How to Probe Cloud Microphysics from JWST Observations

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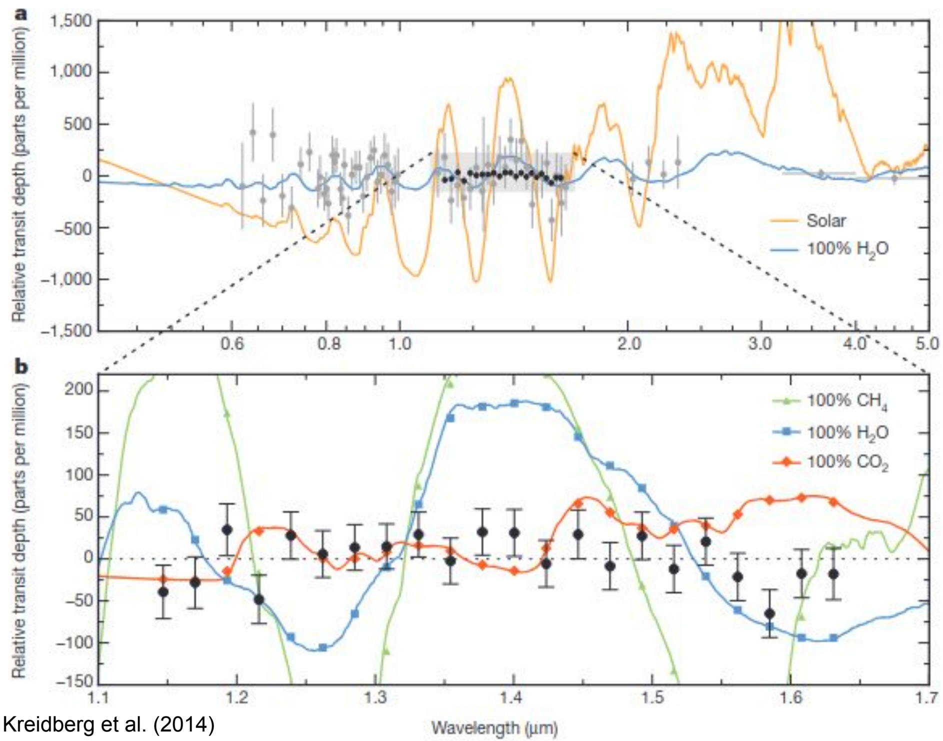
Motivation



Kreidberg et al. (2014)

The "curse" of clouds

→ Mute molecular features

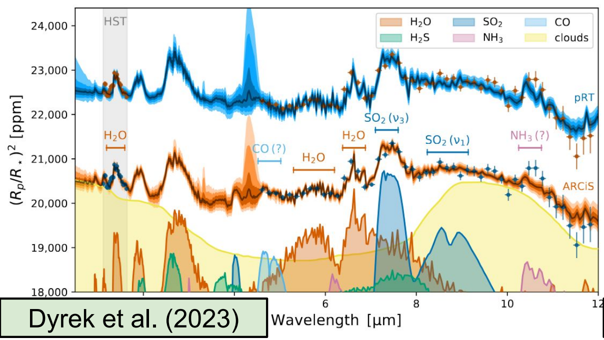
→ Make observations "harder"

I disagree!

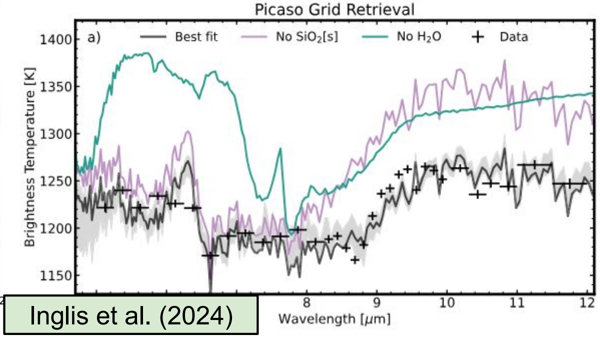
→ Clouds are complex and therefore carry a wealth of information!

→ They do make observations hard

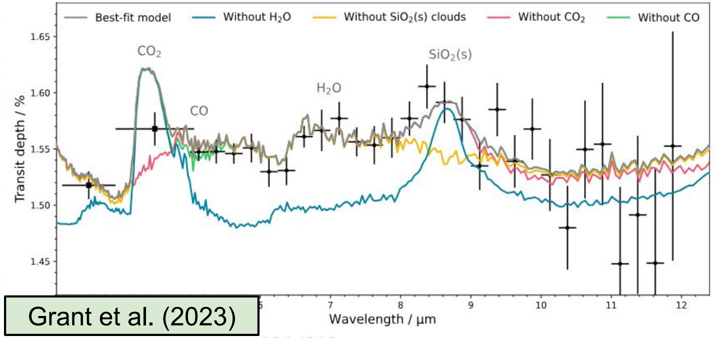
→ **But fear no more! The curse is lifted!**



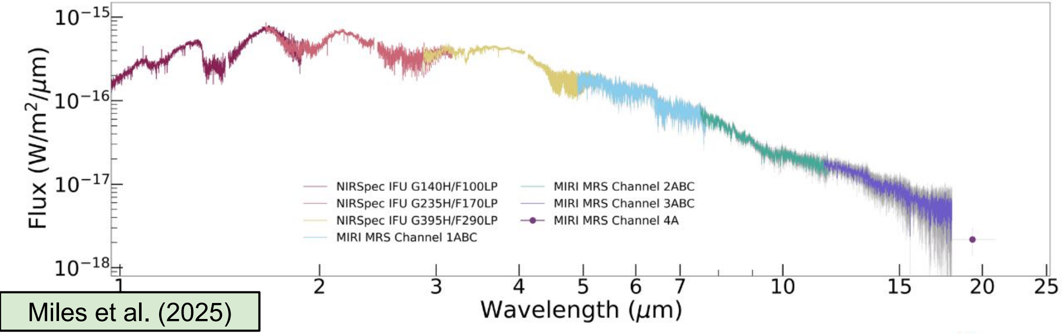
Dyrek et al. (2023)



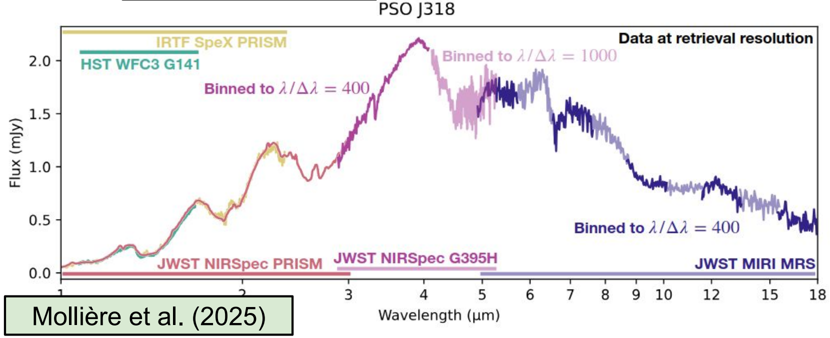
Inglis et al. (2024)



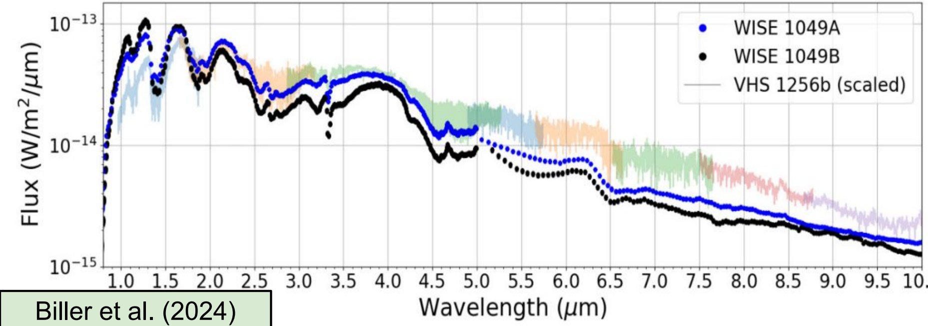
Grant et al. (2023)



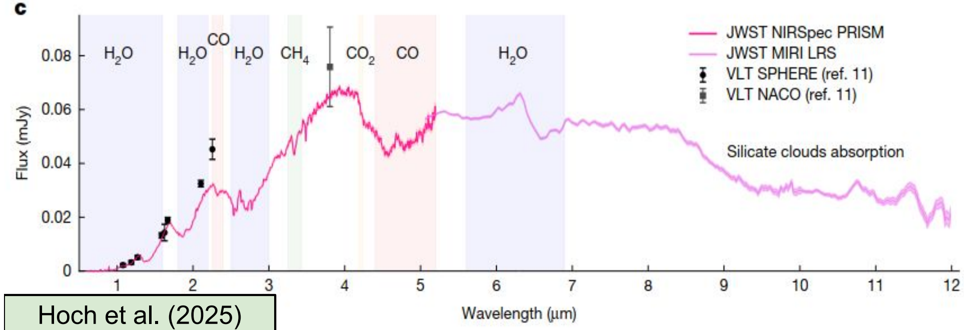
Miles et al. (2025)



Mollière et al. (2025)



Biller et al. (2024)



Hoch et al. (2025)

Clouds on Exoplanets

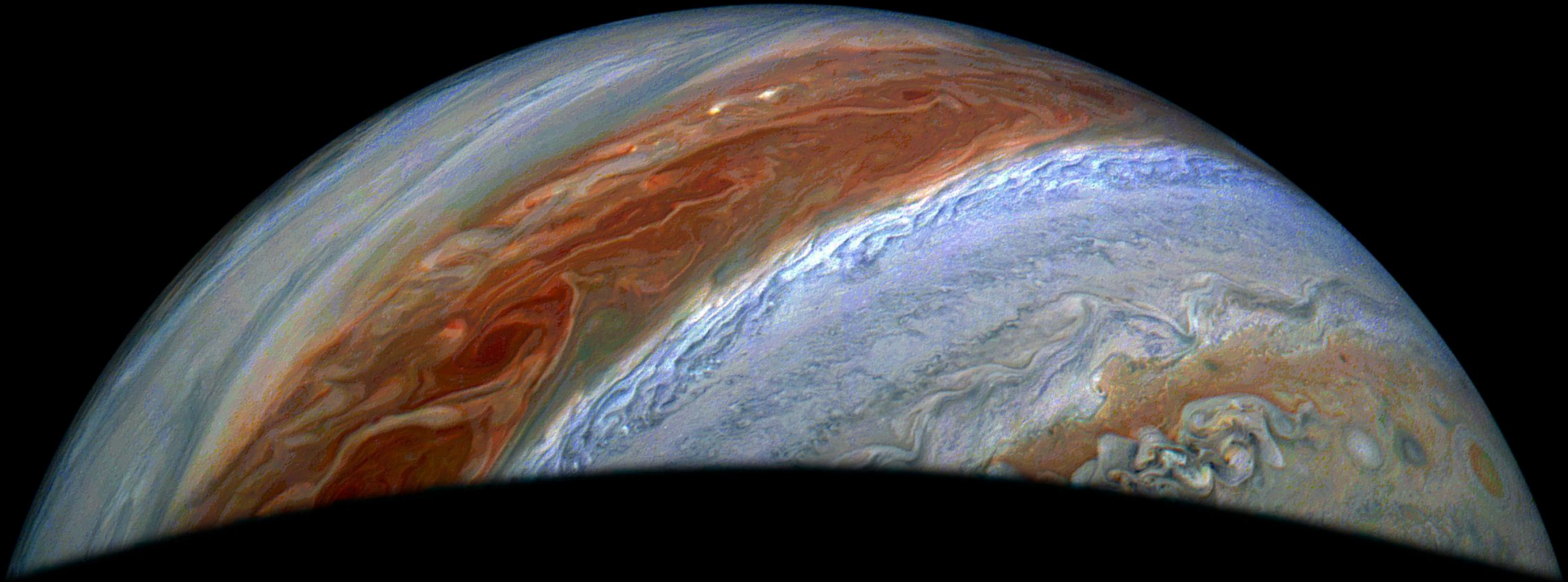
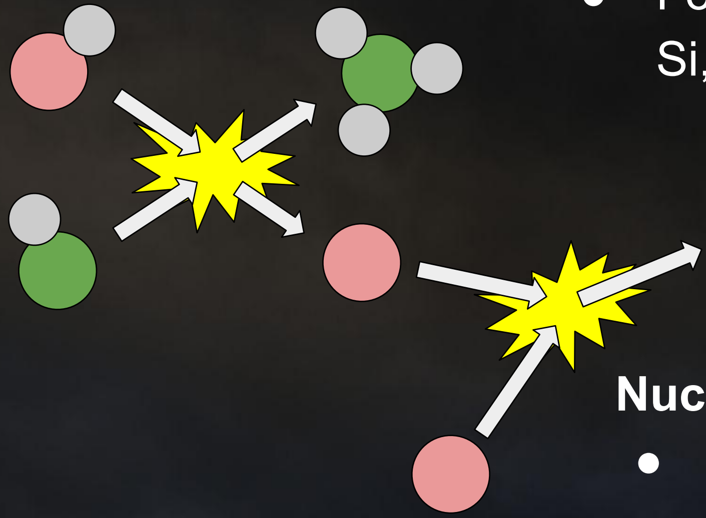


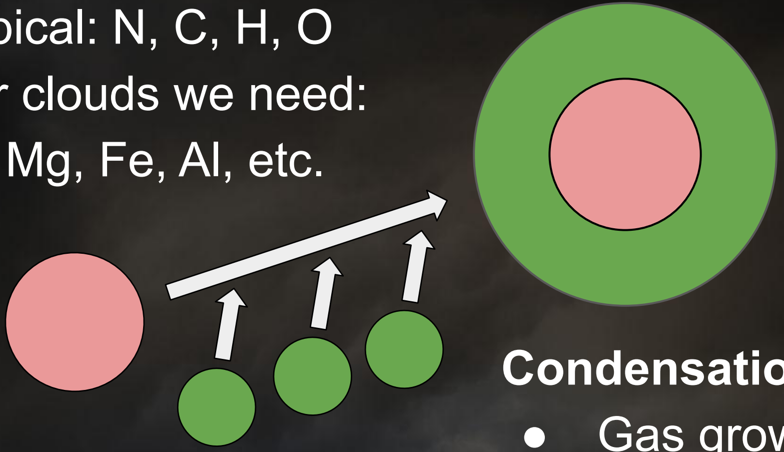
Image Credit: NASA

How Do Clouds Form on Gas-Giants?

Atmospheric Chemistry

- Typical: N, C, H, O
- For clouds we need: Si, Mg, Fe, Al, etc.





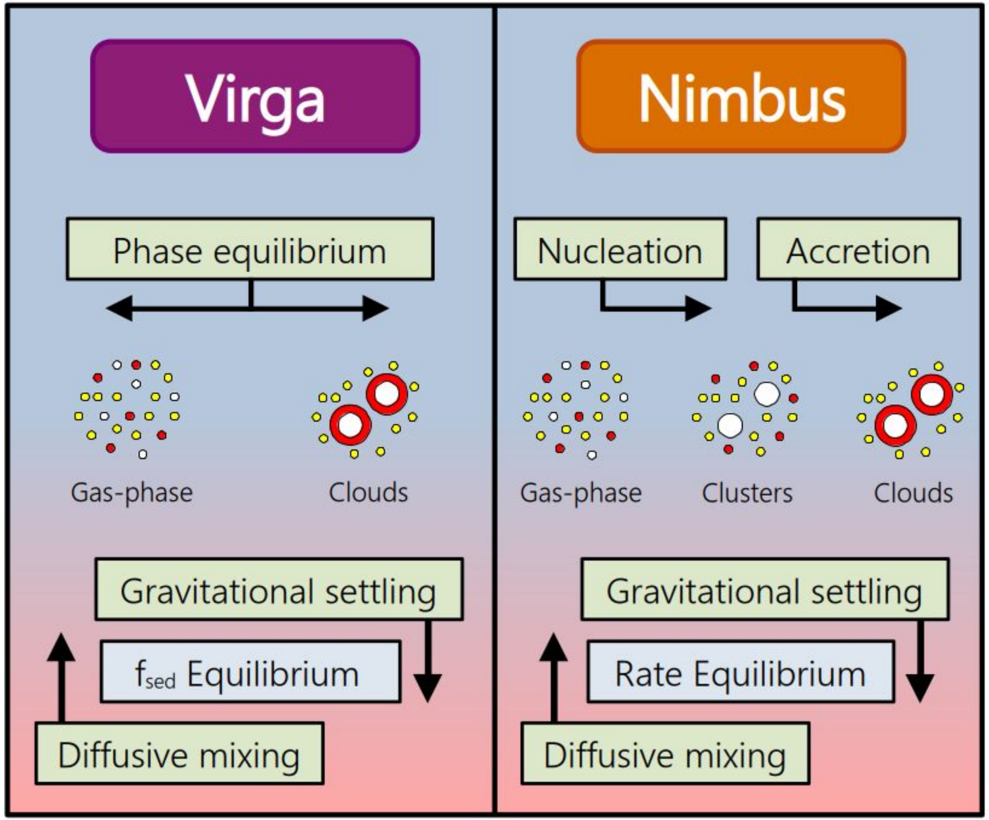
Nucleation

- Gas to solid
- TiO_2, SiO, KCl
- Creates aerosols

Condensation

- Gas grows onto aerosols
- $MgSiO_3$, Fe_2O_3, ZnS
- Can involve complex surface reactions

Our Cloud Formation Models



Virga (Batalha et al. 2025)

➡ EddySed (Ackerman & Marley 2001)

➡ Assumes phase equilibrium

➡ fsed parameterization

Nimbus (Kiefer et al. 2026)

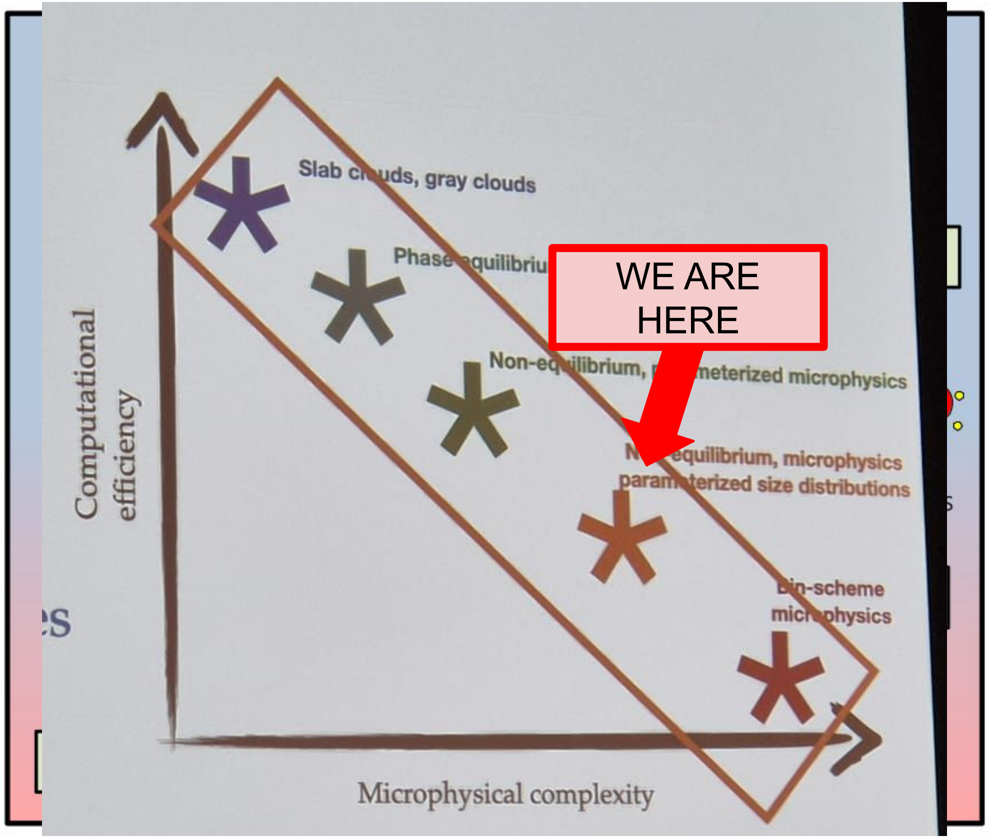
➡ Light-weight microphysical model

➡ Nucleation via MCNT

➡ Growth via vapor pressure

➡ Diffusive replenishment

Our Cloud Formation Models



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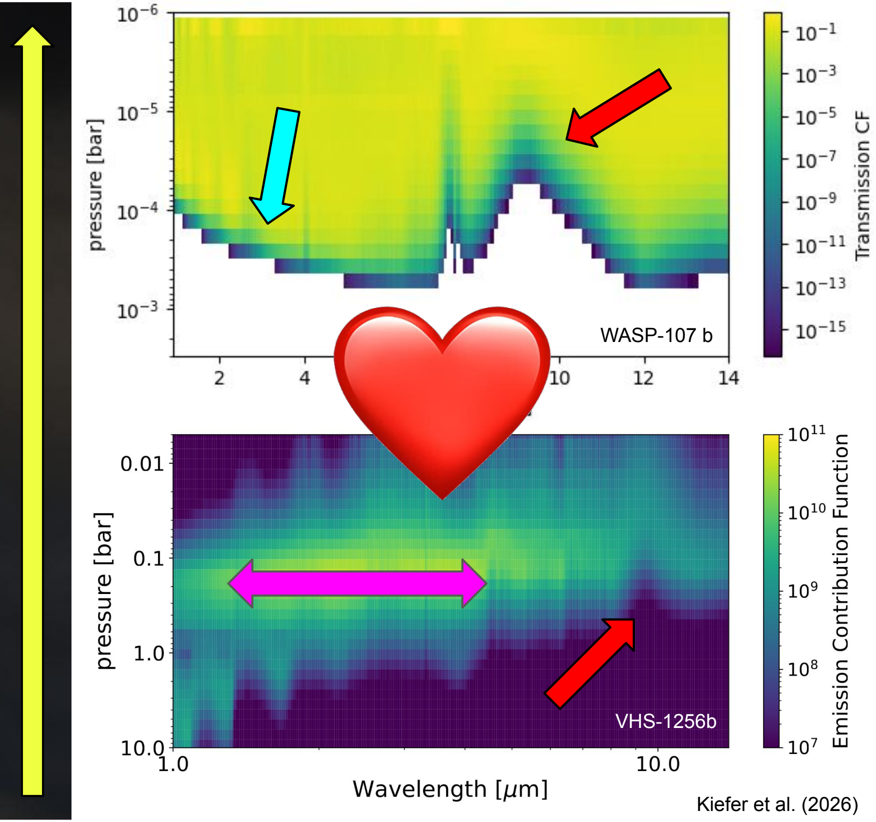
How Do We Probe Exoplanet Atmospheres?

Image Credit: NASA

The Best of Both Worlds!



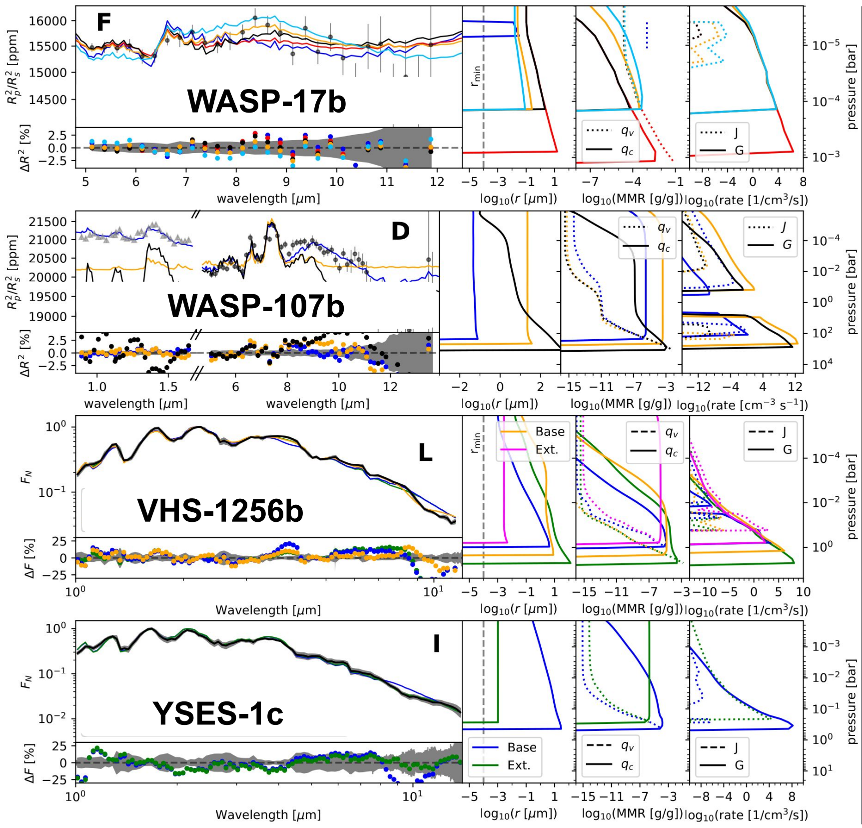
Transmission Spectroscopy

- ➡ probes lower pressure regions
- ➡ Rayleigh slope from cloud and hazes
- ➡ Si-O bond features around 9 micron

Thermal Emission Spectroscopy

- ➡ probes higher pressure regions
- ➡ clouds can dominate the photosphere
- ➡ Si-O bond features around 9 micron

A Striking Similarity: High Altitude Silicate particles



→ On WASP-17b clouds form at high altitudes ✔

→ WASP-107b, VHS-1256b, and YSES-1c require two separate cloud populations: base and extended

How do small cloud particles reach high altitudes?

1) They are created there! (nucleation)
   - → But where does the material come from?
   - → Diffusive replenishment seems inadequate

2) They are advected there! (dynamics)
   - → But why do they not grow and settle?
   - → Diffusion alone requires very inefficient growth
   - → Size Distributions!

Connecting Observations to Cloud Physics

Image Credit: NASA

From Observations to Microphysics

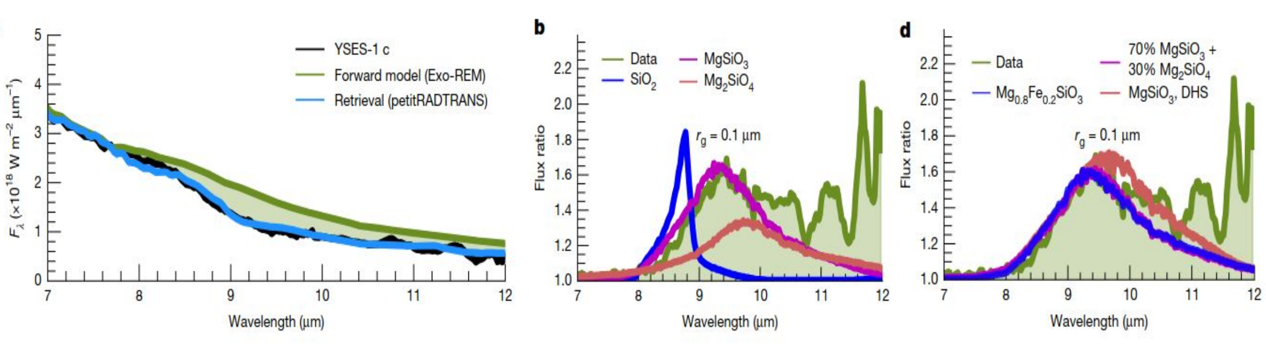
Cloud particle materials

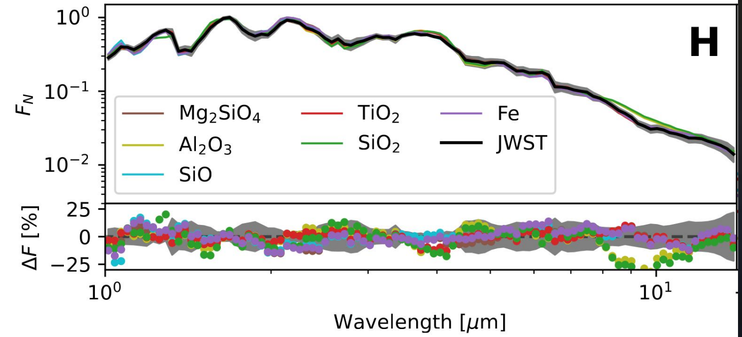
Cloud particle sizes

Sticking coefficients

From Observations to Microphysics

Hoch et al. (2025)





Kiefer et al. (2026)

→ Si–O bond feature can identify cloud material

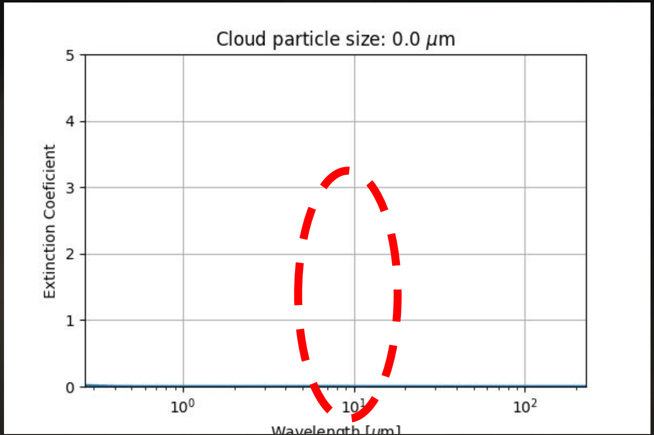
→ It is difficult to identify the cloud material from the cloud base alone

Cloud particle materials

Cloud particle sizes

Sticking coefficients

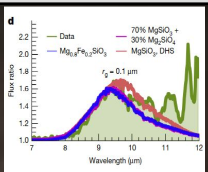
From Observations to Microphysics

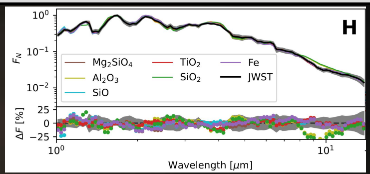


Material: SiO

→ Only particles < 1 µm can produce Si–O features

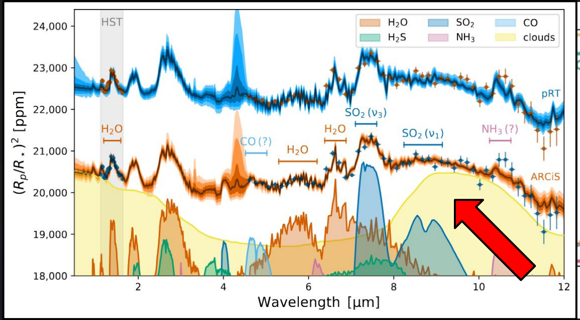
Cloud particle materials





Cloud particle sizes

Sticking coefficients



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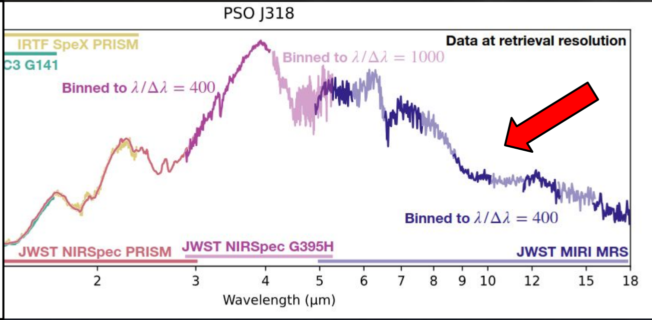
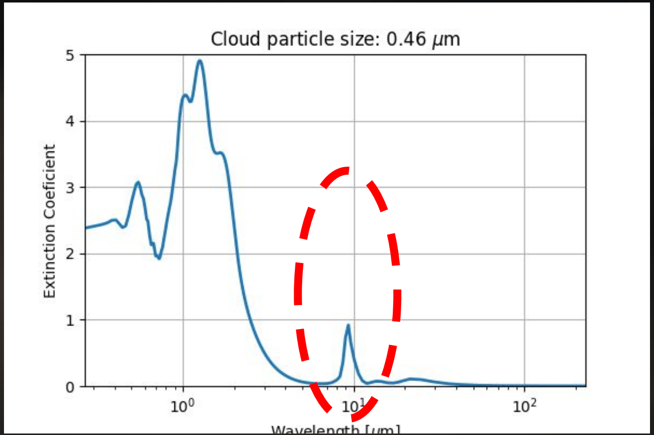


Mollière et al. (2025)

From Observations to Microphysics

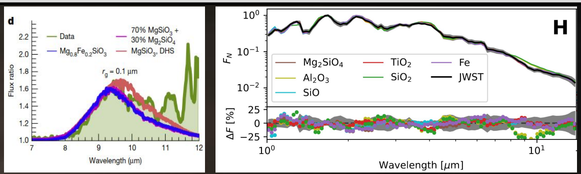


Material: SiO

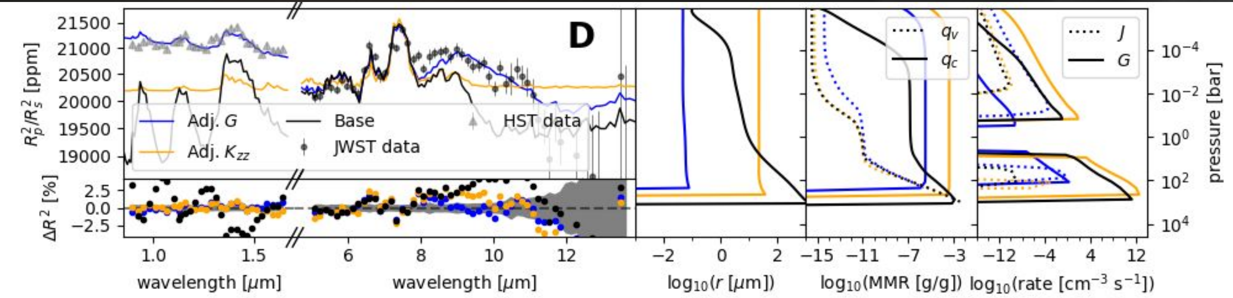
→ Only particles < 1 μm can produce Si-O features

→ Strong mixing (Kzz) leads to too large particles

Cloud particle materials



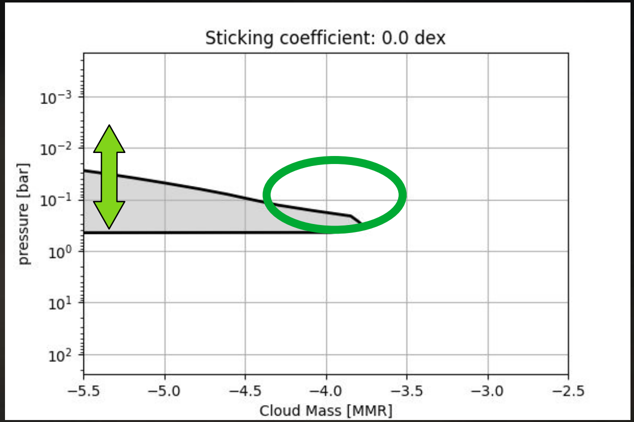
Cloud particle sizes



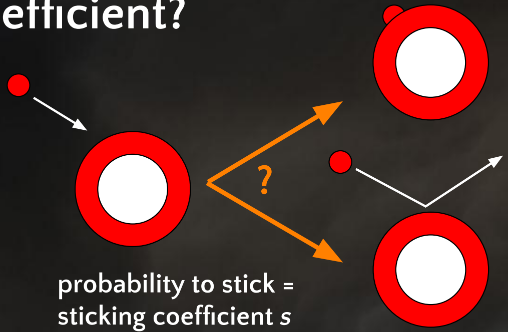
Kiefer et al. (2026)

Sticking coefficients

From Observations to Microphysics

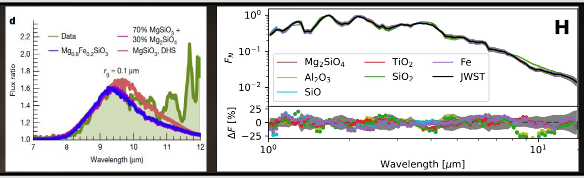


What is the sticking coefficient?

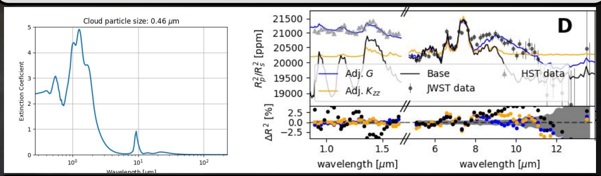


probability to stick = sticking coefficient s

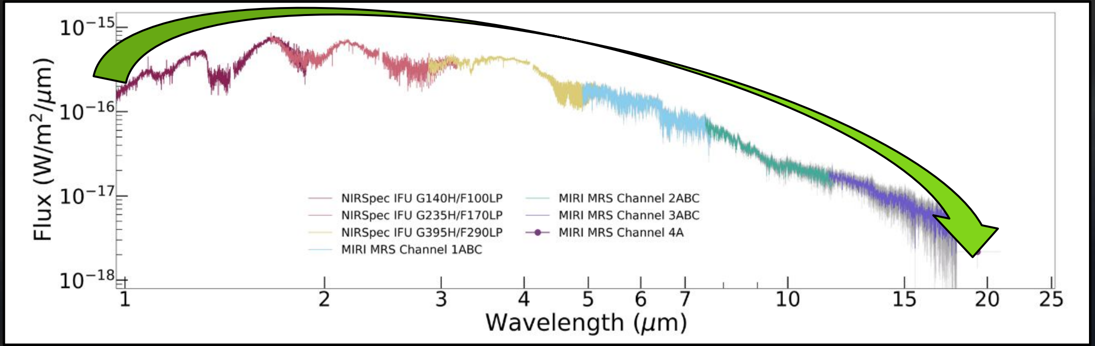
Cloud particle materials



Cloud particle sizes

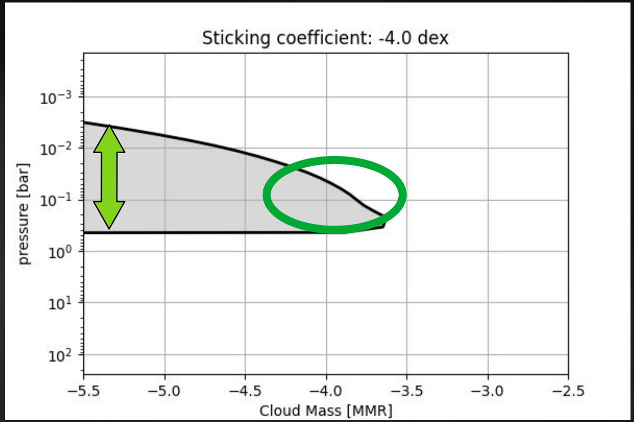


Sticking coefficients



Miles et al. (2023)

From Observations to Microphysics



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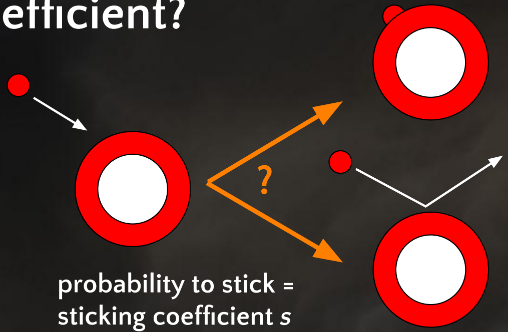
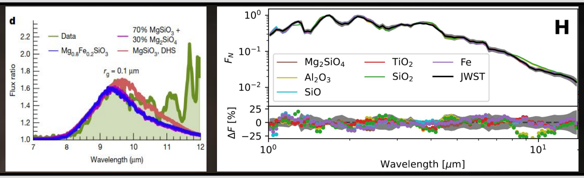


probability to stick = sticking coefficient *s*

Cloud particle materials



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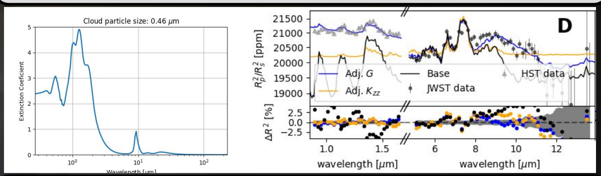
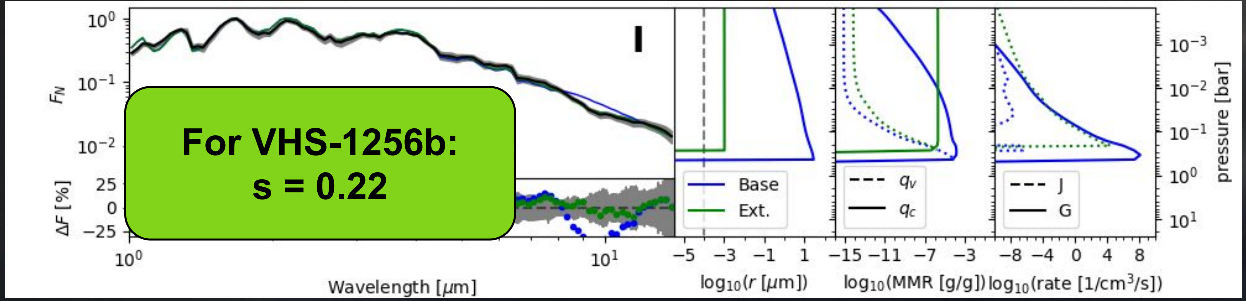


Sticking coefficients



For VHS-1256b: s = 0.22

Kiefer et al. (2026)

What comes next?

Image Credit: Martin Vargic

Using Clouds to Understand Atmospheres

How do small high altitude particles form?

Thermal emission and transmission spectra find high altitude particles

1) Interplanetary dust?
   → P. Arras Poster 143

2) Complex mixing?
   → T. Kennedy Poster 81
   → D. Samra Poster 78
   → R. Frazier Poster 54

Variability! From Climate to Weather

Clouds cause variability in brown dwarfs and likely in many exoplanets too!

1) In thermal emission:
   → N. Klein Poster 131
   → K. Ehrich Poster 115
   → D. Stephens Poster 106

2) In transmission:
   → H. Krause Poster 136

And so much more…

We are just about to learn about the complex structure and interactions of clouds!

1) Fractal cloud particles
   → M. Lodge Poster 92

2) Cloud-haze interaction:
   → V. Nagpal Poster 83

3) Effect on habitability:
   → V. Hartwick Poster 42

Summary

Transmission spectra probe lower pressure layers
➡ Nucleation ➡ Cloud material ➡ Vertical extend

Thermal emission spectra probe higher pressure layers
➡ Sticking coefficient ➡ Cloud material ➡ Cloud base

Panchromatic spectra allow us to probe the physics of exoplanet clouds

Paper:

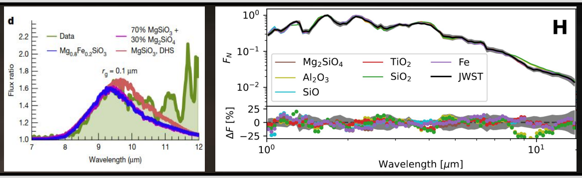
More details in the paper!

Nimbus: github.com/Kiefersv/Nimbus

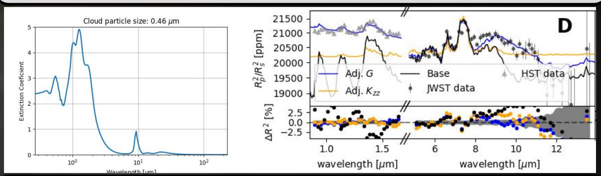
E-mail: sven.kiefer@utexas.edu

Website: kiefersv.github.io

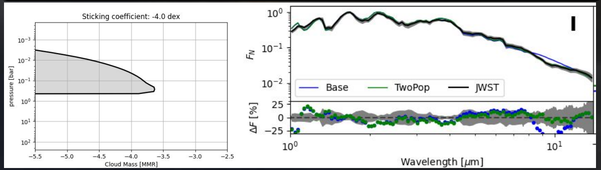
Cloud particle materials



Cloud particle sizes

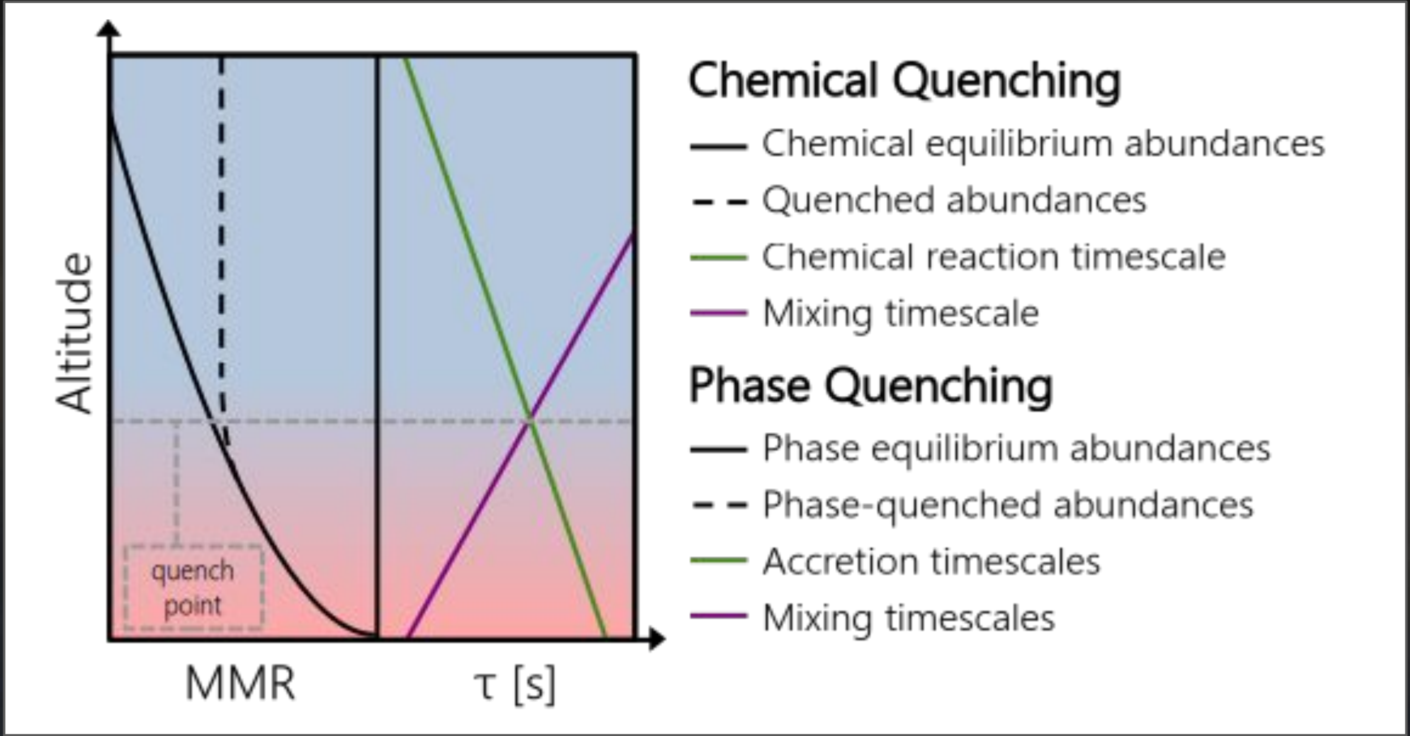


Sticking coefficients

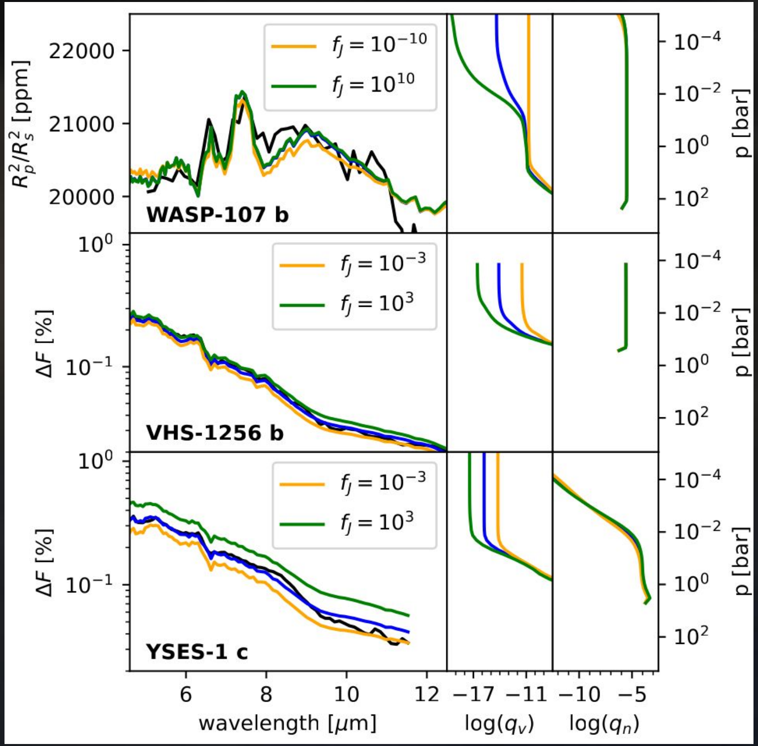


Additional Slides

Phase Quenching



What About the Nucleation Rate?

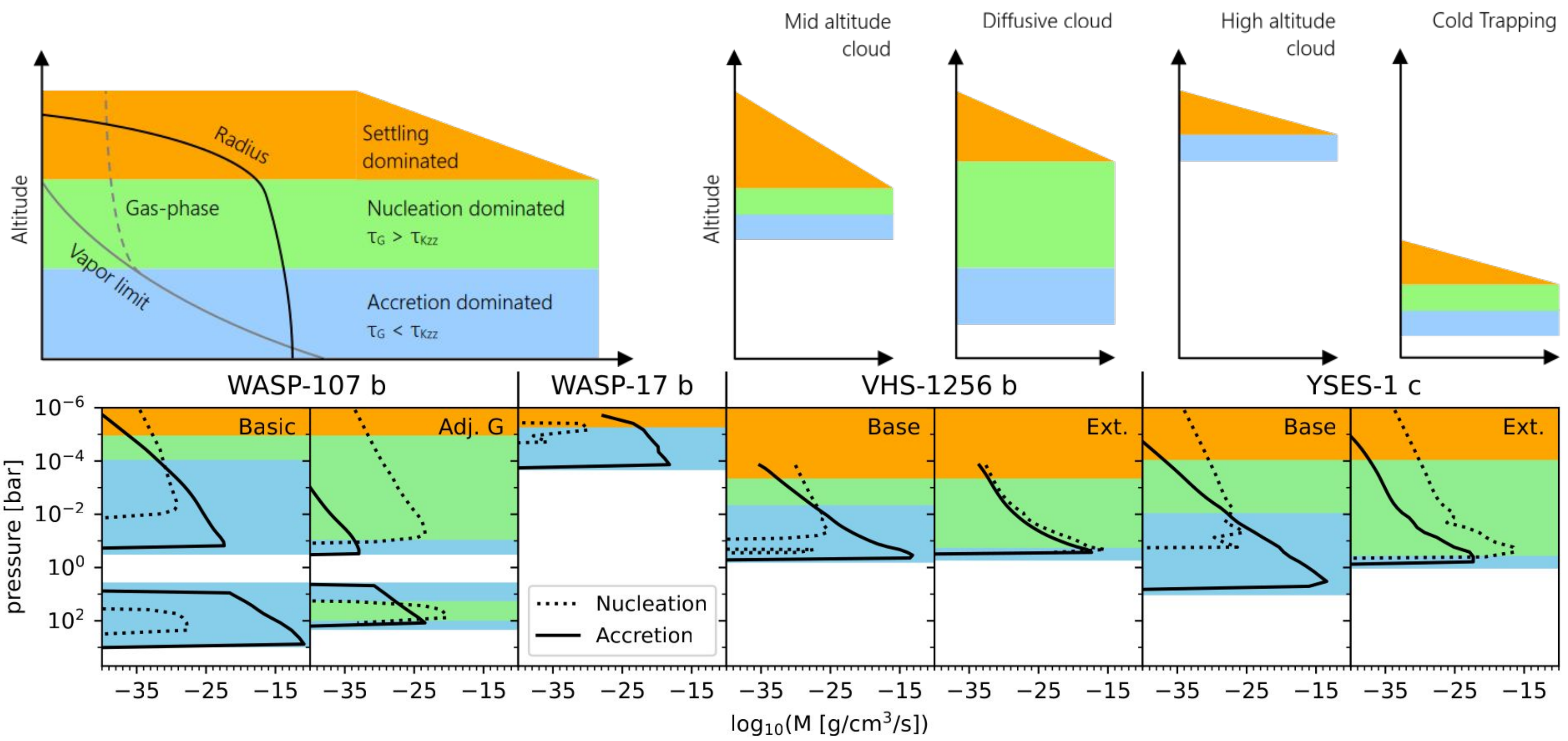


Scaling nucleation rates by a factor fj:

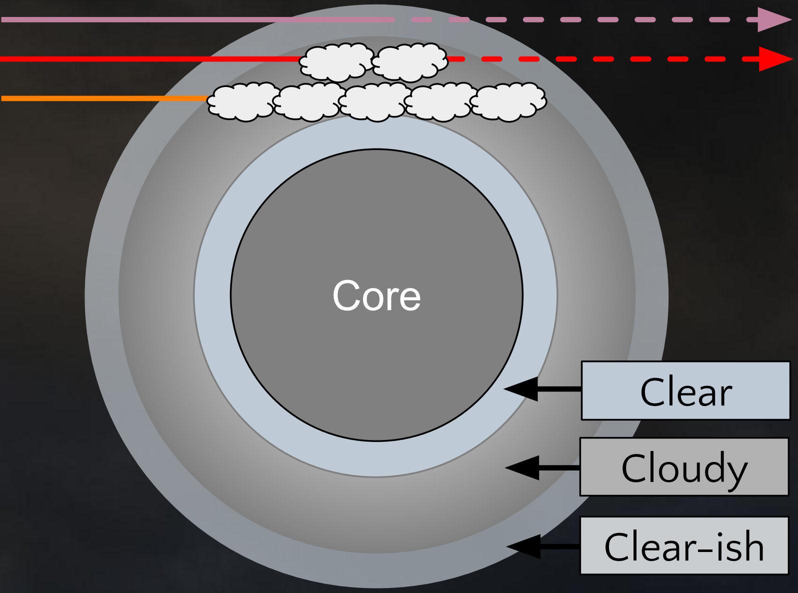
➡ The number density of cloud particles is largely unaffected in phase-quenched layers

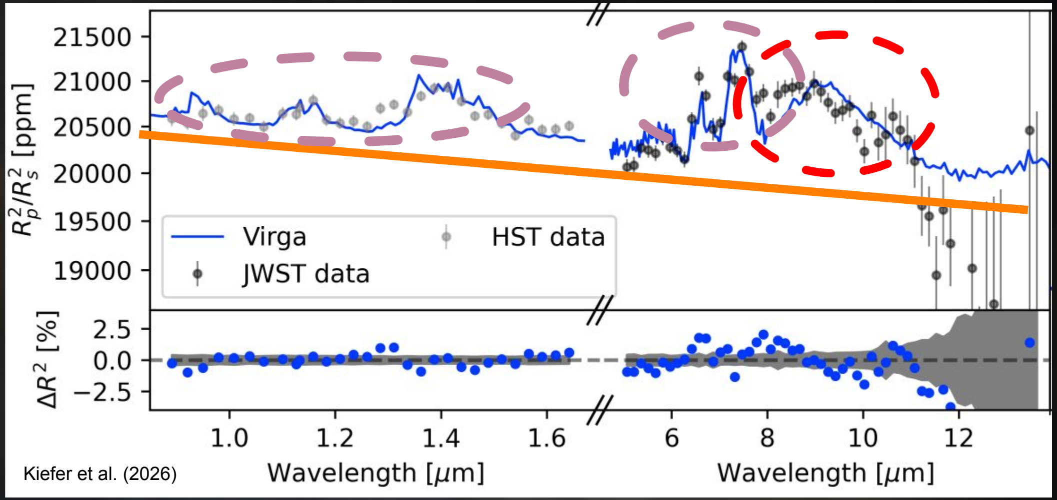
➡ Higher nucleation rates lead to a stronger depletion of the gas-phase abundances

Cloud Structures



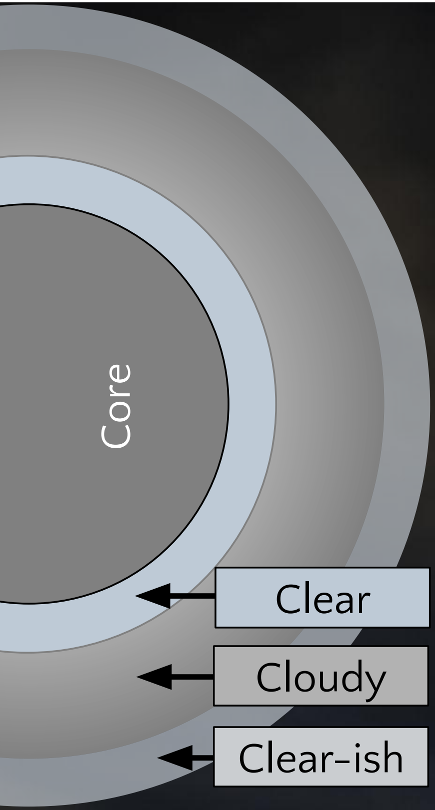
Transmission Spectra – WASP-107b





- Clouds limit how deep we can probe
- Si-O feature indicates high altitude particles
- Transmission spectra probe the vertical extent of cloud structures where we expect nucleation

Thermal Emission Spectra - VHS-1256b



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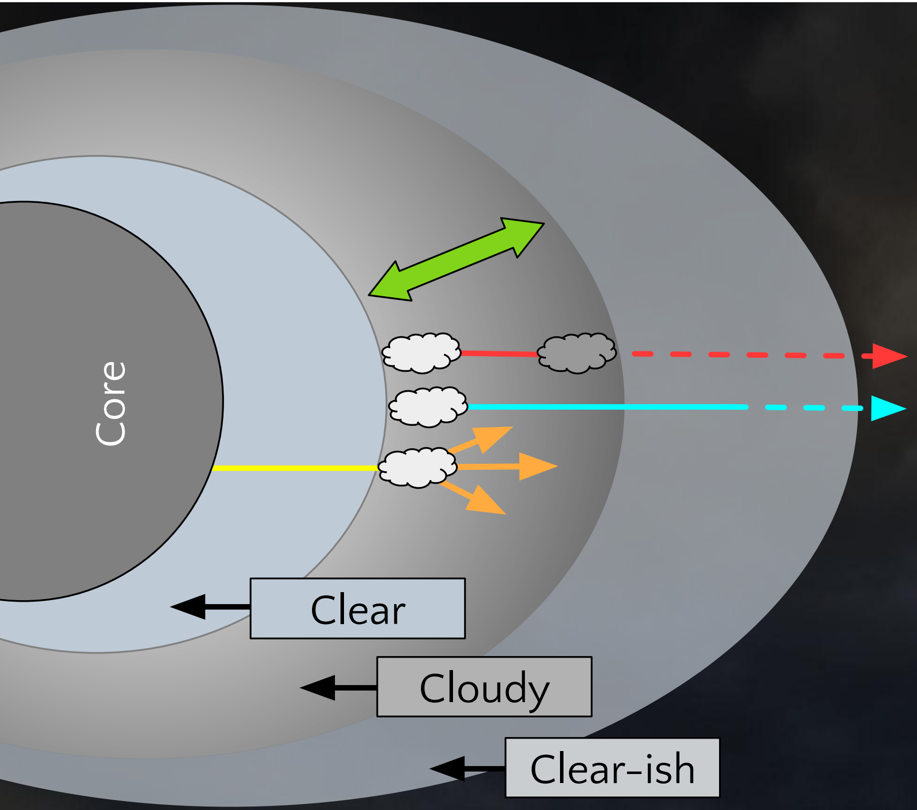
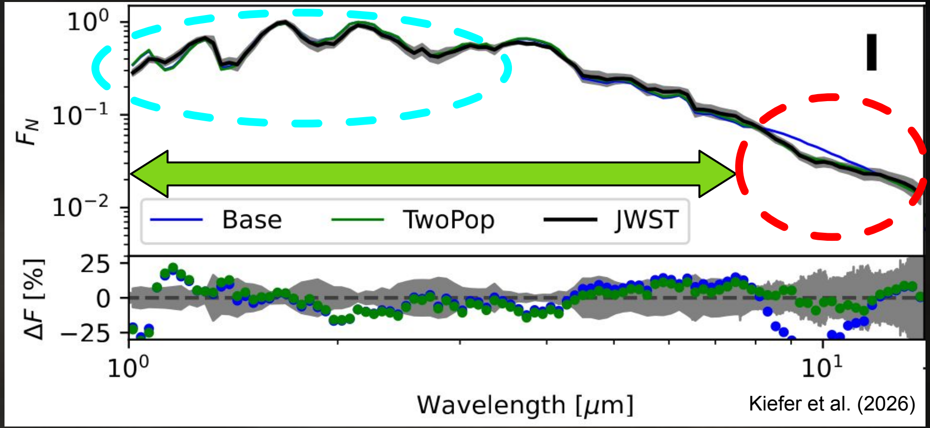
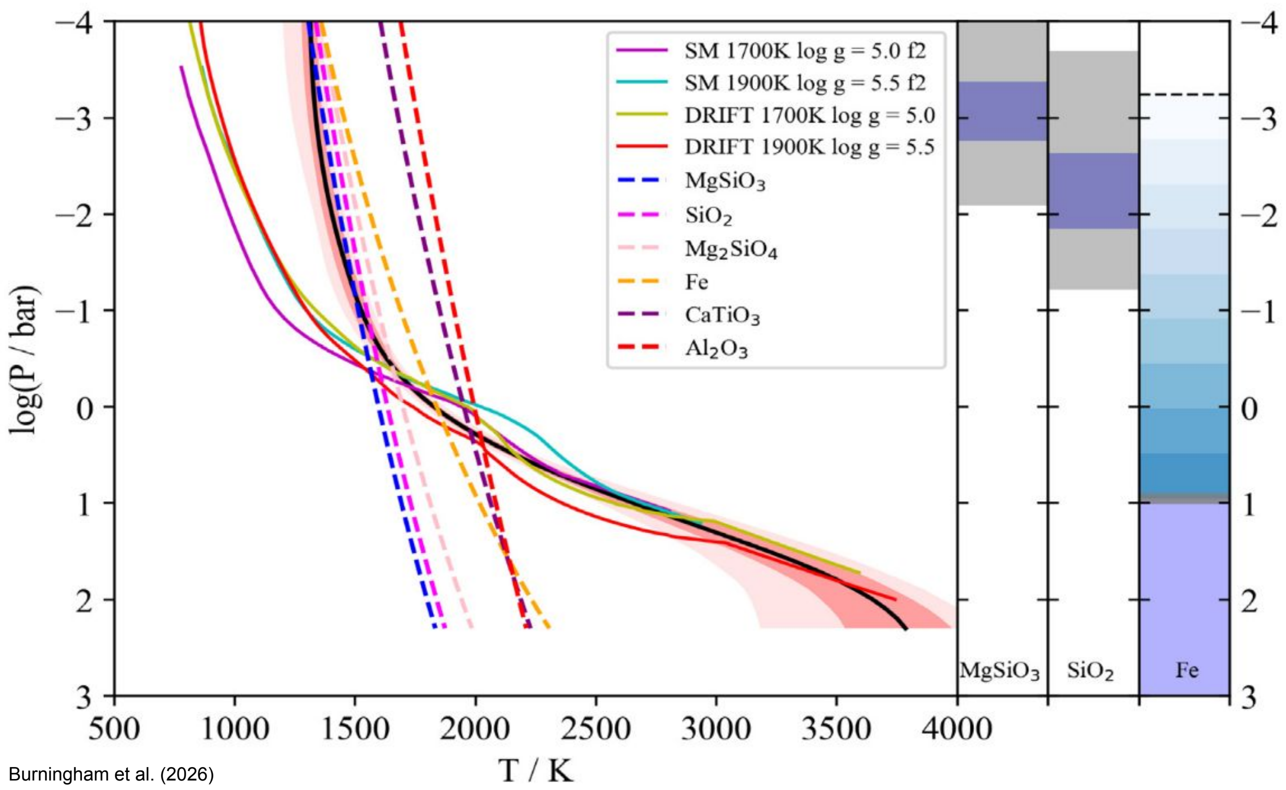




- Clouds block all light from below
- Clouds determine the photosphere extent and therefore the width of the spectra
- Only clouds above the main cloud deck can produce Si-O bond absorption feature

High Clouds are a Known Problem



Burningham et al. (2026)