# Deriving High-Precision Radial Velocities

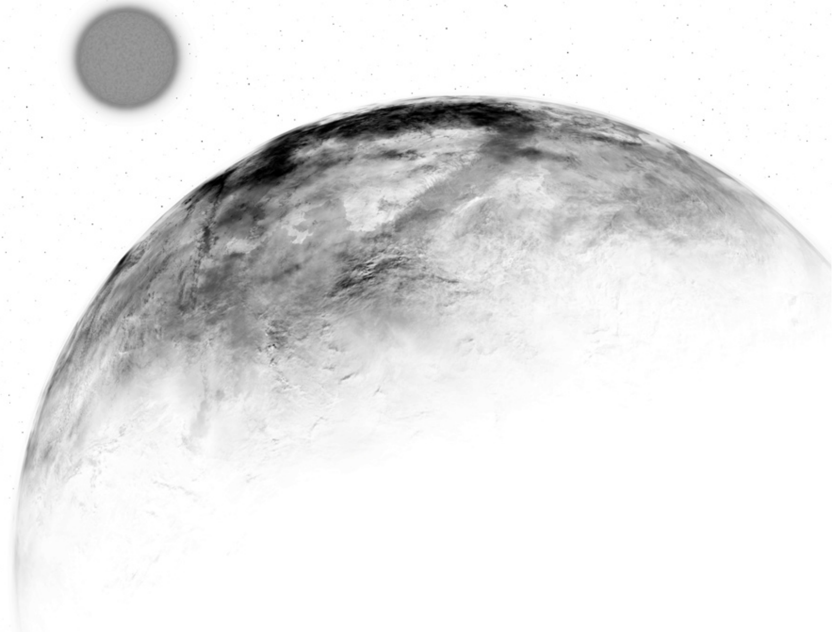
**Pedro Figueira**

instituto de astrofísica
e ciências do espaço

*Asteroseismology & Exoplanets: Listening to stars and searching for New Worlds*

# Outline

- RV precision: what is it?
- Building a spectrograph from scratch.
- On what depends the RV precision?
- Measuring RV's using different wavelength calibration techniques
- Finding planets



# Radial Velocities

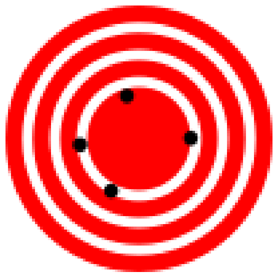
- Radial Velocities are velocities along the line of sight and can be calculated through the Doppler effect measured on spectral lines:

$$\frac{\Delta\lambda}{\lambda} = \frac{v}{c}$$

- It is fundamentally different from measuring directly a velocity on the plane of the sky;
- Precision on RV doesn't depend geometrically on distance to the source (except for noise contribution, always present).

# Accuracy vs Precision

The ***accuracy*** of a measurement system is the degree of closeness of measurements of a quantity to its actual (true) value.



The ***precision*** of a measurement system, also called reproductibility or repeatability, is the degree to which repeated measurements under unchanged conditions lead to the same results.

We are interested in measuring the position (wavelength) of a stellar line with ***high*** precision.

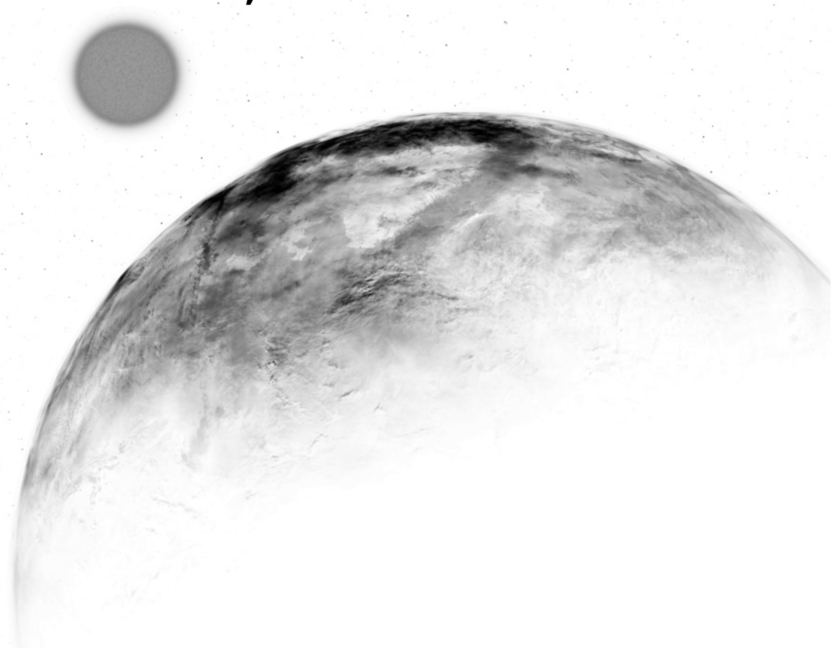
# Radial Velocities

Precise RVs have been used to calculate the velocities of stars and study:

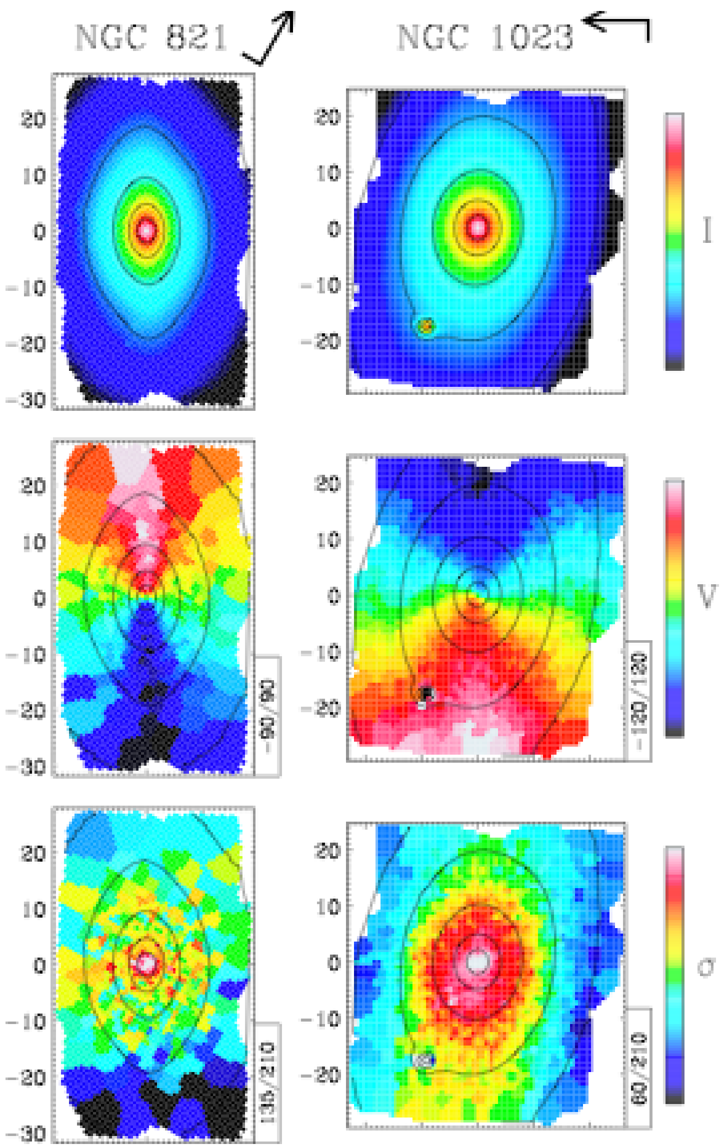
- Galactic Kinematics: σ >10 km/s;
- Stellar binarity and masses: σ ~ 1 Km/s
- Presence of Exoplanets: σ < 100 m/s

or to calculate the relative velocities of lines in the stellar atmospheres and:

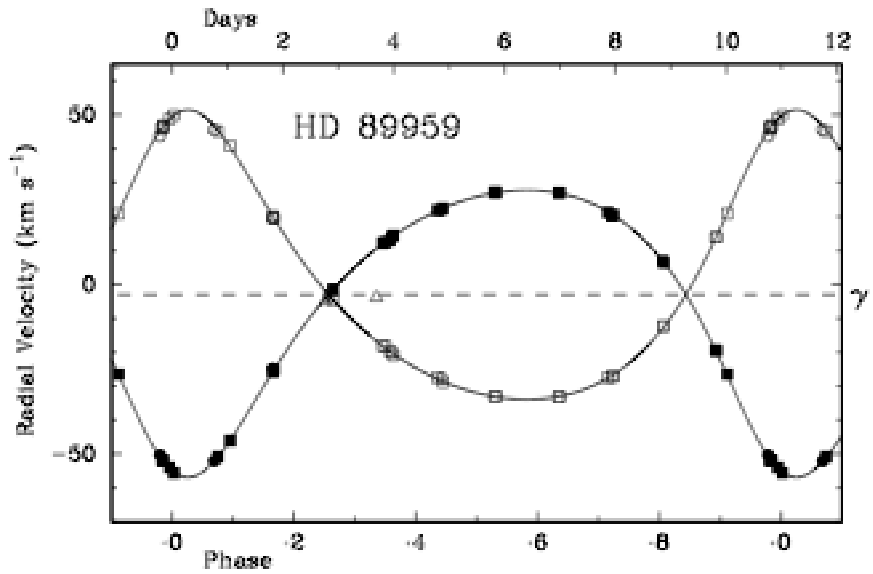
- Measure stellar oscillations, differential line shifts, and line profile variations: σ = 1-100 m/s



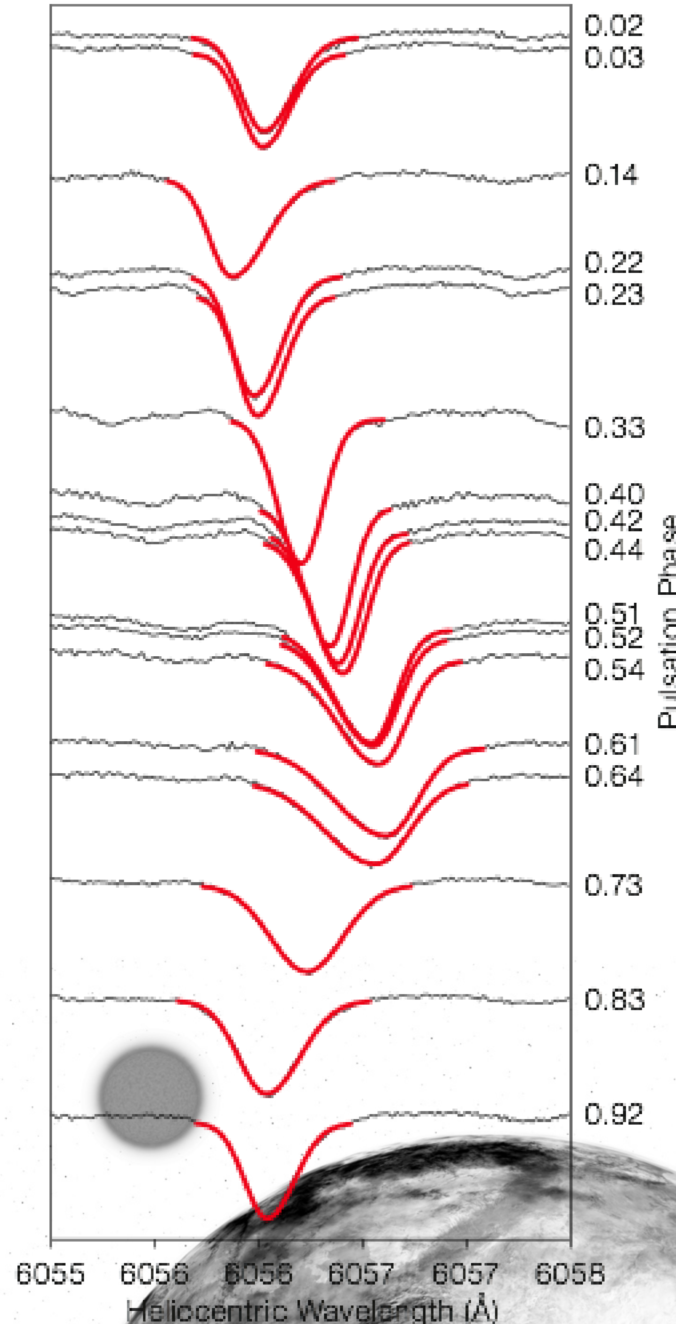
# Radial Velocities




Ensellem et al. (2004)




Griffin & Filiz (2010)

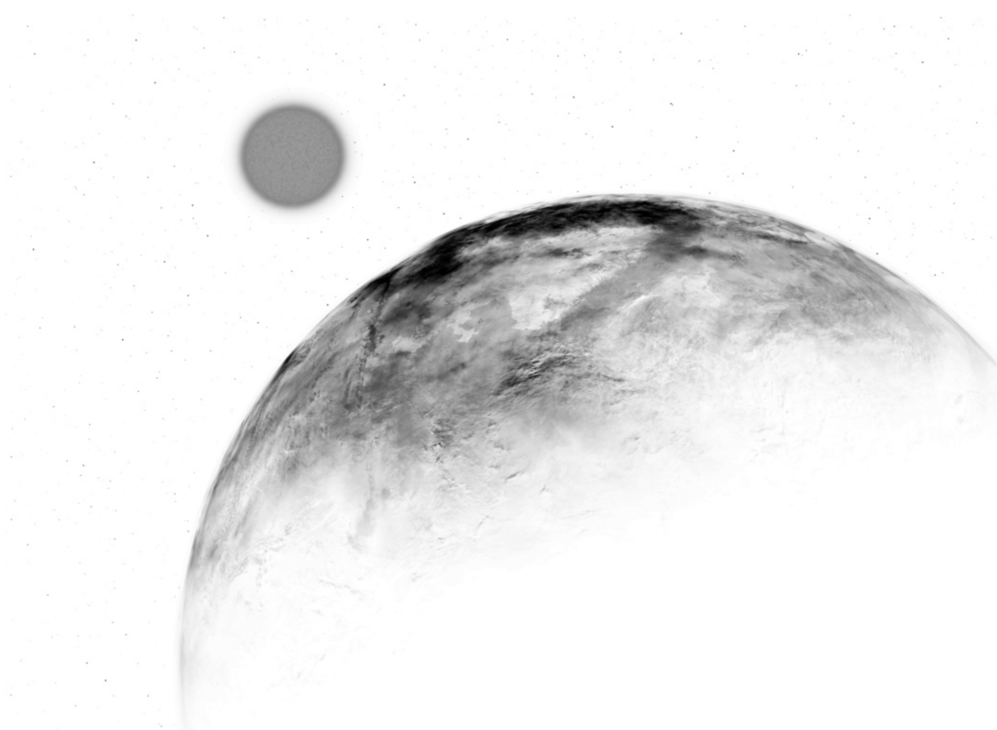



Nardetto et al. (2008)

# Spectrographs

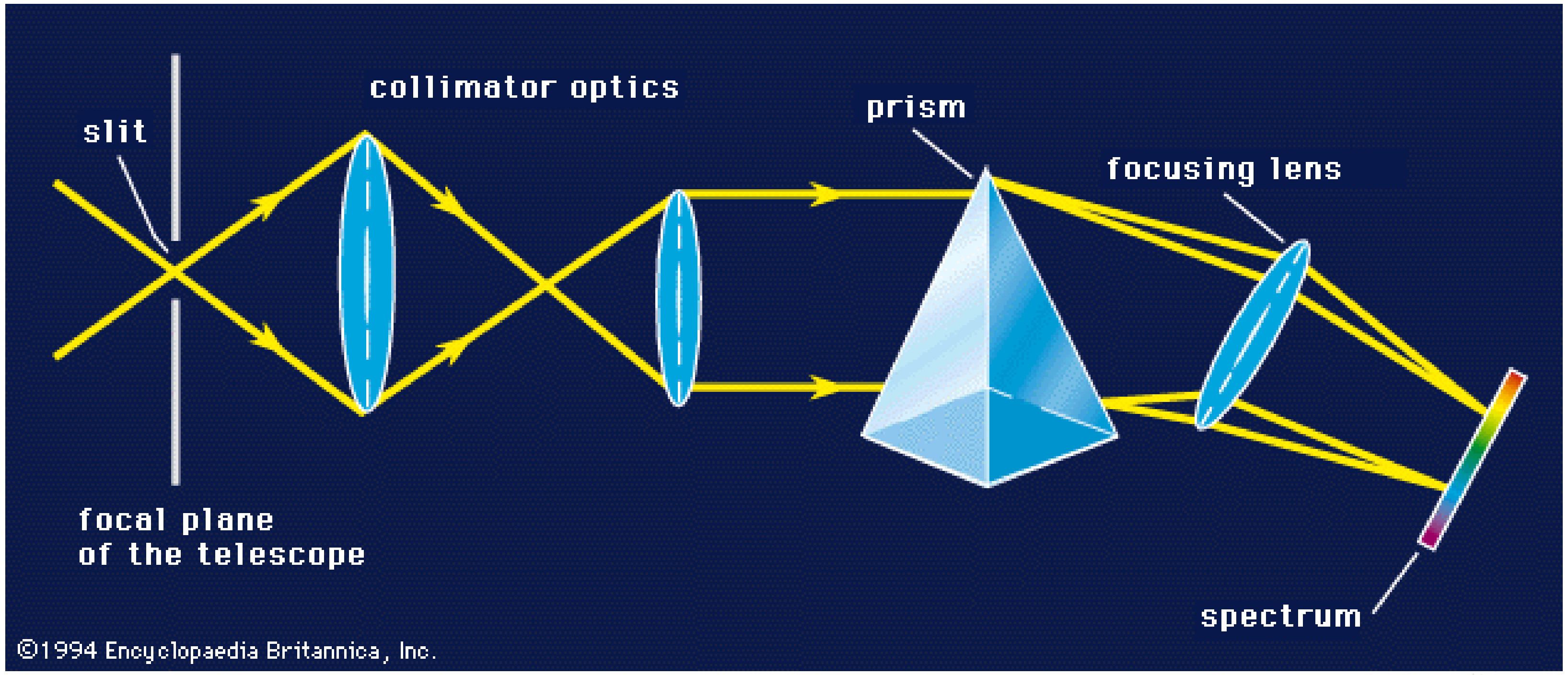
A spectrograph is an instrument that receives light from a telescope, disperses it creating a spectrum, and records it in a detector.

<u>But what is inside it?</u>



# Spectrographs

A spectrograph is an instrument that receives light from a telescope, disperses it creating a spectrum, and records it in a detector.



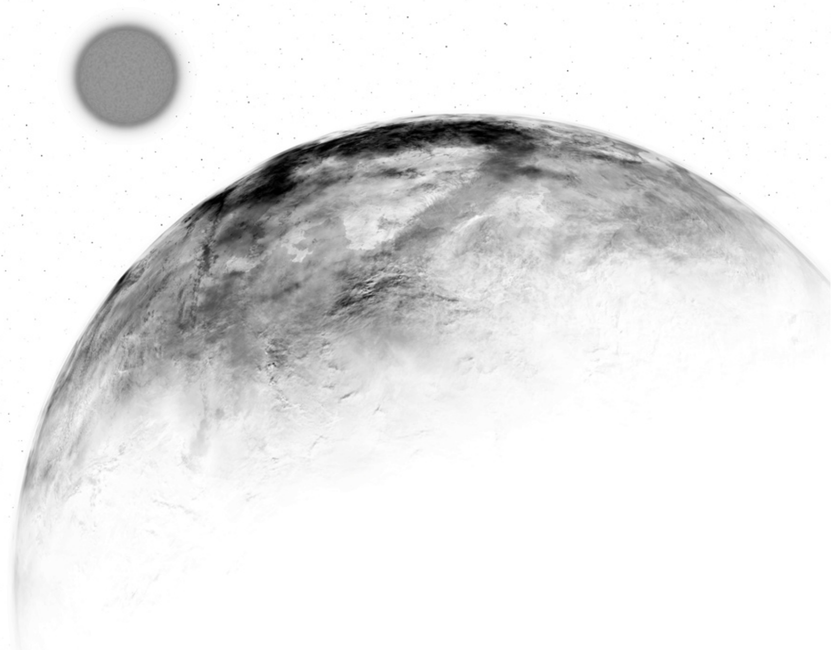

- Light Interface/Feeding (slit, fiber);
- Dispersive Element(s) (prisms, grisms);
- Detector (CCD, CMOS);
- Ancillary Optics;

# Spectrographs – Light feed

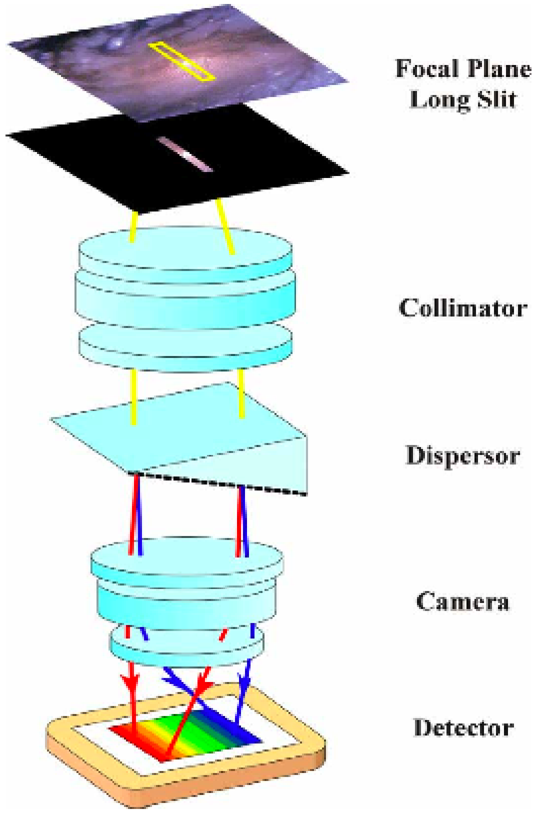
The first element of the spectrograph has a double function:

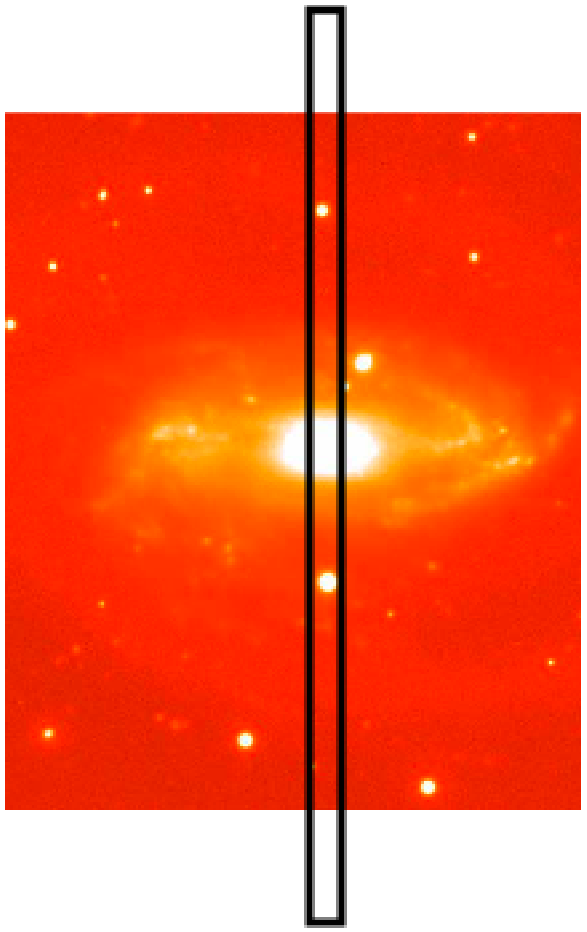
- Select the target(s) of interest in the field of view, so that only its light is fed into the spectrograph;
- Define spatially the resolution element: the image at the entrance of the spectrograph will be projected on the detector.

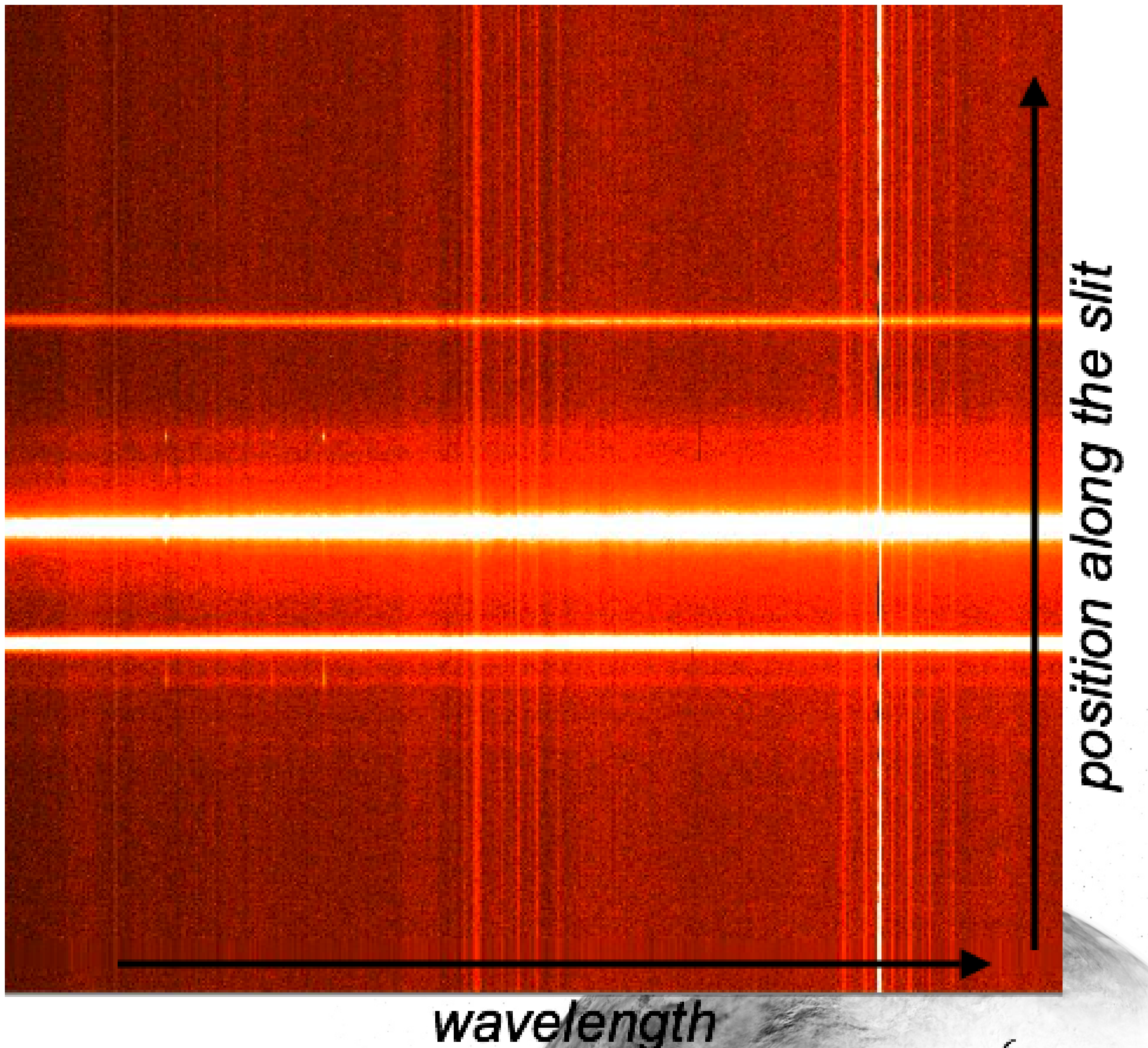
It can be a ***slit*** or a ***fiber***.



# Spectrographs – Slit



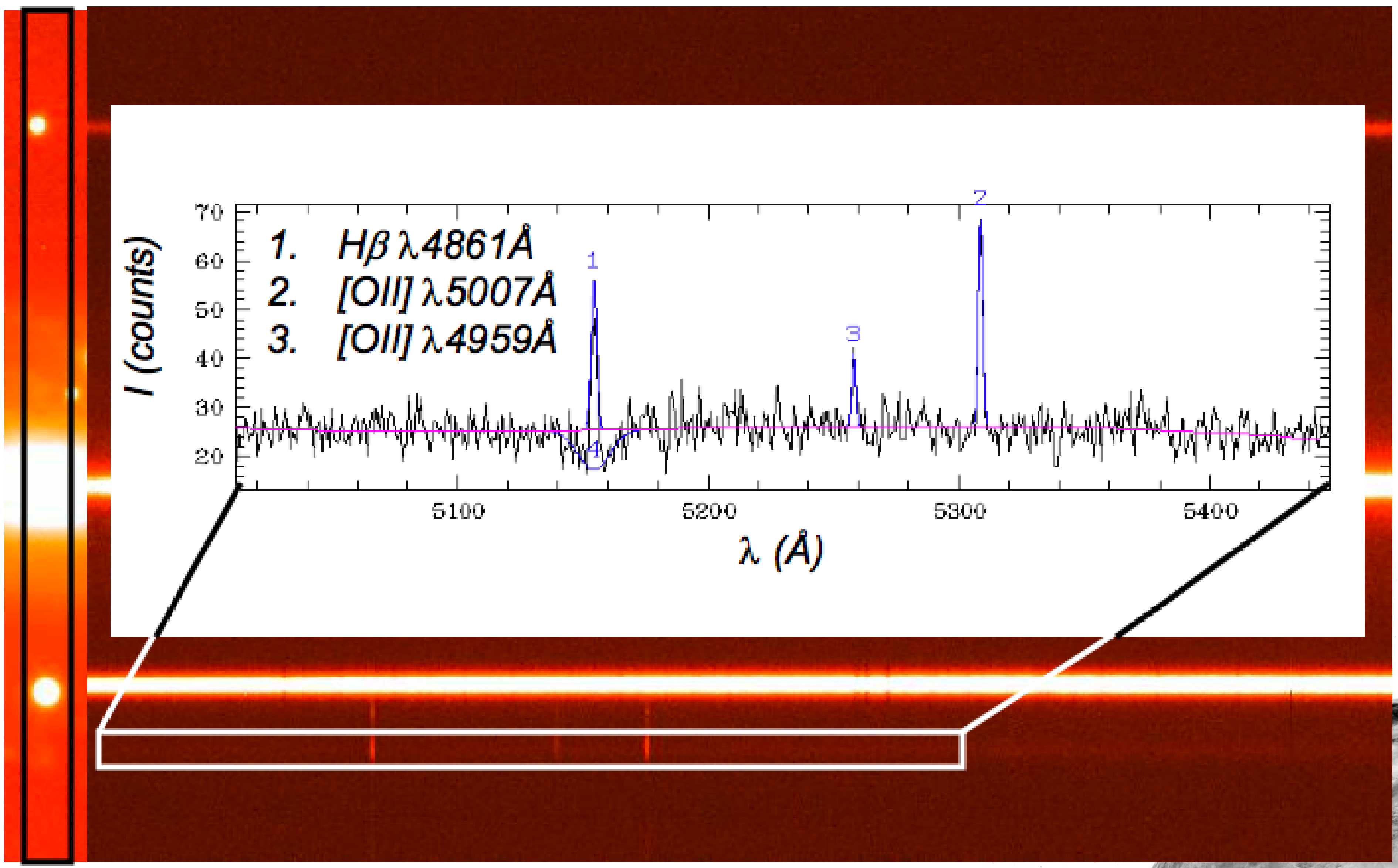







A slit is a mechanical aperture with 2 parallel jaws

# Spectrographs – Slit



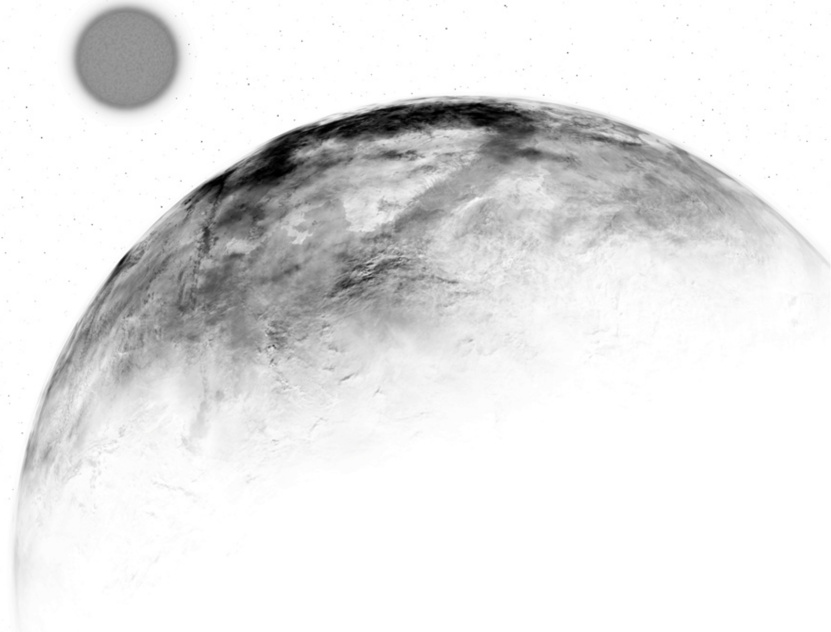
# Spectrographs – Slit

## Advantages:

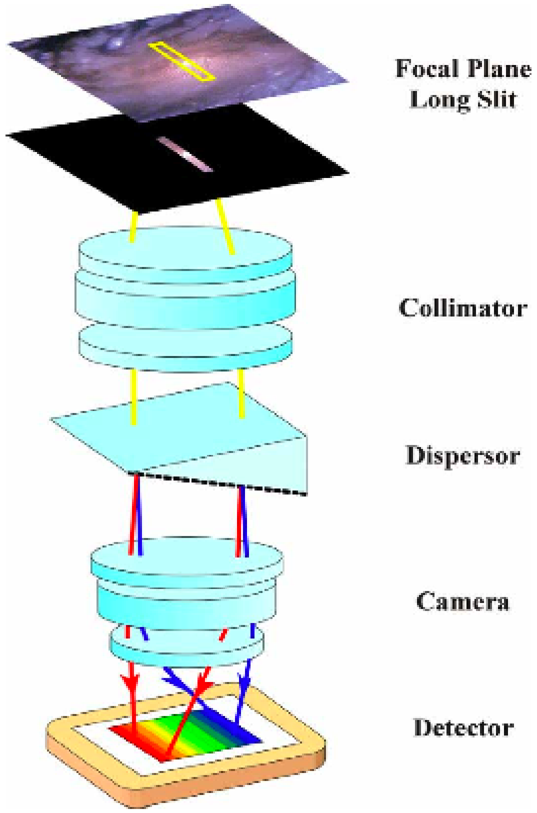
- Preserves one direction of the image - spatial direction - allowing several spectra to be obtained simultaneously, and opening many possibilities;
- One can change slit dimensions on the fly;
- Straightforward to implement.

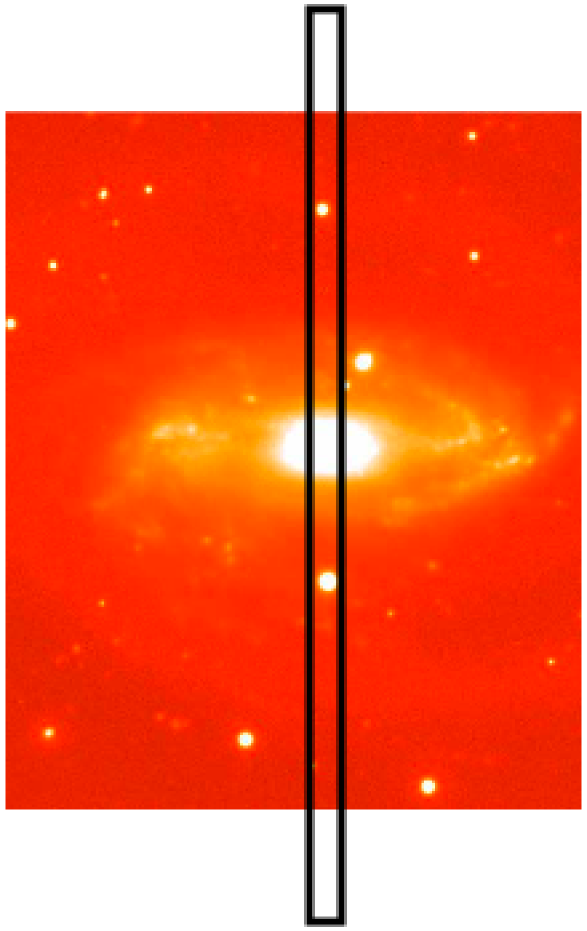
## Disadvantages:

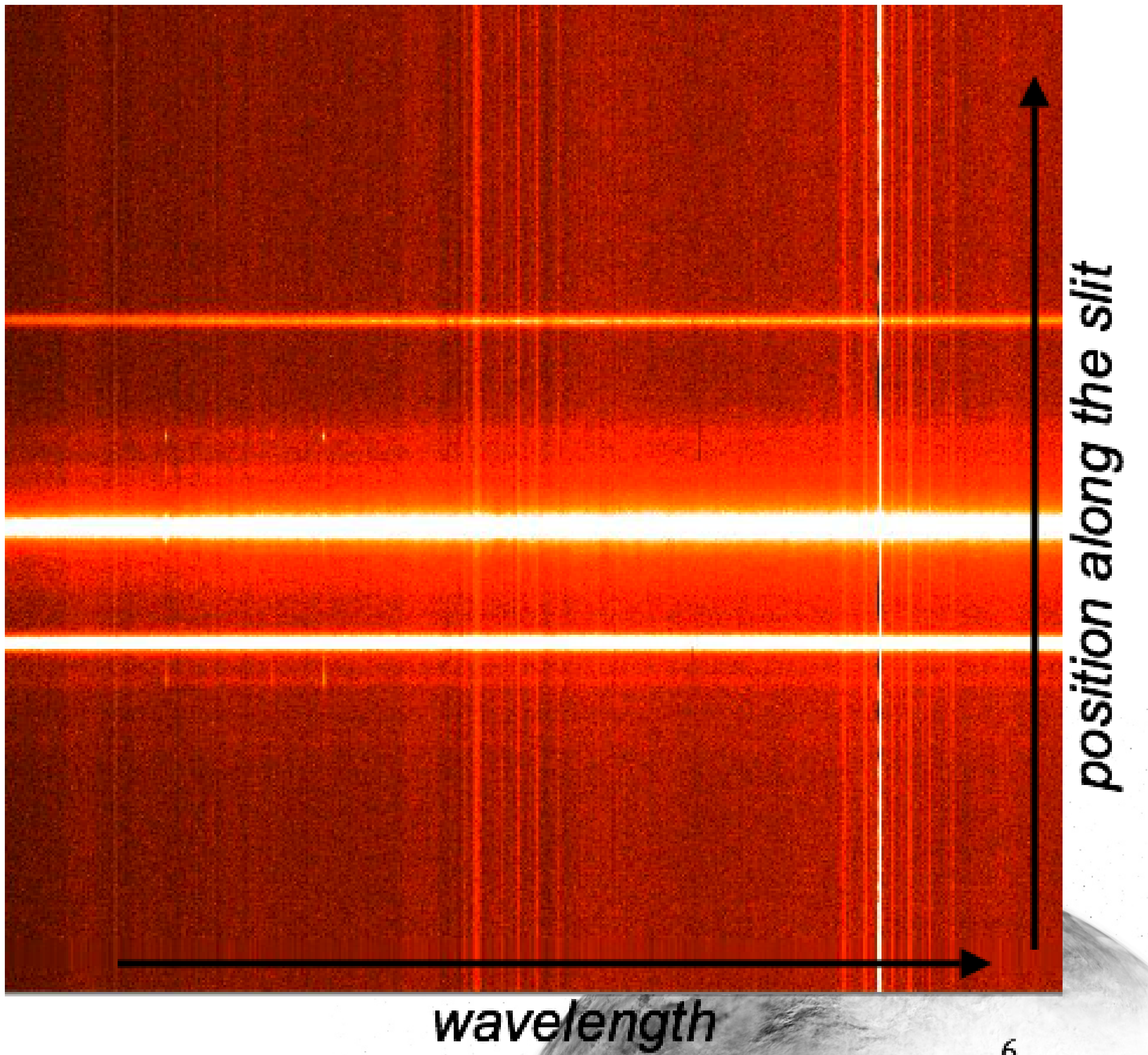
- Collected spectra sensitive to how illumination is done.



# Spectrographs – Slit





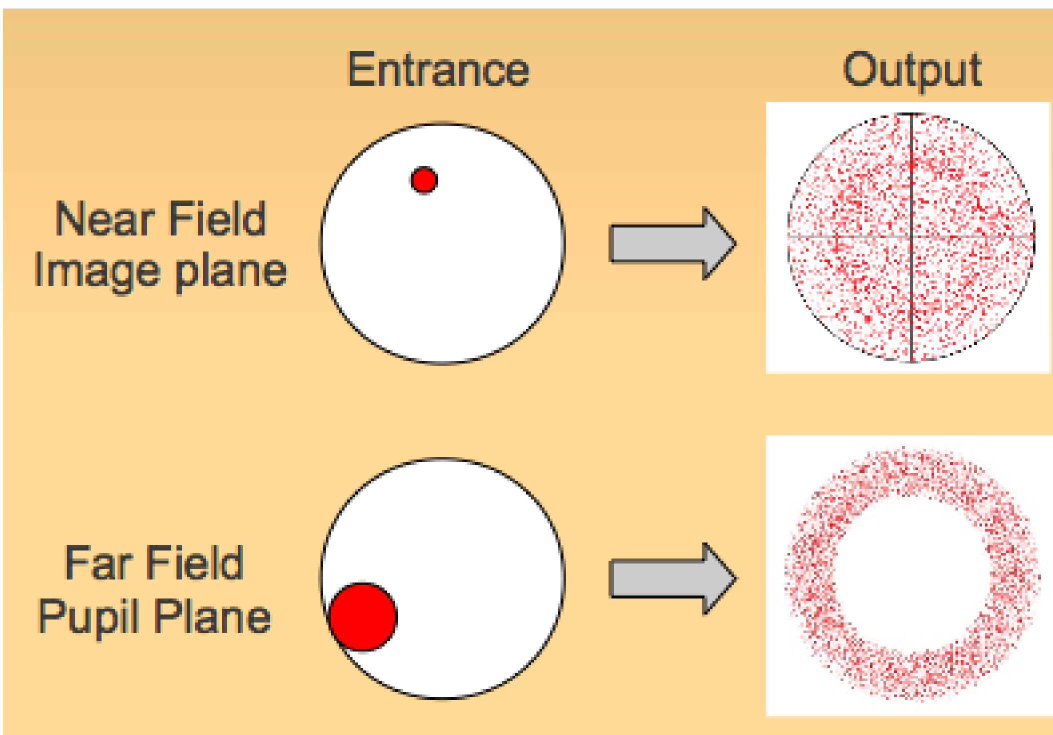





A slit is a mechanical aperture with 2 parallel jaws

# Spectrographs – Fiber

A fiber is a wave-guide that works based on the total internal reflection principle:




Chazelas et al. (2010)

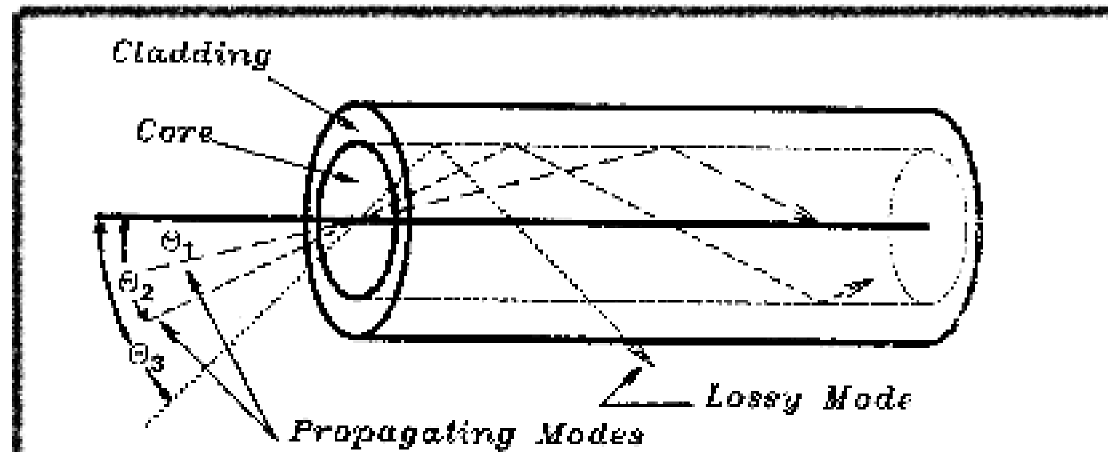



Fig. 1 A typical step index cylindrical fiber is shown with the axis indicated by the solid line. Modes are plane waves incident at a particular angle to the fiber axis. Several incident modes are shown with the dashed lines.

Ramsey (1988) ASPC

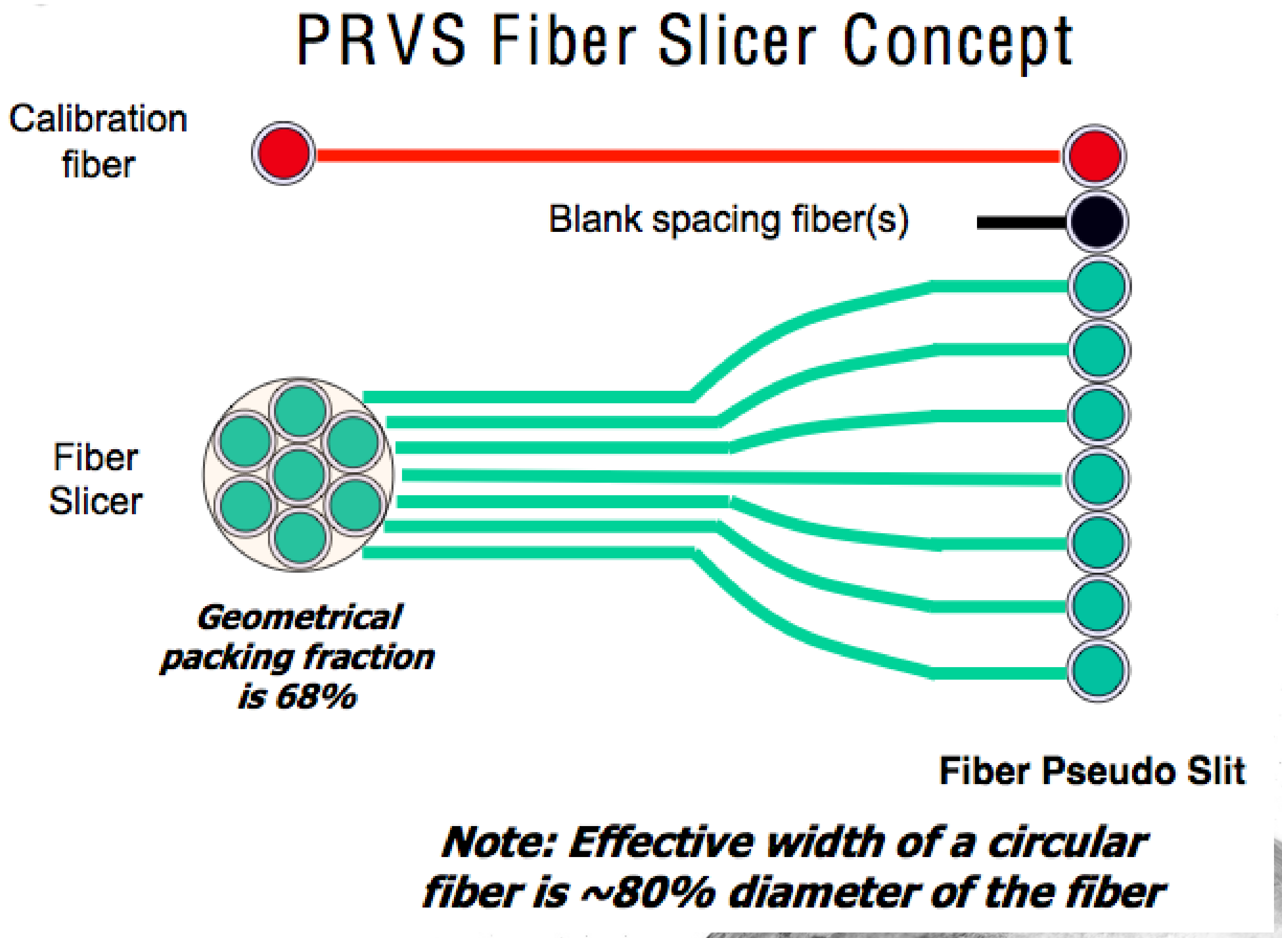
Usually composed of a fused silica core and a cladding.

# Spectrographs – Fiber

Main properties are: **spectral transmission, attenuation and focal ratio degradation**.

Microbends can increase FRD, illumination corrections are not perfect... tricky stuff.

But you can do some pretty neat stuff:




Ramsey (2010) , PRV conference

# Spectrographs – Fiber

Advantages:

- Good azimuthal scrambling (good in azimuthal, but imperfect in radial direction);
- The spectrograph does not need to be mounted at the telescope;
- Multi-source spectroscopy using several fibers.

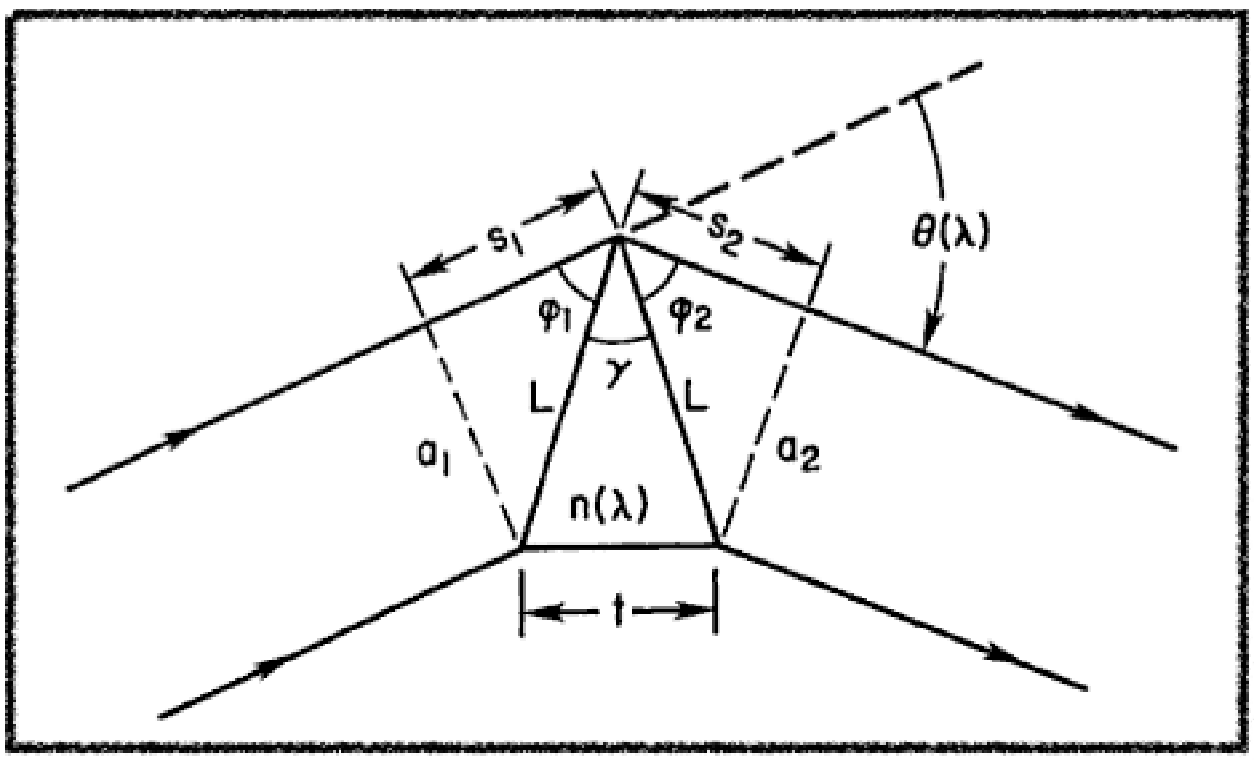
Disadvantages:

- All light sources inside the FOV of the fiber are fed in the detector in the same position, creating a composite spectrum;
- Loss of light at the fiber interface;

# Dispersive elements

Dispersive elements can be ***prisms*** or ***gratings***:

A prism is a refracting optical element that uses Snell's law and the fact that n=n(λ) to disperse incoming light.

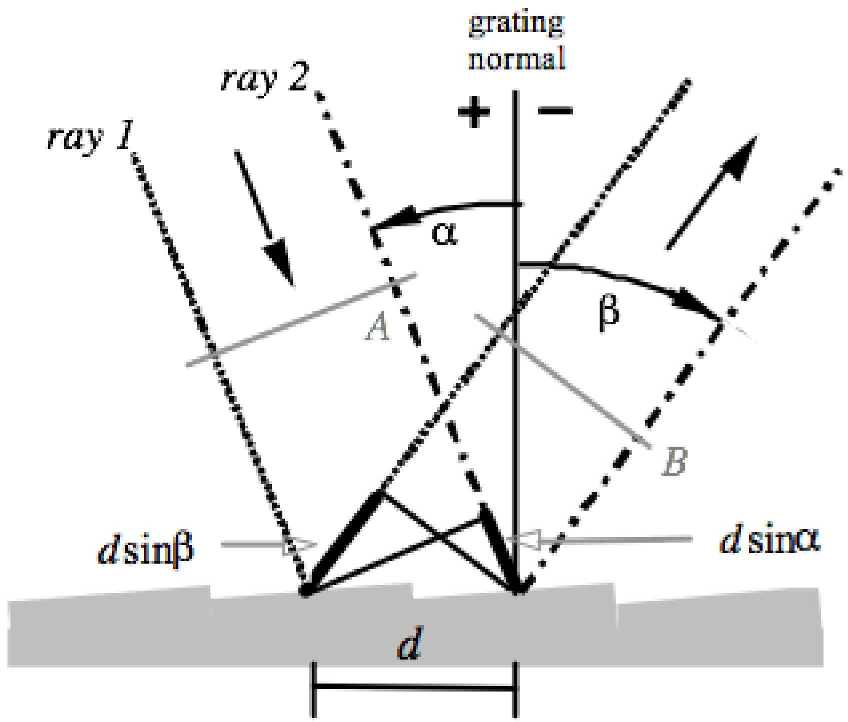



from Astronomical Optics, Schroeder

# Dispersive elements

"A diffraction grating is a collection of reflecting (or transmitting) elements separated by a distance comparable to the wavelength of light under study. It may be thought of as a collection of diffracting elements, such as a pattern of transparent slits (...) or reflecting grooves (...)."

from "Newport Diffraction Grating Handbook"

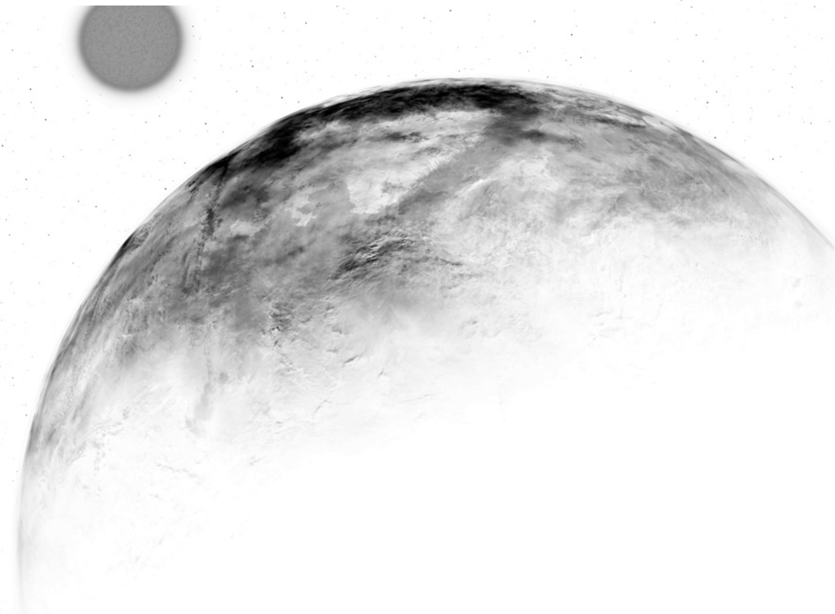



$$m\lambda = d(sin\alpha + sin\beta)$$

<=>

$$\beta(\lambda) = arcsin\left(\frac{m\lambda}{d} - sin\alpha\right)$$

The equation has multiple solutions, of which one is "*Littrow*": α=β



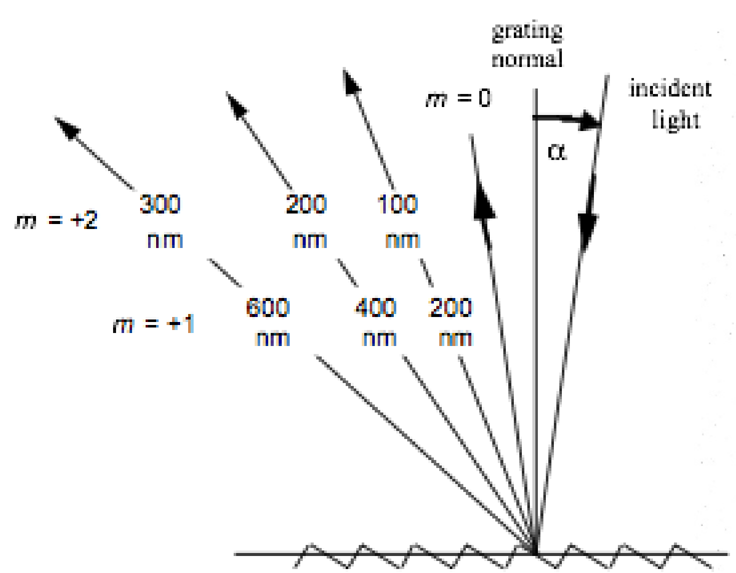
# Dispersive elements

The angular dispersion can be found by differentiating the last equation:

$$\frac{d\beta}{d\lambda} = \frac{m}{d cos\beta} = \frac{sin\beta + sin\alpha}{\lambda cos\beta}$$

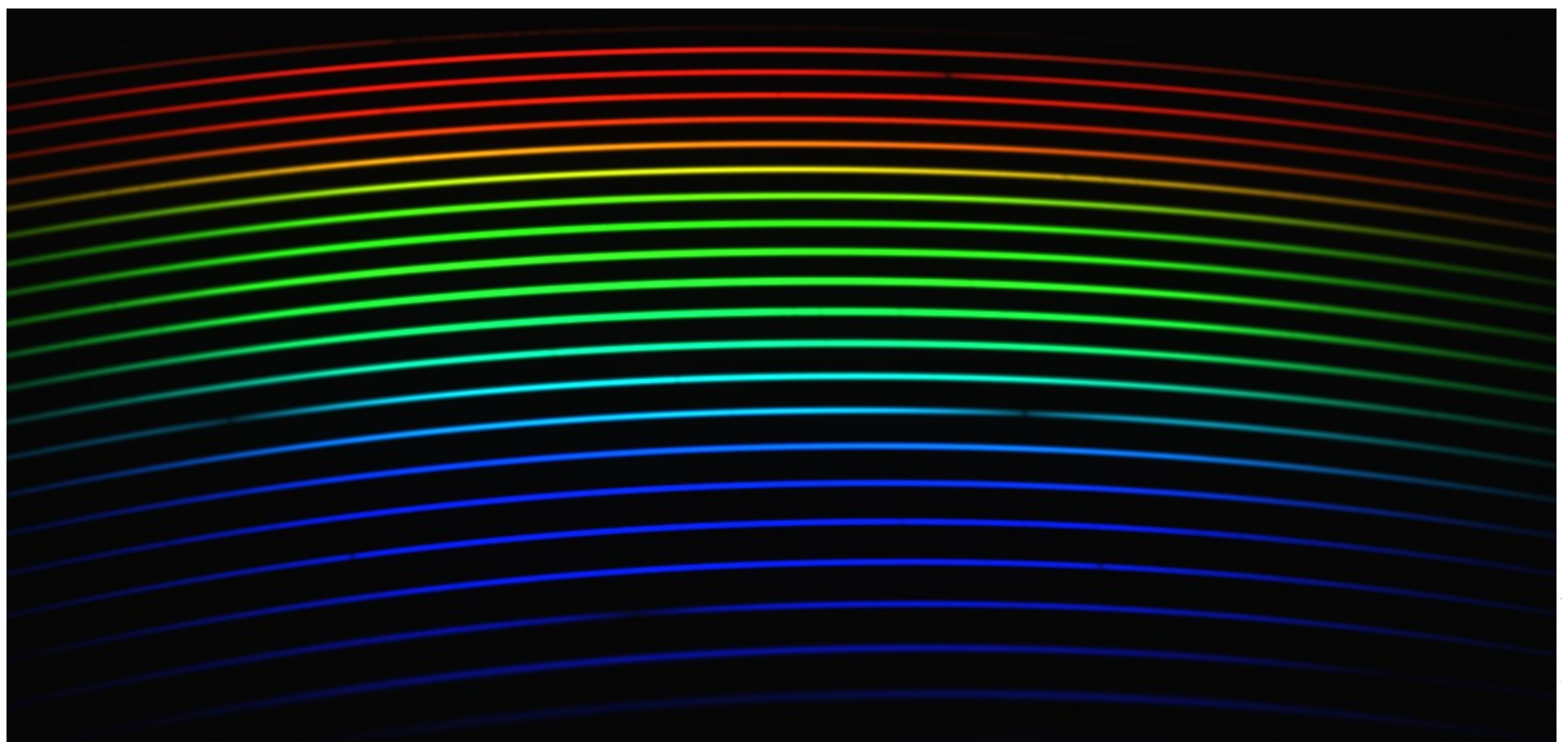
which shows that for a given λ, ***the angular dispersion depends only on α and β***.
The most favorable case is Littrow with a grazing angle

## The problem:



# Echelle spectrographs

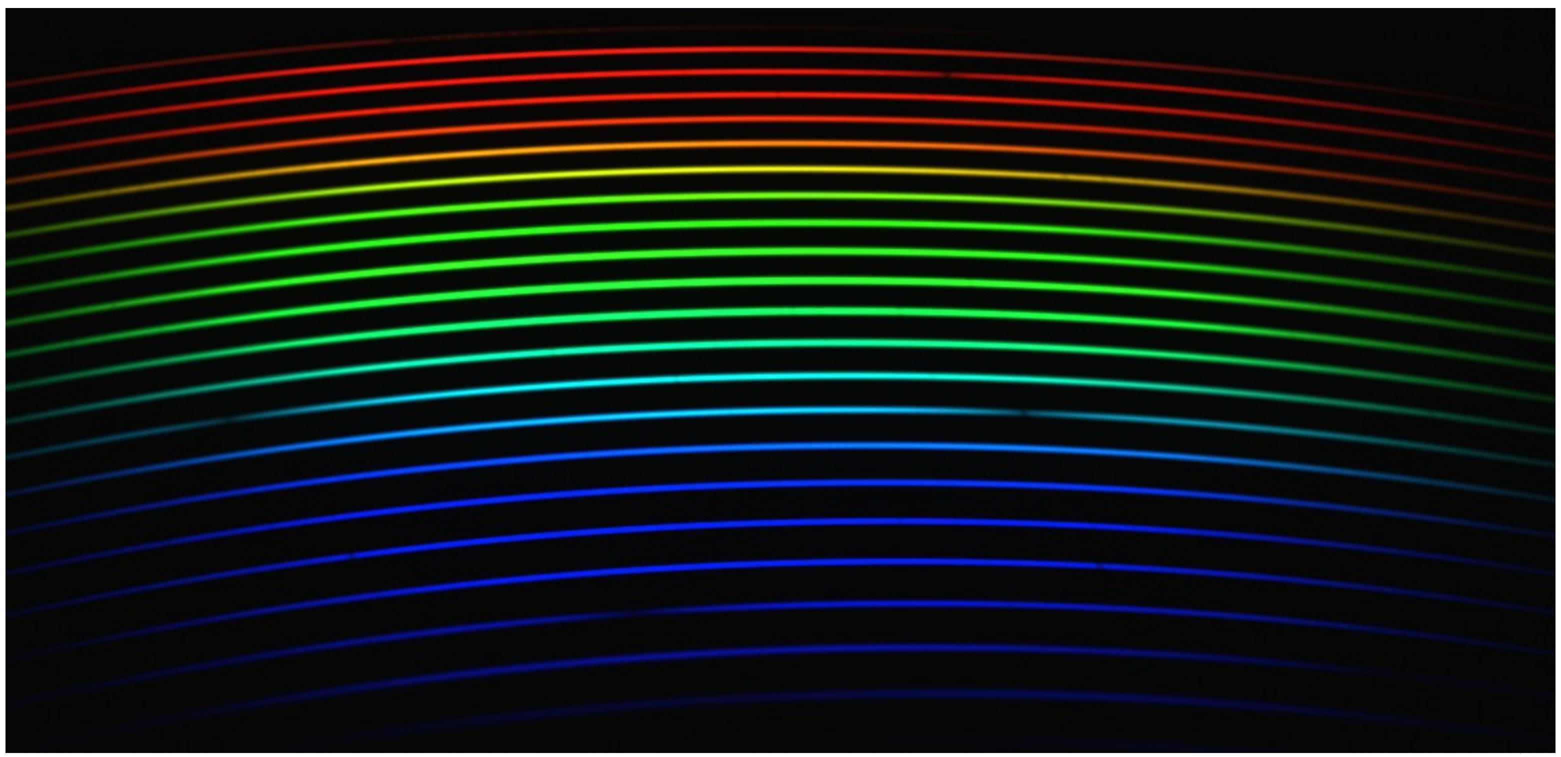
The overllaping orders are then ***cross-dispersed***, projecting a set of parallel orders on the detector.

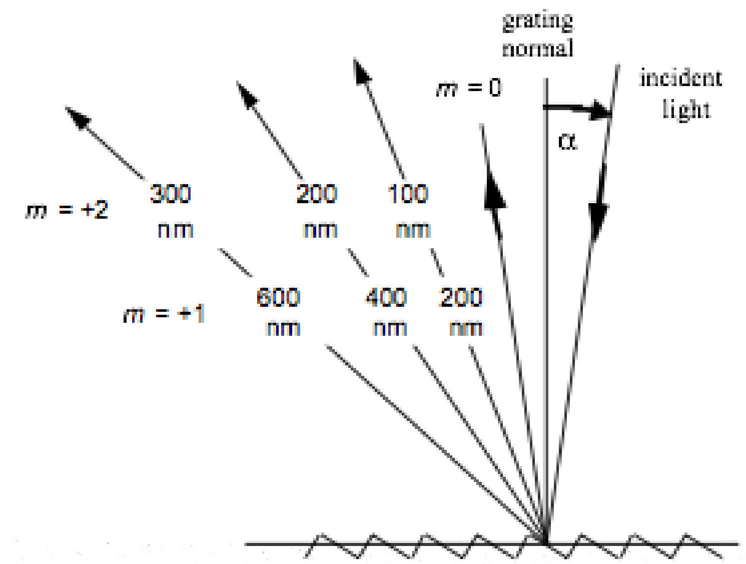


One of the most common gratings are called ***echelle gratings***. These are coarse gratings with large blaze (tilted) angles using with high-number orders

# Echelle spectrographs

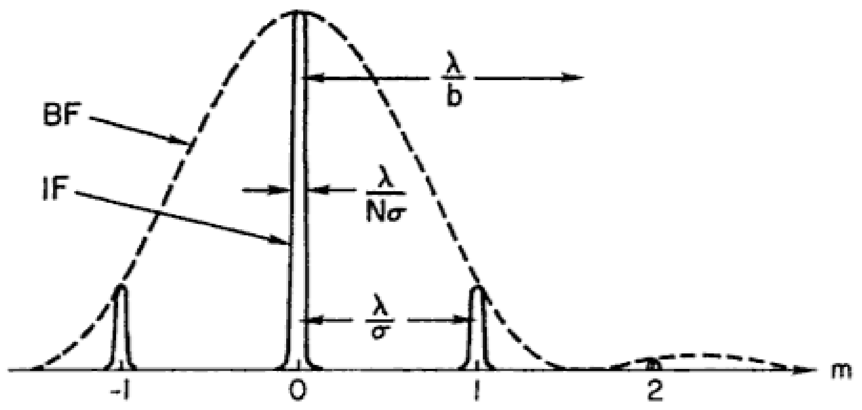
*<u>Why do we use high-number orders when fitting many orders in a detector?</u>*



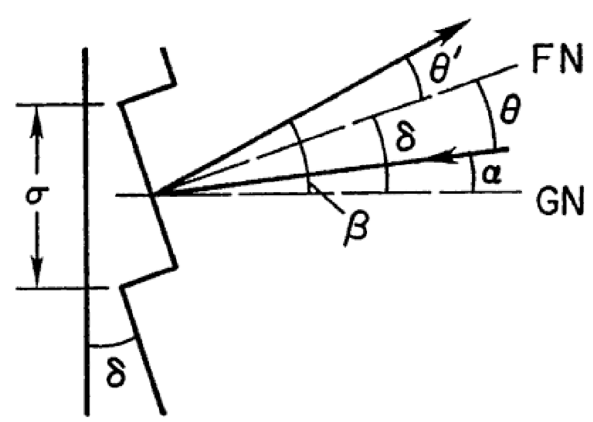


# Dispersive elements II

How does intensity vary with order m?



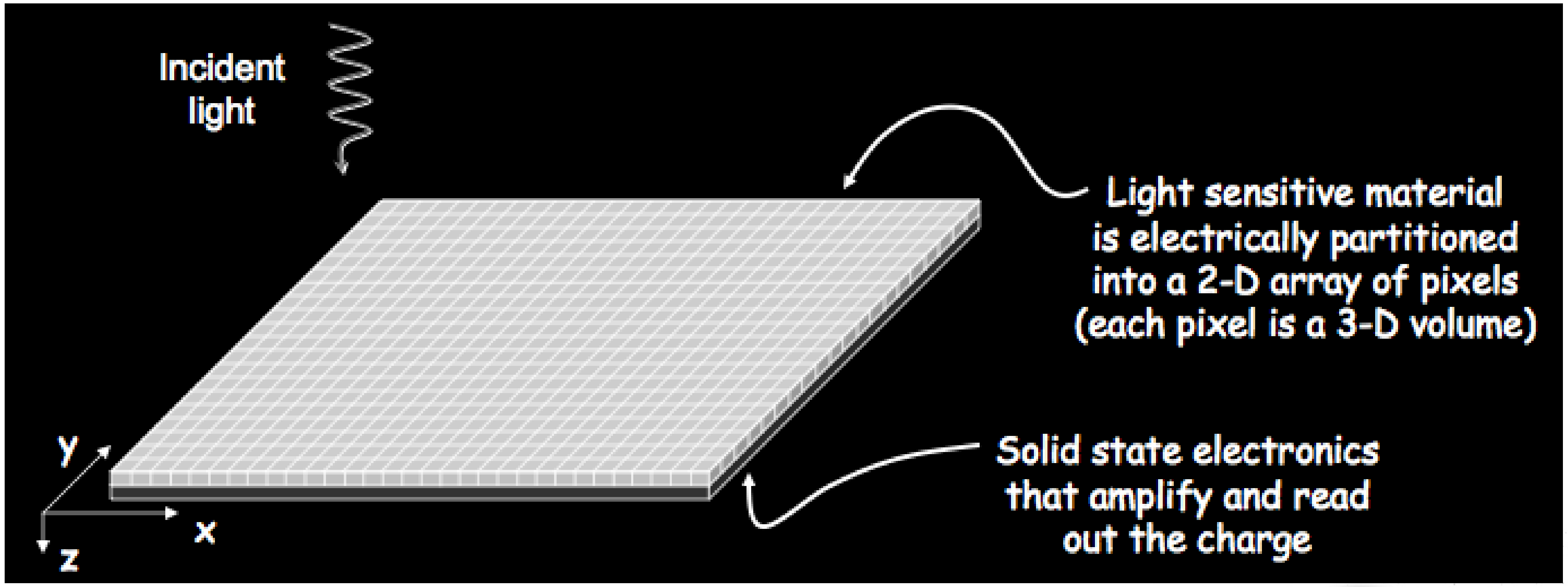

What we can do is tilt the grooves by an angle δ (blaze angle). This will displace the reflecting normal and the order with higher intensity will be




If α=β=δ: Littrow Blaze condition

# Detectors

Detectors are devices that transform the incident light into an electric charge. Detectors can be CCD or CMOS, depending on the electronics



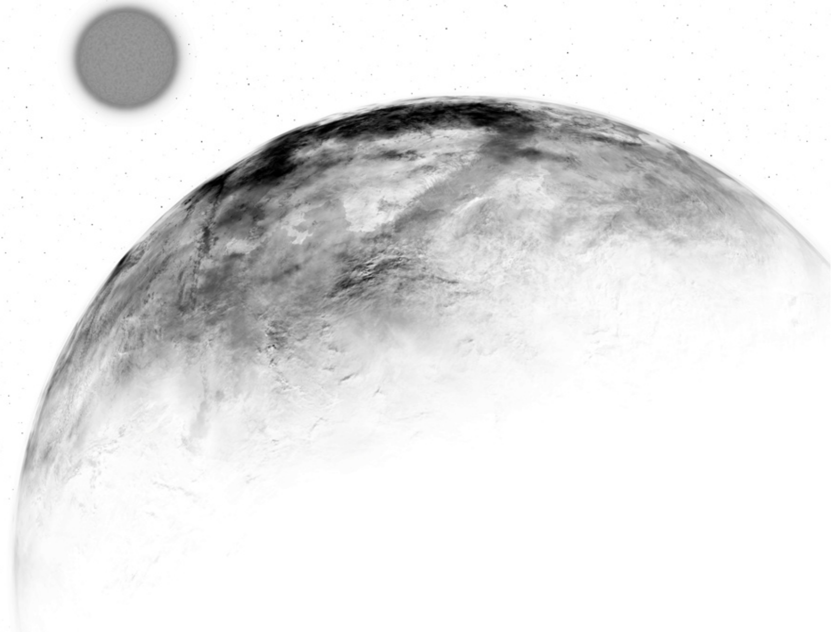

The transformation is done by ***photoelectic effect***.

For fascinating details check the Handbook of CCD astronomy or James Beletic courses

# Detectors

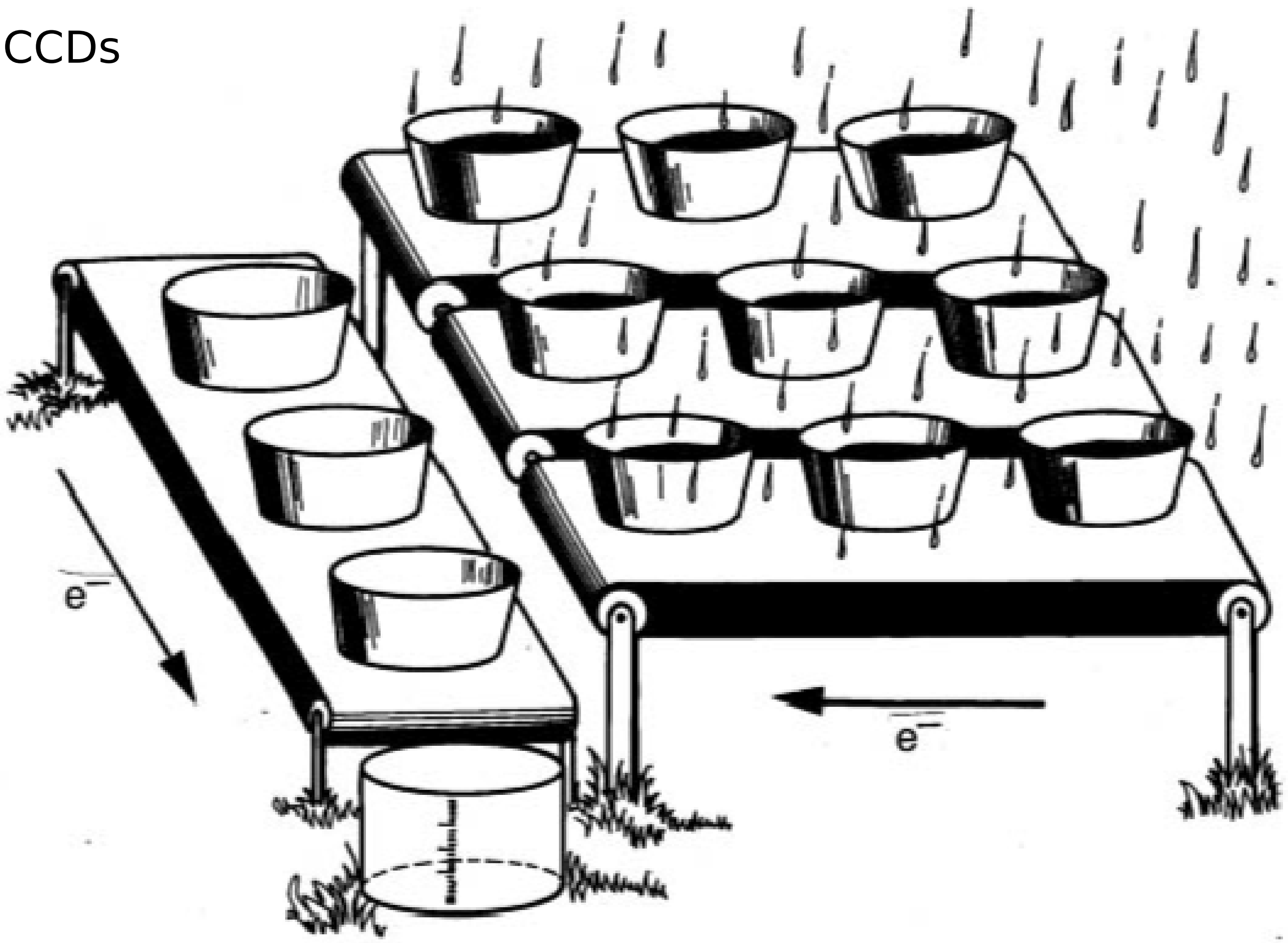
| Material | Symbol | $\varepsilon_g$ [eV] | $\lambda_c$ [$\mu m$] | $T_{op}$ [K] |
|---|---|---|---|---|
| Silicon | Si | 1.12 | 1.1 | 163 - 300 |
| Mer-Cad-Tel | HgCdTe | 0.09 - 1.00 | 1.24 - 14 | 20 - 80 |
| Indium Antimonide | InSb | 0.23 | 5.5 | 30 |
| Arsenic doped Silicon | Si:As | 0.05 | 25 | 4 |

When working in the nIR first main difference is in the detector material; **Si λ cutoff at 1.1μm** makes it useless as infrared photon collection and imposes a **different detector architecture choice**



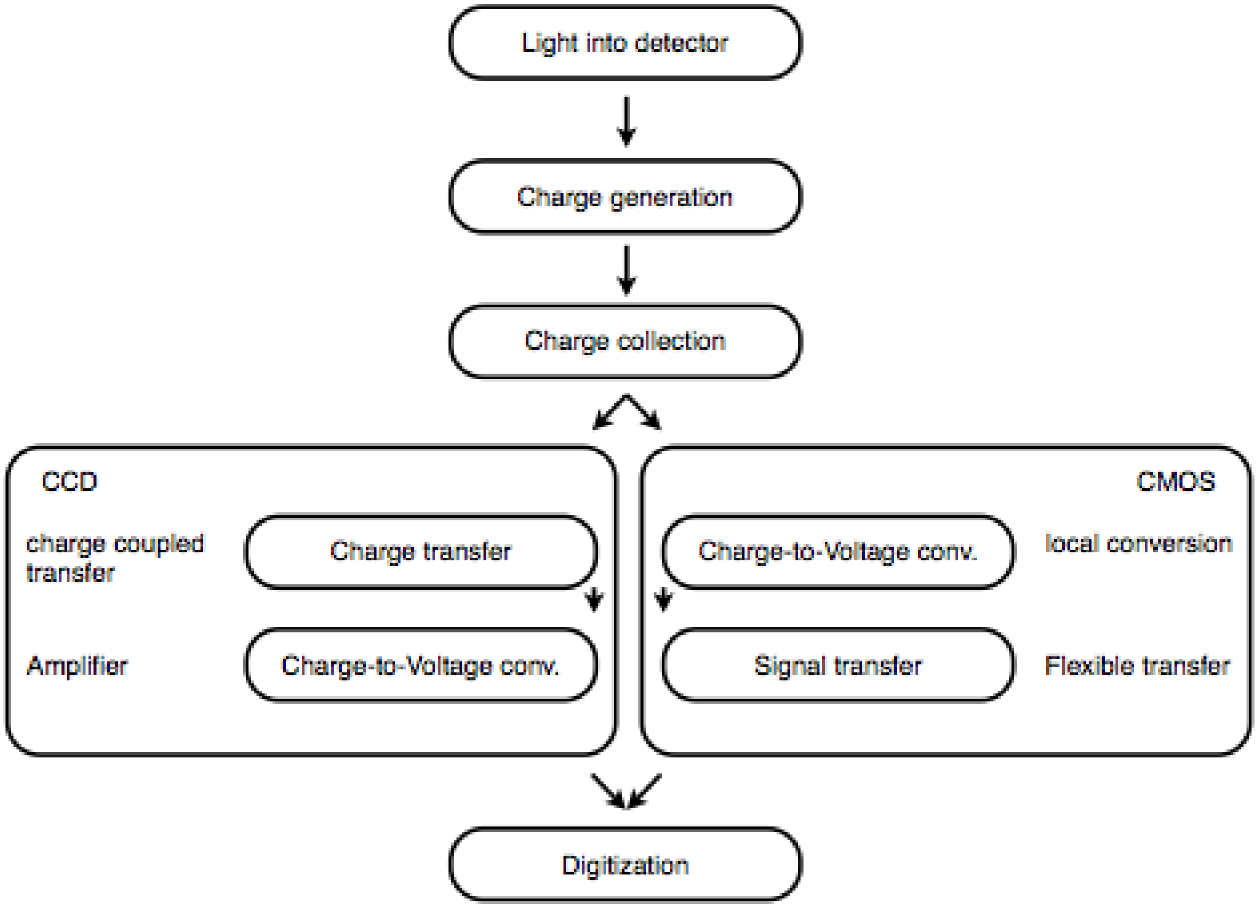
# Detectors

CCDs




The only material we can dope in order to make CCDs is Silicium; that’s why IR detectors are condemned to be CMOS.

# Detectors

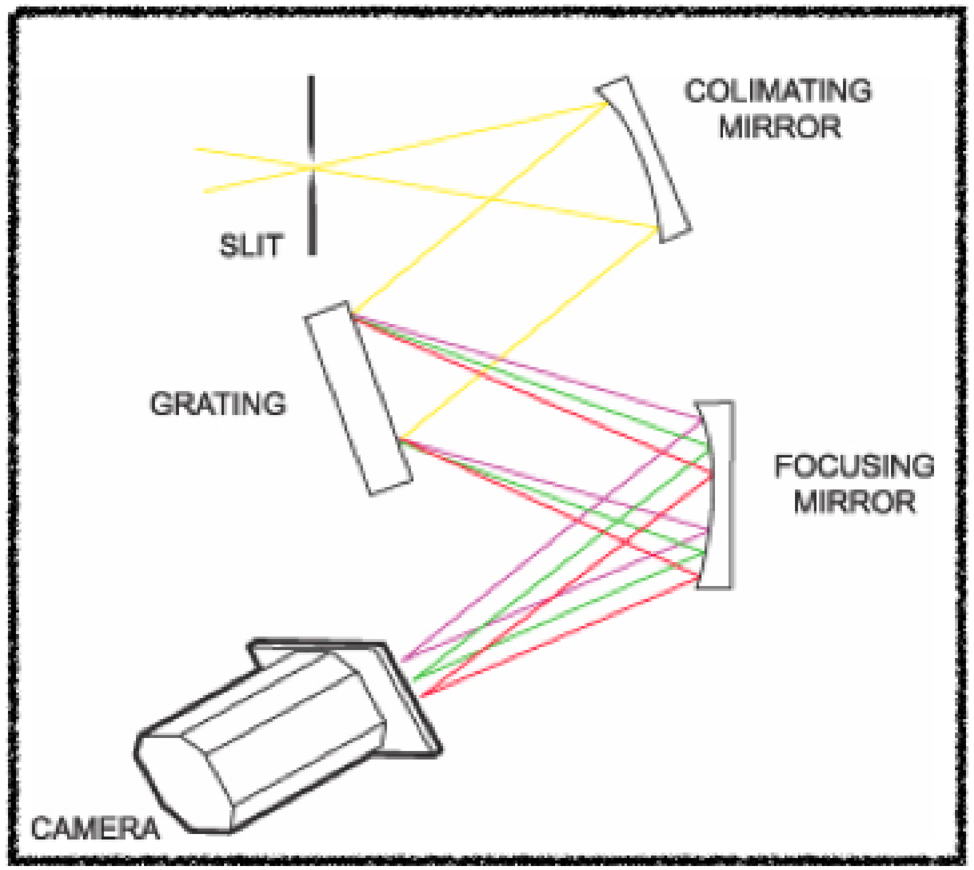



The detector's main properties (there are many others) are:

- Quantum efficiency;
- Gain (overall and pxl-to-pxl);
- Read-out Noise and time;
- Bias and Dark Current.

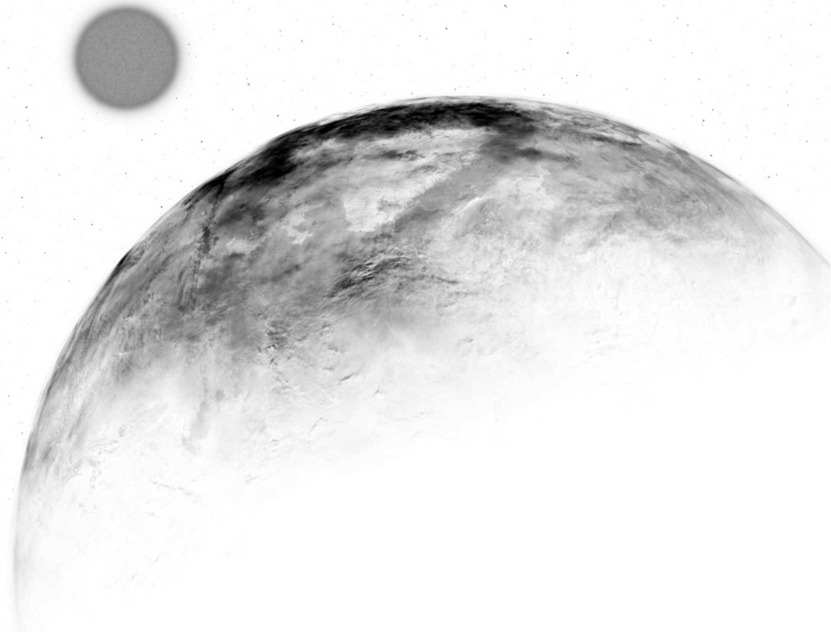
The two main type of detectors are CCD (Charge-Coupled Device) and CMOS (Complimentary Metal Oxide Semiconductor).

# Optics

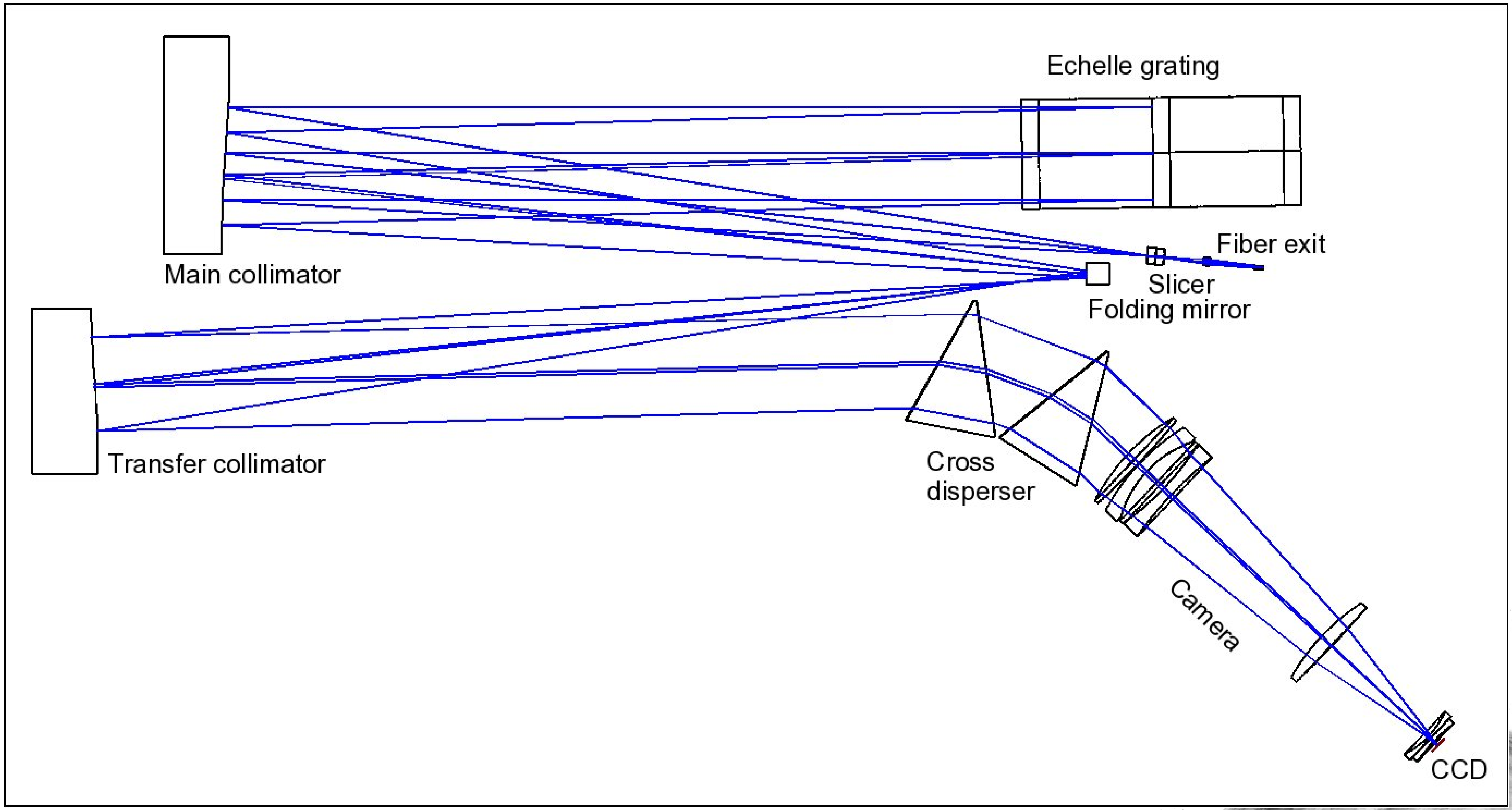



The optics usually consist of:

- Collimating mirror after the slit/fiber;
- lens/mirror to focus the diffracted light into the detector;
- ancillary optics.

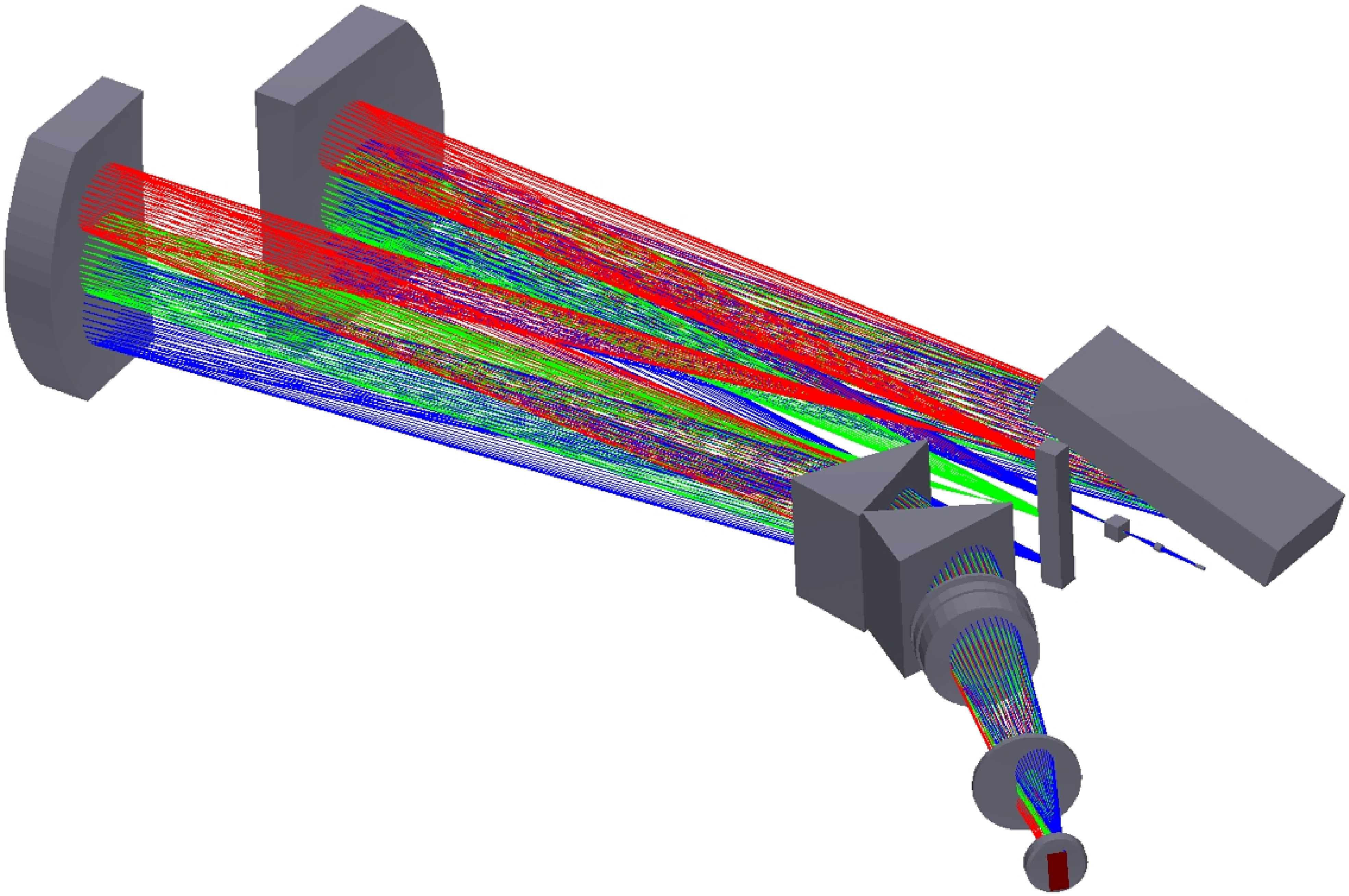


# Optics: Hermes




Source:
http://www.mercator.iac.es/instruments/hermes/

# Optics: Hermes

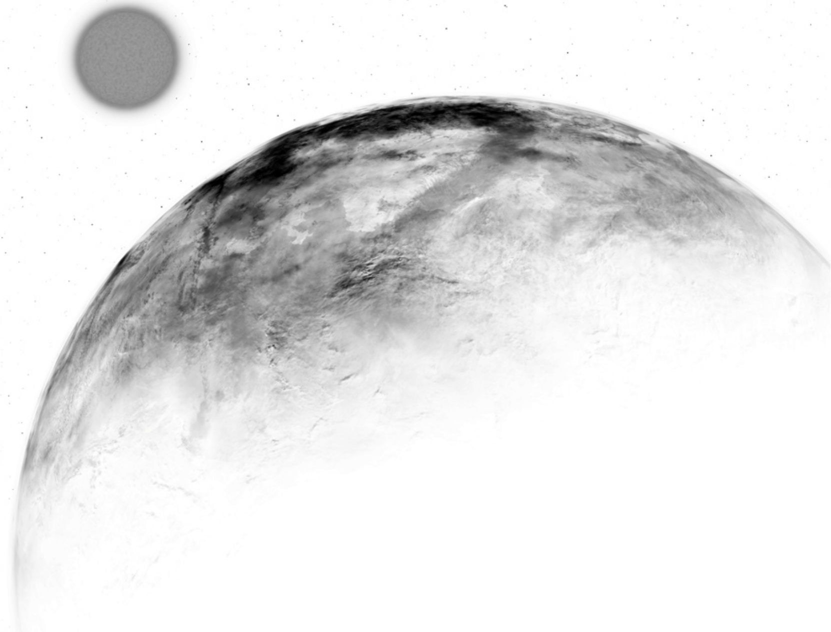


Source:
http://www.mercator.iac.es/instruments/hermes/

# Spectrographs

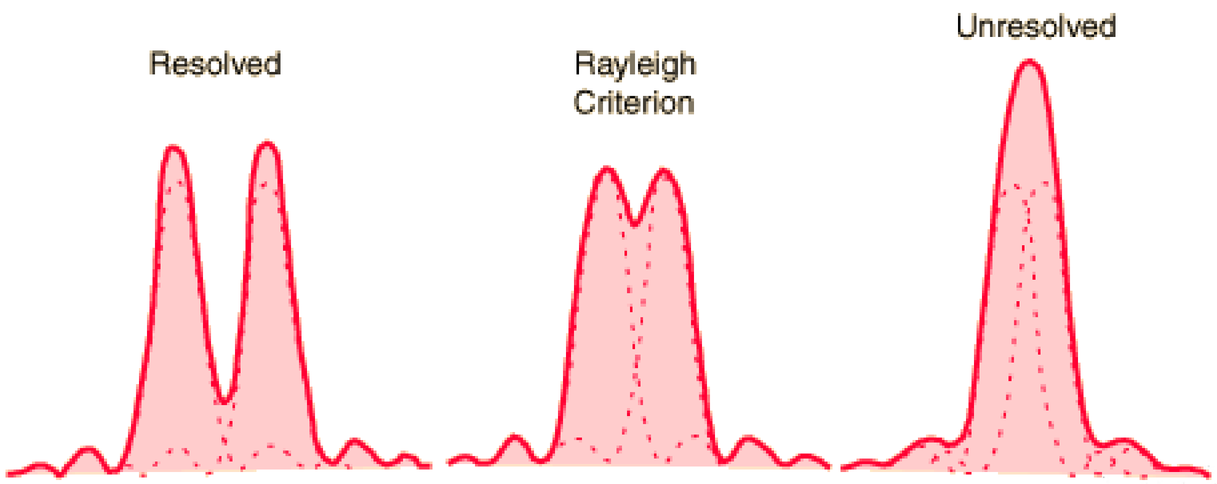
The main properties of a spectrograph are those that have an impact on the spectra, and can thus be considered as properties of the produced spectra:

- Wavelength Range;
- Transmission/Efficiency;
- Resolution;
- Sampling;
- IP Quality & Stability.



# Resolution

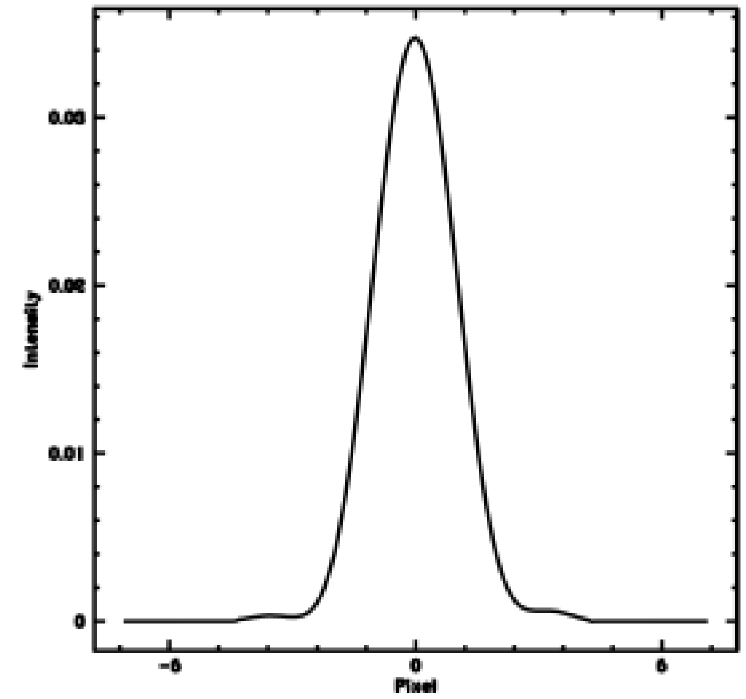
Theoretically, Δλ is defined by the Rayleigh criterion: it is the limit of resolution, ***the smallest difference in wavelength between two lines of equal intensity that can be distinguished***.




In practice, we can use a line with $FWHM_{int}/\lambda << 1/R$ and measure the $FWHM_{obs}$.

# Resolution

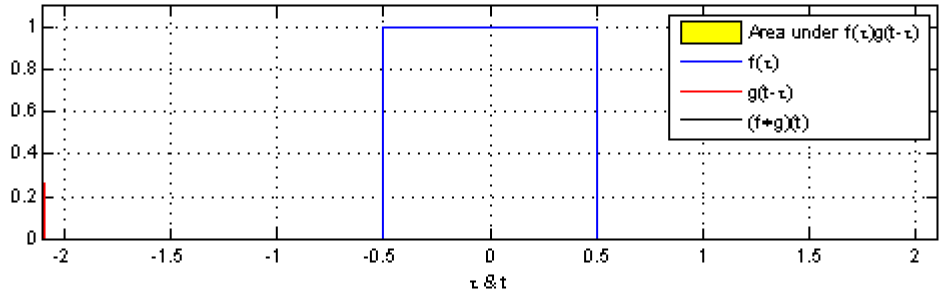
The spectrograph convolves the infinite-resolution spectrum (from the source) with the instrumental profile (IP).



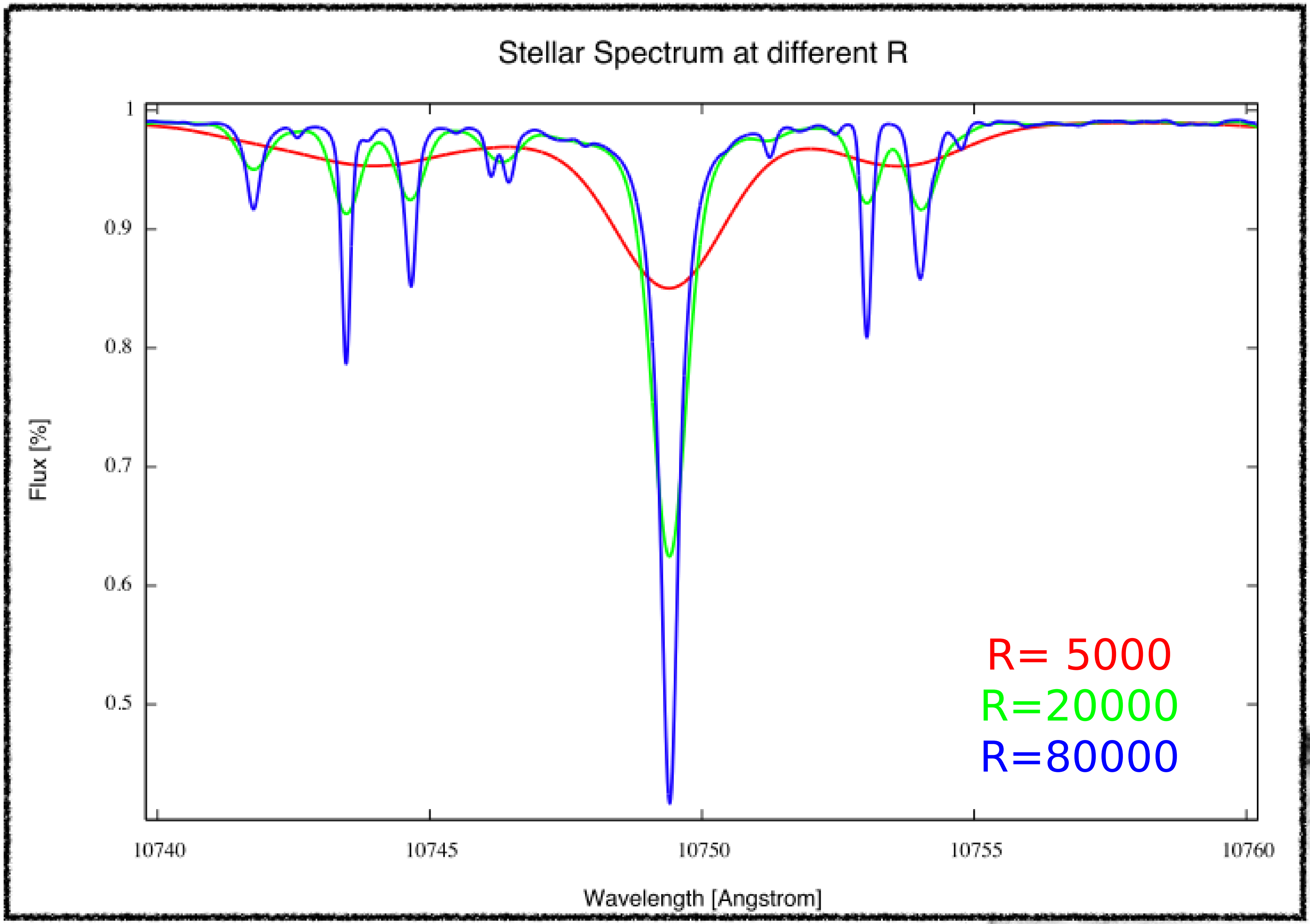
UVES IP from Lovis Diploma Thesis (2002)

Convolution:

$$(f * g)(t) \stackrel{\mathrm{def}}{=} \int_{-\infty}^{\infty} f(\tau)\, g(t-\tau)\, d\tau$$



# Resolution

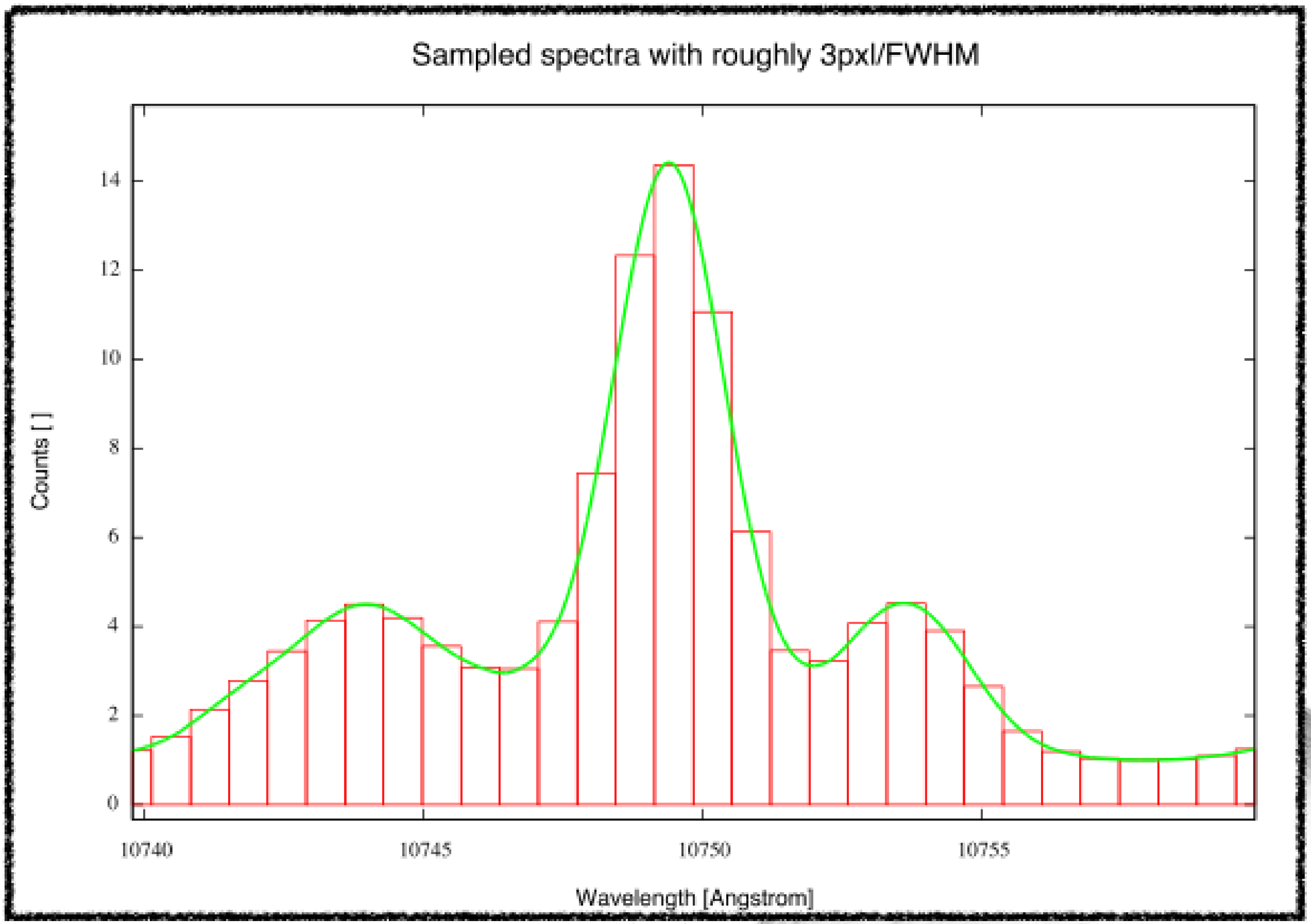


Stellar Spectrum at different R
Flux [%]
1
0.9
0.8
0.7
0.6
0.5
10740
10745
10750
10755
10760
Wavelength [Angstrom]
R= 5000
R=20000
R=80000

# Sampling

Sampling is the number of pixels used to record the light corresponding to one resolution element of the spectrograph

Nyquist Theorem tells us that the sampling must be equal or larger than two in order to avoid losing information



# Optical Quality & Stability

Remember that the ***Instrumental Profile*** (IP) is the profile which is convolved with the theoretical spectra (R=∞, perfect) by observing with the instrument.

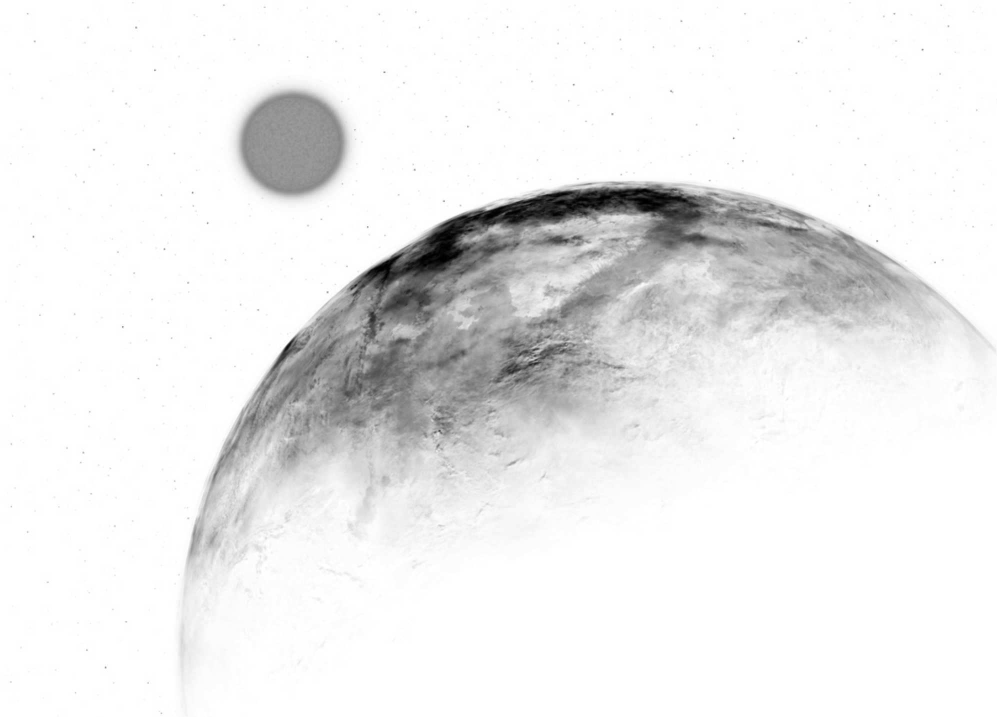
- The Optical Quality is the way the IP varies as function of wavelength, mainly due to optical properties such as aberrations;
- The Optical Stability is the stability of the IP as a function of time.

# Optical Quality & Stability

<u>What is the most frequently present and yet most undesirable optical component in a high-precision spectrograph?</u>

*(or if you prefer)*

<u>What characterizes the perfect (highest-precision) spectrograph?</u>



# Spectrographs @ ESO

| Instrument | Δλ | R | Telescope |
|---|---|---|---|
| CRIRES | 0.92-5.2 μm | <100 000 | UT1 |
| FLAMES | 370-950 nm | 5600 - 46 000 | UT2 |
| FORS2 | 330 - 1100 nm | 100 - 400 | UT1 |
| ISAAC | 1-5 μm | 180 - 10 000 | UT3 |
| NACO | 0.45 - 2.5 μm | 400 - 1100 | UT4 |
| SINFONI | 1.1 - 2.45 μm | 2000 - 4000 | UT4 |
| UVES | 300 - 1100 nm | 40 000 - 110 000 | UT2 |
| VIMOS | 360 - 1000 nm | 180 - 2500 | UT3 |
| VISIR | 8 - 13 μm | 350 - 25 000 | UT3 |
| X-SHOOTER | 300 - 2500 nm | 4000 - 14 000 | UT2 |
| SofI | 0.9 - 2.5 μm | 600 - 2200 | NTT |
| FEROS | 350 - 920 nm | 48 000 | 2.2m |
| HARPS | 380 - 690 nm | 115 000 | 3.6m |

Sources: http://www.eso.org/public/teles-instr/vlt/vlt-instr.html
http://www.eso.org/sci/facilities/lasilla/instruments/index.html

# RV precision

Bouchy, Pepe & Queloz (2001) calculated the optimal weight for each pixel assuming the noise follows $A(i)_{RMS} = \sqrt{A(i)+\sigma_D^2}$

They calculated the RV as the (infinitesimal) shift in a line between a reference spectrum without noise and a noisy one.

$$W(i) = \frac{\lambda^2(i)\,(\partial A_0(i)/\partial\lambda)^2}{A_0(i)+\sigma_D^2}$$

$$\frac{\delta v_{RMS}}{c} = \frac{1}{\sqrt{\sum_i W(i)}}$$

The information is contained on the ***slope of the spectrum***

Note: $A(i)$ - flux measured at pixel i, $A_0(i)$ - flux value in noiseless spectra, $\lambda(i)$ - wavelength at pixel i, $\sigma_D$ - detector read-out noise.

# RV precision

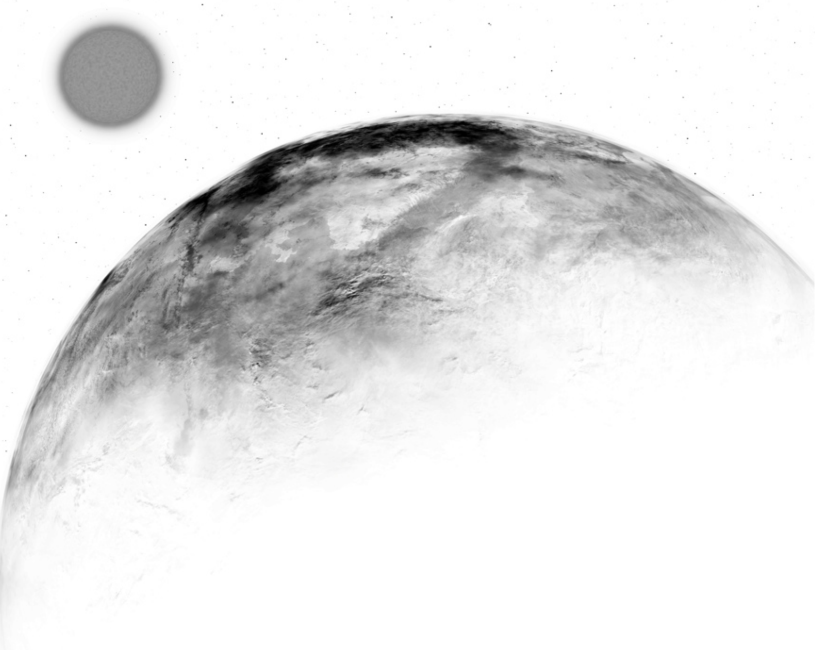
Hatzes & Cochran (1992) presented a (very) general formula that exhibited for a spectrum the properties we saw for single lines:

$$\sigma \propto \frac{1}{\sqrt{F}\,\sqrt{\Delta\lambda}\,R^{1.5}}$$

A different way of writing this is to apply BPQ (2001) to a Gaussian line. This delivers:

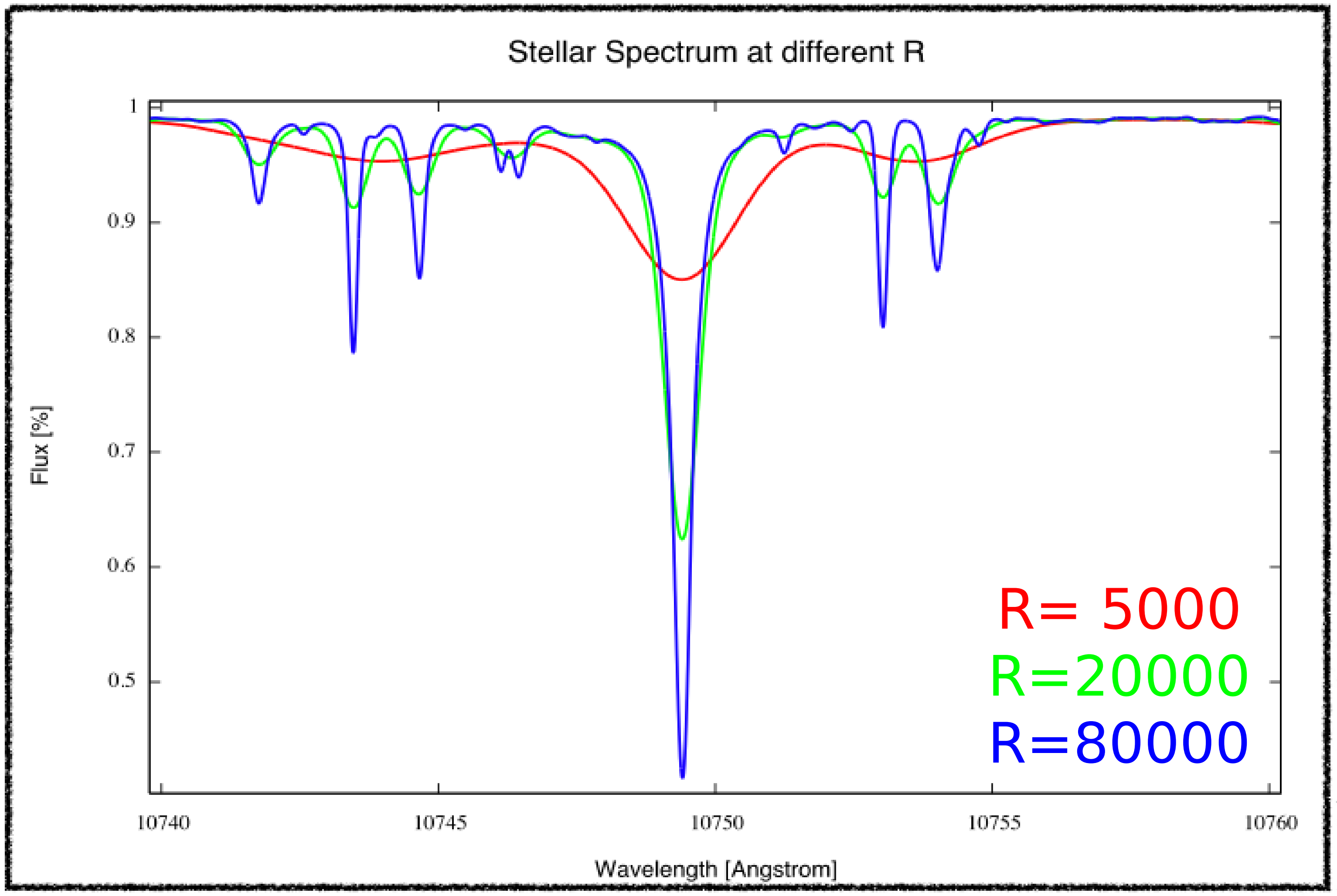
$$\sigma_{RV} = \frac{(\pi.\ln 2)^{-1/4}}{2}\,\frac{\sqrt{FWHM}}{SNR}\,\frac{\sqrt{PXLSC}}{C}\,F(C_{eff})\;[m/s]$$

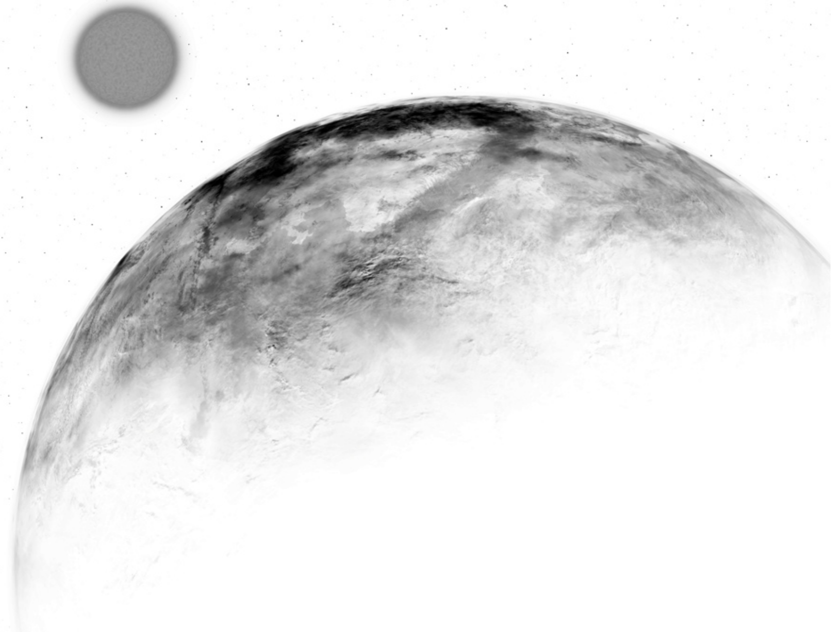
Where $F(C_{eff})$ is a polynomial function of the effective contrast $C_{eff} = \frac{C}{1+\sigma_D^2/A_0}$



# RV precision

These has an important consequence: the larger the FWHM of a star or lower the resolution, the lower the RV precision. This is specially important for rapidly rotating stars (high *v.sini*)



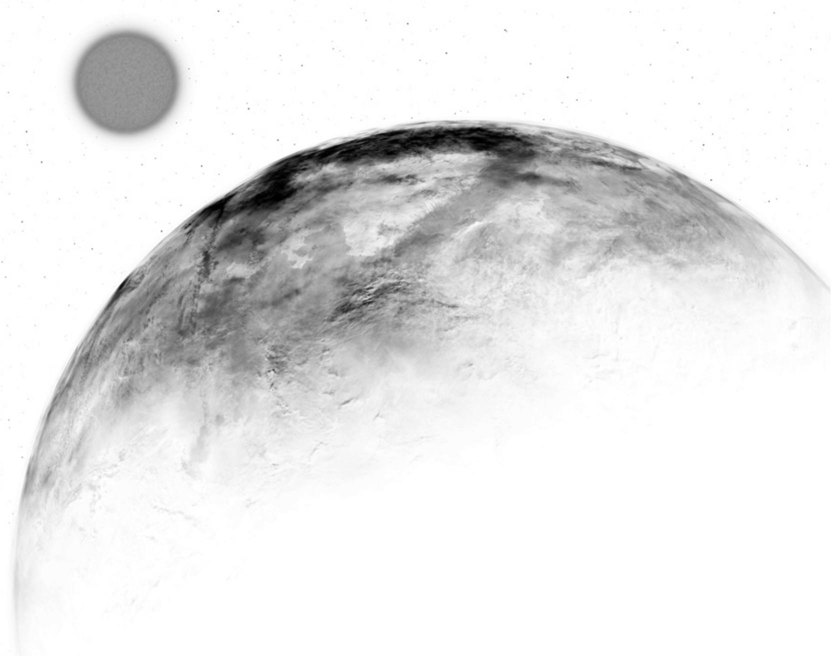



# RV precision

Which type of stars permit the highest-precision measurements (ignoring stellar activity)?

$$\sigma \propto \frac{1}{\sqrt{F}\,\sqrt{\Delta\lambda}\,R^{1.5}}$$

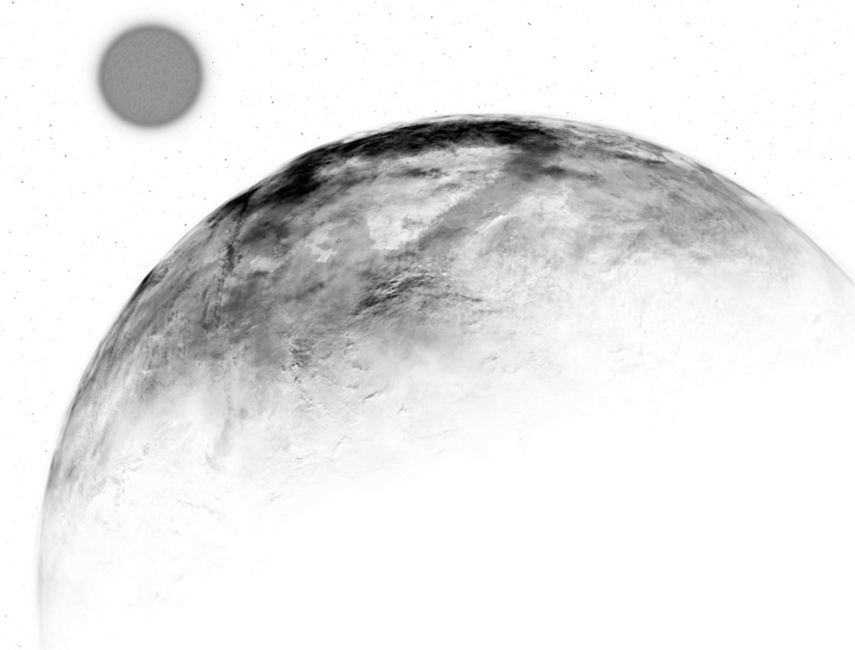
$$\sigma_{RV} = \frac{(\pi.\ln 2)^{-1/4}}{2}\,\frac{\sqrt{FWHM}}{SNR}\,\frac{\sqrt{PXLSC}}{C}\,F(C_{eff})\;[m/s]$$



# RV precision

Which type of stars permit the highest-precision measurements (ignoring stellar activity)?

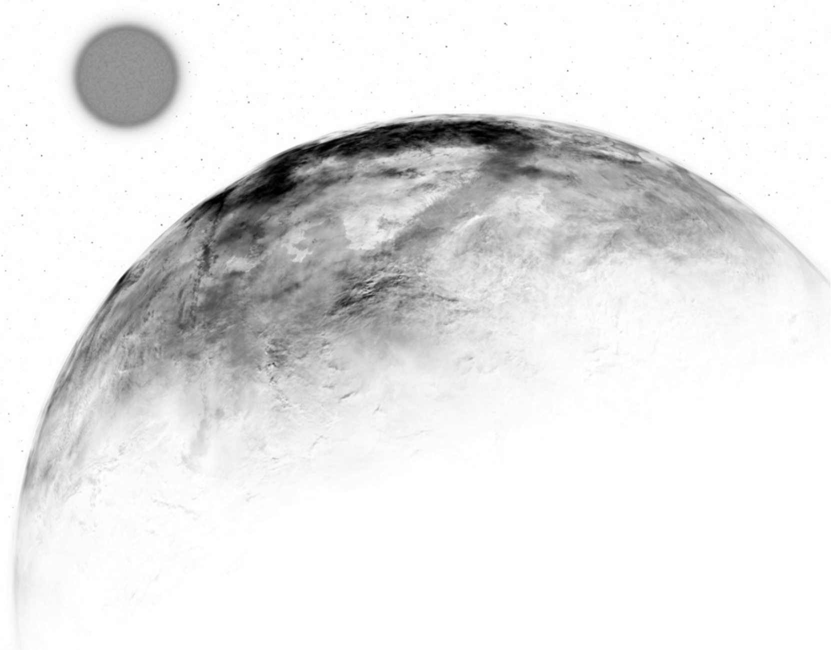
Stars with the ***largest number of sharpest lines*** (i.e. deep and narrow, with a large slope), when **observed at high S/N**. *O* and *B* stars are less interesting than *K* and *G* (and even M) to provide the best RV precision. For these stars to provide good measurements they should ***rotate slowly***.



# RV precision

A change in the instrumental profile (IP) can translate into a change in the measured line RV.
As a consequence there are two schools of thought when it comes to measure RVs in a precise way:

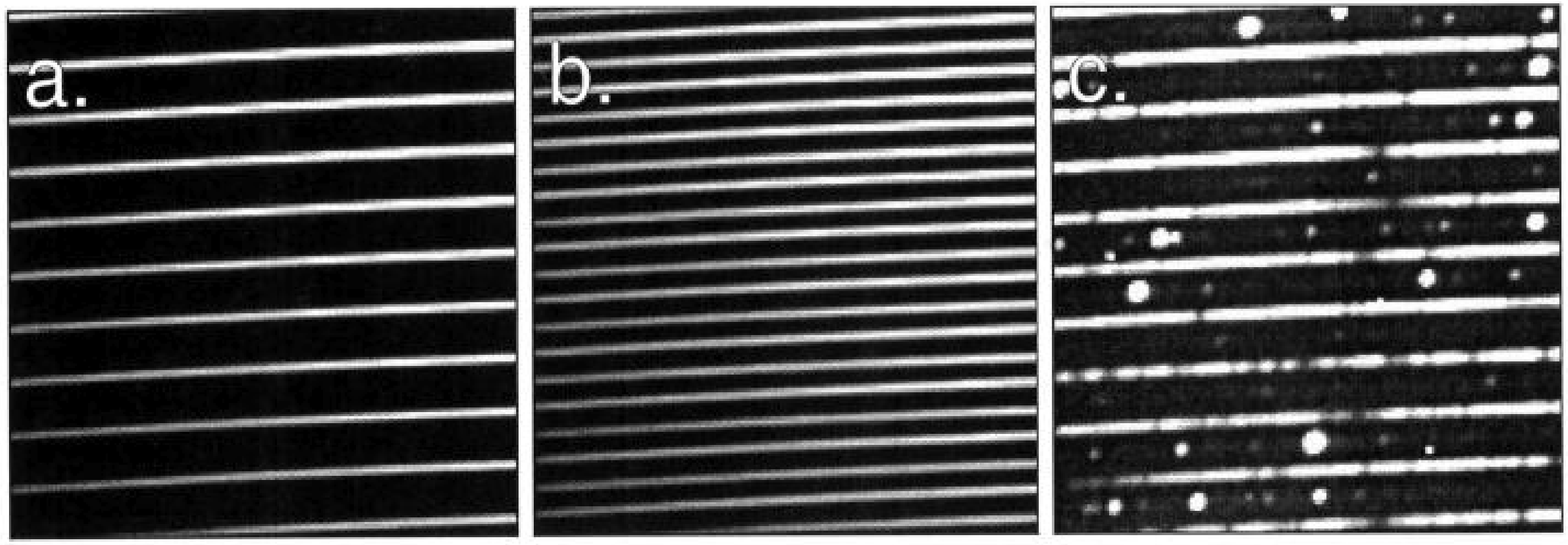
- ***Control the IP*** as much as possible, trying to make it constant as a function of time and ***reduce its impact*** on the RV;
- ***Allow the IP to vary but model it and remove its effect*** from the spectrum.



# IP control

To start with, the instruments scramble the injected light, using fibers or more complex devices, to ***reduce spatial effects on the RV***.

The instrument is designed to ***ensure its IP***, which depends on physical/weather parameters and optical components properties, ***is constant over time***. HARPS is stabilized in pressure and temperature (0.01K and 0.01mBar, respectively).



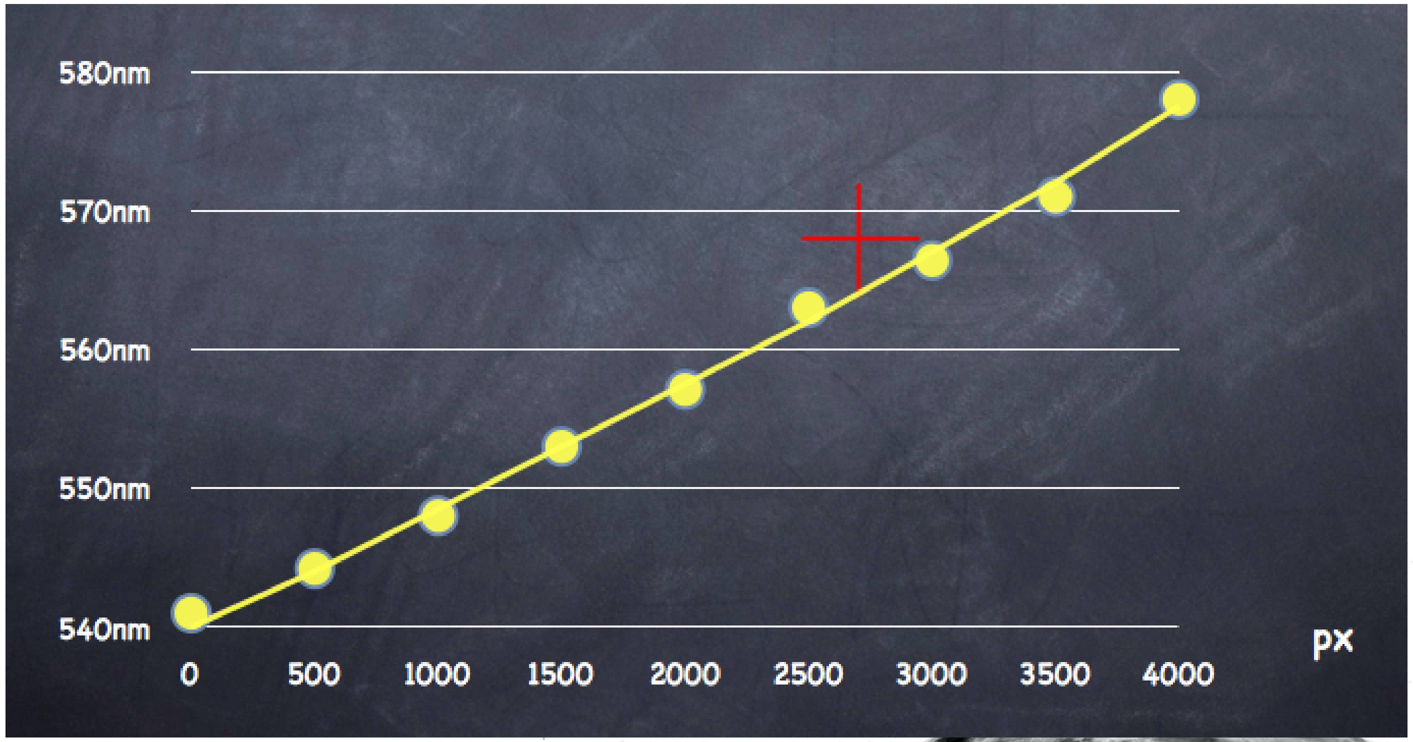

from Baranne (1996), a.: tungsten on science fiber only, b.: tungsten on science and reference fibers, c.: star and Th-Ar.

# IP control

A ***Th-Ar*** lamp illuminates the parallel channel during high-precision observations and both channels at the beginning of the night.

Each pixel is tied to a wavelength by a polynomial fit of the Th-Ar lines wavelength.

One makes the assumption that both sets of orders drift together; the measured Th-Ar RV is subtracted from the science target's RV[†].



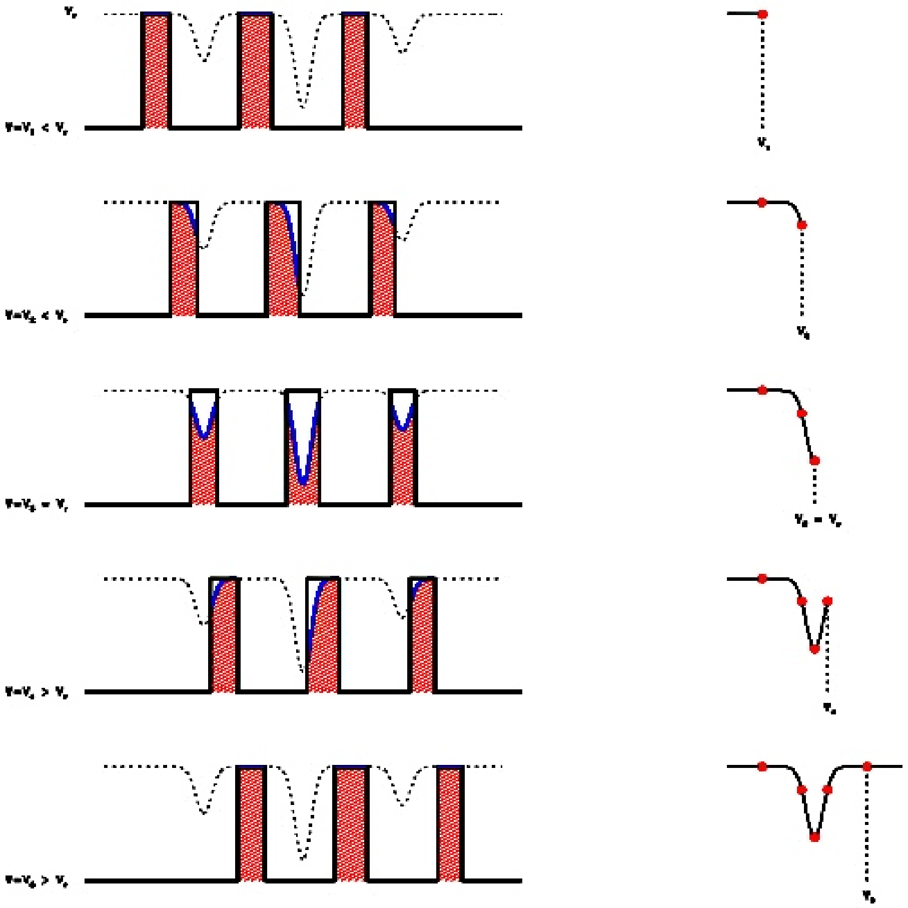

[†] - only valid for small shifts, typically < 50 m/s.

# The CCF

The Cross-Correlation function is a way of condensing the information from several lines in an average line

The obtained spectra are correlated with a template mask (e.g. Baranne et al. 1997)

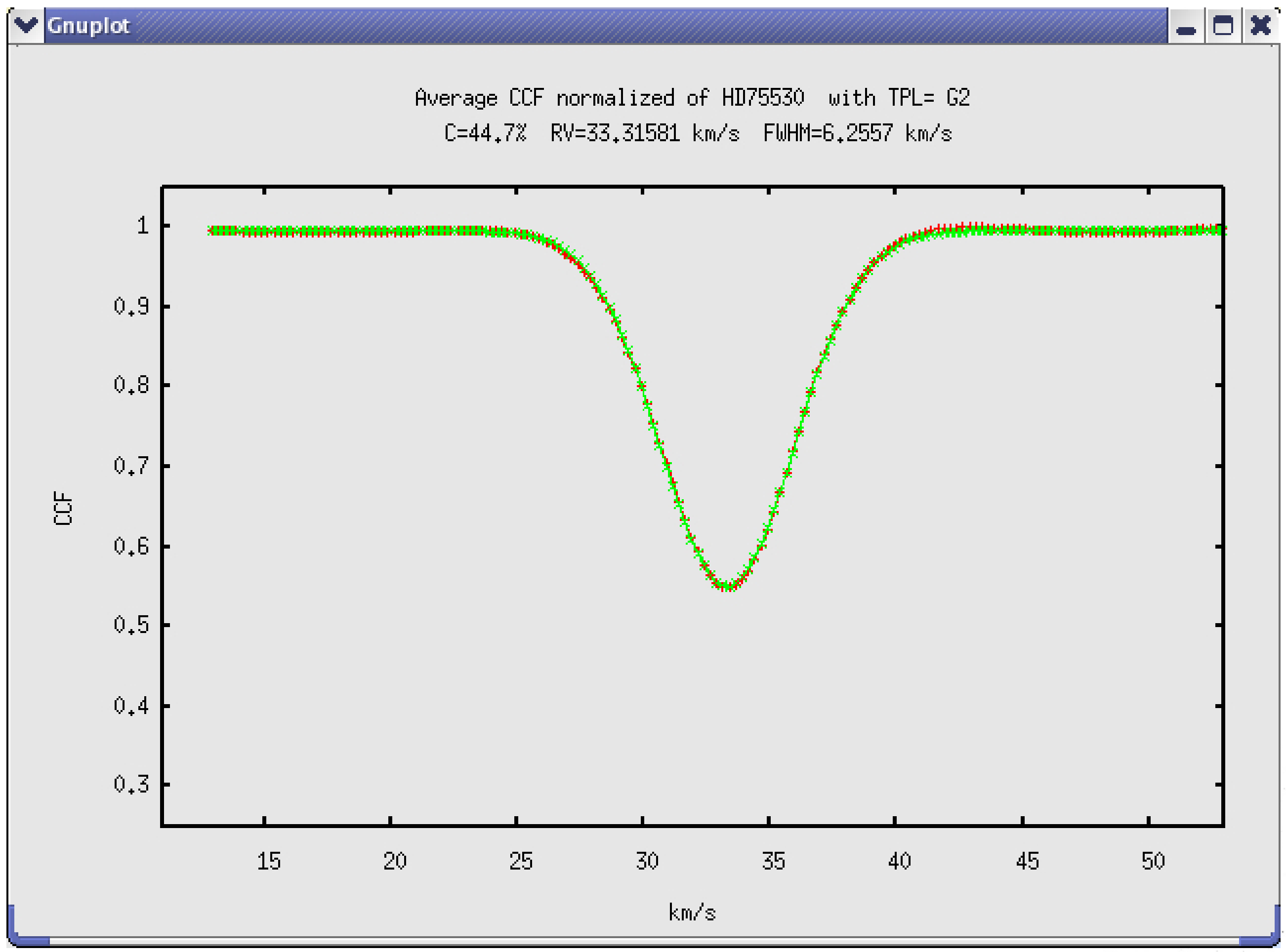
$$CCF(v) = \sum_i A[\lambda(i)]\,.\,M[\lambda(i)\,(1 + v/c)]$$



from Melo (2001), Ph.D. thesis

# The CCF

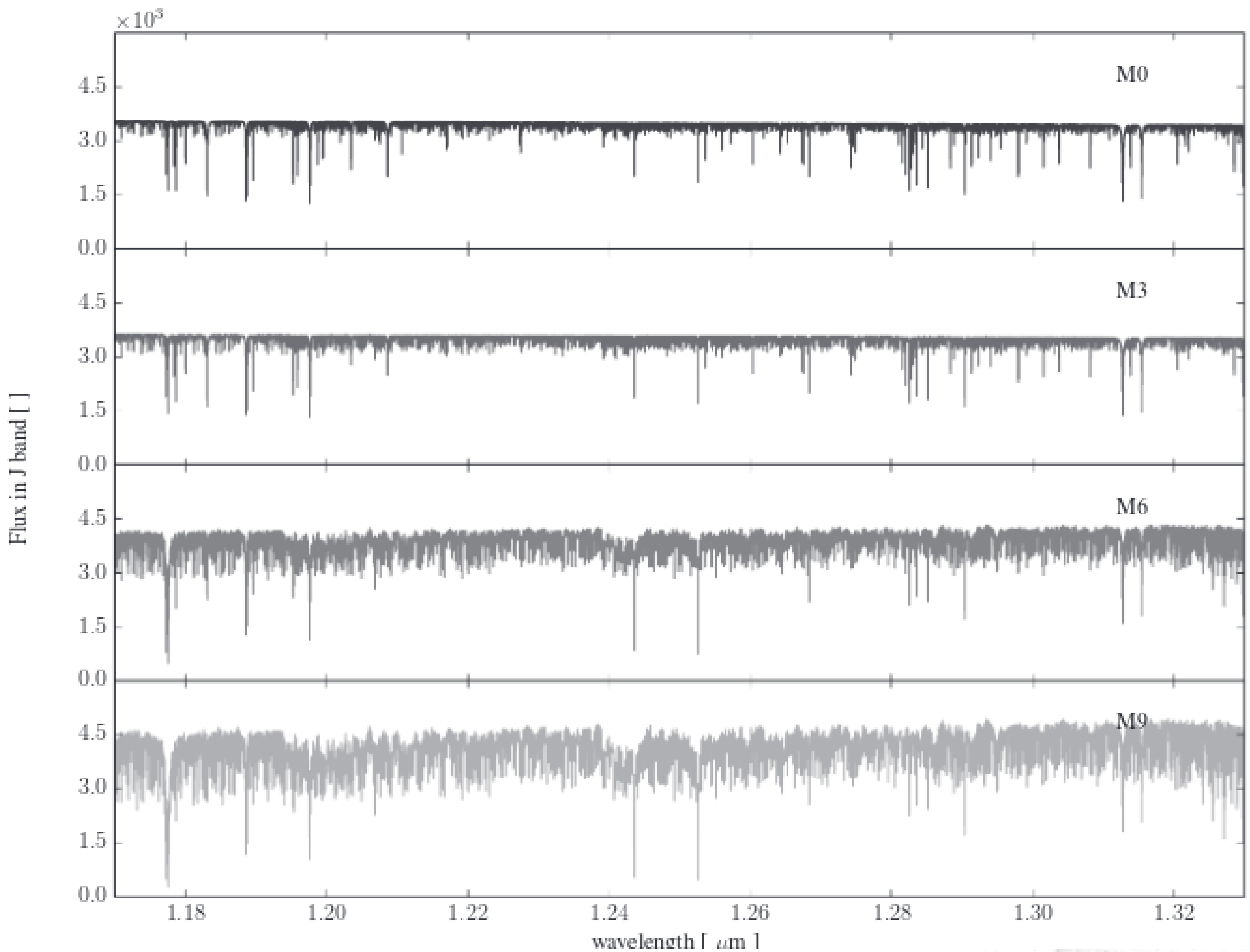
This is what a HARPS CCF looks like (red for line, green for fitted Gaussian).




The CCF is ***an average stellar line***, an average ***calculated over all lines in the mask***. But you can calculate this average in many different ways.

# The CCF

When we go towards late M-dwarfs, the spectra become overpopulated with blended lines, and alternative RV measurement techniques exist, consisting of fitting a spectral template, for instance.



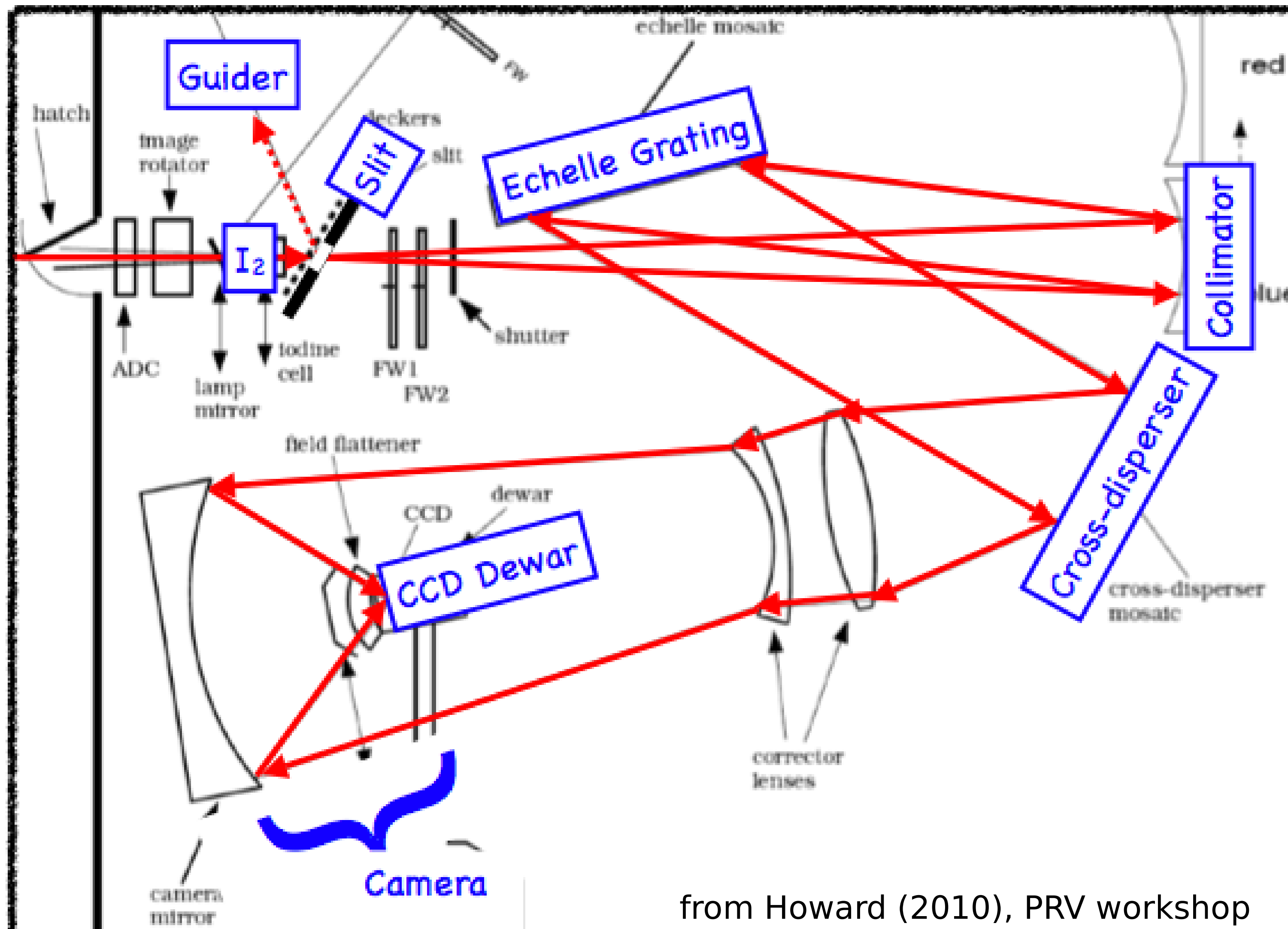

*Figueira et al (2016)*

# IP modeling

A completely different approach is to say that ***we let the IP vary*** (in both its injection and mechanical contributions) and ***then correct for its impact on the spectrum***.

To do this you do not need fiber(s), double channels or a stable spectrograph, you only need a gas-cell.

For more take a look at Butler et al. (1996).

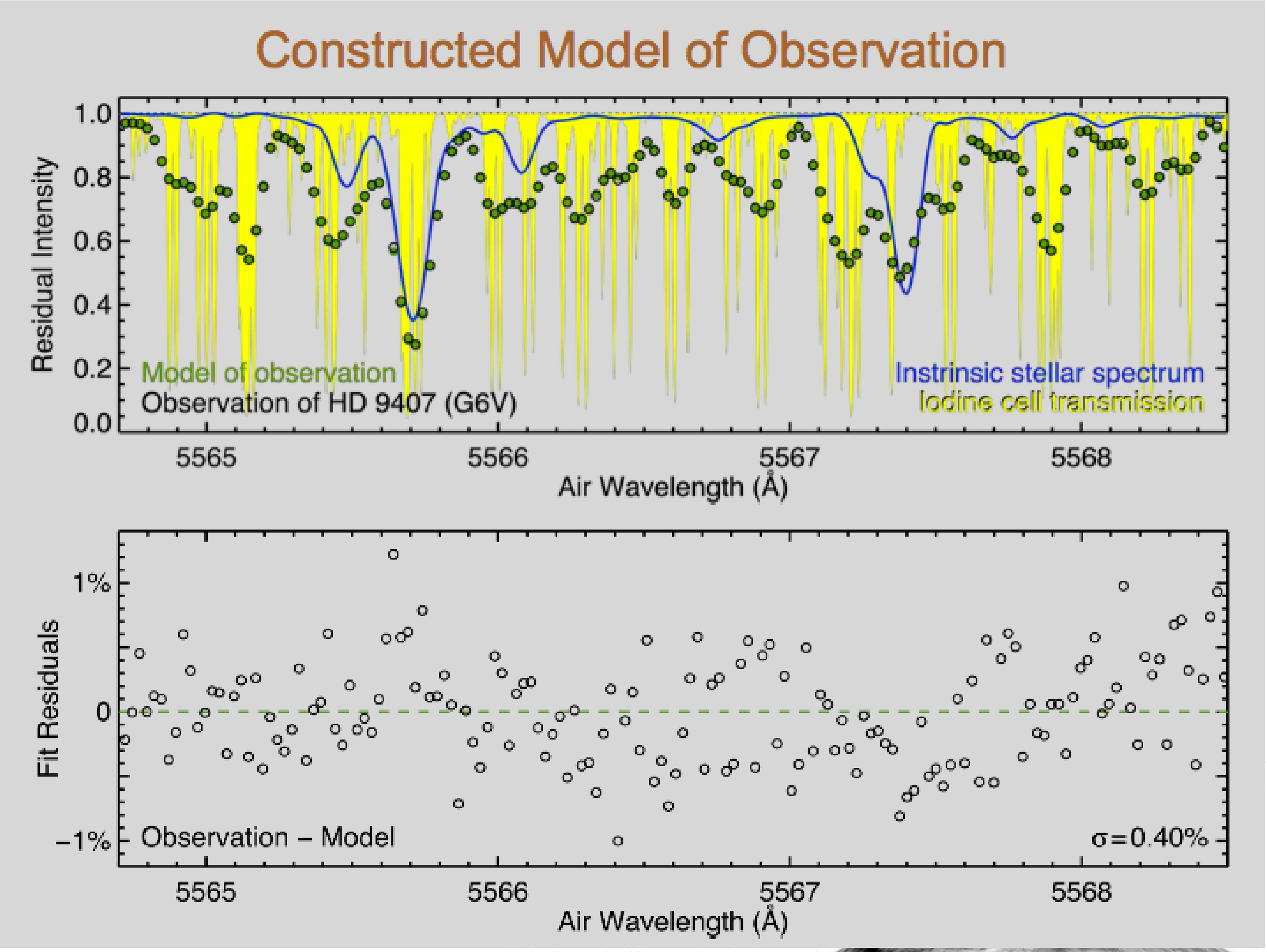


from Howard (2010), PRV workshop

# IP modeling

The gas-cell ***superimposes*** a spectrum that we have characterized very well as a function of wavelength.

We can the use this spectrum to define the wavelength scale on top of the science spectrum.




from Valenti (2010), PRV workshop

# IP modeling

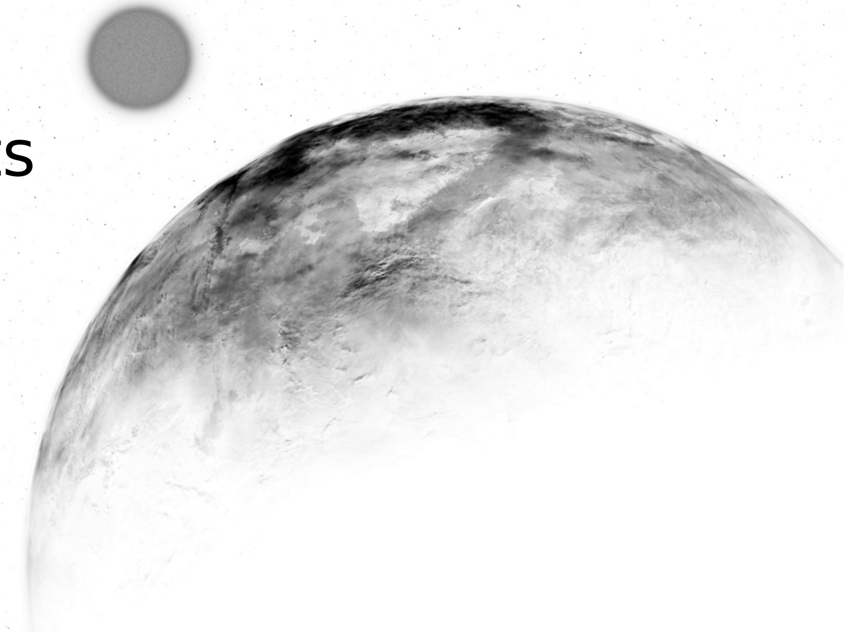
The equation that represents the observed spectrum is:

$$A(\lambda) = \int [I_2(\lambda') \, . \, S(\lambda' + \delta\lambda)] \, . \, IP(\lambda - \lambda') \, . \, d\lambda'$$

where $A(\lambda)$ is the relative intensity as a function of wavelength;
$I_2(\lambda)$ is the iodine cell spectra as a function of wavelength;
$\delta\lambda$ is the relative wavelength shift between science and reference spectra;
and $IP(\lambda)$ is the instrumental profile.

***The observed spectrum is the product of science and reference spectrum convolved with the instrumental IP.***

The objective is to recover the $\delta\lambda$, but with the exception of the Iodine spectrum all other elements on the right hand-side are unknown.



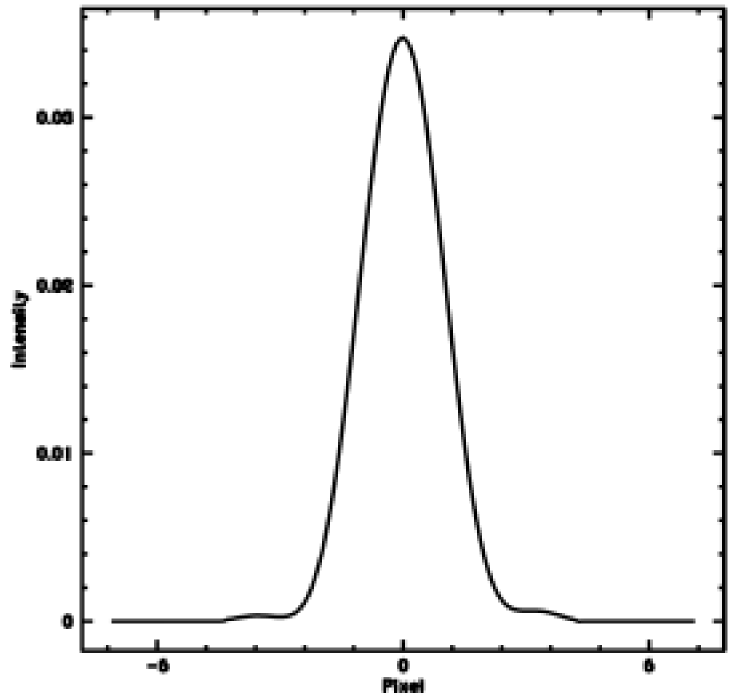
# IP modeling

There is a recipe to reconstruct $$A(\lambda) = \int [I_2(\lambda') \,.\, S(\lambda' + \delta\lambda)] \,.\, IP(\lambda - \lambda') \,.\, d\lambda'$$

- Measure the $I_2$ with a FTS to obtain a cell spectrum with very high resolution and define $I_2(\lambda)$ ;
- Observe a line-less emission spectrum with our spectrograph+cell and deconvolve the $I_2$ to obtain the IP ($\lambda$) ;
- Observe the science target with a very high S/N and without the cell to deconvolve IP from it to get $S(\lambda)$;
- The $\delta\lambda$ is then the only remaining unknown, and its value is estimated by inserting the other elements and finding the best fit to the data.

# IP modeling

However, one has to bear in mind that the ***IP reconstruction is a very delicate process***; the IP varies not only as a function of time but also across the spectrograph




from Lovis (2002), Diploma thesis

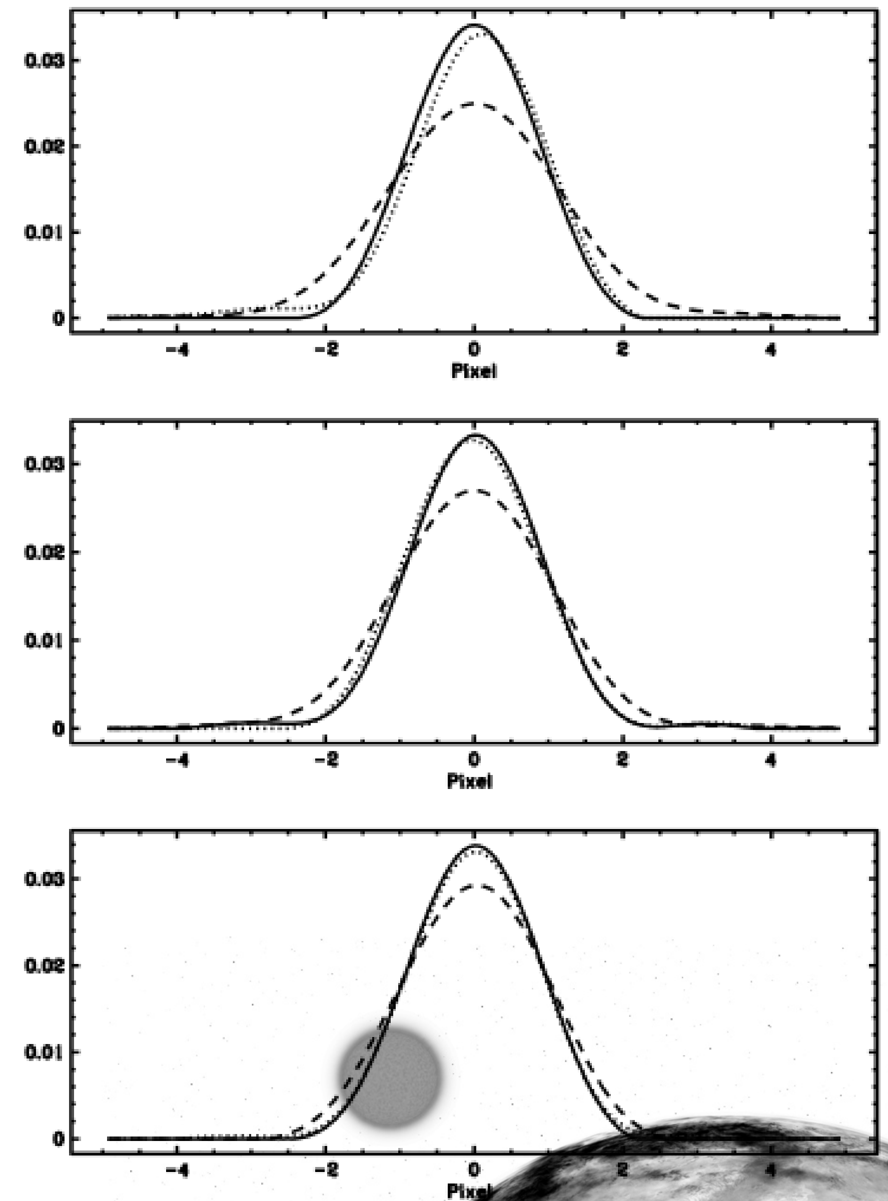
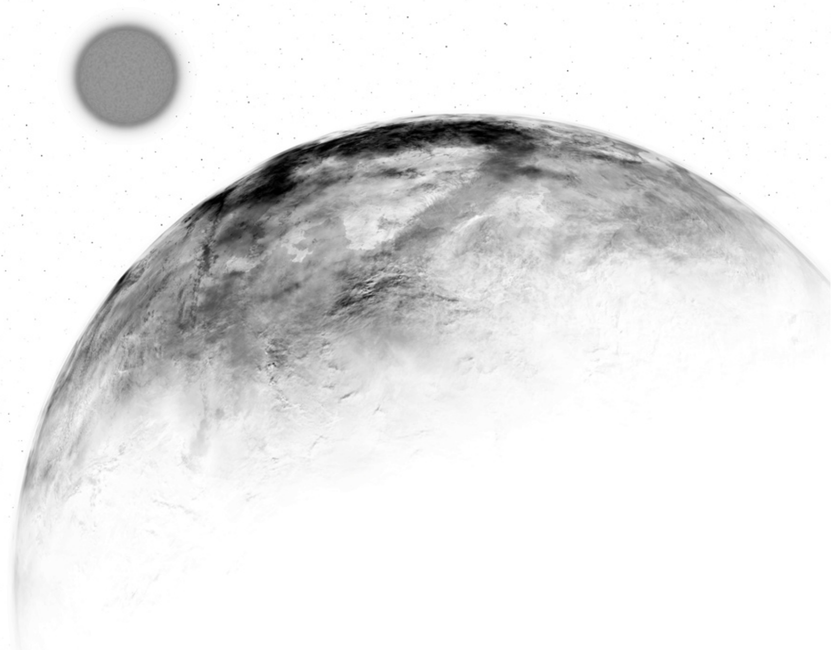



Figure [illegible]: Variations of the IPs along order [illegible] (upper panel), order [illegible] (middle) and order [illegible] (lower panel). Solid lines represent chunk number [illegible], dotted lines chunk [illegible] and dashed lines chunk [illegible]. The IPs become broader from left to right. This effect is examined in more details in Fig.[illegible].

# IP & precision

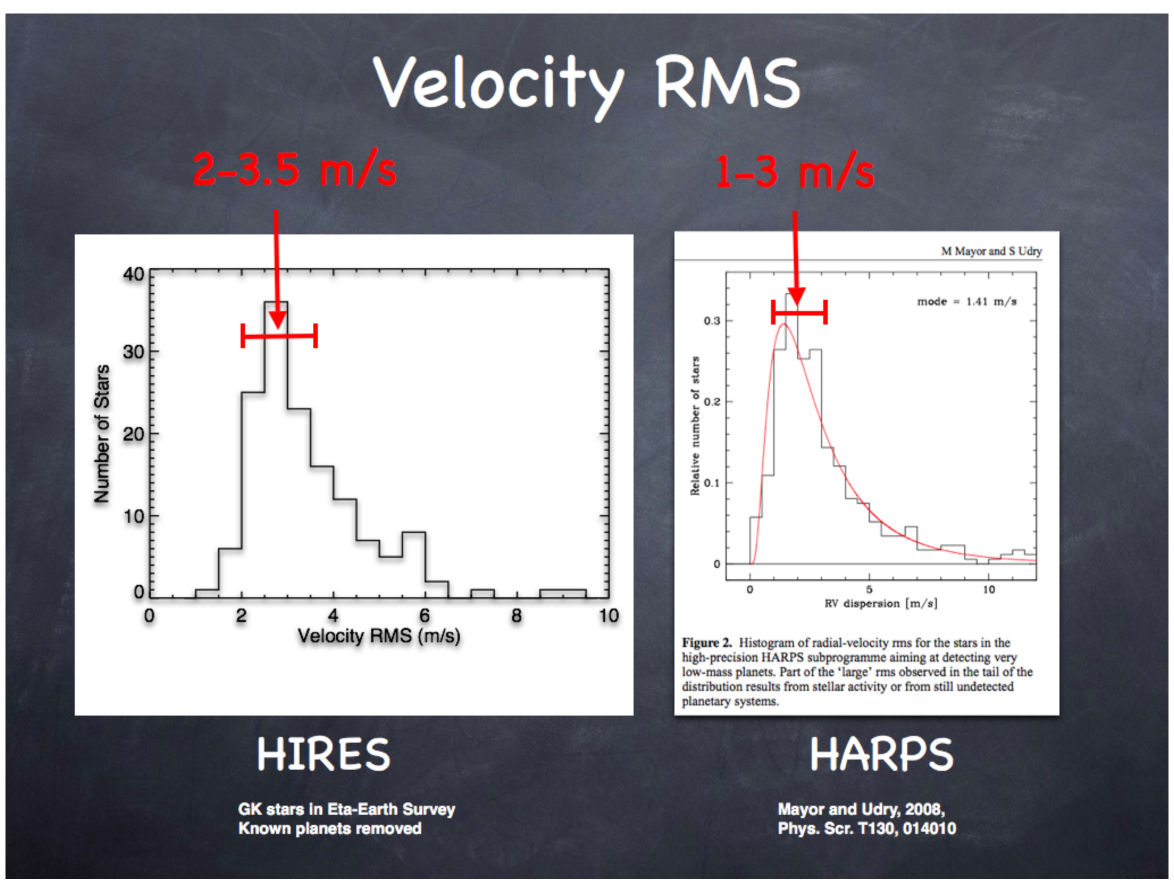
- The Th-Ar technique ***requires a stable spectrograph, both in light injection and in mechanical terms***; one can get the best out of it with a second channel for the (simultaneous) reference. It ***minimizes the impact and reduces spurious RV shifts***.
- The $I_2$ method can be used in a conventional slit spectrograph, and ***models the RV-inducing phenomena, subtracting their effect***. It requires several on-sky calibration and is observationally more expensive (requires more observing time).



# IP & precision

Remember: in HARPS a RV shift of 1 m/s corresponds to a $\Delta\lambda = 1\times10^{-5}$ A, which corresponds to a physical 15 nm displacement of the spectrum (***1/1000 of a pixel***)

It is impossible to answer to which method delivers more precise RVs down to this order of magnitude on pure theoretical grounds.

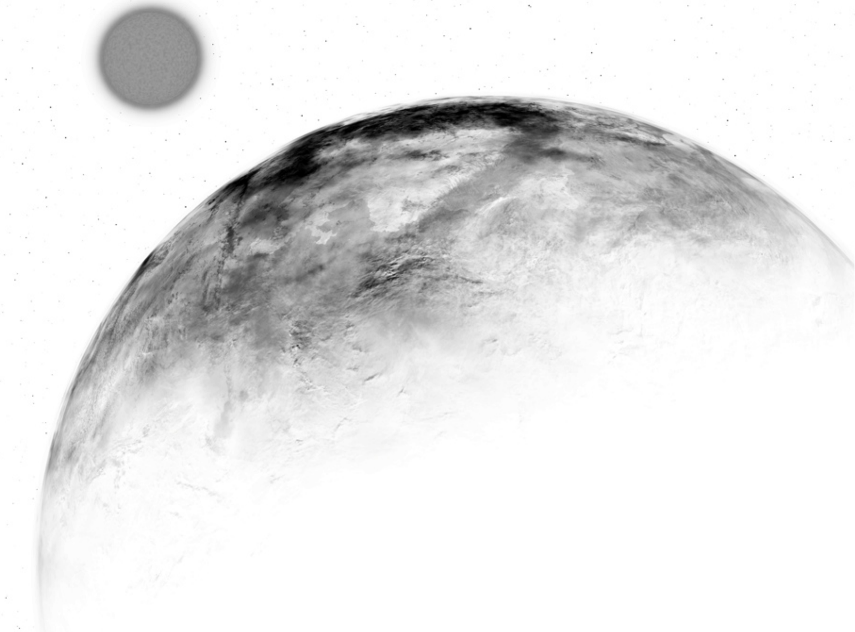


# Barycentric correction et al.

Once the method is selected, and the RV calculation performed, one has to be sure to remove all non-planetary RV signals.

The most obvious one is the RV introduced by the movement of the Earth around the Sun, that will introduce a RV signal with a period of 1 year in the data!

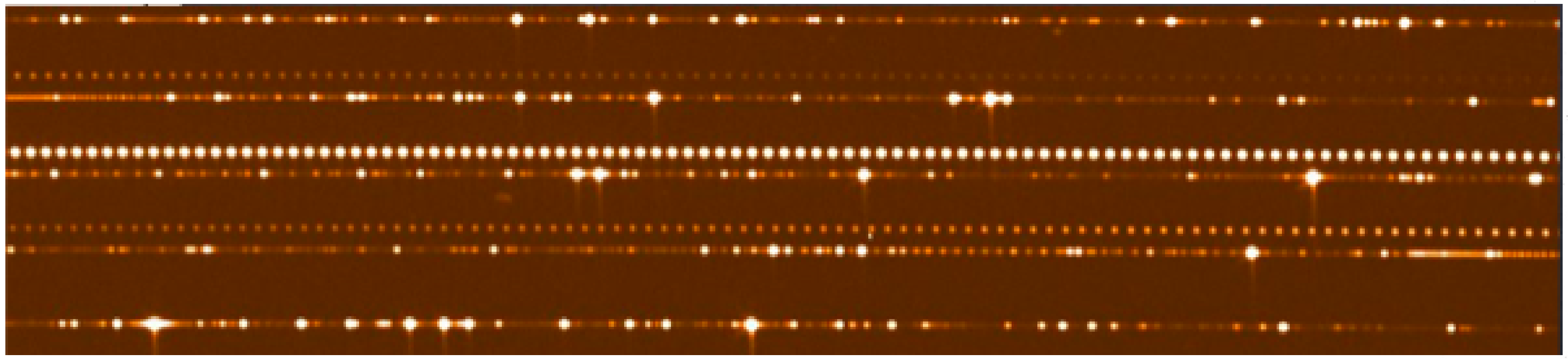
<u>Why is this period of one year? What will happen if we have a defect on the CCD?</u>



# The perfect callibrator

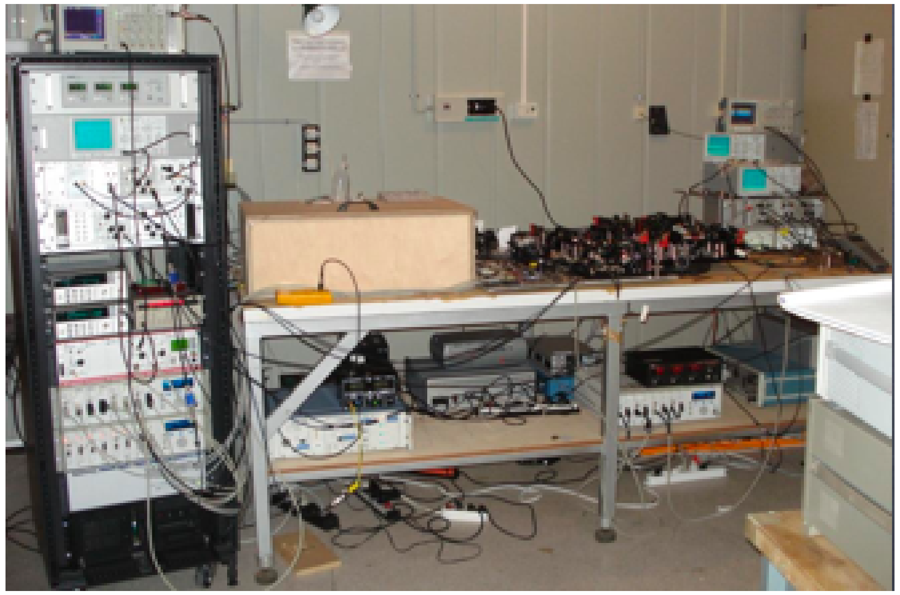
- Covers complete spectral range; Constant line spacing; Lines width < spectrograph resolution;High density of lines, up to one per ~2-3x the Res. Elem. ; All wavelengths precisely known and stable; Homogeneous line intensities, close to saturation but within dynamic range.

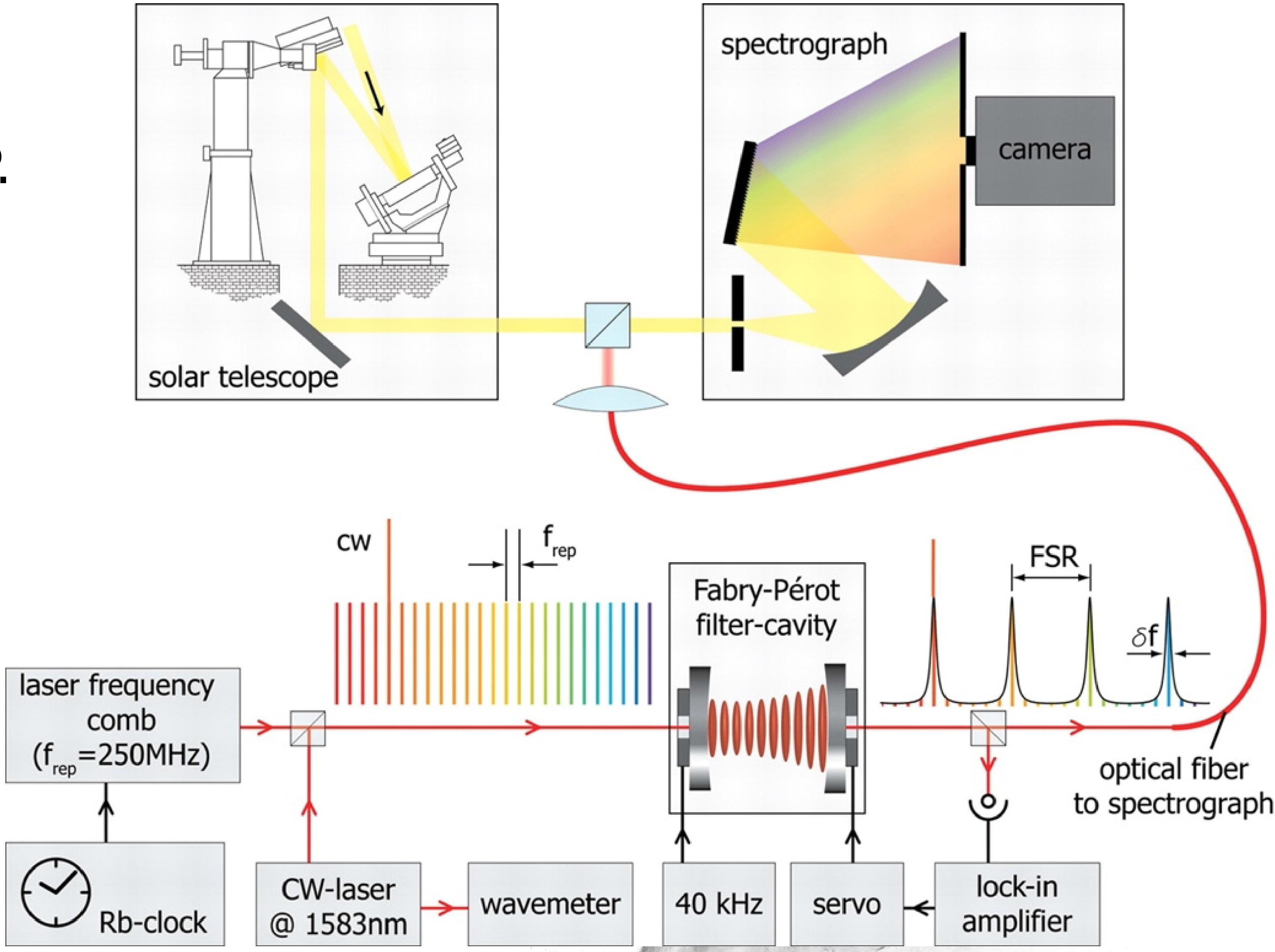
Neither Th-Ar nor $I_2$ are perfect: Th-Ar lamps age, have blended lines and with very high dynamic range; $I_2$ has to be maintained at constant temperature to operate correctly.



# Laser-Comb

The Laser-Comb method uses a femtosecond laser stabilized with an atomic clock to produce a series of modes which are filtered out by an F.P. cavity.

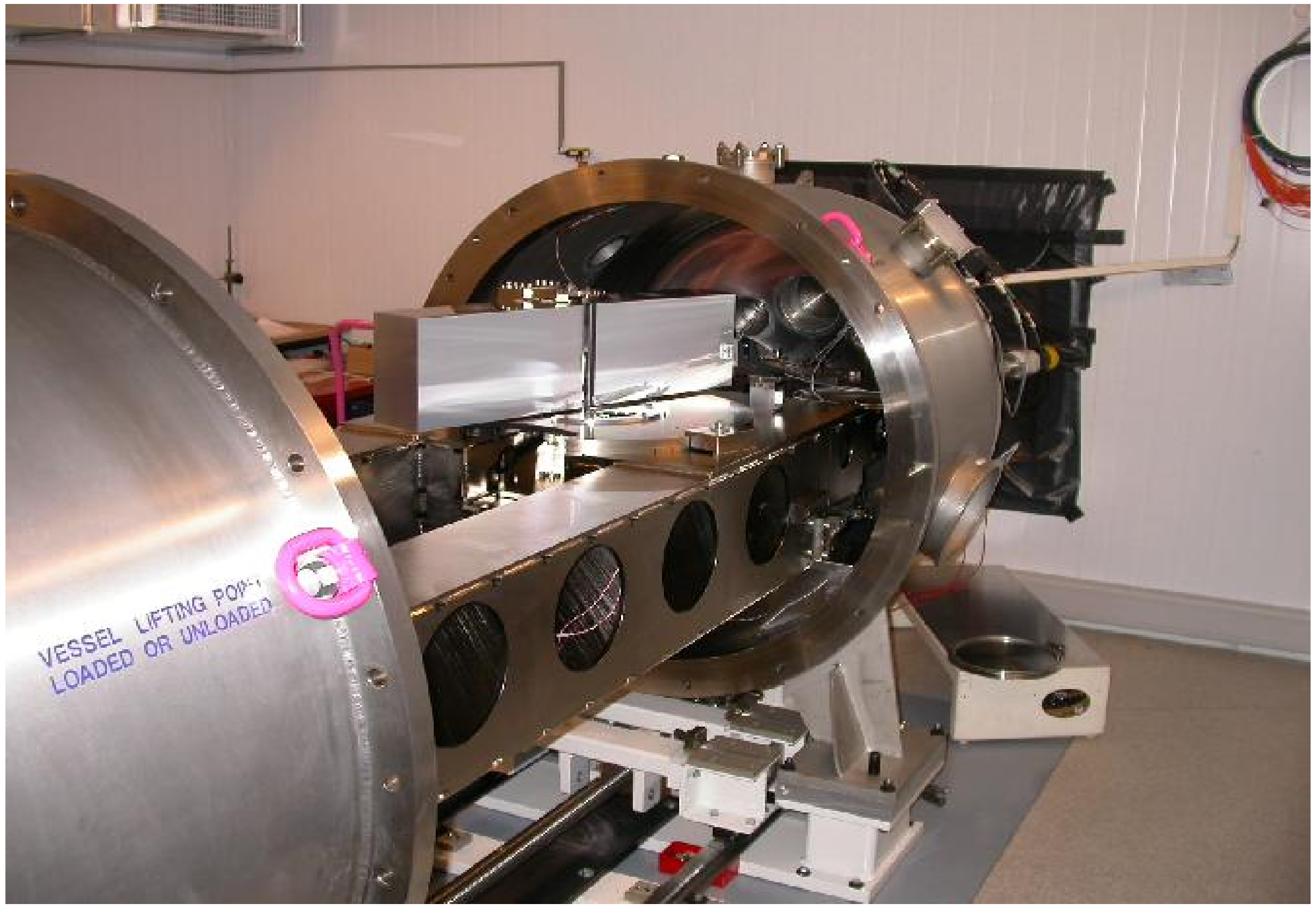


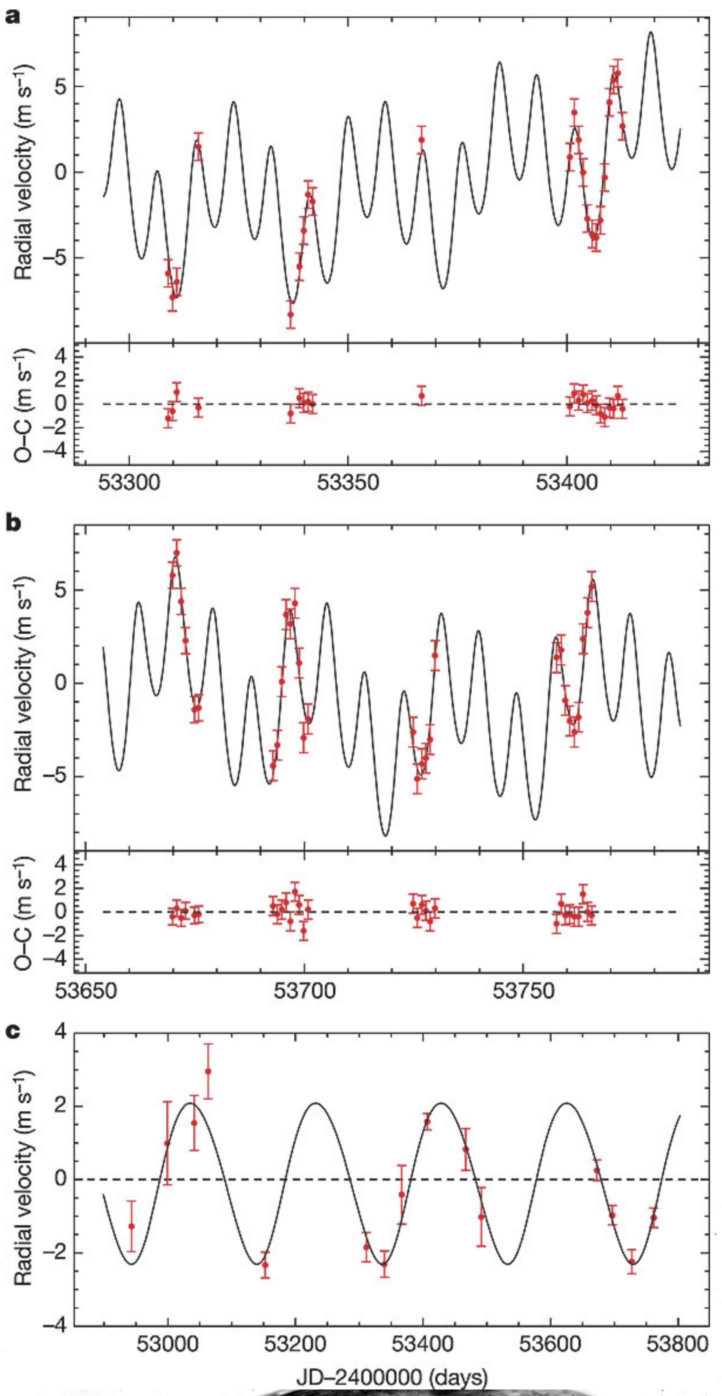



see Murphy et al. (2007), Steinmetz et al. (2008)

# Radial Velocities

HARPS is the most precise spectrograph in the world
$\sigma_{inst}$ < 50 cm/s

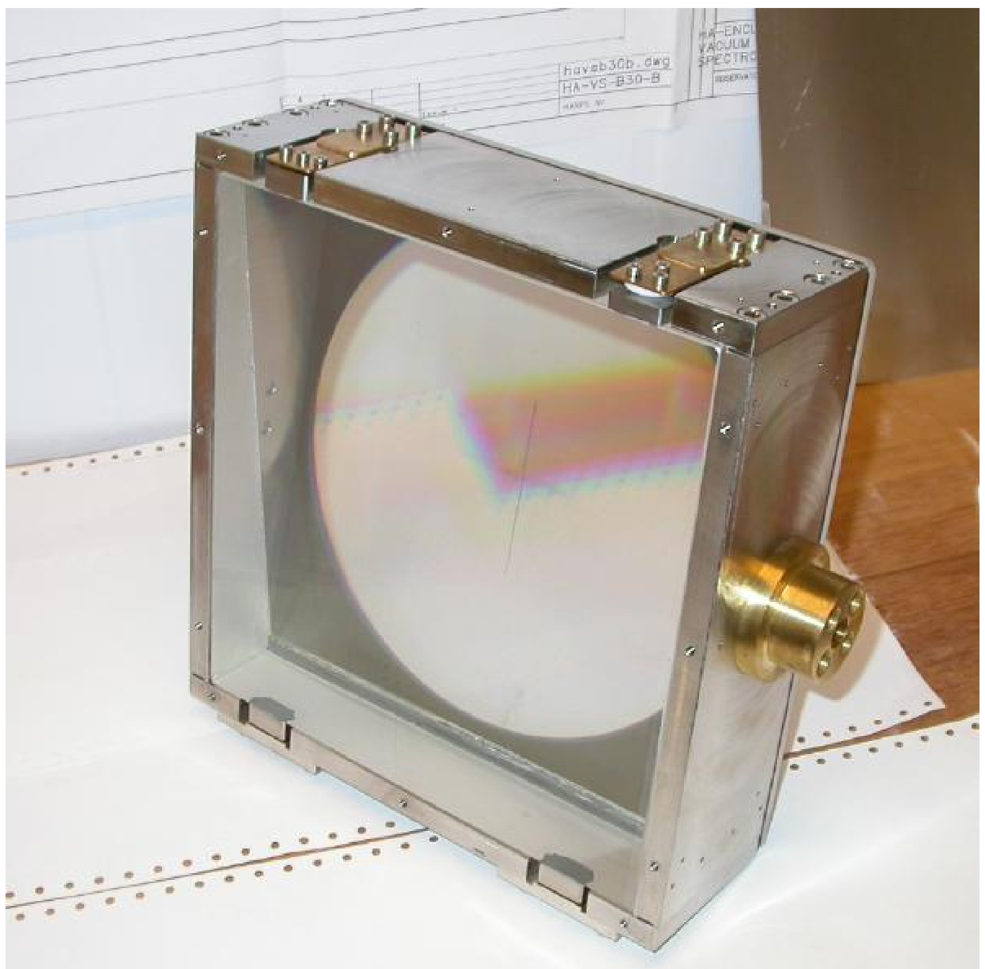





Echelle grating: R4, 31.6 gr/mm blaze angle 75°, efficiency > 65% in the visible; cross dispersing done with a grism.

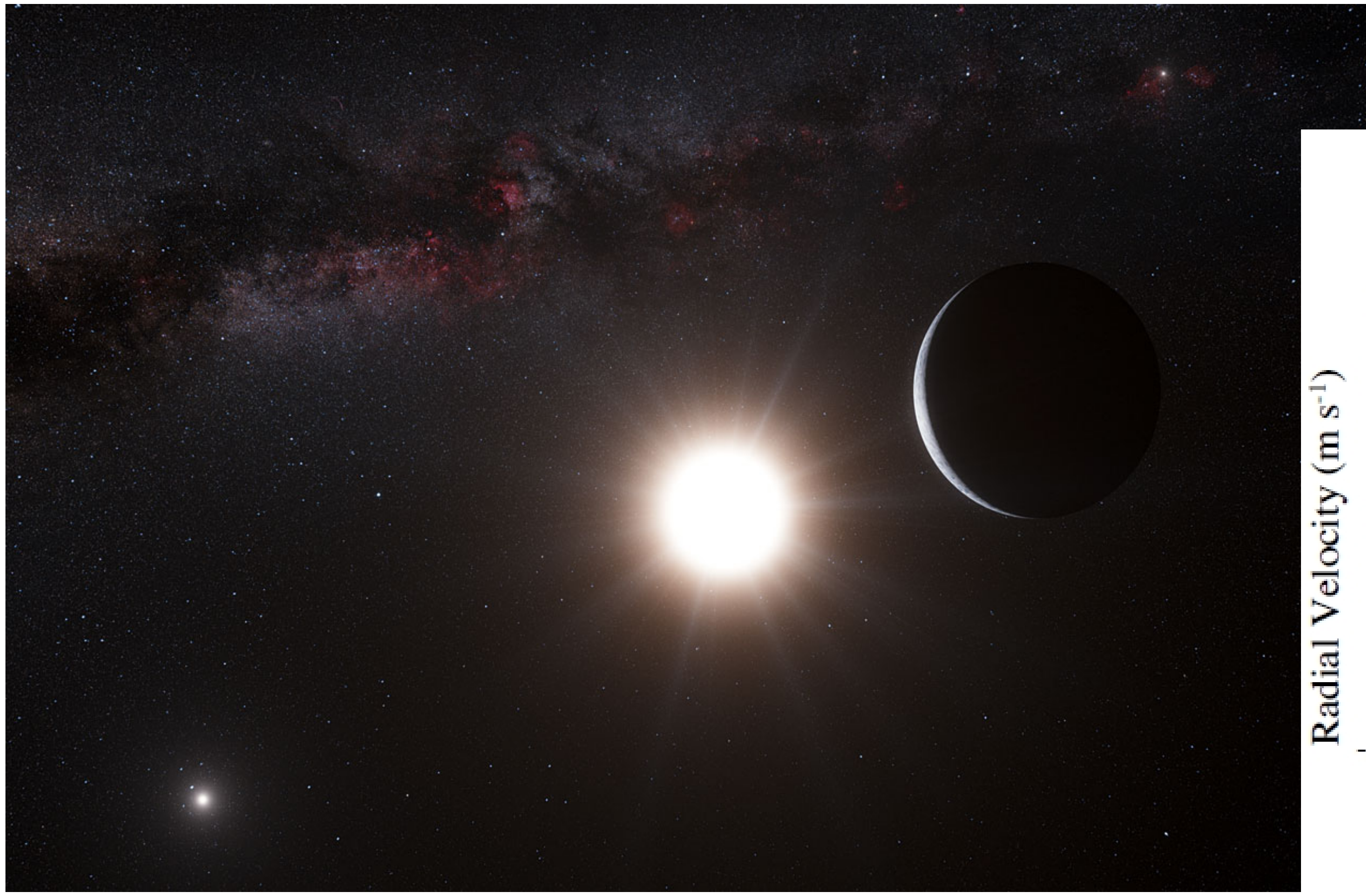
# Inside HARPS

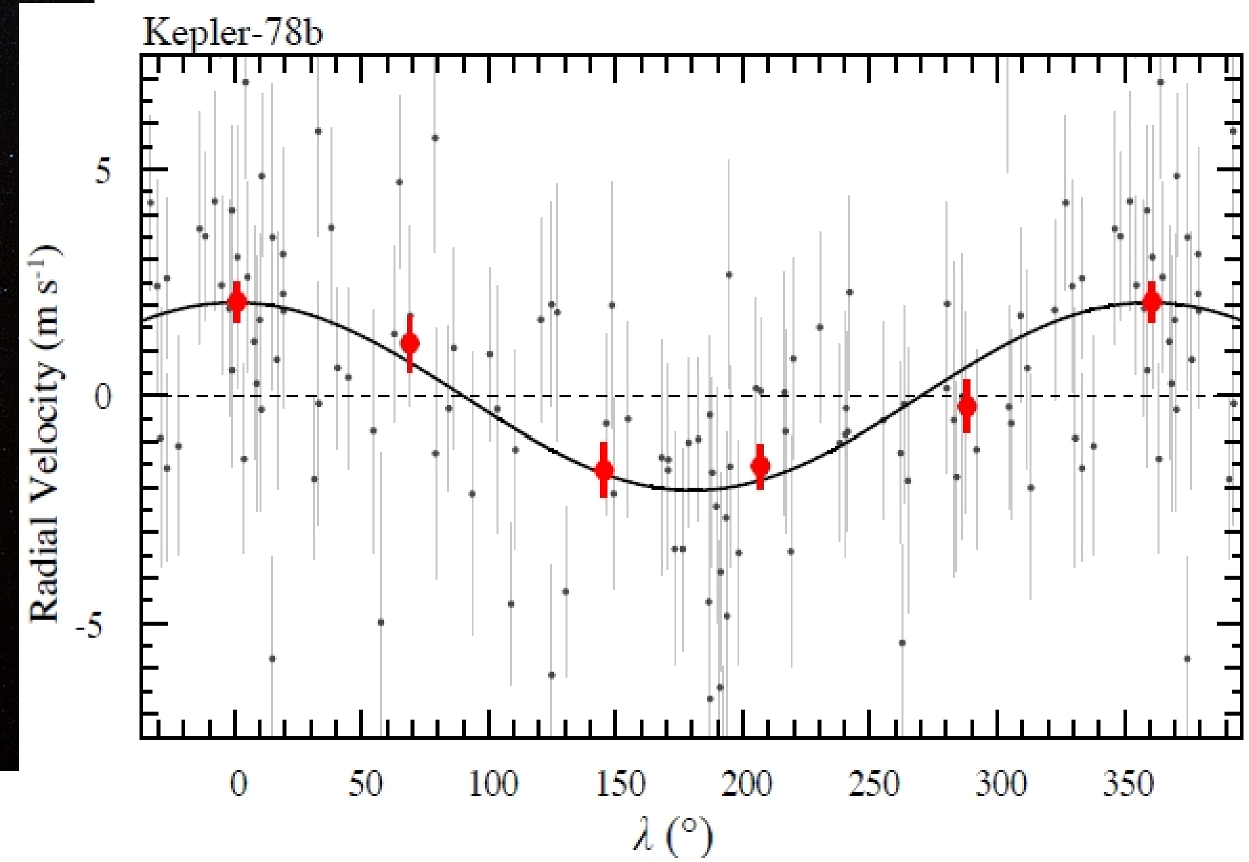
The grism (grating+prism), the camera and the collimating mirror



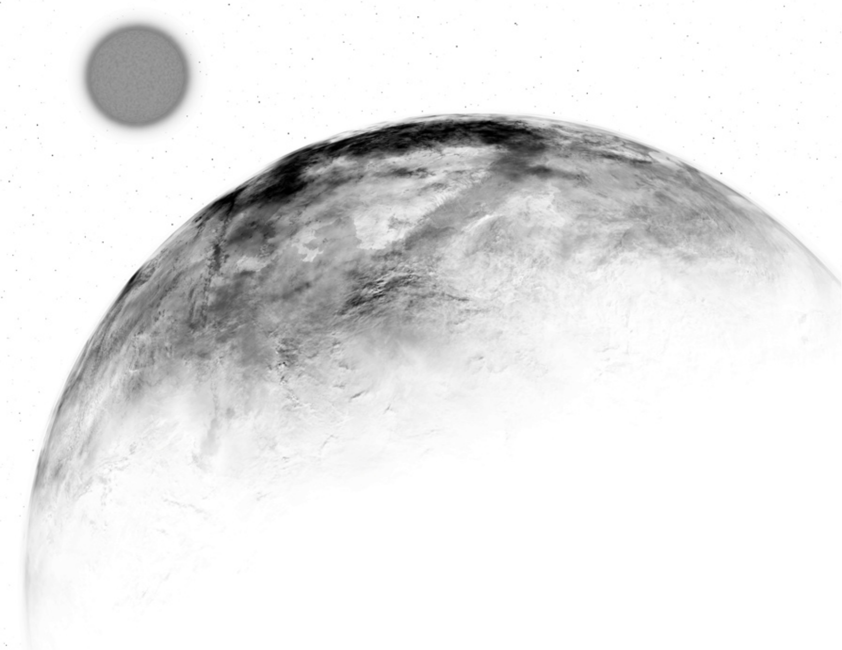
Source: http://www.eso.org/sci/facilities/lasilla/instruments/harps/overview.html

# Radial Velocities





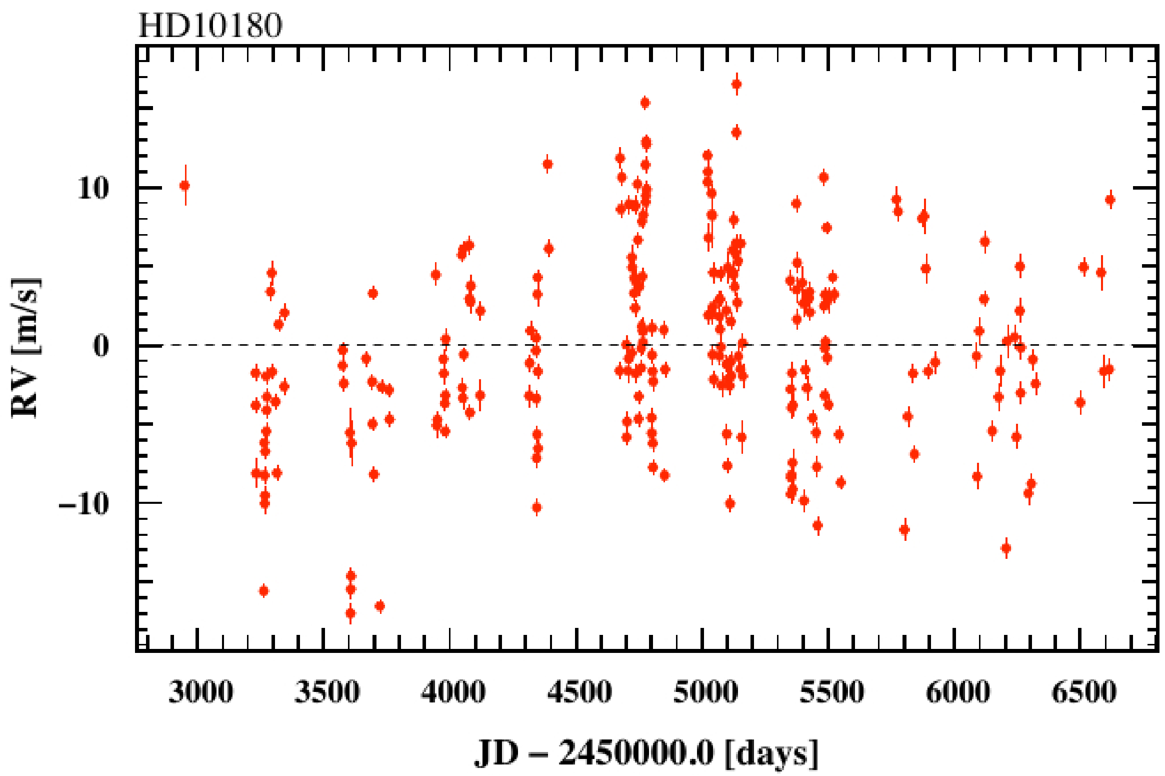

Two very interesting results were the detection of a ***planet with the mass of the Earth*** around ***Alpha Cen B*** and of a ***rocky planet*** around ***Kepler-78*** and ***HD219134***

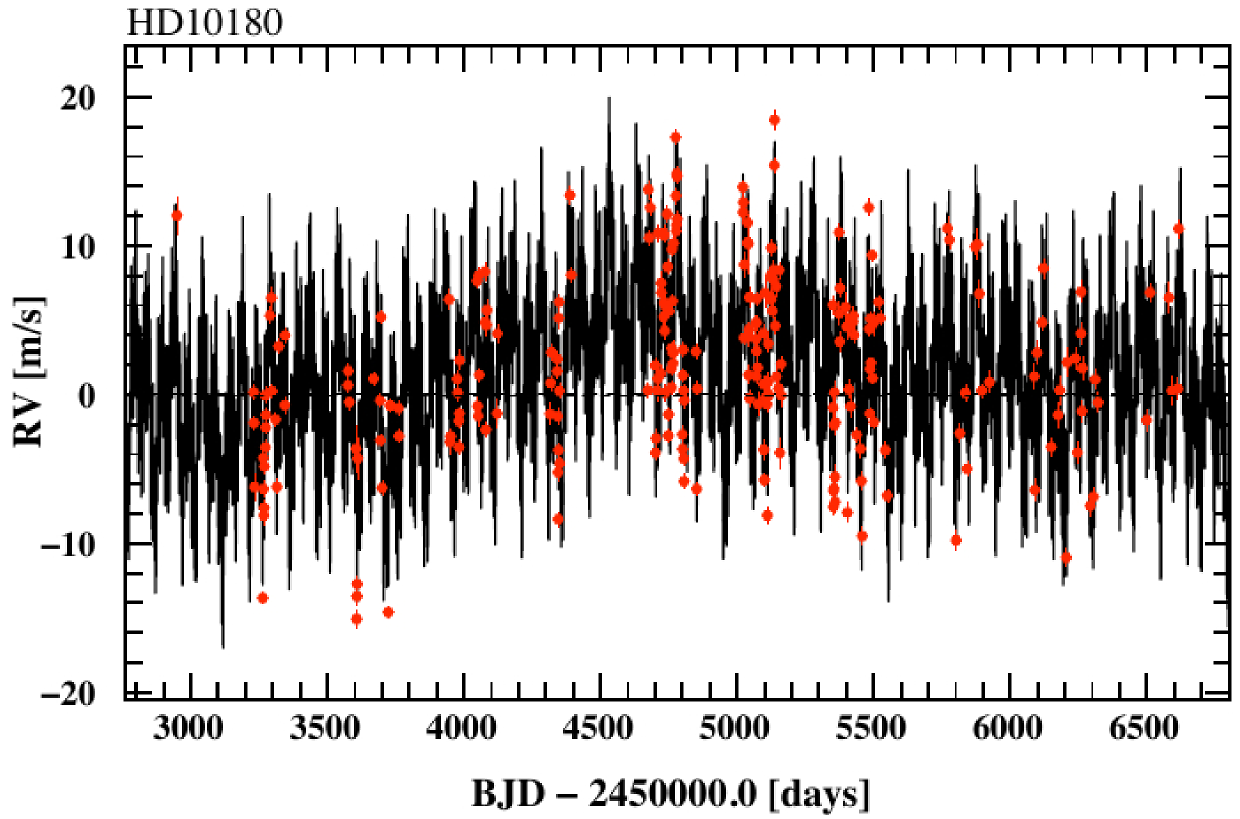


Dumusque et al. (2012), Pepe et al. (2013)

# Radial Velocities

We found several systems of extrasolar planets, like those around *HD10180*



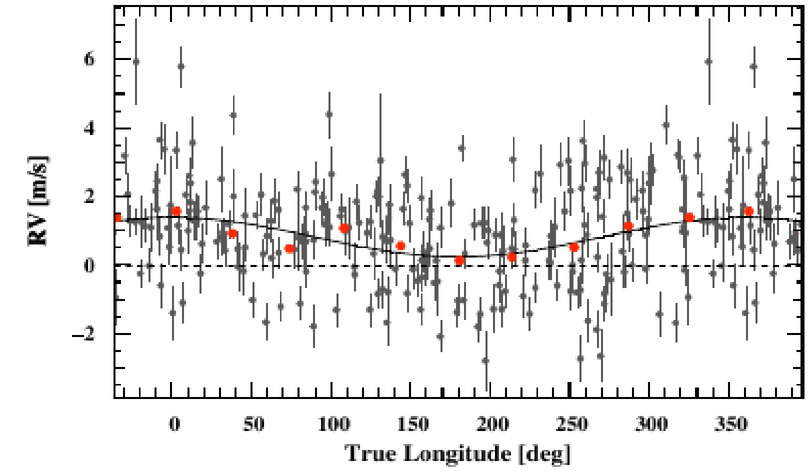



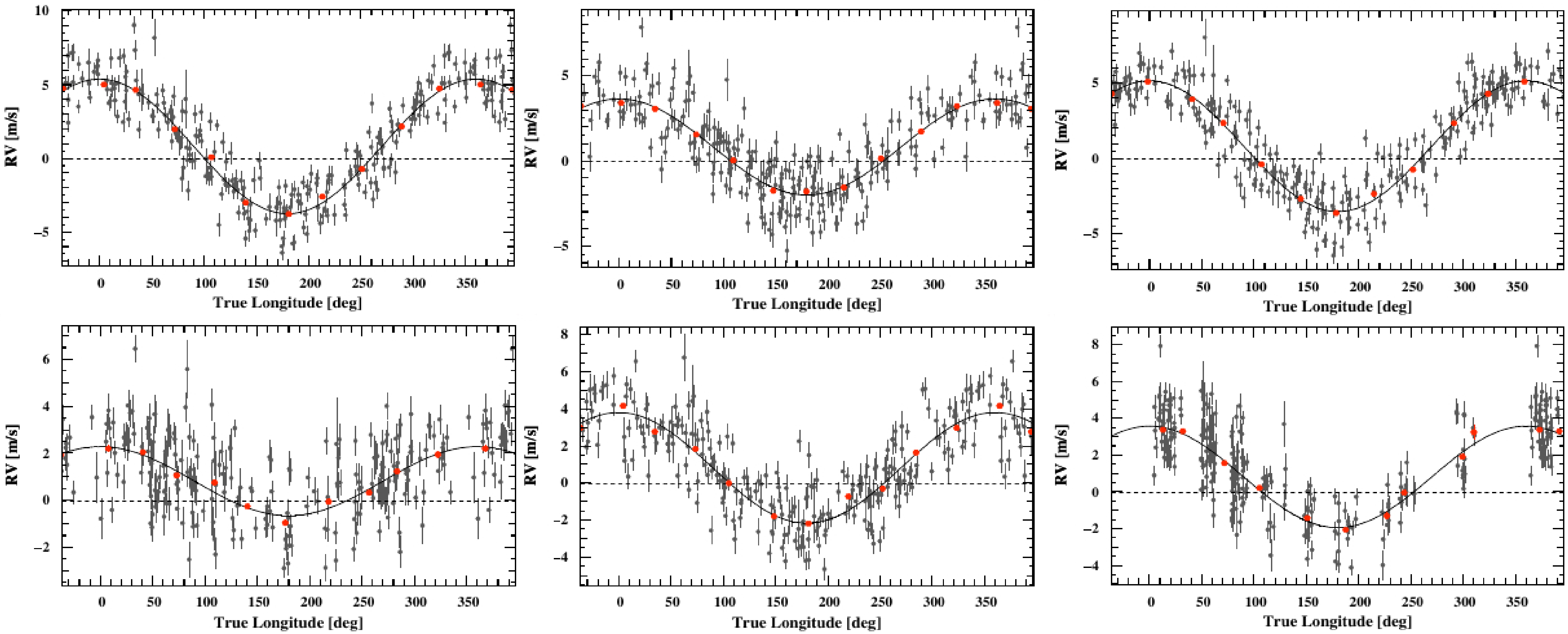

# Radial Velocities

## HD10180 - a 7 planet low mass planetary system

**Lovis et al., A&A 528, A112, 2011**

P = 1.17 .. 2248 days
K=0.85 .. 4.5 m/s
msin(i)=1.4 .. 65 $M_\oplus$
213 meas. O-C rms =1.40 m/s



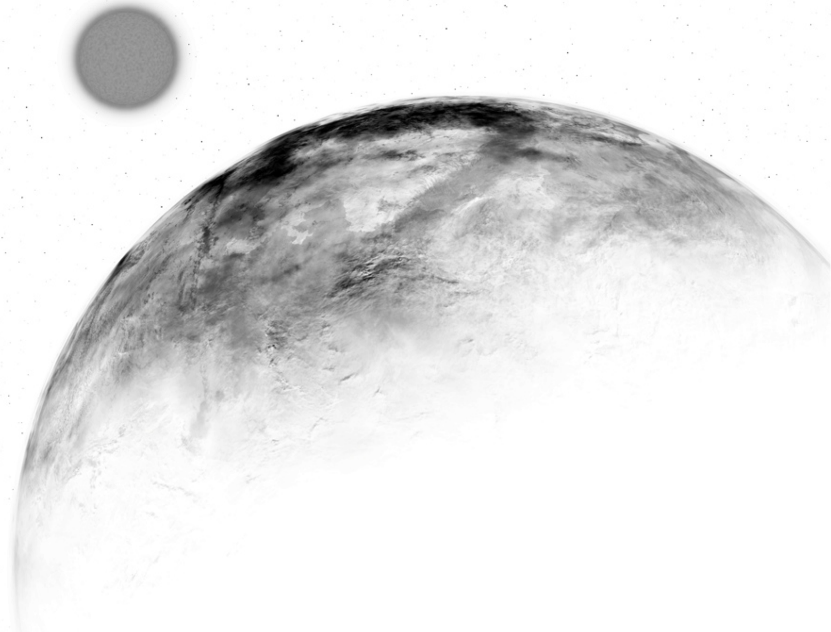



# Radial Velocities

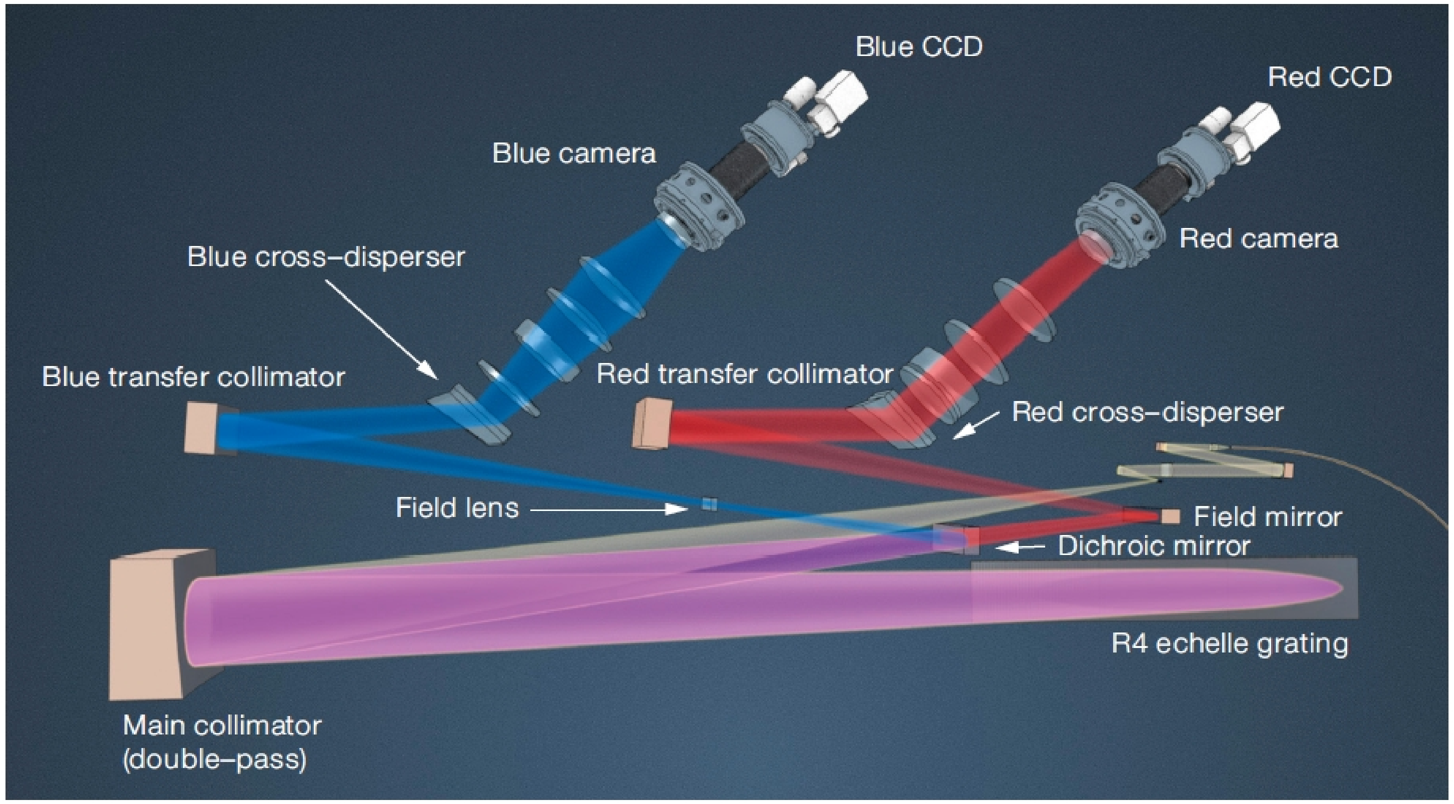
When ***several planets*** are present and with ***amplitudes at the level of instrumental precision***, it is very ***difficult to characterize their orbits***, due to the ***large number of parameters to fit***.

And yet, as we will see, most ***low-mass planets are found in systems***! This prompted an ever-increasing race for precision and motivated the development of refined statistical analysis.

| $m_2$ | $K_1(P = 3\,d)$ | $K_1(P = 1\,yr)$ | $K_1(P = 5\,yr)$ | |
|---|---|---|---|---|
| $M_{Jup}$ | 140.8 | 28.4 | 16.6 | $m/s$ |
| $M_{Nep}$ | 7.60 | 1.53 | 0.90 | $m/s$ |
| $M_{\oplus}$ | 44.3 | 8.9 | 5.2 | $cm/s$ |

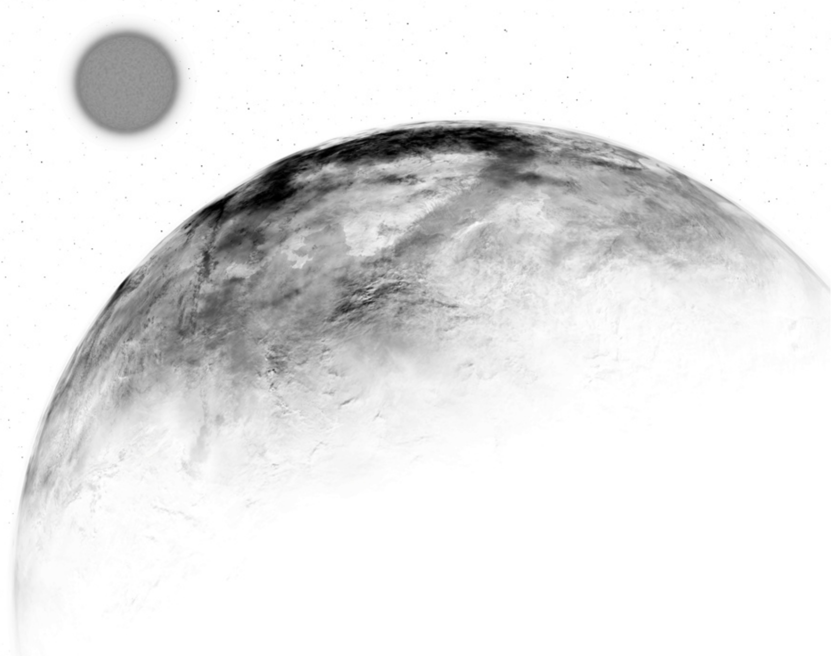


# Radial Velocities




***ESPRESSO*** will use the VLT's large collection power to reach a precision of ***10 cm/s***, making it possible to detect a ***one Earth-mass planet inside the habitable zone around a sun-like star***

*Pepe et al (2014)*



# Radial Velocities: the nIR

***Why the nIR?***

- The reflex motion induced by a given planet on a ***M dwarf is ~3 times larger*** than on a GK star
- The habitable zone is ***3 times closer***

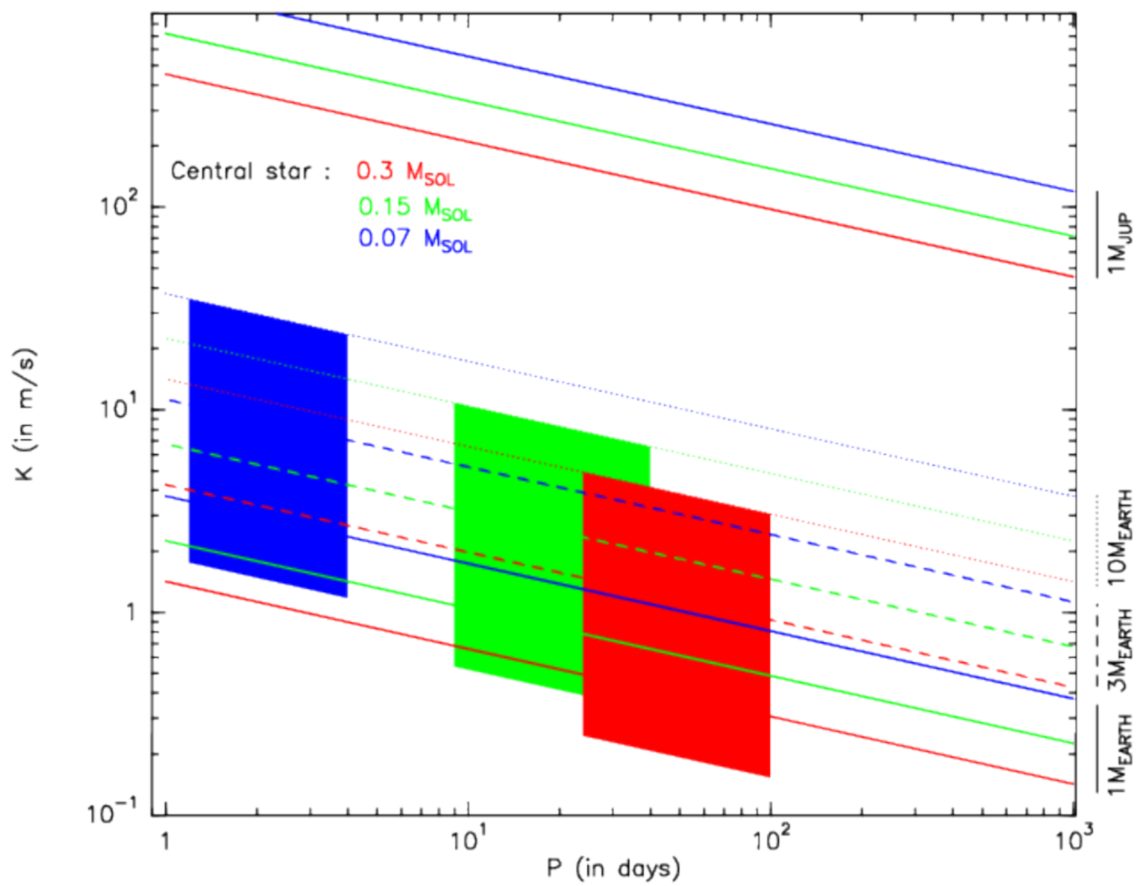
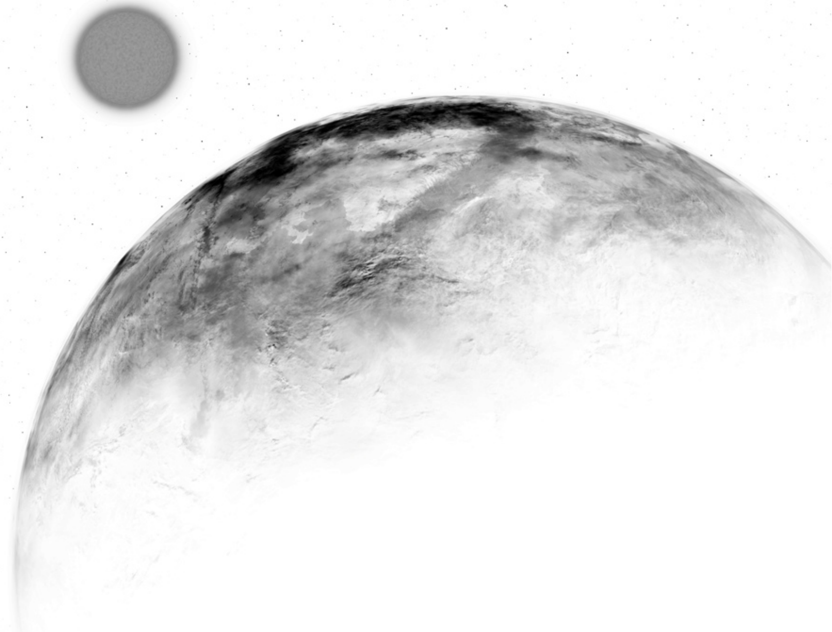



**Fig 3.4:** Radial velocity semi-amplitude K (in m/s) of the reflect motion induced by a planet on its host dwarf as a function of the planet orbital period P (in d), for planet masses of 1 $M_\oplus$ (full lines, bottom), 3 $M_\oplus$ (dashed lines), 10 $M_\oplus$ (dotted lines) and 1 $M_{♃}$ (full lines, top) and for host dwarf masses of 0.3 $M_\odot$ (red), 0.15 $M_\odot$ (green) and 0.07 $M_\odot$ (blue) - corresponding respectively to M4, M6 and early-L dwarfs. The red, green and blue parallelograms illustrate, for each dwarf mass, the RV impact of 0.5-10 $M_\oplus$ planets within the HZs, i.e. with orbital periods of 24-100 d, 9-40 d and 1-4 d for 0.3 $M_\odot$, 0.15 $M_\odot$ and 0.07 $M_\odot$ dwarfs respectively.



# SPIRou

***What will SPIRou (NIRPS, CARMENES) be capable of?***

- Detect and ***measure the frequency*** of ***Earth-mass planets*** around ***M dwarfs***
- ***Study*** how the ***magnetic fields*** impact on star/planet formation

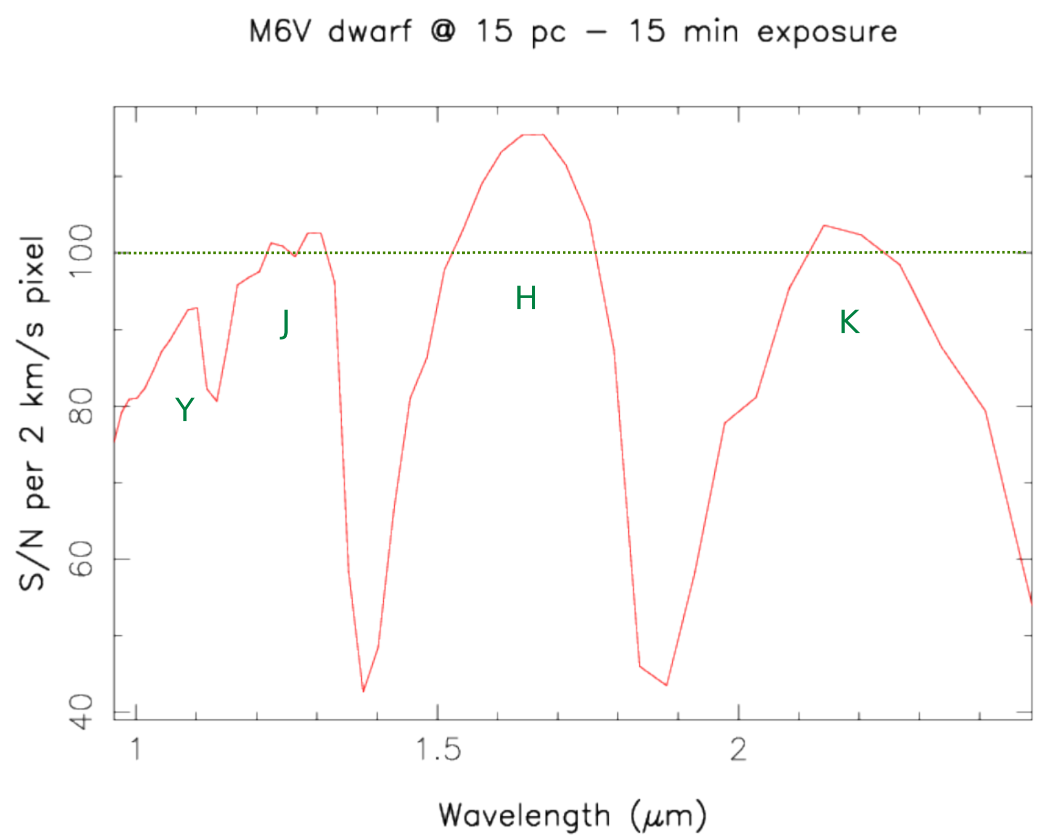
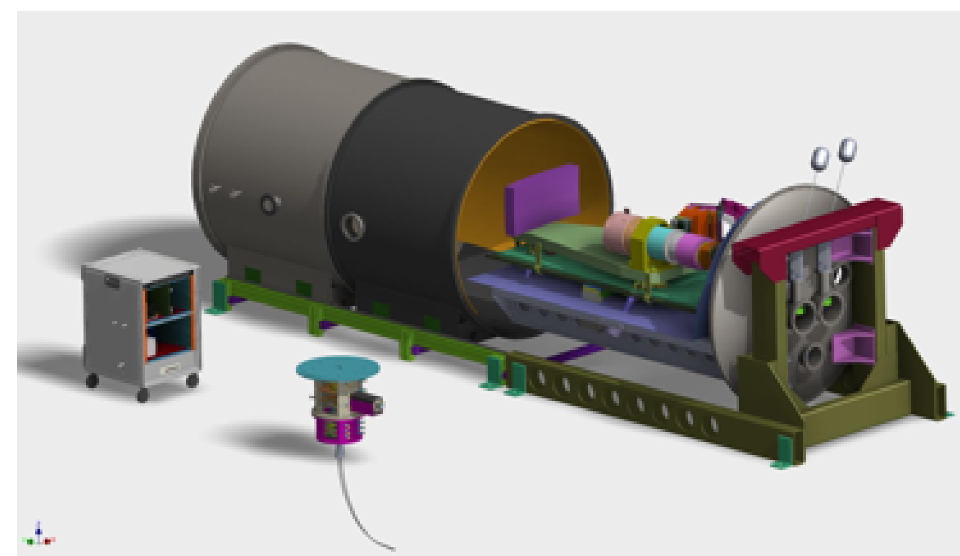
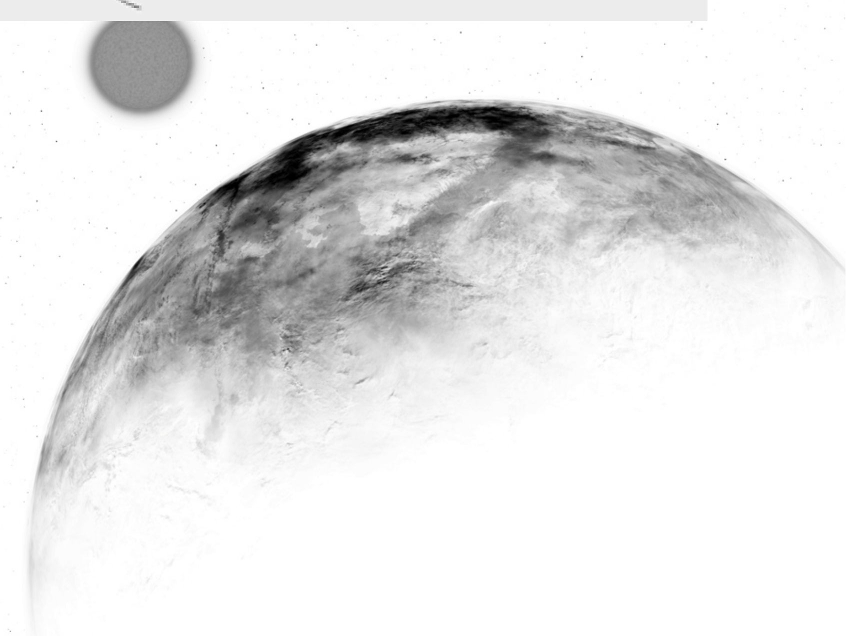



**Fig 8.3:** Estimated S/N (per 2 km/s pixel) as a function of wavelength for a 15 min exposure with SPIRou on a M6 dwarf located at 15 pc (J=10.4, K=9.5). The peak throughput of the instrument (telescope & detector included) is set to 15% and the photon distribution is taken from the NextGen models (Allard et al 1997, ARA&A 35, 137).

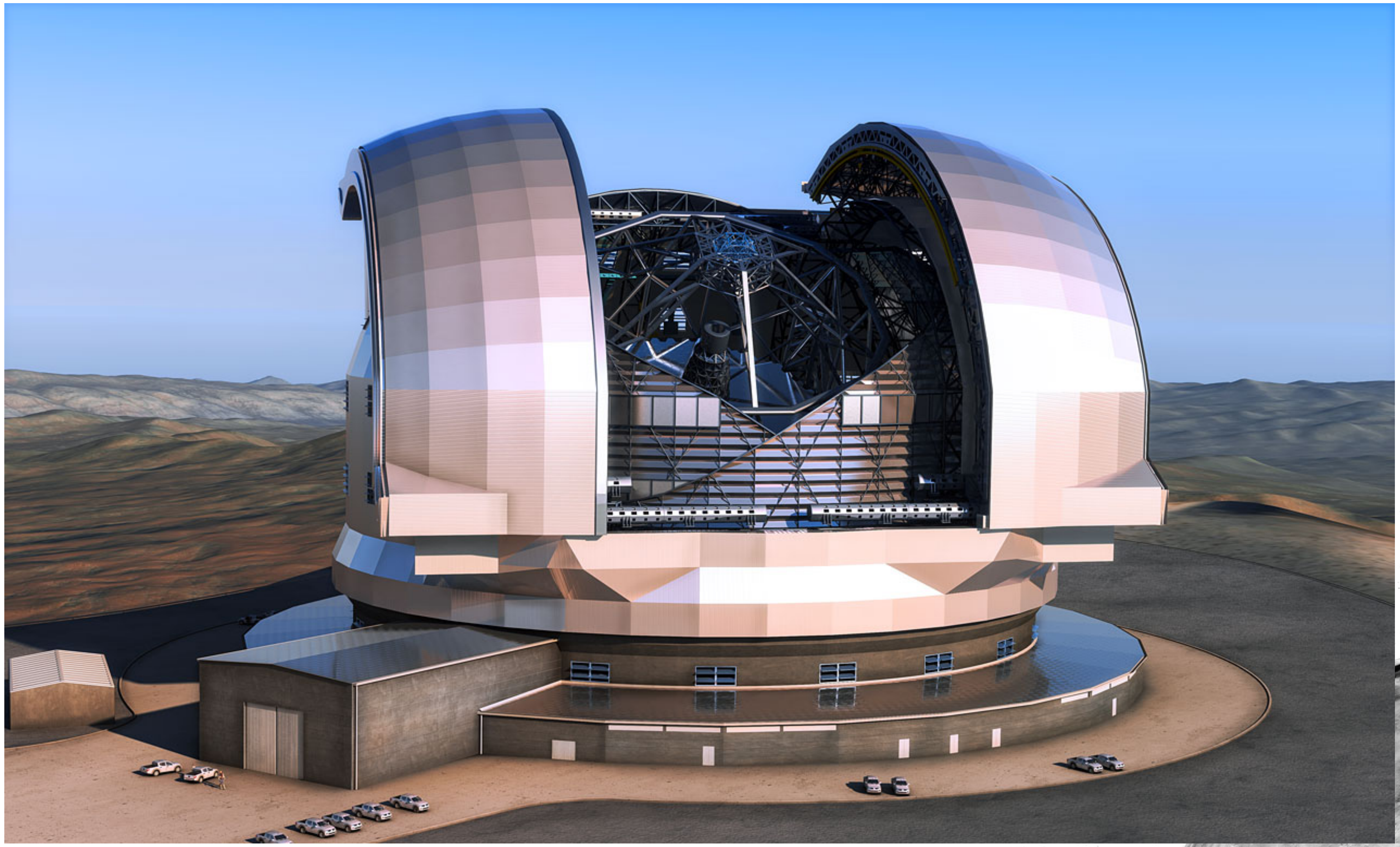




*Moutou et al (2015)*

# E-ELT

The key player at direct detection and extrasolar planets atmosphere characterization will be the E-ELT; it will also help RV studies.



http://www.eso.org/public/teles-instr/e-elt/

# Bibliography


- Chazelas, et al. (2010), *New scramblers for precision radial velocity: square and octagonal fibers, http://adsabs.harvard.edu/abs/2010SPIE.7739E..47C*
- *Astronomical Optics (2nd edition), D. J. Schroeder, Academic Press http://www.sciencedirect.com/science/book/9780126298109*
- *Handbook of CCD Astronomy, Howell, Cambridge University press*
- *James Beletic courses: http://www.ee.ucla.edu/~leosla/documents/James_Beletic_IEEE_Photonics.pdf*
- Bouchy, Pepe & Queloz (2001), *Fundamental photon noise limit to radial velocity measurements, http://adsabs.harvard.edu/abs/2001A%26A...374..733B*
- *Hatzes & Cochran (1992), Spectrograph Requirements for Precise Radial Velocity Measurements, http://cdsads.u-strasbg.fr/abs/1992ESOC...40..275H*
- Baranne et al. (1996), *ELODIE: A spectrograph for accurate radial velocity measurements.*

# Bibliography


- Butler et al (1996), *Attaining Doppler Precision of 3 M s-1*, http://adsabs.harvard.edu/abs/1996PASP..108..500B

- Howard (2010), *PRV error budget*, http://adsabs.harvard.edu/abs/2010aepr.confE...3H

  (online at: http://exoplanets.astro.psu.edu/workshop/ )

- Valenti (2010), *Using a Gas Absorption Cell as a Radial Velocity Reference*, http://adsabs.harvard.edu/abs/2010aepr.confE..32V

  (online at: http://exoplanets.astro.psu.edu/workshop/ )

- Murphy et al (2007), *High-precision wavelength calibration of astronomical spectrographs with laser frequency combs*, http://adsabs.harvard.edu/abs/2007MNRAS.380..839M

- Steinmetz et al (2008), *Laser Frequency Combs for Astronomical Observations*, http://adsabs.harvard.edu/abs/2008Sci...321.1335S

# Bibliography


- Lovis et al. (2011), *The HARPS search for southern extra-solar planets. XXVIII. Up to seven planets orbiting HD 10180: probing the architecture of low-mass planetary systems*, http://adsabs.harvard.edu/abs/2011A%26A...528A.112L

- Moutou, C. (2015), *SPIRou: a spectropolarimeter for the CFH*T, http://adsabs.harvard.edu/abs/2015sf2a.conf..205M

- Dumusque et al. (2012), *An Earth-mass planet orbiting α Centauri B*, http://adsabs.harvard.edu/abs/2012Natur.491..207D

- Pepe et al (2013), *An Earth-sized planet with an Earth-like density*, http://adsabs.harvard.edu/abs/2013Natur.503..377P

- Pepe et al (2014), *ESPRESSO: The next European exoplanet hunter*, http://adsabs.harvard.edu/abs/2014arXiv1401.5918P