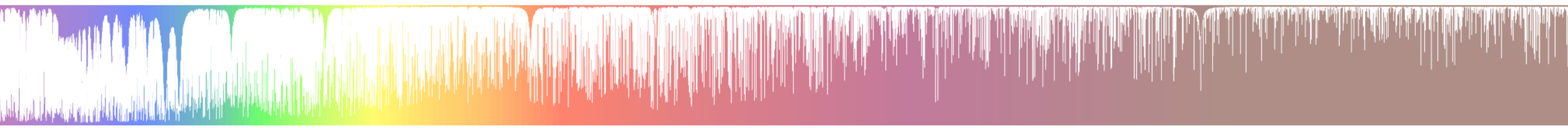
Narrow band transmission spectroscopy



Núria Casasayas Barris
Julia V. Seidel

Atmo 2021 - Workshop

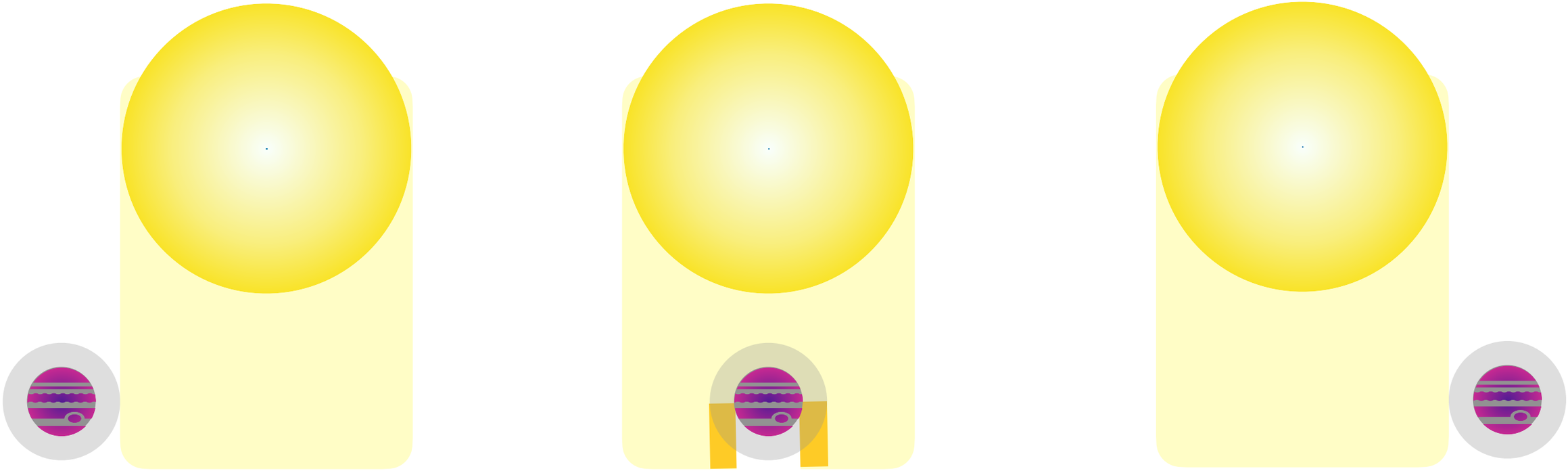
23 August 2021

Transmission spectroscopy

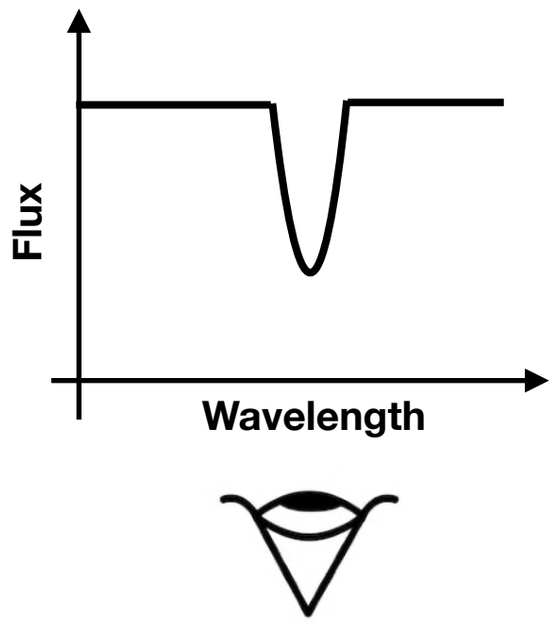
Before the transit

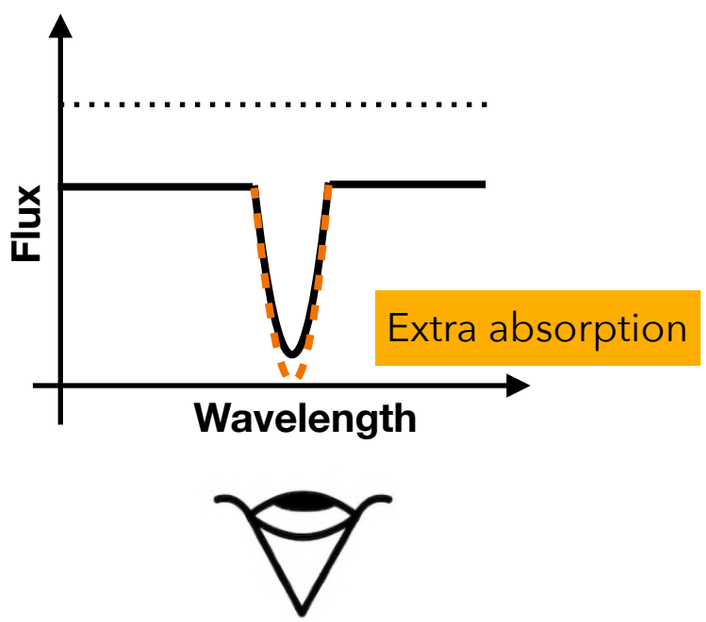
During the transit

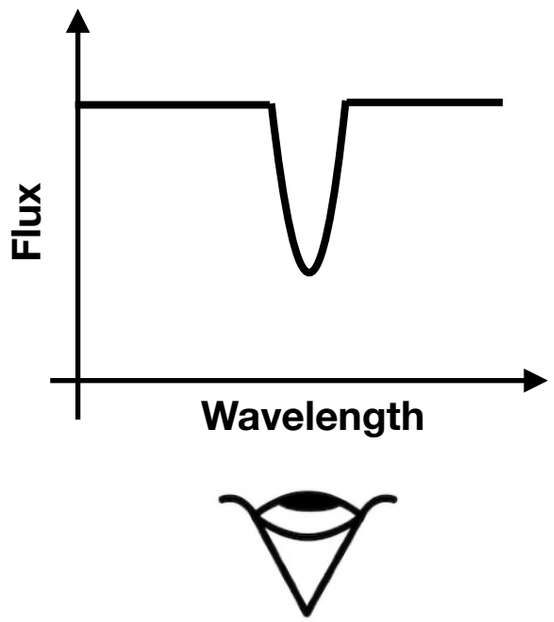
After the transit



Stellar line profile

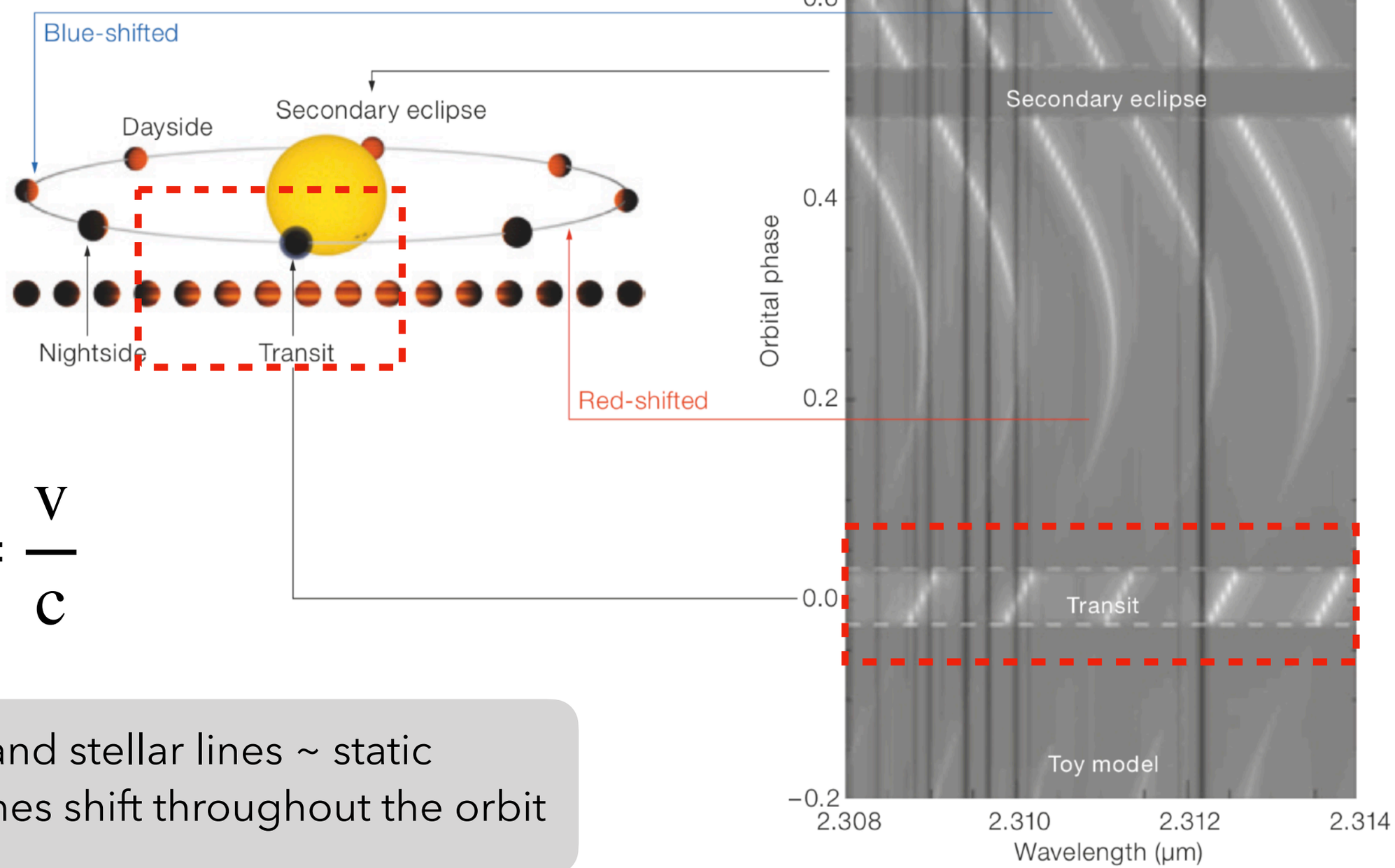






High-resolution transmission spectroscopy

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

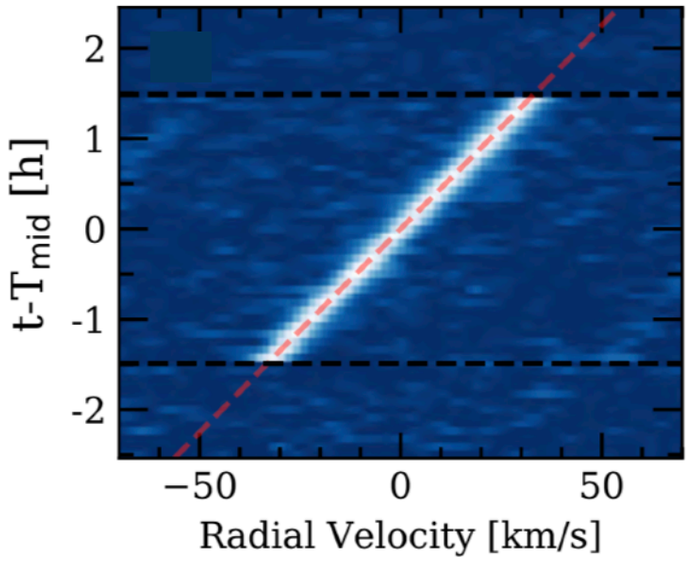


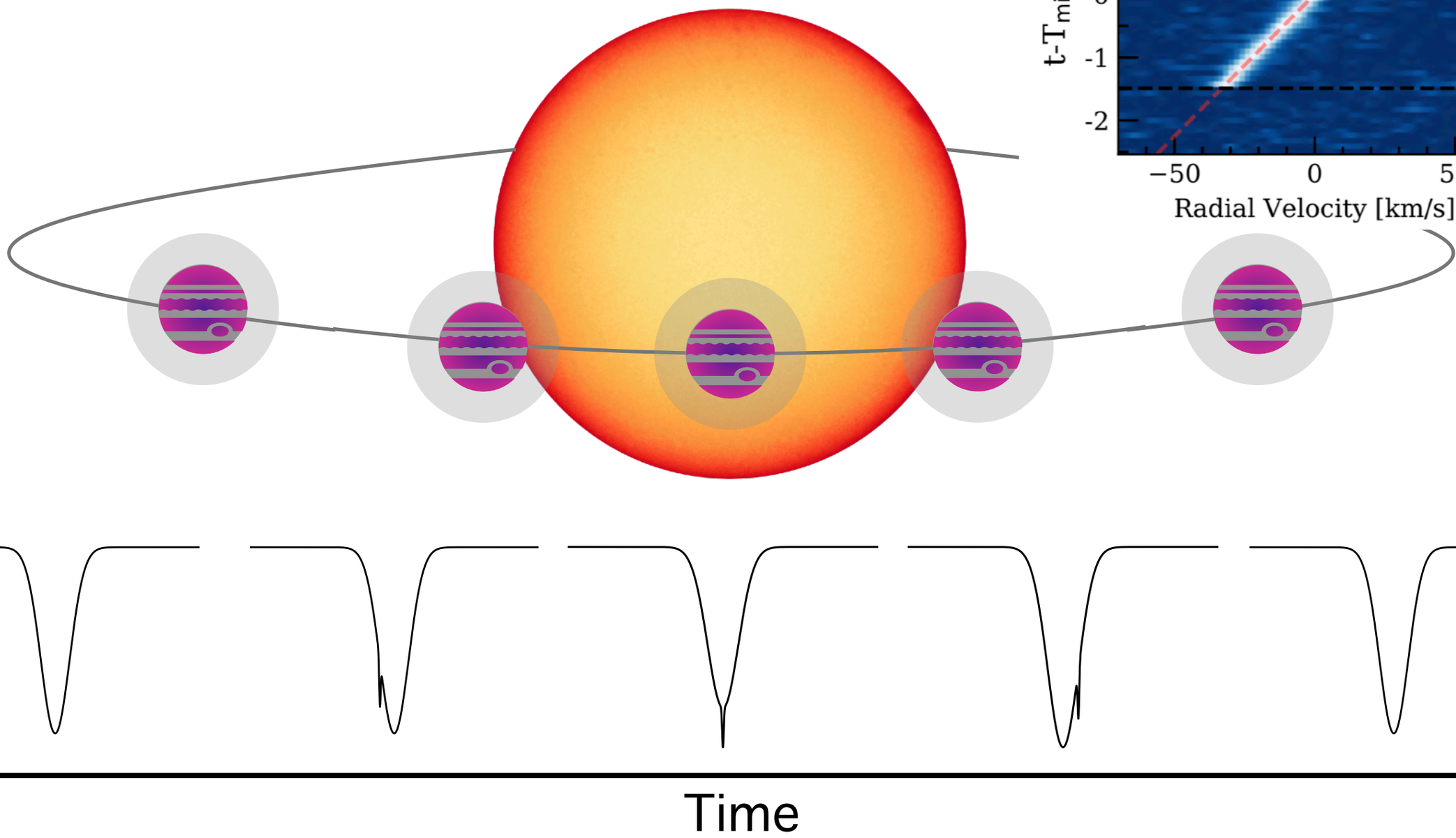
$$\frac{\Delta\lambda}{\lambda_0} = \frac{v}{c}$$

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

High-resolution transmission spectroscopy

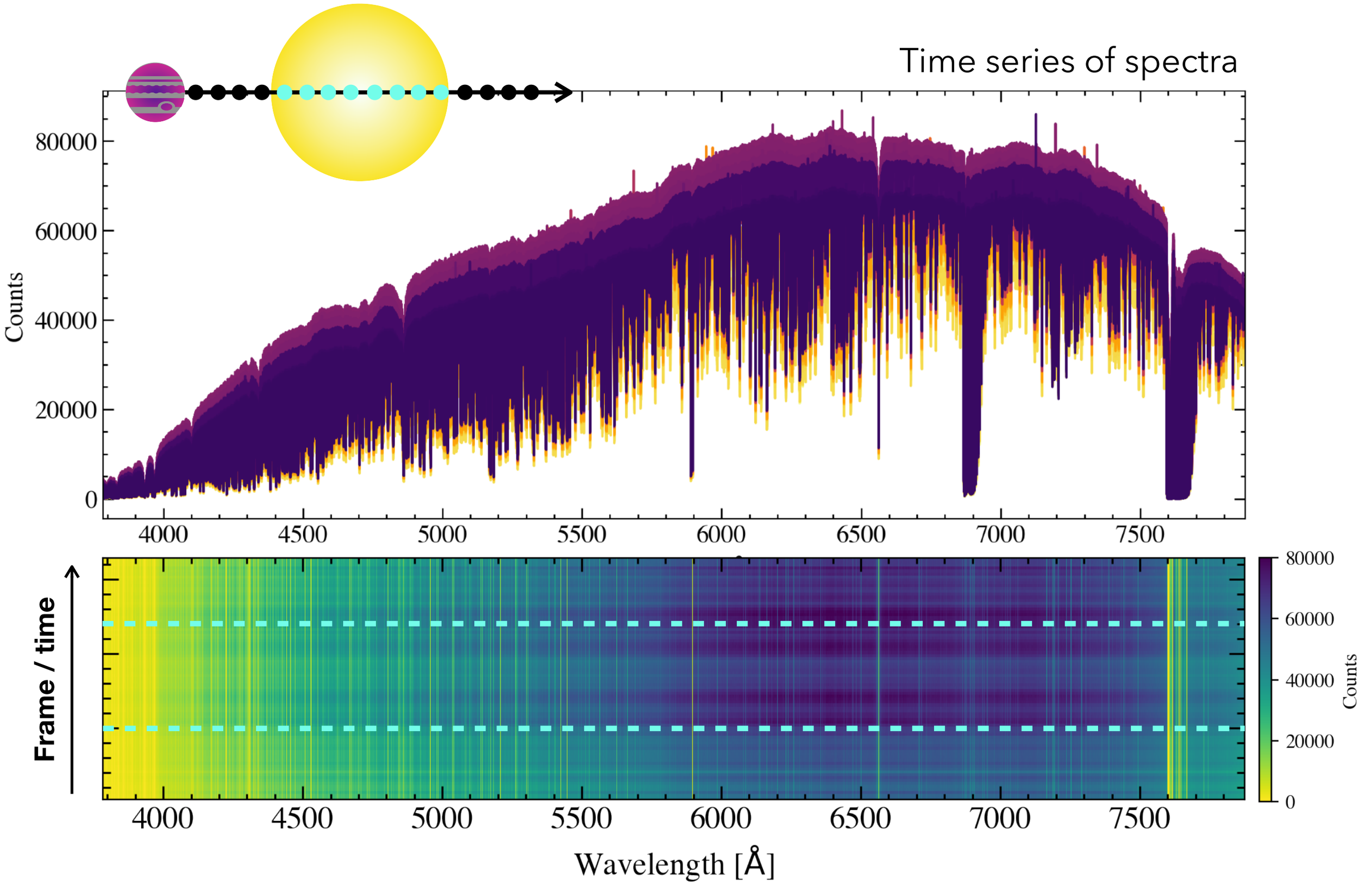
Planet movement



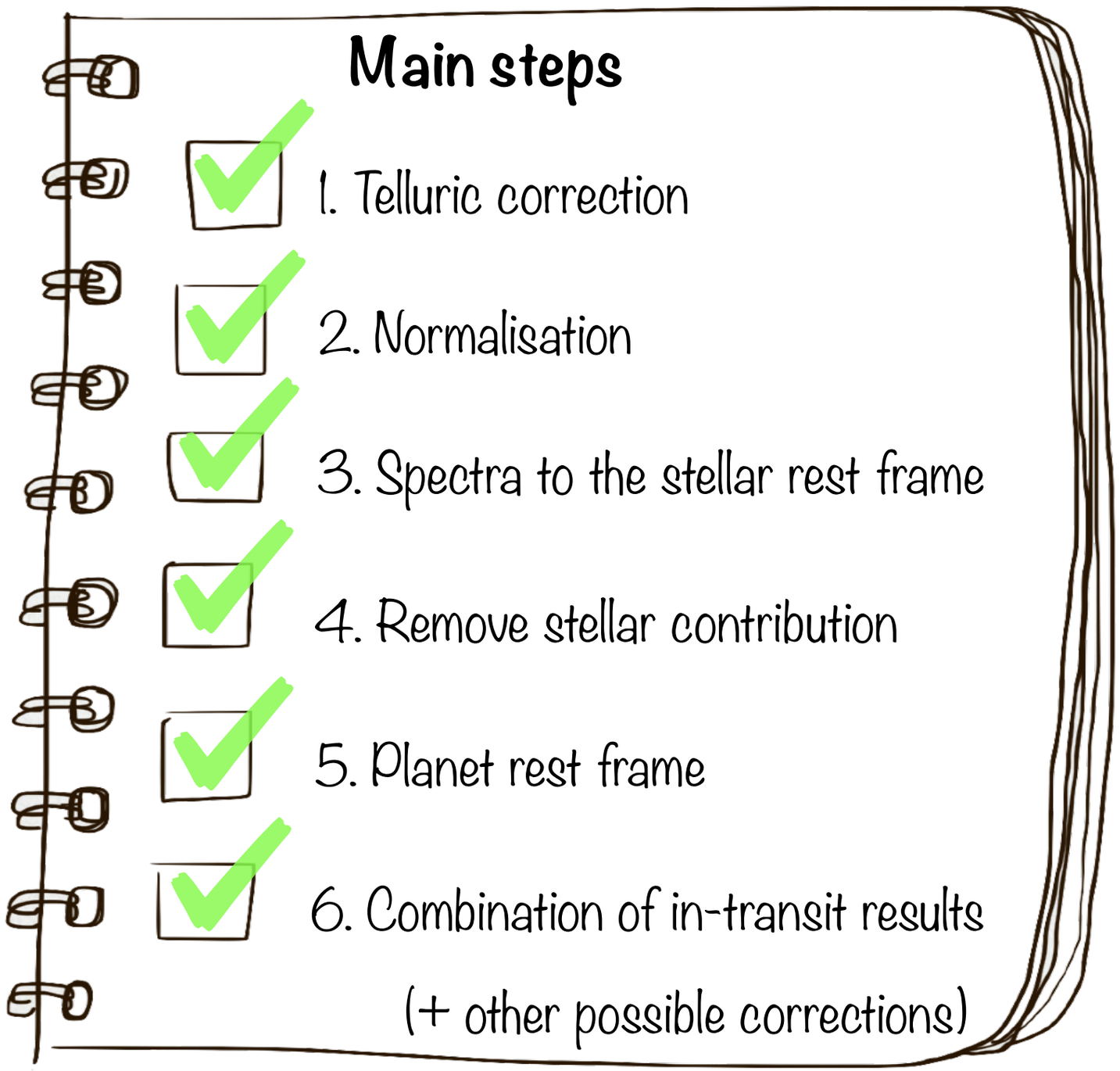


Observations

Observations



Extracting the transmission spectrum

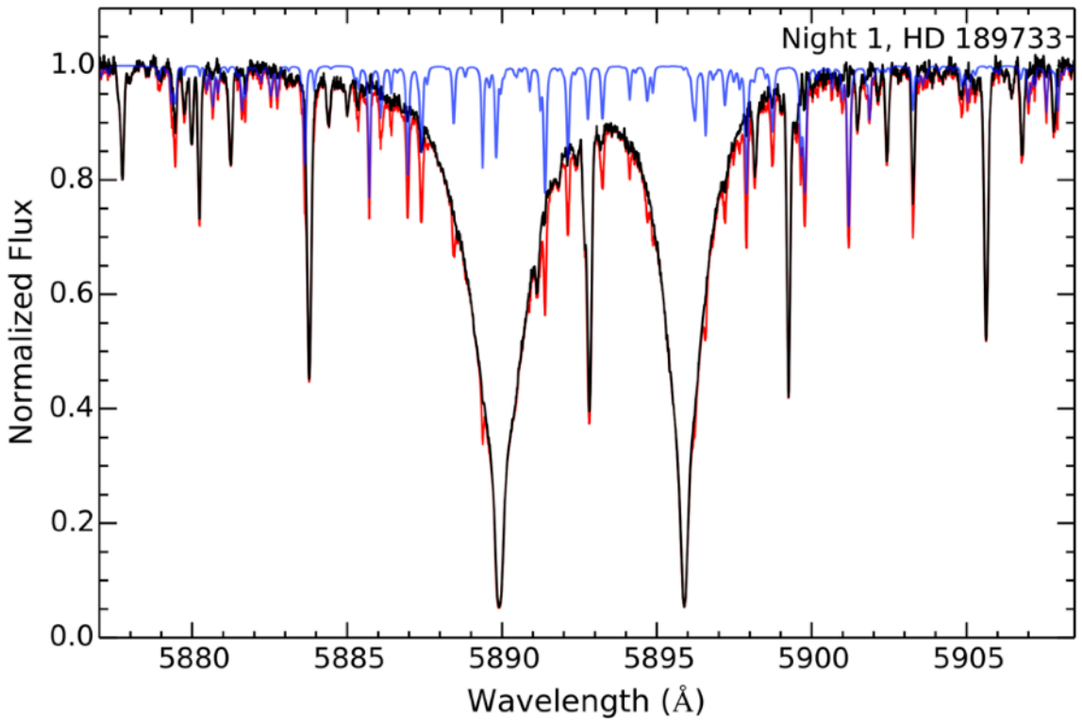


Wyttenbach et al. (2015)

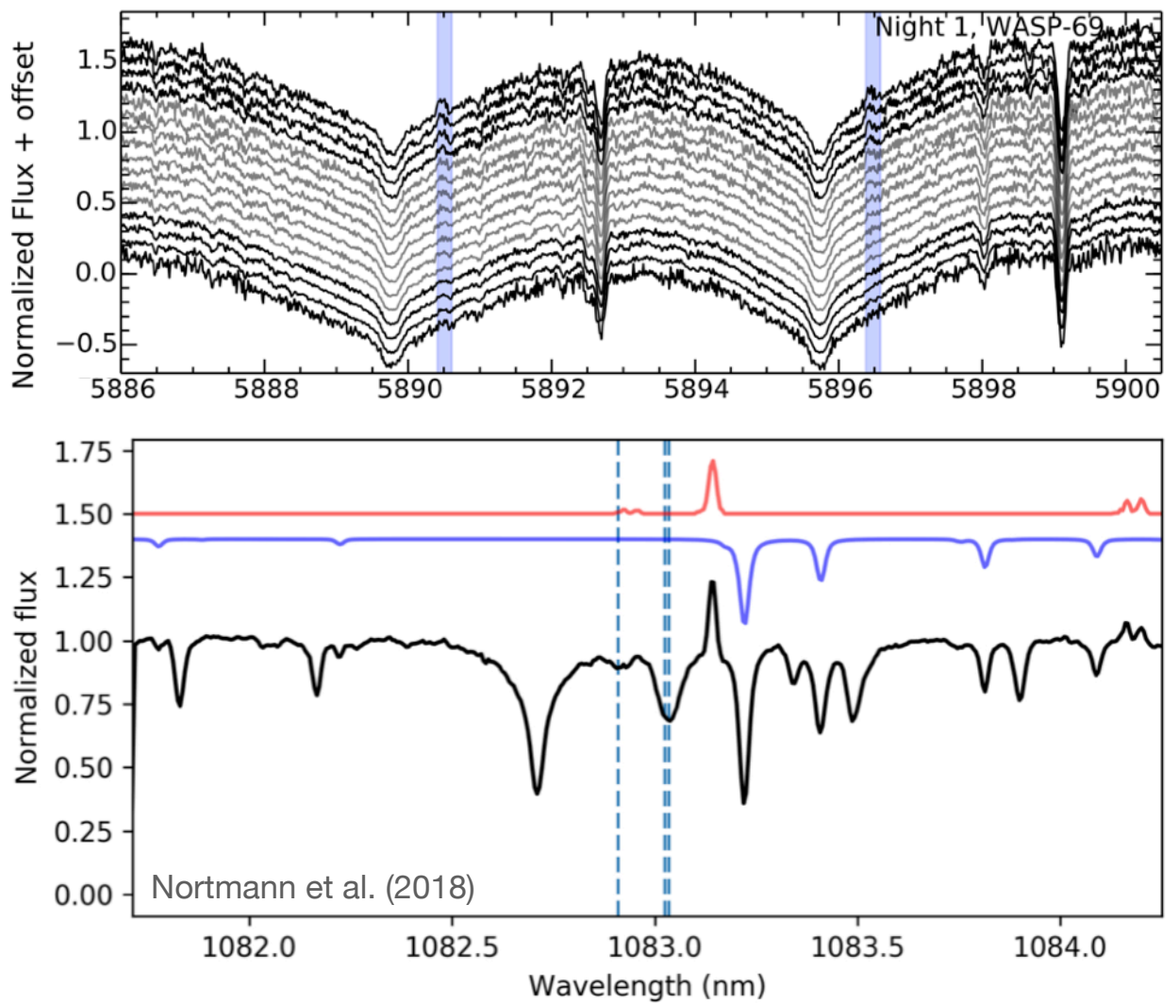
Extracting the transmission spectrum

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!

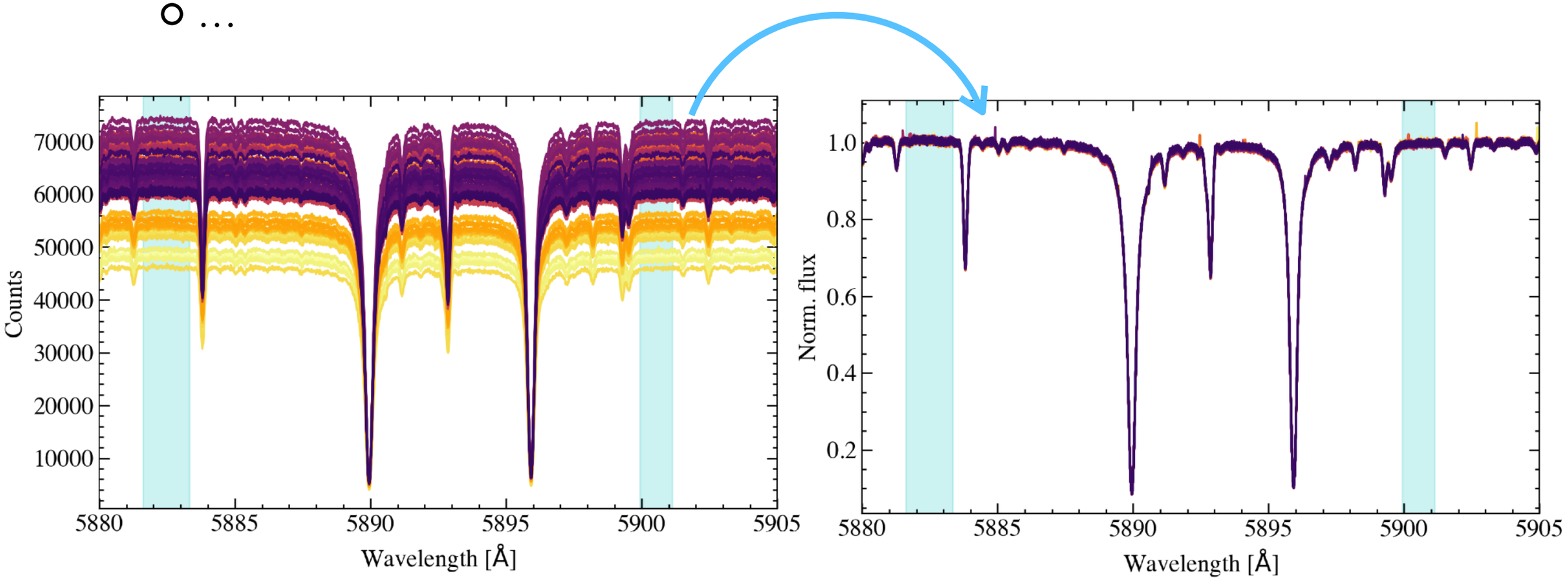
Sky observations with fibre B

Extracting the transmission spectrum

☑ 2. Normalisation

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

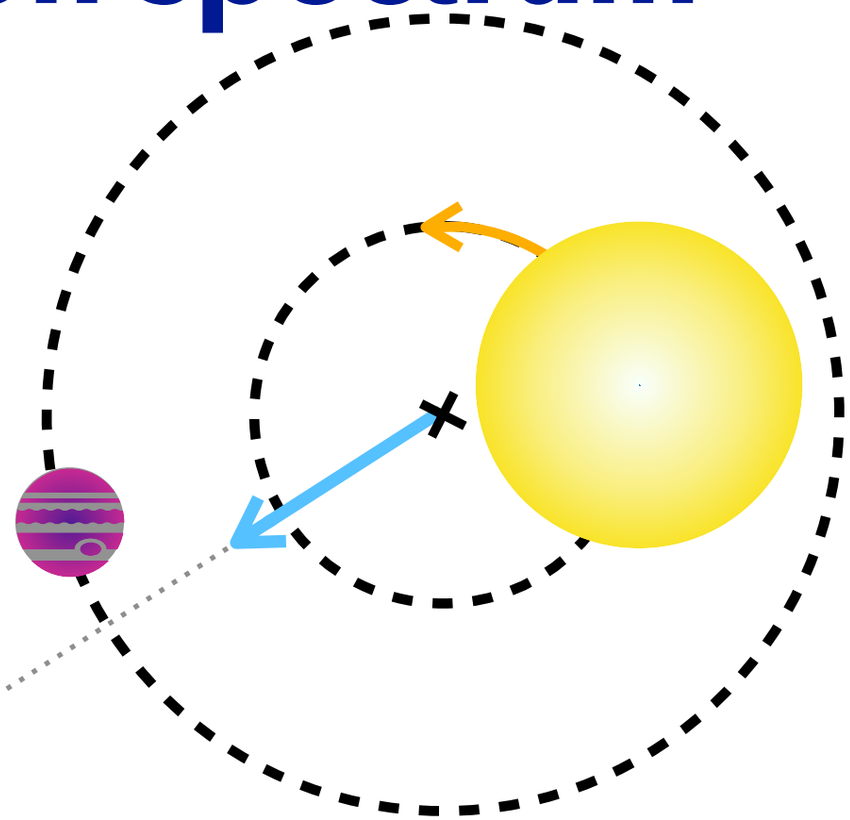
The normalisation can also be performed at the end of the process (see tutorial!)



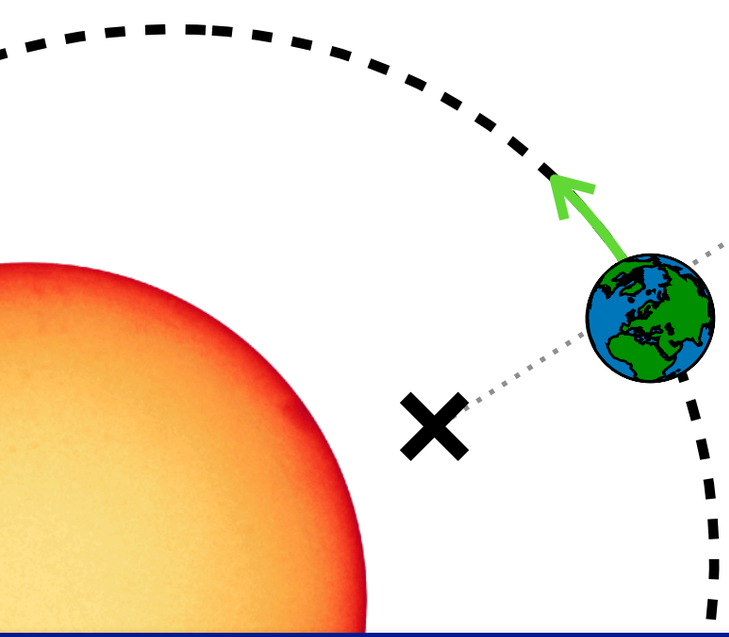
Extracting the transmission spectrum

3. Stellar rest frame

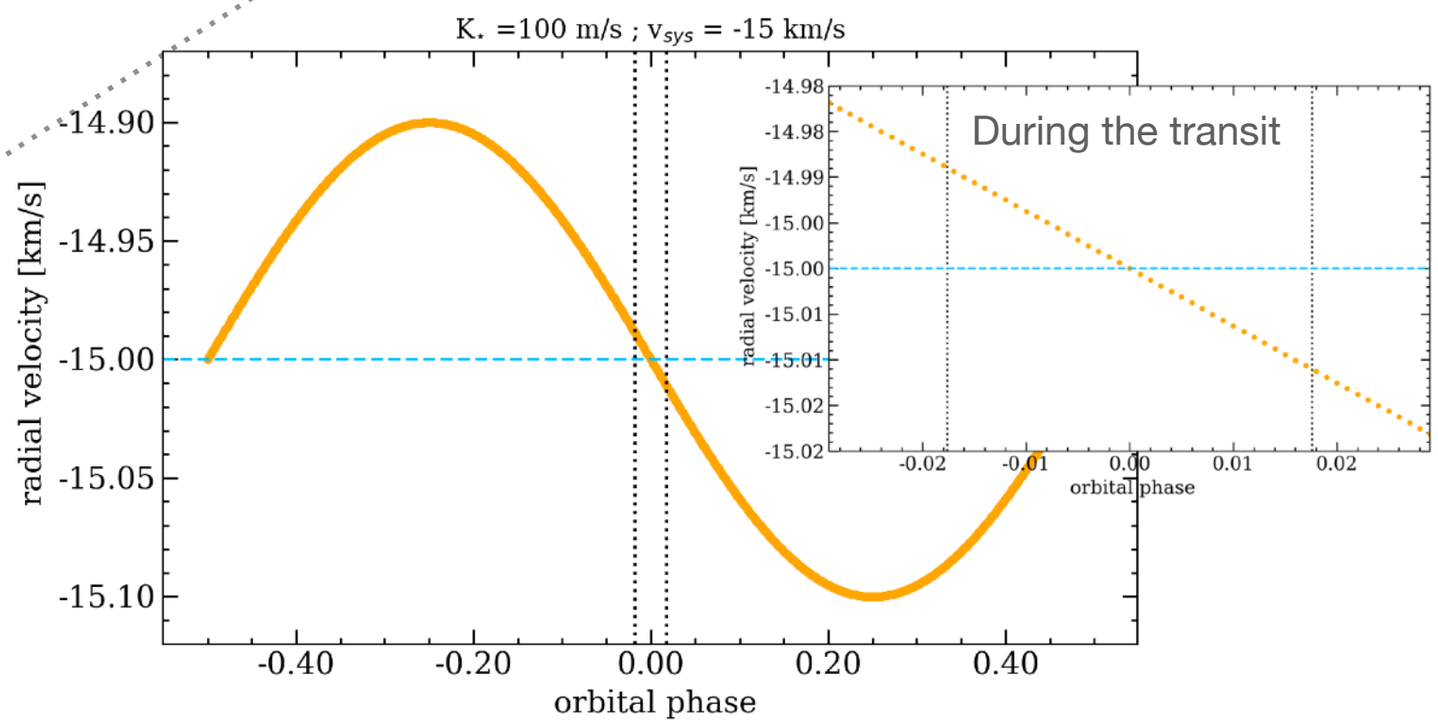
$$\mathrm{RV}^{i}_{\star} \begin{cases} K_{\star} \times \sin(2\pi\phi_i) & \textbf{Stellar motion} \quad \text{~m/s} \\ v_{sys} & \textbf{System velocity} \quad \text{~km/s} \\ \mathrm{RV}^{i}_{\mathrm{Earth}} & \textbf{Earth Radial velocity} \quad \text{~km/s} \end{cases}$$



Solar System

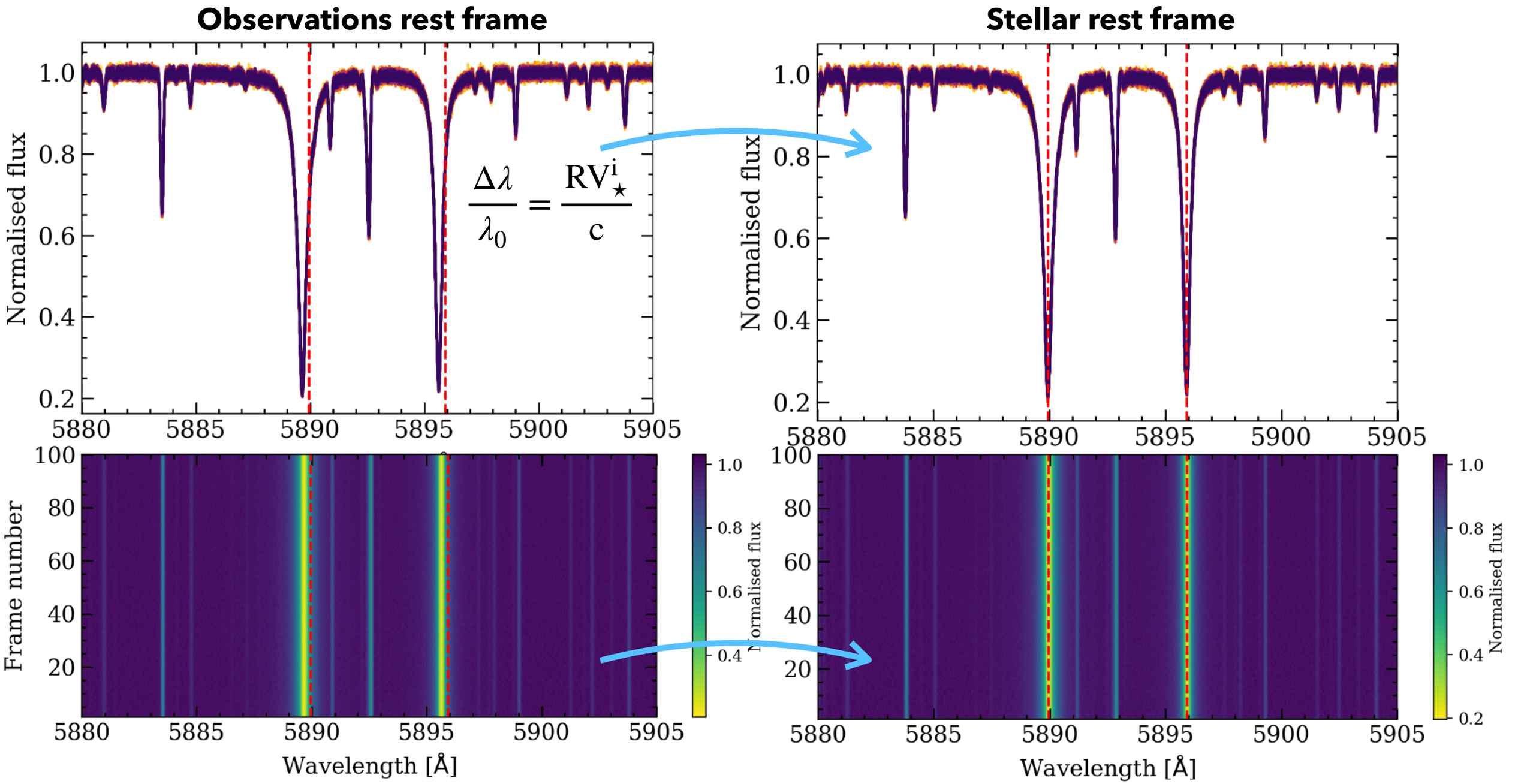


Extrasolar system



Extracting the transmission spectrum

3. Stellar rest frame

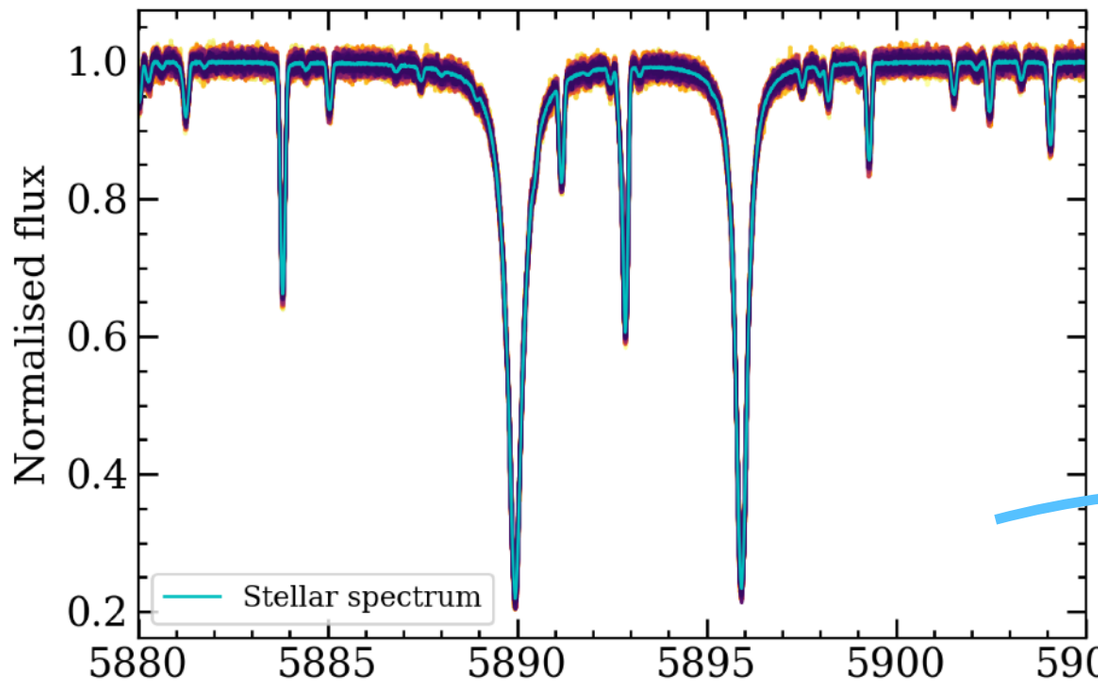


Extracting the transmission spectrum

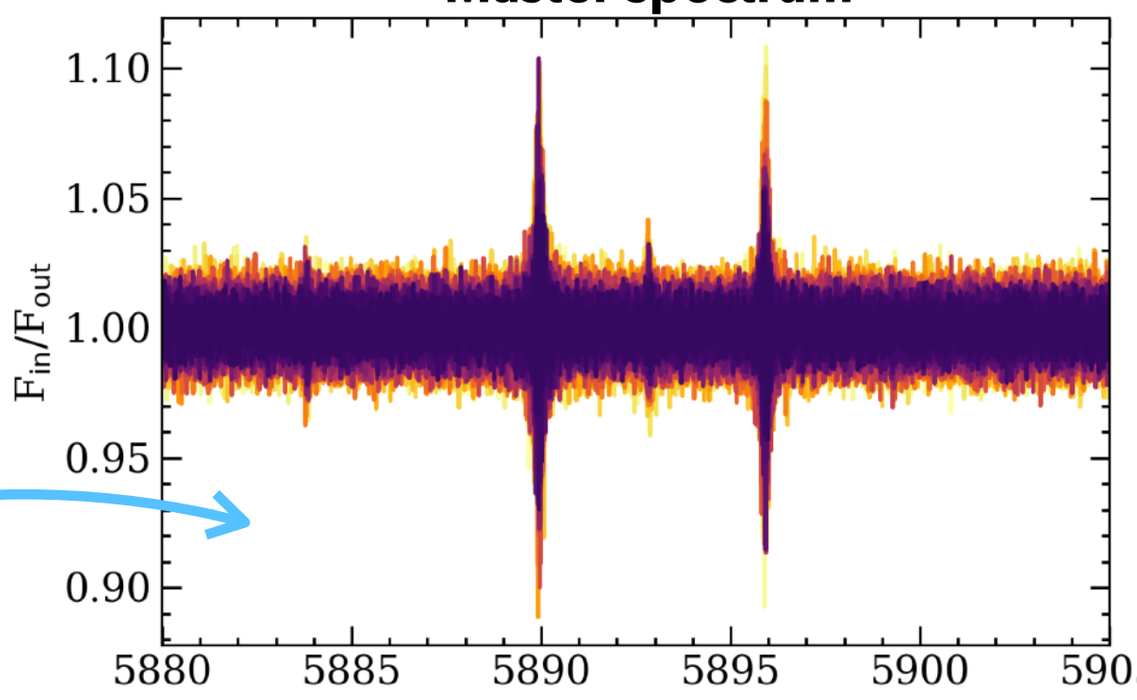
4. Remove stellar contribution

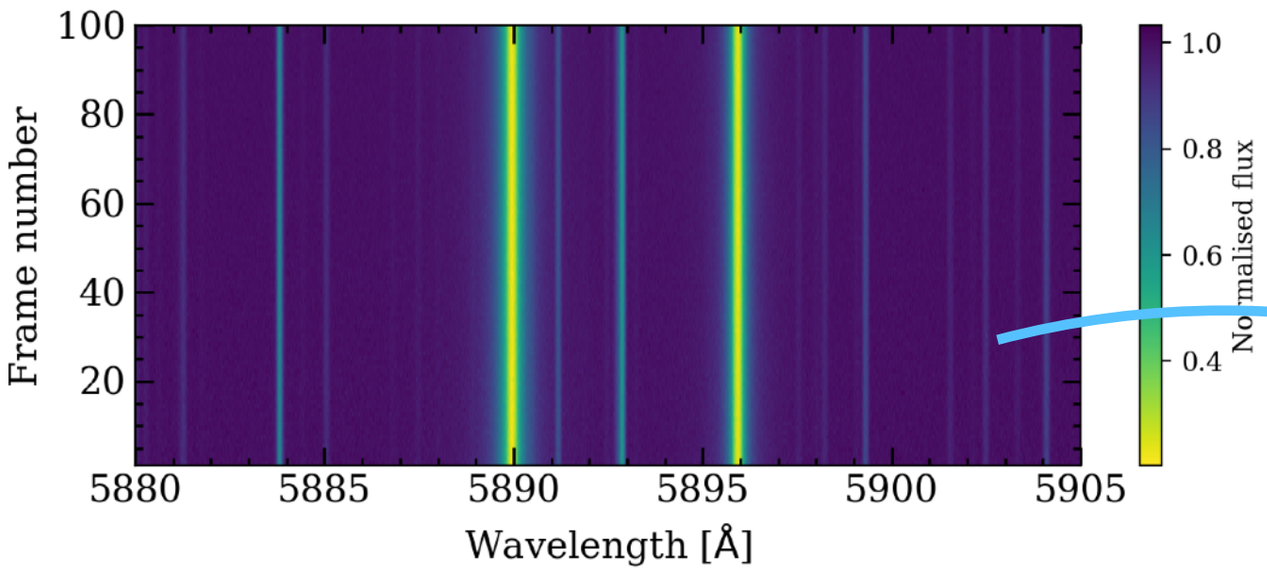
Master out-of-transit stellar spectrum

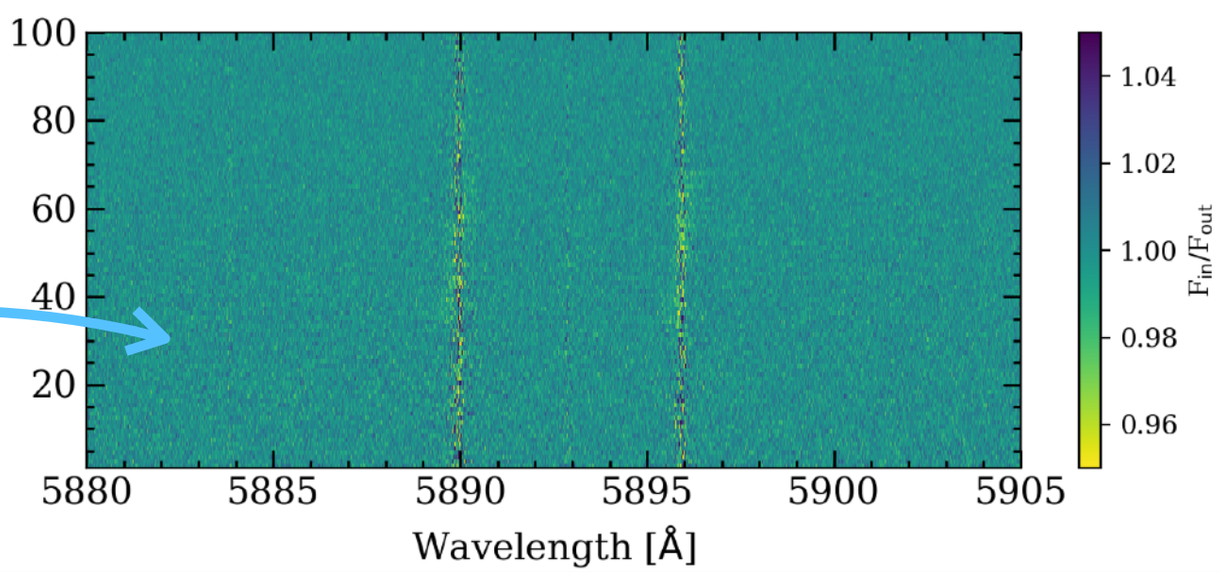
Combination of all out-of-transit spectra



Division of each spectrum by the Master spectrum

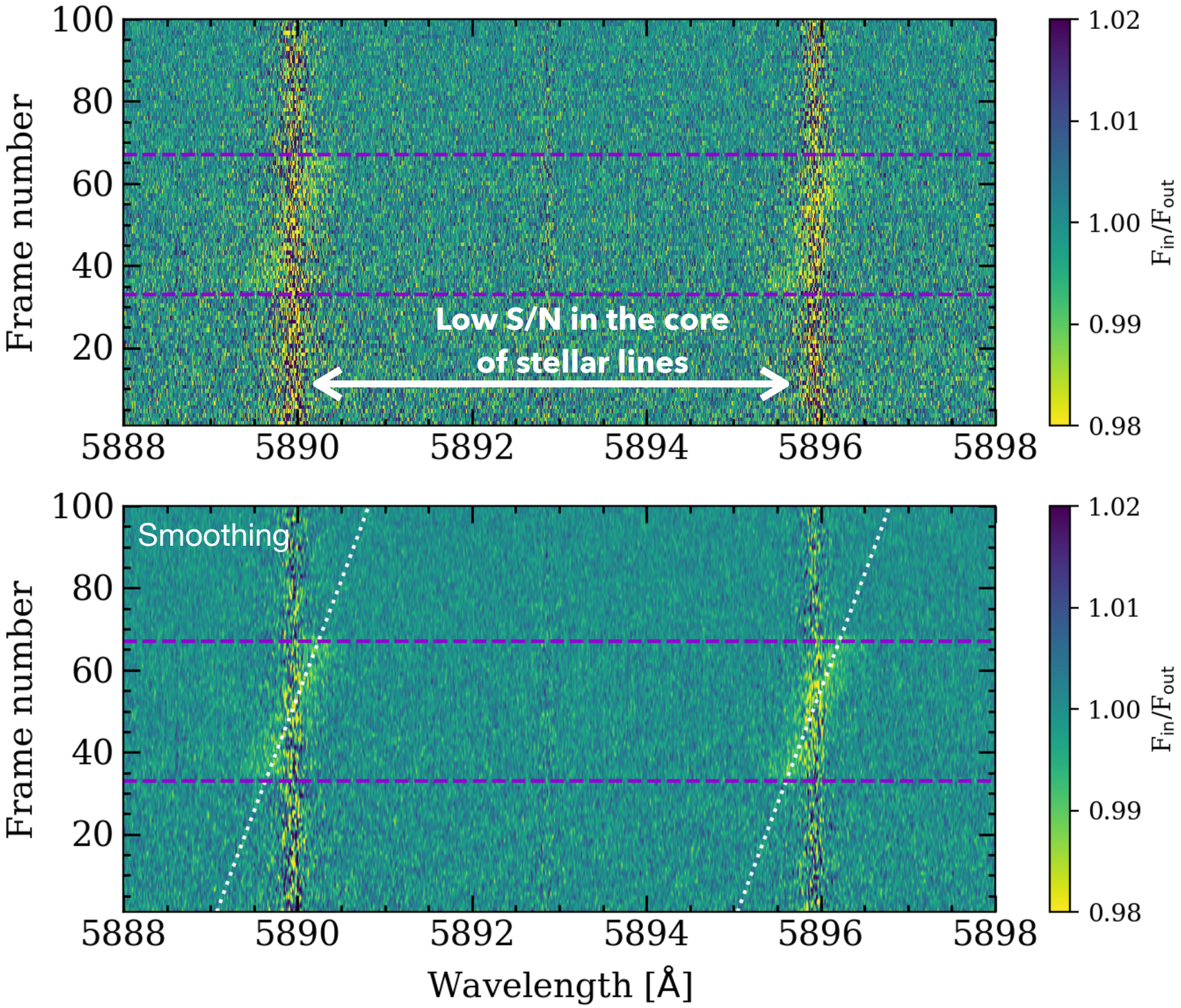






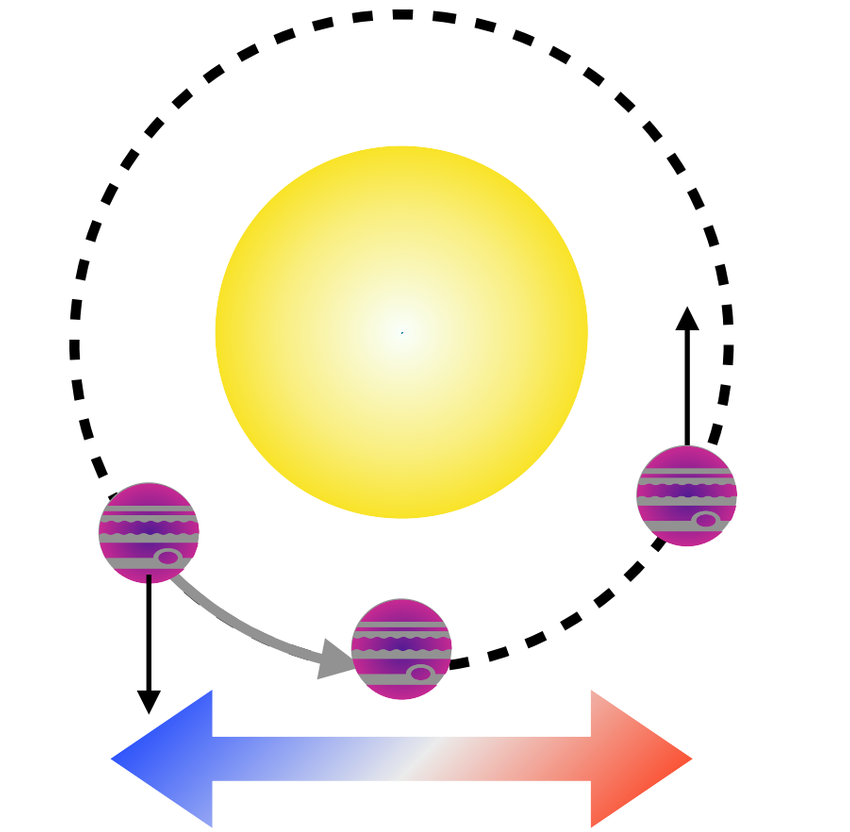
Extracting the transmission spectrum

4. Remove stellar contribution



Extracting the transmission spectrum

5. Planet rest frame

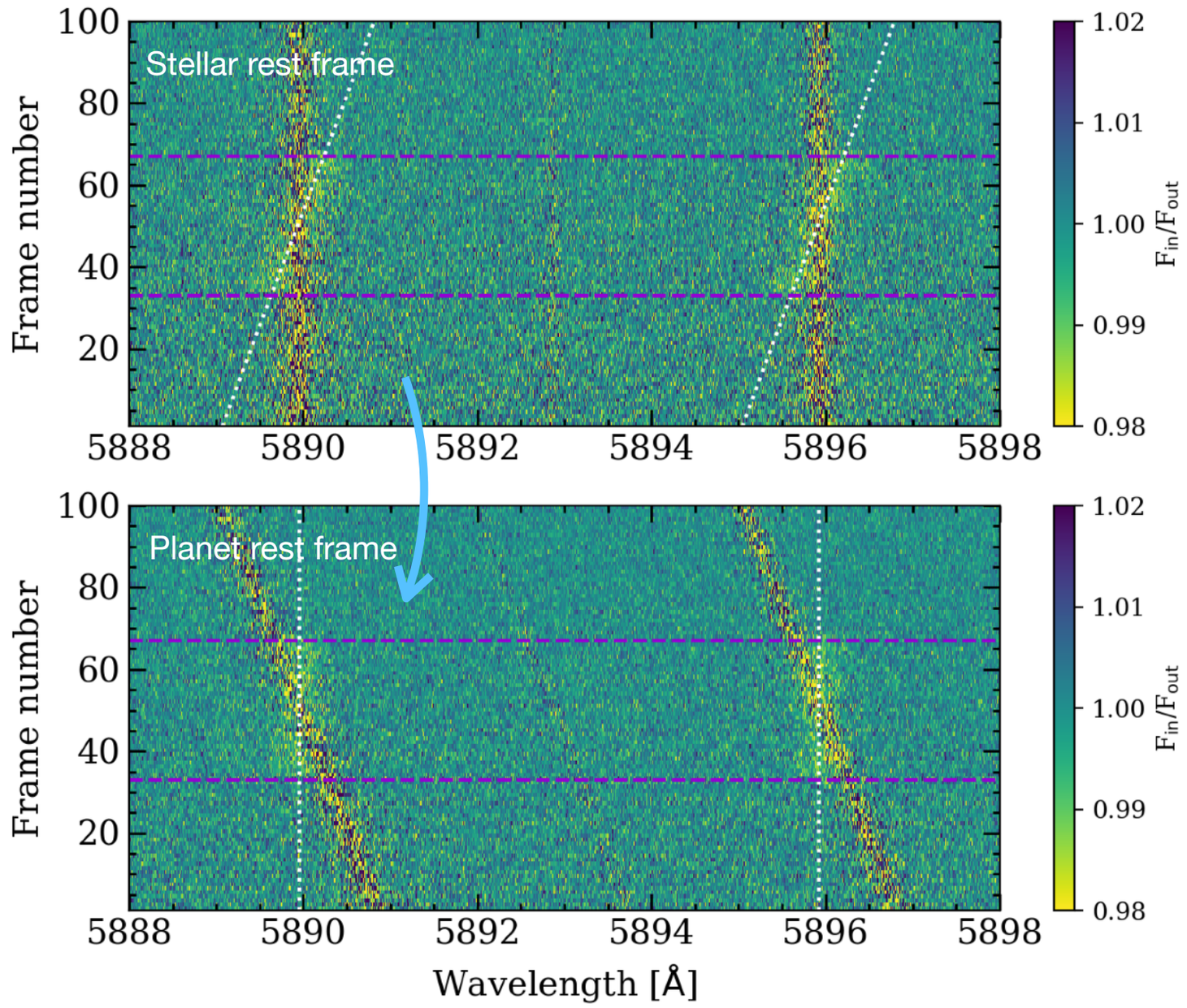


$RV_p < 0$ $RV_p = 0$ $RV_p > 0$

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

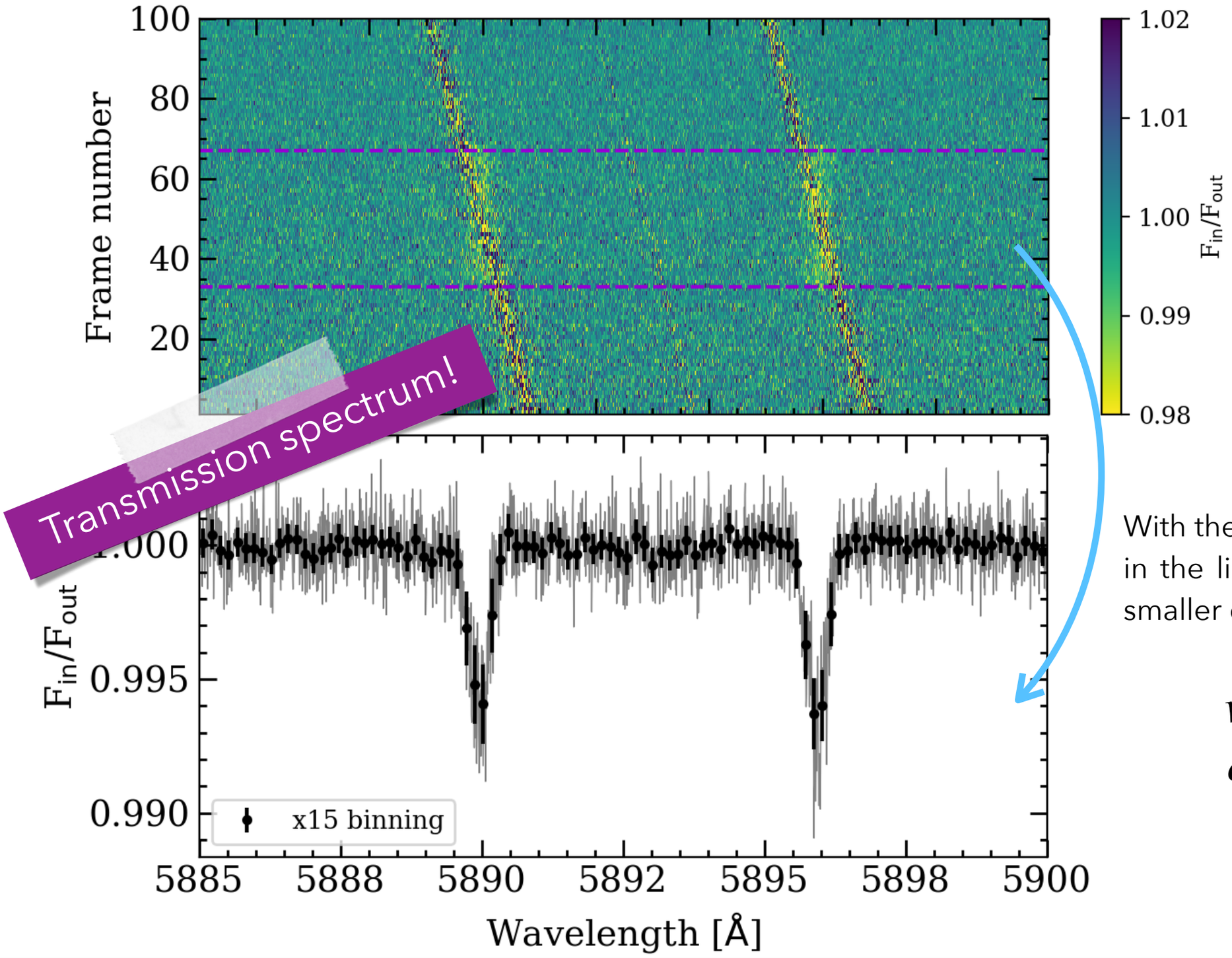
$$K_p = \frac{2\pi a}{P}\sin(i_p) \quad (e = 0 \text{ and } M_p \ll M_\star)$$

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



Extracting the transmission spectrum

6. Combination of in-transit data



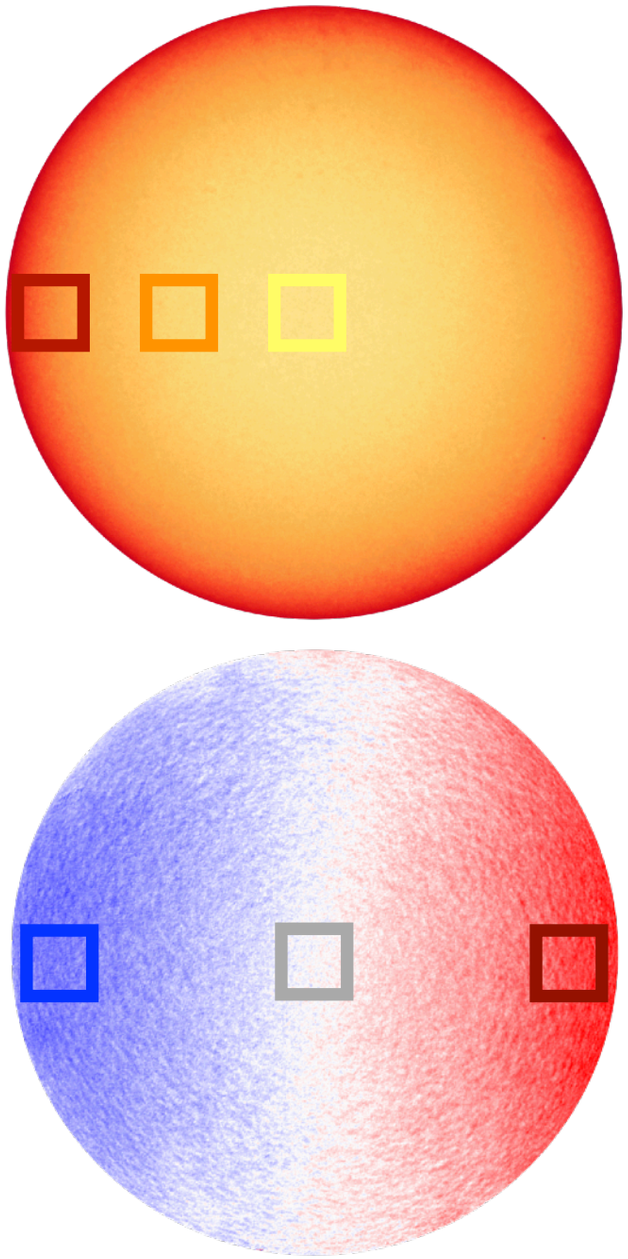
With the weighted mean the pixels in the lines core (low S/N) have a smaller contribution. Usually:

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

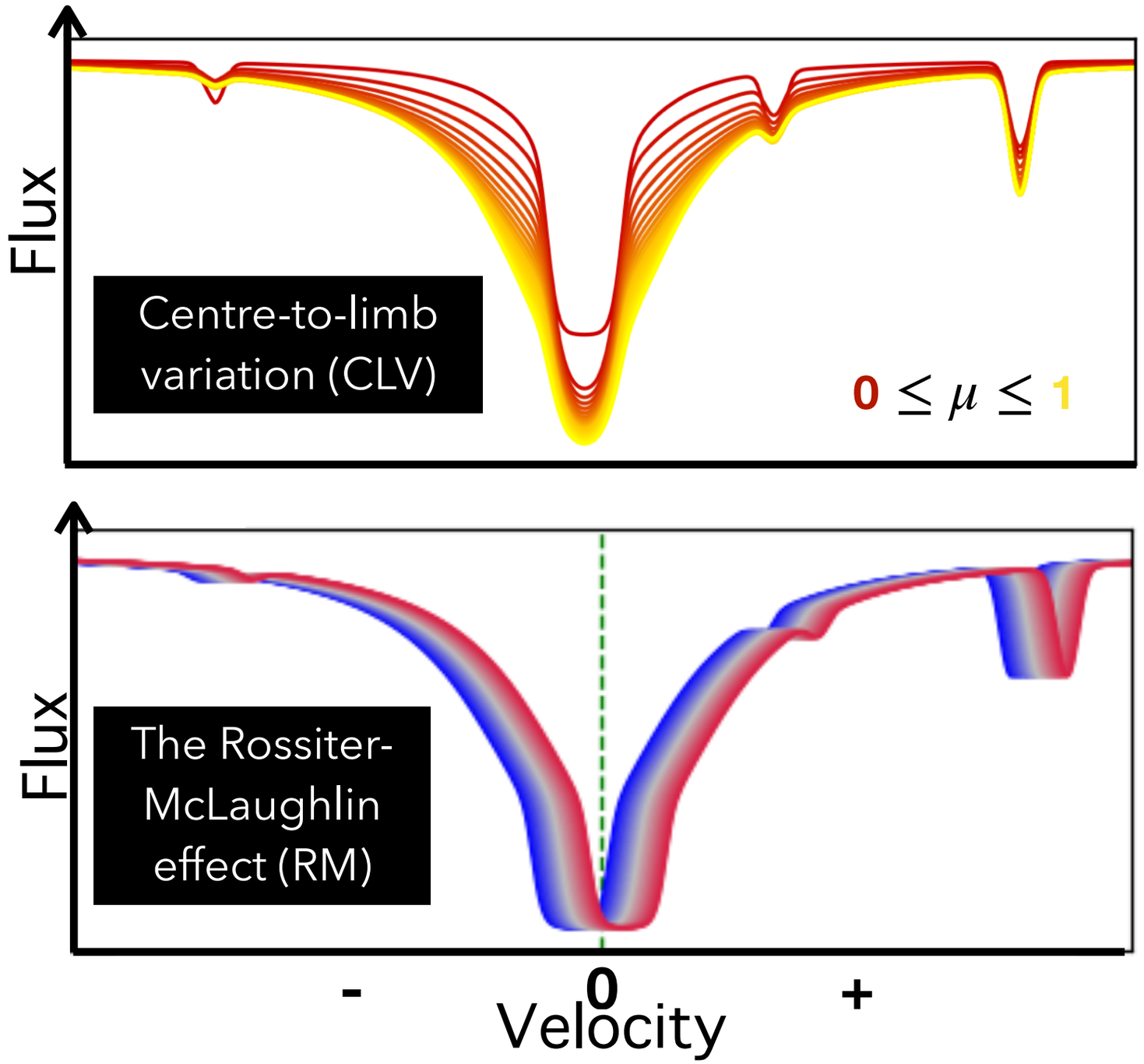
σ_i error of pixel i

Extracting the transmission spectrum

☑ Other corrections: the RM effect and CLV

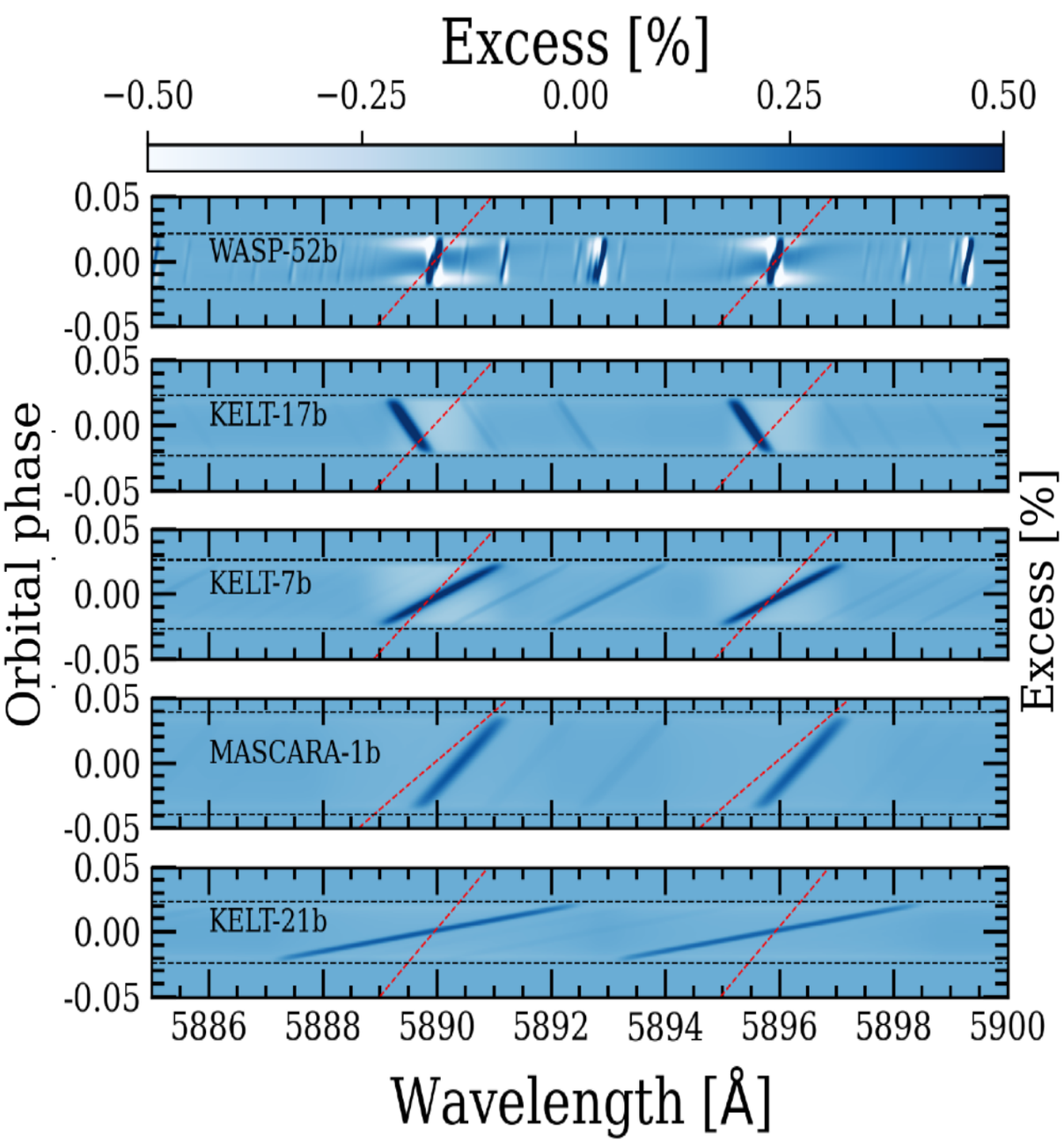


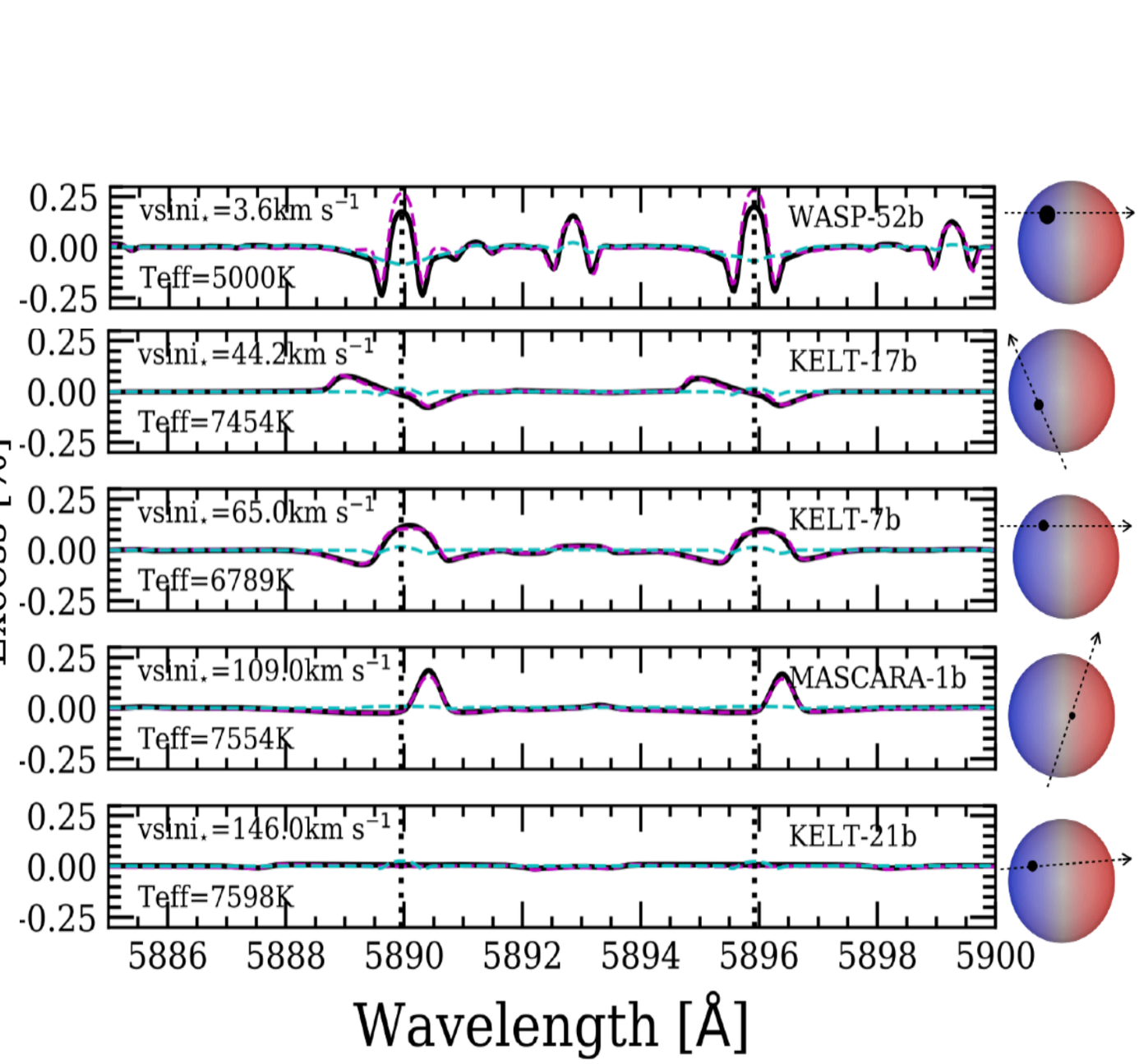
Credit: Solar Orbiter/PHI Team/ESA & NASA



Extracting the transmission spectrum

Other corrections: the RM effect and CLV



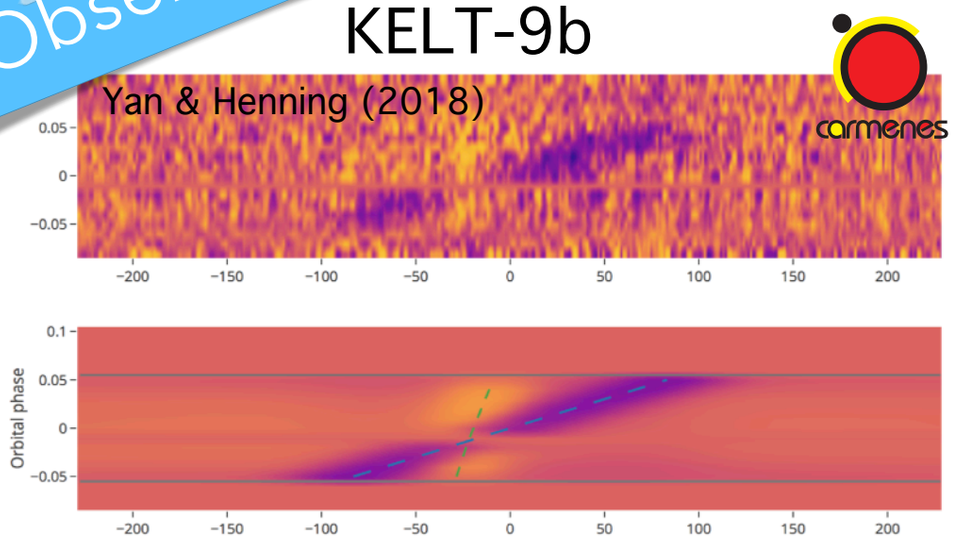


Extracting the transmission spectrum

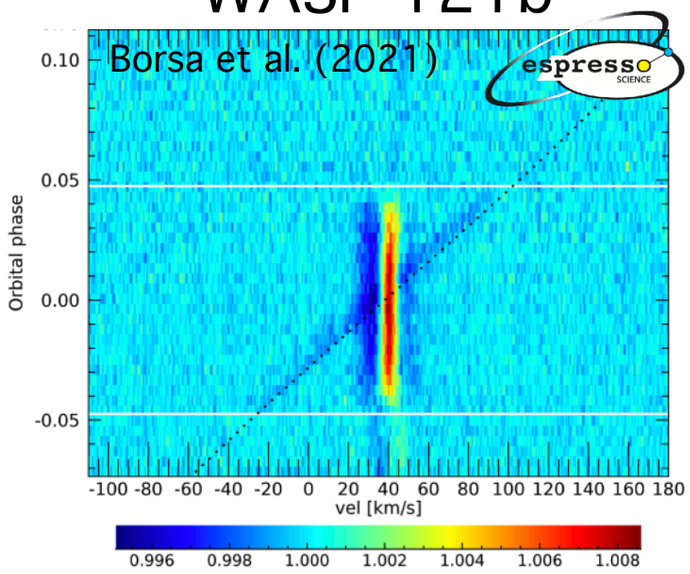
Other corrections: the RM effect and CLV

Observations

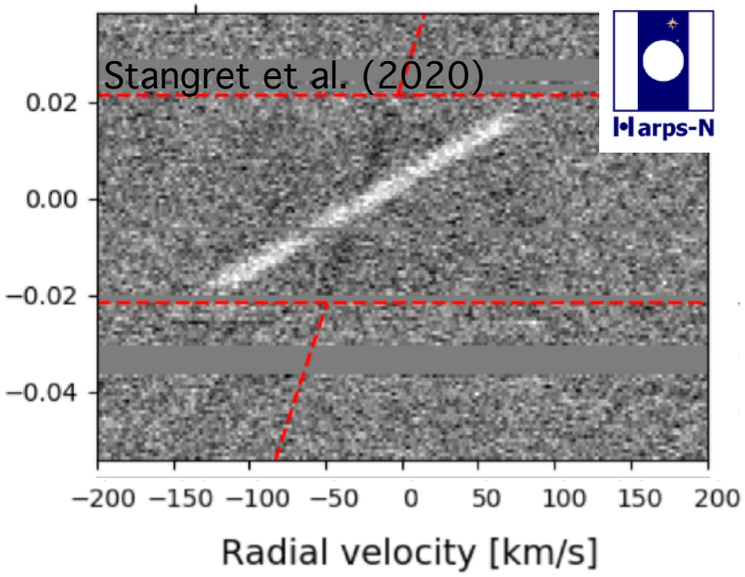
KELT-9b



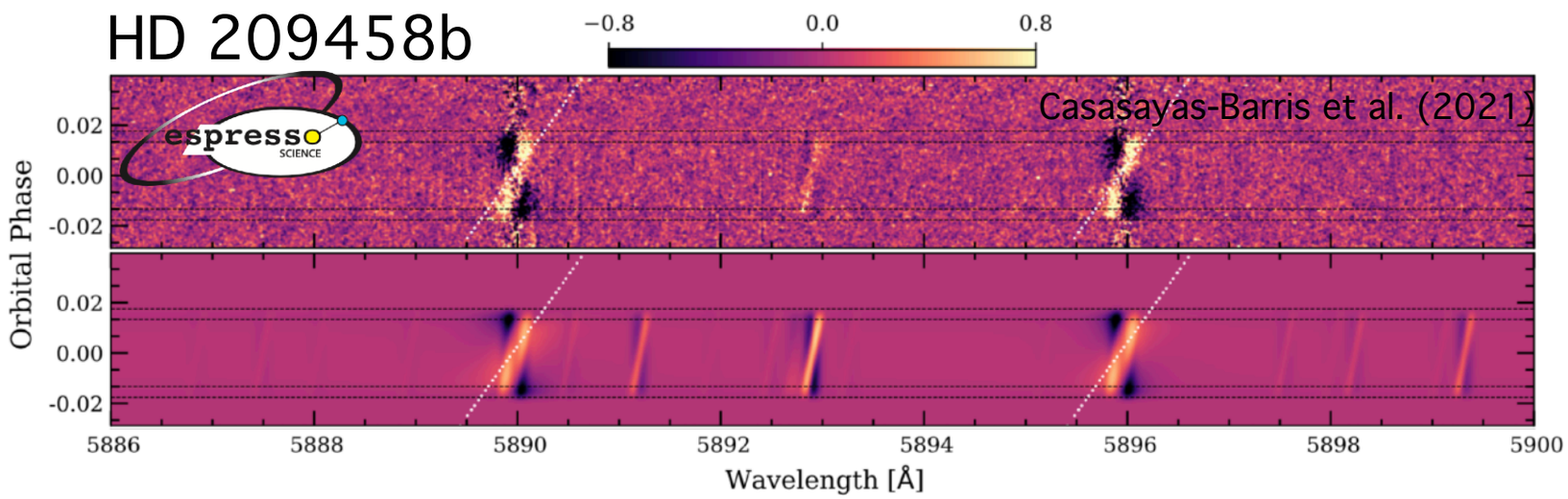
WASP-121b



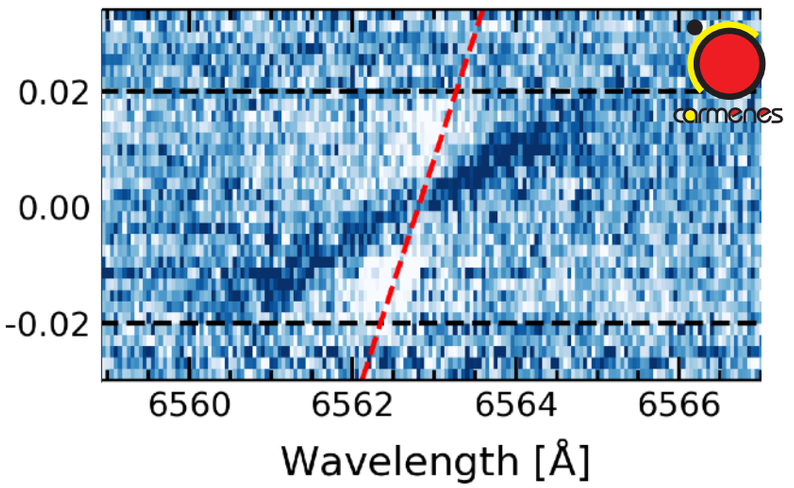
MASCARA-2b



HD 209458b

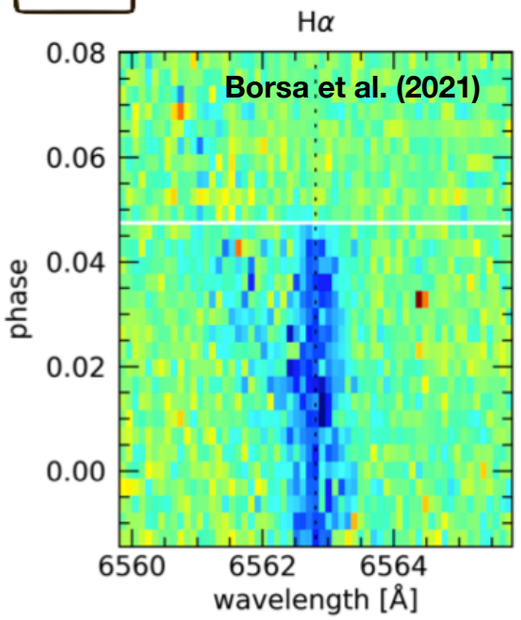


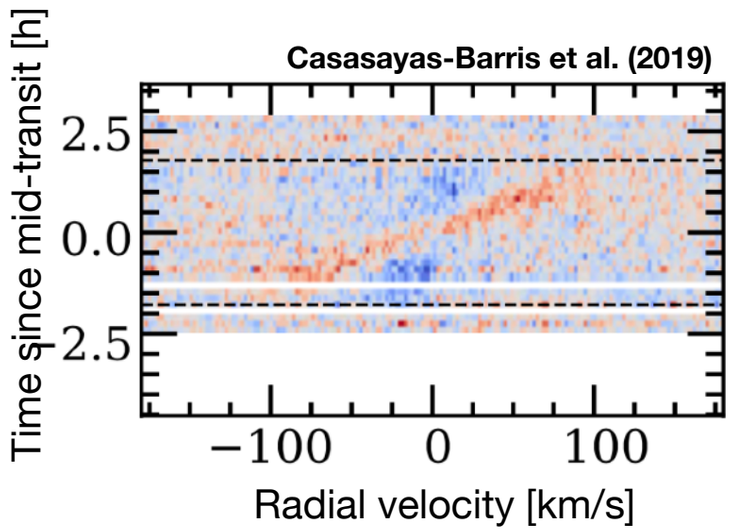
MASCARA-2b



How can we know if the signal has planetary origin?

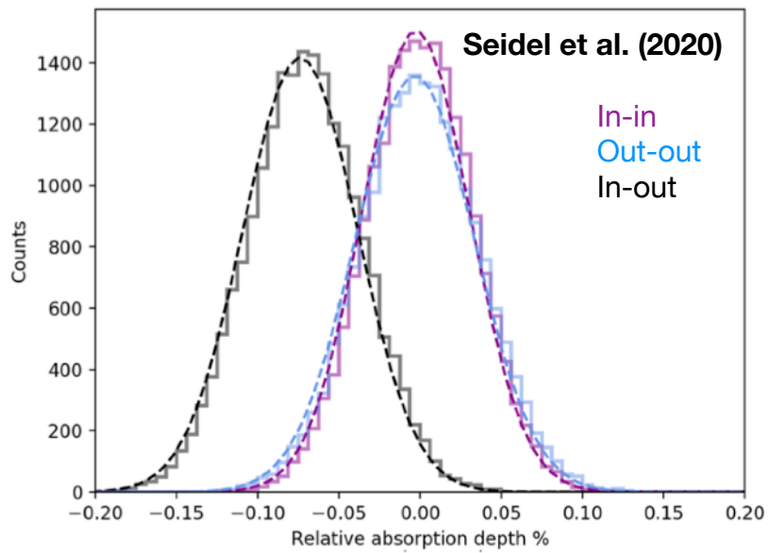
2D tomography maps





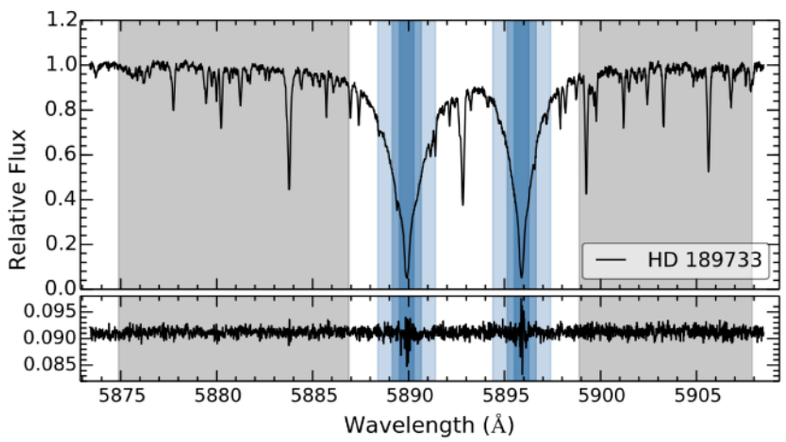
Empirical Monte Carlo

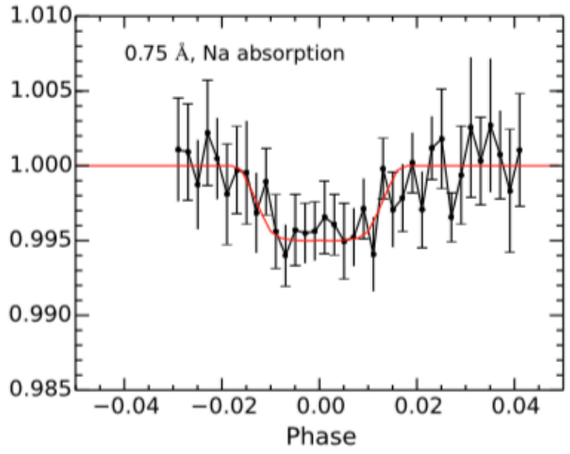
Redfield et al. (2008)



Transmission light curves

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

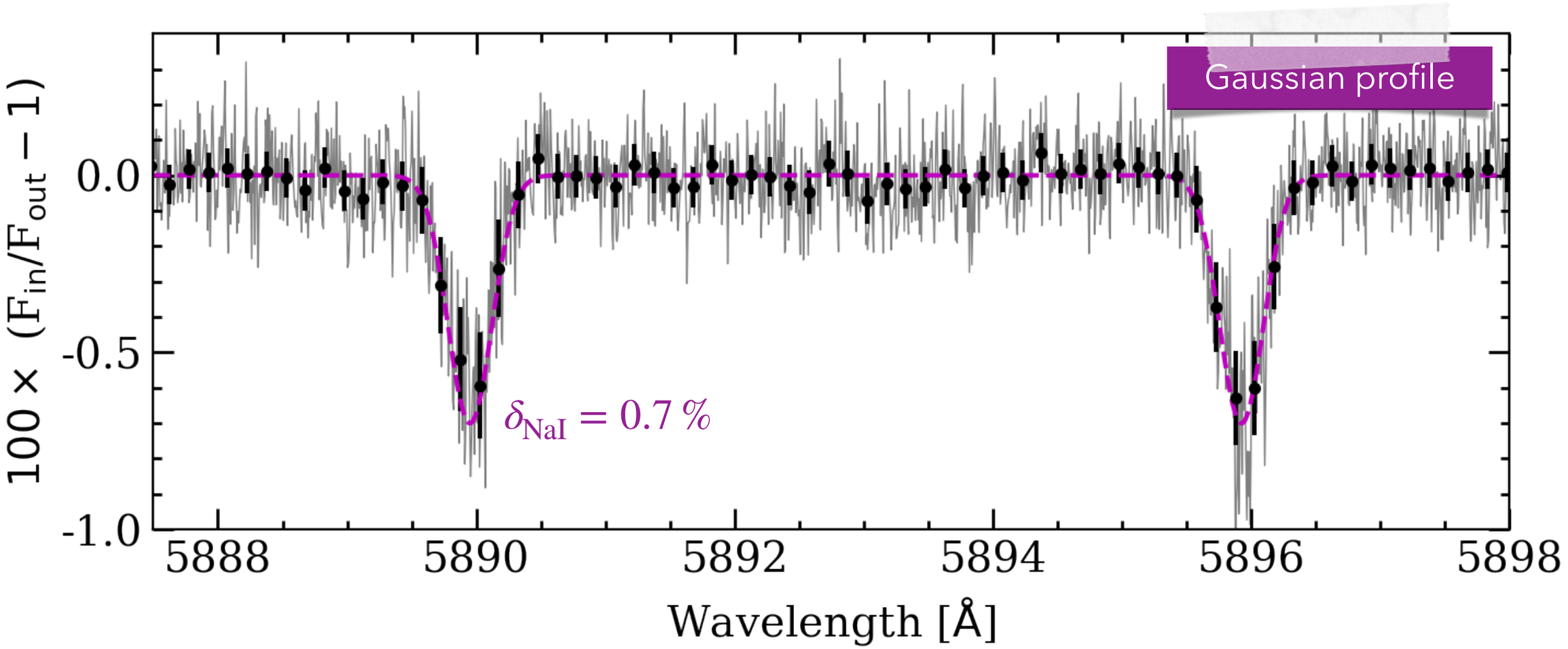




Others:

- 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**

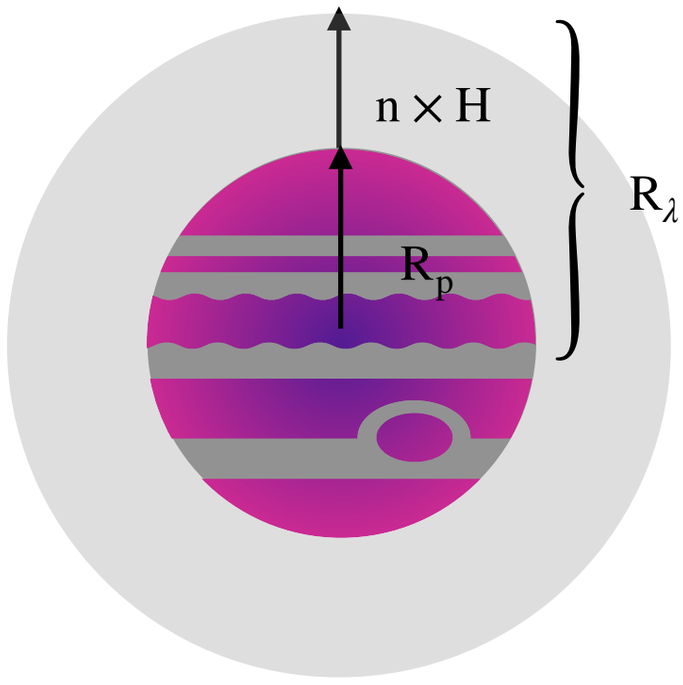
- **Temperature of the layers where the lines form**
- **Broadening due to atmospheric winds, tidally locked rotation…**
- **Overall blue/red shift due to atmospheric winds**
- **…**

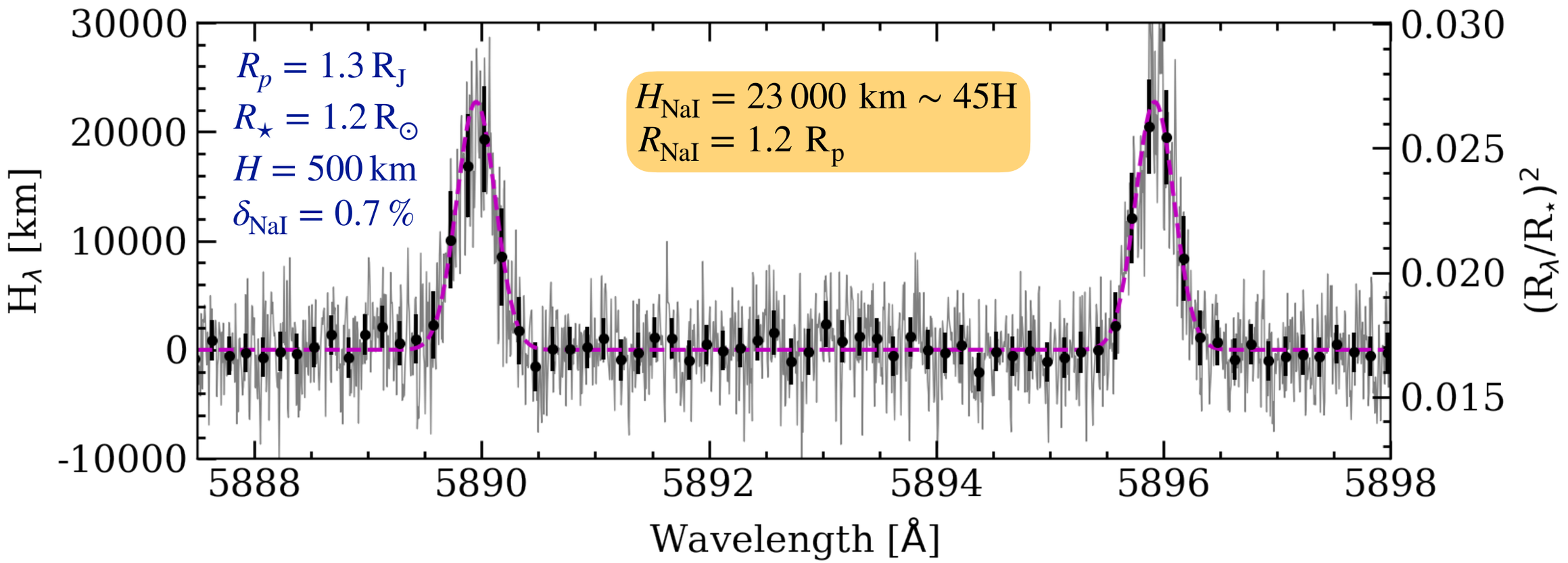
See some results during the conference!

Interpretation of the transmission spectrum

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

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

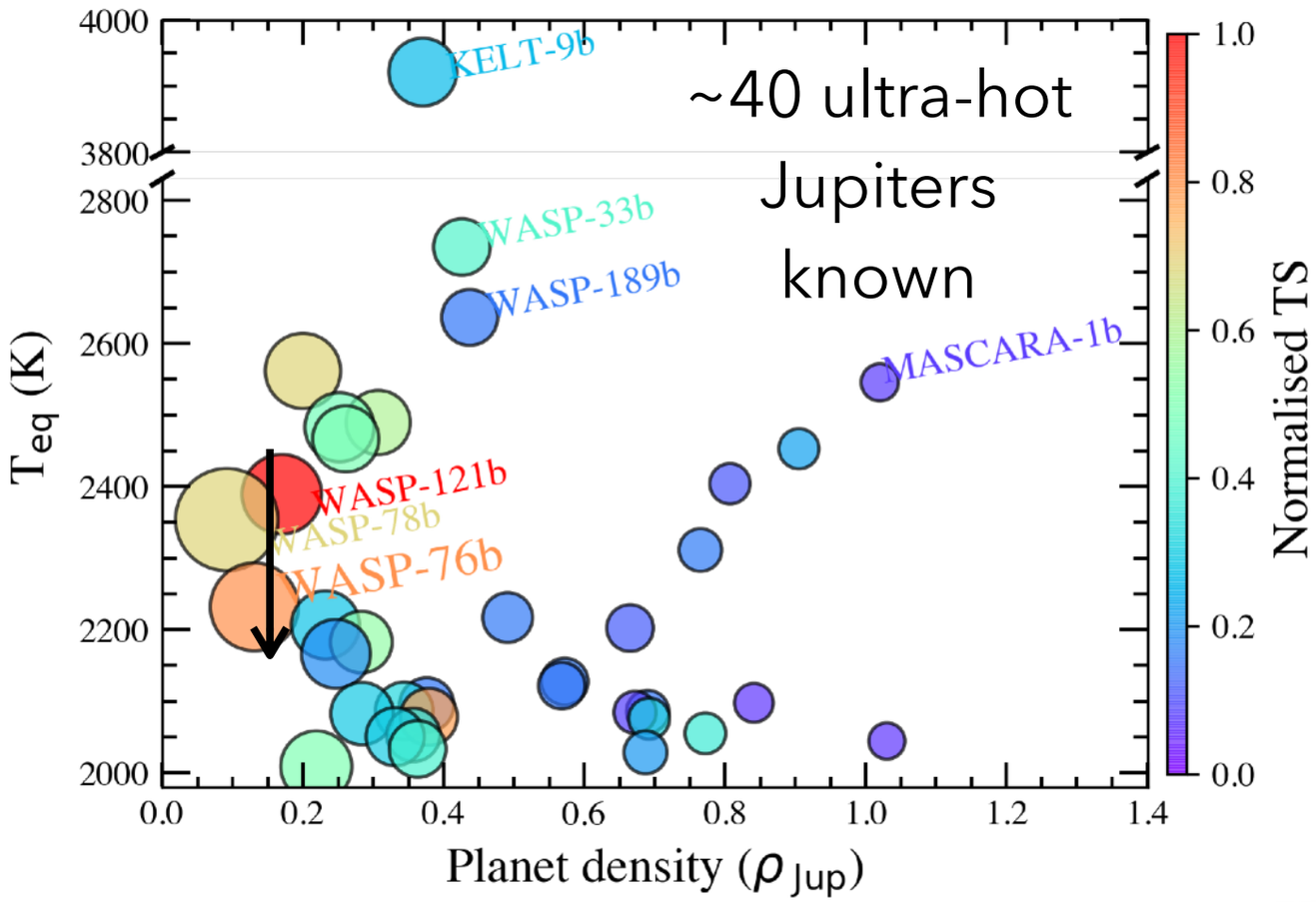




Tutorial: Na I in WASP-76b

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**