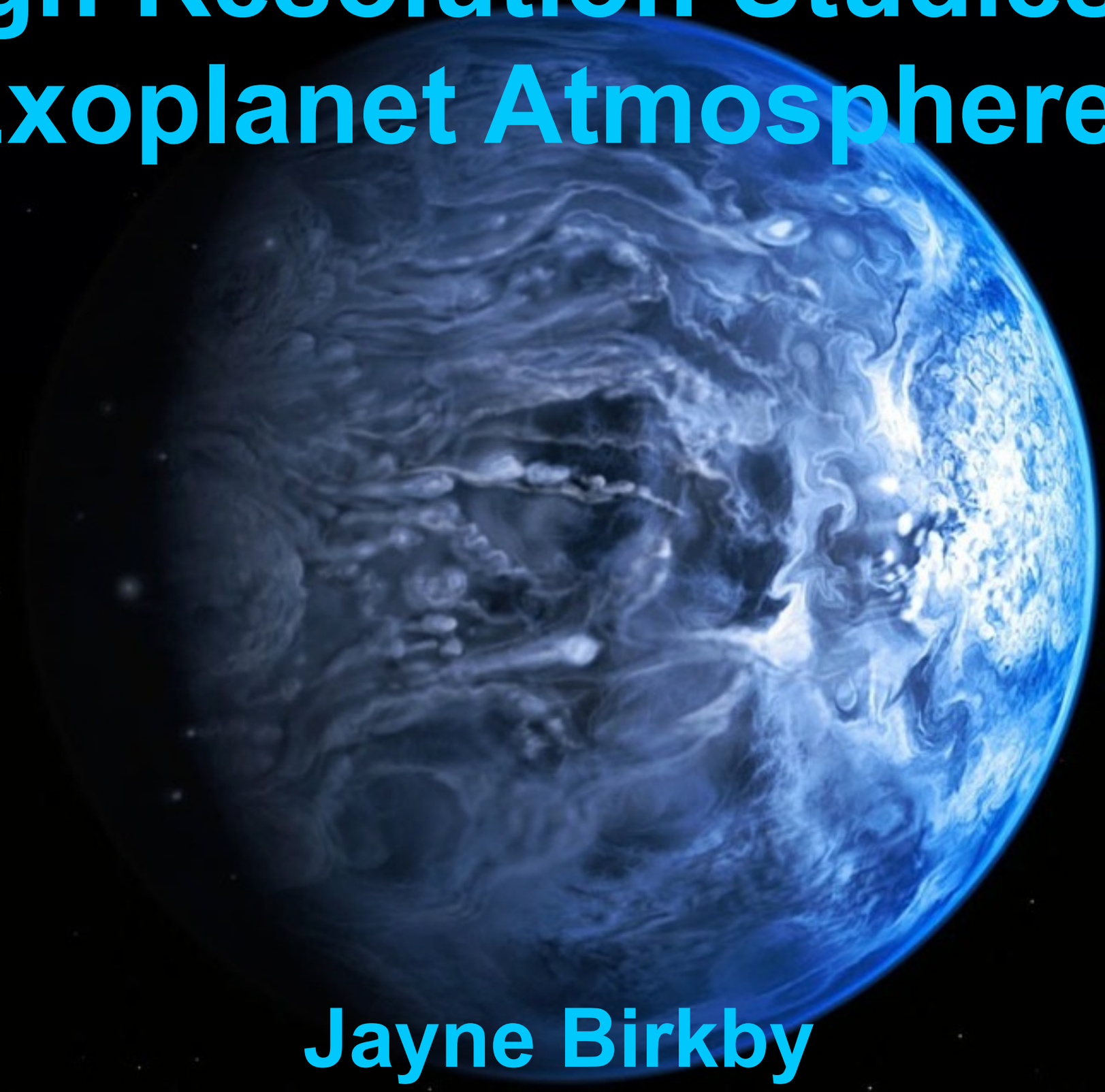
High Resolution Studies of Exoplanet Atmospheres



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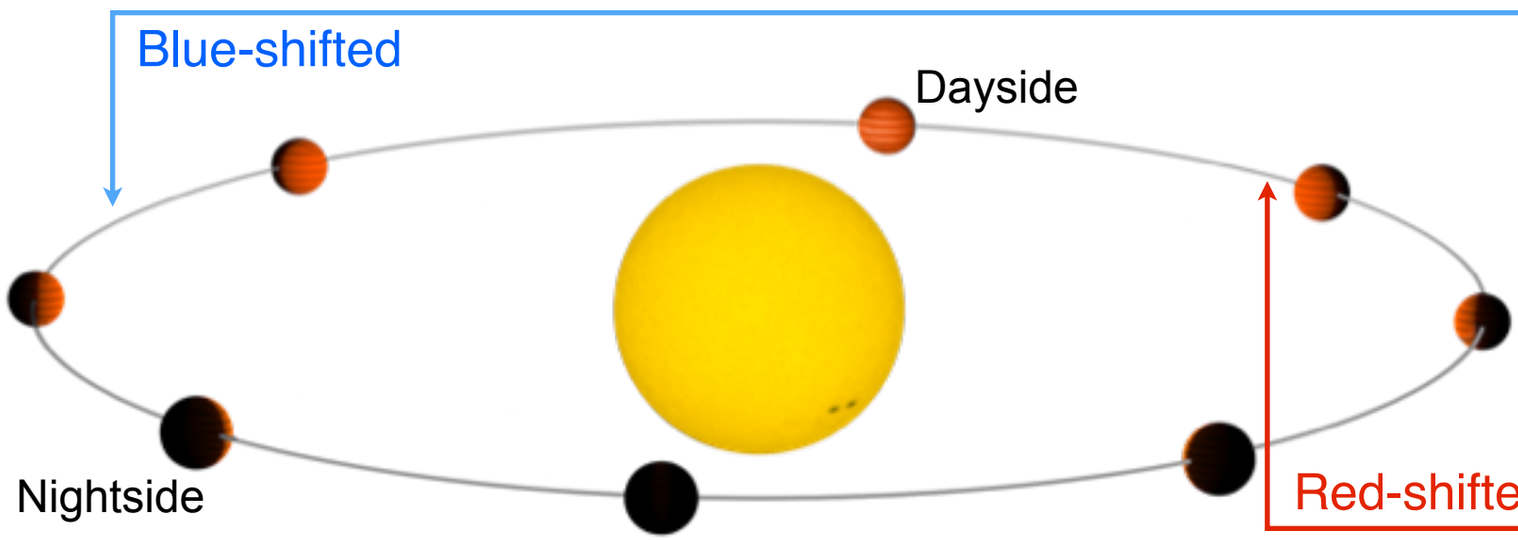
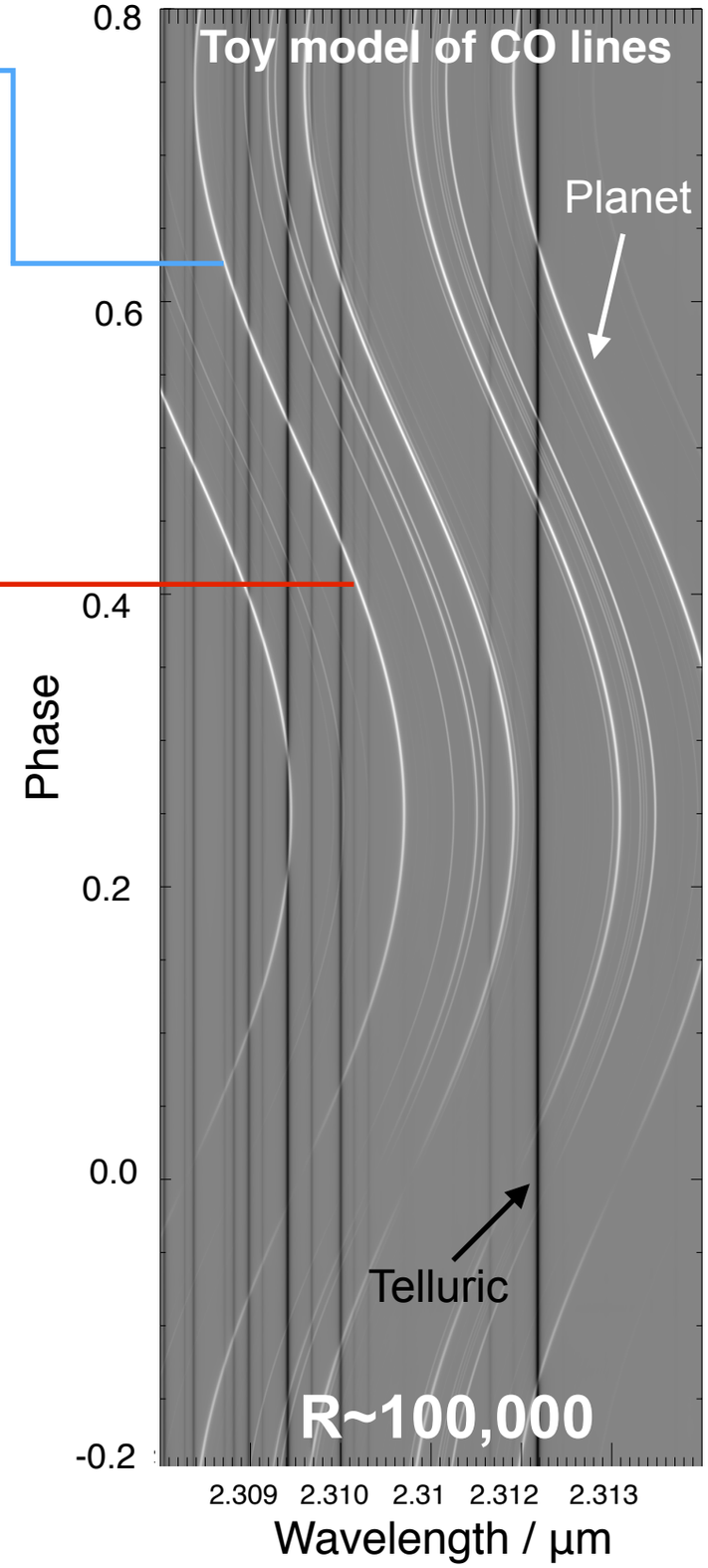
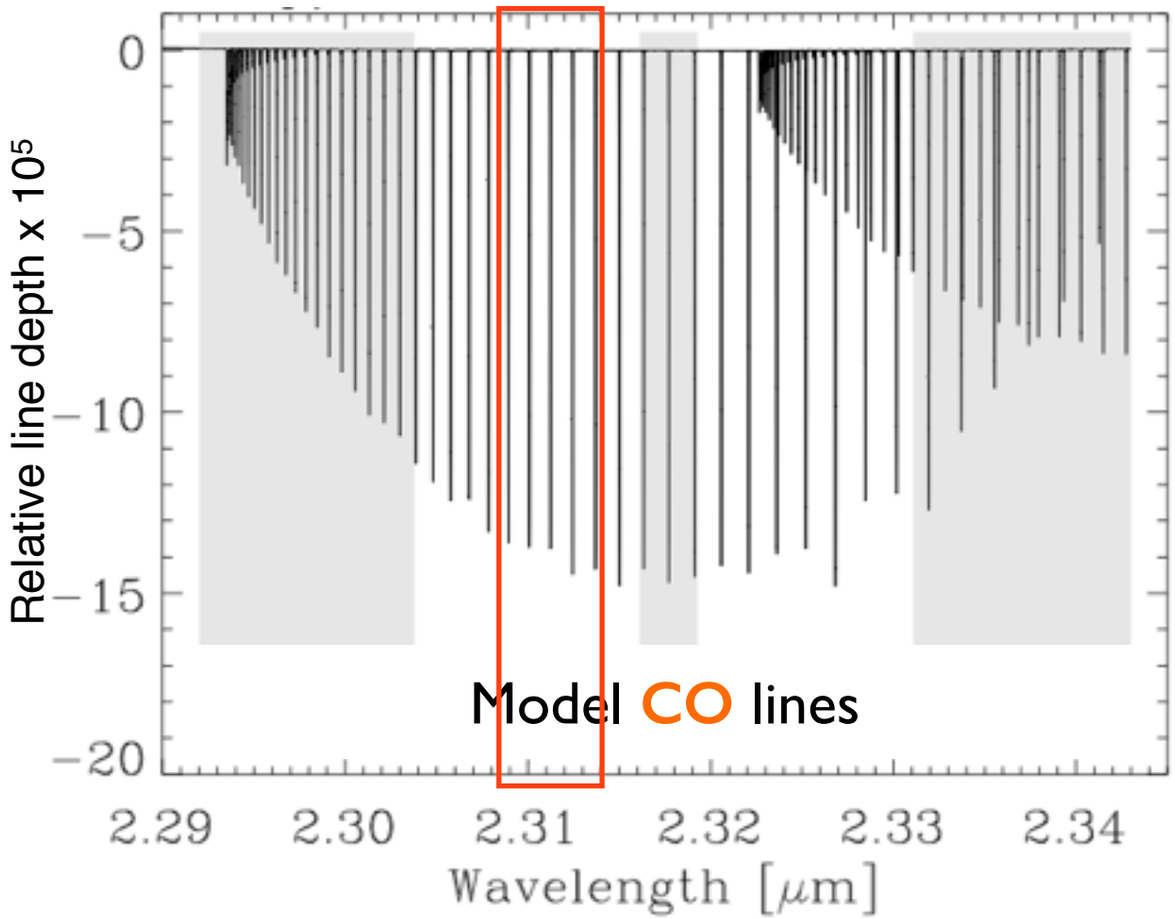
Detecting molecules with High Dispersion Spectroscopy (HDS)

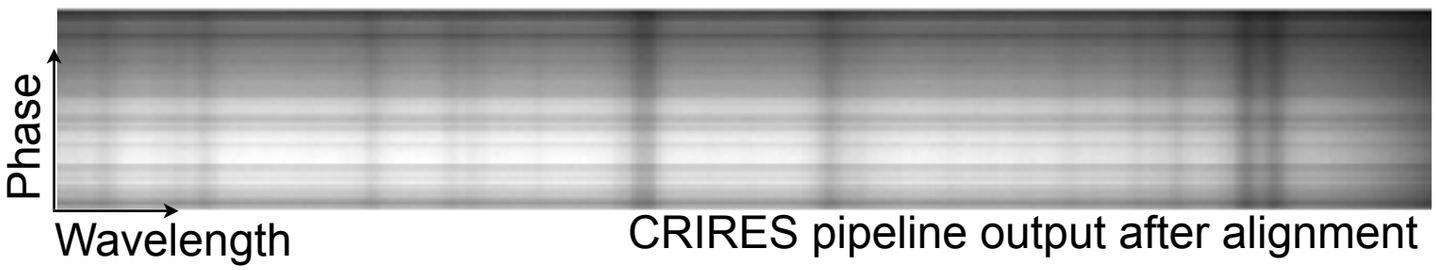
HDS detects the radial velocity shift of the *planetary* spectrum







Telluric features eliminated by identifying and removing common modes in time



CRIRES pipeline output after alignment

Mean-subtracted spectra as input to Sysrem

After first Sysrem iteration, airmass-like trend removed

After optimal Sysrem iterations

10x nominal model injected

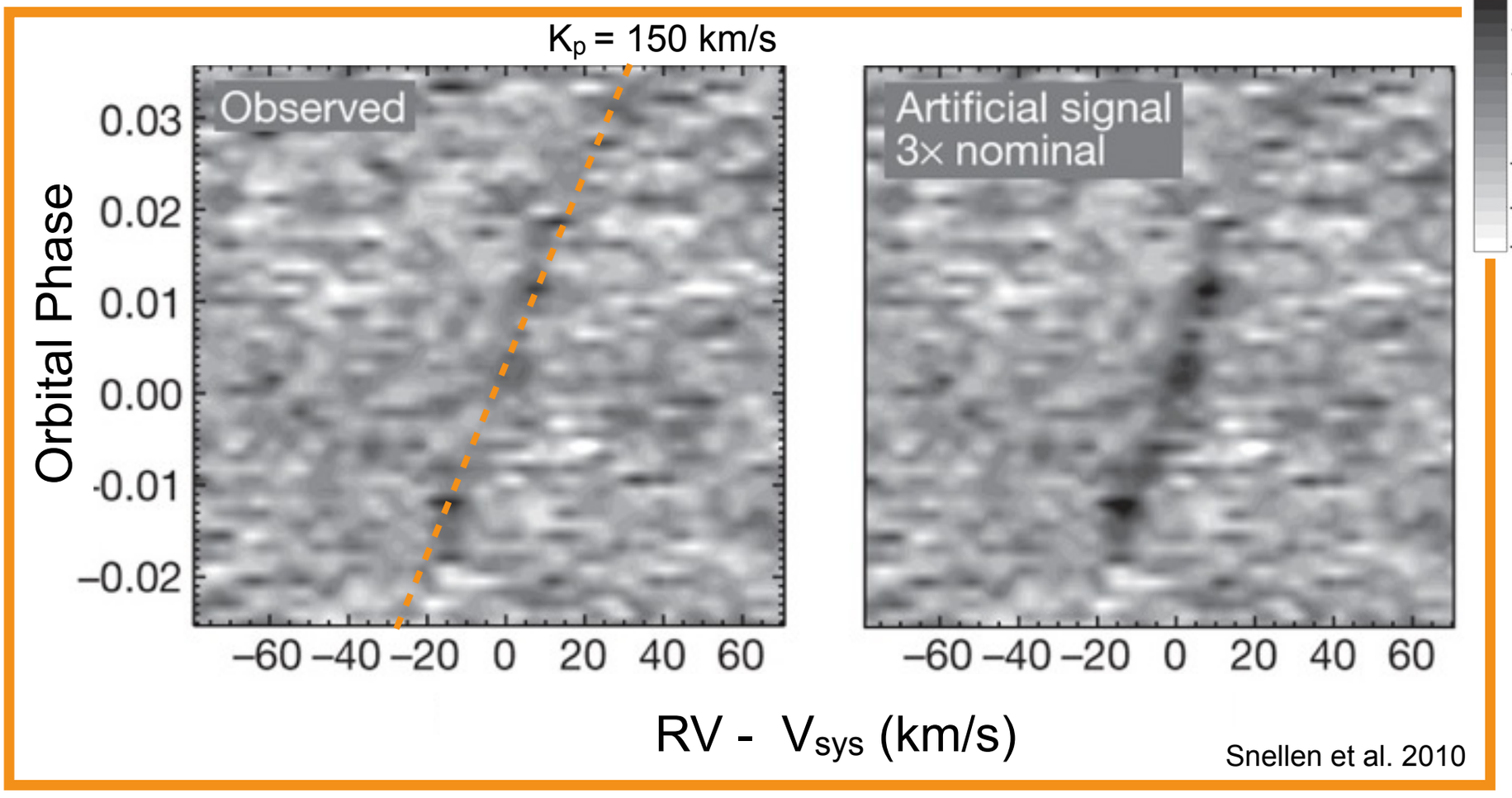
Birkby et al. 2013

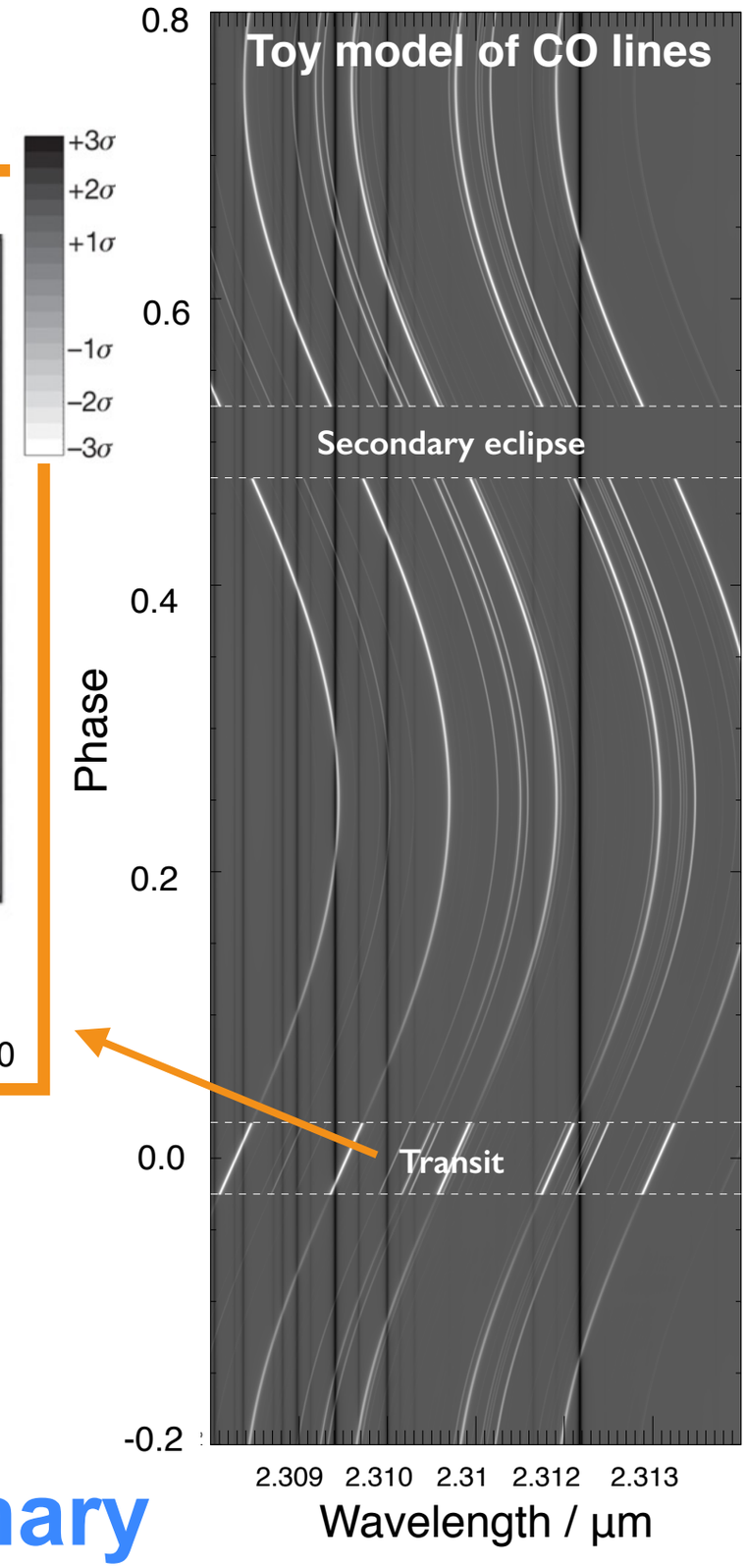
SYSREM

- Treats pixel channels as light curves (1024 light curves per detector)
- PCA-like algorithm identifies trends as a function of time
- Data are ***self-calibrating***

Combine signal from individual lines via cross-correlation

HDS detects carbon monoxide RV trail in a hot Jupiter atmosphere

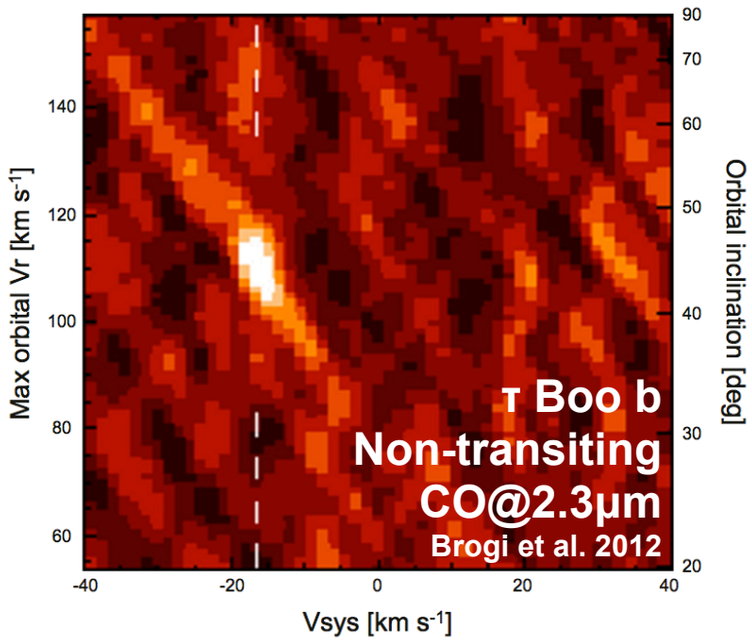


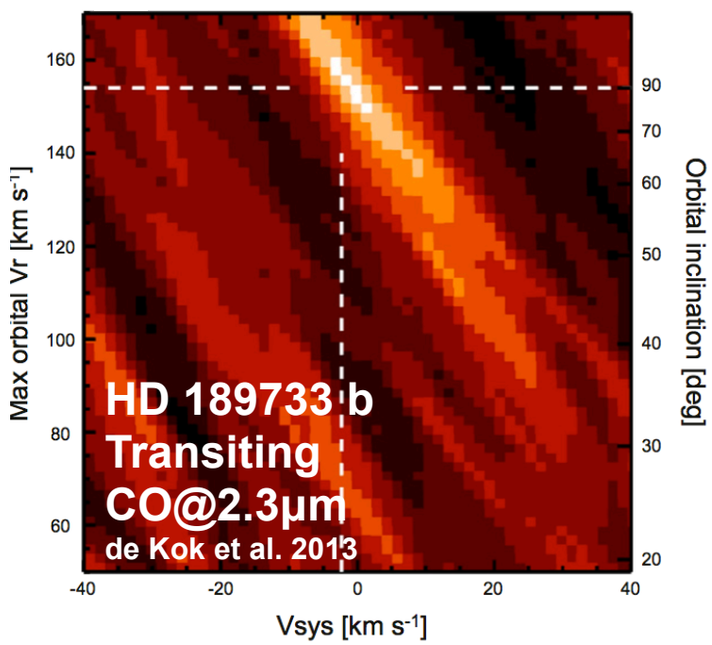


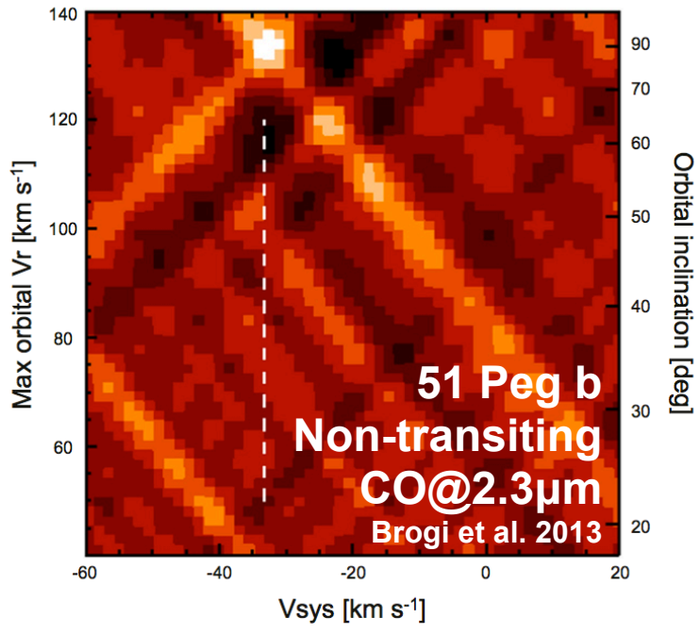
CO detected at **5.6σ** in HD 209458 b
during transit with **5 hrs** on CRIRES/VLT

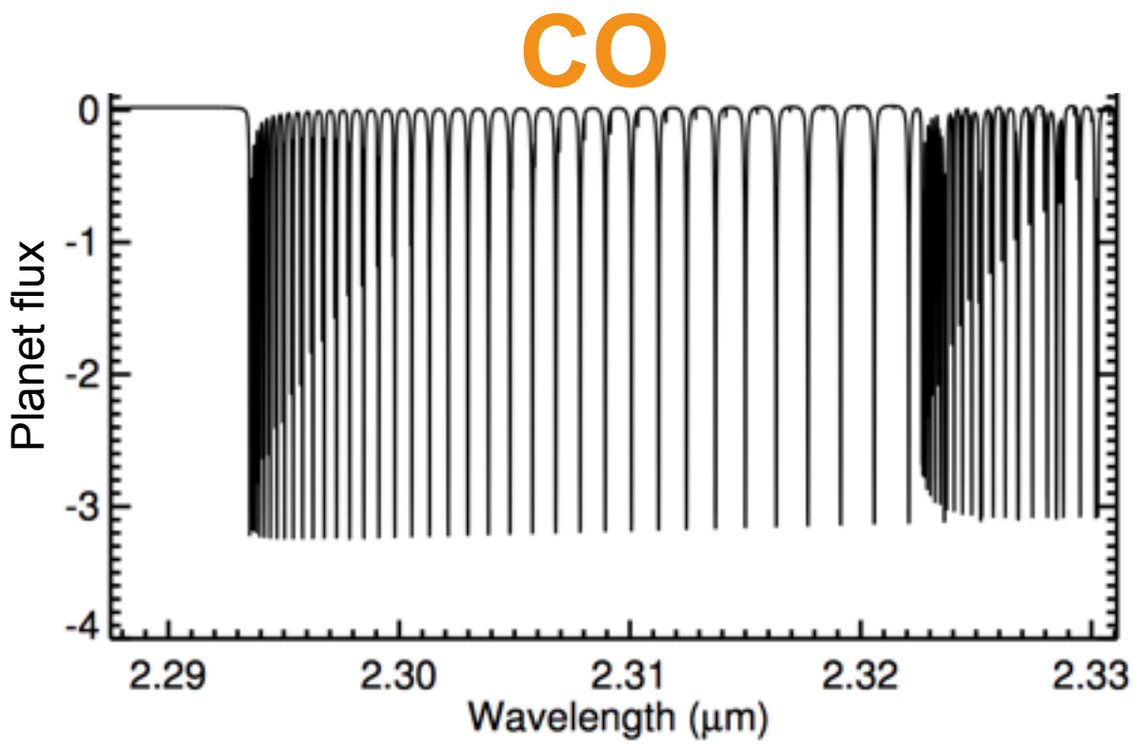
Non-transiting planet = spectroscopic binary

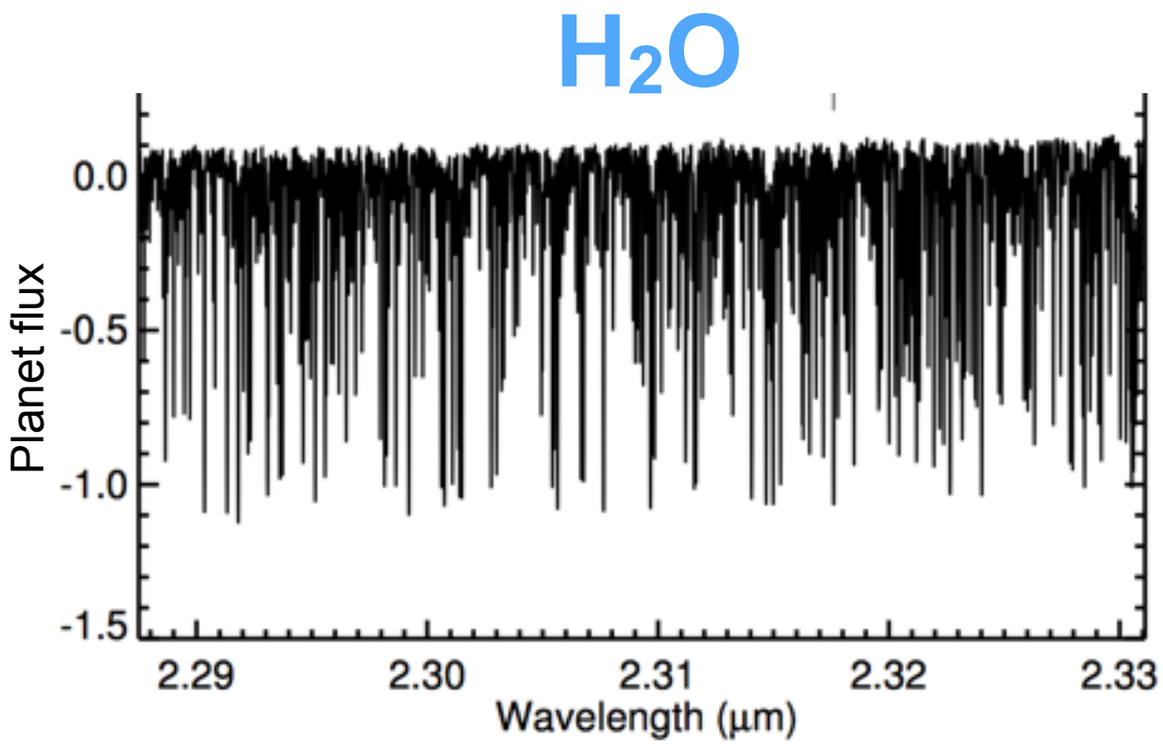
Complex molecules detected in hot Jupiter dayside atmospheres using HDS



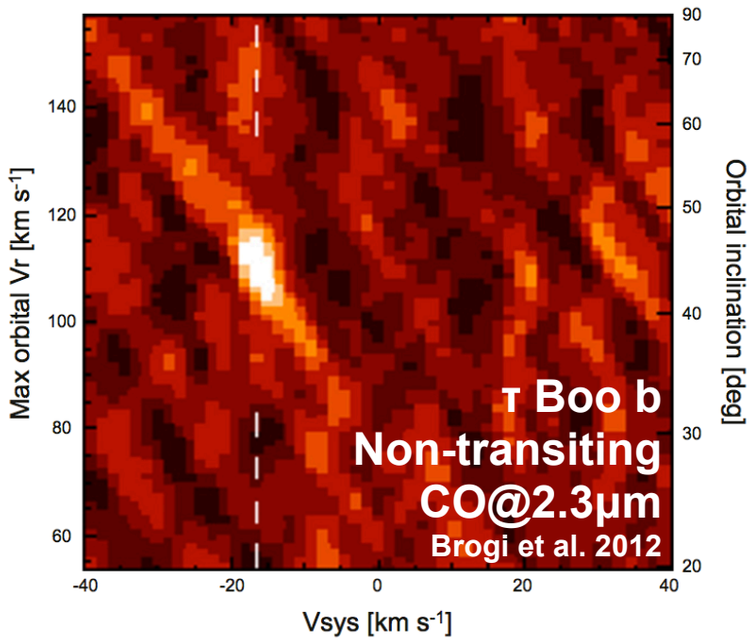


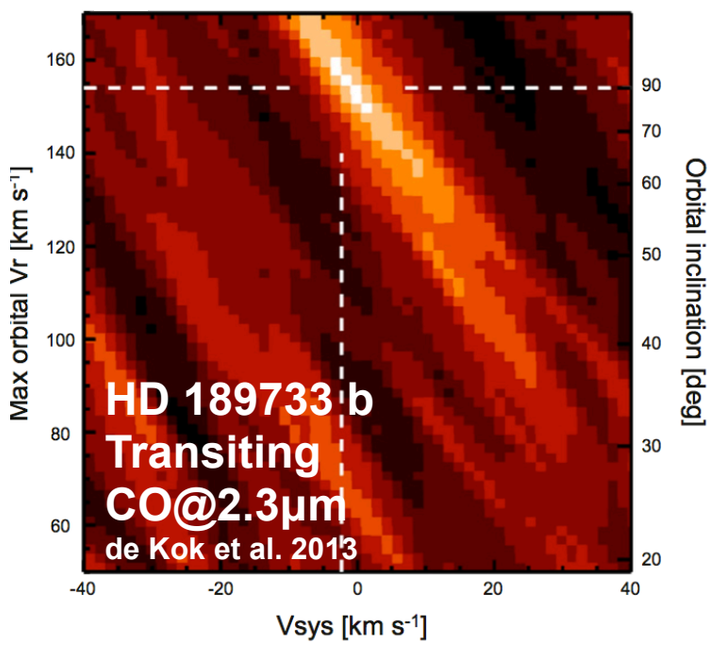


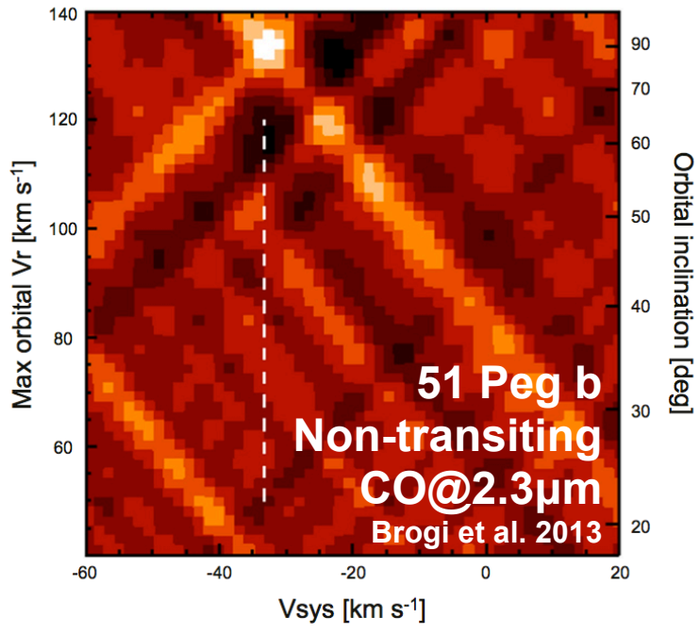


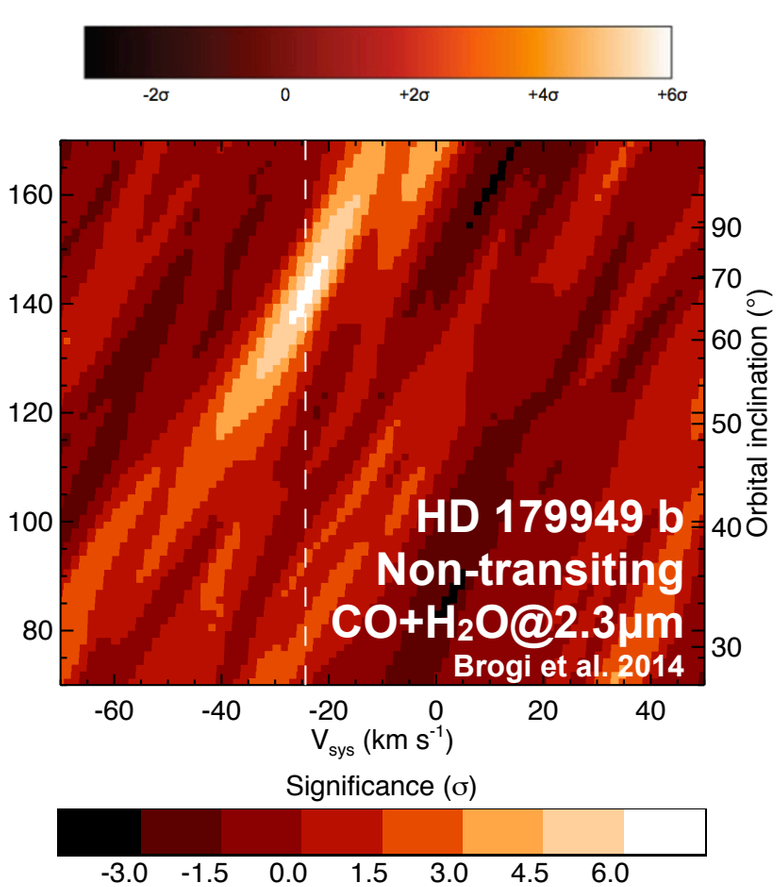


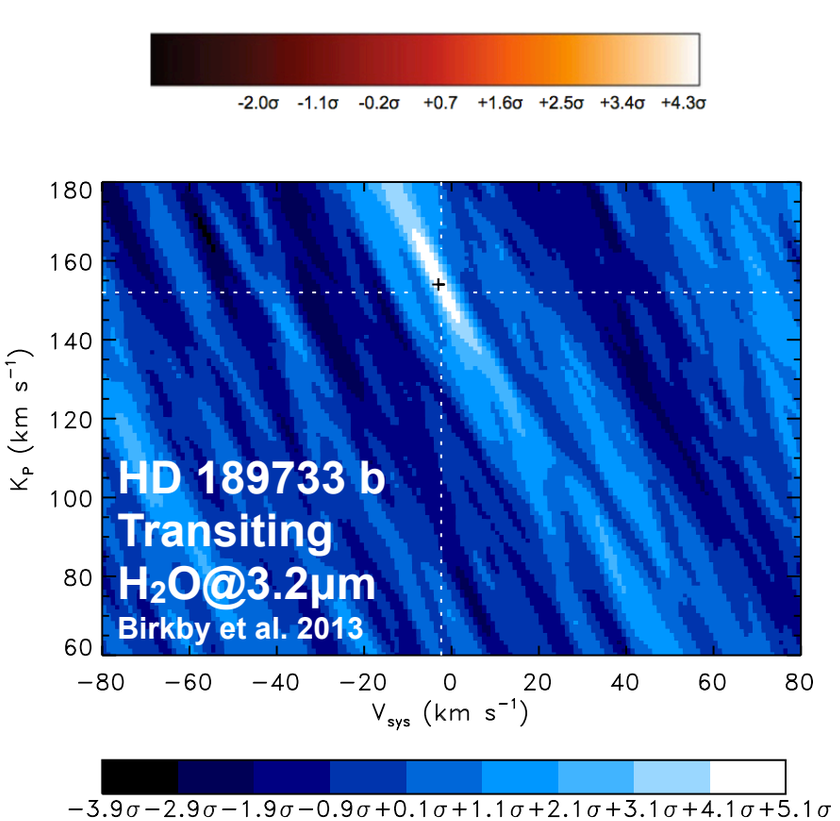
Complex molecules detected in hot Jupiter dayside atmospheres using HDS

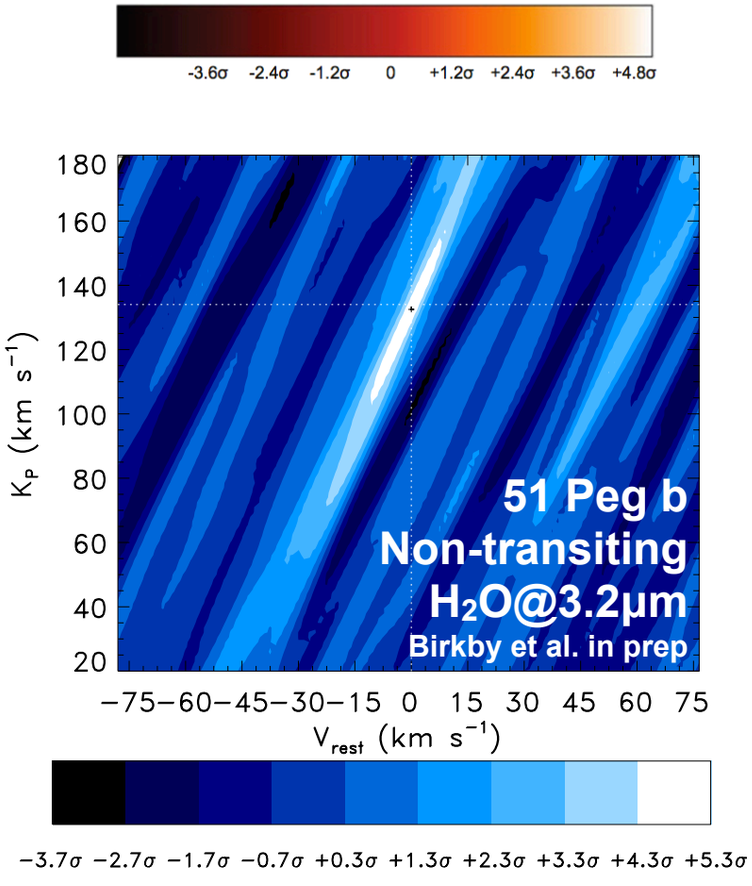








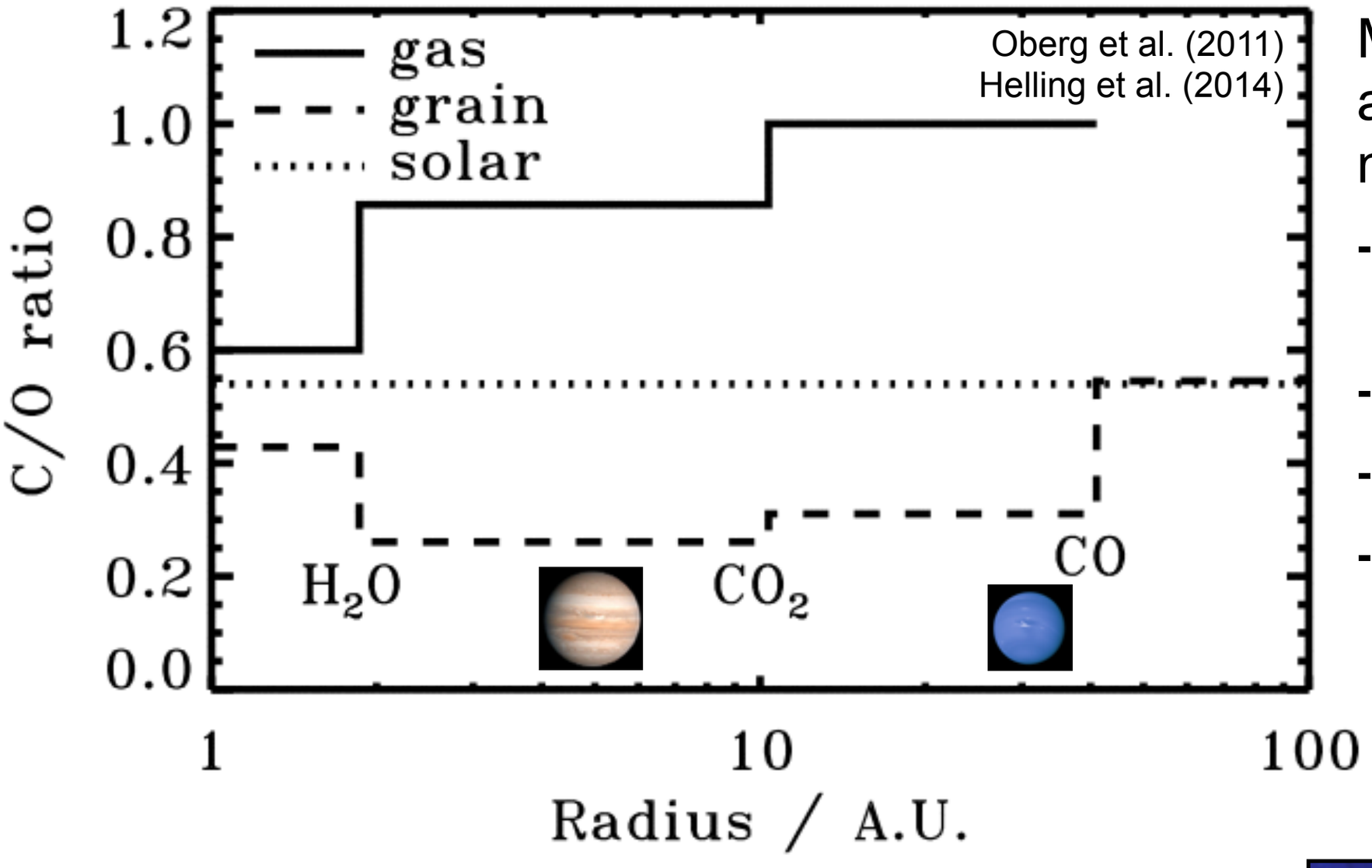




See also Rodler et al. 2012; 2013 (CO in τ Boo b & HD 189733 b); Lockwood et al. 2014 (H_2O in τ Boo b)

Exoplanet atmospheres as fossil records?

C/O ratio could reveal where and how a planet formed in its protoplanetary disk



Measure relative abundances of major molecules:

- **carbon monoxide (CO),**
- **water (H_2O),**
- **methane (CH_4),**
- **carbon dioxide (CO_2)**

Moses et al. (2013)

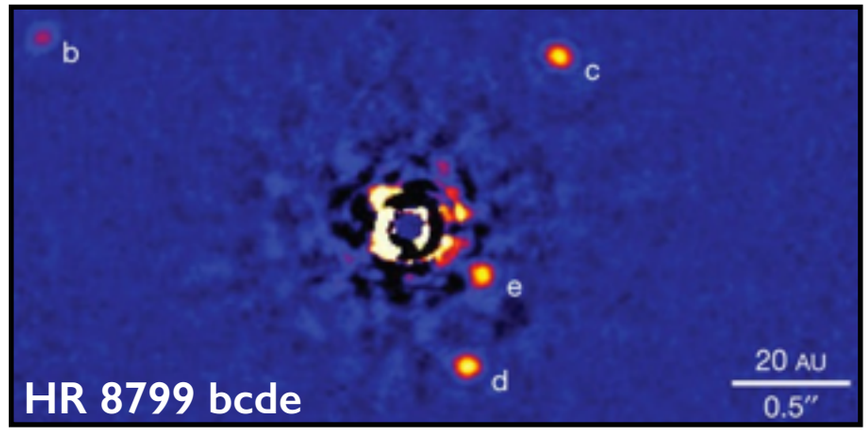
For HR 8799 planets:

i) Super-stellar C/O: core accretion at location

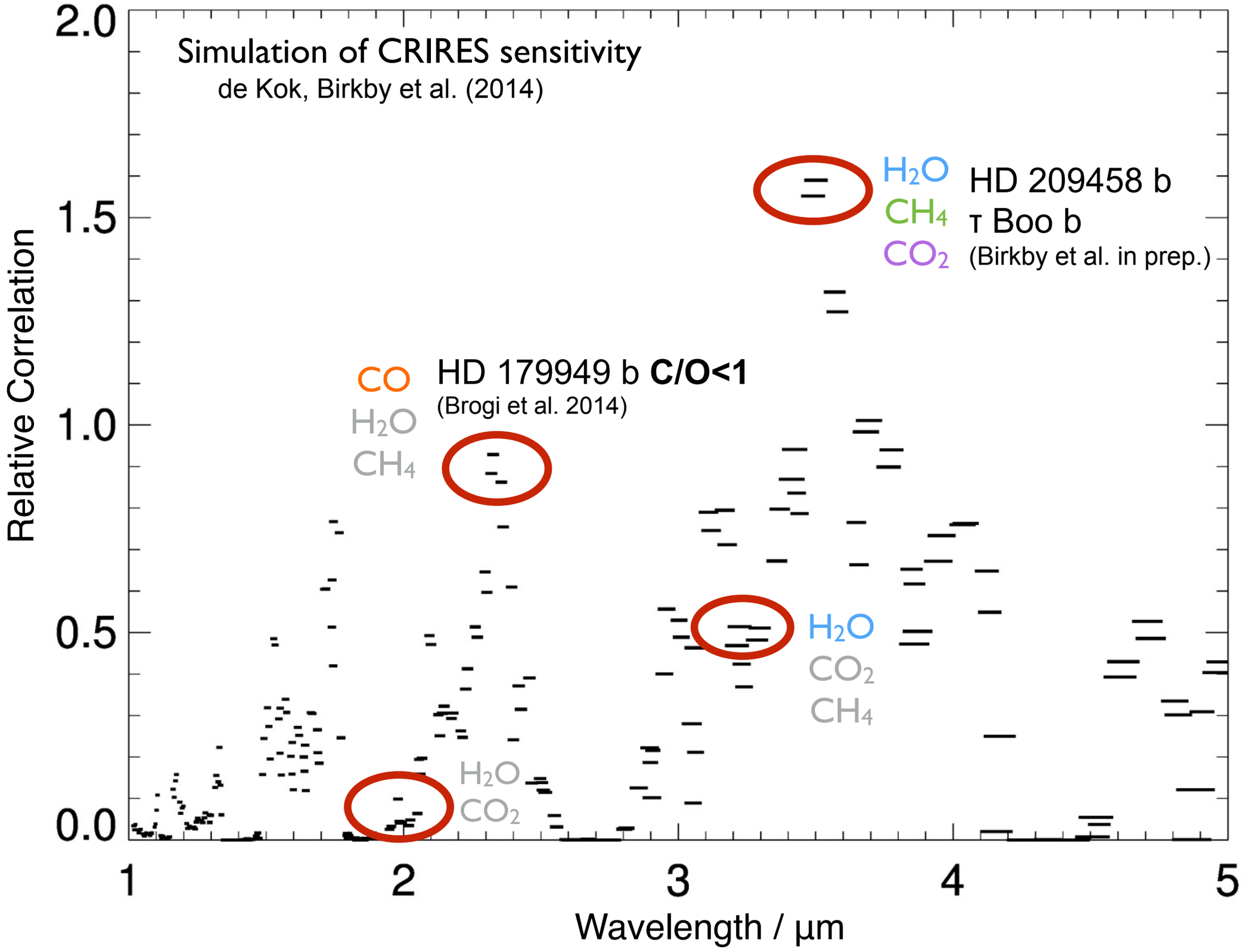
ii) Stellar C/O: gas collapse at location

Barman et al. 2015, Teske et al. 2014

Marois et al. (2010)

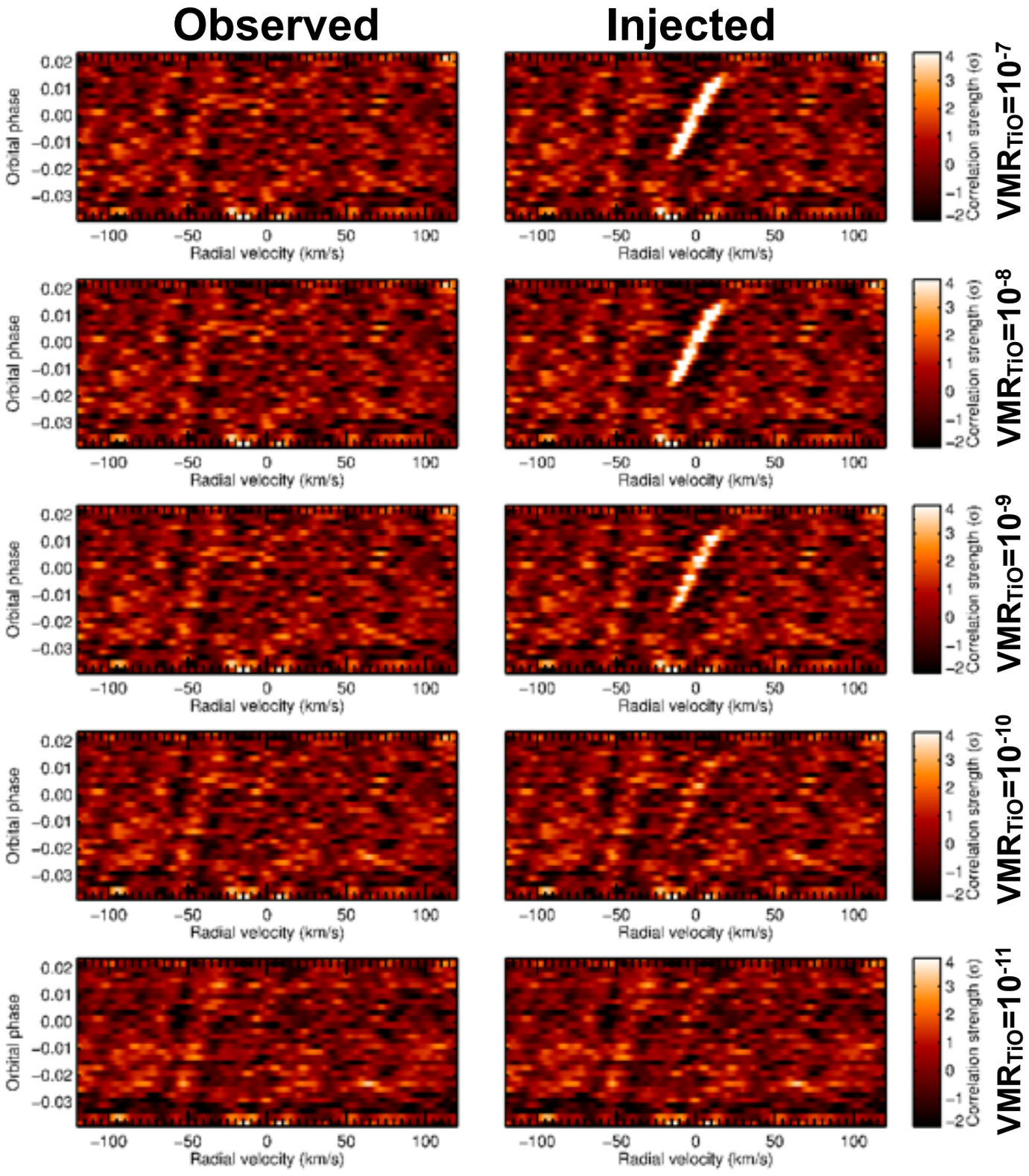


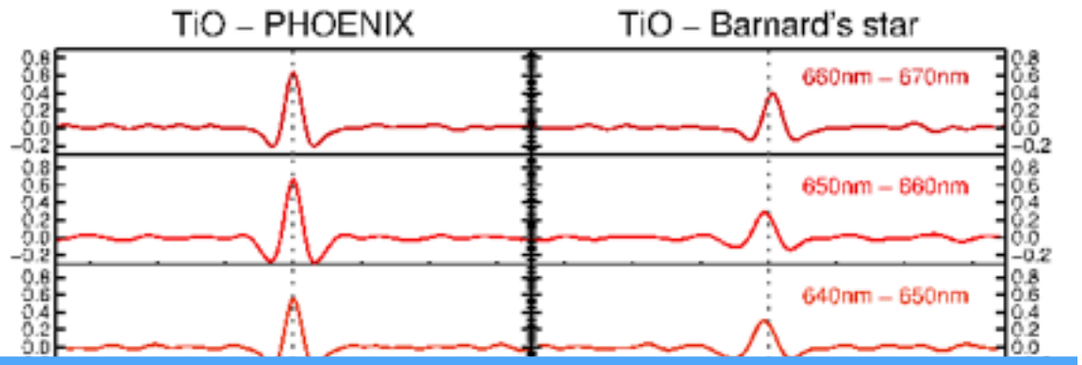
Simulations identify 3.5μm as spectral *'sweet spot'* for measuring C/O ratio



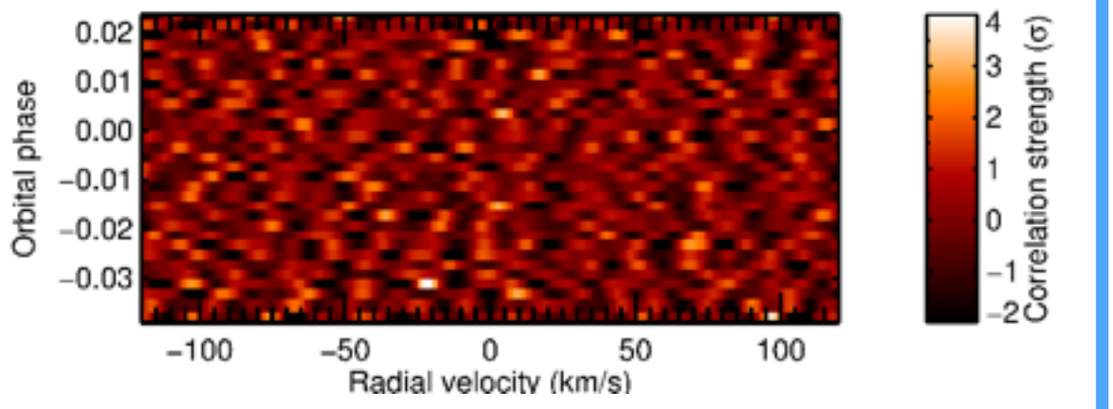
Probing temperature-pressure (T-P) profiles with HDS

HD 209458 b shows no evidence of TiO that could potentially cause an inversion layer

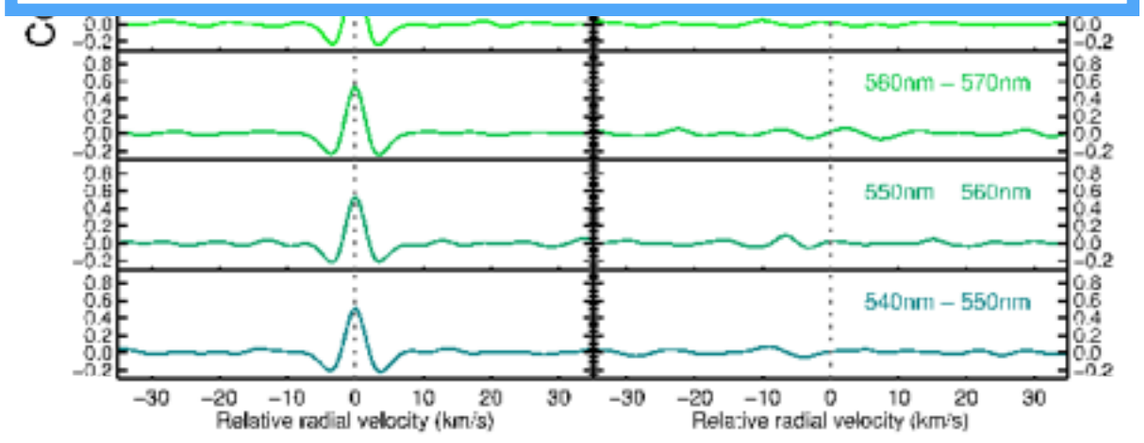




Accurate line lists are crucial for the high resolution technique

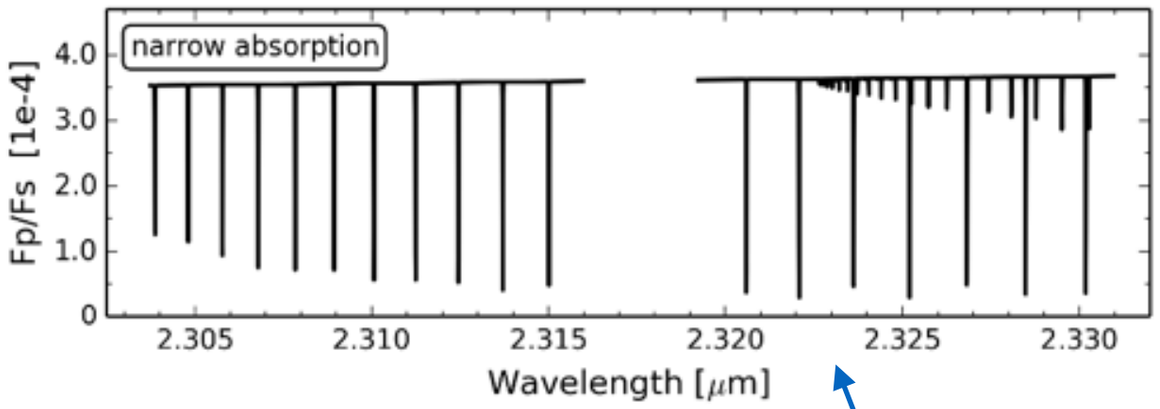


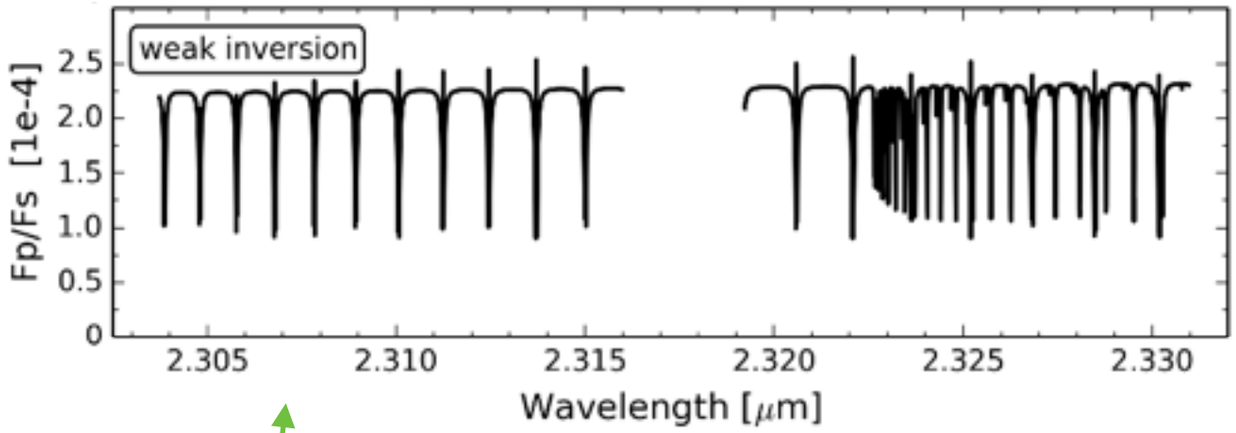
Cross-correlation with Barnard's star (M-dwarf)

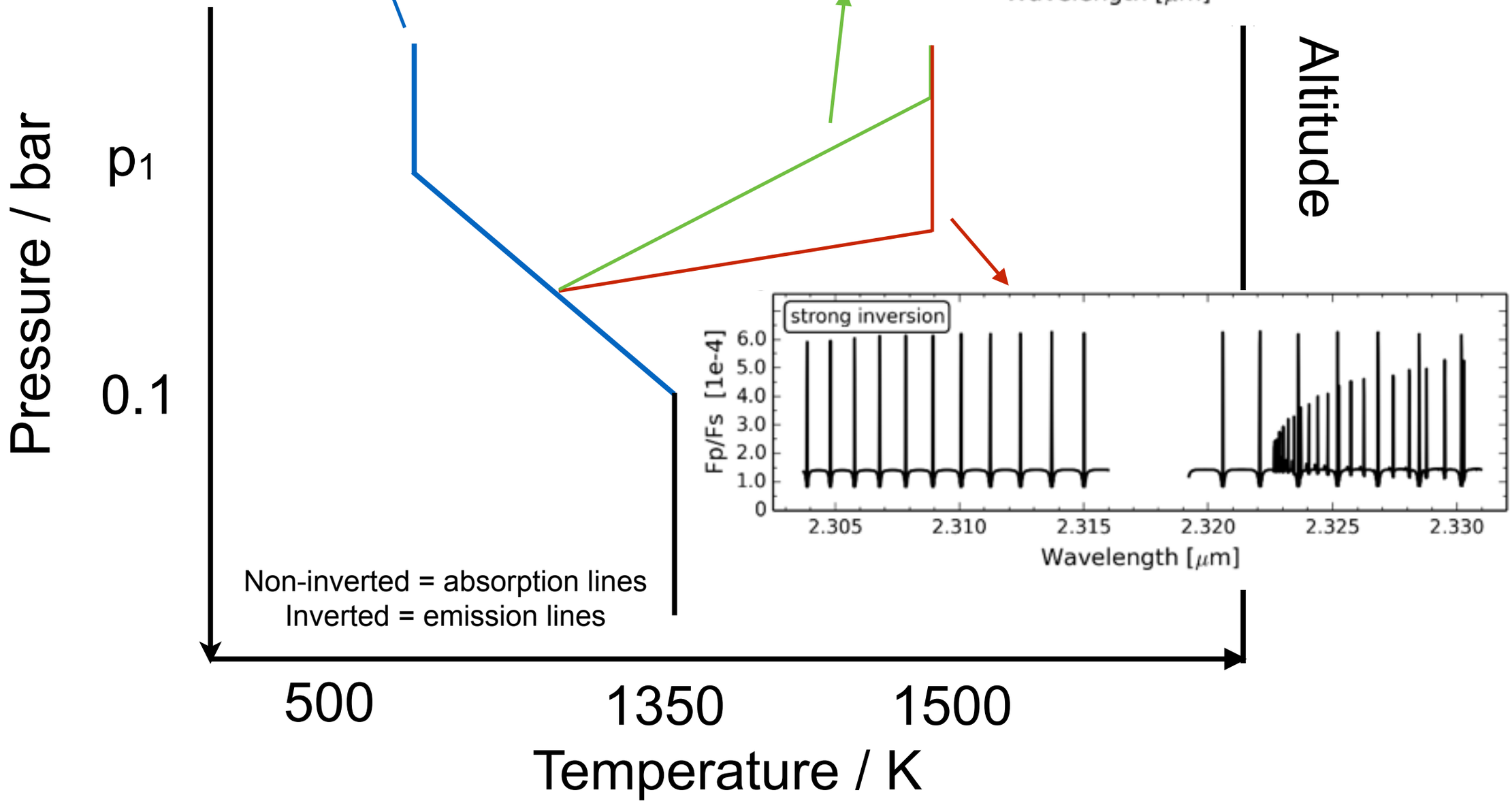


Hoeijmakers, de Kok, Snellen, Brogi, Birkby, Schwarz, 2014

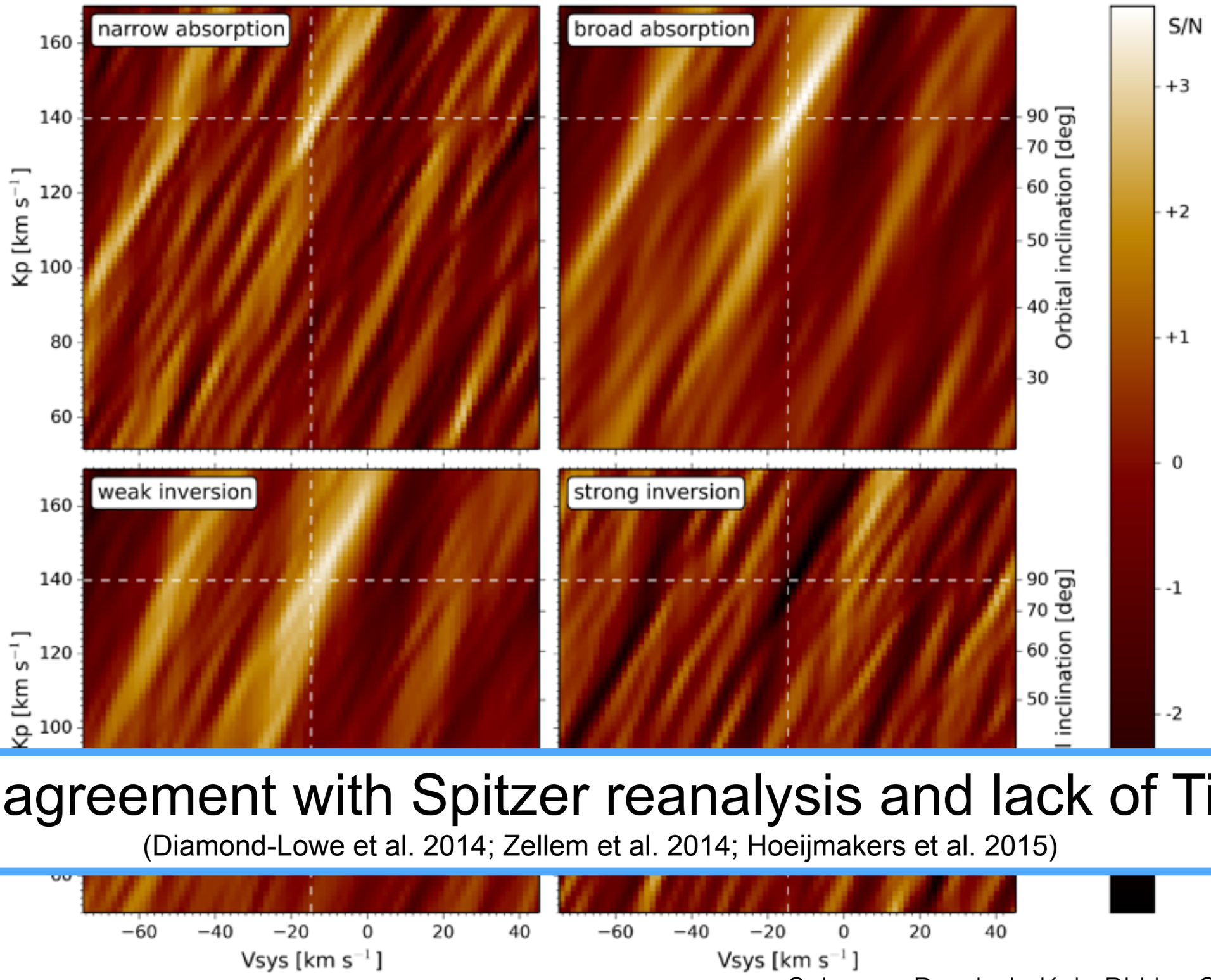
The shape of a planet's spectral lines depends on its T-P profile







Anti-correlation with CO emission lines suggest no inversion layer in HD 209458 b



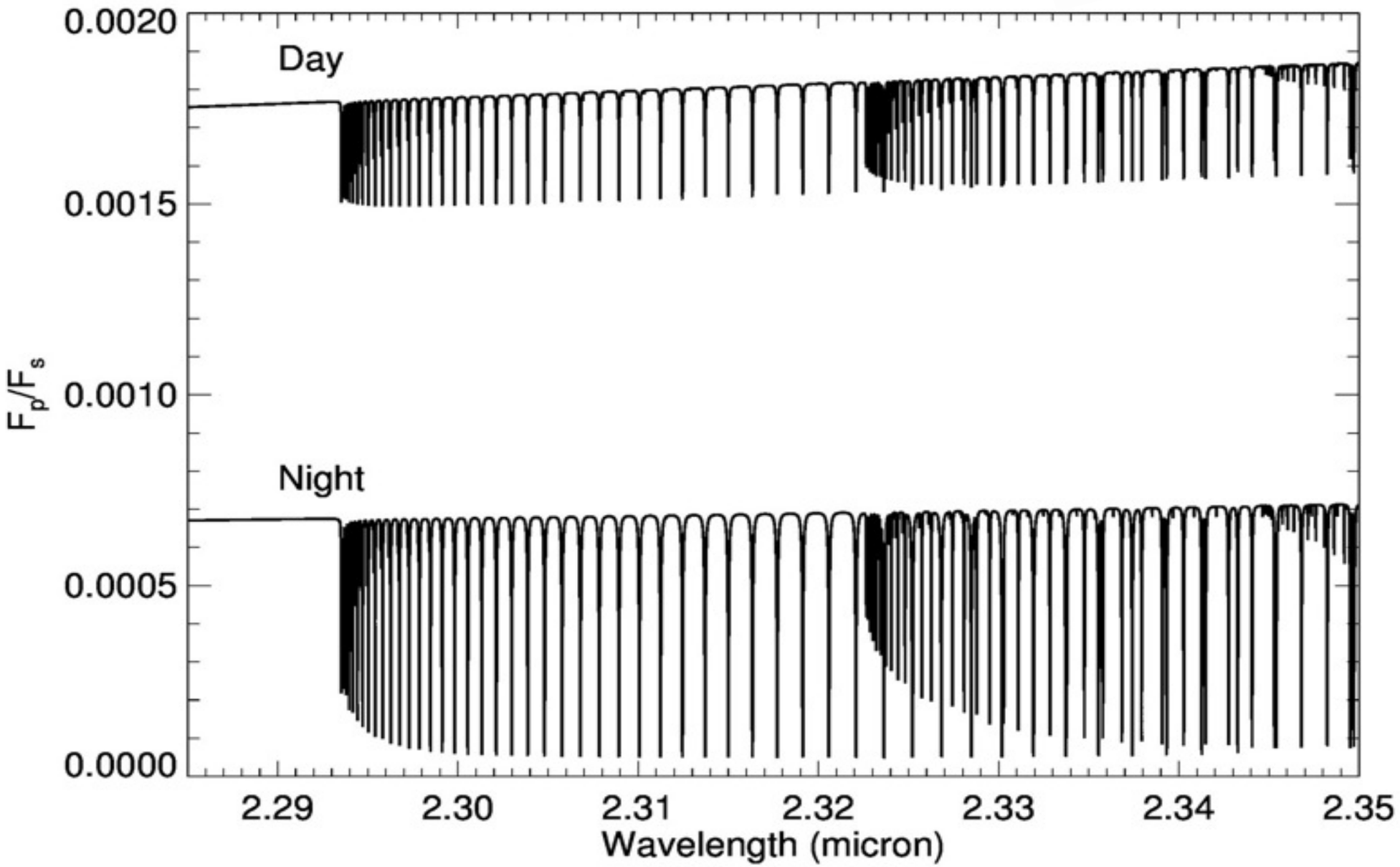
In agreement with Spitzer reanalysis and lack of TiO

(Diamond-Lowe et al. 2014; Zellem et al. 2014; Hoeijmakers et al. 2015)

Schwarz, Brogi, de Kok, Birkby, Snellen (2015)

Monitoring atmospheric dynamics with HDS

Nightside features are deeper and potentially easier to detect

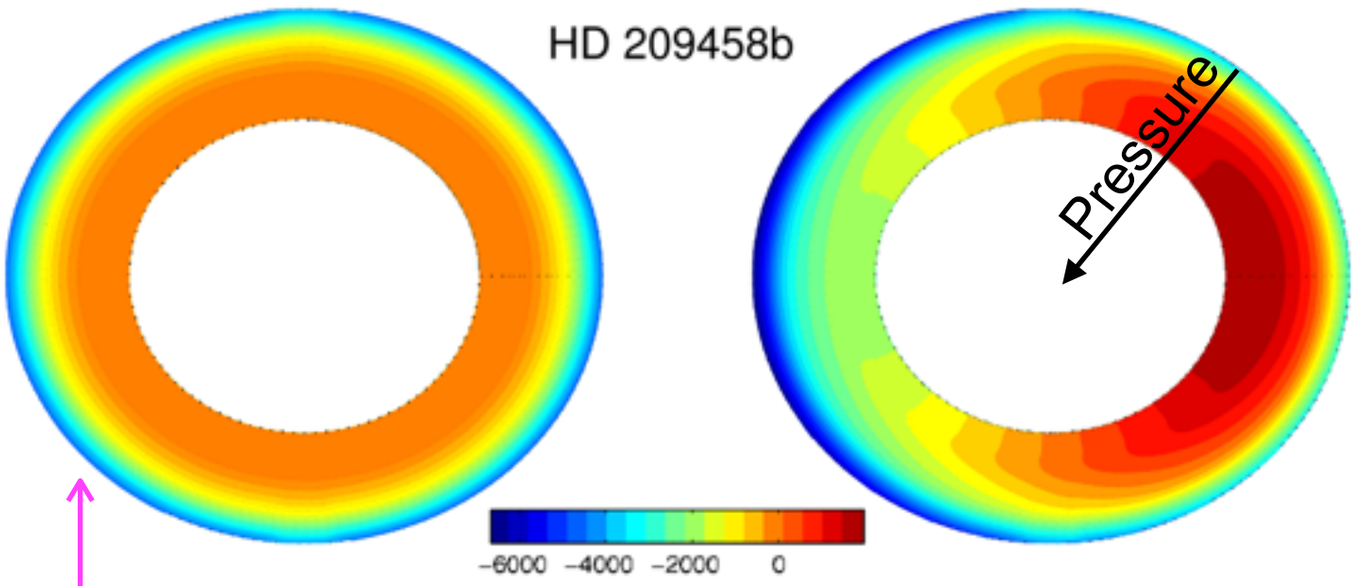


Reveals heat circulation

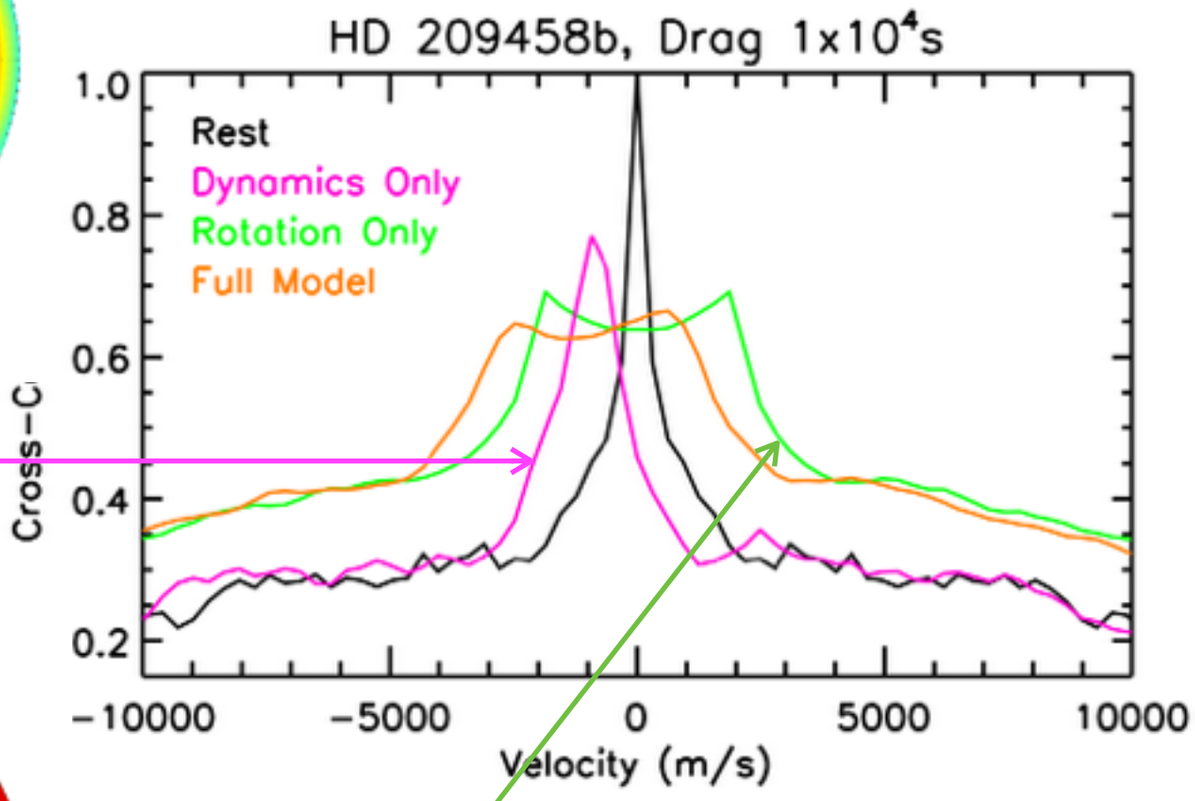
de Kok, Birkby et al. (2014)

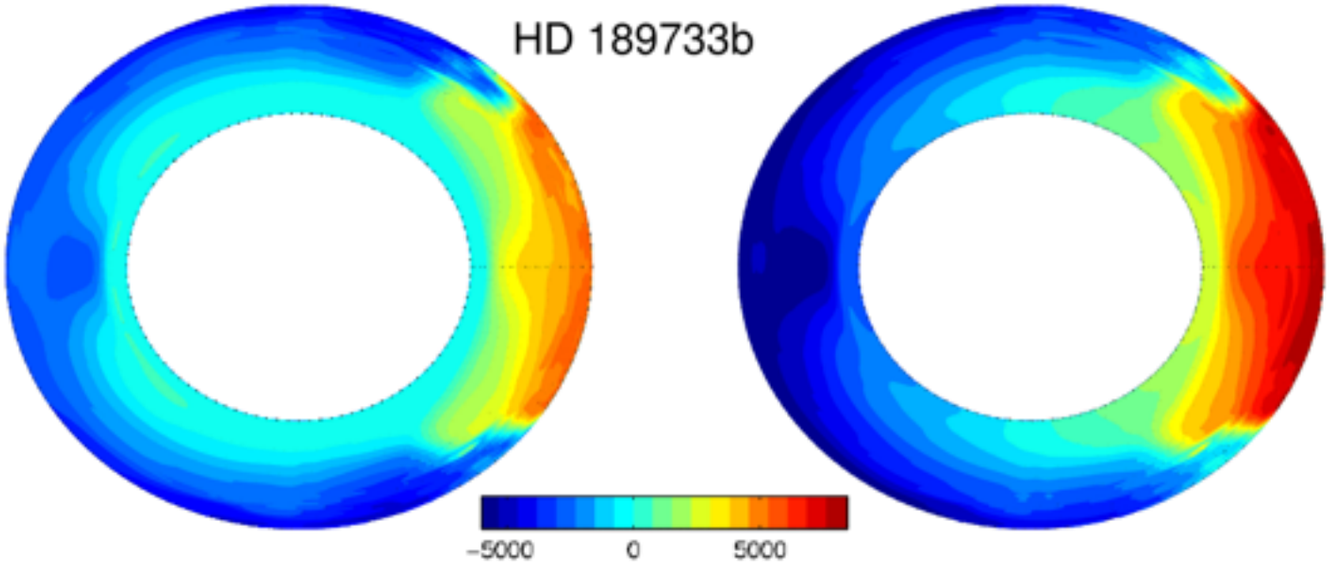
HDS is sensitive to line shape/shift from winds and rotation

Winds only **Winds+rotation**



Winds blue-shift entire upper atmosphere

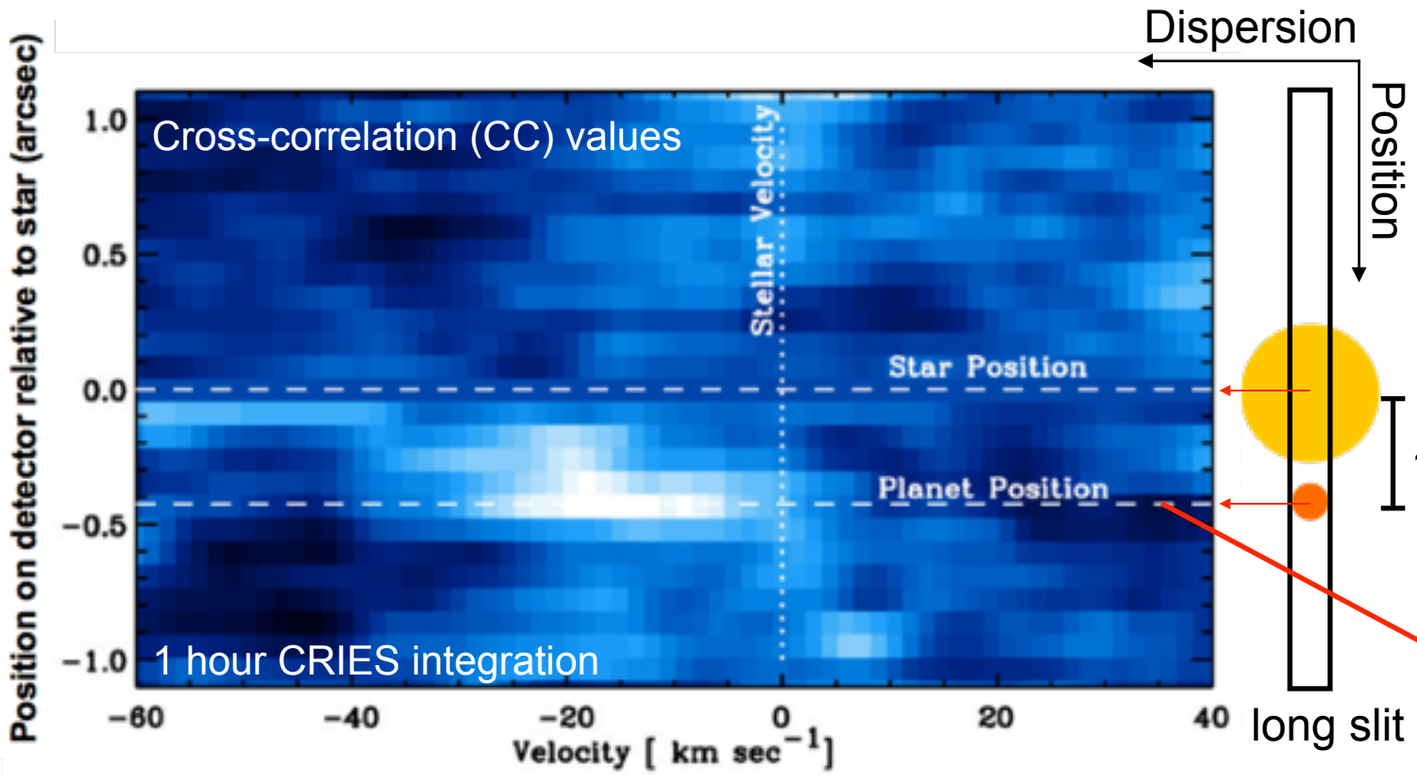


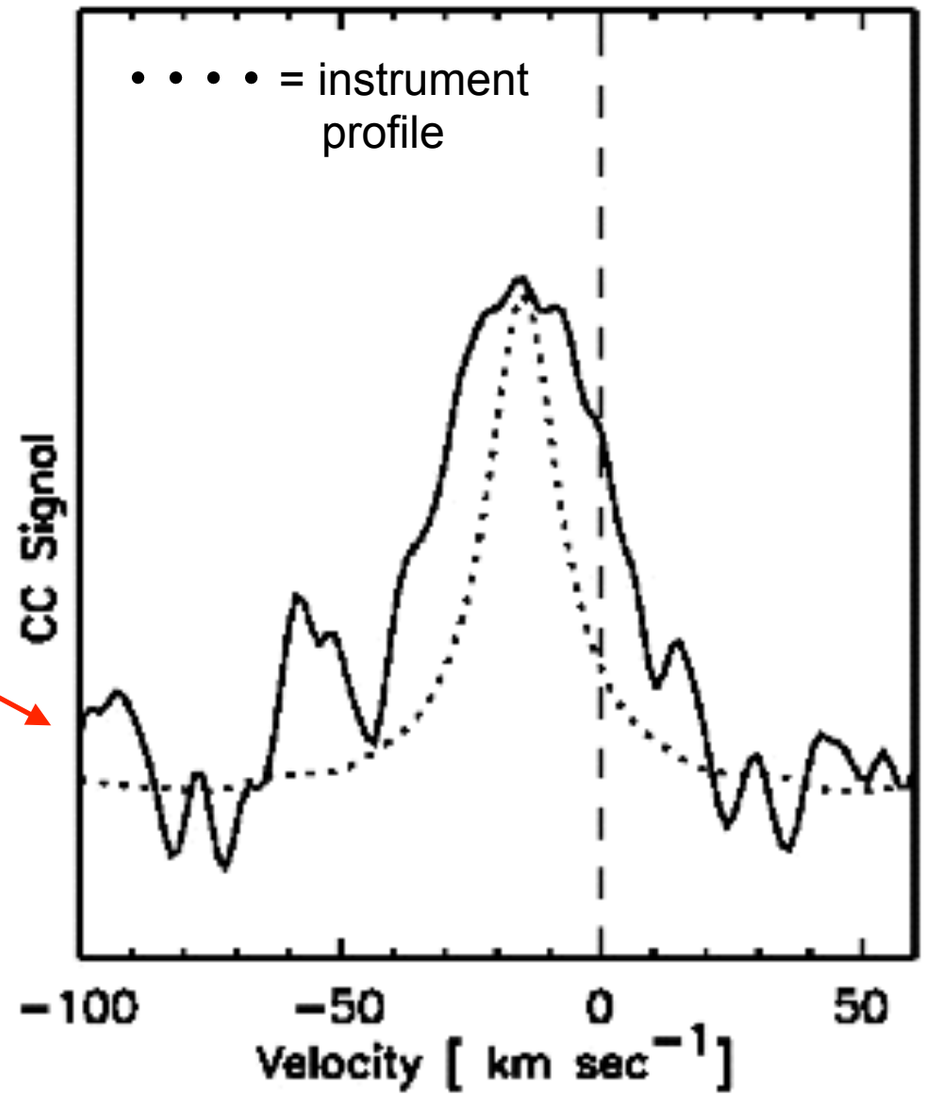


Rotation creates double-peaked line profile

Showman et al. 2013

HDS + high contrast imaging reveals rotation period of directly imaged planets





CO detected in β Pic b

Consistent with position from direct imaging and with a circular orbit. H_2O only seen at SNR~2. No methane.

Angular momentum acquired during formation

V_{rot} = 25 ± 3 km/s

P_{rot} ~ 8.1±1.0 hrs

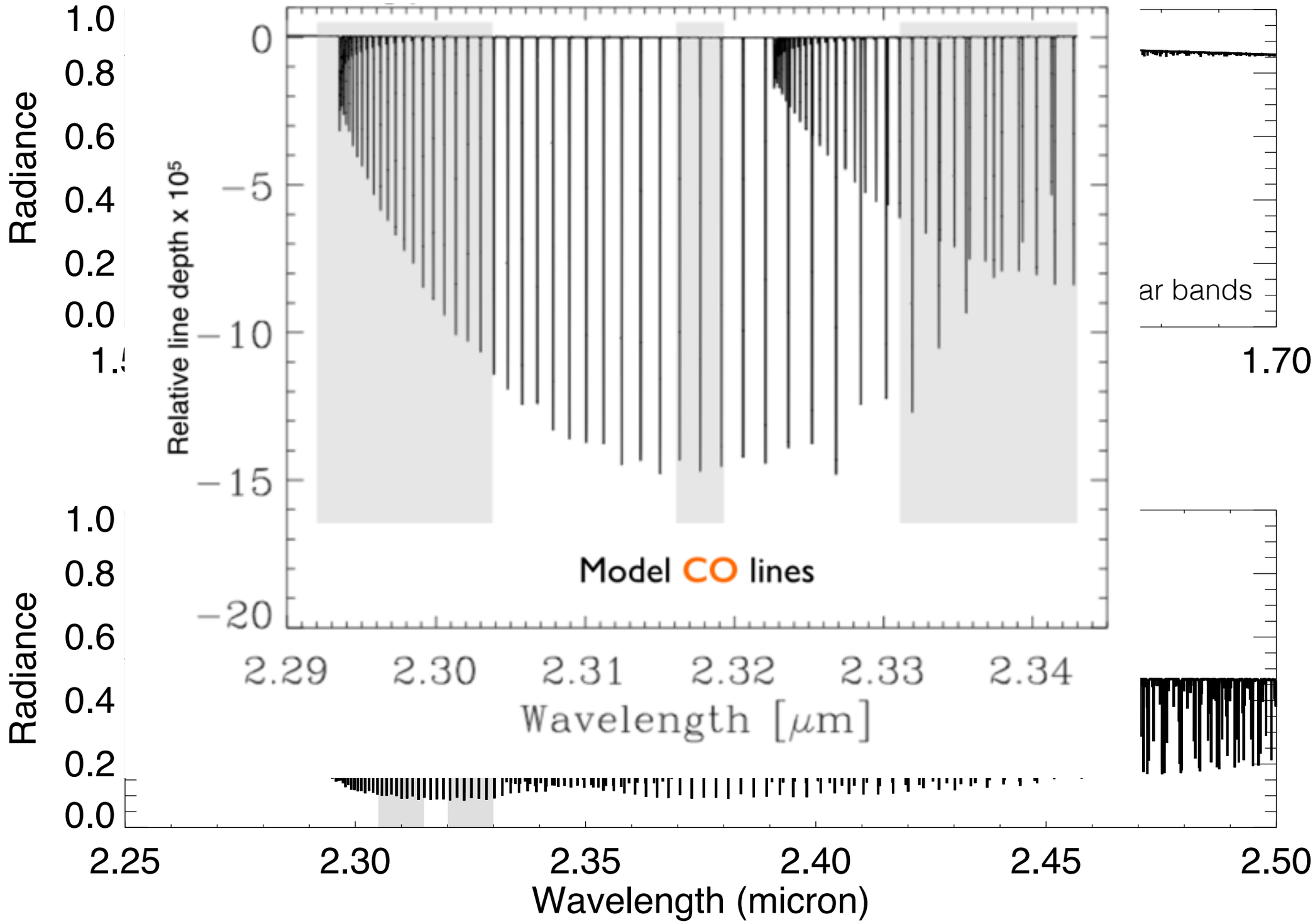
Snellen, Brandl, de Kok, Brogi, Birkby, Schwarz, 2014

Instruments for HDS

ARIES: Arizona Infrared Echelle Spectrograph

ARIES/MMT	CRIRES/VLT
D=6.5 m	D=8.2 m
R=30,000	R=100,000
Δλ=1 μm	Δλ=0.08 μm

Simultaneous wavelength coverage of ARIES covers ~7x more CO lines than CRIRES



Take home messages

- High dispersion spectroscopy (HDS) *unambiguously* identifies **molecular features** in exoplanet atmospheres and probes their **thermal structure**, but *accurate line lists* are crucial.

- **C/O ratios** measured with HDS may reveal planet **formation mechanism** and birth **location** in protoplanetary disk.

- HDS is sensitive to **rotationally broadened** line profiles and combined with high contrast imaging reveals the **rotational velocity** of giant planets at *wide* separations.

- New high-resolution (R > 25,000) infrared spectrographs with ***wide simultaneous wavelength coverage*** will significantly increase detection strength due to greater number of spectral lines observed.

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