Clouds and haze on exoplanets and brown dwarfs

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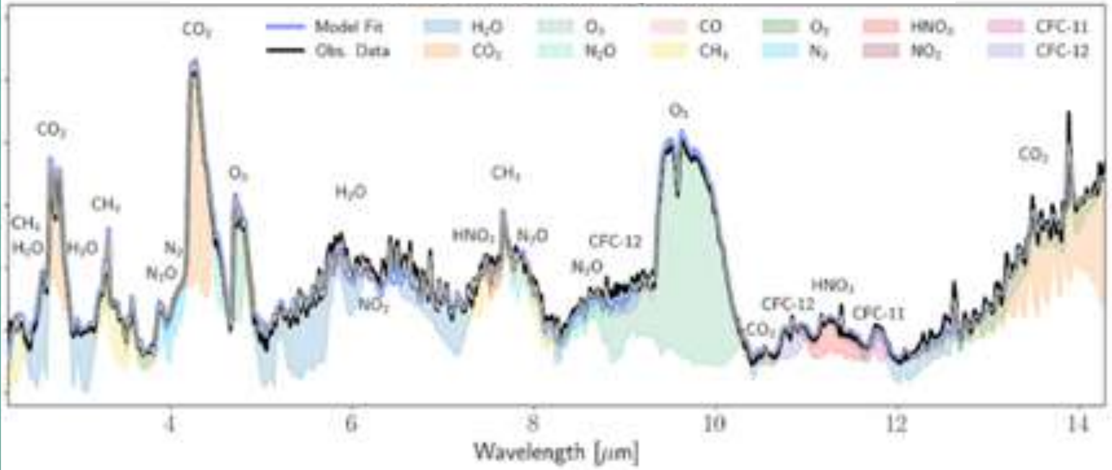
Cycle 3 proposal deadline: October 25, 2023

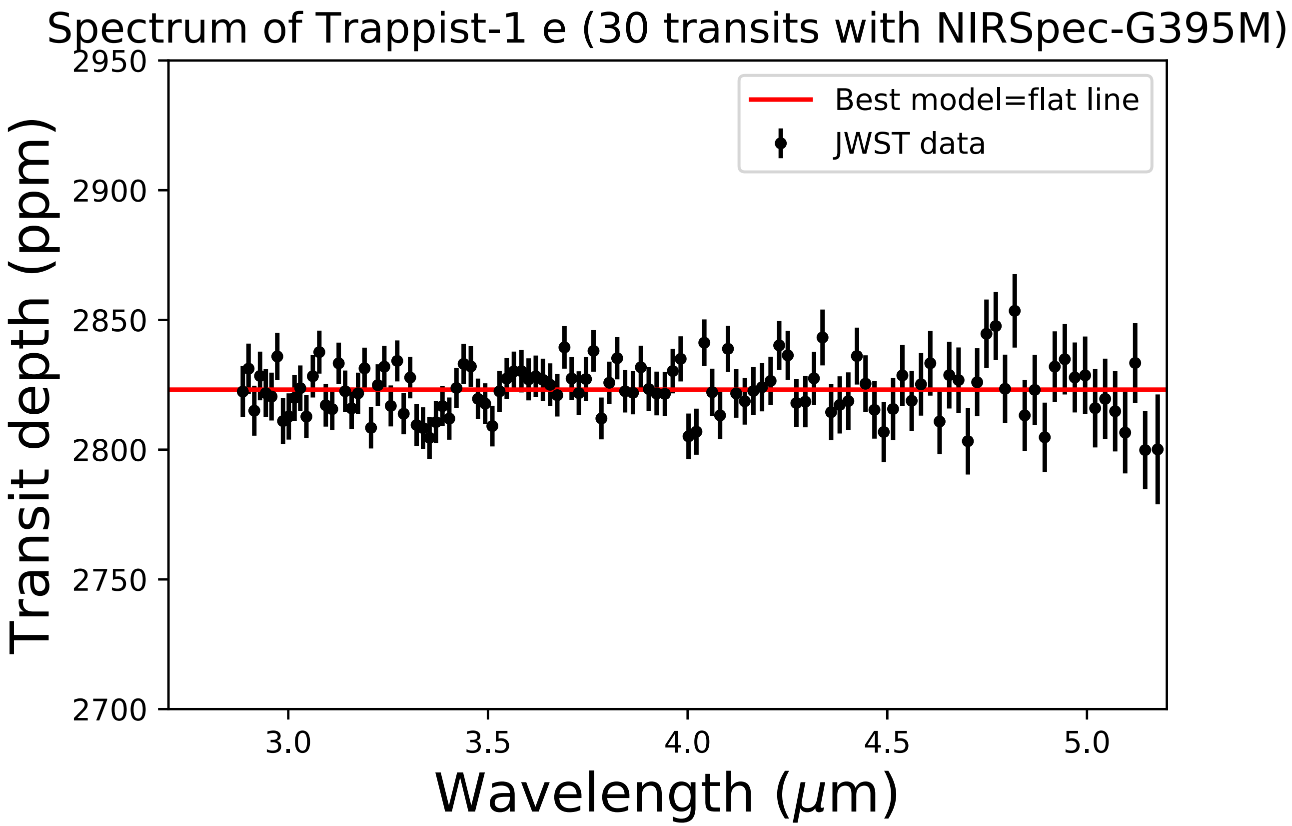
I have a great idea for a JWST proposal: detecting N_2O and DMS as hints for life on Trappist-1 e !!!

Trappist-1 e transmission spectrum



My JWST
proposal is accepted !!!

I received the JWST data !!!



Spectrum of Trappist-1 e (30 transits with NIRSpec-G395M)
Transit depth (ppm)
2950
2900
2850
2800
2750
2700
3.0
3.5
4.0
4.5
5.0
Wavelength (μm)
Best model=flat line
JWST data

"EVIDENCE FOR CLOUDS ON TRAPPIST-1 E"
I WILL SUBMIT IT TO A&A...

Lesson from observations: most of exoplanets are cloudy or hazy

Clouds/haze impact on exoplanetary atmospheres

- Atmospheric composition/chemistry
- Radiative transfert (scattering & absorption)
- Atmospheric dynamics
- Temperature and climate

→ **Atmospheric retrieval**

Clouds seen by astronomers

Clouds seen by atmospheric scientists

Aerosols in exoplanetary atmospheres: clouds or haze

Condensate clouds
(thermodynamic phase change)

Haze
(non-equilibrium chemistry)

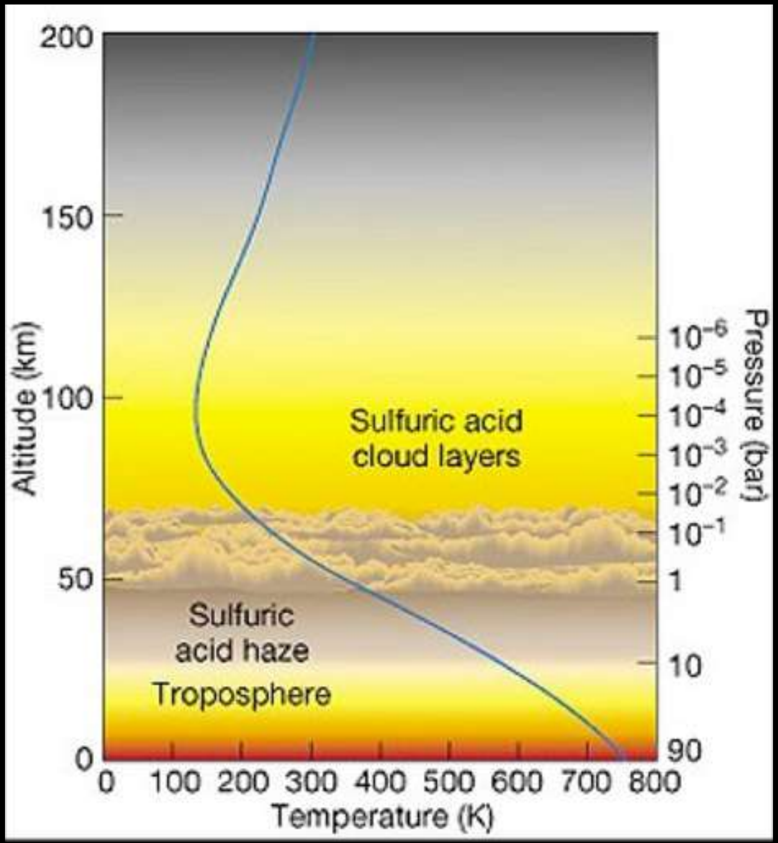
Clouds/haze are everywhere

	Clouds	Haze
Venus	H_2SO_4	H_2SO_4 and other heavier photochemical products like S_8 (?)
Earth	H_2O	Smog
Mars	H_2O, CO_2	No haze (but lots of dust)
Jupiter, Saturn	H_2O, NH_3, NH_4SH	Forms from NH_3, CH_4, H_2S, etc. photochemistry
Titan	CH_4, HCN, C_4N_2, C_2H_6, other organics	Forms from CH_4, N_2, CO, etc. photochemistry
Uranus, Neptune	H_2O, NH_3, NH_4SH CH_4, H_2S	Forms from NH_3, CH_4, H_2S, etc. photochemistry
Triton	N_2	Forms from CH_4, N_2, CO, etc. photochemistry
Pluto	N_2	Forms from CH_4, N_2, CO, etc. photochemistry
Exoplanets	CH_4, NH_3, H_2O alkali metals, iron, silicates, other, etc.	Yes. All the possible kinds.

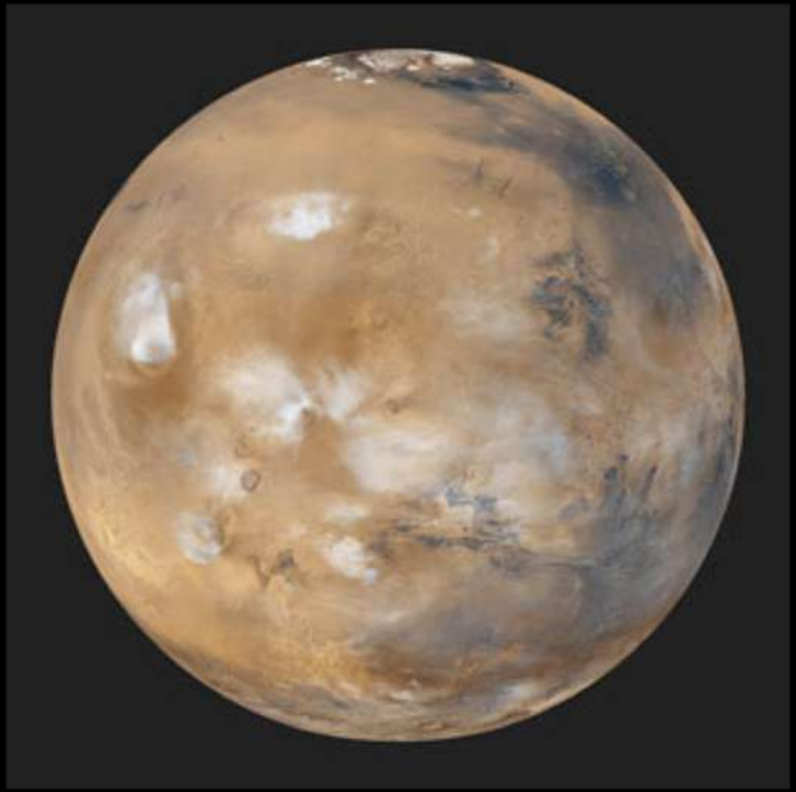
Figure from Sarah Hörst

Venus (H_2SO_4)

[Pioneer Venus, 1979]

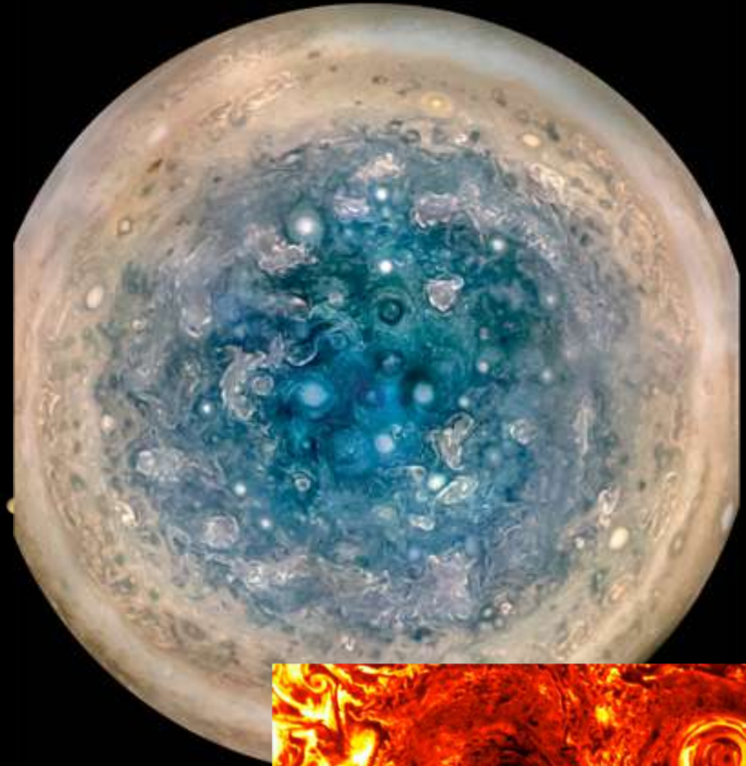


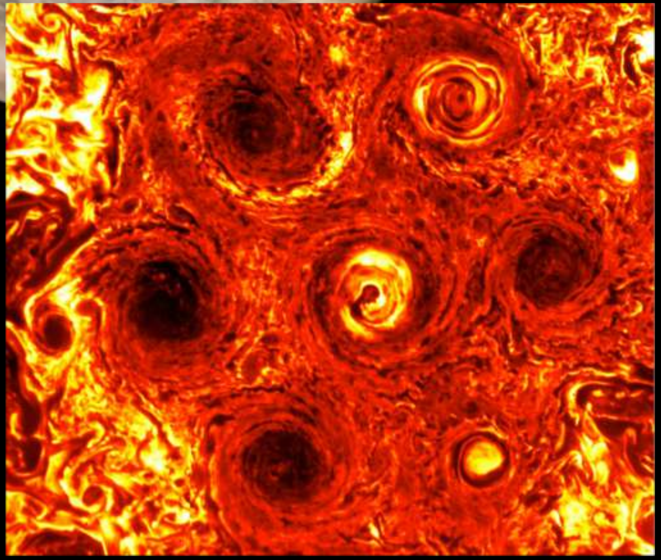
Mars (H_2O and CO_2)



CO_2 clouds from Curiosity

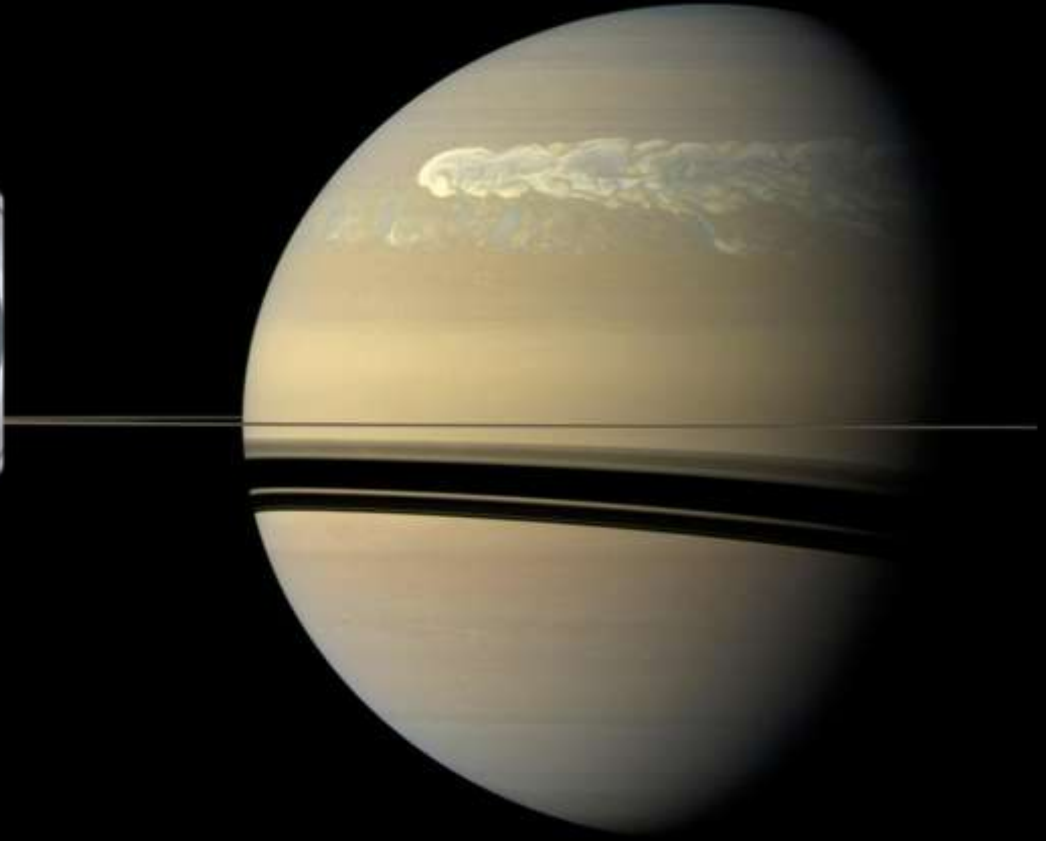
Jupiter (NH_3, NH_4SH, H_2O, Photochemical haze)





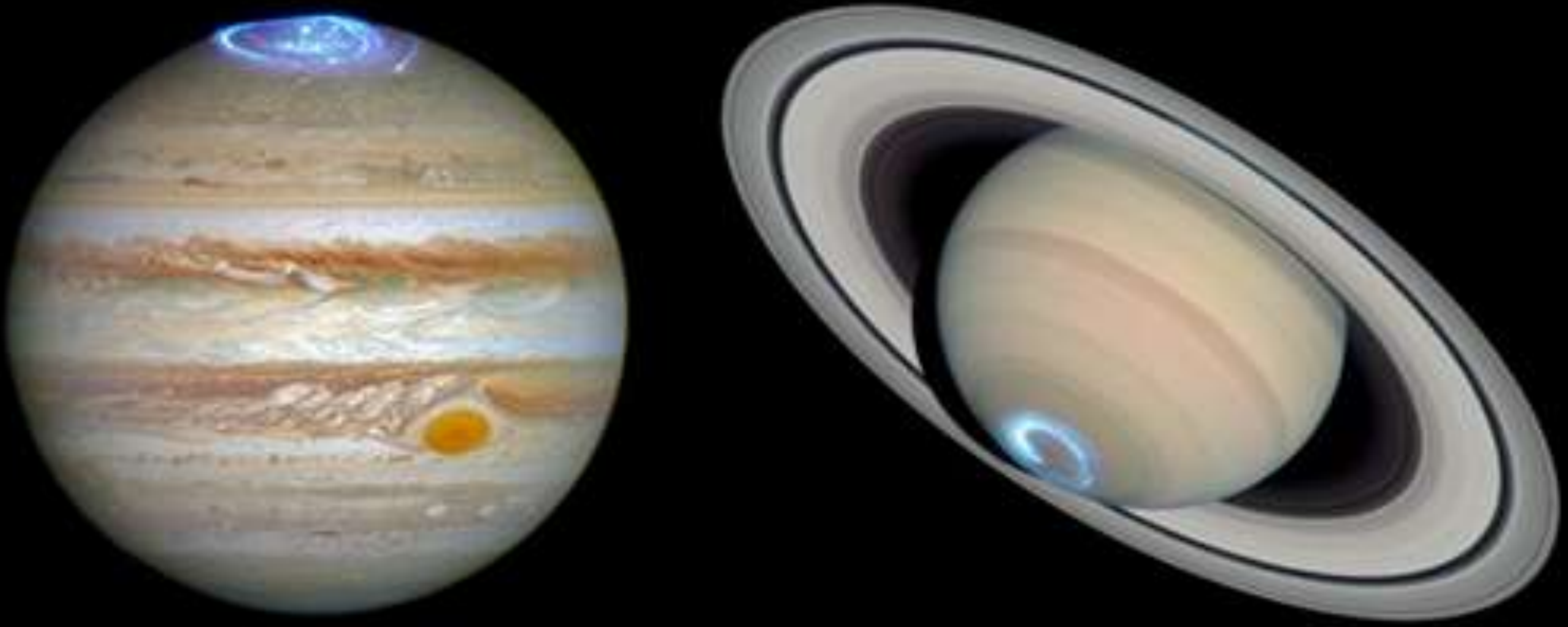
[Adriani et al. Nature 2018]

Saturn (NH_3, NH_4SH, H_2O, Photochemical haze)



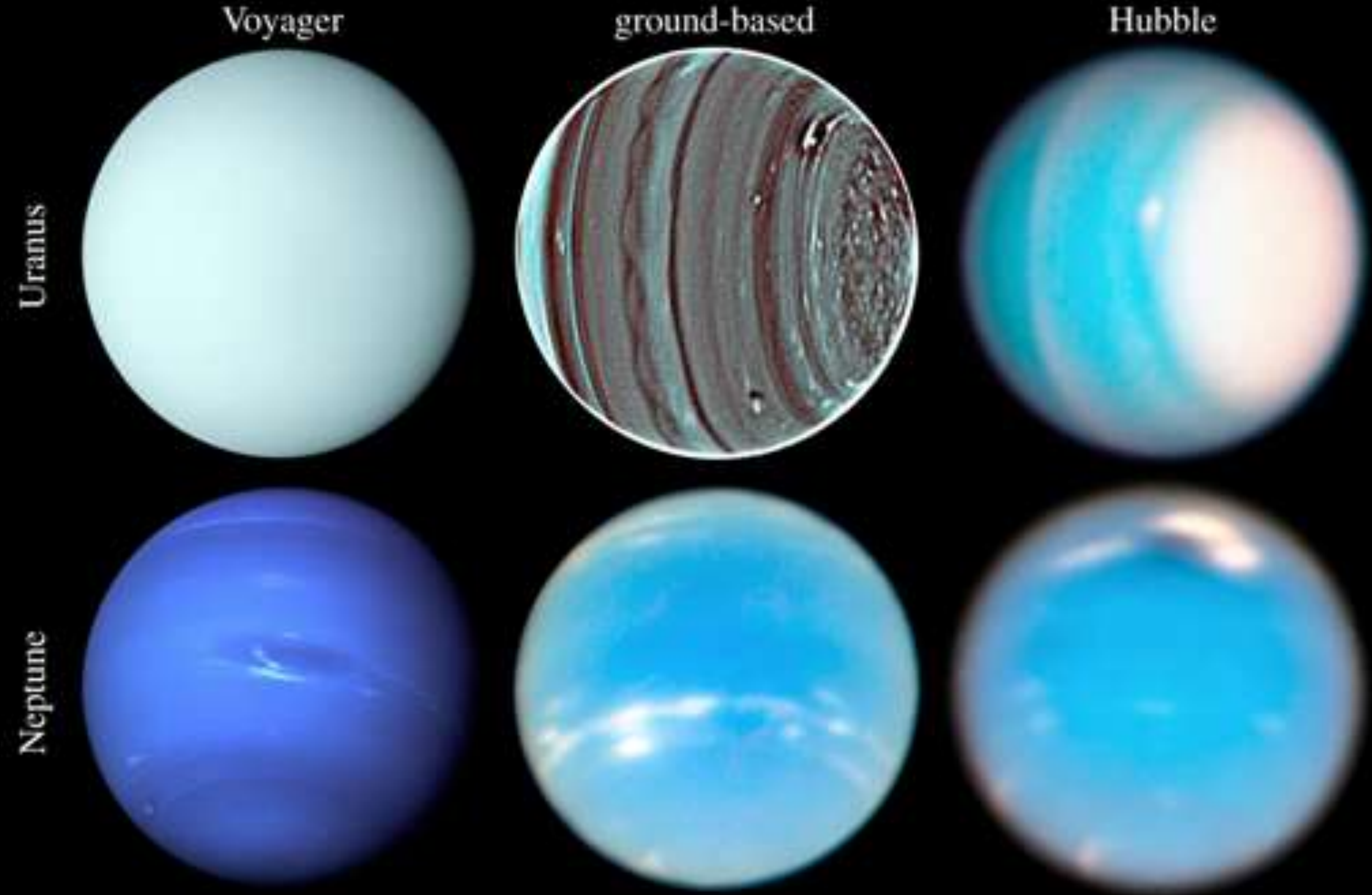
[Image Cassini-Huygens PIA14905]

Aurorae on Jupiter & Saturn

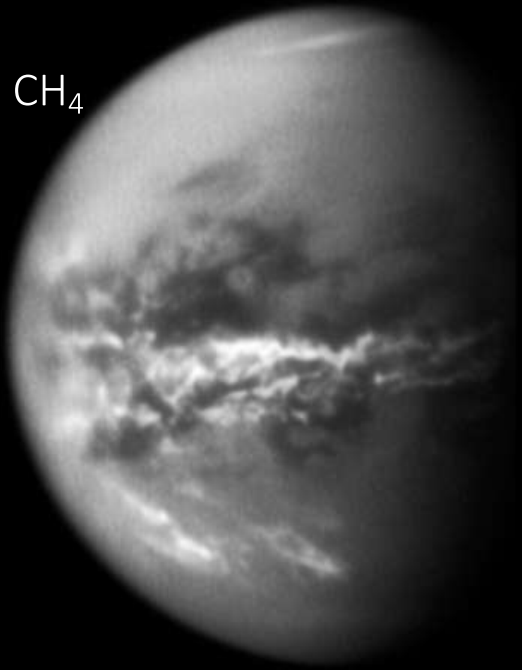


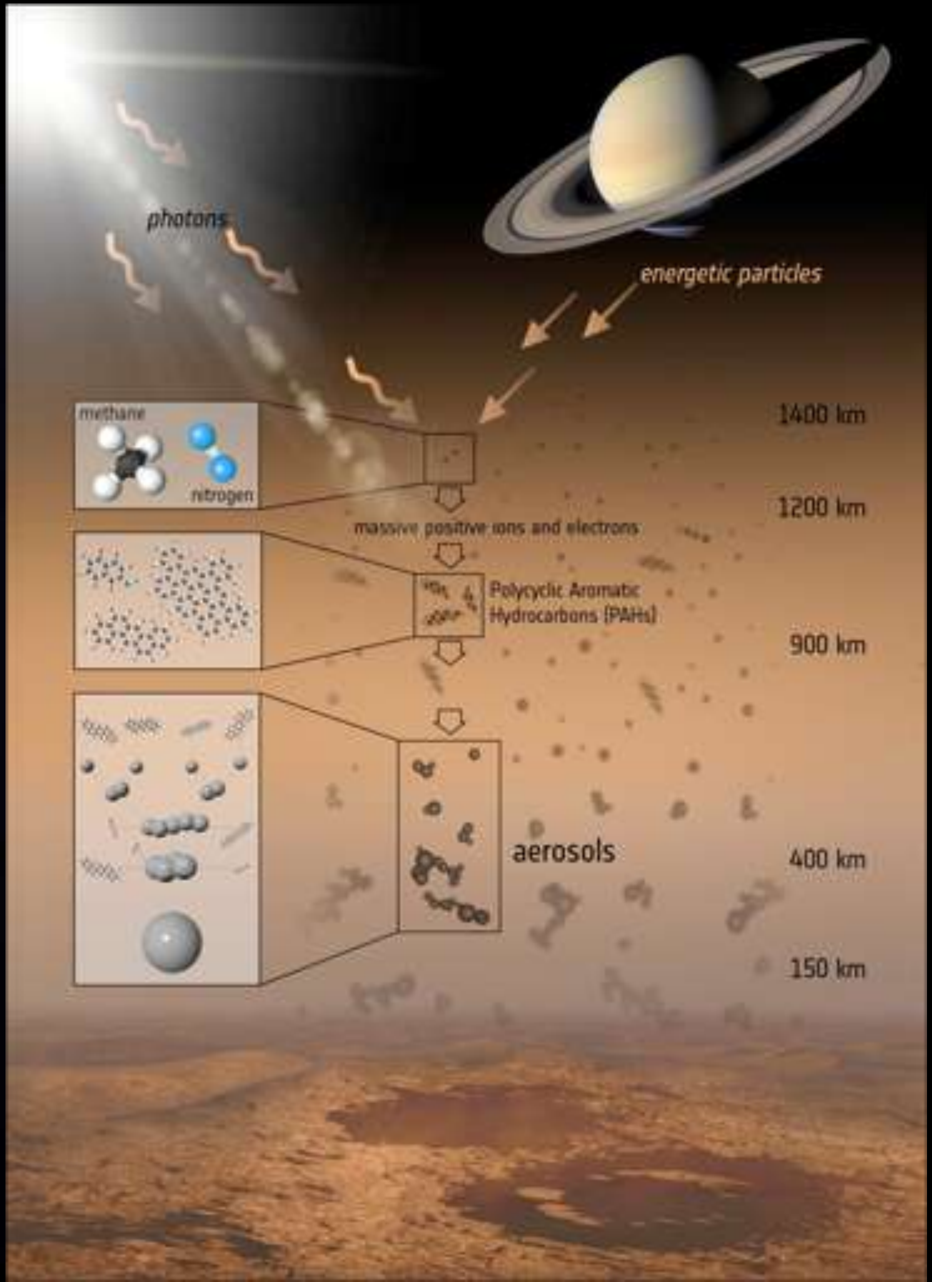
Auroral chemistry and hazes on Jupiter and Saturn

Ice giants: Uranus & Neptune (CH_4, NH_3, NH_4S, H_2S, H_2O)



Titan (CH_4, C_2H_6, HCN, photochemical haze)

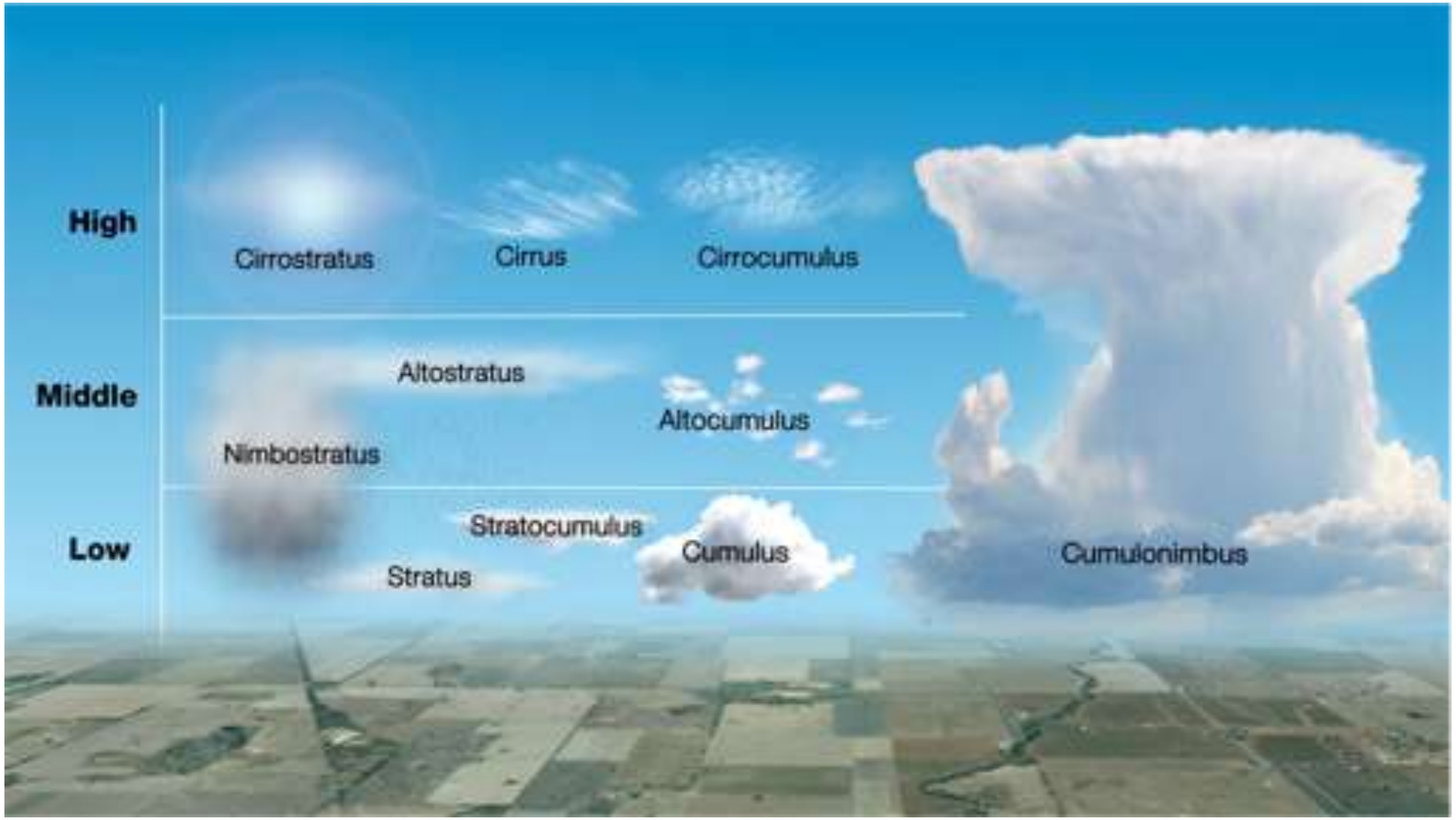




Pluto (N_2, photochemical haze)

MODIS/NASA

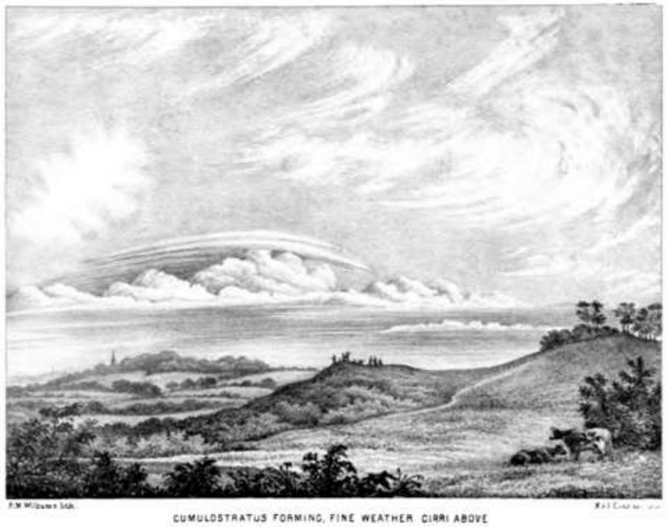
International Cloud Atlas



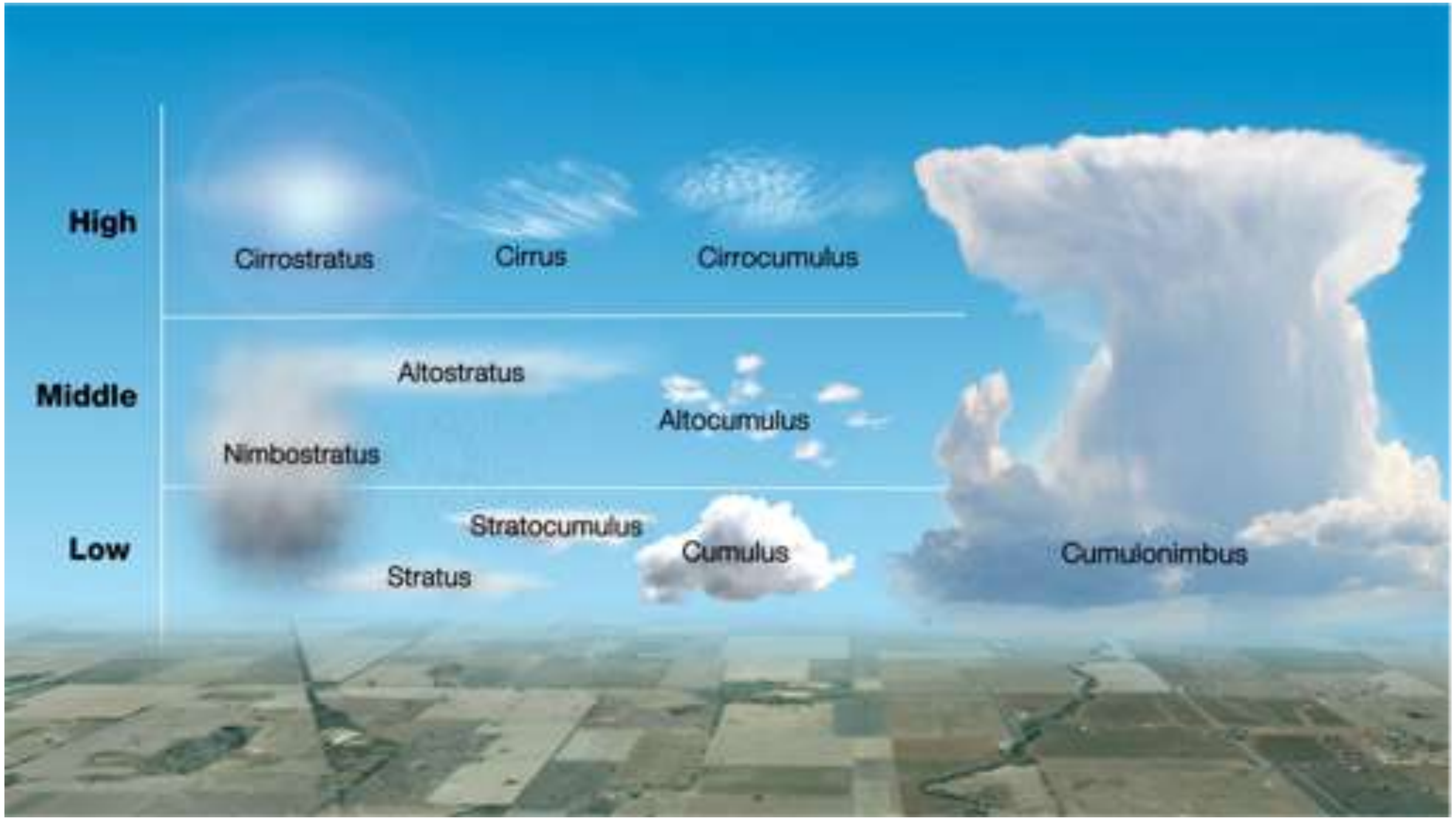
Main clouds are a combination of the following prefixes and suffixes:
- **Stratus/strato**: flat/layered and smooth
- **Cumulus/cumulo**: heaped up/puffy, like cauliflower
- **Cirrus/cirro**: high up/wispy
- **Alto**: medium level
- **Nimbus/Nimbo**: rain-bearing cloud

Luke Howard (1772-1864)

Essay on the Modification of Clouds



International Cloud Atlas



« To be on cloud nine »

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Cloud identification

Cirrus

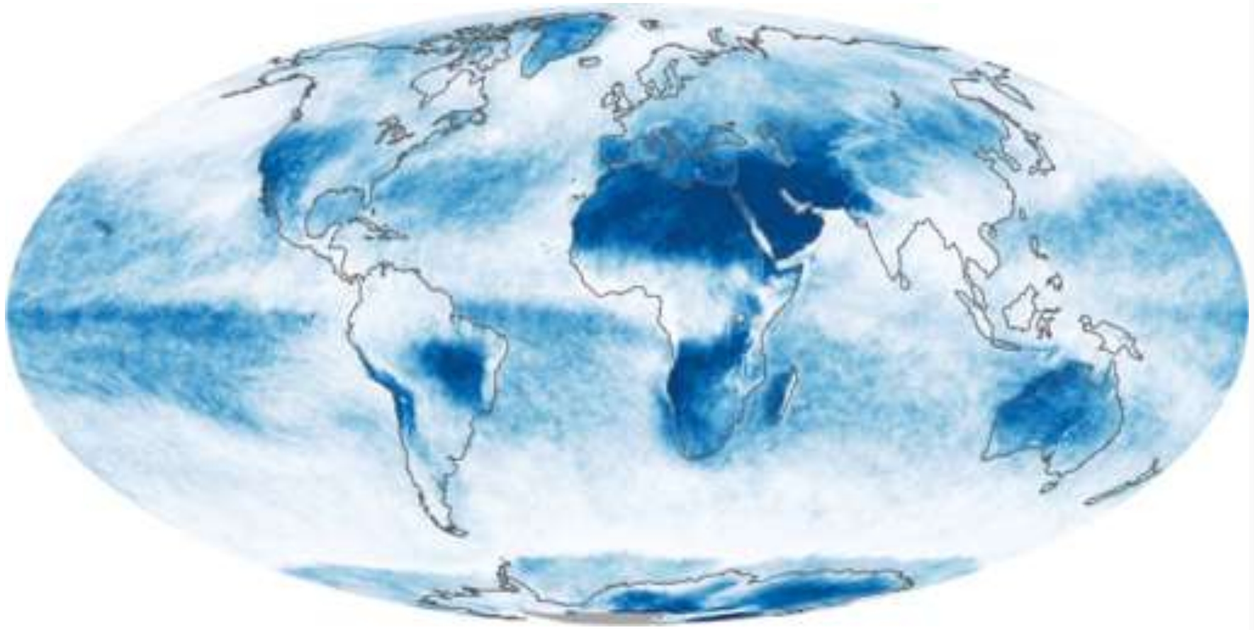
Cloud identification

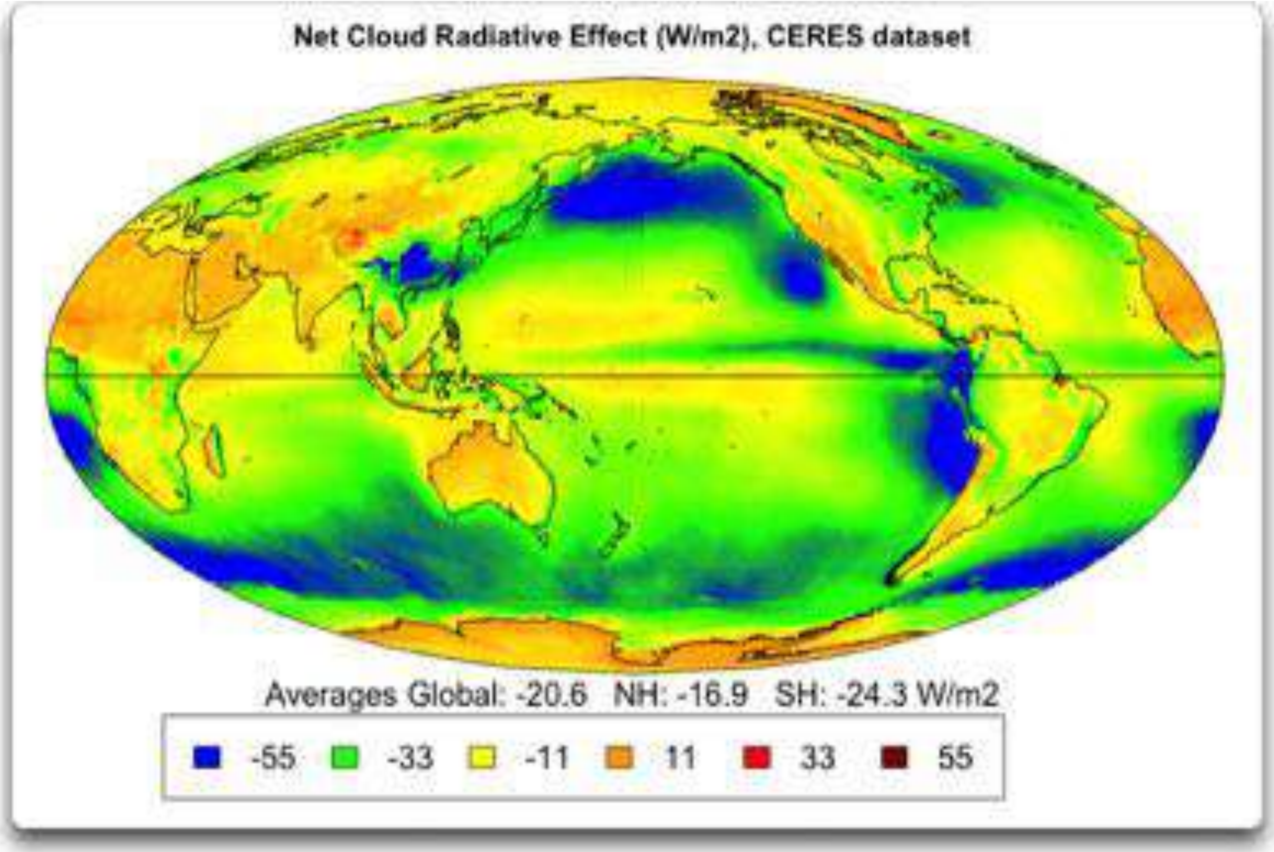
Cirrocumulus

Cloud identification

Nimbostratus

Map of cloud fraction





1) **Scattering of stellar radiation**

→ **surface cooling by albedo effect**

- Stronger effect for lower clouds (e.g. stratus)

2) **Absorption/emission of thermal radiation**

→ **surface warming by greenhouse effect**

- Stronger effect for upper clouds (e.g. cirrus)

Net cloud radiative forcing:

$CRF = R_{cloudy} - R_{clear}$

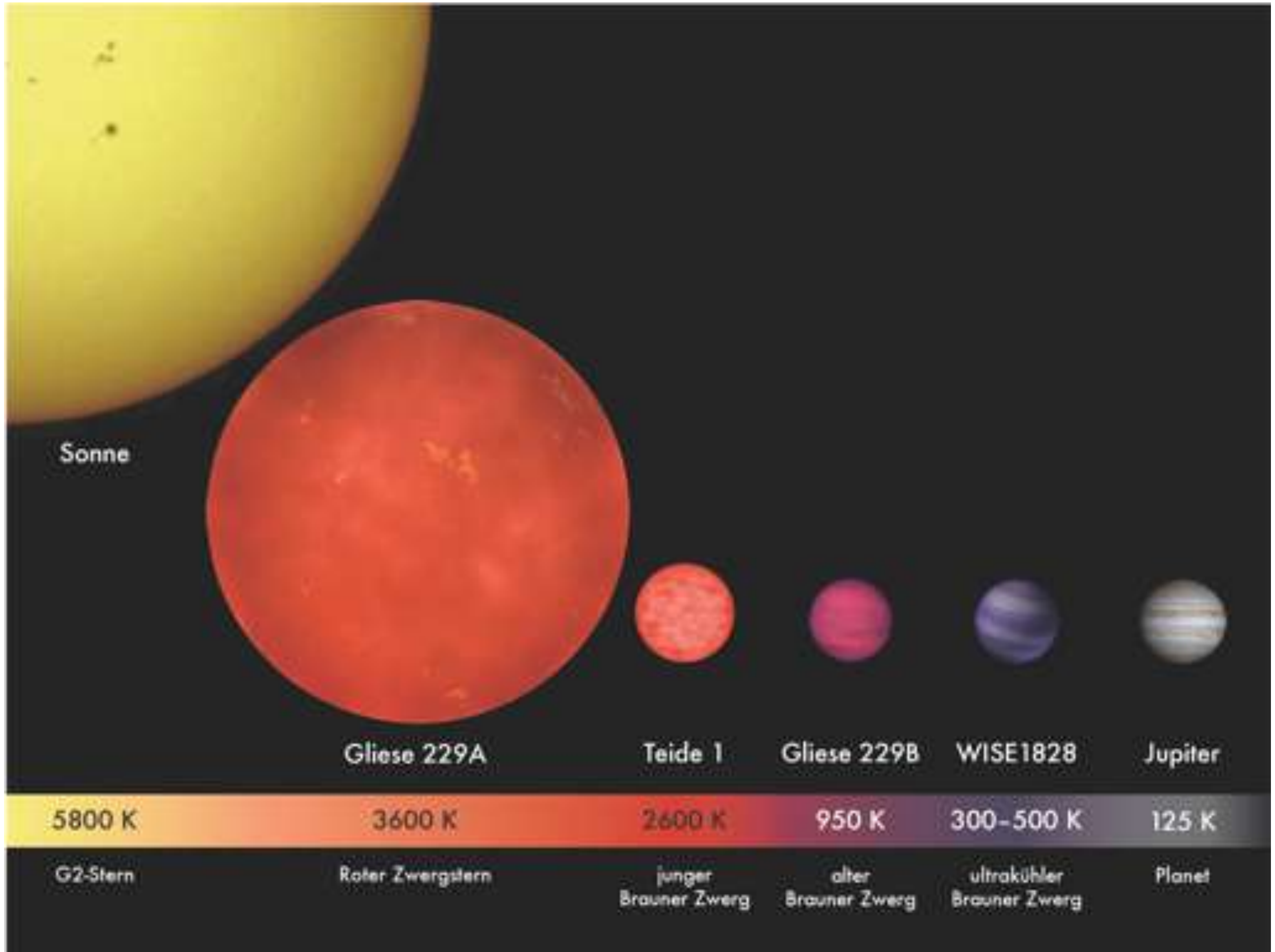
$CRF = (ASR_{cloudy} - OLR_{cloudy}) - (ASR_{clear} - OLR_{clear})$

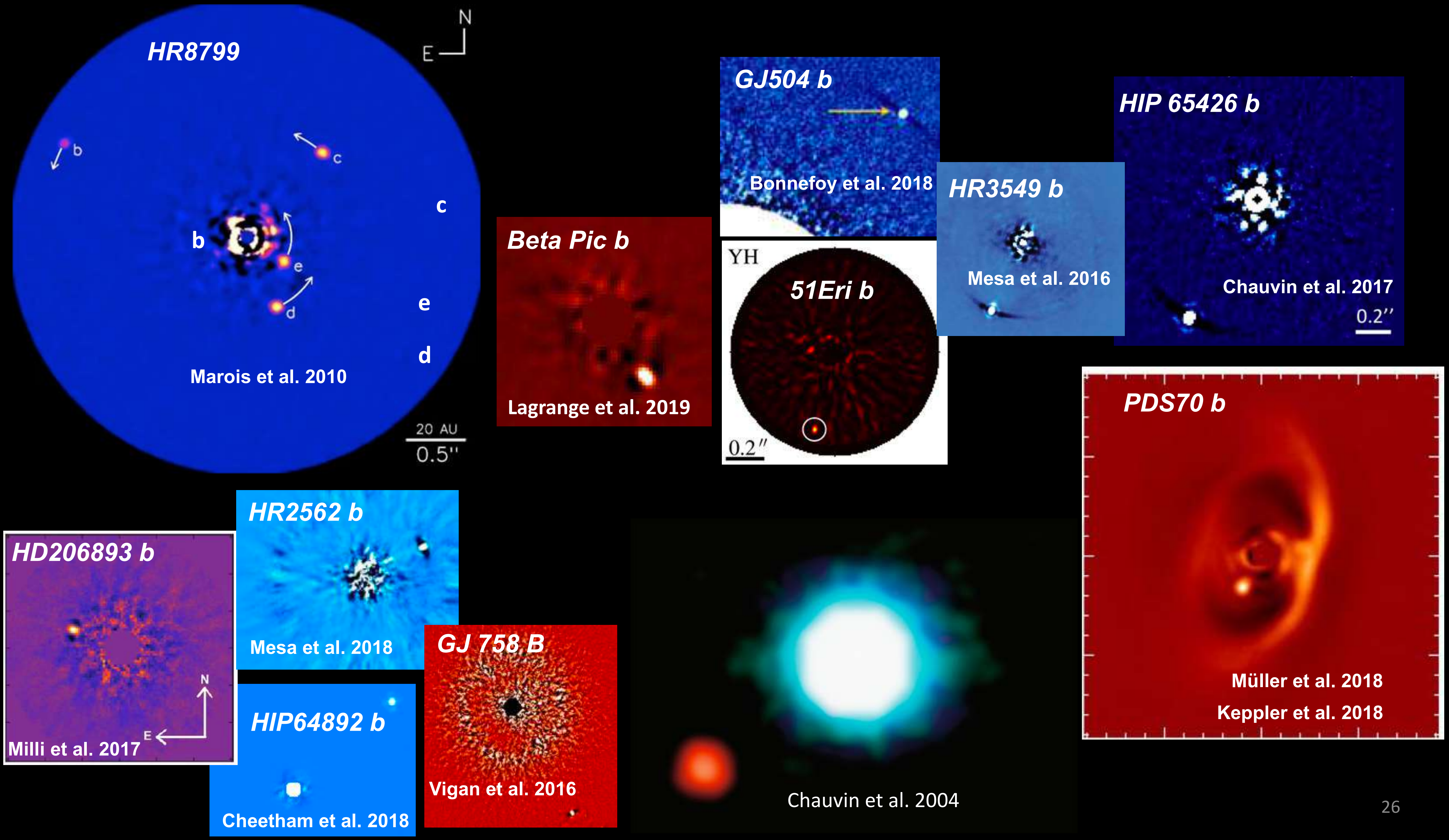
$CRF = (ASR_{cloudy} - ASR_{clear}) + (OLR_{clear} - OLR_{cloudy})$

$CRF = -20.6\ W/m^2$

Observations of clouds in brown dwarfs and young giant exoplanets

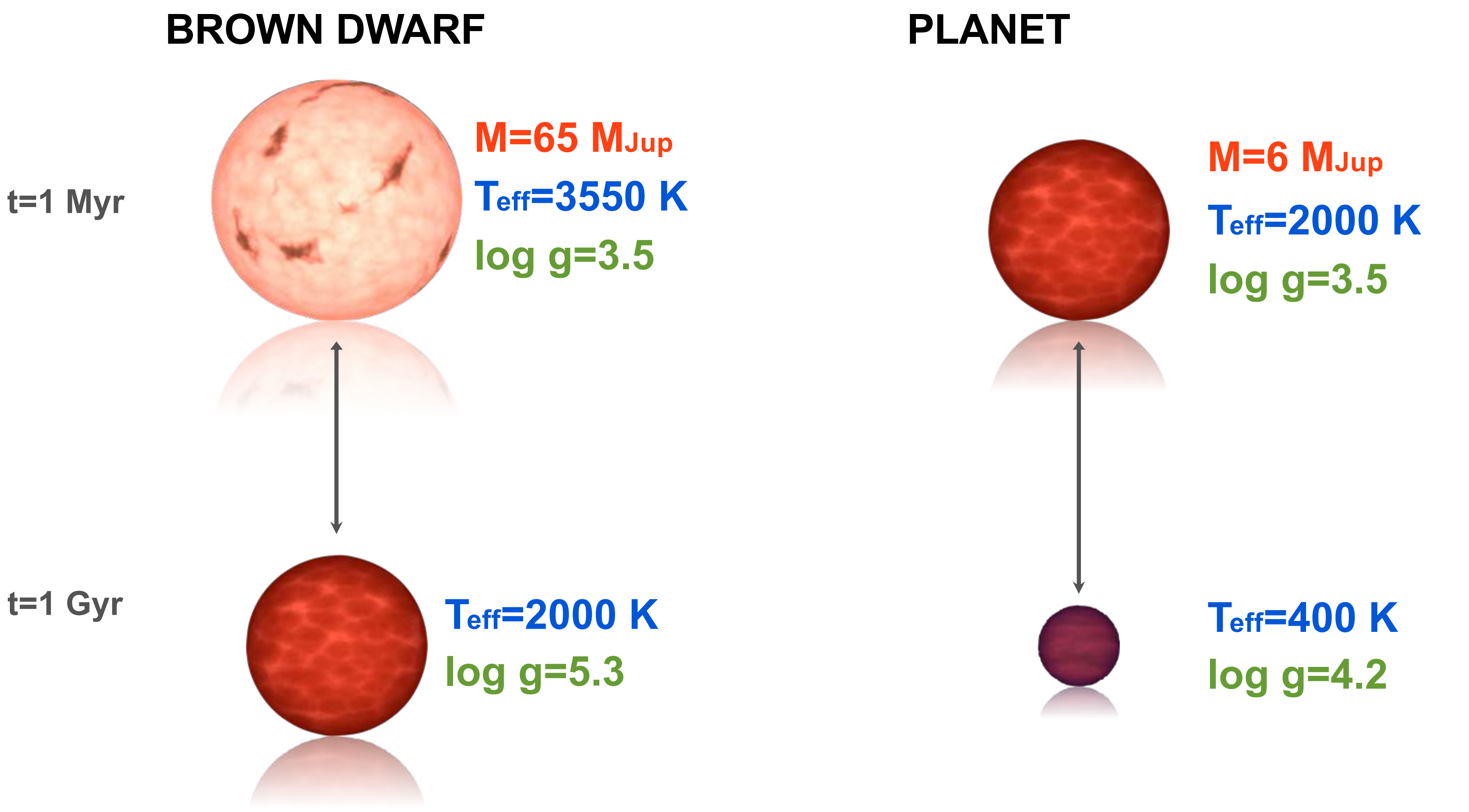
Transitions in brown dwarfs




HR8799
N
E
b
c
b
e
d
c
e
d
Marois et al. 2010
20 AU
0.5"
Beta Pic b
Lagrange et al. 2019
GJ504 b
Bonnefoy et al. 2018
YH
51Eri b
0.2″
HR3549 b
Mesa et al. 2016
HIP 65426 b
Chauvin et al. 2017
0.2″
PDS70 b
Müller et al. 2018
Keppler et al. 2018
HD206893 b
N
E
Milli et al. 2017
HR2562 b
Mesa et al. 2018
HIP64892 b
Cheetham et al. 2018
GJ 758 B
Vigan et al. 2016
Chauvin et al. 2004

Comparison brown dwarfs vs imaged giant planets

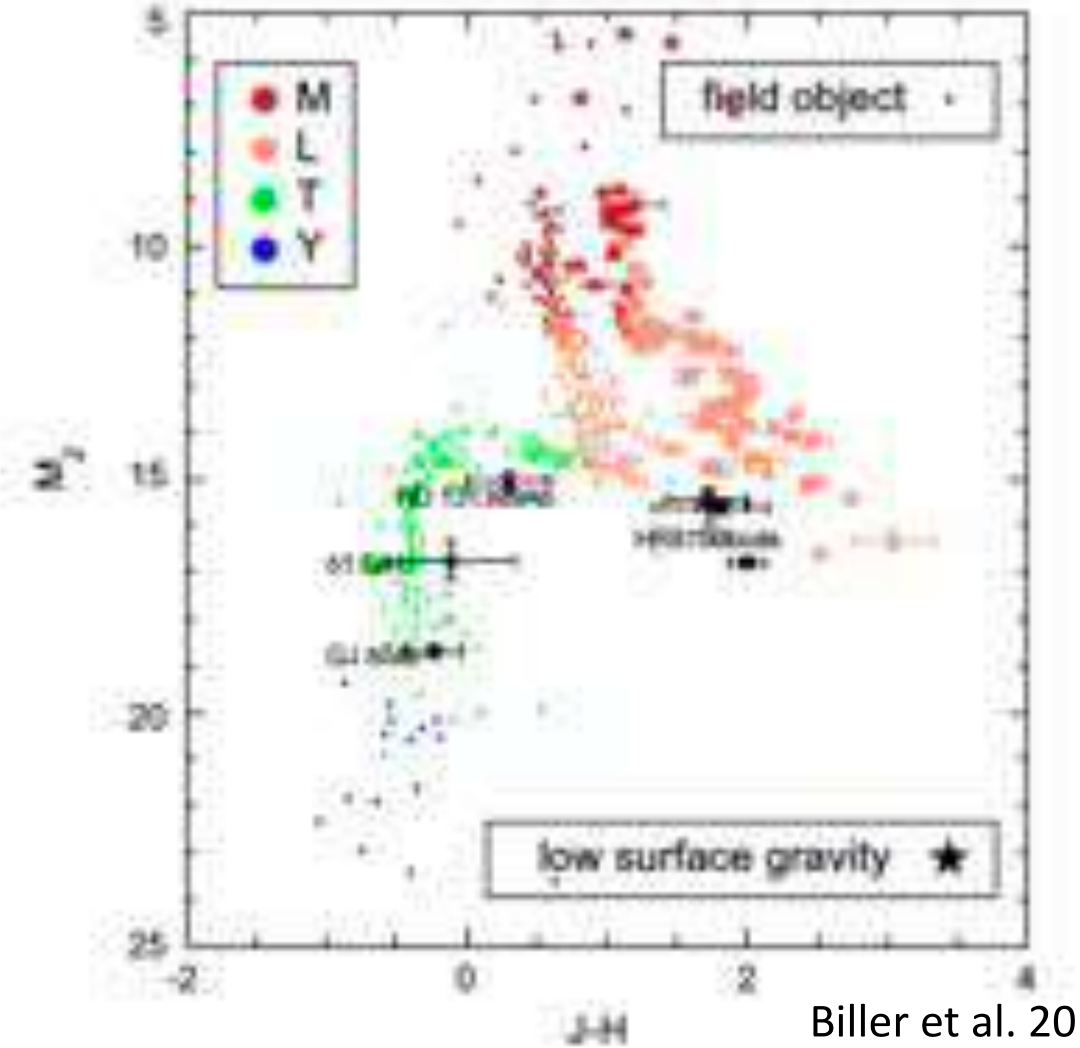
Imaged planets are young ⇒ low surface gravity



Observations of clouds in brown dwarfs and young giant exoplanets

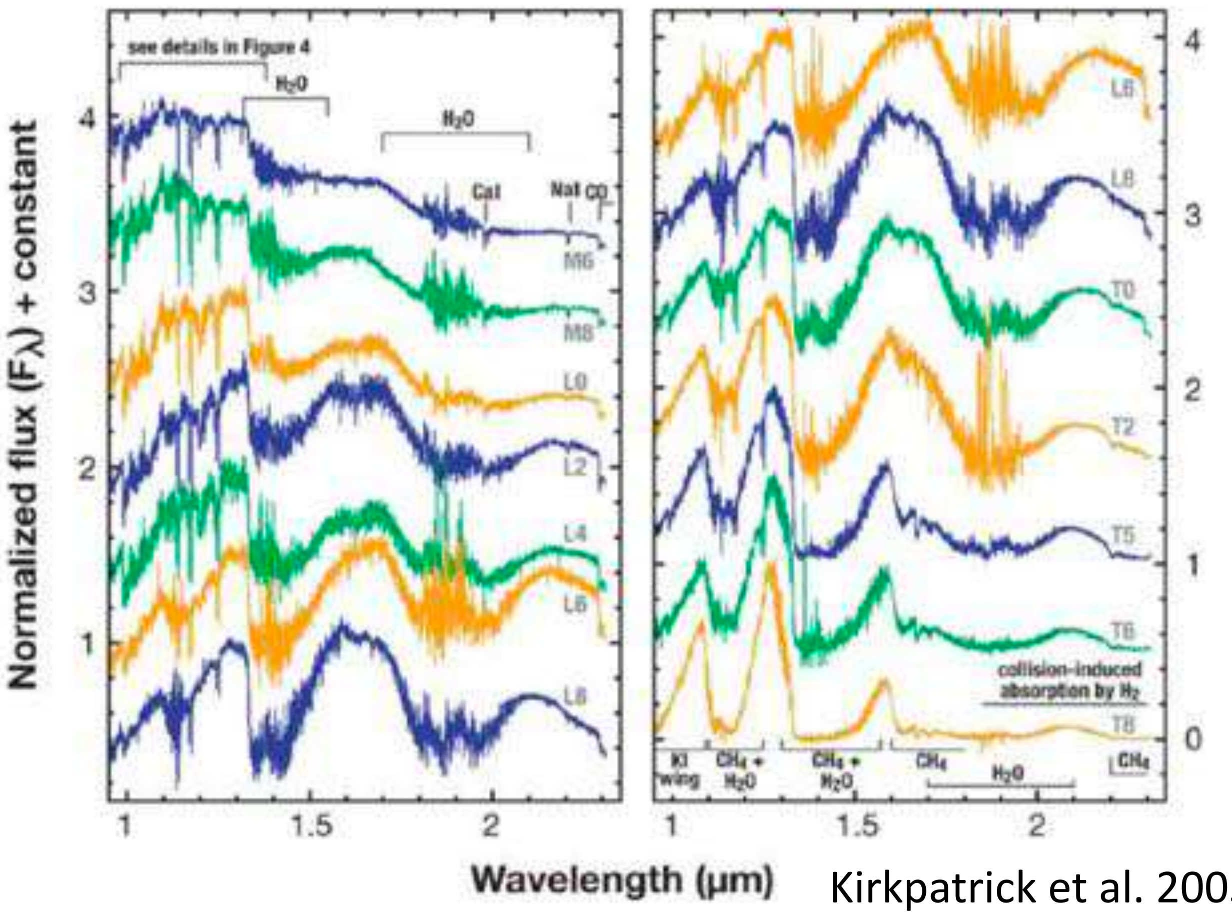
Transitions in brown dwarfs

Photometric sequence



Biller et al. 2017

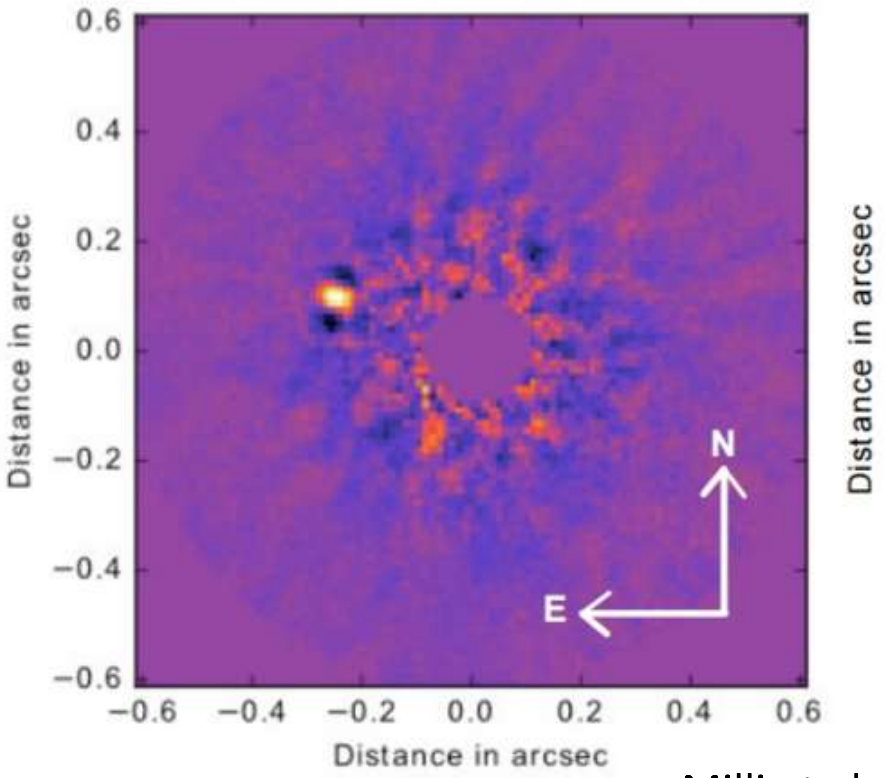
Spectrosopic sequence



Kirkpatrick et al. 2005

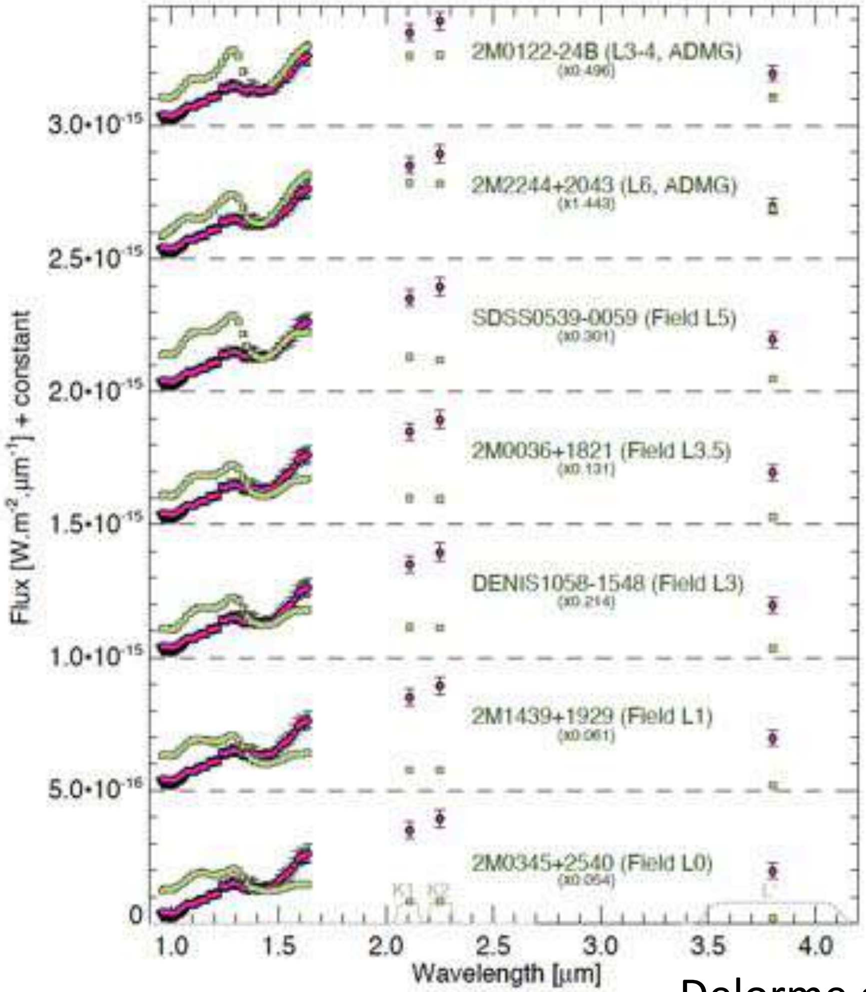
Observations of clouds in brown dwarfs and young giant exoplanets

The red colors and featureless spectra of young giant exoplanets



Milli et al. 2017

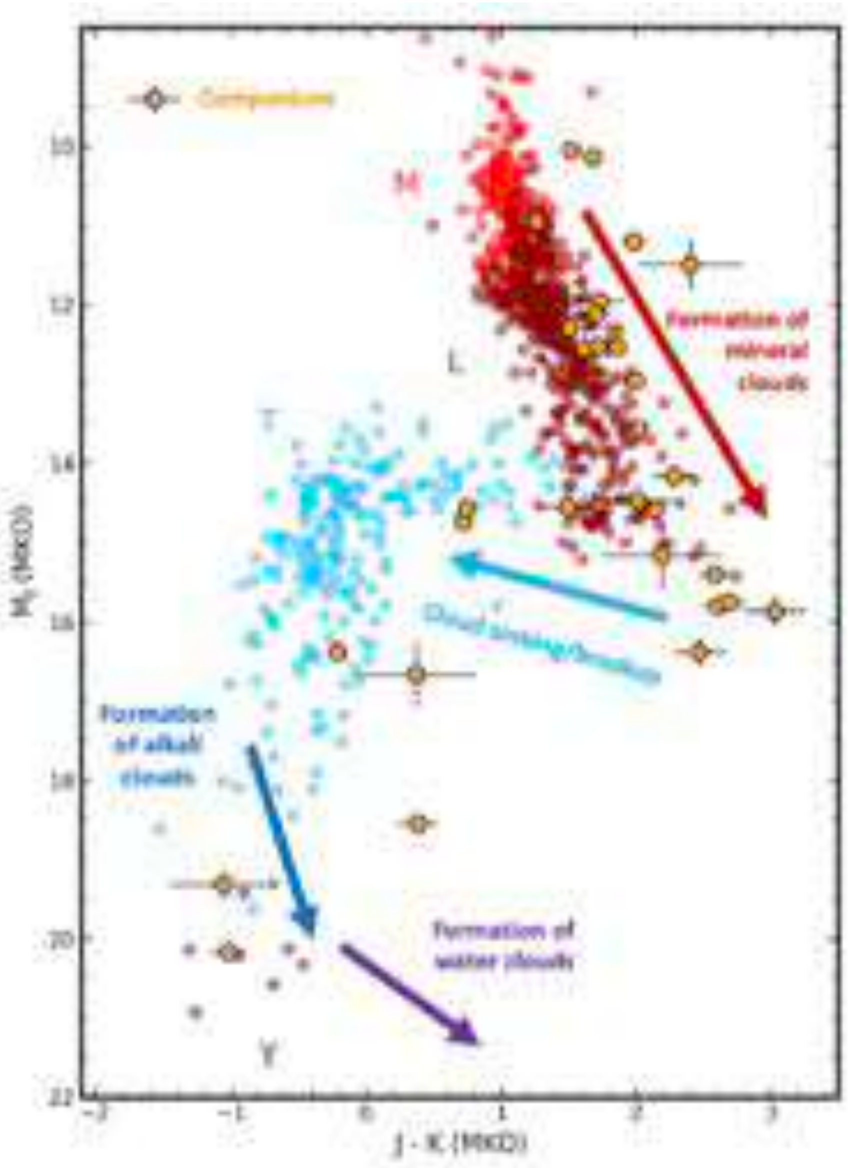
HD206893 b’s spectrum = almost a black body

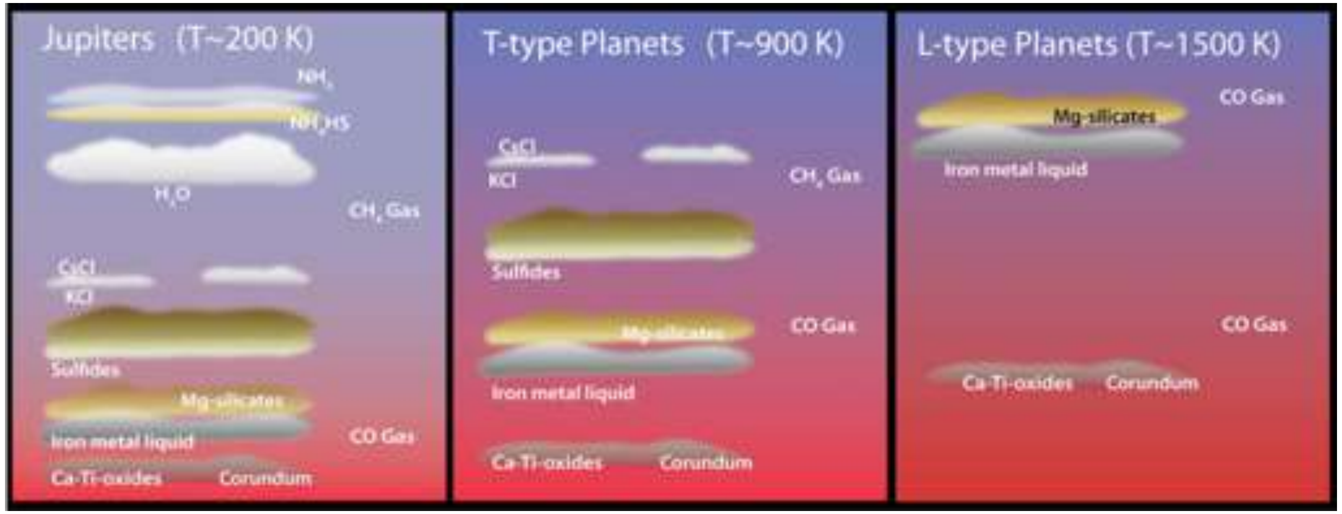


Delorme et al. 2017

Observations of clouds in brown dwarfs and young giant exoplanets

Clouds as the driver of the LT-transition

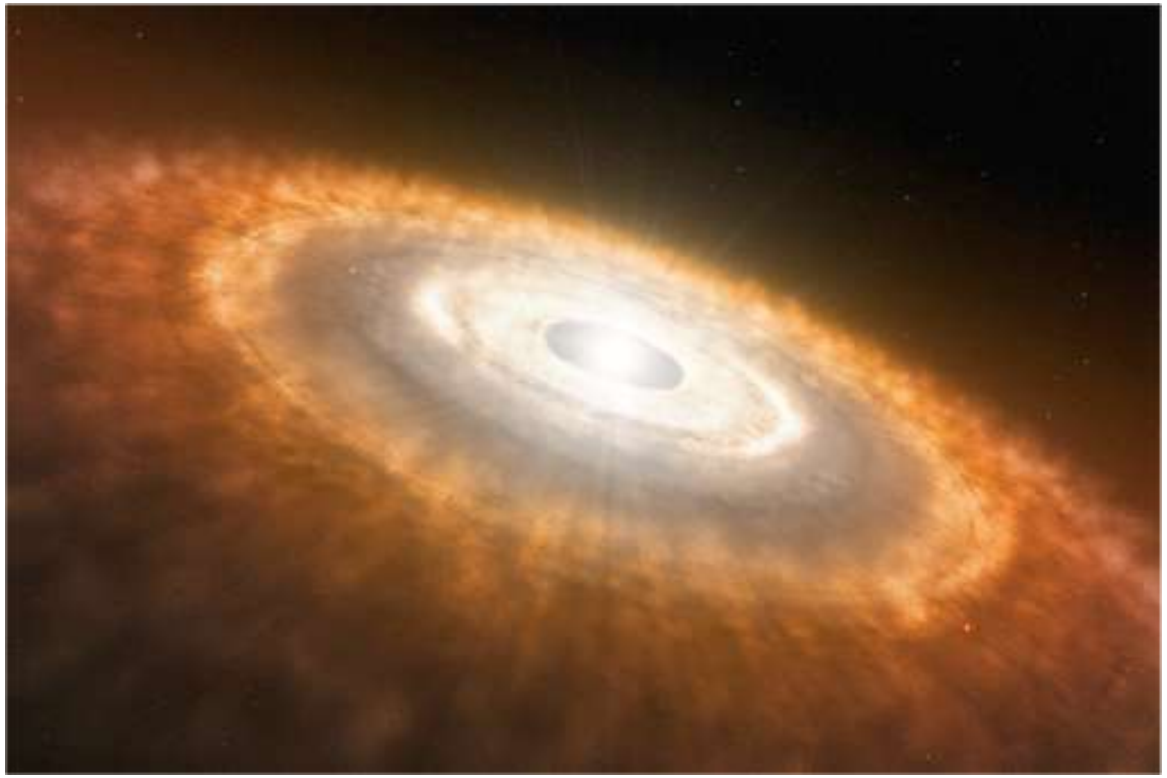


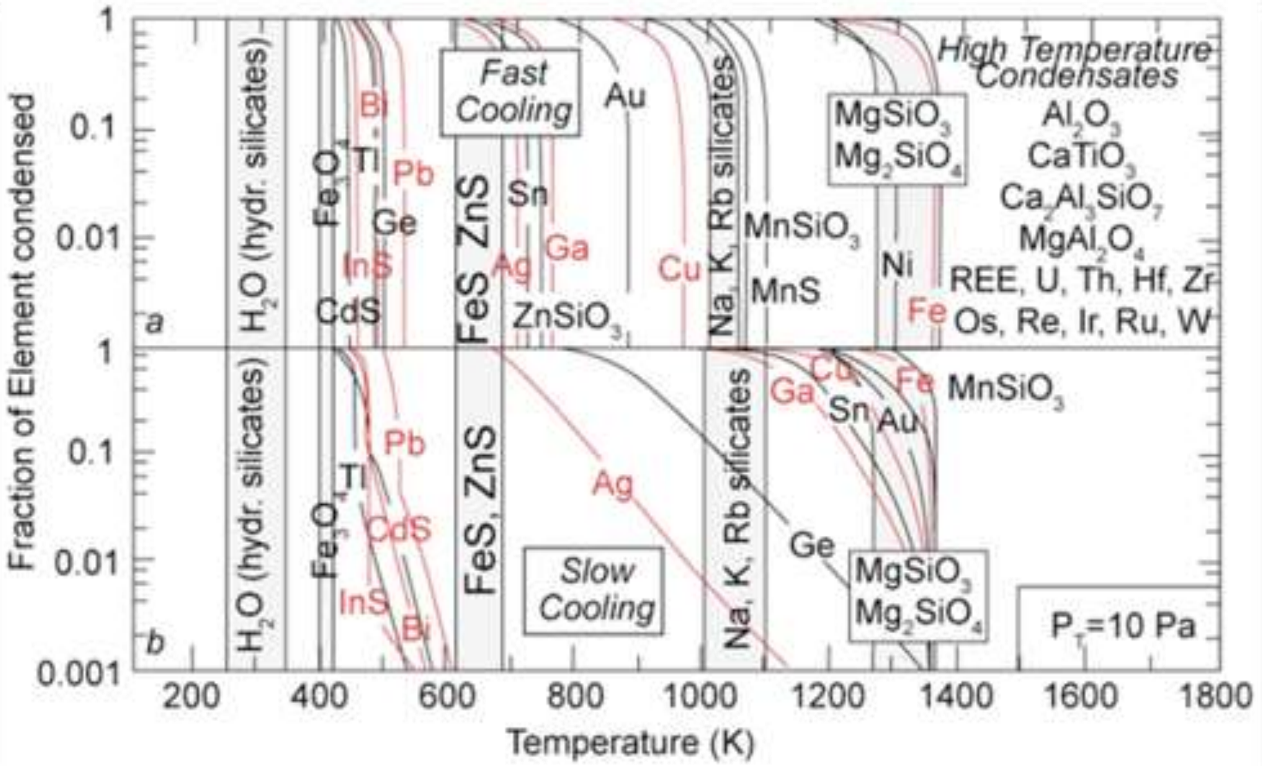


Gao et al. 2020

Observations of clouds in brown dwarfs and young giant exoplanets

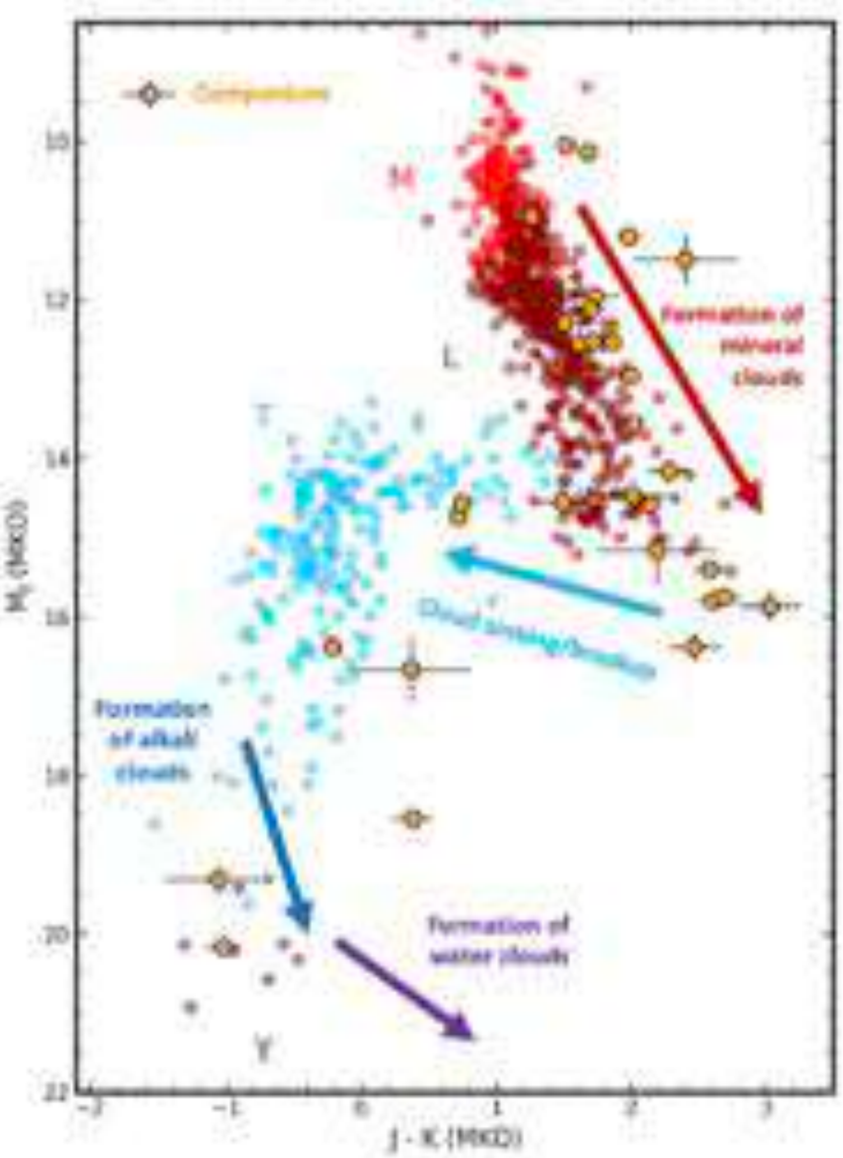
Analogy between cloud formation and the condensation sequence in protoplanetary disks

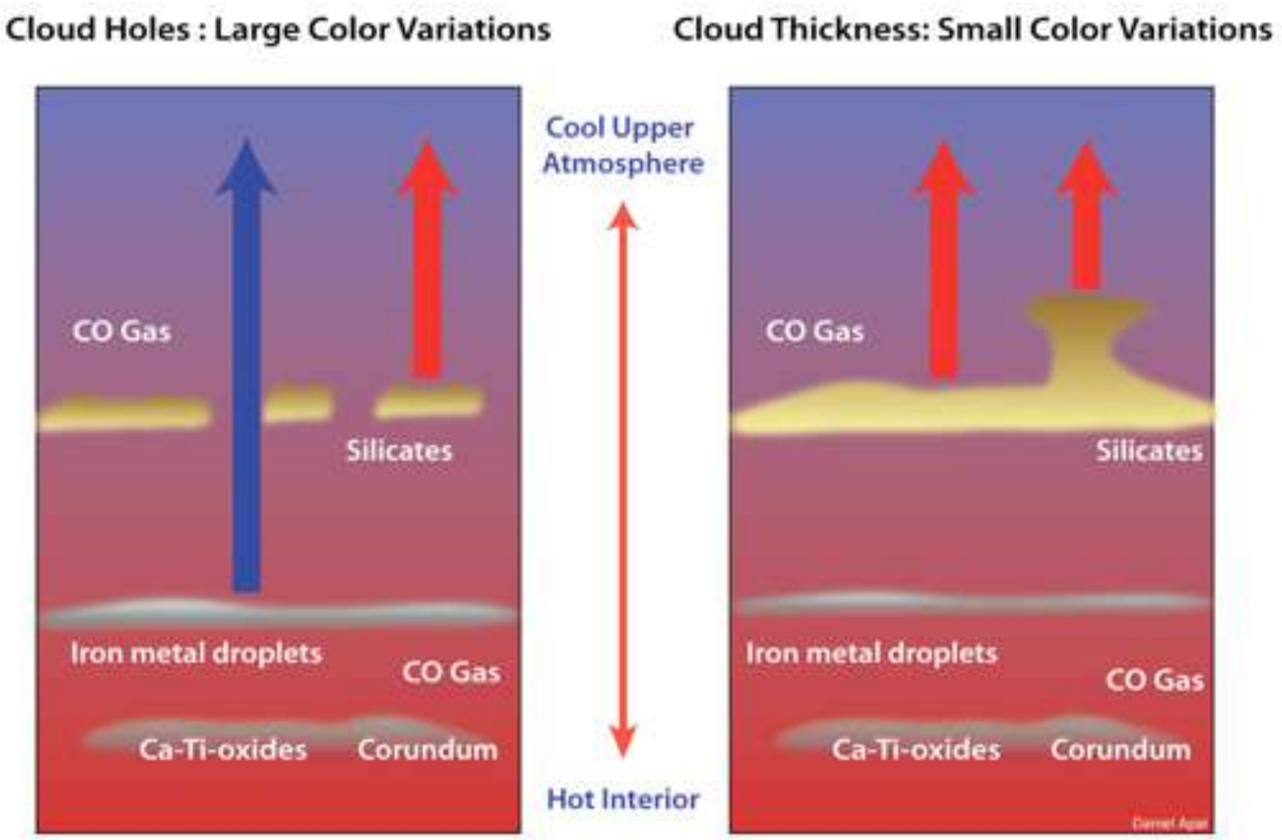




Observations of clouds in brown dwarfs and young giant exoplanets

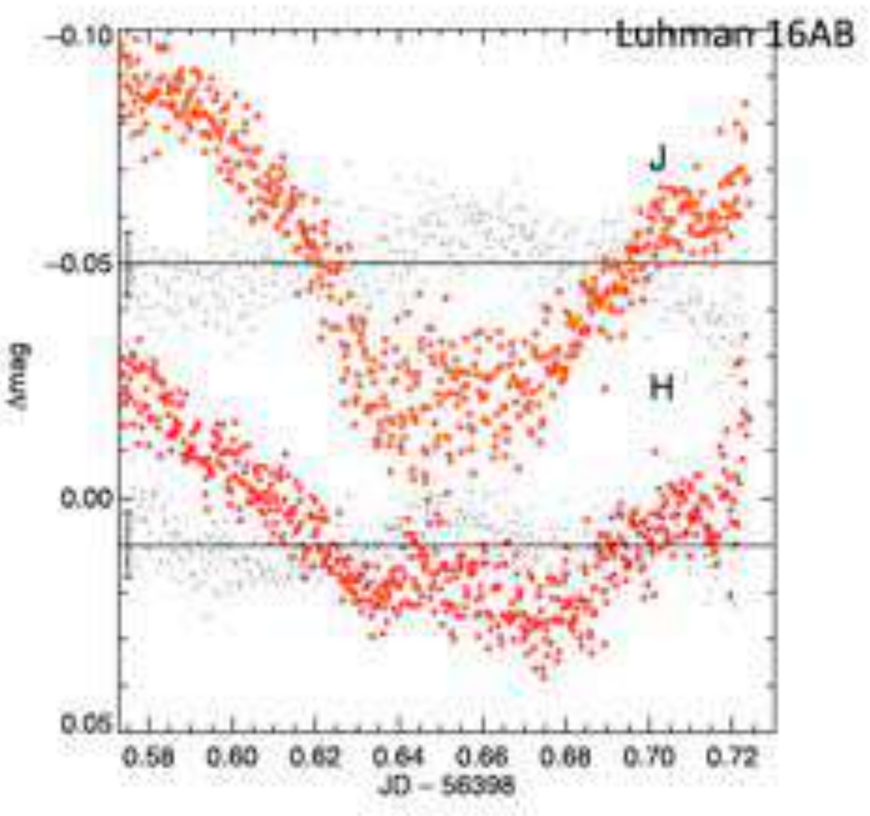
Cloud inhomogeneities at the LT-transition

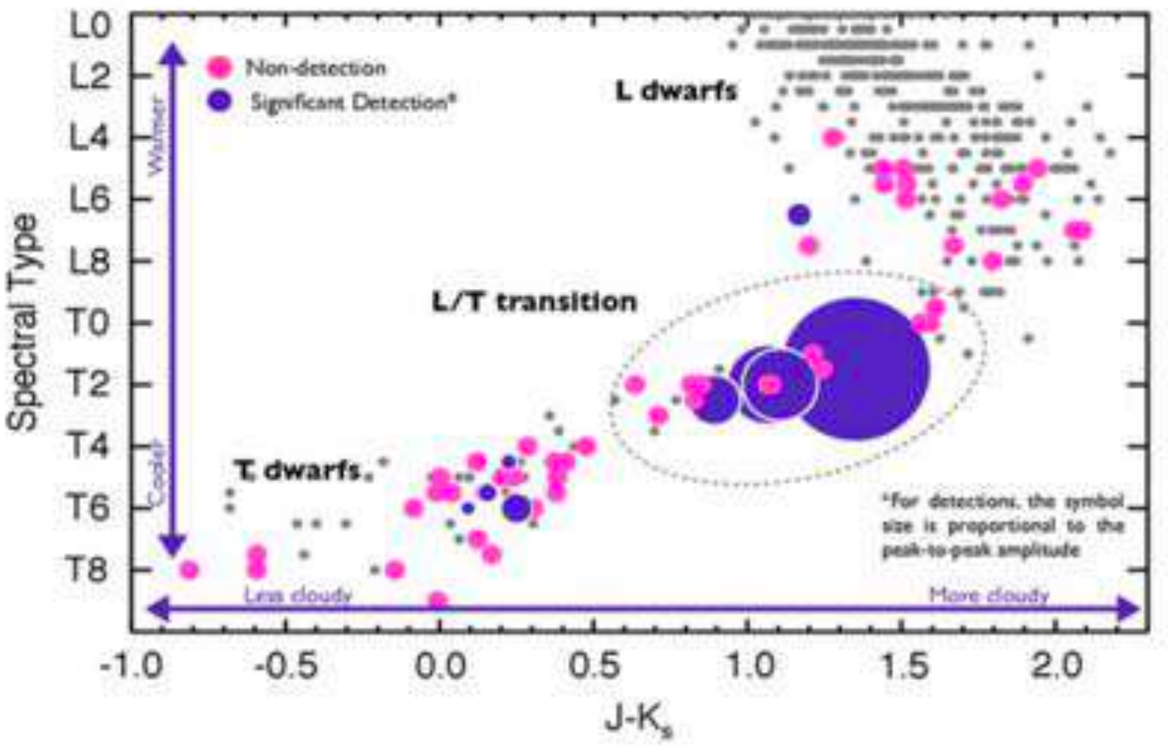




Observations of clouds in brown dwarfs and young giant exoplanets

Variability of brown dwarfs at the L-T transition

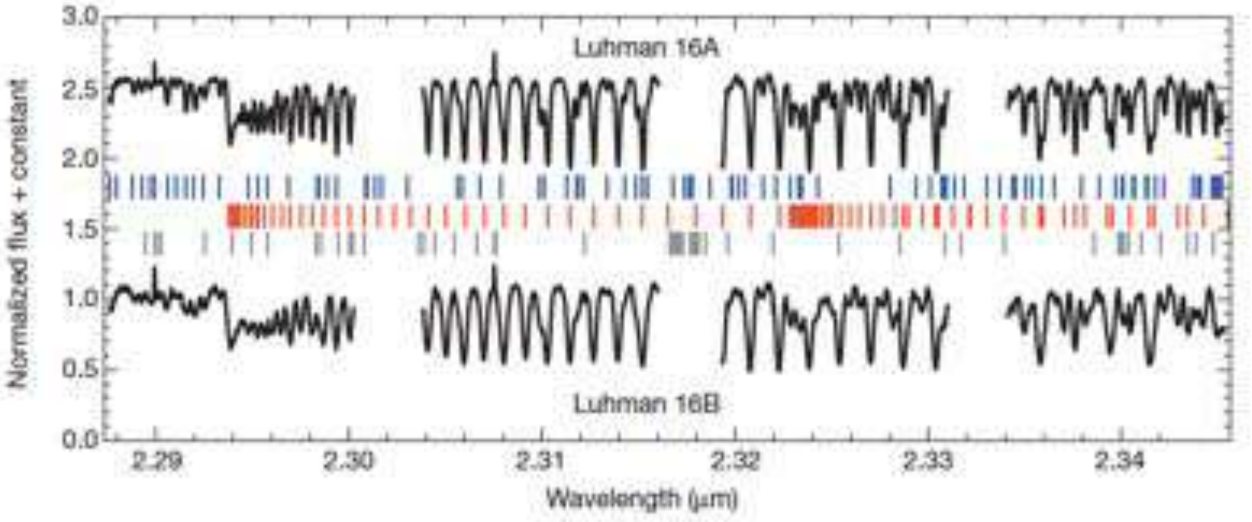


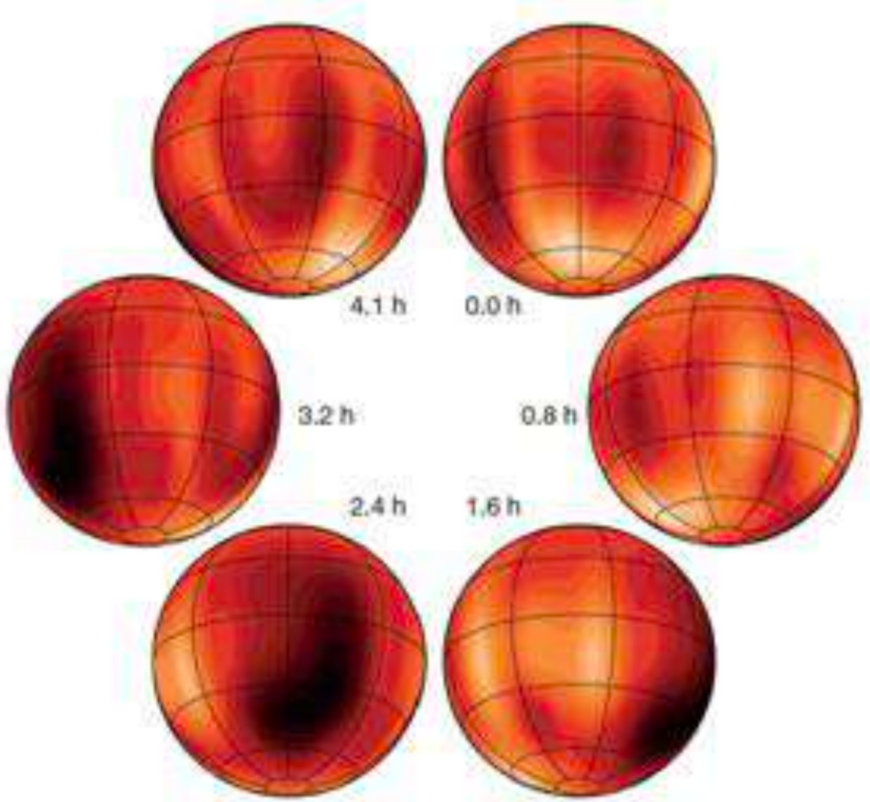


Biller et al. 2017

Observations of clouds in brown dwarfs and young giant exoplanets

Mapping of brown dwarfs at the LT-transition





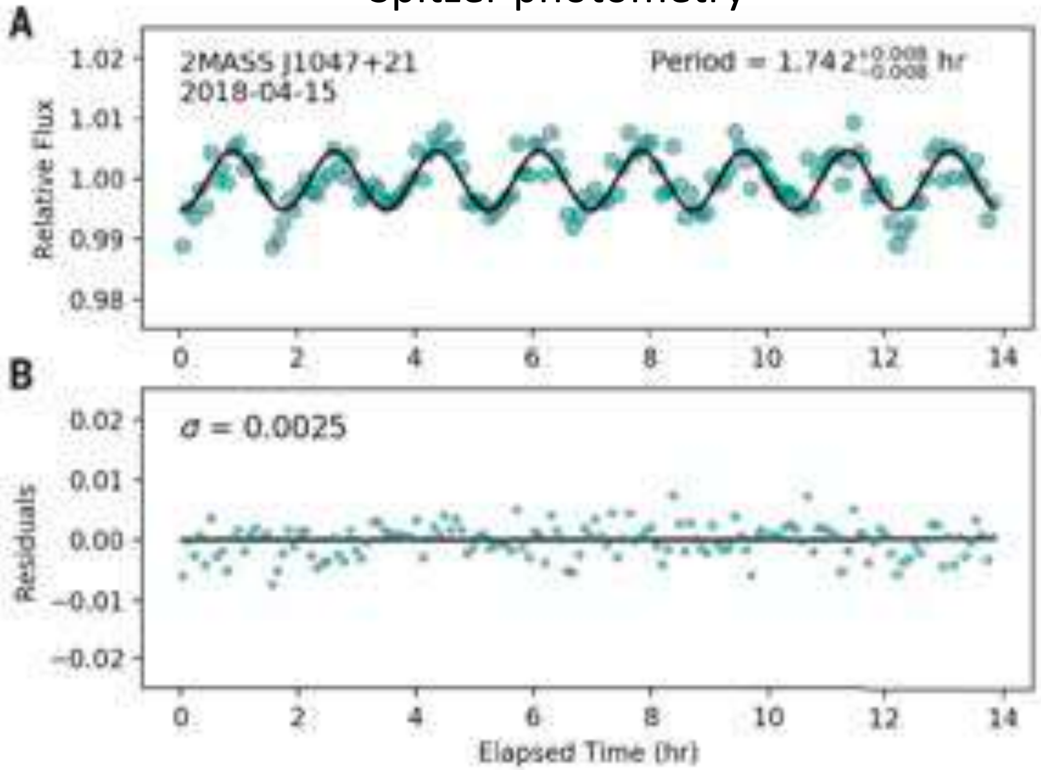
Crossfield et al. 2014

Inhomogeneity in the cloud cover

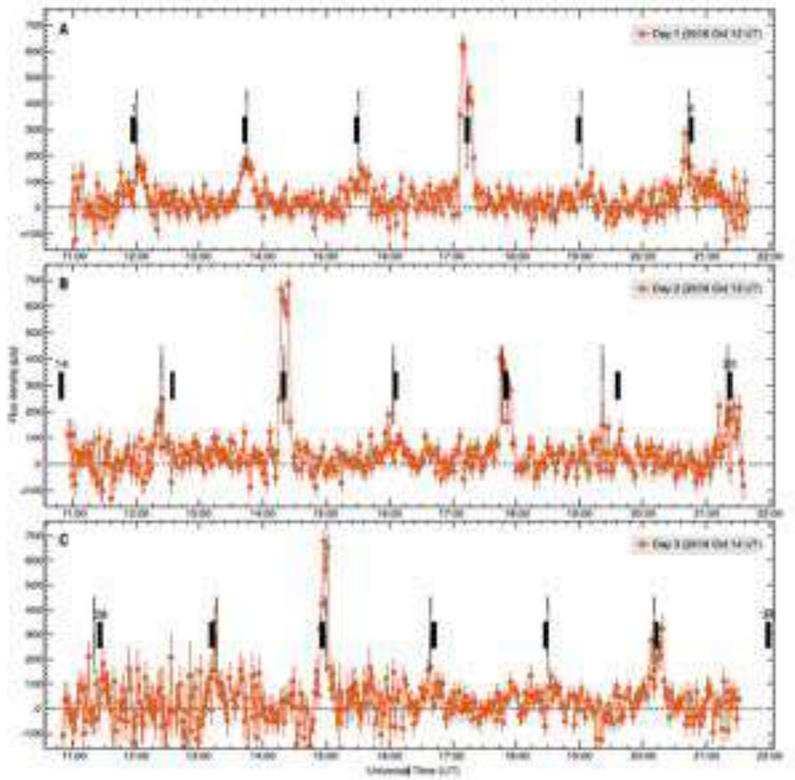
Observations of clouds in brown dwarfs and young giant exoplanets

Measurement of wind speed

Spitzer photometry



Radio light curve



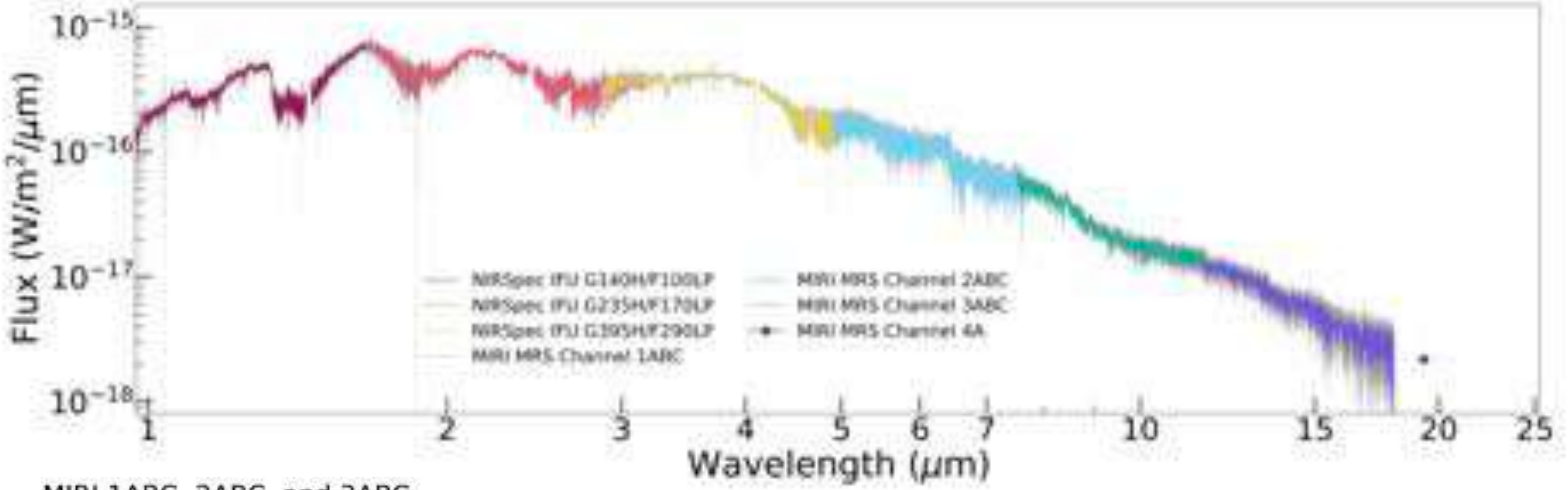
Allers et al. 2020

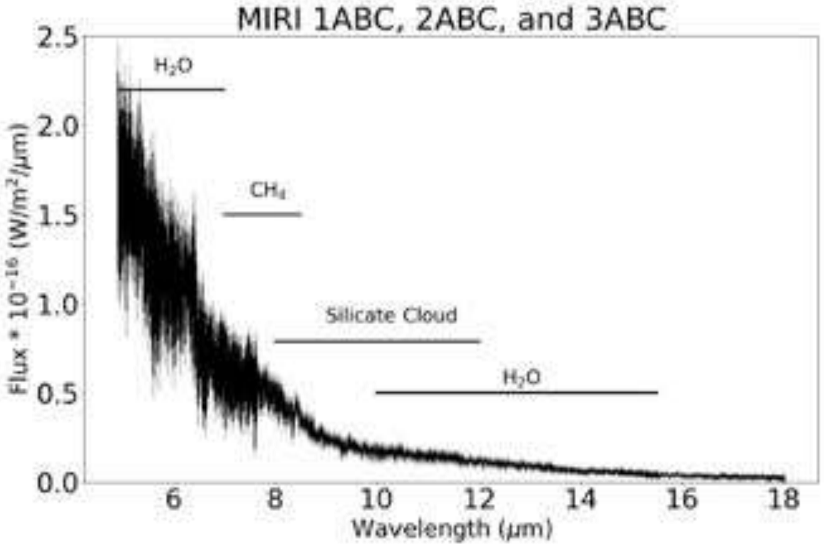
Difference between measured period from photometry (1.741h; clouds) and from radio emission (~1.762h; interior)
=> Eastward jet with wind speed of 650 +/- 310 m/s

Observations of clouds in brown dwarfs and young giant exoplanets

Silicate feature

NIRSpec+MIRI spectrum of VHS 1256 b (ERS program)





Miles et al. 2022

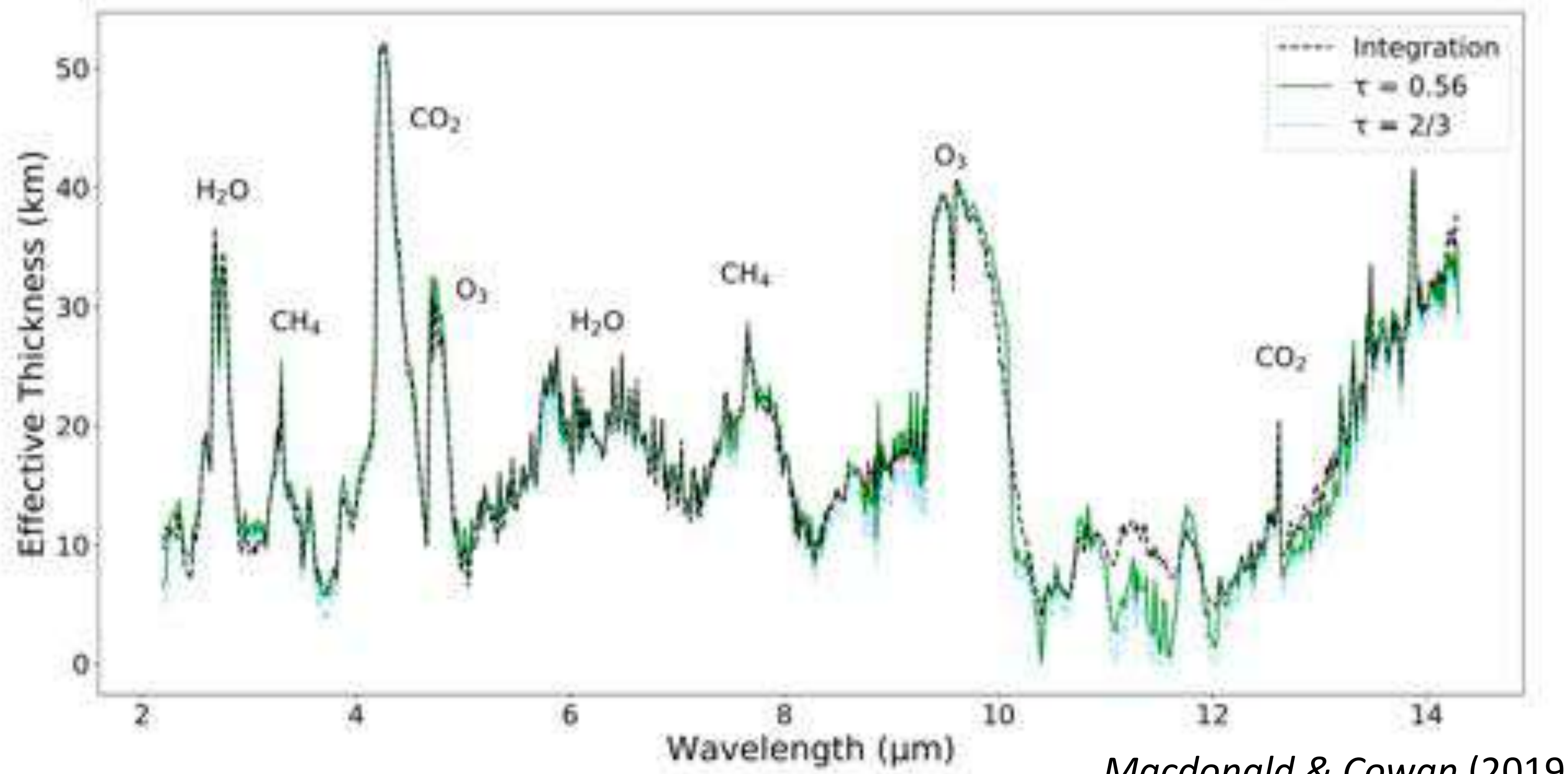
Silicate absorbing band at 10 µm !

Observation of clouds/haze for transiting exoplanets

Observations of clouds & haze in exoplanets

Transit spectroscopy

Synthetic Earth's transit spectrum

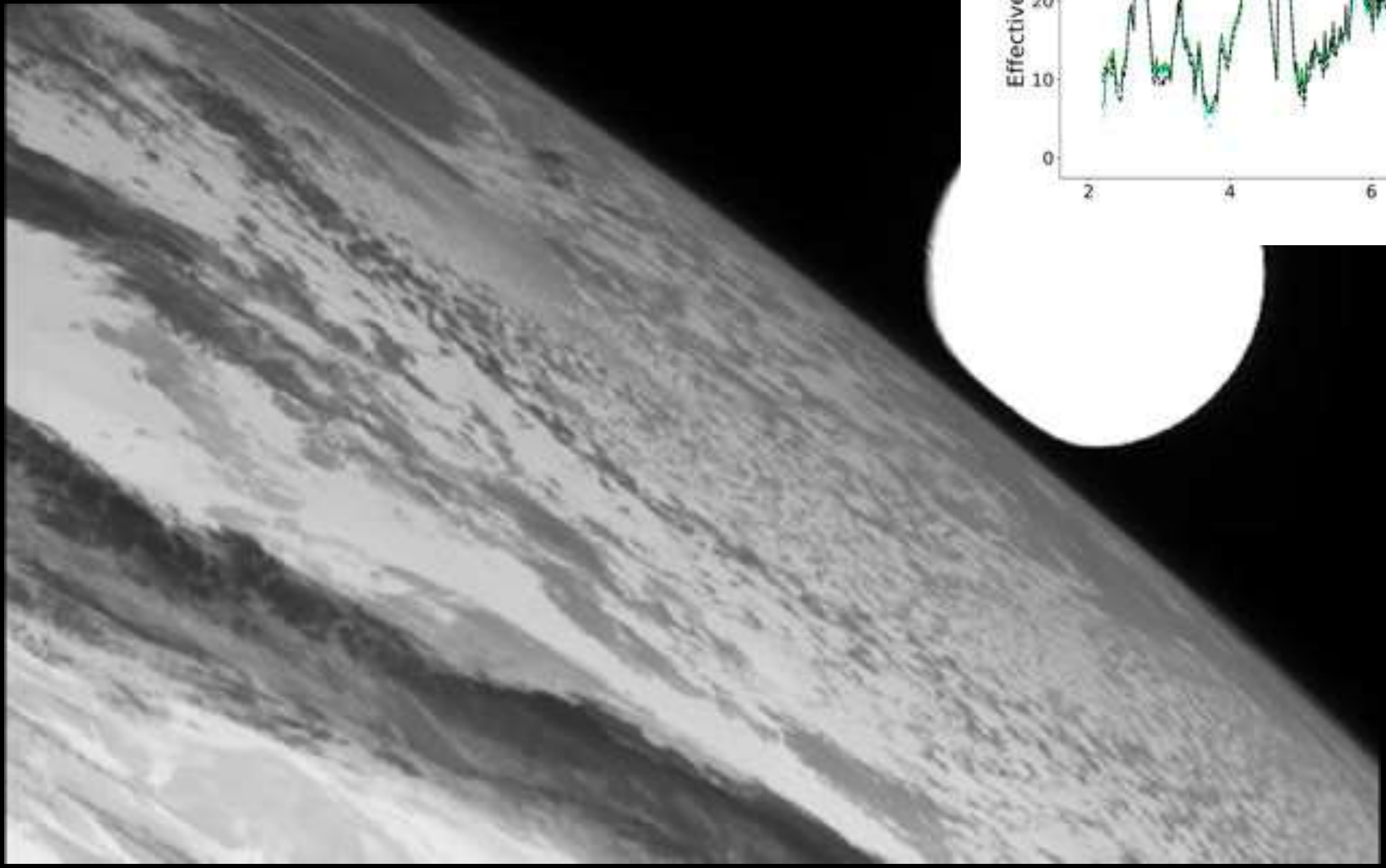


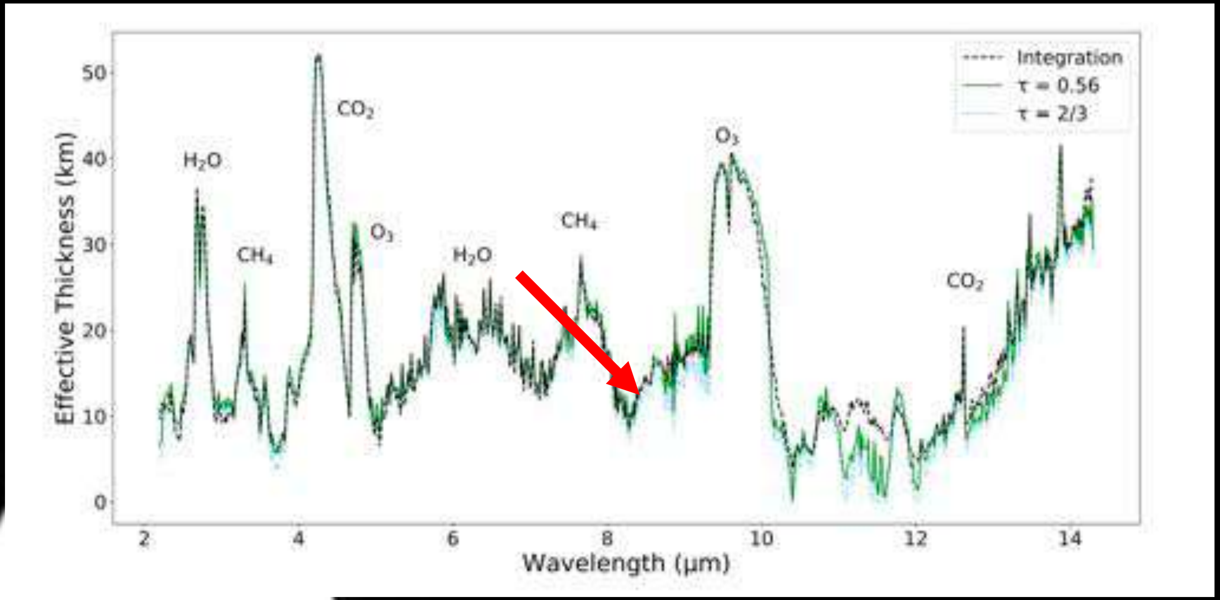
Macdonald & Cowan (2019)

Real color

Credit: Himawary/Simon Proud/Vivien Parmentier

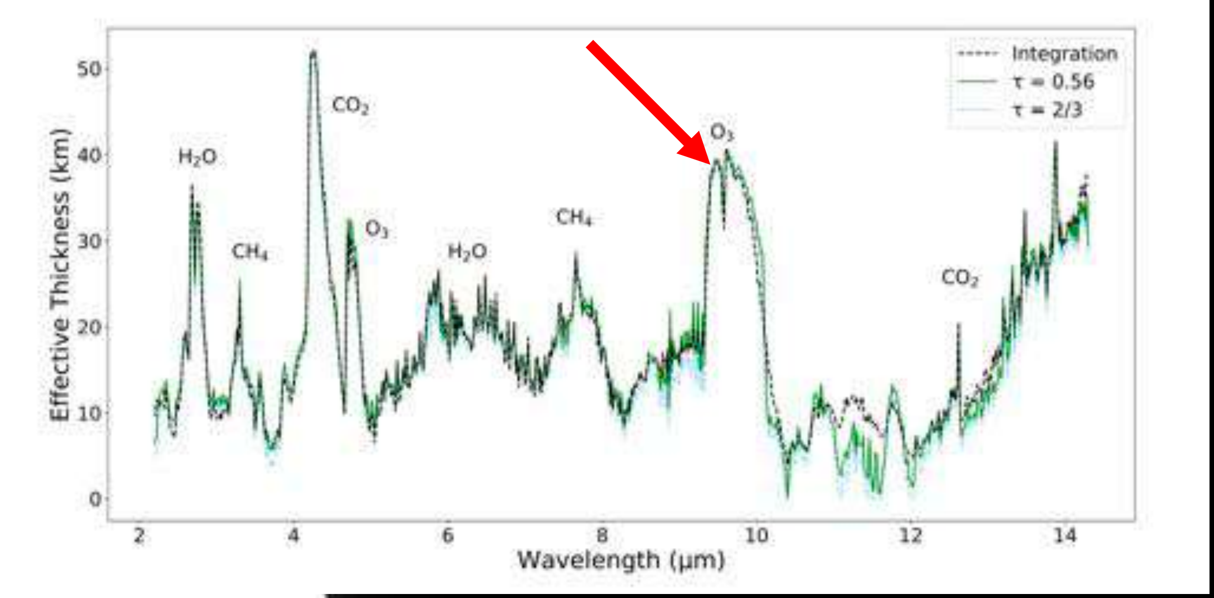
8.6 microns
spectral window (15 km)

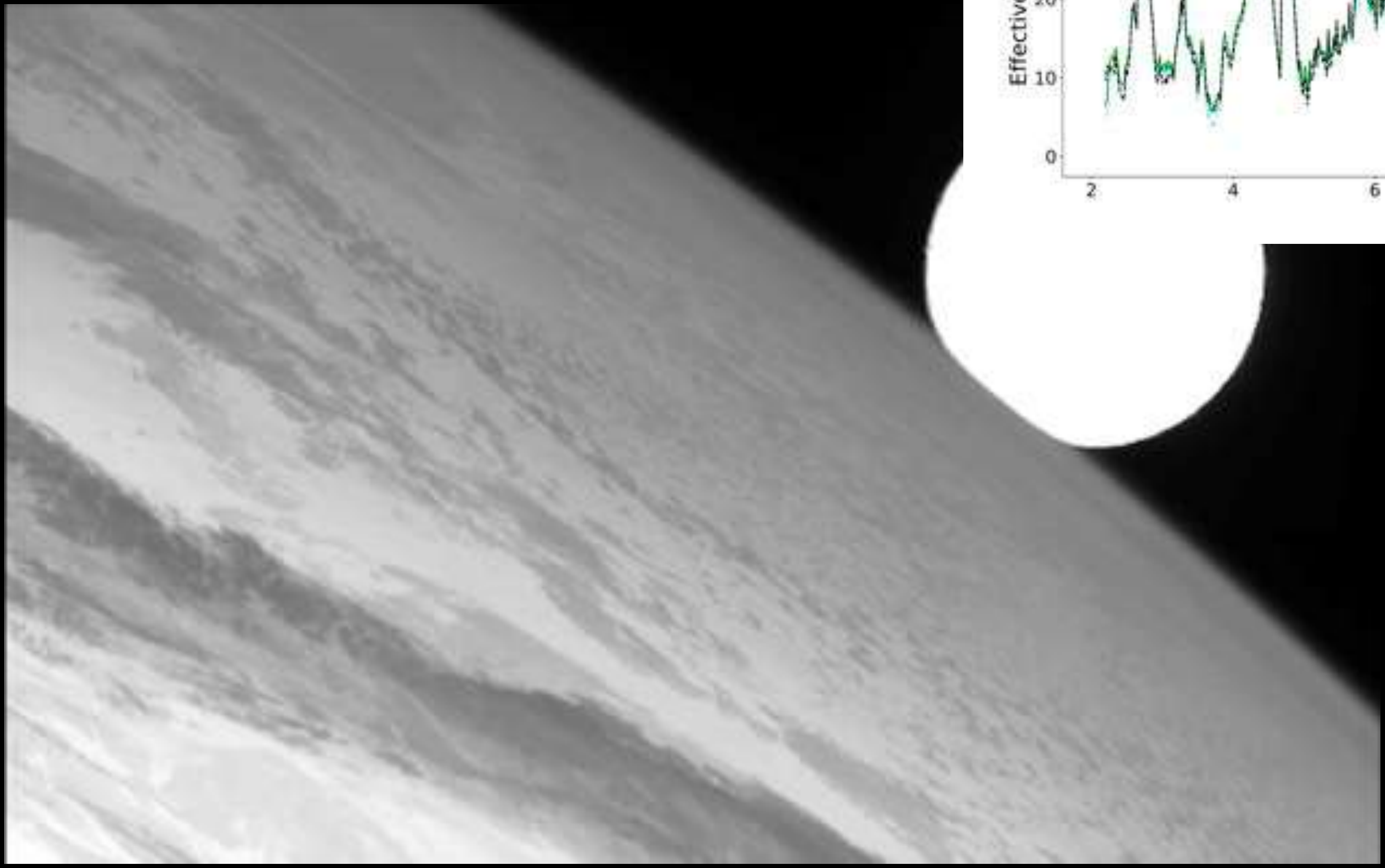




Credit: Himawary/Simon Proud/Vivien Parmentier

9.6 microns
O_3 band (40 km)

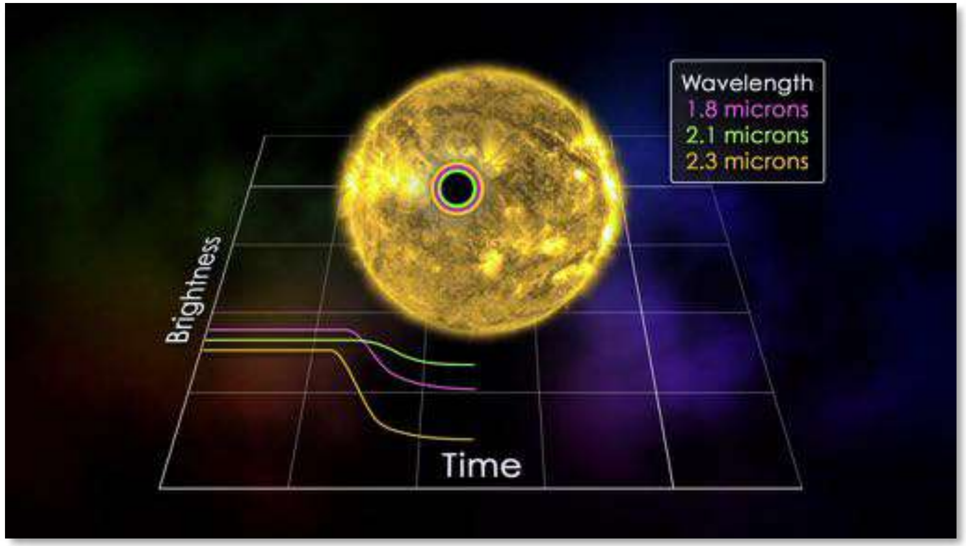




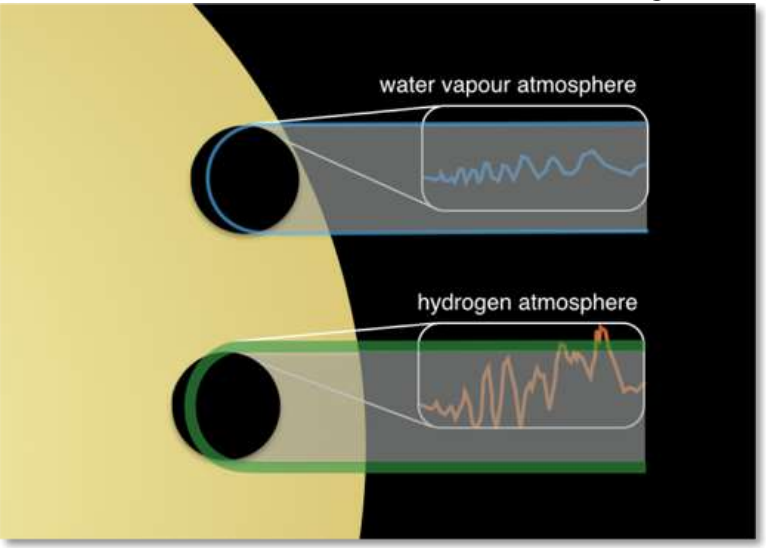
Credit: Himawary/Simon Proud/Vivien Parmentier

Observations of clouds & haze in exoplanets

Transit spectroscopy



Effect of mean molecular weight



Variation of transit depth:

$$\Delta\delta_{tra} = \frac{\pi(R_p + N_H H)^2}{\pi R_\star^2} - \frac{\pi R_p^2}{\pi R_\star^2} \approx \frac{2 N_H R_p H}{R_\star^2}$$

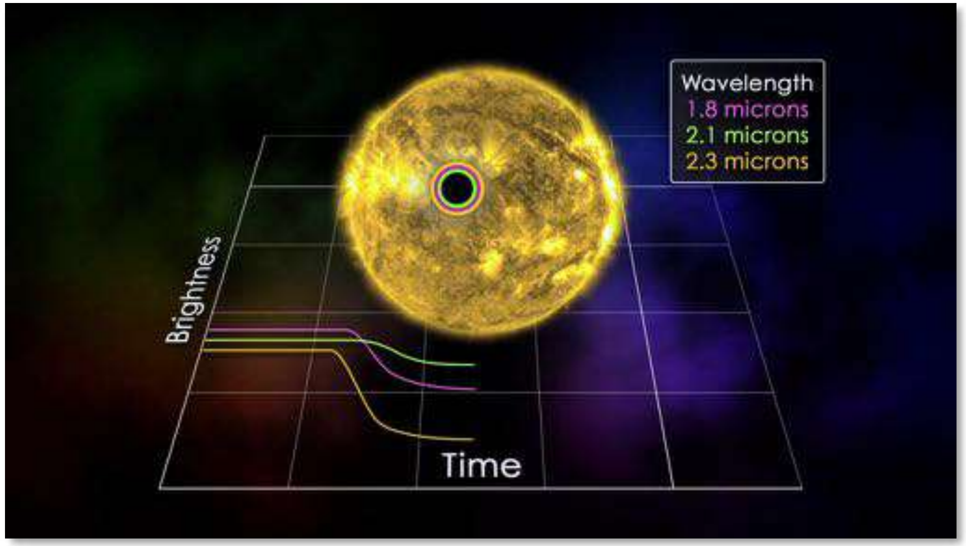
Scale height: $H = \frac{RT}{Mg}$; Number of scale heights: $N_H \approx 5$ (for low resolution)

For an Sun-like star:

- Hot Jupiter (T=1300 K, g=25 m s^{-2}, M=2.3 g/mol): $\delta_{tra} \approx 0.01$, $\Delta\delta_{tra} \approx 4.10^{-4}$
- Earth-like planet (T=280 K, g=10 m s^{-2}, M=28g/mol): $\delta_{tra} \approx 10^{-4}$, $\Delta\delta_{tra} \approx 2.10^{-6}$

Observations of clouds & haze in exoplanets

Transit spectroscopy



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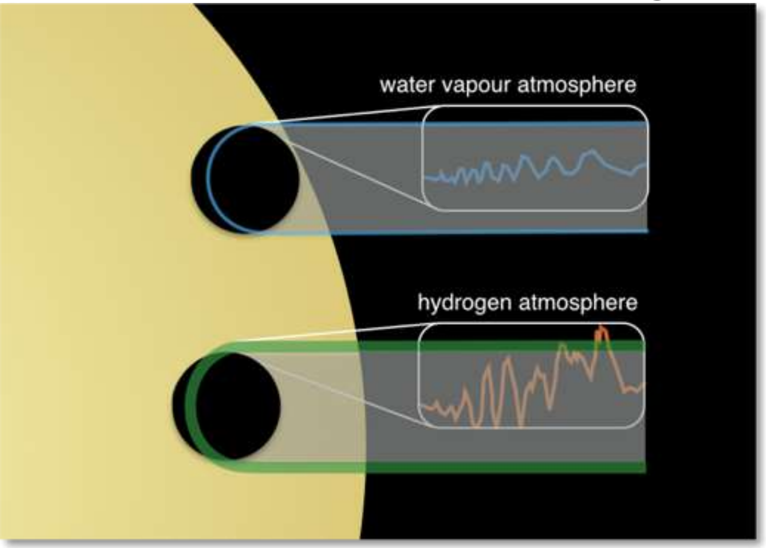

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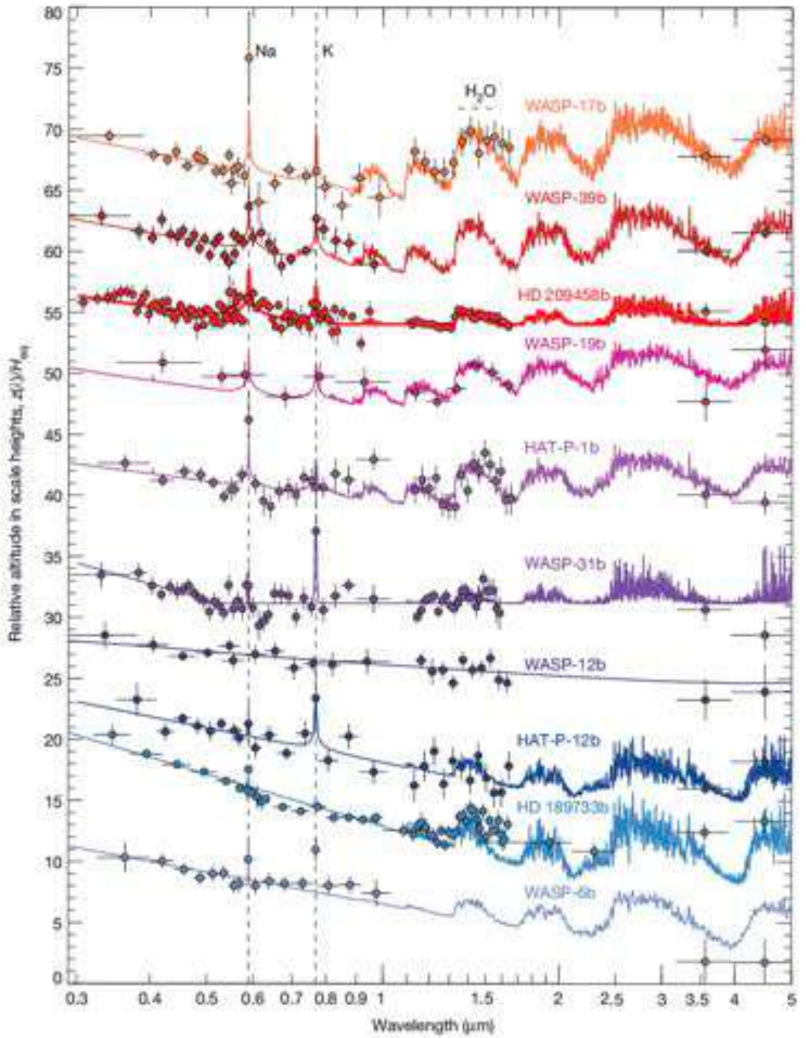
Scale height: $H = \frac{RT}{Mg}$; Number of scale heights: $N_H \approx 5$ (for low resolution)

For Trappist-1 (0.015 R_S):
- Hot Jupiter (T=1300 K, g=25 m s^{-2}, M=2.3 g/mol): $\delta_{tra} \approx 0.7$, $\Delta\delta_{tra} \approx 2.10^{-2}$
- Earth-like planet (T=280 K, g=10 m s^{-2}, M=28g/mol): $\delta_{tra} \approx 6.10^{-3}$, $\Delta\delta_{tra} \approx 10^{-4}$

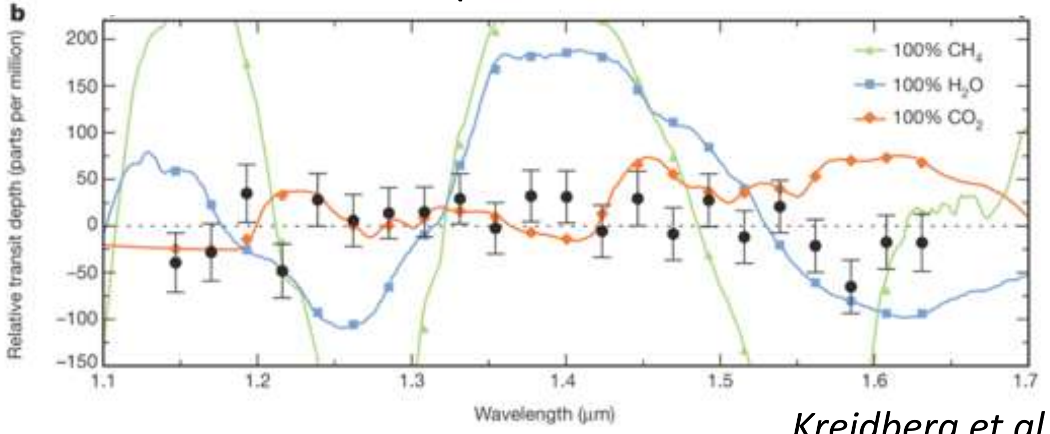
Observations of clouds & haze in exoplanets

A continuum from cloudy to cloud-free planets by transit observations



Sing et al. (2015)

Flat transit spectrum of GJ 1214 b

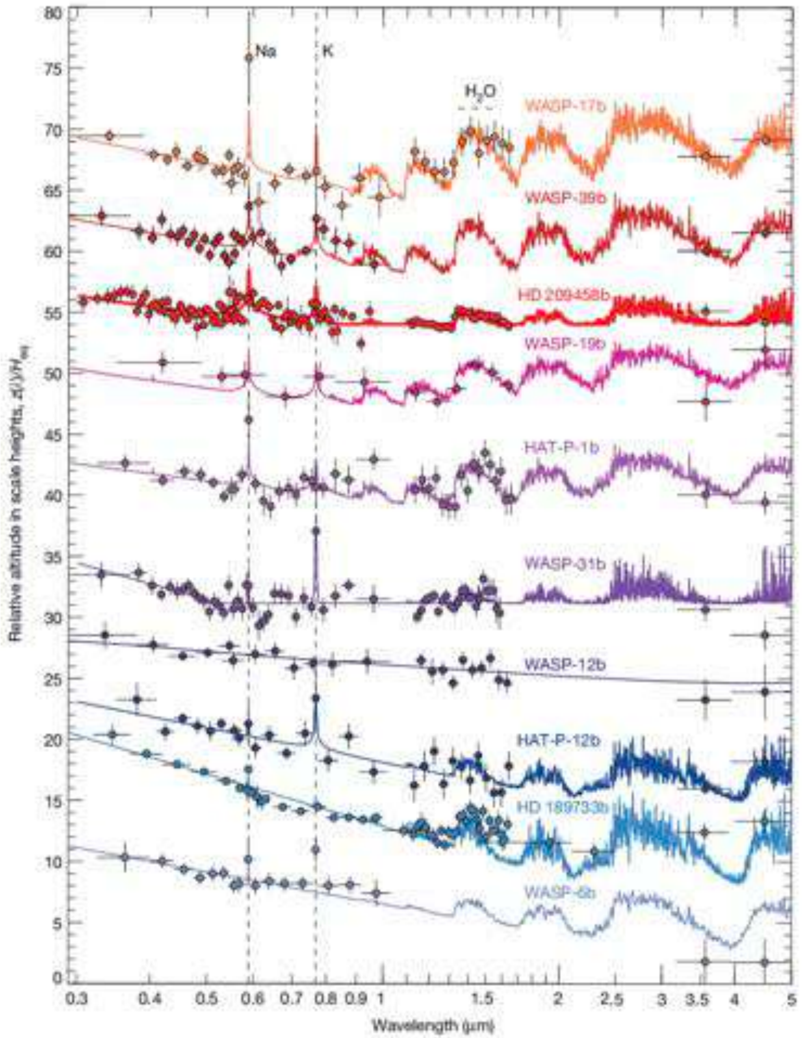


Kreidberg et al. (2014)

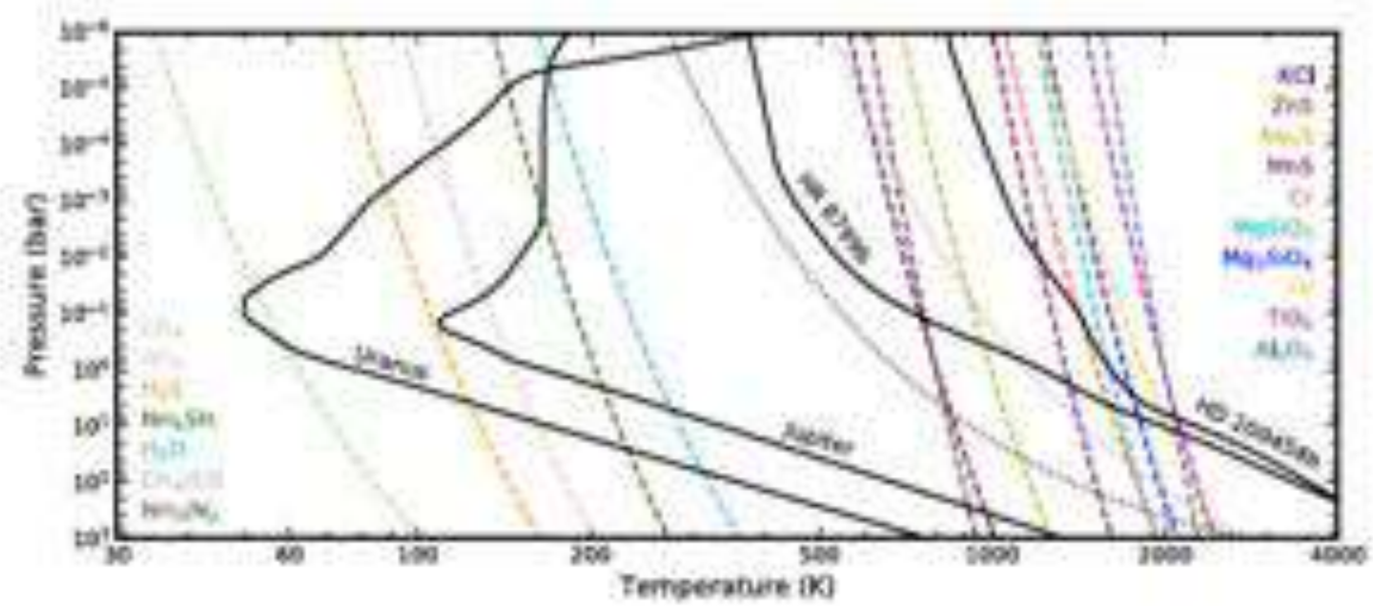
From transit observations:
→ Flat transit spectrum
→ Mie/Rayleigh-scattering slope

Observations of clouds & haze in exoplanets

A continuum from cloudy to cloud-free planets by transit observations



Sing et al. (2015)

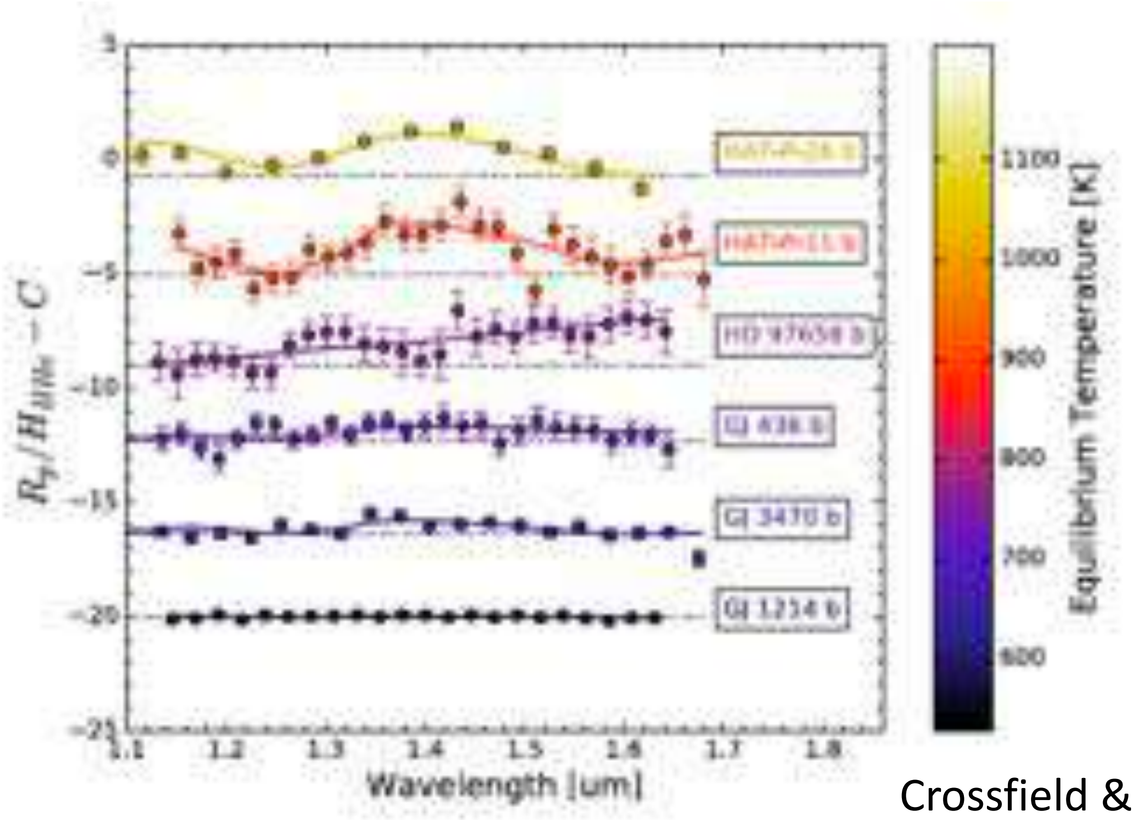


Gao et al. 2021

Observations of clouds & haze in exoplanets

A photometric diagnostic for clouds/haze

The depth of the 1.4 μm water band from HST-WFC3 = number of scale heights (assuming solar metallicity)

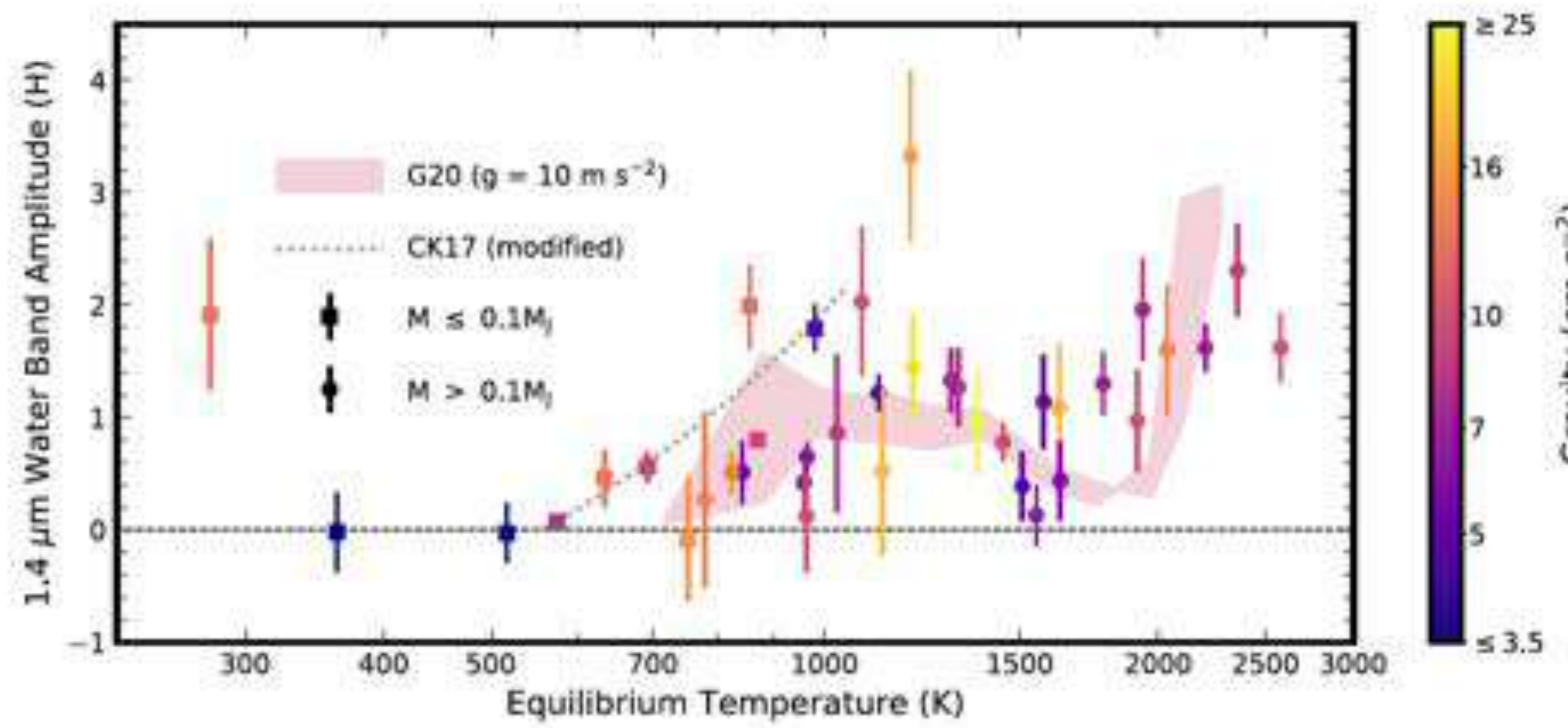


$$A_{H_2O} = \frac{\bar{X}_{[1.35-1.45\mu m]} - \bar{X}_{[1.22-1.29\mu m]}}{2 R_P H / R_\star^2}$$

Crossfield & Kreidberg 2017

Observations of clouds & haze in exoplanets

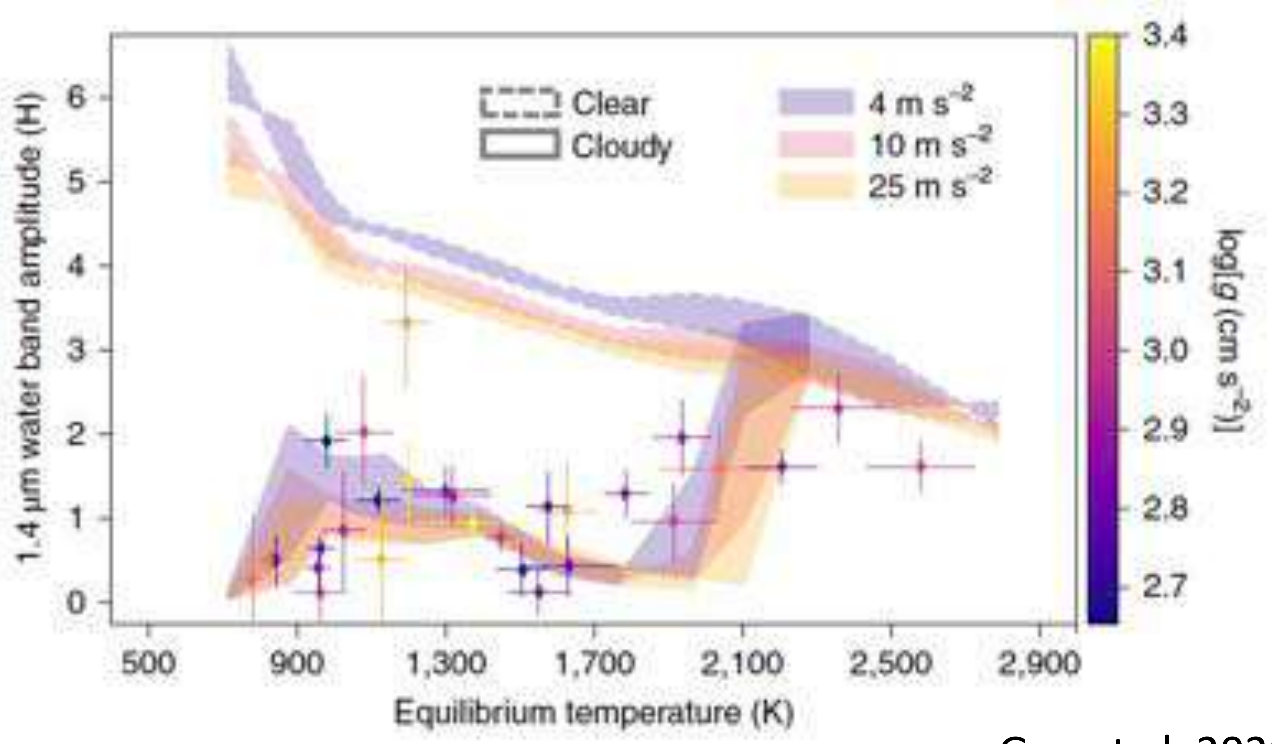
Temperature trends in transit spectra

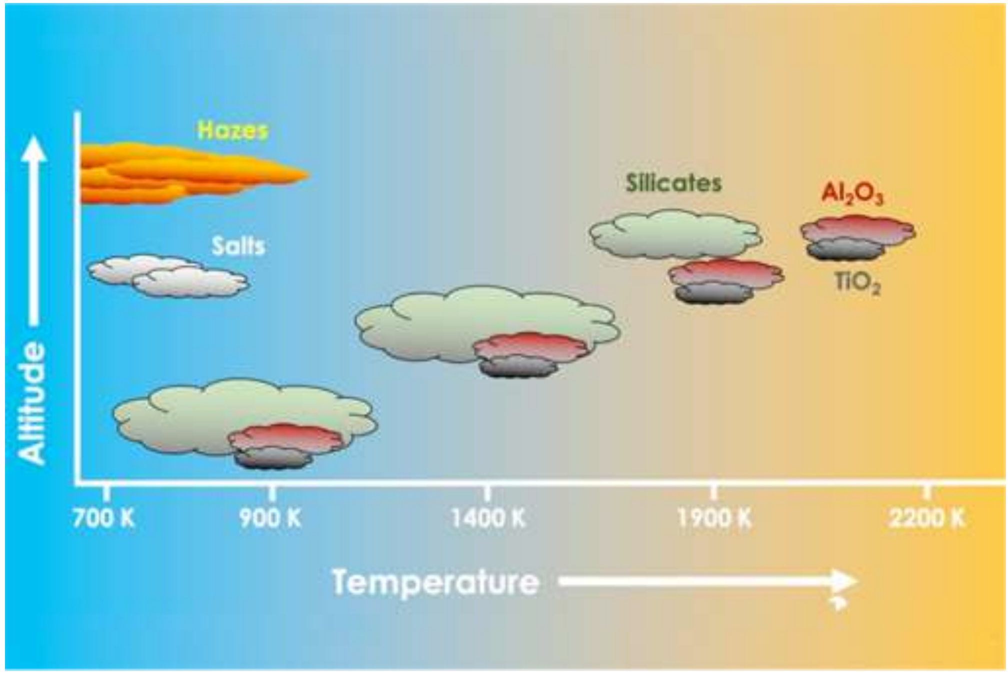


Gao et al. 2021

Observations of clouds & haze in exoplanets

Temperature trends in transit spectra for hot Jupiters





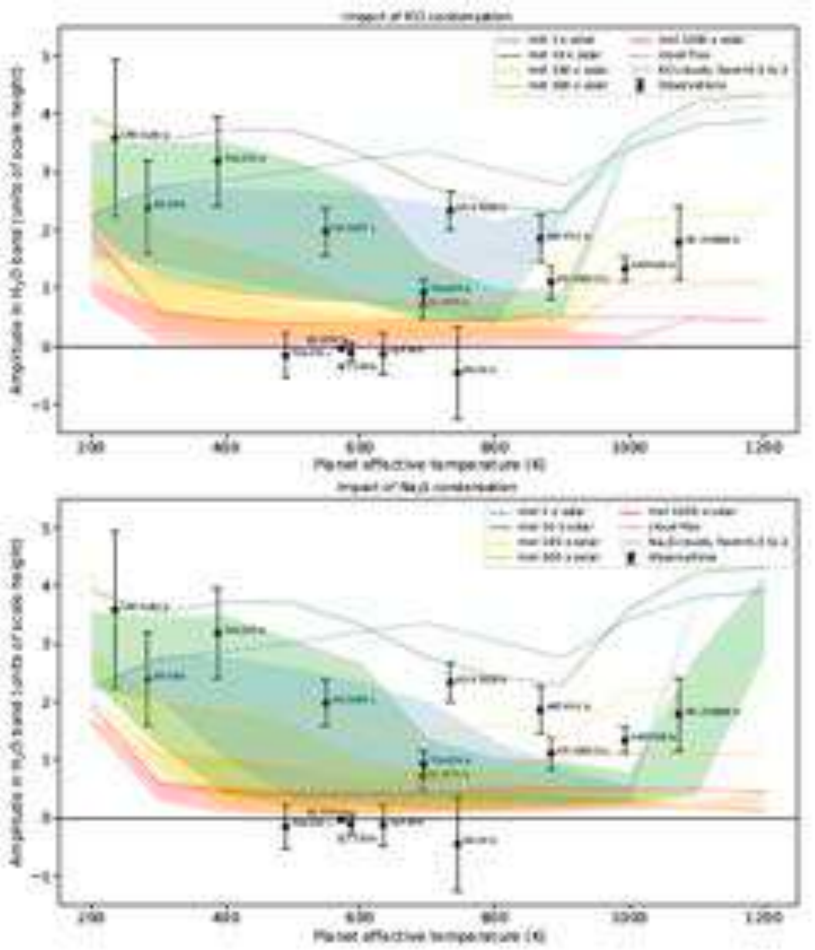
Gao et al. 2020

Main transitions:

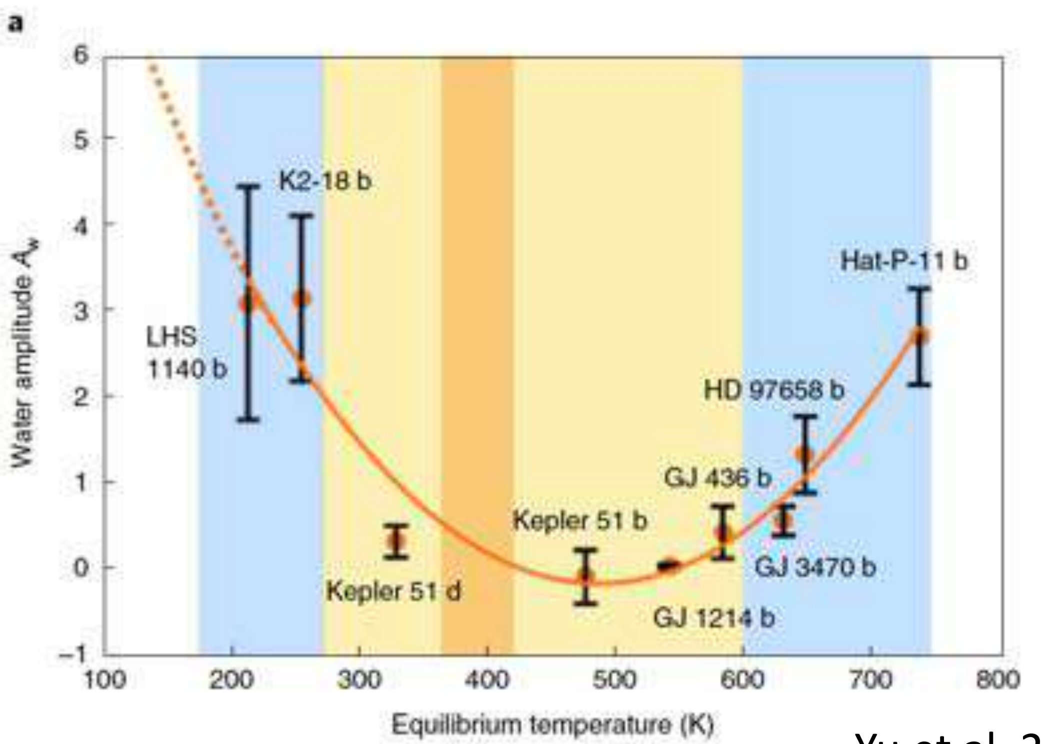
- T < 900 K: Haze and salts
- 1200 < T <2000 K : silicates
- T > 2000 K: clear atmosphere + H_2 dissociation

Observations of clouds & haze in exoplanets

Temperature trends in transit spectra for warm/temperate planets



Gressier et al. in rev

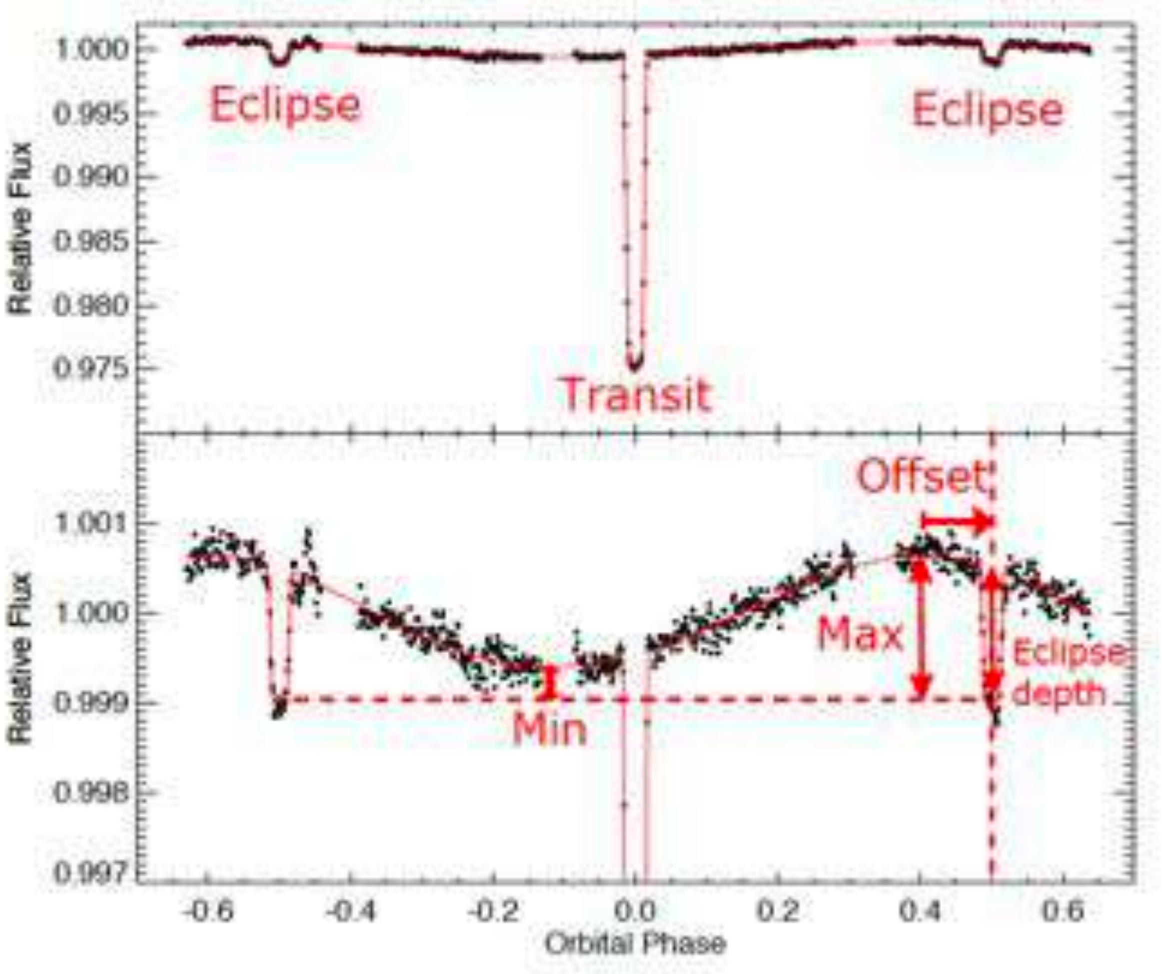


Yu et al. 2021

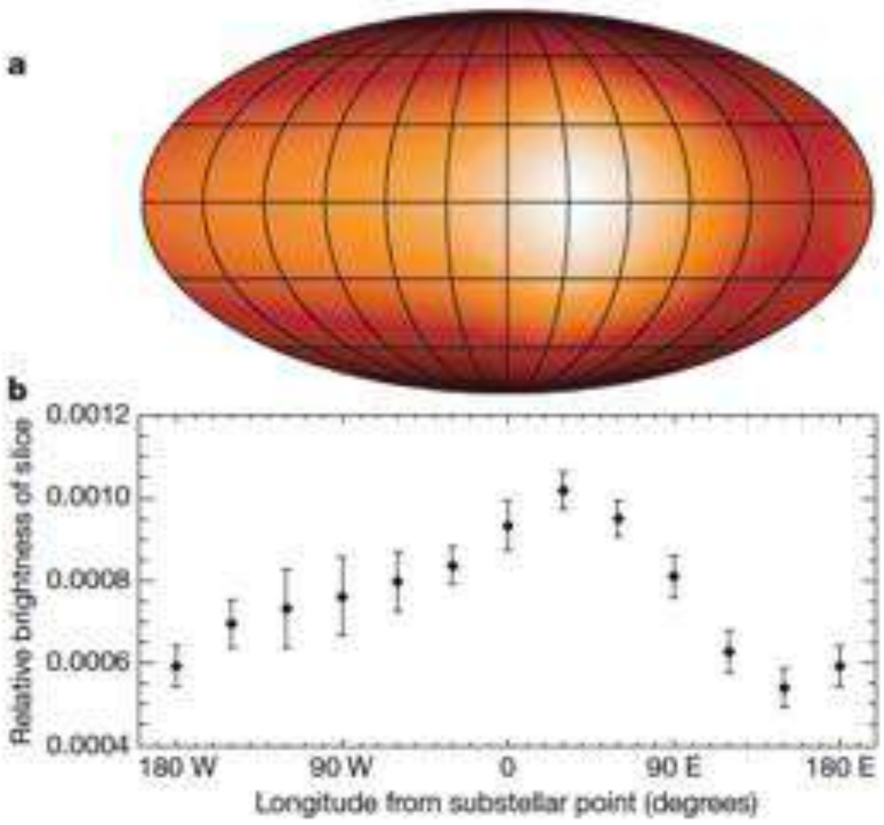
Planets with Teq between 300 and 600 K are very cloudy/hazy.
Less haze below 300 K => wet deposition
But measurements could be biased by the high metallicity of these planets

Observations of clouds & haze in exoplanets

Inhomogeneous cloud cover from phase curves



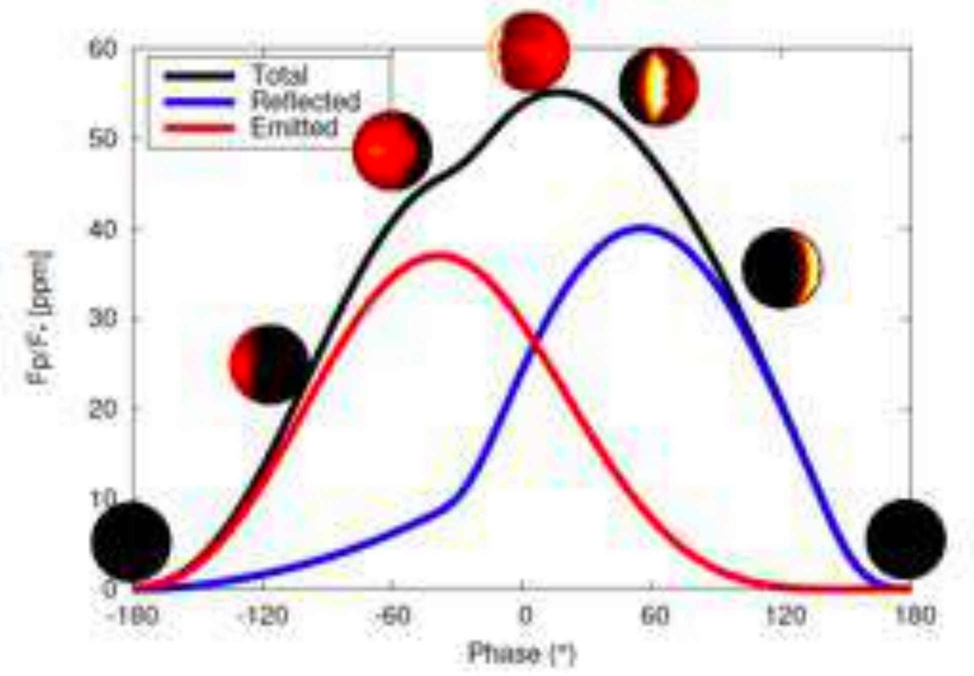
HD 189733 b

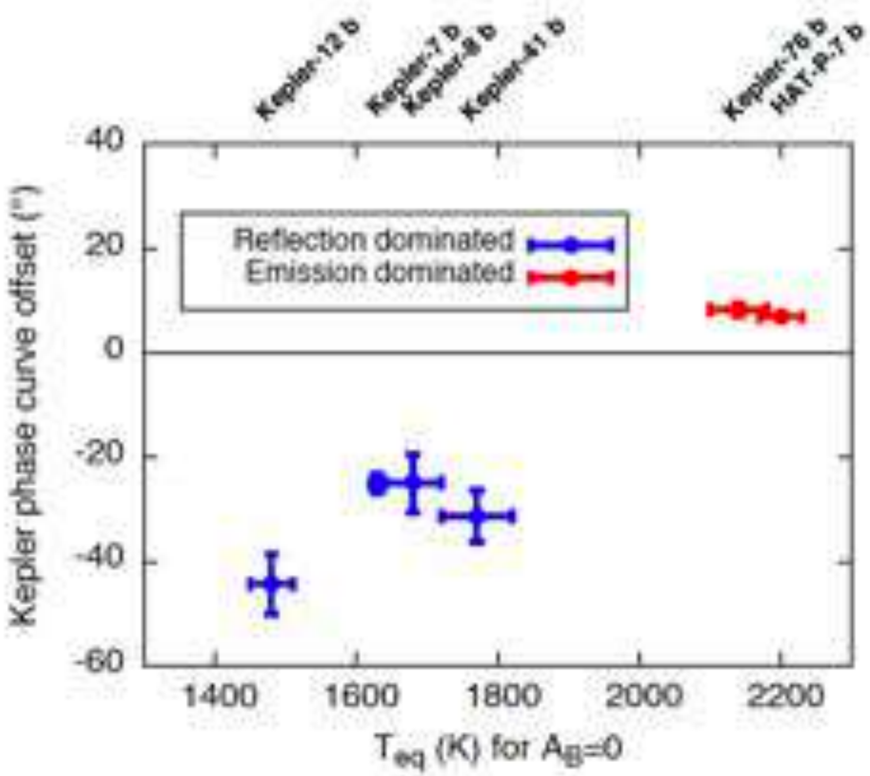


Knutson et al. 2007, 2012

Observations of clouds & haze in exoplanets

Inhomogeneous cloud cover from phase curves



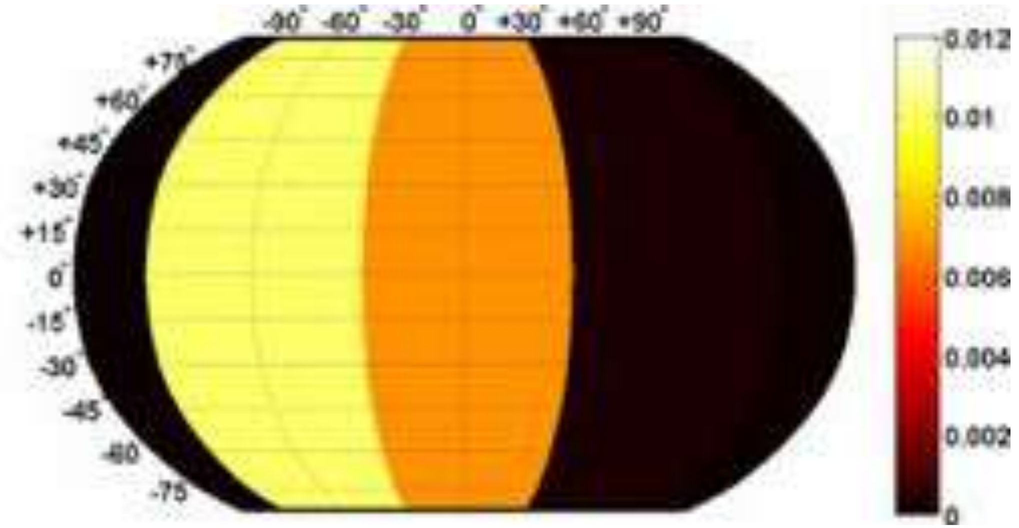


Parmentier et al. 2016

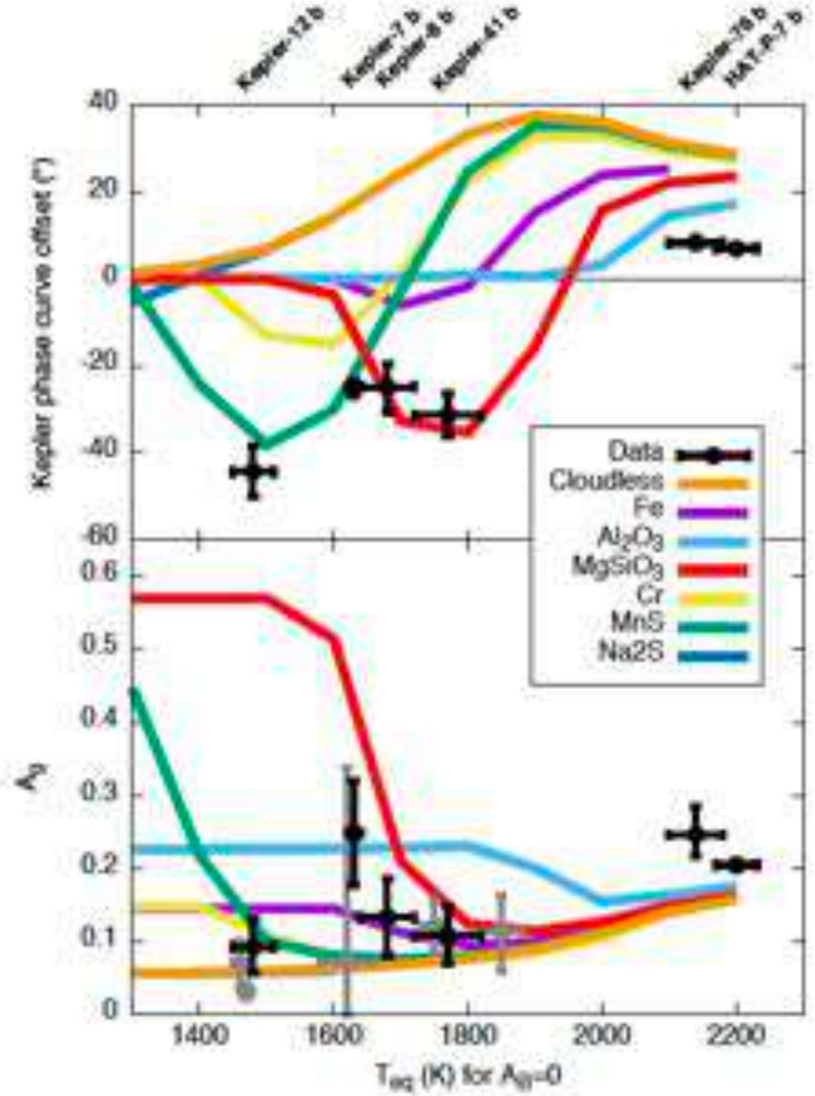
Observations of clouds & haze in exoplanets

Inhomogeneous cloud cover from phase curves

Albedo map of Kepler 7b



Demory et al. (2013)

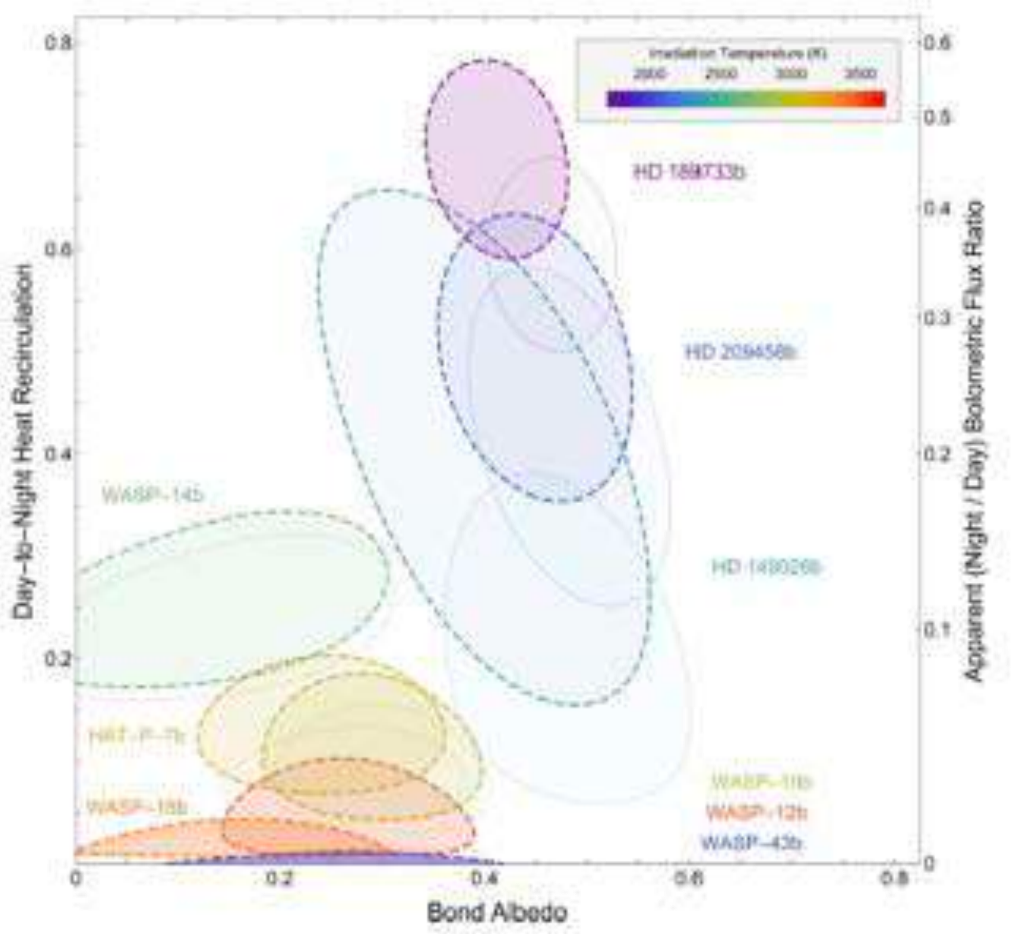


Parmentier et al. 2016

From visible phase curves:
→ Relatively low geometric albedo
→ Inhomogeneous cloud cover

Observations of clouds & haze in exoplanets

The albedo problem for exoplanets



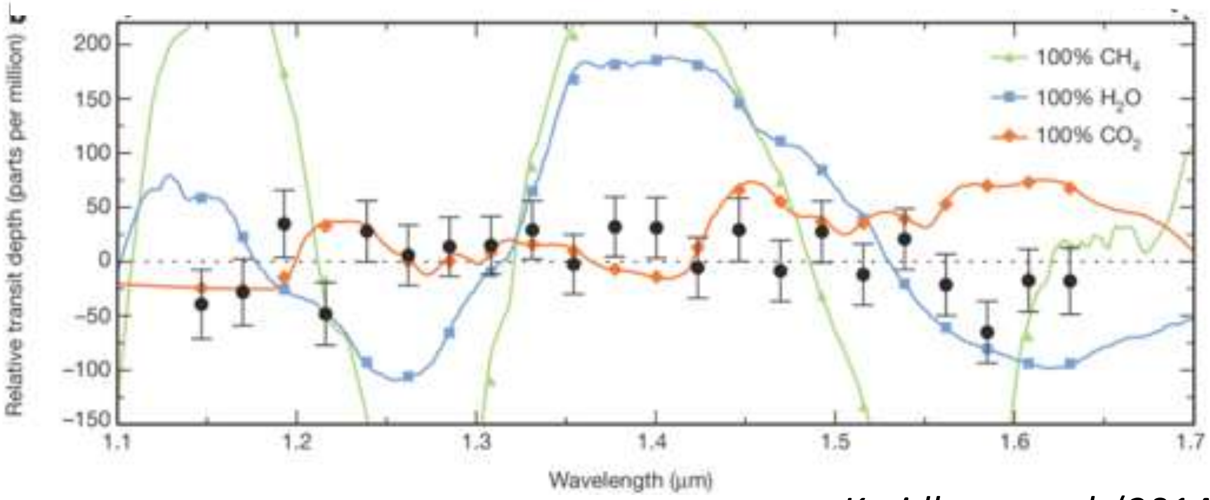
Schwartz 2017

- ➢ Bond albedo from Spitzer phase curve is significantly higher than geometric albedo from Kepler
- ➢ Potential high reflectivity in near-IR

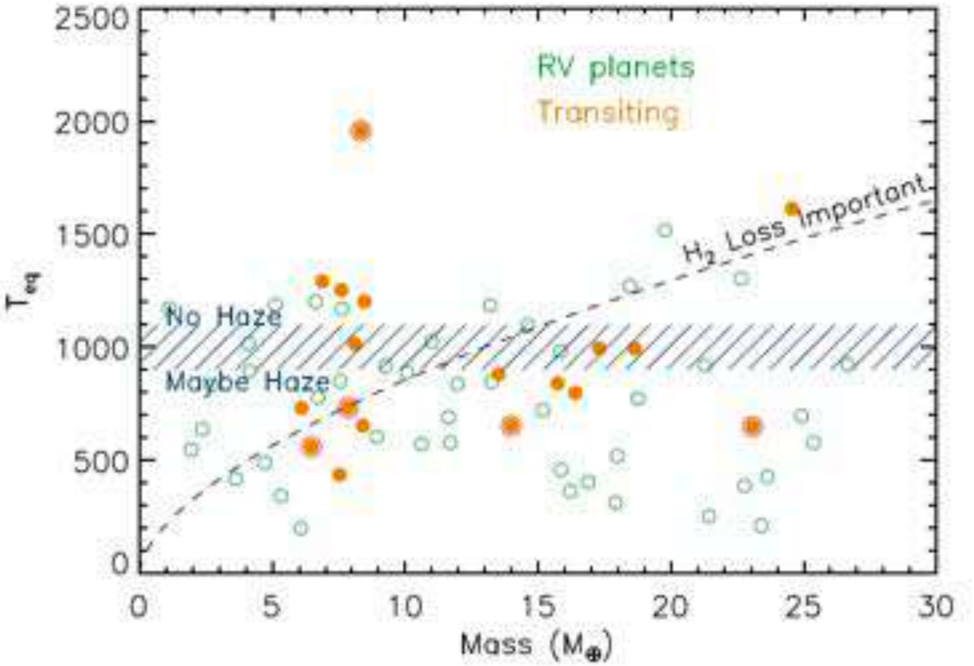
Observations of clouds & haze in exoplanets

Evidence for photochemical haze on warm sub-Neptunes ?

GJ 1214 b



Kreidberg et al. (2014)



Fortney et al. 2013

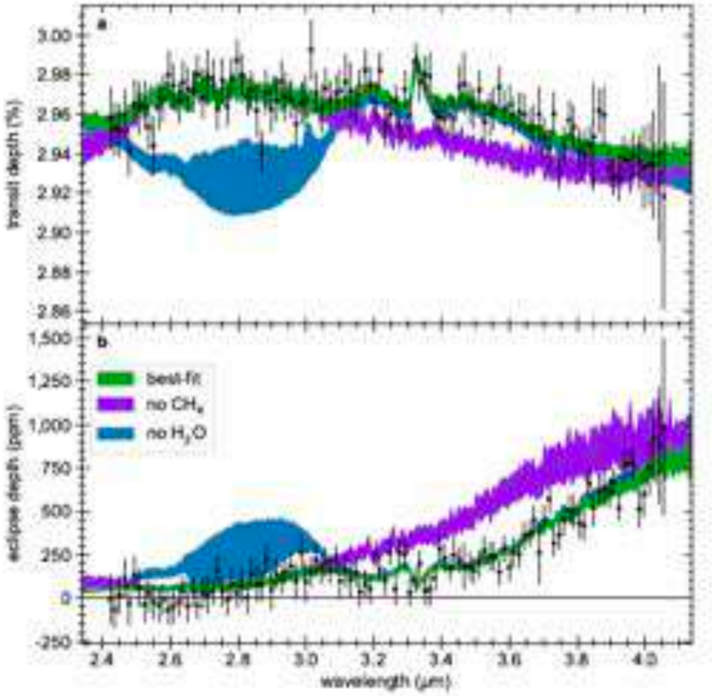
Observations of clouds & haze in exoplanets

Methane depletion on warm sub-Neptunes/Neptunes

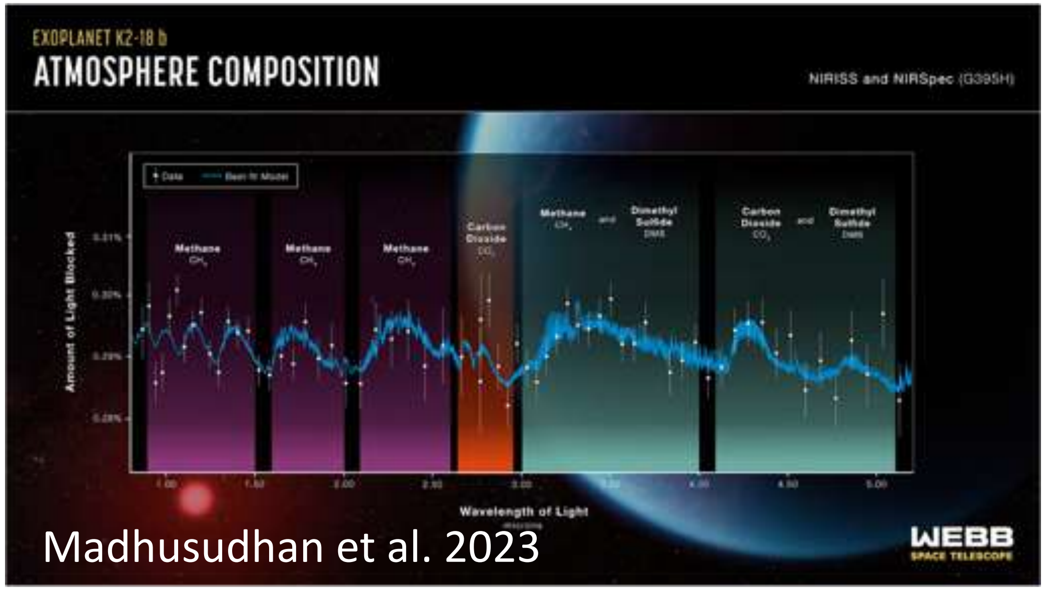
Planet	H_2O	CH_4	CO	CO_2	NH_3	HCN	references [a]
55-Cnc e							T16a
GJ 436 b							
GJ 1132 b							
GJ 1214 b							
GJ 3470 b							B19a, E22
HAT-P-11 b							F14, E22
HAT-P-26 b							W17, MD19, E22
HD 3167 c							G20, MB20, E22
HD 97658 b							E22
HD 106315 c							G20, K20, E22
HD 219666 b							
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)

WASP-80 b



Bell et al. 2023

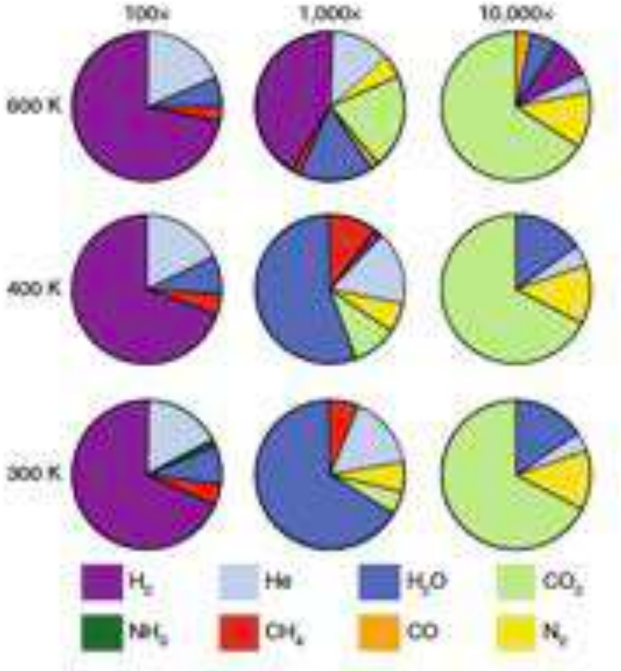


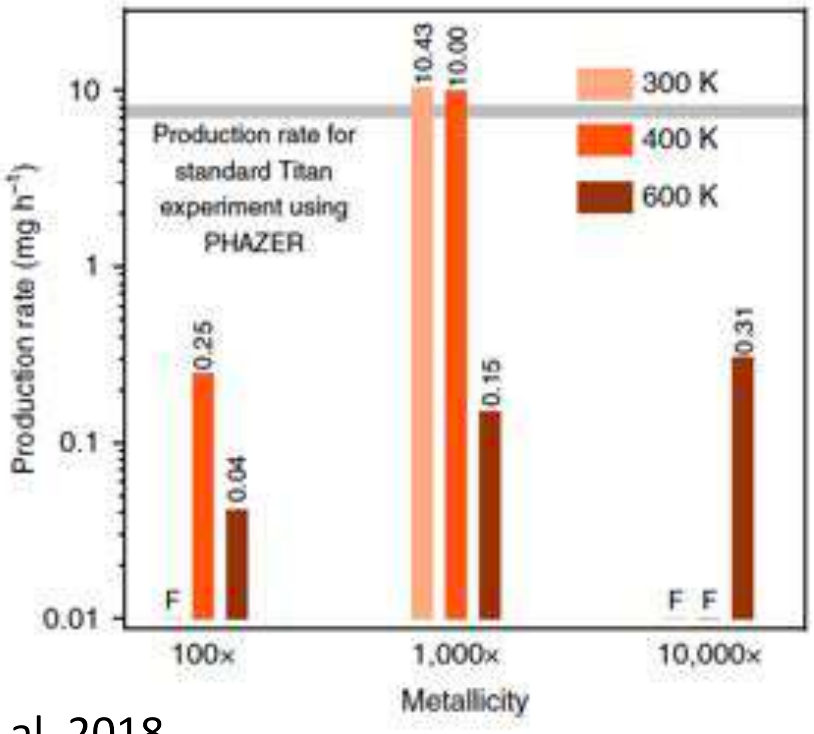
Madhusudhan et al. 2023

Observations of clouds & haze in exoplanets

Lab experiments of haze formation

PHAZER



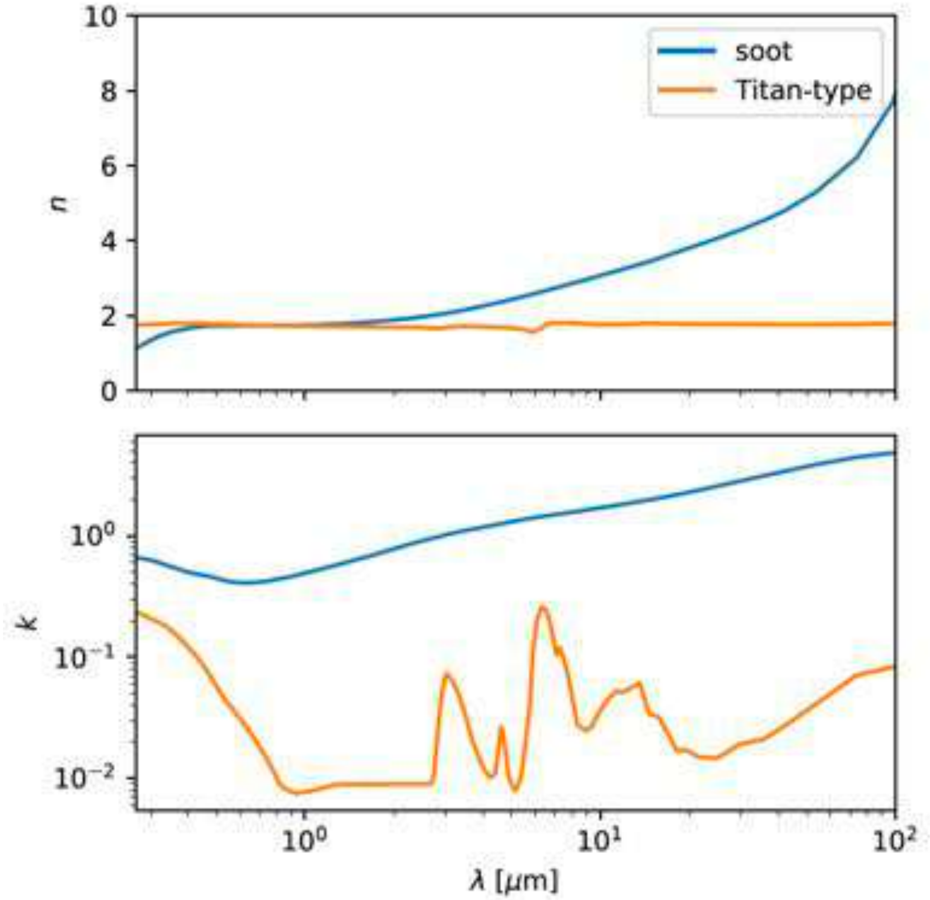


Hörst et al. 2018

Great diversity of haze production rate for sub-Neptunes
Haze production without CH_4

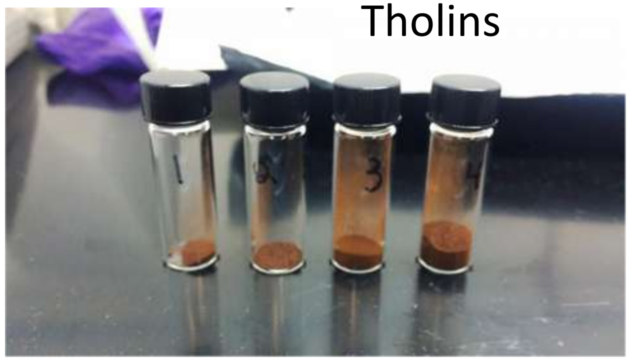
Observations of clouds & haze in exoplanets

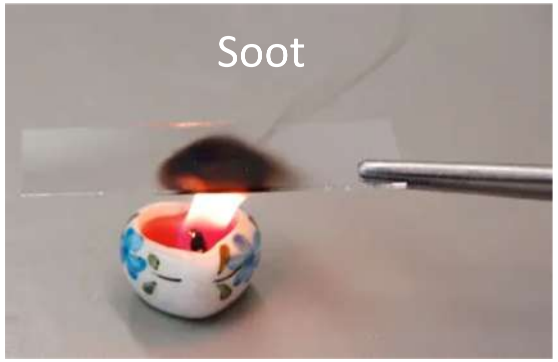
Lab experiments of haze formation

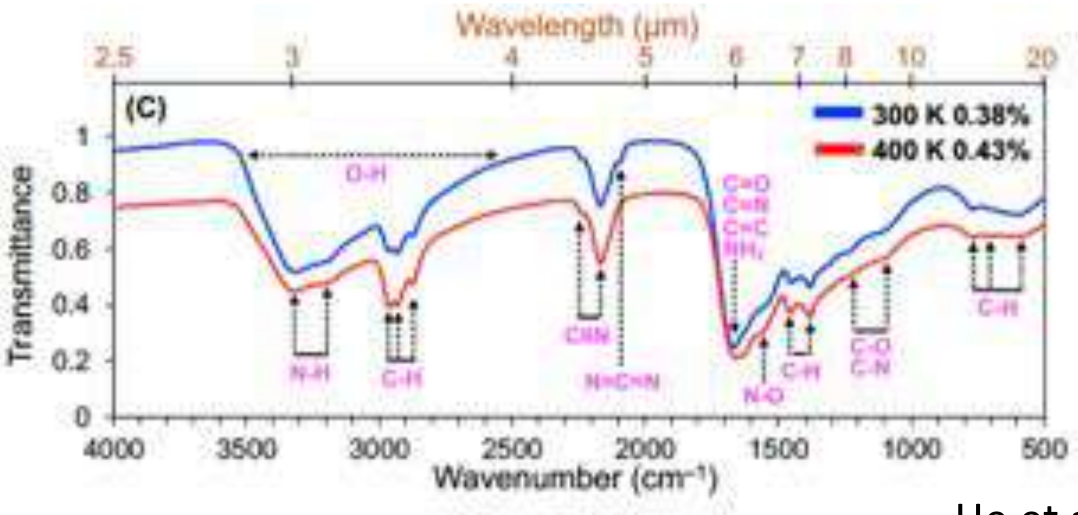


Steinrueck et al. 2023

Tholins



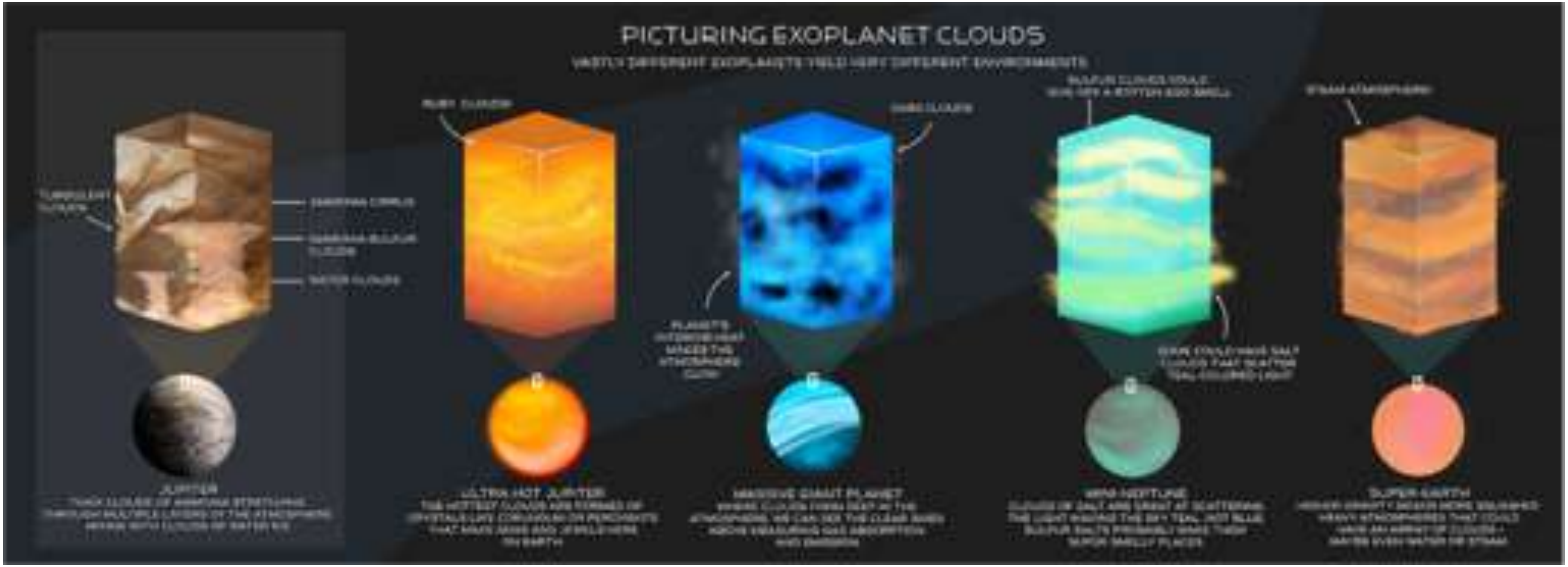




He et al., 2023

Haze features are related to specific chemical bonds

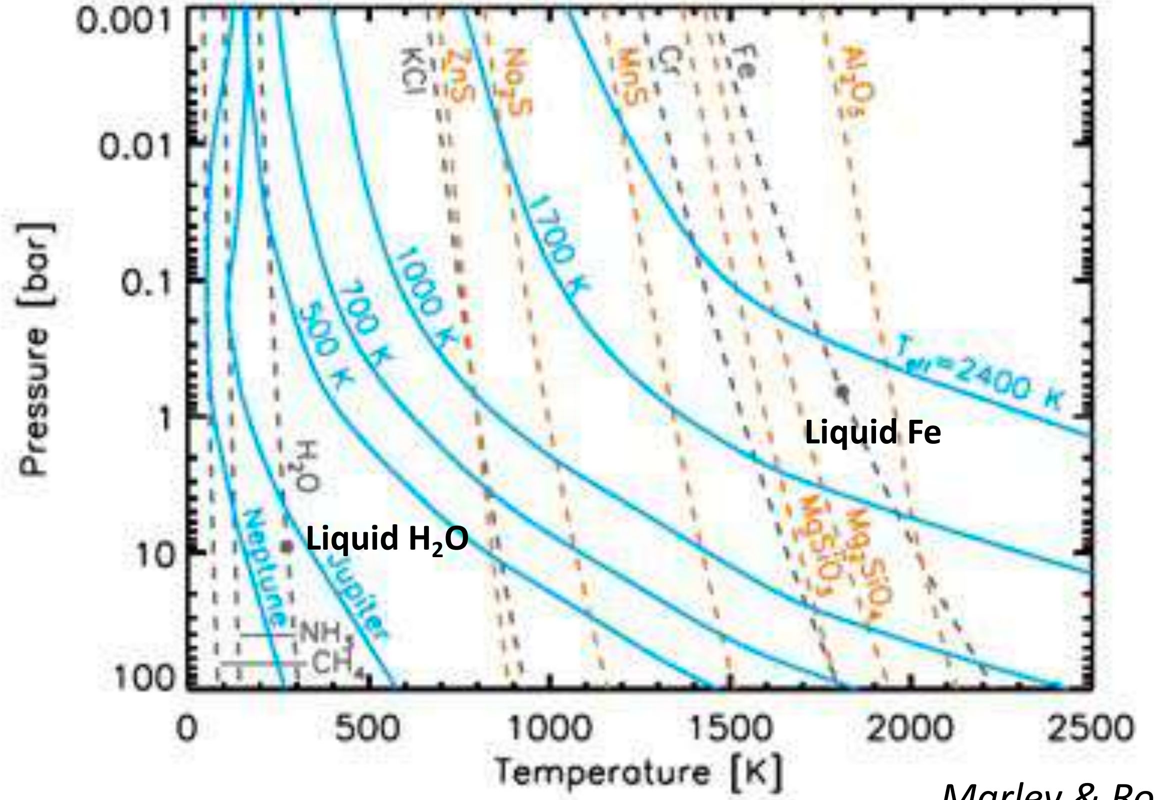
How to model clouds/haze in exoplanetary atmospheres ?



Modeling clouds & haze

Condensation curves

Temperature condensation curves for solar metallicity



Marley & Robinson (2014)

Elemental abundances from *Lodders et al.* (2003)
Temperature condensation curves from *Visscher et al.* (2006, 2010)

Clausius-Clapeyron relation: $P_{sat} = P_{sat}(T_0) e^{-\frac{L}{R}\left(\frac{1}{T} - \frac{1}{T_0}\right)}$

Modeling clouds & haze

1D Cloud models

1) Model with f_{sed} from Ackerman & Marley 2001

At equilibrium :

$$\frac{\partial q_c}{\partial z} = -\frac{\partial q_s}{\partial z} - \frac{V_{sed}}{K_{zz}} q_c$$

- q_c = mass mixing ratio of condensate
- q_s = mass mixing ratio of vapor at saturation
- V_{sed}= sedimentation speed
- K_{zz} = eddy diffusion coefficient

Mixing length theory:

$$K_{zz} = \frac{H}{3}\left(\frac{L}{H}\right)^{4/3}\left(\frac{rF_{conv}}{c_p \rho_a}\right)^{1/3}$$

Ackerman & Marley 2001: Mixing length: *L=H*

Assumption: $\boldsymbol{f_{sed} = \frac{HV_{sed}}{K_{zz}}}$ = **constant** (generally f_{sed}= 1-5)

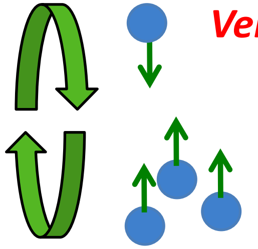
Above condensation: $q_c = qc_0 \left(\frac{P}{P_0}\right)^{f_{sed}}$

Modeling clouds & haze

1D Cloud models

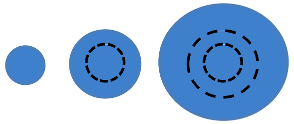
2) Model with simple microphysics using timescales from Rossow 1978

e.g. BT-Settl (*Allard et al.* 2001) and Exo-REM (*Charnay et al.* 2018)



Vertical mixing

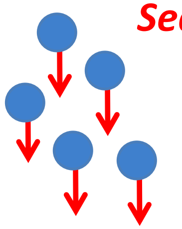
$$\tau_{mixing} = \frac{H^2}{K_{zz}}$$



Condensation growth

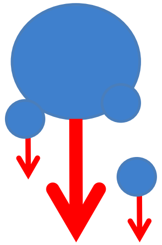
$$\tau_{cond} = \frac{r^2}{(2 f \eta q_s S)} \rho_c$$

$$S = 10^{-3} - 10^{-1}$$



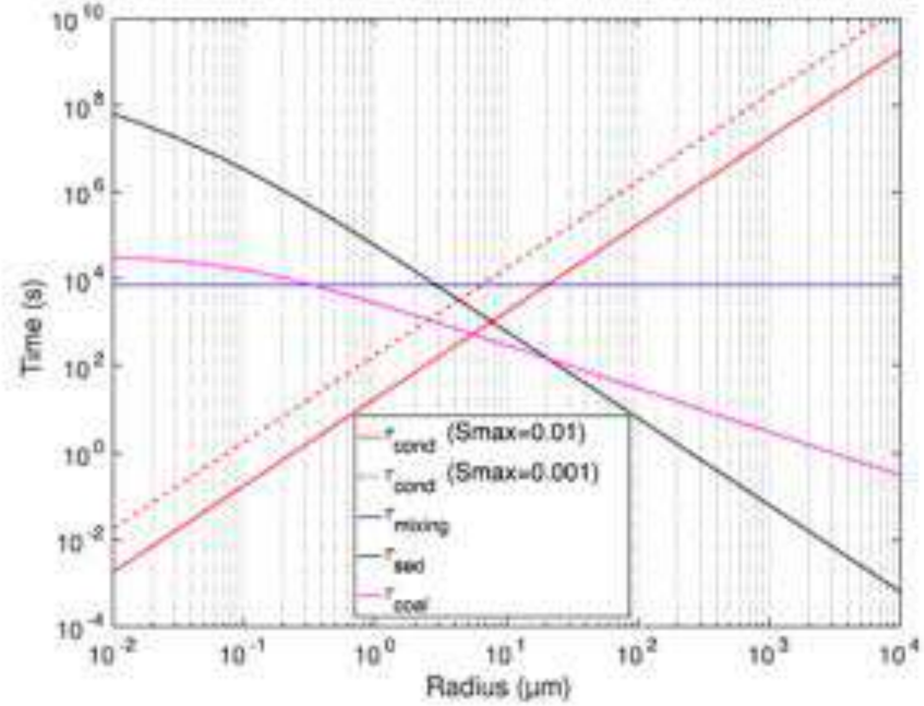
Sedimentation

$$\tau_{sed} = \frac{H}{v_{sed}}$$



Coalescence

$$\tau_{coal} = \frac{4 r \rho_c}{3 \alpha v_{sed} \rho_{air} q_c}$$

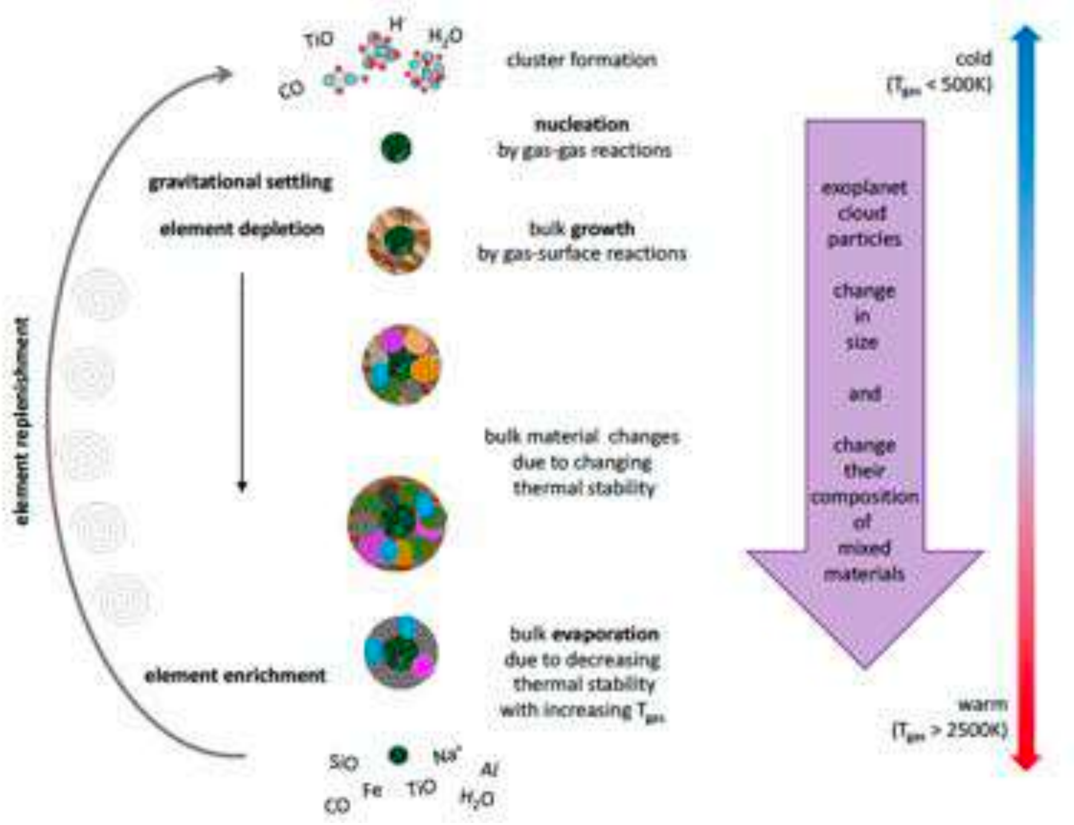


Modeling clouds & haze

1D Cloud models

3) Models with full microphysics

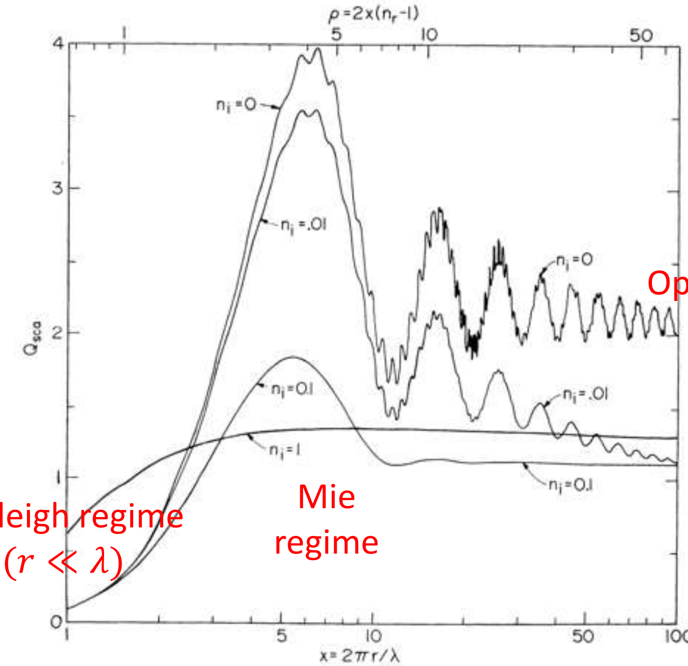
e.g. Drift-Phoenix (*Woitke & Helling* 2003)



Modeling clouds & haze

Opacity

We usually compute aerosol optical properties ($Q_{ext}=\sigma_{ext}/\pi r^2$, ω_0, g) from Mie Theory with optical indexes and assuming spherical particules

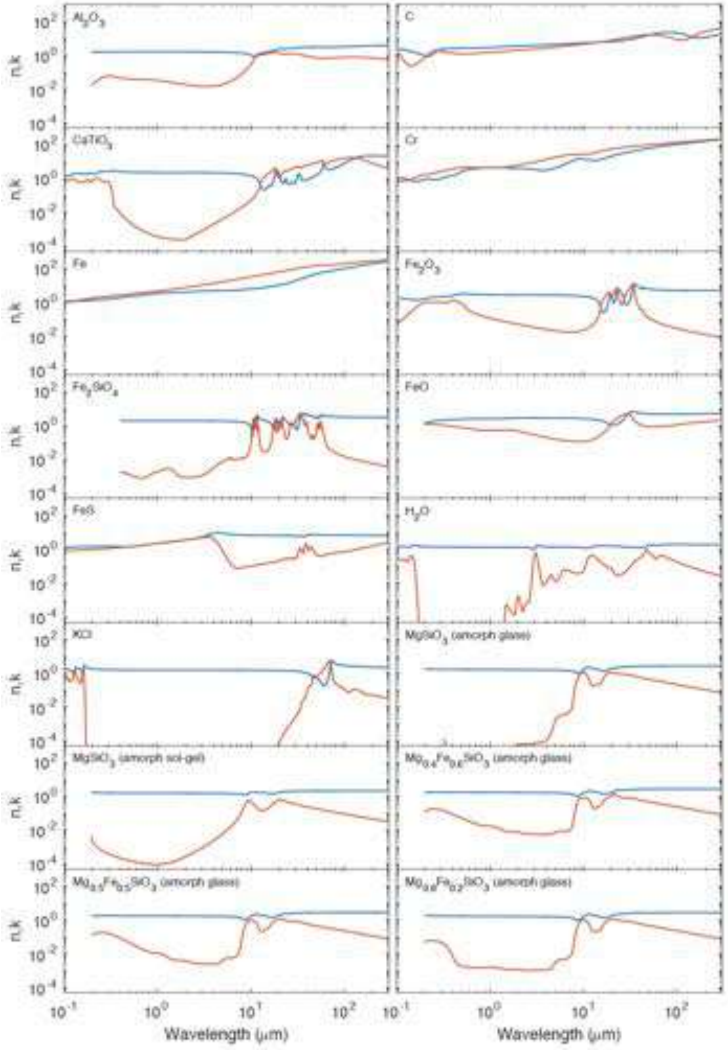


Hansen & Travis (1974)

Cloud optical depth: $\tau_c = \frac{3}{4}\frac{Q_{ext} w}{\rho r e}$

w: mass column
ρ: volumic mass
r_e: effective radius

Optical indexes
(n=real=scattering, k=imaginary=absorption)

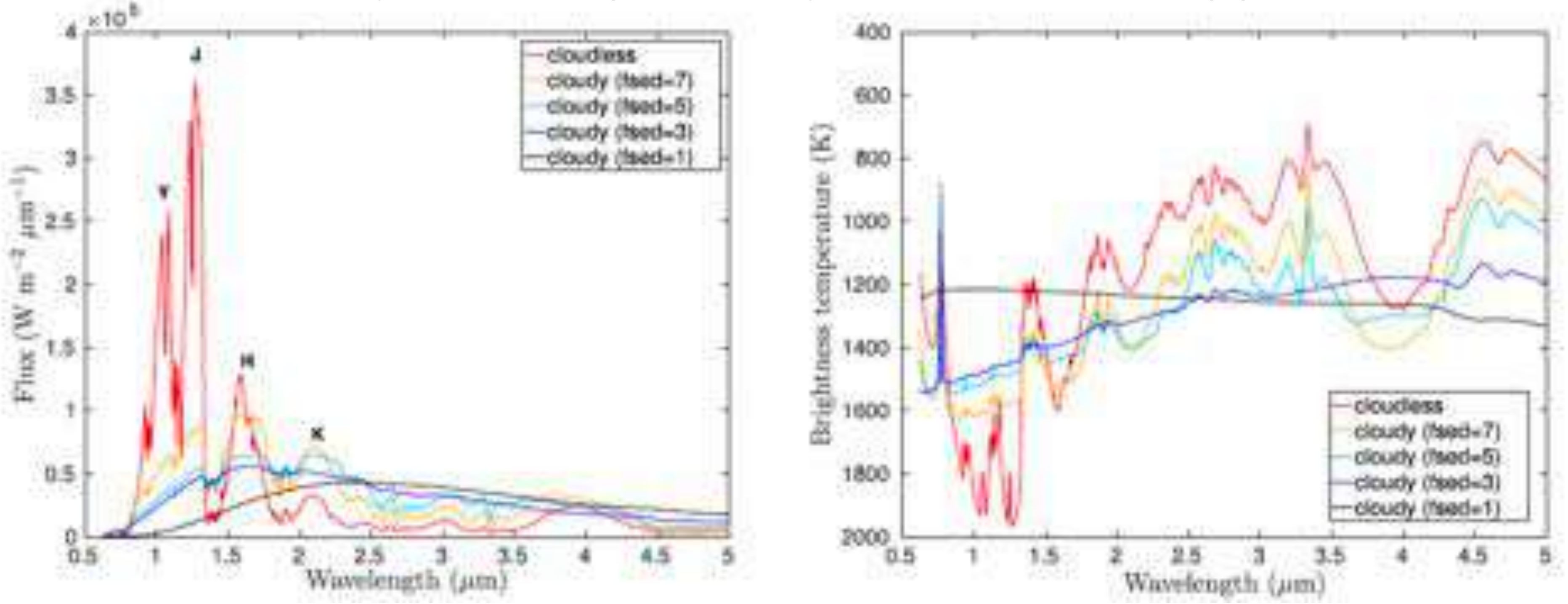


Kitzmann et al. 2017

Modeling clouds & haze

Radiative effects: absorption/emission of thermal radiation

Emission spectra and brightness temperature (Teff=1300K, log(g)=5)

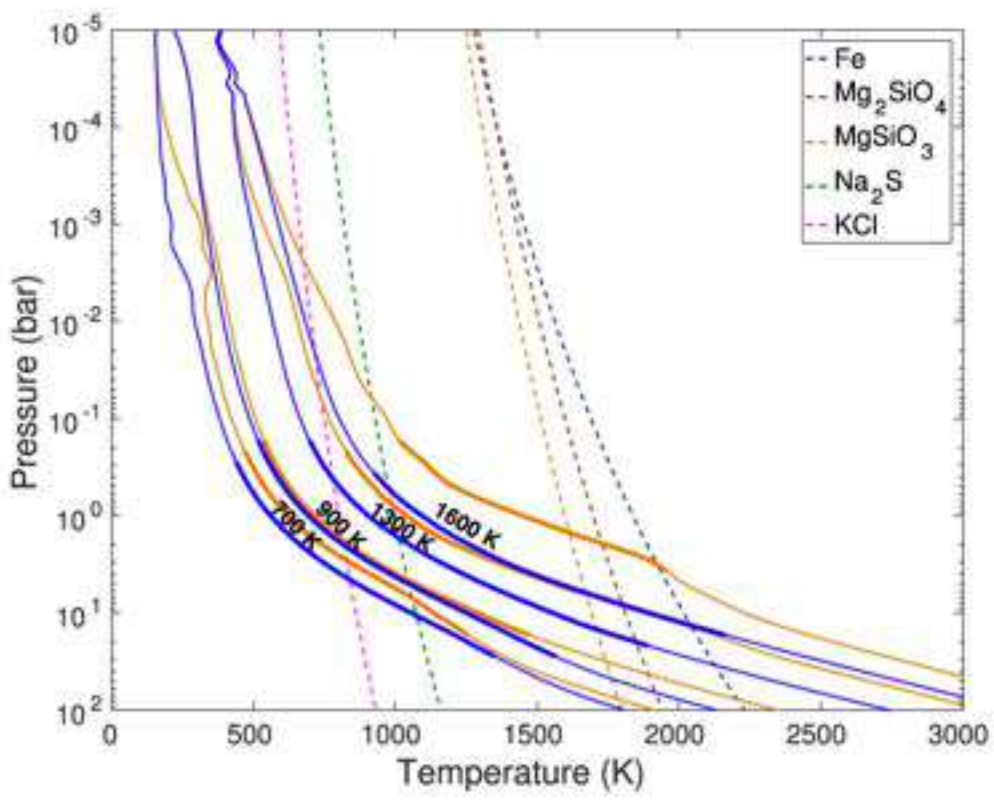


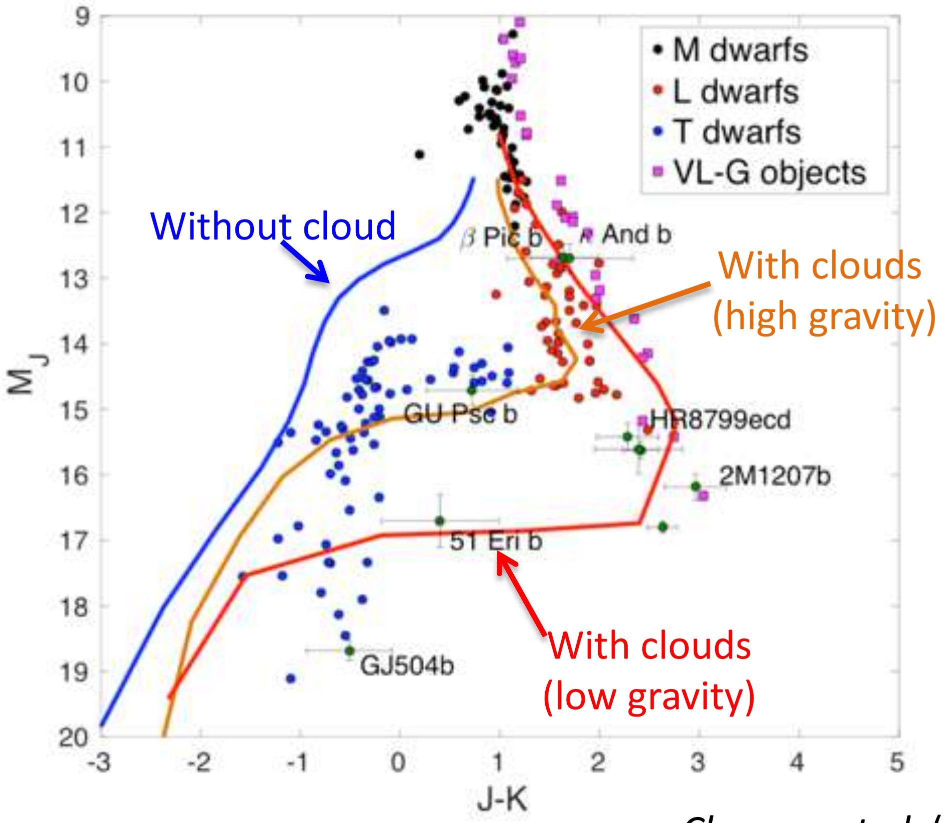
Charnay et al. (2018)

- Clouds produce a decrease of flux in spectral windows and an increase in spectral bands (greenhouse warming).
- With thick clouds, spectrum close to a blackbody

Modeling clouds & haze

Radiative effects: thermal structure and L-T transition





Charnay et al. (2018)

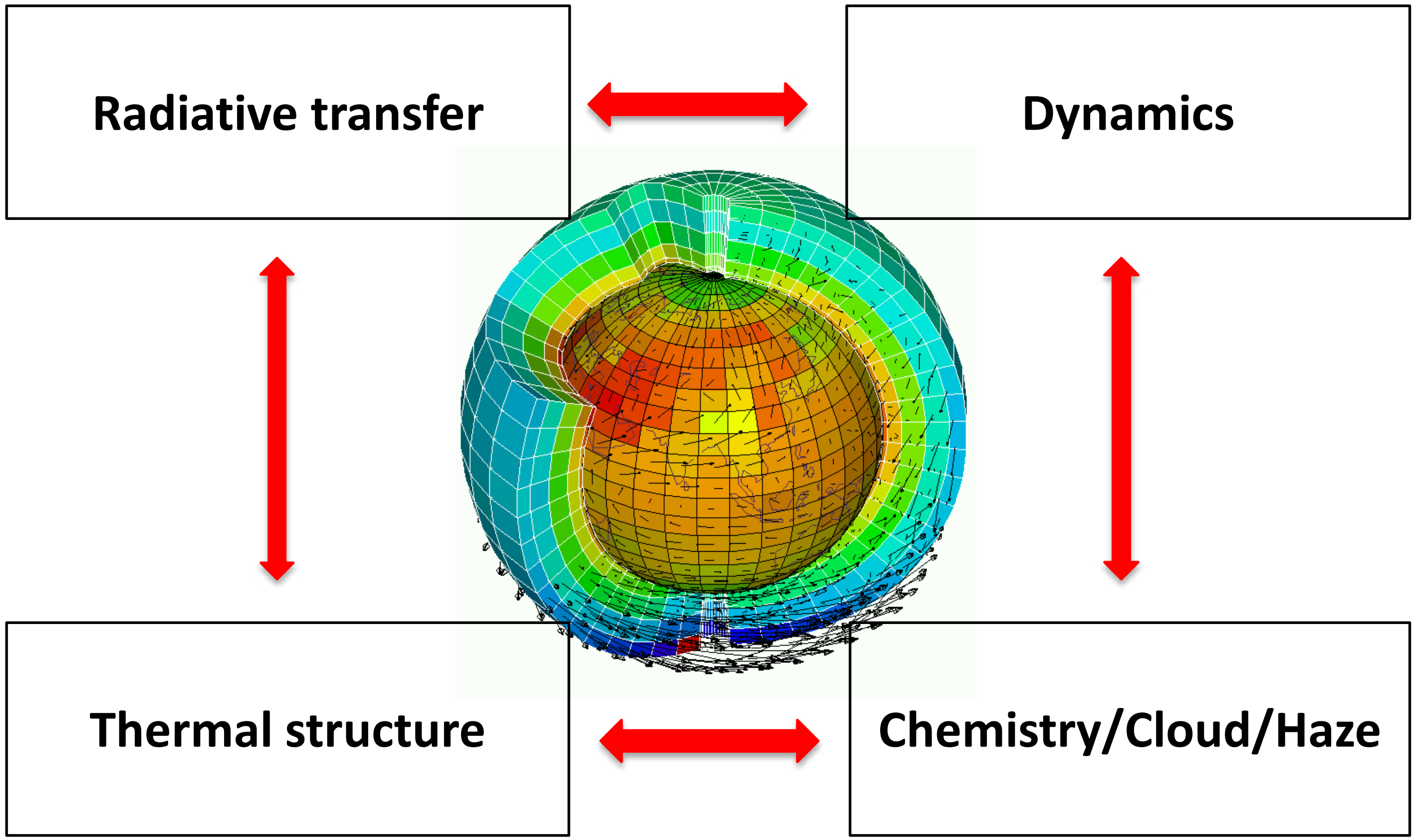
Clouds below photosphere ($\tau \sim 1$) for T_{eff} < 1300 K

$\Rightarrow$ LT transition

Modeling clouds & haze

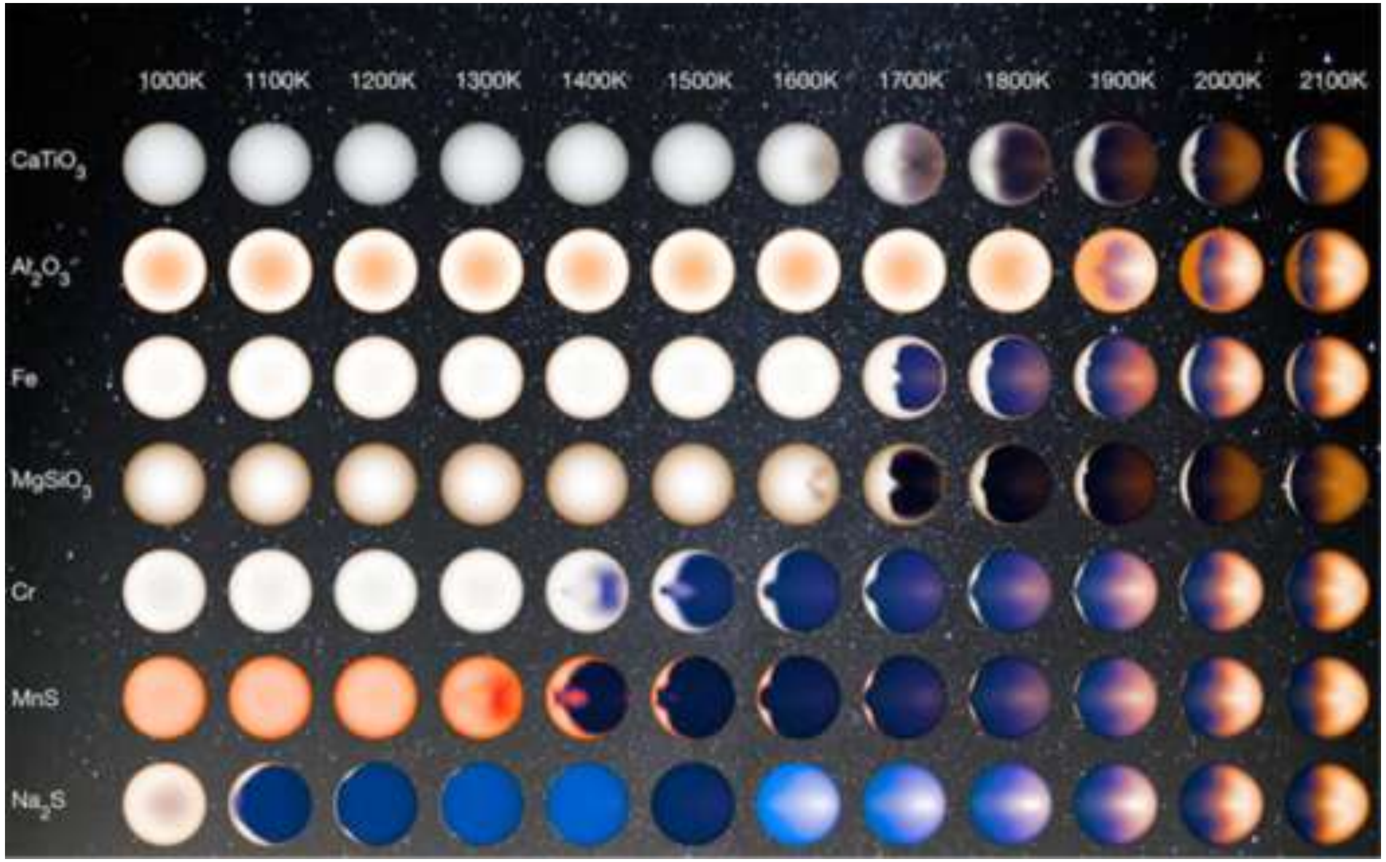
3D models

For strongly irradiated exoplanets, we need 3D GCM !



Modeling clouds & haze

3D models



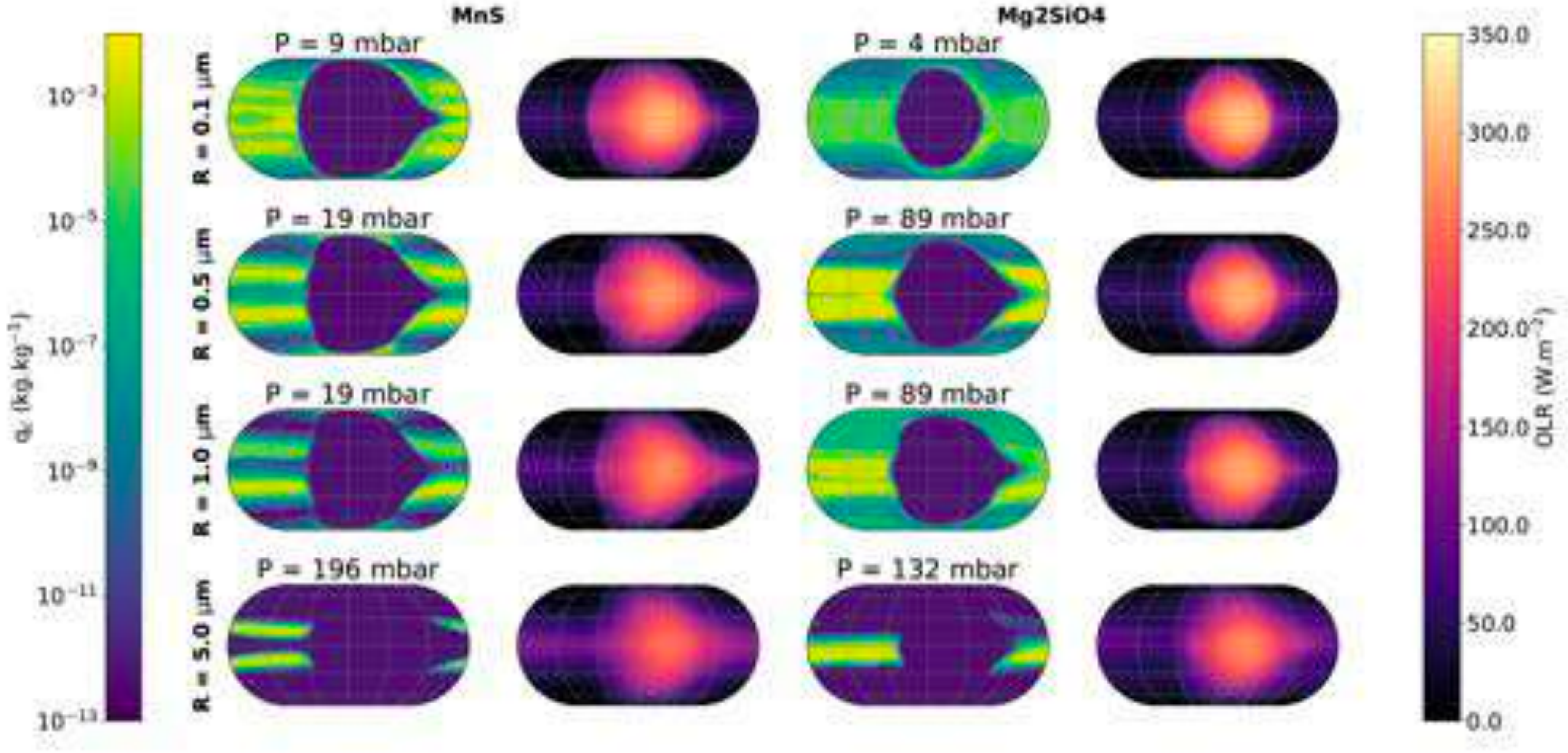
Parmentier et al. 2016

Numerous GCMs are used to simulate clouds with different complexity:

- Post-treatment
- Fixed clouds (e.g. MIT-GCM, THOR)
- Advection of cloud tracers (i.e. Generic PCM)
- Fully coupled to microphysics

Modeling clouds & haze

Nightside clouds on hot Jupiters



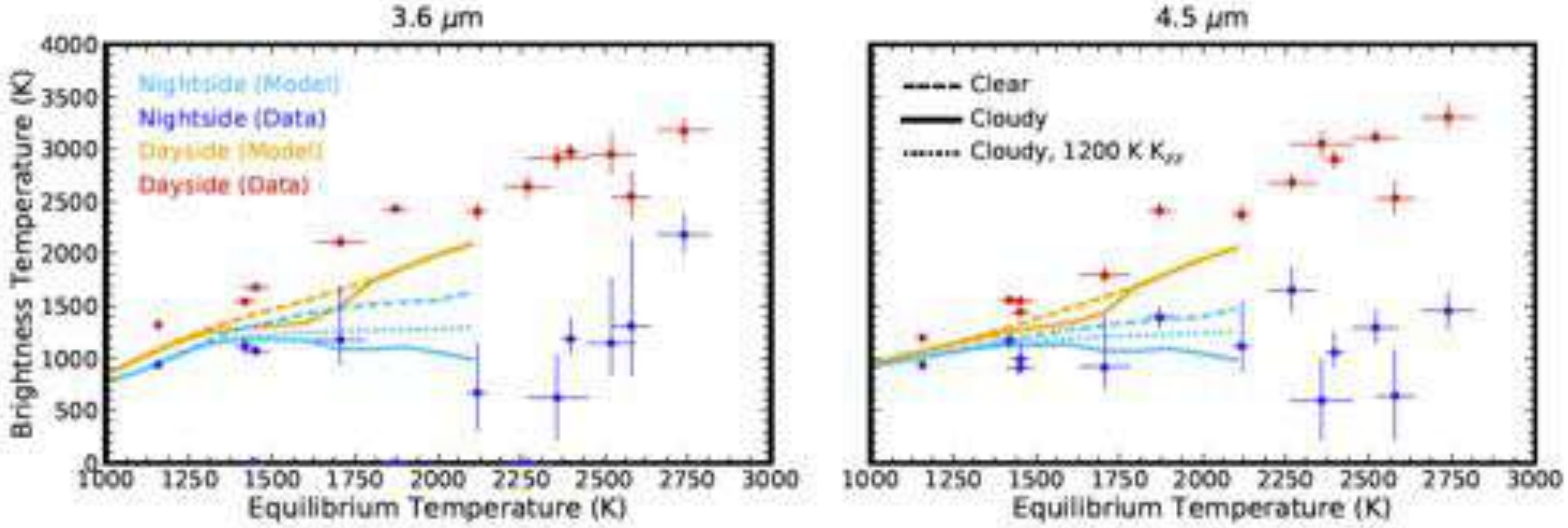
Teinturier et al. in rev.

Silicate and salt clouds form on the nightside
The west (evening) limb is cloudier than the east (morning) limb
Nighside clouds produce a greehouse effect (positive radiative forcing)

Modeling clouds & haze

Nightside clouds on hot Jupiters

Spitzer observations of hot Jupiters

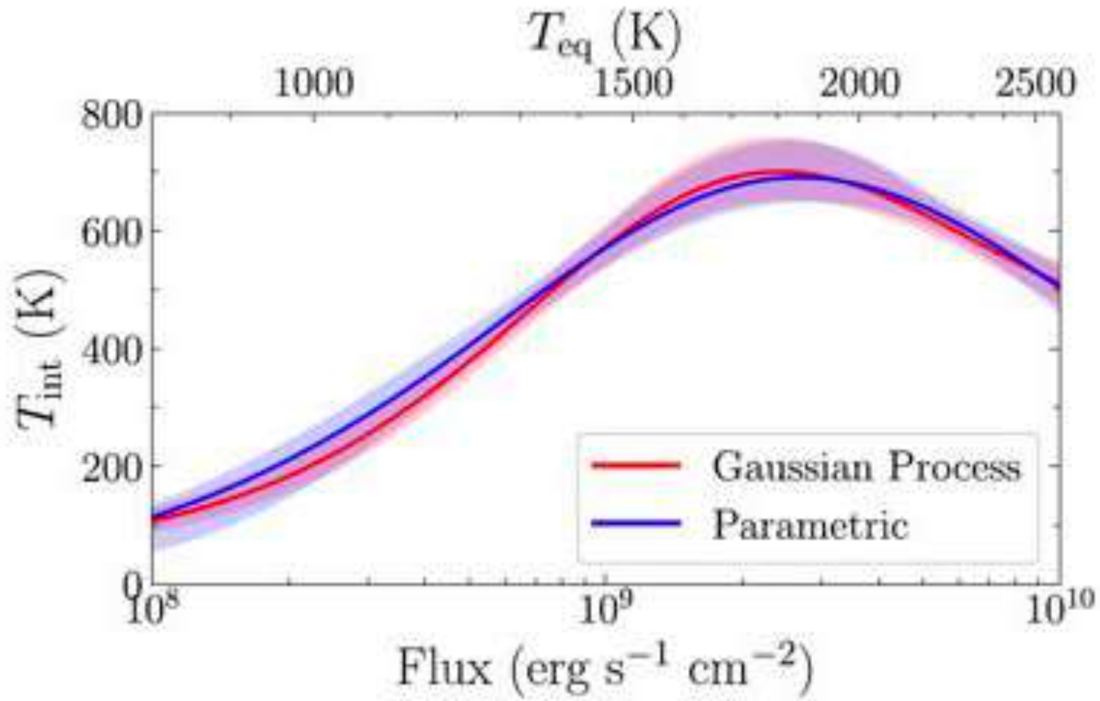


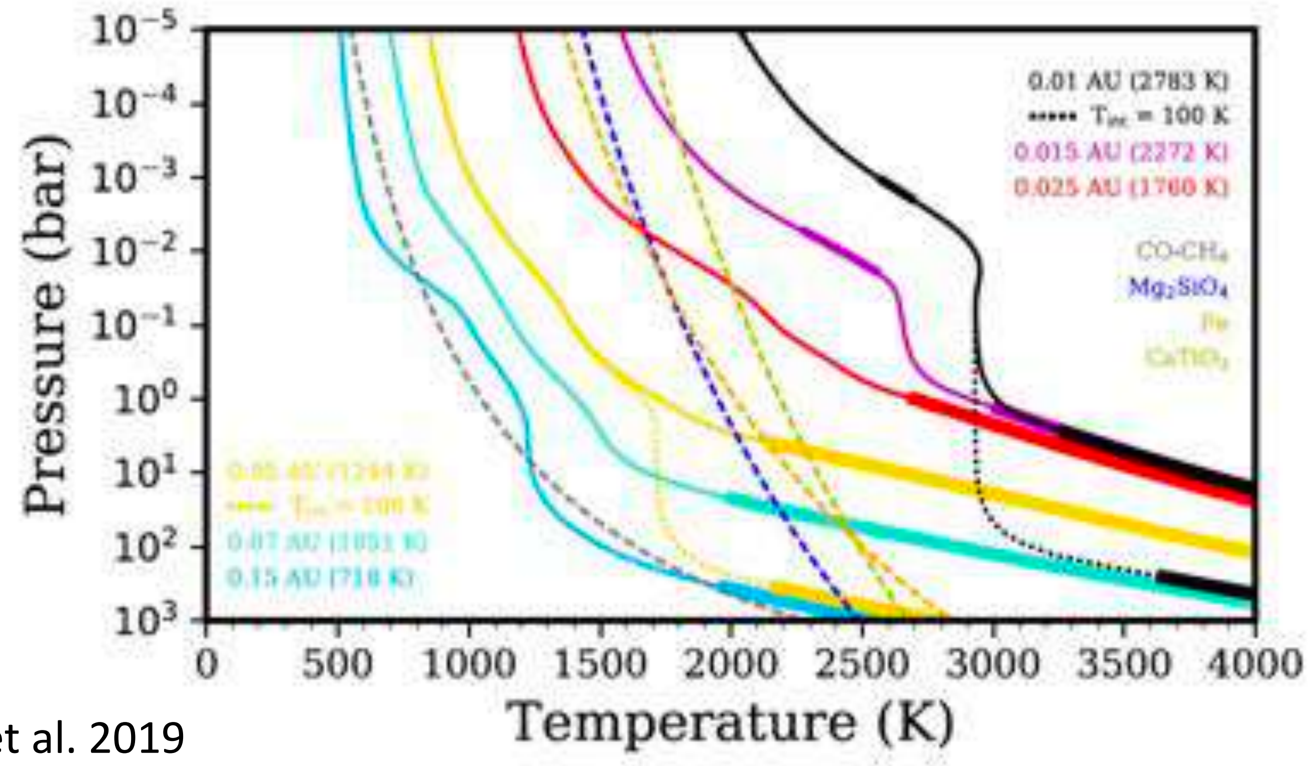
Gao et al. (2020)

From thermal phase curves:
- High thermal emission from the dayside
- Low thermal emission from the nightside
→ consistent with prediction from GCMs

Modeling clouds & haze

A challenge for 3D models: the deep interior conditions



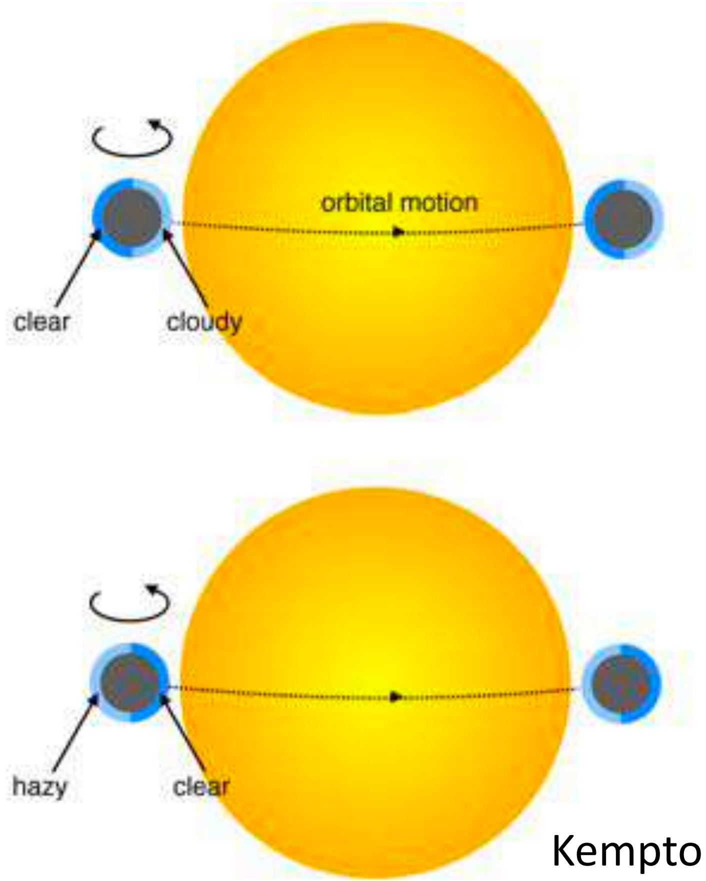


Thorngreen et al. 2019

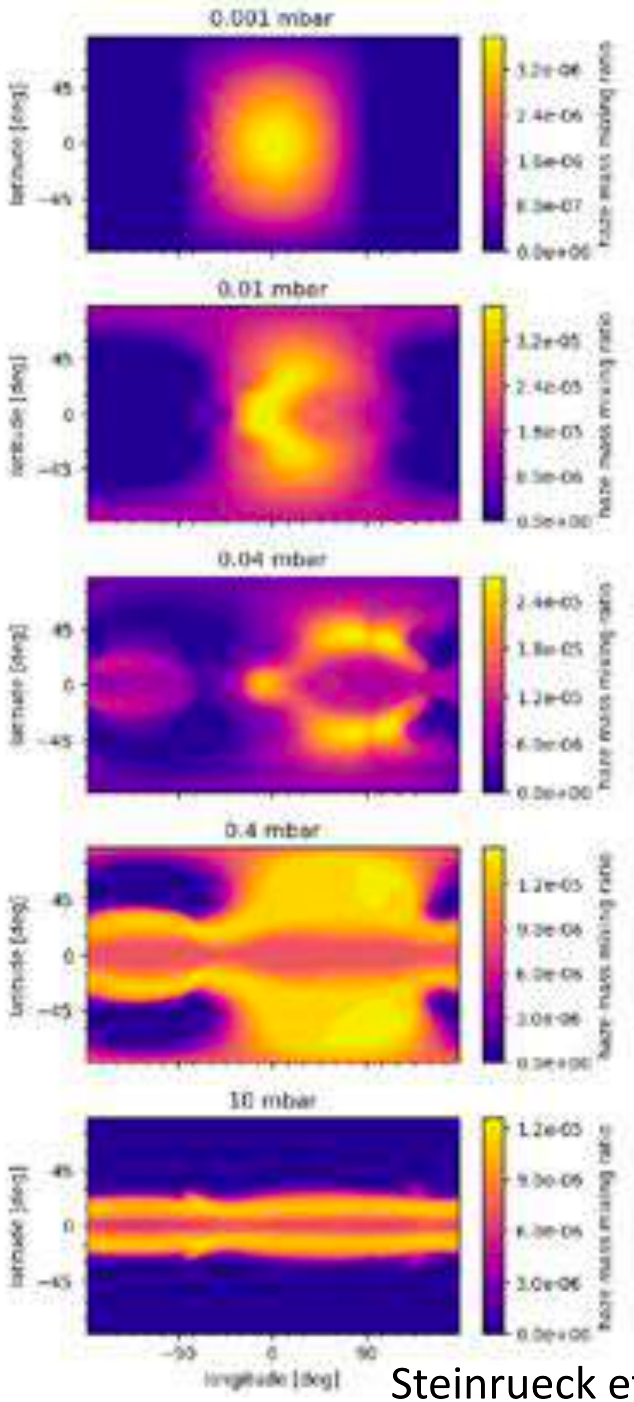
The deep interior temperature strongly affects cloud formation higher in the atmosphere
The radius inflation of hot Jupiters suggests high intrinsic temperature, limiting the cold trapping

Modeling clouds & haze

Photochemical haze on hot Jupiters



Kempton et al. 2017



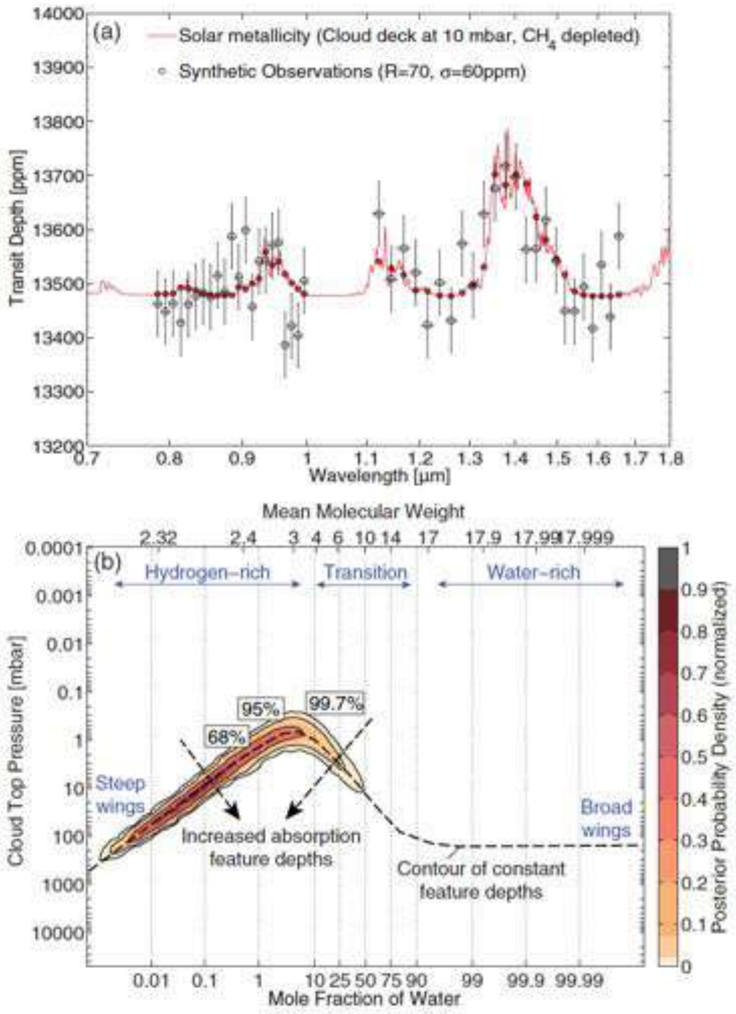
Steinrueck et al. 2020

The east (morning) limb is hazier than the west (evening) limb
=> Potential diagnostic between clouds and haze

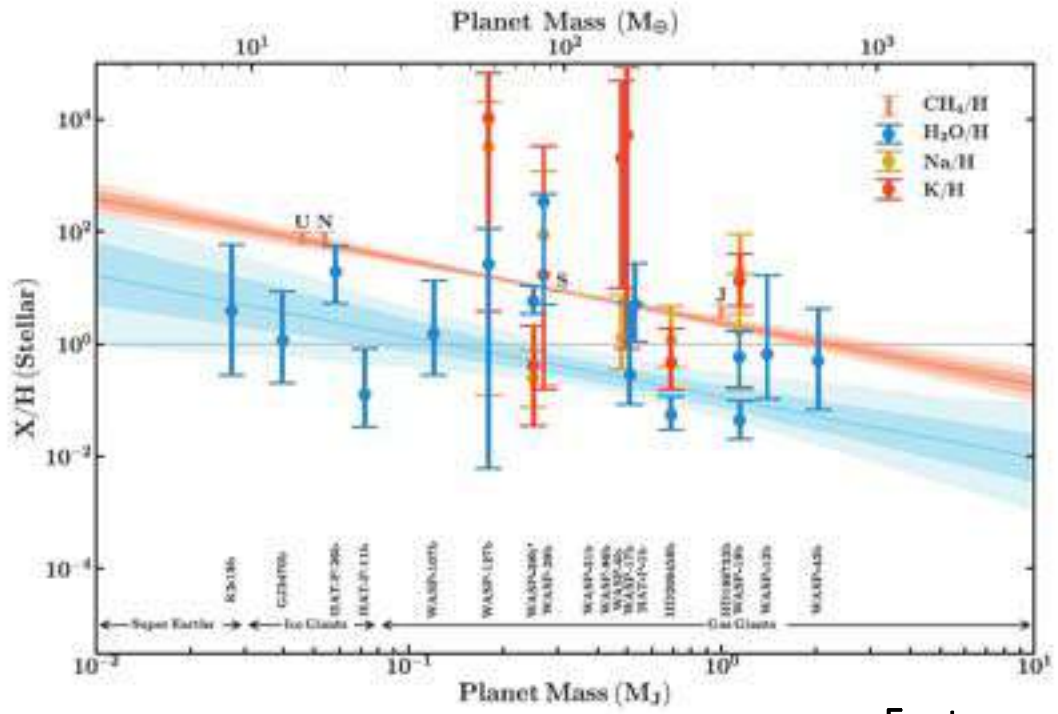
How to probe cloudy atmospheres ?

Probing cloudy atmopshere

Problem: degeneracy between metallicity and clouds



Line & Seager 2013



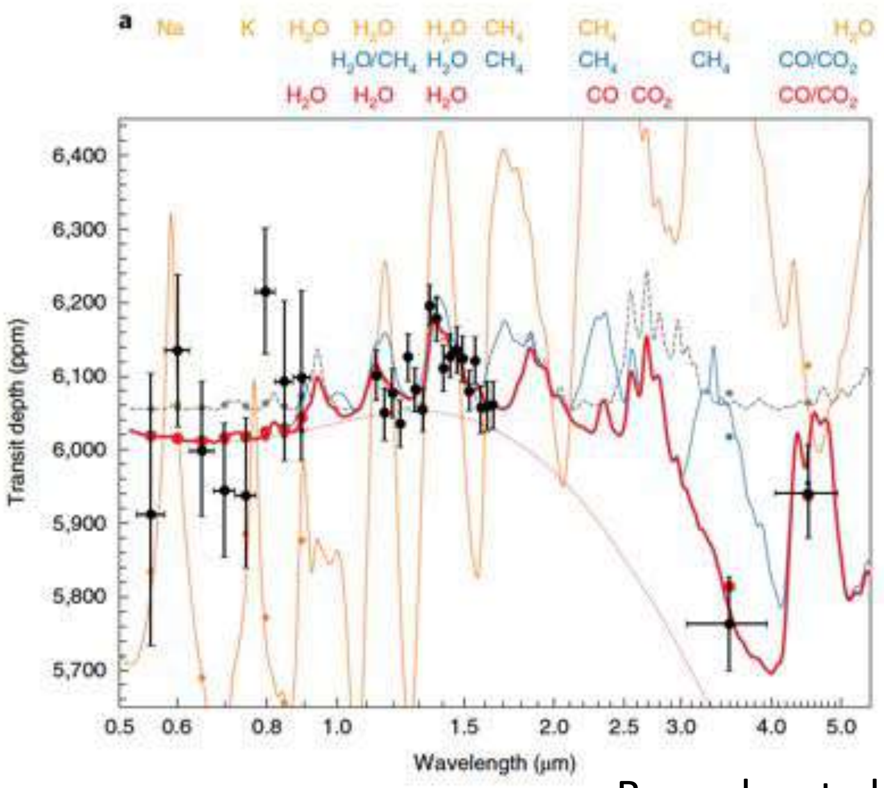
Fortney et al. 2022

Strong biases between metallicity and clouds in atmospheric retrieval

Probing cloudy atmosphere

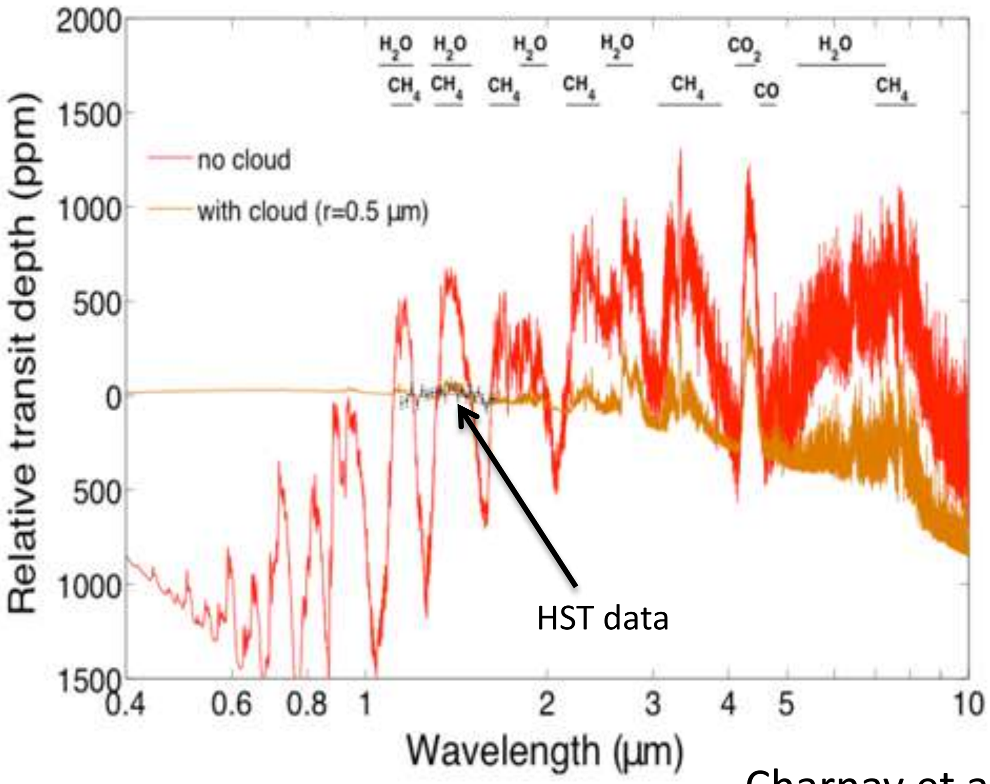
1) **Large spectral coverage (JWST, Ariel)**

HST+Spitzer spectrum of GJ 3470 b



Benneke et al. 2018

HST+model spectra of GJ 1214 b



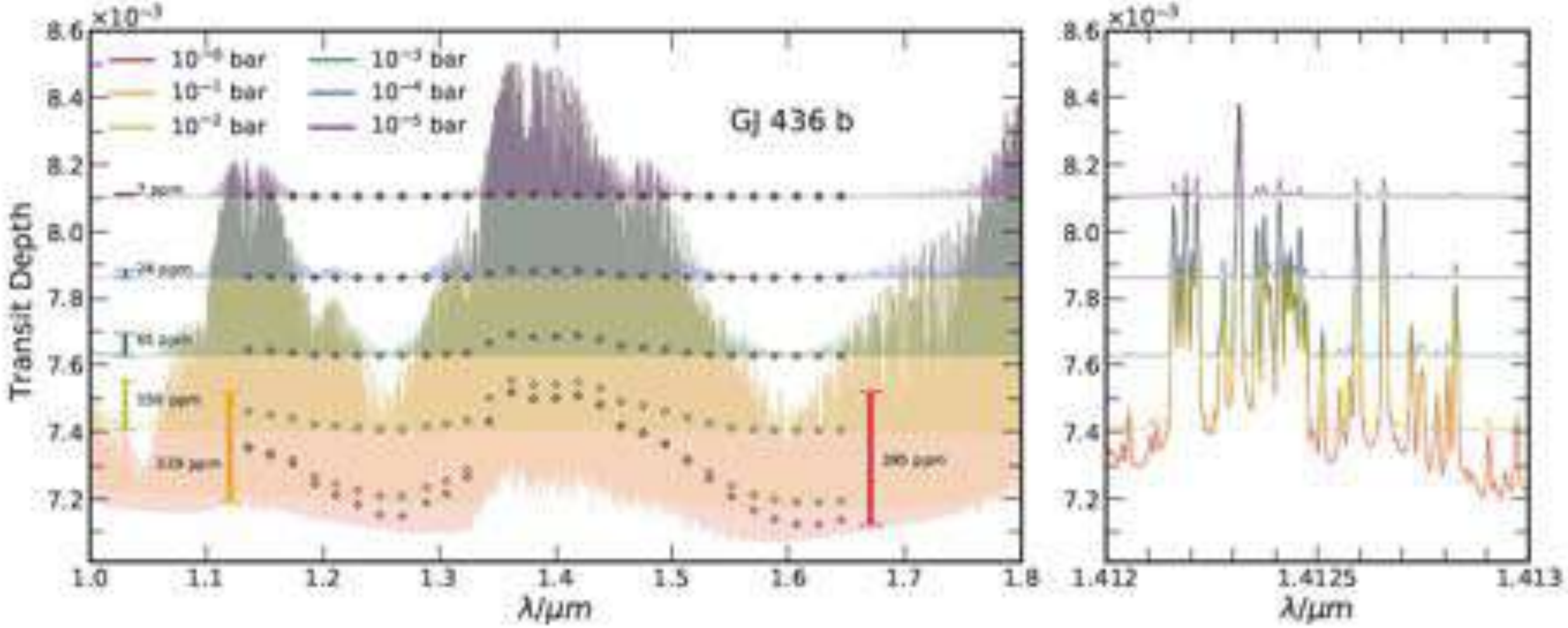
Charnay et al. 2015

Clouds/haze should be optically thinner at long wavelengths where molecular features are stronger

Probing cloudy atmosphere

2) High-resolution spectroscopy (VLT-CRIRES, SPIRou, ELT-ANDES, GMT)

HR spectrum of GJ 436b

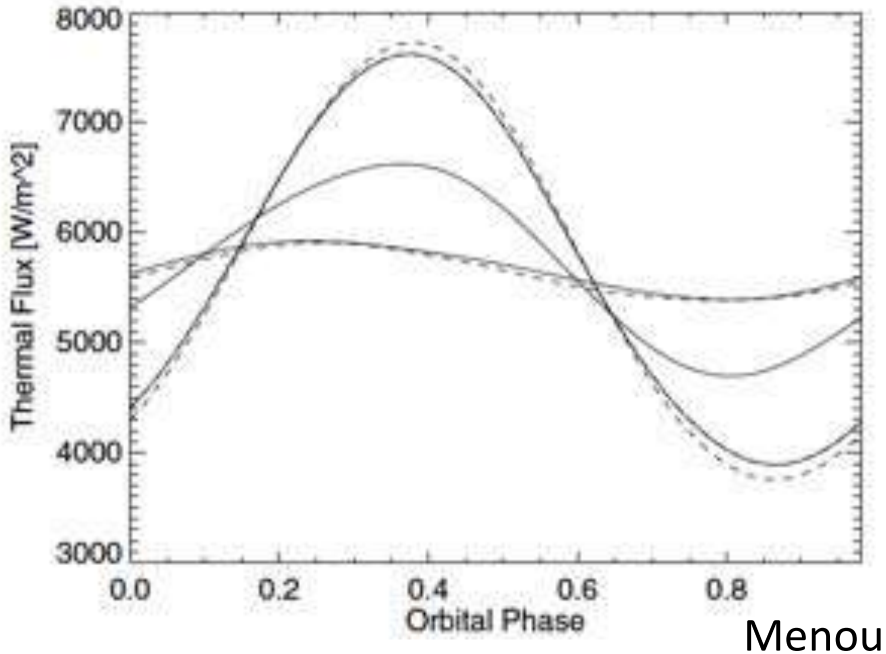


Gandhi et al. 2020

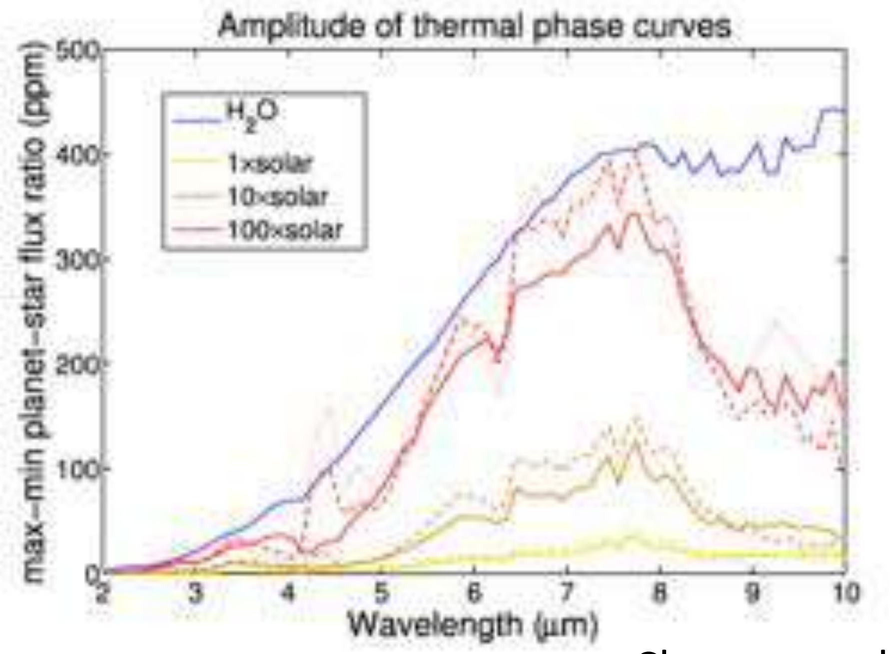
High spectral resolution can probe above clouds for low mean molecular weight

Probing cloudy atmosphere

3) Thermal phase curves (JWST, Ariel)



Menou 2012



Charnay et al. 2015

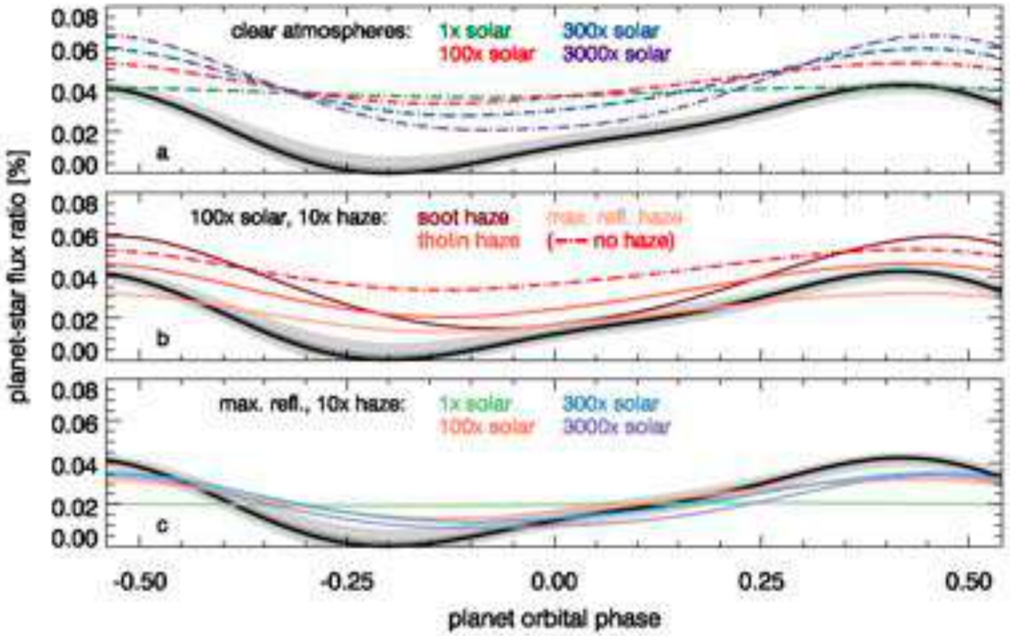
$$\tau_{rad} \sim \frac{c_p P_{phot}}{g \sigma T^3}$$

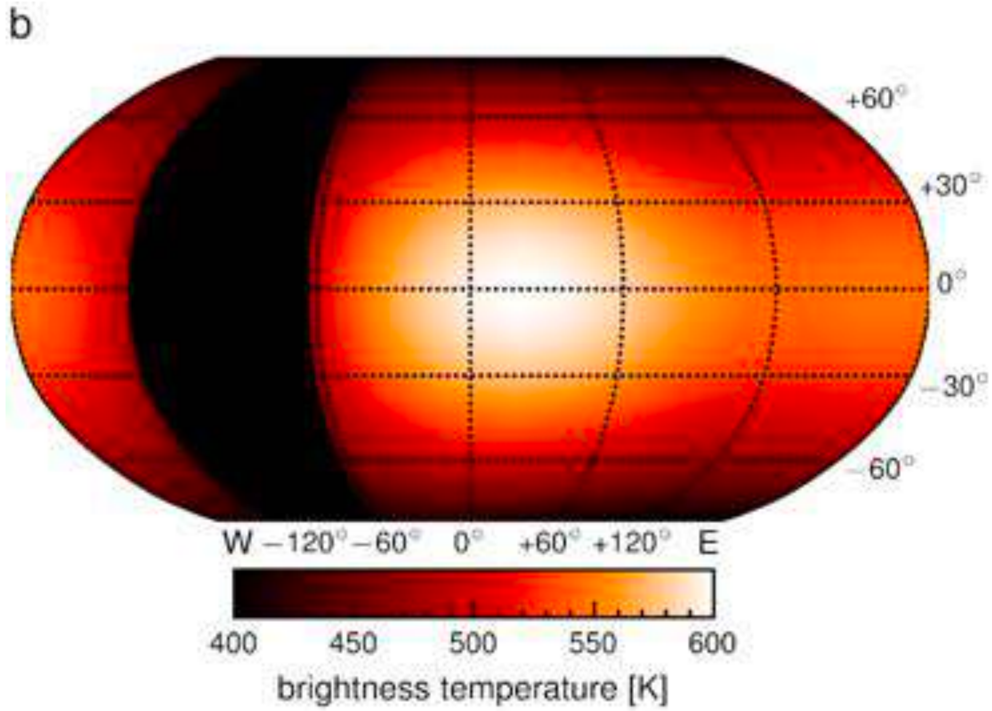
The amplitude of thermal phase curve increases with metallicity

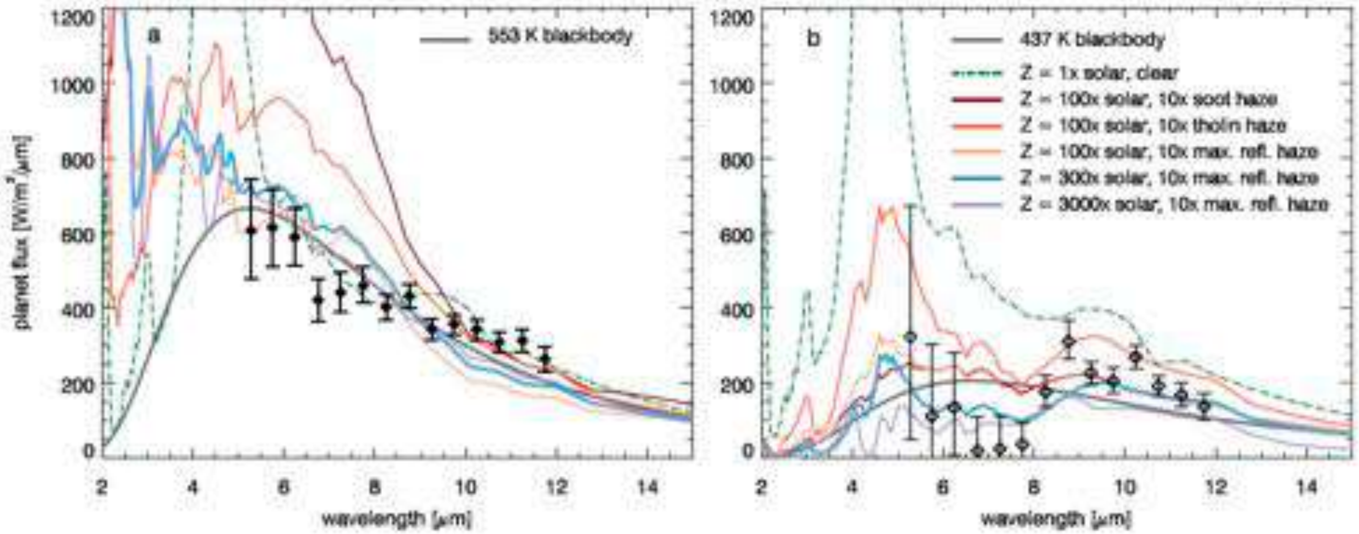
Probing cloudy atmosphere

3) Thermal phase curves (JWST, Ariel)

MIRI phase curve of GJ 1214 b (Kempton et al. 2023)







Evidence for:

- A high metallicity (>100 xsolar)
- Water vapour
- Highly reflective clouds/haze ($A_B \sim 0.5$)

Colors of GJ1214b

Potassium chloride (KCl)

Zinc sulfide (ZnS)

Organic haze

Charnay et al. (2015)

© Manchu & Fossé

Cloud identification

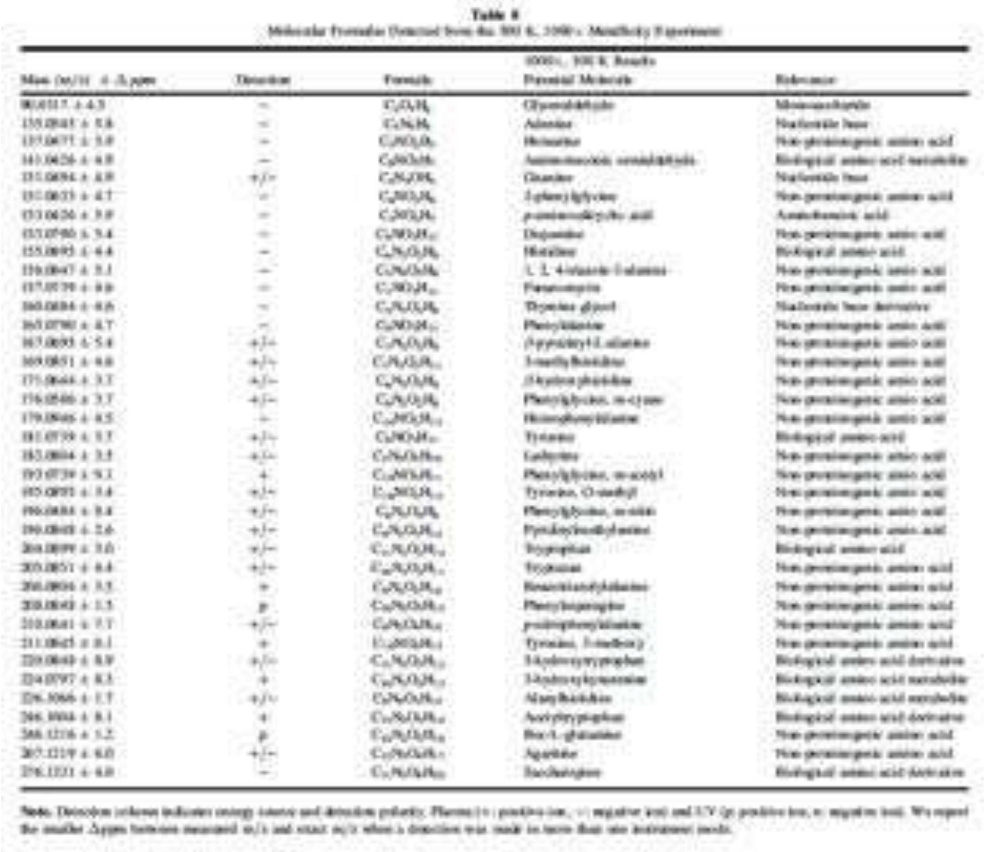
Cumulus

Cloud identification

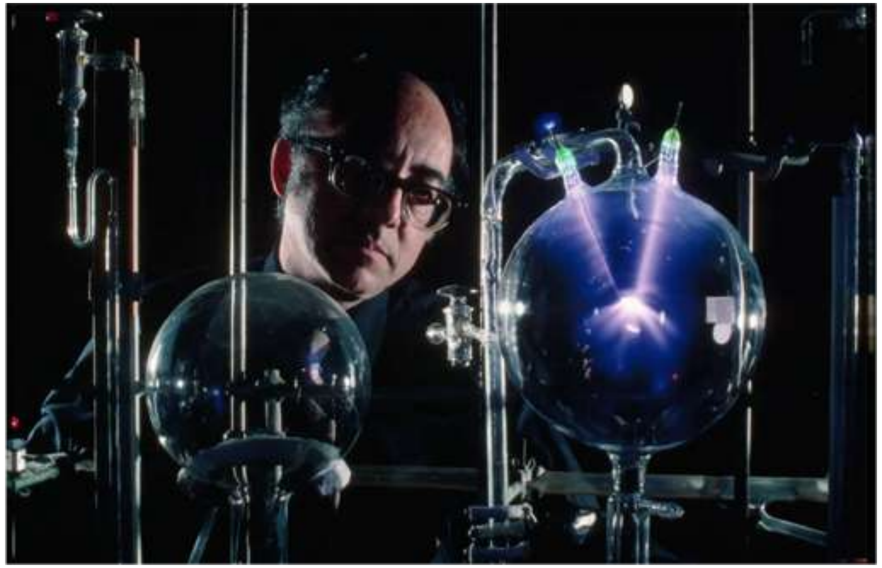
Cirrostratus

Observations of clouds & haze in exoplanets

Lab experiments of haze formation



Experiment of Miller-Urey



Moran et al. 2020

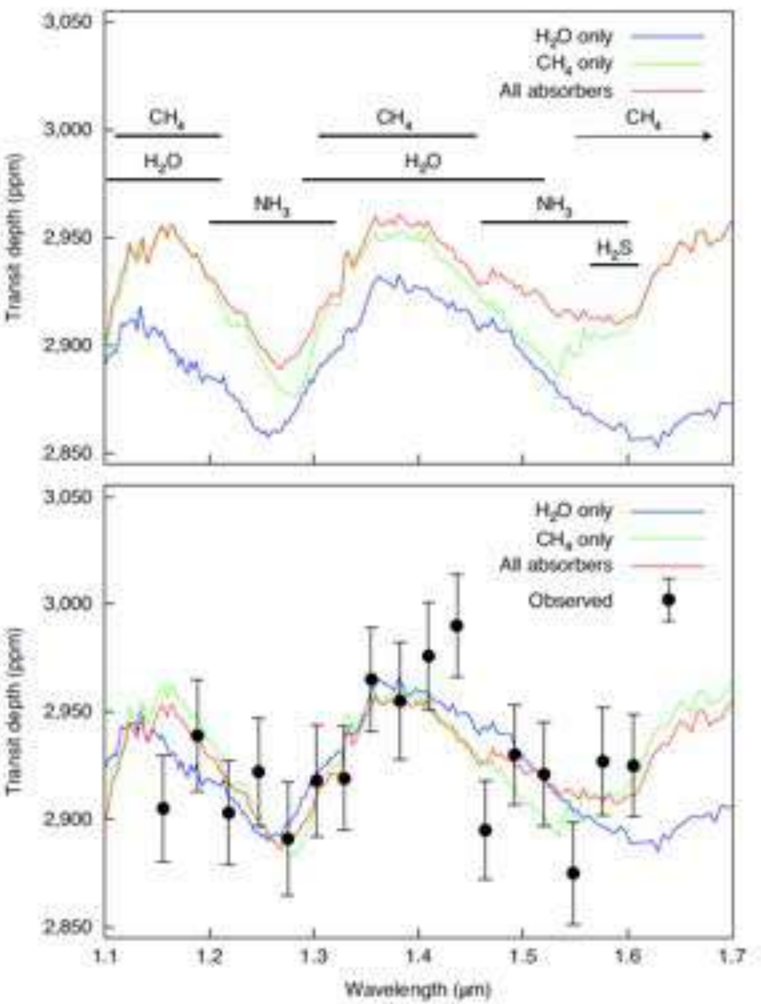
Formation of amino acids and nucleobases with exoplanet haze.
Interest for prebiotic chemistry

Observations of clouds & haze in exoplanets

Methane depletion on warm sub-Neptunes/Neptunes

Planet	H_2O	CH_4	CO	CO_2	NH_3	HCN	references[a]
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							

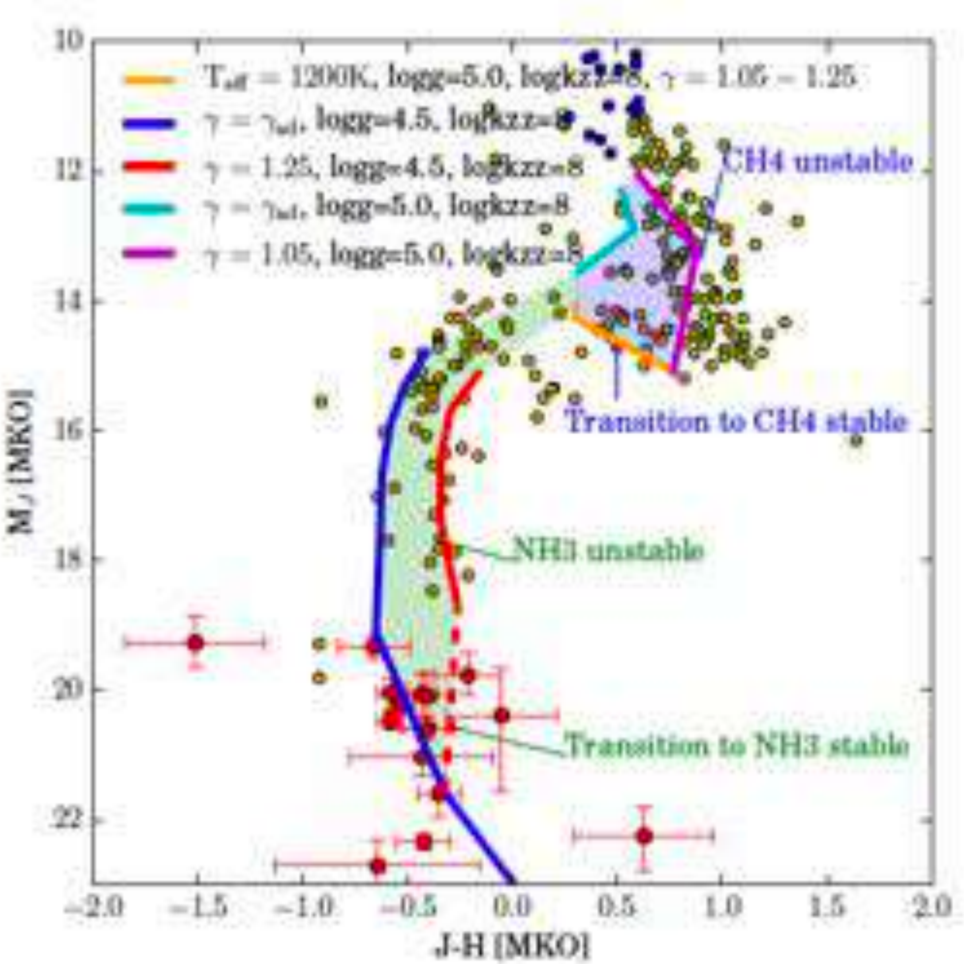
Gressier et al. (2022)



Bézard, Charnay & Blain 2021

Observations of clouds in brown dwarfs

Fingering convection as the driver of the LT-transition



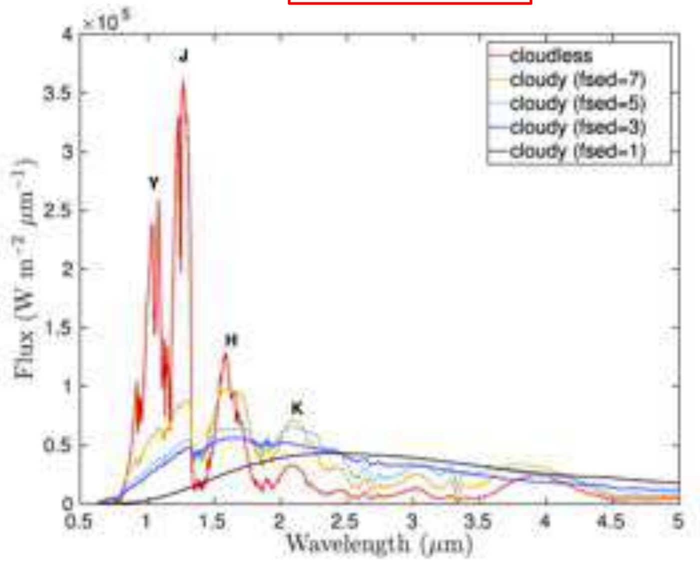
Tremblin et al. 2015, 2016, 2017

Probing cloudy atmosphere

Biases: isothermal/clouds

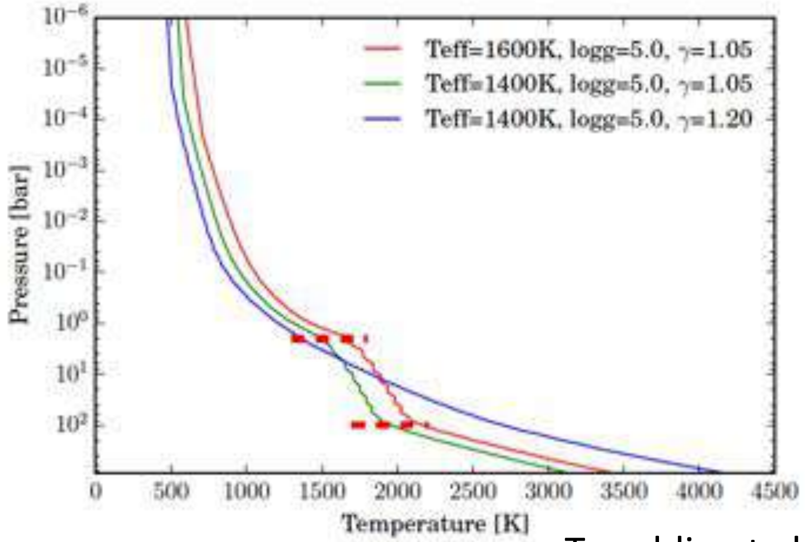
How to reduce spectral features in emission spectra ?

Clouds



Charnay et al. (2018)

Reduced thermal gradient

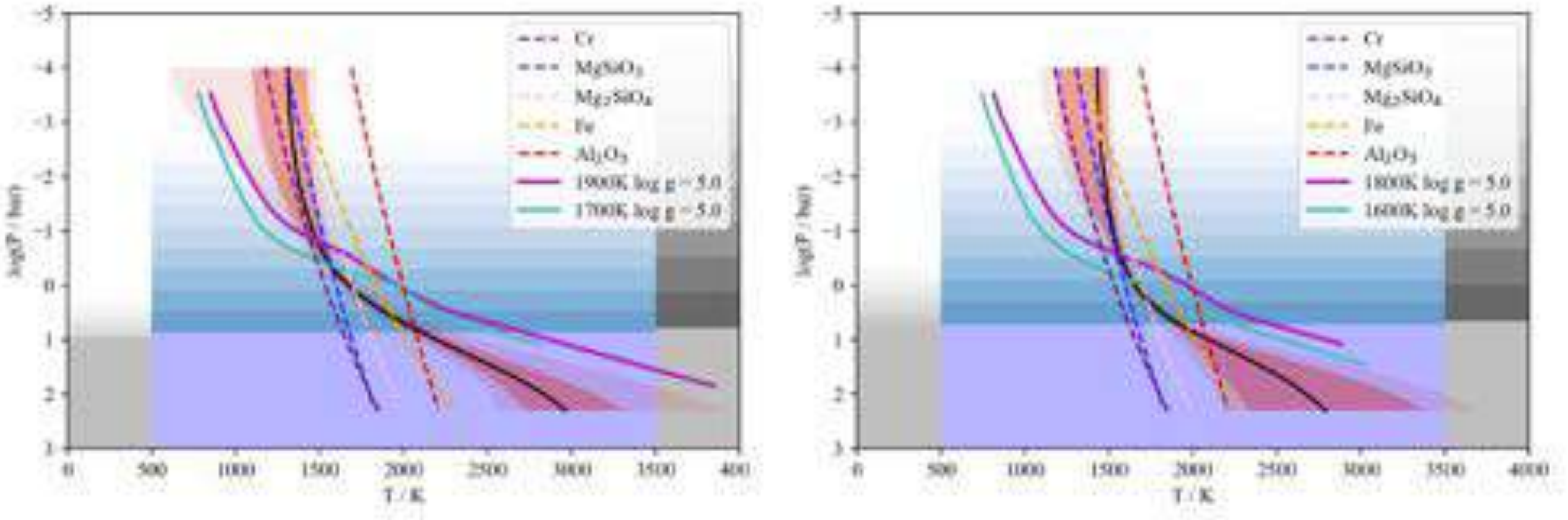


Tremblin et al. (2017)

Probing cloudy atmosphere

4) Biases: isothermal/clouds

Atmospheric retrieval of two L dwarfs by Burningham et al. (2017):



Both clouds + reduced thermal gradient !

But the retrieval might be biased by its relatively simple cloud model

Probing cloudy atmosphere

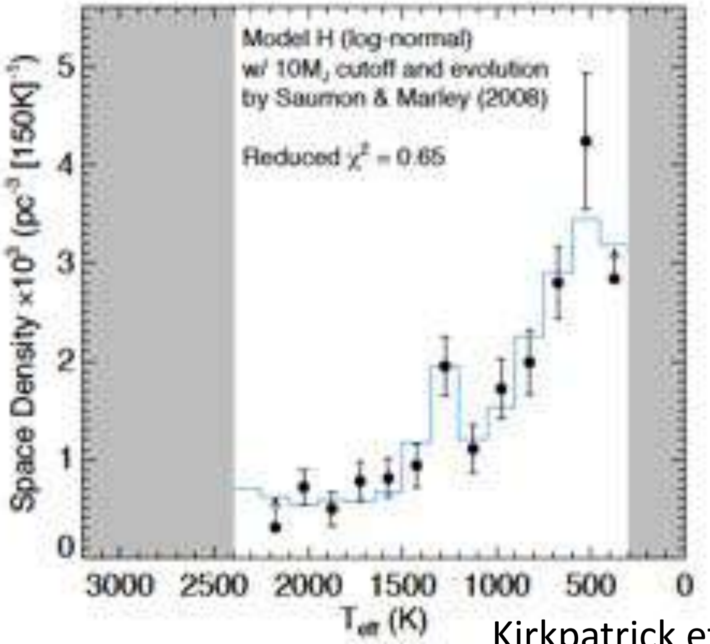
4) Biases: isothermal/clouds

How to break degeneracis between clouds and reduced thermal gradient ?

1) Cloud absorption features

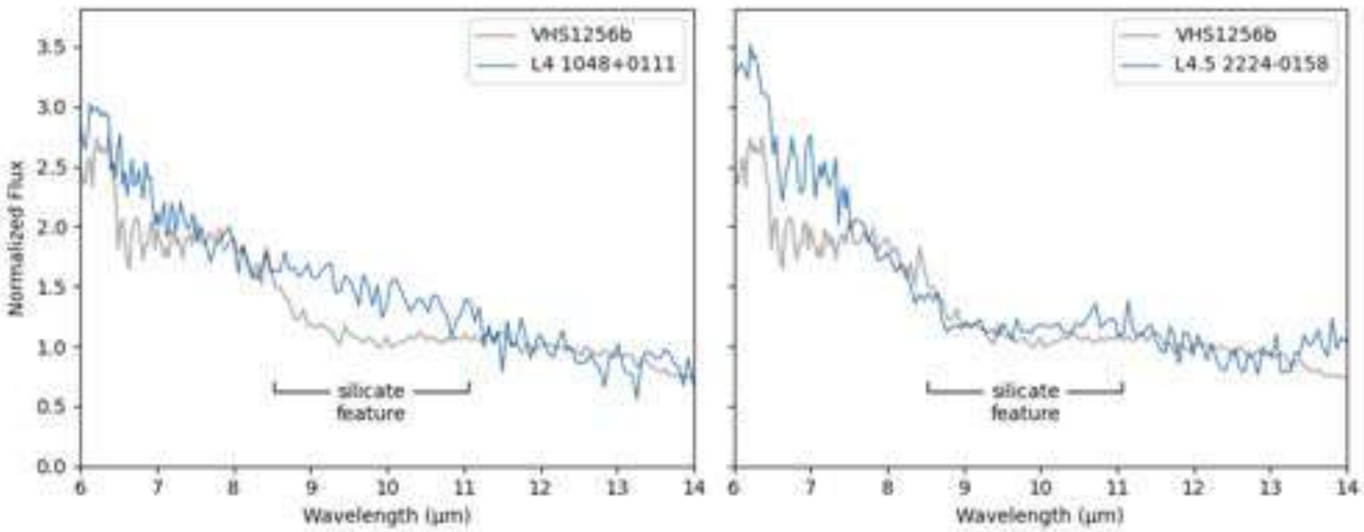
2) Thermal evolution

Excess of BD at the LT transition



Kirkpatrick et al. (2020)

Silicate feature on VHS 1256 b



Miles et al. (2022)

But:

1) Clouds can be a mixture of species (e.g. Jupiter's clouds)
2) Best et al. 2020 found a minimum of BD at the LT transition

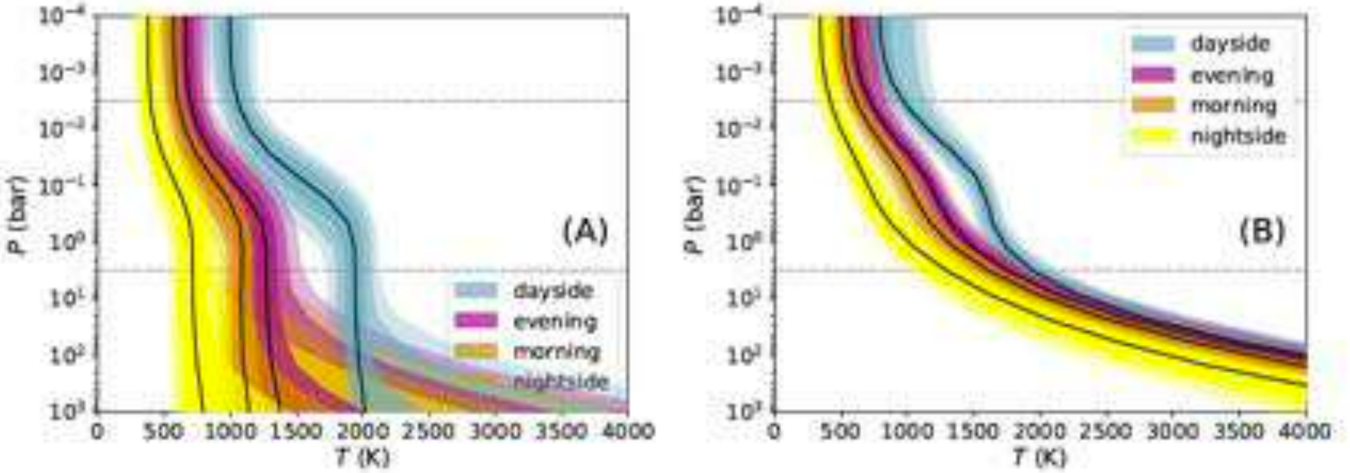
Lessons from models and retrieval

5) Biases: 3D structure

Improvement with global/2D retrieval
(e.g. Chubb & Min 2022, Irwin et al. 2019, Changeat et al. 2021)

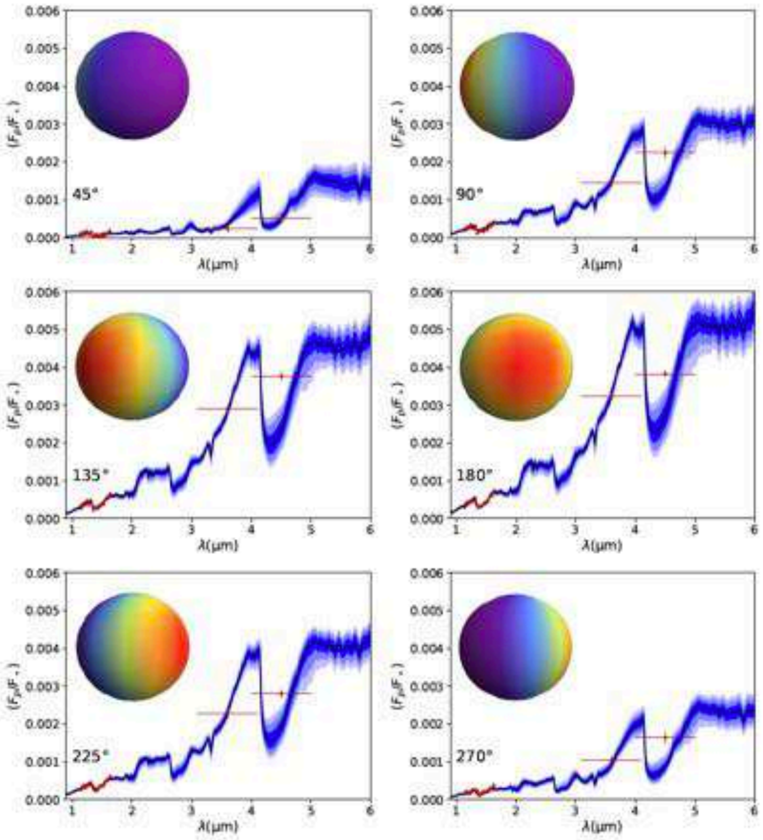
Without cloud

With clouds



Chubb & Min (2019)

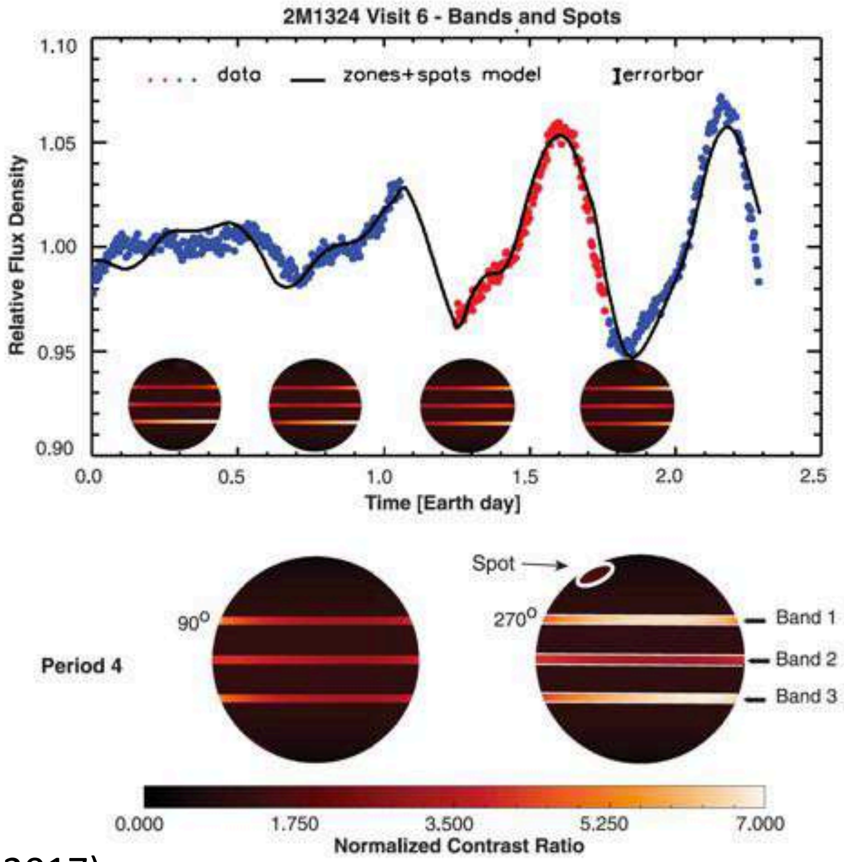
Without clouds



Lessons from models and retrieval

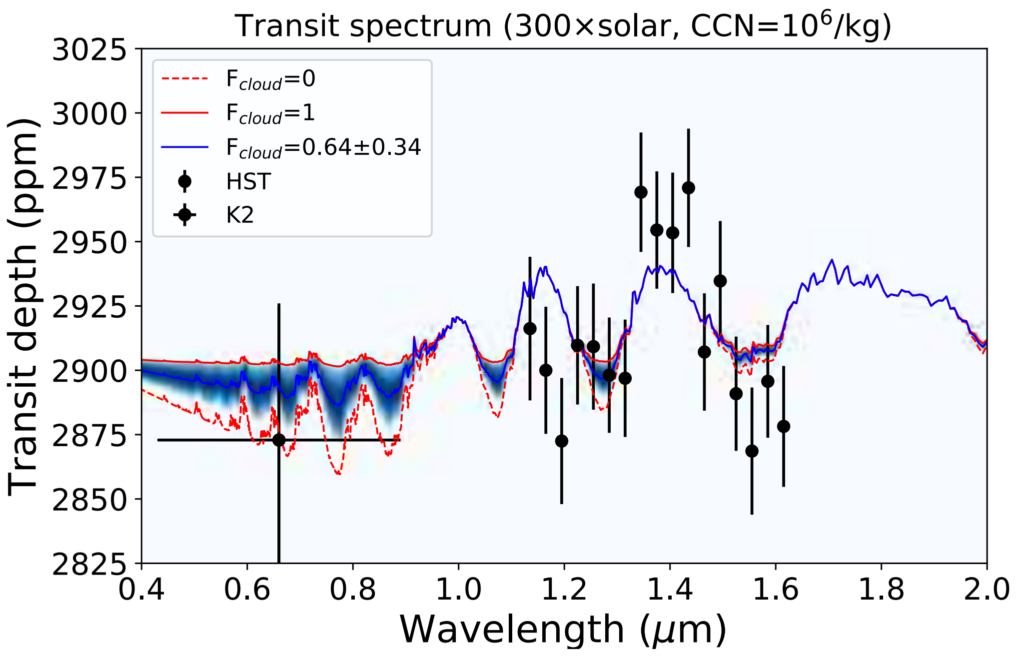
6) Biases: time-variability

Variability of a brown dwarf with Spitzer



Apai et al. (2017)

3D simulation of K2-18 b with water clouds

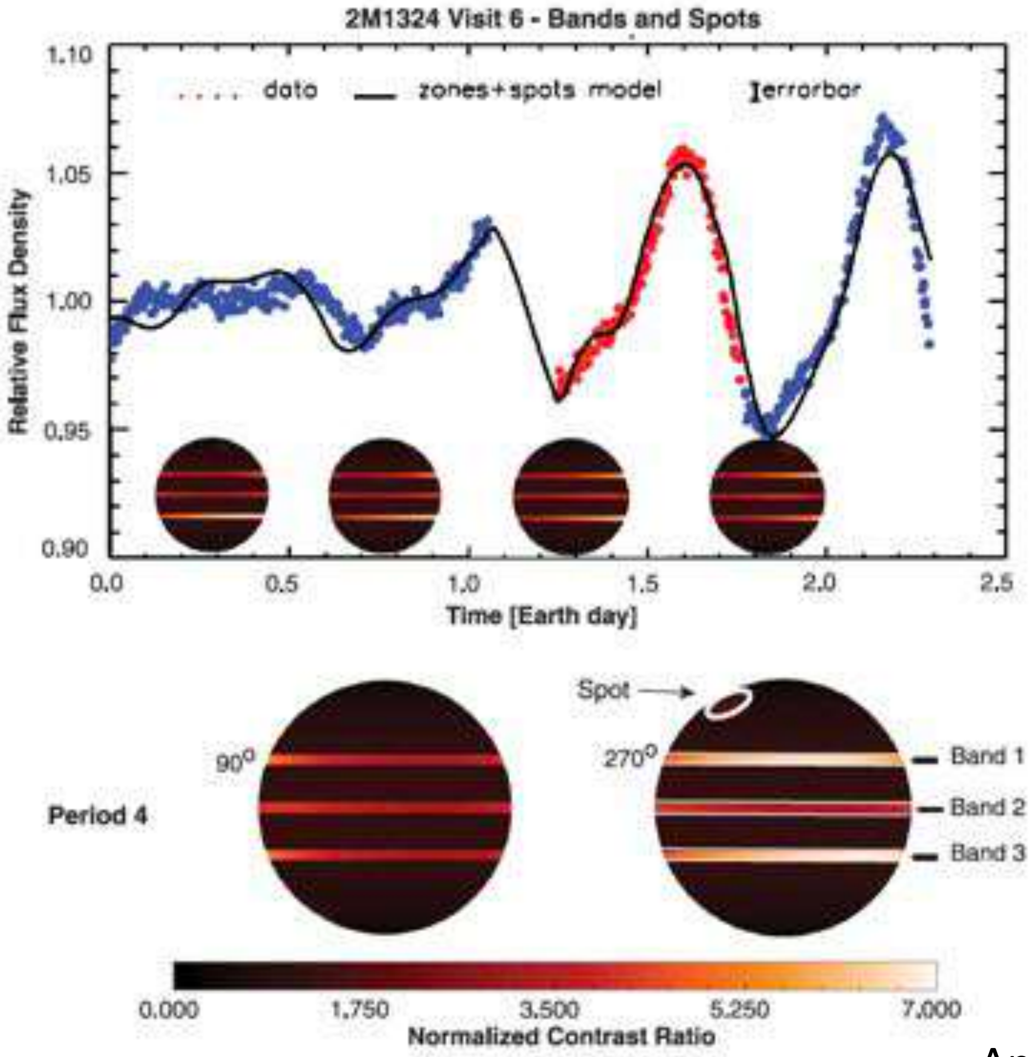


Charnay et al. (2021)

Possible variability of cloudiness and spectra

Observations of clouds in brown dwarfs

Variability of brown dwarf at the LT transition



Apai et al. 2017

Observations of clouds in brown dwarfs

Measurement of rotational period