Atmospheric characterization of exoplanets with the medium resolution spectrometer on JWST/MIRI

Mathilde MÂLIN

LESIA l'Observatoire de Paris | PSL

Laboratoire d'Études Spatiales et d'Instrumentation en Astrophysique

cnes SORBONNE UNIVERSITÉ

Workshop COBREX

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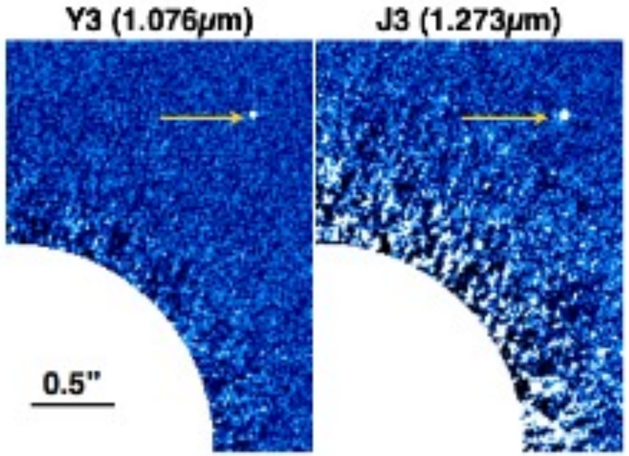
Direct Imaging



Example GJ 504 b

High contrast image and best-fitting model spectra with photometry point

Bonnefoy et al. (2018)

A need for mid-IR data

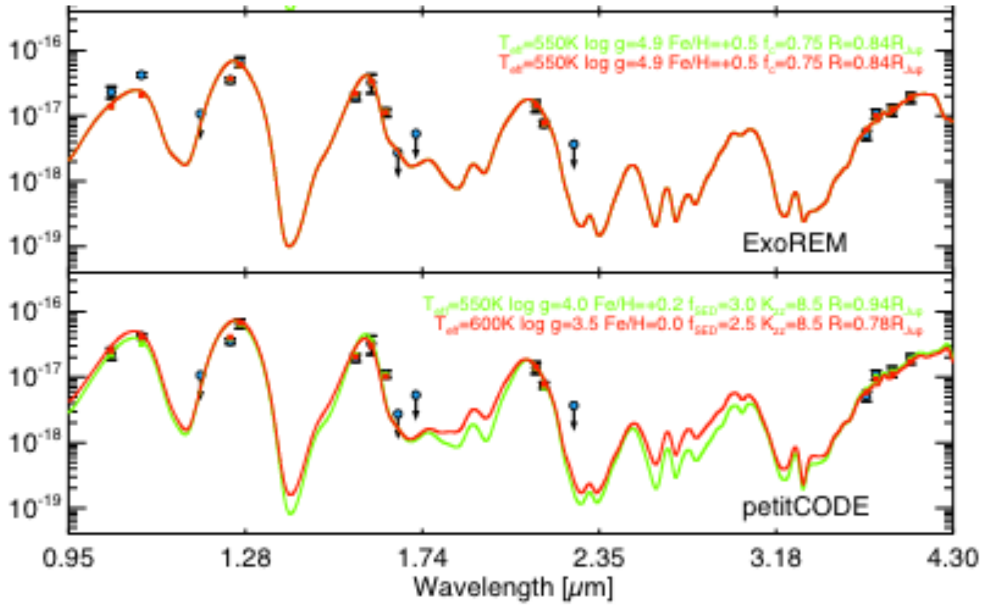
→ Contrast star/planet reduce

→ Emission of the young giant planets

→ Complementary to near IR data

→ Access to molecular species: H_2O, CO, CO_2, CH_4, NH_3, PH_3, HCN, H_2S

→ Planetary formation



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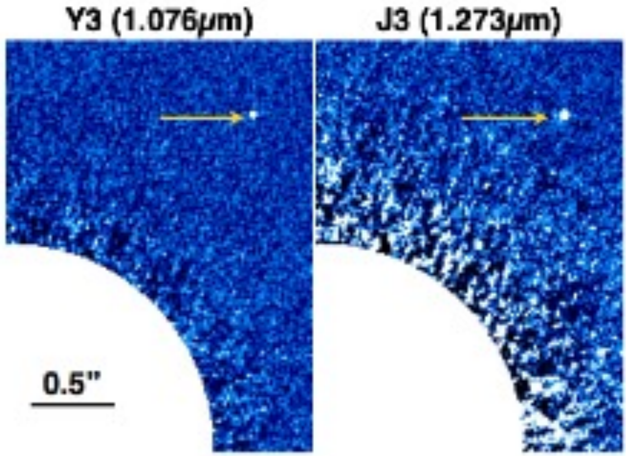
→ Planetary formation

→ Need spatial instrument



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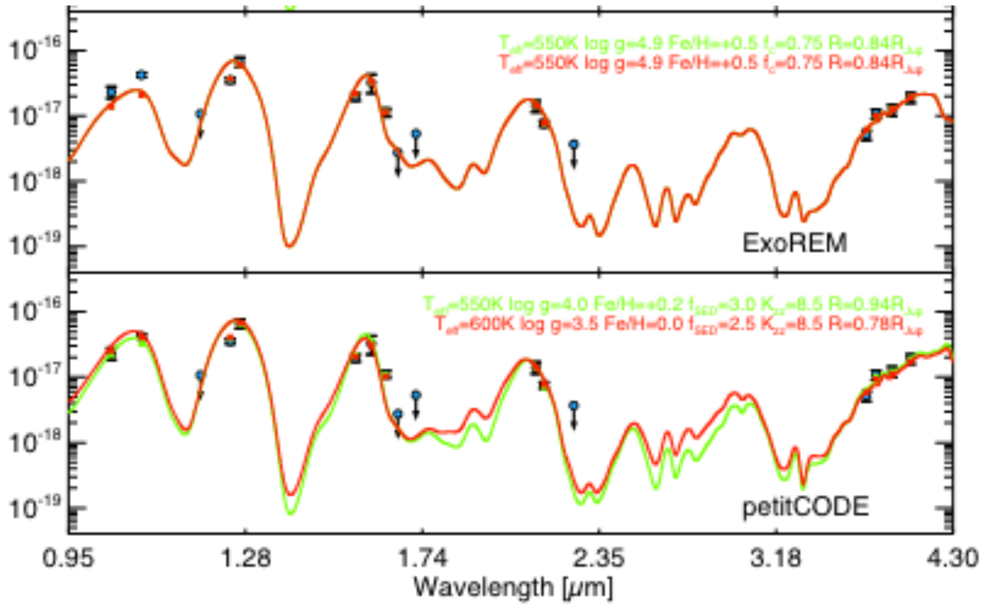


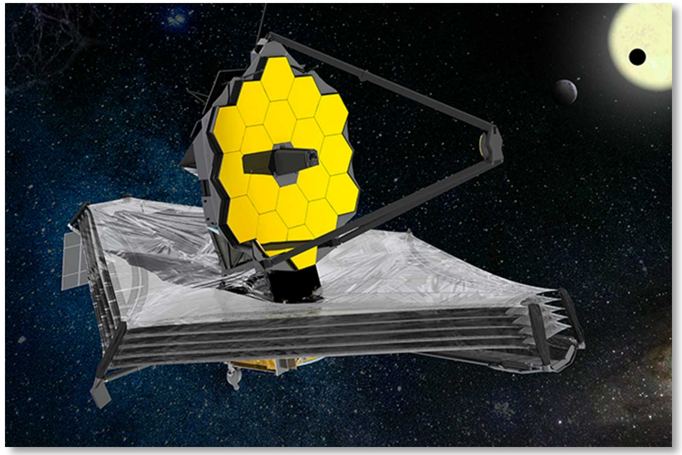
JWST - MIRI

MIRI : Mid-IR Instrument

→ Spectral range from 5 to 28 μm

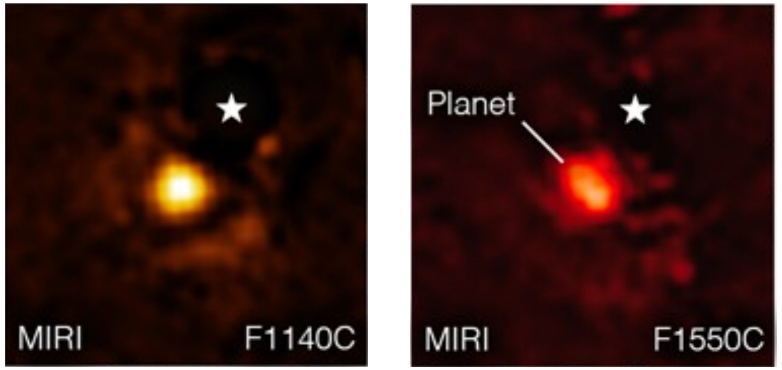
First data available for direct imaging above 5 μm!

→ Advantages of spatial instruments



MIRI coronagraphs:

First imaged exoplanet (HIP 65426 b)

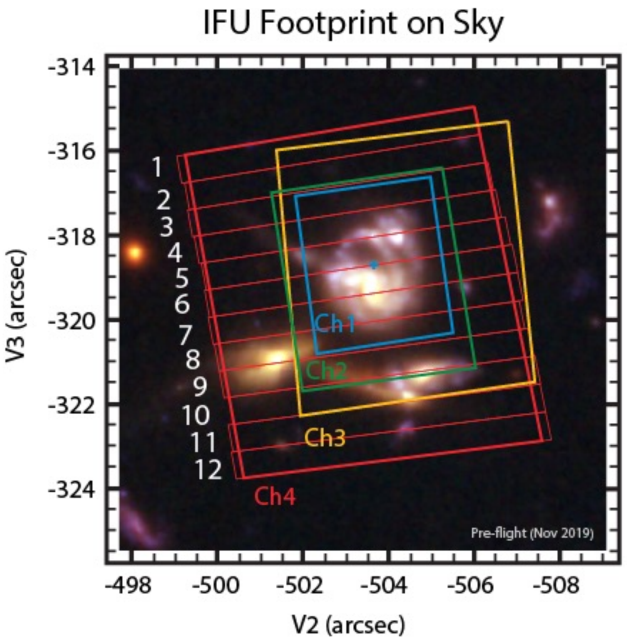


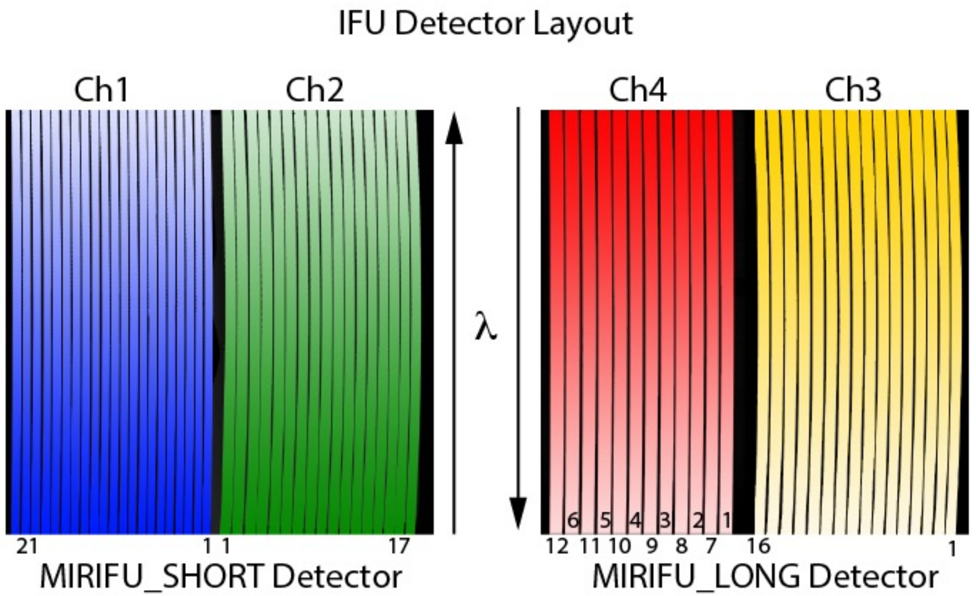
Carter et al. (2022)

Observing modes: Imager, Coronagraph, Low Resolution Spectrometer and **Medium Resolution Spectrometer**

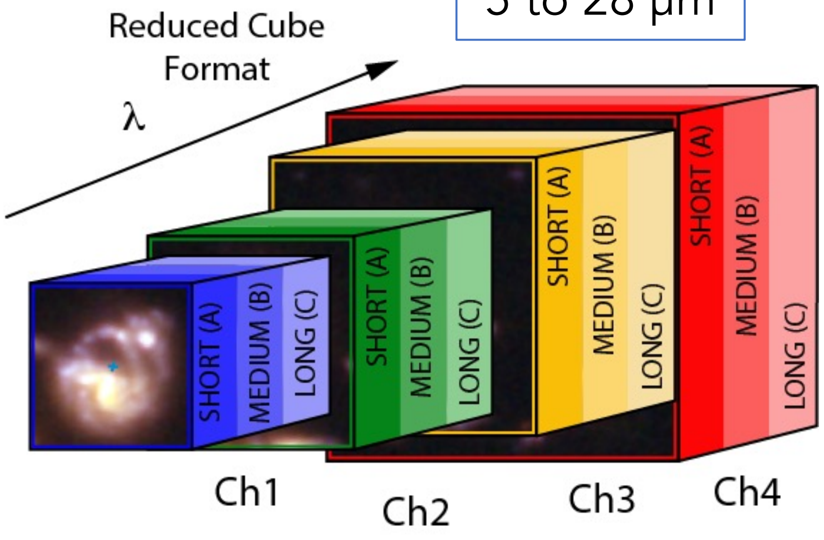
MRS : Medium Resolution Spectrometer

- Integral field spectrometer with a resolution up to $\boldsymbol{\lambda}/\Delta\boldsymbol{\lambda}$ = 3700
- 4 channels ; 3 observations needed to observe the full wavelength range
- Slicer to dispersed the scene onto the detectors





5 to 28 μm



Wells et al. (2015)

JWST Data reduction

Stage 1

Detector Processing → process raw ramps data into uncalibrated slopes data.

⇩

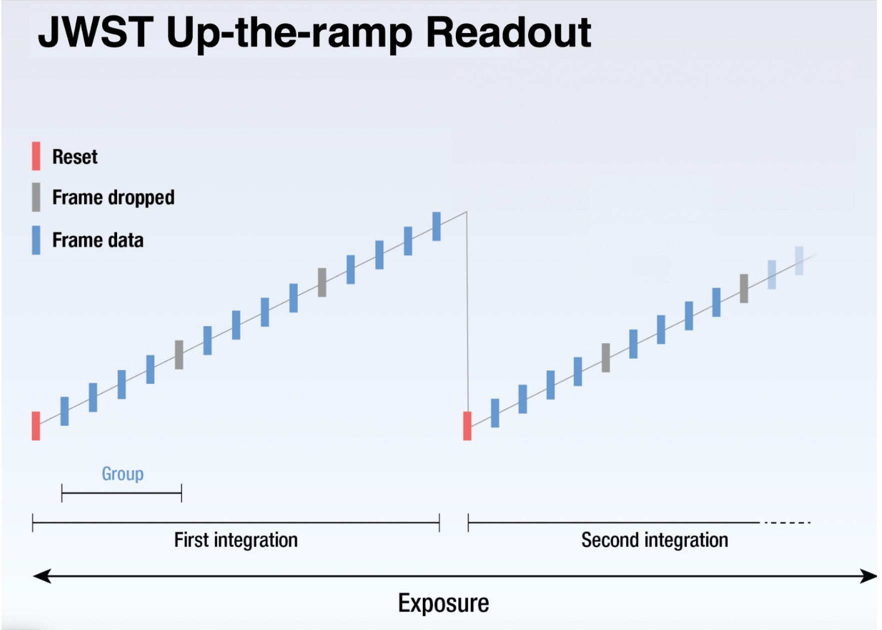
Stage 2

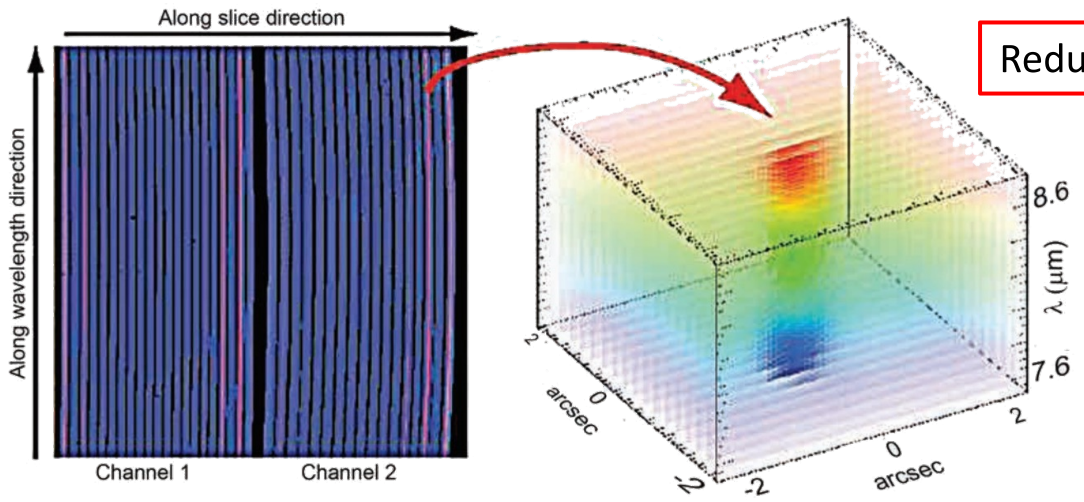
Spectroscopic Processing / Calibration + additional residual fringe step

⇩

Stage 3

Cube reconstruction
Combine exposure and dither position





Detector image

Reduced data (cubes)

MRS : First targets

GTO target :

- Brown Dwarfs : WISE J1828, WISE J0458+6434, WISE J085510.83, WISEPC J121756, Eps Ind Ba+Bb, WISEPA J173835.53
- **Exoplanets** : 2M 1207 b, PSO J318, ROSS 458 AB c

ERS 1386 :

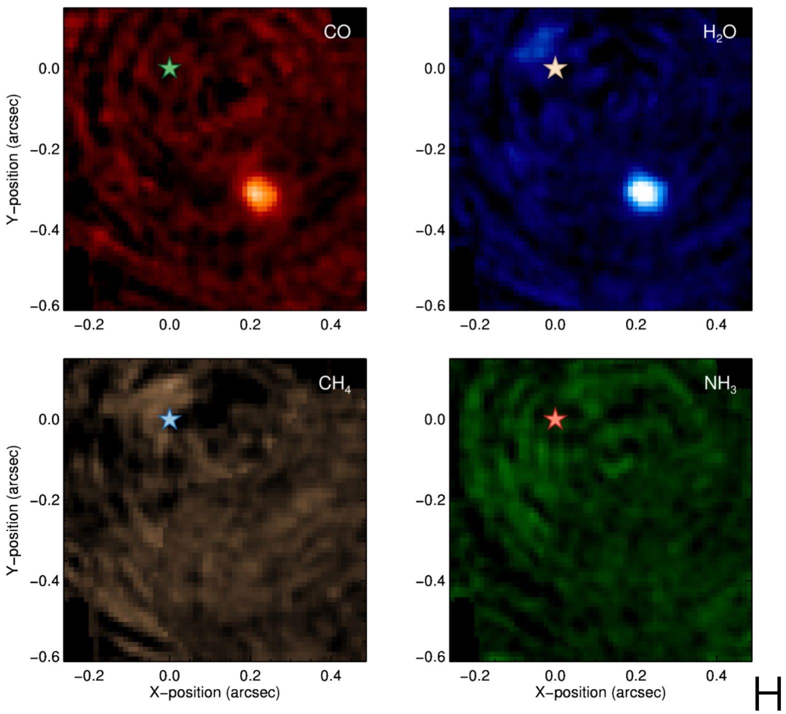
- VHS 1256 b

How to observe companions that are less bright and closer to their star ?

Molecular mapping method

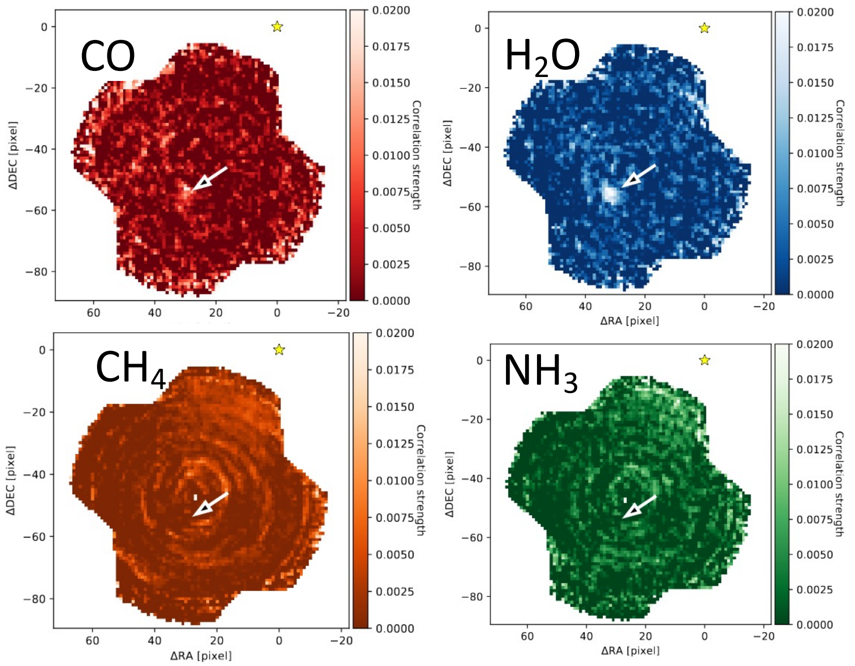
- Disentangle **spectrally and spatially** the light from the star and that of the planet
- **Cross-correlation** with a synthetic spectrum
- Detect and retrieve **molecules**

Examples with VLT/SINFONI (R = 1500–4000)



Beta Pictoris b

Hoeijmakers et al. (2018)



HIP 65426 b

Petrus et al. (2021)

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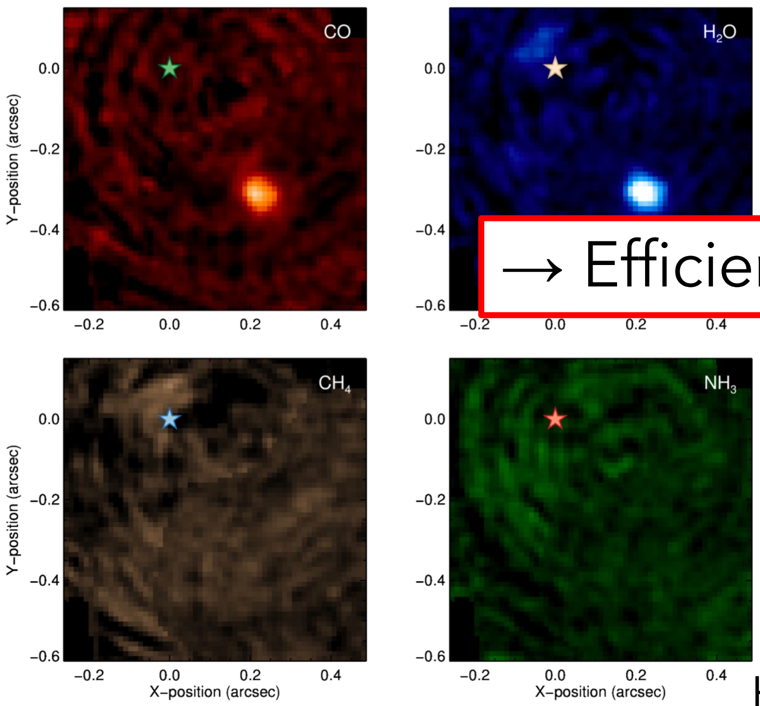
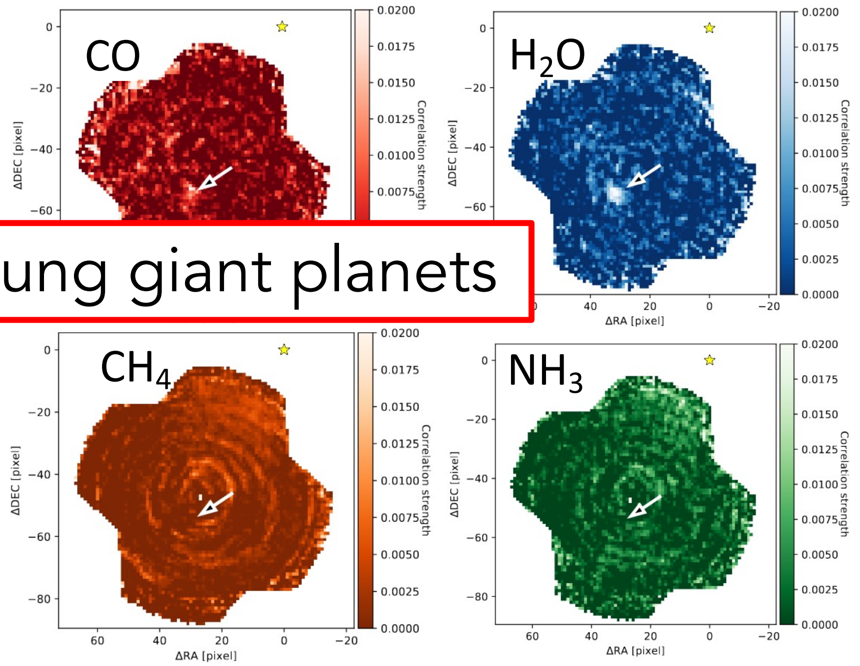


→ Efficient method for young giant planets

Hoeijmakers et al. (2018)

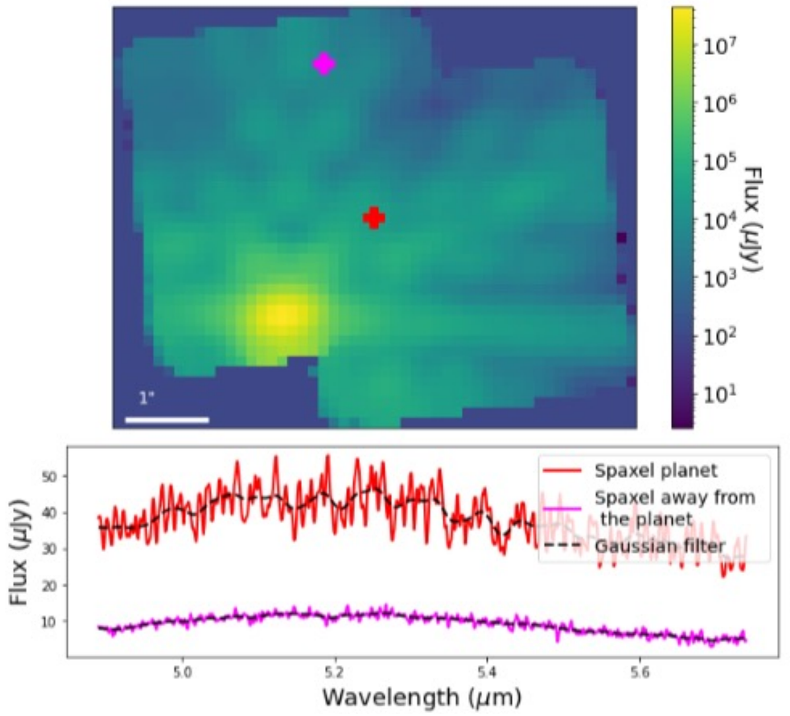
HIP 65426 b



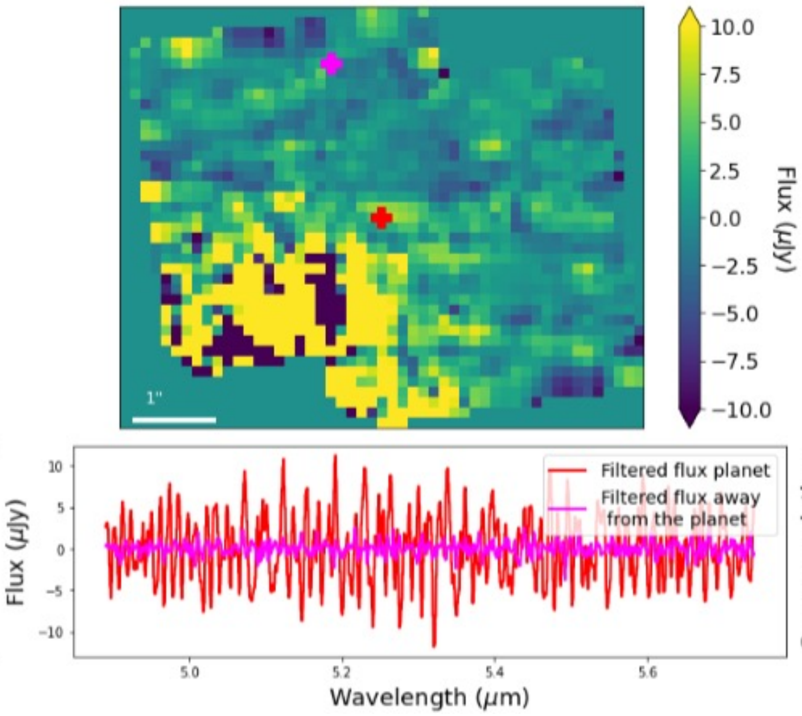
Petrus et al. (2021)

Molecular mapping on MRS/MIRI data

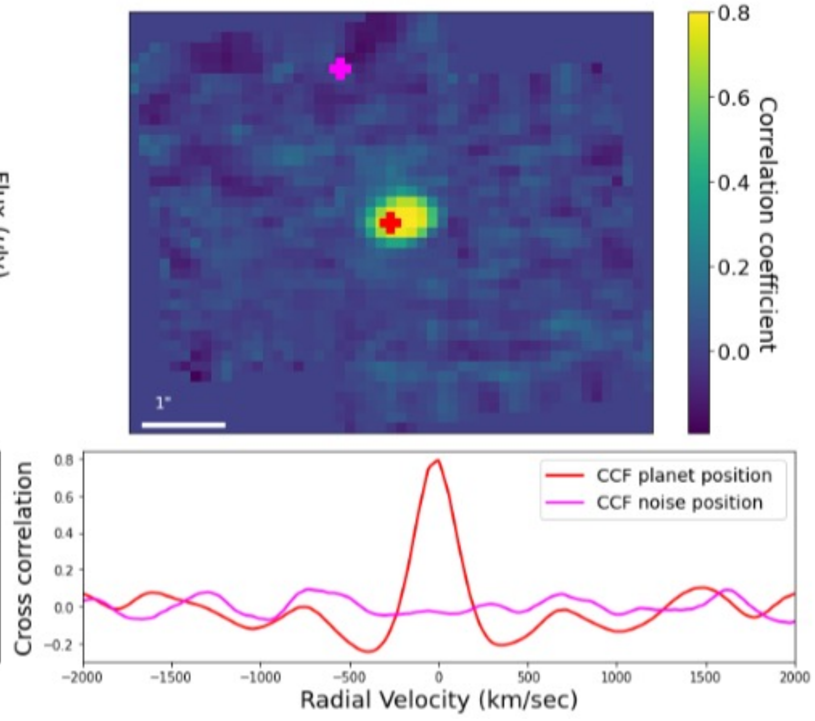
Simulation with MIRISim



Subtracting low frequencies



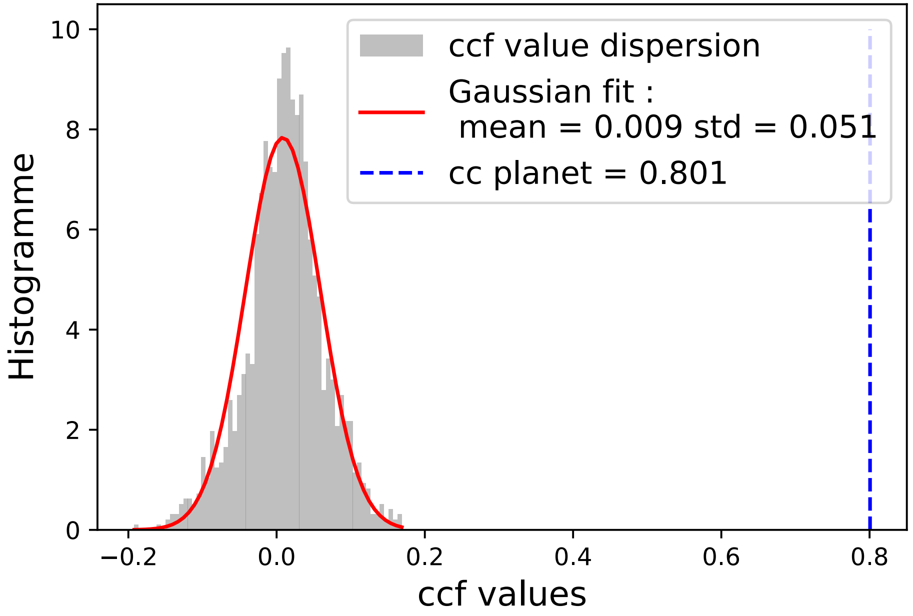
Correlation maps



Planet : 1000 K - R = 1 R_{jup}
Star : 6000 K (BT-NextGen models)
Separation = 1.8 ″

Using Exo-REM models : 1D radiative – convective equilibrium model (*Baudino et al. 2015, Charnay et al. 2018*)

S/N measurement (previous methods)



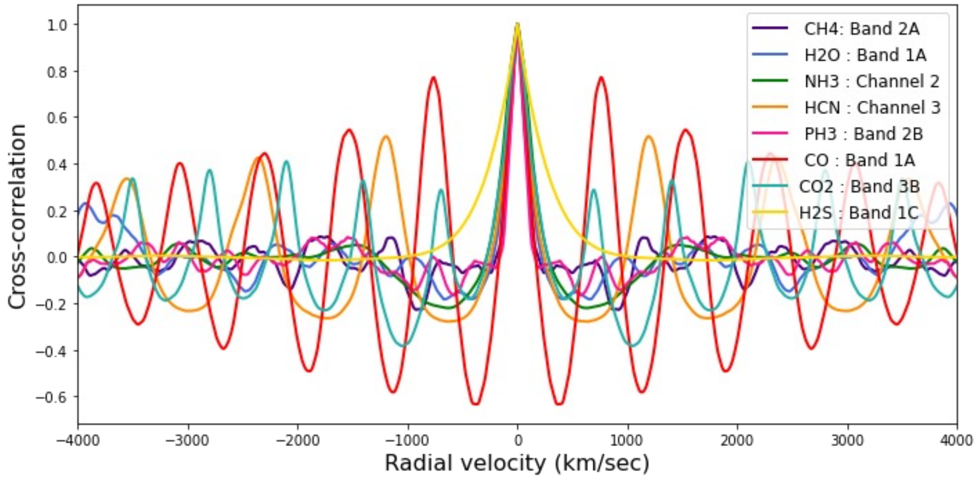
Signal of the planet: peak of the CCF at the position of the planet; averaging CCF (circular aperture centered on the planet position).

Noise: annulus away from the peak signal at RV away from the planet in the CCF; sigma of the gaussian distribution of spaxels away from the planet.

→ Mostly based on the CCF

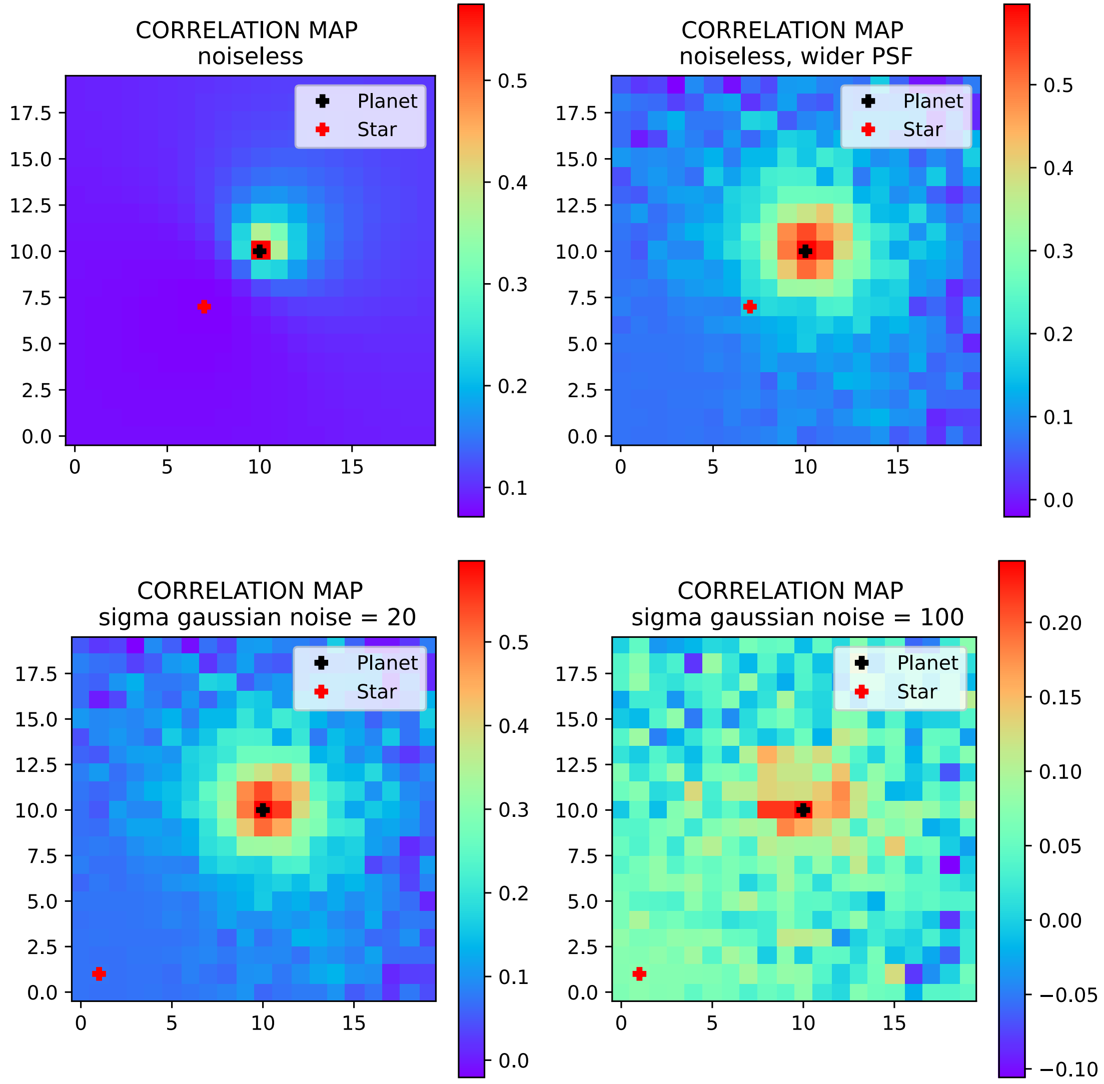
Main issues :

- Planet signal is not focused in one spaxel
- Autocorrelation (due to harmonics in molecular spectral) can be dominant in the CCF
- Noise in correlation maps is not always gaussian



Autocorrelation in the MRS wavelength range

Comments on the correlation pattern



Basic simulations :

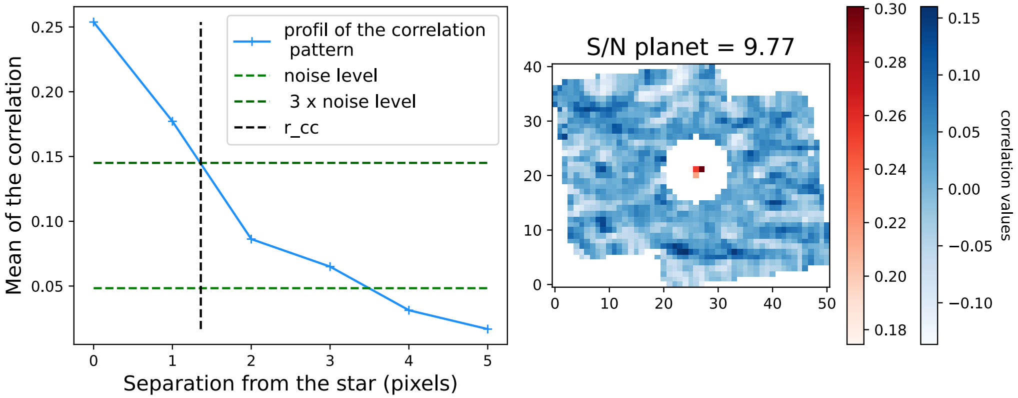
- Center of the correlation pattern does not correspond perfectly to the planet's position (mostly of the star is close)
- The correlation pattern is not a PSF
- Shape and size of the correlation pattern depends on several parameters : PSF, strength of the correlation, noise.
- Noise is not necessarily gaussian

→ Difficult to identify the size of the correlation pattern

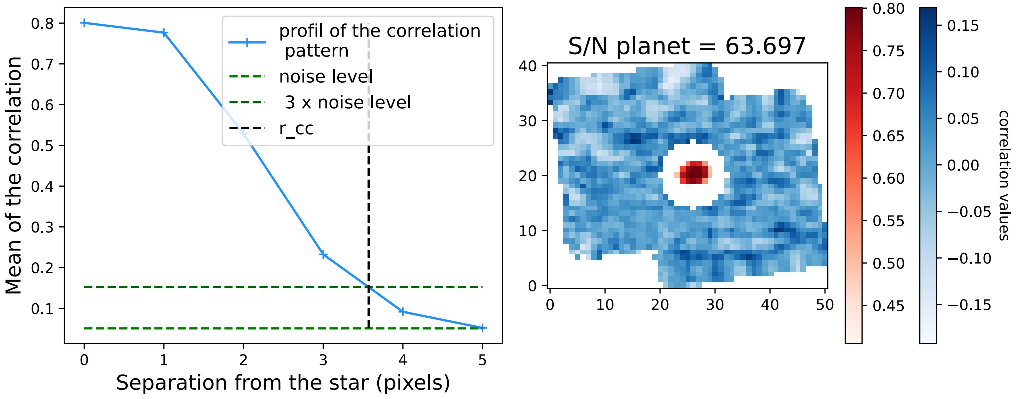
S/N measurement

Method based on the shape of the correlation pattern (example on 2 simulations) :

High noise level



Low noise level



Radial azimuthal profile of the correlation pattern

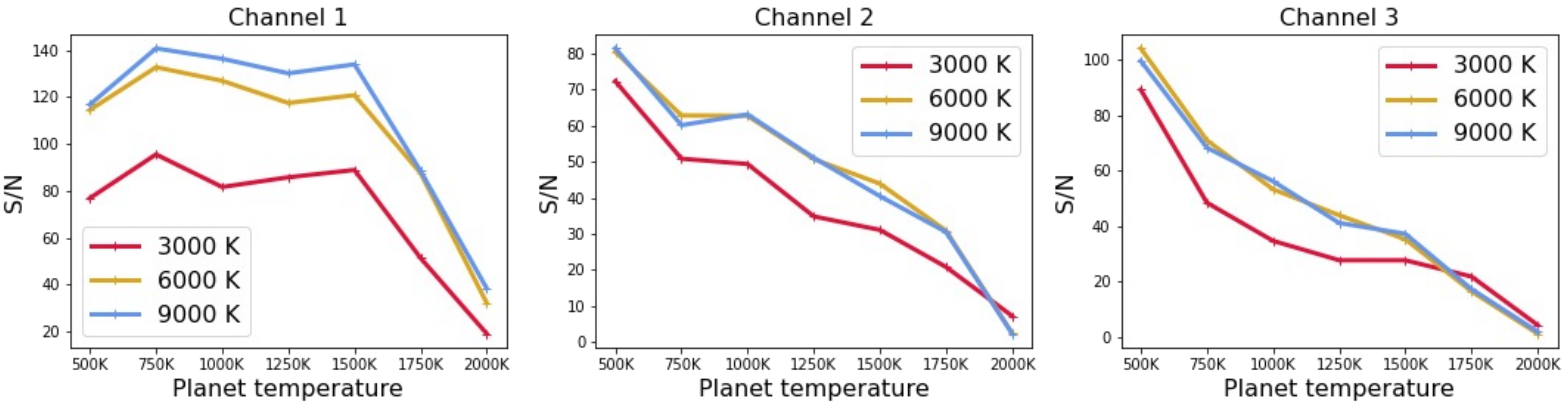
- define a correlation radius (r_cc) based on the noise level
- define a threshold values to take into account only the highest values of correlation

- **Noise**: standard deviation of the correlation values away from the planets (**σ**)
- **Signal** : sum on the correlation pattern (C_i)

$$S/N = \frac{\sum_i C_i}{\sqrt{N_S} \times \sigma}$$

Parametric study

Impact of the spectral type

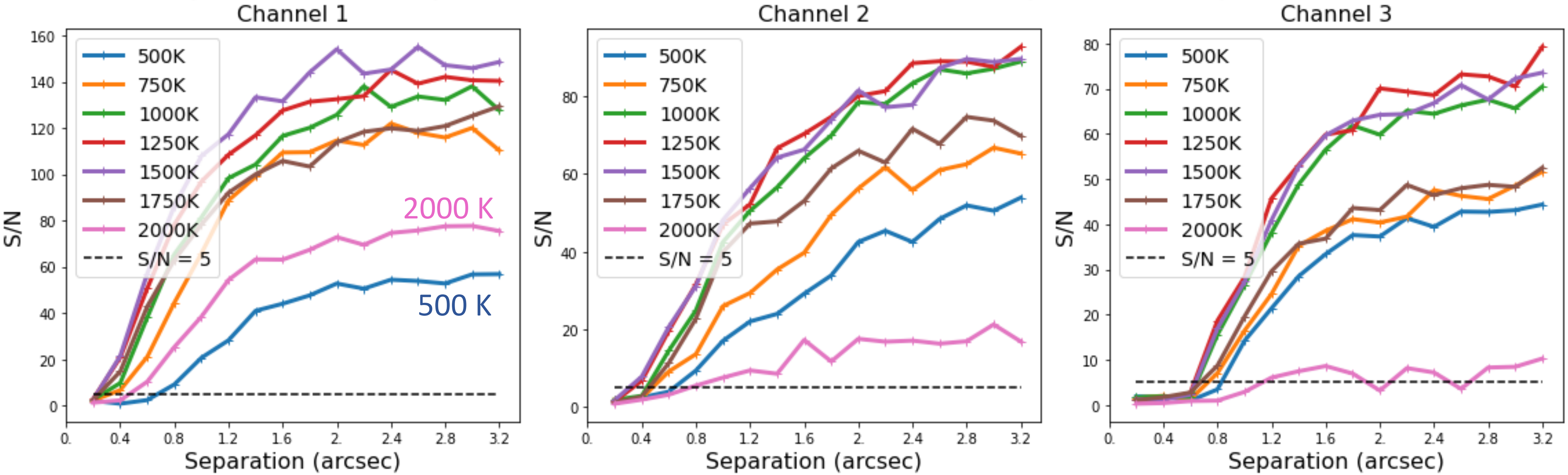


- Systems at 30 pc
- Constant contrast : 10^3
- Separation = 1.4 "

- Similar trends in each bands and channels
- Low impact of the stellar spectra
- More efficient for planets : T < 1500 K

Parametric study

Impact of the separation with host star and of the planet temperature



- Systems at 30 pc
- G type star (6000K)
- $R_{Planets} = 1\ R_{jup}$

- Similar trends in each bands and channels
- Most efficient for planets with T = [750K - 1500K] **and** angular separation > 1''

Apply on known directly imaged planets

Planetary systems	Planet temperature	Star spectral type	Separation (based on June 2023 astrometry)
GJ504	550 K	G0V	2.5″
HR8799	b : 1100 K c, d, e : 1200 K	A5V	1.72″ 0.94″ – 0.7″ – 0.38
Beta Pictoris	1700 K	A6V	0.55″
2M1207	1000 K or 1600 K	M8	0.78″
HD 106906	1800 K	F5V	7.11″
HD 95086	800 K or 1400K	A8III	0.63″
HIP 65426	1550 K	A2V	0.81″
51 Eri	750 K	F0IV	0.34″
GJ 758	600 K	G9V	1.36″

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GJ 504

High contrast Image (Subaru/HiCIAO)

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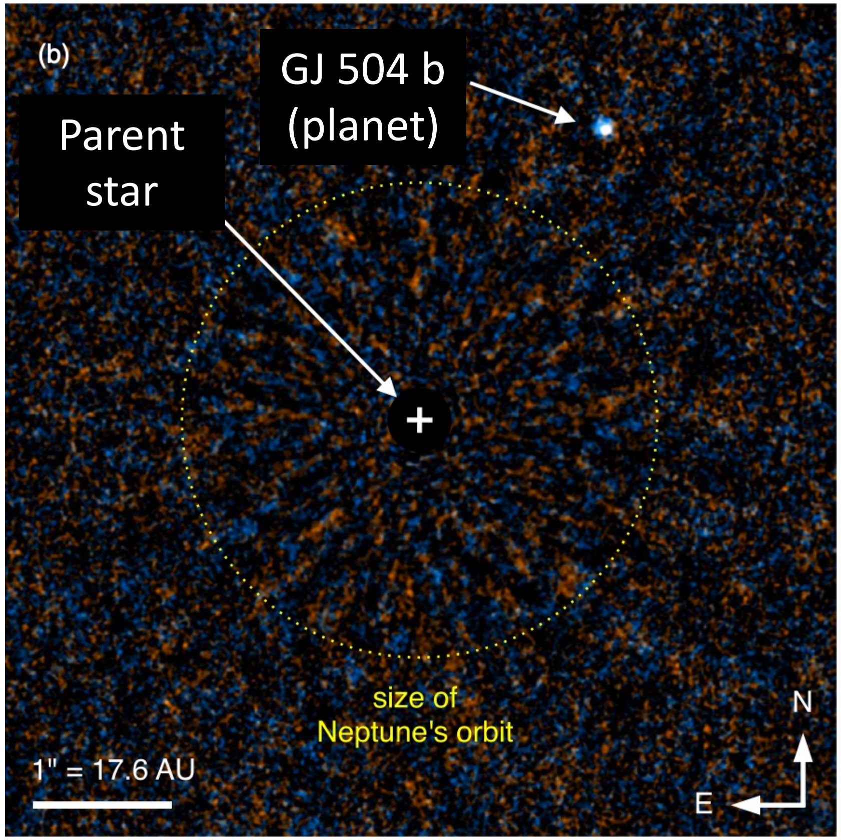
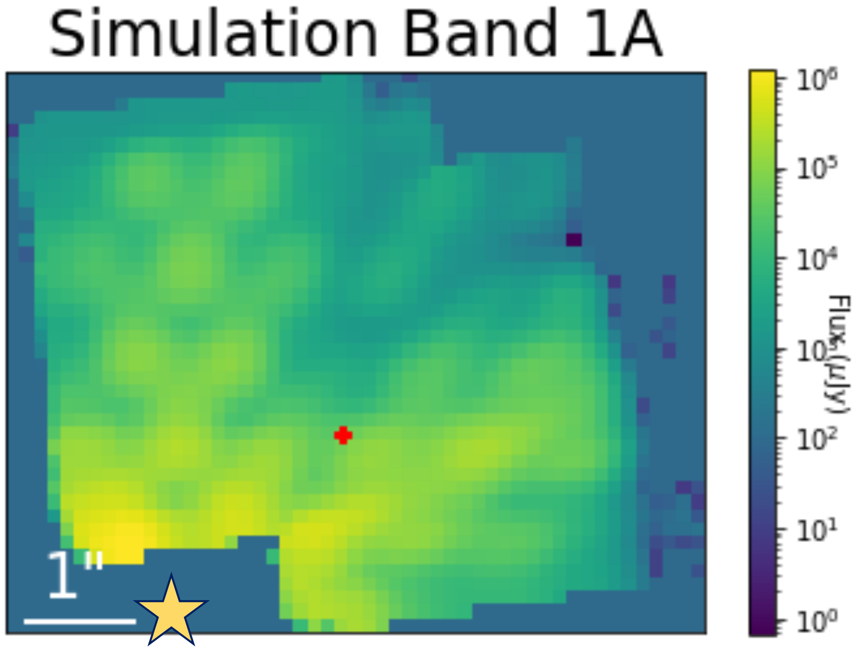


Kuzuhara et al. (2013)

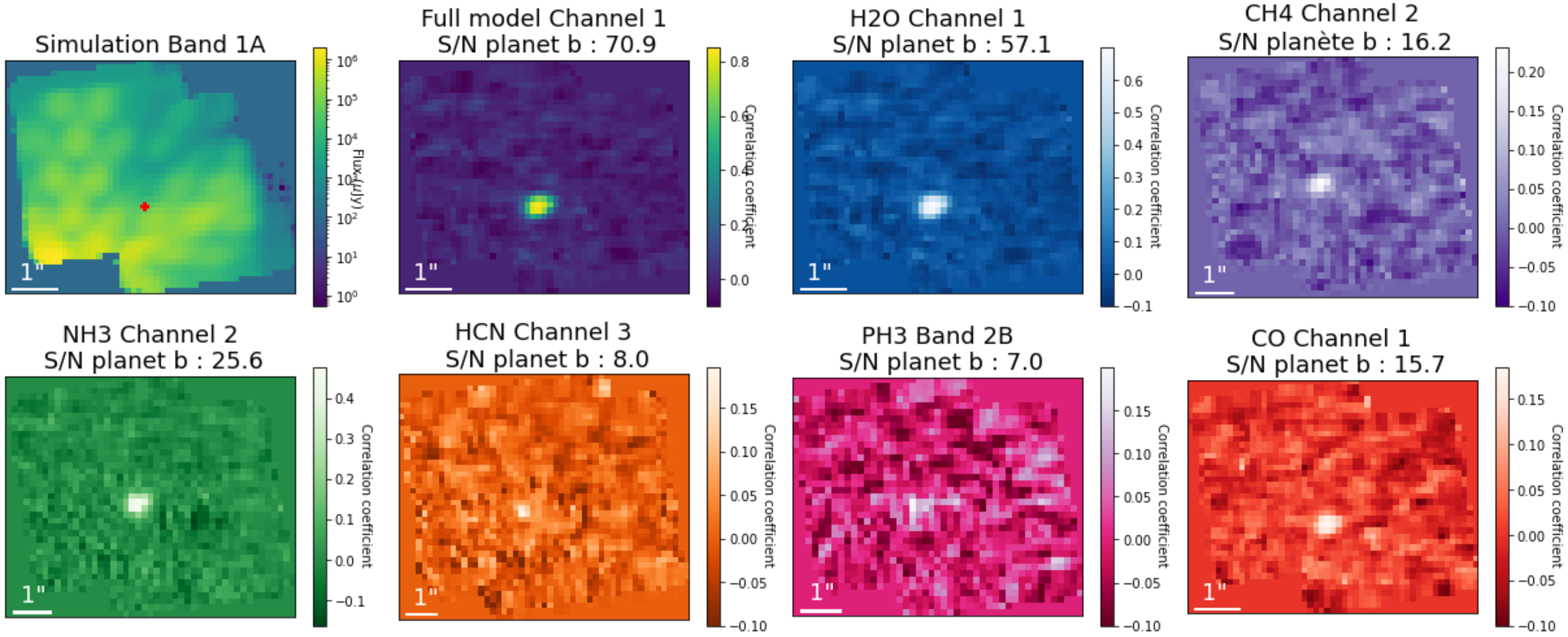
GJ 504

- Star G type : 6200 K
- System at 17.56 pc
- Age uncertain : 21 Myr to 4 Gyr
- Planet : 550 K
- Separation : 43.4 AU - 2.5 arcsec



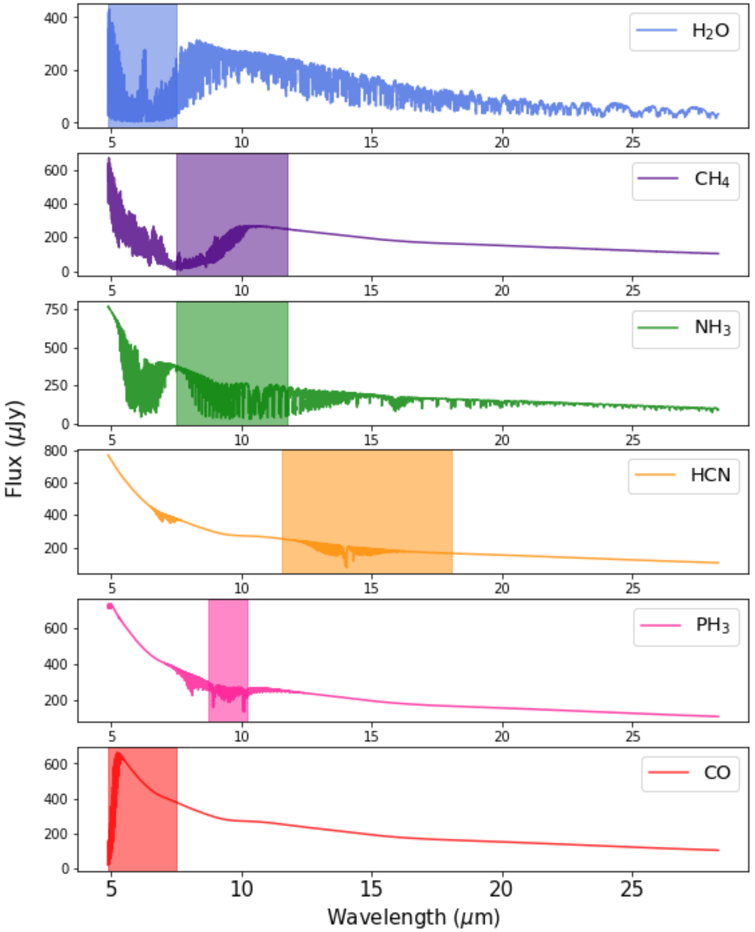
GJ 504

Simulation and correlation maps :



Mâlin et al. (subm)

Exo-REM models



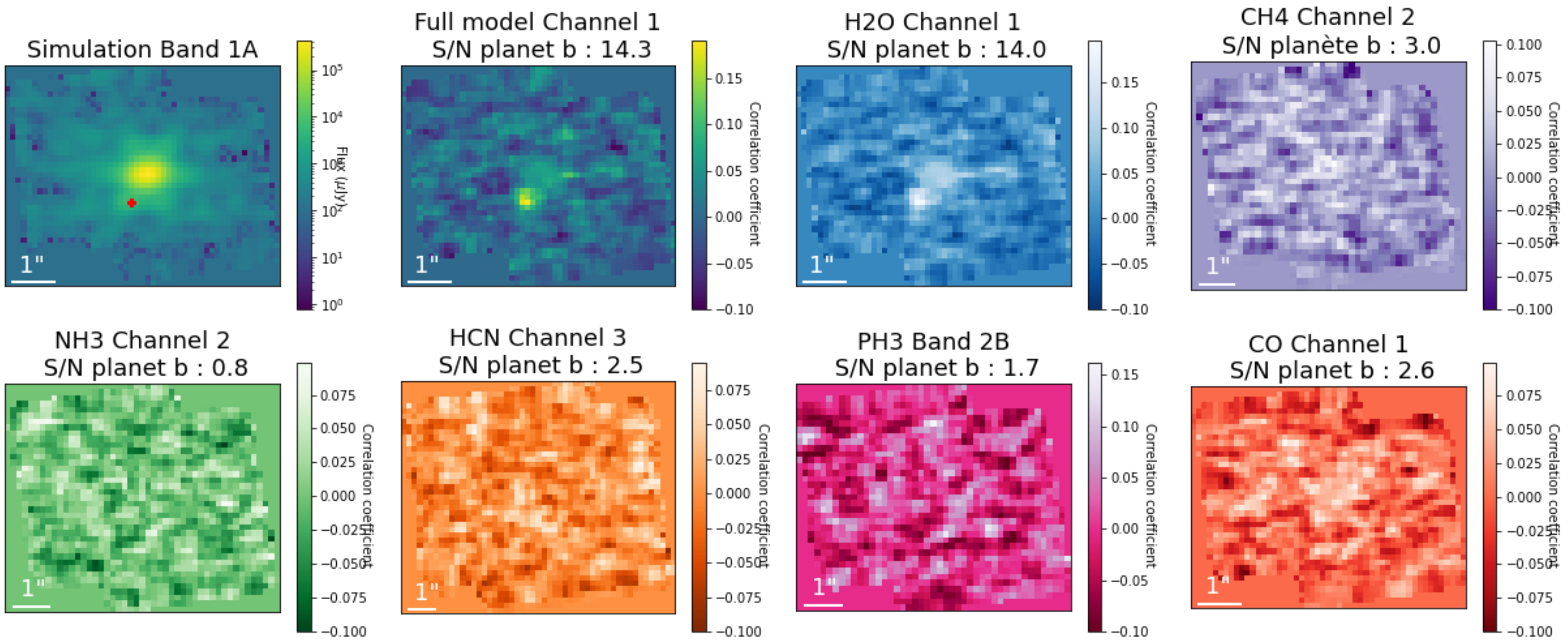
PH_3 has not yet been detected in any exoplanet's atmosphere
Strong detection of NH_3, CH_4, HCN → planetary formation

Globally in agreement with Patapis et al. (2021)

2M 1207

Hypothesis 1 : Planet at 1600 K and R = 0.5 R_{jup} (Patience et al. 2010)

- Brown Dwarf : 2600 K
- System at 52.4 pc
- Young system : 8 Myr
- Separation : 42 AU – 0.78 "

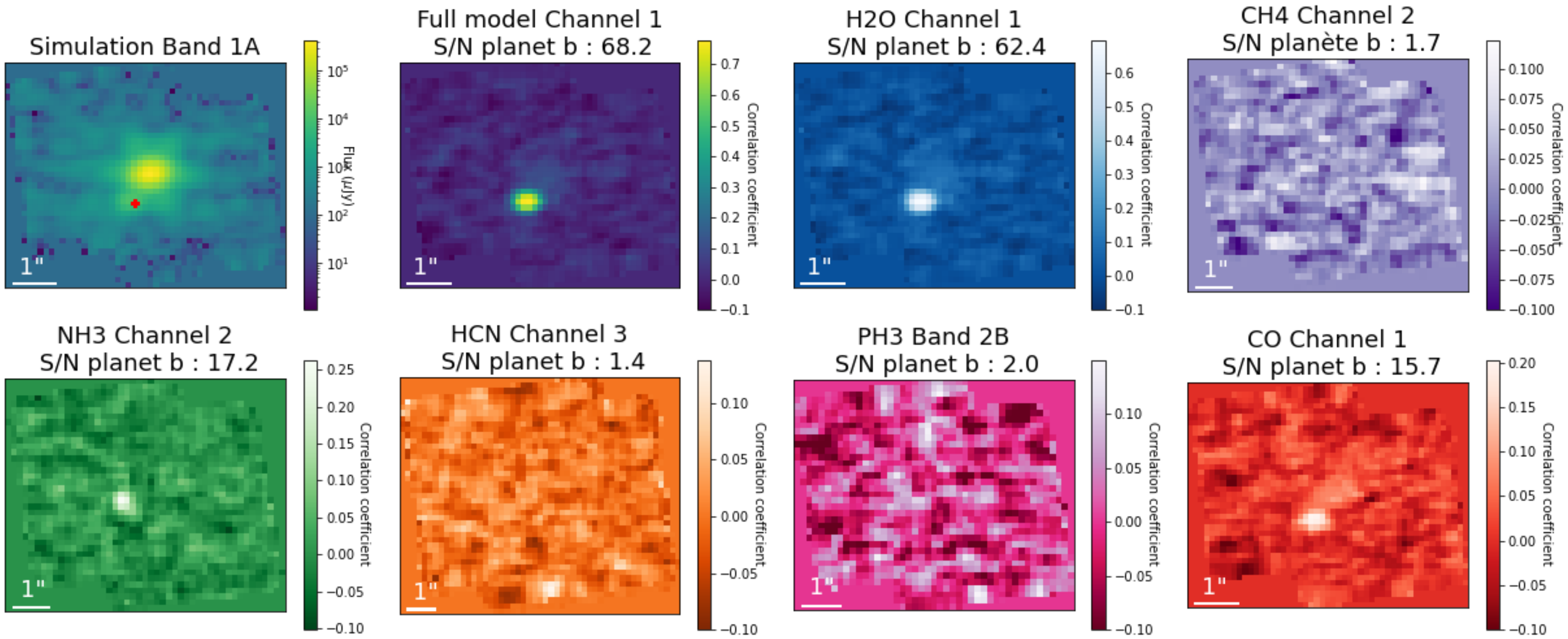


Mâlin et al. (subm)

2M 1207

Hypothesis 2 : Planet at 1000 K and R = 1.5 R_{jup} (Barman et al. 2010)

- Brown Dwarf : 2600 K
- System at 52.4 pc
- Young system : 8 Myr
- Separation : 42 AU – 0.78 "



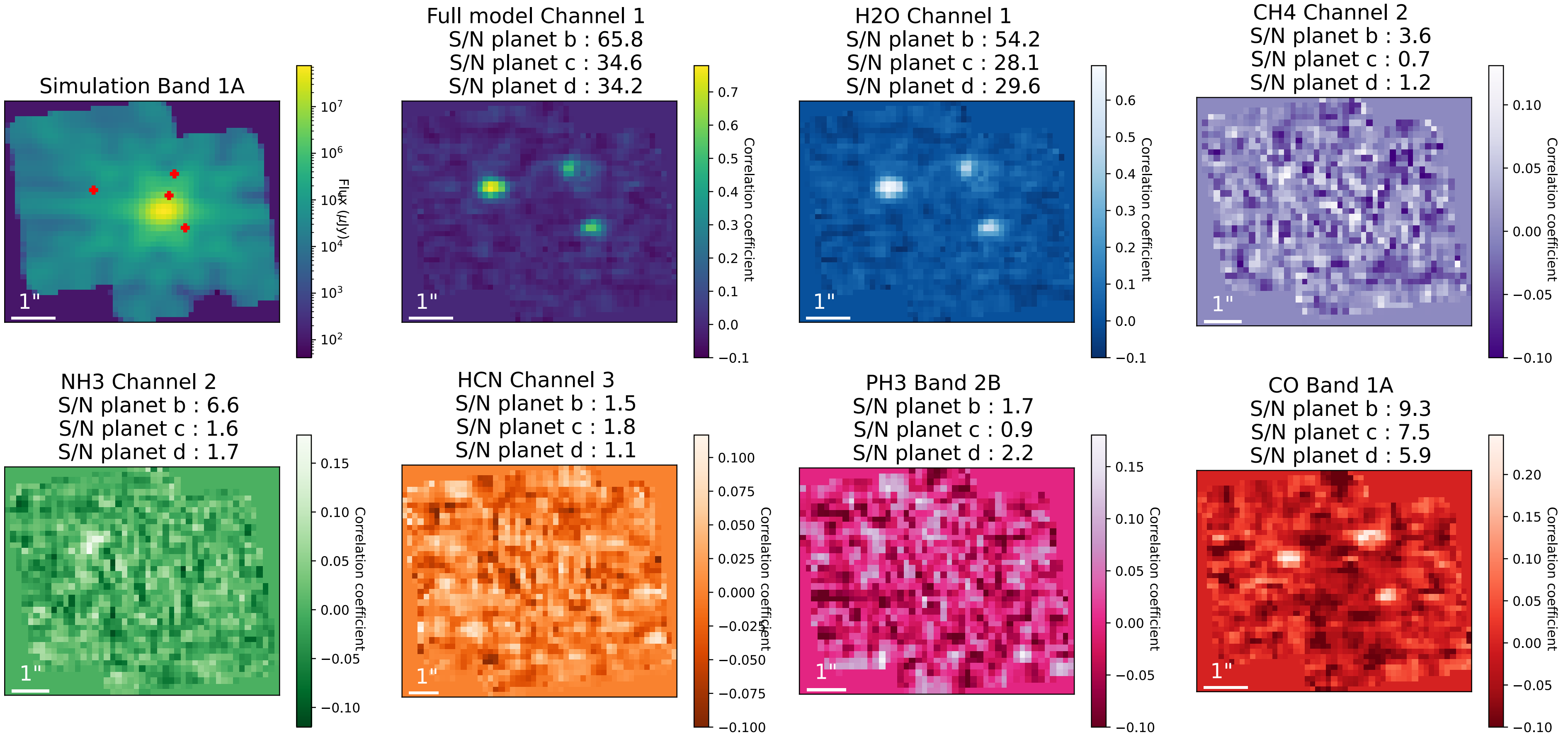
Mâlin et al. (subm)

Detection of molecules as indicators for the temperature of the planets

HR 8799

4 planets

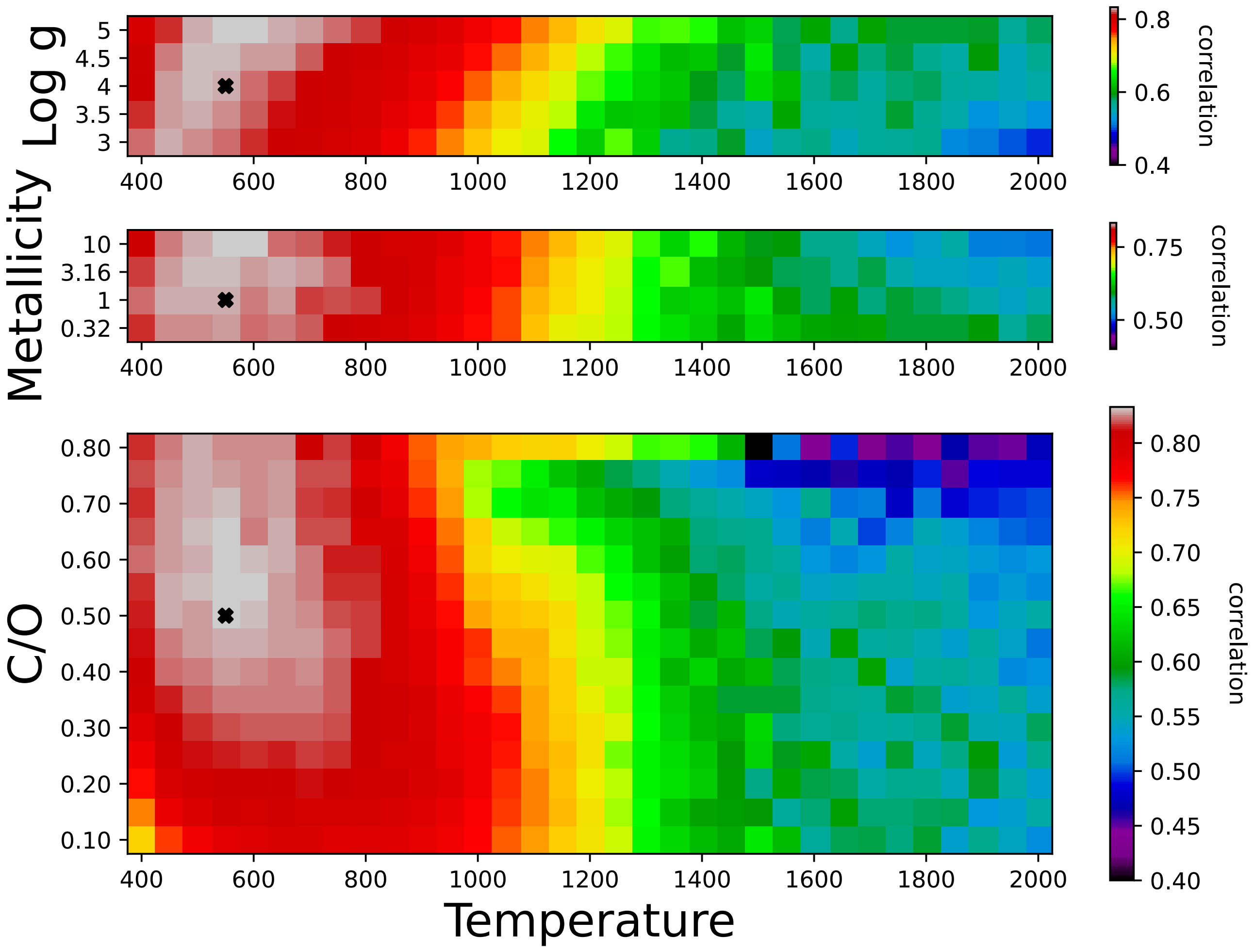
- Star: 7600 K
- System at 39.4 pc
- Young system: 8 Myr
- Planets :
  1000 K (planet b)
  1100 K (planet c d e)
- Separation :
  68 AU – 1.72''
  43 AU – 0,95''
  27 AU – 0,70''
  16 AU – 0,39''



Mâlin et al. (subm)

Correlation with grids of models

Exemple on the best target GJ 504 b

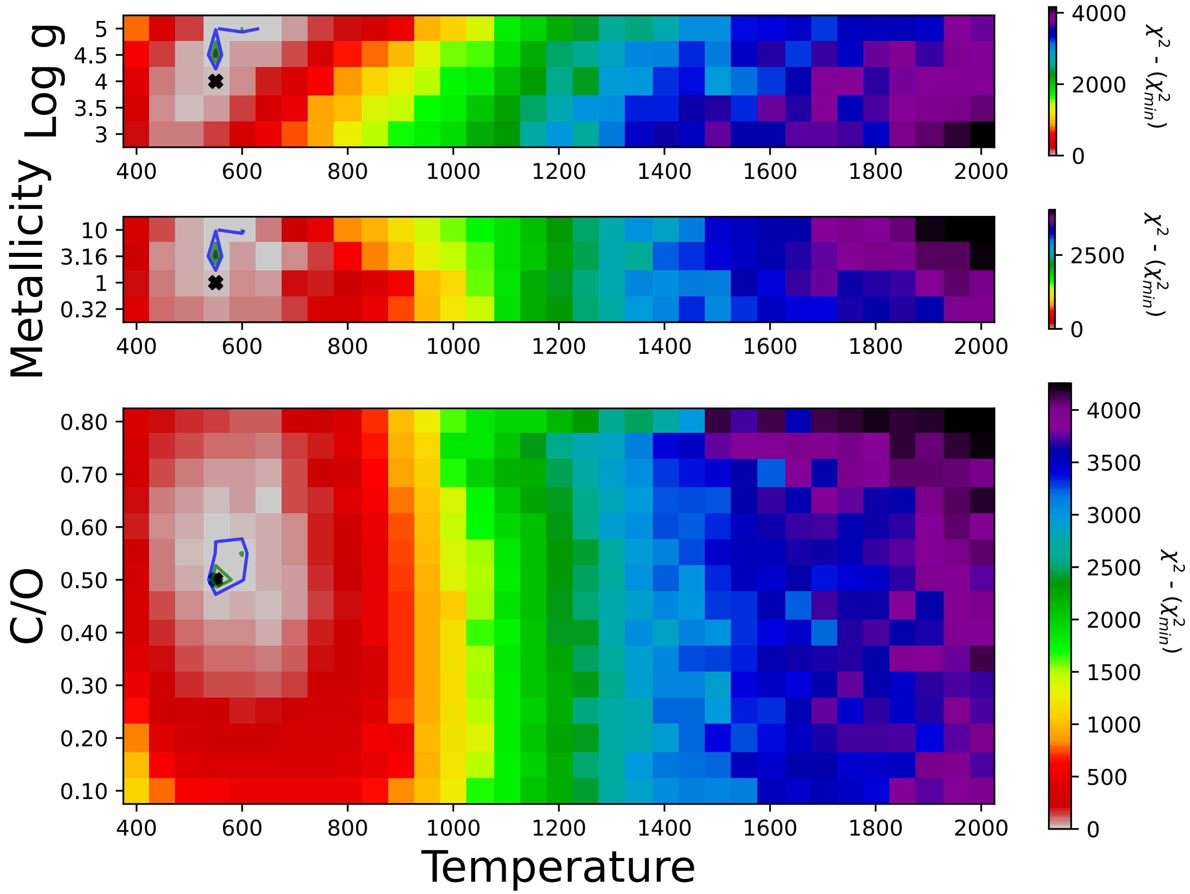


Correlation value at the planet's position when correlating the data with a grids of Exo-REM models

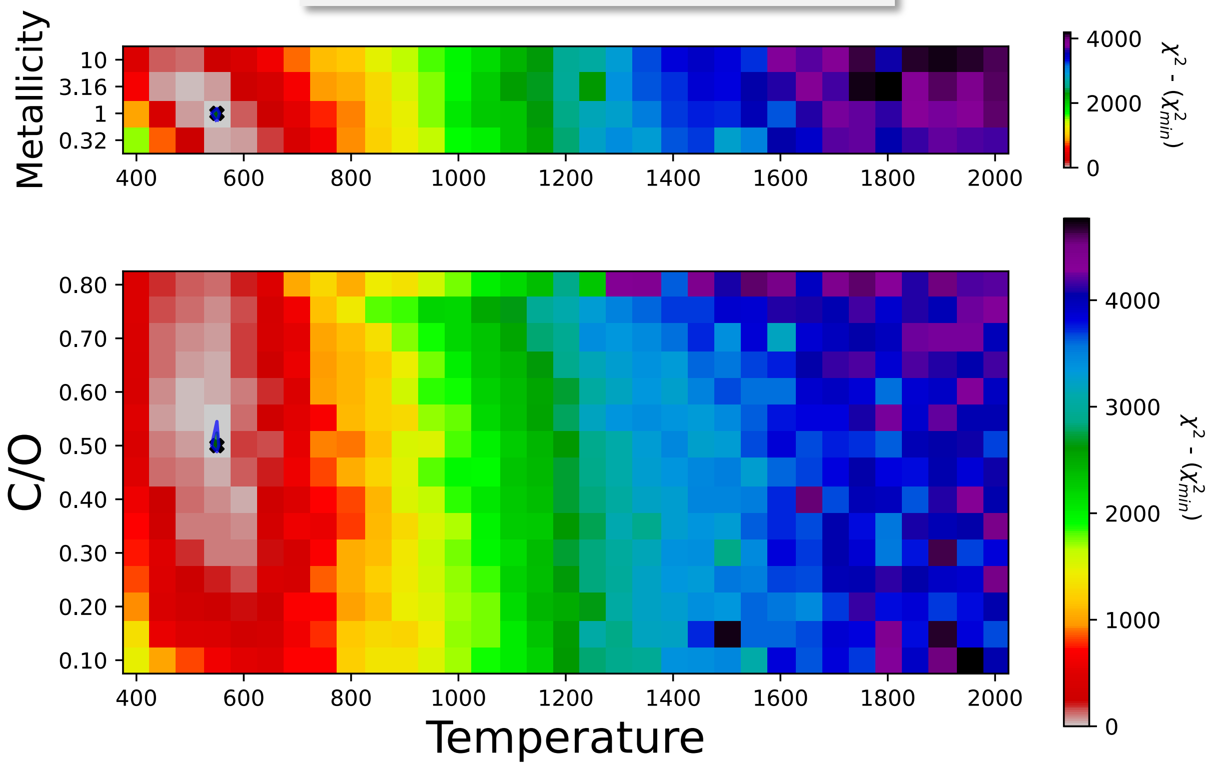
- Still detect the planet with similar model as the one in input
- Not very sensitive to recover atmospheric parameters

χ^2 grids

Extraction of a HF spectrum at the planet's position



With surface gravity fixed



Contours : 3-sigma, 2-sigma, 1-sigma

Conclusion

- MIRI/MRS is able to detect molecules (H_2O, CO, NH_3, CH_4, HCN, PH_3) at angular separation about > 1''.

- Very efficient for planets colder than T < 1500 K - Complementarity with coronagraphy

- We have developed tools to simulate and analyze different known systems in direct imaging to get ready for cycle 2 of JWST GO observations. Our parametric study allows to anticipate the ability to characterize planets yet to be detected.

- Perspectives:
  - Future methods of stellar subtraction should improve the performance of detection and characterization of planets < 1''.
  - Better define the constraints on the atmosphere (bayesian analysis, complementarity with coronagraphic data from GTO MIRI)
  - Better understand the correlation pattern and how it varies (S/N measurement)