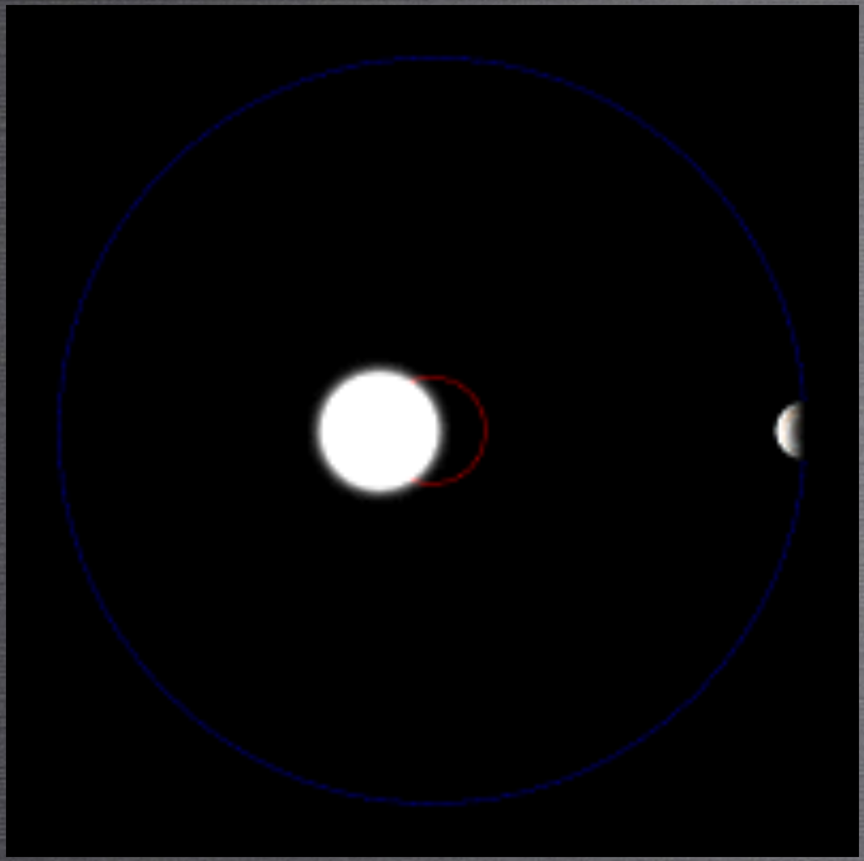
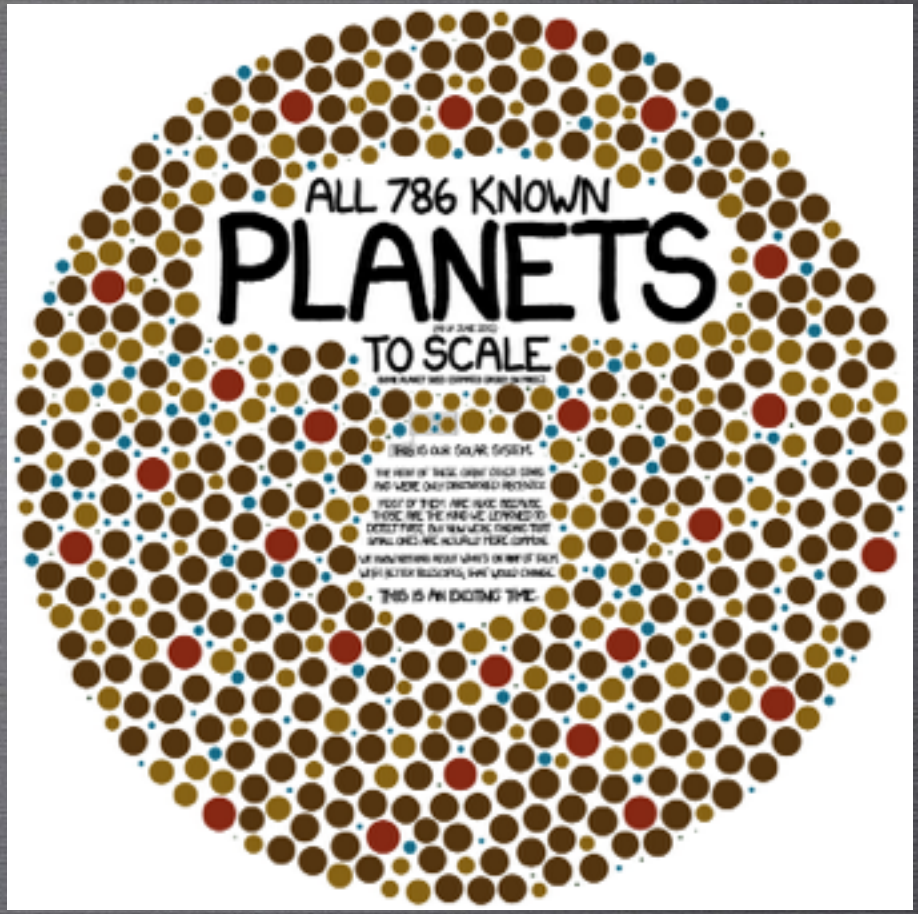




Precise NIR Radial Velocities with CSHELL

Ipac Fellow Talk 2014

Jonathan Gagné

Peter Plavchan, Peter Gao, Elise Furlan, Michael Bottom, Angelle Tanner, Cassy Davison, Carolyn Brinksworth

Why Near-Infrared ?

- Stellar activity (spots, etc.) can mimick a planetary signal
- Recent example with GJ 581 d !
- A Doppler signal is wavelength-independent, but stellar activity is not !
- Thus NIR + optical follow-up can rule-out stellar activity

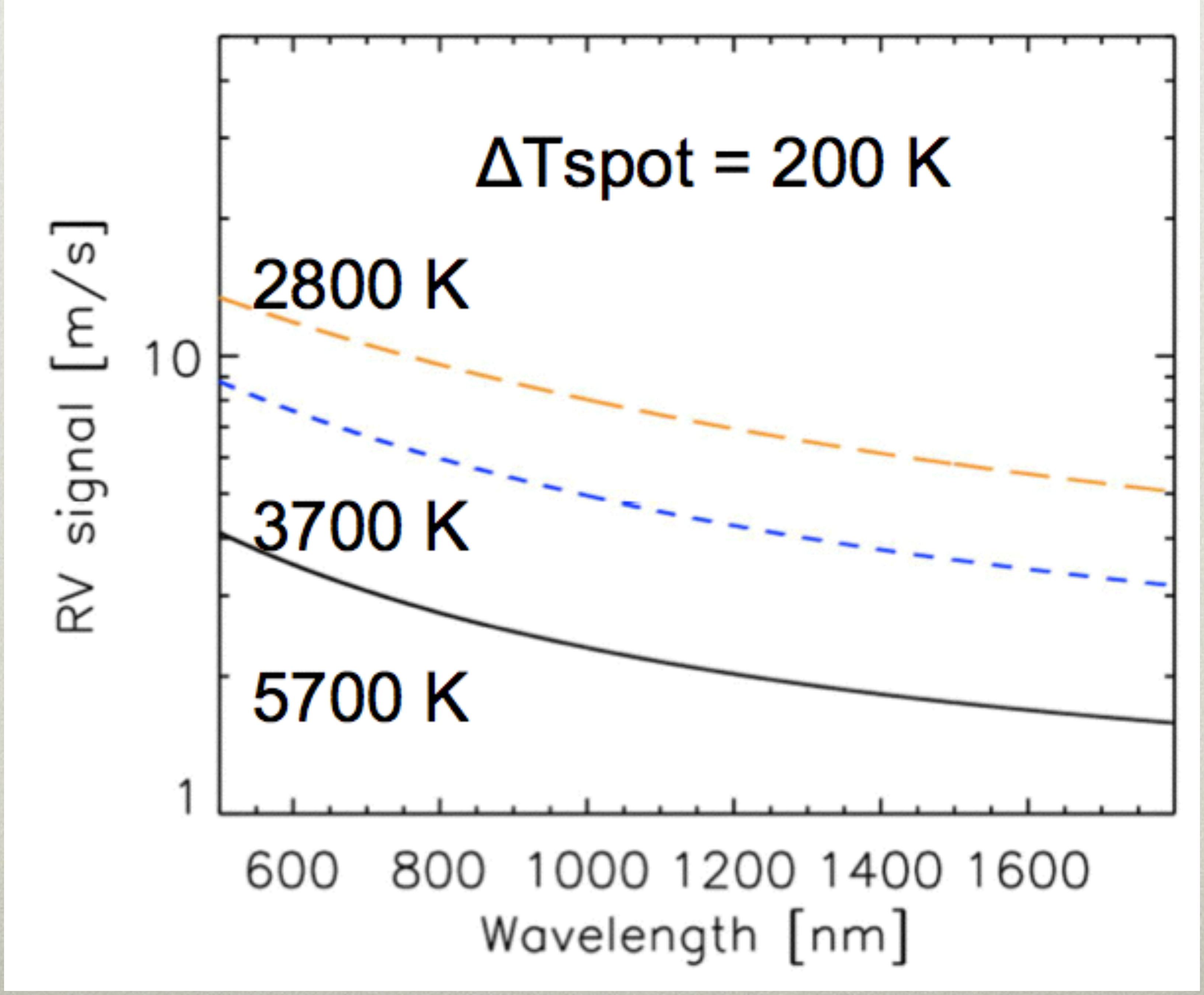
Stellar Activity Masquerading as Planets in the Habitable Zone of the M dwarf Gliese 581

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

[1]Department of Astronomy and Astrophysics, The Pennsylvania State University
[2]Center for Exoplanets & Habitable Worlds, The Pennsylvania State University
[3]The Penn State Astrobiology Research Center, The Pennsylvania State University
[4]McDonald Observatory, The University of Texas at Austin

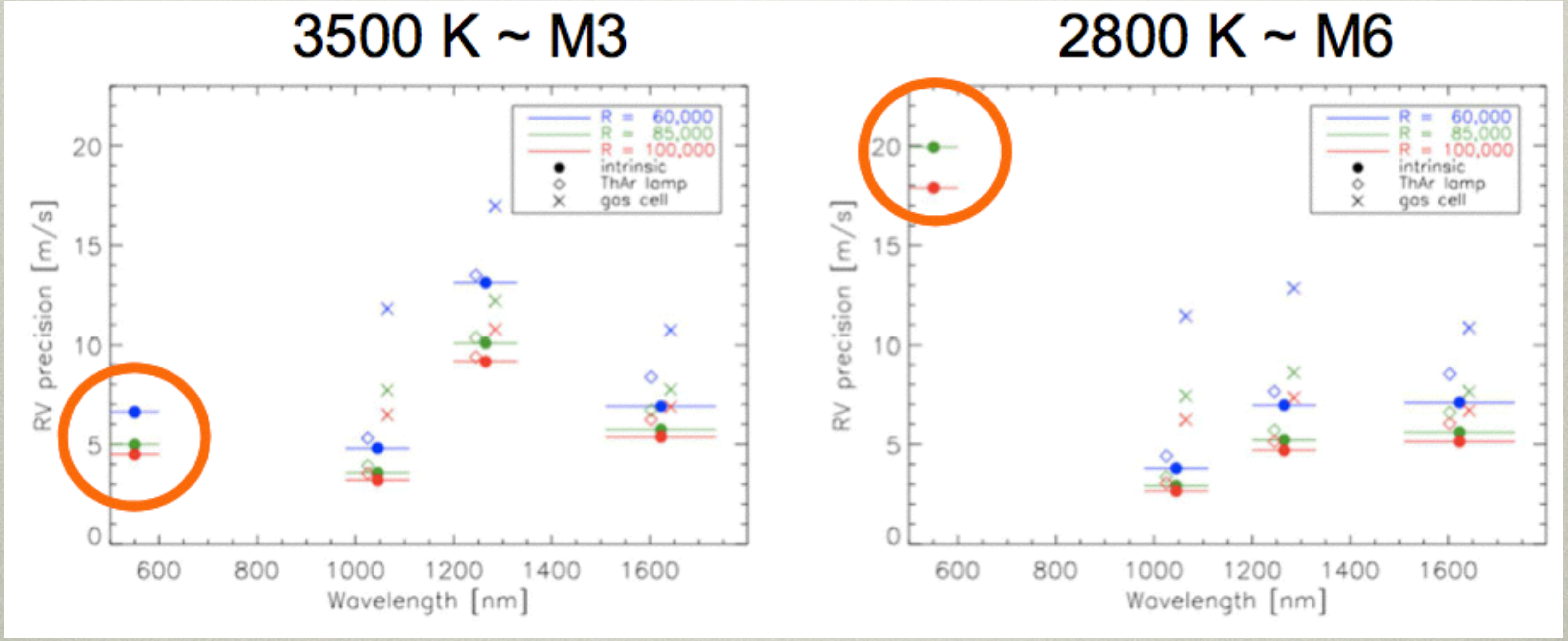
Why Near-Infrared ?

- Stellar spots are less important in NIR



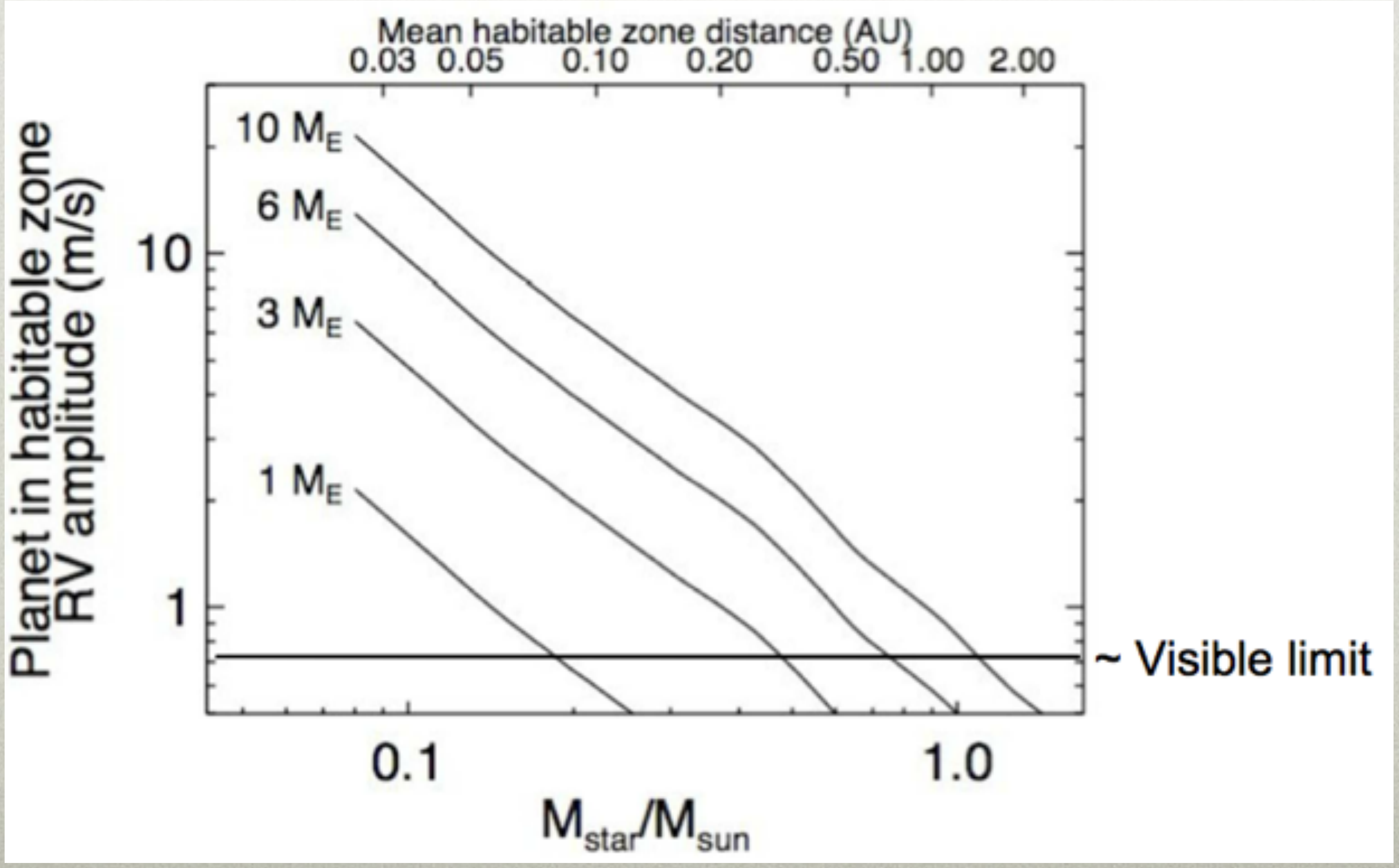
Why Near-Infrared ?

- Access to later-type objects (M stars) ; More flux, more lines.



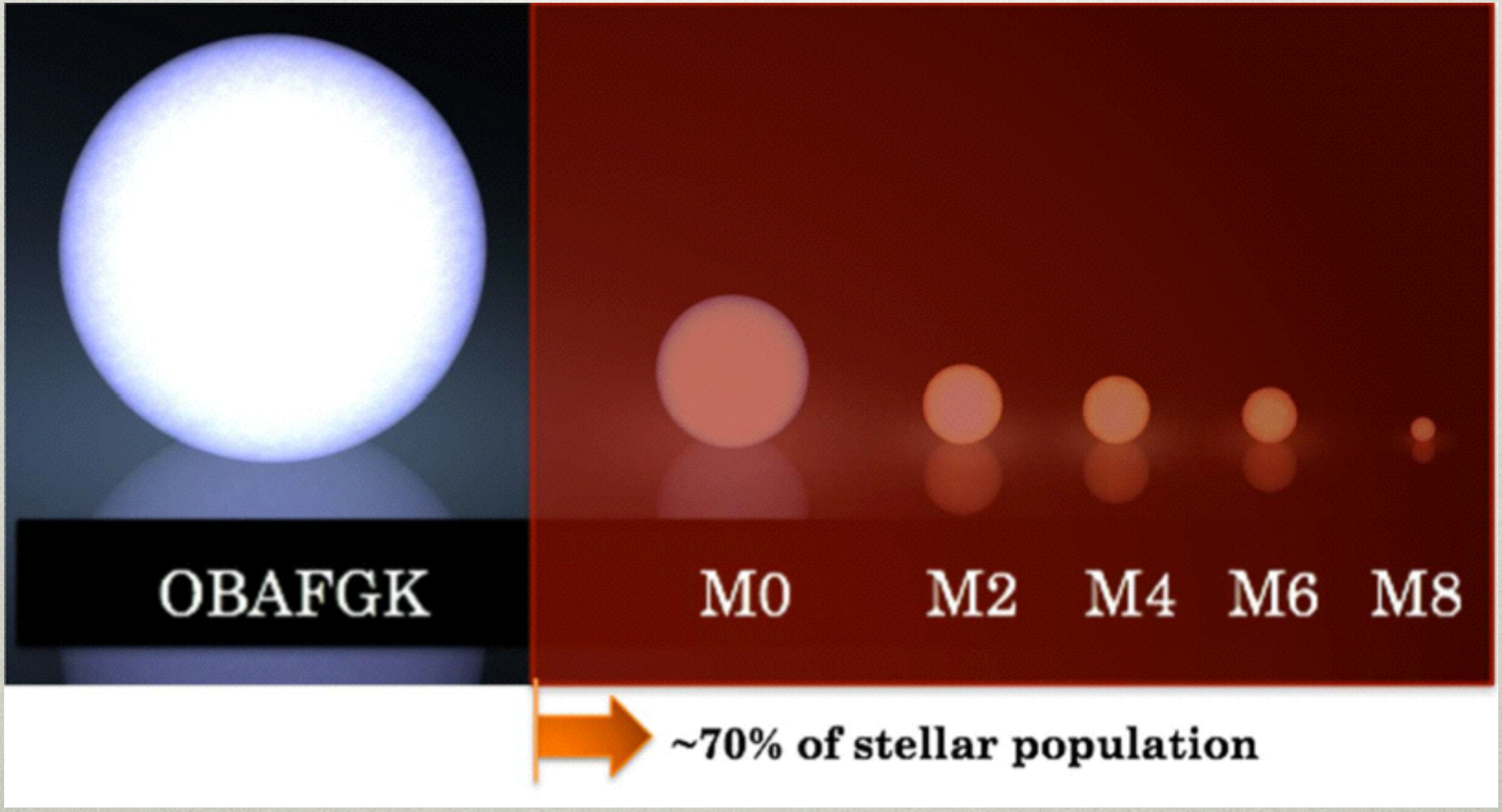
Why M stars ? 4/35

- More small planets around small stars ! (Howard et al. 2012)
- Host is fainter -> Easier to a do transit follow-up (if properly aligned)
- Habitable zone is closer-in -> Larger RV amplitude, larger alignment probability for transit.



Why M stars ? 5/35

- Last but not least; M stars represent 70% of the stellar population !



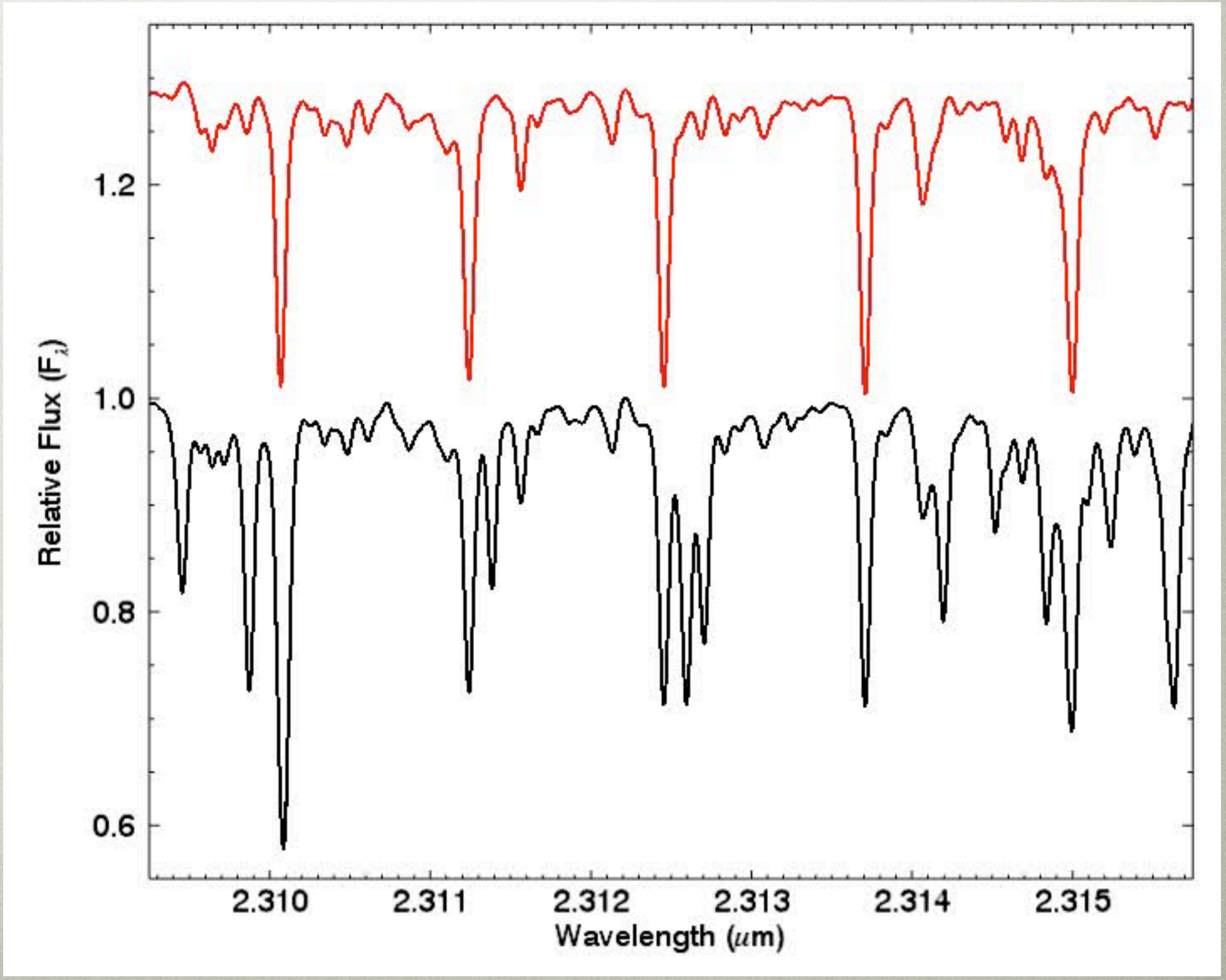
The Methane Gas Cell

- We use a *methane isotopologue* gas cell developed at JPL.
- Placed in-beam on the telescope
- Star light passes trough the gas cell and inherits CH_4 lines
- Why not regular methane ? We don't want its lines to be "unique" !

Stellar spectrum affected by gas cell lines

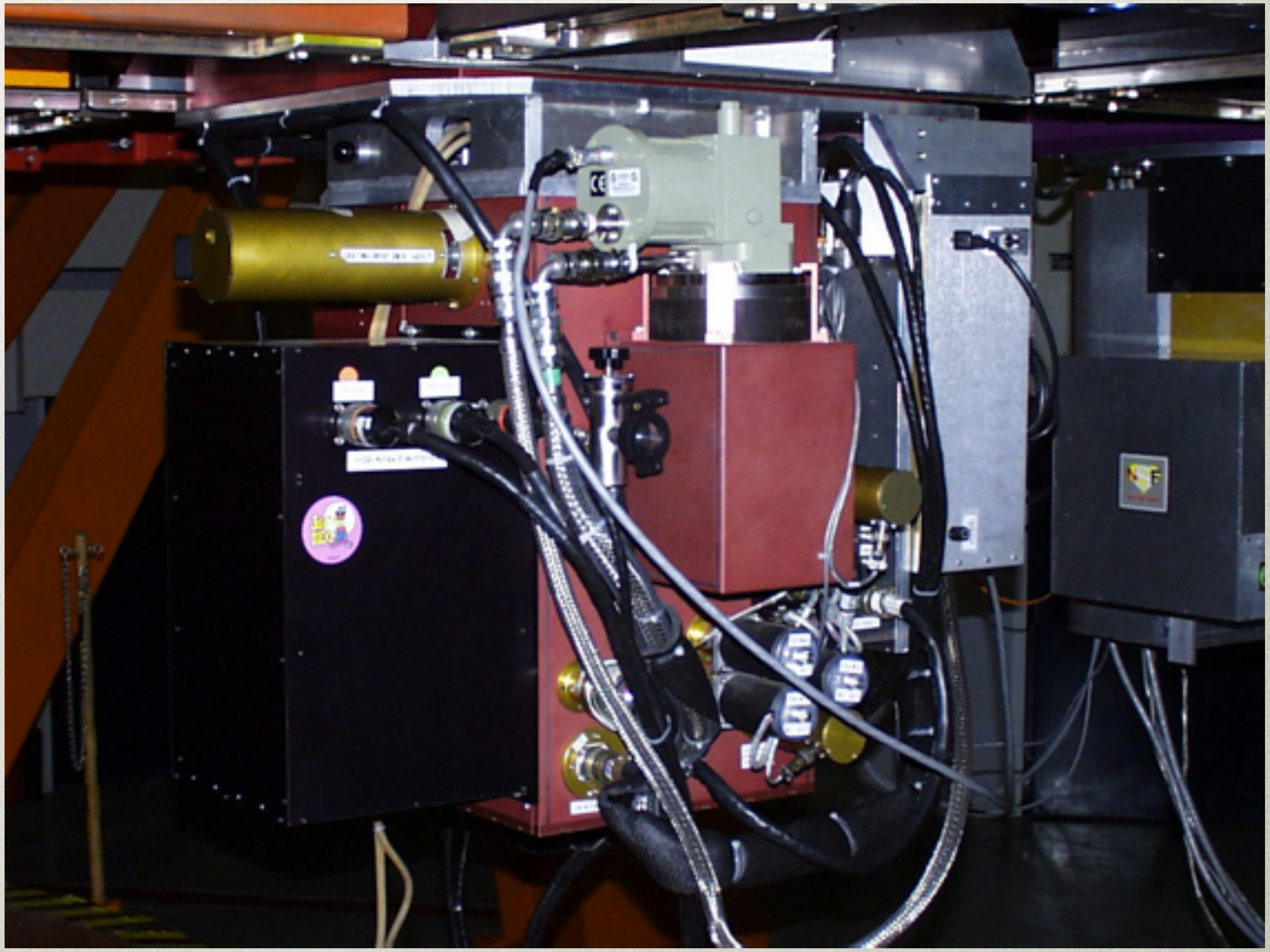
Red = Synthetic Stellar Spectrum of ~ M2 star

Black = Star ⊗ Gas Cell



CSHELL 7/35

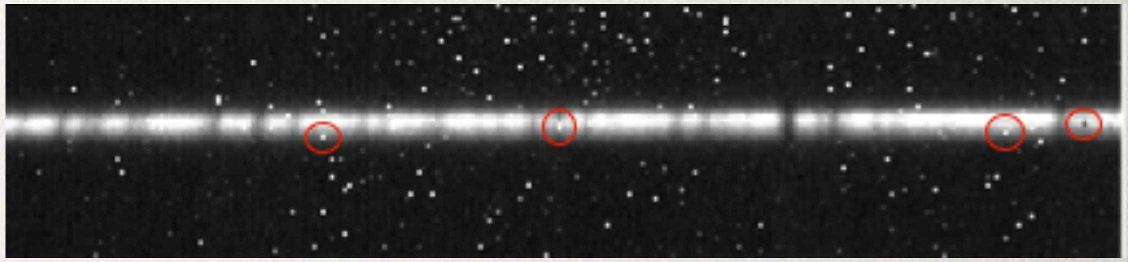
- 256 x 256 pixels detector
- Resolution R ~ 30,000
- Window centered at 2.3125 μm to get 5 CO lines in M stars.
- 1 Pixel ~ 3.5 km/s, and we want precisions down to < 20 m/s
- We are pushing CSHELL to its limits !
- Need to understand systematics

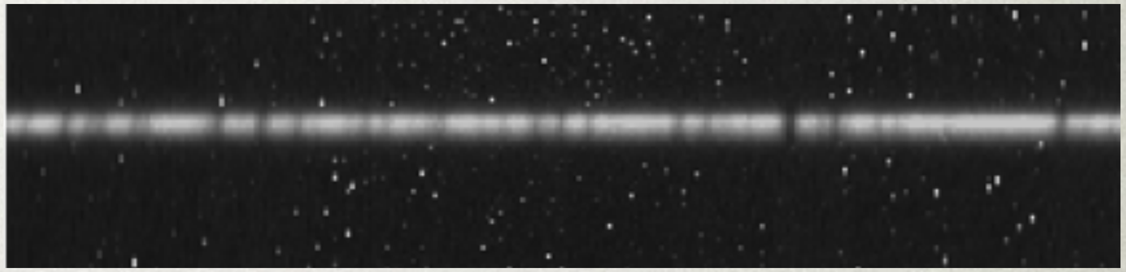


The CSHELL Camera

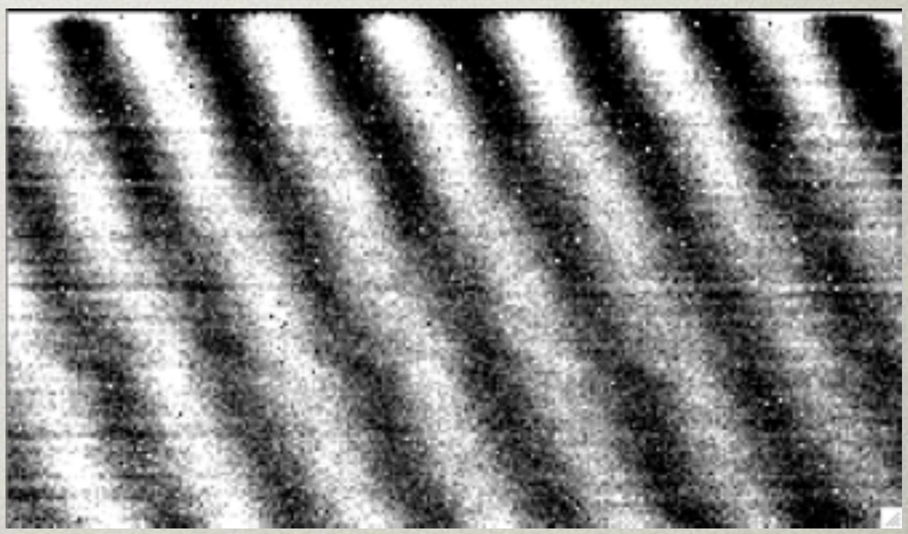
CSHELL Systematics

- Trace not perfectly straight - Affects Signal/Noise
- Unstable bad pixels - We want every pixel we can have.
- We never interpolate in the spectral direction !
- Flat fields are very much needed
- "Fringing-less" CVF filter *has* fringing at the sub-% level and it *does* bother us
- We must account for fringing both in flat fields and in the data



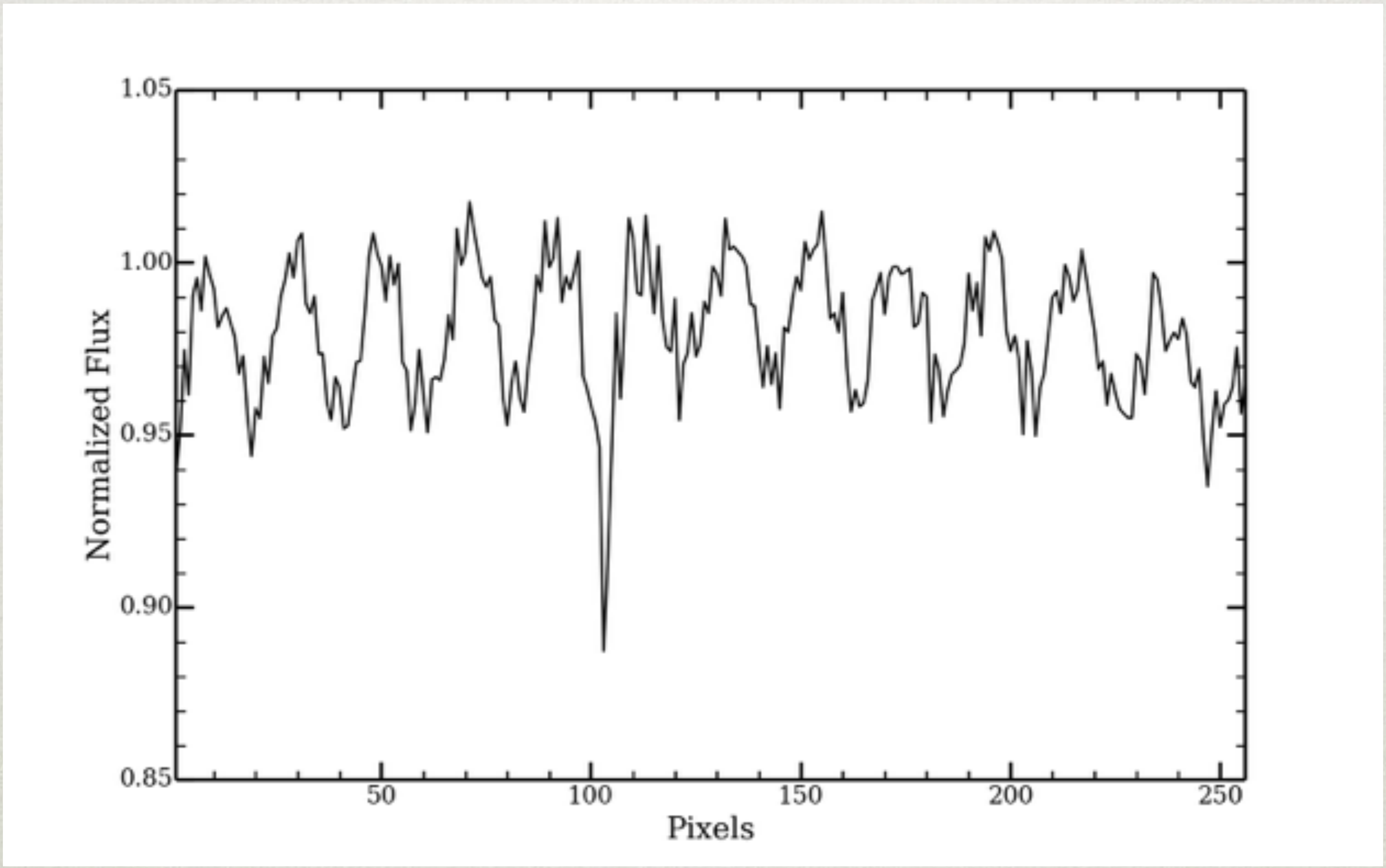


On-trace correction of bad pixels



~ 0.5% fringing in the flat field

Fringing



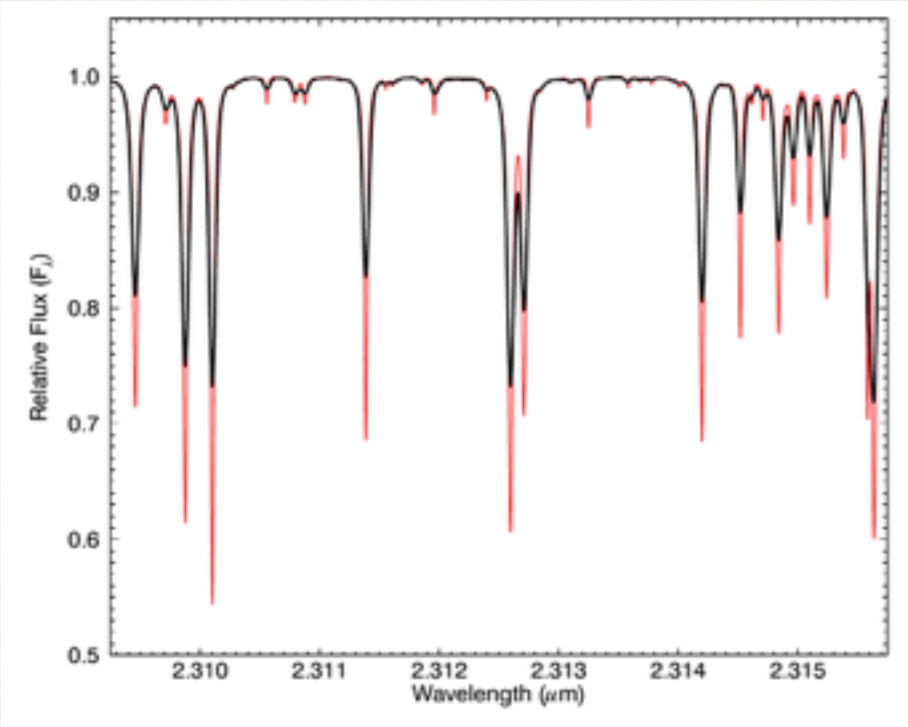
Fringing in a flat
A star spectrum

Line at pixel ~ 100 is telluric

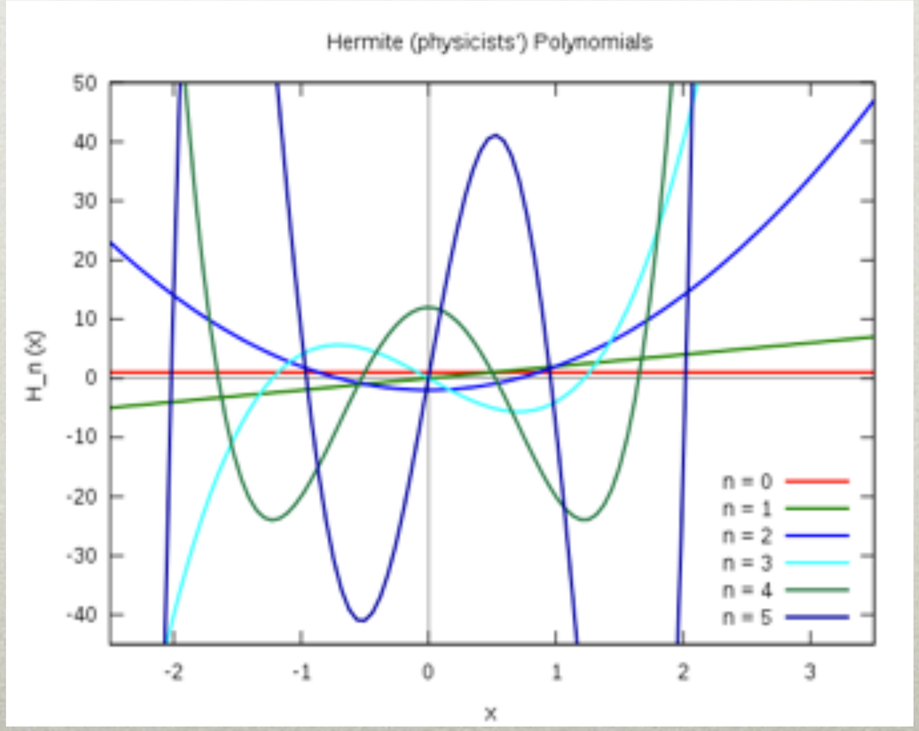
- There's fringing in the data too !
- We cannot easily correct it
- Need to add a fringing component in our fitting procedures

The LSF

- LSF = Linear Spread Function
- 1D analog of the PSF
- Convolving an “ideal” spectrum with LSF reproduces the effect of the slit + the atmosphere
- => LSF depends on seeing and weather conditions. Not stable !
- We use Hermite Functions (Gaussian x Hermite polynomials)



Effect of the LSF (black) on the “perfect” gas cell spectrum (red)

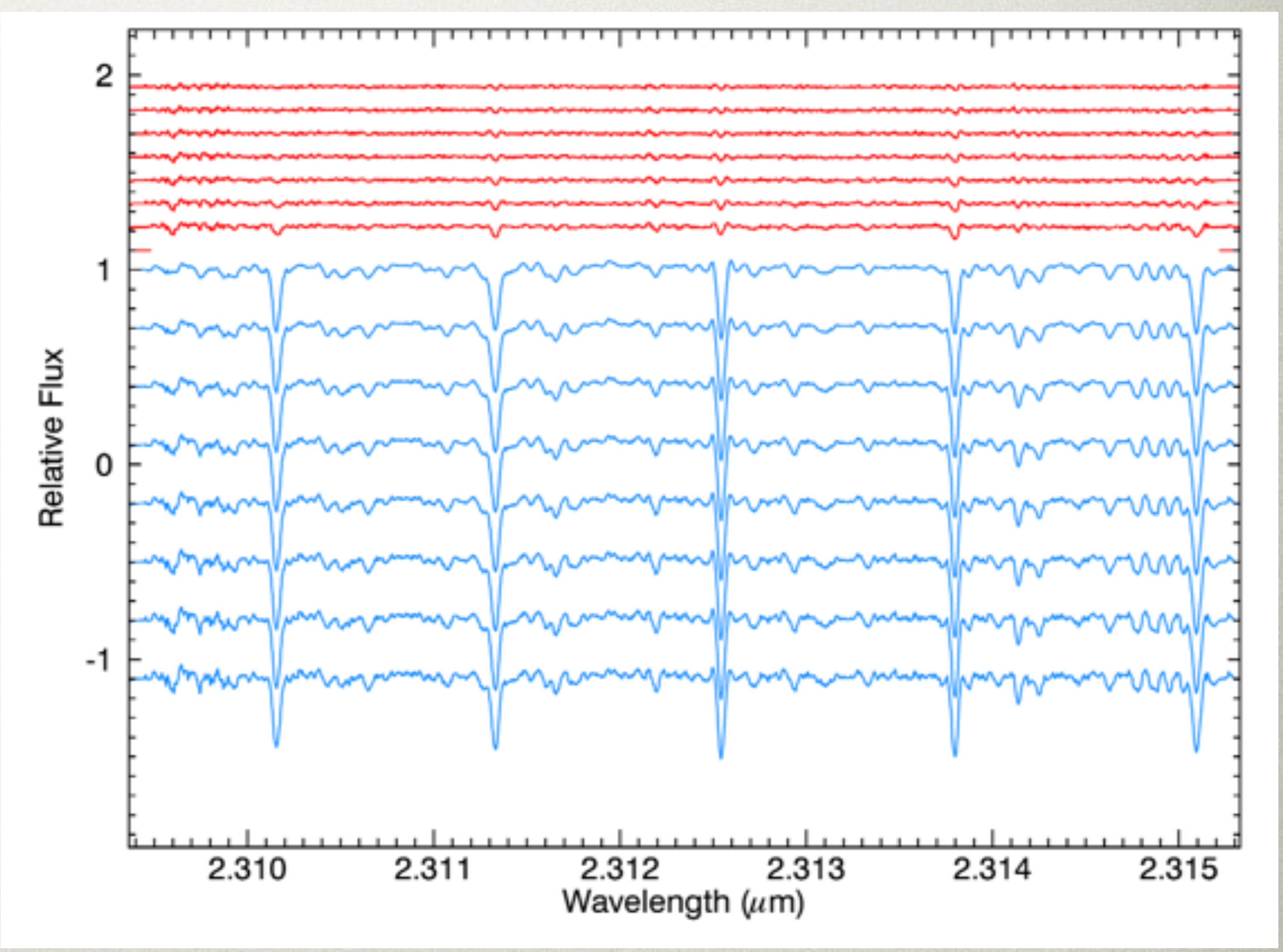


Hermite polynomials

(Wikipedia creative commons license)

Our Unique RV Pipeline

- Does not use telluric lines for wavelenth calibration.
- => Uses gas cell lines for this
- Does not need a stellar template.
- Iteratively builds the stellar template
- Yields only relative RVs



Evolution of Template & Residuals with iterations

Templates (blue) from top to bottom ; Residuals (red) from bottom to top

Our Unique RV Pipeline

1. Fit all spectra with a flat stellar template

2. Detect & mask stellar lines with residuals, repeat #1

3. De-convolve each residuals with LSF then co-add to get a stellar template

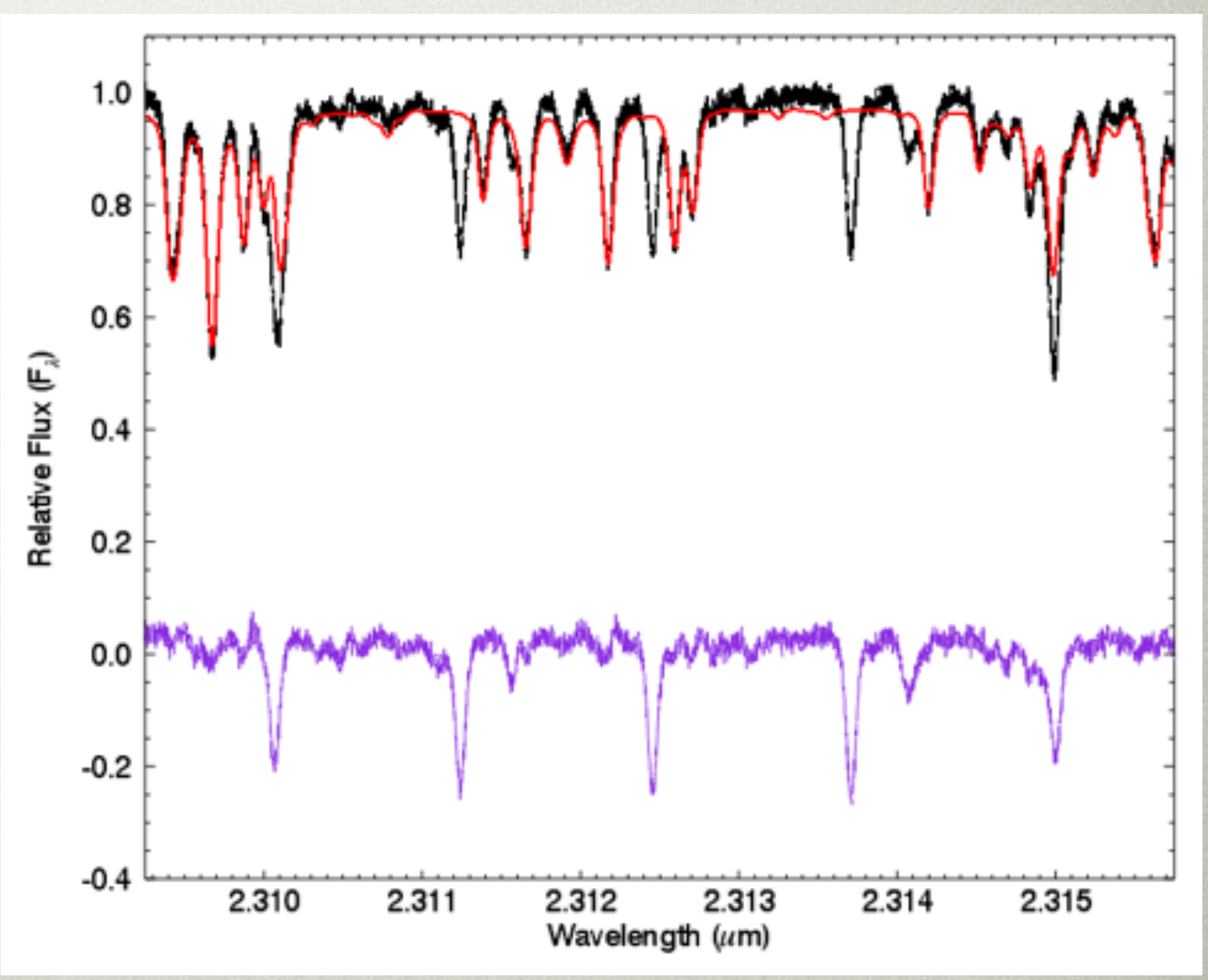
4. Fit all spectra now with a stellar spectrum

5. Repeat 3 & 4 N times.

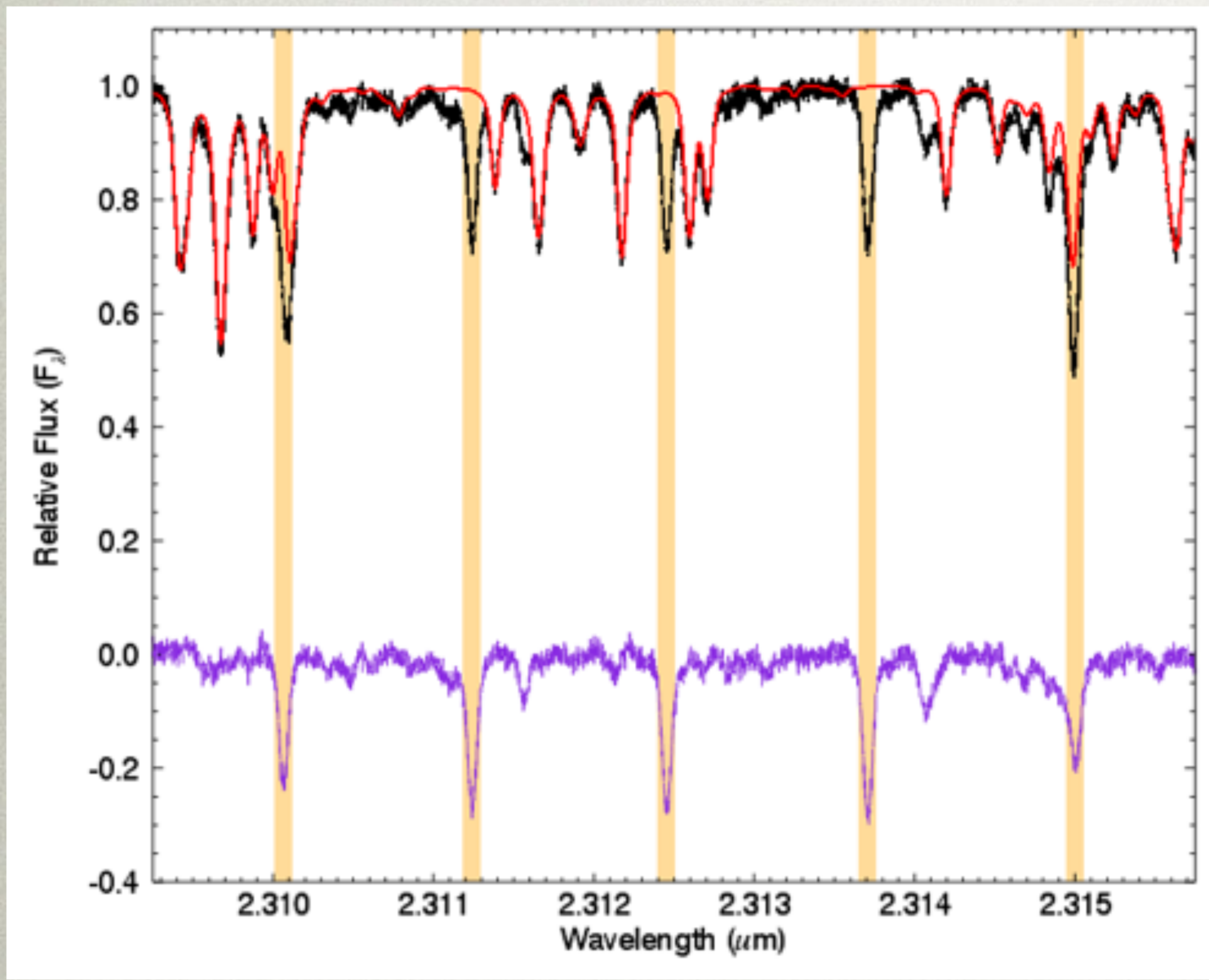
Our Unique RV Pipeline

1. Fit all spectra with a flat stellar template

- Fitting LSF + fringing + telluric + λ solution + continuum all at once
- Black = Data
- Red = Model
- Purple = Residuals
- Fit is not perfect, but now we can see stellar lines in the residuals



Our Unique RV Pipeline



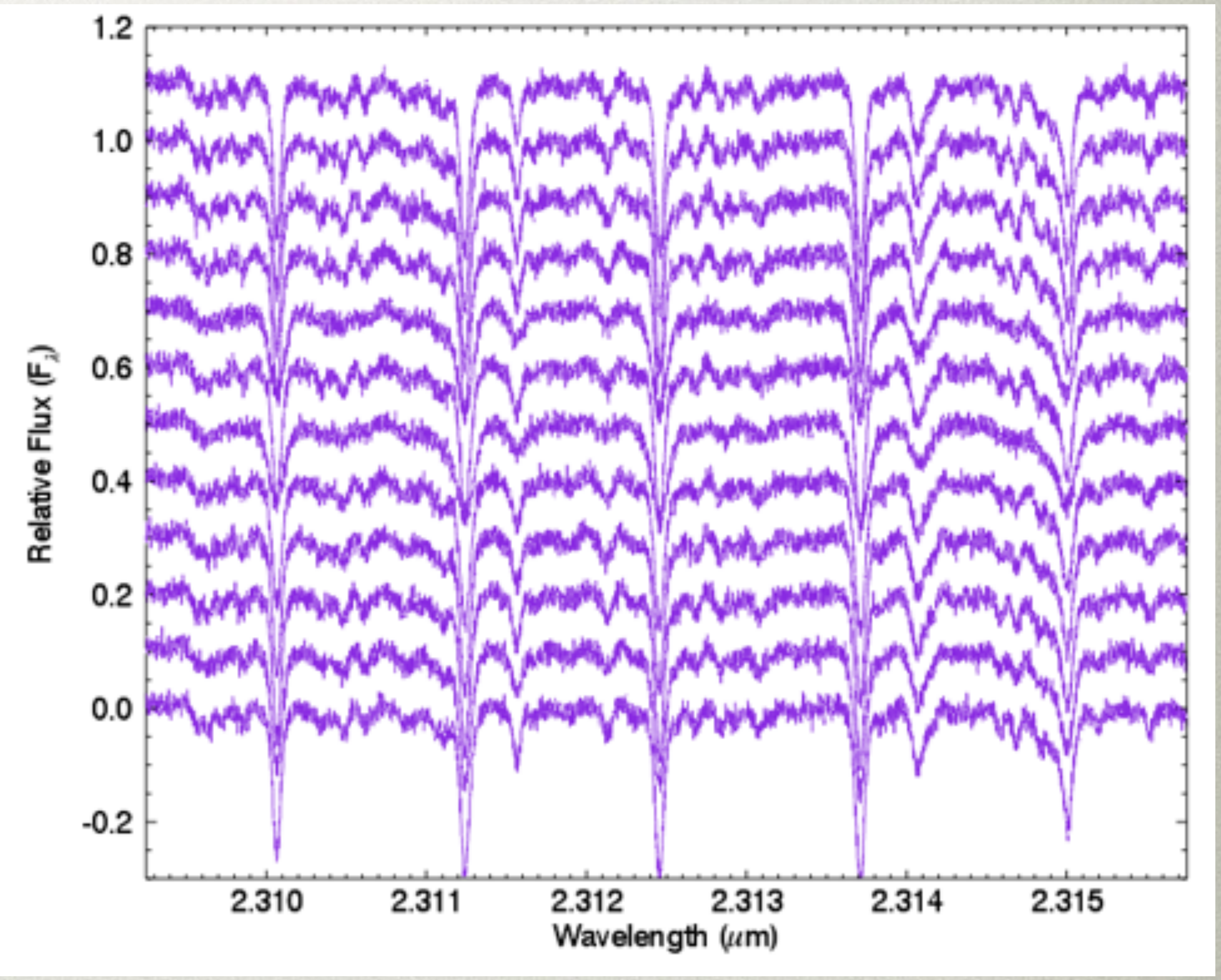
2. Detect & mask stellar lines with residuals, repeat #1

- Orange = Masks
- The fit is now better since we ignored the stellar lines that cannot be reproduced

Our Unique RV Pipeline

- All N spectra have different LSFs (seeing, flexure)
- But we know the LSF, so we can…

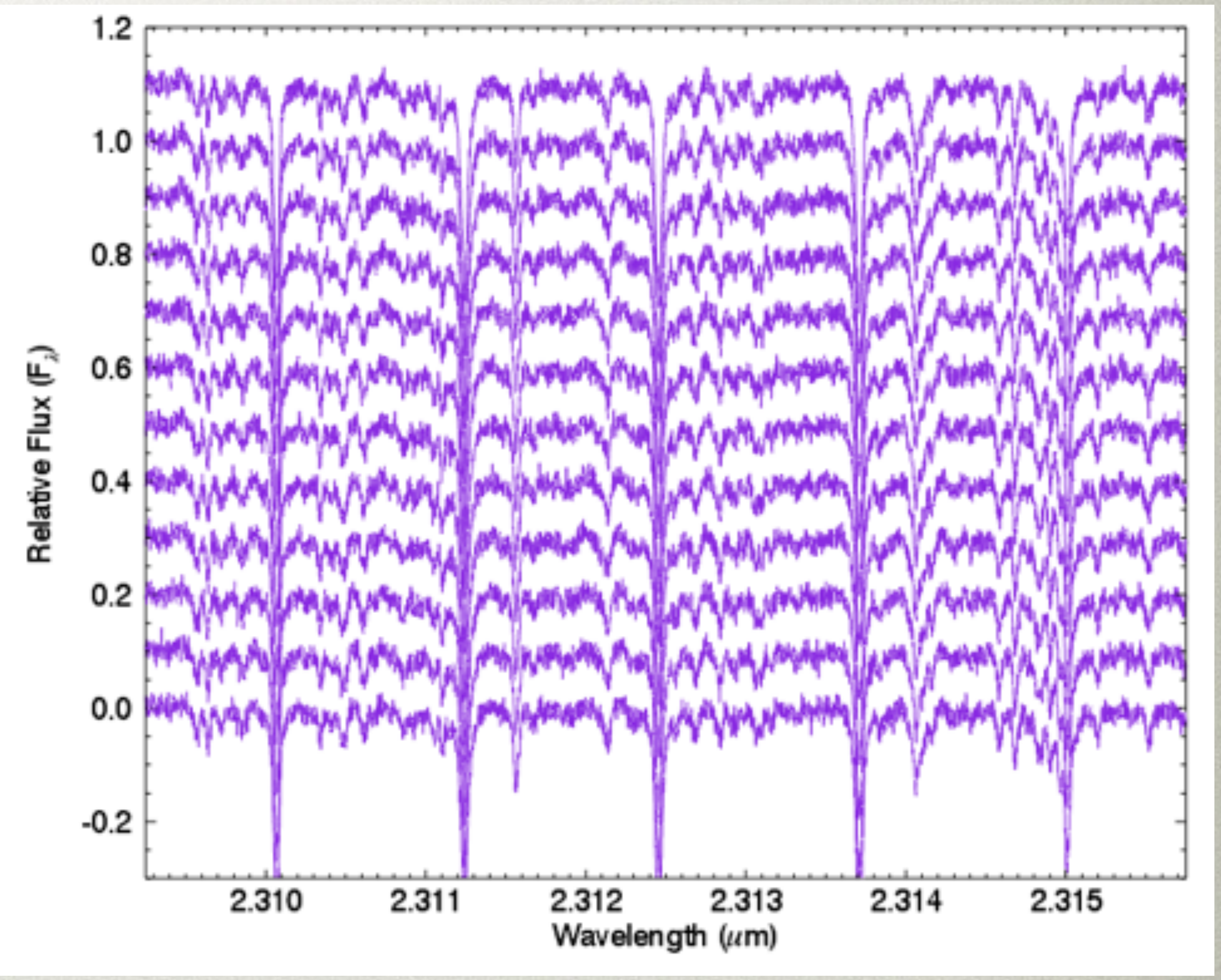
3. De-convolve each residuals with LSF then co-add to get a stellar template



Our Unique RV Pipeline

Deconvolve !

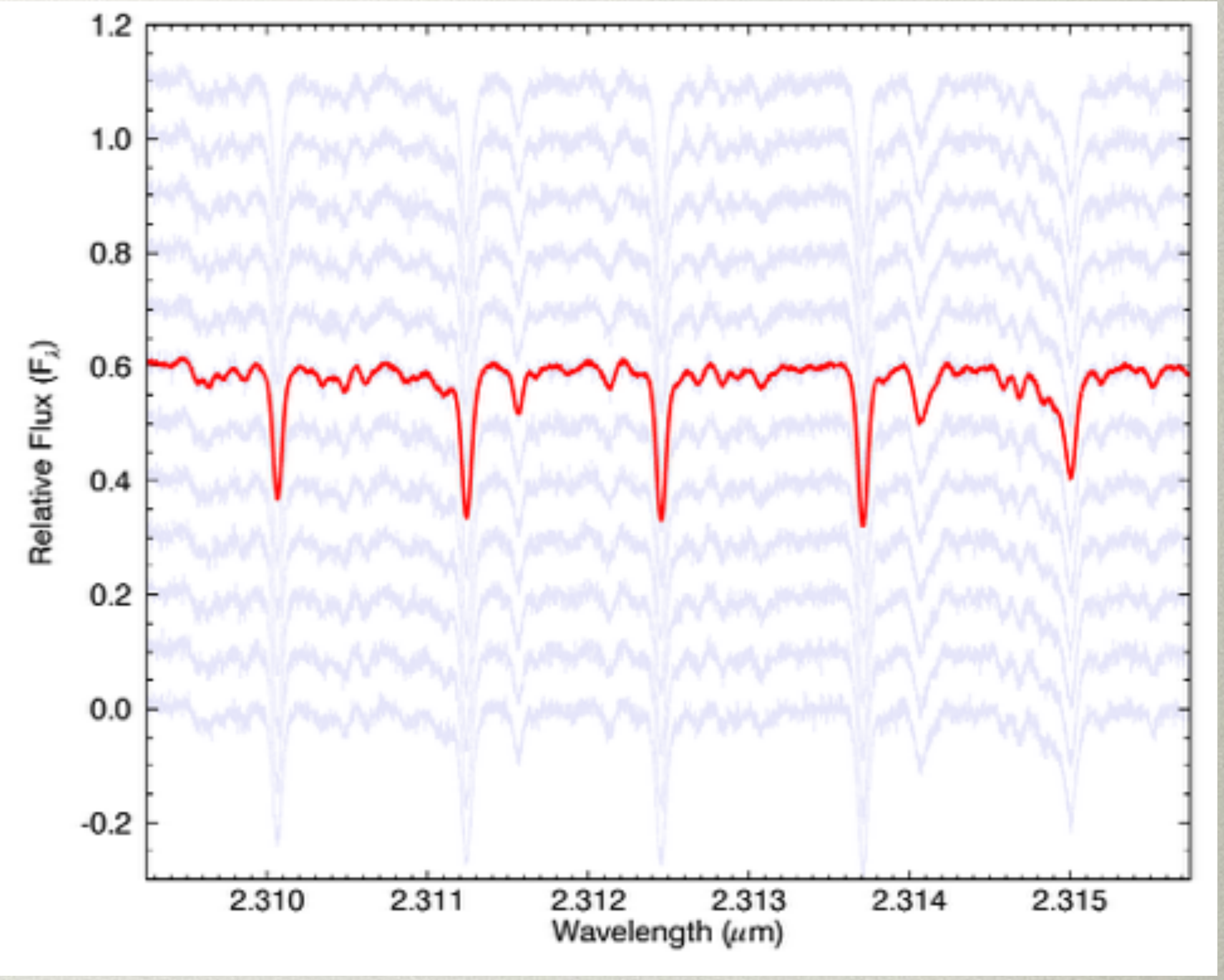
3. De-convolve each residuals with LSF then co-add to get a stellar template



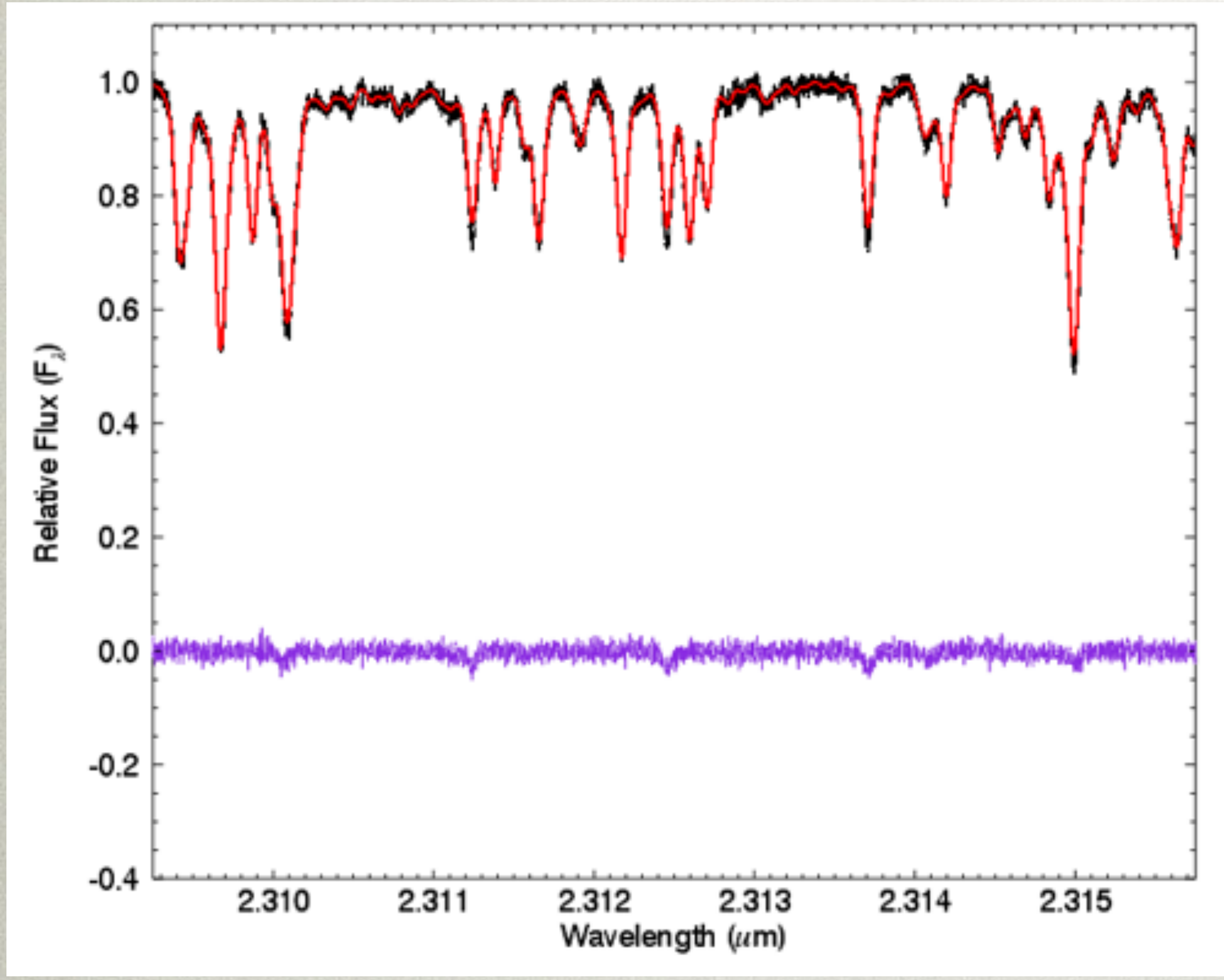
Our Unique RV Pipeline

And then combine !

3. De-convolve each residuals with LSF then co-add to get a stellar template



Our Unique RV Pipeline



- Now the residuals contain almost just noise
- We can repeat the steps above to derive a correction for the template
- The correction is simply added back to the template

4. Fit all spectra now with a stellar spectrum

5. Repeat 3 & 4 N times.

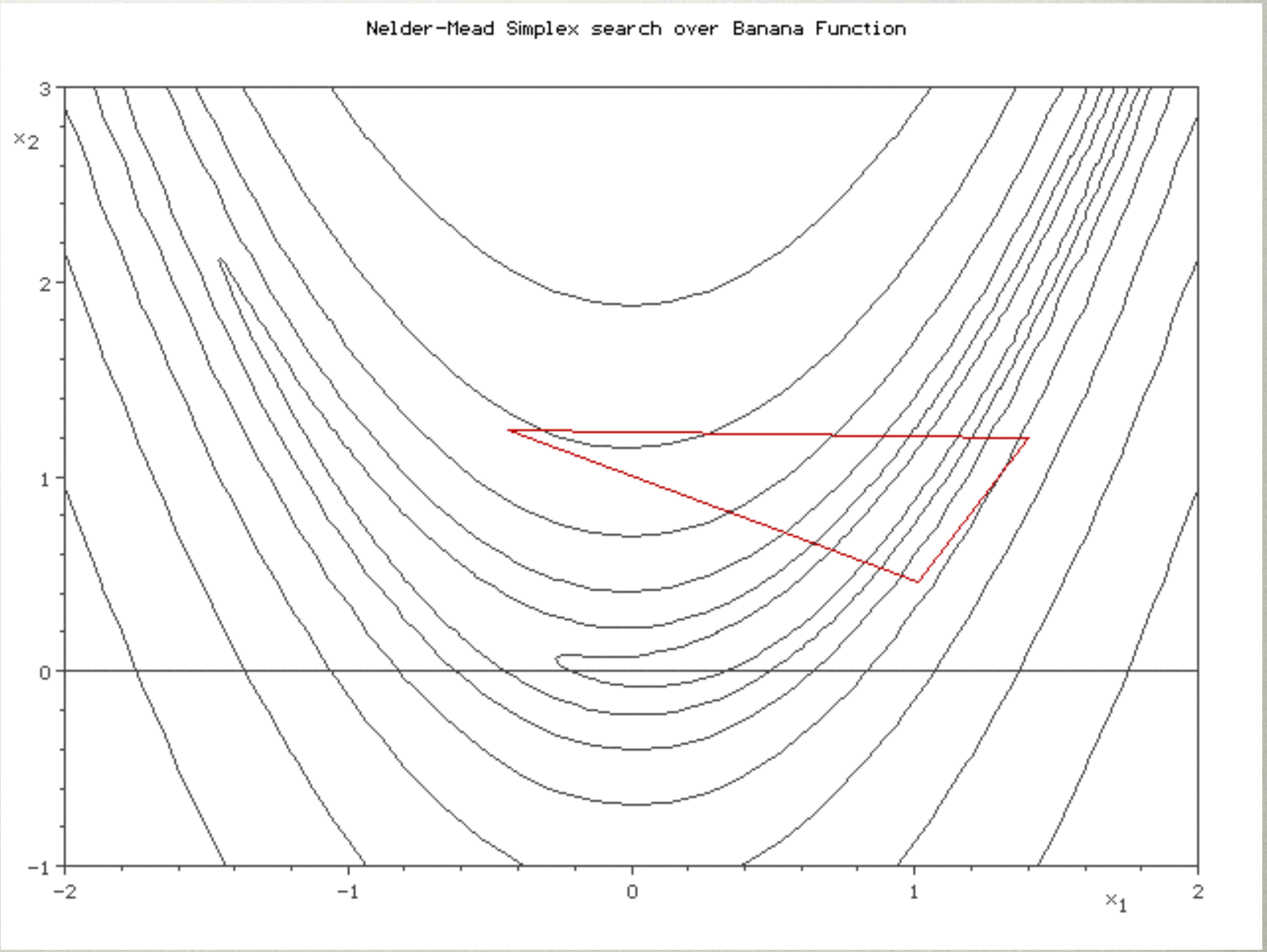
Our Unique RV Pipeline

- Solves RV + LSF + fringing + telluric + λ solution + continuum all at once
- Upper blue = Data
- Red = Fit
- Orange = Stellar spectrum
- Purple = Residuals
- Green = zero line
- Lower blue = Fringing * 3

Typical fit to an observed spectrum

The Amoeba that lives in the Pipeline

- Solving more than 15 parameters at once is not easy !
- The amoeba is a small creature that lives in an N-parameters space
- It has N+1 legs and follows very simple rules to move around
- It can grow, shrink and move, depending on what its legs "feel"
- Very robust to find global minima in a bumpy environment
- Does not assume linearity

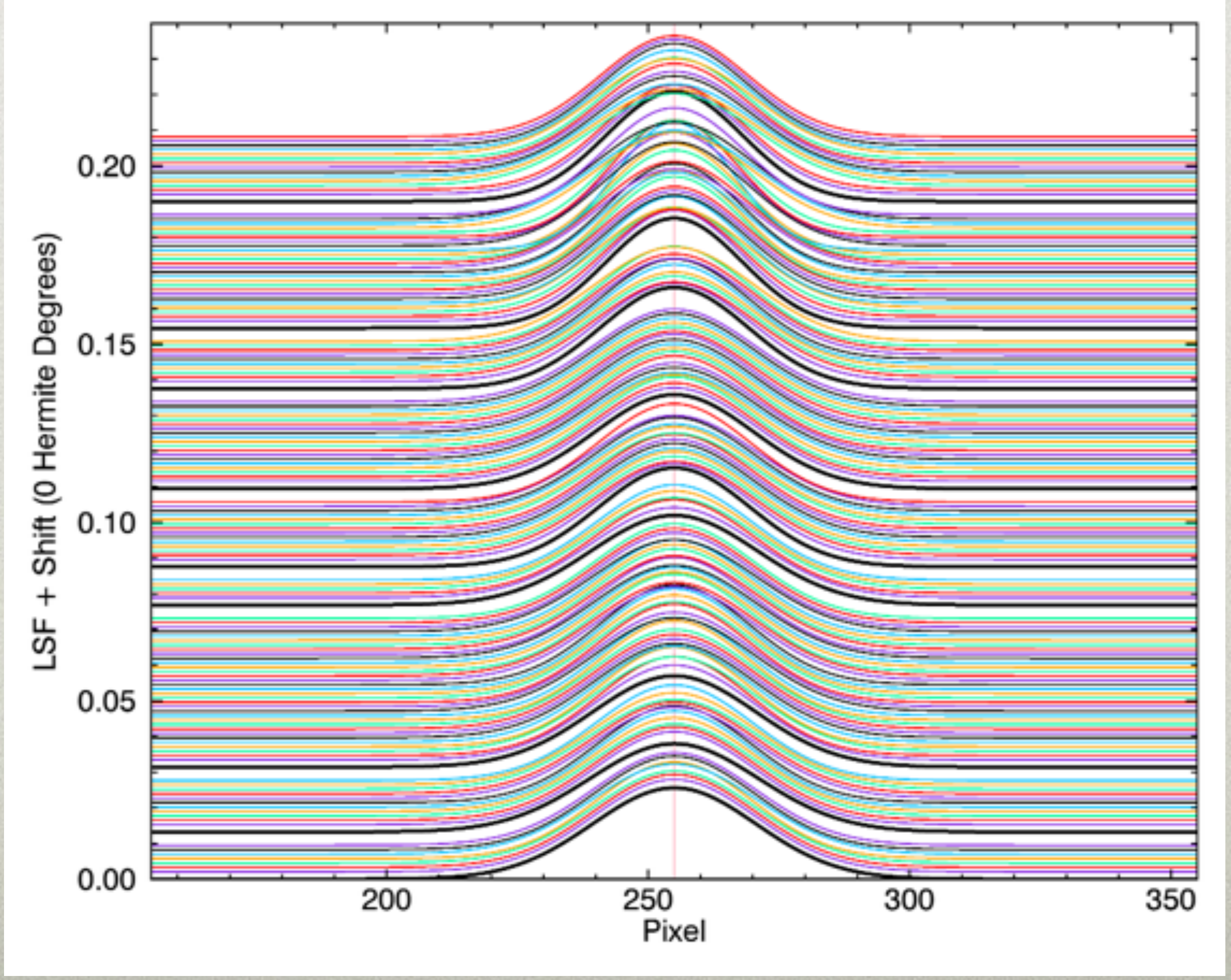


Amoeba exploring the 2D Banana Function

LSF Stability

- How many Hermite degrees do we want to use ?
- More means a potentially better LSF, but also more free parameters

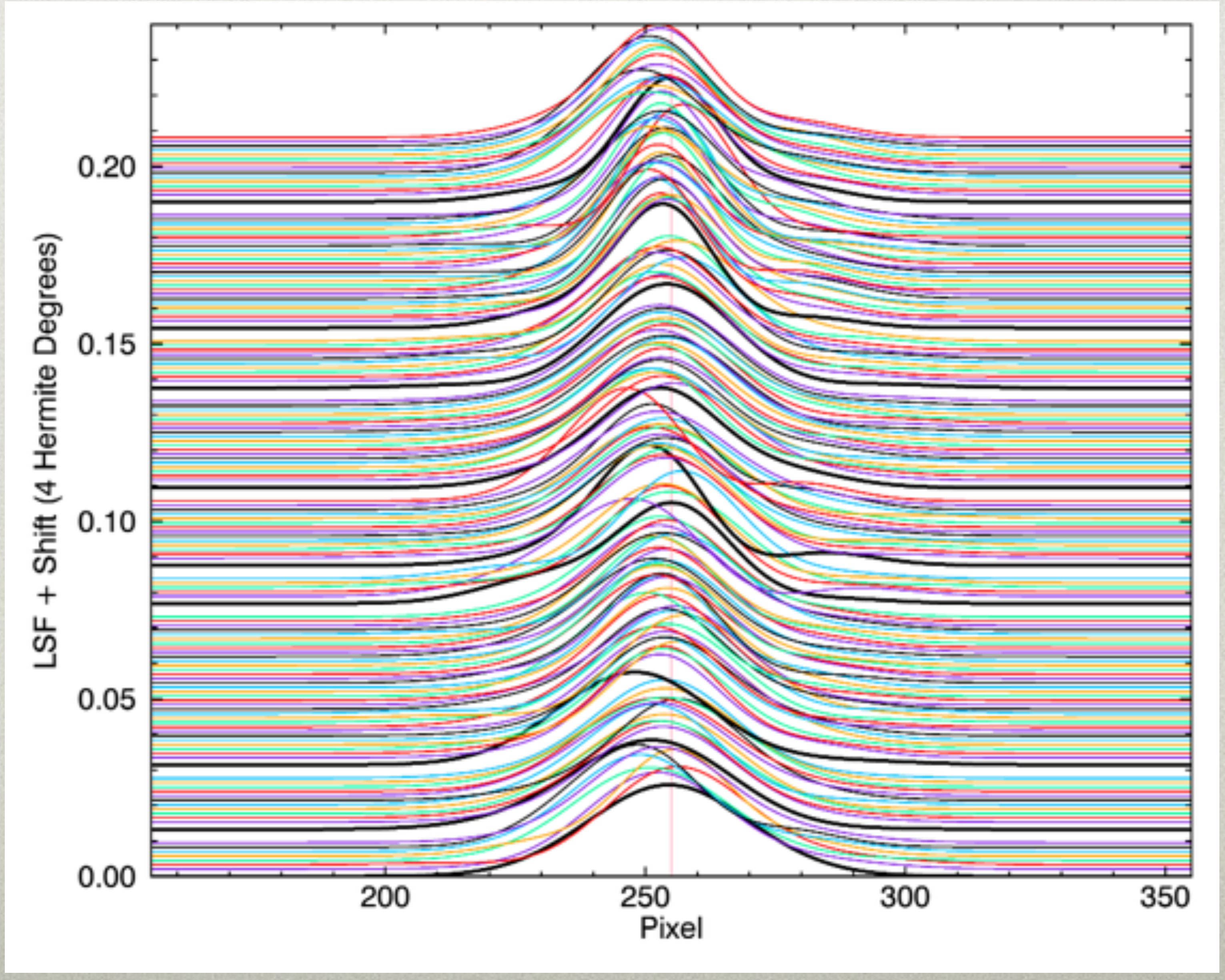
Gaussian LSF as a function of time for a bright A0 star



LSF Stability

- How many Hermite degrees do we want to use ?
- More means a potentially better LSF, but also more free parameters

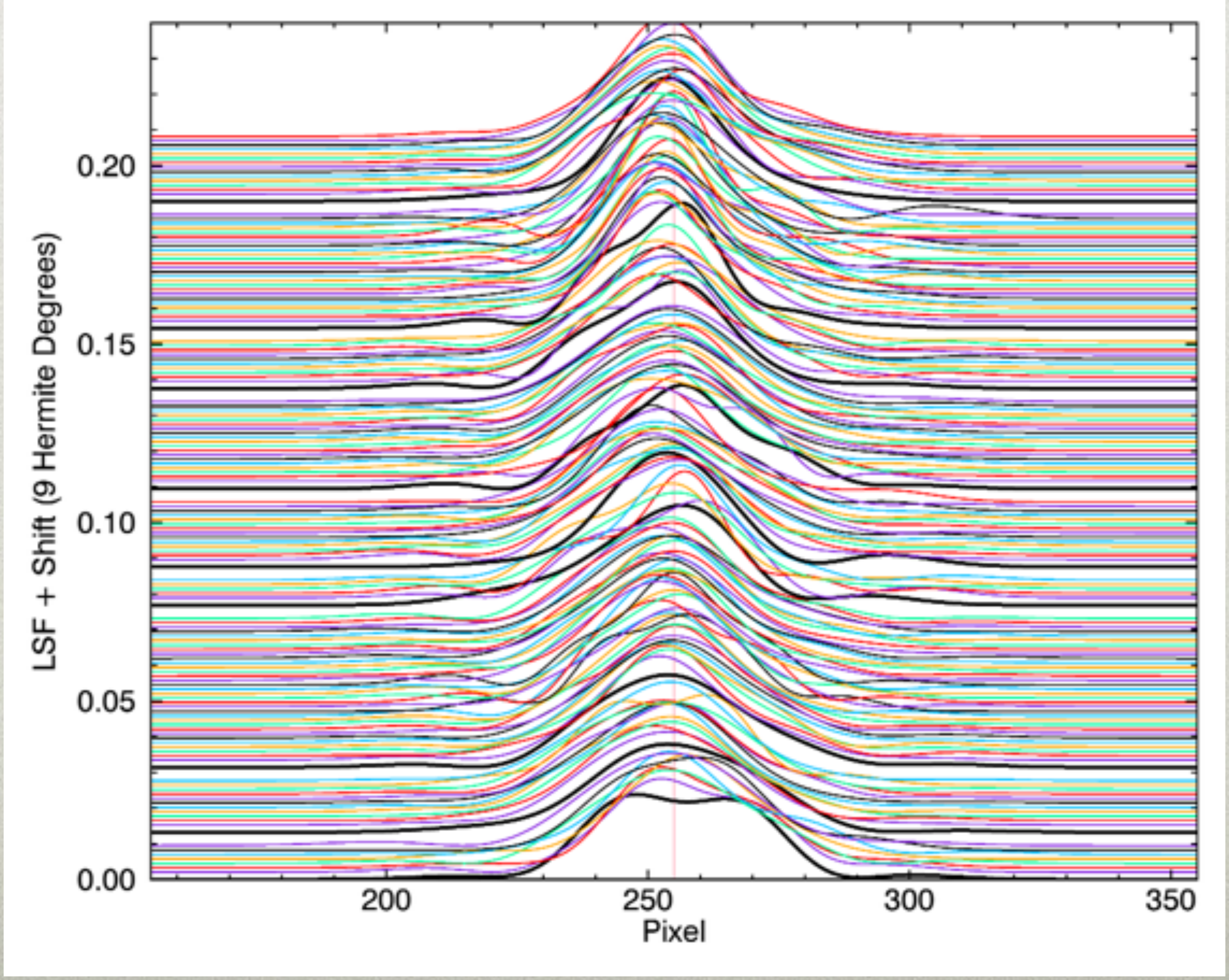
Gaussian + 4 Hermite degrees LSF as a function of time for a bright A0 star



LSF Stability 19/35

- How many Hermite degrees do we want to use ?
- More means a potentially better LSF, but also more free parameters

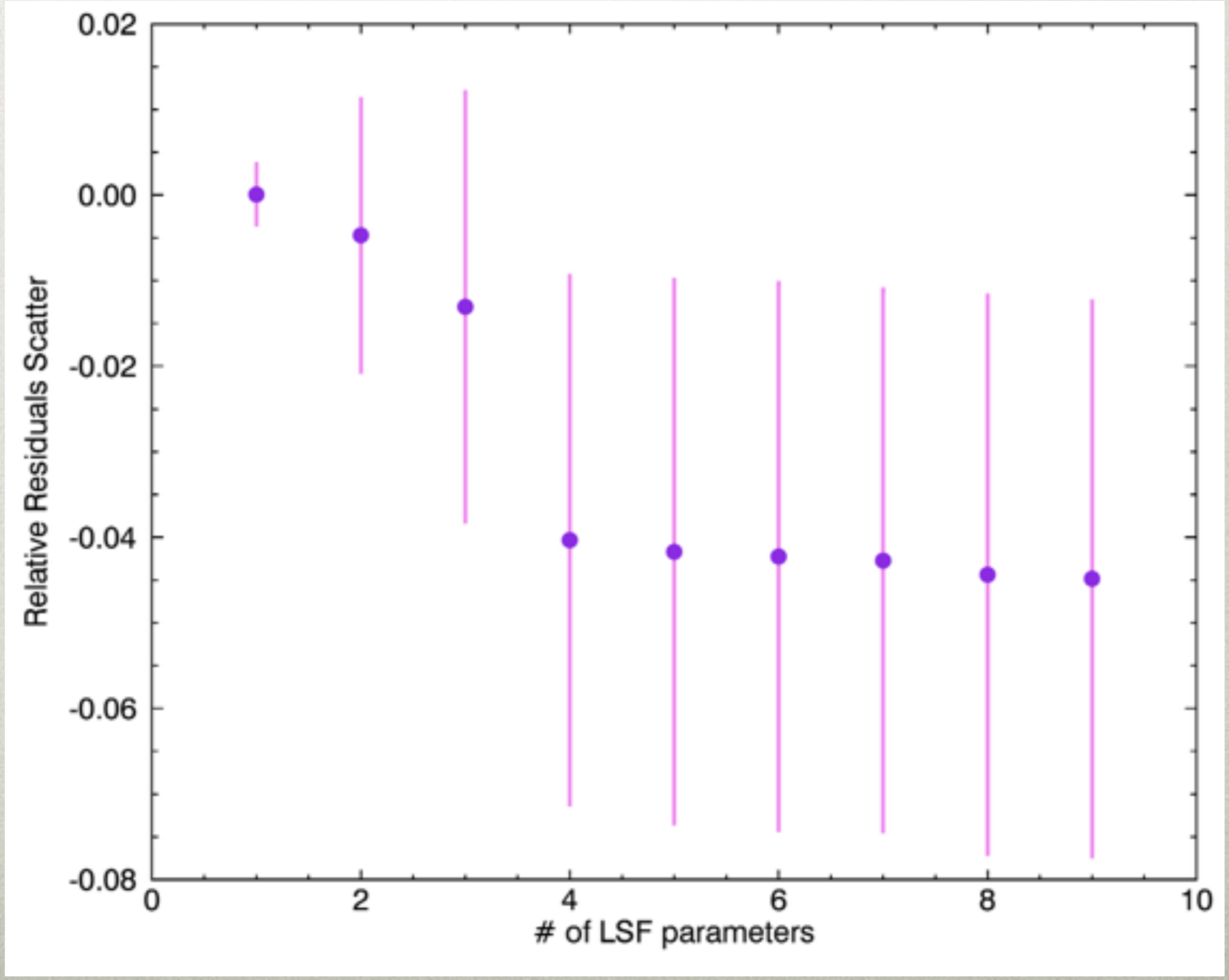
Gaussian + 9 Hermite degrees LSF as a function of time for a bright A0 star



J. Division et al. (1979)

LSF Stability

- The residuals of the best-fit decreases with more LSF parameters
- But after 4 degrees, it doesn’t change much - We thus use 4 !



4 Hermite degrees are enough

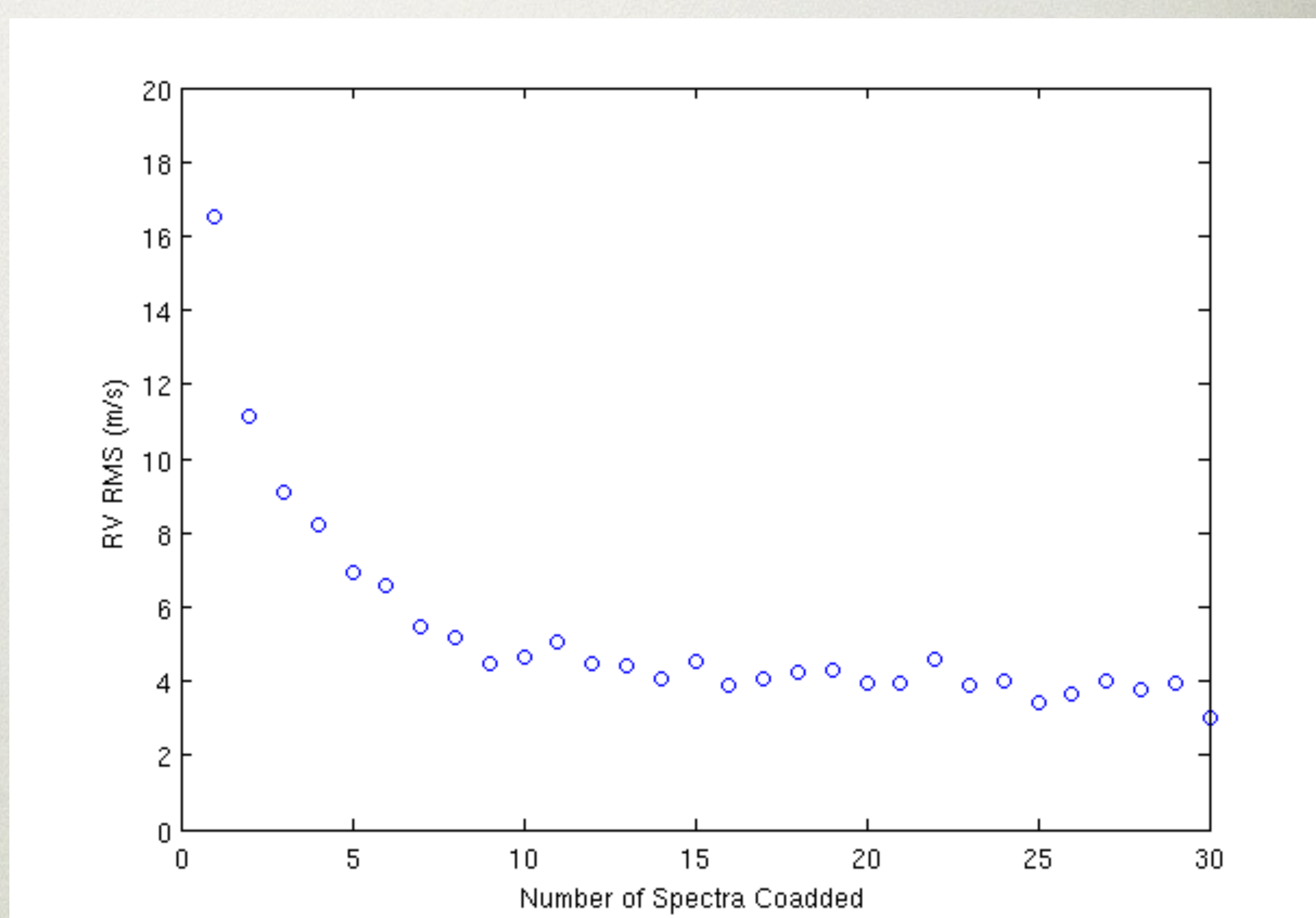
Observing 21/35

- Pilot data (2010 - 2012) 1,400 spectra for 16 targets
- We obtained 45 IRTF nights in 2014 A.
- 1,000+ spectra for 22 targets.
- For 2014+ data we get S/N ~ 200 per night per target
- Recently obtained 18 more nights for 2014 B !

The IRTF on Mauna Kea

Preliminary Results

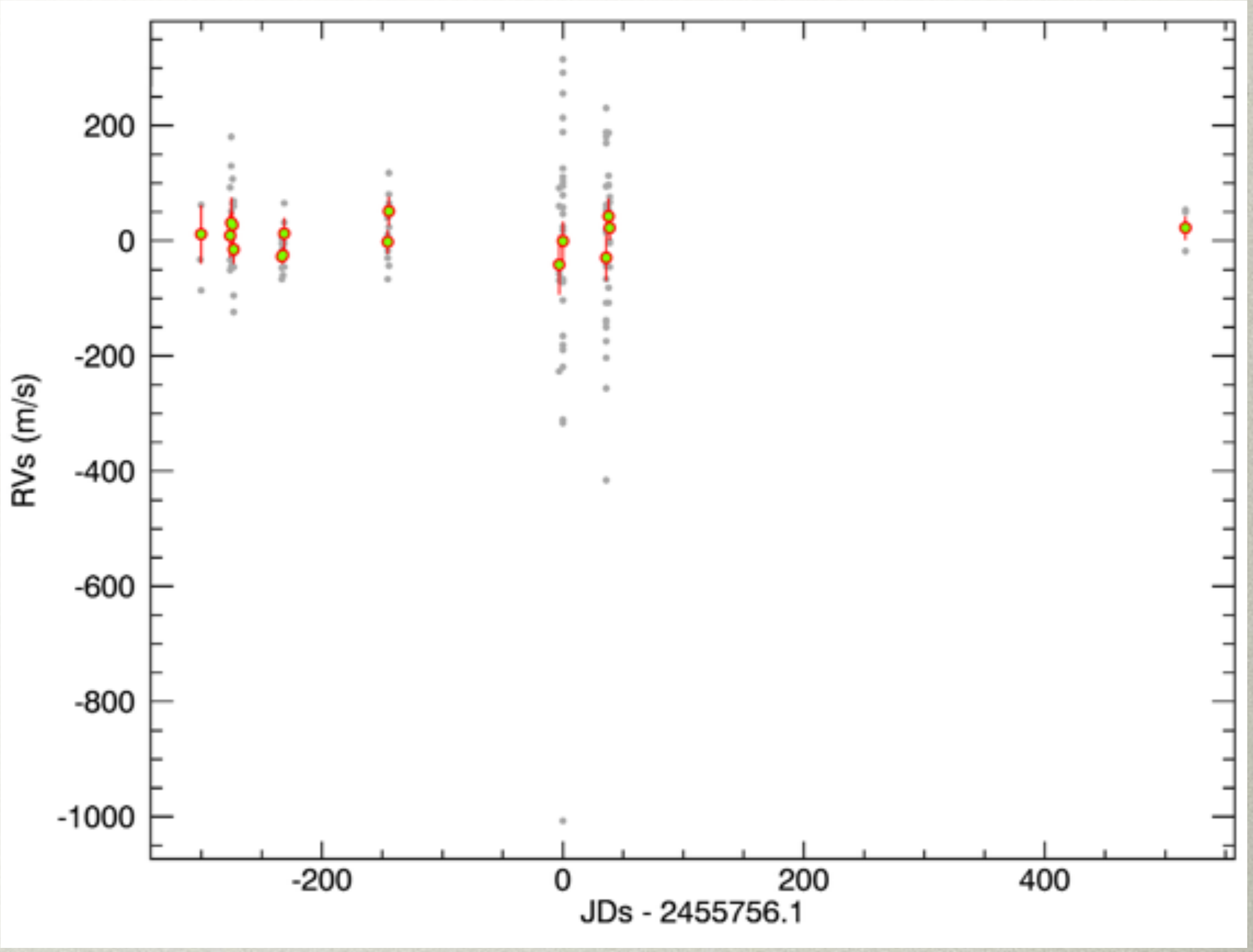
- High S/N on bright star SV Peg
- Reveals a ~ 4 m/s noise floor *within* one night
- But "mysterious" systematics double the RMS on multiple-nights data



RV precision for SV Peg within a single night

Preliminary Results

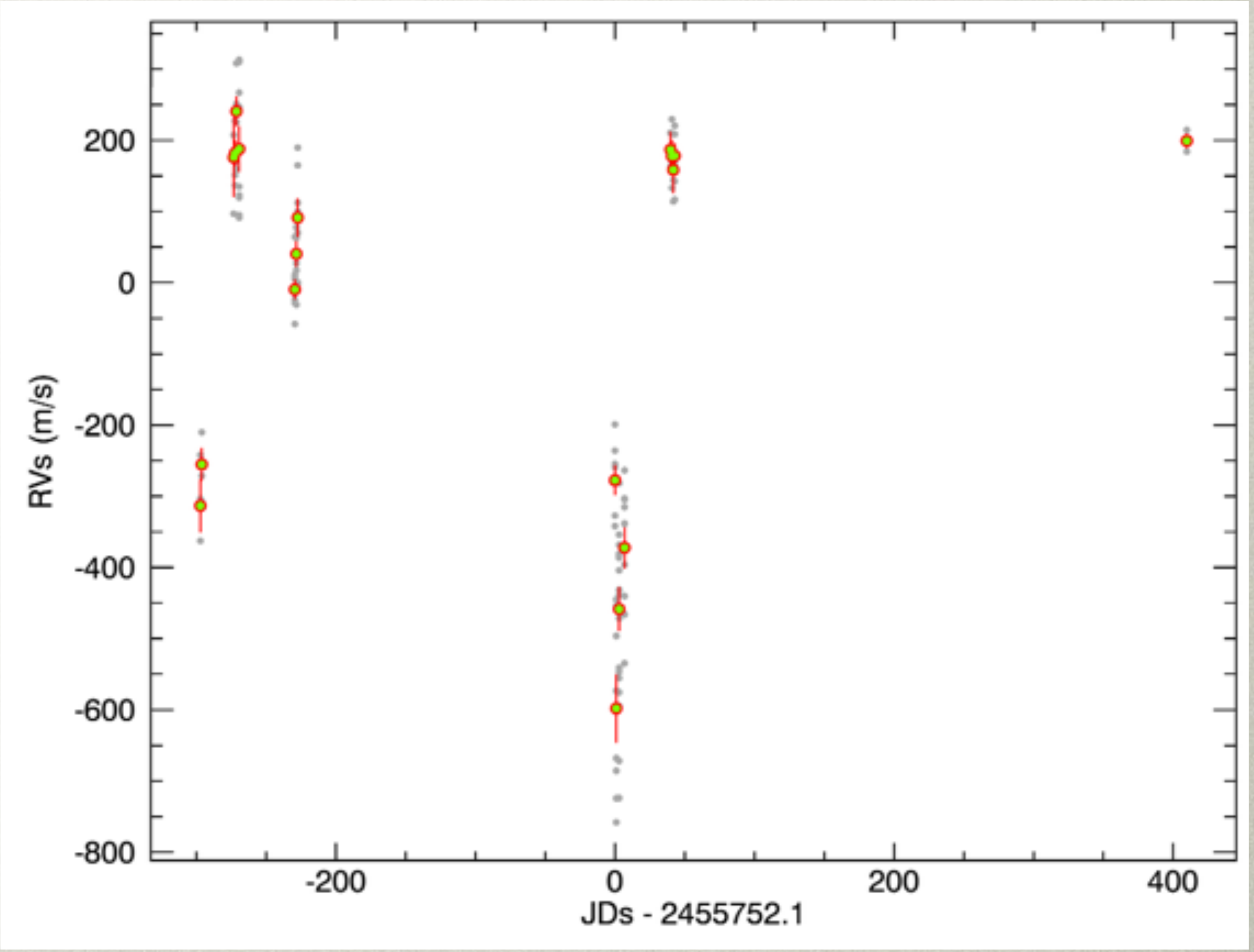
- GJ 15 A : M2, RV stable star
- ~ 50 m/s precision if wavelength solution floats
- ~ 20 m/s precision (photon noise limit) if we constrain wavelength solution



RV Curve for the quiet star GJ 15 A

Preliminary Results 24/35

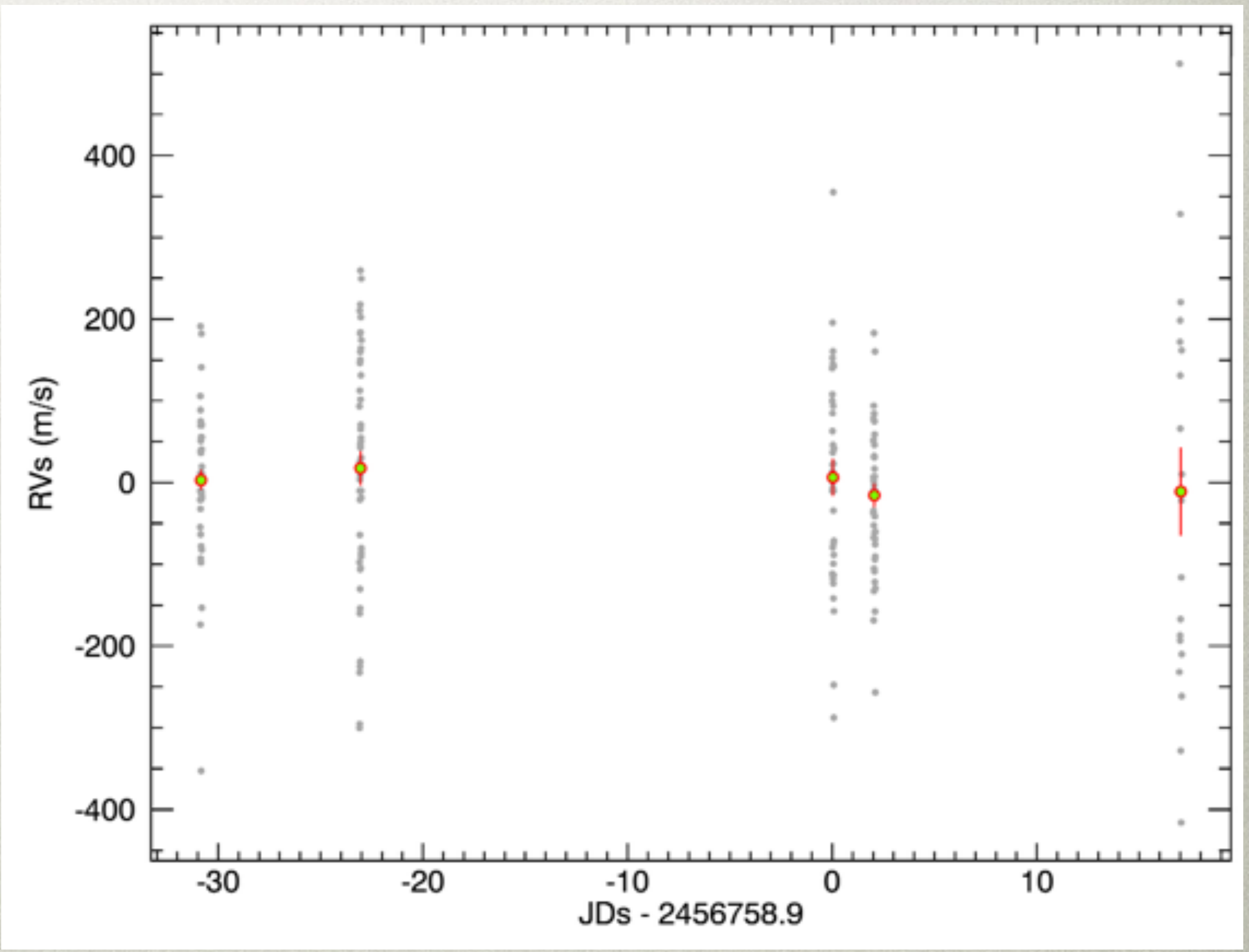
- We retrieve the signal for the 4-planet system of GJ 876
- And we find the right period !



RV Curve for known planetary system GJ 876 Abcde

Preliminary Results

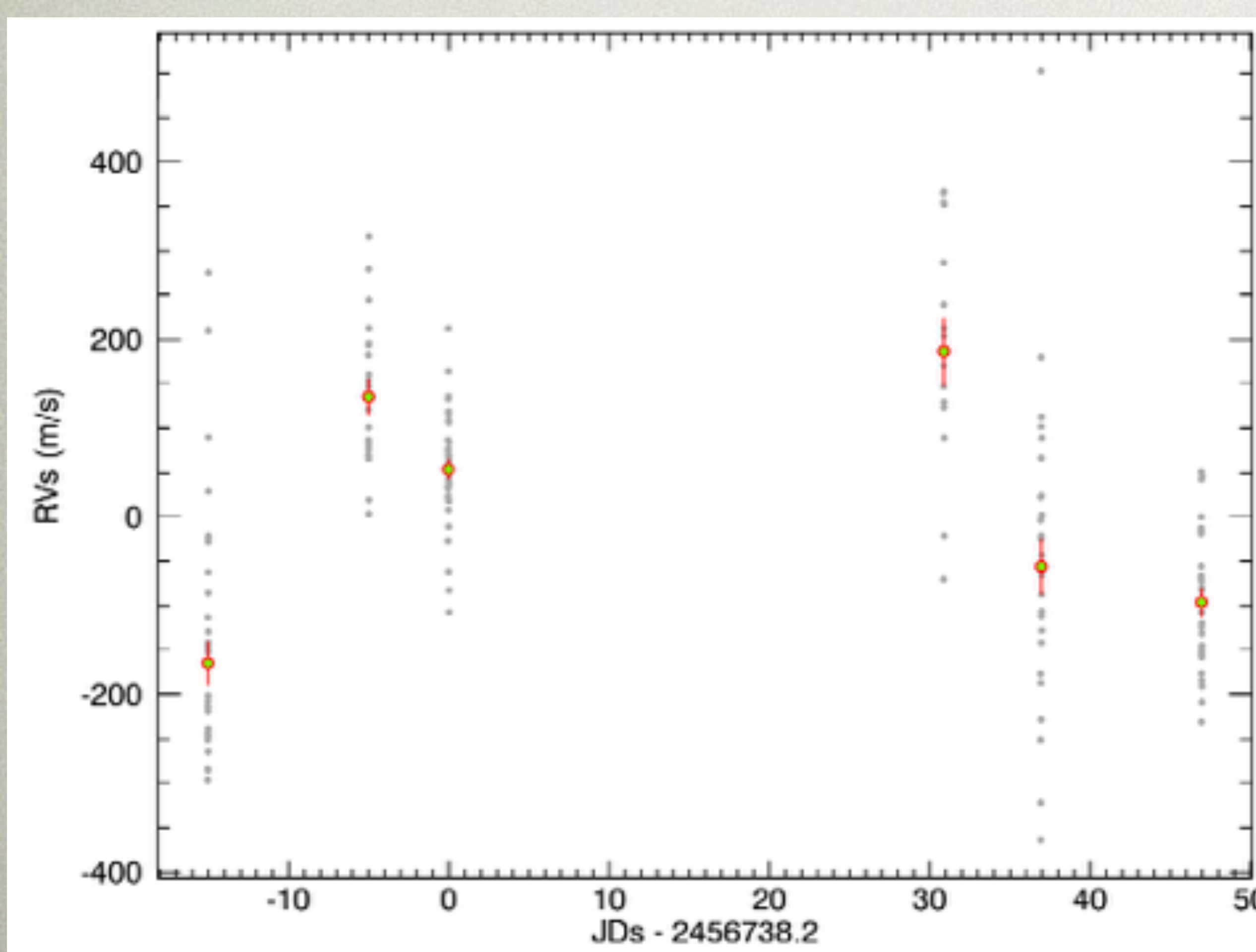
- Another quiet M0 star
- RV scatter ~ 15 m/s
- RV scatter increases with iterations

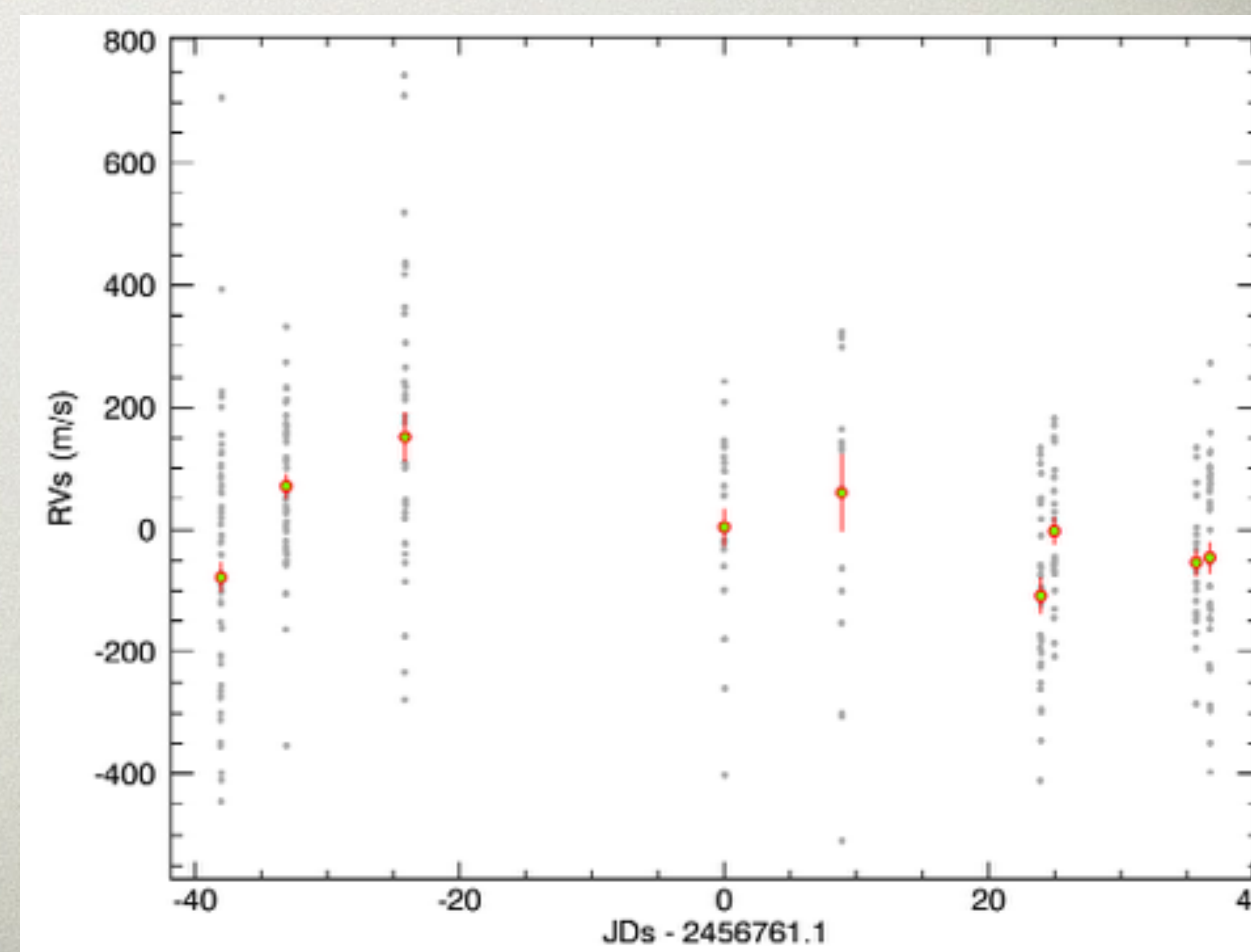


RV Curve for a new quiet M0 star

Preliminary Results

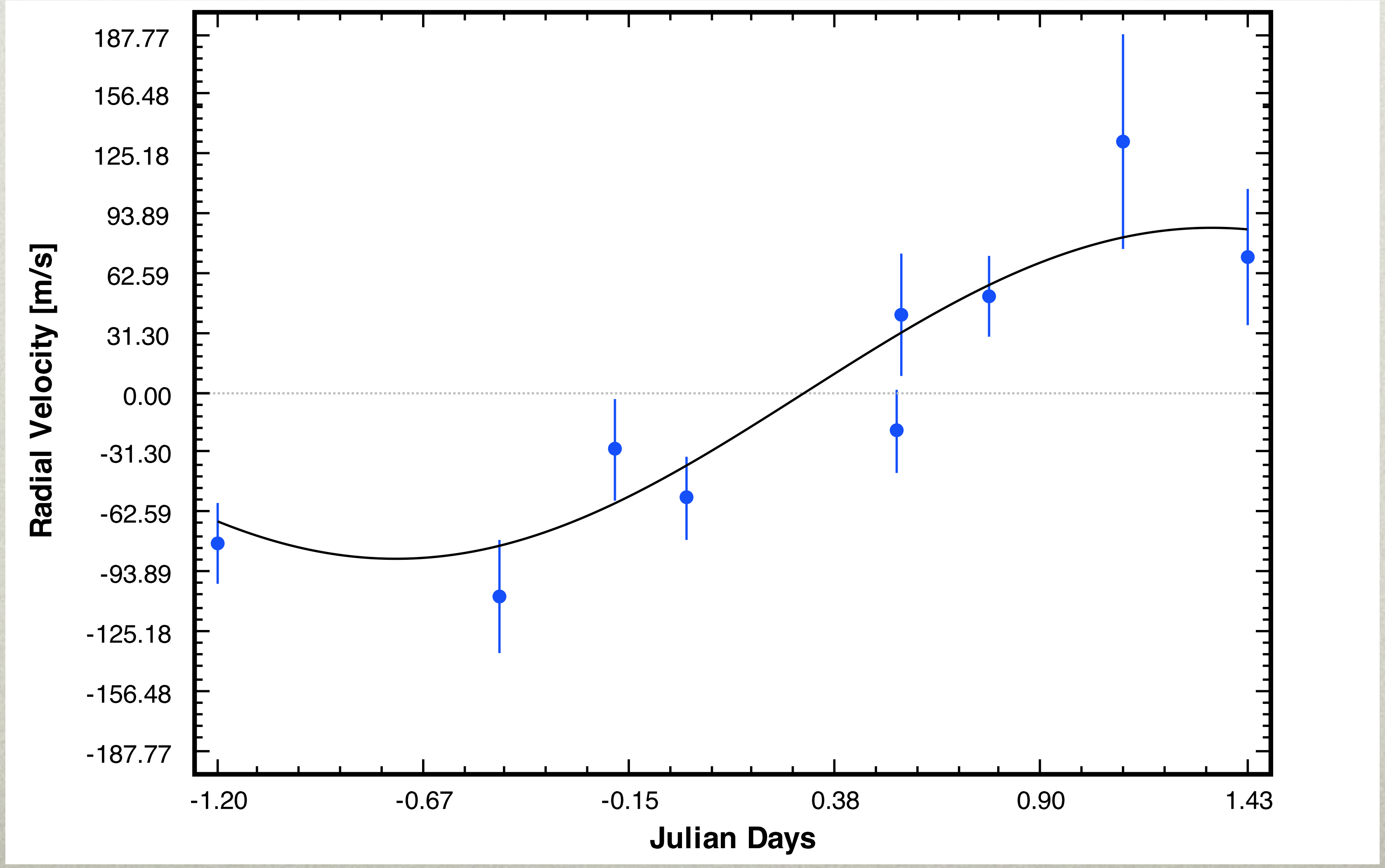
- Several stars with > 75 m/s scatter
- Right panel seemed like a compelling companion…





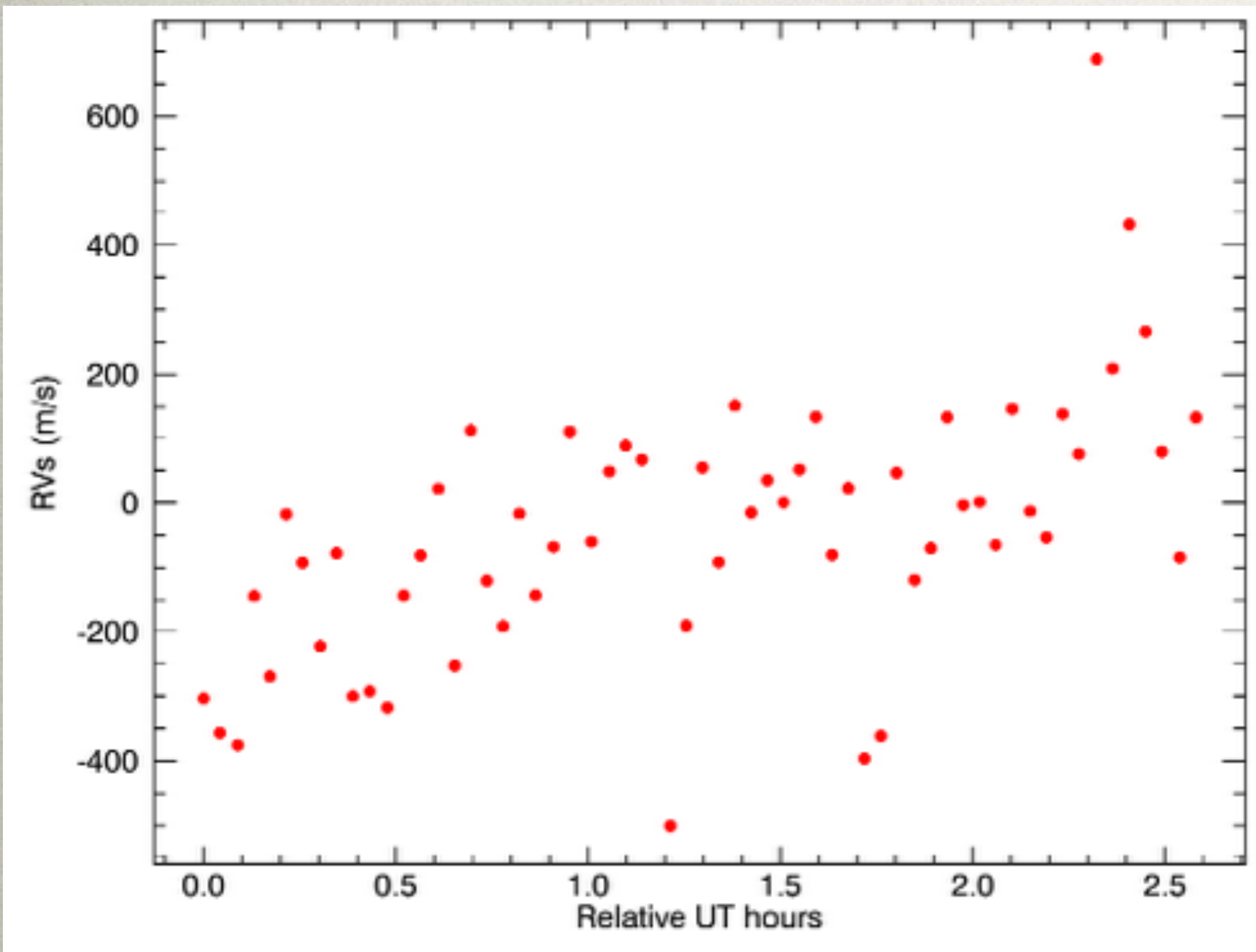
Preliminary Results

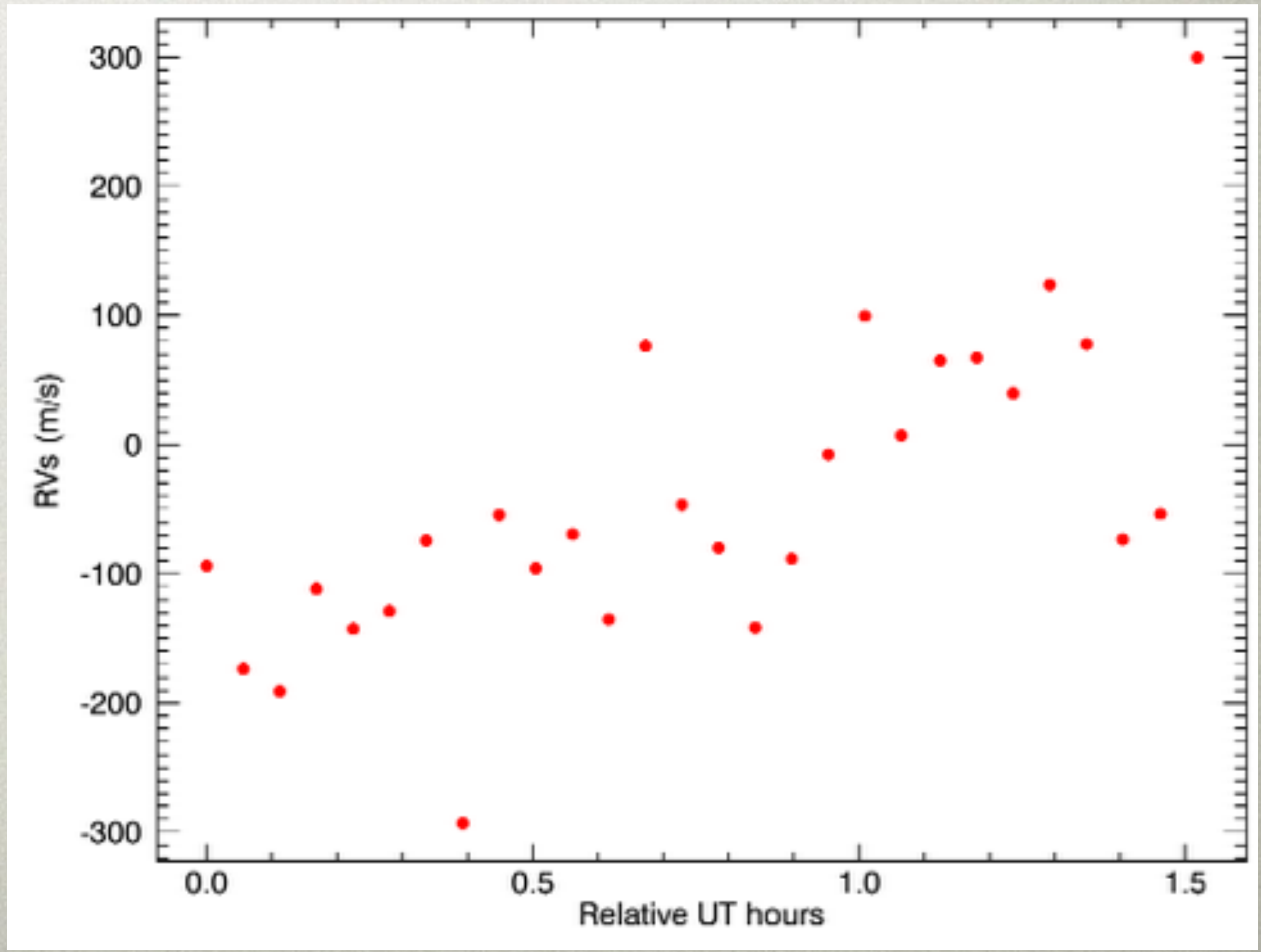
- Folded data for the right panel
- 4.16-day period ; 56 m/s amplitude
- Corresponds to ~ 0.6 Jupiter Mass at 0.2 AU



Preliminary Results

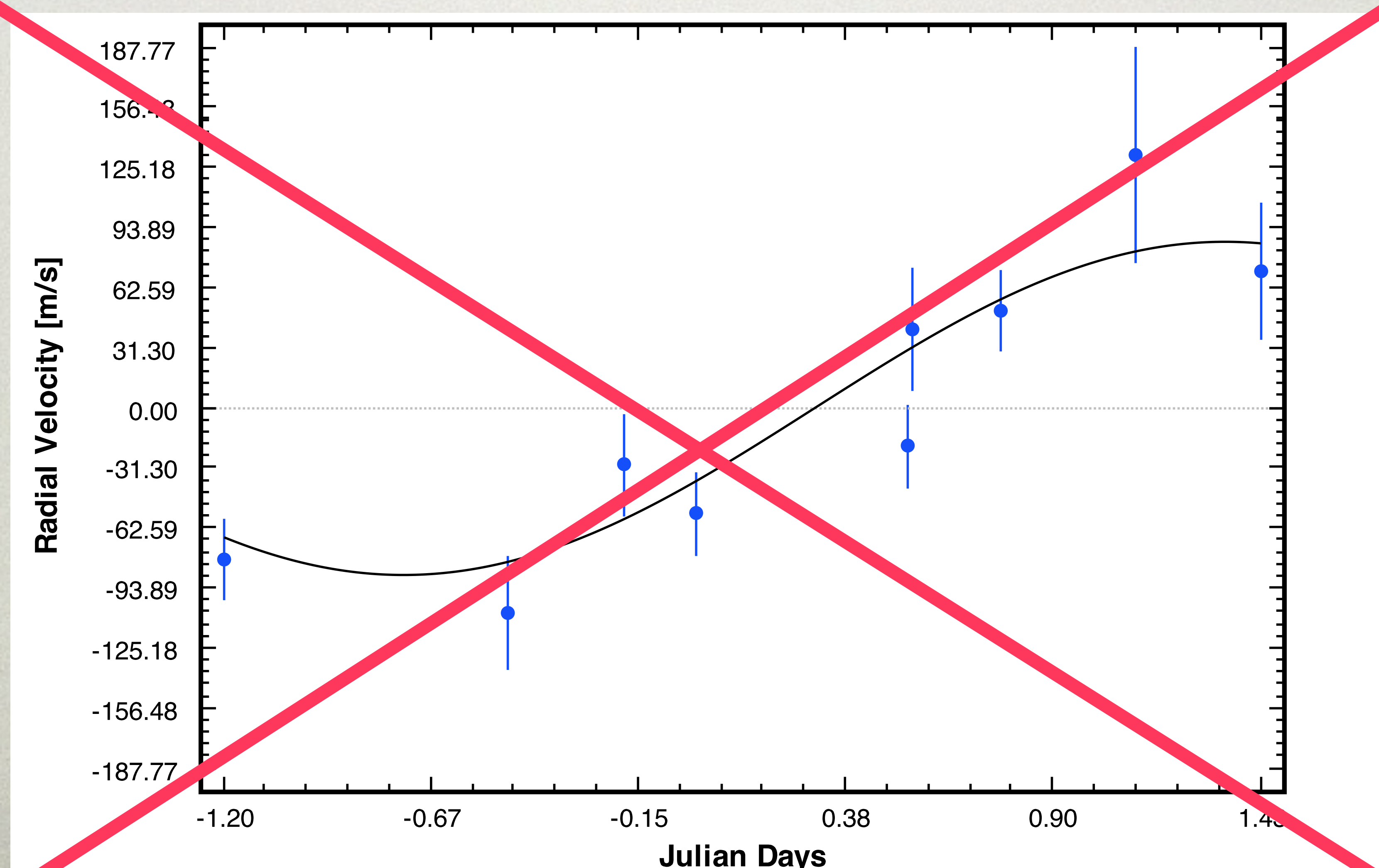
- Some nights even have a significant linear trend

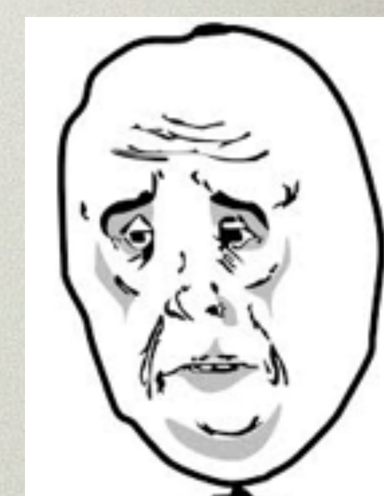




Preliminary Results

- … But a RV follow-up in the optical revealed stability within 4 m/s !





Bi-Sector Analysis 30/35

- Is it stellar activity in the NIR ?
- If so, the shape of stellar lines could change
- Slope of bi-sector is a good diagnostic of the shape

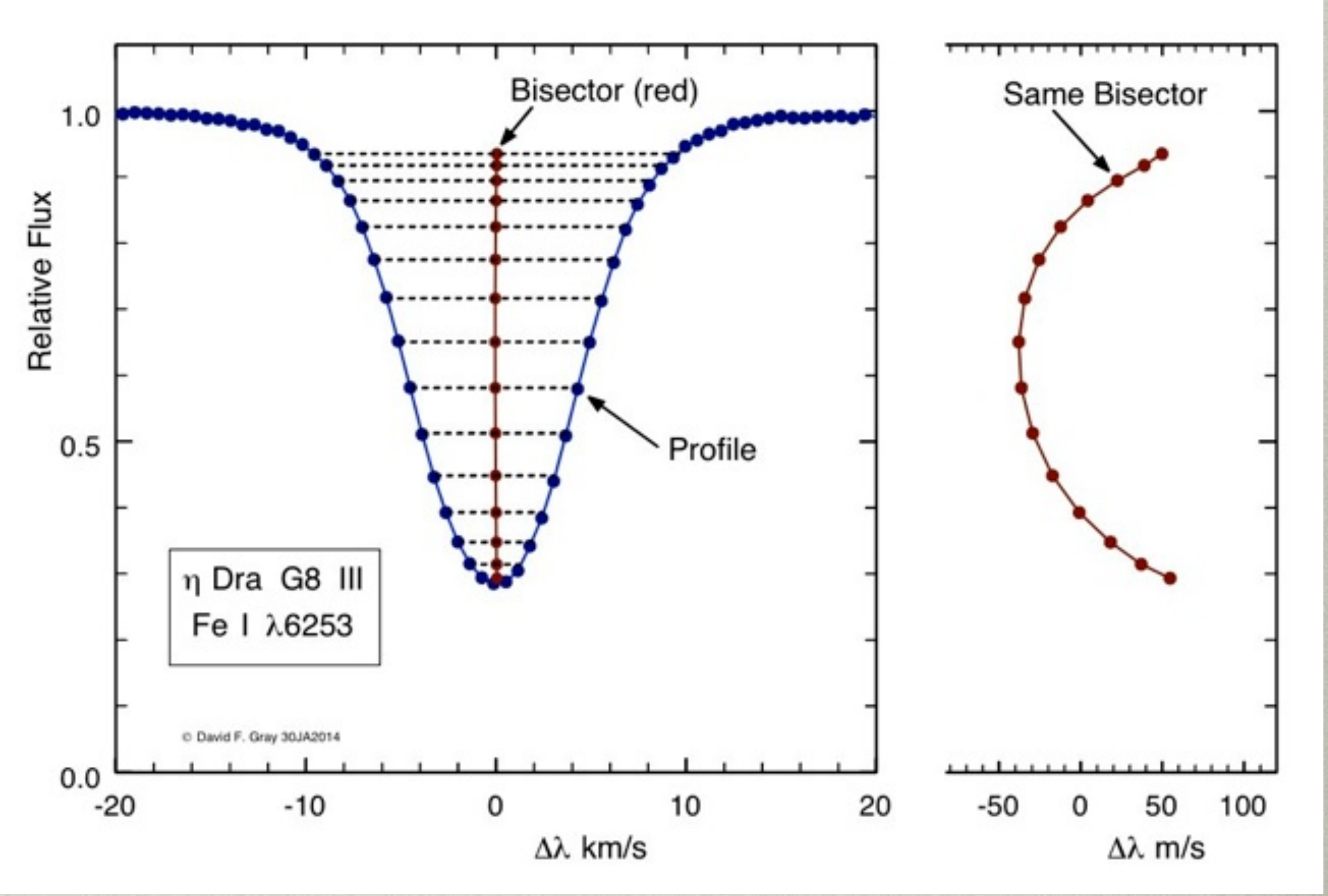
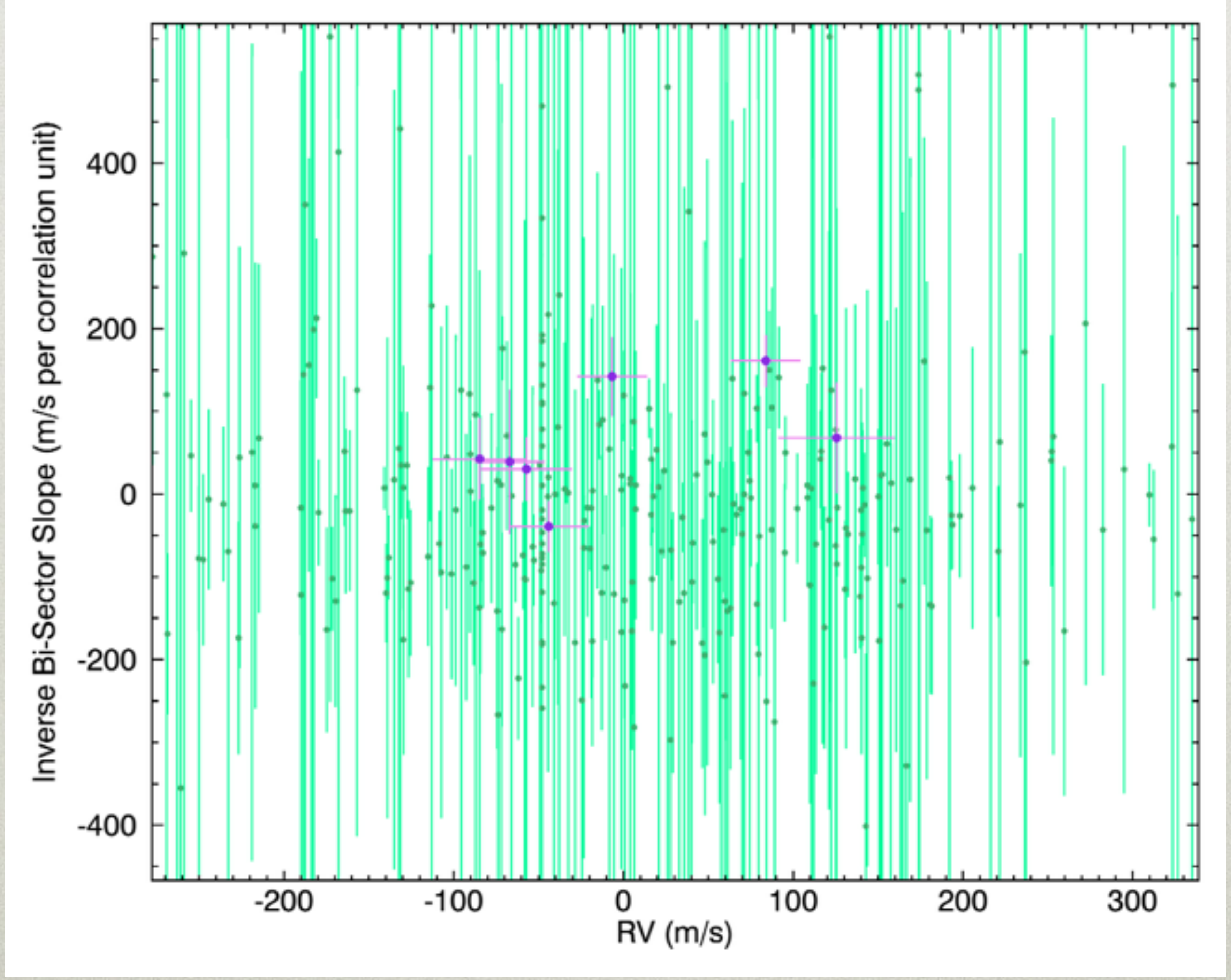


Figure from *The Observation and Analysis of Stellar Photospheres* (D. F. Gray *et al.*, 2005)

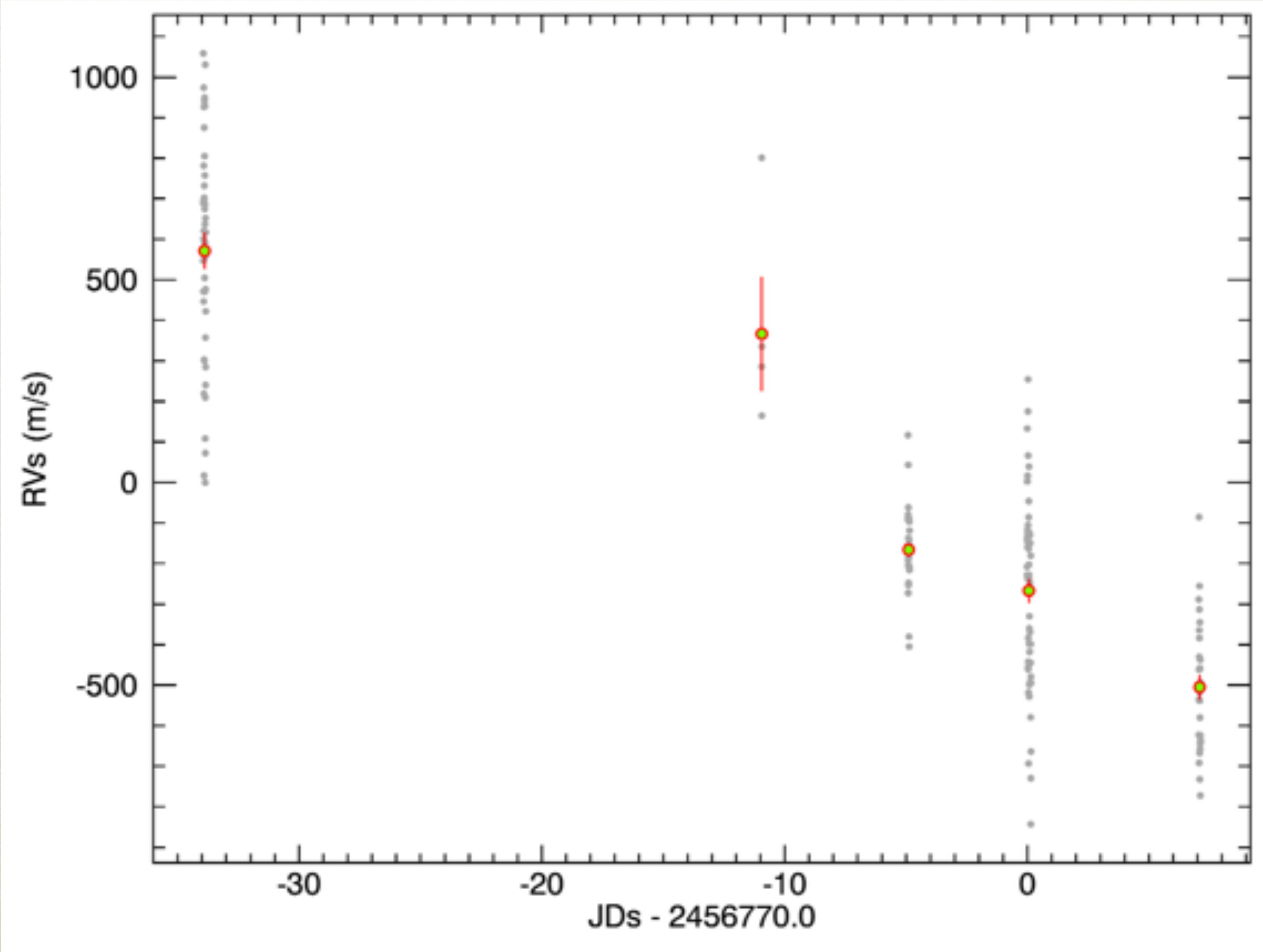
Bi-Sector Analysis



No obvious correlation between bisector slope and RV !

Preliminary Results 32/35

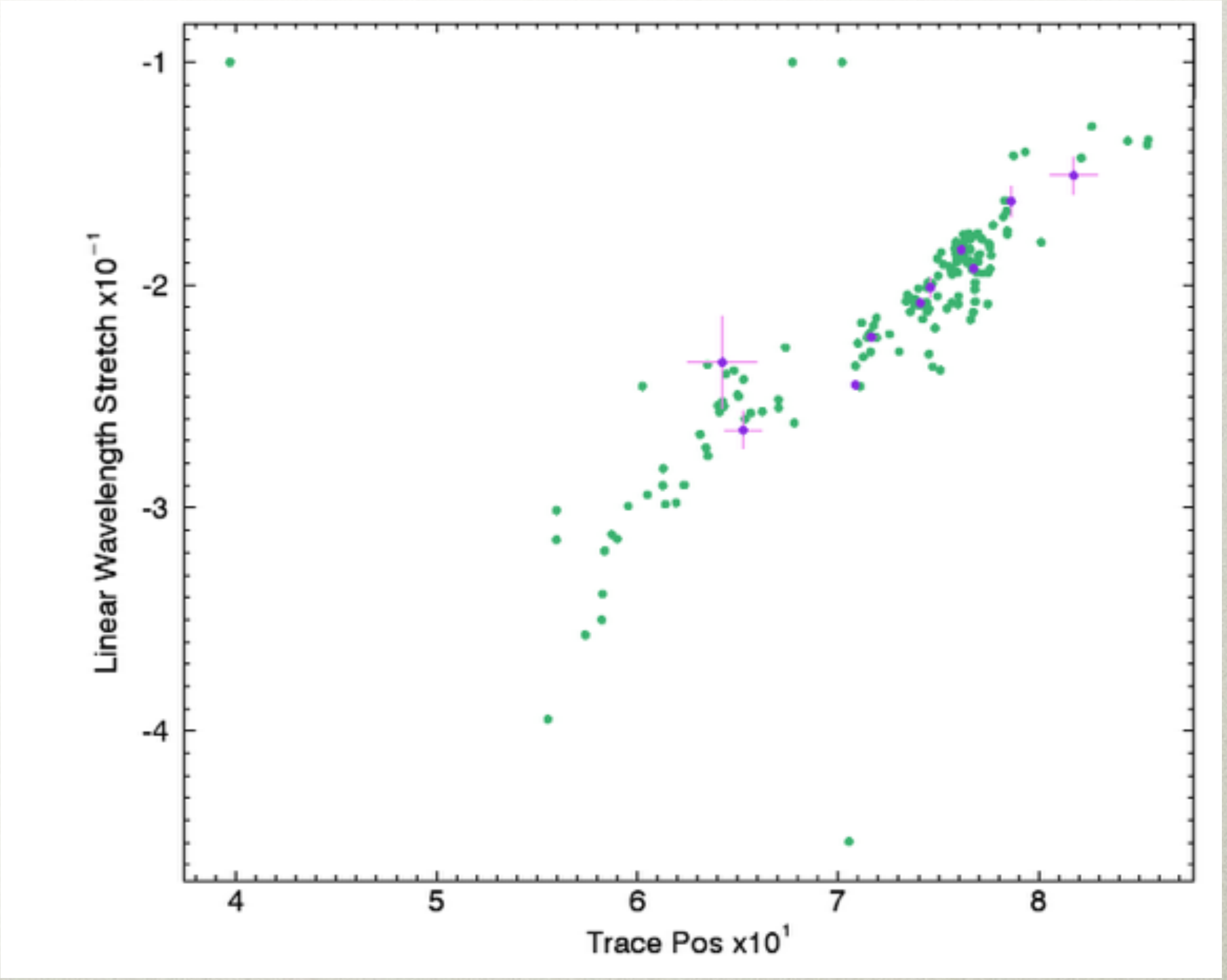
- Another case with a strong linear trend
- Puts a mass constraint of a few M_{Jup} at least
- But we still need to understand the case of the false planet !



Large RV slope for an M0 star !

What's next ? 33/35

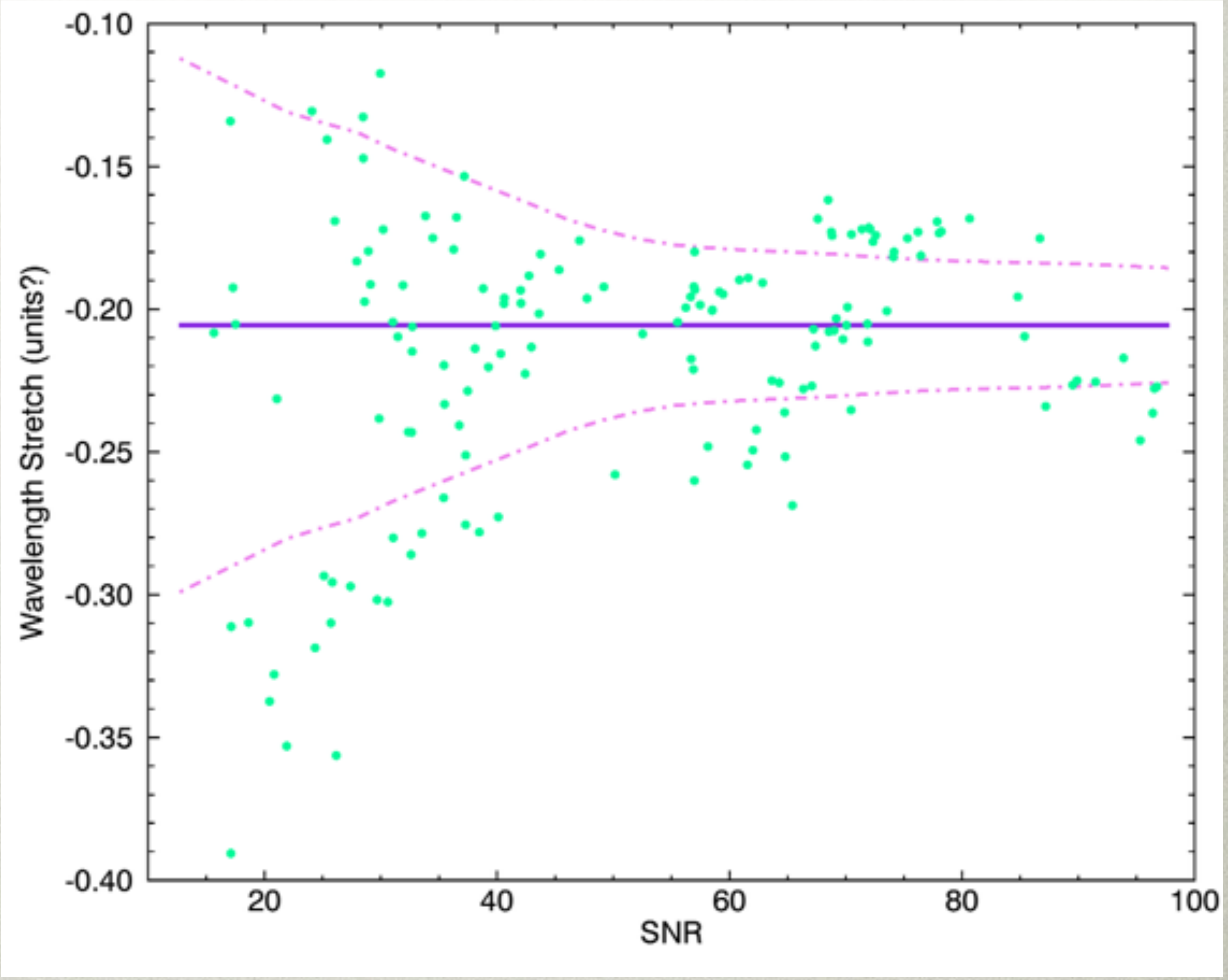
- Implement the wavelength solution VS trace position
- Search for more systematics
- Publish results !



Wavelength solution is strongly correlated with trace position

Wavelength Solution Stability

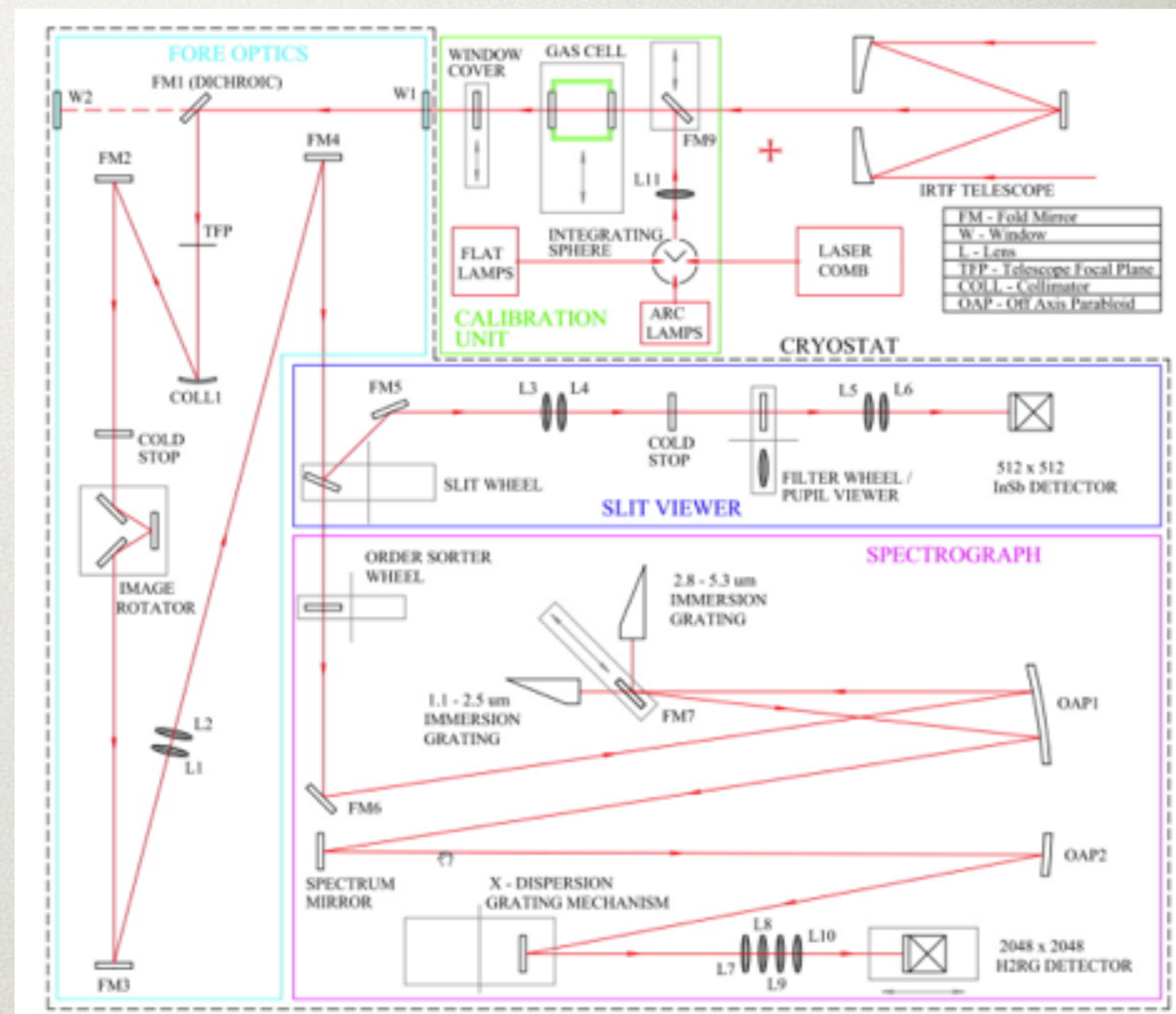
- Our wavelength solution is a 2nd-degree polynomial
- Dispersion (degree 1) not correctly retrieved when S/N too low
- Need to define tight bounds



Dispersion is not well constrained in the low-SNR regime

iShell

- We're doing all this to prepare for iShell !
- Better sensitivity
- R ~ 80,000
- Cross-dispersed
- 2048 x 2048 array
- Best NIR resolution in the Northern hemisphere



iShell optical design

Thanks !

IPAC Fellowship 2014 Talk