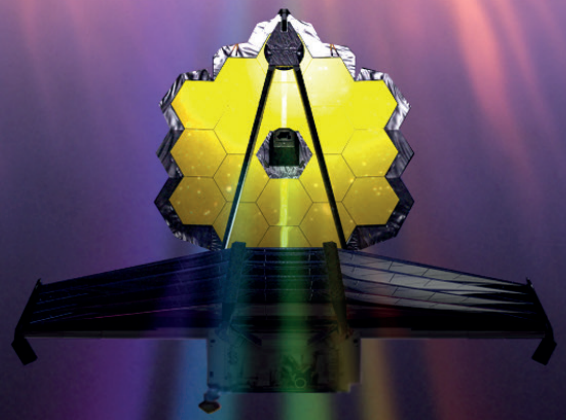
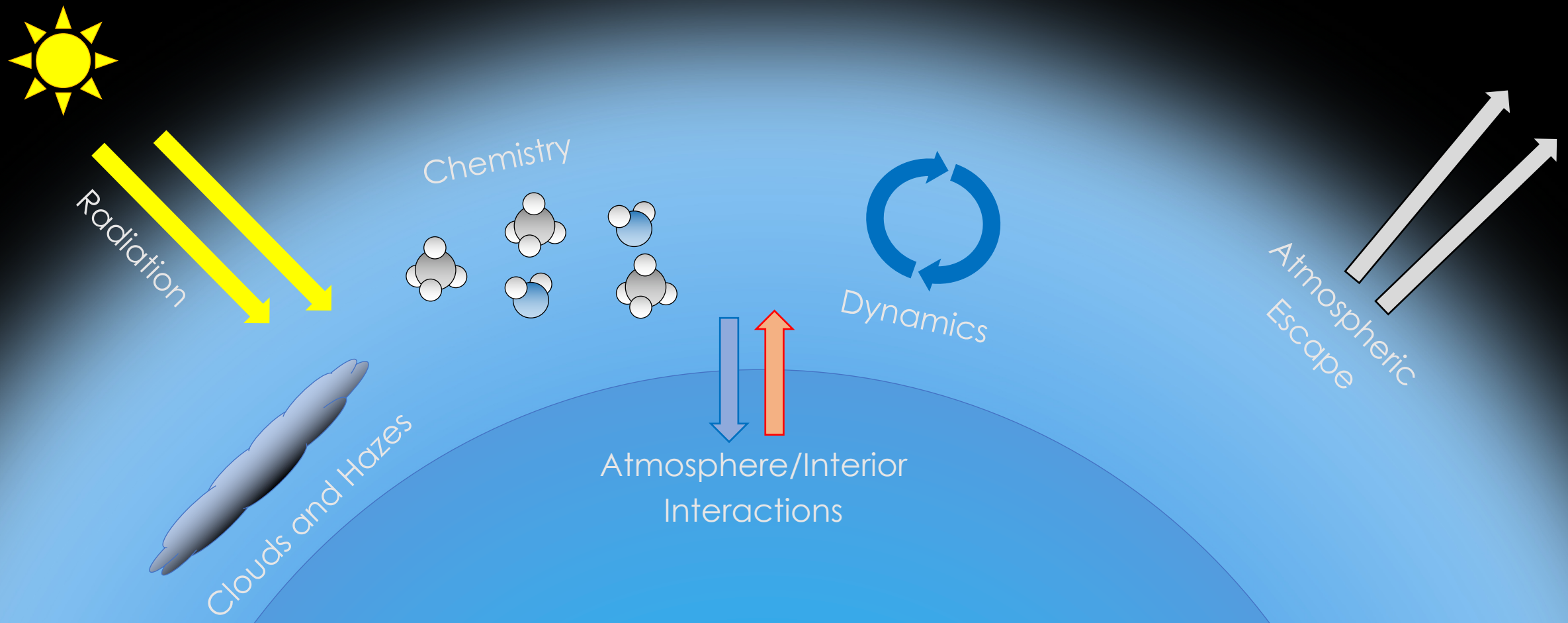
Looking Through (and Understanding) Clouds and Hazes with JWST (and other things)

Peter Gao | Carnegie EPL | @PlanetaryGao

Sagan Summer Workshop 2023 | #sagan2023 | July 27th, 2023

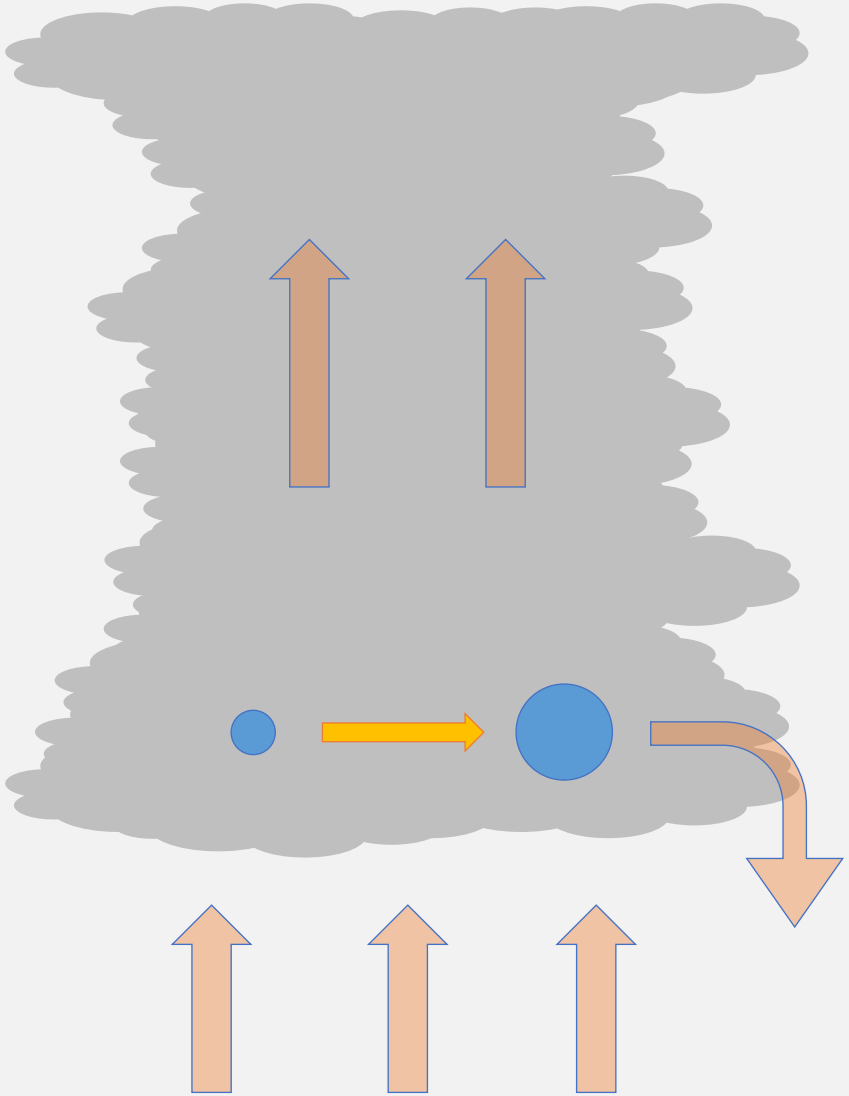


Clouds and Hazes are Fundamental Components of Planetary Atmospheres

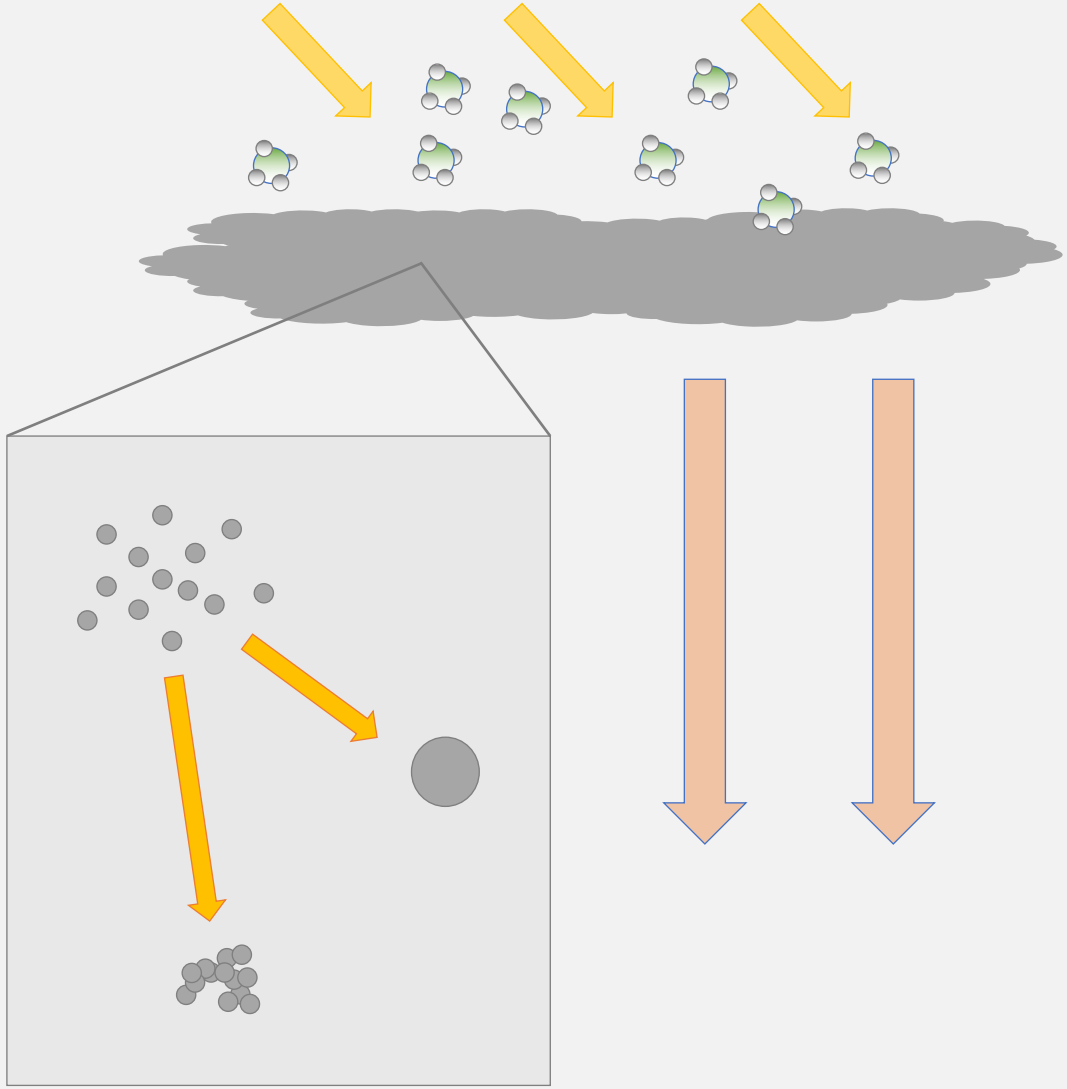


What Are Exoplanet Clouds and Hazes Like?

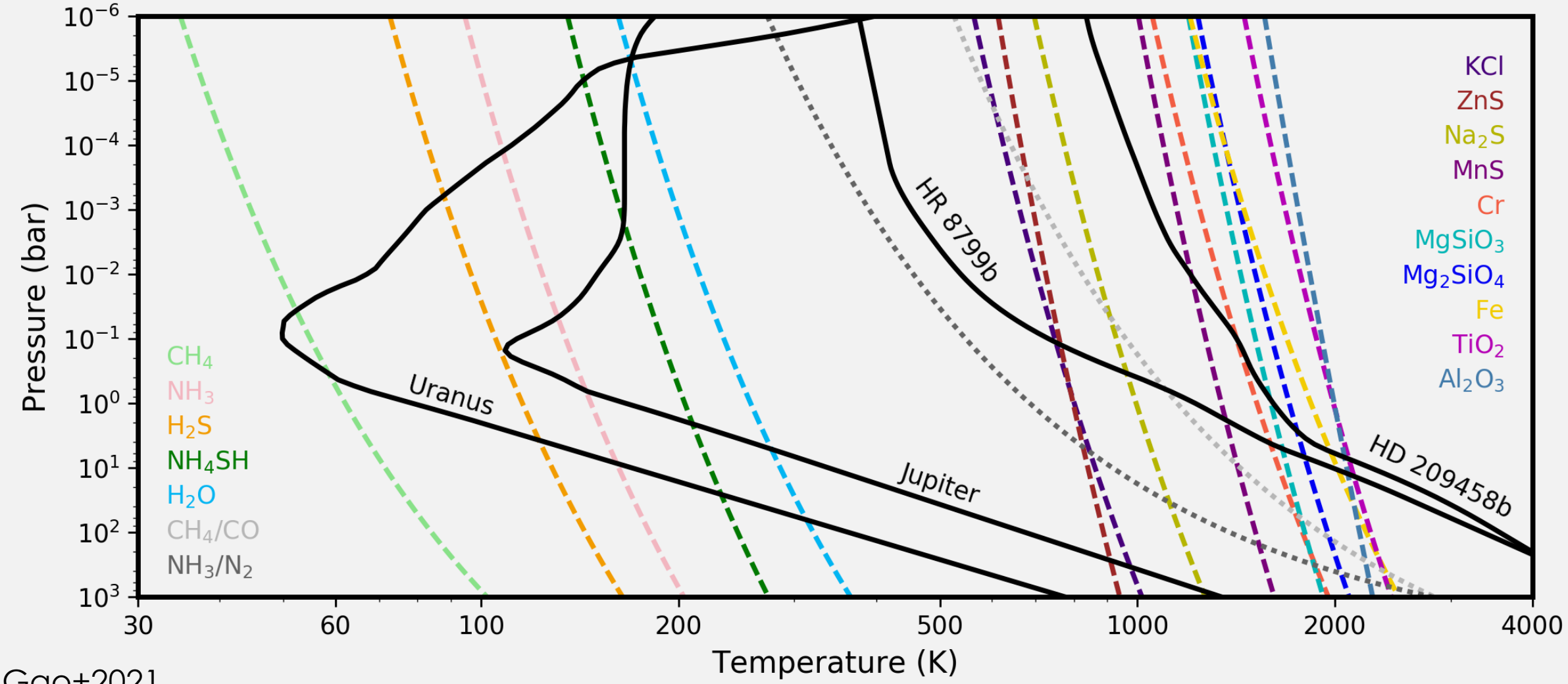
Clouds



Hazes

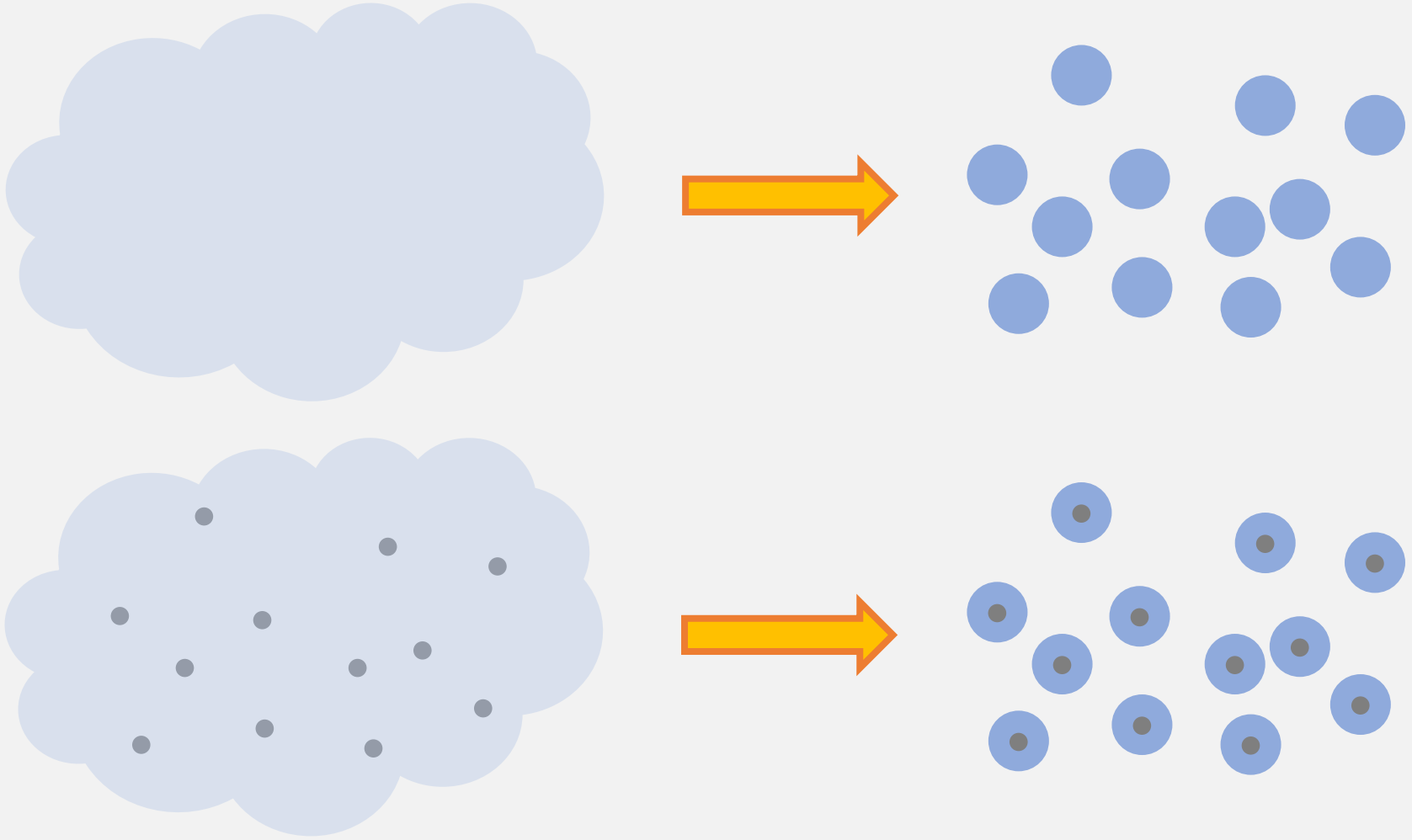


Equilibrium chemistry predicts a diverse set of condensates with temperature



Gao+2021

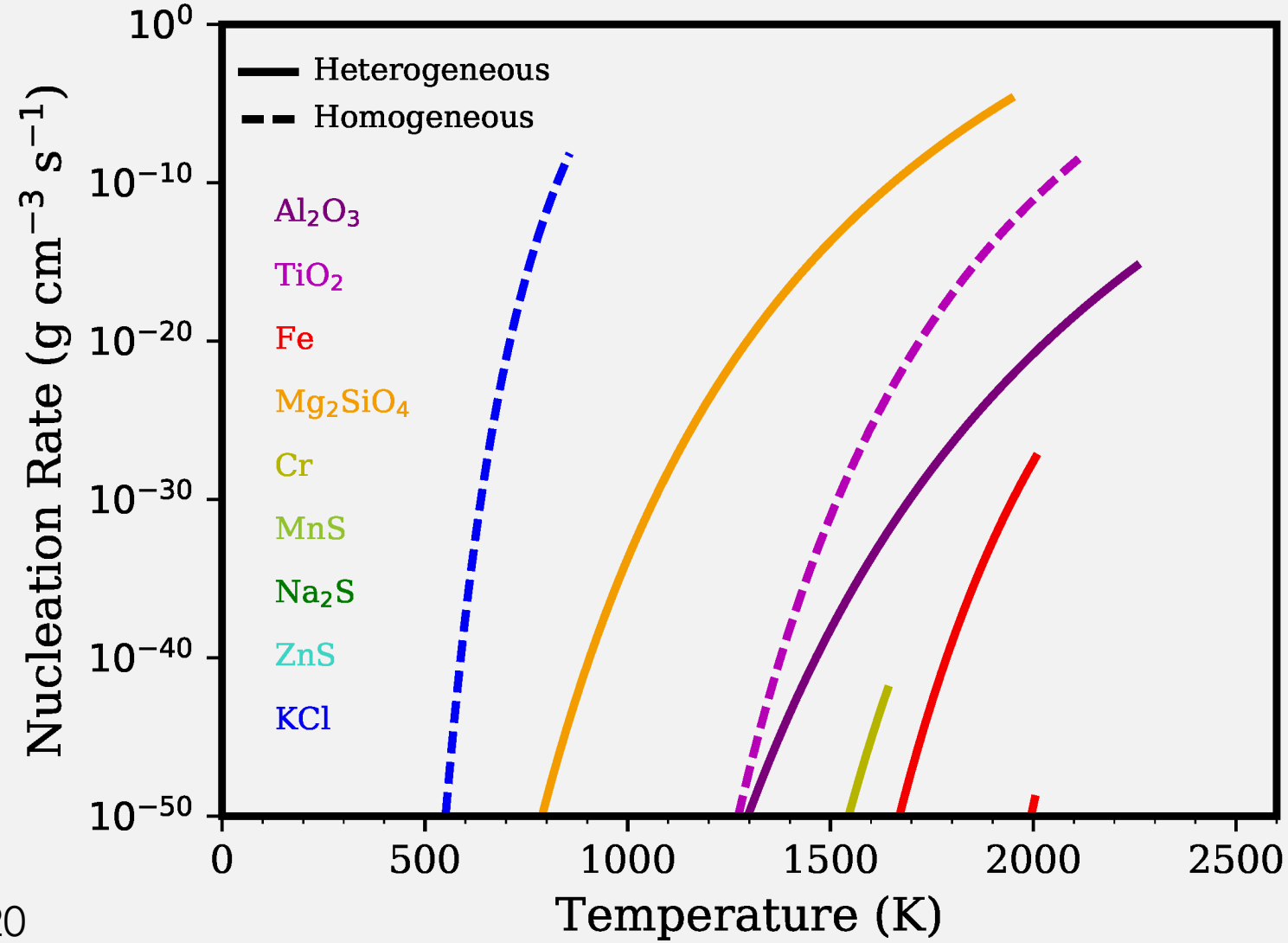
How do cloud particles form?



Homogeneous Nucleation

Heterogeneous Nucleation

Cloud formation can be inhibited by the nucleation barrier



Gao+2020

σ_{TiO2} ~ 500 ergs cm^{-2}

σ_{For} ~ 436 ergs cm^{-2}

σ_{Cor} ~ 690 ergs cm^{-2}

σ_{Fe} ~ 1850 ergs cm^{-2}

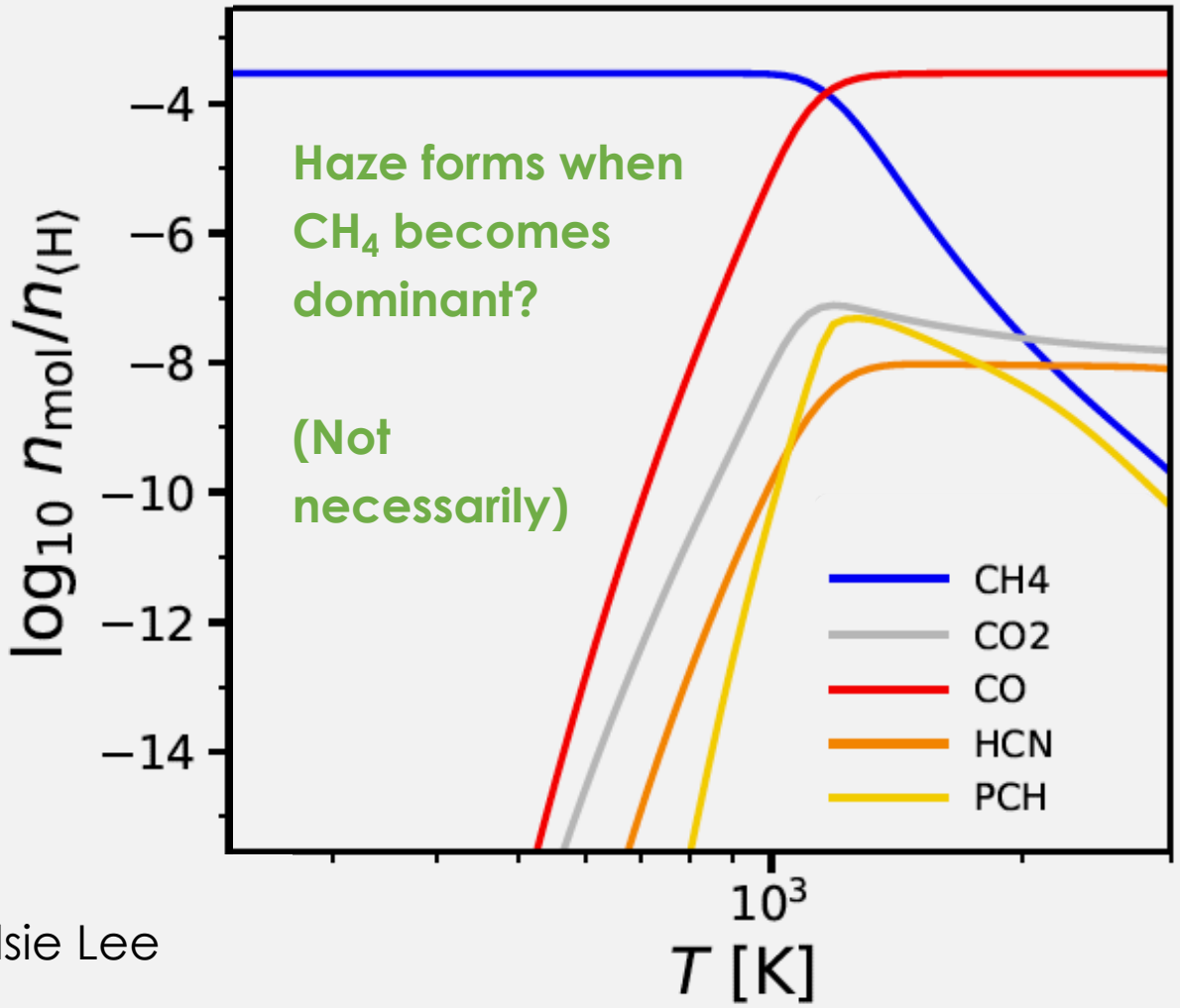
σ_{Cr} ~ 1800 ergs cm^{-2}

σ_{MnS} ~ 2300 ergs cm^{-2}

σ_{KCl} ~ 150 ergs cm^{-2}

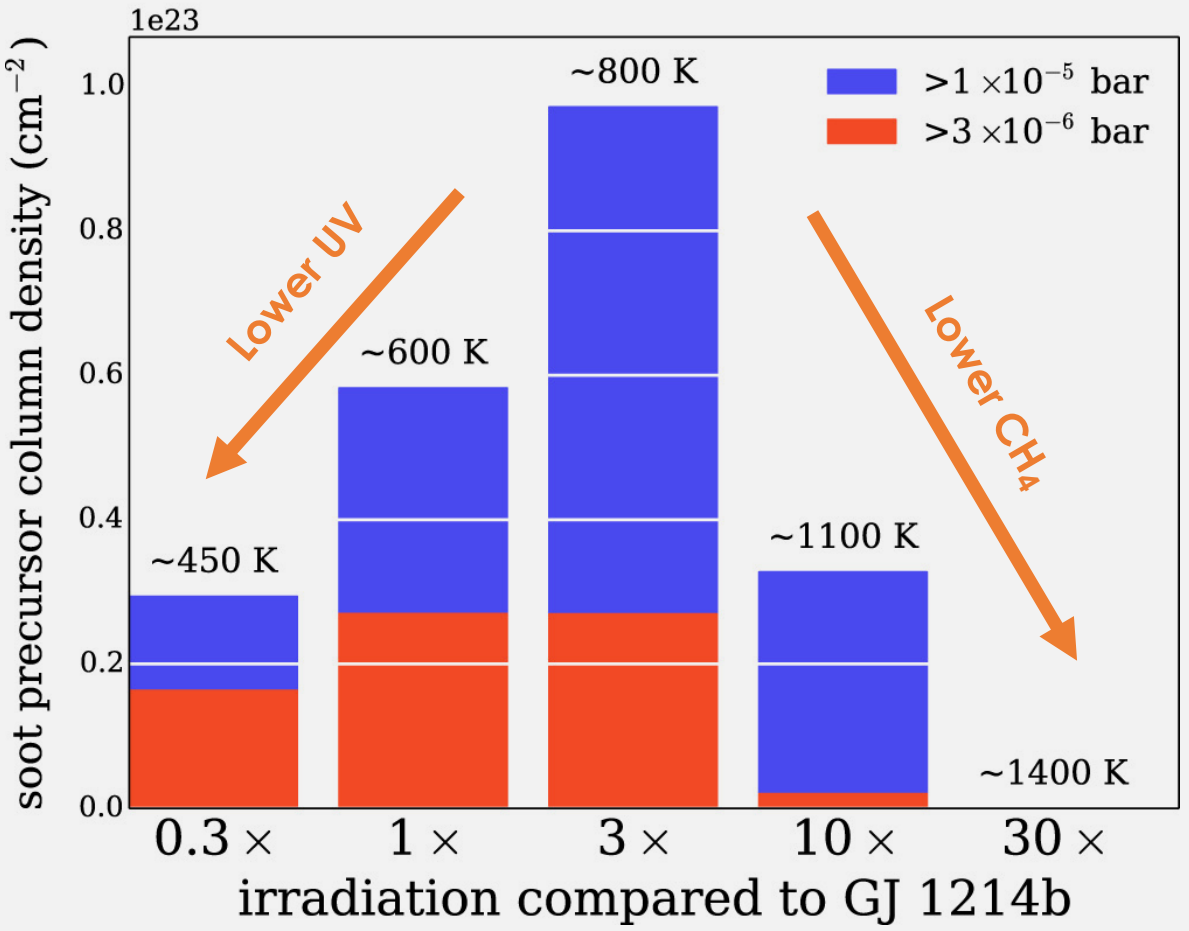
$$J \propto e^{f(\sigma^3)}$$

Photochemical haze production is likely tied to abundance of simple "haze precursors"

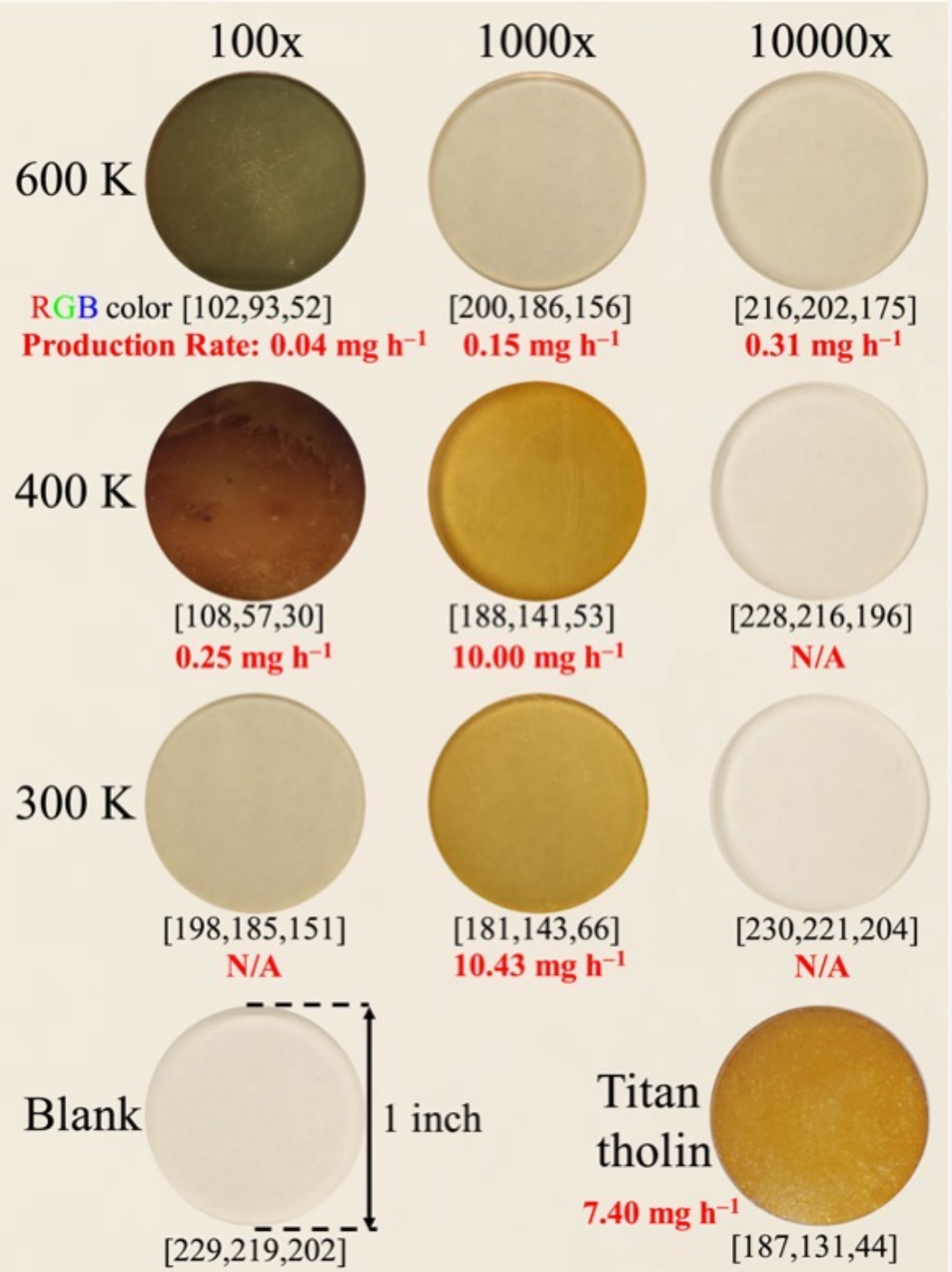


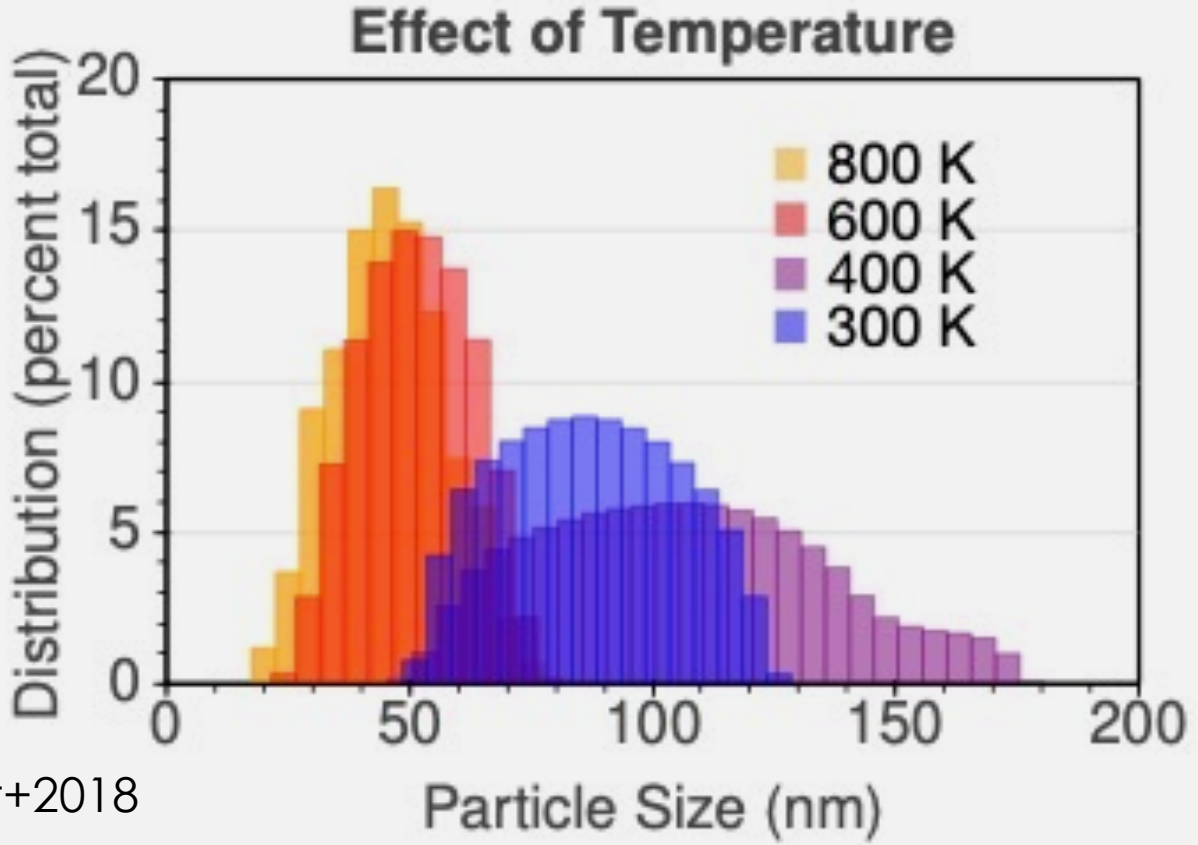
Elsie Lee

Morley+2015



Laboratory experiments shed light on complexities of haze formation and composition



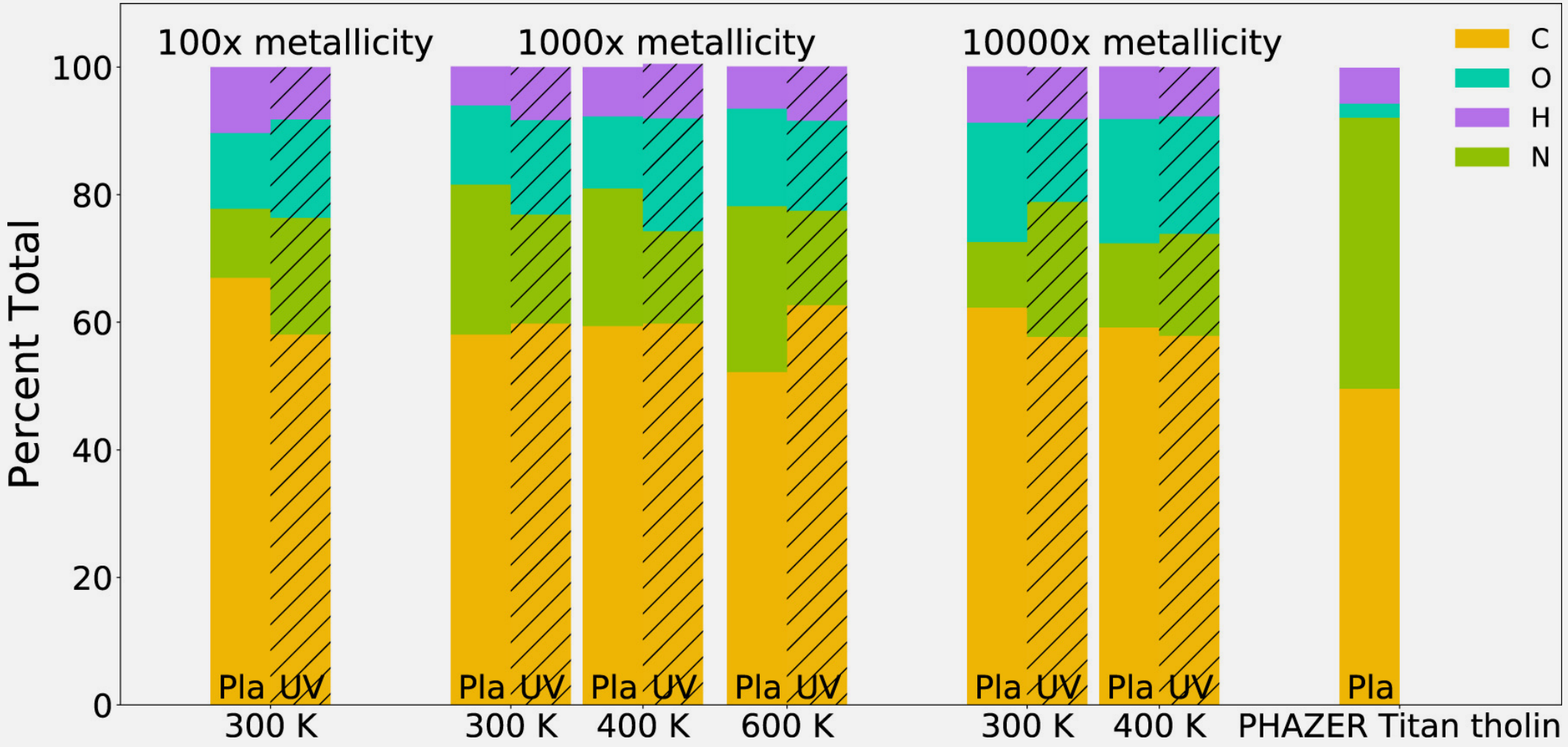


Hörst+2018

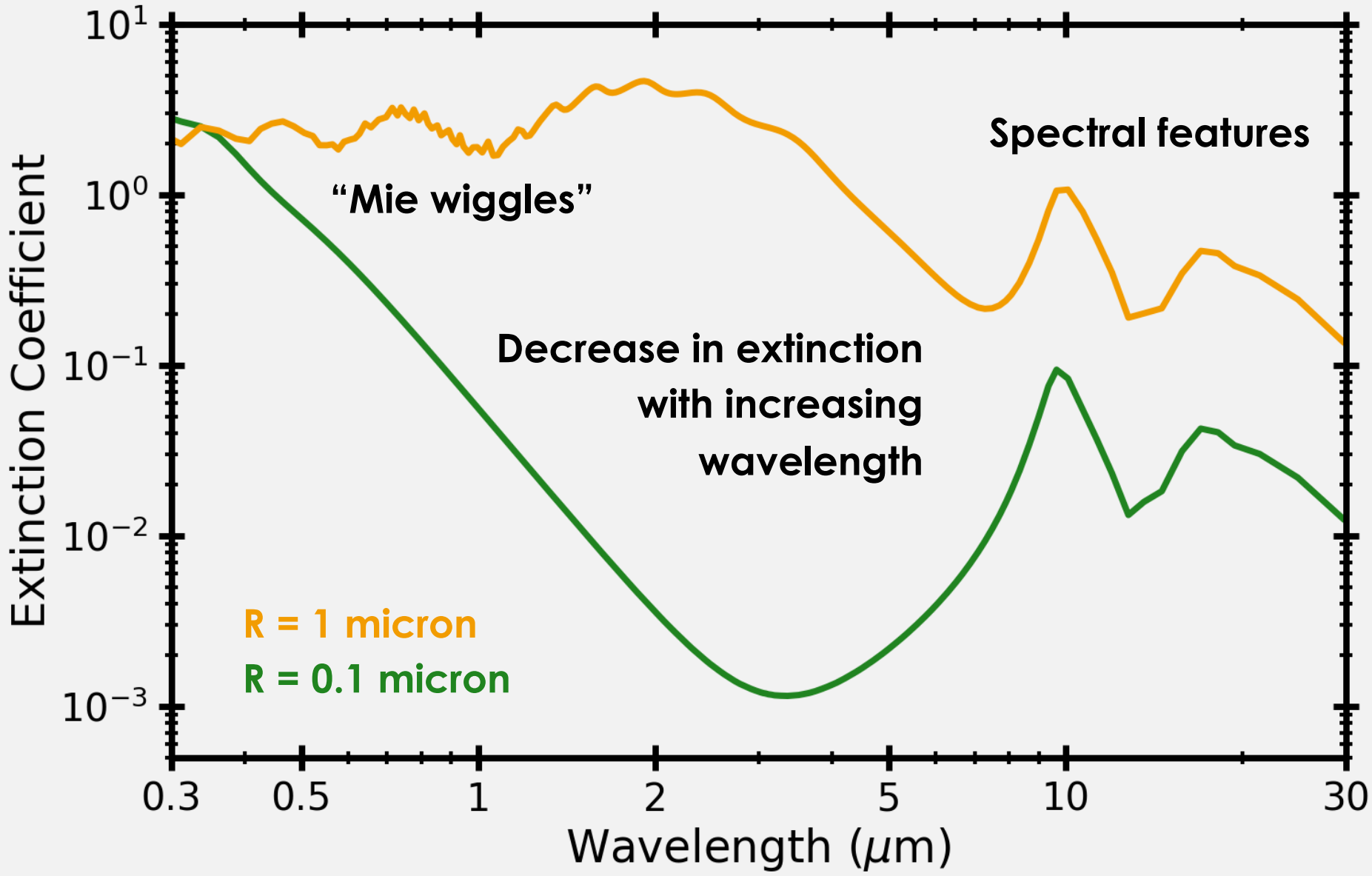
He+2018

Laboratory experiments shed light on complexities of haze formation and composition

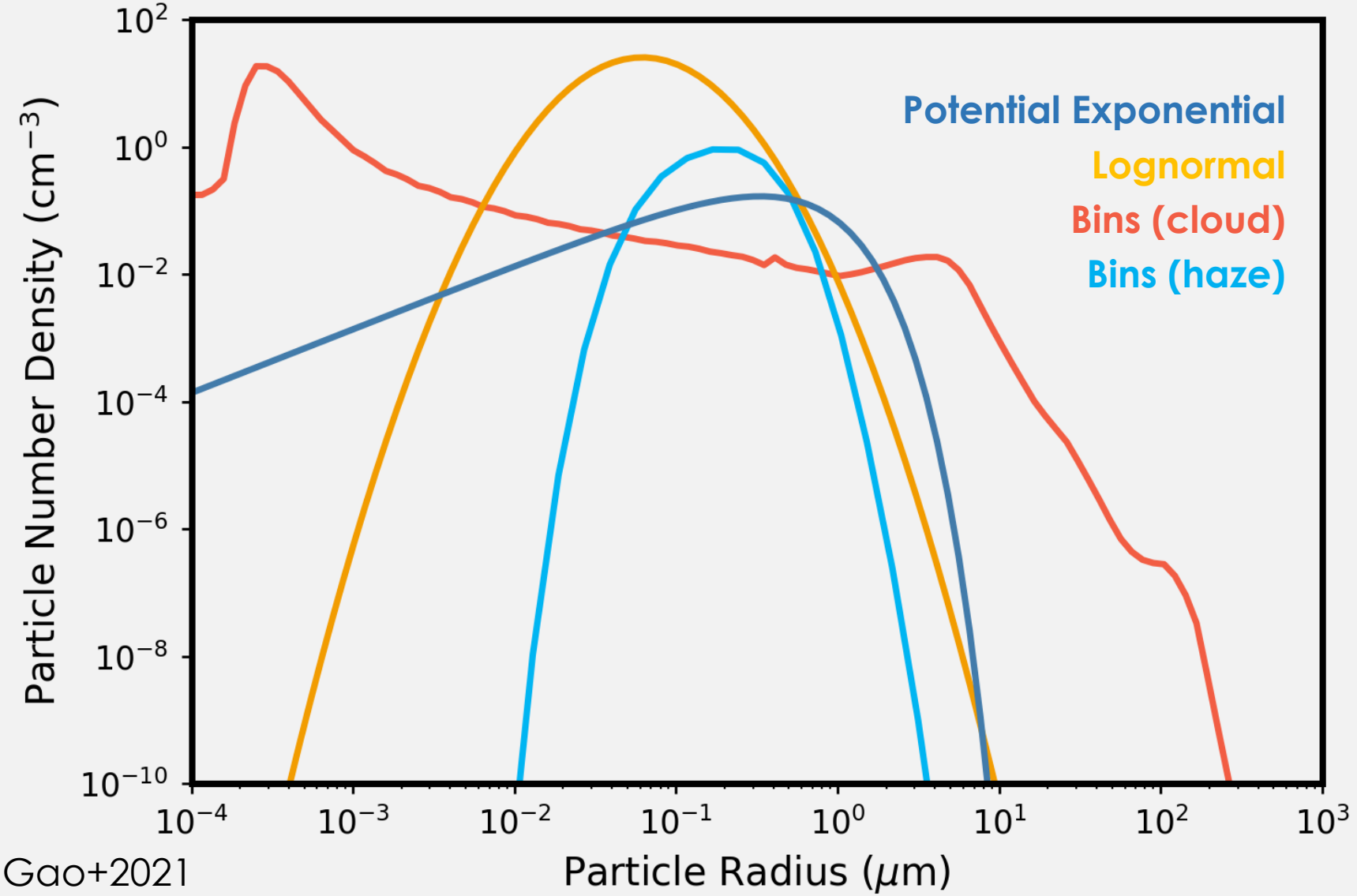
Moran+2020



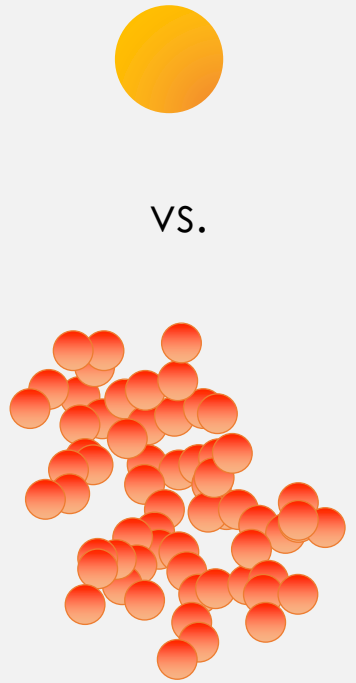
Optical properties depends on size, composition, shape and impact the large scale thermal structure of exoplanets



Cloud particle size distributions (and shapes) can be complex



Gao+2021



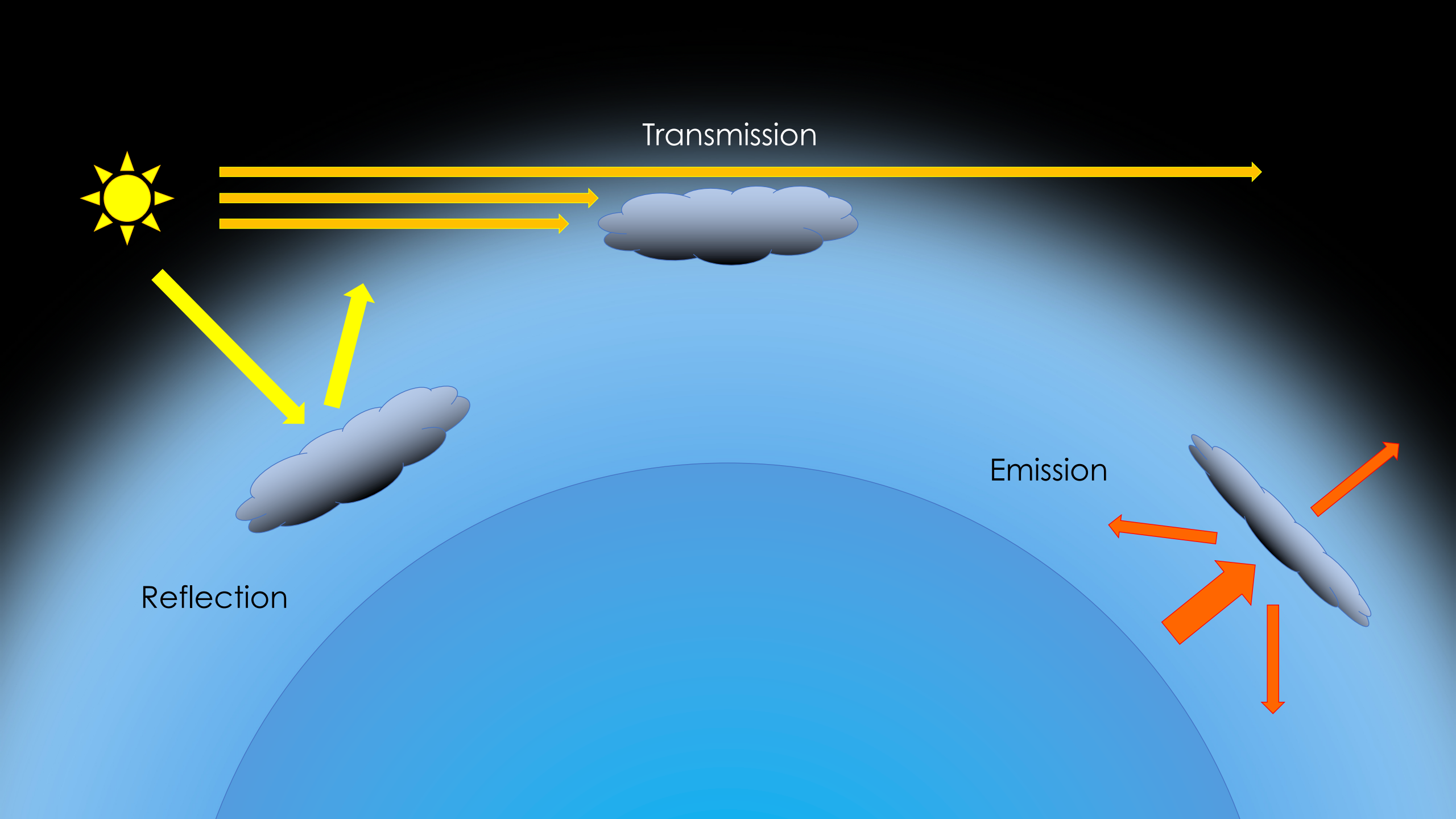
vs.

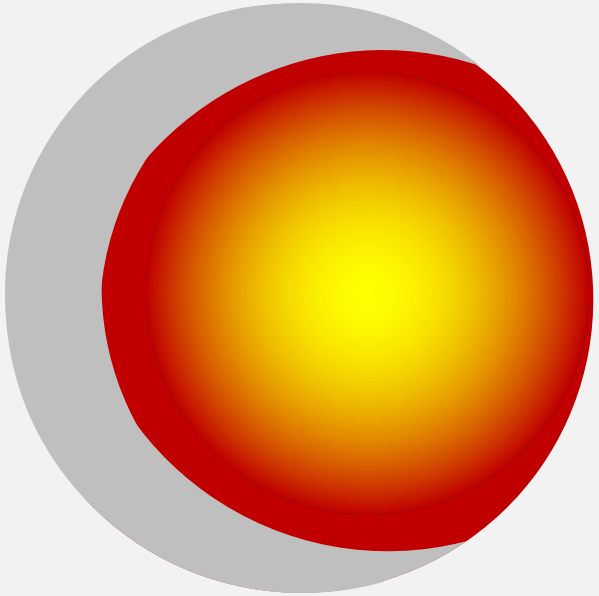
vs.

???

Clouds and hazes are complicated

How do Clouds and Hazes Impact Exoplanet Atmospheres and Observations?


Transmission
Reflection
Emission



Effects of exoplanet clouds and hazes range from global to local scales

Global Scale (T ~ hours – days):

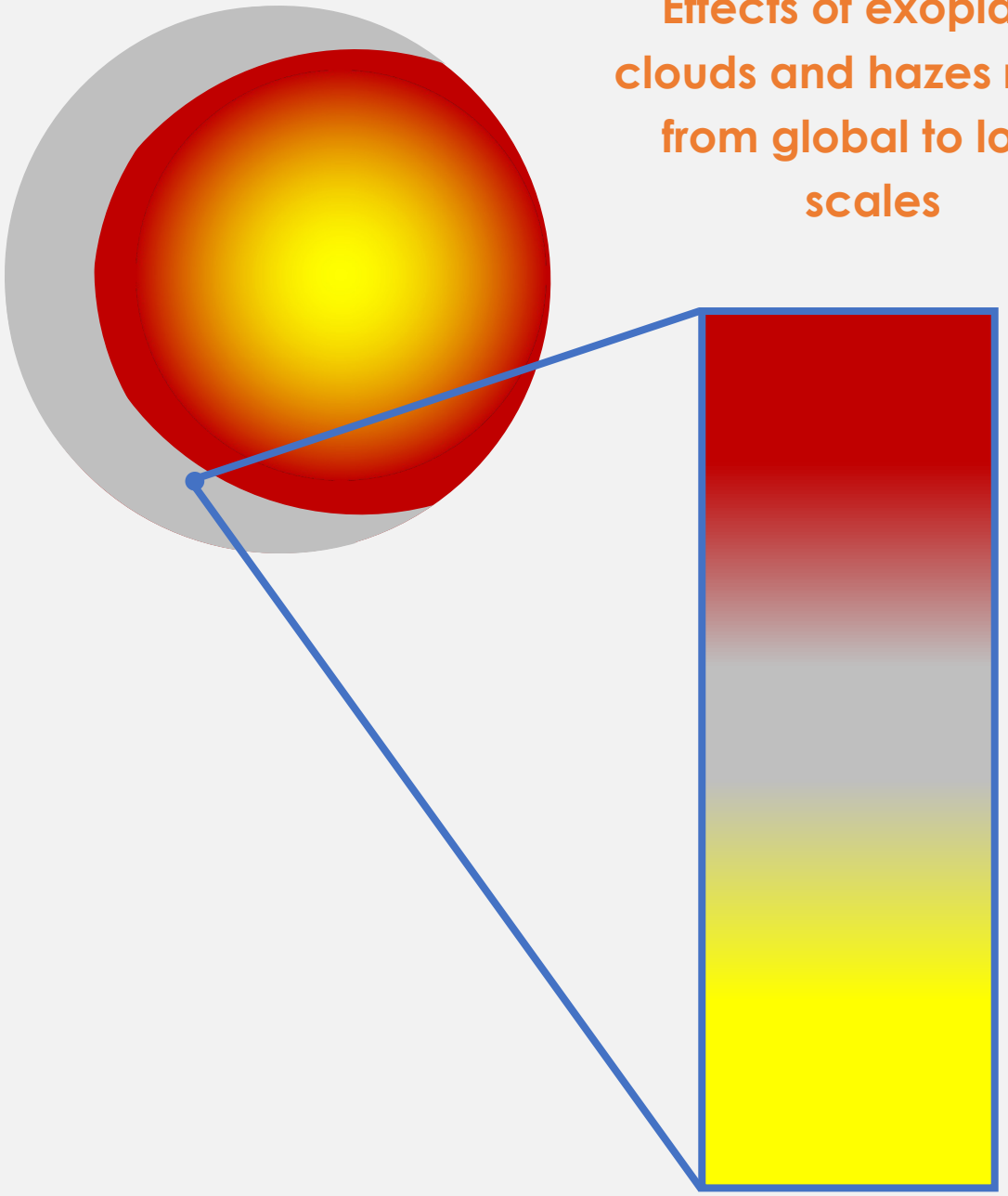
Phase curve

Energy balance

Dynamics

Gas composition (e.g. rain out)

Effects of exoplanet clouds and hazes range from global to local scales



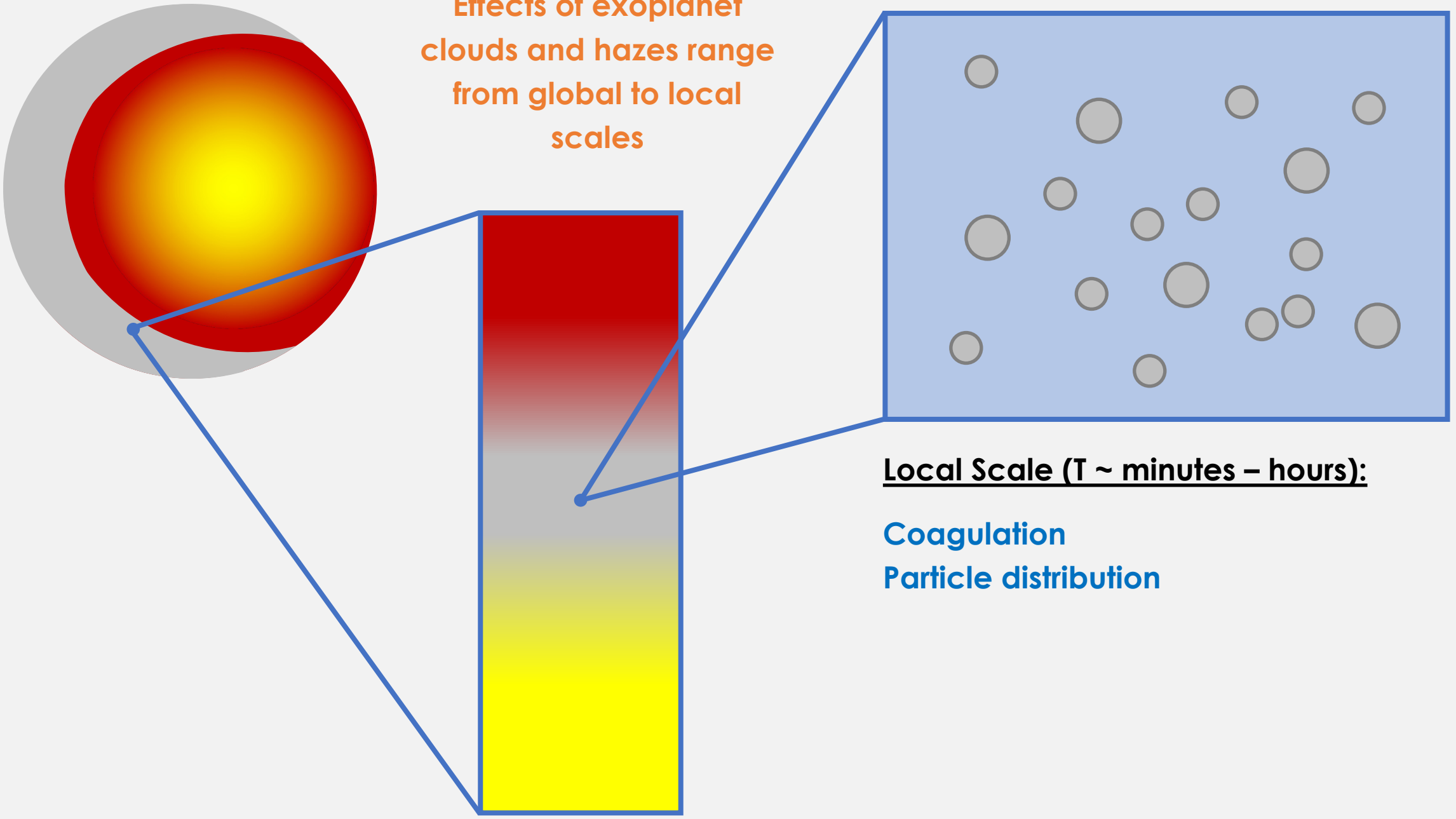
Column Scale (T ~ hours – days):

Transmission spectra

Emission/reflection spectra

Thermal structure

Effects of exoplanet clouds and hazes range from global to local scales

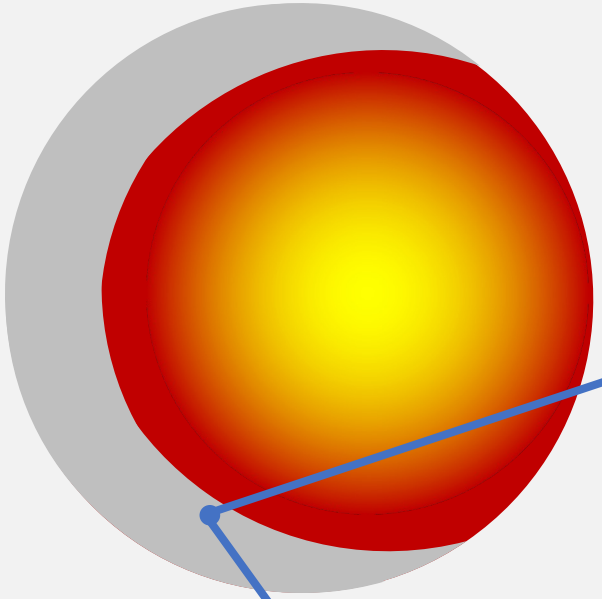


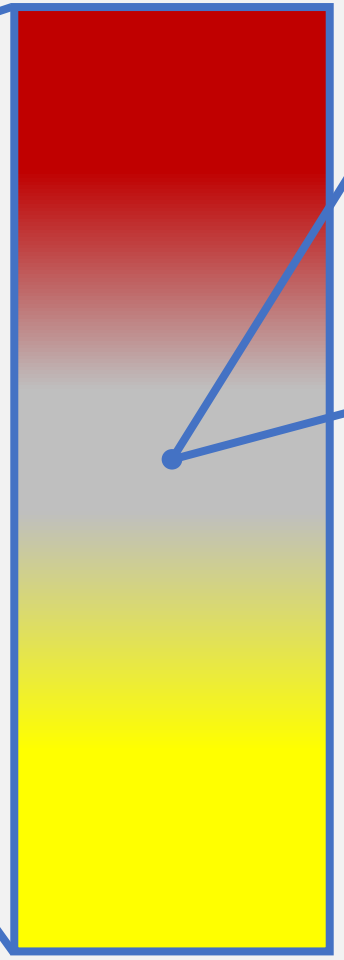
Local Scale (T ~ minutes – hours):

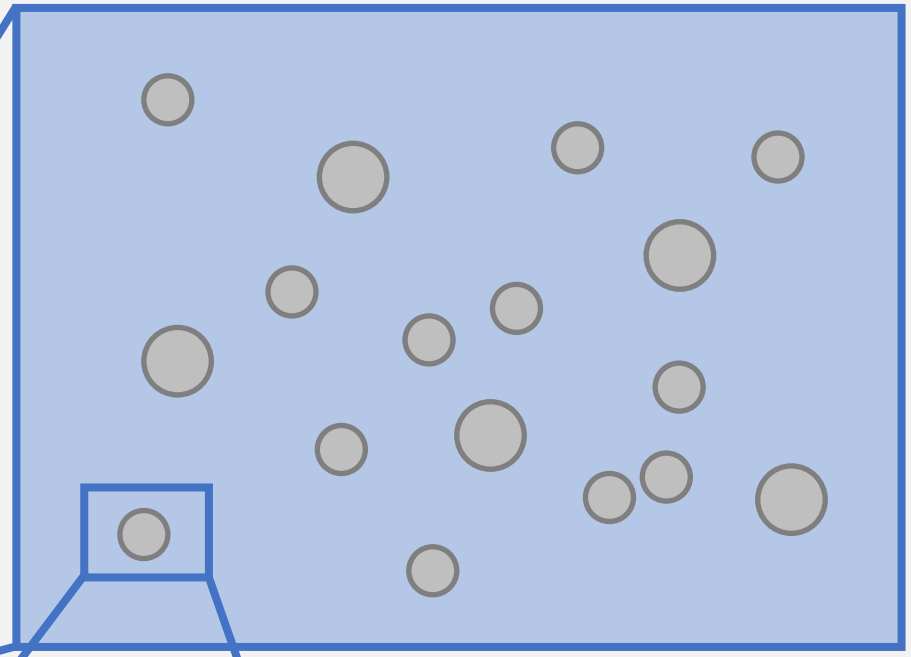
Coagulation

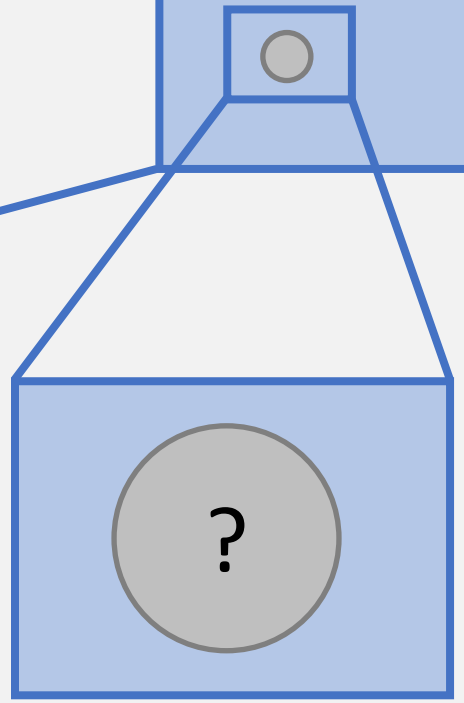
Particle distribution

Effects of exoplanet clouds and hazes range from global to local scales









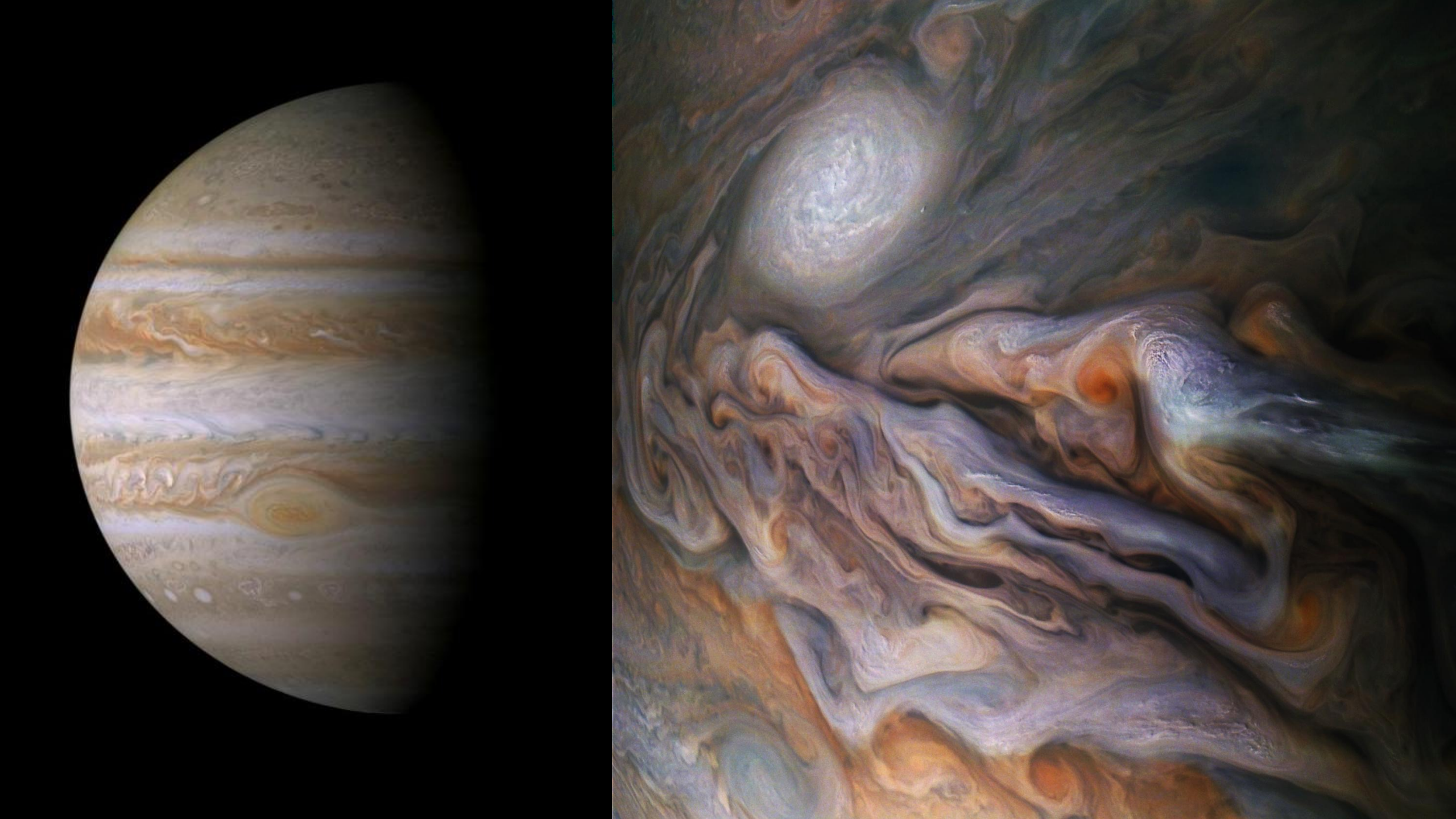
Particle Scale (T ~ seconds):

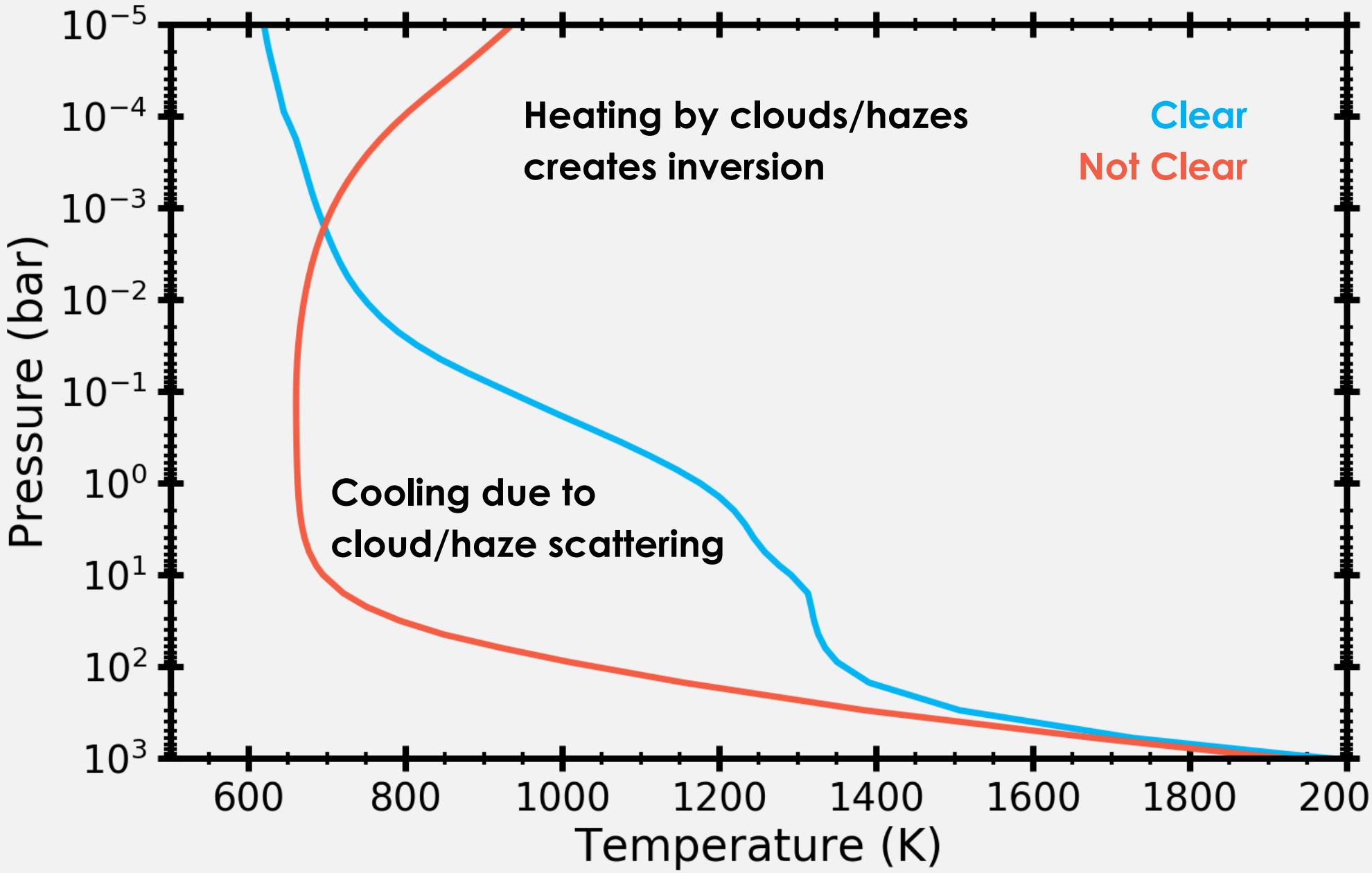
Condensation/chemistry

Composition

Shape

Optical properties

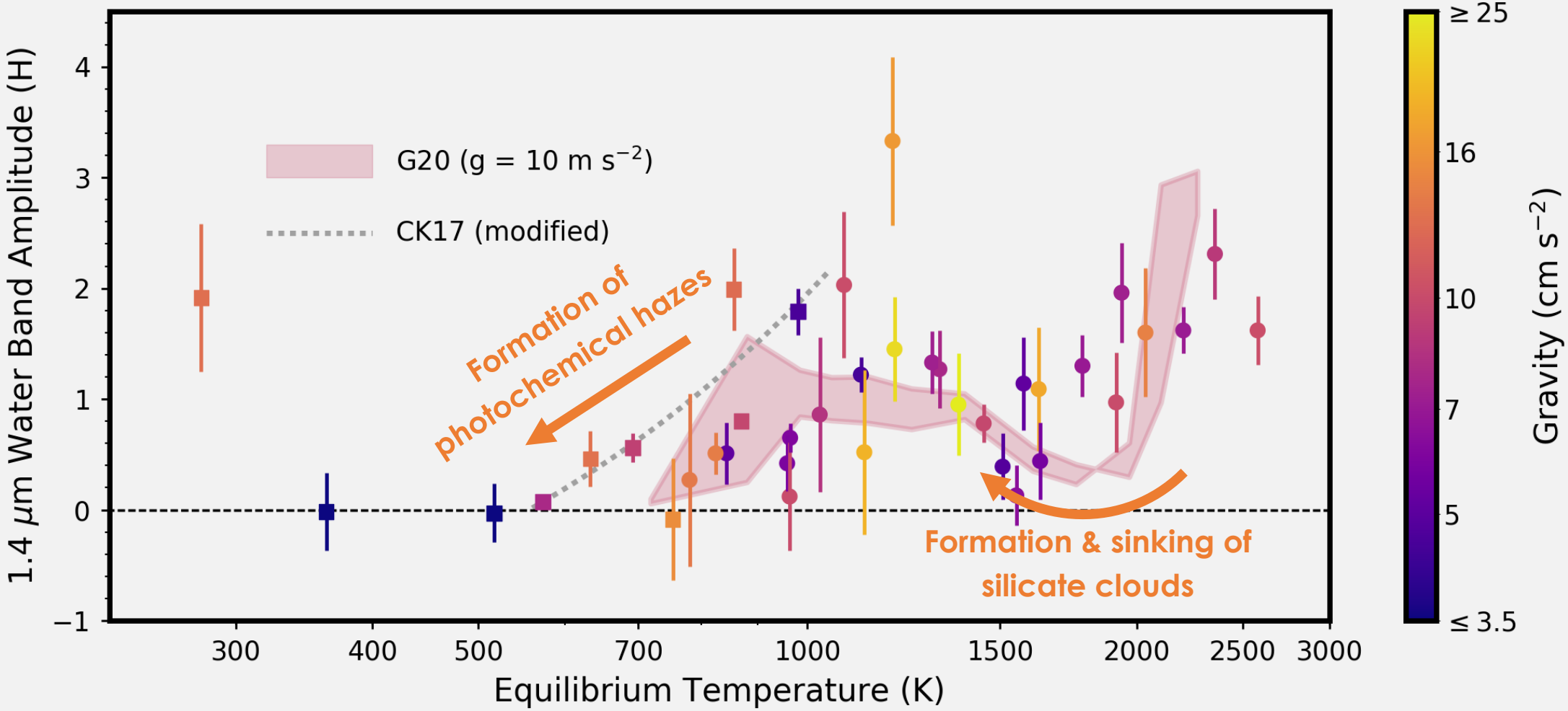



Heating by clouds/hazes
creates inversion
Clear
Not Clear
Cooling due to
cloud/haze scattering
Pressure (bar)
Temperature (K)
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
600
800
1000
1200
1400
1600
1800
200

Clouds and Hazes impact exoplanet atmospheres across a wide range of spatial and temporal scales

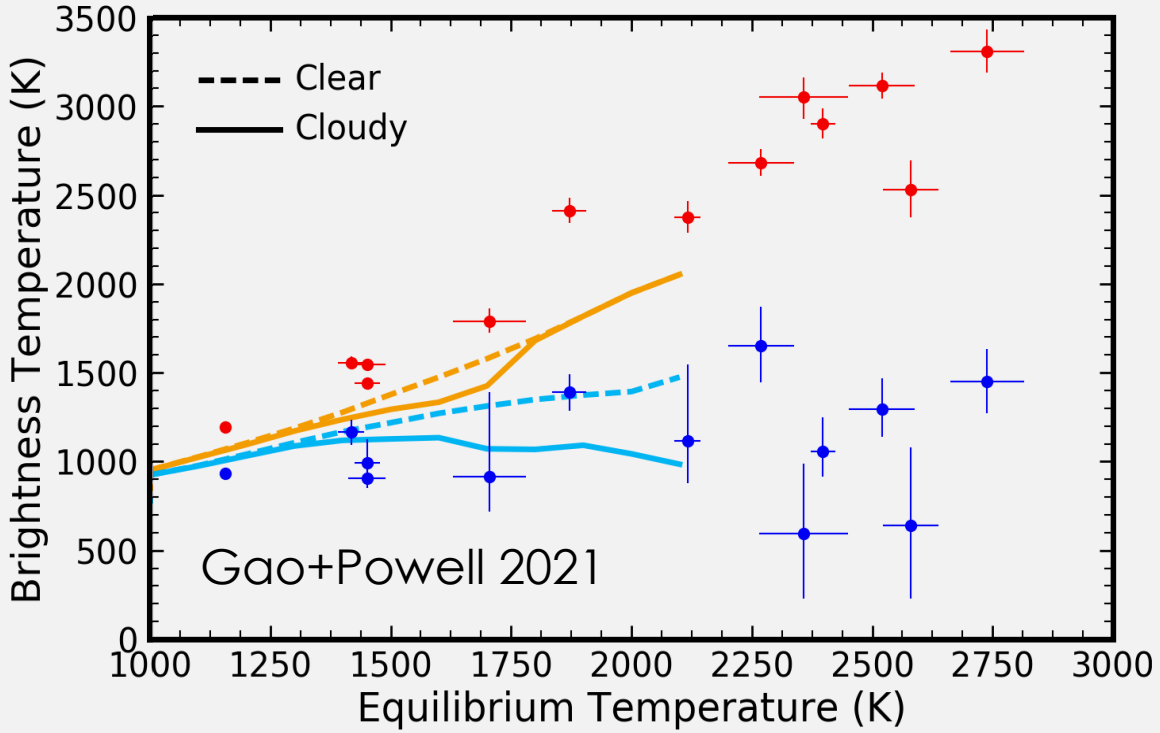
How Do We Better Understand Clouds and Hazes?

Task 1: Look at Cloudy/Hazy-ness on a population level

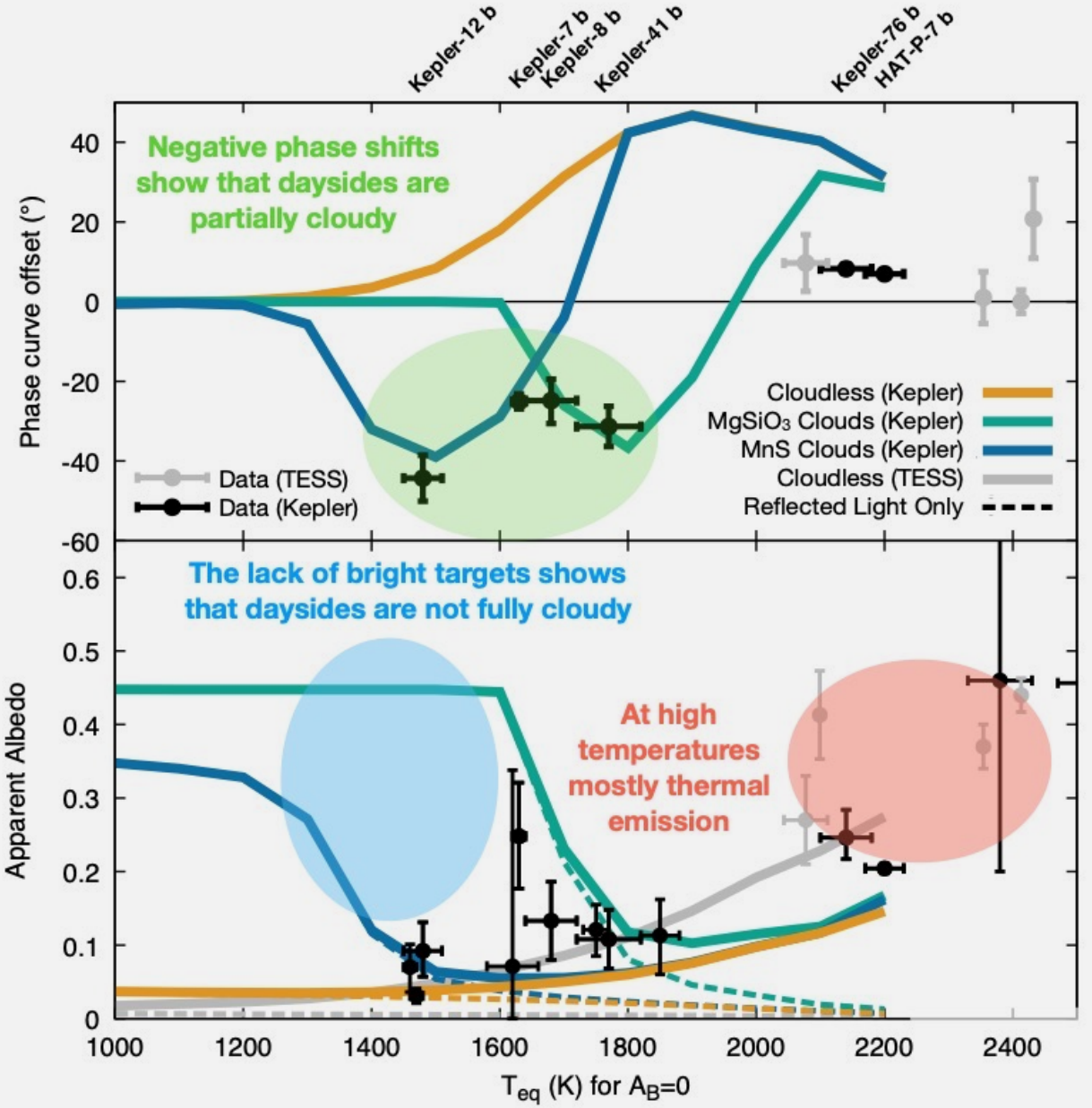


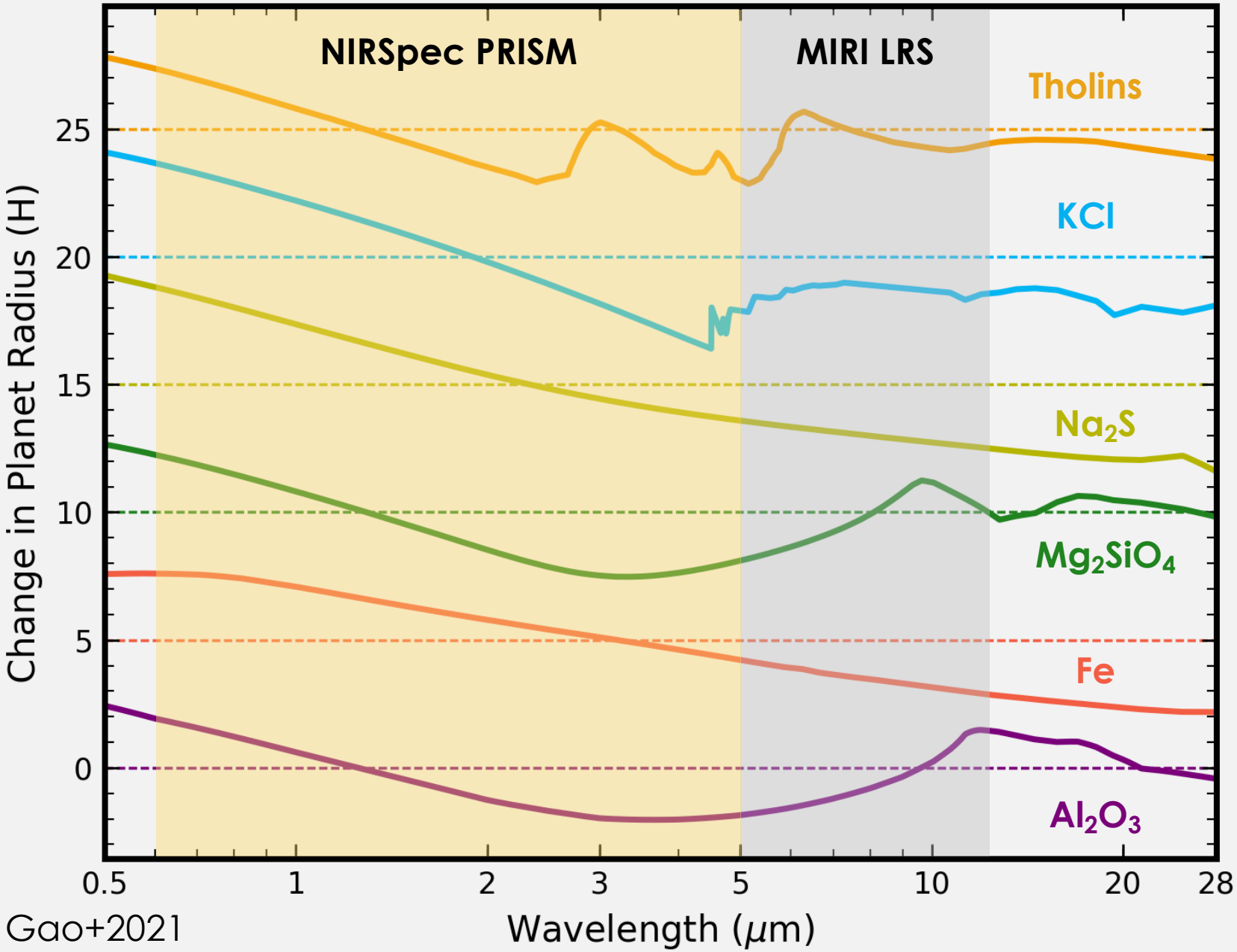
Gao+2021

Task 1: Look at Cloudy/Hazy-ness on a population level



Parmentier+2016, 2021





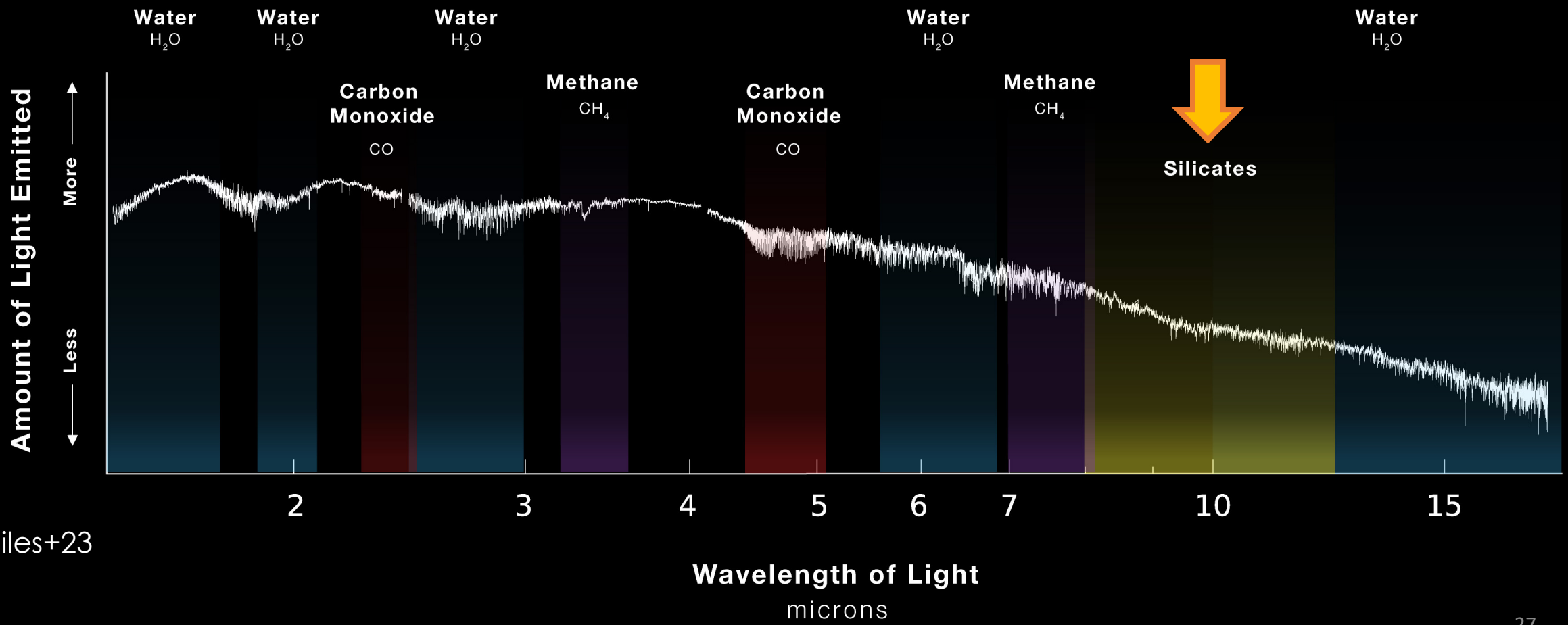
Task 2: Look for the spectral finger-prints of clouds and hazes

Updated laboratory measurements of optical constants needed

EXOPLANET VHS 1256 b

EMISSION SPECTRUM

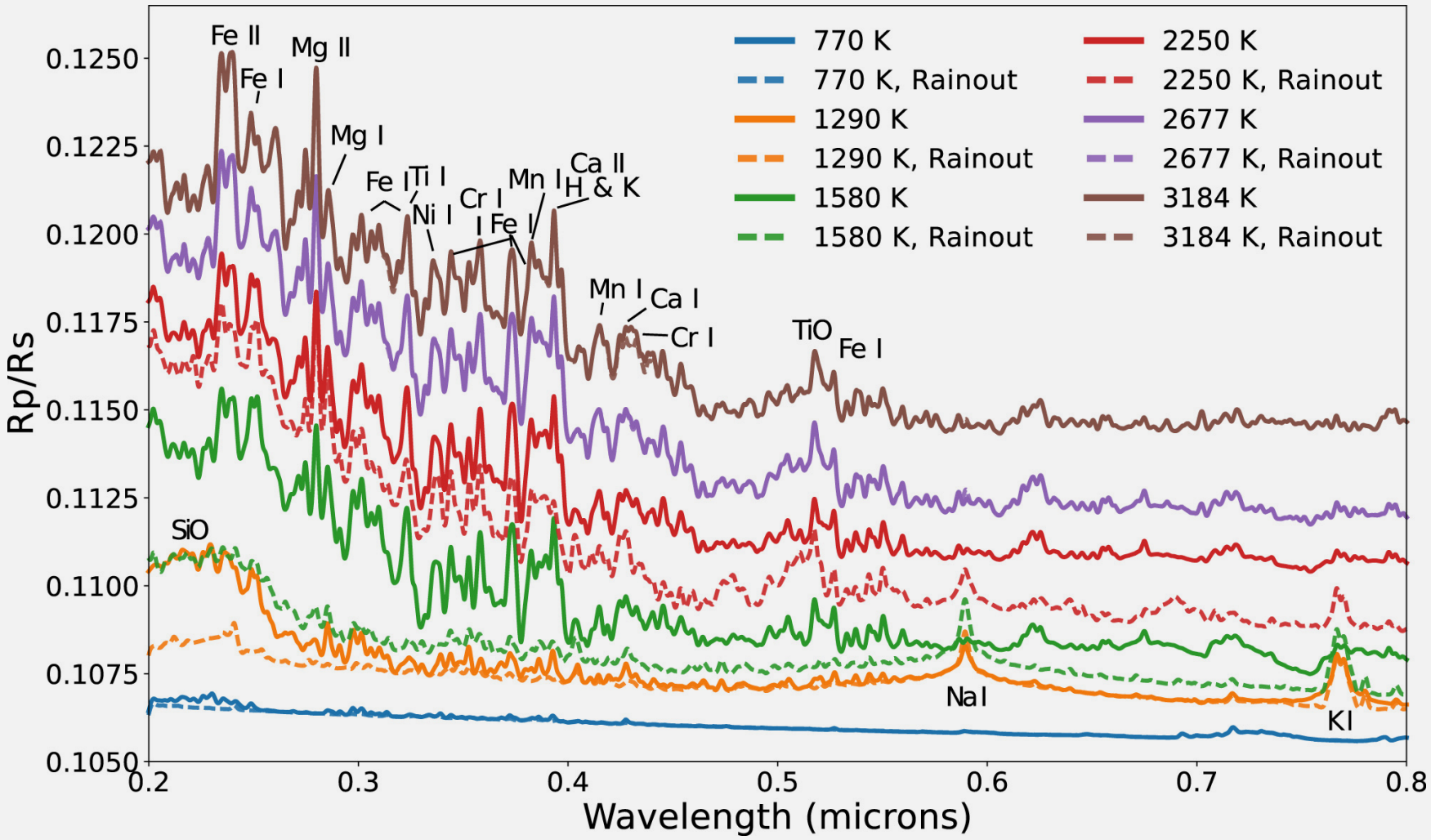
NIRSpec and MIRI | IFU Medium-Resolution Spectroscopy



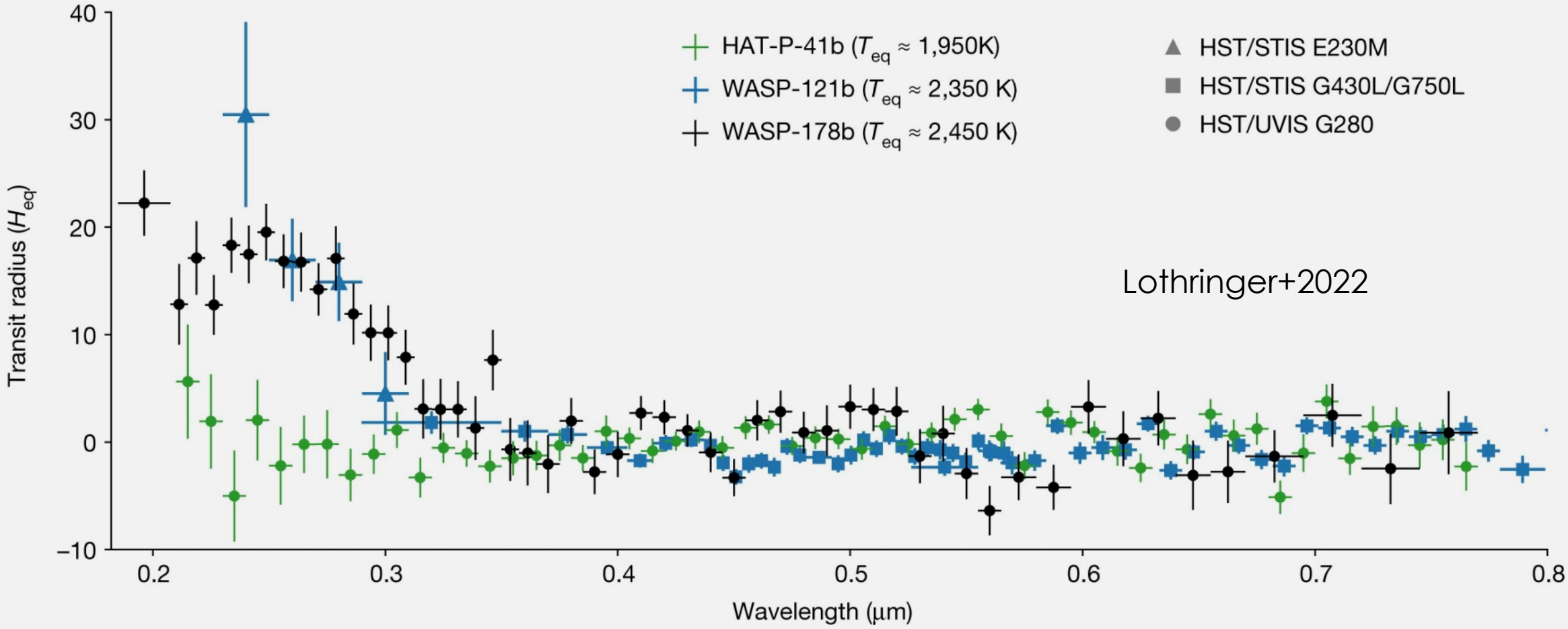
Miles+23

Task 3: Look for the lack of condensation

Lothringer+2020



Task 3: Look for the lack of condensation



Lothringer+2022

Task 4: More lab work!

Yu+2021

Plasma	100×	1,000×	10,000×
600 K	$\theta \approx 78° \pm 2°$ 	$\theta \approx 45° \pm 1°$ 	$\theta \approx 82° \pm 5°$ 
400 K	$\theta \approx 103° \pm 4°$ 	$\theta \approx 65° \pm 1°$ 	$\theta \approx 92° \pm 2°$ 
300 K	$\theta \approx 87° \pm 1°$ 	$\theta \approx 33° \pm 3°$ 	$\theta \approx 85° \pm 3°$ 

Takeaways

Looking through clouds and hazes is not an option: Their impacts on planetary atmospheres are unavoidable

Understanding clouds and hazes requires a combination of **observational**, **theoretical**, and **experimental** efforts – every bit helps!

Review papers:

Marley+2013: https://ui.adsabs.harvard.edu/abs/2013cctp.book..367M/abstract

Helling 2019: https://ui.adsabs.harvard.edu/abs/2019AREPS..47..583H/abstract

Gao+2021: https://ui.adsabs.harvard.edu/abs/2021JGRE..12606655G/abstract