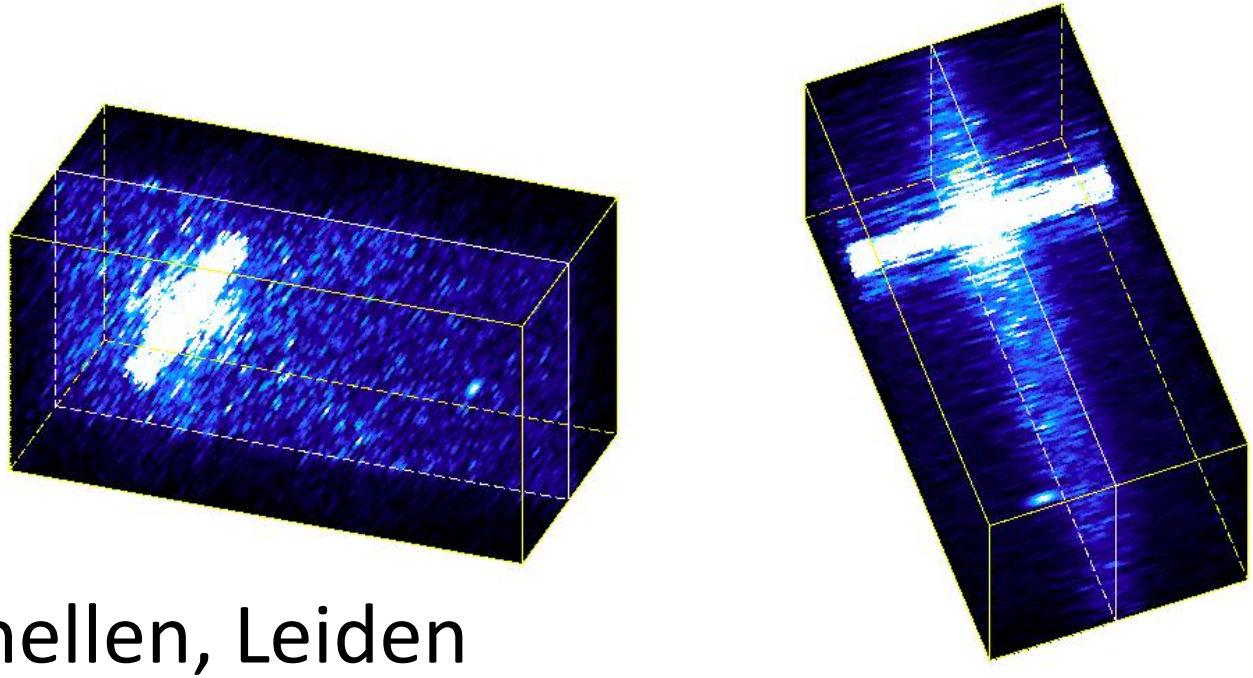
Combining
High-dispersion spectroscopy with
High-contrast imaging
to probe Earth-like planets

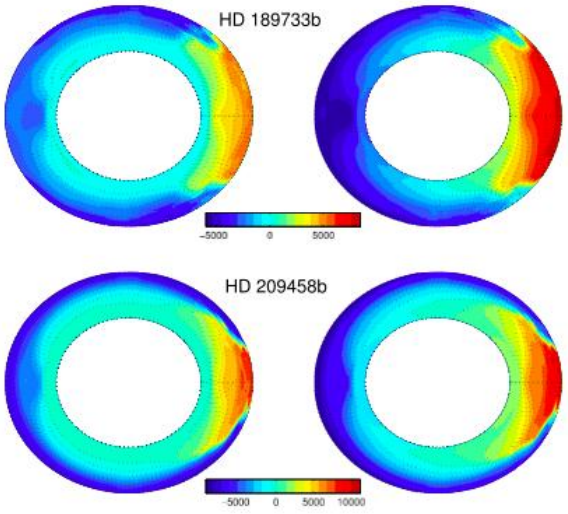


Ignas Snellen, Leiden

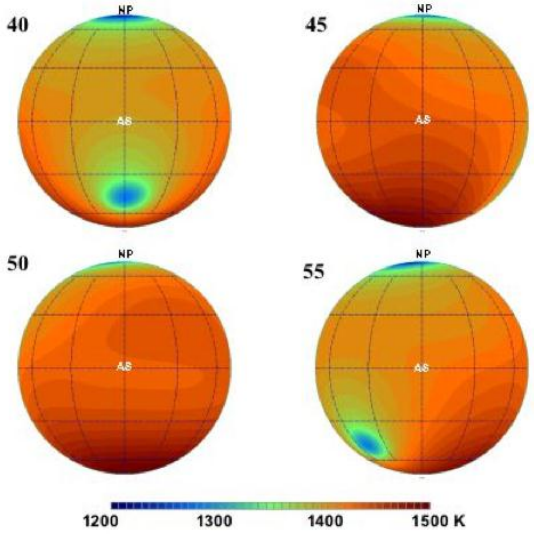
Matteo Brogi, Jayne Birkby, Bernhard Brandl, Christoph Keller, Henriette Schwarz, Matthew Kenworthy, Remco de Kok

High-resolution spectroscopy (R=100,000)
Unique ELT Science in the JWST era
HIRES (<2.5 um) and METIS (>3 um)

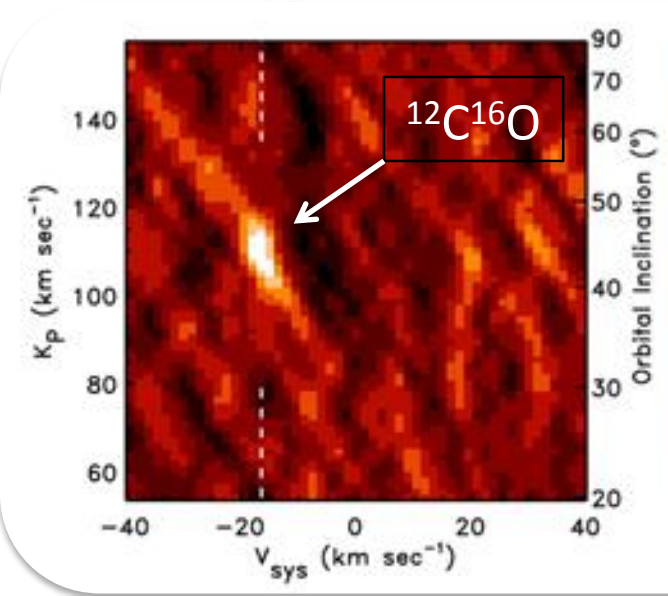
Planet rotation and circulation



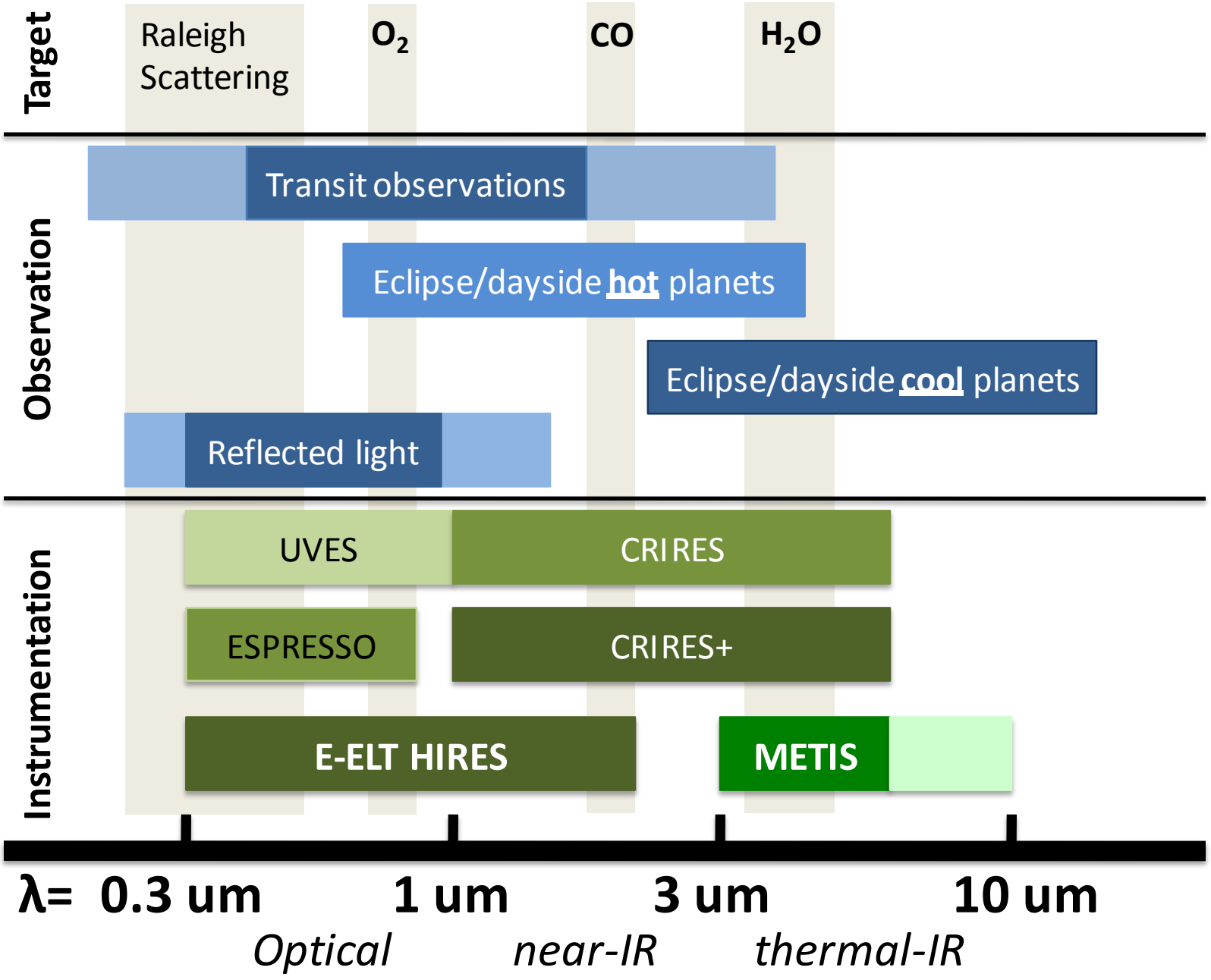
Molecular signals as function of orbital phase

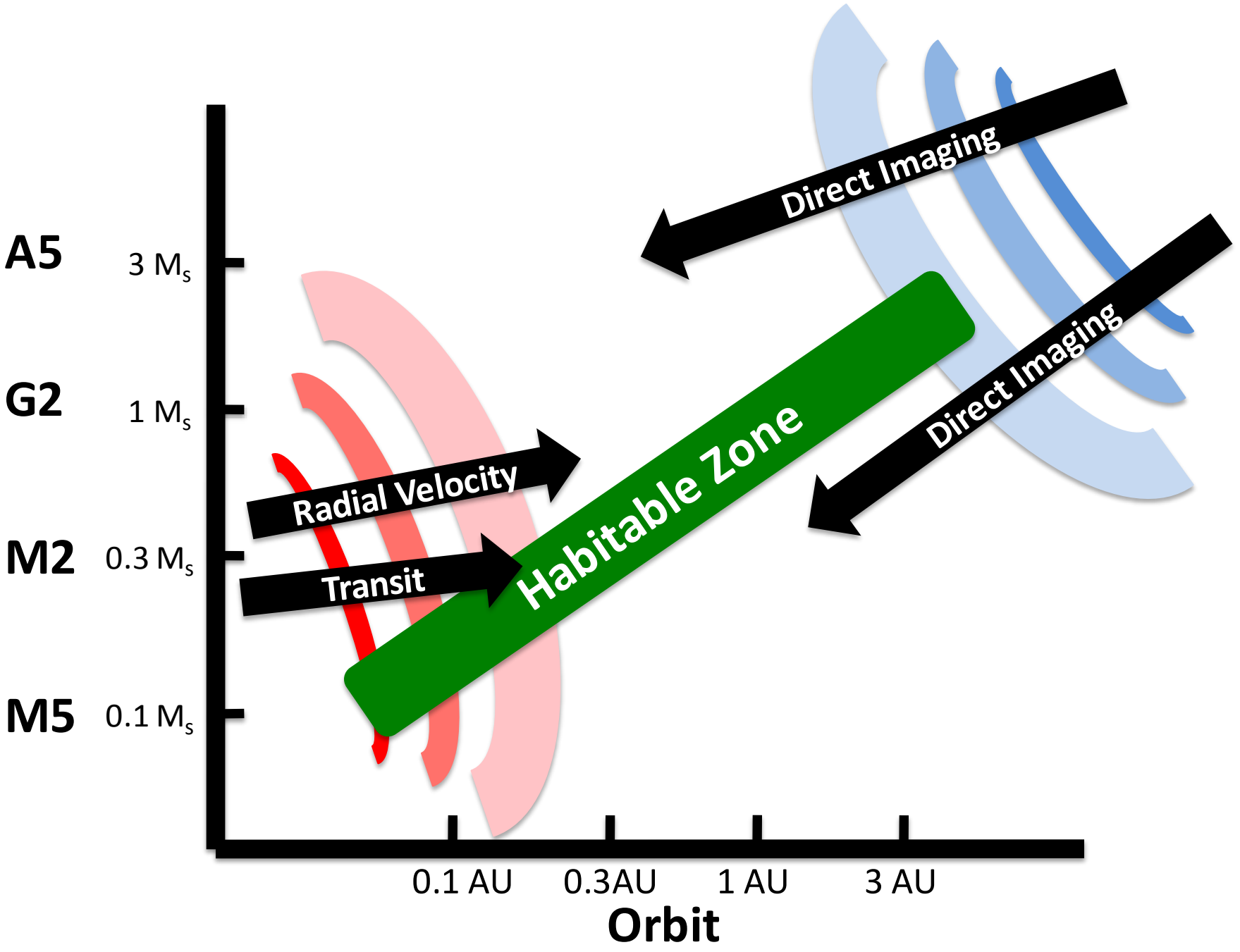


Isotopologues?

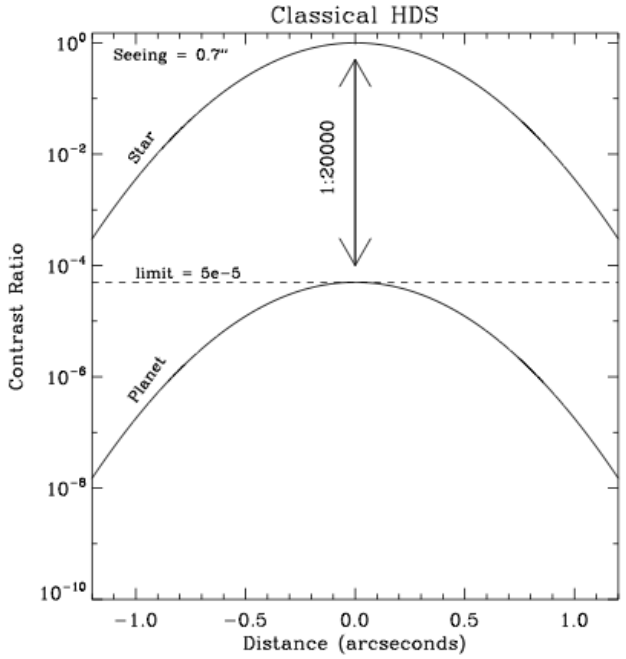


See previous talks by
Brogi, Crossfield, Rodler, ……


Target
Raleigh Scattering
O_2
CO
H_2O
Observation
Transit observations
Eclipse/dayside hot planets
Eclipse/dayside cool planets
Reflected light
Instrumentation
UVES
CRIRES
ESPRESSO
CRIRES+
E-ELT HIRES
METIS
λ= 0.3 um
1 um
3 um
10 um
Optical
near-IR
thermal-IR


A5
3 M_s
G2
1 M_s
M2
0.3 M_s
M5
0.1 M_s
Direct Imaging
Direct Imaging
Radial Velocity
Transit
Habitable Zone
0.1 AU
0.3AU
1 AU
3 AU
Orbit

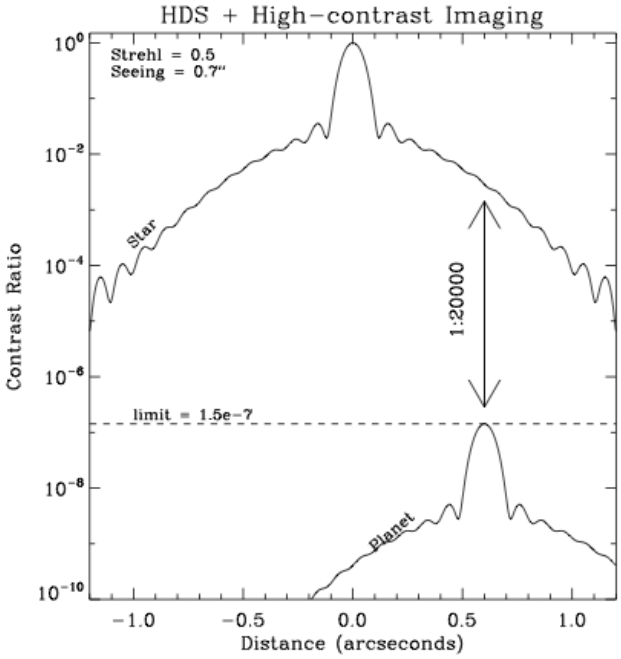
Classical HDS



$$SNR = \frac{S_{planet}}{\sqrt{S_{star} + \sigma_{bg}^2 + \sigma_{RN}^2}}$$

Limits: 10^{-5} with VLT

HDS + HCI

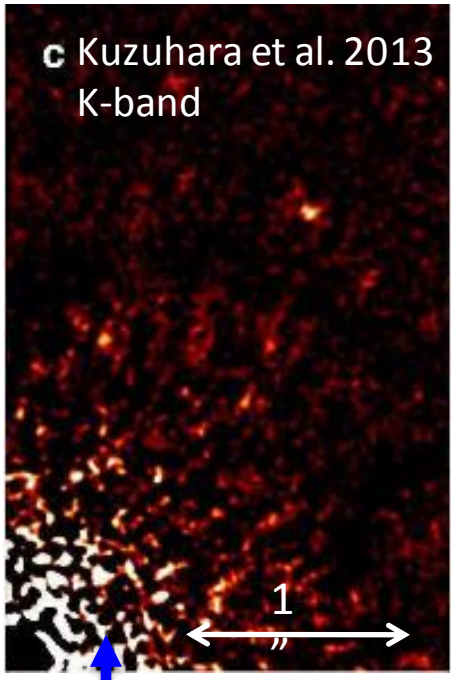


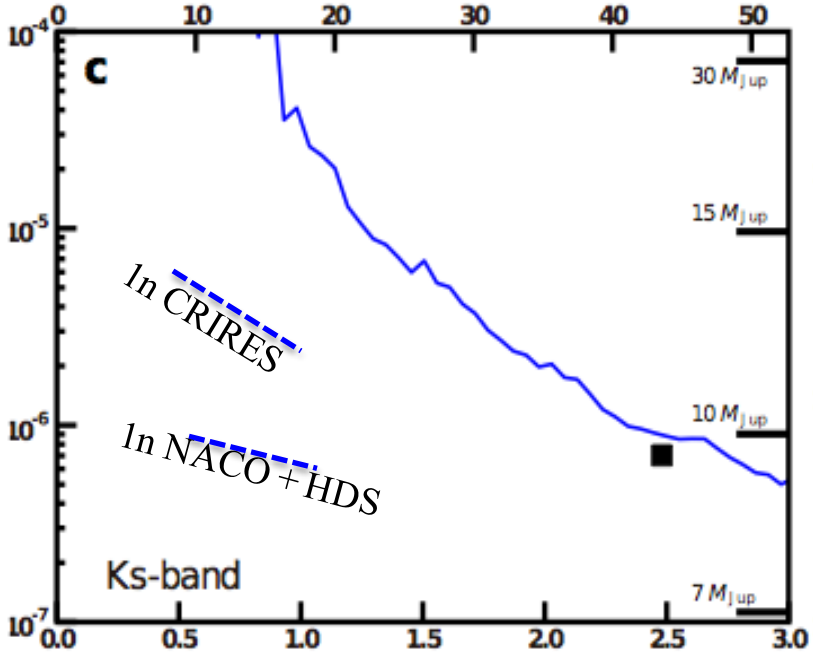
$$SNR = \frac{S_{planet}}{\sqrt{S_{star}/K + \sigma_{bg}^2 + \sigma_{RN}^2}}$$

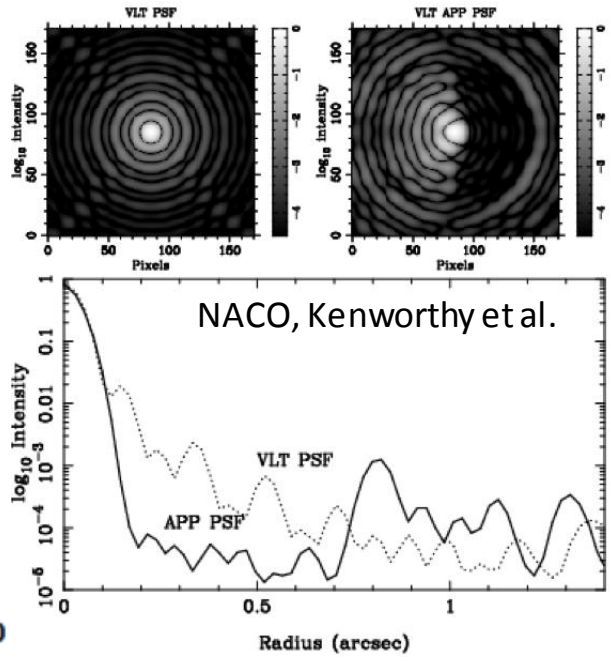
Limits: $10^{-5}/\sqrt{K}$ with VLT

How far can we push this with the E-ELT?

Why should this work??
Comparison to “classical” high-contrast imaging







All the light in this image has the spectrum of the star, except the planet
Speckles can be removed (down to <1^{e}-5 level)

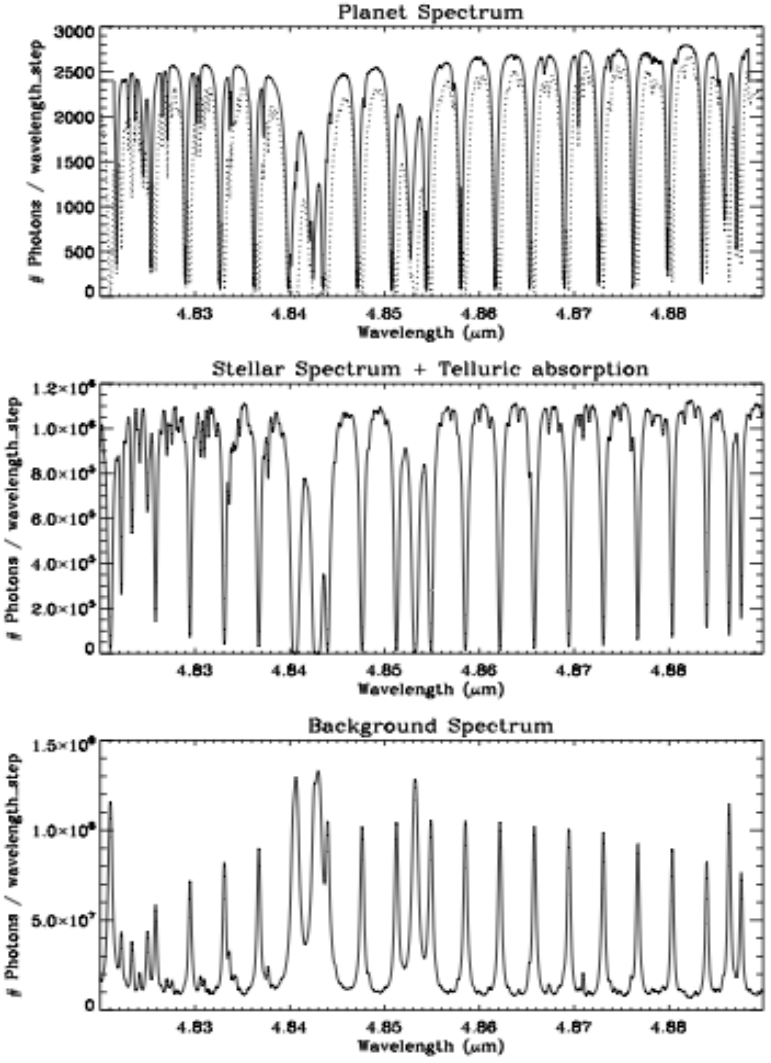
This idea is **not** new (at lower resolution)
Sparks & Ford 2003
Konopacky et al. 2013

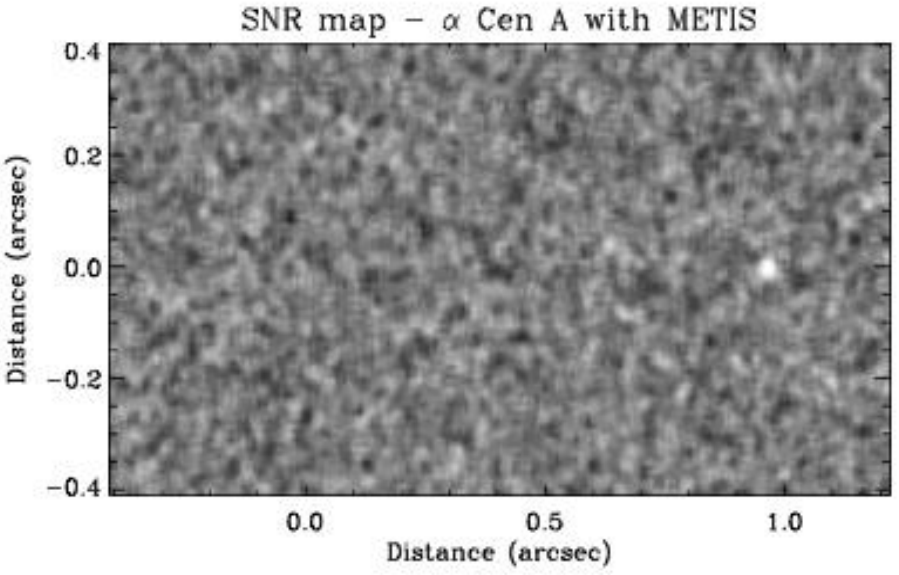
Note : a R=100,000 IFU is required (in baseline design of METIS)

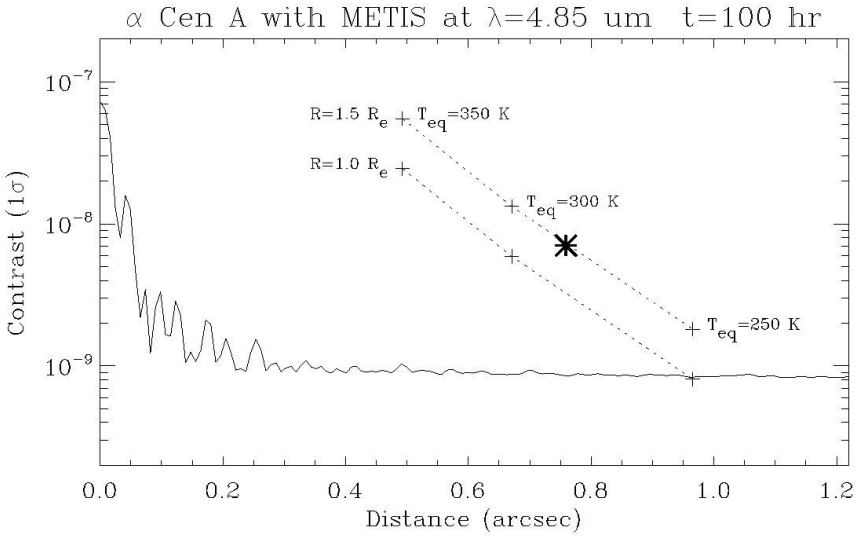
E-ELT simulations - CASE 1

A Super-Earth in the Habitable Zone of Cen A at 4.85 um

METIS+E-ELT PSF simulation in M-band (Strehl=0.9), baseline METIS set-up. 100 hours Earth-spectrum, T=273 K, 1.5 R_earth.





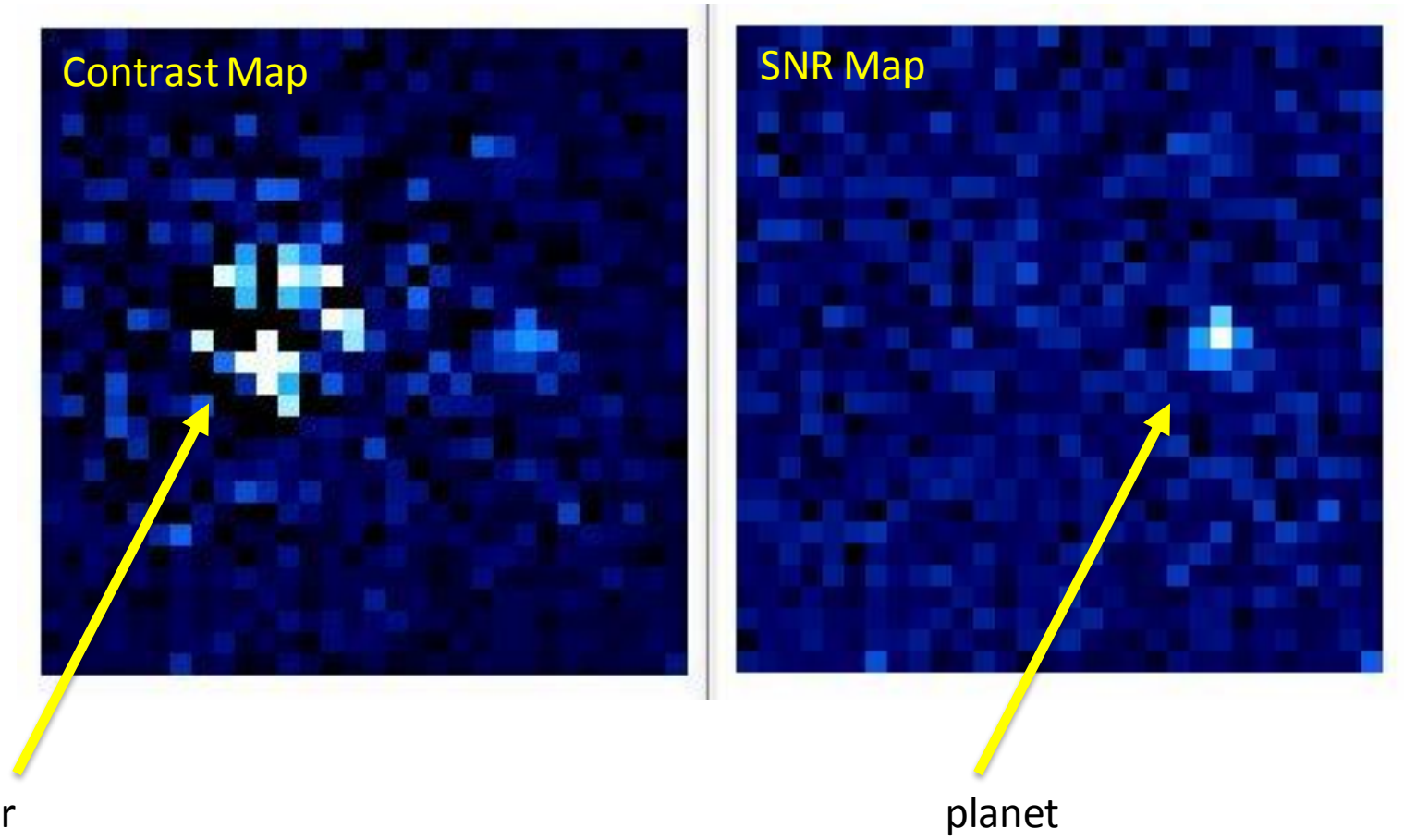


E-ELT simulations - Optical IFU (HIRES/PCS)

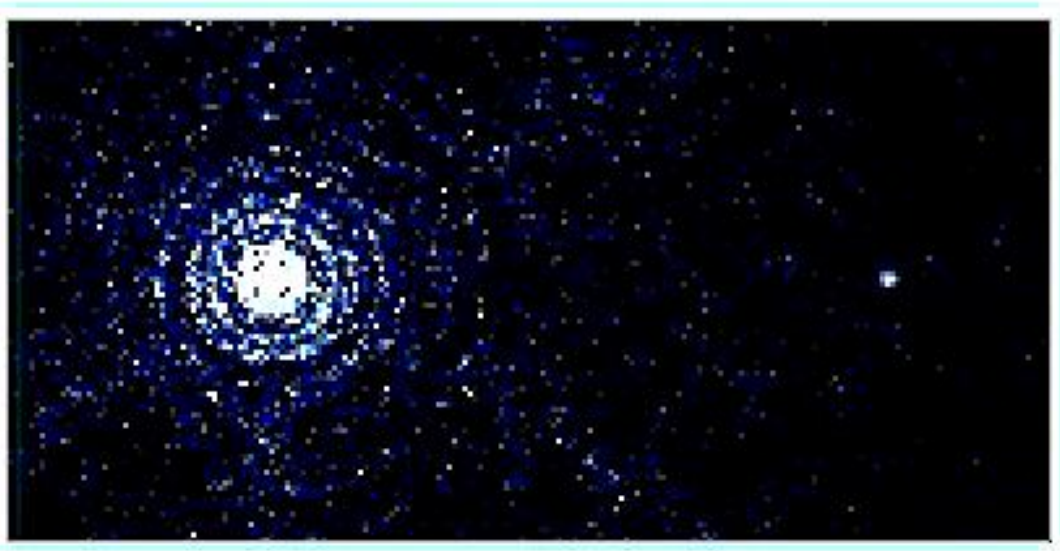
CASE 2: A Super-Earth in the Habitable Zone of Proxima

E-ELT (Strehl=0.5), 10 hours, R=100,000, $\Delta\lambda = 600 - 900$ nm
Earth-spectrum, T=273 K, 2 R_earth.

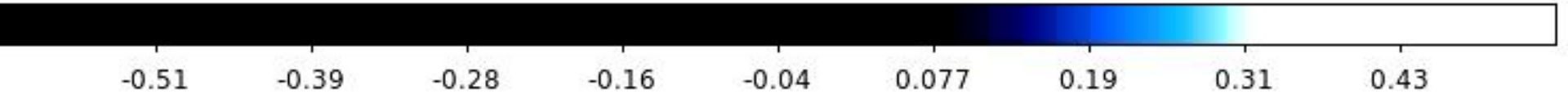
Snellen et al. In prep



Planet spectrum is a copy of that of the star, but velocity shifted



METIS @ E-ELT, Snellen et al. In prep.



Conclusions

- HDS is so far the only successful ground-based technique to detect molecules in hot Jupiter atmospheres → the power of HIRES & METIS
- Combining HDS + HCI promises to be a very powerful technique, capable to characterize rocky planets in the habitable zones of our nearest neighbours with the E-ELT.
- CRIRES(+) is a crucial path-finder for the E-ELT