



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

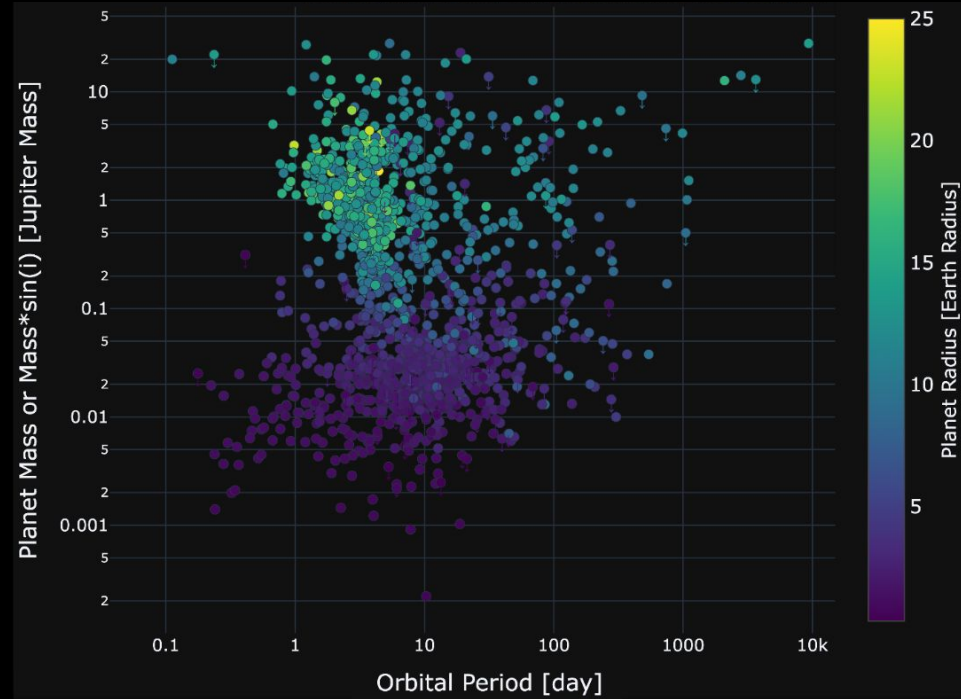
Daniel Dupkala

Motivation - Exoplanet Atmospheres

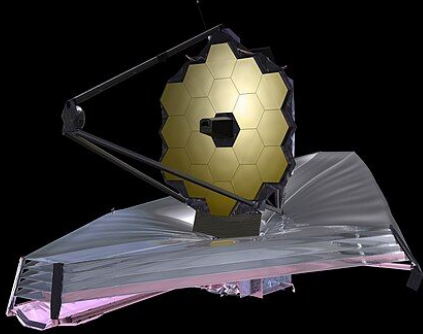
- We study **exoplanet atmospheres** by analysing how they absorb and modify starlight
- Hot and **ultra-hot Jupiters** provide large possibilities for the study of exoplanetary atmospheres
- When transiting, exoplanet atmosphere can be probed via **transmission spectroscopy**

Atmospheric retrievals

- A Bayesian framework that infers atmospheric composition and temperature structure by comparing forward models to observed spectra
- High- and Low-resolution retrievals



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
- Recent advances → a 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**

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: **$1.27492504(15) d$**
- Inclination: **$88.49^\circ \pm 0.16^\circ$**

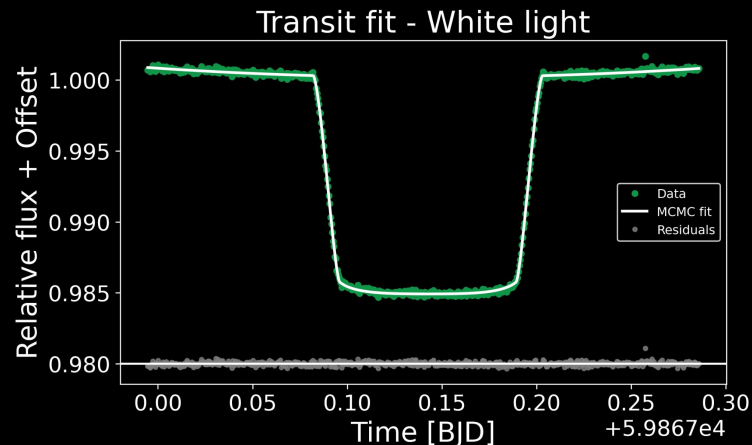
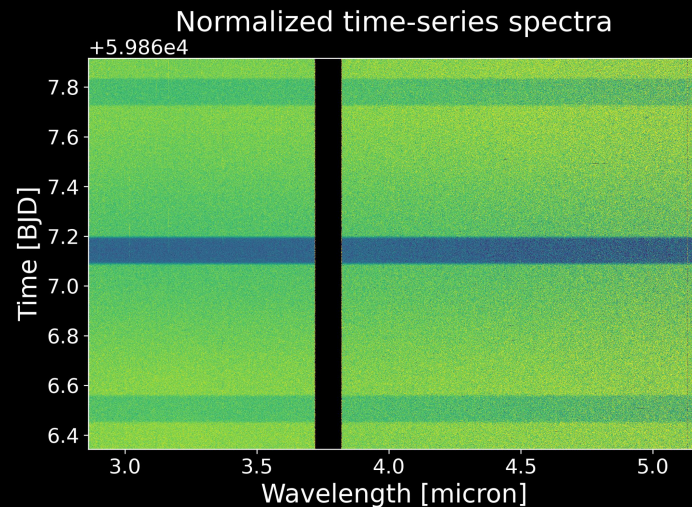
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Low-resolution Spectroscopy

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

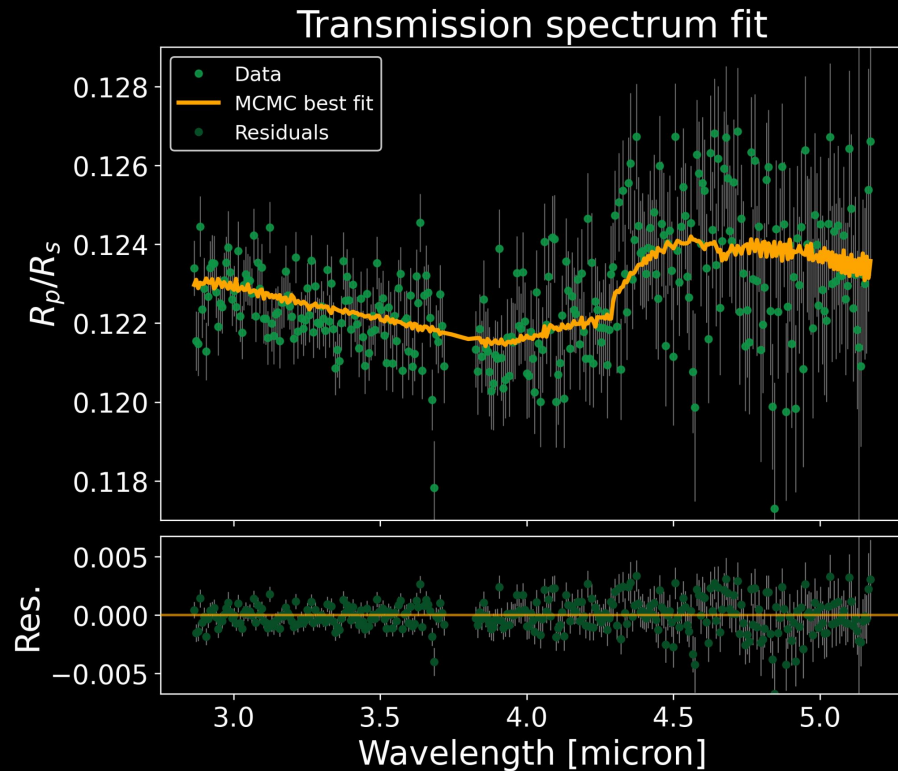


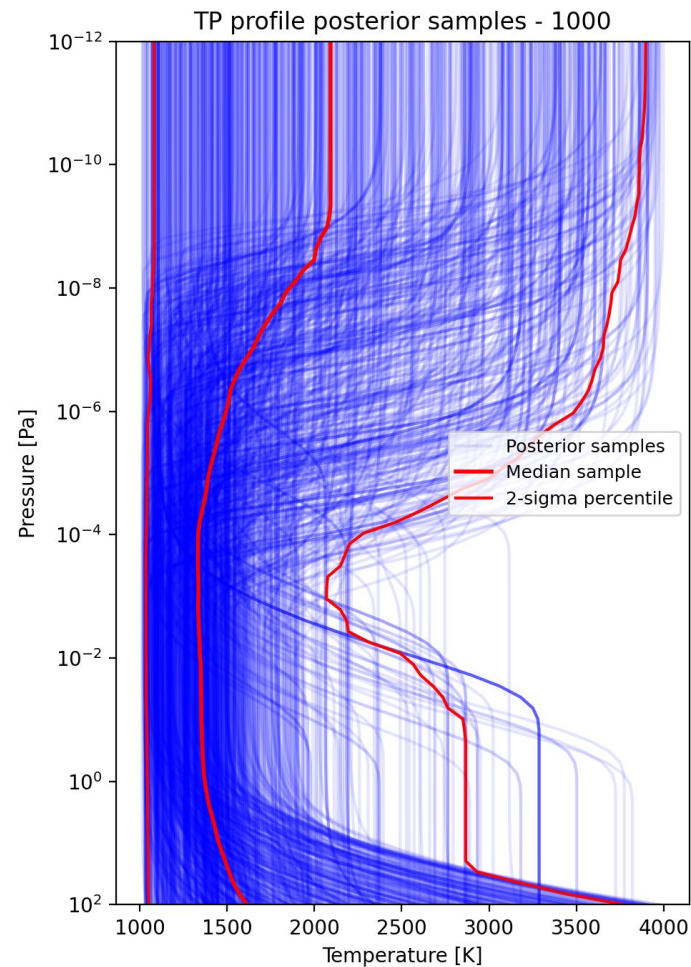
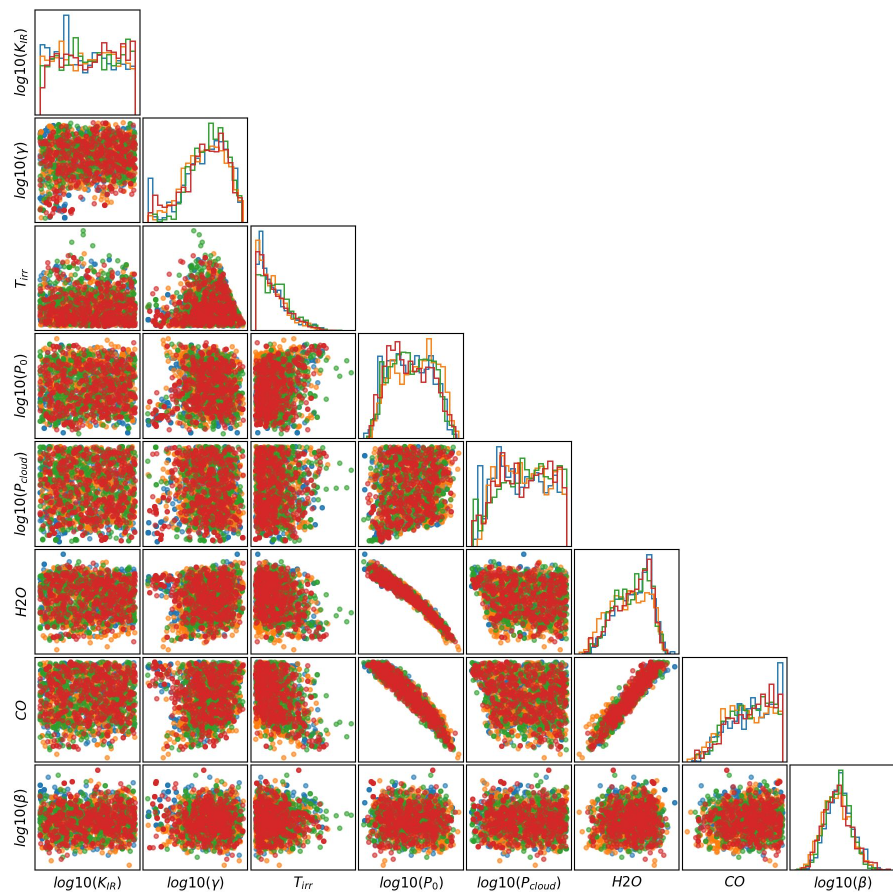
Low-resolution Spectroscopy

- 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 opacities, and noise parameter)

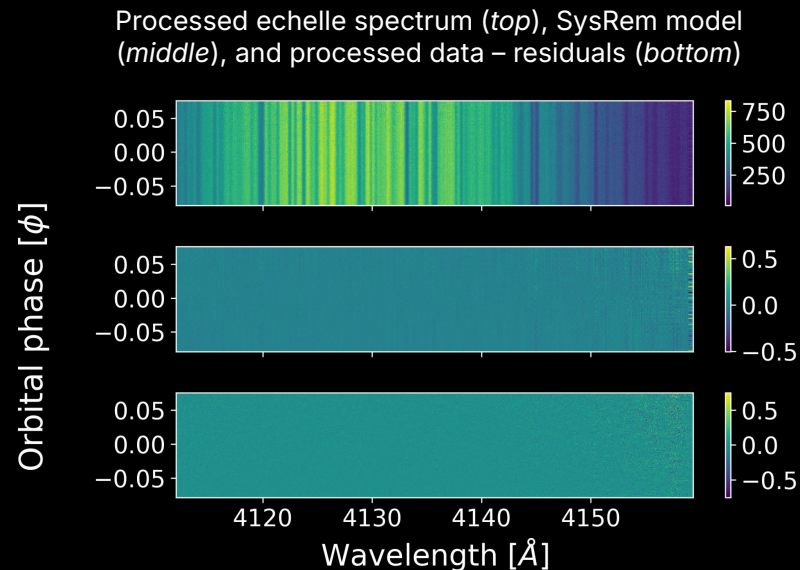




High-resolution Spectroscopy

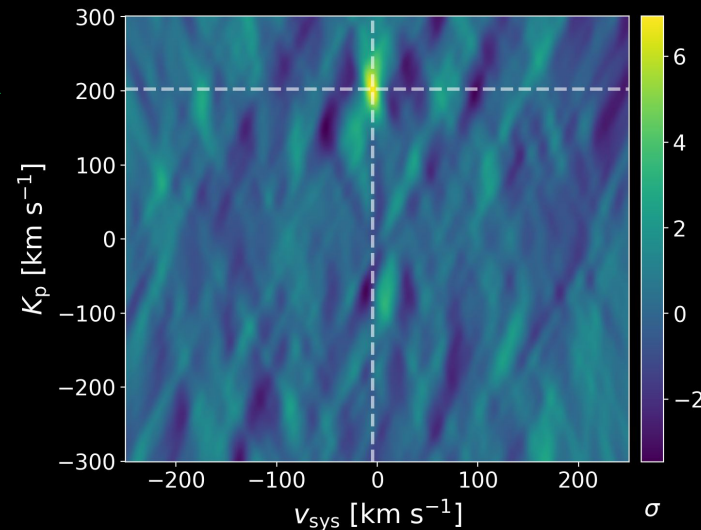
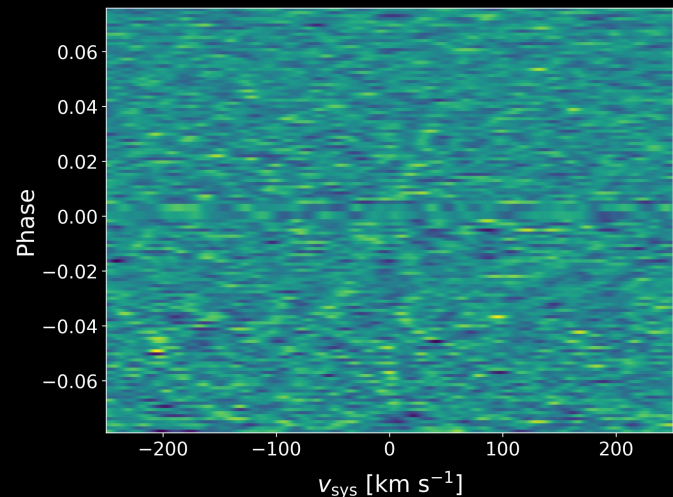
High-resolution Spectroscopy

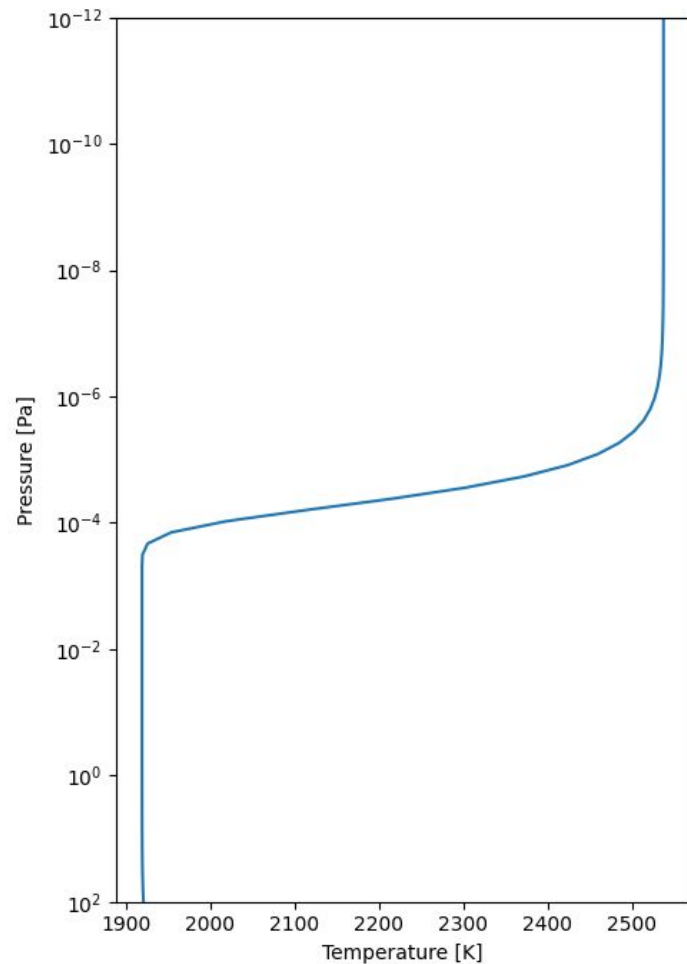
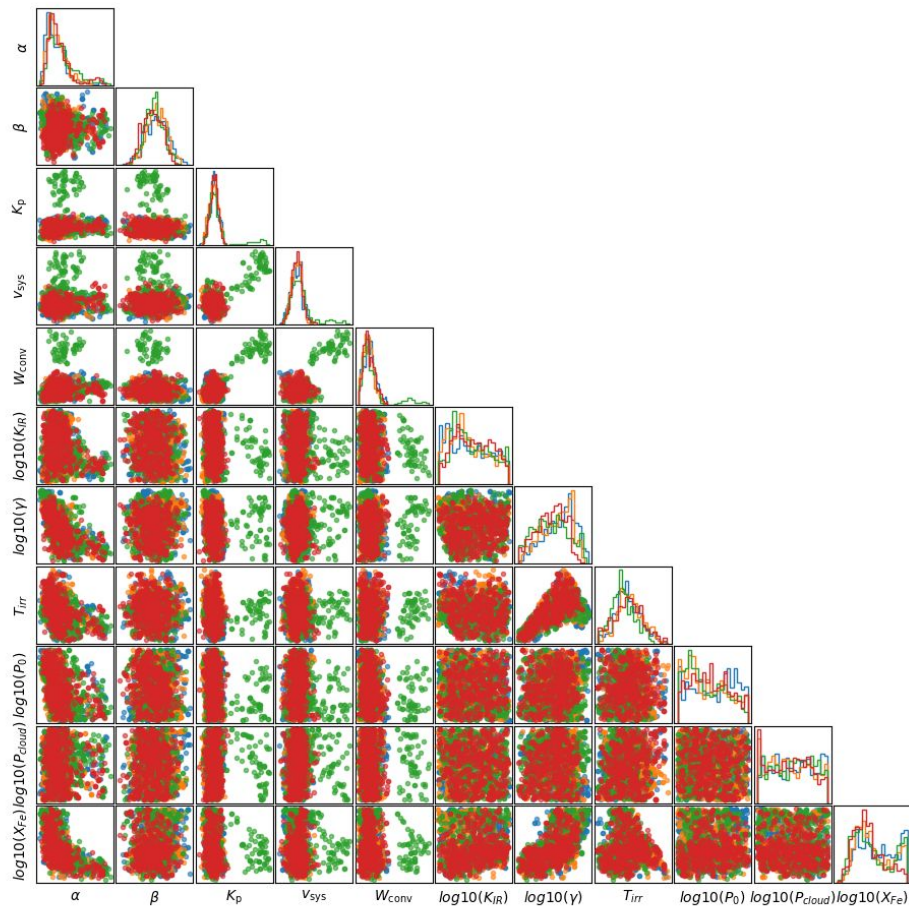
- High-res **echelle spectra** of WASP-121b from VLT/UVES transit observation (pre-processed)
- Analyzed blue arm with $R \sim 80,000$ and wavelengths from ≈ 3750 to $4990 \text{ \AA}$ over 31 orders
- Removed stellar/telluric spectrum with the **SysRem** alg. (dividing first by the median spectrum, 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 **$K_p \approx 204 \text{ km}\cdot\text{s}^{-1}$**



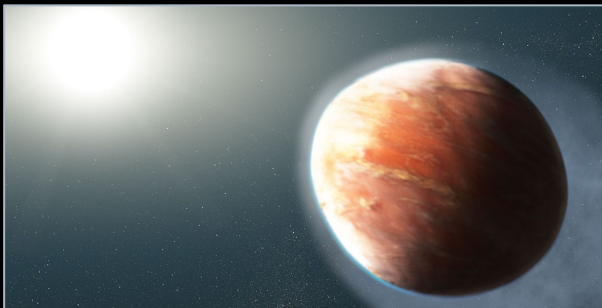


Outlook for the Future Work

Joint Retrievals - Forward Plan

- Based on the same high-resolution **atmospheric model** and a same chemical composition → joint parameter vector
- Initial retrievals for **neutral iron Fe I**
 - Various species in future – features detectable in both datasets
- Difference in wavelength grid
- **Joint posterior** created as a combination of two separate likelihoods

First joint retrievals performed!



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Following steps

- Optimization of the joint retrieval framework
- Testing and validation of results
- Publication of results for VLT/UVES and JWST/NIRSpec data of WASP-121b

Adding new datasets/targets

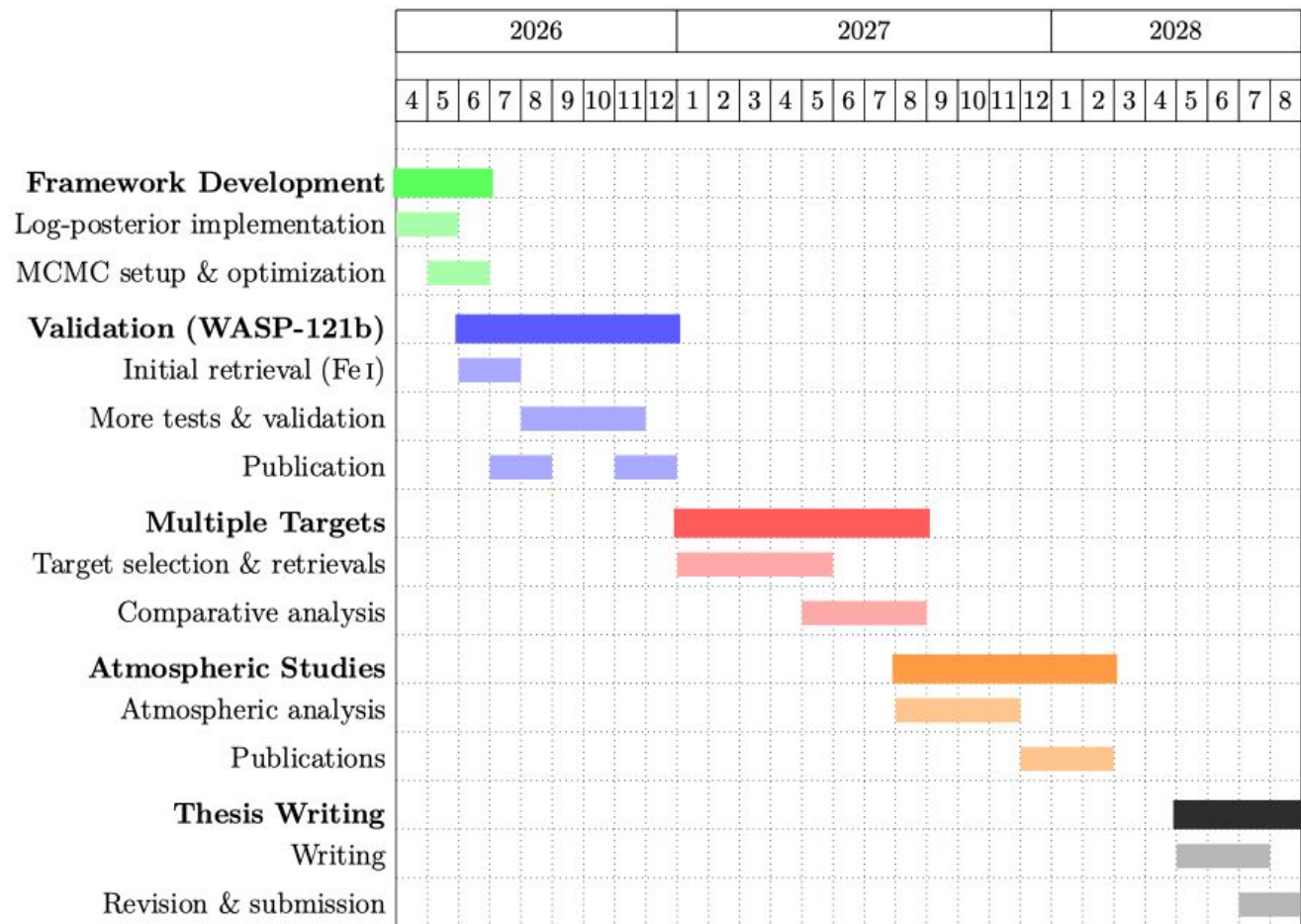
- Utilizing more observations of WASP-121b
- Identification of targets for joint retrievals
 - Well-observed transiting ultra-hot Jupiters
- Comparing the results for possible refinement of the framework

Broader atmospheric studies

- Using the joint retrieval framework for deeper studies of exoplanet atmospheres

Parameter	Prior	Low-res posterior	High-res posterior	Joint posterior
α	$\mathcal{U}(0.1, 6)$	—	0.92 ± 0.83	1.39 ± 0.39
β	$\mathcal{U}(0.1, 2)$	—	0.7899 ± 0.0002	0.7898 ± 0.0002
K_p	$\mathcal{U}(170, 250)$	—	204.2 ± 7.2	201.5 ± 3.3
v_{sys}	$\mathcal{U}(-10, 10)$	—	-4.54 ± 1.24	-5.35 ± 0.80
δf	fixed	—	0	0
W_{conv}	$\mathcal{U}(1, 50)$	—	1.47 ± 0.47	1.30 ± 0.30
$\log_{10}(\kappa_{\text{IR}})$	$\mathcal{U}(-2, 6)$	-1.95 ± 1.53	-0.40 ± 1.43	1.70 ± 1.38
$\log_{10}(\gamma)$	$\mathcal{U}(-2, 20)$	-1.50 ± 0.95	0.52 ± 0.74	-1.70 ± 0.70
T_{irr}	$\mathcal{U}(1200, 4000)$	1222 ± 254	2153 ± 511	1231 ± 513
T_{int}	fixed	20	20	20
$\log_{10}(P_0)$	$\mathcal{U}(-12, 2)$	-1.56 ± 0.79	-7.72 ± 3.91	-0.90 ± 0.47
$\log_{10}(P_{\text{cloud}})$	$\mathcal{U}(-2, 10)$	3.45 ± 3.04	9.43 ± 3.46	4.85 ± 3.18
$\log_{10}(\chi_{\text{Ray}})$	fixed	1	1	1
$\log_{10}(\chi_{\text{Fe}})$	$\mathcal{U}(-10, -2)$	—	-1.71 ± 1.71	-3.95 ± 0.79
β_{at}	$\mathcal{U}(-3, 3)$	1.0031 ± 0.0001	—	0.116 ± 0.016

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



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Parameter	Description	Prior	Posterior
T_0	Mid-transit time	$\mathcal{U}(-\infty, \infty)$	59867.14260 ± 0.00002
P	Orbital period (days)	fixed	1.2749255
$a/R_\star$	Scaled semi-major axis	$\mathcal{U}(0, \infty)$	3.770 ± 0.011
$R_p/R_\star$	Planet-to-star radius ratio	$\mathcal{U}(0, \infty)$	0.12193 ± 0.00011
b	Impact parameter	$\mathcal{U}(0, \infty)$	0.183 ± 0.019
c_1	Linear limb-darkening coefficient	see text	0.006 ± 0.008
c_2	Quadratic limb-darkening coefficient	see text	0.152 ± 0.018
f_{oot}	Out-of-transit flux normalisation	$\mathcal{U}(-\infty, \infty)$	1.00020 ± 0.00002
T_{grad}	Linear baseline trend	$\mathcal{U}(-\infty, \infty)$	$(-2.87 \pm 2.63) \times 10^{-6}$
$T_{\text{grad}2}$	Quadratic baseline trend	$\mathcal{U}(-\infty, \infty)$	$(5.25 \pm 0.23) \times 10^{-5}$
σ	White-noise parameter	$\mathcal{U}(0, \infty)$	$(1.32 \pm 0.04) \times 10^{-4}$

Table 1: Inputs and results for the model parameters for fitting the white light curve using MCMC.