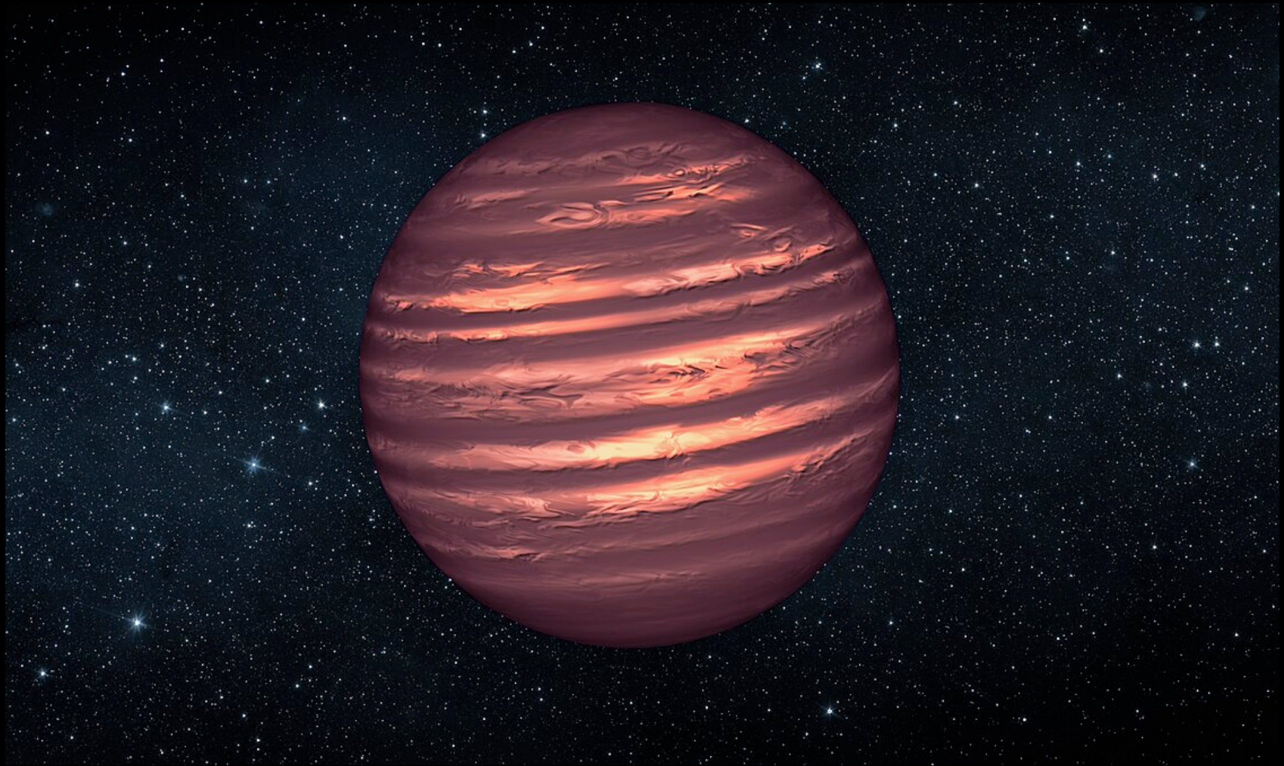
Mapping latitudinal variations in the atmospheres of brown dwarfs and exoplanets



Benjamin Charnay[1,2], Sam de Regt[3], Matthieu Ravet[4,5], Lucas Teinturier[1], Flavien Kiefer[1], Gaël Chauvin[5], Allan Denis[6], Mickaël Bonnefoy[7], Paulina Palma-Bifani[1], Alice Radcliffe[1], Arthur Vigan[6]

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[3]Leiden Observatory
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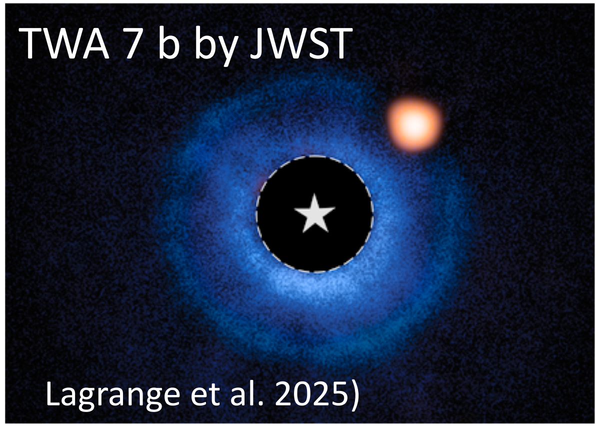
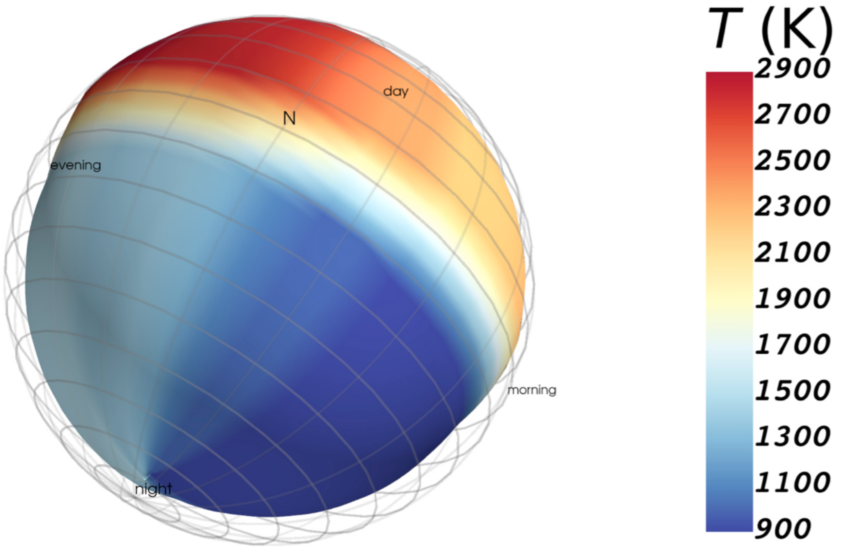
[6]LAM
[7]IPAG

Exosystems 2026

Mapping exoplanets and brown dwarfs:
How to transform a dot into a 3D map?





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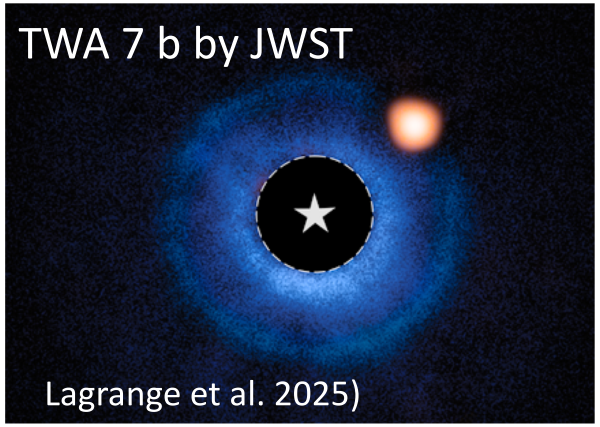
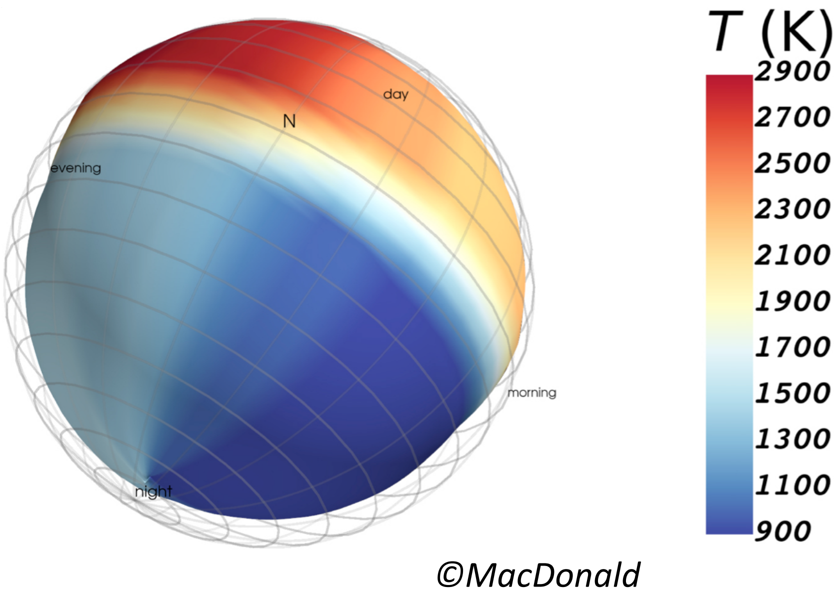
Mapping exoplanets and brown dwarfs:
How to transform a dot into a 3D map?

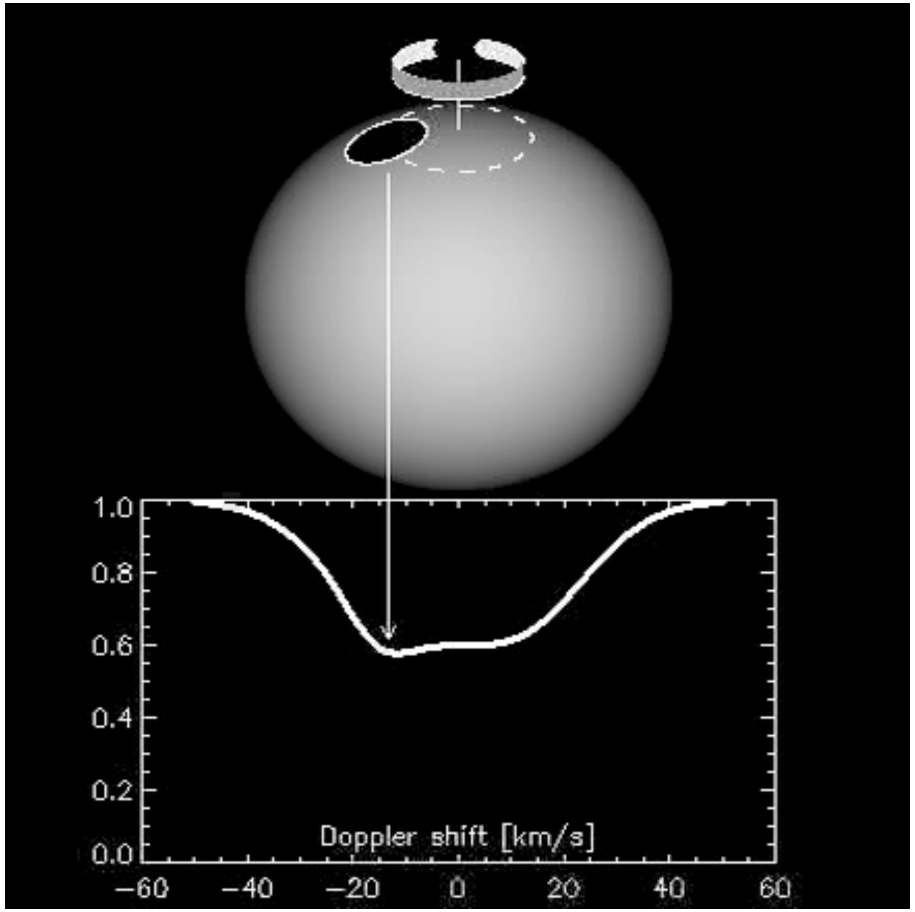




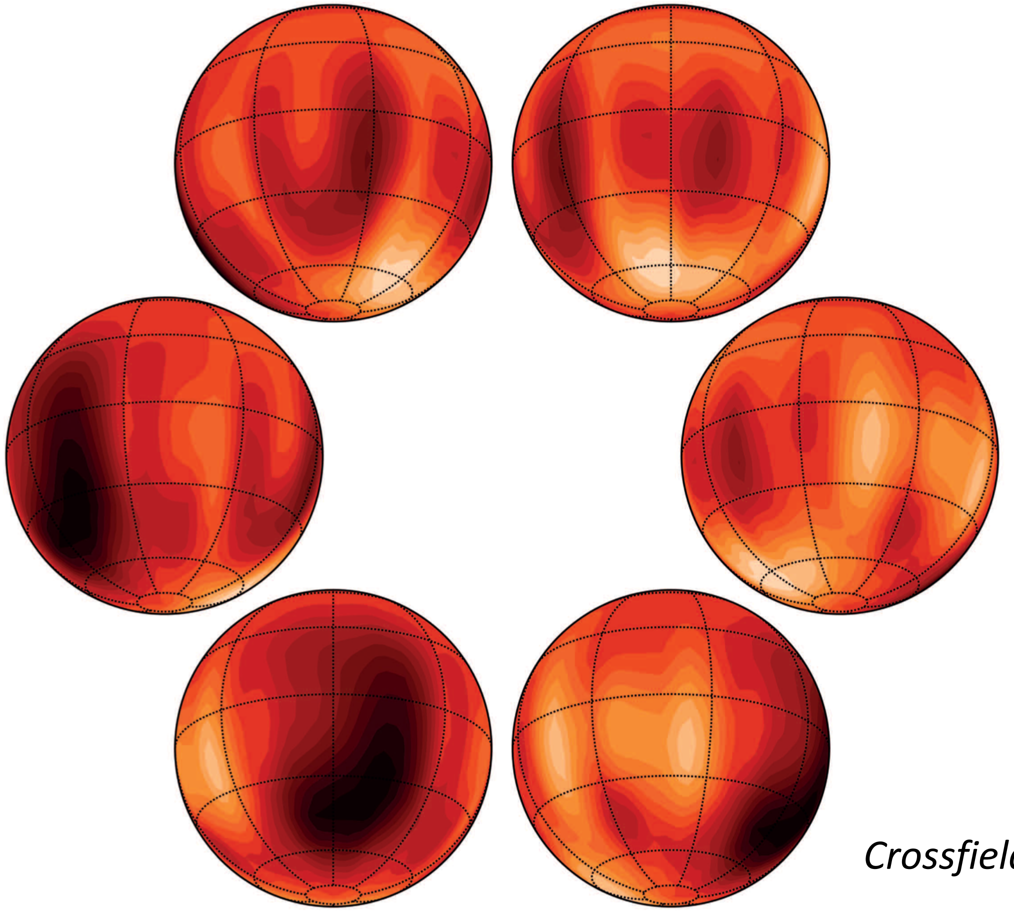
Dimension	Technique
Altitude	Emission spectroscopy
Longitude	Phase variations
Latitude	1) Eclipse mapping **2) HR spectroscopy using Doppler effects from the rotation**

Observations of clouds in brown dwarfs and young giant exoplanets

Observation of variability and inhomogeneous cloud cover



Inhomogeneous cloud cover of Luhman 16A by doppler imaging



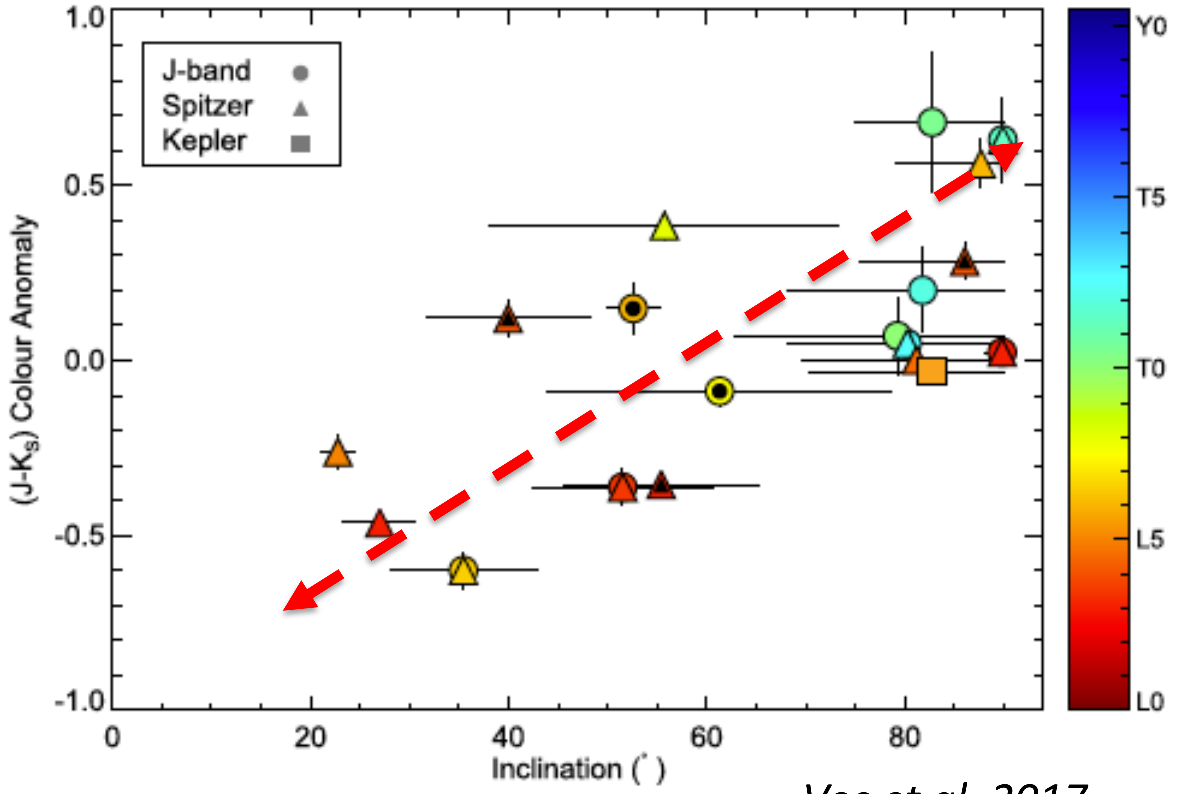
Crossfield et al. 2014

Powerful technique but can only be applied to two brown dwarfs (Luhman 16 A & B) with current instruments

Observations of clouds in brown dwarfs and young giant exoplanets

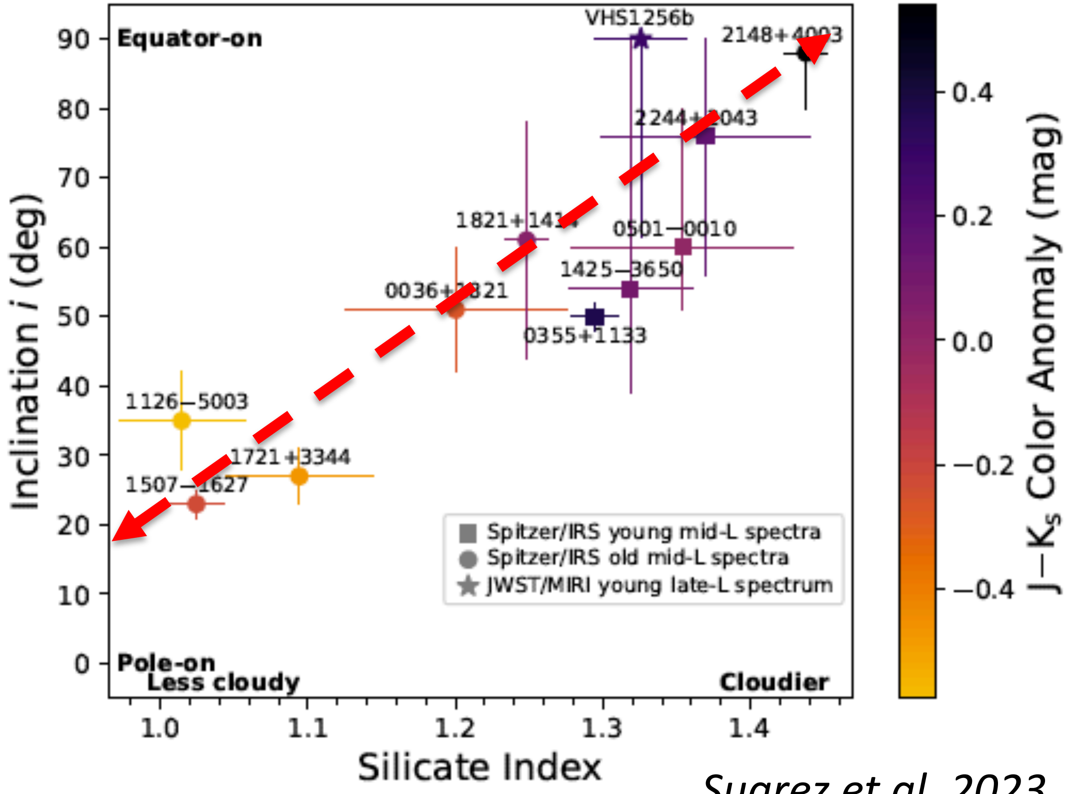
Population study of brown dwarfs: correlation between colors and inclinaison

BD are redder for high inclinations



Vos et al. 2017

Silicate absorption at 9 µm stronger for high inclinations



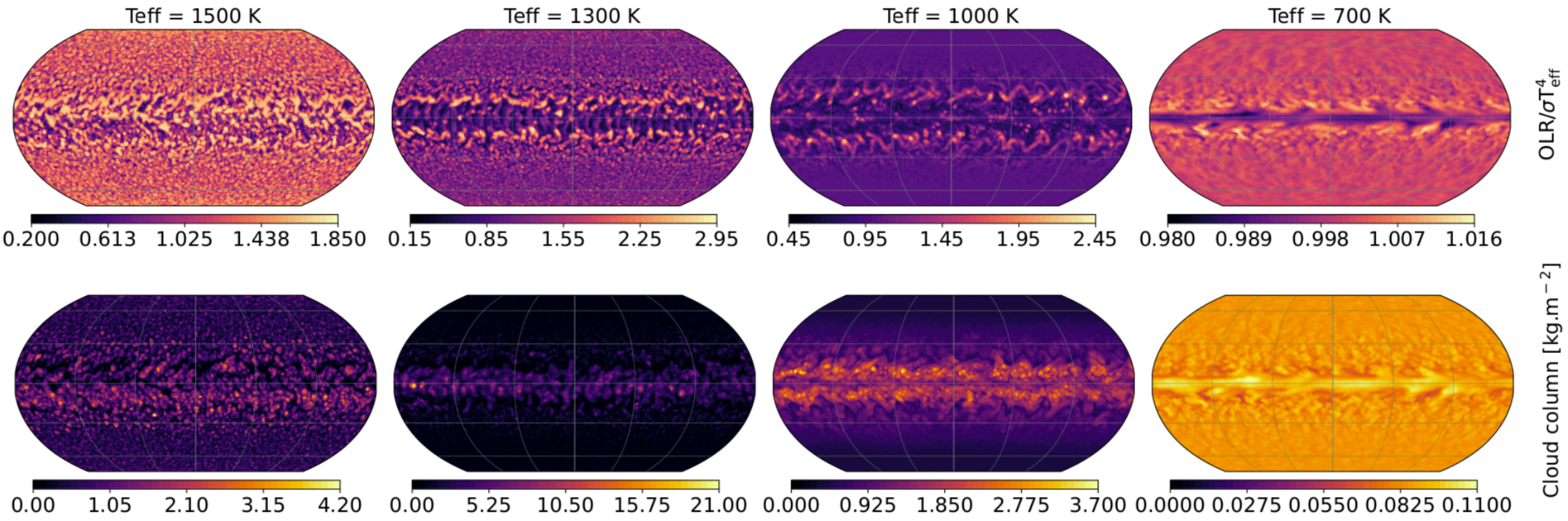
Suarez et al. 2023

Evidence for cloudier equatorial latitudes

3D modeling of clouds on brown dwarfs

Cloud distribution

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

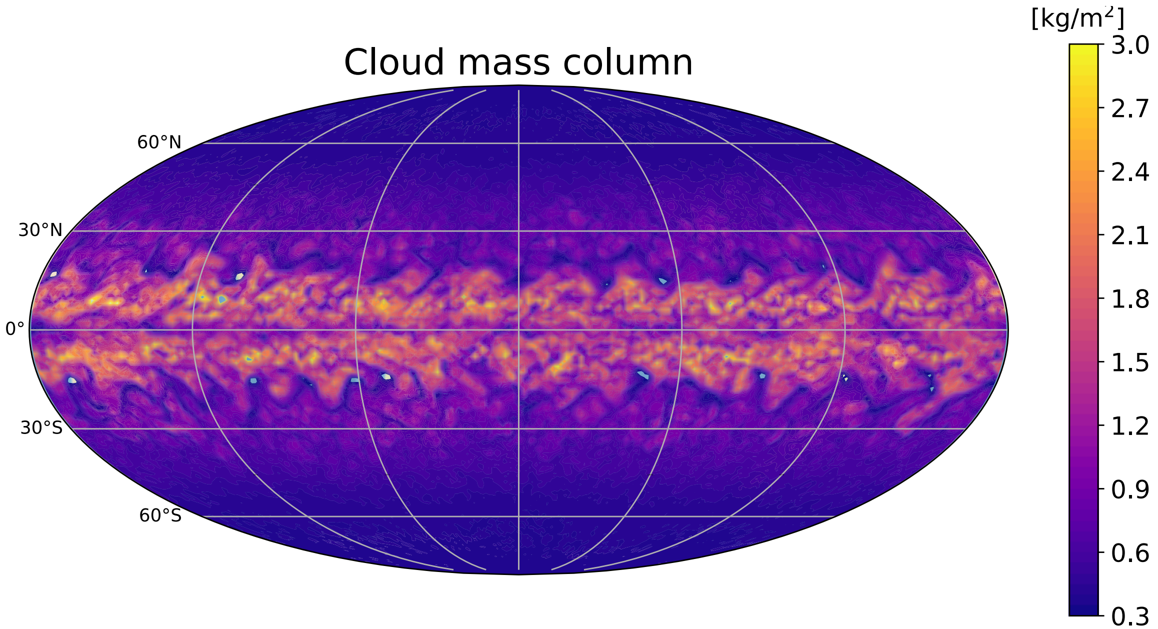


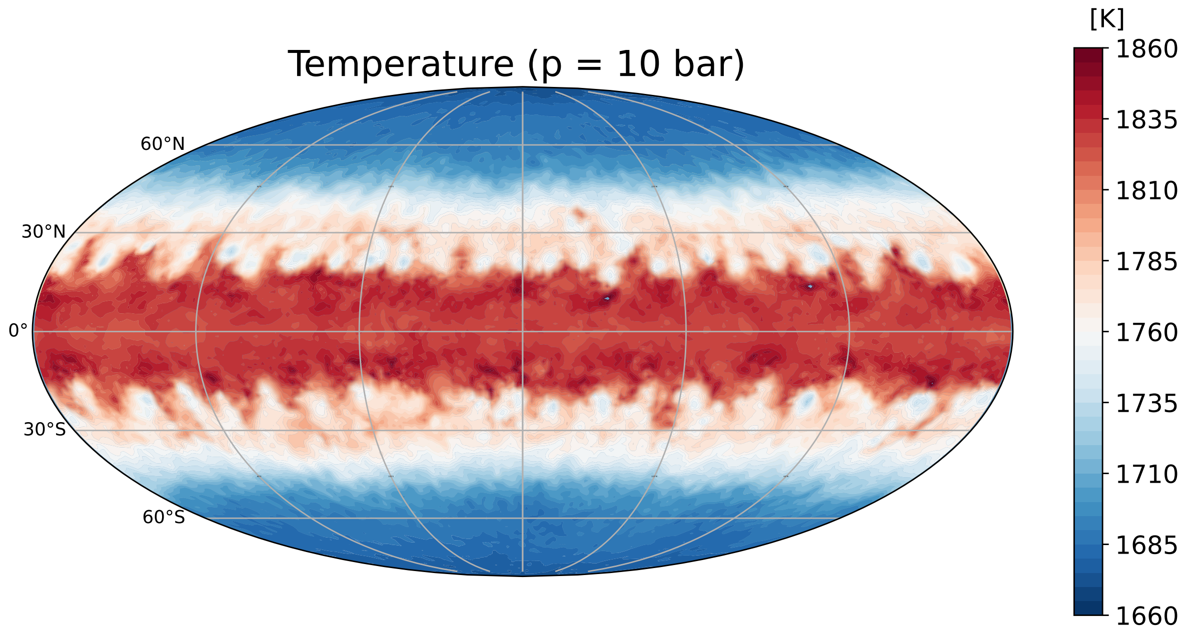
Preferential cloud formation at low latitudes reducing thermal flux

Lucas Teinturier, Benjamin Charnay, Aymeric Spiga & Bruno Bézard:
« Clouds as the driver of variability and colour changes in brown dwarf atmospheres », *Nature Astronomy, 2026*

3D modeling of clouds on brown dwarfs

Thermal structure





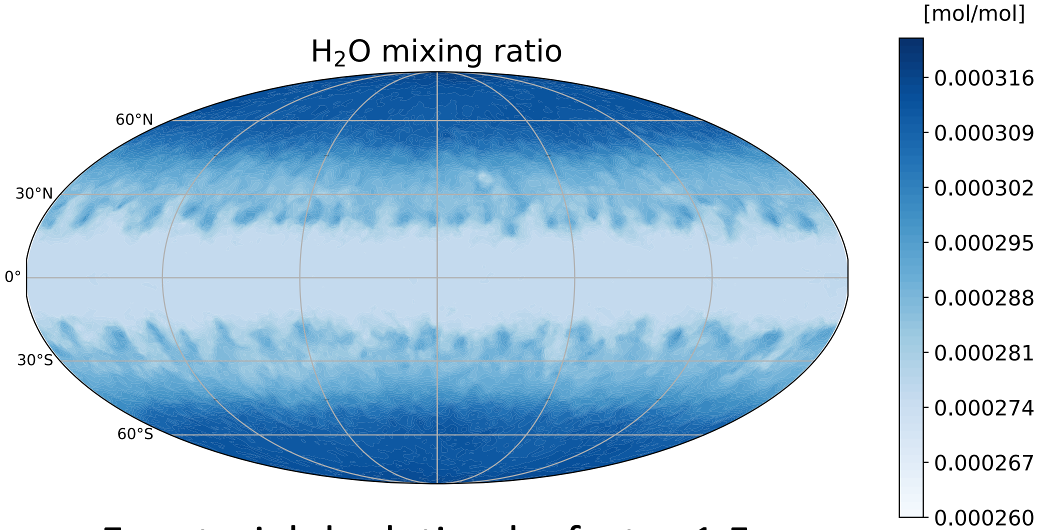
Teinturier et al. 2026

- **Warming by clouds (greenhouse effect)**
- **The equator is warmer than the poles (up to ∼200 K of difference)**

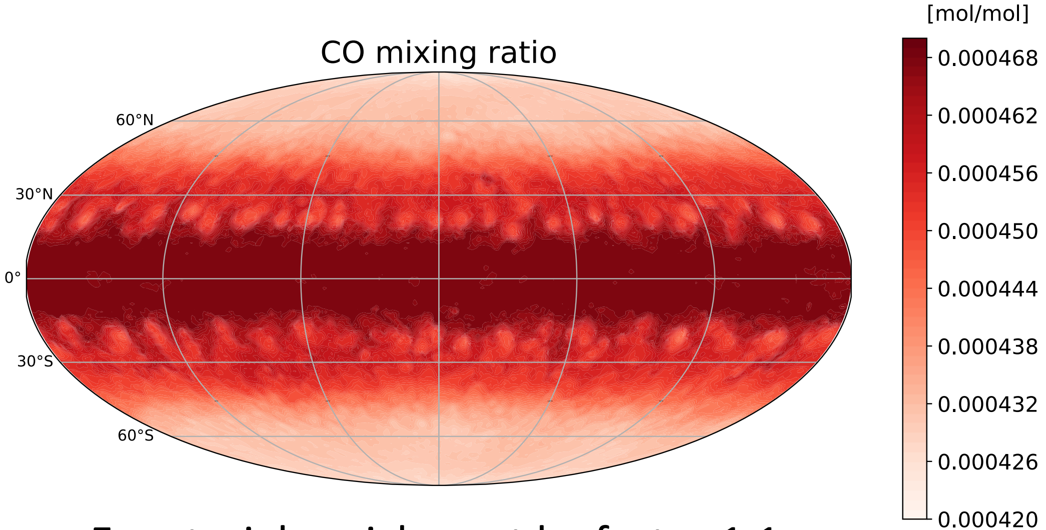
Impact on the chemical composition

$CO + 3\,H_2 = CH_4 + H_2O$

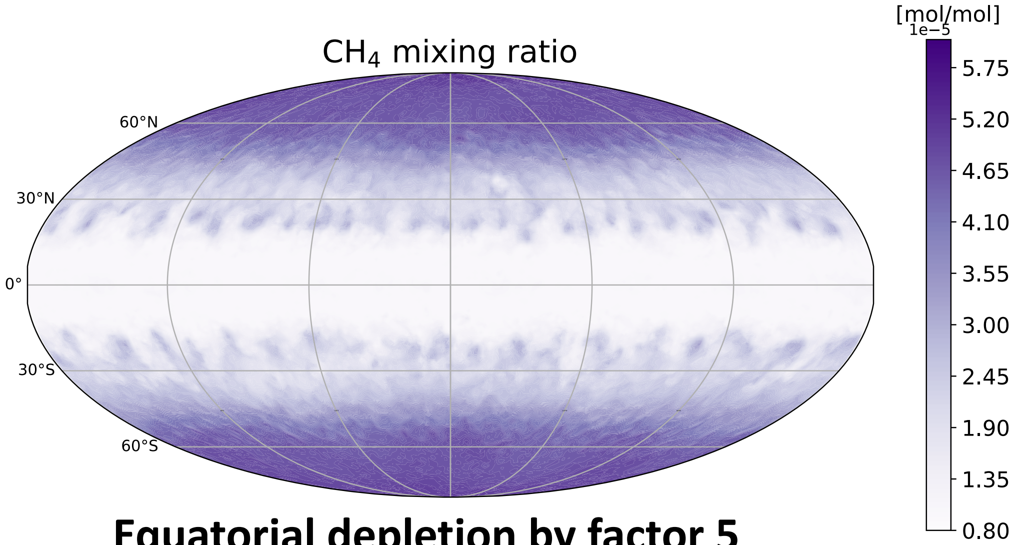
$N_2 + 3\,H_2 = 2\,NH_3$



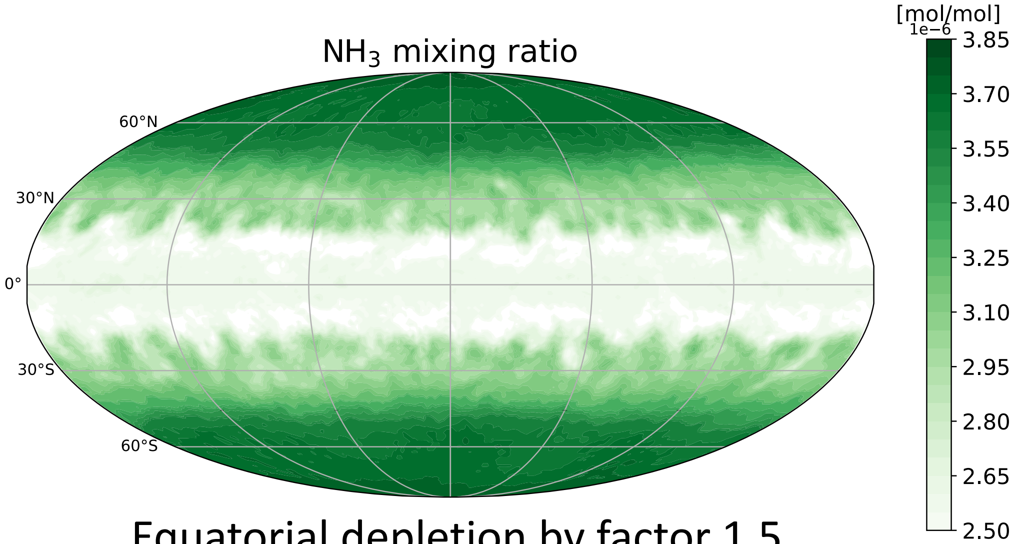
Equatorial depletion by factor 1.5



Equatorial enrichment by factor 1.1



Equatorial depletion by factor 5

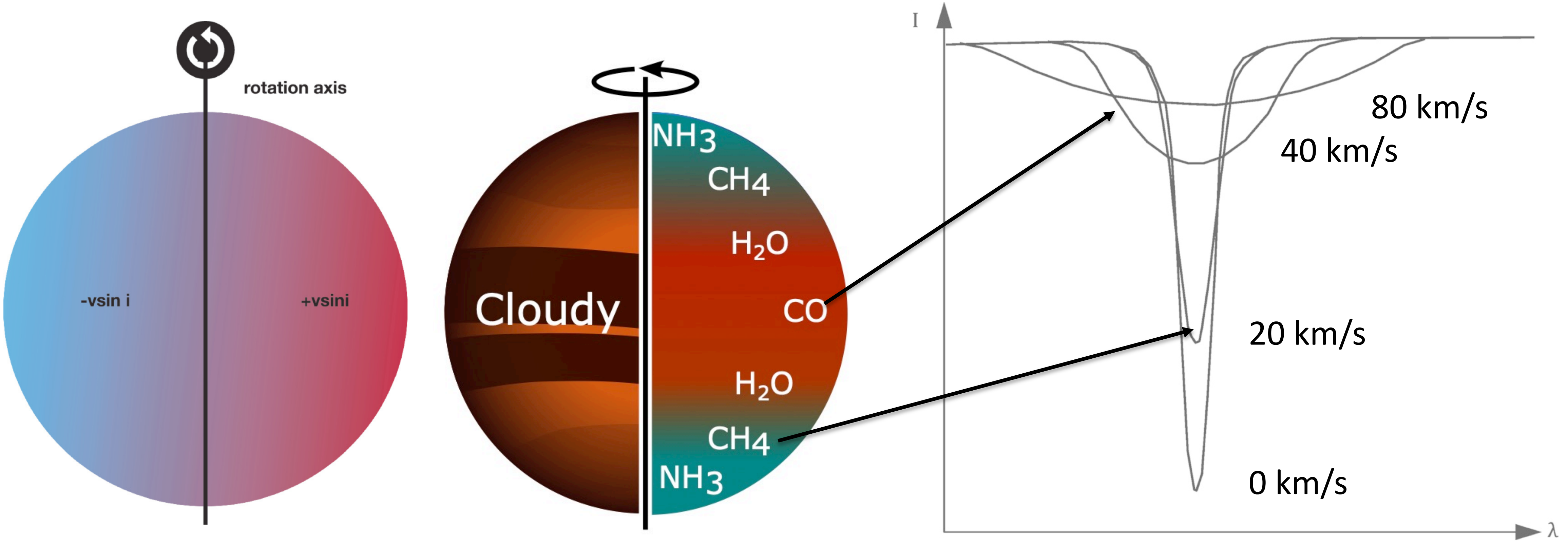


Equatorial depletion by factor 1.5

Charnay et al. in rev.

How to detect chemical latitudinal variations ?

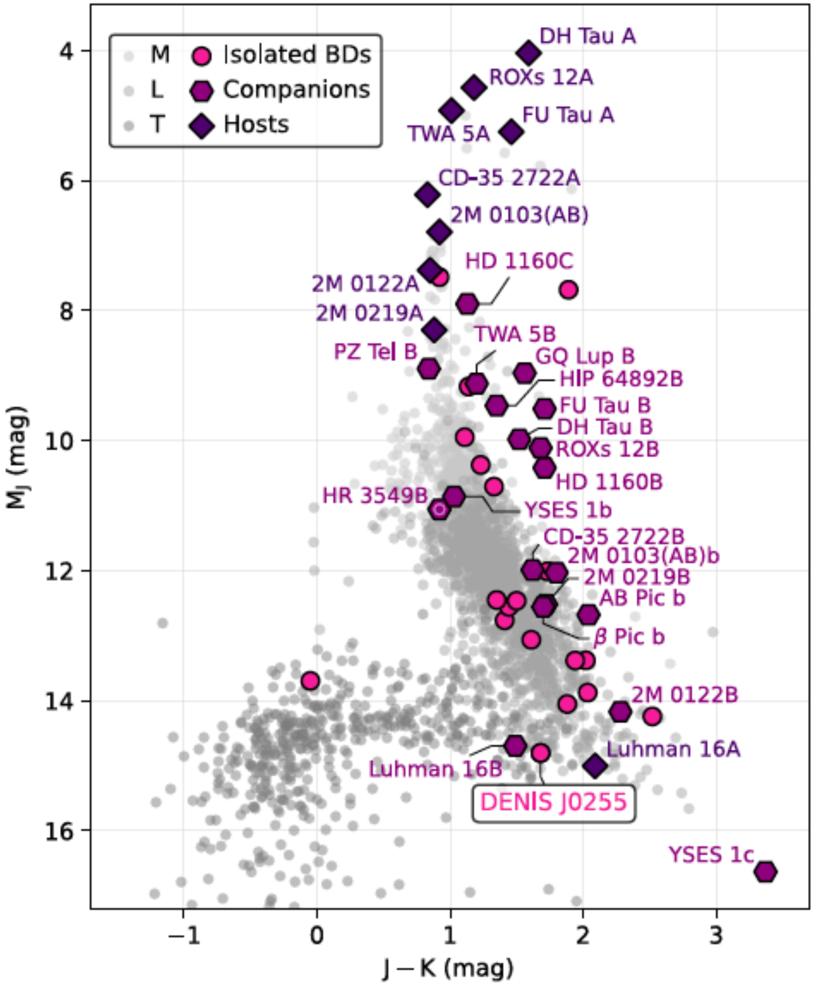
« Differential Molecular Rotational Broadening »
(comparing rotational broadening between two molecules)



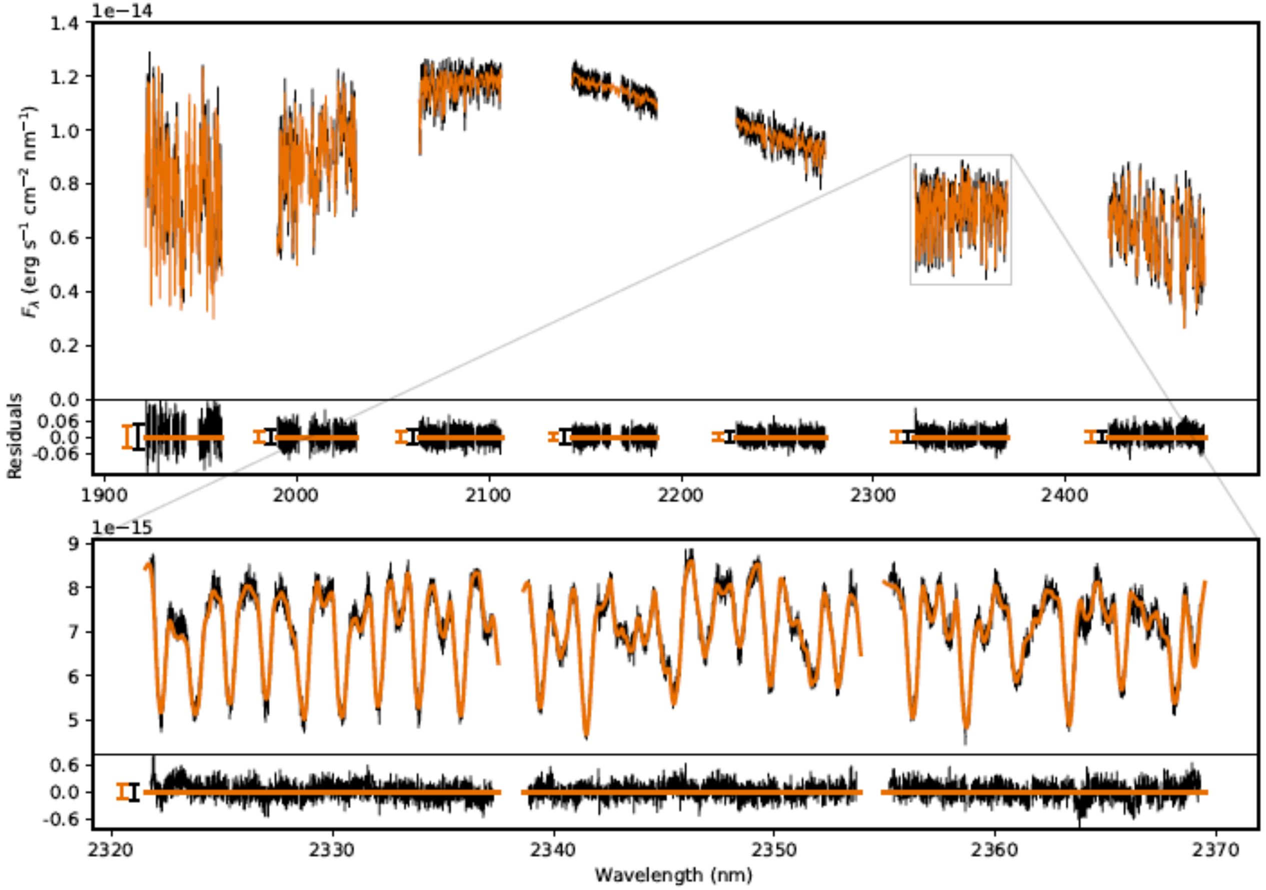
Enrichment of CH_4 and NH_3 at high latitudes ⇒ **low vsini**

<u>Calculation with synthetic spectra:</u>
A depletion by a factor of 5 of CH_4 between +/- 20° should decrease vsini by 7 %

Observations with CRIRES+ of the late L-dwarf DENIS J0255-4700: A test case for differential molecular rotational broadening



De Regt et al. 2024



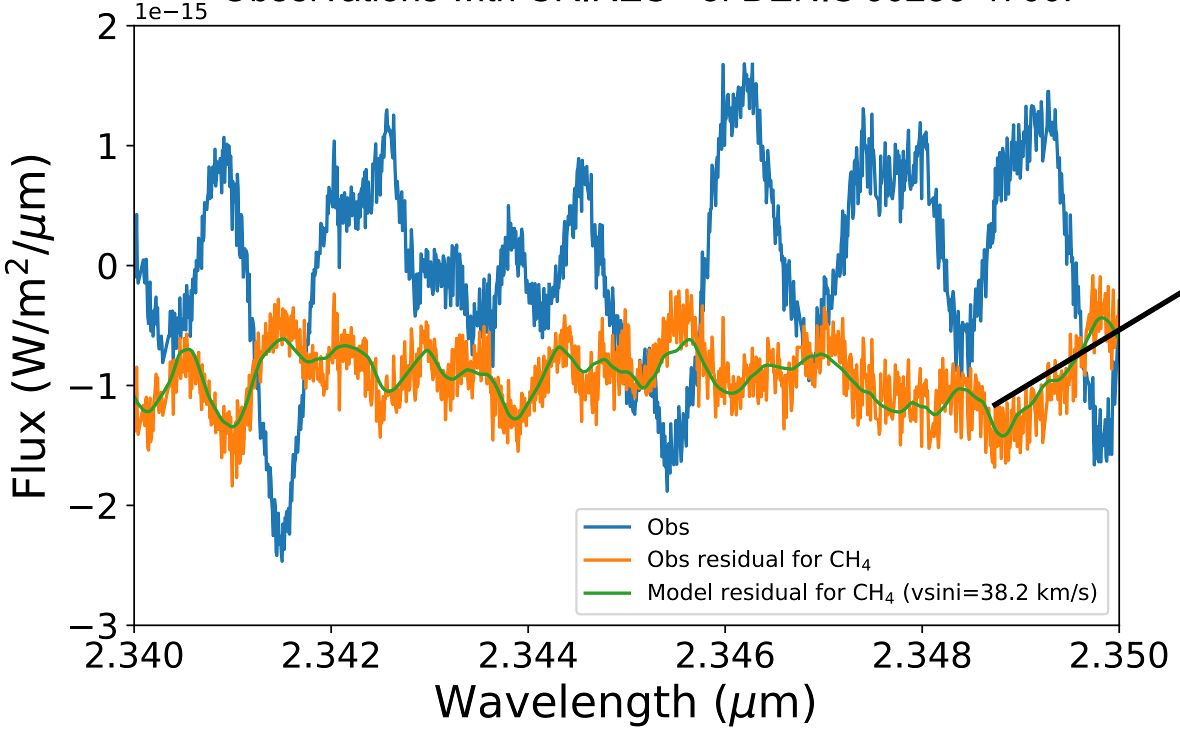
- ➢ **Clear detections of H_2O, CO, CH_4, NH_3**
- ➢ **Fast rotator: *v*sin*i*~41 km/s**
- ➢ **Rotation period < 2.3 h**

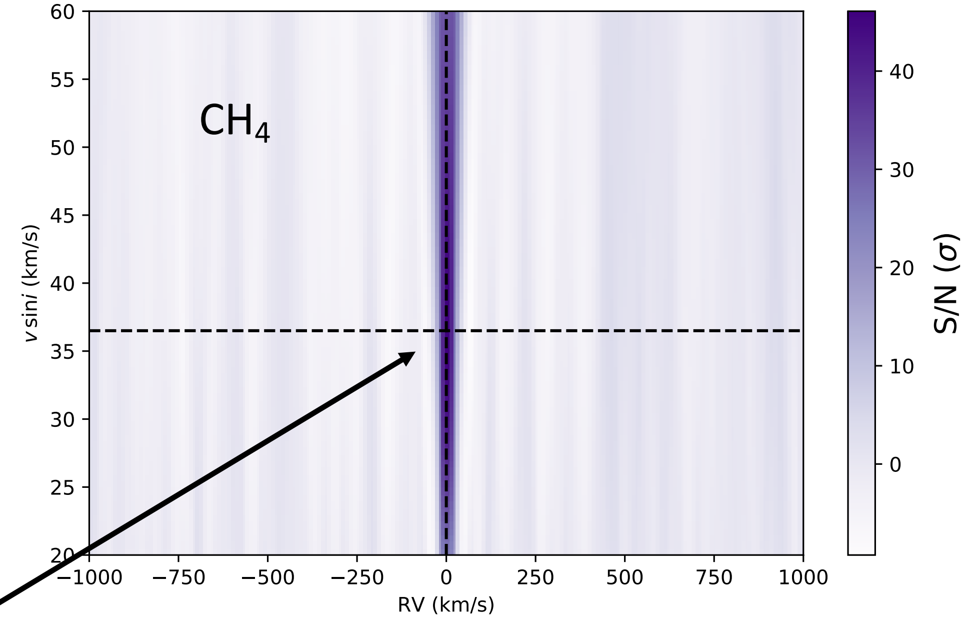
Measurement of individual molecular broadening

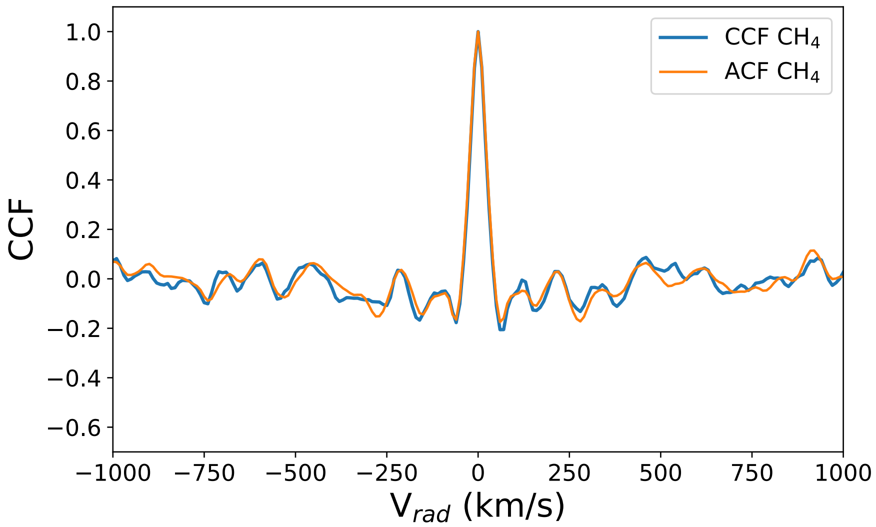
$$F_{CH_4}^{obs\,residual} = F^{obs} - F_{no\,CH_4}^{model}$$

$$F_{CH_4}^{model\,residual} = F^{model} - F_{no\,CH_4}^{model}$$

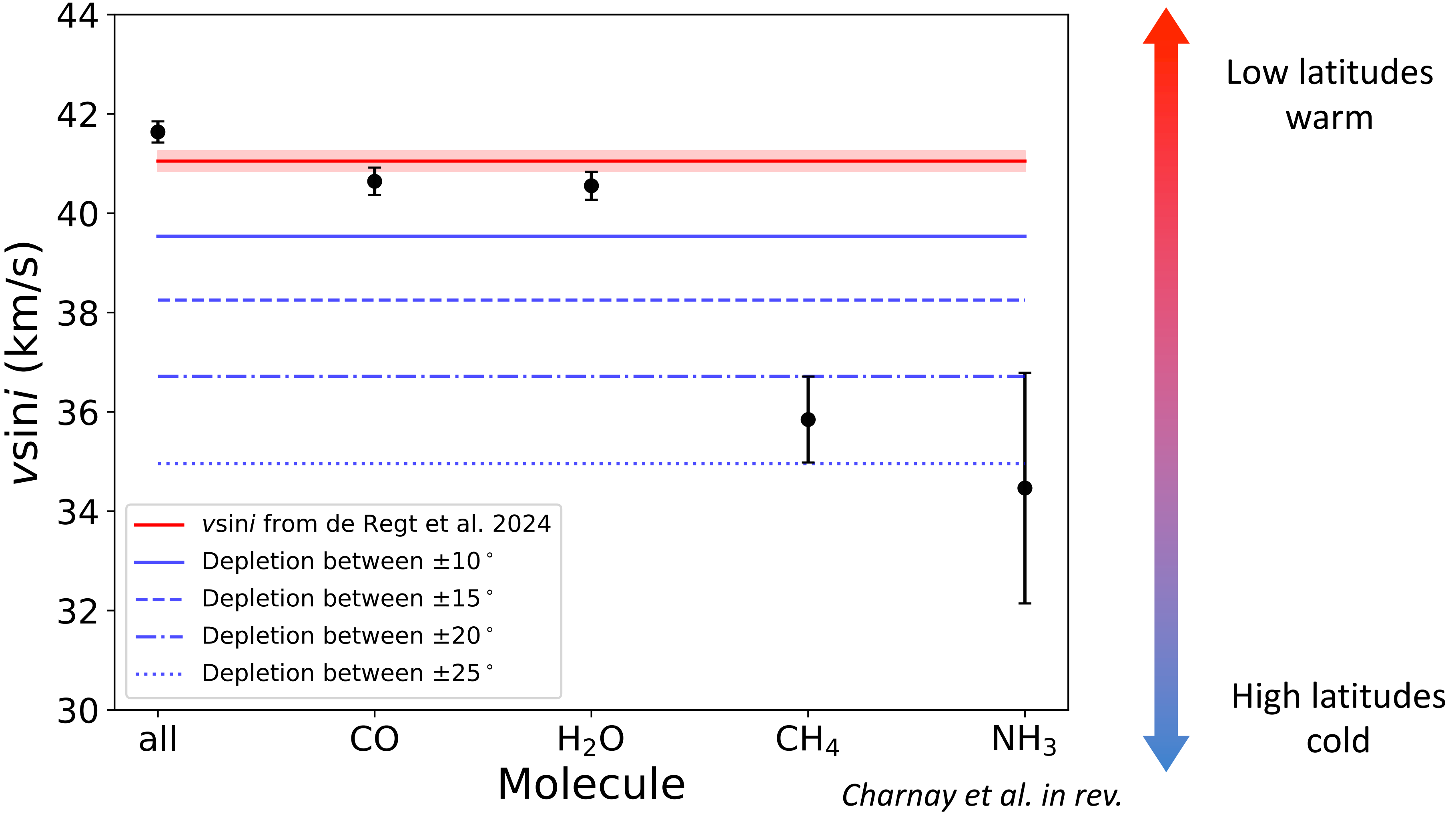
Observations with CRIRES+ of DENIS J0255-4700:







Differential Molecular Rotational Broadening (DMRB) for DENIS J0255-4700

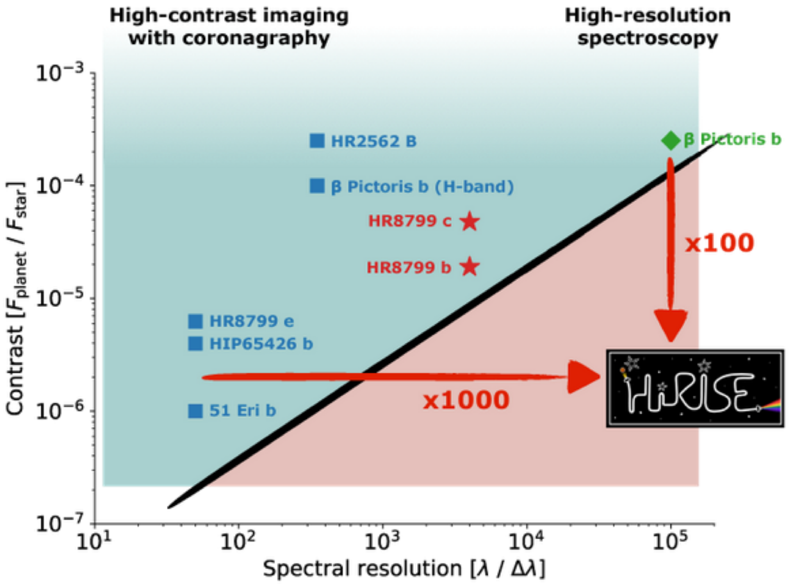


Charnay et al. in rev.

Low vsini for CH_4 and NH_3 compatible with an equatorial cloud belt

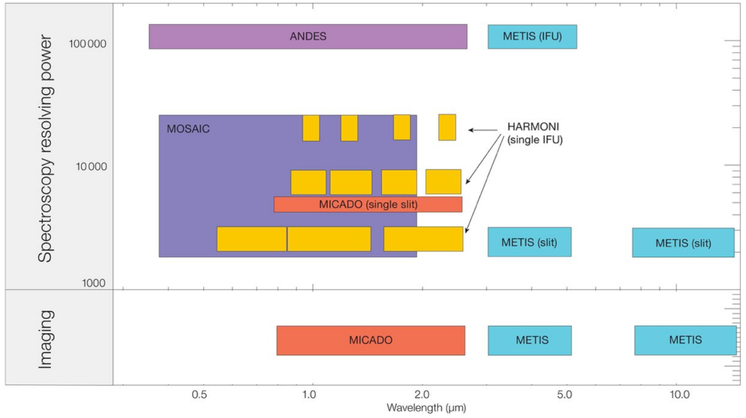
Perspectives with current instruments

- Accepted proposals for CRIRES+ (PI: S. de Regt) and SPIRou (PI: M. Ravet) on the T dwarf SIMP J013656 and on DENIS J2055-4700
- Application to HiRISE data of young giant exoplanets

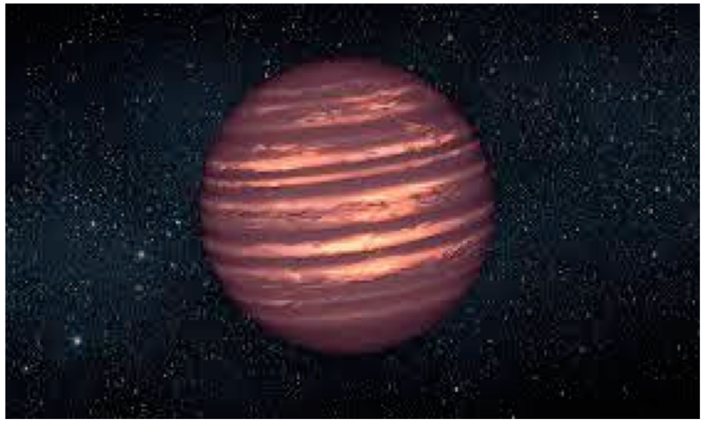


Perspectives with the ELT

- Most instruments can do medium/high resolution spectroscopy for exoplanets (i.e. ANDES, METIS, HARMONI, MICADO)
- PCS (Planetary Science Camera) currently in design phase



Take-home messages

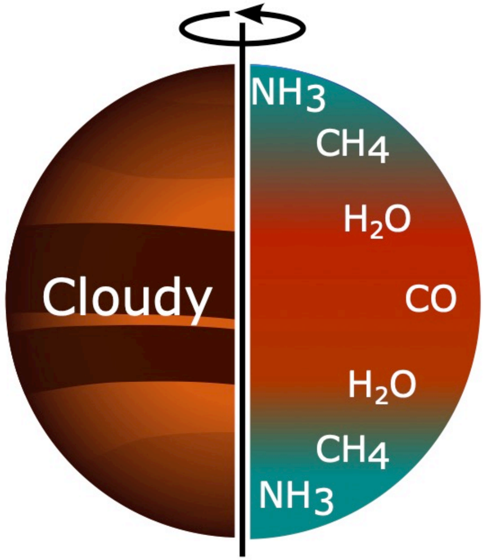


3D simulations of BDs:

- Maximum of cloudiness and temperature at the equator
- Prediction of latitudinal chemical variations
- These variations should be detectable by HR spectroscopy

Differential molecular rotational broadening:

- New technique to probe latitudinal variations
- First detection of latitudinal chemical variations on a brown dwarf
- Spectroscopic evidence for an equatorial cloud belt



Perspectives:

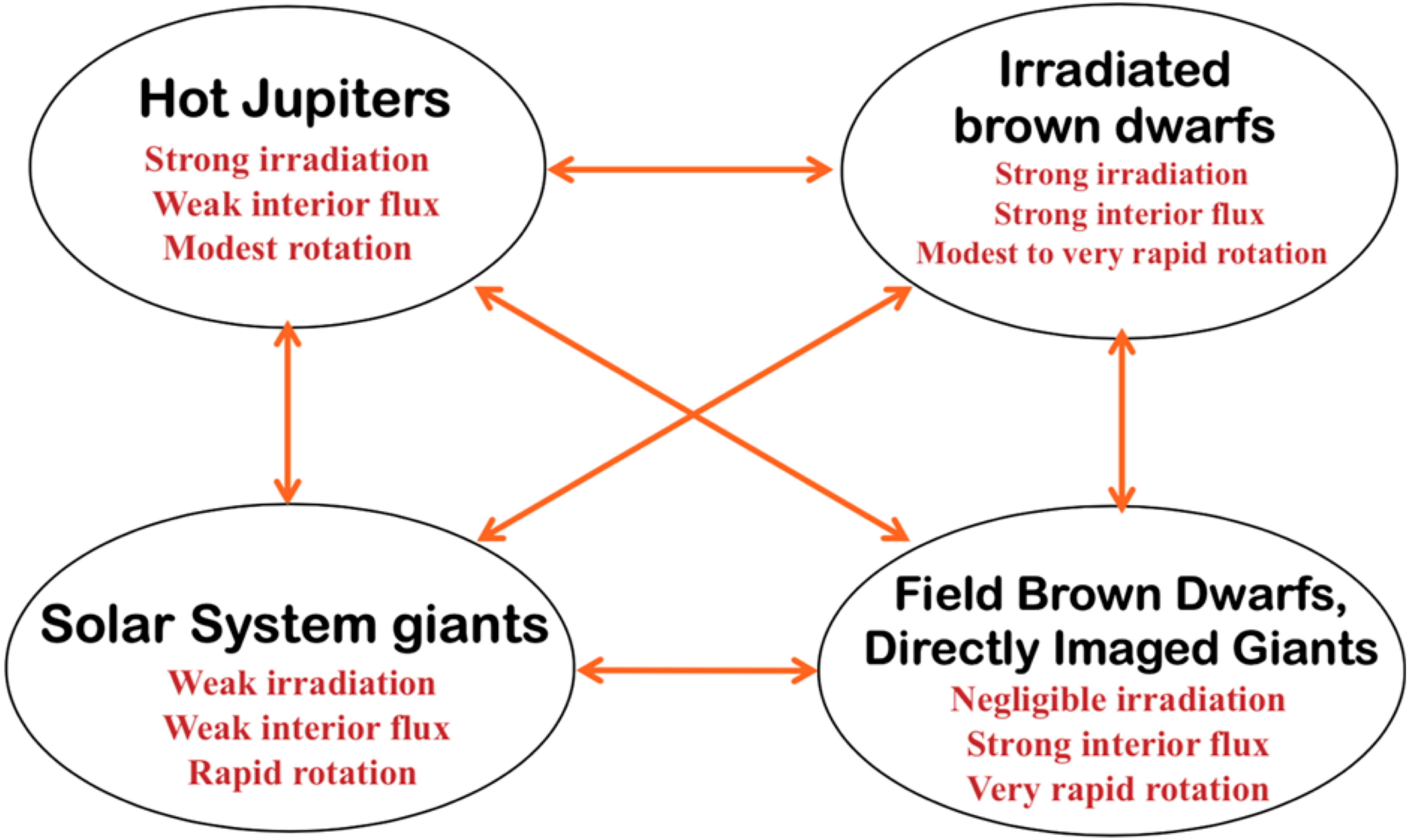
- High potential for latitudinal mapping of BD and exoplanets with current and future observatories (ELT)

⇒ Need the development of a 2D retrieval code

Teinturier, Charnay, Spiga & Bézard: « Clouds as the driver of variability and colour changes in brown dwarf atmospheres », *Nat. Astro., 2026*

Charnay, de Regt, Ravet, Teinturier, et al.: « Latitudinal chemical and cloud variations in the atmosphere of a brown dwarf », *in revision*

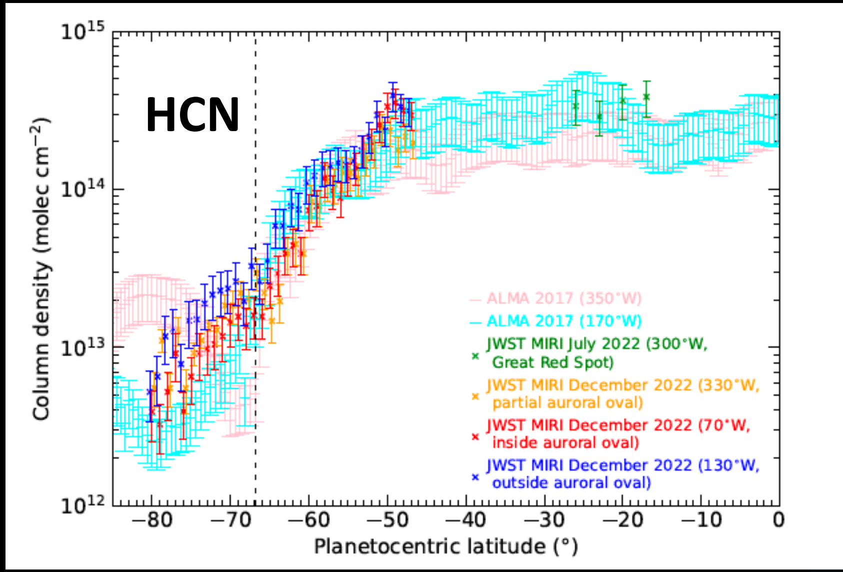
Brown dwarfs and directly imaged giants as a laboratory for atmospheric dynamics



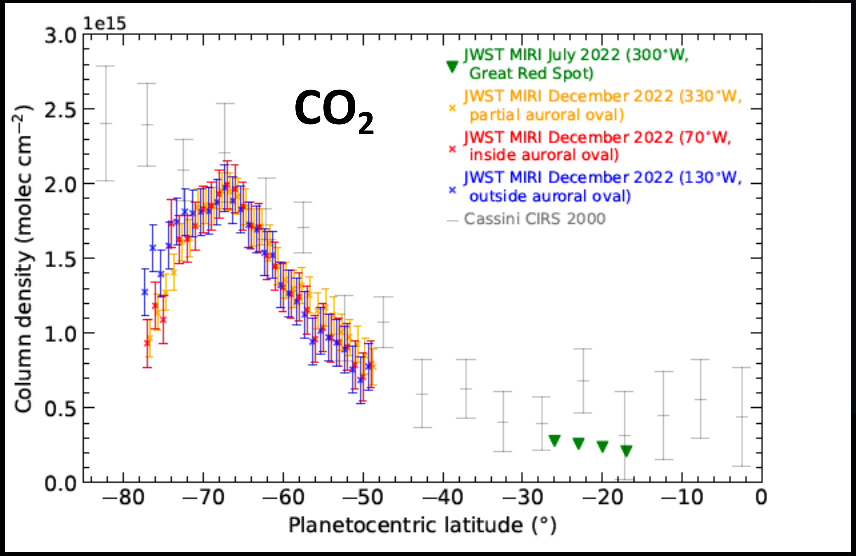
This opens the possibility of synergy between subfields

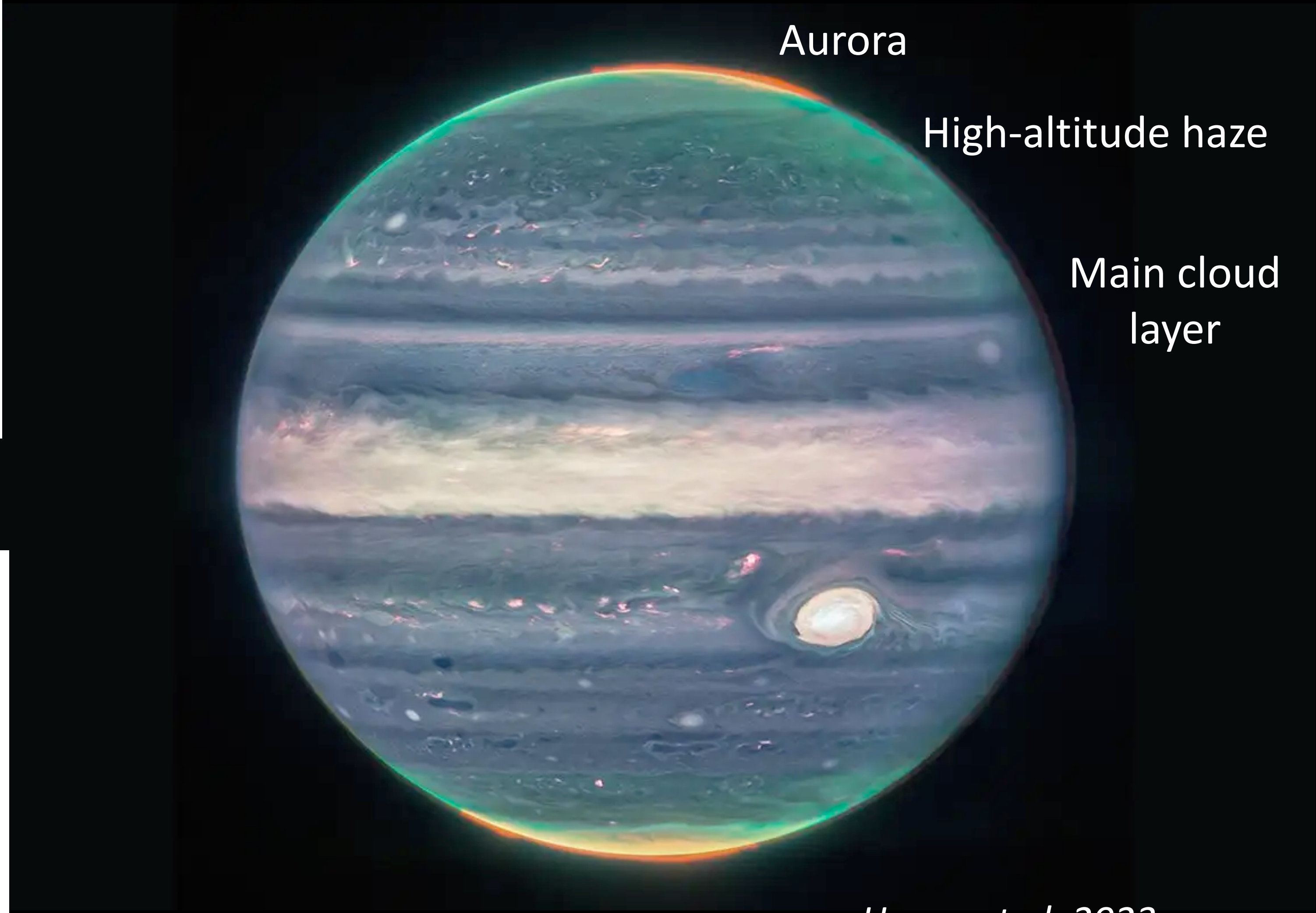
Showman et al. 2020

JWST



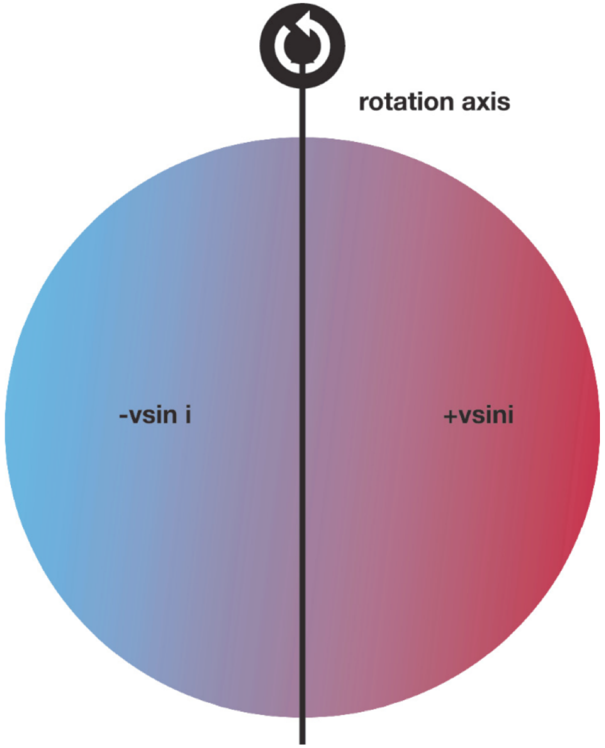
Rodriguez-Ovalle et al. 2025





Hueso et al. 2023

Calculation of rotational broadening



Formula by David Gray 1976 for a homogeneous star with limb darkening:

$$F_v^{broad} = F_v^{nobroad}(\lambda) * G(\lambda)$$

$$G(\lambda) = c_1\left[1-\left(\frac{\Delta\lambda}{\Delta\lambda_L}\right)^2\right]^{1/2} + c_2\left[1-\left(\frac{\Delta\lambda}{\Delta\lambda_L}\right)^2\right]$$

$$\Delta\lambda_L = \frac{\lambda}{c} v\sin(i)$$

Case for emission from high latitudes (above latitude +/- α) :

$$F_v^{broad} = F_v^{nobroad}(\lambda) * G'(\lambda)$$

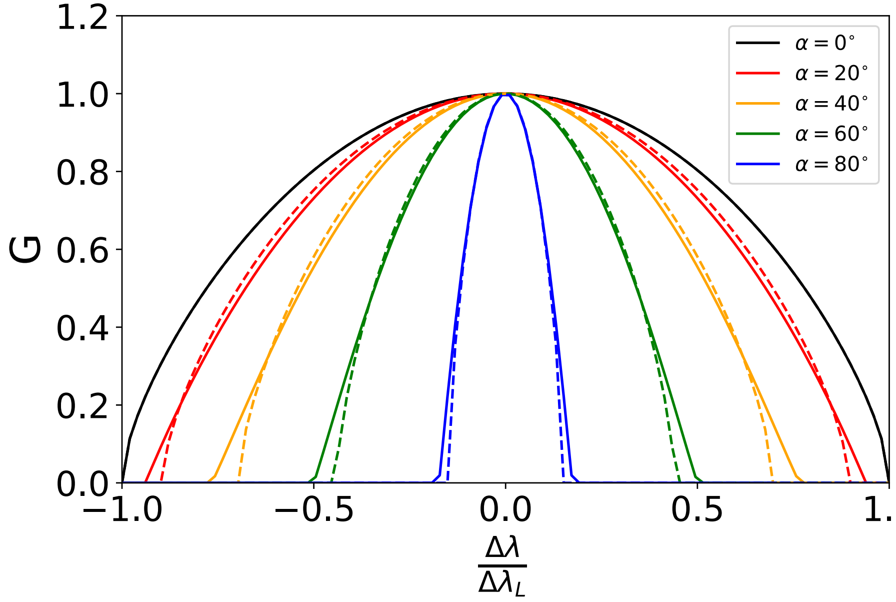
$$G'(\lambda) \sim G(\lambda, \Delta\lambda_L{}')$$

$$\Delta\lambda_L{}' = \Delta\lambda_L\left(1-\sin(\alpha)^{3/2}\right)^{1/2}$$

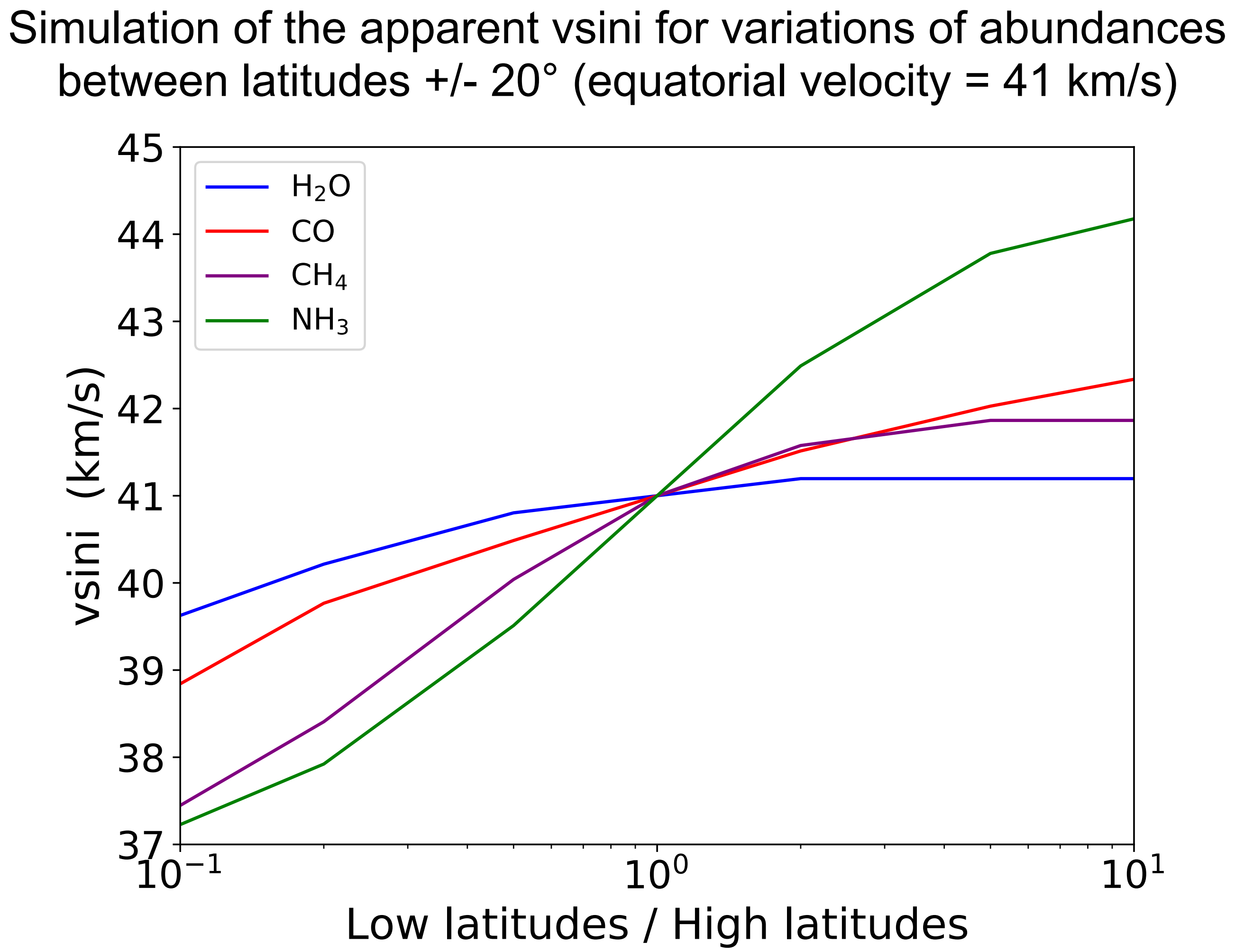
For α=15°: $v\sin(i)' = 0.93\ v\sin(i)$

Detection at 3σ: SNR~30

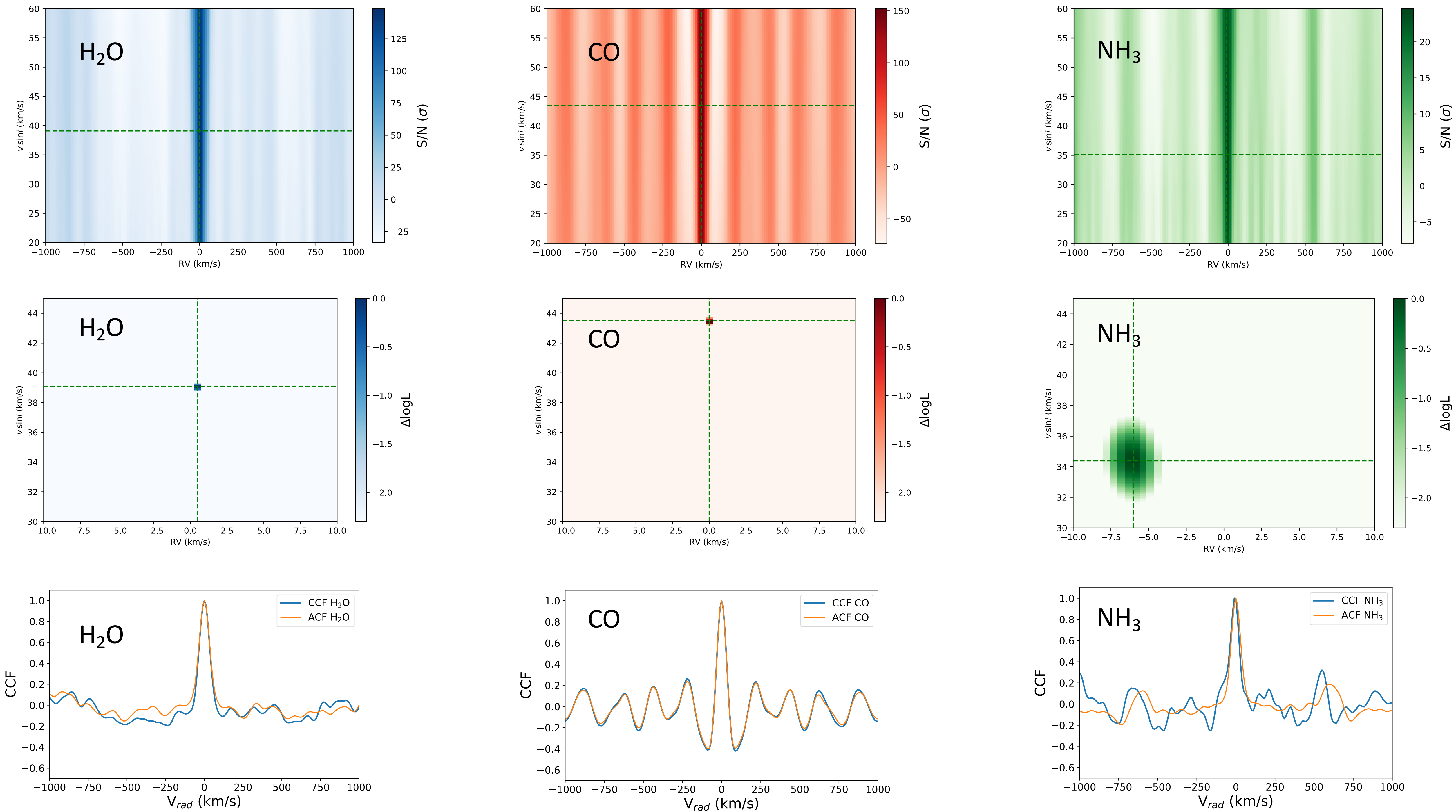
Comparison between $G'(\lambda, \Delta\lambda)$ and $G(\lambda, \Delta\lambda_L{}')$



Prediction on the change of *v*sin*i* for latitudinal chemical variations



An equatorial depletion of CH_4 by factor 5 should reduce its *v*sin*i* by ~3 km/s



H2O
CO
NH3
S/N (σ)
v sini (km/s)
RV (km/s)
ΔlogL
CCF H2O
ACF H2O
CCF CO
ACF CO
CCF NH3
ACF NH3
CCF
V_rad (km/s)