# Narrow band transmission spectroscopy

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# Narrow band transmission spectroscopy


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**Atmo 2021 - Workshop**

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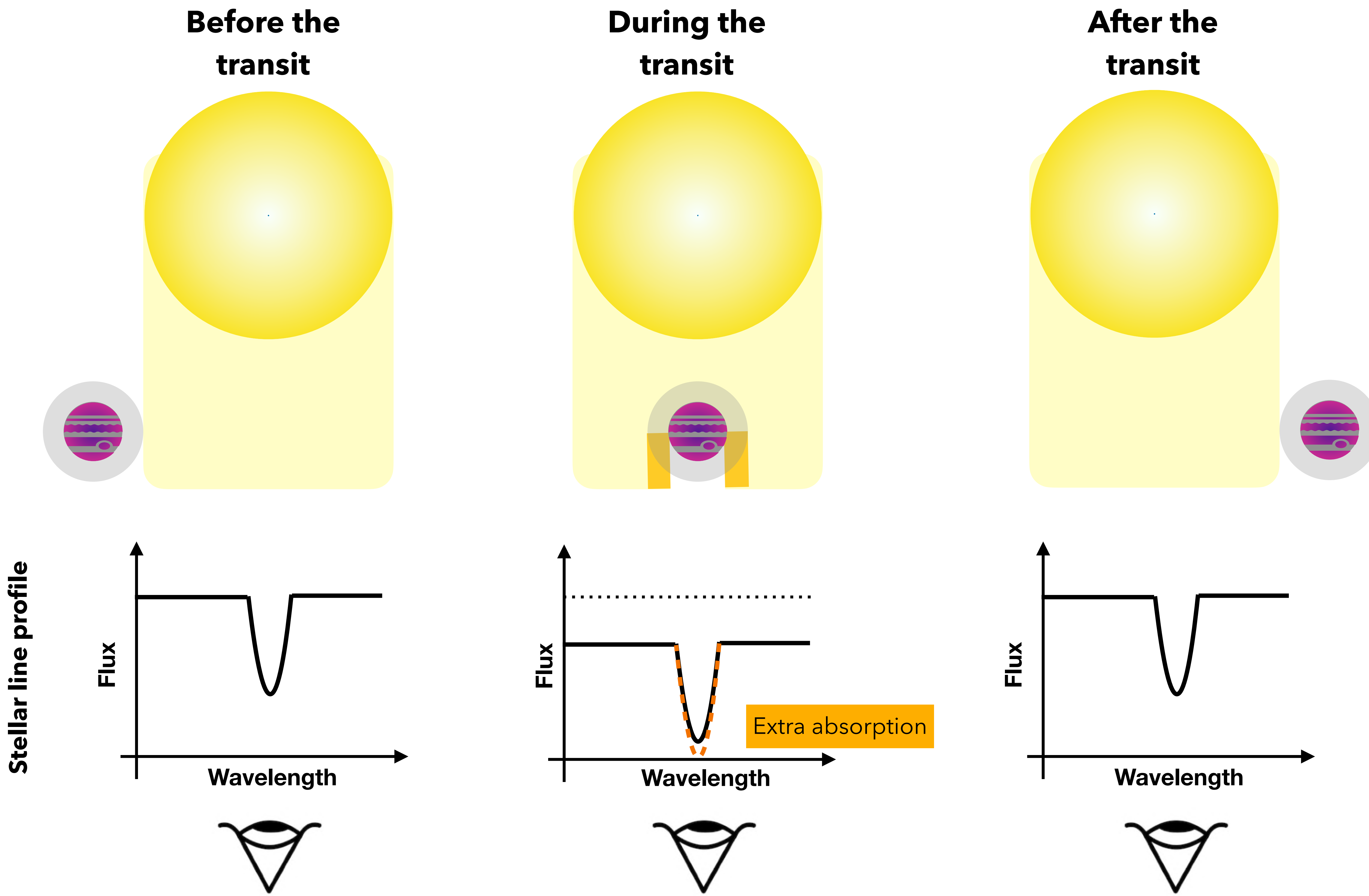
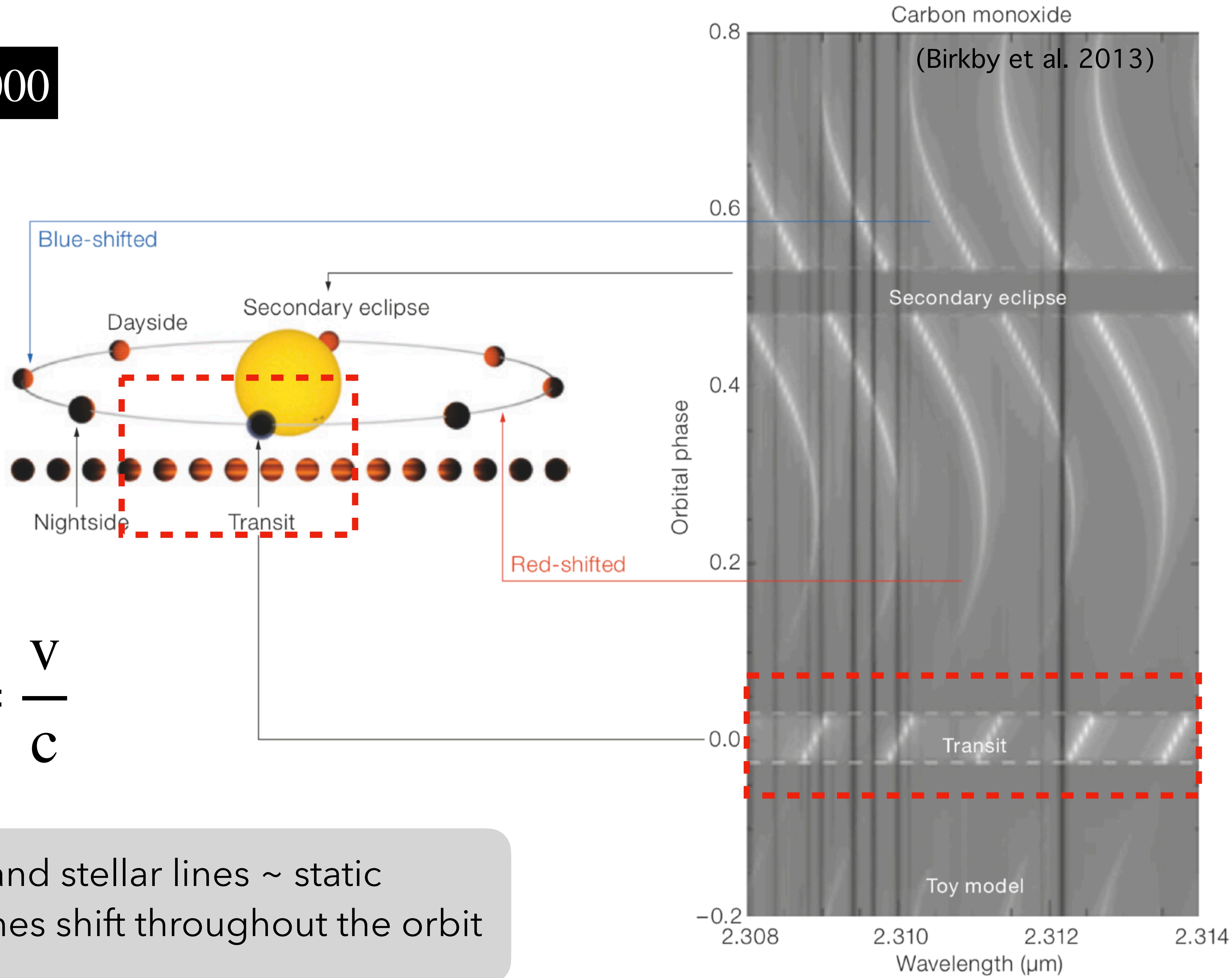
# Transmission spectroscopy



# High-resolution transmission spectroscopy



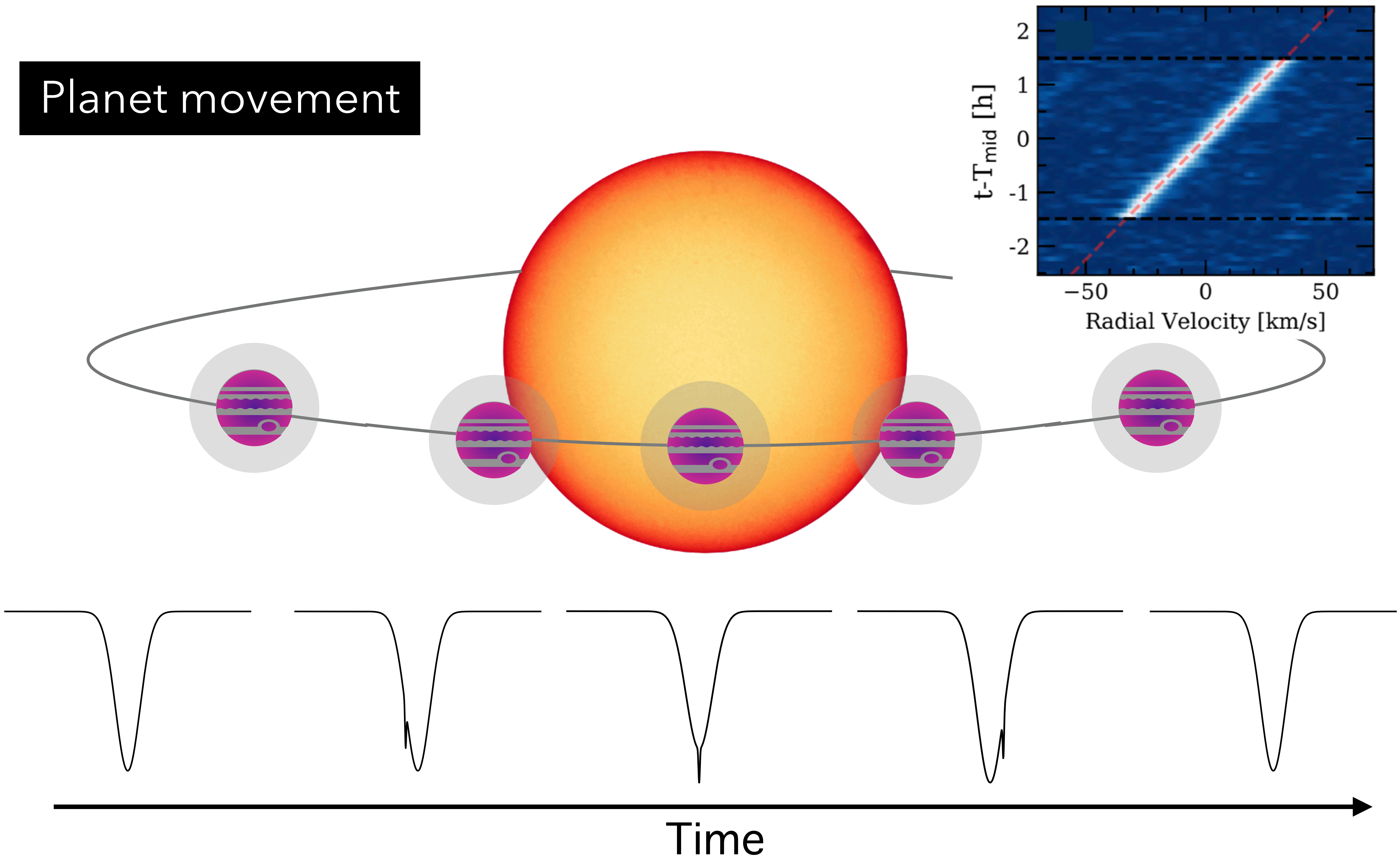
$\mathfrak{R} > 50\,000$




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

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

# High-resolution transmission spectroscopy



# Observations

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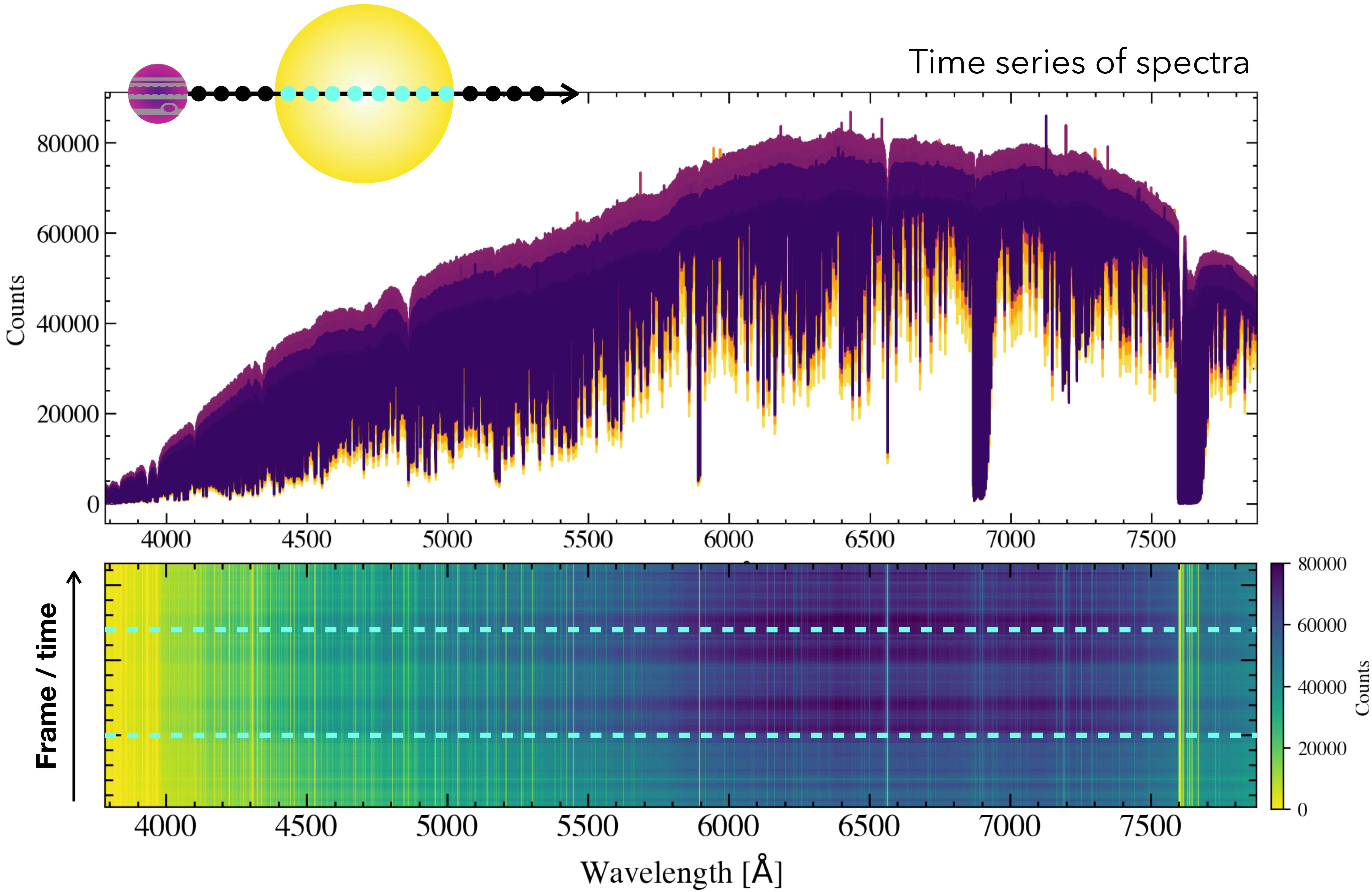


# Extracting the transmission spectrum



## 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

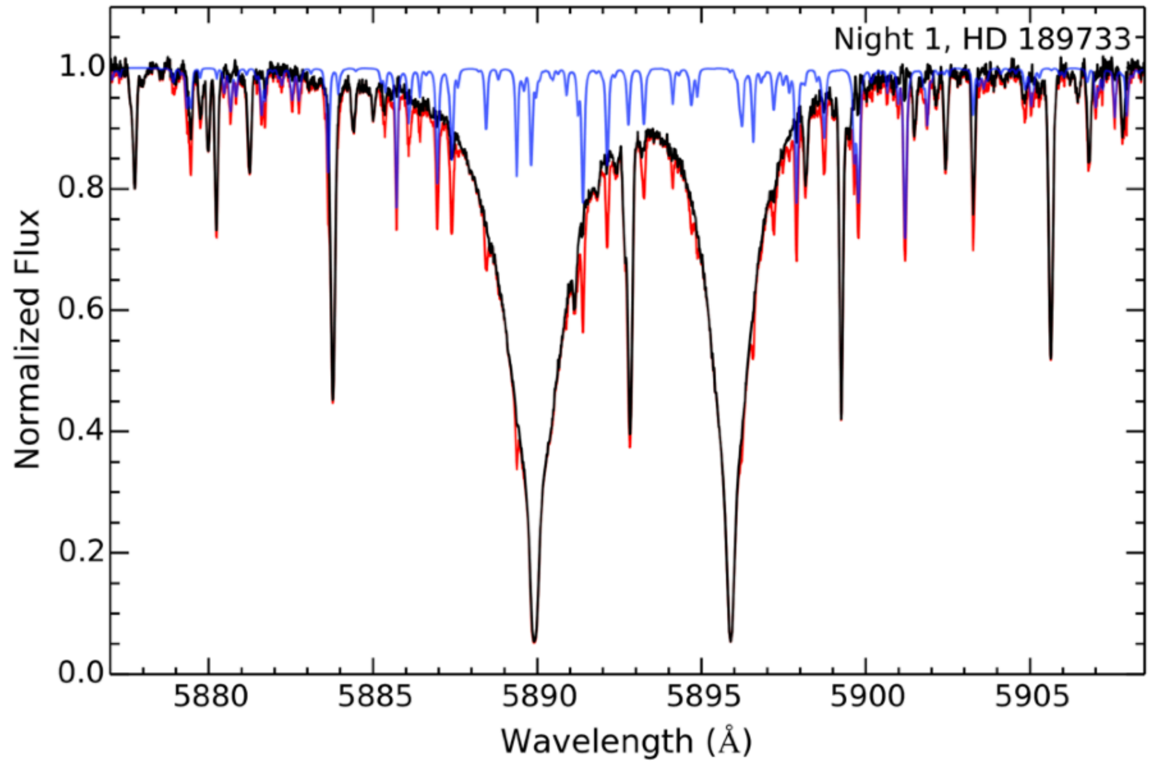
(+ other possible corrections)

Wyttenbach et al. (2015)

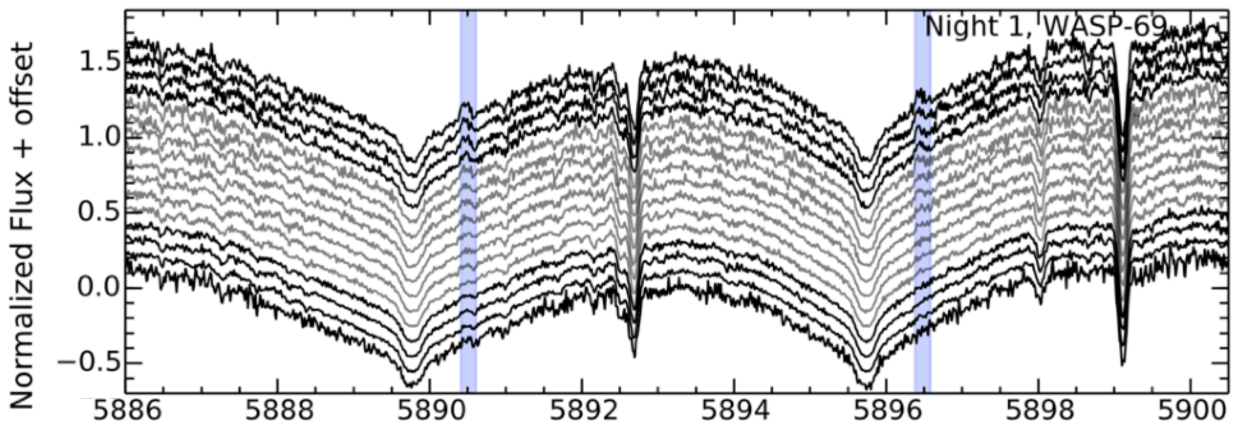
# Extracting the transmission spectrum

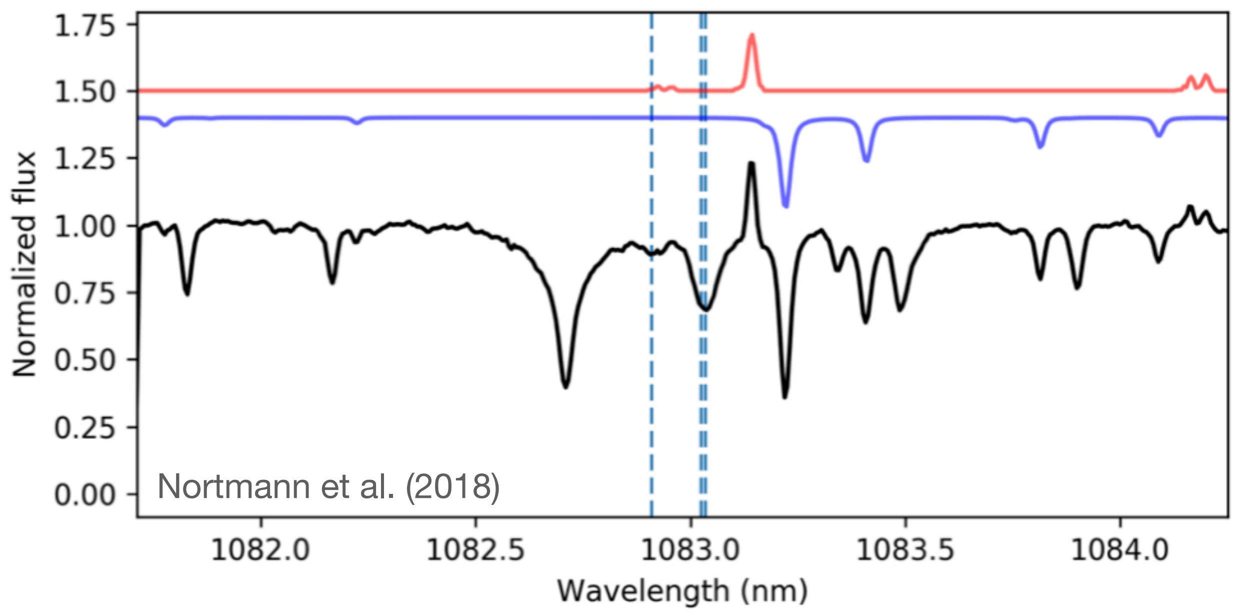
## 1. Telluric correction

- **Telluric absorption:** $H_2O, O_2$




- **Telluric emission:** $NaI, OH\ldots$




Different methodologies:

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

Molecfit lecture!

Sky observations with fibre B

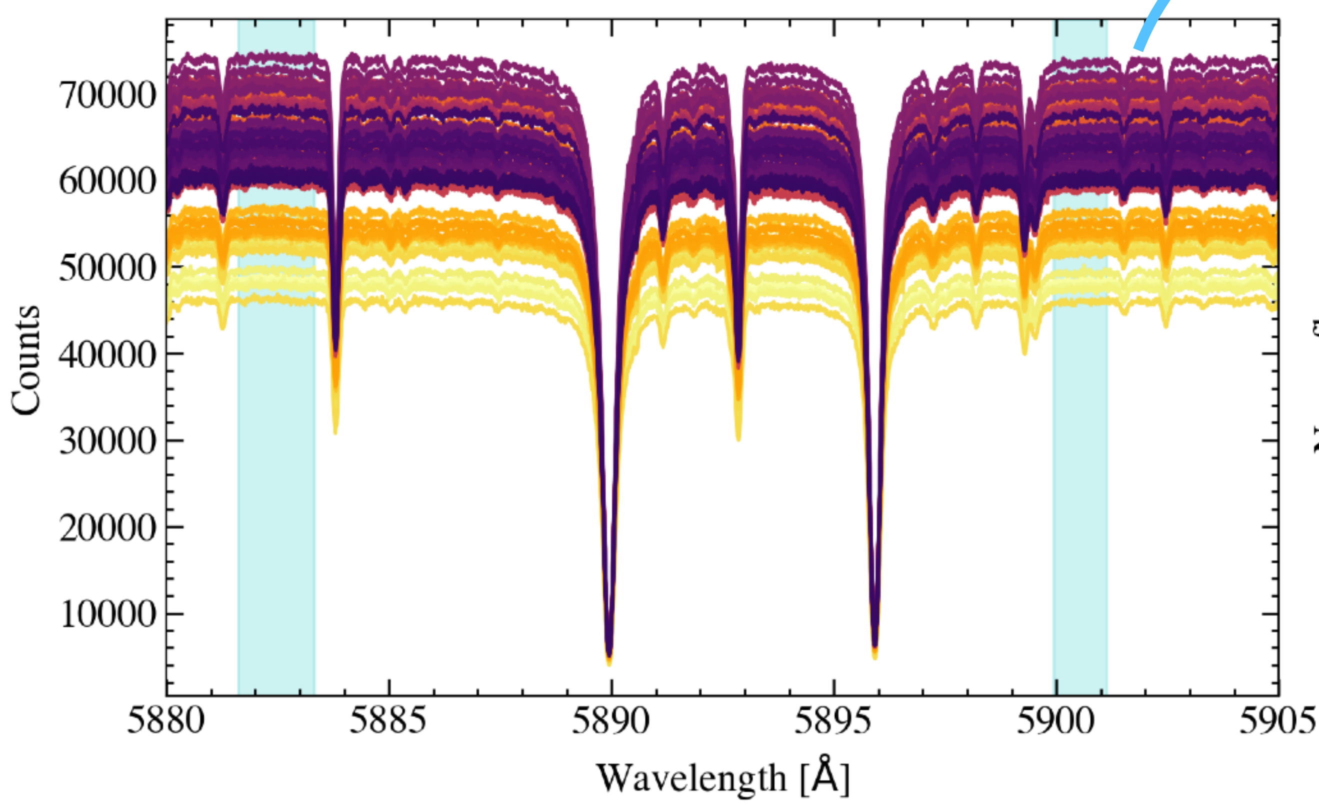
# Extracting the transmission spectrum

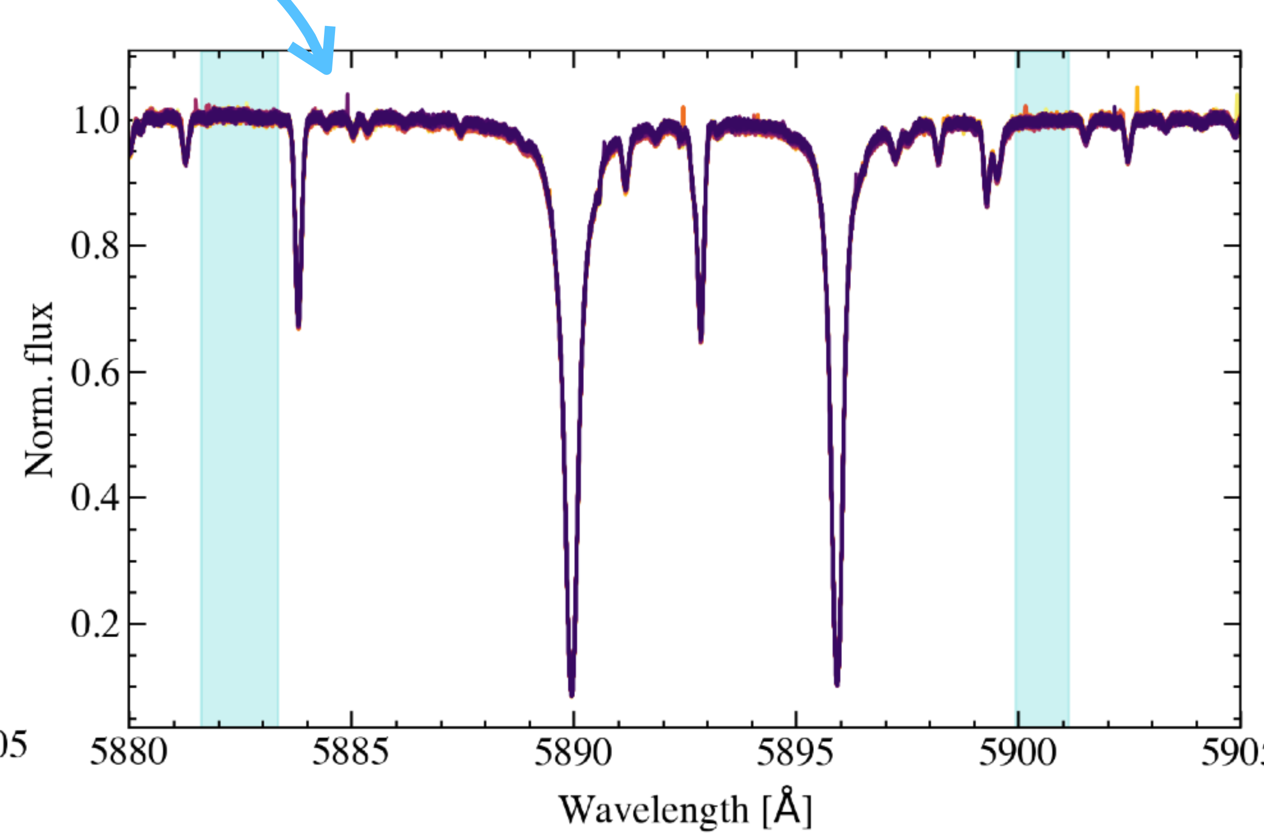


## 2. Normalisation

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

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

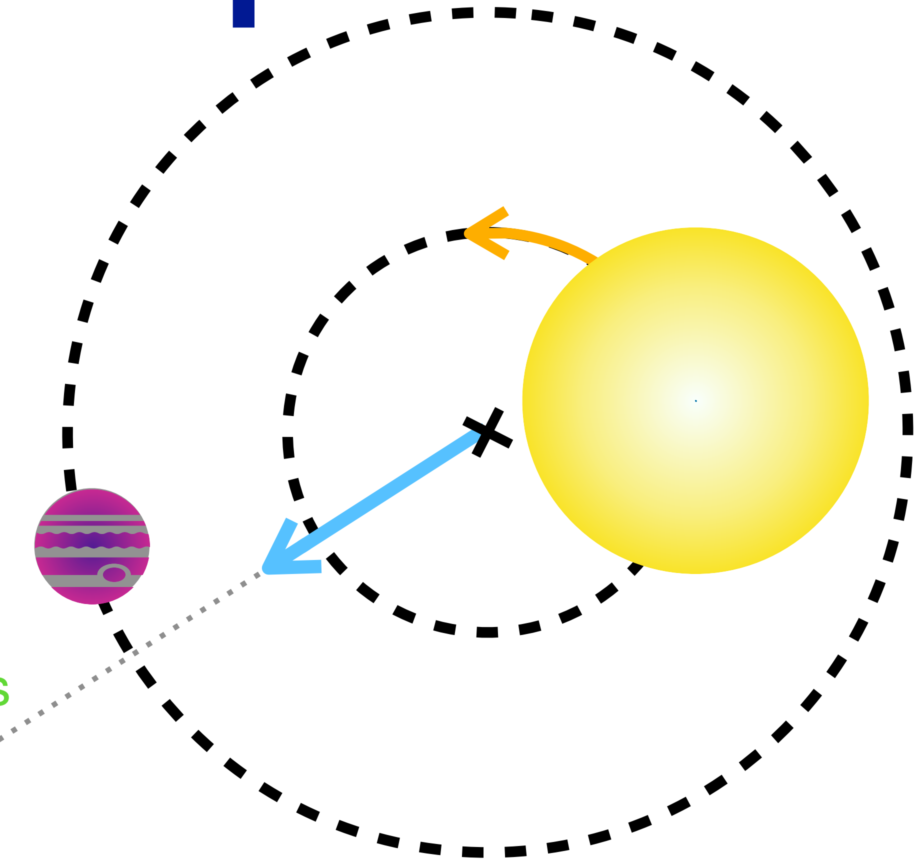


# Extracting the transmission spectrum

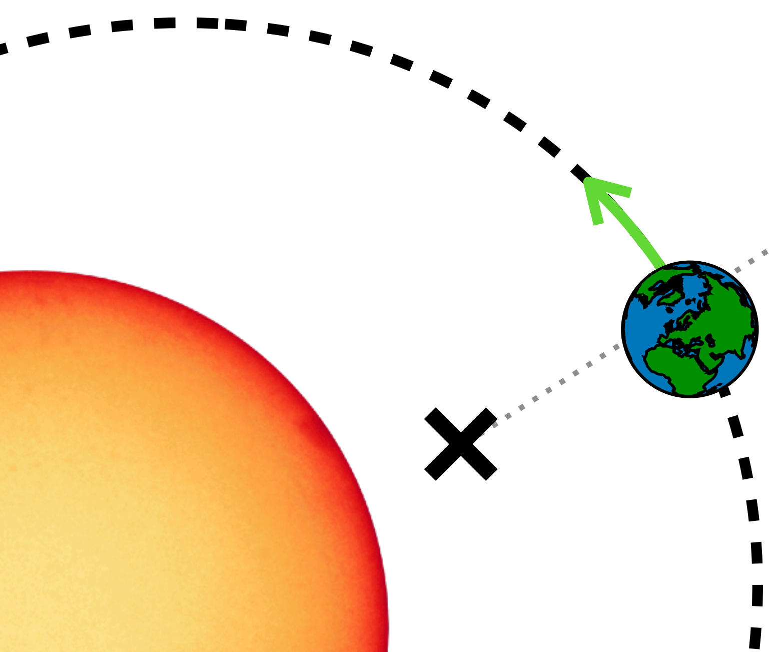
## 3. Stellar rest frame

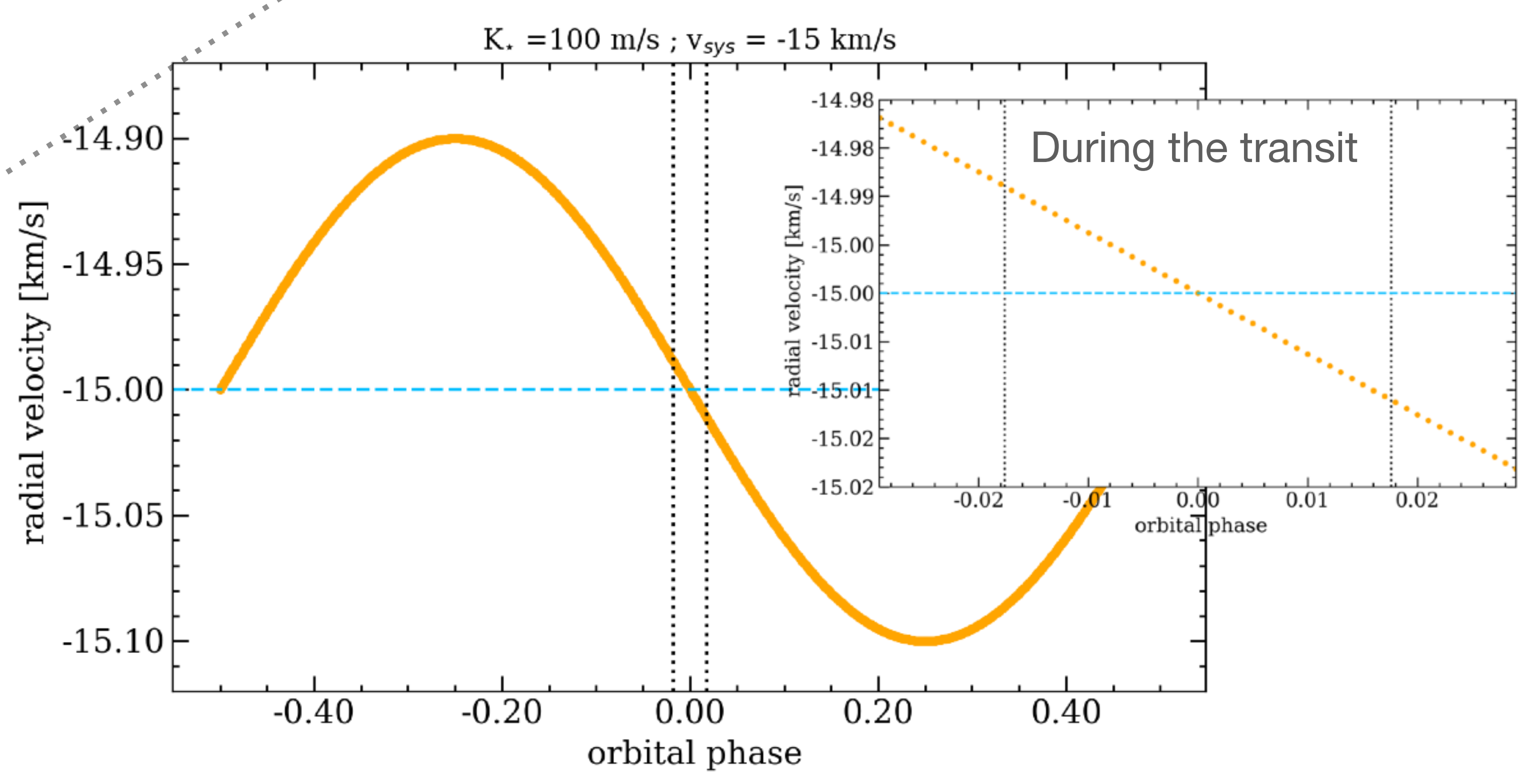
$$
RV^{i}_{\star}
\begin{cases}
K_\star \times \sin(2\pi\phi_i) & \text{Stellar motion} \quad \sim\text{m/s} \\
v_{sys} & \text{System velocity} \quad \sim\text{km/s} \\
RV^{i}_{Earth} & \text{Earth Radial velocity} \quad \sim\text{km/s}
\end{cases}
$$



Extrasolar system

Solar System

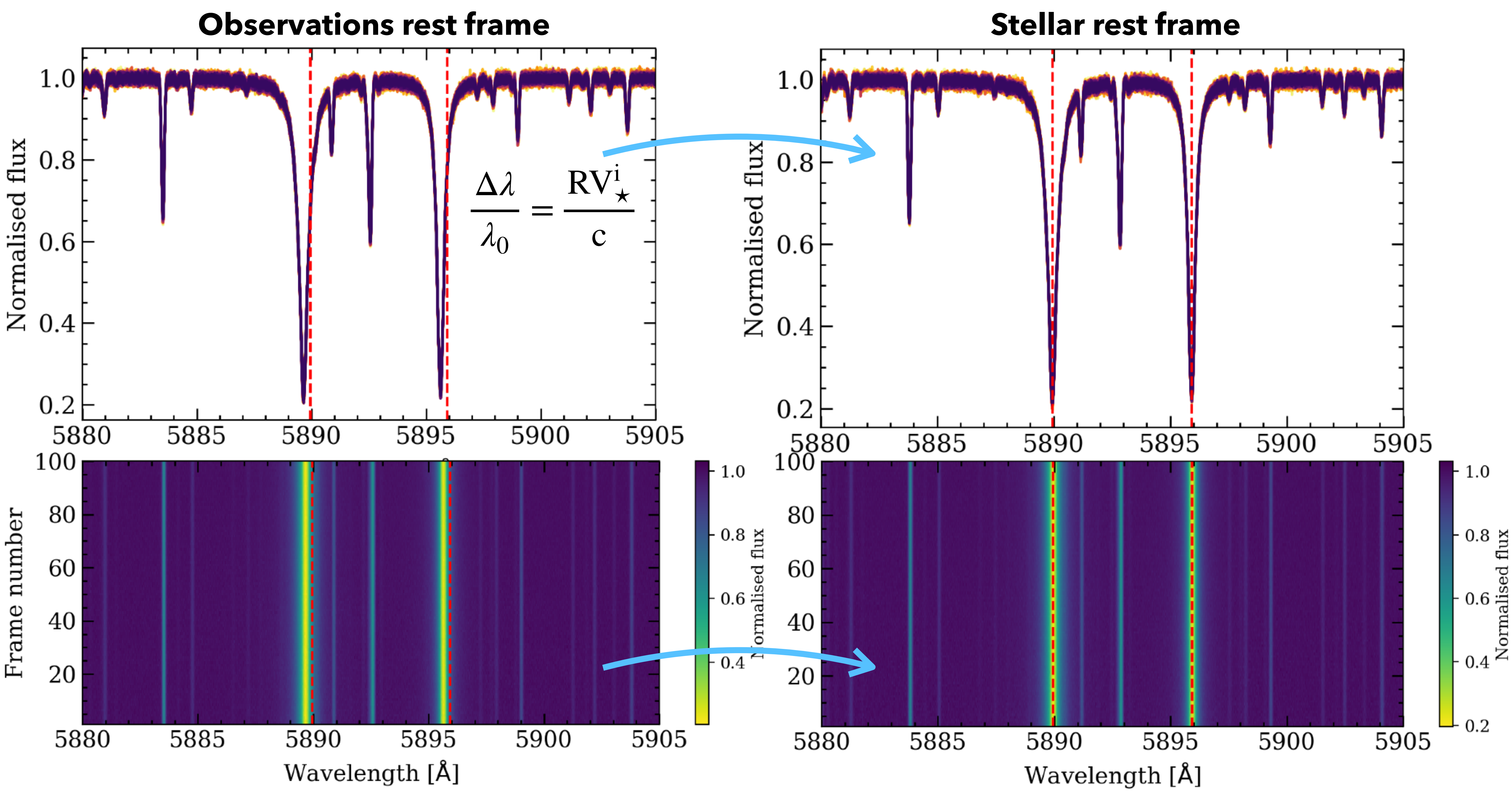




# Extracting the transmission spectrum



## 3. Stellar rest frame



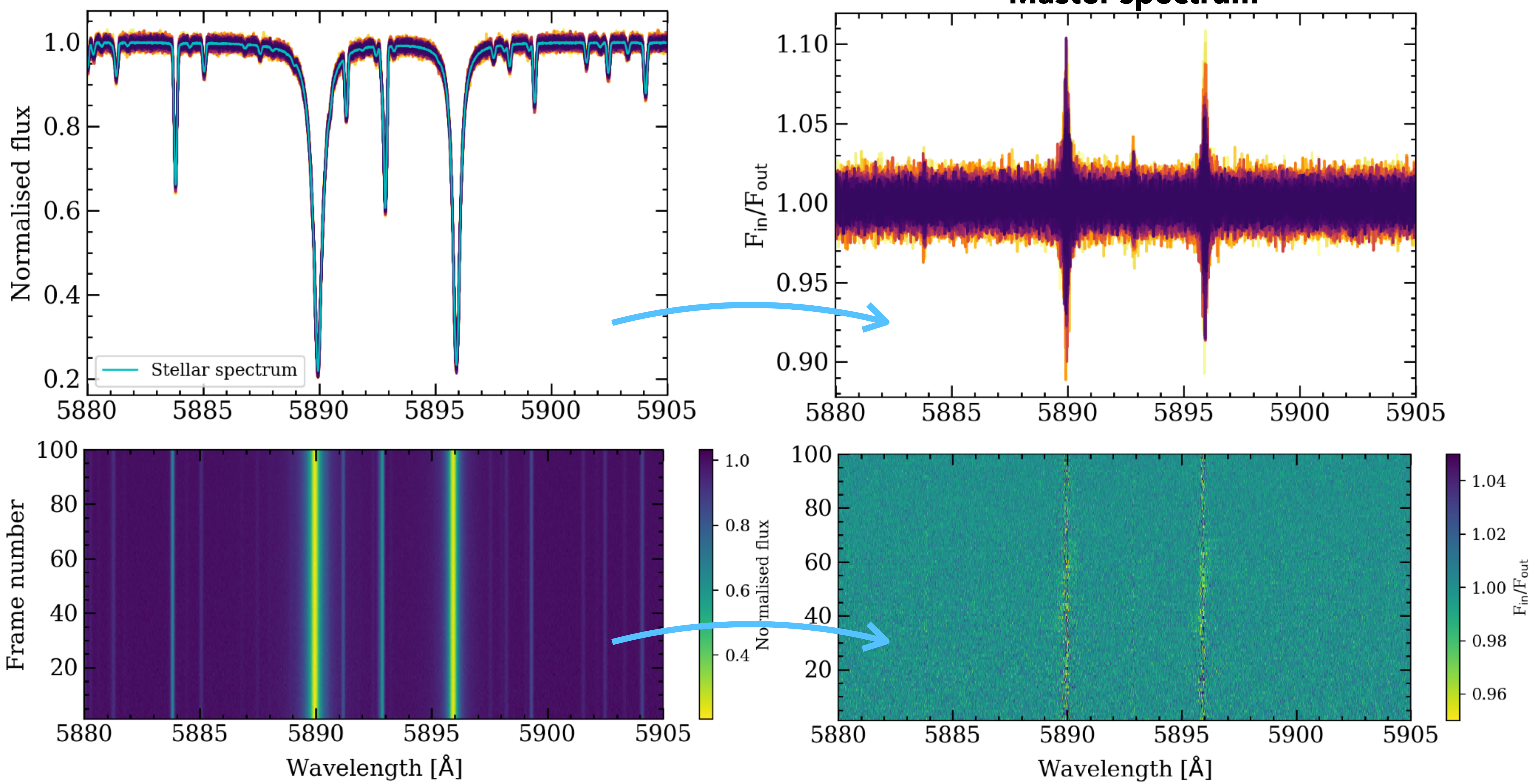
# Extracting the transmission spectrum

## 4. Remove stellar contribution

**Master out-of-transit stellar spectrum**

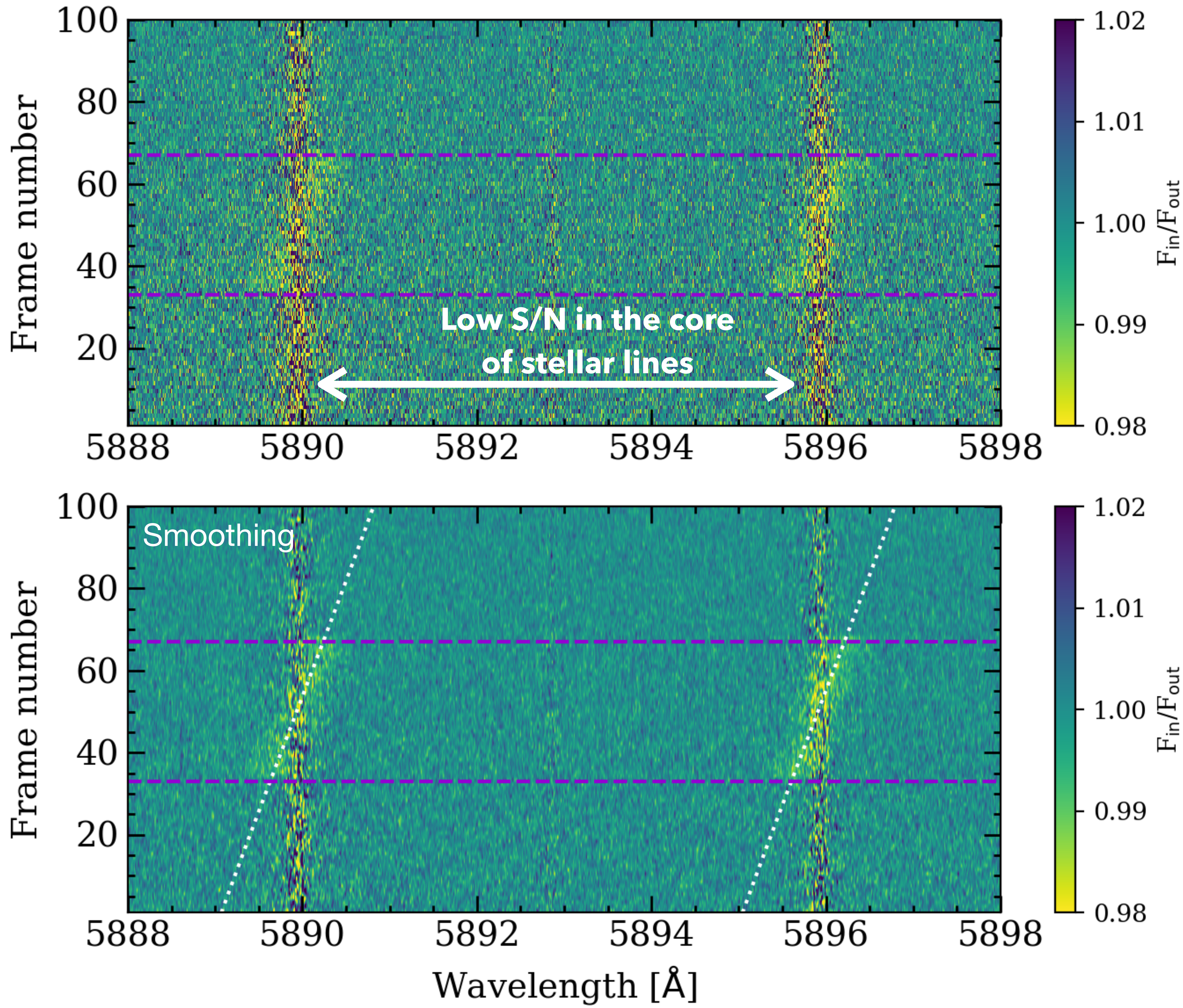
Combination of all out-of-transit spectra

**Division of each spectrum by the Master spectrum**



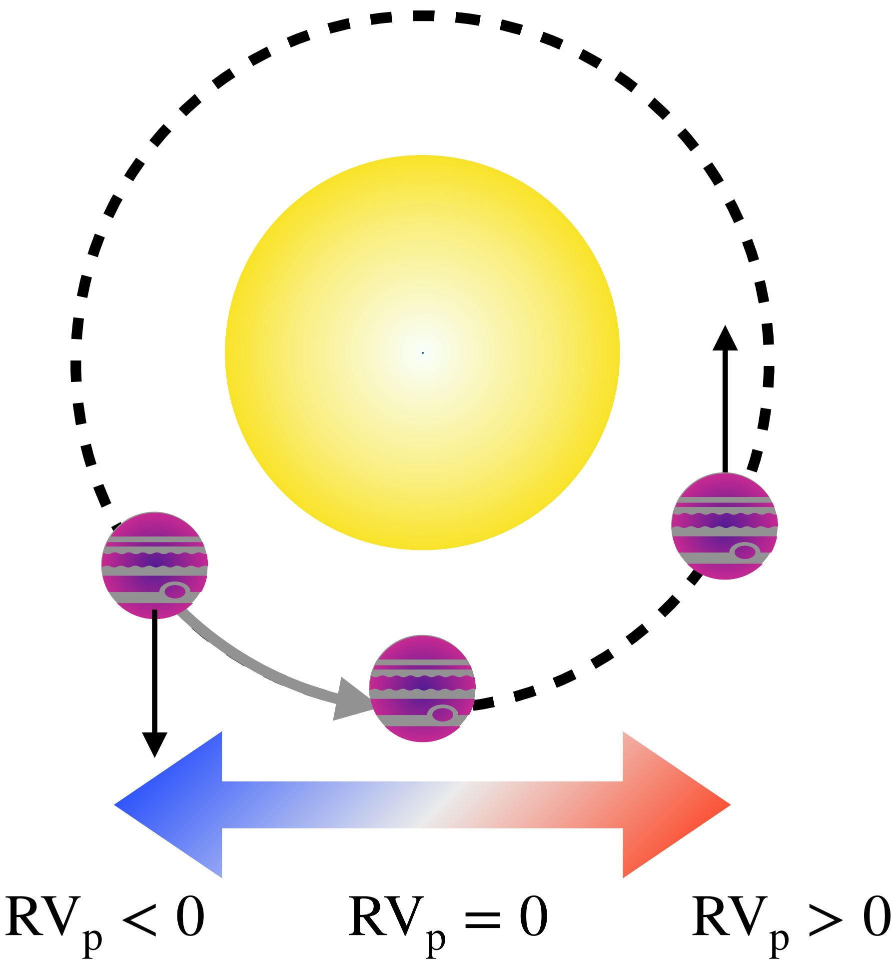
# Extracting the transmission spectrum

## ☑ 4. Remove stellar contribution



# Extracting the transmission spectrum

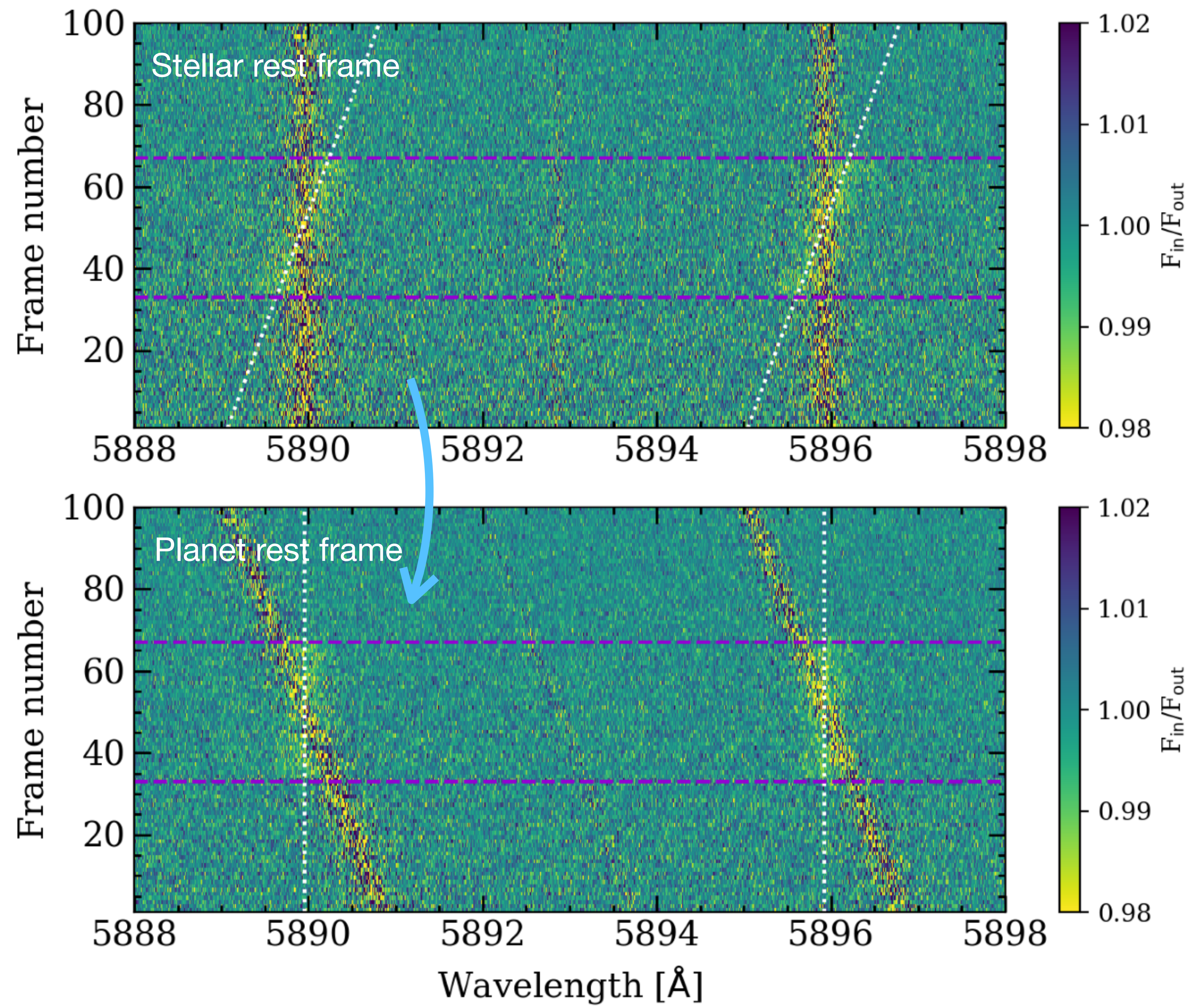
## 5. Planet rest frame




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

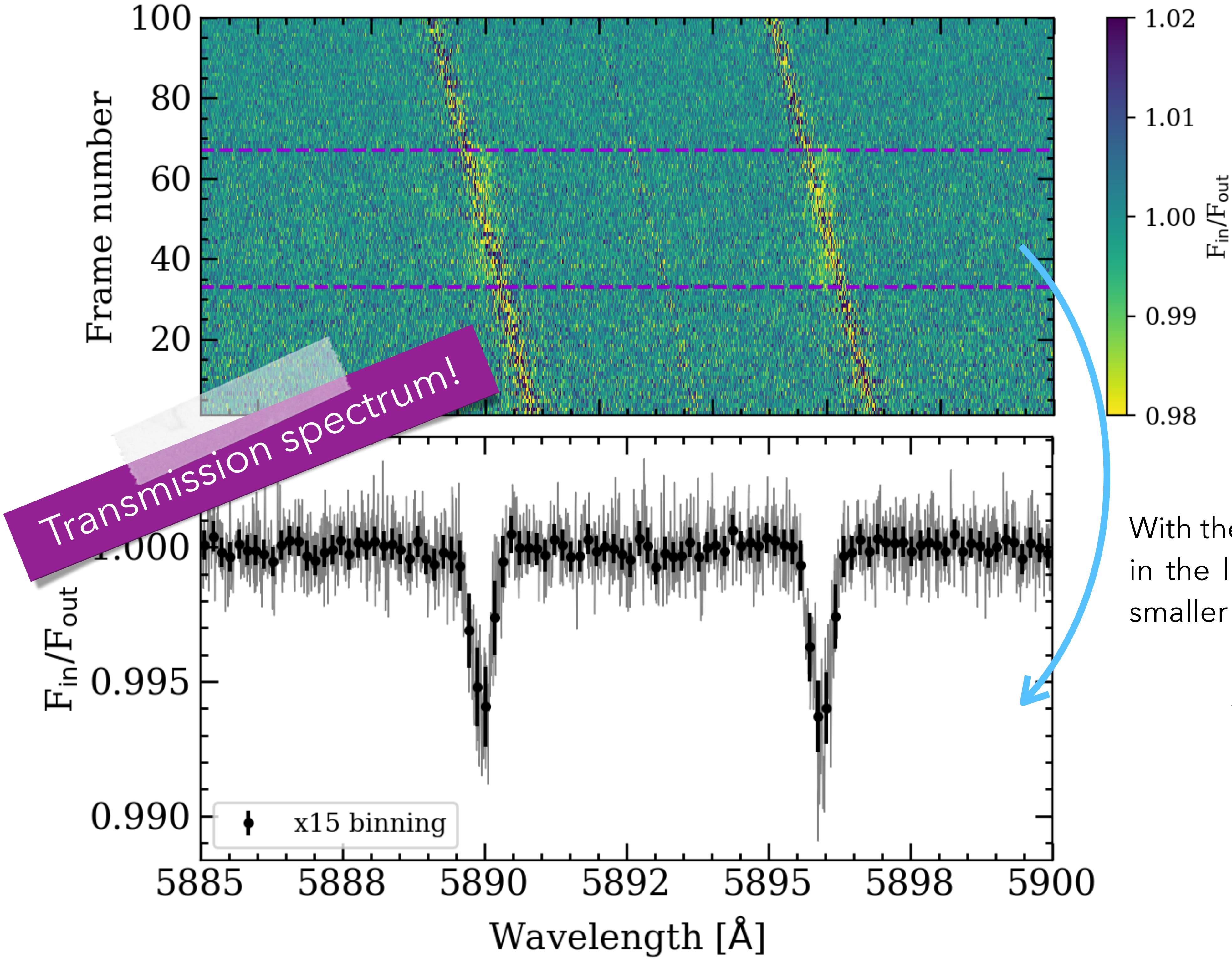
$$K_p = \frac{2\pi a}{P}\sin(i_p) \quad (e = 0 \text{ and } M_p \ll M_\star)$$

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



# Extracting the transmission spectrum

## 6. Combination of in-transit data



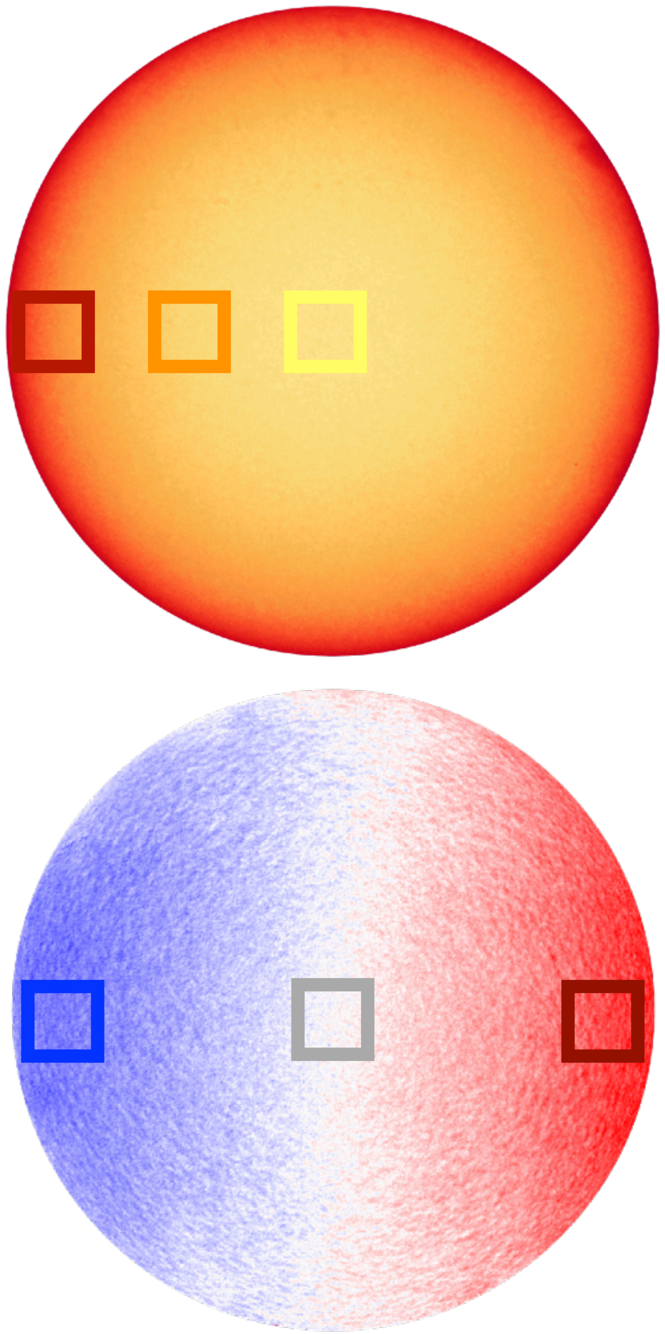

With the weighted mean the pixels in the lines core (low S/N) have a smaller contribution. Usually:

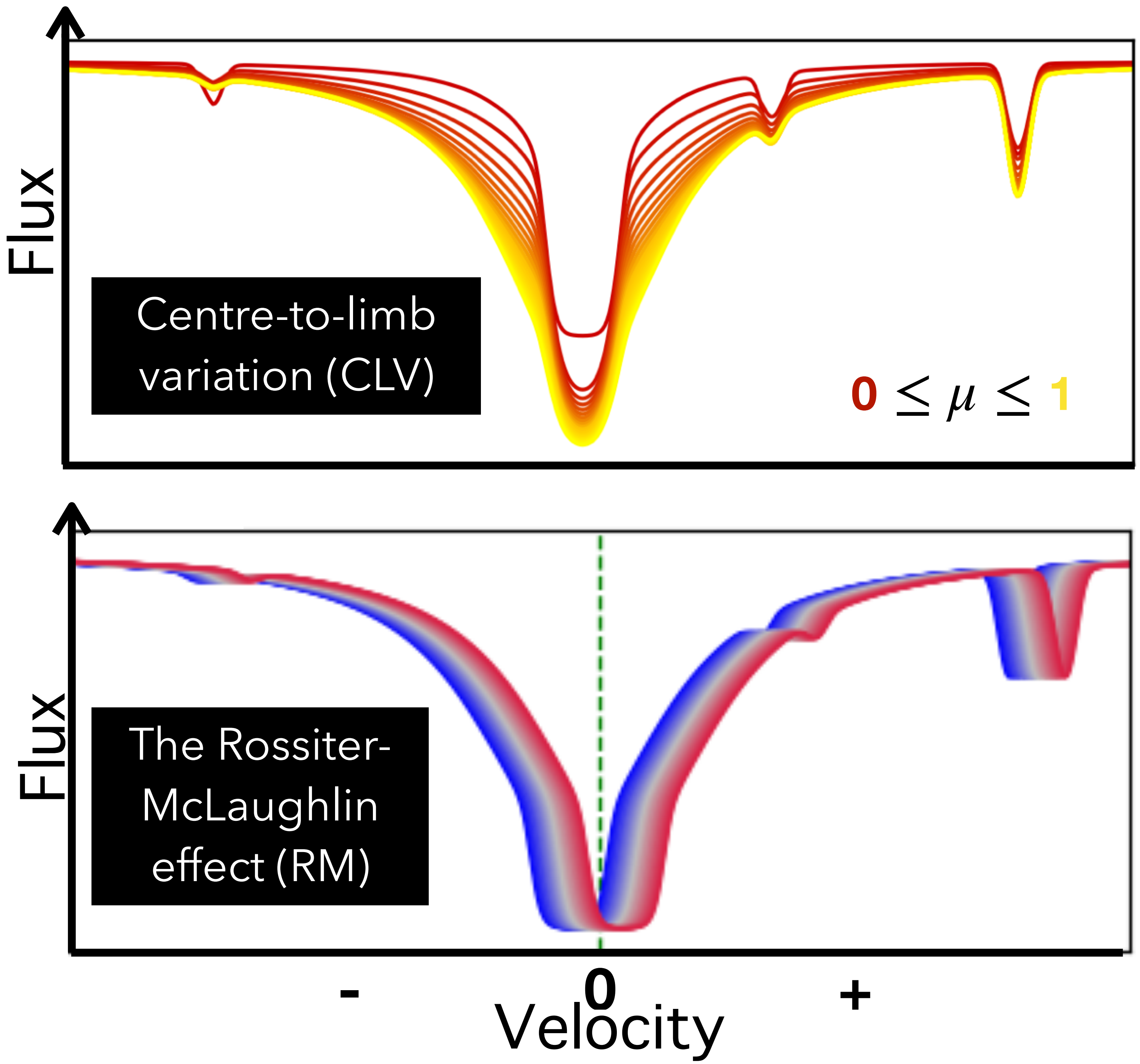
$$w_i = 1/\sigma_i^2$$

$\sigma_i$ error of pixel $i$

# Extracting the transmission spectrum

## Other corrections: the RM effect and CLV



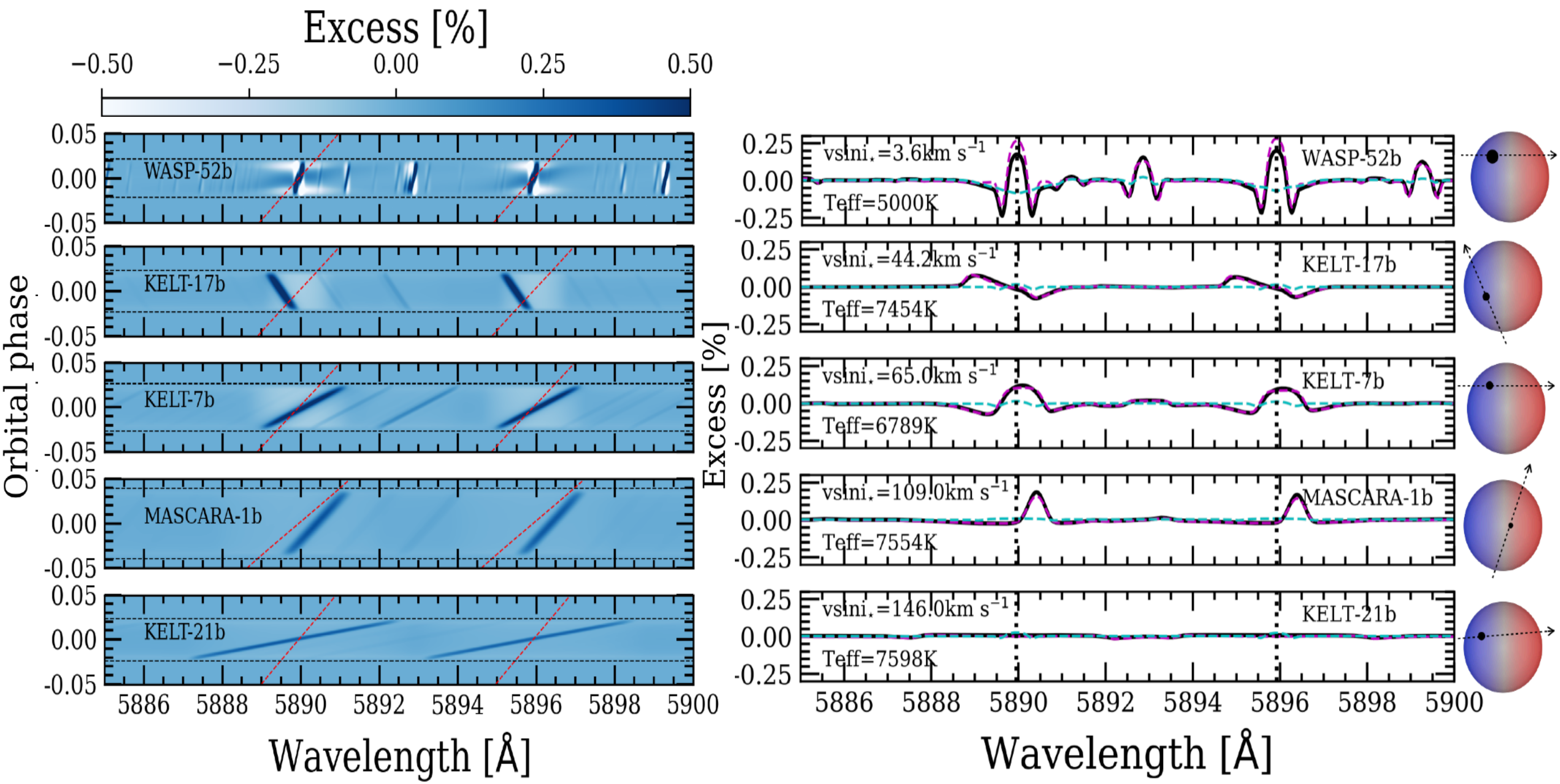



Credit: Solar Orbiter/PHI Team/ESA & NASA

# Extracting the transmission spectrum



## Other corrections: the RM effect and CLV



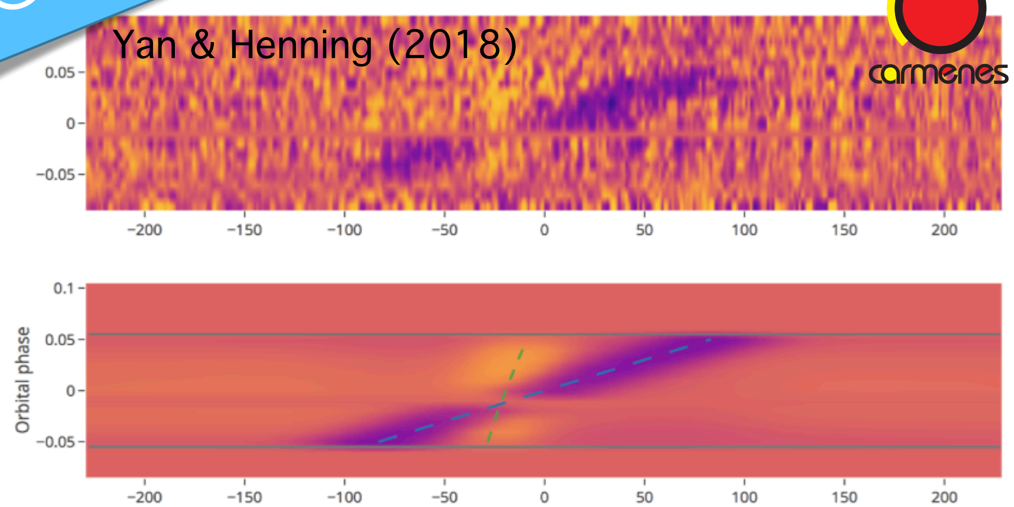
# Extracting the transmission spectrum



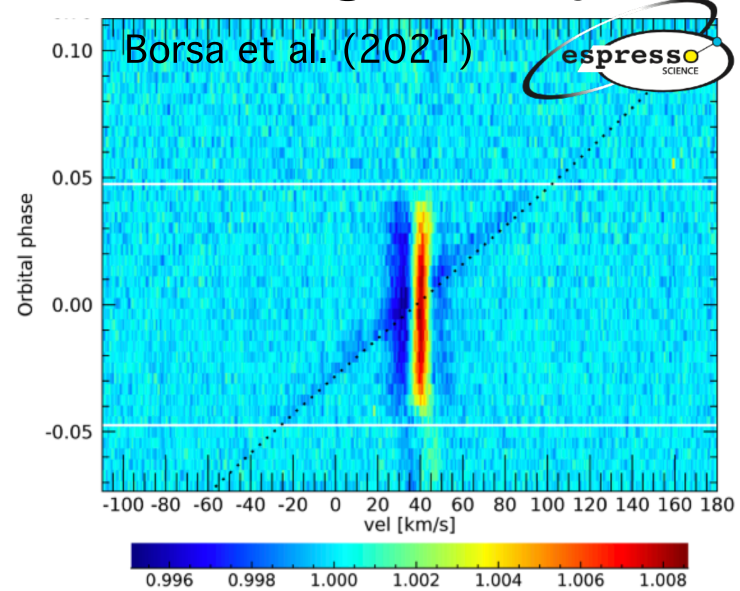
## Other corrections: the RM effect and CLV

Observations

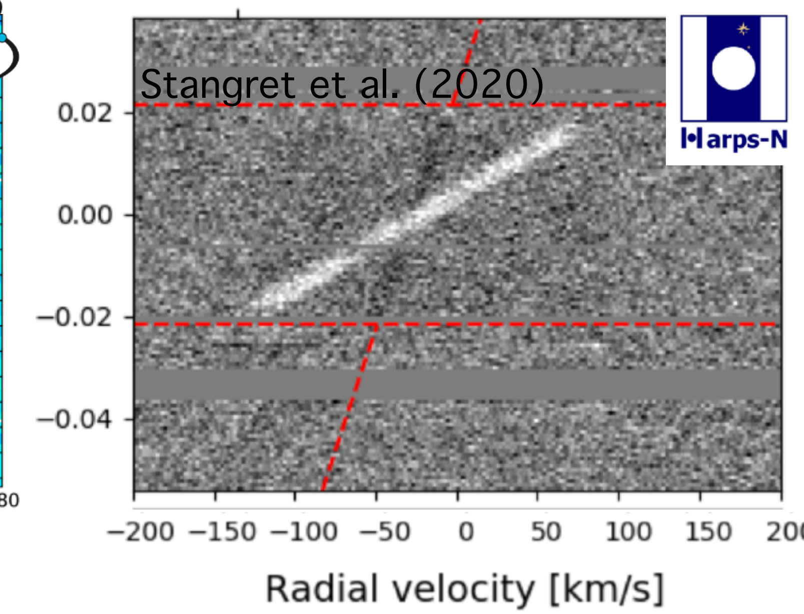
KELT-9b



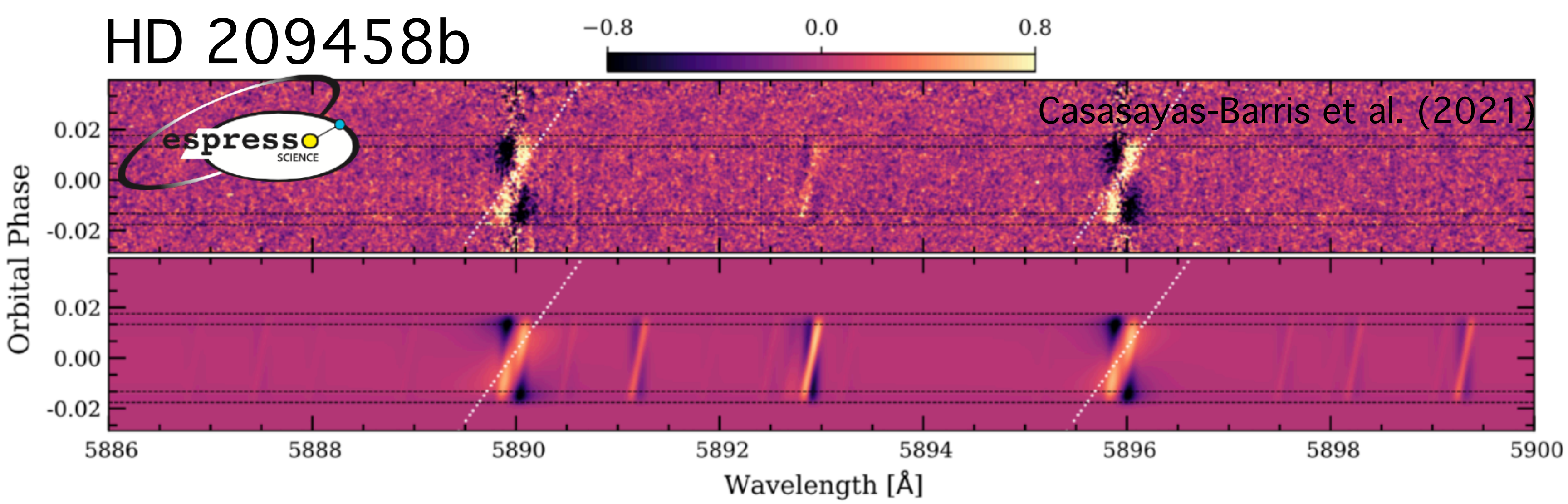

WASP-121b



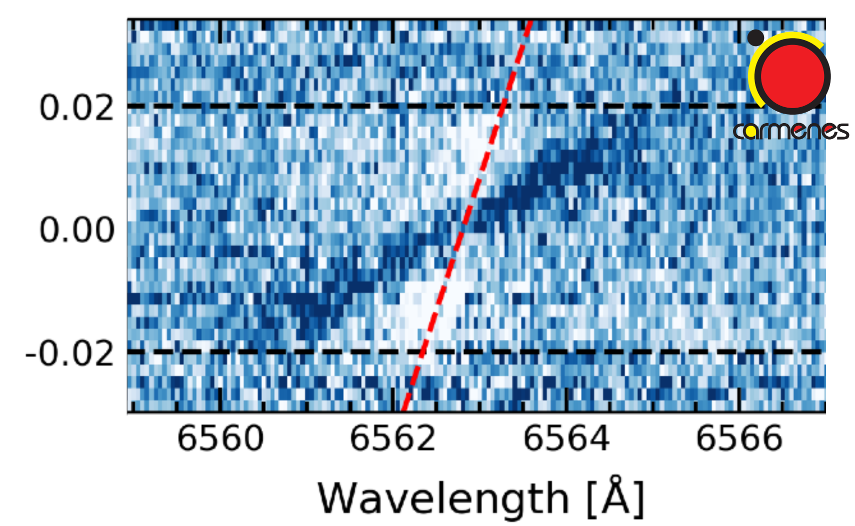

MASCARA-2b




HD 209458b

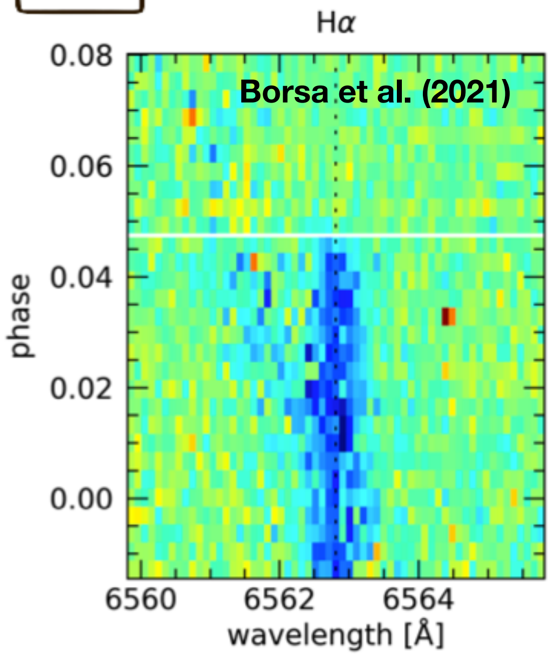


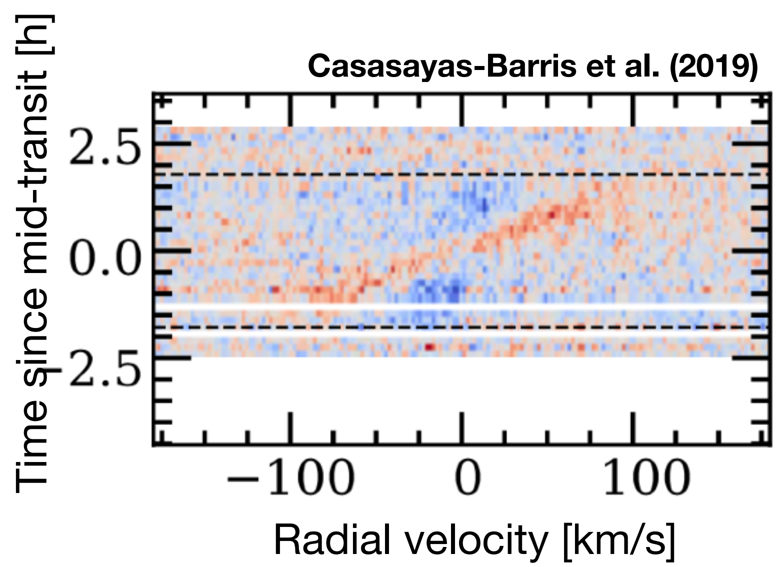

MASCARA-2b



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

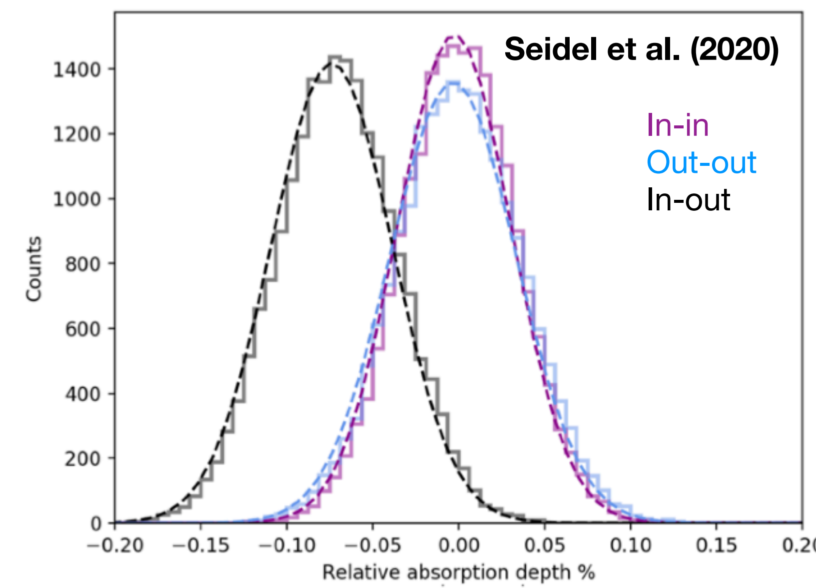
## 2D tomography maps



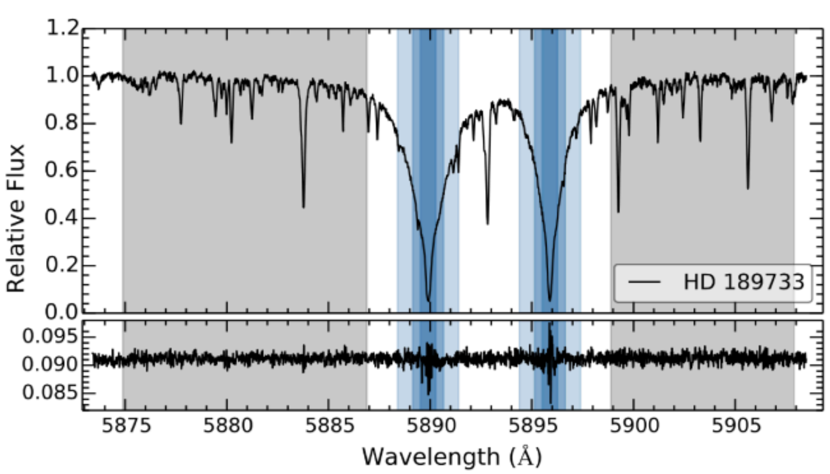

## Empirical Monte Carlo

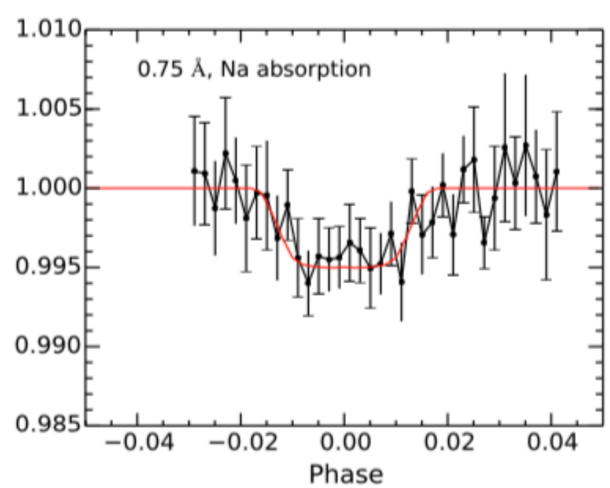
Redfield et al. (2008)




## Transmission light curves

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

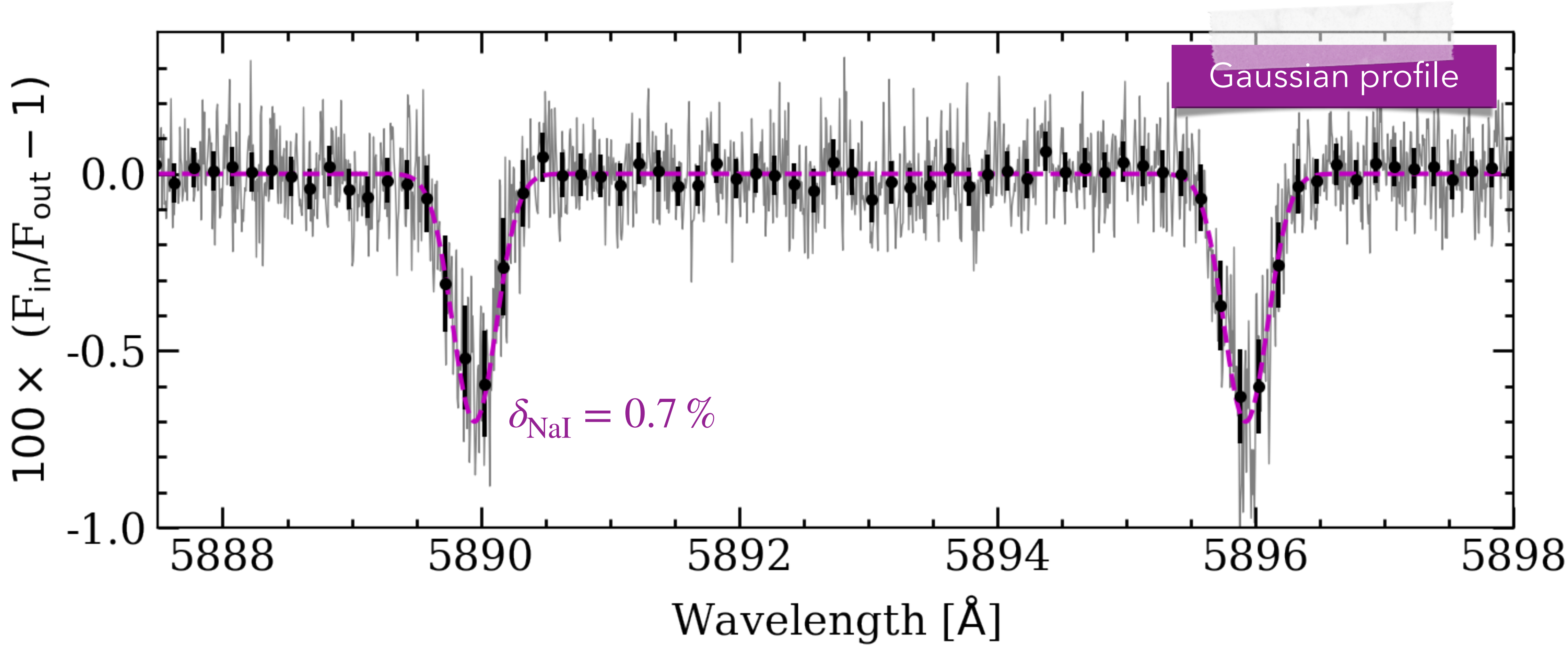



## Others:

- 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**

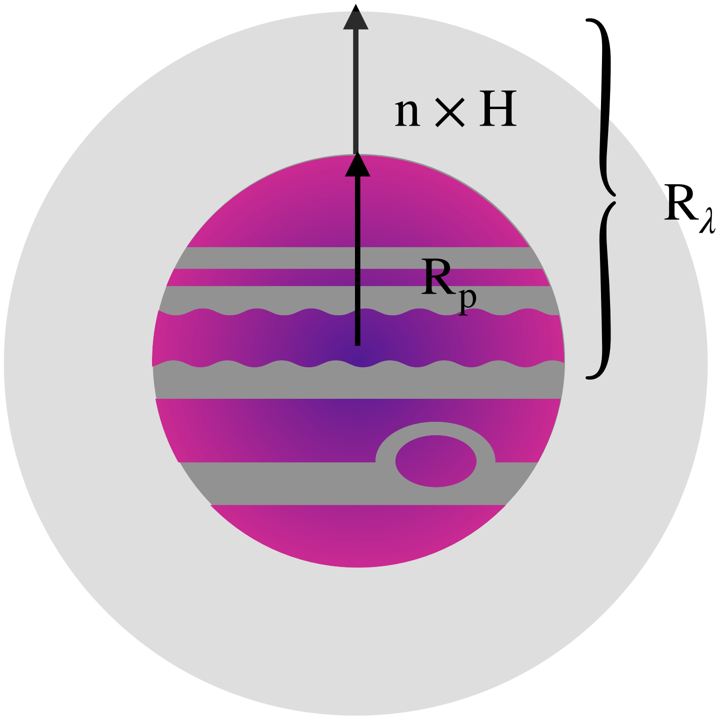
- **Temperature of the layers where the lines form**
- **Broadening due to atmospheric winds, tidally locked rotation…**
- **Overall blue/red shift due to atmospheric winds**
- **…**

See some results during the conference!

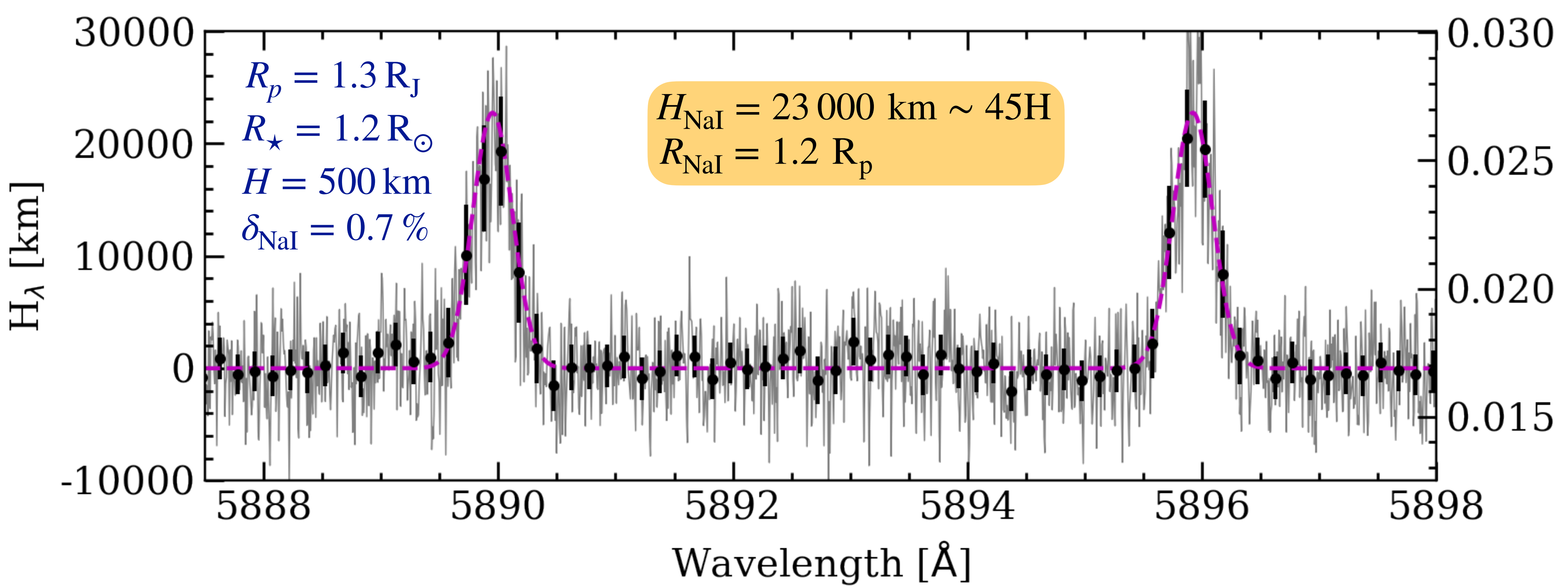
# Interpretation of the transmission spectrum



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



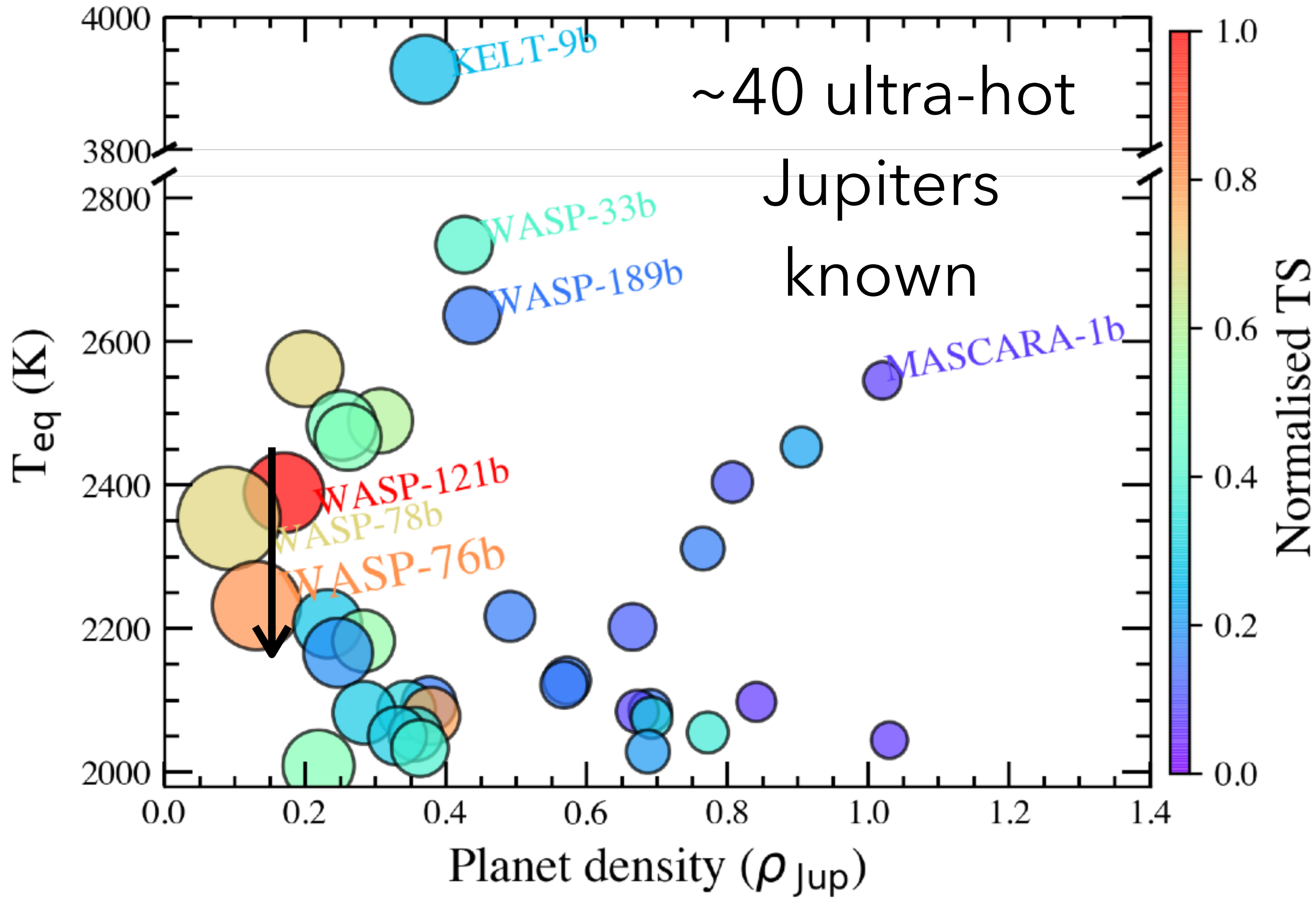

$$\delta_\lambda = \Delta_\lambda - \Delta_0 \approx \frac{2R_pH_\lambda}{R_\star^2}$$



# 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 NaI

## The data

- 1 transit of WASP-76b observed with HARPS