Exoplanets through the lens of AO-assisted NIR spectroscopy

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Why?

- NIR photometry suffers degeneracy (=objects with different logg/R have same J,H,K colours)
- Accretion properties of the exoplanet/brown dwarf companions
- Atmospheric properties: young vs. old planets; dusty vs. clear atmospheres

1. In principle we might want to obtain information on C/O ratio + metallicity and compare them with the host star (this impacts on different formation mechanisms: core accretion vs disc instability and gives information on WHERE the planet form within the disc)
2. Gravity indicators (Na,K lines in the NIR regime) which allows also to put independent constraints on the age
3. Clouds presence and structures

- If the resolution is sufficiently high (R> 5000): RADIAL VELOCITY of the PLANETS! And for R> 10 000 also rotational velocities → ORBITAL and ROTATIONAL properties

Exoplanet atmosphere

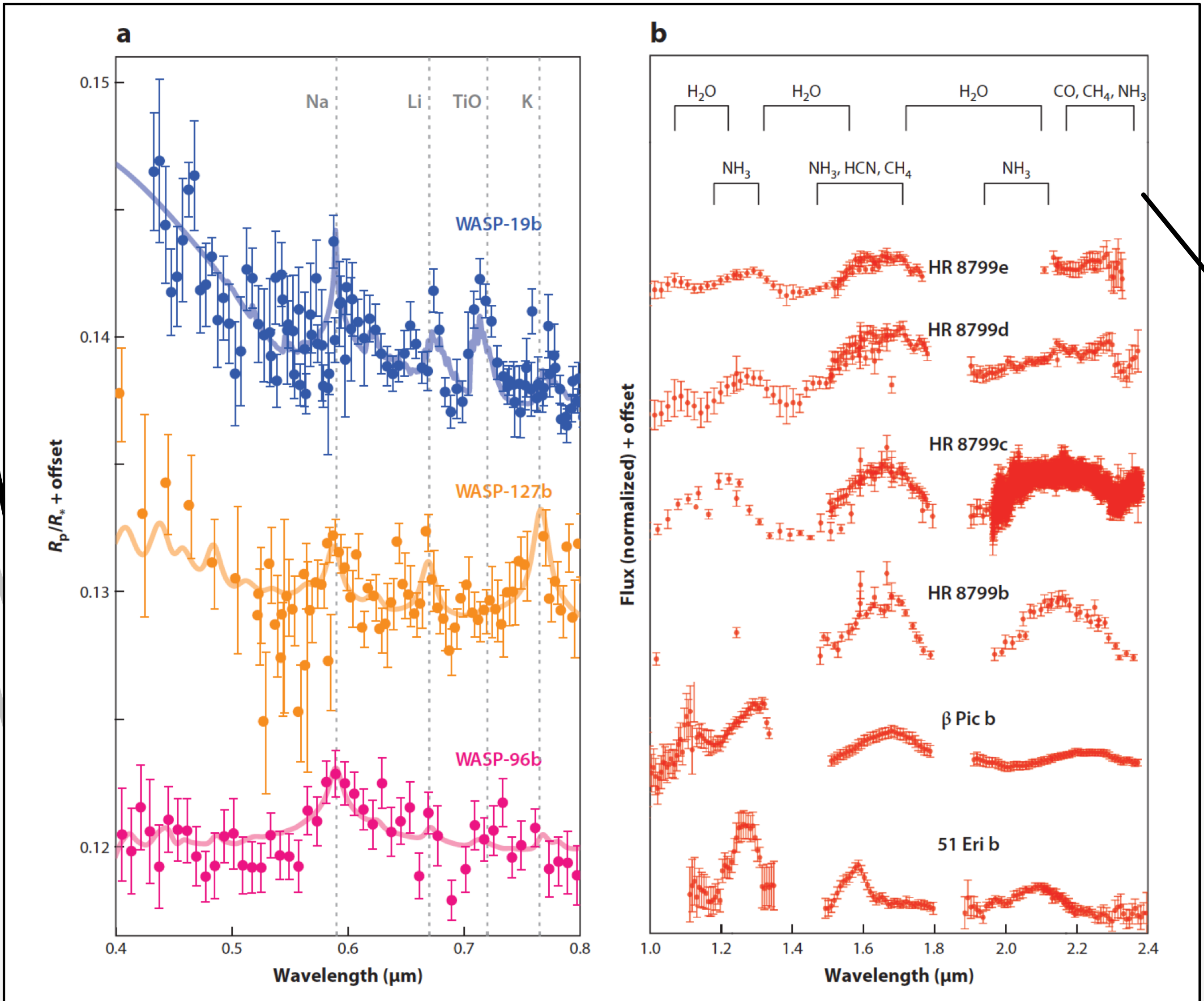


Figure 4

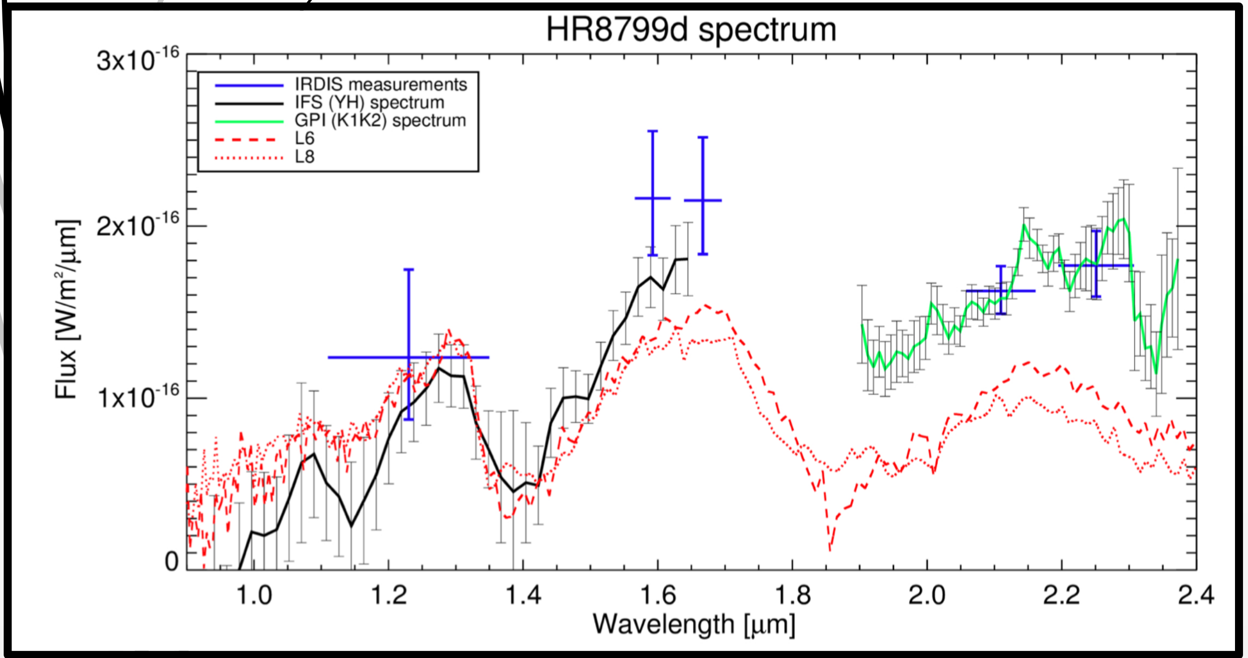
We focus on direct imaging (see Madhusudhan 2019 for an extensive review on exo-atmospheres)

Direct imaging	
H_2O	HR 8799b (Barman et al. 2015), HR 8799c (Konopacky et al. 2013), HR 8799d (Lavie et al. 2017b, Bonnefoy et al. 2016), HR 8799e (Lavie et al. 2017b, Bonnefoy et al. 2016), κ And b (Todorov et al. 2016), 51 Eri b (Macintosh et al. 2015), Gl 570D (Line et al. 2015), HD 3651B (Line et al. 2015), β Pic (Chilcote et al. 2017), ULAS 1416 (Line et al. 2017)
CH_4	HR 8799b (Barman et al. 2015), 51 Eri b (Macintosh et al. 2015), GJ 504 (Janson et al. 2013), GJ 758 B (Janson et al. 2011), Gl 570D (Line et al. 2015), HD 3651B (Line et al. 2015), ULAS 1416 (Line et al. 2017)
NH_3	Gl 570D (Line et al. 2015), HD 3651B (Line et al. 2015), ULAS 1416 (Line et al. 2017)
CO	HR 8799b (Barman et al. 2015), HR 8799c (Konopacky et al. 2013)

How ?

High-contrast low resolution spectroscopy available in SPHERE@VLT, GPI@Gemini

1. Integral field spectrographs (IFS)
2. Long-slit coronagraphic spectroscopy (only in SPHERE and soon SHARK-NIR)



Zurlo+(2016) IFS spectrum of HR8799d

Acquisition of spectra of YOUNG, non-strongly irradiated and self-luminous giant planets

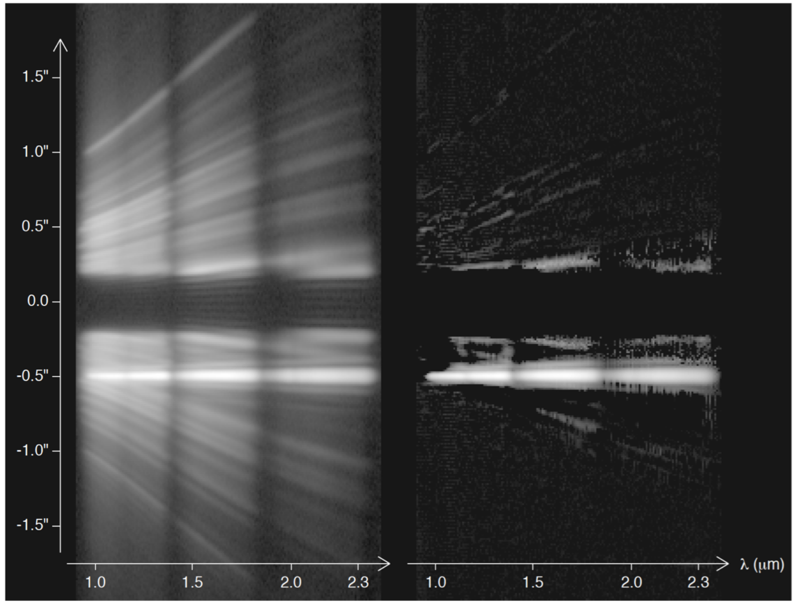
[to be compared with information for old planets coming from transmission/emission or Doppler spectroscopy]

Long-slit coro spectroscopy
→ Speckle removal and planet spectrum (for free!)

The concept

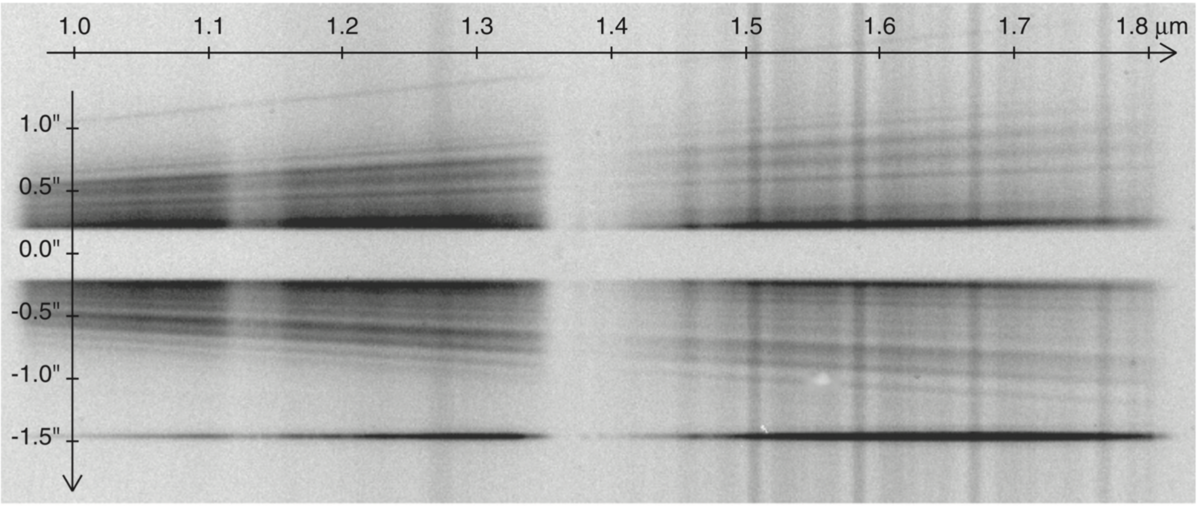
the slits and coronagraphic masks have been merged into a single device →
The obscured part between ±0.2" corresponds to the position of the opaque coronagraphic mask.

Vigan+ (2008)



LRS data obtained on PZ Tel (H=6.5) →
The spectrum of the companion PZ Tel B is visible as a straight line at an angular separation of ~0.5"

Hinckley+ (2015)



MRS data for 2MASS J01225093–2439505 (H=9.5)
The spectrum of the companion is visible at 1.45"

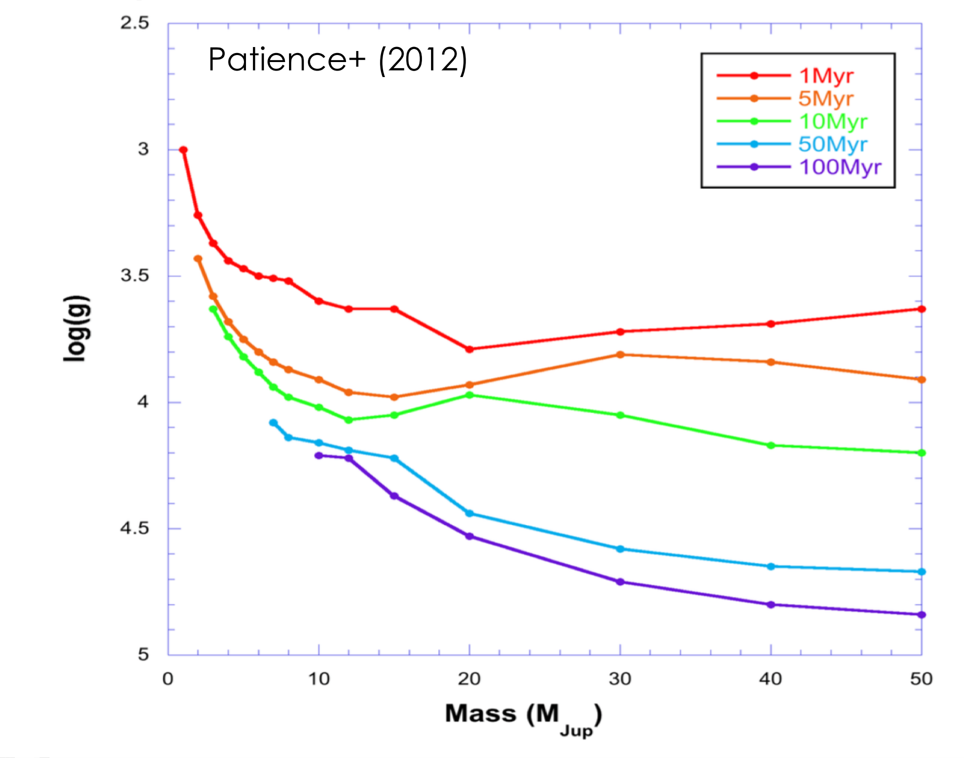
Key diagnostics for gravity estimates

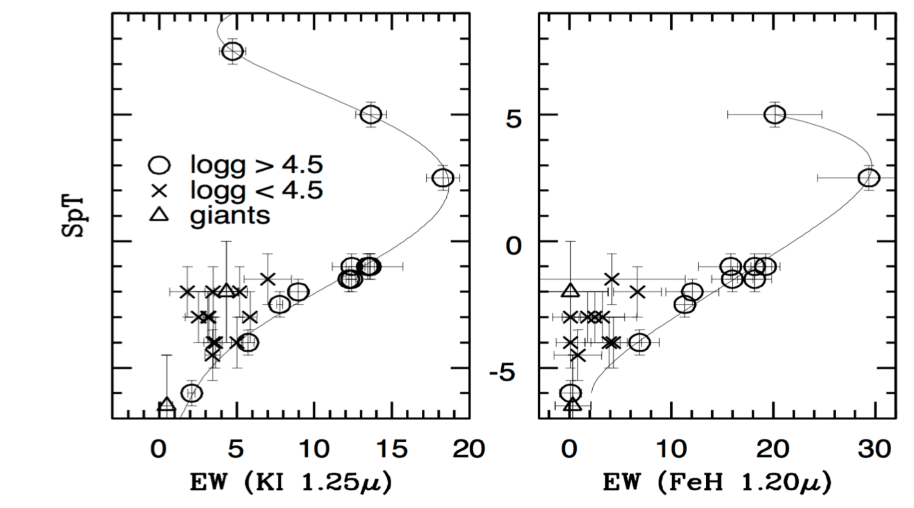
One way to distinguish between young and old brown dwarfs is to look for gravity-sensitive spectral features.

young objects can exhibit significantly lower surface gravities (10–100 times) than the more massive evolved dwarfs of the same spectral type.

Gorlova et al. (2003) showed that the K I lines in the J band are very sensitive to surface gravity.

Other key lines:
Na I at 1.14 um (Allers+2007) and FeH at 0.99 um (McGovern+ 2004)





HIP 19176

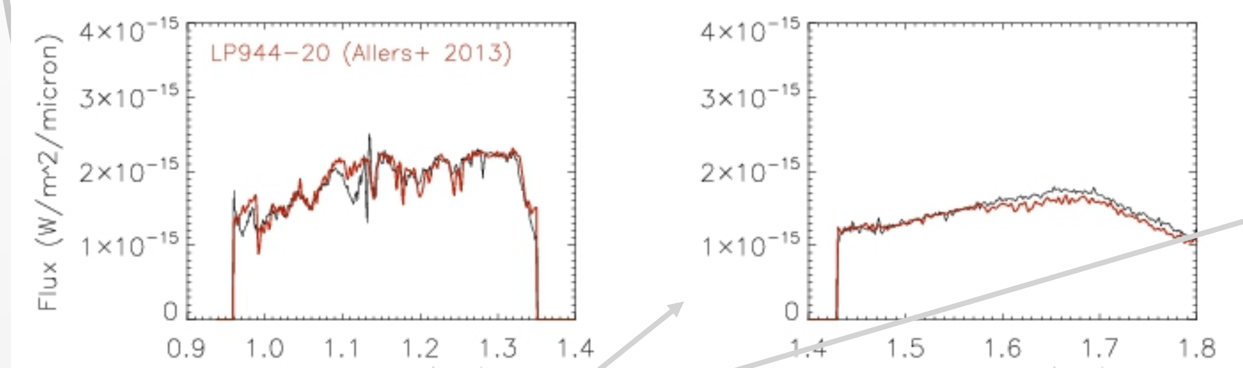
Bonavita+ (2014) survey of 74 targets in the Taurus SFR → Discovery of 18–50 M_{Jup} companion at a projected separation of ~400 AU from the F8 star HIP 19176.

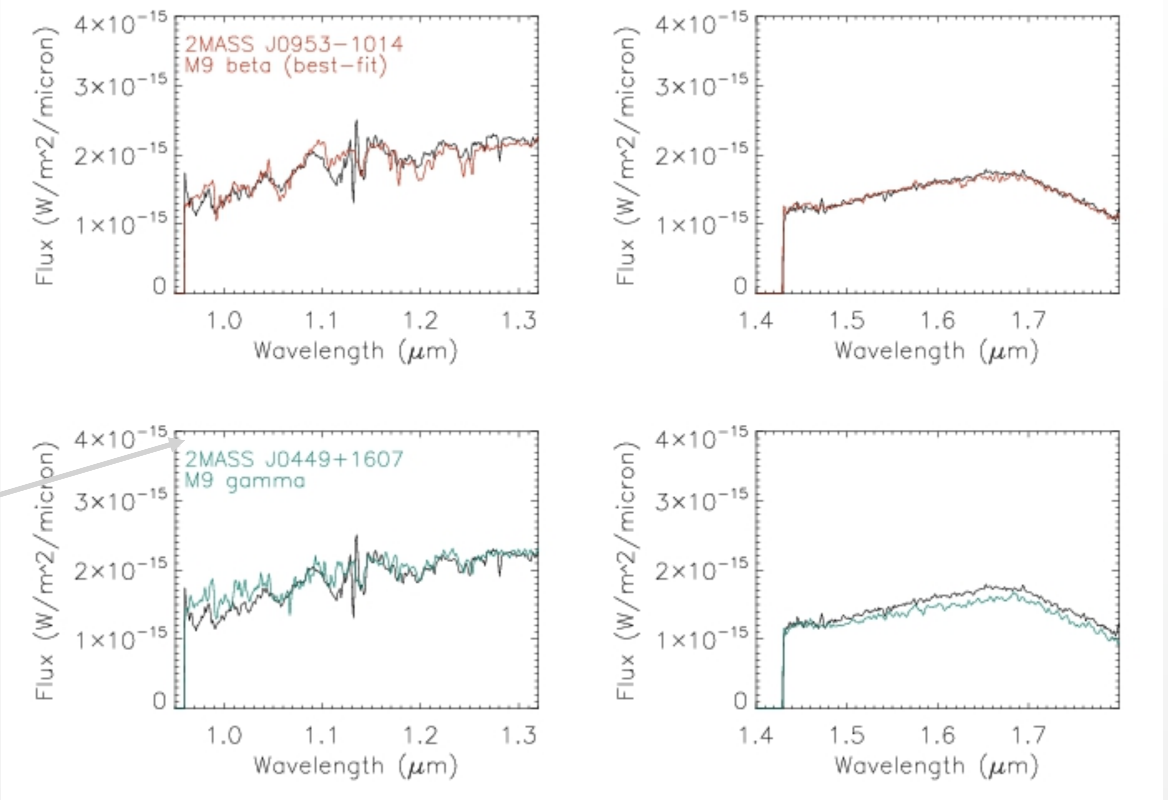
Table 1
Summary of Properties of Both HD 284149 and Its Companion

Parameter	Host Star	Companion	Ref.
V (mag)	9.653 ± 0.060		2
$B - V$	0.58		3
$V{-}I$	0.675 ± 0.088		4
J (mag)	8.479 ± 0.043	15.516 ± 0.043	5, 1
H (mag)	8.208 ± 0.021	14.715 ± 0.047	5, 1
K (mag)	8.100 ± 0.029	14.332 ± 0.040	5, 1
Parallax (mas)	9.24 ± 1.58		6
$E\,(B{-}V)$	0.05 ± 0.05		1
RV (km s^{-1})	14.0 ± 2.0		7, 8
Ew Li m(Å)	208		7
Prot (days)	1.079		9
$\log L_x/L_{bol}$	-3.3 ± 0.1		1
$v \sin i$ (km s^{-1})	27.0 ± 1.9		8
Age (Myr)	25^{+25}_{-10}		1
Sp. Type	G1-F8	M8-L1	7, 8, 1
T_{Eff} (K)	5970–6100	2537^{+95}_{-182}	1
Mass	$1.14 \pm 0.05\ M_{\odot}$	$32^{+18}_{-14}\ M_{Jup}$	1

Previous estimates: spectral type between M8 and L1while our study: M8+/0.5
→ Confirmation of young age thru Na & Ka lines (weak)

Bonavita, D'Orazi, Mesa+ 2017

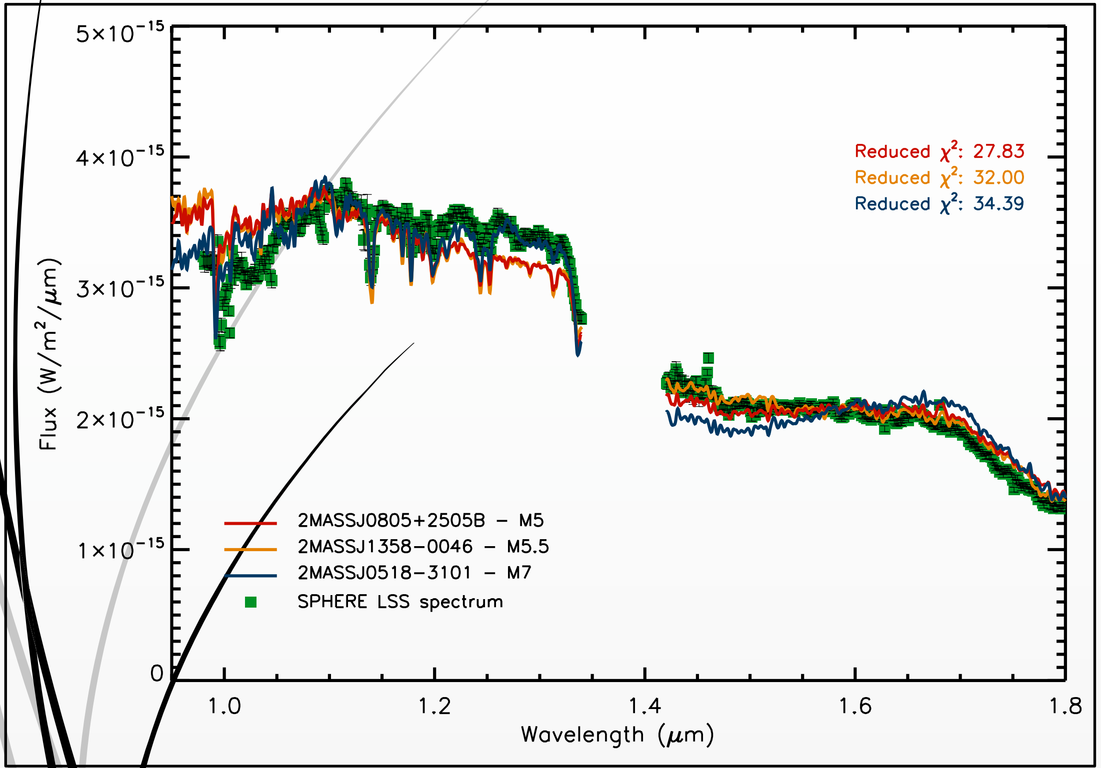




IRDIS LSS MRS spectra

HD 1160 and HD 19467

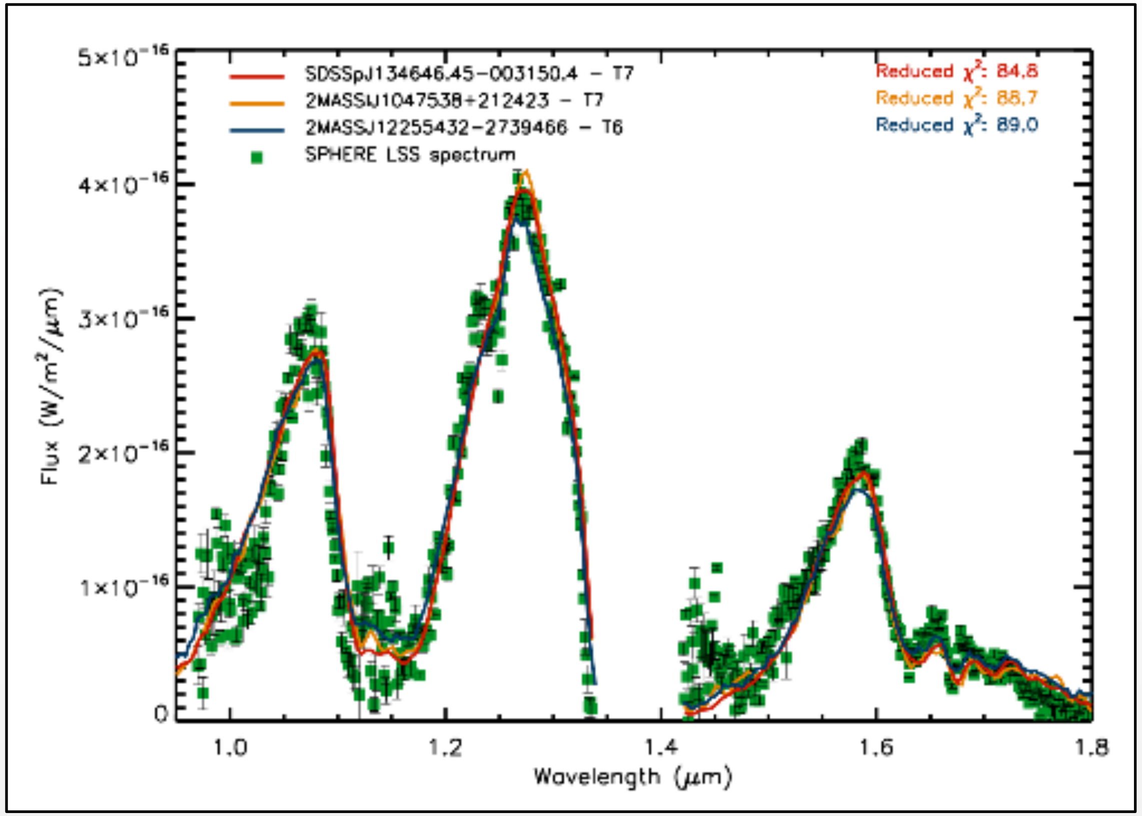
Mesa, D'Orazi, Vigan, Gratton+ 2020 in prep.



M type but large uncertainties on the age → mass (20 – 120 Mjup!)

work in progress to exploit atomic lines!

T-type objects. Very old age (~8 Gyr).
Slightly sub-solar ([Fe/H]=-0.11+/-0.05 dex)

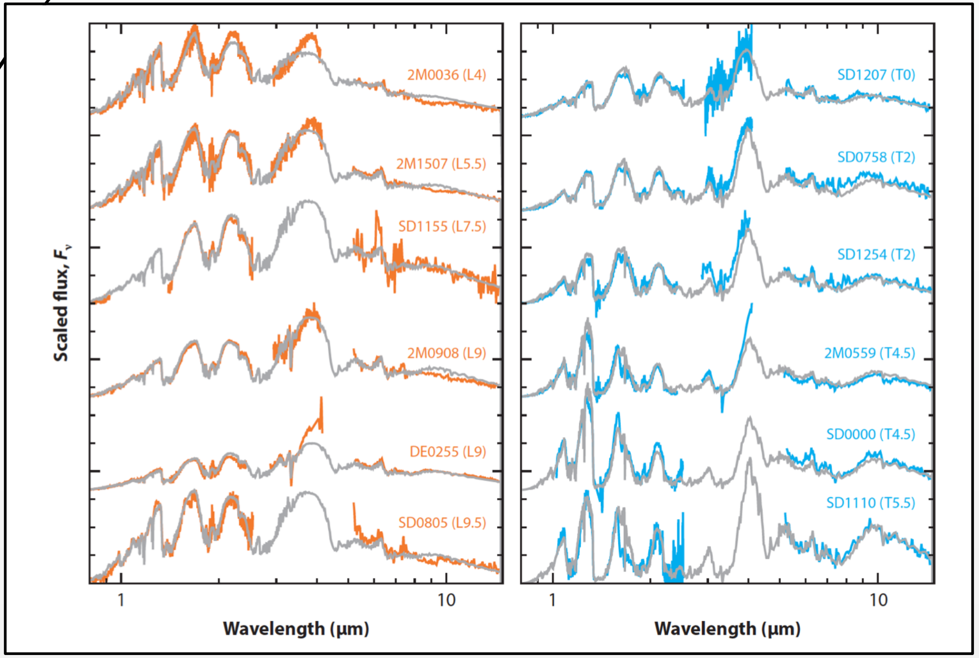


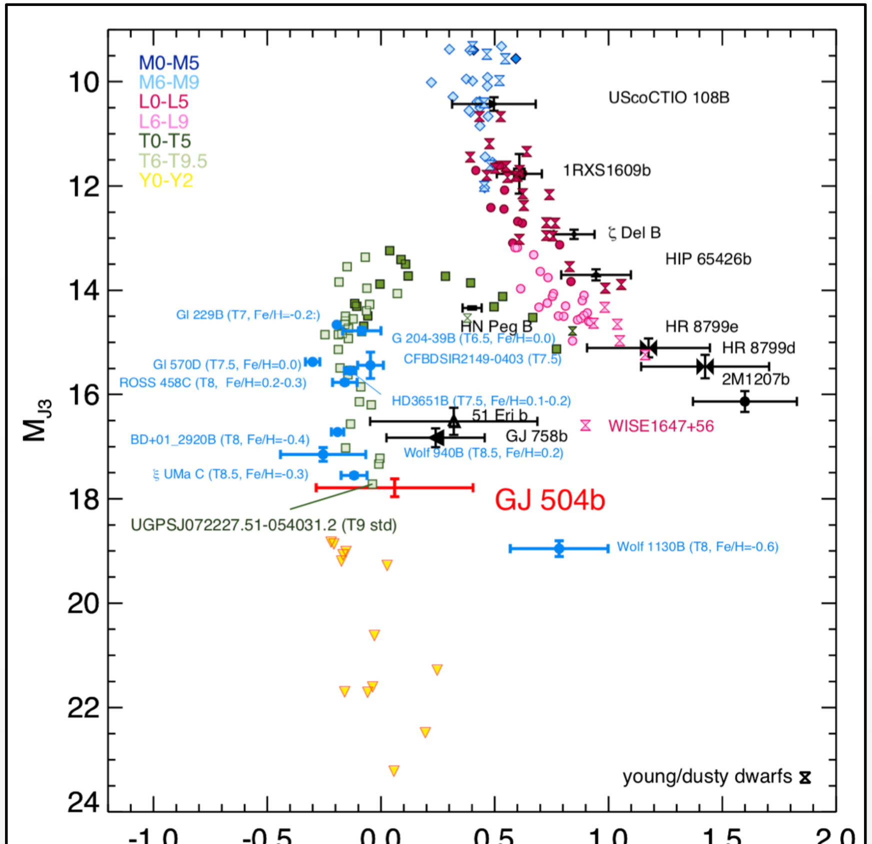
The Clouds and the L-T transition

Shed light on L-T transition and on the characteristics of BDs and giant planets, which are expected to somewhat overlap but also significantly differ in terms of chemistry of the atmospheres and mechanisms of clouds formation

Clouds, are the product of condensation and sedimentation, and their presence has the effect of both veiling features in the spectra and reddening the NIR colors (key diagnostics e.g., FeH at 0.99 um)

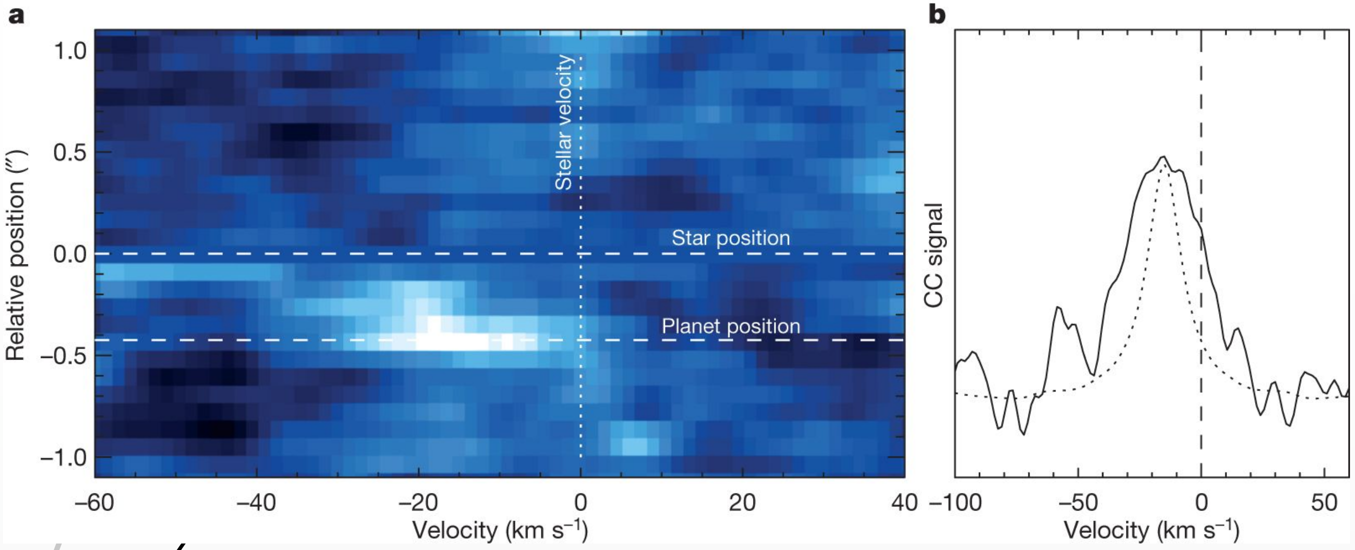
clouds have been inferred in directly imaged planets through the modulation of their spectral features in the IR (Marley & Robinson 2015).





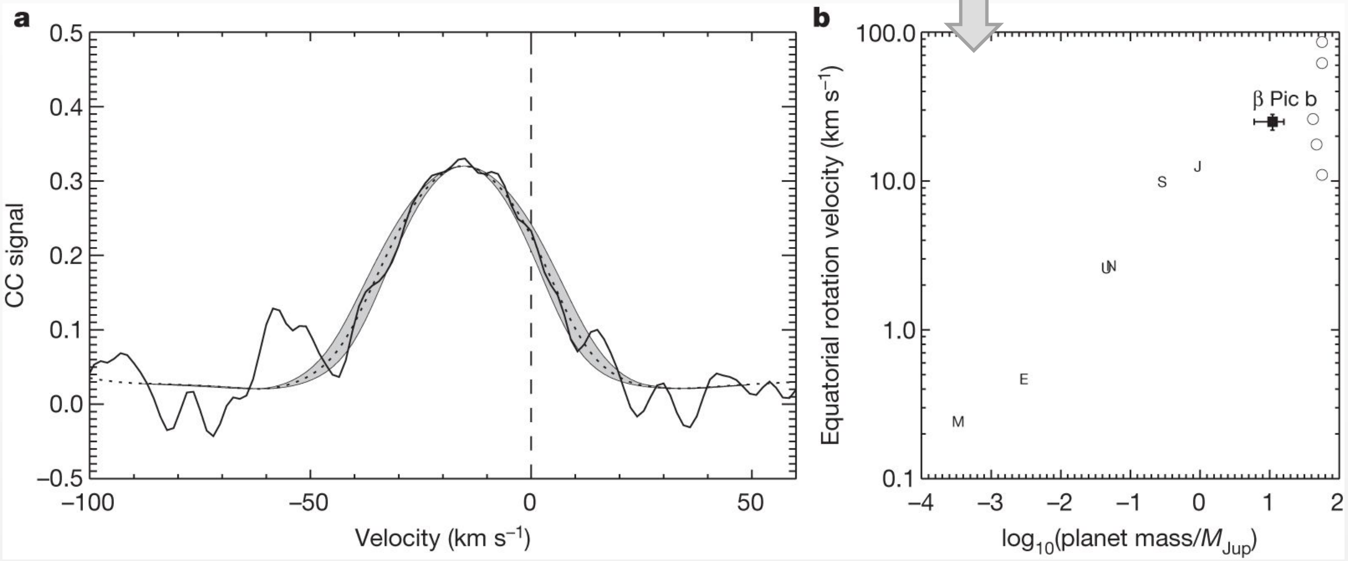
Bonnefoy+ (2018)

Spin velocity for Beta Pic B with CRIRES high-resolution spectroscopy *Snellen+ 2014*

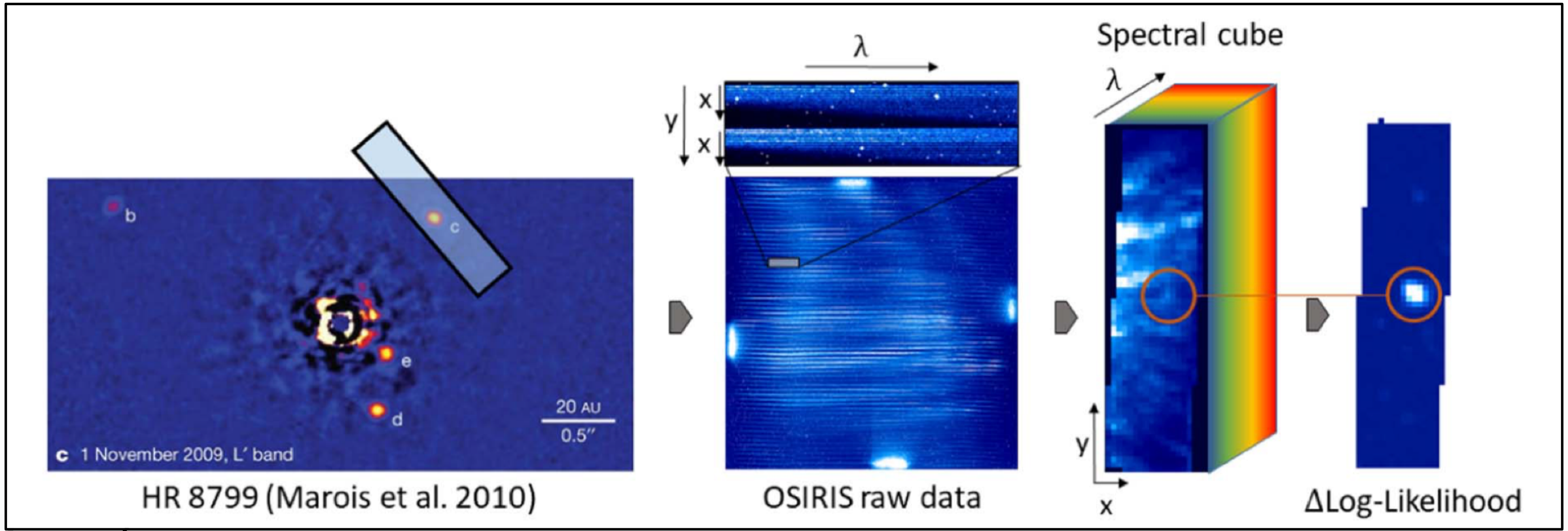


Beta Pic B follows the relationship of our SS planets

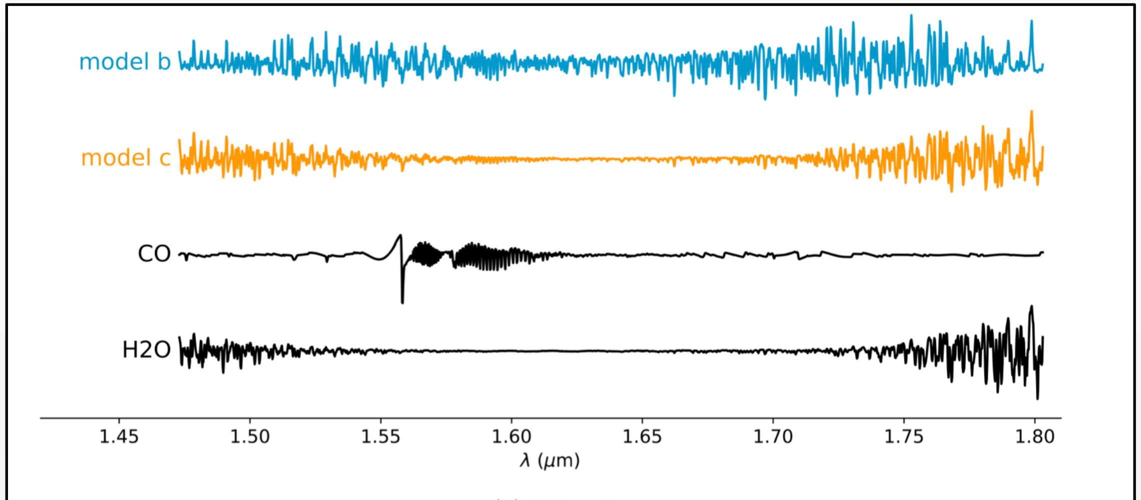
Vspin=25+/-3 km/s



Radial velocity measurements of HR 8799b and c with Medium resolution spectroscopy
→Observations in H and K bands with Keck/Osiris (R = 4000)



Ruffio+ 2019

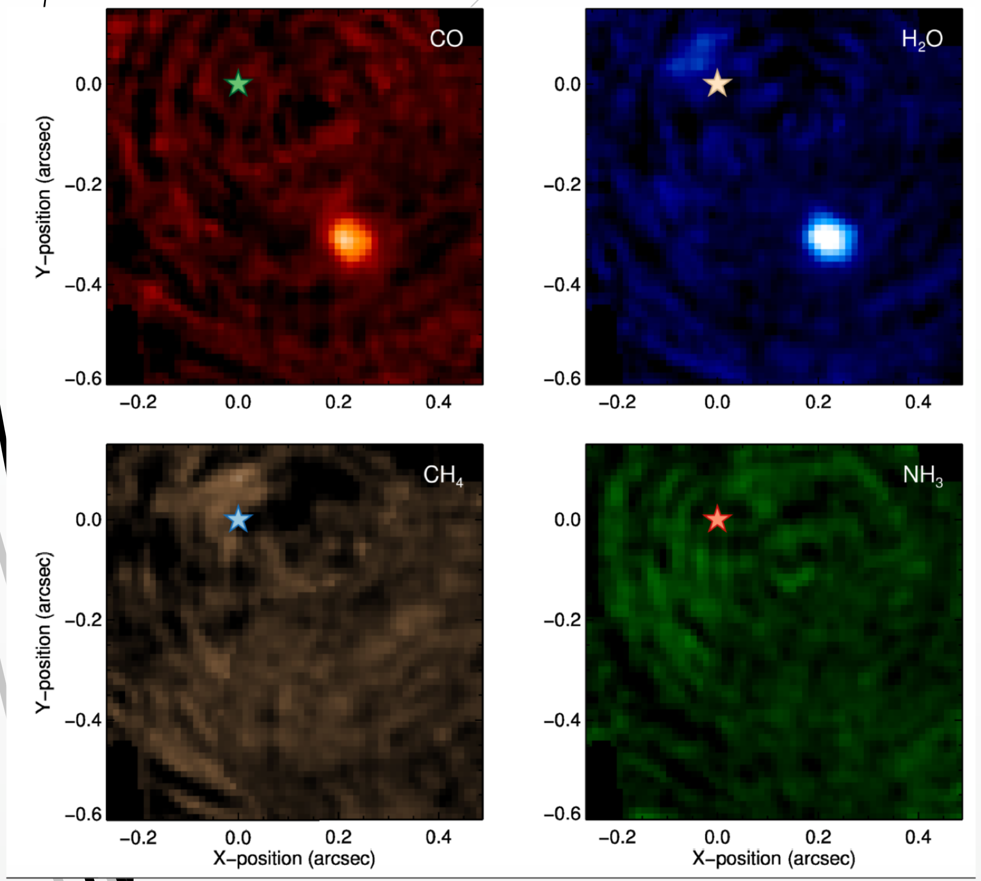


(b) H-band

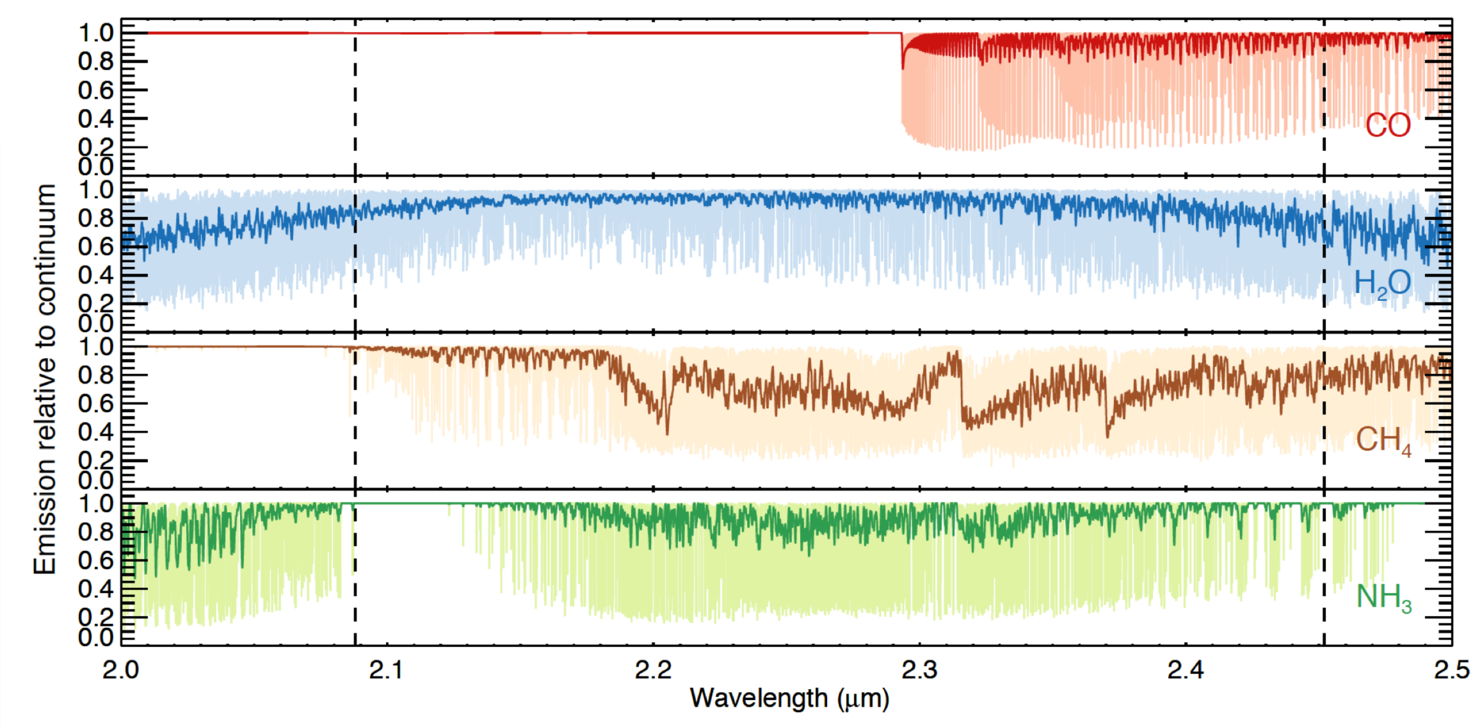
HR 8799b V_{rad}= -9.2+/- 0.5 km/s
HR8799c V_{rad}=-11.6+/- 0.5 km/s

Molecular mapping of Beta pic with SINFONI@VLT

Aim: boosting detection performances & spectral information (RV and somehow chemical composition)



Hoeijmakers+ 2018



Next and Far future instrumentation

ERIS-Spiffier → IFU with R up to ~ 8000;
wavelength 1-2.5 μm

SHARK-NIR → LSS coro mode with R=100 and R=700; wavelength: YH bands)

SPHERE+ → updates include HiRiSE = CRIRES + SPHERE
and medium- or high-resolution spectrograph in NIR,
under discussion)

METIS → IFU-fed high-resolution spectrograph bands R~100,000;
wavelength: L and M bands

MICADO → LSS NO coro but R = 20 000;
wavelength: 0.45 – 2.46 μm and 0.84 – 1.48 μm