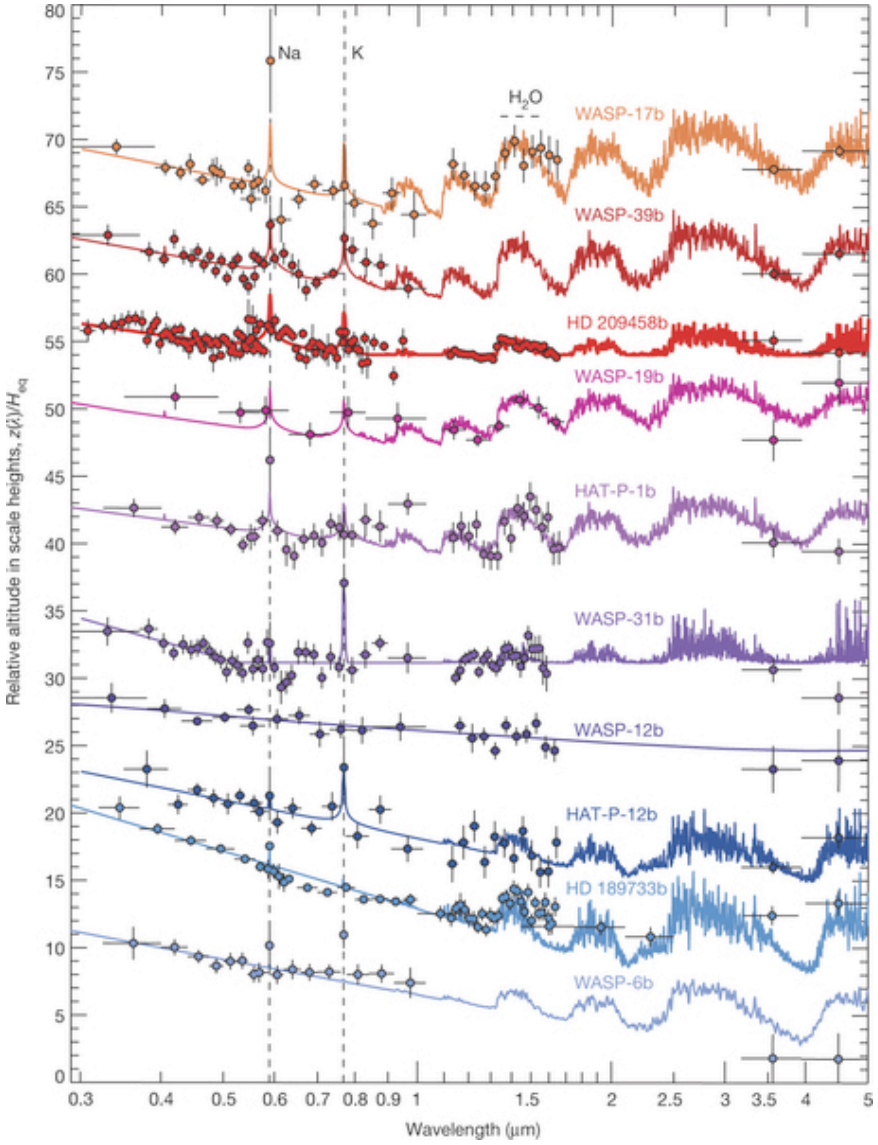
Modélisation des nuages dans les atmosphères d'exoplanètes chaudes

Benjamin Charnay[1],
Victoria Meadows[2], Jérémy Leconte[3], Giada Arney[2],
Bruno Bézard[1], Anthony Boccaletti[1]

[1]LESIA, Paris Observatory, France
[2]University of Washington (Seattle)
[3]Bordeaux LAB, France

Clouds on transiting exoplanets

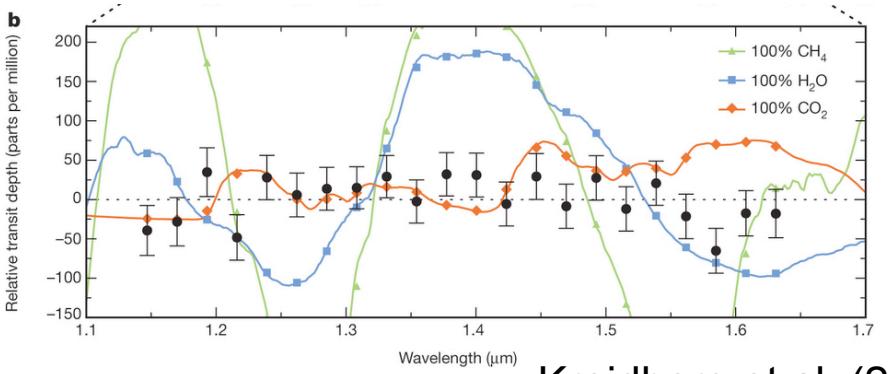
Slope in transit spectra



Sing et al. (2015)

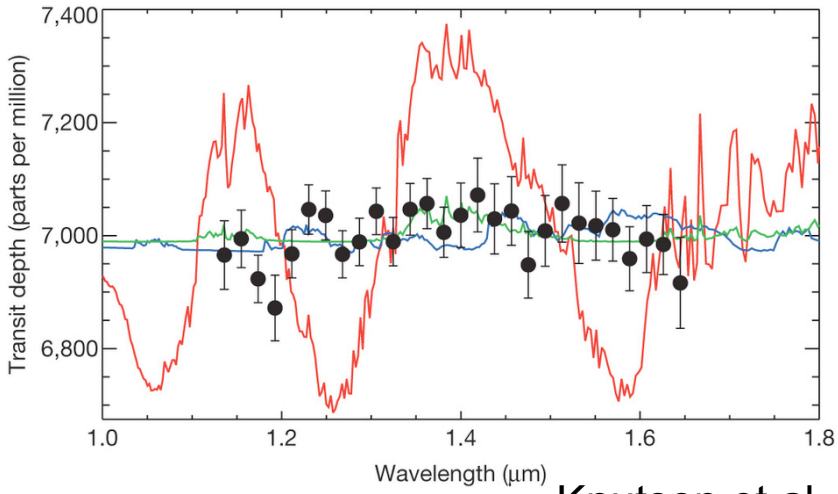
Flat transit spectrum for low mass planets

GJ1214b



Kreidberg et al. (2014)

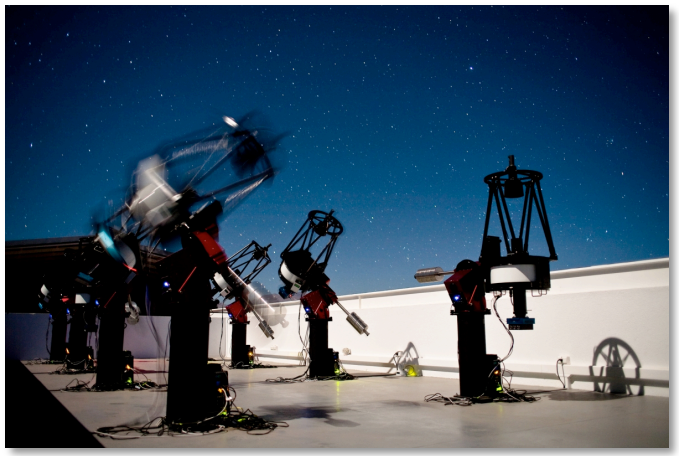
GJ436b



Knutson et al. (2014)

GJ1214b

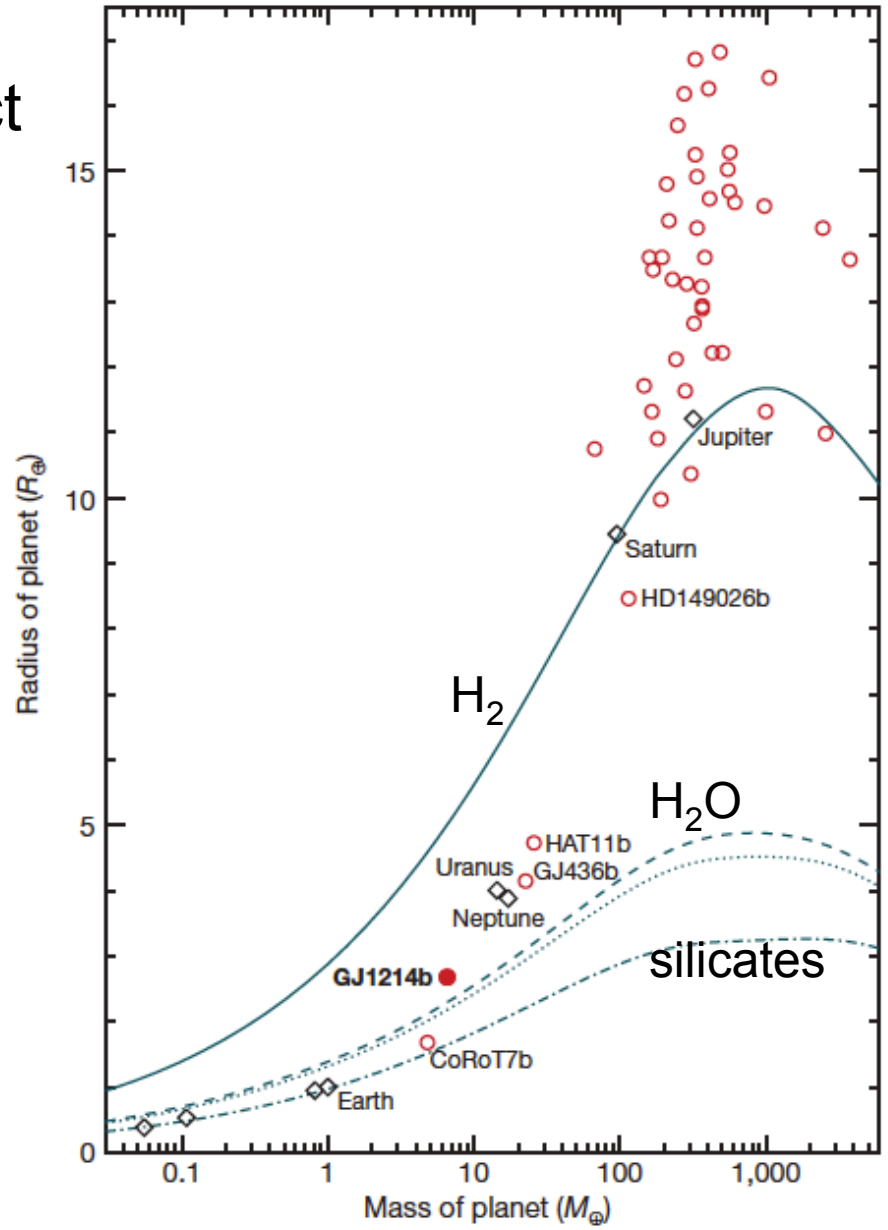
Discovered by the MEarth project
(Charbonneau et al. 2009)

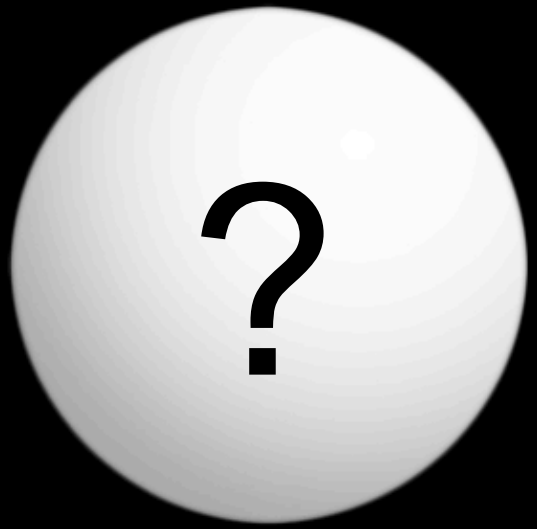


mass = 6.55 M_E
Radius = 2.68 R_E
T_{eff} = 555 K

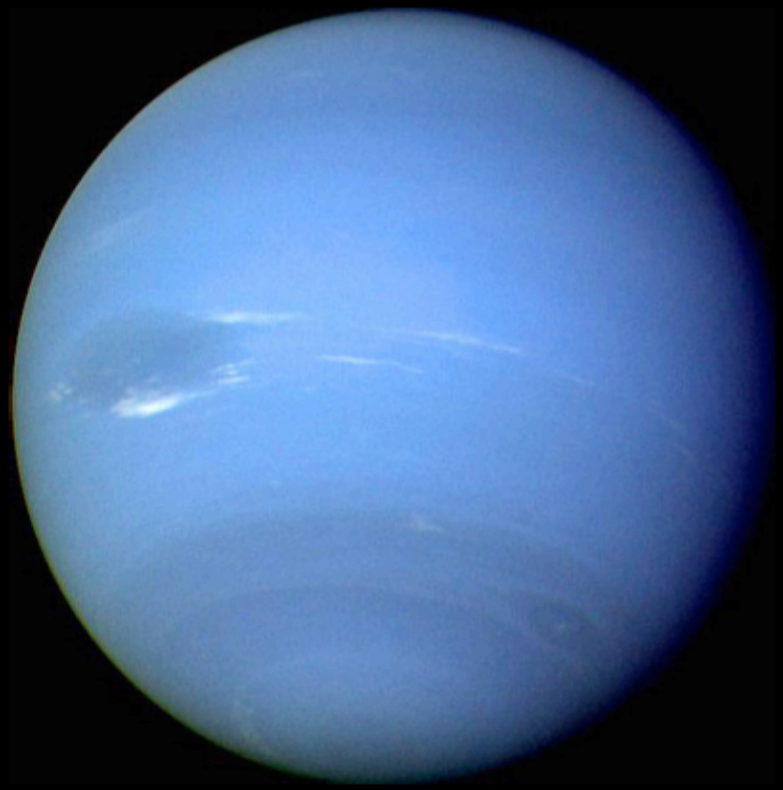
Host star (GJ1214)

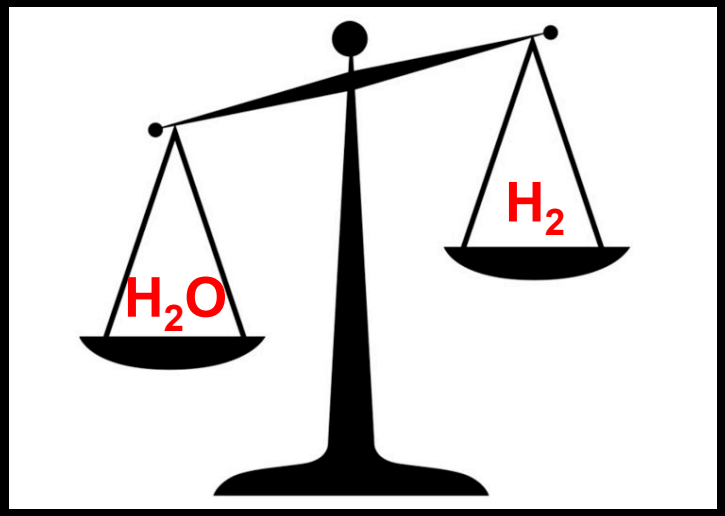
distance = 42 light years
mass = 0.16 M_{sun}

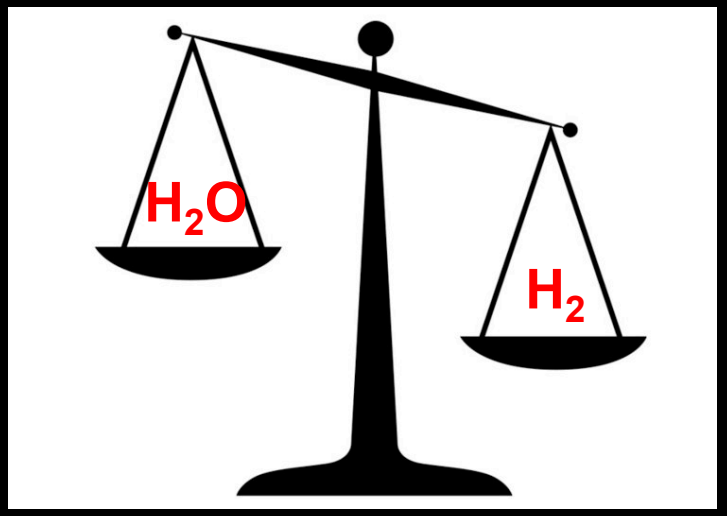


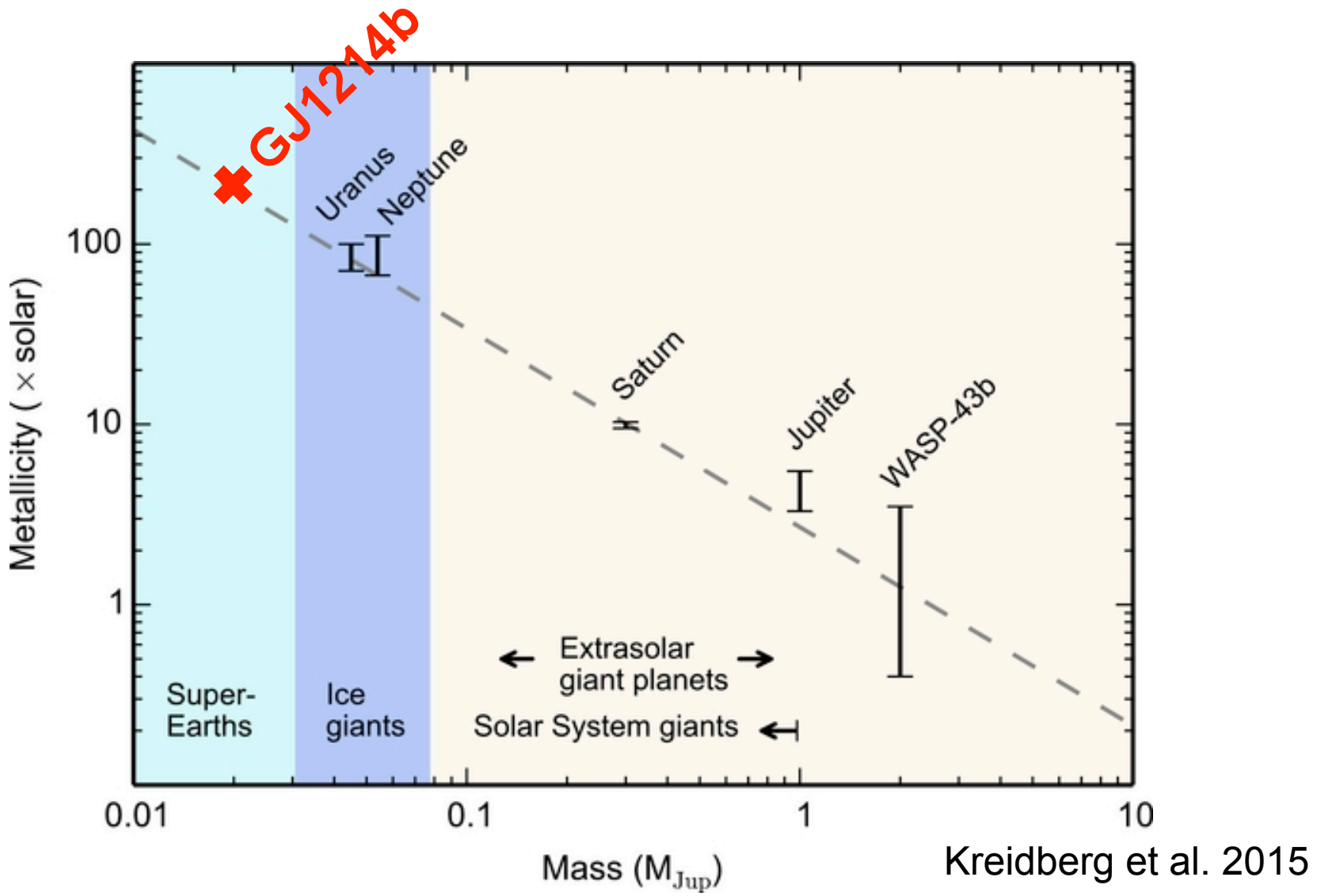


GJ1214b





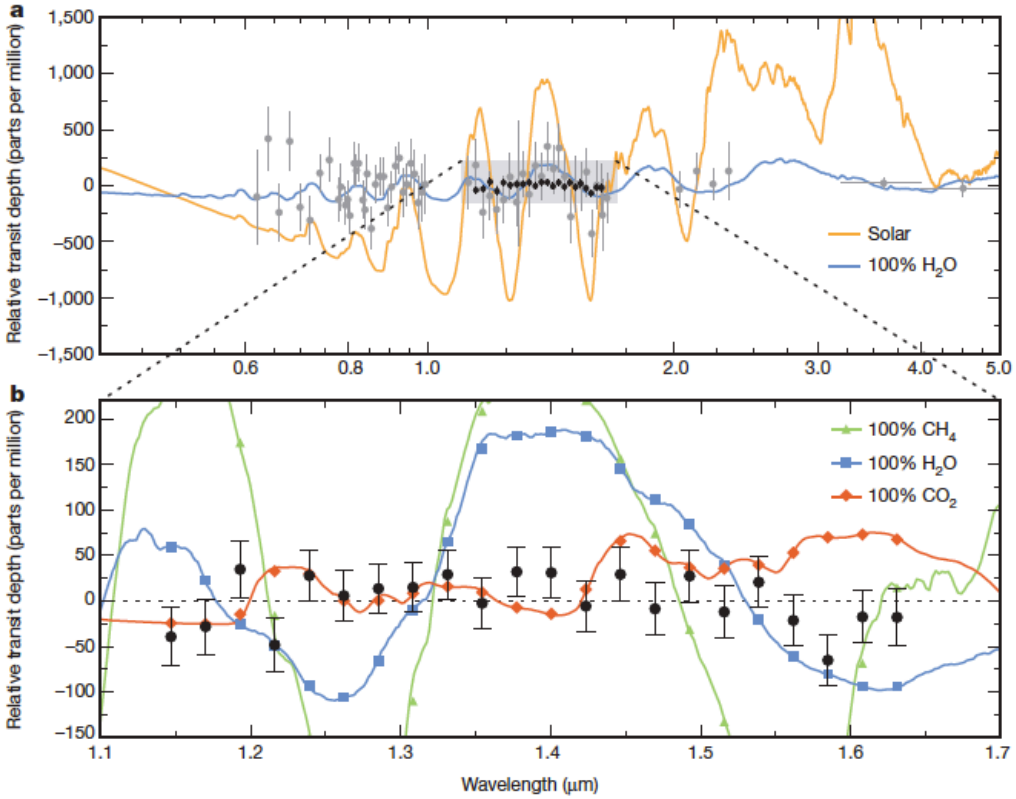




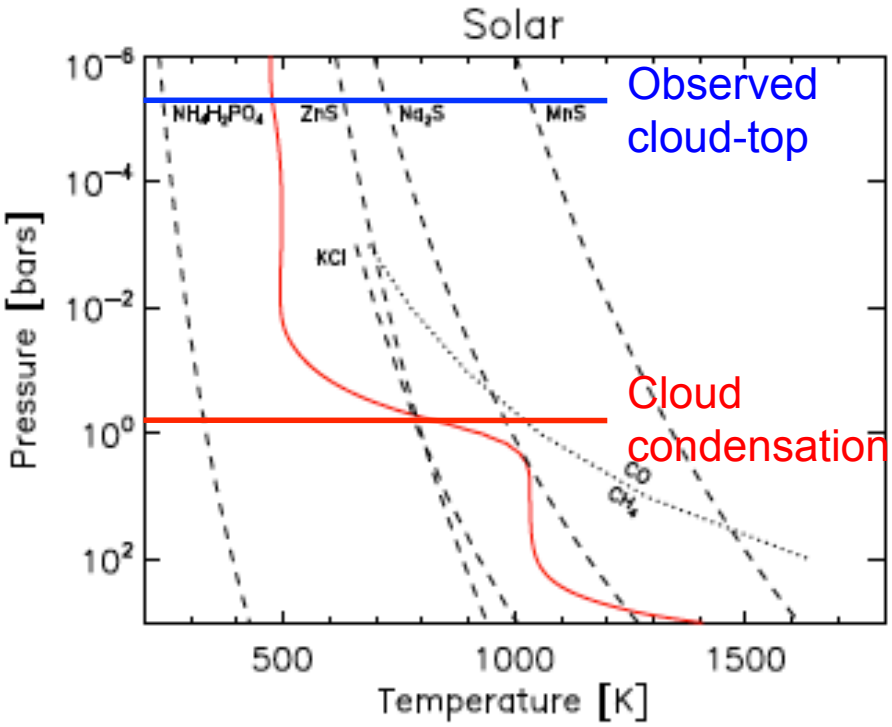
Kreidberg et al. 2015

High metallicity expected for GJ1214b
(≈200xsolar)

Observations of high clouds on GJ1214b



Kreidberg et al. (2014)



Miller-ricci et al. (2012)

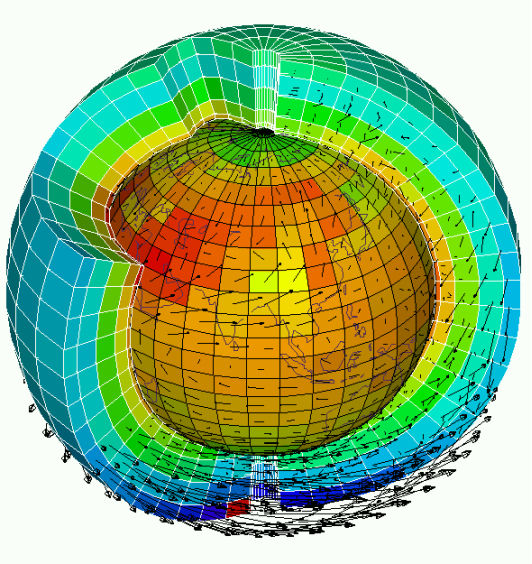
Flat spectrum

Presence of high clouds or photochemical haze (as on Titan)

Condensate clouds form at ≈0.1-1 bar

Strong circulation

Goal: 3D modeling of GJ1214b for different atmospheric compositions (H-rich and water-rich) with clouds, using the **Generic LMDZ**.



Recent applications:

- early atmospheres (Earth, Mars, Titan)
- habitability of exoplanets
- giant planets (Saturn & Jupiter)
- icy bodies (Pluto & Triton)

❑ Simulations with non-gray opacities

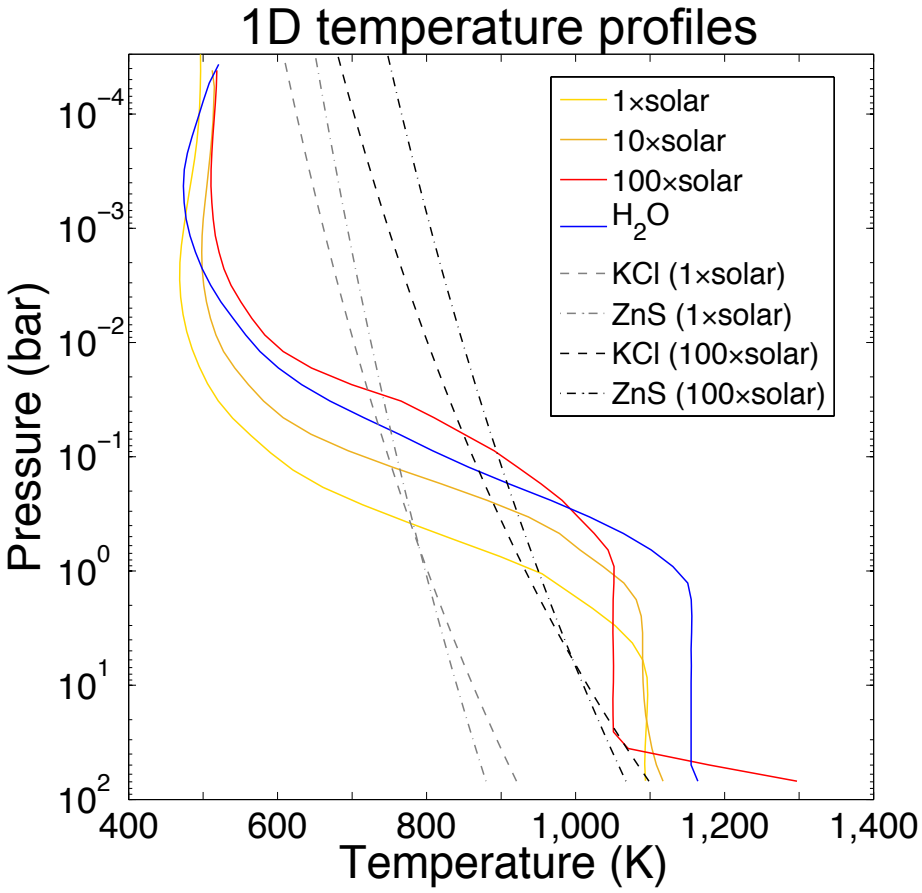
- Composition at thermo-chemical equilibrium (1, 10, 100x solar and pure water)
- Correlated-k radiative transfer code computed with HITRAN 2012 & HITEMP

❑ Simulations with KCl/ZnS clouds (radiatively active)

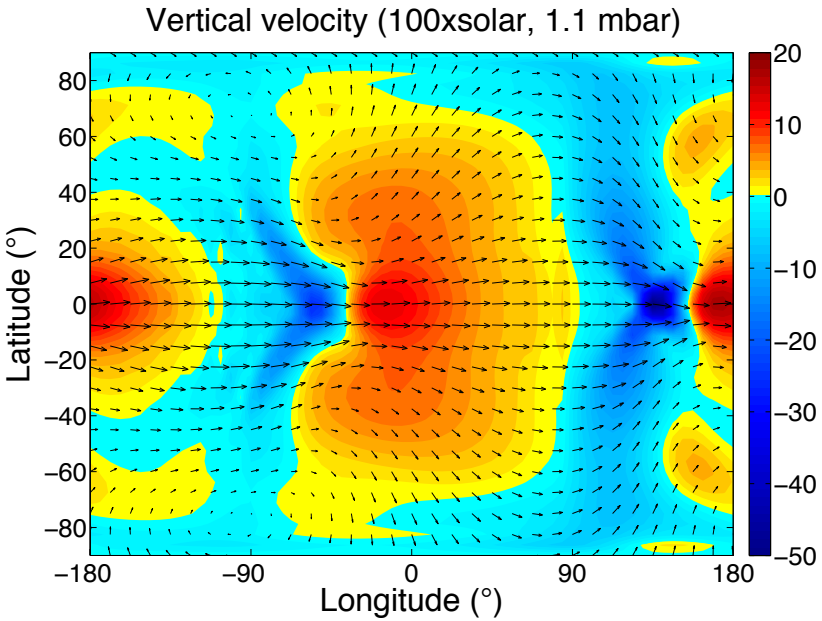
❑ Production of transmission/emission/reflection spectra and phase curves (with the GCM and SMART)

Cloud formation:

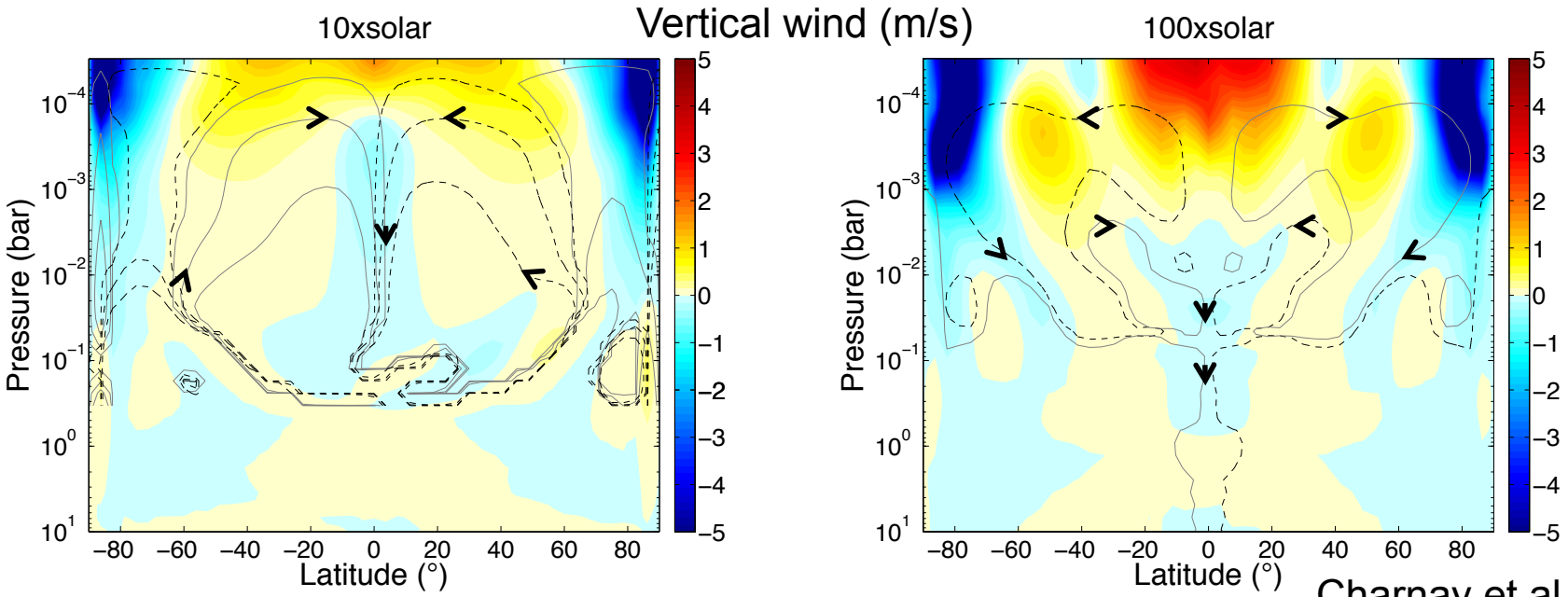
- Vapor mixing ratio fixed in the deepest layers (Lodders 2003)
- Condensation/evaporation with latent heat release (Morley et al 2012)
- Fixed cloud radius
- Sedimentation at terminal velocity (v_{sed}~10 m/s at 10^{-5} bar)



Circulation on synchronously rotating planet

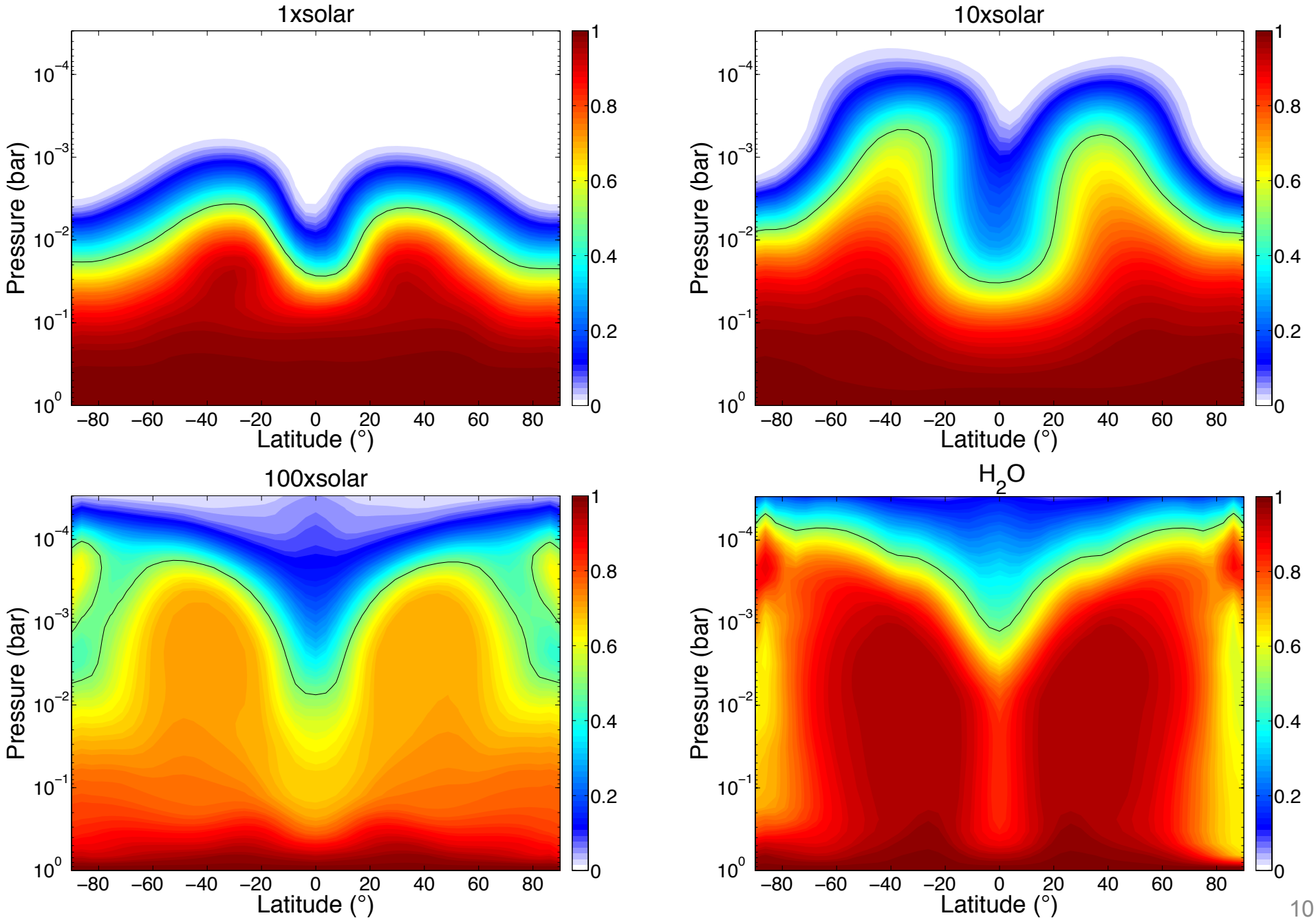


Zonally averaged circulation = reverse Hadley cells



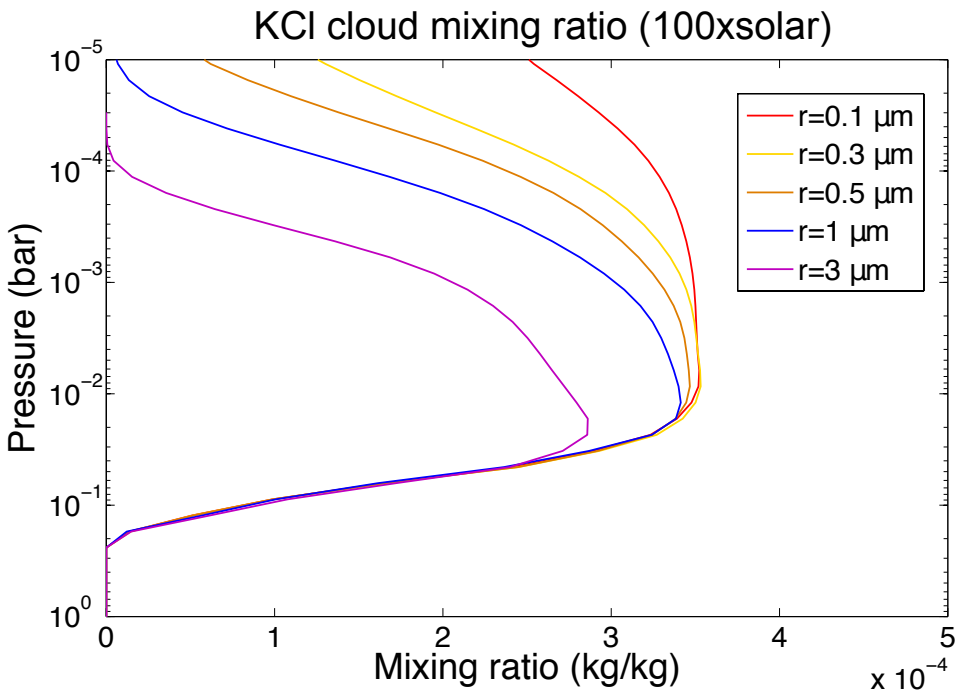
Charnay et al. 2015a

Zonally averaged tracer distribution



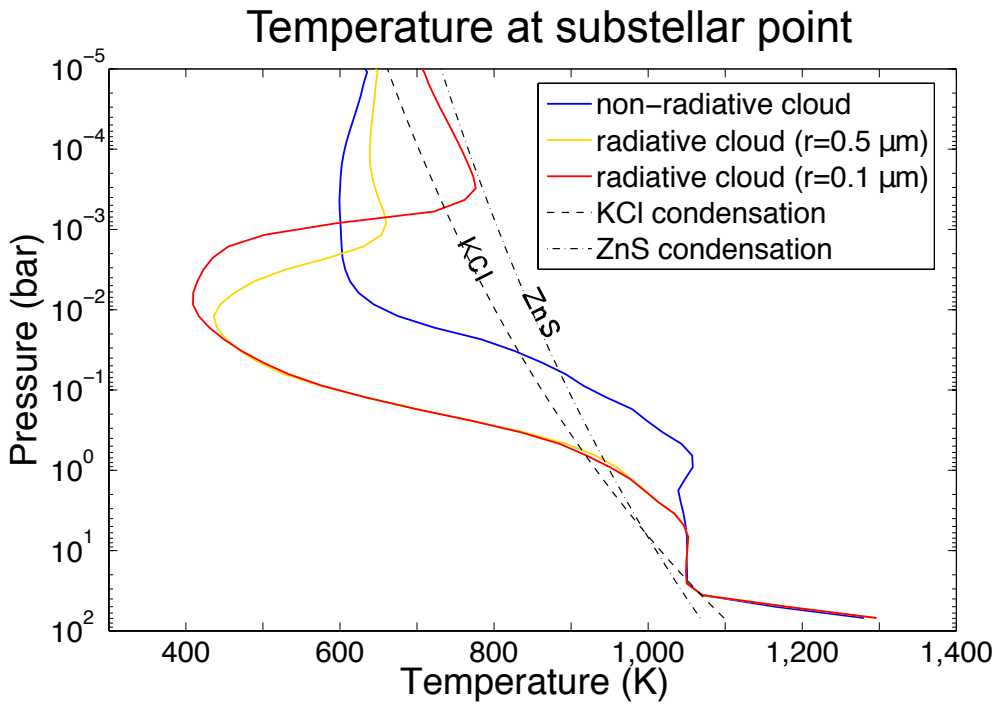
Global vertical mixing

- efficient mixing for r<1 micron
- limit on the size of particles

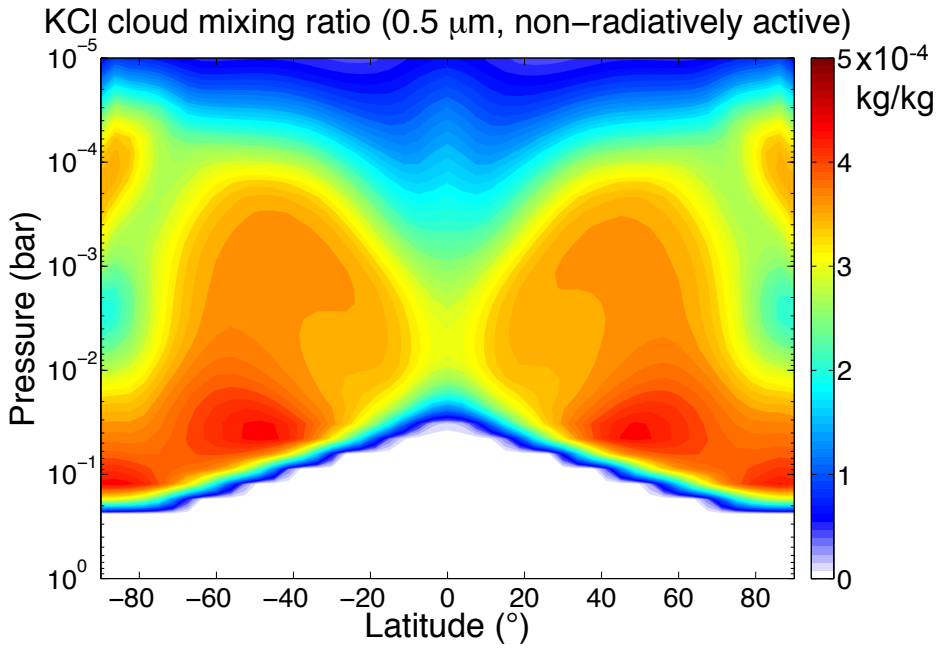


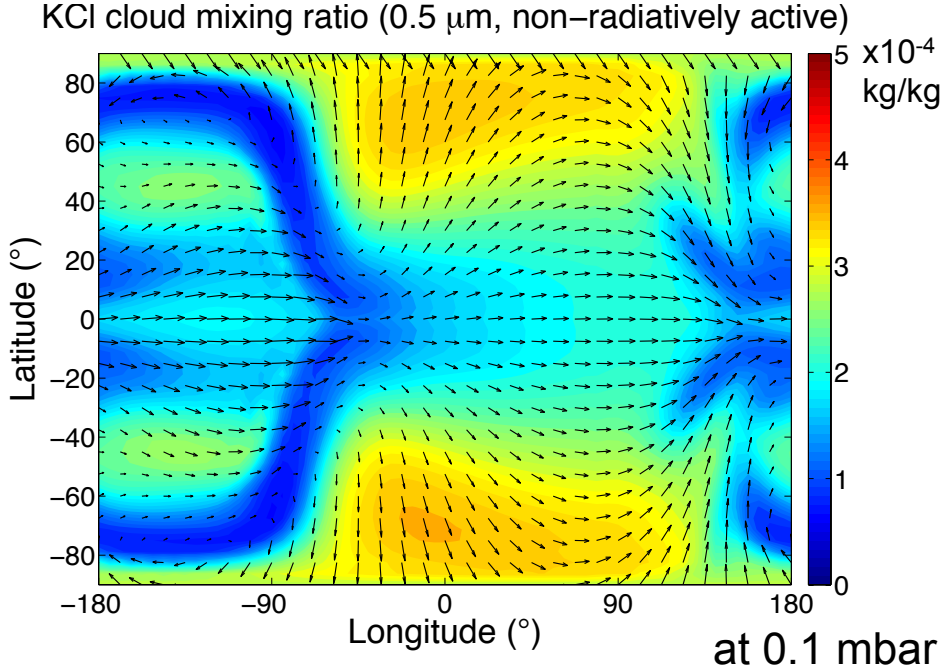
Thermal structure

- albedo => ~0.4-0.6
- cooling below 1 mbar
- stratospheric thermal inversion
- possible evaporation of KCl

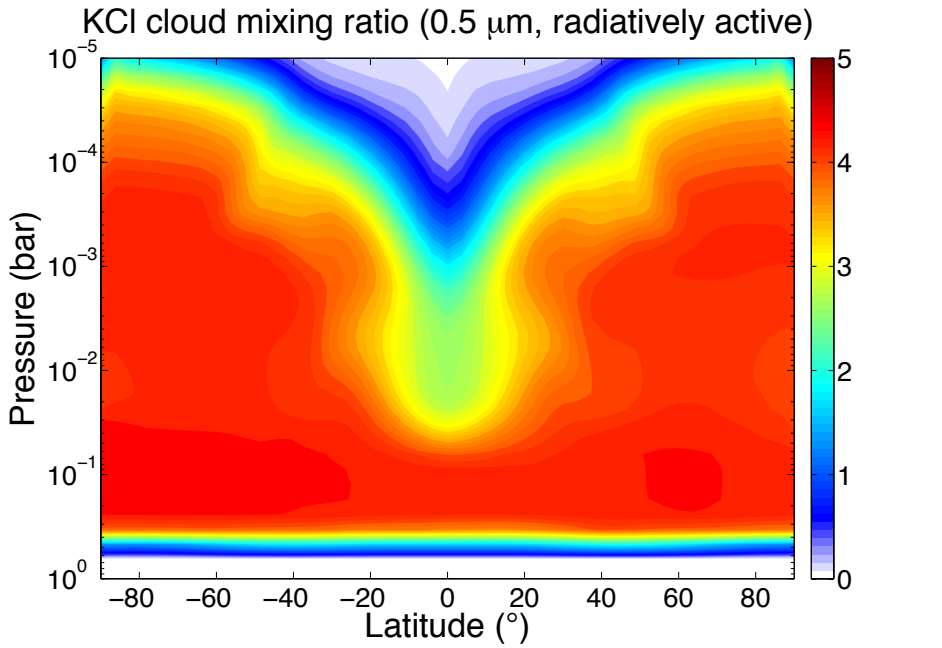


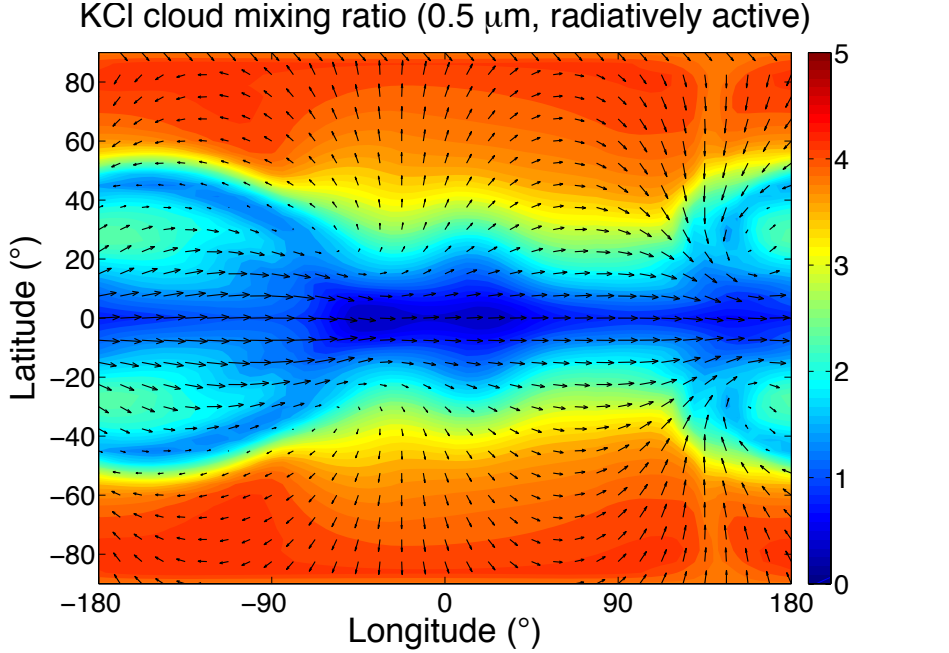
Inhomogeneous cloud distribution



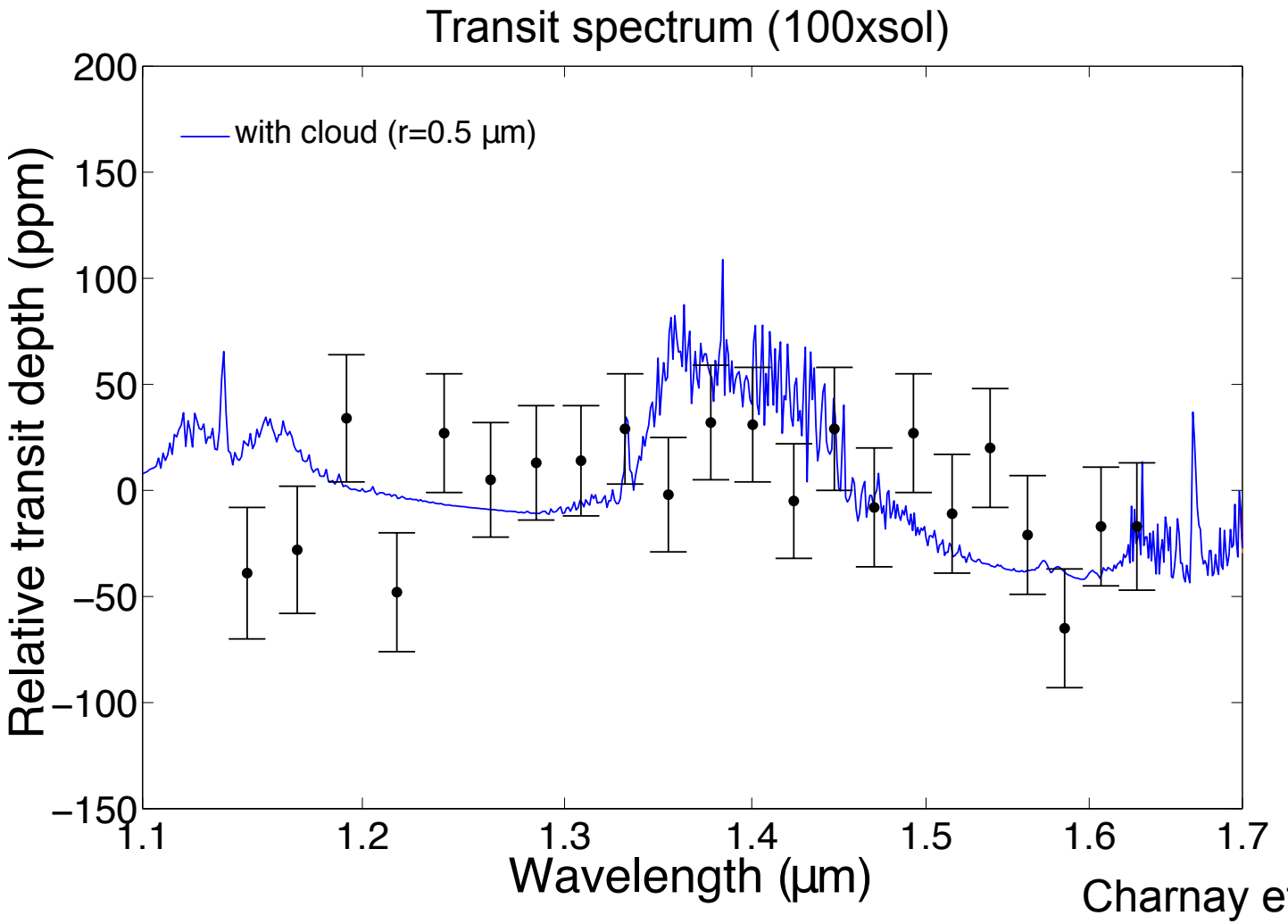


at 0.1 mbar





Transit spectra of GJ1214b

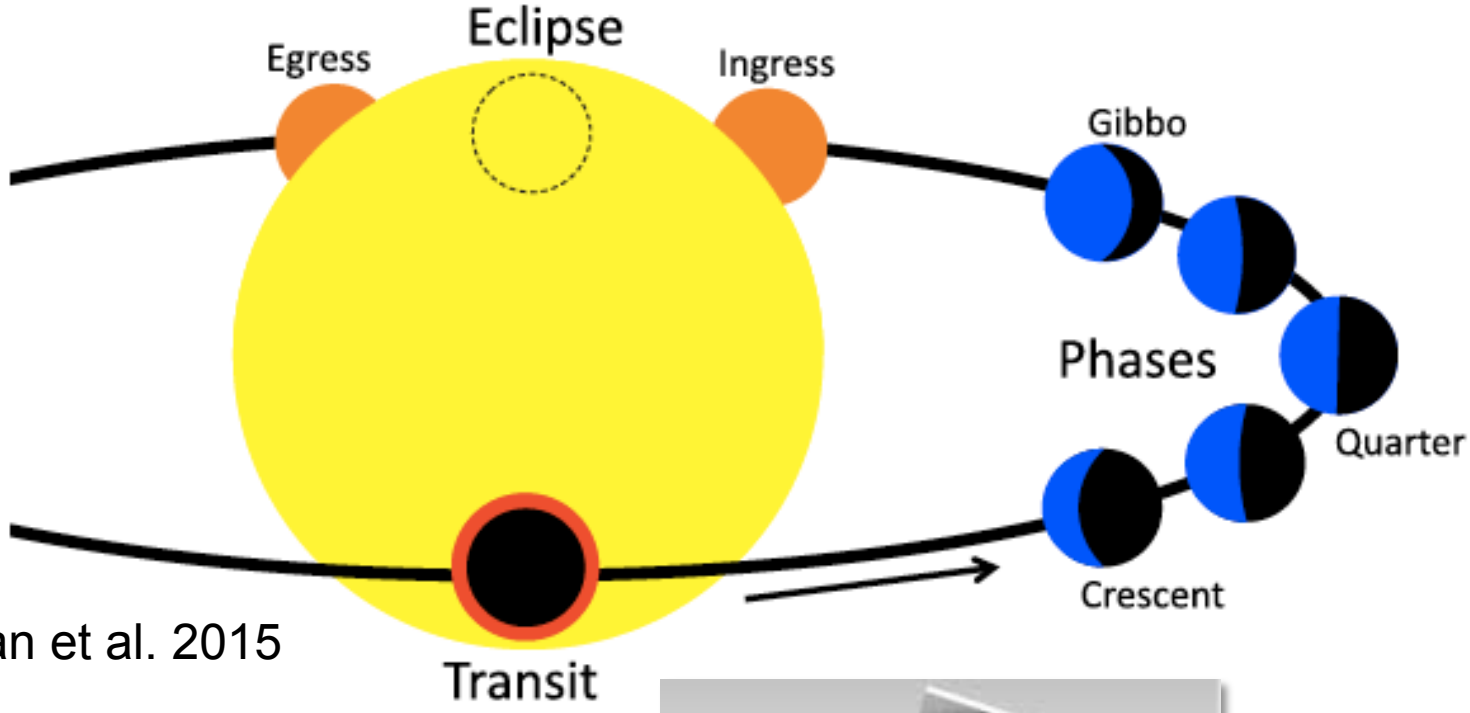


Charnay et al. 2015b

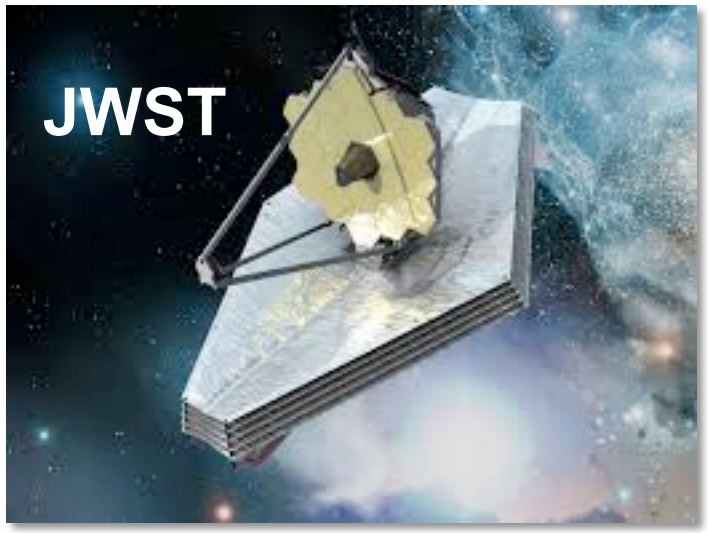
χ^2_{red}=1.3 (1.0 for perfectly flat spectrum)

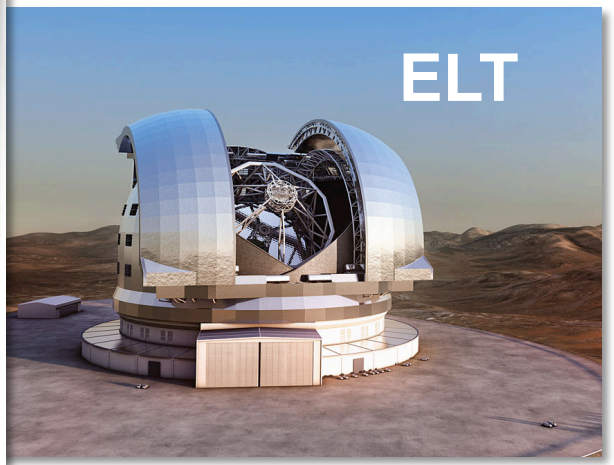
Flatter with a higher metallicity

How to see through clouds?

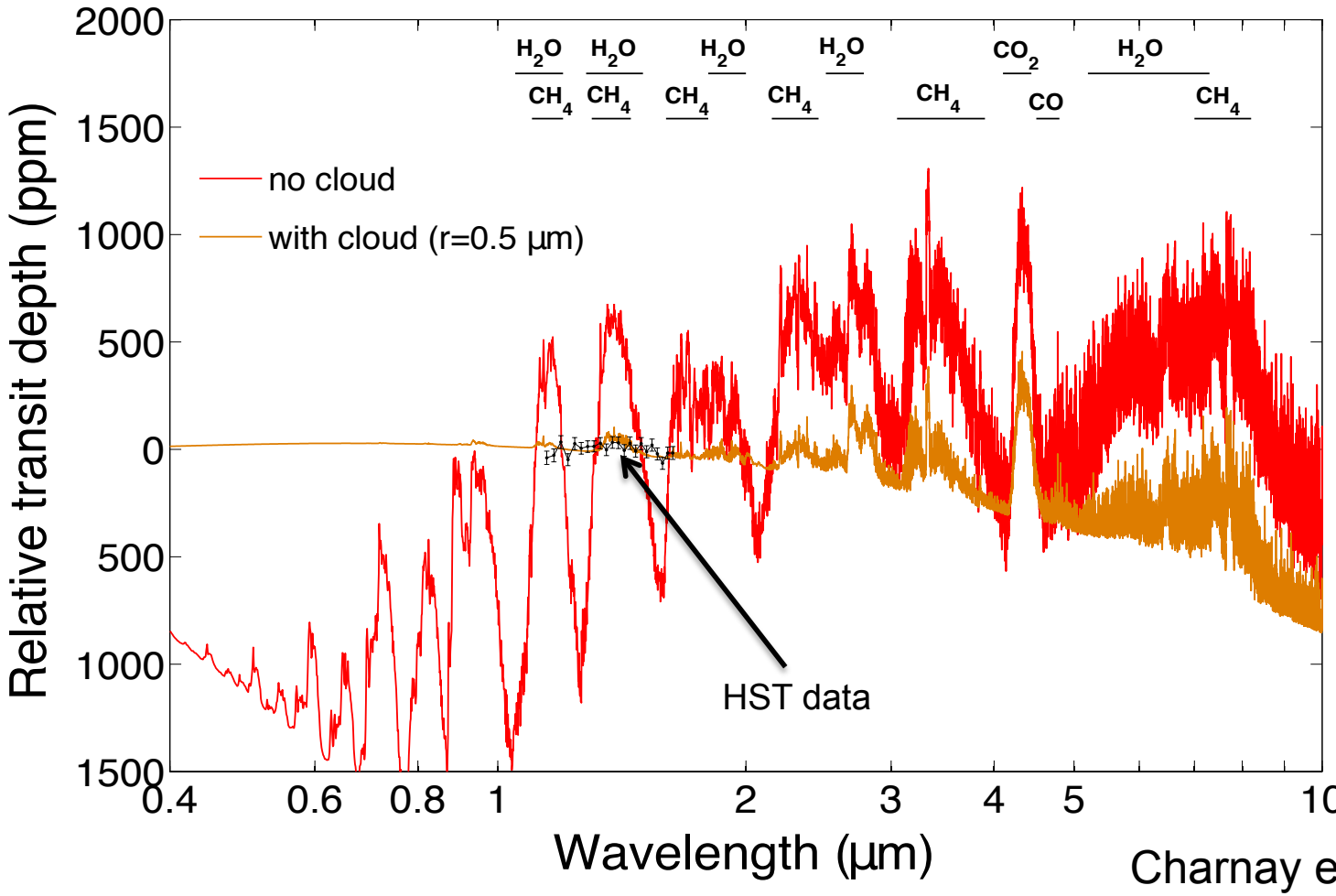


Cowan et al. 2015





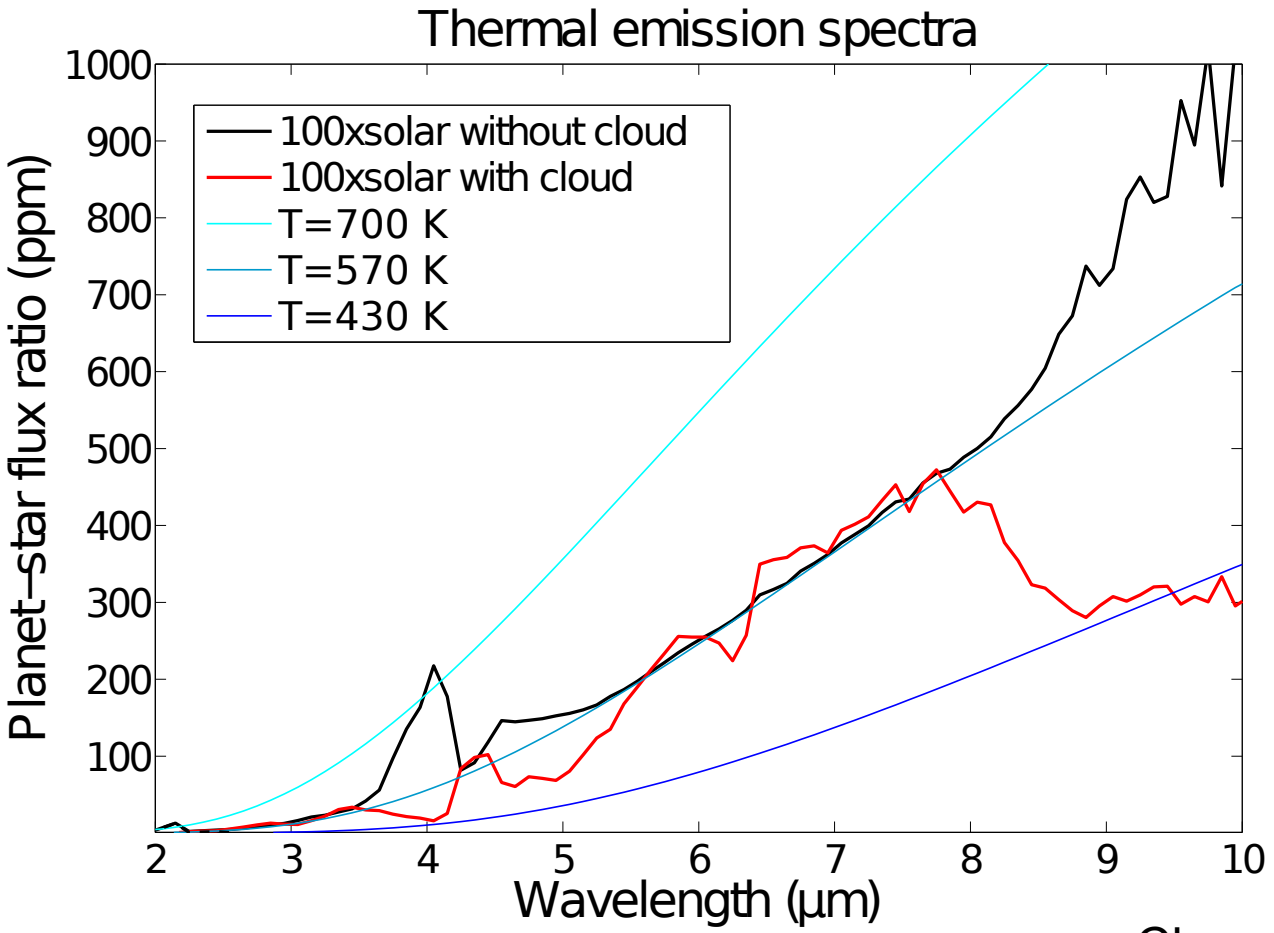
Predictions for future observations



Charnay et al. 2015b

- Molecular features in transit at longer wavelengths
- Mie slope detectable

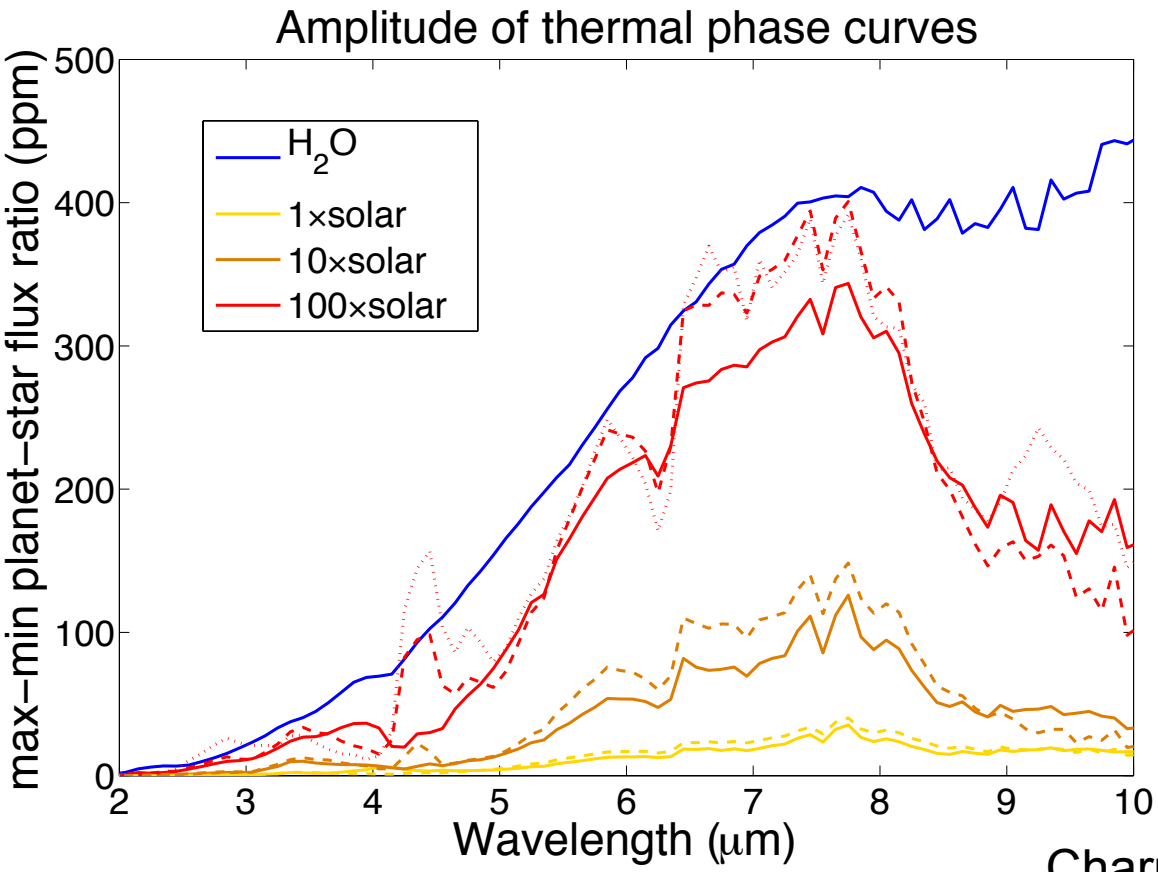
Predictions for future observations



Charnay et al. 2015b

Thermal inversion detectable in secondary eclipses

Predictions for future observations



Charnay et al. 2015b

- Phase curves strongly impacted by the metallicity
- Phase curves slightly impacted by clouds

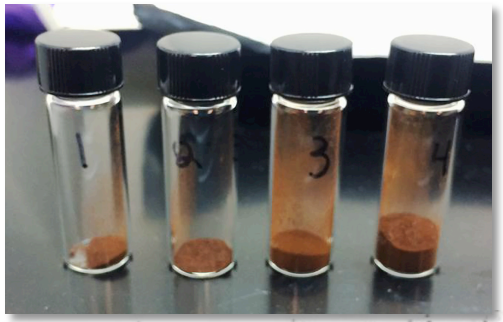
➔ Estimation of metallicity (H_2O or H_2-dominated atmosphere)

Colors of GJ1214b

Potassium chloride (KCl)

Zinc sulfide (ZnS)

Organic haze



sun	no cloud	KCl	ZnS	KCl+ZnS	organic haze
GJ 1214	no cloud	KCl	ZnS	KCl+ZnS	organic haze

Summary

- Strong circulation lofting particles to low presure and producing a flat spectrum but physical limit on the size of particles
- Minimum of cloud at the equator by an anti-Hadley circulation
- Thermal inversion by absorbing cloud particles
- Molecular features in transit at longer wavelength
- Thermal phase curves strongly depend on metallicity but are sligthly impacted by clouds

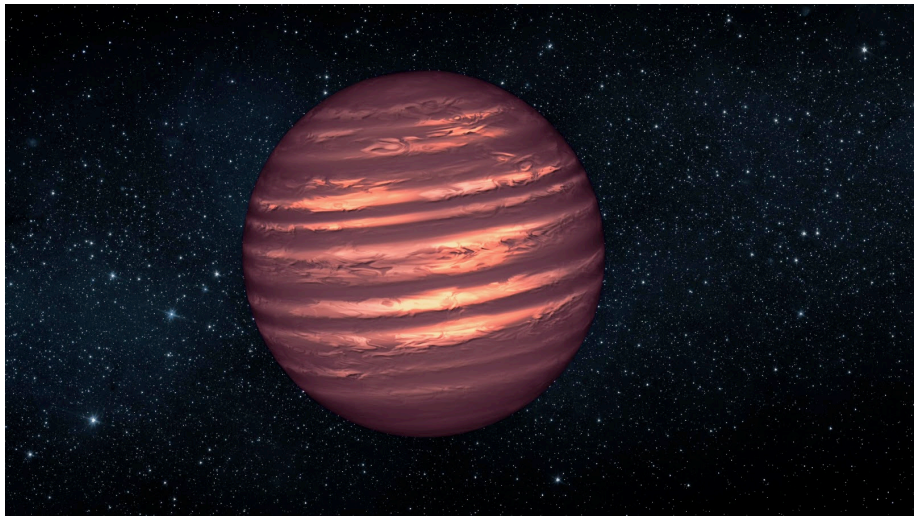
JWST/ARIEL should provide constraints on the nature of mini-Neptune atmospheres and clouds/hazes

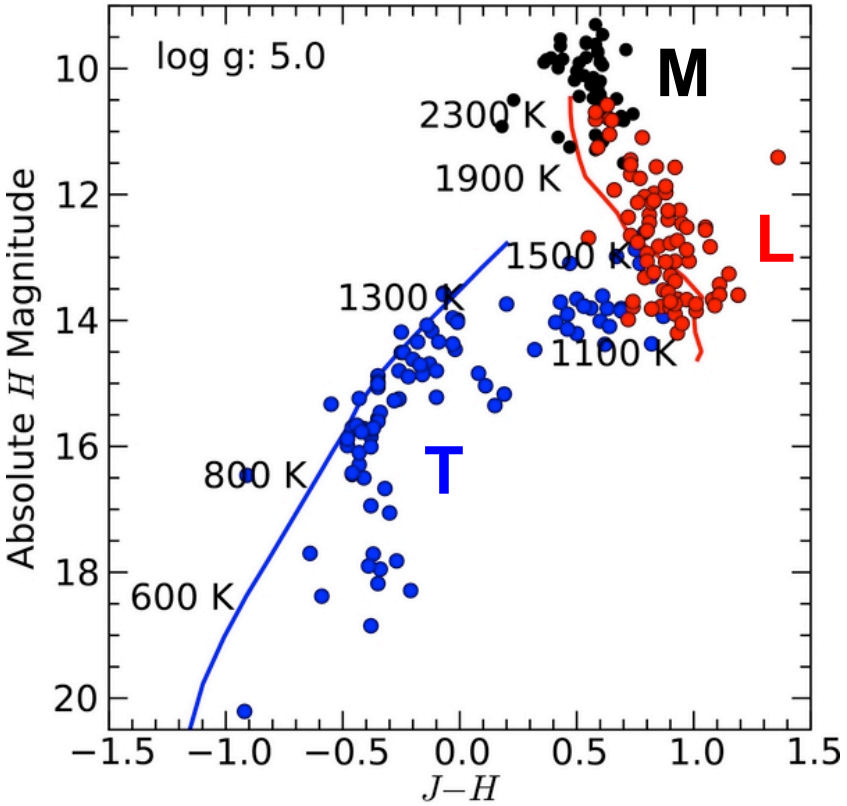
---

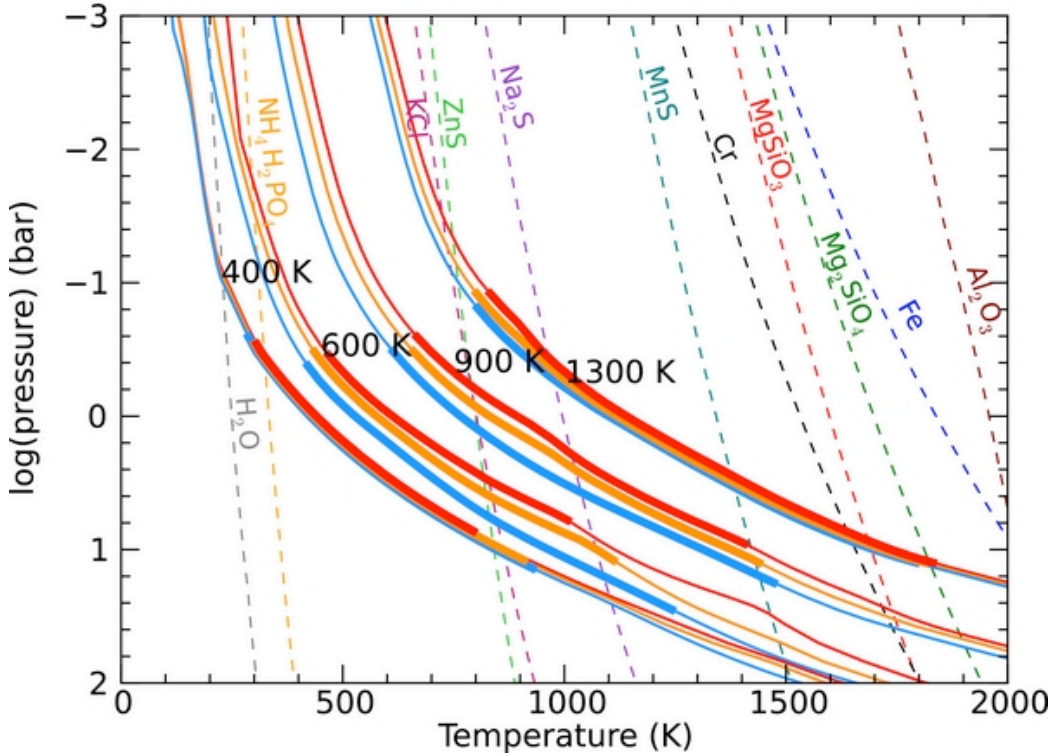
Charnay, Meadows & Leconte, 3D modeling of GJ1214b's atmosphere: vertical mixing driven by an anti-Hadley circulation, ApJ 2015

Charnay, Meadows, Misra, Leconte & Arney, 3D modeling of GJ1214b's atmosphere: formation of inhomogeneous high clouds and observational implications, ApJL 2015

Clouds on brown dwarfs and young giant planets



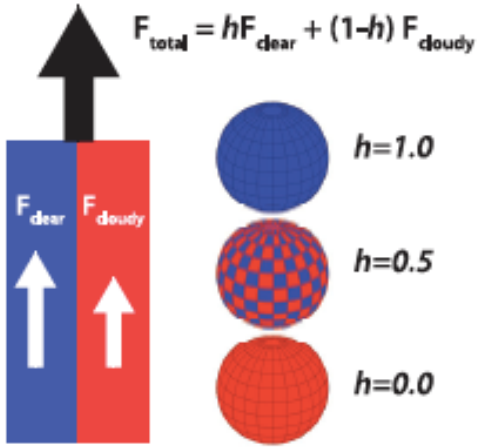




Morley et al. 2012

Development of clouds in Exo-REM
Application to SPHERE data

Cloud fraction



Vertical mixing:

$$K_{zz}\frac{\partial q_t}{\partial z} = -v_{sed} q_c$$

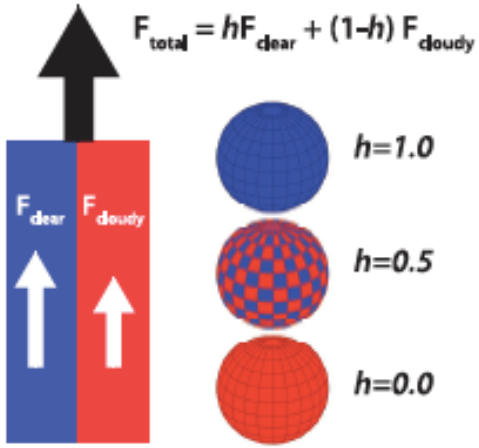
Parametrization for K_{zz}

Example from Ackerman & Marley 2002:

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

Development of clouds in Exo-REM
Application to SPHERE data

Cloud fraction

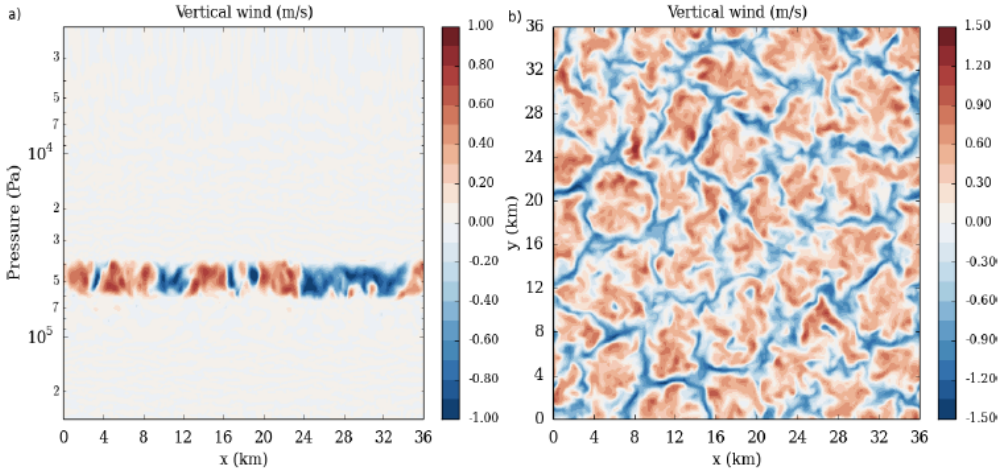


Vertical mixing:

$$K_{zz}\frac{\partial q_t}{\partial z} = -v_{sed} q_c$$

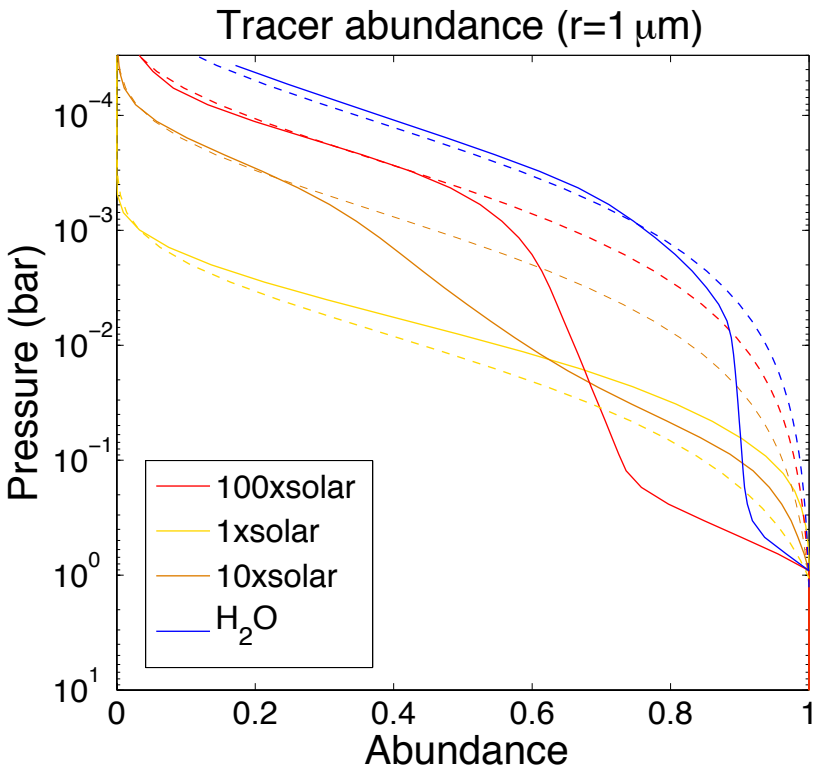
Parametrization for K_{zz}

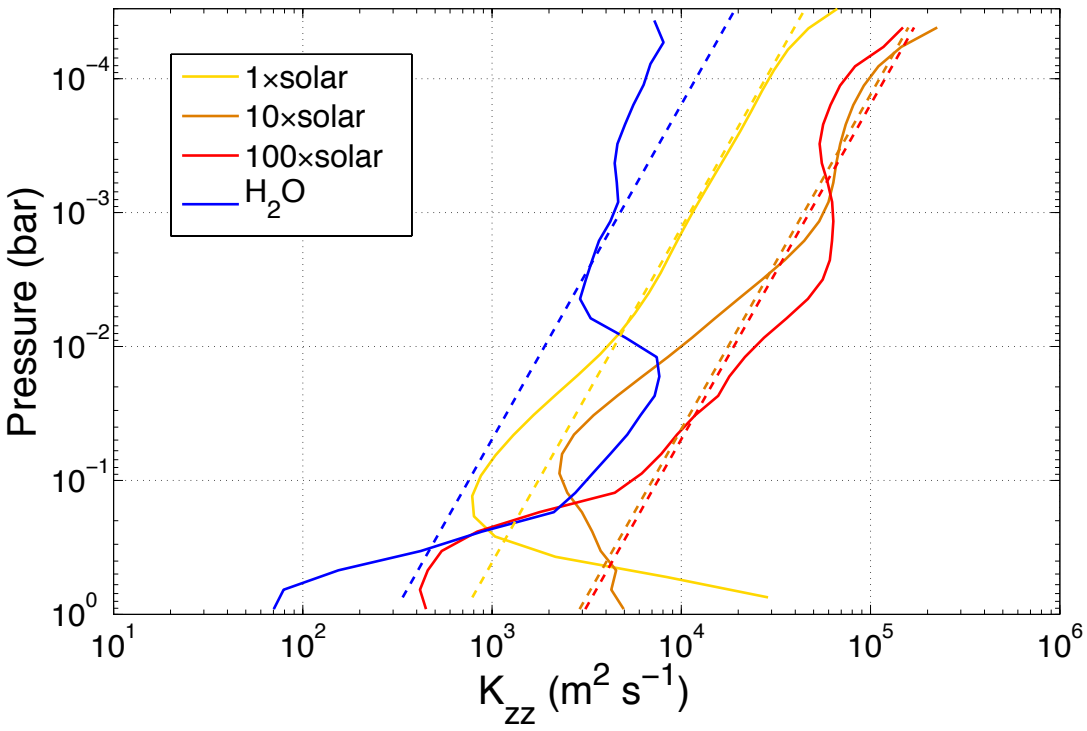
Mesocale simulations with Maxence Lefèvre & Aymeric Sipa



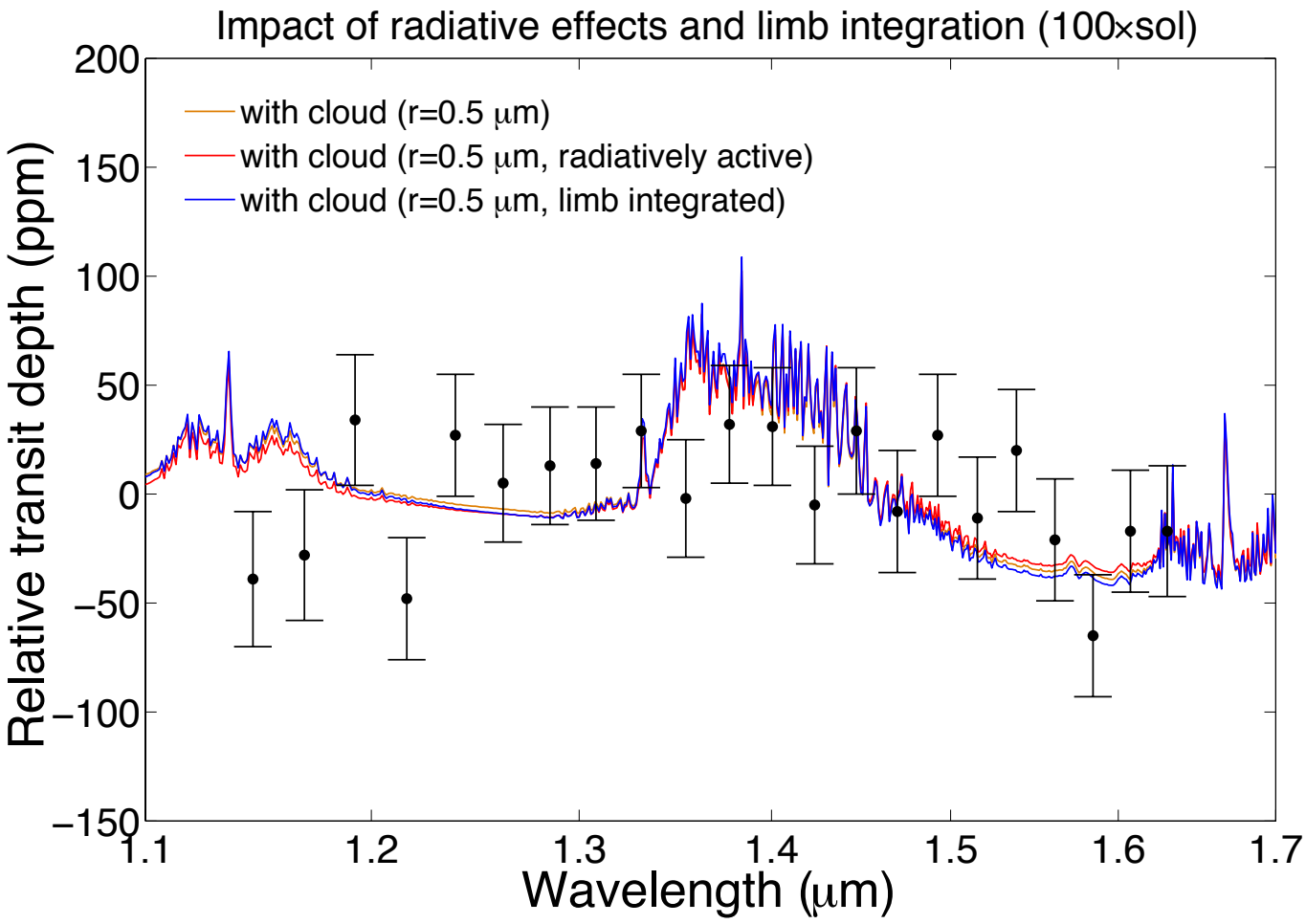
Venus (Lefèvre et al.)

Vertical Mixing





Transit spectra of GJ1214b



χ^2_{red}=1.3 (1.0 for perfectly flat spectrum)

Flatter with a higher metallicity

Predictions for future observations