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The Netherlands

Narrow band transmission spectroscopy

Casasayas Barris, N.; Seidel, J.

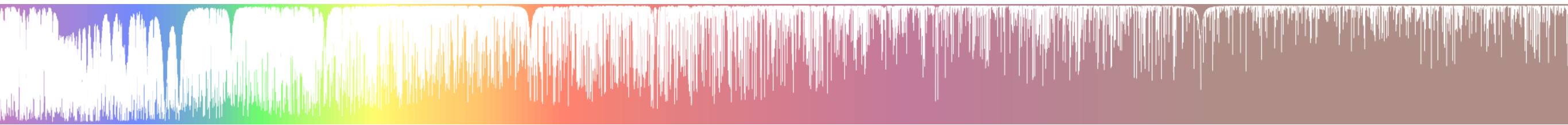
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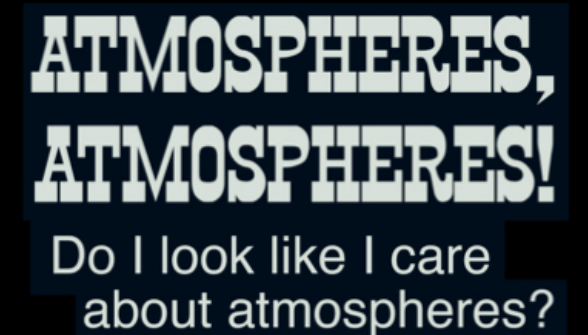
Narrow band transmission spectroscopy



Núria Casasayas Barris
Julia V. Seidel

Atmo 2021 - Workshop

23 August 2021

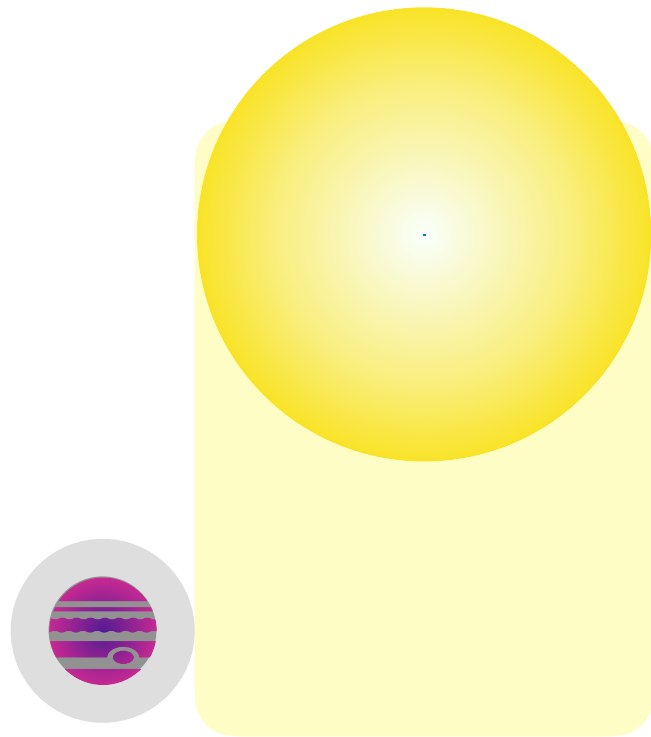
A meme featuring a black speech bubble with a red border. Inside the bubble, the word 'ATMOSPHERES,' is written twice in a bold, white, sans-serif font. Below this, the text 'Do I look like I care about atmospheres?' is written in a smaller, white, sans-serif font.

ATMOSPHERES,
ATMOSPHERES!
Do I look like I care
about atmospheres?

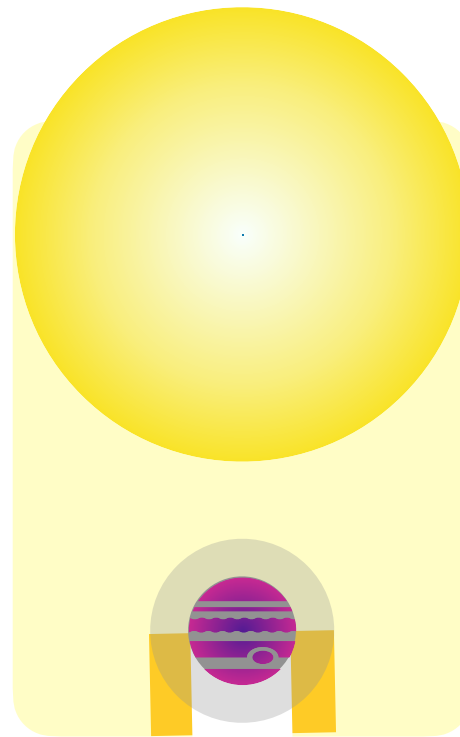
Transmission spectroscopy

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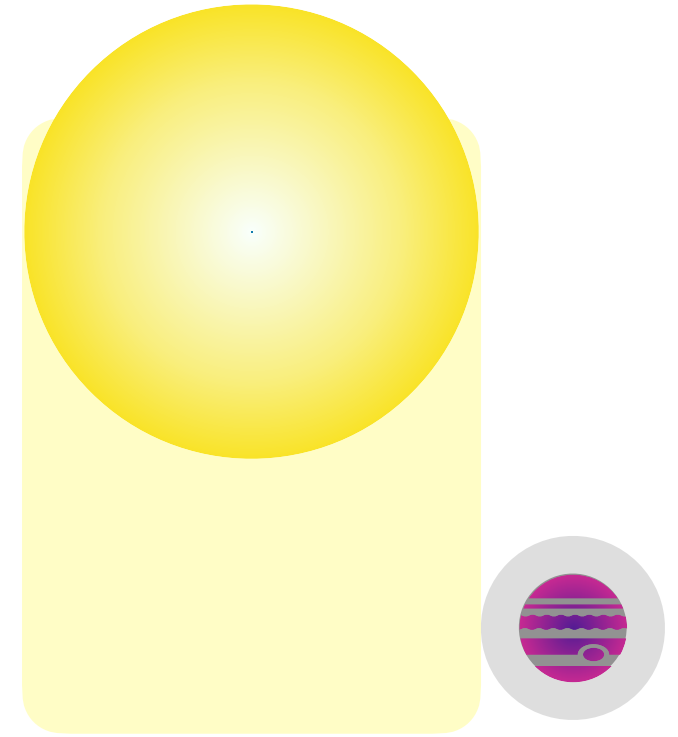
Before the transit



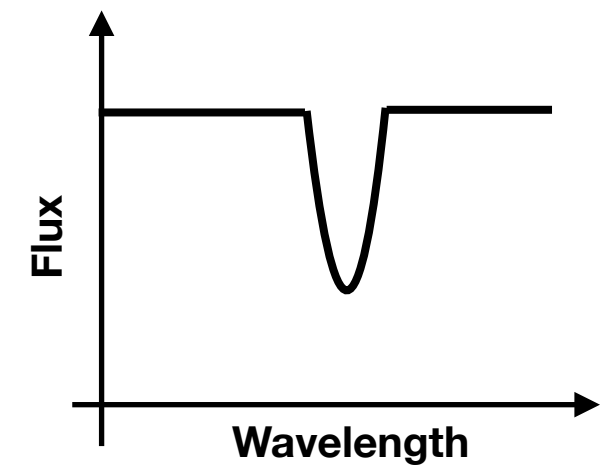
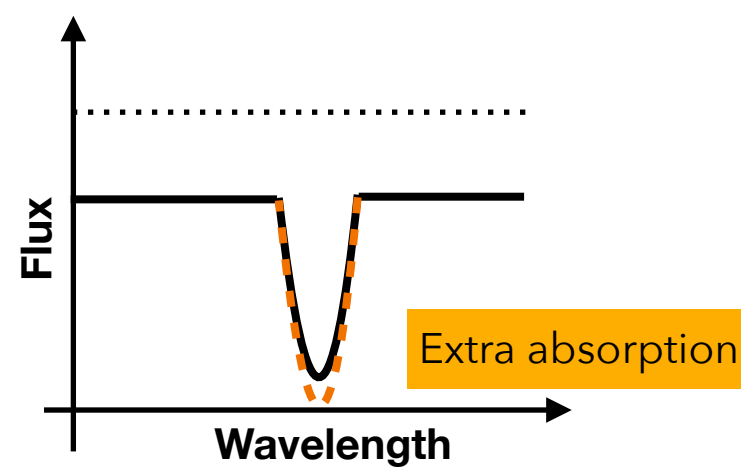
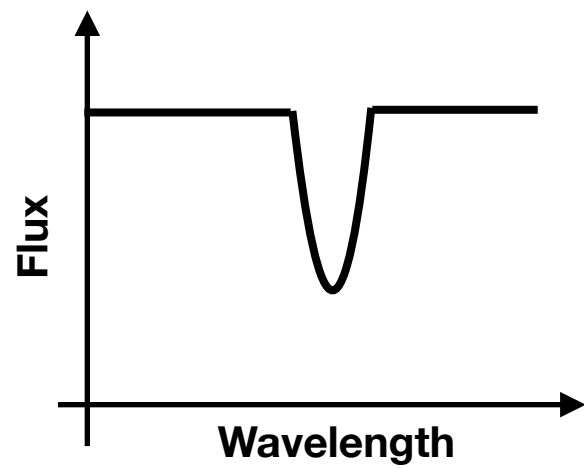
During the transit



After the transit



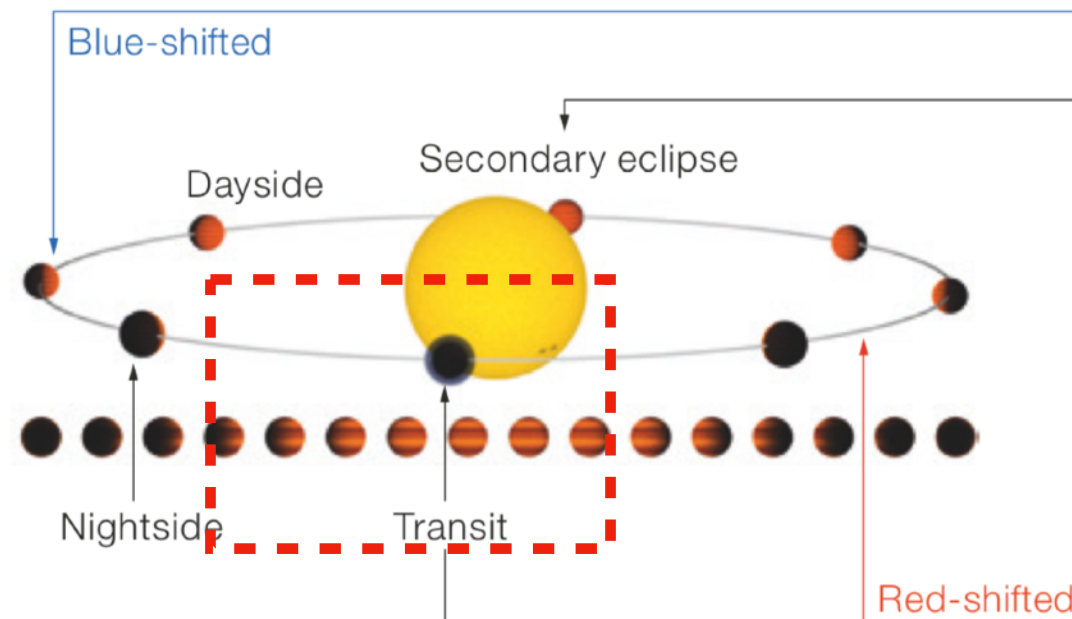
Stellar line profile



High-resolution transmission spectroscopy

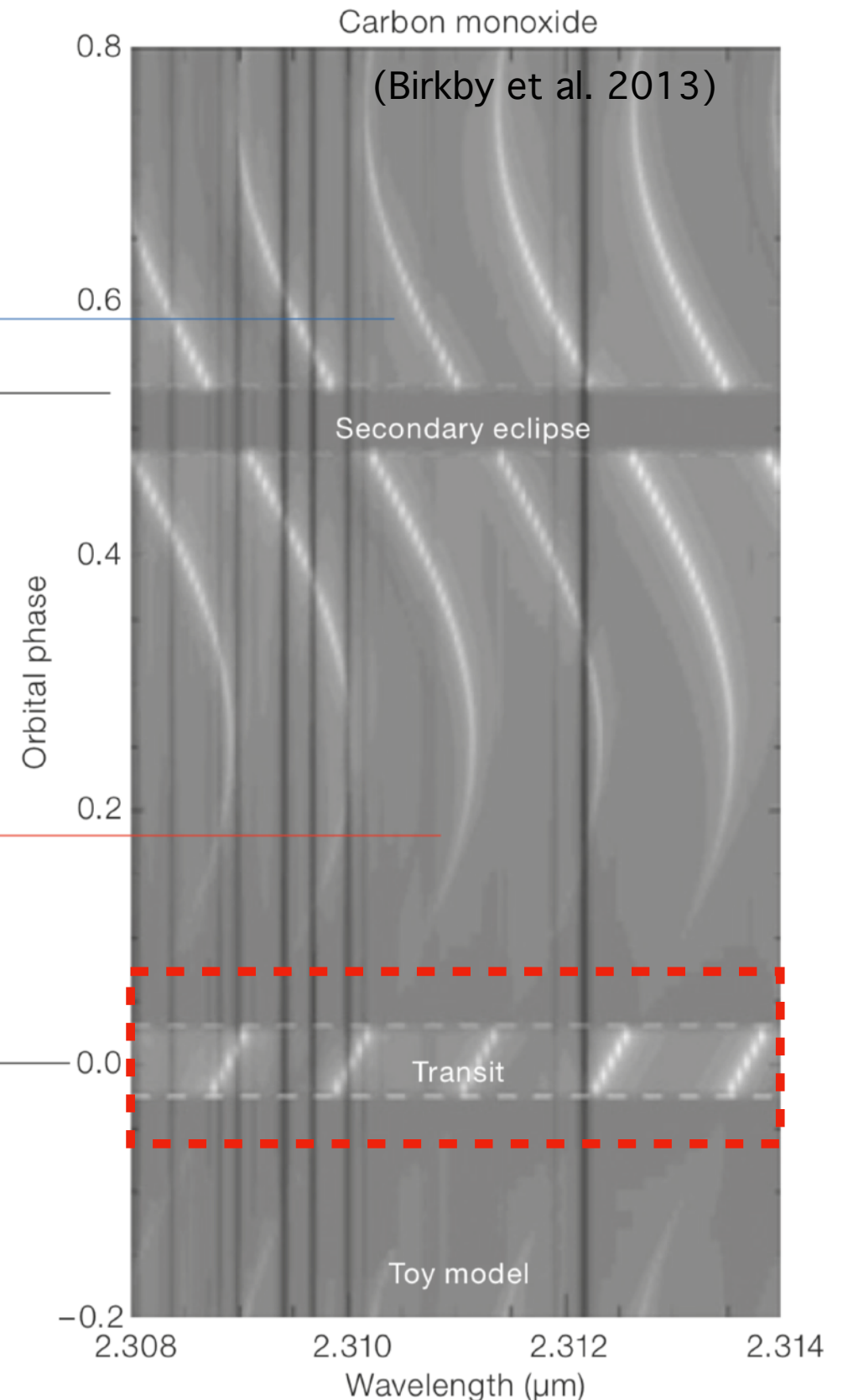
3

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



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

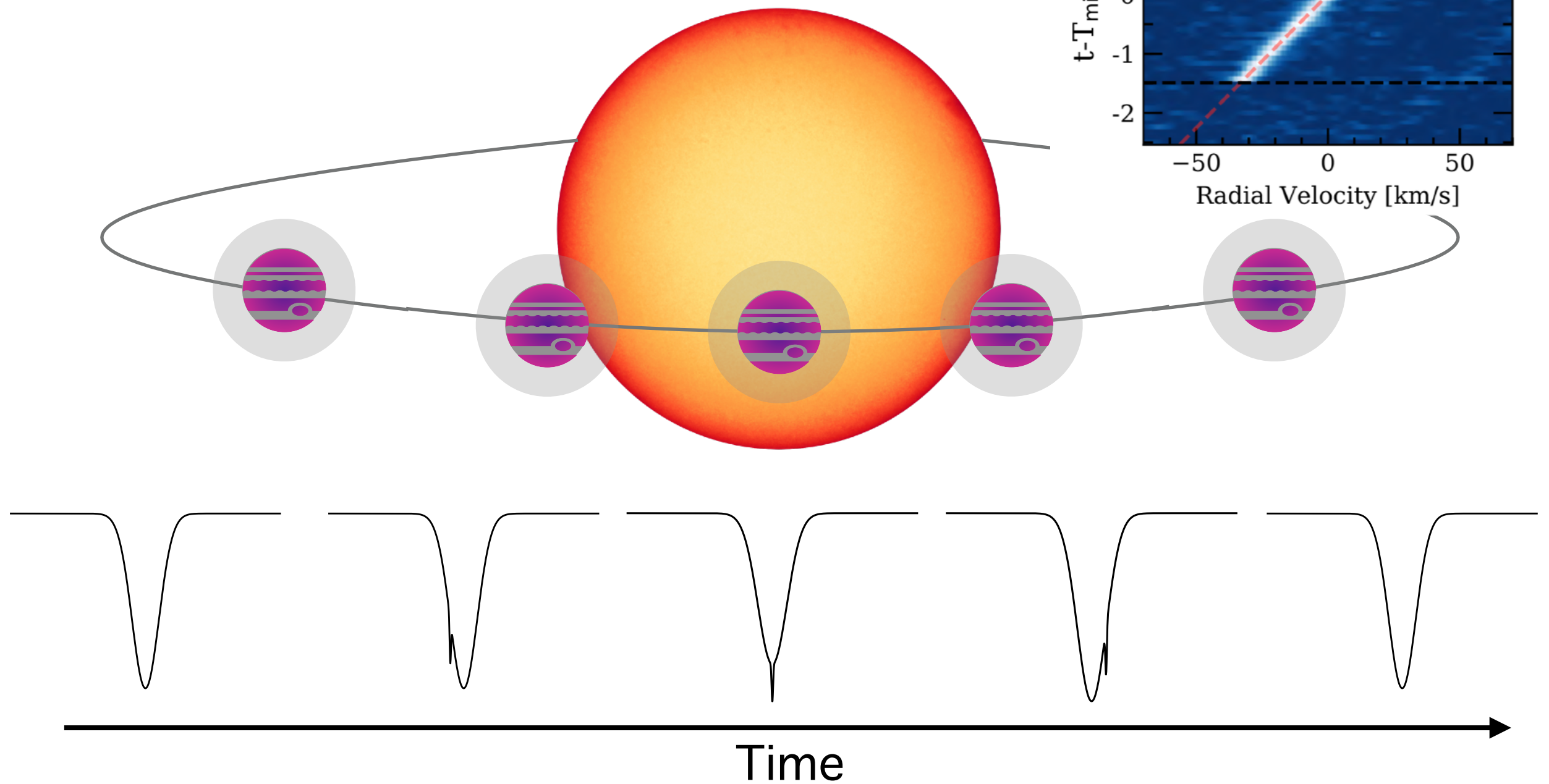
Telluric and stellar lines ~ static
Planet lines shift throughout the orbit



High-resolution transmission spectroscopy

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Planet movement



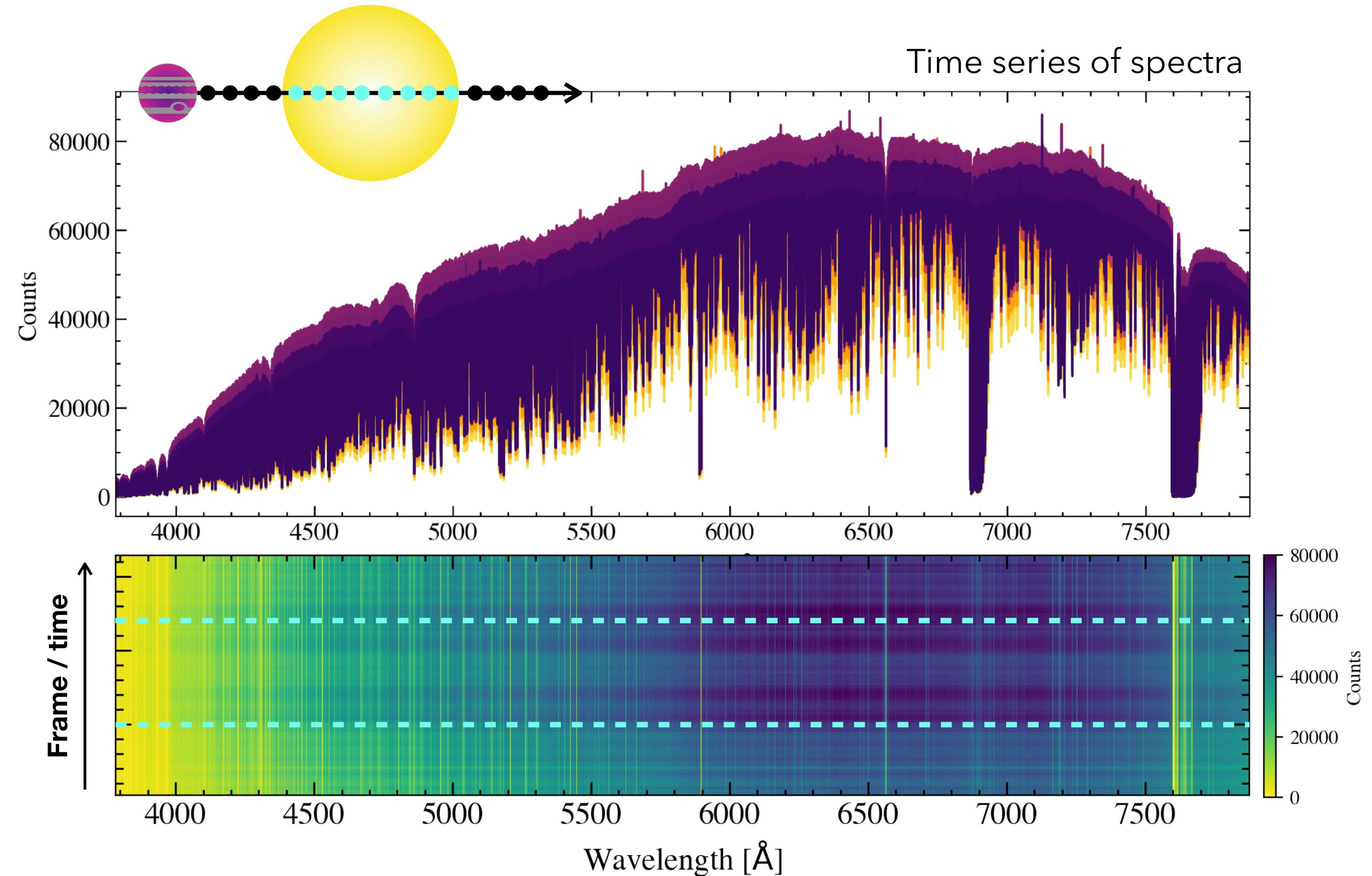
Observations

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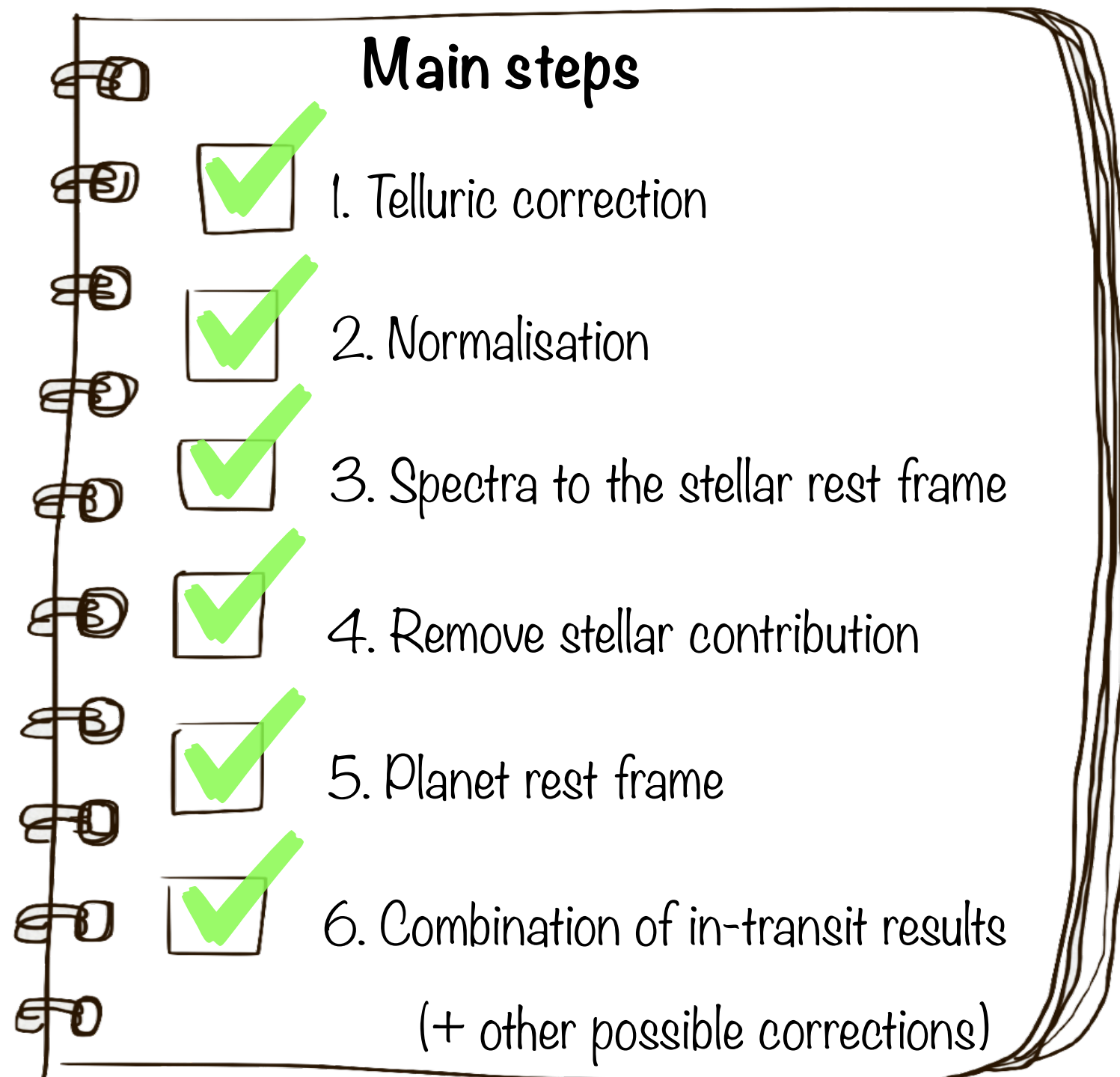
Observations

Time series of spectra



Extracting the transmission spectrum

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Wytttenbach et al. (2015)

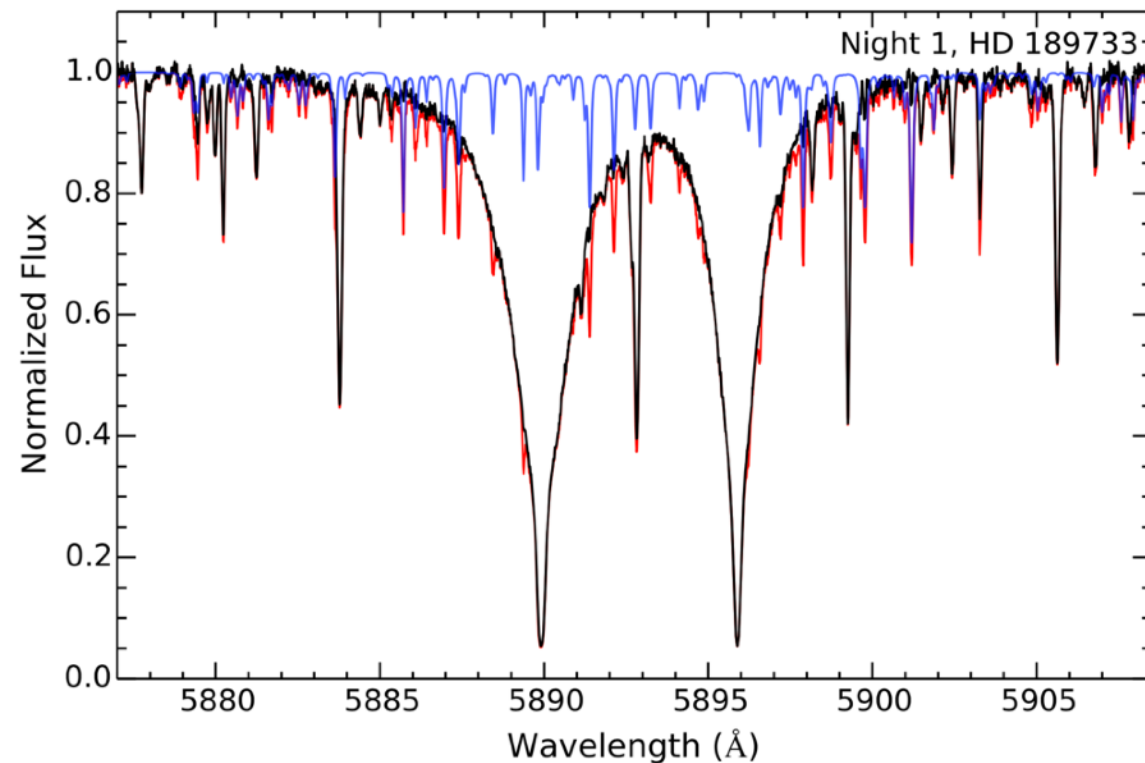
Extracting the transmission spectrum

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1. Telluric correction

○ Telluric absorption: H_2O , O_2

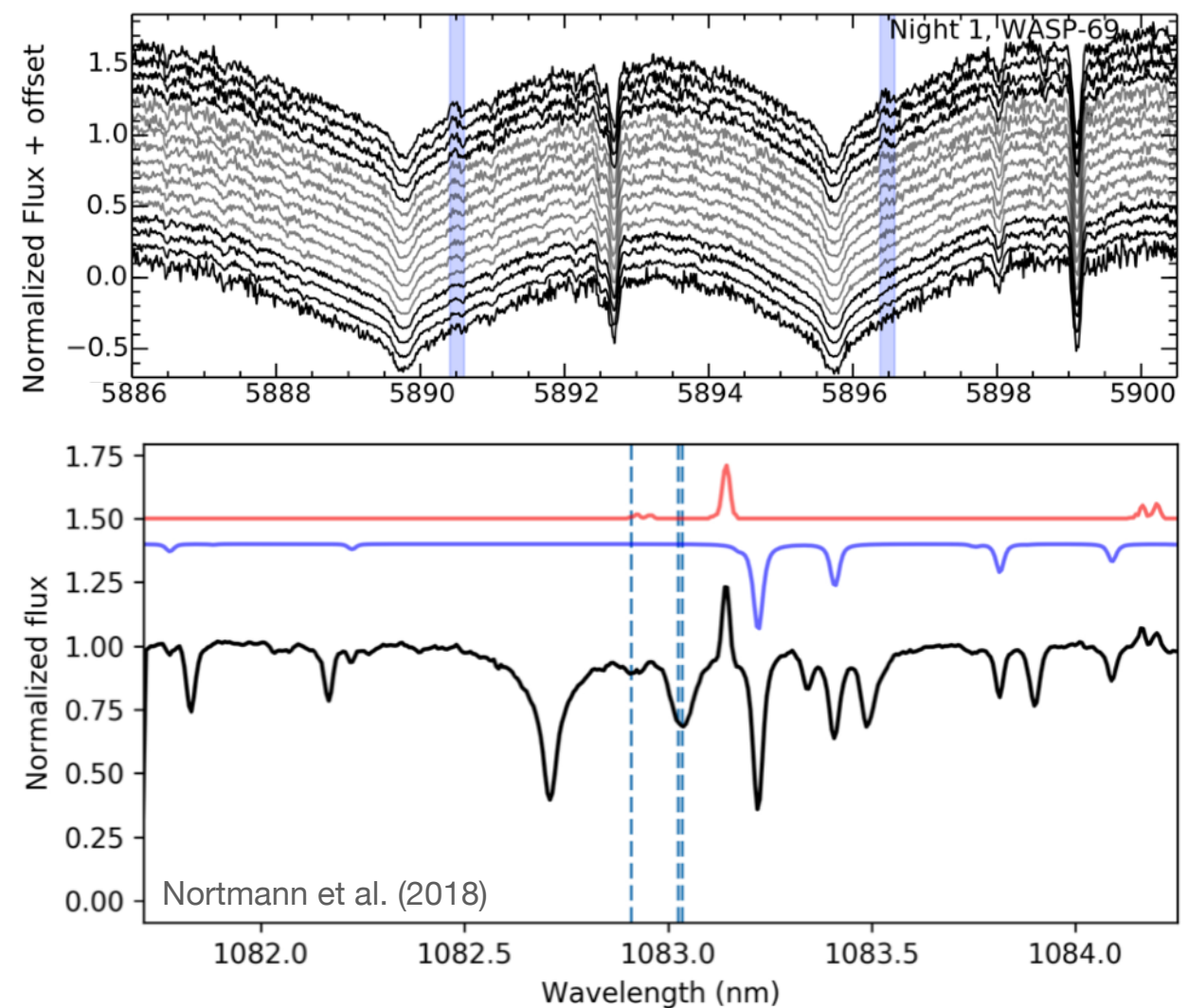


Different methodologies:

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

Molecfit lecture!

○ Telluric emission: NaI, OH...



Sky observations with fibre B

Extracting the transmission spectrum

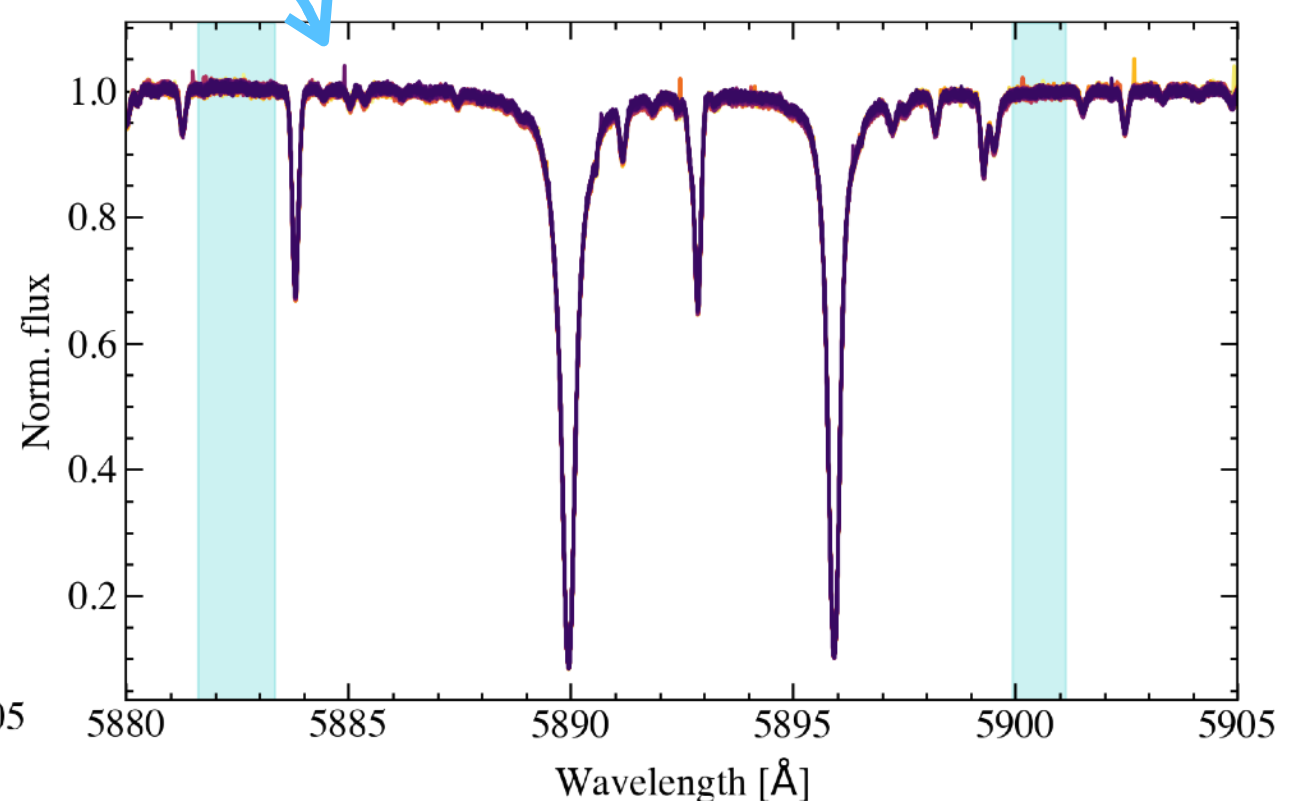
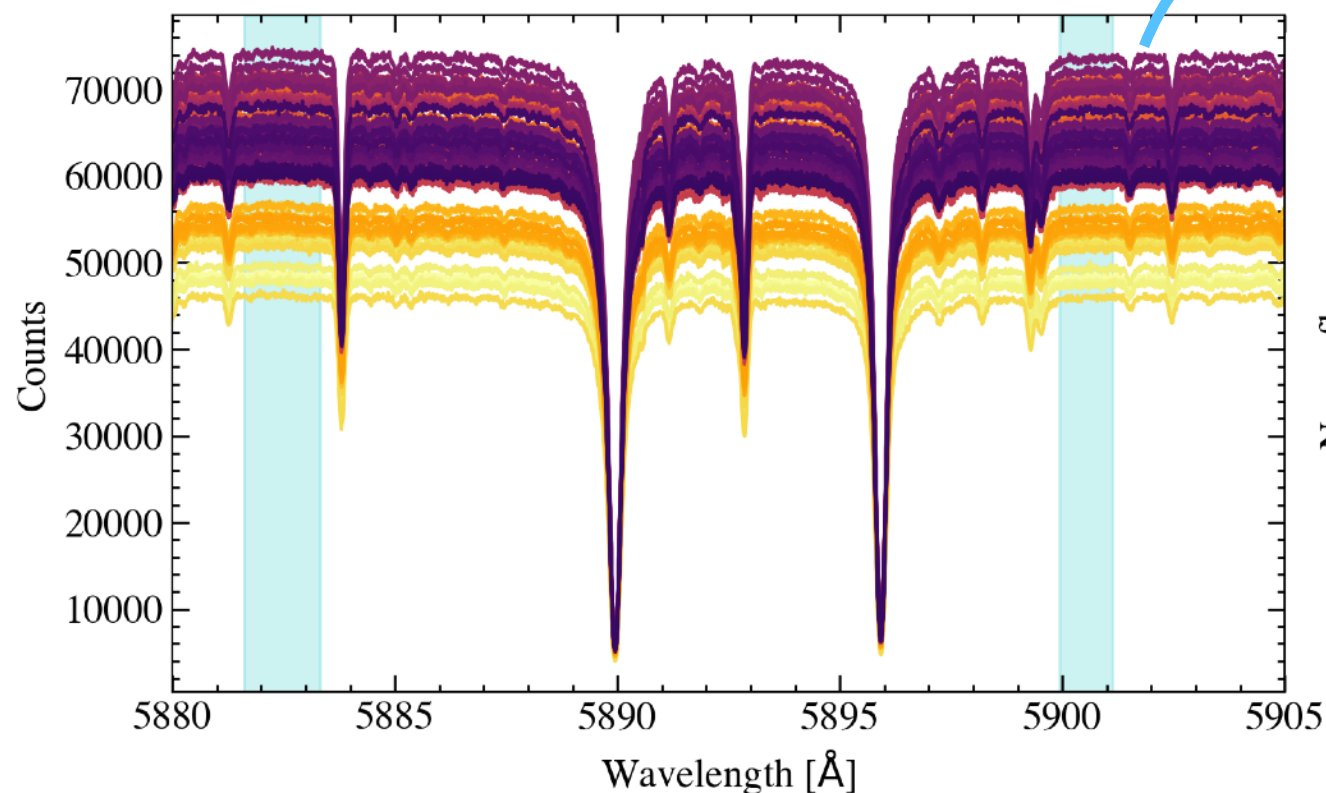
9



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!)

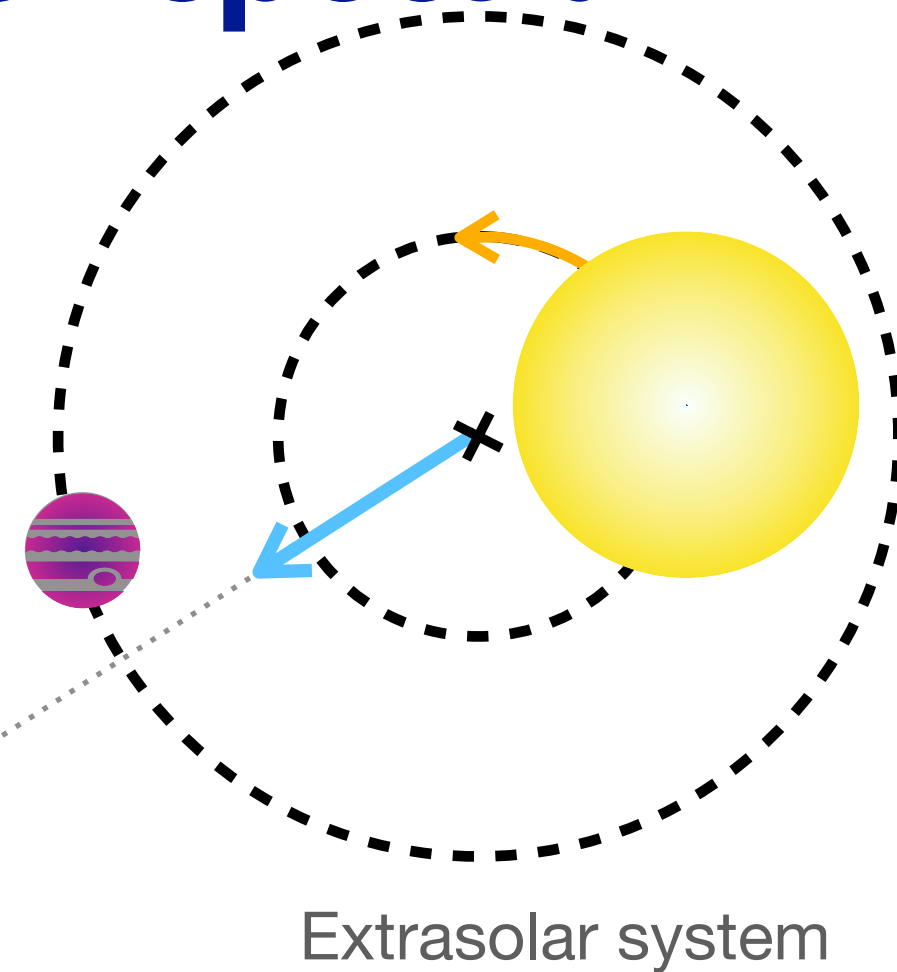


Extracting the transmission spectrum ¹⁰

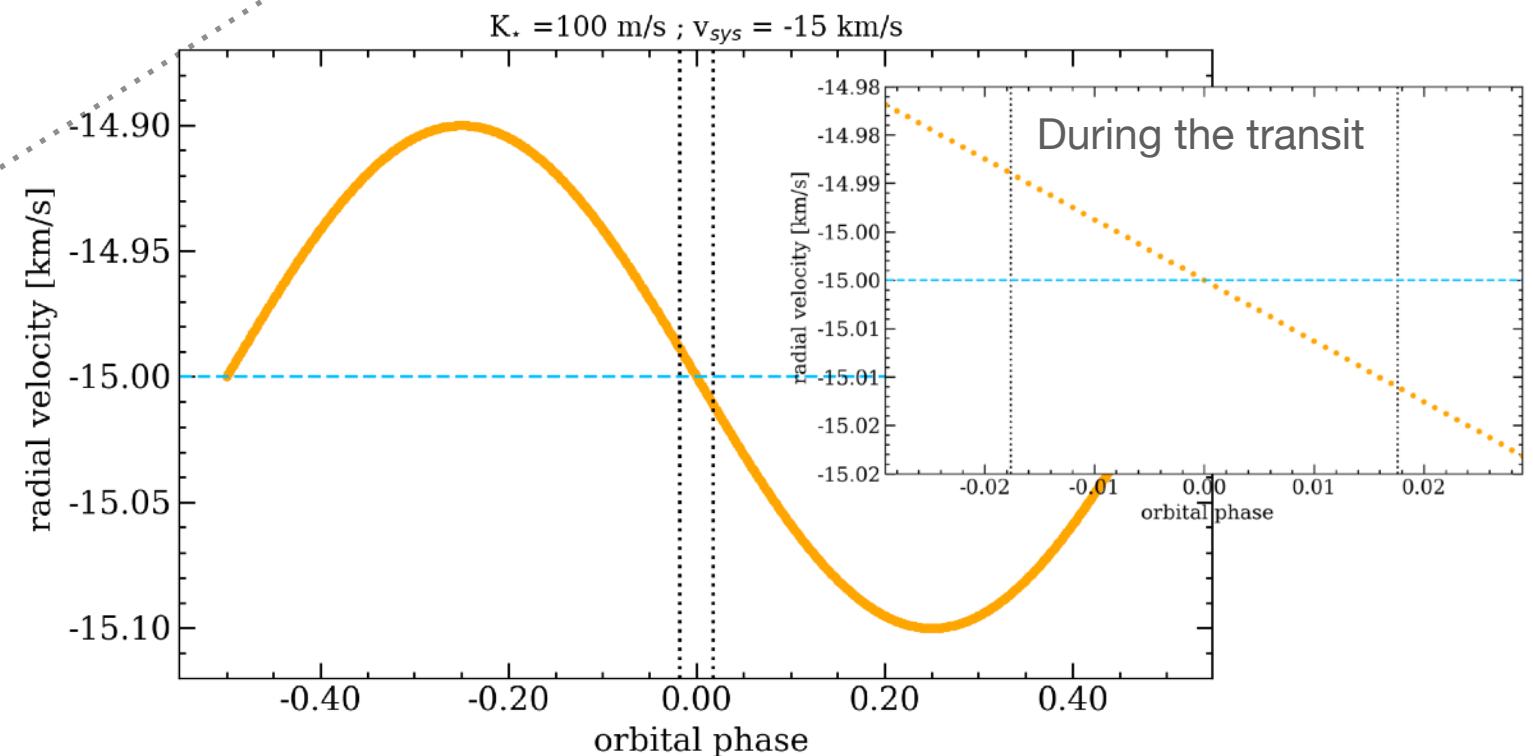
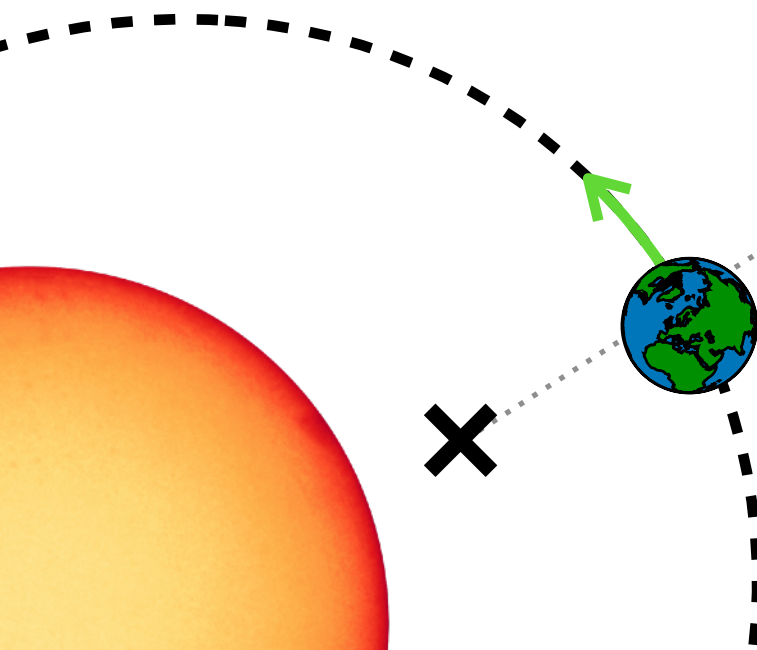


3. Stellar rest frame

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



Solar System



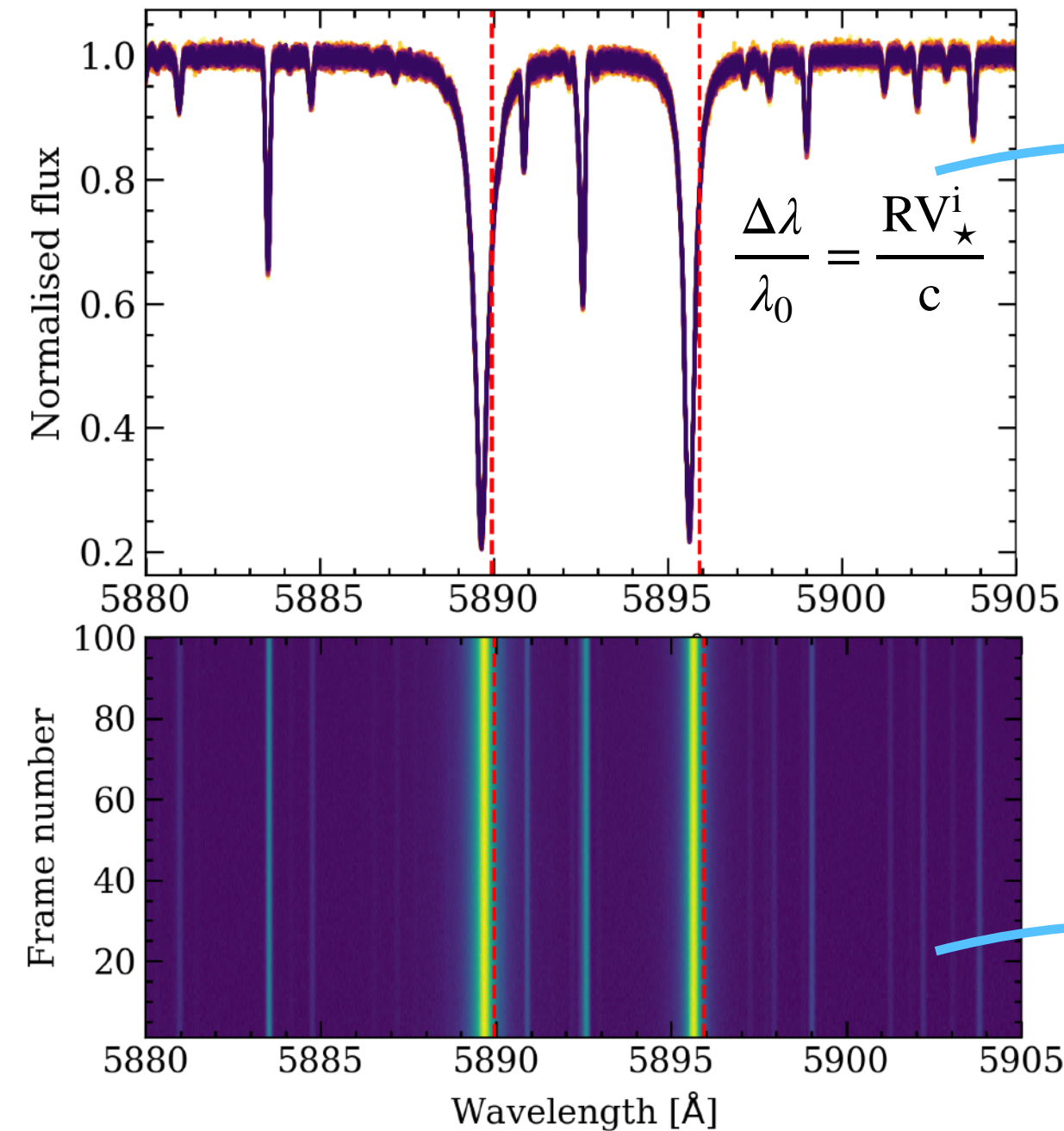
Extracting the transmission spectrum

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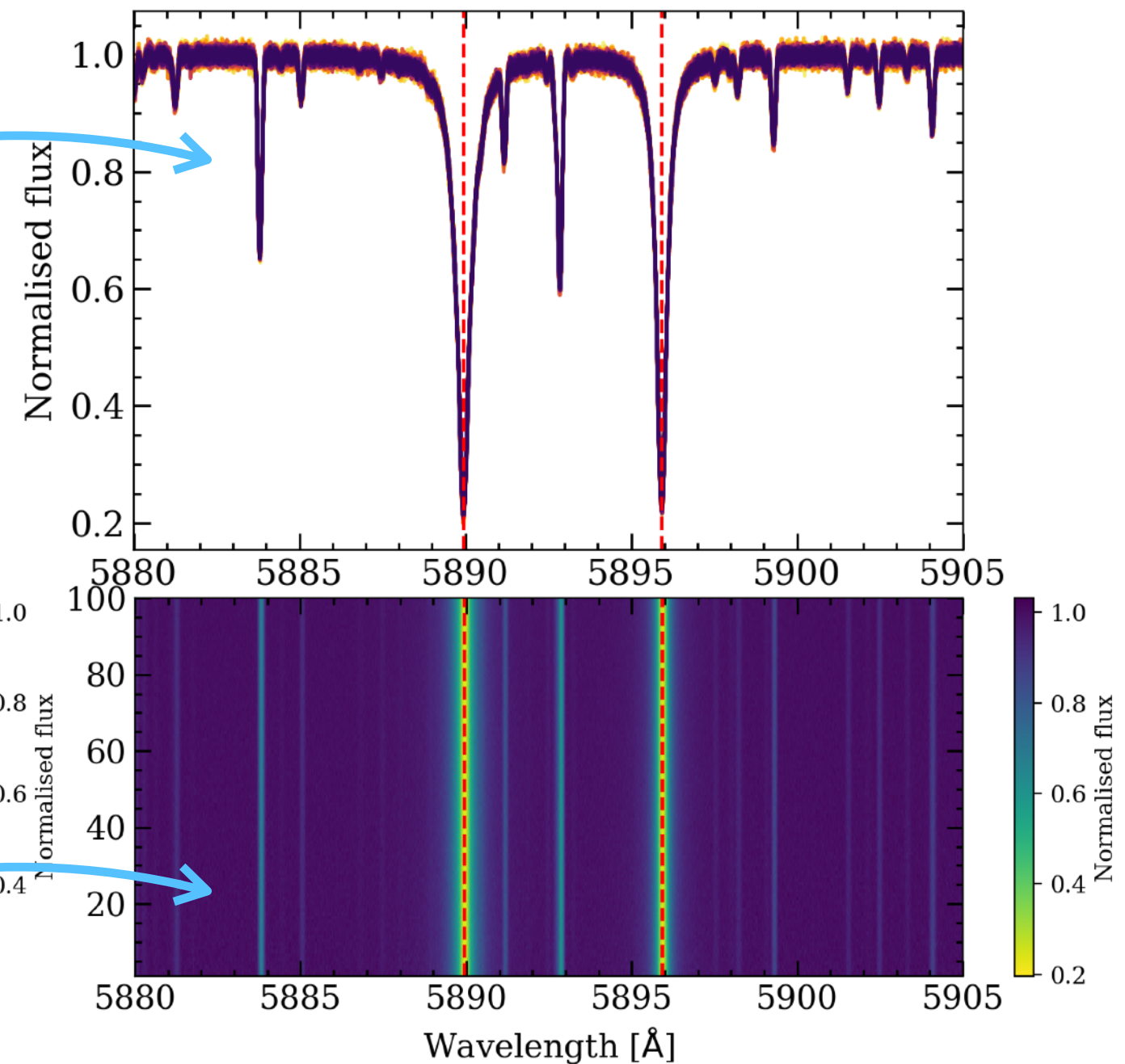


3. Stellar rest frame

Observations rest frame



Stellar rest frame



Extracting the transmission spectrum

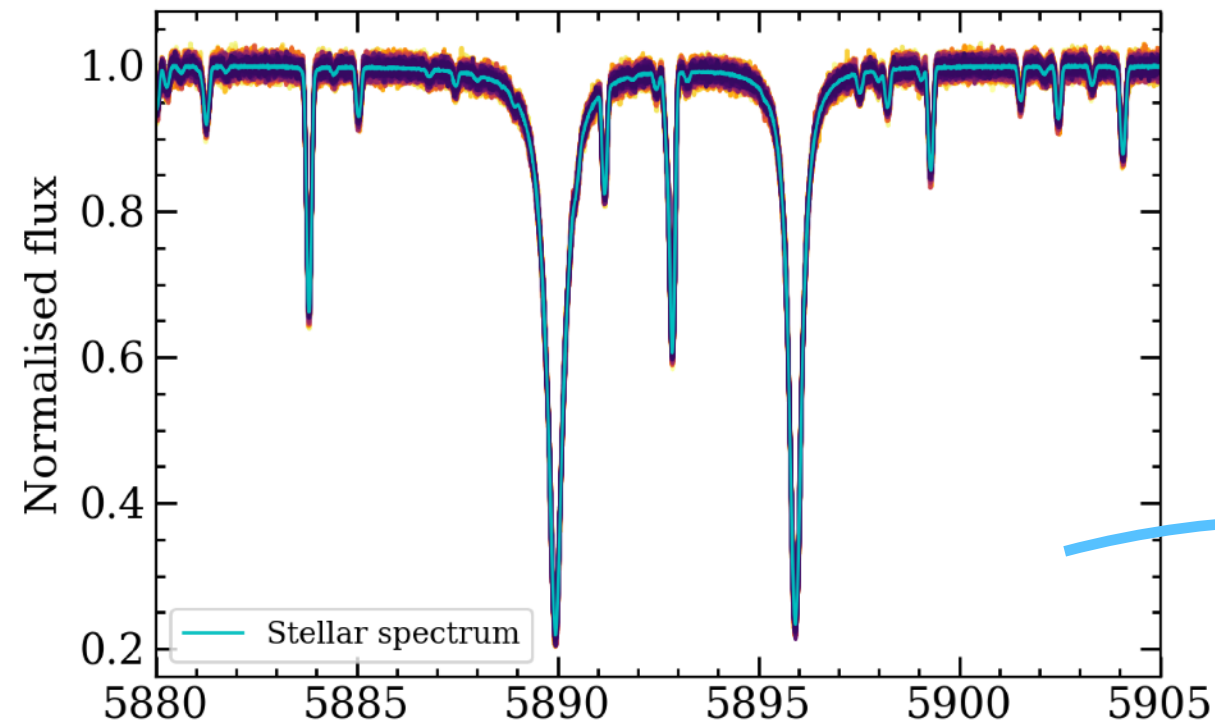
12



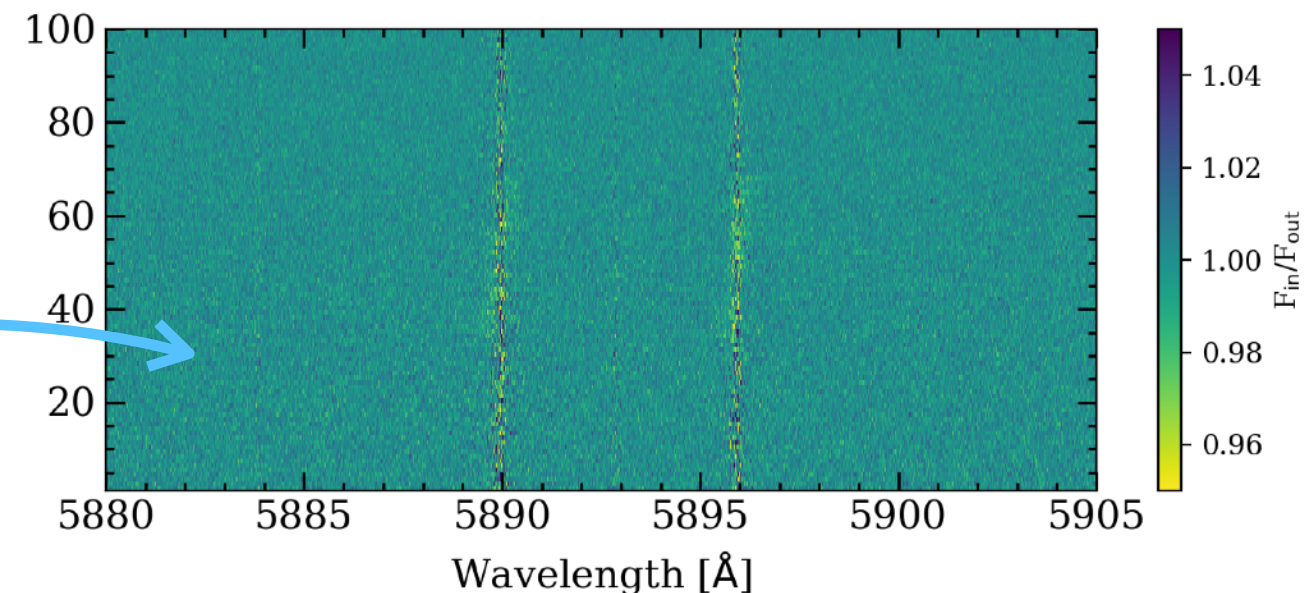
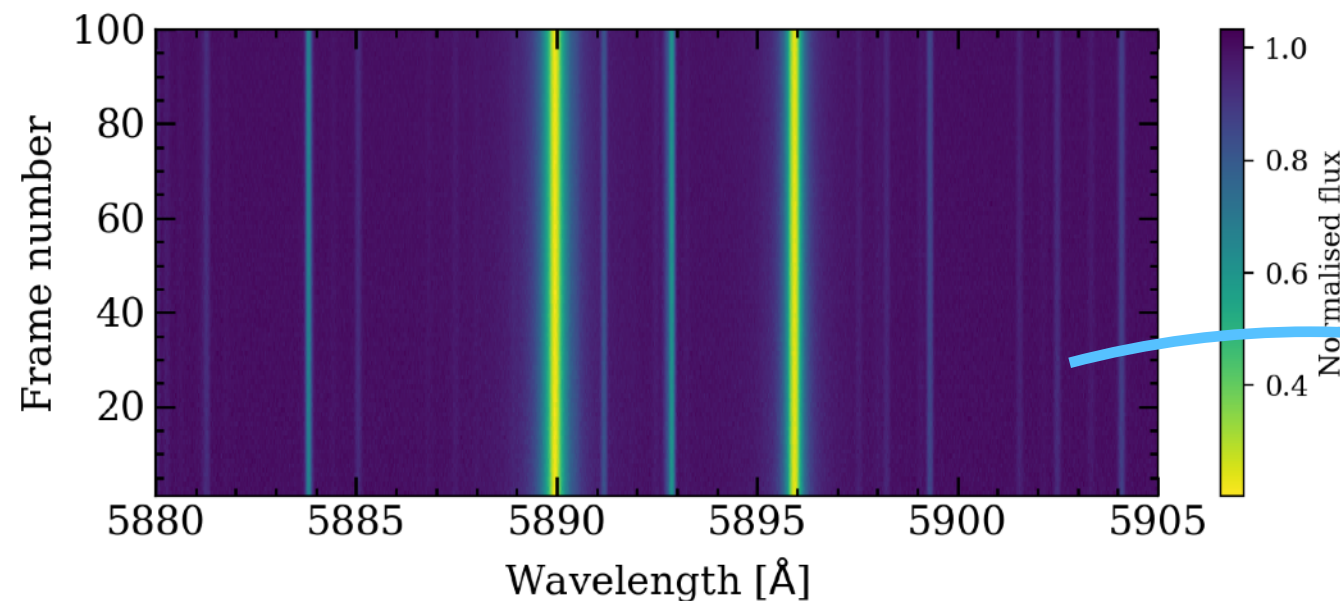
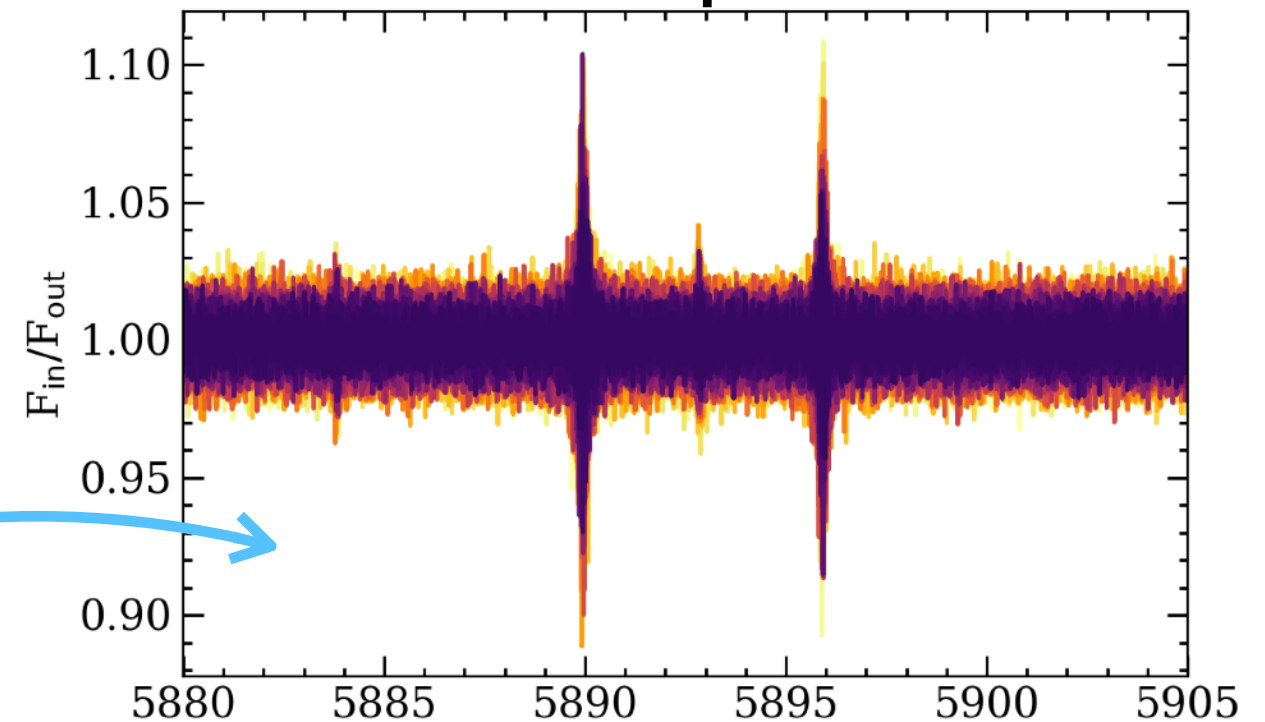
4. Remove stellar contribution

Master out-of-transit stellar spectrum

Combination of all out-of-transit spectra



Division of each spectrum by the Master spectrum

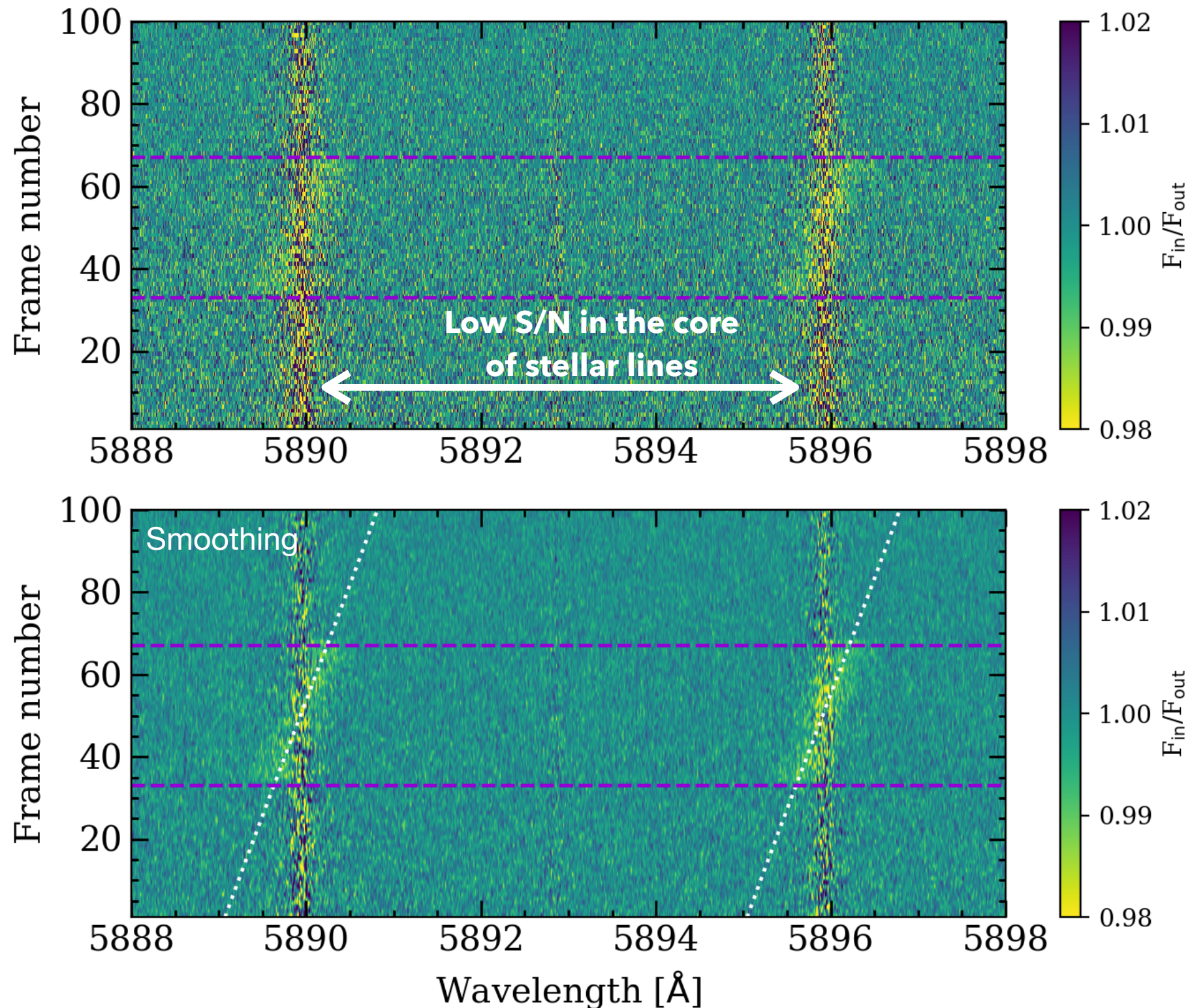


Extracting the transmission spectrum

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4. Remove stellar contribution

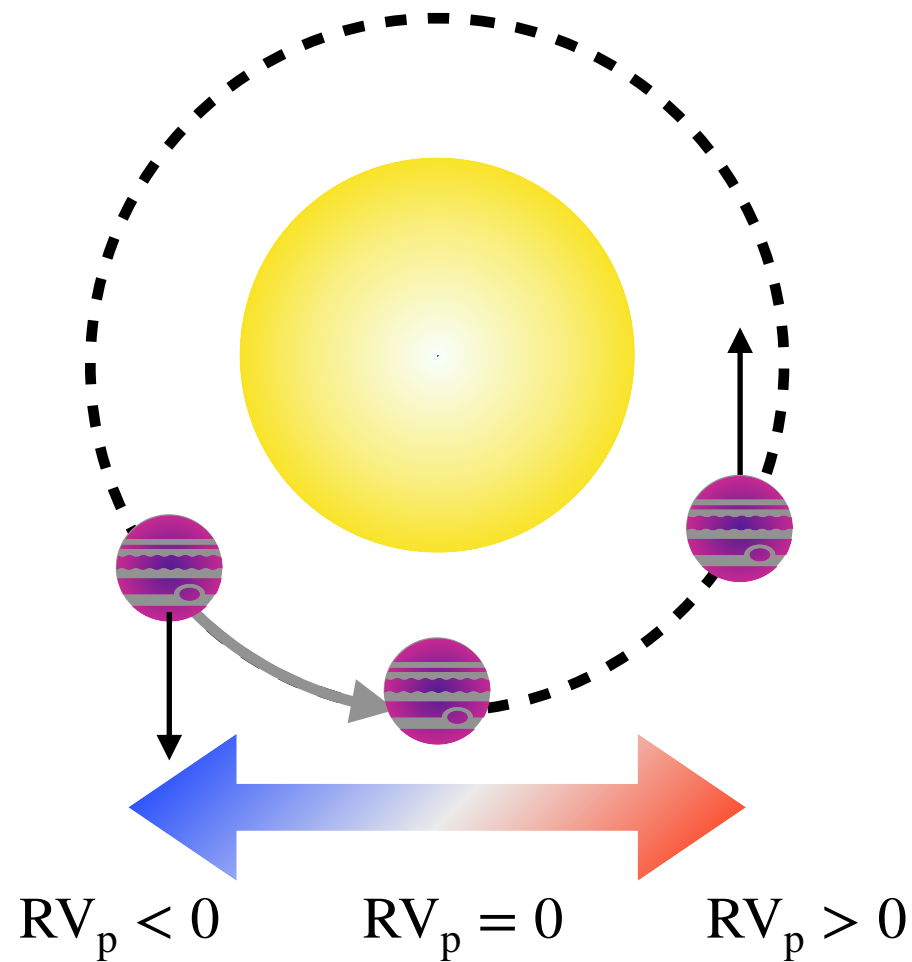


Extracting the transmission spectrum

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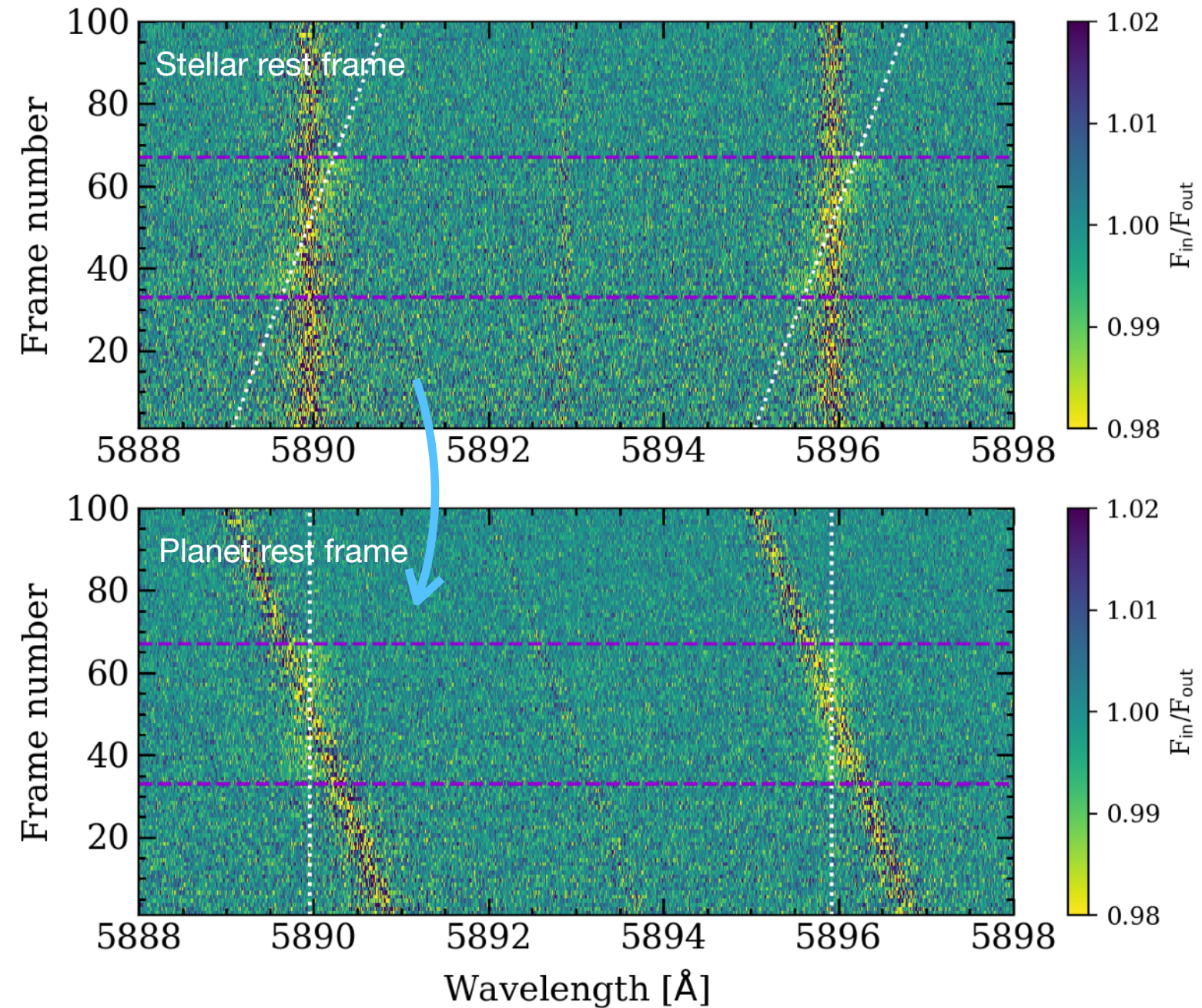
5. Planet rest frame



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

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

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

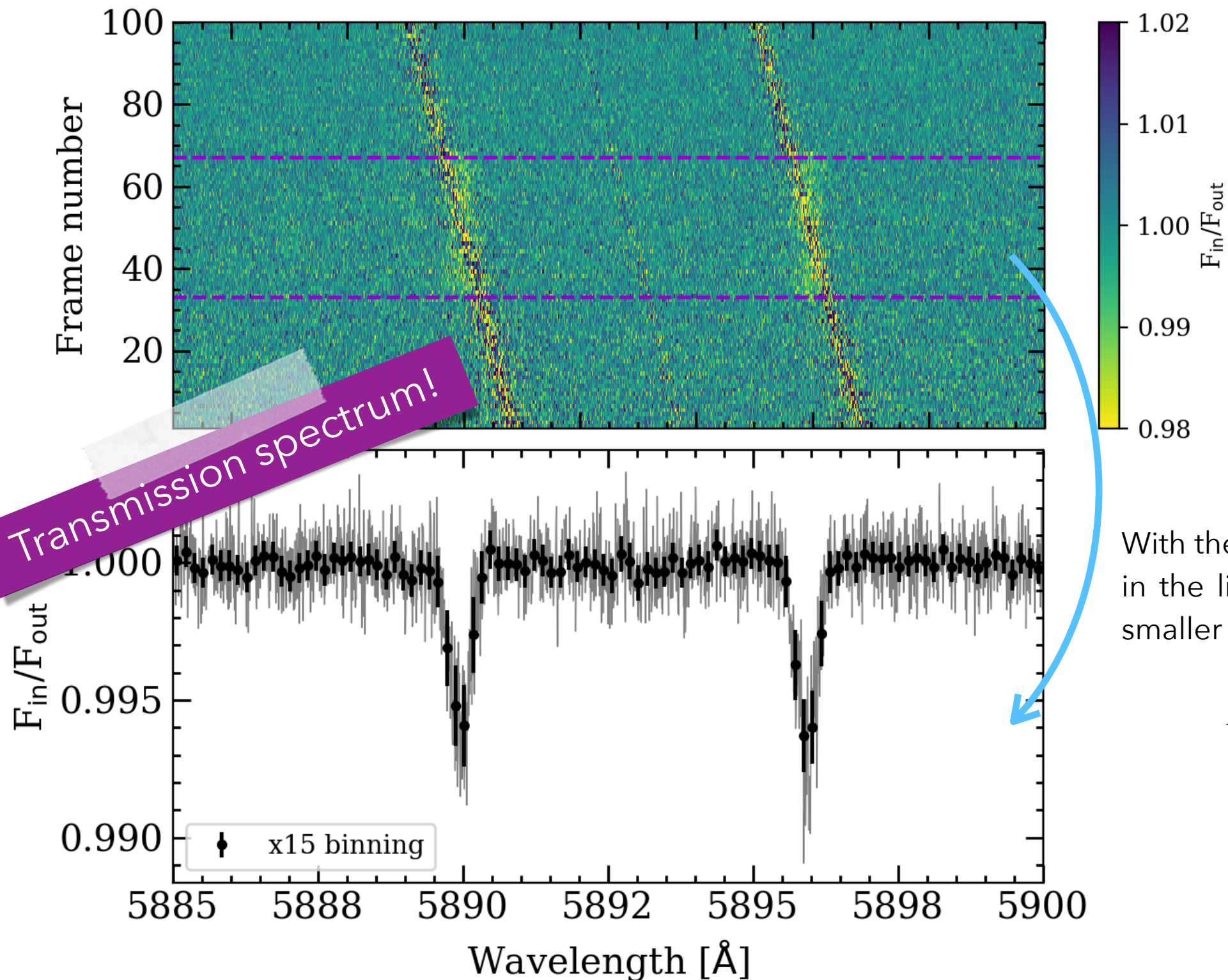


Extracting the transmission spectrum

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6. Combination of in-transit data



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

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

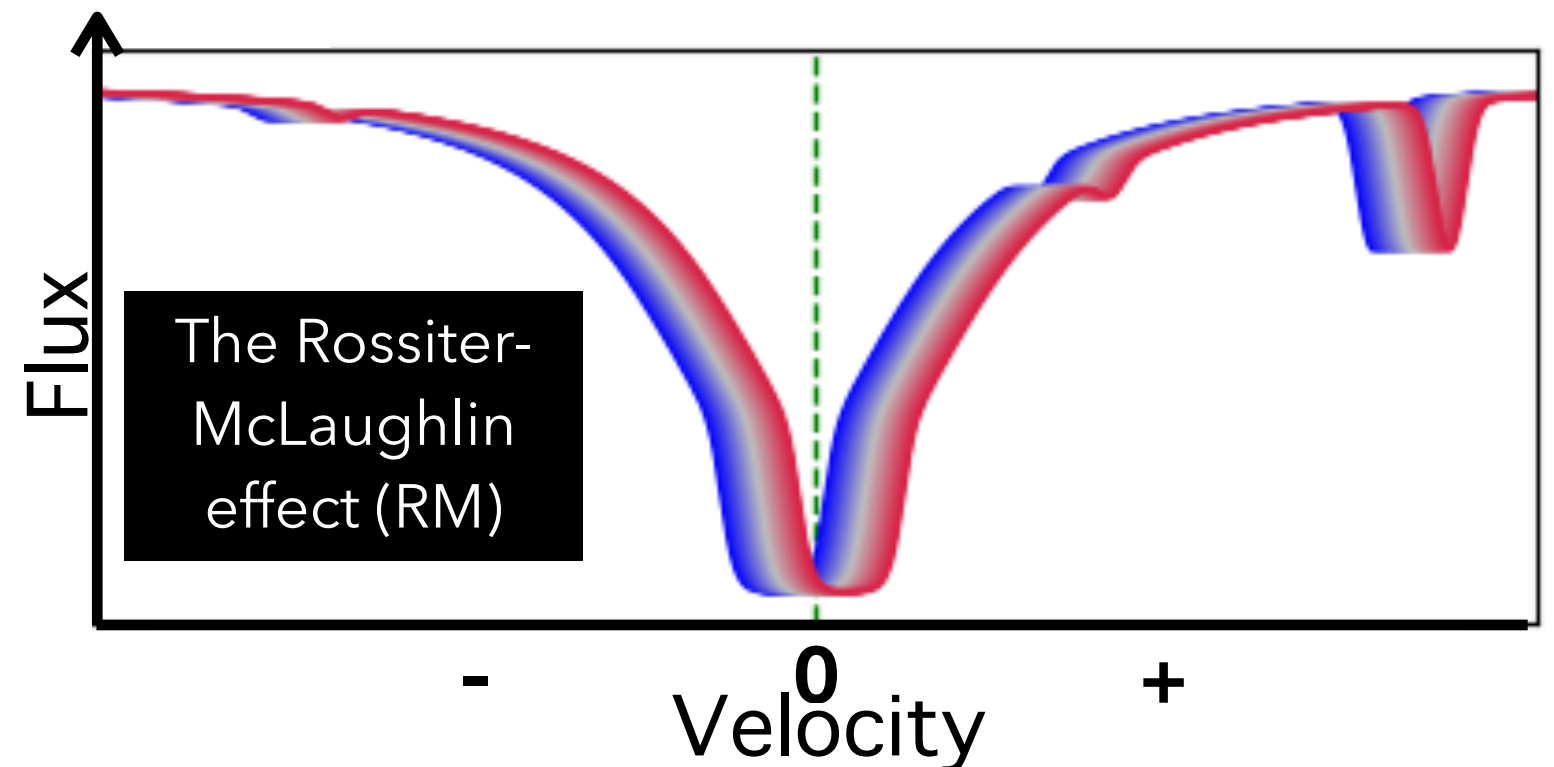
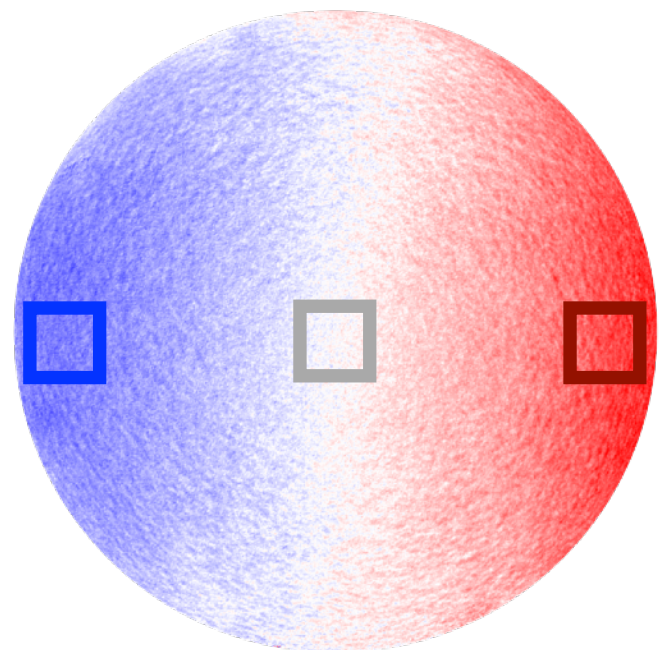
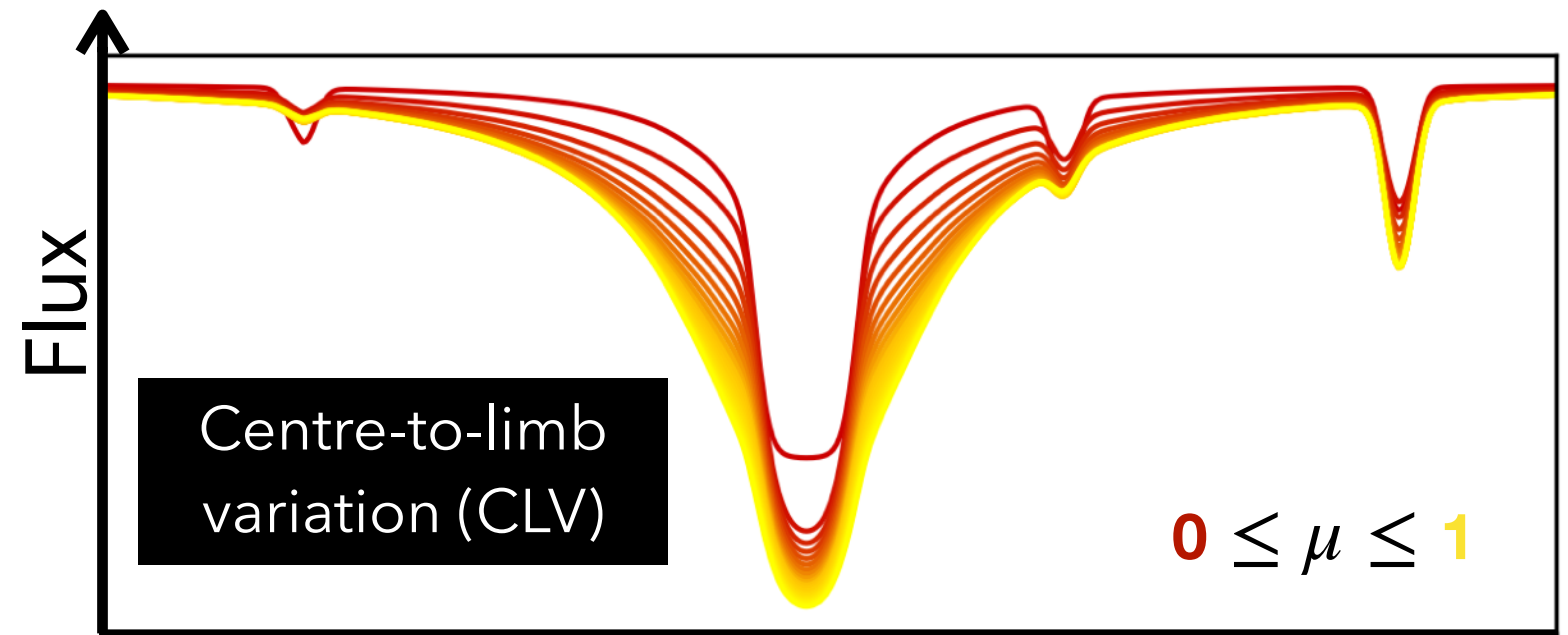
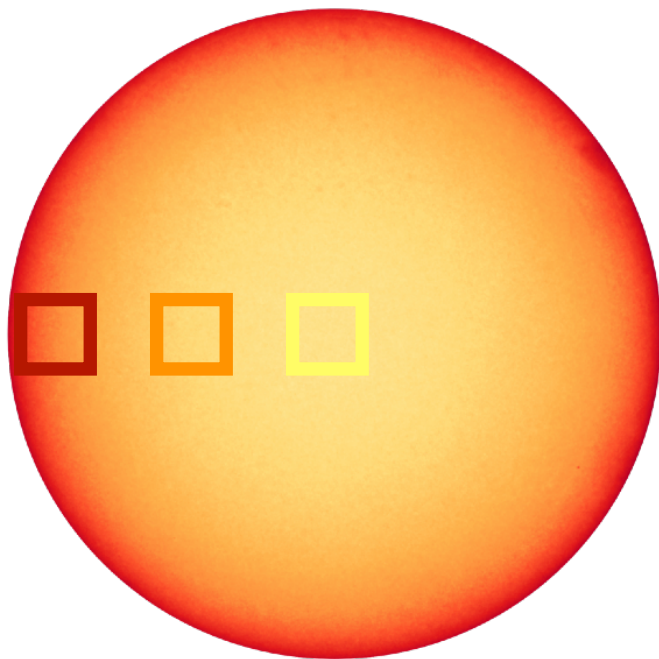
σ_i error of pixel i

Extracting the transmission spectrum

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Other corrections: the RM effect and CLV

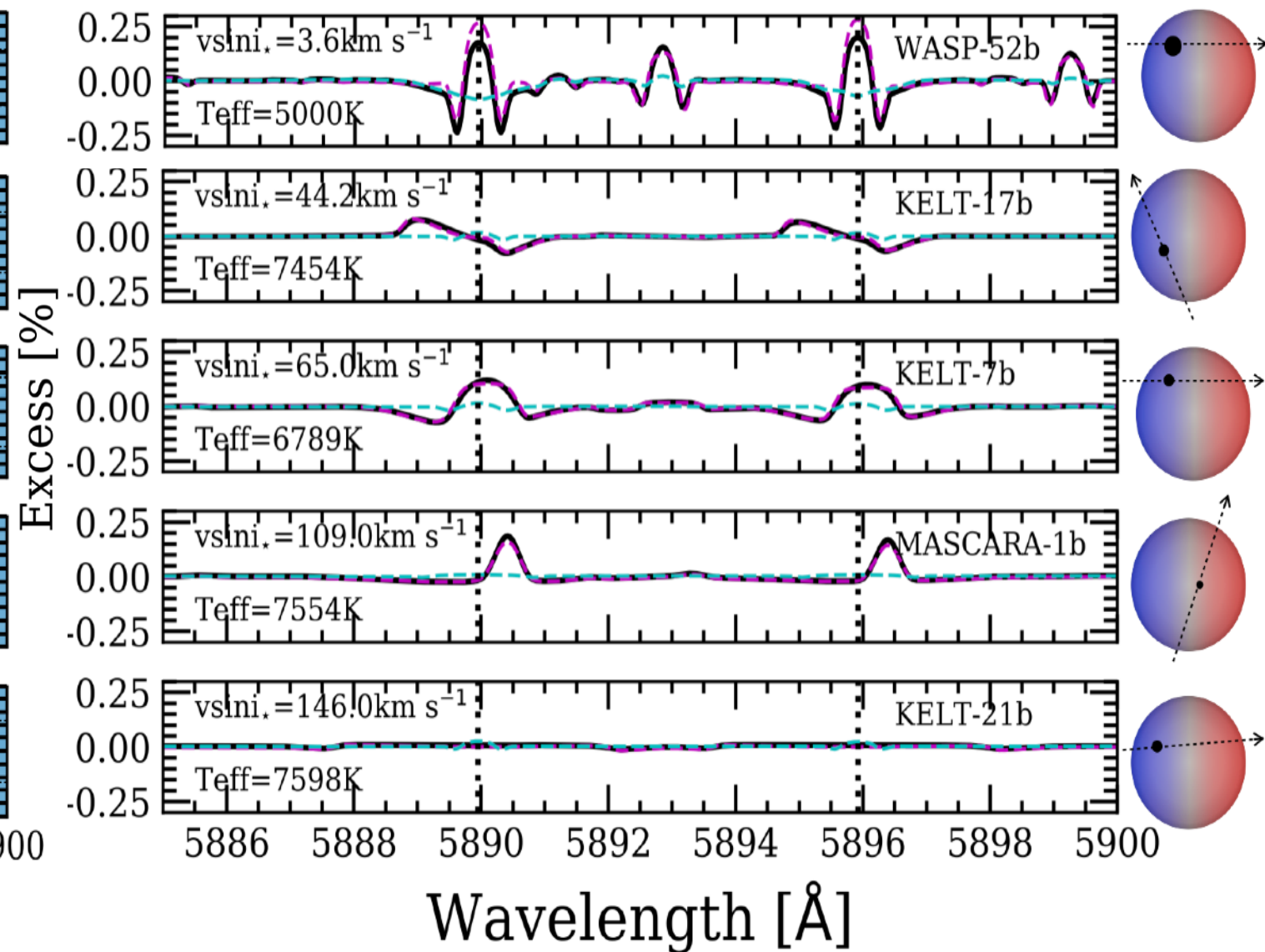
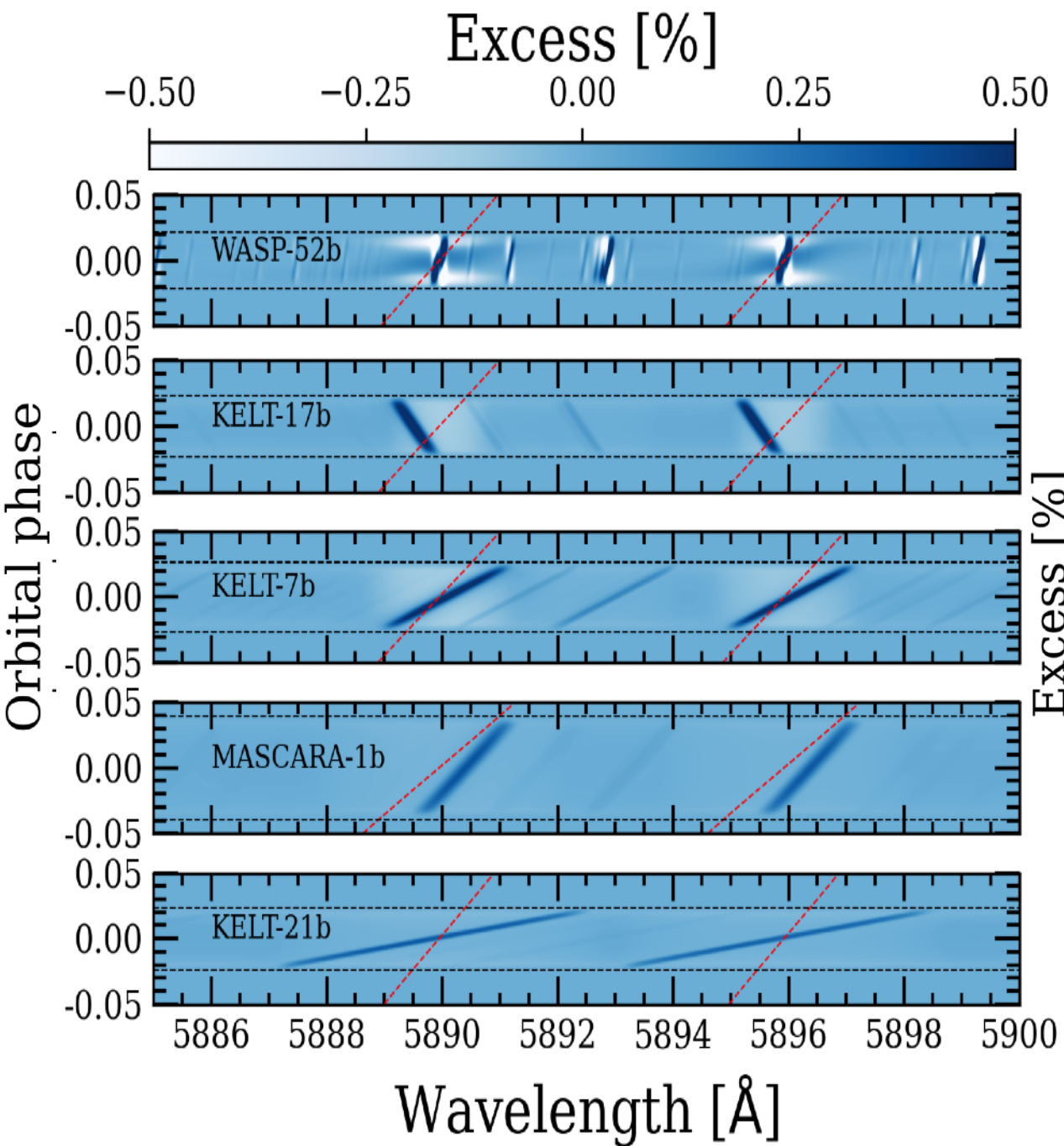


Extracting the transmission spectrum

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Other corrections: the RM effect and CLV



Extracting the transmission spectrum

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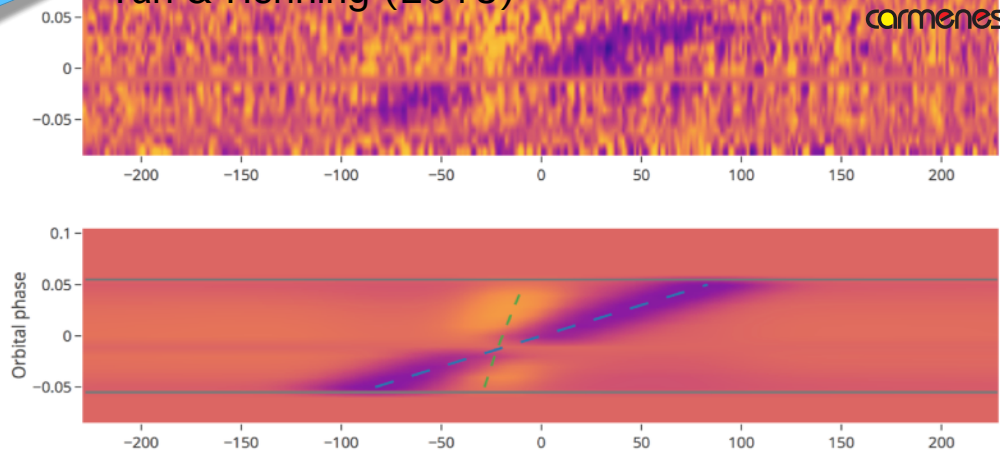


Other corrections: the RM effect and CLV

Observations

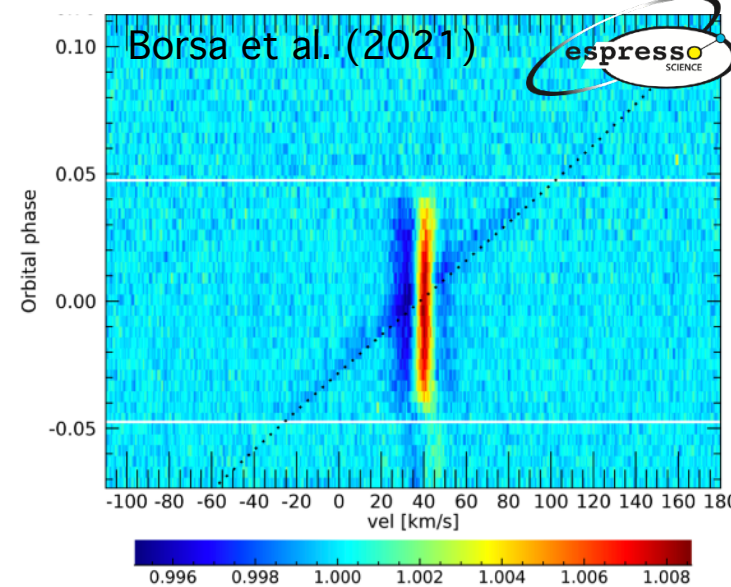
KELT-9b

Yan & Henning (2018)



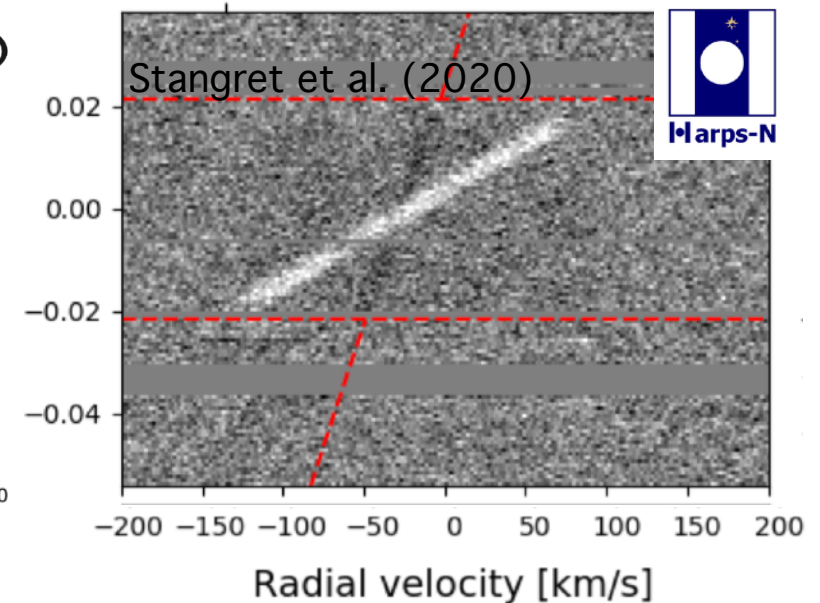
WASP-121b

Borsa et al. (2021)



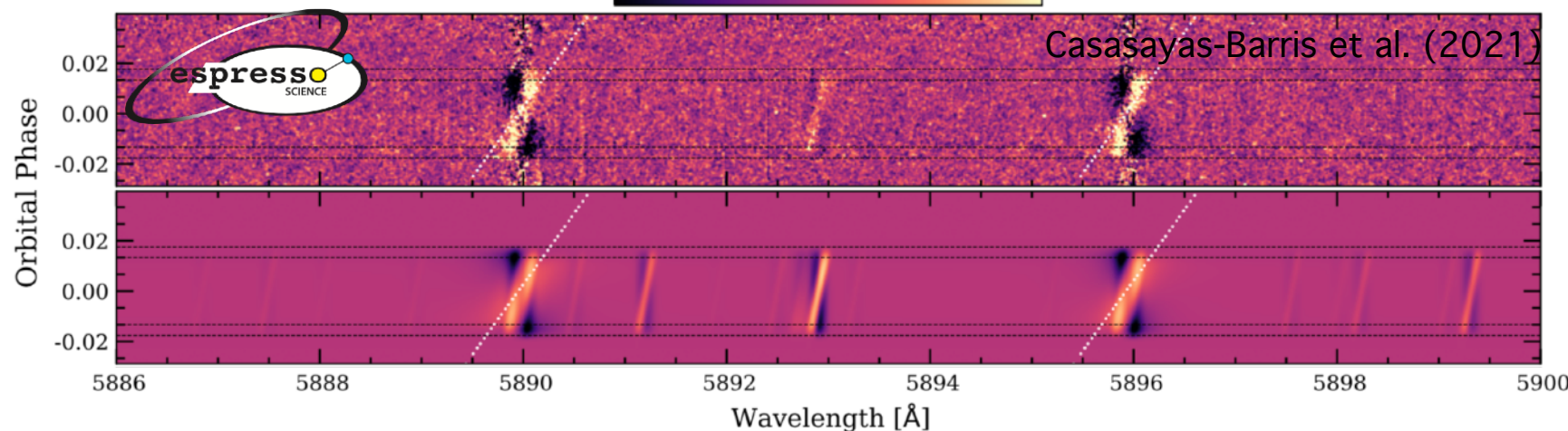
MASCARA-2b

Stangret et al. (2020)



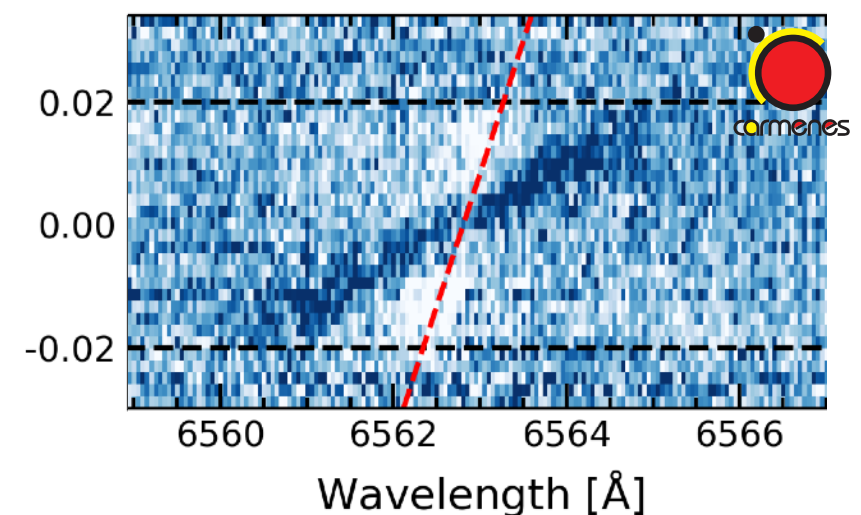
HD 209458b

-0.8 0.0 0.8



Casasayas-Barris et al. (2021)

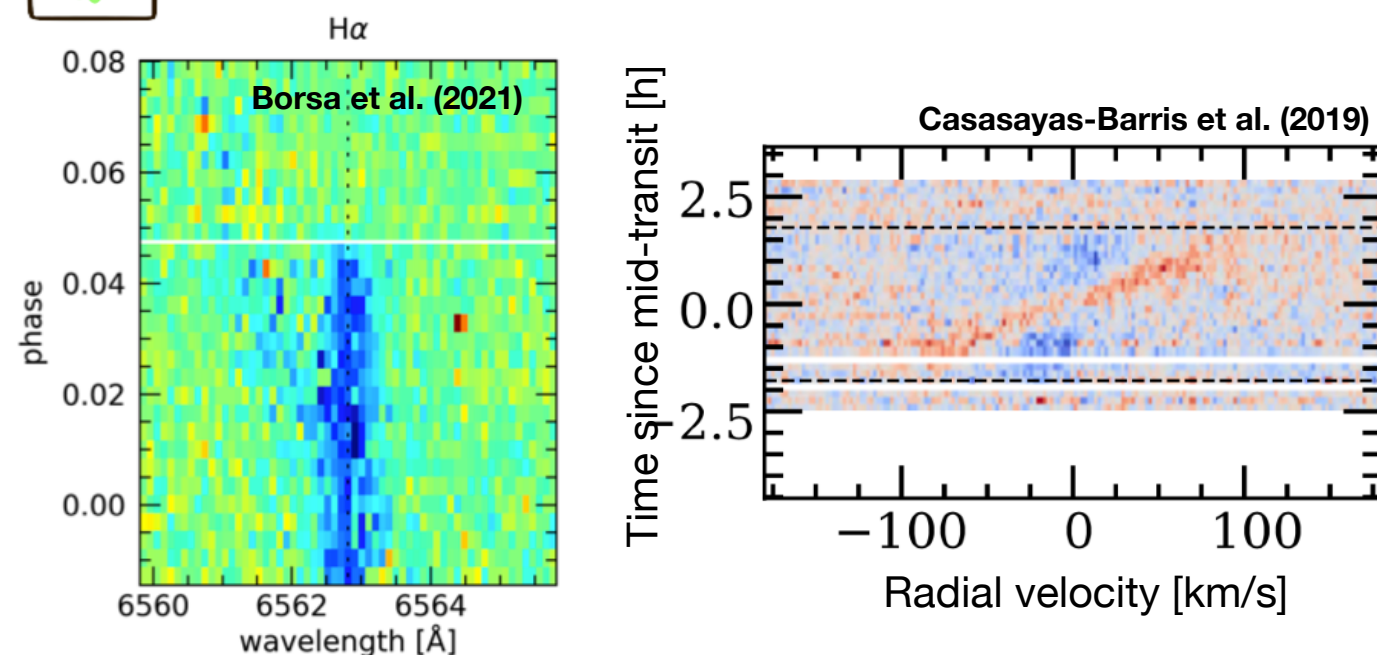
MASCARA-2b



How can we know if the signal has planetary origin?

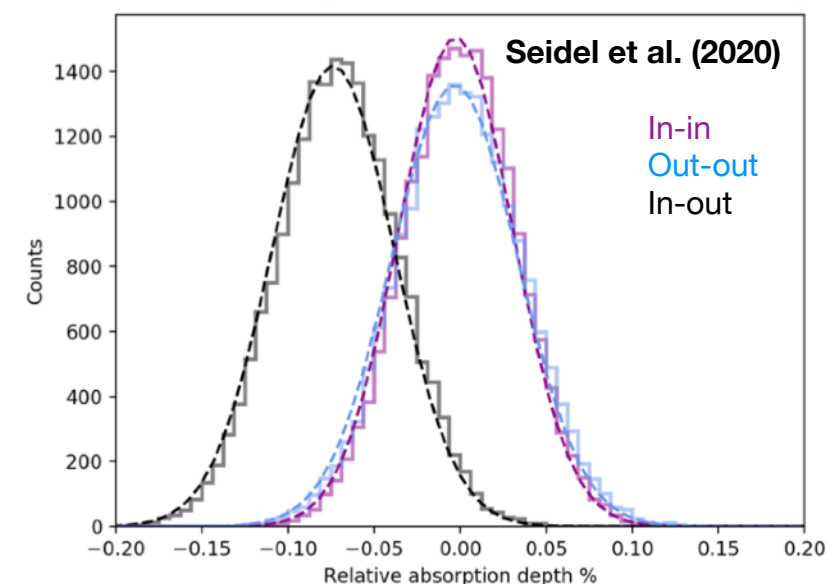


2D tomography maps



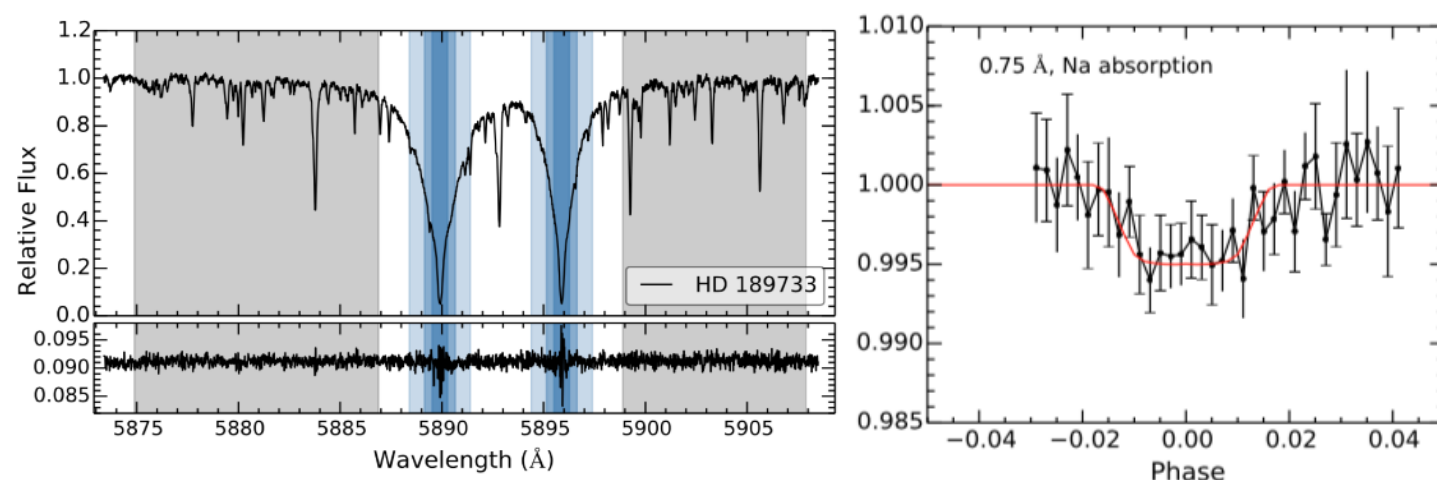
Empirical Monte Carlo

Redfield et al. (2008)



Transmission light curves

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

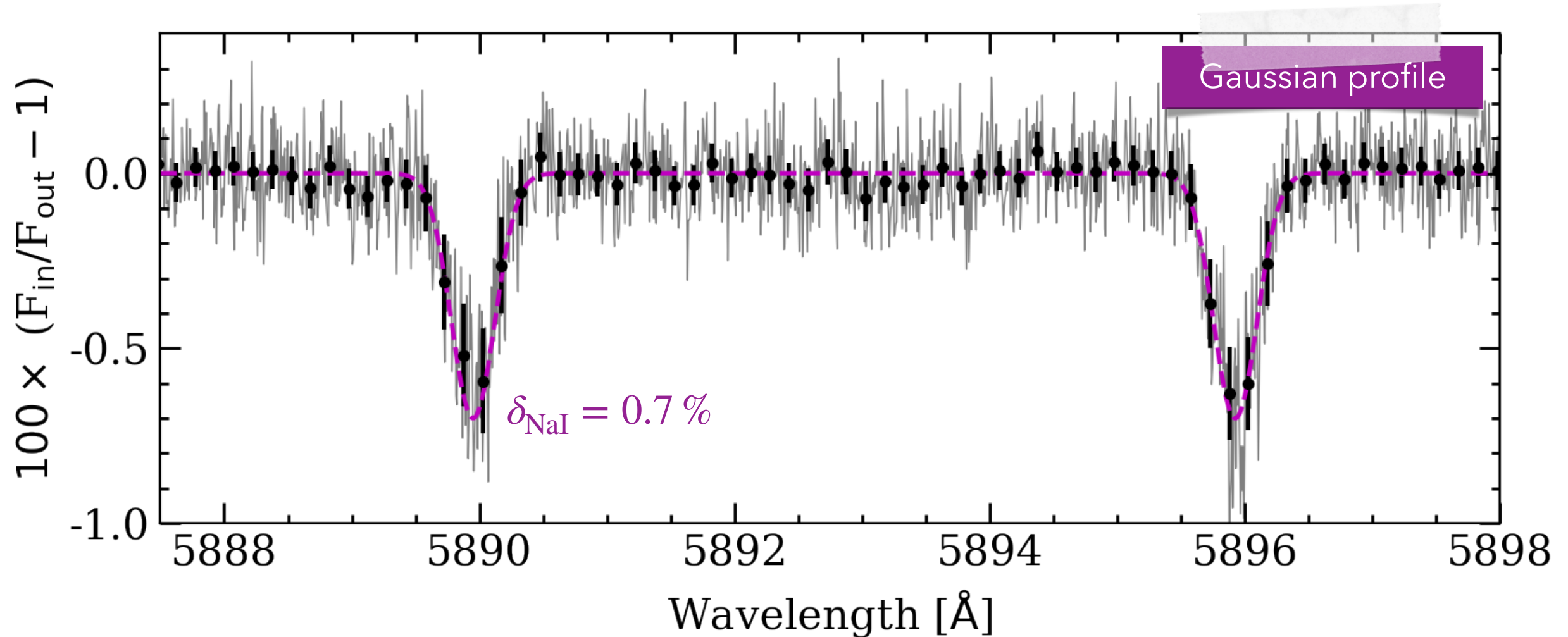


Others:

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

Interpretation of the transmission spectrum

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- **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**

- ...

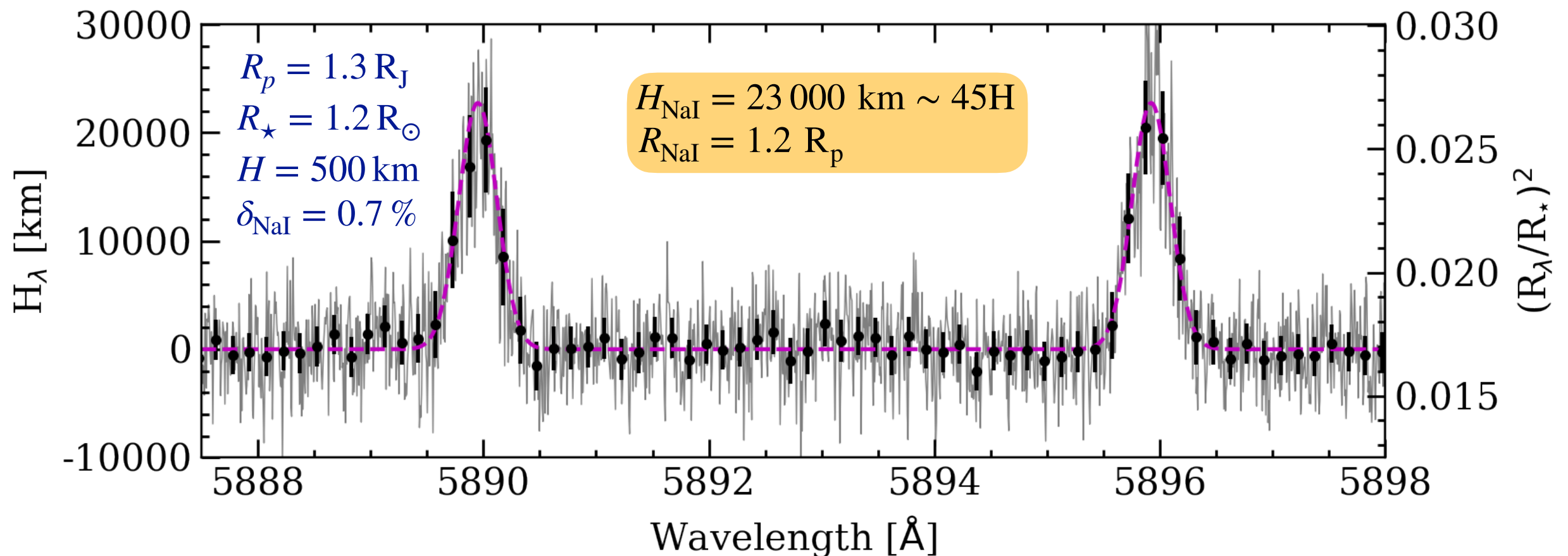
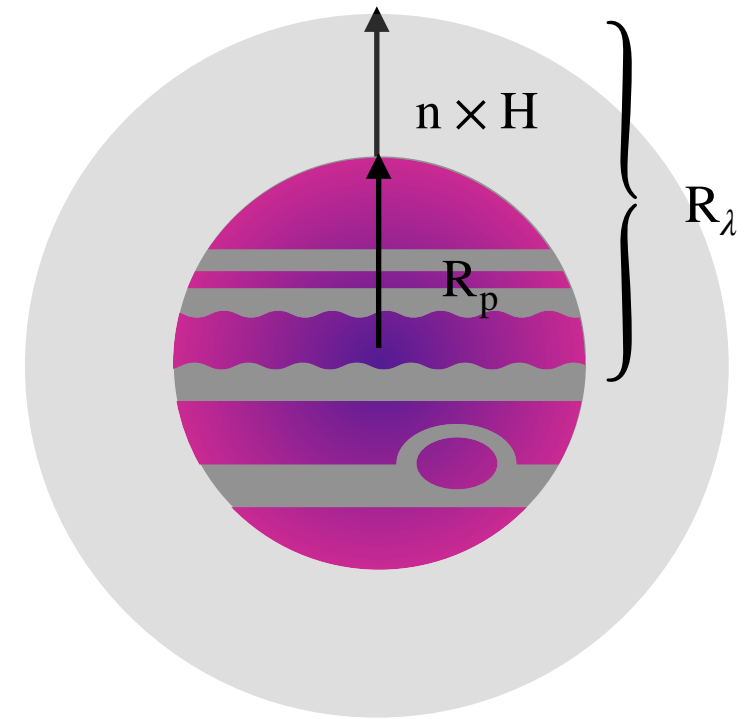
See some results during the conference!

Interpretation of the transmission spectrum

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

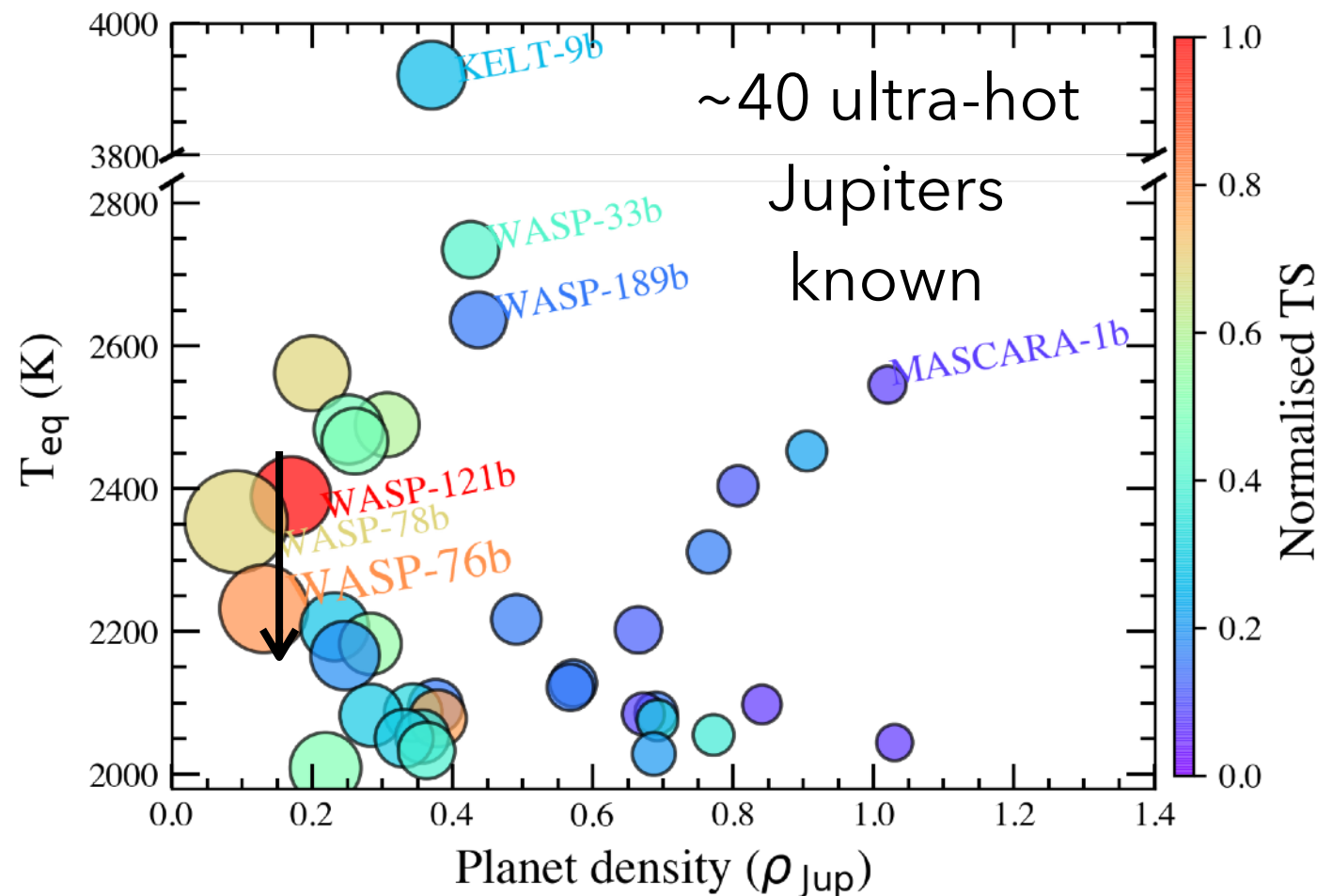
$$\delta_\lambda = \Delta_\lambda - \Delta_0 \approx \frac{2R_p H_\lambda}{R_\star^2}$$



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
UJ in general during the
conference!

Tutorial: Na I in WASP-76b

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Objective

- Extract the transmission spectrum of WASP-76b around the NaI

The data

- 1 transit of WASP-76b observed with HARPS

