Neglected Polymorphs of Silica Clouds in Substellar Atmospheres

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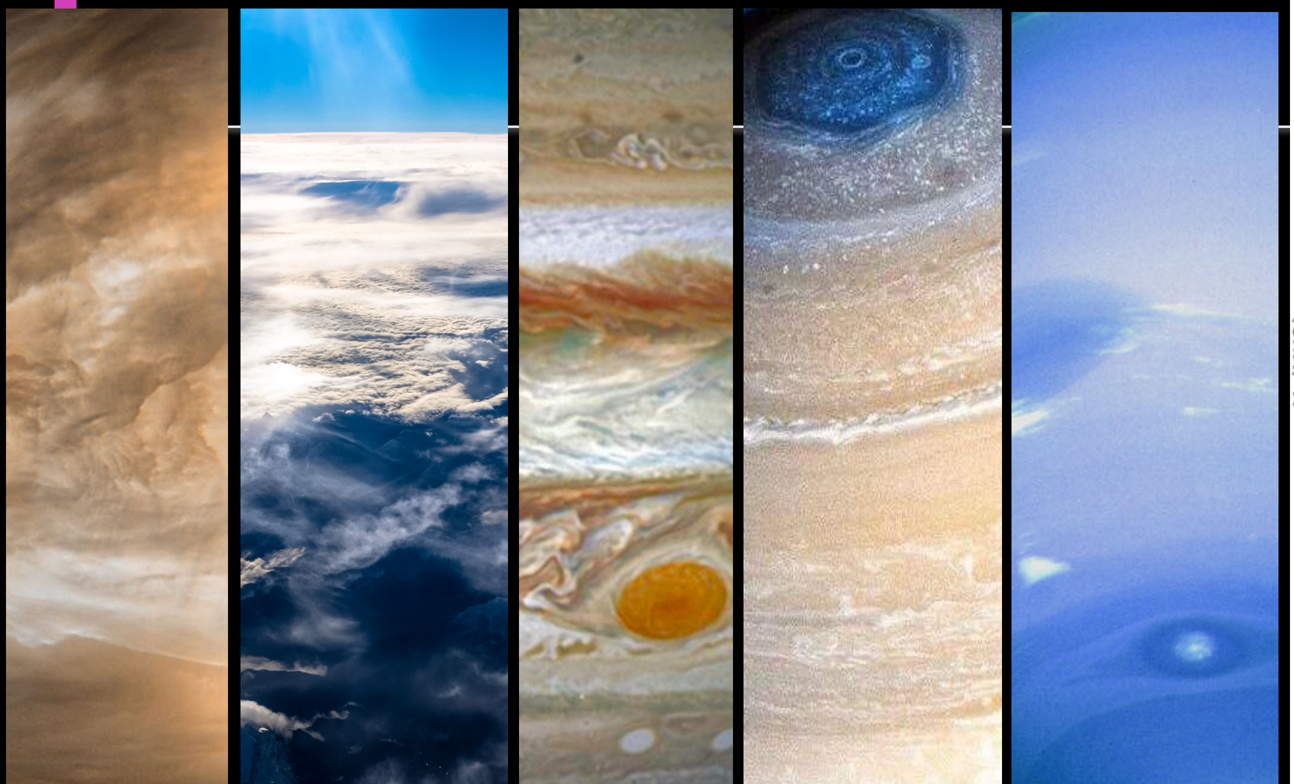
NHFP Symposium || 20 September 2024

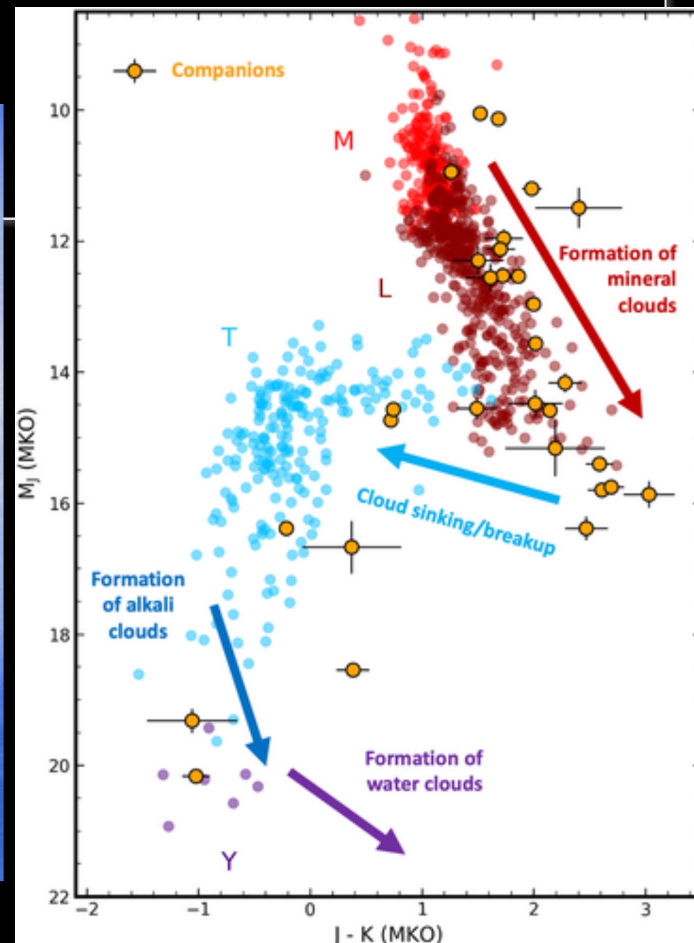
LPL

NASA Goddard

NHFP NASA Hubble Fellowship Program

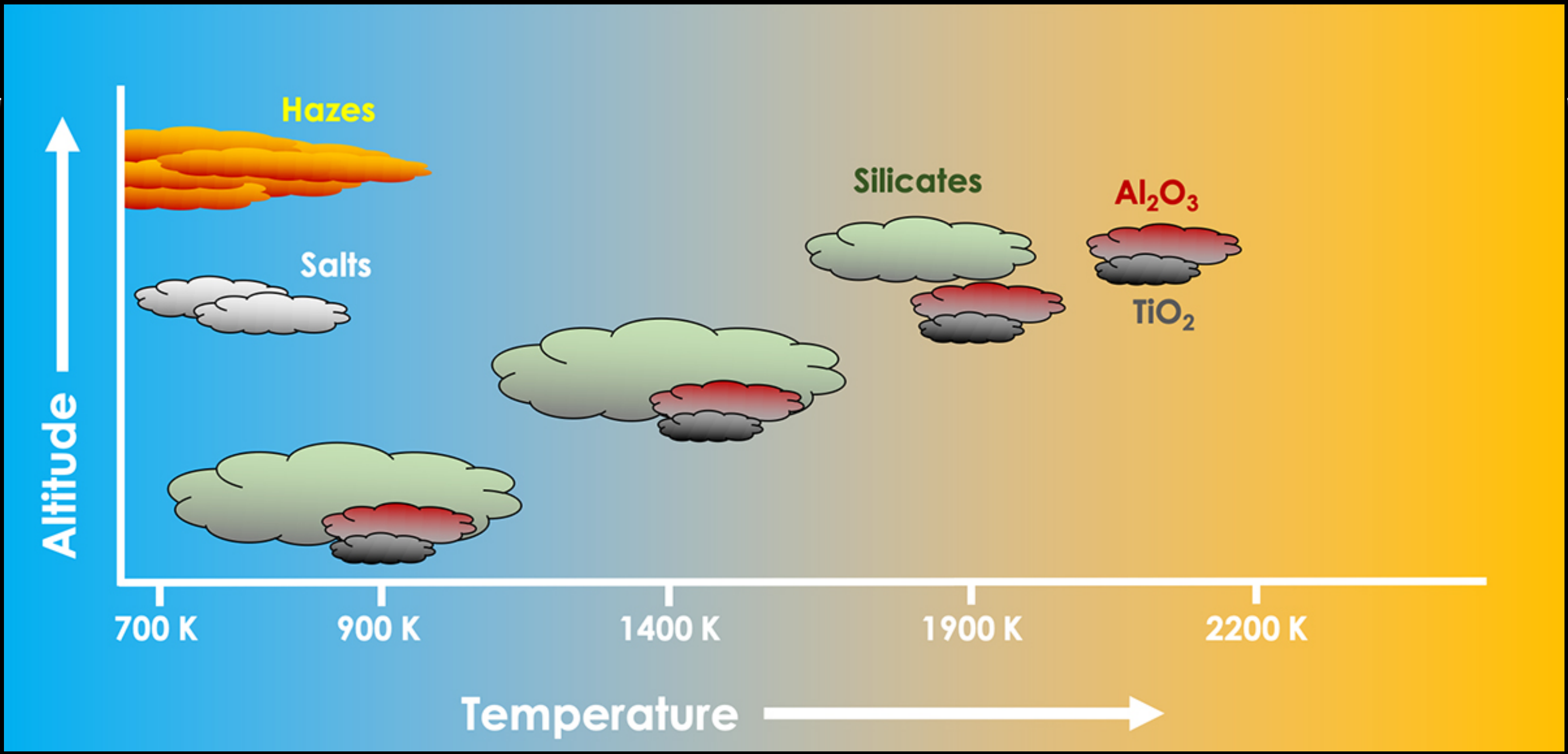
Clouds are a *fundamental* part of brown dwarf and planetary atmospheres





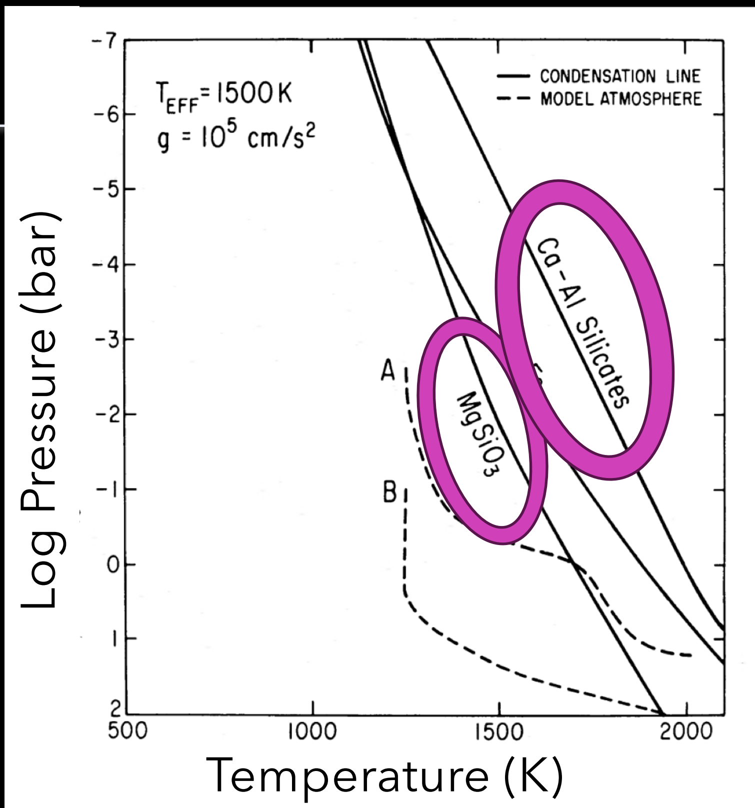
Gao, Wakeford, Moran, Parmentier, 2021

Clouds (and hazes) are **tracers** of the physics and chemistry of these atmospheres

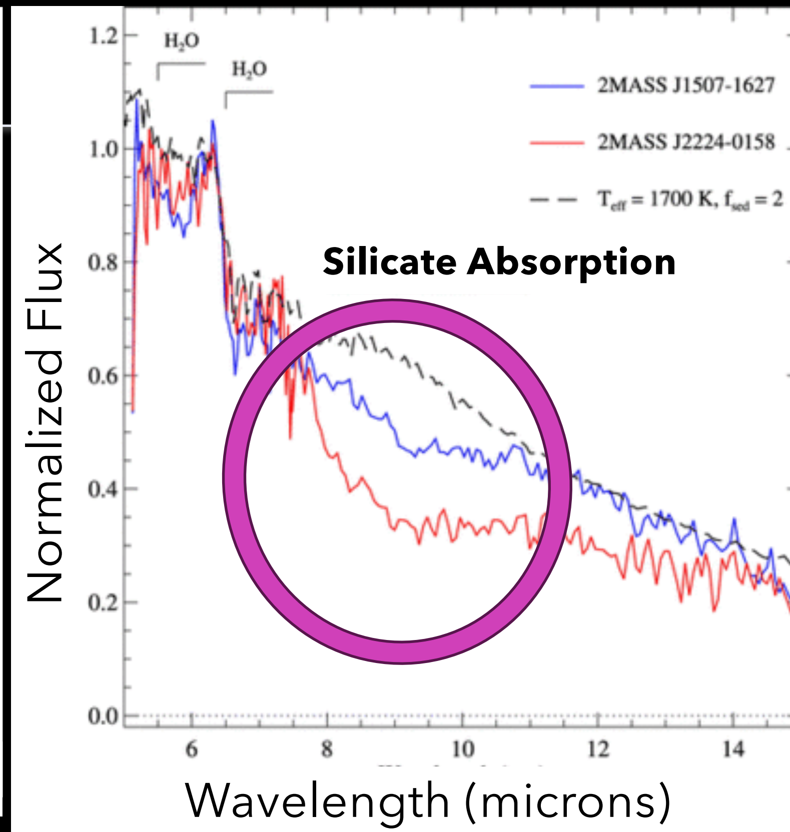


Gao et al., *NatAstro*, 2020

Spitzer **observationally confirmed** that brown dwarf clouds were made of silicates, long **predicted** by theory



Lunine, Hubbard, and Marley, *ApJ,* 1986

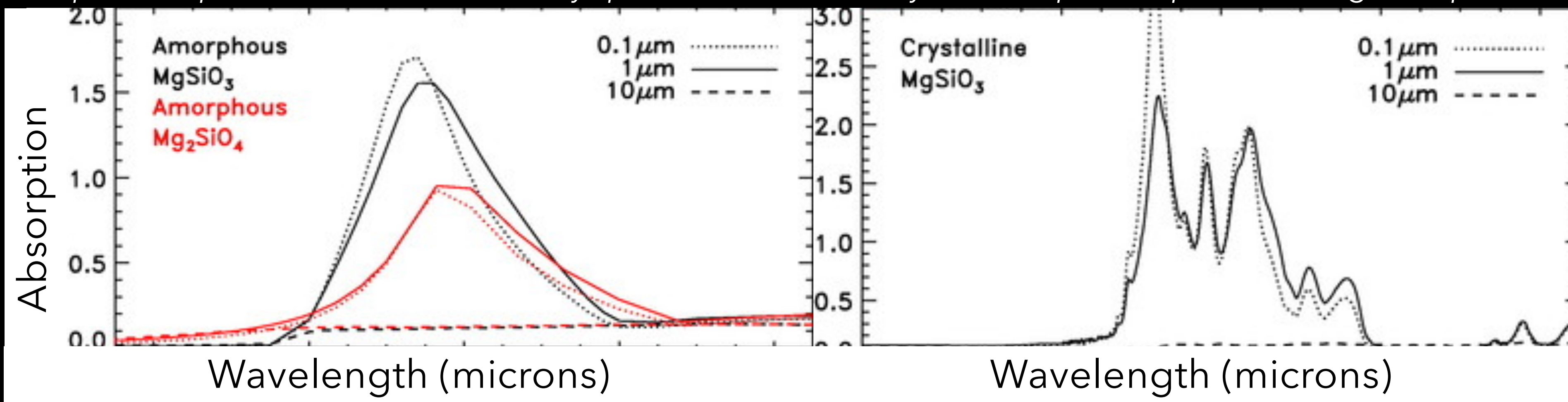


Burgasser et al., *ApJ,* 2008

Amorphous or crystalline particle structure reveals how these clouds formed

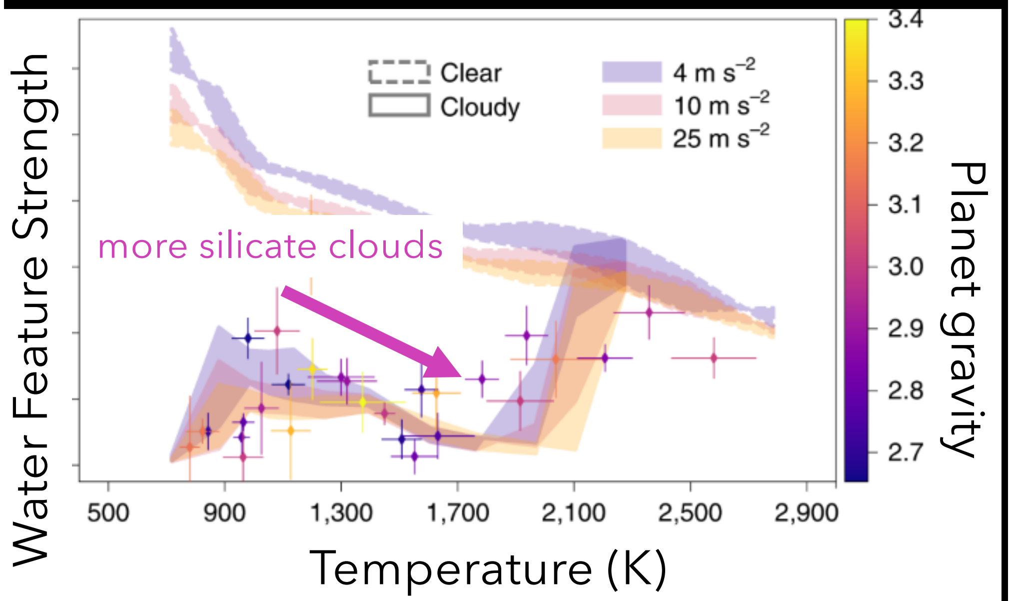
Amorphous = particles form, immediately quenched

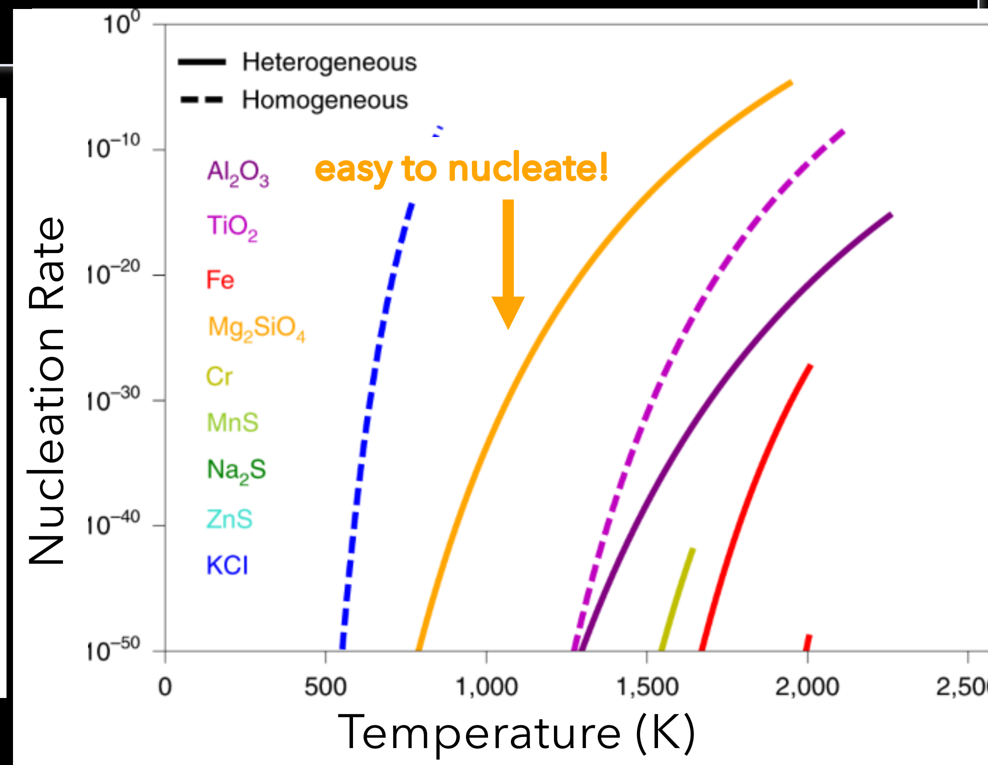
Crystalline= particle persists at high temperature



Cushing et al., *ApJ*, 2006

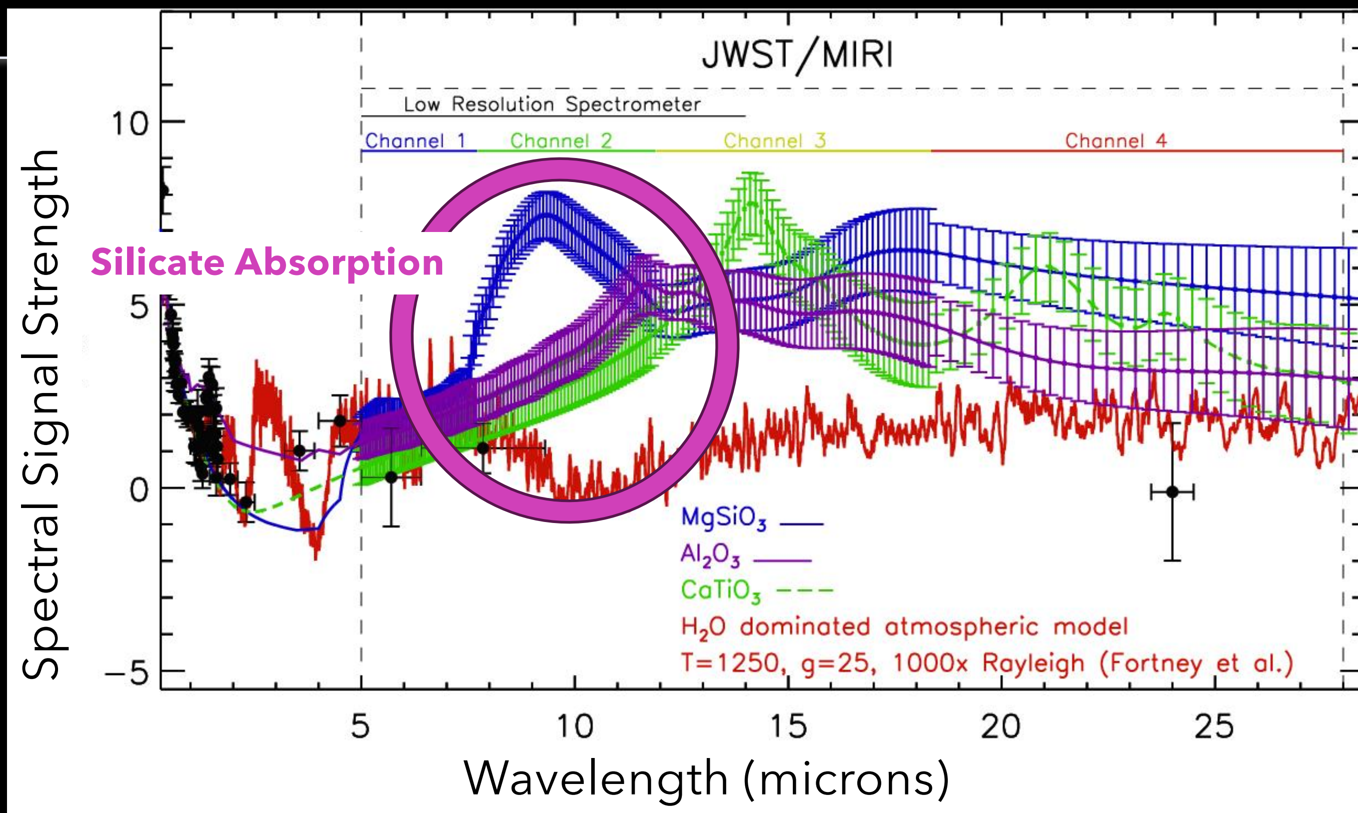
Surveys of hot Jupiters also suggest the dominance of silicate clouds





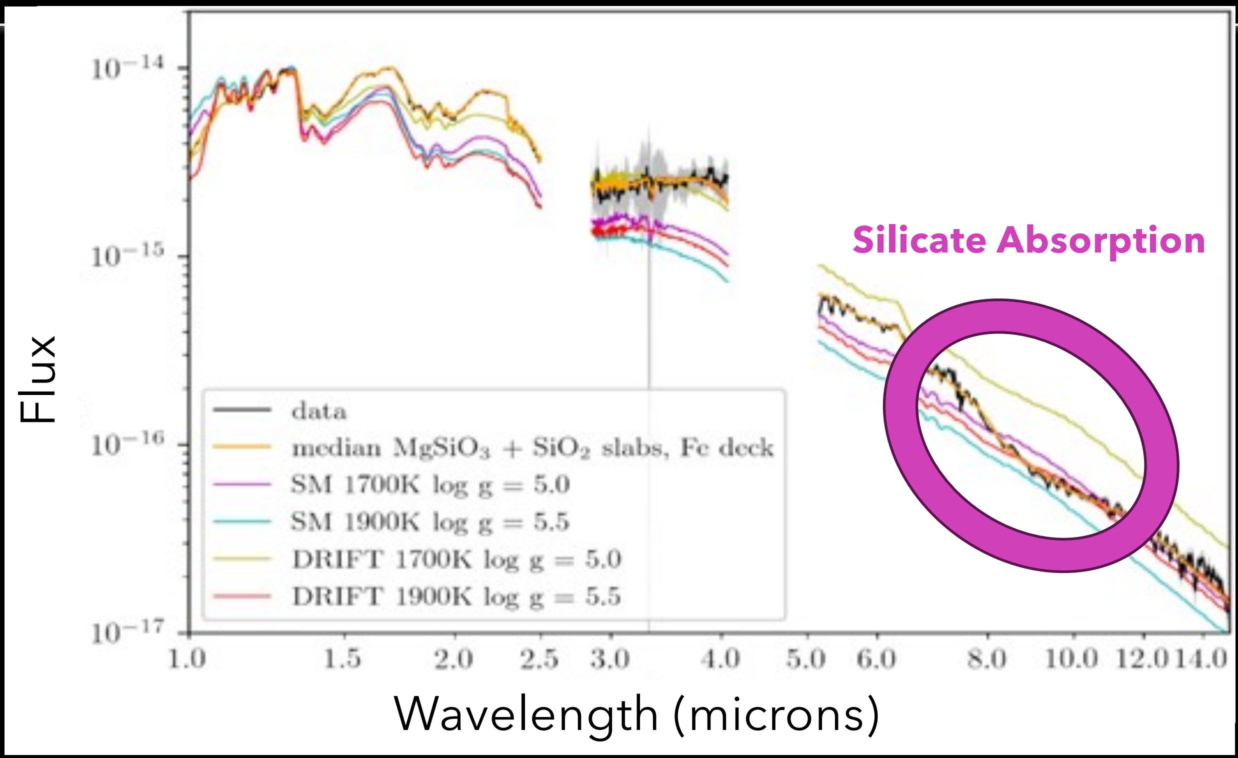
Gao et al., *Nature Astronomy*, 2020

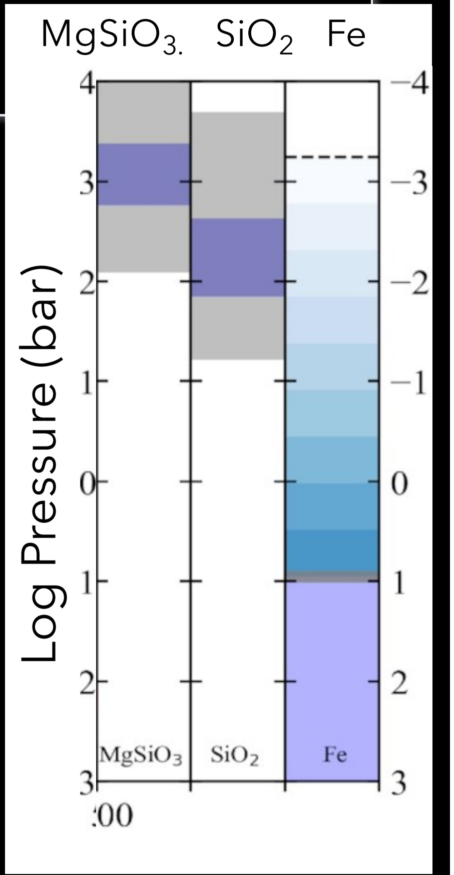
We had lost cooled Spitzer to confirm cloud identities…we needed JWST!



Wakeford & Sing, 2015

Amorphous **SiO_2**, not just $MgSiO_3$ or Mg_2SiO_4, is discovered in an L dwarf





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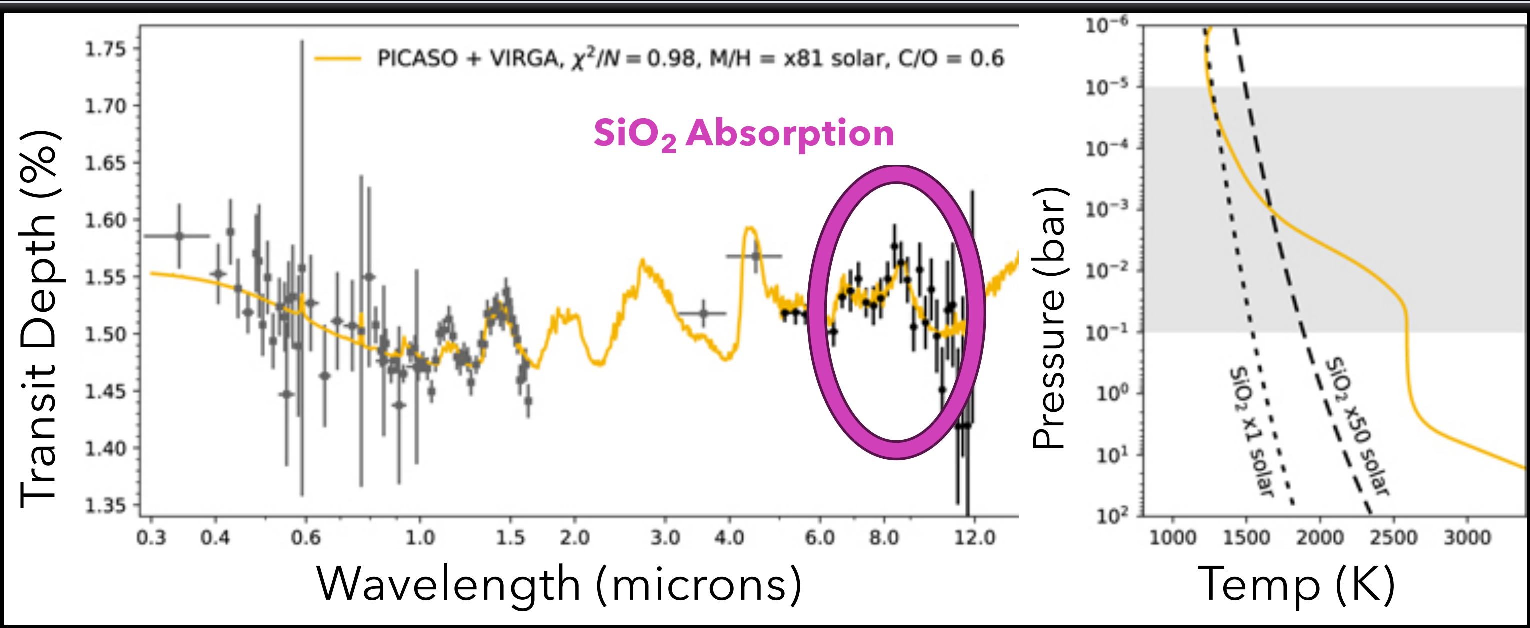
Burningham et al., *MNRAS*, 2021

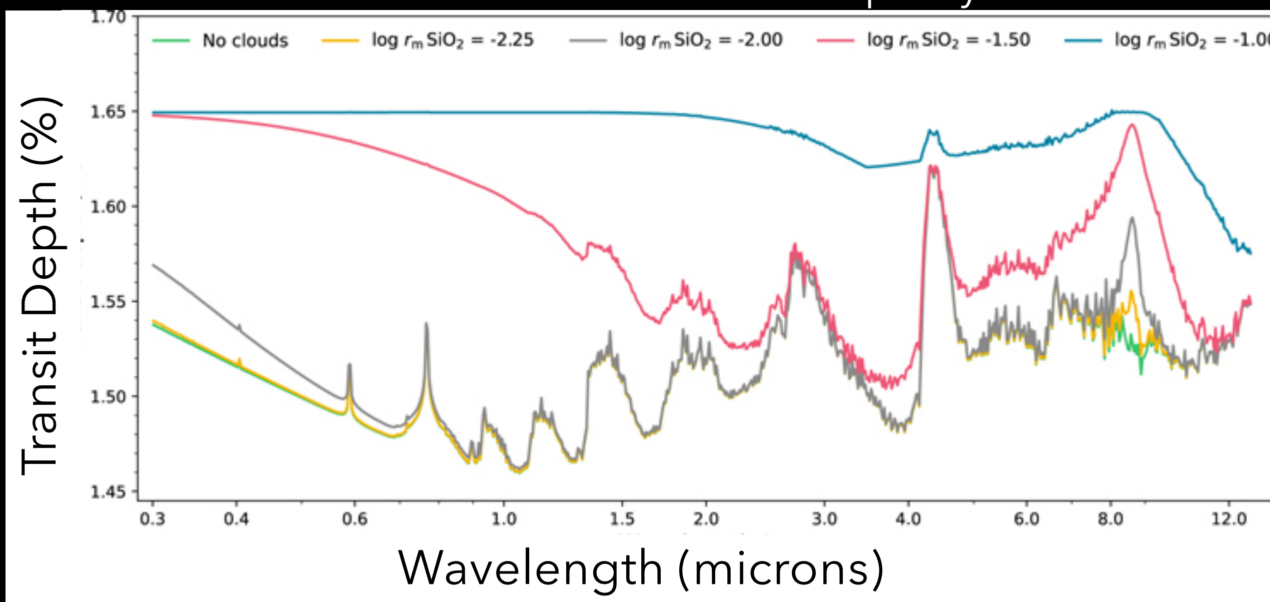
With JWST MIRI LRS, SiO_2 is discovered in the hot Jupiter WASP-17b

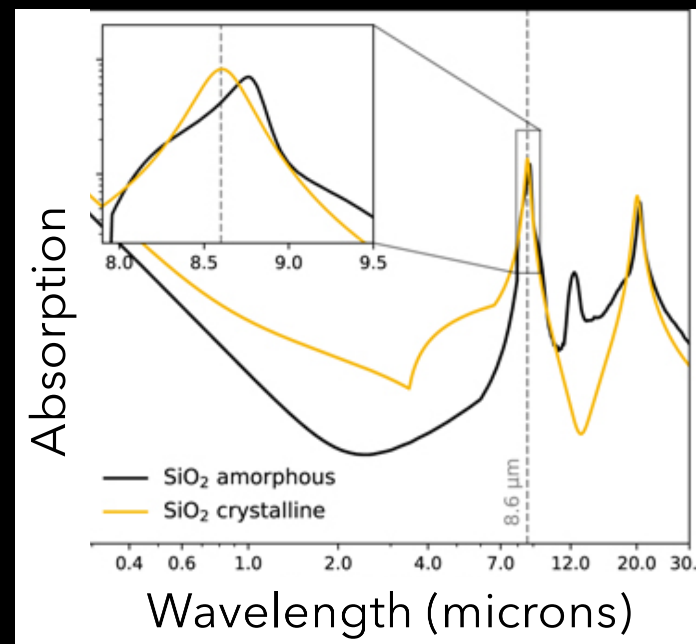


Grant et al., *ApJL* 2023

WASP-17b's SiO_2 clouds seem to be **crystalline**, not amorphous, with sub-micron sized particles

Particle size controls the opacity!





Grant et al., *ApJL* 2023

Cloud **composition** and **structure** are powerful atmospheric **tracers** of chemistry and physics

oxygen sequestration

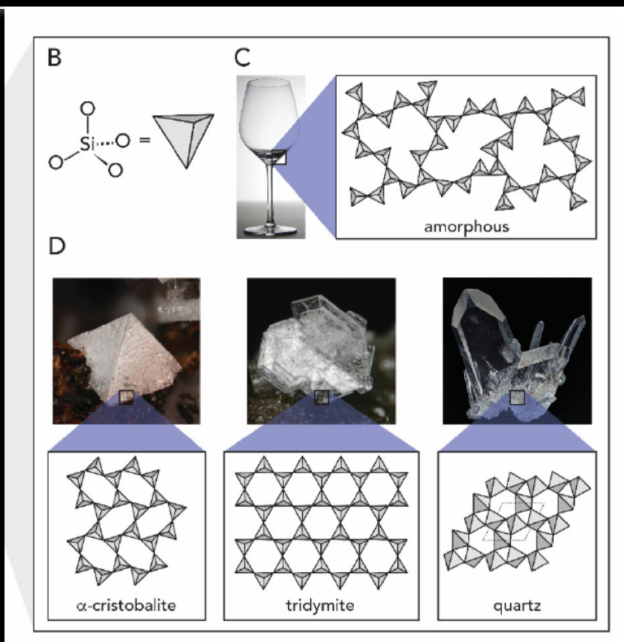
particle size, shape, and distribution

atmospheric temperature, mixing

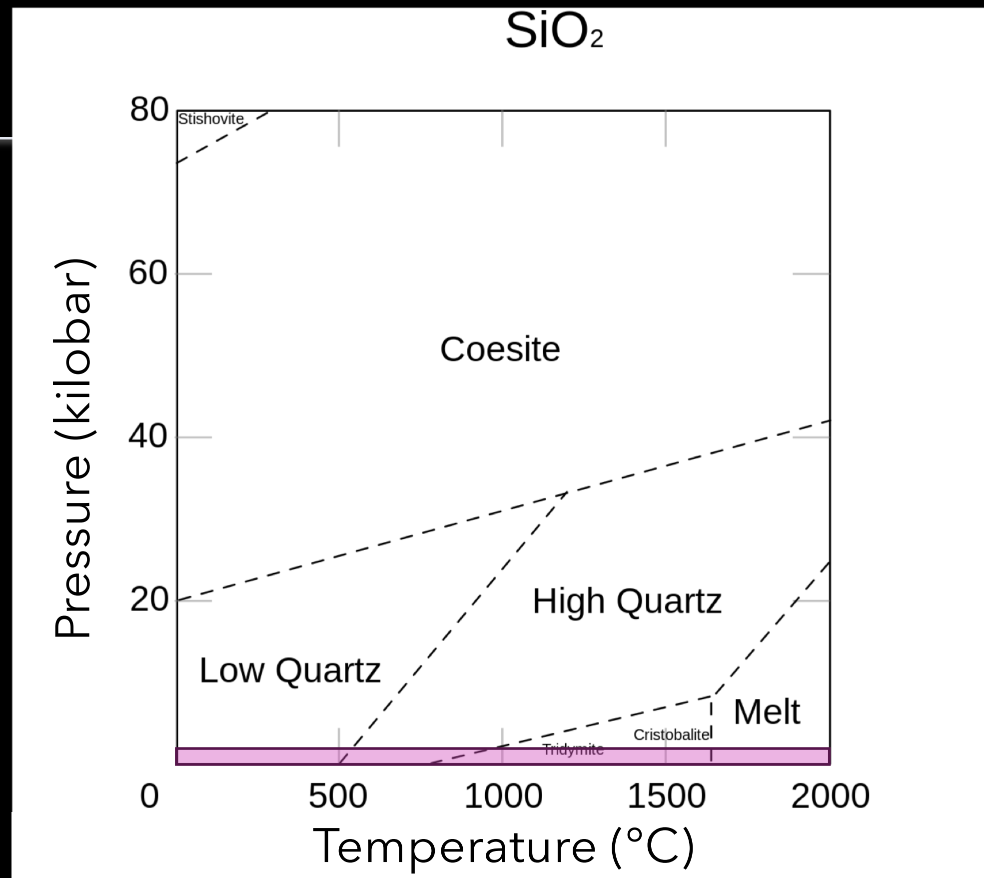
bulk composition of planet and host star

~But we can go deeper~

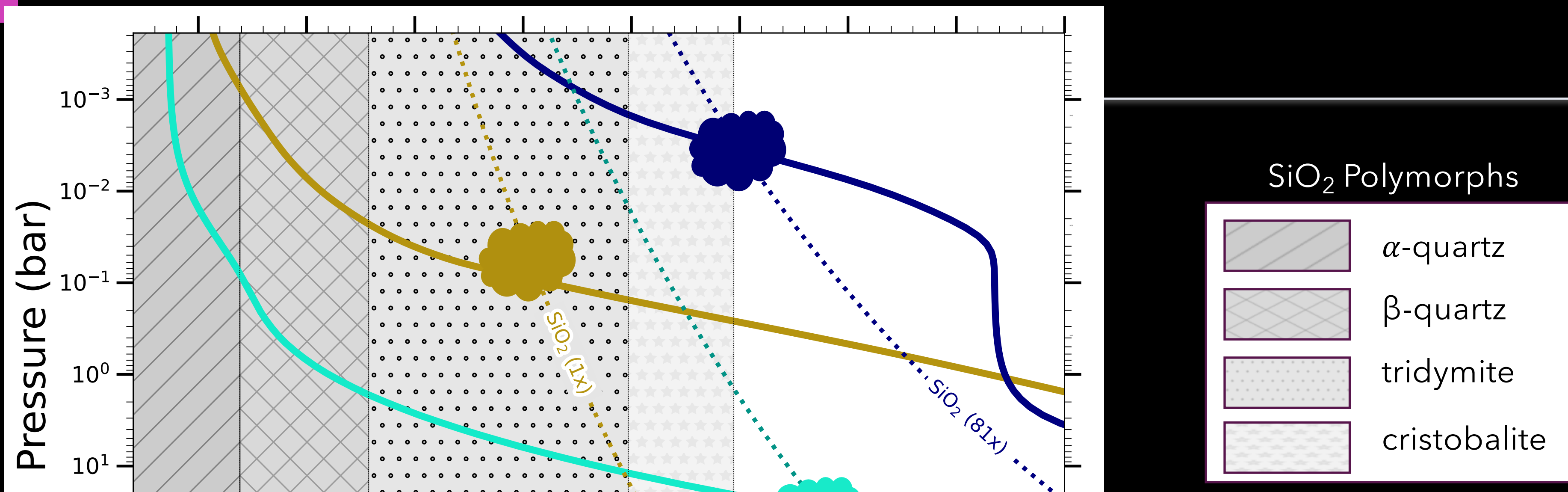
There are multiple stable **polymorphs** of SiO_2 at high temperature/low pressure conditions

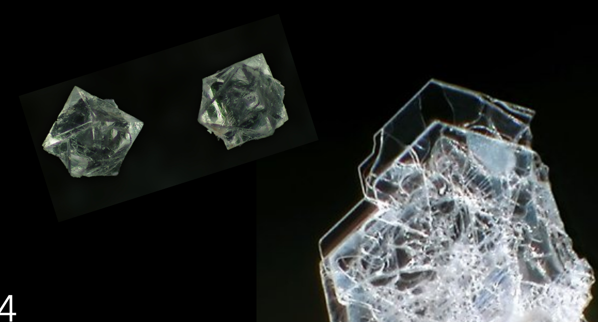


Moura et al., 2020, *Biomimetics*



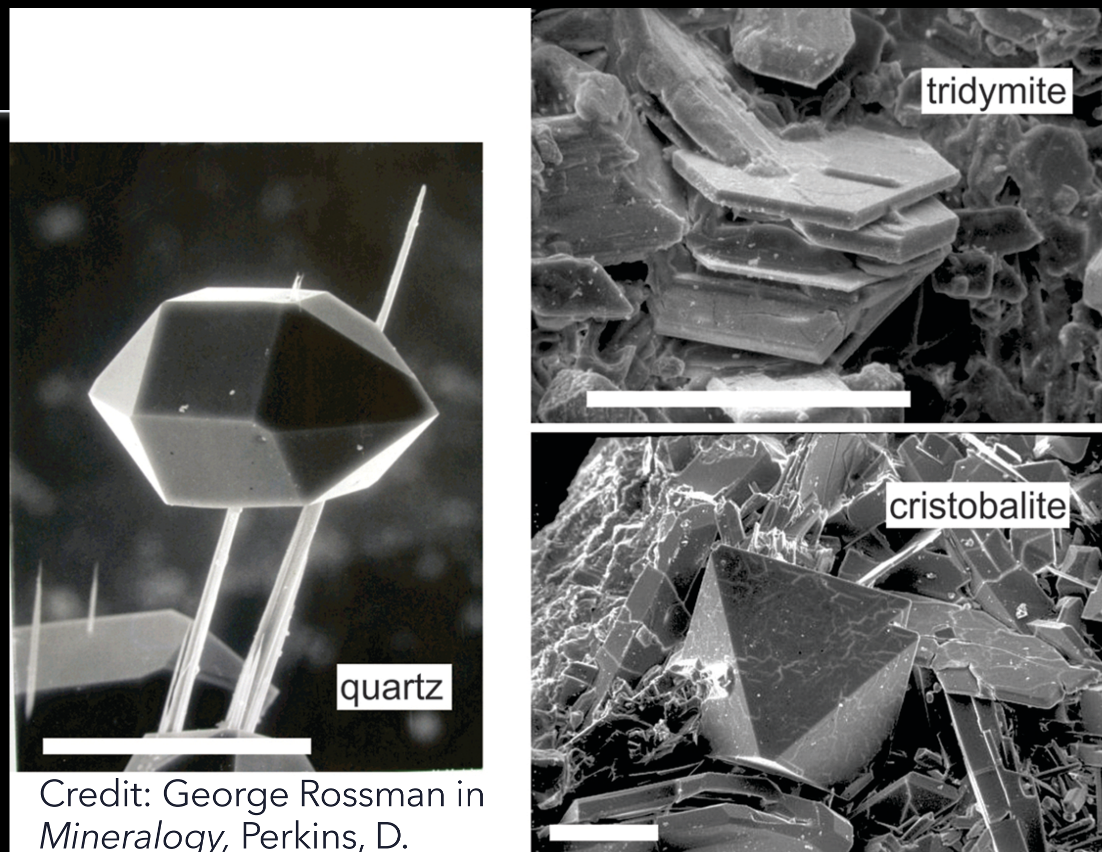
There are multiple stable **polymorphs** of SiO_2 at high temperature/low pressure conditions





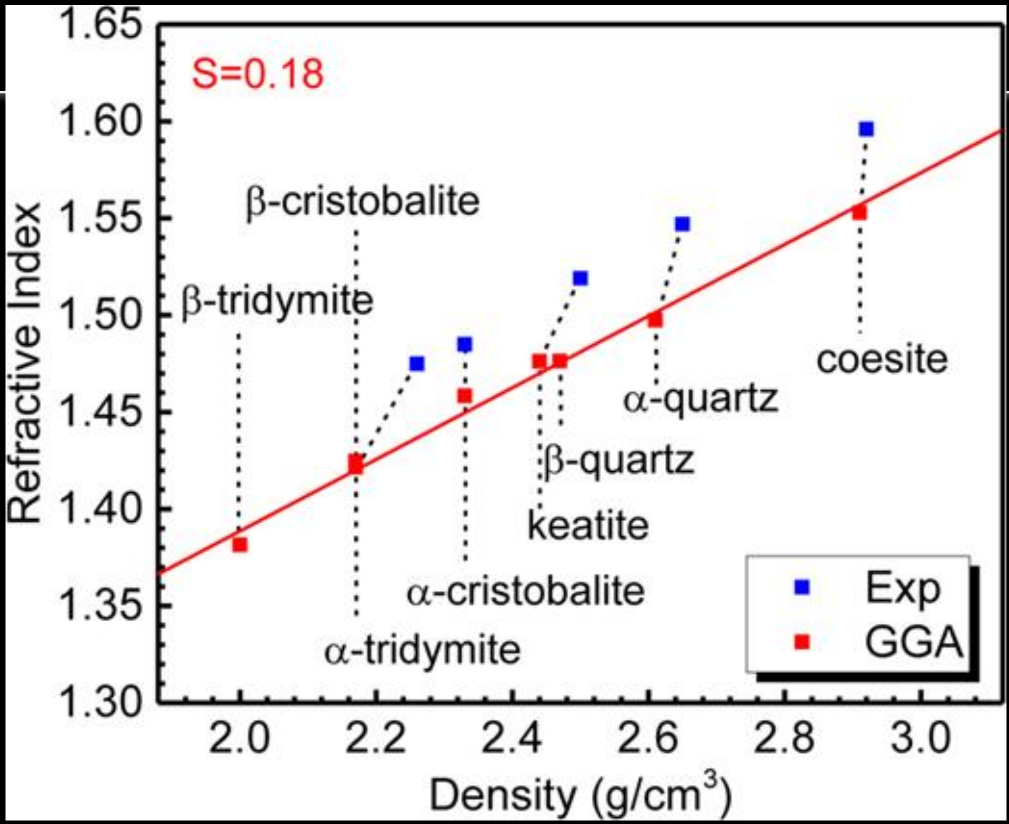
Moran, Marley, & Crossley, *ApJL*, 2024

Different crystal structure means different bond lengths, arrangements, and energies



Credit: George Rossman in *Mineralogy*, Perkins, D.

These polymorphs of SiO_2 have different physical and optical properties



Chen et al., *J. Appl. Phys.*, 2023

Do cristobalite and tridymite cloud particles influence substellar atmospheric spectra?

Cloud Model

VIRGA

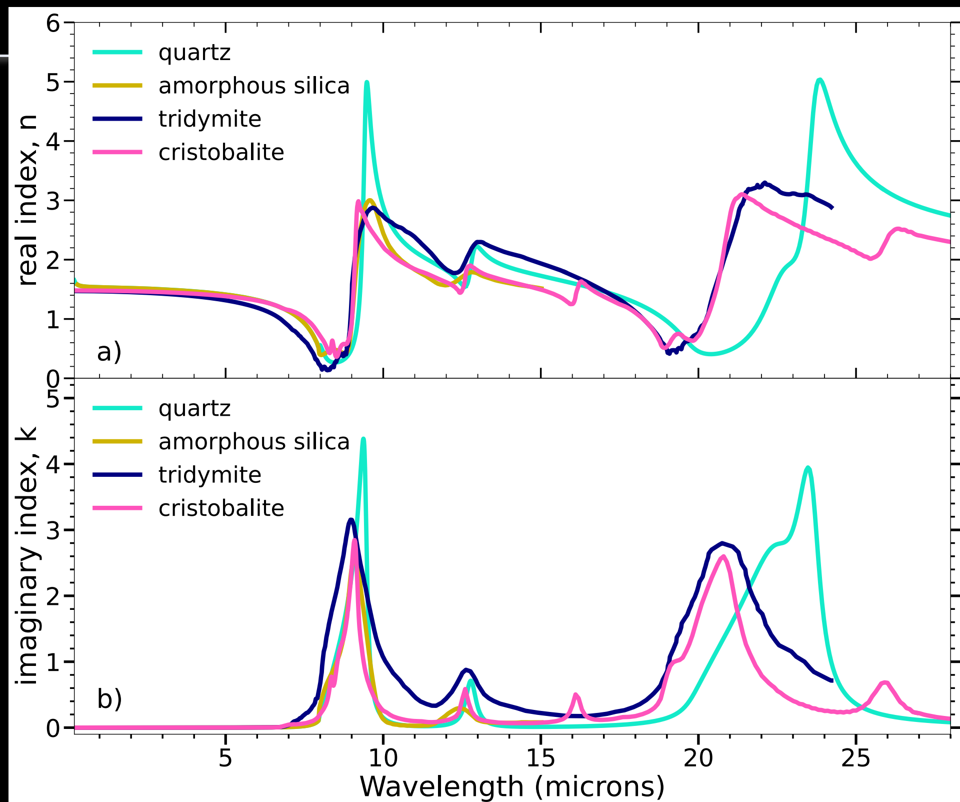
Batalha et al., 2020; Rooney et al., 2022
based on Ackerman and Marley, 2001

Climate, chemistry, radiative transfer

PICASO

Batalha et al., 2019; Mukherjee et al., 2023
based on Marley et al., 1996

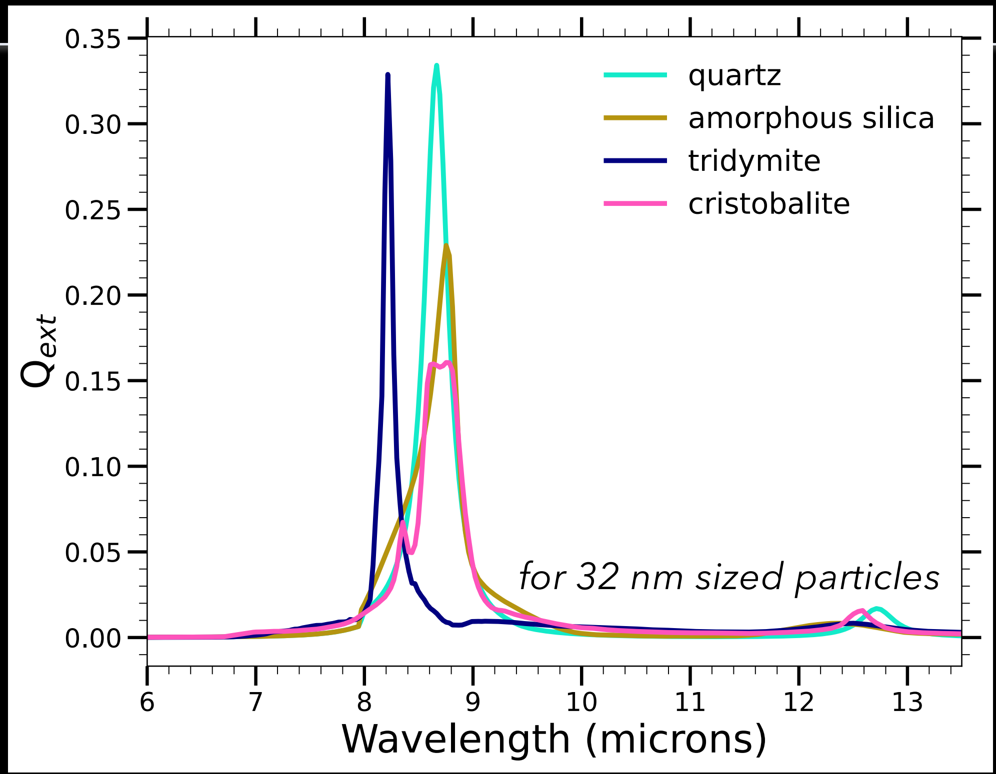
With the available data**, we compile a set of optical properties for tridymite and cristobalite



** ask me to expand on this if you want a rant on the state of mineral laboratory data

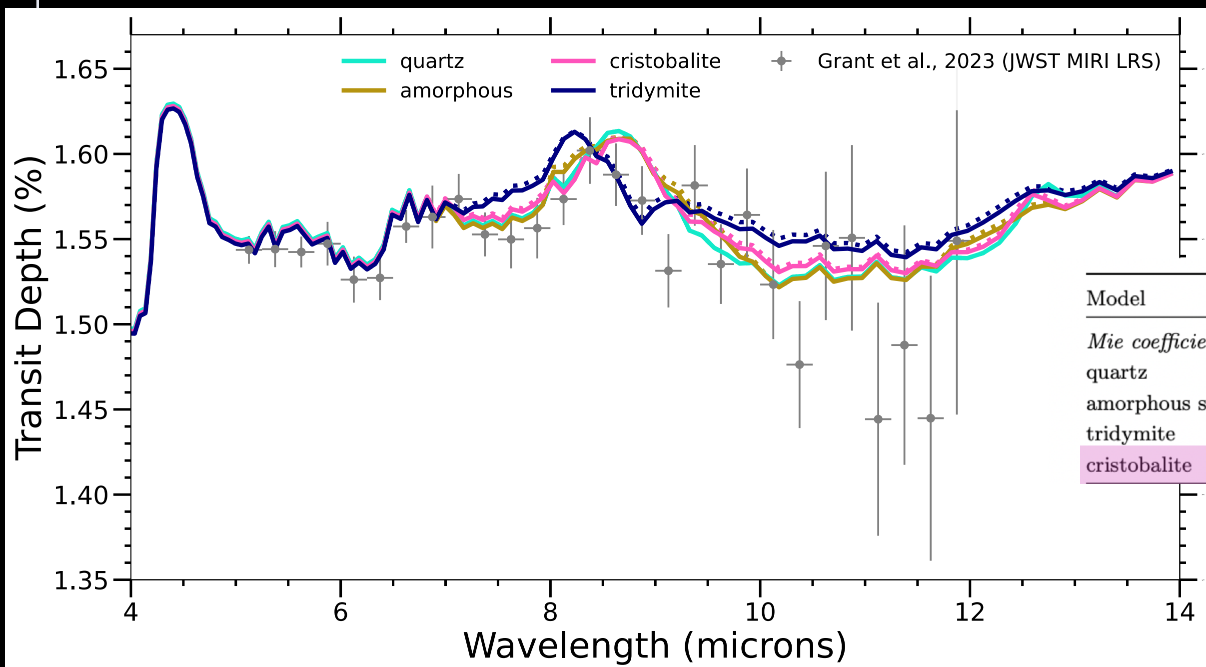
Moran, Marley, Crossley, *ApJL,* 2024

Mie coefficients are noticeably different at JWST MIRI wavelengths for the various SiO_2 polymorphs



Moran, Marley, Crossley, *ApJL*, 2024

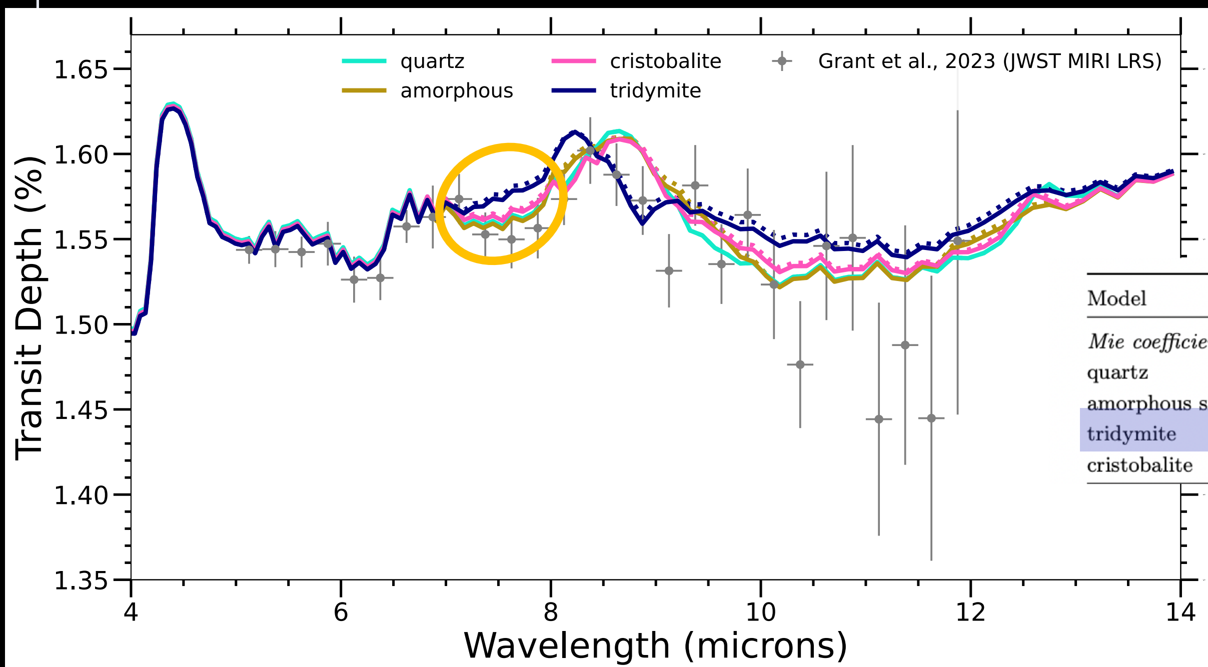
Cristobalite clouds **are a better fit** to the WASP-17 b JWST data compared to either quartz or amorphous silica



Model	χ^2	χ^2/n	BIC	ΔBIC
Mie coefficients, BIC k = 1, n = 95, dof = 94				
quartz	126.3	1.330	130.9	0.6
amorphous silica	126.0	1.327	130.6	0.3
tridymite	131.0	1.379**	135.6	5.3
cristobalite	125.7	1.323	130.3	–

Moran, Marley, Crossley, *ApJL*, 2024

Tridymite clouds **are *not* a better fit**** to the WASP-17 b JWST data compared to either quartz or amorphous silica



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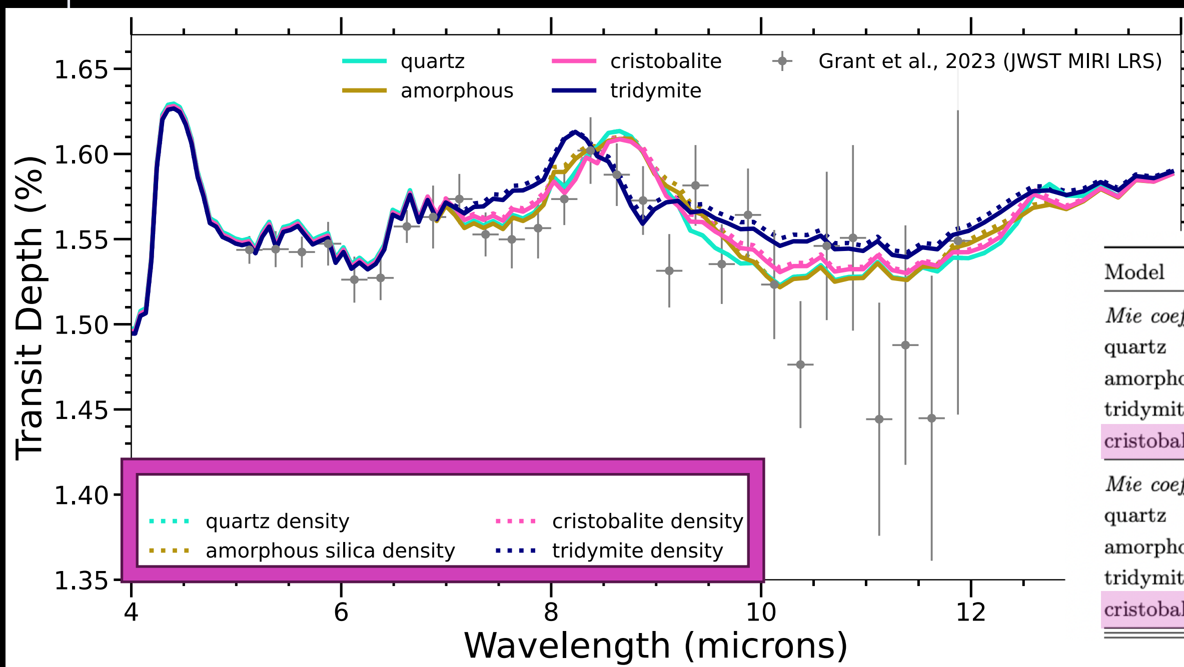
Moran, Marley, Crossley, *ApJL*, 2024

**But! The region that causes the bad fit is right where we had to do the most egregious stitching and scaling of the old lab data….

Density differences in silica polymorph particles cause further divergences but **very minorly**



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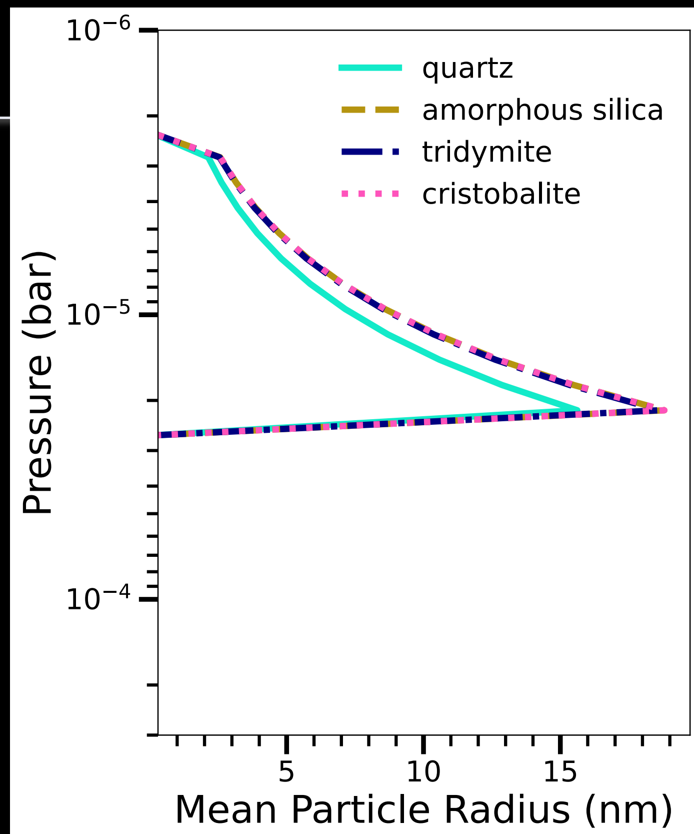
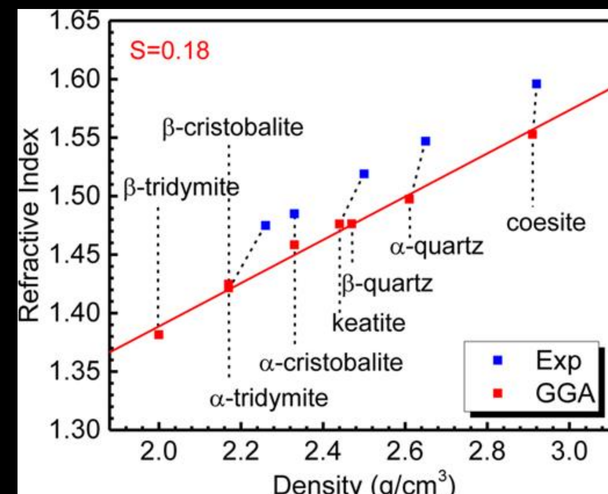
amorphous silica	126.0	1.327	130.6	0.3
tridymite	131.0	1.379**	135.6	5.3
cristobalite	125.7	1.323	130.3	–
Mie coefficients and density, BIC k = 2, n = 95, dof = 93				
quartz	126.3	1.330	135.4	5.1
amorphous silica	125.4	1.320	134.5	4.2
tridymite	131.9	1.389	141.0	10.1
cristobalite	125.2	1.318	134.3	4.0

Moran, Marley, Crossley, *ApJL*, 2024

Polymorph densities aren't different enough to drastically change the particle size distributions

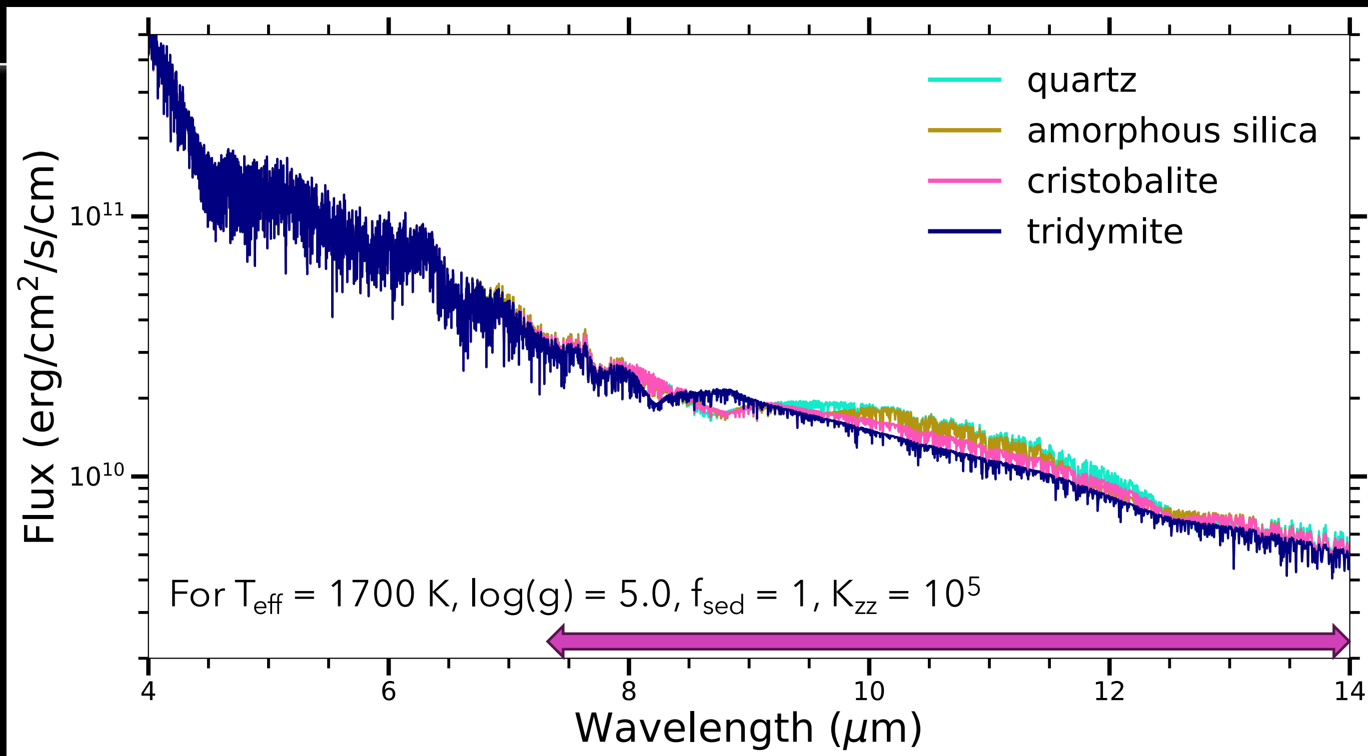


Moran, Marley, & Crossley, *ApJL*, 2024



Chen et al., *J. Appl. Phys.*, 2023

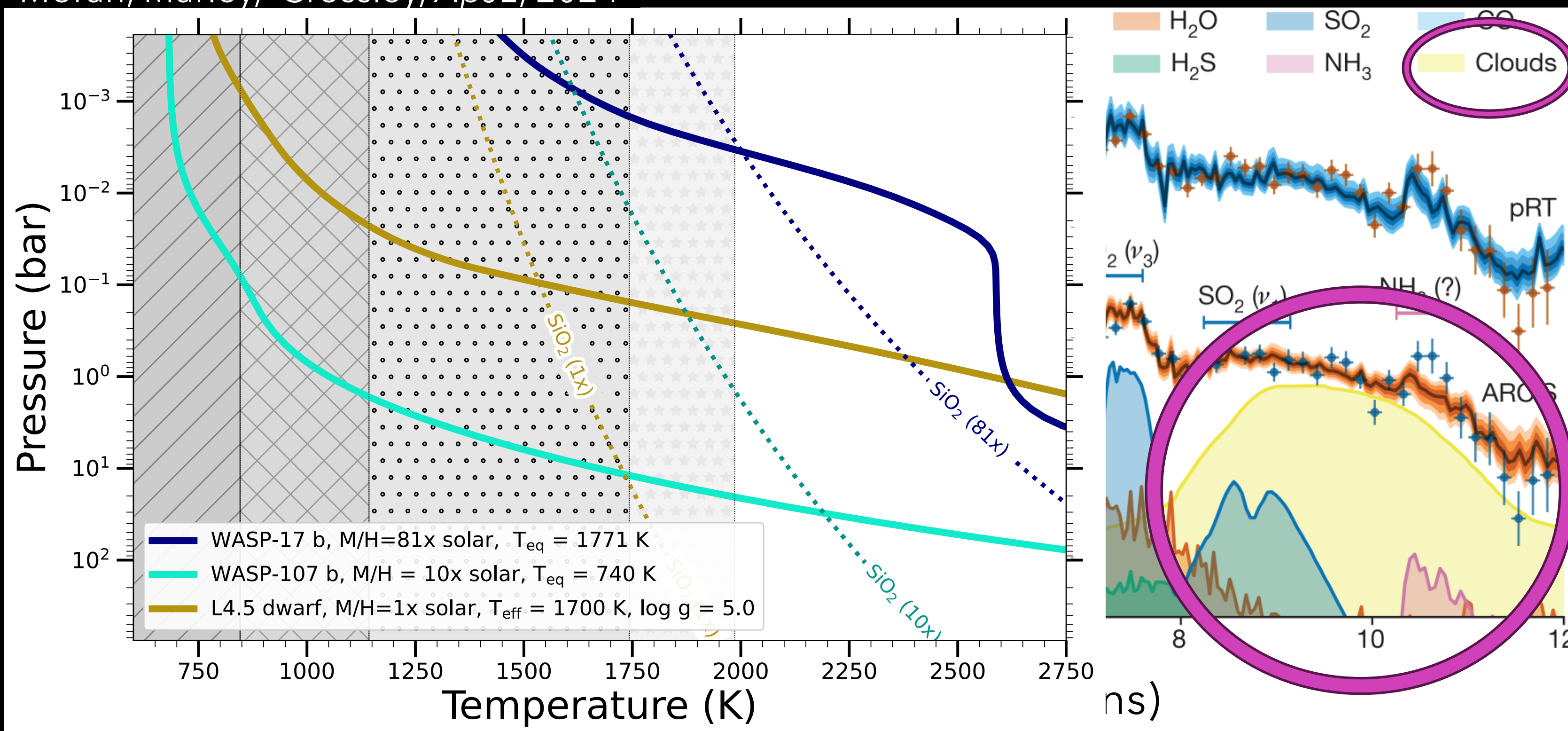
For a "typical" L-dwarf, cristobalite and tridymite particles affect emission spectra at JWST wavelengths if particle size distributions are narrow



Moran, Marley, & Crossley, *ApJL*, 2024

Case study: WASP-107 b and liquid, crystal, or amorphous cloud particles

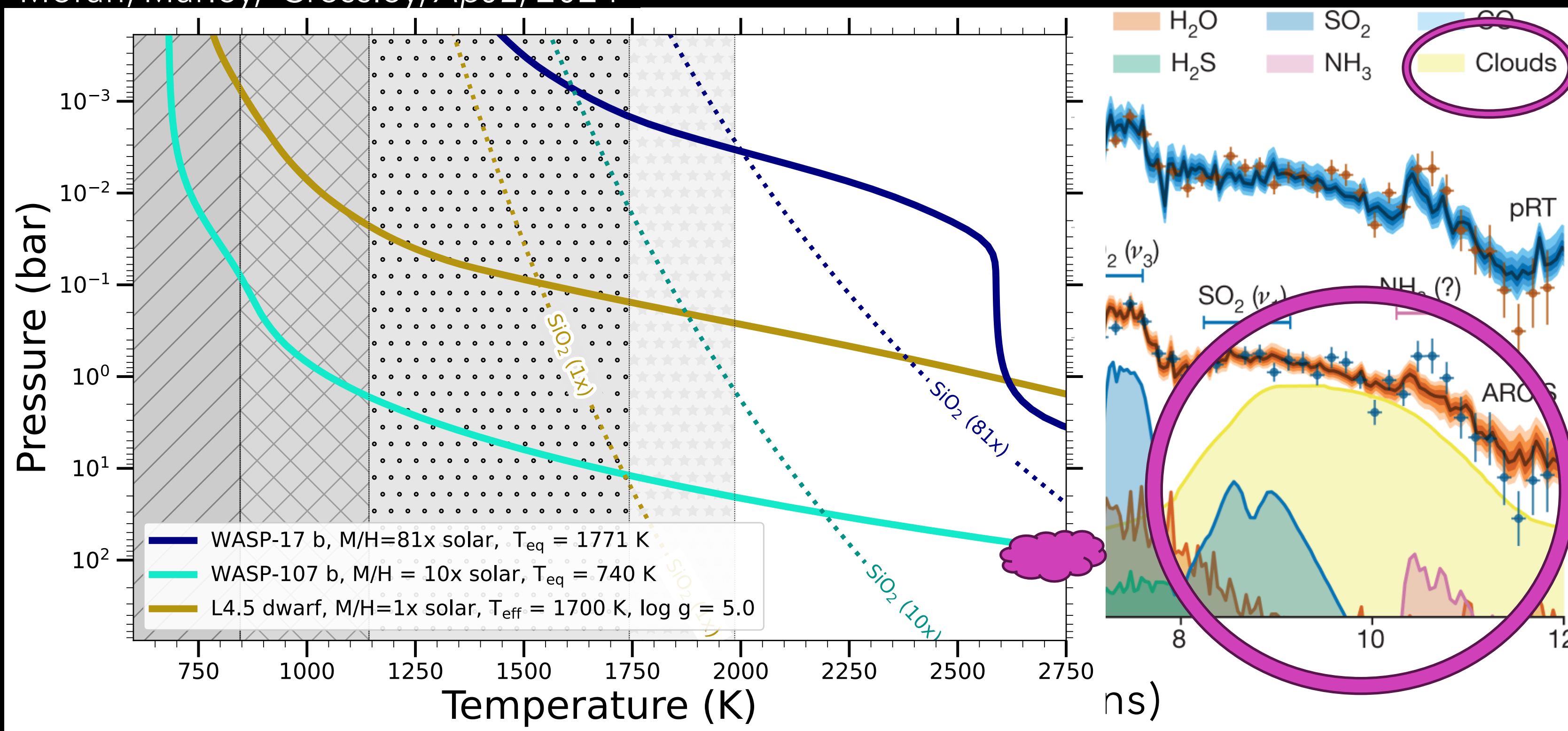
Moran, Marley, Crossley, *ApJL*, 2024



Dyrek et al., *Nature*, 2024

Case study: WASP-107 b and liquid, crystal, or amorphous cloud particles

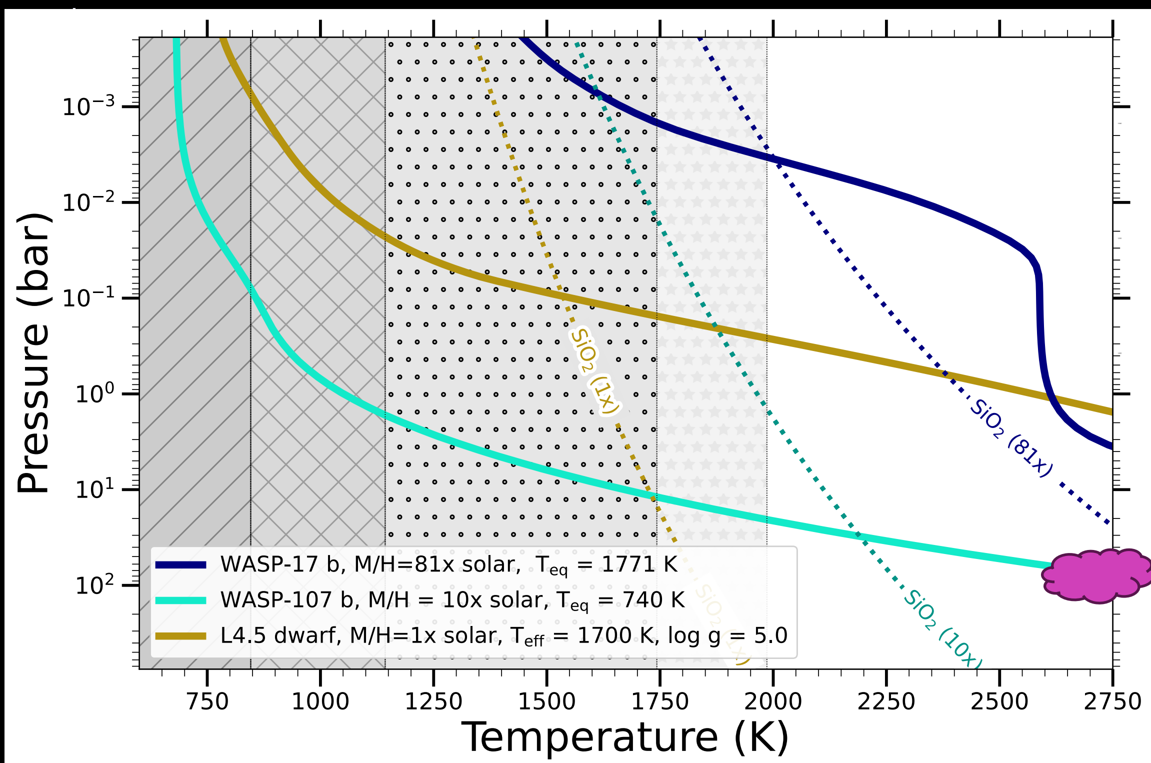
Moran, Marley, Crossley, *ApJL*, 2024



Dyrek et al., *Nature*, 2024

Case study: WASP-107 b and liquid, crystal, or amorphous cloud particles

Moran, Marley, Crossley, *ApJL*, 2024



$$\tau_{dyn} \approx \frac{H}{K_{zz}}$$

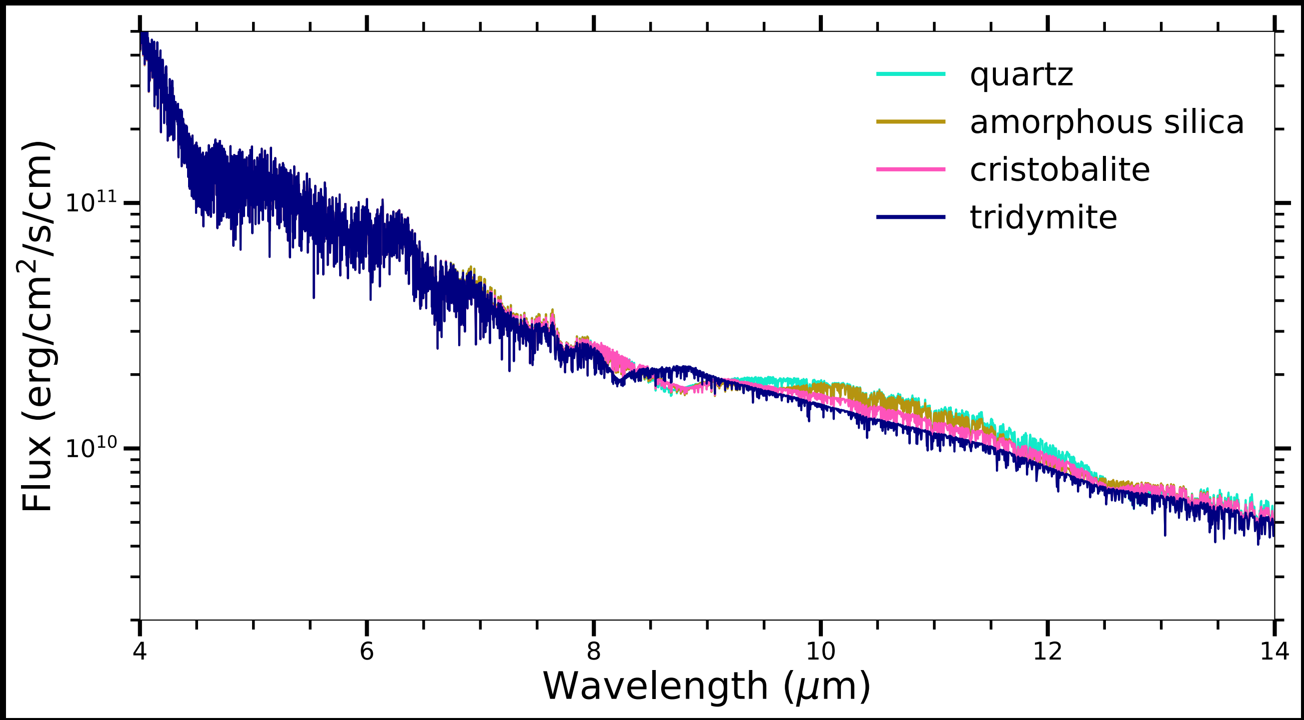
H = 800 km, $K_{zz} = 10^{12}$ cm/s^2

τ_{dyn} = 1.3×10^4 s = 3.5 hours

→ particle speed = 220 km/h
(Cat 4 hurricane, straight up!)

30 bars to 1 mbar = 10 scale heights
→ 40ish hours for our cloud to rise!

Mixed crystal phase clouds are thus likely for a variety of atmospheres… potentially explaining amorphous signatures?



Moran, Marley, & Crossley, *ApJL* 2024

An abbreviated list of things I think this impacts…

1. Lab work needed to refine all this!
2. Lava worlds…
3. Other mineral polymorphs…!
4. Global circulation models and atmospheric dynamics…

Takeaways

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SiO_2 discoveries and JWST have ushered in a **new era** of (silicate) cloud studies

Accounting for **polymorphs** takes clouds a tracers of physics and chemistry to a new level

One of the more stable phases of SiO_2 at WASP-17b conditions better matches **JWST data**

There's a lot of exciting **experimental, theoretical, and observational follow-up** here

→ We are proposing a silicate condensation sequence based not just in chemistry, but also in **mineralogy**