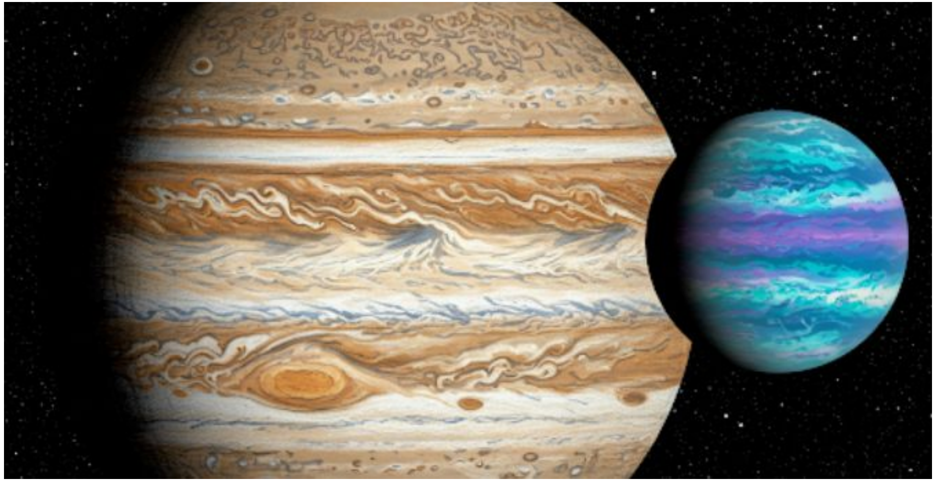
A comprehensive picture about Jovian clouds and hazes from Juno/JIRAM infrared spectral data, and applications to exoplanets



F. Biagiotti, D. Grassi, A. Mura, T. Guillot, L. N. Fletcher, S. K. Atreya, G. Piccioni, P. Rannou, G. Liuzzi, G. Villanueva, and the Juno/JIRAM and JWST/ERS teams

Outline of the talk

1) Introduction and rationale
2) What do we know about Jovian clouds ? Results from literature
3) Analyzing JIRAM data
4) Analyzing NIRSpec data
5) Wrap up results
6) Application to exoplanets

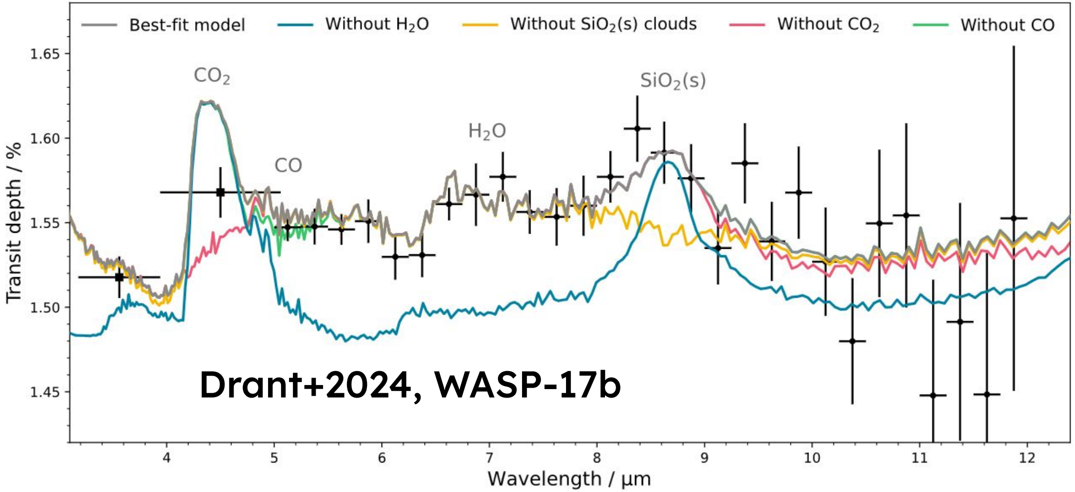
Introduction and rationale

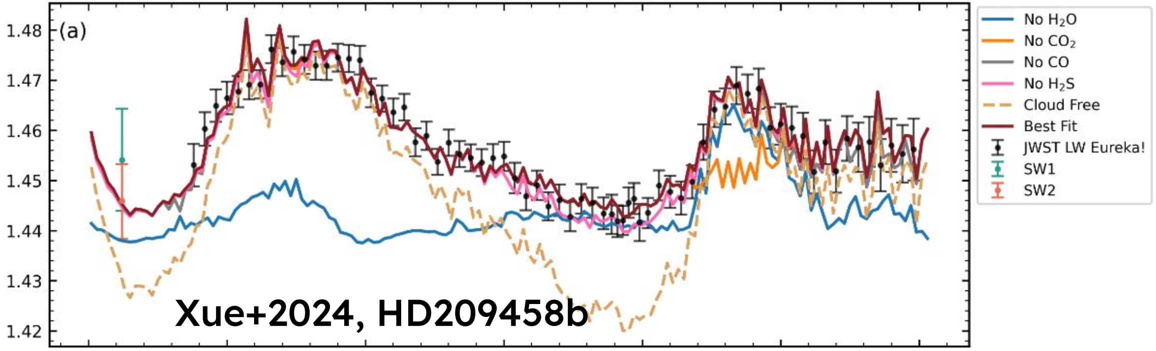
Introduction and rationale

Thanks to JWST we know that clouds seem to be frequent also in exoplanetary atmospheres.

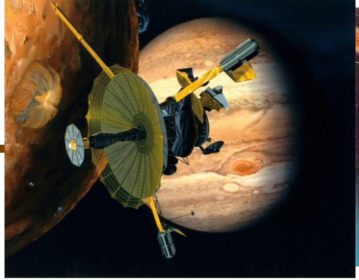
Jupiter is the cloudiest gas giant planet in our solar system.

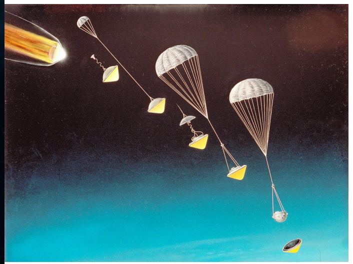
Is it possible to extend the “Jovian” methods and results to exoplanets ?





Jupiter: the Rosetta Stone



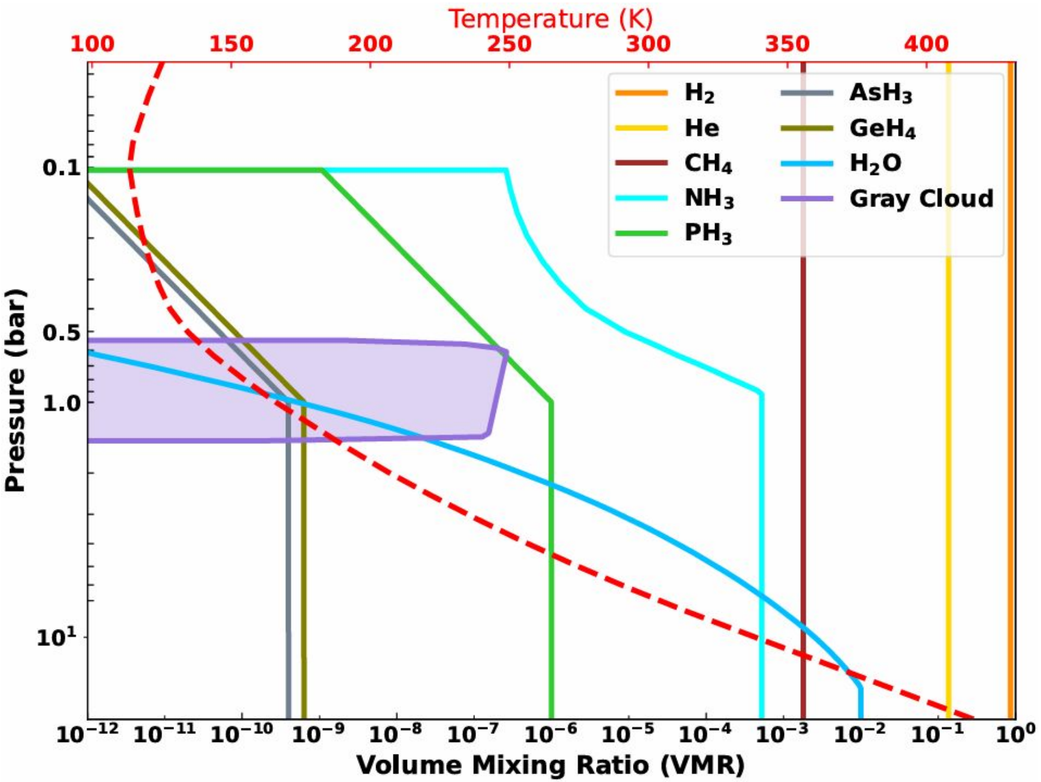


Jupiter has been visited by two orbiter missions since 1980s

Thanks mostly to the Galileo entry probe we know with high precision:

- the pT profile
- the H_2, He, CH_4 profiles
- the structure of the atmosphere and its dynamics

the presence of minor species was inferred mostly from spectroscopy



Jupiter: how do we study clouds

Sadly, the Galileo probe entered a very dry and cloud-free region, called ‘hotspot’. The only direct measurements of clouds cannot be extended to other regions (and to the whole disk).

Therefore we rely mainly on theoretical models and atmospheric retrievals to infer cloud properties.

This is similar to what is done for exoplanets

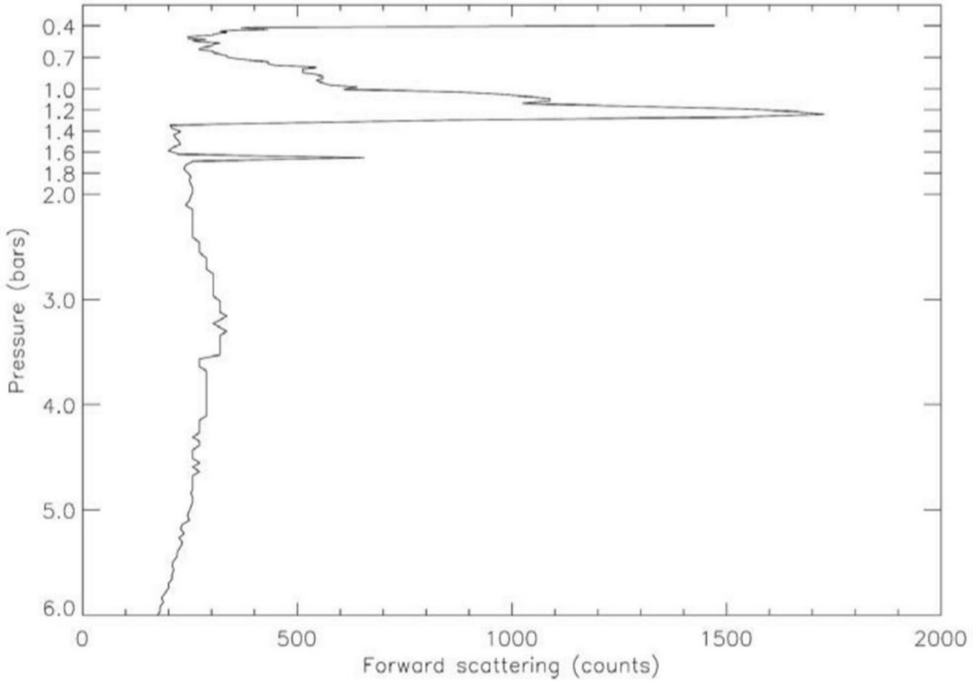
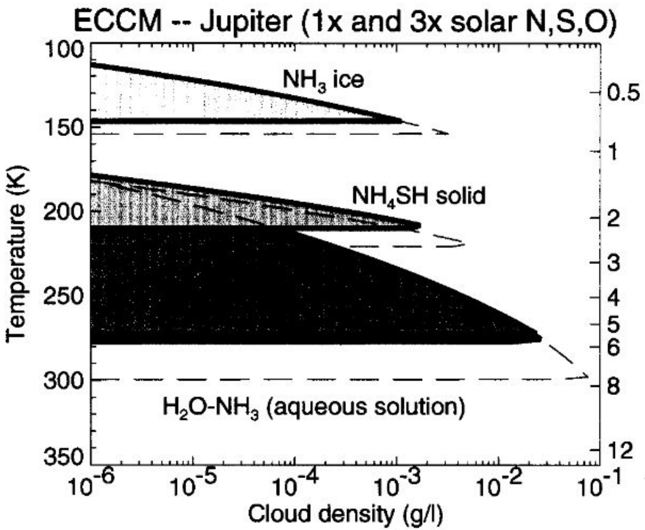


Figure 4.9. Relative cloud profile of Jupiter deduced from the *Galileo* probe nephelometer experiment cloud results. From Ragent *et al.* (1998).

Theoretical cloud formation models

Equilibrium Chemistry Condensation Models: gas vaporization + condensation

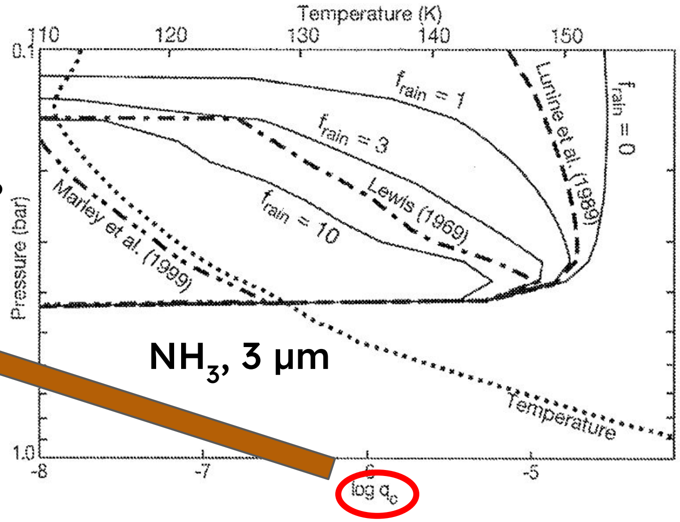


Atreya+1999

A&M2001: It considers the balance between turbulent diffusion (upward movement) and sedimentation (downward settling) of cloud particles.

qc=VMR=10^{-5} / 10^{-6}

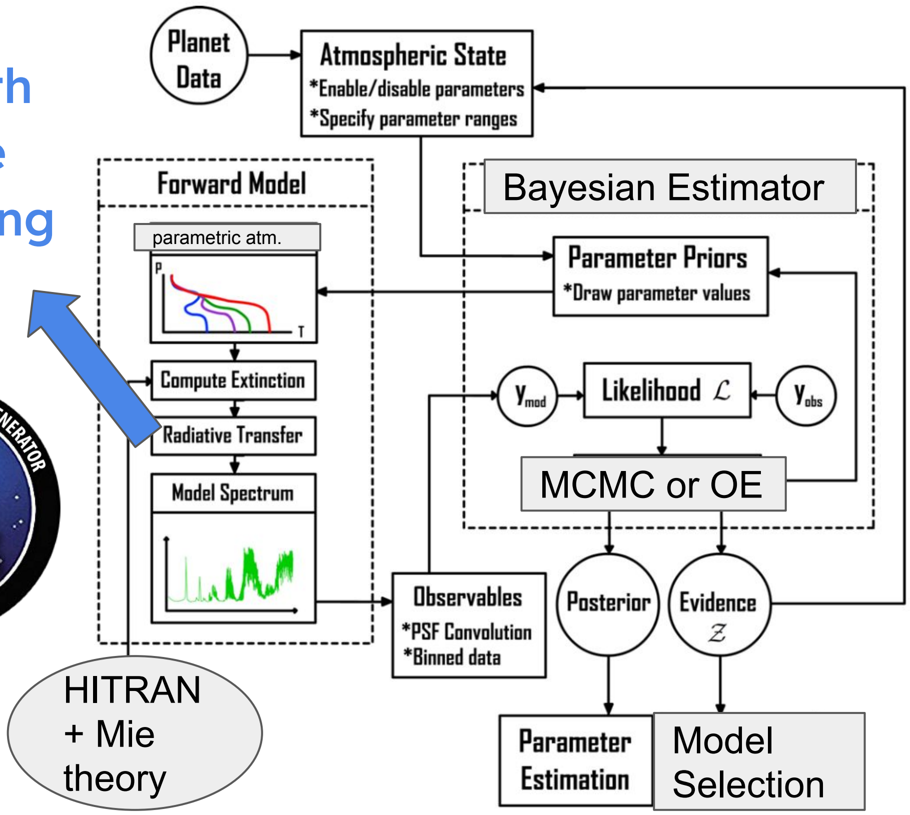
⇒ 10^{-3} / $5*10^{-4}$ g/l



Marley+1999

Multiple scattering atmospheric retrievals

It must deal with multiple scattering !!!

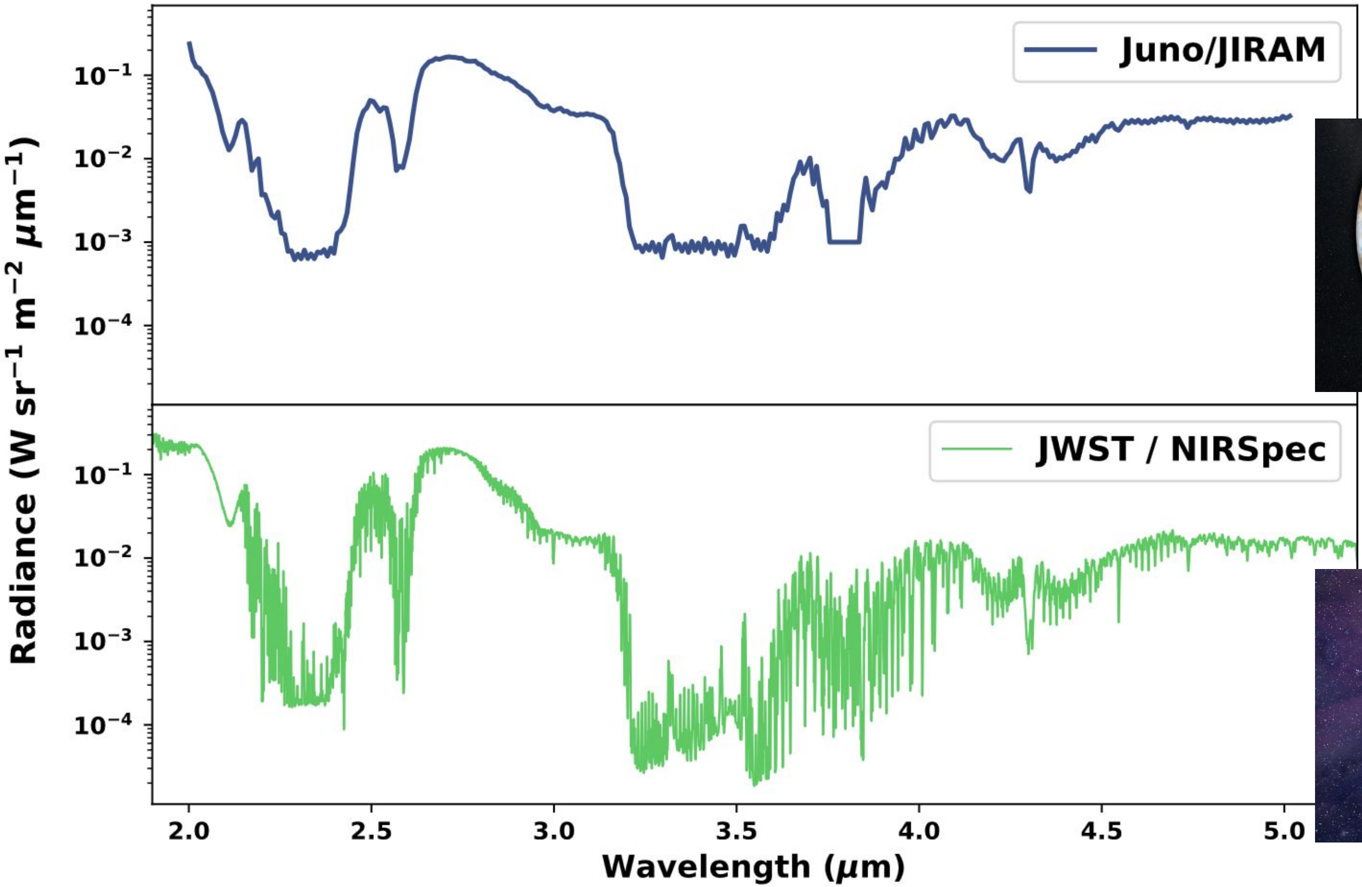


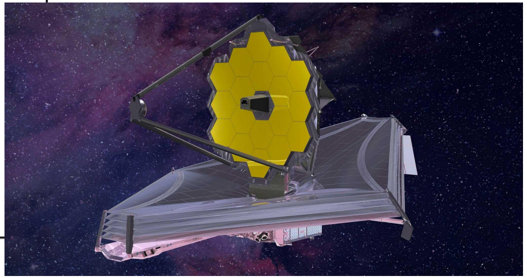
In the ideal case the retrieval should be well constrained

In the real one they are degenerate = different cloud profiles can held the same results

Moreover, clouds tend to flatten and reflect signals and rarely show absorption features

Juno/JIRAM and JWST/NIRSpec

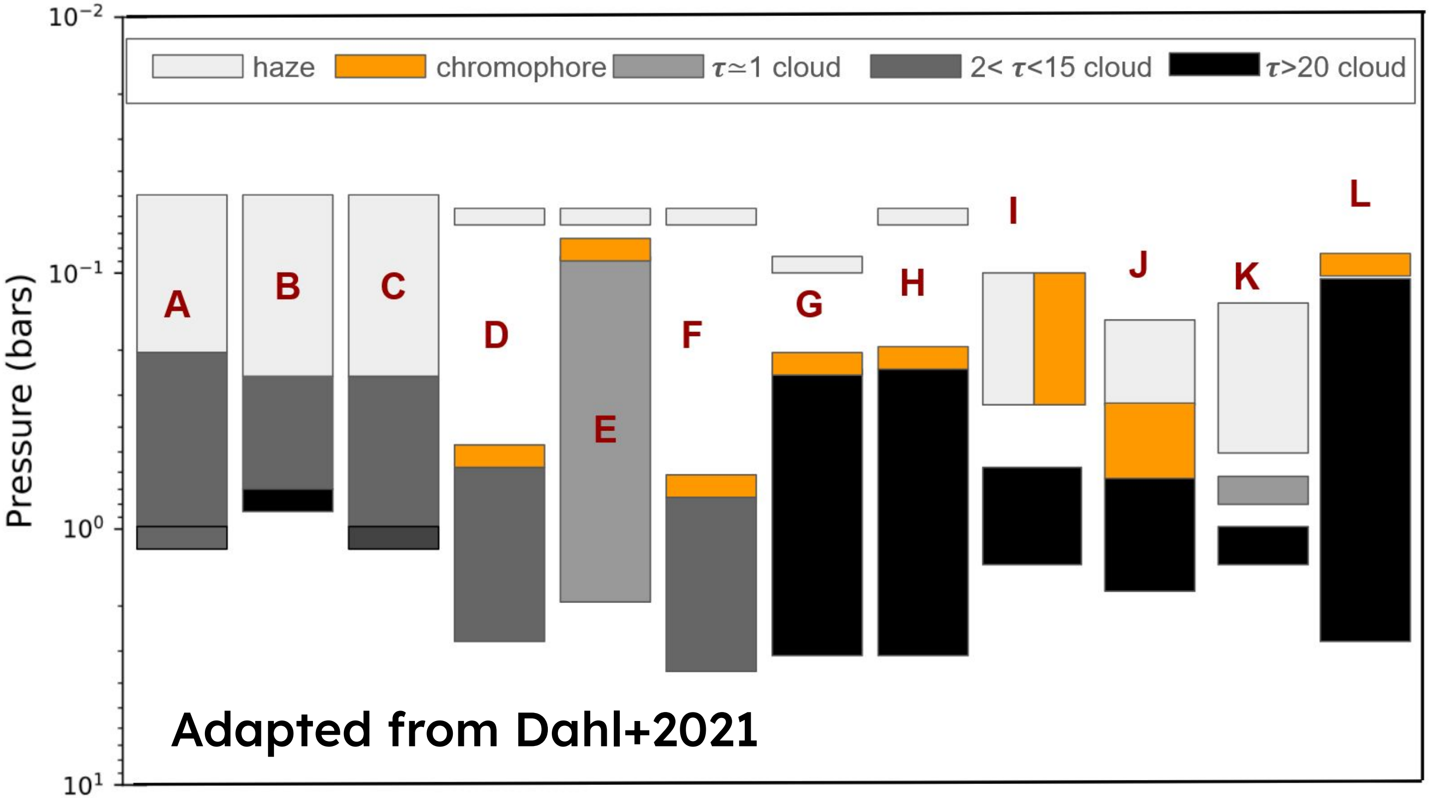




What do we know about Jovian clouds ?
Results from literature

Results from literature: aerosol structures

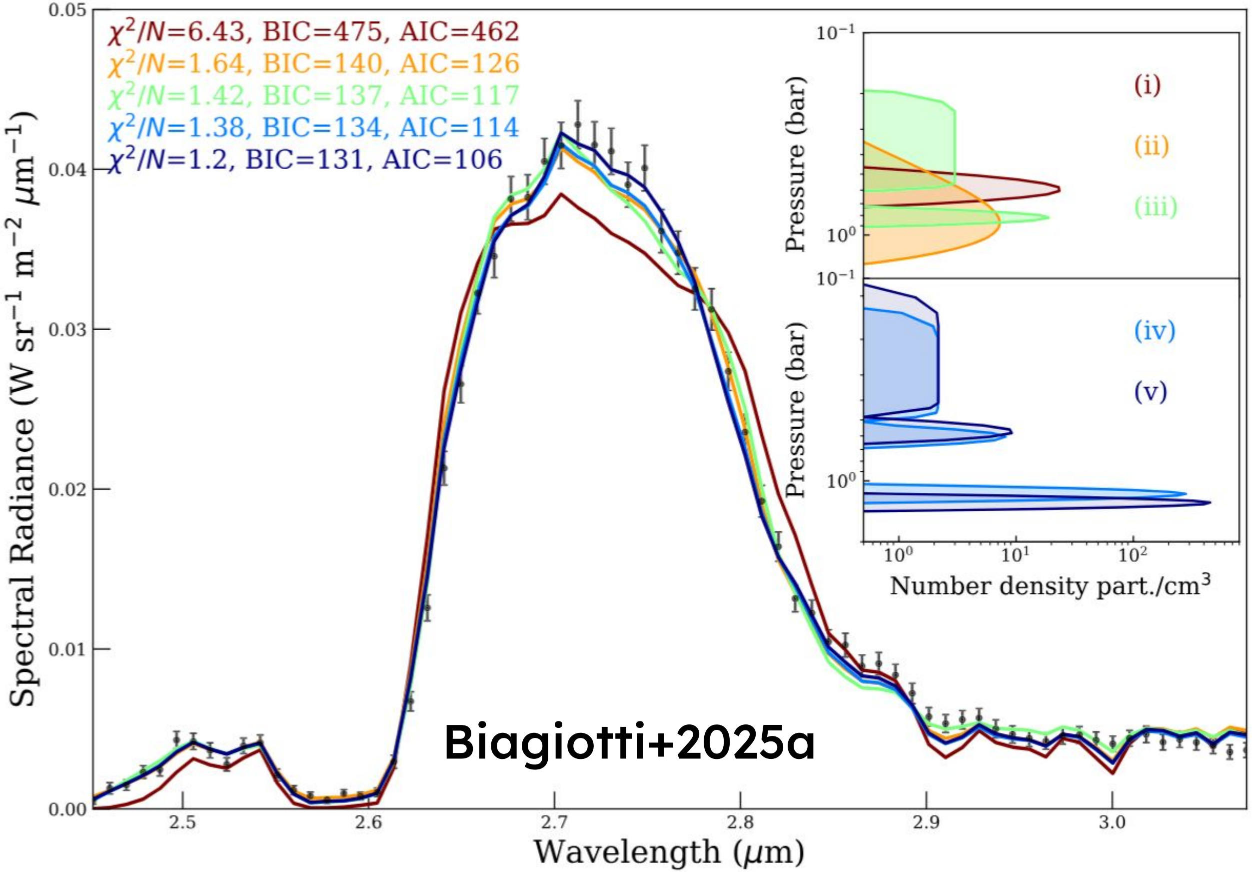
Atmospheric retrieval both in the visible and in the NIR showed that a mass of small haze particles is needed in the upper troposphere to obtain good fits



Results from literature: beware of degeneracy

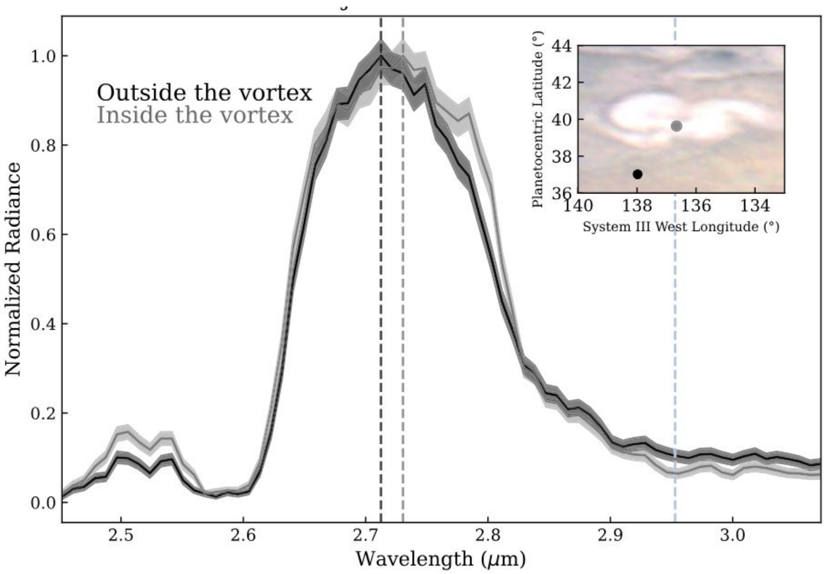
You noticed a variety of cloud profiles and parameterizations in the previous slide. This is due to the degeneracy of the inverse problem.

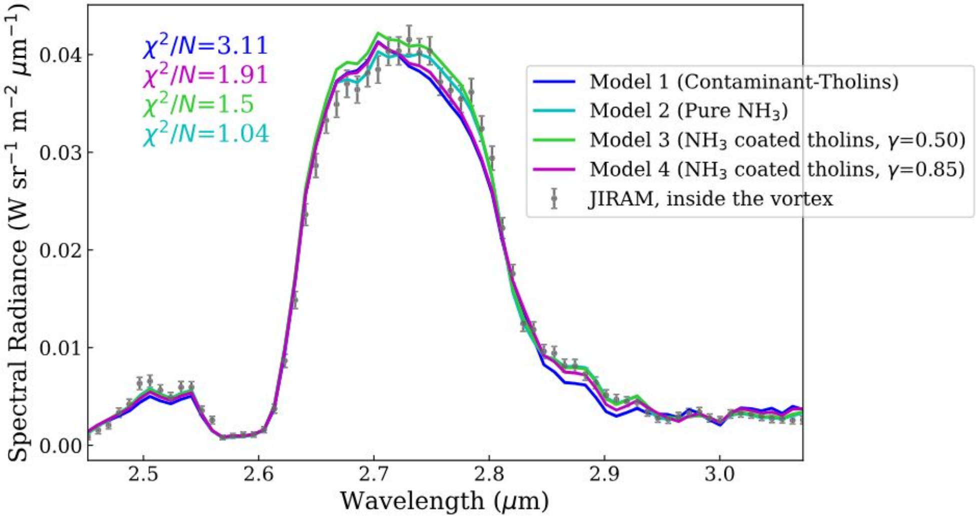
Physics can guide us.



Biagiotti+2025a

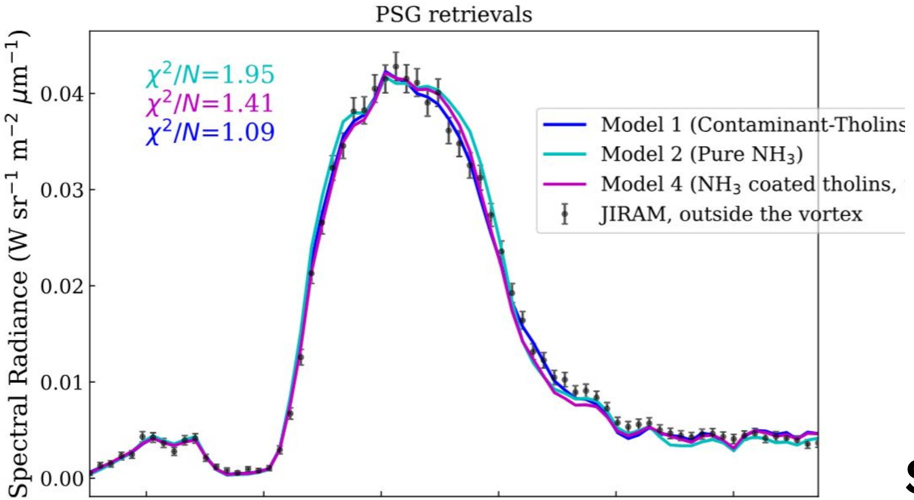
Results from literature: the problem with pure NH_3

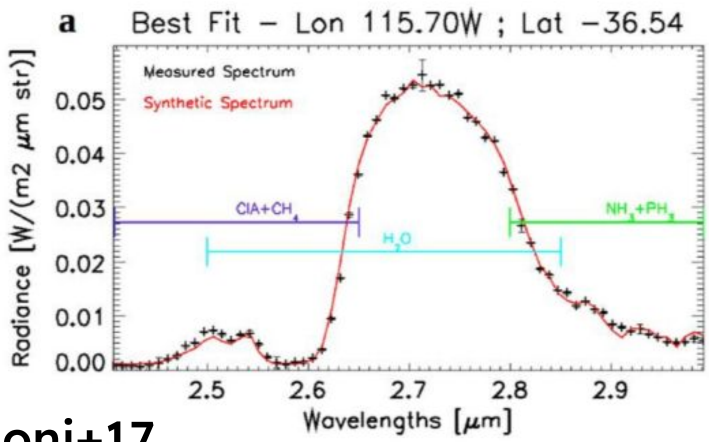




Pure ammonia ice clouds provide good fits only of specific regions characterized by strong convective events (Baines+2002; Biagiotti+2025a)

Results from literature: the problem with pure NH_3



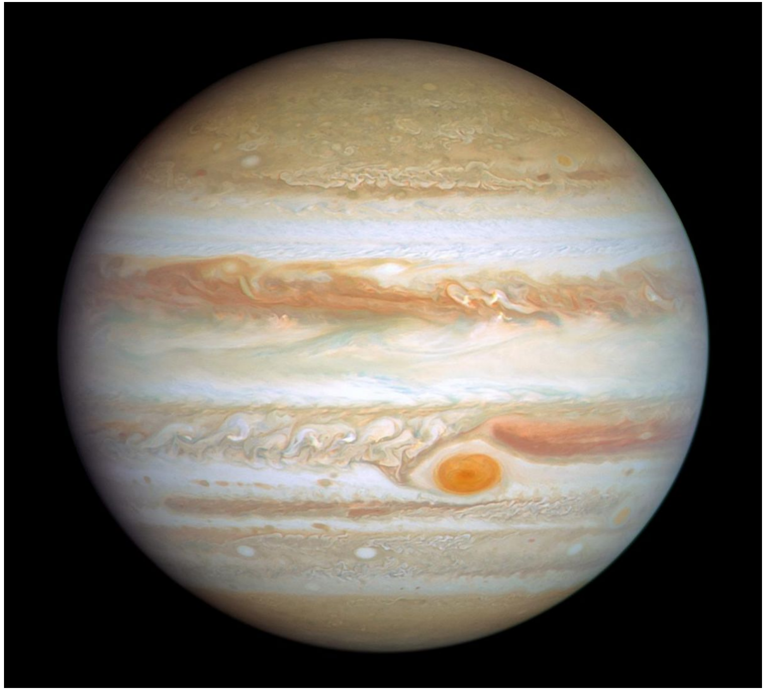


Sindoni+17

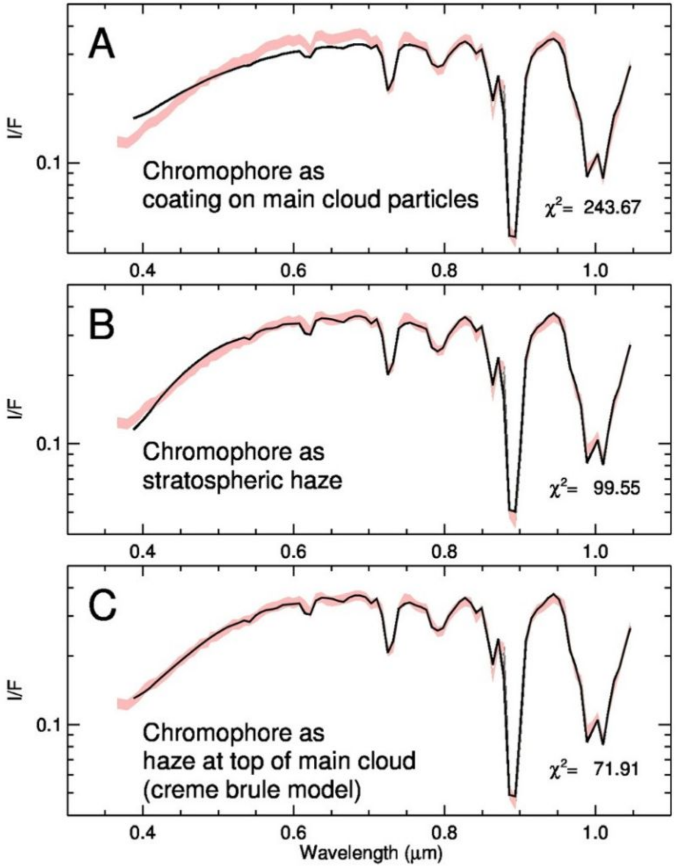
JIRAM data for instance can be well fitted when tholins measured by Imanaka+2012 are invoked. These tholins are produced considering 90 % of N2 and 10 % of CH4. On Jupiter the ratios are way more different. However, these tholins can be considered as a proxy for the real material composing Jovian clouds.

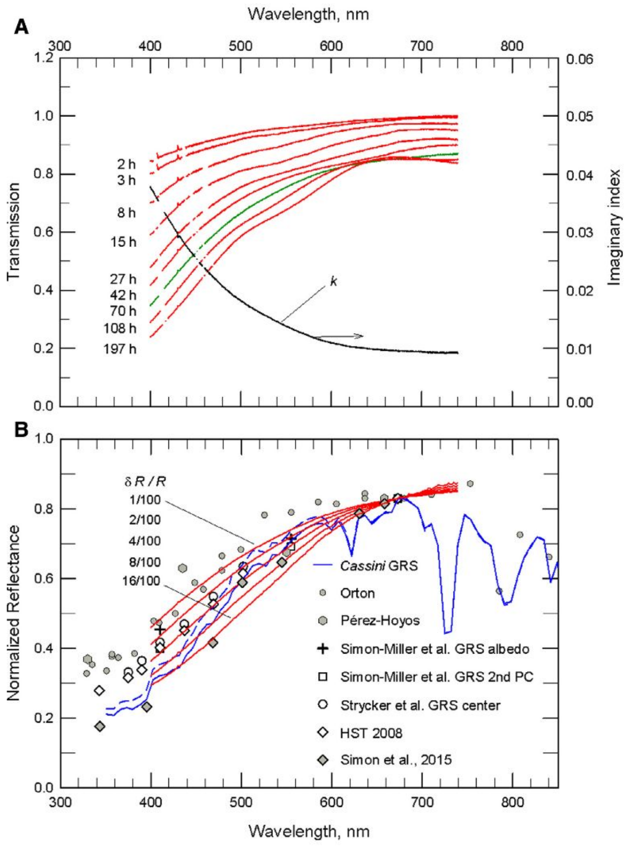
Results from literature: the problem with pure NH_3

NH_3 should form white clouds in the visible while we know Jupiter to be more colorful ! This is encouraging, but it also tells us that we have to refine our models and methods



Results from literature: chromophores !





Excellent fits of the visible spectra are obtained using materials resulting from chemical reactions between photolyzed NH_3 and C_2H_2

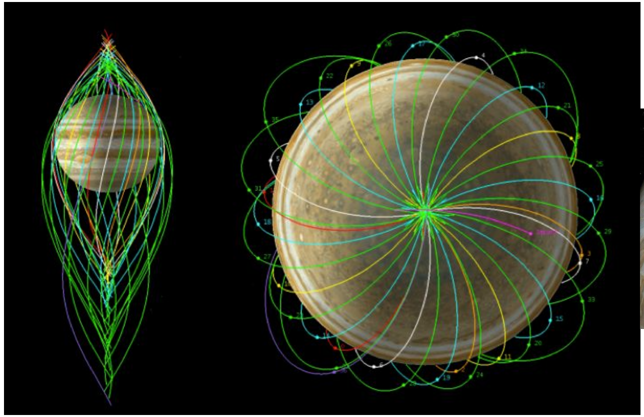
(Carlson+16, Baines+19)

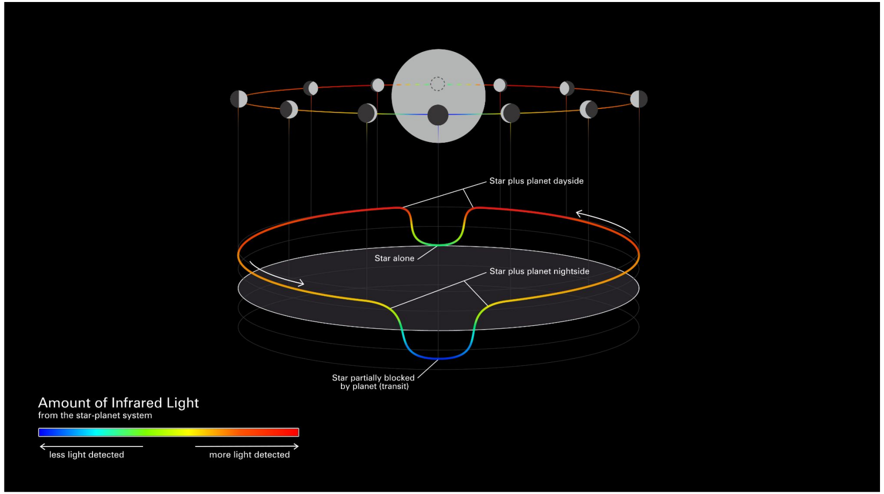
Results from literature: the problem with densities

Due to the degeneracy of the problem **it is not trivial to obtain information about cloud densities.** Usually people working in the field use a parameter that changes drastically the shape of the simulated spectra, the so-called **optical depth**. The OD is a degenerate function of the wavelength, radius, density, vertical extension, and composition of the clouds. Most of works in the literature only give the optical depth as a result, and use arbitrary cloud vertical parametrization. Therefore a comparison with theoretical models is not trivial.

Analyzing JIRAM data

JIRAM: understand PJ1 data

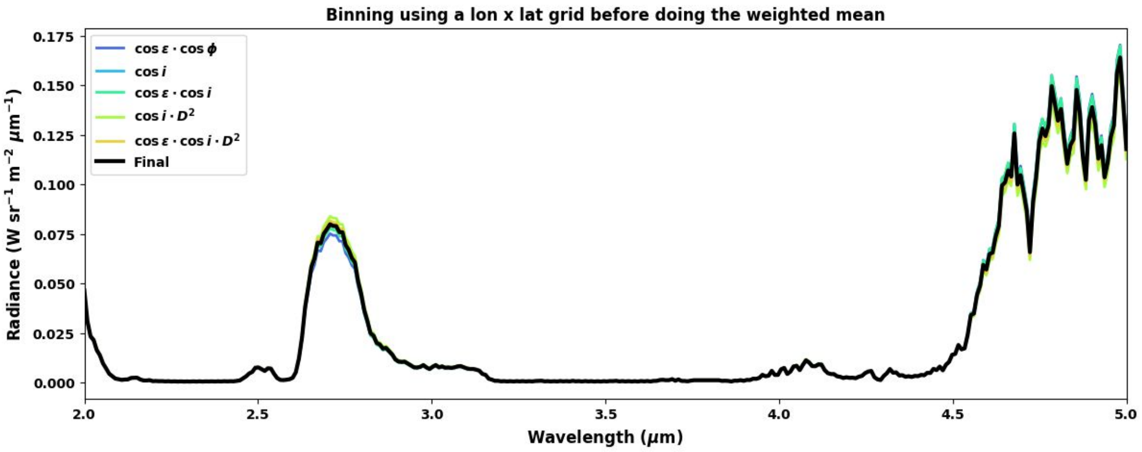


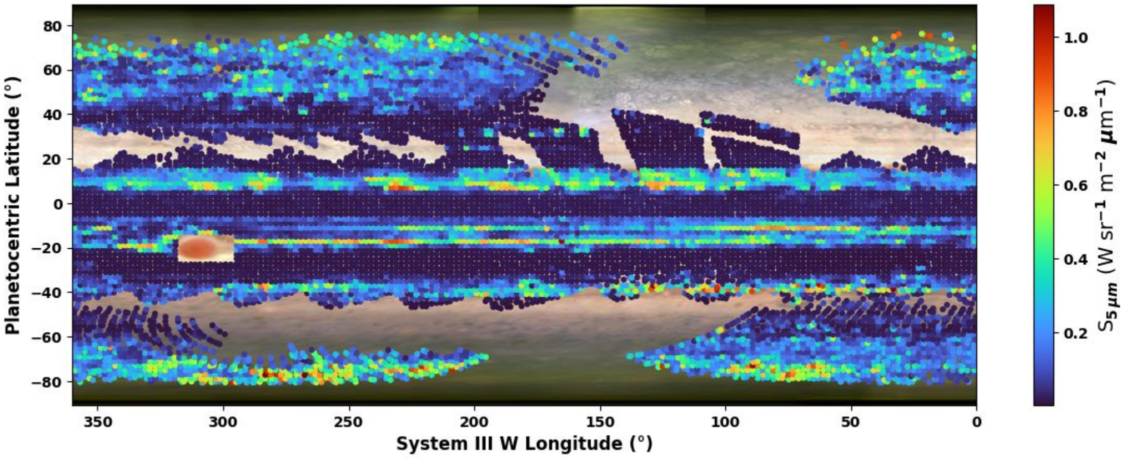


As a combination of the spinning acquisition of Juno and of its orbit, all the data during PJ1 (the best passage in terms of data quality) have been acquired at a phase angle of 90°

In direct imaging the best orbital phase to observe exoplanets is the maximum elongation point, orbital phase = 90°. If the orbital inclination is close to 90° it corresponds also to a phase angle of 90°.

JIRAM: whole disk

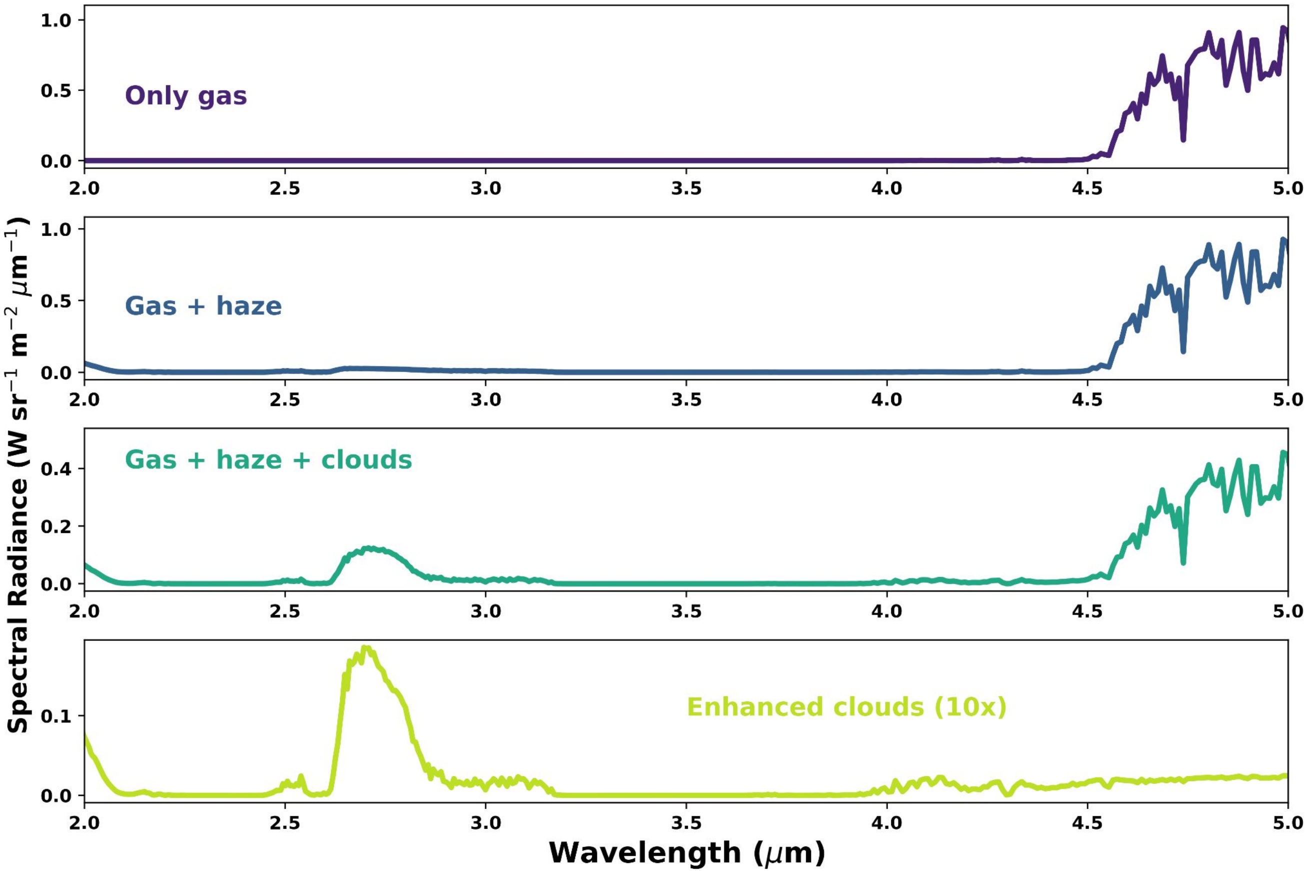




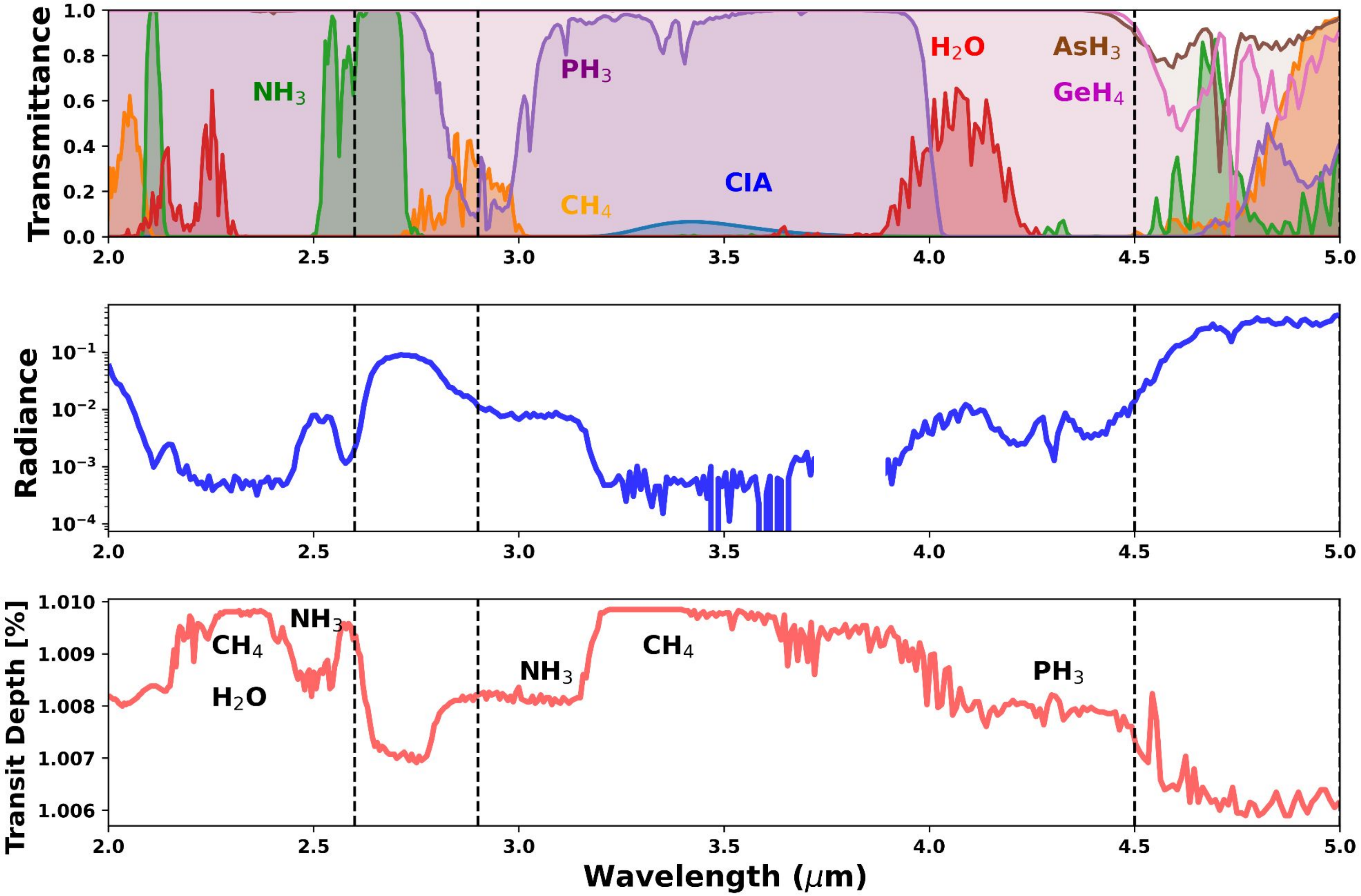
We used JIRAM PJ1 data (-90°:90° lat, 0°:360° lon) to obtain a full disk mean spectrum of Jupiter choosing:

- to remove NaNs and spikes
- to mask the GRS
- to perform a lon x lat binning of 2° to avoid spectral overdensity
- to perform a weighted mean using different weights

JIRAM: how clouds affect the spectrum

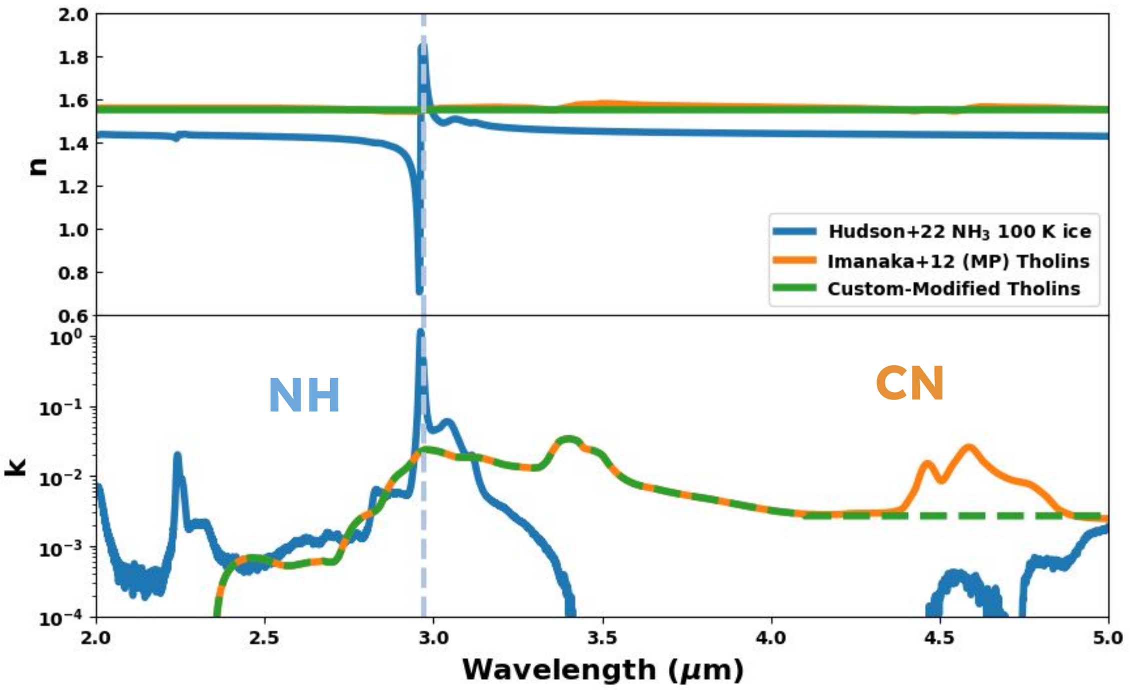


The aerosol on Jupiter do not present clear absorption features. Instead they tend to **reflect** the solar radiation (2-3 micron) and **block** the thermal emission from the interiors (>4 micron)



We can observe these effects because of wavelength windows of **high gaseous transmittance**

JIRAM: retrieval strategy



We then performed different retrievals using NASA PSG. We fixed pT, H_2, and CH_4 profiles. We changed only the composition of the condensation cloud. We used:

- pure ammonia ice
- tholins (N2:CH4 = 90:10) (Imanaka+2012)
- modified tholins that do not present the 4.7 micron absorption

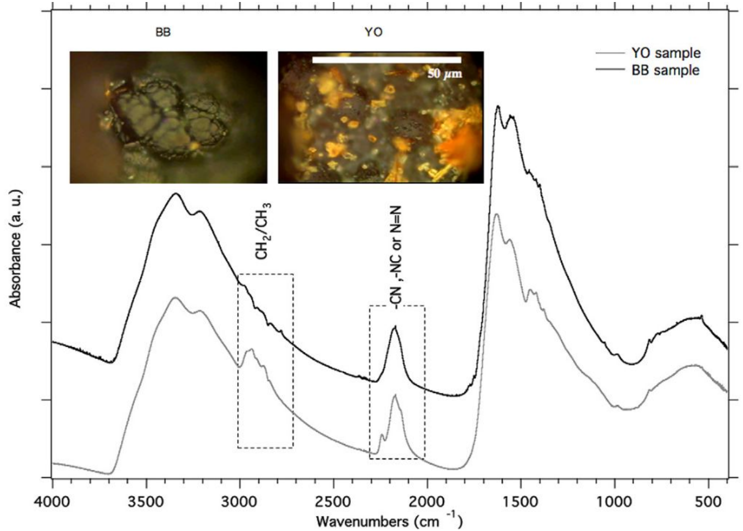
What are the modified tholins ?

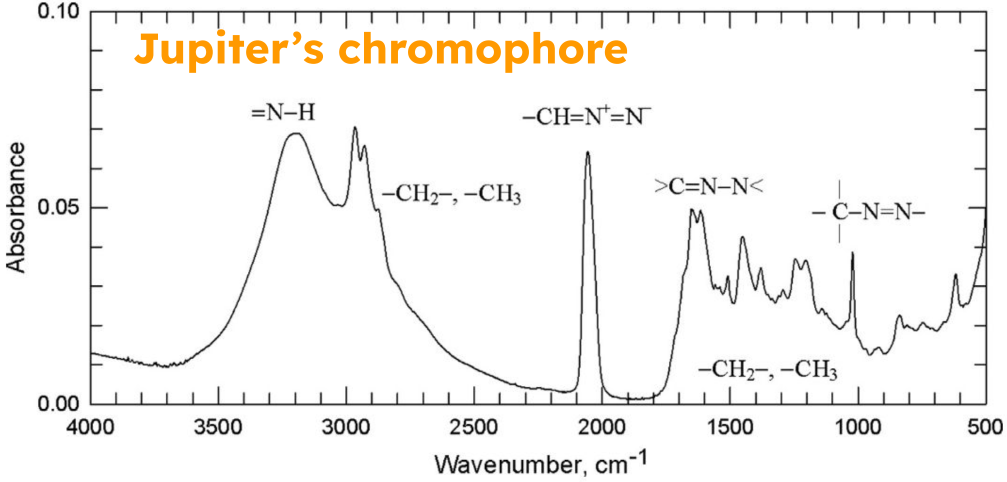
Jupiter and Titan have different composition. N is way more present on Titan, while it is bounded to ammonia on Jupiter.

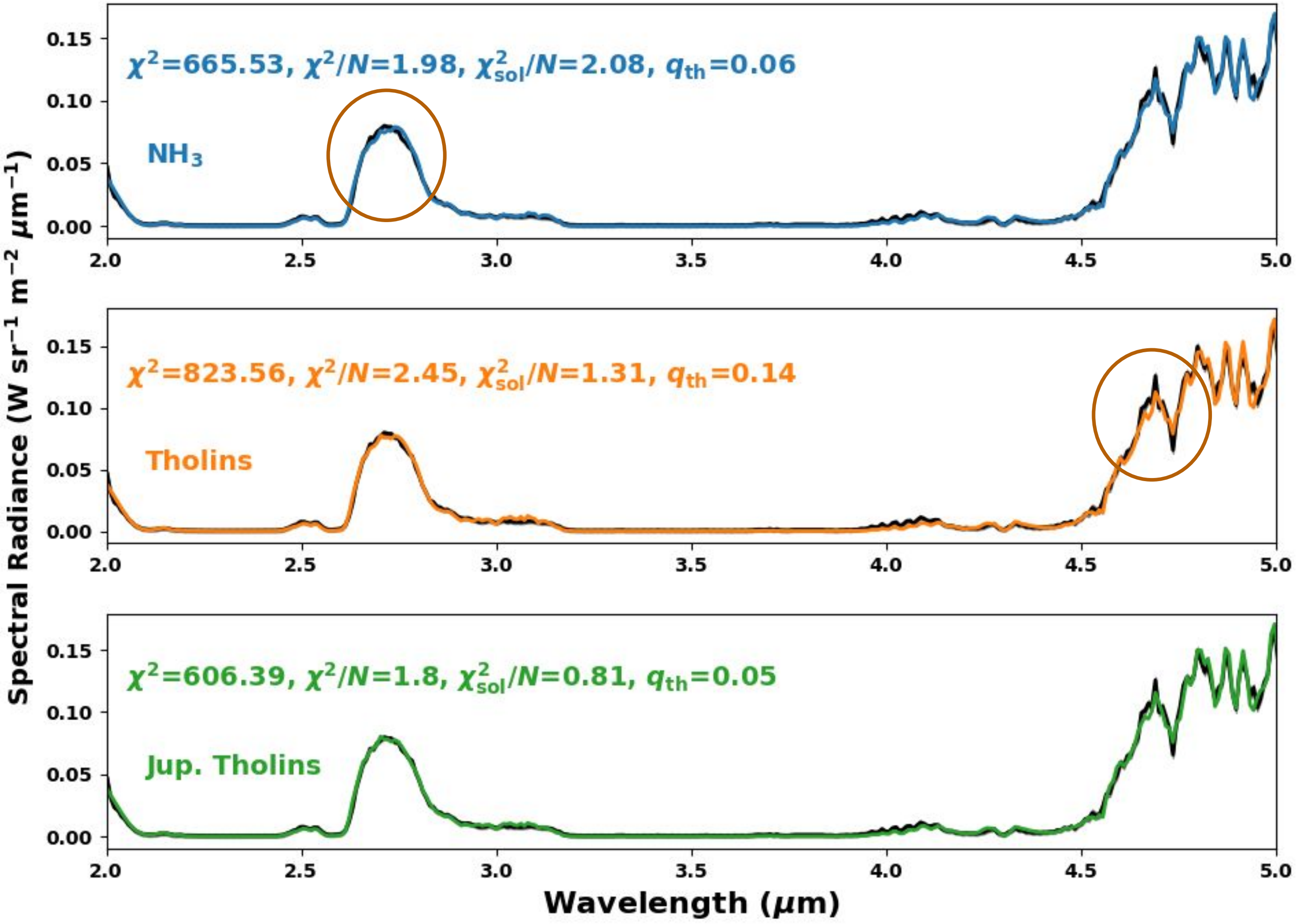
Therefore, as a rule of thumb, C-N bounds should be weaker, while CHN ones stronger. This is confirmed by Carlson+2016 measurements at >5 um.

Also the feature between 4.5 and 5 um should be weakened. **N.B. the 2100 cm-1 feature in Carlson+2016 is induced by the presence of N+**

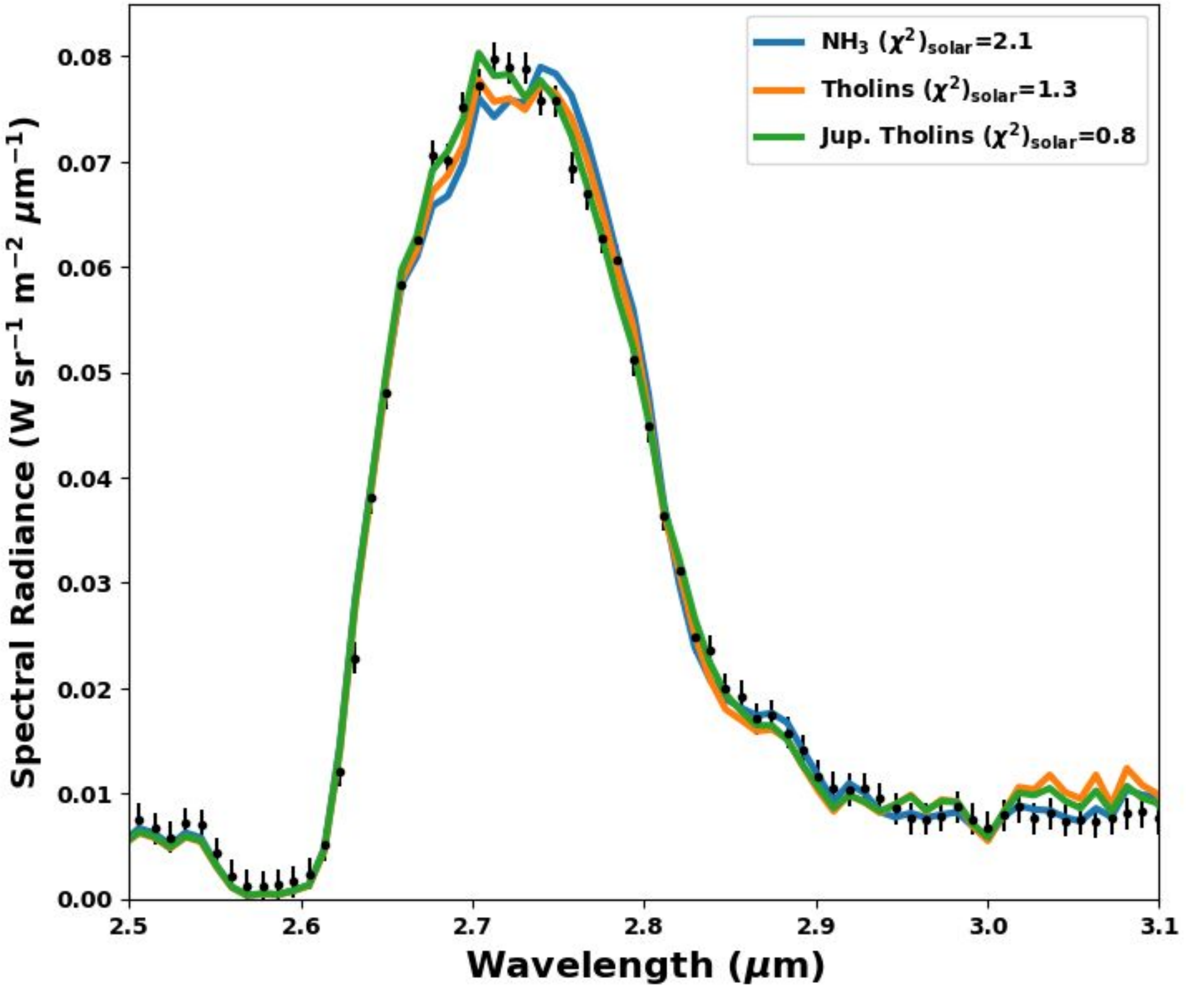
Titan's tholins







χ²=665.53, χ²/N=1.98, χ²sol/N=2.08, qth=0.06
NH3
χ²=823.56, χ²/N=2.45, χ²sol/N=1.31, qth=0.14
Tholins
χ²=606.39, χ²/N=1.8, χ²sol/N=0.81, qth=0.05
Jup. Tholins
Spectral Radiance (W sr⁻¹ m⁻² μm⁻¹)
Wavelength (μm)
0.00
0.05
0.10
0.15
2.0
2.5
3.0
3.5
4.0
4.5
5.0



As observed by Biagiotti+25a, pure ammonia ice particles induce a “redshift” in the solar reflection peak that is not consistent with observed radiances. This shift is only observable thanks to JIRAM excellent spectral resolution.

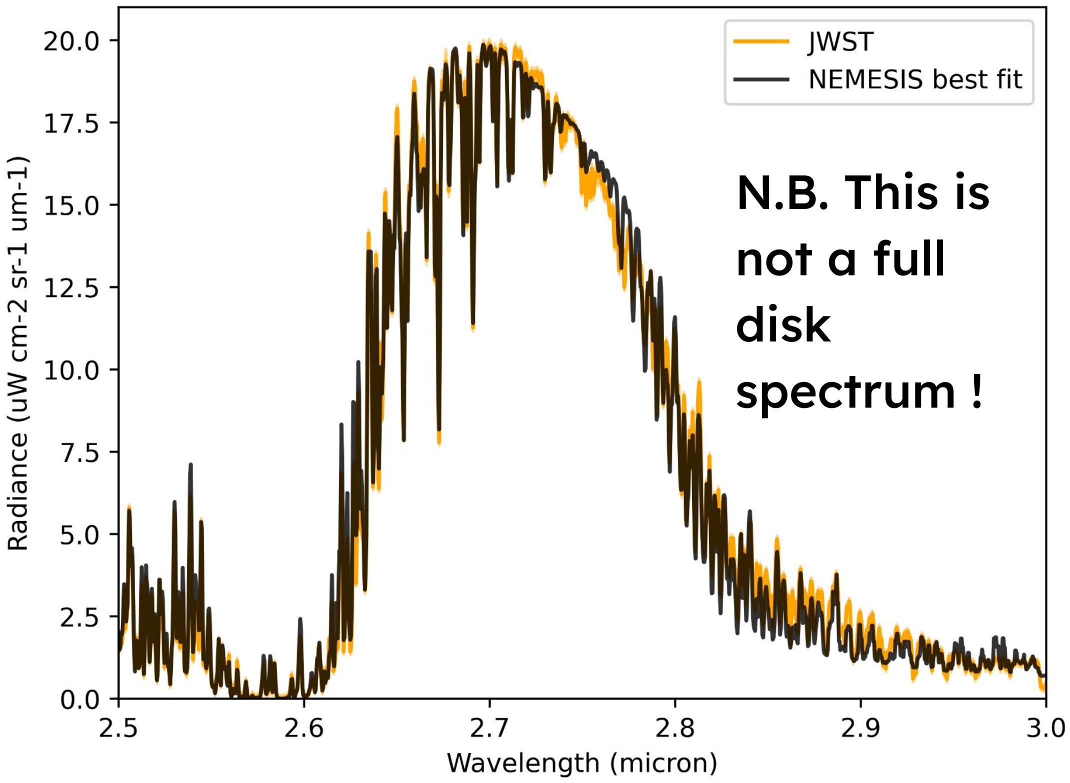
Analyzing NIRSpec data

JWST retrievals

NIRSpec observed Jupiter in July 2022. Only GRS and South Pole were observed

The observations confirm that the only compound able to reproduce the solar reflected peak are tholins similar to the Imanaka+2012 ones

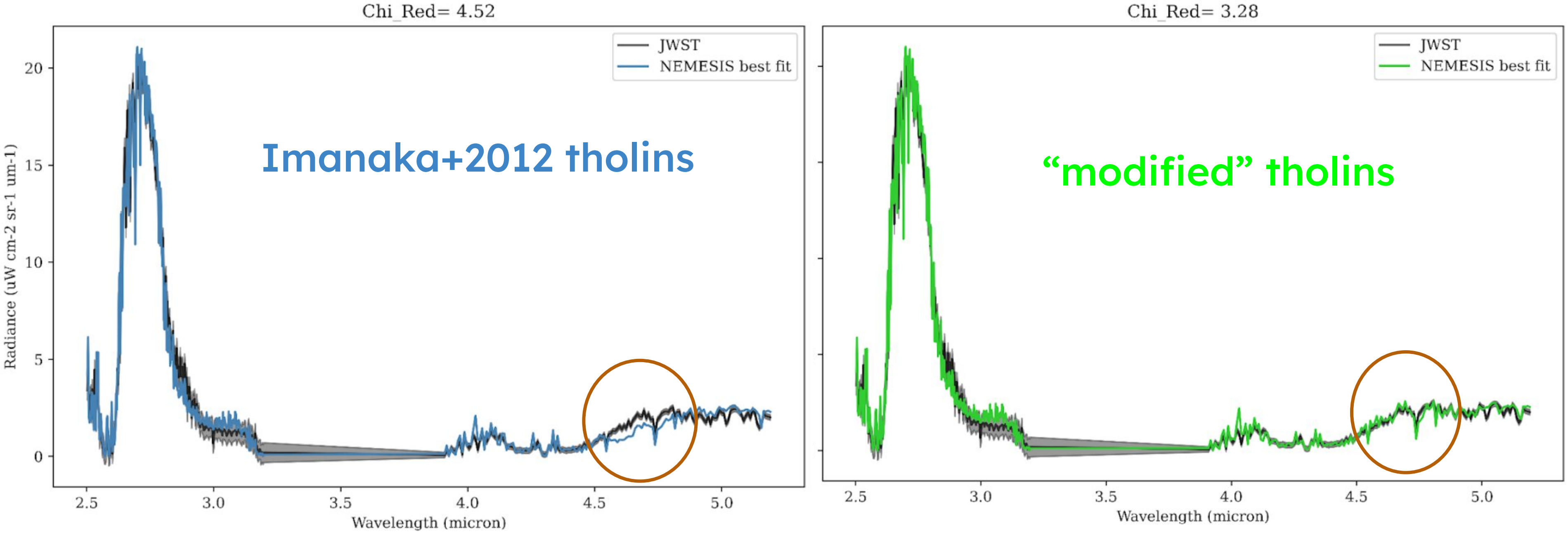
This consistency between Juno (R=500) and JWST (R=2700) was not trivial due to the difference in spectral resolution



N.B. This is not a full disk spectrum !

JWST retrievals

Also in this case “modified tholins” are favored



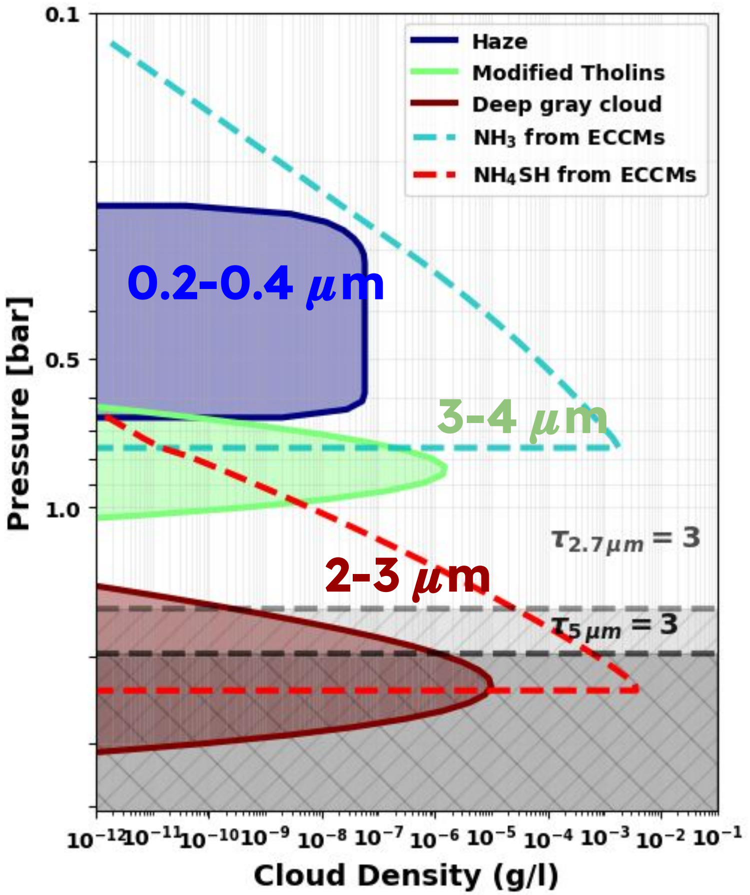
Wrap up results

Results: Comparison with models

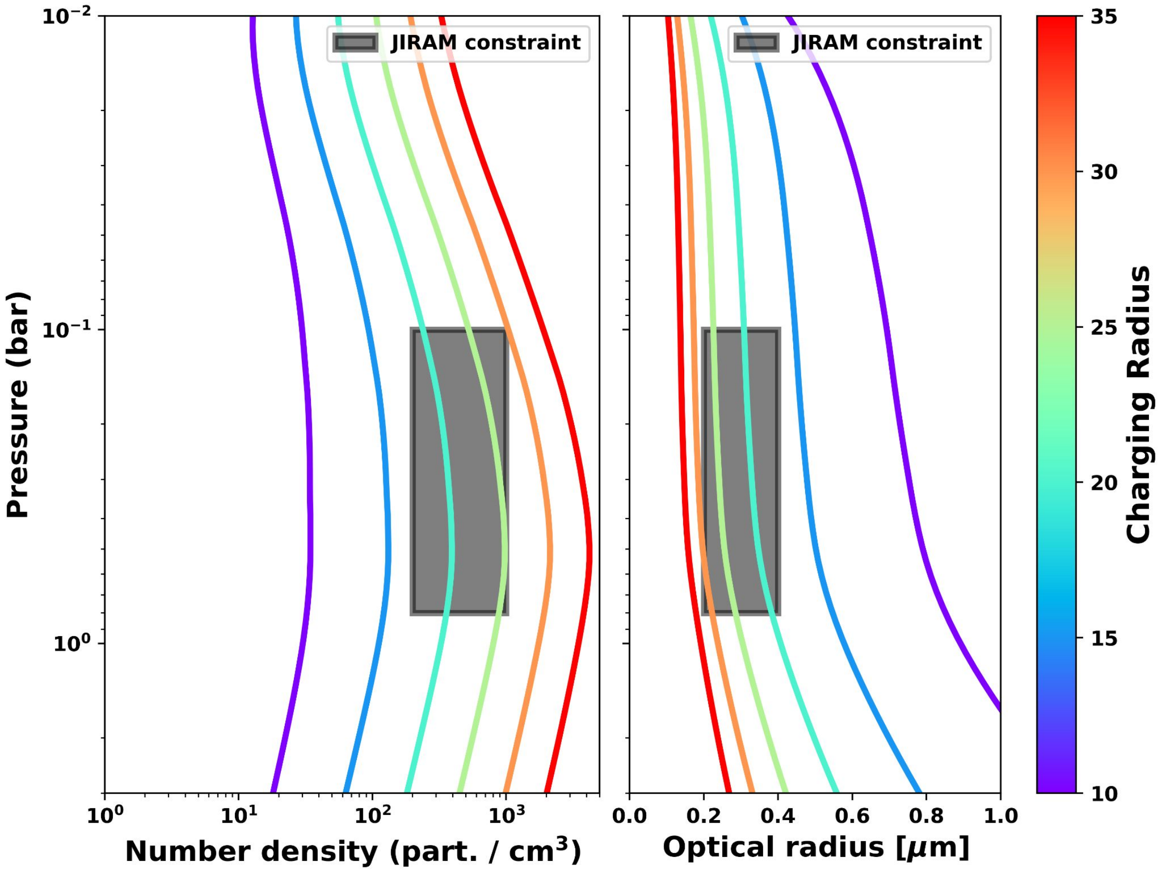
We can draw three main conclusions:

1) the retrieved densities of the upper and deep clouds are far from the ones estimated by theory
2) retrieved clouds pressure levels are consistent with theory
3) tholins (of any kind) and hazes are not predicted by theory and can be produced by photochemistry and photolysis

Therefore we think that on Jupiter aerosols are strictly connected to photochemistry (even at 5.2 AU). Photochemistry plays a fundamental role also in hot Jupiters (WASP-39b) and hazy sub-Neptunes (GJ-1214b, K2-18b). And Tholins can survive up to 500 K (He+2014) !!!



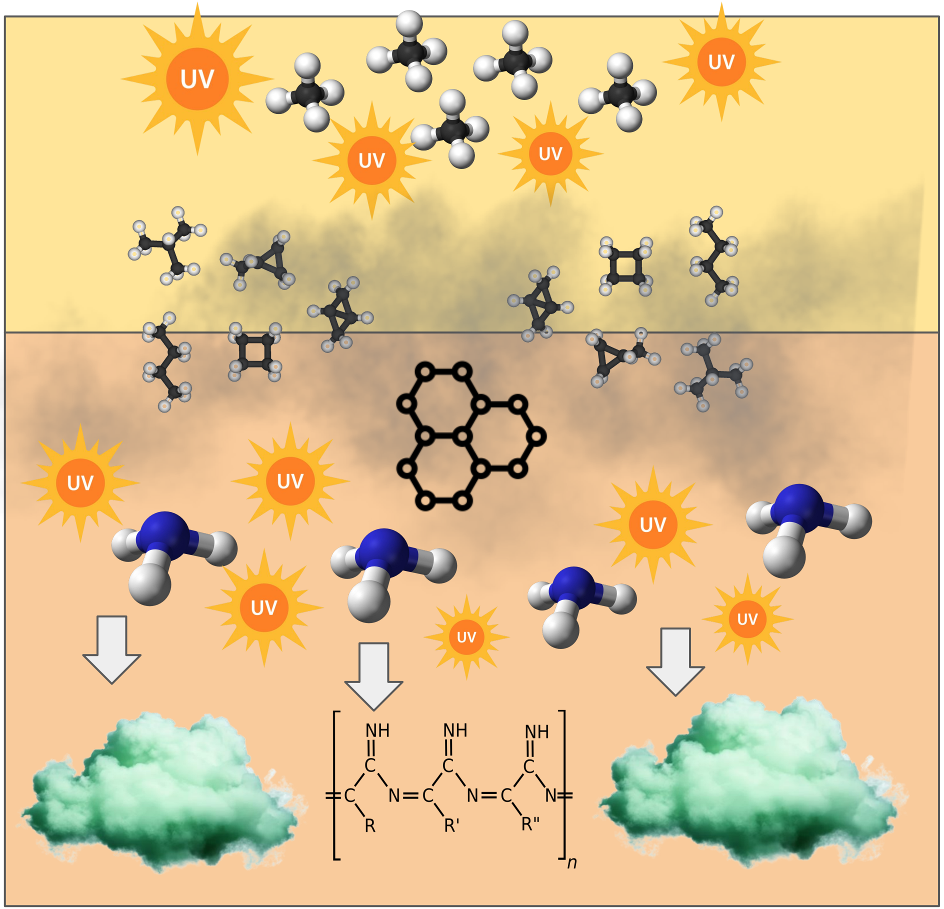
What is the haze ?



We used the code presented in Rannou+2003 (for Titan) to obtain constraint on the haze formation.

JIRAM retrievals are consistent with a **production zone close to 1 mbar and a production rate between 5-10 times the one at Titan.** This is consistent with the work of Moses+2005 and with the haze being residual hydrocarbon products of **methane photochemistry in the stratosphere**

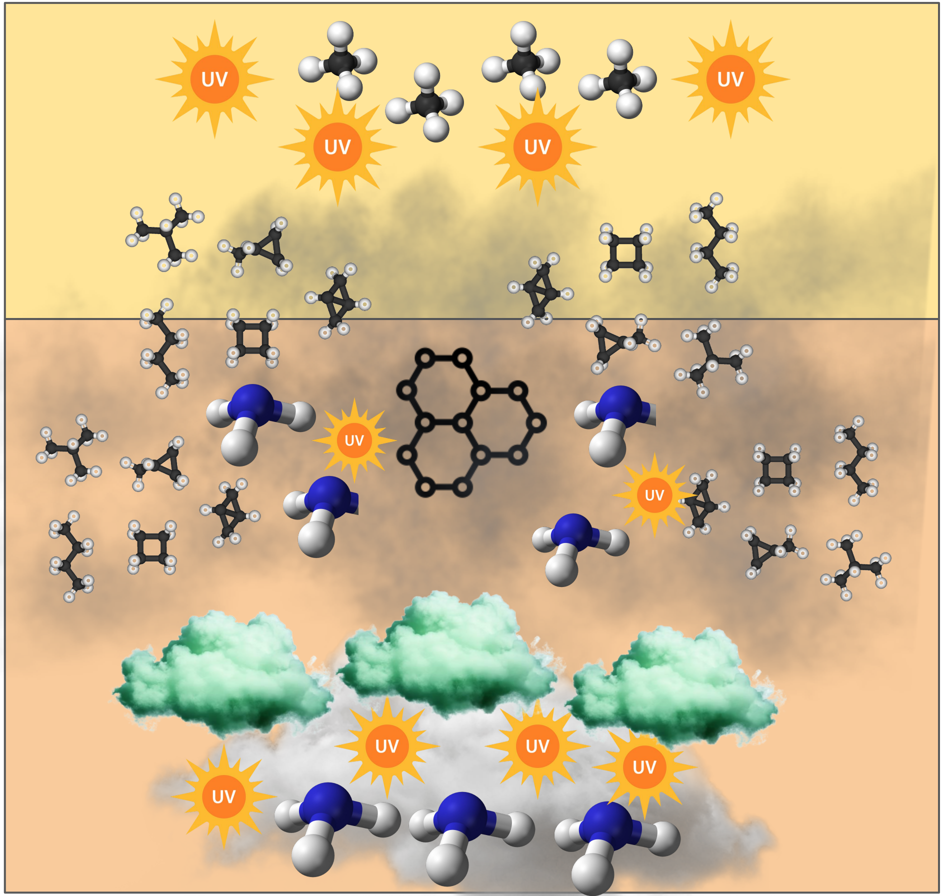
Origins of the “modified” tholins - Hypothesis n.1



The “modified” tholins are the result of successful coagulation of some **haze hydrocarbon small particles** and the products of **(gaseous) ammonia photolysis** at pressures between 0.2 and 0.7 bar (N.B. **UV radiation** can penetrate up to the 1.1-1.6 bar level on Jupiter).

However, we have to test **if this process can efficiently create large particles around 3 microns (JIRAM retrievals)**

Origins of the “modified” tholins - Hypothesis n.2

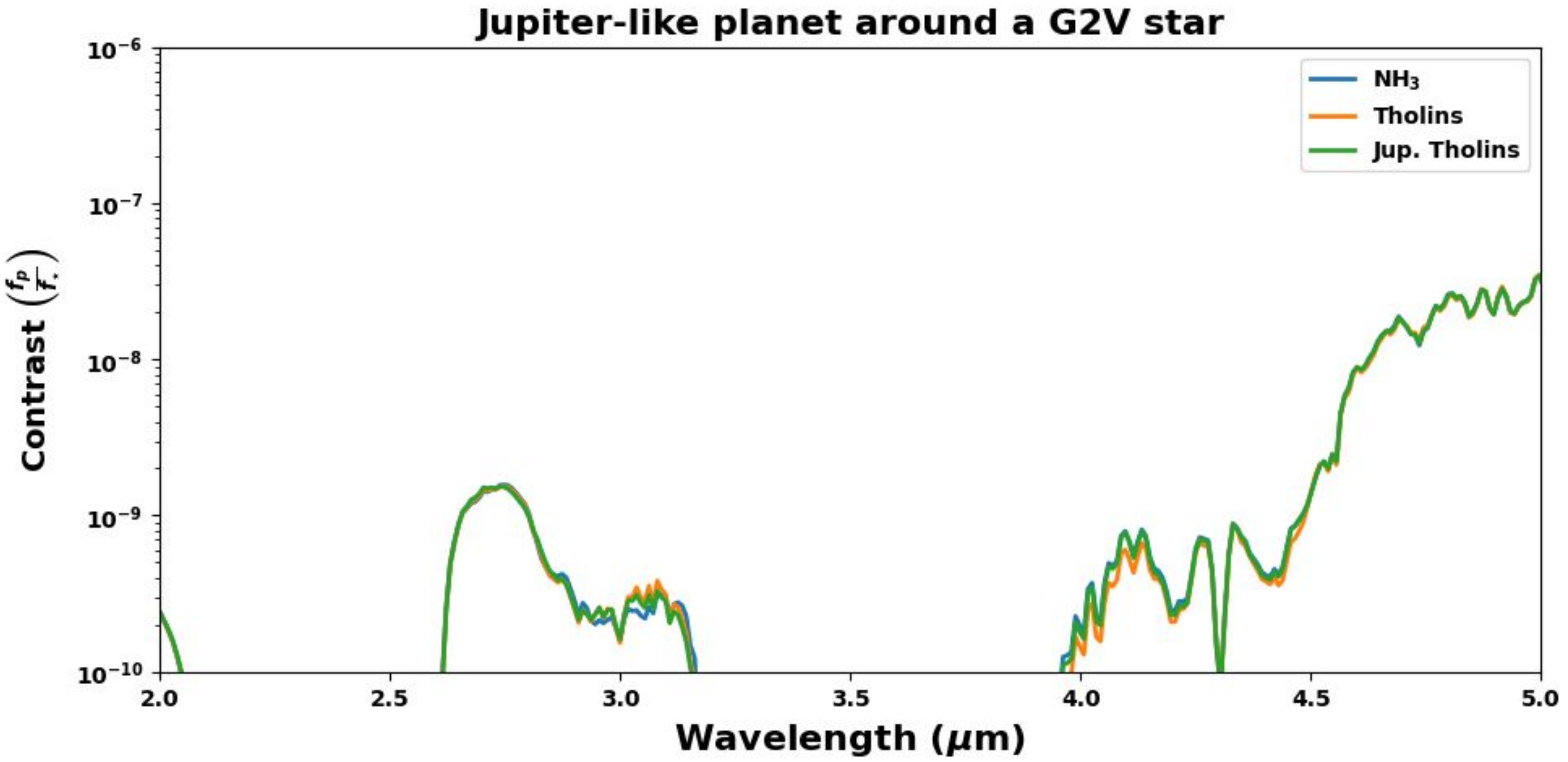


The **“modified” tholins** can be produced at the **top of freshly produced ammonia ice clouds.** Here, **UV radiation** can easily dissociate larger ice particles that successively can react with **hydrocarbons** and the **gaseous ammonia photolysis products**. This scenario is particularly intriguing as it should be consistent with the so-called **“chromophore model”**

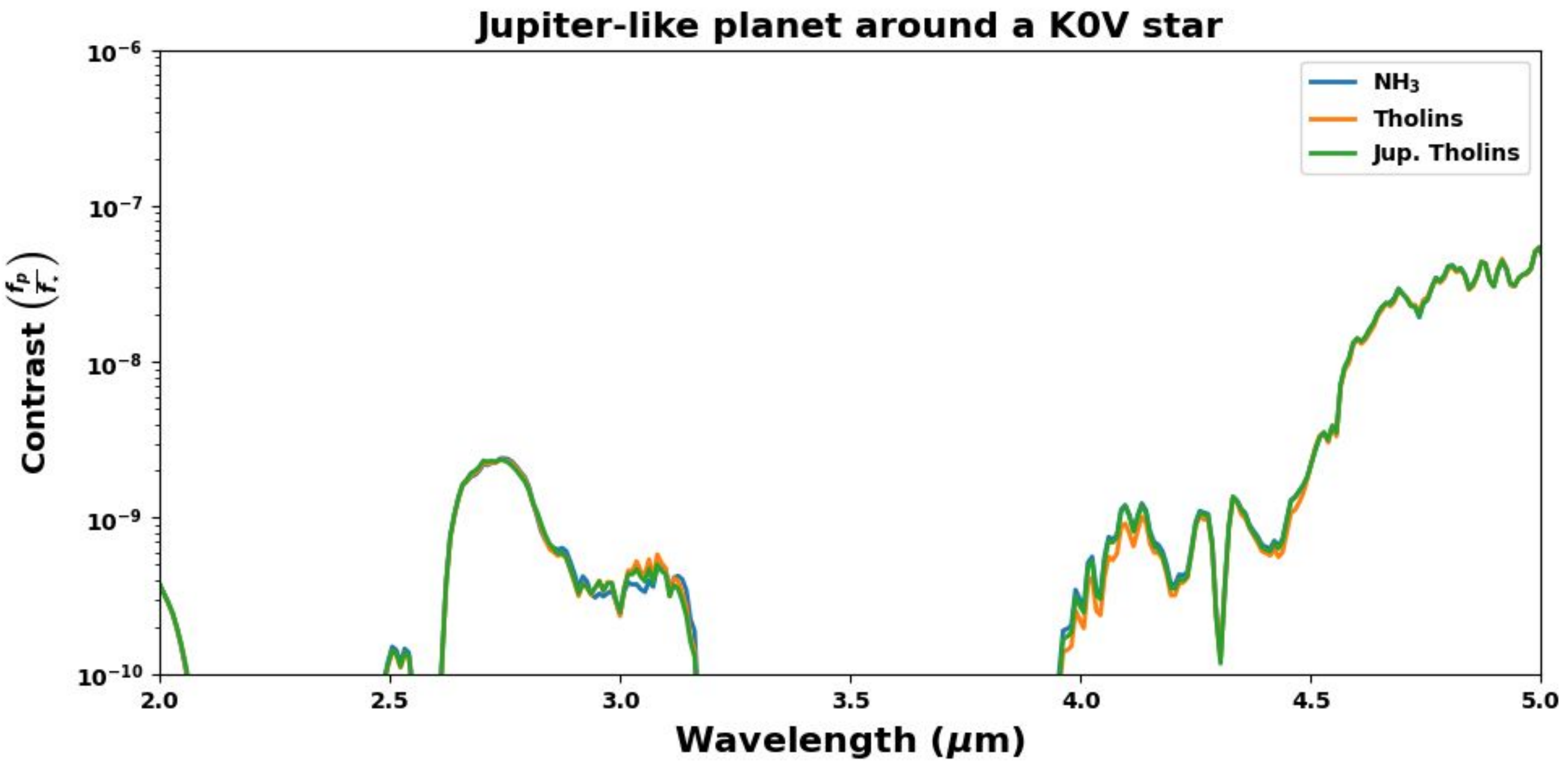
Application to exoplanets

Followed strategy

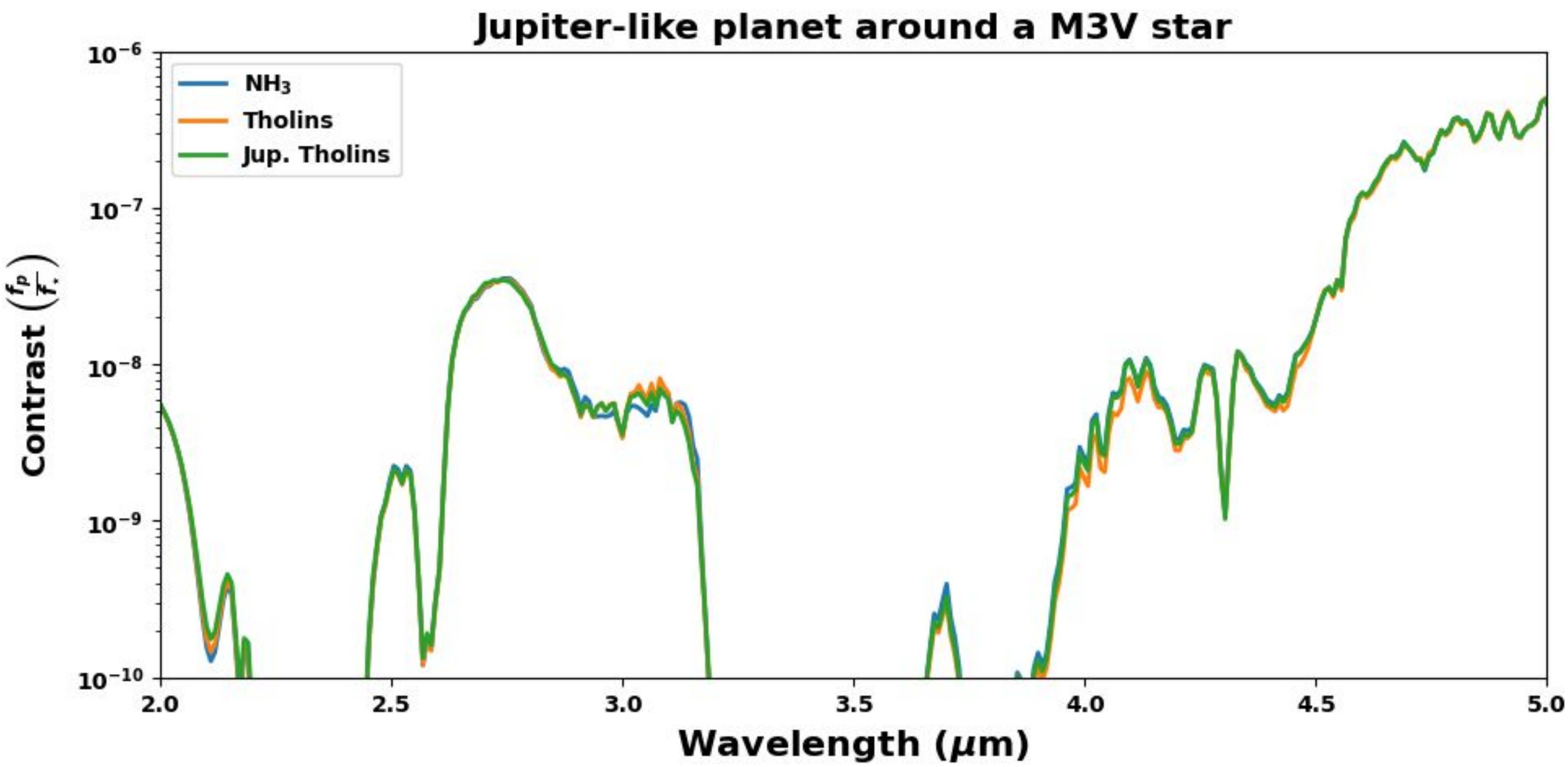
- I extracted stellar spectra for different stars, G2V-K0V-M3V. I computed the corresponding orbital distance in order to have a Jupiter-like exoplanet with a T=125 K. Finally, **I computed the contrast spectra** considering the best-fitting models obtained from the JIRAM full disk spectrum. I also compared them to the no-clouds and ECCMs cloud-like scenarios.
- I computed the vertical optical depth spectra from the best-fitting models the no-clouds and ECCMs cloud-like scenarios. I then converted them in slab optical depth spectra and **extracted a tentative transmission spectrum (around a Sun-like star)**.

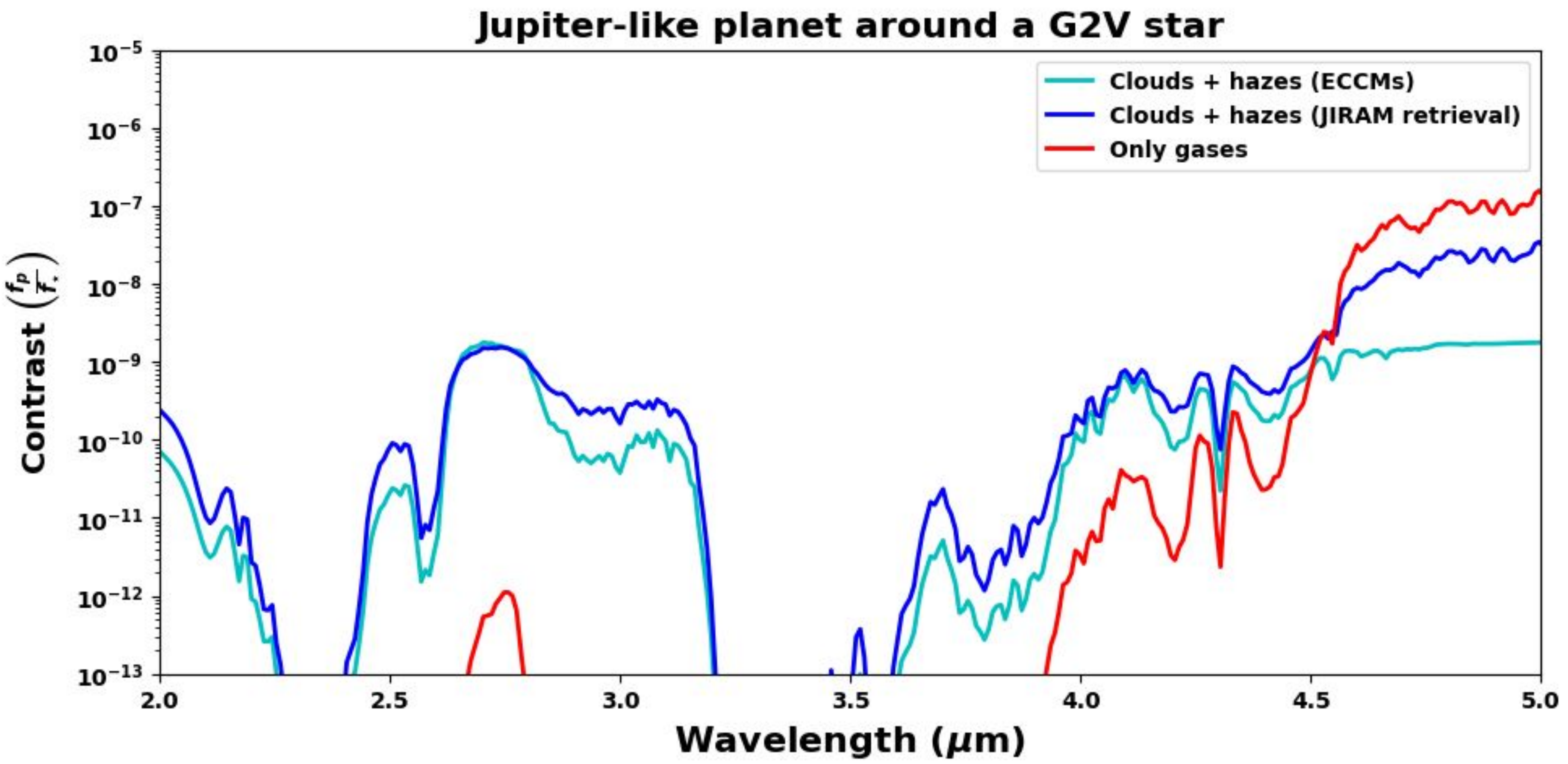


Jupiter-like planet around a G2V star
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
Contrast $\left(\frac{f_p}{f_*}\right)$
2.0
2.5
3.0
3.5
4.0
4.5
5.0
Wavelength (μm)
NH_3
Tholins
Jup. Tholins

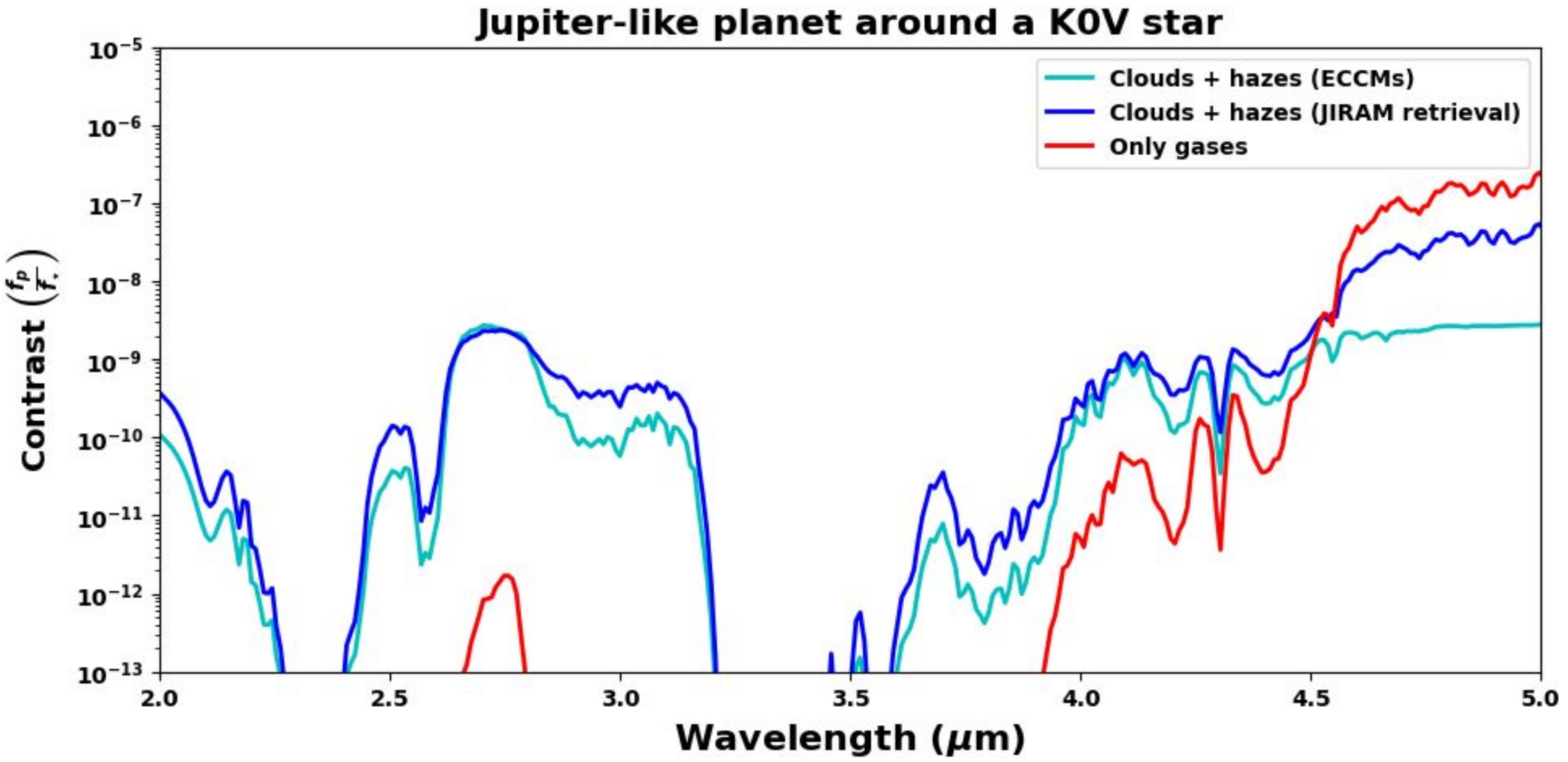


Jupiter-like planet around a K0V star
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
Contrast $\left(\frac{f_p}{f_*}\right)$
2.0
2.5
3.0
3.5
4.0
4.5
5.0
Wavelength (μm)
NH_3
Tholins
Jup. Tholins

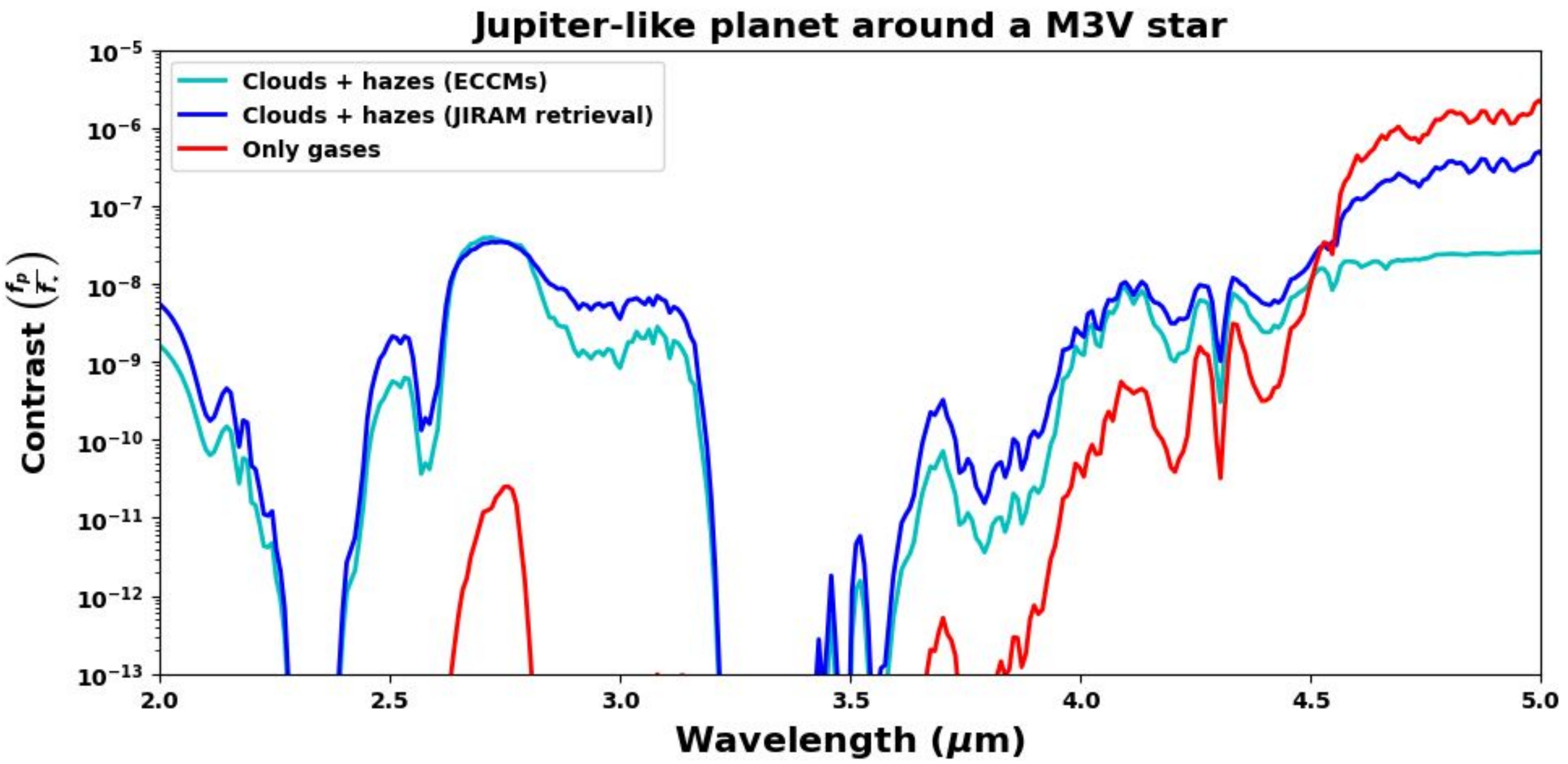

Jupiter-like planet around a M3V star
NH$_3$
Tholins
Jup. Tholins
Contrast $\left(\frac{f_p}{f_*}\right)$
Wavelength (μm)
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
2.0
2.5
3.0
3.5
4.0
4.5
5.0

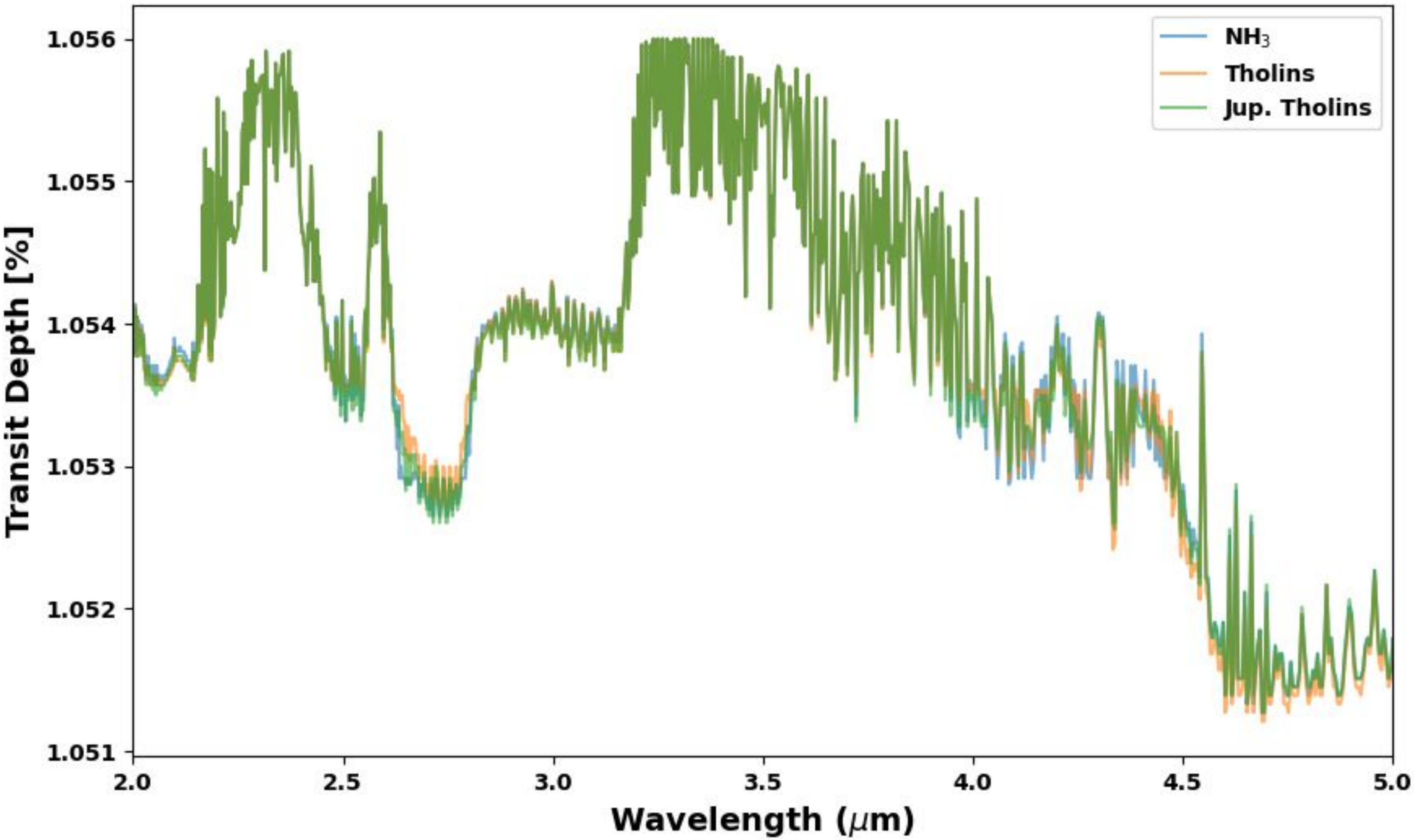


Jupiter-like planet around a G2V star
Clouds + hazes (ECCMs)
Clouds + hazes (JIRAM retrieval)
Only gases
Contrast $\left(\frac{f_p}{f_*}\right)$
Wavelength (μm)
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
2.0
2.5
3.0
3.5
4.0
4.5
5.0

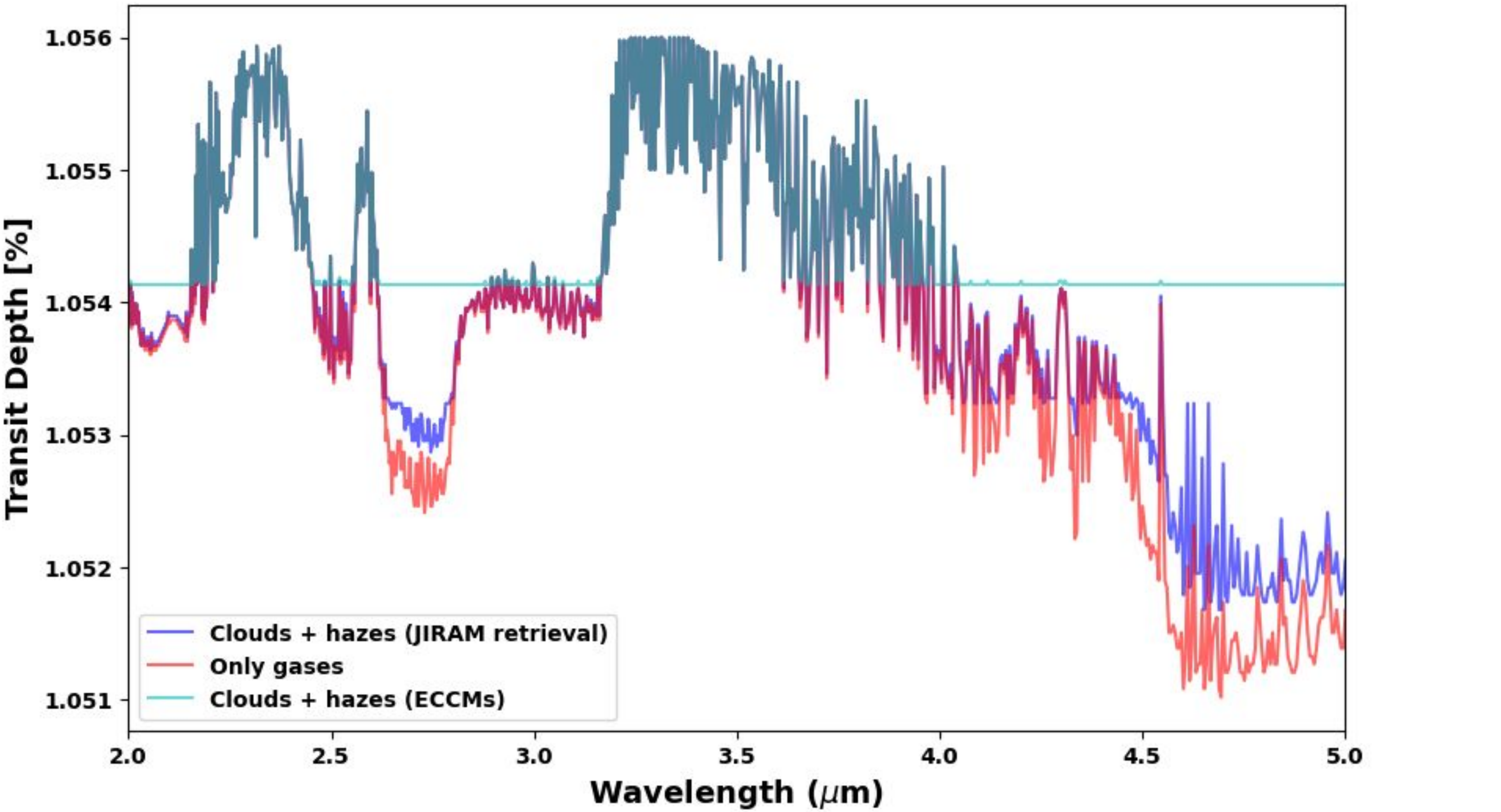


Jupiter-like planet around a K0V star
Clouds + hazes (ECCMs)
Clouds + hazes (JIRAM retrieval)
Only gases
Contrast $\left(\frac{f_p}{f_*}\right)$
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
2.0
2.5
3.0
3.5
4.0
4.5
5.0
Wavelength (μm)


Jupiter-like planet around a M3V star
Clouds + hazes (ECCMs)
Clouds + hazes (JIRAM retrieval)
Only gases
Contrast $\left(\frac{f_p}{f_*}\right)$
Wavelength (μm)
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
2.0
2.5
3.0
3.5
4.0
4.5
5.0



NH3
Tholins
Jup. Tholins
1.056
1.055
1.054
1.053
1.052
1.051
Transit Depth [%]
2.0
2.5
3.0
3.5
4.0
4.5
5.0
Wavelength (μm)



Transit Depth [%]
1.056
1.055
1.054
1.053
1.052
1.051
2.0
2.5
3.0
3.5
4.0
4.5
5.0
Wavelength (μm)
Clouds + hazes (JIRAM retrieval)
Only gases
Clouds + hazes (ECCMs)

Preliminary conclusions

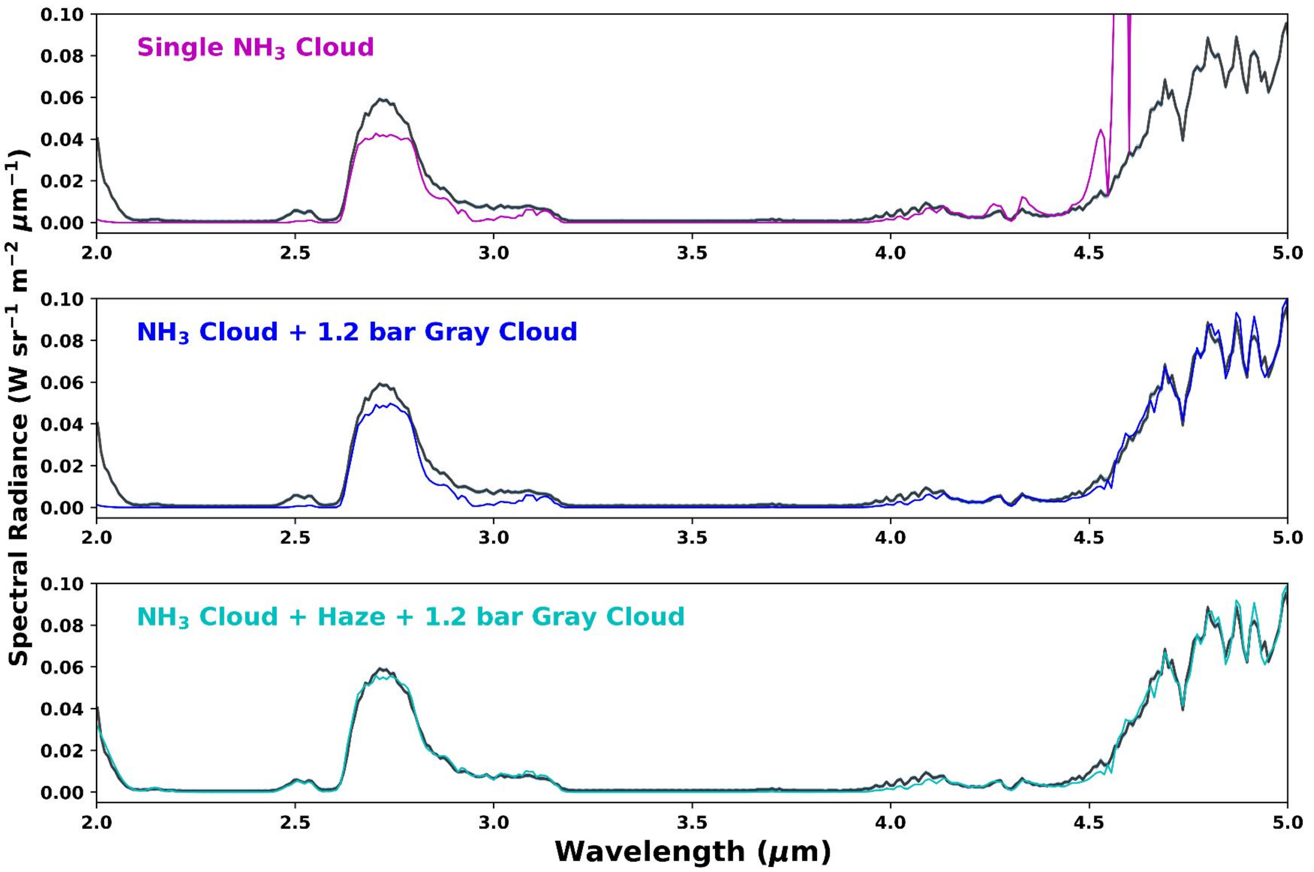
- Jupiter-like cloudy planets **can be detected** (contrast > 10^{-10}) around all the selected stars by instruments like HWO or LIFE
- As expected, **it is really hard to discriminate between different upper cloud compositions** using both with HWO and JWST resolutions, and both in direct imaging and transmission
- **It is possible to easily discriminate between cloudy or cloud-free Jupiter-like planets** in direct imaging. In transmission it depends on the host star (smaller star radius induce larger transit depths signals)
- Using ECCMs densities can induce observable errors both in transmission and direct imaging !

Conclusions

- We studied Jovian aerosols using a full-disk spectrum obtained from PJ1 Juno/JIRAM infrared spectral data
- We performed retrievals using PSG and emcee and varying the aerosol properties, structures, and composition
- The best fit of JIRAM data was obtained when a uniform haze of 0.3 micron and a main cloud composed of 3-4 micron "modified" tholins were invoked. Pure ammonia ice clouds cannot explain well JIRAM data.
- These "modified" tholins are obtained from Imanaka+2012 data removing the prominent C-N absorption in the thermal range.
- We propose that both the hazes and these Jovian tholins are created by photochemistry, but future laboratory experiments are essential

Backup slides

JIRAM: how clouds affect the spectrum



Preliminary simulations revealed that a single condensation cloud is not enough to explain the observed radiation.

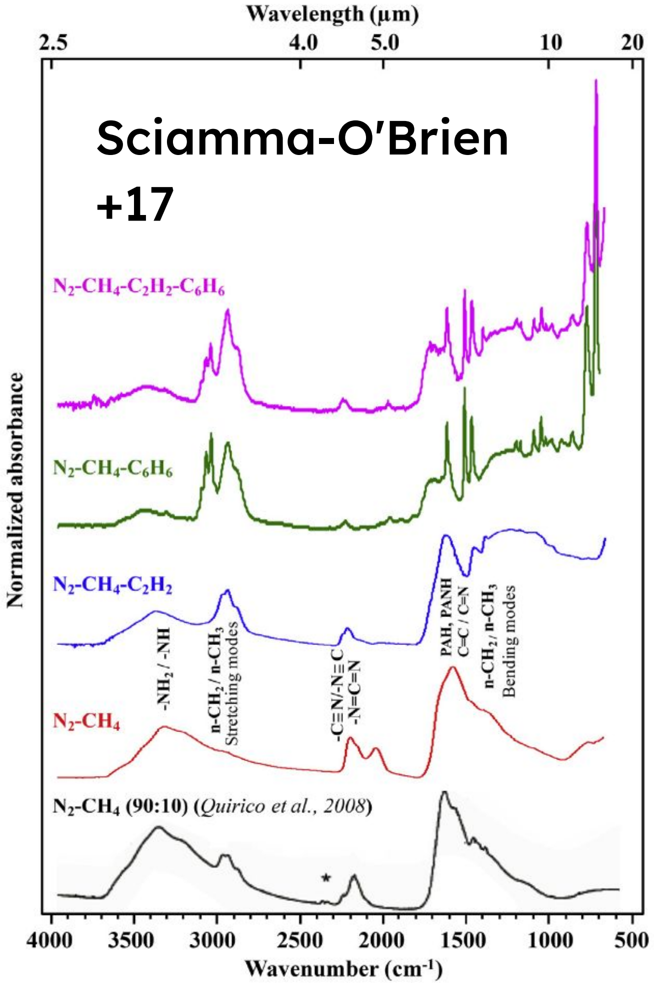
Instead a mass of high altitude small tropospheric aerosols (haze) and an optically thick source at 1.2 bar (maybe top of NH_4SH ?) are needed

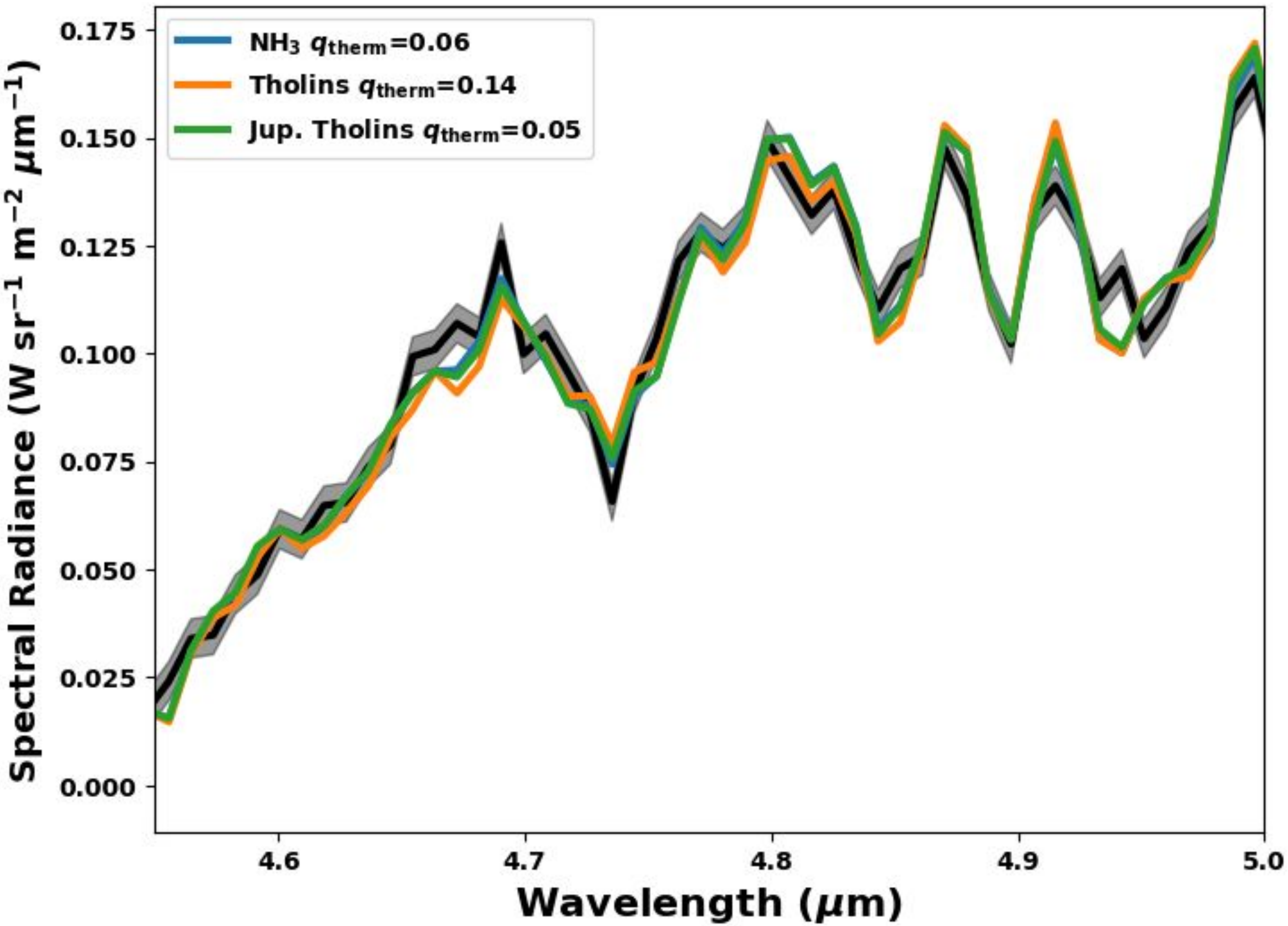
What are the modified tholins ?

Jupiter and Titan have different composition. N is way more present on Titan, while it is bounded to ammonia on Jupiter.

Therefore, as a rule of thumb, C-N bounds should be weaker, while CHN ones stronger. This is confirmed by Carlson+2016 measurements at >5 um.

Also the feature between 4.5 and 5 um should be weakened. **N.B. the feature in Carlson+2016 is induced by the presence of N+**





NH3 qtherm=0.06
Tholins qtherm=0.14
Jup. Tholins qtherm=0.05
Spectral Radiance (W sr−1 m−2 μm−1)
0.000
0.025
0.050
0.075
0.100
0.125
0.150
0.175
4.6
4.7
4.8
4.9
5.0
Wavelength (μm)