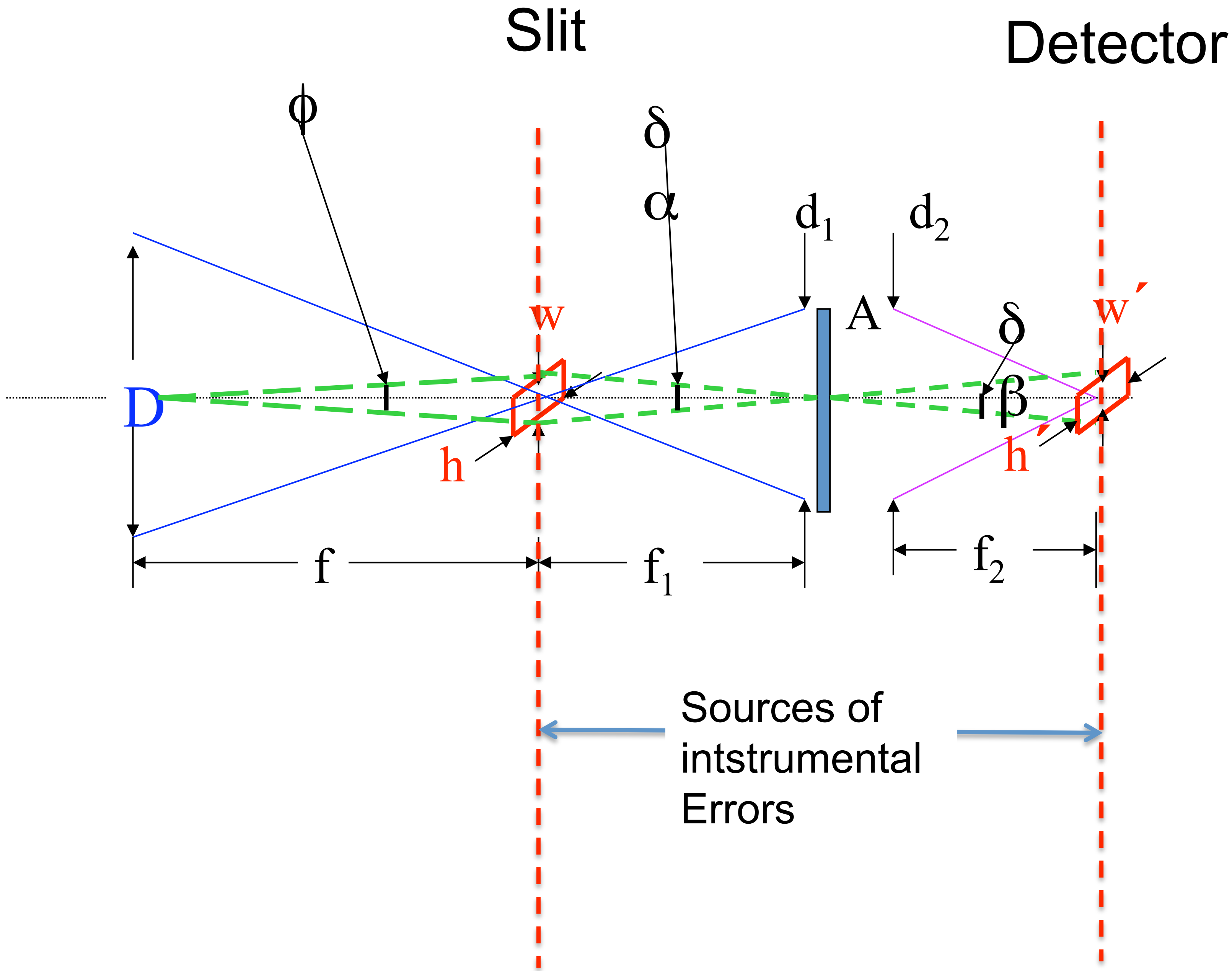
Sources of Errors
(Instrumental and Stellar)


Slit
Detector
φ
δ
α
d_1
d_2
A
δ
β
w
w´
h
h´
D
f
f_1
f_2
Sources of
intstrumental
Errors

The RV error comes from an error Budget

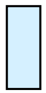
The total radial velocity error is the sum of a complete error budget. A stable wavelength reference is just one component

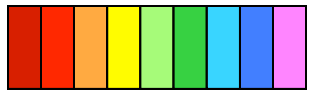
1. Guide errors
2. Changes to setup (e.g. resolution)
3. Stable wavelength reference
4. Changes in the optical system (changes in the instrumental profile)
   a) Stabilize the spectrograph (HARPS)
   b) Monitior IP (Iodine, Laser Comb)
5. The Detector (often ignored)

6. Proper motion/barycentric corrections
7. Intrinsic stellar variability

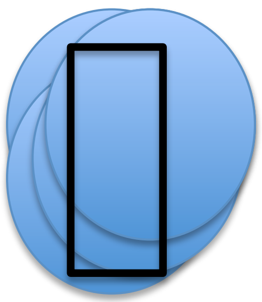
1. Guide Errors: Seeing and Image motion

Remember: At the spectrograph detector your stellar line is an image of a slit.

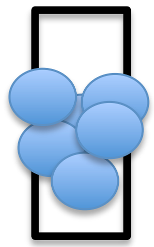




Stellar image in bad seeing

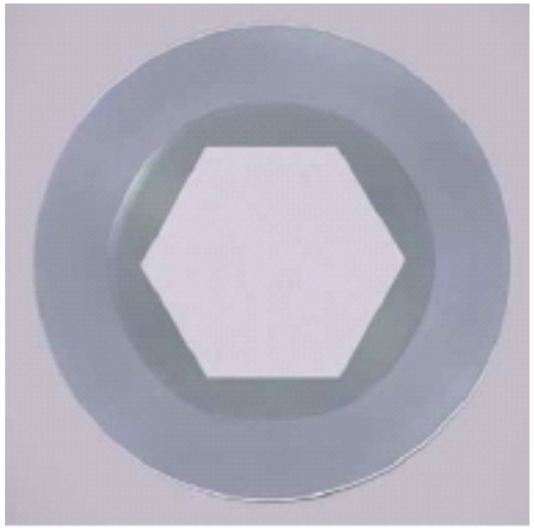


Stellar image in good seeing



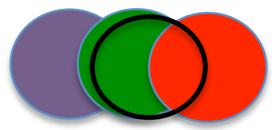
1. Minimizing Guide Errors: Fiber Scrablers

1. Move and bend fibers for better scrambling
2. Double Scrambling. Price: less efficiency
3. Hexagonal fibers for better scrambling



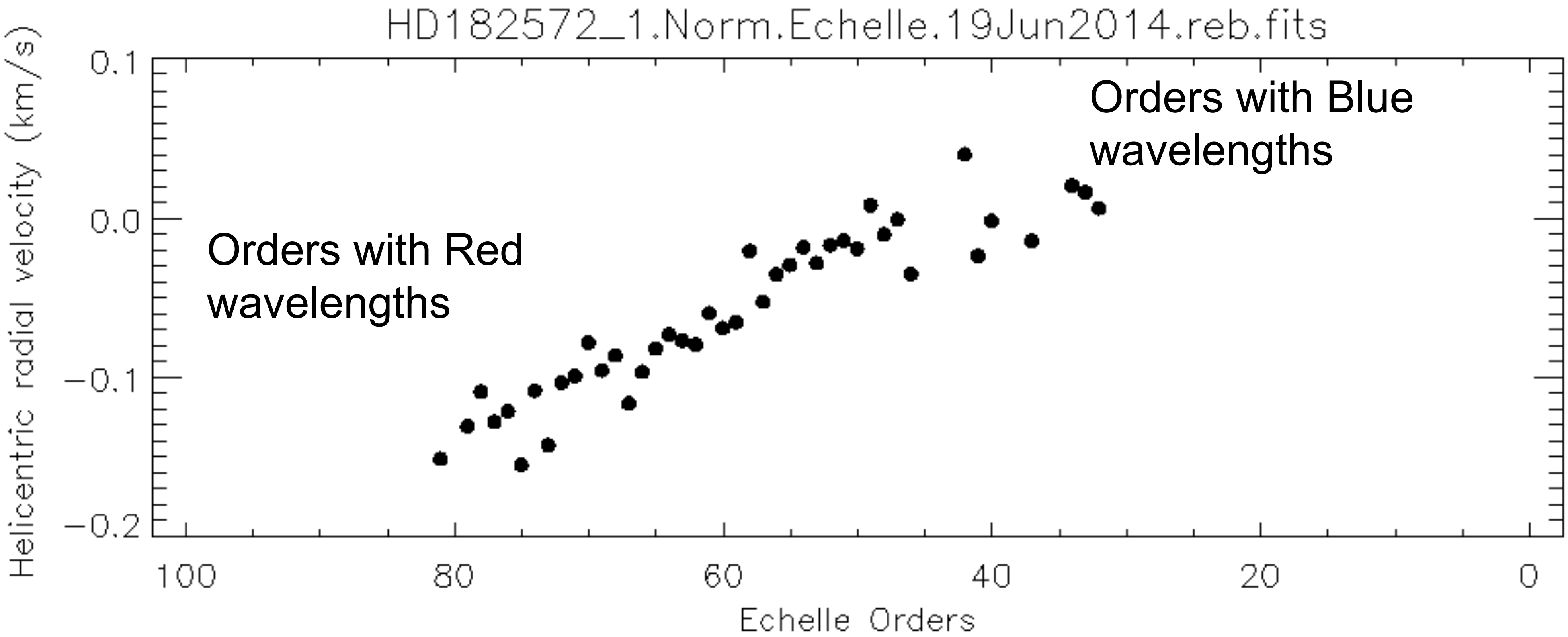
1. Guide Errors: Atmospheric Dispersion

Atmosphere disperses the image



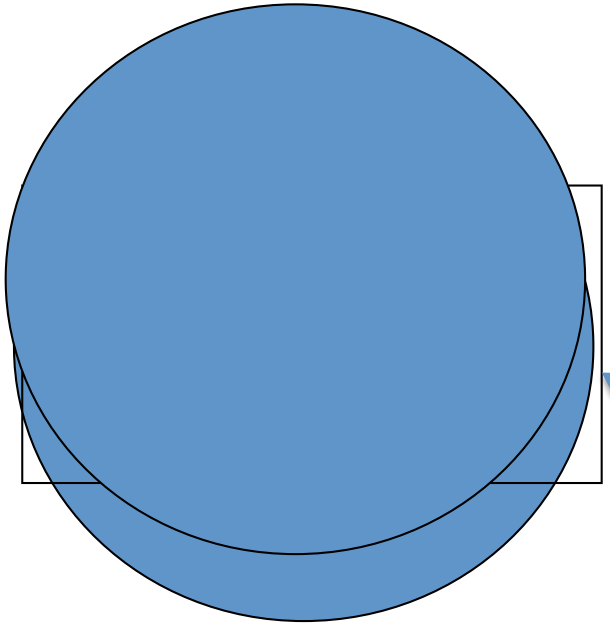
Atmosphere produces a dispersed image of the star (several stellar images of different colors). Some images will not fall properly on the fibre (in this case) or slit

Wavelength as a function of spectral orders



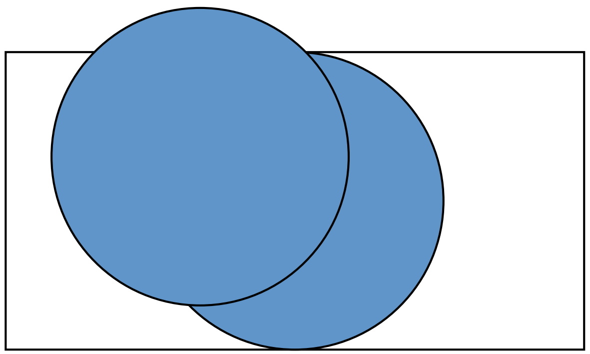
From Davide Gandolfi

Tricks to minimize guide errors: masking



Insensitive to guide errors and image motion

Grating

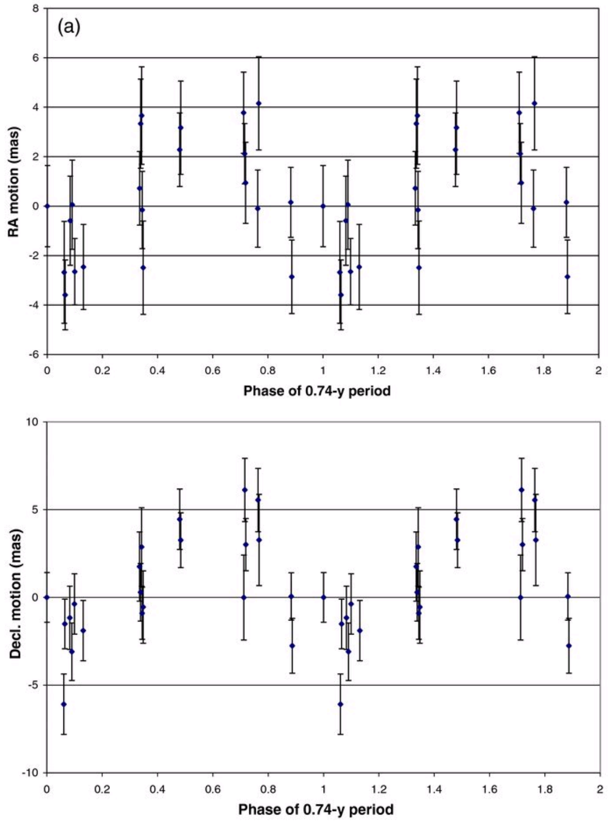


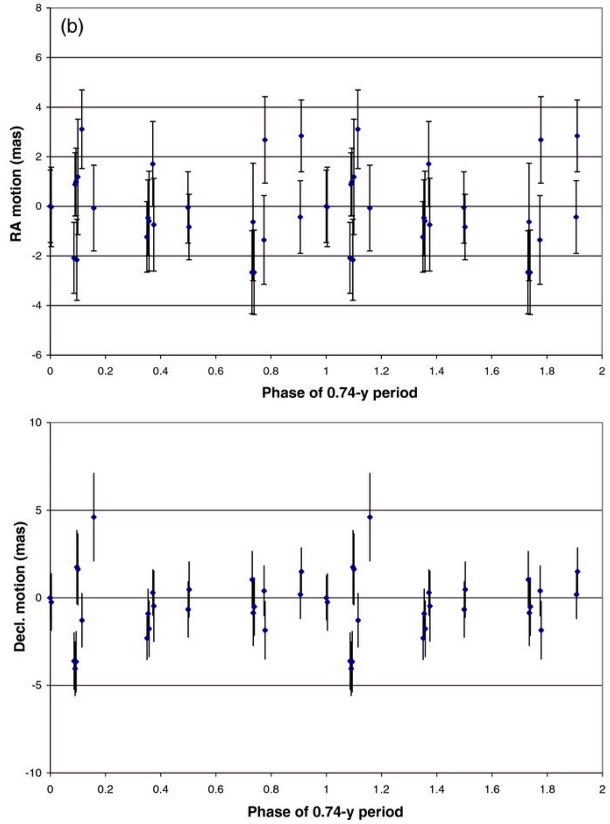
Sensitive to guide errors and image motion. Can be reduced by masking the echelle

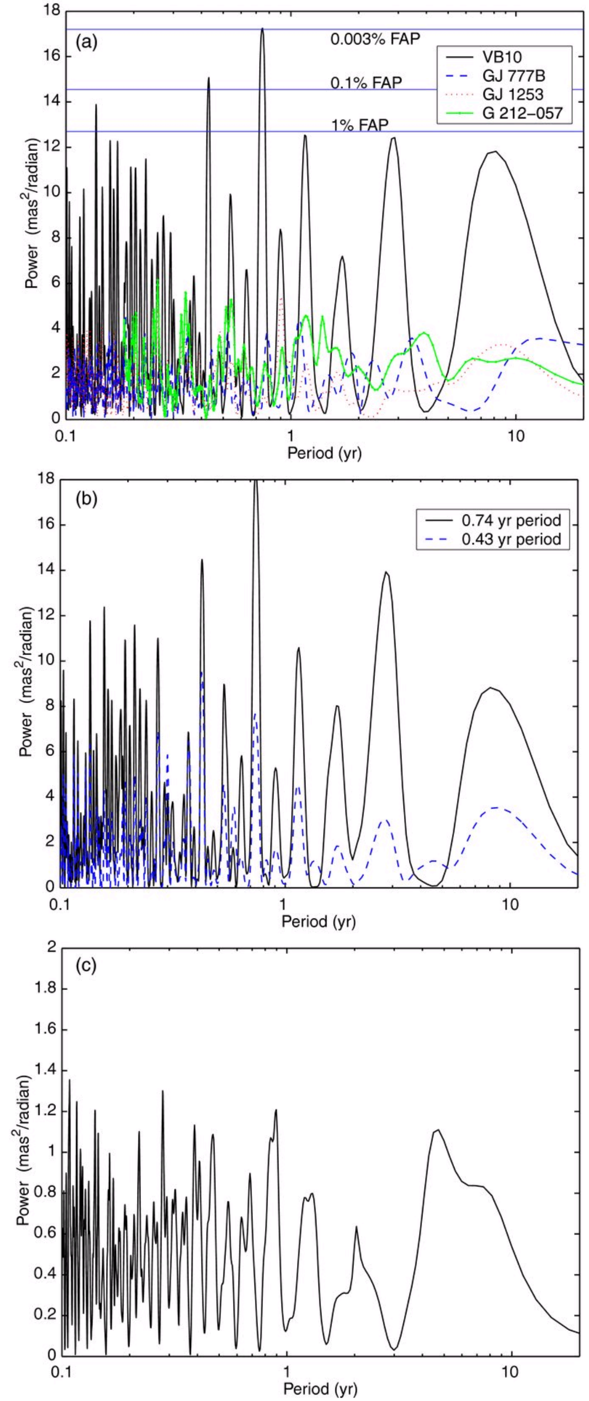
2: Changing Set-up

Vb 10

Control star







Period =0.74 years

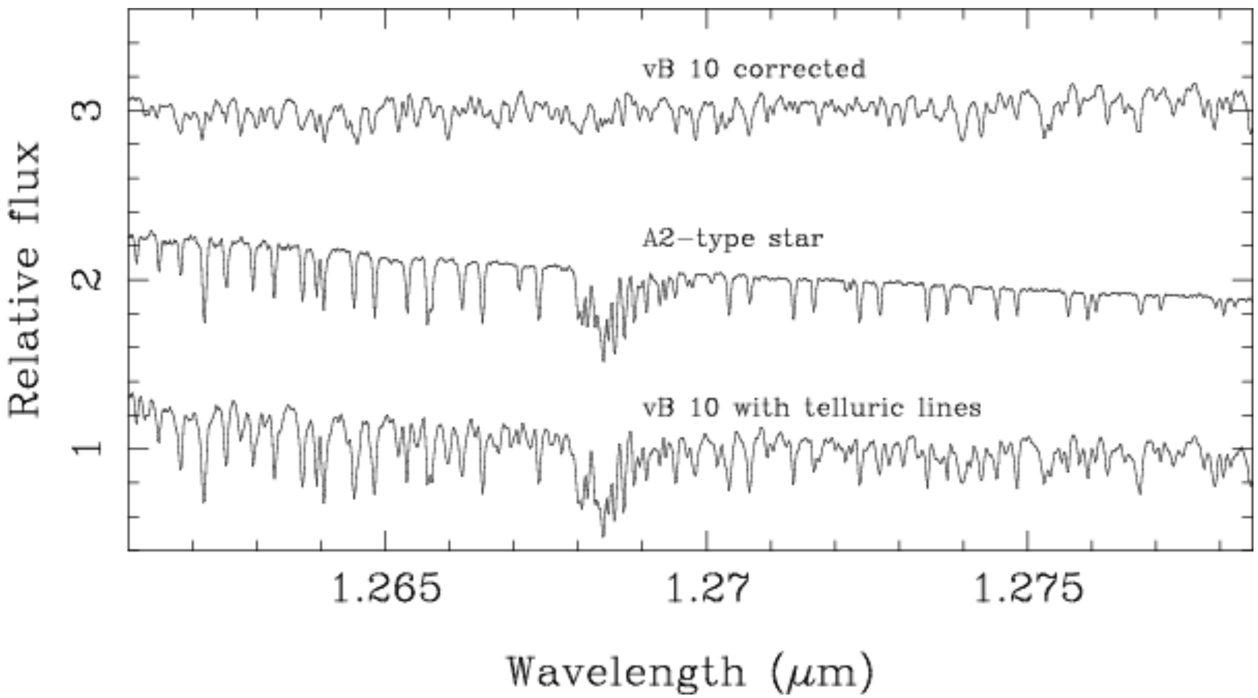
A&A 505, L5–L8 (2009)
DOI: 10.1051/0004-6361/200912869

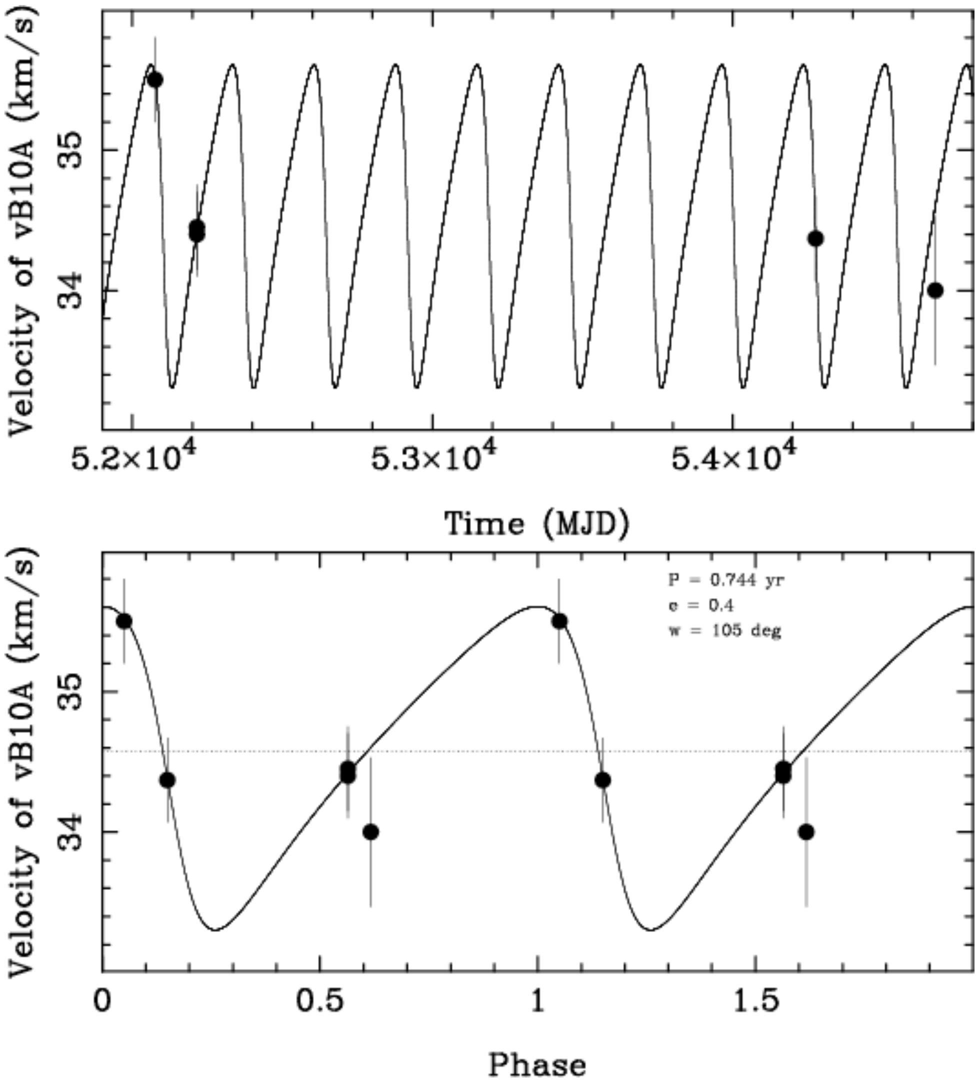
Astronomy & Astrophysics

Letter to the Editor

Infrared radial velocities of vB 10★

M. R. Zapatero Osorio[1,2], E. L. Martín[1,2,3], C. del Burgo[4], R. Deshpande[3], F. Rodler[5], and M. M. Montgomery[3]



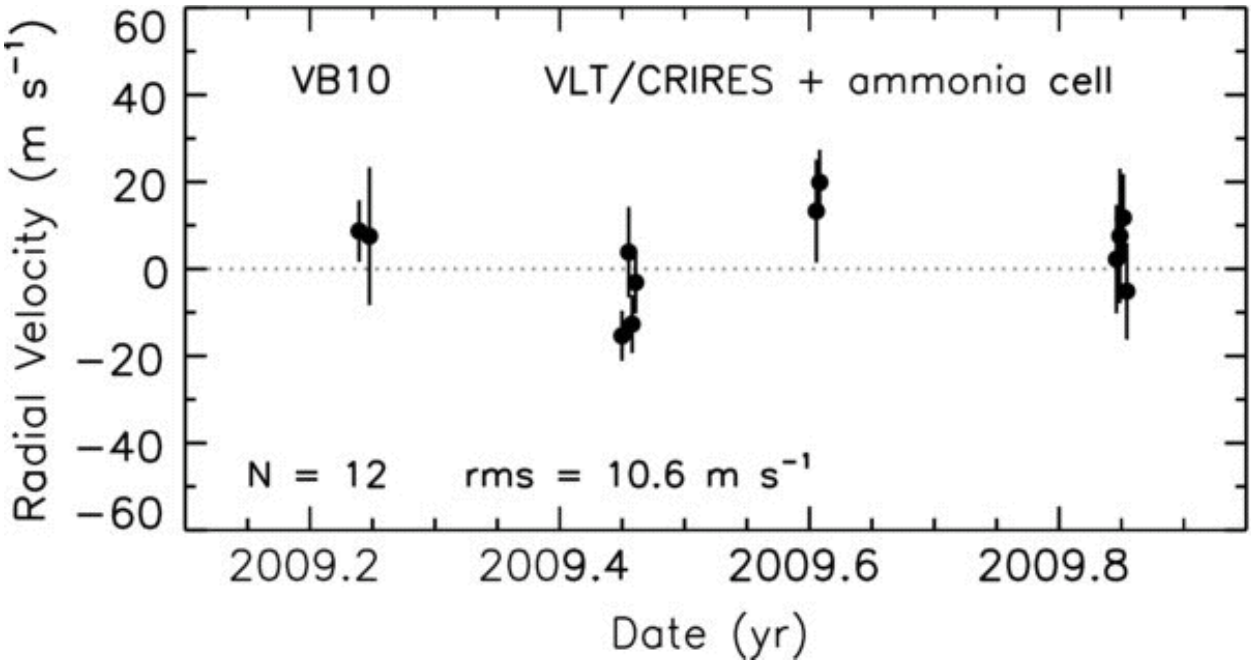


The "confirmation" of the first planet discovered via astrometry

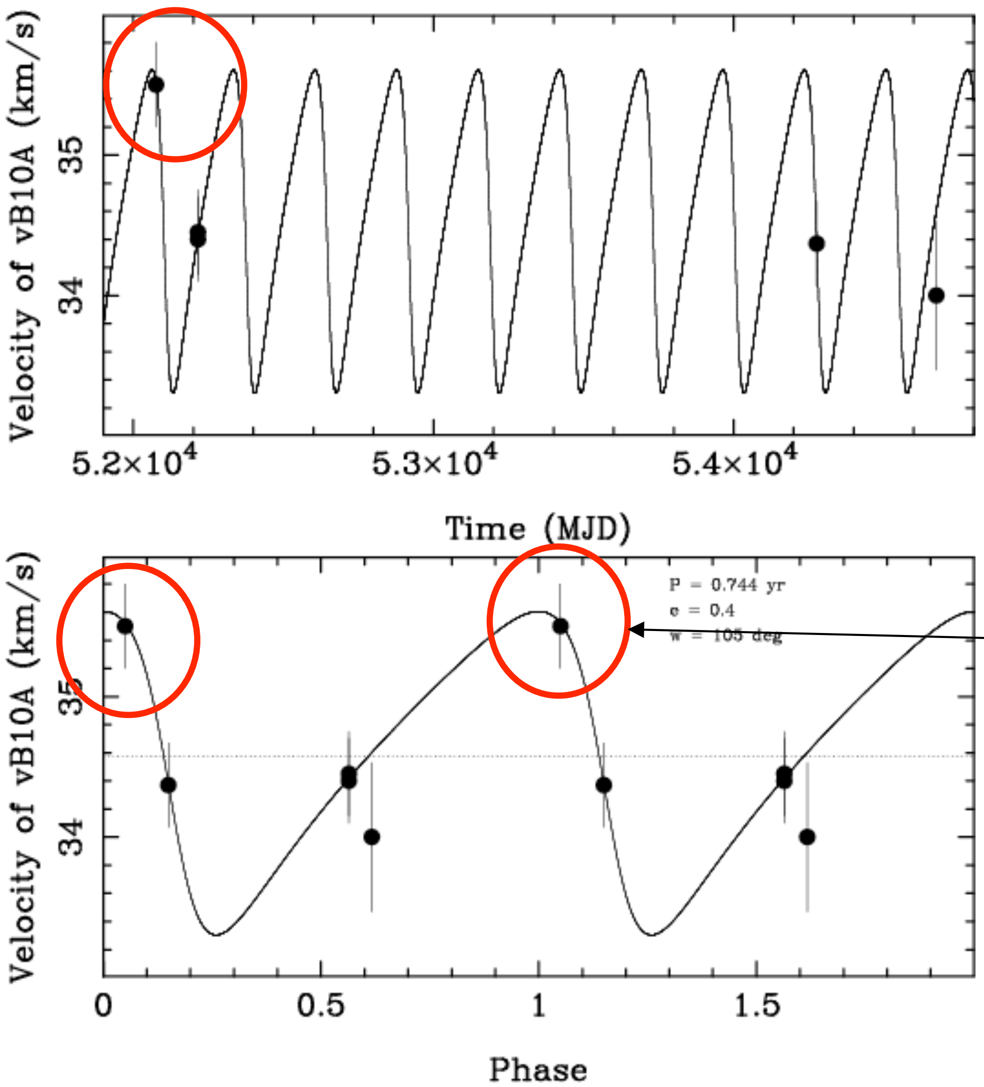
THE ASTROPHYSICAL JOURNAL LETTERS, 711:L19–L23, 2010 March 1
doi:10.1088/2041-8205/711/1/L19

THE PROPOSED GIANT PLANET ORBITING VB 10 DOES NOT EXIST*

JACOB L. BEAN[1,6], ANDREAS SEIFAHRT[1,2], HENRIK HARTMAN[3], HAMPUS NILSSON[3], ANSGAR REINERS[1,7], STEFAN DREIZLER[1], TODD J. HENRY[4], AND GÜNTER WIEDEMANN[5]



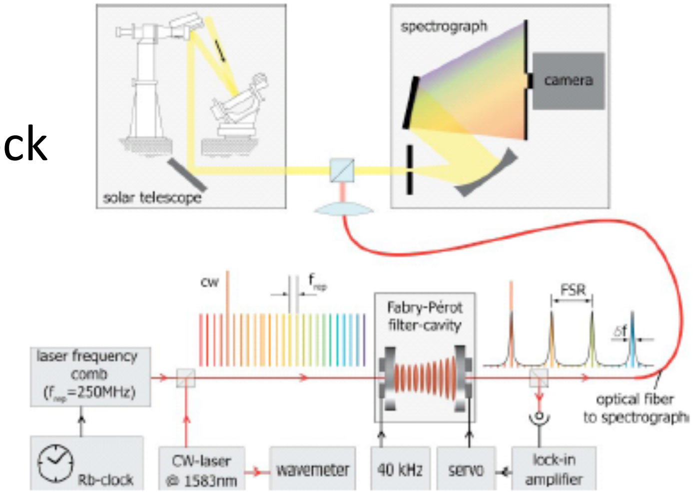
Is there something different about the first point?

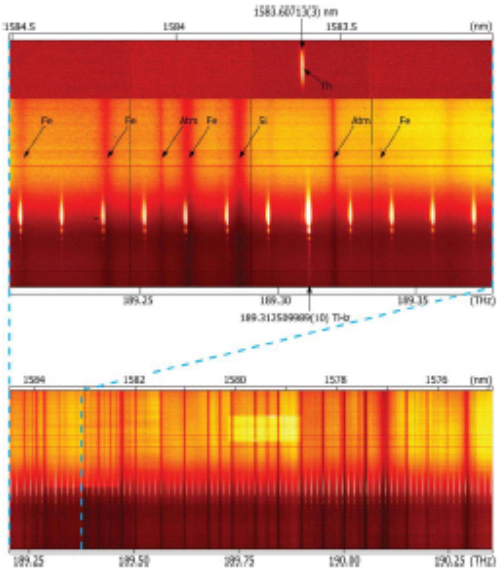


Taken with a different slit width!

3. Improved Wavelength Reference

- Laser Frequency Combs
  - Provides a series of perfectly equidistant lines
  - Covers a large wavelength domain
  - Stabilized at the 10^{-11} to 10^{-15} level
  - The absolute reference linked to an atomic clock

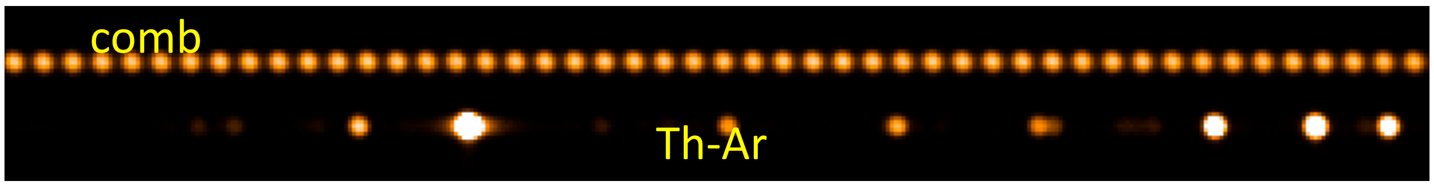




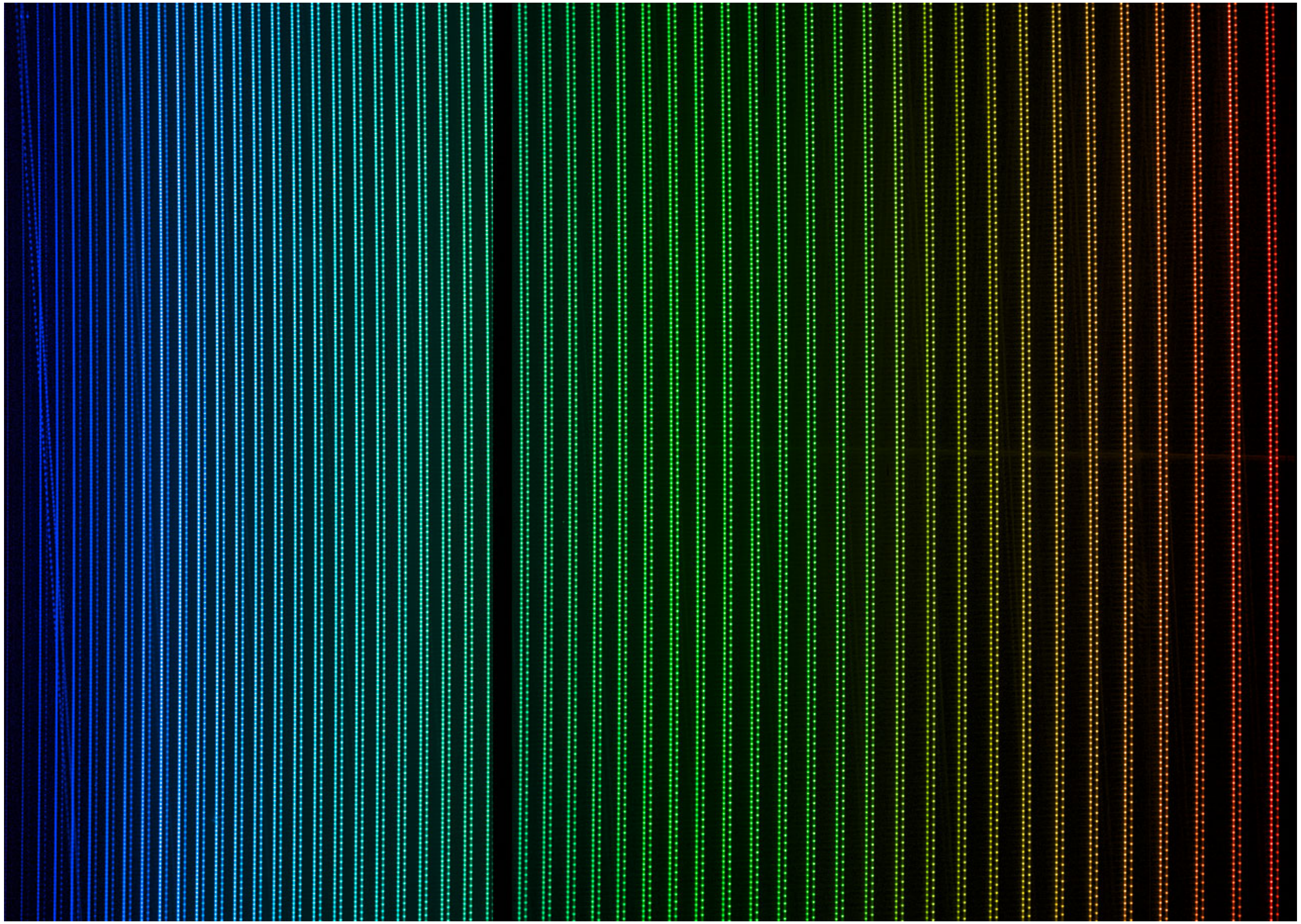
System has been developed and test in HARPS shows excellent performances:

Astro-comb: ~450 lines per order
5cm/sec PHOTON NOISE LIMITED stability in short term

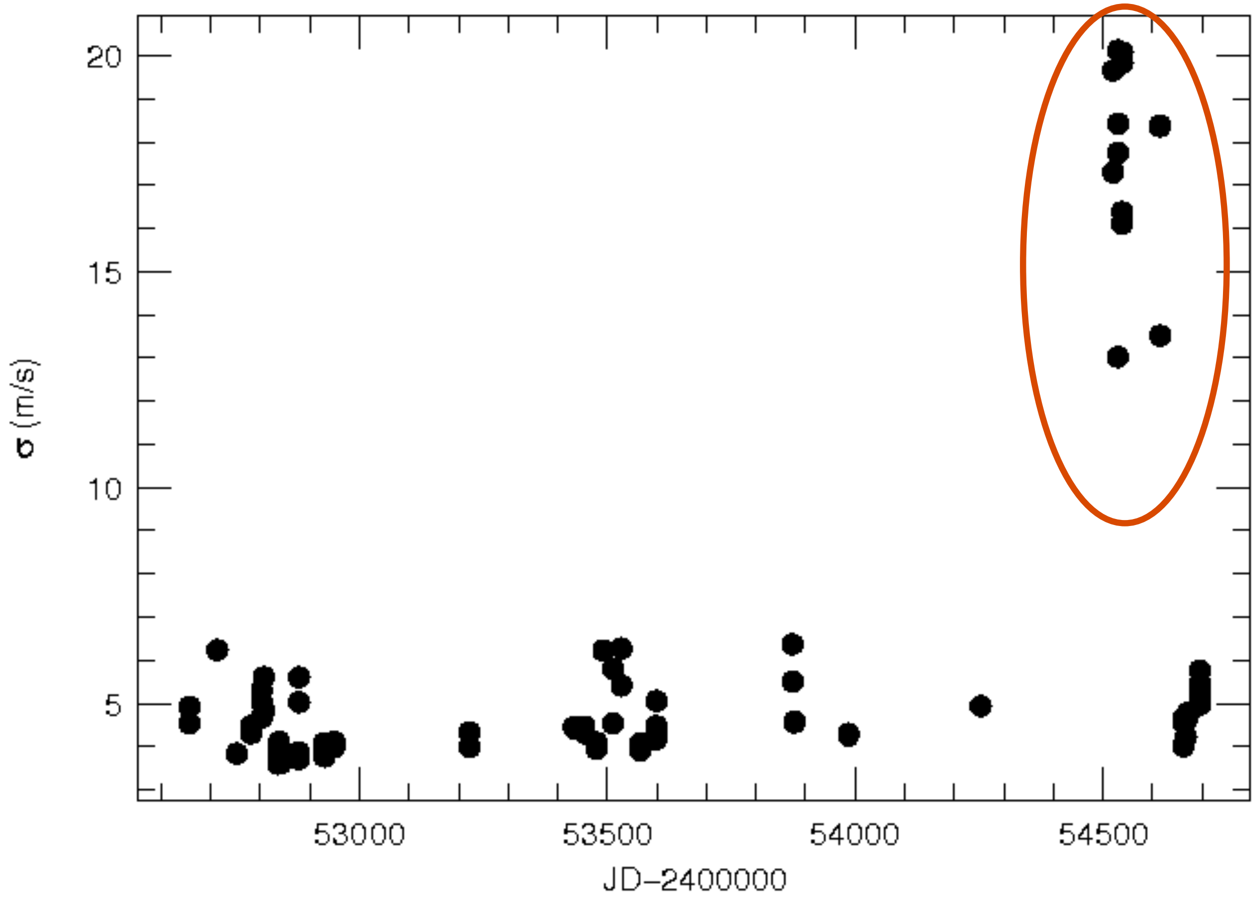
Th-Ar: ~150 lines per order
24cm/sec



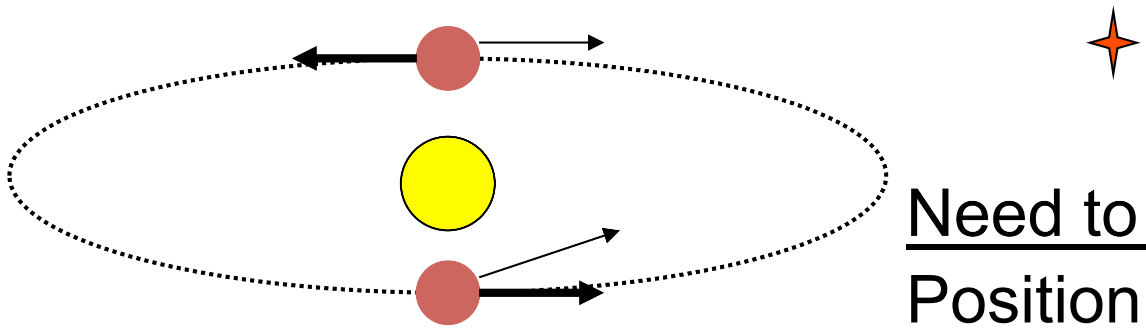
Laser frequency comb installed on HARPS



5. Stable Detectors!



6. Barycentric Correction



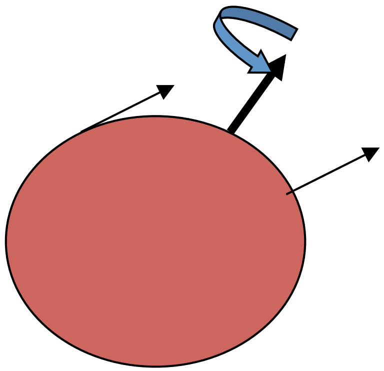
Earth’s orbital motion can contribute ± 30 km/s (maximum)

<u>Need to know:</u>

Position of star

Earth‘s orbit

Exact time



Earth’s rotation can contribute ± 460 m/s (maximum)

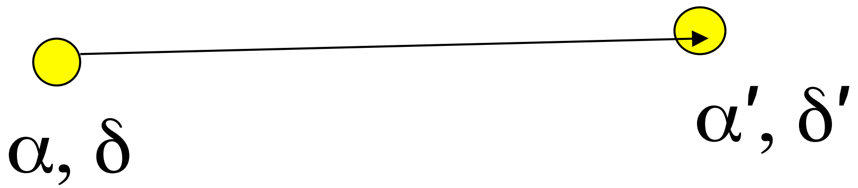
<u>Need to know:</u>

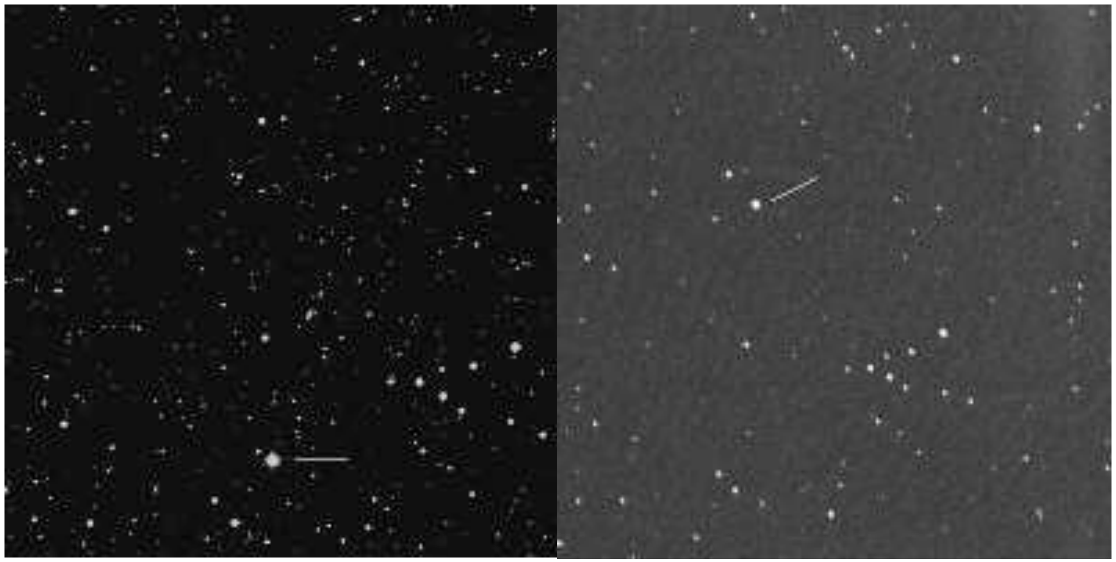
Latitude and longitude of observatory

Height above sea level

Needed for Correct Barycentric Corrections:

- Accurate coordinates of observatory
- Distance of observatory to Earth‘s center (altitude)
- Accurate position of stars, including proper motion:

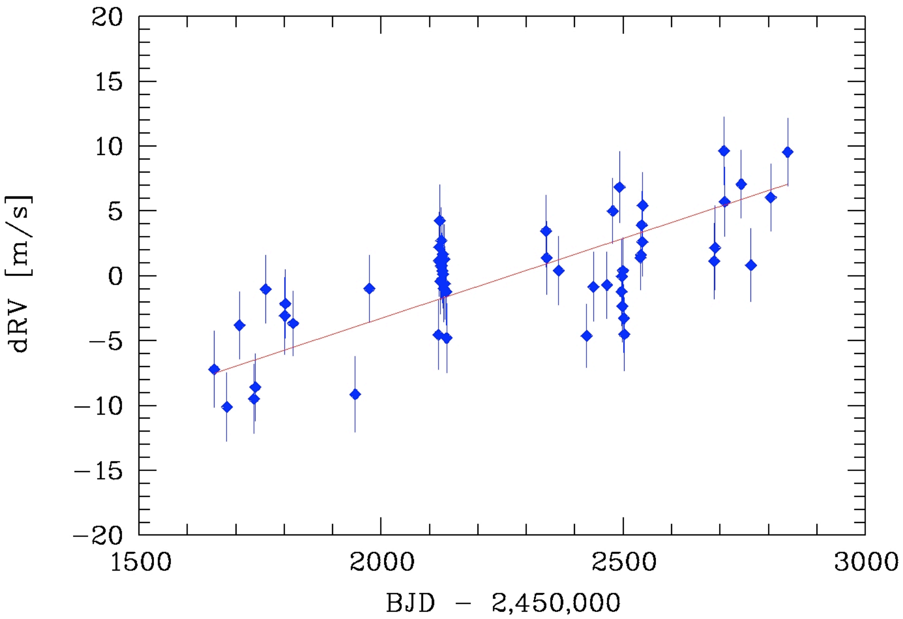


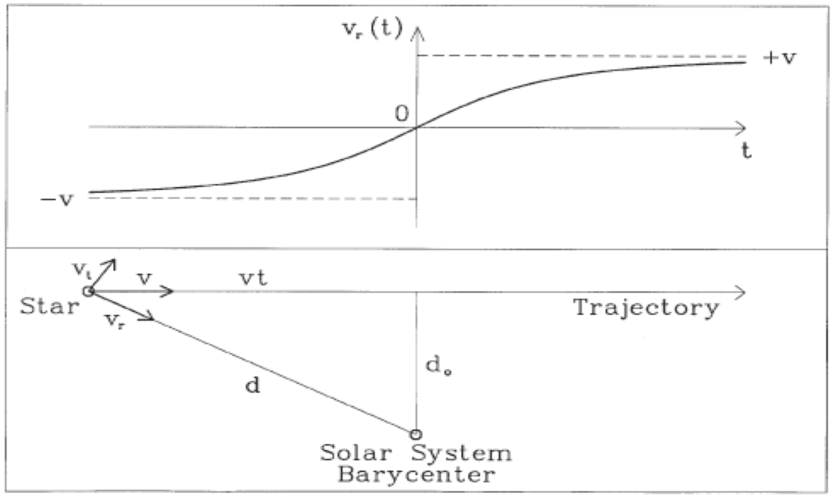


Worst case Scenario: Barnard‘s star

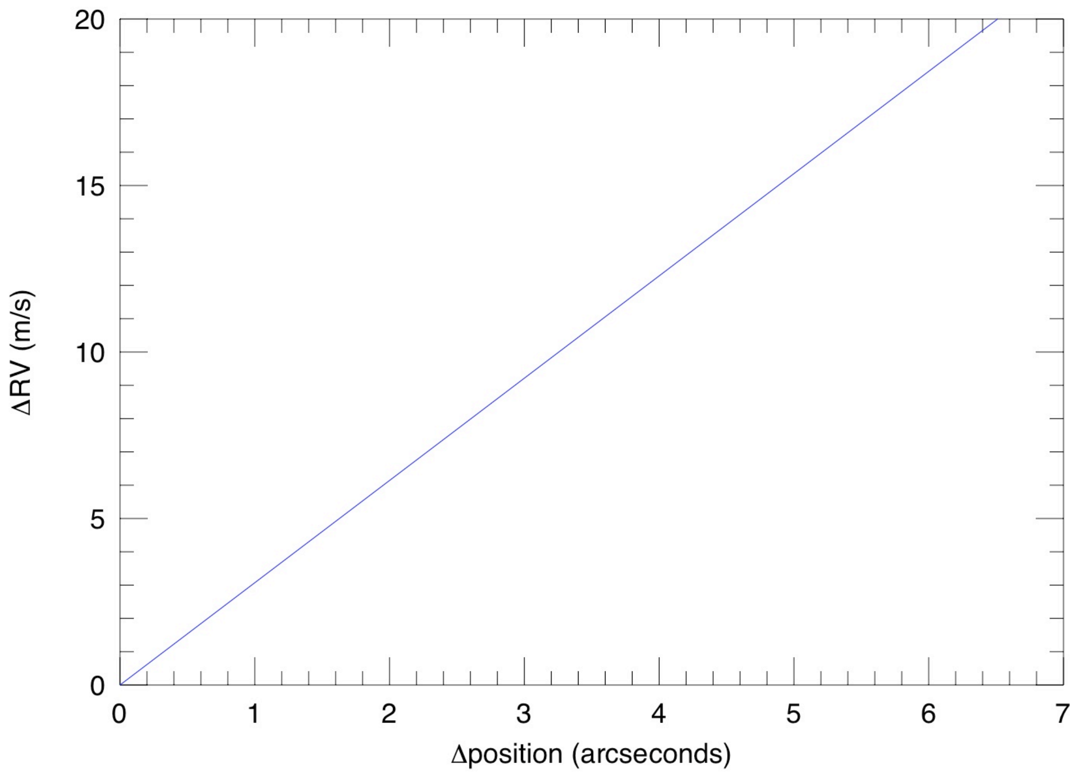
Most programs use the JPL Ephemeris which provides barycentric corrections to a few cm/s

The Secular Acceleration of Barnard's Star (Kürster et al. 2003).



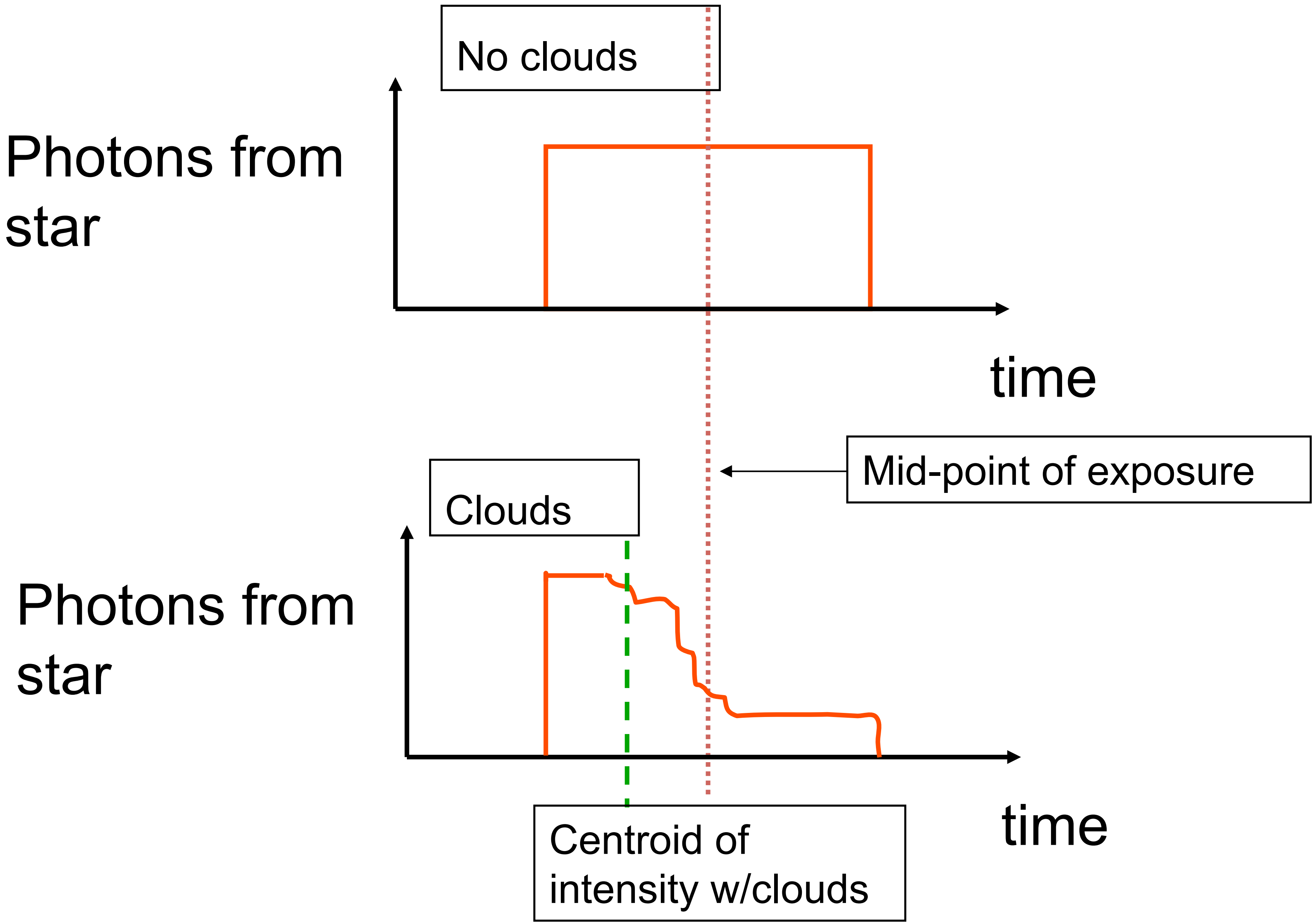


Error due to wrong coordinates

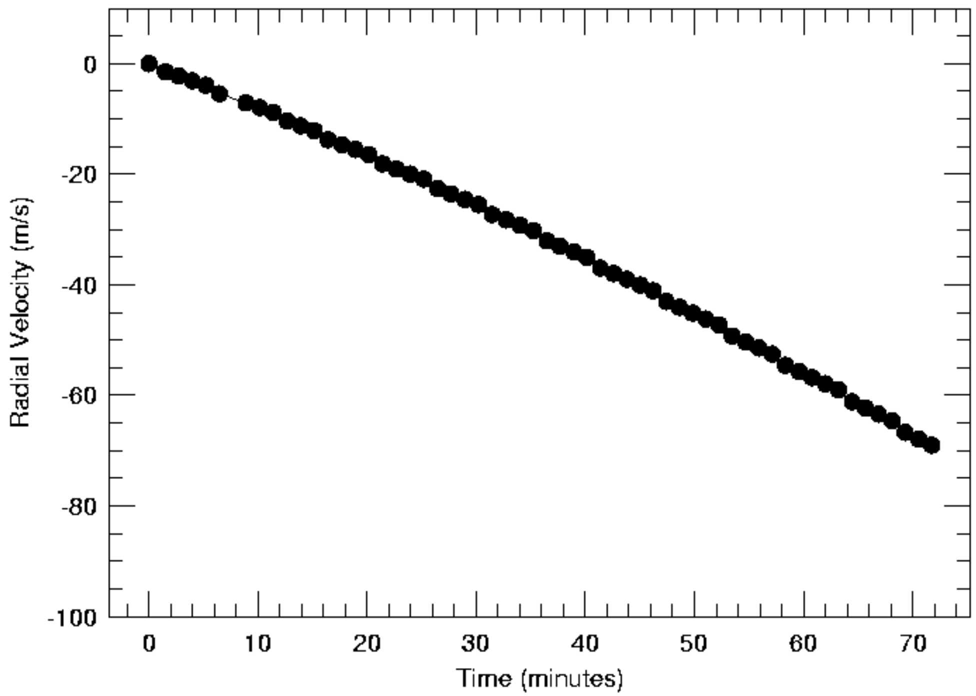


To get an error less than 10 cm/s (Earth at 1 AU) you need to know the position of the star to within 3 milliarcsecs in RA and Dec AND proper motion

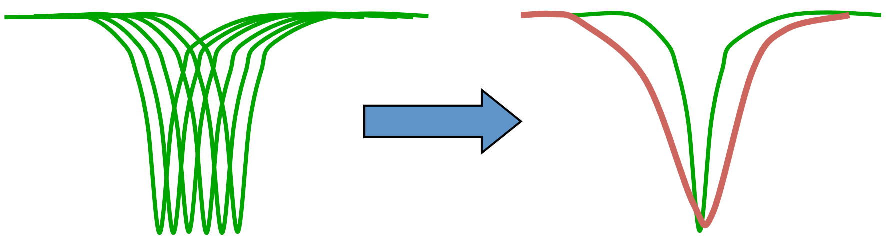
For highest precision an exposure meter is required



Differential Earth Velocity:



Causes „smearing“ of spectral lines

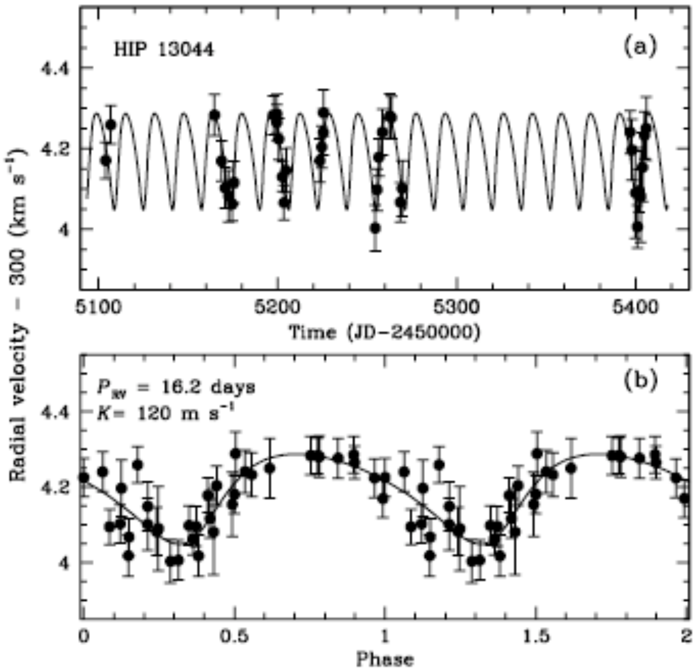


Keep exposure times < 20-30 min

Footnote: Don't put too much faith in pipeline reduction programs!

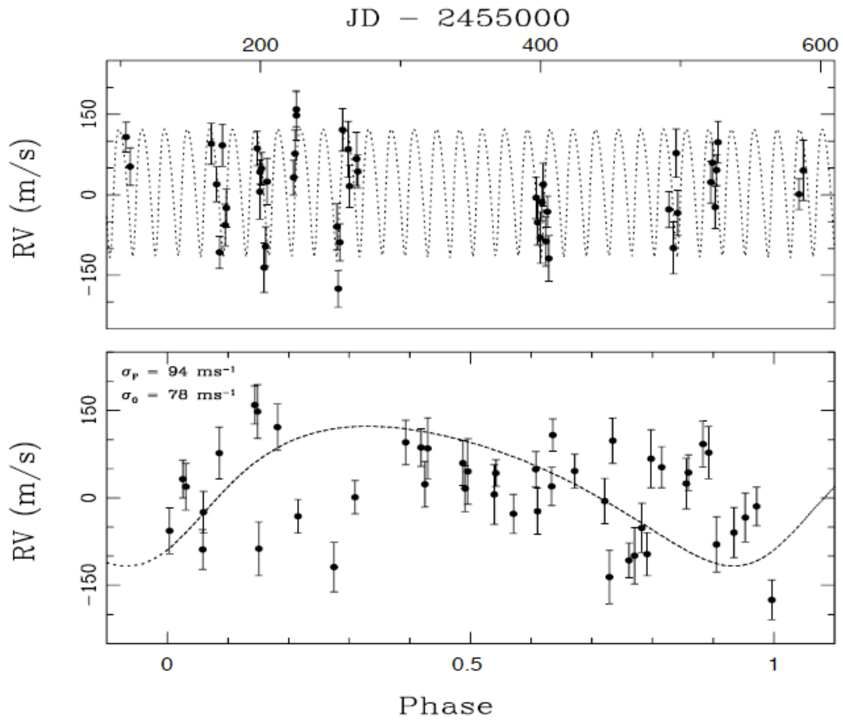
A Giant Planet Around a Metal-poor Star of Extragalactic Origin

Johny Setiawan[1], Rainer J. Klement[1], Thomas Henning[1], Hans-Walter Rix[1], Boyke Rochau[1], Jens Rodmann[2], Tim Schulze-Hartung[1]



No evidence of the planet orbiting the extremely metal-poor extragalactic star HIP13044.*

M. I. Jones[1,2] and J. S. Jenkins[2]



5. Intrinsic Stellar Variability

or

What really limits your RV accuracy

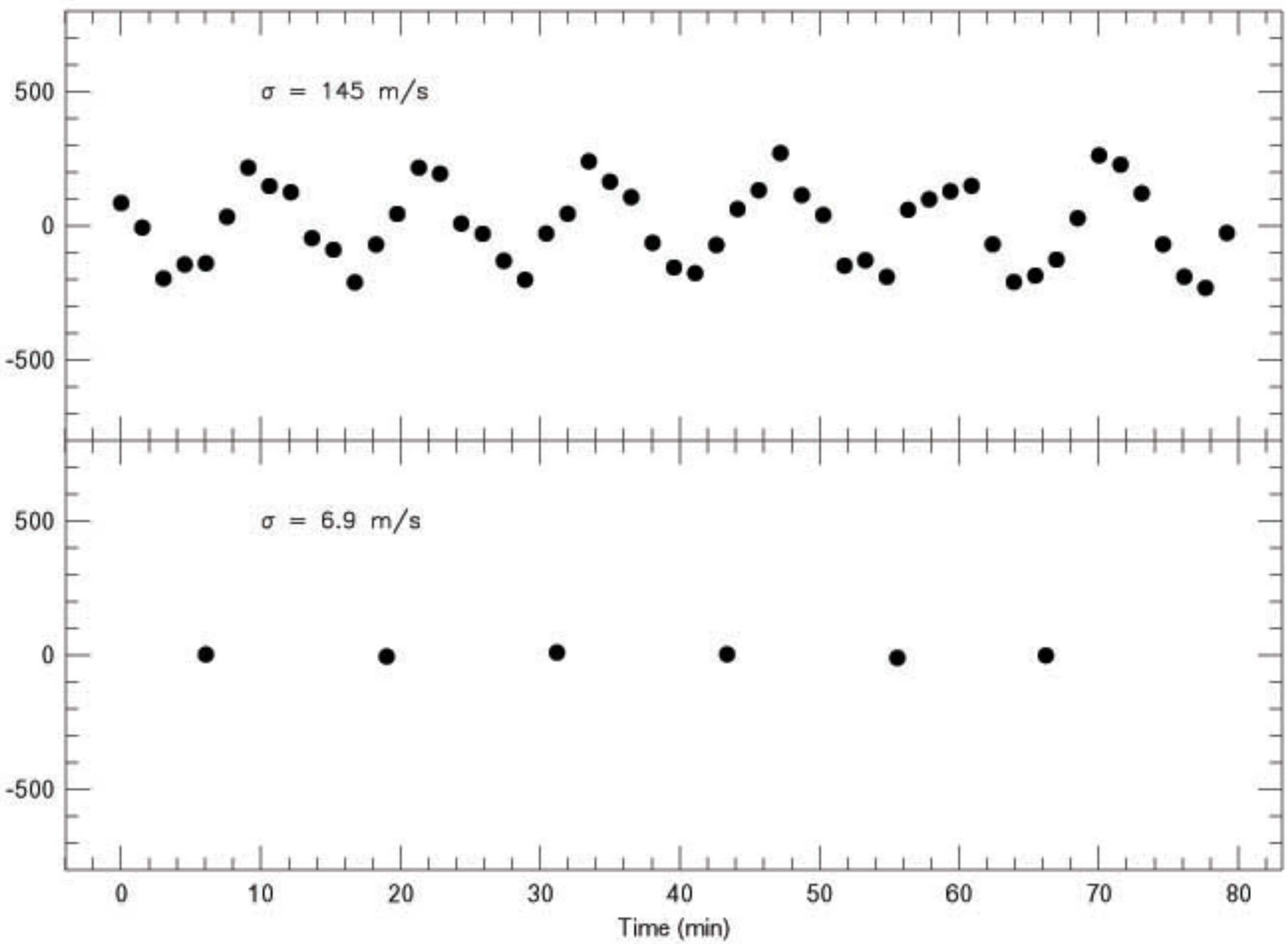
Major sources of intrinisic noise in solar-like stars

Phenomenon	Timescales	Amp. (m/s)
Oscillations	5-10 min	0.3-0.5
Spots/Activity	**4-50 days**	**1-100**
Convection	**0.1-20 yrs**	**~10**

No matter how advanced or stable your spectrometer is, the ultimate RV precision will be limited by intrinsic stellar variability.

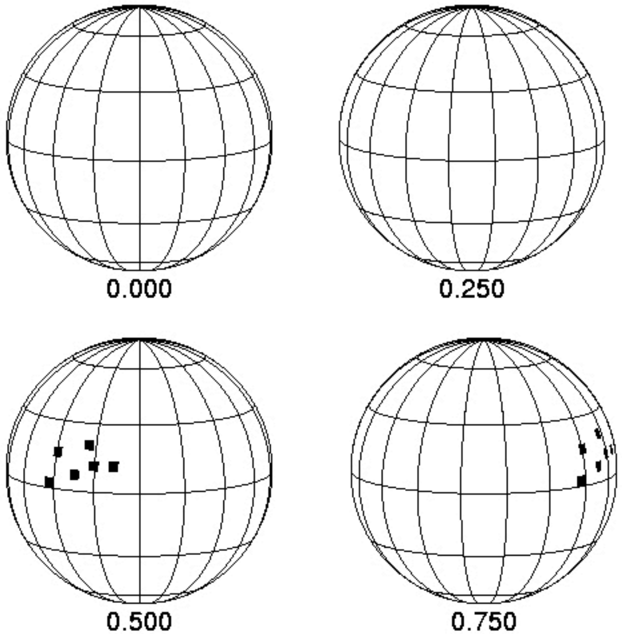
„Quietest“ stars may be constant to no better than 0.5 – 1 m/s

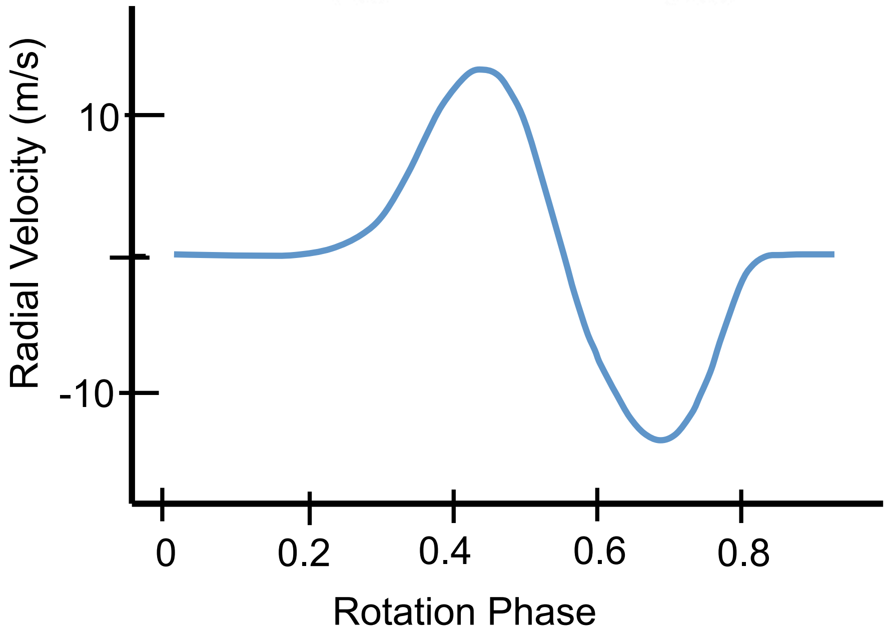
Stellar Oscillations are not a problem

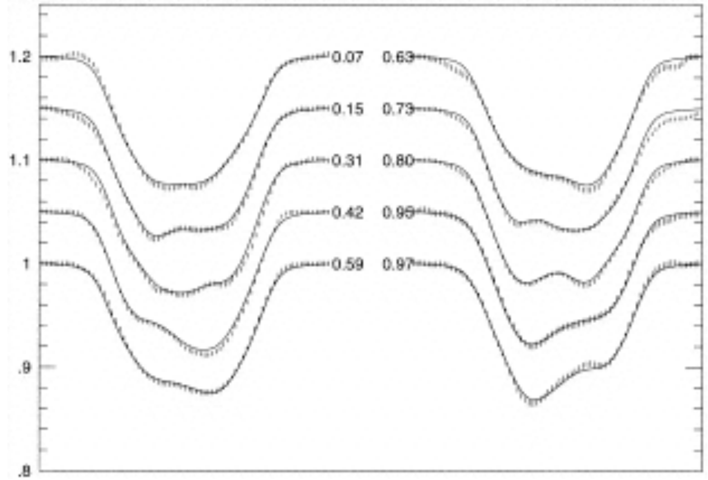


A rapidly oscillation Ap star with P = 11 min

Radial Velocity Variations from Starspots

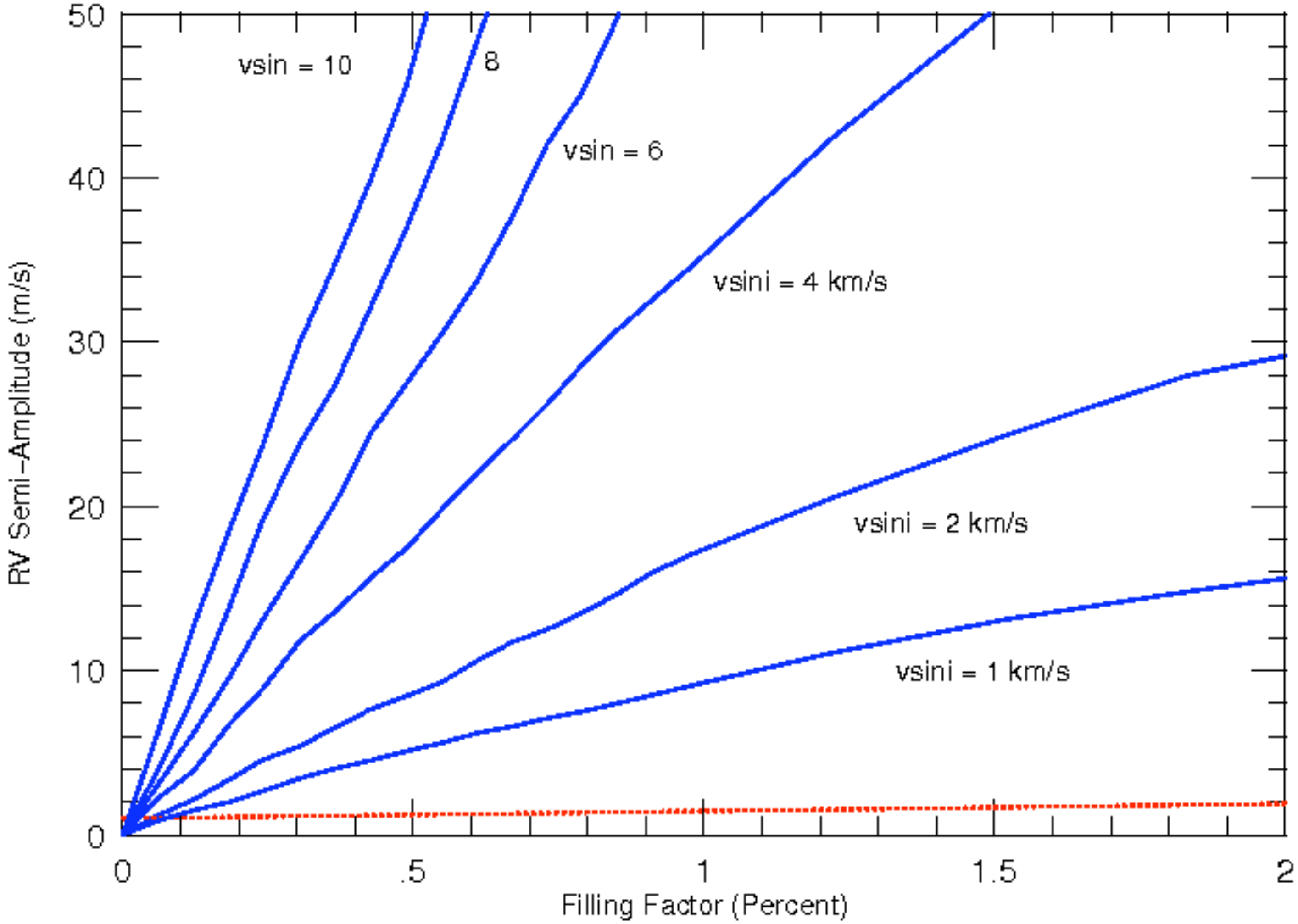




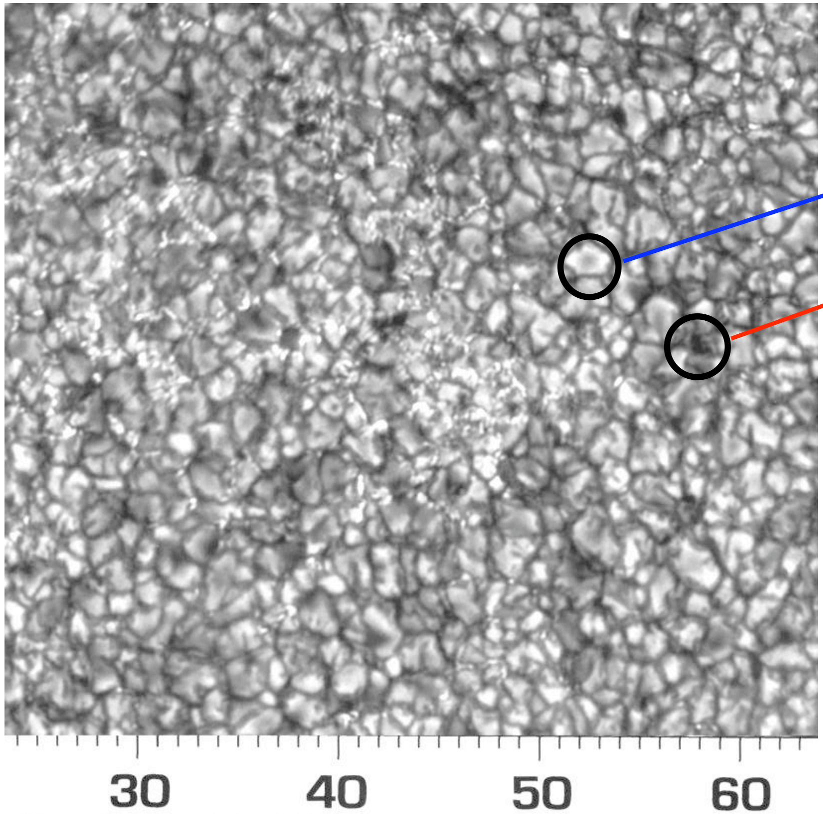


Spectral line distortions in an active star that is rotating rapidly

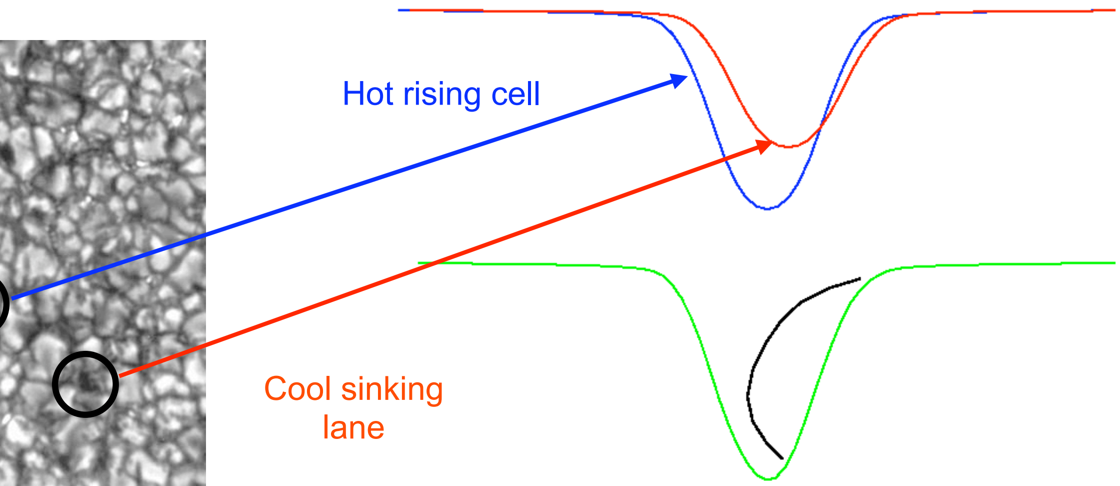
Spots are a problem



So is convection



Photospheric granulation, G. Scharmer
Swedish Vacuum Solar Telescope
10 July 1997



- The integrated line profile is distorted.
- The ratio of dark lane to hot cell areas changes with the solar cycle

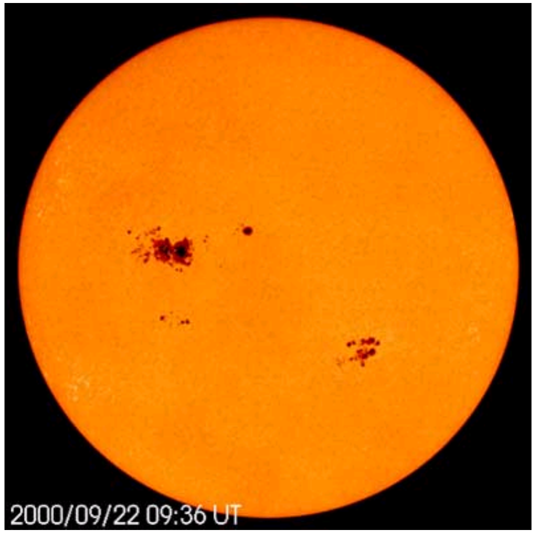
RV changes can be as large as 10 m/s with an 11 year period

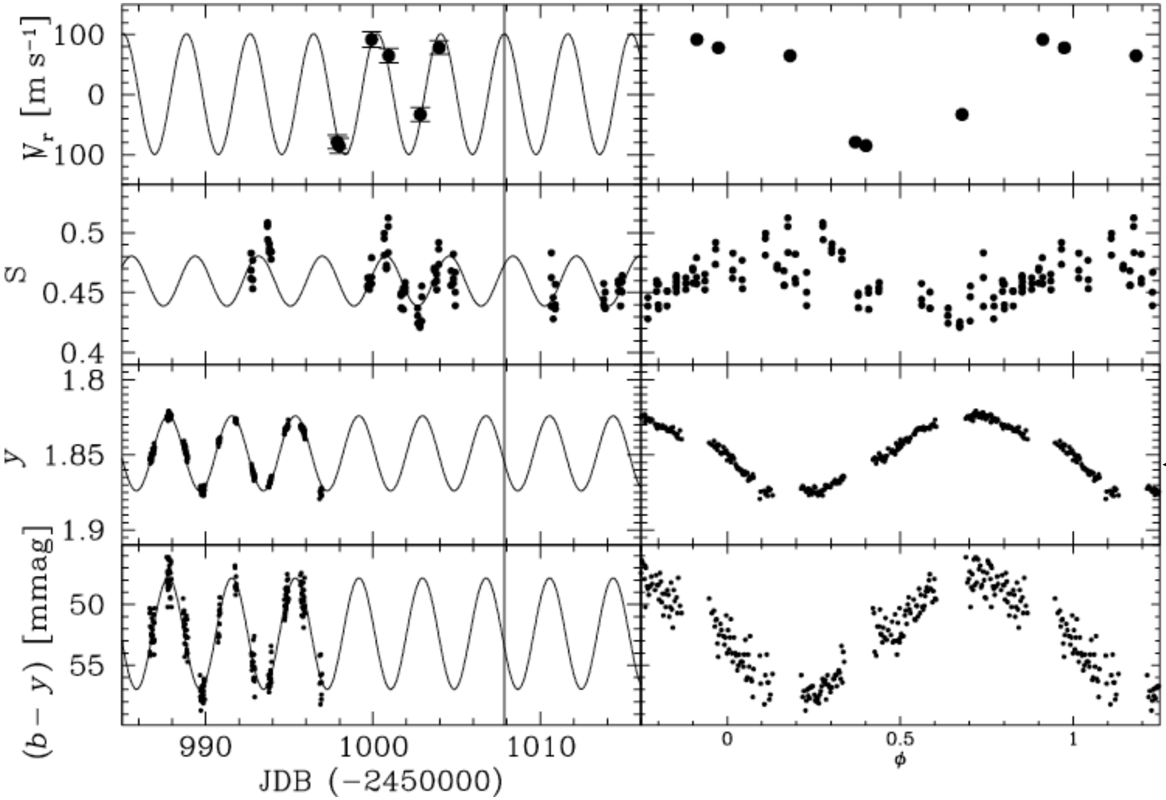
➡ This is a Jupiter!

One has to worry even about the nature of long period RV variations

Tools for confirming planets: Photometry

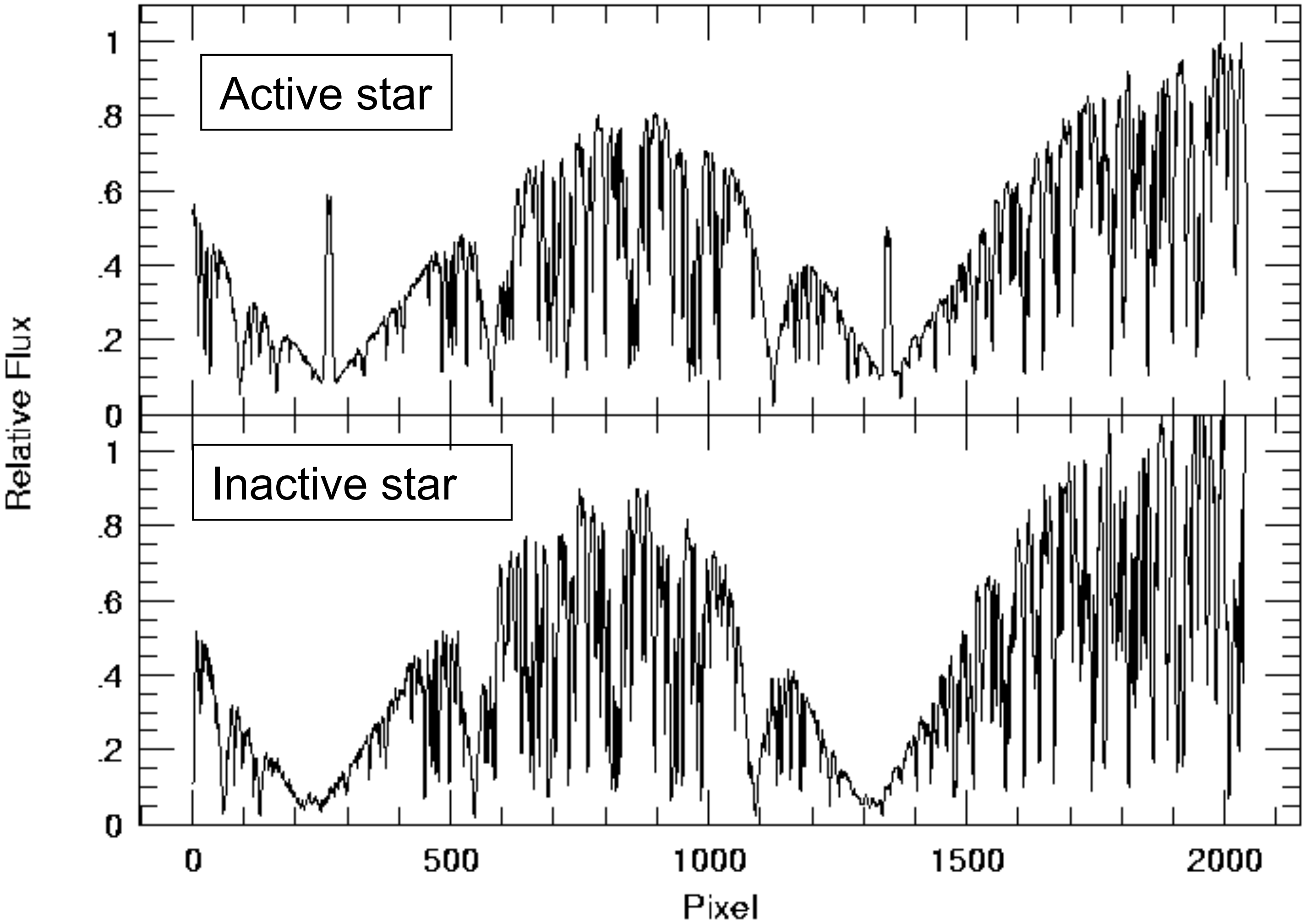
Starspots are much cooler than the photosphere





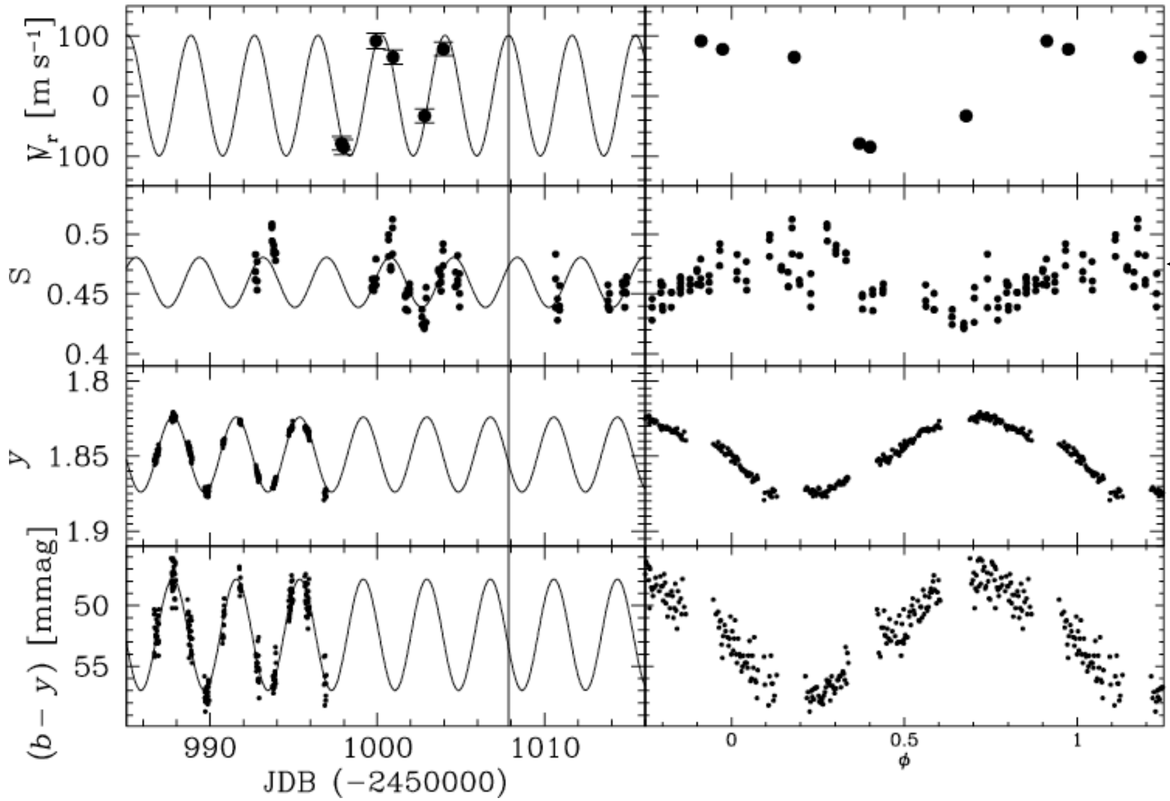
Relatively easy to measure

Tools for confirming planets: Ca II H&K



Ca II H & K core emission is a measure of magnetic activity also the Hydrogen Hα Balmer line:

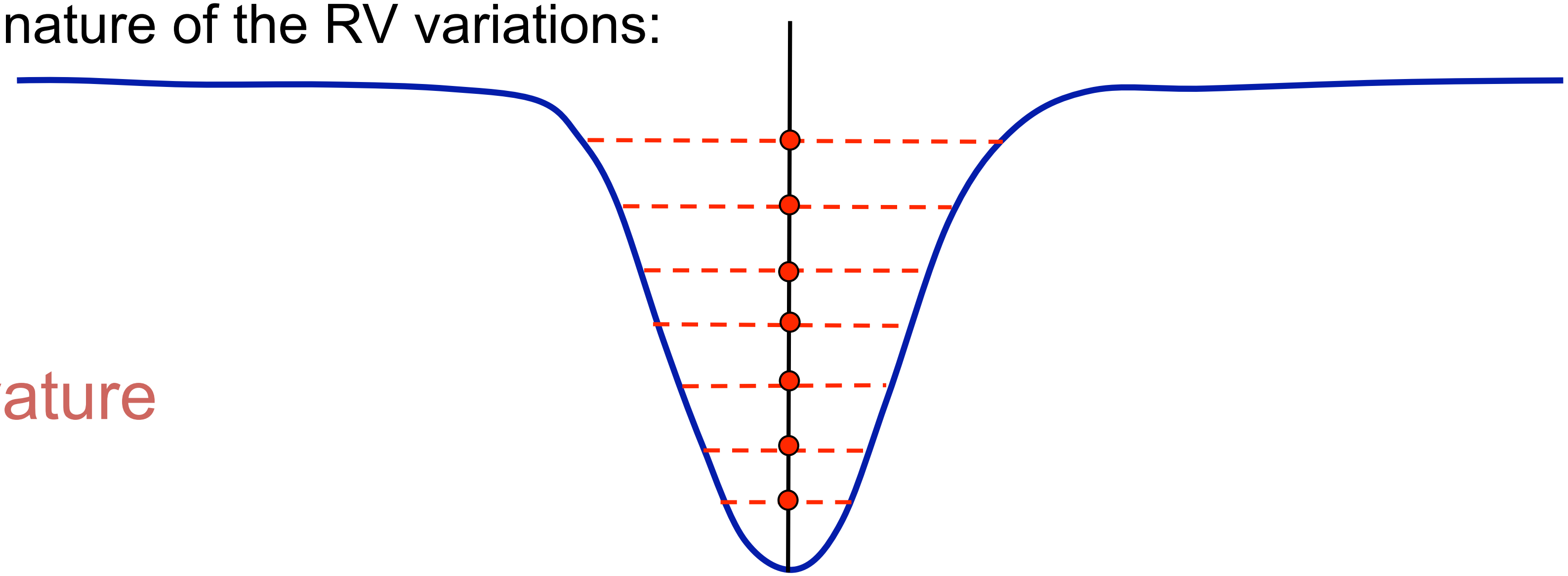
HD 166435

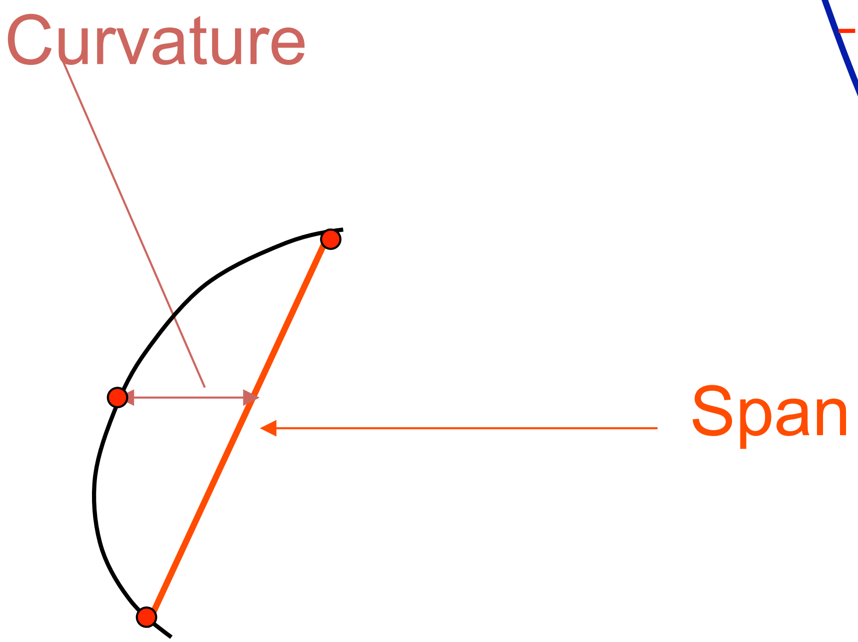


Ca II emission measurements

Tools for confirming planets: Bisectors

Bisectors can measure the line shapes and tell you about the nature of the RV variations:

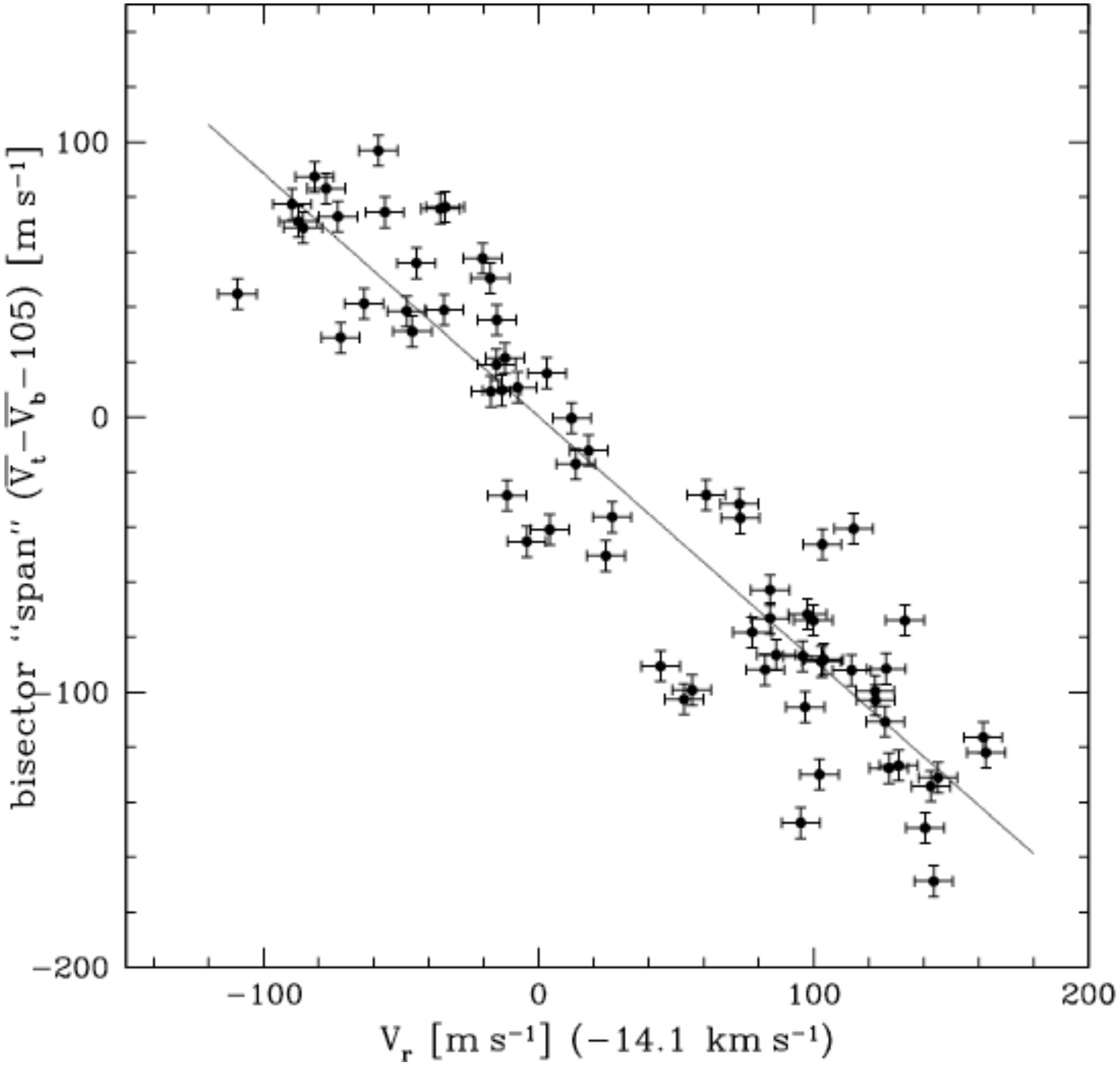




What can change bisectors:

- Spots
- Pulsations
- Convection pattern on star

Spots produce an „anti-correlation“ of Bisector Span versus RV variations:

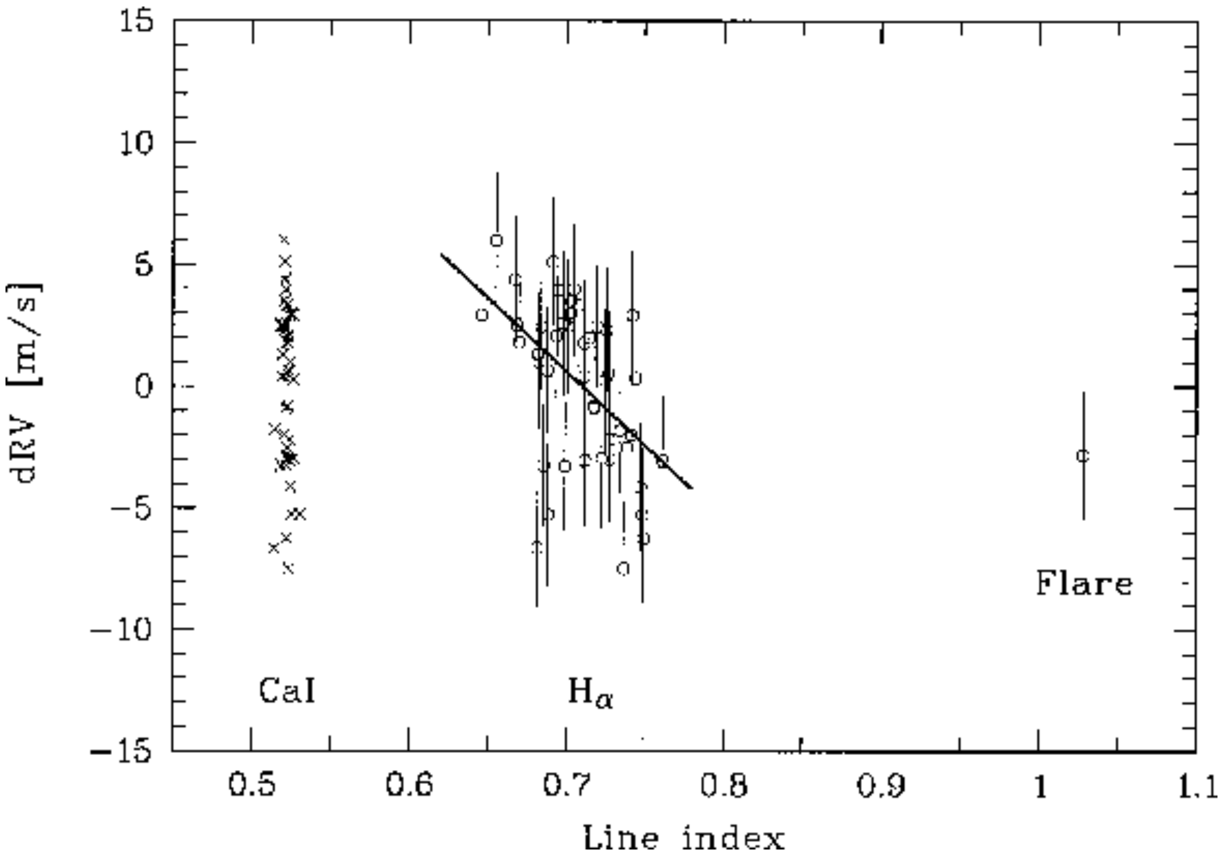


Correlation of bisector span with radial velocity for HD 166435

Tools for confirming planets: Hα

Barnard's star (M2)

Kürster et al. 1997



RV variations with amplitude of 5 m/s and time scales ~30-60 days. Not a planet but changes in the convection pattern.

Convective Red/Blue Shifts also a Problem

Tools for confirming planets: IR Measurements

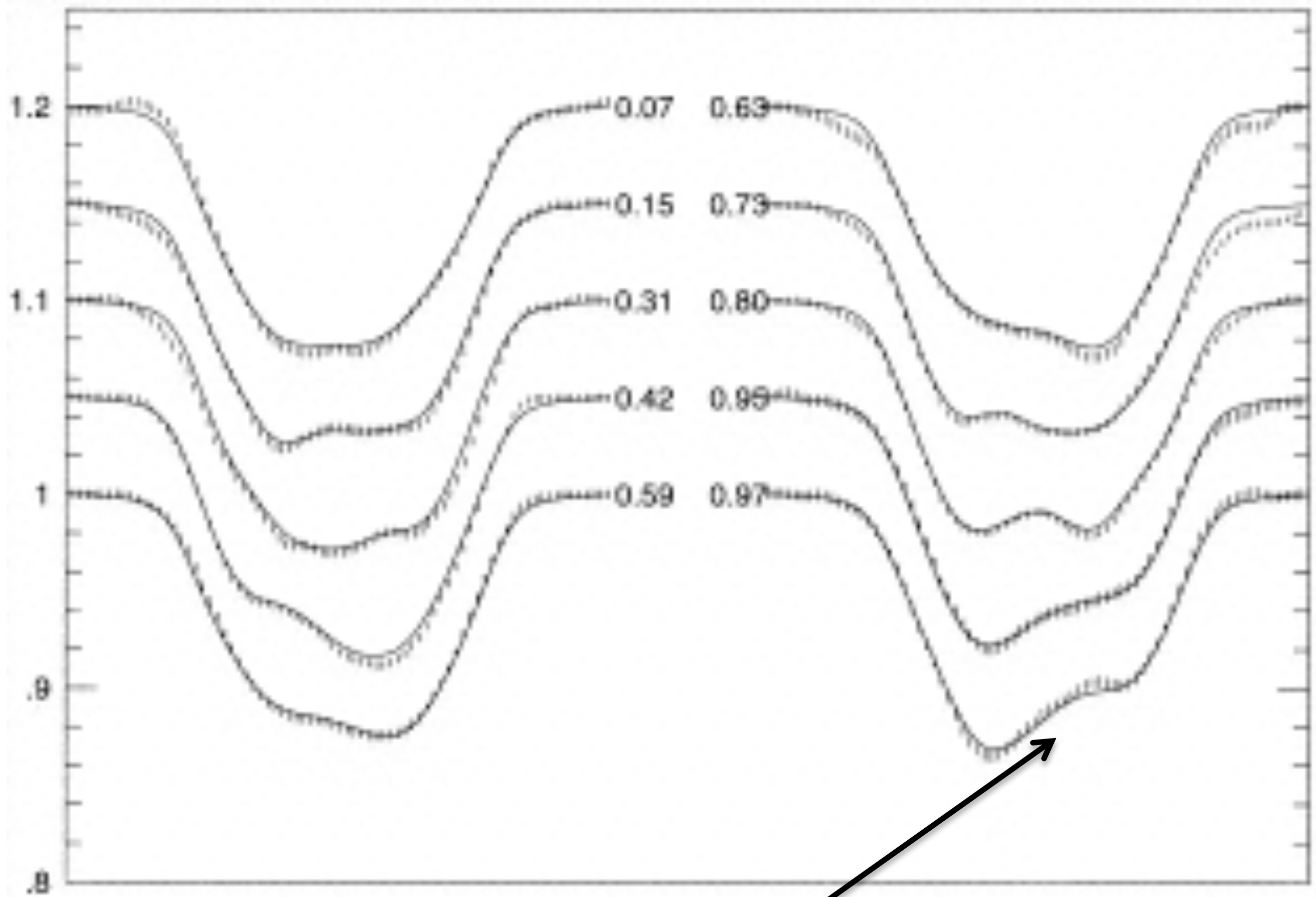
Flux from photosphere = $\dfrac{2\pi hc^2/\lambda^{-5}}{e^{hc/k\lambda T_p} - 1}$

$T_{Spot} = 3000$ K
$T_{phot} = 5500$ K

Flux from spot = $\dfrac{2\pi hc^2/\lambda^{-5}}{e^{hc/k\lambda T_s} - 1}$

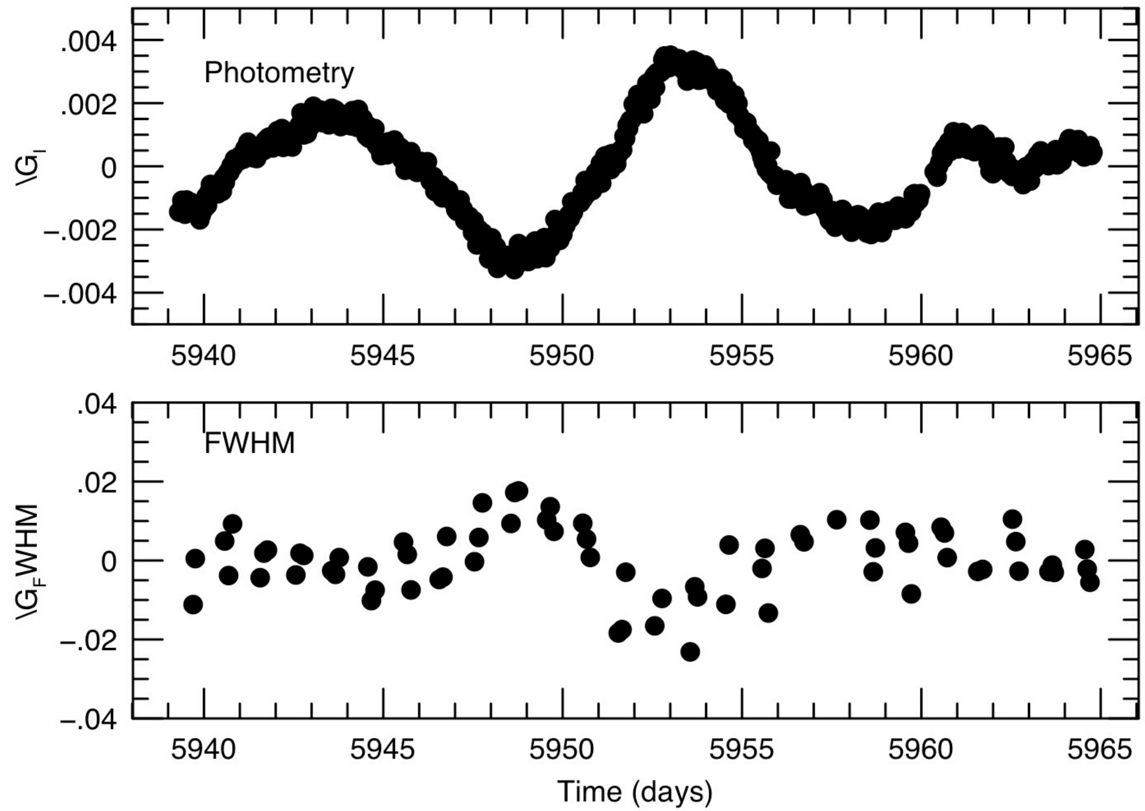
$F_s/F_p = \dfrac{e^{hc/k\lambda T_p} - 1}{e^{hc/k\lambda T_s} - 1}$

@5500 A $F_p/F_s = 53$
@1.5mm $F_p/F_s = 5$



Smaller contrast ratio means the distortions will not be as strong

Tools for confirming planets: FWHM of the CCF



RV max (+)
BVS min(-)
I Max
FWHM Max

RV zero
BVS zero
I Min
FWHM Max

RV min (-)
BVS max (+)
I Max
FWHM Max

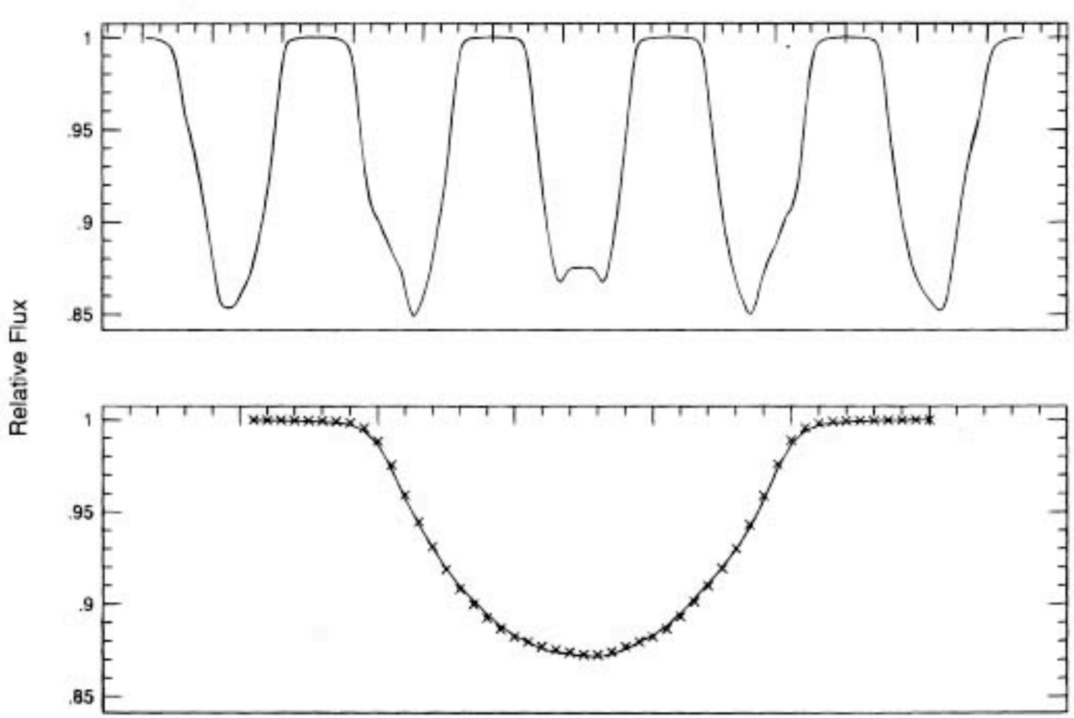
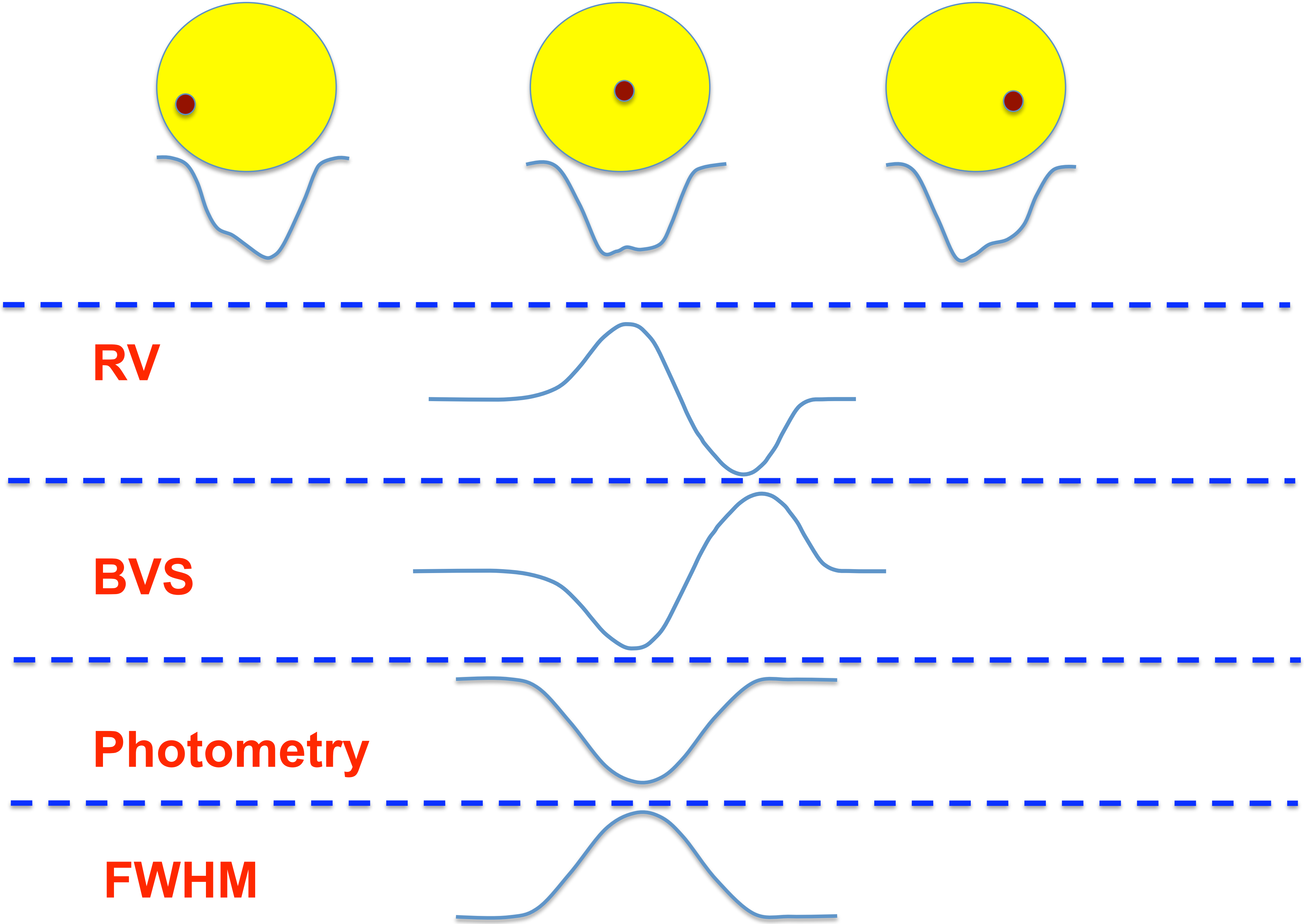
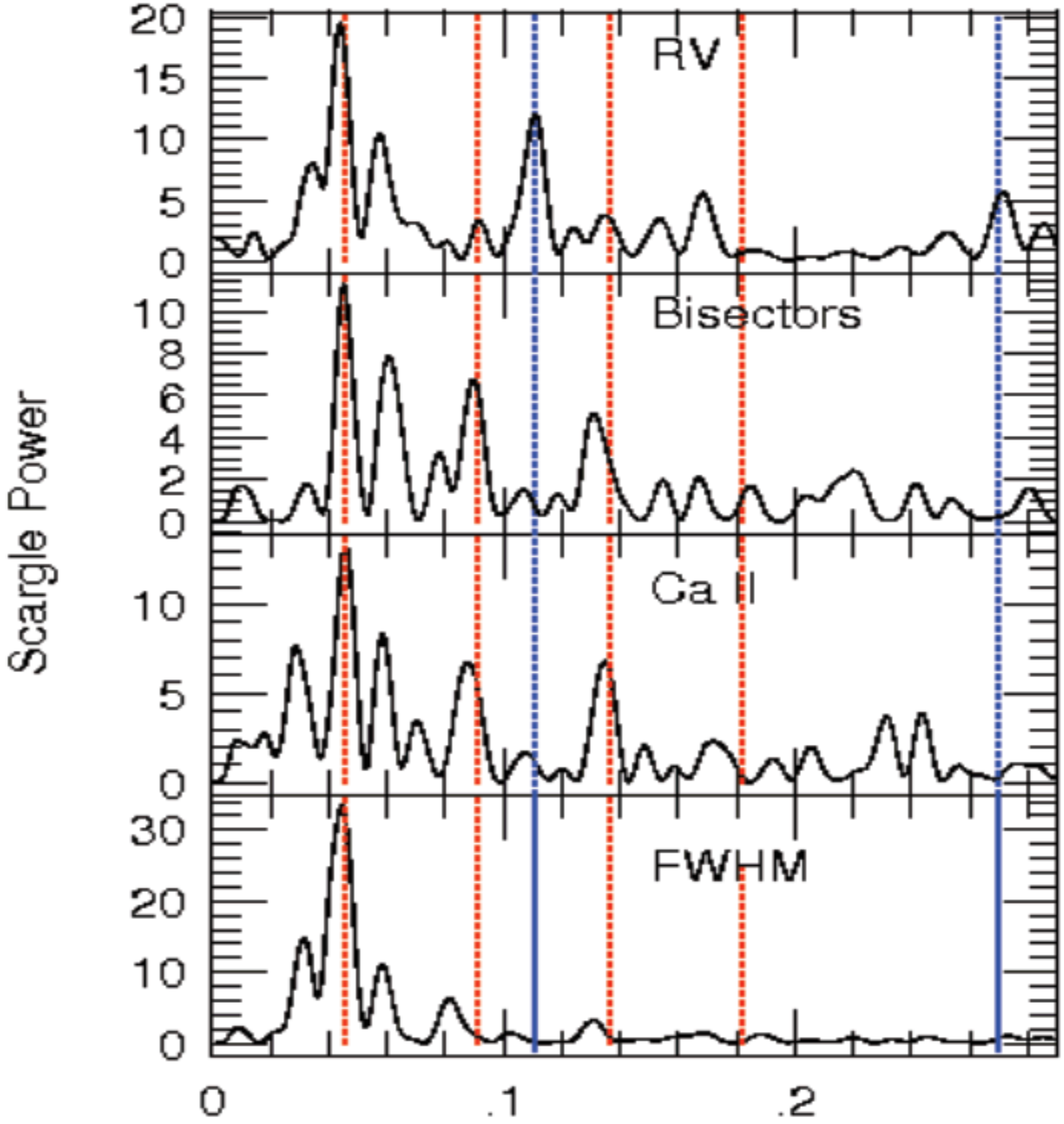


FIG. 2.—*Top:* The spectral line profiles at five rotation phases (separated by 0.063 in phase) of the Ca I 6439 Å profile from a star with a cool (ΔT = 1200 K) spot with a radius of 15° at latitude +20°. The star has a v sin i of 50 km s^{-1} and an inclination of 60°. *Bottom:* The mean Ca I profile (*line*) for the five phases and the profile from an unspotted star (*crosses*).


RV
BVS
Photometry
FWHM



RV
Bisectors
Ca II
FWHM
Scargle Power
0
.1
.2

Some Cautionary Tales

The Planet around TW Hya?

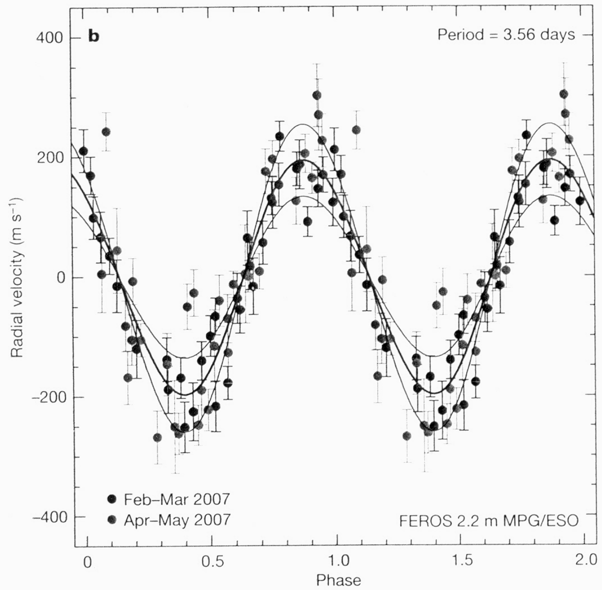


Figure 2 | Radial velocity variation of TW Hya. **a**, The RVs were obtained during two observing runs with 12 consecutive nights (between 28 February and 12 March 2007) and 20 consecutive nights (24 April to 13 May 2007). With typically three spectra per night, we sampled possible variability periods from about 1 to 12 days. For the RV calculations we used a cross-correlation technique, in which about 1,300 spectral lines were cross-correlated with a numerical template. The error bars are standard errors of the mean RV value. The typical accuracy of the individual RV is about 40 m s^{-1}, which is mostly due to the rapid rotation and activity of TW Hya. For comparison, the typical accuracy achieved with FEROS for quiet and slow rotating solar-type stars is about 5 m s^{-1}. The solid line shows a keplerian fit with a period of 3.56 days. The scatter of the data points around this curve (residuals) is probably due to stellar activity. **b**, The phase-folded (with $P = 3.56$ days) RV curve (blue line) of the planet around TW Hya. This periodic variation is stable within the observation time window. The amplitude of RV variation is 196 ± 61 m s^{-1}. The black lines represent the uncertainty of ±61 m s^{-1} below and above the blue curve.

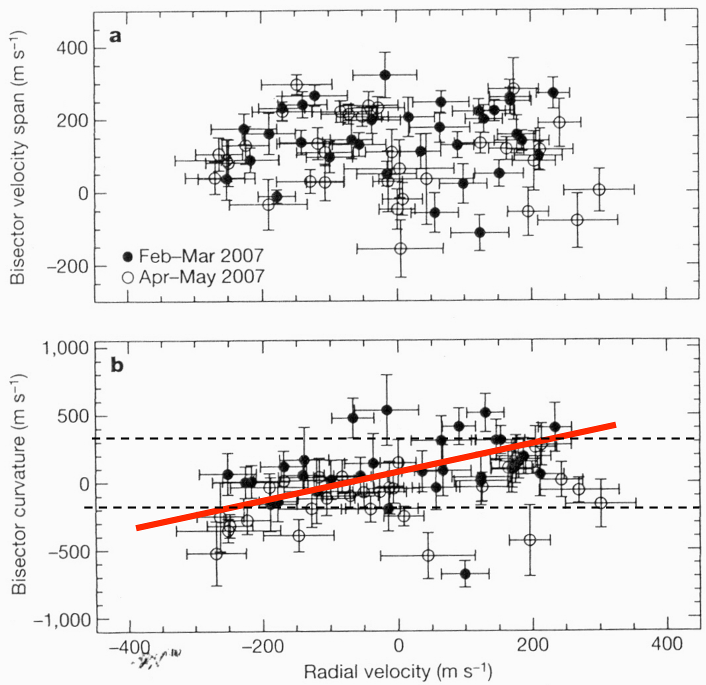
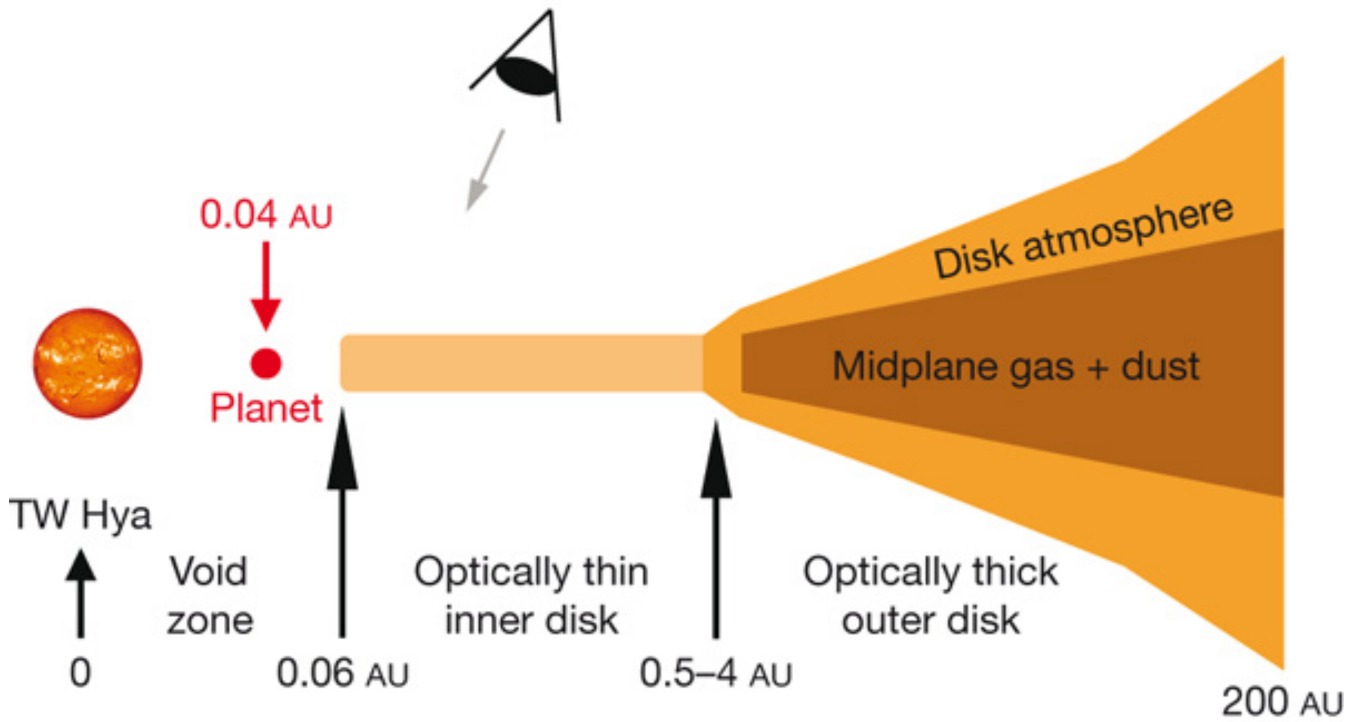
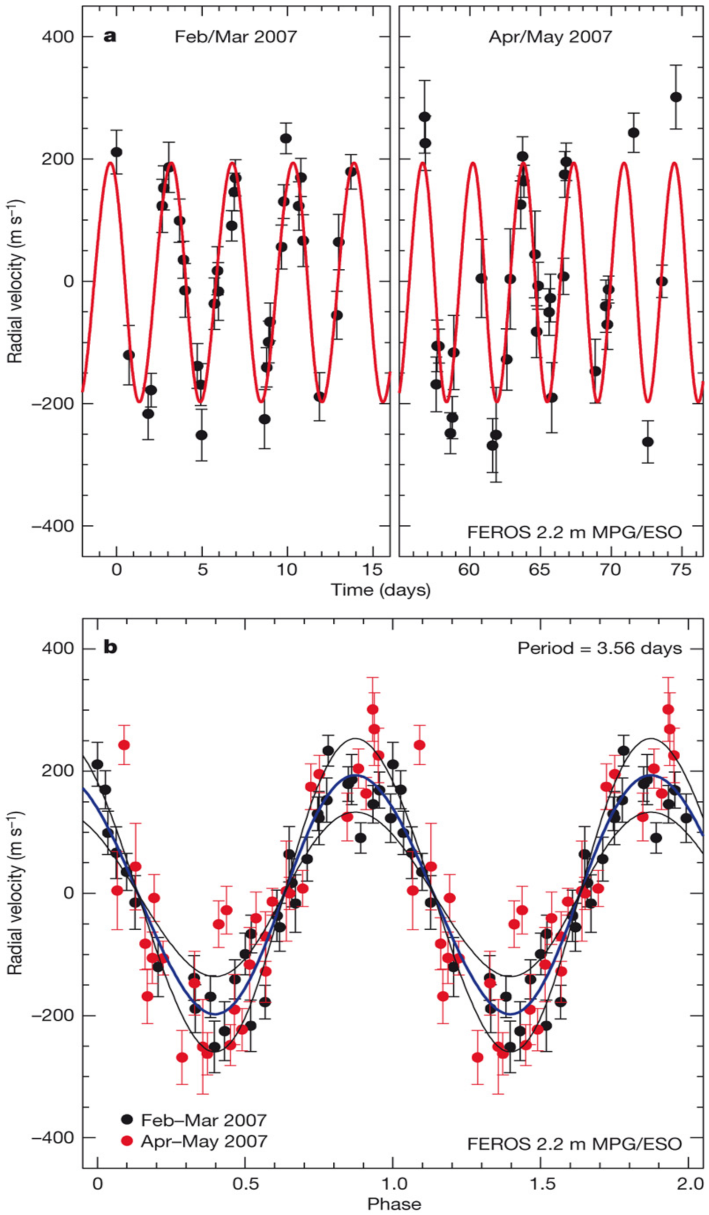


Figure 4 | Bisector analysis of line profile asymmetry. We used a cross-correlation technique, using several hundred spectral lines of TW Hya. We measured the bisector velocity spans (**a**) and bisector curvatures (**b**), which are well known as excellent stellar activity indicators. **a**, Bisector velocity span versus RV for the entire data set. There is no significant correlation (correlation coefficient ~0.2), indicating that the 3.56-day RV variation is not caused by the line profile changes. **b**, The bisector curvature does not show a significant correlation with the RV (correlation coefficient ~0.3), confirming that stellar activity is not responsible for the observed 3.56-day RV variation. The error bars are the standard mean errors of the mean bisector velocity span/curvature, computed from the bisectors of each echelle order.

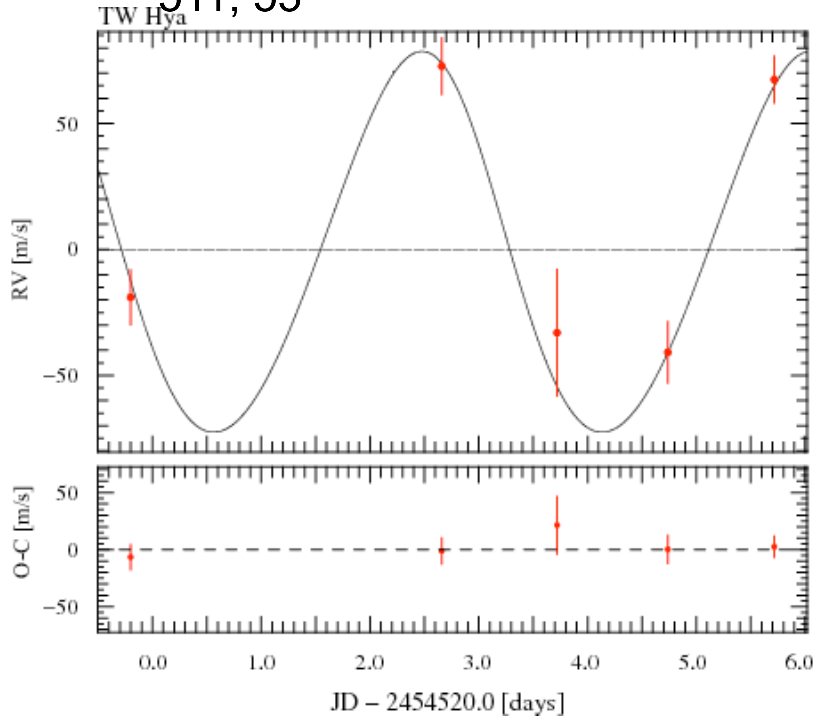


0.04 AU
Planet
Disk atmosphere
Midplane gas + dust
TW Hya
Void
zone
Optically thin
inner disk
Optically thick
outer disk
0
0.06 AU
0.5–4 AU
200 AU

The Non-Planet around TW Hya

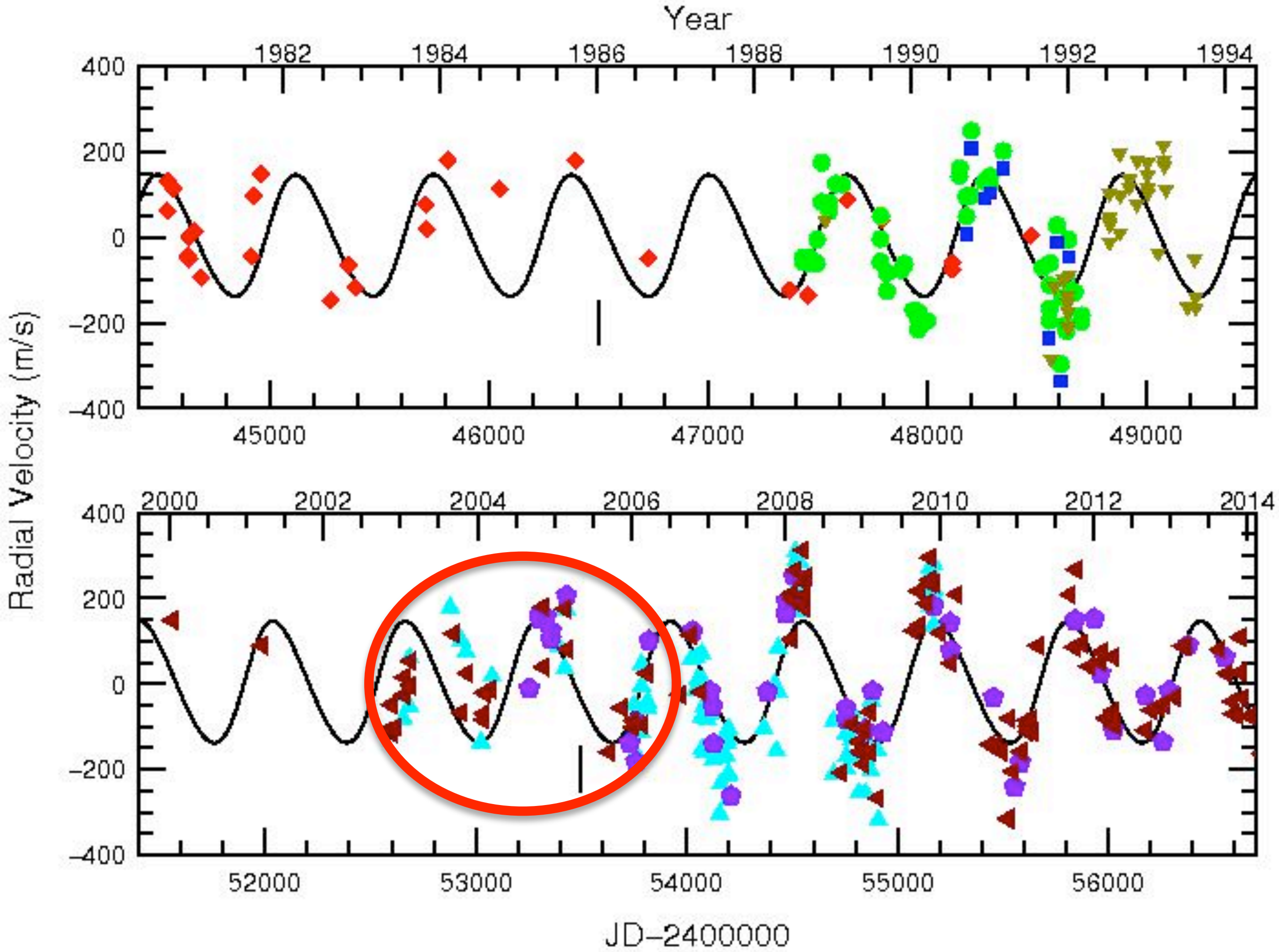


Figueira et al. 2010,
Astronomy and Astrophysics,
511, 55



Points: IR measurements, Solid line is the orbital solution using optical radial velocity measurements, but with one-third the optical amplitude → No planet!

33 Years of Radial Velocity Measurements of Aldebaran

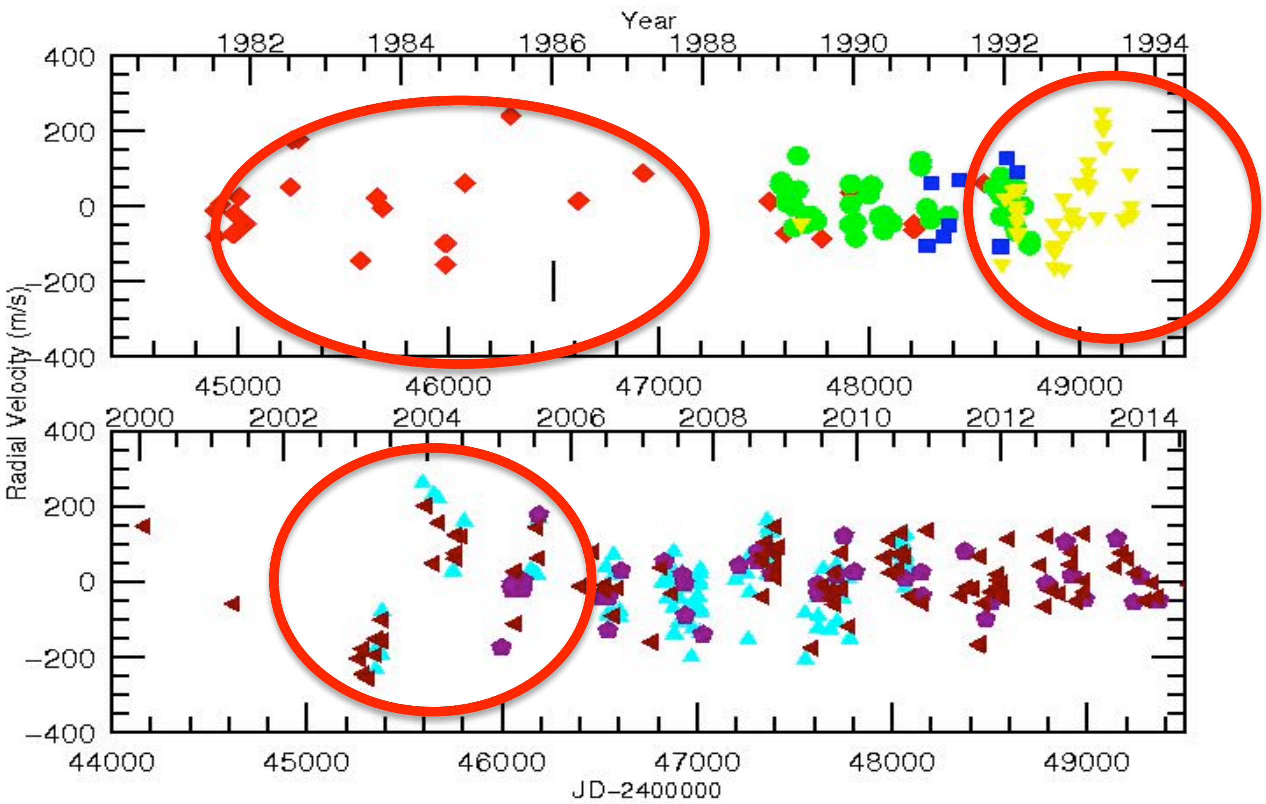


Planet Signal

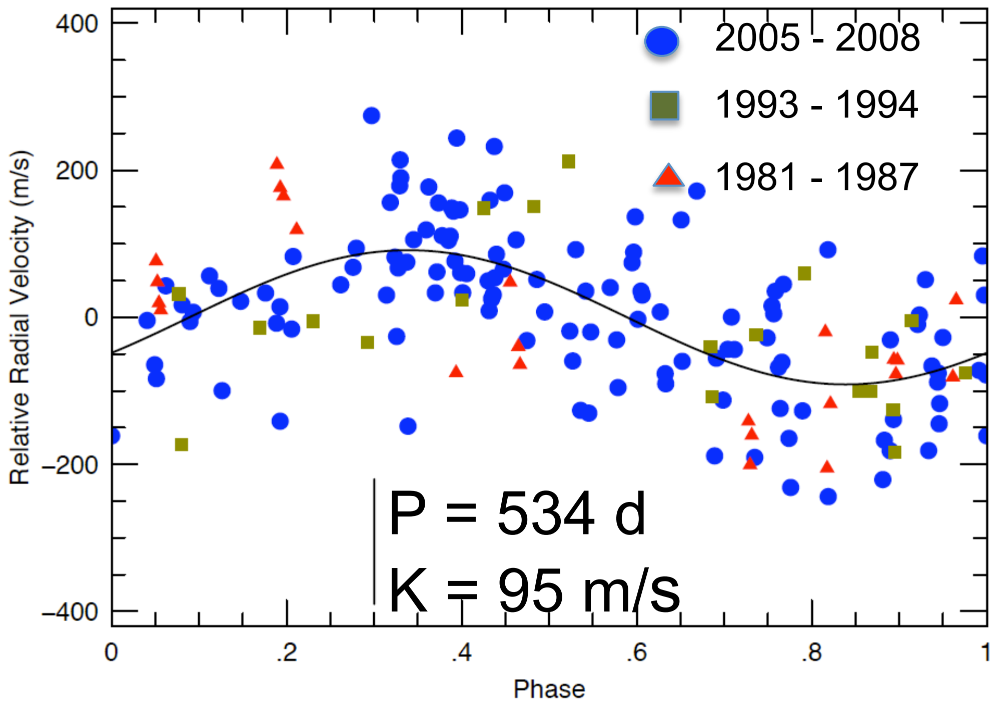
P = 630 d

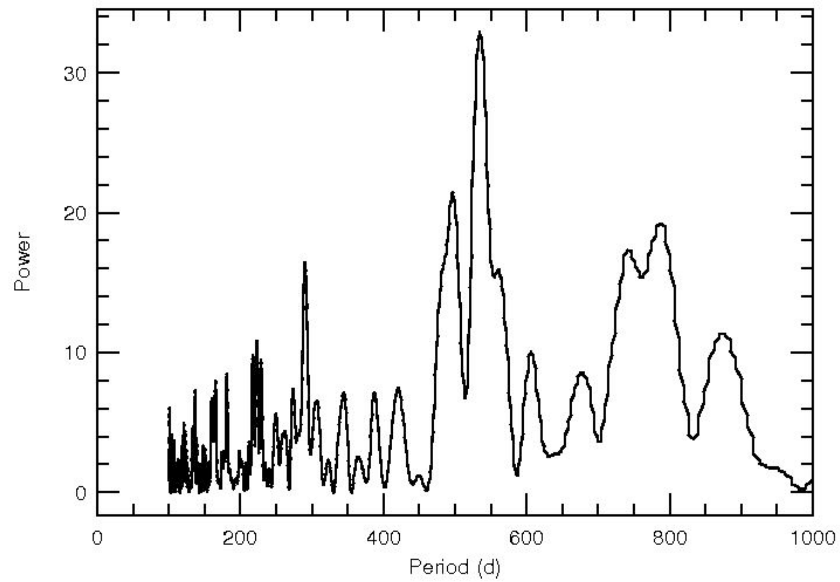
m sin i = 6.5 M_{Jup}

A signal in the residual RVs?



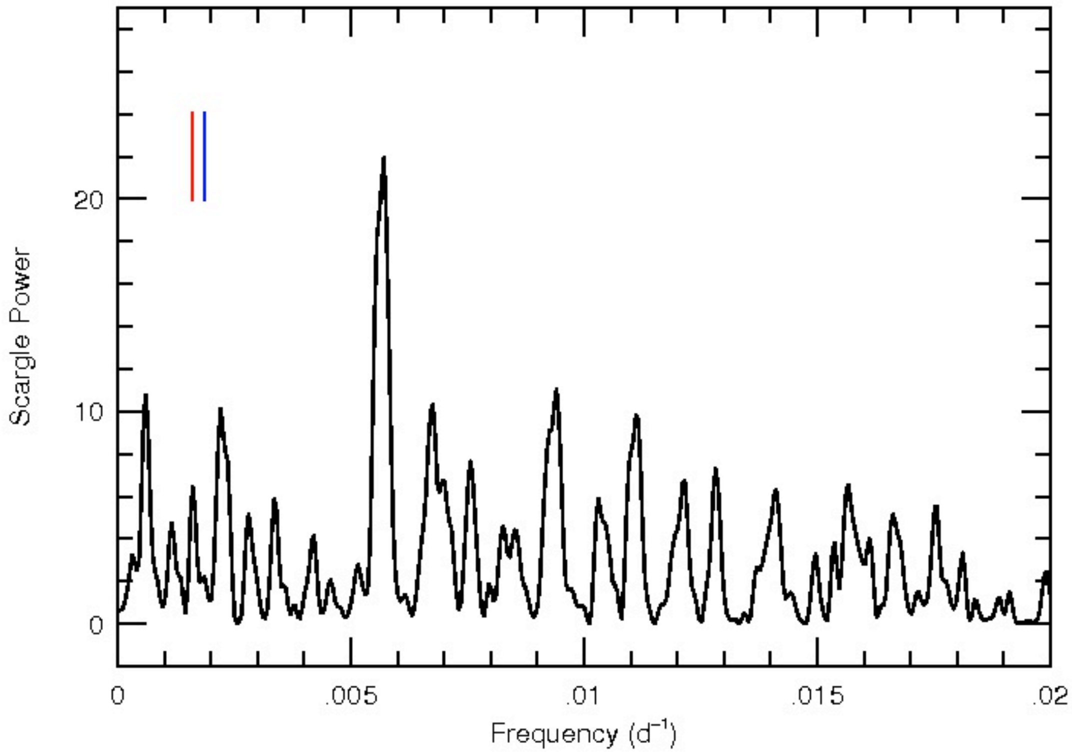
Second RV Period due to Activity





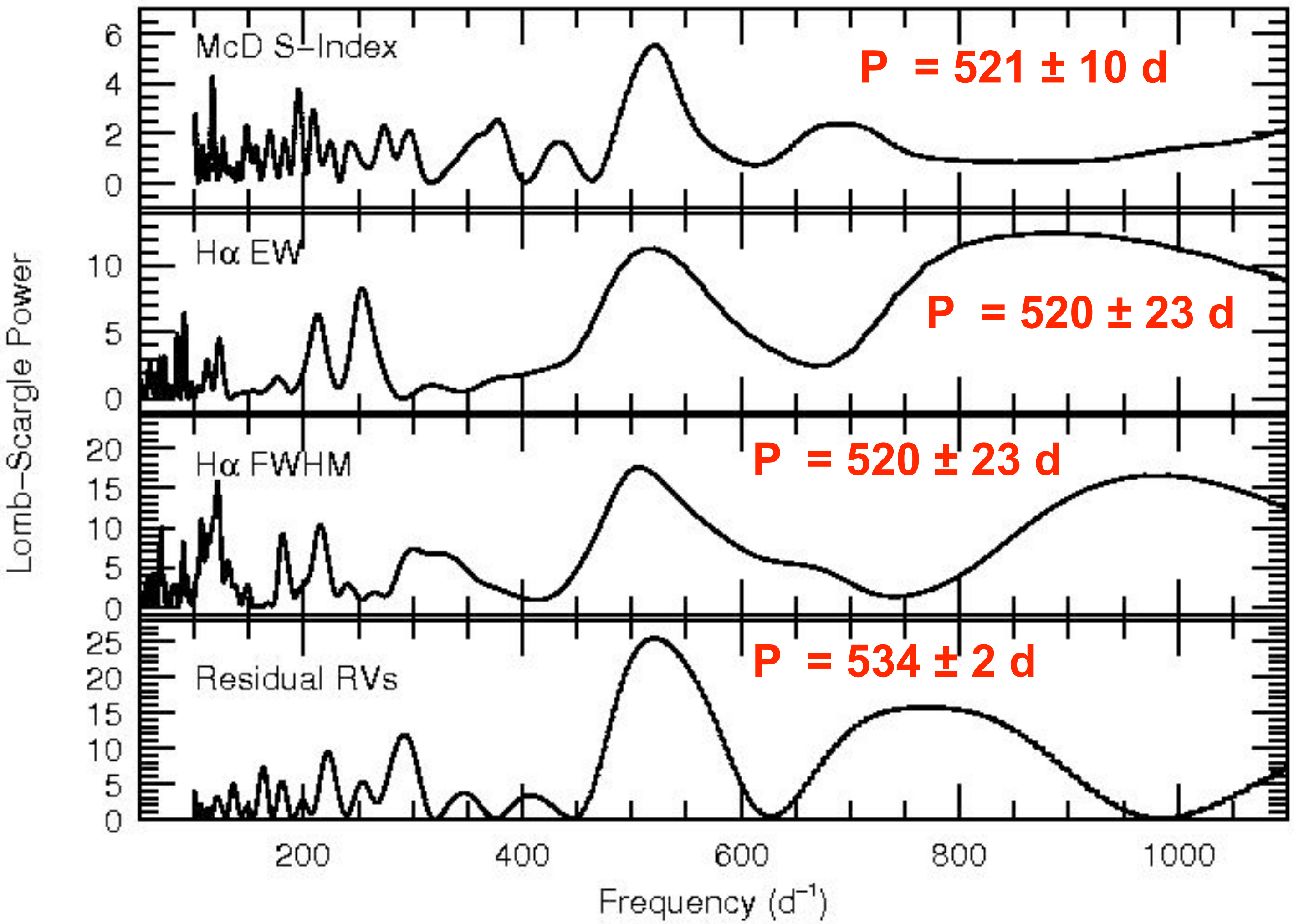
Resdiual RV variations are consistent with a planet with a “planet” with M = 4.8 M_{Jup}

Bisectors for Aldebaran



Red mark: P = 629 d
Blue mark: P = 534 d
Peak: 175 d ≈ 534/3 d

Activity Indicators



THE LICK–CARNEGIE EXOPLANET SURVEY: A 3.1 $M_\oplus$ PLANET IN THE HABITABLE ZONE OF THE NEARBY M3V STAR GLIESE 581

STEVEN S. VOGT[1], R. PAUL BUTLER[2], E. J. RIVERA[1], N. HAGHIGHIPOUR[3], GREGORY W. HENRY[4], AND MICHAEL H. WILLIAMSON[4]
[1] UCO/Lick Observatory, University of California, Santa Cruz, CA 95064, USA

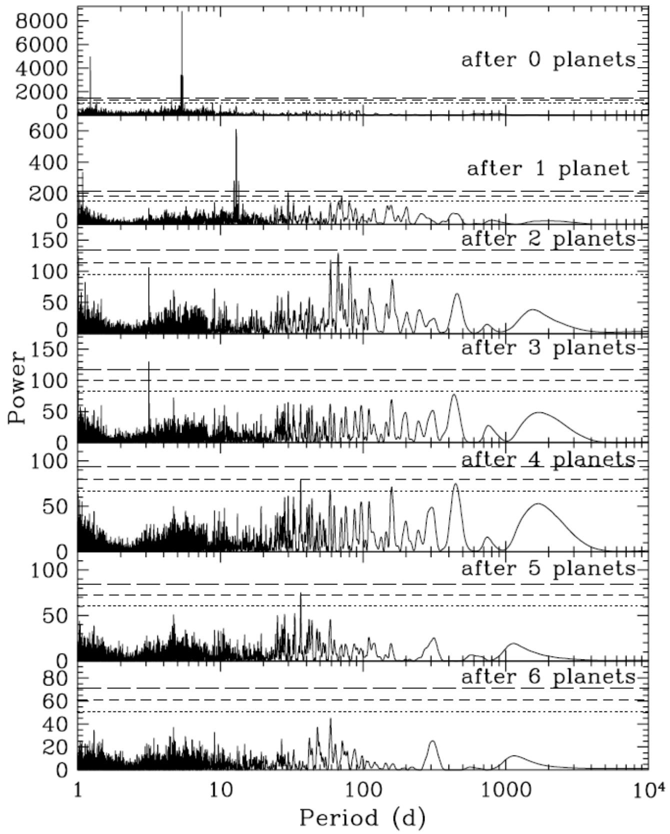


Figure 3. From top to bottom, power spectra of the residuals to the 0-, 1-, 2-, 3-, 4-, 5-, and 6-planet solutions, respectively. The horizontal lines in each periodogram roughly indicate the 0.1%, 1.0%, and 10.0% false-alarm probability (FAP) levels from top to bottom.

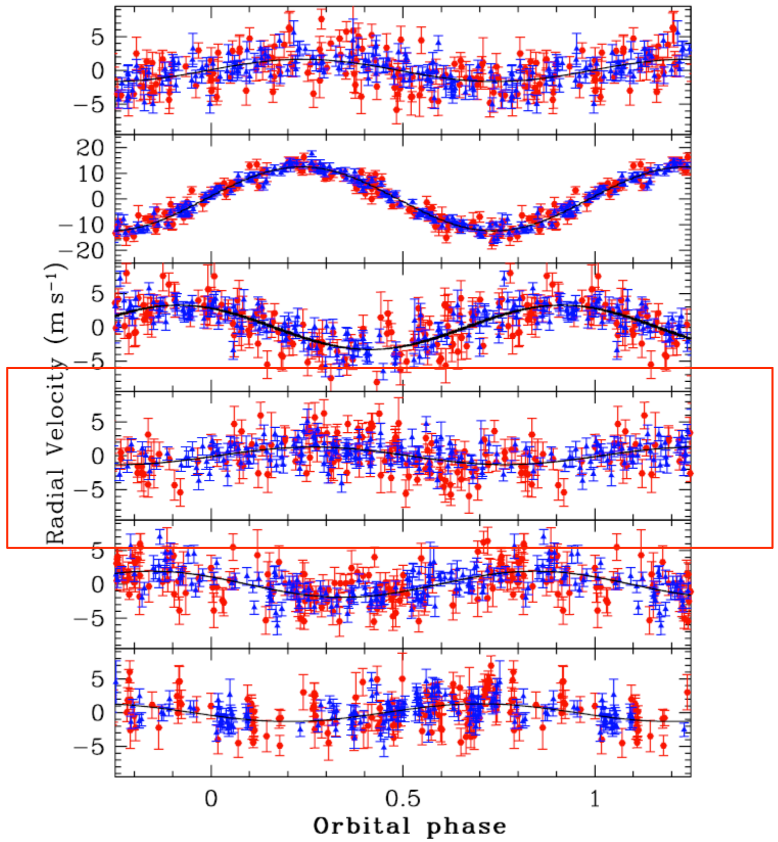
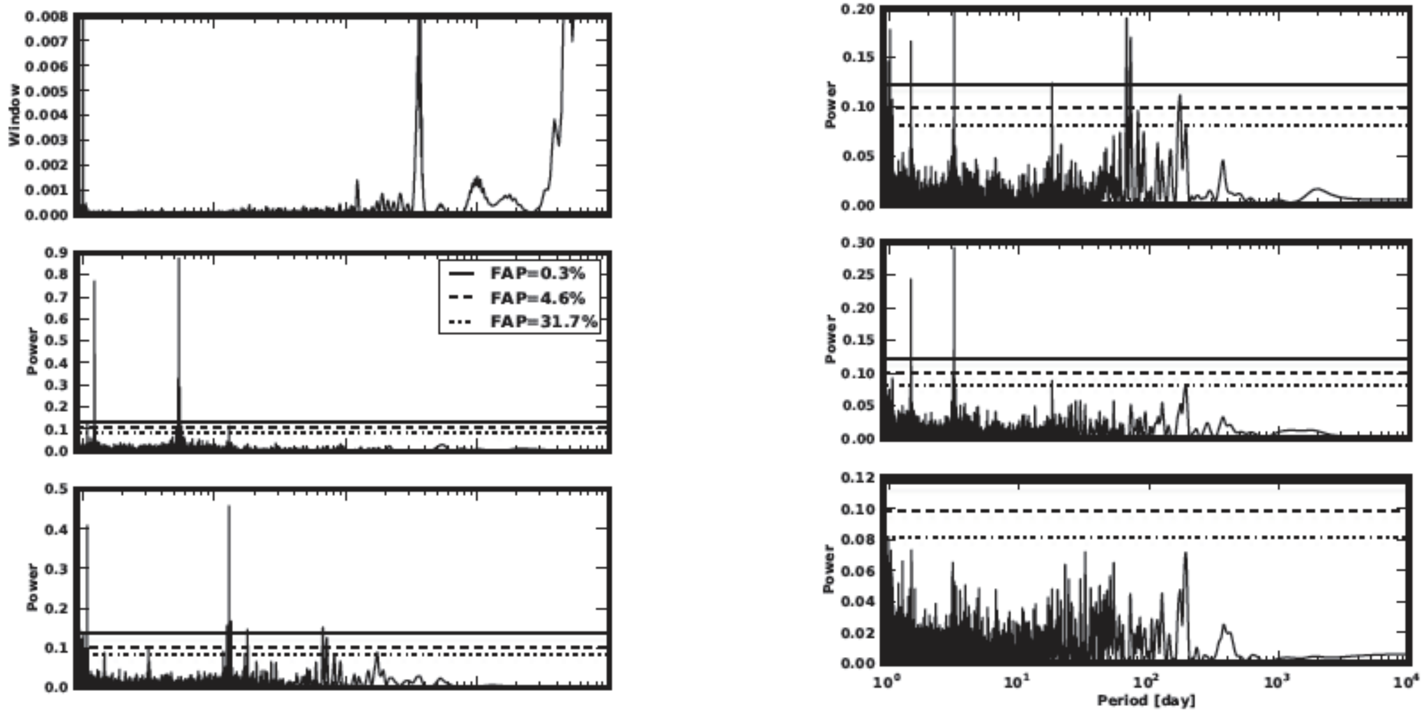


Figure 5. Phased reflex barycentric velocities of the host star due individually to the planets at 3.15 days, 5.37 days, 12.9 days, 37 days, 67 days, and 433 days from the all-circular fit of Table 2. Filled (red) hexagon points are from Keck while filled (blue) triangles are from HARPS.

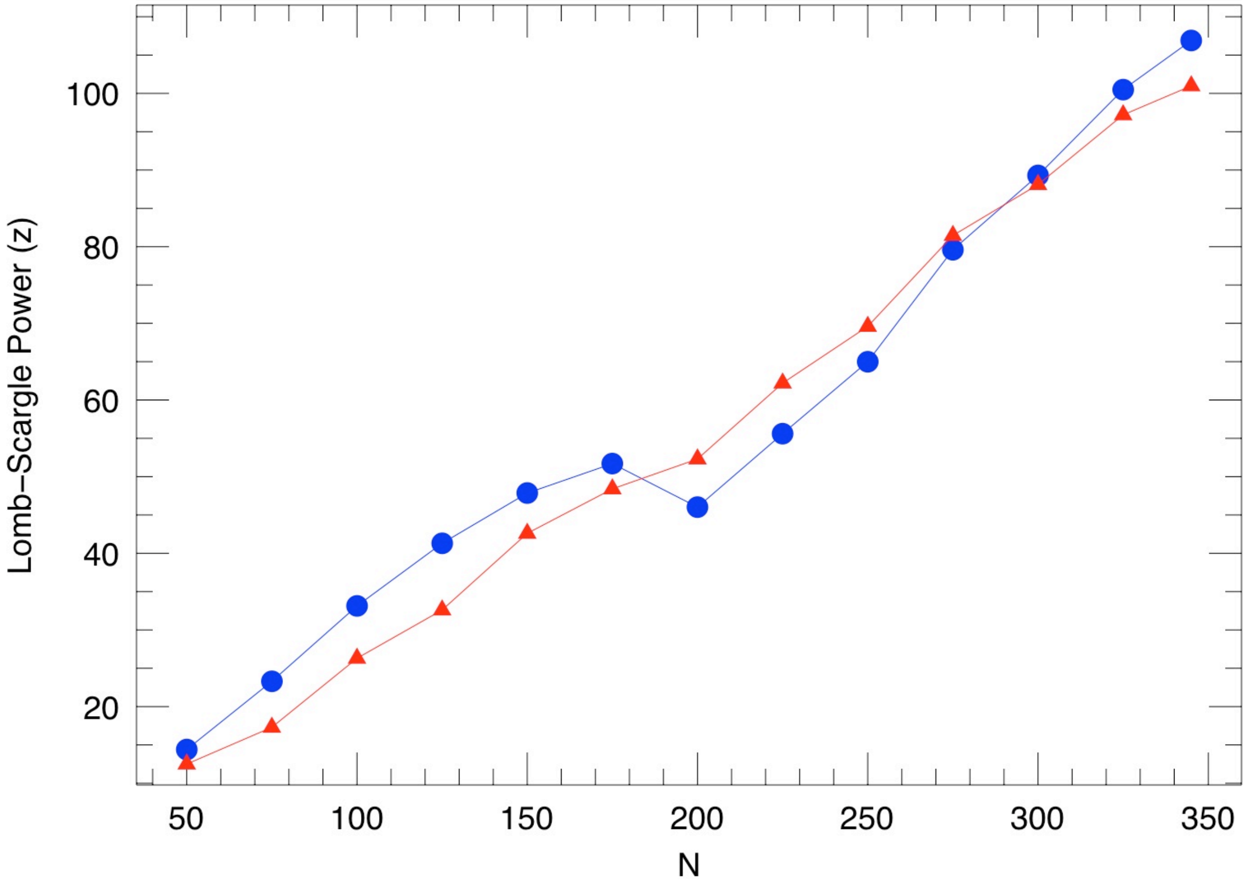
The HARPS search for southern extra-solar planets ⋆

XXXII. Only 4 planets in the Gl 581 system

T. Forveille[1,2], X. Bonfils[1], X. Delfosse[1], R. Alonso[3], S. Udry[3], F. Bouchy[4,5], M. Gillon[6], C. Lovis[3], V. Neves[1,7,8], M. Mayor[3], F. Pepe[3], D. Queloz[3], N.C. Santos[7,8], D. Ségransan[3], J.-M. Almenara[9,10,11], H.J. Deeg[10,11], and M. Rabus[10,11,12]

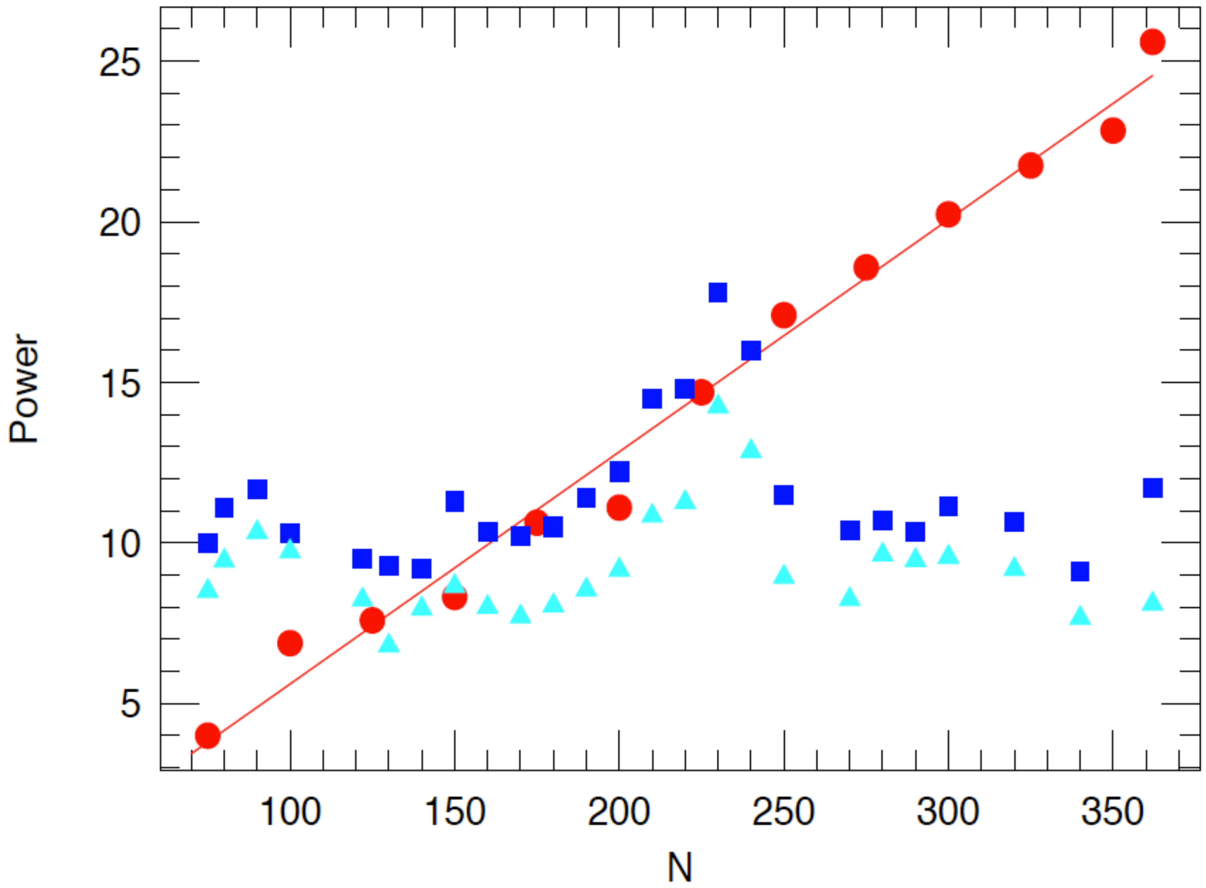


The Scargle Power should increase as you add more data:



630-d signal in Aldebaran

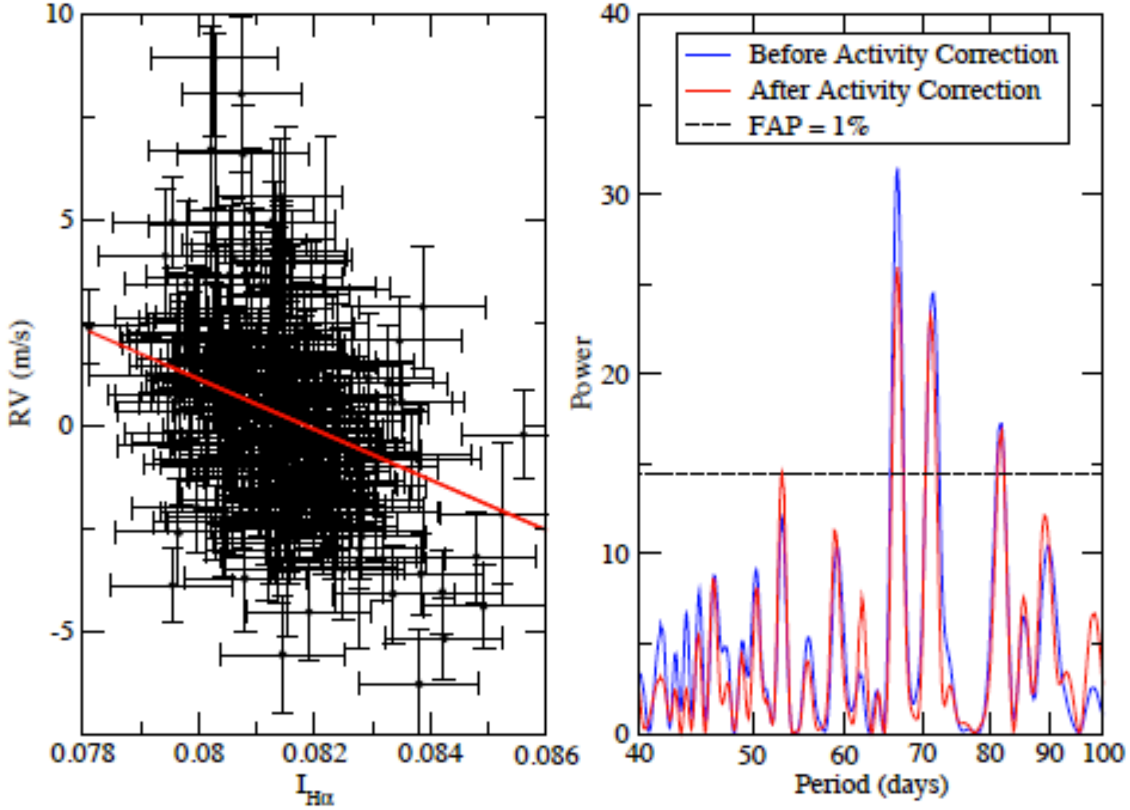
The first hint GL 581g was not real

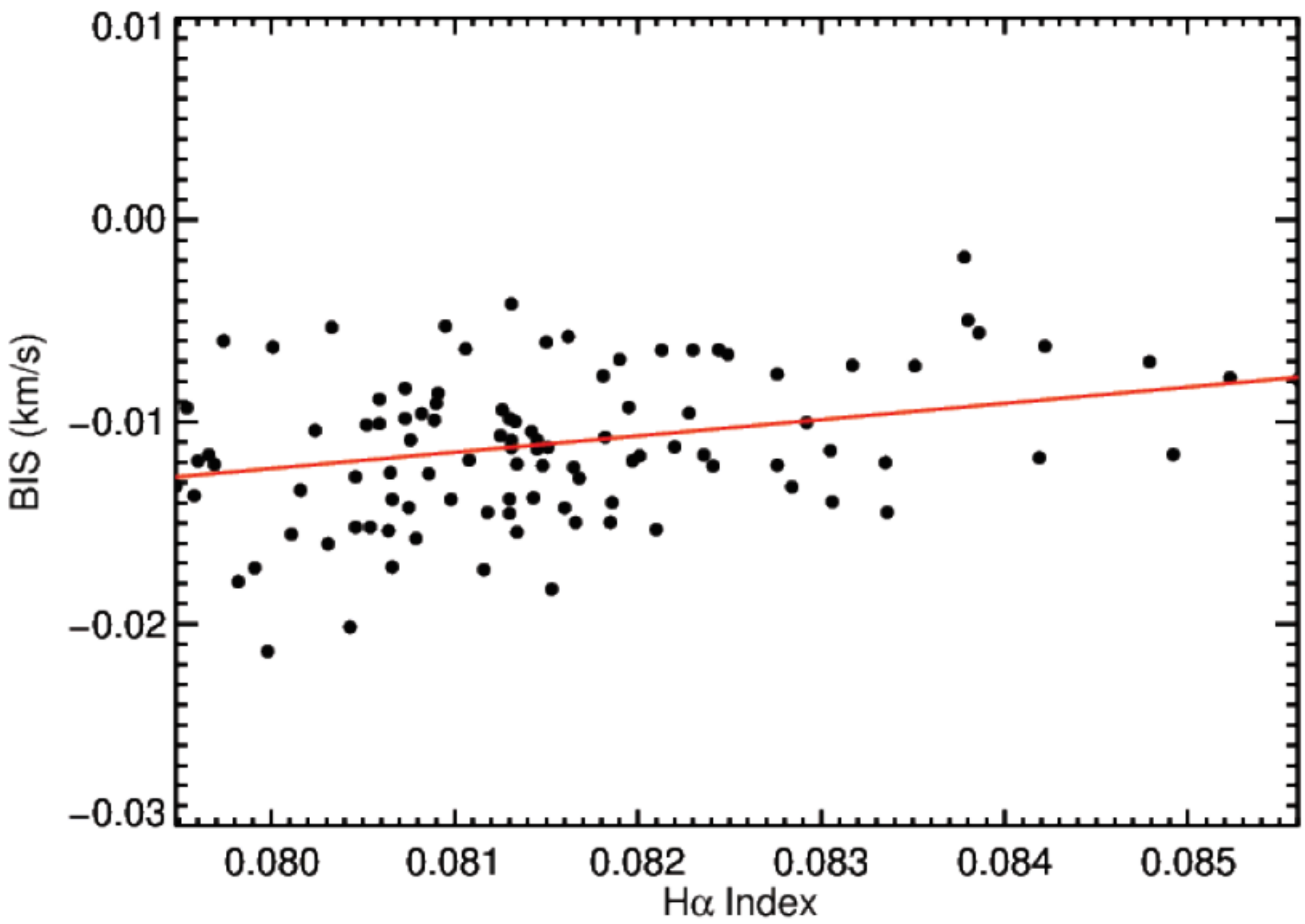


What about GL 581d?

Stellar Activity Masquerading as Planets in the Habitable Zone of the M dwarf Gliese 581

Paul Robertson[1,2], Suvrath Mahadevan[1,2,3], Michael Endl[4], Arpita Roy[1,2,3]




0.01
0.00
−0.01
−0.02
−0.03
BIS (km/s)
0.080
0.081
0.082
0.083
0.084
0.085
Hα Index

How do you know you have a planet?

1. Is the period of the radial velocity reasonable? Is it the expected rotation period? Can it arise from pulsations?
    - E.g. 51 Peg had an expected rotation period of ~30 days. Stellar pulsations at 4 d for a solar type star were never found
2. Do you have Ca II data? Look for correlations with RV period.
3. Get photometry of your object
4. Measure line bisectors
5. And to be double sure, measure the RV in the infrared!