Towards the detection of optical reflected light from other worlds

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Why to detect reflected light spectrum

- Represents a direct detection of an exoplanet
  - Complementary to IR observations (yesterday's talk by I. Snellen)
- Allows to probe planetary atmosphere
  - Geometric albedo
  - Atmosphere physics (e.g. winds - e.g. Snellen et al. 2010)
- Allows to derive the velocity of the planet
  - Derive its real (dynamical) mass (e.g. Brogi et al. 2012)
- Complementary physics: planet rotation (e.g. Kawahara 2012)
- Important: can be applied even for *non transiting* planets

The difficulties

- Reflected light (even broad band) is not easy to detect
  - Recently possible using CoRoT and Kepler
    (e.g. Alonso et al. 2009; Borucki et al. 2009; Kipping et al. 2011)
- Jovian planet with P=3 days, A_g=0.3
  - Expected $F_p/F_* = 4.2 \times 10^{-5}$ (maximum value)
- Hot Jupiters: former results suggest low geometric albedos?
  (e.g. Collier Cameron et al. 2002, Rowe et al. 2008, Langford et al. 2010)
  - Though Ag values around 0.3 or higher have been found
    (e.g. Santerne et al. 2011; Cowan et al. 2011)

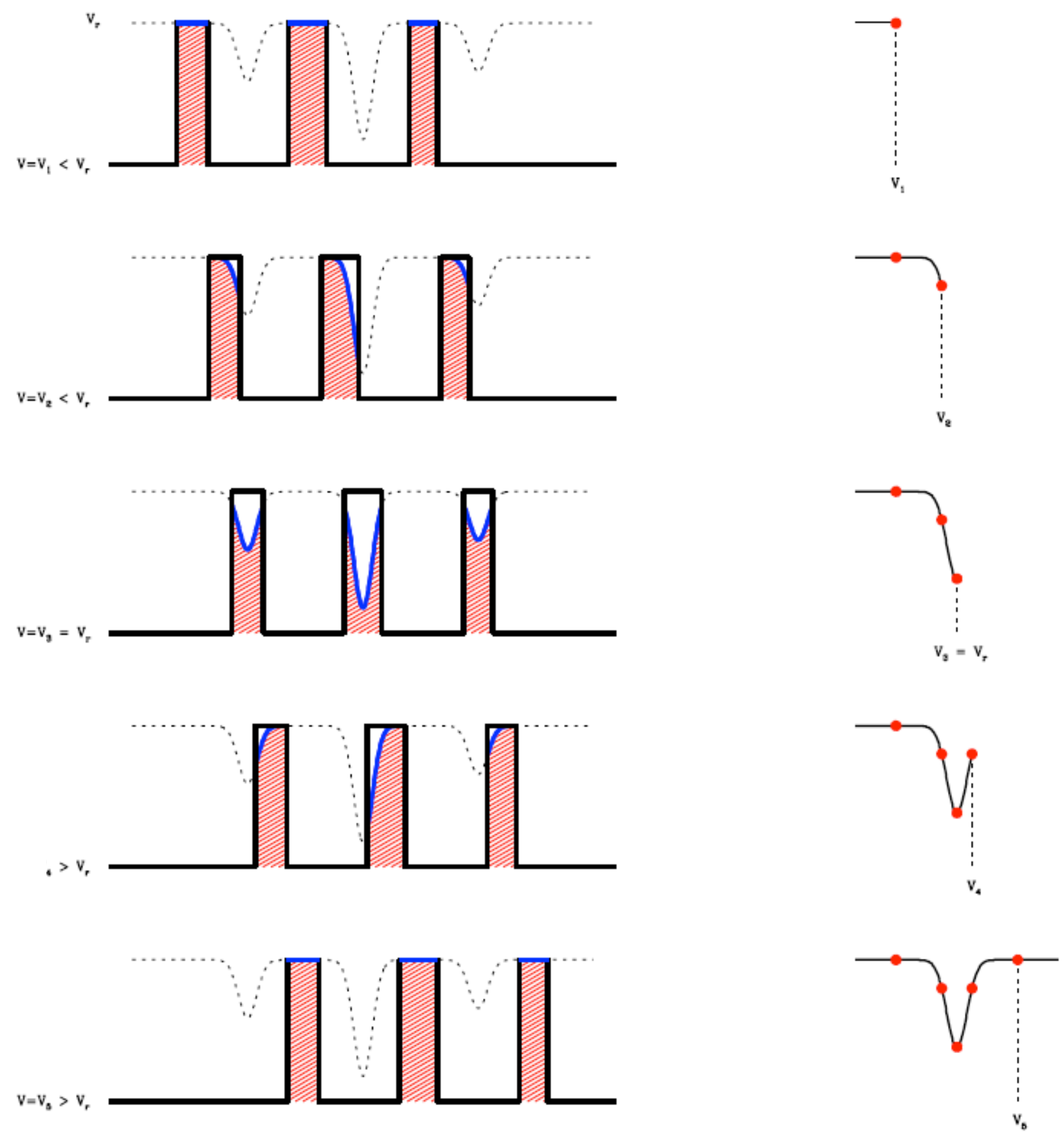
Using the power of the Cross-Correlation Function

- By construction, the Cross-Correlation Function (CCF) represents an average spectral line

$$CCF(v) = \sum_i A[\lambda(i)]\,.\,M[\lambda(i)\,(1 + v/c)]$$

Stellar spectrum

Binary mask



Using the power of the Cross-Correlation Function

- All lines in the CCF mask/spectrum are "stacked"
- The S/N in each corresponding "resolution element" (pixel on the CCD) of the CCF is given, as a good approximation, by:

$$S/N_{CCF} = S/N_{spe} \times \mathrm{sqrt}(N_{lines})$$

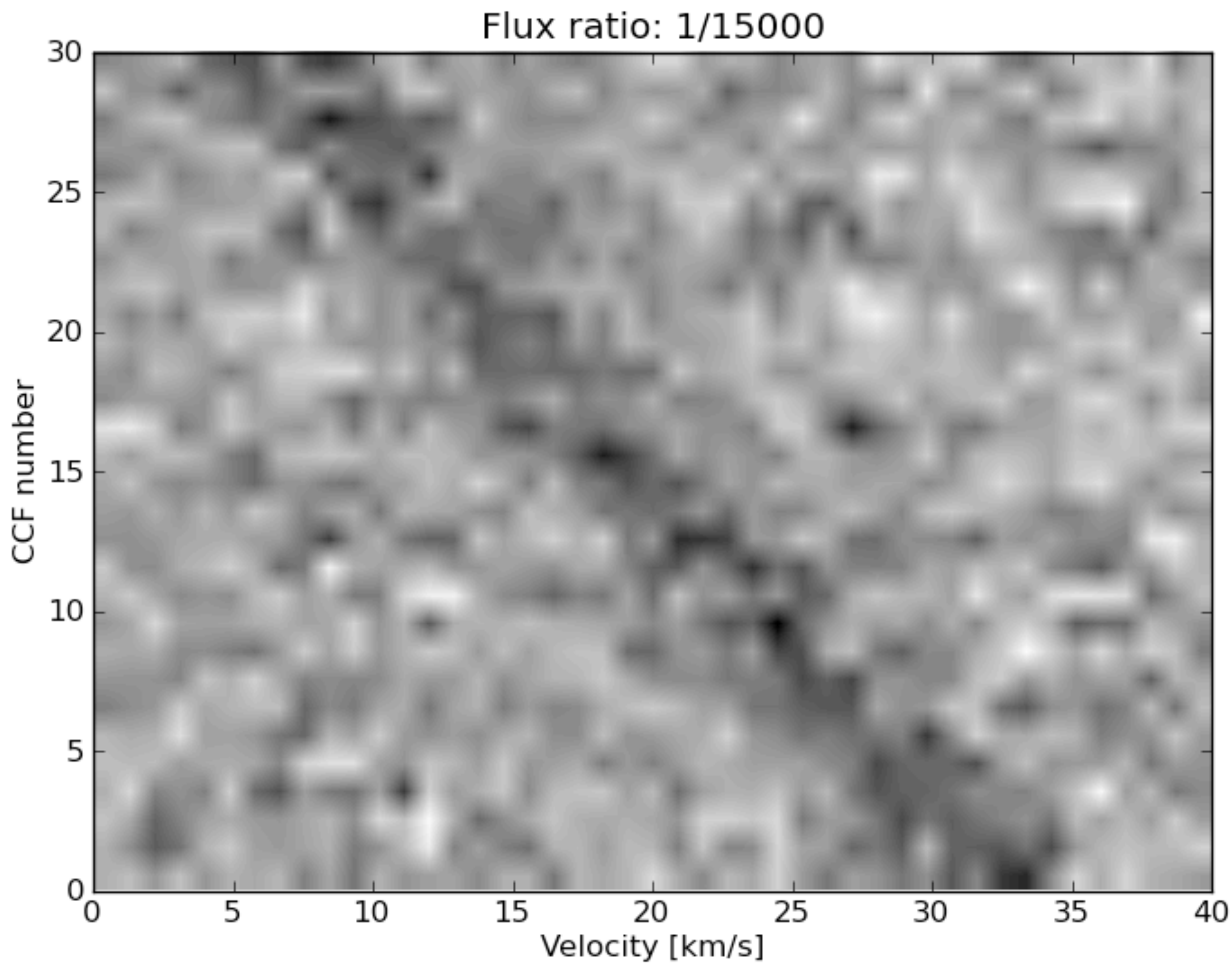
- Example:
  - Spectrum with $\langle S/N_{spe} \rangle = 1000$
  - $N_{lines} \sim 3600$ (HARPS G2 mask)
  - Expected $S/N_{CCF} = 60\ 000$

Simulations: testing the concept with *real* data

1. Initial set of high S/N HARPS data
   - Built from random stack of 20 spectra taken same night
   - Average S/N ~1000
   - Compute CCF
2. Add another spectrum/CCF (taken in a different night) to simulate planetary signal:
   - Multiplied by factor of $\mathbf{6x10^{-5}}$ (1/15 000)
   - Vary its velocity: simulate planetary motion
3. Subtract stellar contribution with template CCF

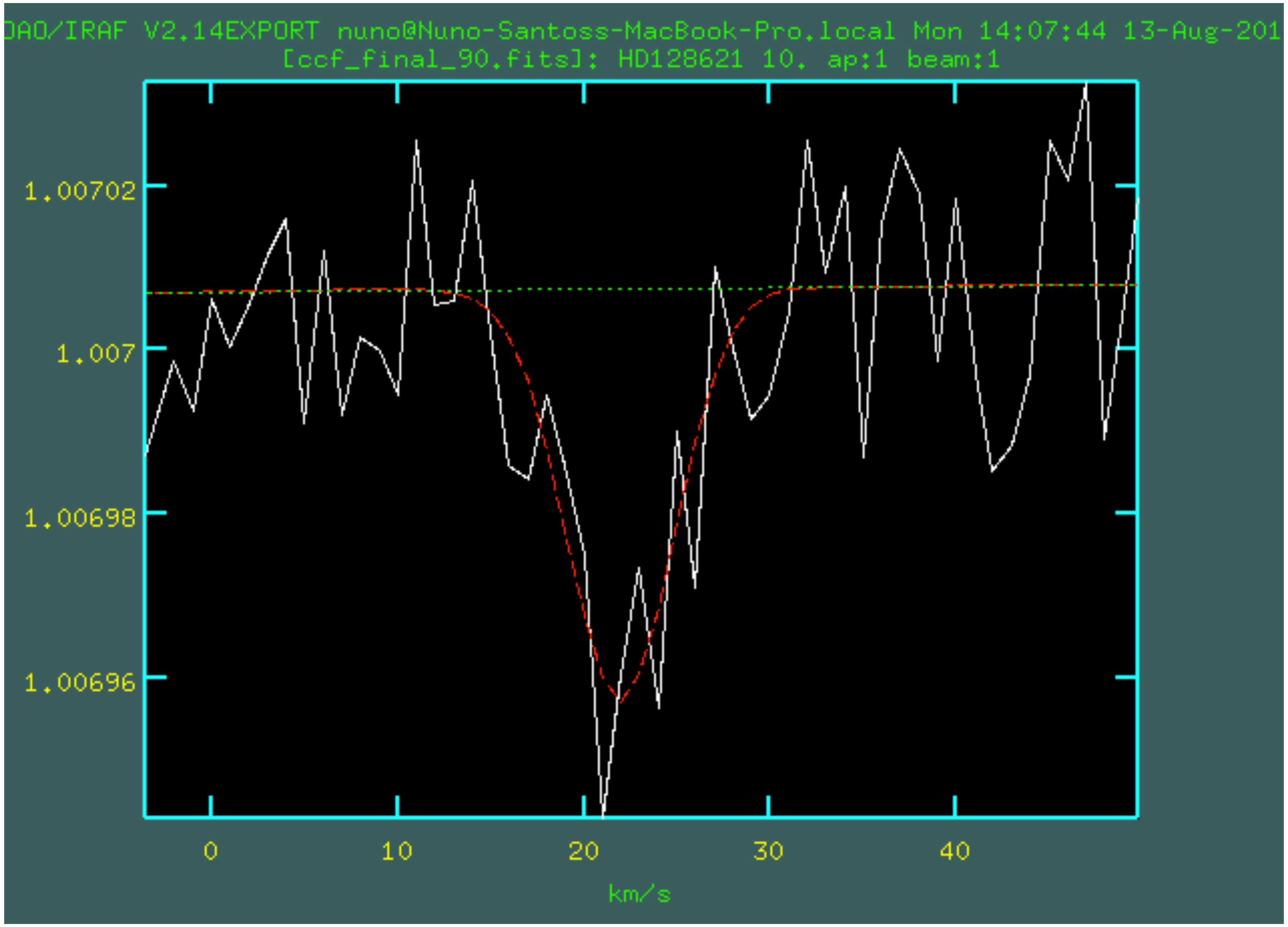
- Expected S/N_{CCF} ~ 60 000 (residuals of ~$2x10^{-5}$)
- I.e., we expect a 3-sigma detection

Simulations: results

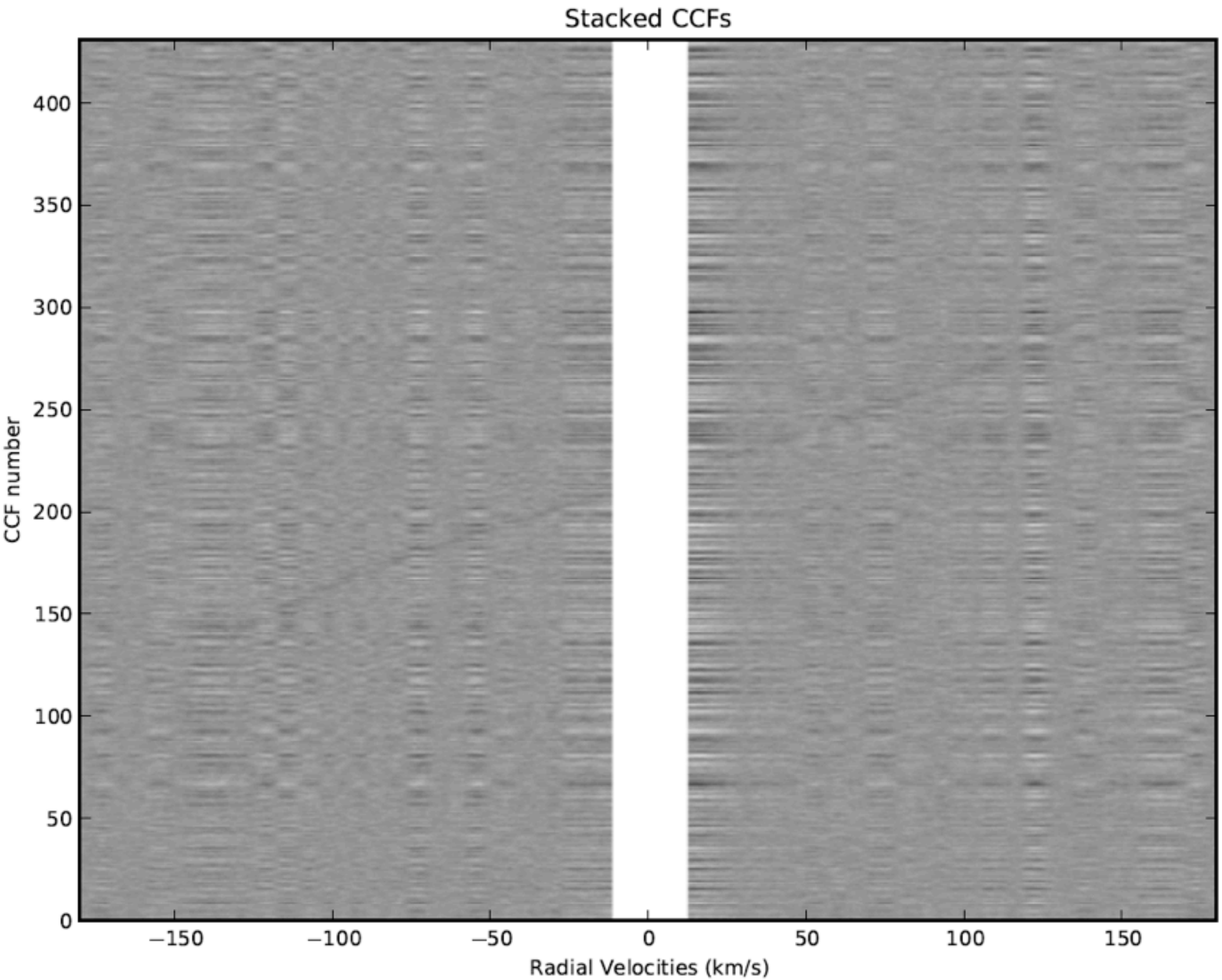


Simulations: results

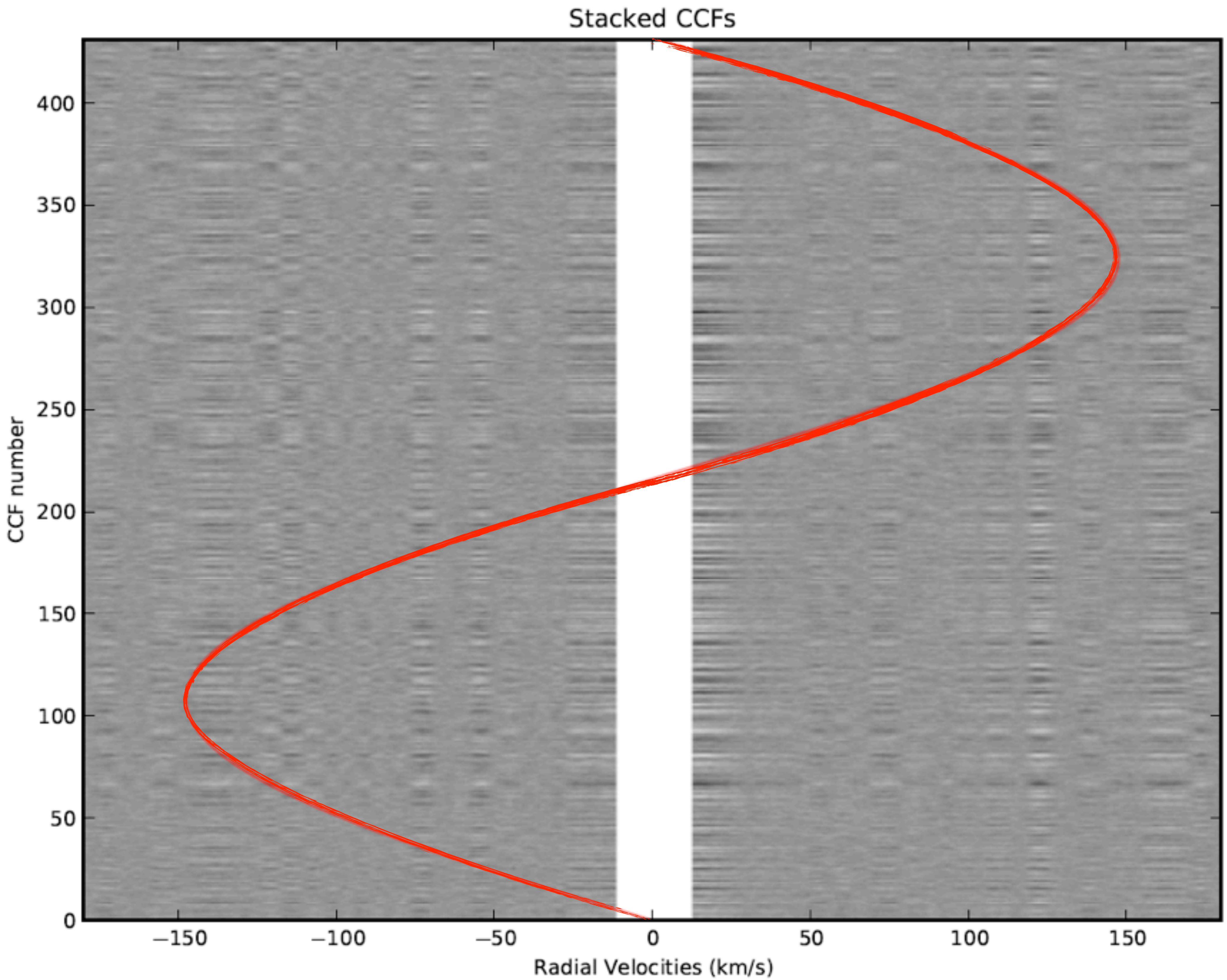
- Example of resulting CCF (one single phase)
- 3-sigma detection as expected!



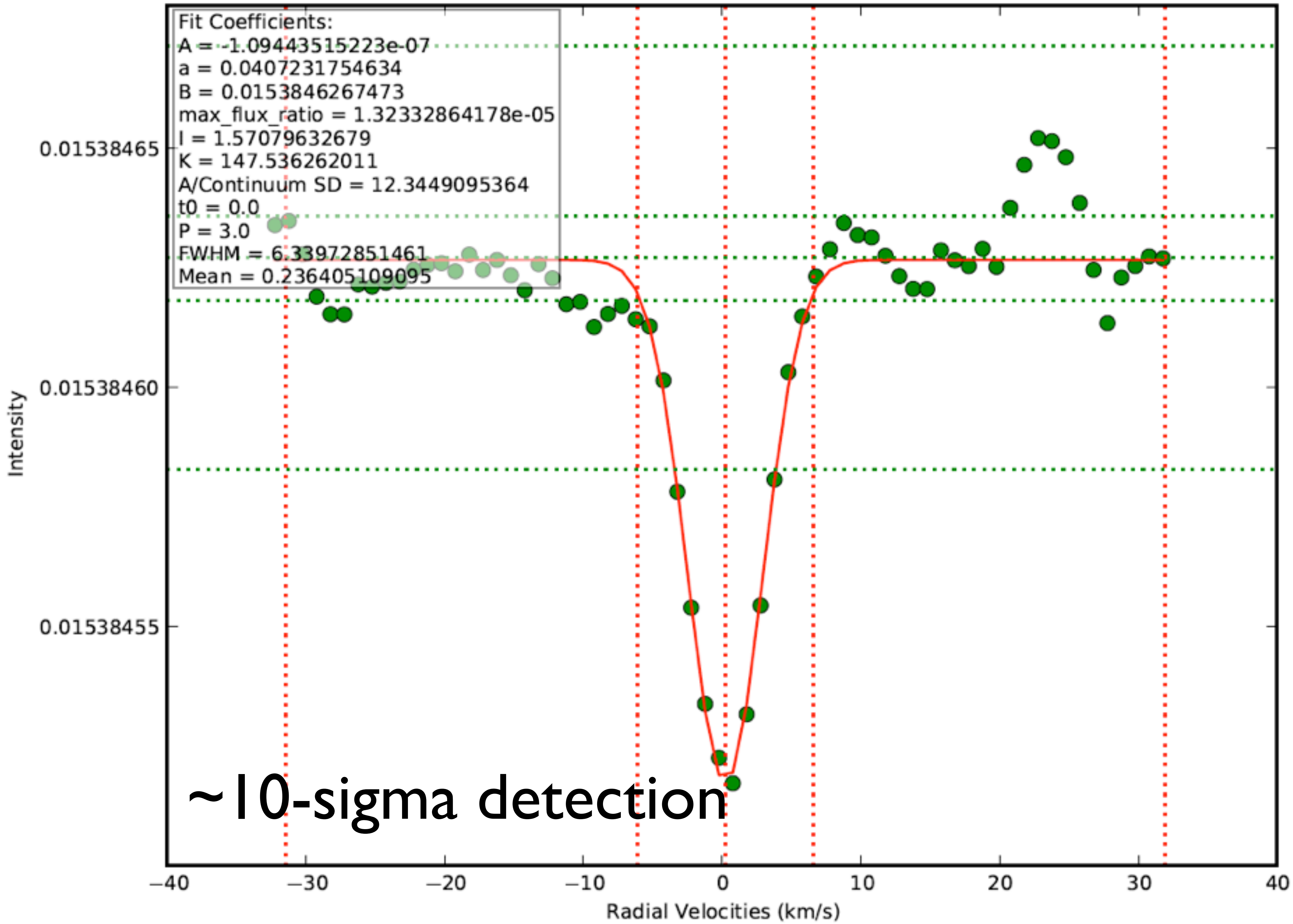
Jupiter, A=0.3, P=3days, S/N_{spec} = 2000 / 10 min.



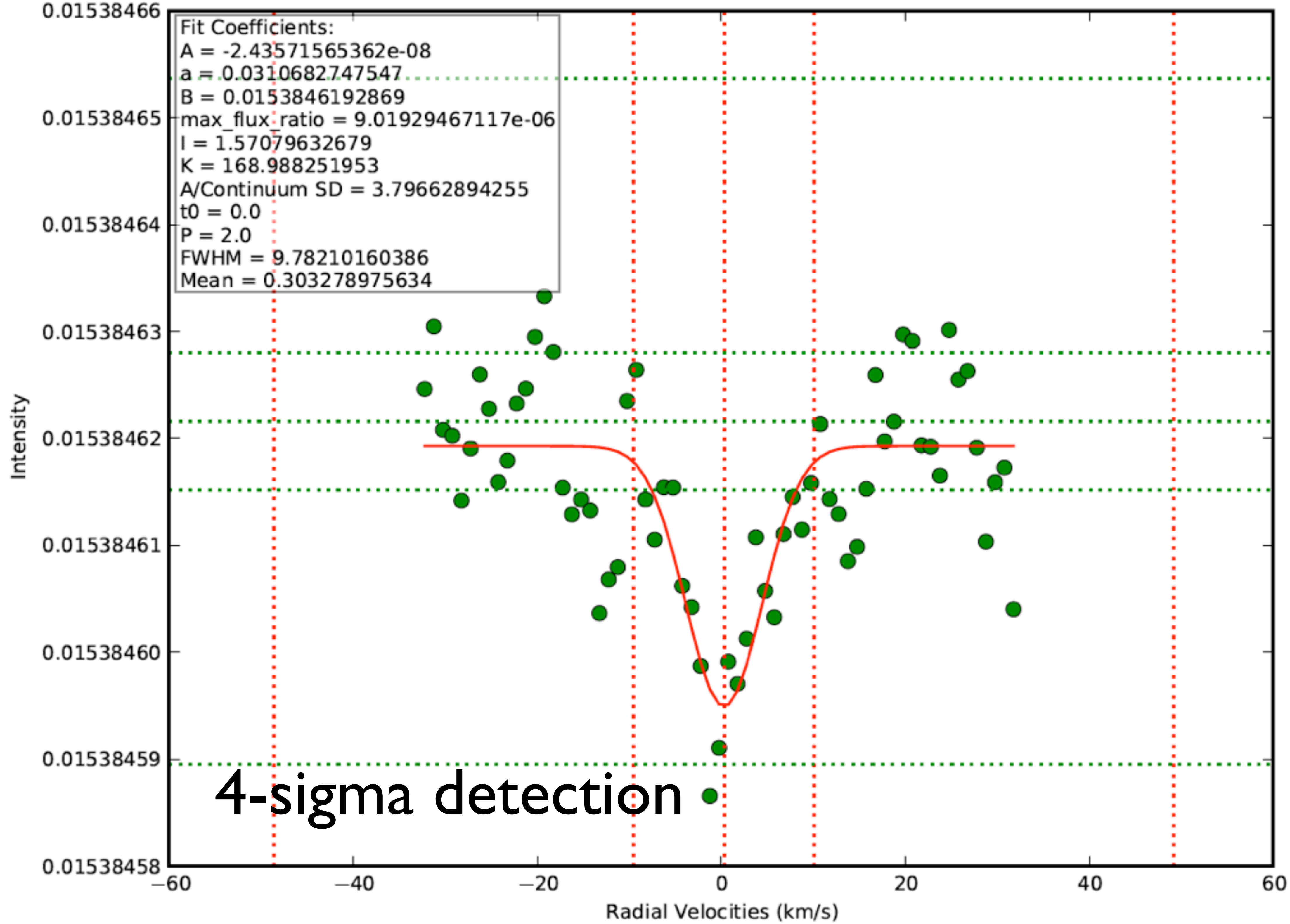
Jupiter, A=0.3, P=3days, S/N_{spec} = 2000 / 10 min.



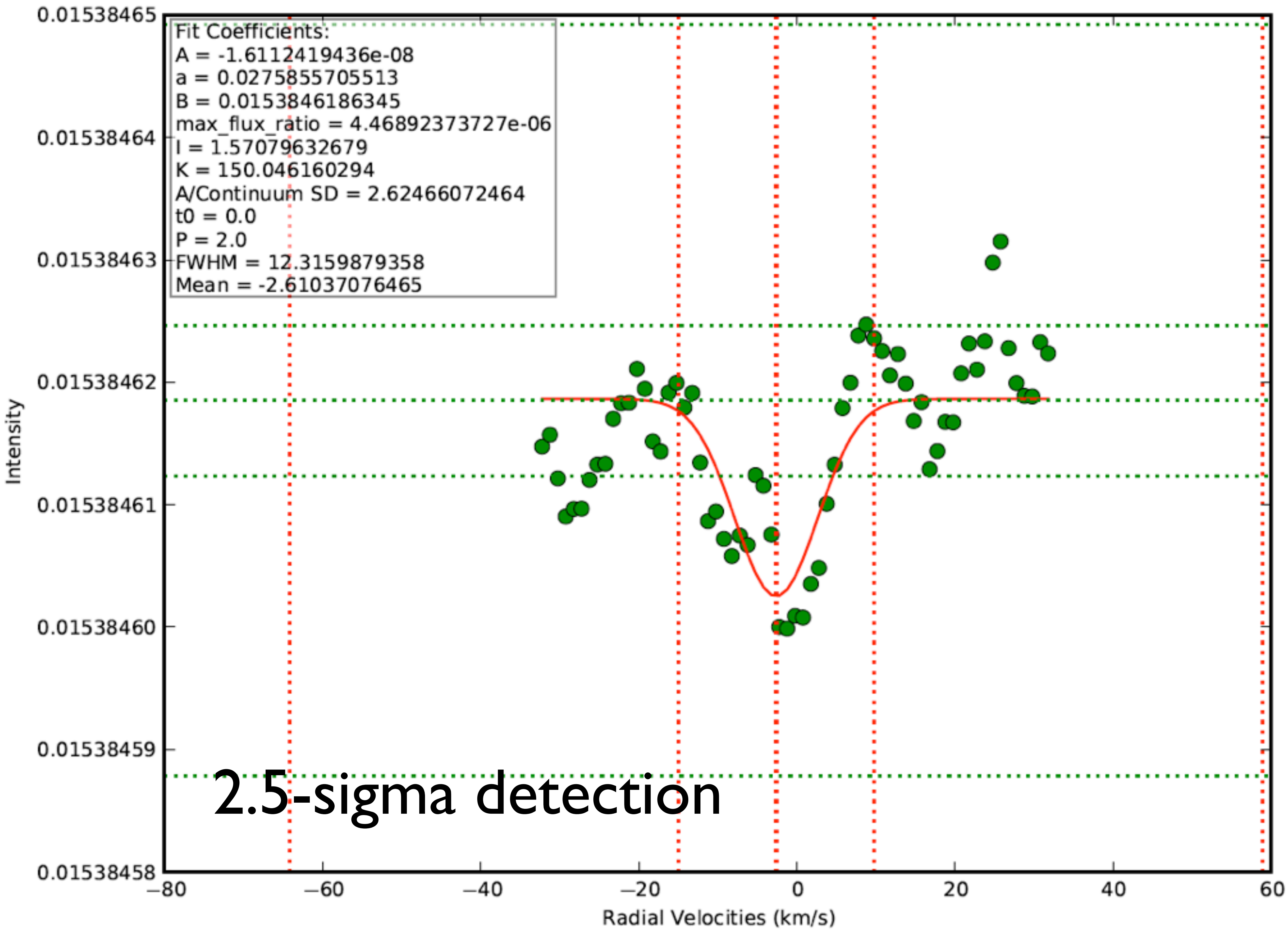
Jupiter, A=0.3, P=3days, S/N_{spec} = 2000 / 10 min.



Neptune, A=0.3, P=2days, S/N_{spec} = 2000 /10 min.



Super-Earth, A=0.3, P=2days, S/N$_{spec}$ = 3000 / 10 min.



Estimates for 2-sigma detections

Planet	Ag *	Needed S/N_{spe}
P=3days, R=1 R_{jup}	0.3	800
P=3days, R=1 R_{Nept}	0.3	6000
P=1day, R=1 R_{Nept}	0.3	1700
P=1day, R=2 R_{Earth}	0.3	6000
P=1day, R=1 R_{Earth}	0.67 (Venus)	10 000

*0.3 is reasonable value according to Cowan & Agol (2011) and Santerne et al. (2011)

HIRES@ELT

- From a simple extrapolation from UVES@VLT:
  - HIRES@ELT: G2V, mv~7, T_{exp}=900s => S/N~5000
  - Many available targets!!!

The challenges

- **Flux**: detect signals that are of the order of 10^{-5}
  - ELT collecting power critical
  - Relatively short exposure times (due to planetary motion)
- **Spectral fidelity**
  - Very good FF correction (stable detector/well characterized)
  - PSF stability needed
- **High resolution (~10^5)**: keep line contrast

In brief: we need a stable spectrograph and a large telescope! HIRES@ELT will be the right instrument.

Thank you!

Questions?