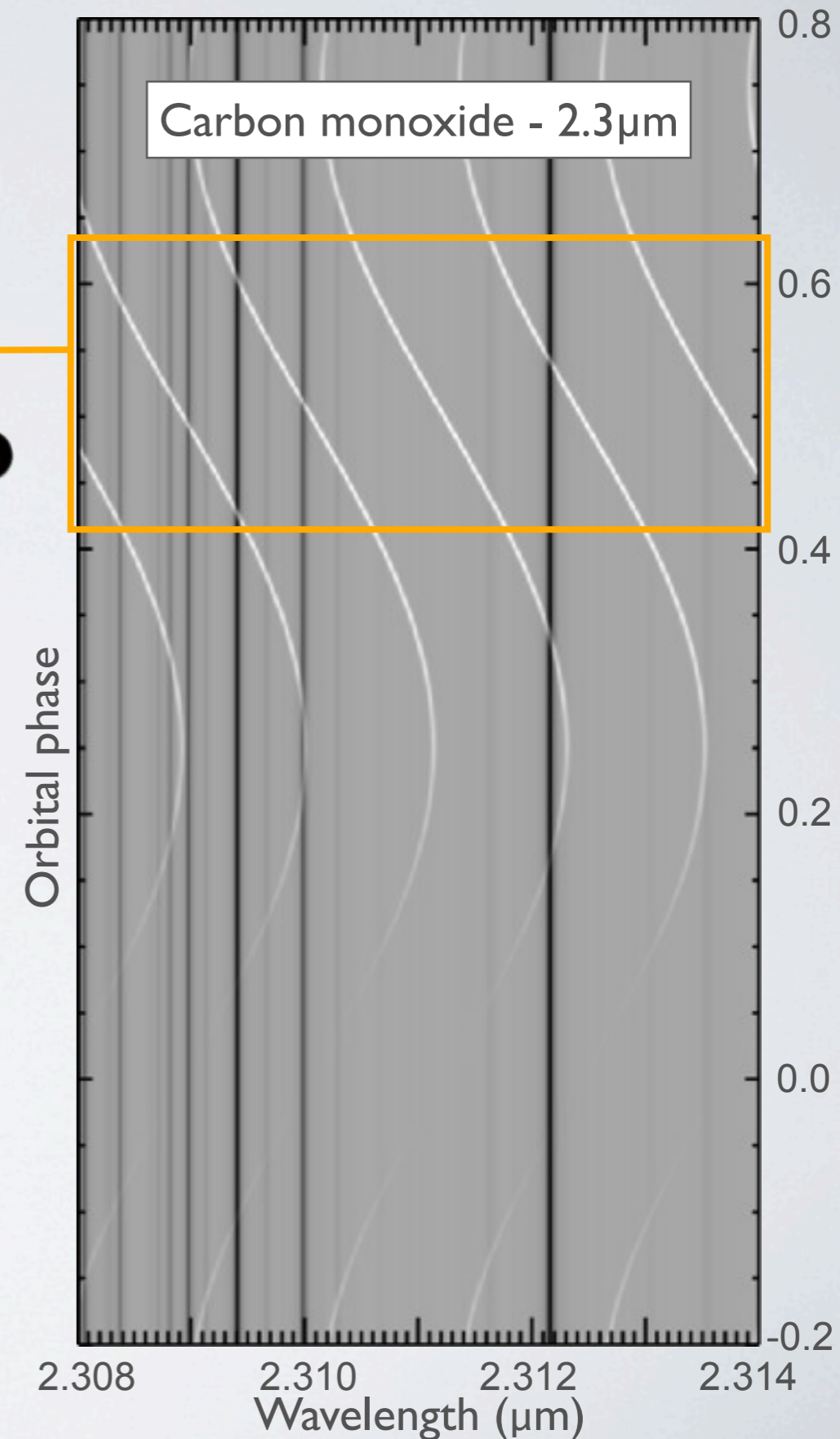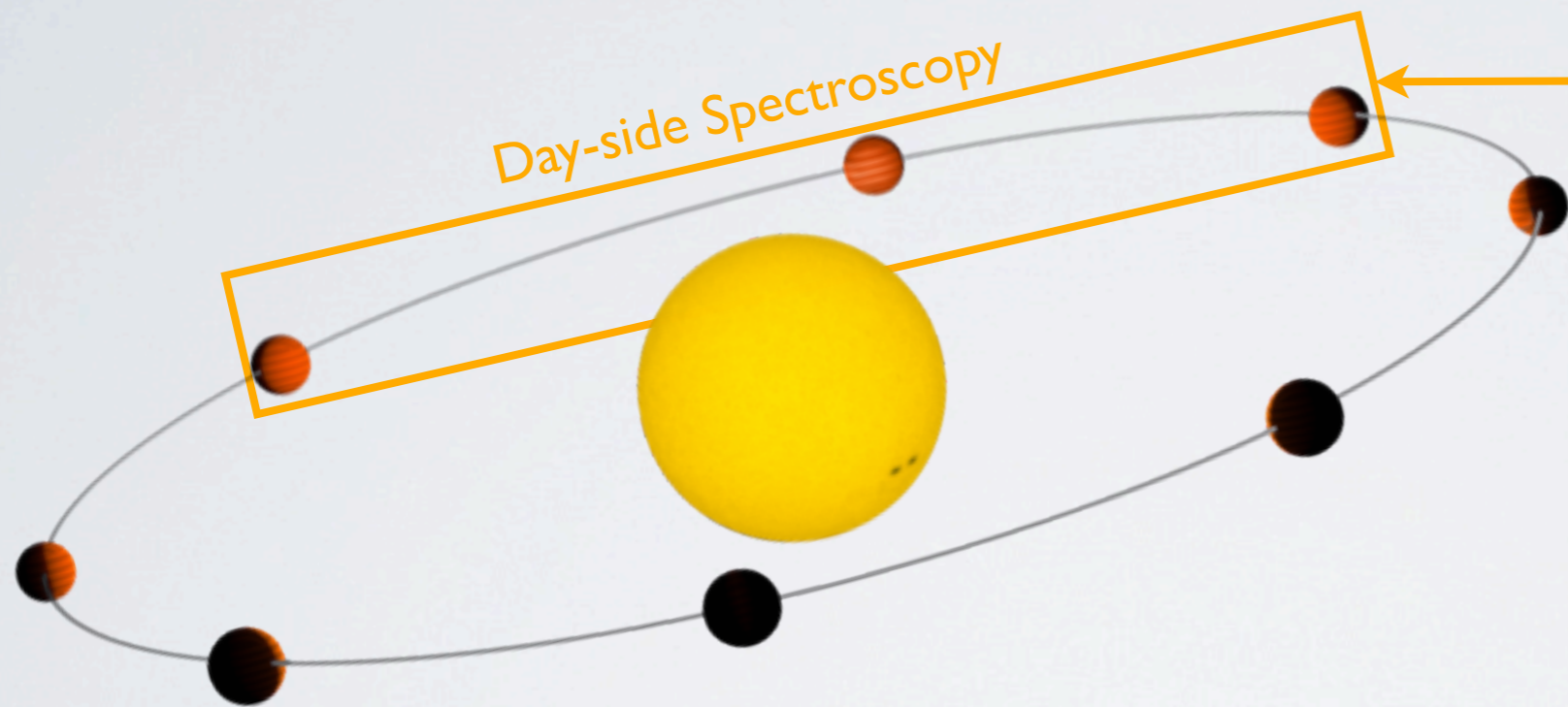# Probing the atmospheres of non-transiting planets

Matteo Brogi[1]

Ignas Snellen
Simon Albrecht
Jayne Birkby
Jens Hoeijmakers
Remco de Kok
Ernst de Mooij
Henriette Schwartz

The **thermal spectrum** of the planet is targeted.

Day-side Spectroscopy

Carbon monoxide - 2.3μm

Orbital phase

Wavelength (μm)

Molecules resolved into individual **lines**
⇒ Robust identification via line matching

Planet **motion** resolved
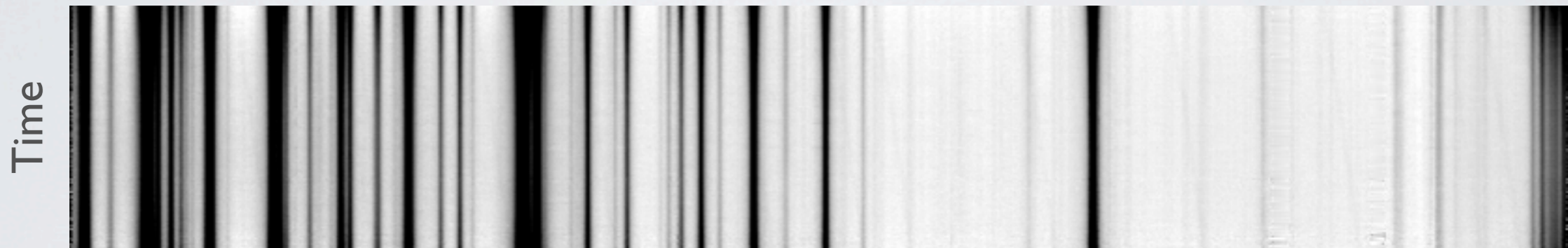⇒Telluric and planet signal disentangled

Extraction of the planet signal
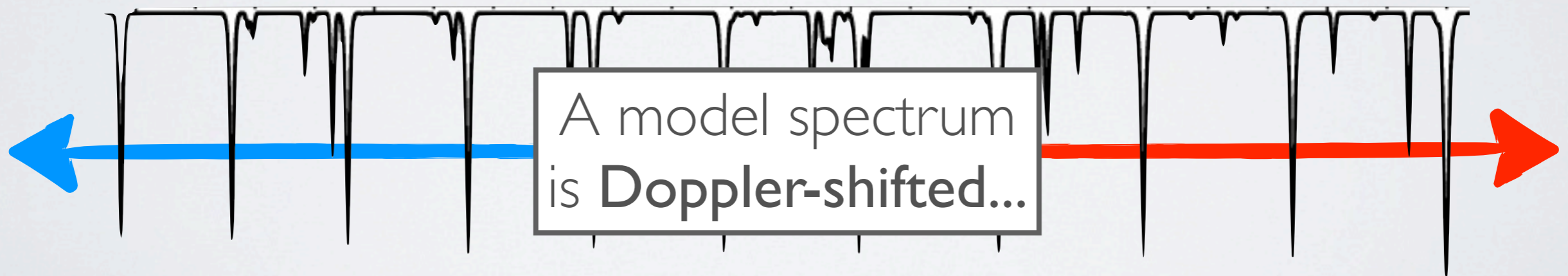
Earth's **atmosphere**: static w.r.t the observer
Planet spectrum: changing Doppler shift

Each resolution element (data column) = light curve

VLT/CRIRES - R=100,000 - 2.3μm - Detector #2 - 5 hours

Time

Wavelength

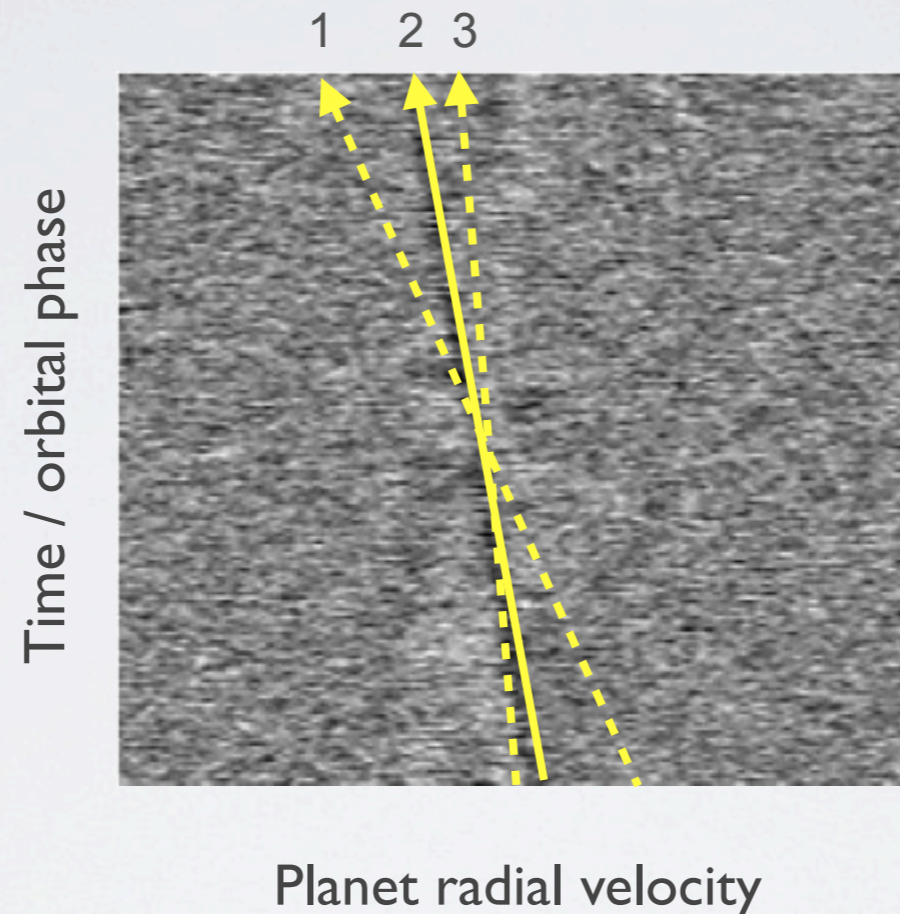A model spectrum
is **Doppler-shifted...**

...and **cross-correlated** with each observed spectrum

The planet RV curve

Cross-correlation signal → f(RV, time)
Portion of the planet RV curve

Orbital inclination:
1 - High
2 - Intermediate
3 - Low

Time / orbital phase

Planet radial velocity

5hrs data
20x planet signal

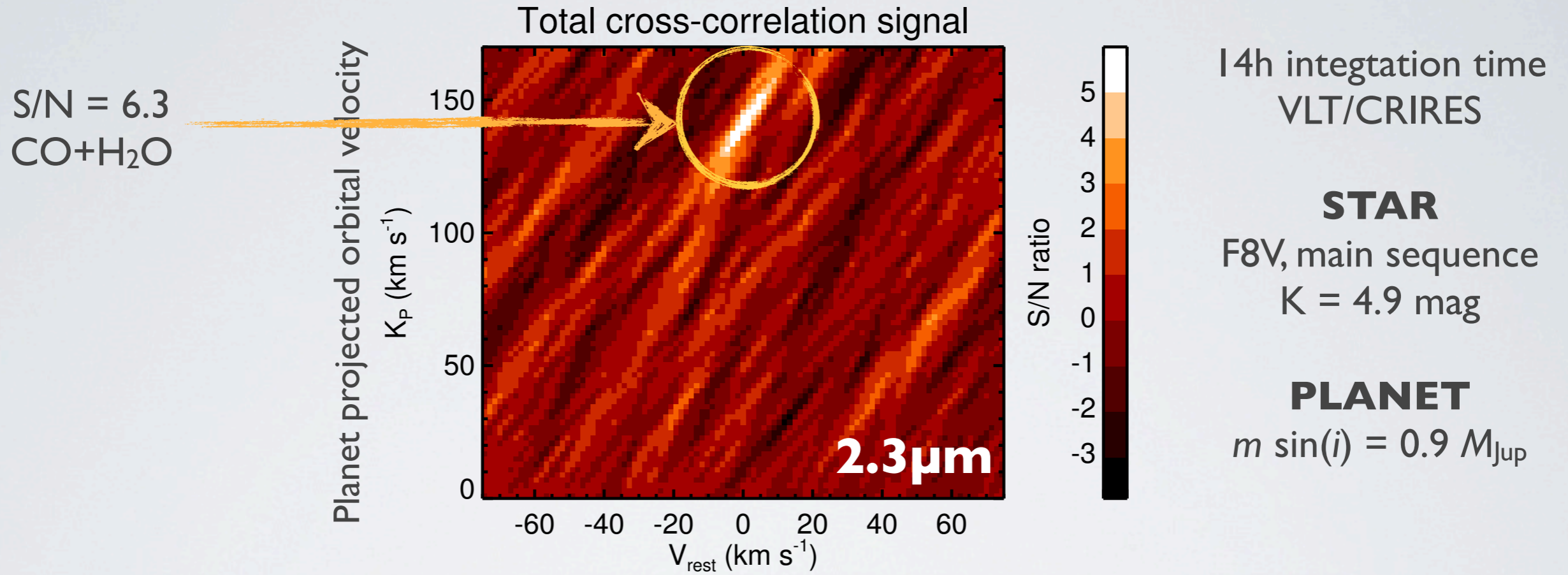The cross-correlation signal is **summed in time**

CCFs shifted to the planet rest frame
Unknown inclination → various planet **orbital velocities** (slopes)

The atmosphere of HD179949b unveiled

(Brogi et al. submitted)

Total cross-correlation signal

S/N = 6.3
CO+H_2O

Planet projected orbital velocity

K_P (km s^{-1})

S/N ratio

V_{rest} (km s^{-1})

2.3μm

14h integtation time
VLT/CRIRES

STAR
F8V, main sequence
K = 4.9 mag

PLANET
$m \sin(i) = 0.9\ M_{Jup}$

STELLAR & PLANET RVs ARE BOTH KNOWN

Measured
$K_P = 142.8 \pm 3.4$ km/s
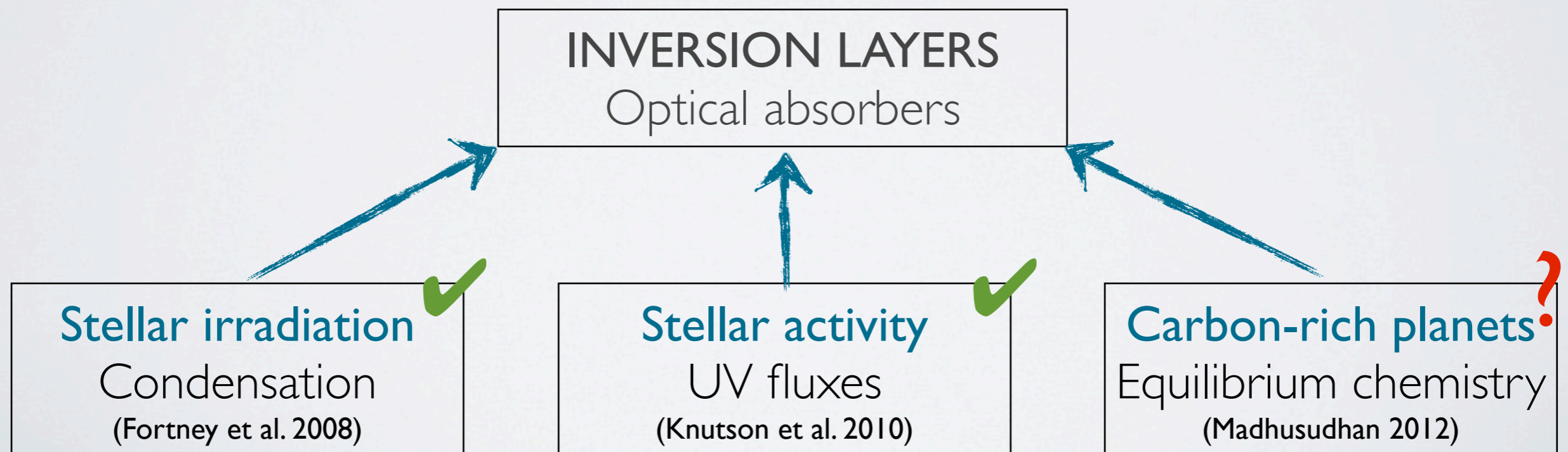$K_s = 112.6 \pm 1.8$ m/s
$M_P / M_S = 1268 \pm 36$

Inferred
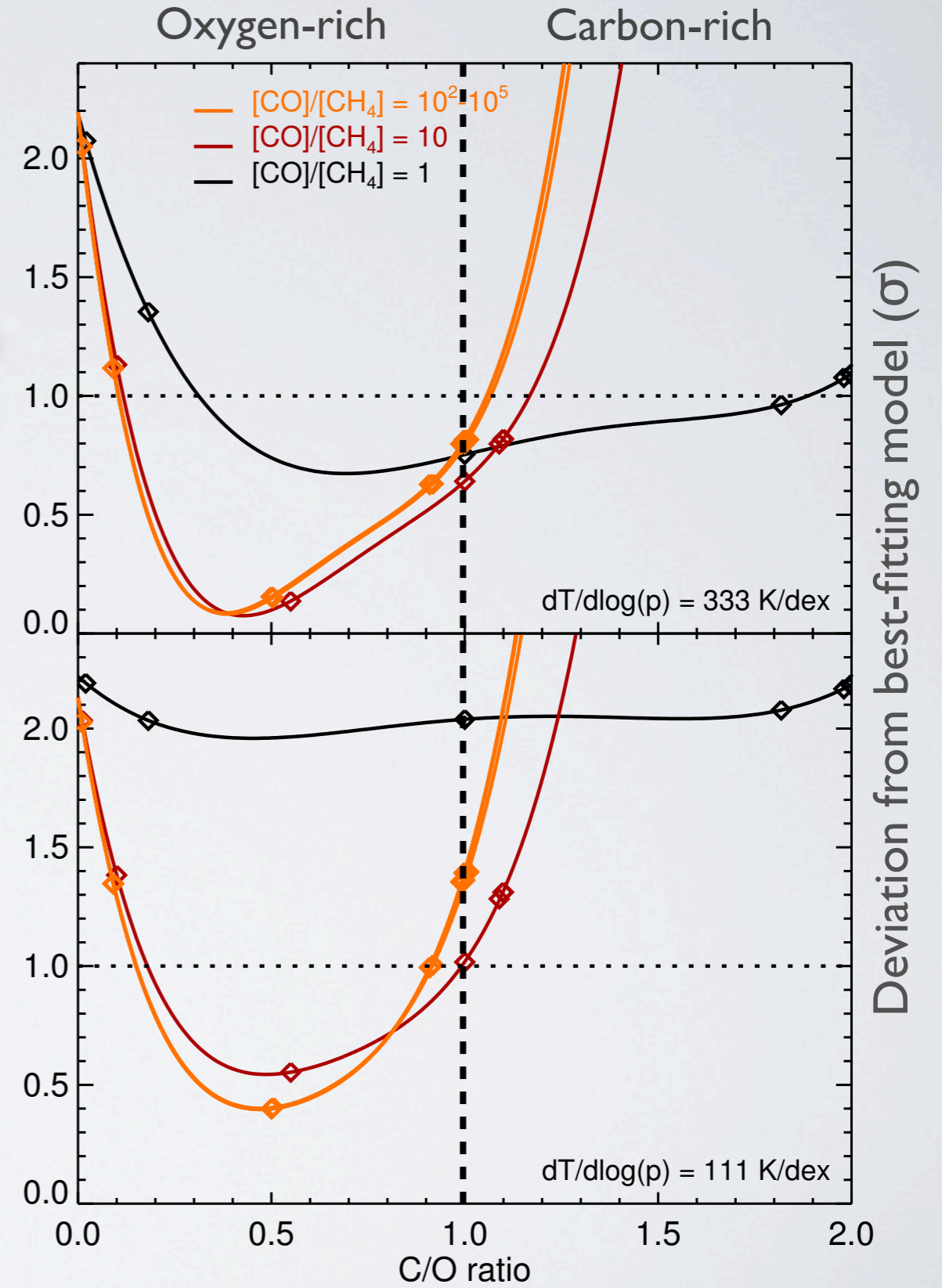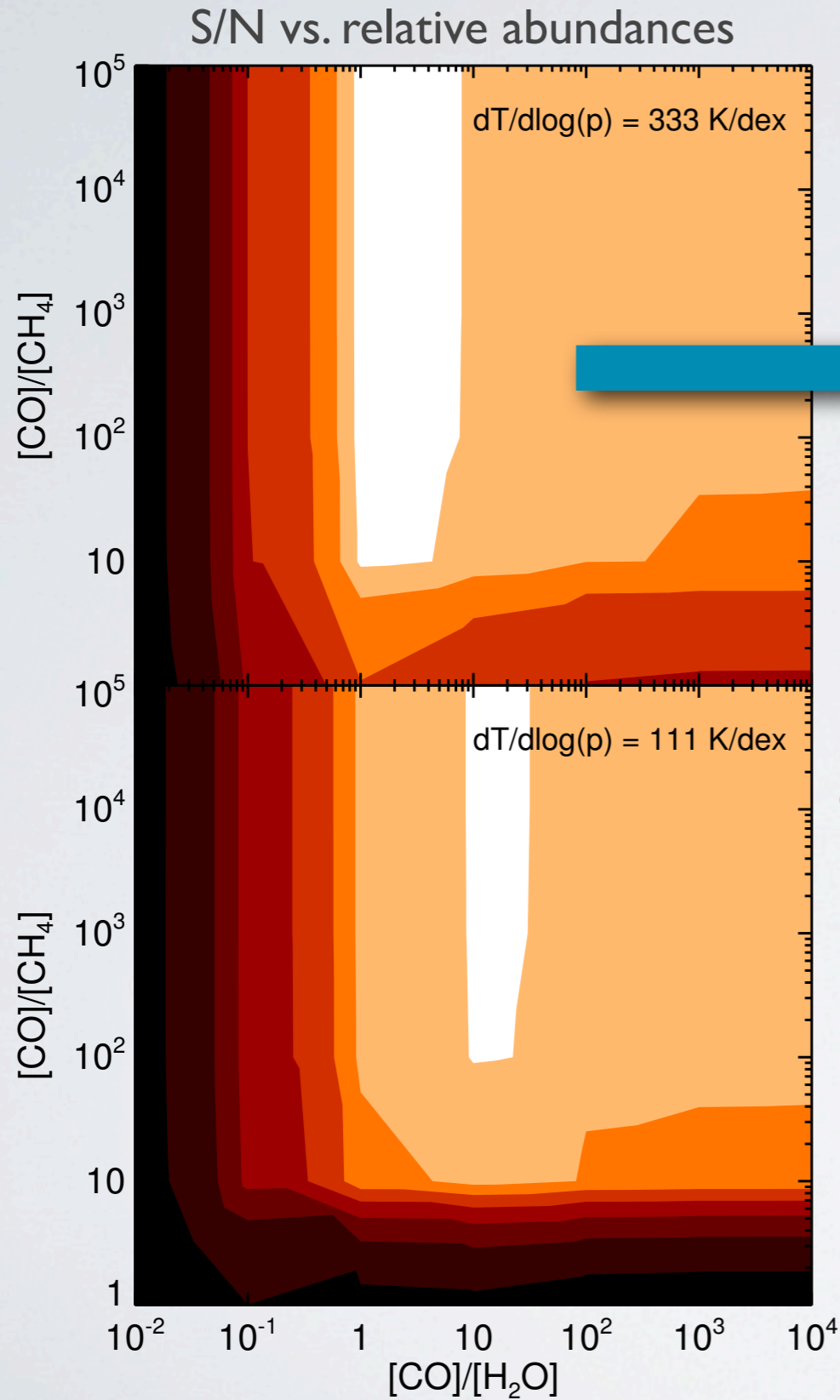$M_P = 0.98 \pm 0.04\ M_{Jup}$
$i = 67.7 \pm 4.3°$

ALL $f(M_S)$!

Atmospheric properties

Cross correlation with a **grid** of models (T, p, abundances)

- Molecular composition $\Rightarrow$ CO, H_2O (no CH_4)

- Vertical structure $\Rightarrow$ No inversion (only absorption)

- Degeneracies $\Rightarrow$ No absolute molecular abundances

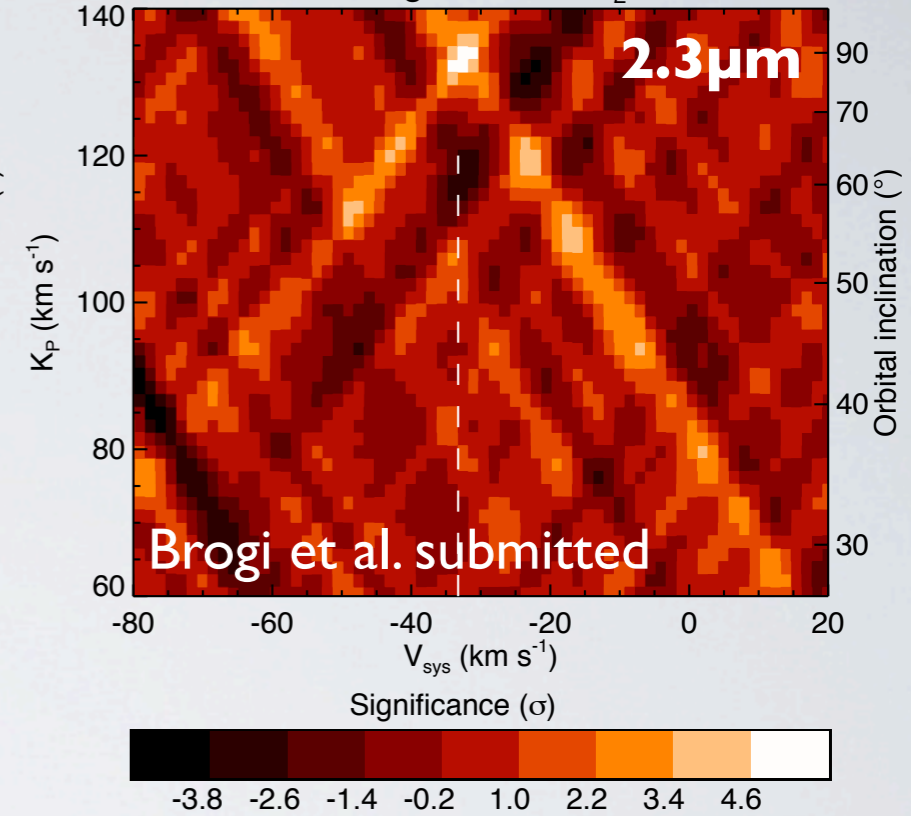- Relative molecular abundances $\Rightarrow$ C/O ratio
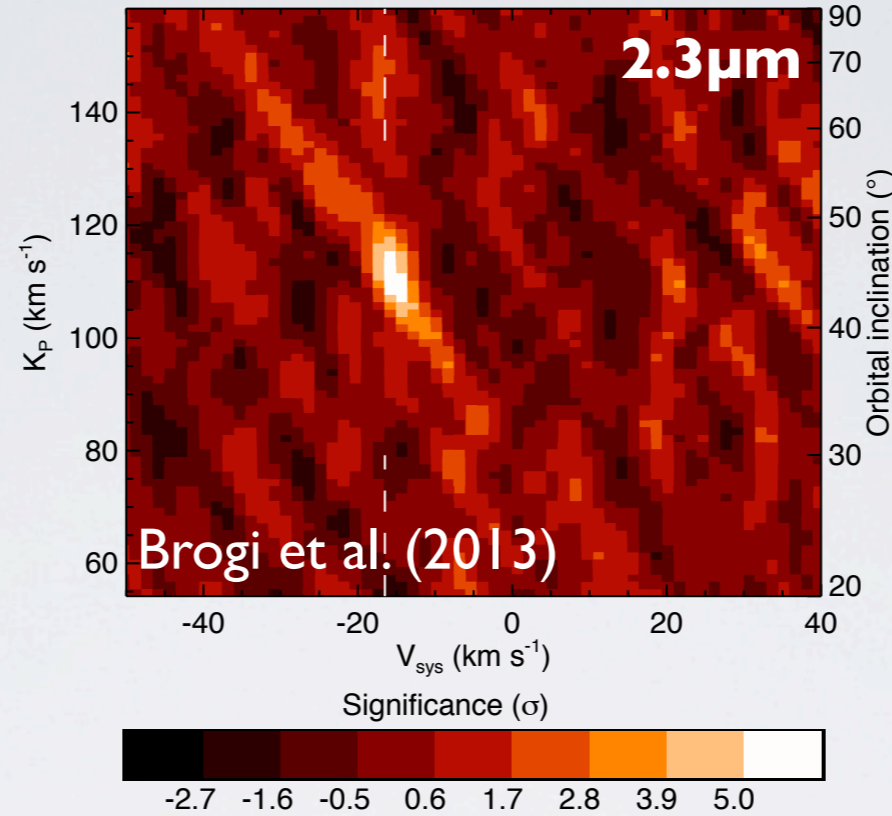
INVERSION LAYERS
Optical absorbers

Stellar irradiation
Condensation
(Fortney et al. 2008)

Stellar activity
UV fluxes
(Knutson et al. 2010)

Carbon-rich planets
Equilibrium chemistry
(Madhusudhan 2012)

C/O ratio from relative abundances

S/N vs. relative abundances

Oxygen-rich   Carbon-rich

Results from our survey

HD 179949b - CO + H_2O — 2.3µm
Brogi et al. (2012) (also Rodler et al. 2012)

τ Boo b - CO — 2.3µm
Brogi et al. (2013)

51 Peg b - CO + H_2O — 2.3µm
Brogi et al. submitted
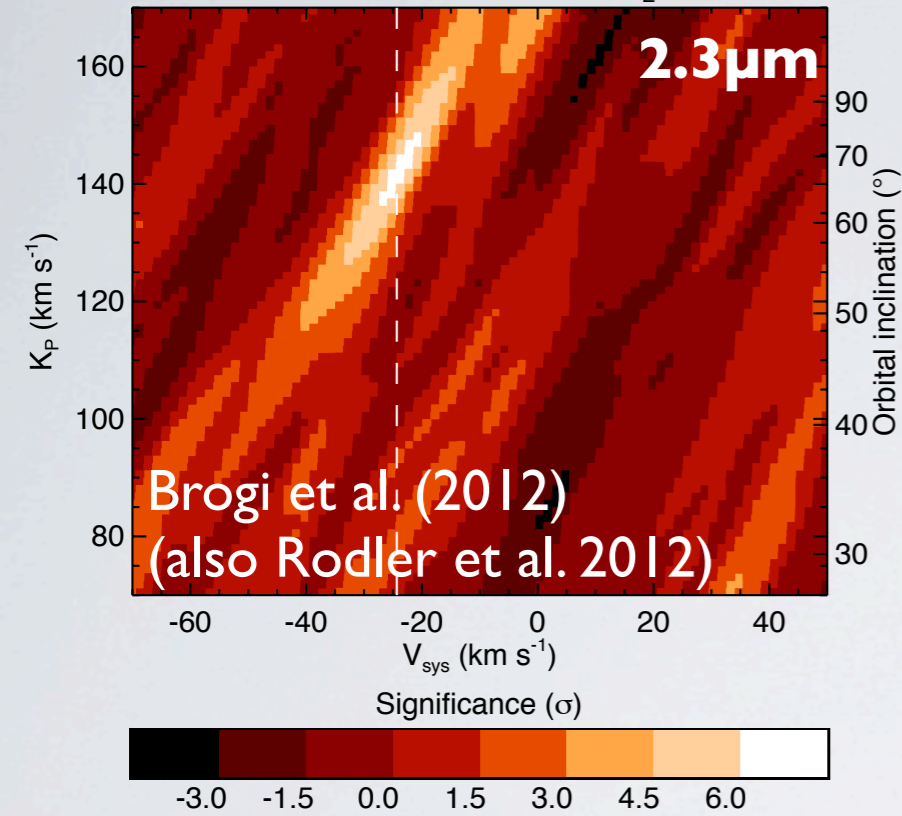
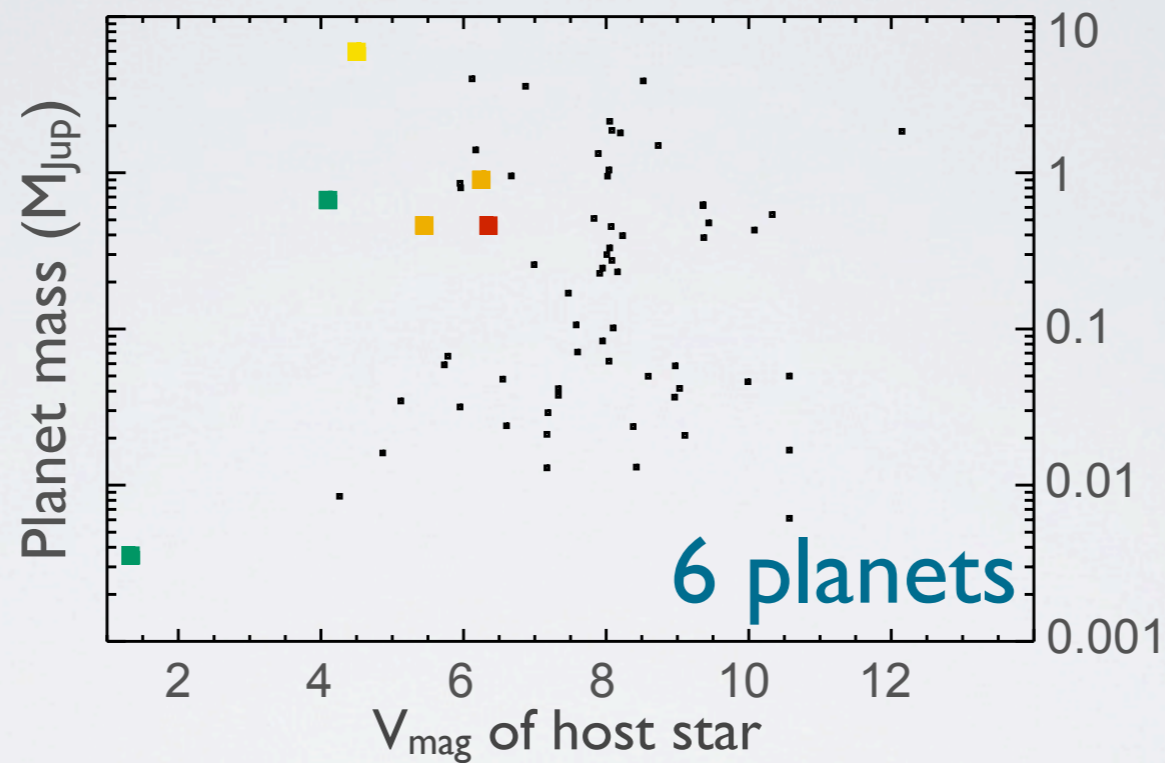|	τ Boo b	51 Peg b	HD179949
Integr. time	18 hrs	10 hrs	14 hrs
Molecules	CO	CO, H2O	CO, H2O
S/N	6.2	5.9	6.3
Mass	5.95	0.46	0.98
Inclination	44.5°	≥ 79.6°	68.0°

51 Peg b − H_2O at 3.2 micron — 3.2µm
Birkby et al. (in prep)
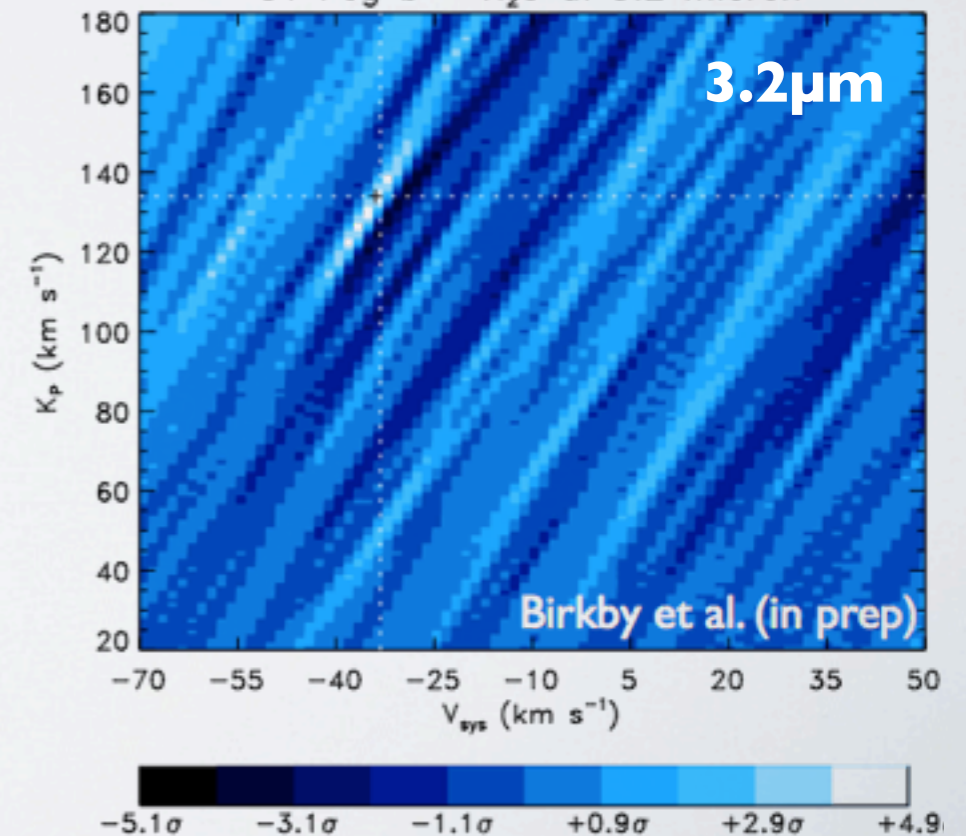
Current and future sample (non-transiting)

This method need **bright** systems and **close-in** planets

VLT

Easy
Robust
Tentative

Planet mass (M_{Jup})

6 planets

V_{mag} of host star

20h telescope time

VLT
Current CRIRES, 8m

E-ELT
39m mirror
6x spectral range
2x throughput

E-ELT

Planet mass (M_{Jup})

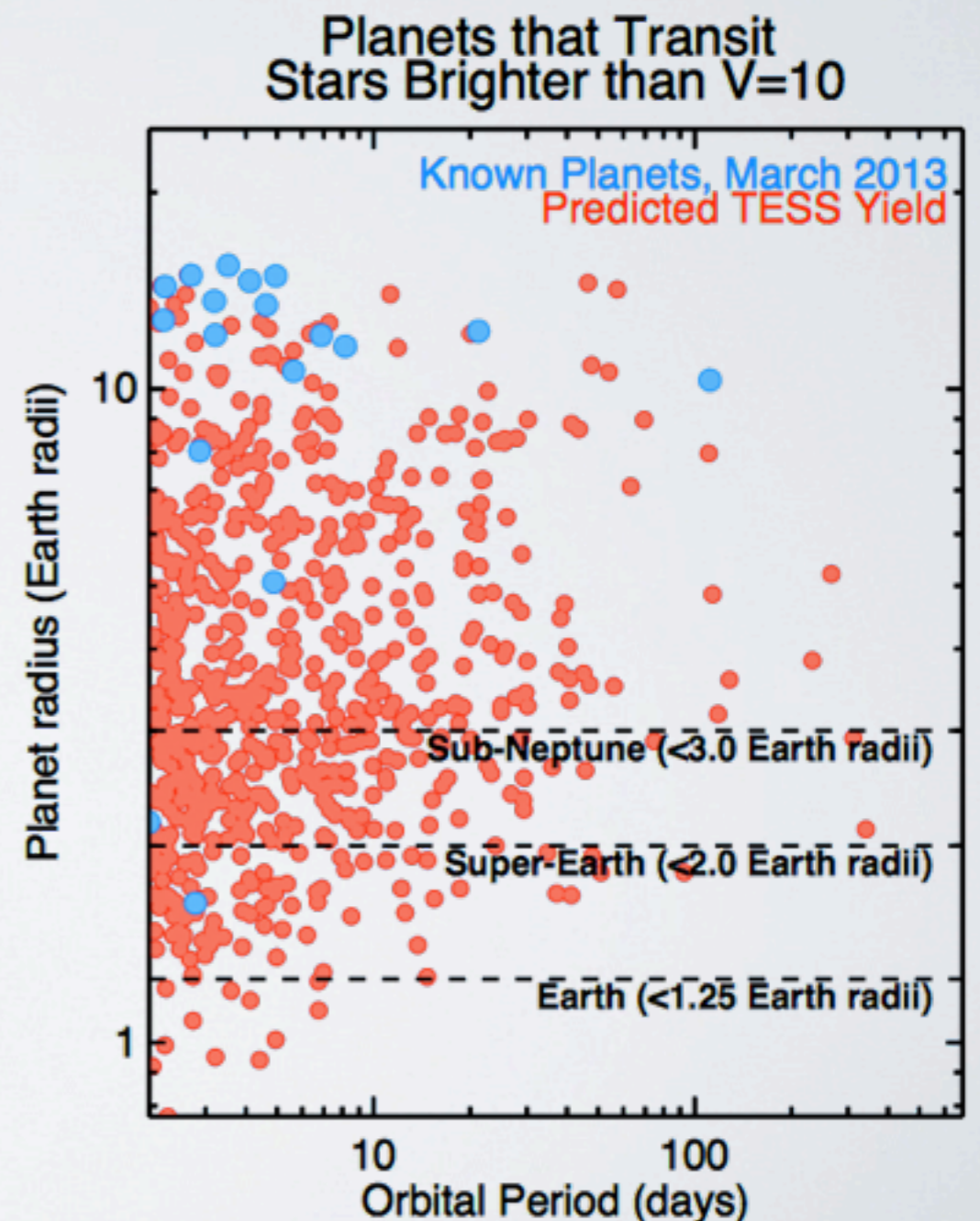1.75μm

31 planets

2.3μm

35 planets

3.5μm

38 planets

V_{mag} of host star
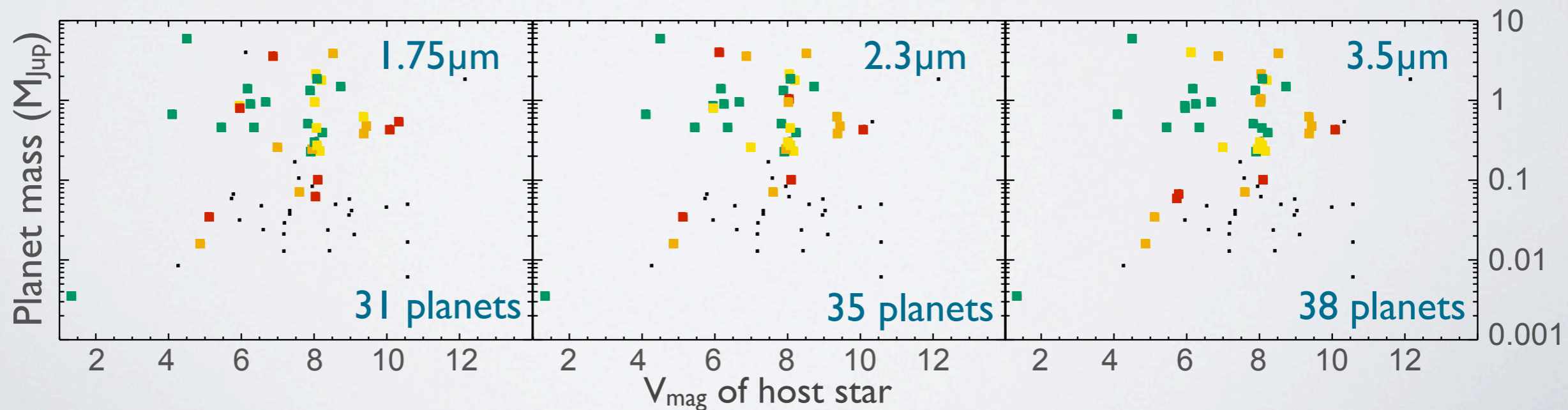
Current and future sample (all planets)

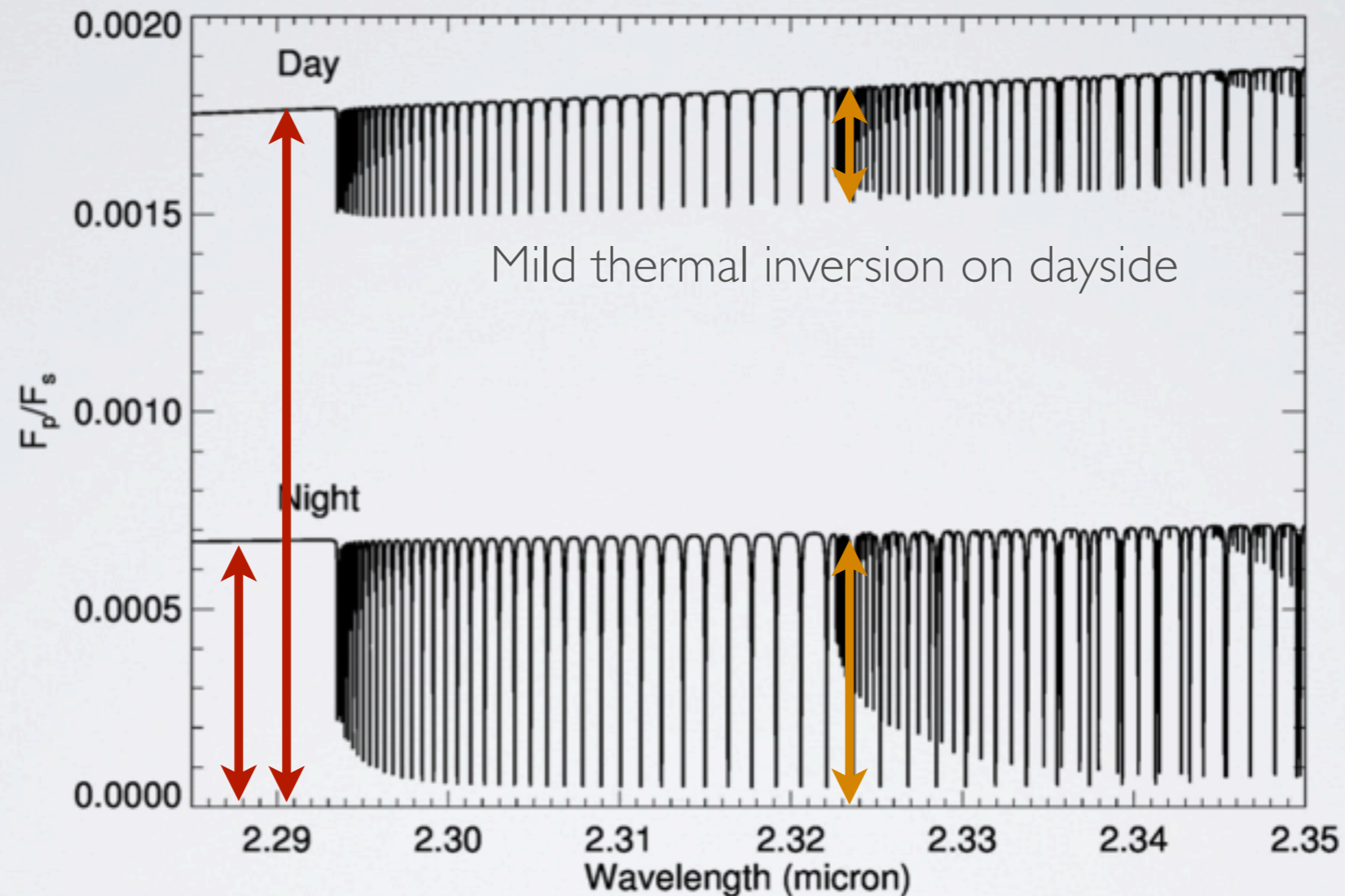This method need **bright** and **close-in** planets
[K≥8 mag]   [P≤10 days]
⇒ ~20 planets

- Deeper surveys

- Instrument design
  - Increase throughput
  - Wider spectral range

- Planets around bright stars!

Planets that Transit
Stars Brighter than V=10

Phase curves with an E-ELT

Broad-band phase curve ≠ CCF phase curve

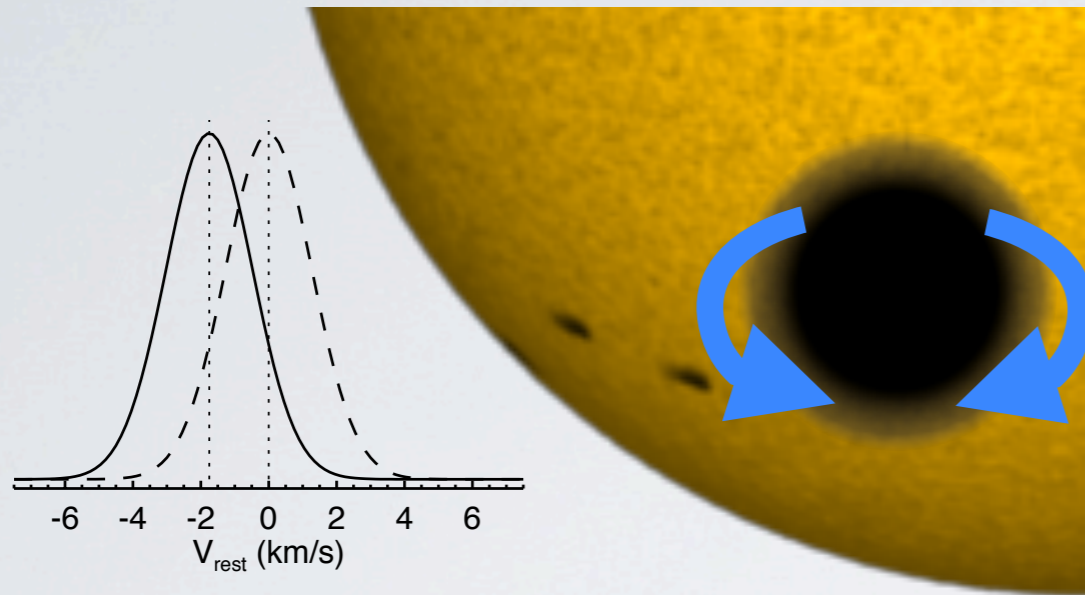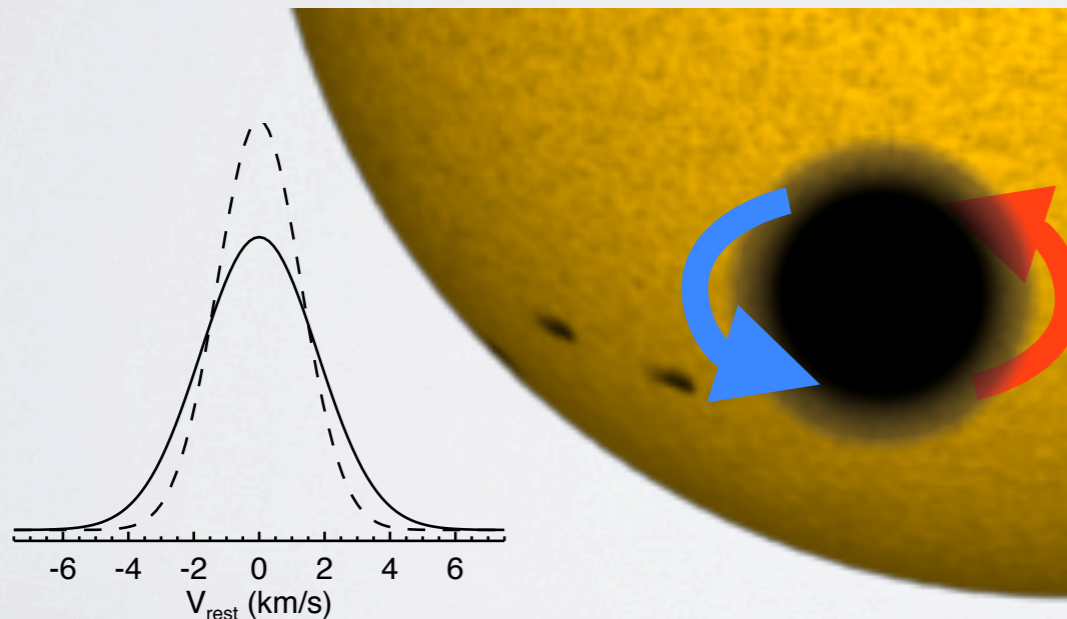*T/p* profiles on the night-side can be **steeper** than on the day-side

- Broad-band ⇒ Energy redistribution, day/night contrast

- Hi-res ⇒ Changes in *T/p* profile - vertical structure

Atmospheric circulation patterns

Transiting hot-Jupiters observed in transmission spectroscopy

Strong day- to night-side flow
⇒ **Blue-shifted** CC peak

Atmospheric (super-)rotation
⇒ **Broadened** CC peak

See e.g. Showman et al. (2013)

Conclusions

PROBING THE ATMOSPHERES OF NON-TRANSITING PLANETS
Ground-based, high-resolution spectroscopy

- Robust molecular detections
- Mass, inclination
- Bulk atmospheric thermal structure
- Atmospheric circulation, phase curves, C/O ratios.

- No absolute abundances
- Need to improve relative abundances (multiple wavelengths)
- **Need for bright targets and bigger telescopes!**