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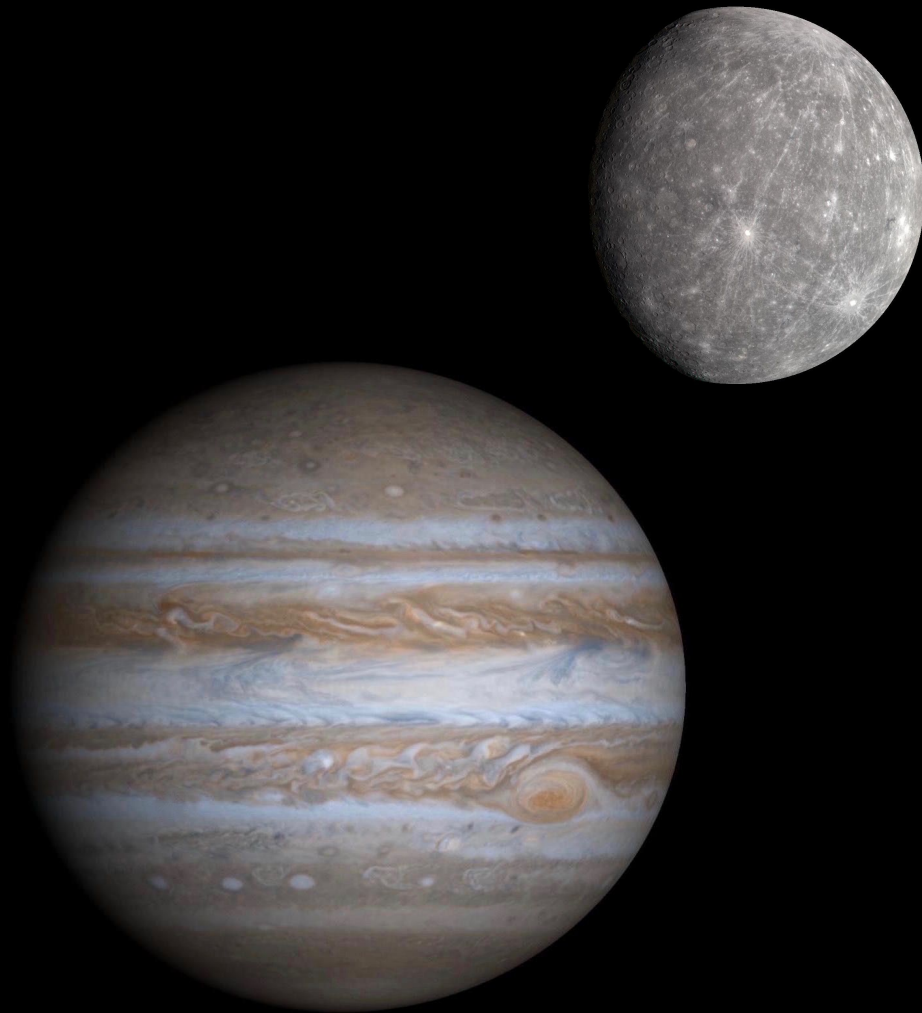
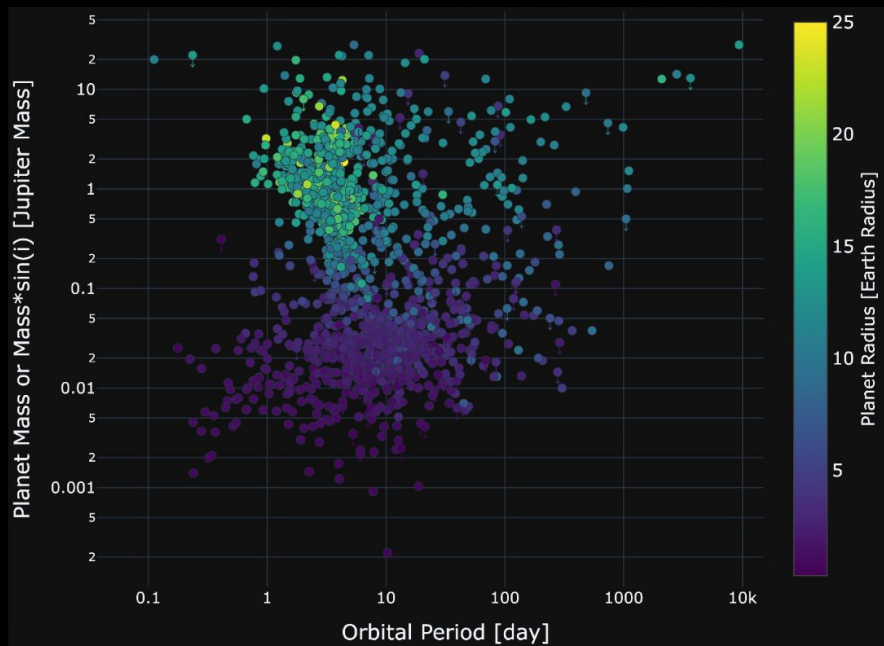
Bridging Ground-based High-resolution and JWST Low-resolution Spectroscopy for In-depth Exoplanet Atmosphere Analysis

Daniel Dupkala

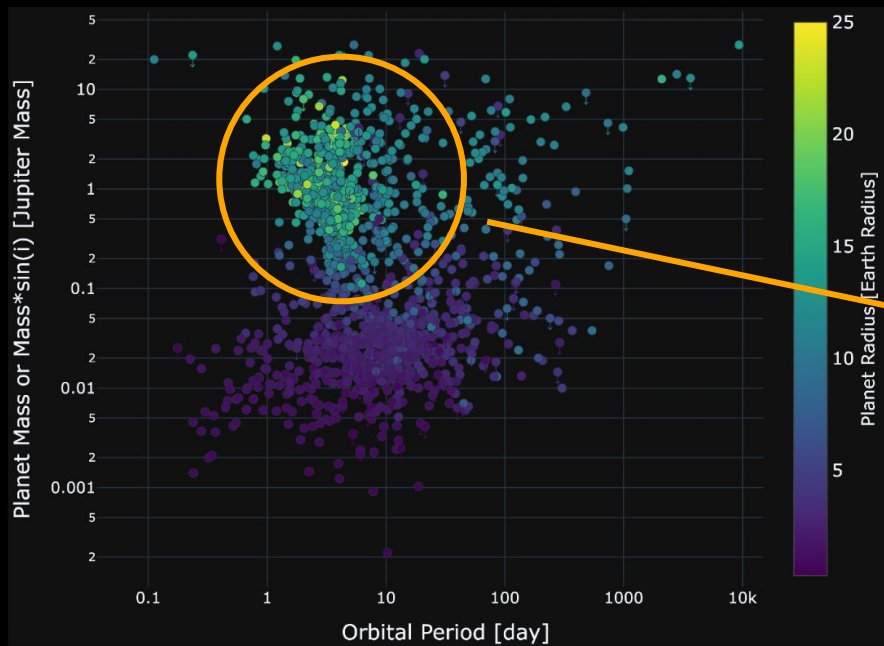
ICPS 2026 Rabat, Morocco

August 1-7, 2026

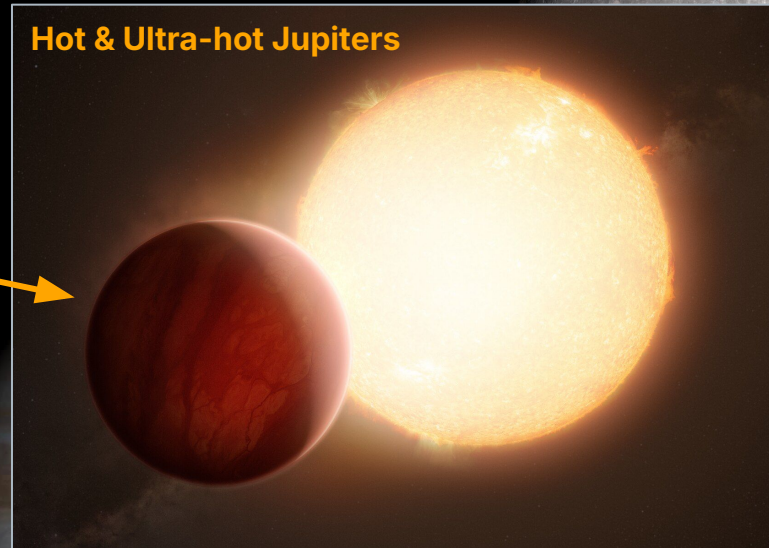
Motivation - Extrasolar Planets



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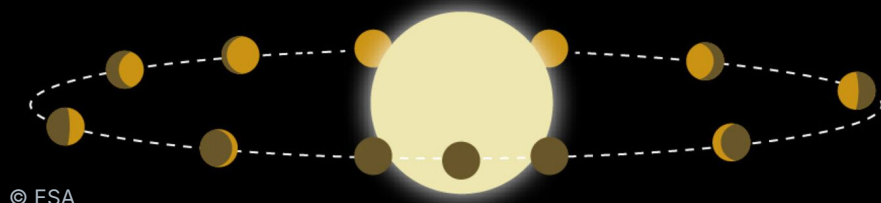
Hot & Ultra-hot Jupiters



Motivation - Atmospheres of Exoplanets

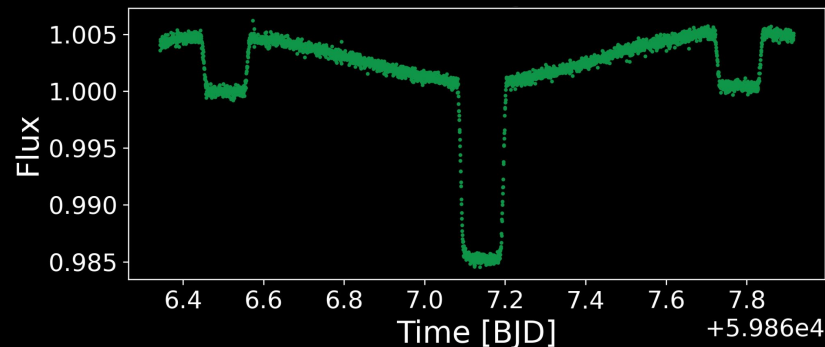


Transiting Exoplanets

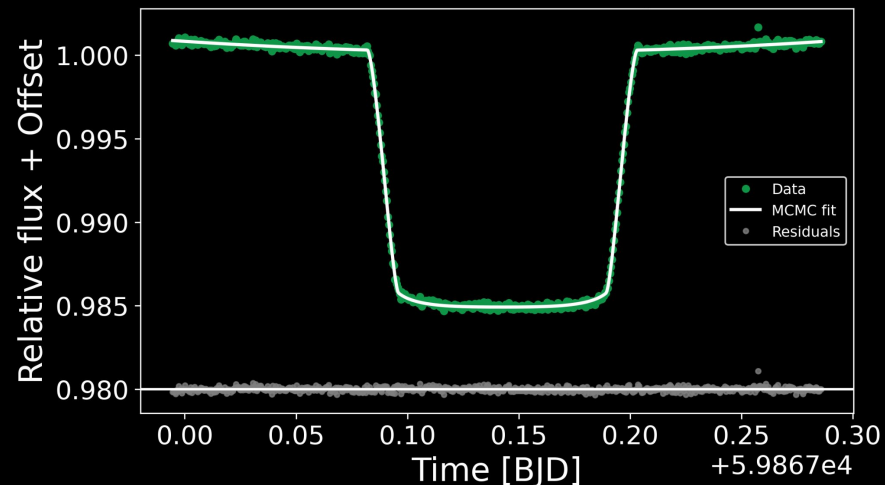


- When transiting, stellar light passes through the exoplanet atmosphere
 - **Doppler shifted absorption lines** via high-resolution cross-correlation techniques
 - **Transmission spectroscopy** via low-resolution space-based spectroscopy

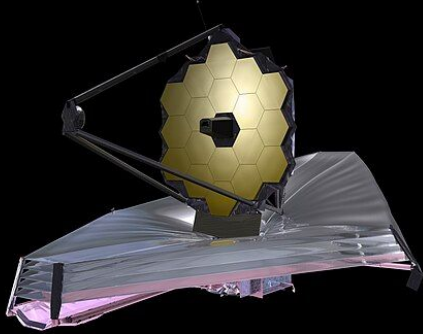
Phase light curve of **WASP-121 b** (JWST/NIRSpec)



Transit light curve of **WASP-121 b** (JWST/NIRSpec)



Motivation - Atmospheric Retrievals



Low-resolution ($R \lesssim 1,000$)

- Space-based – JWST, HST
- Broad spectral coverage (continuum), dominant species, no telluric contamination
- Limitations:
 - No line resolution $\rightarrow$ species degeneracies
 - Limited sensitivity to dynamics



High-resolution ($R \gtrsim 50,000$)

- Ground-based – ESPRESSO, HARPS, UVES, etc.
- Resolves spectral lines and their shapes
 - $\rightarrow$ Doppler shifts, dynamics
- Sensitive to many species
- Limitations:
 - Telluric contamination
 - No continuum information

Combining High- and Low-Resolution

- **High-** and **Low-resolution** spectroscopy have both provided spectacular new discoveries in exoplanet atmospheres in recent years
 - Probe **different parts** of the atmosphere, sensitive to different physics
- The aim of my PhD project is **to create a framework to simultaneously analyze** JWST and ground-based high-resolution spectroscopy
 - Aiming to get **better constraints on atmospheric parameters**
- **Atmospheric retrievals** - a Bayesian framework that infers atmospheric composition and temperature structure by comparing forward models to observed spectra

WASP-121b

- Primary target for its ideal parameters and broad data availability
- Ultra-hot Jupiter orbiting a main sequence star (F6V)
- Planetary mass¹: **$1.157 \pm 0.070 M_J$**
- Mean radius: **$1.753 \pm 0.036 R_J$**
- Orbital period: **$1.27492504(15) \text{ d}$**
- Inclination: **$88.49^\circ \pm 0.16^\circ$**

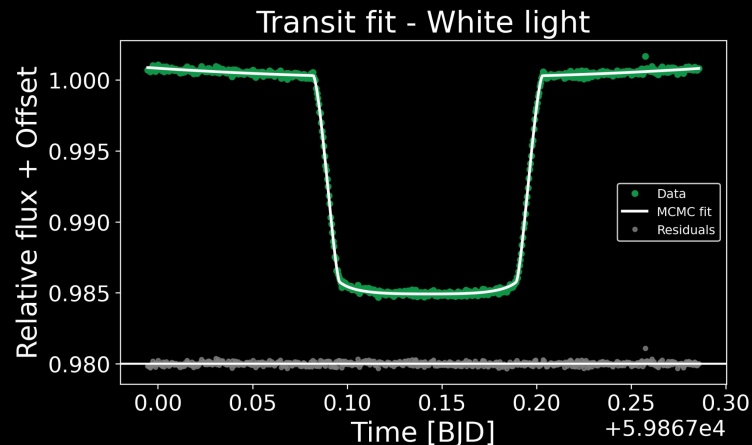
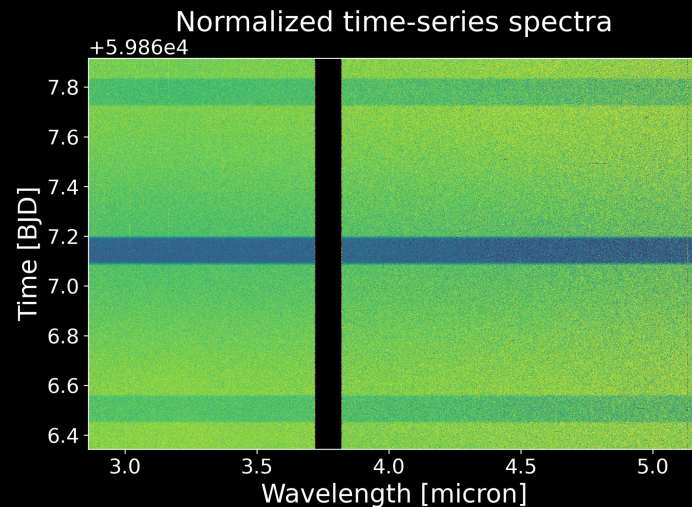
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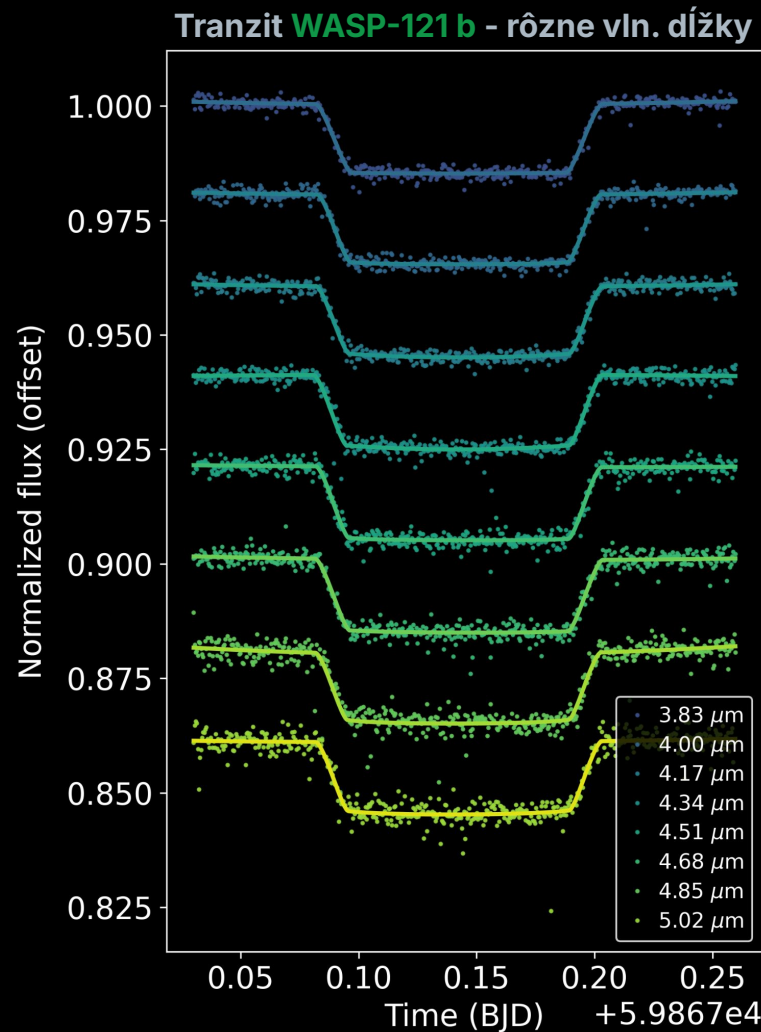
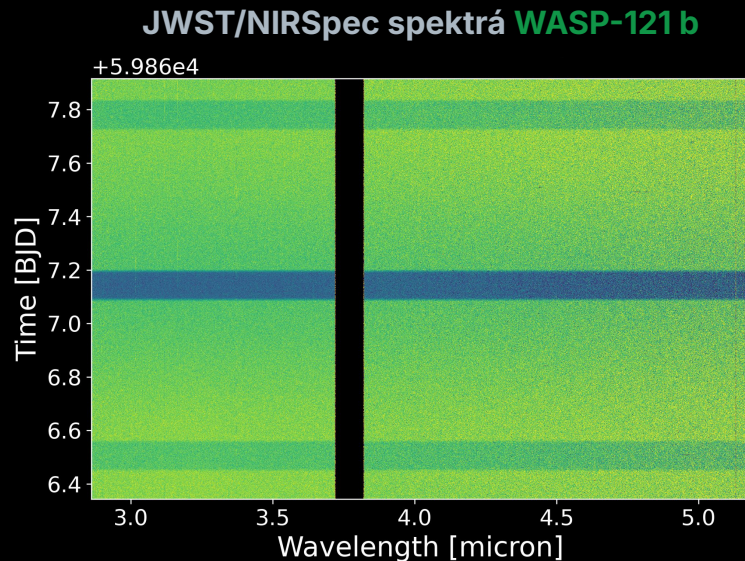
Low-resolution Spectroscopy

Low-resolution Spectroscopy

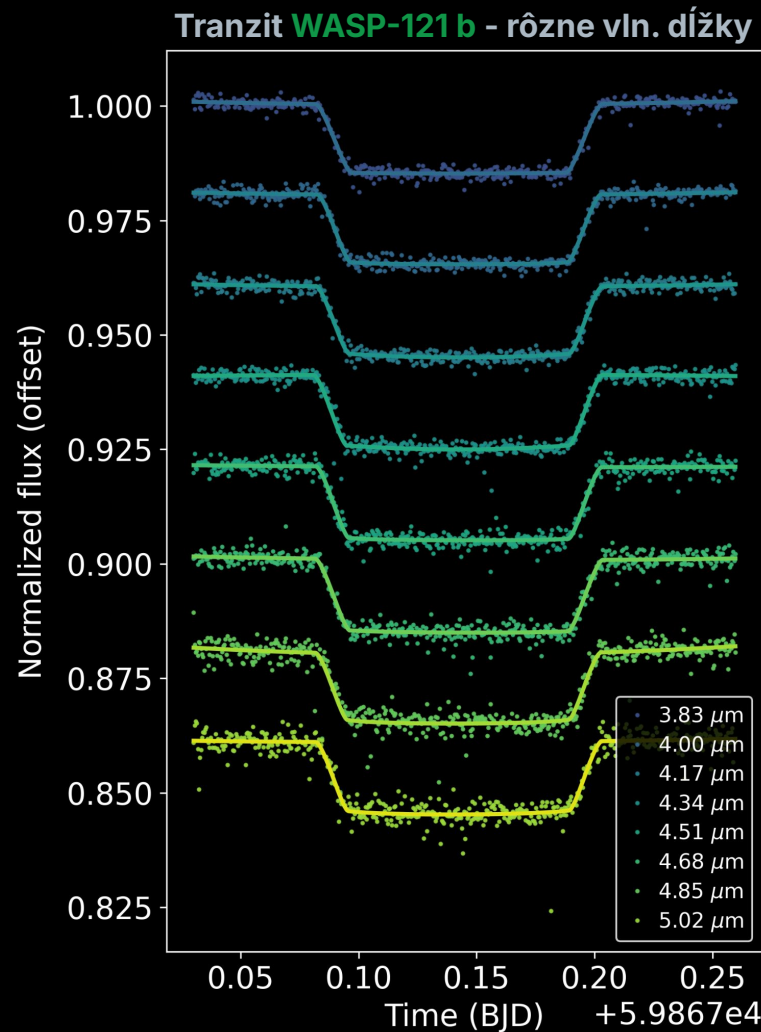
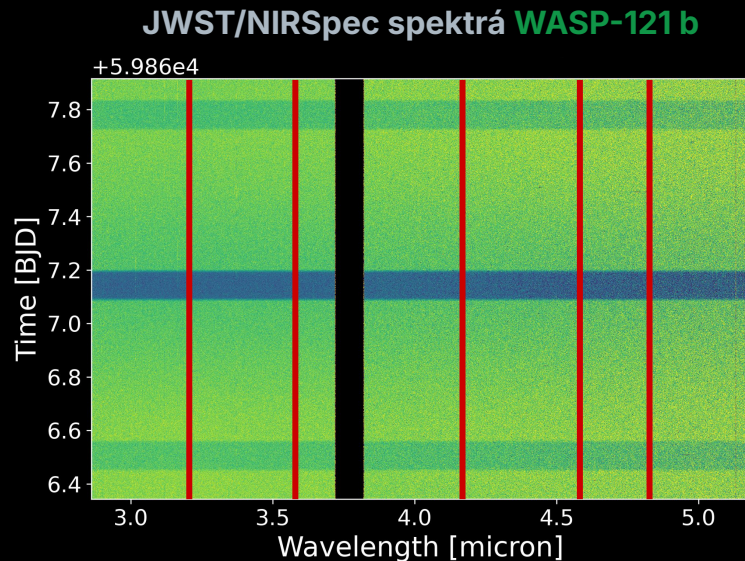
- **Time series spectra** of WASP-121b observed with JWST/NIRSpec (wavelength range 2.54-5.15 μm)
- Data are split between NRS1 & NRS2 detectors (combined analysis from both detectors)
- Time series normalized and divided into wavelength bins to generate spectroscopic light curves
 - **Binning over 10 pixels** $\rightarrow$ resolution of **$R \sim 600$** (with JWST data possible to get even higher resolution)
- Transit fitting first for the **white light curve**
 - **MCMC** fitting for 10 parameters (T_0 , a/R_S , R_P/R_S , b , f_{out} , 2 limb darkening coefficients, 2 baseline trend params., and noise parameter)
 - Results used as an initial guess for the spectroscopic fitting



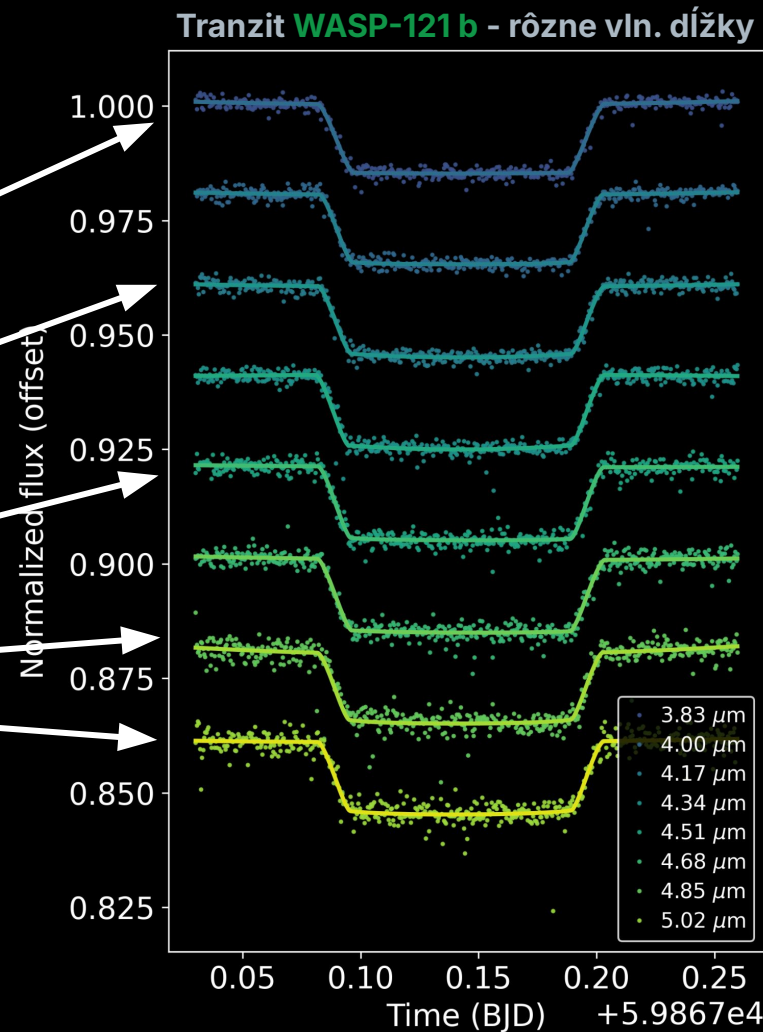
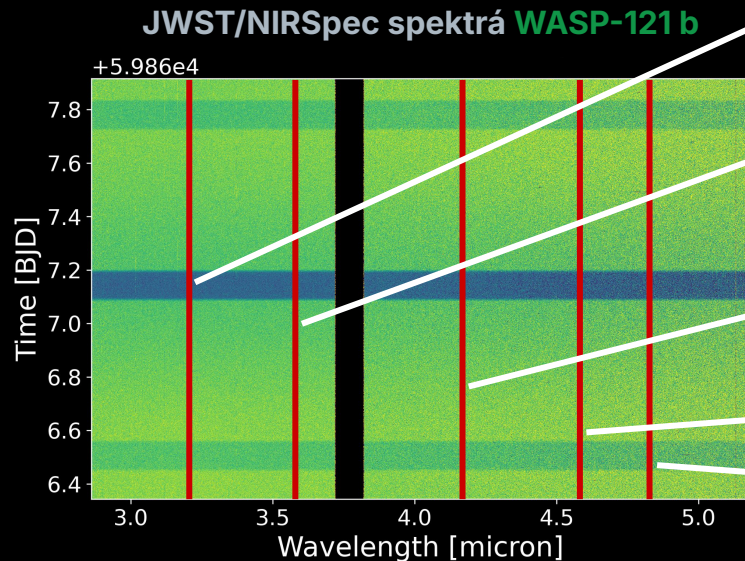
Transmission Spectroscopy



Transmission Spectroscopy



Transmission Spectroscopy

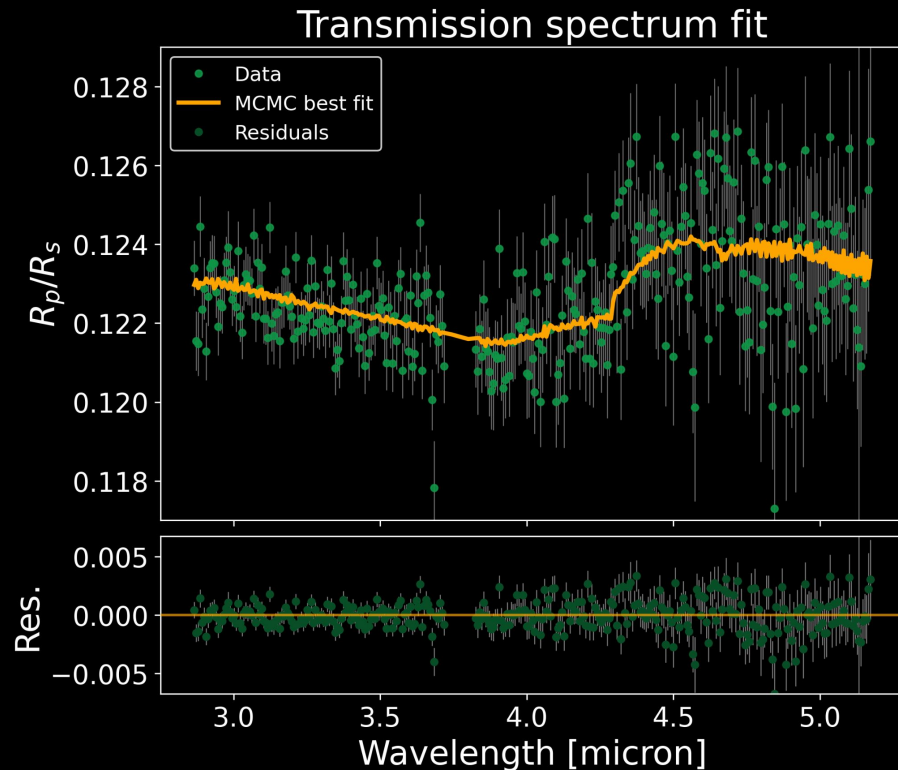


Low-resolution Spectroscopy

- Spectroscopic fitting - MCMC fit for 7 parameters (T_0 , a/R_s , and b additionally fixed based on the white light fit)
- Resulting posterior distribution gave us R_p/R_s for the transmission spectrum

Transmission spectrum fit

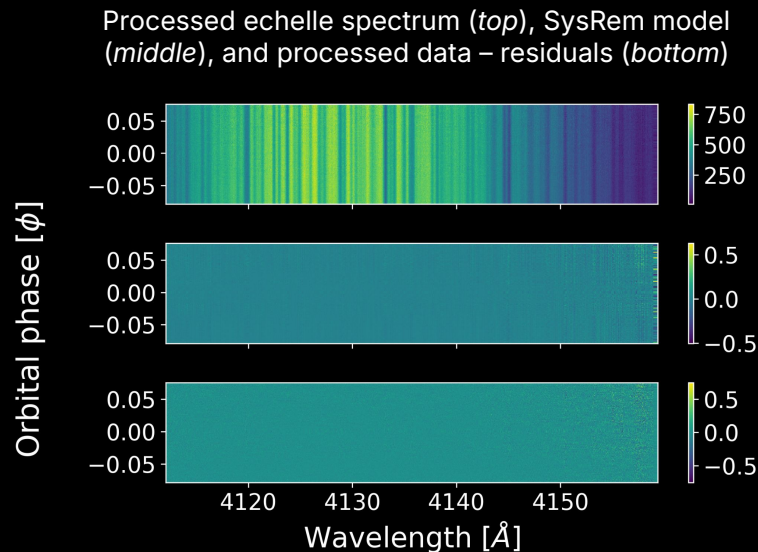
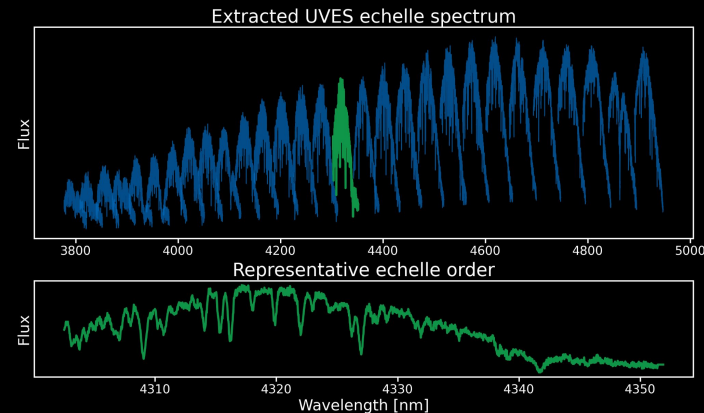
- Atmospheric model for T/P profile and cross-sections with *irradiator* package
 - resolution $R = 200,000$
 - pressure grid with 80 layers (log scale with pressures from 10^2 to 10^{-12} bar)
 - Model binned to actual data resolution
- MCMC fitting in Metropolis–Hastings mode for 8 parameters (3 for T/P profile, P_0 , P_{Cloud} , H_2O , CO & SiO opacities)



High-resolution Spectroscopy

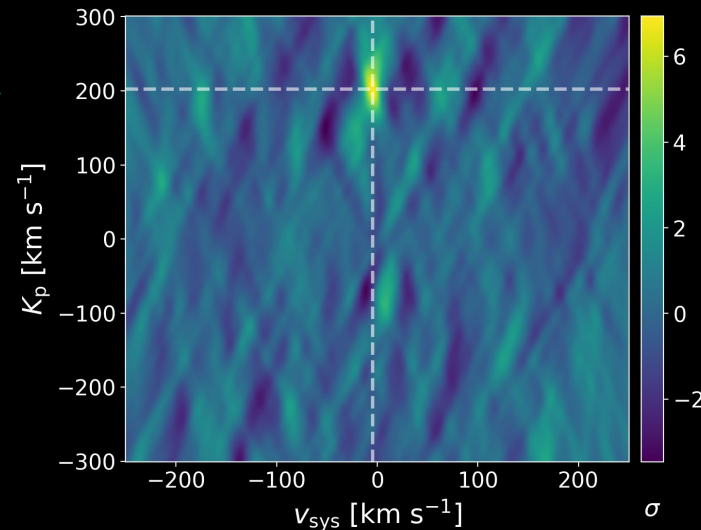
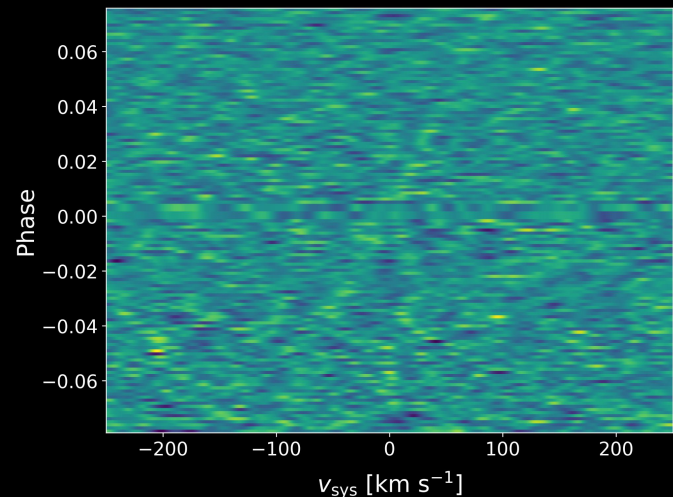
High-resolution Spectroscopy

- High-res **echelle spectra** of WASP-121b from VLT/UVES transit observation (pre-processed)
- Analyzed blue arm with $R \sim 80,000$ and wavelengths from ≈ 3750 to $4990 \text{ \AA}$ over 31 orders
- Removed stellar/telluric spectrum with the **SysRem** alg. (dividing first by the median spectrum, same for uncertainties)
- The **same atmospheric model** as for the low-resolution
 - Model filtering applying the same processing as for the data
 - Model template is Doppler-shifted according to planet's orbital motion and **cross-correlated** with the (residual) data
- Performing retrieval using **MCMC fitting** for 11 parameters (adding 5 param. for cross-correlation model to previously used atmospheric param. and **Fe** opacity)



High-resolution Spectroscopy

- From retrieval – **model template** constructed using the maximum posterior (best-fit) parameters
- Template **cross-correlated** over range of systemic velocities followed by summation over every order
→ **Cross-correlation map**
- Summation over the expected velocity of planet to produce a **K_p - v_{sys} map** (localises signal in velocity space)
 - **K_p** – semi-amplitude of the planet's orbital radial velocity
 - **v_{sys}** – systemic velocity of the star-planet system
- Normalization of the map with standard deviation to get a significance of the detection
- Detection of neutral iron **Fe I** with the significance **7.1σ** and peak location at **$v_{\text{sys}} \approx -4.5 \text{ km}\cdot\text{s}^{-1}$** and **$K_p \approx 204 \text{ km}\cdot\text{s}^{-1}$**

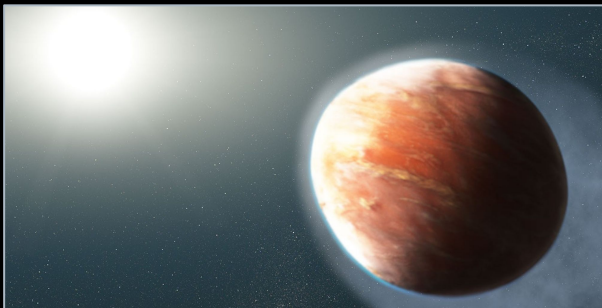


Joint Retrievals of WASP-121b

Joint Retrievals - Initial Results

- Based on the same high-resolution **atmospheric model** and a same chemical composition → joint parameter vector
- Each dataset has its own wavelength grid
- **Joint posterior** created as a combination of two separate likelihoods:

$$\ln \mathcal{L}_{\text{joint}} = \ln \mathcal{L}_{\text{LRS}} + \ln \mathcal{L}_{\text{HRS}}$$



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Performed retrievals

- Forward model is generated with resolution $\lambda/\Delta\lambda$
R = 100,000
- **Free chemistry** retrievals using **MCMC** framework
- Fitting for **13 free parameters** (4 for CC-model, 3 for T/P profile, P0, Pcloud, and **H2O**, **CO**, **SiO** & **Fe** opacities)

Current status

- Functioning framework - analysis of the posteriors
- Comparing the results for possible refinement of the framework

Next steps

- Utilizing more observations of WASP-121b
- More targets - well-observed transiting UHJs

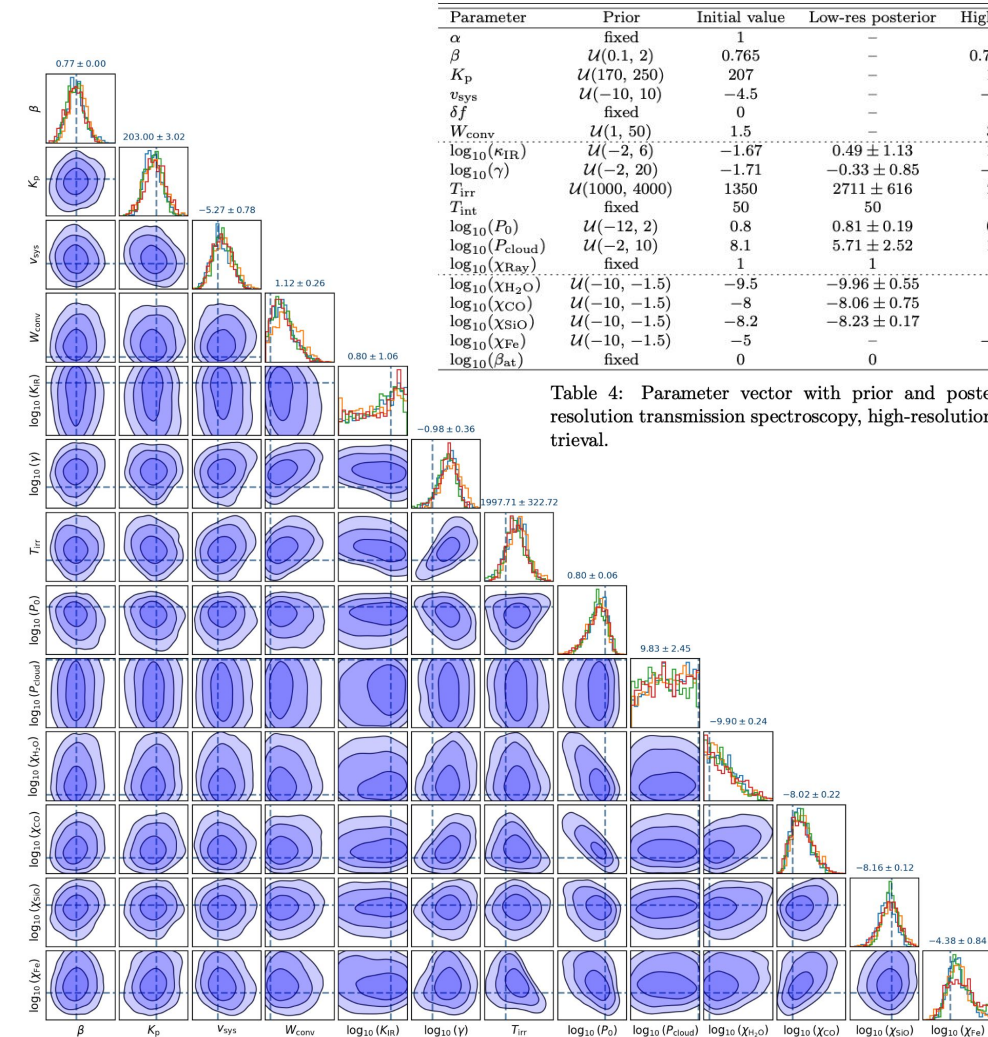
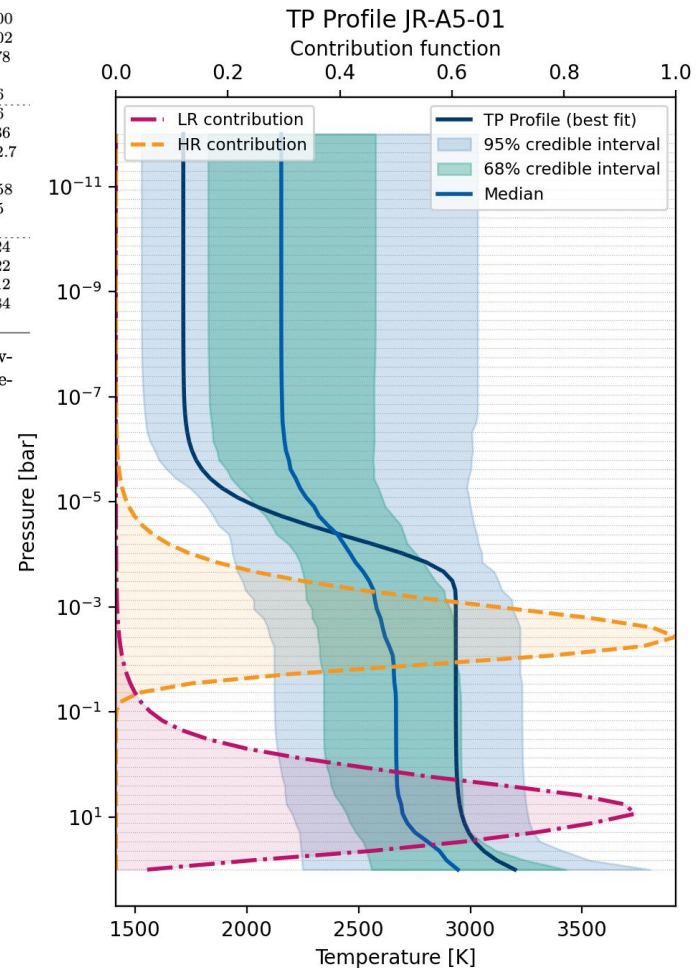


Table 4: Parameter vector with prior and posterior distributions for low-resolution transmission spectroscopy, high-resolution spectroscopy, and joint retrieval.



References

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Gapp, C., et al. (2025): WASP-121 b's Transmission Spectrum Observed with JWST/NIRSpec G395H Reveals Thermal Dissociation and SiO in the Atmosphere. AJ, 169, 341 [doi:10.3847/1538-3881/ad9c6e](https://doi.org/10.3847/1538-3881/ad9c6e)



The research conducted in this presentation was funded by Taighde Éireann - Research Ireland under grant number GOIPG/2024/5155.

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