Exoplanets

Fall/Winter 2025/2026
Lecture 3
30.10.2025

Outline

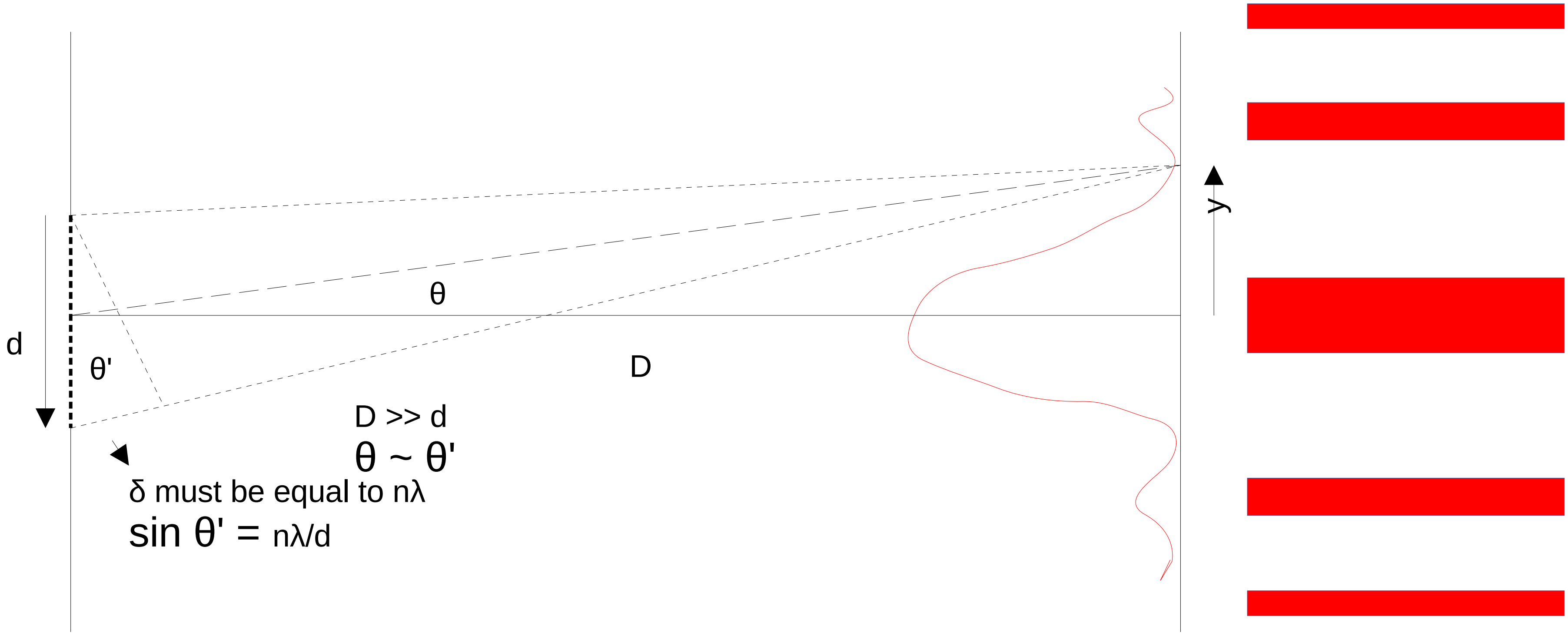
- Spectrographs and how do they work?
- CCD/NIR detectors
- Photometry and exoplanets detection
- This will be pain but you will be ready for the exoplanet talk

Spectrographs, how do they work?

- Components
  - lens
  - fiber/slit
  - prism/grism/grating
  - detector (now CCD)
- Physics behind the spectrograph
  - diffraction equation

    $n\lambda = d \sin \theta$

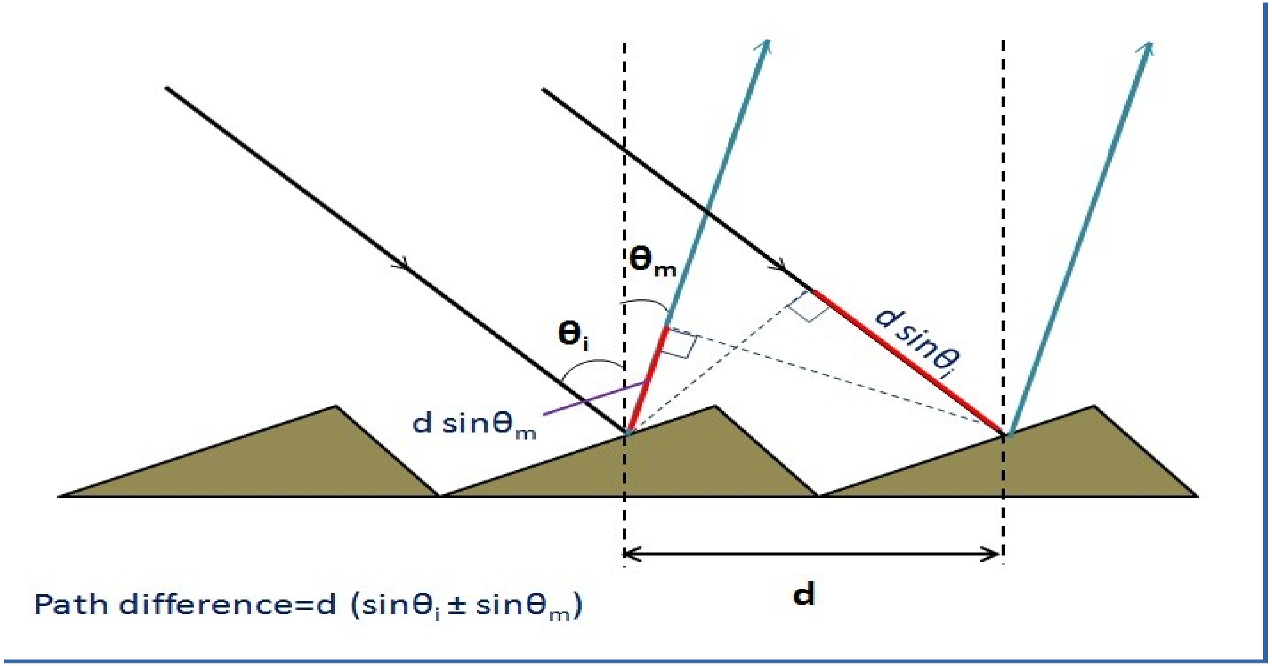
Diffraction on grating



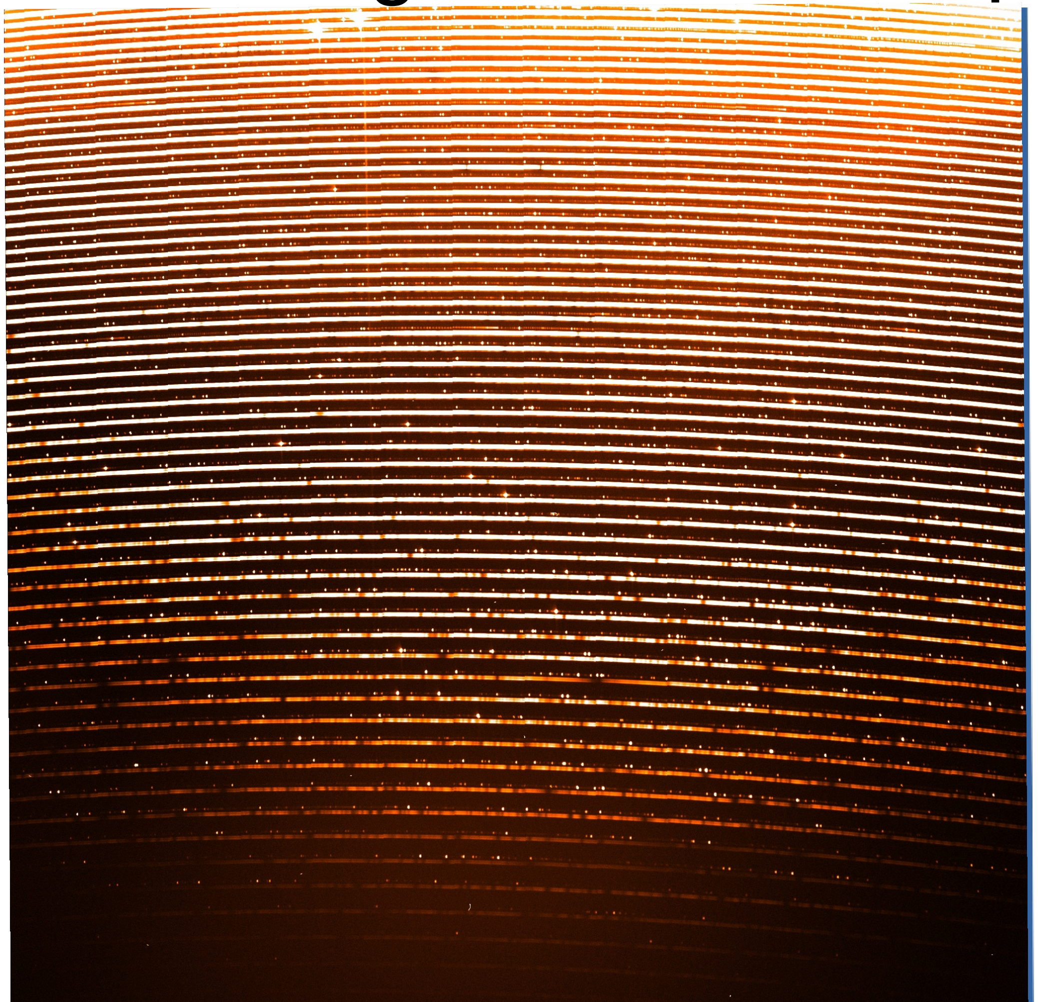
If interested, read more here:
http://web.mit.edu/8.02t/www/802TEAL3D/visualizations/coursenotes/modules/guide14.pdf

Echelle Spectrographs

Blazed grating with many grooves



Echellogram - PLATOSpec



Echellogram

See page:
http://astronomy.nmsu.edu/cwc/Teaching/ASTR605/Lectures/spectra.pdf

Echellogram

- Blaze function

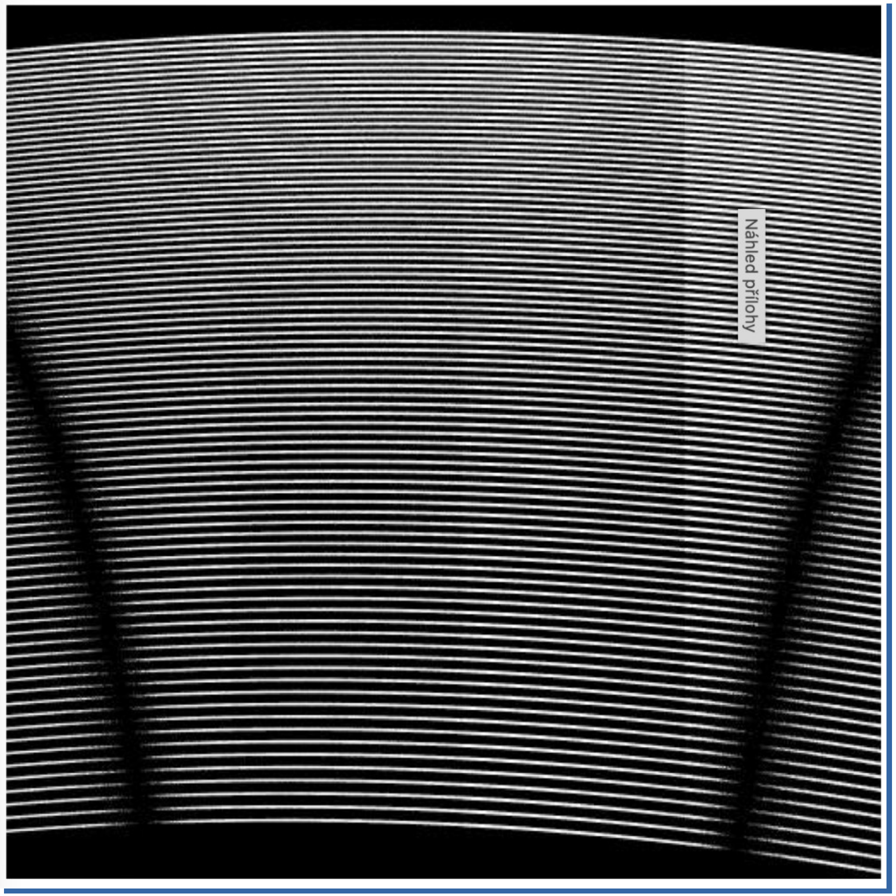
  - interference along

  the facet, curving

  the “orders”

- http://astronomy.nmsu.edu/cwc/Teaching/ASTR605/Lectures/spectra.pdf

Overlapping orders



Crossdispersers

- Orders will overlap
- Crossdisperser prism separates them

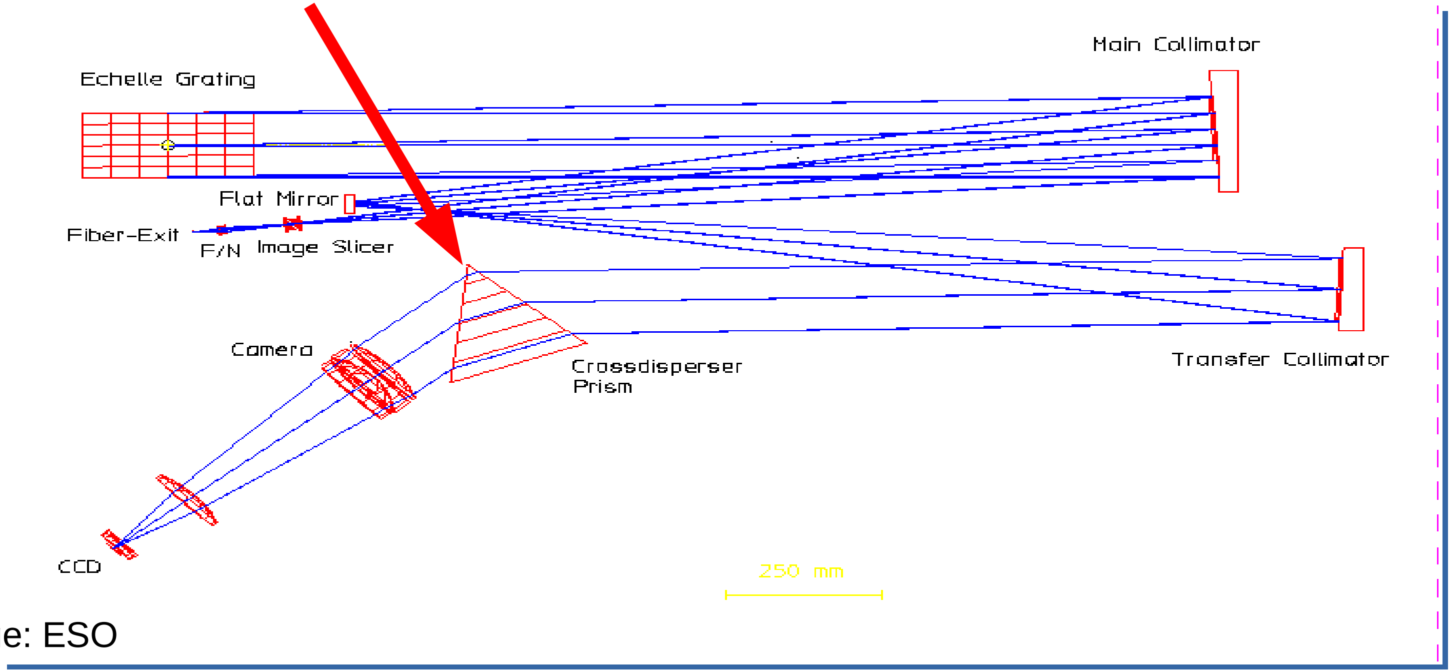


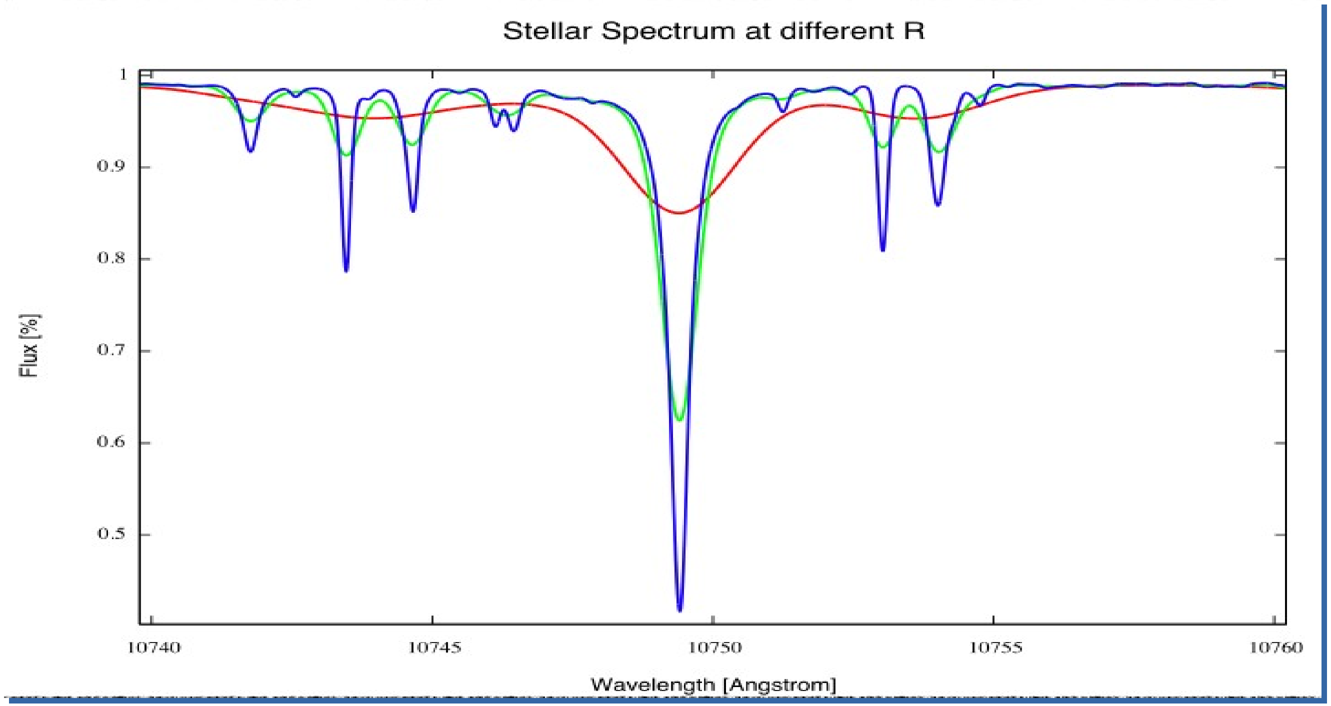
Image: ESO

Main parameters of the spectrograph

- Fiber or slit size
- Fiber avoids too many optical surfaces
- Resolving power $R=\lambda/\Delta\lambda=nN$ (N – number of grooves)

  - separation between two spectral lines considered as just resolved
- $R < 1000$ low resolution
- $1000 < R < 10000$ intermediate resolution
- $R > 10000$ high resolution

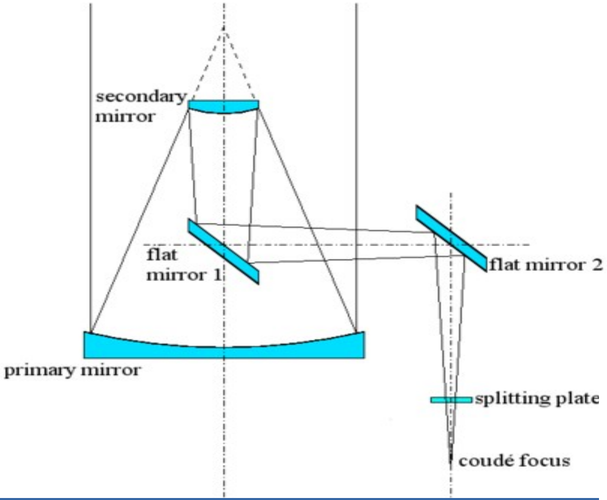
Effect of the resolving power



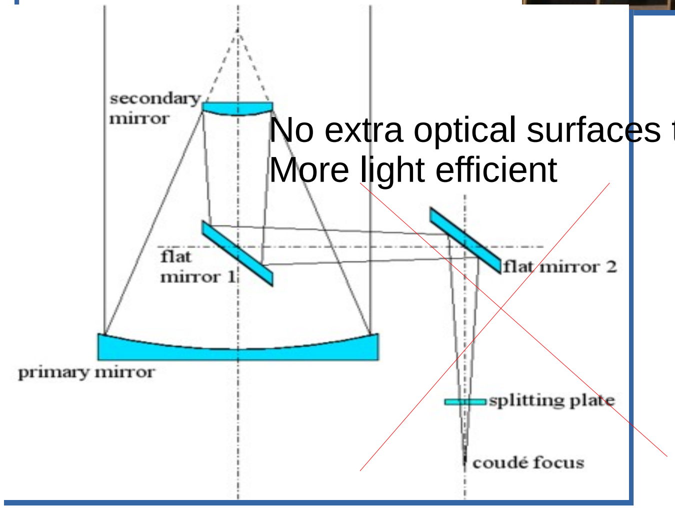
Graph by: P. Figueira

Fiber vs. classical (Perek 2m)

- Classical



spectrograph



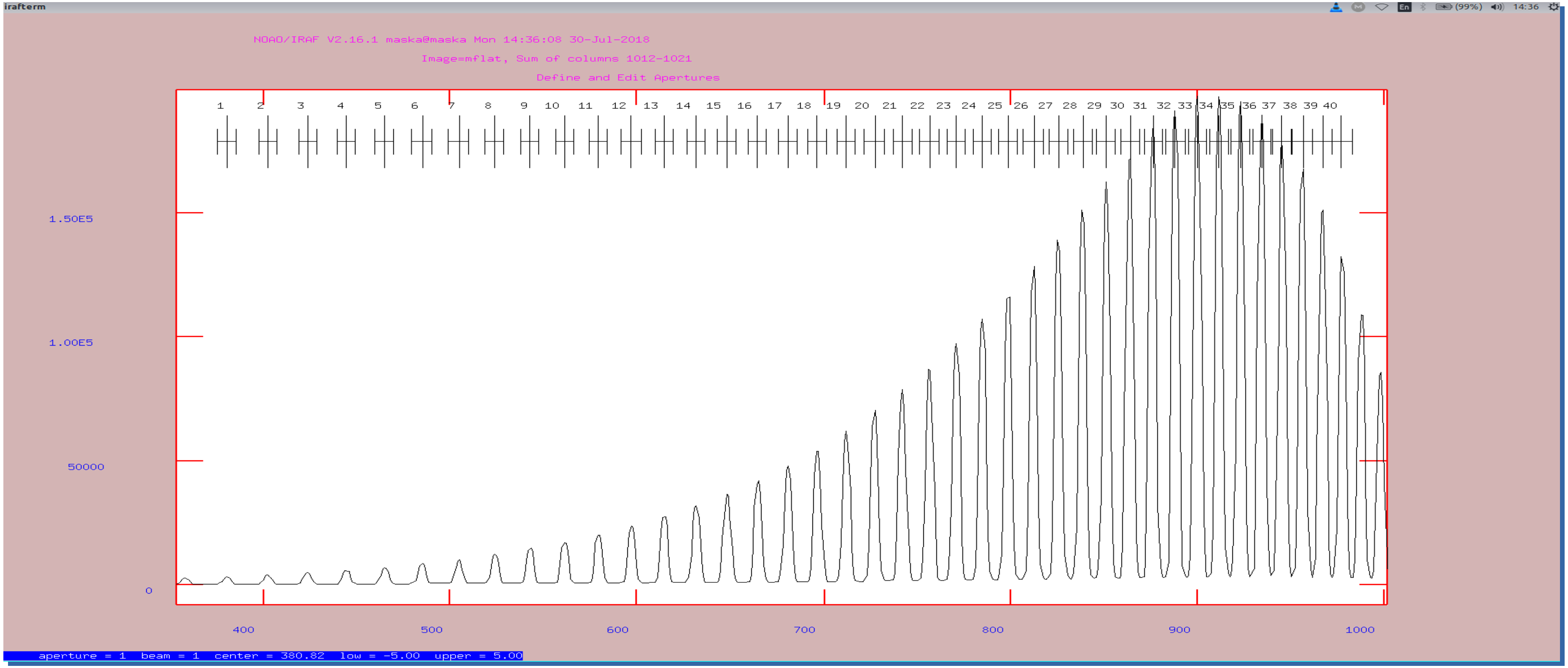
No extra optical surfaces to spectrograph
More light efficient

spectrograph

Doppler effect

- $\Delta\lambda/\lambda = v/c$ (non relativistic)
- First we need to perfectly calibrate the wavelength
- Then we can measure the velocities, well shifts in wavelength due to the movement of the object
- Let`s have a look how to calibrate the wavelengths
- Could you find out the link between R and v?

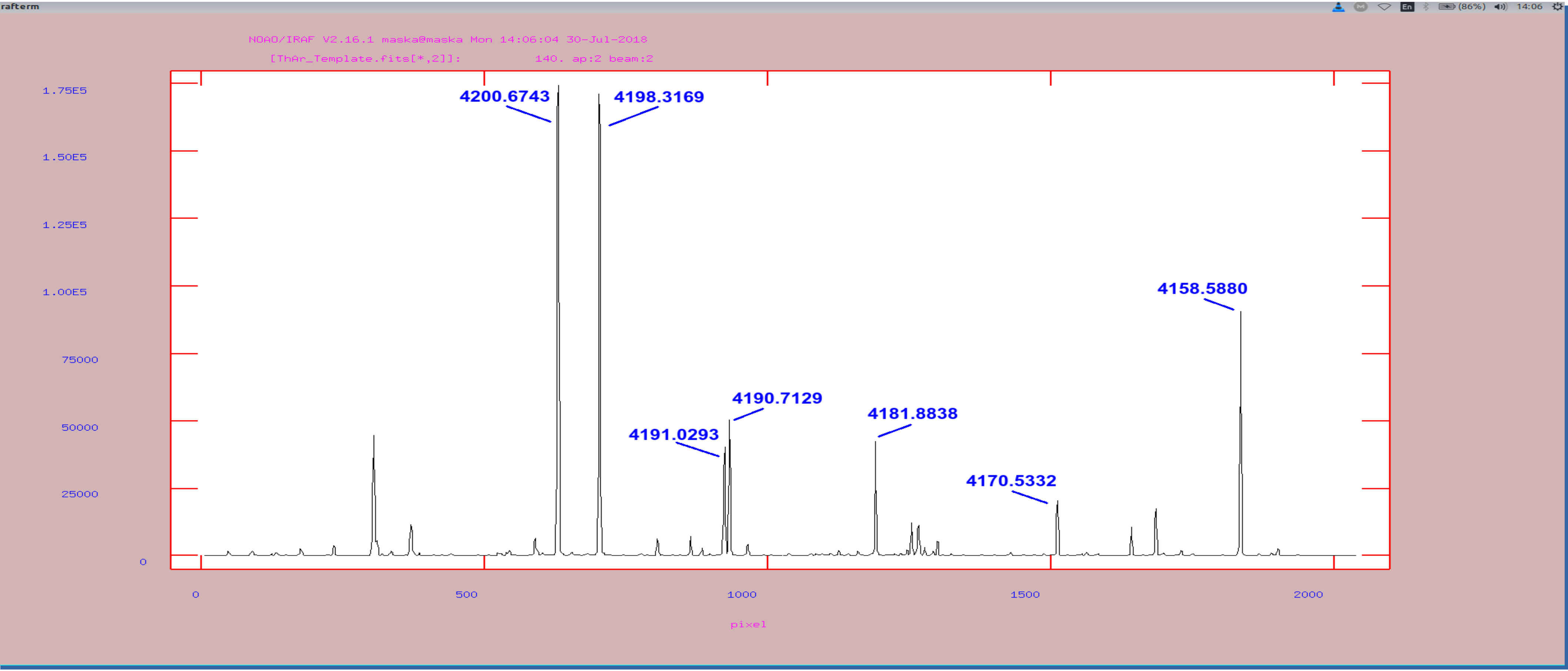
Extraction of spectra



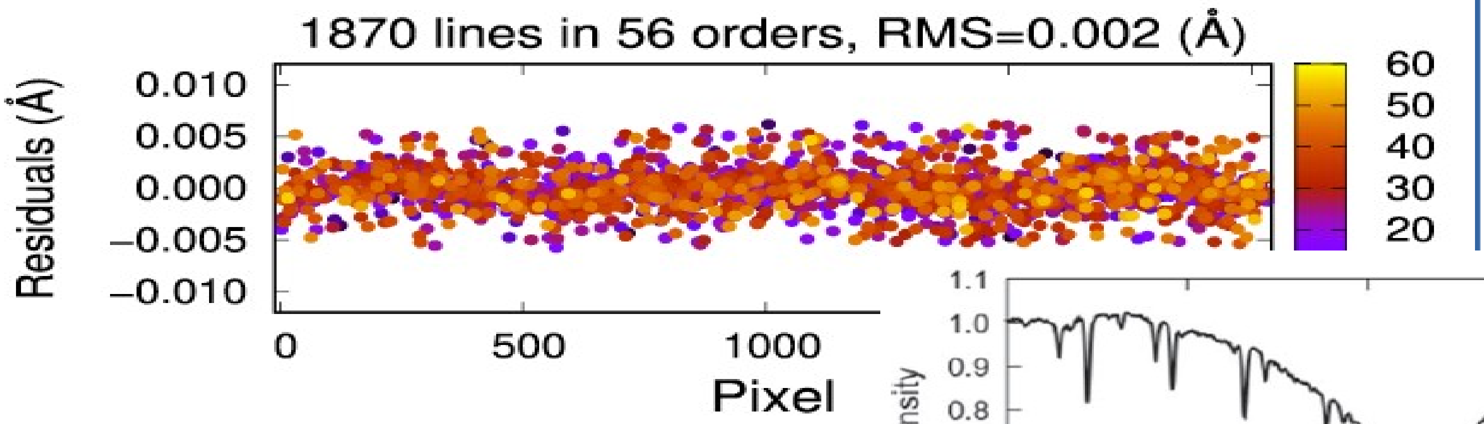
ThAr lamp for calibration

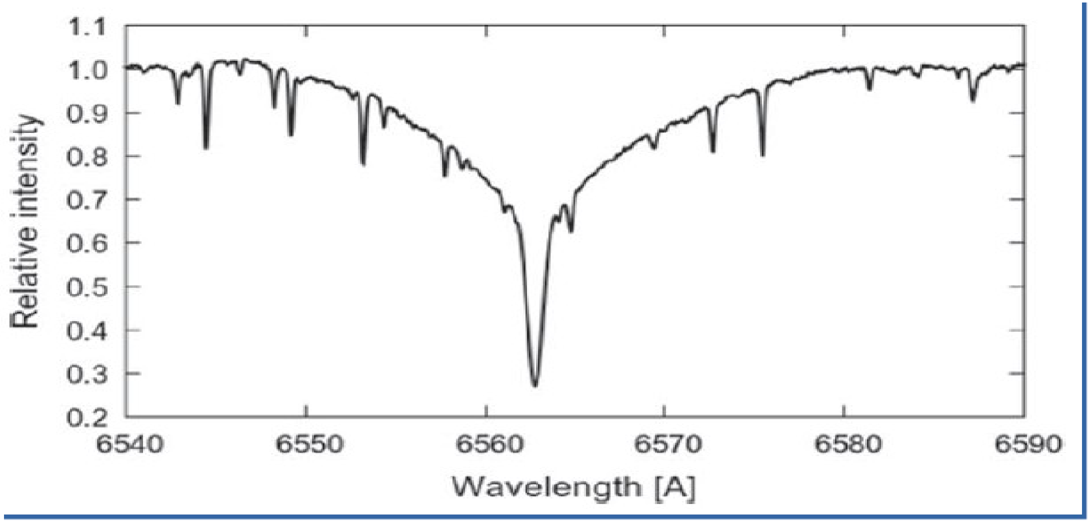
- Th-Ar gas
- Many emission lines
- Precise atlas for the
- Wavelegth calibration
- Calibration taken before/after science or simultaneously (see later fiber fed)

Reference atlas – ThAr lines

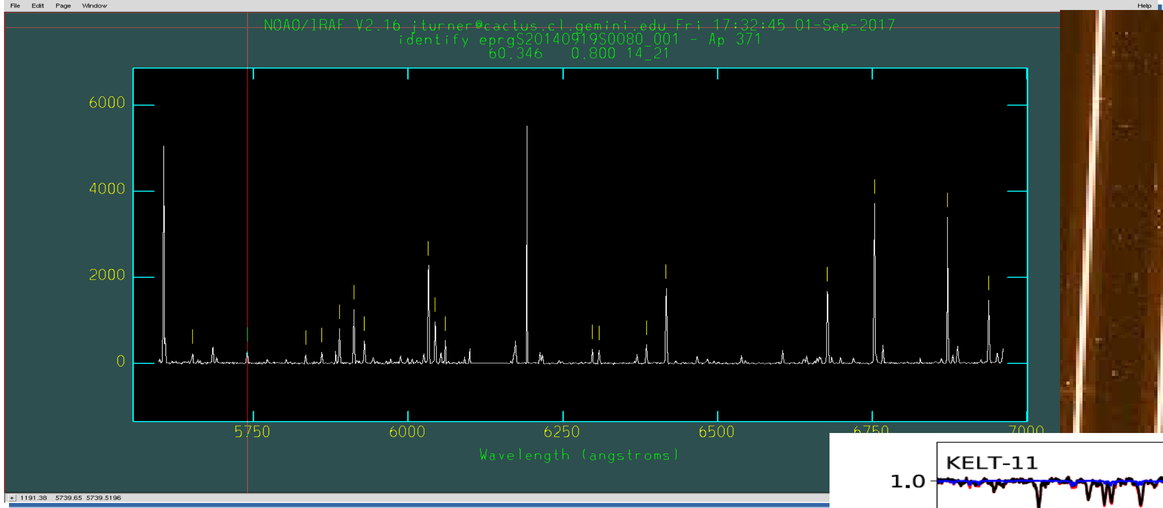


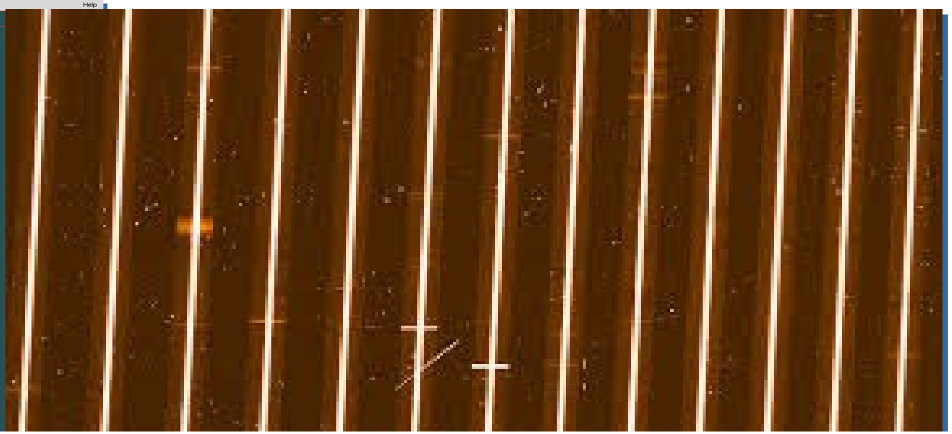
Wavelength solution

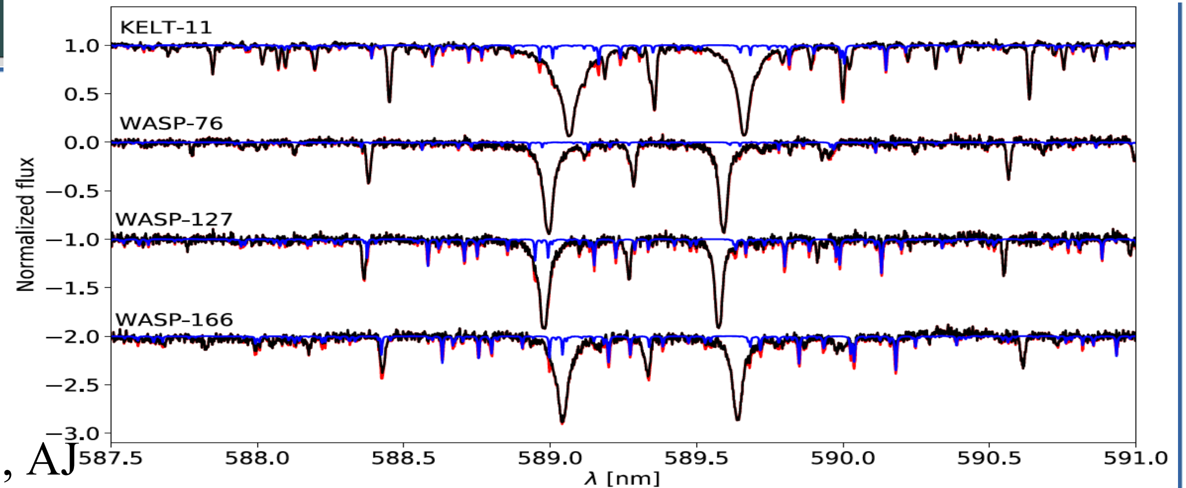




From the raw spectra to calibrated spectrum and RVs







1. Raw spectra
2. Extraction of orders
3. Wavelength calibration
4. Wavelength solution
5. Reduced spectra
6. Radial velocities

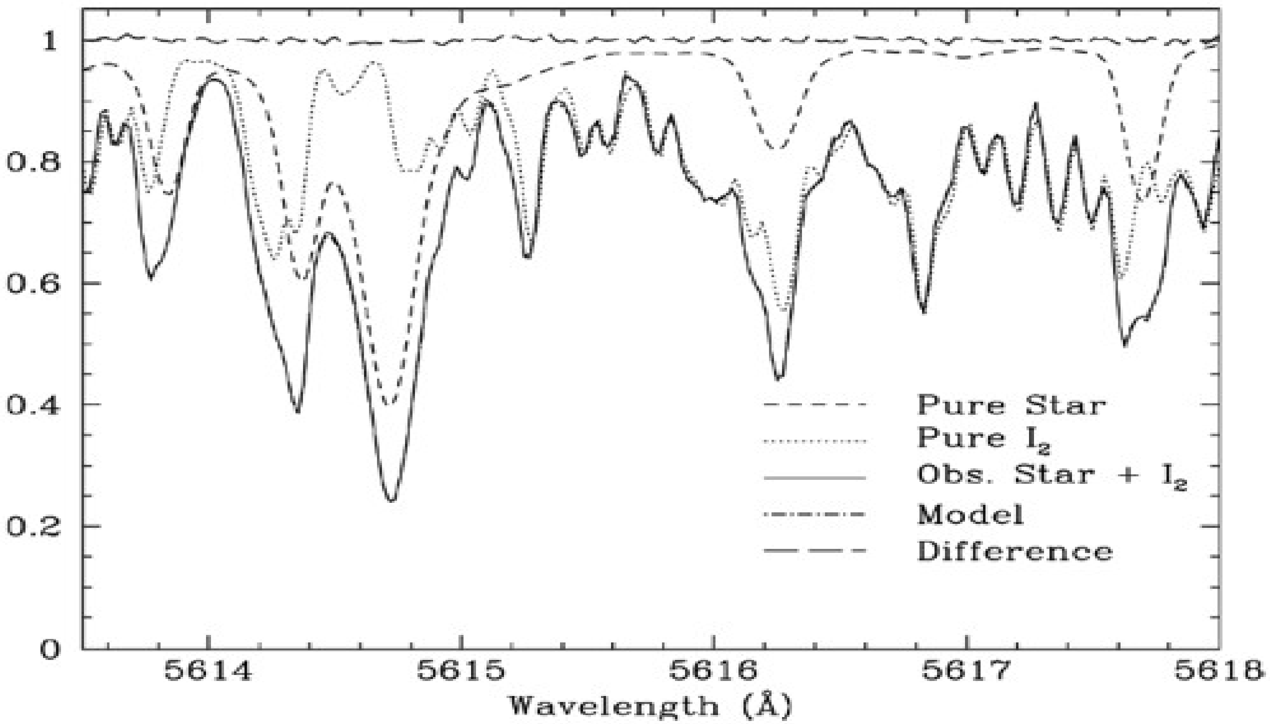
Reduced spectra example from: Zak et al. 2019, AJ

Bruce Campbell and Gordon Walker First usage fo absorption cells

- First spectroscopic exoplanet survey 1971
- Hydrogen Fluoride cell for calibration
- The goal is to convert pixel scale (detector) into wavelength as accurately as possible
- http://articles.adsabs.harvard.edu/pdf/1979PASP...91..540C

https://dtm.carnegiescience.edu/news/brief-personal-history-exoplanets

Iodine

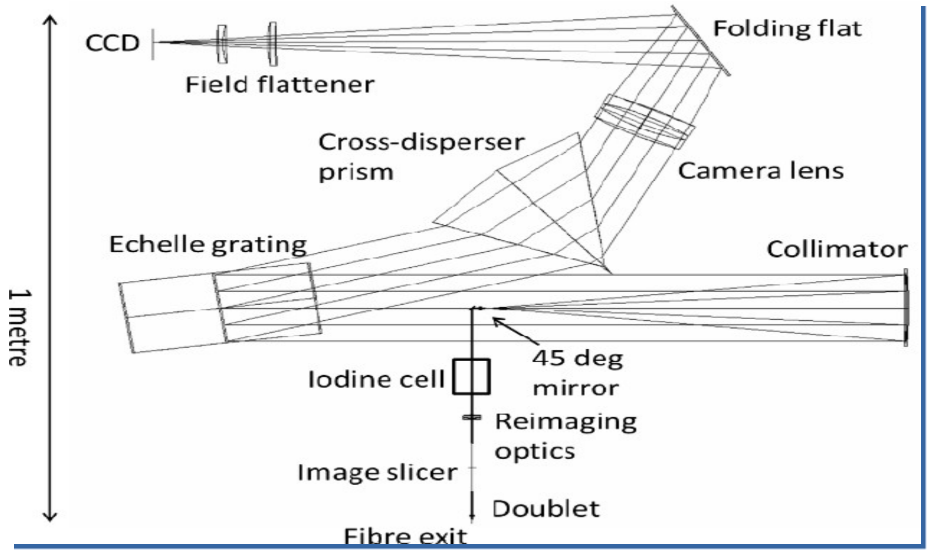


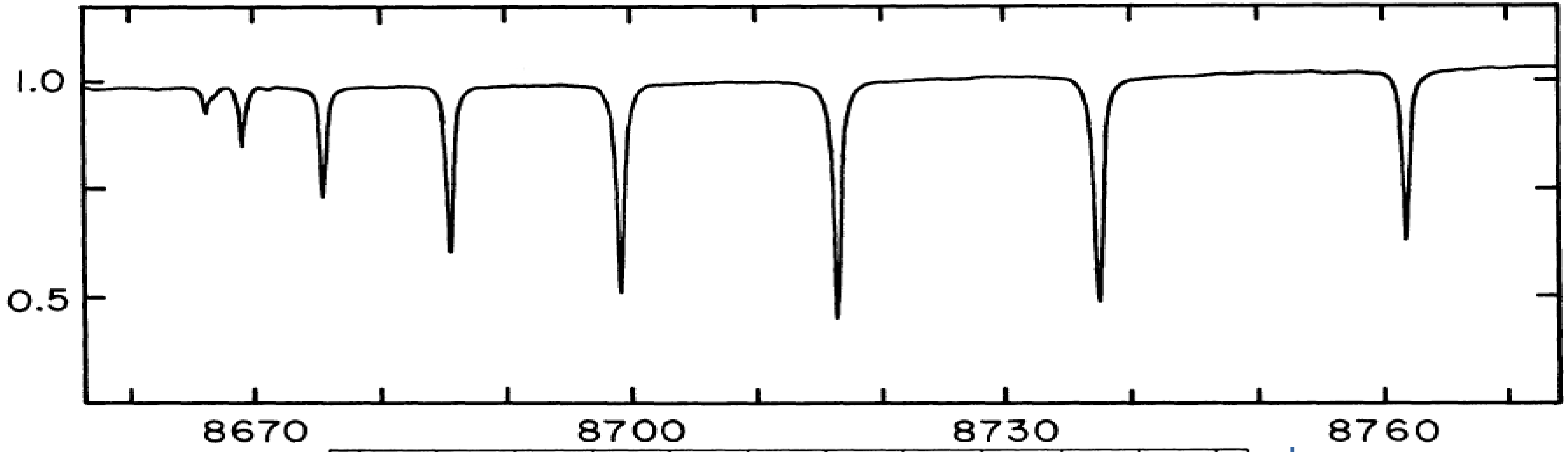
From A. Hatzes:
The detection of extrasolar planets using precise stellar radial velocities

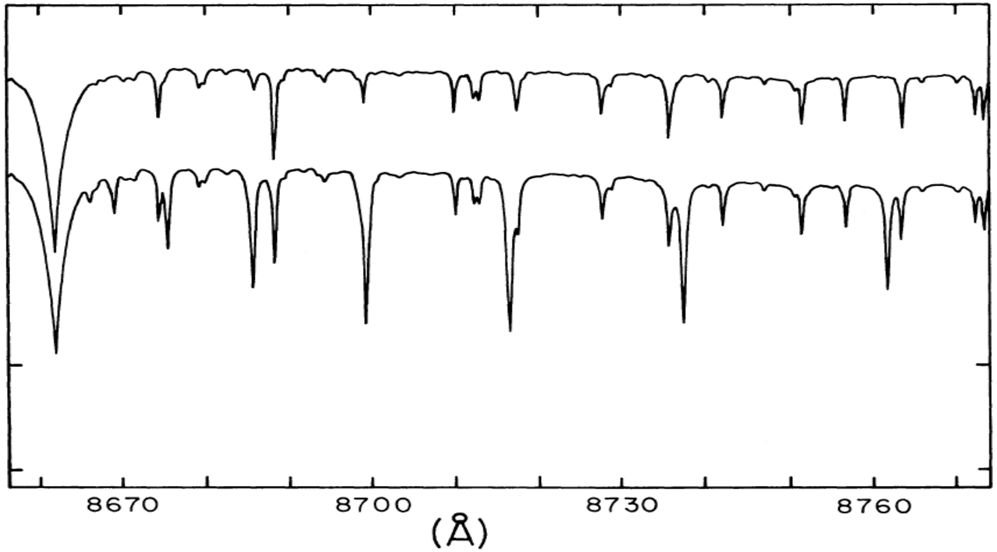
Why an absorption cell?

- HF lines clearly defined
- Increasing the stability
- Precision down to 15 m/s
- However HF is dangerous!
- Needs to be filled for each night
- Lines cover limited wavelengths
- Iodine was another choice
- Iodine is less dangerous

Chiron design CTIO - Schwab et al. 2010, SPIE

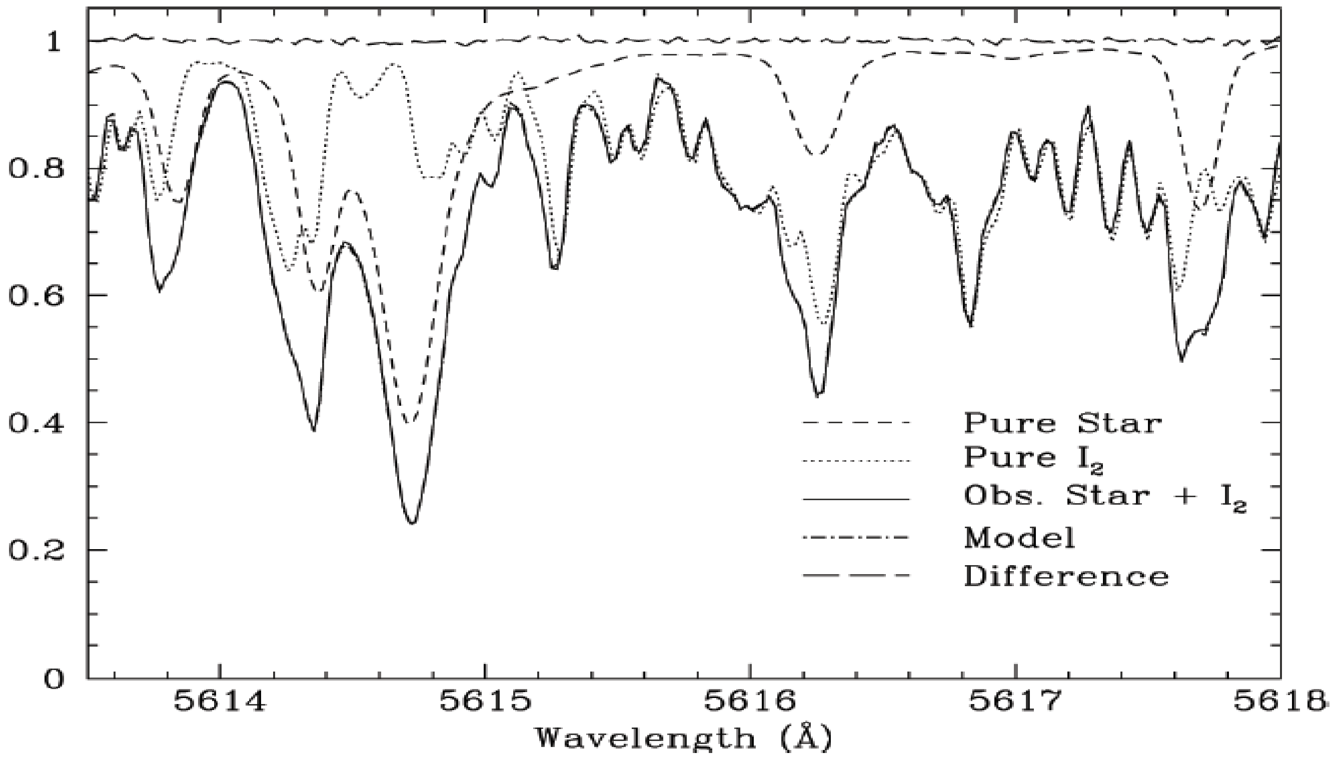






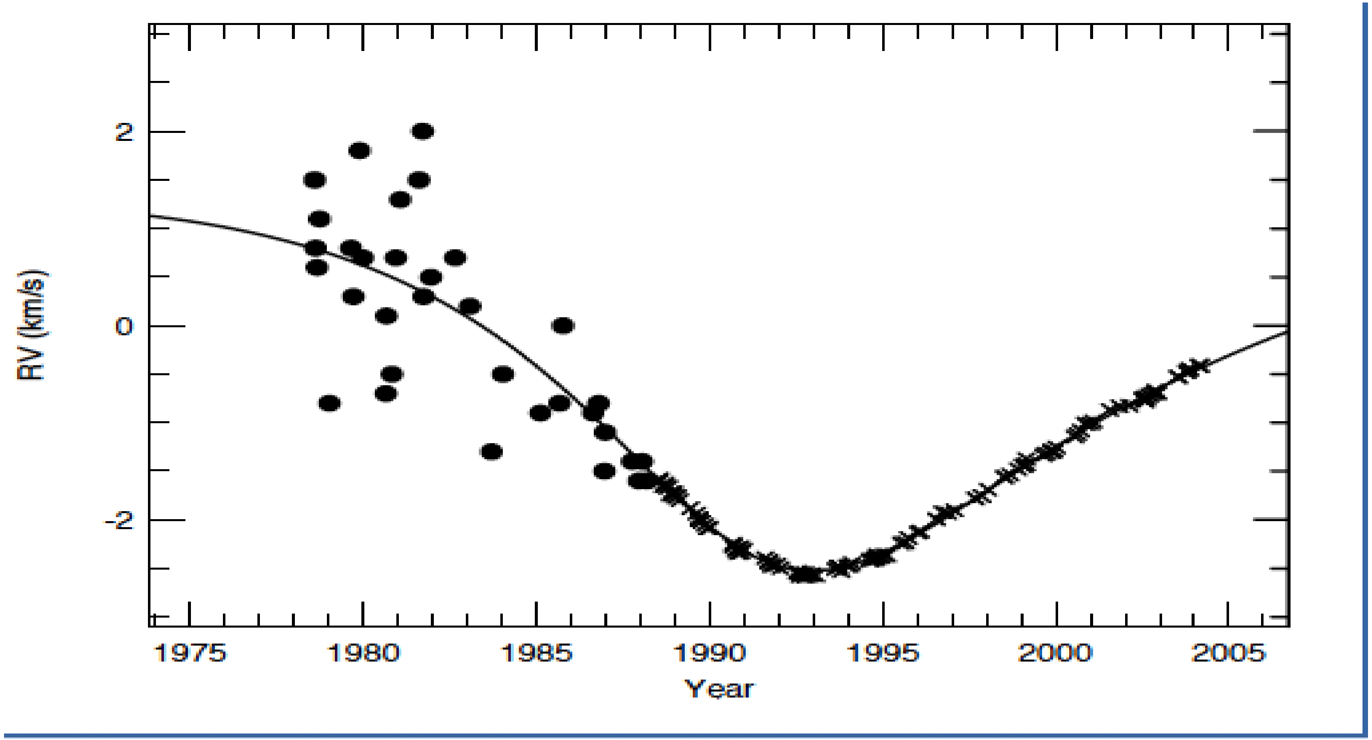
http://articles.adsabs.harvard.edu/pdf/1979PASP...91..540C

Iodine



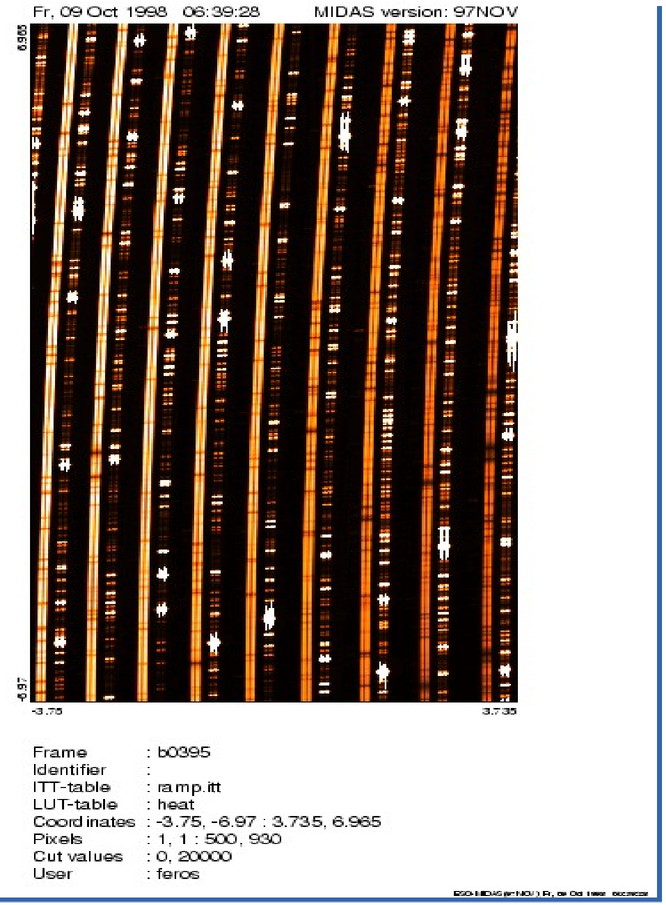
From Hatzes, Cochran and Endl - The Detection of Extrasolar Planets using Precise Stellar Radial Velocities

Iodine and no iodine



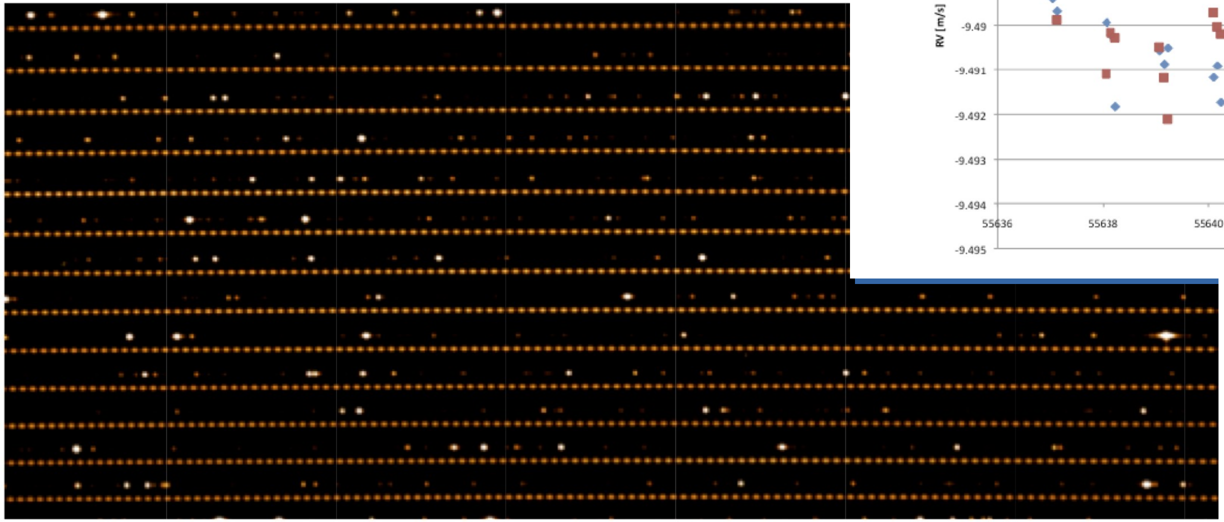
Gamma Cep with Iodine and without Iodine cell - figure from Hatzes, Cochran and Endl - The Detection of Extrasolar Planets using Precise Stellar Radial Velocities

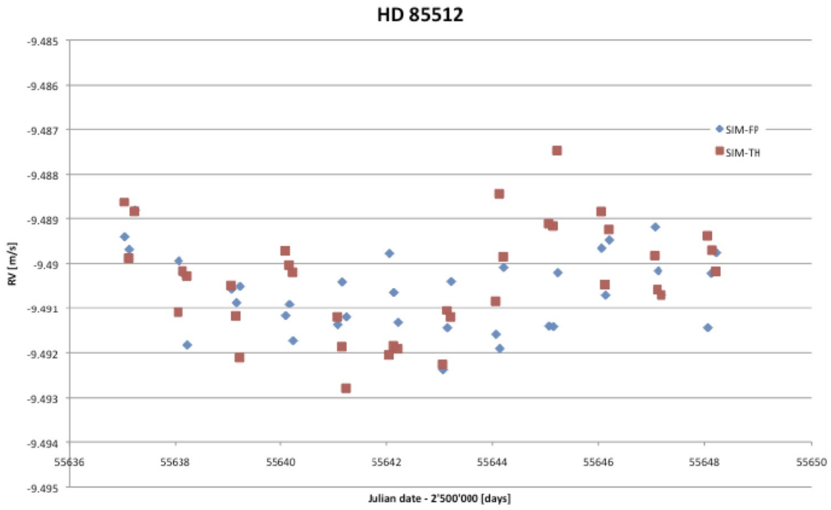
Simultaneous ThAr calibration

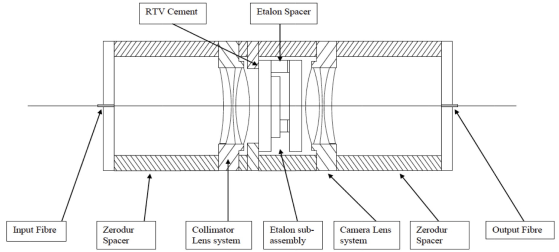


Fabry Perot etalon

- More stable than ThAr
  cm/s level, more lines
- for calibration



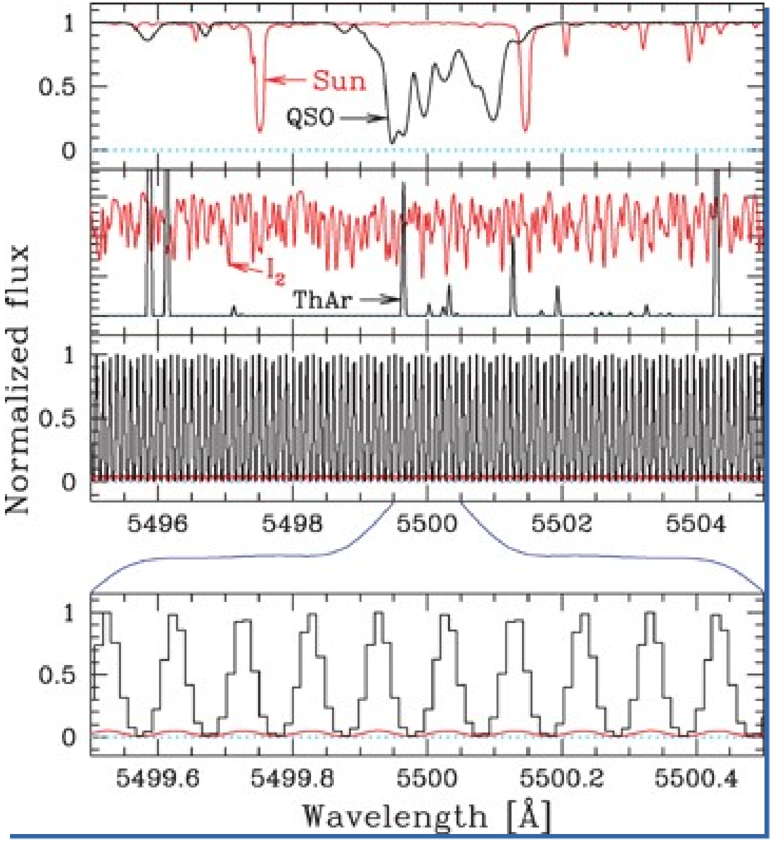




http://obswww.unige.ch/~wildif/publications/2011_8151-51.pdf

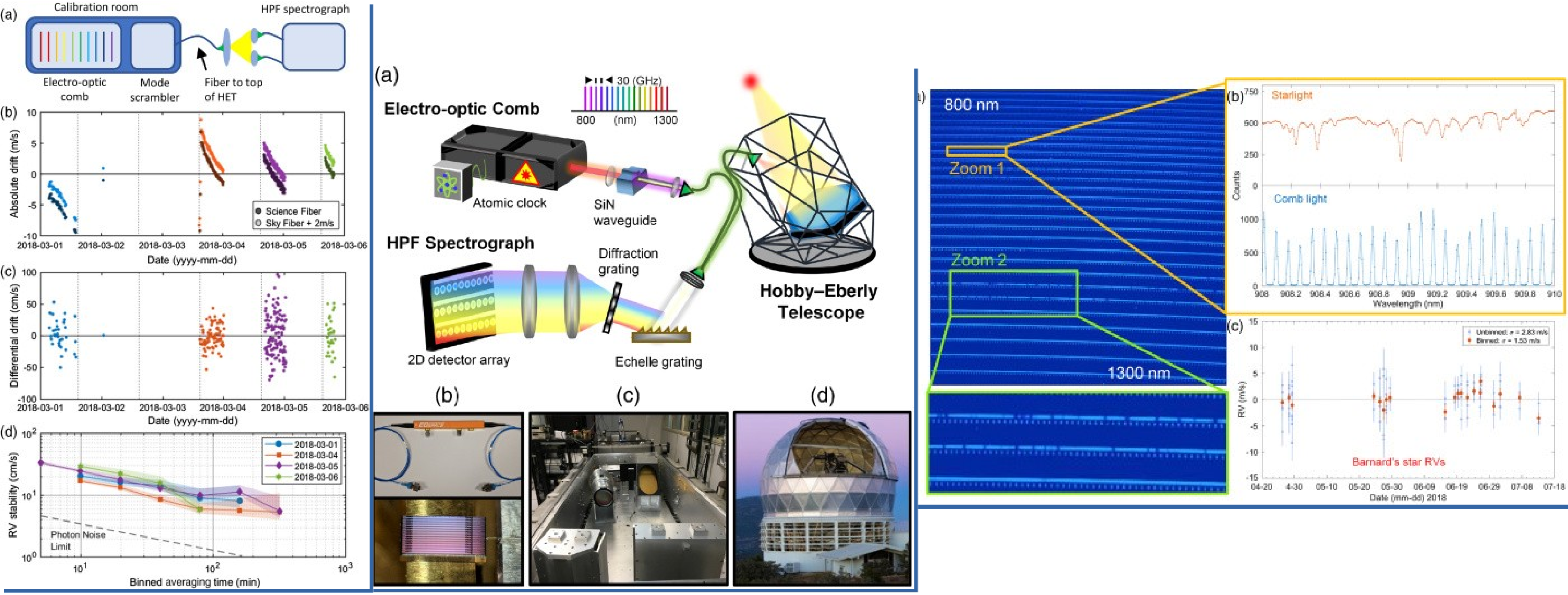
Laser frequency combs calibration

- Femtosecond lasers
- Very precise, laser combs related to atomic clock
- Many very precise calibration lines



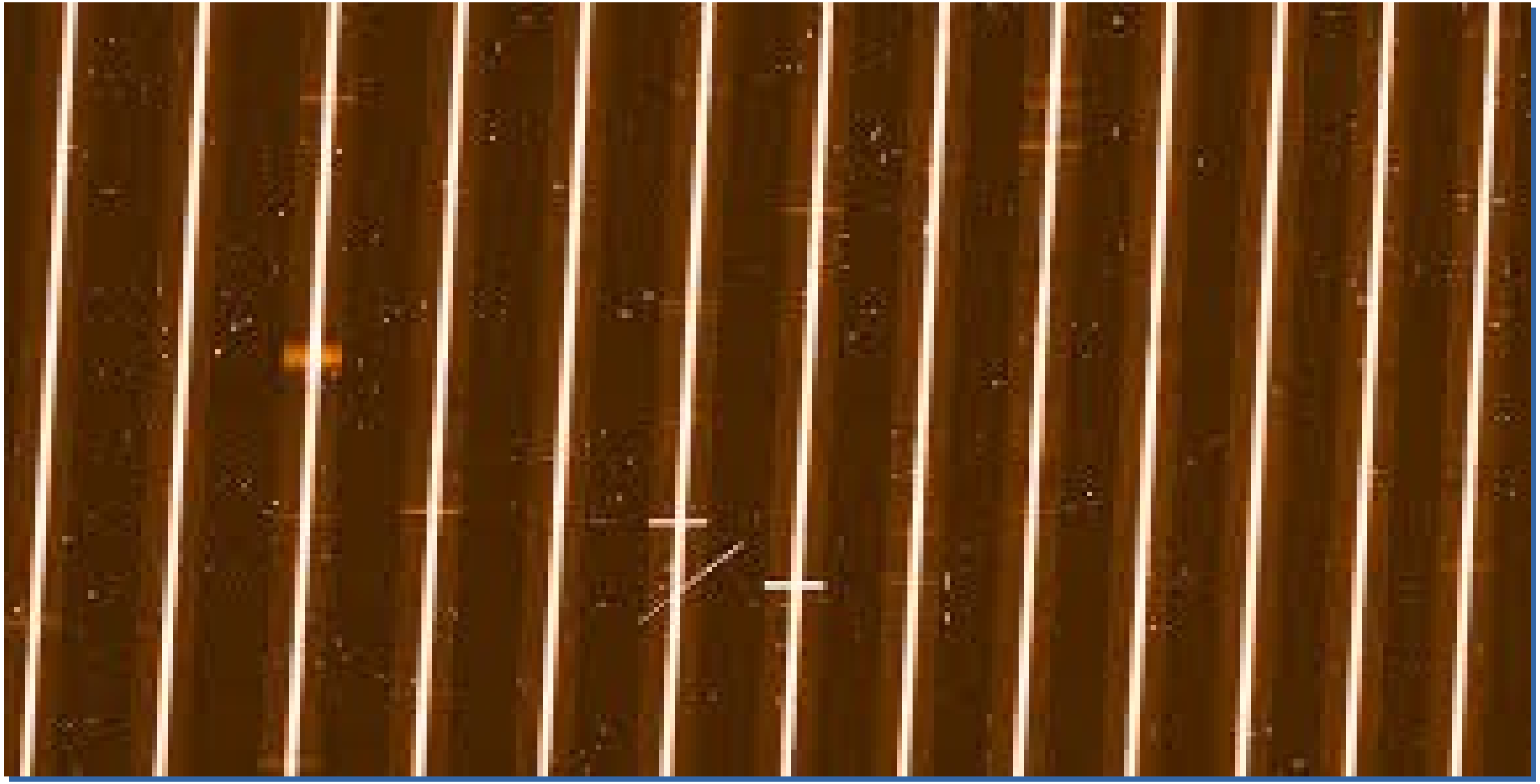
M. T. Murphy, Th. Udem, R. Holzwarth, A. Sizmann, L. Pasquini, C. Araujo-Hauck, H. Dekker, S. D'Odorico, M. Fischer, T. W. HÃ¤nsch, A. Manescau, High-precision wavelength calibration of astronomical spectrographs with laser frequency combs,Â Monthly Notices of the Royal Astronomical Society, Volume 380, Issue 2, August 2007, Pages 839â€"847,Â
https://doi.org/10.1111/j.1365-2966.2007.12147.x

Laser frequency combs nowadays



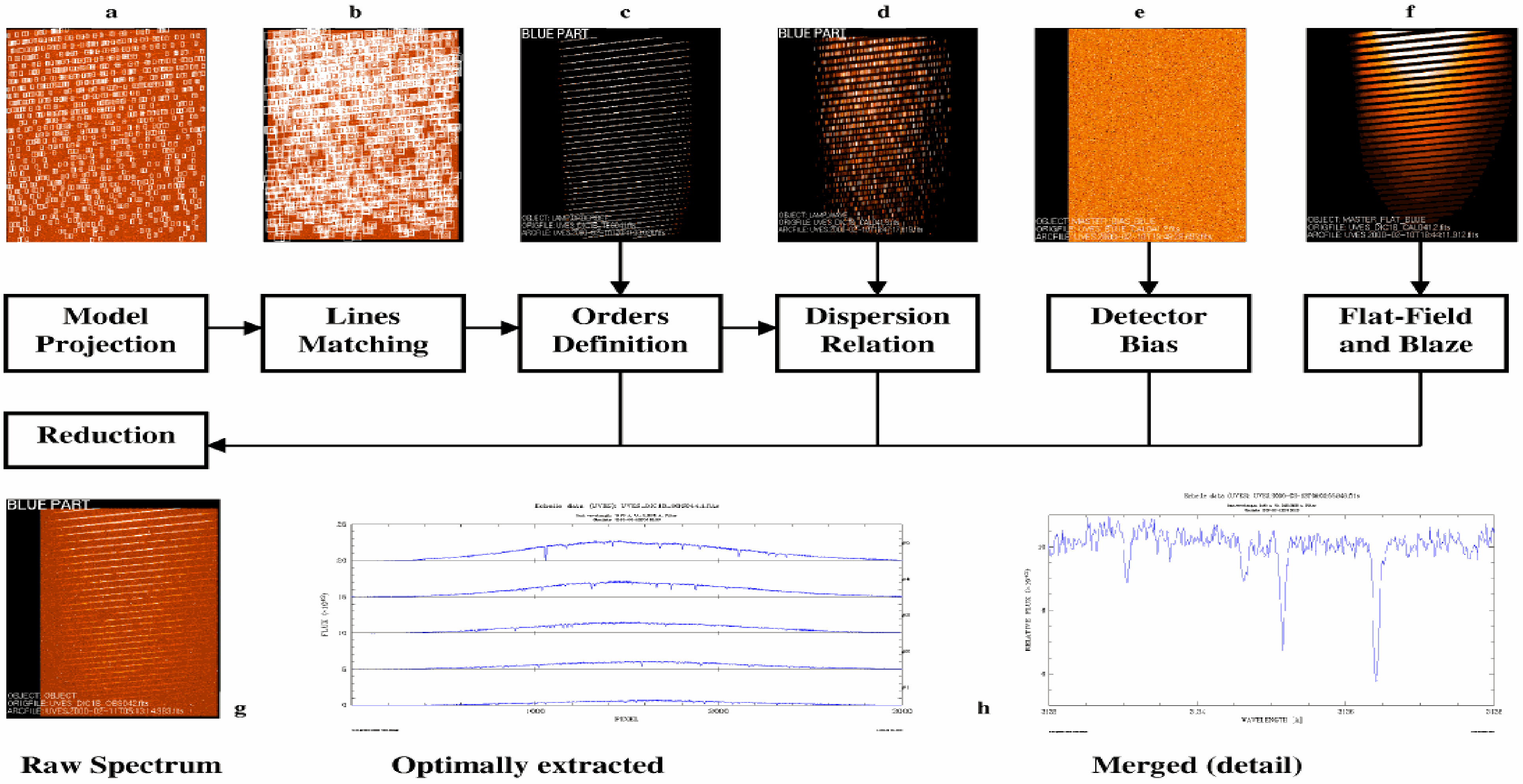
Metcalf et al., 2019, https://opg.optica.org/optica/fulltext.cfm?uri=optica-6-2-233&id=405187

UVES frame example



Credit: ESO

ESO UVES data reduction process – from raw frame to reduced spectra



Ballester, et al.

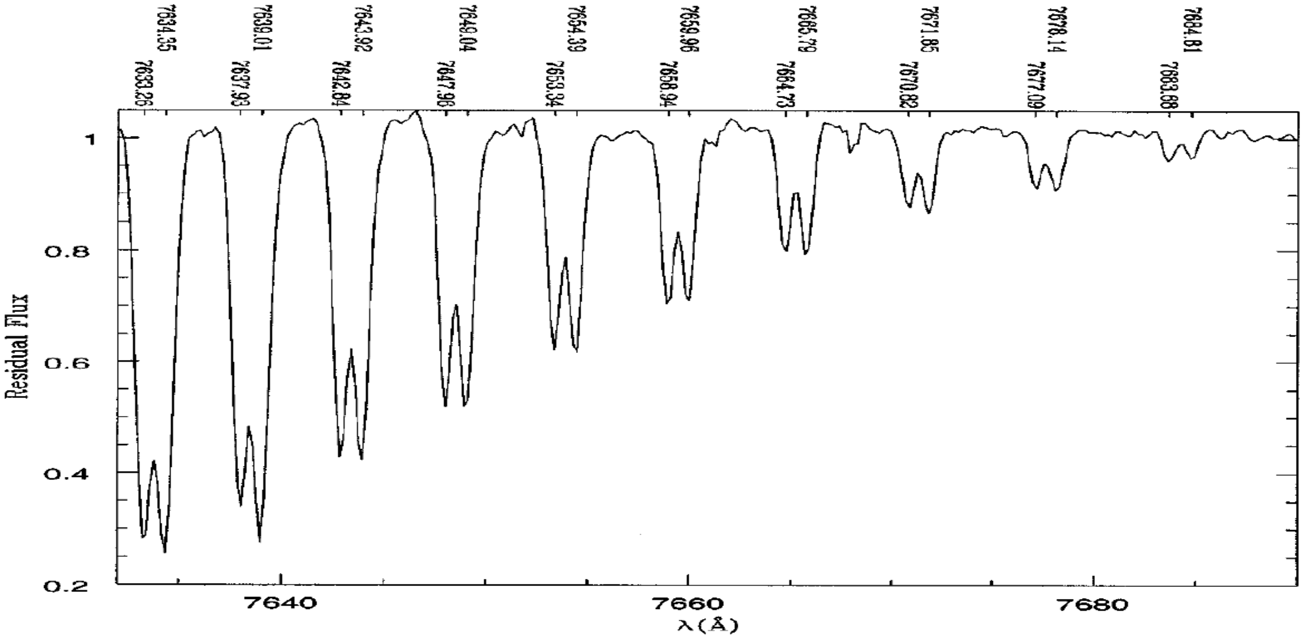
https://www.eso.org/observing/dfo/quality/publ/Messenger/UVES_Messenger_101.html

How can we measure RVs

- Cross correlation method
- One spectrum is the reference
- Other spectra are cross correlated with the reference
- Measuring relative shifts in RVs
- Using additionally Telluric (sky) lines for correction of the instrumental effects

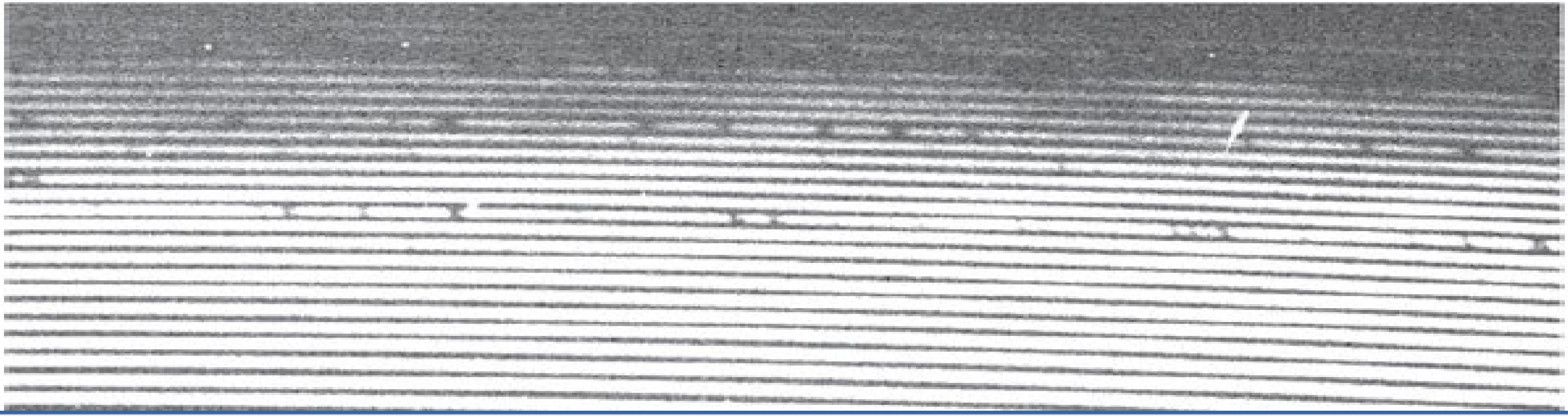
Precise RVs with telluric lines

- Sky lines
- They do not move because the sky is rotating with the Earth
- They should thus be at same wavelength at every frame
- If not, the shift is due instrumental effects
- Fig. From Catanzaro et al. 1998



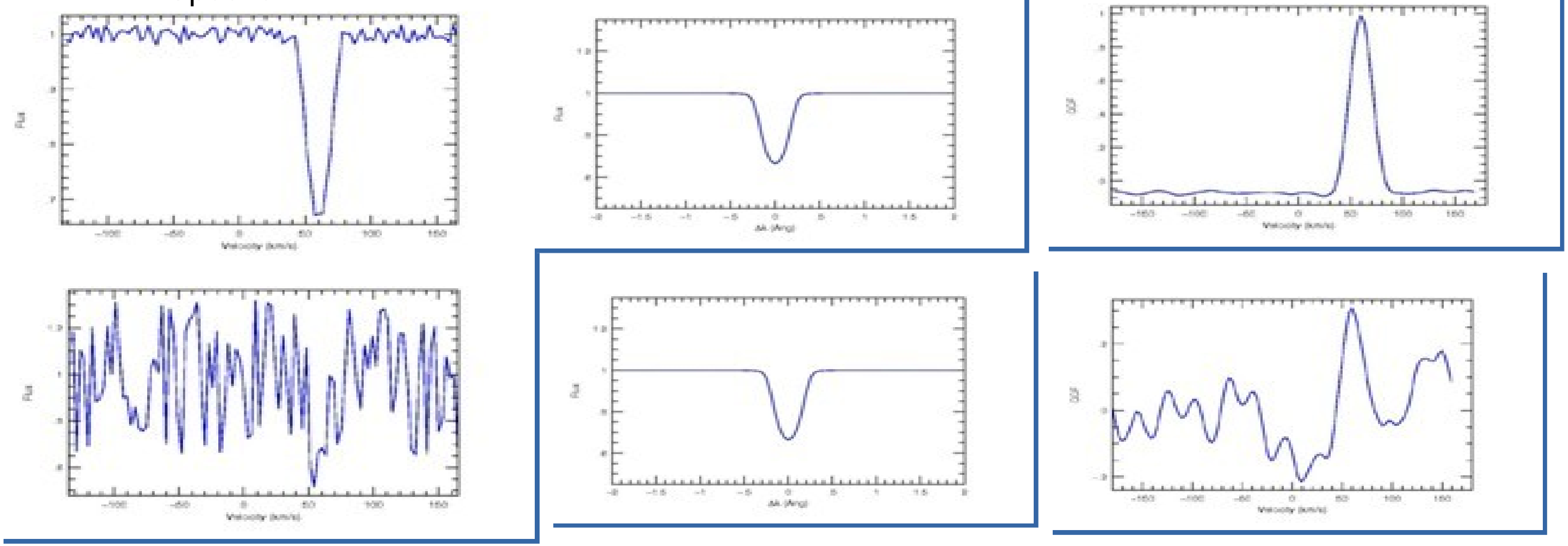
Telluric lines - example

- Red part of OES spectrum with telluric lines
  (black lines at the top in the continuum)



The Cross Correlation Method – getting the RVs

Spectrum | Template | Cross correlation function



Images: A. Hatzes

OES at Perek telescope - example

Table 3
Instrumental Characteristics of OES

Parameter	Value
Slit width (mm)	0.6
Slit width (arcsec)	1.8
Echelle (Milton Roy)	54.5 g mm^{-1}
Blaze angle (θ)	69°
Spectral resolution	51,600 (500 nm)
Linear reciprocal dispersion (Å mm^{-1})	2.4
Pixel size Å pix^{-1}	0.0324
Pixel size (km s^{-1})	1.8
Spectral range (Å)	3753–9195
Spectral orders	56
Spectral order number range	92–36
Inter order separation (in pix—blue)	27
Inter order separation (in pix—red)	12
Limiting magnitude (*V*mag)	13

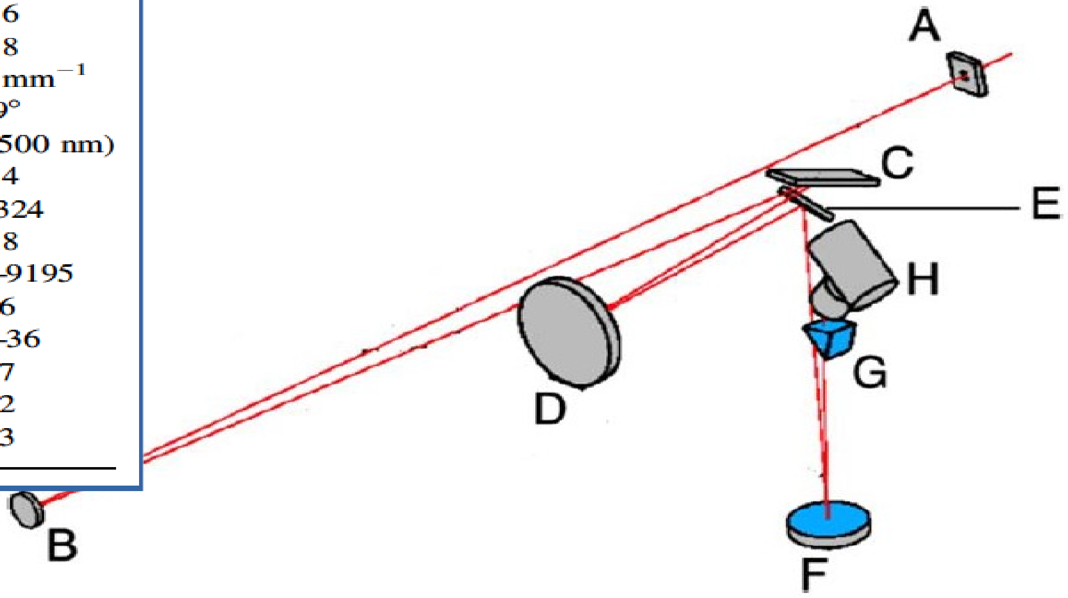
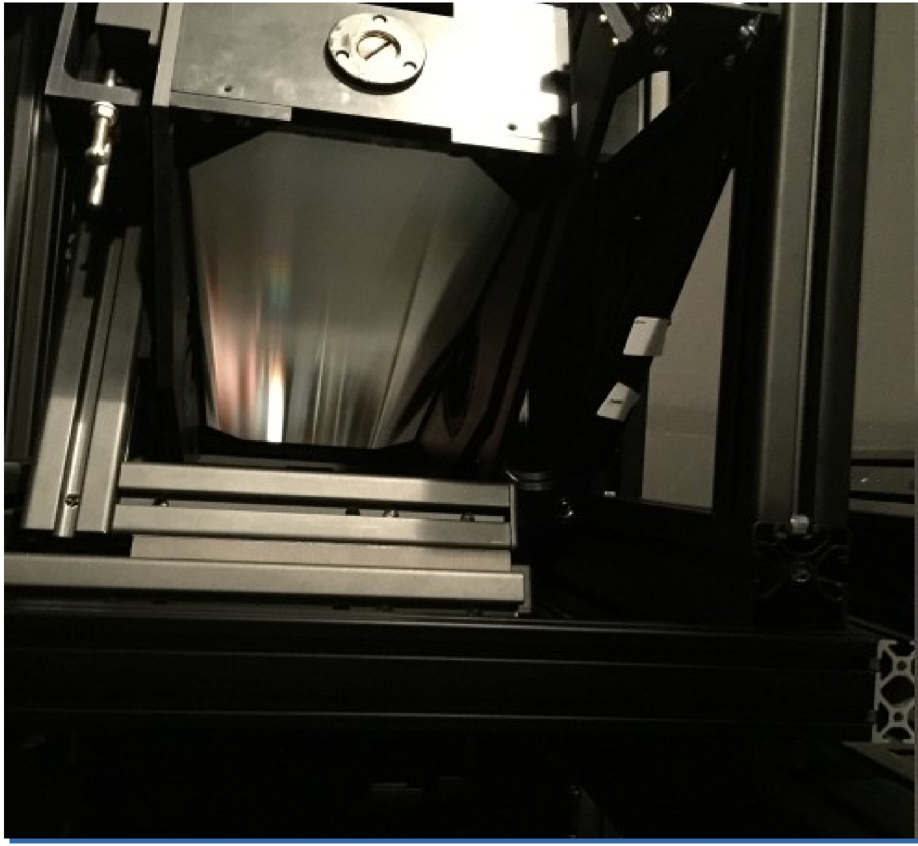
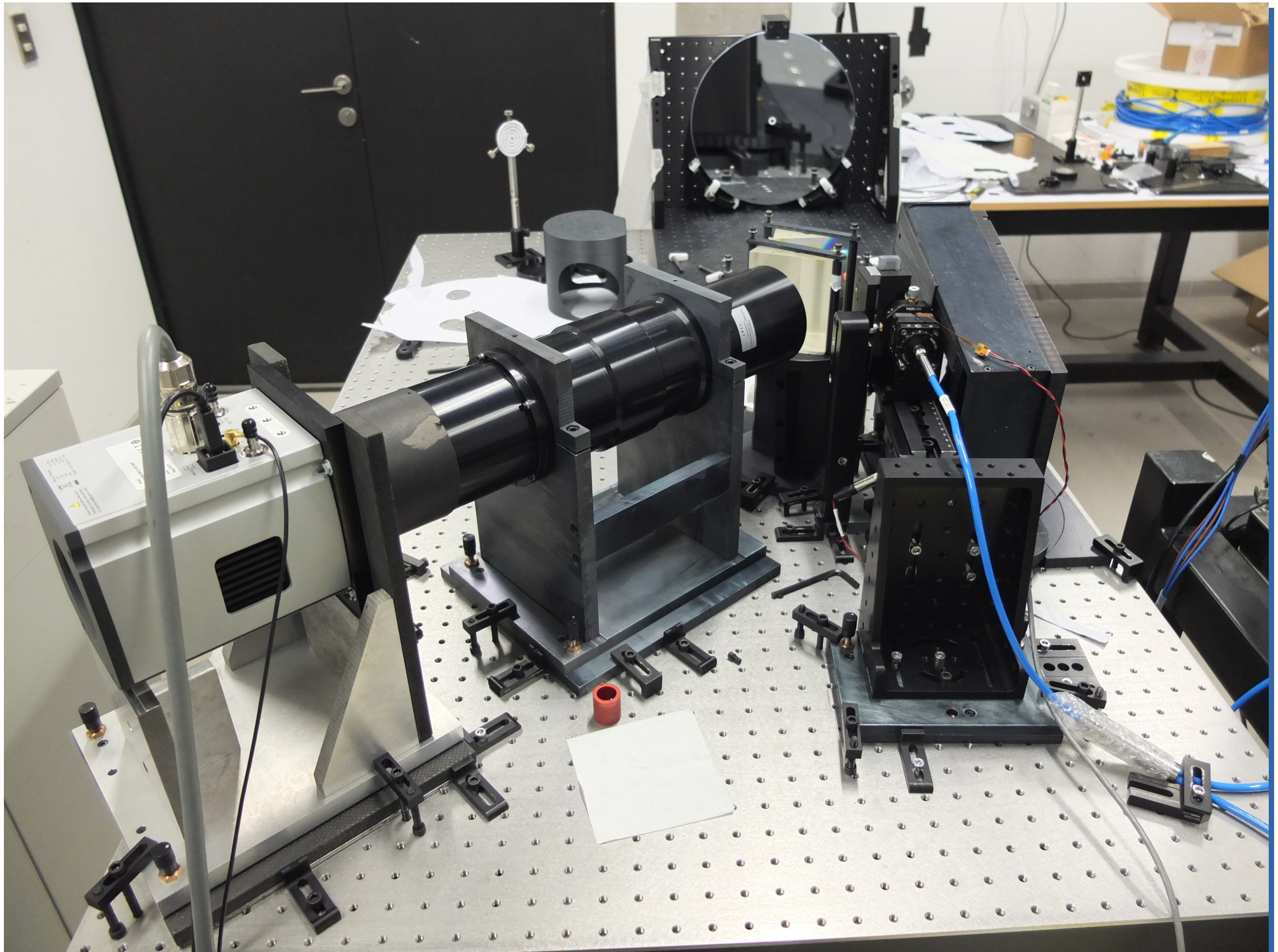


Figure 2. OES light comes from the Coudé room through the slit A to collimator B. From the collimator the light beam travels to an échelle grating C and later to a parabollic mirror D and a plane mirror E. Second collimator F is in front of the cross-disperser which is the last element before the CANON lense objective H with a detector. Courtesy of Mirsolav Šlechta.
(A color version of this figure is available in the online journal.)

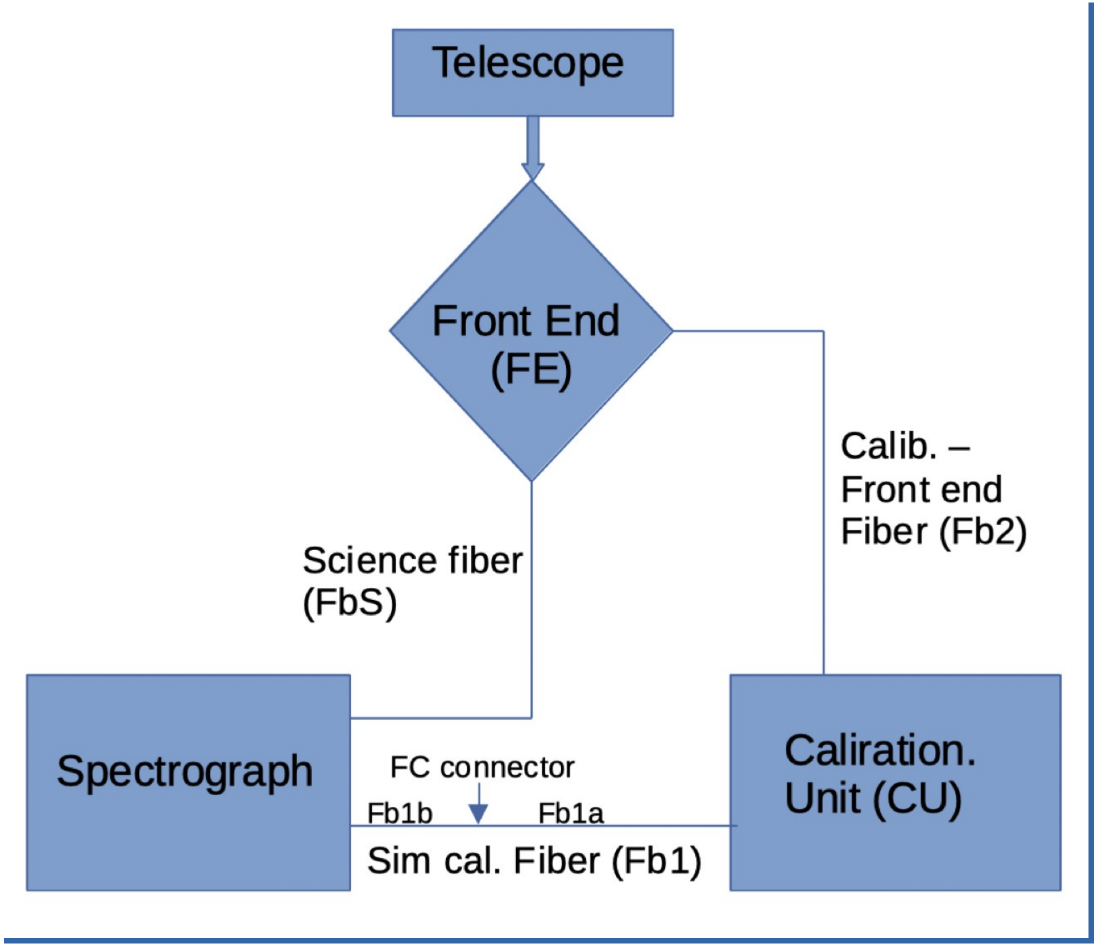
OES

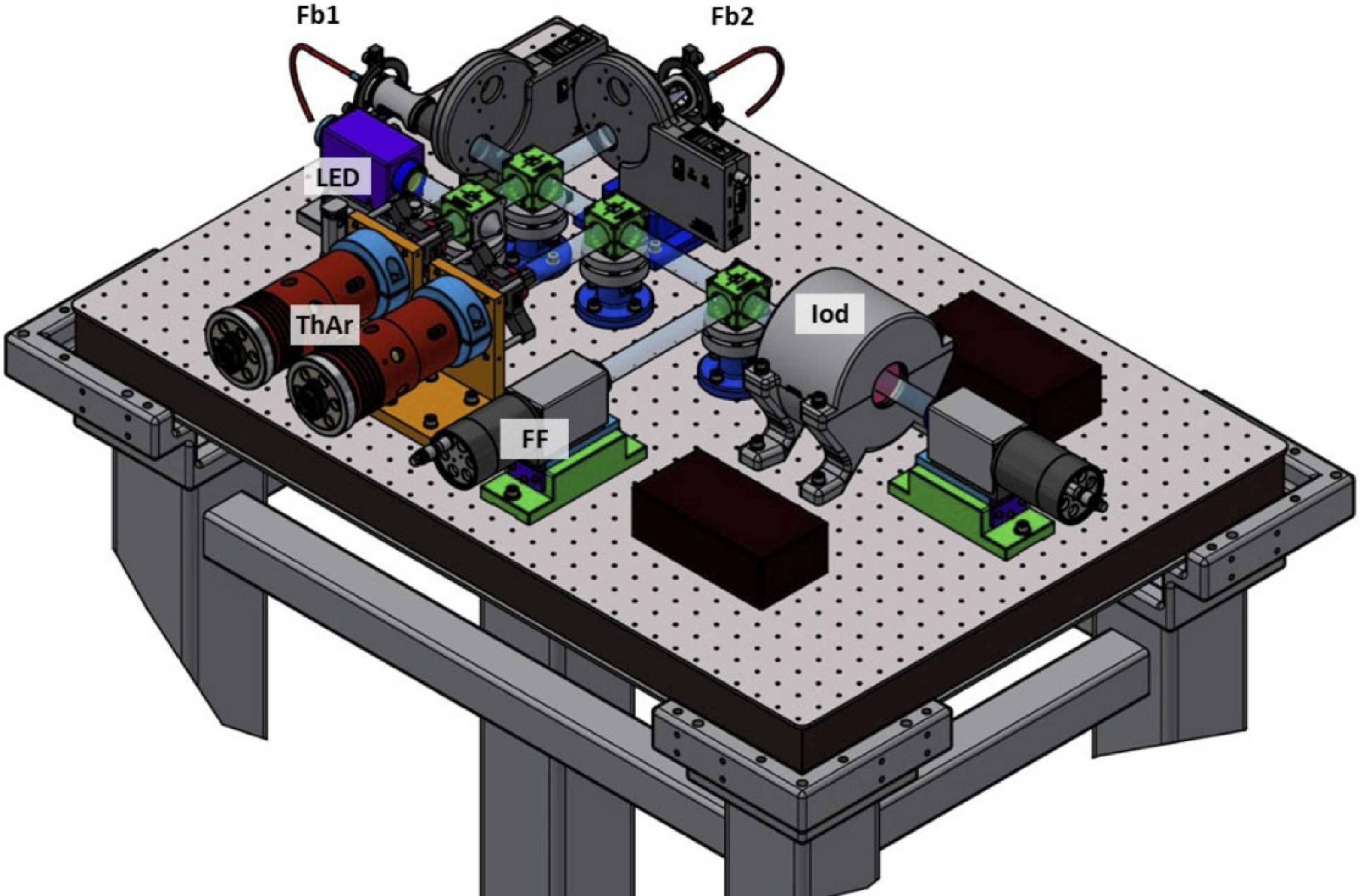


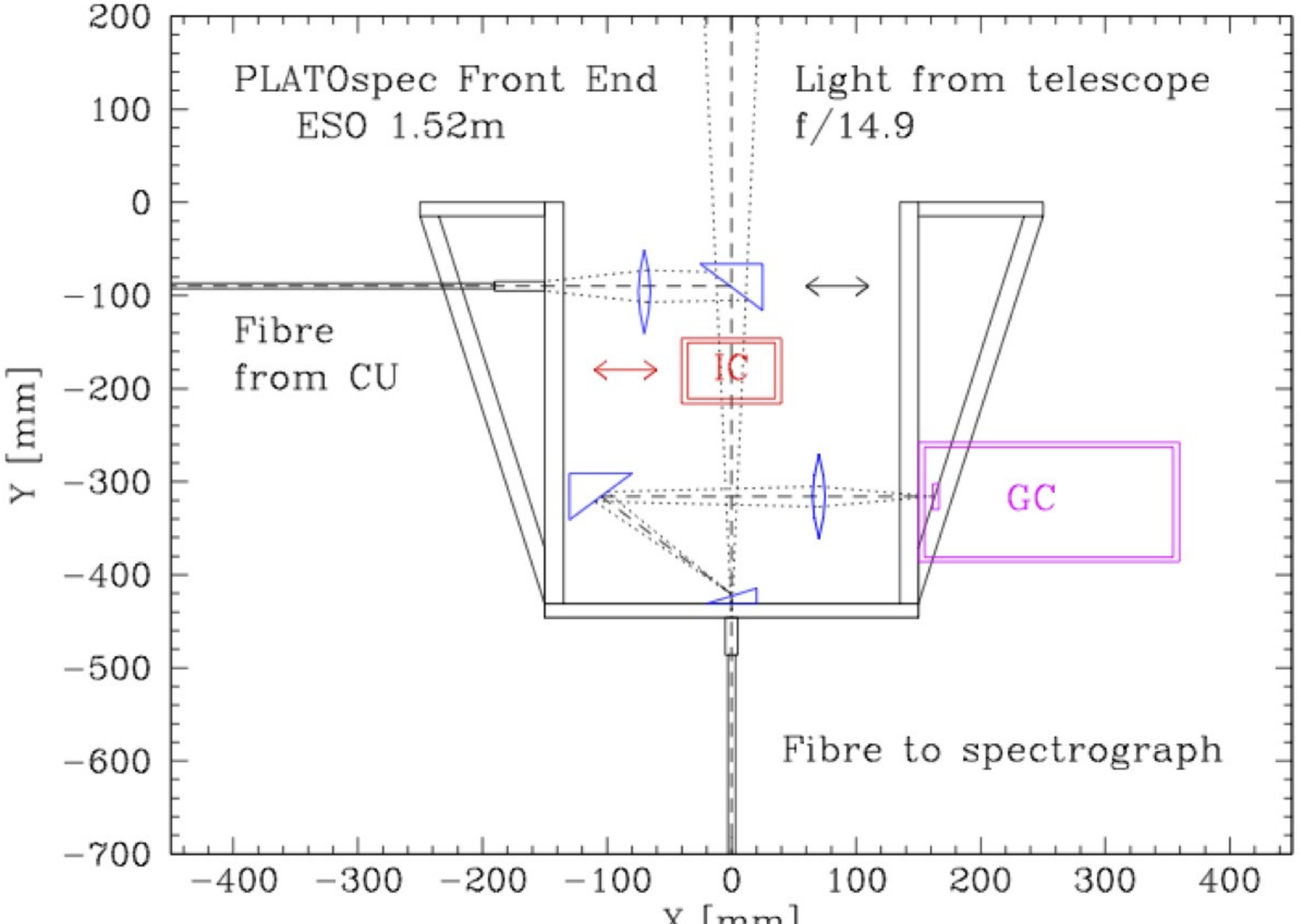
PLATOSpec



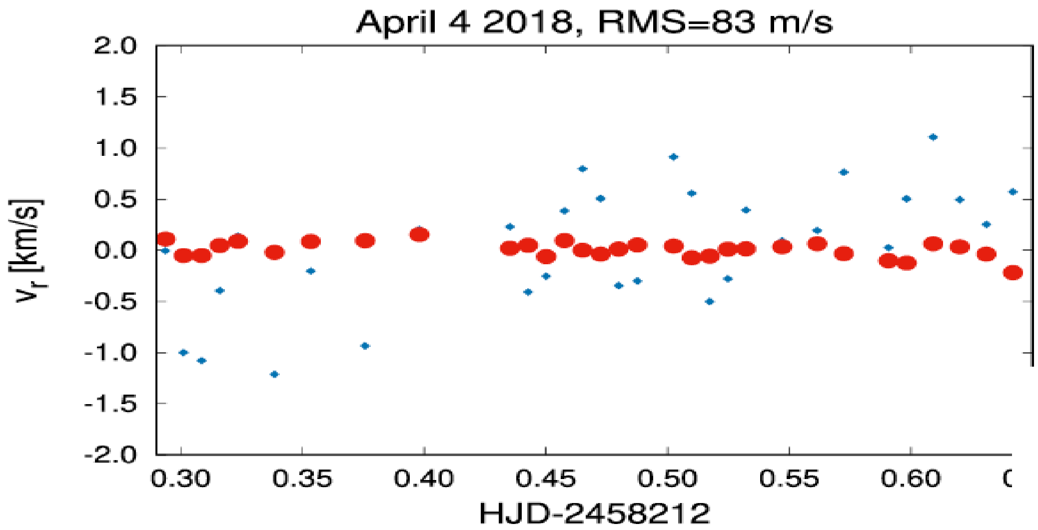
- From Kabath et al 2025 MNRA

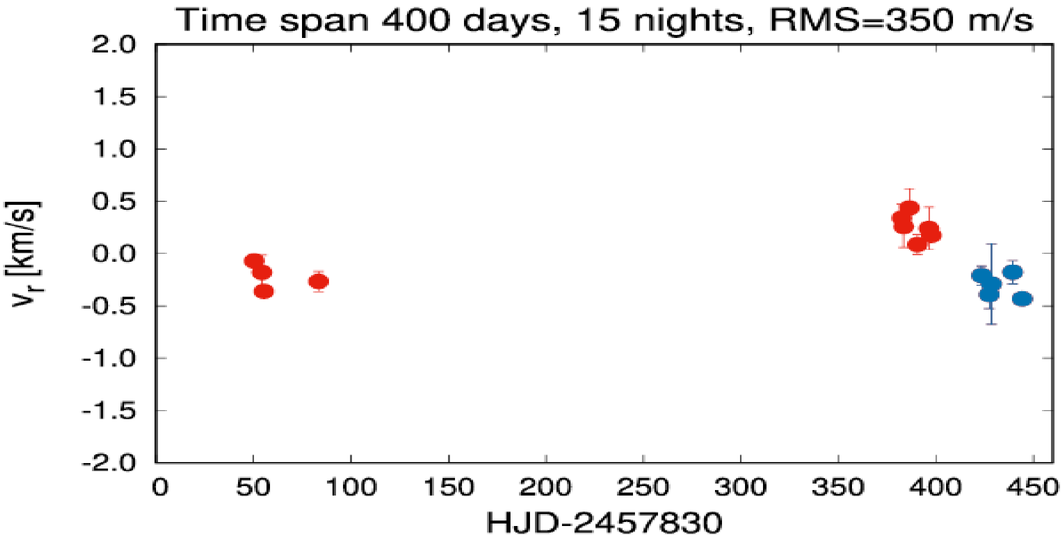



Fb1
Fb2
LED
ThAr
Iod
FF


PLATOspec Front End
ESO 1.52m
Light from telescope
f/14.9
Fibre
from CU
IC
GC
Fibre to spectrograph
Y [mm]
X [mm]
200
100
0
−100
−200
−300
−400
−500
−600
−700
−400
−300
−200
−100
0
100
200
300
400

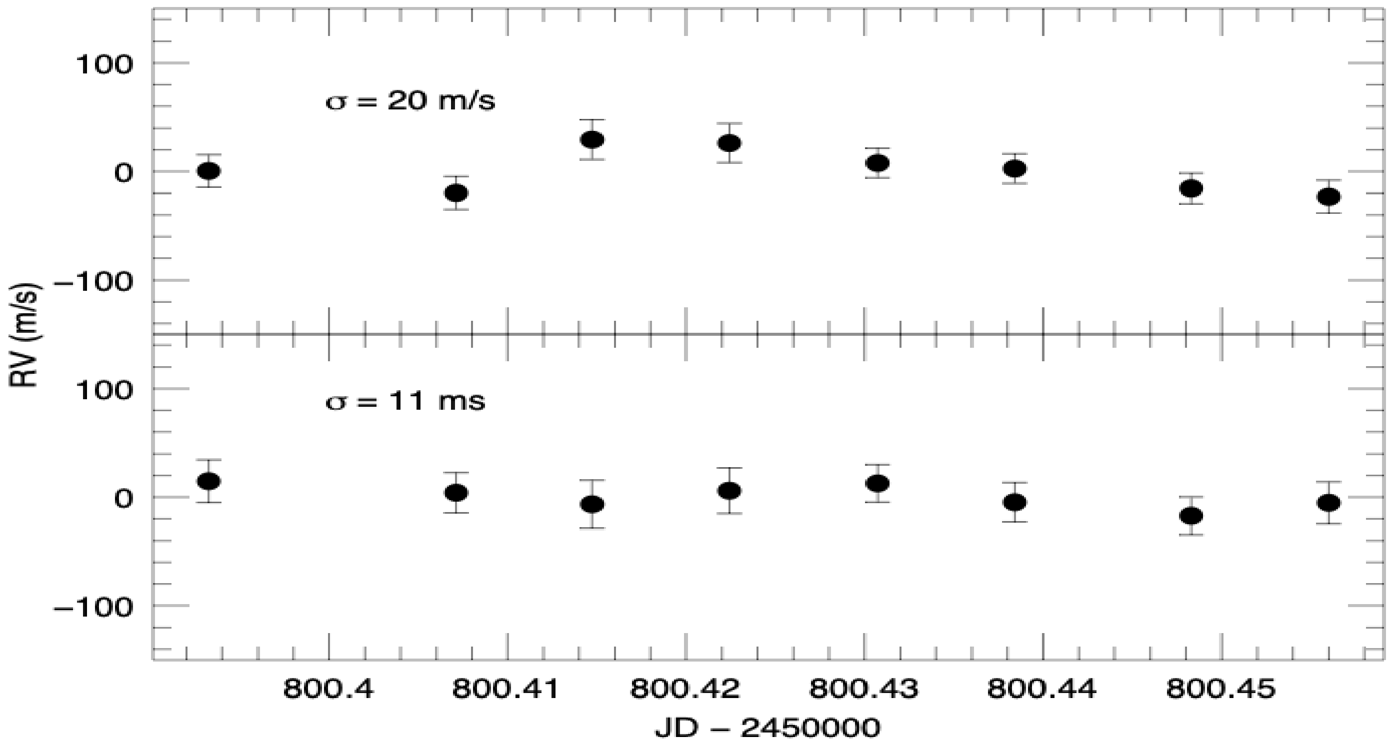
How good can we measure RVs (OES)





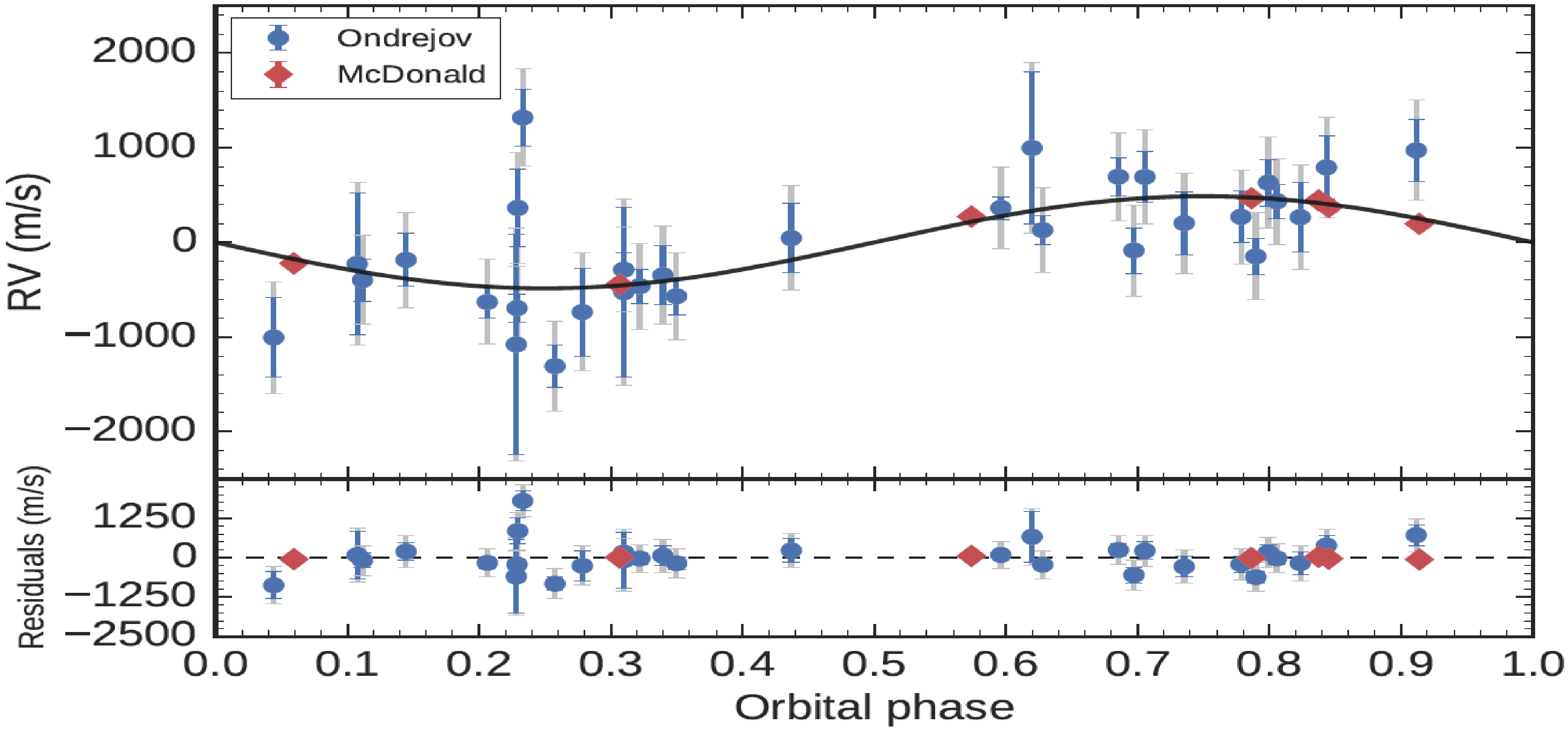
OES RV stability from Kabath et al. 2020

OES with Iodine

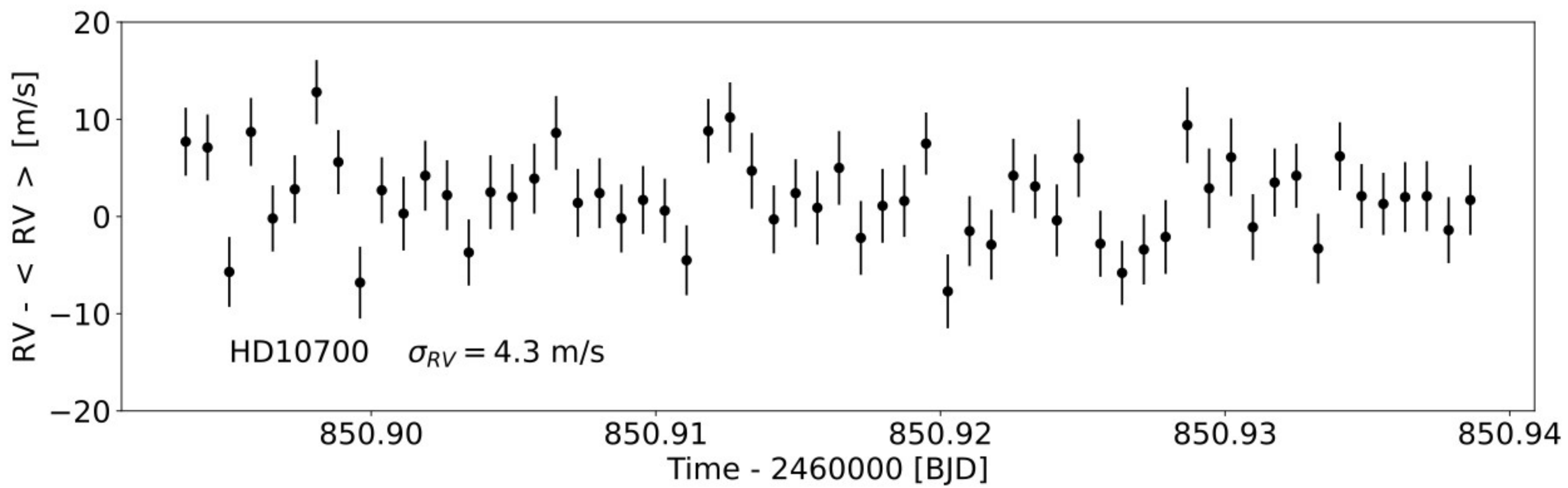


Processed by Artie Hatzes

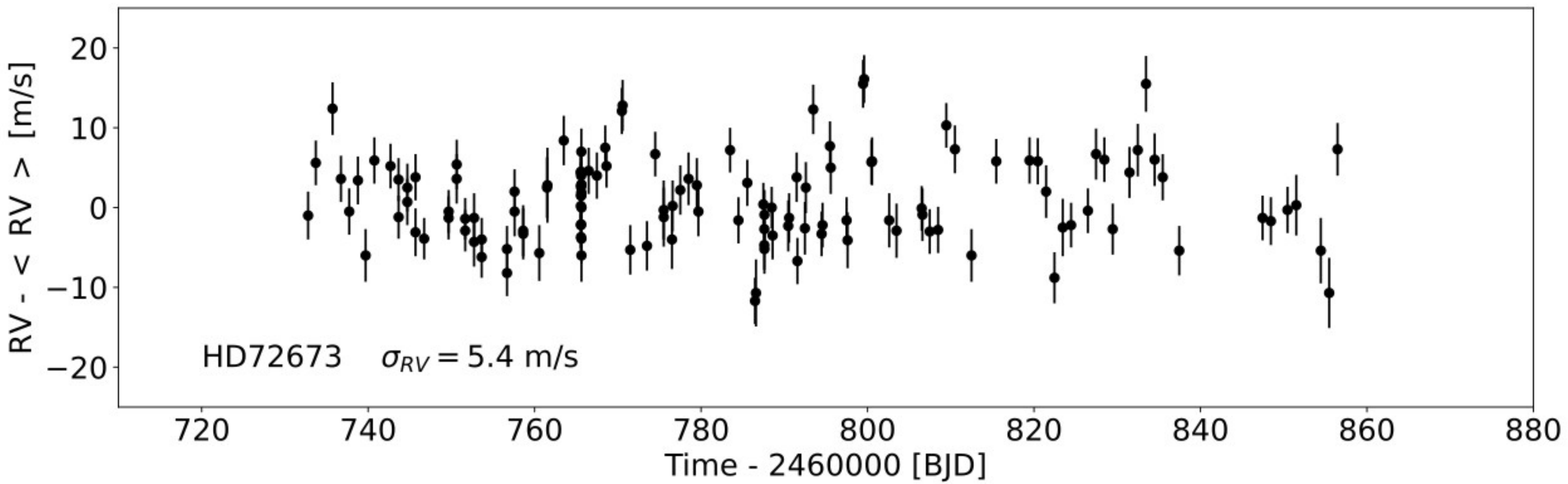
Hot Jupiter from TESS/OES



PLATOSpec RVs



PLATOSpec RVs



HARPS at La Silla

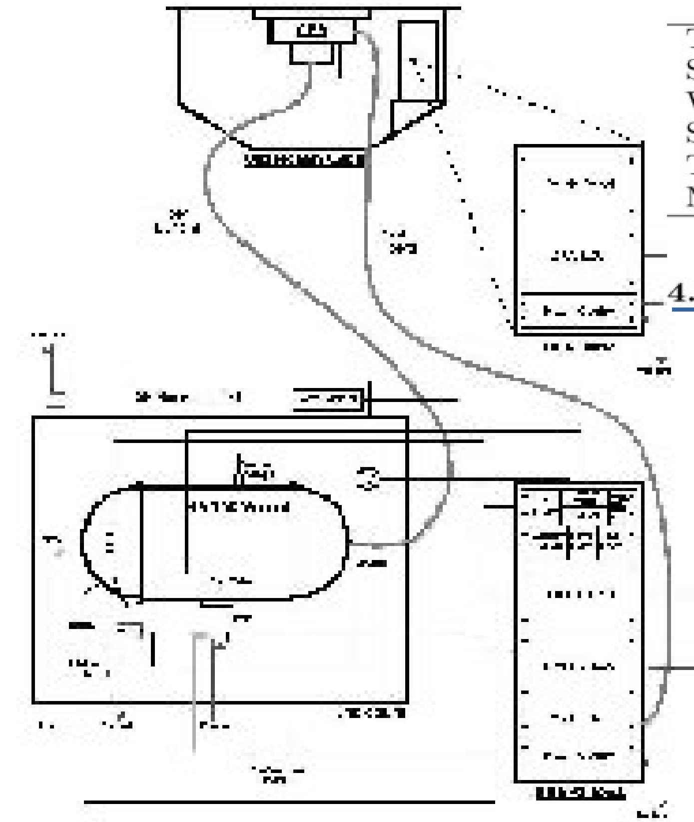
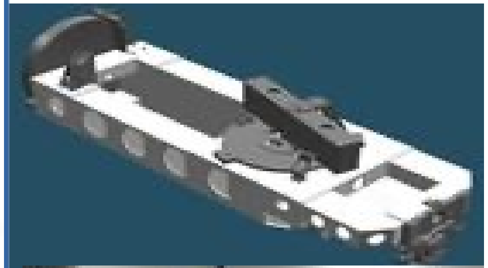
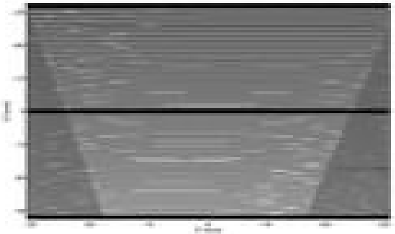


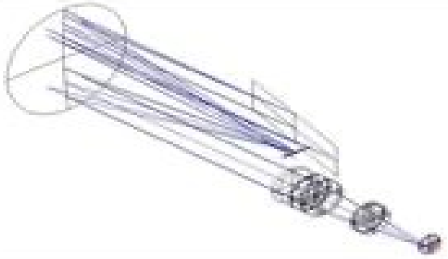
Table 1. Main characteristics of the HARPS spectrograph

Telescope	ESO 3.6-m telescope at La Silla observatory
Spectrograph	Cross-dispersed, fiber-fed echelle spectrograph
Wavelength range	380 - 690 nm
Spectral resolution	R = 90000
Total efficiency	T_{tot} = 5% (atmosphere and telescope included)
Mode	Simultaneous ThAr reference

4.2. Simultaneous ThAr Reference vs. Iodine Cell







Images: ESO

HARPS planets

- Proxima Cen b
- Earth sized planet (1.3Mearth)
- M dwarf star
- In the Habitable zone

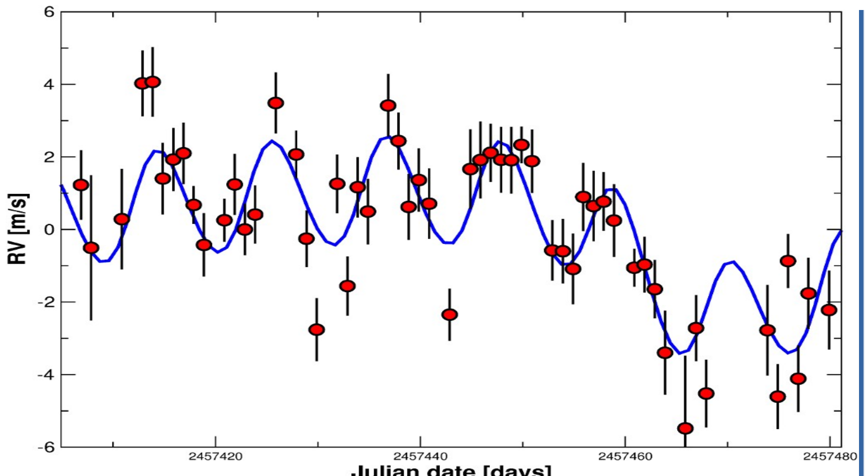


Image from ESO
Graph from Anglada Escude et al 2016, Nature

ESPRESSO

- Located at ESO Paranal
- Unprecedented precision – cm/s
- Using up to 4 8-m telescopes together

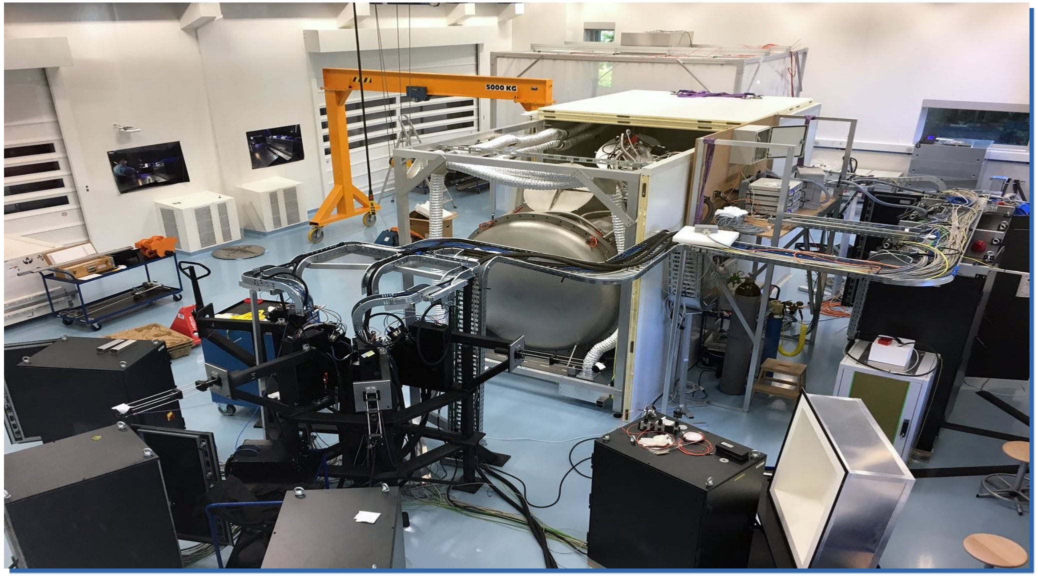


Image ESO

ESPRESSO parameters

	HR (1-UT)	**UHR (1-UT)**	**MR (4-UT)**
Wavelength range	380–788 nm	380–788 nm	380–788 nm
Resolving power (median)	140,000	190,000	70,000
Aperture on sky	1".0	0".5	4x1".0
Total efficiency	11%	5%	11%
RV precision (requirement)	< 10 cm/s	< 5 m/s	< 5 m/s
Limiting V-band magnitude*	~17	~16	~20
Binning	1x1, 2x1	1x1	4x2, 8x4
Spectral sampling (average)	4.5 px	2.5 px	5.5 px (binned x2)
Spatial sampling per	9.0 (4.5) px	5.0 px	5.5 px (binned x4)

Image ESO

UTs working together

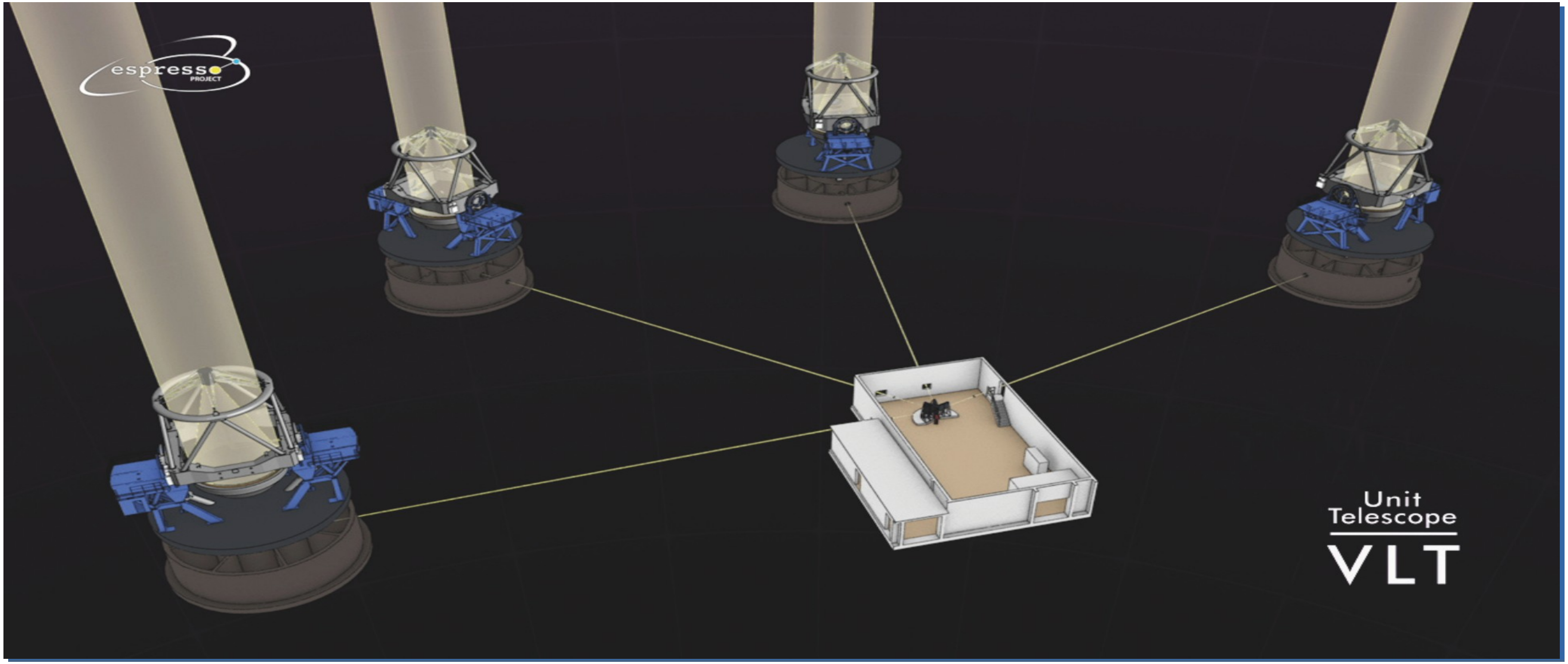


Image ESO

Between the telescopes and the spectrograph

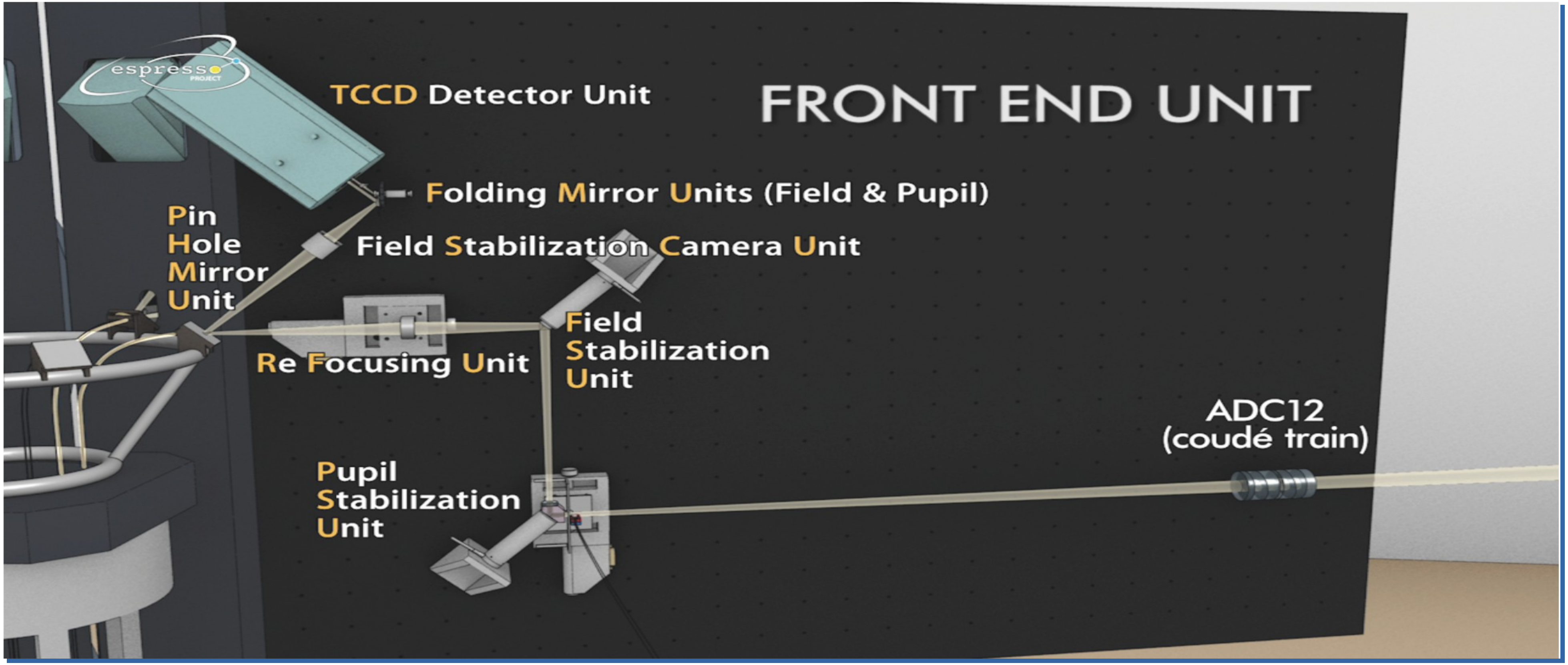


Image ESO

Spectrograph (ESPRESSO)

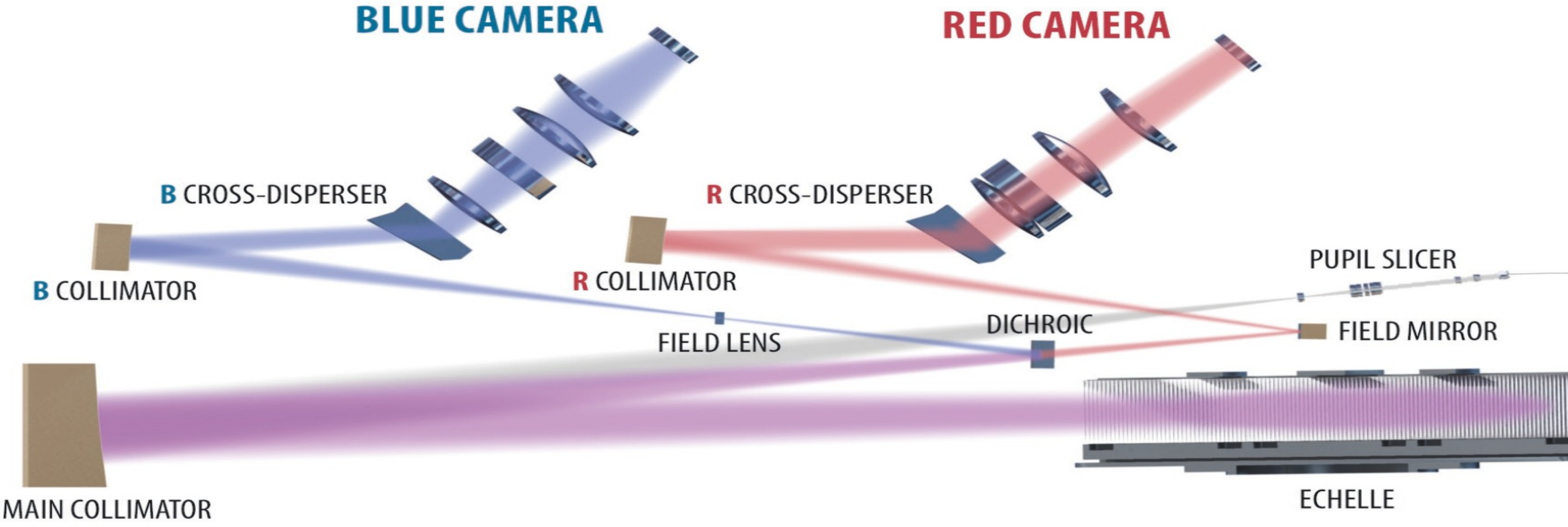
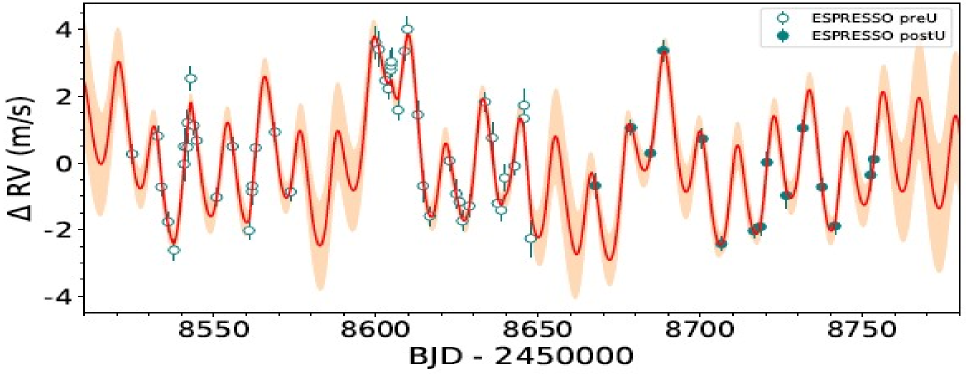
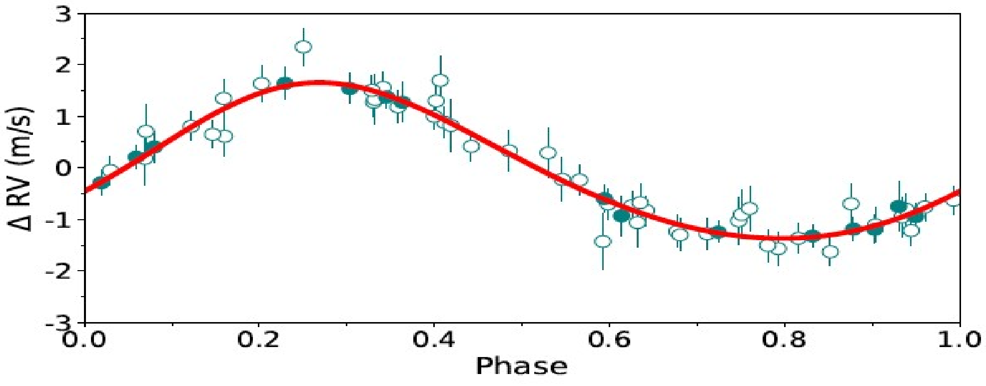


Image ESO

Exciting planets with ESPRESSO

- Alpha Cen b
- Is there another planet with 0.5 M Earth and 5 days period?





Mascareno et al. 2020, A&A, 639, 77

Precision of spectrographs

- Depends on the Signal to noise
- Depends on the stability of the spectrograph

  (vacuum, temperature control, etc..)
- Precision is given by:

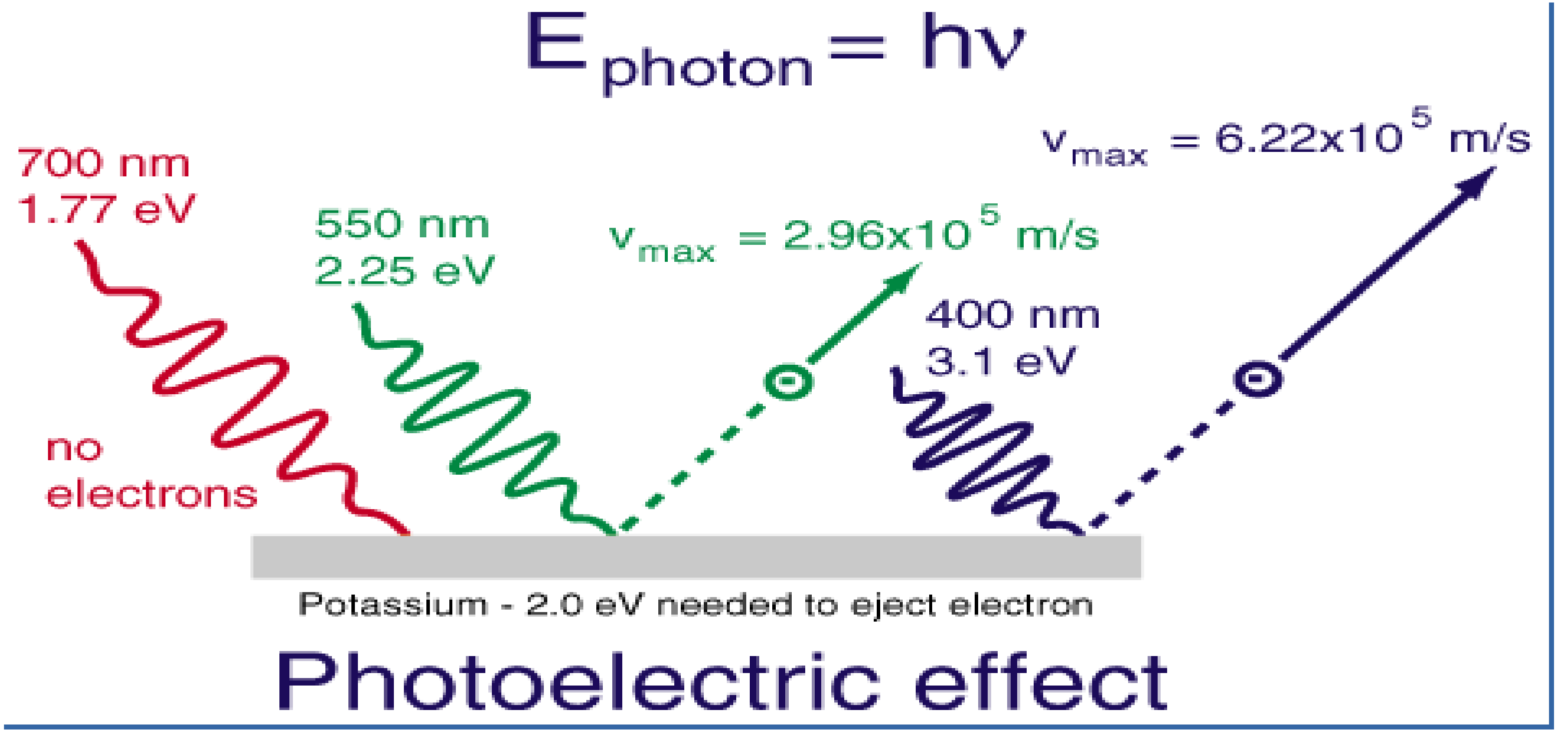
  - C is instrument specific constant, R is resolving power, Δλ wavelength range of the spectrograph

$$\sigma_{\mathrm{RV}} = C \times (\mathrm{S/N})^{-1} \times \Delta\lambda^{-0.5} \times R^{-1.5}$$

tps://ui.adsabs.harvard.edu/abs/1992ESOC...40...17G/abstract

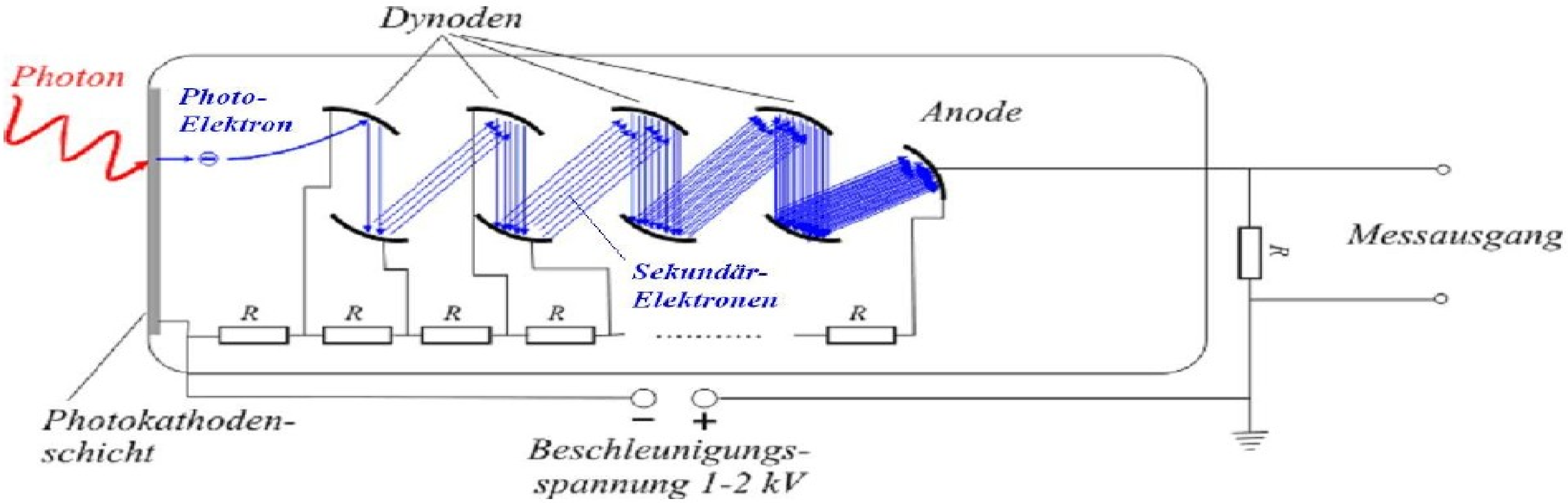
Photometric camera

- Photoelectric effect
-



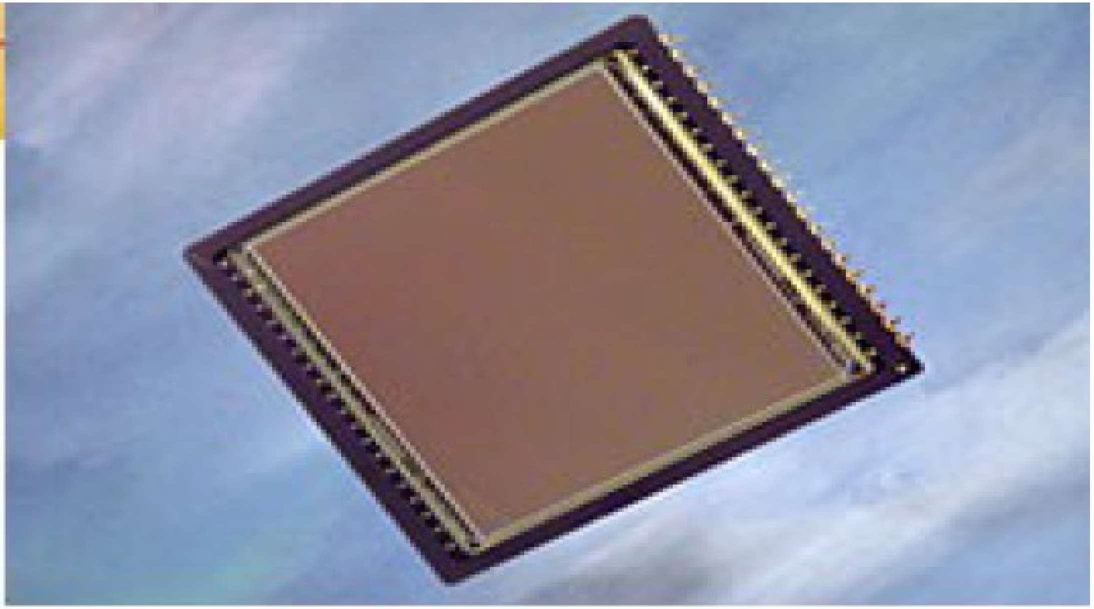
The photomultiplier in astronomy

Computer History Museum
Mountain View, Calif., U.S.



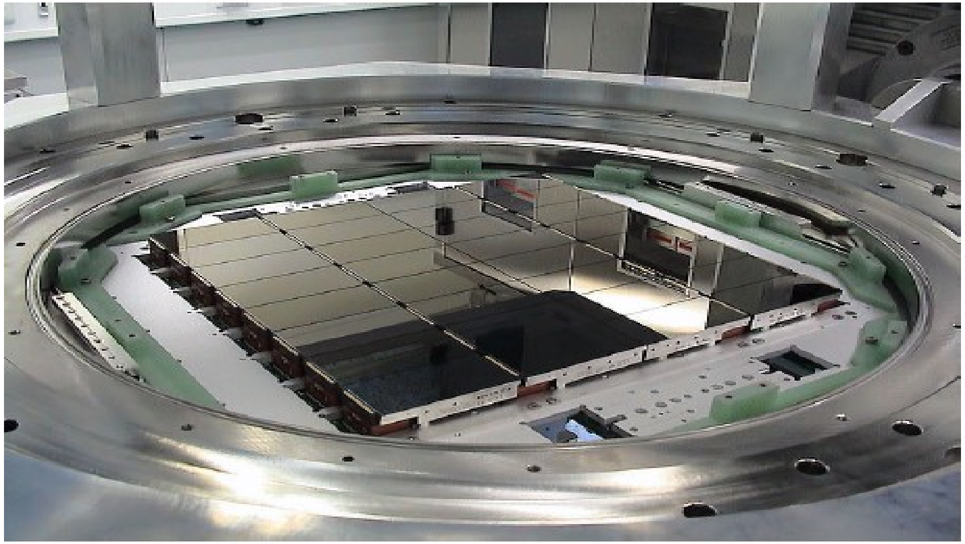
DESY Zeuthen

The CCD



Kodak

- Developed in 1969 by AT & T's Bell
- silicon substrate
- large chip arrays
- large FoV
- high QE
- linear
- sensitivities in optical till 1.1 micron
- mostly linear in dynamic range



Omegacam at Paranal - ESO

- Detector consists of pixels of microns size
- Photodiodes sit in p-Silicon substrate
- A gate is an electrode controlling the charge transfer in the Si substrate
- Photon creates a pair hole + electron in Silicon substrate
- Electron moved to the surface, hole to the deeper substrate – electrons kept in the potential well
- Voltage applied on the gates to move the charge to the register = readout
- Why is CCD good in optical?
- Si – bandgap about 1.1eV energy < 1.1 micron = OPTICAL
- To release electron in a Si semiconductor an incident photon needs to carry at least 1.1eV energy or higher!

Nice reading:
http://www.physics.udel.edu/~jlp/classweb/ccd.pdf

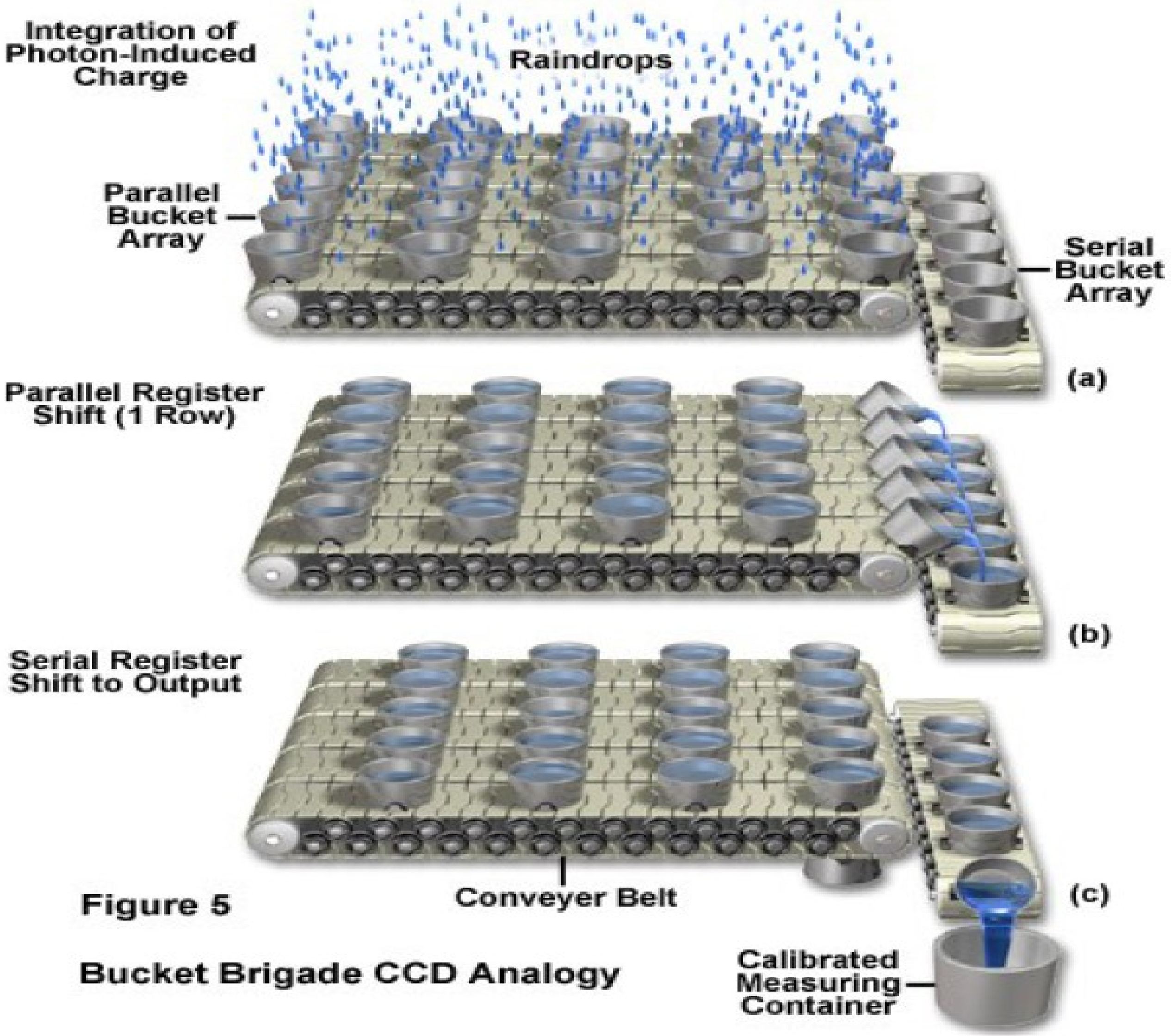
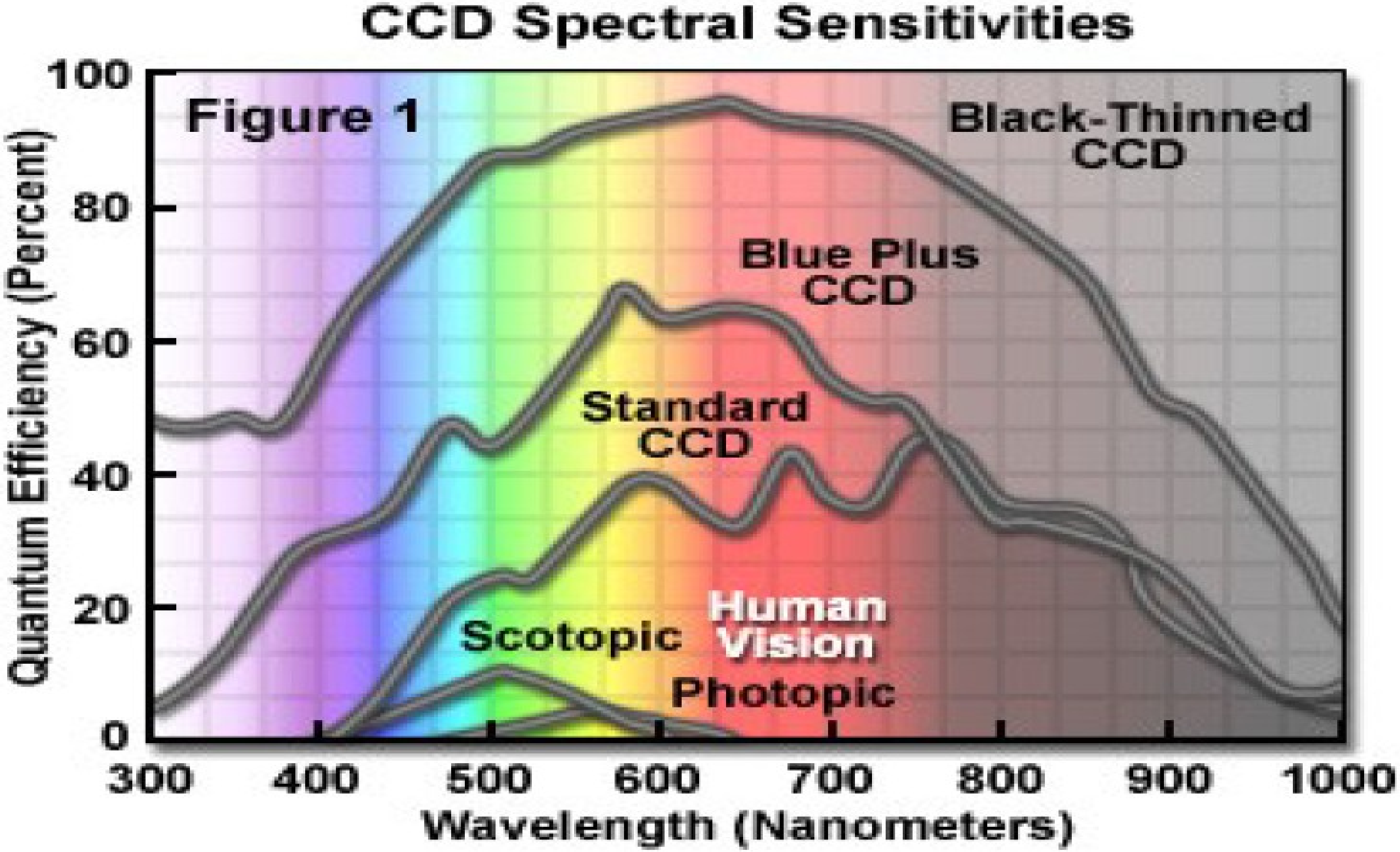


Figure 5

Bucket Brigade CCD Analogy

Image by NIKON

Quantum efficiency, sensitivity



http://www.olympusmicro.com/primer/digitalimaging/concepts/quantumefficiency.html

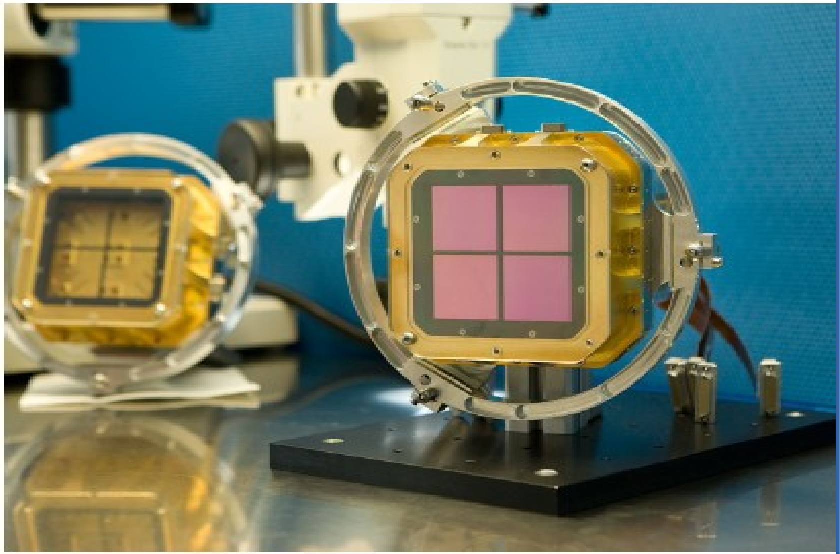
IR detectors (1+ microns)

- Extremely important for exoplanets as the planetary radiation is usually peaking in NIR
- Thermal noise contributing significantly to the error budget
- Are useful for detection of exoplanetary atmospheres
- Are useful for monitoring of day night variations

IR detectors (NO CHARGE TRASNFER)

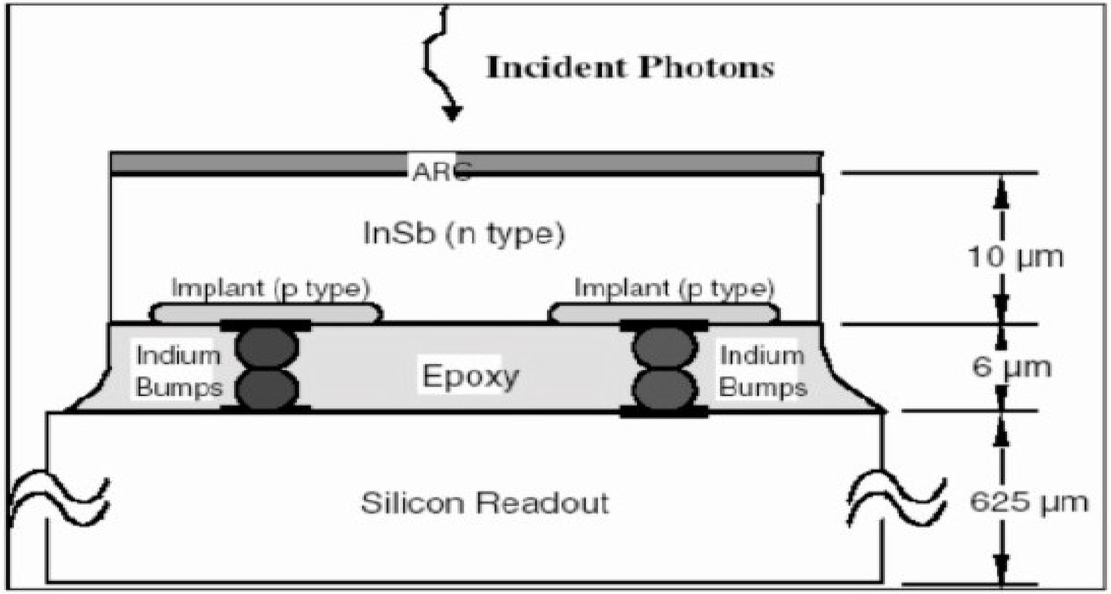
- no charge transfer
- but photoelectric effect in charge!
- electronic readout
- typically Id and Hg due to suitable band gaps
- cooling required

HgCdTe 0.48 eV = 2.55 μm
InSb 0.23 eV = 5.4 μm



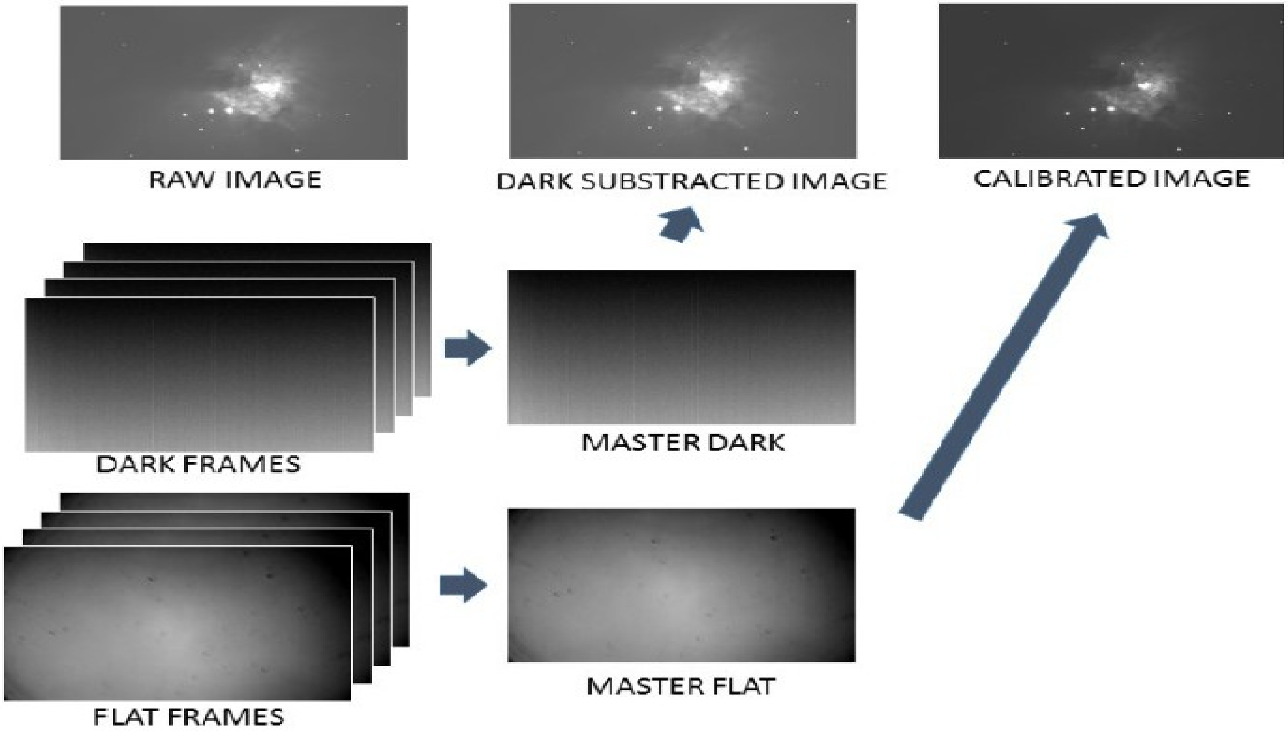
IR detectors

Readouts
 NON-Destructive
   - DCS
   - Fowler
DIT vs. NDIT
Temperature sensitive
 - high sky counts
 - instrument/telesc. heat
3+ micron
nodding/chopping = M2/telescope offsets
Cooling + vacuum for NIR detectors is a must!



Joyce, D., NOAO Gemini data workshop 2010

From photon to the light curve



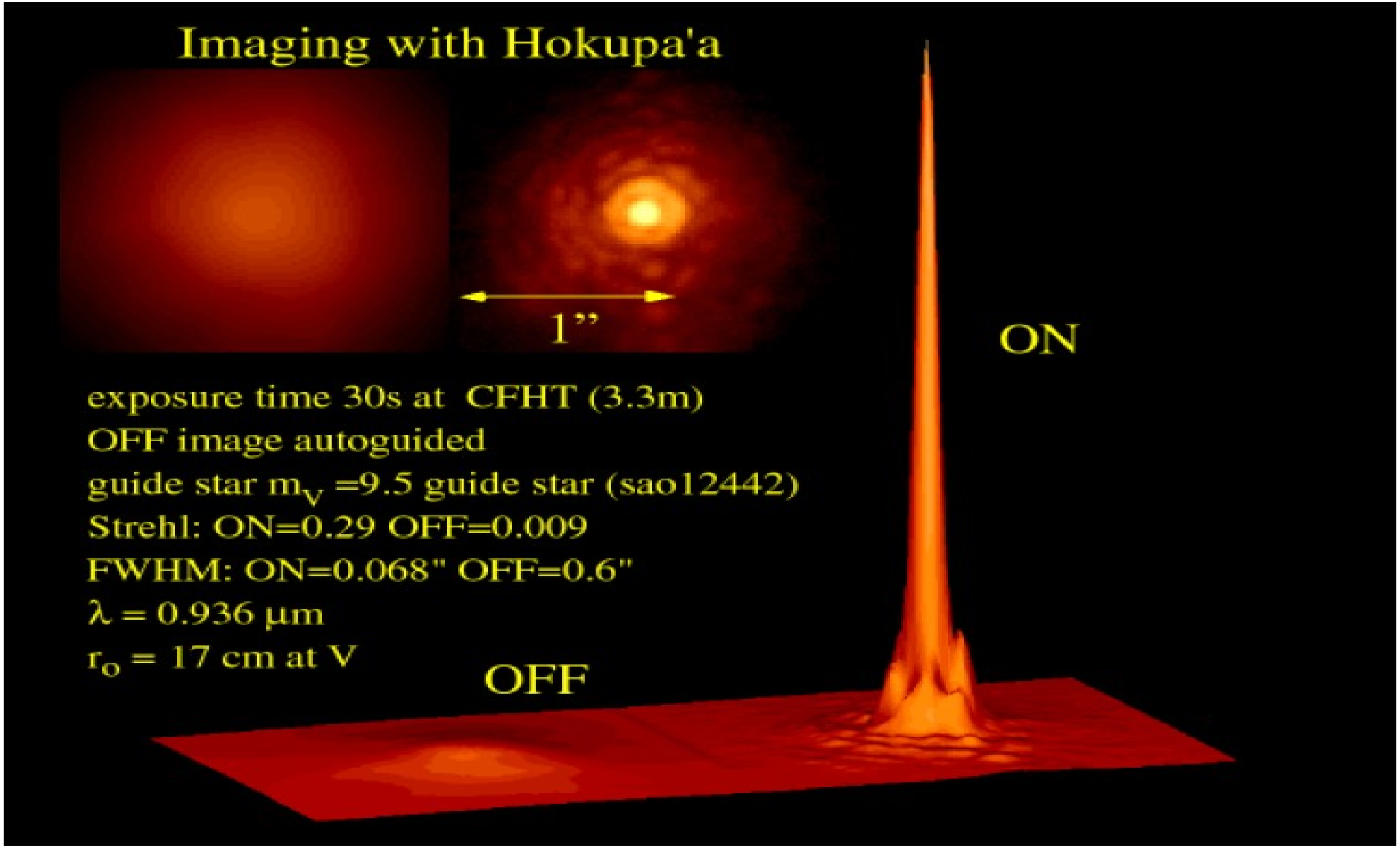
- Schematic way – photometric data reduction

https://astroblueowl.wordpress.com/2016/03/05/image-processing-in-astrophysics/

Image characteristics

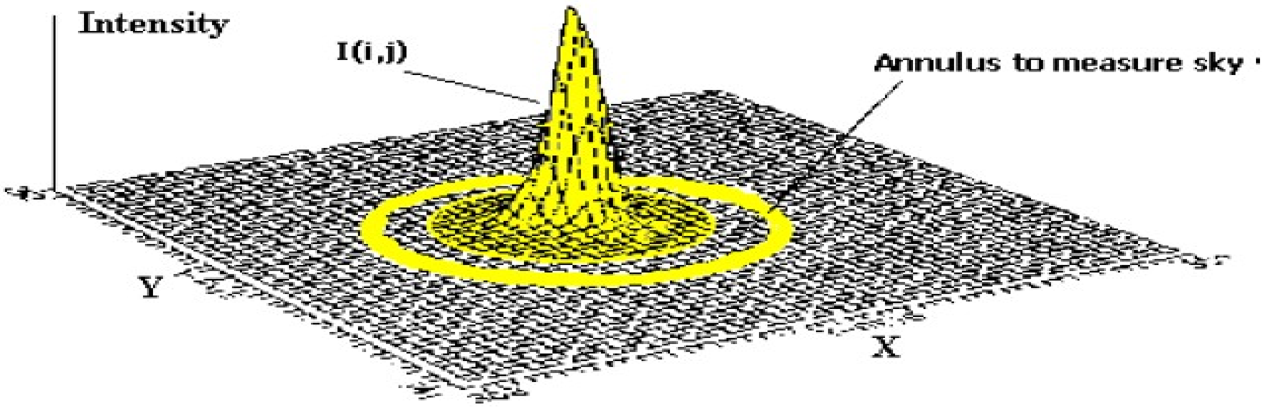
- SNR = signal to noise ratio
  - Poisson noise – sqrt(Signal)
- PSF – point-spread-function of stars
- Various kinds of noises – shot noise (photon noise), red noise, pink noise, dark noise, bias

PSF and the seeing/AO

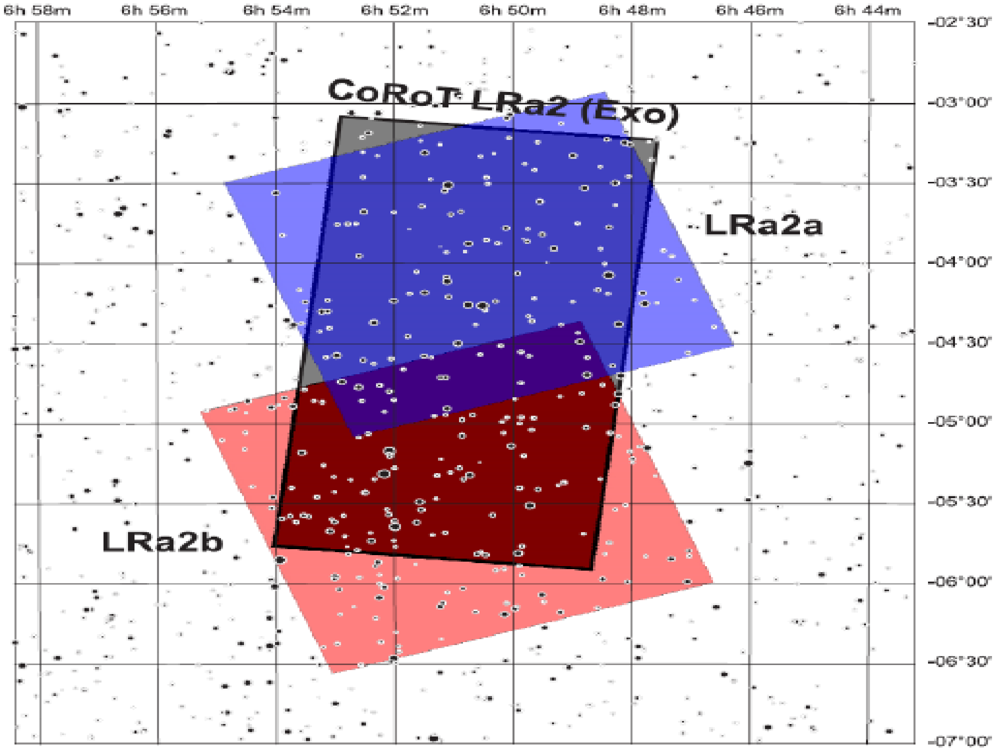


Aperture photometry

- Measuring the flux in the aperture around stellar SPF
- The flux is sky subtracted

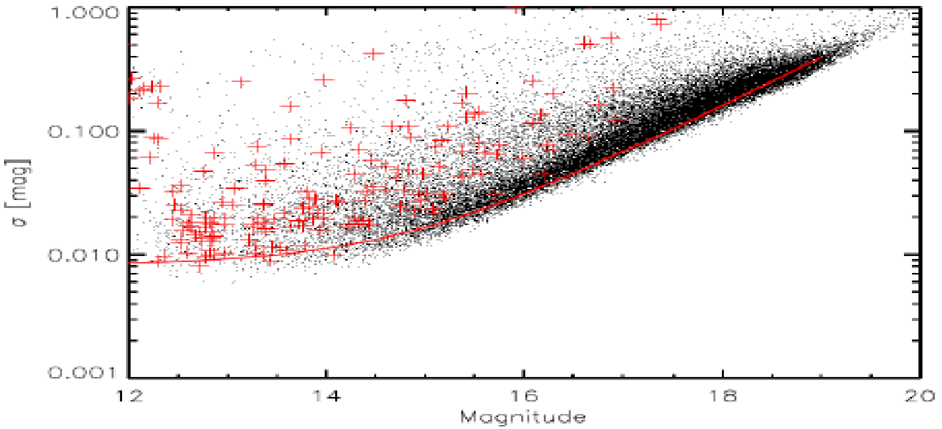


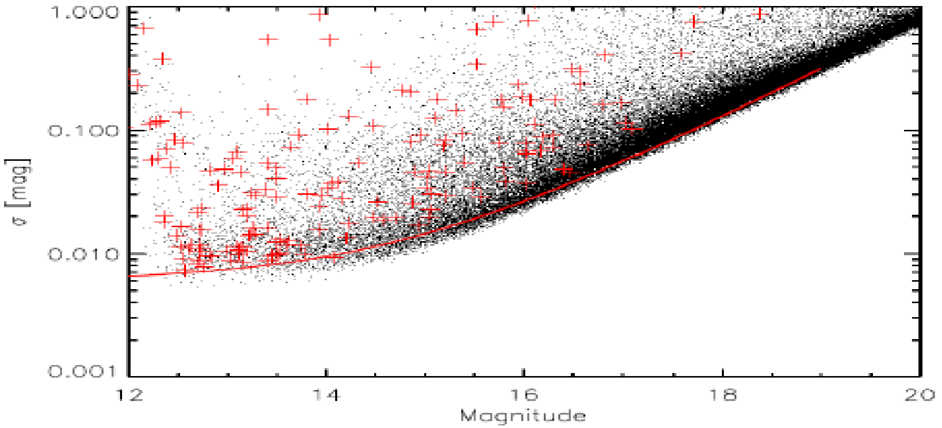
Illustraton of noises



g. 1. The orientation of BEST II LRa02 subfields with respect CoRoT's LRa2b field (coordinates J2000.0).

ıe field of view (FOV) of the system covers 1.7° × 1.7° on





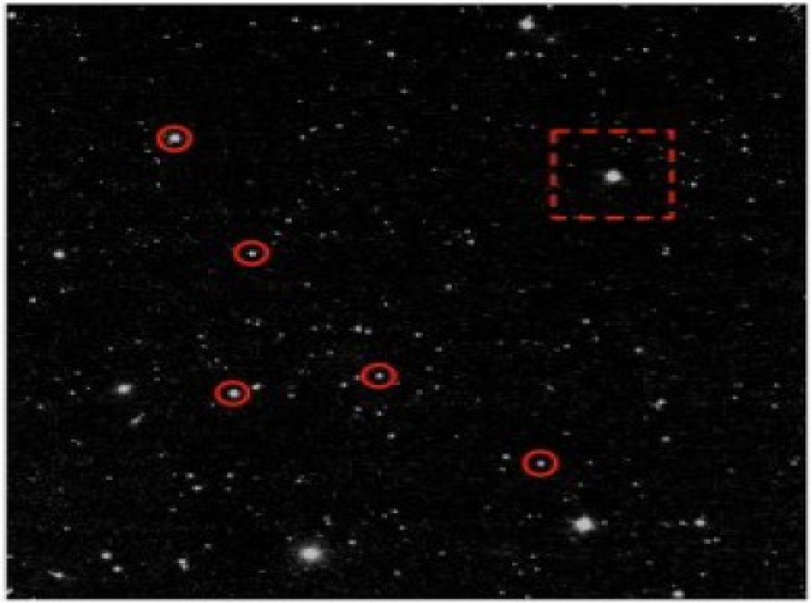
- Kabath et al. 2009

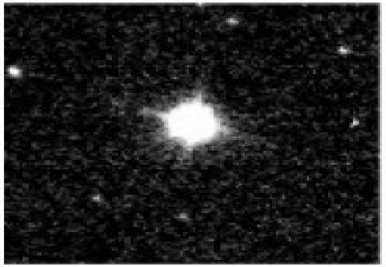
Flux vs. magnitude

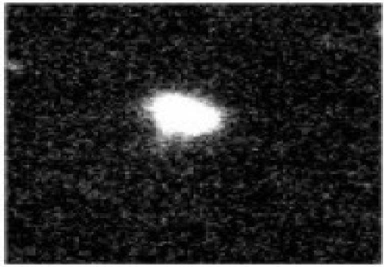
- Flux is linear, you can take flux of two stars and divide etc…
- Magnitude is logarithmic!! Be sure you eaither work with flux or with magnitudes
- $m=-2.5x\log(F/F0)$!!

From image till LC

- Gibson et al. 2014 HAWKI Wasp-19b







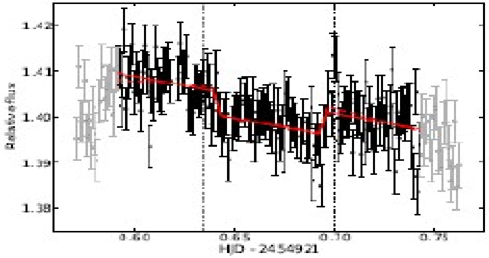
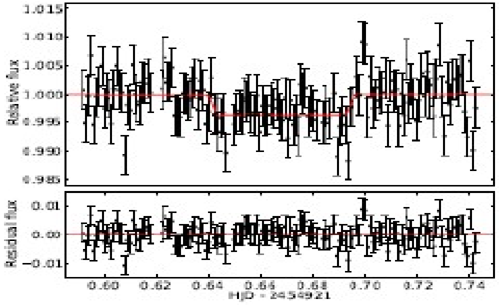


Figure 3. Raw VLT/HAWK-I light curve of the secondary transit of WASP-19. The dashed–dotted lines show the expected start and end of transit, assuming the planet is in a circular orbit. A



LC with Perek telescope differential photometry

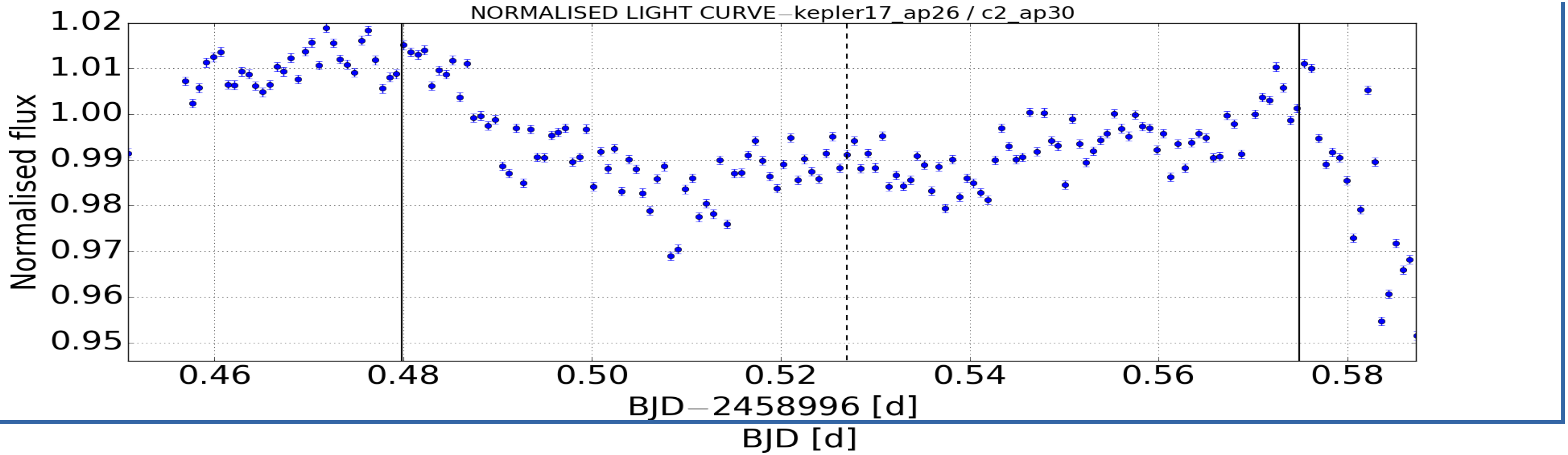
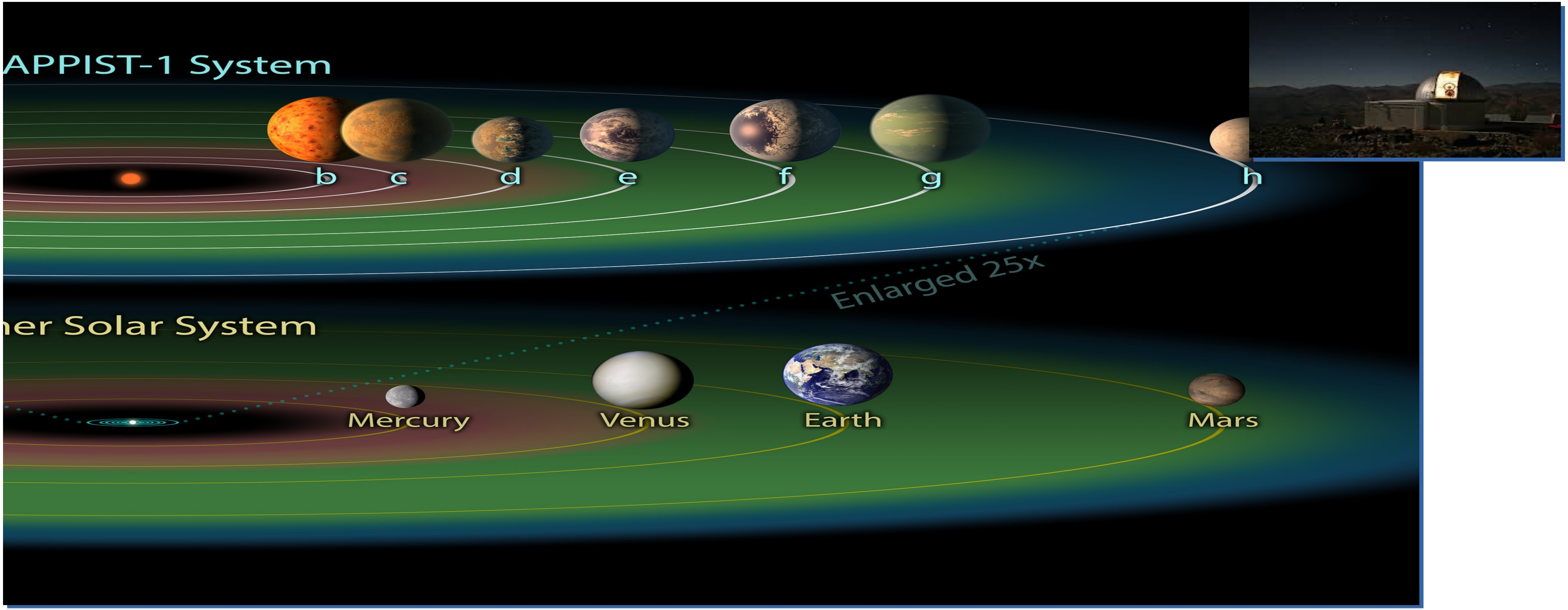


Figure: M. Blazek

Ground based exciting detections example

Trappist-1 – Gillon et al., 2016, Nature, **Temperate Earth-sized planets transiting a nearby ultracool dwarf star**



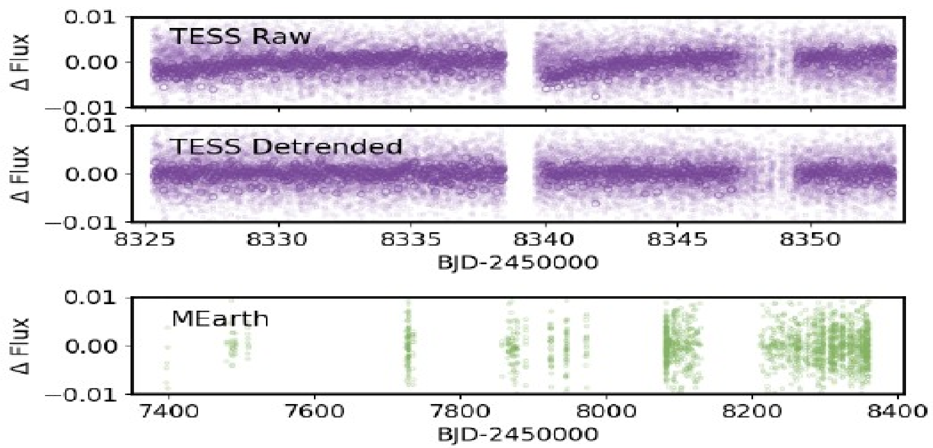
mages: ESA/NASA and ESO

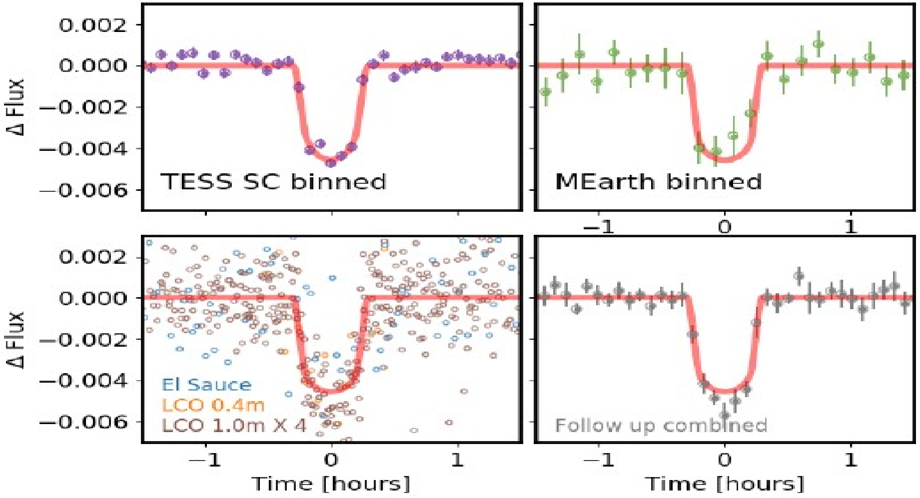
Space missions

- Advantage of continuous coverage (more or less)
- No atmosphere – no additional noise source
- Unprecedented precision
- Constrained by their orbits, by fuel, by their cost
- CoRoT, KEPLER, TESS

Space based exciting detections

- Ultra short period planet, TESS – LHS3844 b
- 1.5 Mearth
- Period = 11 hours





Vanderspeck et al. 2018, ApJL - https://arxiv.org/abs/1809.07242

Recap from Lecture 1-2

- For transits detection as many star as possible
  - favoring CCD over photomultiplier
  - more comparison sources on frame, saves time
- High duty cycle needed (many frames in short time)
  - CCD capable of many exposures
- Bright targets needed for ground based follow-up

Reading

- http://slittlefair.staff.shef.ac.uk/teaching/phy217/lectures/instruments/L17/index.html
- http://astronomy.nmsu.edu/cwc/Teaching/ASTR605/Lectures/spectra.pdf
- http://www.iastro.pt/research/conferences/faial2016/files/presentations/CE3.pdf
- http://web.ipac.caltech.edu/staff/fmasci/home/astro_refs/aperture_phot2.pdf

Next lecture

- Tour of OES facilities
- Detection process of an exoplanetary candidate
- How to get the space mission data?