Radial velocity measurements and exoplanets

OUTLINE:

Principle

- Signal amplitude
- Required spectral resolution

Echelle Spectrographs

Calibration

- gas cell
- laser comb

Scientific results

Signal amplitude

relativistic term neglected (usually OK when considering RV variations)

radial velocity

$$\lambda = \lambda_0\,(1 - RV/c)\,/\,\mathrm{sqrt}(1-(v/c)^2) \sim \lambda_0\,(1 - RV/c)$$

relativistic term

Jupiter	→ 12.7 m/s
Jupiter-mass planet at 1AU	→ 28.4 m/s
Neptune-mass planet at 1 AU	→ 1.5 m/s
Earth	→ 9 cm/s

RV amplitude for Jupiter mass planet at 1 AU from Sun

inclination

RV ampl larger for close-in planets

$$\text{RV amplitude} = 28.4\ \text{m/s}\ \ (M_{planet}/M_{Jupiter})\ \sin(i)\ (M_{star}/M_{Sun})^{-1/2}\ (a/1AU)^{-1/2}$$

RV ampl is proportional to planet mass

RV ampl larger around low mass stars

Radial velocity: Signal measurement & challenges

1 m/s = c / 3e8 → microscopic change in spectra (=1.7e-6 nm shift in visible)
→ extremely precise and accurate spectra, with stability over ~yr timescale
→ photon noise can be a challenge

1 m/s < 1/1000th of line width (see next slide)
→ shift is a small fraction of spectral line width, or spectral resolution
→ need to average many lines

1 m/s ~ 0.01 K temperature change ~ 0.01 mbar pressure change
→ need to compensate for / measure local atmospheric conditions

Earth around Sun = 29 km/s
Earth rotation = 465 m/s (at equator)

→ accurate knowledge of local orbital effects required (can be derived from source position on sky, observation epoch, observer location)

Required spectral resolution

Ideally limited by the intrinsic spectral line width:
- stellar rotation: typically few km/s (2 km/s for Sun, up to 100 km/s for fast rotating stars)
- convection cells on star
- thermal line broadening

→ R ~ 100000 suitable to resolve lines

Emission line:

$\boldsymbol{\sigma_{RV}} \sim$ **FWHM / SNR ~ FWHM / sqrt(N_{ph})**

Absorption line:

$\boldsymbol{\sigma_{RV}} \sim$ **FWHM / (SNR C)**

line full width at half maximum

continuum signal to noise ratio

line contrast

photon-noise limited precision
Assuming a single line

Many lines, σ_i = RV precision for line i:

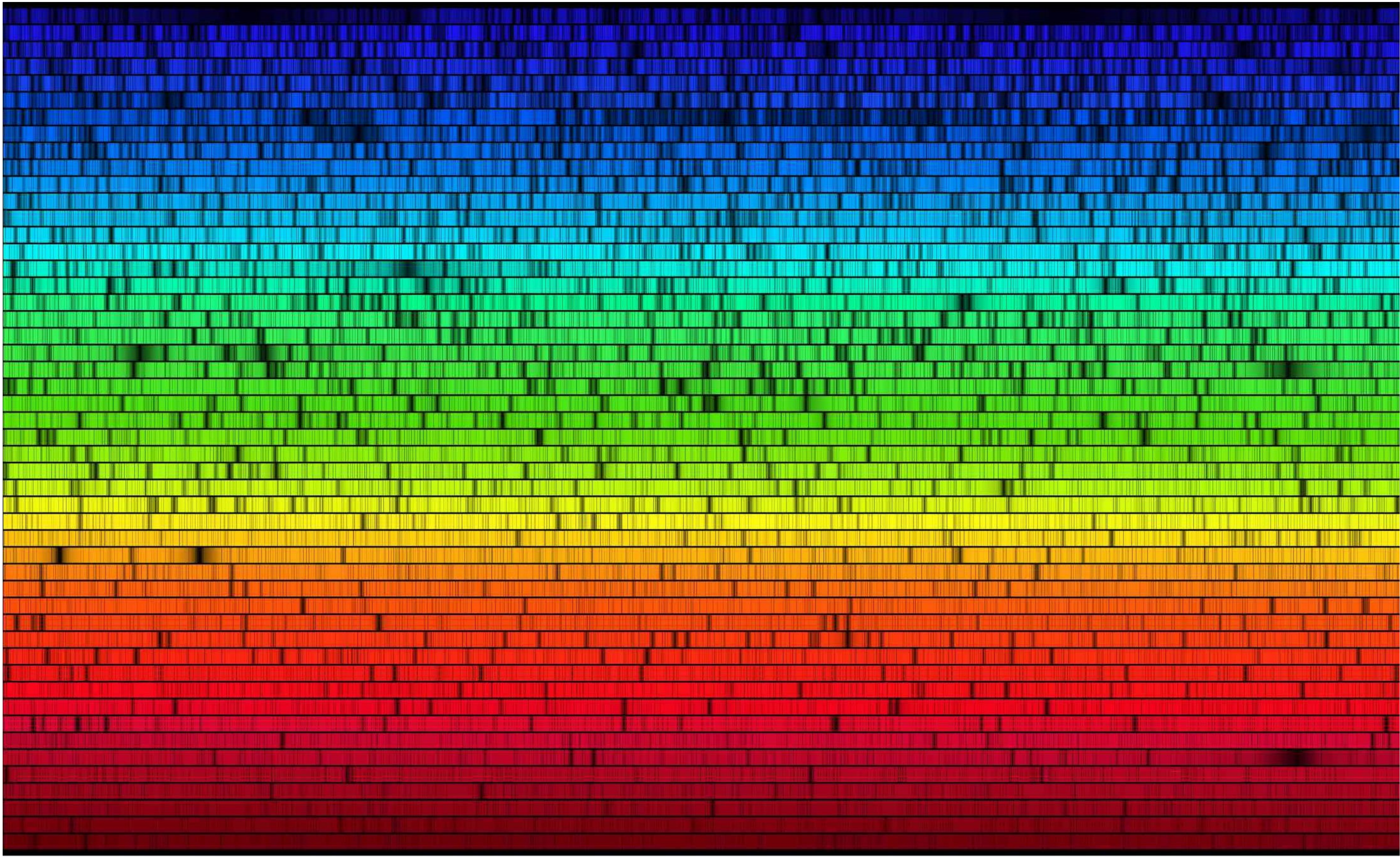
$$(1/\boldsymbol{\sigma_{RV}})^2 = \Sigma\,(1/\boldsymbol{\sigma_i})^2$$

High precision RV requires high spectral resolution (R ~ 100000) and wide spectral range to simultaneoulsy capture many lines

Stars have more absorption lines than emission lines: RV measurement is using absorption lines

Solar spectra

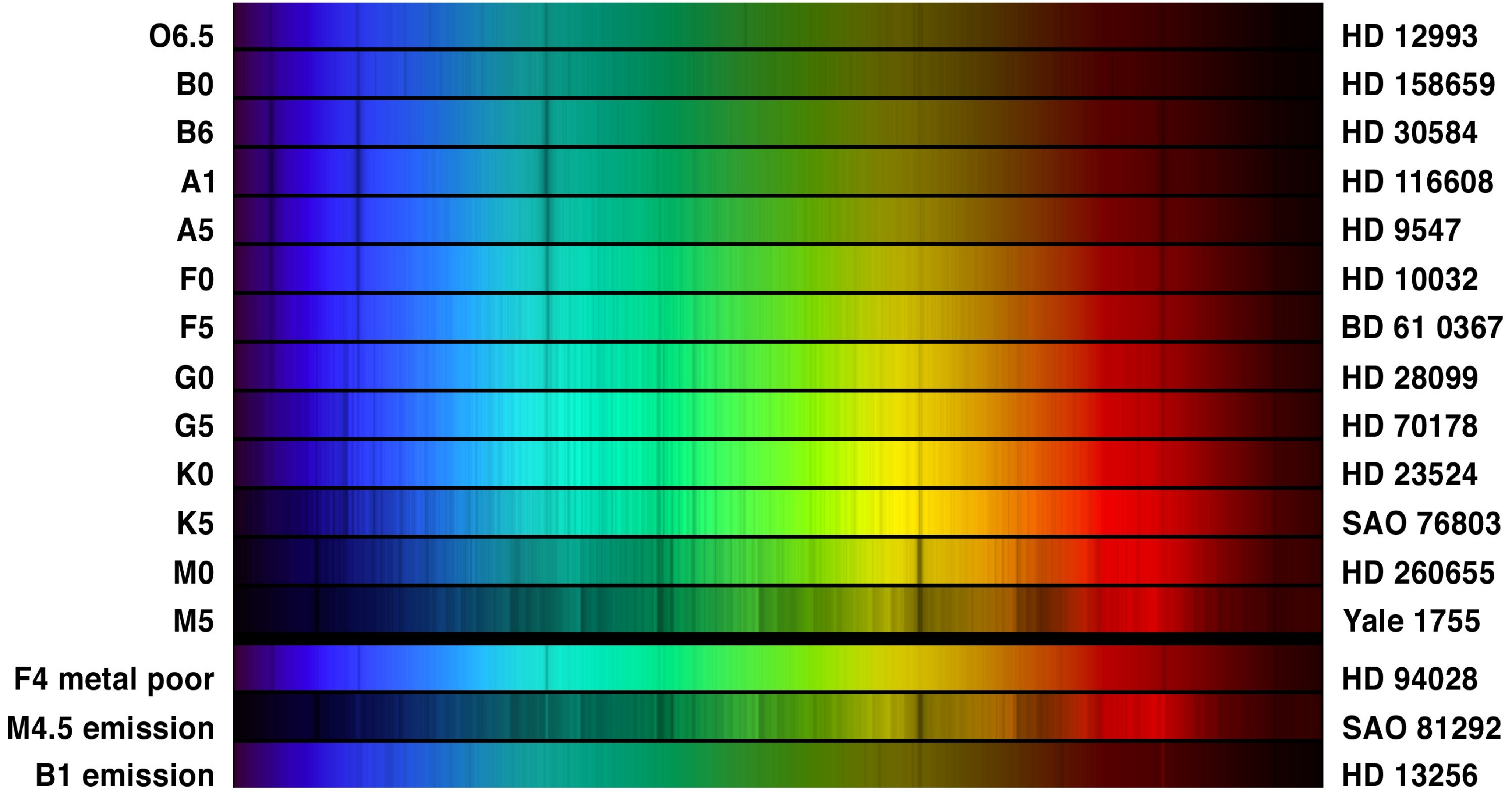
392nm to 692nm (blue - red)
Multiple absorption lines, few emission lines



credit: KPNO

Stellar types

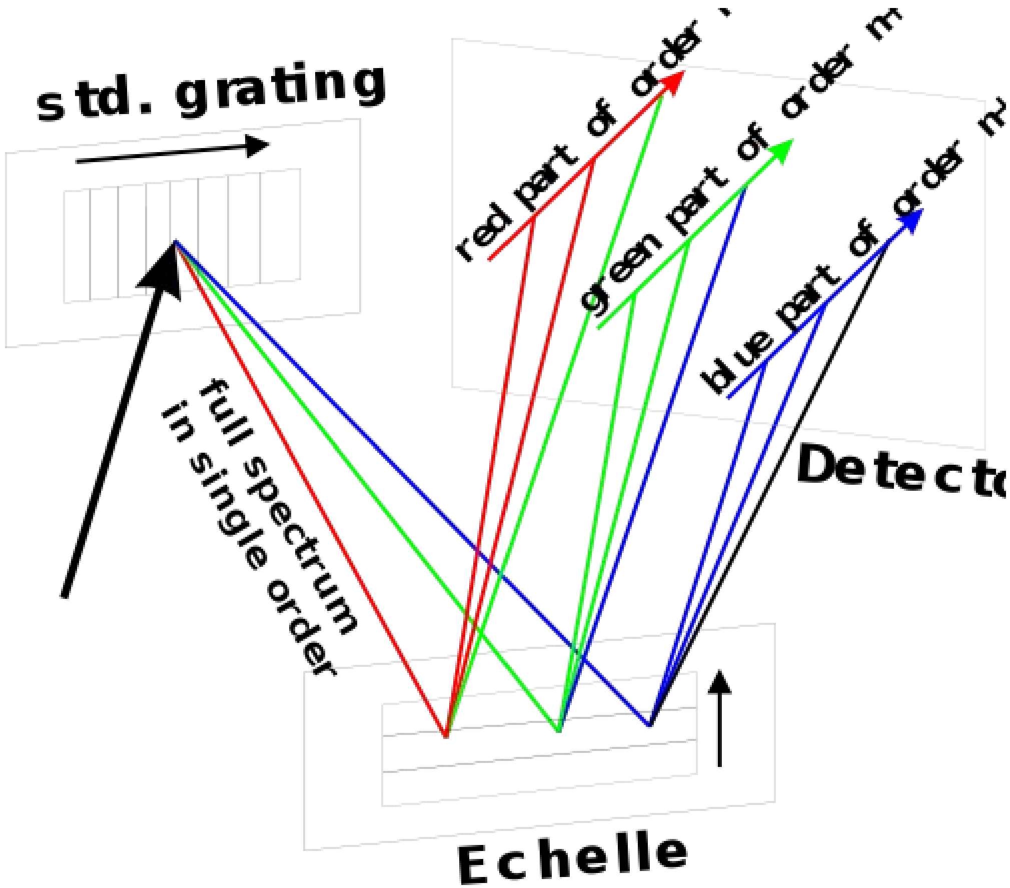
Hot stars (O, B type) → not enough spectral lines
Cool stars (M type) → too faint (except in near-IR)

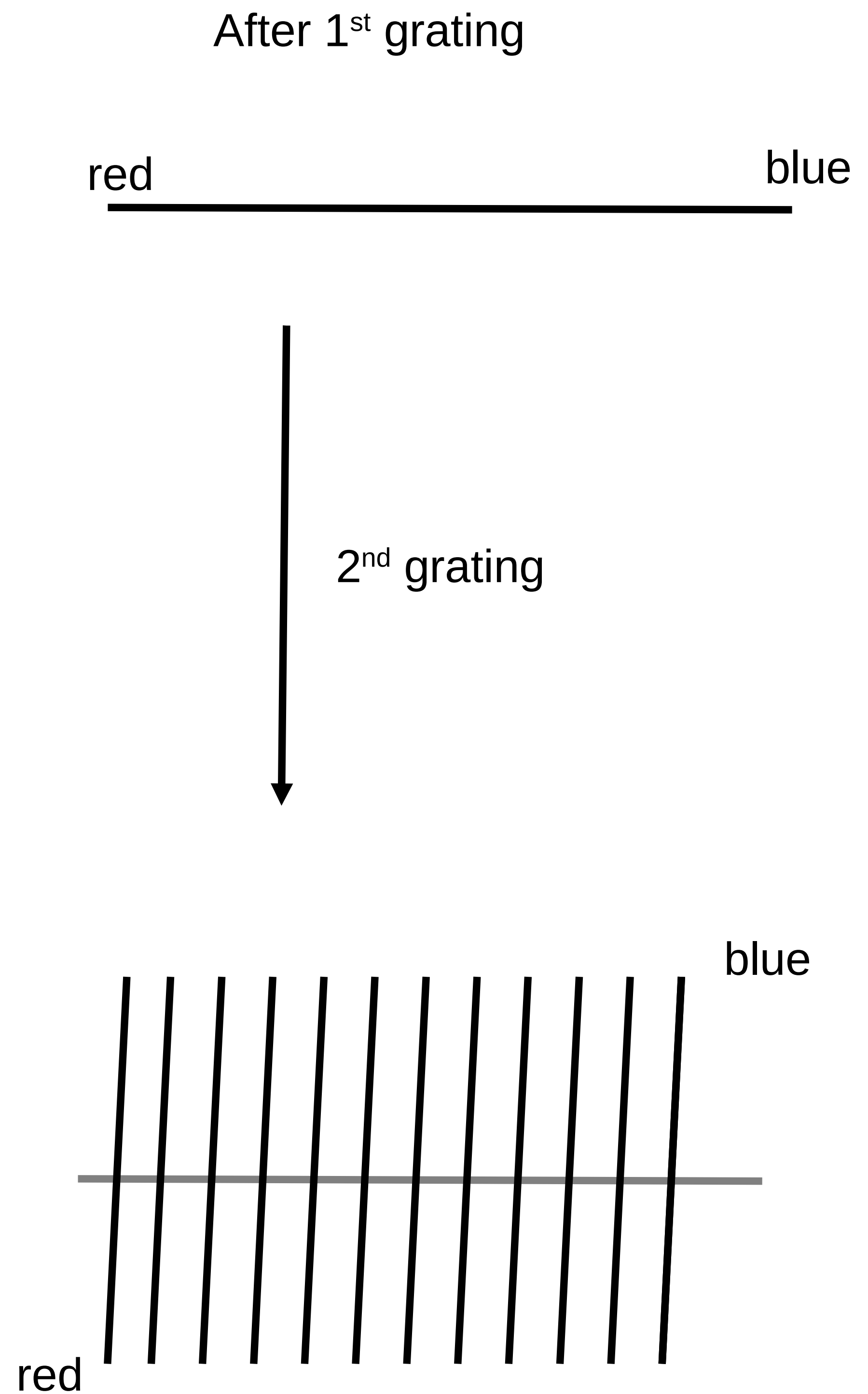


credit: NOAO

Echelle spectrograph

Concept:
2 gradings, 90 deg relative orientation
1st grating is low dispersion, all light in 1st order
2nd grating is high dispersion, multiple orders





Echelle spectrograph

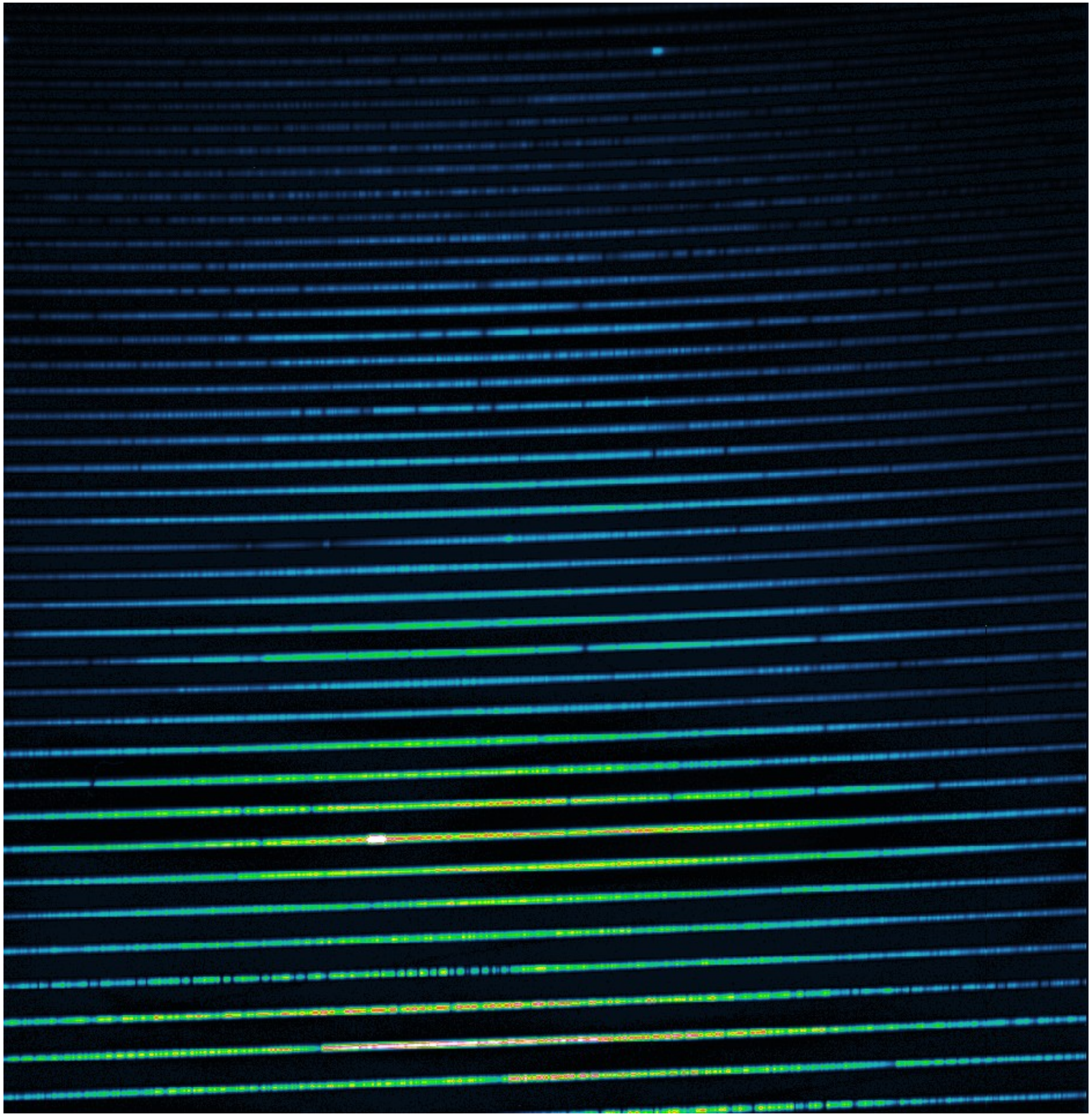
Allows use of large format 2D detector for high resolution, large coverage spectroscopy

2k x 2k device = 4 Mpix

assuming 4 pix buffer, 4 pix wide specta

→ 0.25 Mpix long spectra possible = 125 kelements

→ R~100000 over dlambda/lambda~1



Example Echelle spectrum (AD Leo, near-IR)
Credit: Thüringer Landessternwarte 'Karl Schwarzschild' Tautenburg

Calibration - absorption

Iodine (I_2) cell body (credit: Yale)

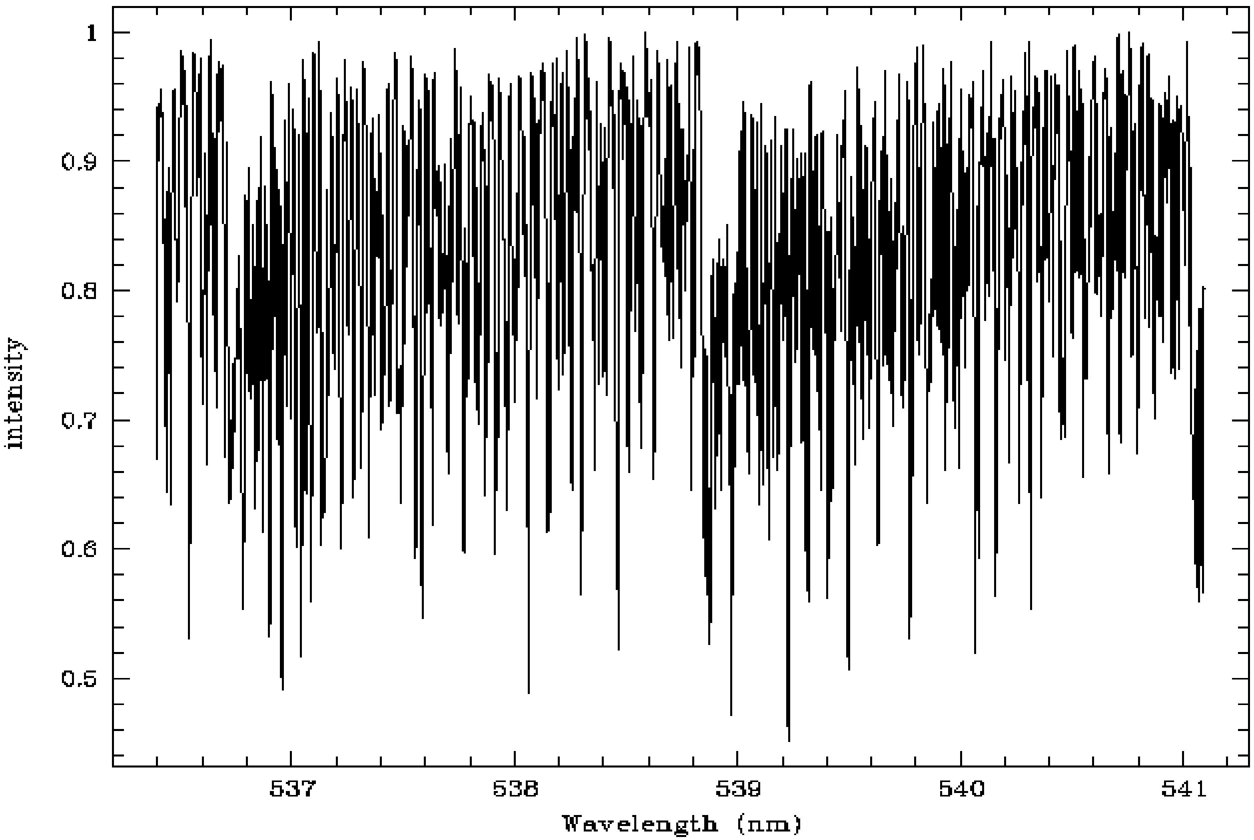
Principle:

Insert gas cell in beam
Measured spectra = source x gas absorption spectra

Gas chosen to have rich absorption spectra, with many narrow lines

Simple to implement if suitable gas exists (visible light OK, near-IR more challenging)

Some loss in SNR due to absorption



Iodine (I_2) absorption spectra at R=100000 (credit: ESO)

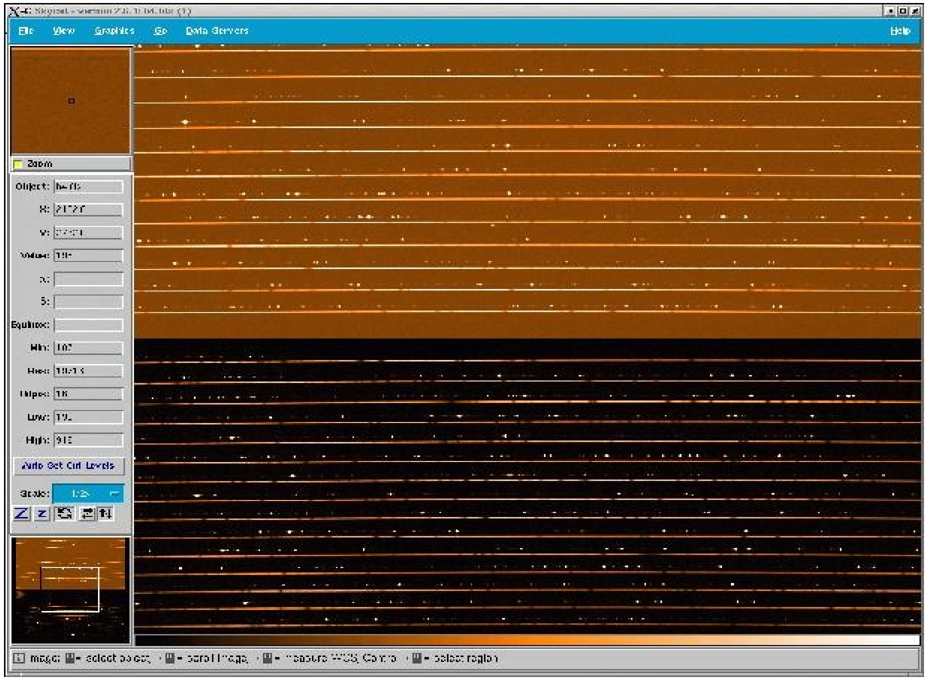
Calibration - emission

Two techniques:

Emission lamp, with many lines (Example: ThAr)
Ideally, lines should be densely spaced across full spectrum

Laser frequency comb
Laser designed to produce regularly spaced emission lines
This is ideal emission spectra for RV calibration, but technique not as mature

In both cases, emission spectrum needs to be injected in instrument to be simultaneously acquired with source spectrum



Thorium-Argon lamp emission

Calibration – emission: Laser Frequency Comb

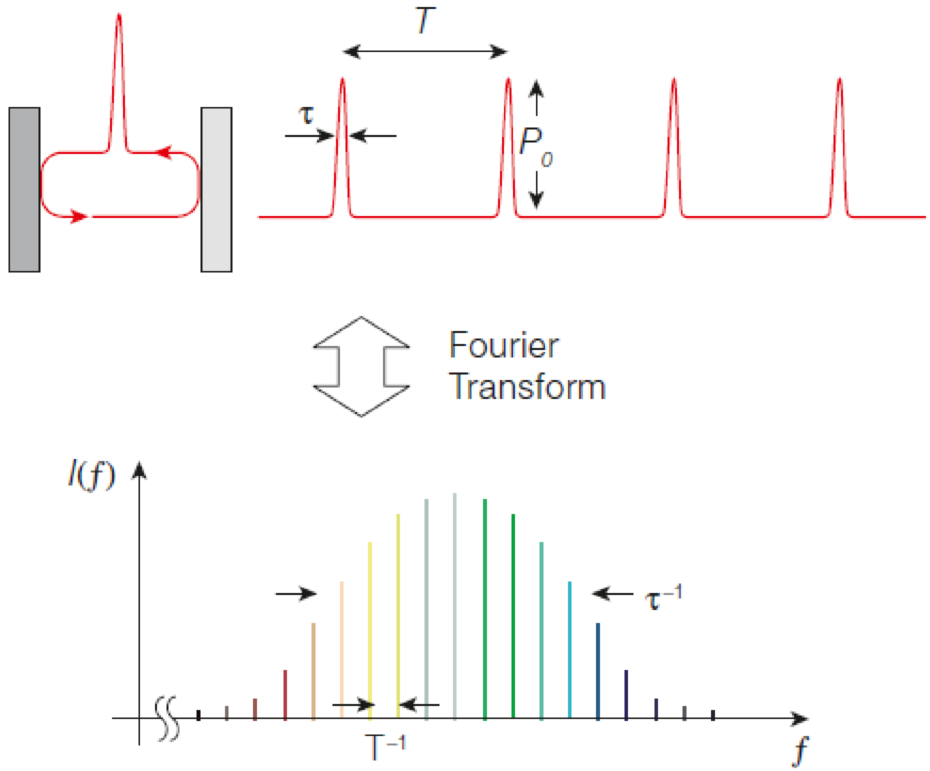


Figure 1: In the time domain, the pulses of a typical mode-locked laser (in red), characterised by its pulse repetition rate (T) and its pulse duration τ ~ fs, are shown (top). Shown below in the frequency domain, the pulse of the above mode-locked laser produces the frequency comb, with its parameters, the repetition frequency T^{-1} and spectral width τ^{-1}.

Laser frequency comb
ESO messenger, sept 2007

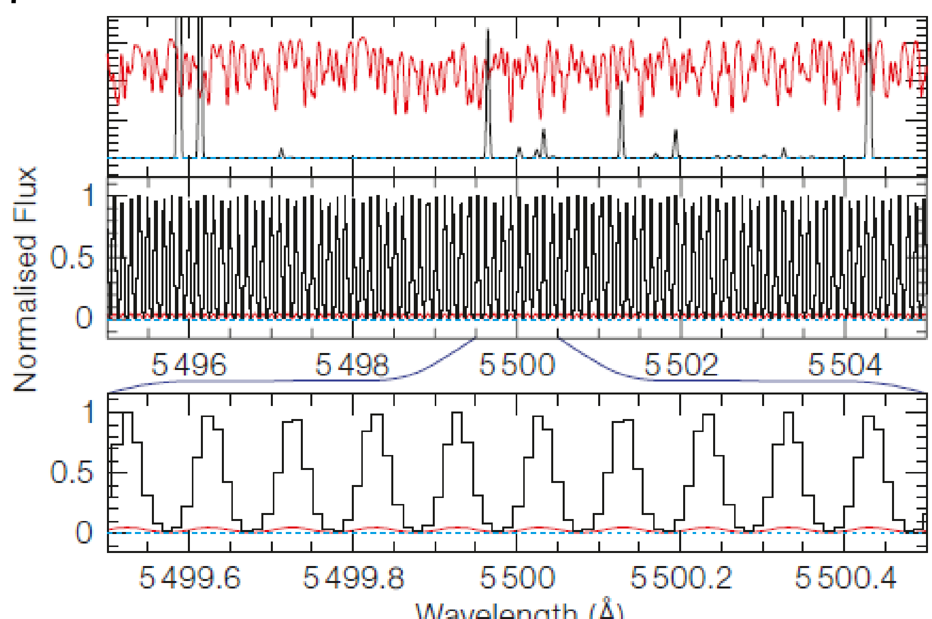


Figure 2: Th-Ar lamp (red) and the iodine cell spectra (black) as recorded at the focal plane of a high-resolution spectrograph (top), *versus* the simulated frequency comb spectra for the same spectral region (middle). In the lower frame is shown a zoom of the comb spectra for a 1 nm window, where the red solid line shows the error array, exaggerated by a factor of 25 (see Murphy et al. 2007).

Example RV instrument: HARPS (ESO)

Table 1: **HARPS spectrograph characteristics**

Optical design	fibre-fed, cross-dispersed echelle spectrograph
Technique	simultaneous ThAr Reference
Number of fibres	2
Fibre aperture on sky	1 arcsec
Collimated beam diameter	208 mm
Covered spectral range	380 nm to 690 nm
Spectral resolution	R=115,000
Spectral format	72 echelle orders 61.44 x 62.74 mm
CCD chip	mosaic, 2xEEV2k4 pixel size=15µm
Sampling	3.2 pixels/SE
Min. inter-order	33 pixels

Fiber-fed vacuum spectrograph, R=115000
Simultaneous Thorium-Argon reference
mK level temperature stability
Achieves < 1 m/s

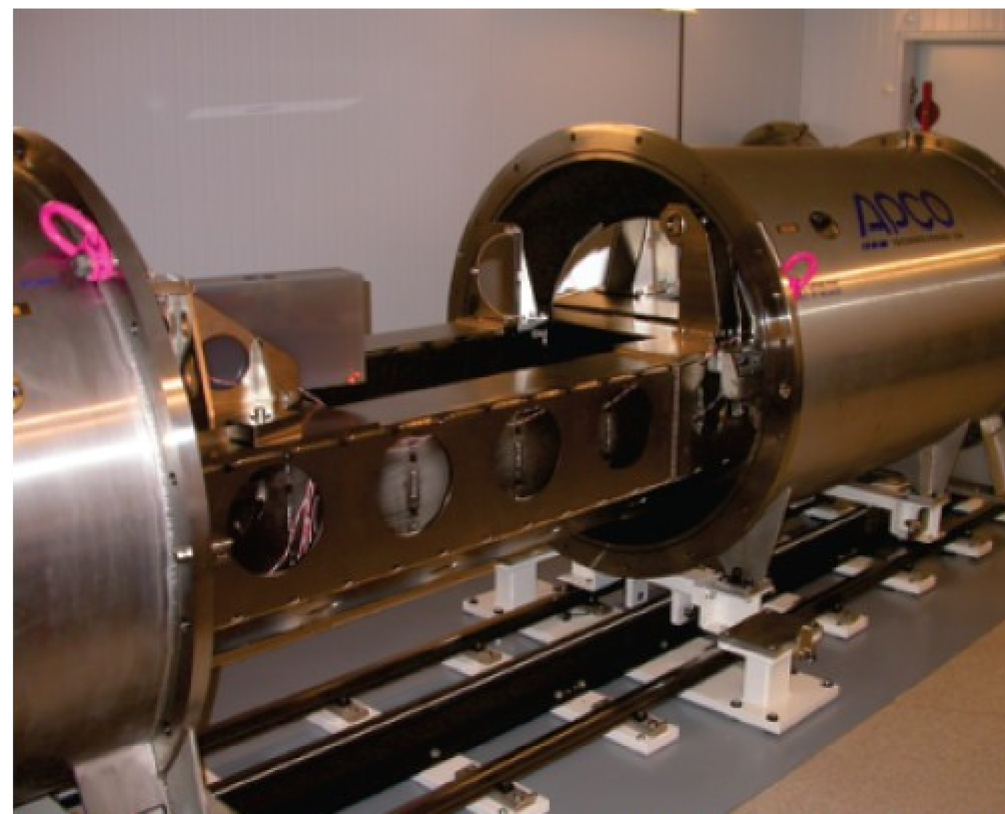
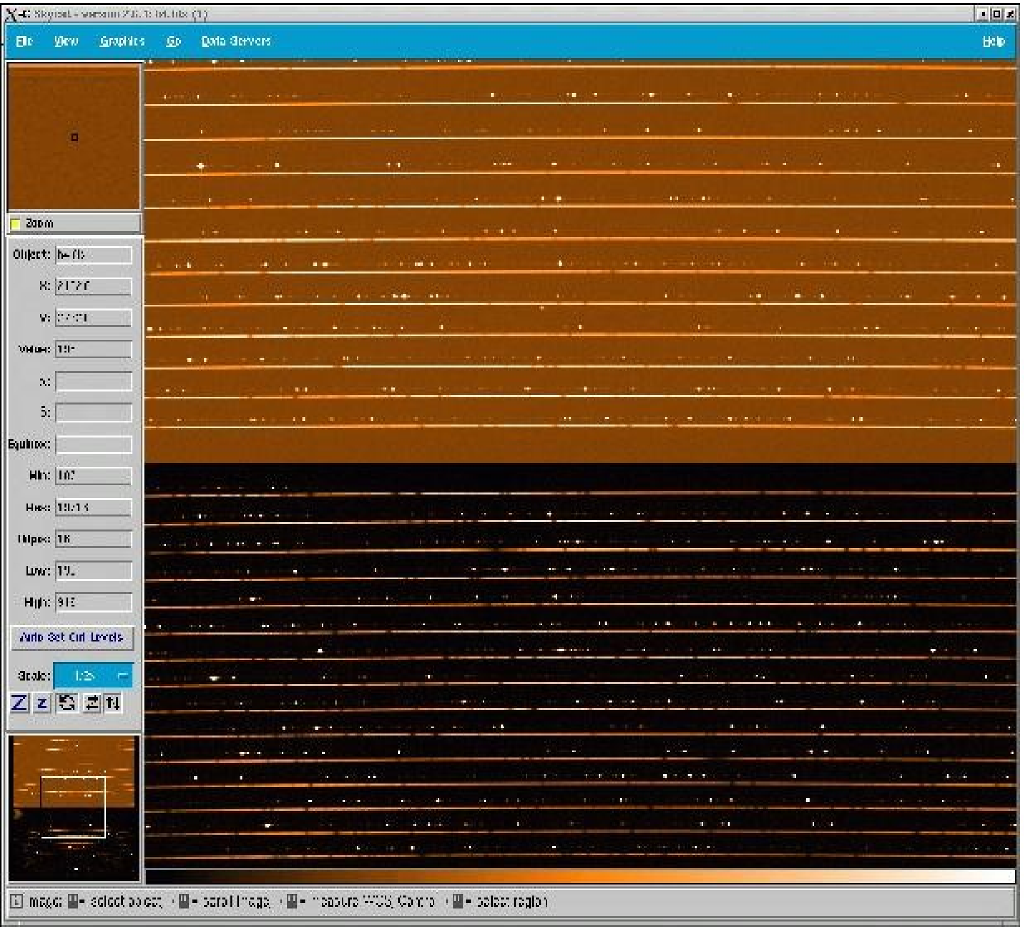


Figure 1: The HARPS spectrograph inside the air-conditioned room at La Silla just before closed and evacuated.

Example RV instrument: HARPS (ESO)



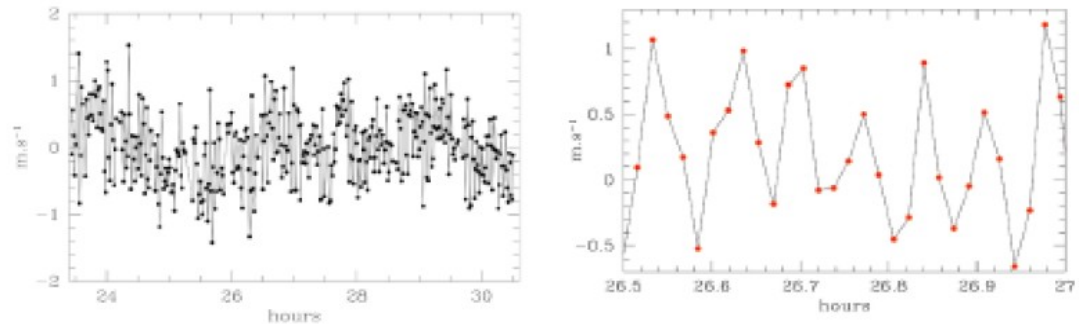


Figure 4: a) Series of 7 hours and 420 exposures on α Centauri B proving the extraordinary short-term precision of HARPS. b) Zoom of figure a) to illustrate the presence of a periodic signal produced by the stellar pulsation.

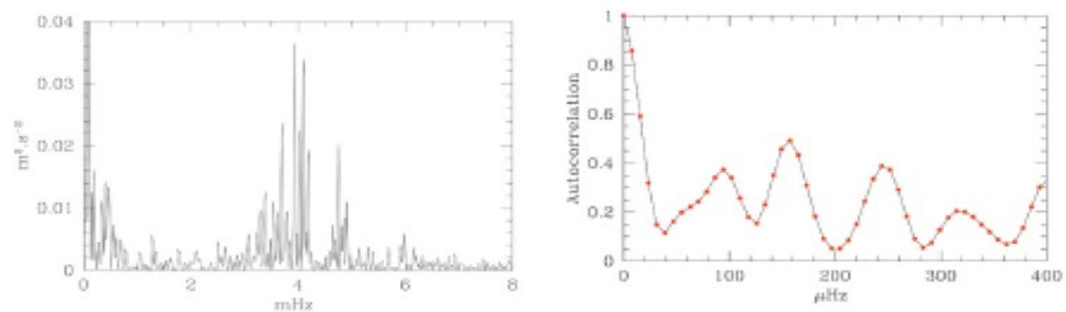
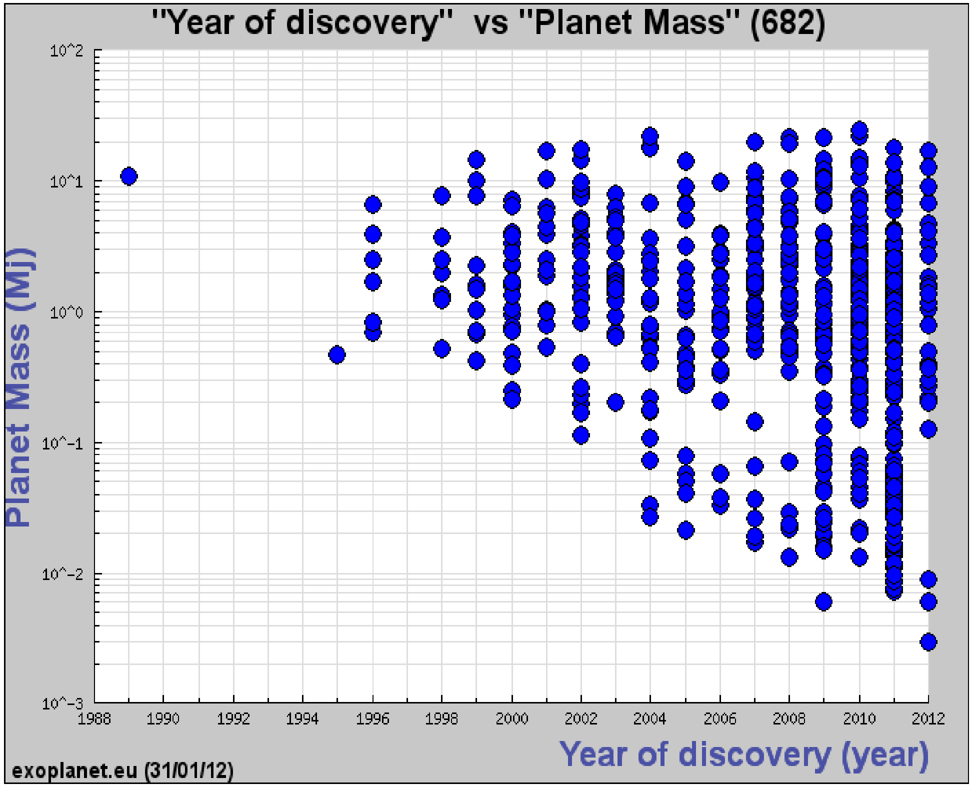


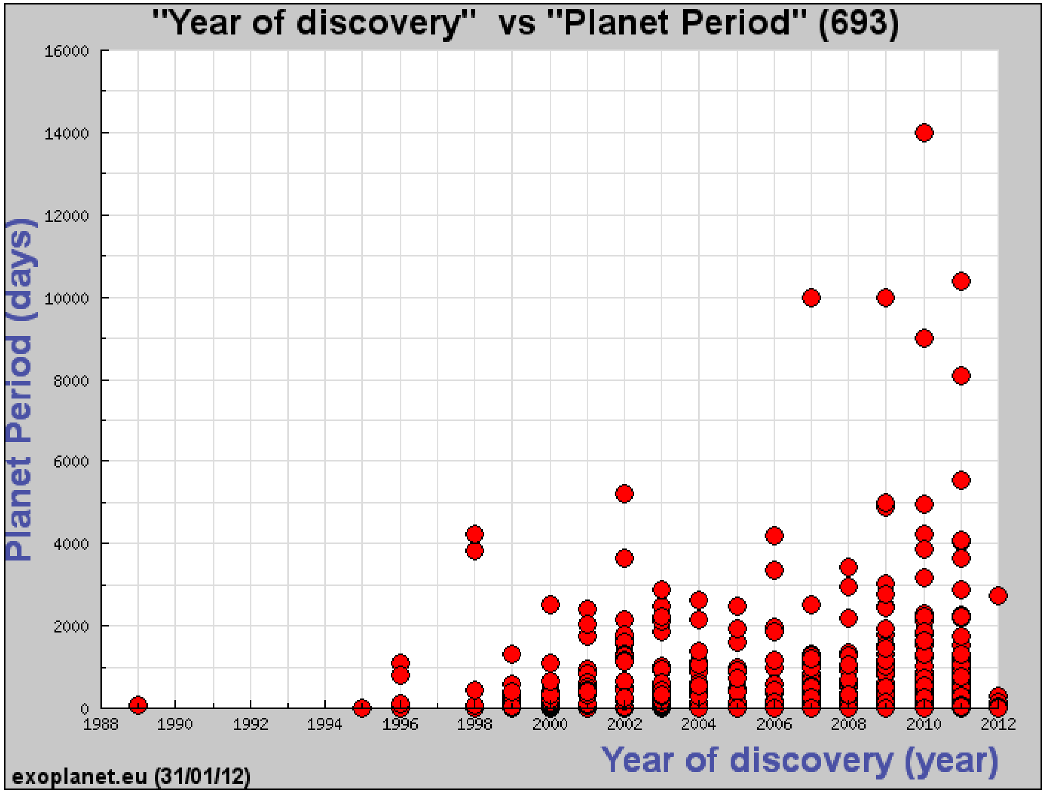
Figure 5: a) Power spectrum of α Cen B. The acoustic modes corresponding to the 4-minutes oscillation are clearly identified and emerge well above the noise. b) Autocorrelation of the power spectrum of α Centauri B.

HARPS detector image shows simultaneous source and ThAr lamp spectra next to each other

< m/s precision
(note: RV also needs long term stability)

Planets identified by RV





Precision still improving + longer time baseline → more RV planets

Follow-up RV of transit target can detect measure the mass of Earth-mass planets (example: COROT 7-b)

Future projects:

EXPRESSO @ VLT
Goal < 10 cm/s

CODEX for E-ELT
Goal ~ 2 cm/s

Status

- Schedule: First light on telescope: goal 2016
- Preliminary Acceptance Europe, October 2015
- Final Design Review, April 2013
- Preliminary Design Review, November 2011
- Kick off Meeting, January 2011
- Phase A Study Review Meeting, March 2010

Baseline Specification

Requirement	Standard 1-UT	4-UT	Very-High Res 1-UT
Wavelength Range	380-686 nm	380-686 nm	380-686 nm
Resolving Power	120.000	30.000	220.000
Aperture on Sky	1.0 arcsec	4x1.0 arcsec	0.5 arcsec
Sampling (average)	3.3 pixels	4.0 pixels (binned x2)	2.1 pixels
Spatial Sampling	6.9 pixels	4.0 pixels (binned x2)	3.5 pixels
Simultaneous reference	Yes (no sky)	Yes (no sky)	Yes (no sky)
Sky subtraction	Yes (no sim. ref.)	Yes (no sim. ref.)	Yes (no sim. ref.)
Total Efficiency	>10% at peak	>10% at peak	> 7% at peak
Instrumental RV precision (requirement)	<10 cm/sec	<=5 m/sec	<=5 m/sec

Scientific Objectives

The main scientific drivers for ESPRESSO are:

- the measurement of high precision radial velocities of solar type stars for search for rocky planets
- the measurement of the variation of the physical constants
- the analysis of the chemical composition of stars in nearby galaxies