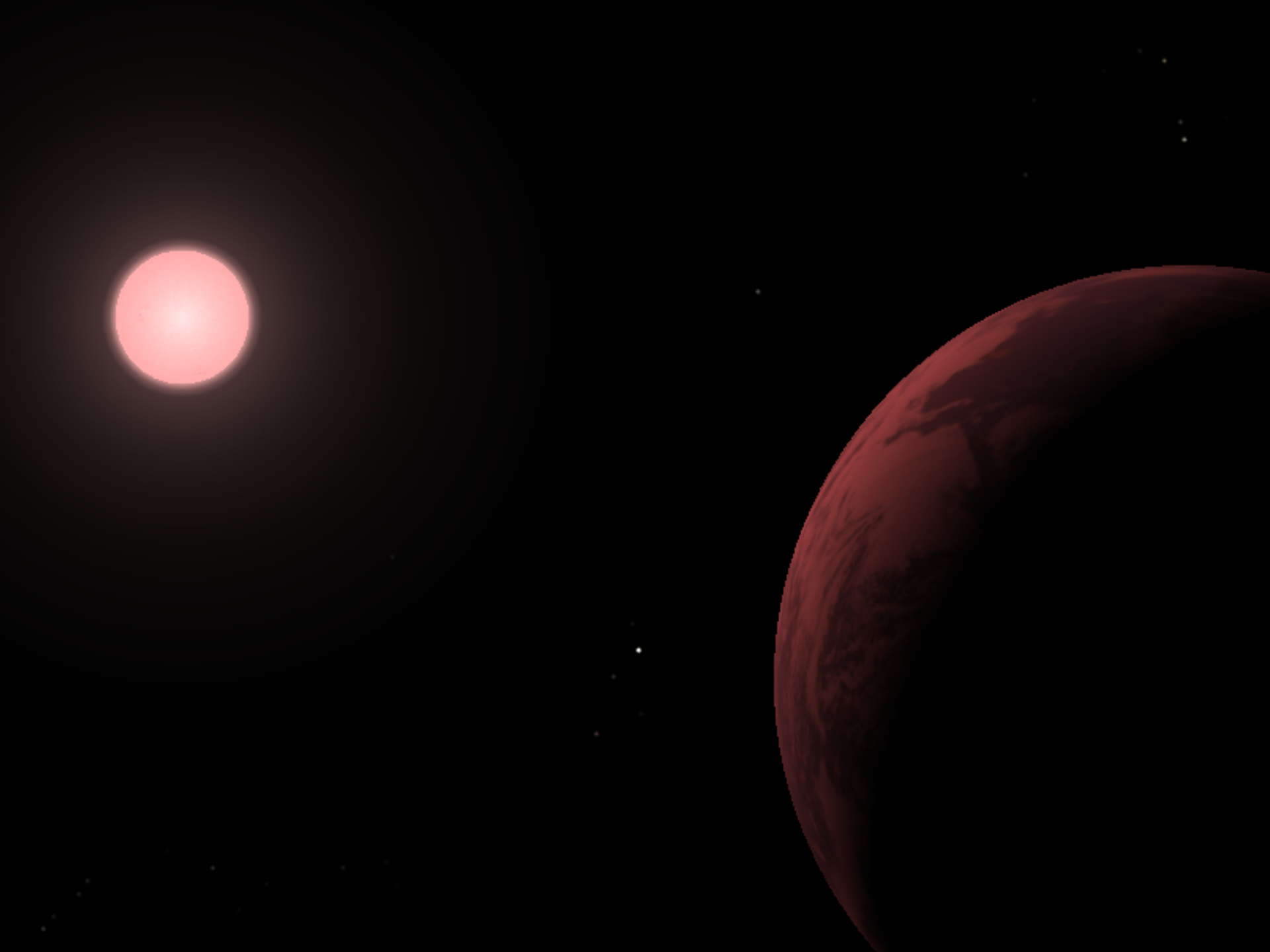




Beyond 1 m/s : advances in precision Doppler spectroscopy

Guillem Anglada-Escude

Postdoctoral scientist

Georg-August-Universität Göttingen

Institute for Astrophysics

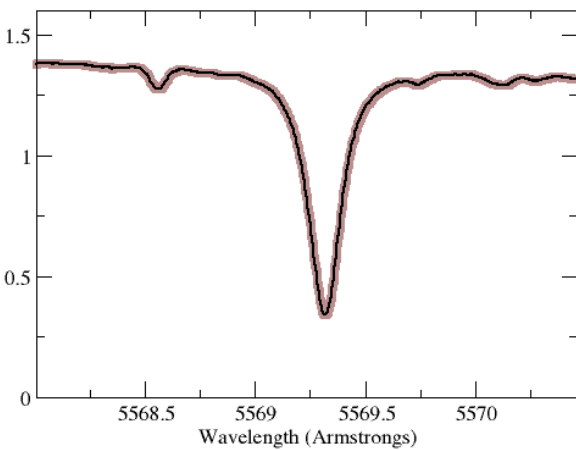
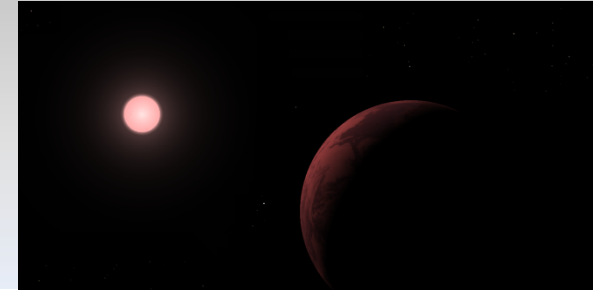
Oct 2012



Ansgar Reiners, Mathias Zechmeister (U. Goettingen)
Paul Butler, Steve Vogt (UCSC-Carnegie)
Mikko Tuomi, Hugh Jones, John Barnes (Hertfordshire Univ.)
James Jenkins (U. Chile)
Enrico Gerlach (TU Dresden)
Peter Plavchan (IPAC)

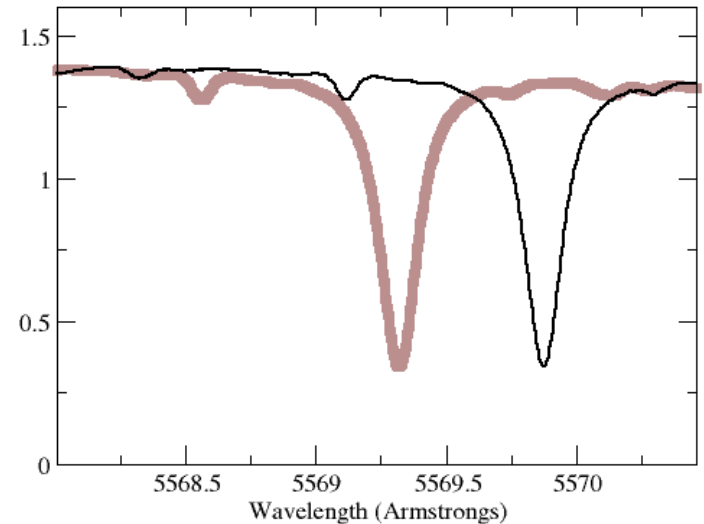


Precision radial velocities



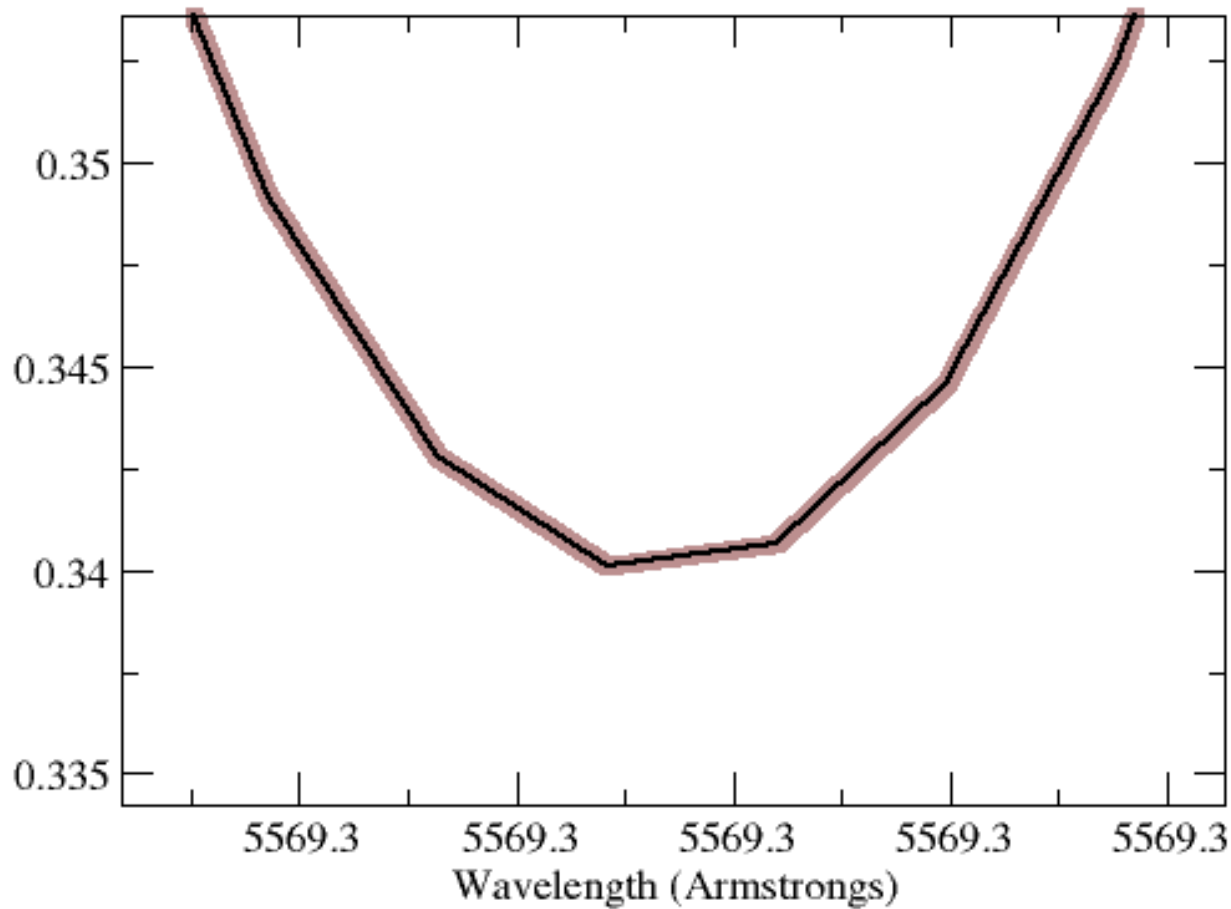
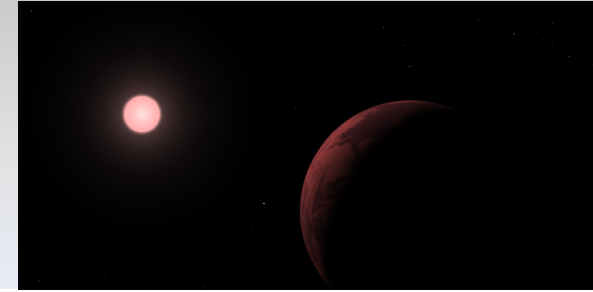
**Width of a typical
solar line is 15 km/
s**

**Spectroscopic
binary
 $K=30$ km/s**



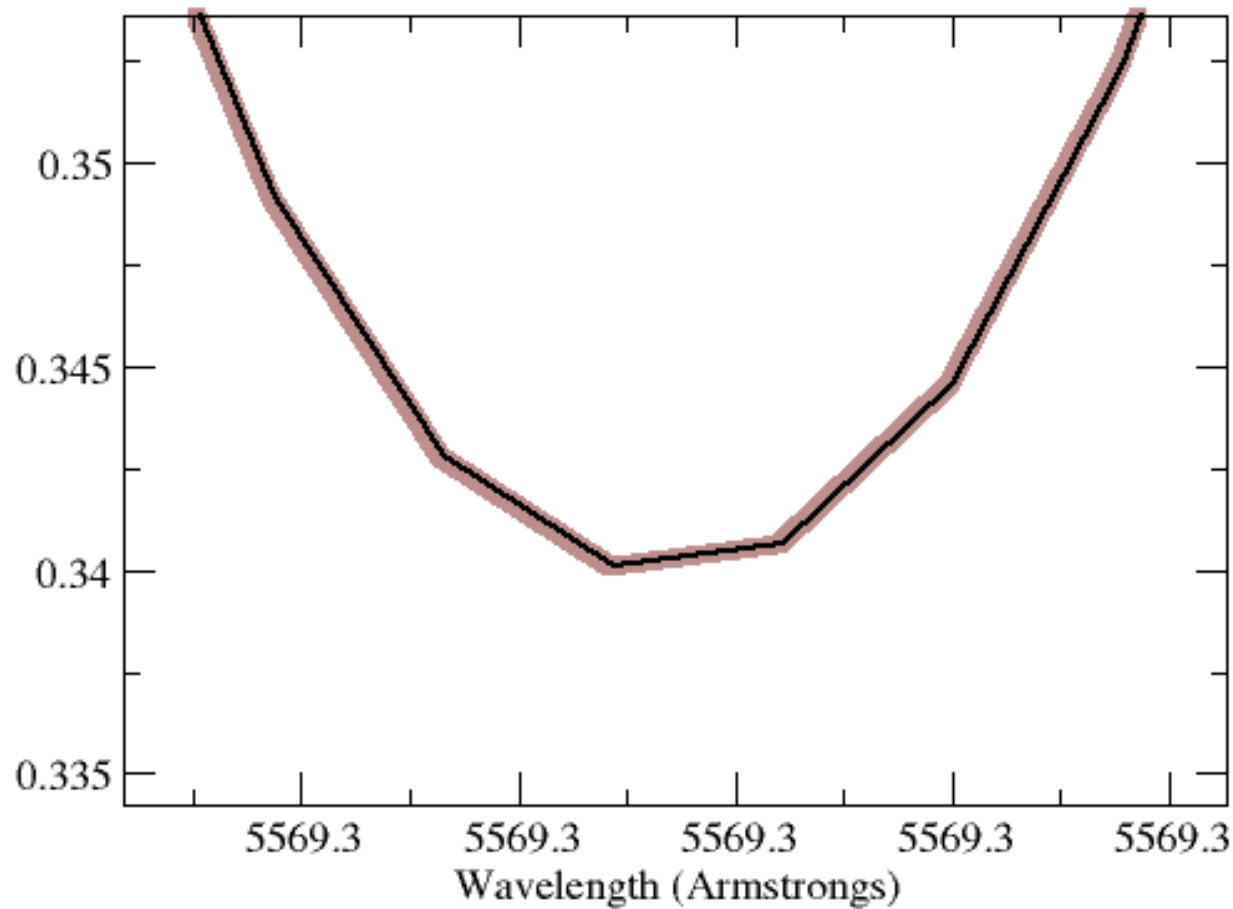
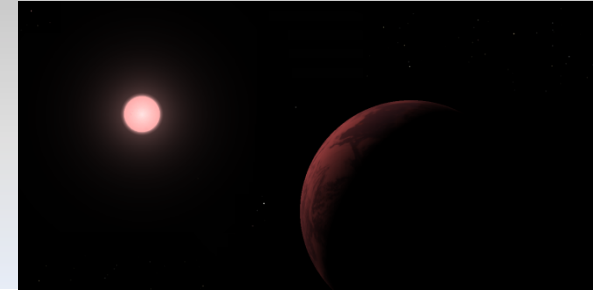
Super-Earth -> 1/10 000

Precision radial velocities



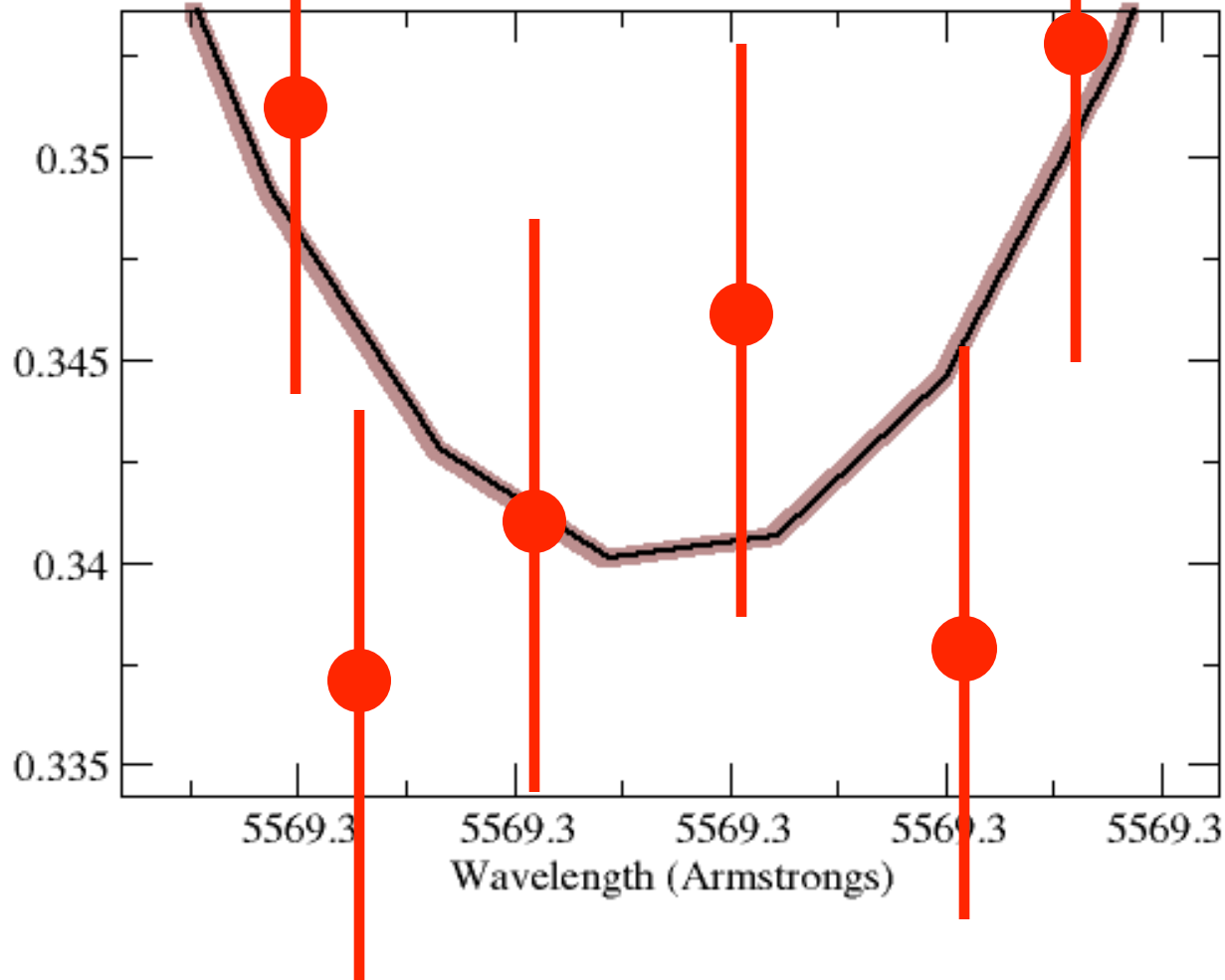
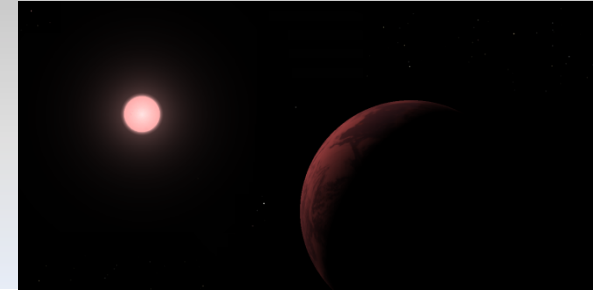
0 m/s

Precision radial velocities



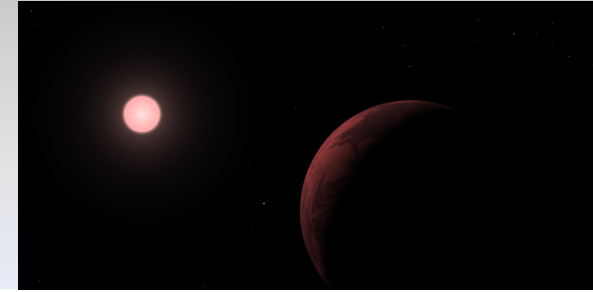
+ 3 m/s

Precision radial velocities



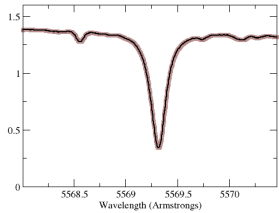
+ 3 m/s

Precision radial velocities



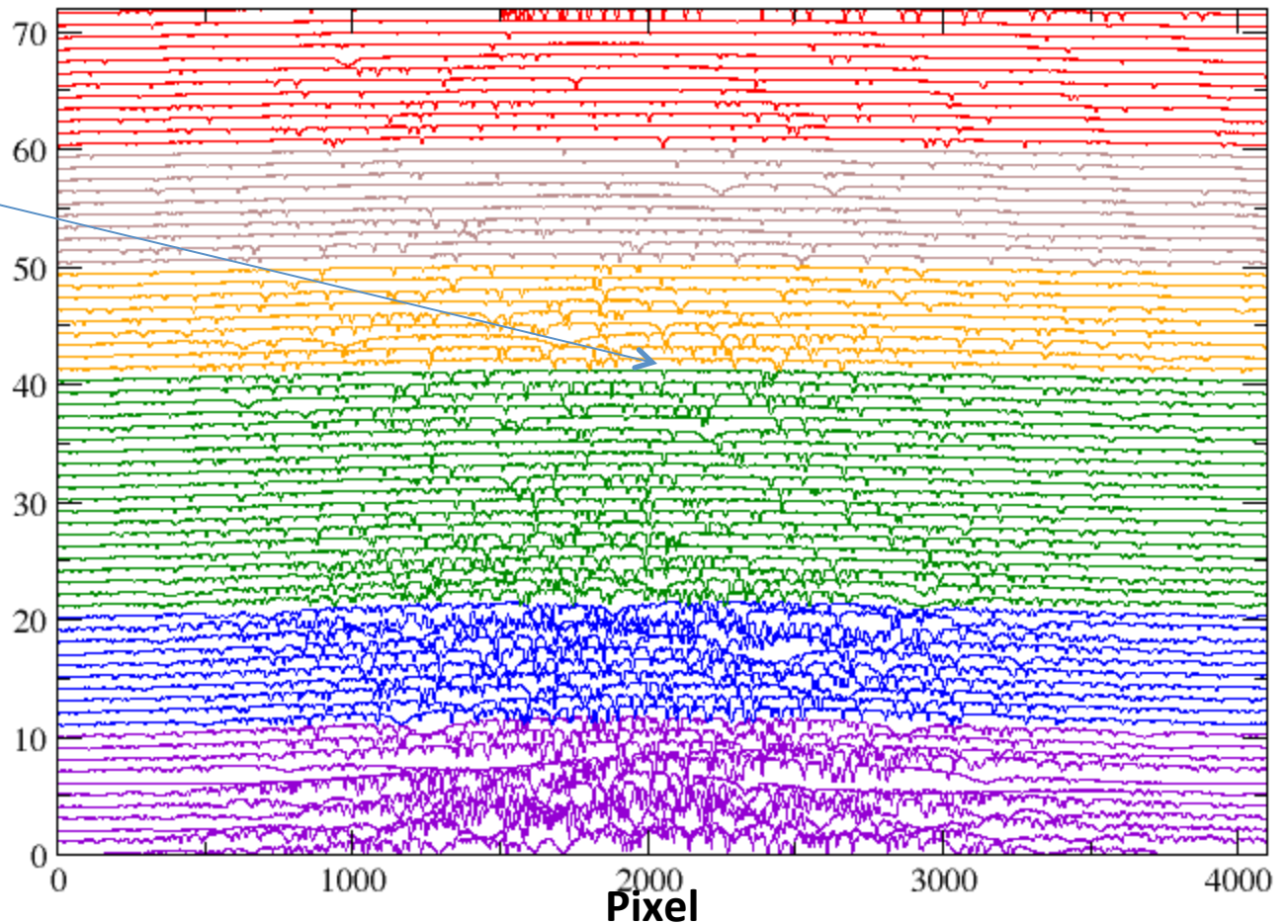
Tau Ceti G8.5V

6900 Å

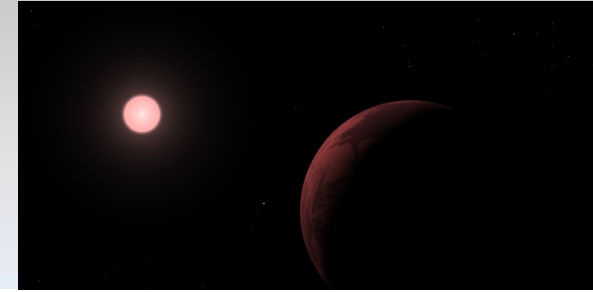


Order

3800 Å

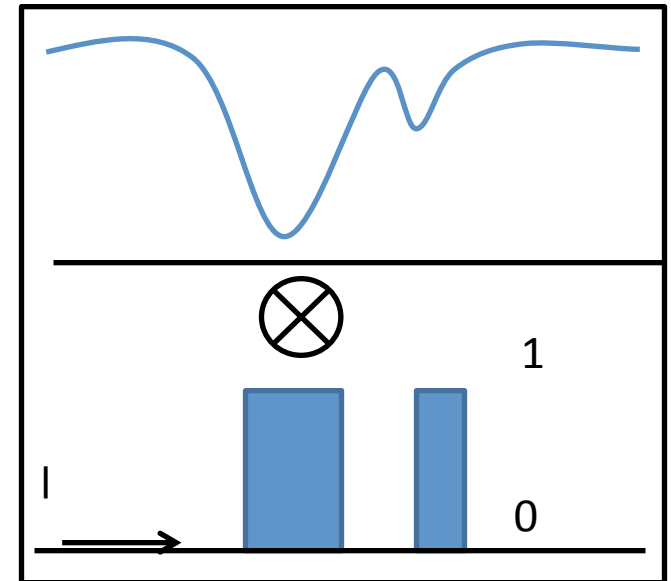
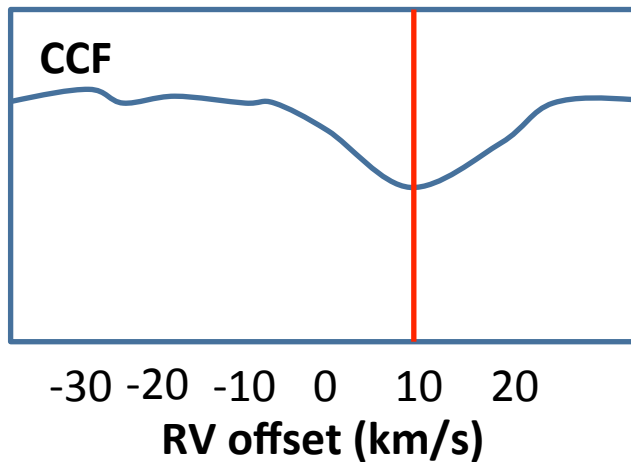


HARPS-Data Reduction Software

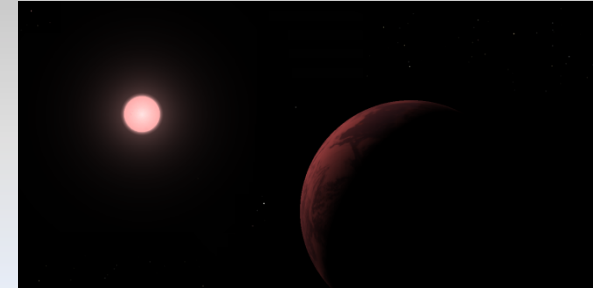


Cross Correlation Function (CCF)

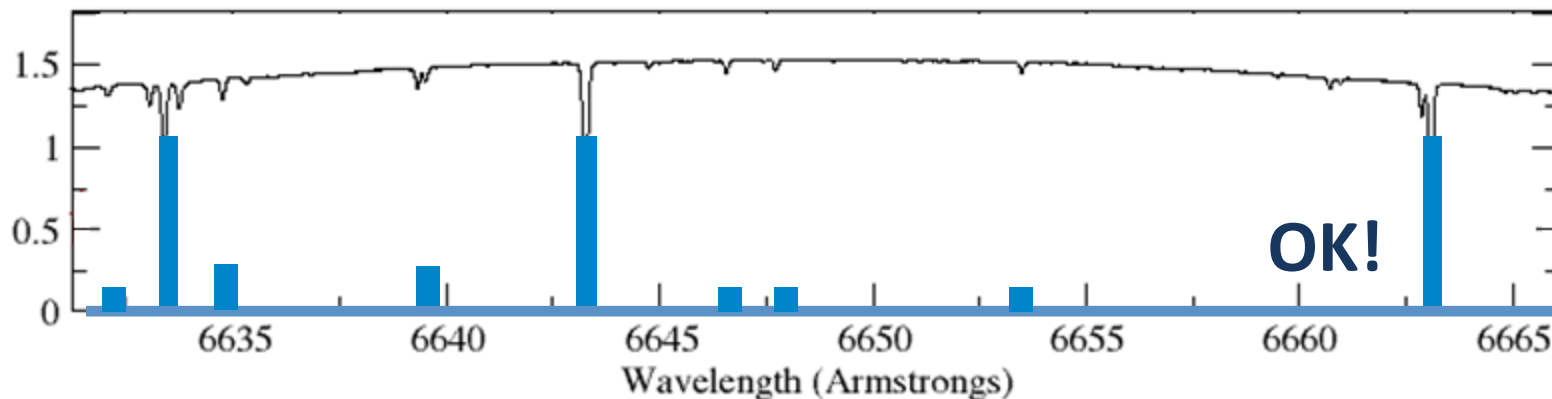
D. Queloz, Proc. IAU Symposium 1995



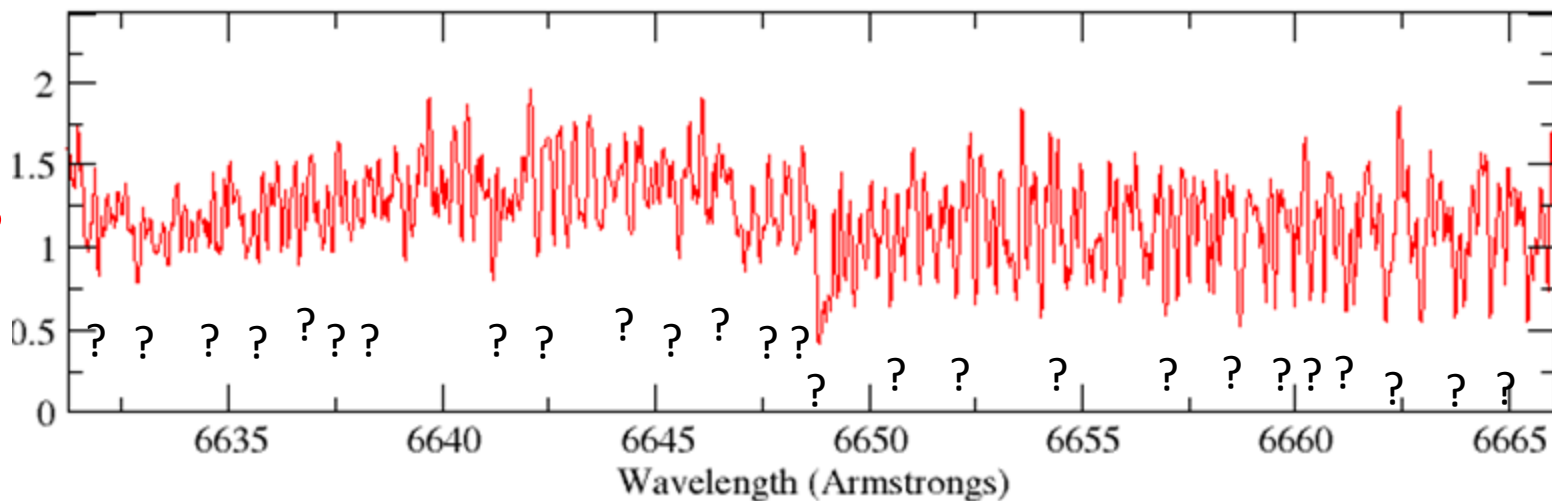
HARPS – CCF with Weighted binary masks



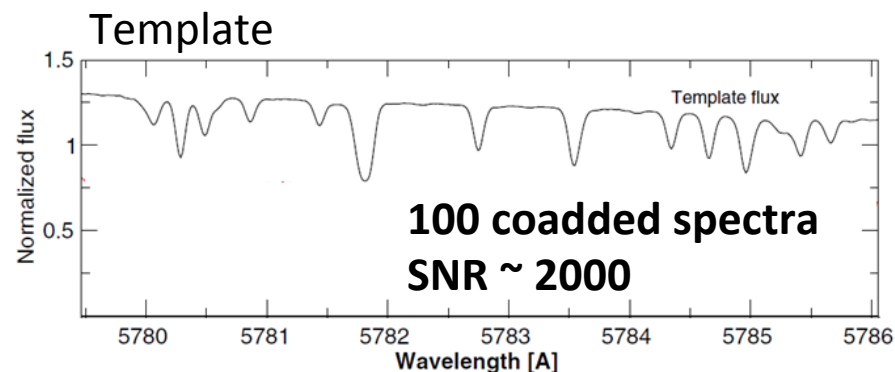
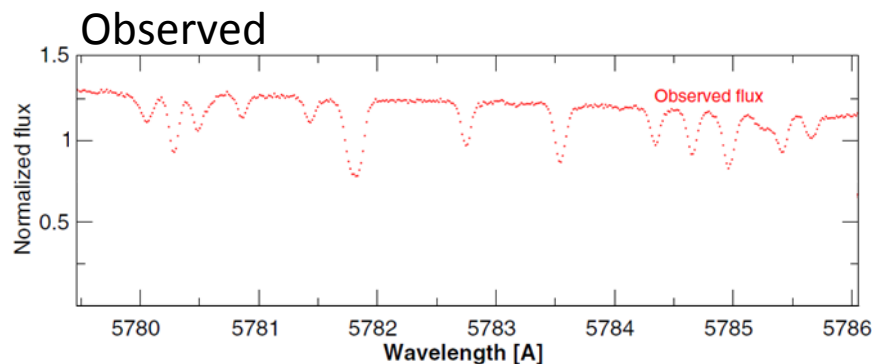
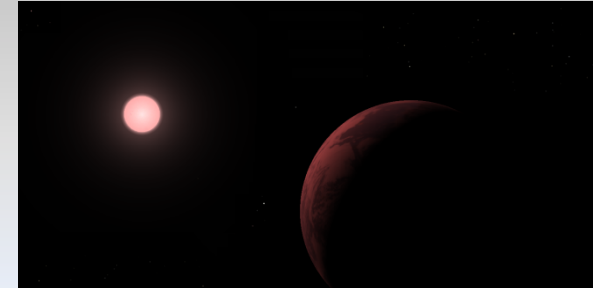
**Tau Ceti
G8.5V**



**Barnard's
M4V**

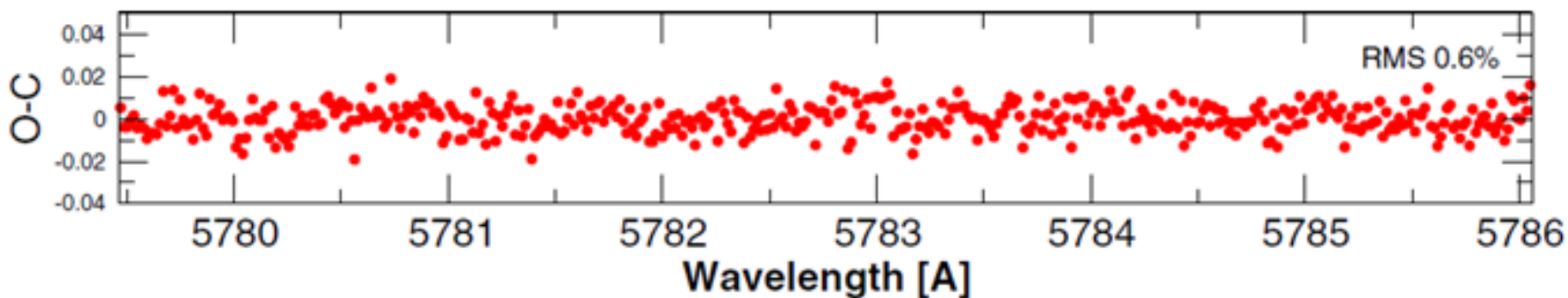


HARPS-TERRA

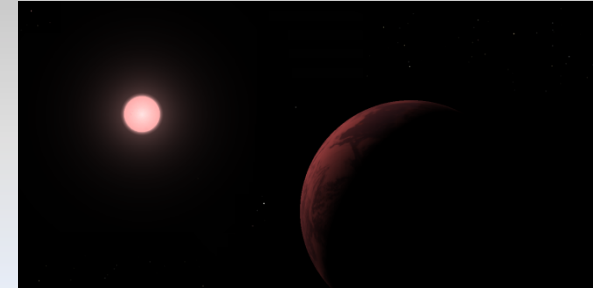


$$\lambda' = (1 - \beta)\lambda$$

$$f(\lambda') = (a + b\lambda' + c\lambda'^2) * T(\lambda')$$

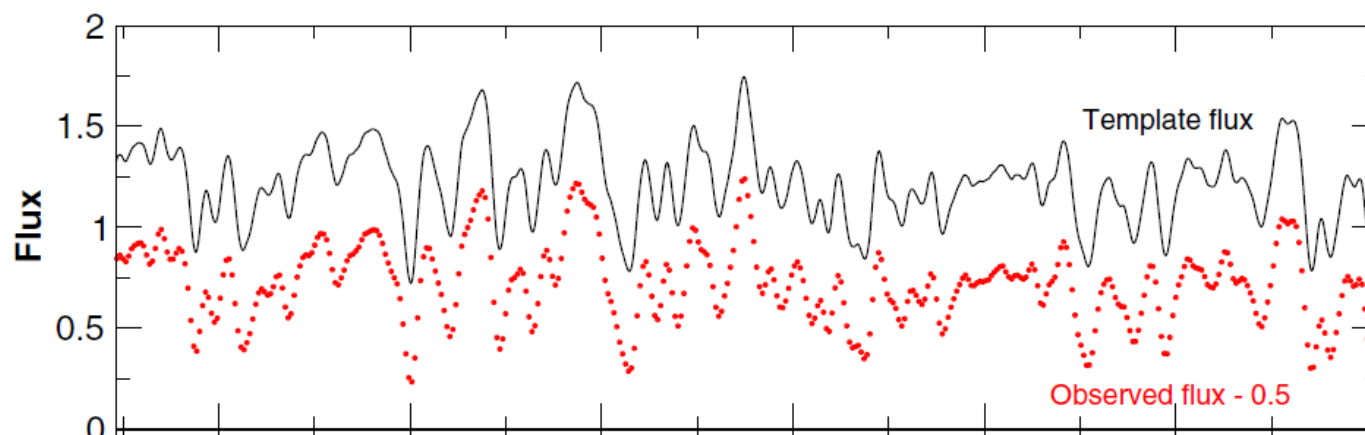


HARPS-TERRA

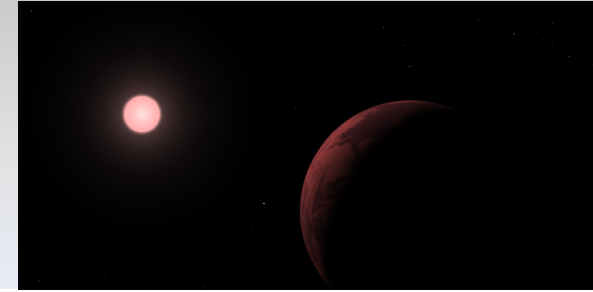


Template Enhanced Radial velocity Re-analysis Application

Barnard's star, M4V

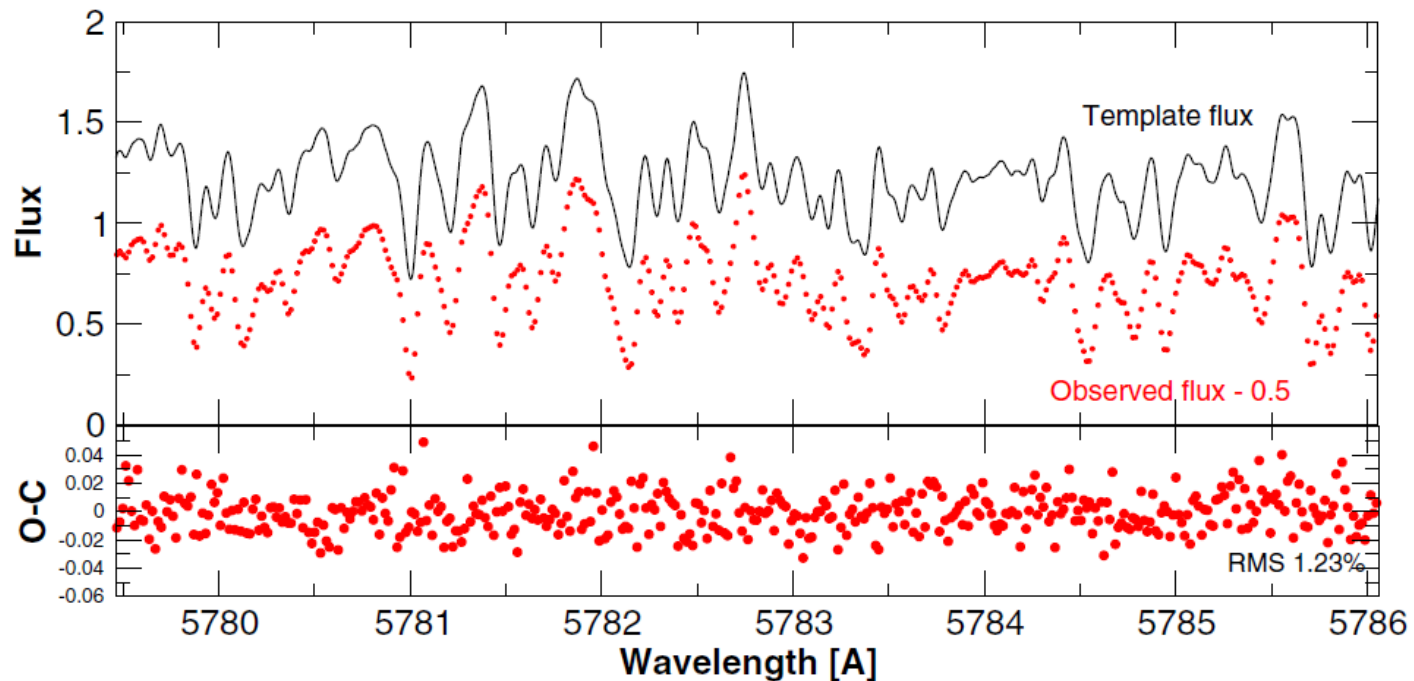


HARPS-TERRA

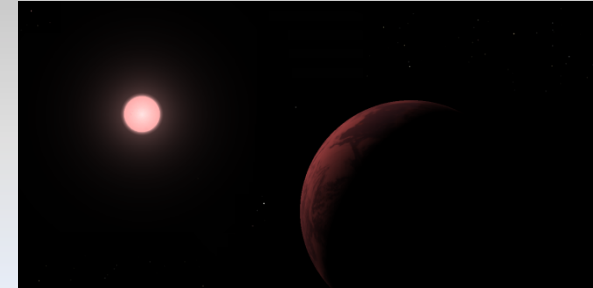


Template Enhanced Radial velocity Re-analysis Application

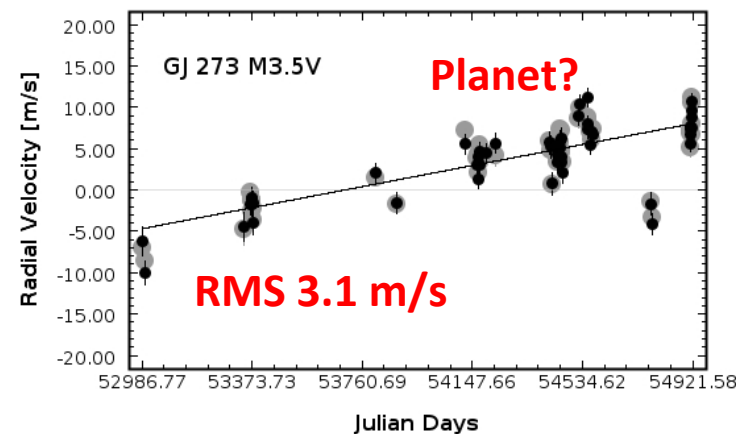
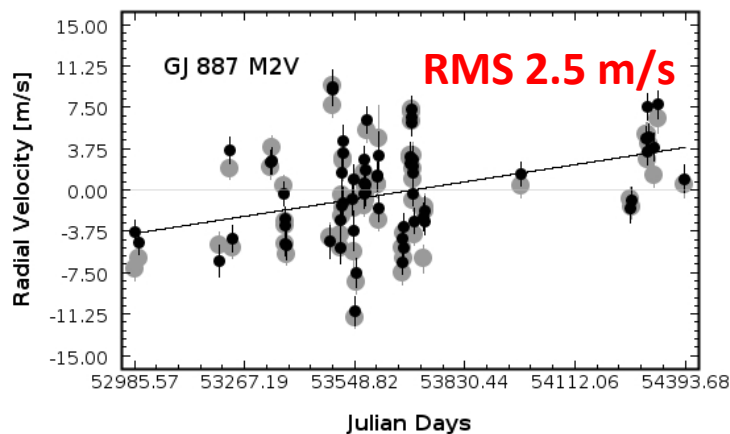
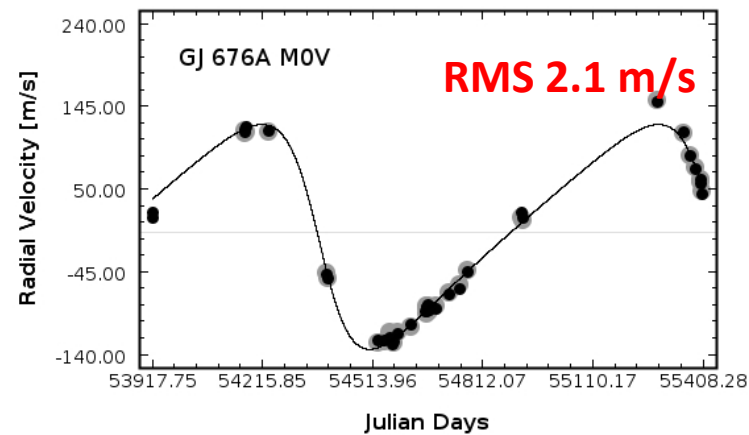
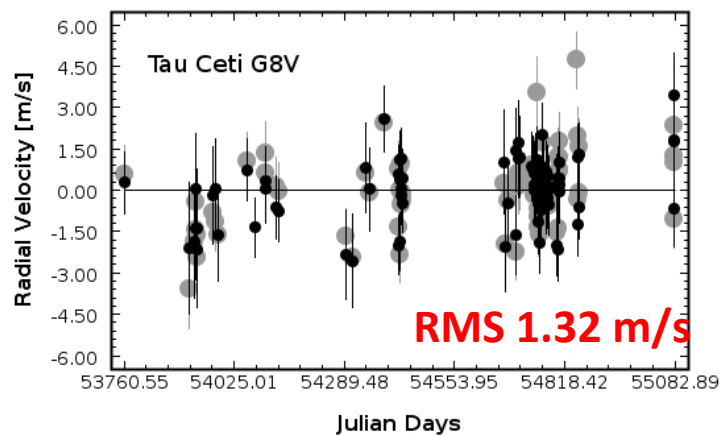
Barnard's star, M4V



HARPS-TERRA



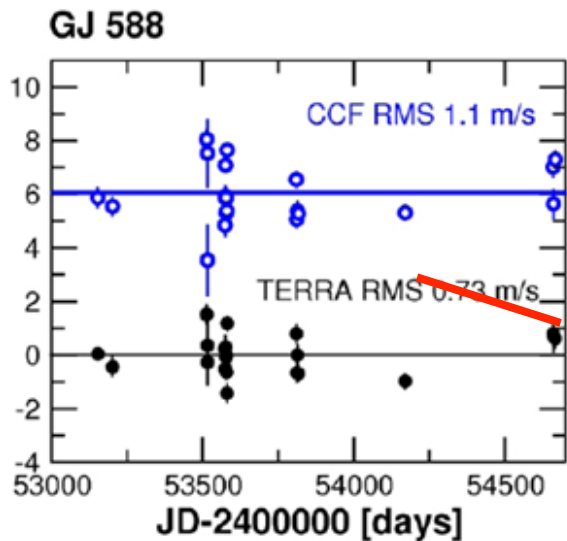
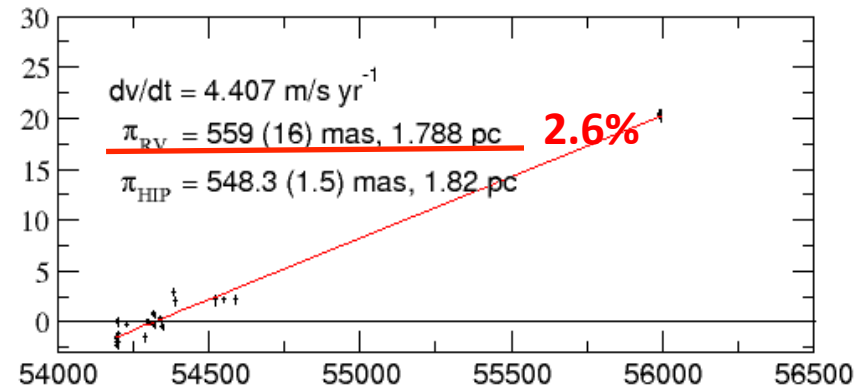
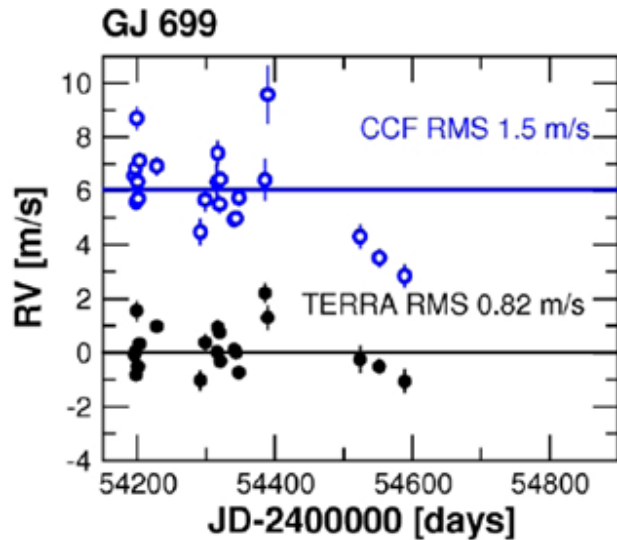
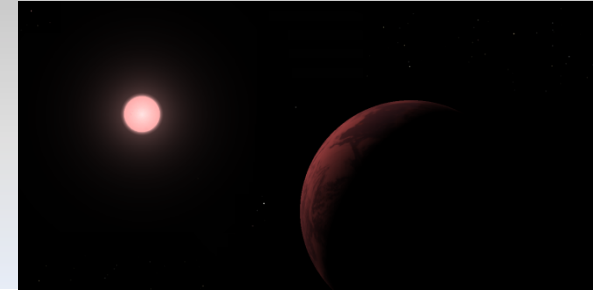
... does it work?



“The HARPS-TERRA project I...”,
Anglada-Escude, G., Butler, P. 2012, ApJS

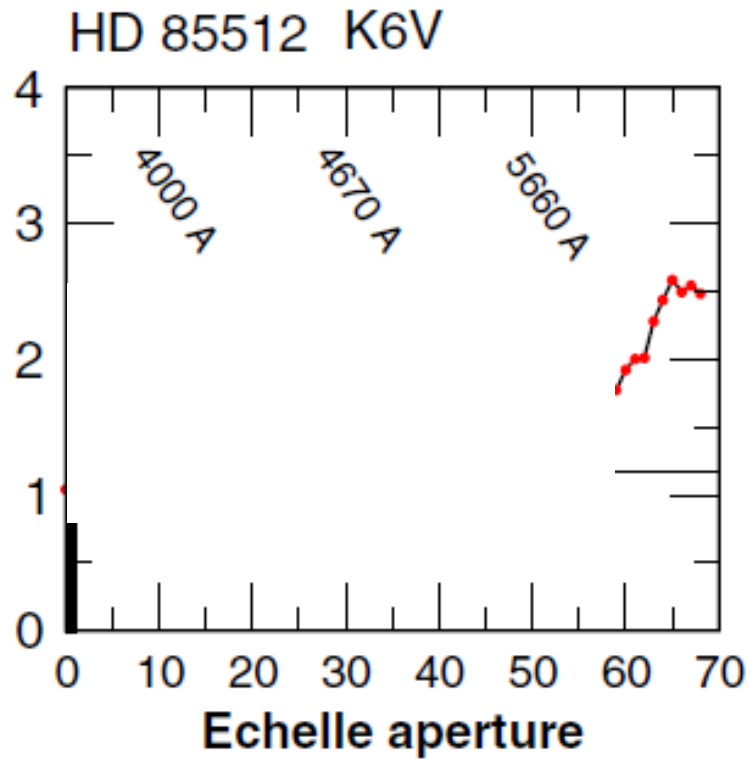
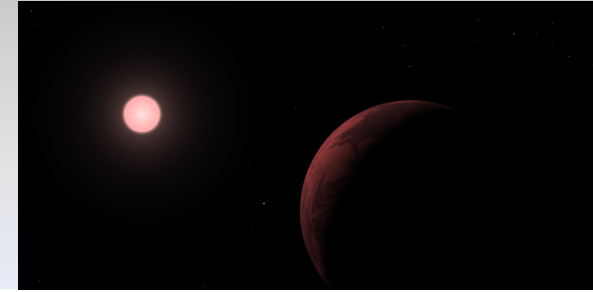
YES!

HARPS-TERRA

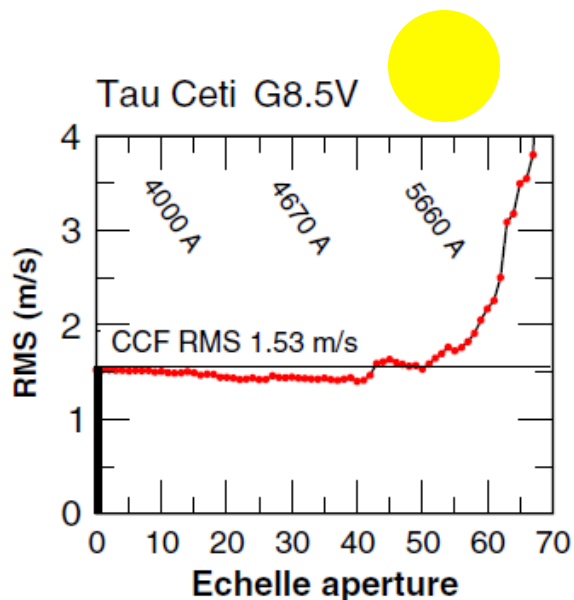
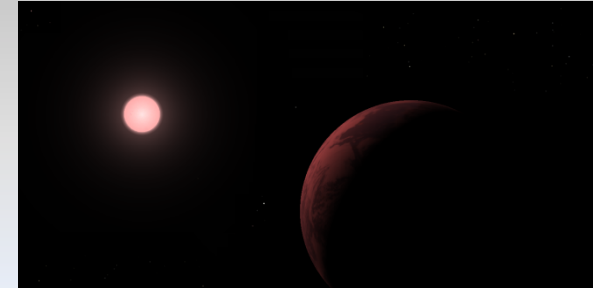


0.67 m/s
New world record!

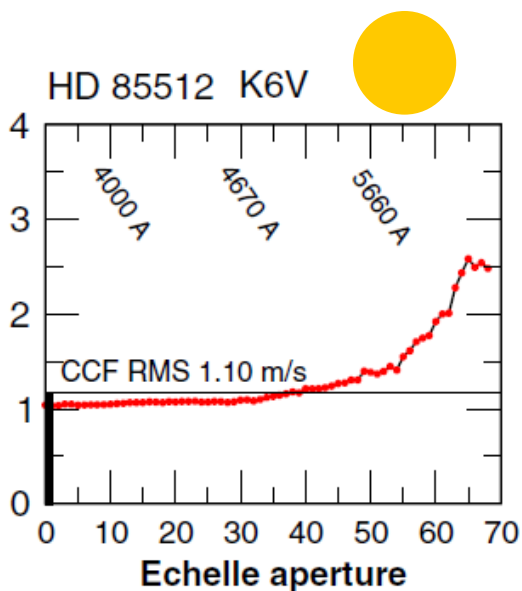
HARPS-TERRA



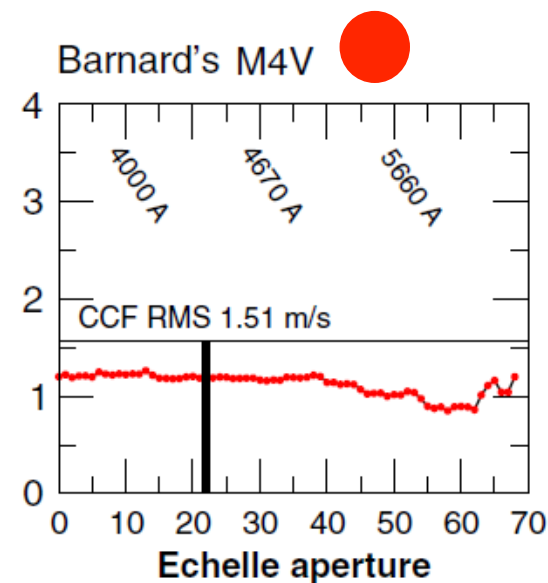
HARPS-TERRA : evidence for wavelength dependent 'noise'



?



OK!



?

Correlation with Chromospheric emission

Positive

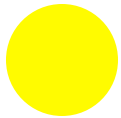
+

0

Negative

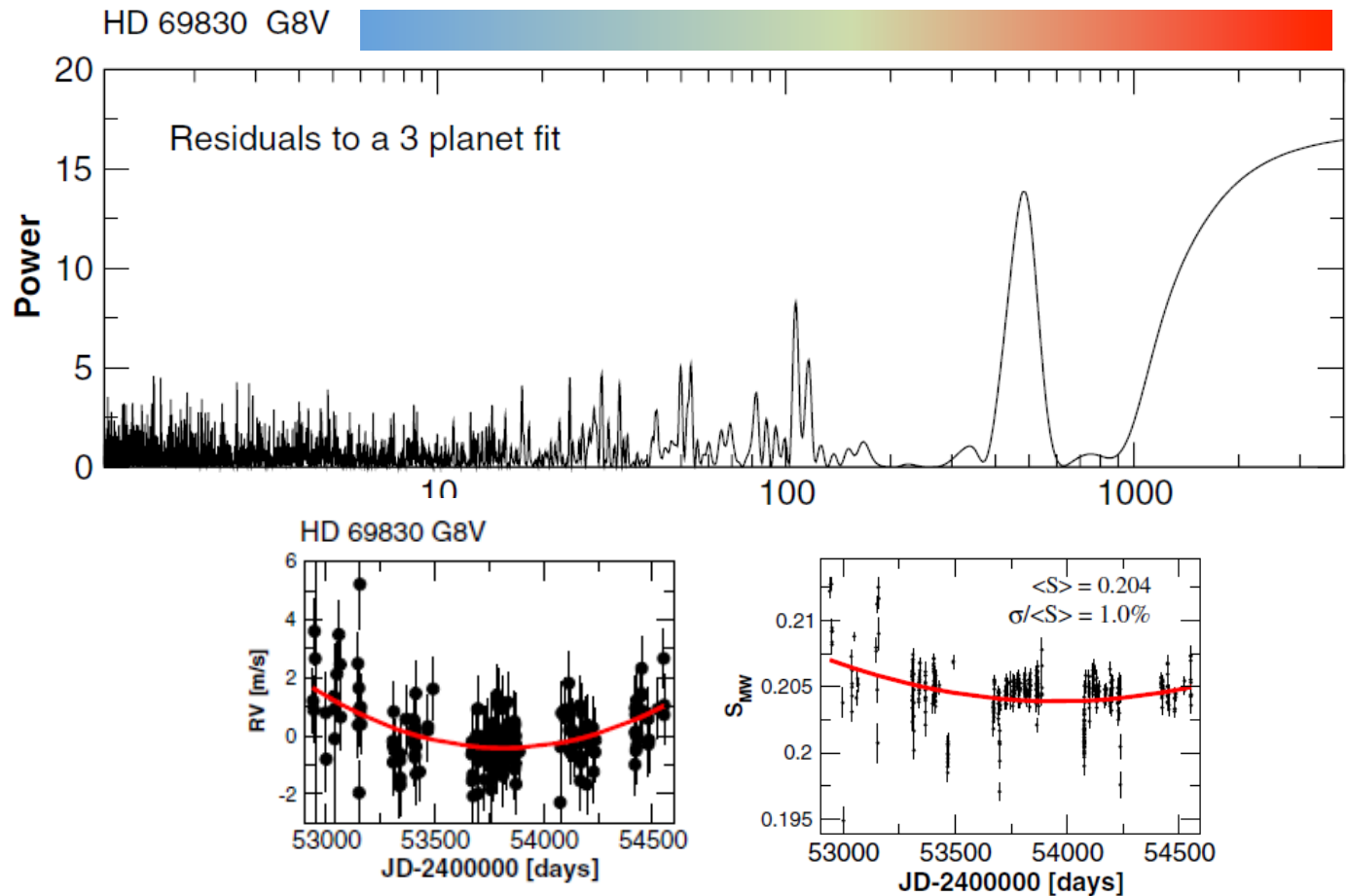
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Wavelength dependence of the stellar “noise”

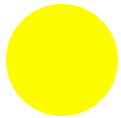


3 Neptune mass planets

Lovis et al. 2006, Nature

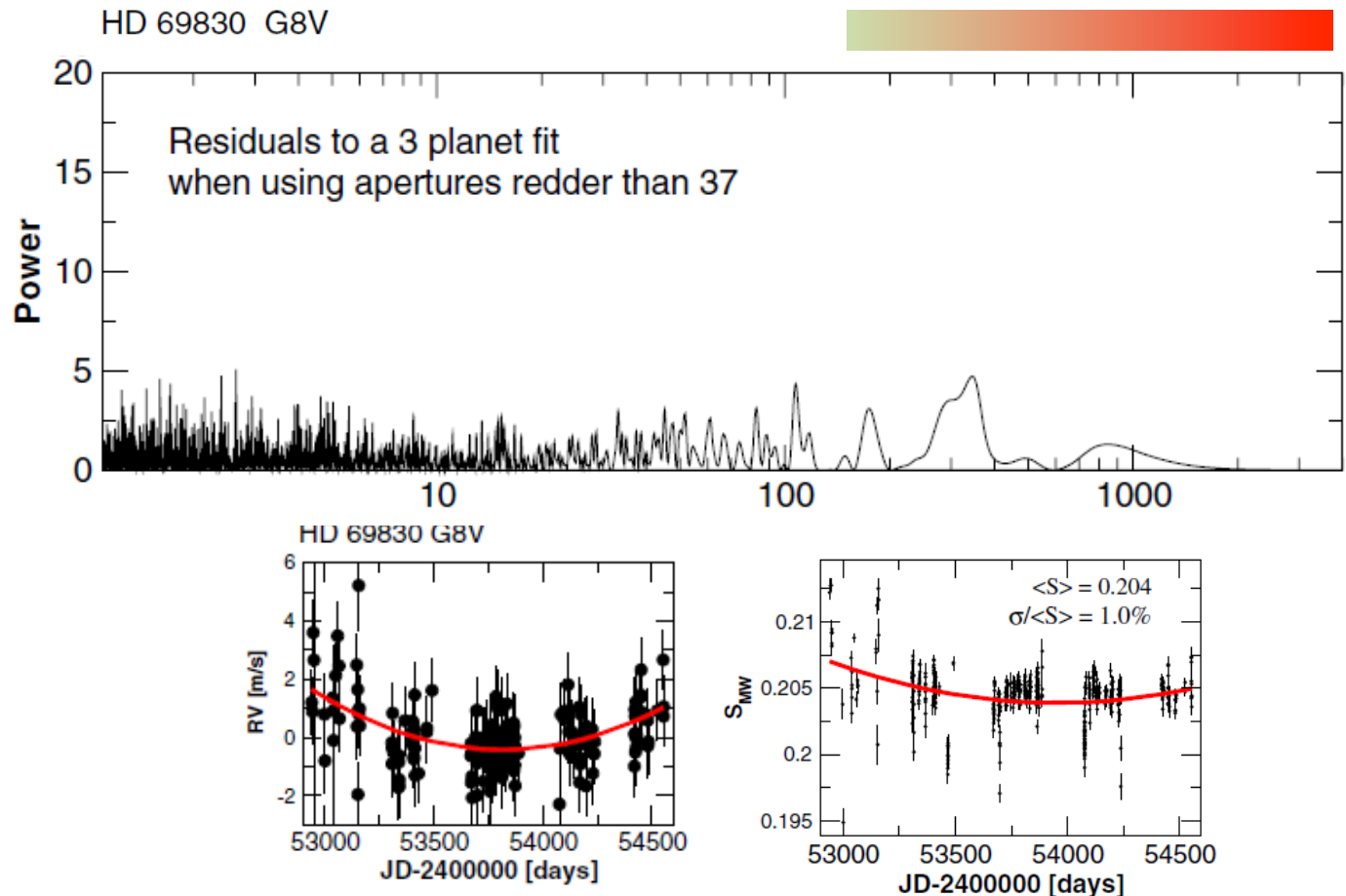


Wavelength dependence of the stellar “noise”

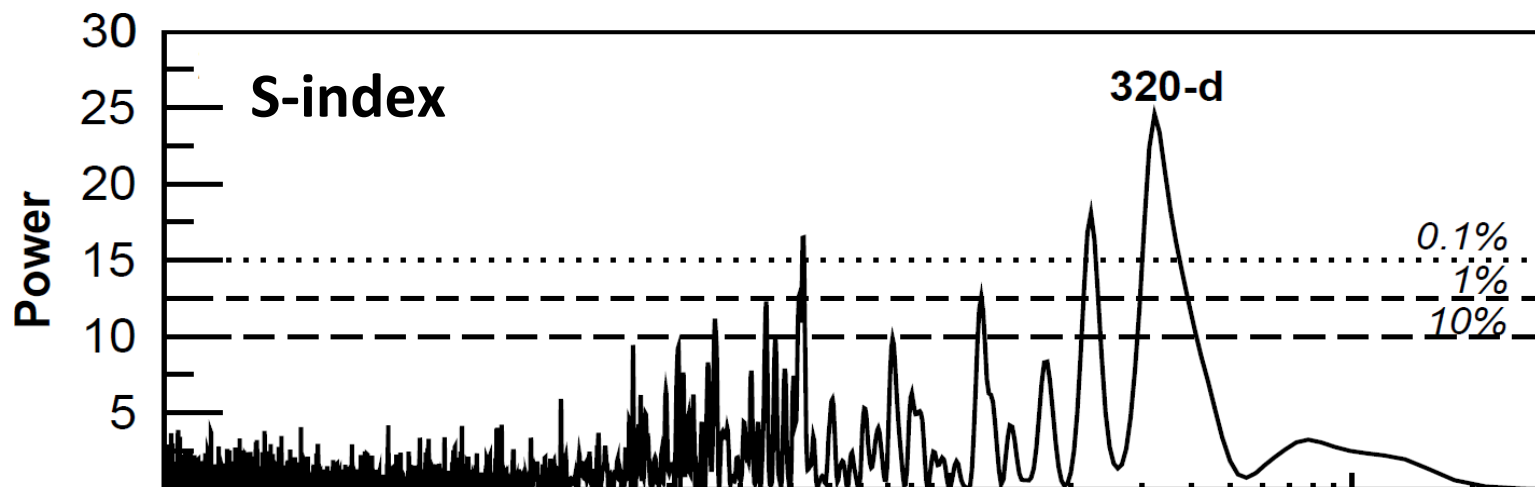
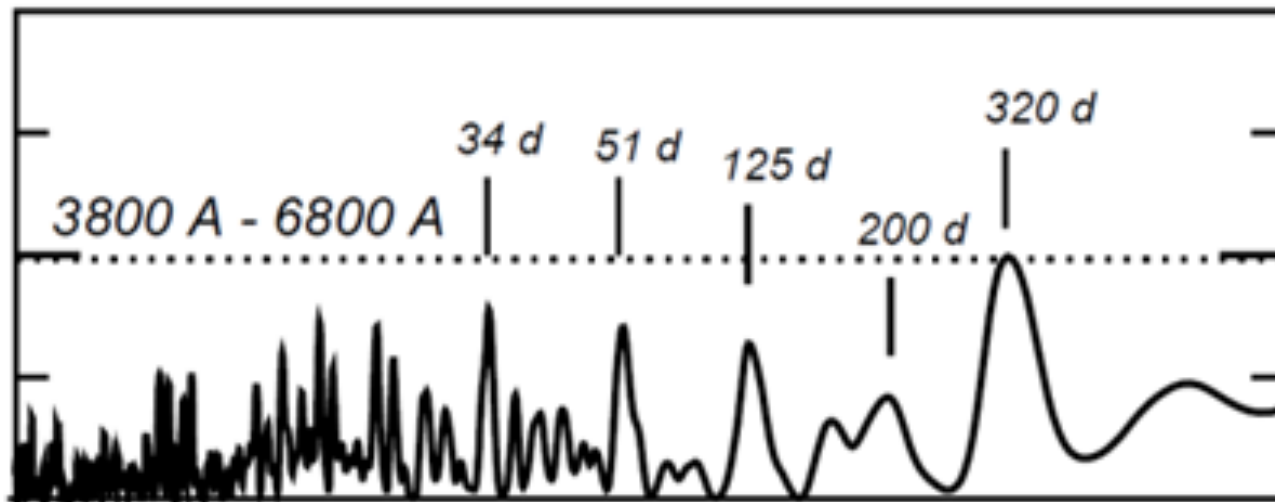


3 Neptune mass planets

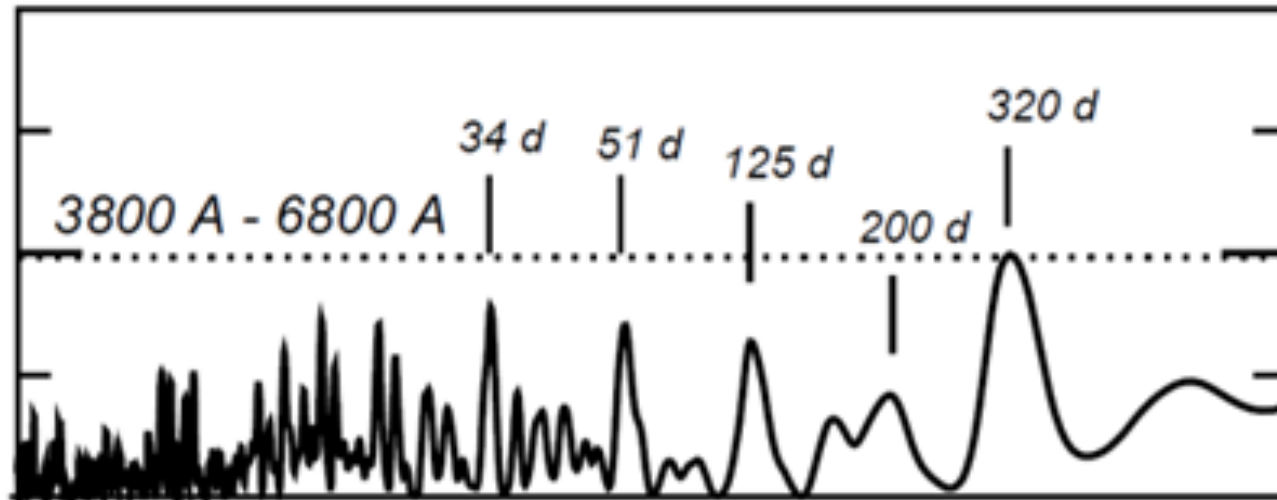
Lovis et al. 2006, Nature



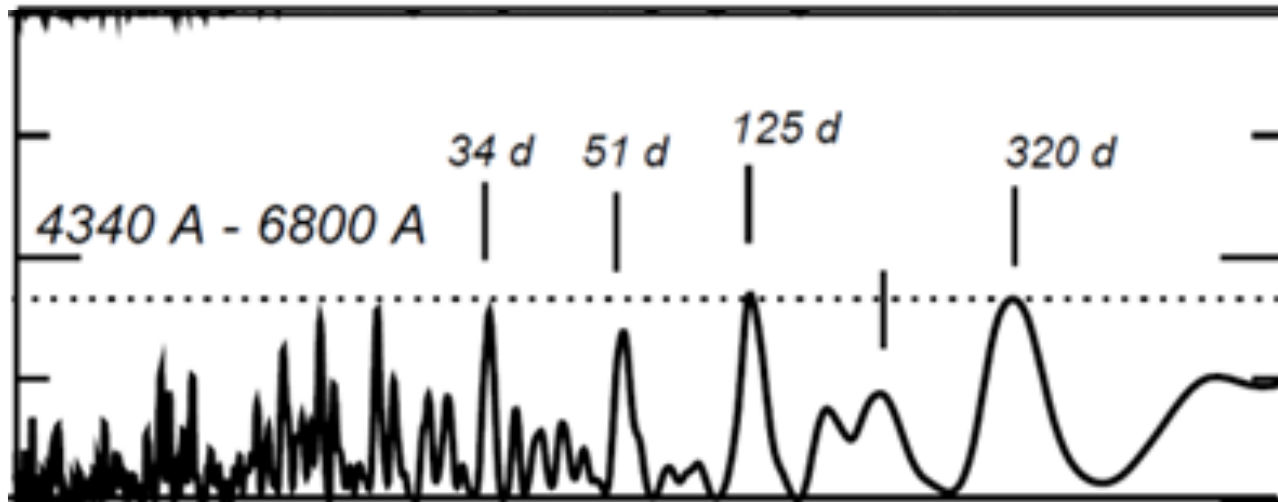
Wavelength dependence of the stellar “noise”



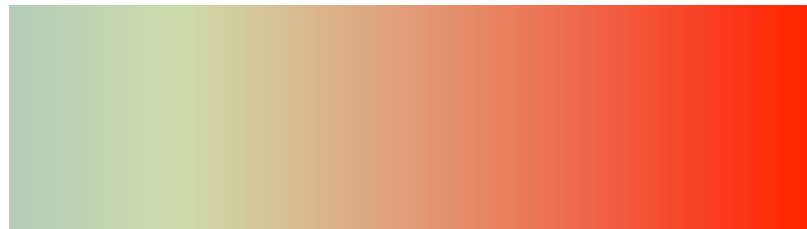
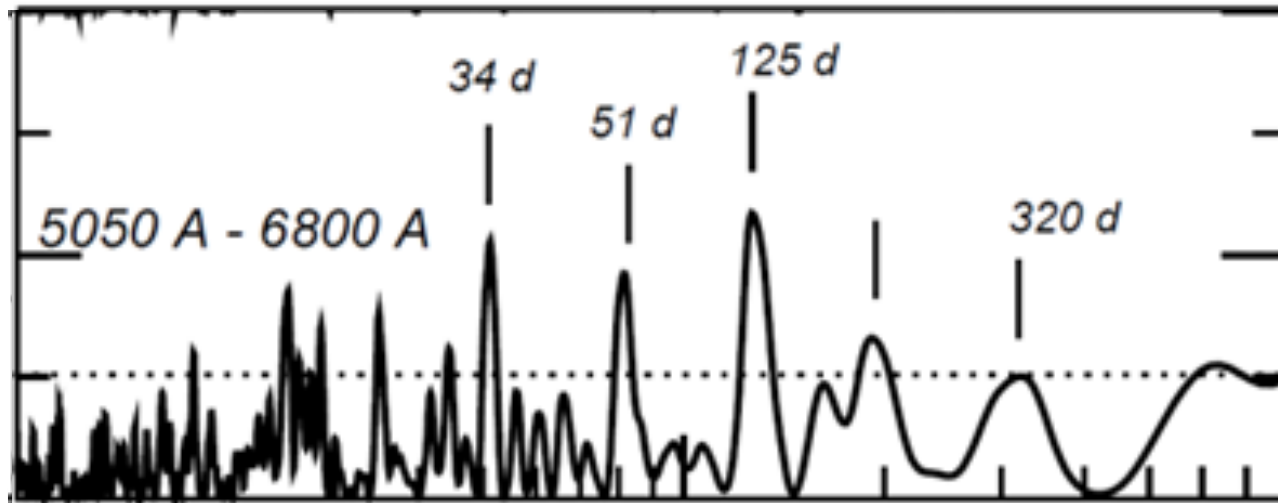
Wavelength dependence of the stellar “noise”



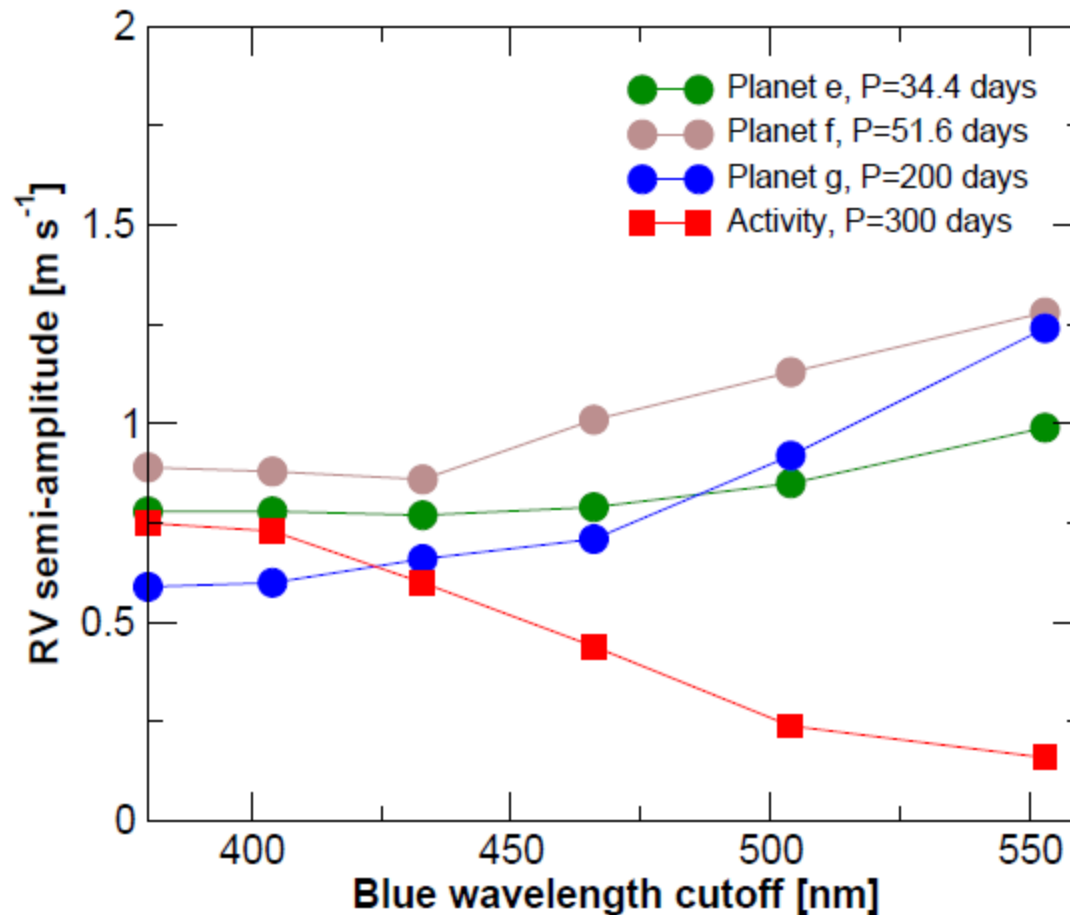
Wavelength dependence of the stellar “noise”



Wavelength dependence of the stellar “noise”

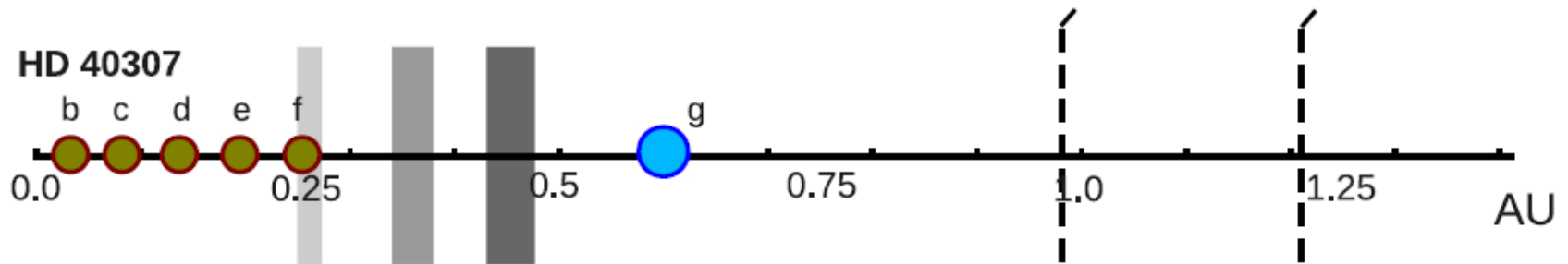
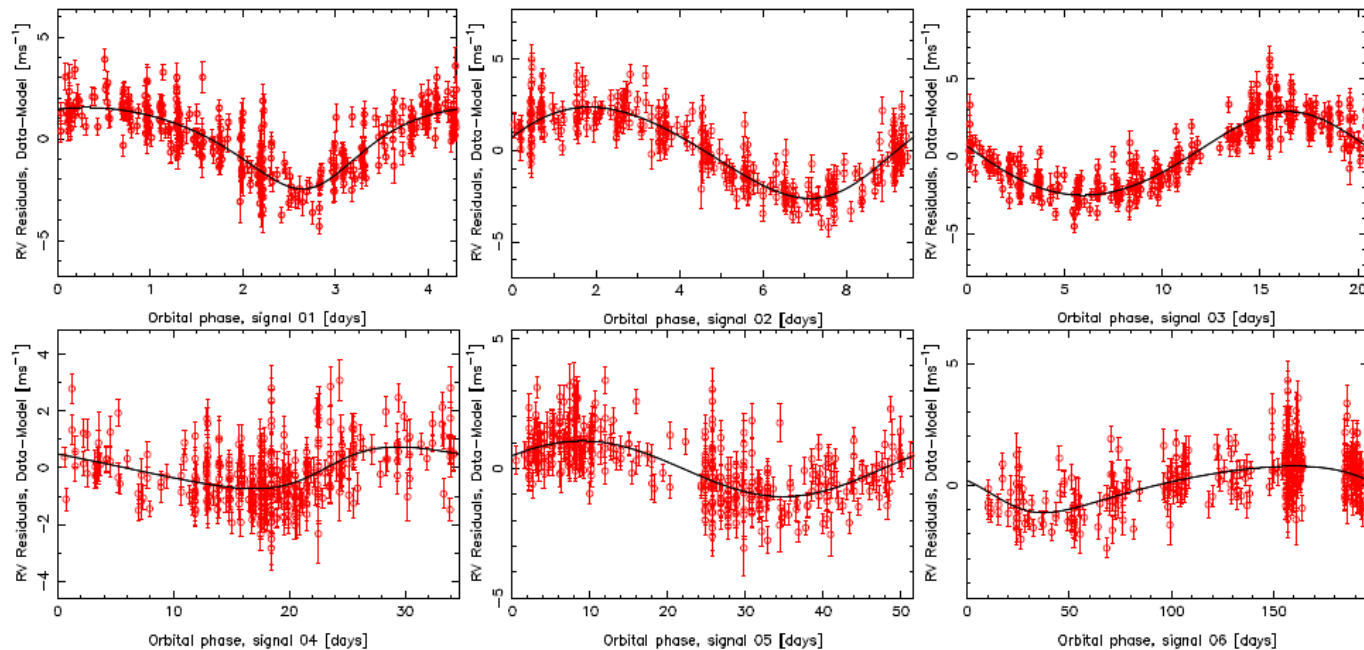


Wavelength dependence of the stellar “noise”



A super-Earth in the HZ of a six-planet system around the K2.5V dwarf HD 40307

Tuomi, Anglada-Escude et al. 2012 A&A

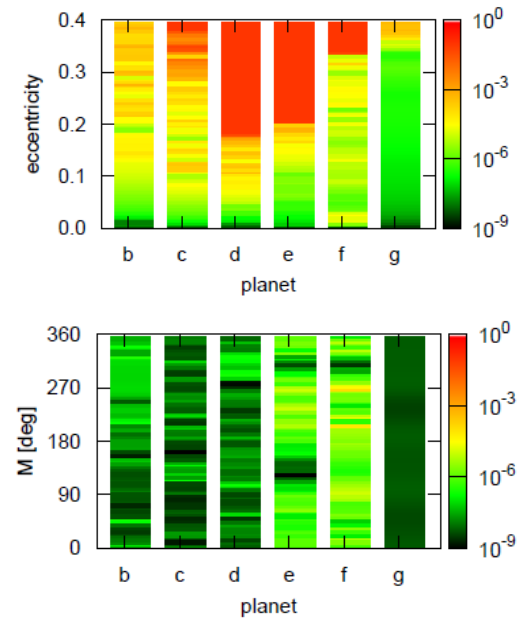
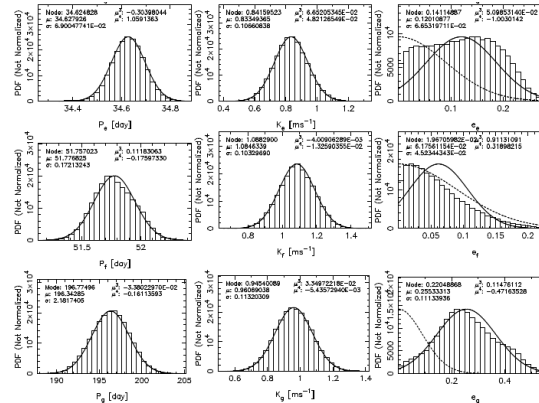
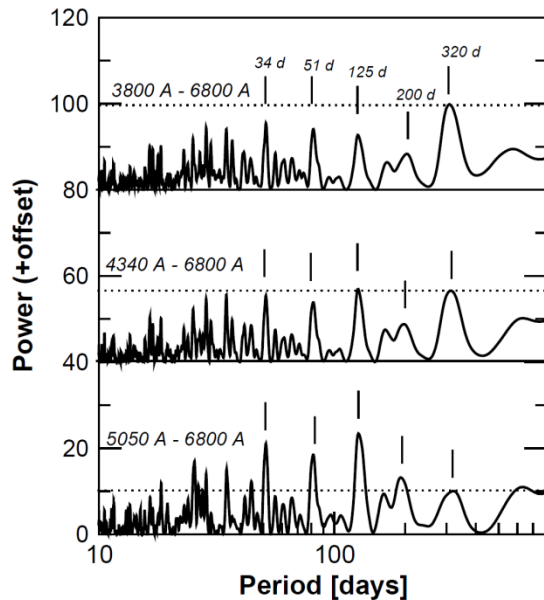
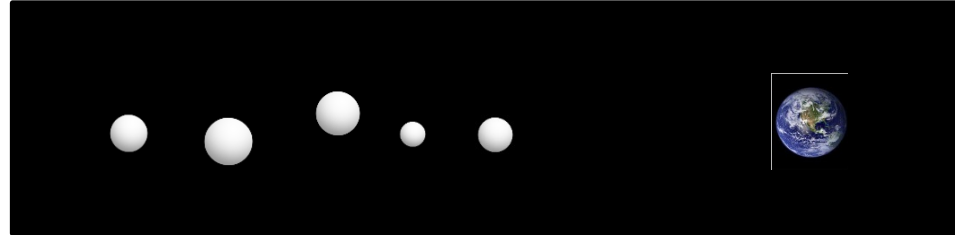


HARPS-TERRA + Bayesian + dynamic stability

A super-Earth candidate in the habitable zone of a six-planet system around the K2.5 dwarf HD 40307

Tuomi M., Anglada-Escude G., Gerlach E., Jones H.R.A., A.

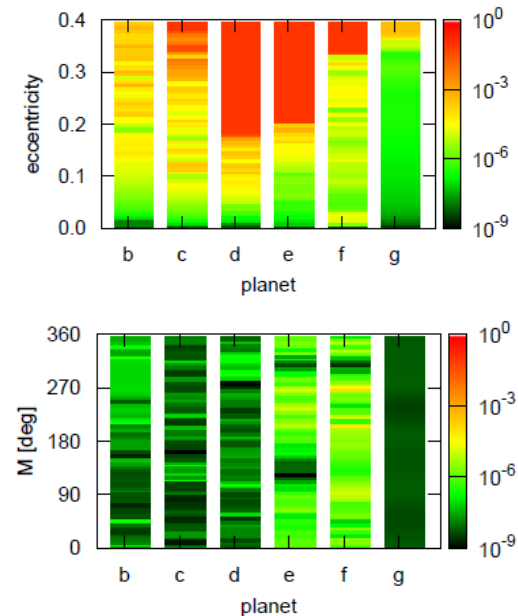
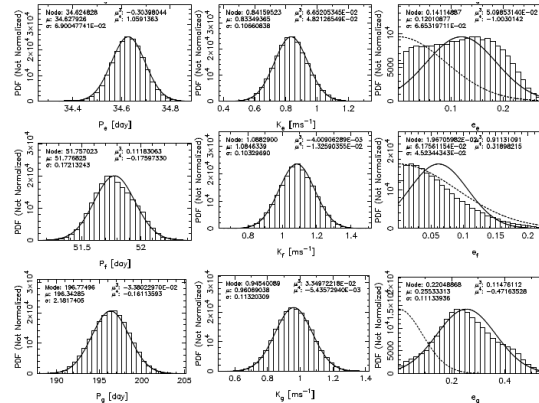
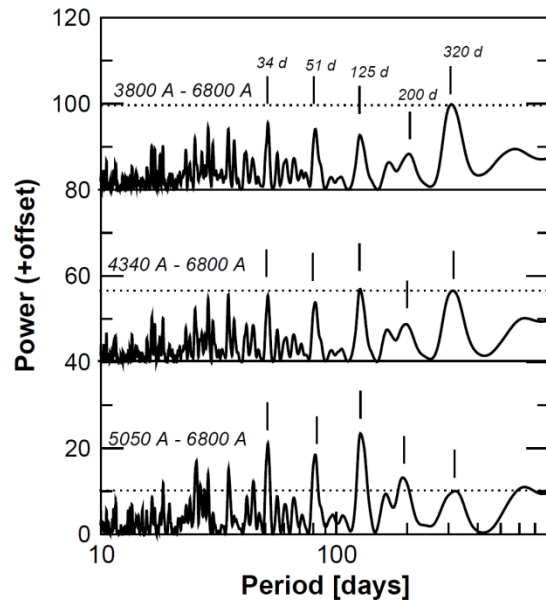
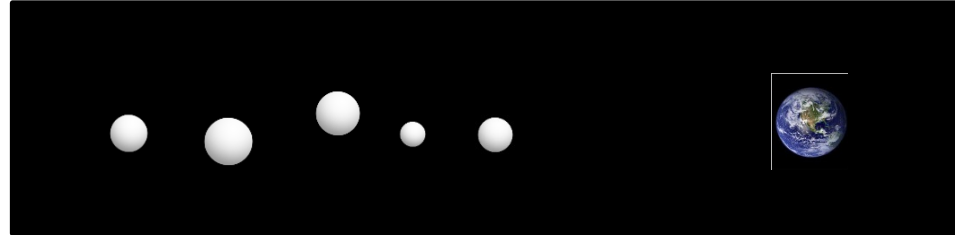
Reiners, Rivera E., Vogt S., Butler, P 2012 A&A



Bayesian + HARPS-TERRA + dynamic stability

A super-Earth candidate in the habitable zone of a six-planet system around the K2.5 dwarf HD 40307

Tuomi M., Anglada-Escude G., Gerlach E., Jones H.R.A., A. Reiners, Rivera E., Vogt S., Butler, P 2012 A&A

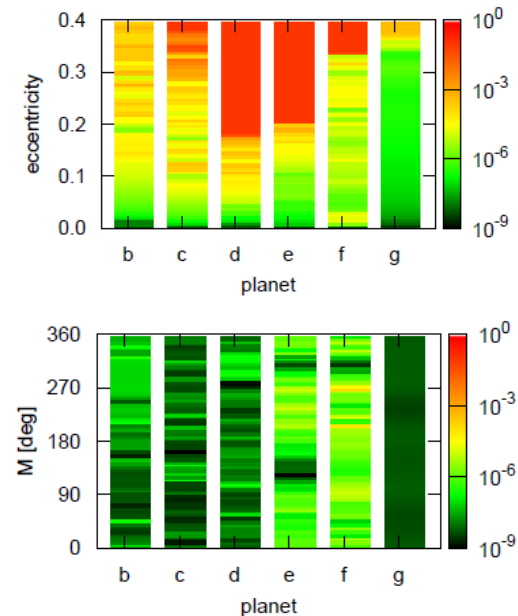
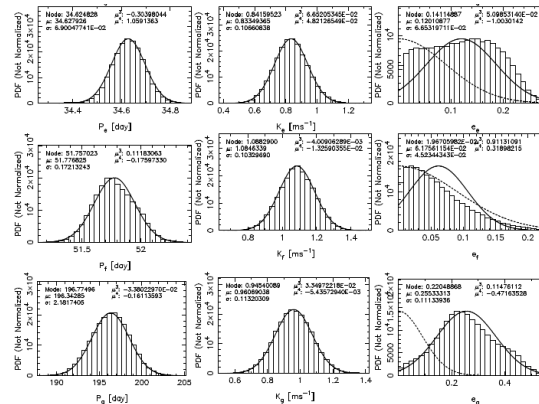
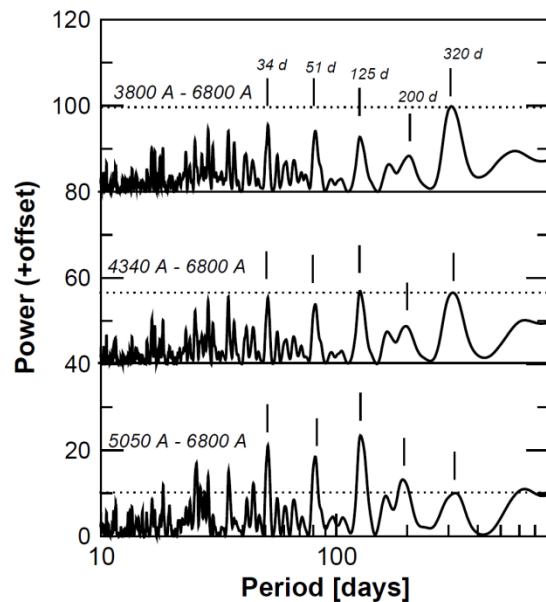
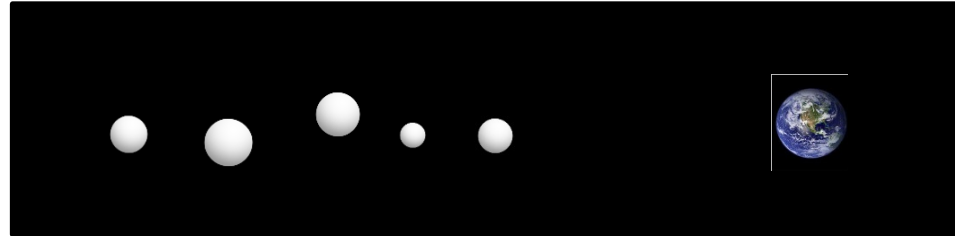


Dynamic stability + Bayesian + HARPS-TERRA

A super-Earth candidate in the habitable zone of a six-planet system around the K2.5 dwarf HD 40307

Tuomi M., Anglada-Escude G., Gerlach E., Jones H.R.A., A.

Reiners, Rivera E., Vogt S., Butler, P 2012 A&A



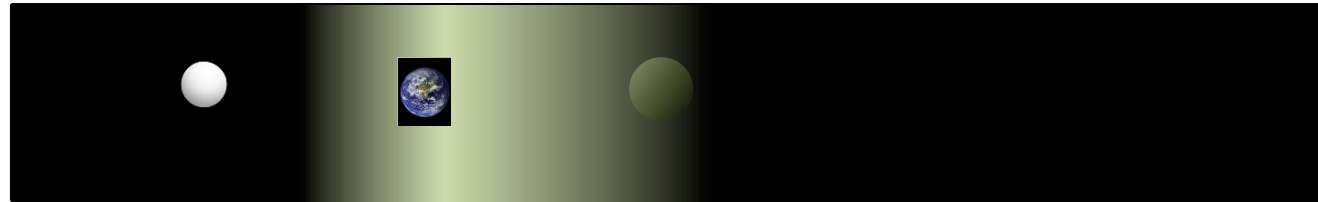
Planetary systems

GJ 667C, M2V

Bonfils et al 2011, A&A acc

Anglada-Escude et al, 2012 ApJL

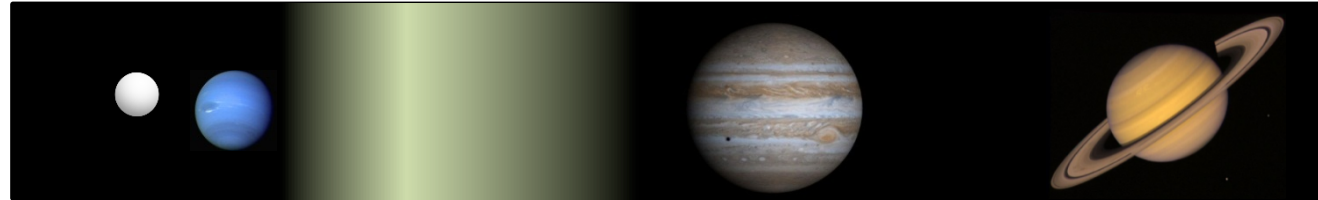
Delfosse et al. 2012, 2012 A&A sub.



GJ 676A, M0V

Anglada-Escude & Tuomi,

2012 A&A



HD 40307, K7V

Tuomi, Anglada-Escude et al.

2012 (accepted ApJ)



K7V – low Fe/H

Arriagada, Anglada-Escude et al, 2012

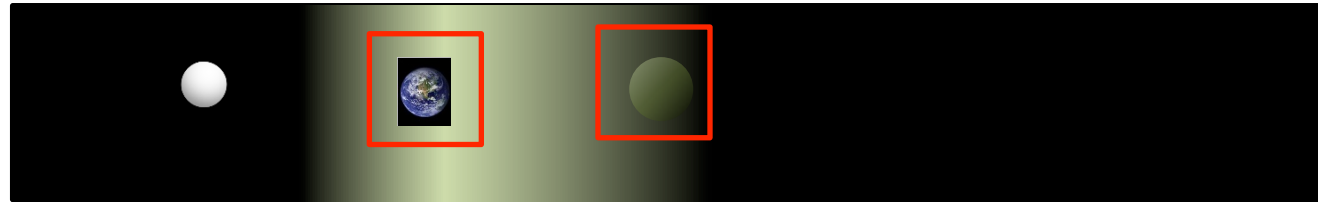
(submitted ApJ)



Planetary systems

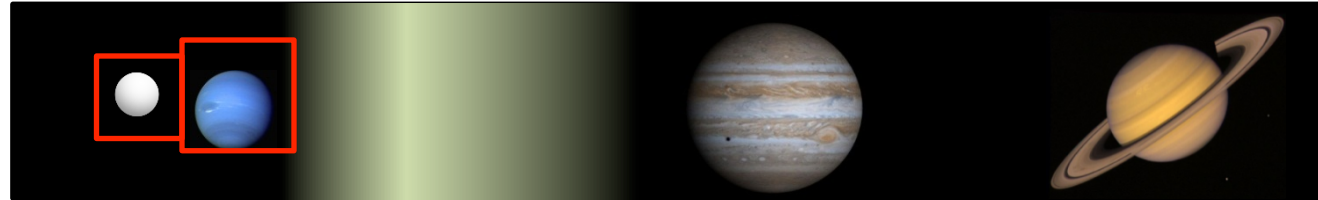
GJ 667C, M2V

Bonfils et al 2011, A&A acc
Anglada-Escude et al, 2012 ApJL
Delfosse et al. 2012, 2012 A&A sub.



GJ 676A, M0V

Anglada-Escude & Tuomi,
2012 A&A



HD 40307, K7V

Tuomi, Anglada-Escude et al.
2012 (accepted ApJ)



K7V – low Fe/H

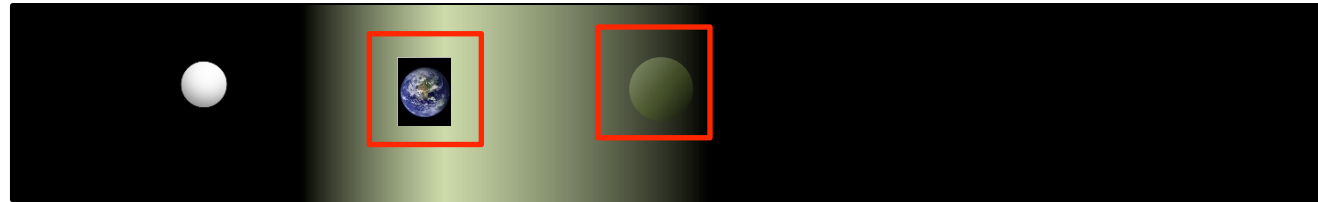
Arriagada, Anglada-Escude et al, 2012
(submitted ApJ)



Planetary systems

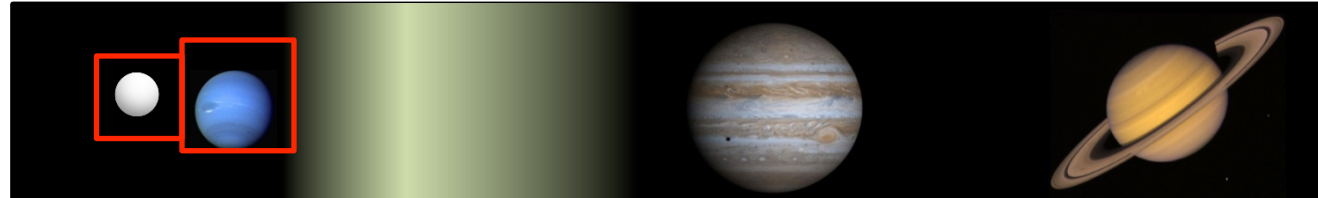
GJ 667C, M2V

Bonfils et al 2011, A&A acc
Anglada-Escude et al, 2012 ApJL
Delfosse et al. 2012, 2012 A&A sub.



GJ 676A, M0V

Anglada-Escude & Tuomi,
2012 A&A



HD 40307, K7V

Tuomi, Anglada-Escude et al.
2012 (accepted ApJ)

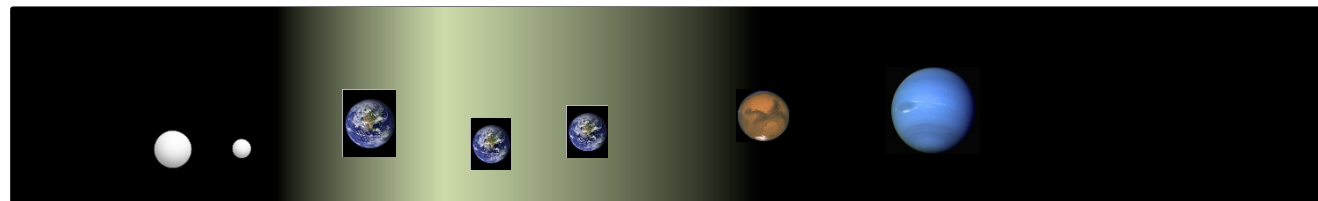


K7V – low Fe/H

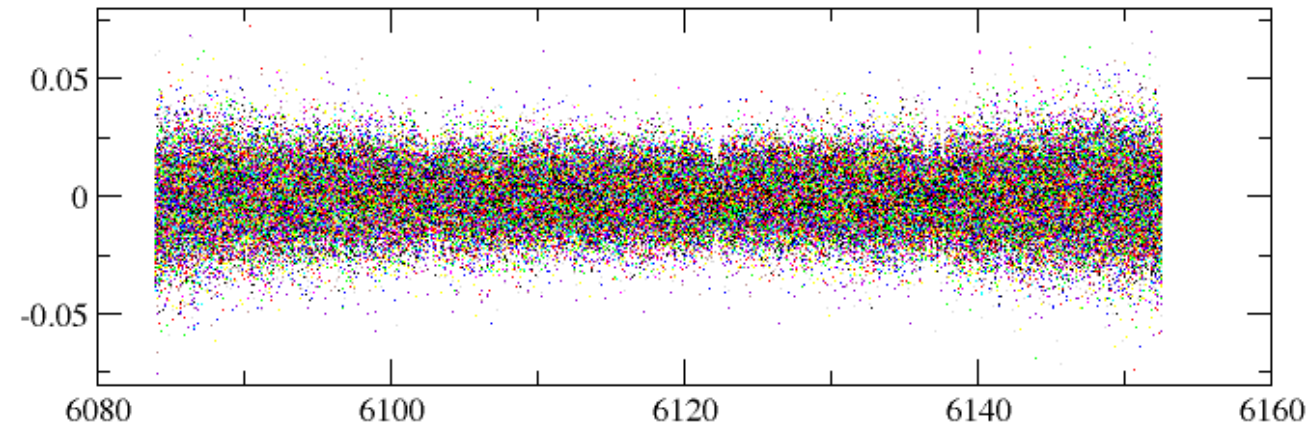
Arriagada, Anglada-Escude et al, 2012
(submitted ApJ)



Coming soon?

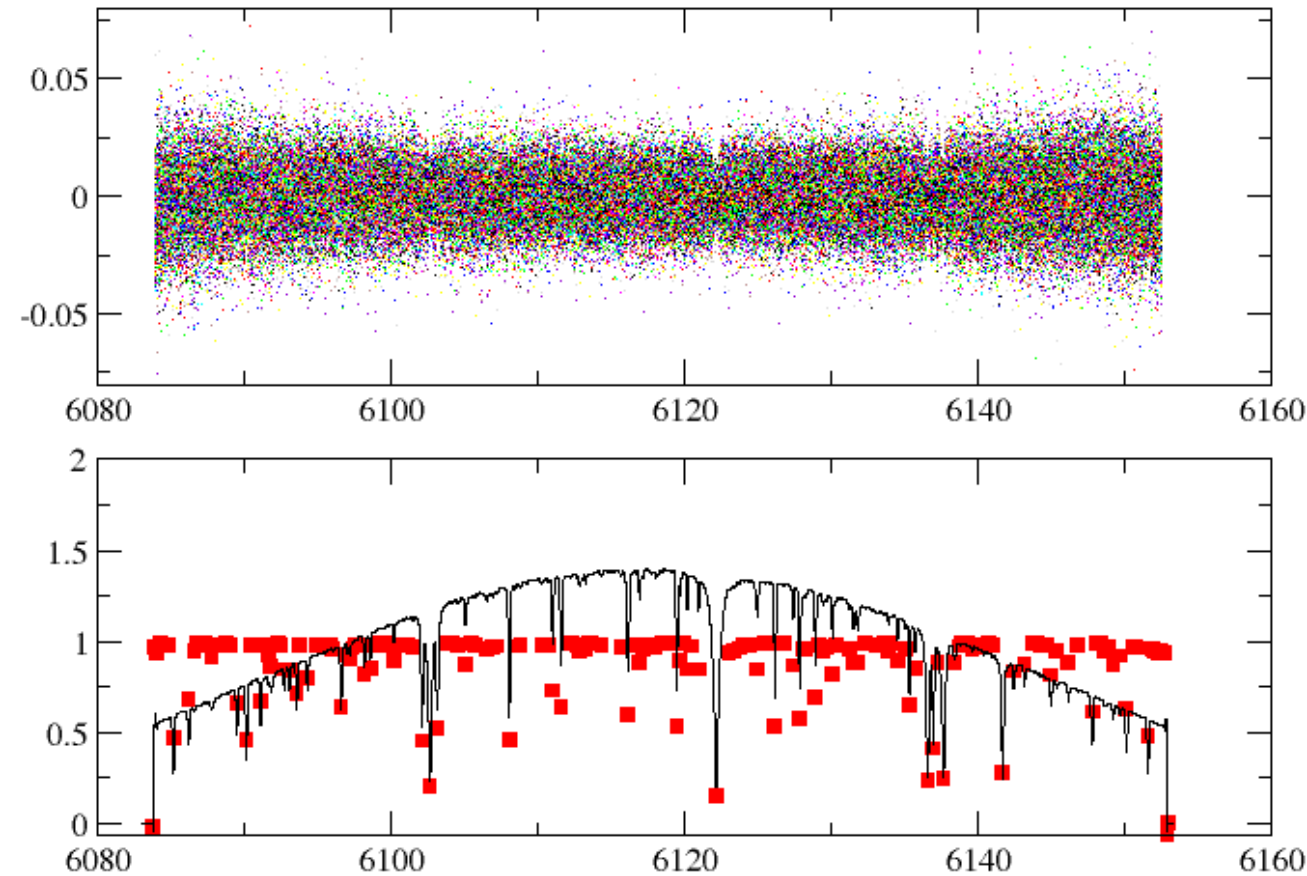


Template methods + Stabilized spectrographs : more than RVs



**~40 consecutive
spectra**

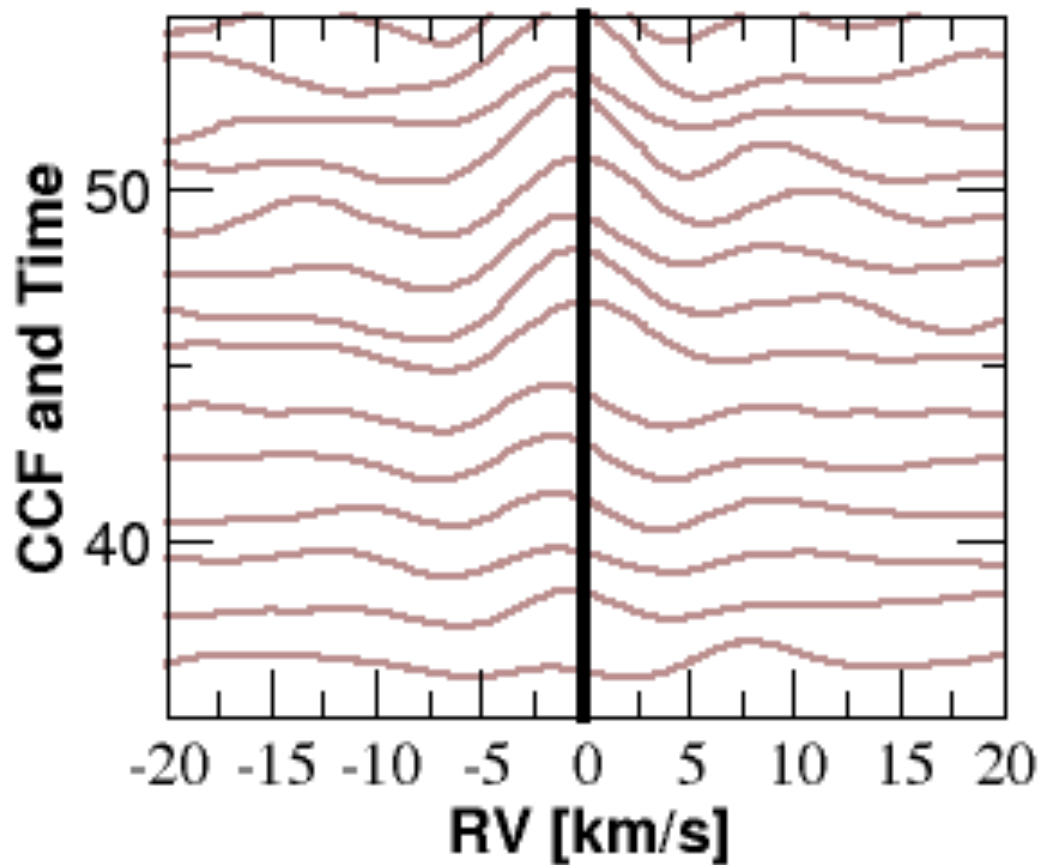
Template methods + Stabilized spectrographs : more than RVs



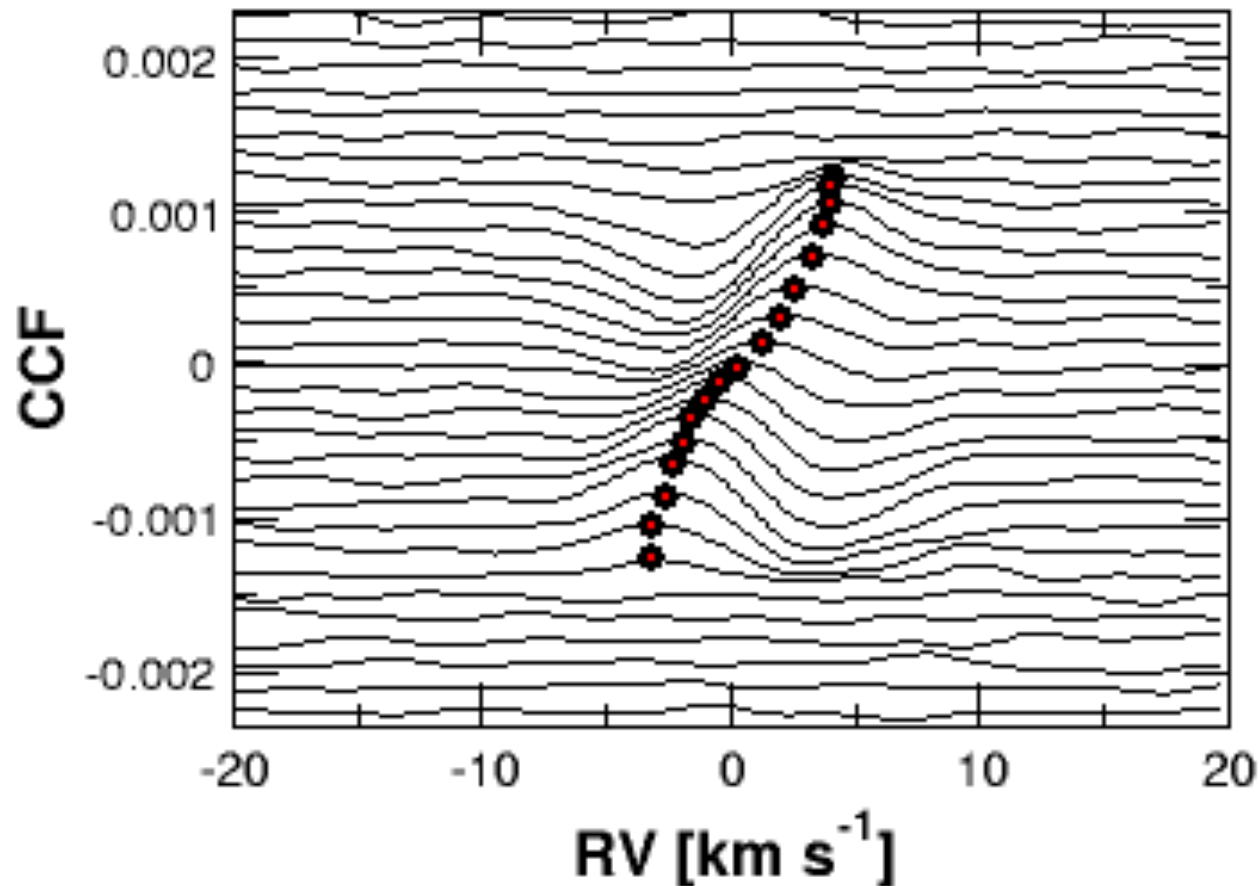
**~50 consecutive
spectra**

**Mask from
Template**

Template methods + Stabilized spectrographs : more than RVs

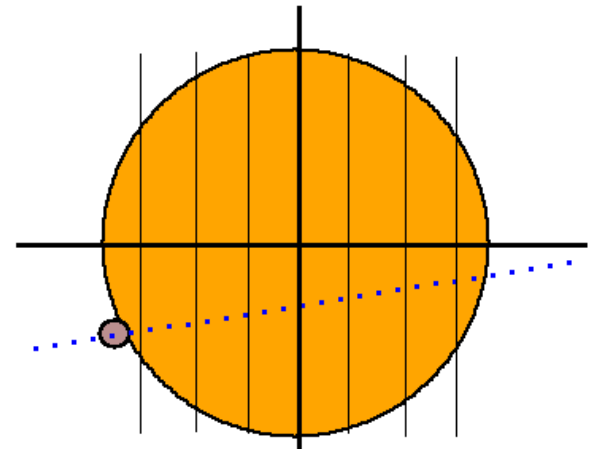
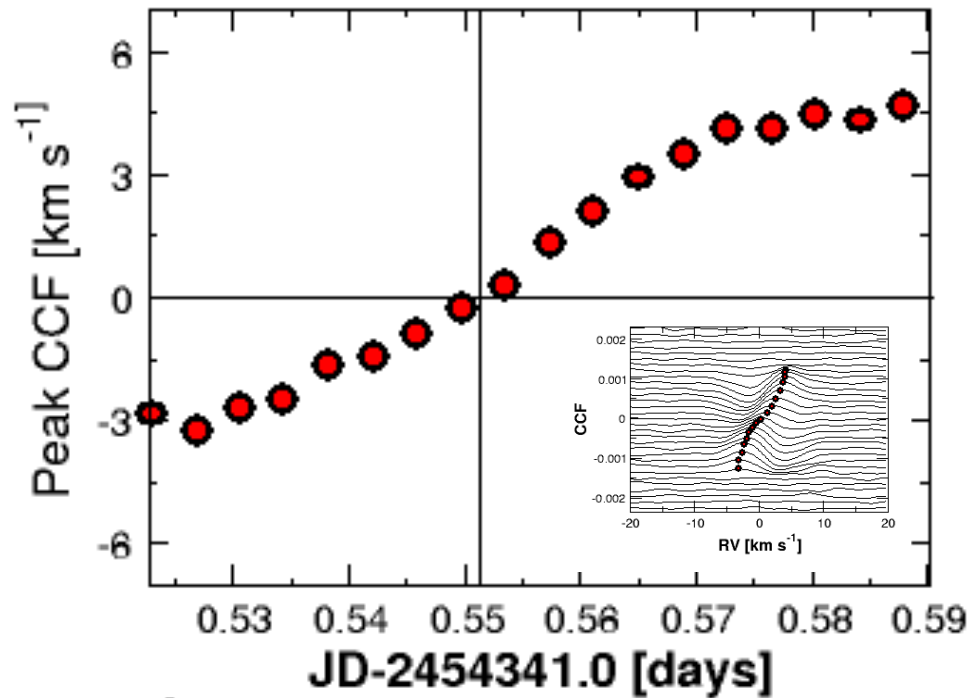


Template methods + Stabilized spectrographs : more than RVs



Same principle as Cameron et al. 2009 PASP, but completely model independent

Template methods + Stabilized spectrographs : more than RVs



Conclusions

**There is more than 1 Doppler measurement in a spectra
(HARPS : 72 orders x 4096 pix)**

HARPS-TERRA : higher precision on K and M dwarfs

Stabilized spectrographs : tons of information

Observations are not repeatable -> release spectra

PS. I do not believe Alpha Cen Bb is real...

A background image of outer space featuring a dark field with numerous stars of varying brightness. In the upper right corner, a portion of a planet with a blue and white atmosphere is visible. In the lower center, there is a small, bright red star.

... but I would like to.

There are ‘reasonable’ doubts about the candidate signal
(see Hatzes, A., Nature News & Views)

To ESO :
PLEASE release the SPECTRA
of published papers

Including Alpha Cen B, GJ 581, GJ 667C data, HD 88512, HD 20794, Tau Ceti...

... or at least, respond to e-mails