Radial Velocities with CRIRES

Pedro Figueira

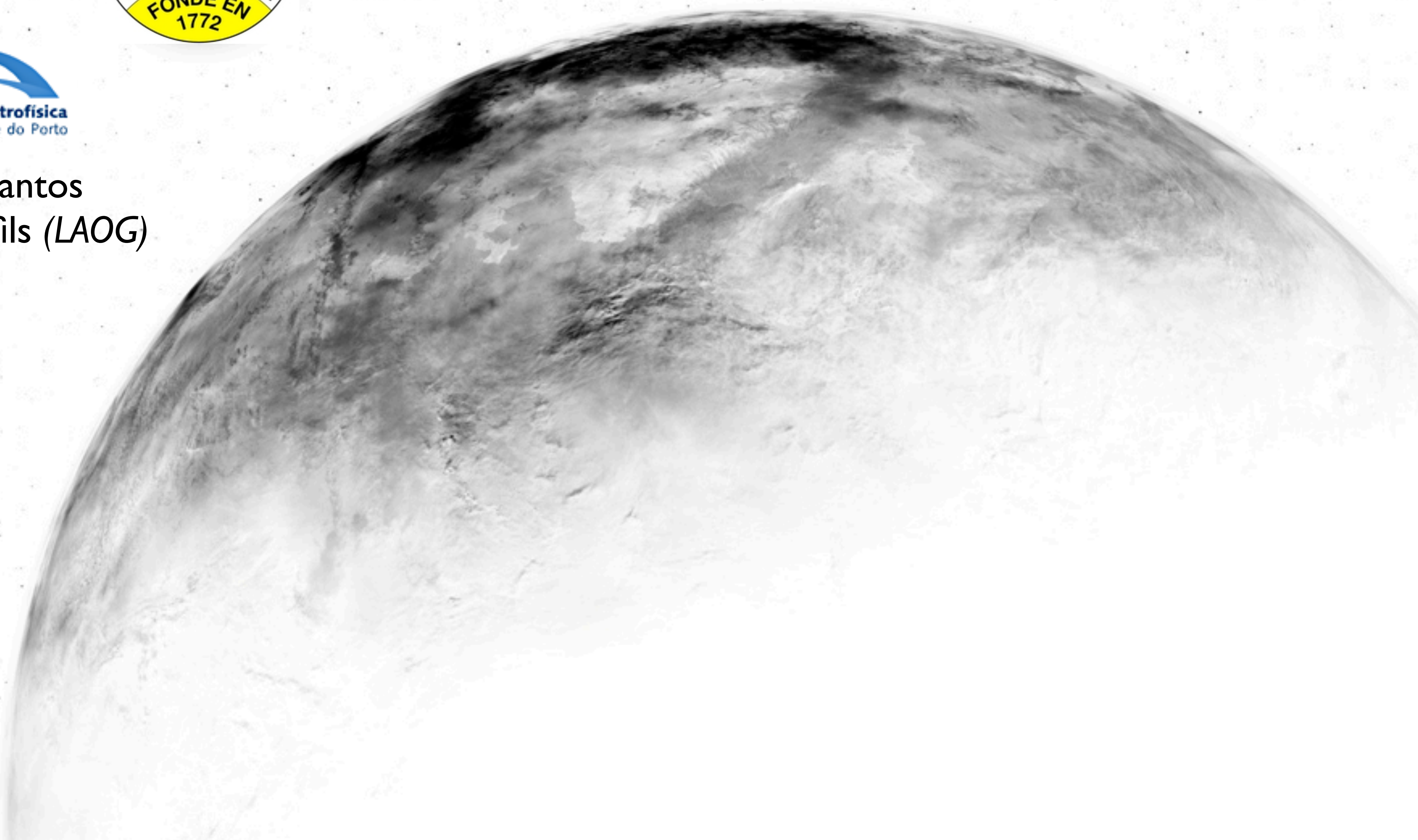
Centro de Astrofisica da Universidade do Porto

Workshop on PRV, 17th August 2010

Francesco Pepe
Christophe Lovis
Michel Mayor...

Claudio Melo
Alain Smette

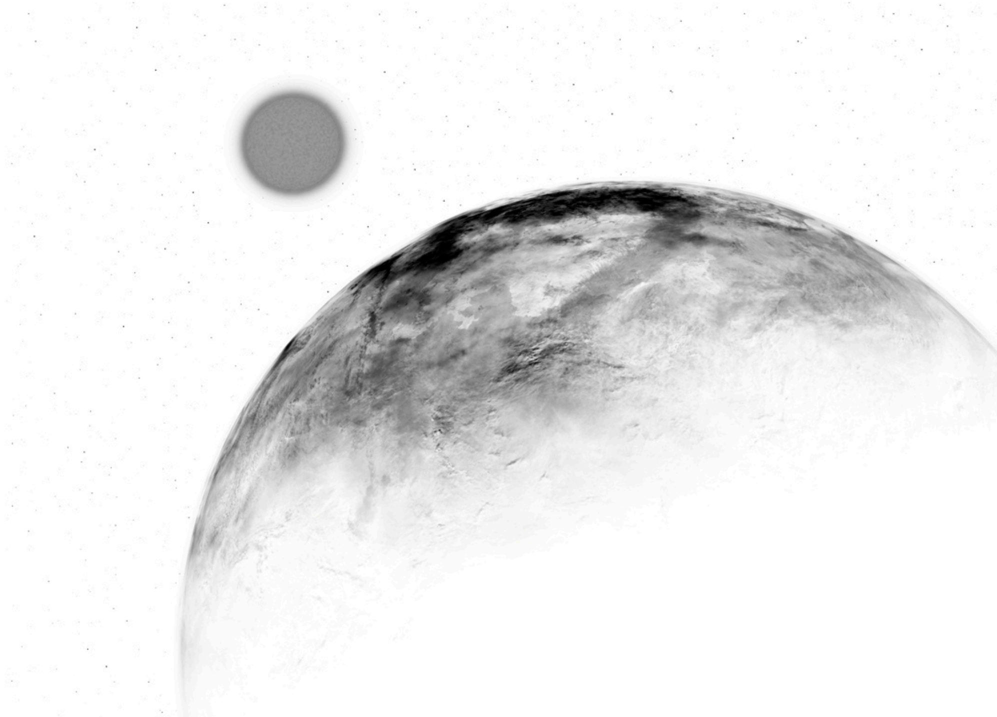
Nuno Santos
Xavier Bonfils *(LAOG)*



Workshop on PRV, 17th August 2010

Outline

- Reasons to use IR RVs;
- Calibrating CRIRES;
- TW Hya and Gl 86;
- Atmospheric Lines;
- New results!
- Conclusions.



Exploring the near-IR

Measuring RVs in the near-IR is interesting to:

- Observe optically faint M dwarfs;

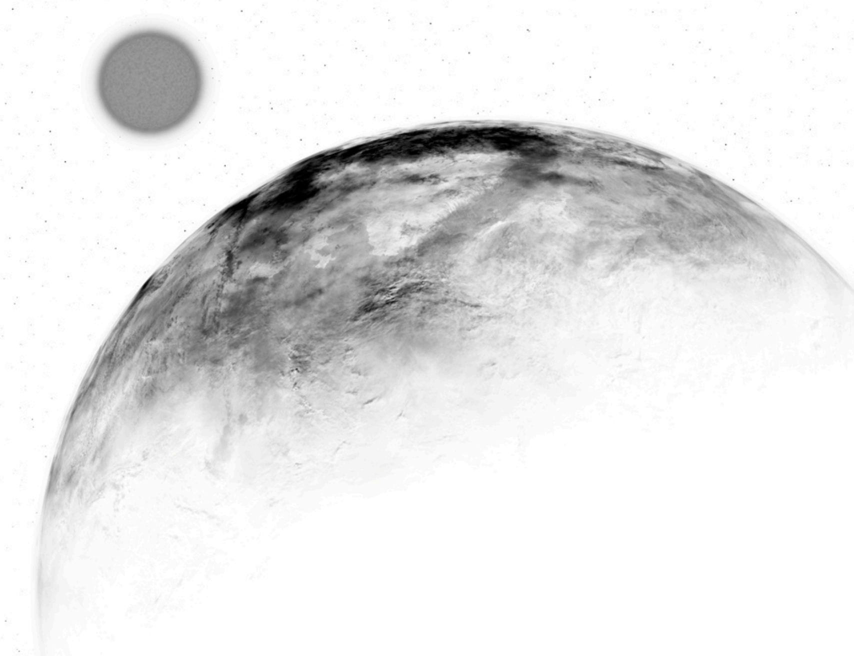
yesterday: Plavchan & Tanner talks
e. g.: Blake et al. 2007, ApJ 666 1198, and his talk
Bean et al. 2010, ApJL 711 19

- Explore a favorable planet-to-star contrast;

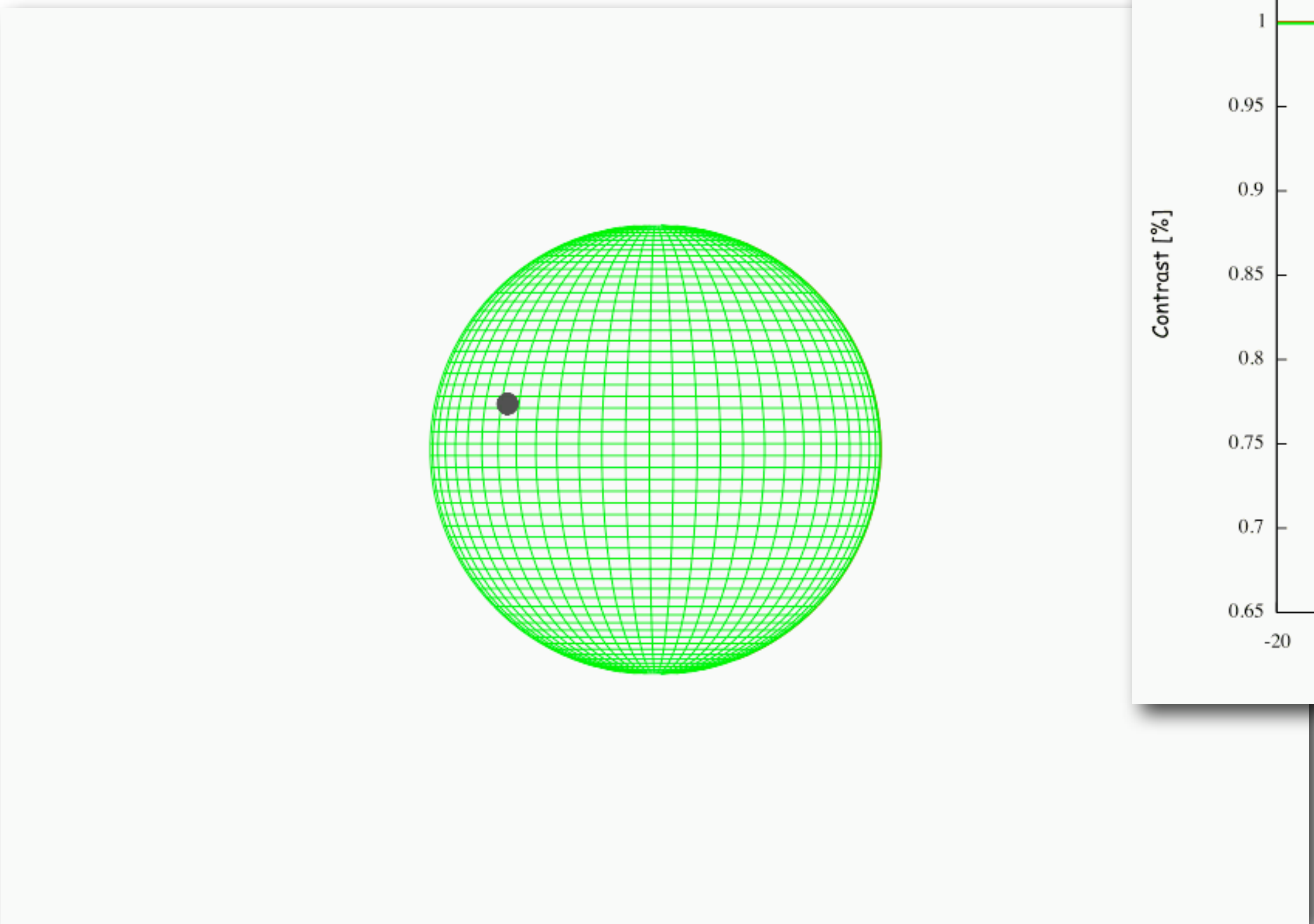
e. g.: Barnes et al. 2010 MNRAS 401 445
Snellen et al. 2010, Nature 465 1049

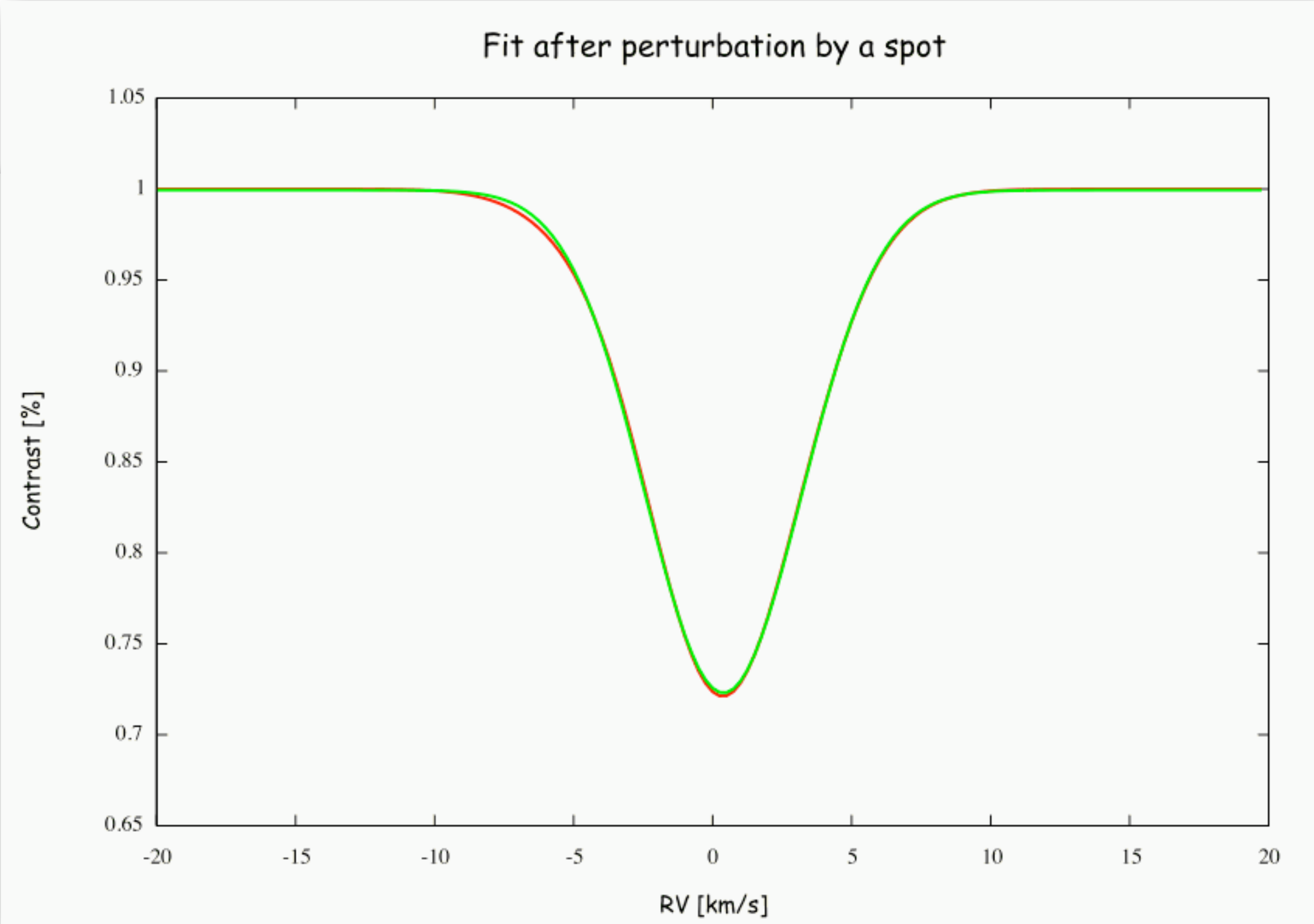
- Reduce spot's effect on RV.

e. g.: Martin et al, 2006, ApJ 644 75
Huèlamo et al. 2008, A&AL 489, 9



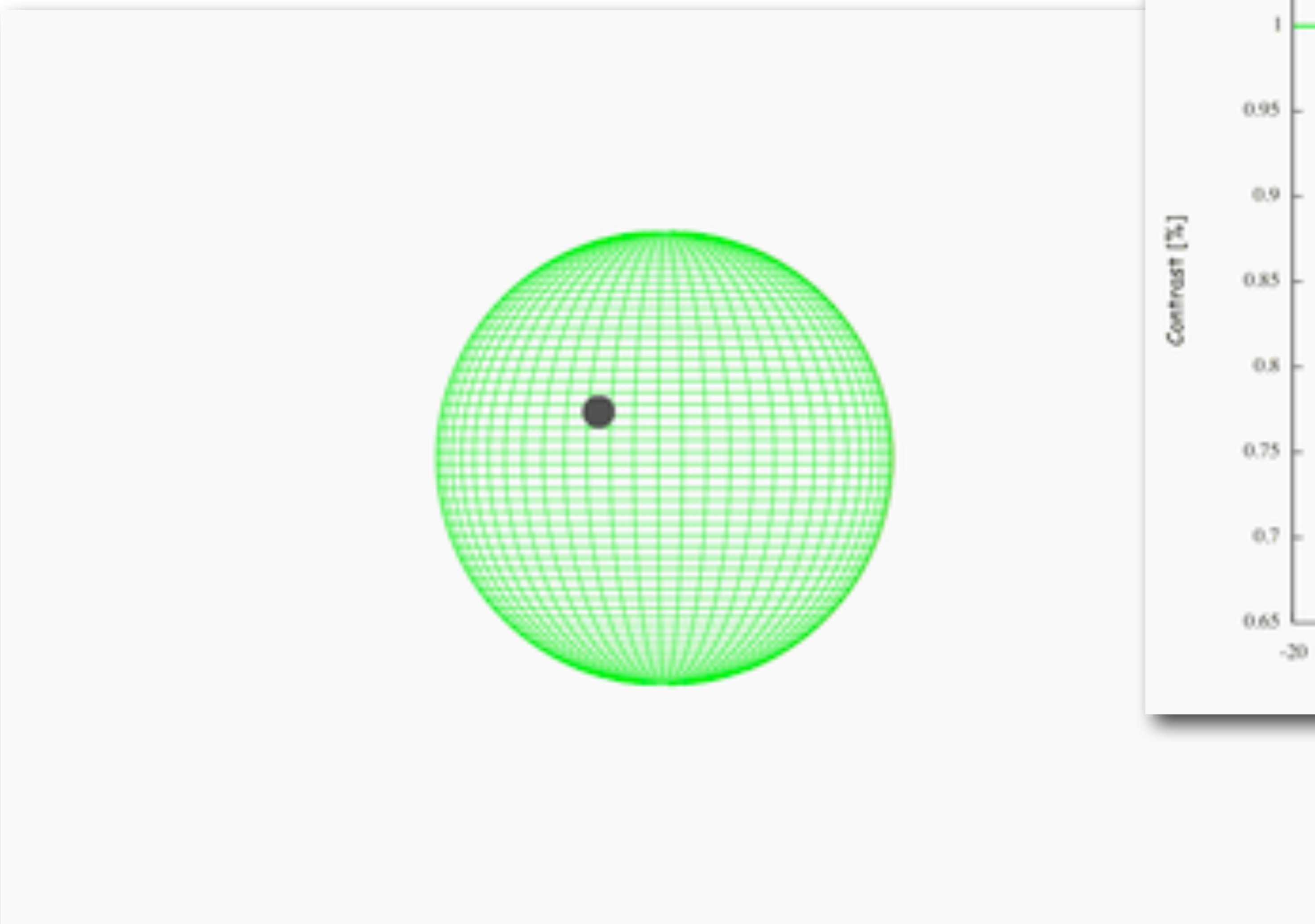
Spots mimicking Planets

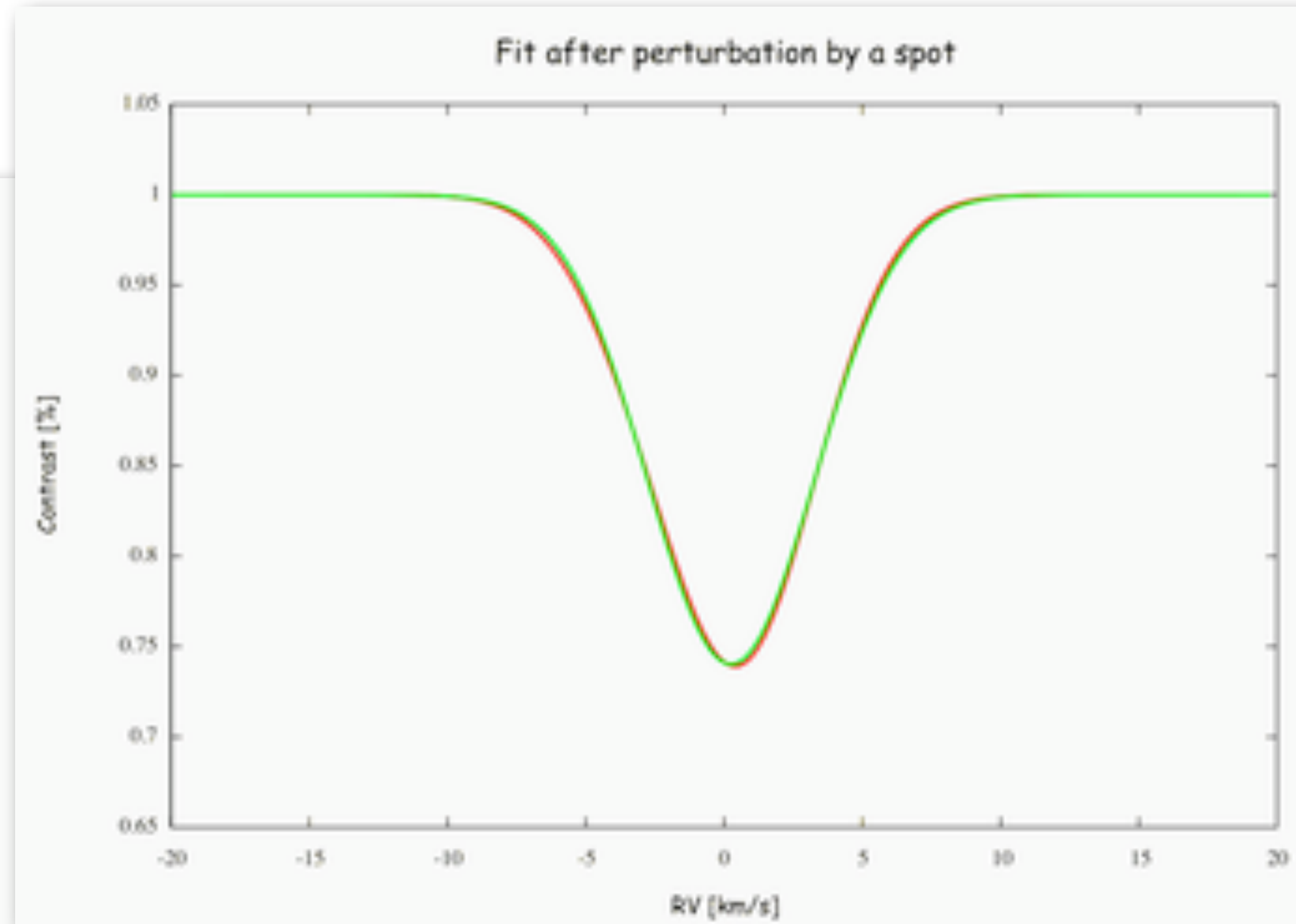


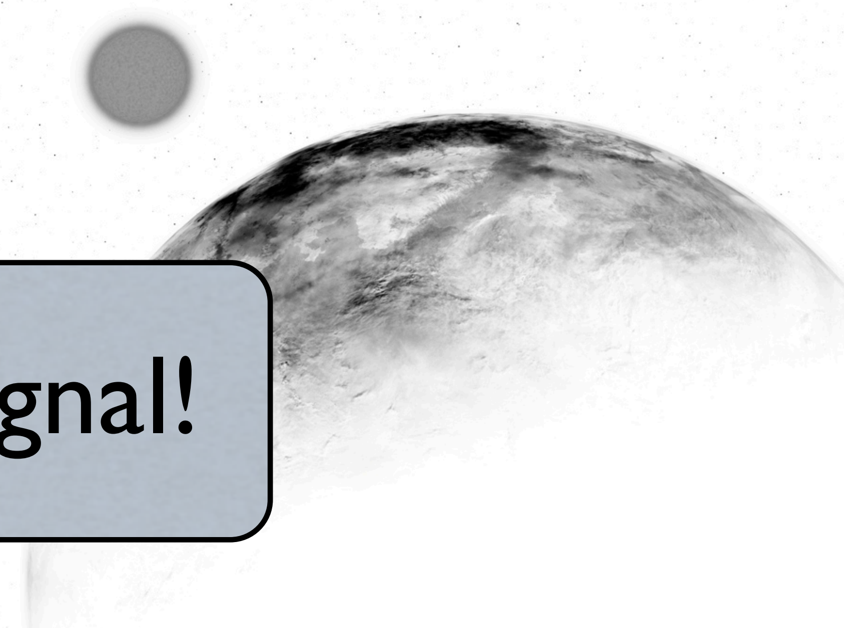


Stellar line deformation creates a RV signal!

Spots mimicking Planets







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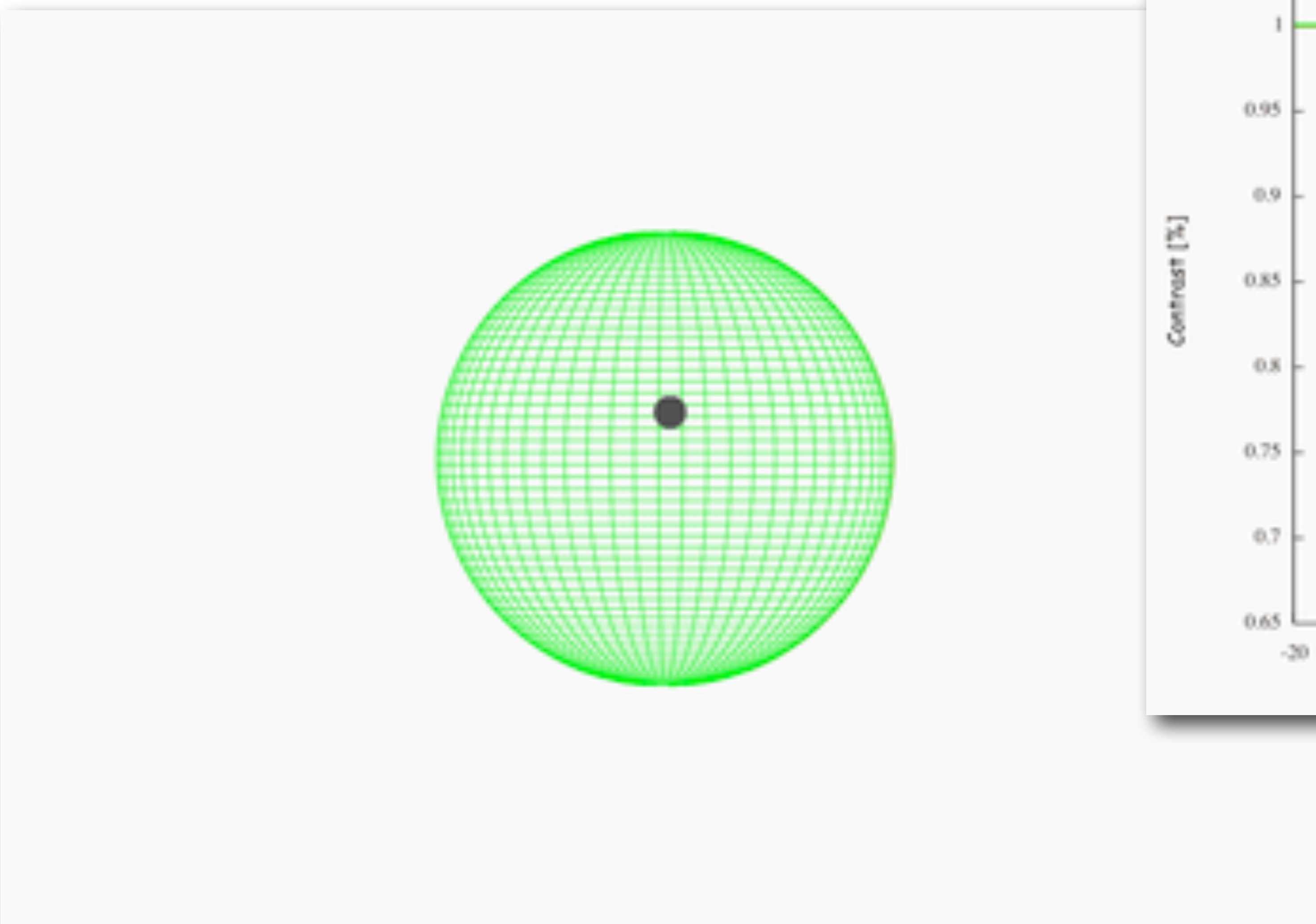

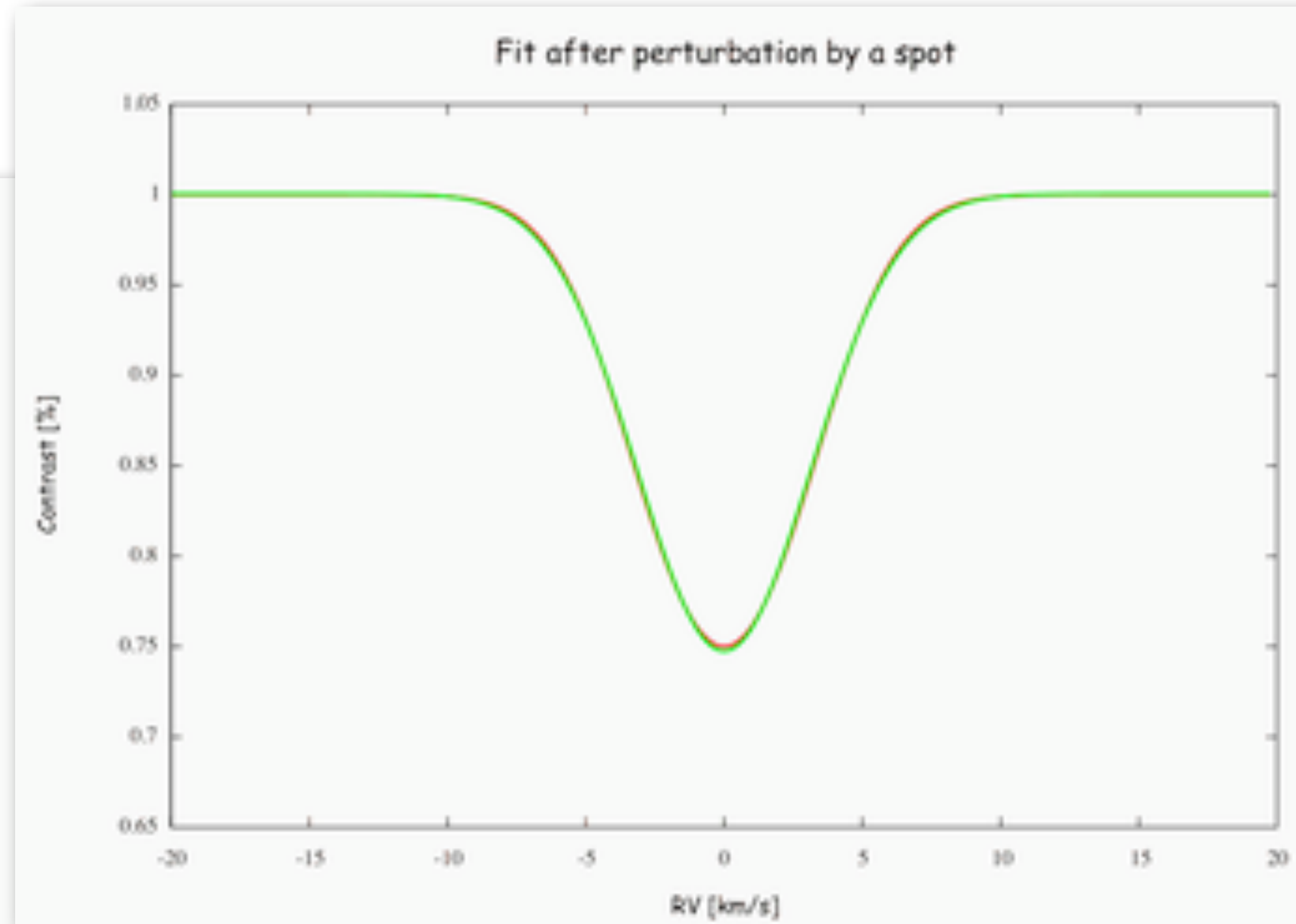

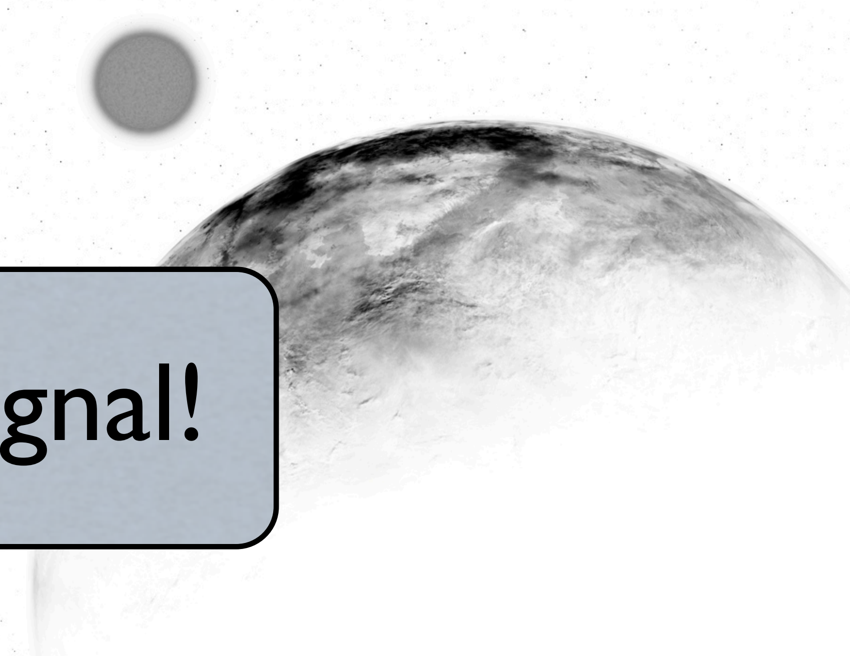

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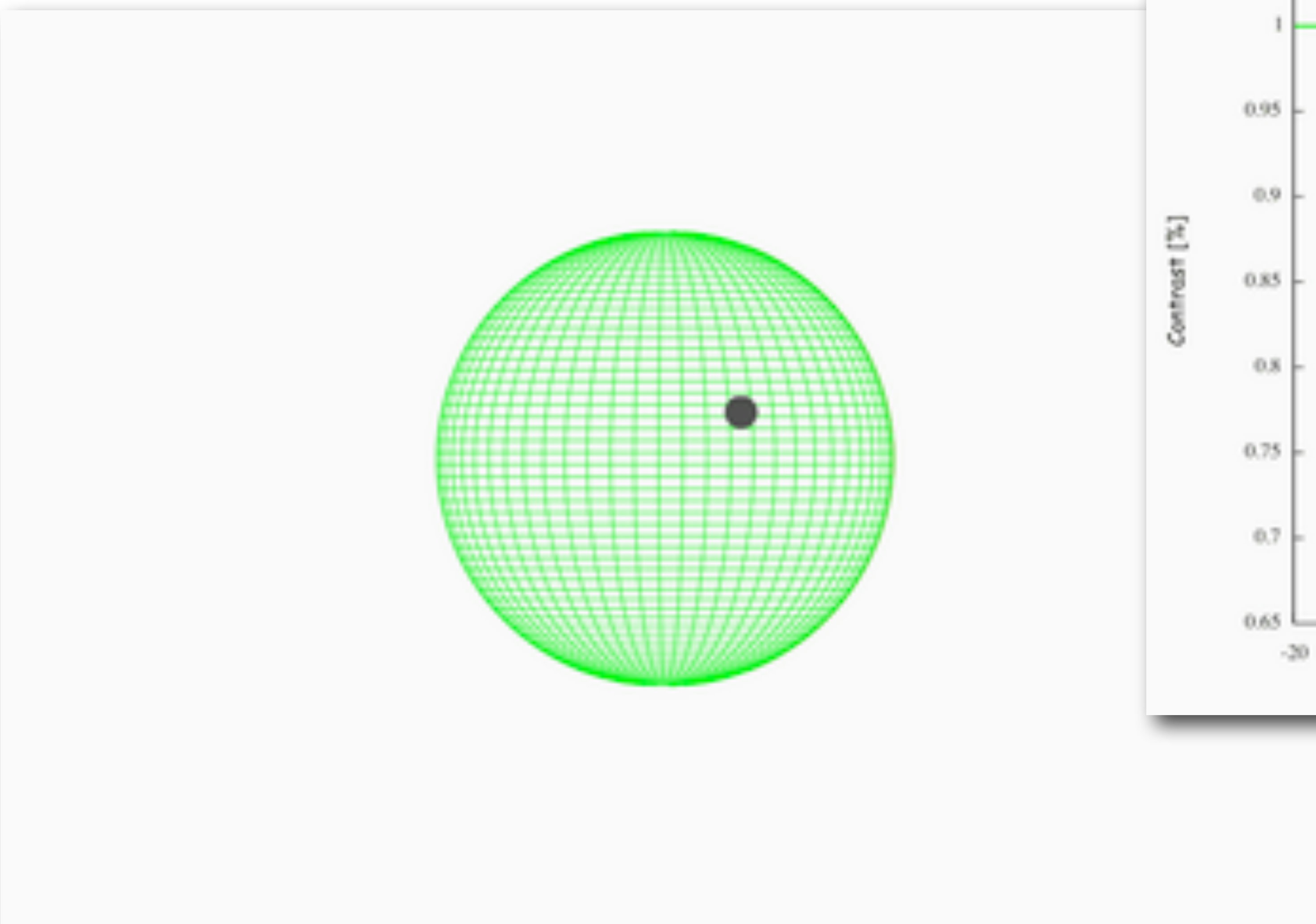

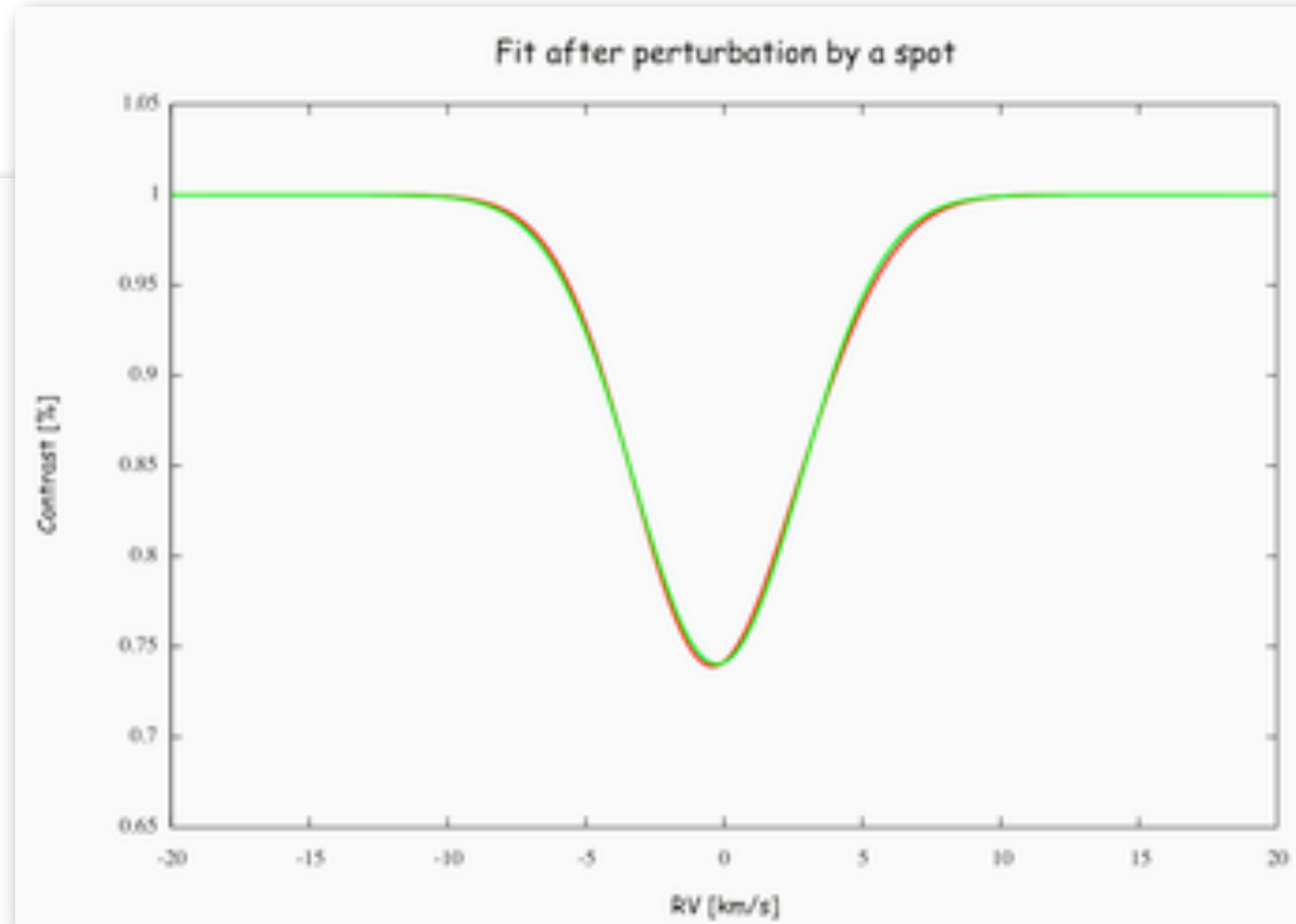

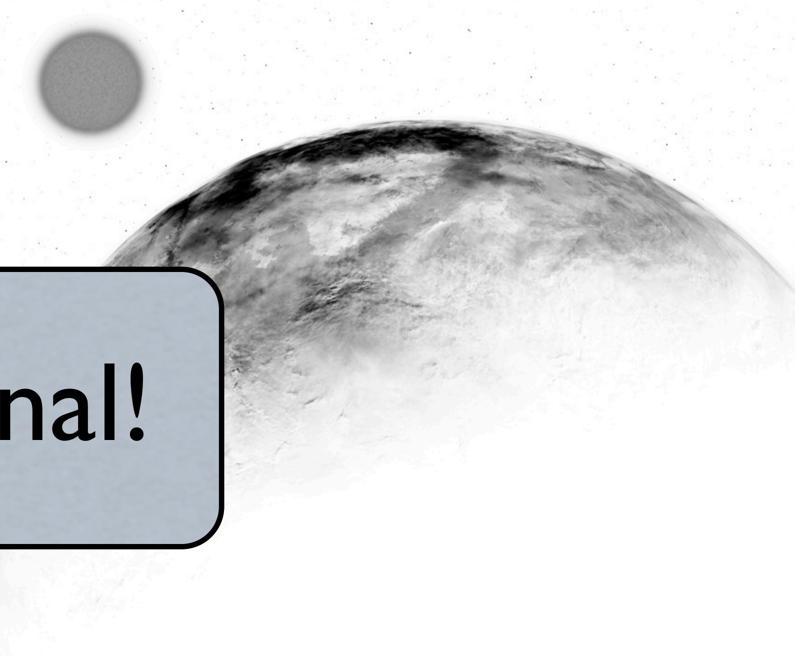

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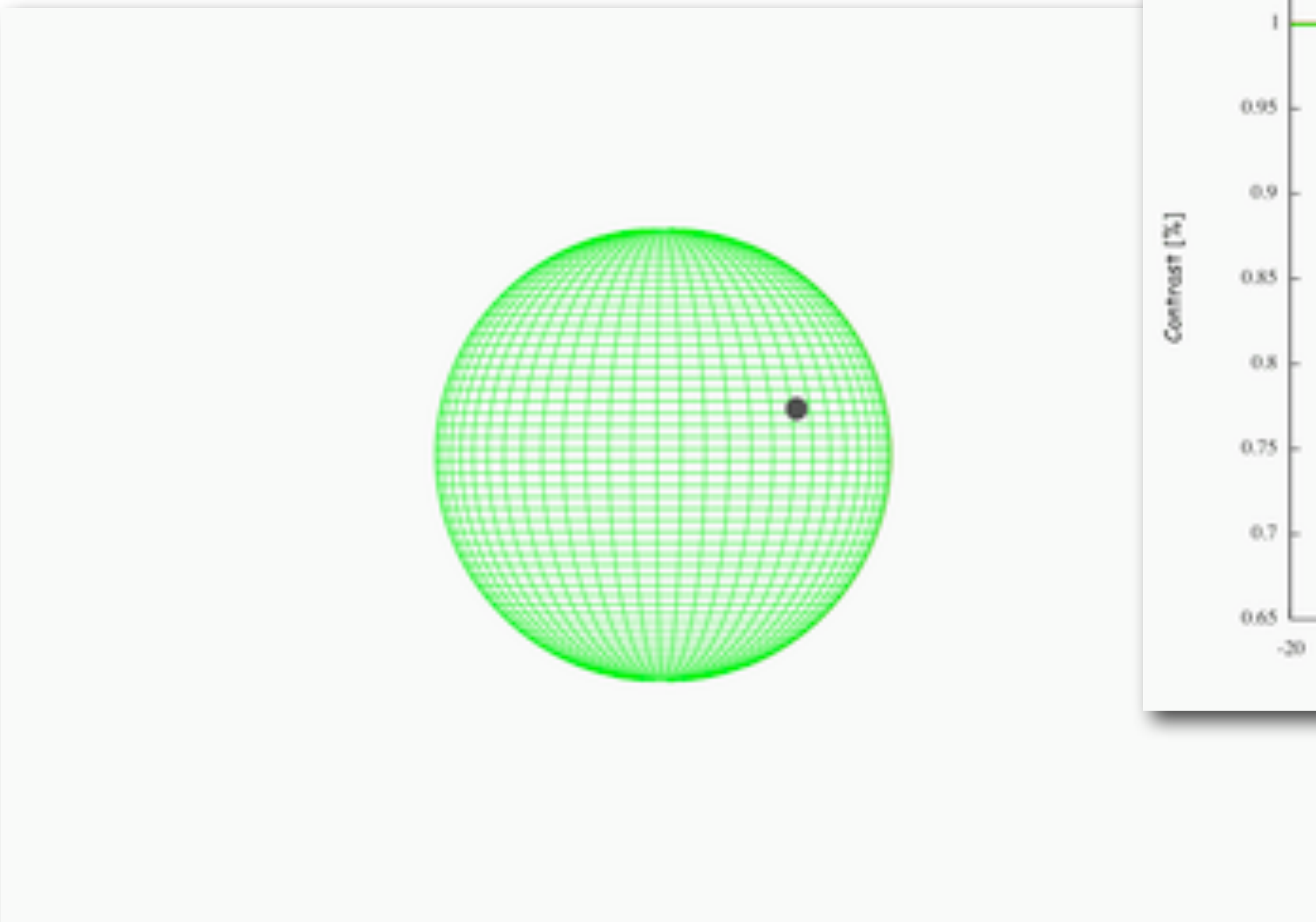
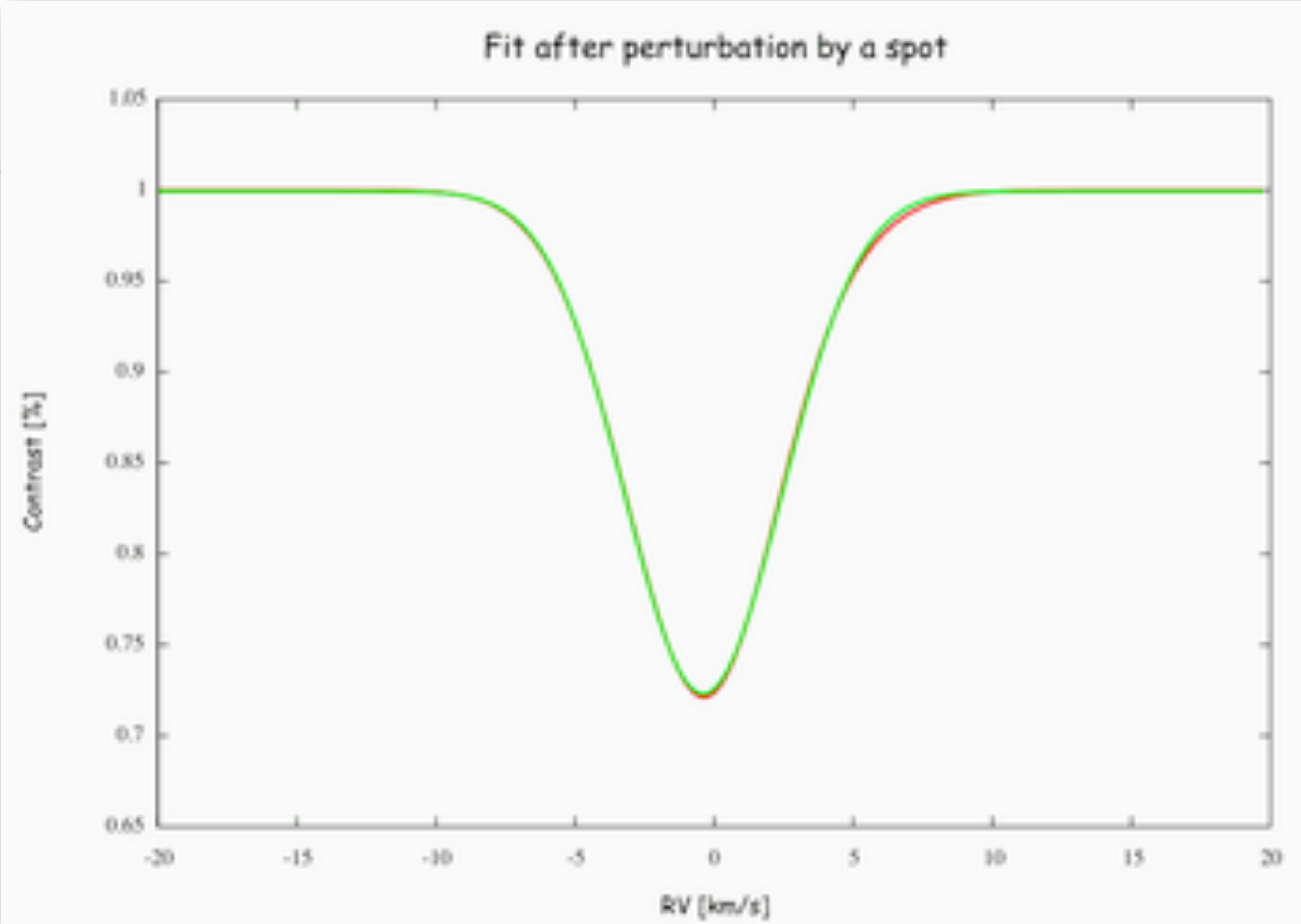
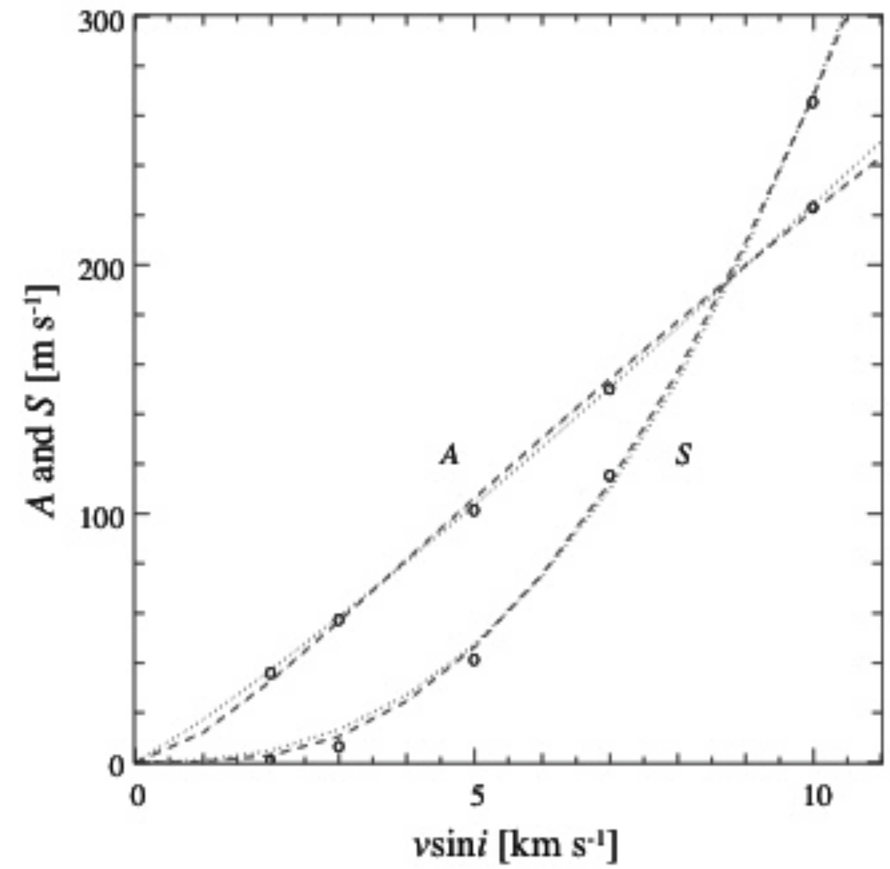




Stellar line deformation creates a RV signal!

Spots mimicking Planets

Bisector measures the line profile and can be used to identify spots' effect

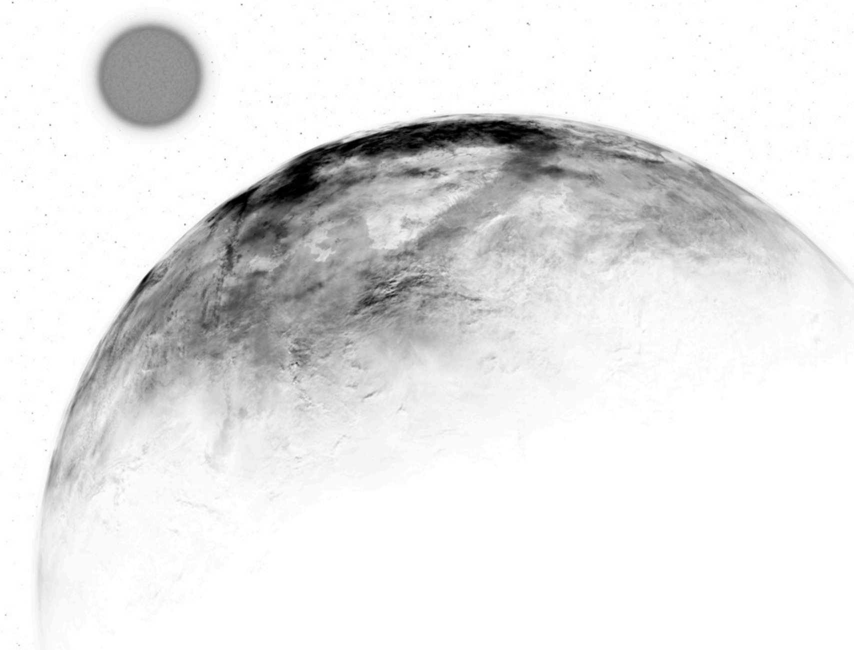


Desort et al. (2007)

Detectability of bisector variation decreases faster than the impact of line asymmetries on RV (Sahar & Donahue 1992)

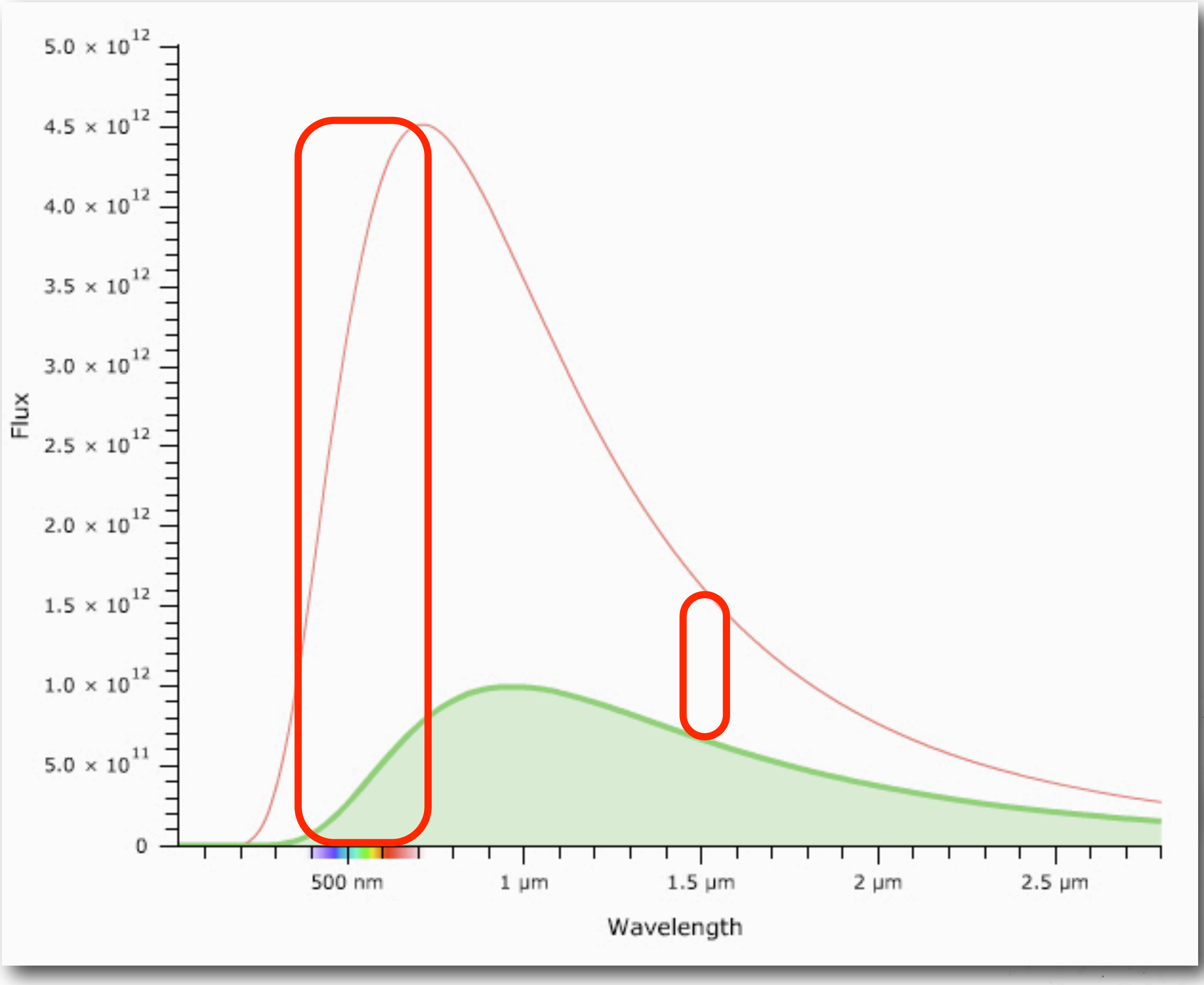
Photometry and Ca II indicators can be used too but **none** of the three is **100% efficient**

We need a better diagnosis method!



Spots mimicking Planets

If an RV signal is created by a spot, it results from the contrast between the stellar disk and the cold spot

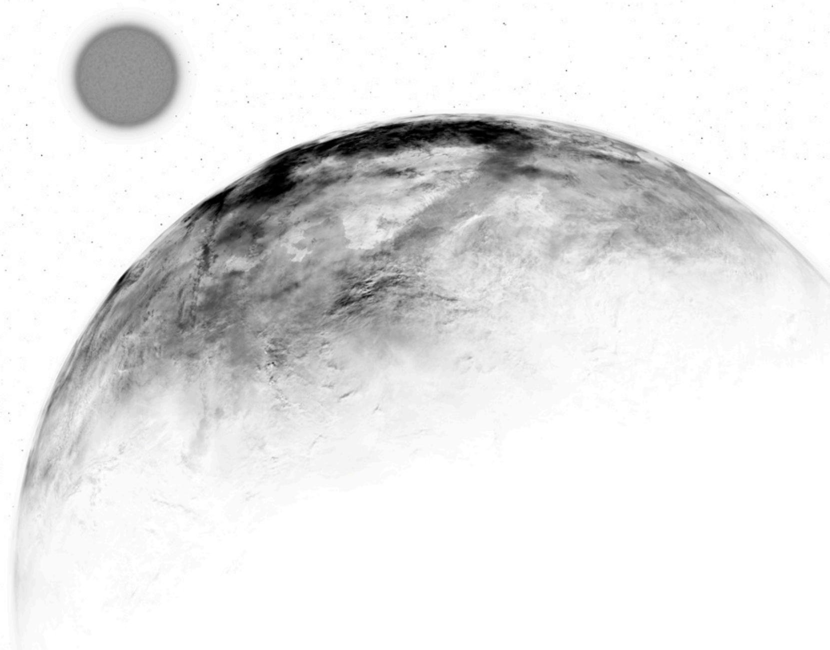


If we observe in the IR, the amplitude of the effect will be significantly reduced!

Exploring the near-IR

The infrared presents some unique technical challenges:

- Cold Optics and Detector Properies (CMOS vs CCD) ;
- Atmospheric Features;
- Establishment of a reliable RV calibrator.



CRIRES

The **CR**yogenic high-resolution **I**nfra**R**ed **E**chelle **S**pectrograph was developed by ESO and mounted on VLT UT1

Explores the spectral range from **0.95 to 5.4 μm** with a simultaneous wavelength coverage of **λ/70** and provides a **R** of up to **100 000**

The detectors are four Aladdin III InSb arrays and a MACAO system is used to optimize the signal-to-noise ratio and the spatial resolution.

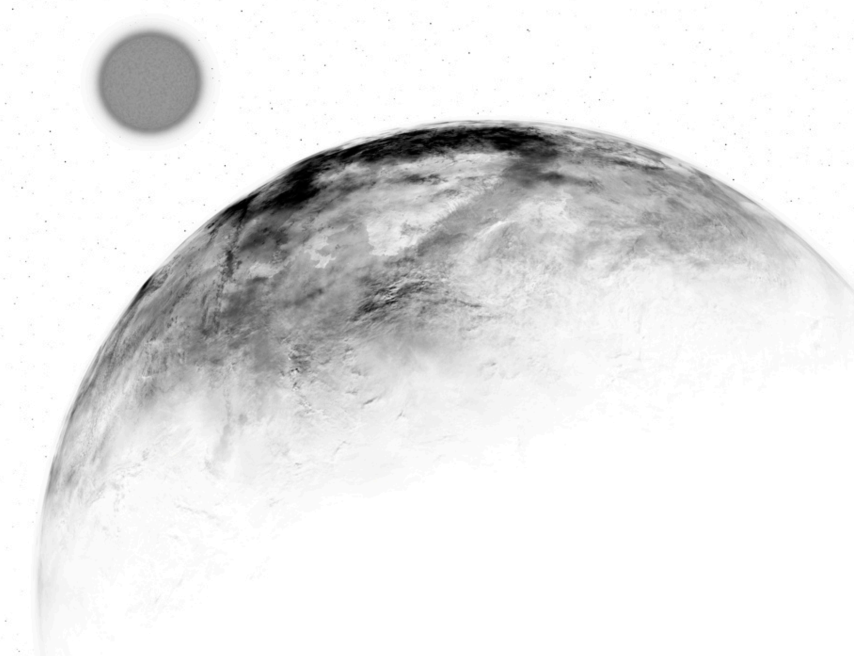
In order to reach m/s precision, we need a **simultaneous** wavelength calibration technique.

Calibrating Spectrographs

CRIRES is, by construction, stabilized in Pressure and Temperature: small instrumental IP variations

Several authors have proved back in the 80's that optical O_2 atmospheric lines were very stable, down to *5 m/s*

Are there nIR equivalents that being sharp, deep and easy to identify, provide for a reliable wavelength calibration, without introducing confusion in our spectra?



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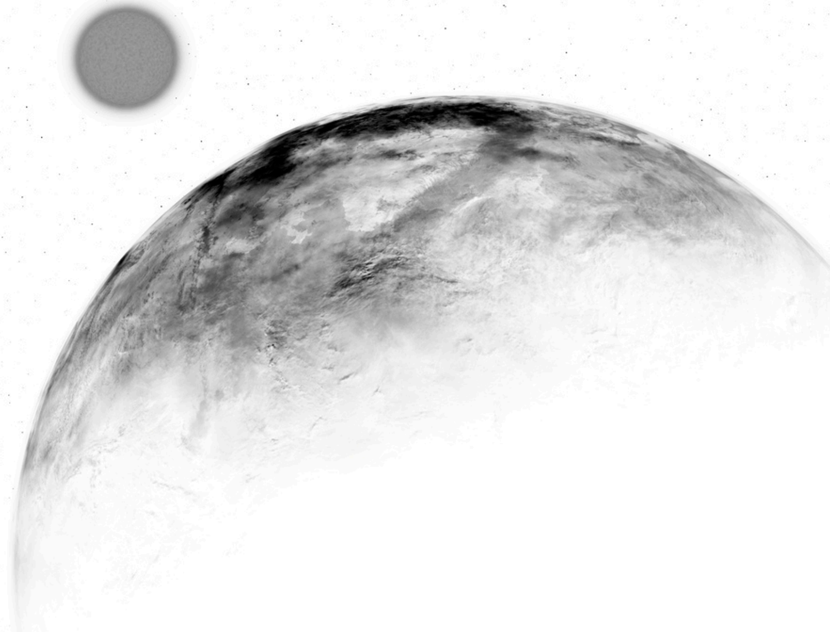
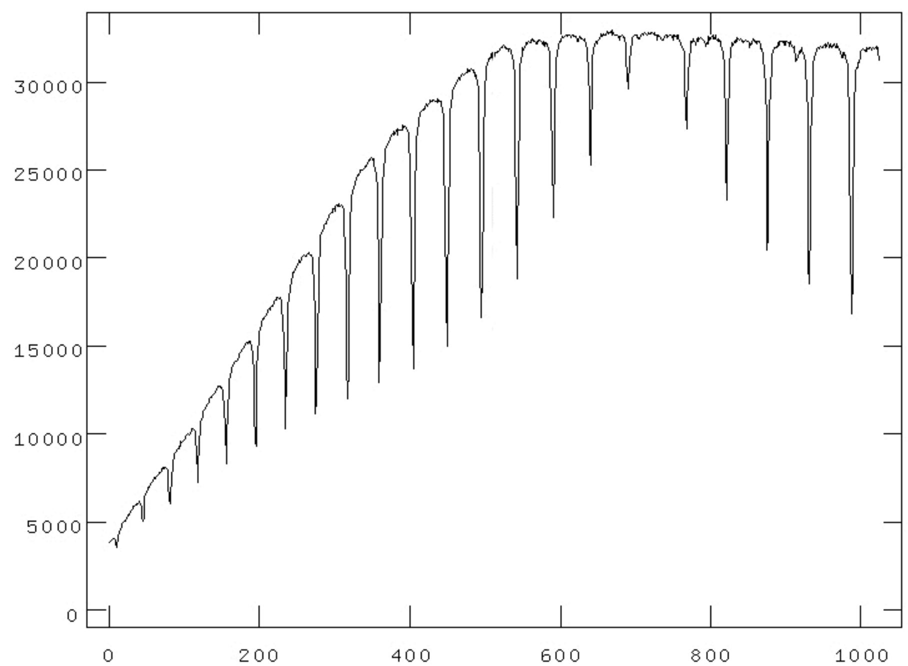
CO_2 lines provide for all these characteristics, creating a ready to use, always present gas cell!

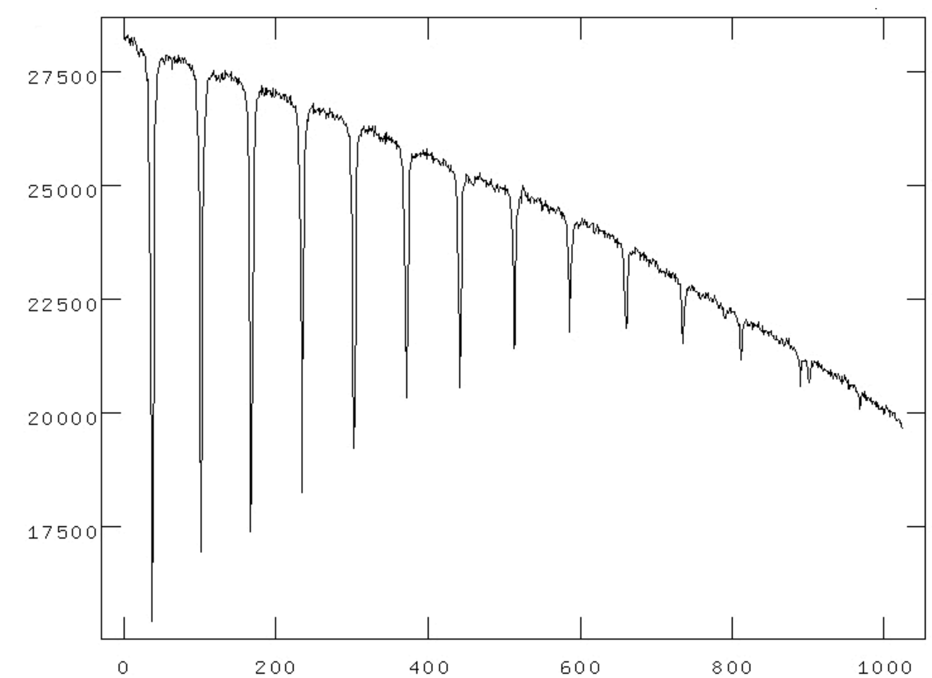


Calibrating Spectrographs

We observed TW Hya with CRIRES in the H band, domain where we could use the atmospheric CO_2 lines as wavelength reference



Det. 1

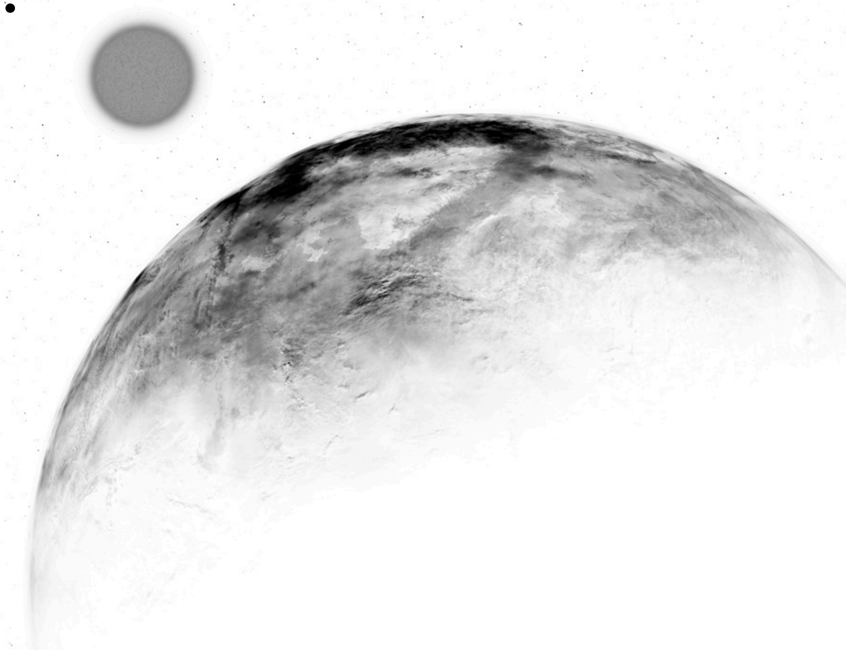


Det. 2

The science observations were followed by the measurement of a RV standard, HD108309, known to be stable down to 5 m/s, to correct for unaccounted systematics

Calibrating Spectrographs

- In order to reduce the illumination effects on the RV the observations are done without AO (and with the smallest slit);
- Note that the atmospheric lines go through the same optical path as the science target, and provide for on-spectra calibration;
- The wavelength calibration is calculated independently for each spectrum, i.e., each nodding position.



Data Reduction

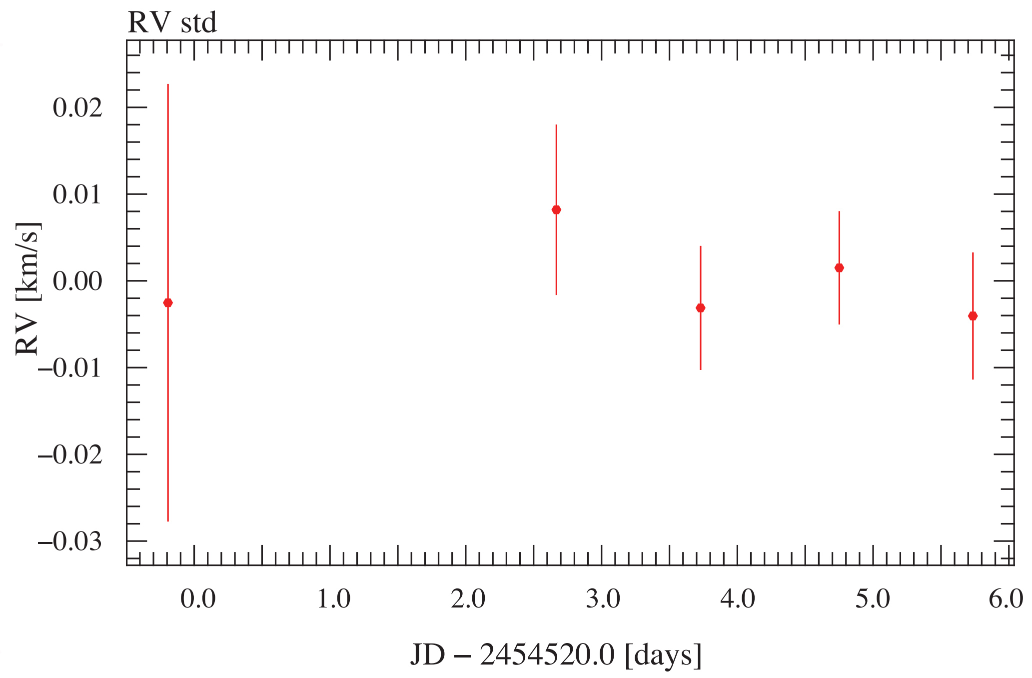
The data were reduced using a custom pipeline, programmed in IRAF, that performed:

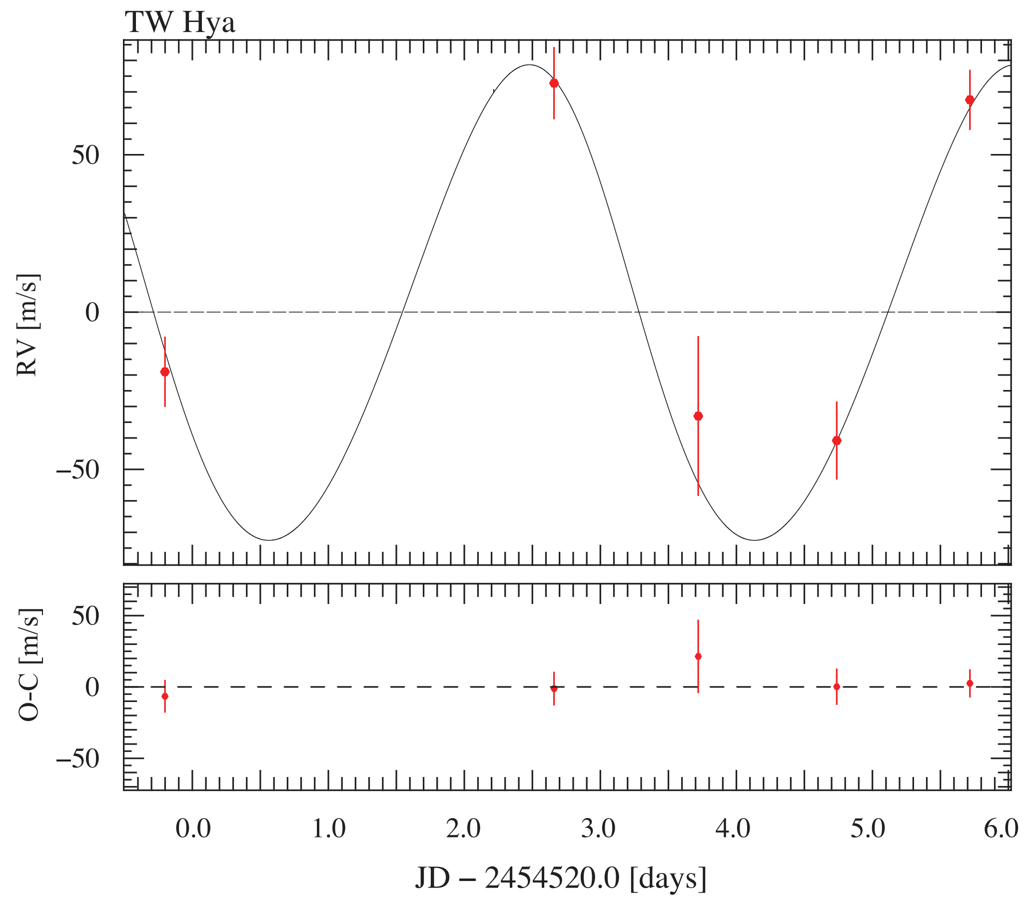
- dark subtraction;
- linearity correction;
- flat-fielding, corrected for spectrograph blaze function variation;
- nodding subtraction to correct for artifacts.

The data products were analyzed by a Geneva-inspired pipeline which:

- fitted a wavelength solution on each individual frame;
- performed a correlation with a stellar template mask, clean from telluric pollution;
- corrected for earth movement around the Sun, delivering heliocentric RV's.

TW Hya by CRIRES

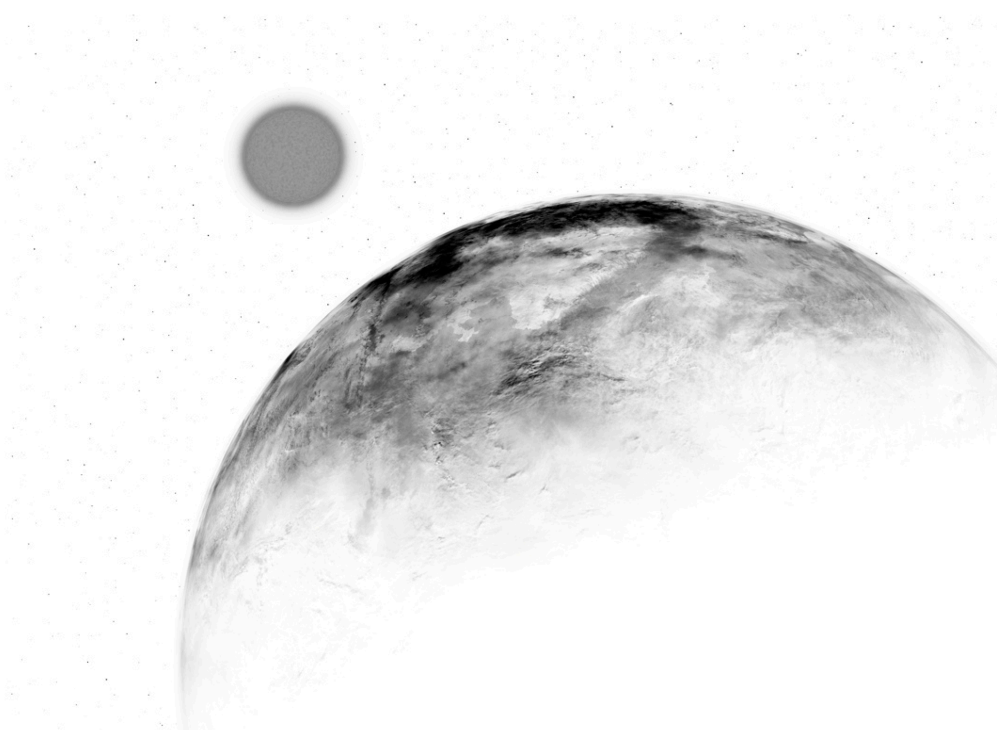




For the standard star we reached, over a time-span of 6 days:

5 m/s r.m.s.!

Figueira et al. 2010, A&A 511A, 55



Gl86 by CRIRES

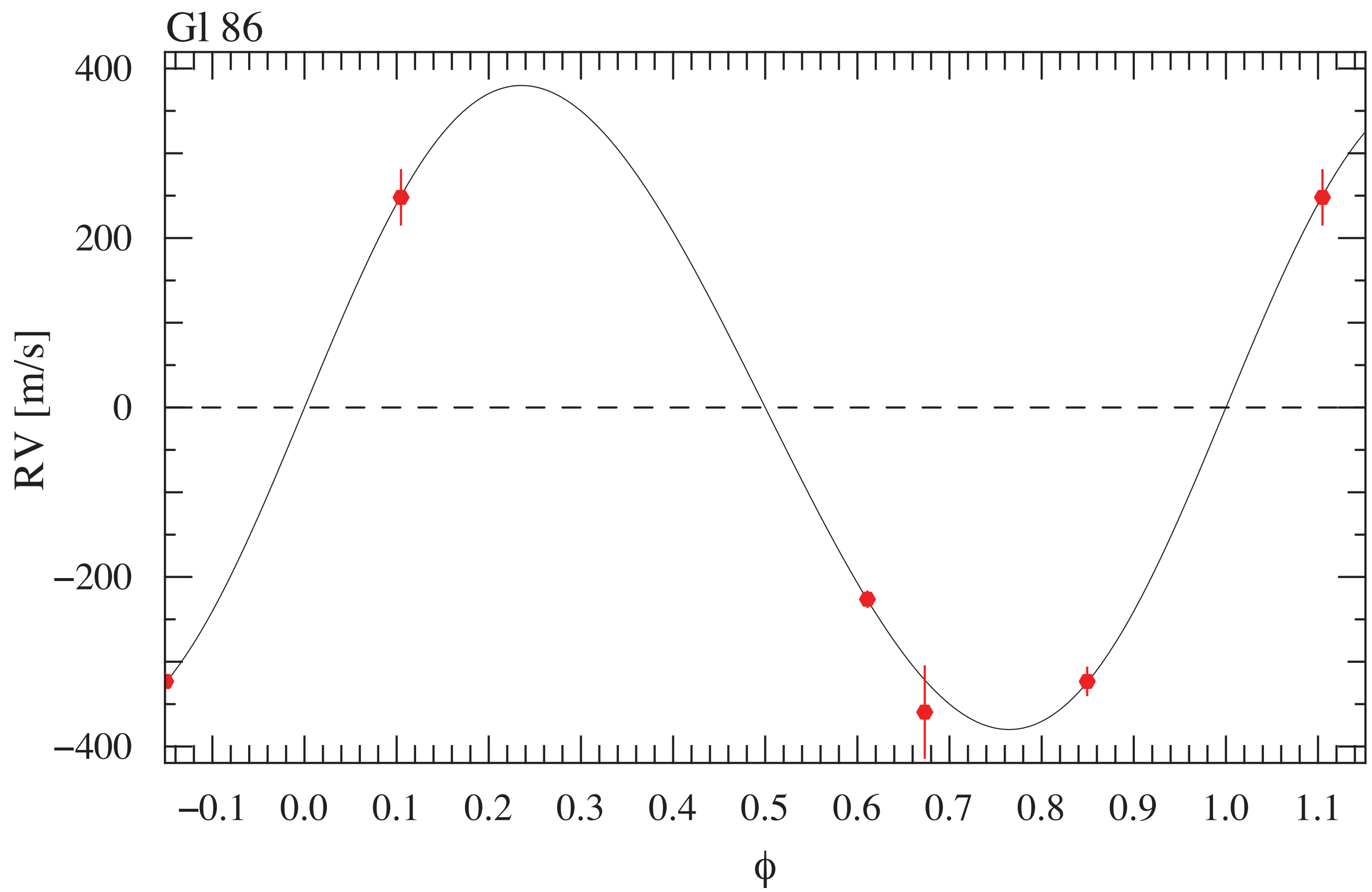


Table 1. Orbital elements of Gliese 86 after correction of the 0.36 m s^{-1} d^{-1} linear drift of the γ-point.

P	15.78	$\pm$ 0.04	d
T	2451146.7	$\pm$ 0.2	d
e	0.046	$\pm$ 0.004	
$V_r^{\dagger}$	56.57	$\pm$ 0.01	km s^{-1}
ω	270	$\pm$ 4	$^{\circ}$
K_1	380	$\pm$ 1	m s^{-1}
$f_1(m)$	$8.9 \cdot 10^{-8}$	$\pm\ 0.1 \cdot 10^{-8}$	$M_{\odot}$
$(O-C)^{\ddagger}$	7		m s^{-1}
N	61		

(†) At $T_0 = 2451150$ d
(‡) Without the drift correction the O-C of the fit would be 13 m s^{-1}

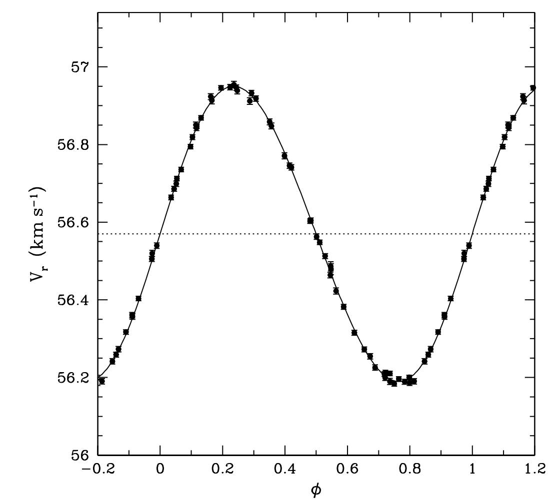
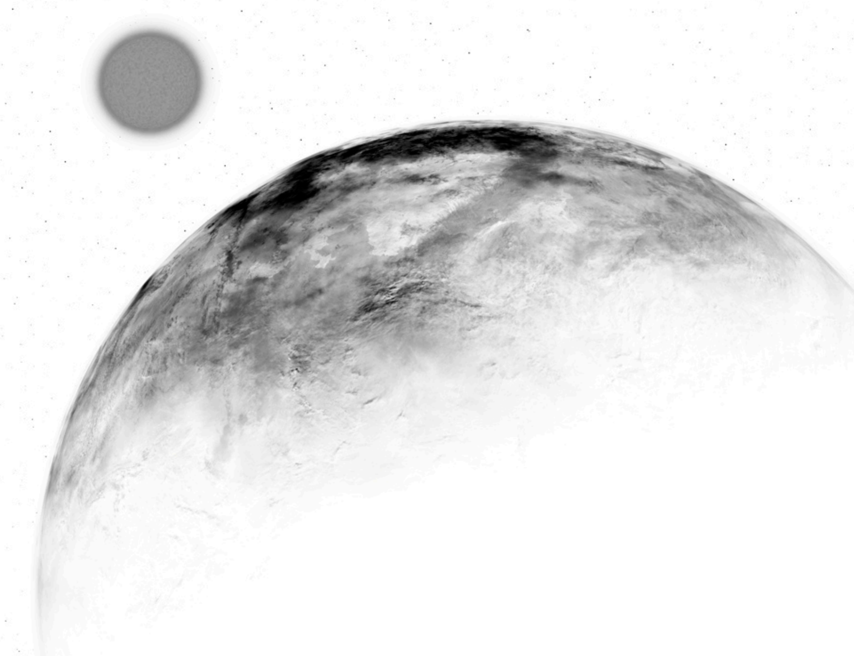


Fig. 1. Phased orbital motion of Gliese 86 corrected from the long term drift. The solid line is the best fit orbit. See orbital elements in Table 1

Queloz et al. 2000, A&A 354, 99



CRIRES data reproduces well the published orbit!

Figueira et al. 2010, A&A 511A, 55

Noise analysis

	External Dispersion [m/s]	Intra-Night Dispersion [m/s]	Photon Noise [m/s]	(O–C) [m/s]
RV std	5.77	7.03	6.48	—
TW Hya	54.57	12.12	12.10	7.93
Gl 86	122.47	12.77	7.62	5.41

The different RV precision indicators on the RV std, TW Hya, and Gl 86.

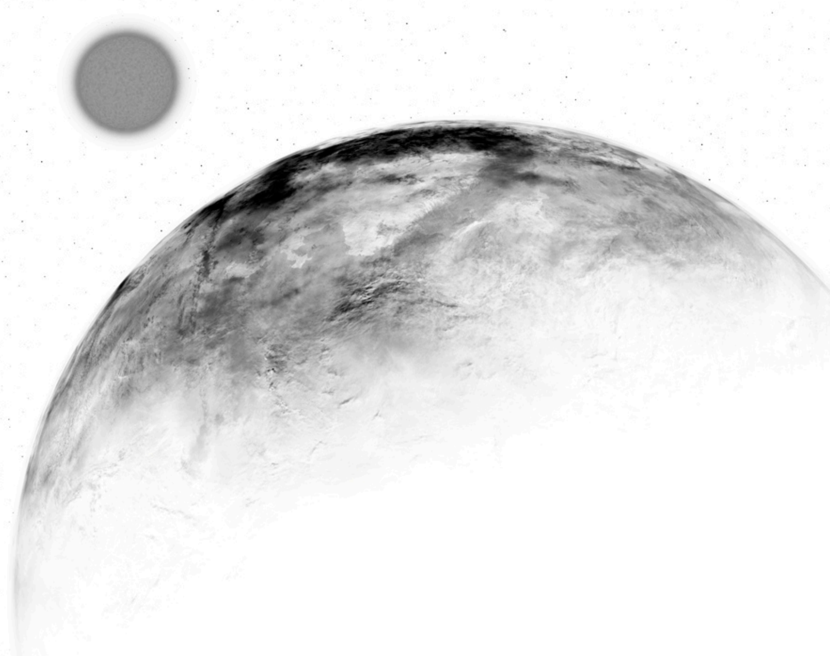
Figueira et al. 2010, A&A 511A, 55

The scatter is very similar to that delivered by photon noise estimators.

Note we have 20 spectra for RV std, 20 for TW Hya and 24 for Gl 86.

The question that remains is...

How stable are atmospheric lines?



Atmospheric Lines

HARPS:

We selected 3 bright stars which were observed routinely during 6 years and with high-cadence data-sets:

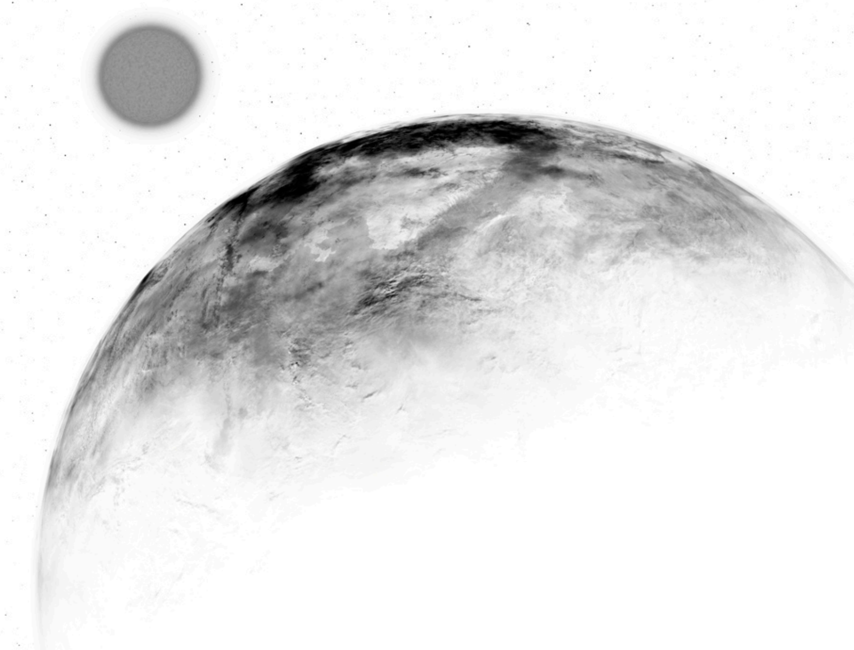
Target	# of observations	# of days with observations	$\overline{\text{\#observations/day}}$	time span [d]	$\overline{\text{S/N}}$
Tau Ceti	5270	110	47.9	2308	260
μ Ara	2868	117	24.5	2303	176
ϵ Eri	1527	104	14.7	2217	316

Table 1. The summary of the data set properties for the stars used in this paper. Note that the S/N is calculated at the center of order 60.

And we correlated them with a telluric mask drawn from HITRAN database.
In this mask we used only O_2 lines.

Target	σ [m/s]	σ_{ph} [m/s]
Tau Ceti	10.74	0.98
μ Ara	10.31	1.35
ϵ Eri	10.82	0.76

Table 2. The dispersion and photon noise of the stars used in our campaign.



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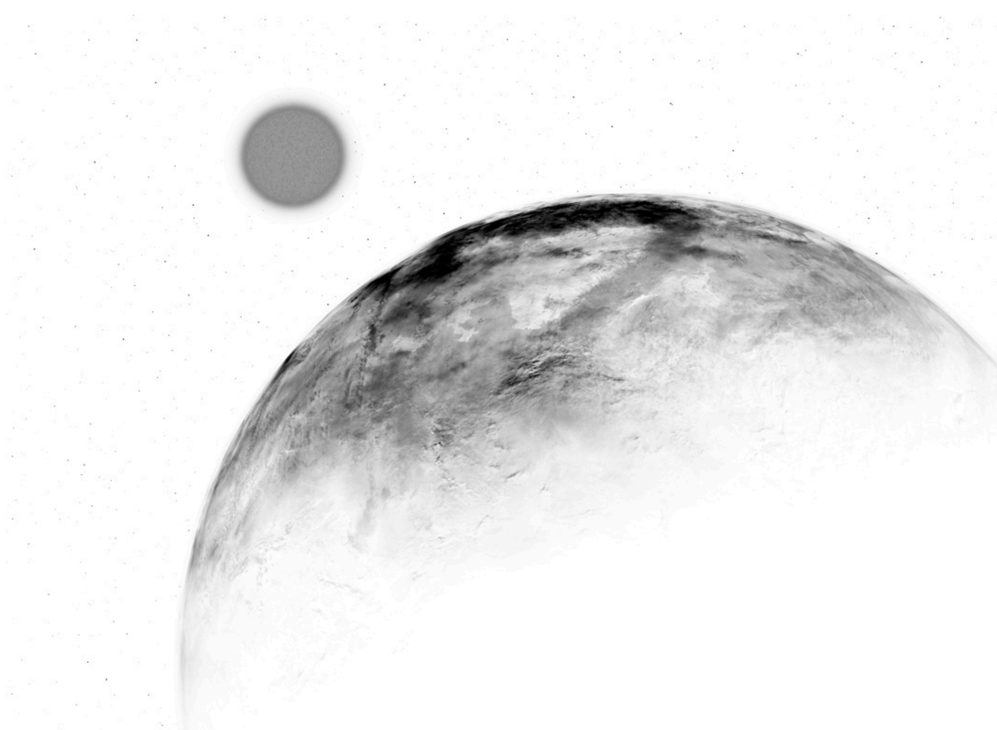

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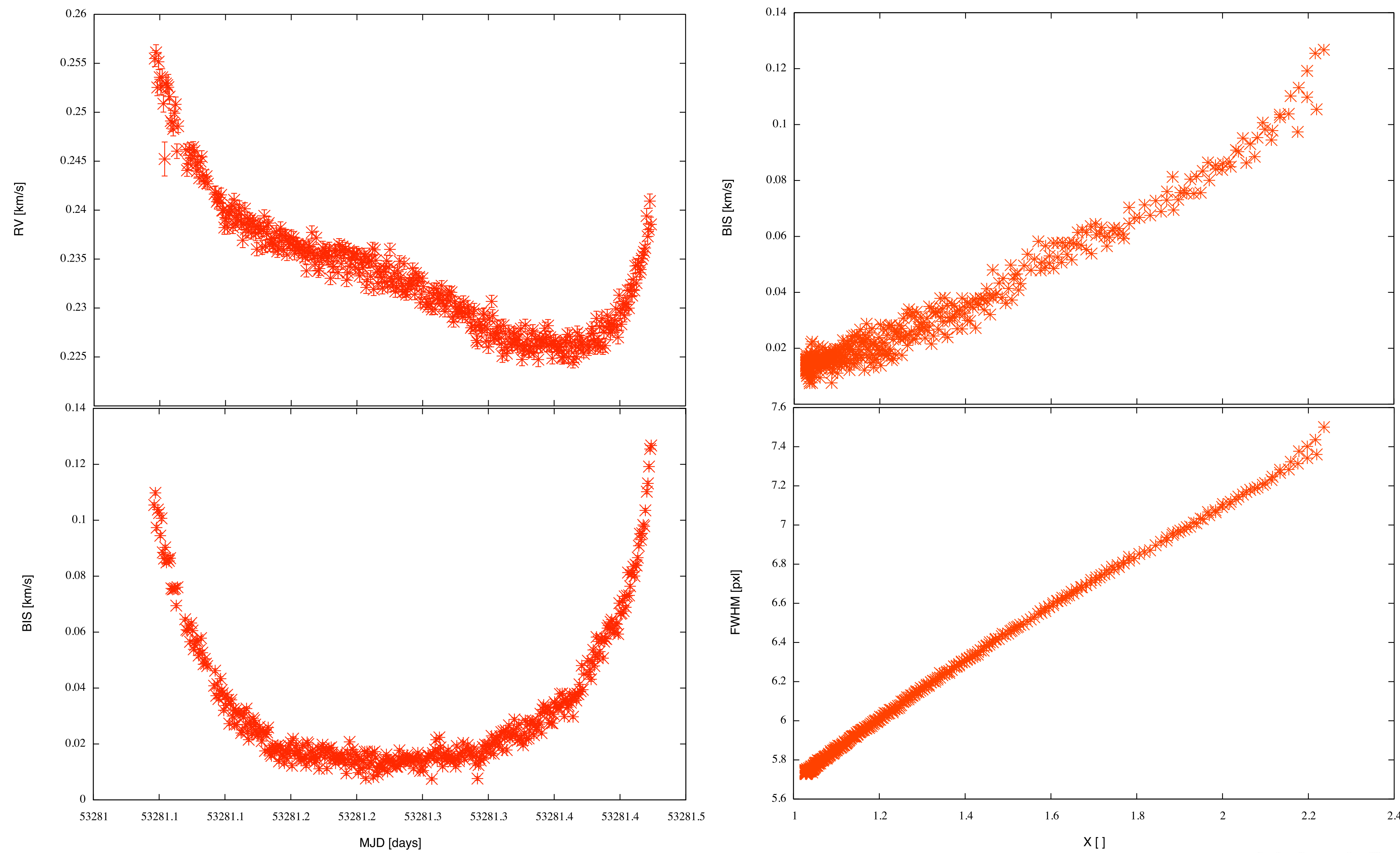


Fig. 2. Telluric RV measurements on Tau Ceti over a full night. Note the clear shape drawn by the RV *(left panel, top)* and the associated bisector *(left panel, bottom)* as function of time. In the right panel we depict the correlation between BIS and airmass *(right panel, top)* and FWHM and airmass *(right panel, bottom)*. The plotted errorbars in RV and BIS correspond to photon errors. Photon errors in the BIS are approximated to be twice the RV errors.

The variation within the 10 m/s is not white noise!

Atmospheric Lines

Let us fit the measured RV variations:

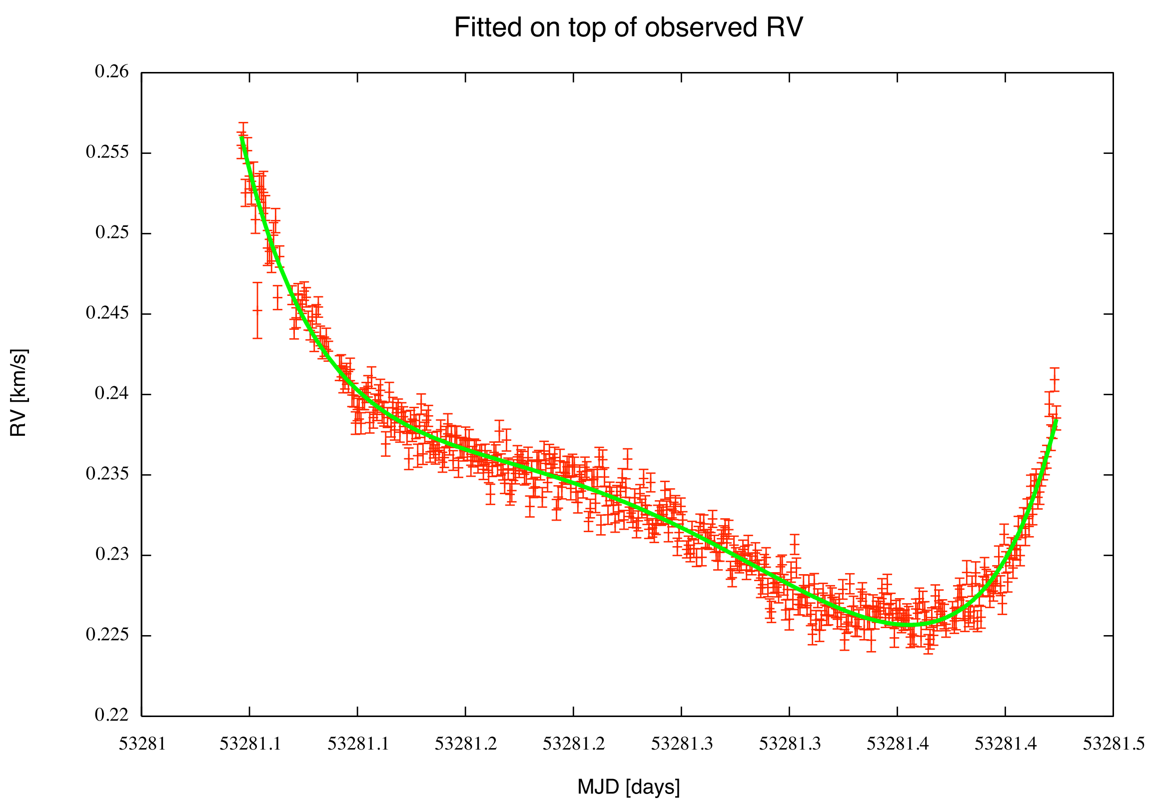


Fig. 2. The fit of atmospheric variation for the first night of the asteroseismology run of Tau Ceti. The fitted model is described by Eq. 2 and the parameters are presented in Tab A.1.

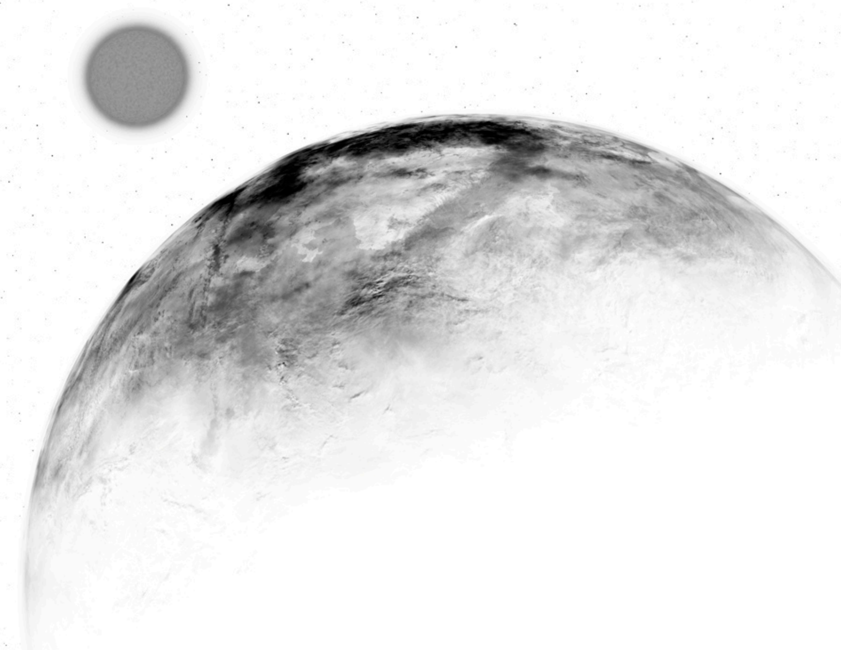
$$\Omega = \alpha \times \left(\frac{1}{sin(\theta)} - 1\right) + \beta \times cos(\theta) \times cos(\phi - \delta) + \gamma$$

α - wind speed per airmass unit [m/s]
β - average horizontal wind speed [m/s]
γ - spectral line zero-point [m/s]
δ - wind direction [ ]

θ - telescope elevation [ ]
φ - telescope azimuth [ ]

The residuals correspond to less than twice the photon noise - down to 2 m/s!

Figueira et al. 2010, A&A, 515A, 106



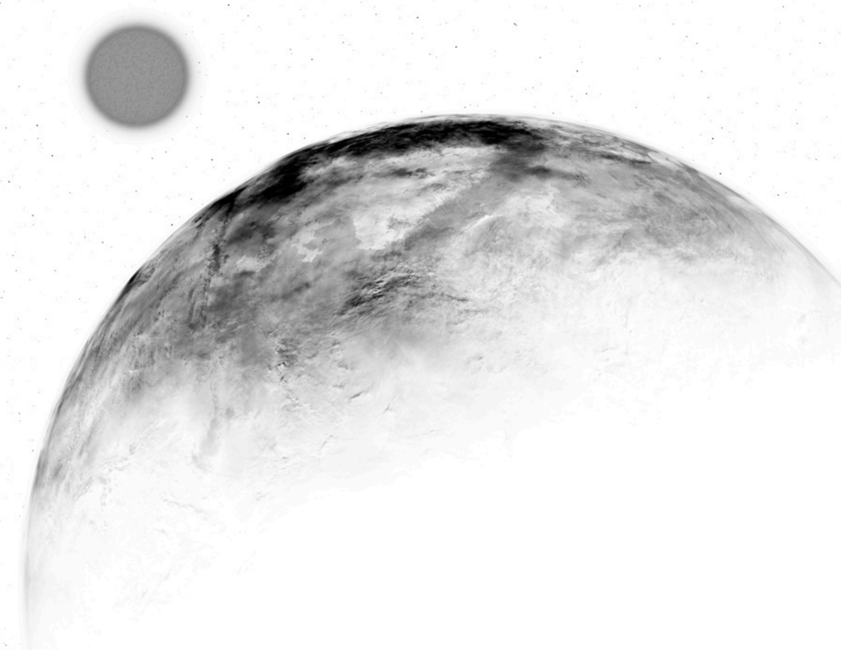
Atmospheric Lines

Let us fit the measured RV variations:

Target	data set	#obs	σ [m/s]	$\sigma_{(O-C)}$ [m/s]	σ_{ph} [m/s]	χ^2_{red}	α [m/s]	β [m/s]	γ [m/s]	δ [^{o}]
Tau Ceti	2004-10-03	437	6.40	1.67	0.64	†	17.75	43.39	222.01	-167.21
	2004-10-04	438	7.98	1.33	0.65	†	—	27.89	—	-154.15
	2004-10-05	599	7.12	2.03	0.79	†	—	15.17	—	-133.95
μ Ara	2004-06-04	278	6.90	1.90	1.27	†	—	33.27	—	-155.37
	2004-06-05	274	8.35	2.50	1.30	†	—	29.34	—	-140.20
	2004-06-06	285	8.94	1.72	1.11	†	—	27.45	—	-136.20
	2004-06-07	286	4.48	1.60	1.03	†	—	23.62	—	-165.43
	2004-06-08	275	3.98	1.81	1.07	†	—	36.61	—	-168.70
	2004-06-09	214	6.88	4.02	1.34	†	—	41.89	—	-164.93
	2004-06-10	202	6.92	2.55	1.81	†	—	41.74	—	-142.11
	2004-06-11	273	8.41	3.51	2.07	†	—	48.87	—	-155.55
Both stars	all data	3562	11.79	2.27	1.09	4.01				

Notes. In this fit, α and γ are imposed to be the same for all data sets. Since the fit is made simultaneously for all data sets, the χ^2_{red} calculation is not applicable for a single night and the respective table entries are indicated by a †. The table structure is left unchanged to allow for an easier comparison with Tables A.1 and A.2. Note that δ=0 corresponds to the south-north direction.

Table 3. The fitted parameters and data properties, before and after the fitted model is subtracted from it.



Even in the most strict stituation the model provide a very good description of the measured RV

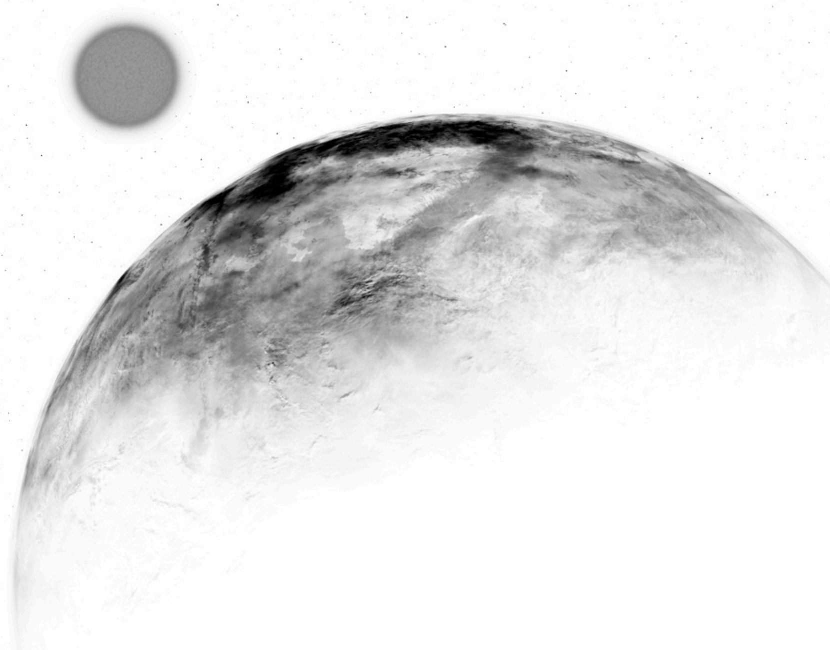
Figueira et al. 2010, A&A, 515A, 106

Food for thought

- With our method, we separated two aspects that contributed to error budget: atmospheric lines ***stability*** and atmospheric lines ***contamination***;

- Even if one doesn't want to use the atmospheric lines as a reference, their ***characterization is necessary*** to ***ensure a precise modeling***;

- The larger the time-span of observation and the wider the spectral range of the spectrograph, ***more difficult*** the ***characterization*** will be.



Conclusions

- By observing in the IR one can reduce the effect of spots on RVs and tell spots from planets;
- CRIRES can deliver precise RVs using atmospheric lines as reference, as the data on TW Hya, Gl 86, and the new datasets testify;
- Atmospheric Lines are stable down to 10 m/s over a 6 years timescale and down to 2 m/s if you correct for atmospheric effects.