Physics and chemistry of exoplanet and brown dwarf atmospheres

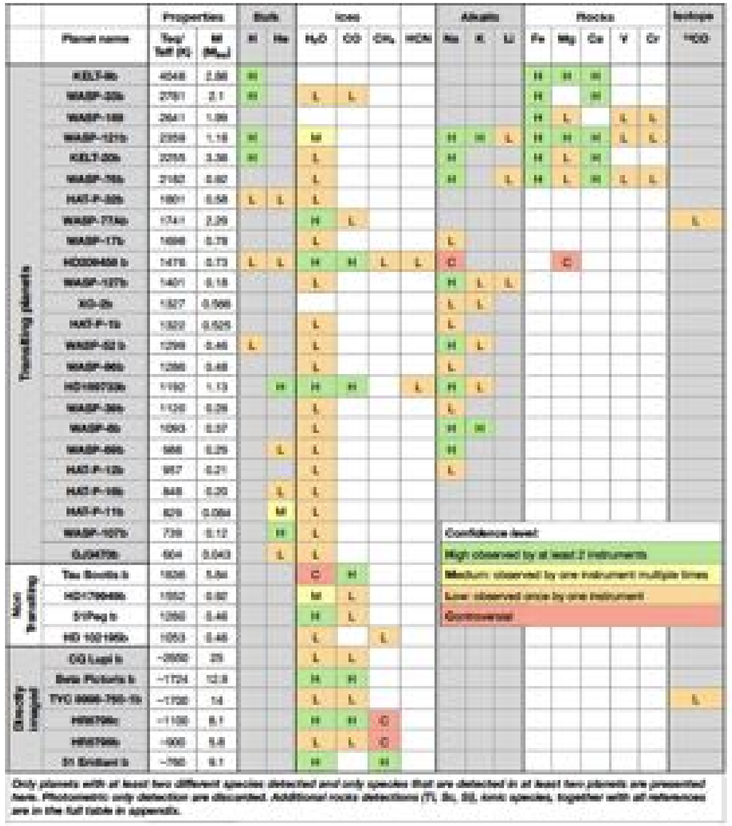
Benjamin Charnay, Lucas Teinturier, Matthieu Ravet,
Mickaël Bonnefoy, Simon Petrus & Paulina Palma-Bifani

LESIA Observatoire de Paris | PSL

MATISSE Science Days, *2024*

Two decades of exoplanet atmospheric characterization

- Exoplanet atmospheric observations are now done routinely
- Observations revealed a great diversity of atmospheres
- Plenty molecules/atoms detected (H_2O, CO, CH_4, NH_3, HCN, CO_2, C_2H_2, H, He, Na, K, Cr, V, Fe, FeH, TiO, VO, $C^{13}O$)
- JWST has opened a new era for the characterization of exoplanetary atmospheres



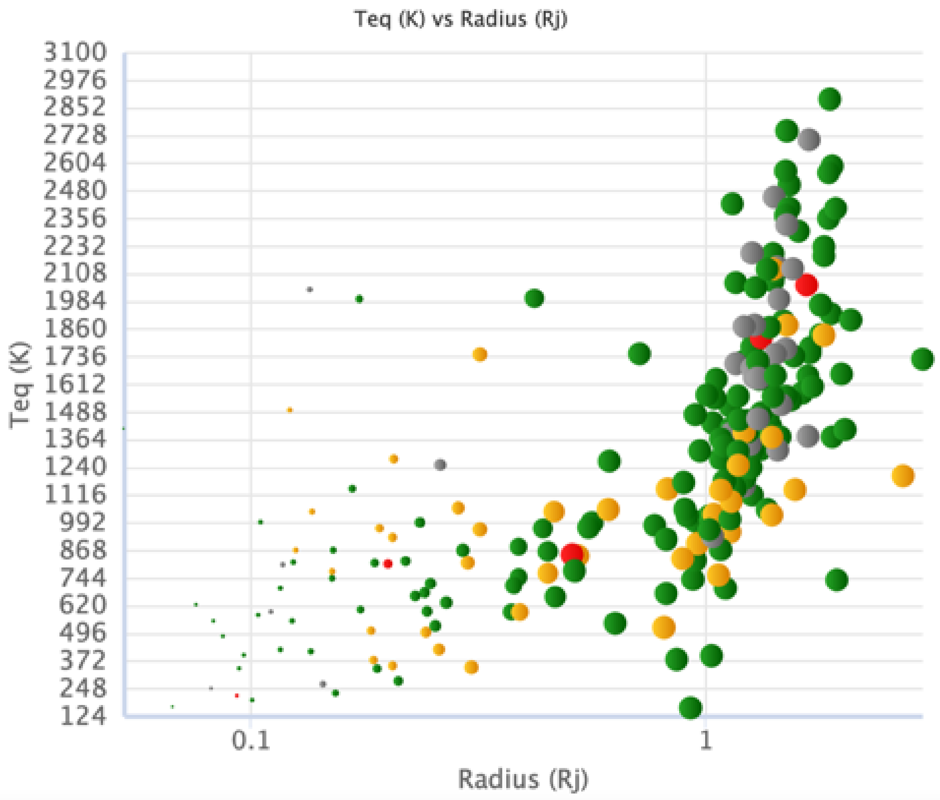
		Properties		Bulk		Ices				Alkalis			Rocks					Isotope
	Planet name	Teq/Teff (K)	M (M_{Jup})	H	He	H_2O	CO	CH_4	HCN	Na	K	Li	Fe	Mg	Ca	V	Cr	^{13}CO
Transiting planets	KELT-9b	4048	2.88	H									H	H	H			
	WASP-33b	2781	2.1	H		L	L						H		H			
	WASP-189b	2641	1.99										H	L		L	L	
	WASP-121b	2358	1.18	H		M				H	H	L	H	H	H	L	L	
	KELT-20b	2255	3.38	H		L				H			H	L	H			
	WASP-76b	2160	0.92			L				H		L	H	L	H	L	L	
	HAT-P-32b	1801	0.58	L	L	L												
	WASP-77Ab	1741	2.29			H	L											L
	WASP-17b	1698	0.78			L				L								
	HD209458 b	1478	0.73	L	L	H	H	L	L	C				C				
	WASP-127b	1401	0.18			L				H	L	L						
	XO-2b	1327	0.566							L	L							
	HAT-P-1b	1322	0.525			L				L								
	WASP-52 b	1299	0.46	L		L				H	L							
	WASP-96b	1285	0.48			L				L								
	HD189733b	1192	1.13		H	H	H		L	H	L							
	WASP-39b	1120	0.28			L				L								
	WASP-6b	1093	0.37			L				H	H							
	WASP-69b	988	0.29		L	L				H								
	HAT-P-12b	957	0.21			L				L								
	HAT-P-18b	848	0.20		L	L												
	HAT-P-11b	829	0.084		M	L												
	WASP-107b	739	0.12		H	L												
	GJ3470b	604	0.043		L	L												
Non Transiting	Tau Bootis b	1626	5.84			C	H											
	HD179949b	1552	0.92			M	L											
	51Peg b	1250	0.46			H	L											
	HD 102195b	1053	0.46			L		L										
Directly imaged	GQ Lupi b	~2650	25			L	L											
	Beta Pictoris b	~1724	12.8			H	H											
	TYC 8998-760-1b	~1700	14			L	L											L
	HR8799c	~1100	8.1			H	H	C										
	HR8799b	~900	5.8			L	L	C										
	51 Eridani b	~750	9.1			H		H										

Confidence level:
- High: observed by at least 2 instruments
- Medium: observed by one instrument multiple times
- Low: observed once by one instrument
- Controversial

Only planets with at least two different species detected and only species that are detected in at least two planets are presented here. Photometric only detection are discarded. Additional rocky detections (Ti, Sc, Si), ionic species, together with all references are in the full table in appendix.

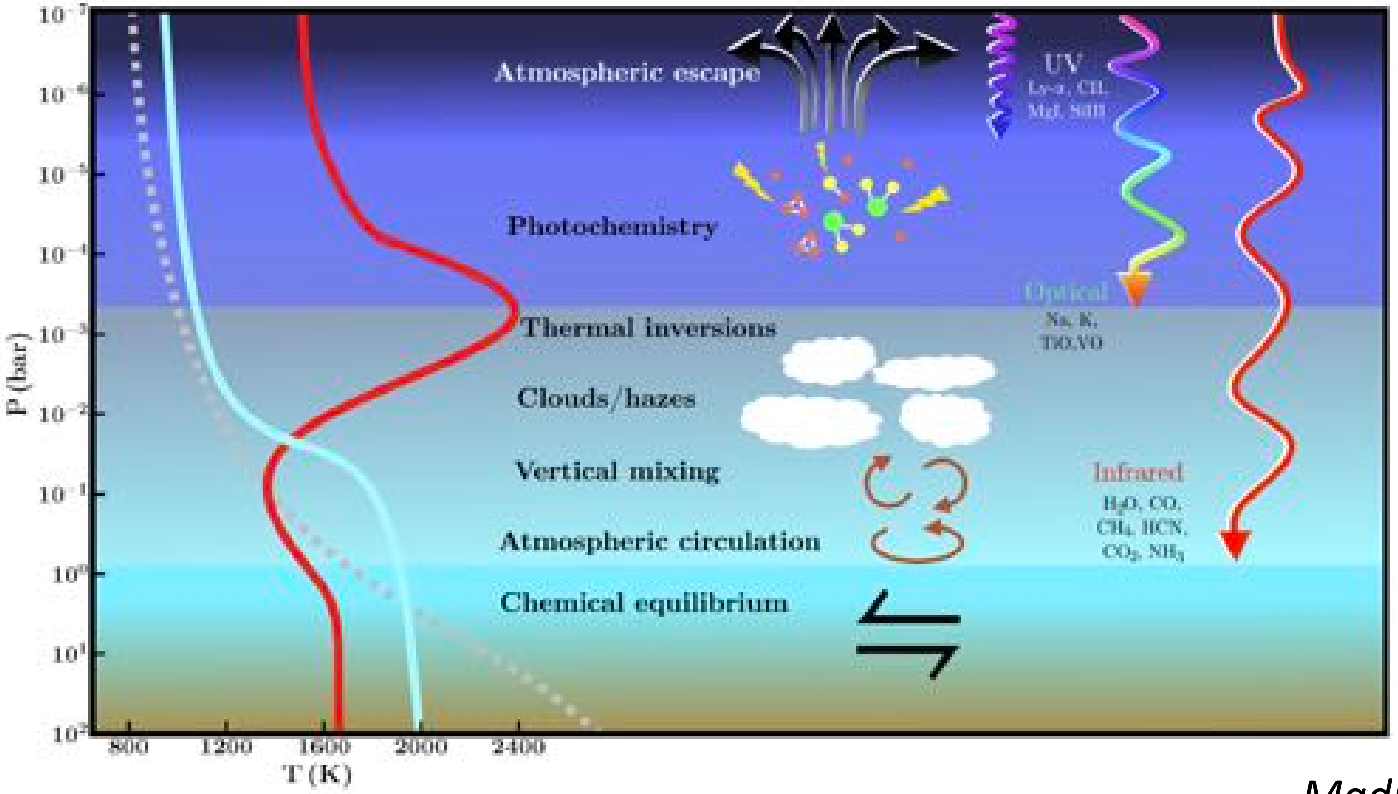
Guillot et al. 2022

ExoAtmospheres database



Main science questions for the coming decade

1) Which physical/chemical processes shape exoplanet and BD atmospheres?



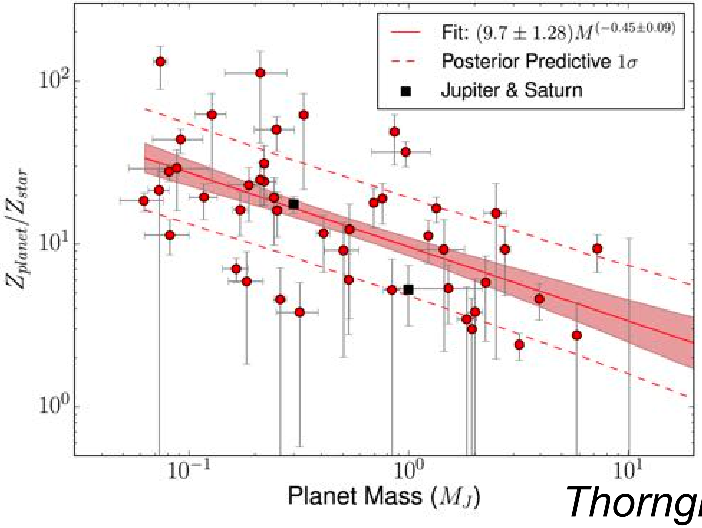
Madhusudhan 2019

- What is the thermal structure of exoplanetary atmospheres and BD ?
- Where does non-equilibrium chemistry play an important role?
- How clouds/hazes form and vary (spatially and temporally)?

Main science questions for the coming decade

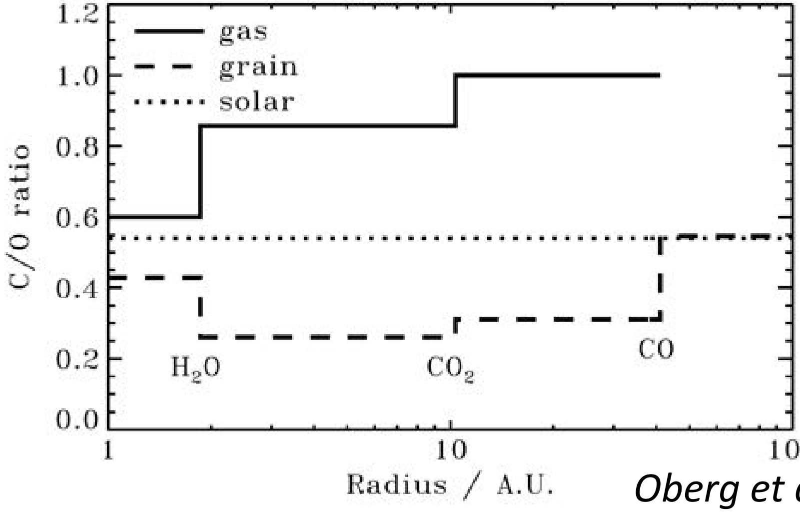
2) Can we constrain planetary formation/evolution from the atmospheric composition ?

Link between atmospheric metallicity and planetary mass



Thorngren et al. 2016

Link between C/O and distance to the host star

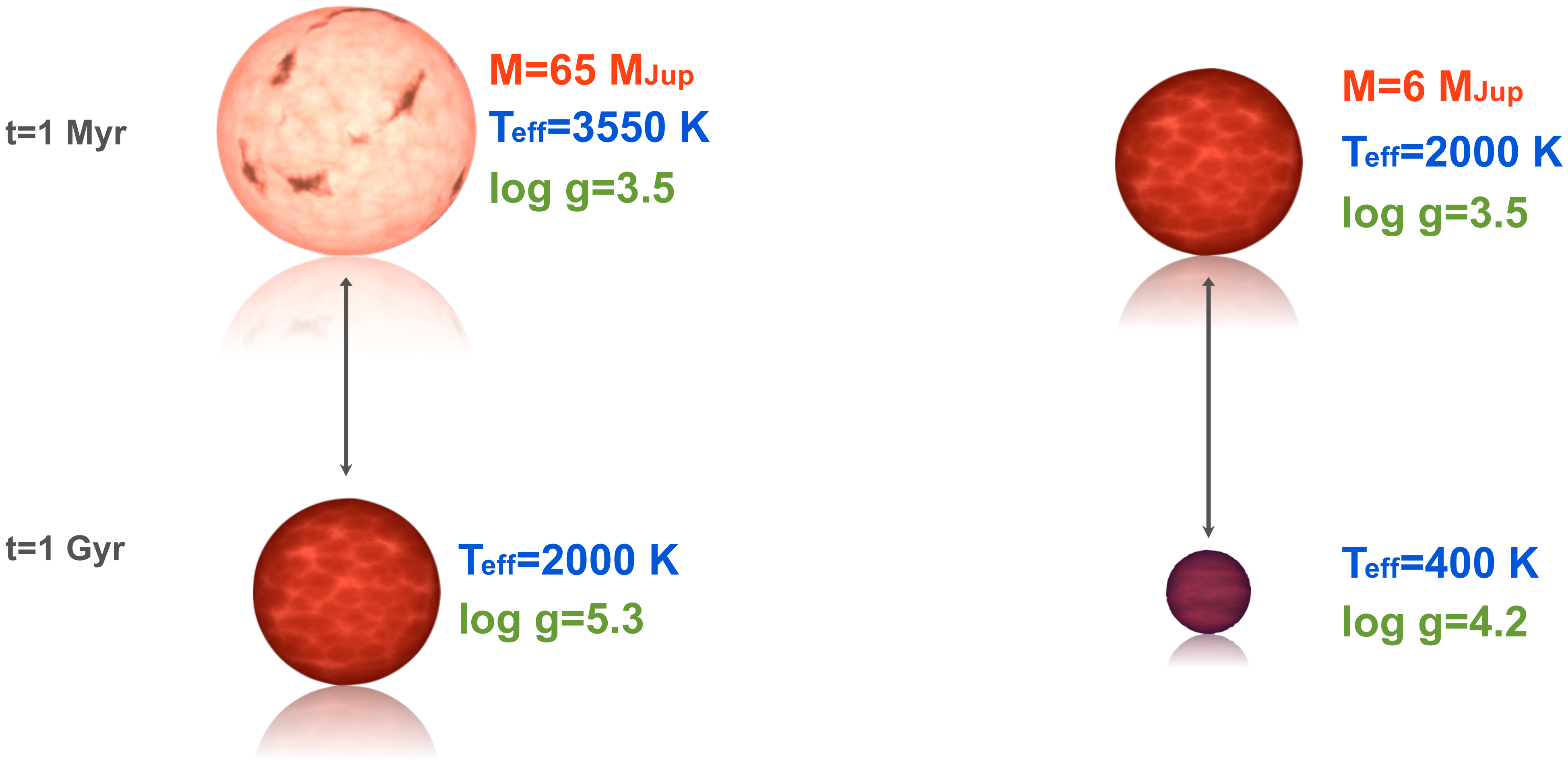


Oberg et al. 2013

Comparison brown dwarfs vs imaged giant planets

Imaged planets are young ⇒ low surface gravity

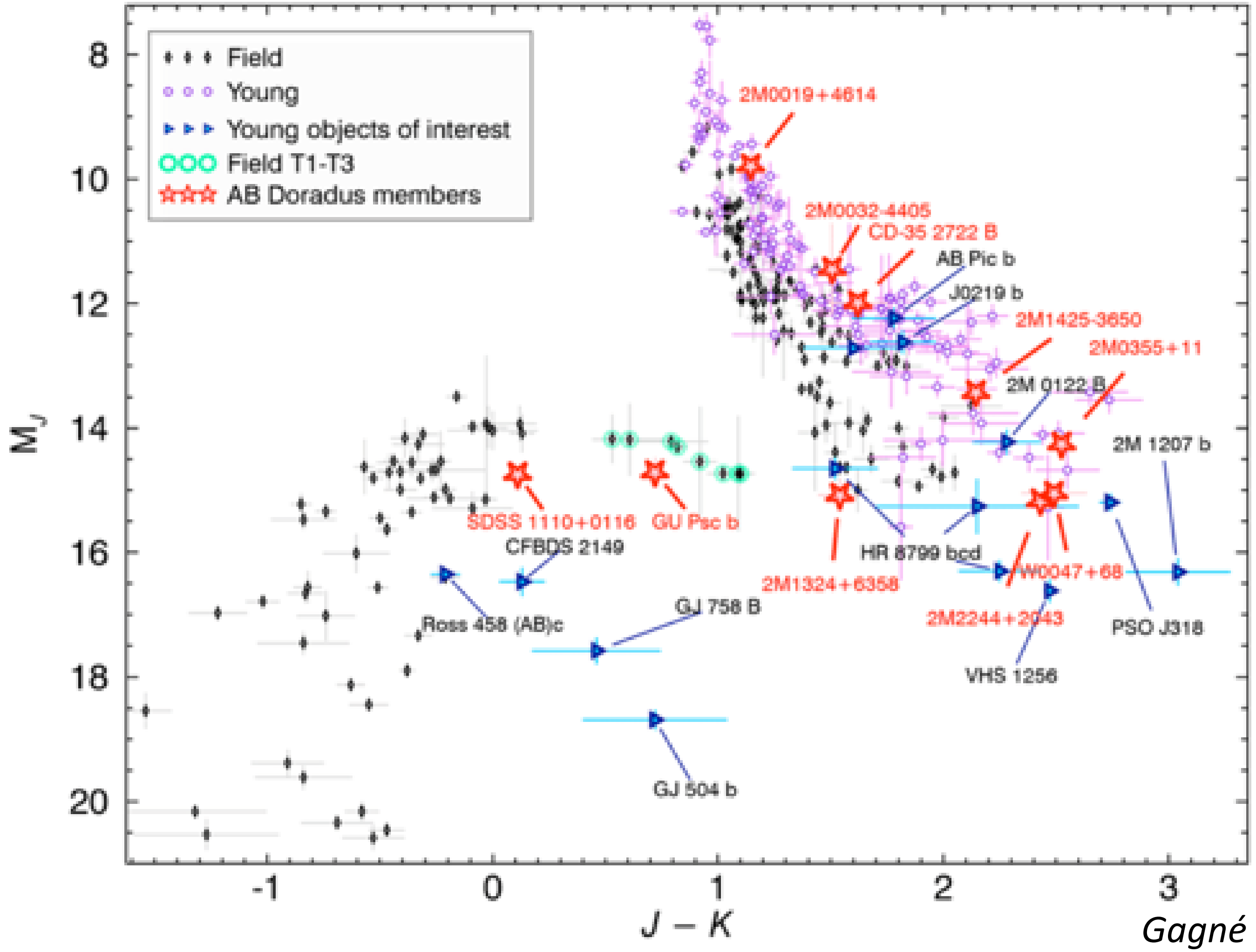
BROWN DWARF | **PLANET**



The LT transition for BD and young giant exoplanets

Imaged planets are young ⇒ low surface gravity

Young giant planets are red with a delayed L-T transition

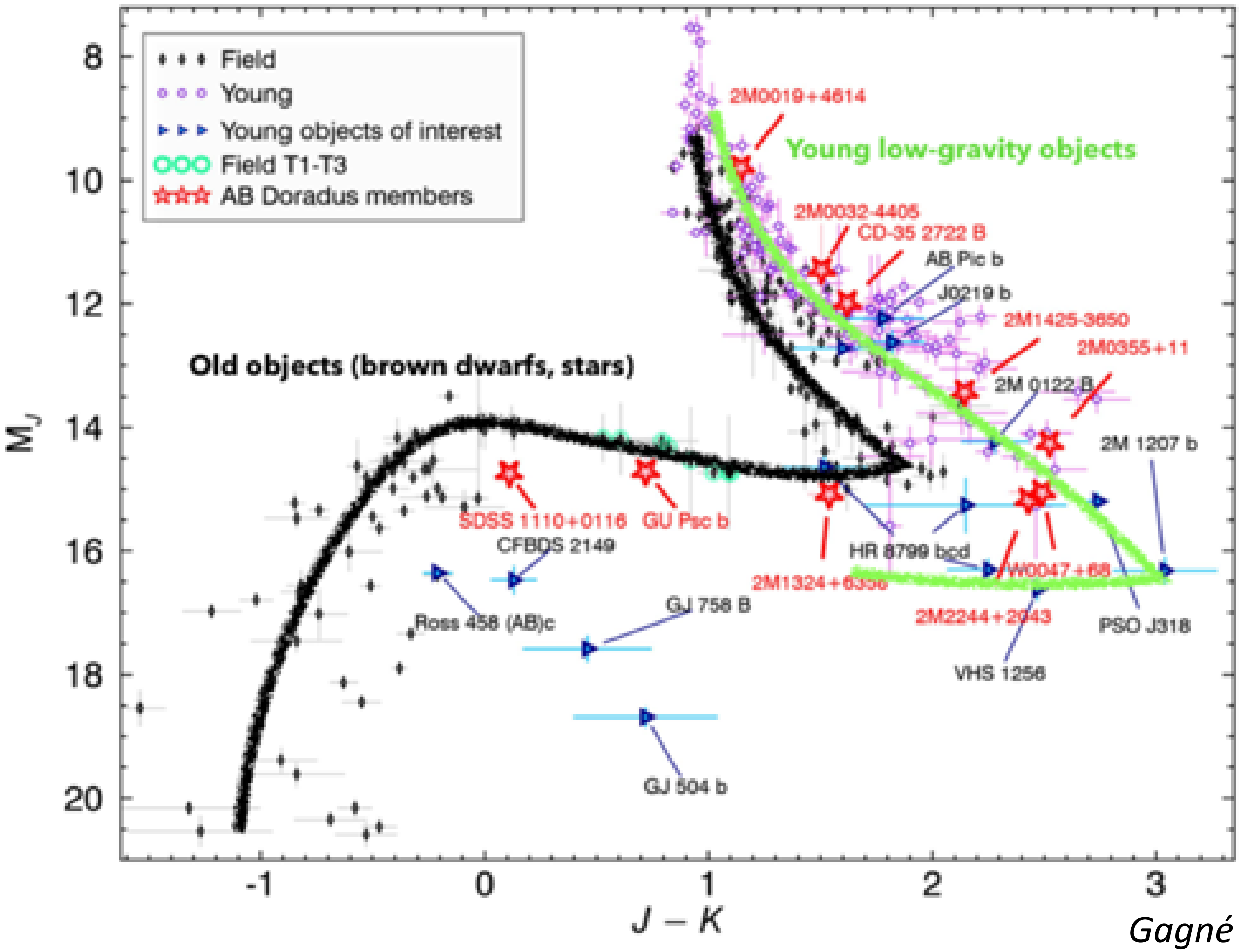


Gagné et al. 2018

The LT transition for BD and young giant exoplanets

Imaged planets are young ⇒ low surface gravity

Young giant planets are red with a delayed L-T transition

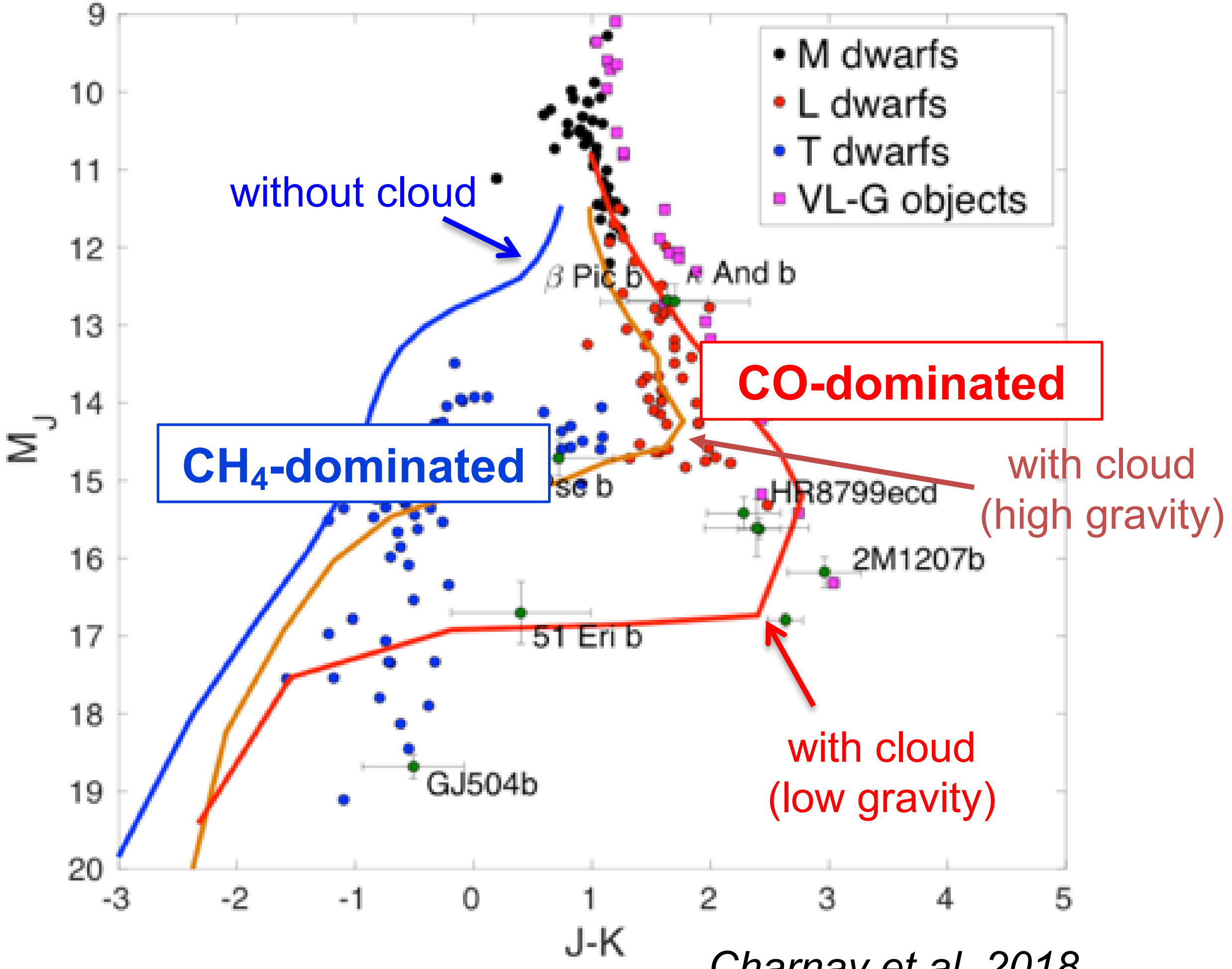


Gagné et al. 2018

The LT transition for BD and young giant exoplanets

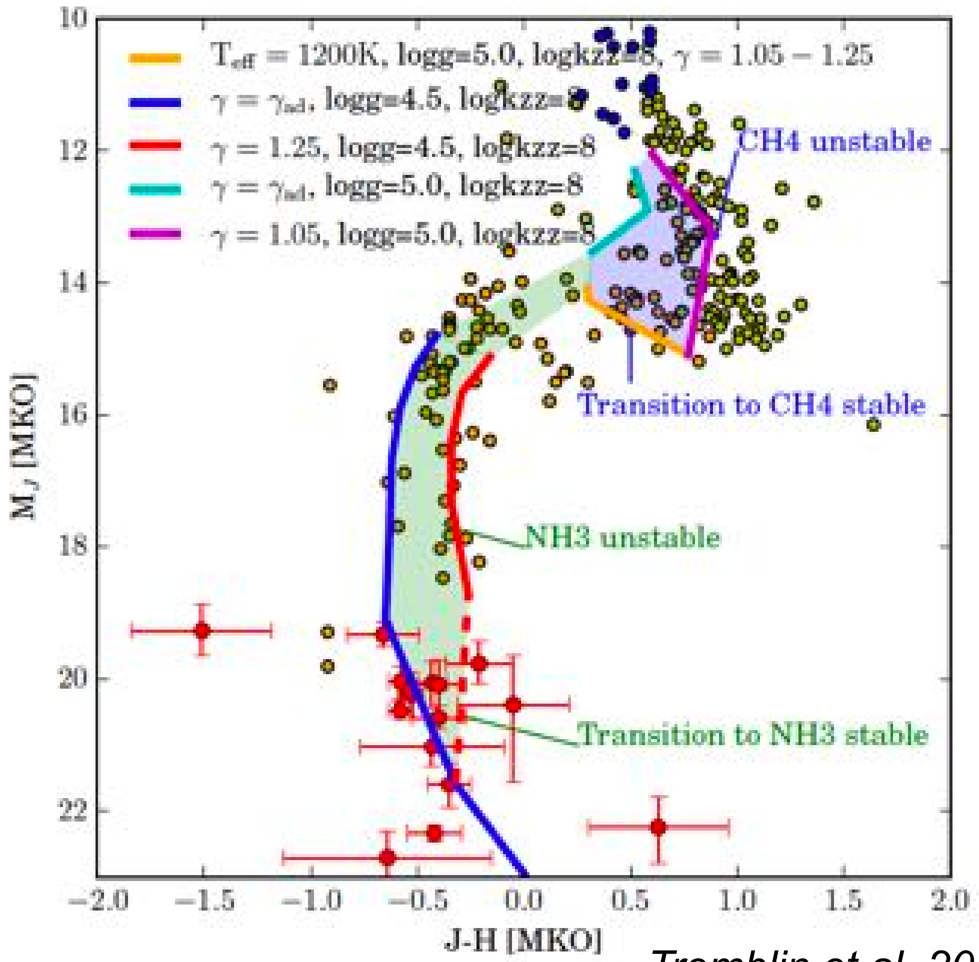
Explanations by 1D models: clouds or fingering convection

Model with clouds (Exo-REM)



Charnay et al. 2018

Model with fingering convection (ATMO)

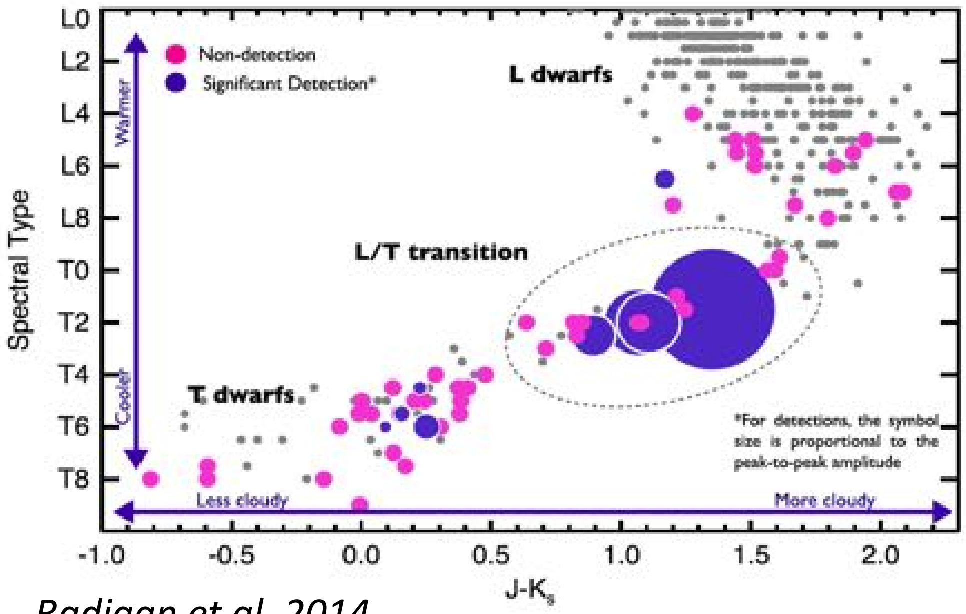


Tremblin et al. 2016

Clouds on BD and young giant exoplanets

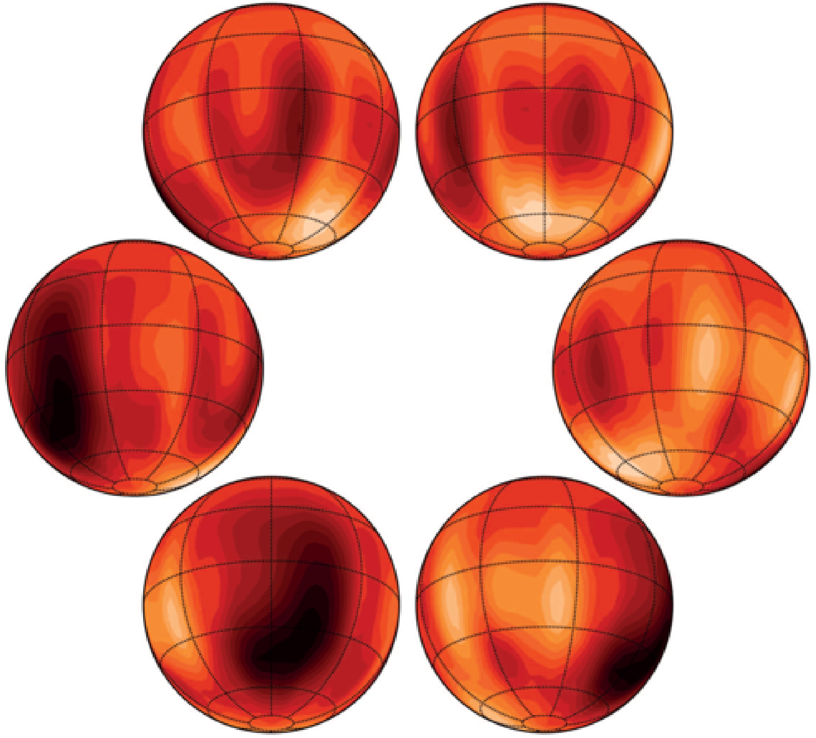
Observation of variability and cloud cover

Variability of brown dwarfs

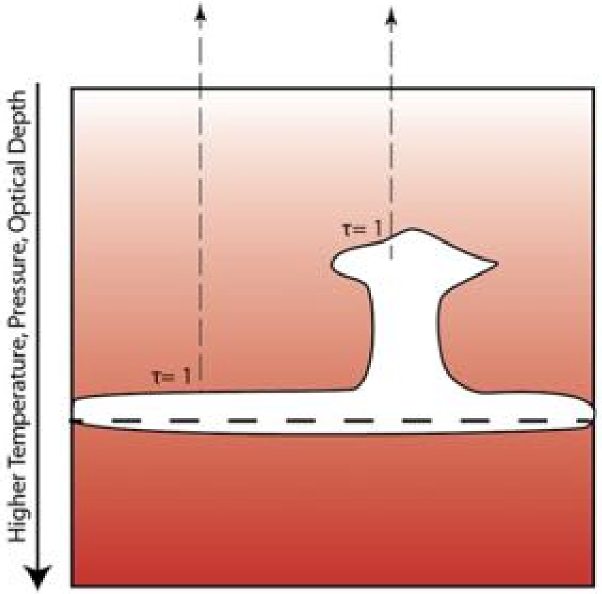


Radigan et al. 2014

Inhomogeneous cloud cover of Luhman 16A by doppler imaging



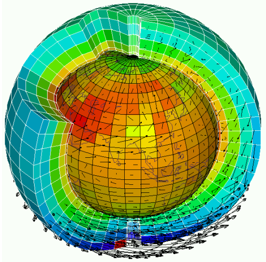
Crossfield et al. 2014



Apai et al. 2013

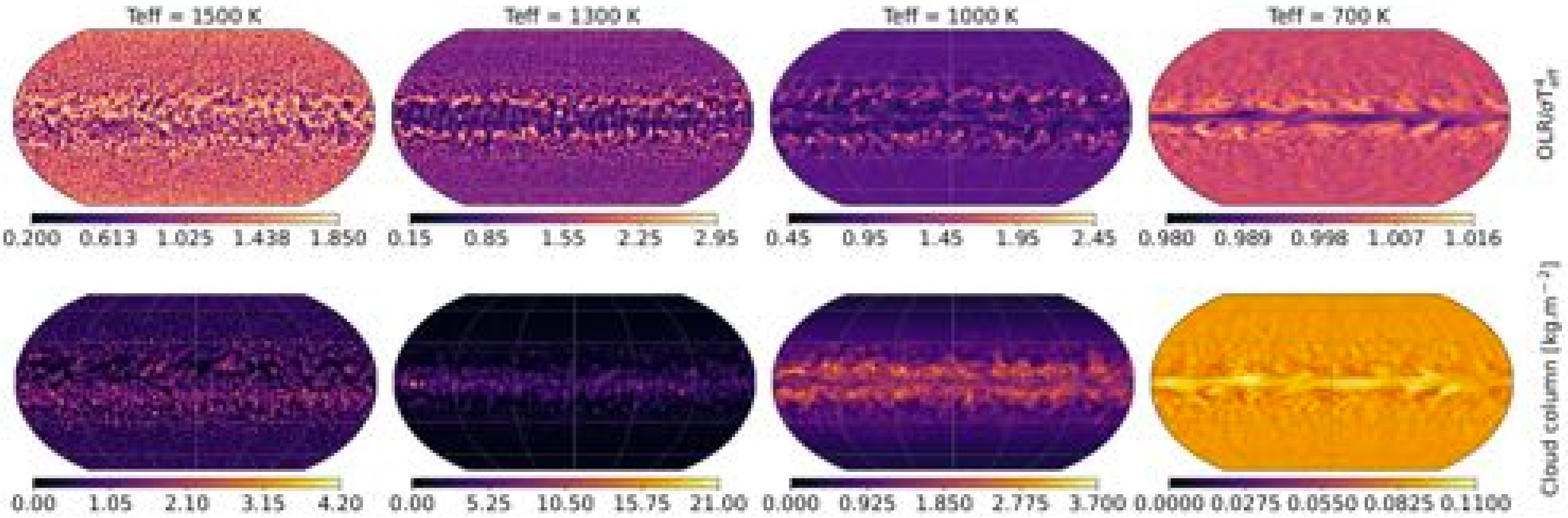
Clouds on BD and young giant exoplanets

3D modelling of cloud dynamics



Generic PCM

3D simulations of L-T dwarfs with silicates clouds (P=5h, log(g)=5)

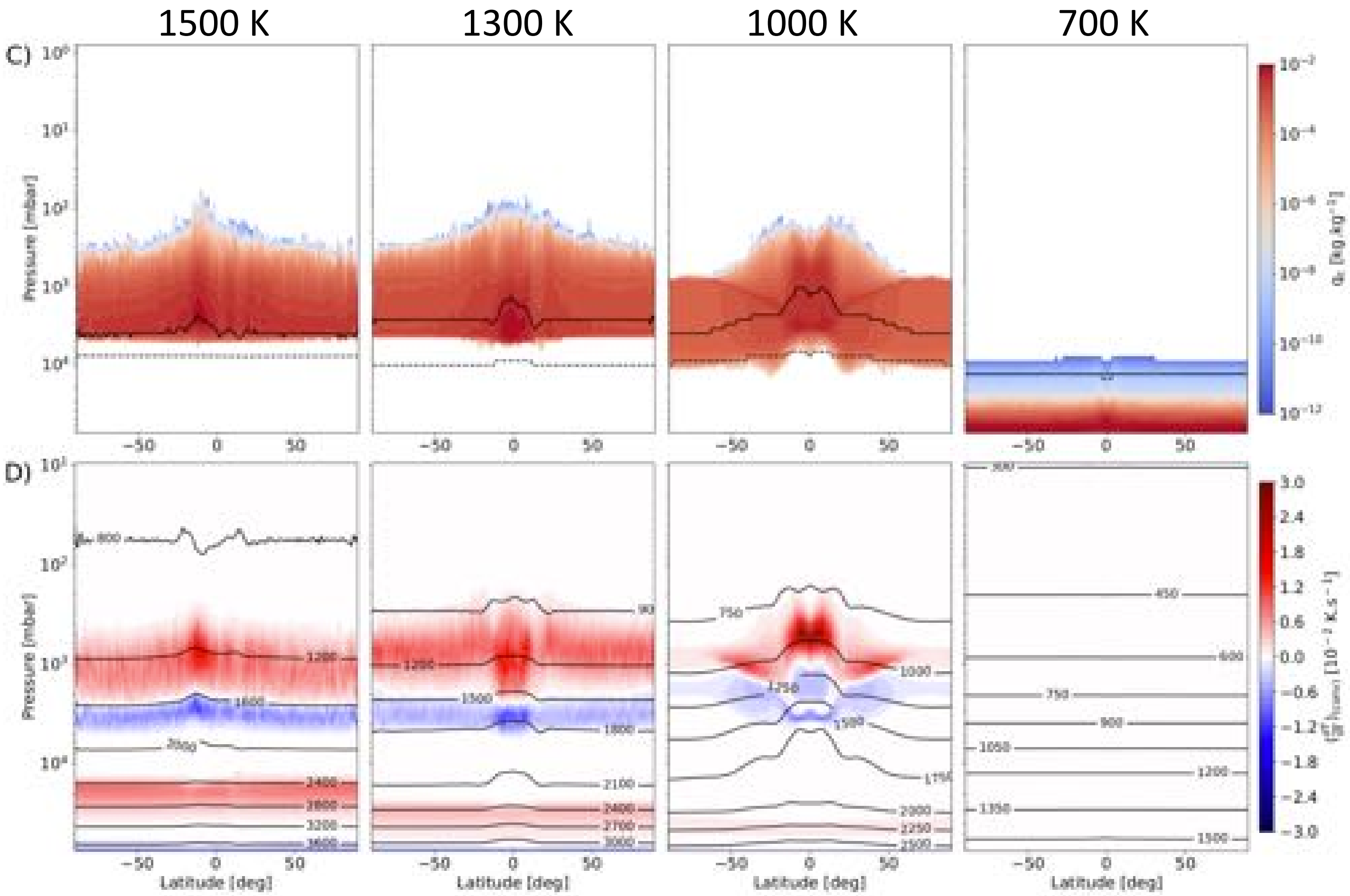


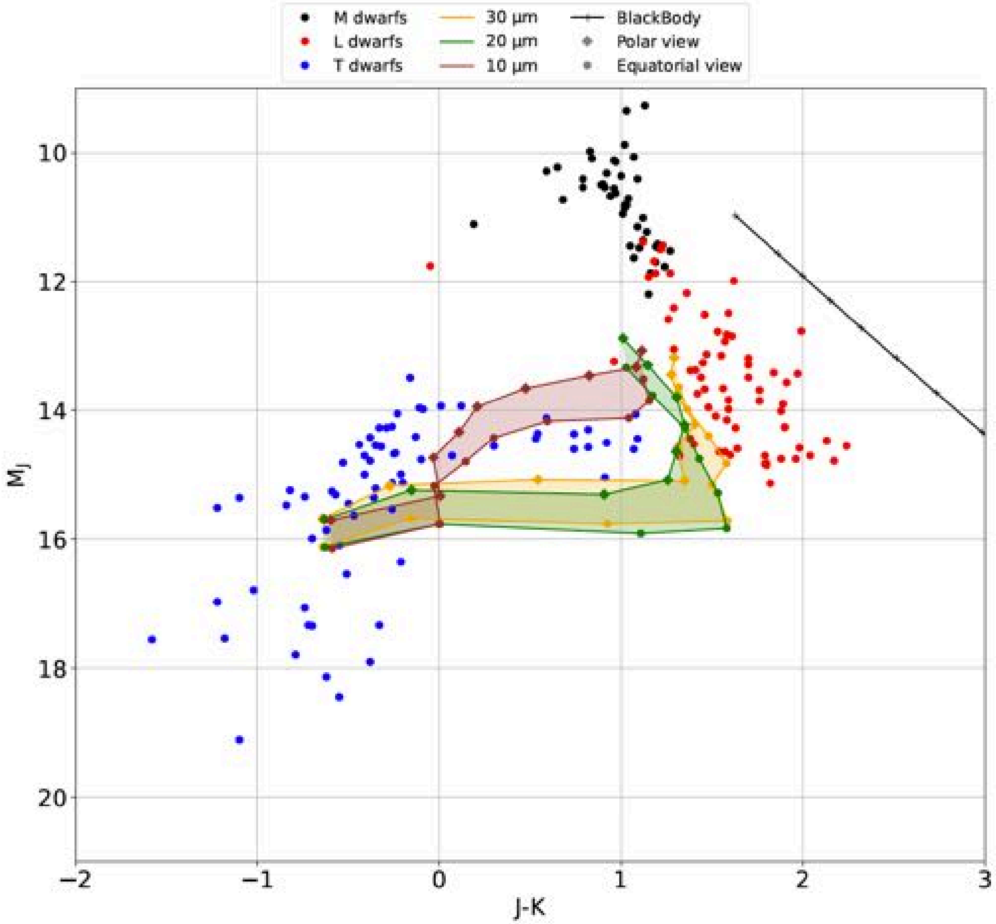
Teinturier, Charnay et al., submitted

➢ Preferential cloud formation at low latitudes reducing thermal flux

Clouds on BD and young giant exoplanets

3D modelling of cloud dynamics





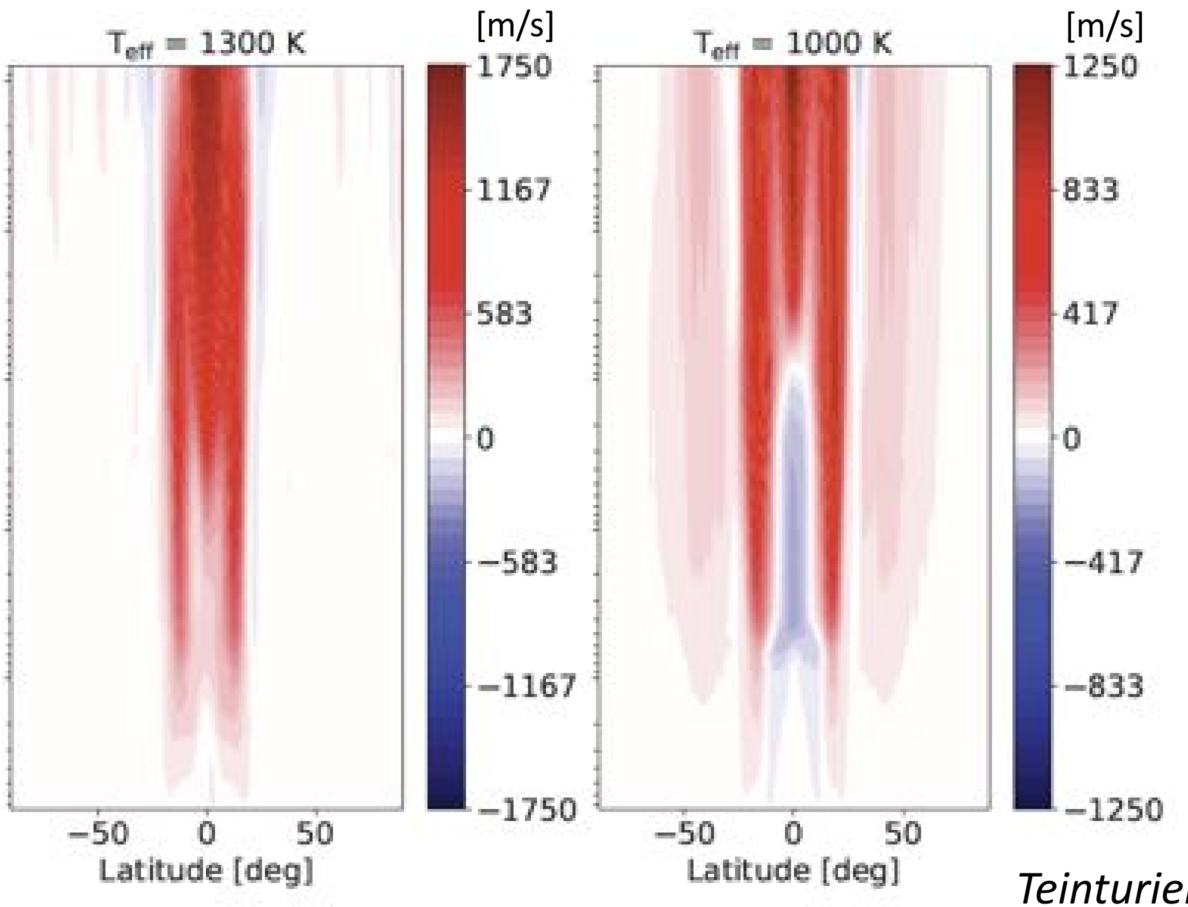
Teinturier, Charnay et al., submitted

- ➢ Cloud radiative effects trigger convection maintaining a thick cloud layer
- ➢ This cloud feedback induces a sharp LT transition

Clouds on BD and young giant exoplanets

3D modelling of cloud dynamics

Zonal wind

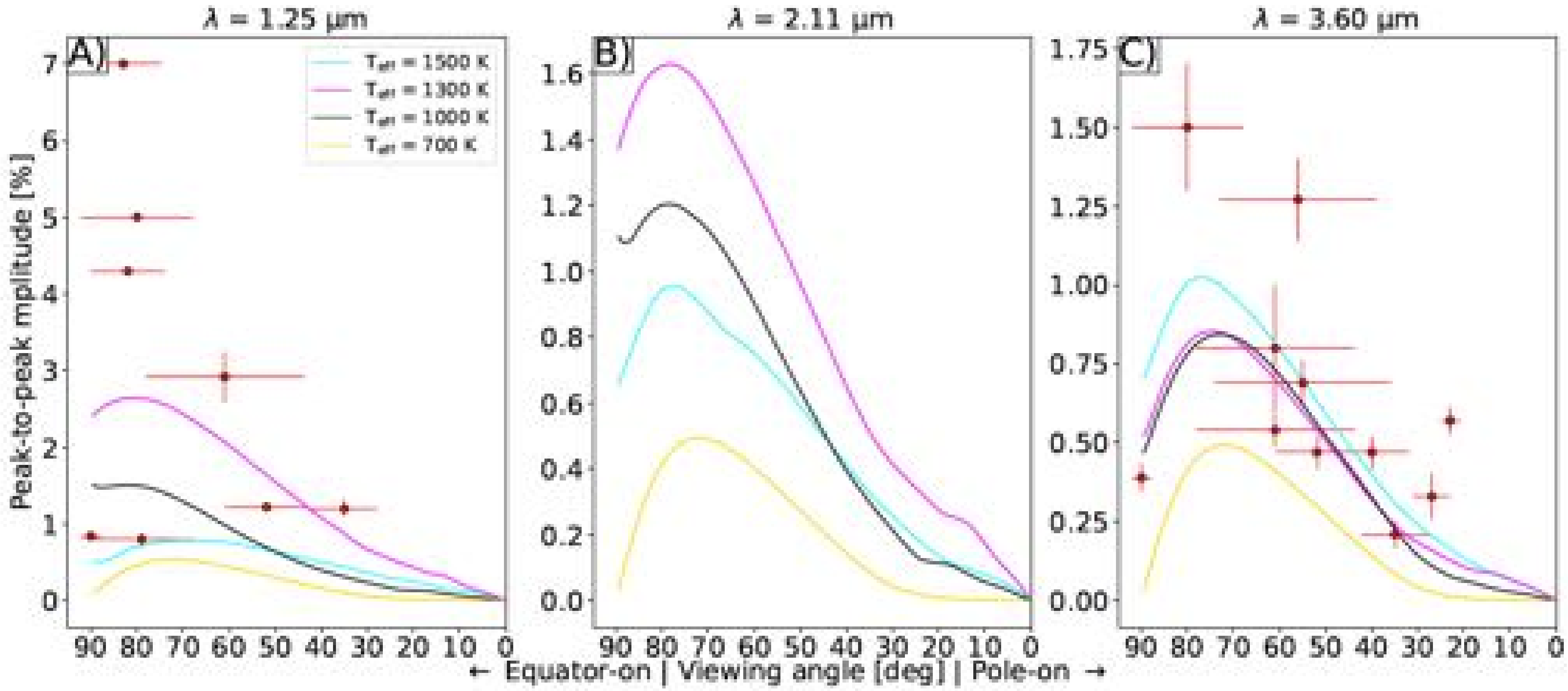


Teinturier, Charnay et al., submitted

- Formation of a prograde equatorial jet
- Wind speed compatible with measurements of 2MASS J10475385 (650 ± 300 m/s, *Allers et al. 2020*)

Clouds on BD and young giant exoplanets

3D modelling of cloud dynamics



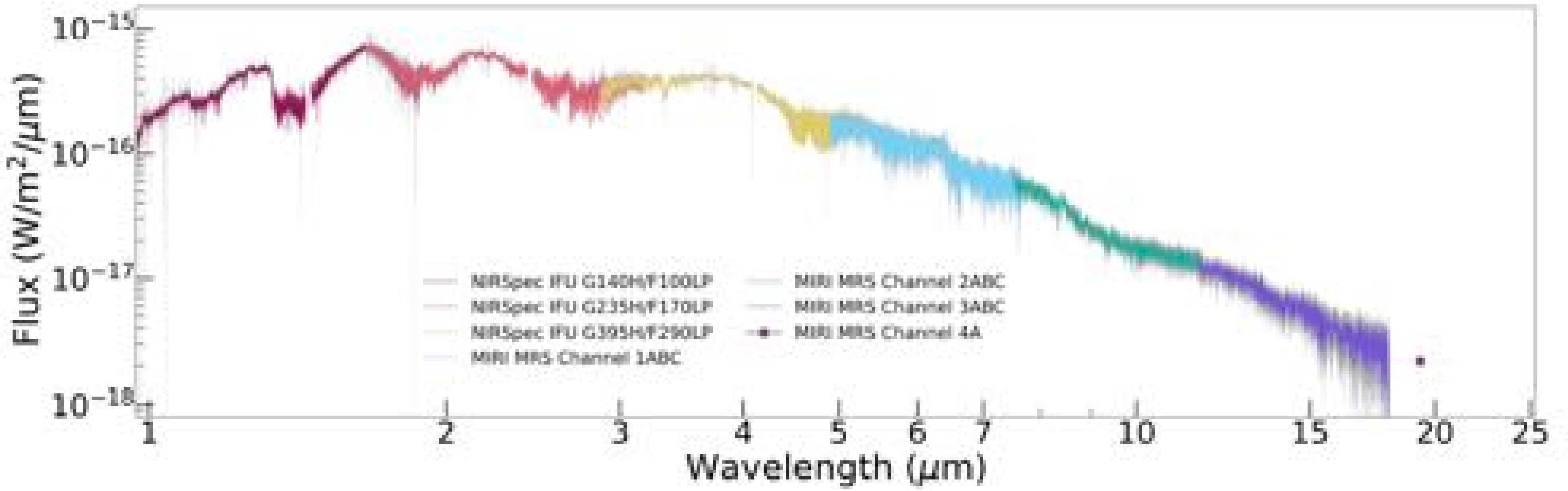
Teinturier, Charnay et al., submitted

- Maximal variability at low latitudes and at the LT transition
- Compatible with measurements (*Vos et al. 2017, 2018*)
- Variability could be searched on YGPs (potentially higher than on BD) in particular with GRAVITY

Clouds on BD and young giant exoplanets

Silicate absorption feature

JWST spectrum (NIRSpec + MIRI) of VHS 1256 b

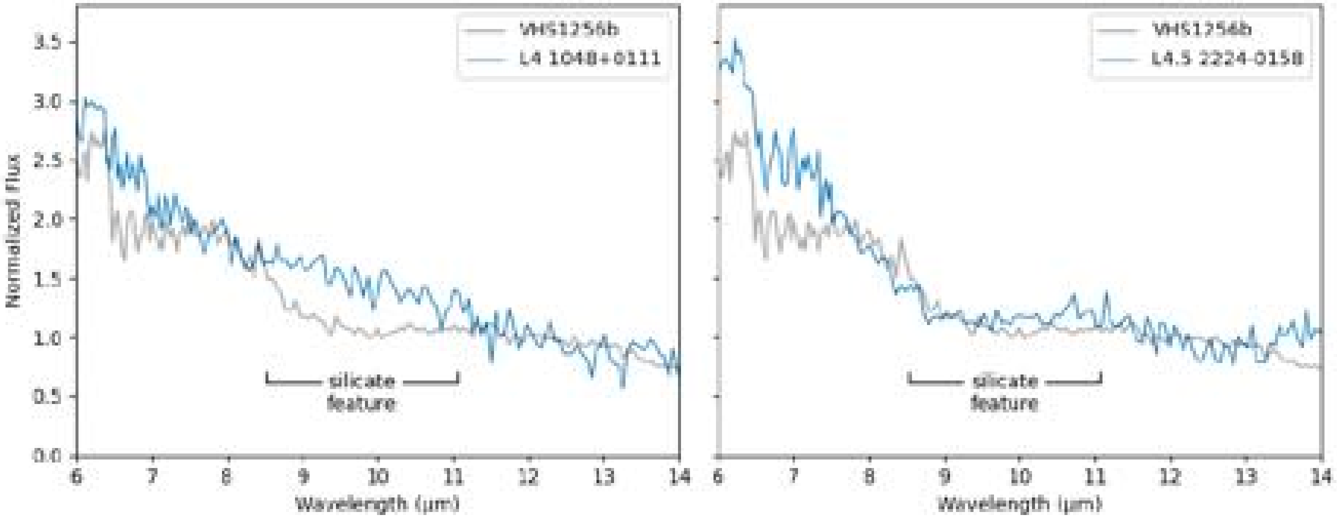


Miles et al. 2022

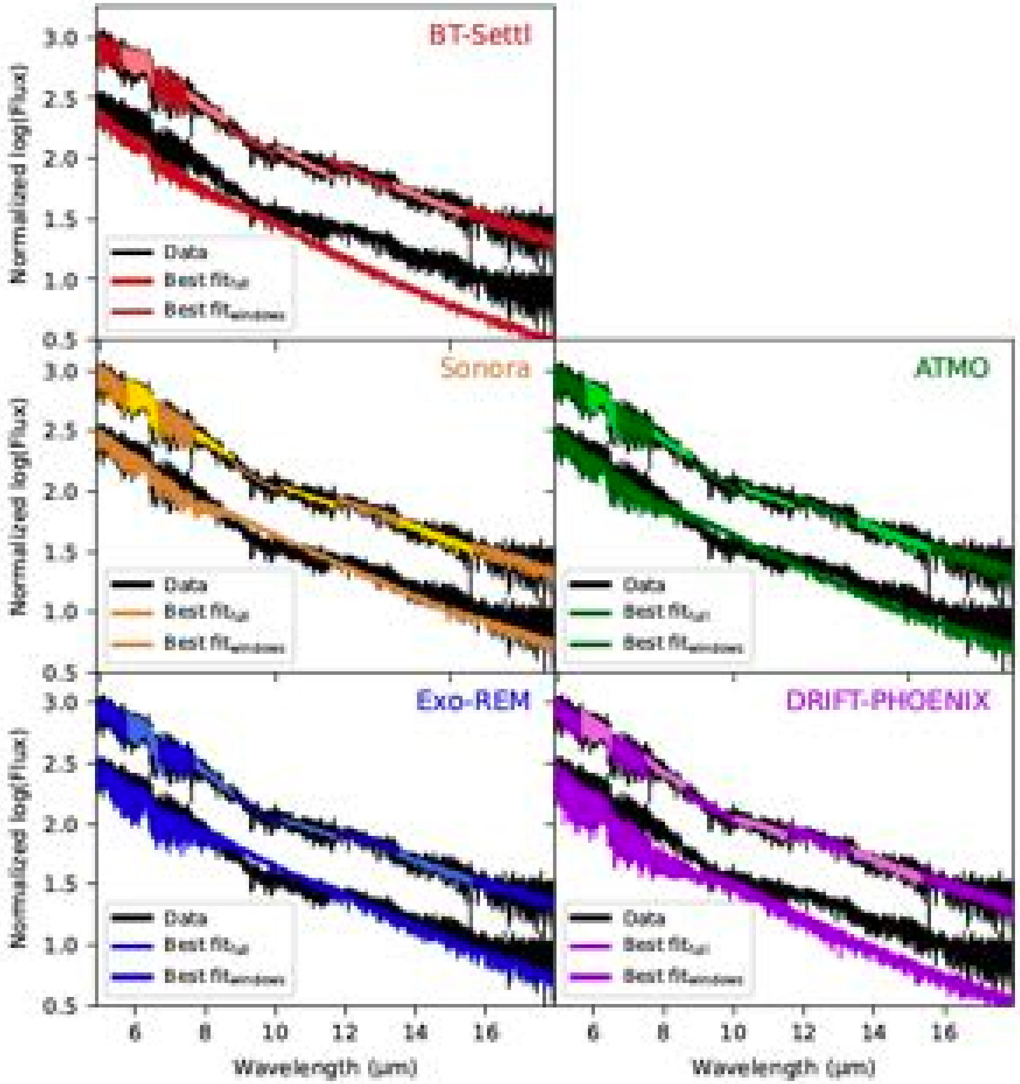
Clouds on BD and young giant exoplanets

Silicate absorption feature

JWST-MIRI spectrum of VHS 1256 b



Miles et al. 2022



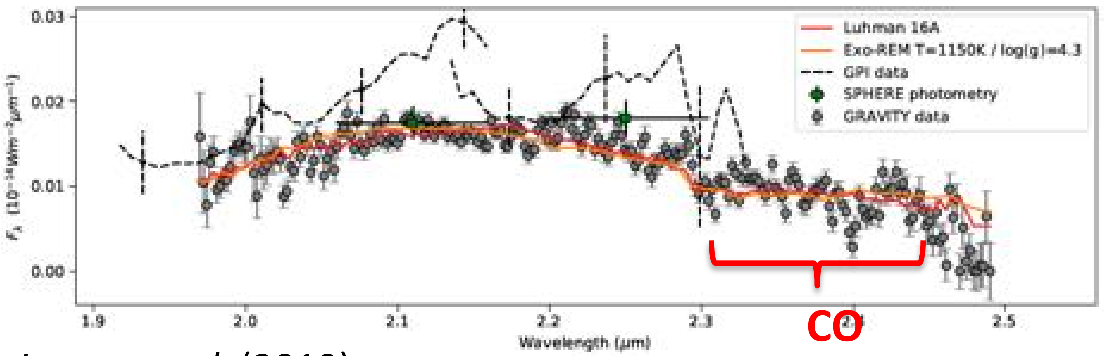
Petrus et al., submitted

- ➢ Silicate features not systematically present on L-type objects
  → Detached upper cloud layer ?
- ➢ Difficulty for 1D models to reproduce the silicate band at 10 µm
- ➢ Could it be detected by MATISSE in N band ?

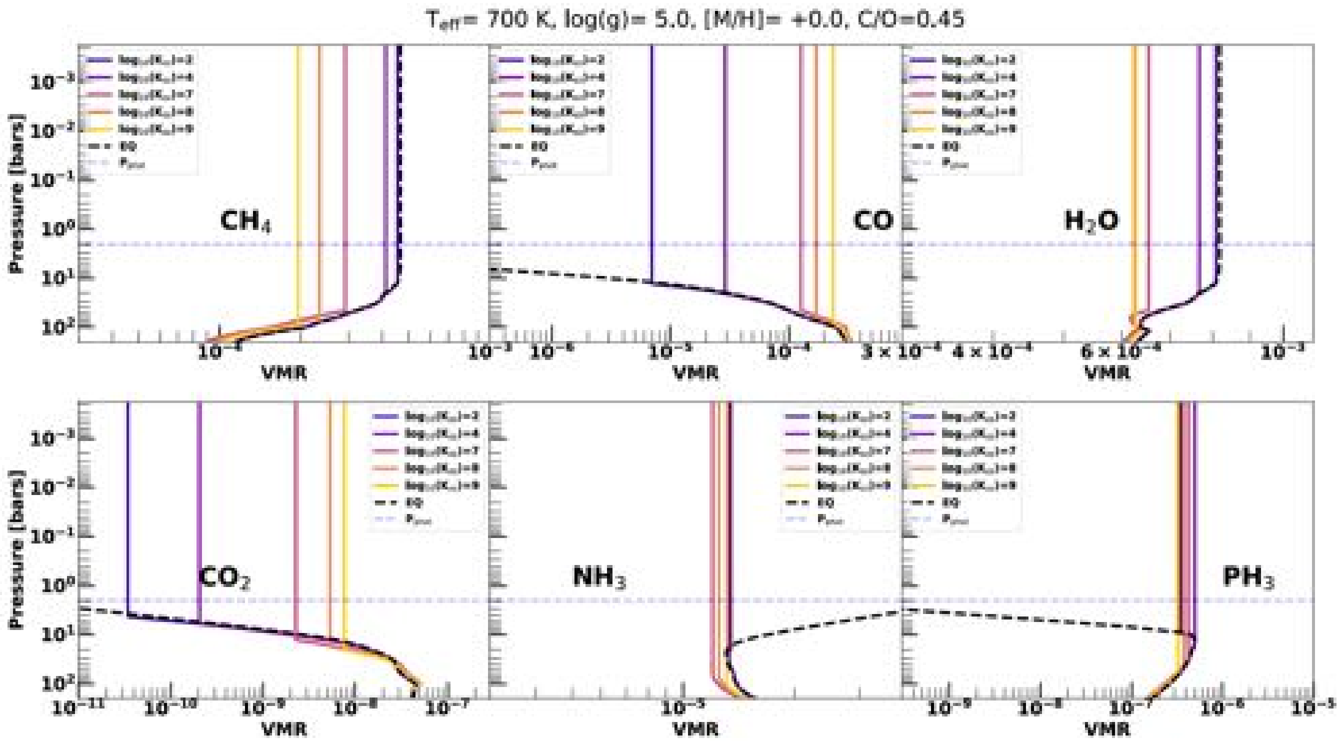
Chemical disequilibrium

Lesson from observations of YGPs

Methane depletion on HR8799 e by VLT-GRAVITY



Lacour et al. (2019)



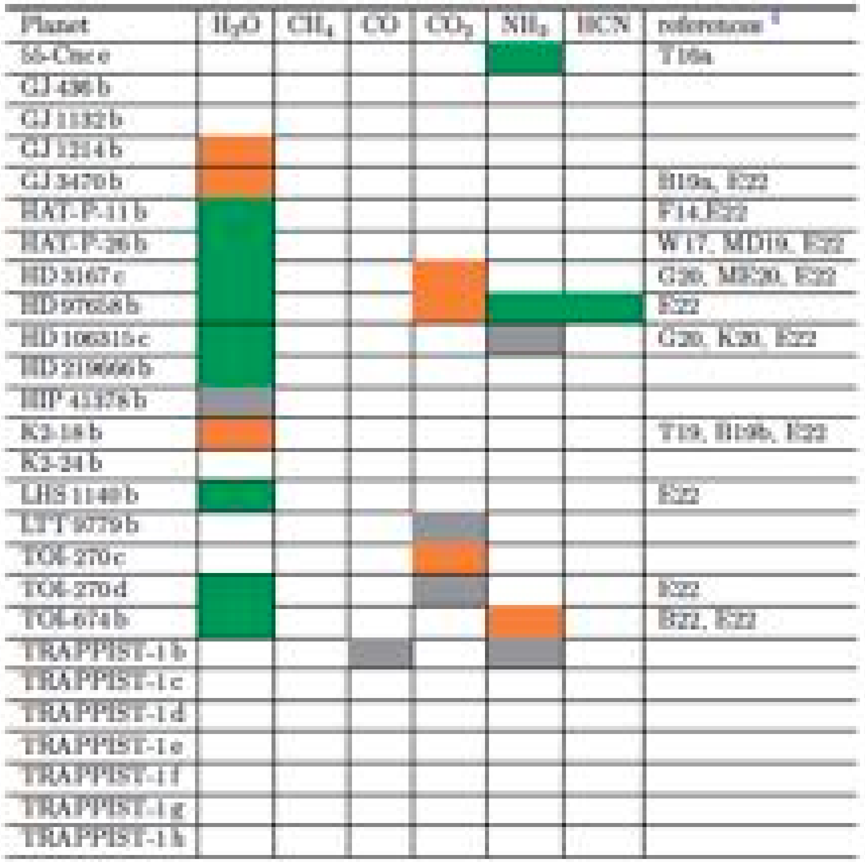
Mukherjee et al. 2024

Chemical disequilibrium by vertical mixing is a key process controlling the chemical composition of exoplanetary atmospheres

Chemical disequilibrium

Lesson from observations of transiting exoplanets

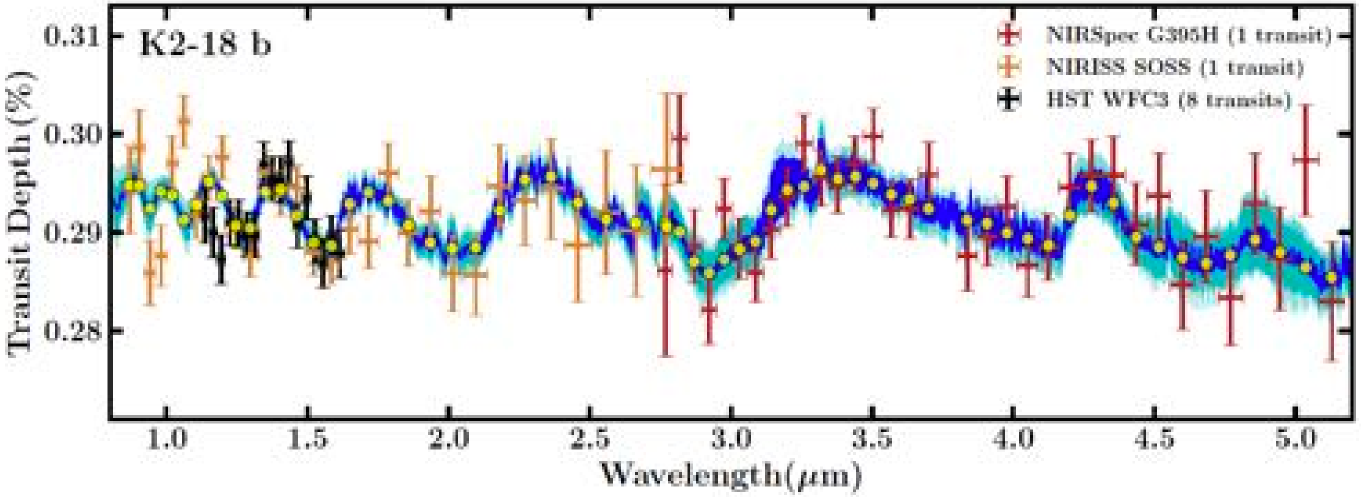
The « missing methane problem »
for transiting exoplanets with HST



Planet	H_2O	CH_4	CO	CO_2	NH_3	HCN	references
55-Cnc e							T16a
GJ 436 b							
GJ 1132 b							
GJ 1214 b							
GJ 3470 b							B19a, E22
HAT-P-11 b							F14,E22
HAT-P-26 b							W17, MD19, E22
HD 3167 c							G20, MB20, E22
HD 97658 b							E22
HD 106315 c							G20, K20, E22
HD 219666 b							
HIP 41378 b							
K2-18 b							T19, B19b, E22
K2-24 b							
LHS 1140 b							E22
LTT 9779 b							
TOI-270 c							
TOI-270 d							E22
TOI-674 b							B22, E22
TRAPPIST-1 b							
TRAPPIST-1 c							
TRAPPIST-1 d							
TRAPPIST-1 e							
TRAPPIST-1 f							
TRAPPIST-1 g							
TRAPPIST-1 h							

Gressier et al. (2022)

JWST spectrum of K2-18 b dominated by CH_4 and CO_2



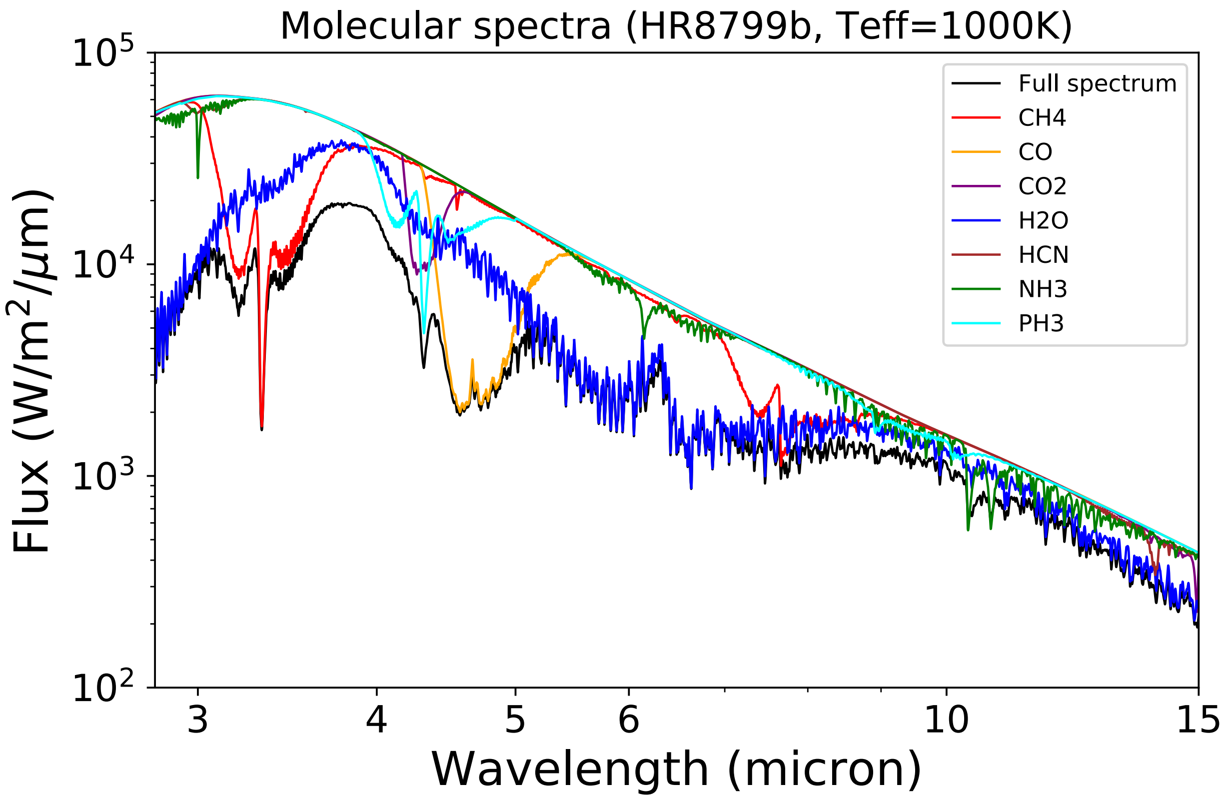
Madhusudhan et al. 2023

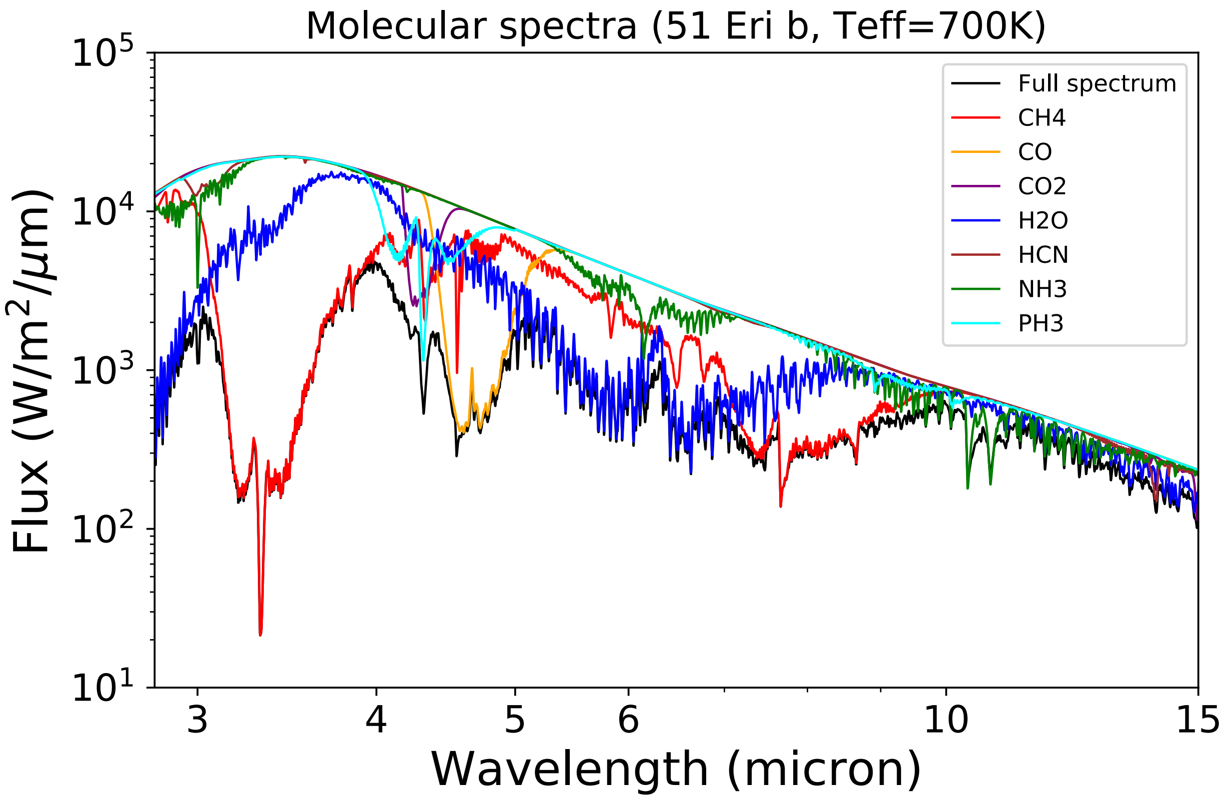
- HST not efficient to detect CH_4
- High intrinsic temperature for some planets

→ Tidal heating or ohmic dissipation?

MATISSE for young giants exoplanets

The wealth of L and M bands





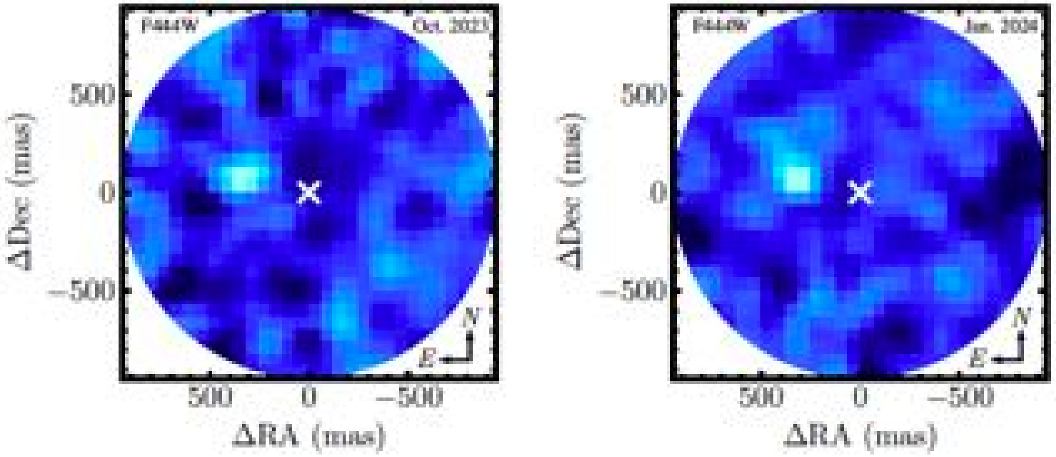
MATISSE could probe:

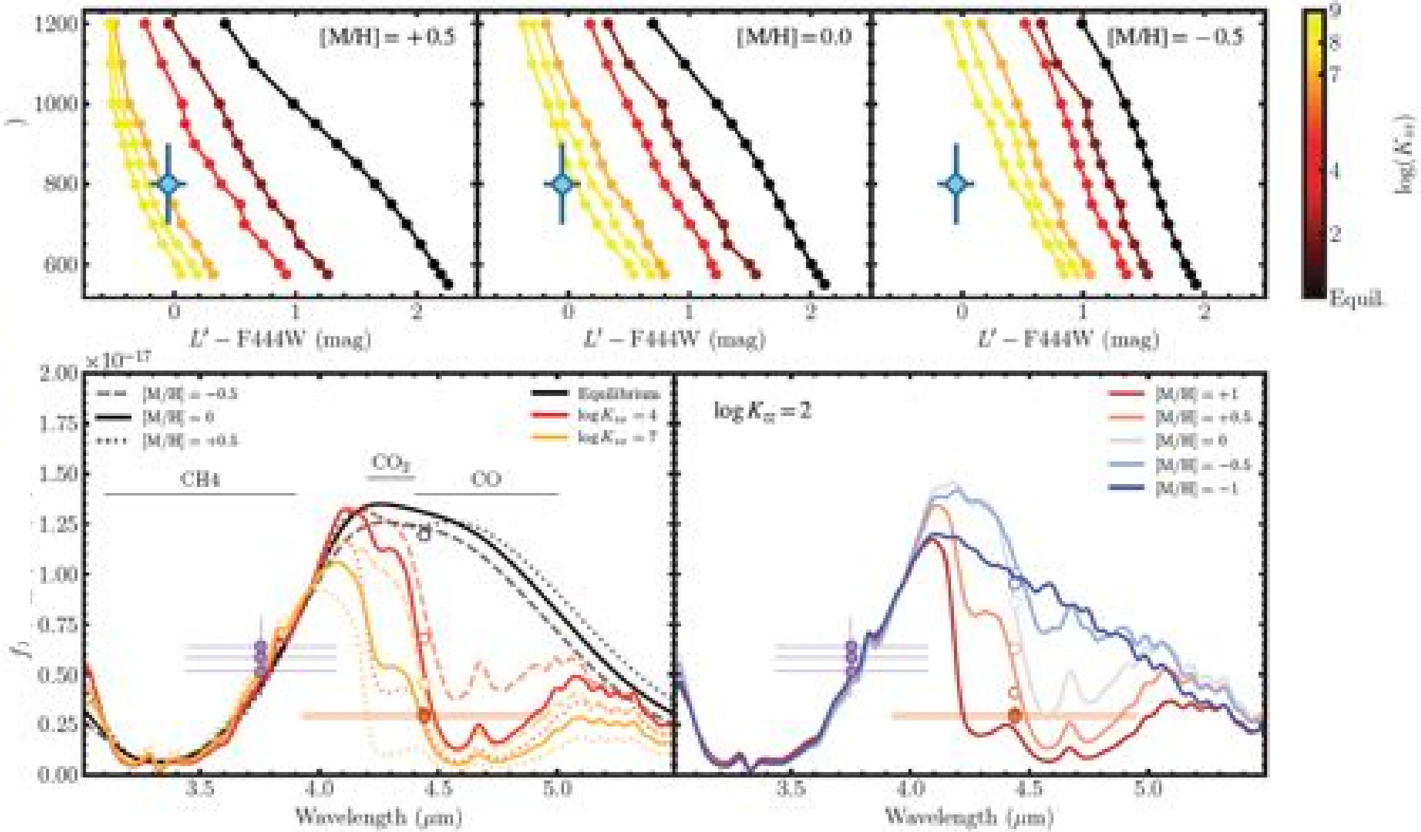
- Chemical disequilibrium by measuring both CO (4.7 μm) and CH_4 (3.3 μm)
- PH_3 (4.2 μm) and P chemistry
- CO_2 (4.3 μm) and atmospheric metallicity

MATISSE for young giants exoplanets

Breaking the degeneracy between metallicity and chemical disequilibrium from NIRCam

NIRCam observations of AF Lep b



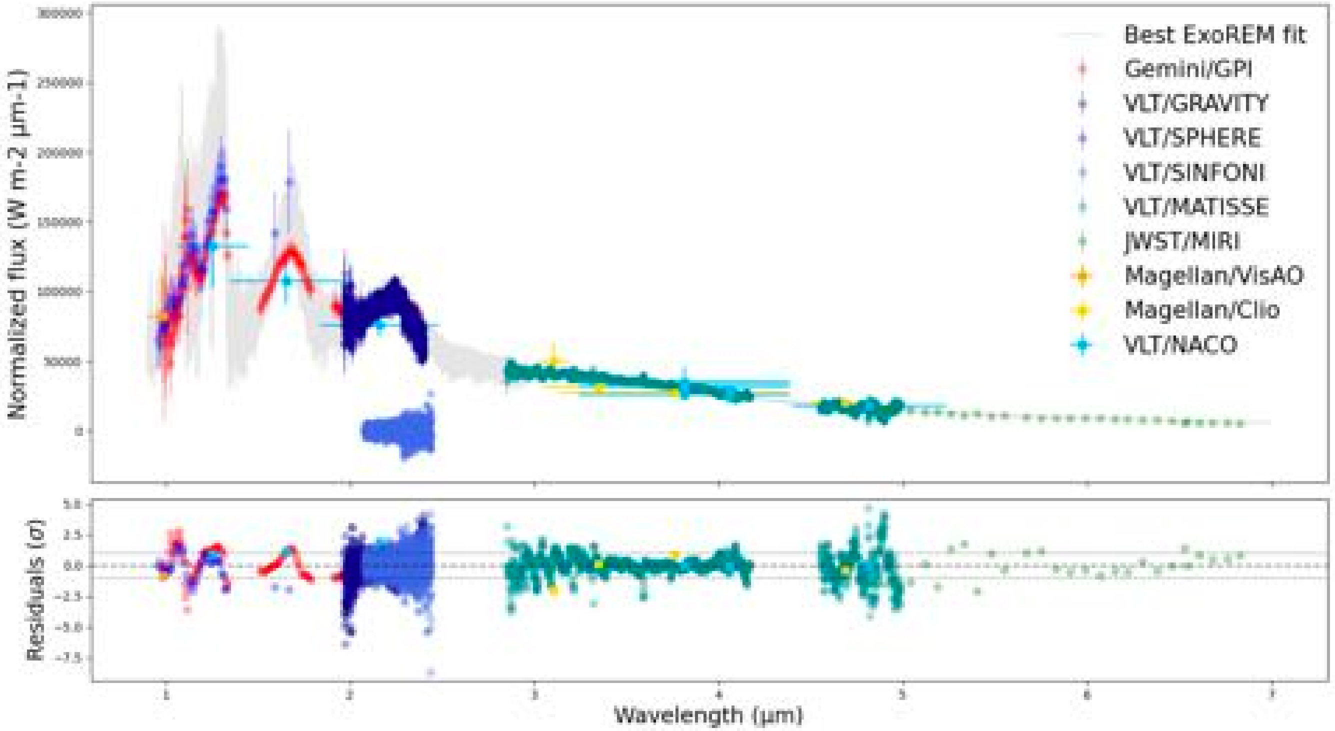


Franson et al. 2024

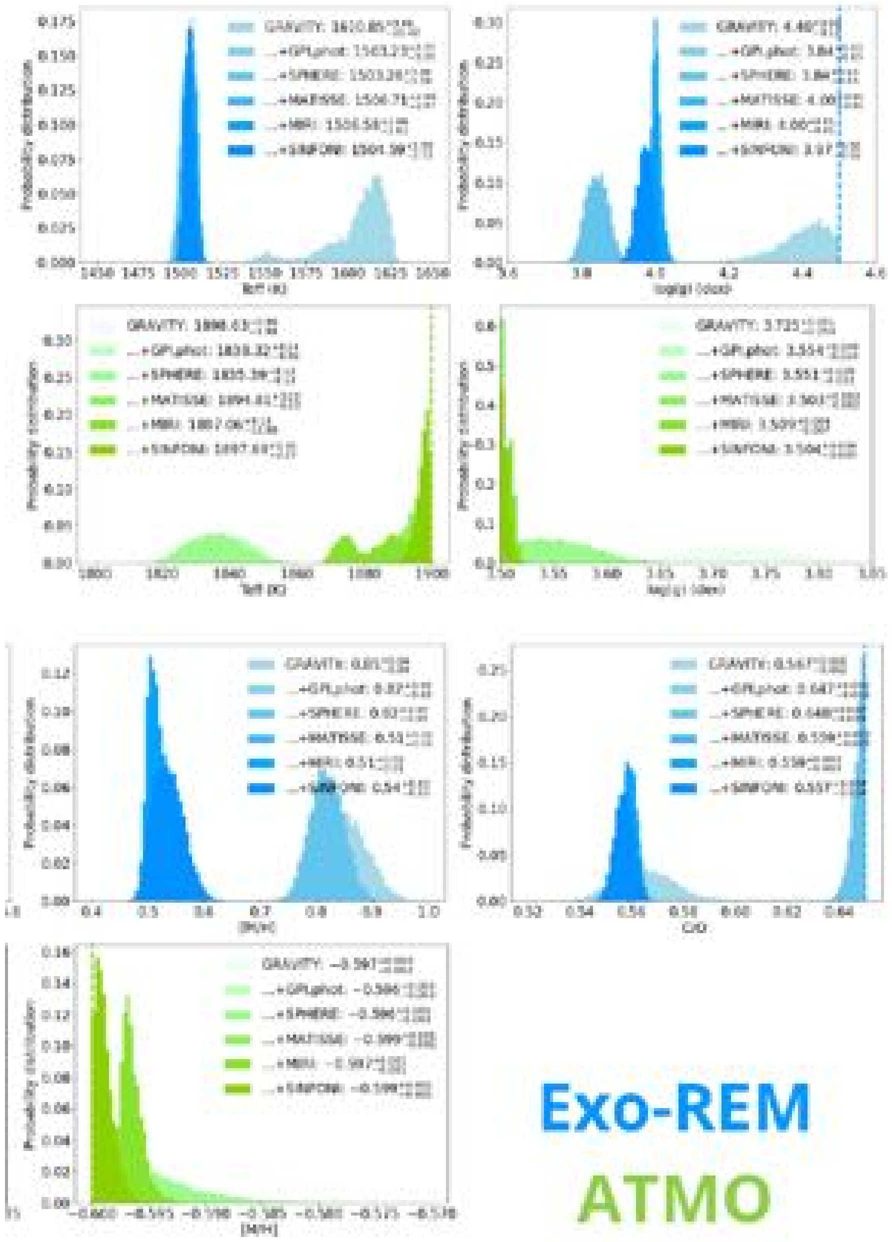
- ➢ MATISSE observations can distinguish a high metallicity from a strong disequilibrium by probing CO at 4.7 µm
- ➢ MATISSE can observe planets with lower angular separation than NIRCam

MATISSE for young giants exoplanets

Filling the SED with multi-intrument observations

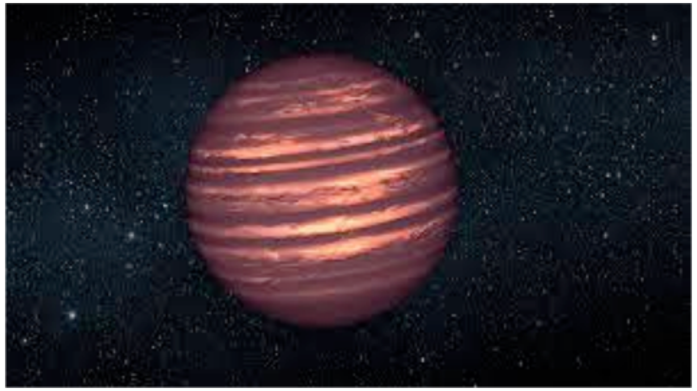


Ravet et al. in prep
(see also Mathis Houllé talk)



➡ MATISSE observations help to constrain some parameters (i.e. solar C/O ratio)

Take-home messages



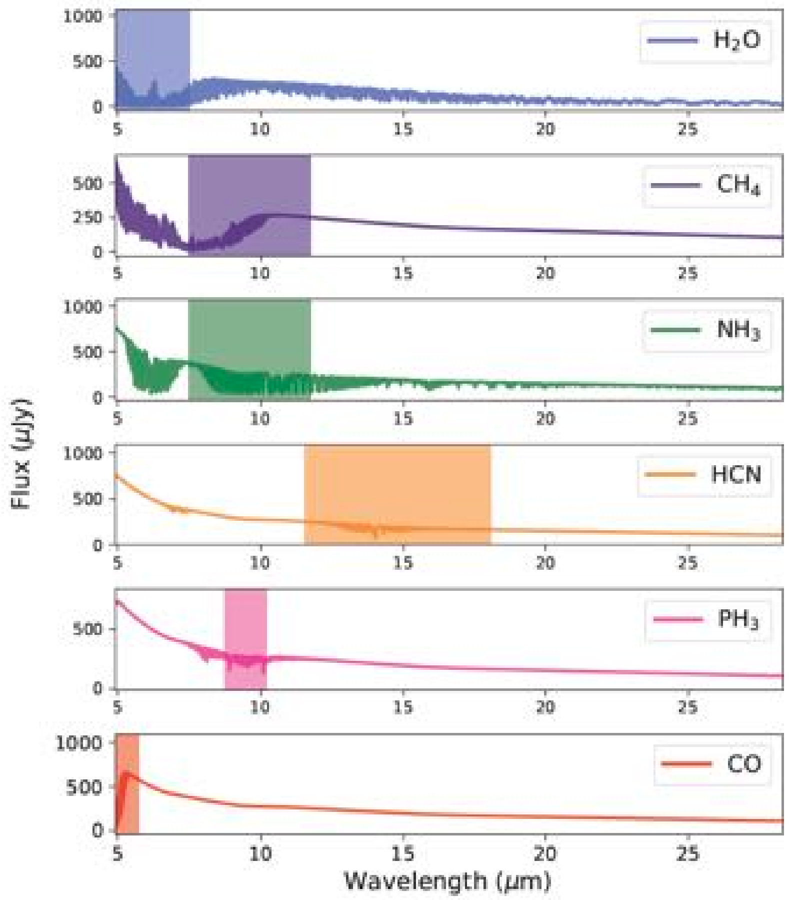
- **We are now in the golden age of exoplanet atmospheres !**
- **The physics and chemistry of BDs and YGPs is similar, the main difference is the gravity**
- **3D simulations show the importance of cloud radiative effects on the dynamics, variability and LT transition**
- **Chemical disequilibrium is a major process controlling chemical composition of BD and YGP**
- **MATISSE could probe:**

- Chemical disequilibrium by measuring CO (4.7 µm) and CH_4 (3.3 µm)
- Potentially PH_3 (4.2 µm) and CO_2 (4.3 µm)
- Silicate cloud feature (10 µm)
- Emission continuum to break degeneracies in atmospheric retrieval
- Exoplanets at lower angular separation than JWST-NIRCam/MIRI

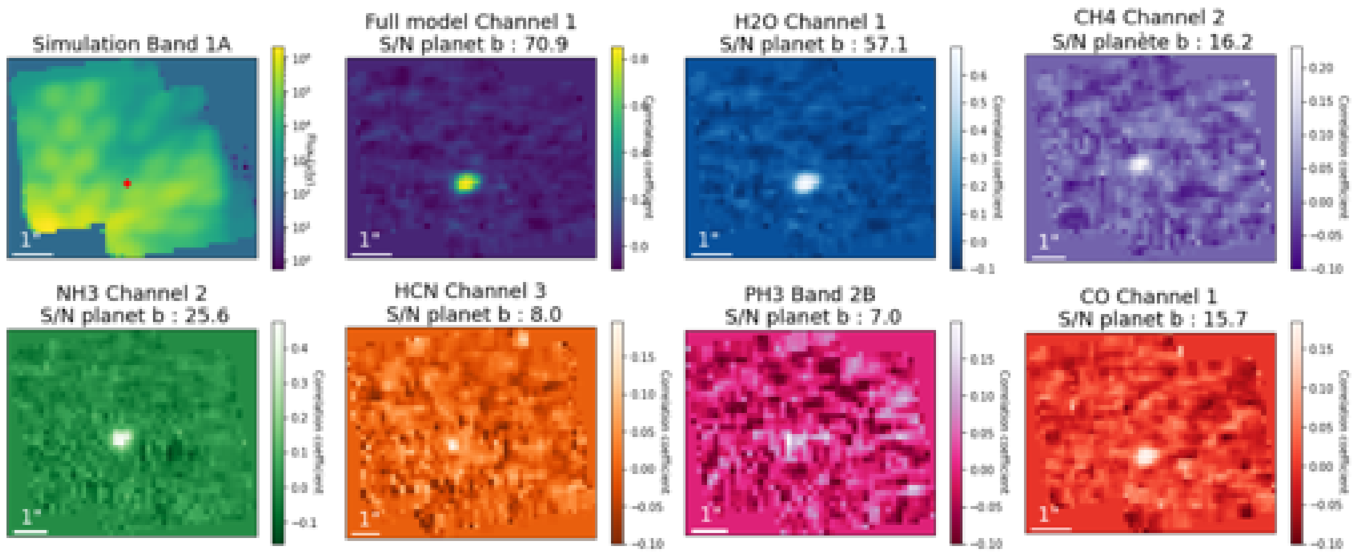
MATISSE for young giants exoplanets

Complementarity with MIRI-MRS

Molecular templates



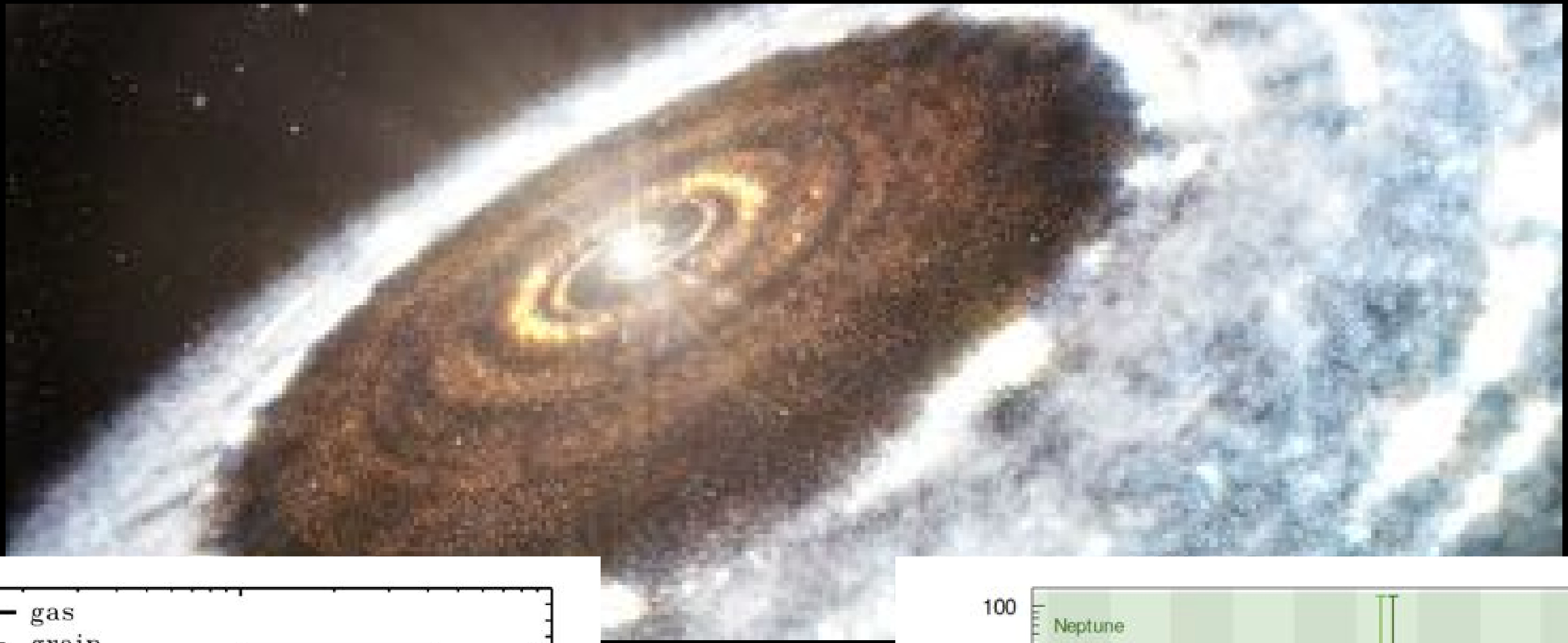
Simulation of molecular mapping for GJ504 b with JWST-MIRI-MRS
(cross-correlation of observations with model spectra)

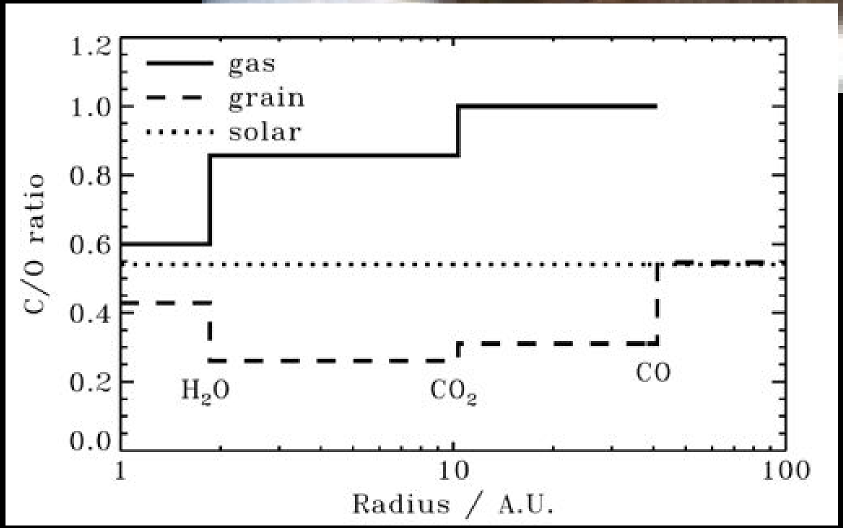


Mâlin et al. 2023
(see also Polychronis et al. 2022)

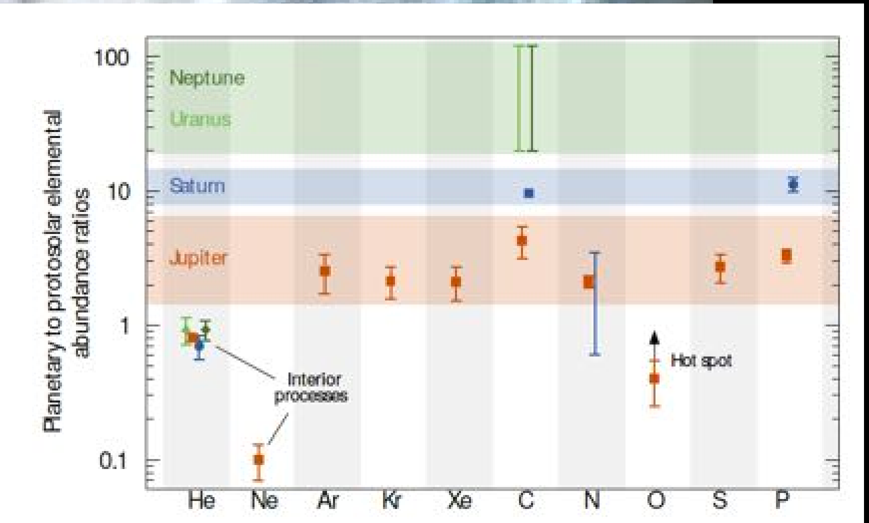
➡ « Cold » planets (e.g. GJ 504 b) are ideal for molecular mapping
Proposal on GJ 504 b (PI: P. Patatis, co-PI: M. Mâlin)

Atmospheres as a probe of planetary formation: effect of snowlines on C/O





Öberg al. (2011)

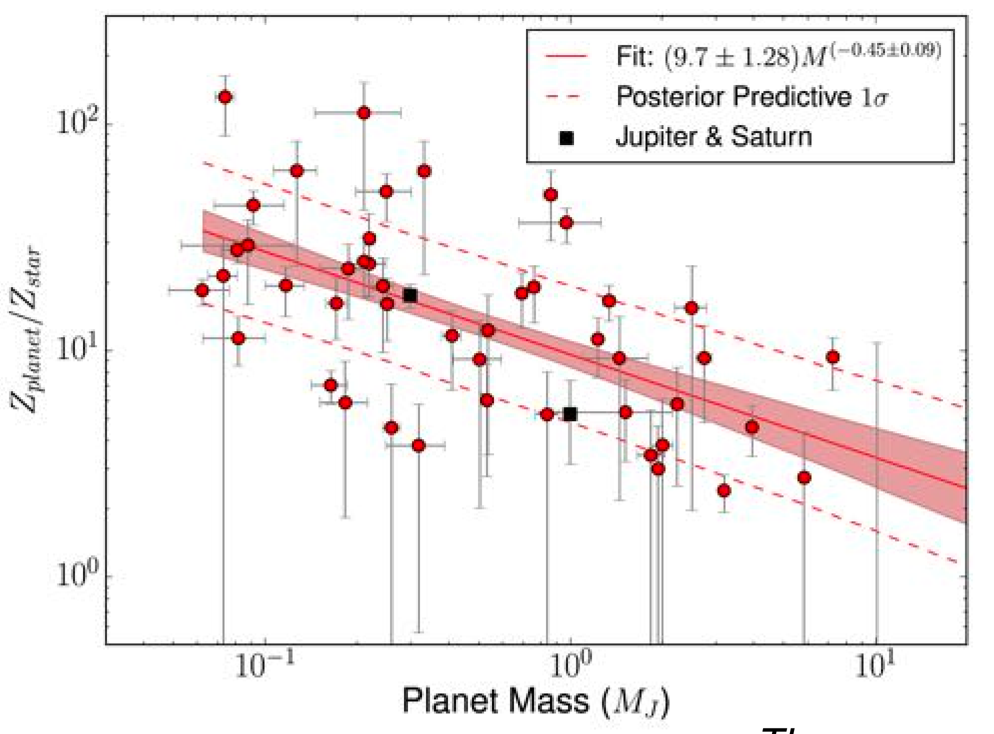


Mousis al. (2018)

Atmospheres as a probe of planetary formation: effect of snowlines on C/O

Metallicity = fraction of heavy elements (heavier than H and He)
For Solar System atmospheres, metallicity ≈ $[C]/[C]_{solar}$
For exoplanetary atmospheres, metallicity ≈ $[O]/[O]_{solar}$

Mass & radius



Atmospheric retrieval (transit with HST)