Doppler Spectroscopy for the Detection of a Temperature Inversion in Hot Jupiters

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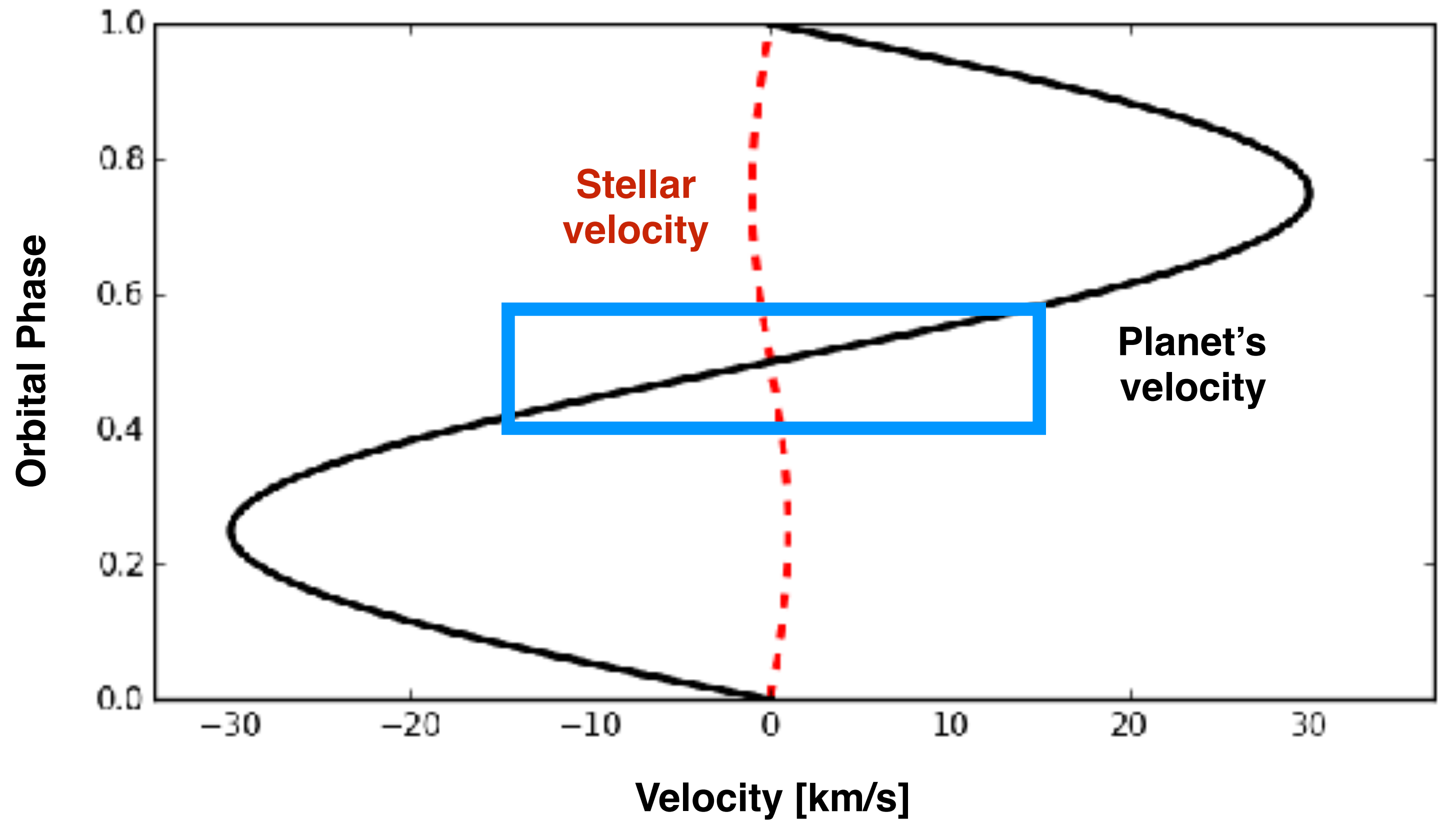
Image Credit: Engine House VFX, At-Bristol Science Centre, University of Exeter

Outline

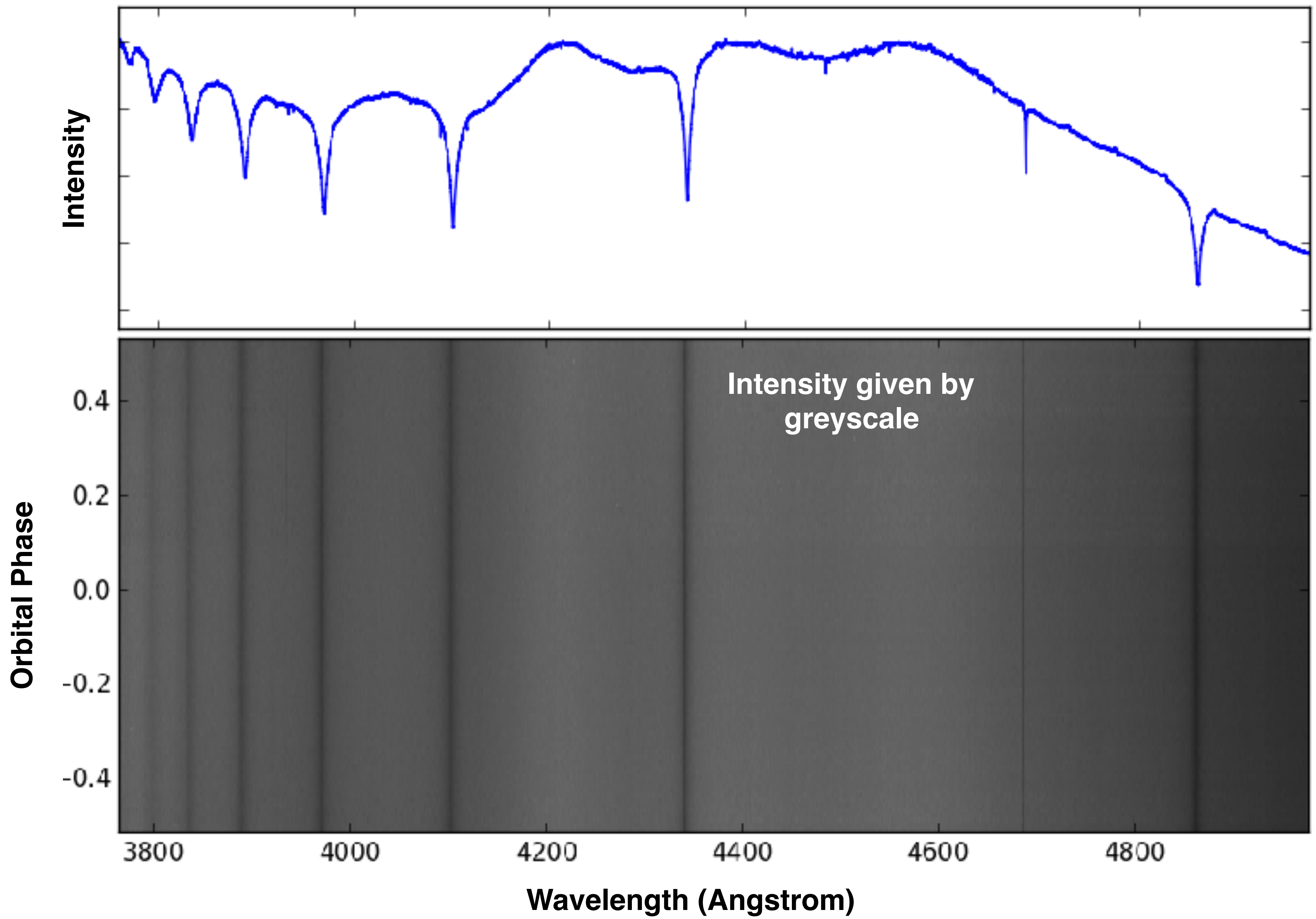
- High-resolution spectroscopy in exoplanet atmospheres
- Temperature inversions: what are they and why should we care?
- WASP-121b: a massively-inflated super-hot Jupiter
- Testing the techniques for UVES: simulations with artificial signals
- Next steps and future work

Doppler Spectroscopy

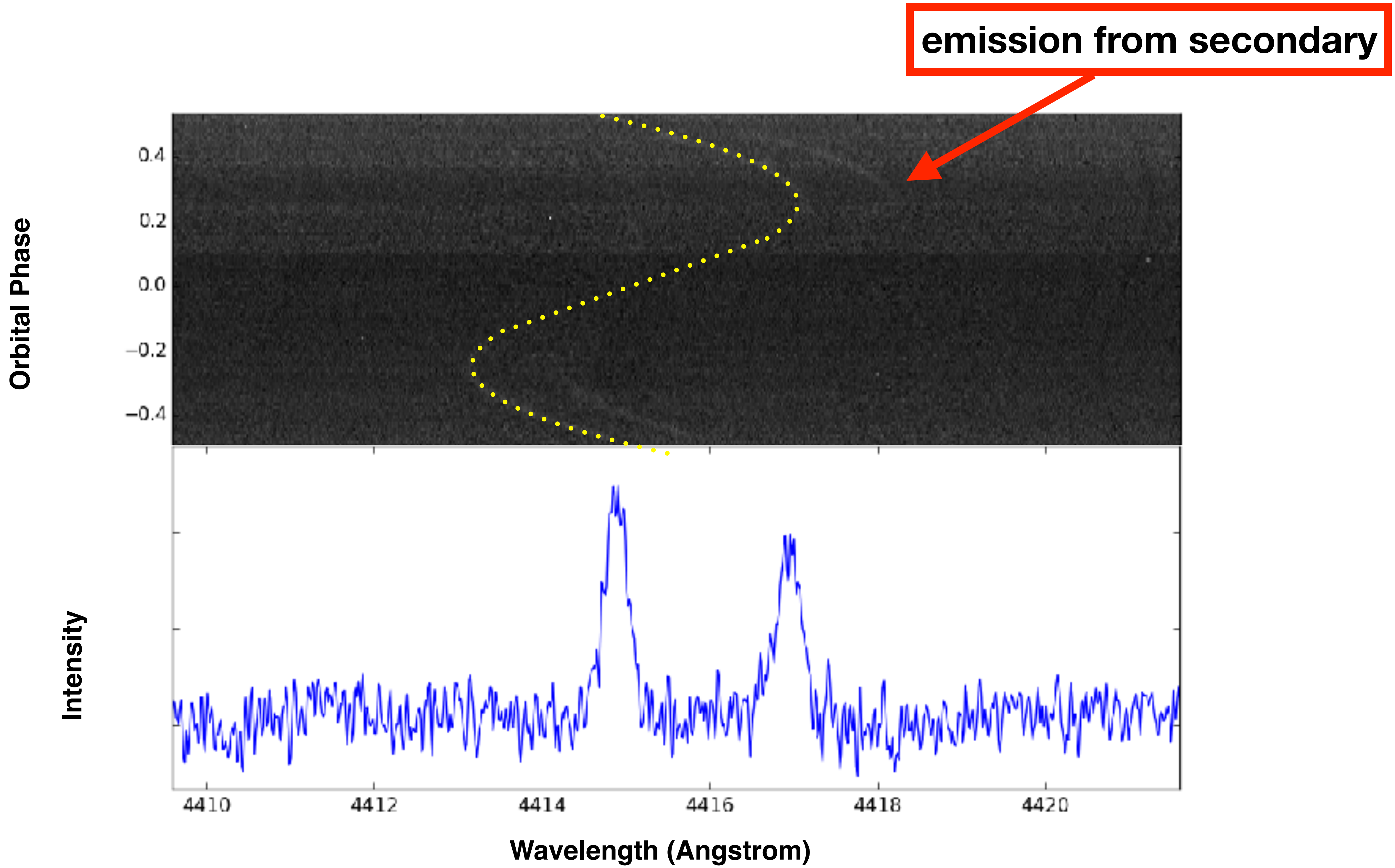


- Planet and star orbit a common centre of mass
- Planet's mass significantly lower: radial velocity much higher (ratio ~1000)
- Can treat spectral lines from star as essentially stationary over short periods
- Can take advantage of this to disentangle planetary spectral features

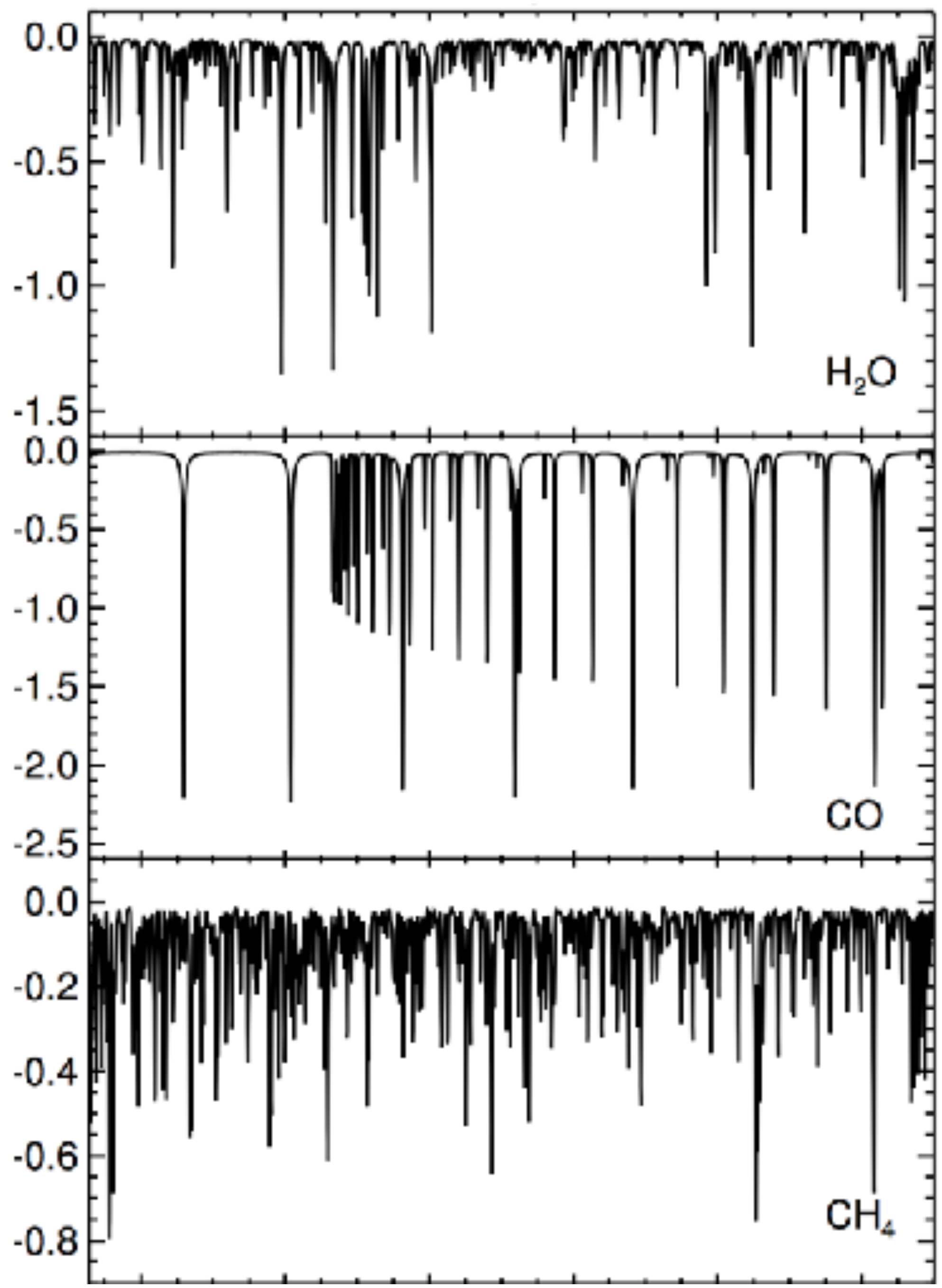
Doppler Spectroscopy



Doppler Spectroscopy



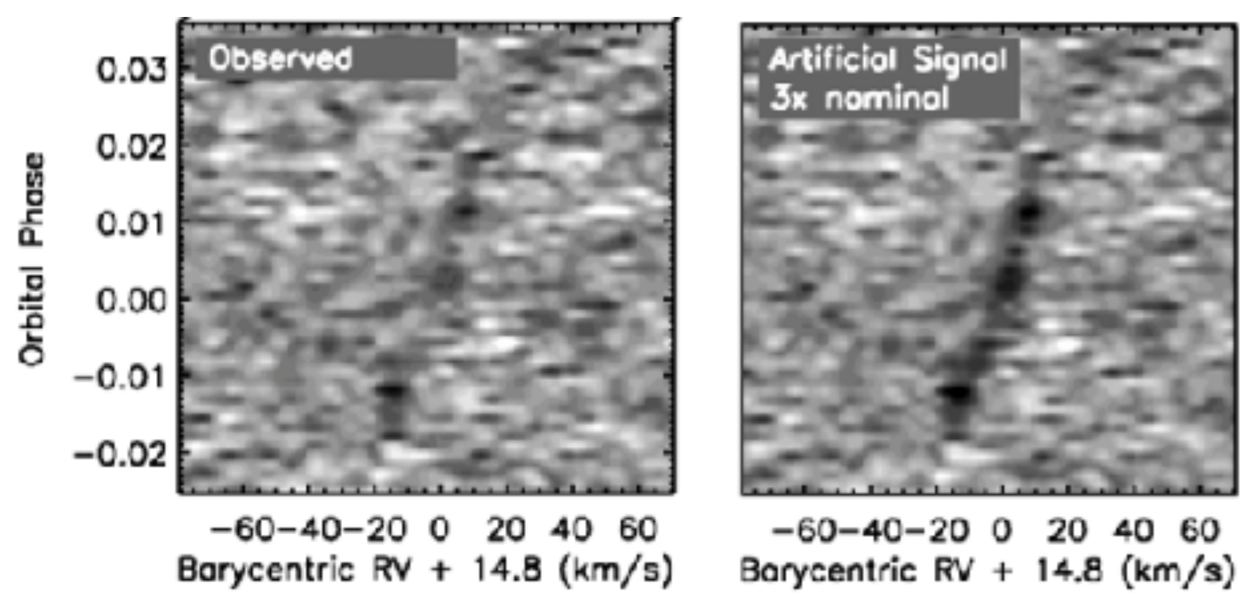
Doppler Spectroscopy



Brogi et al. (2015)

- Molecular spectra contain many 100s of spectral lines
- Cross-correlate high-resolution spectra with template spectrum
- Difficult to obtain abundances, only useful for molecular species
- Requires high-resolution time series spectra, bright targets ($V_{mag} < 12$)

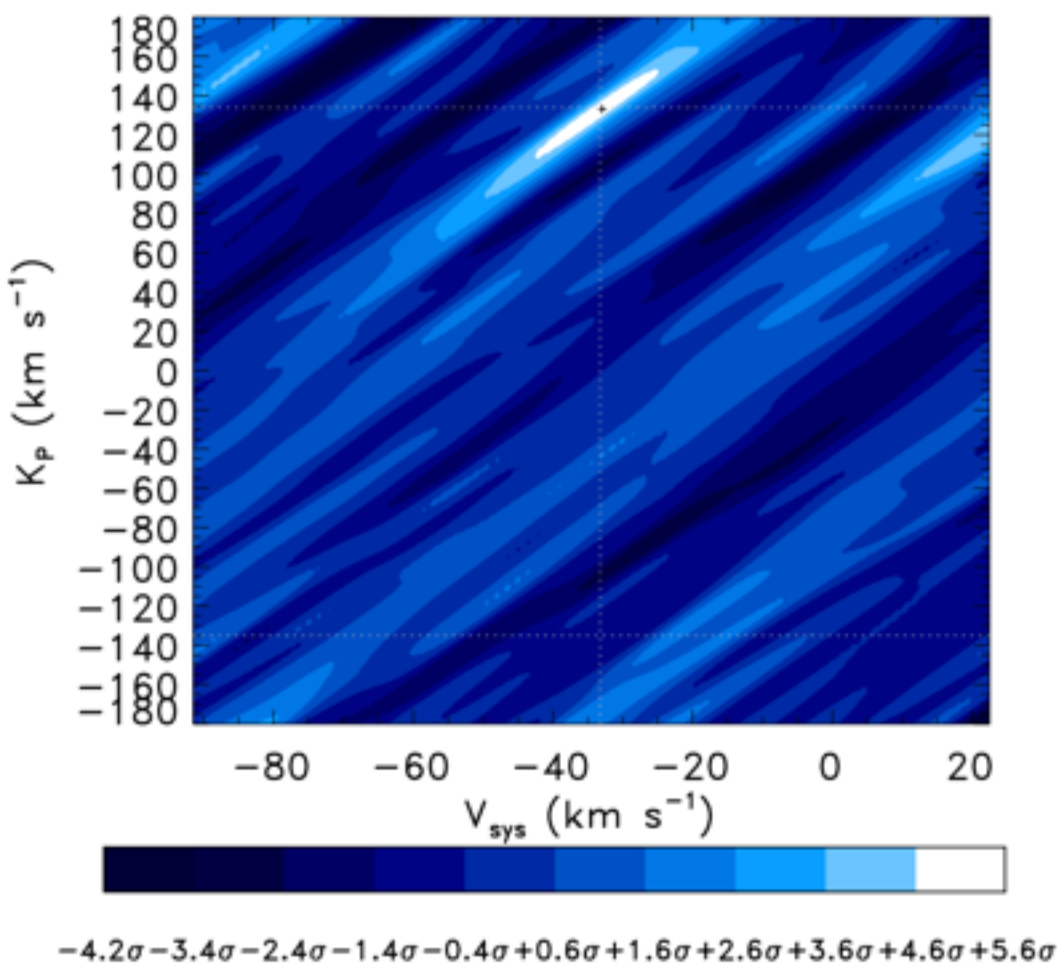
Detection of CO in HD 189733b in transmission:



Snellen et al. (2010)

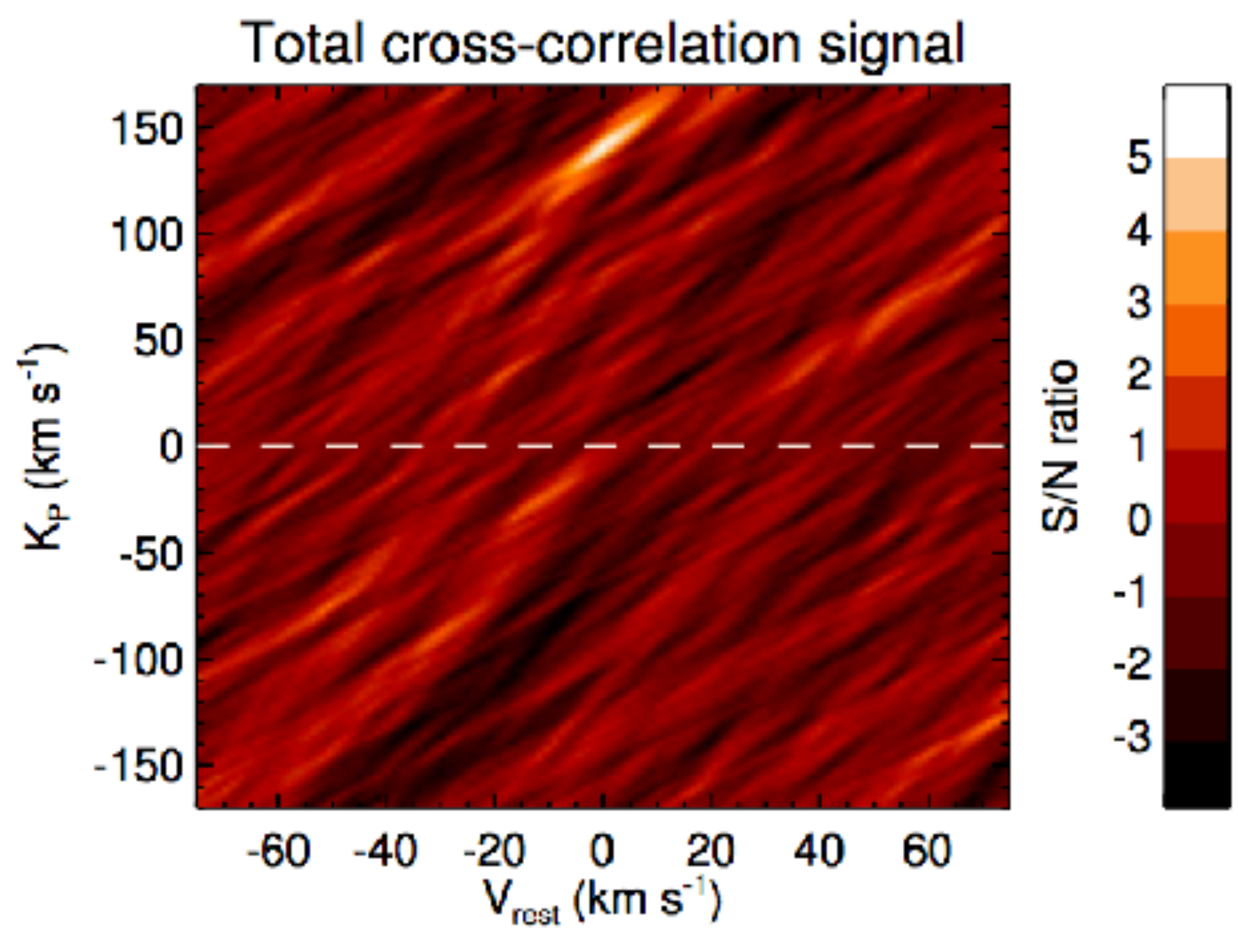
Doppler Spectroscopy

H2O in 51 Peg b



Birkby et al. (2017)

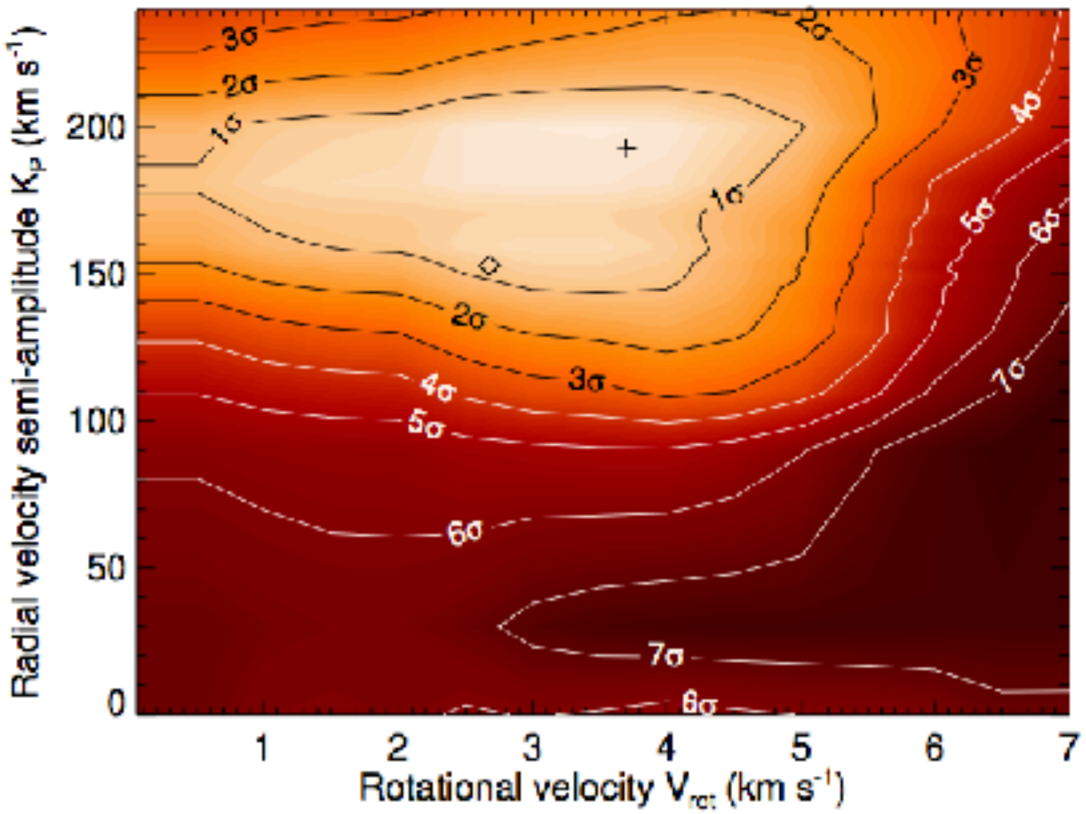
CO and H_2O in HD179949b



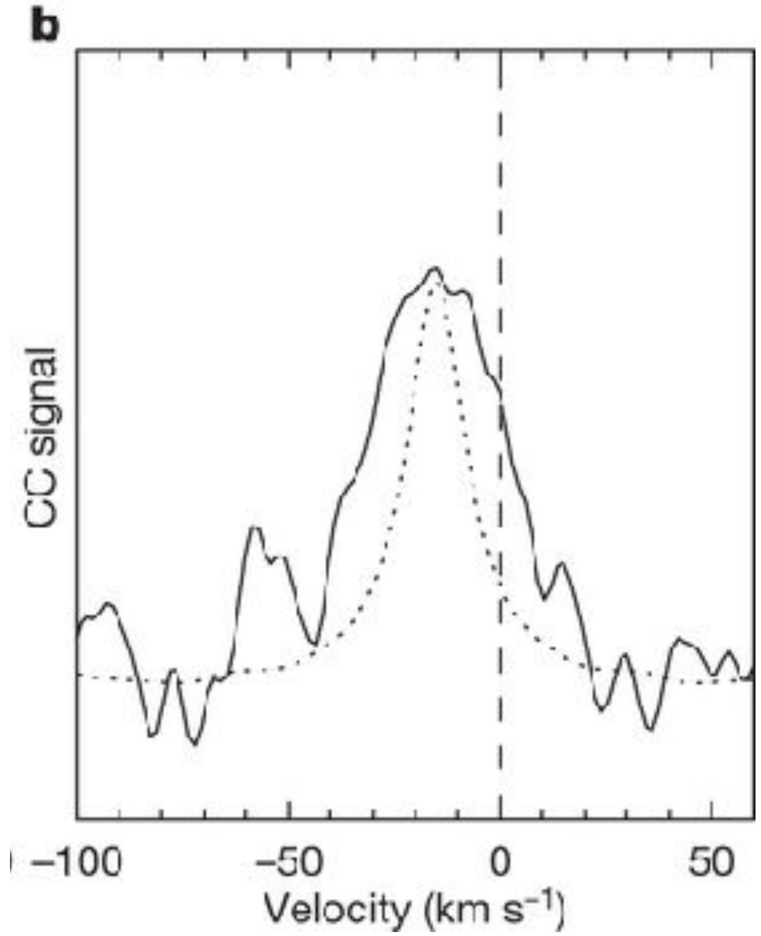
Brogi et al. (2014)

Doppler Spectroscopy

- Result is unambiguous: almost impossible for any other effect to mimic retrieved signal
- Can extract planetary rotation and suggest the presence of high-altitude winds on the planet (Snellen et al. 2010, 2013; Brogi et al. 2015)

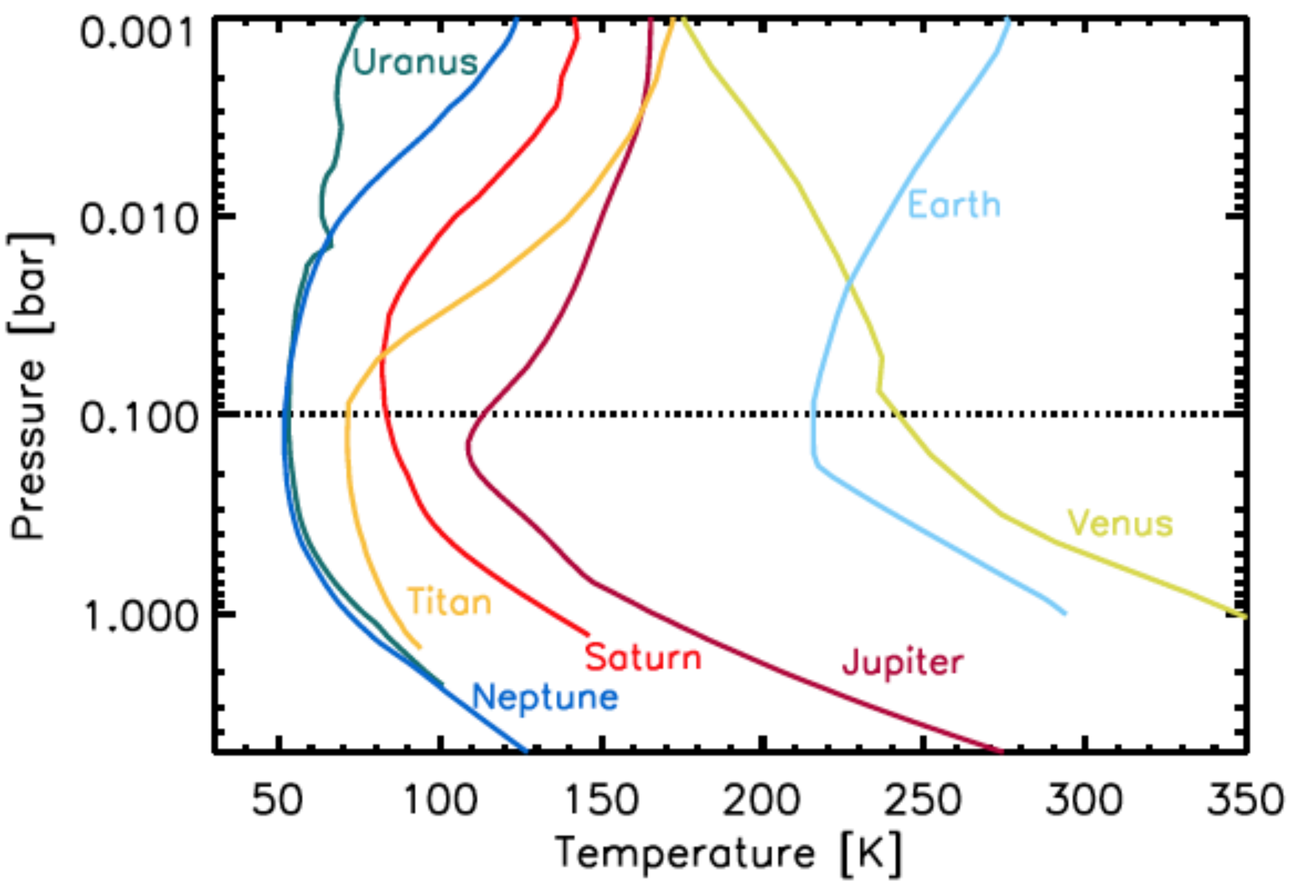


Brogi et al. (2015)

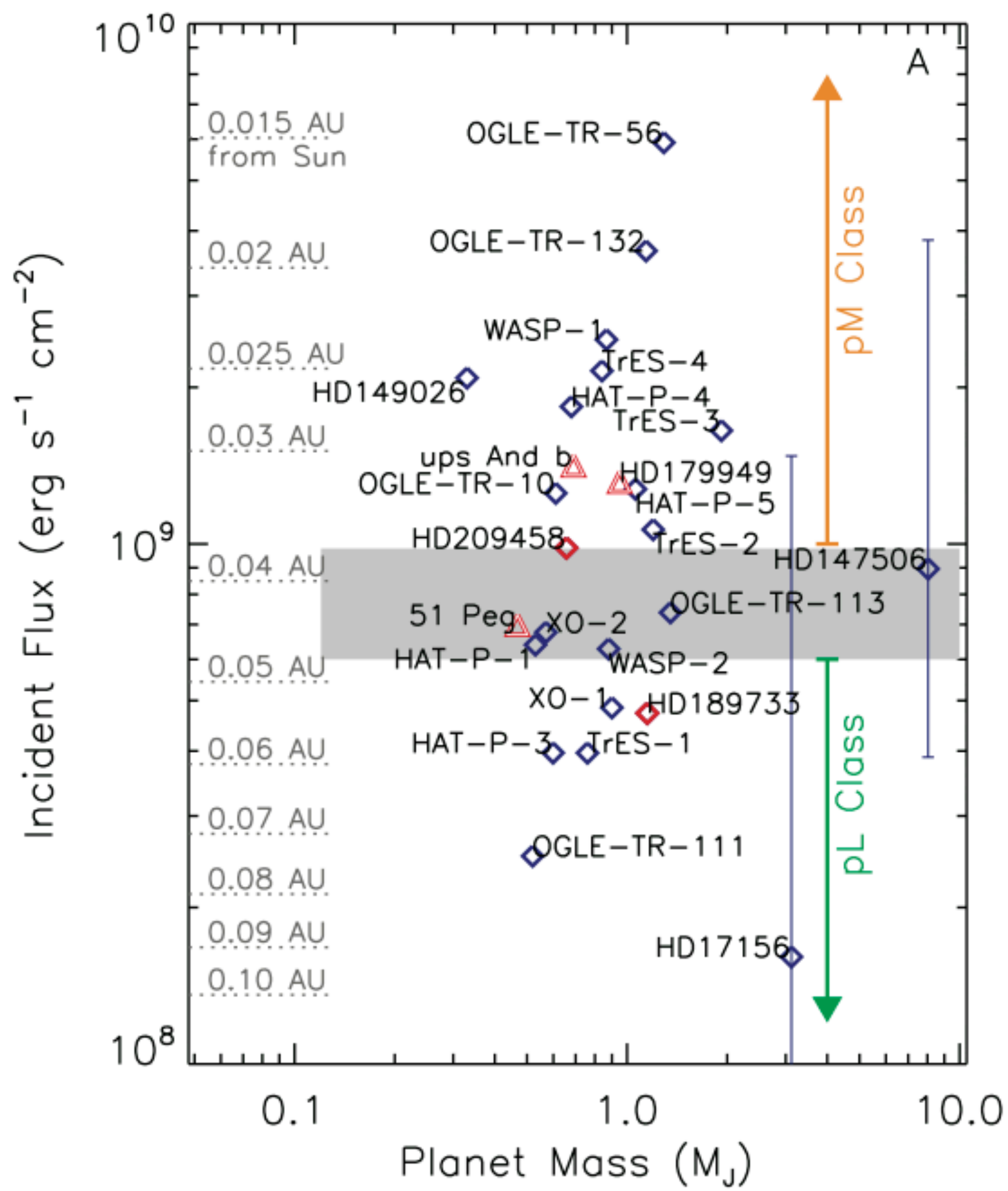


Snellen et al. (2016)

Temperature Inversions



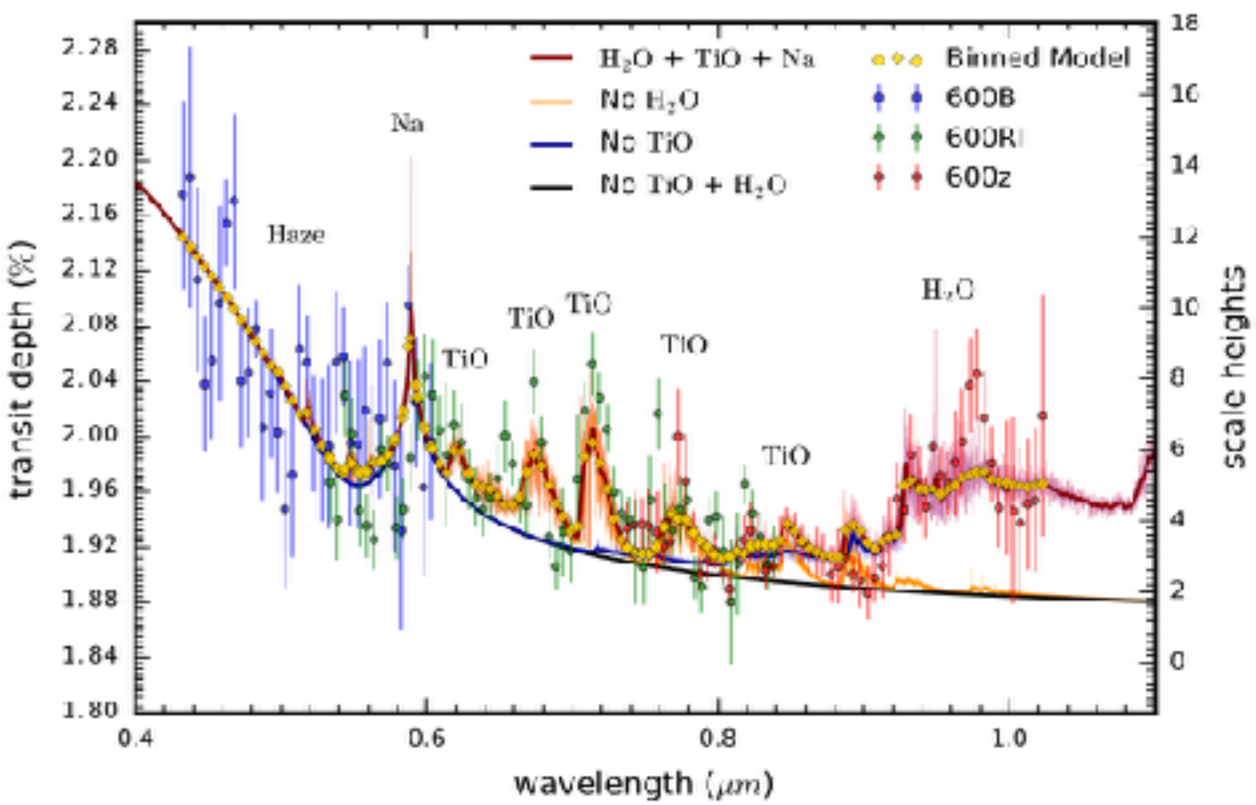
- Presence of absorbing species in atmosphere cause temperature to rise with altitude
- Early models suggested highly-irradiated hot Jupiters had temperature inversions caused by gaseous TiO and/or VO



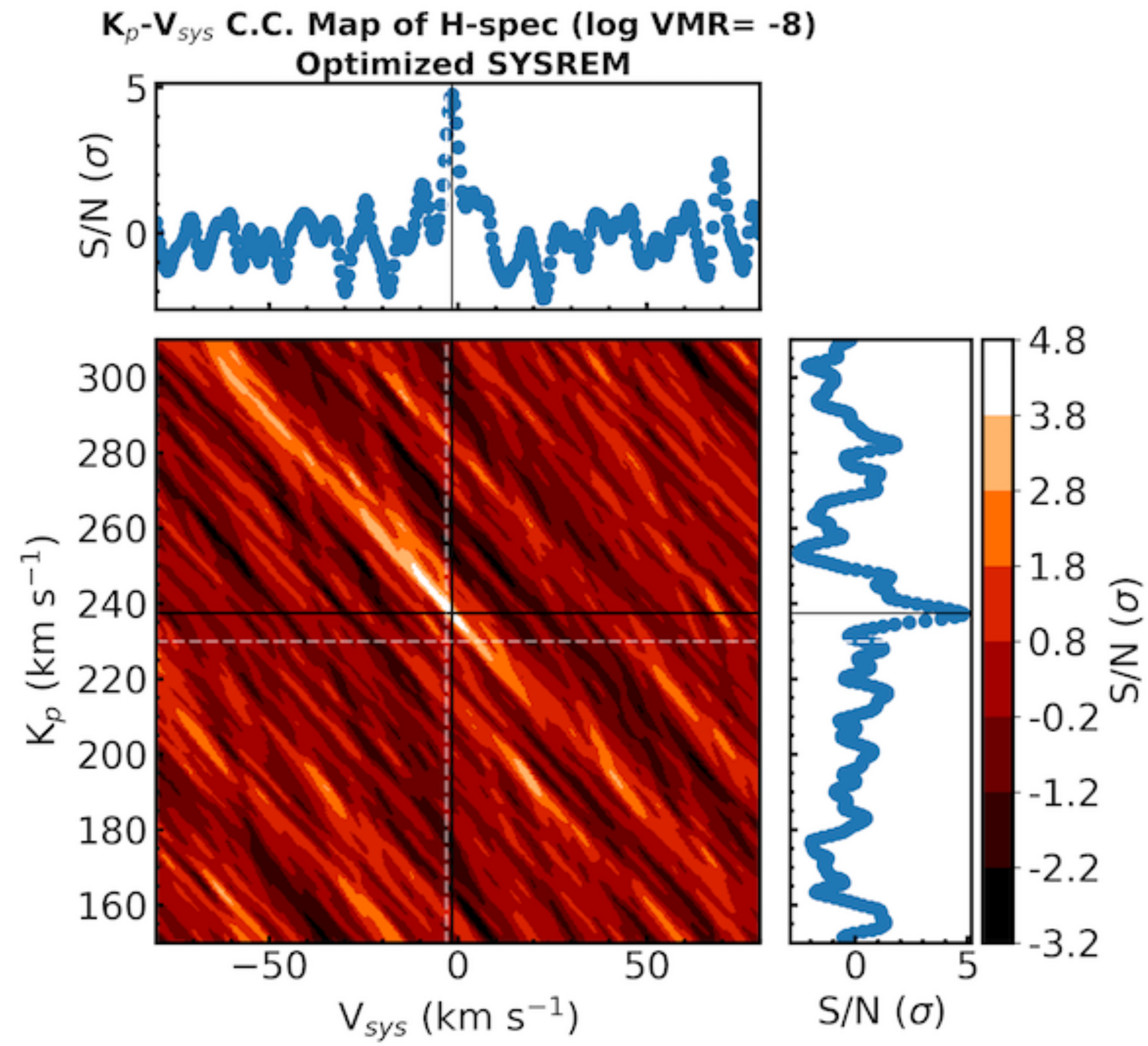
Fortney et al. (2008)

Temperature Inversions in Hot Jupiters

- Observational evidence elusive until very recently
- Low-resolution transmission spectroscopy: best fit model for WASP-19b contains TiO
- High-resolution spectroscopy in emission: TiO detected in WASP-33b



Sedaghati et al. (2017)



Nugroho et al. (2017)

WASP-121b

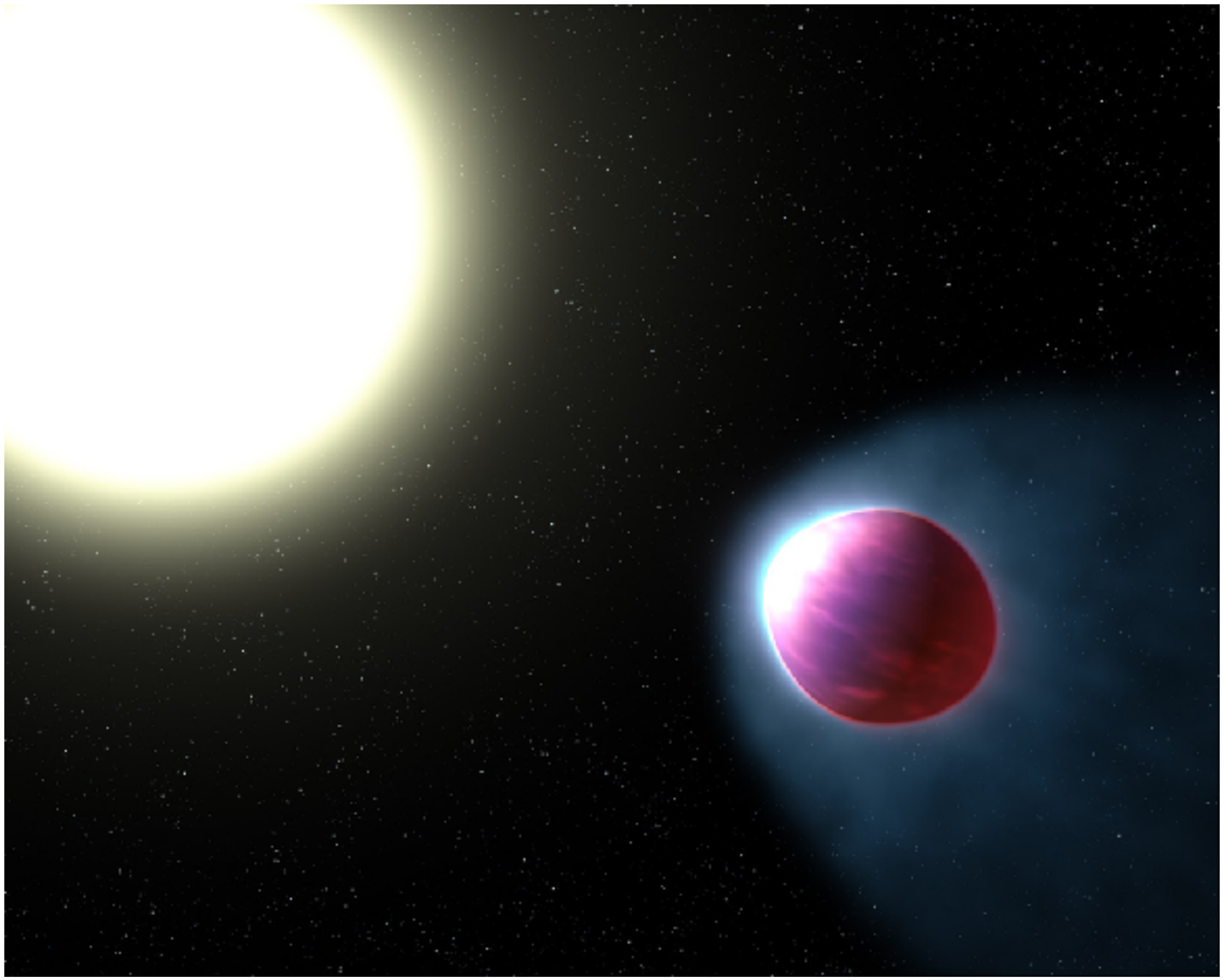


Image credit: NASA, ESA, and G. Bacon (STSci)

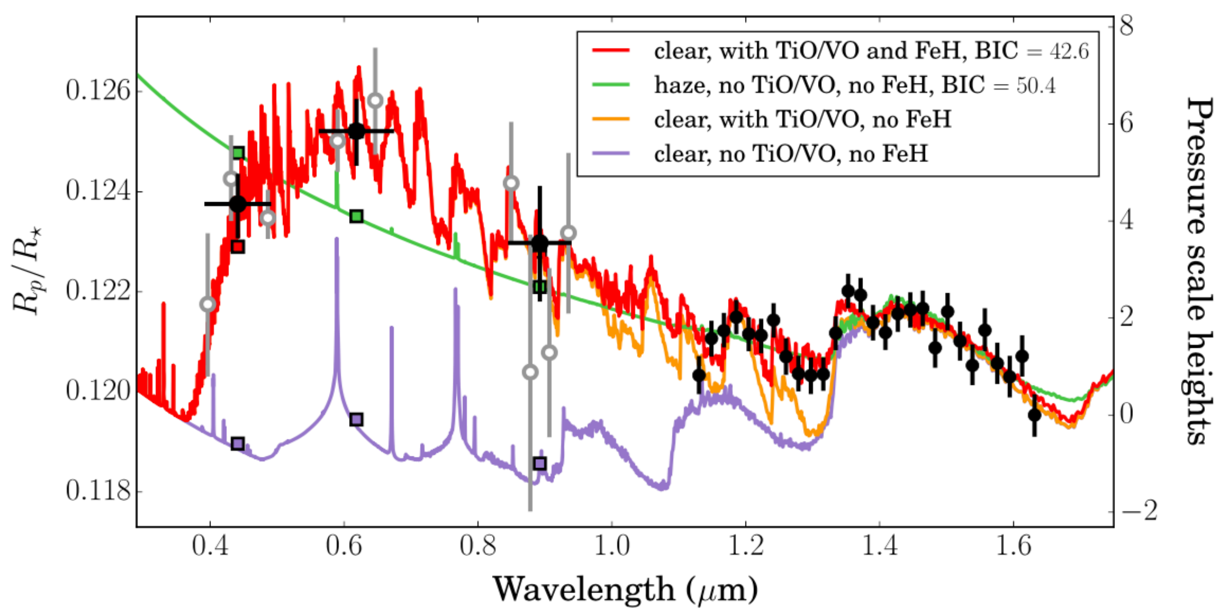
WASP-121b:

mass	1.183 M_J
radius	1.865 R_J
semi-major axis	0.025 AU
temperature	2350K
scale height	1100km

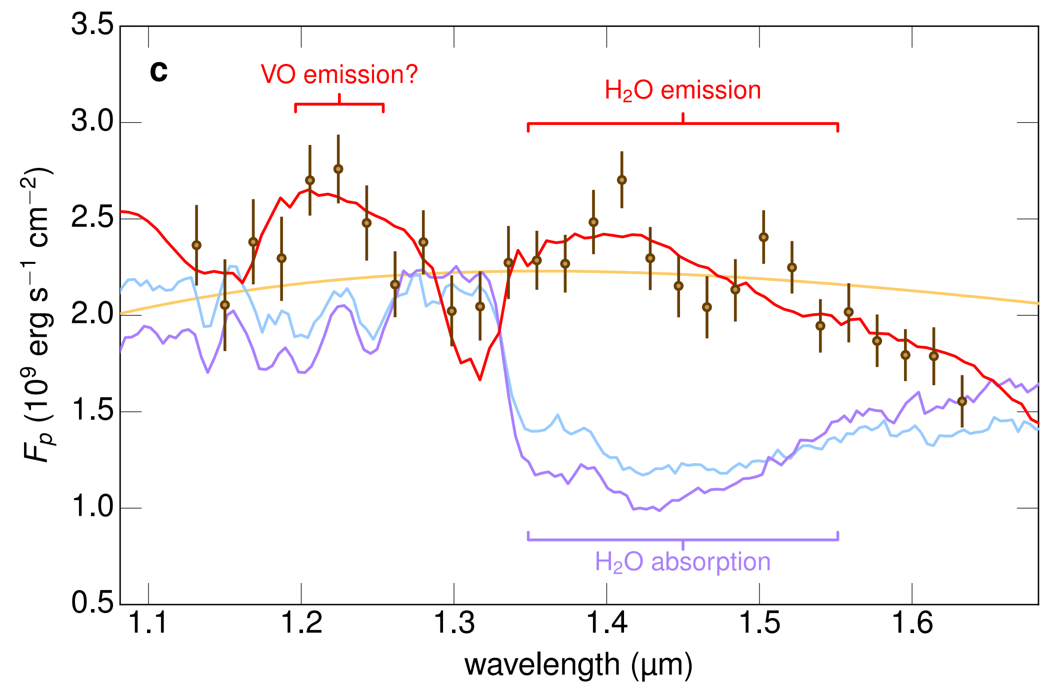
Delrez et al. (2016)

A Temperature Inversion?

- Water feature discovered in emission and potential discovery of TiO/VO by Evans et al. (2015, 2017, 2018 in press) indicates temperature inversion



Evans et al. (2015)

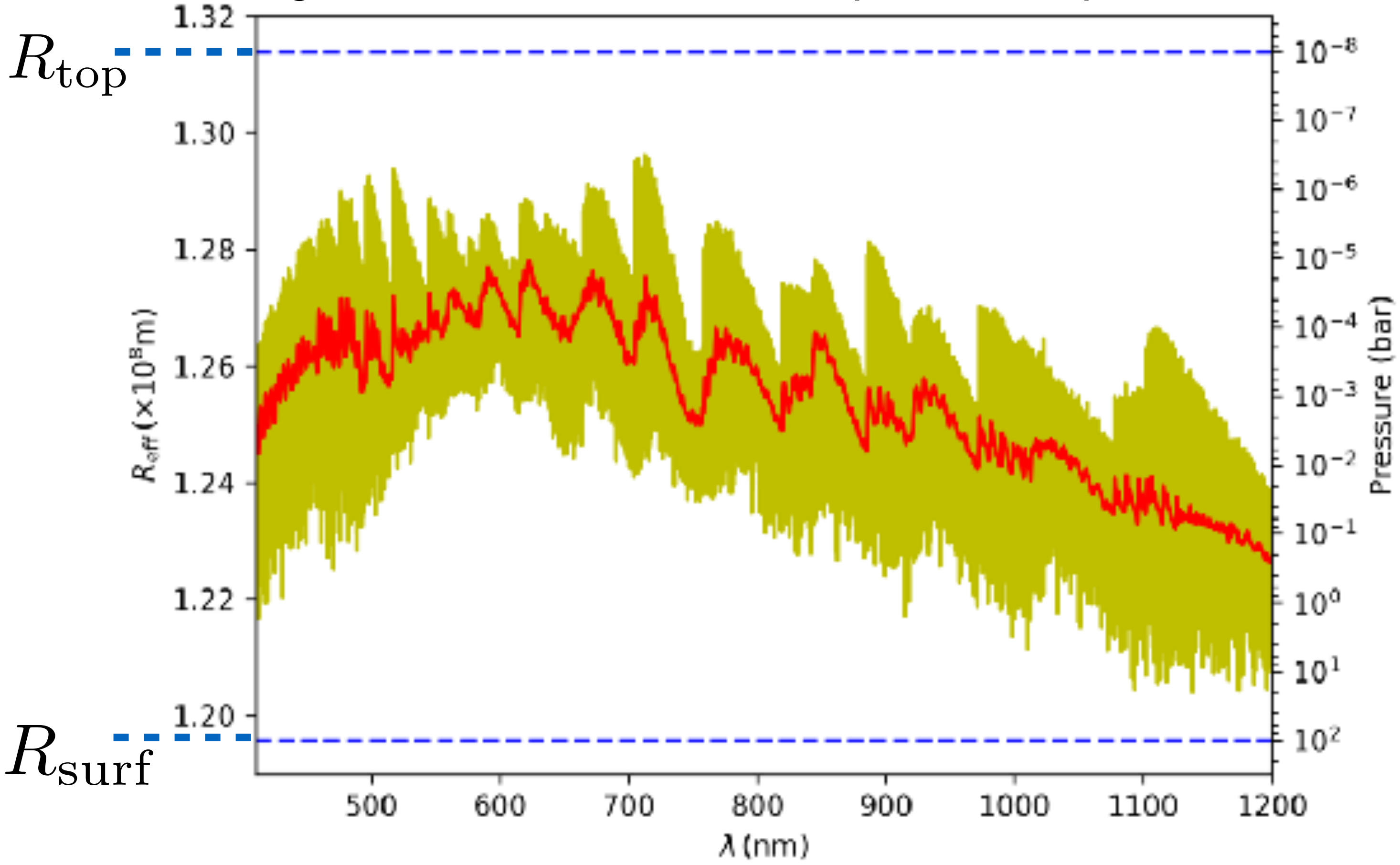


Evans et al. (2017)

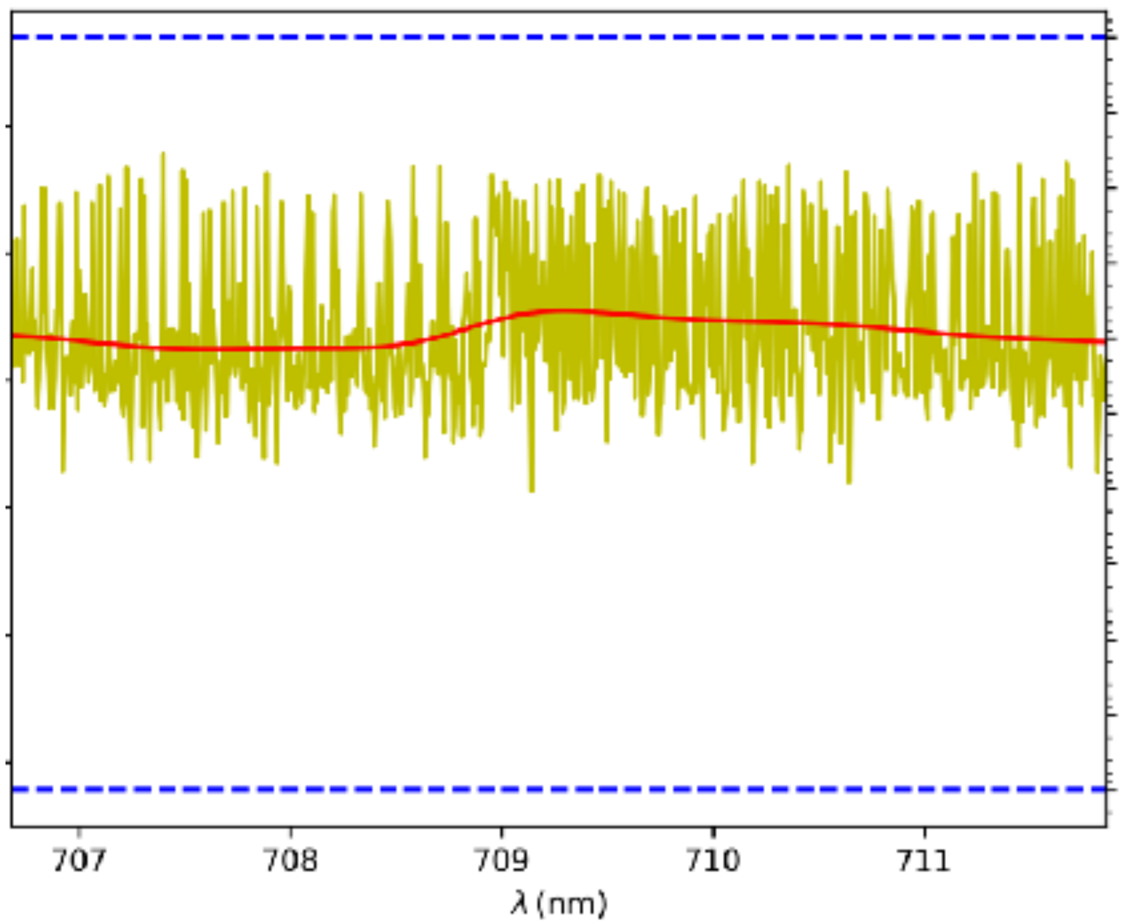
Motivation

- Confirming result of Evans et al. (2017): detecting TiO in WASP-121b
- UVES (on the VLT) operates in optical wavelengths (300 -1100nm) where TiO lines appear with R ~ 80,000 (blue end) -- 100,000 (red end)
- Doppler spectroscopy provides unambiguous detection of molecular signal: many TiO lines strengthen cross-correlation signal

- e.g. for a H_2, He + TiO Hot Jupiter atmosphere:

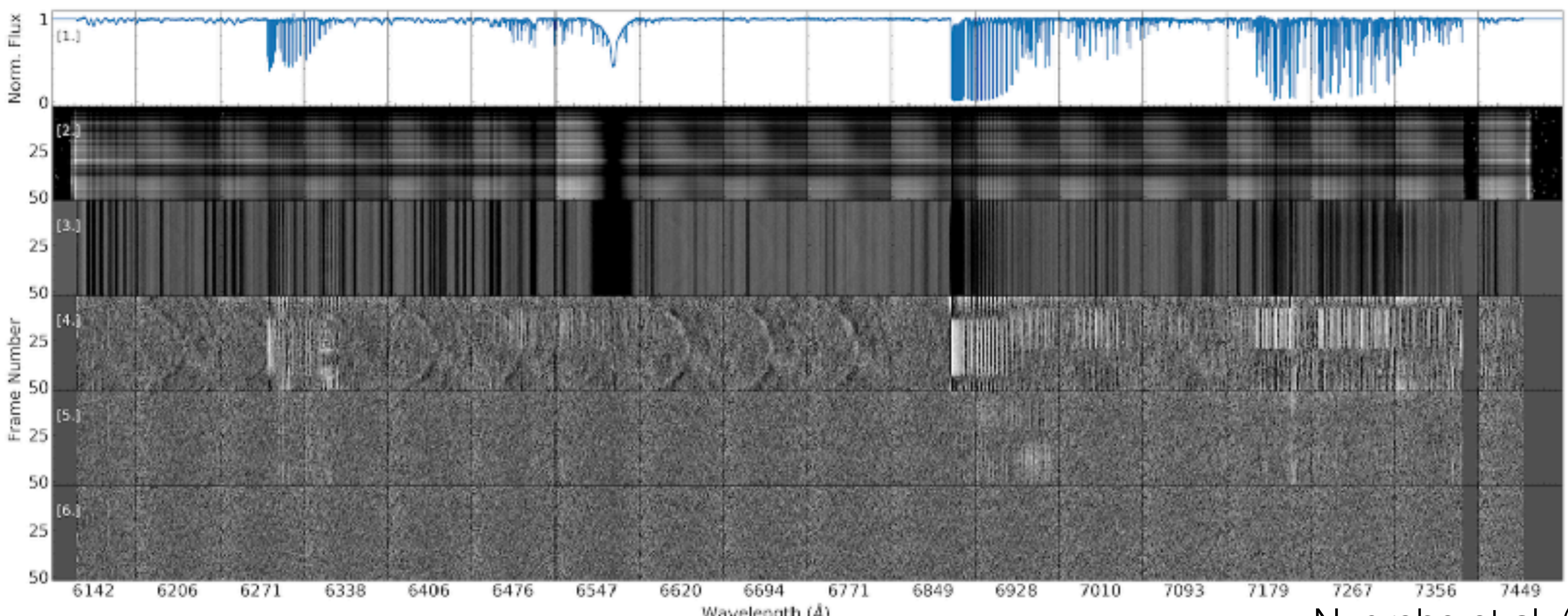


- and at high resolution:



Motivation for Simulations

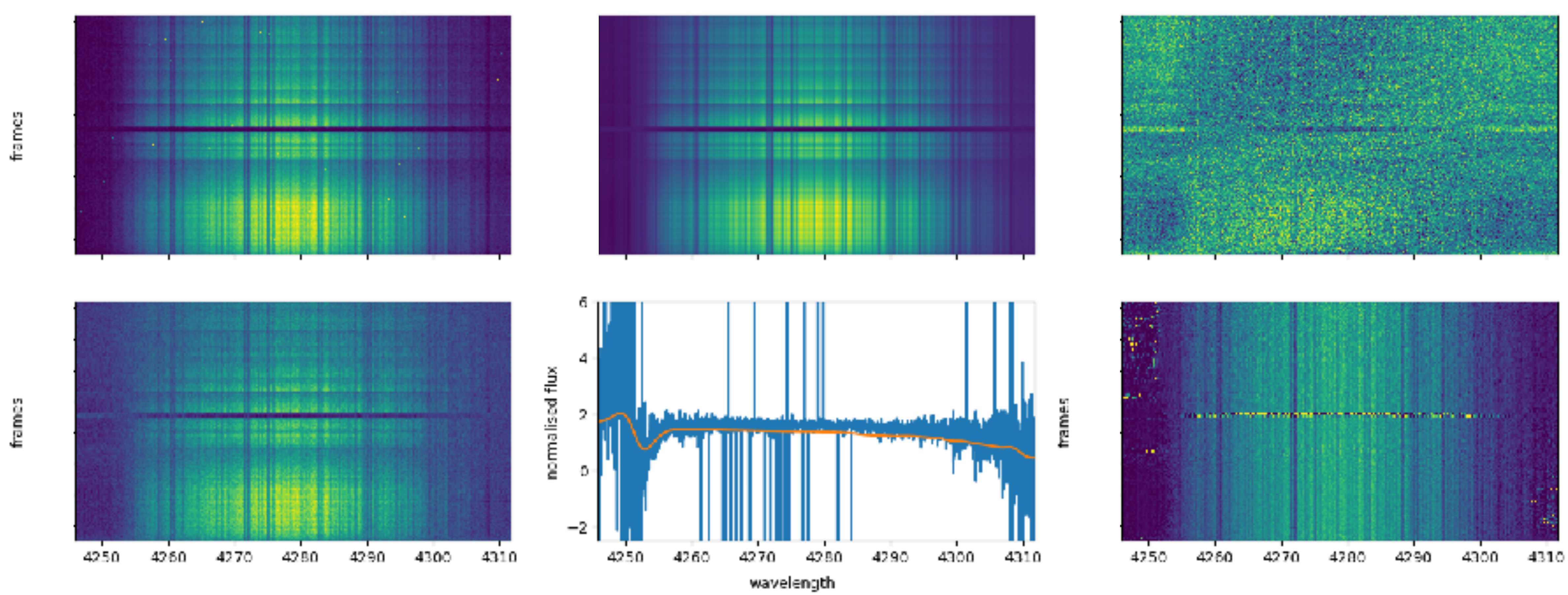
- New technique -- high-resolution spectroscopic exoplanet characterisation has never been attempted with UVES
- Building a robust codebase for future work
- Testing different methods of cleaning/blaze-correcting spectral data, removing telluric and stellar lines
- Line lists for molecules at hot-Jovian temperatures/pressures known to be inaccurate



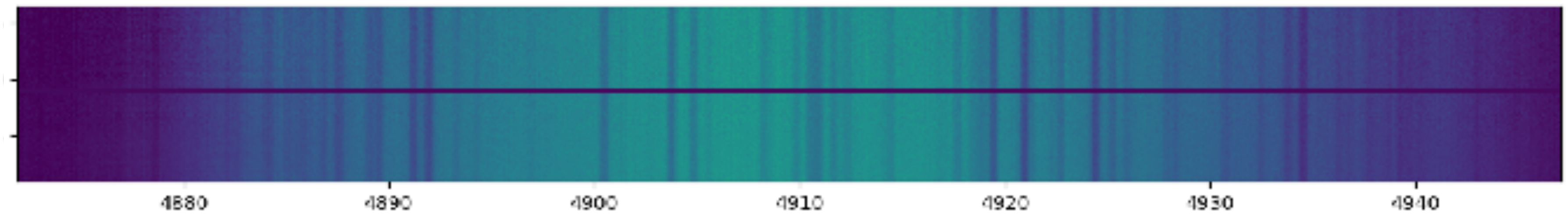
Nugroho et al. (2017)

Data Processing

- Blaze function of UVES variable in time: data "cleaned" of outliers and all spectra placed on the same blaze
- Principal component extraction used to remove dominant signals (telluric/stellar lines), outliers clipped and spectra divided through by a filter comprised of a smoothed function of the median spectrum



Preliminary Results



Next Steps

- Tellurics currently imperfectly removed (time dependence in depth of telluric lines over the night): options include fitting function of airmass to columns (eg: Brogi et al 2018), linear basis models
- SYSREM (Tamuz et al. 2005): algorithm very similar to PCA/ICA/NNMF but "weighted" by uncertainties: does this perform better?
- Insertion of TiO template instead of randomised artificial signals
- Eventual use of radiative transfer template spectrum for WASP-121b to attempt to recover TiO signal in UVES dataset
- Production of robust and well-tested techniques for future work in this area using UVES

The Future

- Proving ground-based high-resolution spectroscopy and UVES to be adept at detecting molecules in exoplanetary atmospheres
- Doppler spectroscopy used alongside transmission/emission spectroscopy to confirm discoveries with high confidence
- Future instruments and telescopes (CRIRES+, E-ELT, JWST) could detect molecular oxygen in super-Earths, potentially paving the way for the discovery of extra-terrestrial life