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"Planet Formation around Snowline"
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東京大学 THE UNIVERSITY OF TOKYO

TOHOKU UNIVERSITY

High-resolution Spectroscopic Detection of TiO and a Stratosphere in the Day-side of WASP-33b

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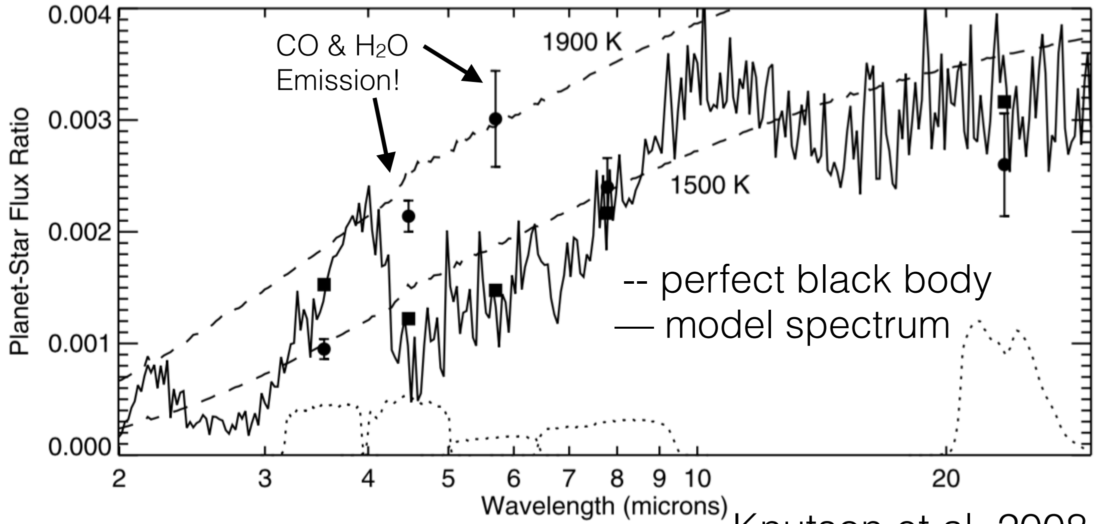
exoclimes.com

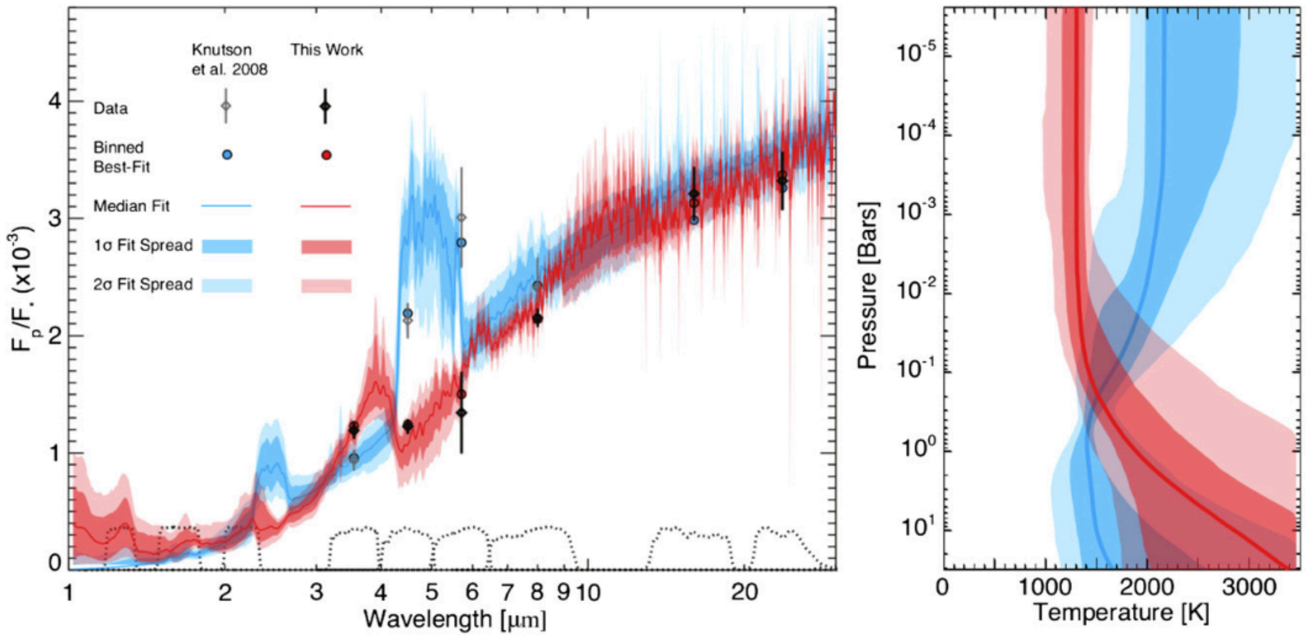
First evidence of inversion layer (or not)

First evidence!
Inversion layer in the day side of HD 209457b's atmosphere



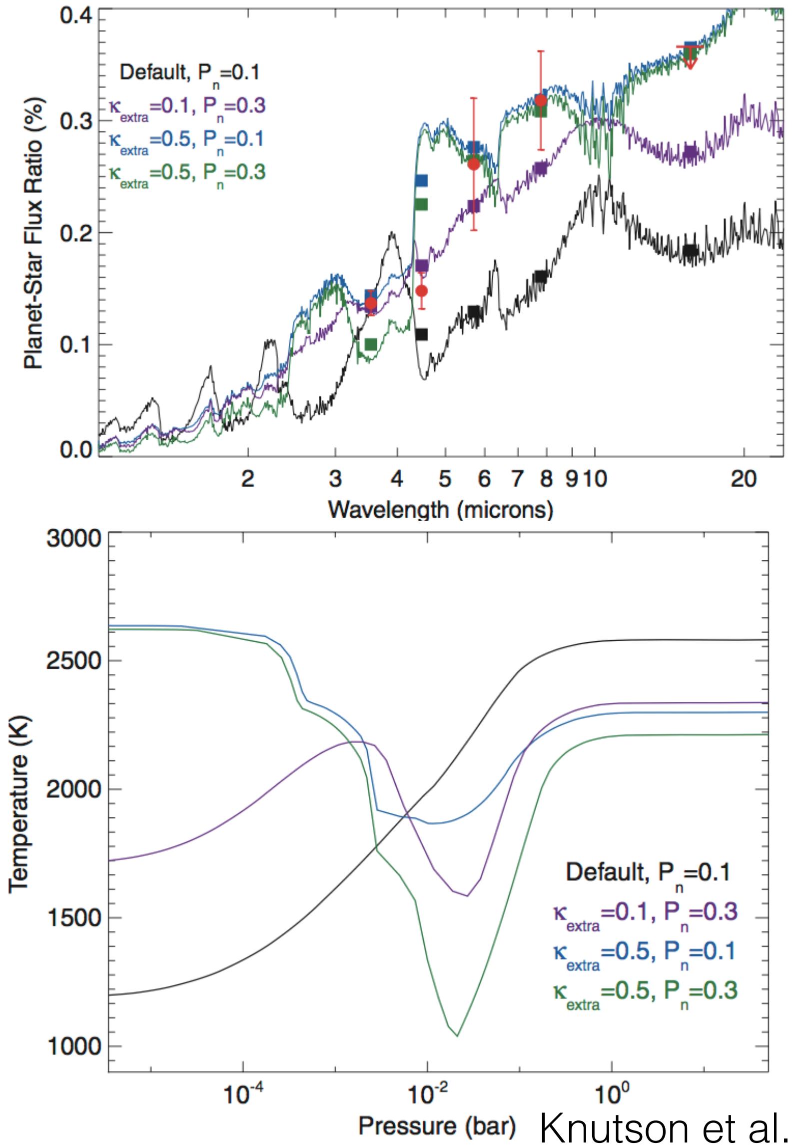
Knutson et al. 2008

But with new version of the data pipeline and latest methodology, Diamond-Lowe et al. 2014 reported no inversion in HD 209458b atmosphere

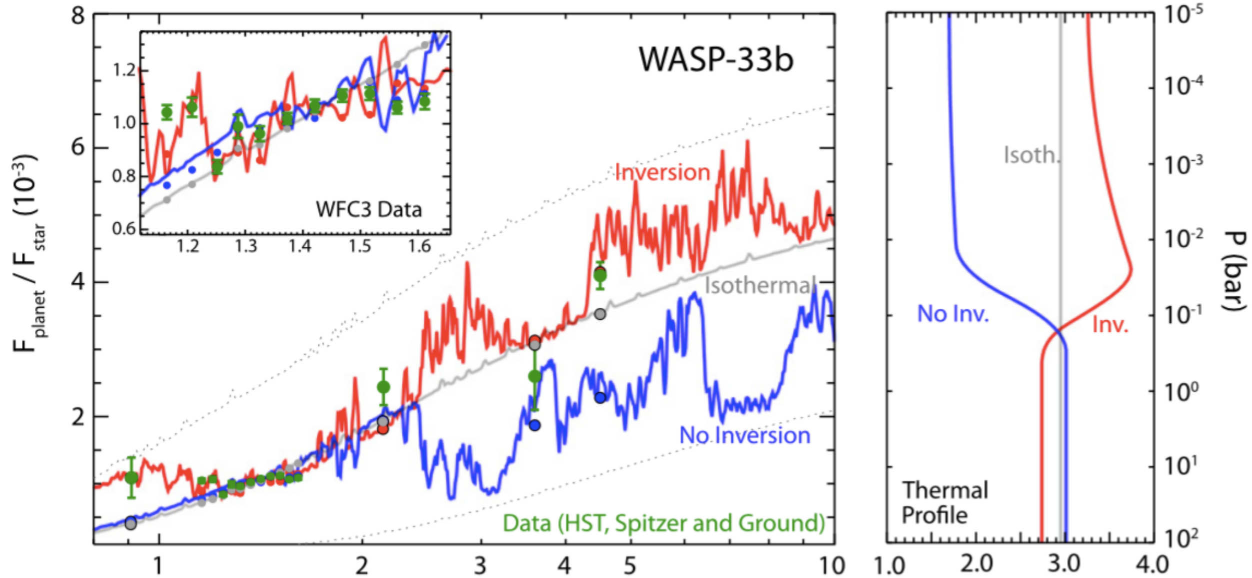


More Evidences from Spitzer and HST Observation

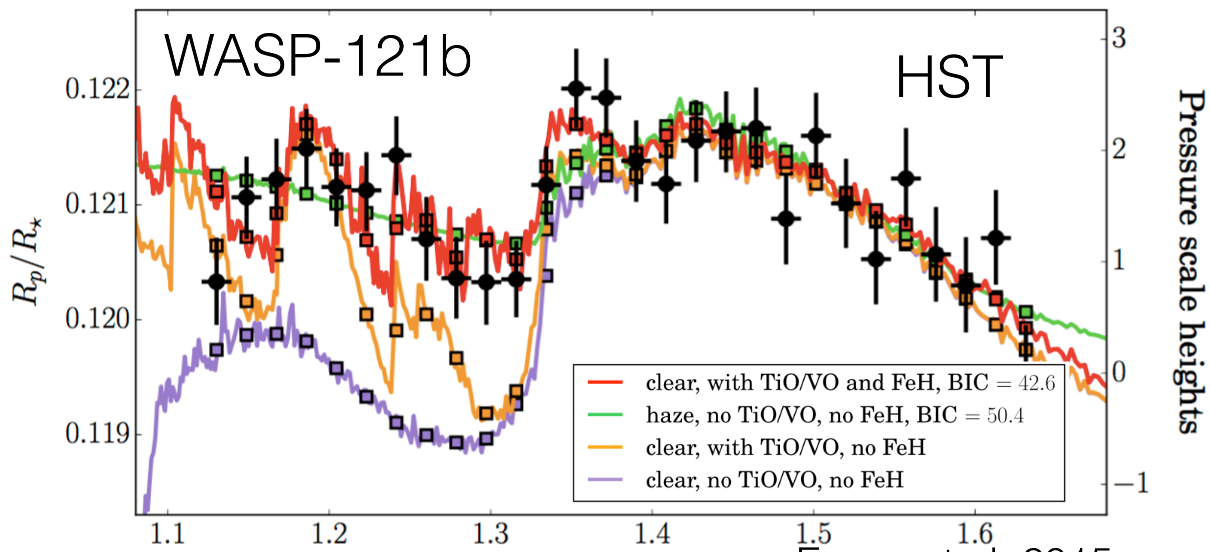
TrES-4b



Knutson et al.



Haynes et al. 2015

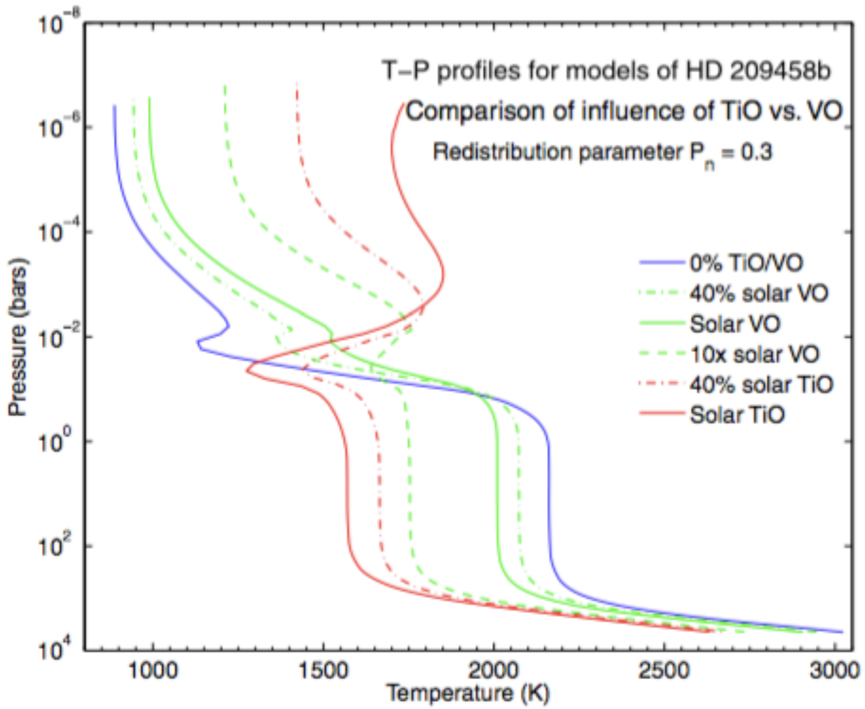


Wavelength (μm)

Evans et al. 2015

No direct detection of TiO/VO, can TiO/VO really explains temperature inversion?

Theoretical study

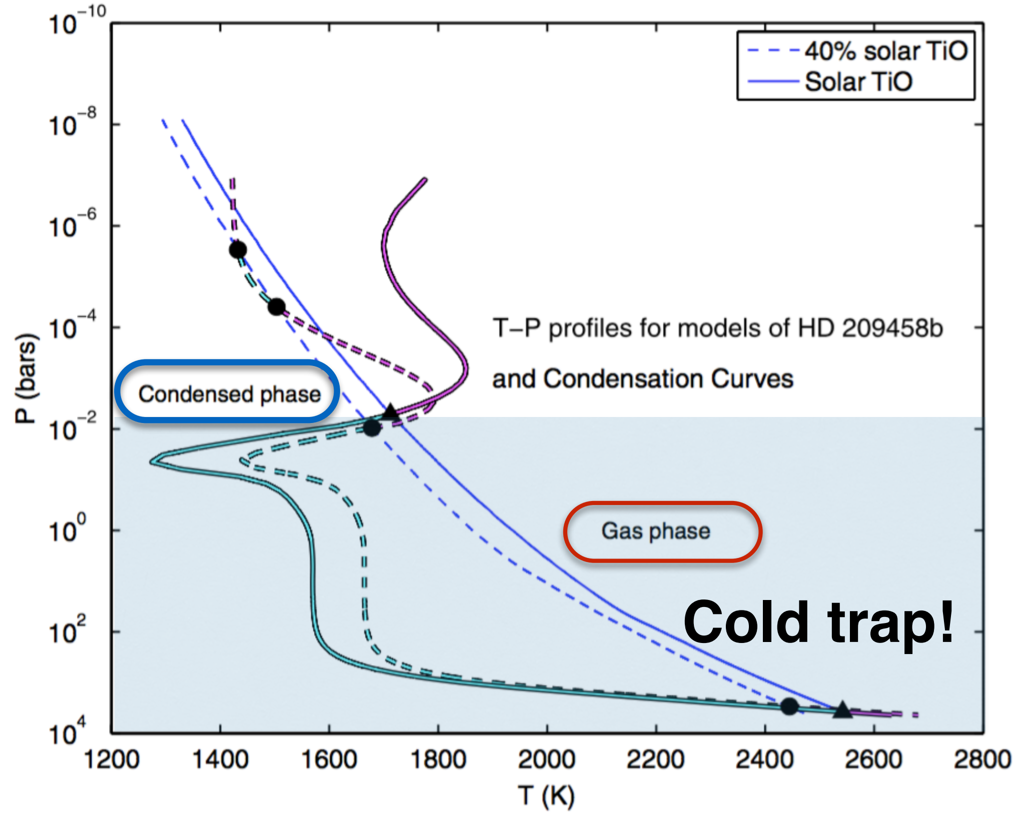


log VMR_{TiO}= -7

log VMR_{VO}= -8 (Anders & Grevesse 1989)

Spiegel et al. 2009

For moderate temperature Hot Jupiters..



Spiegel et al. 2009

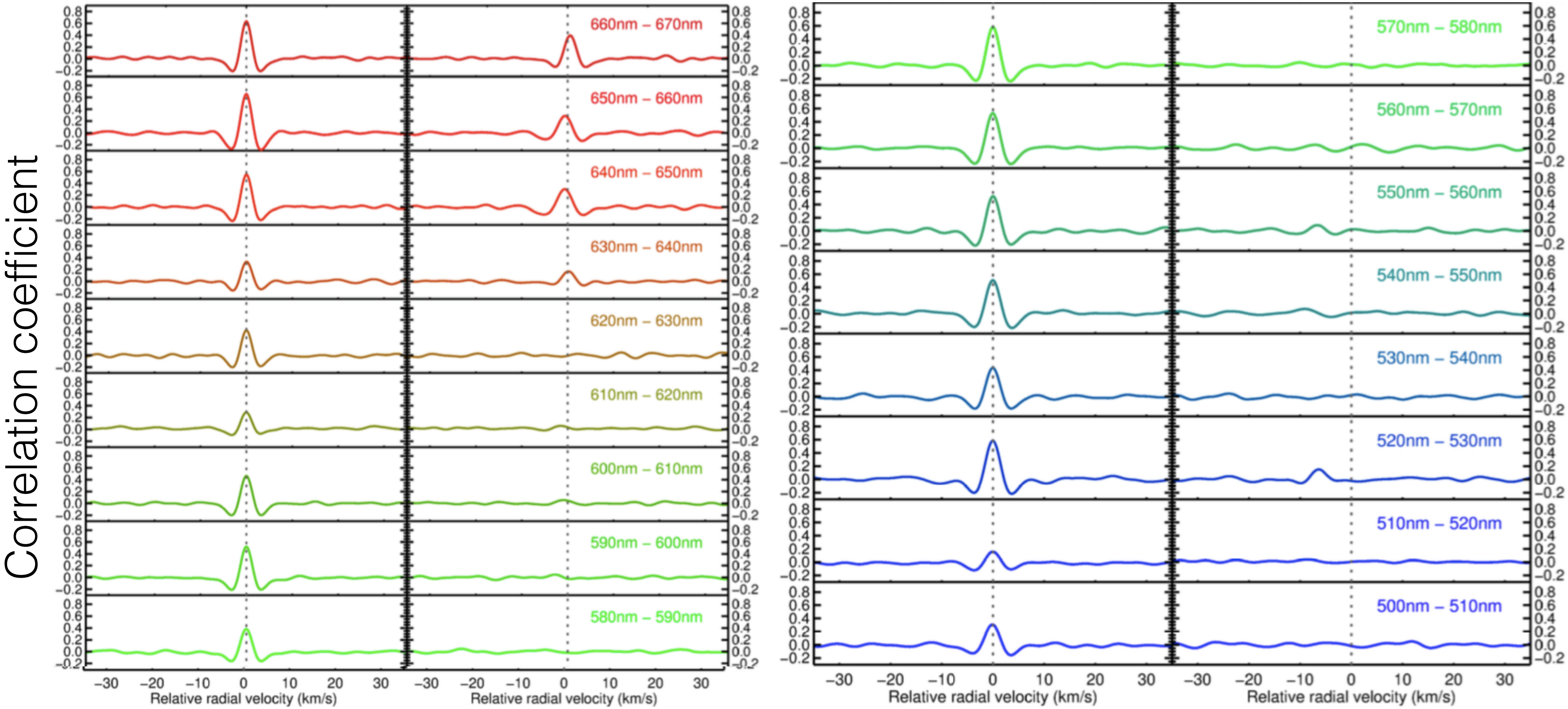
TiO Direct Detection Trial using HDS

Checking the model

Inaccuracies in the line database!

TiO-PHOENIX TiO-Barnard

TiO-PHOENIX TiO-Barnard



>630 nm, the TiO template appears to match the data better, increasing in correlation toward longer wavelengths

Hoeijmakers et al. 2014

Challenges

1. Spitzer data result is controversial. The Spitzer bands are overlapping with each other make it extremely difficult to get the independent flux.
2. Cold trap exists in the moderate temperature Hot Jupiters
3. Active host stars might have destroyed the compound that responsible for the thermal inversion
4. The line list of TiO has inaccuracy issue

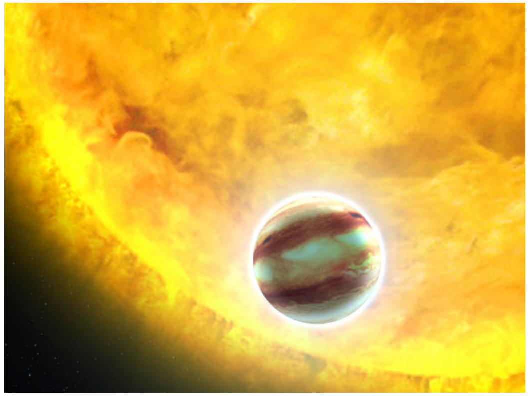
WASP 33 b orbiting WASP 33 (Delta Scuti star)

2015 October 26 and 27 HST
Using HDS in Subaru telescope (PI: H. Kawahara)

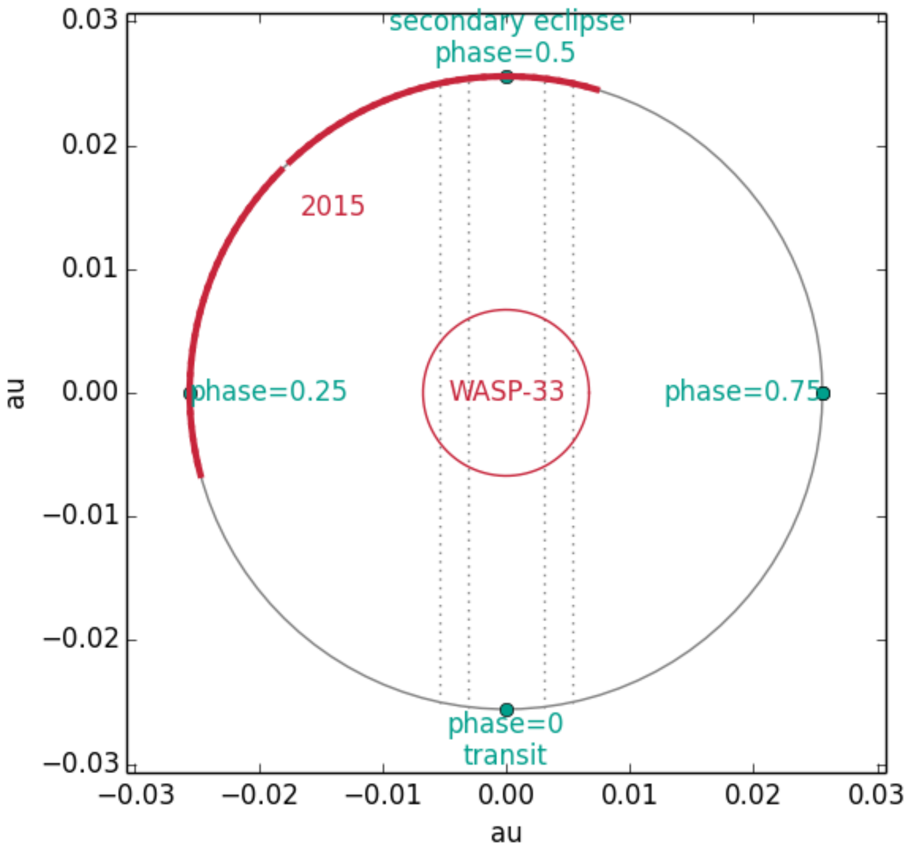
Image slicer #3 (slit width= 0.”2 each) was used to get the highest spectral resolution of R~165,000 and to maximize the throughput.

18 orders covering **6170-7402 Å (Blue CCD)**
12 orders covering **7594-8817 Å (Red CCD)**

52 spectra of WASP 33 @$t_{exposure}$= 600 s
6 spectra of HD 13041 @$t_{exposure}$= 200 s
2 spectra of Barnard star @$t_{exposure}$= 600 s
5 spectra of HD 95735 @$t_{exposure}$= 300 s



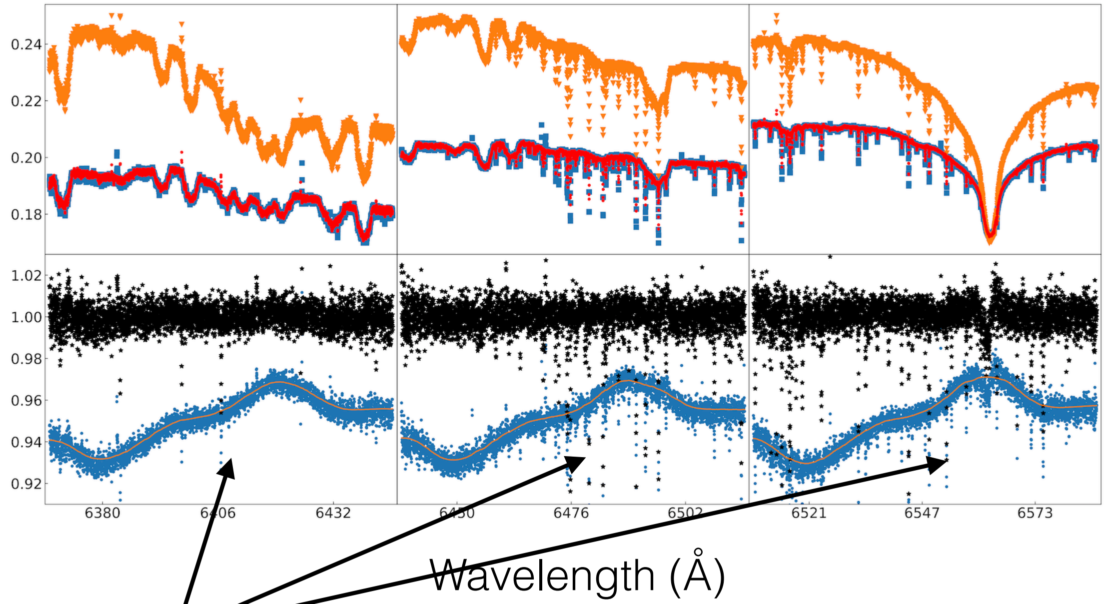
The orbital phase of WASP-33b that covered by our observation.



Data Reduction

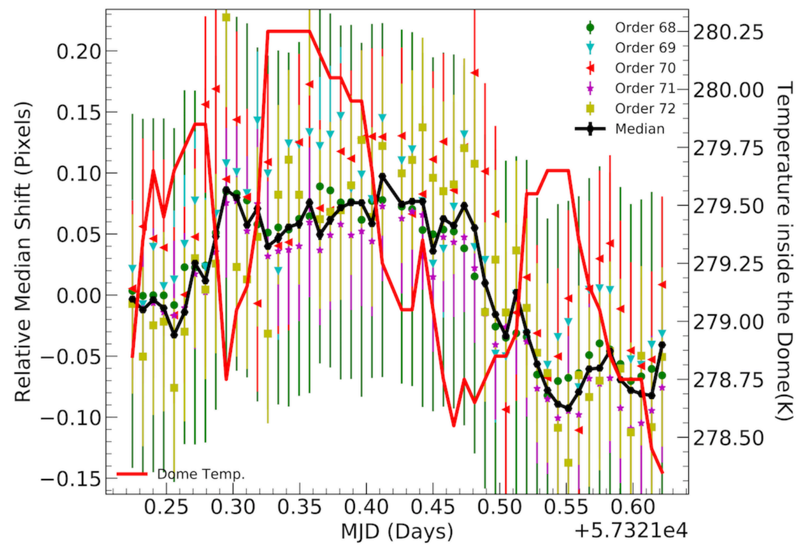
Standard reduction using IRAF and custom build CL script to extract 1D spectrum

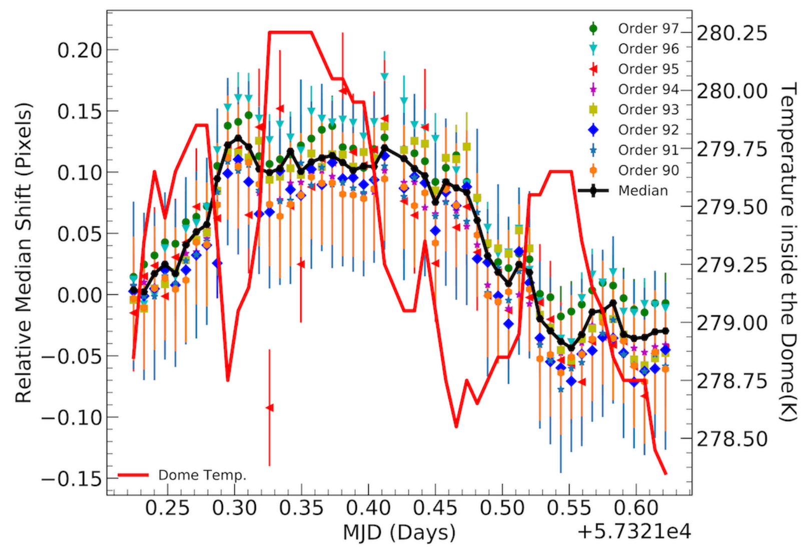
Blaze function variation



Similar pattern

Wavelength shift during observation

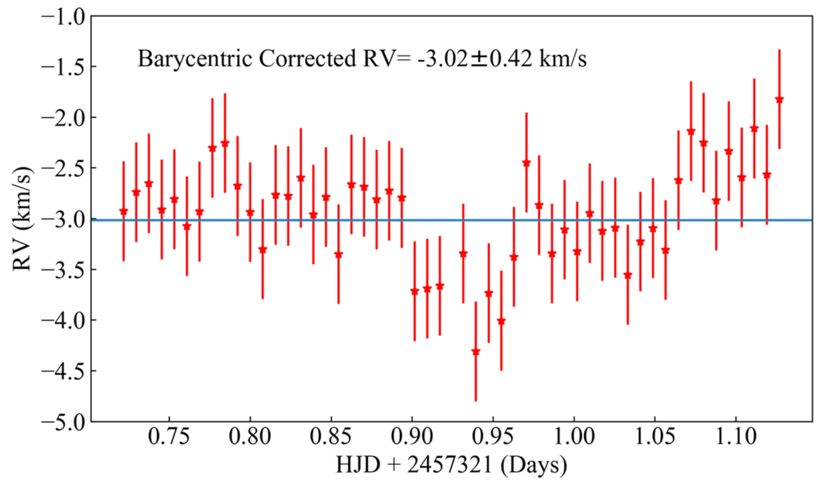




Checking RV of WASP-33 and the Accuracy of TiO Line List

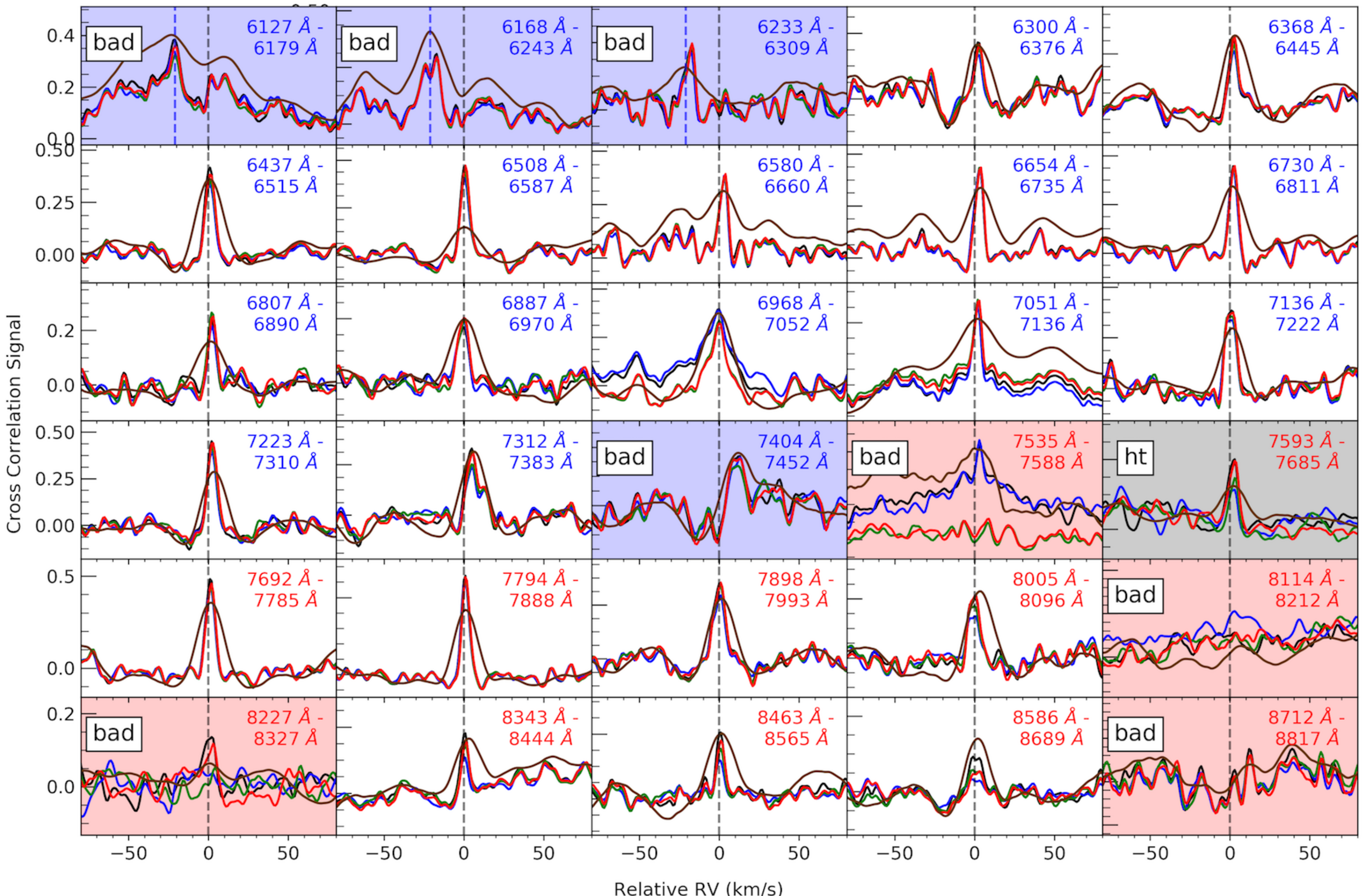
RV of WASP-33
Cross correlate blue CCD WASP-33 spectra with model spectrum from Coelho (2014) with:

Teff = 7500 K, log g= 4.5, [Fe/H]= +0.2, and [α/Fe] = 0.



Accuracy of TiO line list
Cross Correlating WASP 33 b TiO Model Template vs M type stars

Checking RV of WASP-33 and the Accuracy of TiO Line List



Removal of Telluric and Stellar lines by SYSREM (Tamuz et al. 2004)

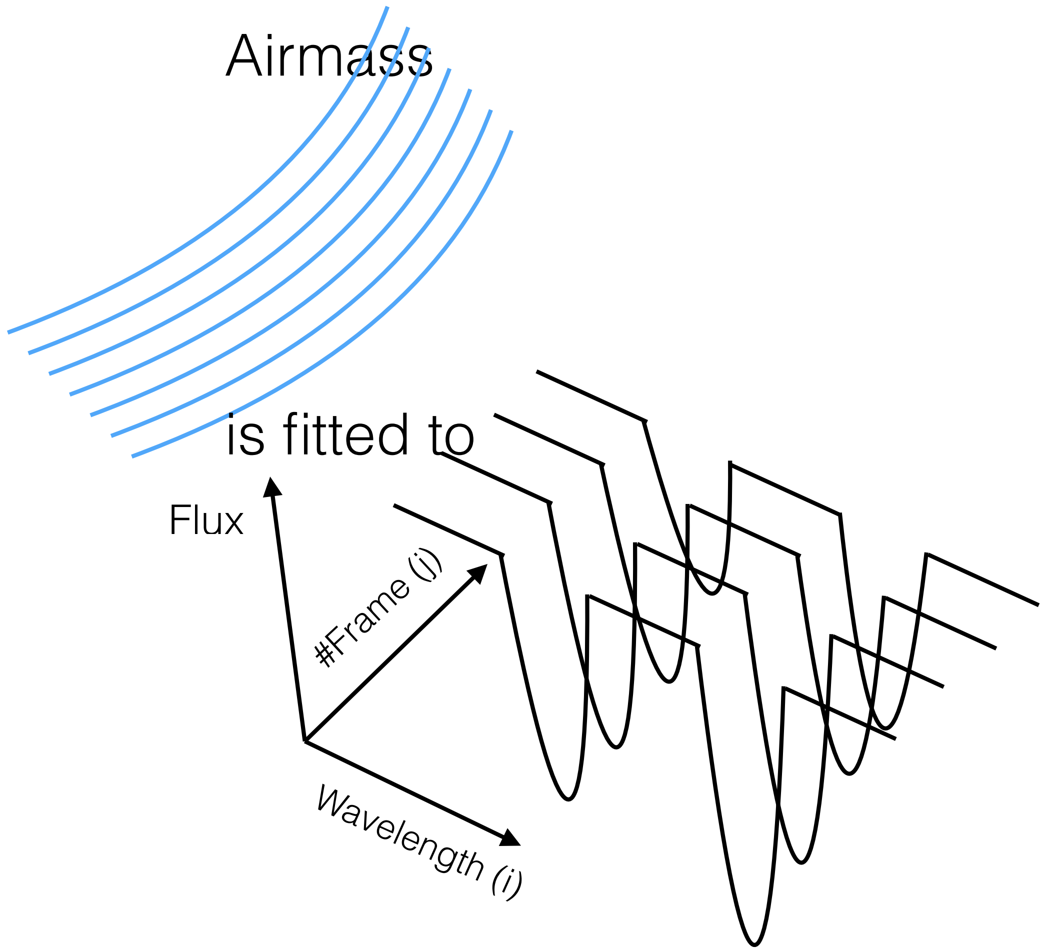
For N light-curves (stars), each consists of M measurements

Find "optimum $\mathbf{c_i}$ $\{c_i; i = 1, N\}$ and $\mathbf{a_j}$ $\{a_j; j = 1, M\}$ that minimize:

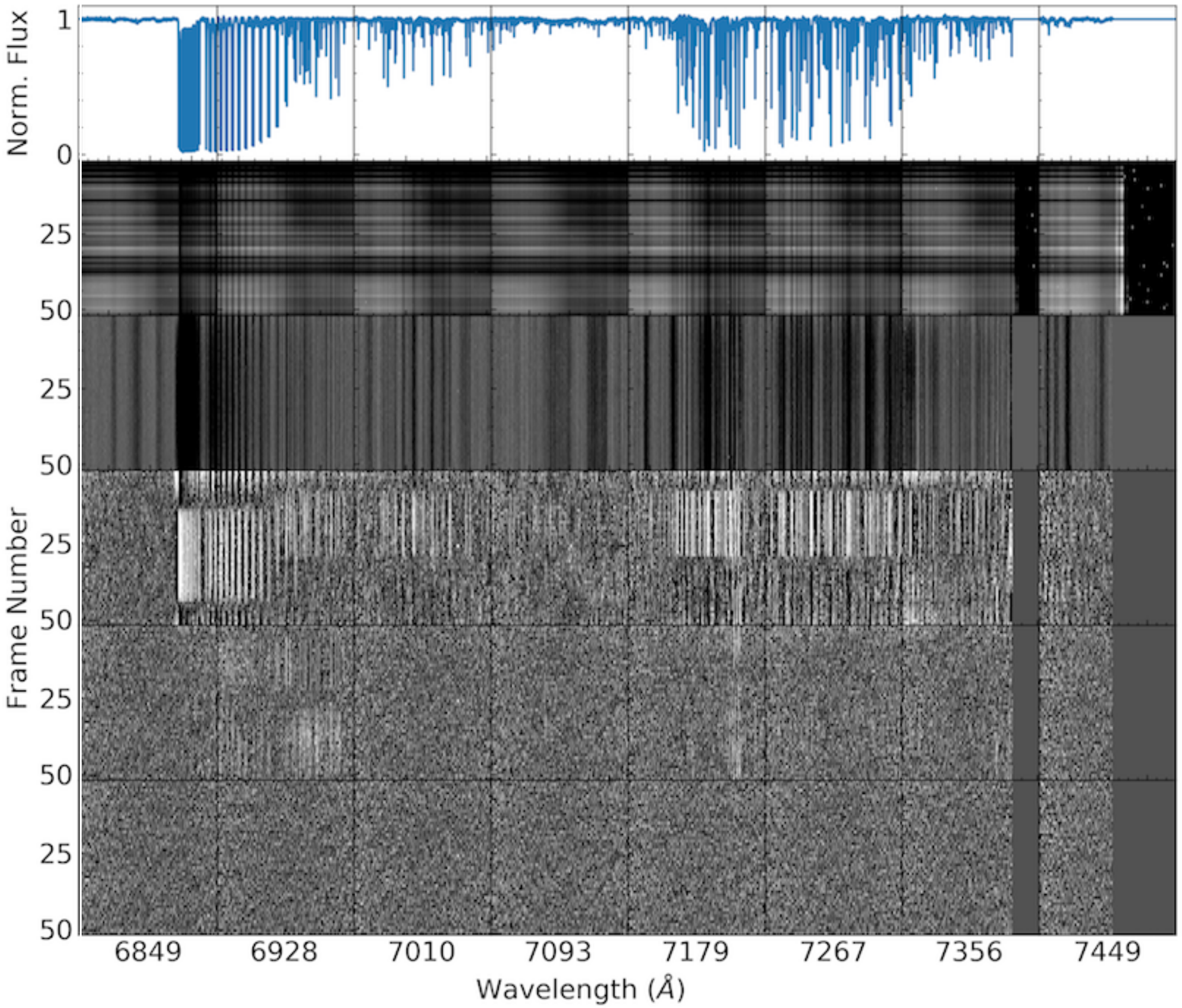
$$R^2 = \sum_{ij} \frac{(r_{ij} - c_i a_j)^2}{\sigma_{ij}^2}$$

$\mathbf{r_{ij}}$= average-subtracted stellar magnitude
$\mathbf{c_i}$= best linear fit slope (extinction coefficient) for *i* light-curve
$\mathbf{a_j}$= airmass at *j*

The prior is the known airmass



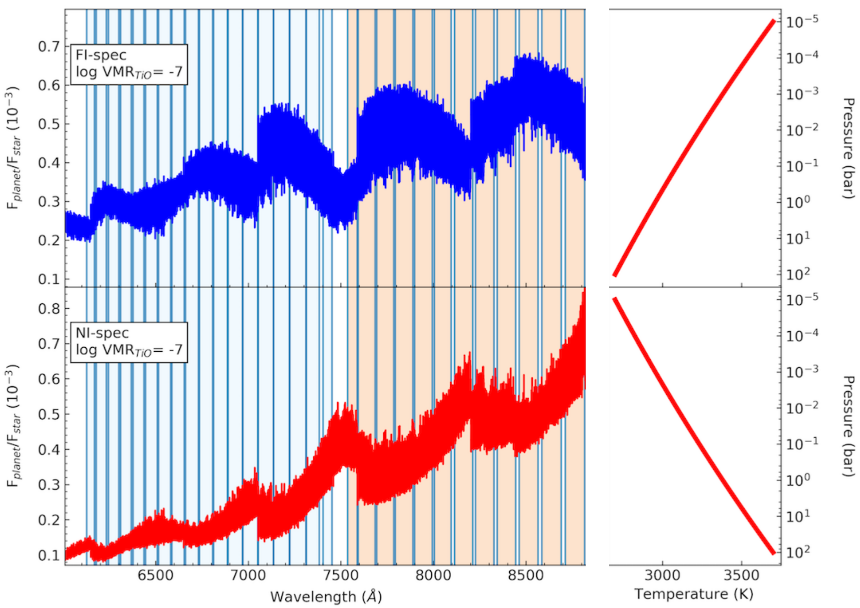
Applying SYSREM to Our Data



- 1D normalized data
- Raw data
- After the a function variation correction and the common wavelength grid iteration
- The mean subtracted spectra as the input to SYSREM.
- The residual spectra after running 1 SYSREM iteration
- The residual spectra after running 4 SYSREM iteration

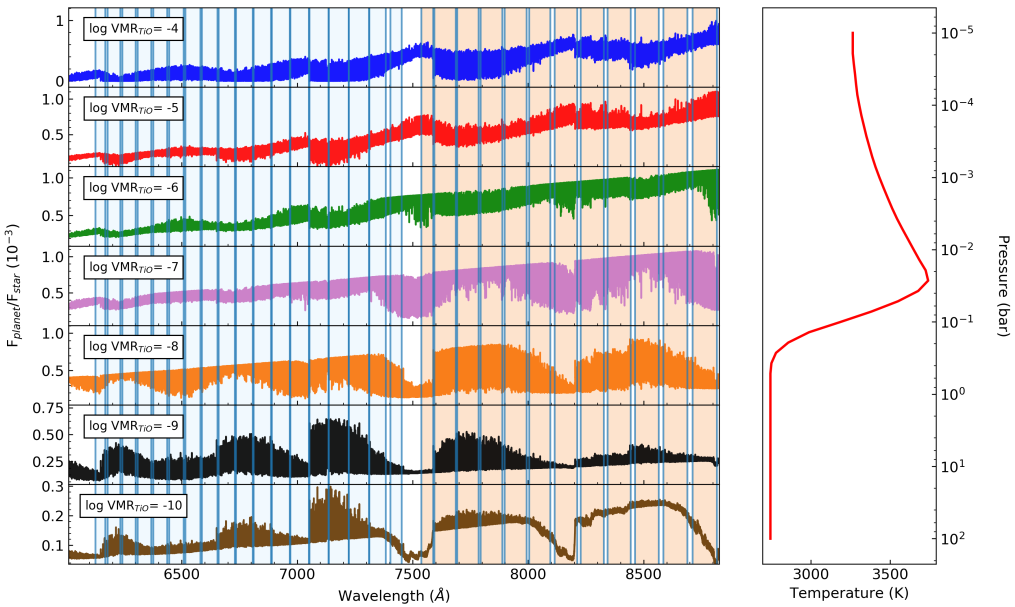
WASP-33b Model Spectrum

Using TiO line list from Plez 1998
Calculate the cross section using Py4CATS-> combined into absorption coefficient->integrated along the line of sight through the atmosphere



Full inversion model (FI-spec)

Non inversion model (NI-spec)

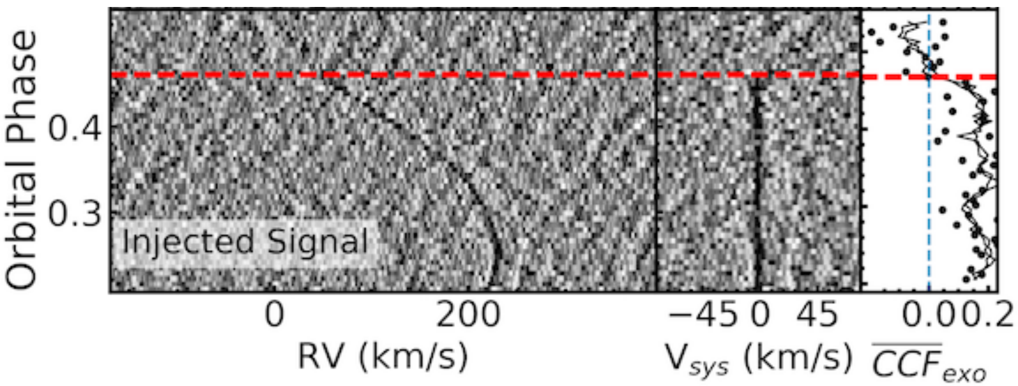


Haynes et al. 2015 model (H-spec)

Cross Correlation of Residual with Spectral Template

Cross-correlated with the Doppler shifted model spectrum covering

-169.69 km/s $< RV_p <$ $+393.30$ km/s with 0.5 km/s step



The CCF of the frames (40 frames in total, **excluding** the frames when WASP-33b in **the secondary eclipse phase**) are integrated along the expected RV_p curve

$$\mathrm{RV_p}(t) = K_\mathrm{p} \sin(2\pi\phi(t)) + V_\mathrm{sys} + v_\mathrm{bary}(t)$$

$$\phi(t) = \frac{t - T_0}{P},$$

for

The planet semi amplitude

$+150$ km/s $< K_p <$ $+310$ km/s

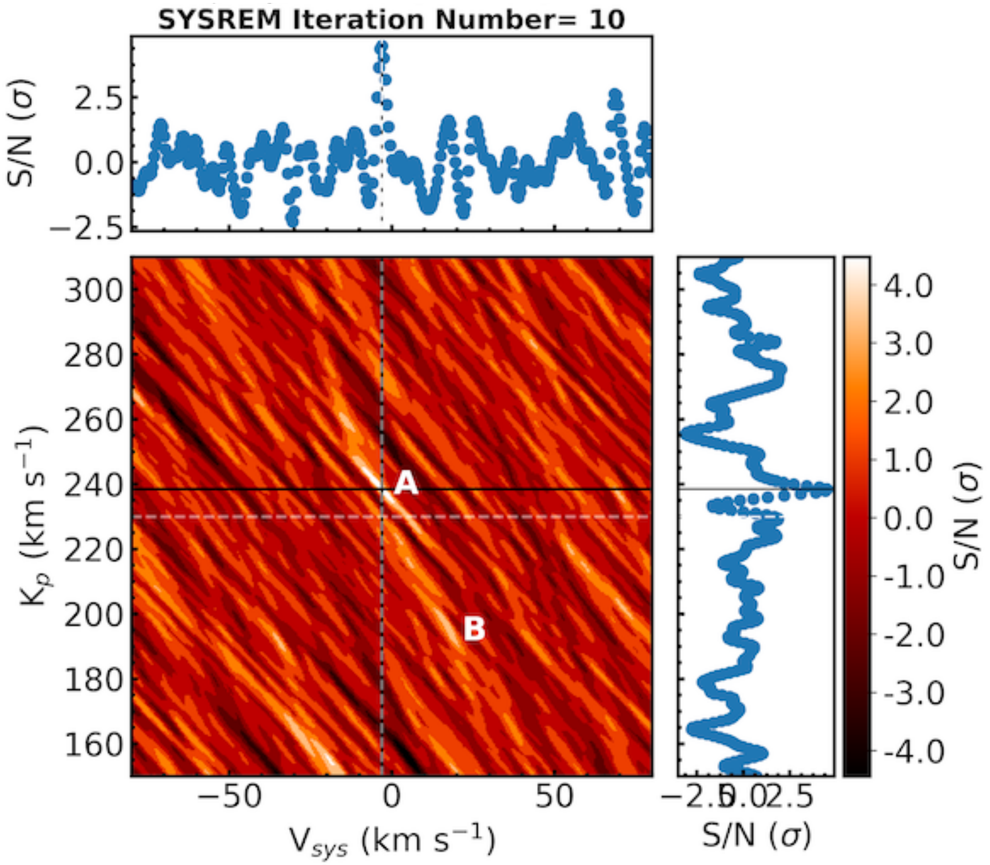
The systemic velocity

-80 km/s $< V_{sys} <$ $+80$ km/s

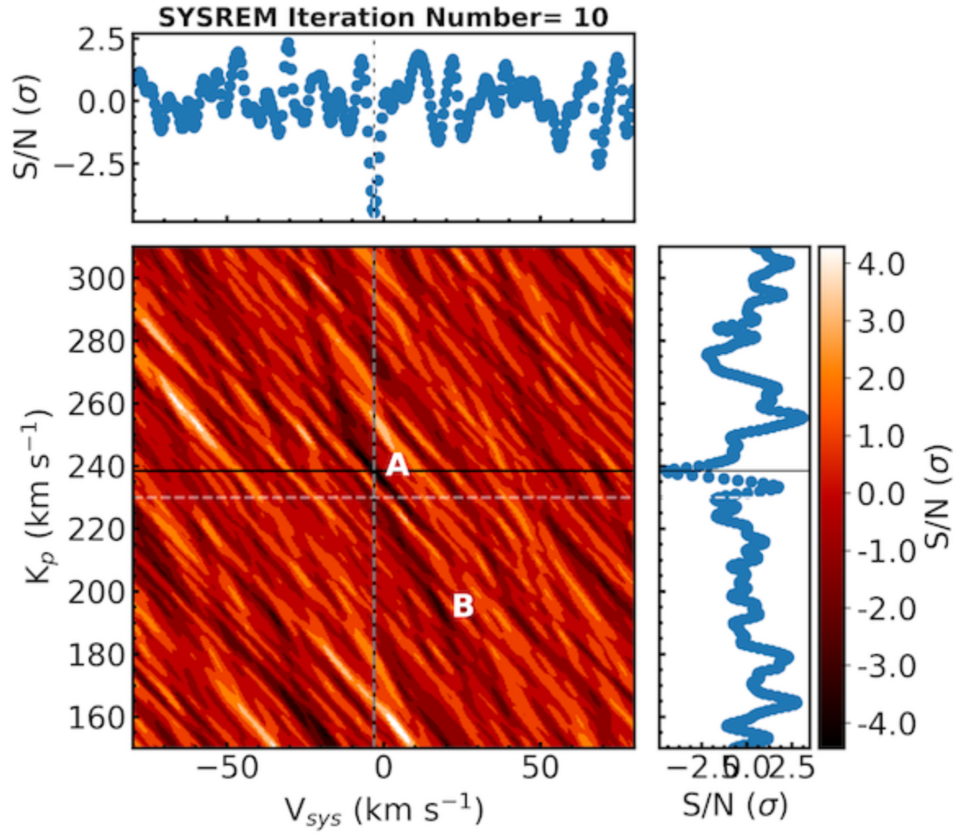
with 0.5 km/s steps

TiO Signal Detection

With FI spec



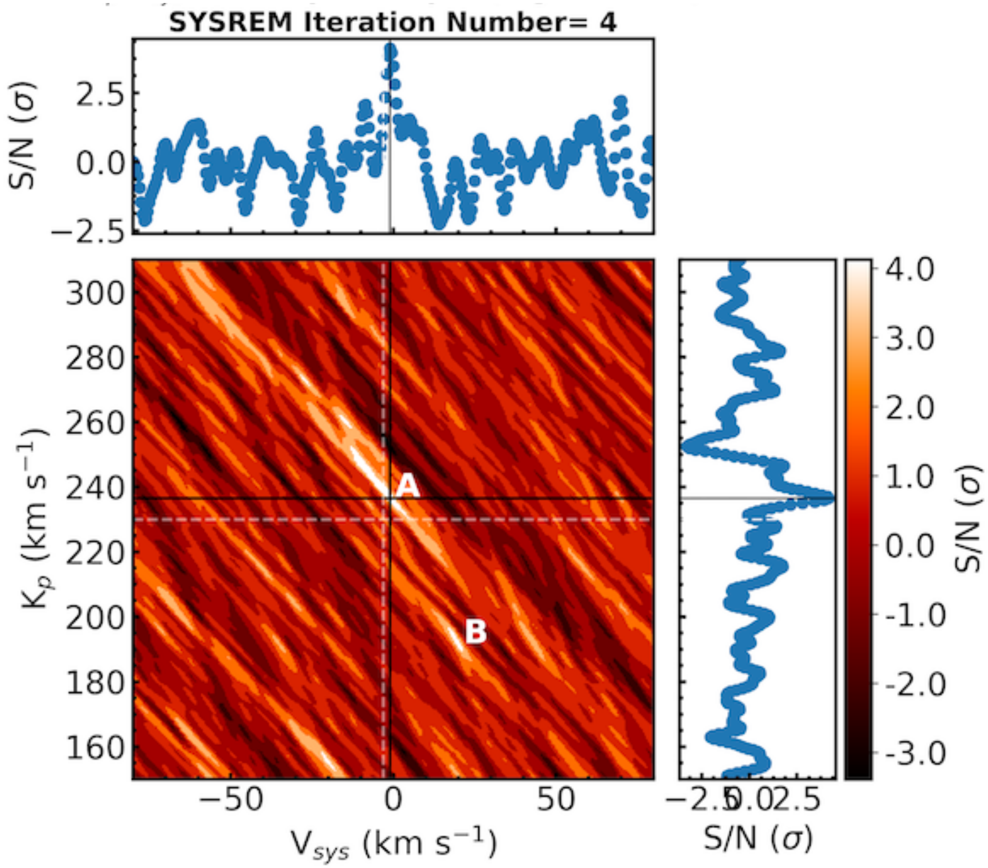
With NI spec

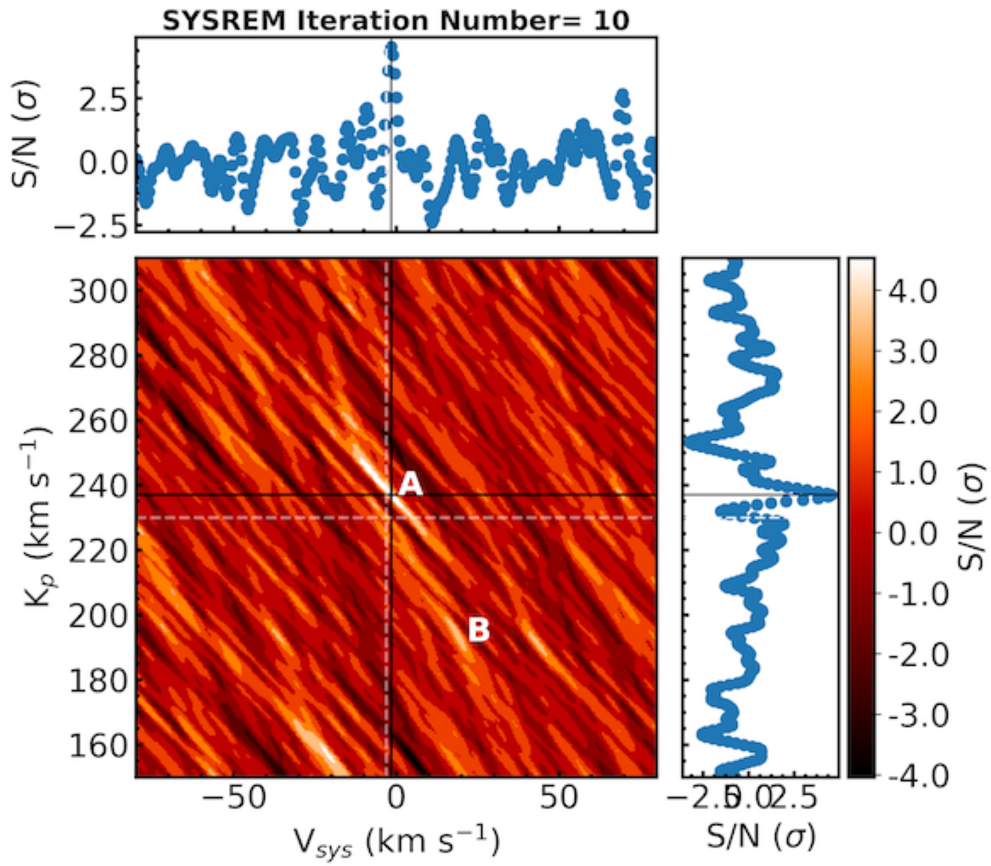


Evidence of emission spectrum -> stratosphere!

TiO Signal Detection

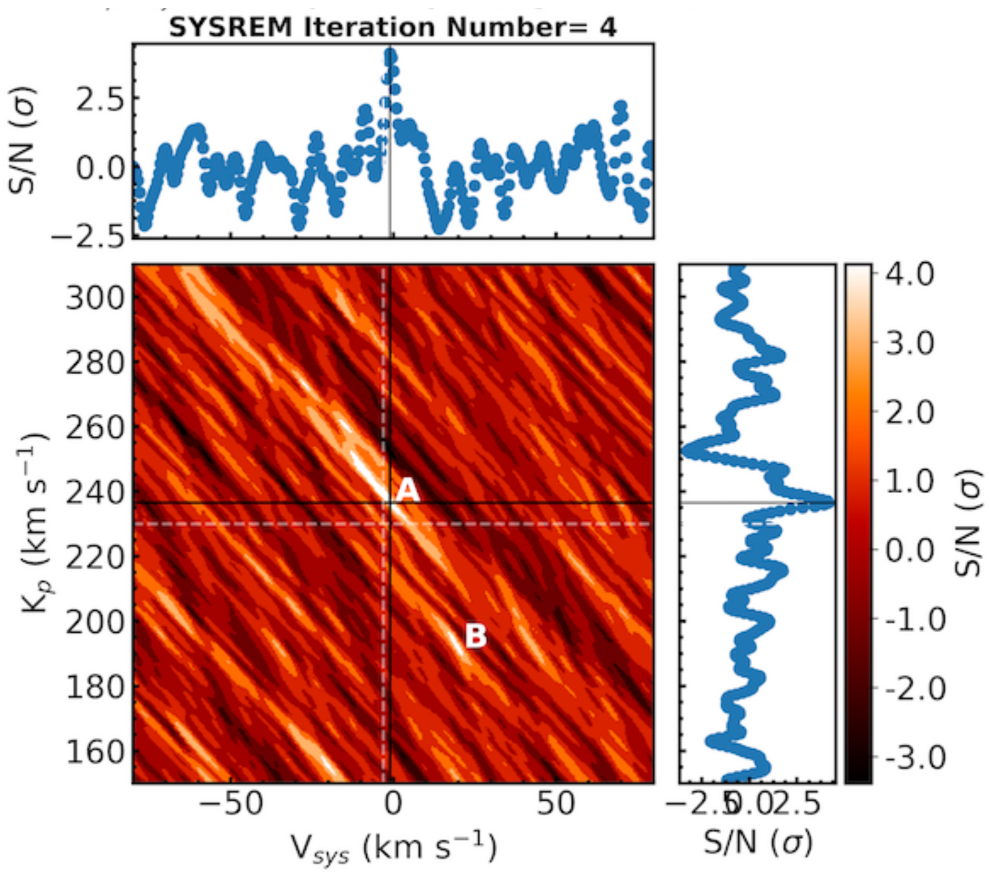
With H spec

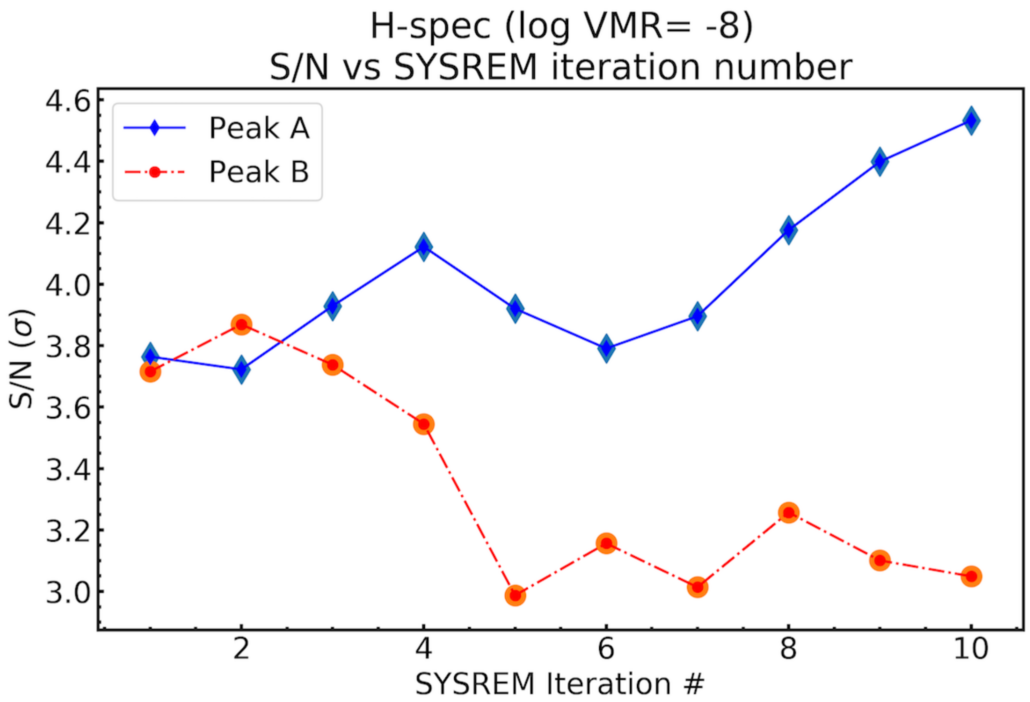




TiO Signal Detection

With H spec





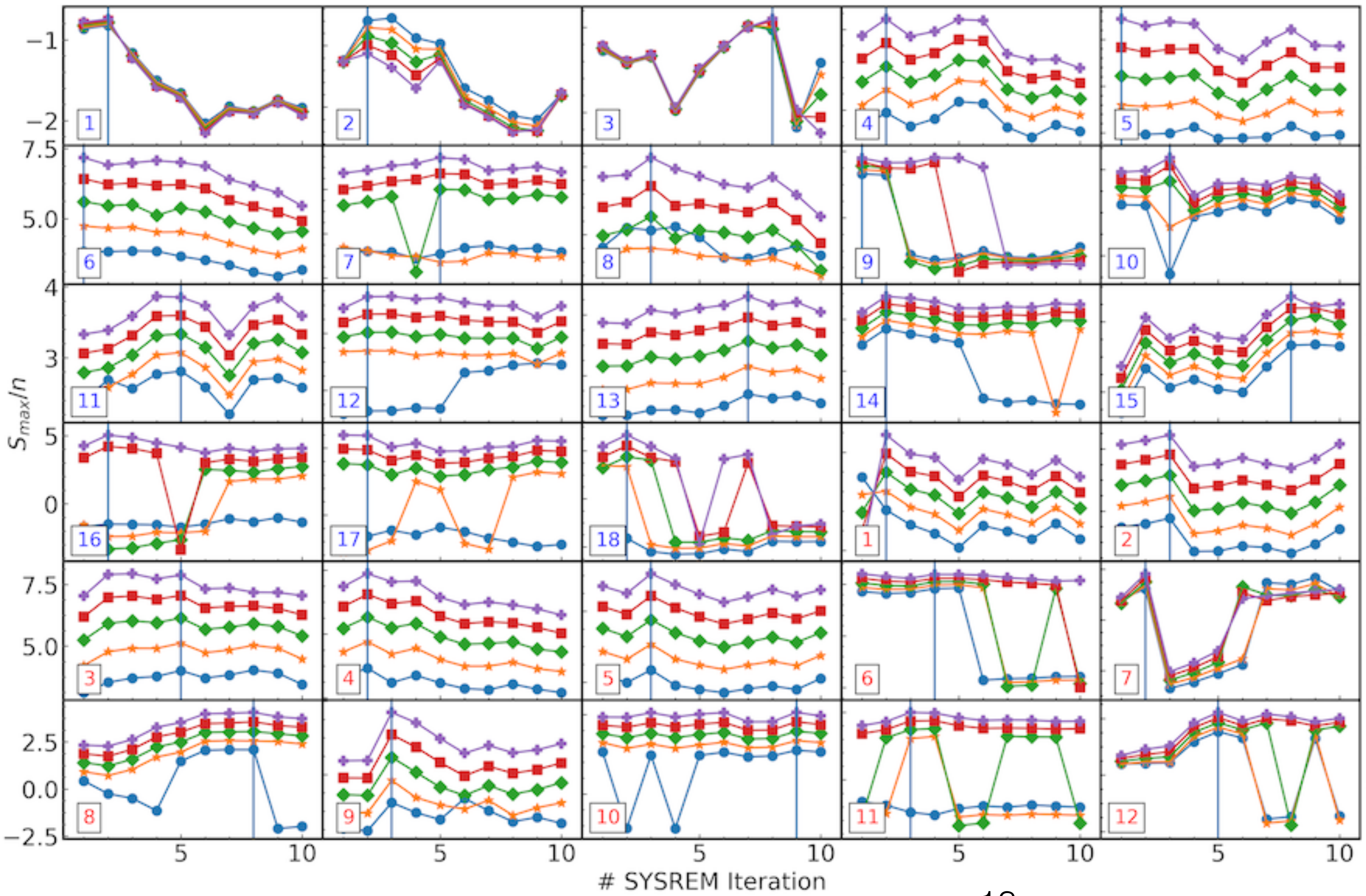
Order-based SYSREM Optimization

Inject the scaled artificial signal with different sc (scaling constant)

$$F_{\text{scaled pm}}(\lambda) = sc \times \frac{F_{\text{pm}}(\lambda)}{F_{\text{star}}(\lambda)} \left(\frac{R_{\text{p}}}{R_{\text{star}}} \right)^2$$

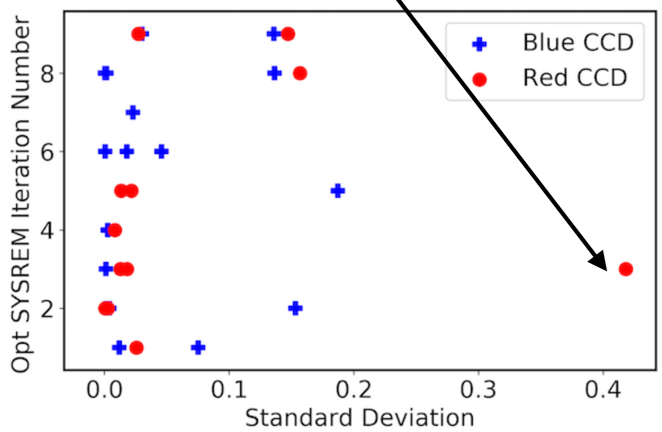
→ Planet to star flux contrast

sc= [20%, 40%, 60%, 80 %, 100 %]

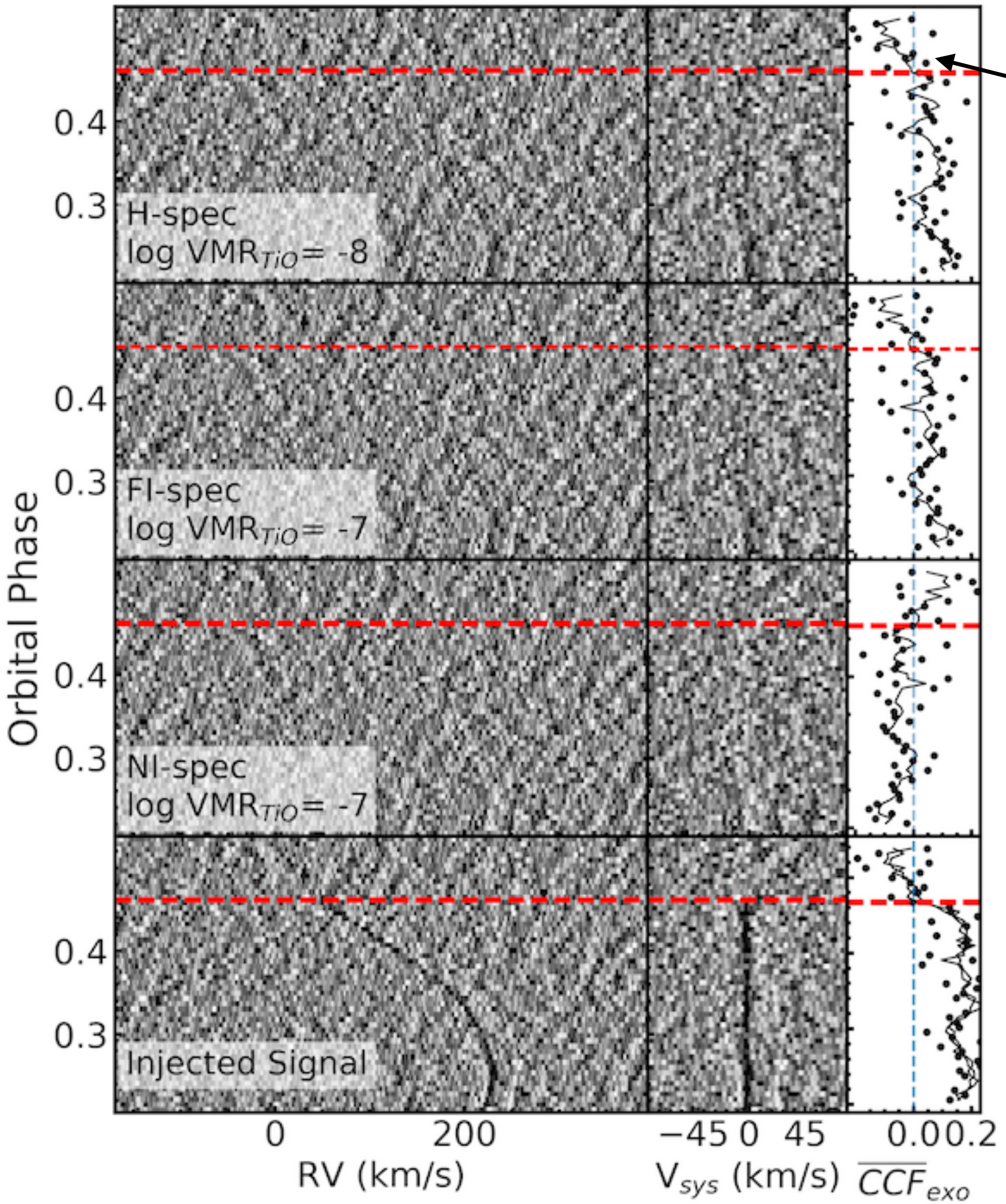


Order 2 of Red CCD

Forest of O_2 Telluric lines

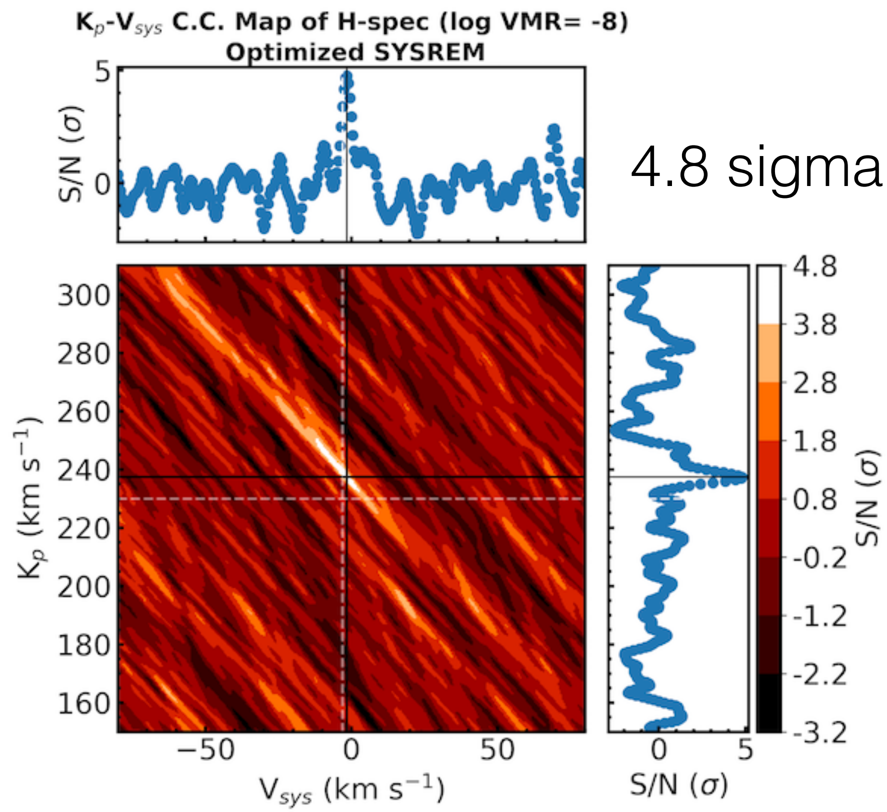


Final result



No signal during the secondary eclipse phase

Signal near the secondary eclipse should be stronger but it is not because of the smearing effect

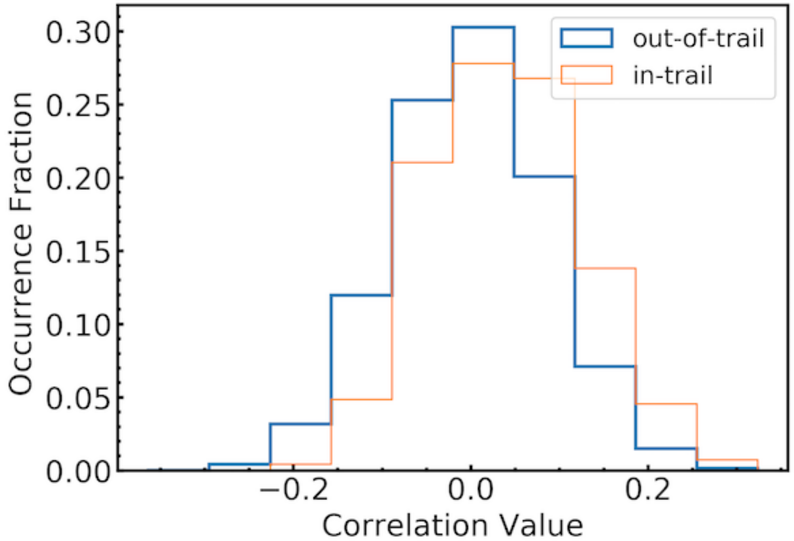


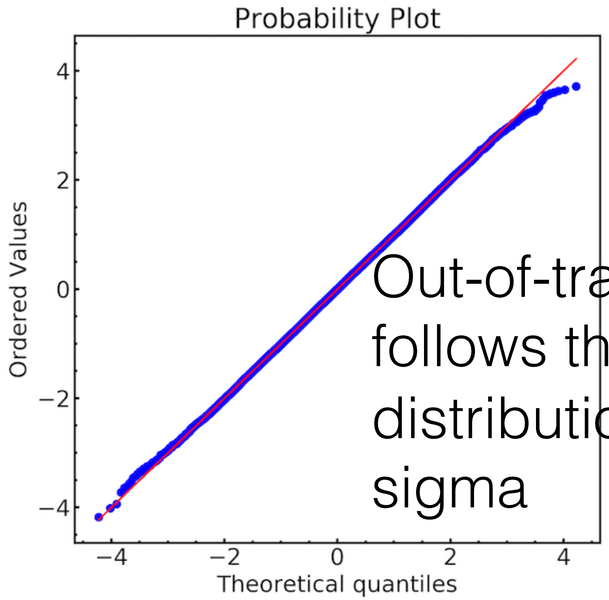
4.8 sigma

Nugroho et al. 2017

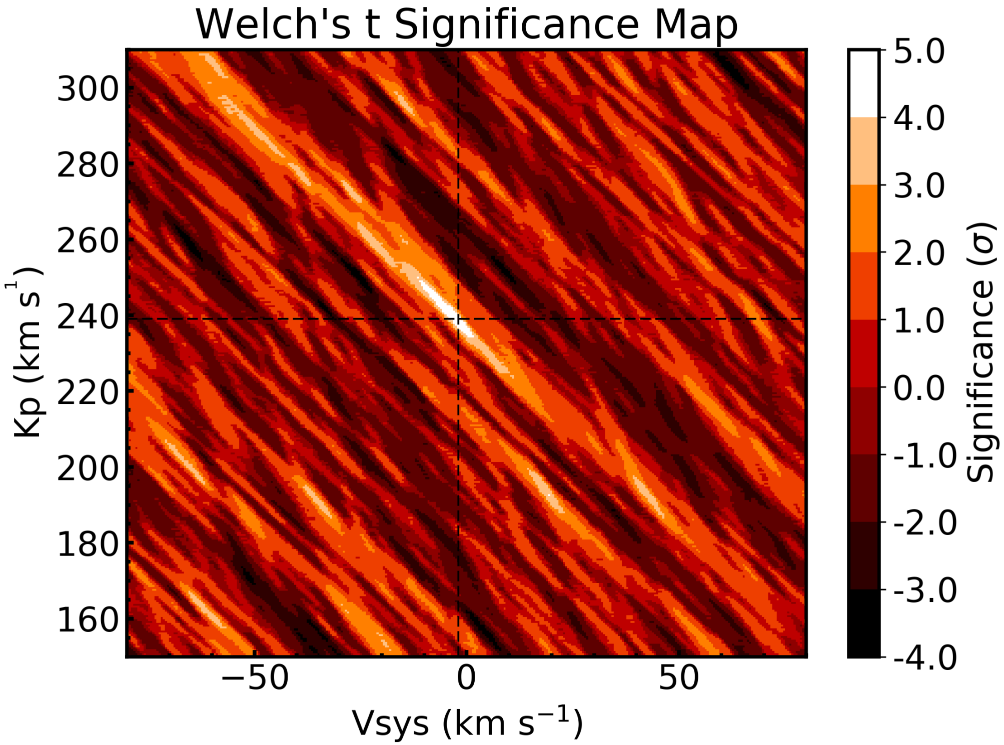
Statistical Tests

The in-trail signal was compared with the out-of-trail signal





Out-of-trail signal follows the Gaussian distribution until 4-sigma



Welch's t test showed that the in-trail signal distribution deviates from the out-of-trail signal distribution by 5-sigma

Nugroho et al. 2017

Summary

- Confirmed the inaccuracy of TiO line list for < 6300 Å and found that for > 6300 Å the TiO line list is accurate.
- Confirmed the RV of WASP-33 to be ~3 km/s in agreement with Collier Cameron et al. 2010 measurement.
- Provided the first orbital velocity measurement Kp= 239.0 (+2.0 -1.0) km/s
- Provided the first dynamical measurement of the mass of WASP-33 to be 1.73 (+0.04 -0.02) M_{sun}, heavier than the latest estimation
- Detected TiO emission signature and a stratosphere in the day side of WASP-33b with 4.8 sigma confidence level