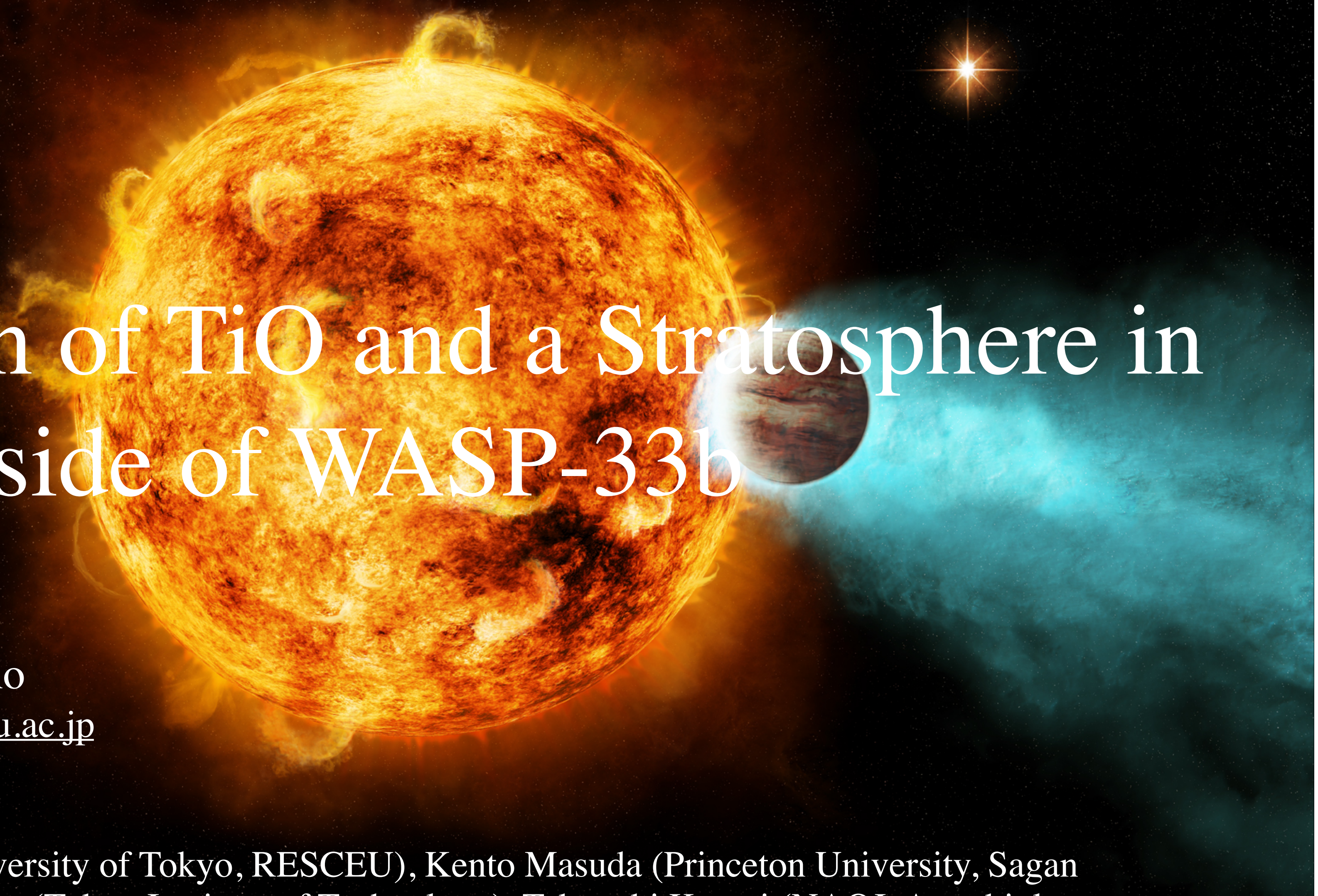
Subaru User Meeting FY2017
NAOJ, Mitaka

東京大学 THE UNIVERSITY OF TOKYO

TOHOKU UNIVERSITY

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



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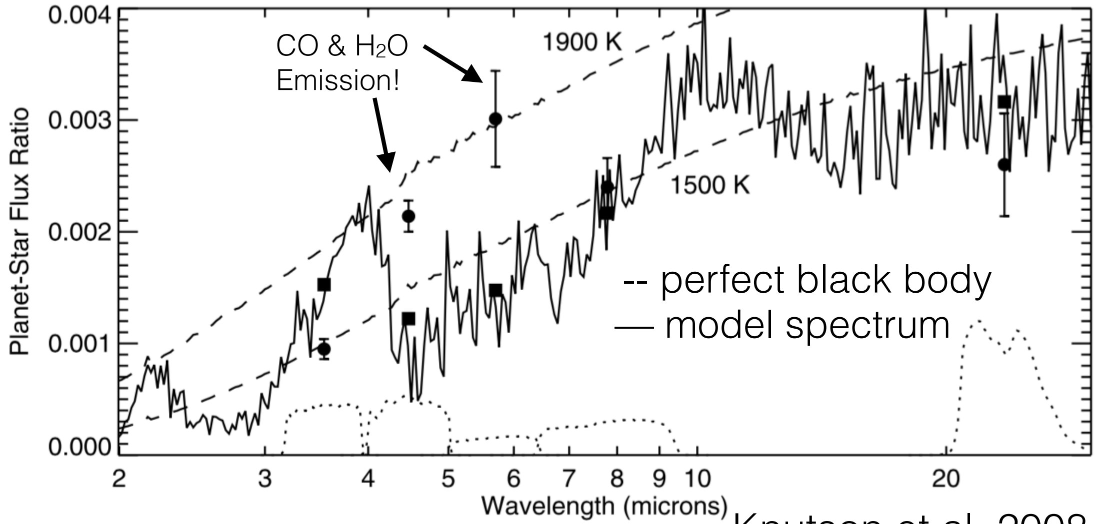
Collaborators:
Hajime Kawahara (University of Tokyo, RESCEU), Kento Masuda (Princeton University, Sagan Fellow), Teruyuki Hirano (Tokyo Institute of Technology), Takayuki Kotani (NAOJ, Astrobiology Center) and Akito Tajitsu (Subaru telescope)

exoclimes.com

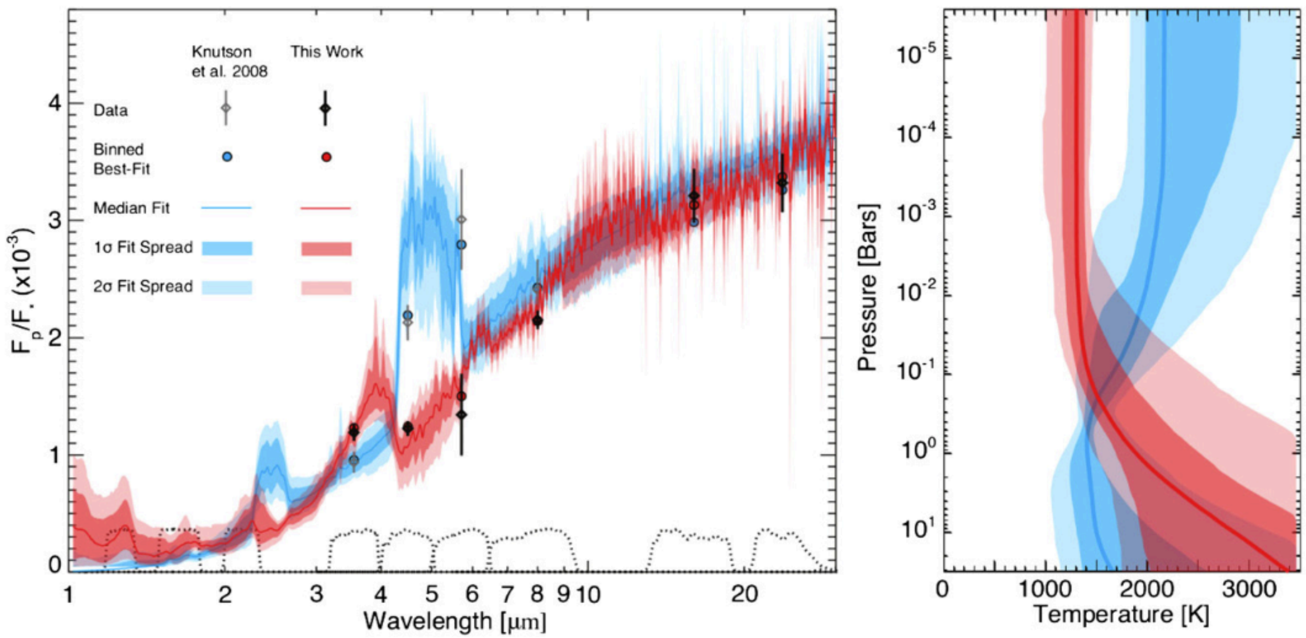
First evidence of inversion layer (or not)

First evidence!
Inversion layer in the day side of HD 209458b's atmosphere



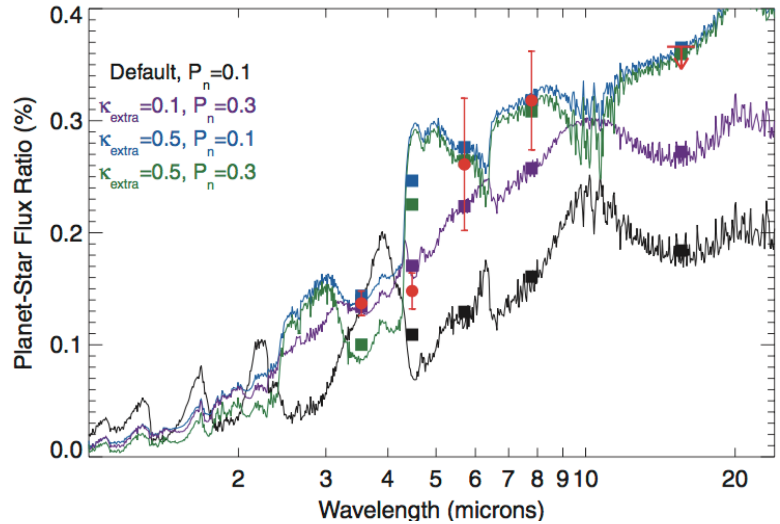
Knutson et al. 2008

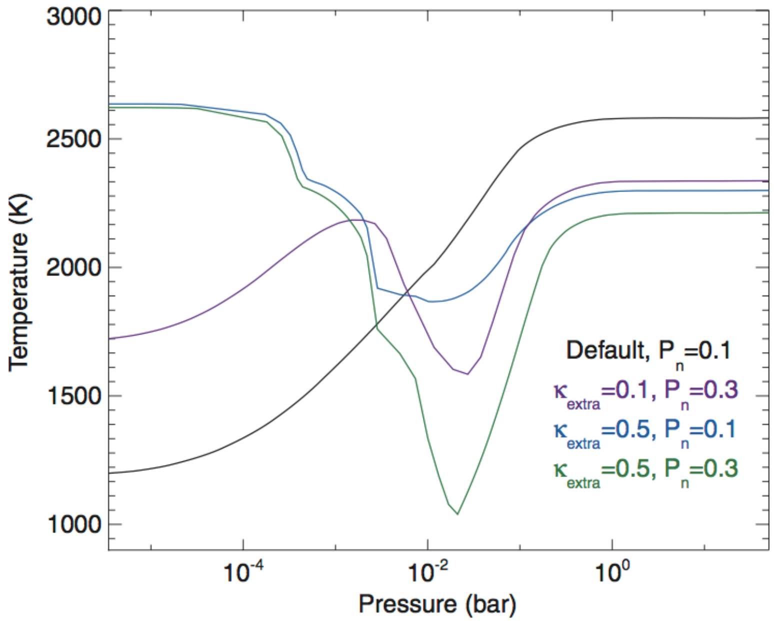
But with new version of the data pipeline and latest methodology, Diamond-Lowe et al. 2014 reported no inversion in HD 209458b atmosphere



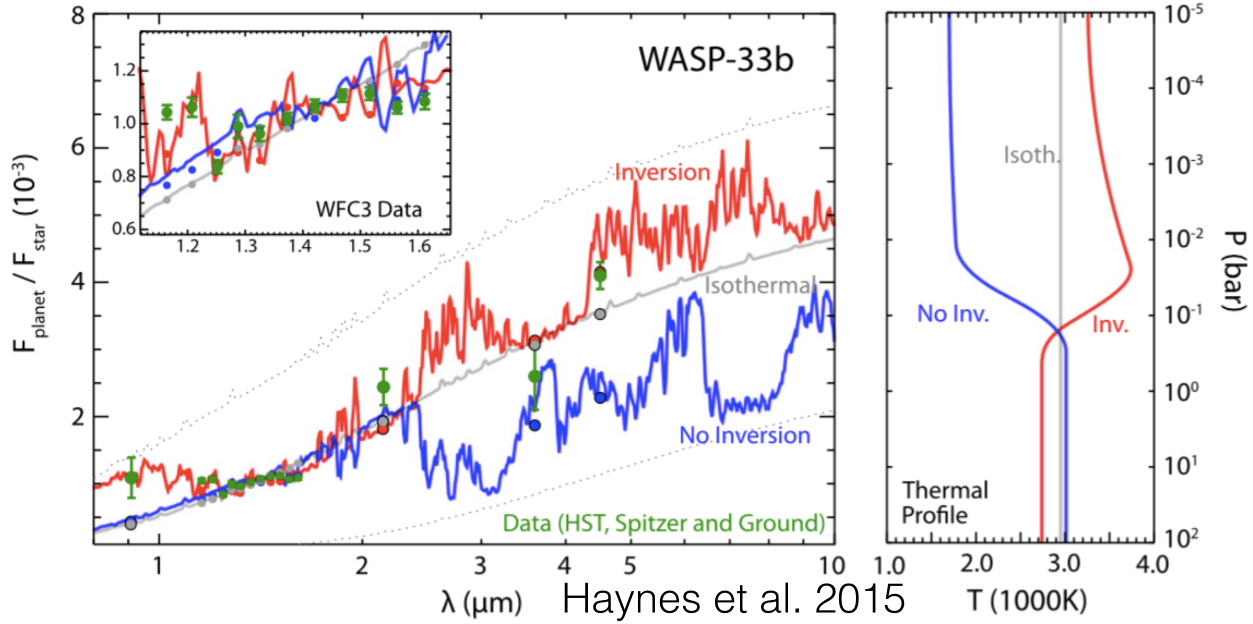
More Evidences from Spitzer and HST Observation

TrES-4b

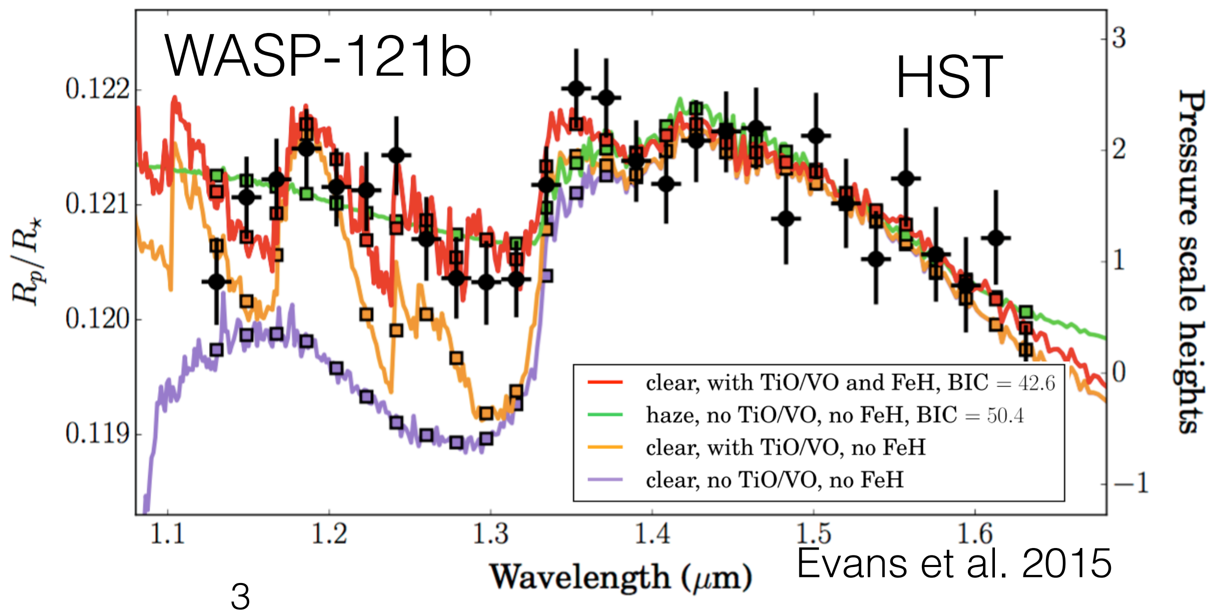




Knutson et al. 2009

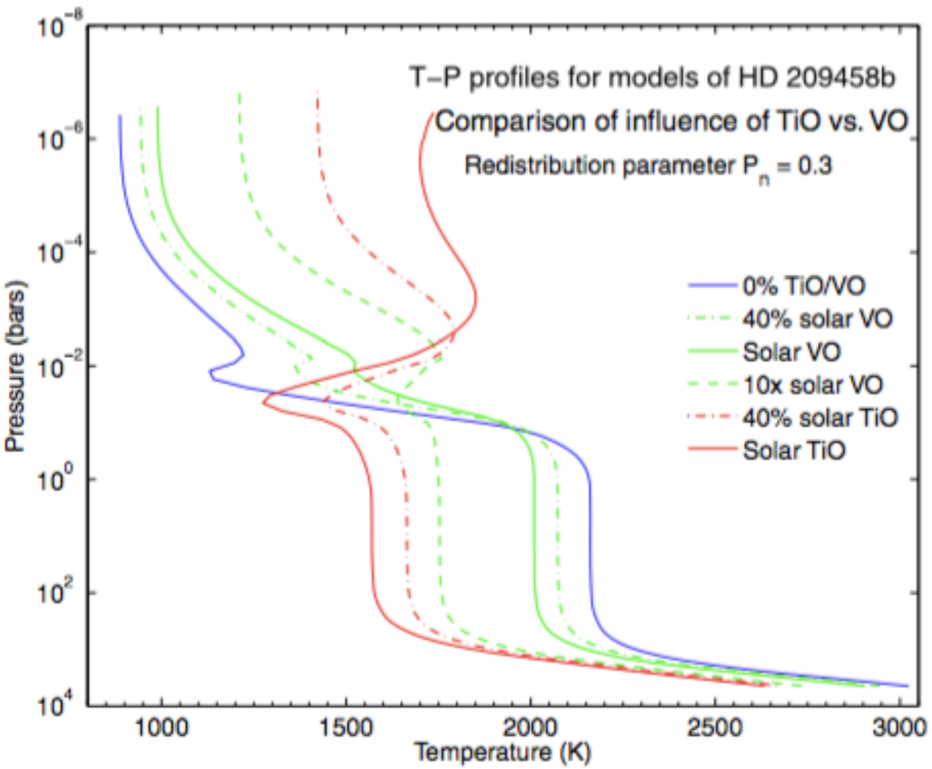


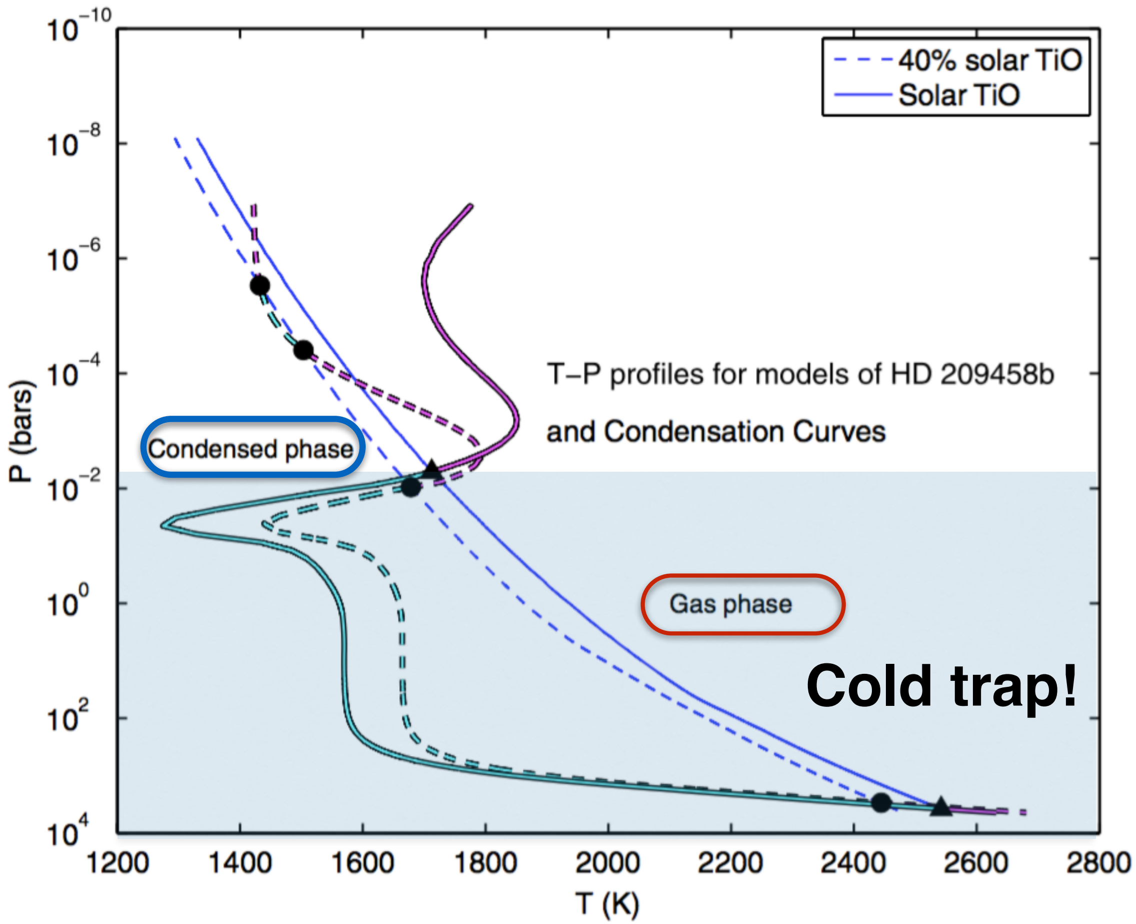
Haynes et al. 2015



Evans et al. 2015

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

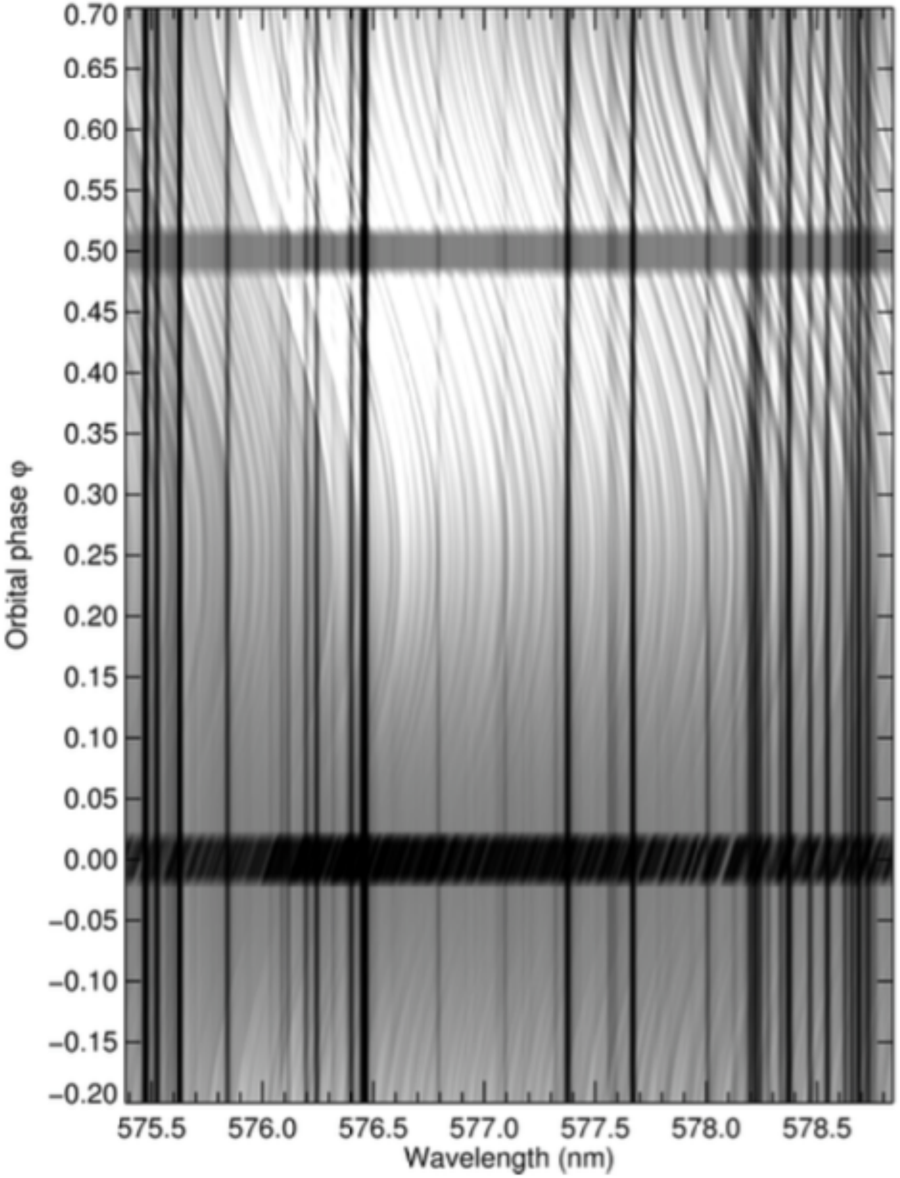


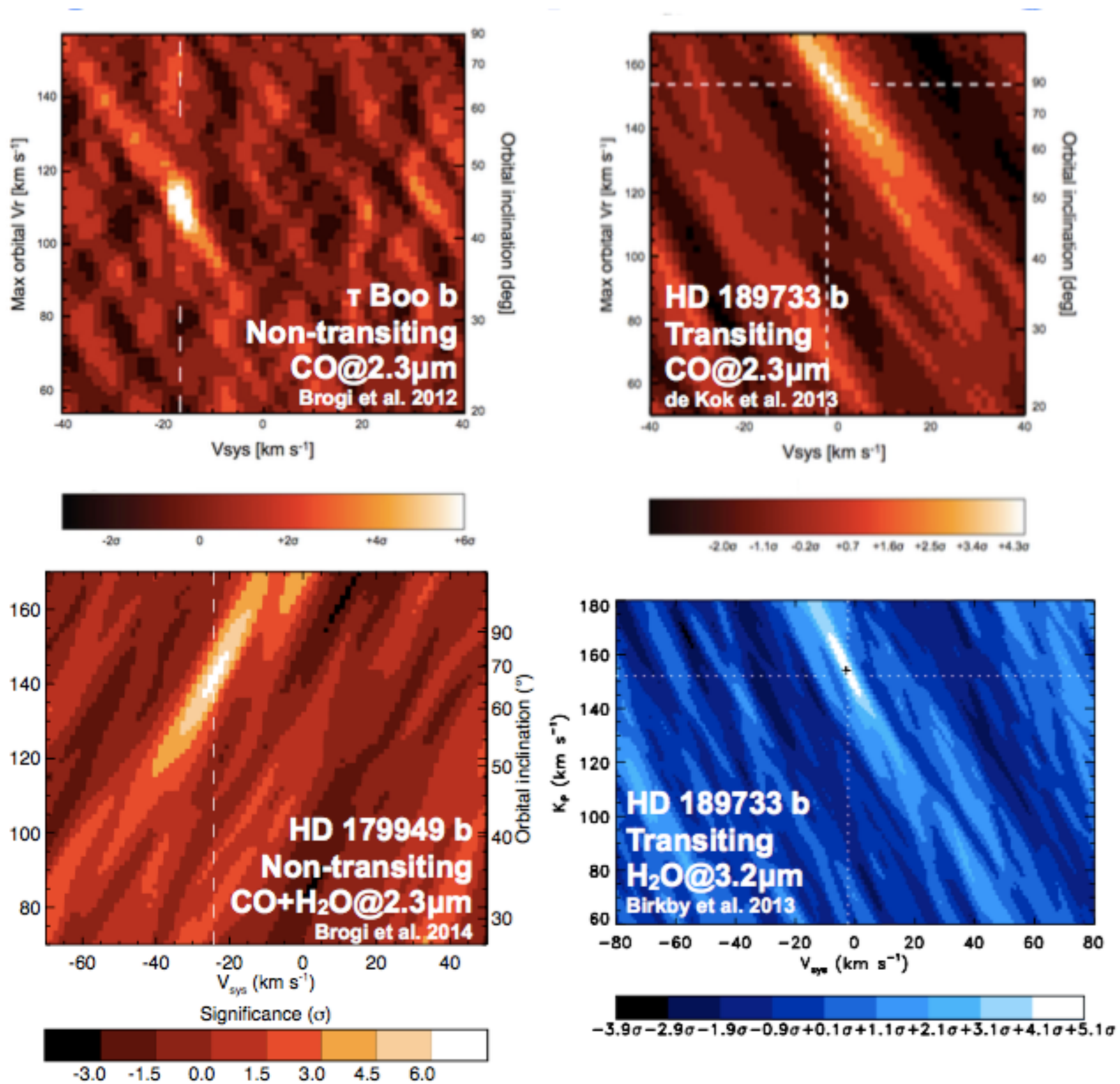


TiO cold trap is likely to exist between the hot convection zone and the hot upper atmosphere on the irradiated day sides of planets

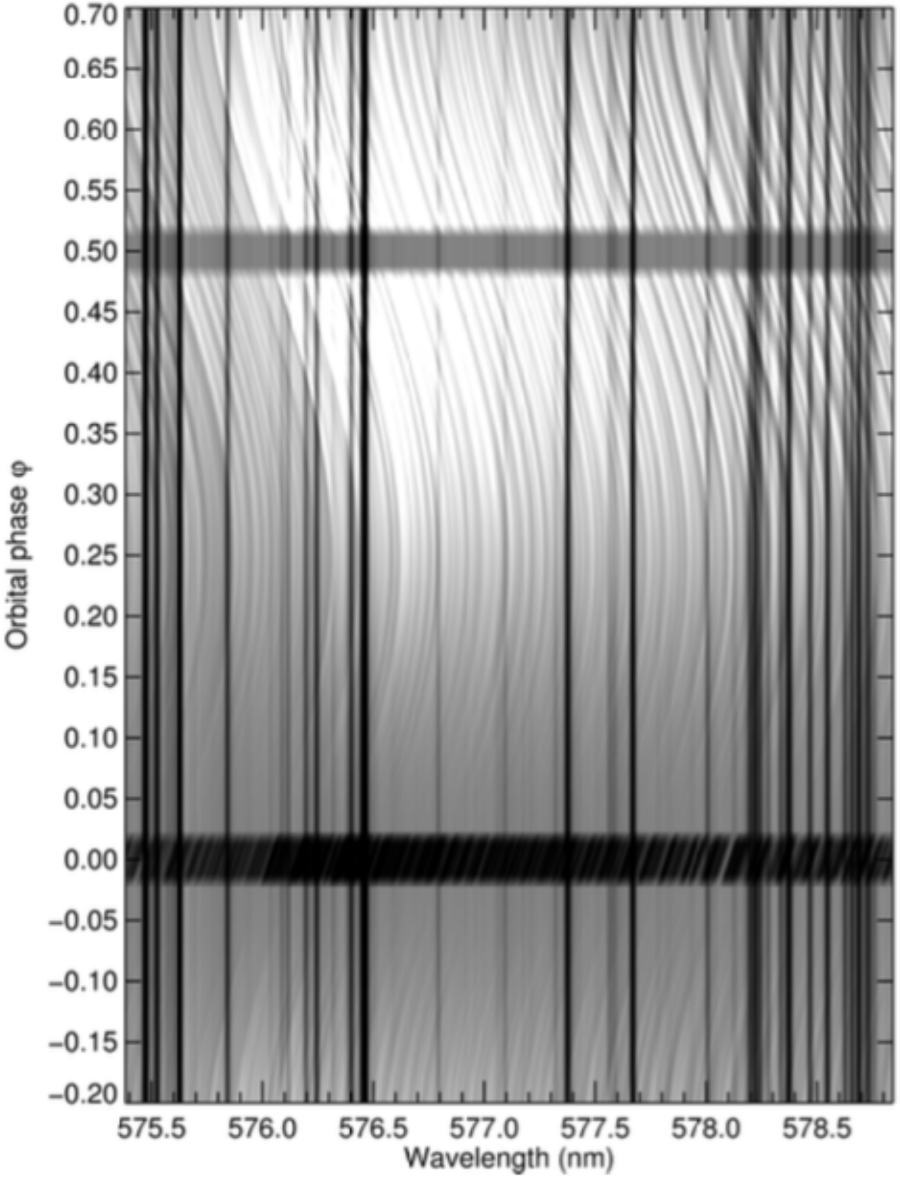
Spiegel et al. 2009

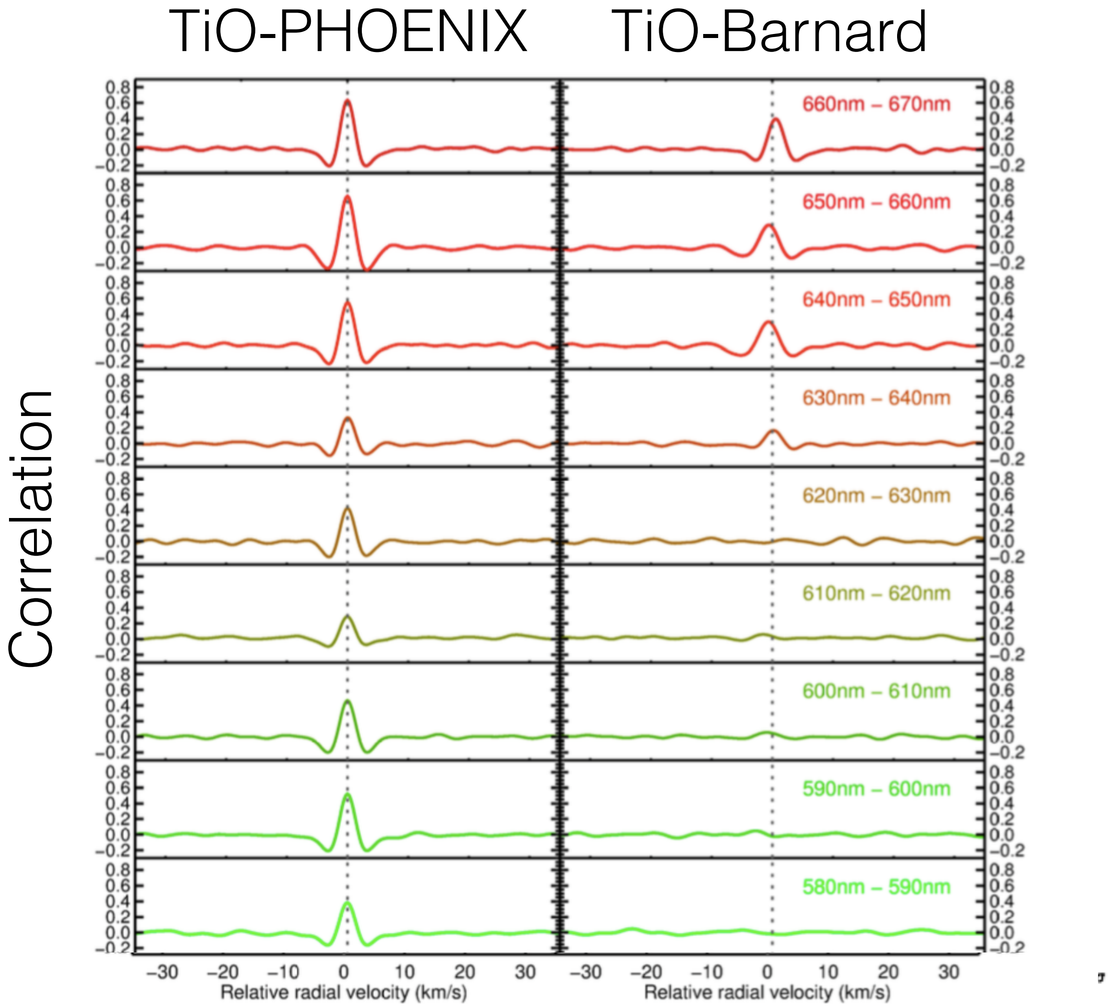
Attempt to detect TiO using HDS





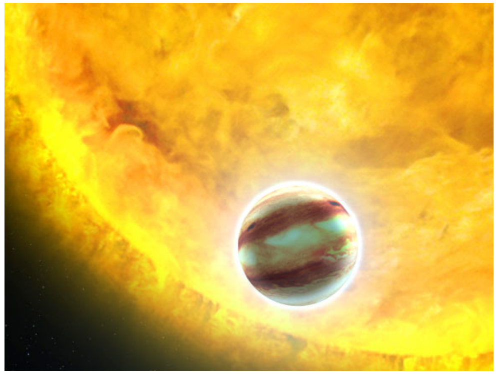
Attempt to detect TiO using HDS

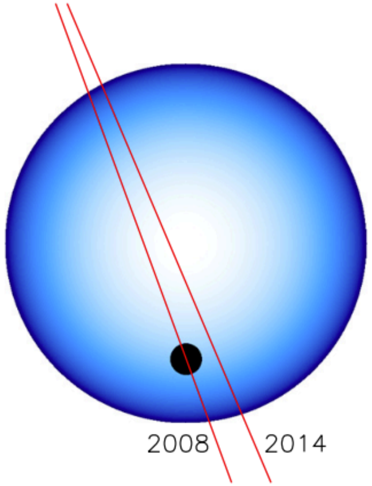




Hoeijmakers et al. 2014

WASP 33 b orbiting WASP 33 (Delta Scuti star)



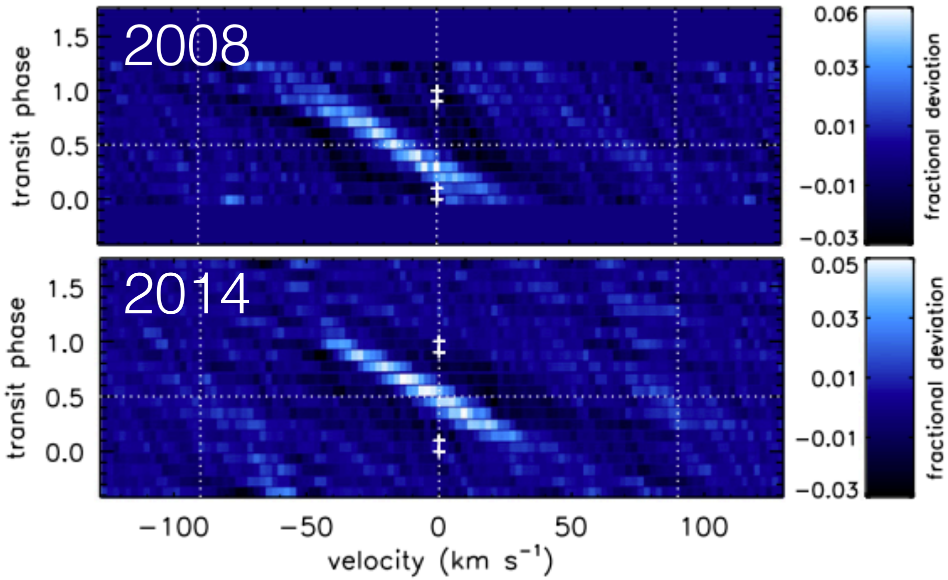


2015 October 26 and 27 HST
Using HDS in Subaru telescope (PI: H. Kawahara)

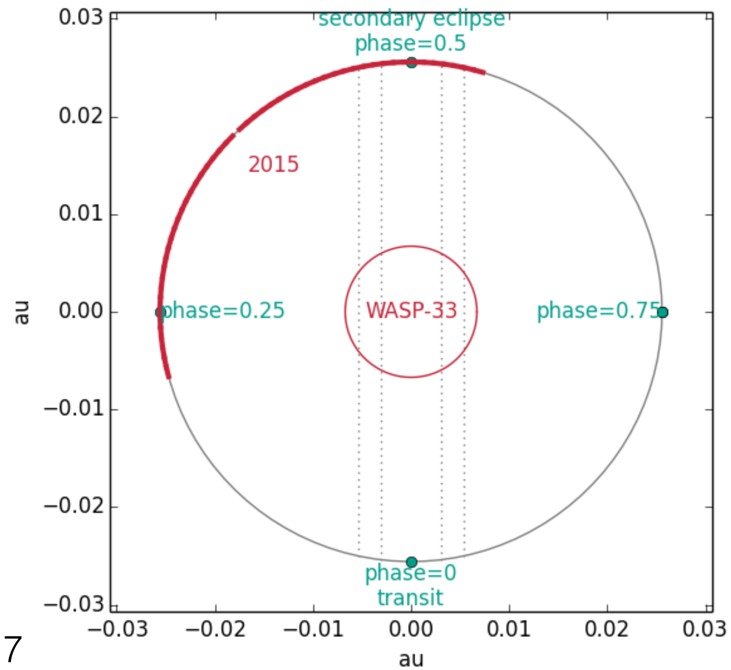
Image slicer #3 (slit width= 0.”2 each)
R~165,000

6170-7402 Å (Blue CCD)
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



Johnson et al. 2015

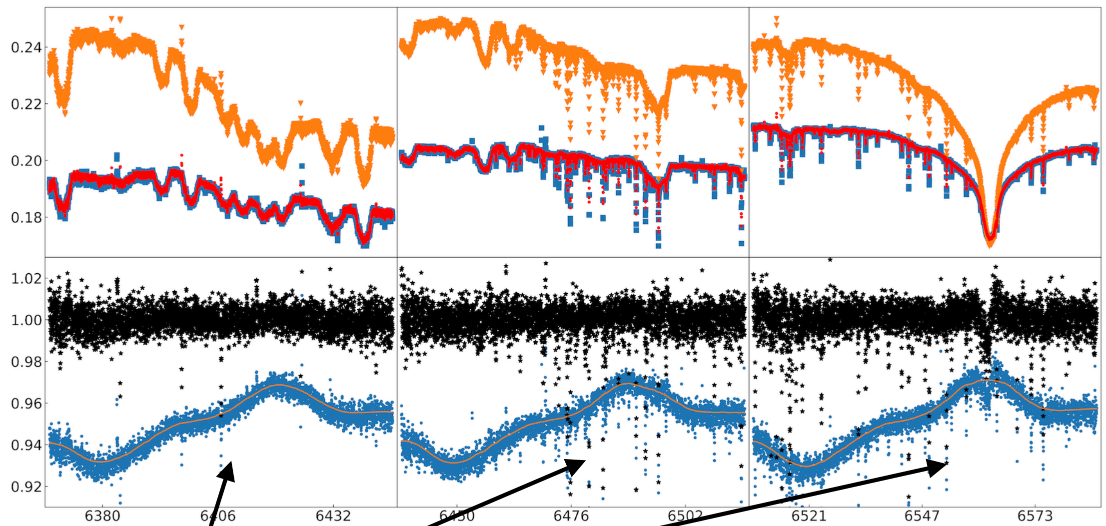


The orbital phase of WASP-33b that covered by our observation.

Data Reduction

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

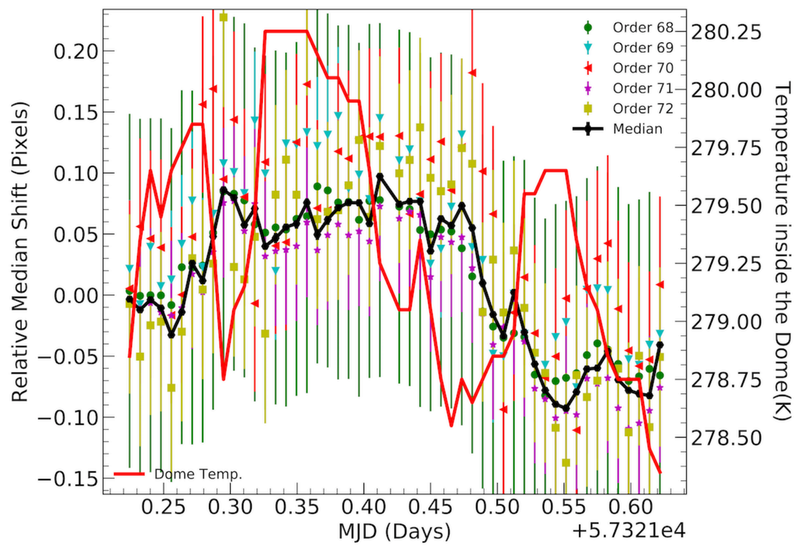
Blaze function variation

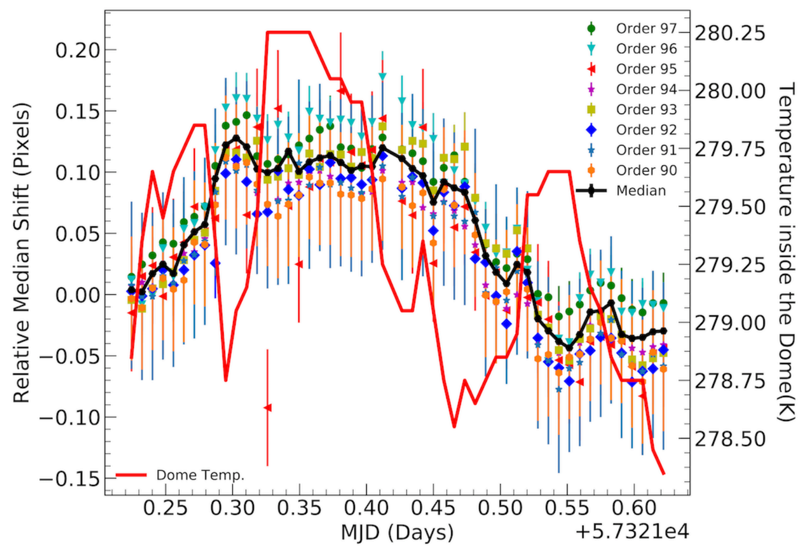


Wavelength (Å)

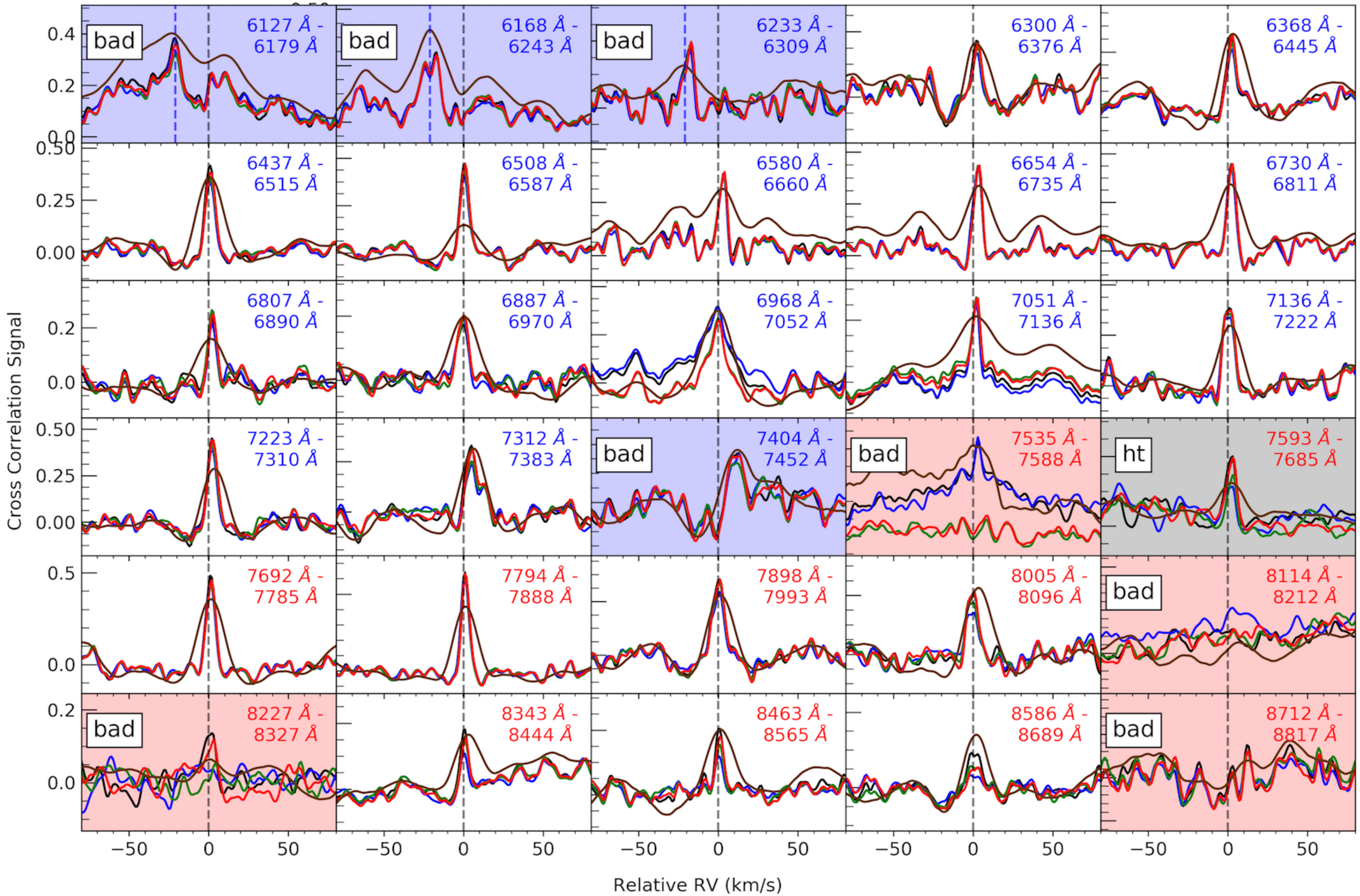
Similar pattern

Wavelength shift during observation





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



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

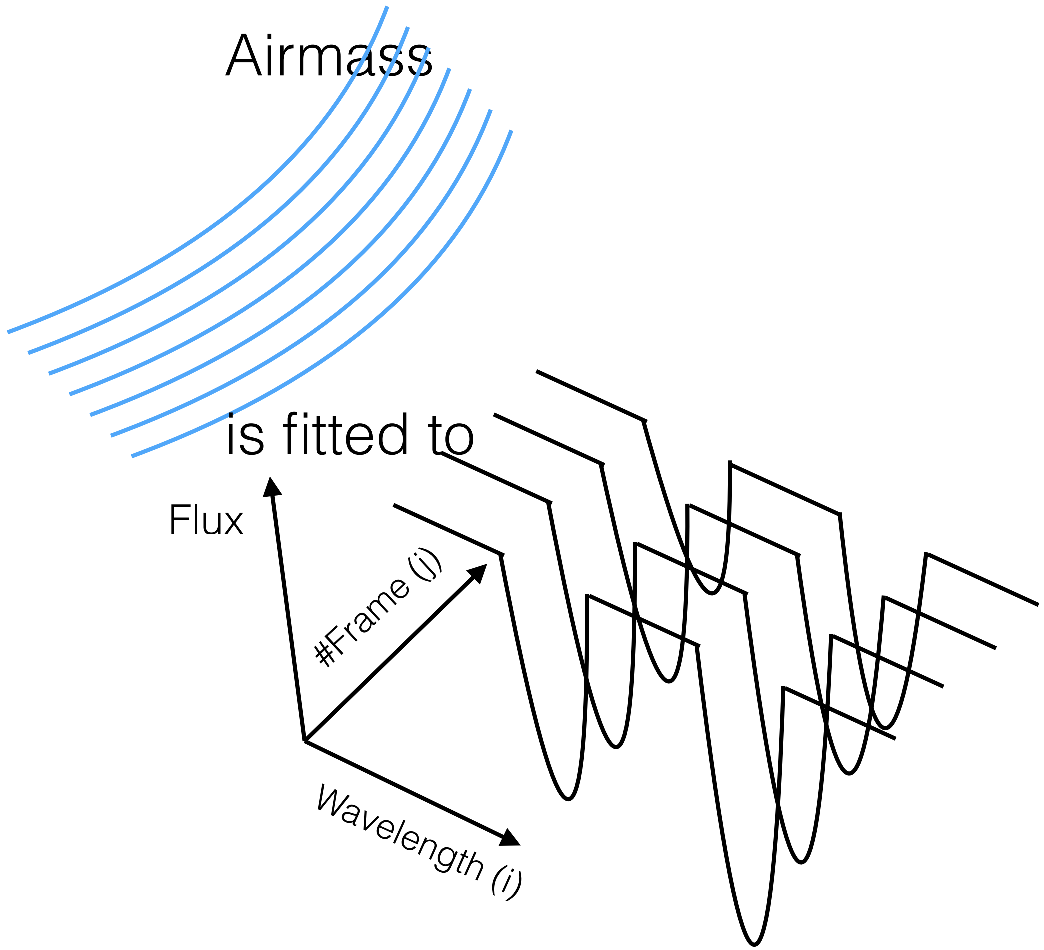
For N light-curves (stars), each consists of M measurements

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*

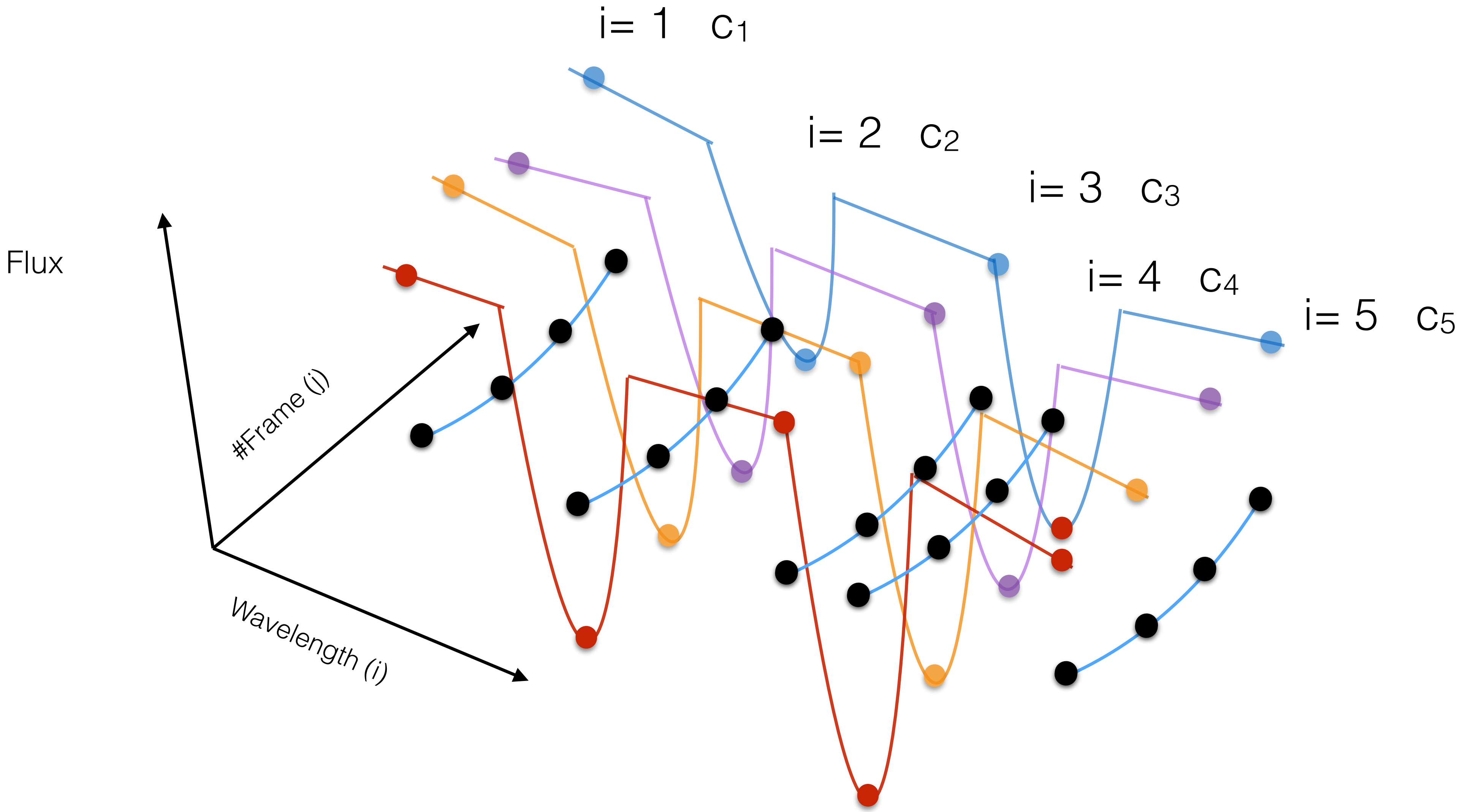
The prior is the known airmass



1st step

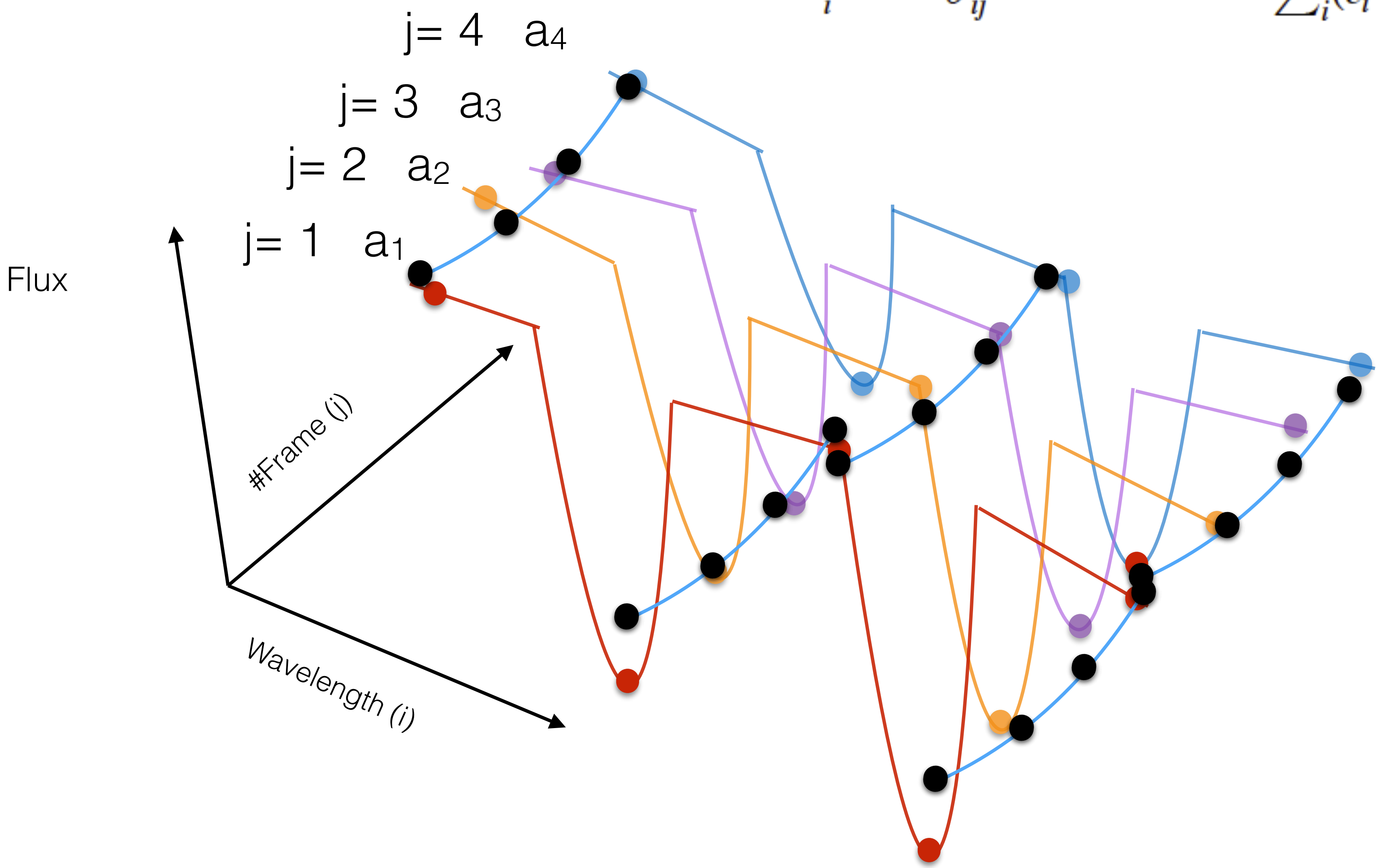
Prior= known airmass

$$R_i^2 = \sum_j \frac{(r_{ij} - c_i a_j)^2}{\sigma_{ij}^2} \qquad c_i = \frac{\sum_j (r_{ij} a_j / \sigma_{ij}^2)}{\sum_j (a_j^2 / \sigma_{ij}^2)}.$$



2nd step

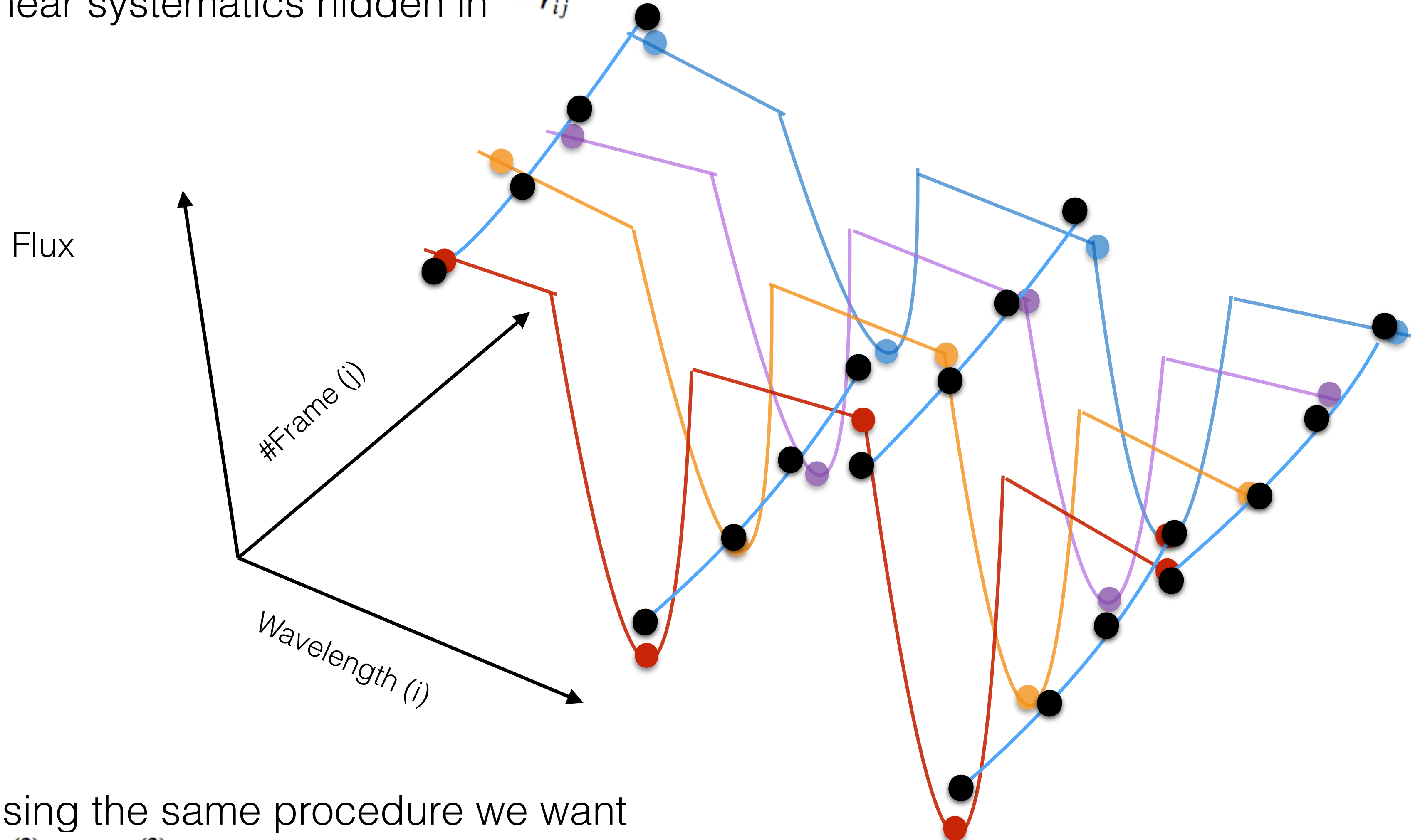
$$R_j^2 = \sum_i \frac{(r_{ij} - c_i a_j)^2}{\sigma_{ij}^2} \qquad a_j^{(1)} = \frac{\sum_i (r_{ij} c_i / \sigma_{ij}^2)}{\sum_i (c_i^2 / \sigma_{ij}^2)}$$



Doing that iteratively will give us optimized ${}^{(1)}\bar{c}_i {}^{(1)}\bar{a}_j$

After removing this effect then the new residuals is define as: ${}^{(1)}r_{ij} = r_{ij} - {}^{(1)}\bar{c}_i {}^{(1)}\bar{a}_j$

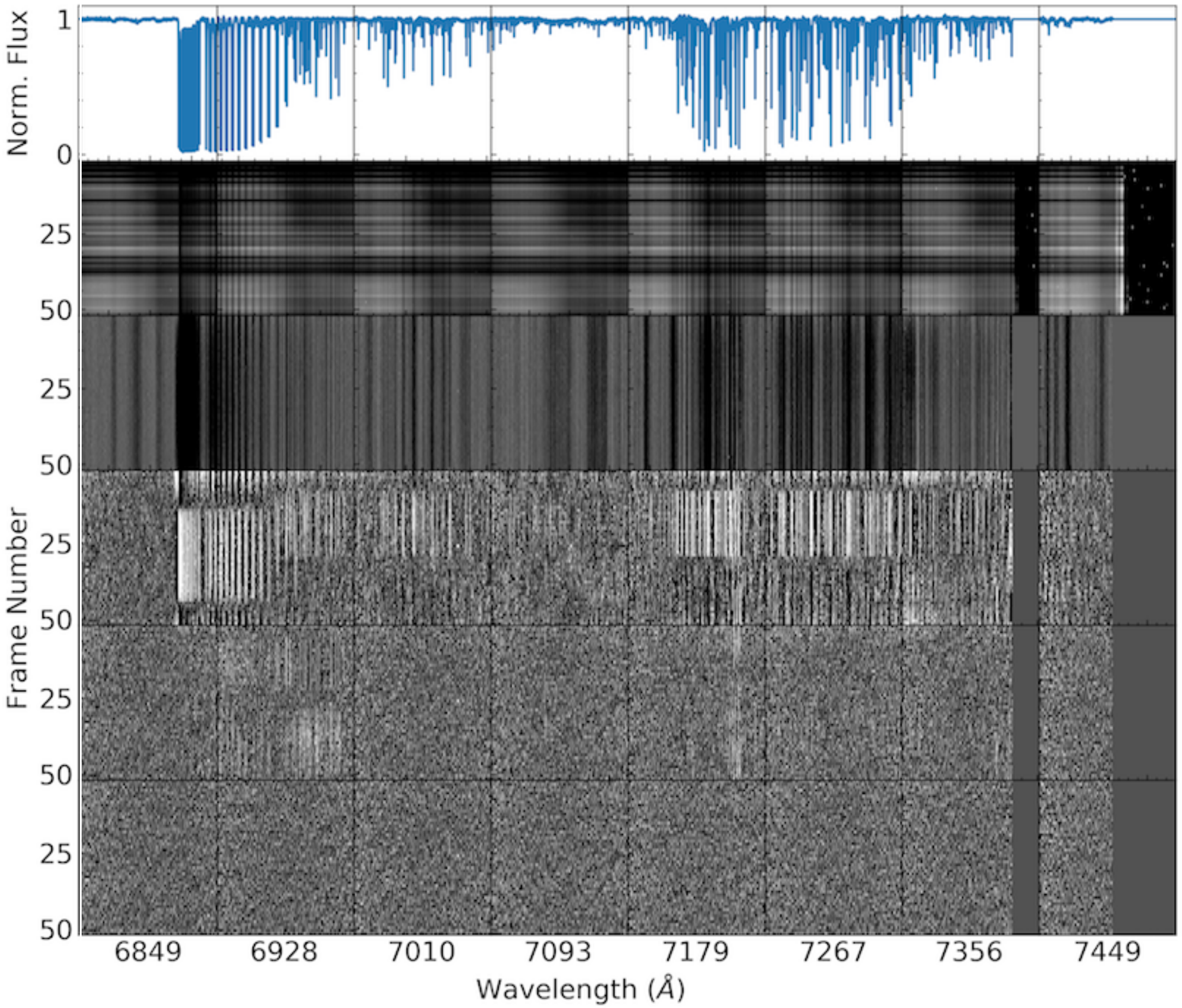
Then we can proceed to remove the next linear systematics hidden in ${}^{(1)}r_{ij}$



Now using the same procedure we want to find ${}^{(2)}c_i$ and ${}^{(2)}a_j$ that minimize

$$ {}^{(1)}S^2 = \sum_{ij} \frac{\left({}^{(1)}r_{ij} - {}^{(2)}c_i {}^{(2)}a_j\right)^2}{\sigma_{ij}^2} $$

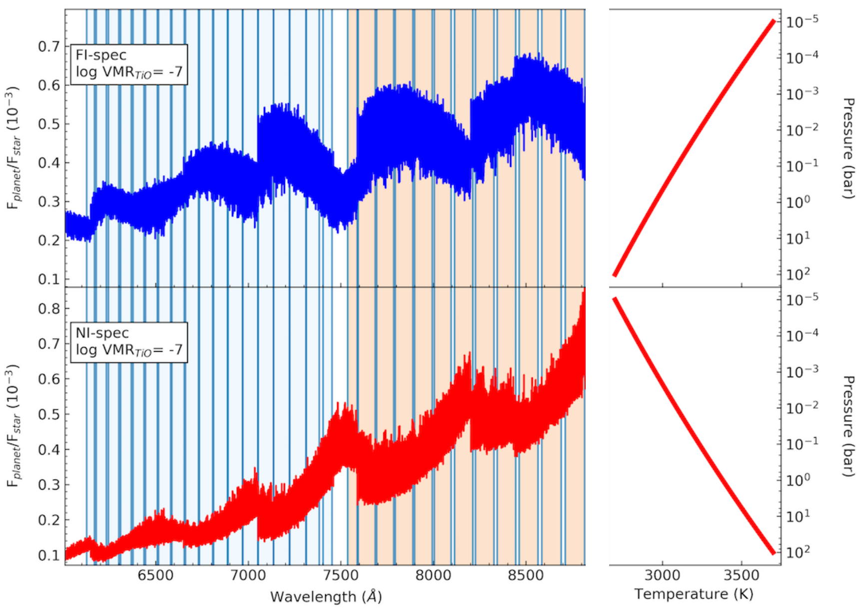
Applying SYSREM to Our Data

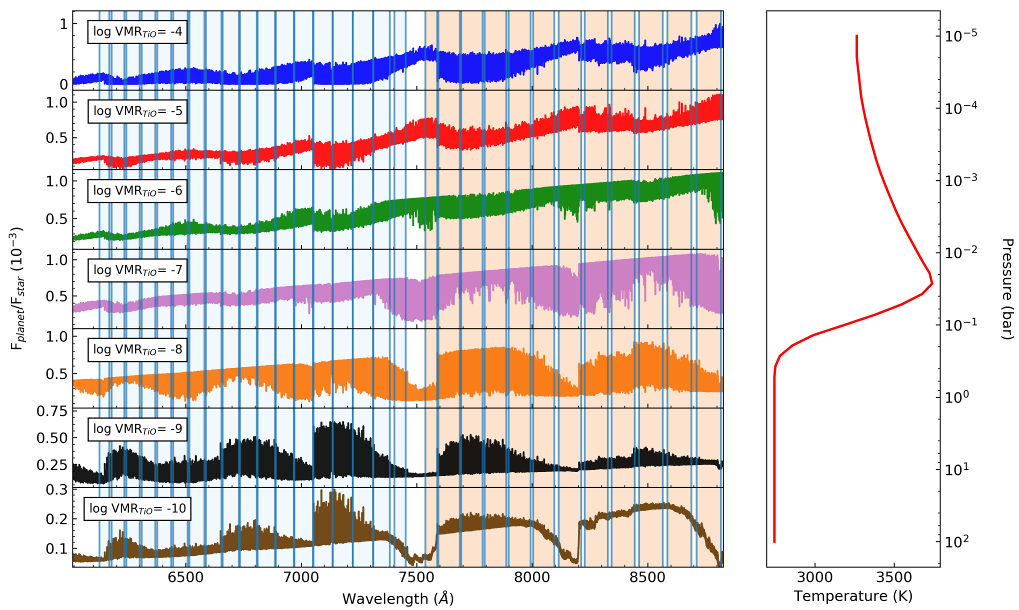


- 1D normalized data
- Raw data
- After the a function variation correction and the common wavelength grid iteration
- The mean subtracted spectra as the input to SYSREM.
- The residual spectra after running 1 SYSREM iteration
- The residual spectra after running 4 SYSREM iteration

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

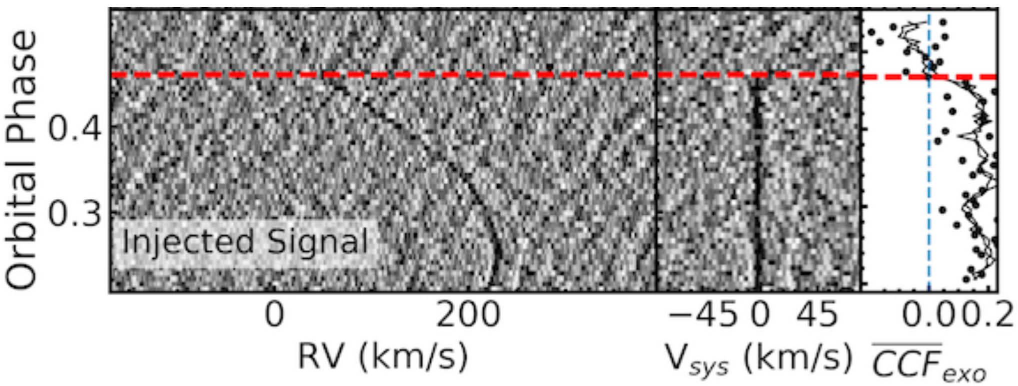
Cross-correlated with the Doppler shifted model spectrum covering

-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

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

Orbital phase $\phi(t) = \dfrac{t - T_0}{P},$



for

The planet semi amplitude

+150 km/s < Kp < +310 km/s

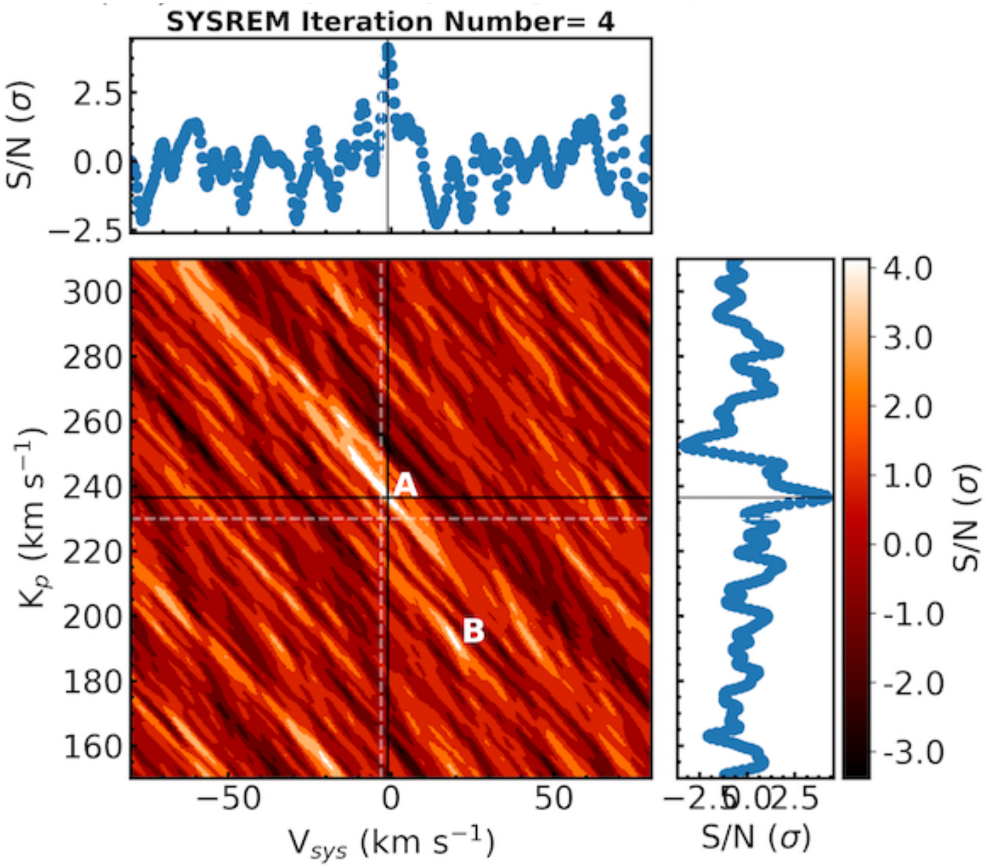
The systemic velocity

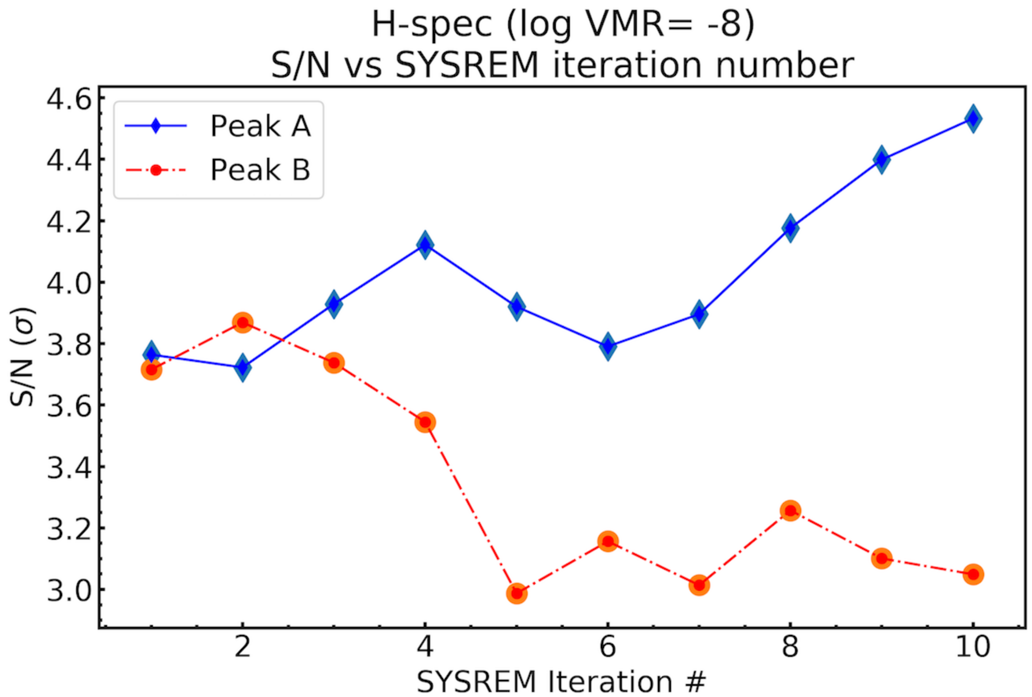
−80 km/s < Vsys < +80 km/s

with 0.5 km/s steps

TiO Signal Detection

With H spec





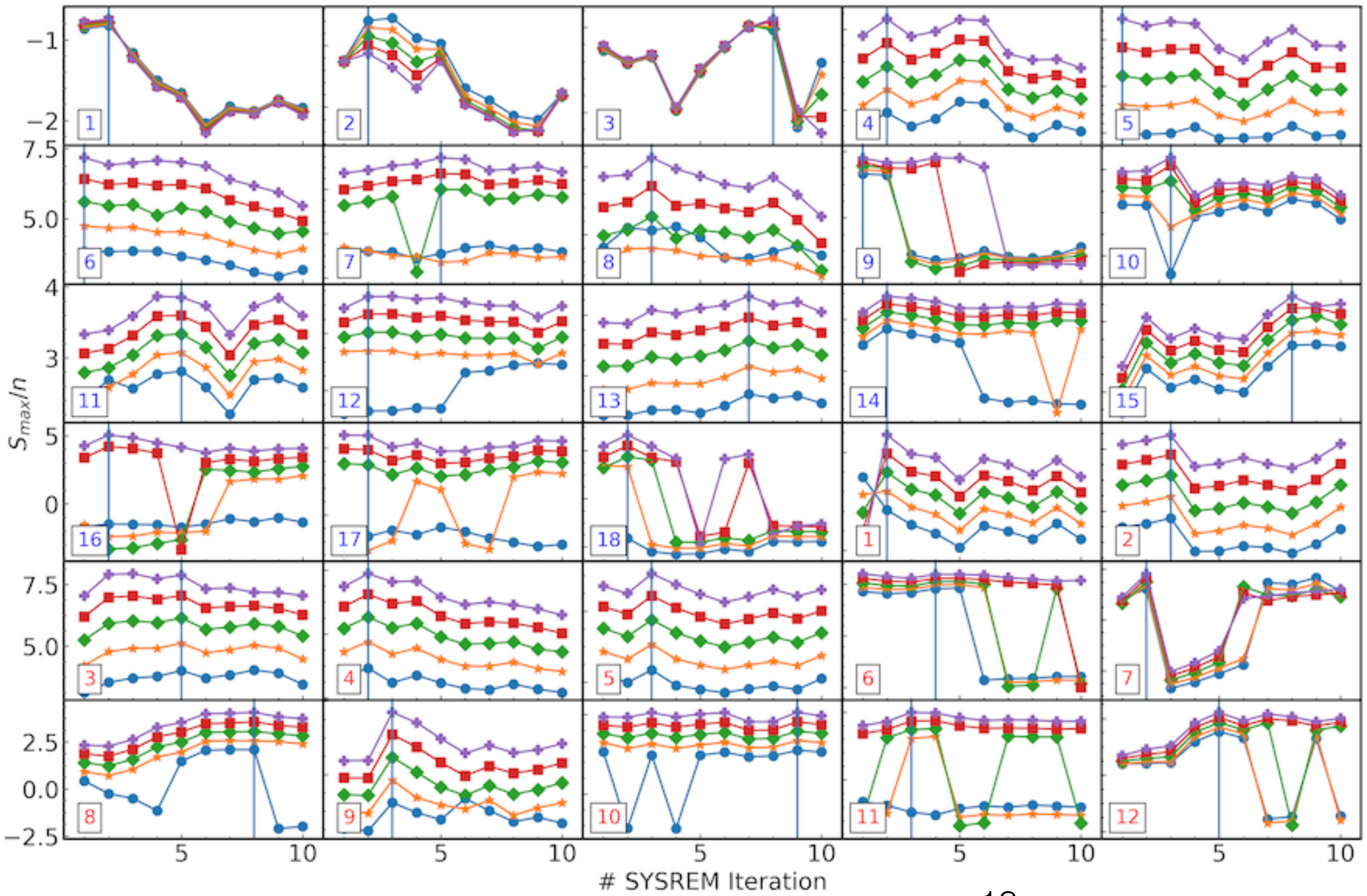
Order-based SYSREM Optimization

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

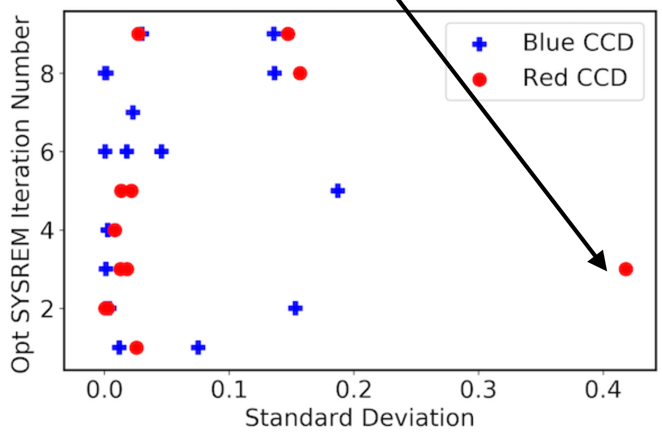
$$F_{\text{scaled pm}}(\lambda) = sc \times \frac{F_{\text{pm}}(\lambda)}{F_{\text{star}}(\lambda)}\left(\frac{R_{\text{p}}}{R_{\text{star}}}\right)^2$$

→ Planet to star flux contrast

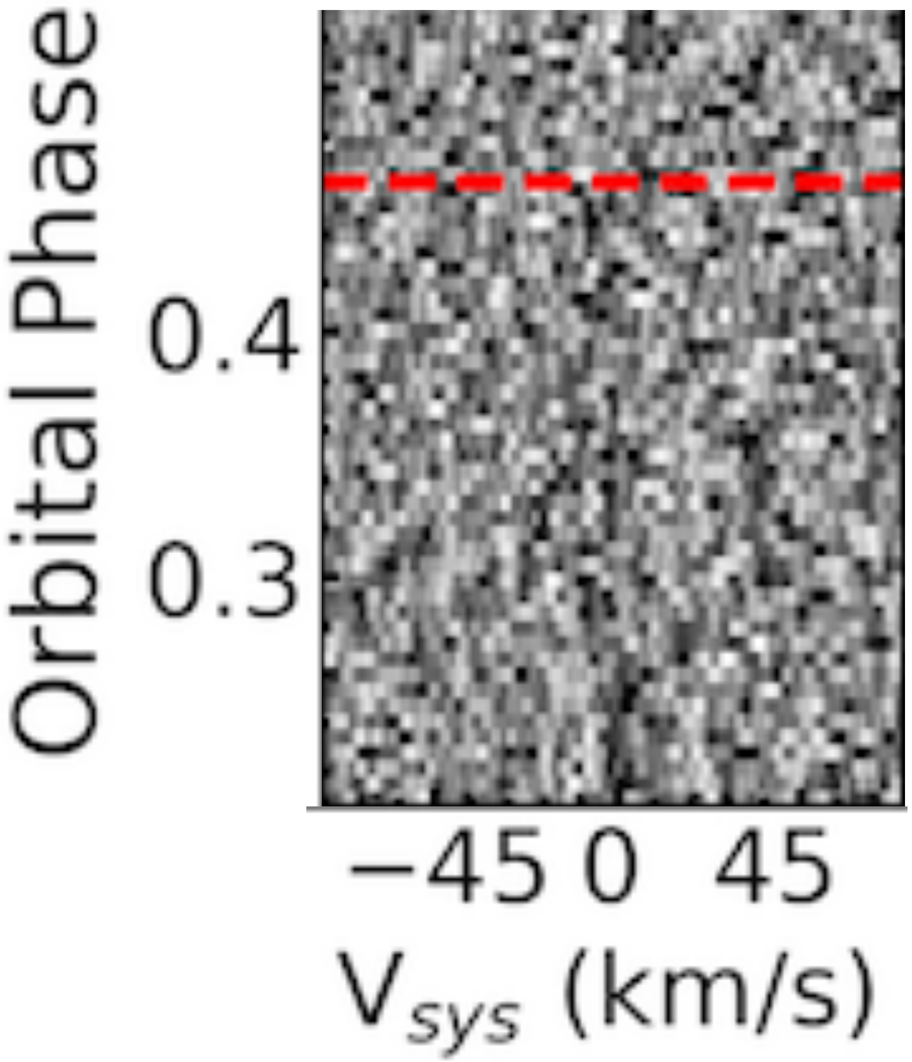
sc= [20%, 40%, 60%, 80 %, 100 %]



Order 2 of Red CCD
Forest of O_2 Telluric lines

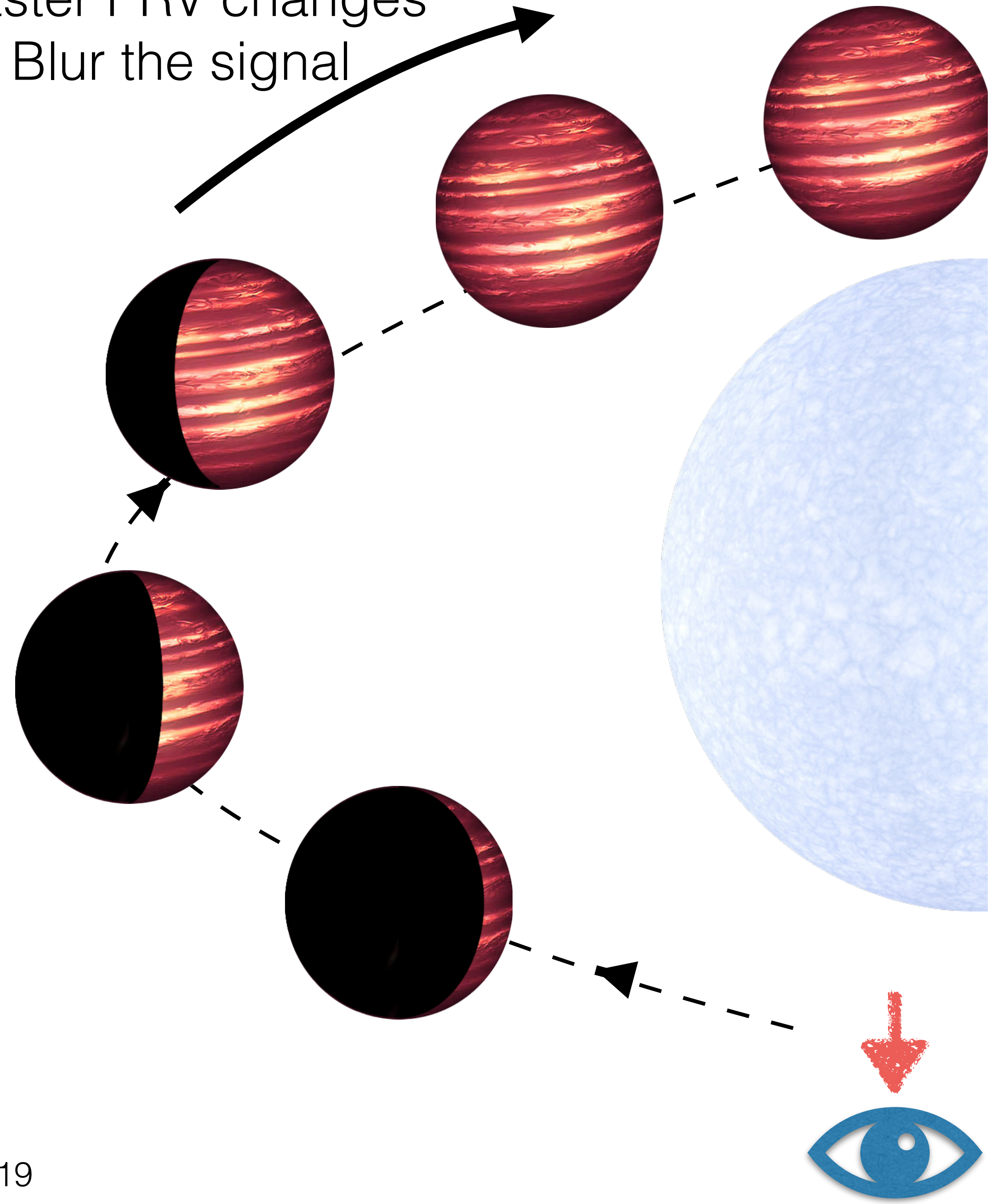


Final Result

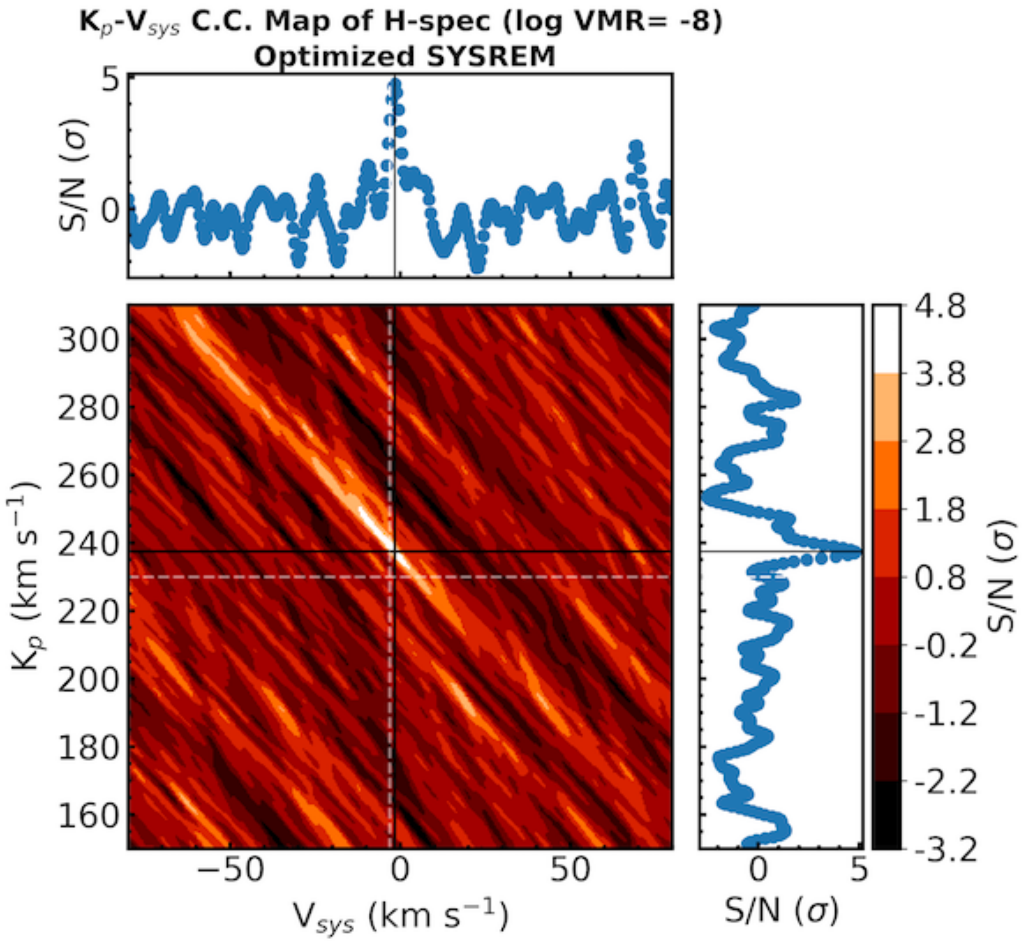


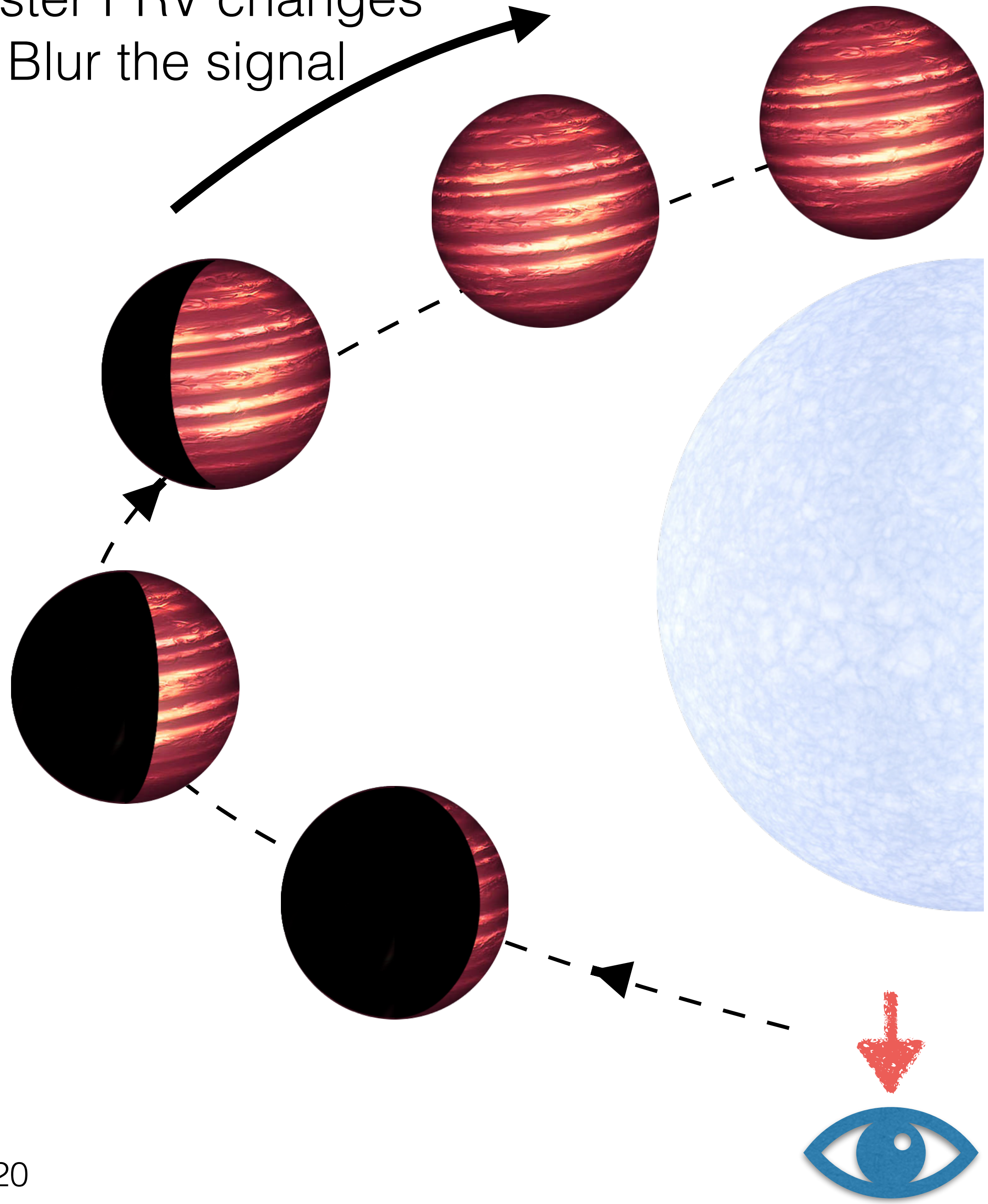
Faster PRV changes
-> Blur the signal

No signal at the
s. Eclipse phase



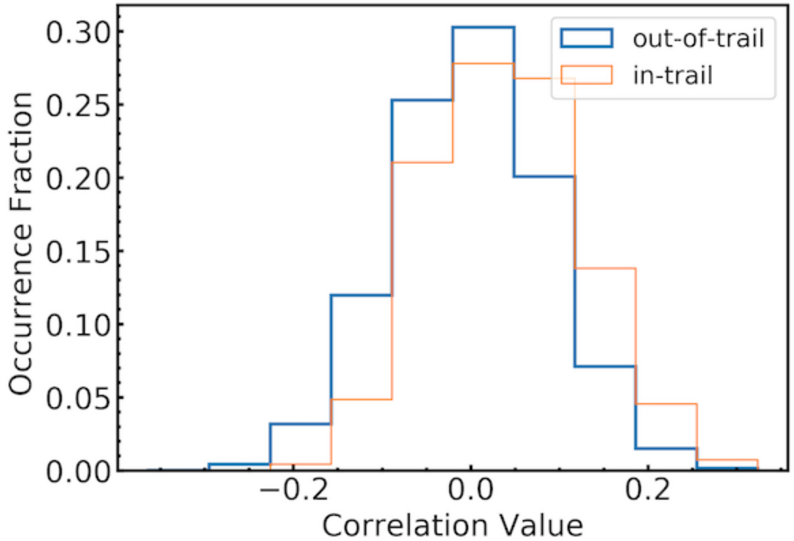
Final Result

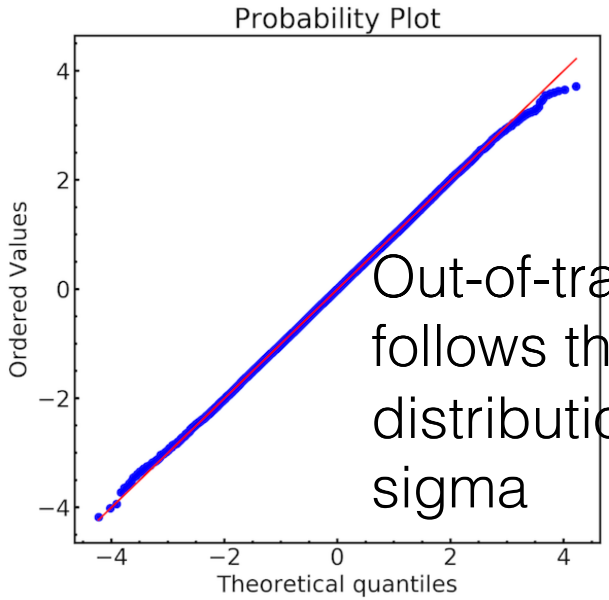




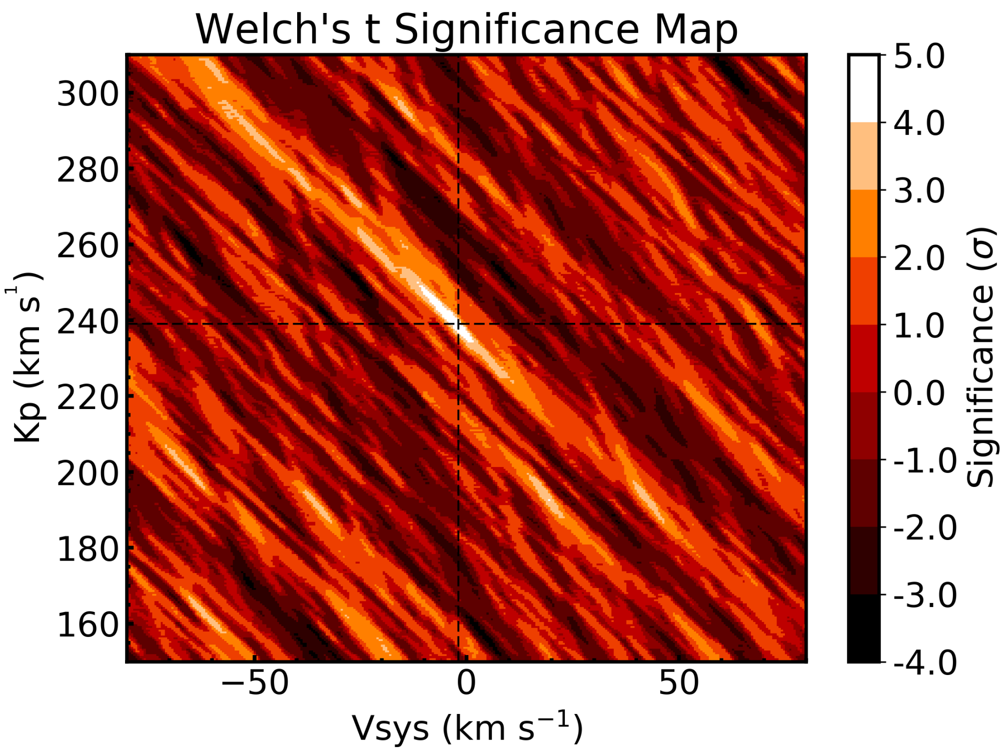
Statistical Tests

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





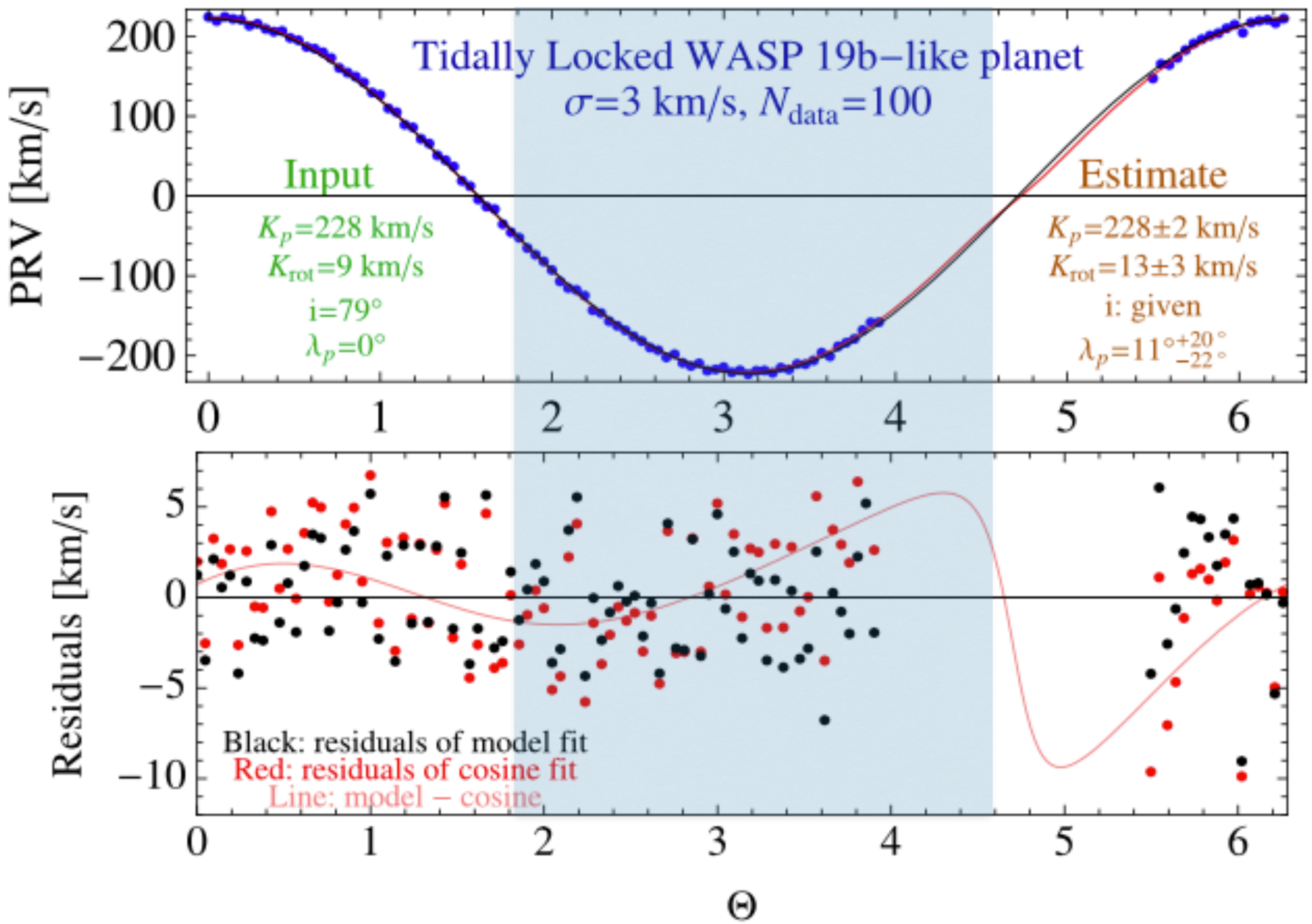
Out-of-trail signal follows the Gaussian distribution until 4-sigma

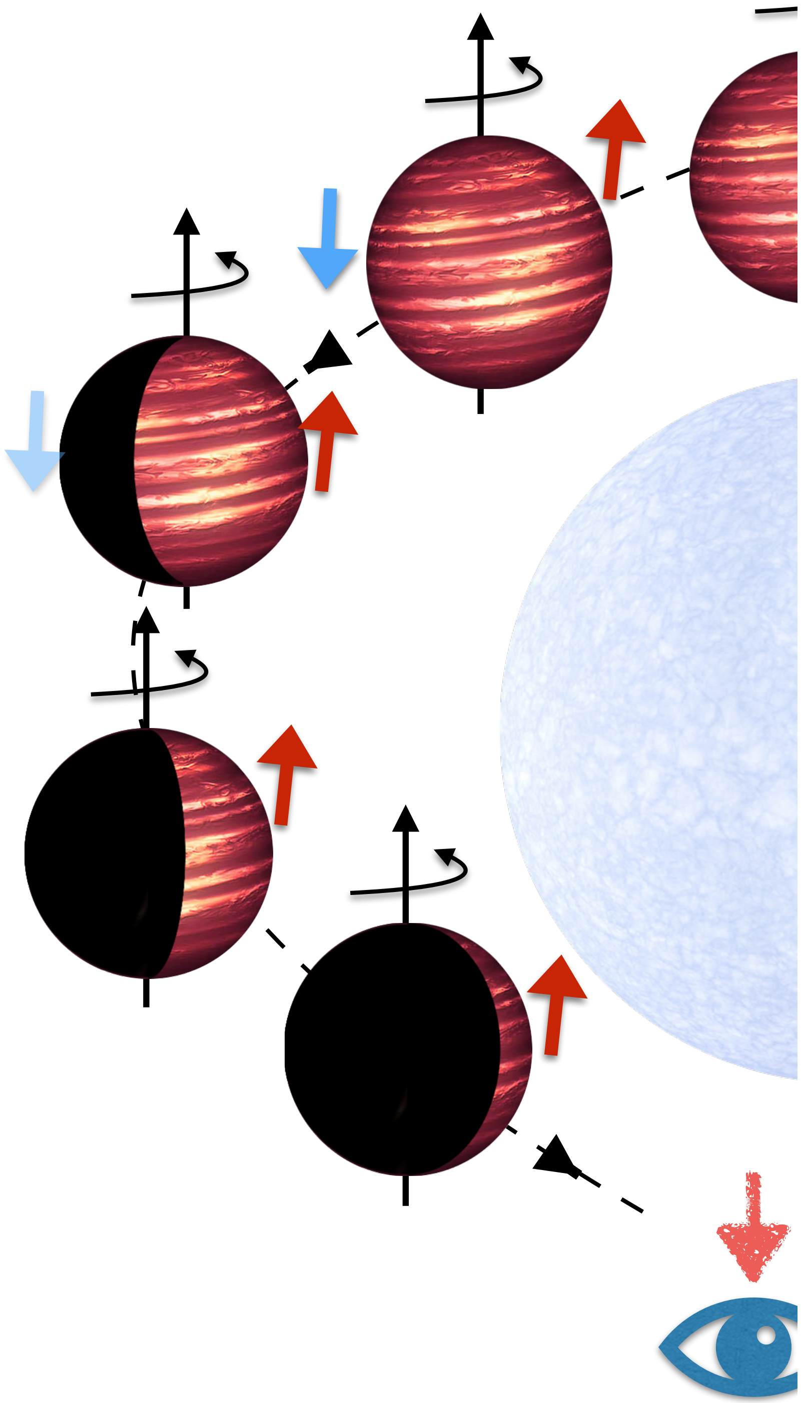


Welch’s t test showed that the in-trail signal distribution deviates from the out-of-trail signal distribution by 5-sigma

Nugroho et al. 2017

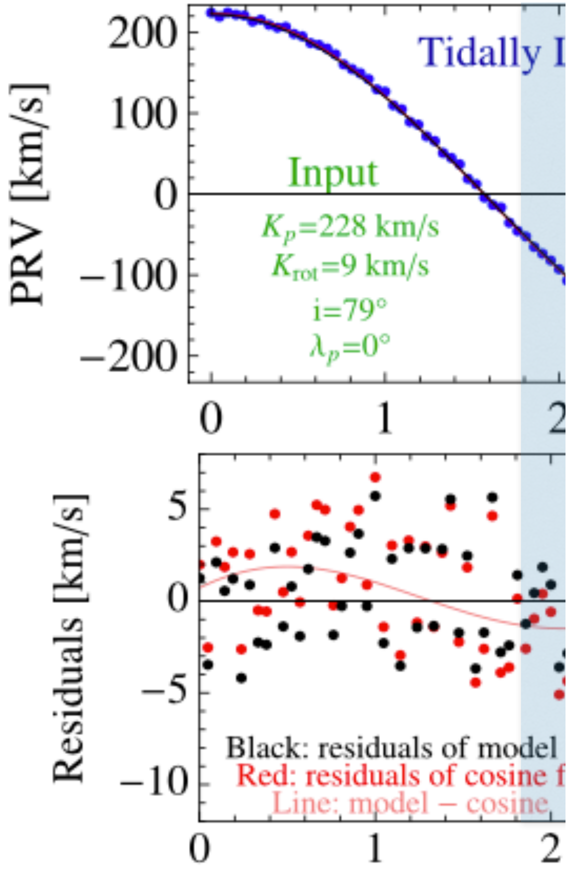
Future works

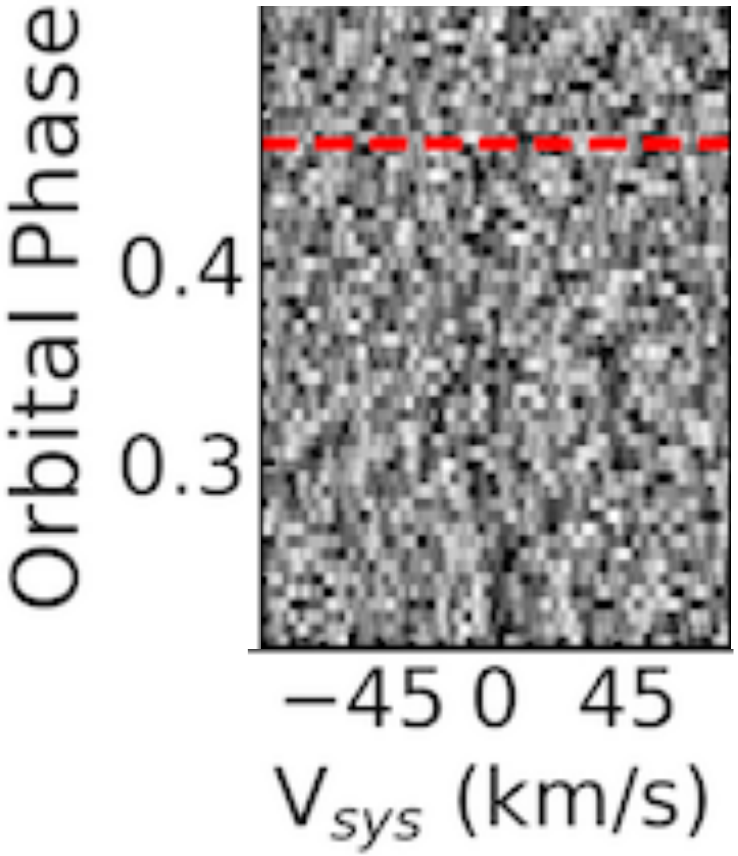


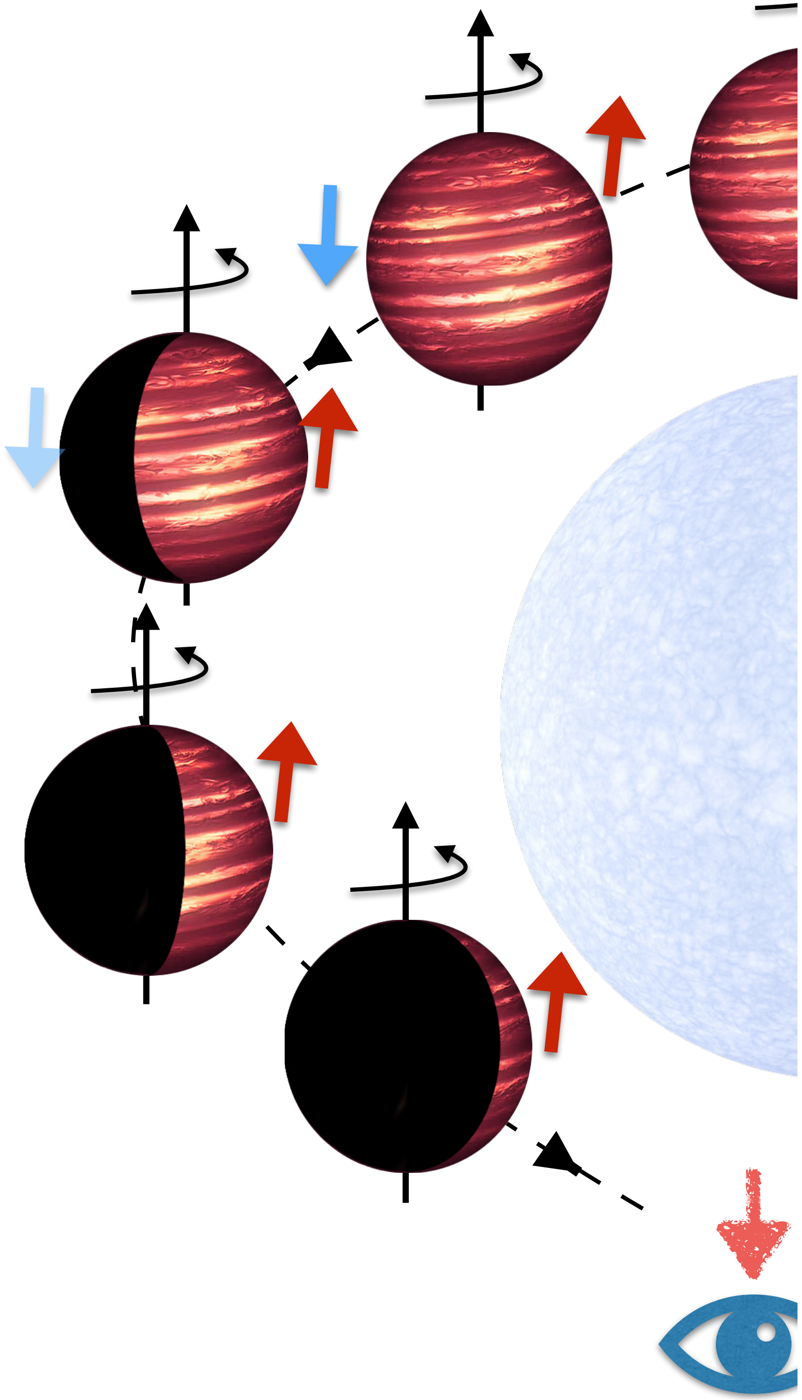


For more details: Kawahara 2012

Future works



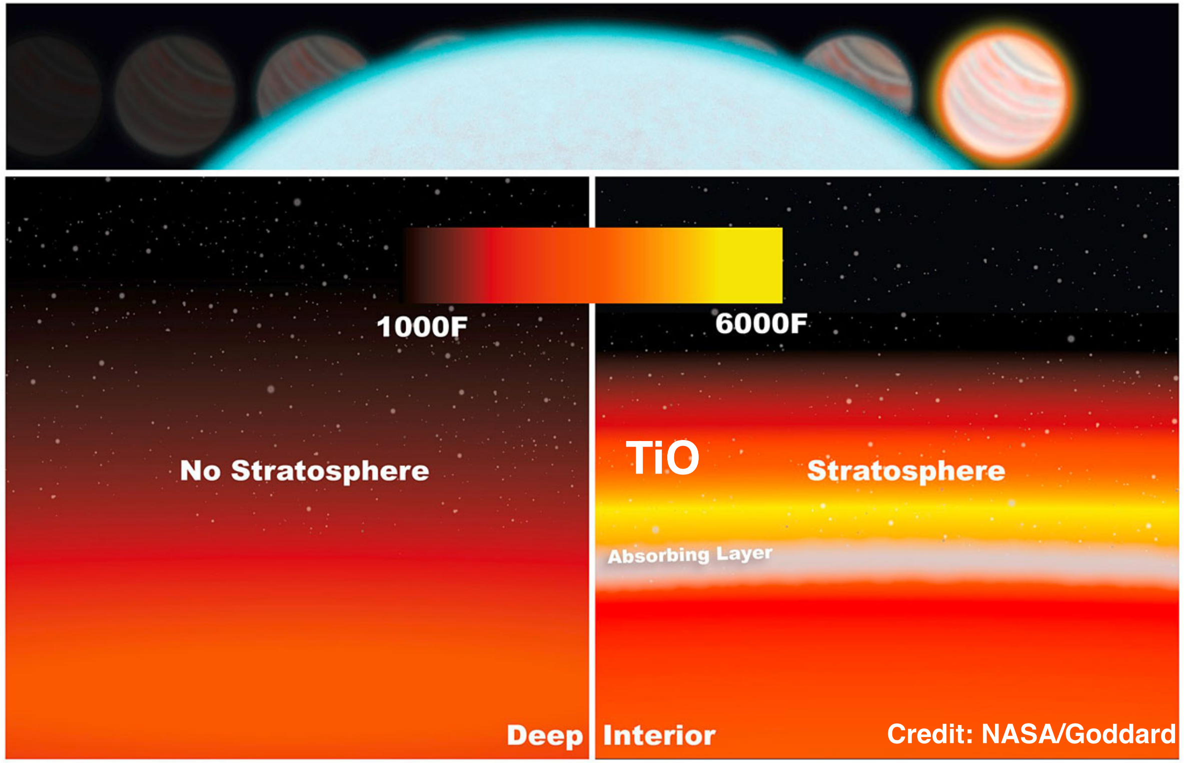




For more details: Kawahara 2012

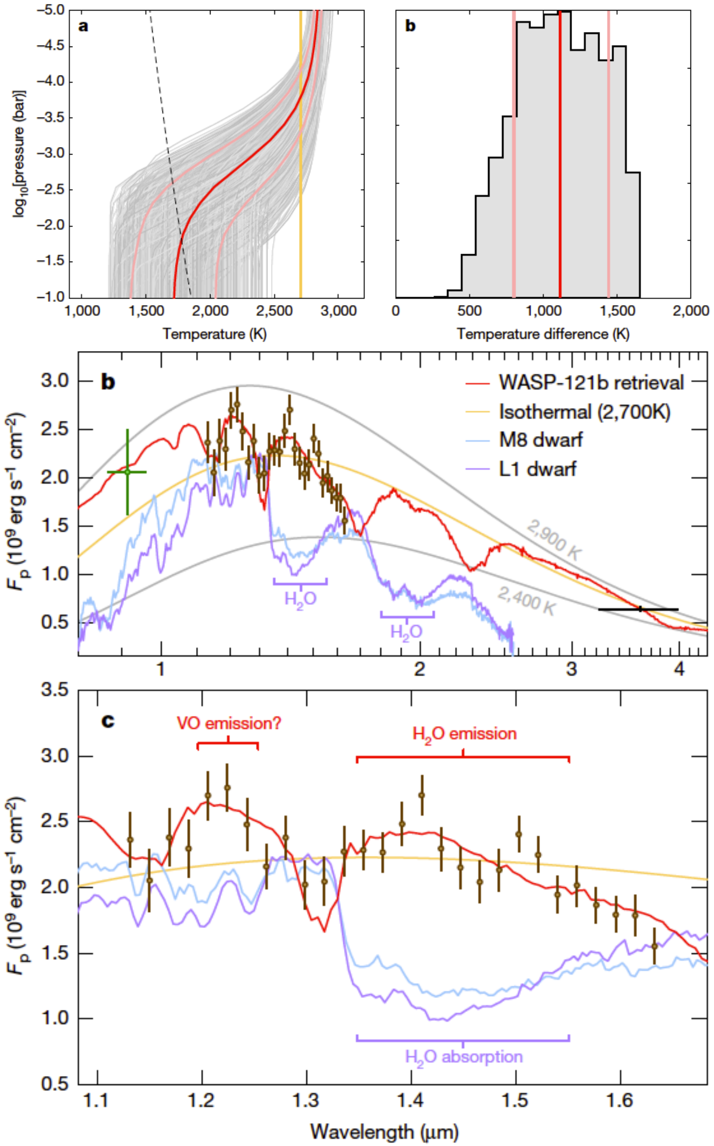
Summary

- 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



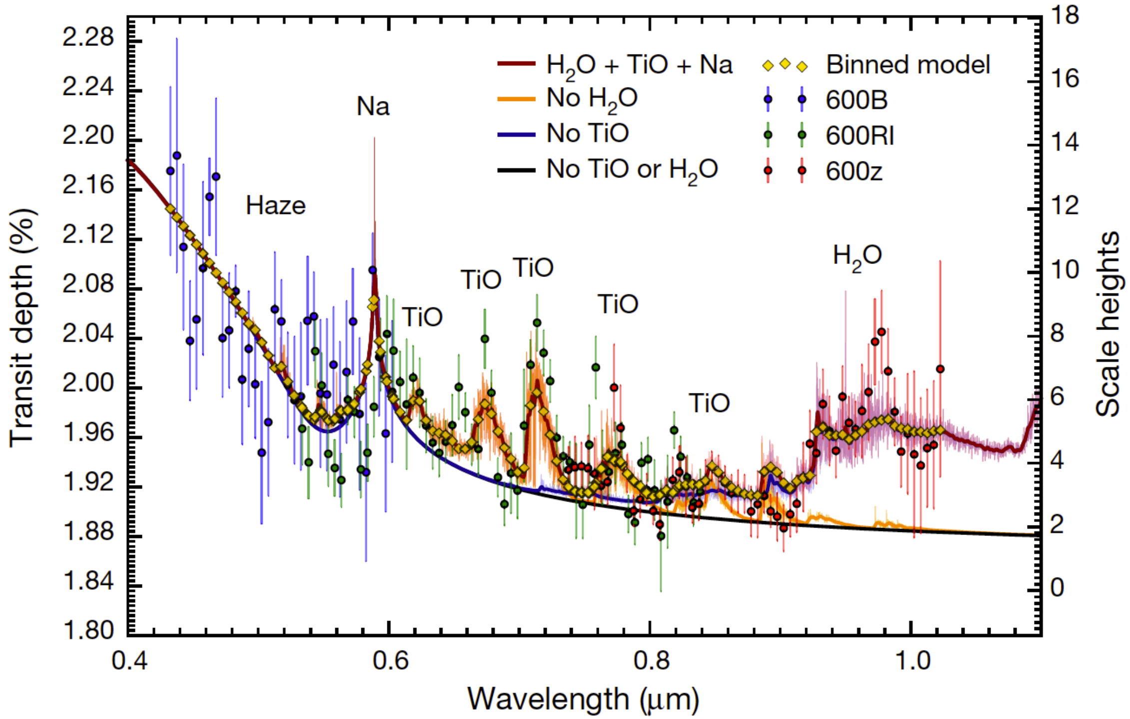
Thank you

An ultrahot gas-giant exoplanet with a stratosphere (Evans et al. 2017)

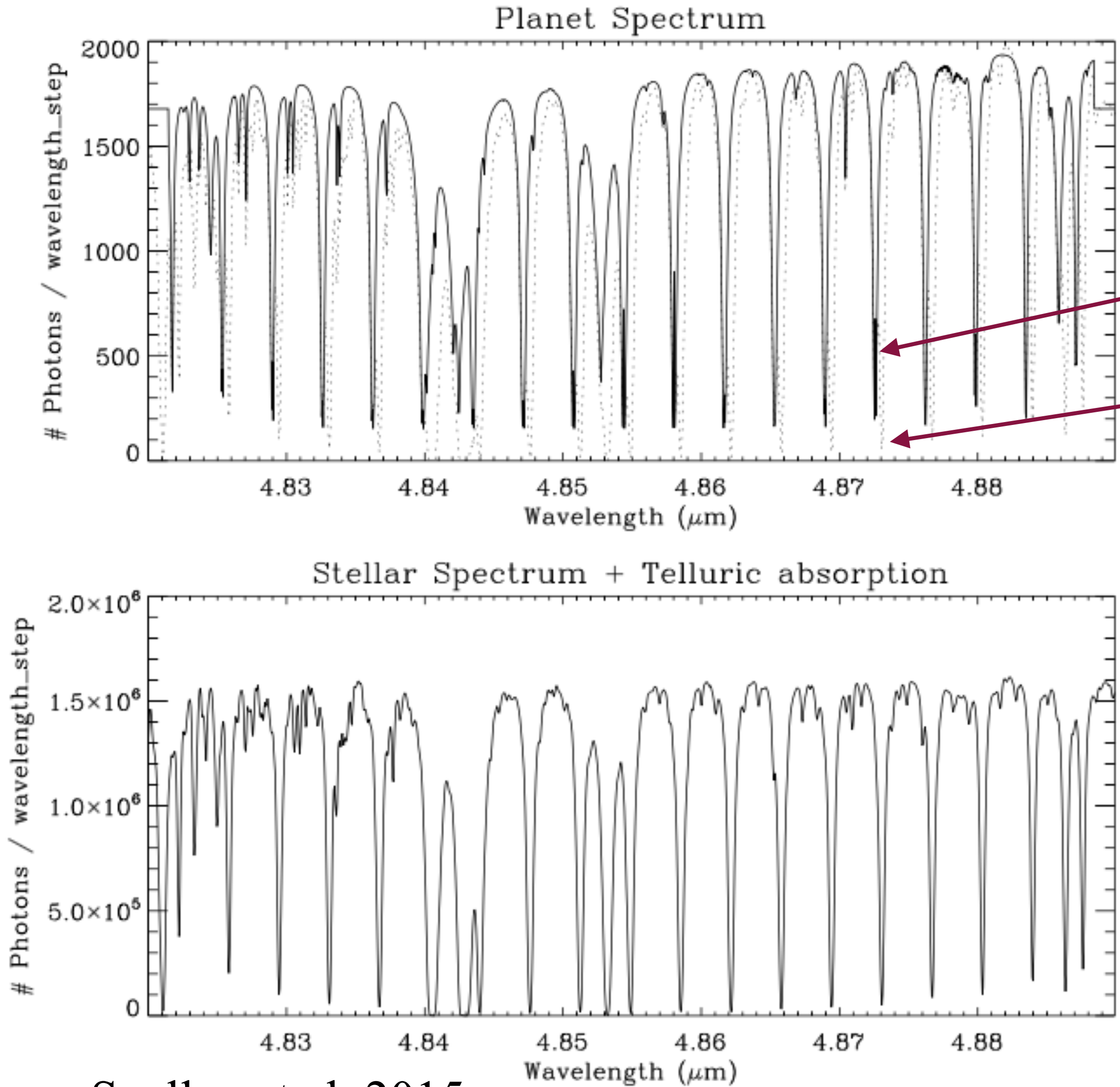


Detection of titanium oxide in the atmosphere of hot Jupiter (Sedaghati et al. 2017)

WASP-19b revolves around G8V star (m_V= 12.3) on a 0.789-day orbit



High-Dispersion Spectroscopy



Snellen et al. 2015

Separate planet spectrum from telluric spectrum

Doppler shifted Earth-like exoplanet

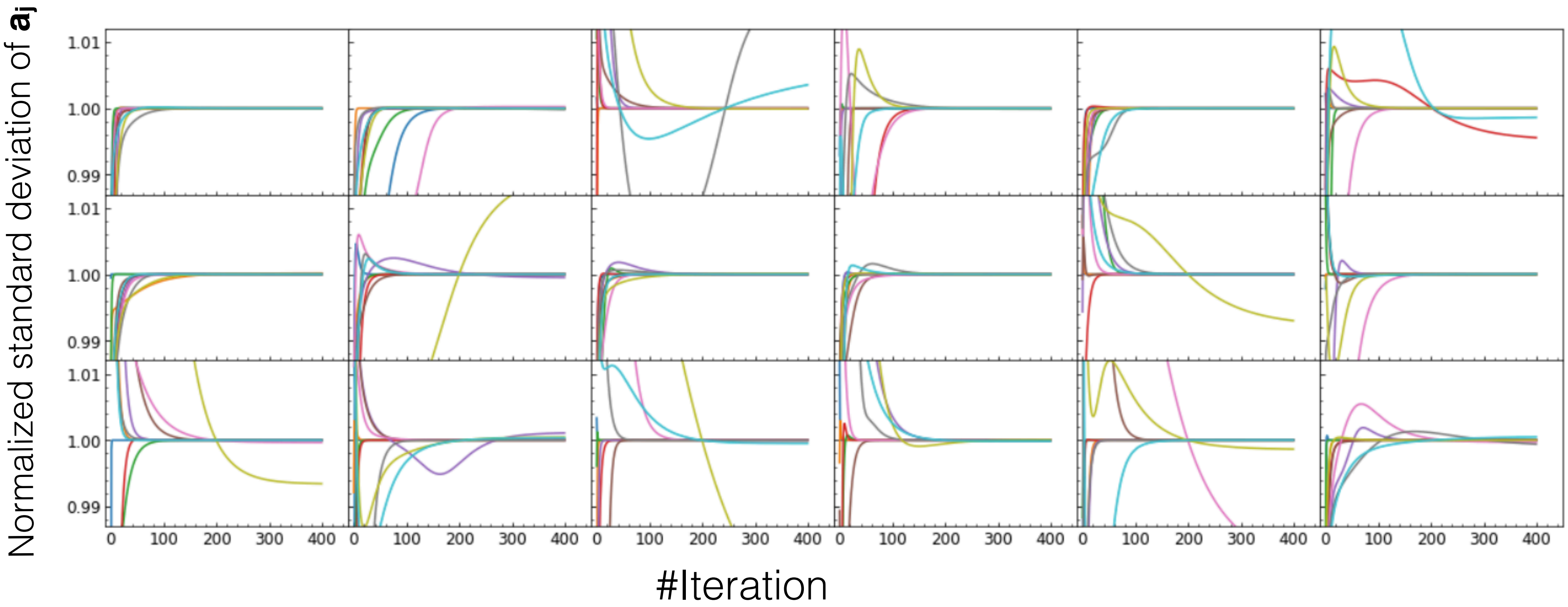
Earth's telluric spectra

$$S/N = \frac{S_{\text{planet}}}{\sqrt{S_{\text{star}} + \sigma_{\text{bg}}^2 + \sigma_{\text{RN}}^2 + \sigma_{\text{Dark}}^2}} \sqrt{N_{\text{lines}}} \qquad (1)$$

lines	velocity	origin
Planetary lines	$V_p + V_{\text{sys}}$	$A(\lambda)$ in $f_{\text{p}}(\lambda)$
Scattered stellar lines	$V_p + V_{\text{sys}}$	$F_\star(\lambda)$ in $f_{\text{p}}(\lambda)$
Speckle stellar lines	V_{sys}	$f_{\text{speckle}}(\lambda)$
Telluric lines	0	$T(\lambda)$
Airglow	0	$f_{\text{sky}}(\lambda)$

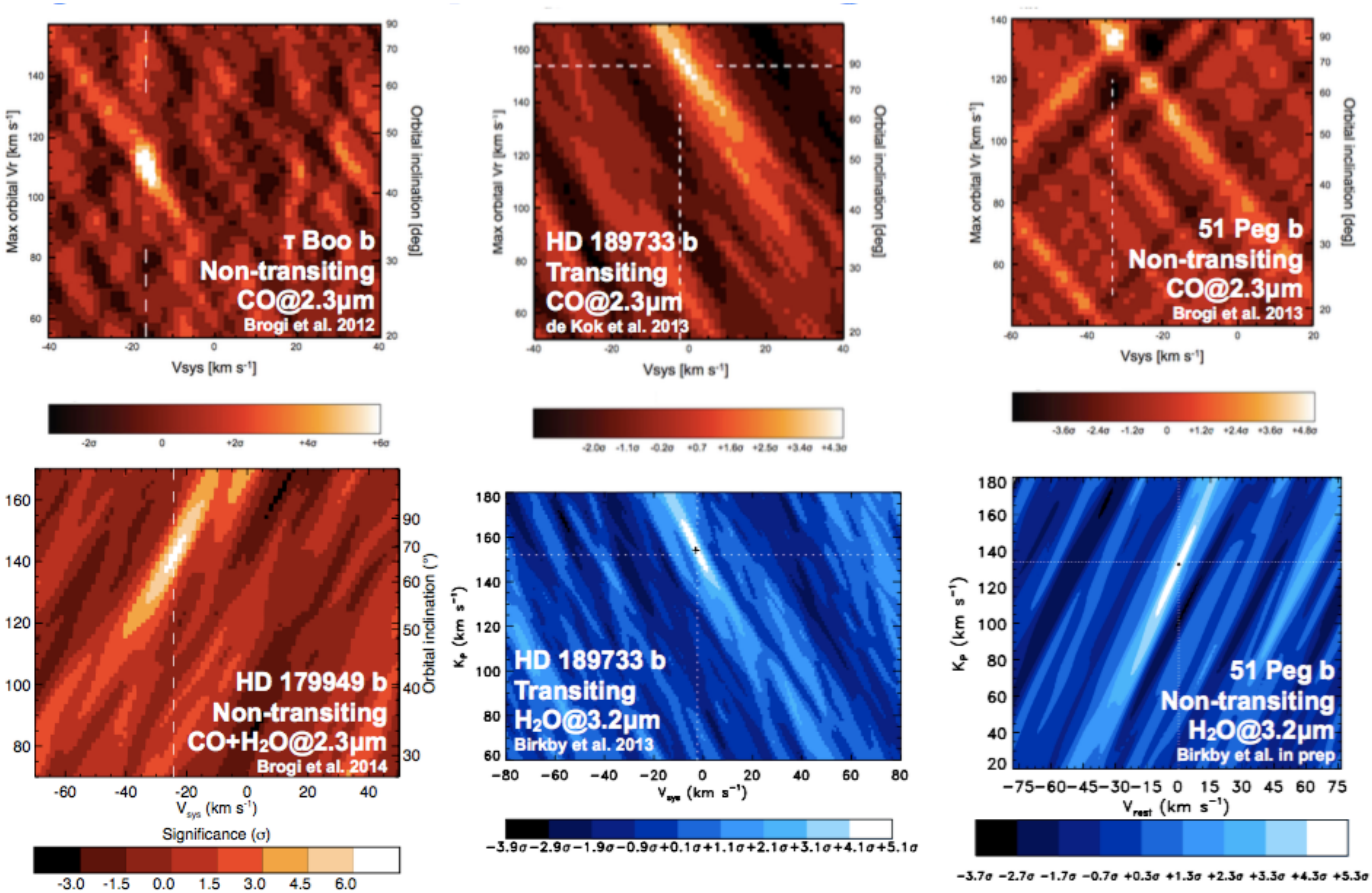
Kawahara et al. 2014

Evaluating on how many iteration for one systematics model should we do



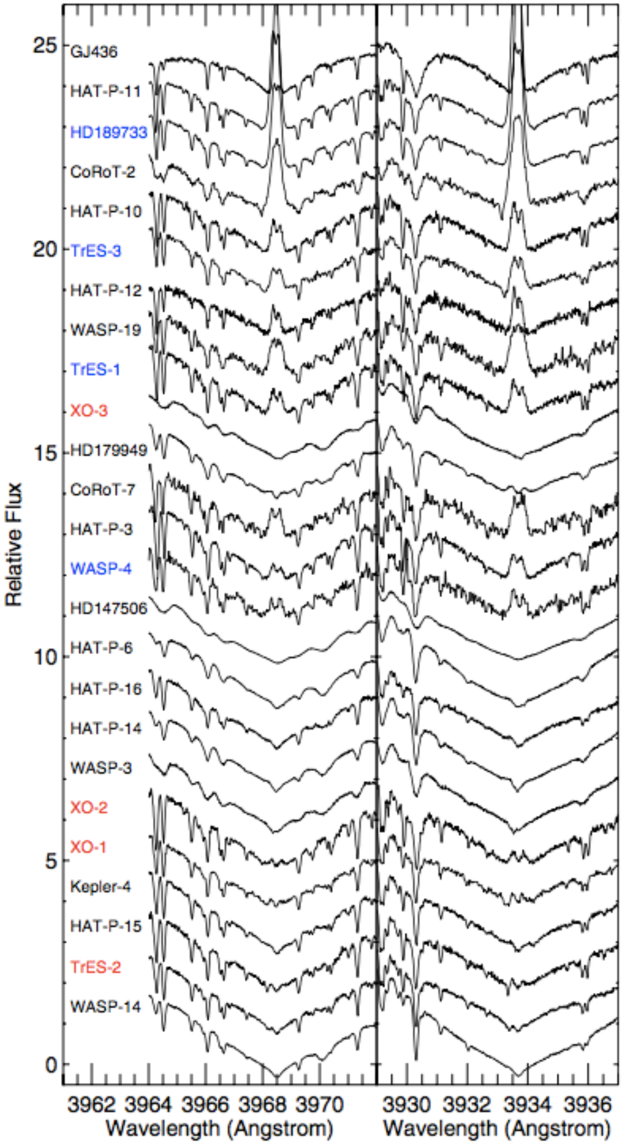
Until the <u>standard deviation</u> of $\mathbf{a_j}$ and $\mathbf{c_i}$ does not change

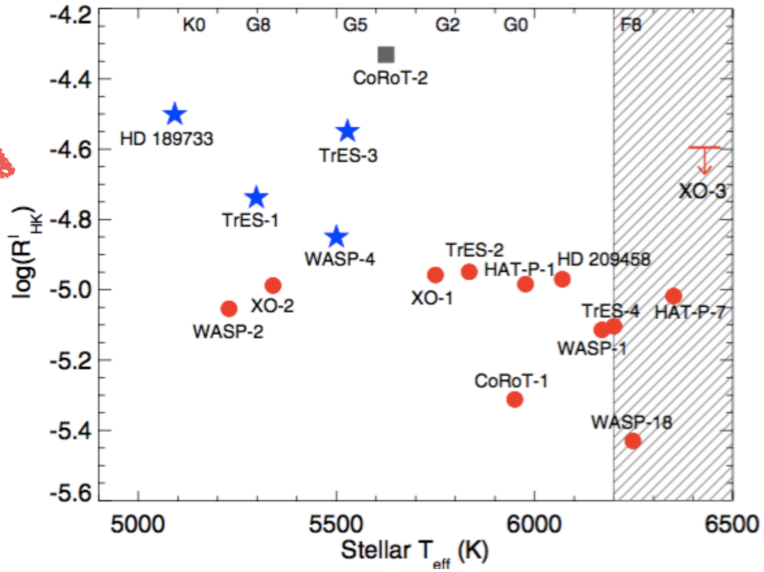
High Dispersion Spectroscopy

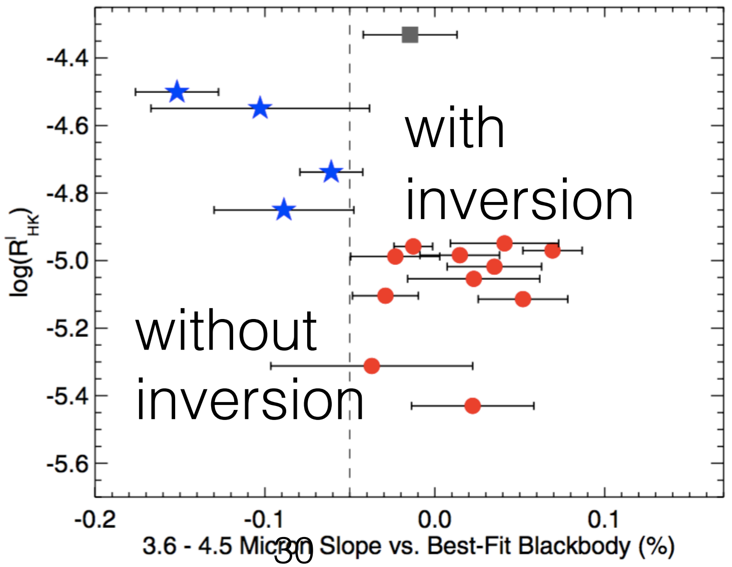


Well, some are hot enough but no temperature inversion

Possible Explanation: UV Chromospheric Stellar Activity?







Planets **with** strong inversions

< fluxes at 3.6 μm

> fluxes at 4.5 μm

Planets **without** inversions

> fluxes at 3.6 μm

< fluxes at 4.5 μm

compared to best-fit blackbody function

Knutson et al. (2010)