



Universiteit  
Leiden  
The Netherlands

## **Narrow band transmission spectroscopy**

Casasayas Barris, N.; Seidel, J.

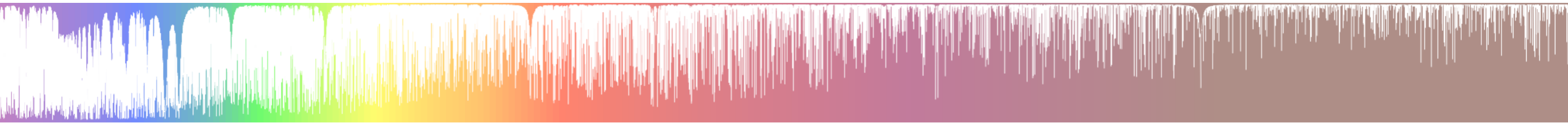
### **Citation**

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# Narrow band transmission spectroscopy



**Núria Casasayas Barris**  
**Julia V. Seidel**

**Atmo 2021 - Workshop**

23 August 2021

**ATMOSPHERES,  
ATMOSPHERES!**

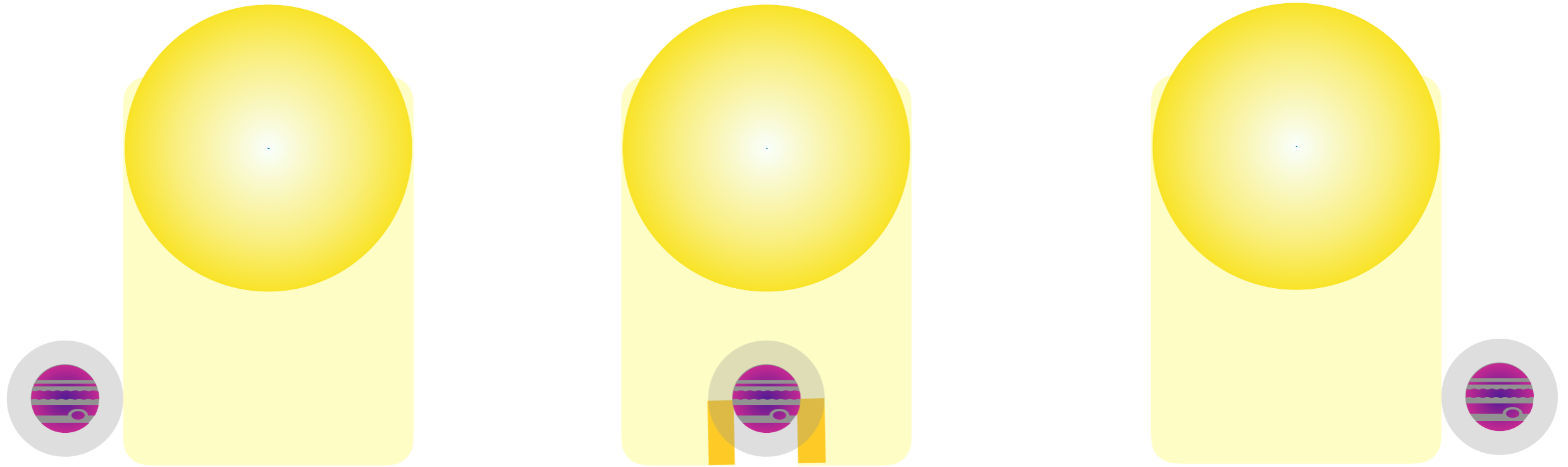
Do I look like I care  
about atmospheres?

# Transmission spectroscopy

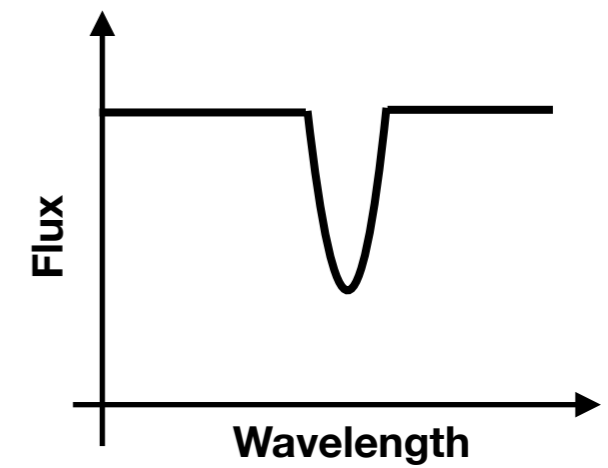
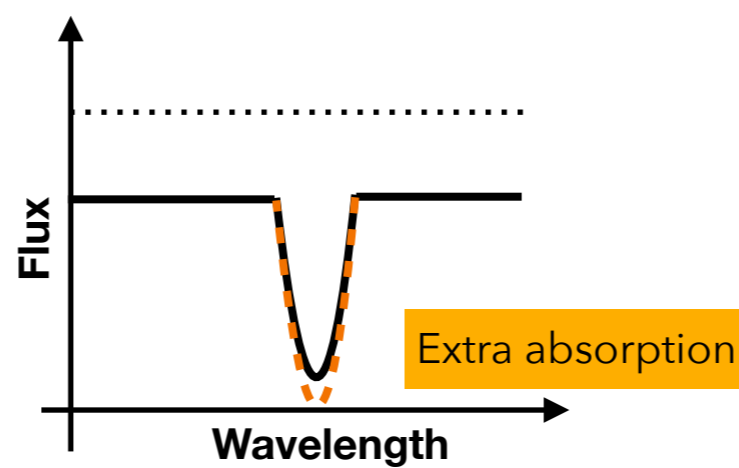
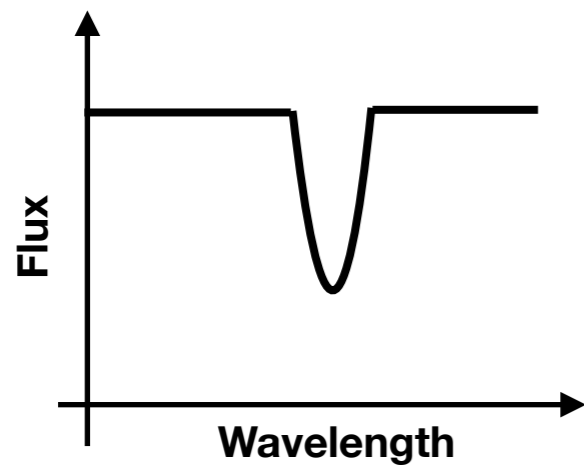
Before the transit

During the transit

After the transit

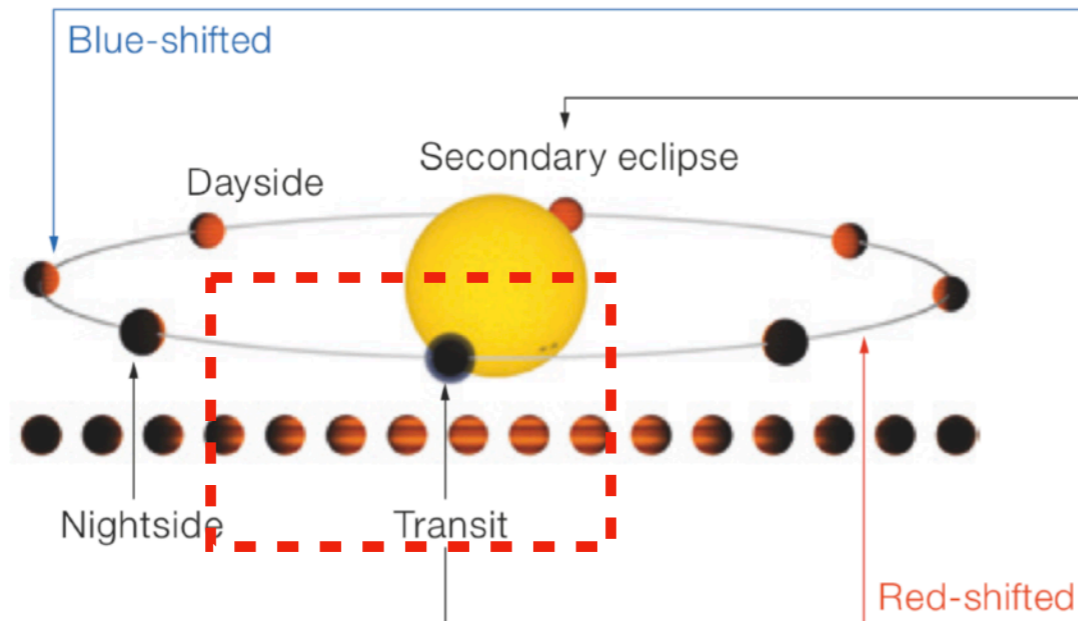


Stellar line profile



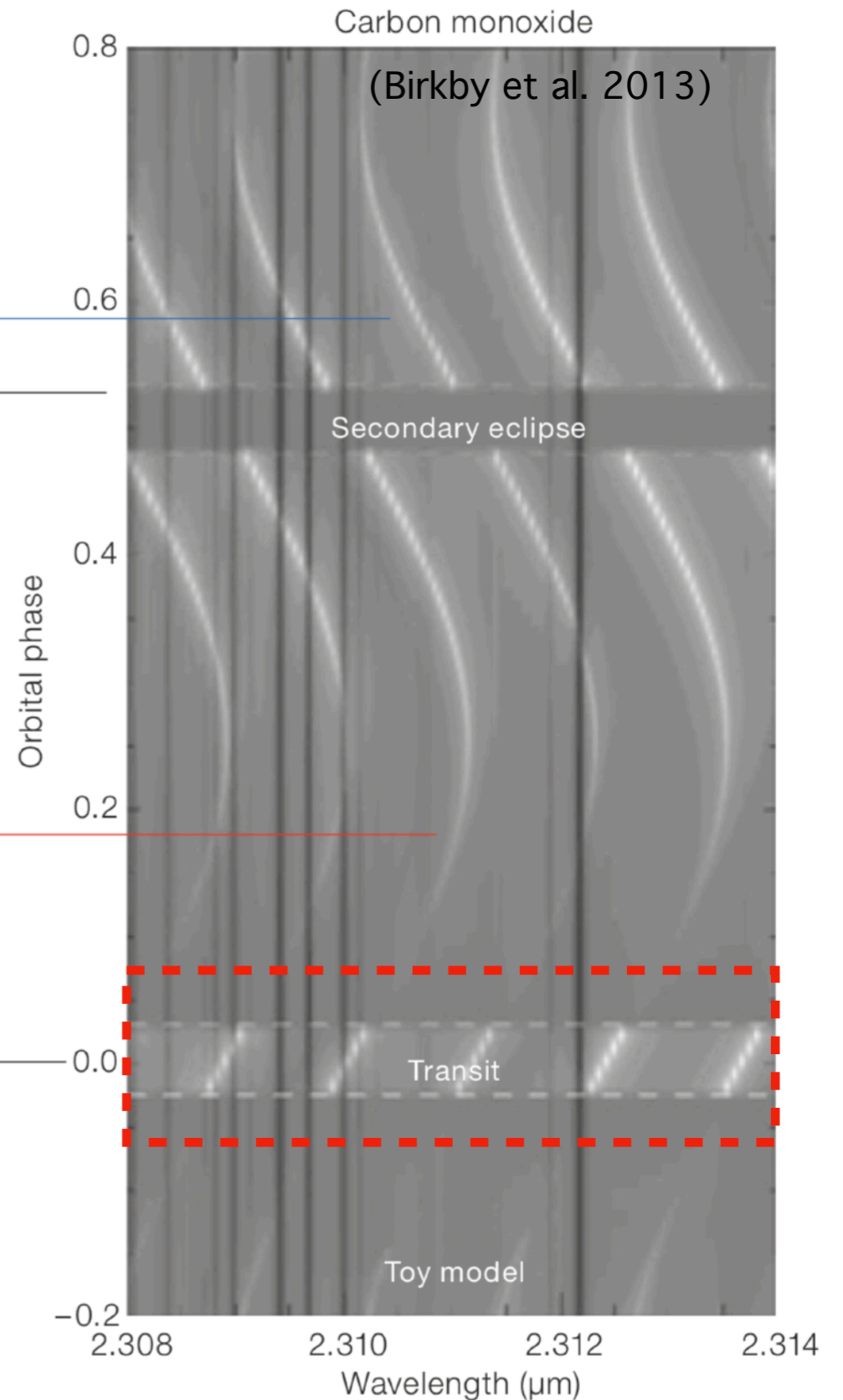
# High-resolution transmission spectroscopy

$\mathcal{R} > 50\,000$



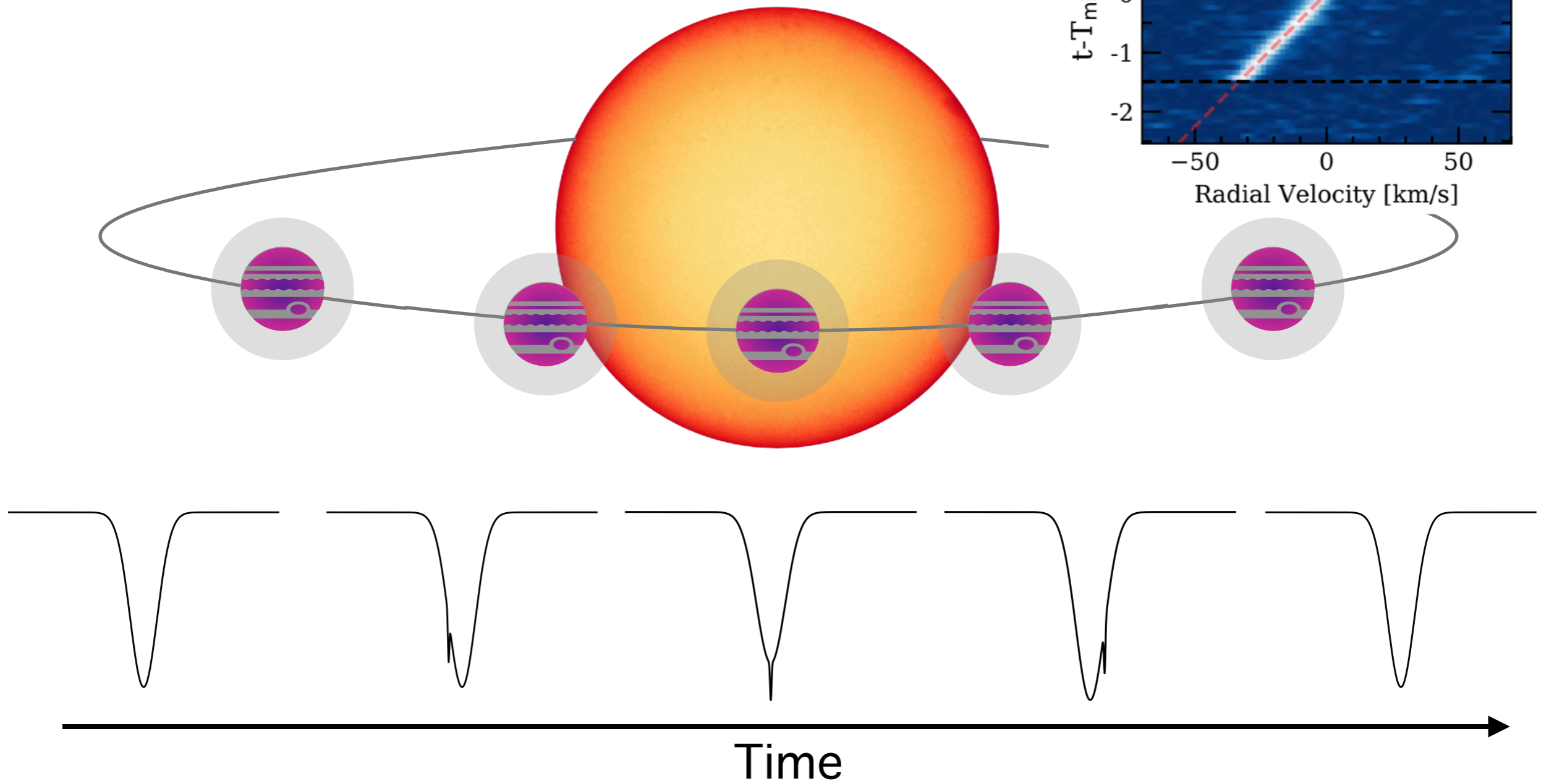
$$\frac{\Delta\lambda}{\lambda_0} = \frac{v}{c}$$

Telluric and stellar lines ~ static  
Planet lines shift throughout the orbit



# High-resolution transmission spectroscopy

Planet movement



# Observations



**HDS@Subaru**

Credit: NOAO

**ESPRESSO@VLT**

Credit: ESO

**HARPS@3.6m  
La Silla**

Credit: ESO

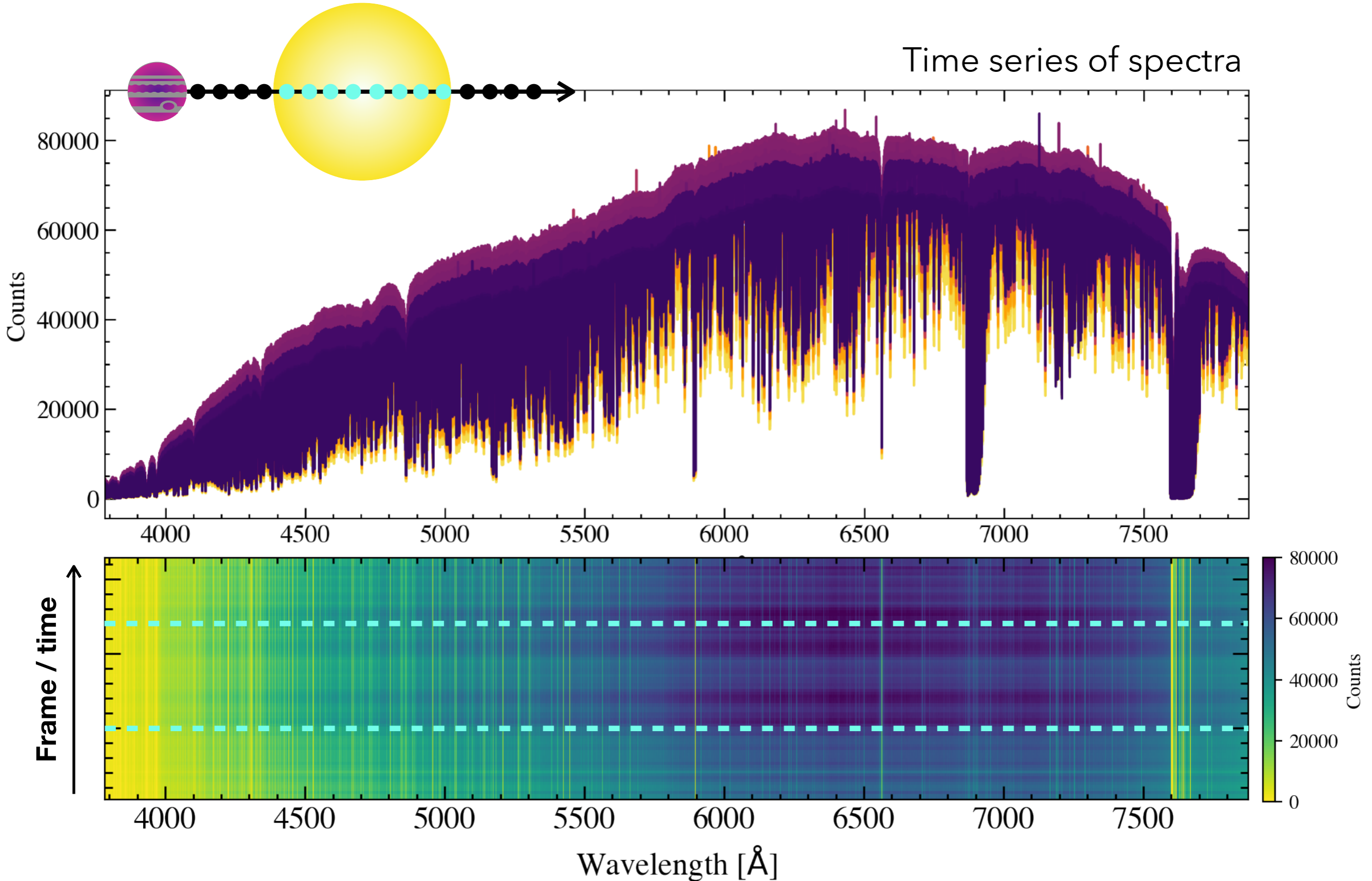
**HARPS-N@TNG**

**CARMENES@3.5CAHA**

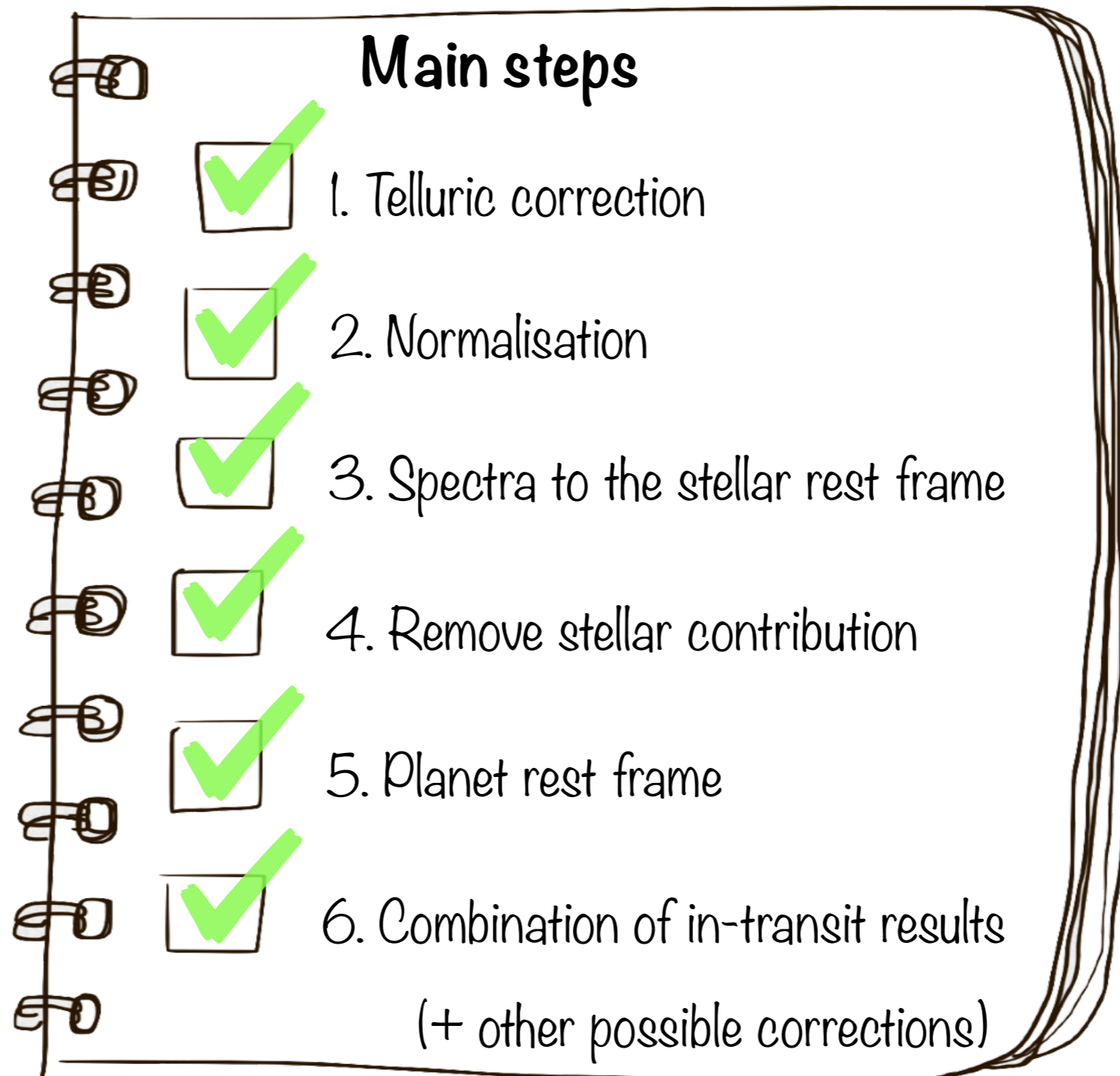
**carmenes**

# Observations

Time series of spectra



# Extracting the transmission spectrum

- 
- Main steps**
- 1. Telluric correction
  - 2. Normalisation
  - 3. Spectra to the stellar rest frame
  - 4. Remove stellar contribution
  - 5. Planet rest frame
  - 6. Combination of in-transit results
- (+ other possible corrections)

Wytttenbach et al. (2015)

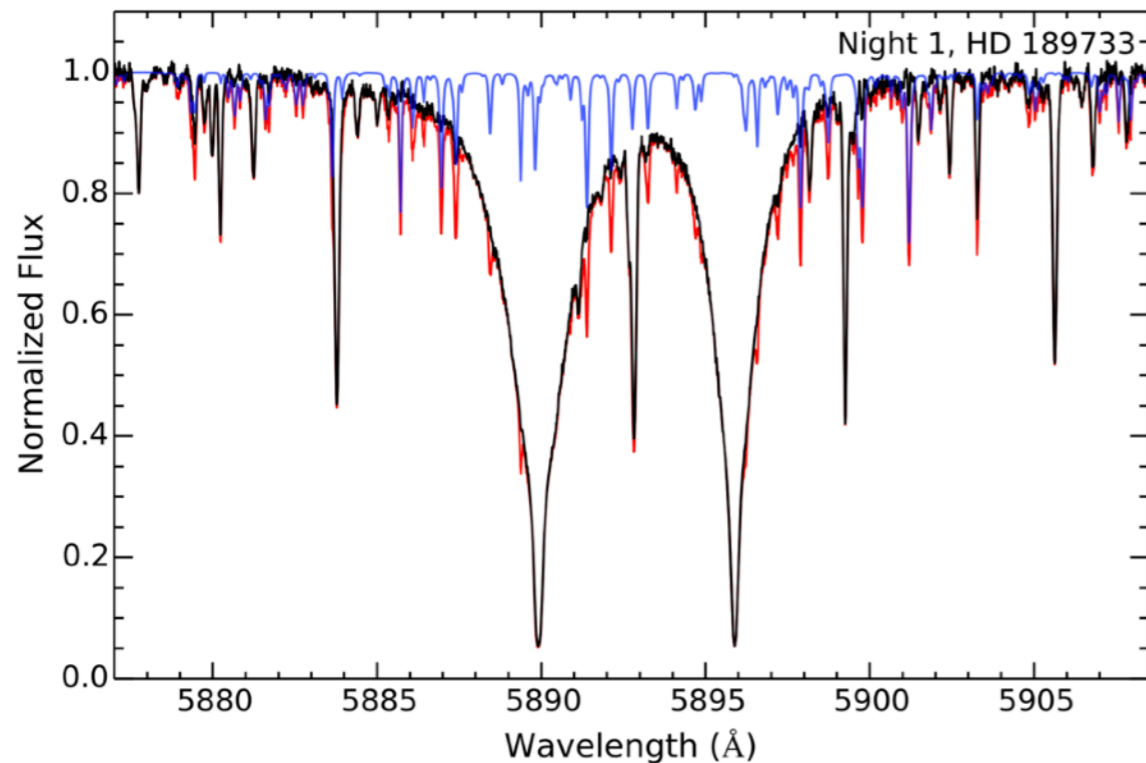


# Extracting the transmission spectrum

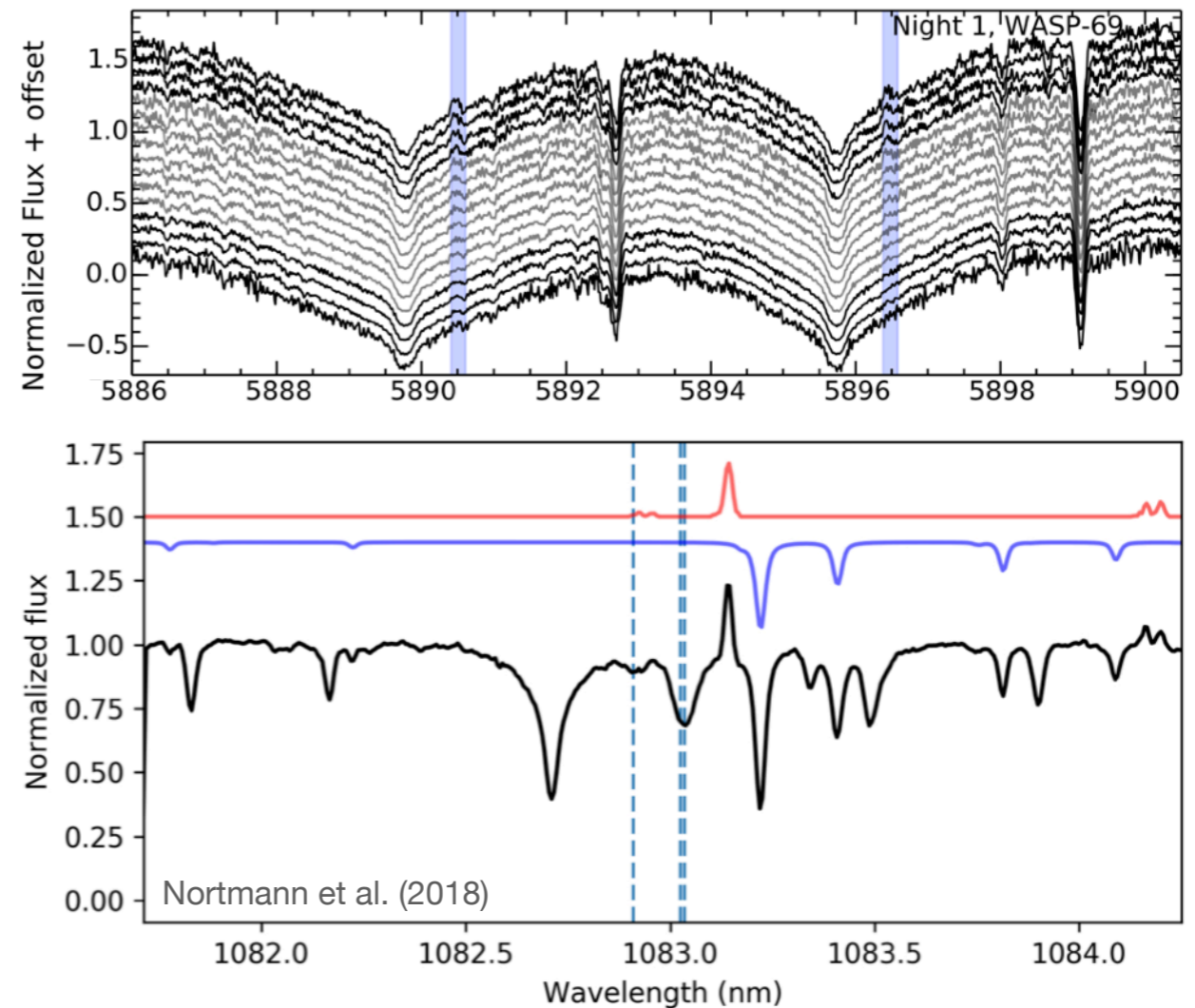


## 1. Telluric correction

○ **Telluric absorption:** H<sub>2</sub>O, O<sub>2</sub>



○ **Telluric emission:** NaI, OH...



Different methodologies:

- Airmass evolution (Wytenbach et al. 2015)
- **Molecfit** (Allart et al. 2017)
- ...

Molecfit lecture!

Sky observations with fibre B

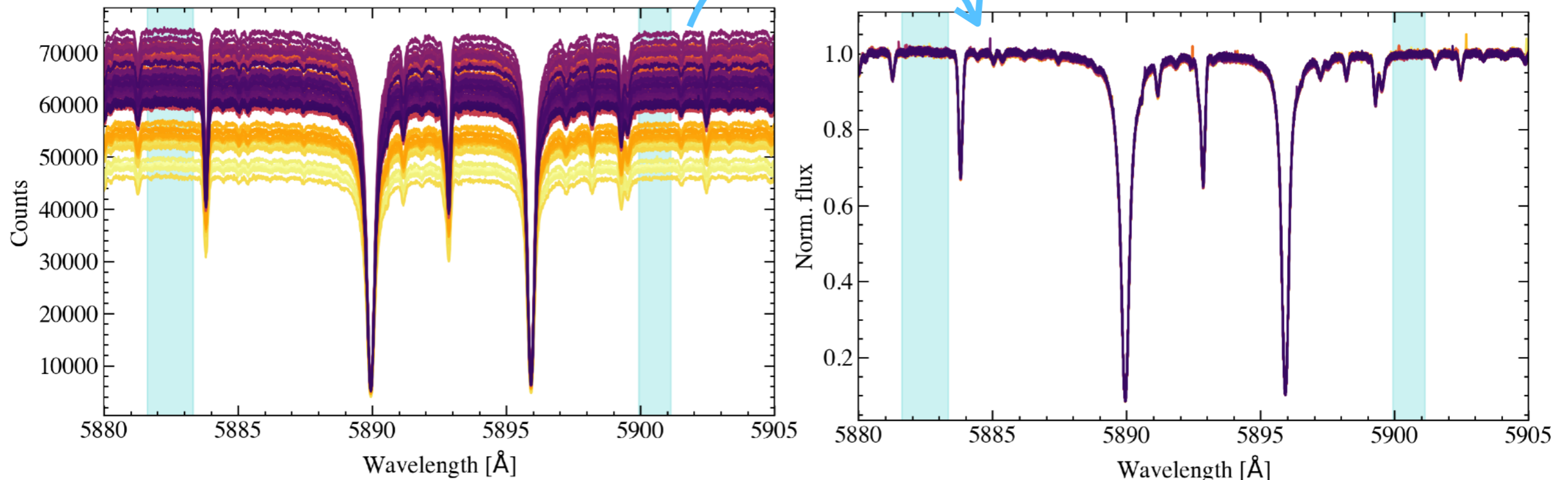
# Extracting the transmission spectrum



## 2. Normalisation

- Several methodologies
  - Fit the continuum with polynomial
  - Mean counts in a region of the continuum
  - Specific tools for normalisation
  - ...

The normalisation can also be performed at the end of the process (see tutorial!)

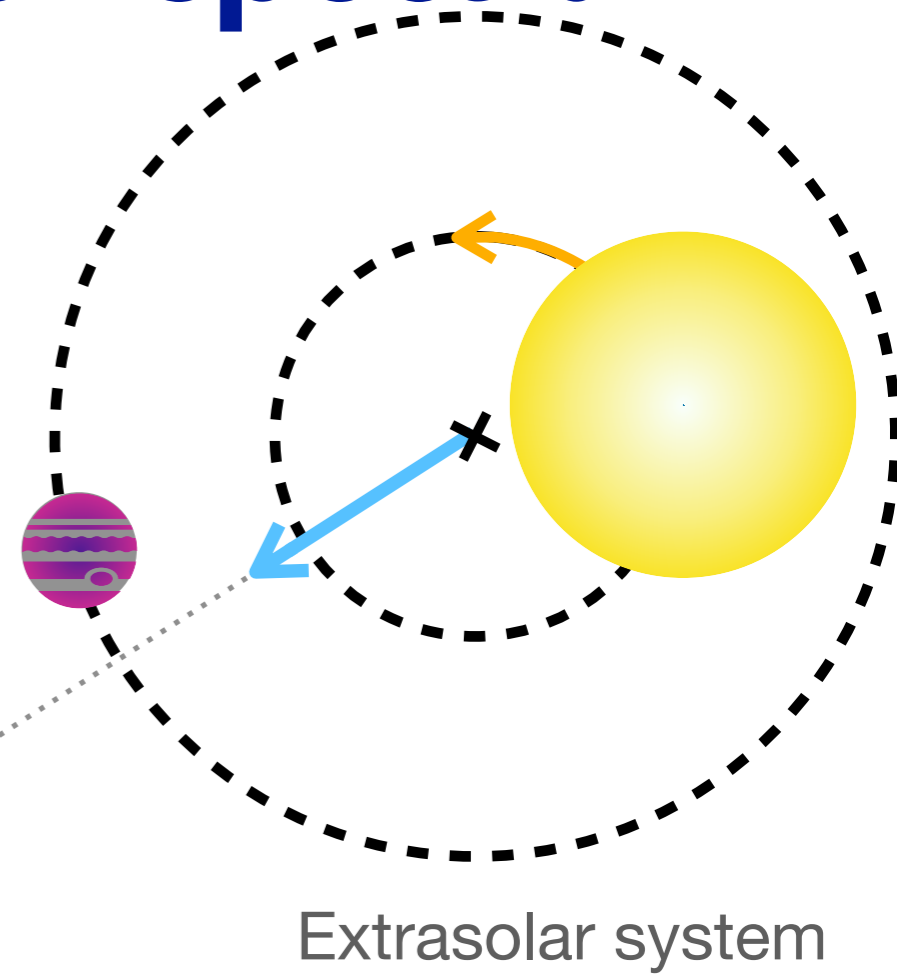


# Extracting the transmission spectrum



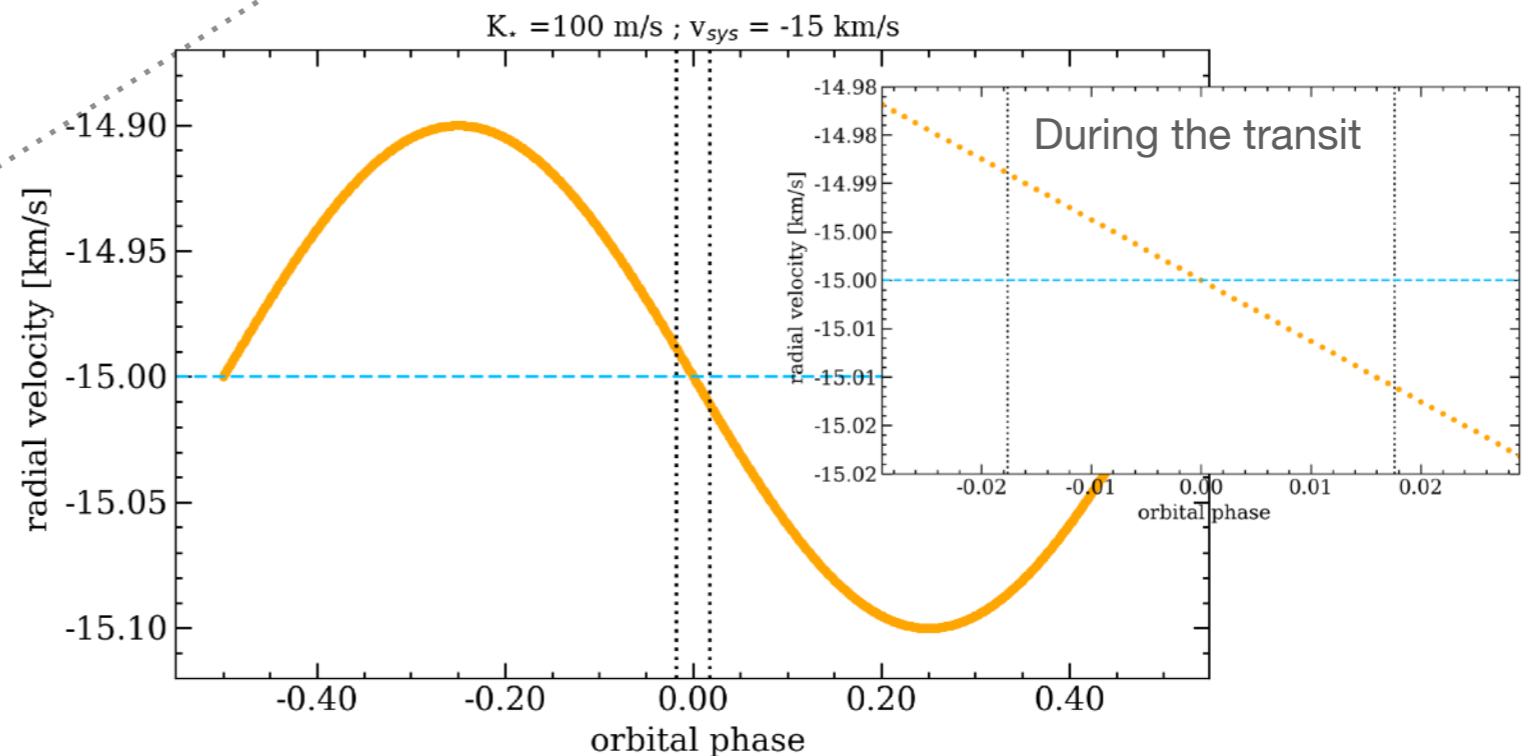
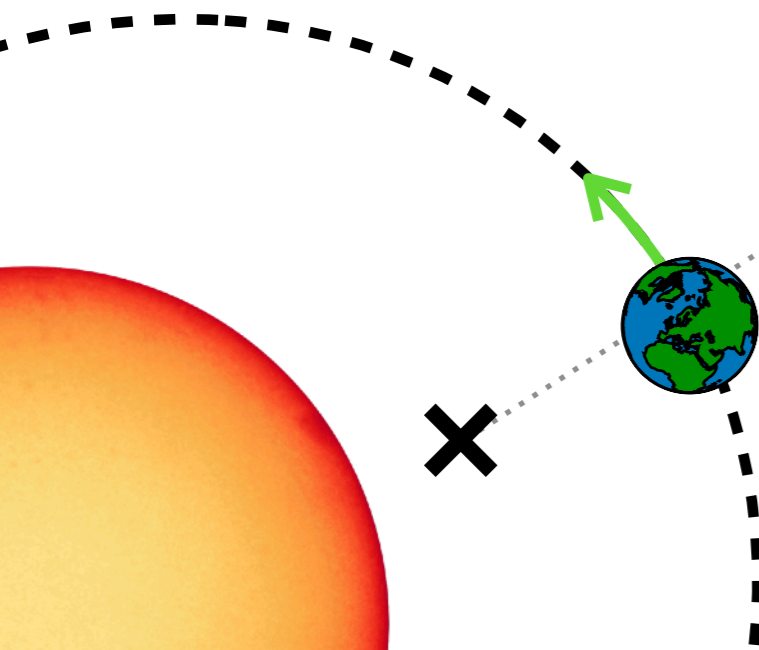
## 3. Stellar rest frame

$$RV_{\star}^i = \begin{cases} K_{\star} \times \sin(2\pi\phi_i) & \text{Stellar motion} \quad \sim \text{m/s} \\ v_{\text{sys}} & \text{System velocity} \quad \sim \text{km/s} \\ RV_{\text{Earth}}^i & \text{Earth Radial velocity} \quad \sim \text{km/s} \end{cases}$$



Extrasolar system

Solar System



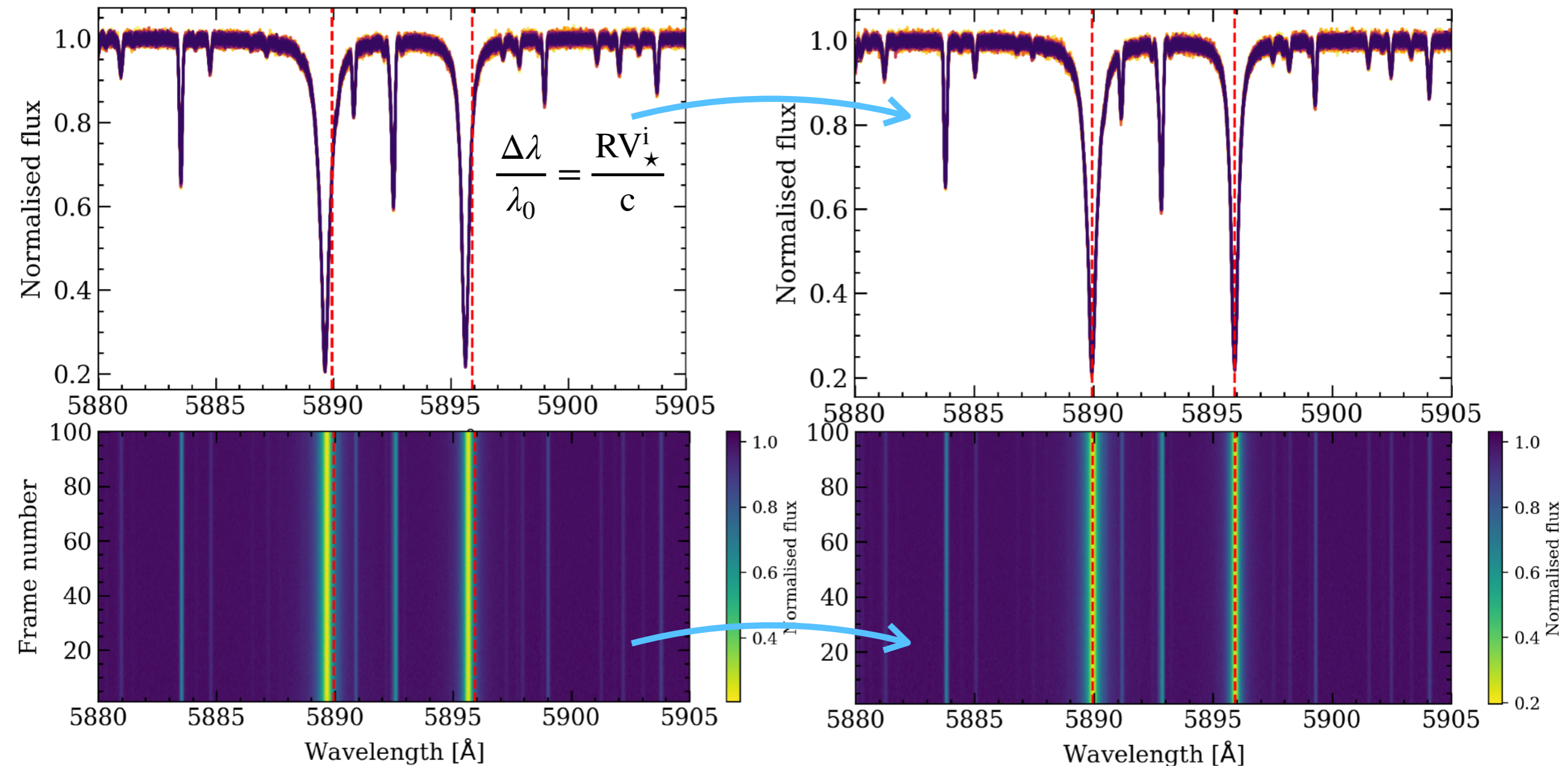
# Extracting the transmission spectrum



## 3. Stellar rest frame

Observations rest frame

Stellar rest frame



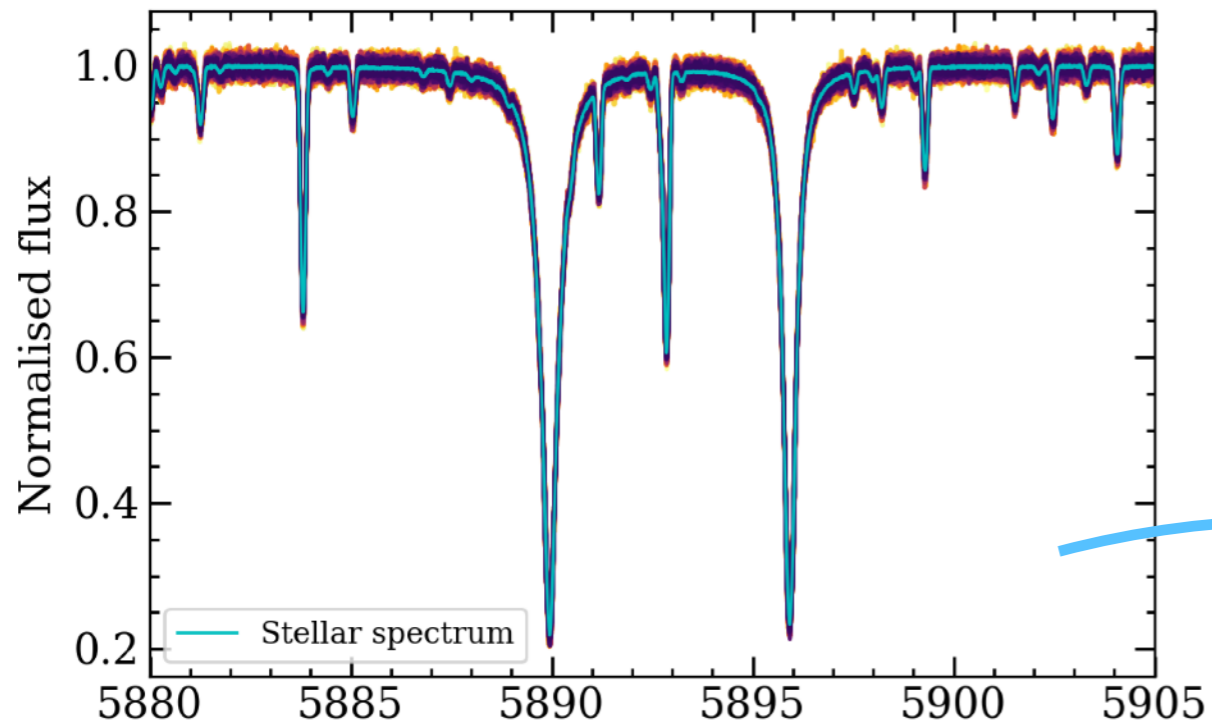
# Extracting the transmission spectrum



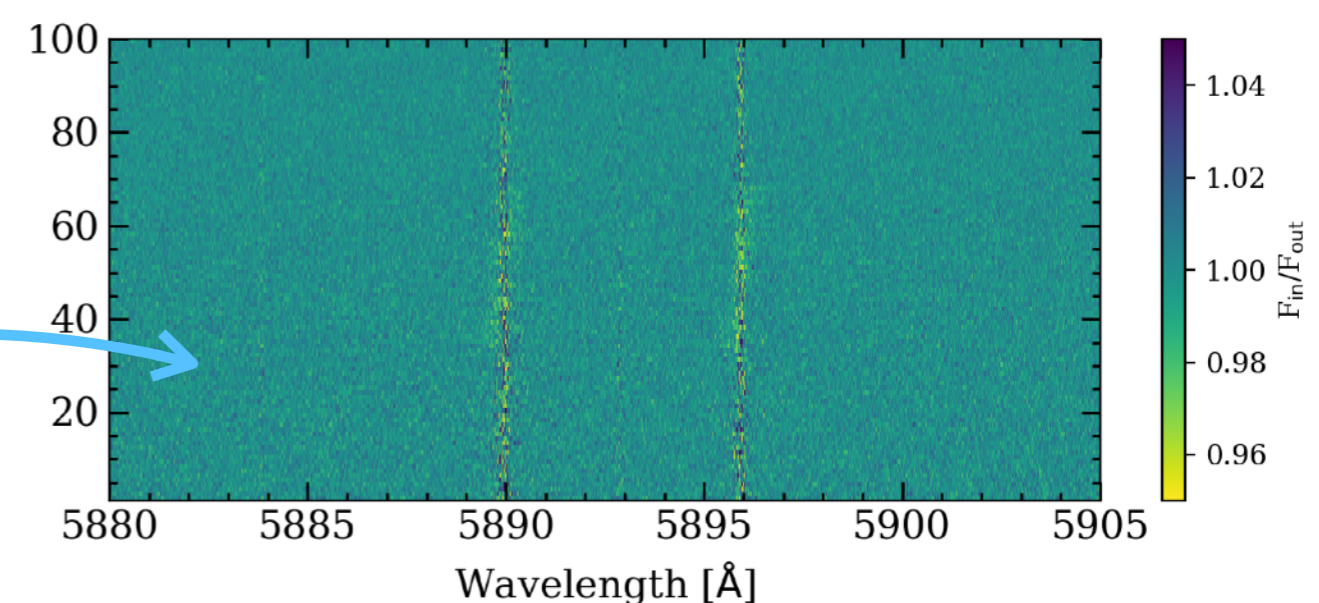
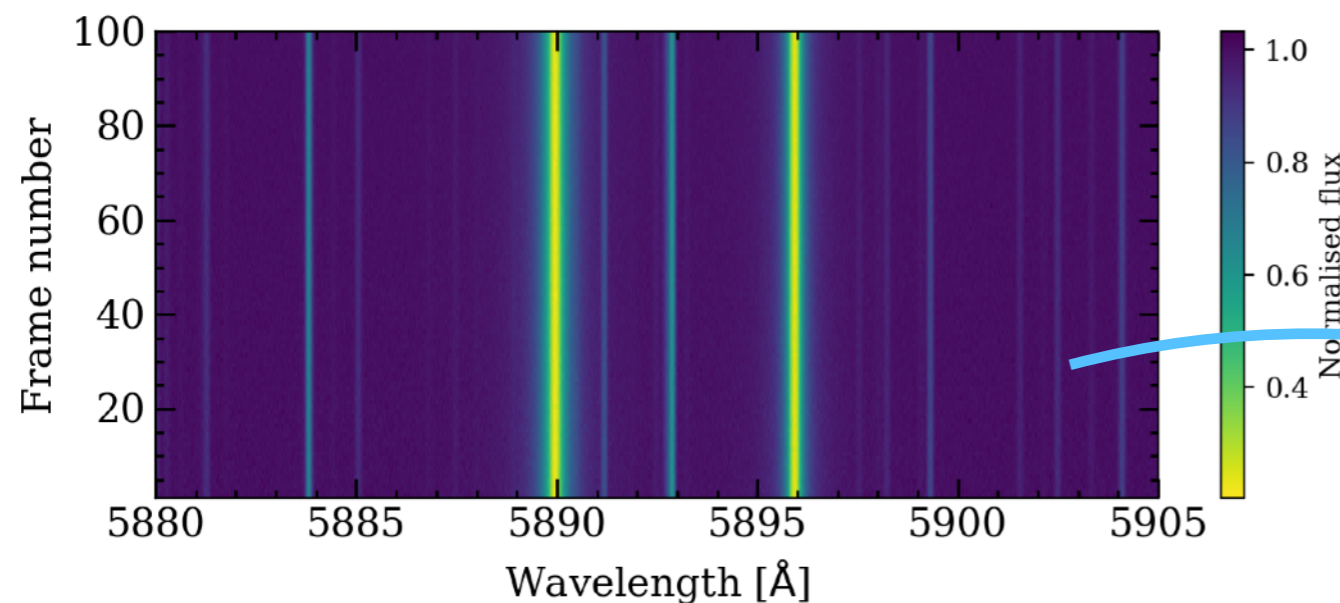
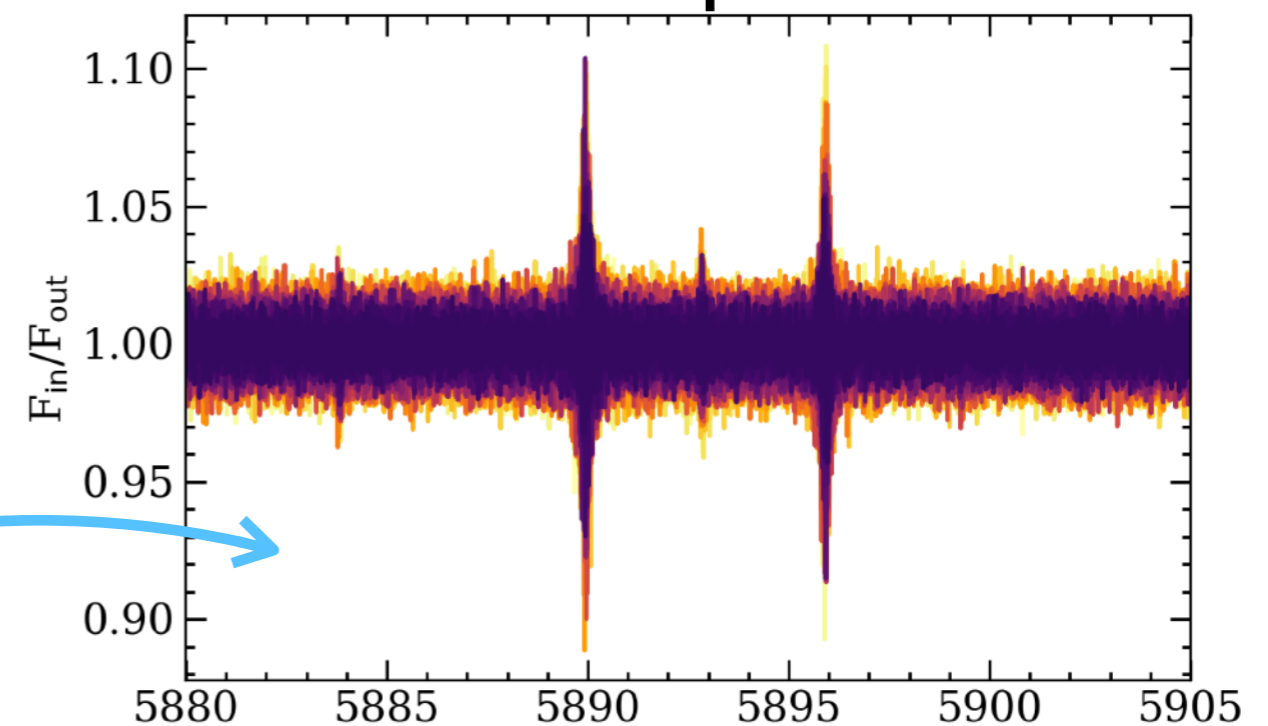
## 4. Remove stellar contribution

### Master out-of-transit stellar spectrum

Combination of all out-of-transit spectra



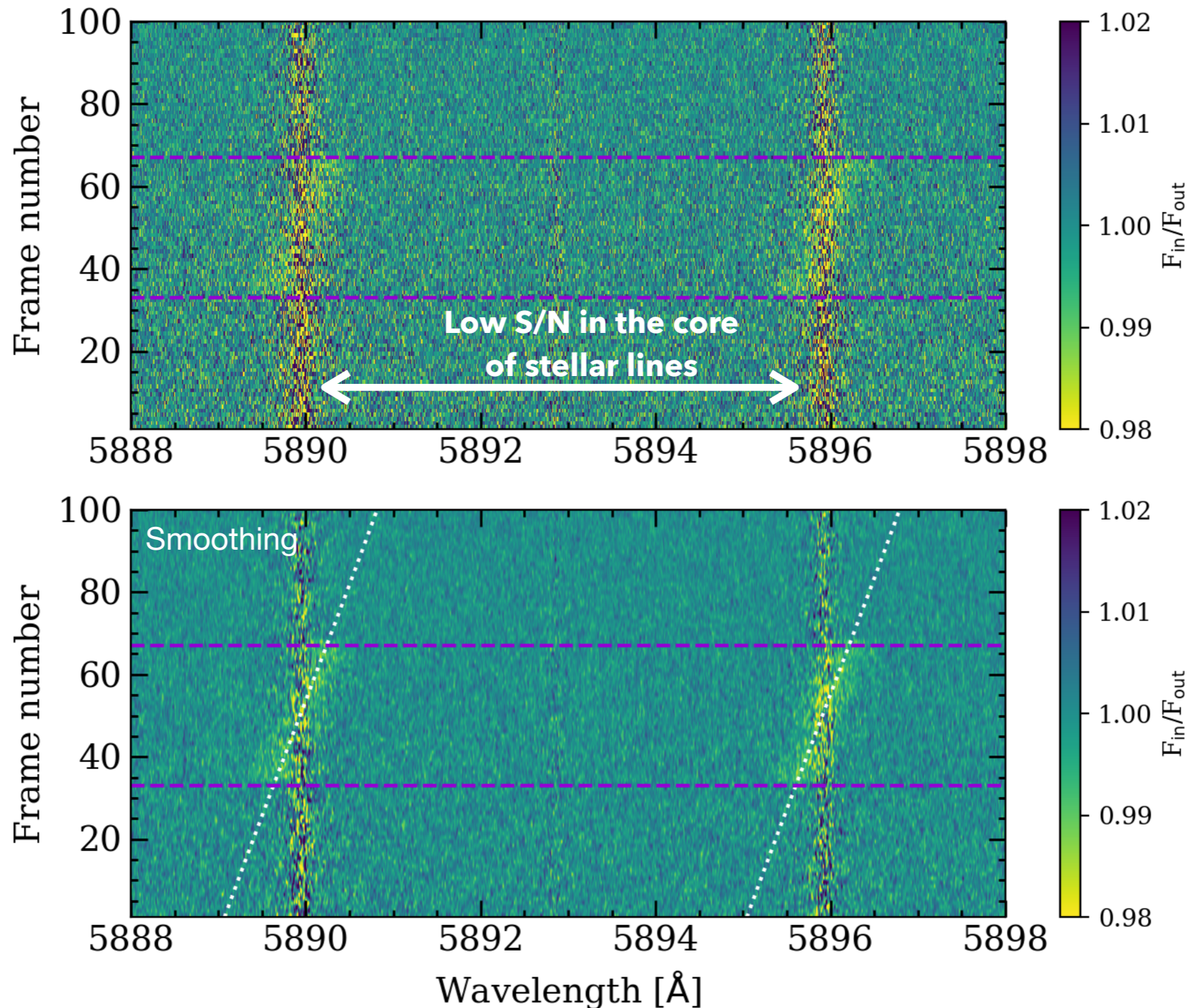
### Division of each spectrum by the Master spectrum



# Extracting the transmission spectrum



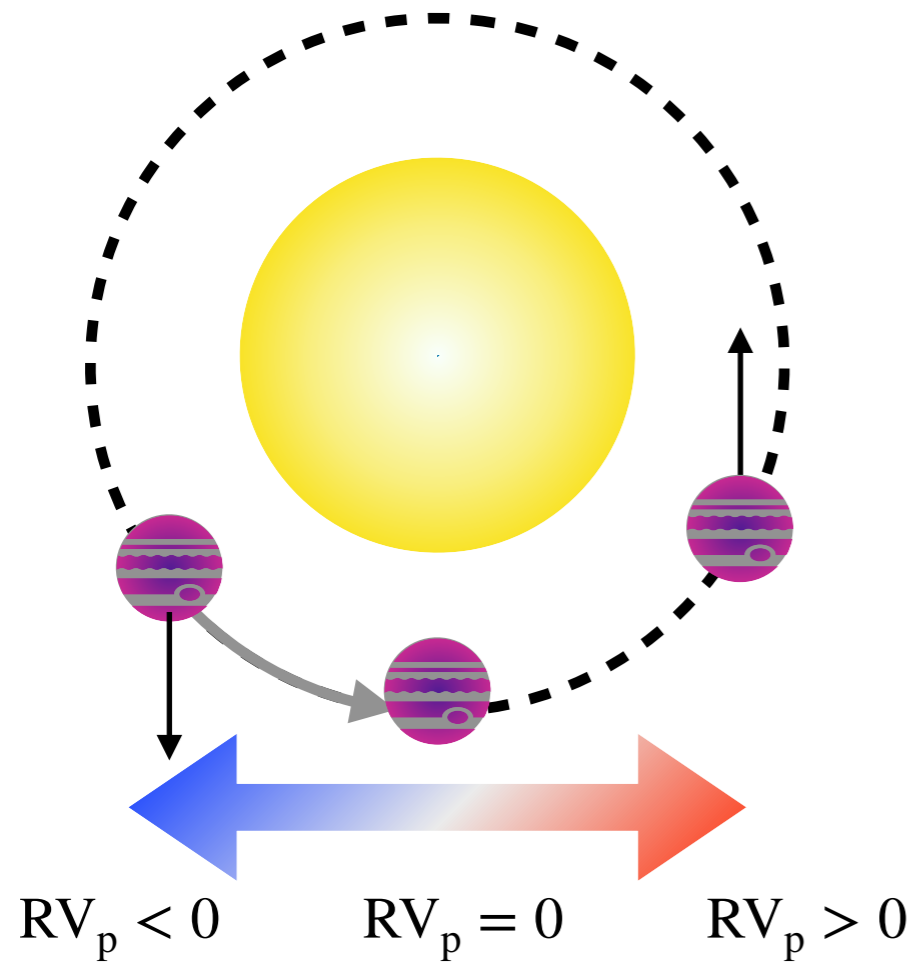
## 4. Remove stellar contribution



# Extracting the transmission spectrum



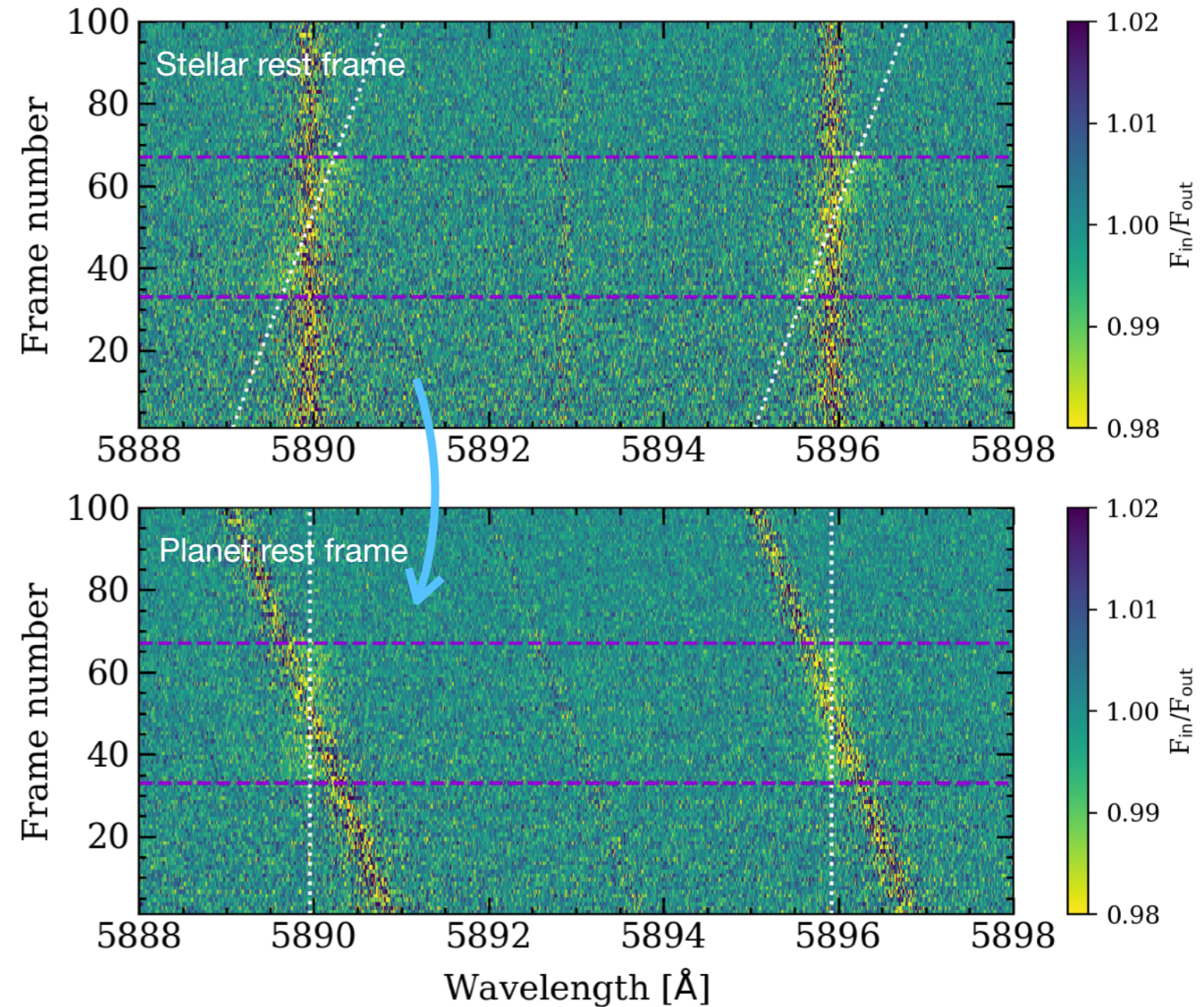
## 5. Planet rest frame



$$RV_p^i = K_p \times \sin(2\pi\psi_i)$$

$$K_p = \frac{2\pi a}{P} \sin(i_p) \quad (e = 0 \text{ and } M_p \ll M_\star)$$

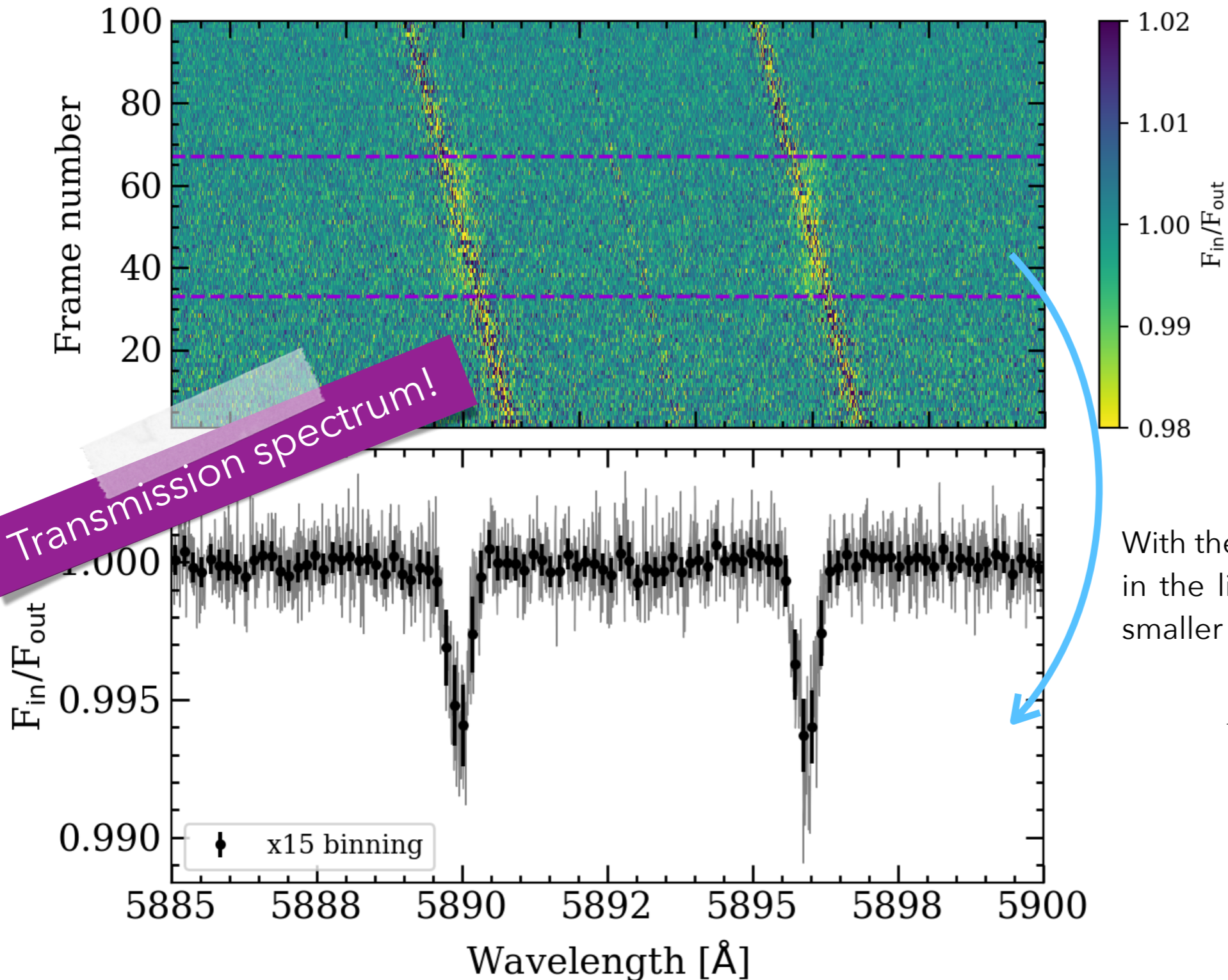
$$K_p = K_\star \frac{M_\star}{M_p}$$



# Extracting the transmission spectrum



## 6. Combination of in-transit data



With the weighted mean the pixels in the lines core (low S/N) have a smaller contribution. Usually:

$$w_i = 1/\sigma_i^2$$

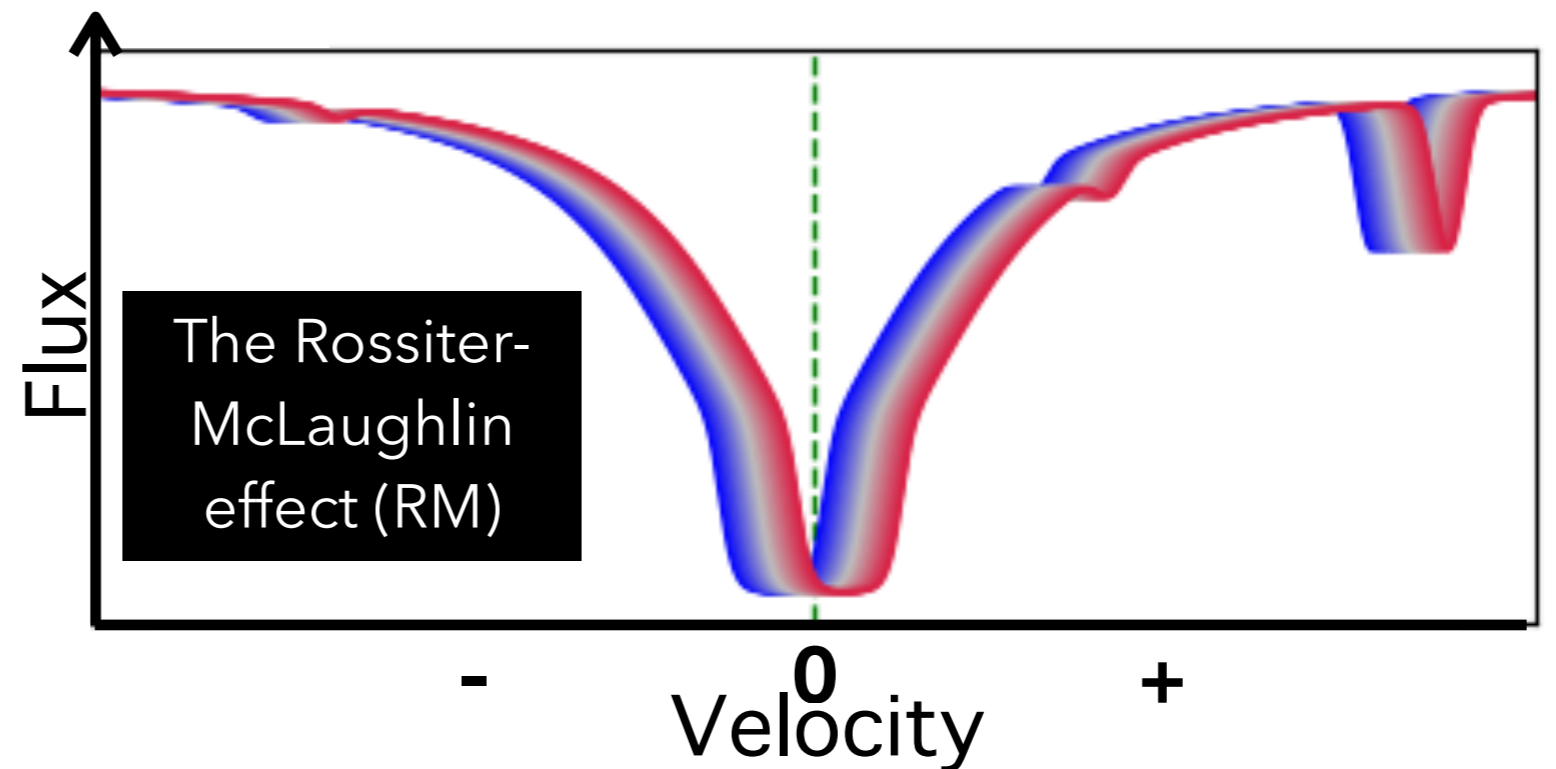
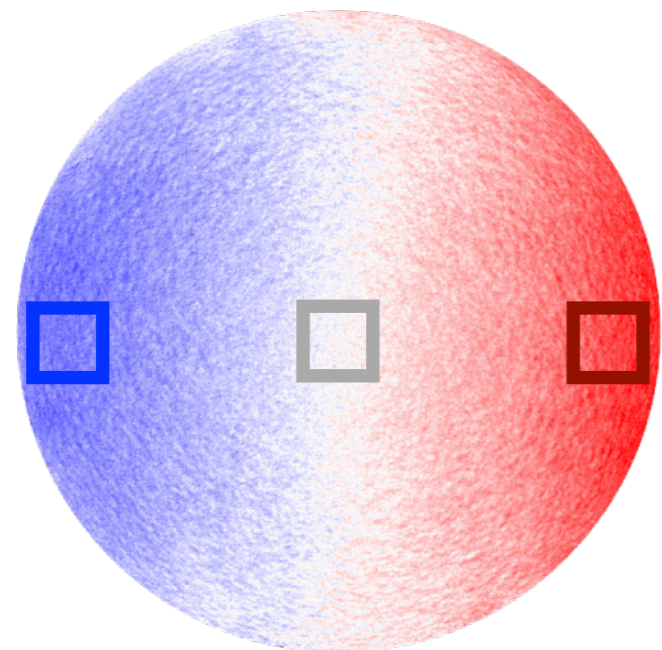
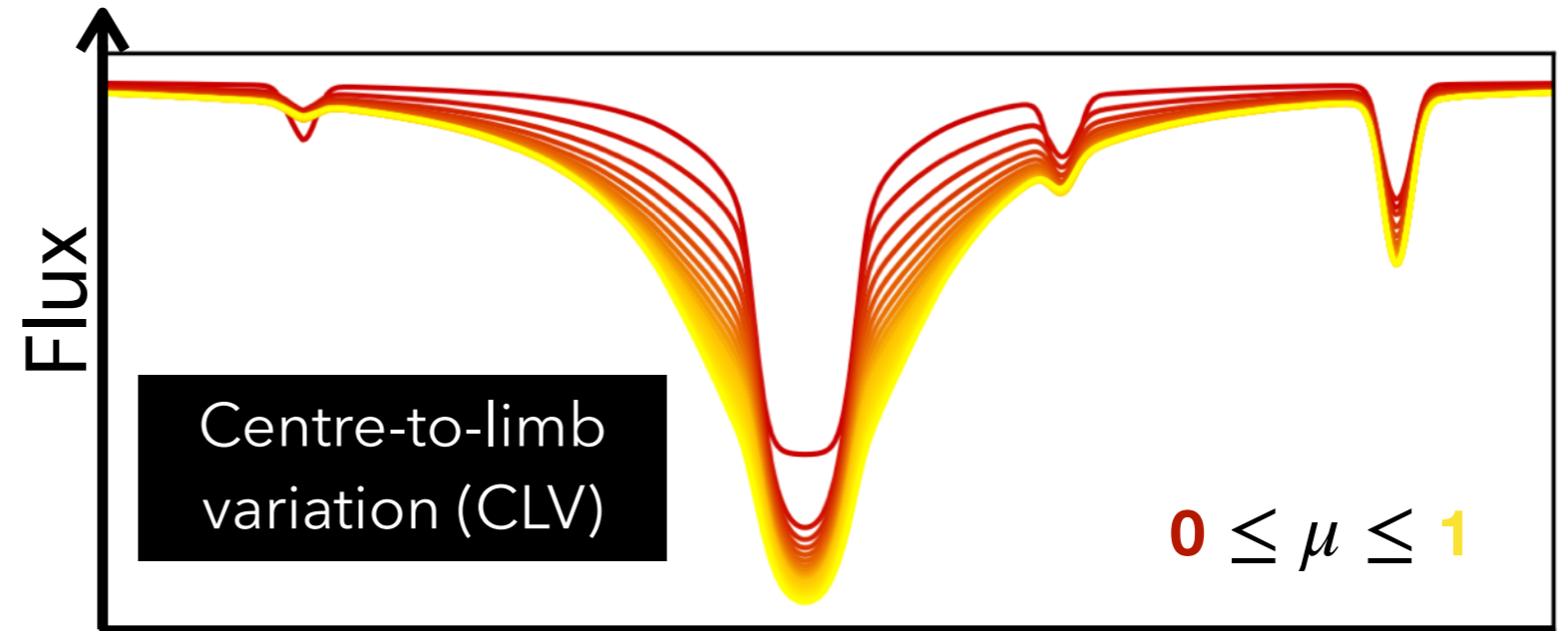
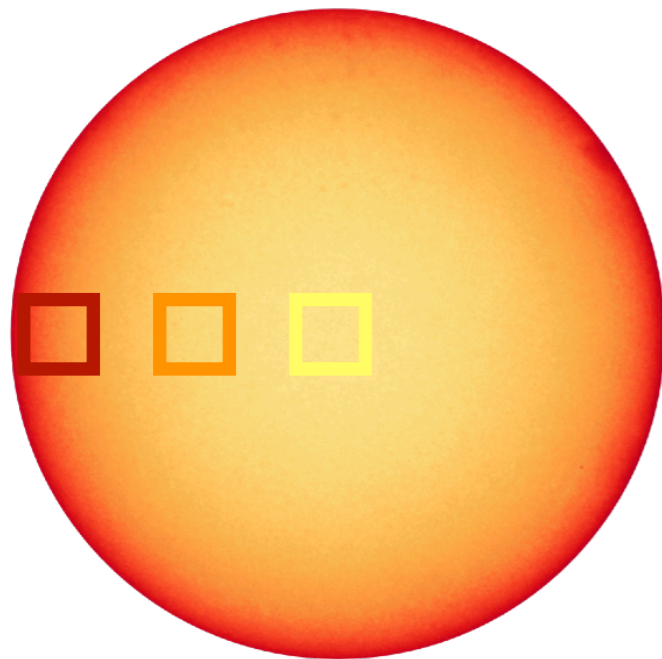
$\sigma_i$  error of pixel  $i$



# Extracting the transmission spectrum



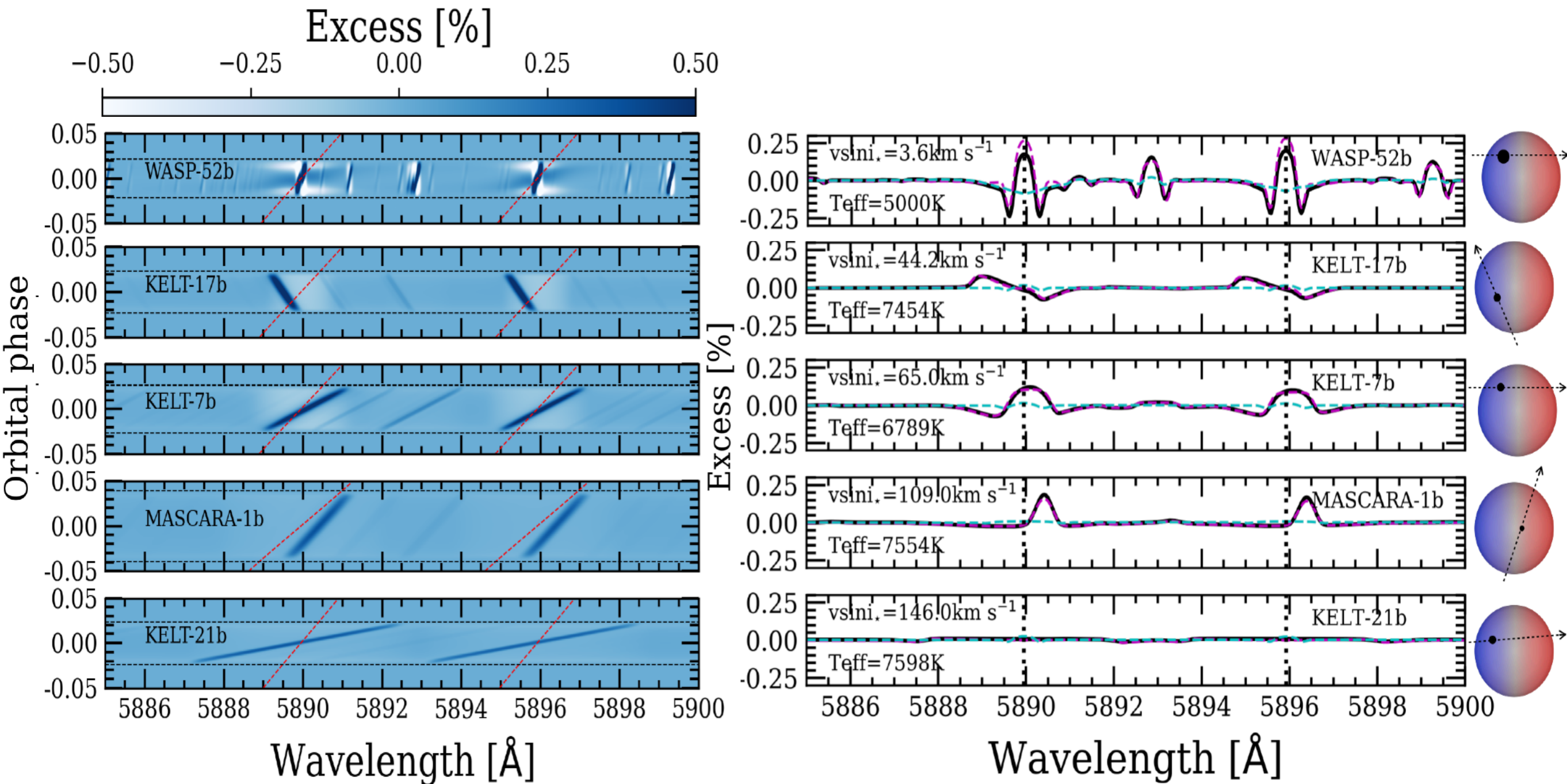
## Other corrections: the RM effect and CLV



# Extracting the transmission spectrum



## Other corrections: the RM effect and CLV



# Extracting the transmission spectrum

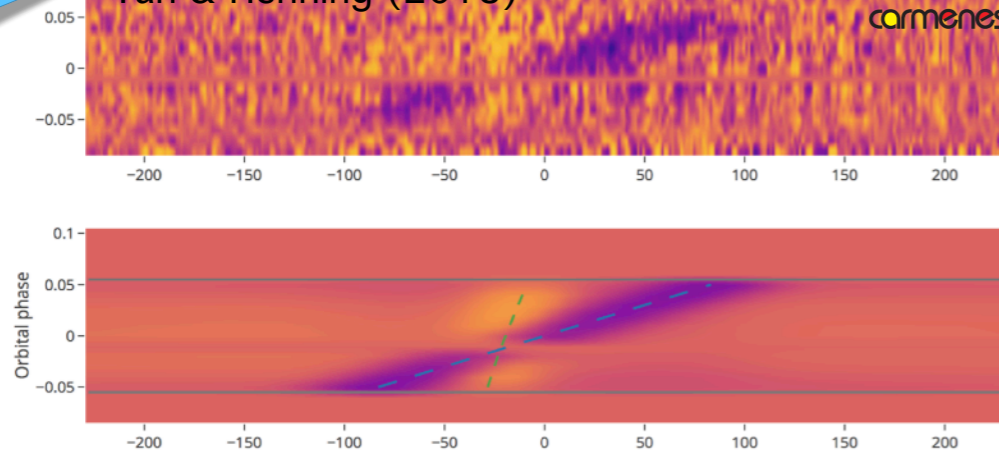


## Other corrections: the RM effect and CLV

Observations

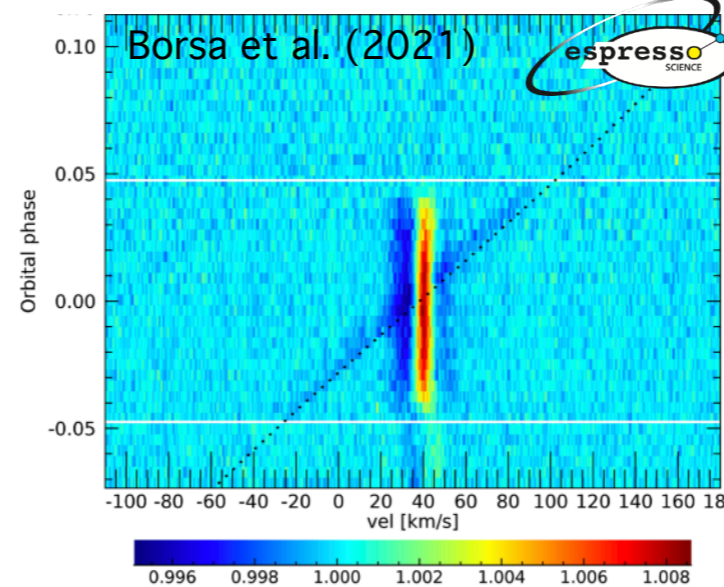
### KELT-9b

Yan & Henning (2018)



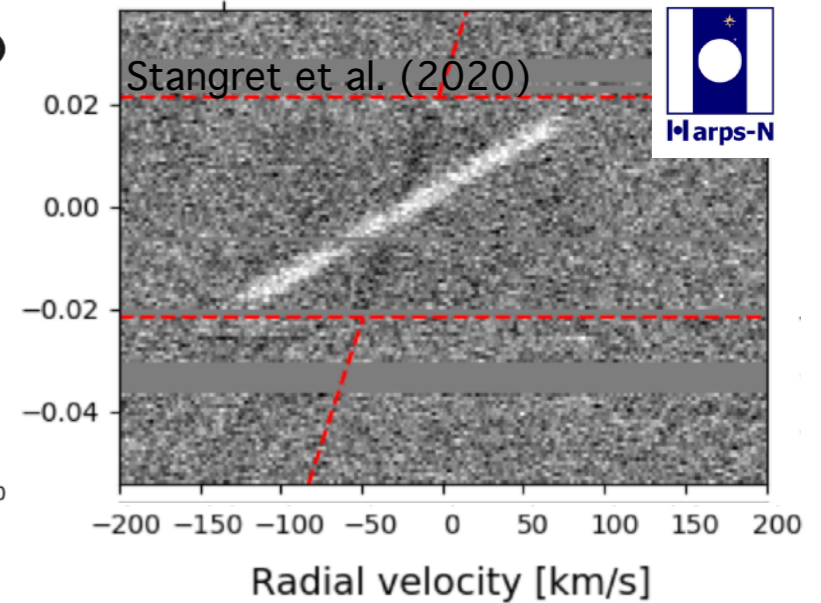
### WASP-121b

Borsa et al. (2021)



### MASCARA-2b

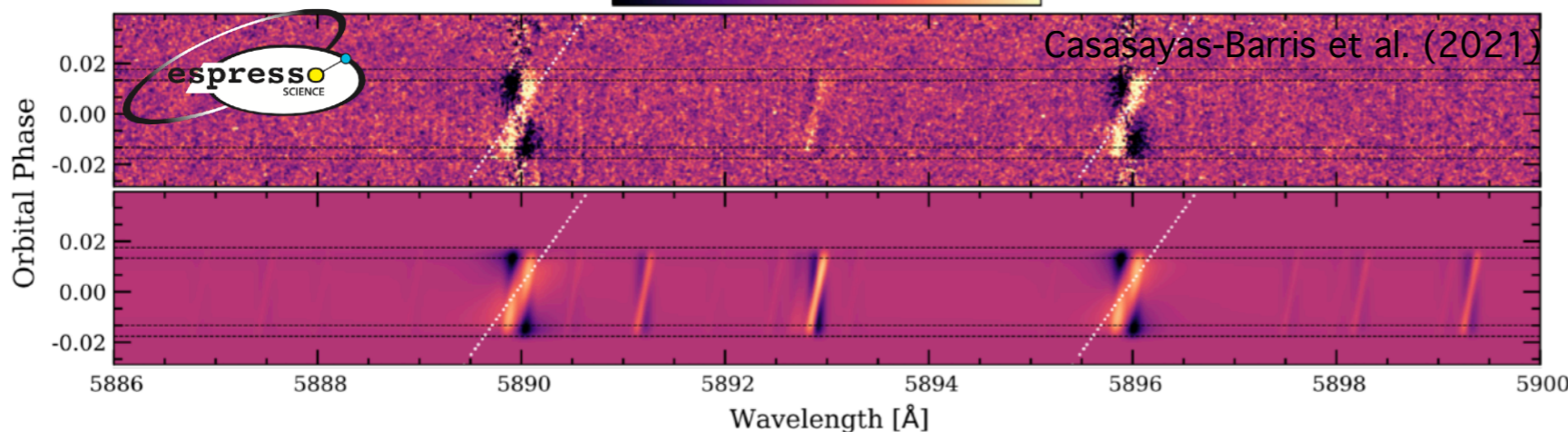
Stangret et al. (2020)



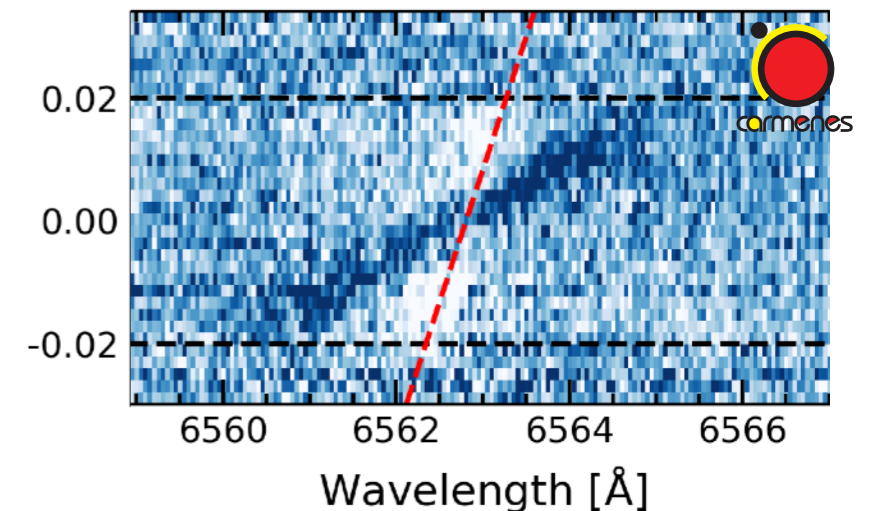
### HD 209458b

-0.8 0.0 0.8

Casasayas-Barris et al. (2021)



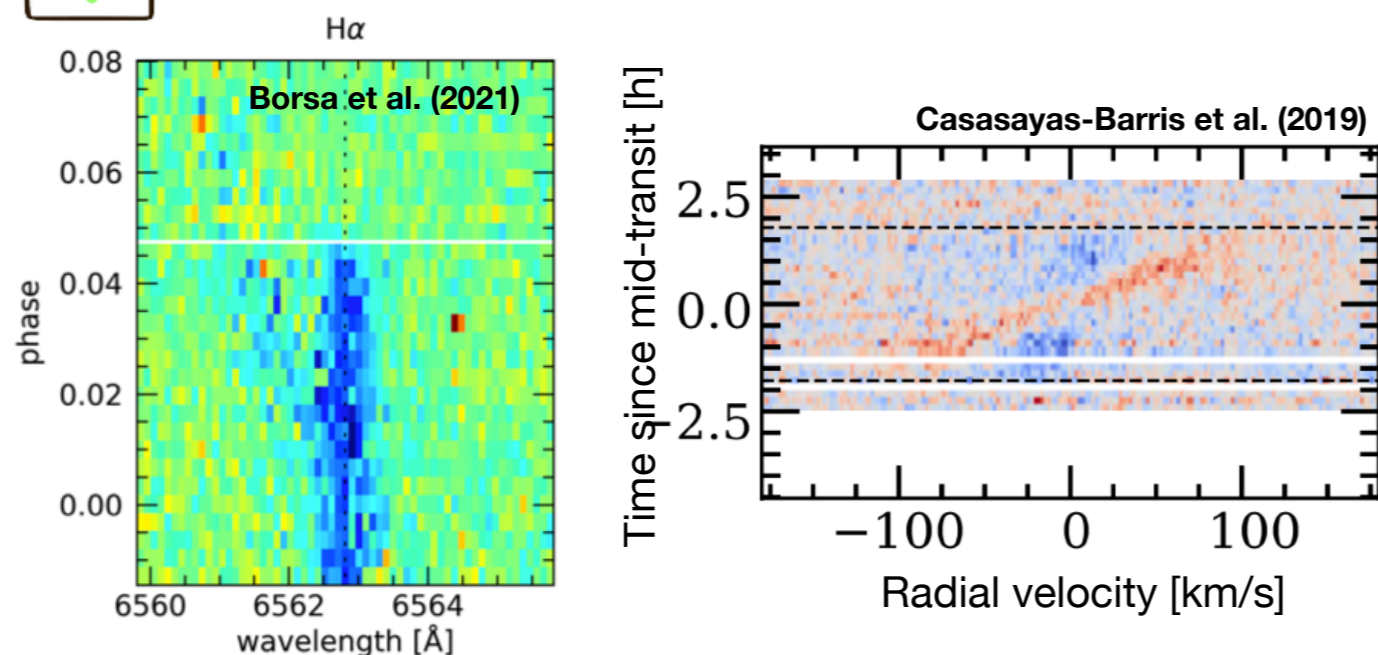
### MASCARA-2b



# How can we know if the signal has planetary origin?

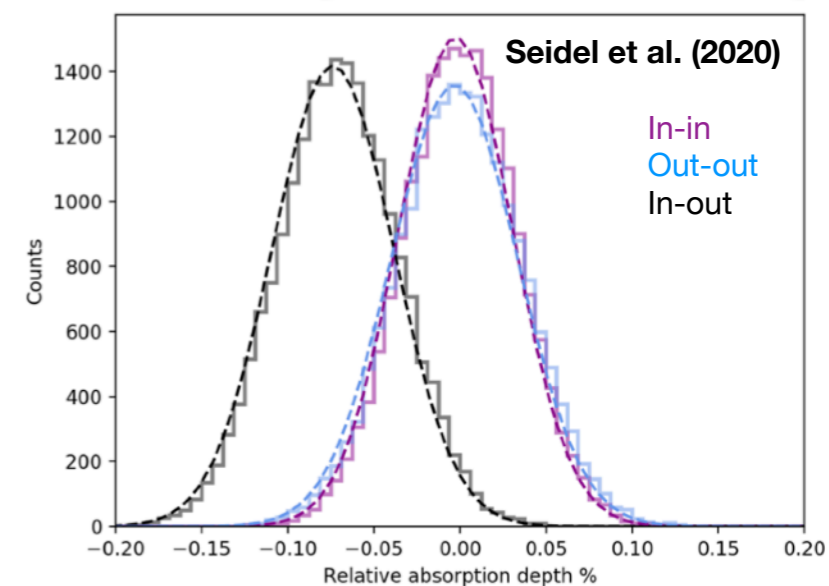


## 2D tomography maps



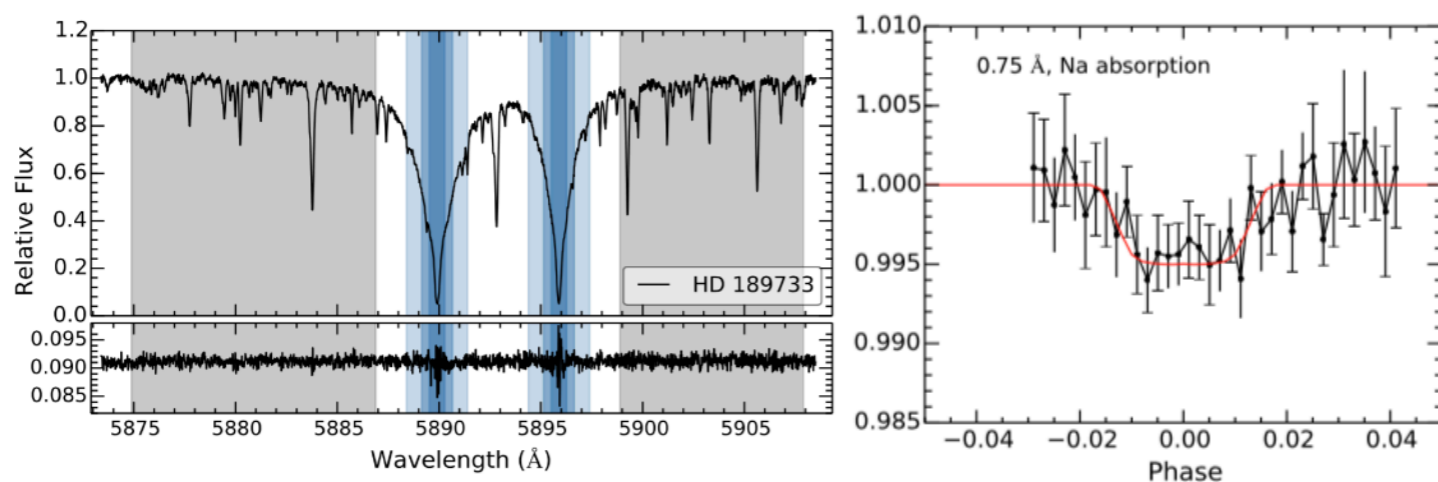
## Empirical Monte Carlo

Redfield et al. (2008)



## Transmission light curves

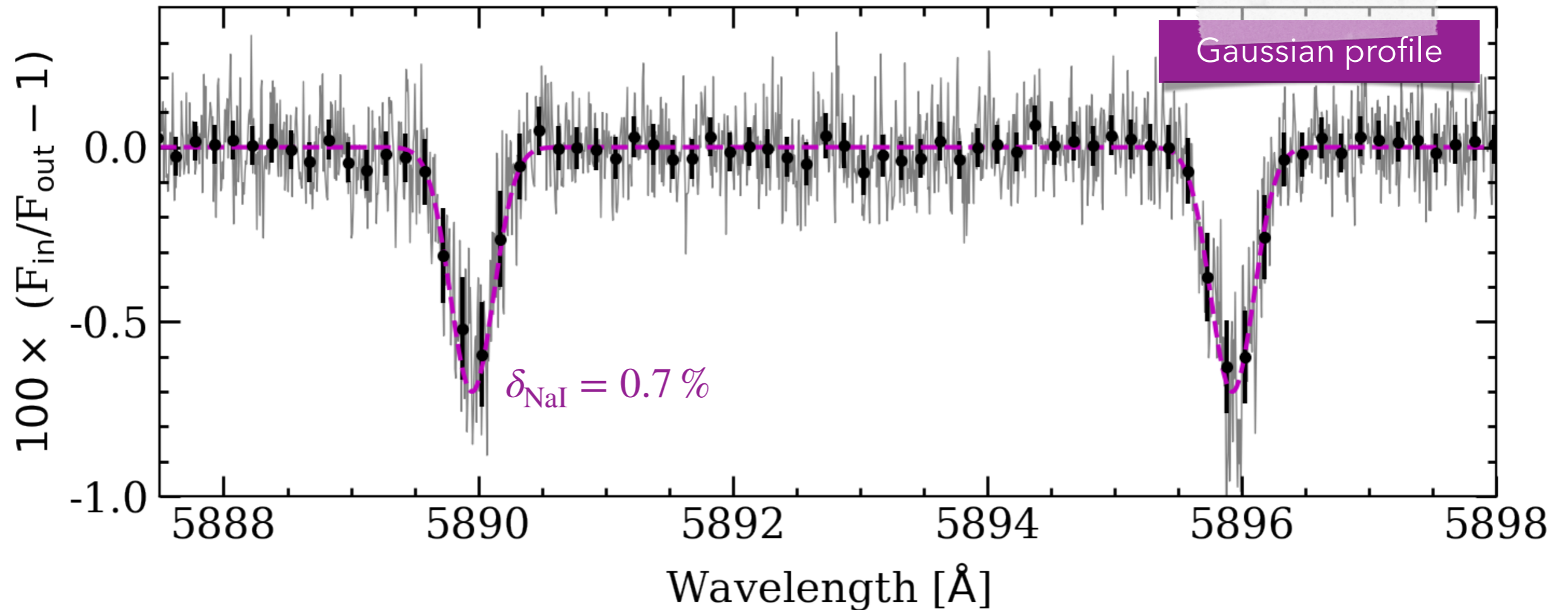
Yan et al. (2017), Snellen et al. (2008)



## Others:

- check other lines as reference
- Kp-velocity maps
- ...

# Interpretation of the transmission spectrum



- **Position of the lines**
- **Width of the lines**
- **Depth of the lines**

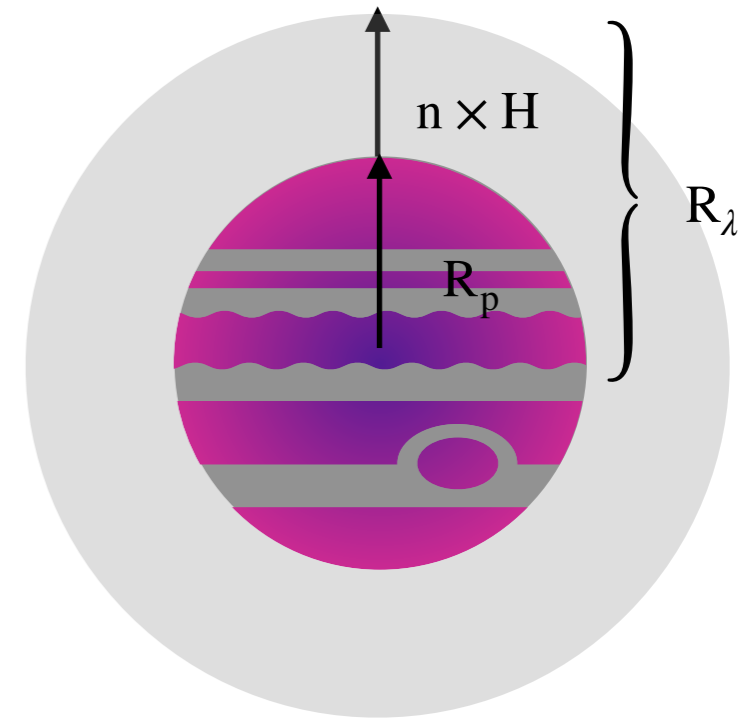


- **Temperature of the layers where the lines form**
- **Broadening due to atmospheric winds, tidally locked rotation...**
- **Overall blue/red shift due to atmospheric winds**
- ...

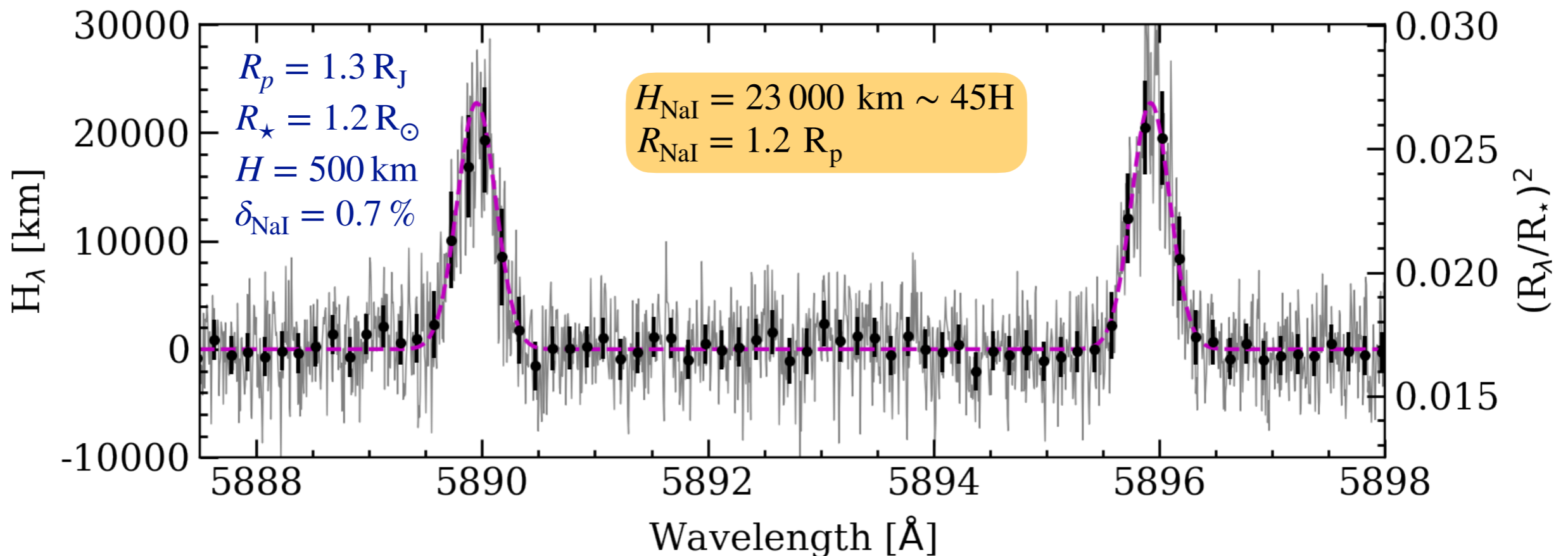
See some results during the conference!

# Interpretation of the transmission spectrum

$$\begin{cases} \Delta_0 = \left(\frac{R_p}{R_\star}\right)^2 \\ \Delta_\lambda = \left(\frac{R_\lambda}{R_\star}\right)^2 = \left(\frac{R_p + H_\lambda}{R_\star}\right)^2 \approx \left(\frac{R_p}{R_\star}\right)^2 + \left(\frac{2R_p H_\lambda}{R_\star}\right) \quad (H_\lambda \ll R_\star) \end{cases}$$



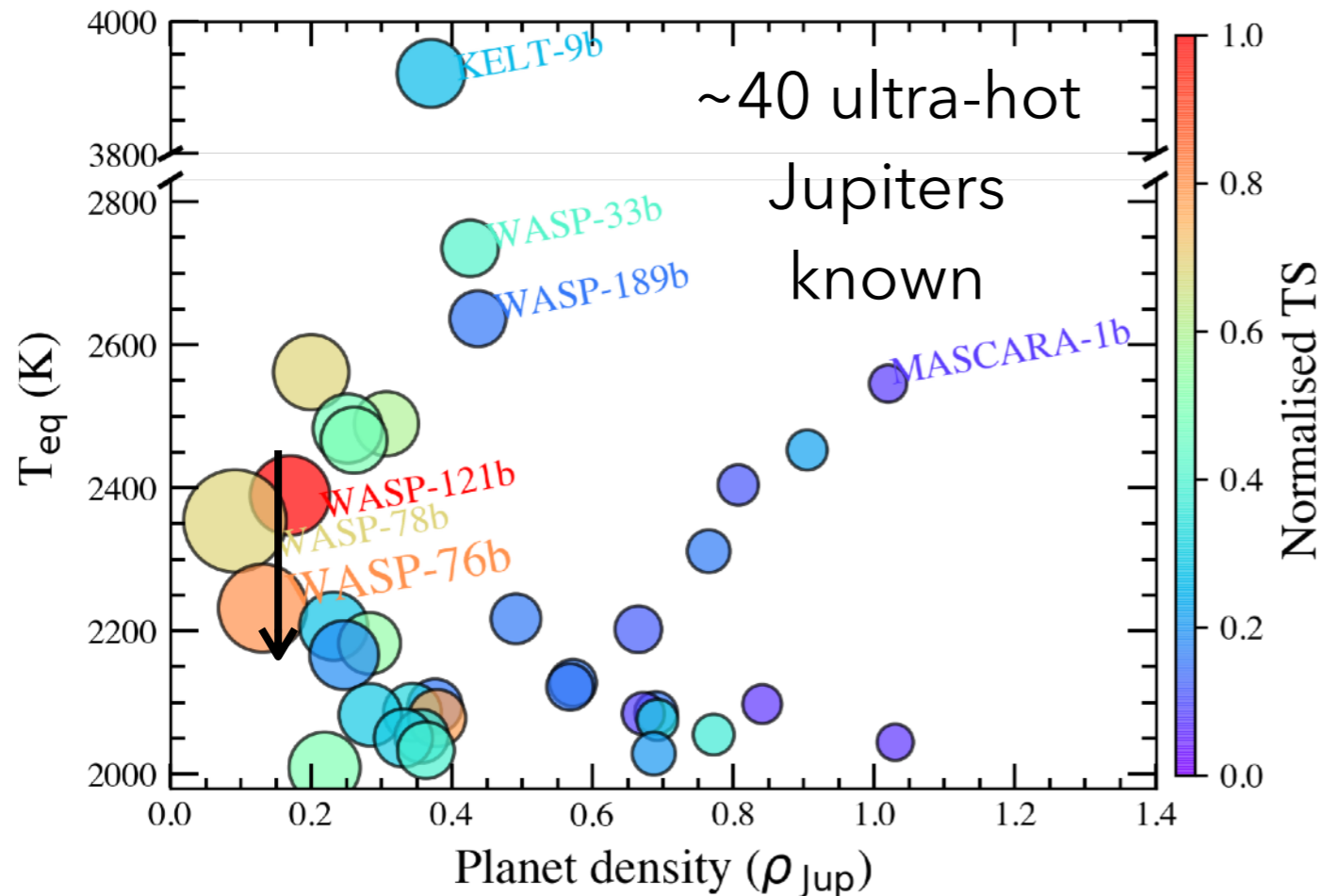
$$\delta_\lambda = \Delta_\lambda - \Delta_0 \approx \frac{2R_p H_\lambda}{R_\star^2}$$



# Tutorial: Na I in WASP-76b

## The target: WASP-76b

### ○ Ultra hot Jupiter ( $T > 2000$ K)



- $T_{eq} = 2250K$
- $R_p = 1.83R_J$ ,  $M_p = 0.92M_J$
- $P = 1.81$  days ( $a = 0.033$  AU)
- $V = 9.5$

Good target for transmission spectroscopy studies!

More about WASP-76b and UHJ in general during the conference!

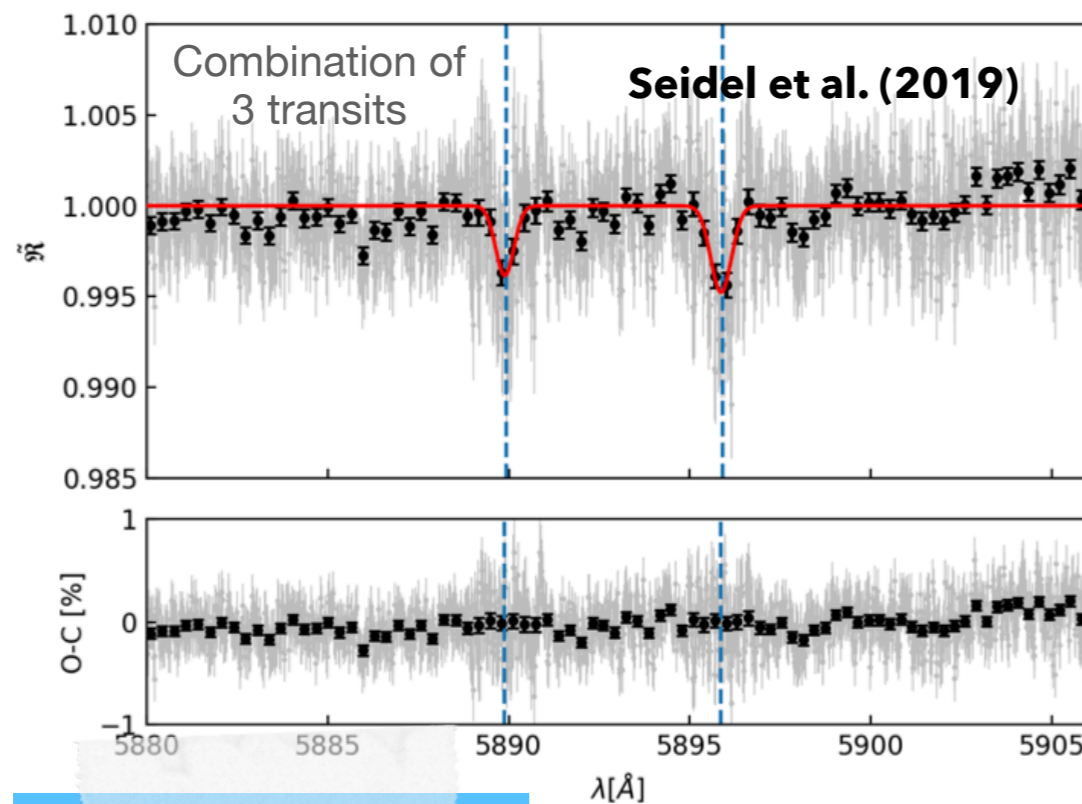
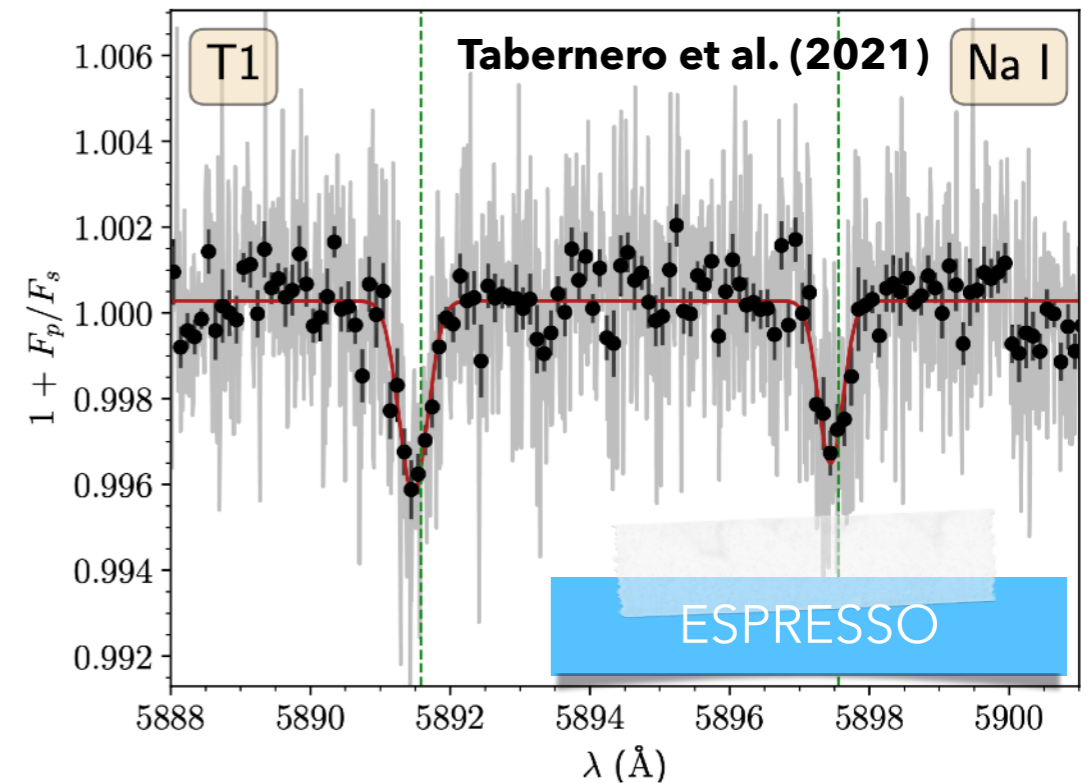
# Tutorial: Na I in WASP-76b

## Objective

- Extract the transmission spectrum of WASP-76b around the Na I

## The data

- 1 transit of WASP-76b observed with HARPS



HARPS

