Exoplanet characterization with high-resolution IR spectroscopy

Nikolai Piskunov and Erik Aronson
Uppsala University

Equations

Matching observations with tellurics removed against normalized stellar flux minus intensity affected by the planet plus intensity passing through planetary atmosphere:

$$\sum \omega_{\lambda,\phi} \cdot \Big[O_{\lambda,\phi}/T_{\lambda,\phi} - \Big(F_{\lambda,\phi} - \sigma_{\text{core}} \cdot I_{\lambda,\phi} + \sigma_{\text{atm}} \cdot I_{\lambda,\phi} \cdot A^{\text{tr}}_{\lambda}\Big) \otimes \gamma_{\text{inst}}\Big]^2 = \min$$

This really does not work:

- We subtract two large values that are marginally different
- Where telluric features are strong we will be dividing noise by zero
- We have all systematics (telluric, flux, intensity and instrumental profile) working directly against us

Equations: alternative

Observed flux is normalized by the theoretical stellar flux and matched against the relative contribution of the planet:

$$\sum_{\lambda,\phi} \omega_{\lambda,\phi} \cdot \left\{ \frac{O_{\lambda,\phi}}{F_{\lambda,\phi} \otimes \gamma_{\mathrm{inst}}} - T_{\lambda,\phi} \cdot \left[1 - \sigma_{\mathrm{core}} \frac{I_{\lambda,\phi} \otimes \gamma_{\mathrm{inst}}}{F_{\lambda,\phi} \otimes \gamma_{\mathrm{inst}}} + \right. \right.$$

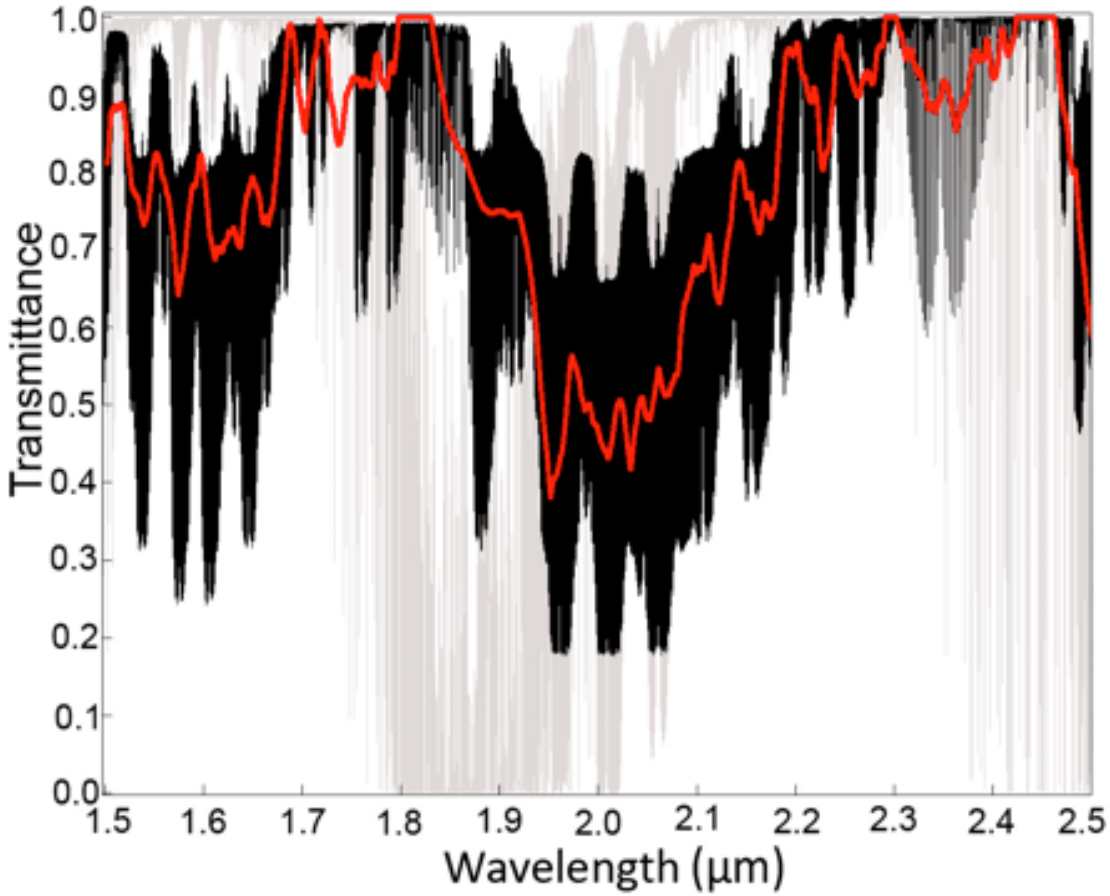
$$\left. \left. + \sigma_{\mathrm{atm}} \frac{(A_\lambda^{\mathrm{tr}} \cdot I_{\lambda,\phi}) \otimes \gamma_{\mathrm{inst}}}{F_{\lambda,\phi} \otimes \gamma_{\mathrm{inst}}} \right] \right\}^2 = \min$$

This is better:

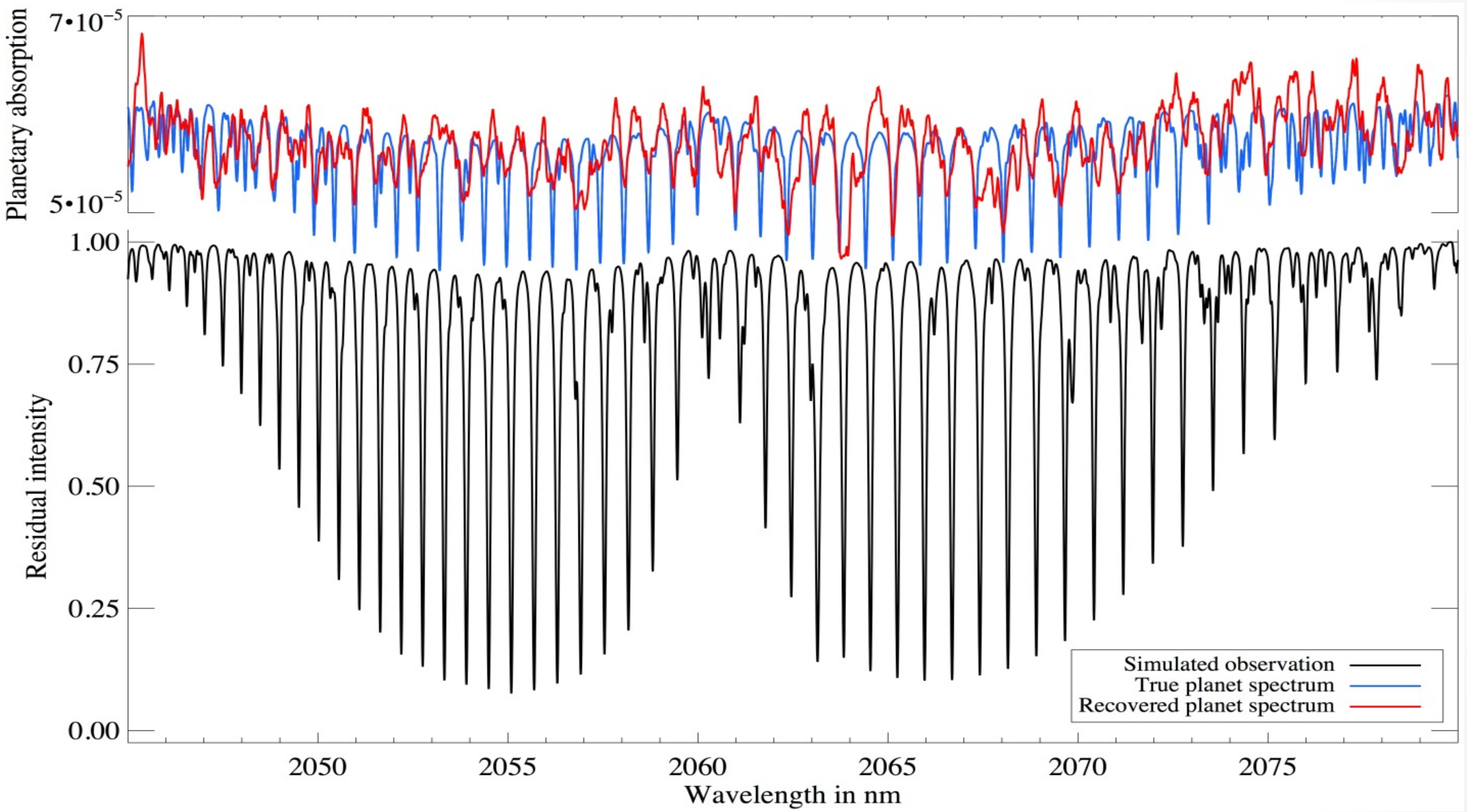
- Systematic errors with instrumental profile cancel out for the exoplanet part.
- The telluric spectrum acts as a weight: wavelengths with strong telluric absorption have less contribution to the total.
- An accurate analytical model of telluric spectrum allows reducing the dynamic range between observations and planetary signatures.

Numerical experiments

Jupiter-size planet in front of a solar-type star. Using 120 exposures during a single transit (S/N=250 per exposure)



Numerical experiments

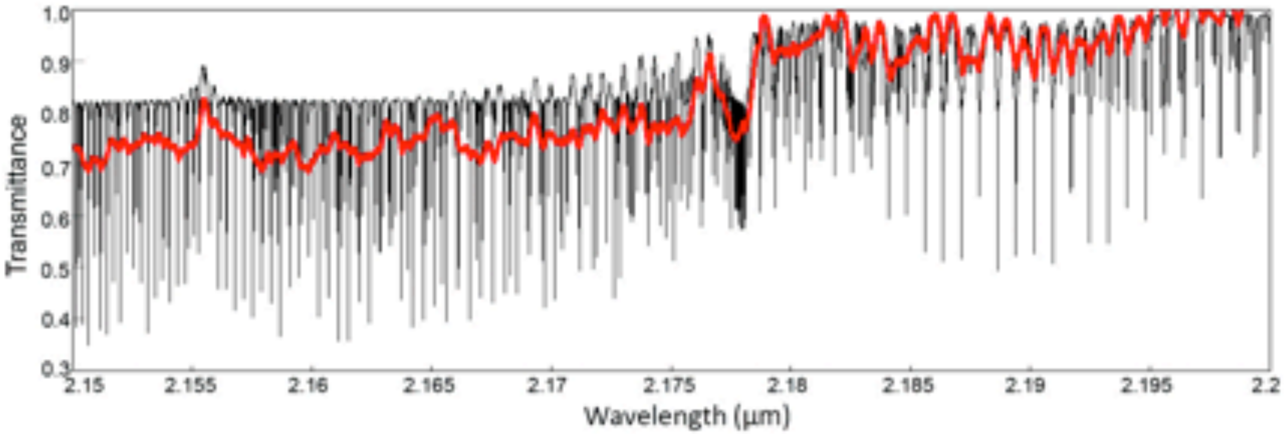


Earth-like planet passing in front of an M5 dwarf. Bottom panel: simulated observations with CRIRES+. Top panel: CO_2 spectrum in planet atmosphere (blue) and its reconstruction from 10 transits (red).

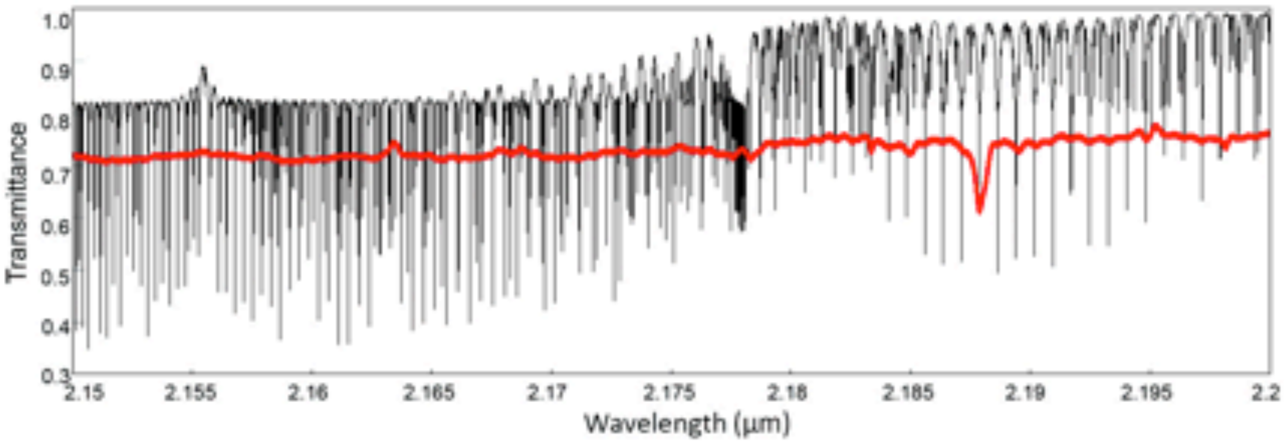
Numerical experiments

Resolution and spectral coverage:

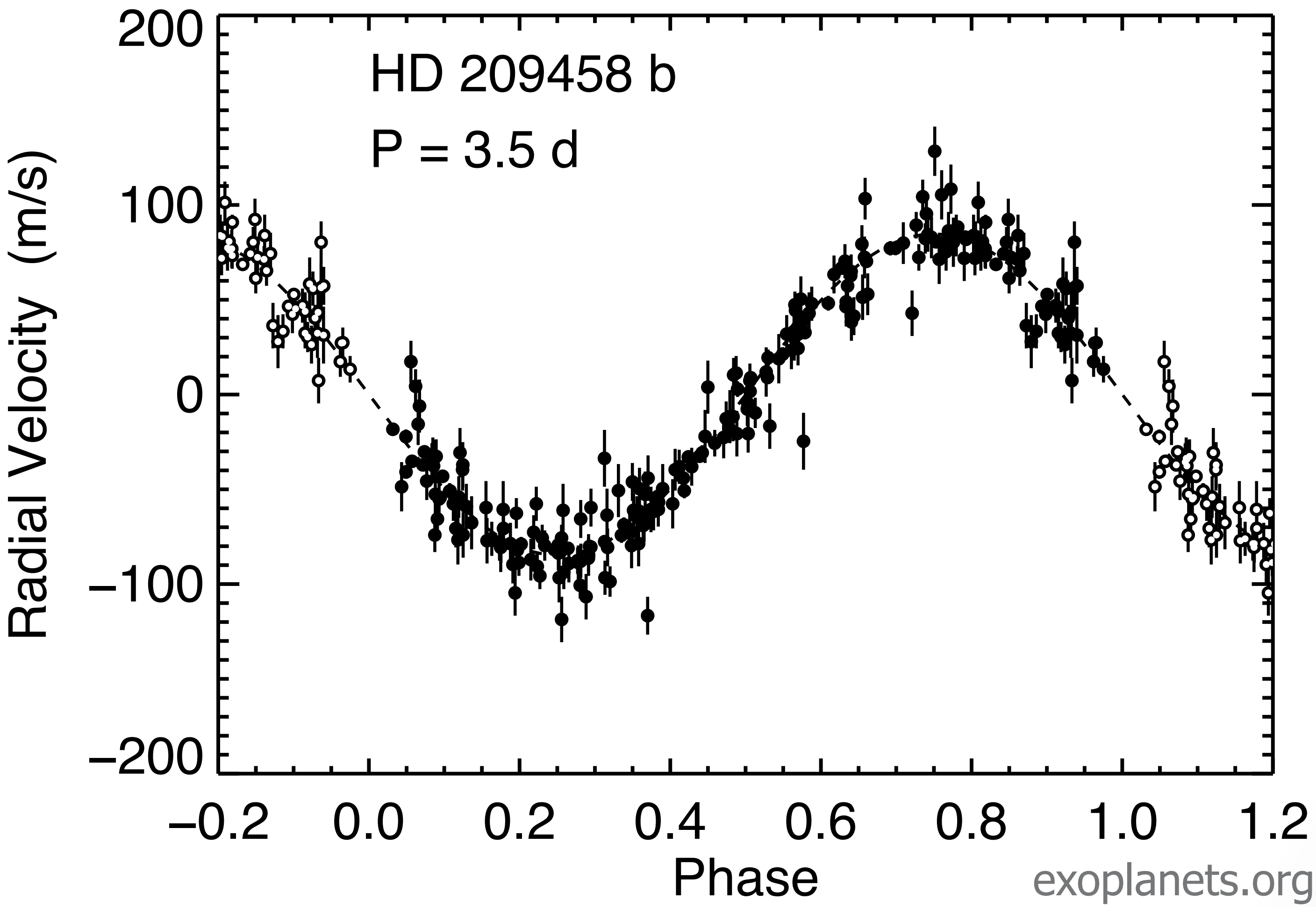
R=100000



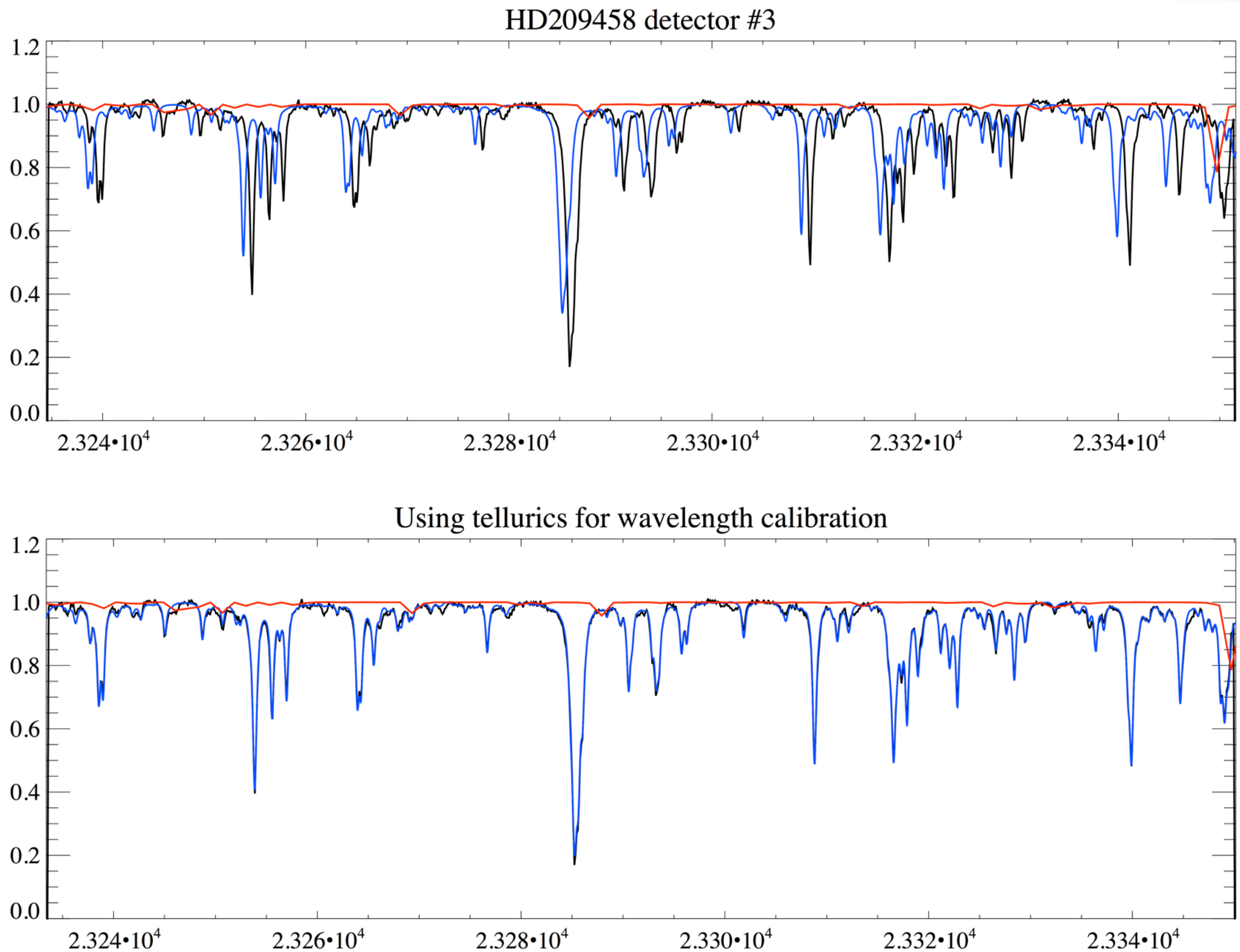
R=10000



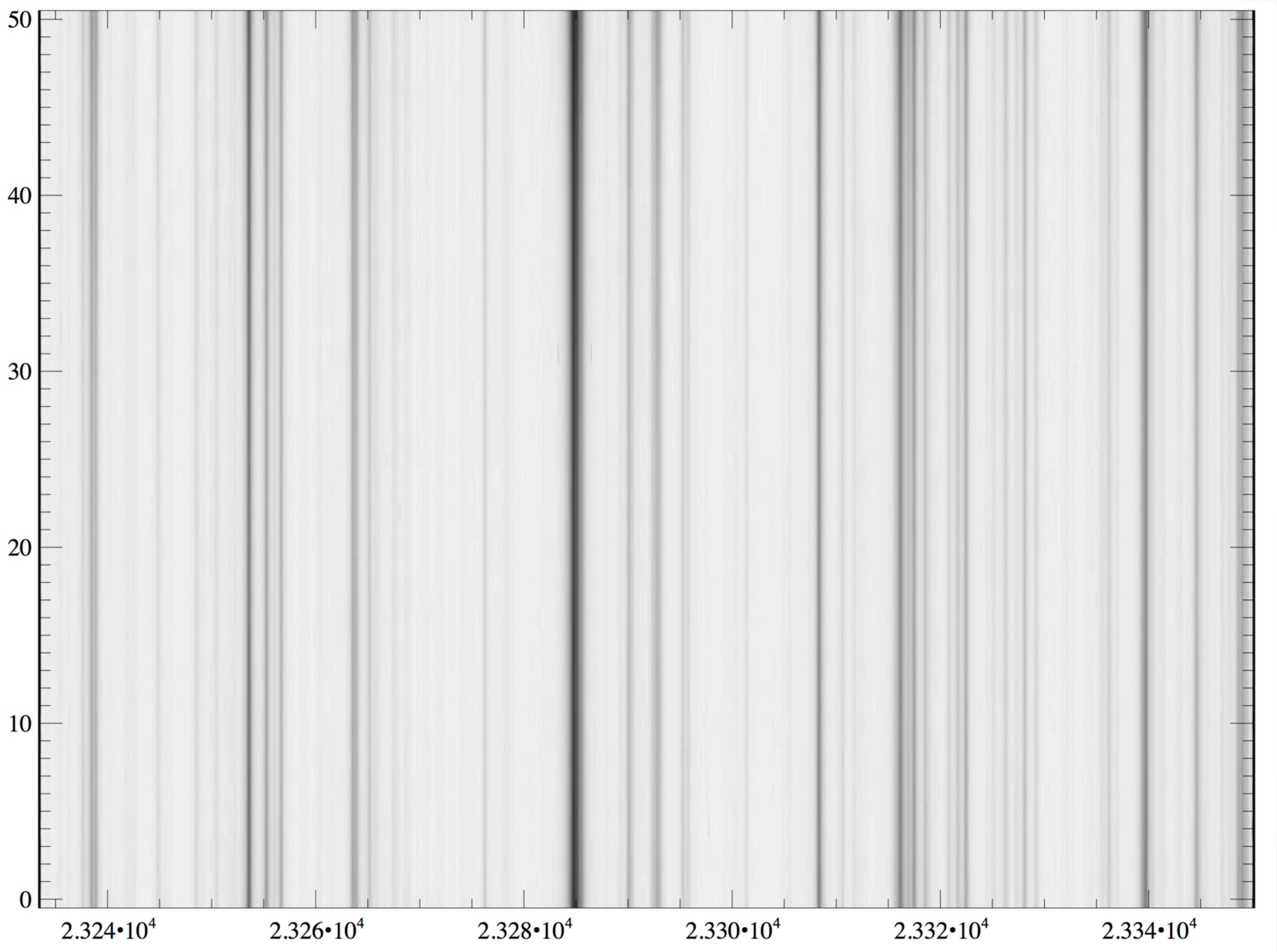
Test object:HD209458 CRIRES observations



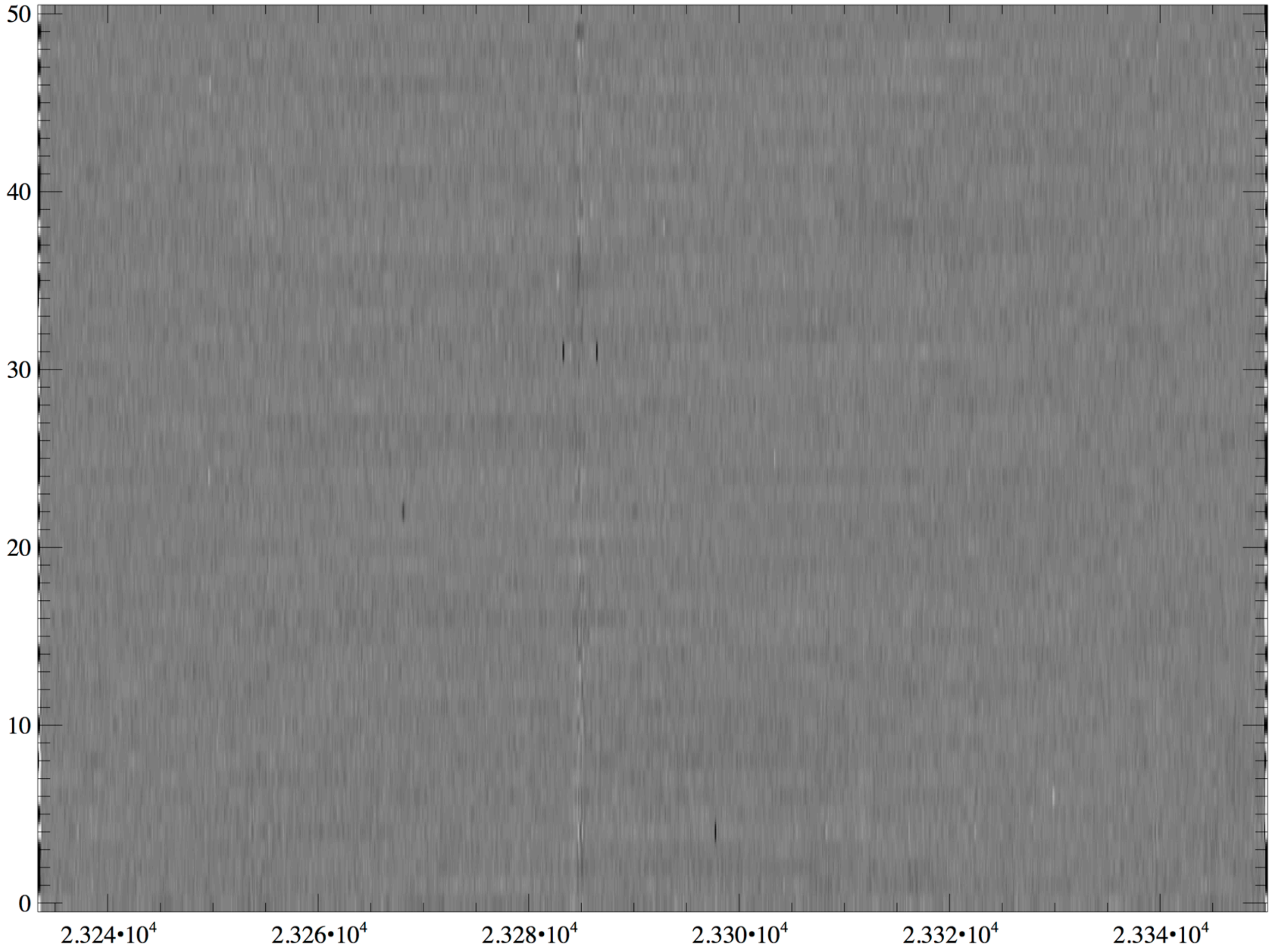
Data reduction: λ-scale



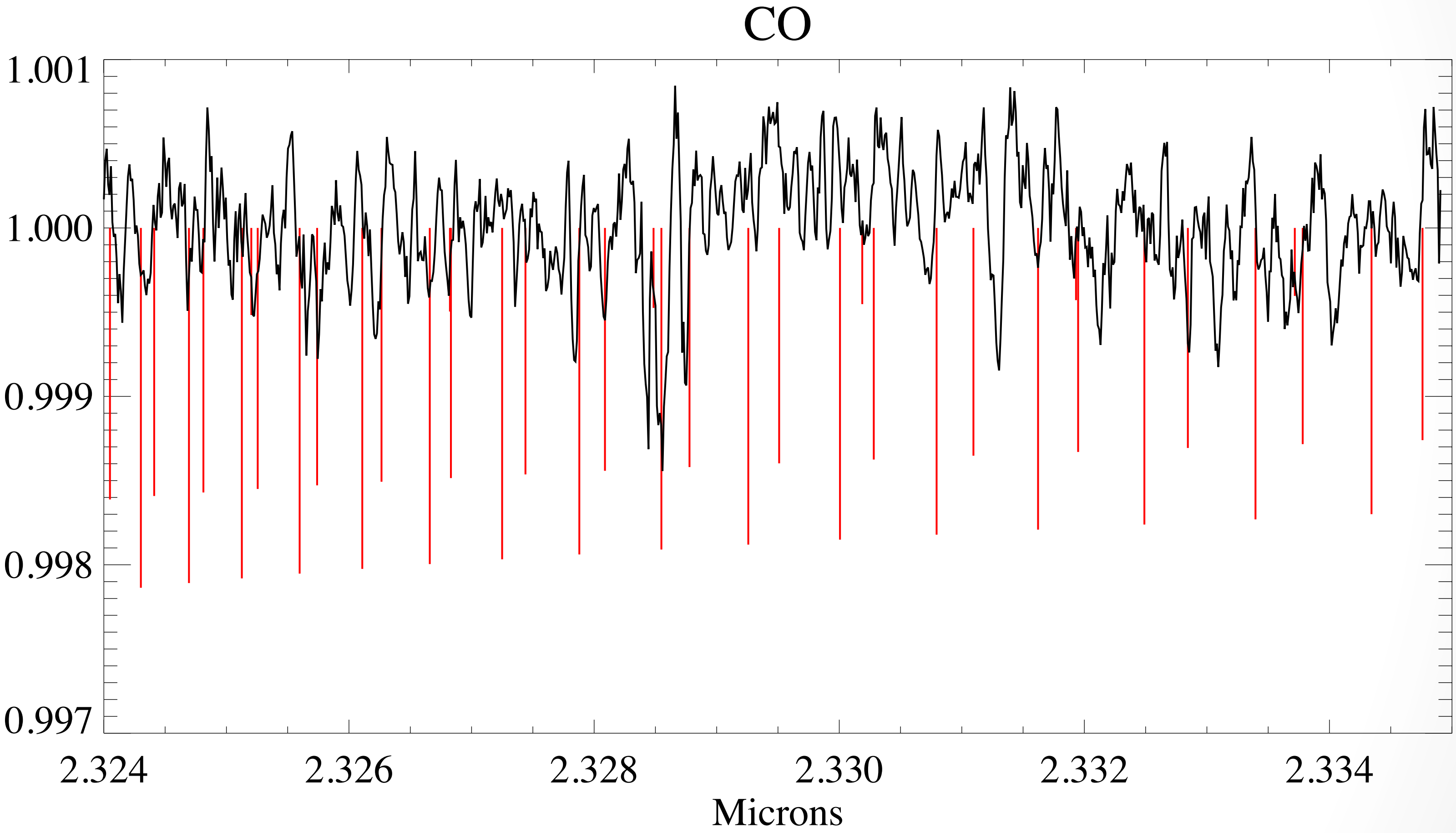
Star rest frame



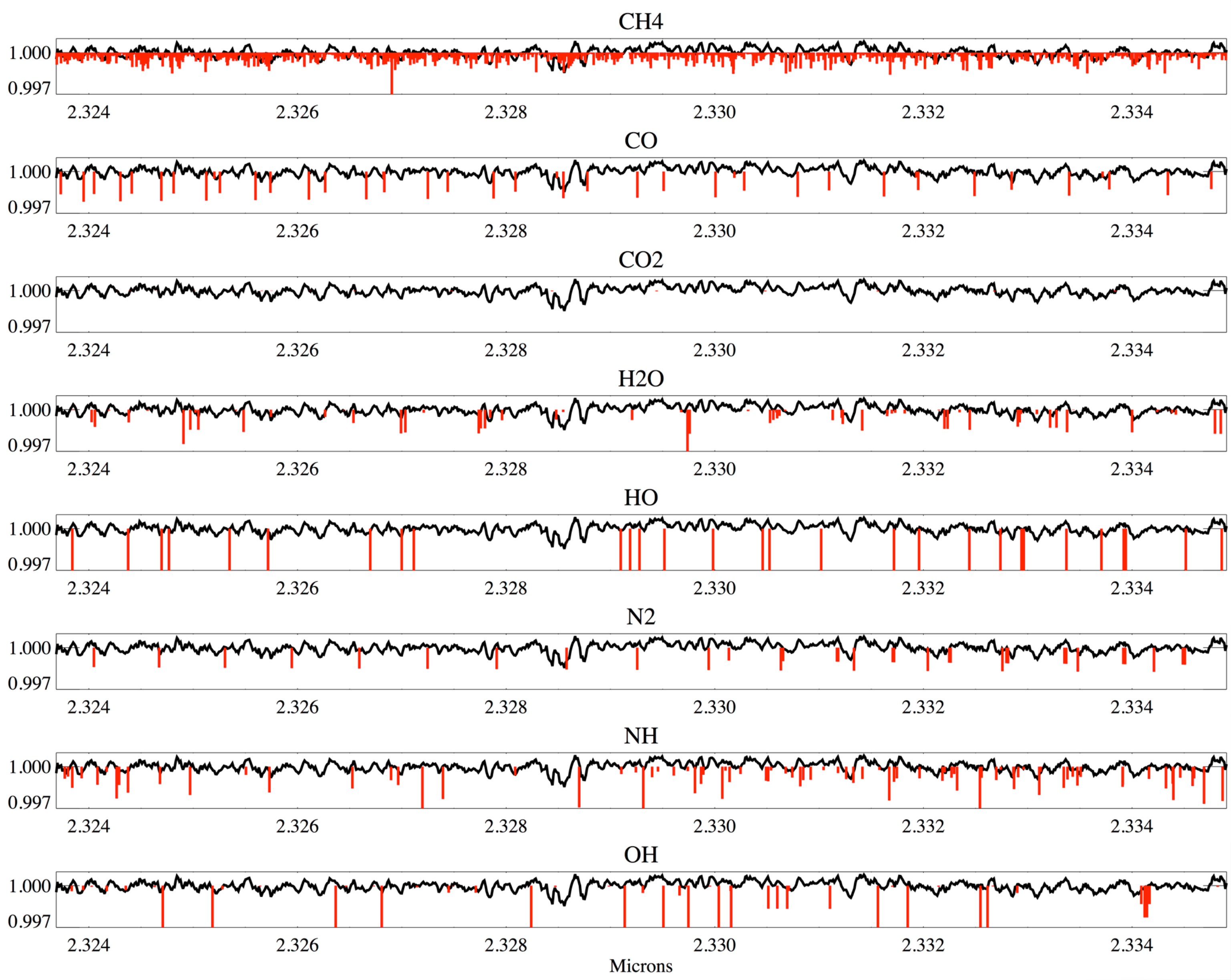
Removal of telluric and stellar features



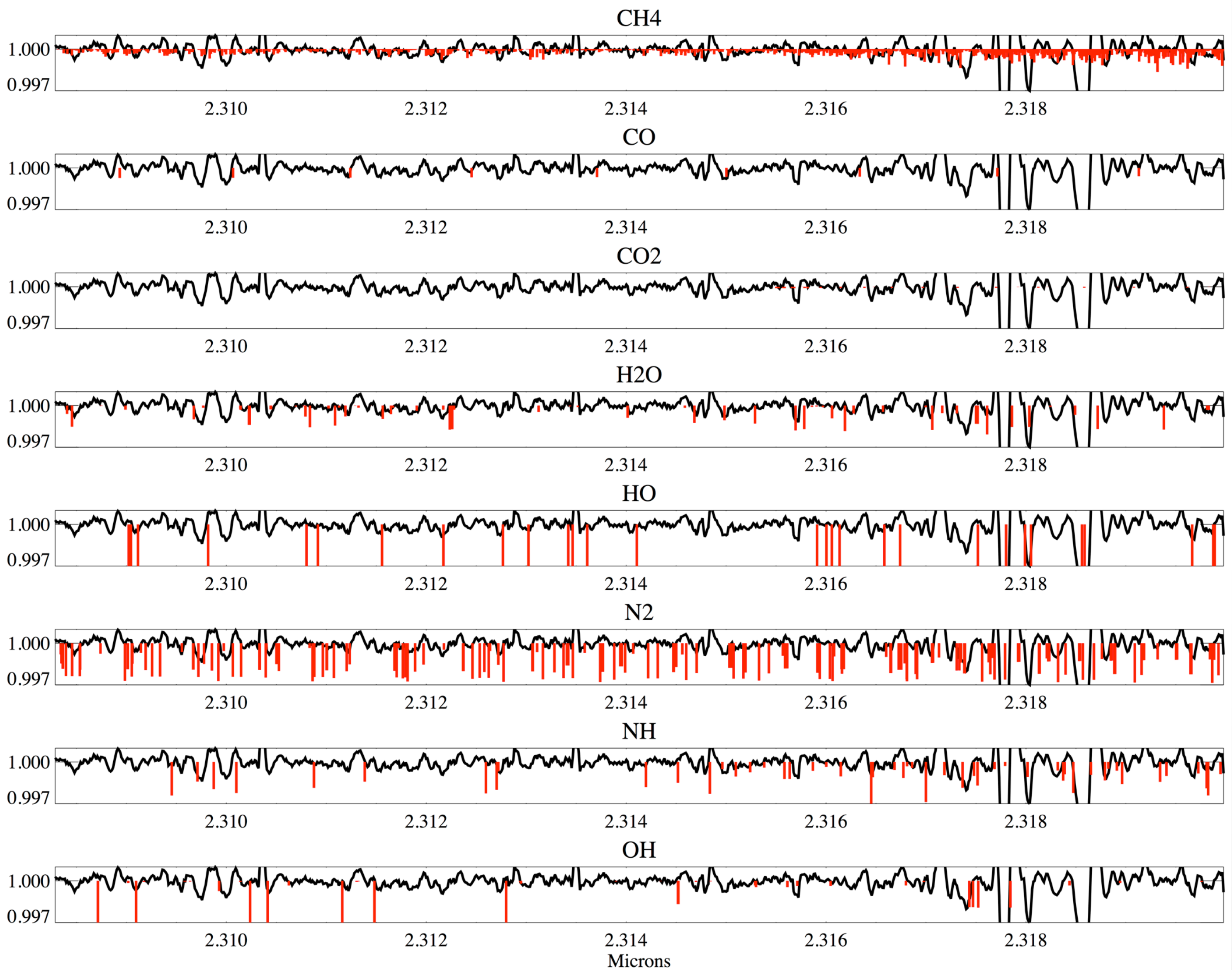
Planet rest frame: almost …



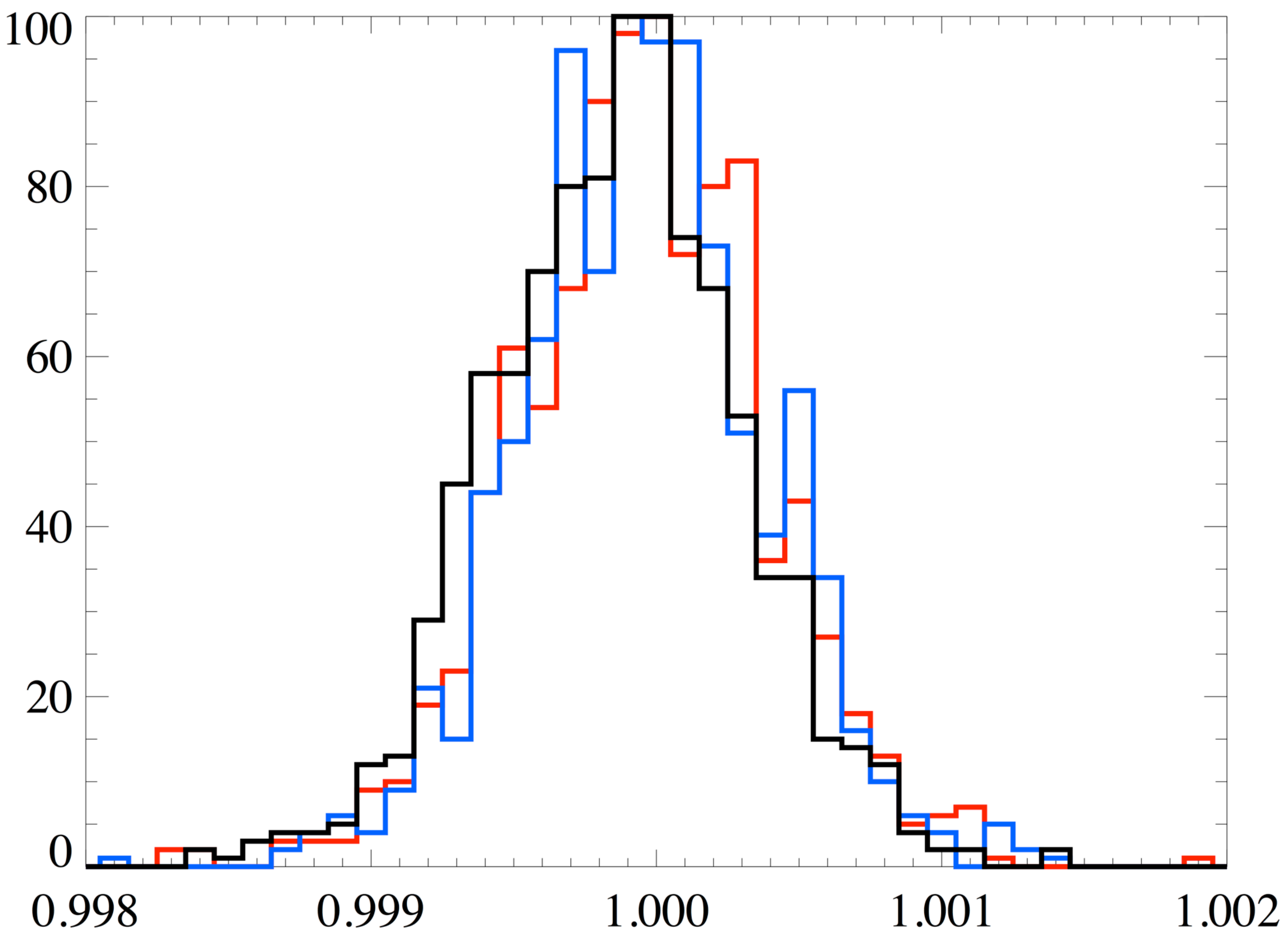
We will look for many molecules



… and in other spectral regions, but we are not there yet with current the data



Well, may be there is something there …



Conclusions

Ground-based high-resolution (IR) spectroscopy has a great potential for true (model independent) characterization of exoplanetary atmospheres.

What we need is:

- High (>300) S/N in a short exposure with a good duty cycle
- High-resolution (R>=100000) to see between telluric lines and take advantage of the Doppler shift variation between exposures
- High wavelength coverage to look at different species and play with combining lines
- Reliable calibrations (wavelength, flat, background, blaze)
- Stability on time-scale of a transit
- Repeatability to use day-time calibrations and connect different transits
- <u>All of the above for tens of targets!</u>

This is a job for ***E-ELT + HiRes***