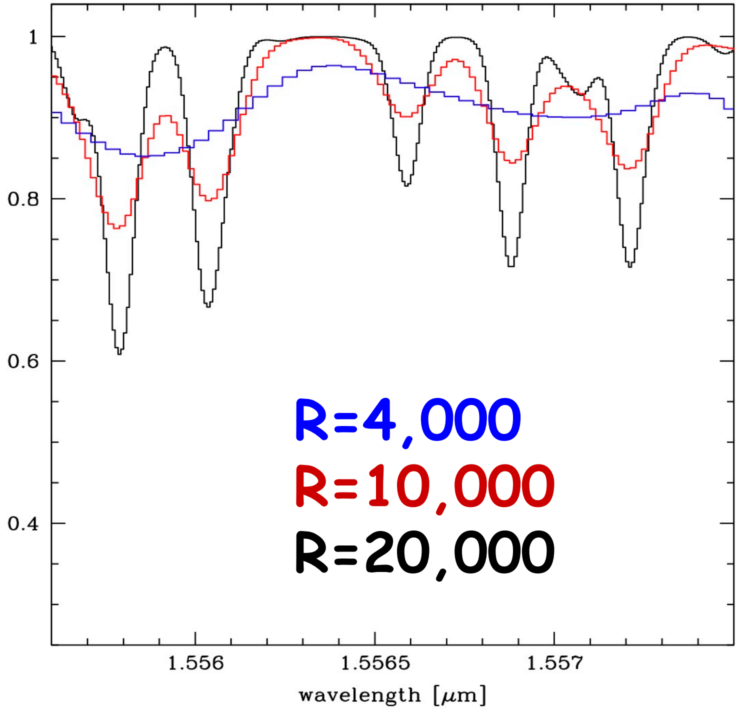
our ability of resolving & measuring individual lines depends on spectral resolution

$$R = \lambda/\Delta\lambda = c/\Delta v$$

R	spectral resolution
λ	wavelength
$\Delta\lambda$	full width half maximum (FWHM) of the instrumental (Gaussian) line profile
c	light speed
Δv	velocity

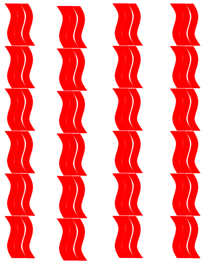
spectrographs are designed to sample the resolution element with >=2 pixels to satisfy the Nyquist theorem

higher R ➔ narrower & stronger lines

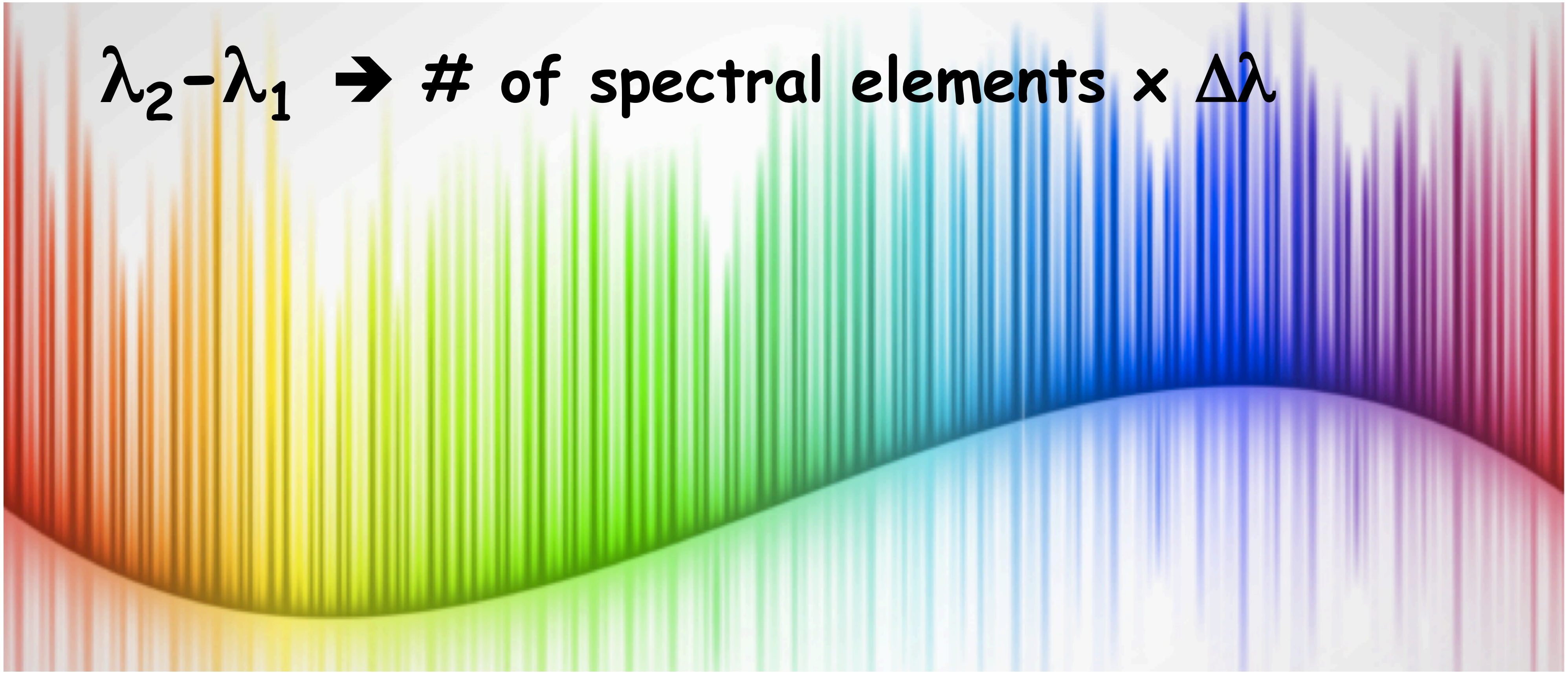


observing stars and stellar populations

spectral coverage ➔ wavelength range



disperser ➔ decomposes light
between λ_1 and λ_2 in steps of $\Delta\lambda$

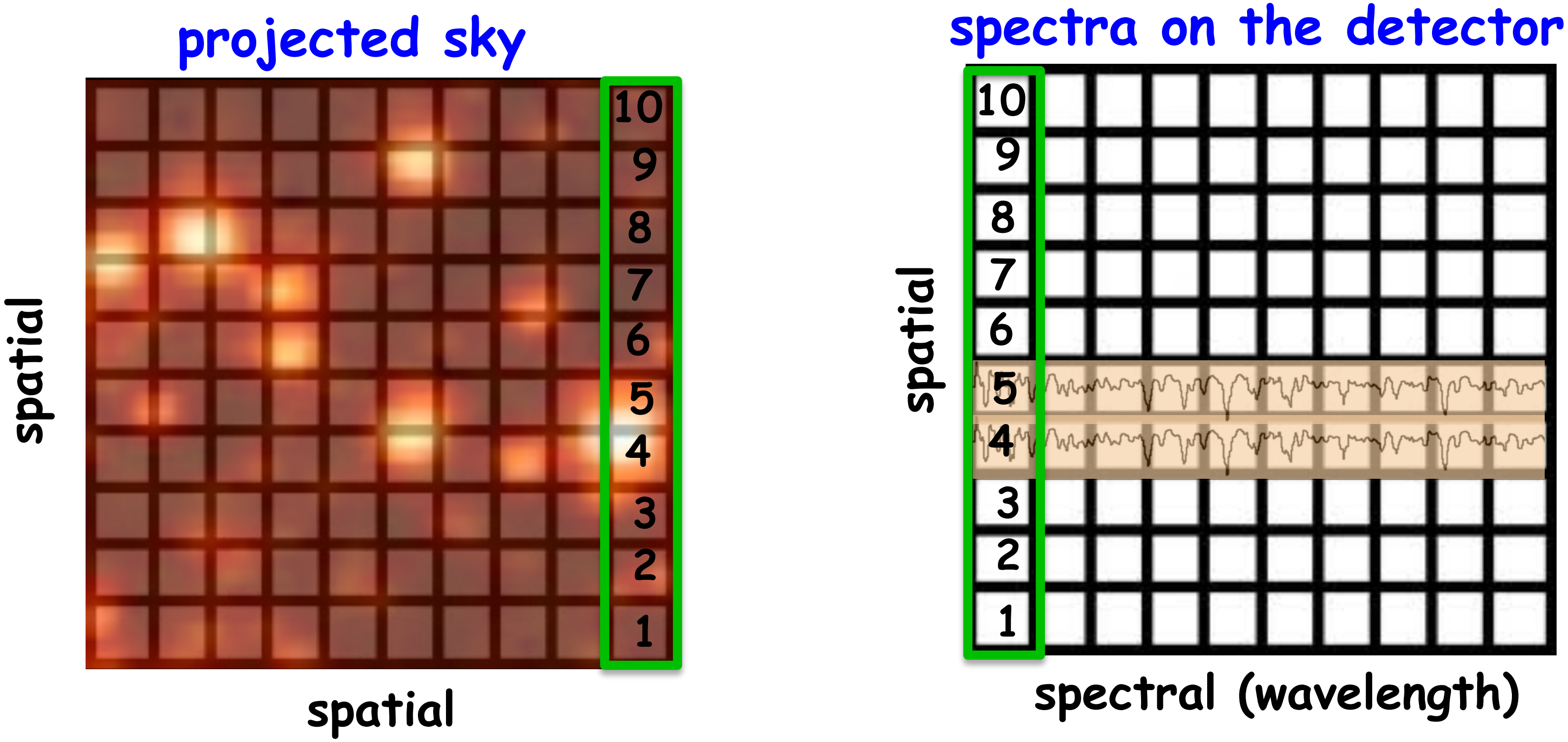


$\lambda_2-\lambda_1$ ➔ # of spectral elements x $\Delta\lambda$

observing stars and stellar populations

observing technique: spectroscopy

spectroscopic configuration: long slit

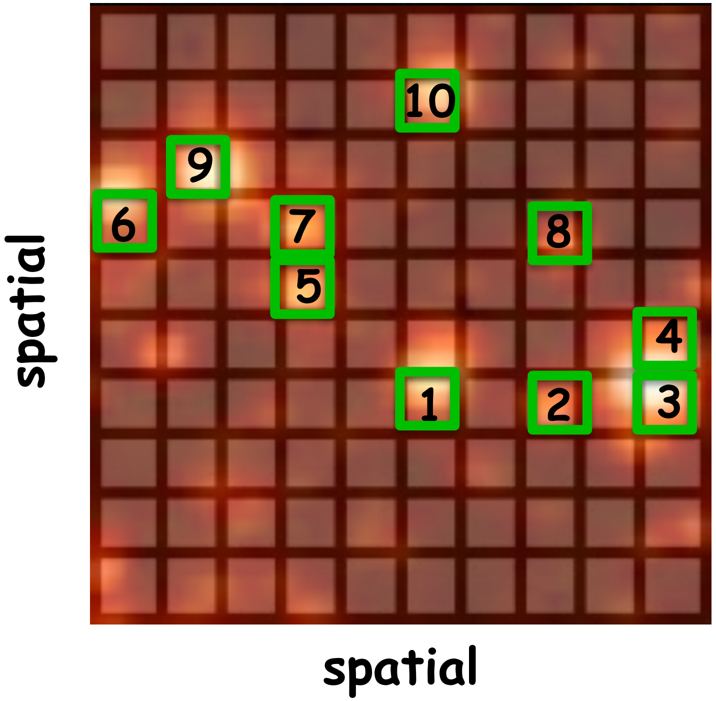


observing stars and stellar populations

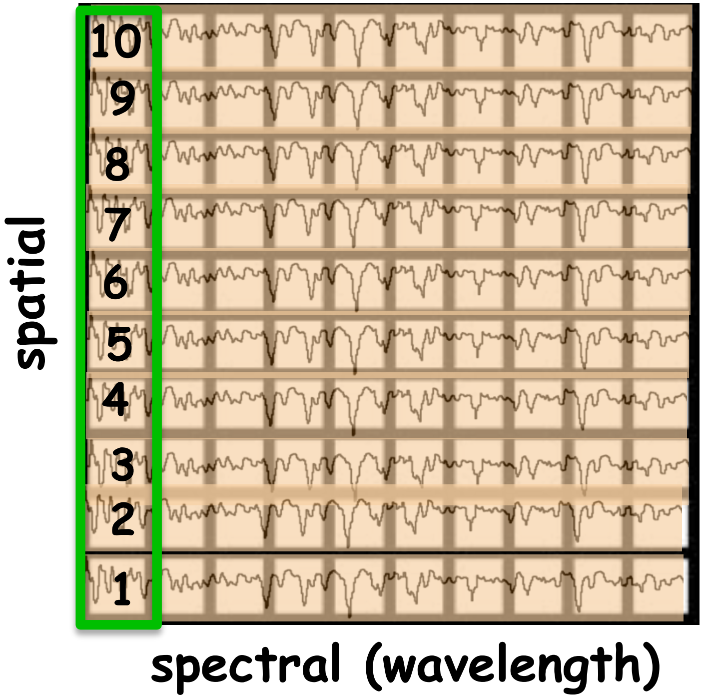
observing technique: spectroscopy

spectroscopic configuration: multi-object

projected sky



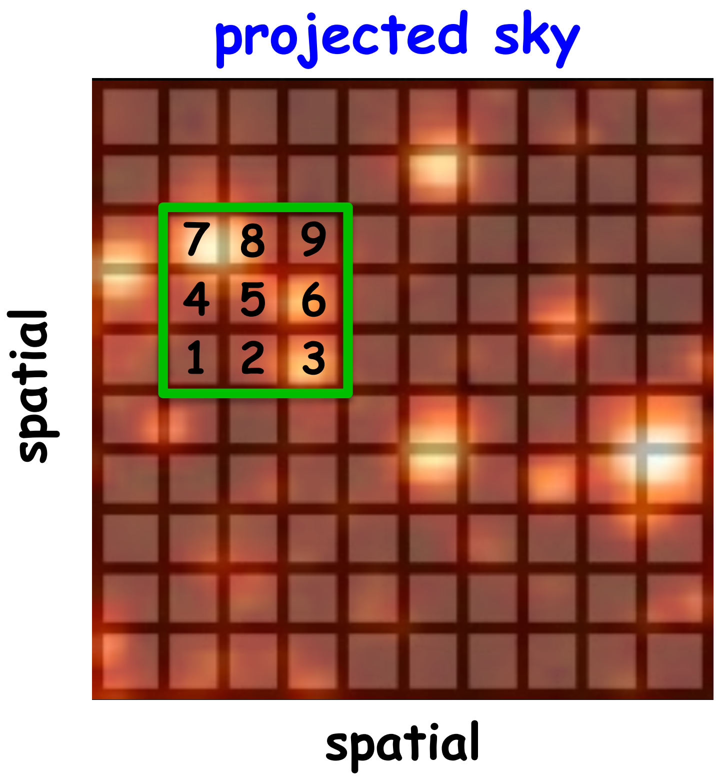
spectra on the detector

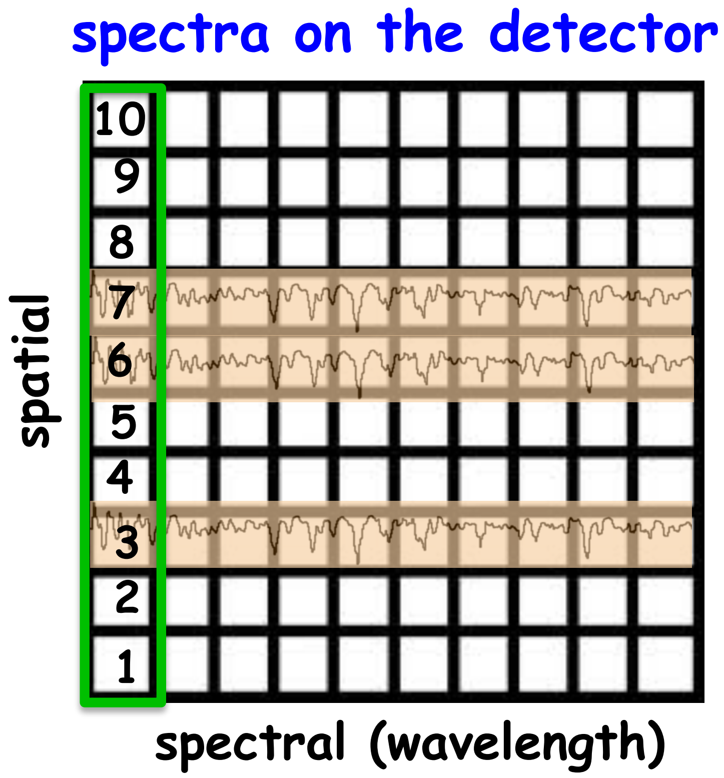


observing stars and stellar populations

observing technique: spectroscopy

spectroscopic configuration: integral field



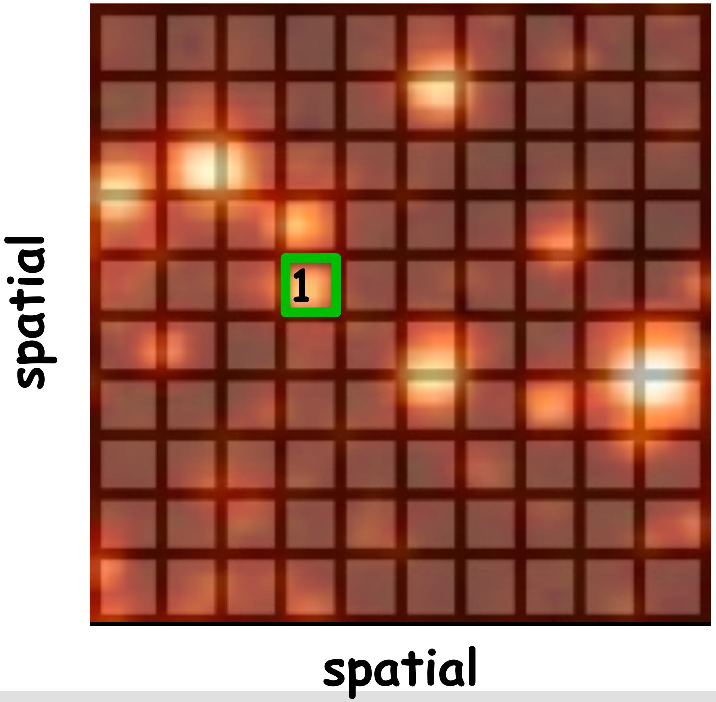


observing stars and stellar populations

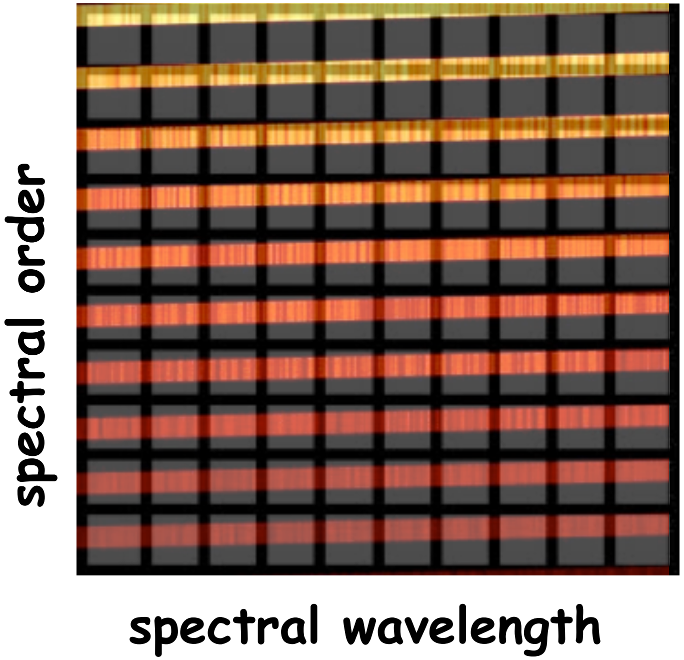
observing technique: spectroscopy

spectroscopic configuration: cross-dispersed echelle

projected sky

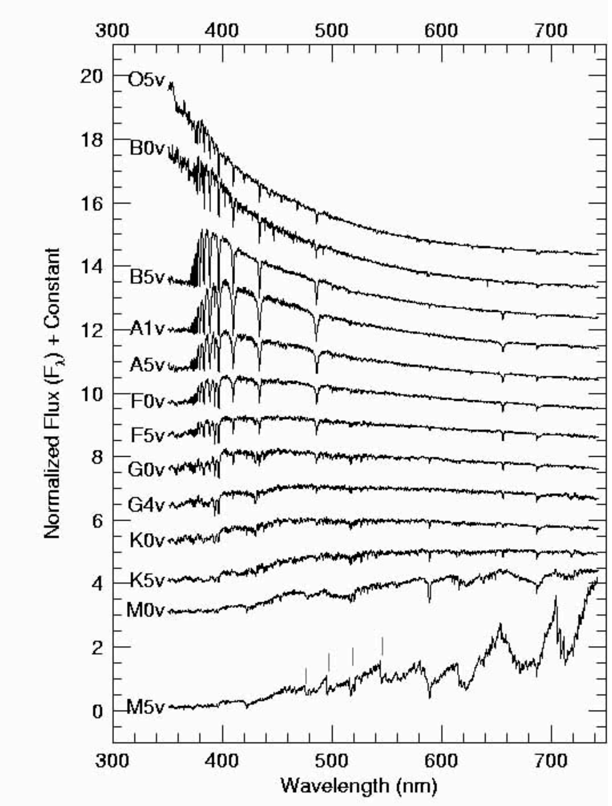


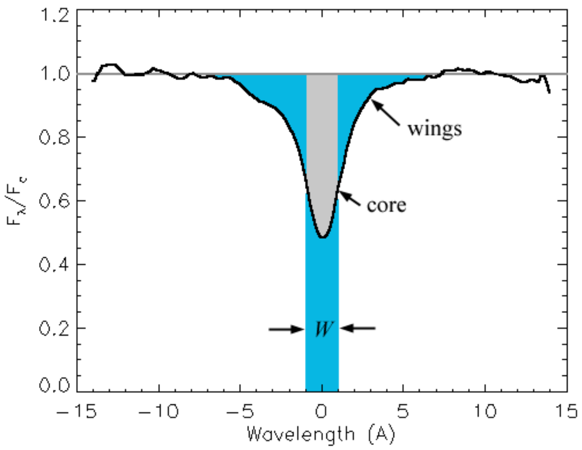
spectrum on the detector



- ✓single object, high spectral resolution + wide spectral coverage
- ✓Y-axis on the detector used to sample different orders, i.e. different wavelength ranges

spectral analysis: absorption spectra





stellar spectrum appearance

- continuum shape
- line profile (centroid, width, depth)
- lines from different chemical species

affected by many parameters

photospheric

temperature, gravity, chemical composition

internal and surface motions

micro and macro turbulence velocity, winds, spots

star motions

radial velocity, rotation

instrumental

spectral coverage, spectral resolution, signal-to-noise

spectral analysis: absorption spectra

from observables to physical quantities

comparison between <u>observed</u> & <u>template</u> spectra with known parameters

spectral libraries

empirical: reliable but incomplete coverage of stellar parameters

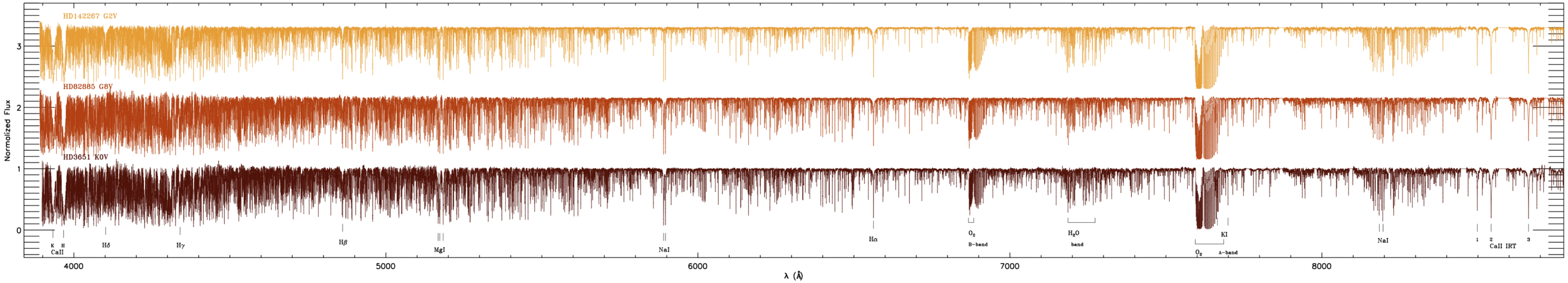
synthetic: complete coverage but model dependent

for <u>chemical abundance analysis</u> a wide space of parameters

<u>astrophysical</u>: temperature, gravity, micro and macro turbulence, rotation,
chemical abundances and abundance patterns, etc.

<u>instrumental</u>: spectral coverage, spectral resolution etc.

need to be covered and with dense spectral grids ➔ <u>synthetic templates</u>



spectral analysis: absorption spectra

how to compute synthetic spectra

sophisticated codes

spectral analysis: absorption spectra

how to compute synthetic spectra

code main ingredients

✓grid(s) of model atmospheres **(1D, spherical, 3D)** ➔ temperature & density structure

✓atomic and molecular line lists: lambda, excitation potential, transition probability (gf)

✓input physics
energy transport (LTE, NLTE)
Saha equations to compute column densities
continuum opacities and partition functions

✓line profile
intrinsic ➔ Voigt: **Doppler core** $(\Delta\nu = \nu_0/c \times (2kT/m + v_{turb}^2)^{0.5})$ + damping wings
broadening ➔ instrumental, rotation, macro-turbulence (convection in the outer layers of cool giant atmospheres)

input parameters

✓**temperature, gravity**

✓**micro & macro turbulence**

✓**chemical abundances**

✓**rotation velocity**

✓**spectral resolution**

output

✓**total (continuum + line) absorption coefficient**

✓line equivalent widths

✓full spectrum

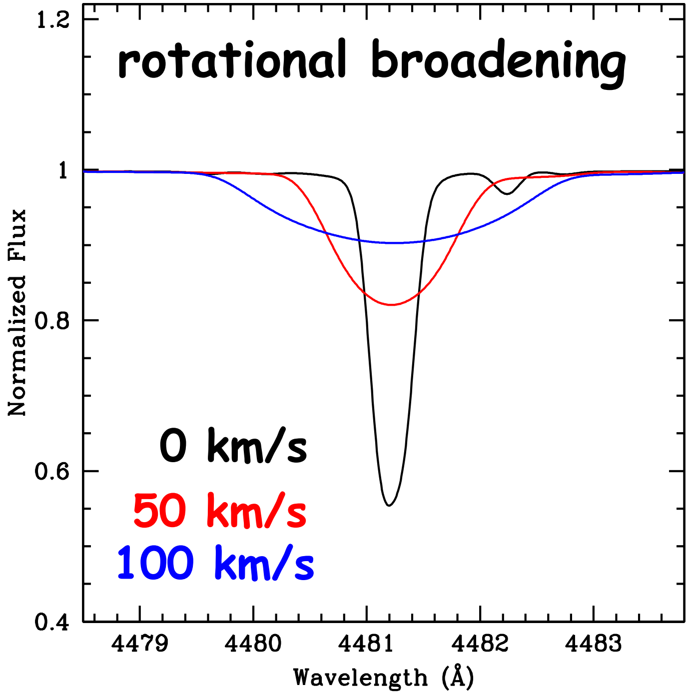
spectral analysis: absorption spectra

from observables to physical quantities

line shift ($\Delta\lambda$) with respect to a zero-velocity template ➔ radial velocity

line multi-components ➔ internal/surface motions, Zeeman (m.f.) and other splittings (atomic structure)

line broadening ➔ instrumental profile, macro-turbulence (Gaussian), rotation



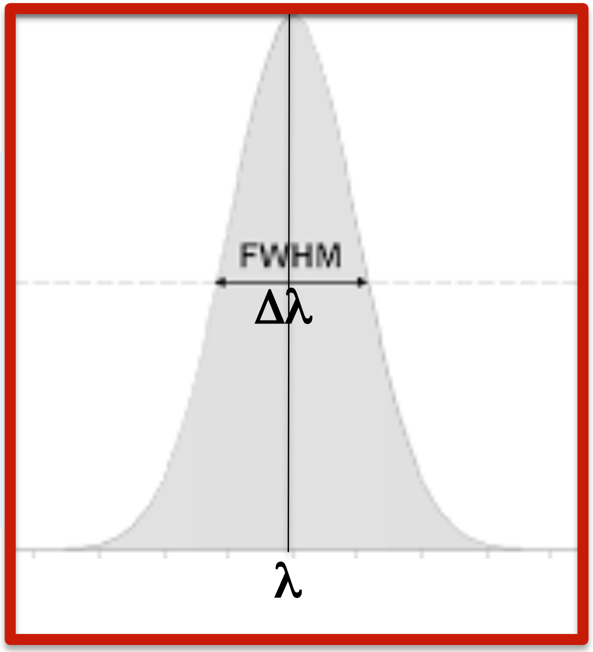
$$\Delta\lambda = \lambda_0/c\ (v \sin i)$$

v = equatorial rotational velocity

$v \sin i$ = projected rotational velocity

spectral analysis: absorption spectra

from observables to physical quantities



line equivalent width (EW)

EW = integral of the line profile

if Gaussian ➔ $EW = \mathrm{sqrt}(2\pi \times \sigma) \times I_{max}$

$\sigma = FWHM/2.35$

EW ➔ degeneracy among various parameters

temperature, gravity, micro-turbulence and chemical abundance

temperature & gravity ➔ photometric and/or spectroscopic estimates

micro-turbulence & chemical abundances ➔ spectroscopic estimates, only

spectral analysis: stellar parameters

photometric estimates

temperature (T_{eff}) ➔ colors, SEDs

gravity ➔ log g = const + 4 log T_{eff} + log M – log L(distance, reddening, BC)

spectroscopic estimates

medium-high resolution spectra

normally Fe lines are used since the most numerous & with the best atomic parameters

minimization algorithms to compute

best temperature ➔ the one which removes any trend between element abundance and excitation potential

best gravity ➔ the one which removes any difference between element abundance derived from neutral and single-ionized lines

best micro-turbulence (v_t) ➔ the one which removes any trend between element abundance and reduced EW (i.e. EW/λ)

other methods

temperature: line wings (e.g. Hα), depth of CO bandheads in cool giants

gravity: damped-line wings (e.g. Ca triplet)

micro-turbulence: shape of CO bandheads in cool giants, *log g* –v_t calibration

spectral analysis: chemical abundances

two main approaches to get chemical abundances

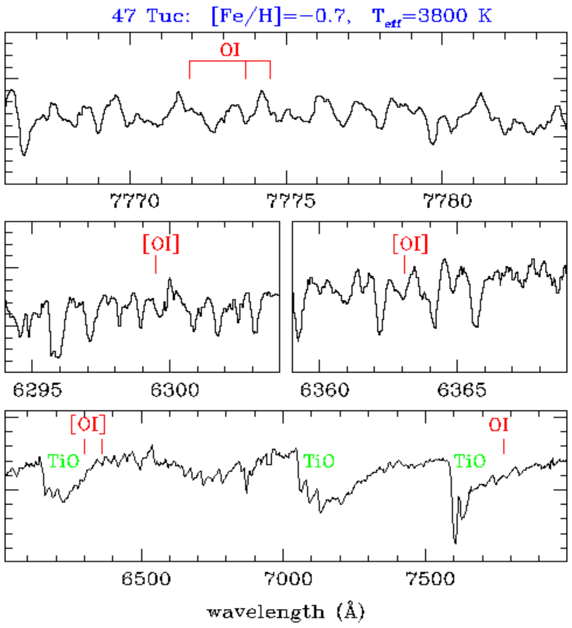
from line EWs   lines are treated in isolation

suitable for high-res spec and with no severe blanketing/blending

from full spectral synthesis

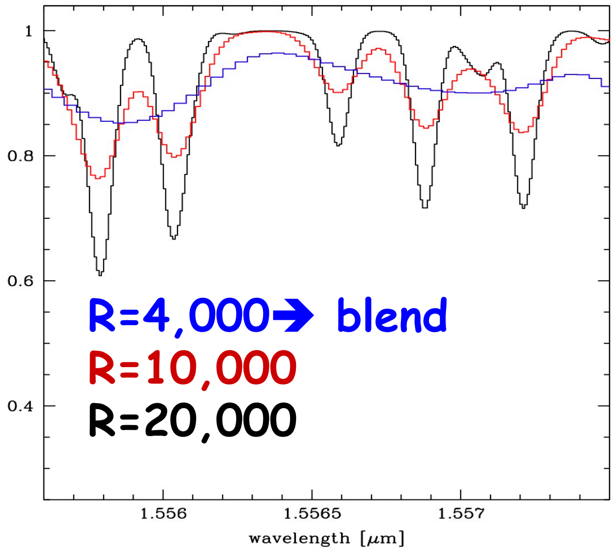
EWs eventually used as a figure of merit

suitable in all cases (although computationally more expensive)
mandatory for medium-low res spec and in case of severe blanketing/blending



blanketing
normally molecular,
mostly affect the
continuum shape and
opacity

blending
confusion among lines
too low resolution
and/or line crowding



spectral analysis: chemical abundances

error budget on relative abundances

$[X/H] = \log_{10}(A_{star}/A_{sun})$ [dex]

random **(medium-high resolution & s/n spectra)**

EW measurements → < 0.1 dex

line to line scatter σ → 0.1-0.15 dex

final accuracy on the derived relative abundances →

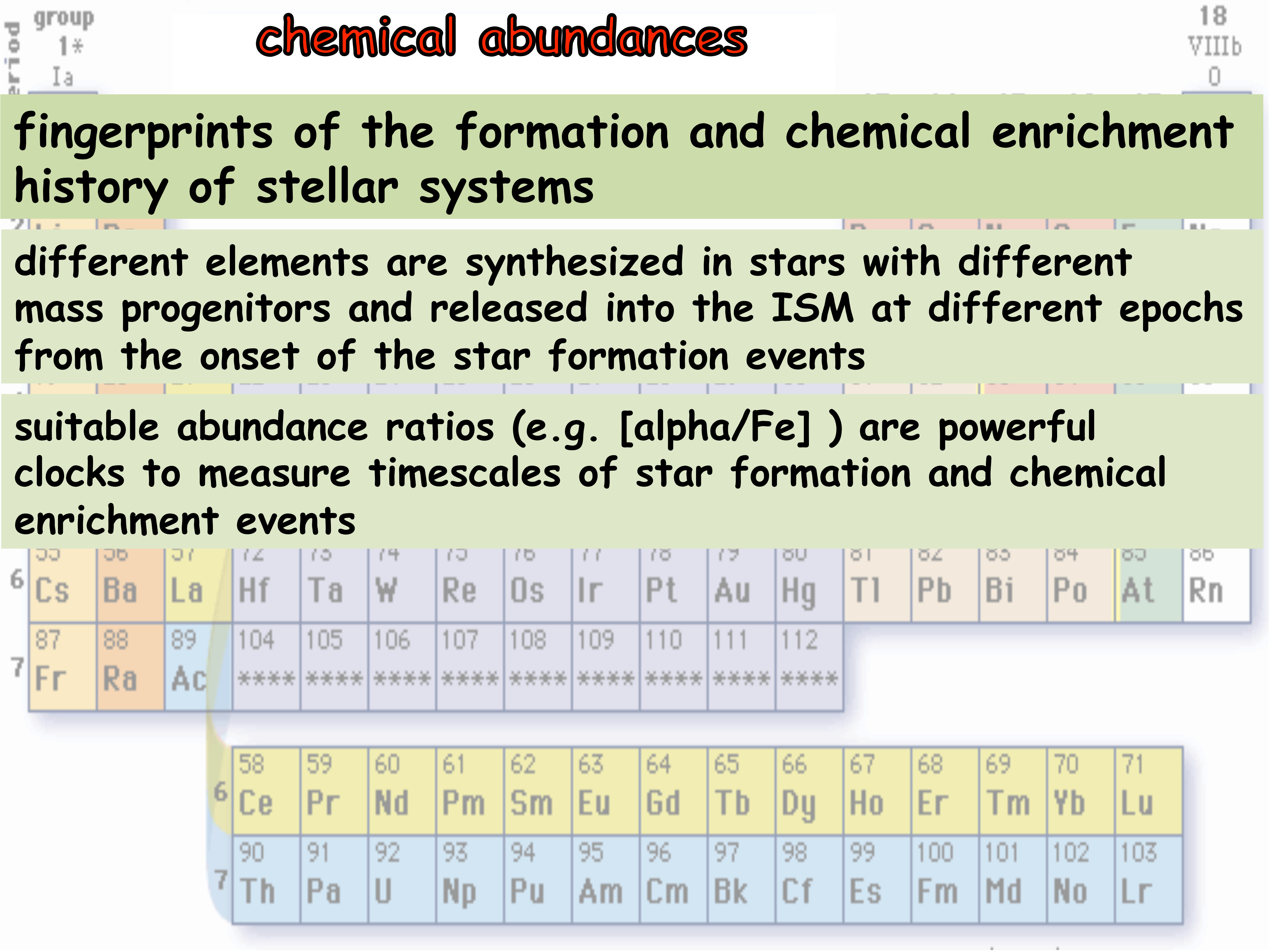
$\Delta[X/H] \sim \sigma/\mathrm{sqrt}(N_{lines})$

systematics

uncertainty in stellar parameters → 0.1-0.2 dex

modeling → < ~0.1 dex >

chemical abundances



fingerprints of the formation and chemical enrichment history of stellar systems

different elements are synthesized in stars with different mass progenitors and released into the ISM at different epochs from the onset of the star formation events

suitable abundance ratios (e.g. [alpha/Fe]) are powerful clocks to measure timescales of star formation and chemical enrichment events

chemical abundances

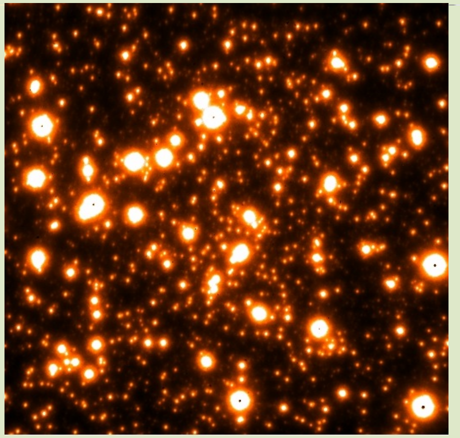
it is of fundamental importance to calibrate the *chemical clock* in the Local Universe, i.e. understanding

1) *nucleosythesis, stellar yields and stellar structure*
2) *chemical evolution of stellar systems*

in order to interpret the high-redshift Universe

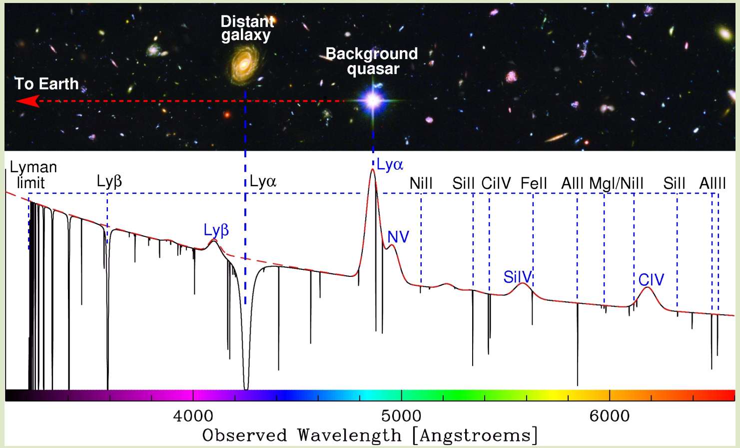
Local and high-redshift Universe critically connected

Local Universe



fossils of the first galactic structures (i.e. the oldest stars & stellar systems)

high-redshift Universe



look-back in time ➔ galactic structures in the process of formation