Characterizing HZ planets with Radial Velocities: From CHIRON to EXPRES

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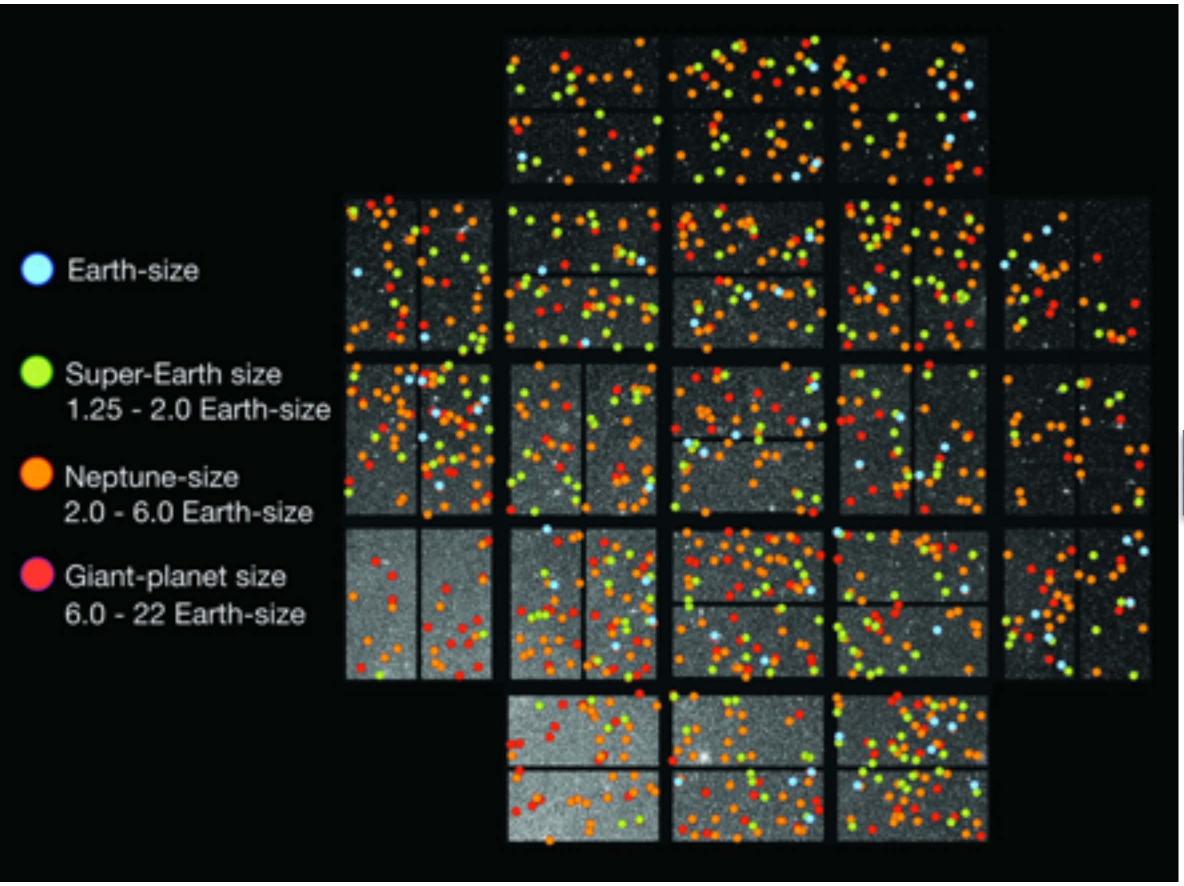
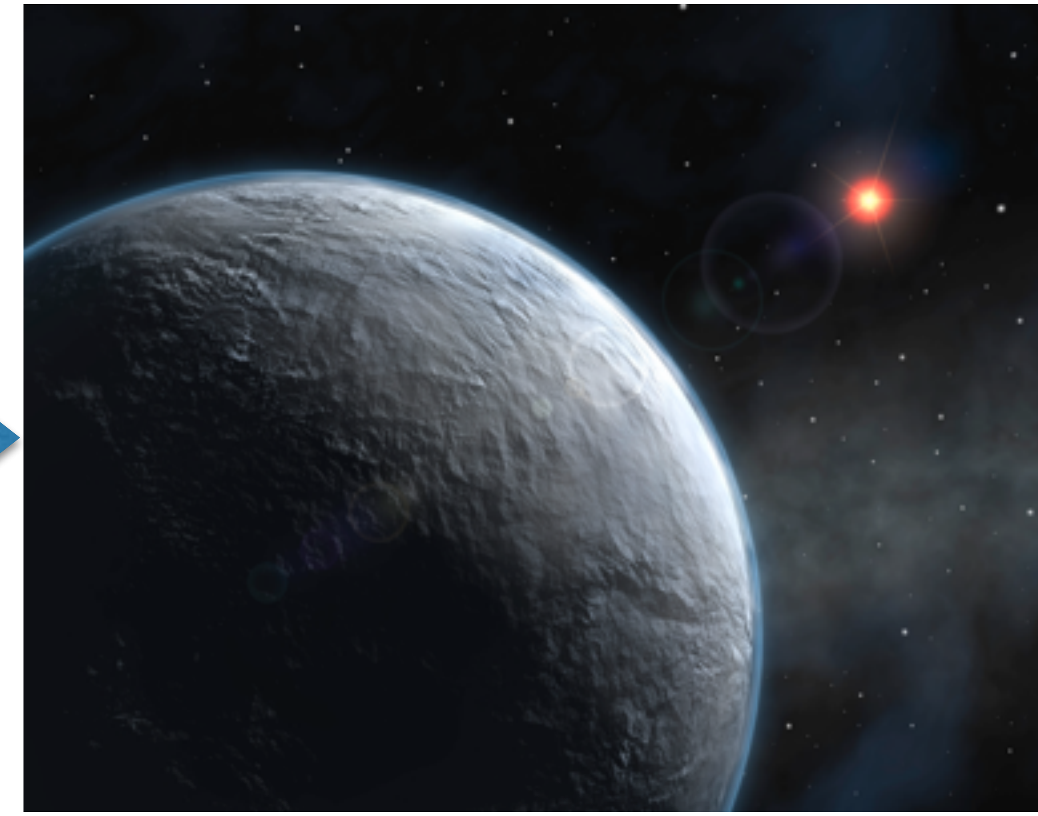
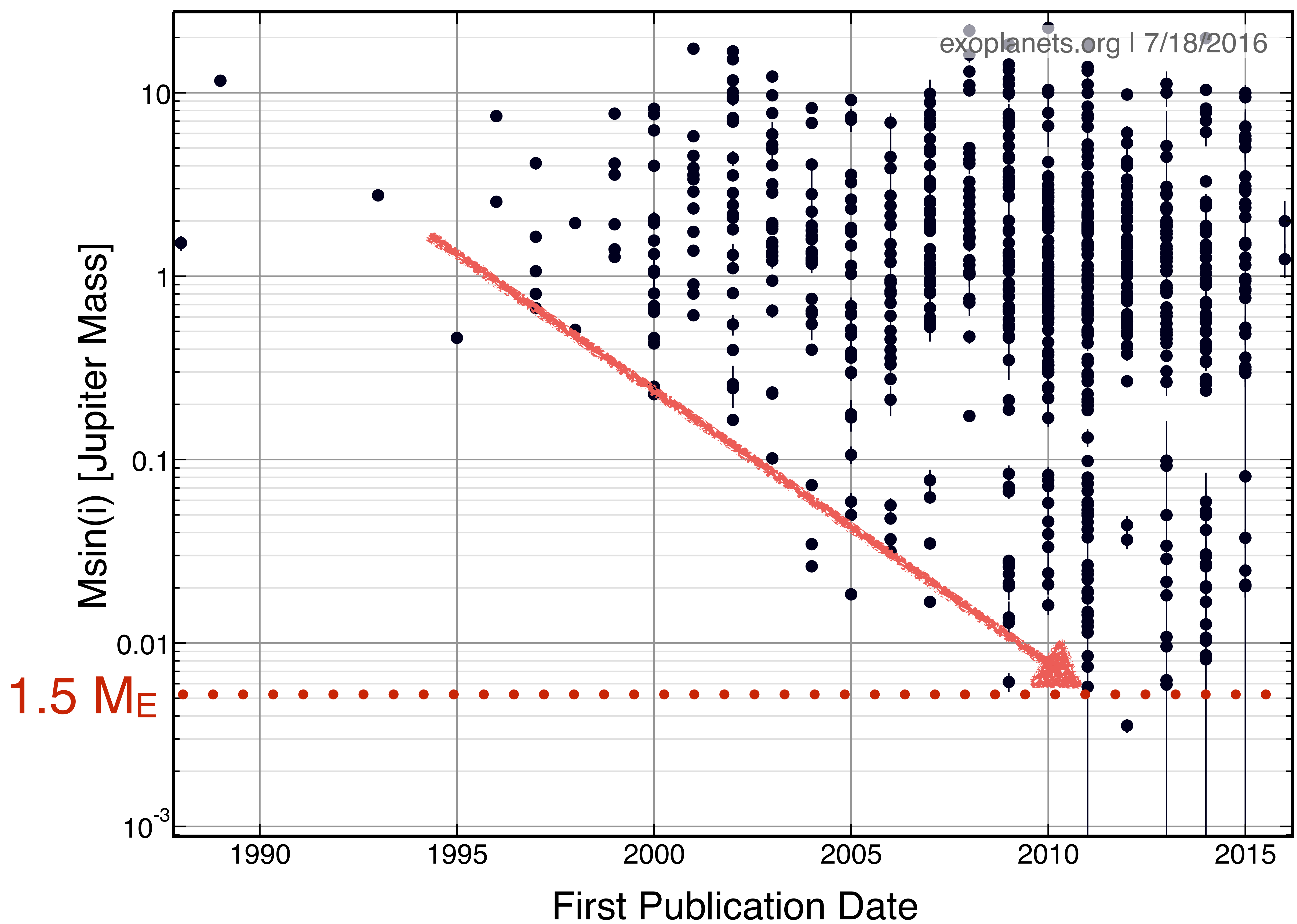




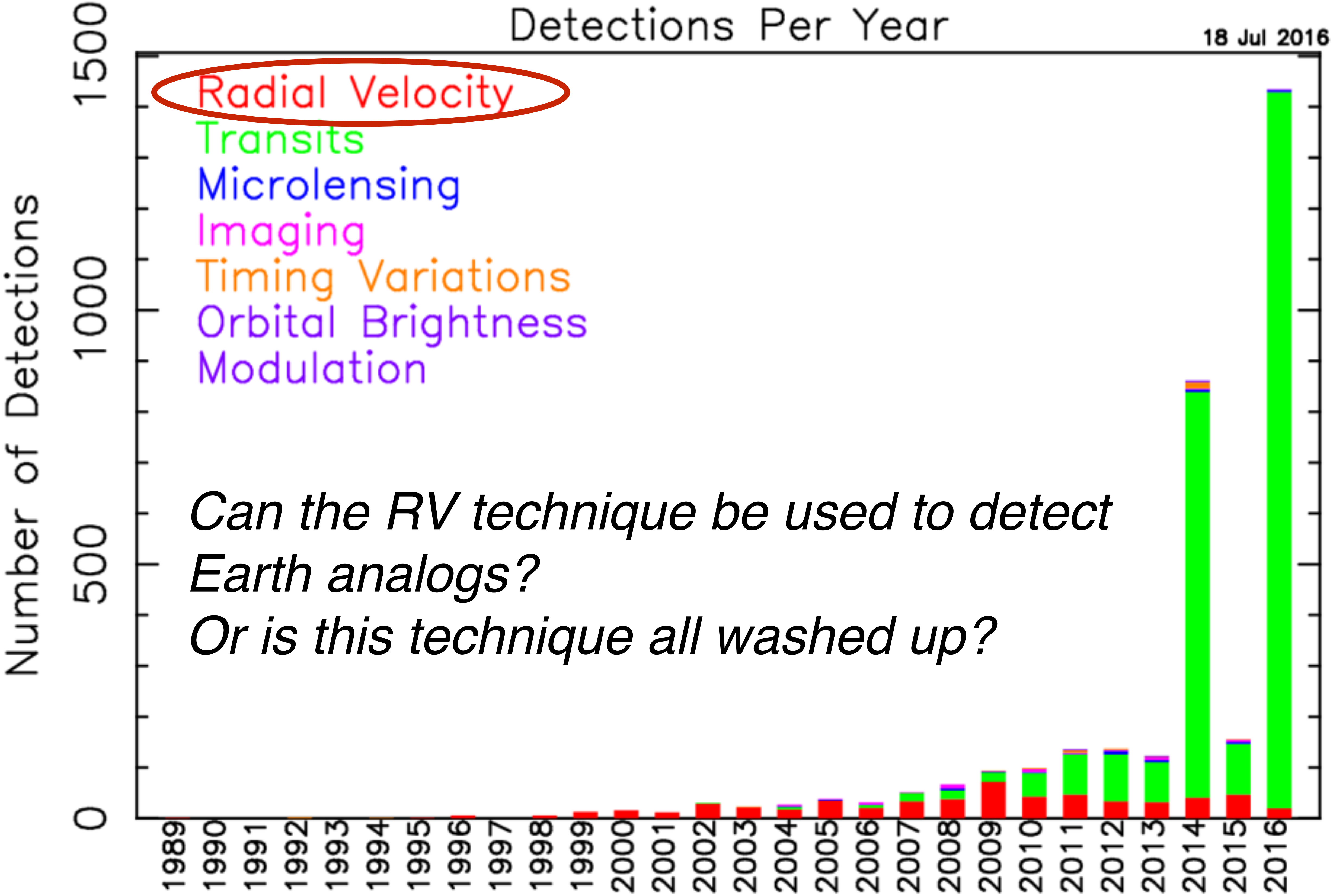
To go from planet radii to real characterization, masses are critical.

Masses => densities for transiting planets, interpretation of exoplanet atmospheres.

If we don’t succeed, the exoplanet bubble may burst.



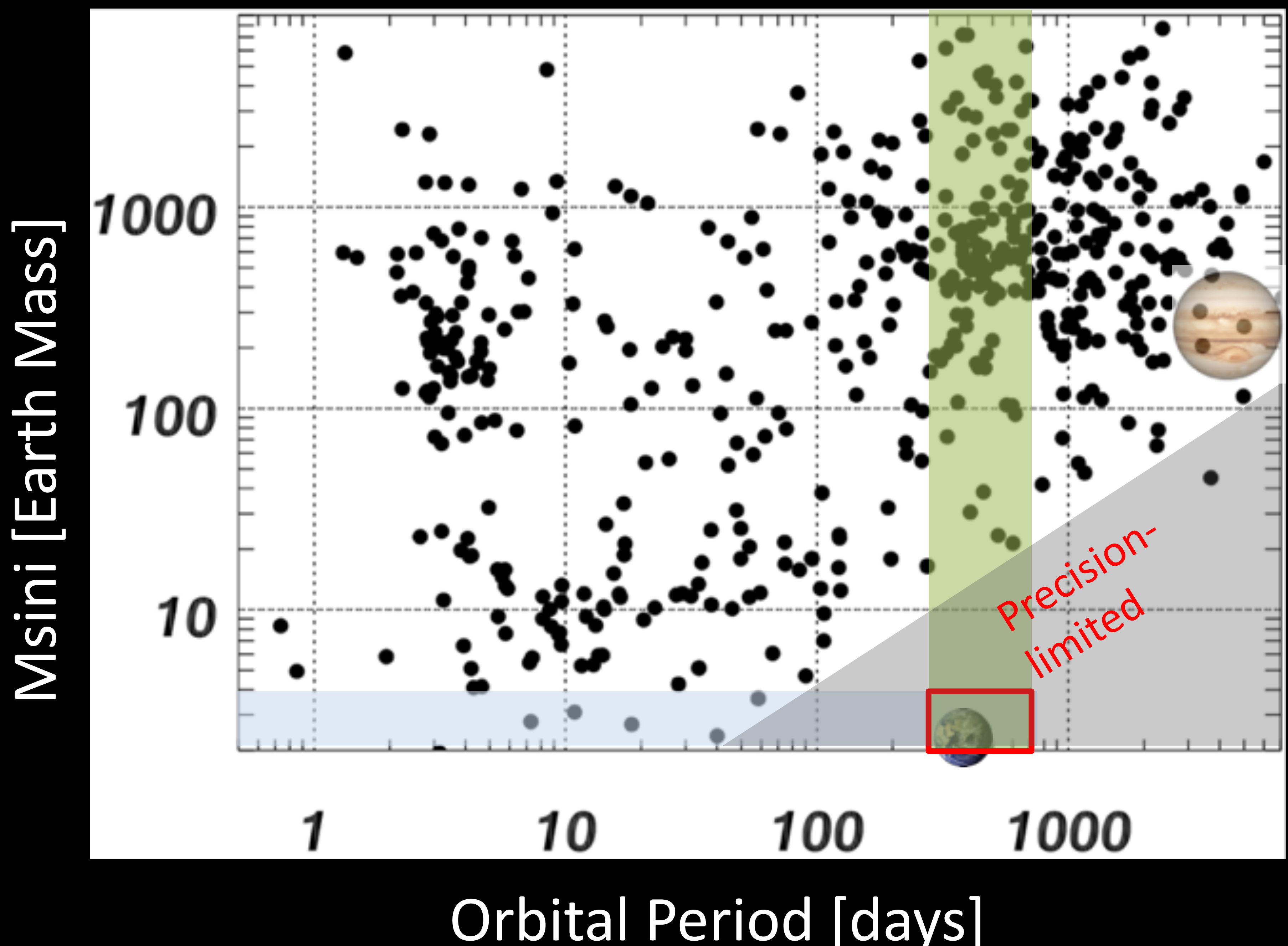
exoplanets.org



Can the RV technique be used to detect Earth analogs?
Or is this technique all washed up?

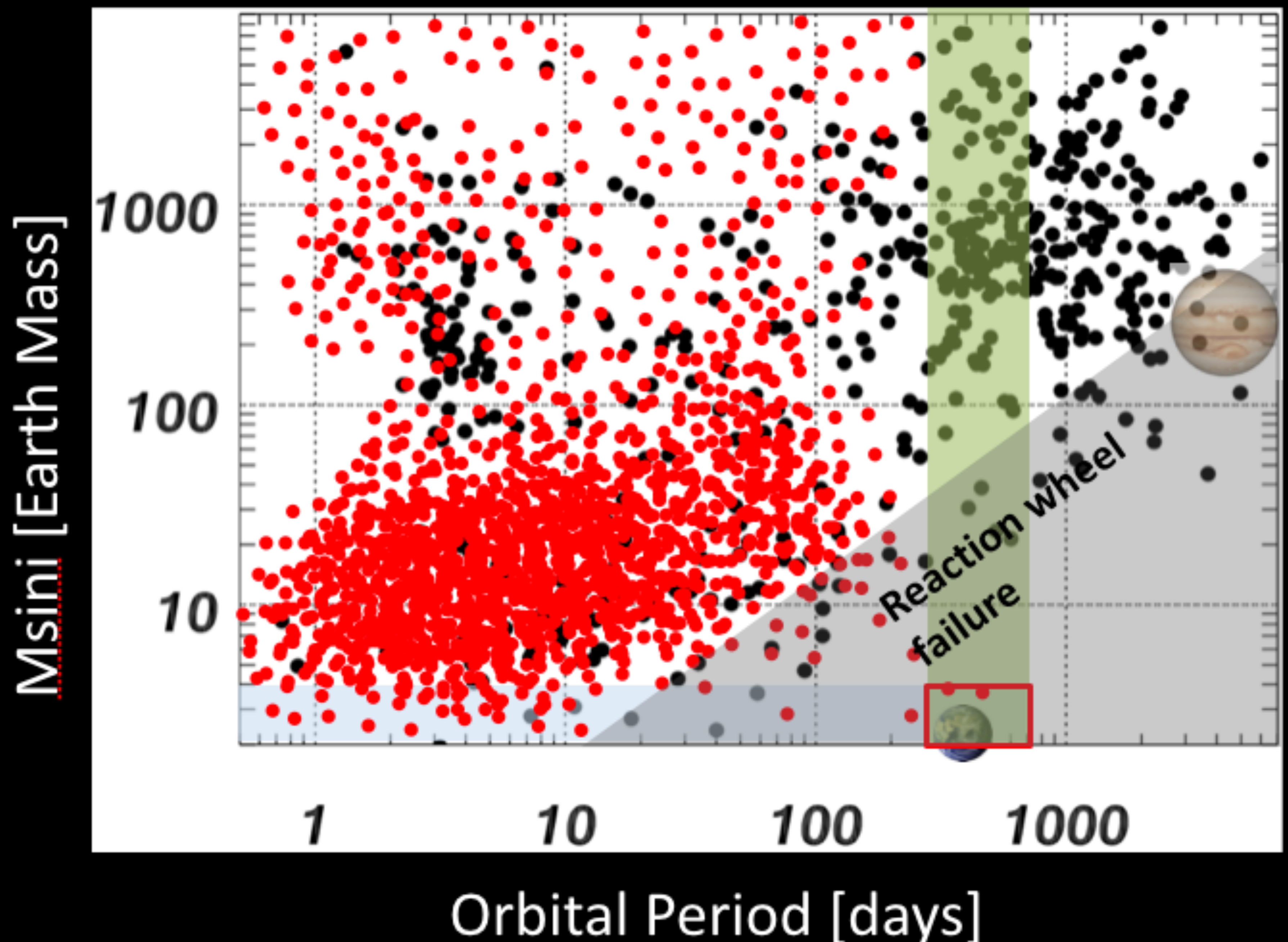
exoplanetarchive.ipac.caltech.edu

Radial velocity discoveries – 1995 to 2016



Radial velocity discoveries plus Kepler transits 1995 to 2016

Is there any technique on the horizon to detect Earth analogs?



“Floor of the Doppler precision set by stellar noise.”

Butler et al. 1996

“Ultimately the limit to velocity precision is set by the stars themselves. On long time scales stellar magnetic cycles, analogous to the solar cycle, could insidiously cause an apparent periodic change in radial velocity (Jimenez et al. 1986; Deming et al. 1987).”

The floor of the RV precision was:

3 m/s in 1996 (Lick / Keck)
1 m/s in 2005 (HARPS)

(Generally matched to our measurement error bars.)

Stellar “jitter” includes Doppler velocities from:

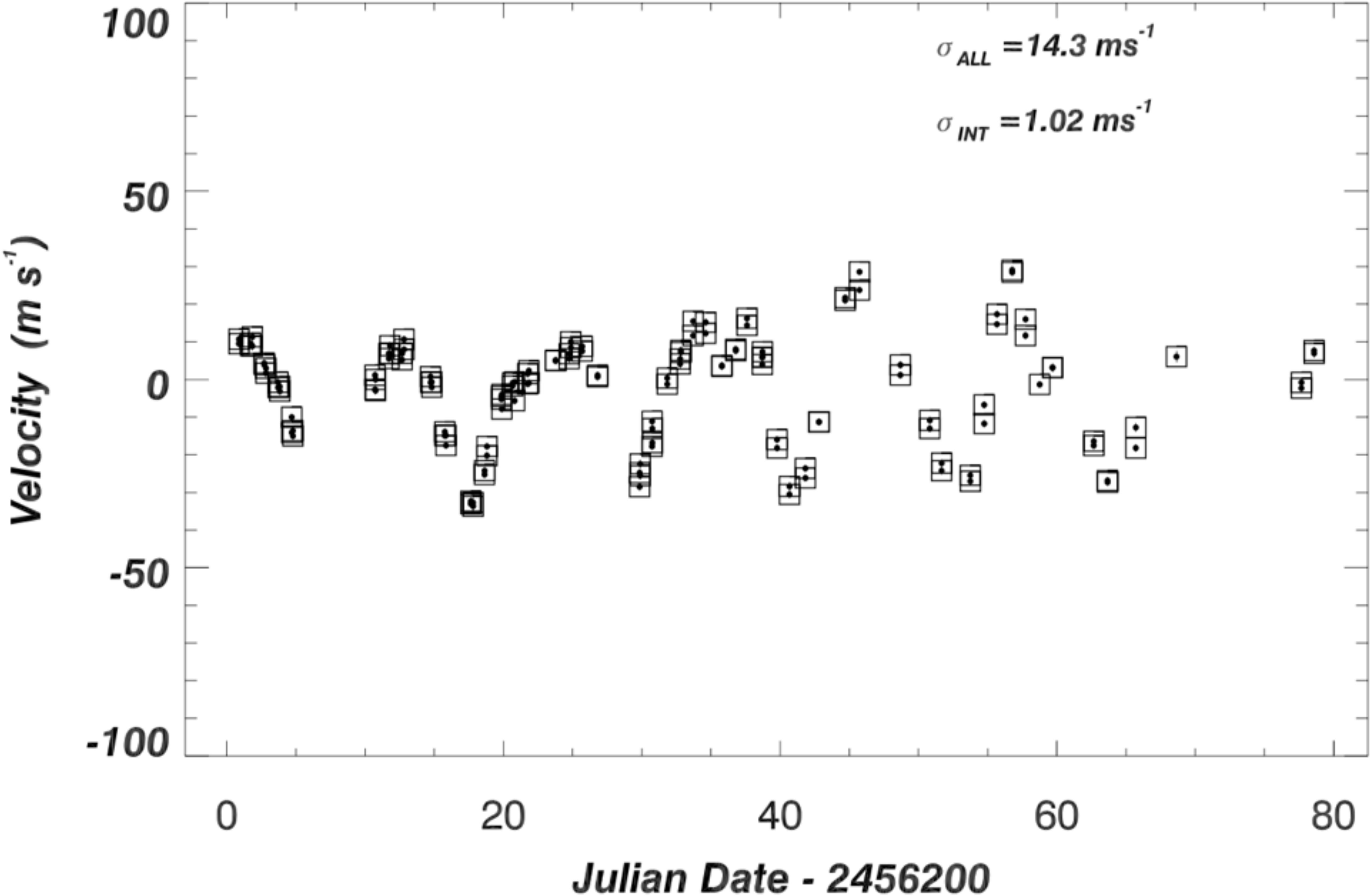
- pulsation
- spots
- faculae
- meridional flows
- time-varying granulation

Recall the spots shown by Xavier Dumusque - a complicated family of spots, not single spots!
Not clear that we will ever be able to model spectral effects from first physical principles.

HOWEVER, stellar jitter has two important properties:

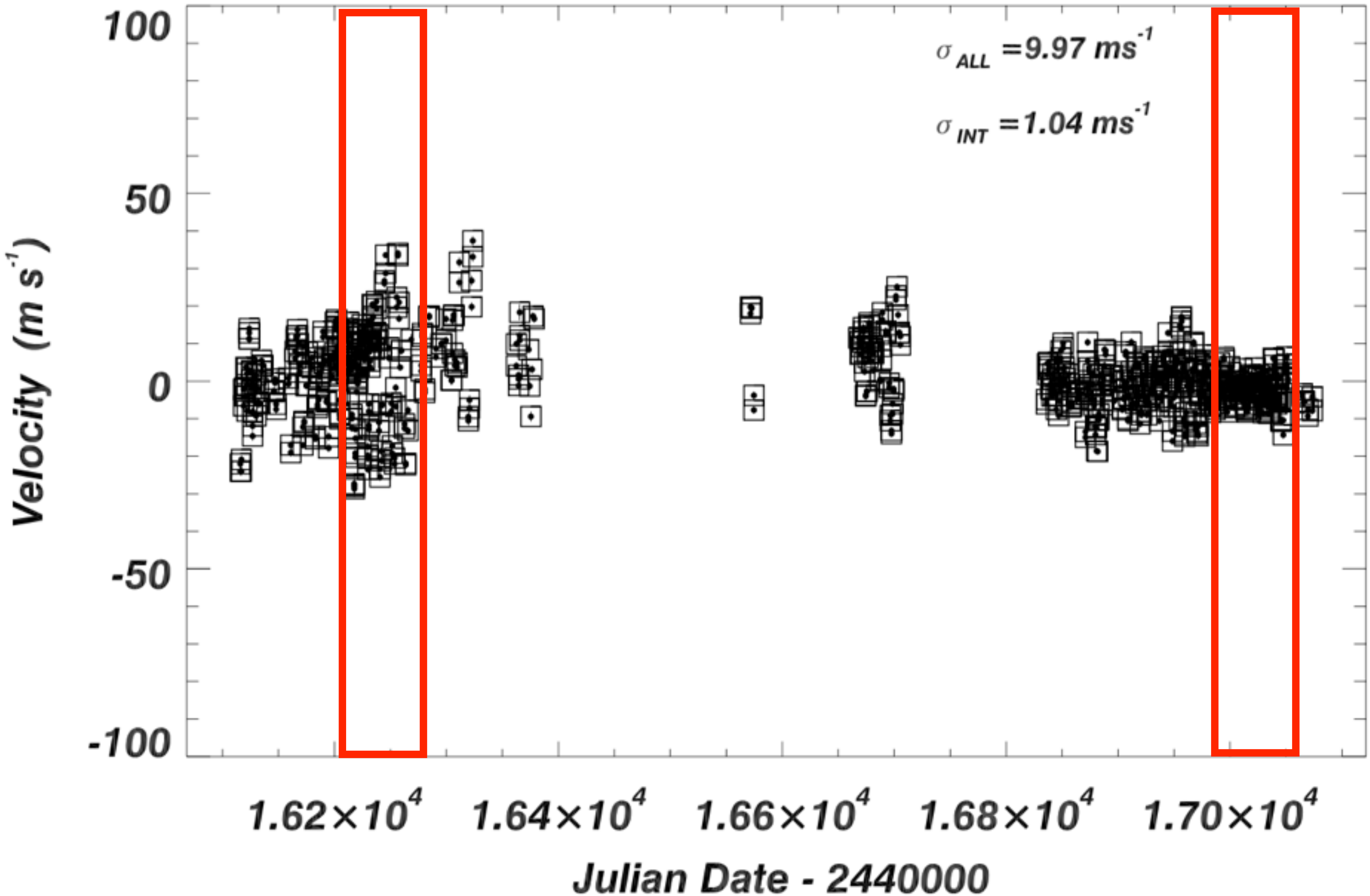
- it is not a persistent Keplerian signal – it waxes and wanes and it varies on timescales that are different from orbital velocities
- the underlying physical phenomena that spawn jitter have line-by-line spectroscopic signatures that should be distinguishable from orbital Doppler shifts.

Dude, is there a planet in my data?



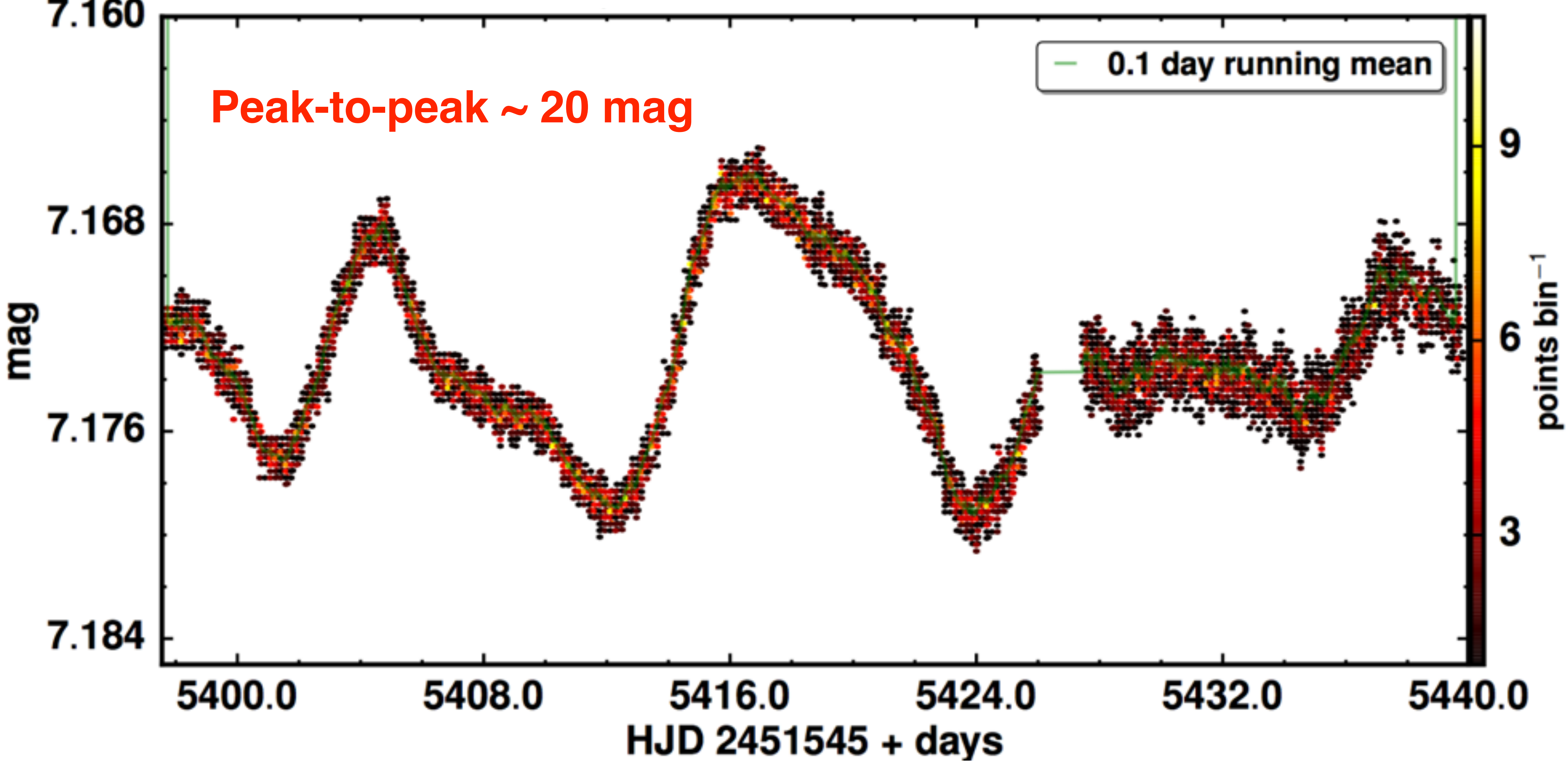
Epsilon Eridani RV Data from CHIRON at CTIO - Fischer

Epsilon Eridani



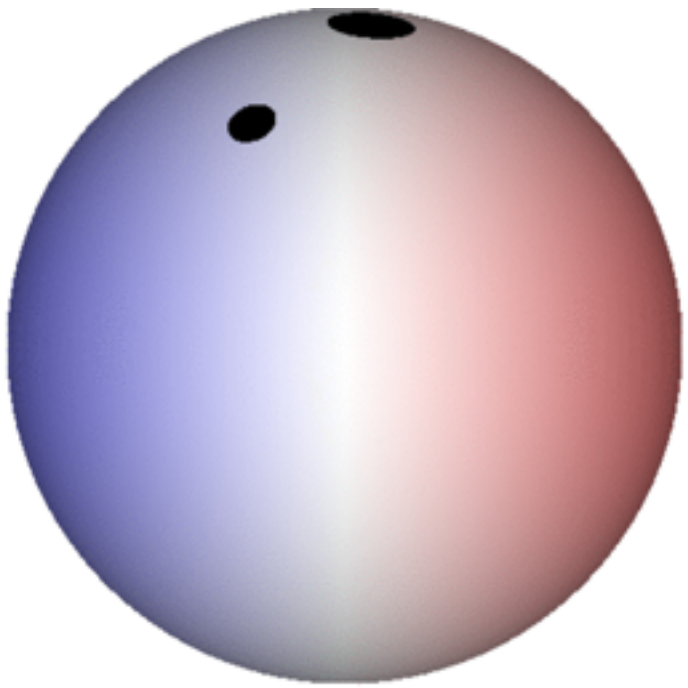
Epsilon Eridani RV Data from CHIRON at CTIO - Fischer

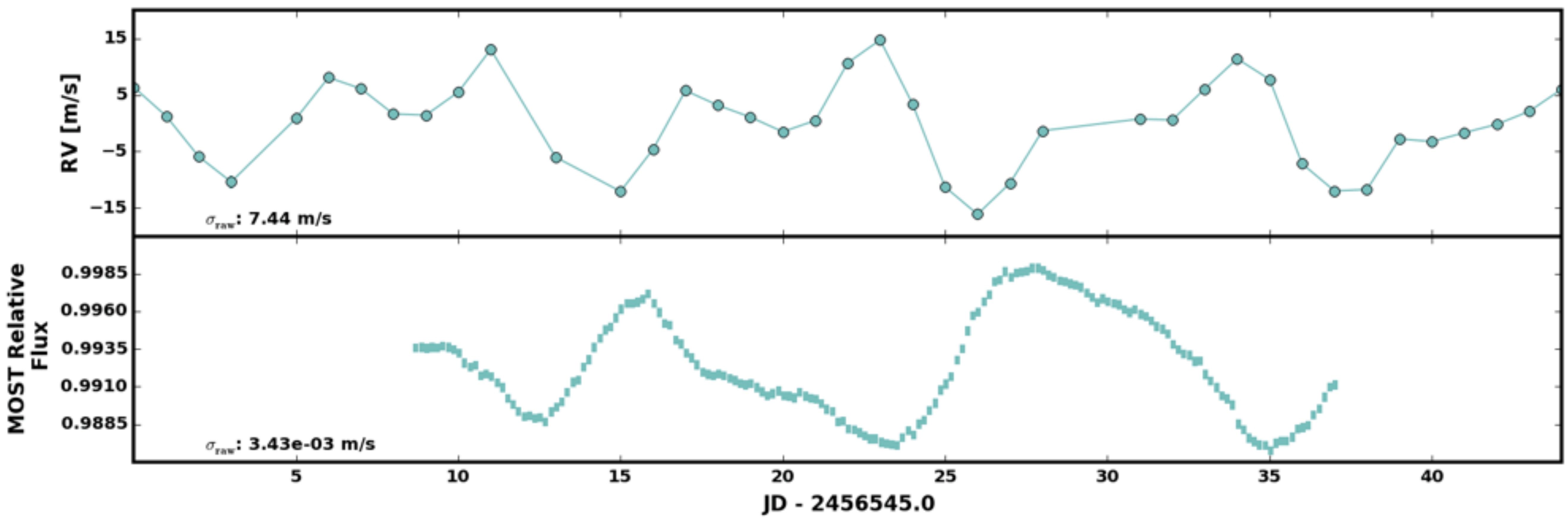
Nov 2014 **MOST** observations of Epsilon Eridani



MOST data extraction: Jaymie Matthews

Epsilon Eridani modeling simultaneous CHIRON + MOST data





Plage (chromosphere) or Faculae (photosphere)?

- EIT images **plage** - energy from magnetic fields is transferred to the low density chromosphere, where it excites atomic transitions. Plage is seen as emission in line cores, like H-alpha.

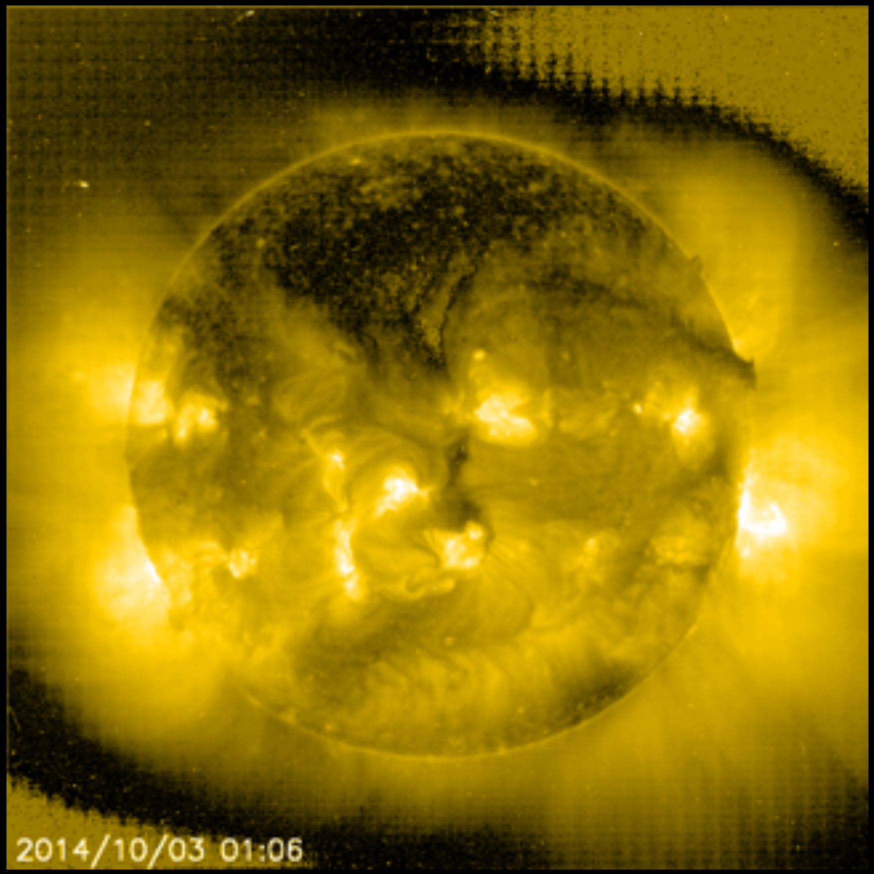
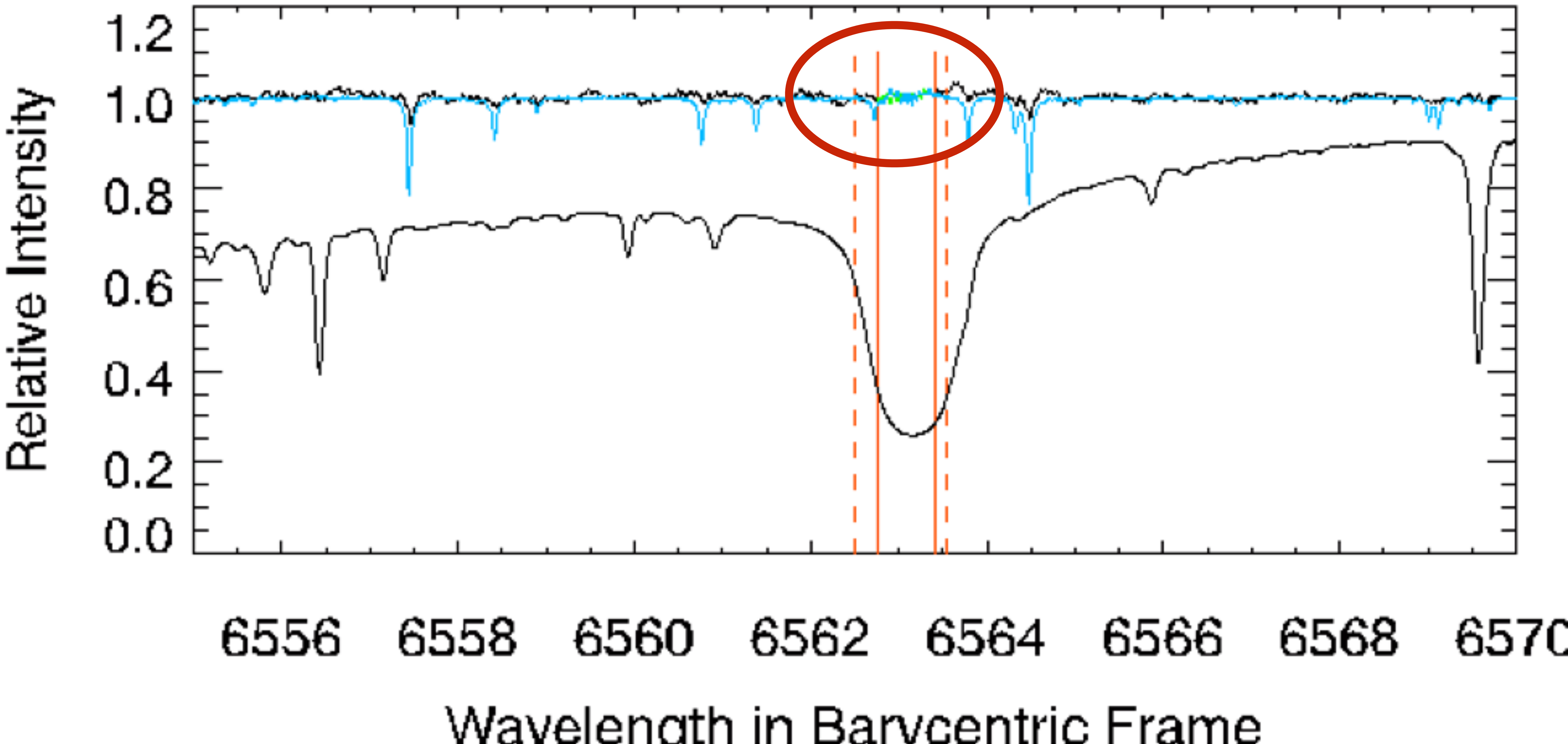


Image credit: SOHO/EIT



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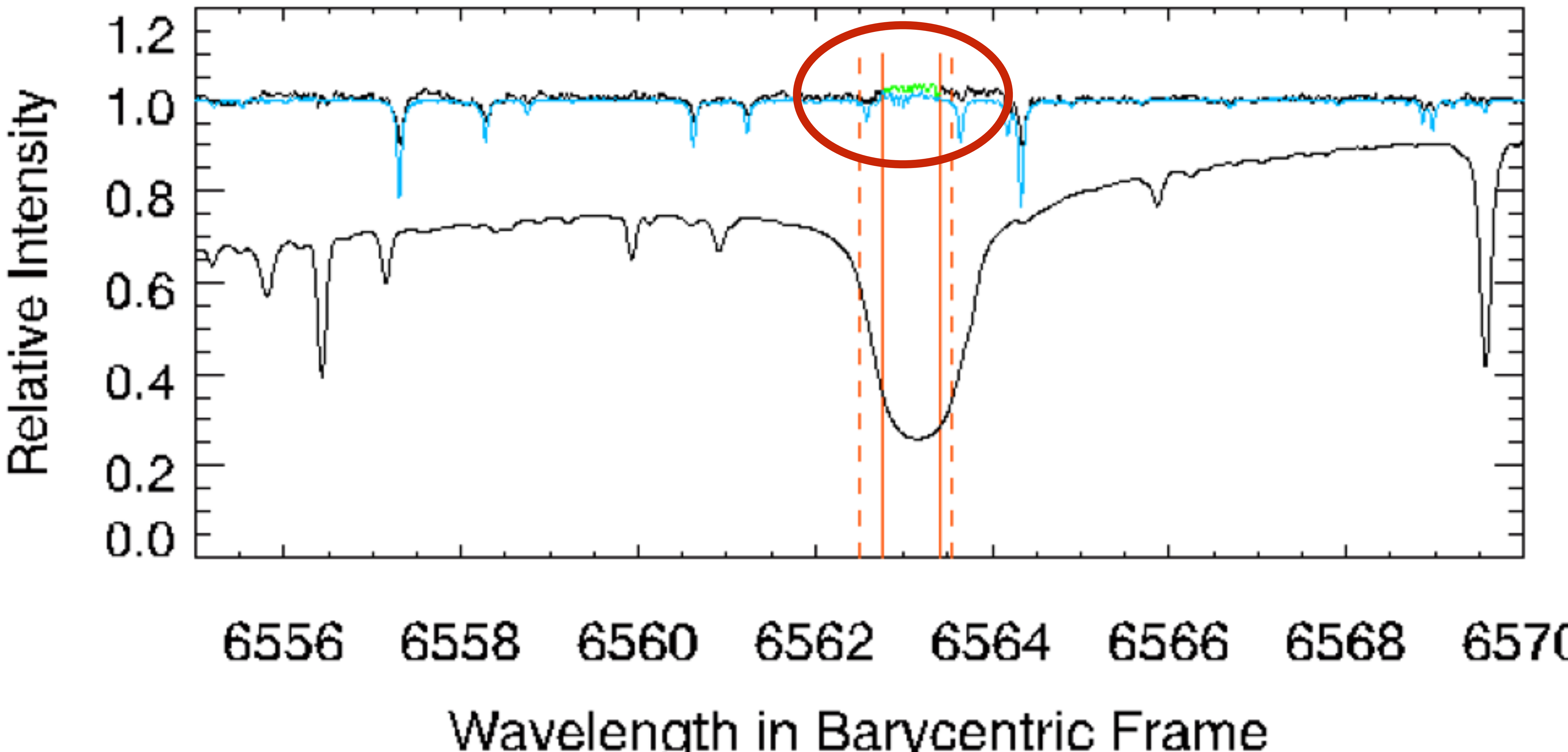
Wavelength in Barycentric Frame



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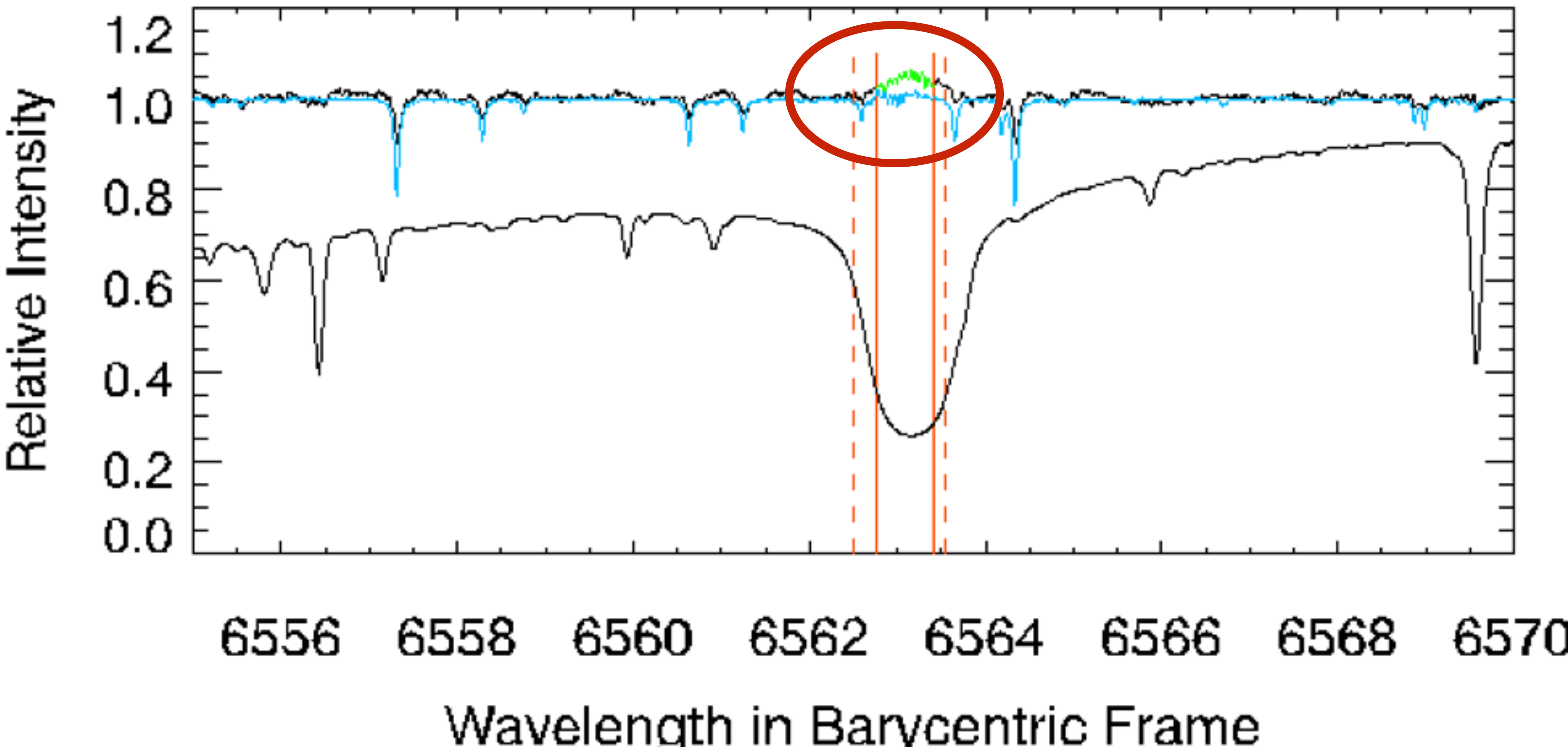

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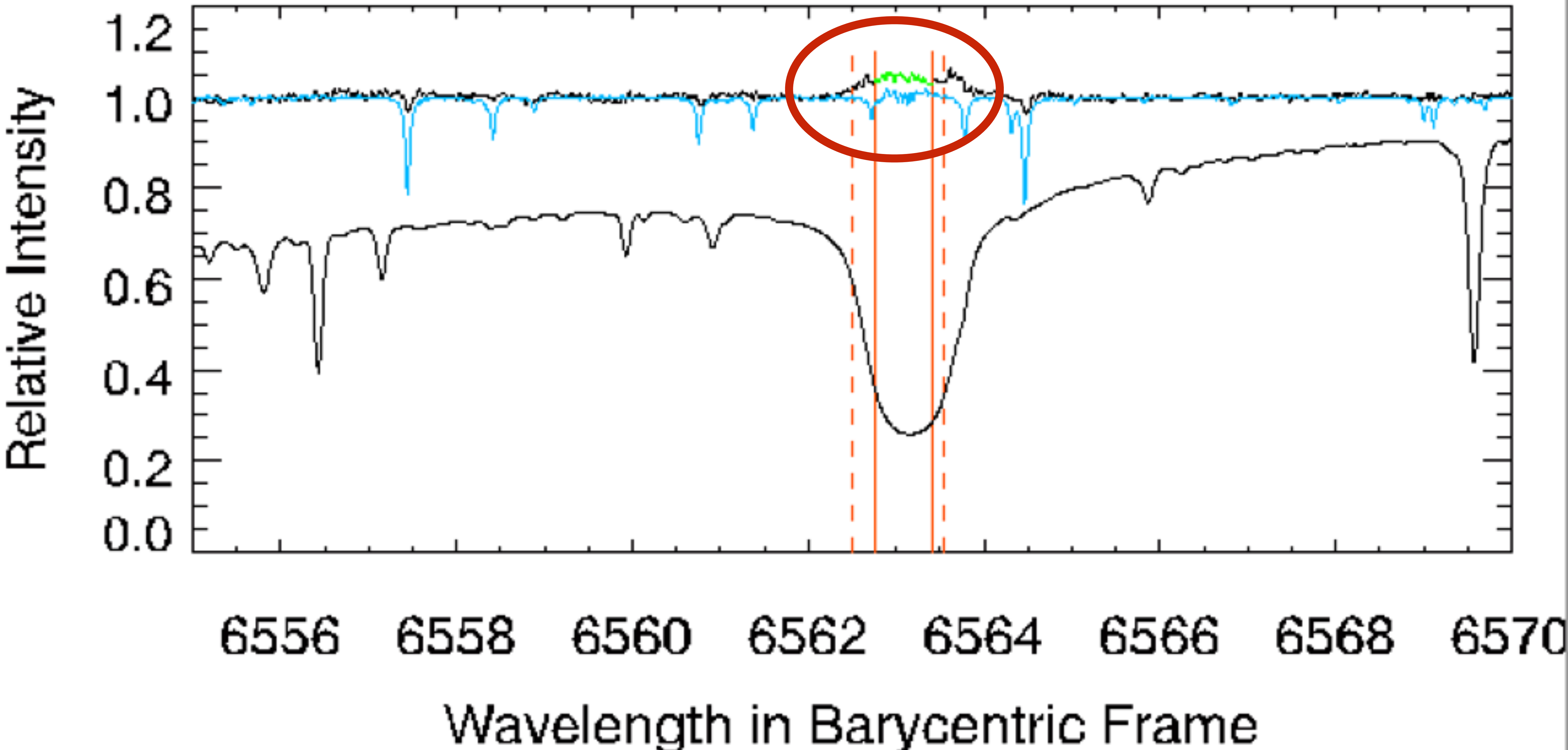
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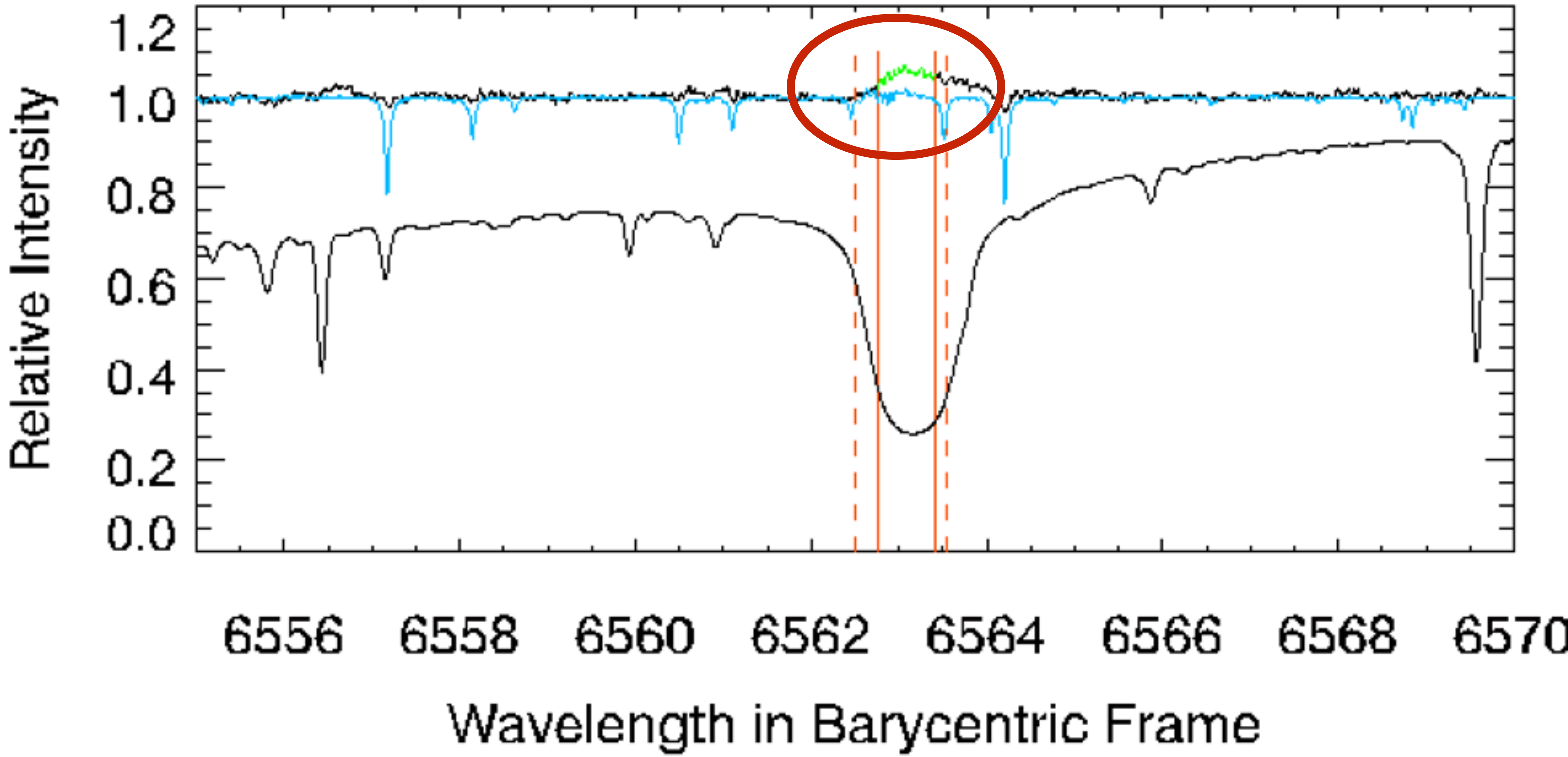

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Plage (chromosphere) or Faculae (photosphere)?

- EIT images **plage** - energy from magnetic fields is transferred to the low density chromosphere, where it excites atomic transitions. Plage is seen as emission in line cores, like H-alpha.

- In the photosphere, these are **faculae**, and manifest as extended regions around spots. Magnetic fields tie plage to faculae and have the effect of suppressing granulation. Energy transfer slows… dark spot, variation granulation velocity field.

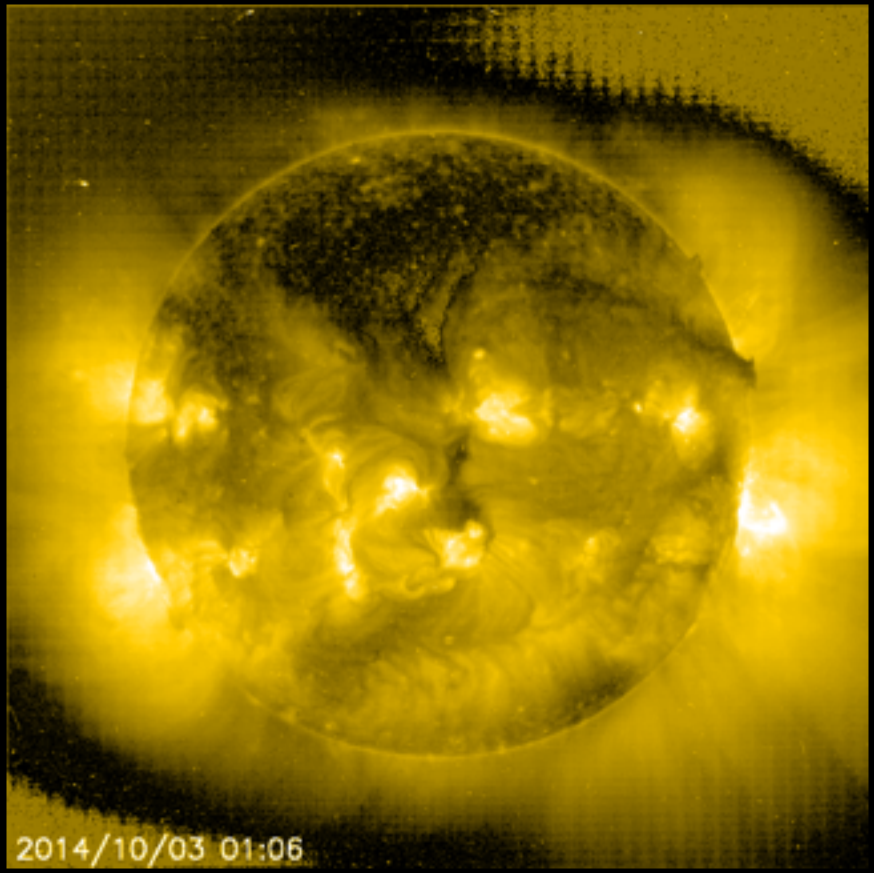
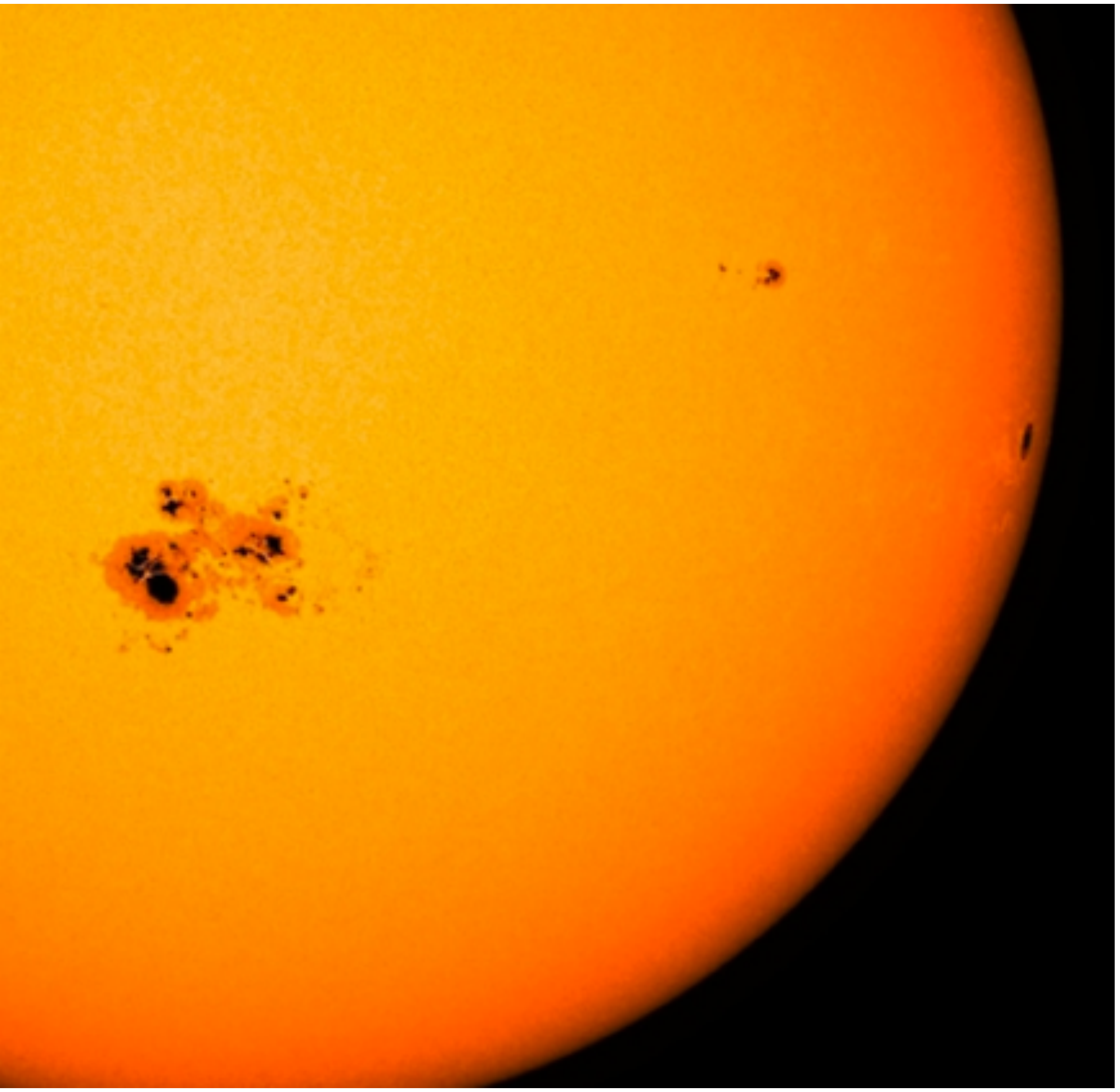


Image credit: SOHO/EIT



Photospheric velocity flows affected by pulsation, granulation, meridional flows, magnetic fields (spots, plage and faculae).

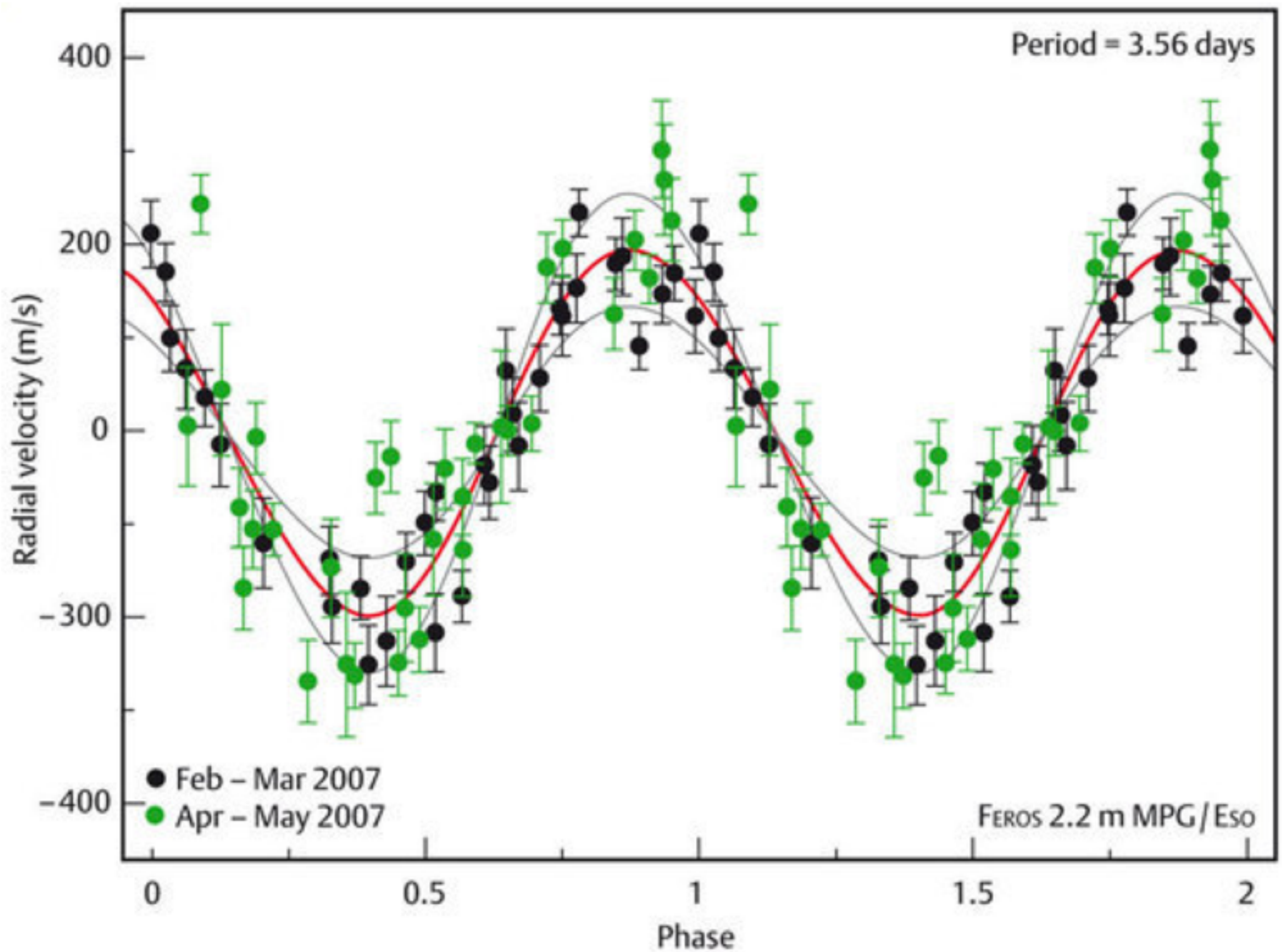
If these were static, they would not cause a problem (static RV offset).

Because they are time-varying, they introduce delta-velocity signals.

Spot number and sizes are stochastic.
Sizes are typically < 0.1%

Solanki & Unruh 2013

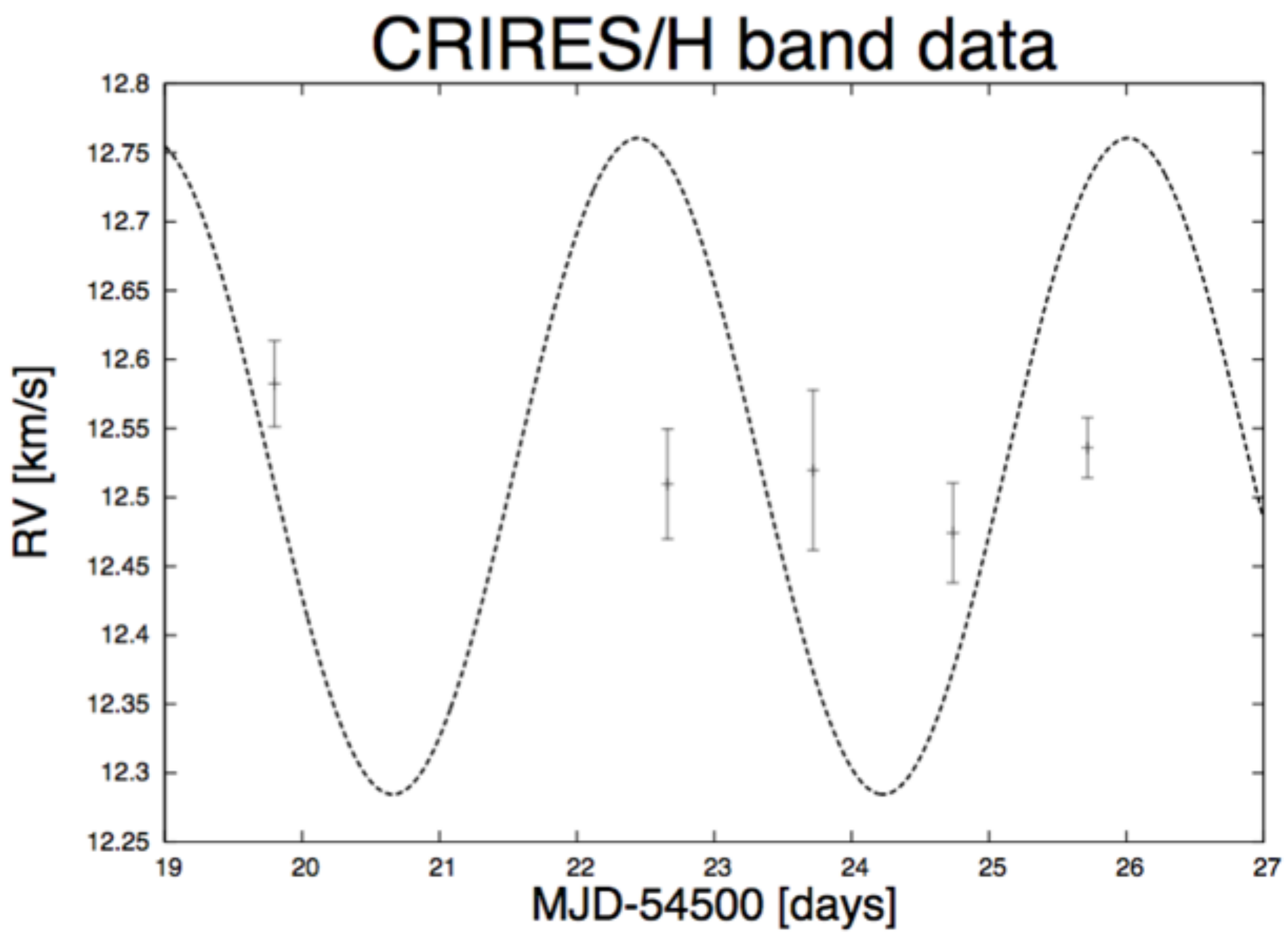
Dude, is there a planet in my data?



Optical high-res spectra; two epochs; no line bisector variation

Setiawan et al. 2007, Nature

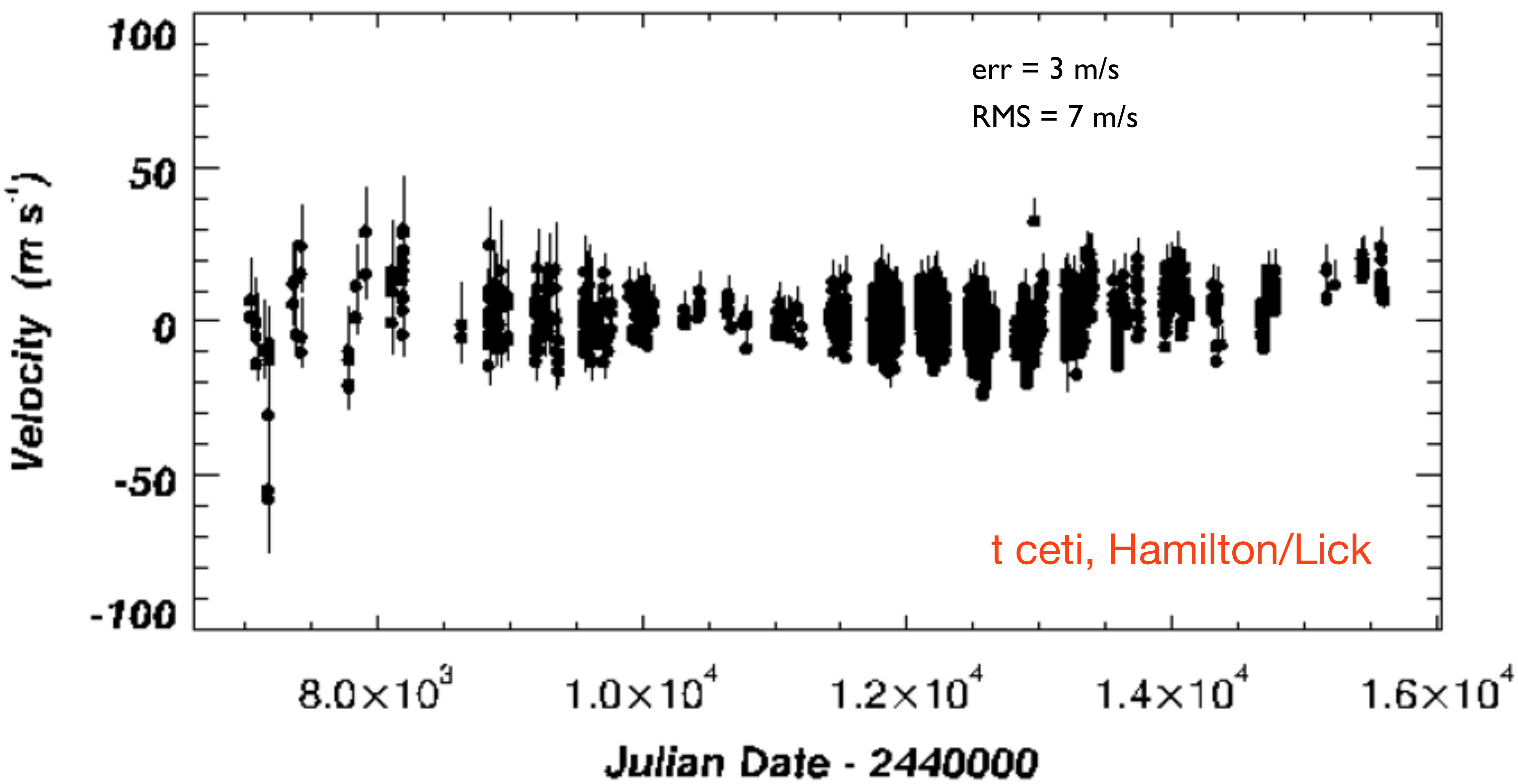
Nope, it's just a star spot!



CRIRES/H-band RVs overplotted on the Setiawan et al. theoretical fit for TW Hyrdrae

A 20 year case study

(Un)stabilized spectrometer 1989 - 2011



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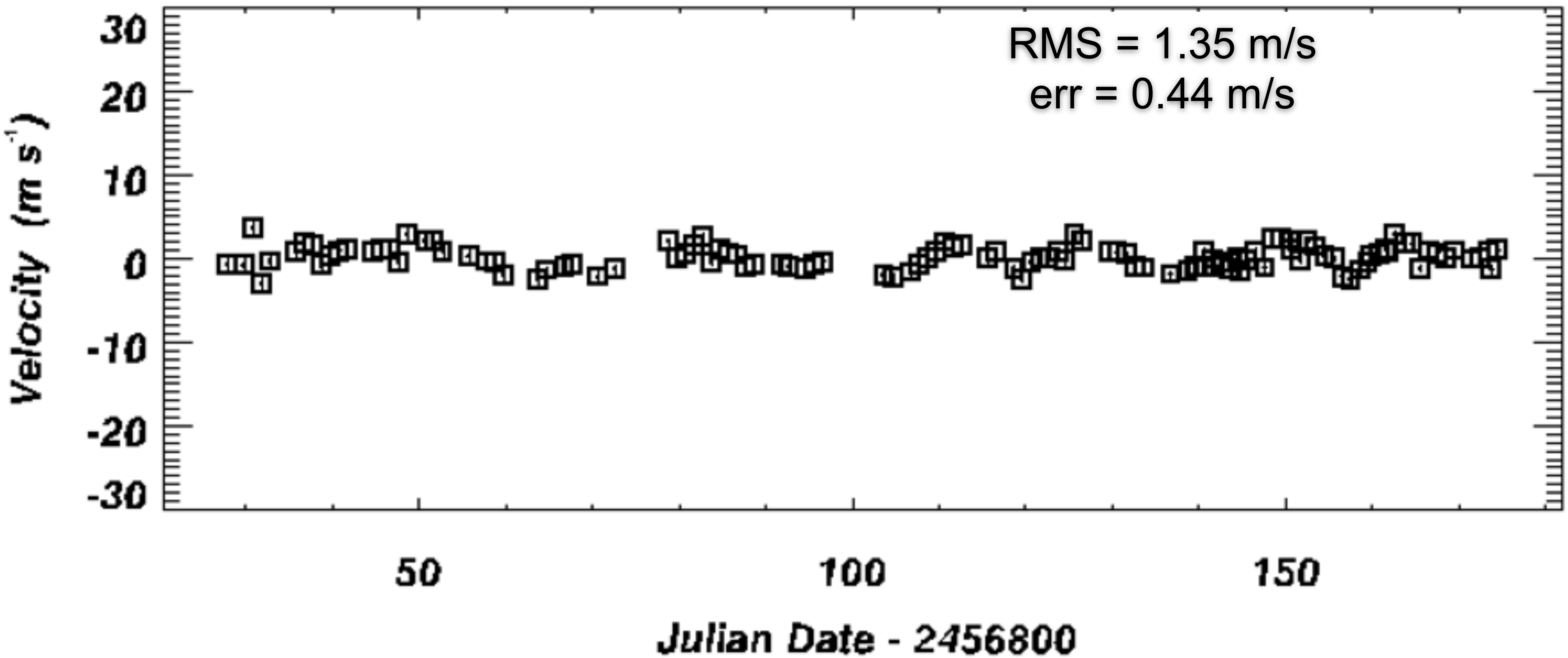
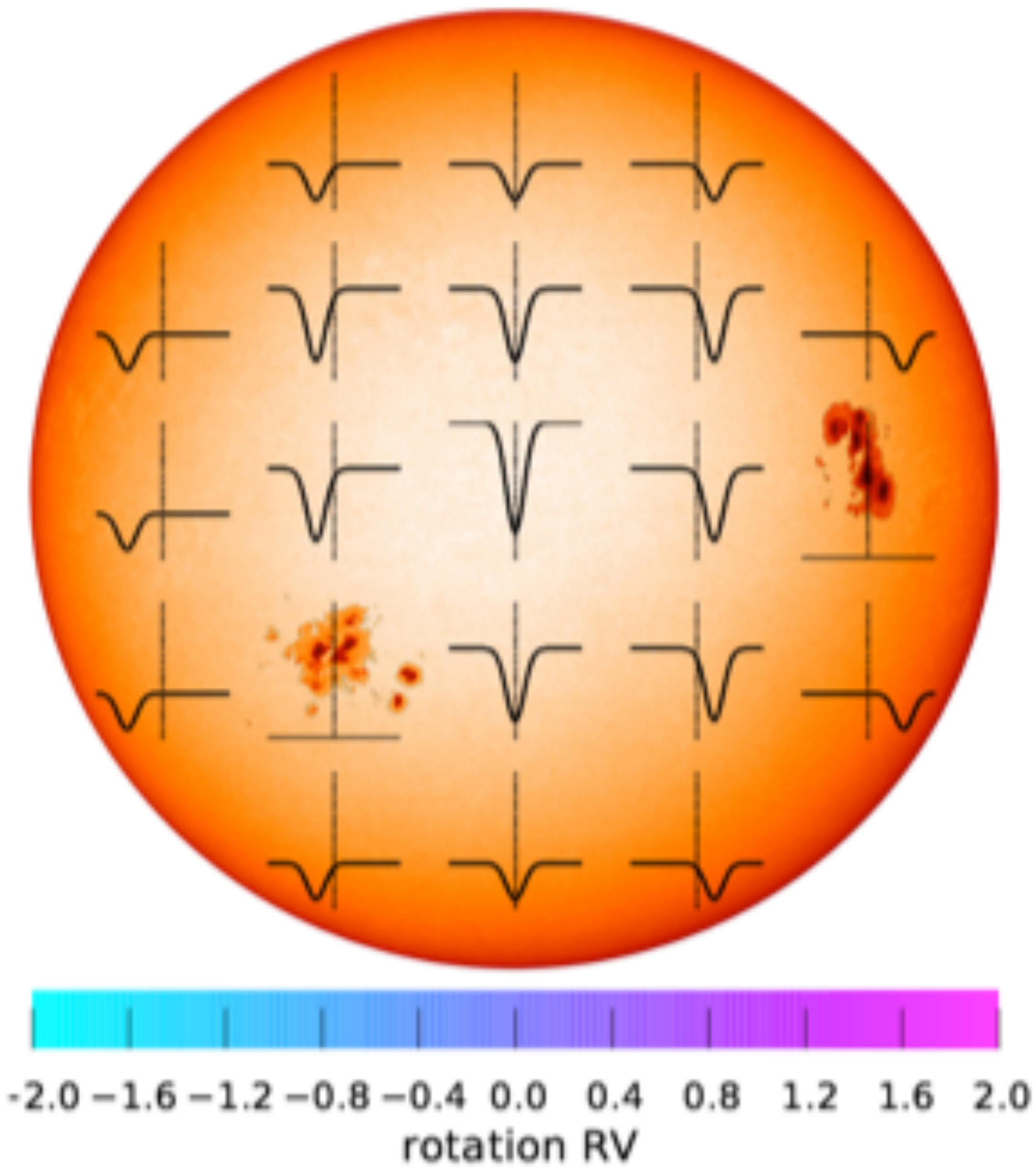


2014: Tau Ceti with CHIRON

Pretty clear power in the periodogram of CHIRON data,

but not in the HARPS data. WTF?

Xavier indulged me with a double-blind study:



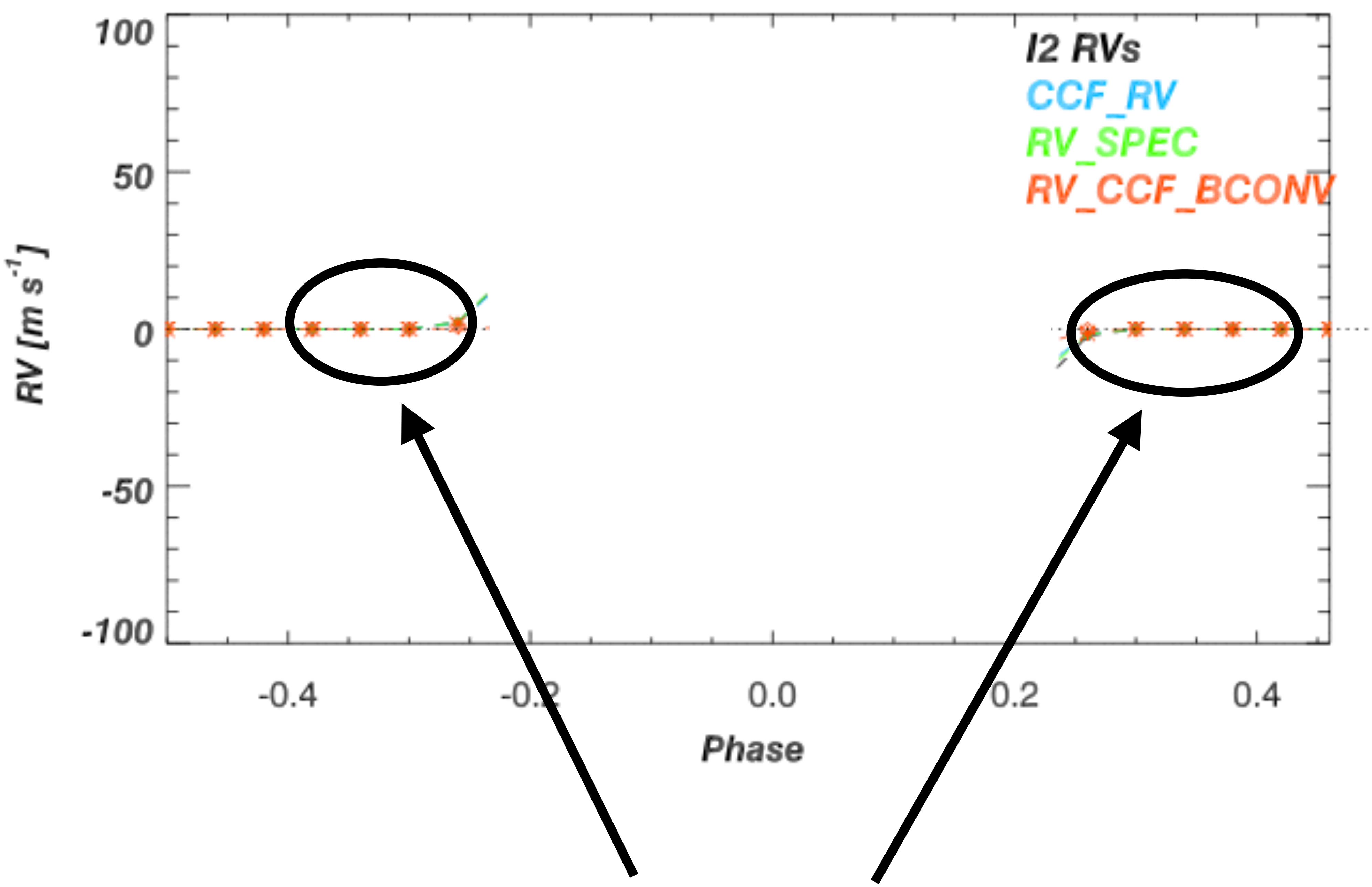
We started with simulated spectra because it's controlled and we know the answers!

Simulated spectra (SOAP 2.0) Xavier Dumusque
with spots, faculae and planets.
R ~ 500,000 and SNR ~1000

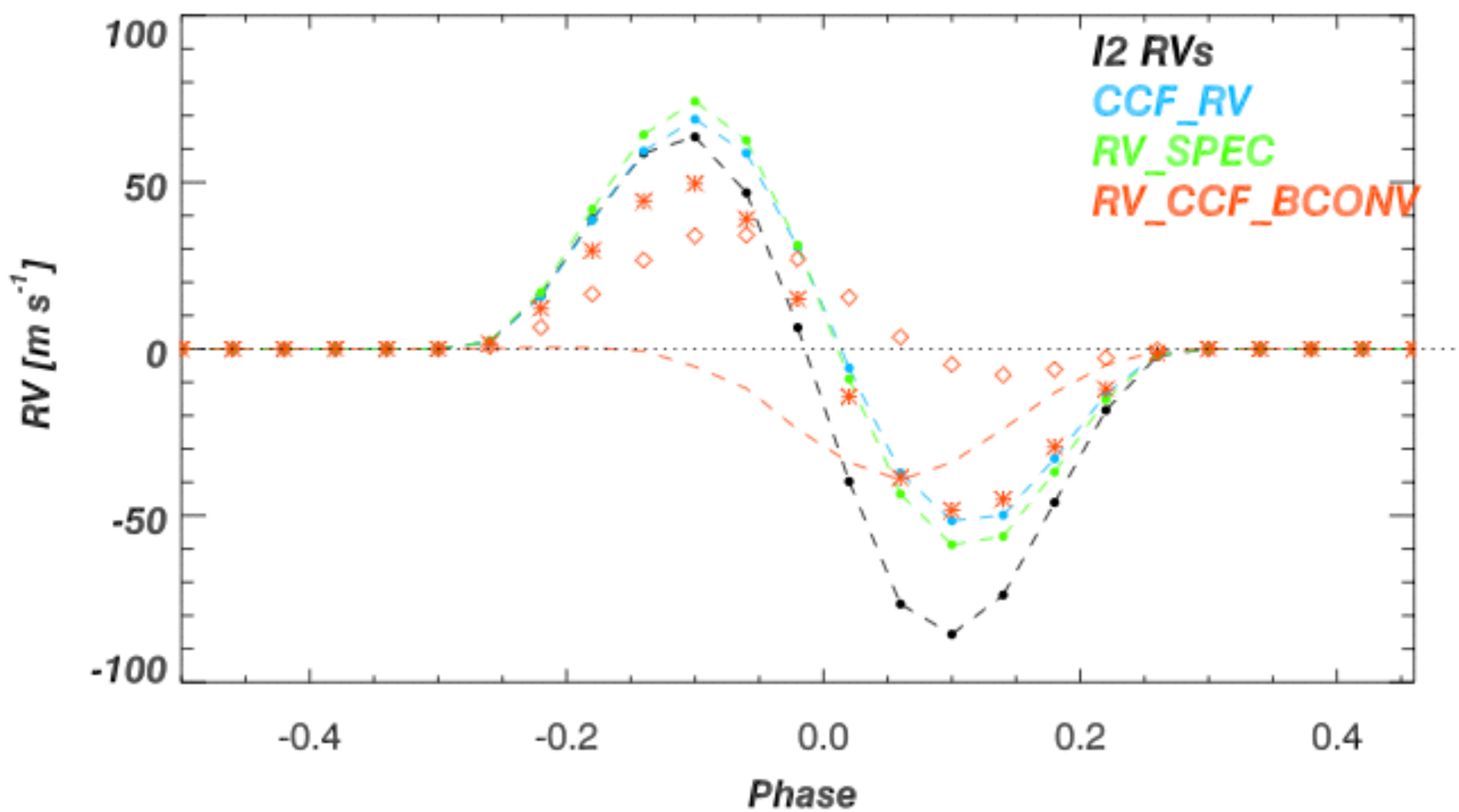
Then… Ji Wang created “iodine spectra” from the SOAP-simulated data (multiply by FTS I2 spectrum and convolve with PSF).

This **zero’s out** any instrument differences (HARPS vs HIRES). Exactly the same data, exactly the same SNR, exactly the same resolution.

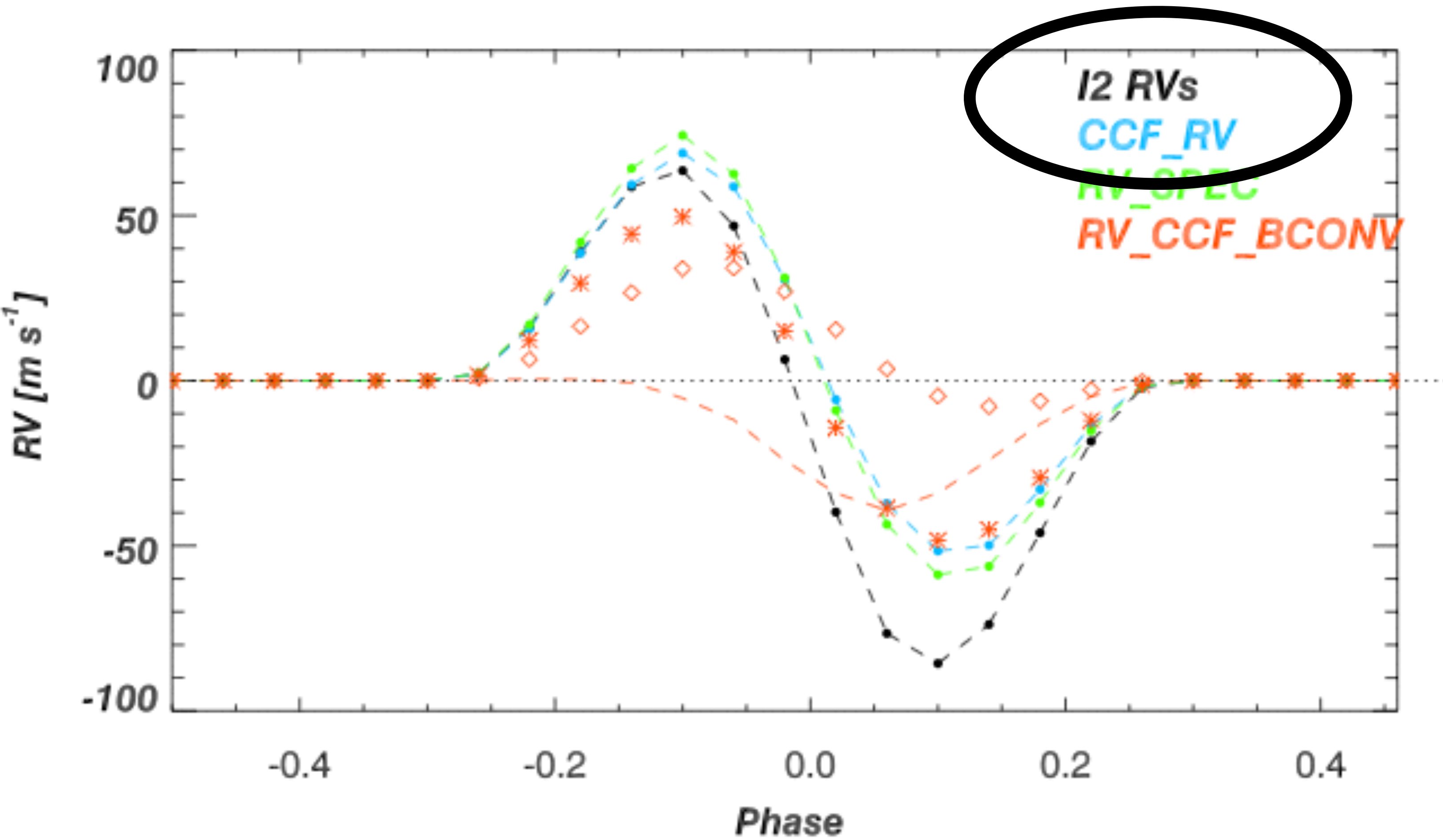
Simple a comparison of CCF and Iodine analysis techniques. (Dumusque vs Fischer).



The I2 and the CCF measure RV's with RMS = 0 for 9 data points when no spot (i.e., spot is behind the star).



No noise added. PSF known for I2 code and hard-wired into the analysis for this 5% (BIG!) spot.



I2 RV RMS = 37.5 m/s
CCF RV RMS = 30.2 m/s

The RV answers depend on whether we use the I2 or CCF code **in the presence of spots.**

No spots, no difference.
Not an instrumental effect!

I2 RV RMS = 37.5 m/s
CCF RV RMS = 30.2 m/s

What does it mean that the CCF and I2 analysis give different answers?

By design (?) the CCF is less sensitive to photospheric velocities.

But they are in the spectra, tugging on the Iodine-analyzed RVs, which model the line depths and line profiles.

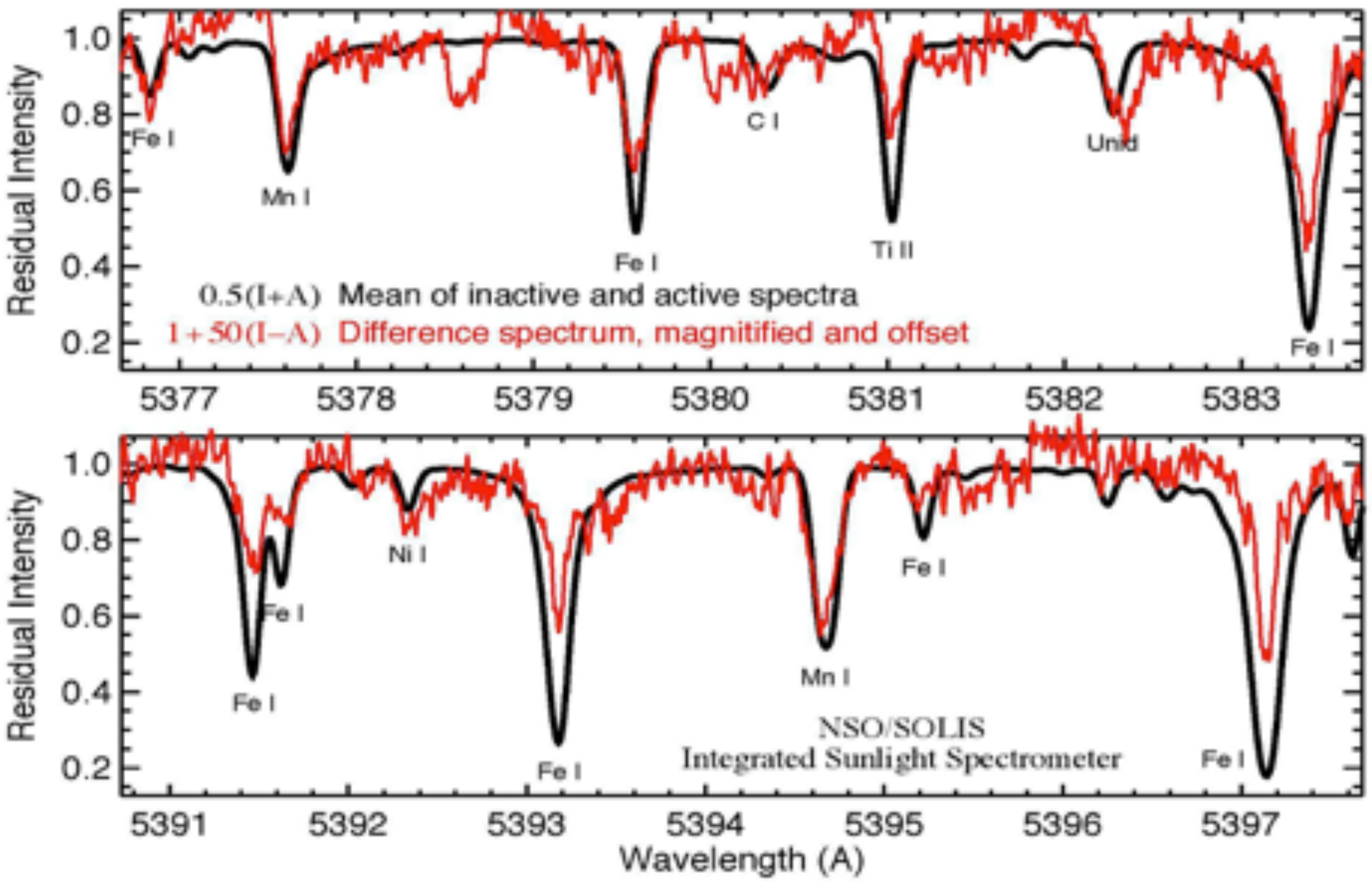
Big hint that photospheric velocities can be distinguished from orbital velocities.

Today:

We derive a velocity measurement from a spectrum.

… some fraction of the velocity that I just measured came from the photosphere. How can I chisel the non-orbital component away? Line bisectors? FWHM of the CCF? Correlation with H-alpha or Ca II H&K? Photometric monitoring? Gaussian processes?

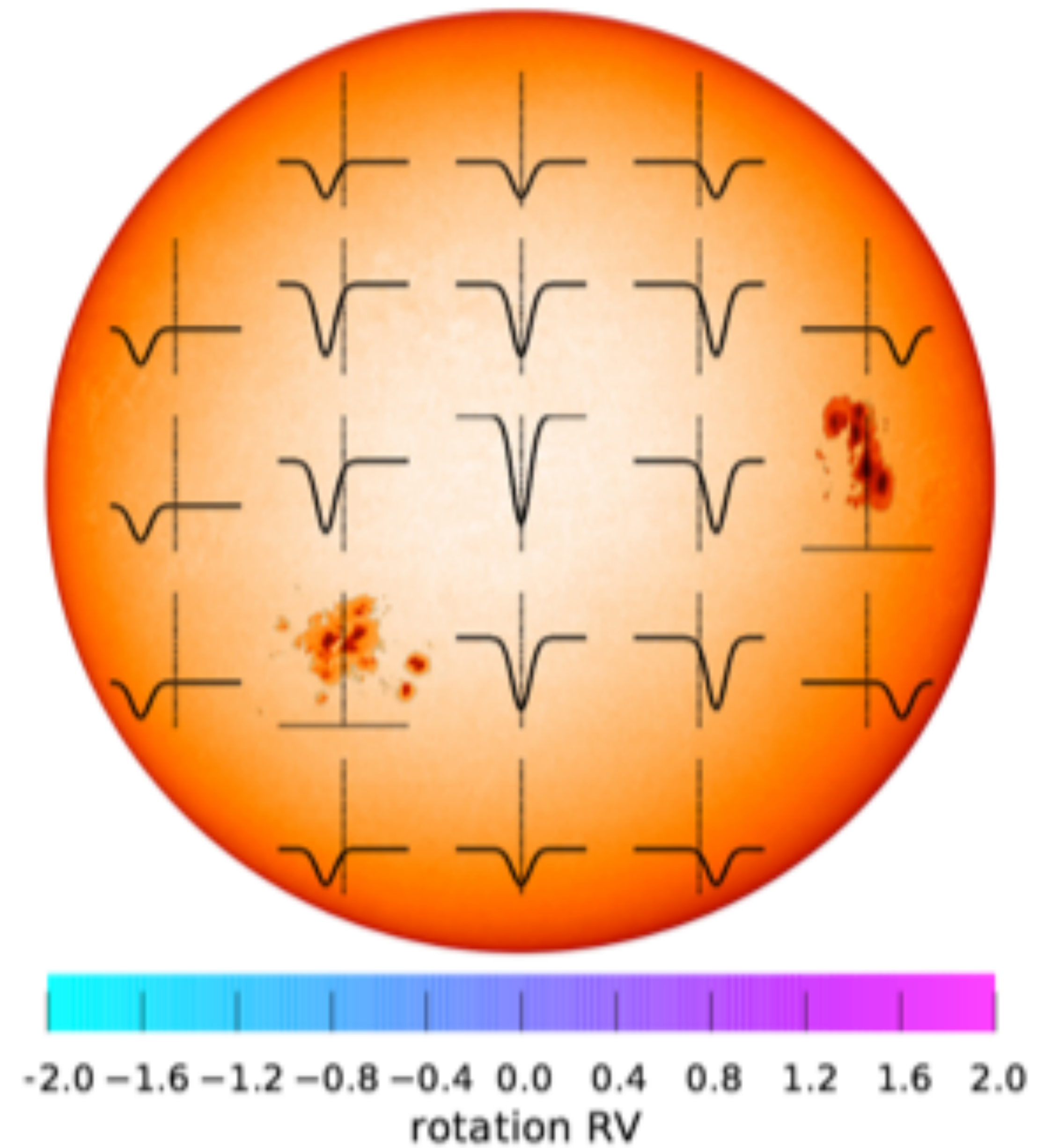
All of these approaches operate on a single number: the radial velocity measurement. They may be insensitive to particular types of “jitter,” but in any case, can only be approximately correct.



Full disk solar spectrum at high / low activity levels. Spectral lines sample photospheric depths differently and hence react differently to changes in granulation velocities over the solar magnetic cycle. These data come from the SOLIS Integrated Sunlight Spectrometer.

Stellar noise for inactive stars may not show up in the line bisector. For slowly rotating stars, there will just be slight variability in the line depth of spot-sensitive lines.

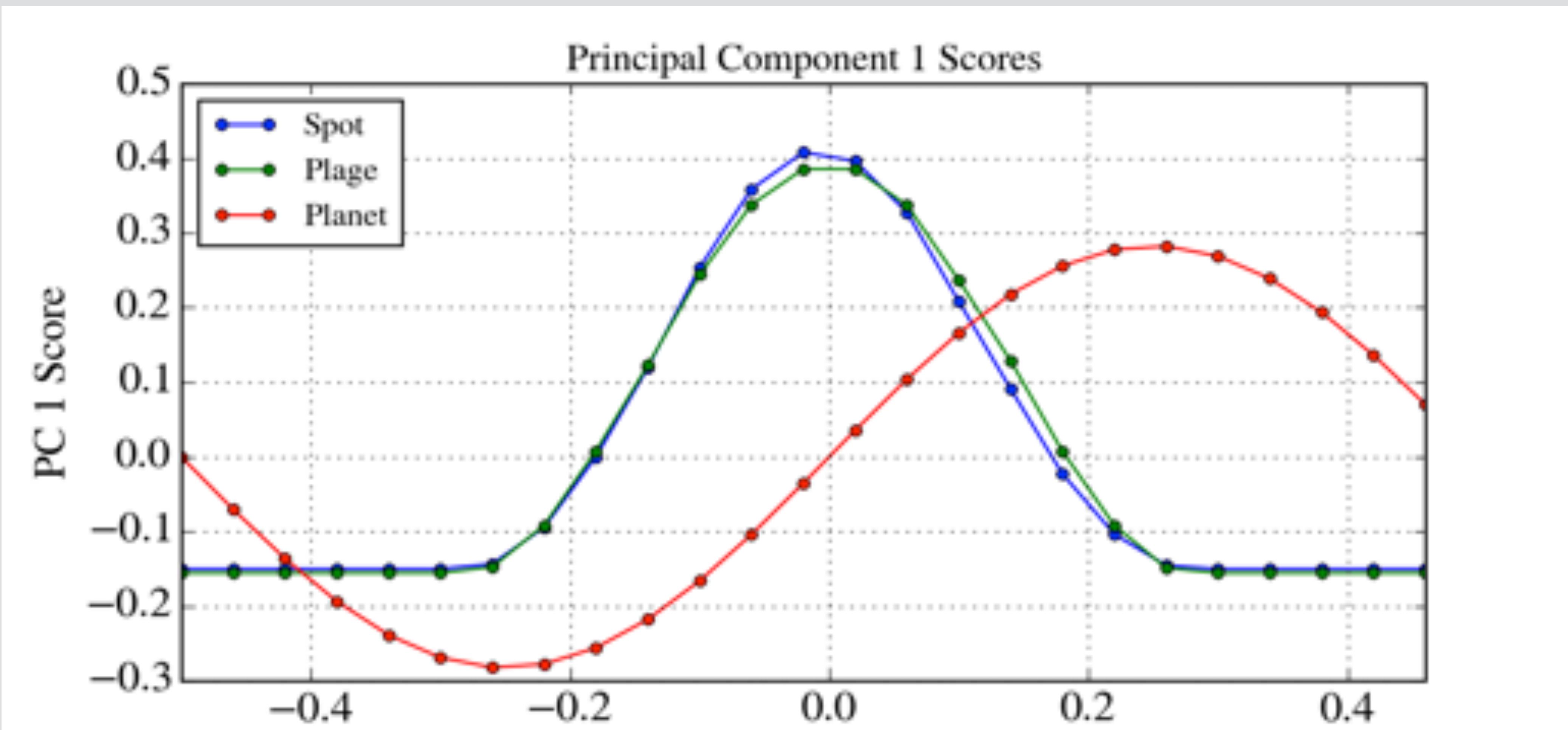
Back to the simulations…. this time to see if we can identify and distinguish stellar variability when we operate on the 400,000 pixels in the spectrum instead of the single RV point.



Simulated spectra (SOAP 2.0) Xavier Dumusque generates time series spectra with spots, faculae, and planets.

R ~ 500,000 and SNR ~1000

PCA can identify axes of maximum variability in the SOAP simulated spectra.
Key: the PCA scores are structurally different for spots, plage, planets - offers hope of distinguishing different velocity features.



Instead of using one number (the extracted RV) for decorrelation, PCA searches for variability among ~400,000 pixels.

Our initial PCA analysis was with R=500,000 and SNR =1000 spectra. No Doppler programs working in this regime! Why? Because the spectral lines are fully resolved at R~70,000. Why waste the photons on higher resolution?

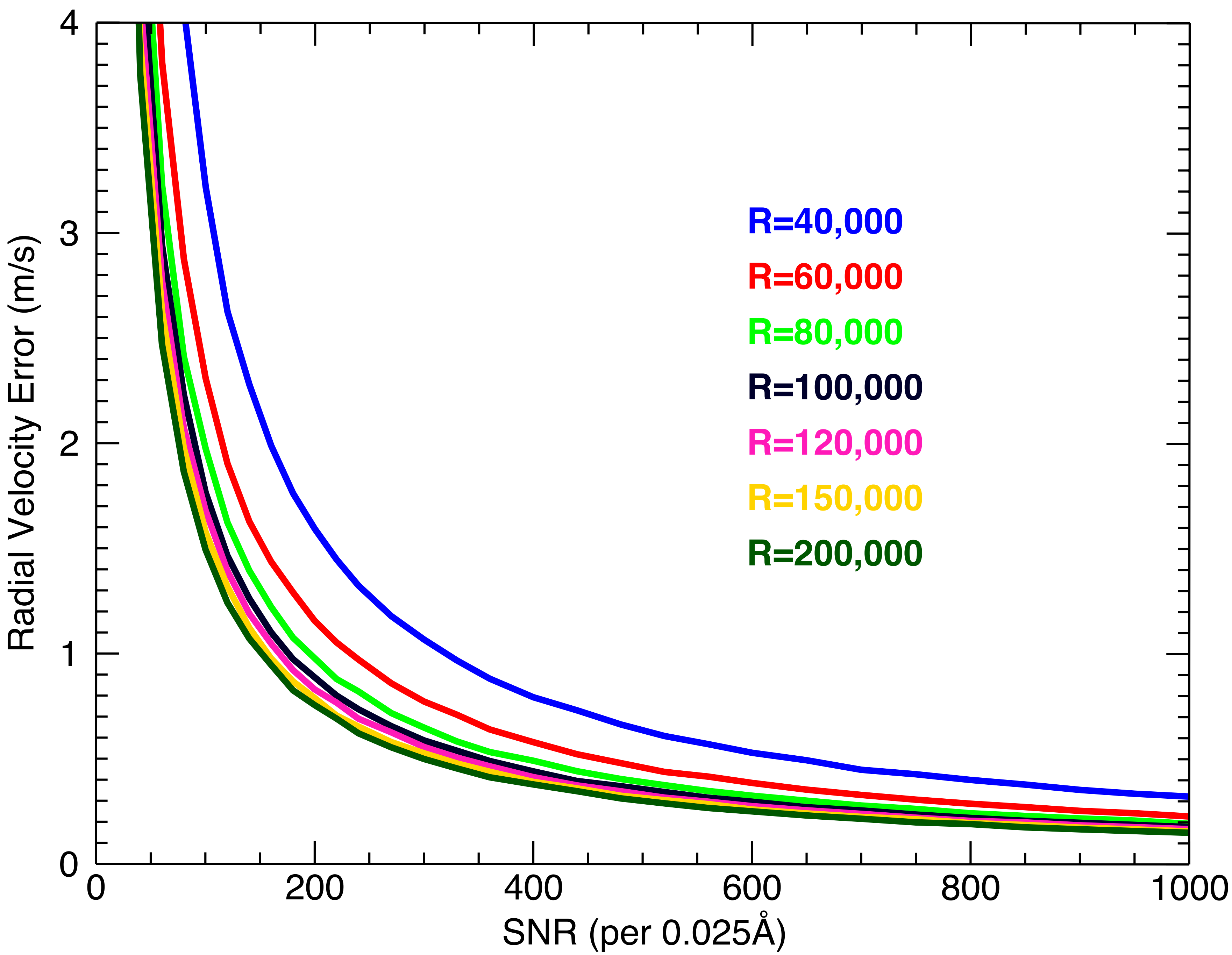
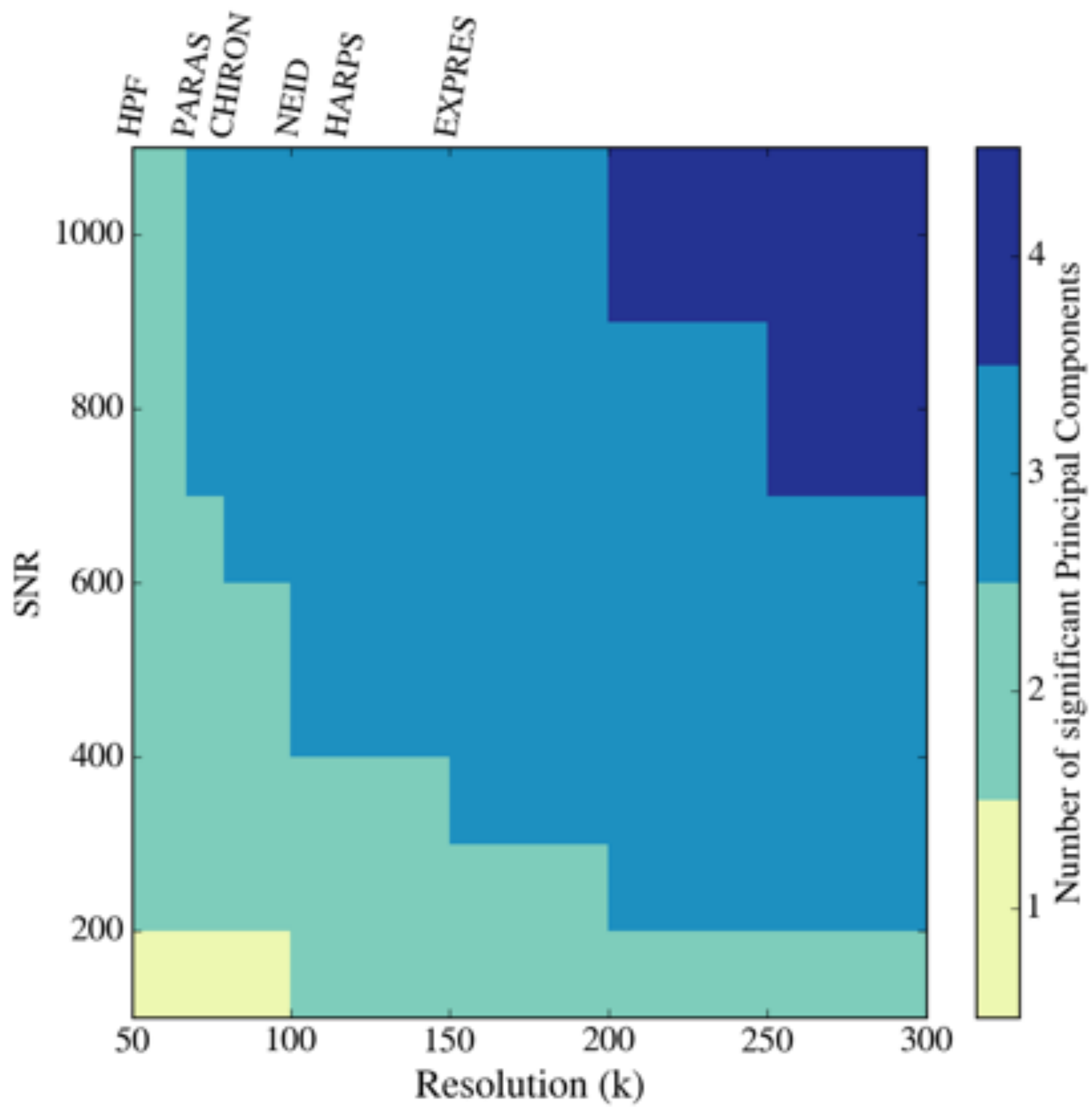


Figure by Jack Moriarty

How does the sensitivity of PCA degrade with decreasing resolution and SNR?

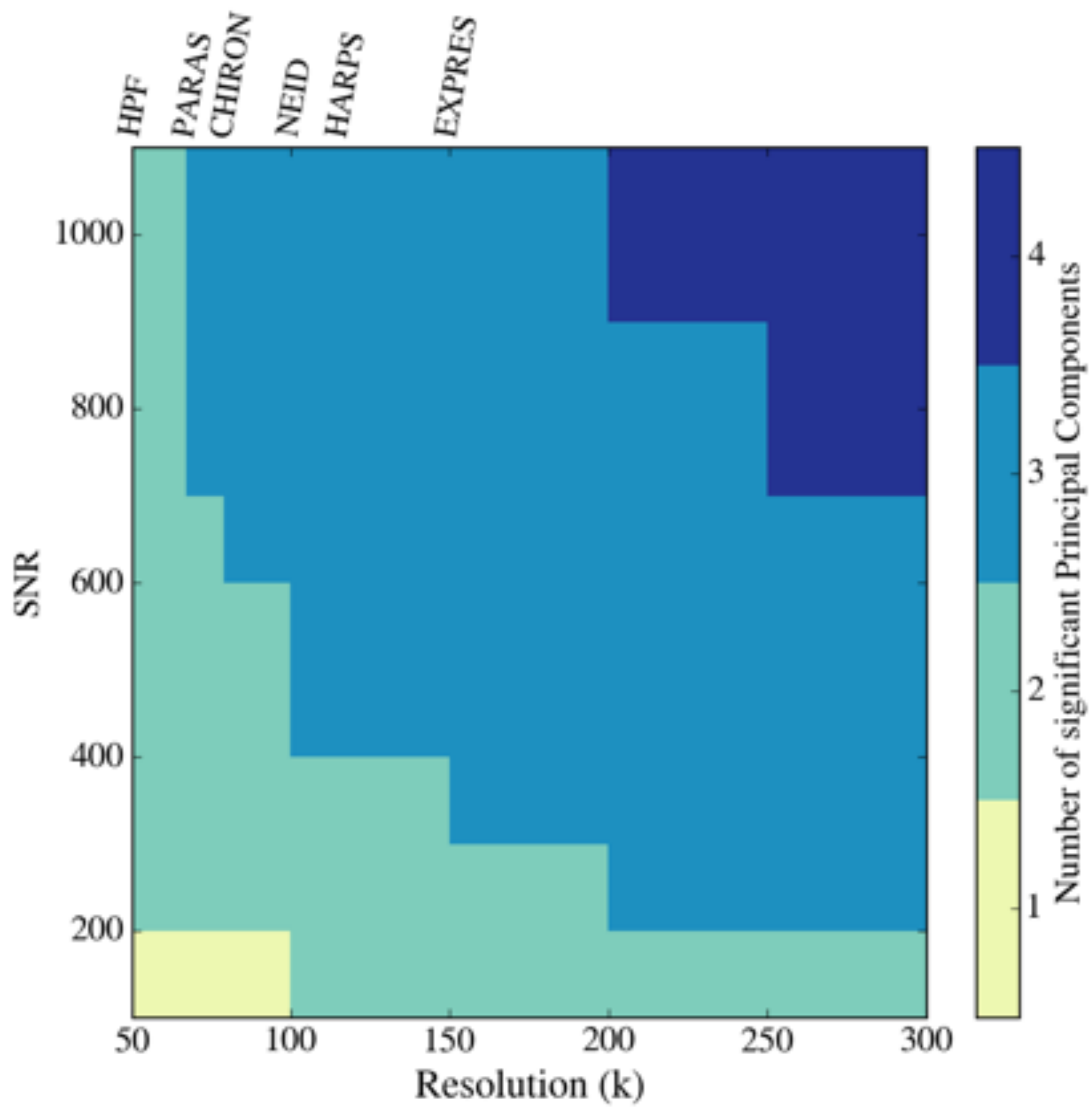


At R<100,000 and SNR < 200 (Lick, Keck) only one PC can be derived. No hope of separating photospheric and orbital effects.

Only approach is to decorrelate with global parameters (LBis, FWHM, activity indicators).

See poster by Allen Davis

How does the sensitivity of PCA degrade with decreasing resolution and SNR?



At higher resolutions, there is a trade that can be made between resolution and SNR.

Increasing resolution is a linear hit to photons (exp times).
Increasing SNR comes at a cost of (exp time)^2.

See poster by Allen Davis

Work to date with PCA has explored the **information content** of simulated spectra. Now, we are working to find techniques that will allow us to model out stellar jitter.

Promising avenues ahead: dictionary learning with sparse representation and other functional analysis techniques (working closely with statisticians) to recover a cleaned spectrum for Doppler analysis.

(a) Original image

(b) Back projection

(c) Proposed sparse reconstruction

A few thoughts:

- If we can separate out jitter we have a hope of improving RV precision to better than 0.5 m/s. If we fail to improve RV precision, our field will have a much flatter trajectory.
- Radial velocities measurements offer an exciting opportunity by working with the pixel-by-pixel variability in very high res spectrs, not possible with photometry measurements.
- If new statistical techniques are successful, optical spectroscopy is “where it’s at” and will bypass putative advantages of IR spectroscopy (lower spot contrast) b/c of telluric lines in the IR and technical issues like detector stability.
- IMO, techniques that operate on RVs are limited (RMS ~1 m/s) and will not propel the field of exoplanet detection forward.
- Photospheric RV signals from active stars will be the easiest to identify - this opens the possibility of carrying out Doppler surveys on young stars like TW Hydrae with **optical** spectroscopy.