Effect of stellar spots on the high-resolution transmission spectra of an Earth-like planet in the habitable zone of a Sun-like star

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Motivation

- Characterizing exoplanet atmospheres is key to understanding habitability.
- Transmission spectroscopy is sensitive to stellar activity.
- Spots and plages can mimic atmospheric signals.
- The impact of stellar activity at a high-resolution level is not fully understood yet.

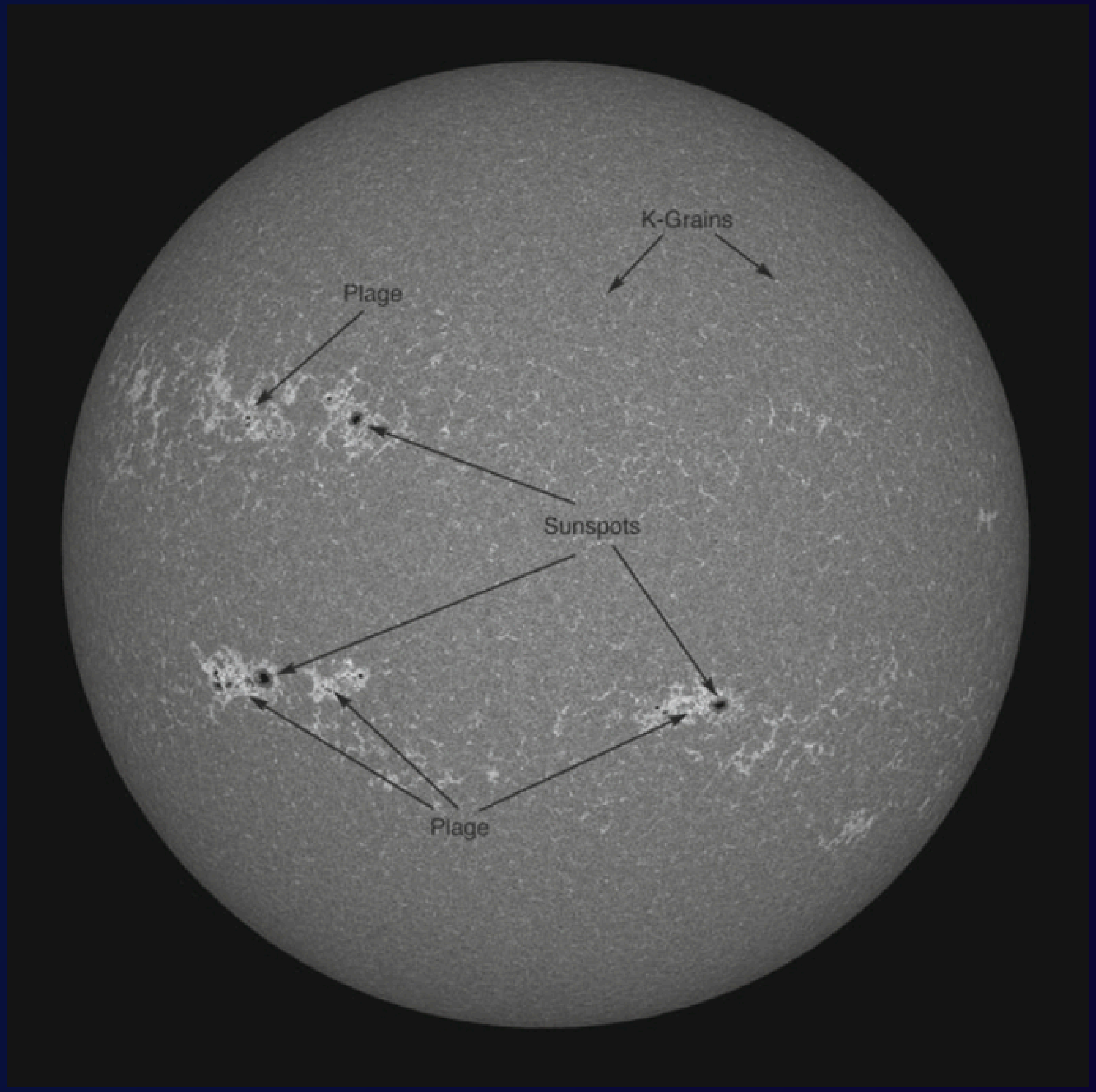

Image obtained by Jenkins et al. (2013)

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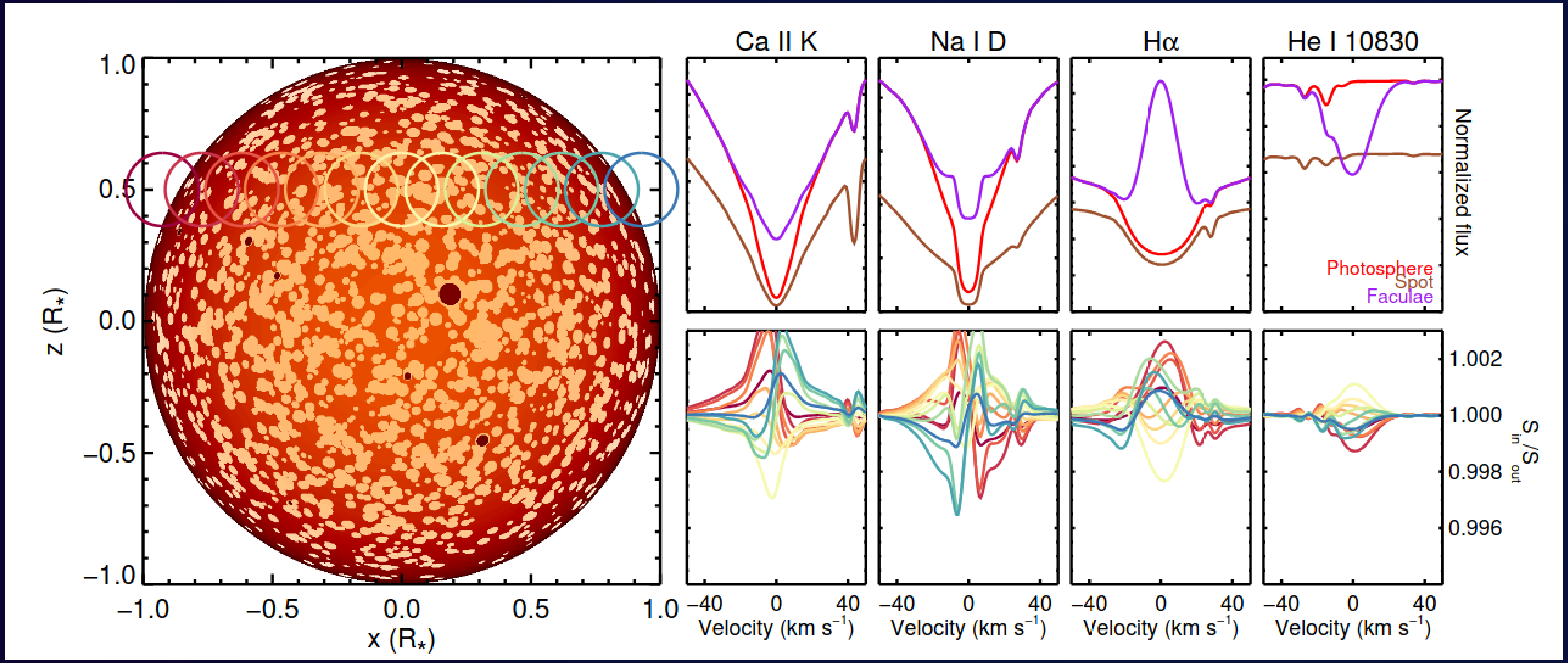
Exoplanets and the effect of stellar activity (high resolution)



Cauley et al. (2018)

- Main contributors to transmission spectra contamination: strong facular emissions and large coverage fractions
- Significant impact on Hα, Ca II K, and Na I D
- Minimal influence from spots
- Contamination depends on the location of active regions and their emission strength

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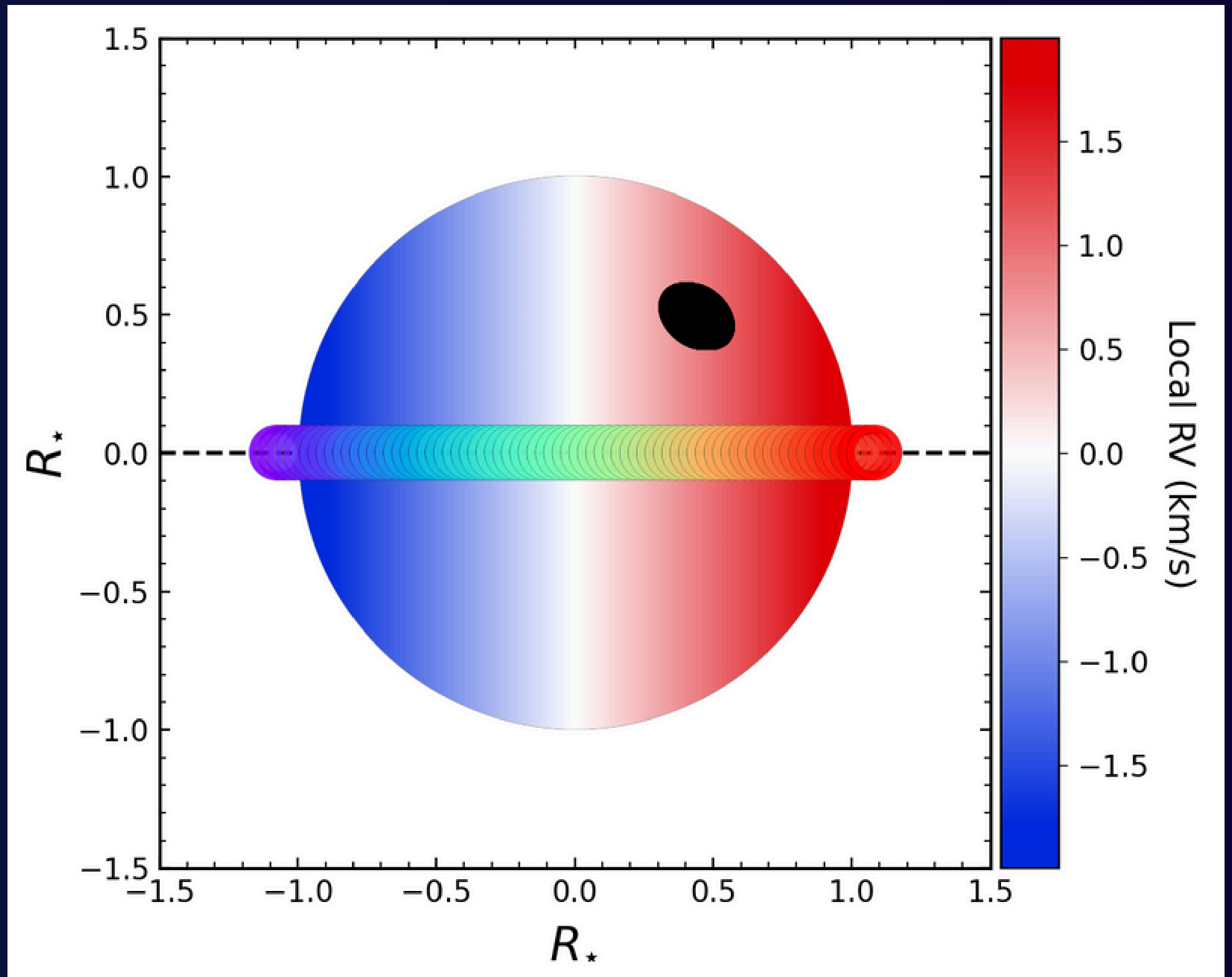
SOAPv4 simulations

- SOAPv4 (Cristo et al. 2025, under review) simulates the stellar spectrum when a planet (with no atmosphere) is in transit and can simulate the effect of stellar activity.
- SOAPv4 can use as inputs observational spectra (FTS) and synthetic spectra (PHOENIX).
- Simulate for different types of star-planet configurations and stellar activity contributions.
- Inputs: wavelength range, stellar parameters, spot properties, resolution.



Doppler map of the hemisphere of the sun-like star.

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Explored parameters

- Different input spectra for star and spot and different configurations.

Table 2. Model parameters and explored values

Parameter description	Symbol	Value range
Spot coverage fraction	f_{sp}	0.1% – 3%
Latitude	θ_{lat}	25° – 80°
Longitude	θ_{lon}	±20° – 80°
Sun rotational velocity	$v\sin i$	2 – 10 (km s^{-1})
Spot temperature difference	ΔT_{spot}	$-663\ K$
Sun effective temperature	T_{eff}	$5778\ K$

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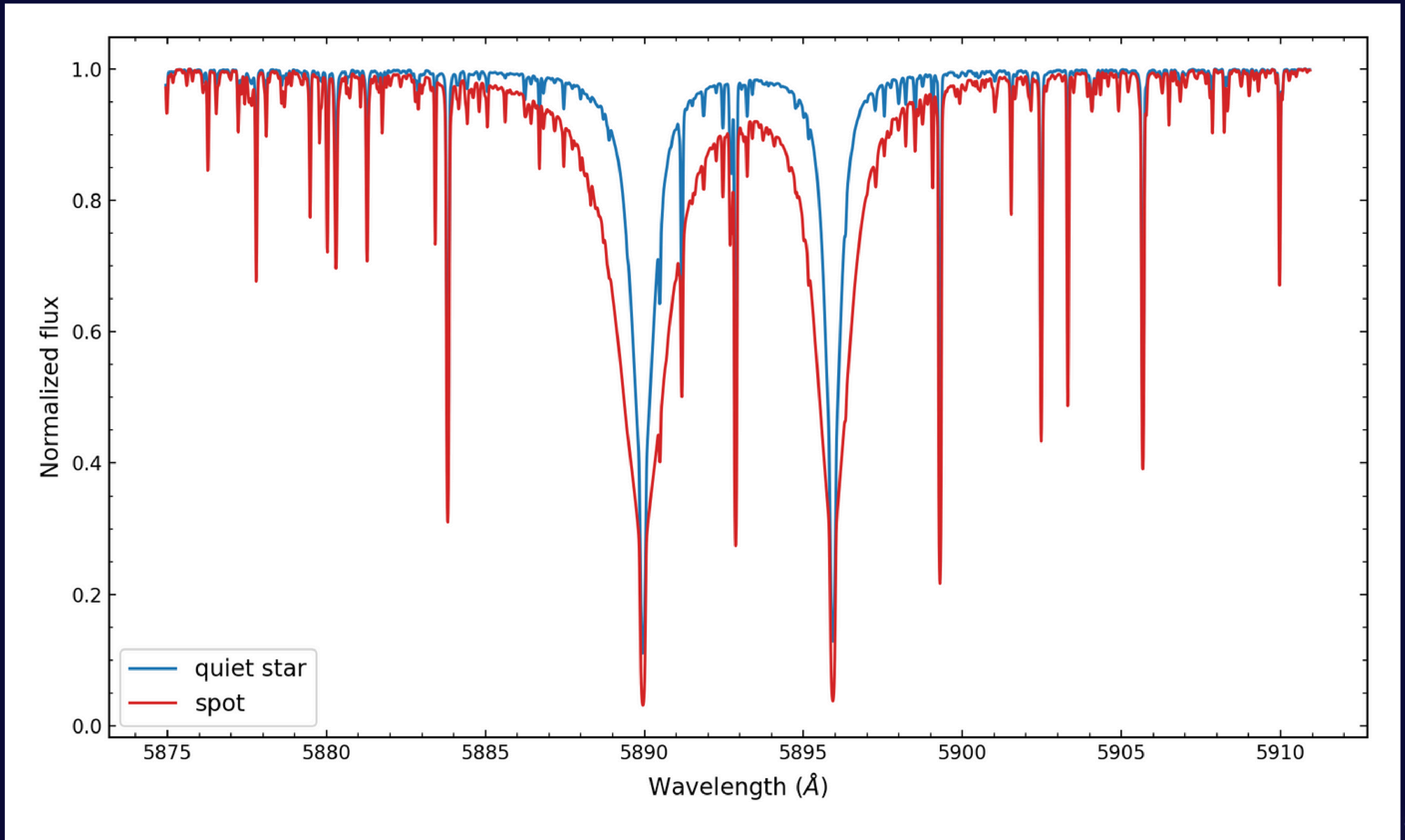
Explored parameters

- Defined input spectra and spectral region for both the star and the spot (PHOENIX)



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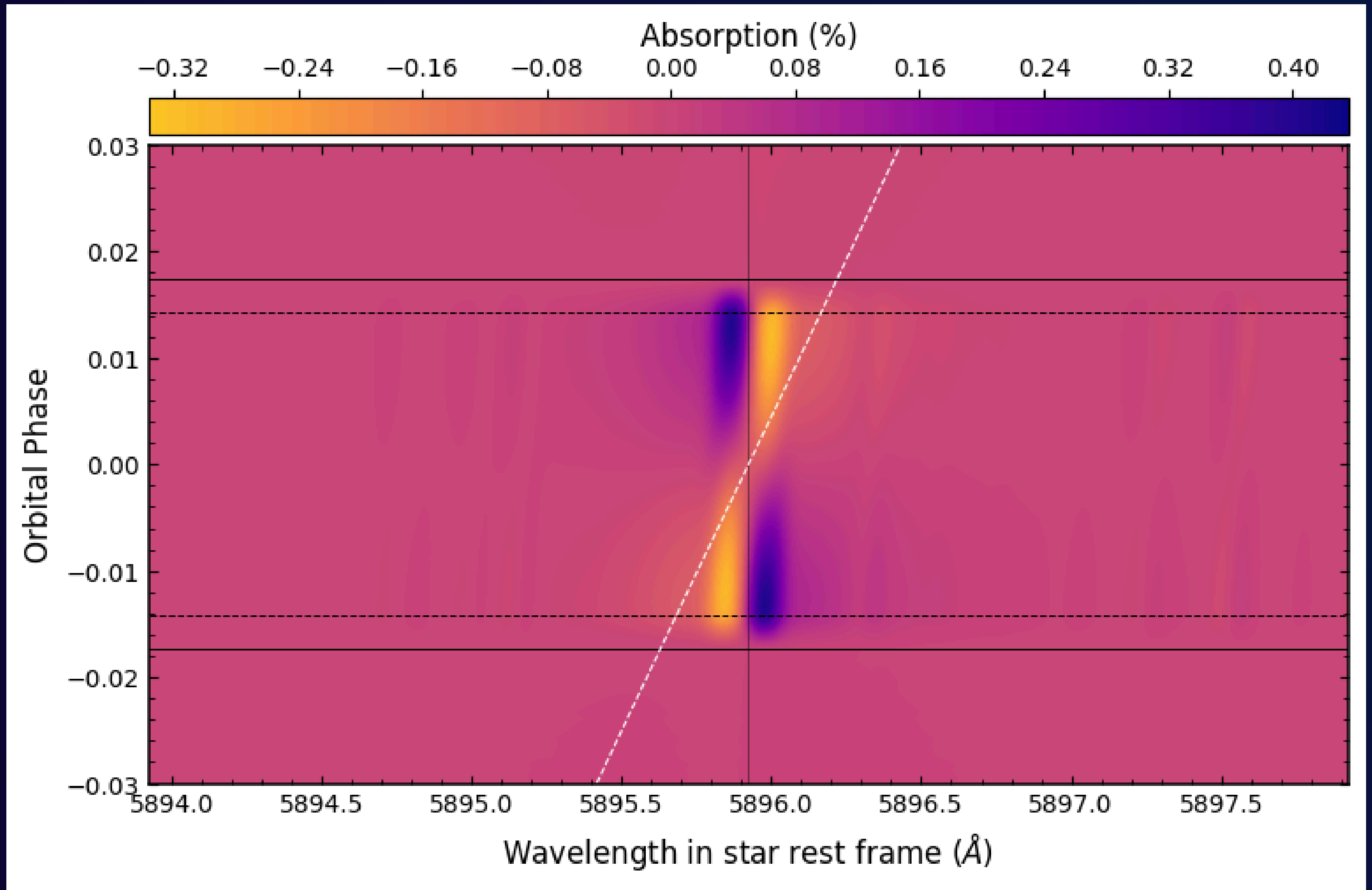
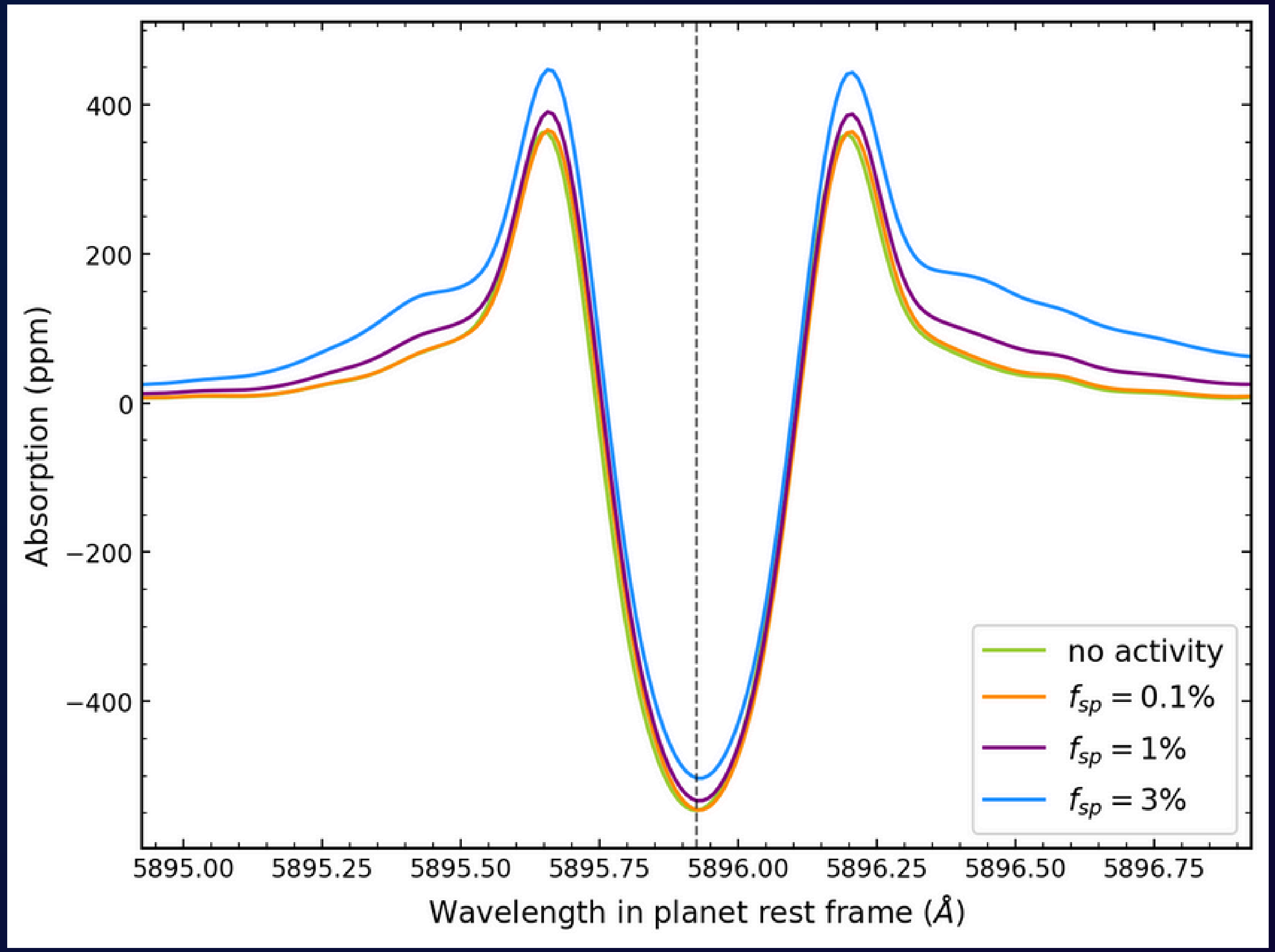
The hot-Jupiter case

- Simulations for a hot-Jupiter planet around a Sun-like star
- Fixed parameters: Lat=25, Lon = 20, *v sin i* = 2km/s
- Spots have a small impact on the Na I line distortions for hot-Jupiter planets , is it the same for an Earth like planet?





P. Lucero et al. 2025 (in prep)

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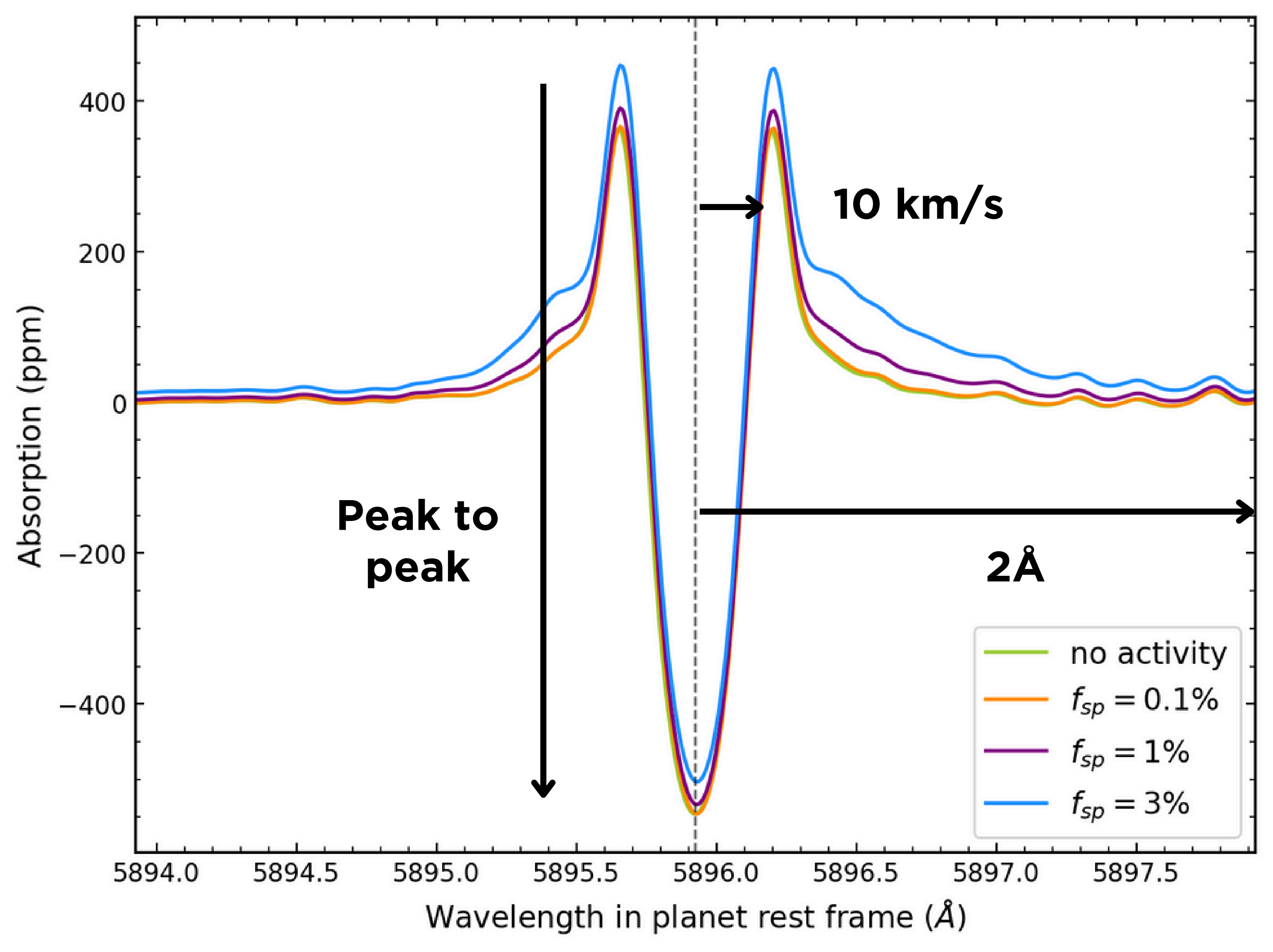
Measuring the absorption and assymetry



Absorption: peak to peak

Compute the flux difference between the min and max peak

Assymetry: Velocity shift

Compute the center of mass of the line in order to obtain the vshift

$$\lambda_{\rm CM} = \frac{\sum \lambda_i f_i}{\sum f_i}$$

$$v_{\rm shift} = c\frac{\lambda_{\rm CM} - \lambda_0}{\lambda_0}$$

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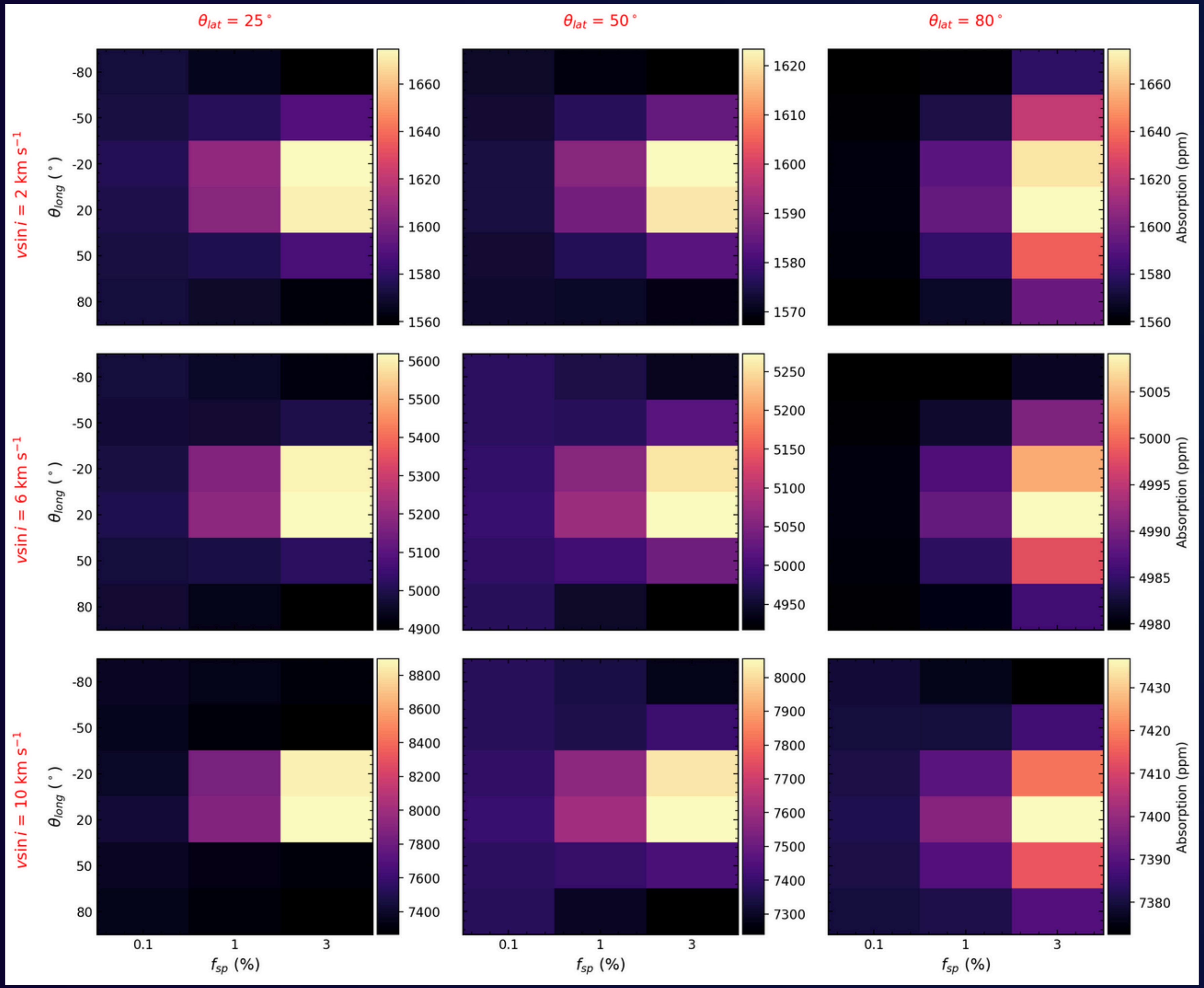
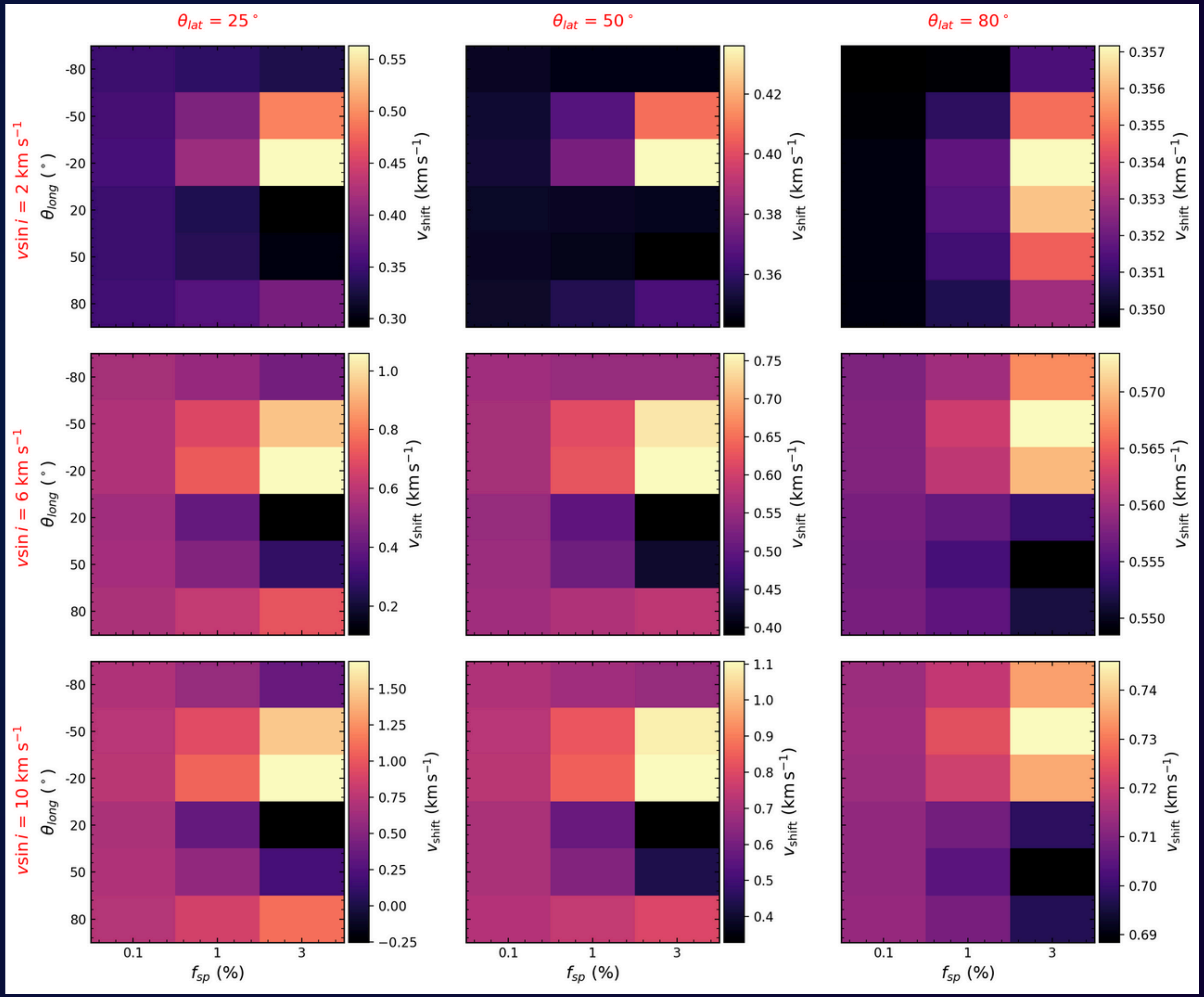
The hot-Jupiter case: combined analysis

Absorption



Asymmetry



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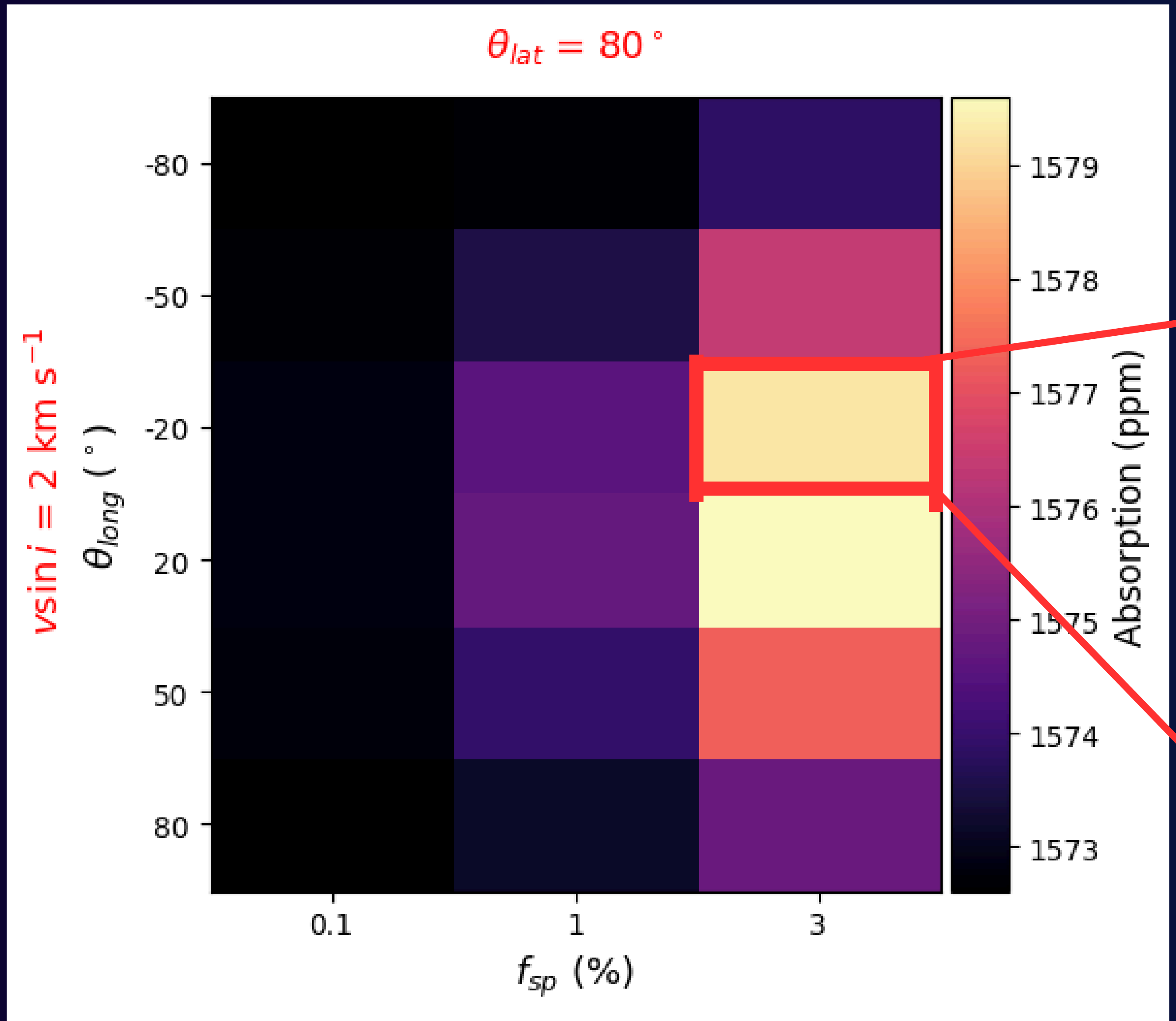
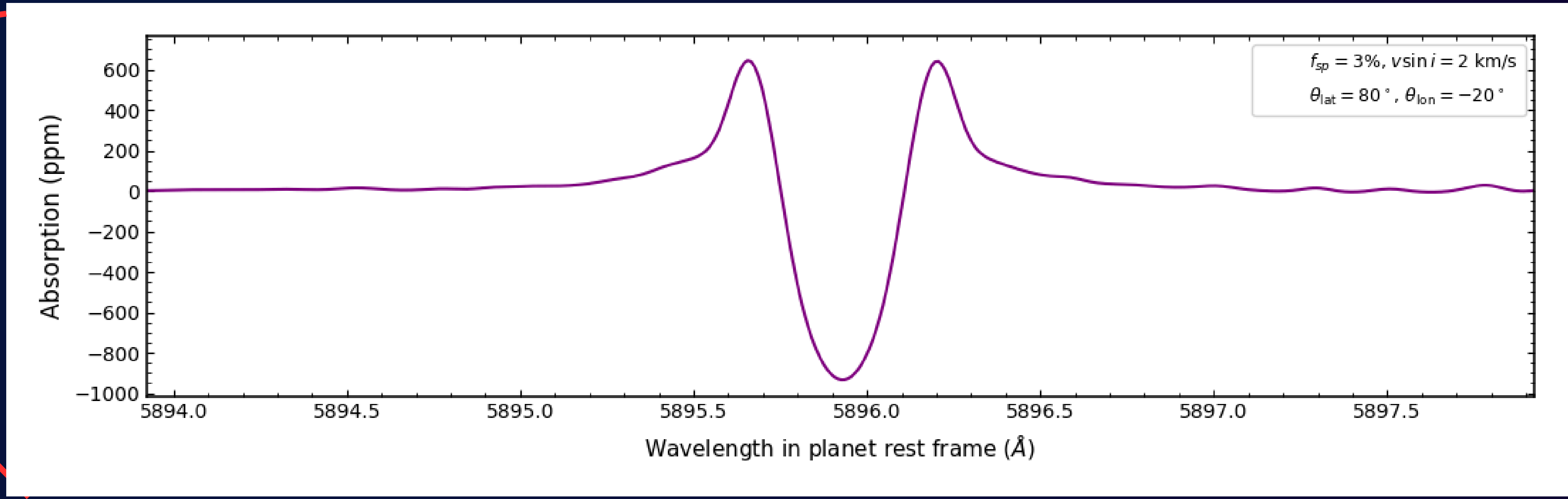
The hot-Jupiter case: combined analysis





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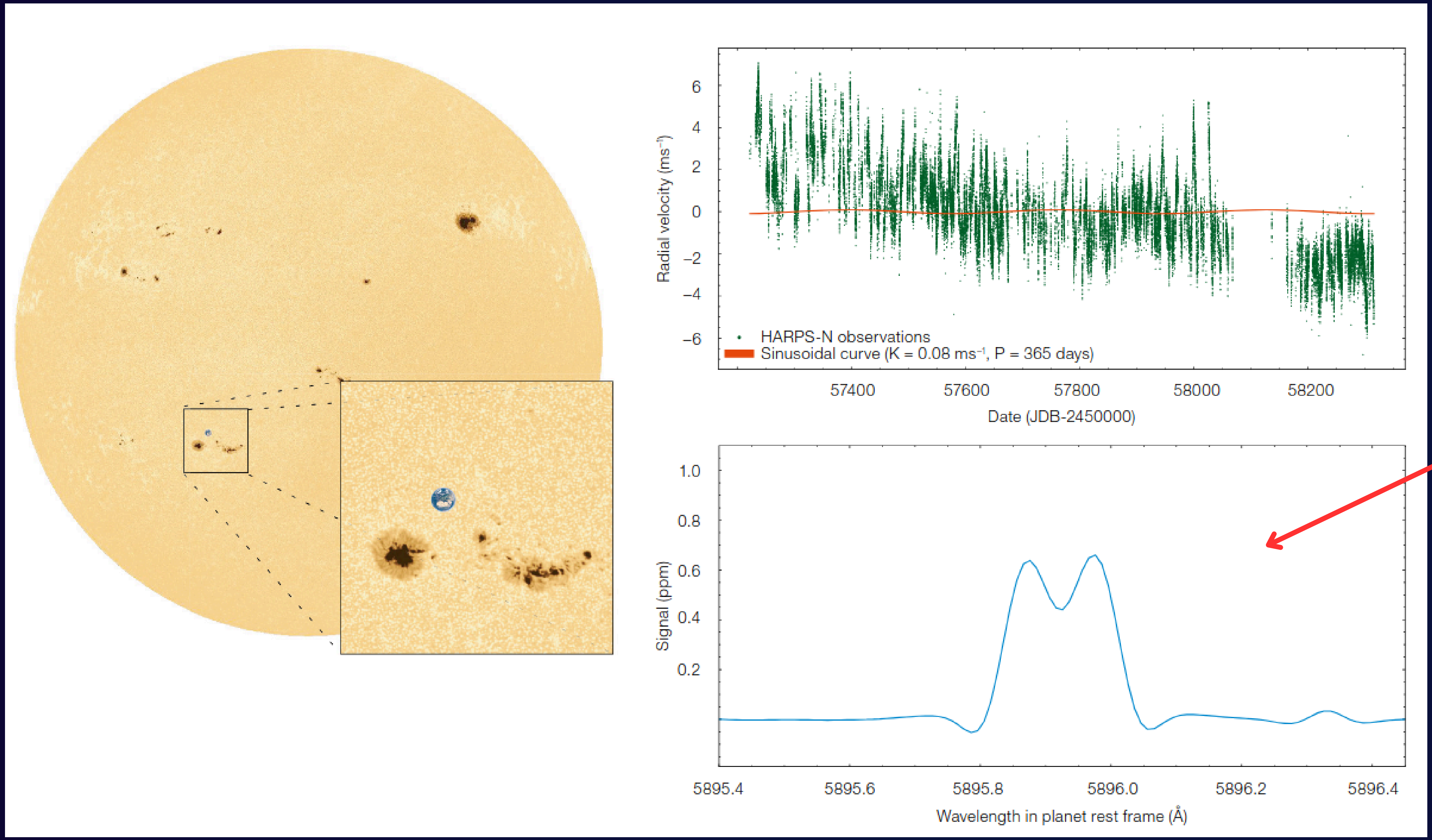
The hot-Jupiter case: main results

- Larger spots cause stronger absorption distortions.
- Distortion amplitude increases with v sin i (2–10 km/s).
- Lower-latitude spots produce stronger distortions. Due to limb darkening and higher contrast near the stellar equator.
- Starspot-induced velocity shifts depend strongly on both projected rotational velocity and spot latitude.

An Earth-like planet in the HZ



Santos et al. (2025)

- Simulation of the transmission spectrum of an Earth-like, atmosphere-less planet transiting a quiet star, accounting only for center-to-limb variations (CLVs).
- The signal amplitude (~1 ppm) is comparable to that of an actual Earth-like atmosphere.
- What happens when you have an active star?

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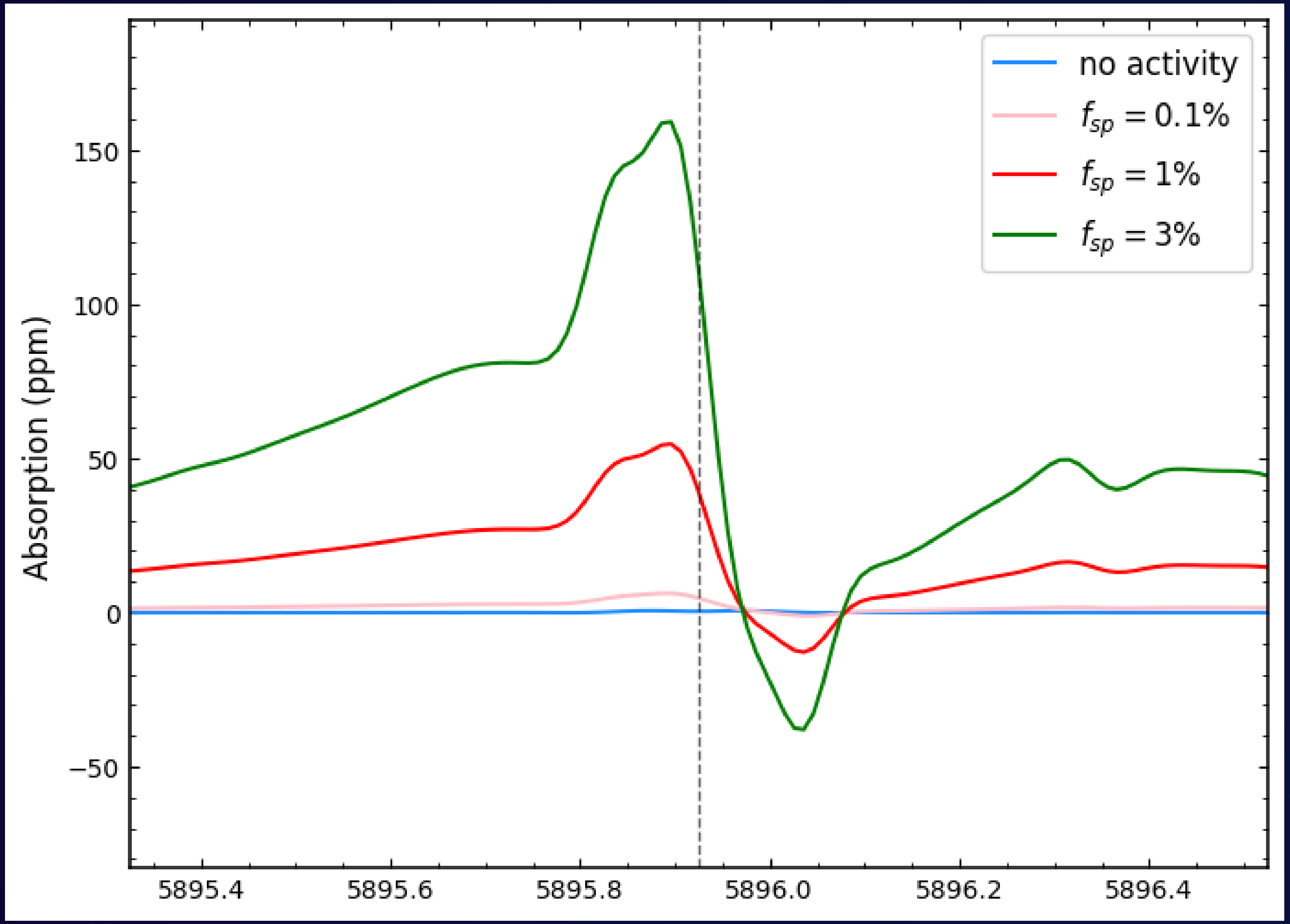
An Earth-like planet in the HZ 

What happens when you have an active star?



- The expected sodium absorption signal from an Earth-like atmosphere is typically ≤ 1 ppm.
- In contrast, stellar spots with coverages as 0.1%–3% can induce absorption signals of 10–150 ppm.
- These signals overwhelm the planetary signature, making it extremely difficult to detect Earth-like atmospheres without correcting for stellar effects.

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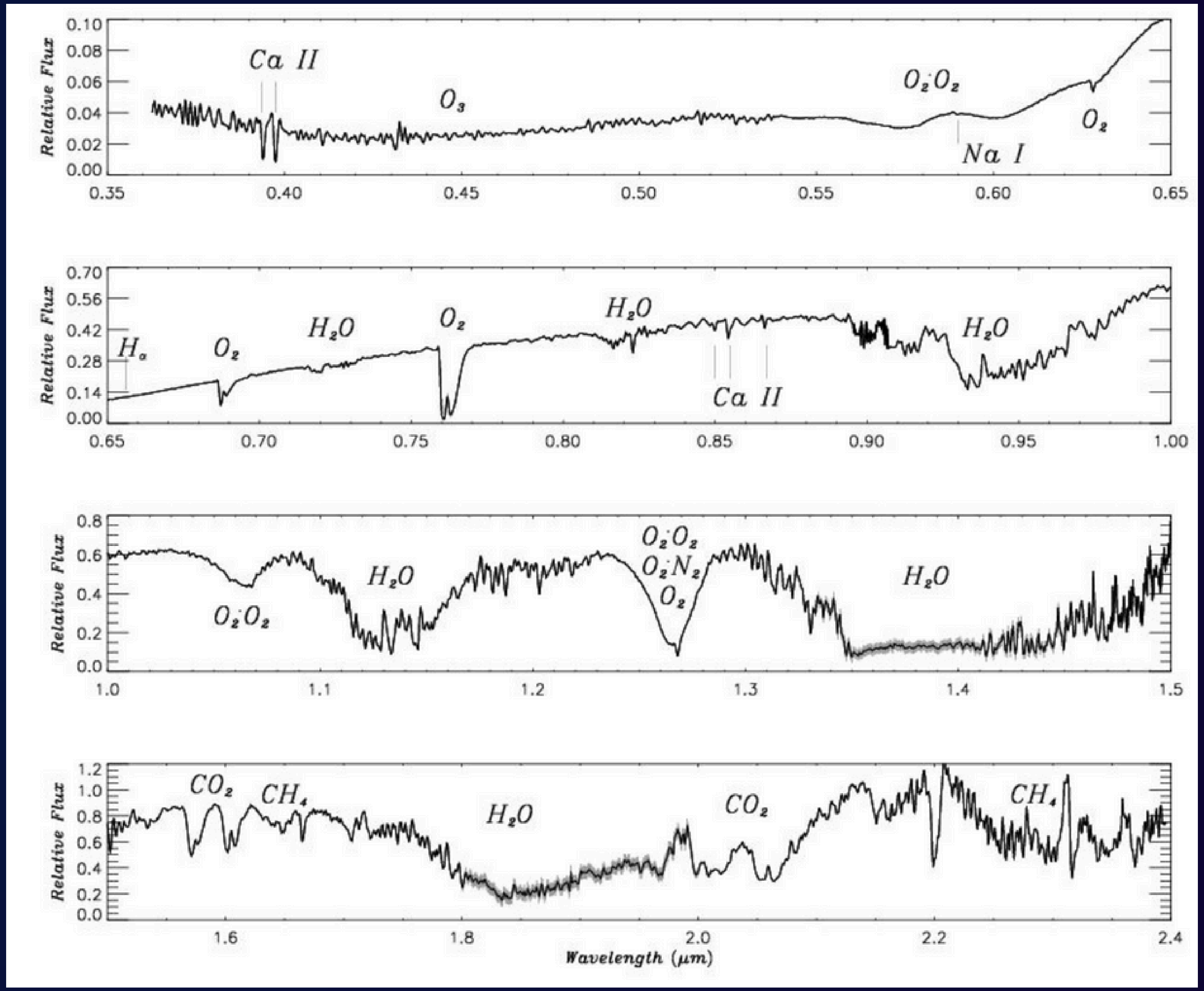
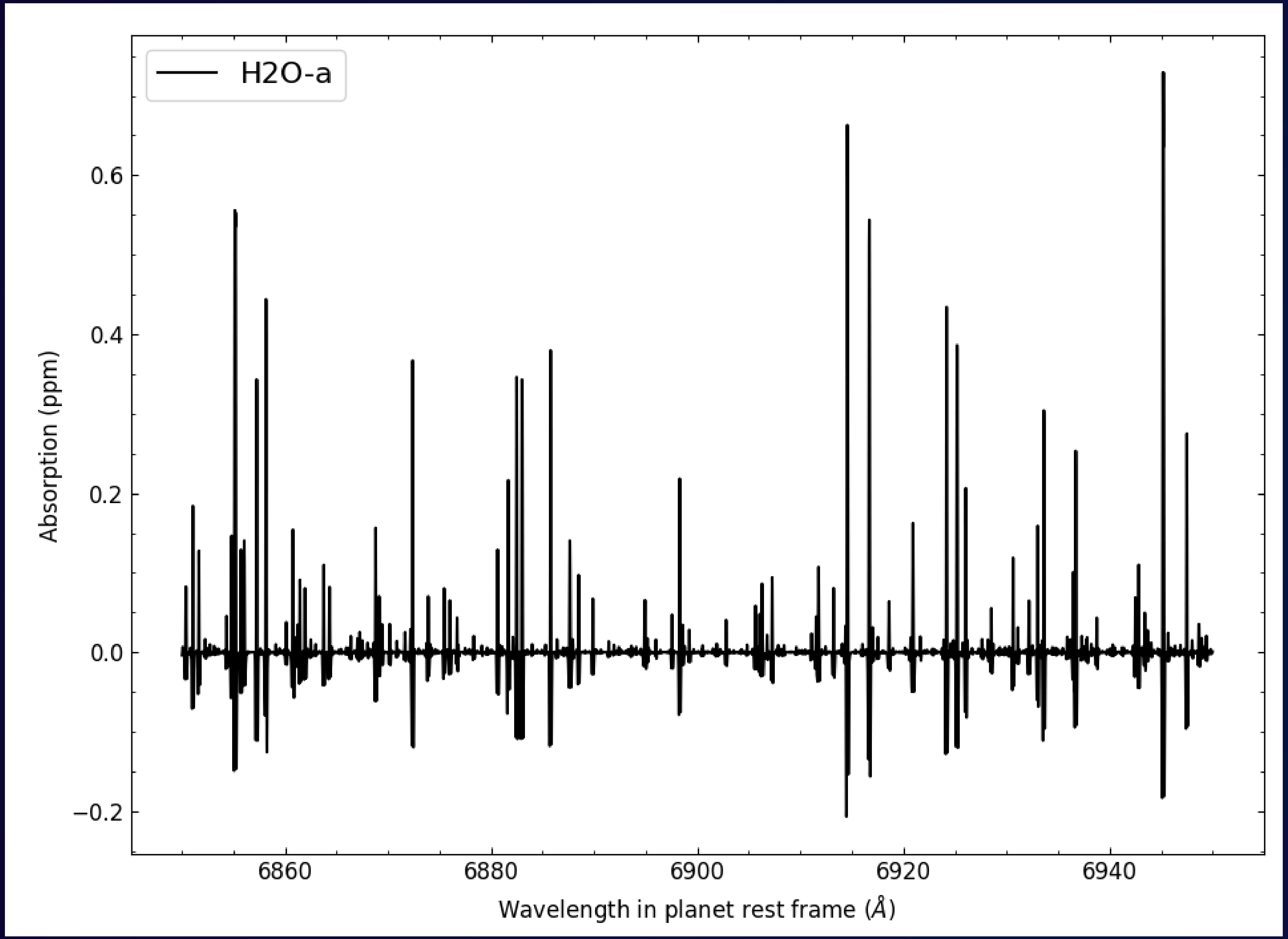
An Earth-like planet in the HZ

- Strong absorption bands from O_2, O_3, H_2O, CO_2, and CH_4 are clearly detected.
- Collision-induced features reveal the presence of N_2.
- Most of these signals are stronger in transmission than in reflection, making them key targets for biosignature detection in Earth-like exoplanets.



Pallé et al. (2009)

Preliminary results and next steps



Absorption spectrum of an Earth-like planet around a Sun-like star for H2O-a. Signal without stellar activity effect.

We want to explore the effect on different atomic and molecular species along the absorption spectrum-

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thank you :)