*Precise Radial Velocities, Penn State University, Aug 17 2010*

# HARPS: concepts, performances, and results

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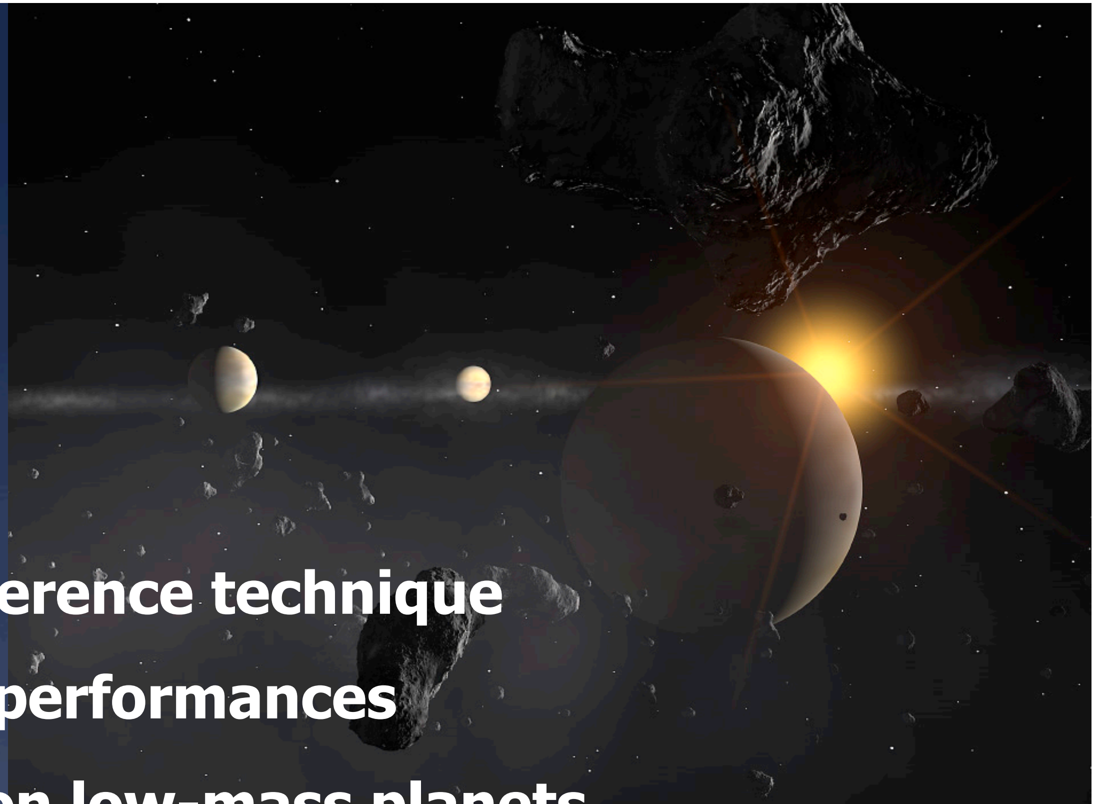
# Outline



- The simultaneous reference technique
- HARPS instrumental performances
- Some recent results on low-mass planets
- High-precision spectroscopy
- Long-term results on a quiet star

# Instrumental challenges to astronomical high-precision « line position » measurements

- Slit illumination:
  1/100 of the slit width <-> 30 m/s @ R = 100,000

- Variations in the index of refraction of air:
  1 m/s <-> 0.01 K <-> 0.01 mbar

- Thermal and mechanical flexures in the spectrograph:
  ~10-100 m/s (temperature, gravity, setup changes)

- Wavelength calibration
  High line density, high repeatability/accuracy, good modeling/fitting

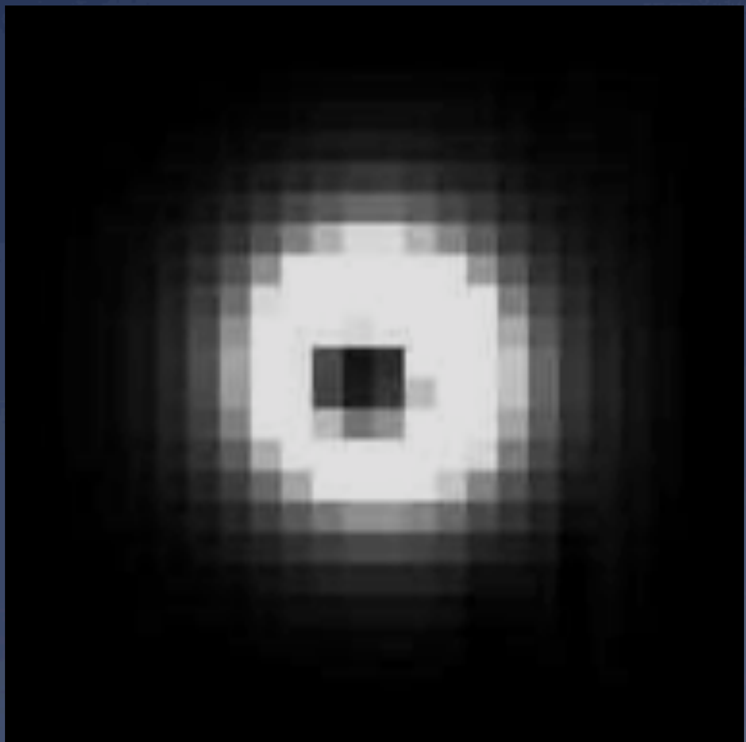
- Detector-related effects
  Pixel inhomogeneities, CTE effects, flat-fielding, etc.

# « Simultaneous reference » philosophy: address individual effects and minimize them

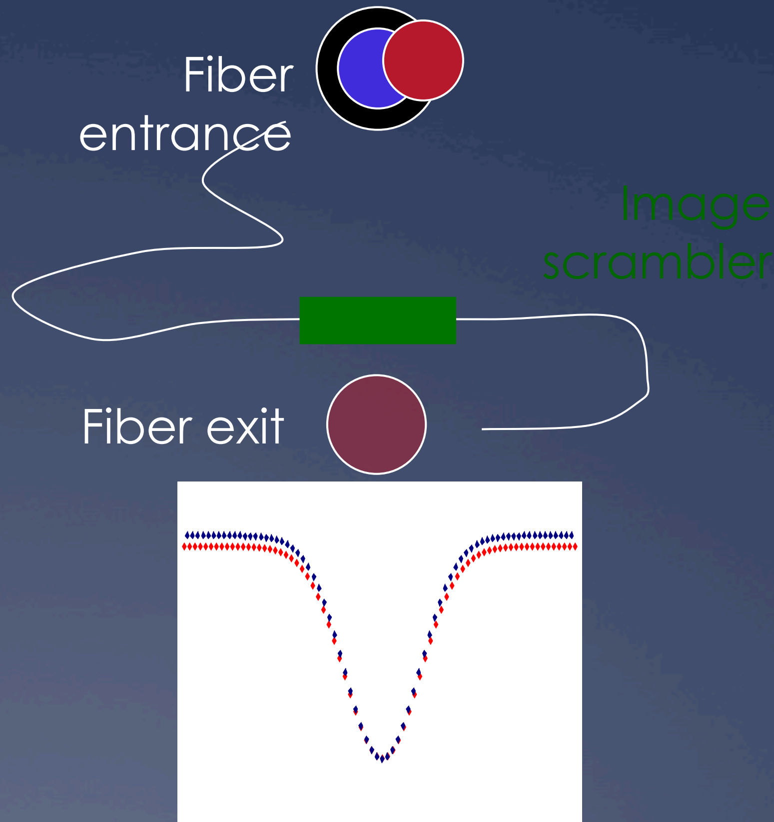
| | |
|---|---|
| • Slit illumination | Light feed / guiding |
| • Variations in the index of refraction of air<br>• Thermal and mechanical flexures | Spectrograph |
| • Wavelength calibration | Calibration source |
| • Detector-related effects | CCD |

# Slit illumination

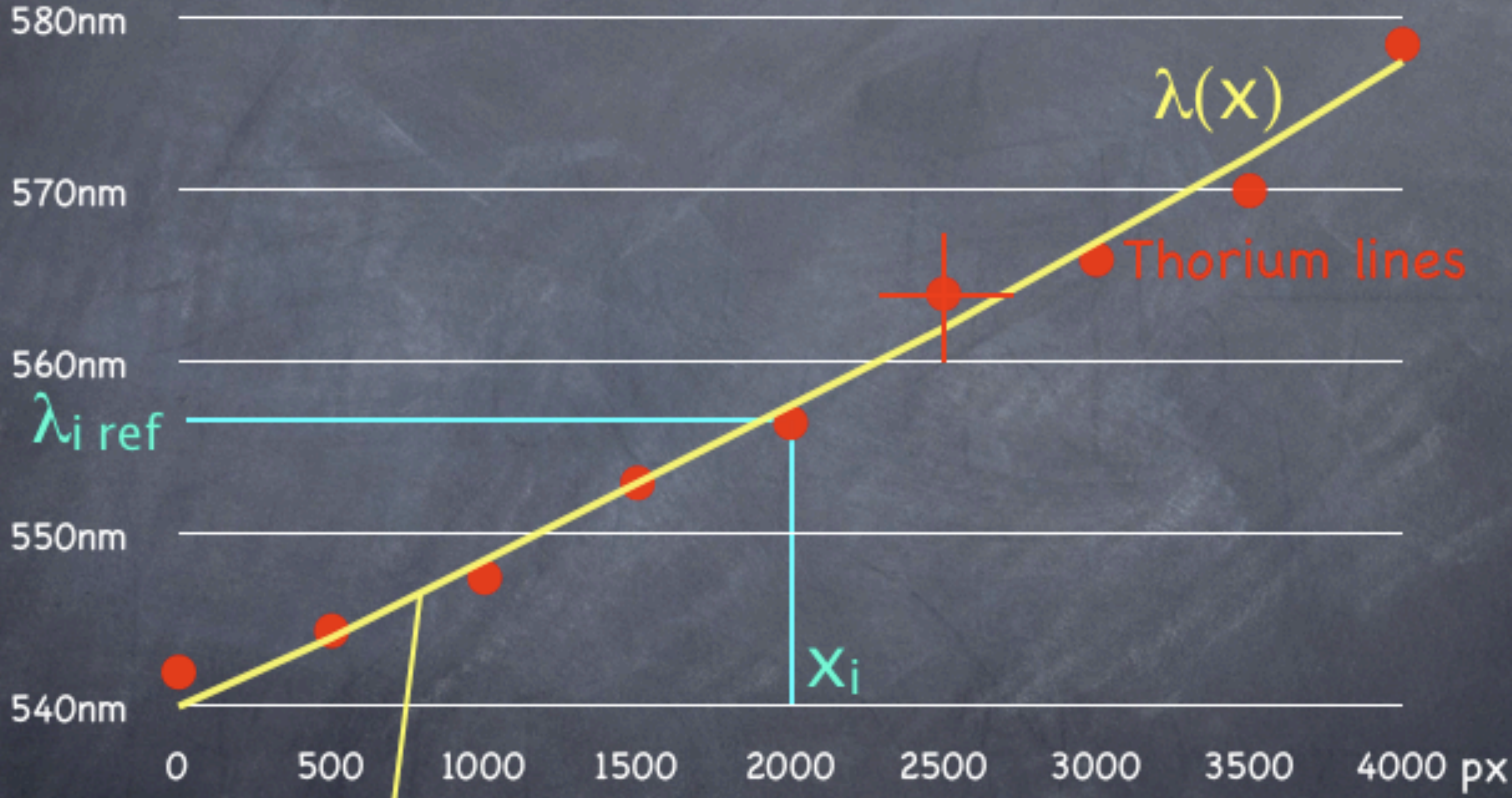
Guiding error:
0.5″ → 2-3 m/s
for a HARPS-like spectrograph



Fiber-fed spectrograph



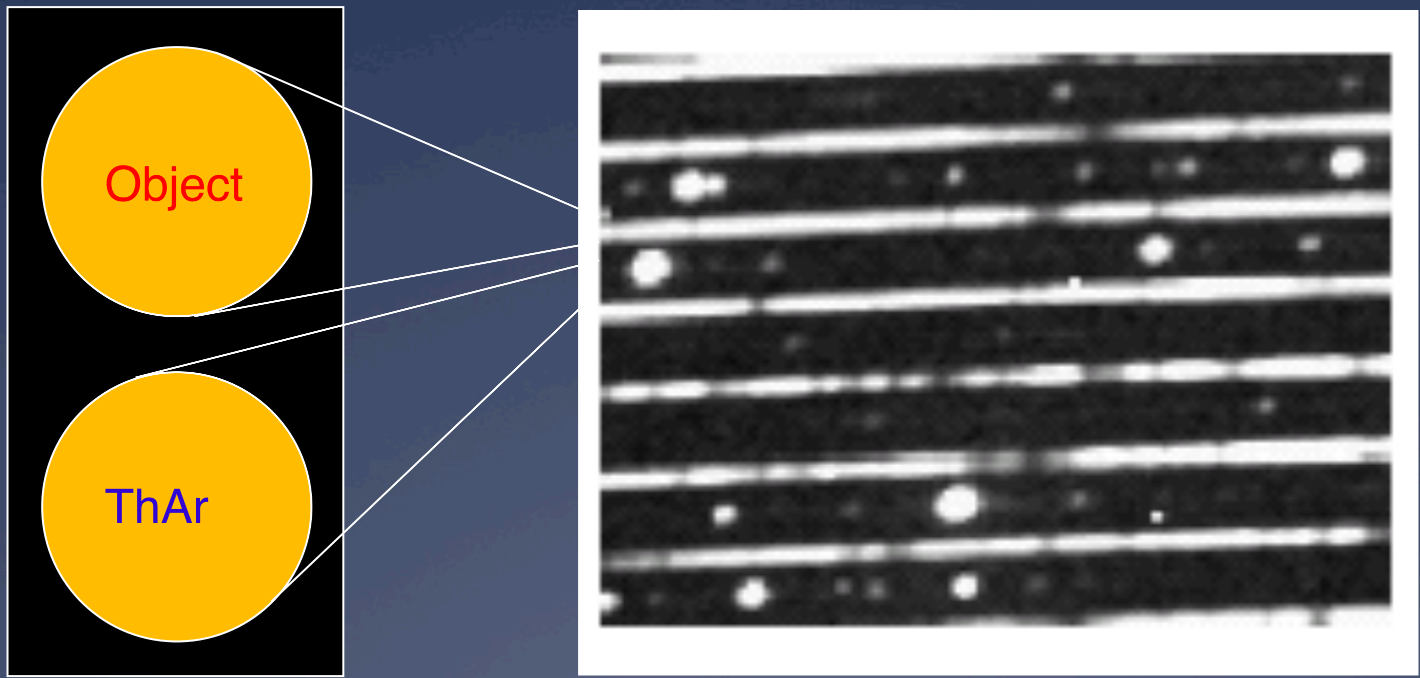
# The wavelength solution

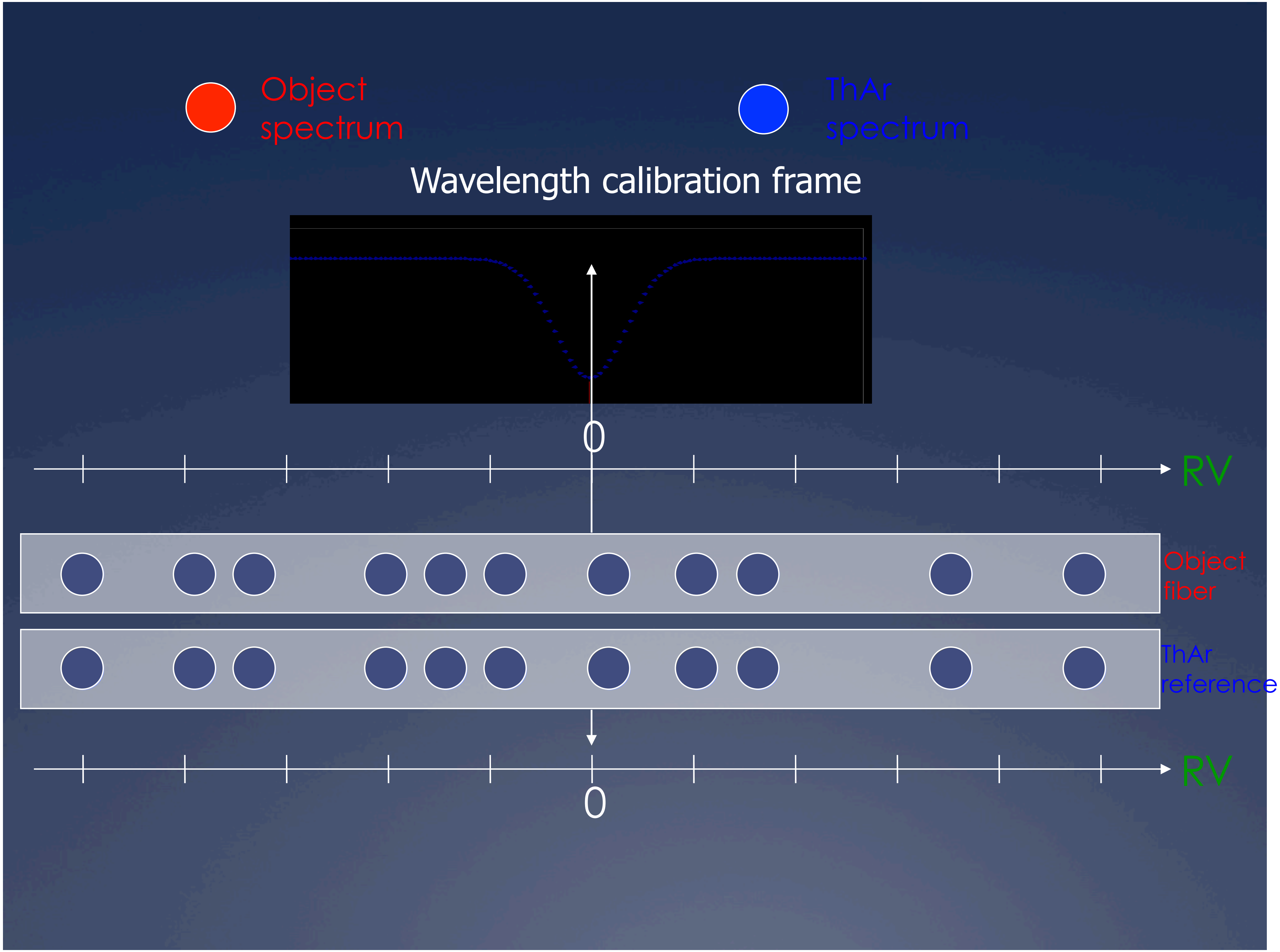



| | | |
|---|---|---|
| Requirements on $\Delta\lambda/\lambda$: | (Absolute) accuracy: | "none" |
| (for 1 $ms^{-1}$ precision) | Scale factor: | ~$10^{-5}$ |
| | Repeatability (global): | ~$10^{-9}$ |

# Simultaneous ThAr reference

Assumption: science and reference beams follow almost the same path from the slit to the detector, and will thus experience the same internal drifts



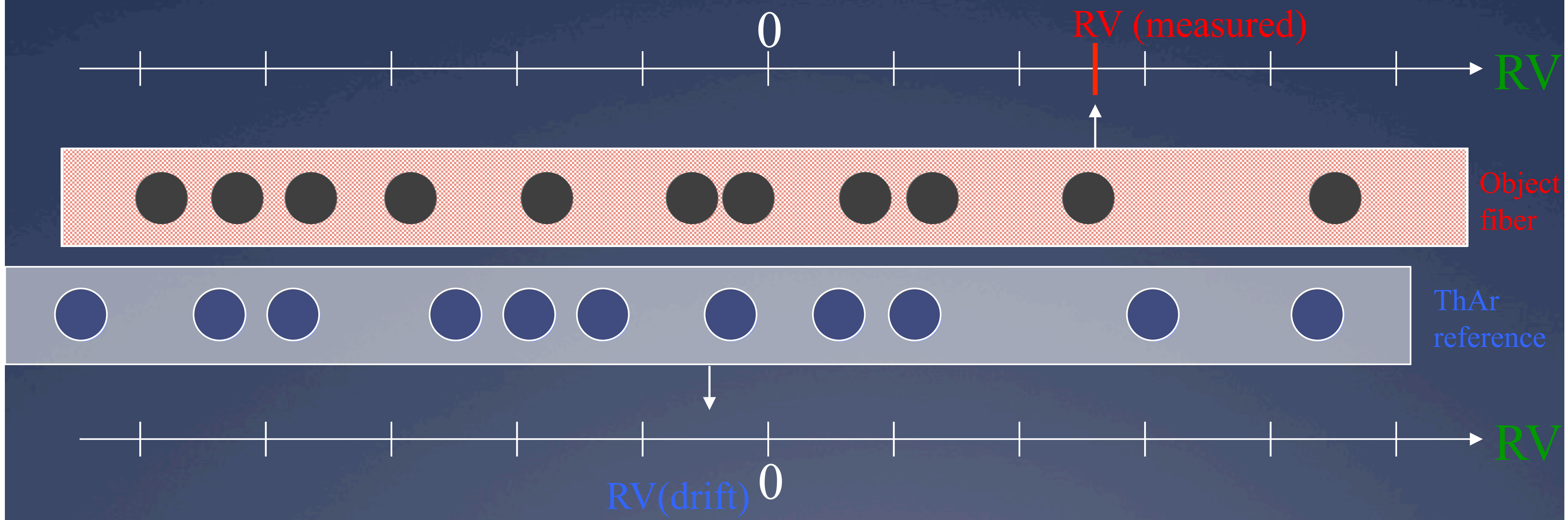


Object spectrum
ThAr spectrum
Wavelength calibration frame
0
RV
Object fiber
ThAr reference
RV
0

Object spectrum ThAr spectrum

# Science exposure

RV (object) = RV (measured) - RV(drift)



# Minimization of internal effects in the spectrograph

ΔRV =1 m/s

⇕

Δλ=0.00001 A

⇕

15 nm

⇕

1/1000 pixel

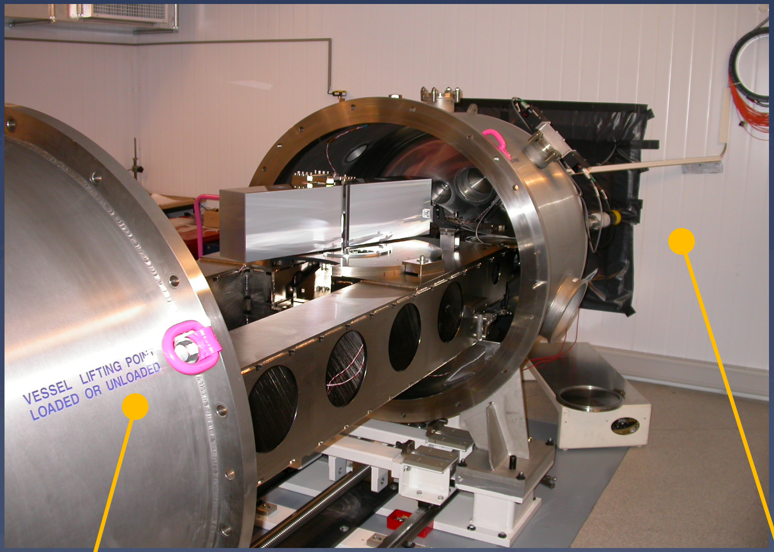
ΔRV =1 m/s

⇕

ΔT =0.01 K

⇕

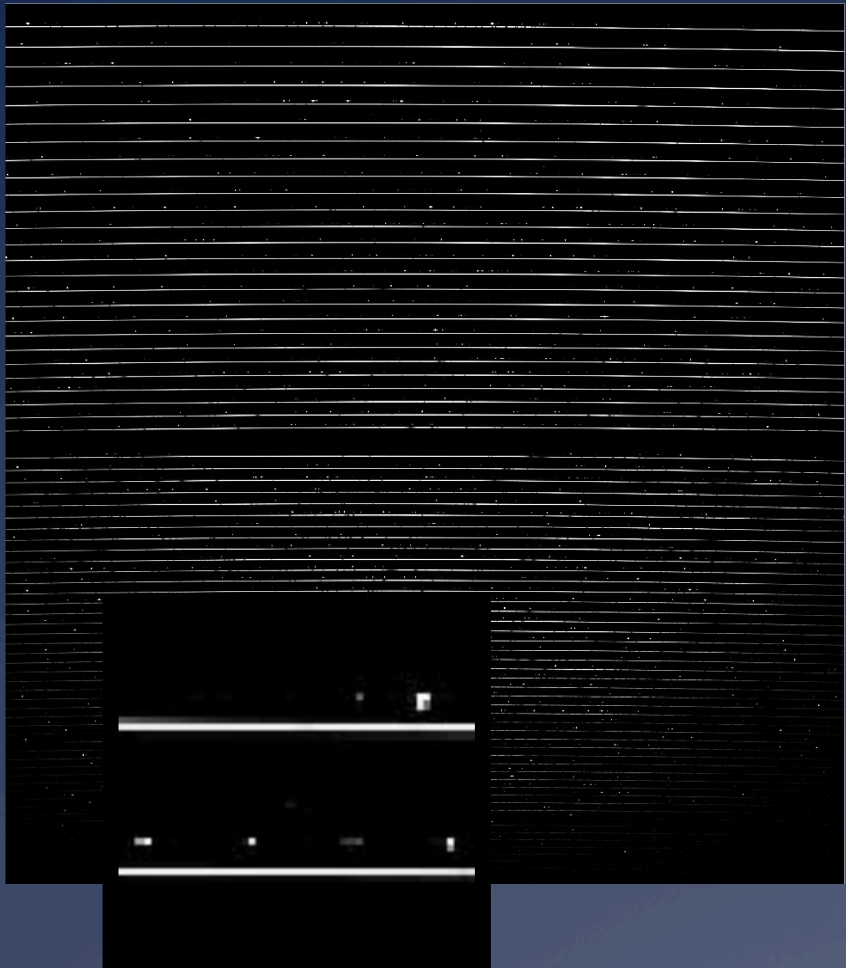
Δp=0.01 mbar

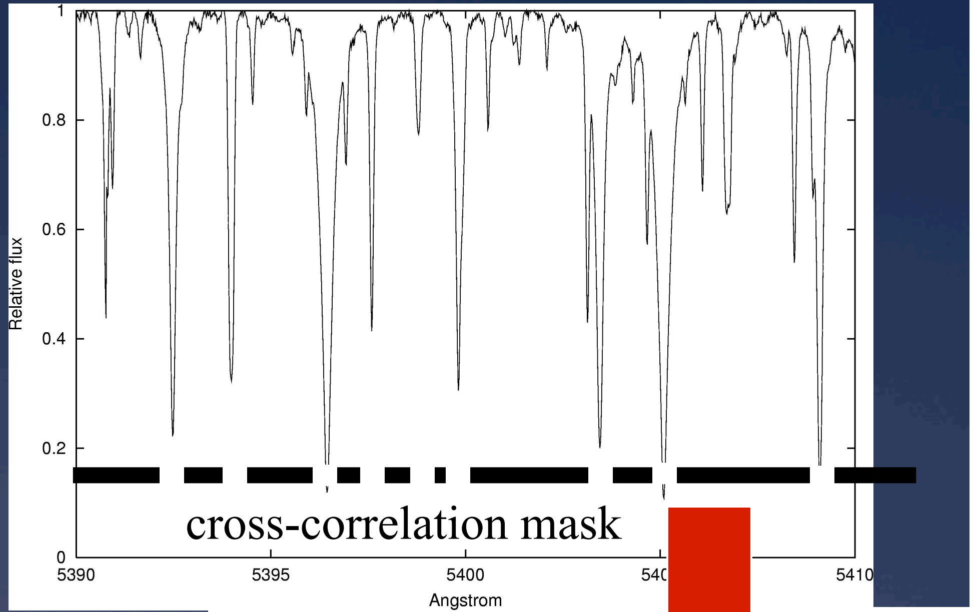


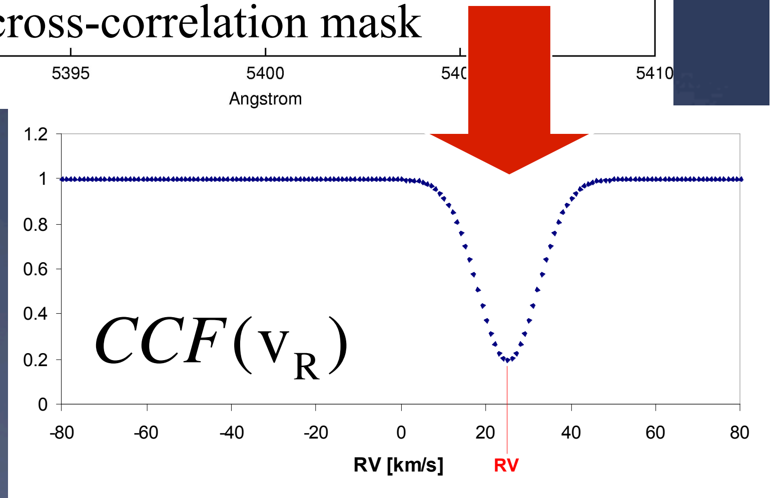

Vacuum operation

Temperature control

# Extraction of the RV information





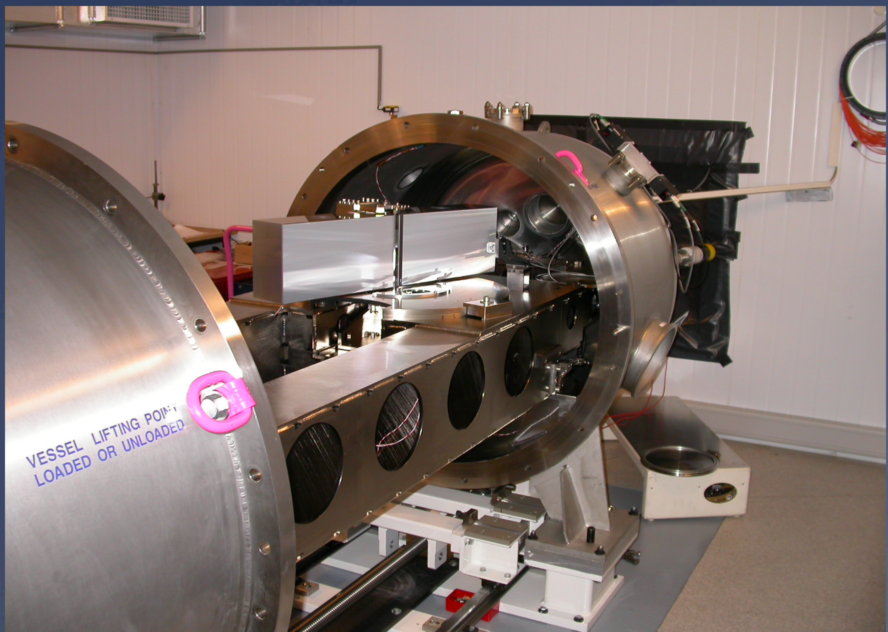




$$CCF(\mathrm{v_R}) = \int_{\lambda} M(\lambda, \mathrm{v_R}) \cdot I(\lambda), \quad \text{where} \quad M(\lambda) = \sum_{i} \theta_i(\lambda - \lambda_i) \cdot w_i$$

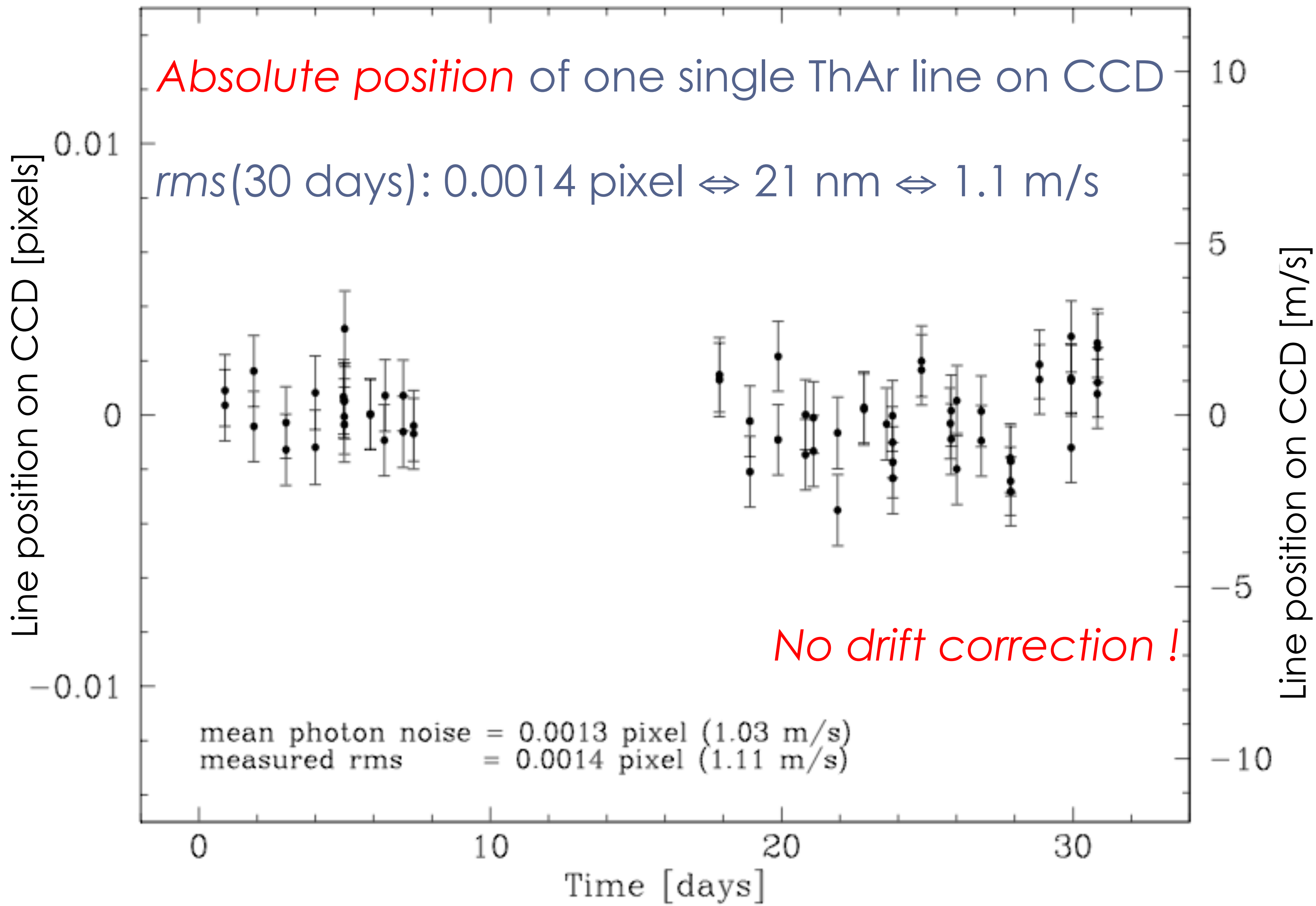
# The HARPS instrument and the quest for low-mass planets

ESO-3.6m @ La Silla

- **Cross-dispersed echelle spectrograph**
- **Spectral range 3785-6915 Å**
- **R = 115,000**
- **Long-term precision < 1 m/s**
- **Observations ongoing since 2003**

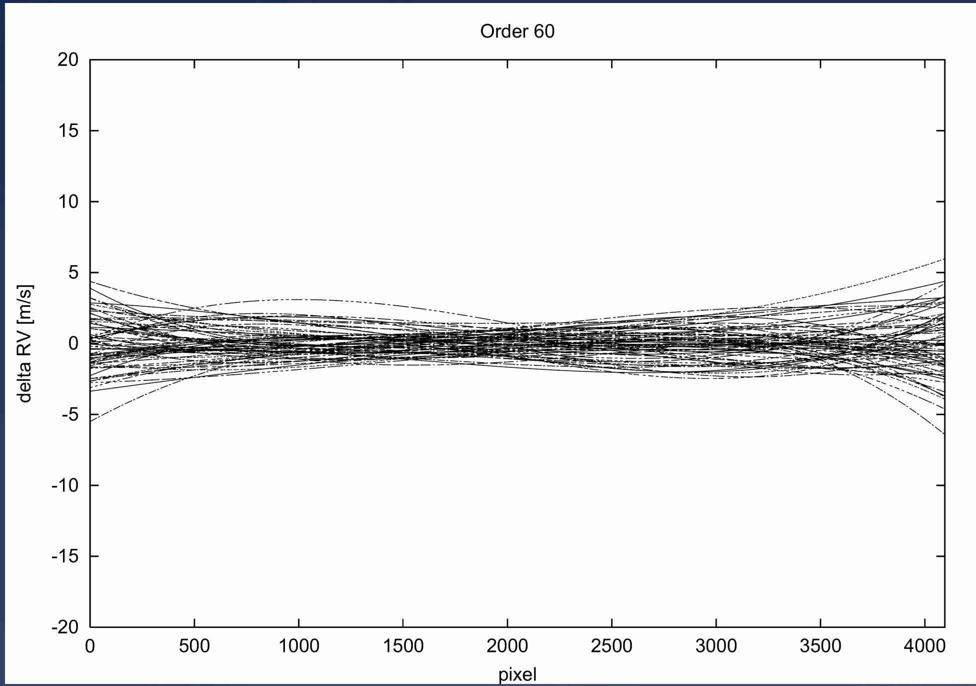



HARPS

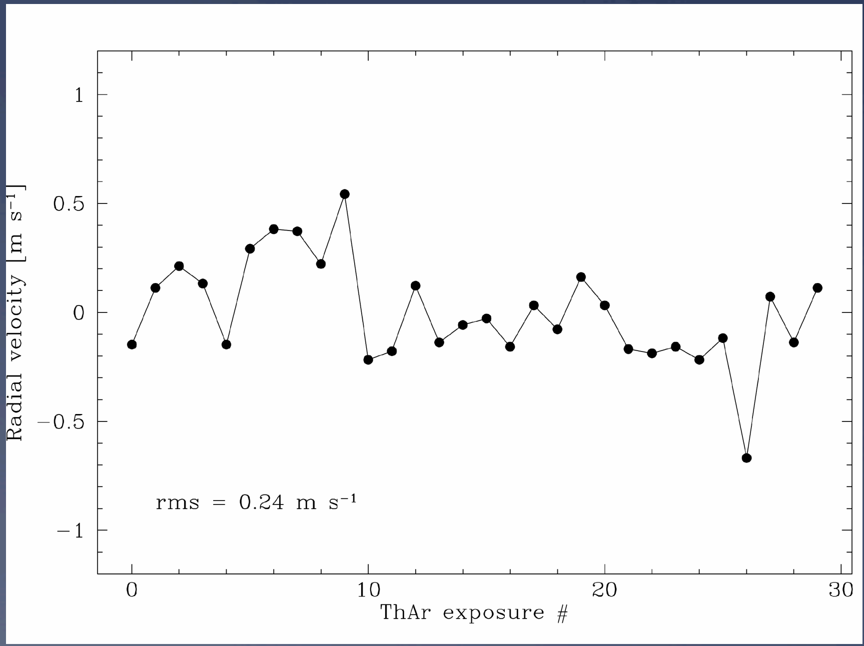


Absolute position of one single ThAr line on CCD
rms(30 days): 0.0014 pixel ⇔ 21 nm ⇔ 1.1 m/s
No drift correction !
mean photon noise = 0.0013 pixel (1.03 m/s)
measured rms = 0.0014 pixel (1.11 m/s)
Line position on CCD [pixels]
Line position on CCD [m/s]
Time [days]
0.01
0
−0.01
10
5
0
−5
−10
0
10
20
30

# Wavelength calibration

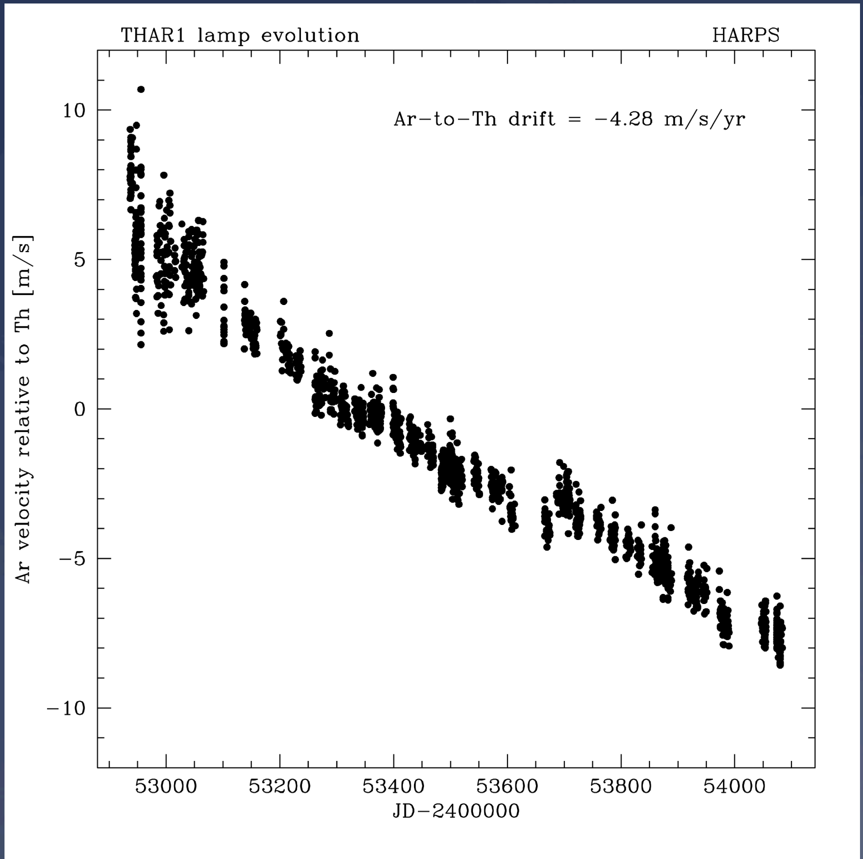


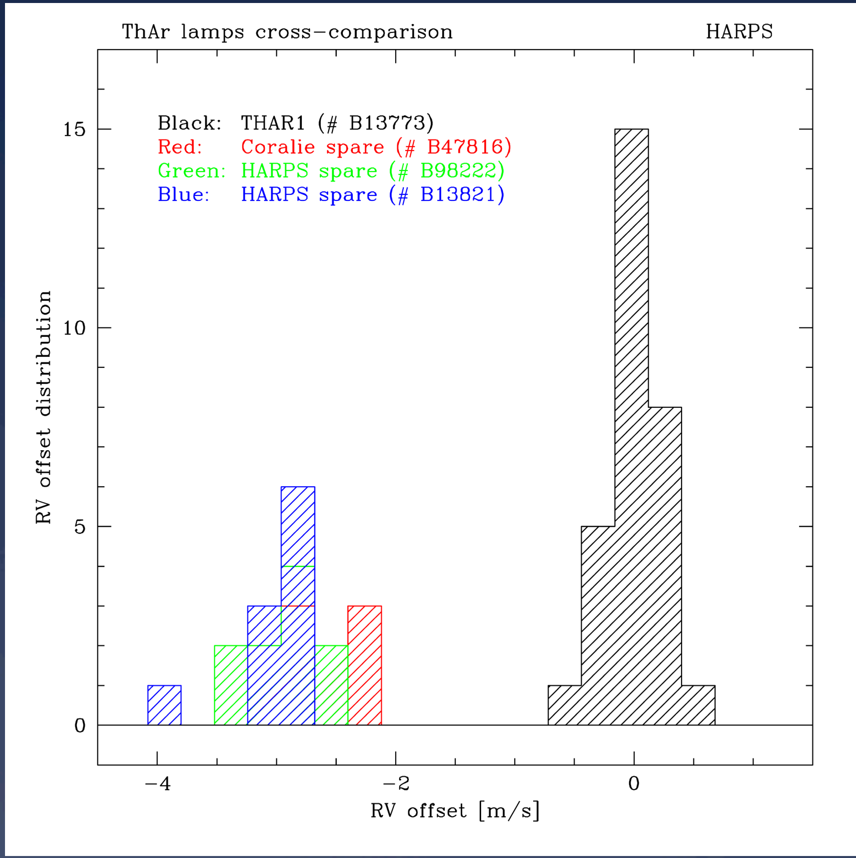

High stability of the wavelength solutions, locally precise to 2-3 m s$^{-1}$




Precision on the global radial velocity zero point: ~30 cm s$^{-1}$

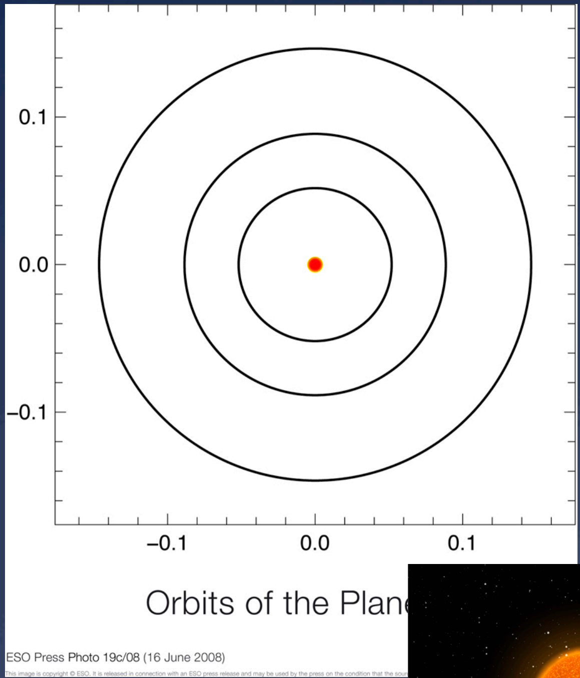
# Intrinsic line shifts in ThAr lamps



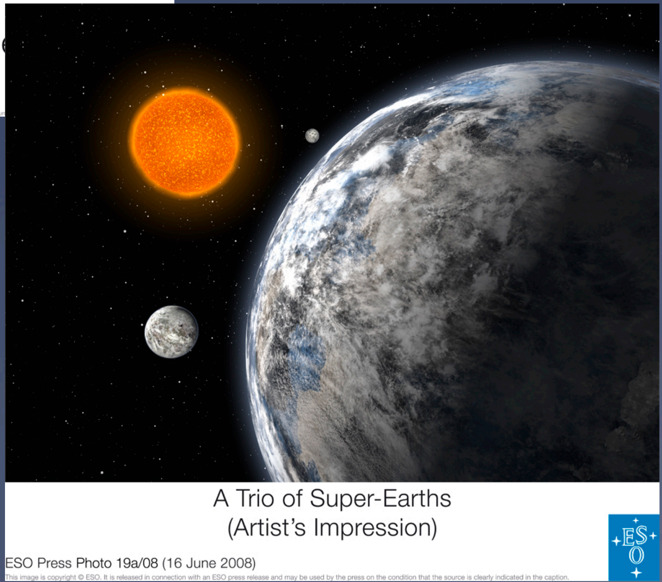




- Lamp aging -> pressure shifts
- Avoid Argon!
- Global Ar-to-Th sensitivity ratio: ~8.3
- Zero point correction using measured Ar line positions!

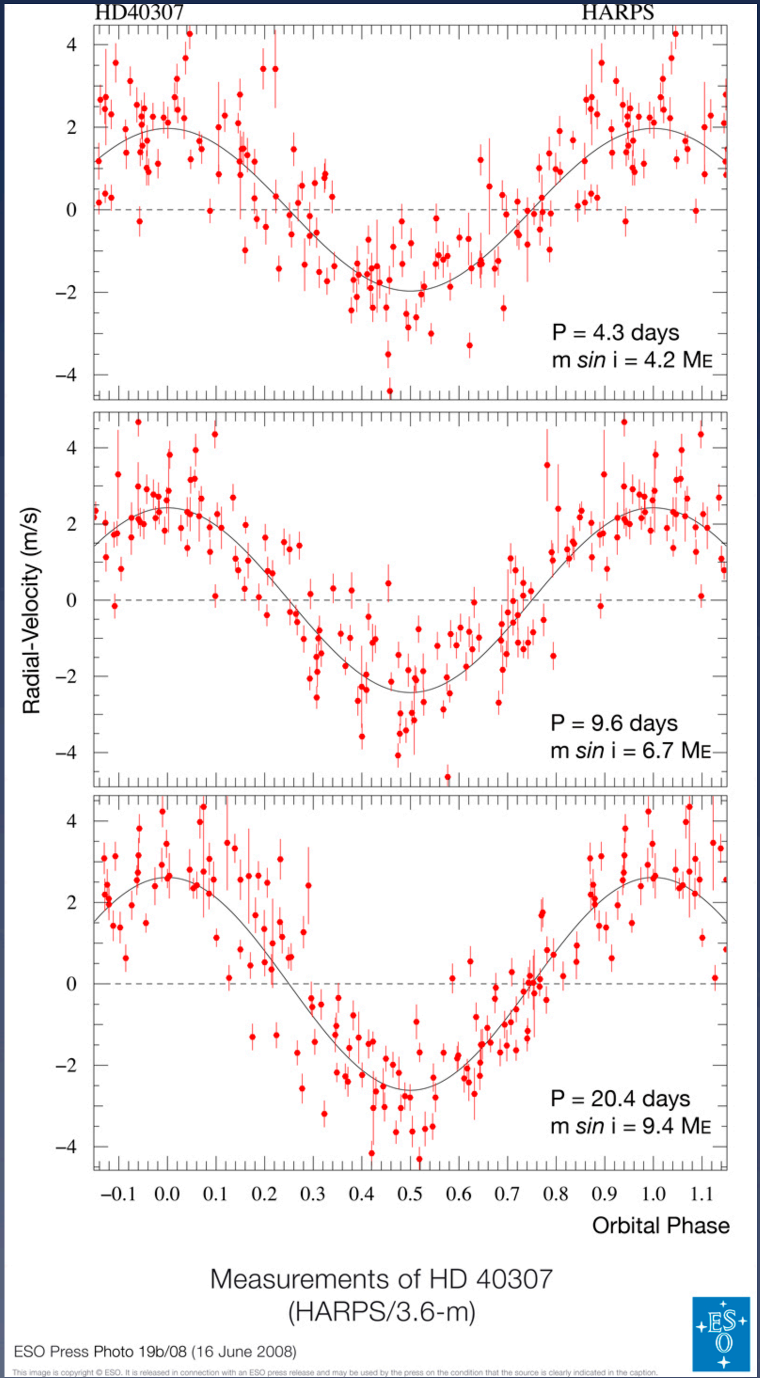
# HD 40307: three close-in super-Earths




rms = 0.85 m/s
Mayor et al. 2009




A Trio of Super-Earths
(Artist's Impression)




Measurements of HD 40307
(HARPS/3.6-m)

# Gliese 581: super-Earths close to the habitable zone ?

**Gl 581 b**

P = 5.37 days
K = 12.5 m $s^{-1}$
m sin(i) = 15.7 $M_\oplus$

**Gl 581 c**

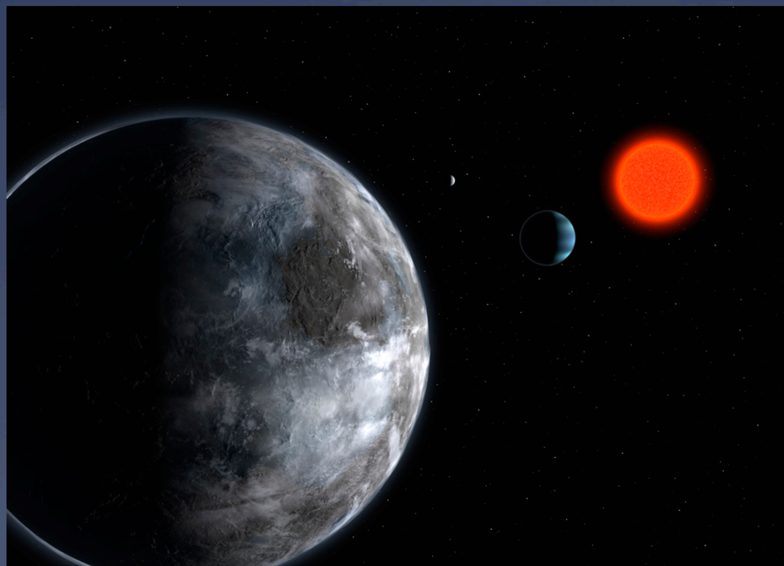
P = 12.9 days
K = 3.24 m $s^{-1}$
m sin(i) = 5.36 $M_\oplus$

**Gl 581 d**

P = 66.8 days
K = 2.63 m $s^{-1}$
m sin(i) = 7.1 $M_\oplus$

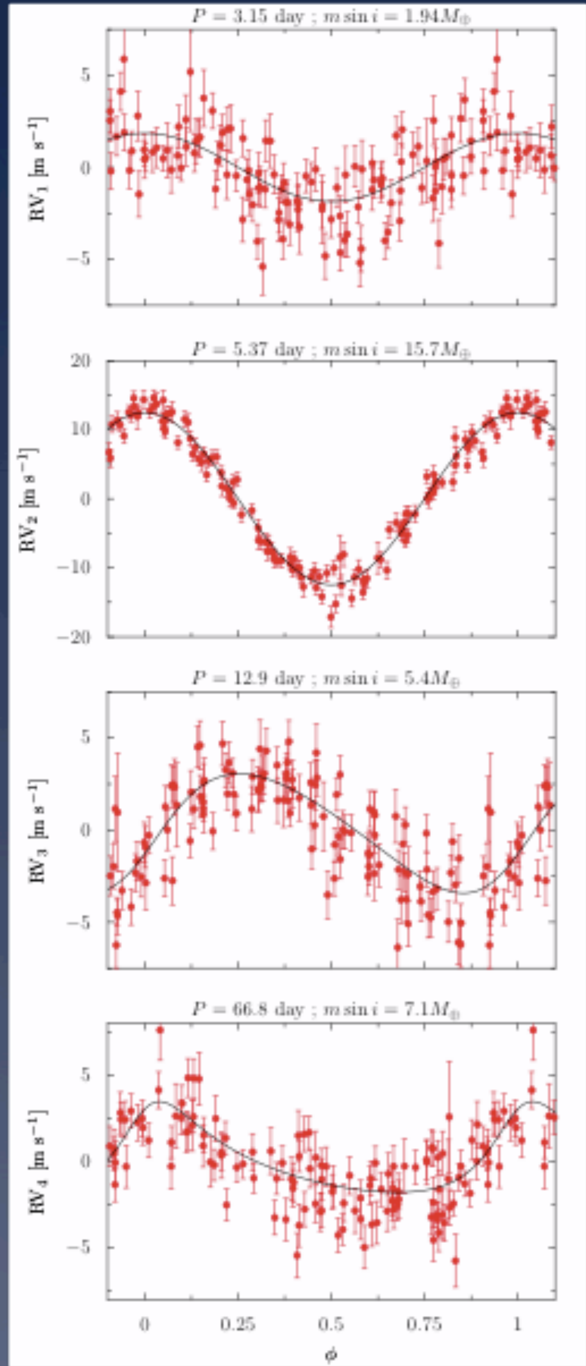
**Gl 581 e**

P = 3.15 days
K = 1.85 m $s^{-1}$
m sin(i) = 1.94 $M_\oplus$



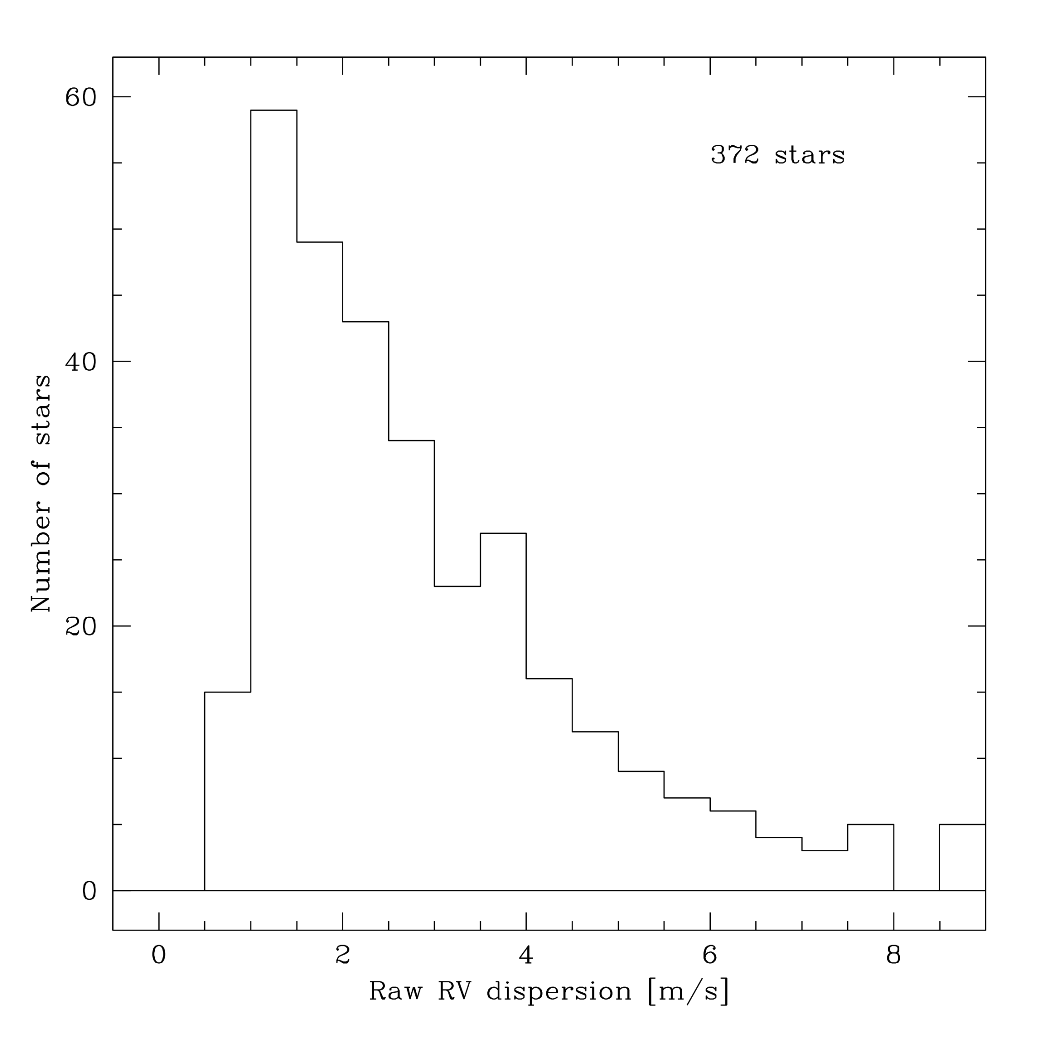
The Planetary System in Gliese 581
(Artist's Impression)
ESO Press Photo 22a/07 (25 April 2007)





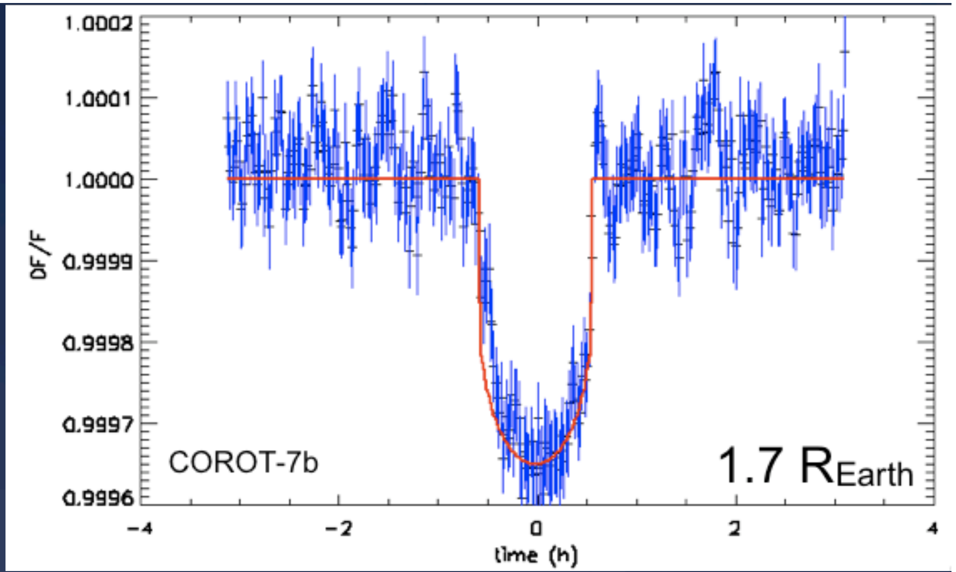

Bonfils et al. 2005
Udry et al. 2007
Mayor et al. 2009

# Global RV dispersion

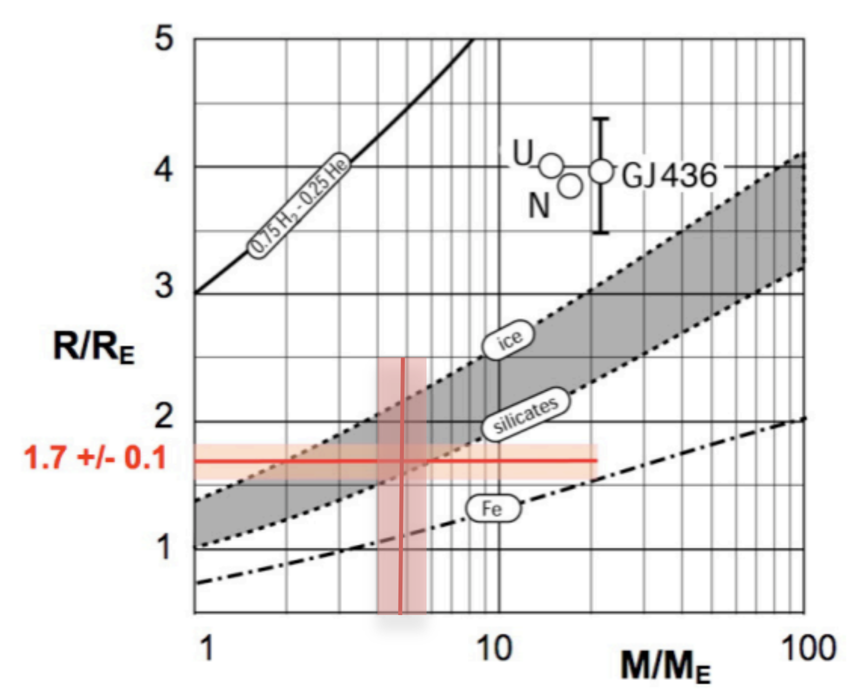



- Peak at ~1.3 m/s
- Many stars ARE as quiet as this!
- All simulations of stellar noise should be compared to that
- Raw rms!
- Includes photon noise, instrumental noise, stellar noise and planets
- Many candidate planet-hosts have rms of 1-3 m/s
- This is still significantly better than other instruments…

# CoRoT-7b: the first transiting super-Earth



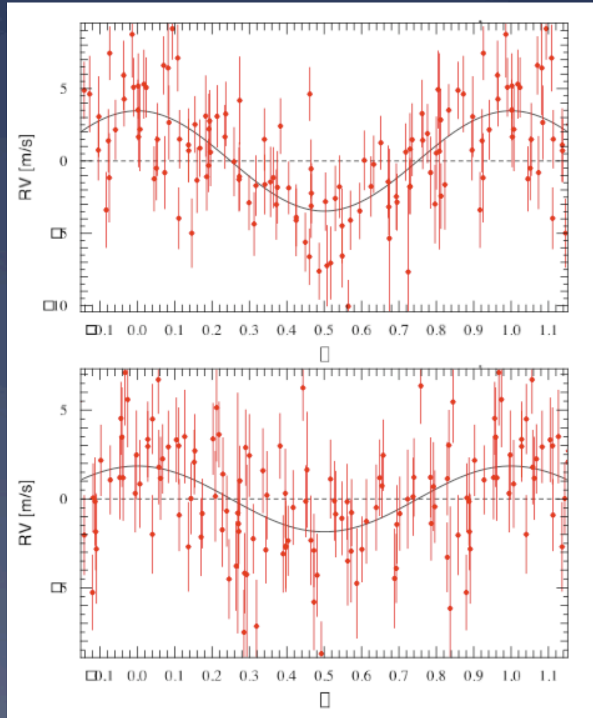

CoRoT lightcurve, Léger et al. 2009




## CoRoT-7

SpT = G9V
V = 11.7
$M_* = 0.93\ M_\odot$
Teff = 5275 K
$\log(R'_{HK}) = -4.60$

**Active star!**




HARPS RVs, Queloz et al. 2009

## CoRoT-7b

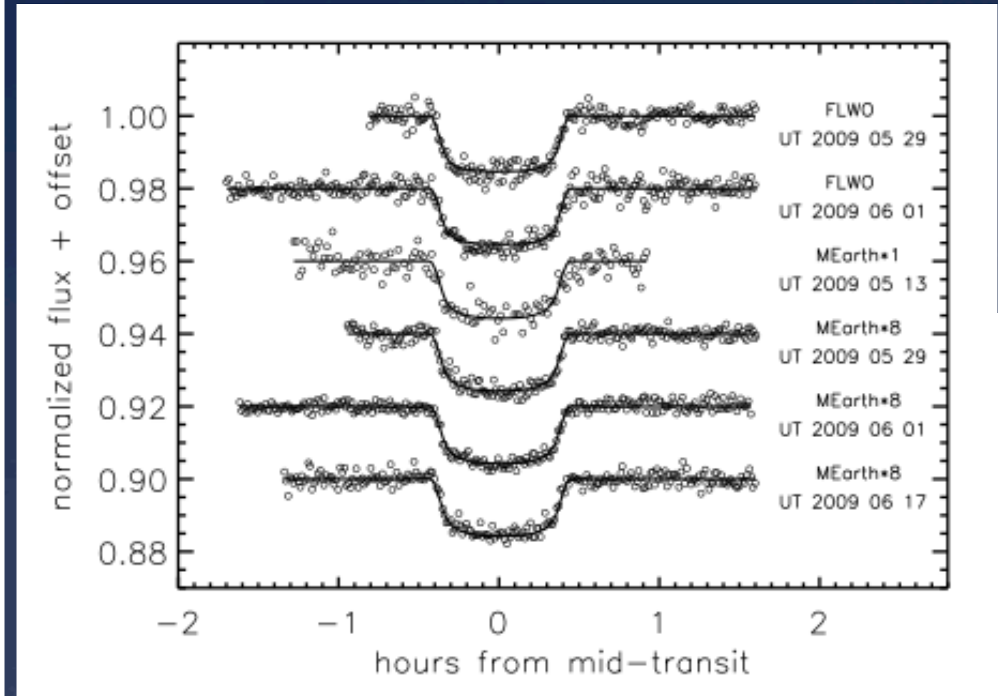
P = 0.85 day
$R_p = 1.7\ R_\oplus$
$M_p = 4.8\ M_\oplus$
$\rho = 5.6\ g\ cm^{-3}$

## CoRoT-7c

P = 3.69 days
$R_p$ = ?
$M_p = 8.4\ M_\oplus$
$\rho$ = ?

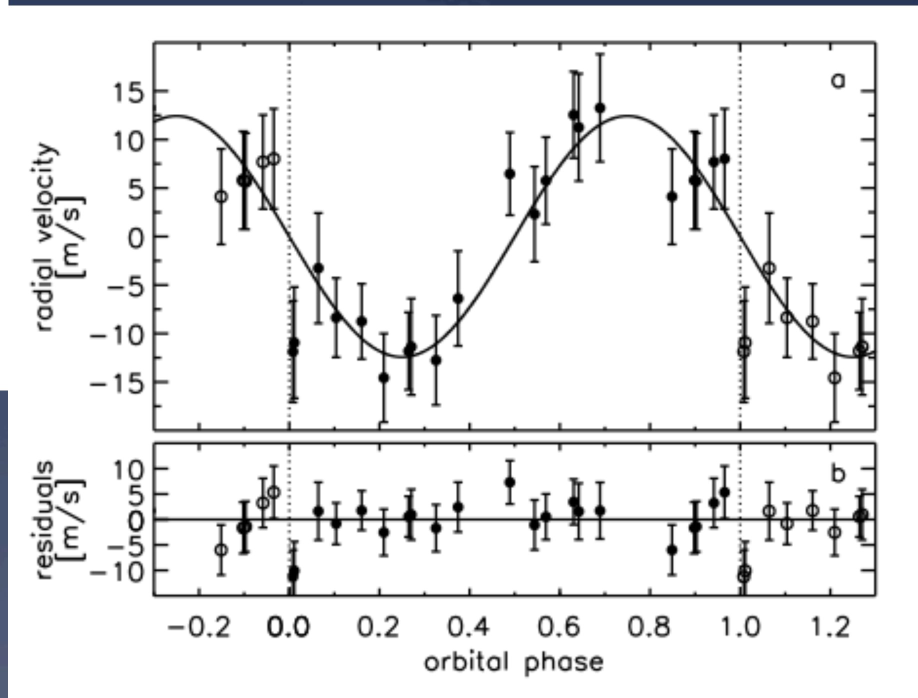
# GJ 1214 b: a super-Earth around a M4.5 dwarf

**Charbonneau et al. 2009**




**MEarth lightcurve**

**HARPS RVs**




### GJ 1214

**SpT = M4.5V**
**V = 15**
**$M_* = 0.16\ M_\odot$**
**Teff = 3000 K**

### GJ 1214 b

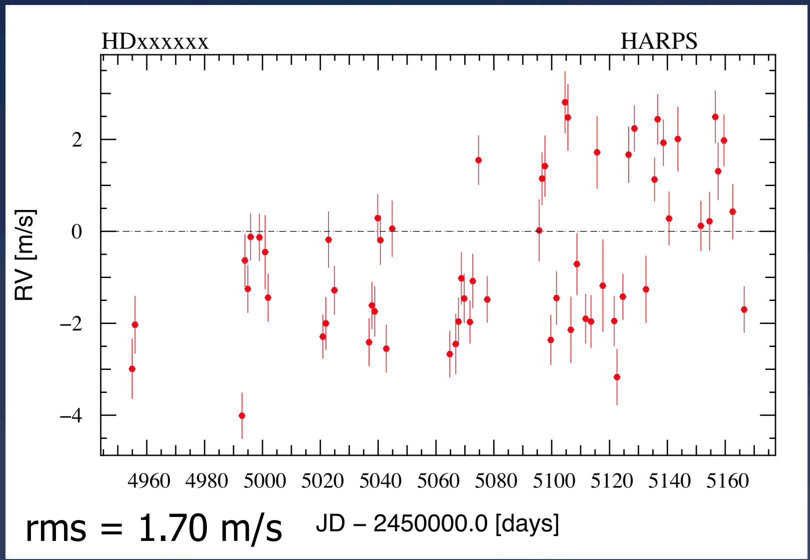
**P = 1.58 day**
**$R_p = 2.68\ R_\oplus$**
**$M_p = 6.55\ M_\oplus$**
**$\rho = 1.9\ g\ cm^{-3}$**

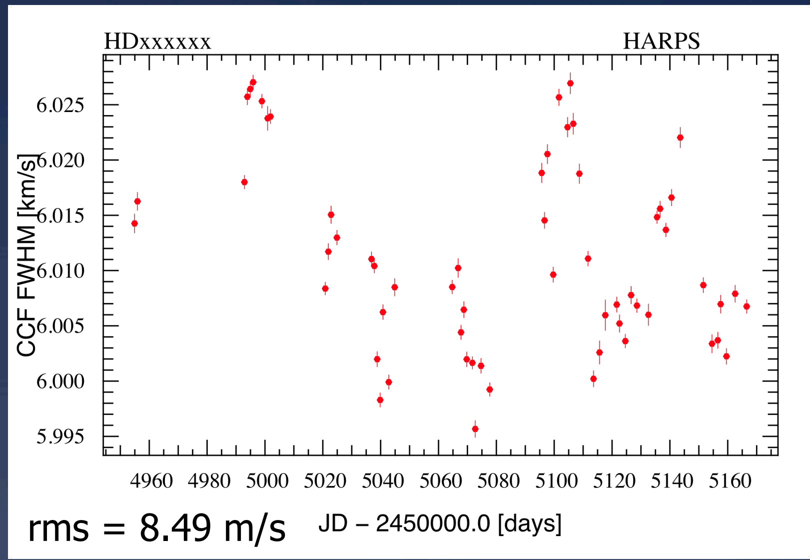
**rms = 5.2 m/s despite V=15, SNR=9, 3.6m aperture, non-optimal correlation mask…**

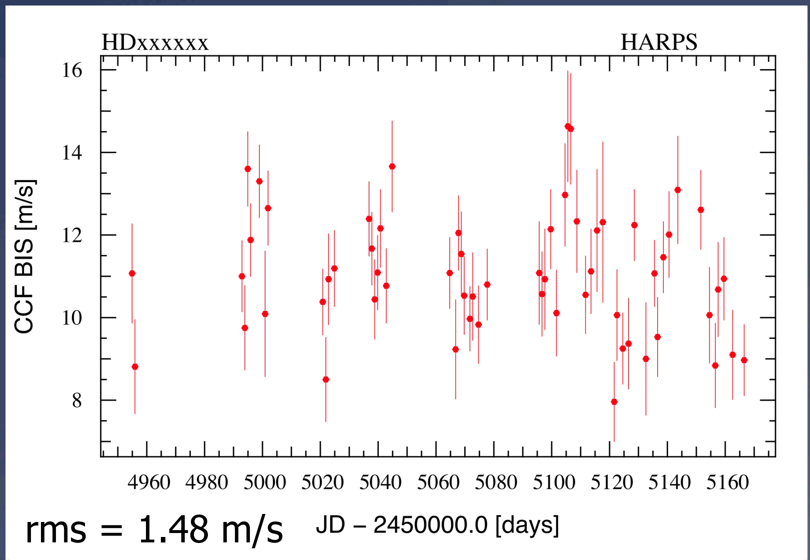
# High-precision spectroscopy

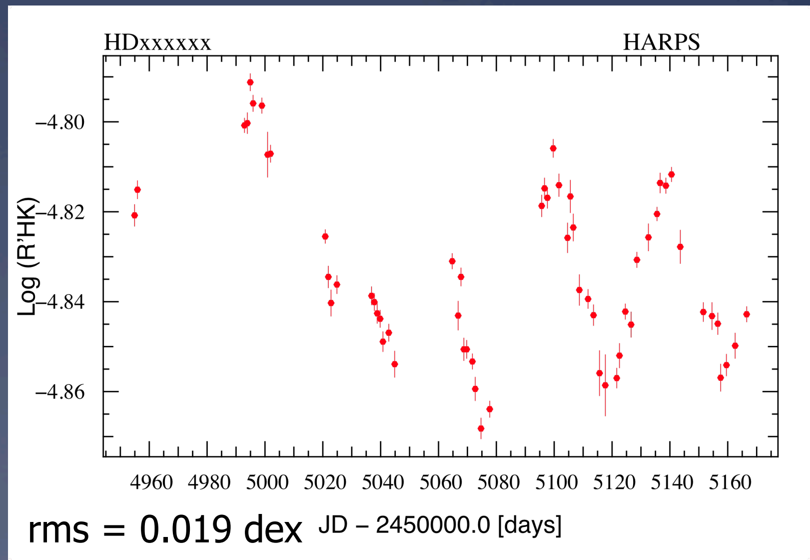
- High stability yields high-precision RVs, but also very good spectroscopy in general
- Benefits to any line position measurement, equivalent widths, line shapes
- Spectrophotometry and spectroscopic indicators very useful diagnostics in the context of planet searches
- Ca II H&K index, CCF FWHM and contrast, bisectors
- What is the behavior of solar-type stars at this level of precision?

# High-precision spectroscopy

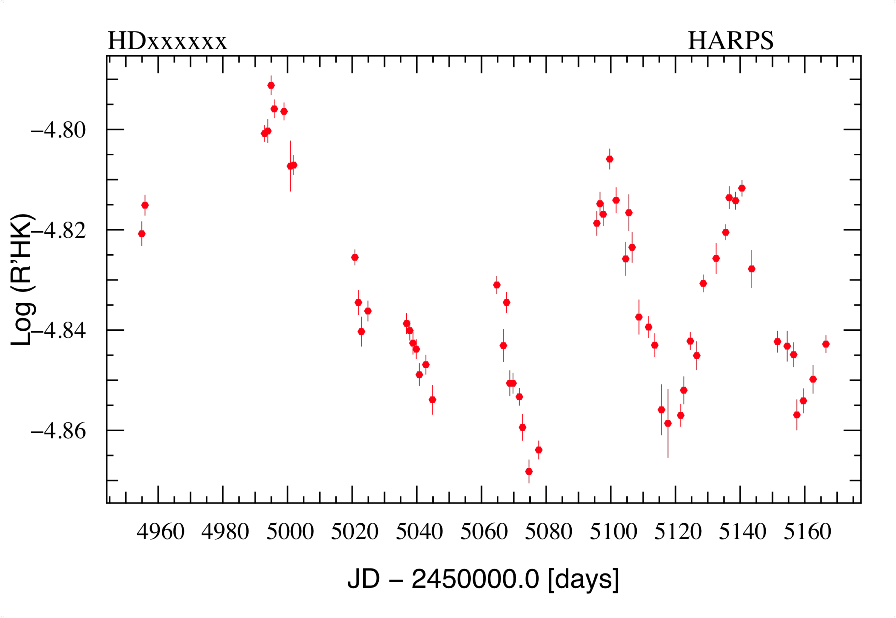


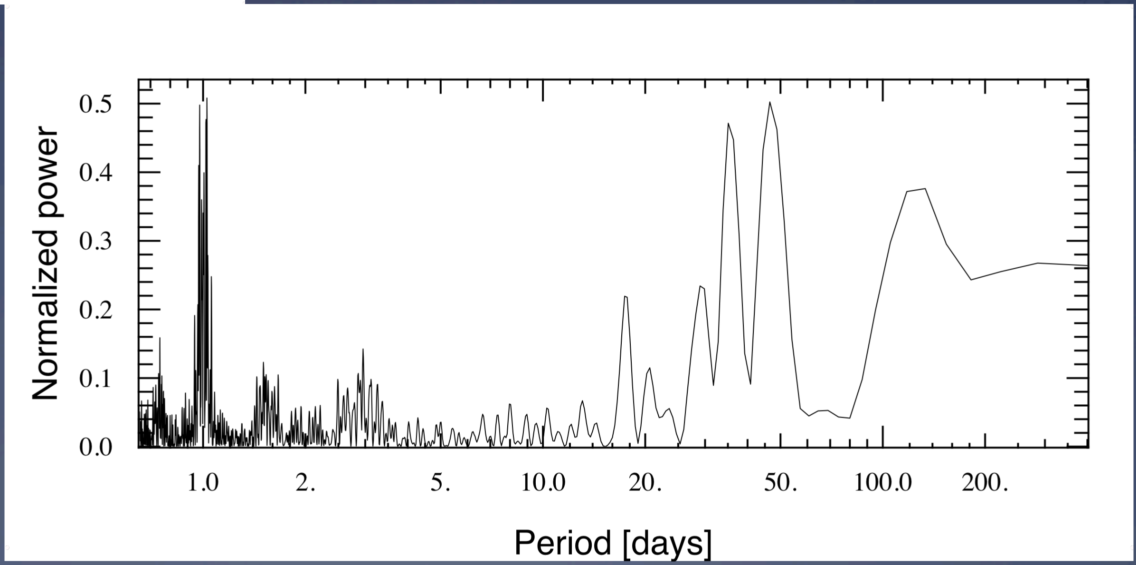



# High-precision spectroscopy




Activity – rotation relation (Noyes et al. 1984, Mamajek & Hillenbrand 2008) gives
$P_{rot}$ = 40.9 +/- 5.6 d

Measured: either 35 or 46 d



# High-precision spectroscopy