



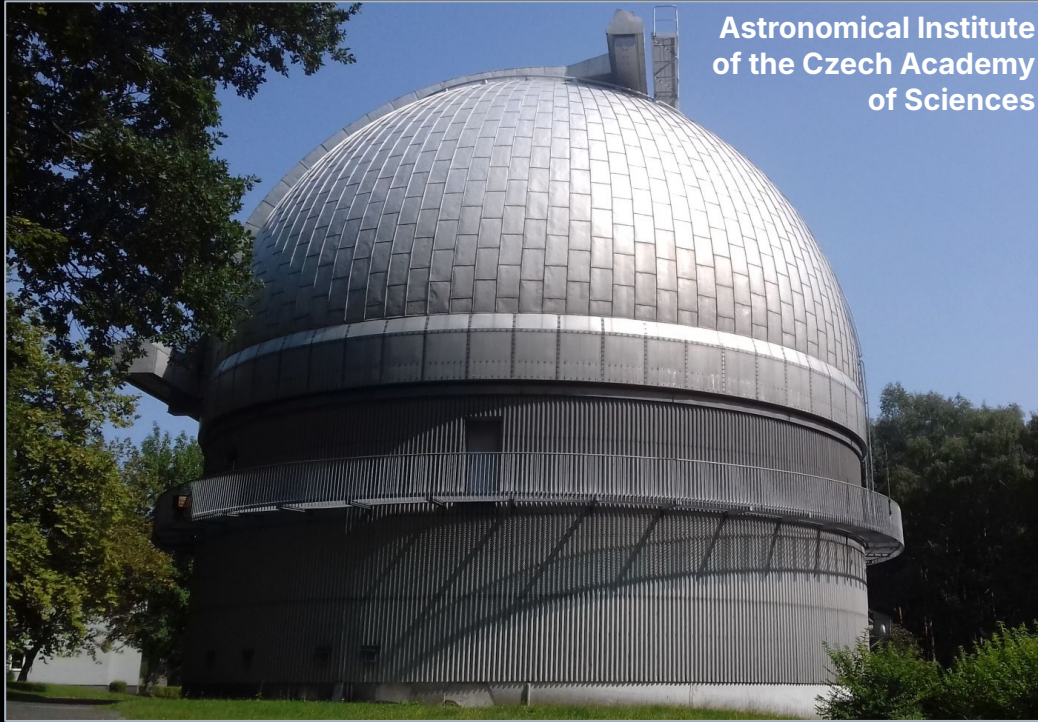
Trinity College Dublin
Coláiste na Tríonóide, Baile Átha Cliath
The University of Dublin



Exoplanet Group Meeting

Daniel Dupkala

Undergrad Research - RV Measurements



Astronomical Institute
of the Czech Academy
of Sciences

Ondřejov Observatory

2-meter Perek Telescope

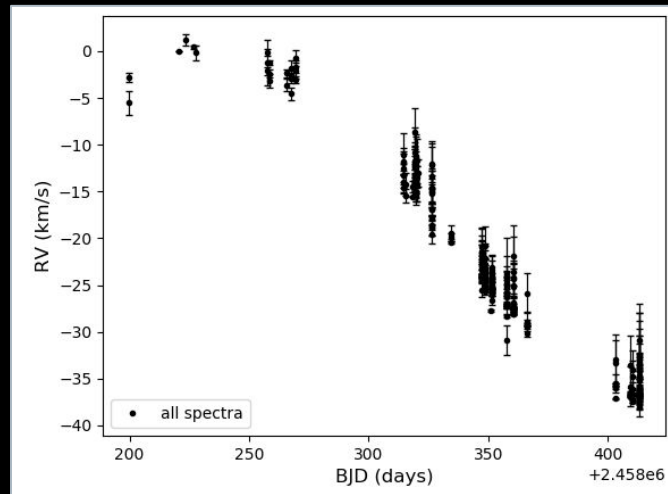
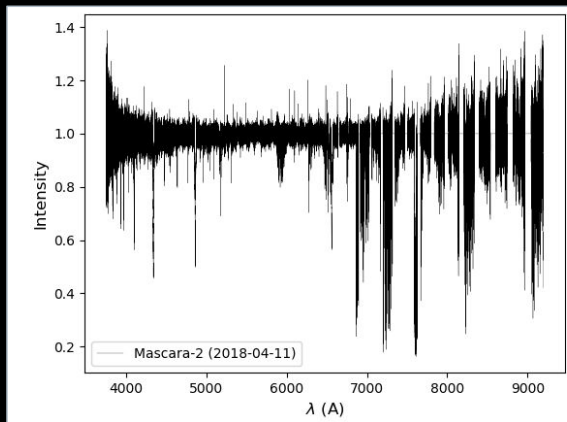


Ondřejov
Echelle
Spectrograph
(OES)



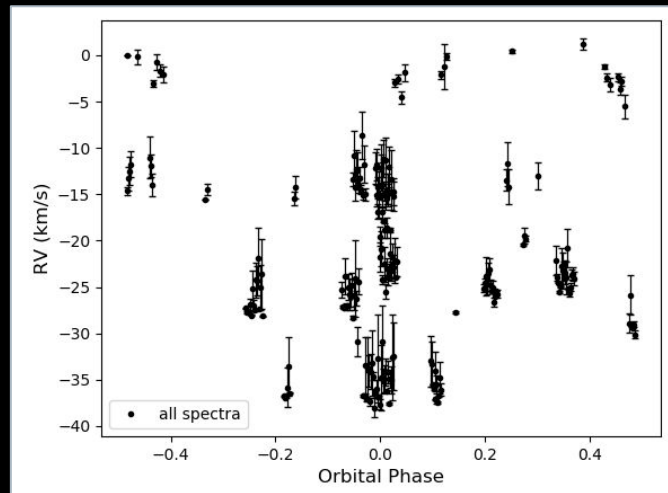
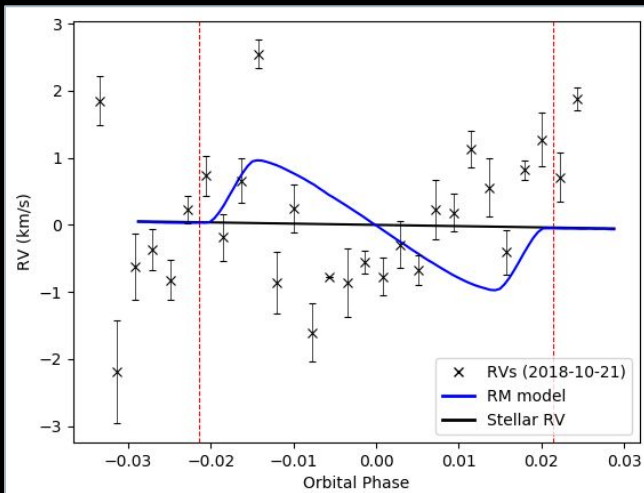
MASCARA-2b

MASCARA-2
2018-04-11
exp. 1800 sec



Change of
RVs in time

Transit night
2018-10-21
exp. 900 sec



Phase
diagram

PhD Research - Atmospheres of Exoplanets

Atmospheric Retrievals of Hot Jupiters

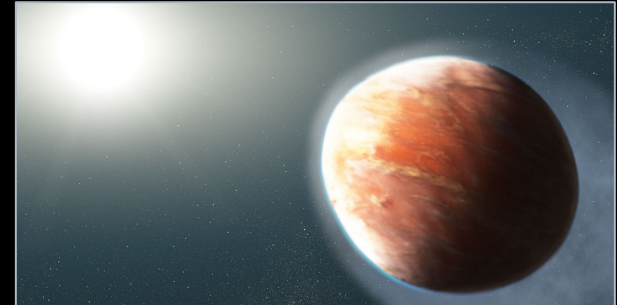
- Hot and ultra-hot Jupiters provide large possibilities for the study of exoplanetary atmospheres
- Spectroscopic methods are one of the key methods of research
- When transiting, exoplanet atmosphere can be probed via **transmission spectroscopy**
- Based on the resolution of spectra we distinguish high-resolution and low-resolution spectroscopy

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
- 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: **$88.49^\circ \pm 0.16^\circ$**
- Stellar type: **F6V (main sq.)**
- Distance to Earth: **858 ly**



High-resolution Spectroscopy

High-resolution Spectroscopy

- Resolution $\geq 50,000$
- Ground-based facilities (e.g. ESPRESSO or CRIRES+ on ESO VLT or HARPS on La Silla)

Pros:

- Ability to resolve individual lines and their Doppler shifts
- Sensitive to line shapes
- Large number of detectable species²
- Useful for study of atmospheric composition and dynamics, i.e. winds or jet streams³
- Probes higher in the atmosphere

Cons:

- Telluric lines / Earth atmosphere's contamination
- Limited information on continuum
- Exoplanet spectrum cannot be directly inspected

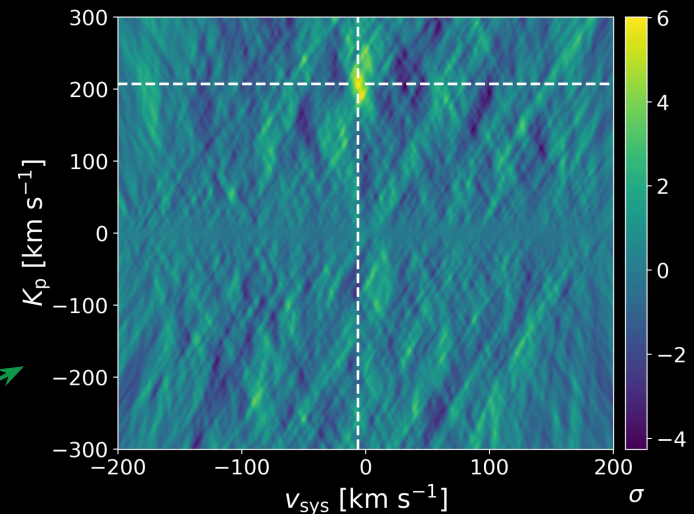
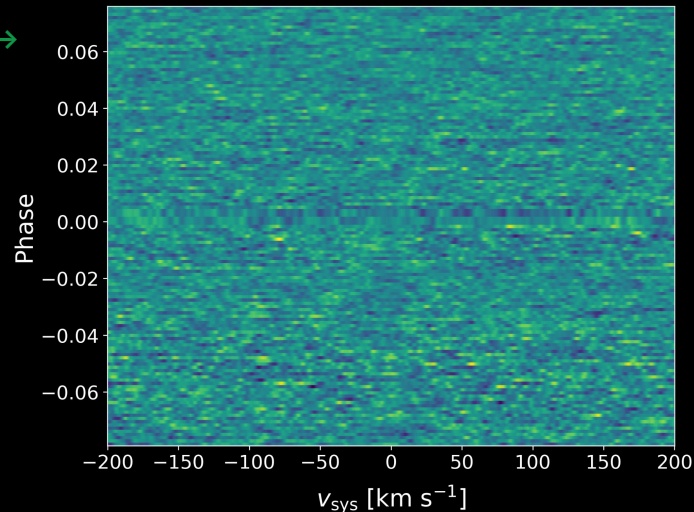
Used Dataset

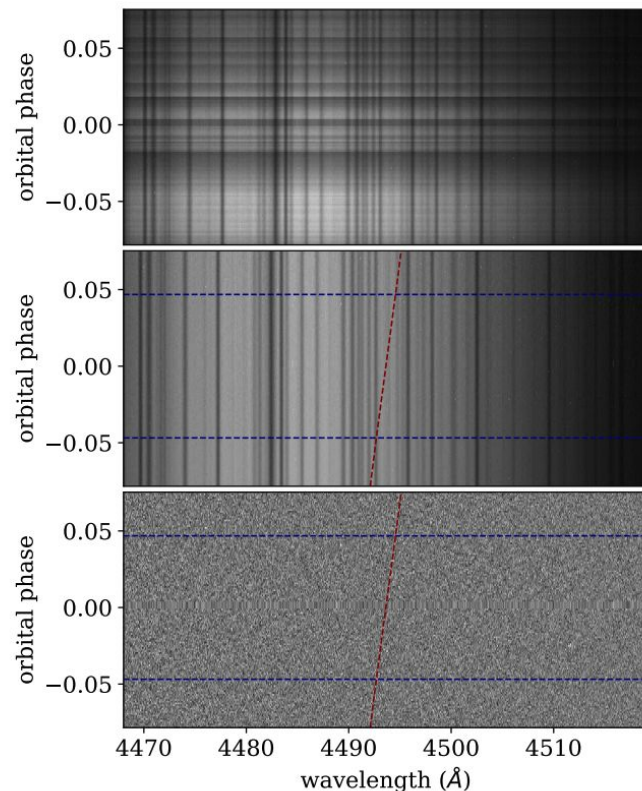
- High-res echelle spectra of WASP-121 from VLT/UVES
- Transit observation (2016 December 25)
- Analyzed blue arm with $R \sim 80,000$ and wavelengths from ≈ 3750 to $4990 \text{ \AA}$ over 31 orders
- Spectra are given as a "3D datacube", where for each **order** it contains information about **wavelength** x **phase** x **intensity**

High-resolution Spectroscopy

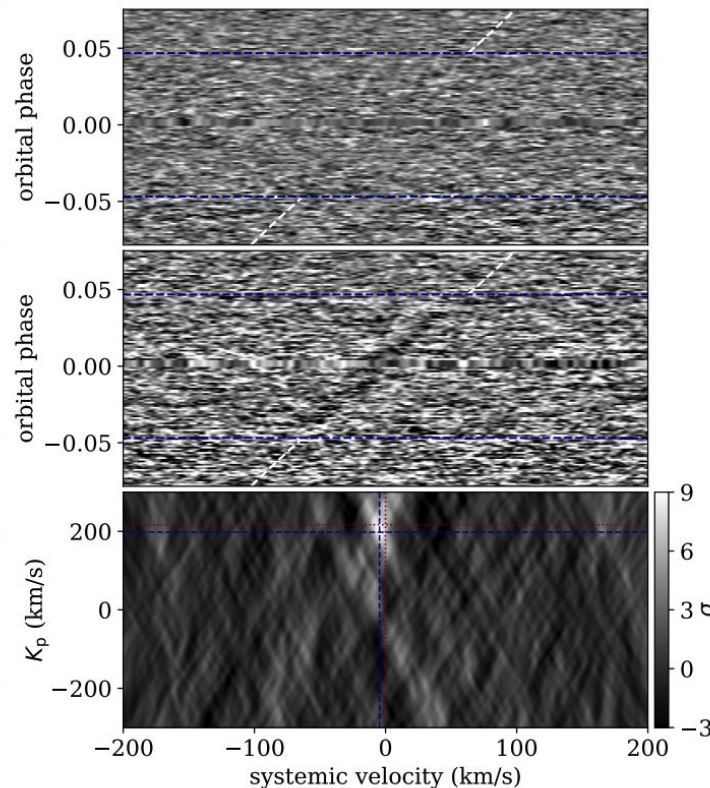
- Pre-processing the data (cleaning the outliers, blaze correction, alignment of the spectra)
- Remove stellar/telluric spectrum with the **SysRem** alg. (dividing first by the median spectrum, same for uncertainties)
- Applying the **cross-correlation** with model template to each order – transmission model created with *irradiator* python package (N. Gibson)
- Summation over the velocity of planet to produce a $K_p - v_{\text{sys}}$ map for each order
 - K_p – semi-amplitude of the planet's orbital radial velocity
 - v_{sys} – systemic velocity of the star-planet system
- Summation of the $K_p - v_{\text{sys}}$ map over every order
- Normalization of the map with standard deviation to get a significance of the detection

CCF sum. map →



Data-processing
of a single order

Left: Data-processing of a single raw order (top), after wavelength-shift and blaze-correction (middle), and after division through by the SysRem model (shown weighted by the uncertainties, bottom).



Right: Cross-correlation of a single order with a model template (top), summed cross-correlation of the bluest 13 orders (middle), and velocity-summed cross correlation map (bottom) as a function of planet orbital velocity (K_p)

Low-resolution Spectroscopy

Low-resolution Spectroscopy

- Resolution usually $\lesssim 1,000$
- Space based observation (e.g. JWST, HST)

Pros:

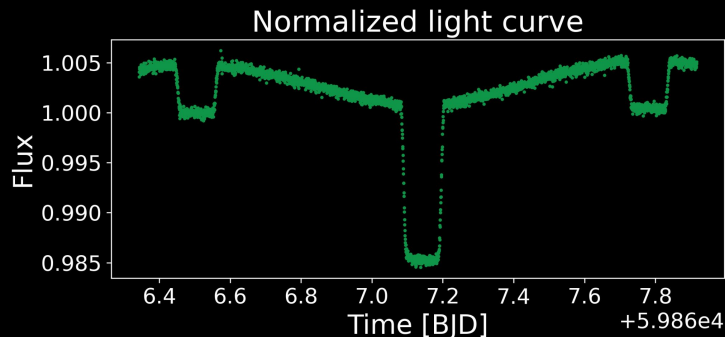
- Broad spectral coverage (study of the continuum)
- Detection of the most dominant species⁴
- No telluric lines contamination from space, better sensitive for small planets
- Useful for T/P profile and climate study³

Cons:

- Individual lines are not resolved: subject to confusion of atmospheric species
- Not sensitive to line shapes or positions
- Less sensitive in the optical part of the spectrum

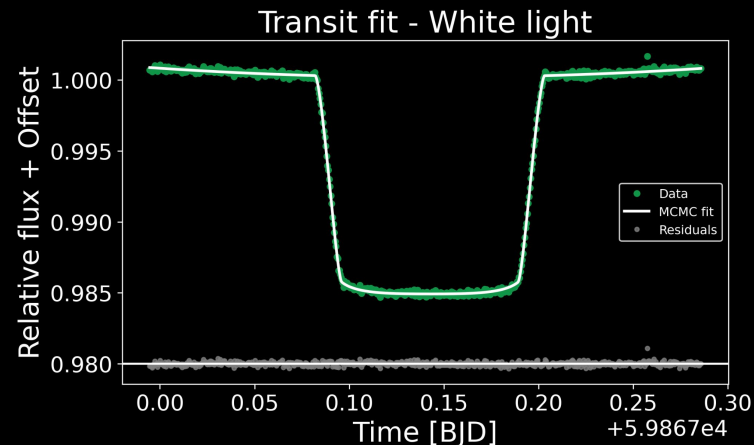
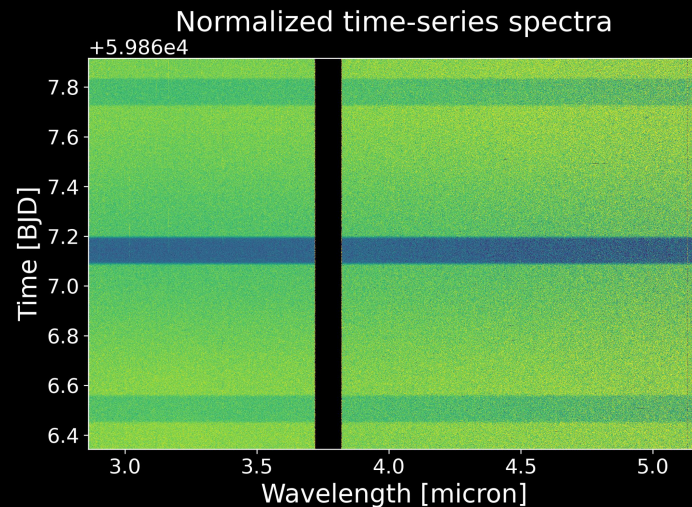
Used Dataset

- Time series spectra for a phase curve of WASP-121b observed with JWST/NIRSpec (37.8 hours long - 1 transit & 2 eclipses)
- Data are split into two channels as there are two detectors – NRS1 and NRS2
- Resulting wavelength coverage is between 2.54 and 5.15 μm (with a gap ranging from 3.72 to 3.82 μm)



Low-resolution Spectroscopy

- Transit-only analysis⁴
- Both detectors analyzed combined
- Time series normalized and divided into wavelength bins to generate spectroscopic light curves
 - **Binning over 10 pixels** → 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

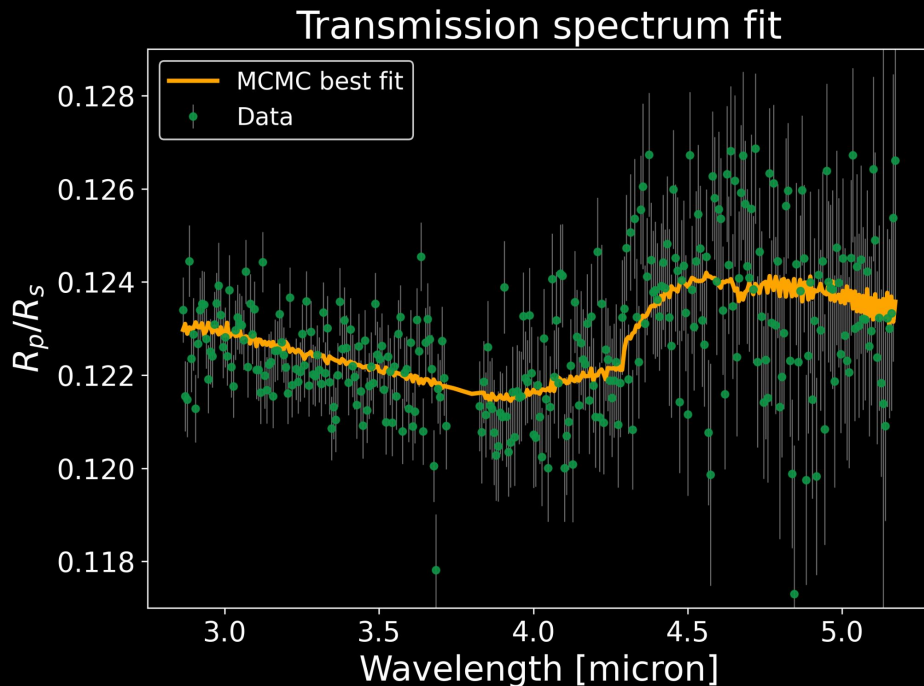


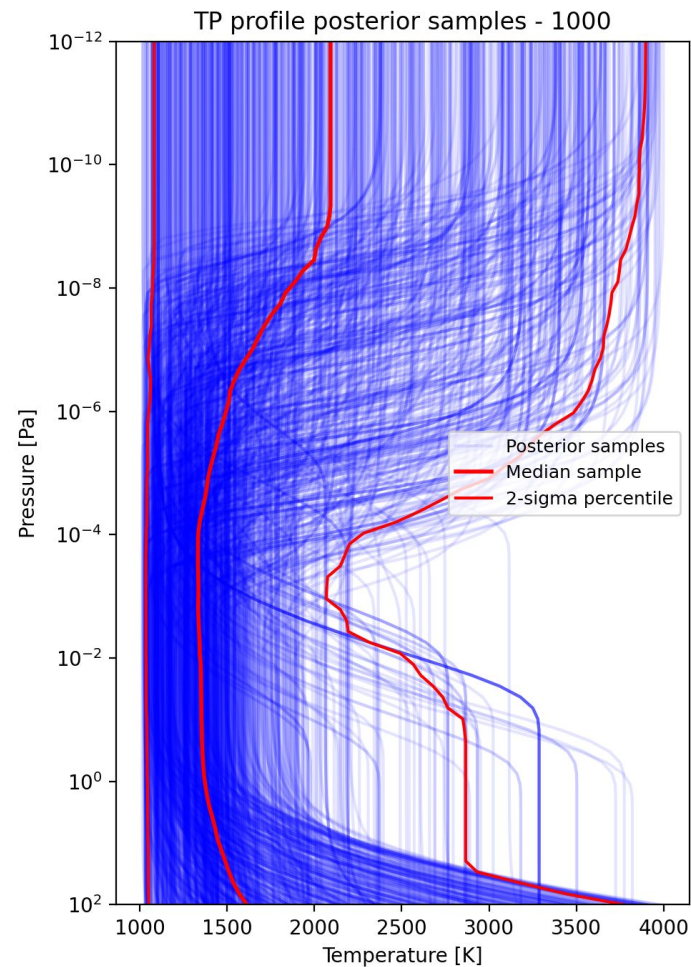
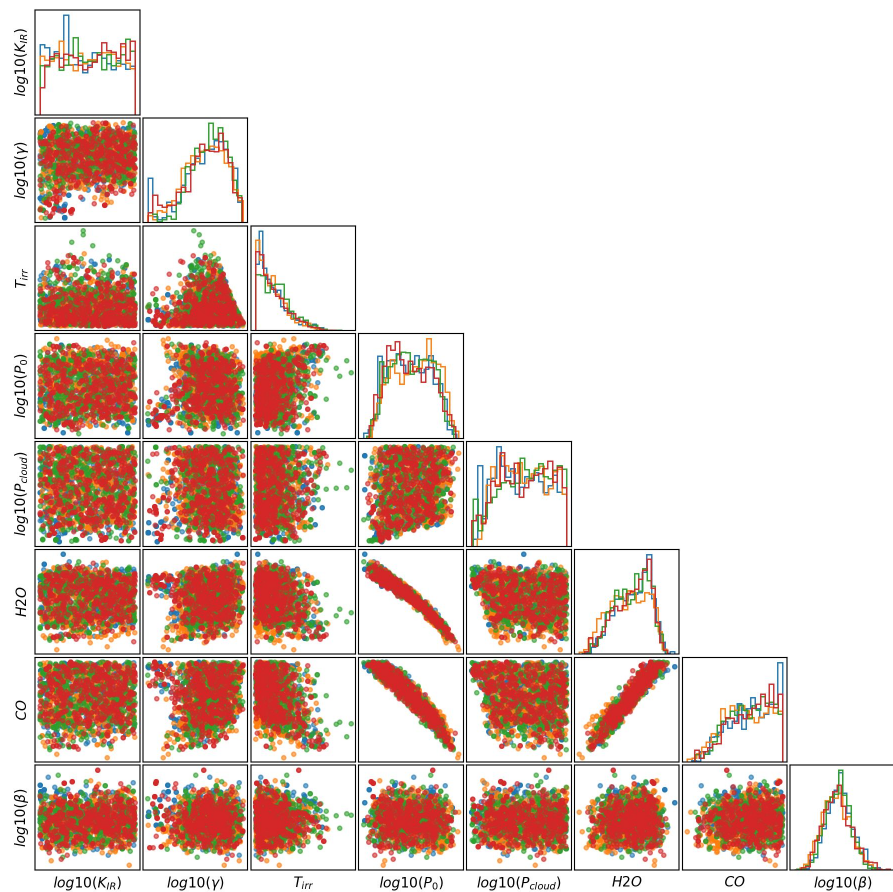
Low-resolution Spectroscopy

- Spectroscopic fitting - MCMC fit for 7 parameters (T_0 , a/R_s , and b additionally fixed based on the white light fit)
→ R_p/R_s for 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 opacities, and noise parameter)





Conclusion

Combining High- and Low-Resolution

- High- and low-resolution spectroscopy have both provided spectacular new discoveries in exoplanet atmospheres in recent years
- However, they both probe different parts of the atmosphere and are sensitive to different physics
- Recent advances in performing high-resolution retrievals have opened up the possibility **to simultaneously retrieve parameters** from both types of data
 - Possible to probe hot Jupiters in more detail
- The aim of my PhD project is **to create a framework to simultaneously analyze** JWST and ground-based high-resolution spectroscopy
 - The overall aim is to provide **better constraints on atmospheric parameters**

Next steps

- High-resolution retrievals from VLT/UVES data (model based on the low-res retrievals)
- Incorporate model filtering (Doppler package - N. Gibson)
- Joint retrievals for two sets of data

© P. Klein and MPIA



References

- ¹ Bourrier V., Ehrenreich D., et al. (2020): Hot Exoplanet Atmospheres Resolved with Transit Spectroscopy (HEARTS). III. Atmospheric structure of the misaligned ultra-hot Jupiter WASP-121b. A&A, 635, A205. doi:[10.1051/0004-6361/201936640](https://doi.org/10.1051/0004-6361/201936640)
- ² Gibson, N.P., et al. (2020): Detection of Fe I in the atmosphere of the ultra-hot Jupiter WASP-121b, and a new likelihood-based approach for Doppler-resolved spectroscopy. MNRAS, 493, 2215 <https://doi.org/10.1093/mnras/staa228>
- ³ Smith, P. C.B., et al. (2024), A Combined Ground-based and JWST Atmospheric Retrieval Analysis: Both IGRINS and NIRSpec Agree that the Atmosphere of WASP-77A b Is Metal-poor. AJ, 167, 110 doi:[10.3847/1538-3881/ad17bf](https://doi.org/10.3847/1538-3881/ad17bf)
- ⁴ 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.

danieldupkala.eu

daniel.dupkala@gmail.com



Trinity College Dublin
Coláiste na Tríonóide, Baile Átha Cliath
The University of Dublin



Taighde Éireann
Research Ireland