Linking Laboratory Data to Atmospheric Models from the Solar System to Exoplanets

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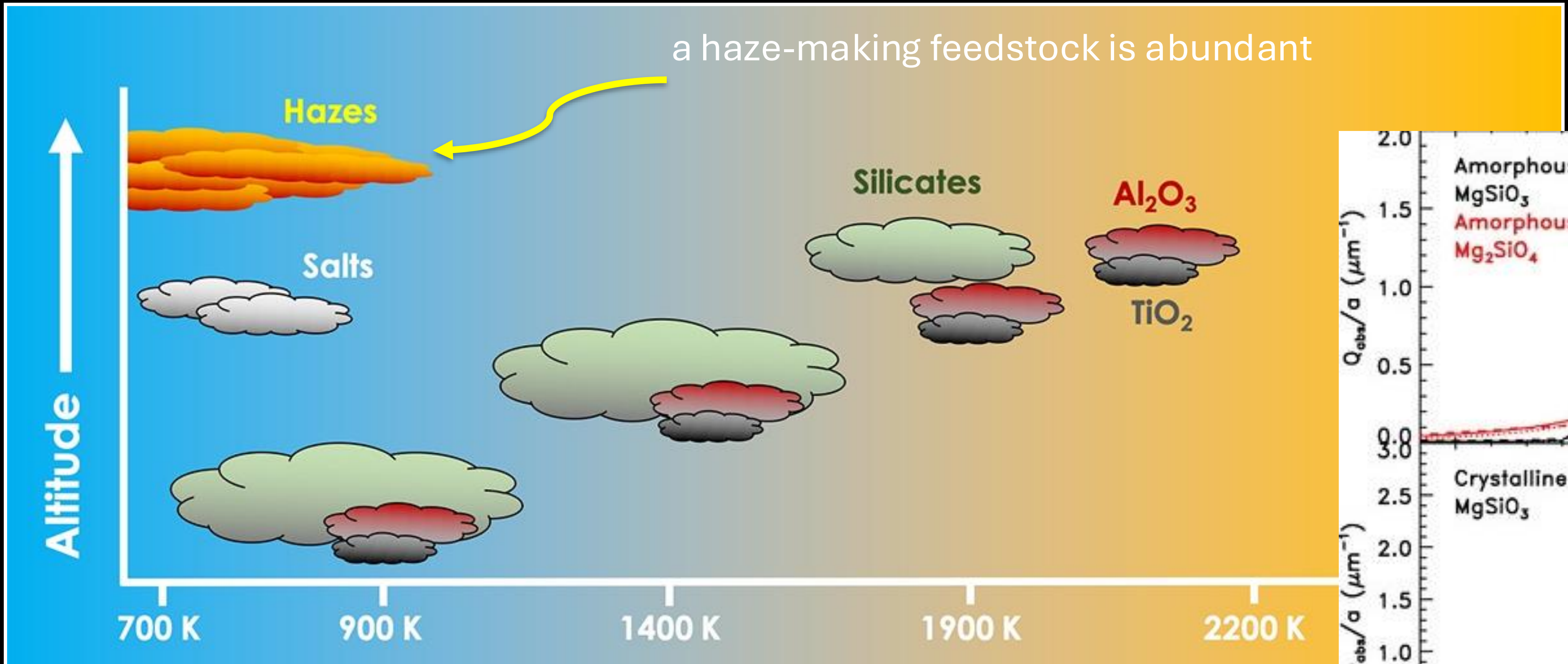
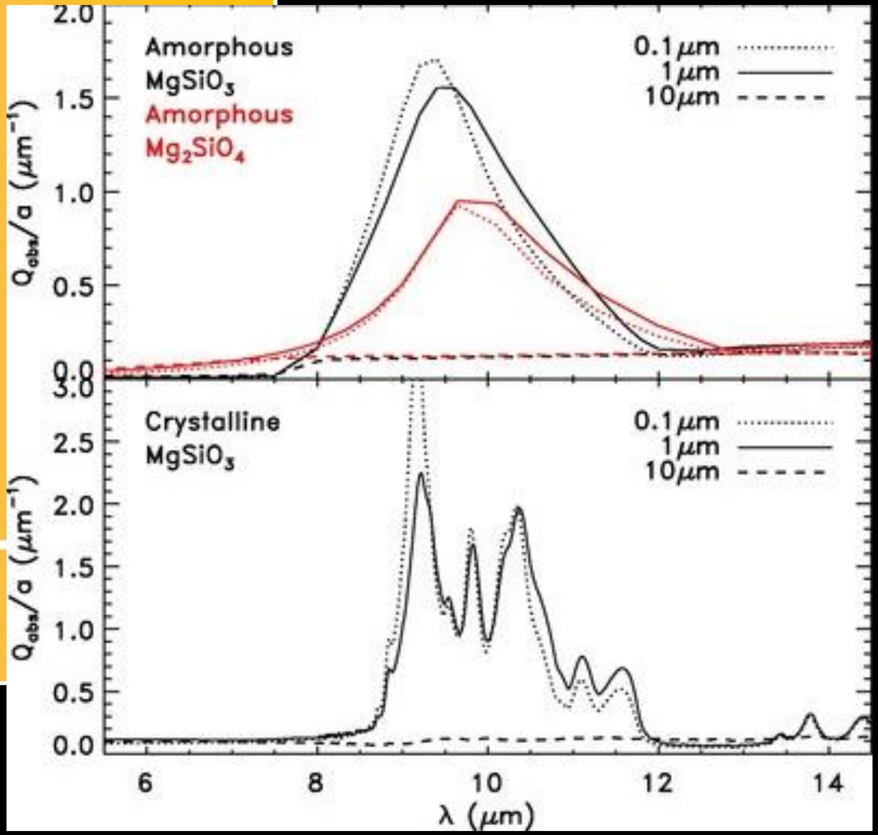
Clouds (and hazes) are a fundamental part of atmospheres whose compositions and morphologies trace **temperature** and **chemical** formation conditions



Gao et al. *Nature Astronomy*, 2020

← many hundreds of degrees this way to solar system worlds

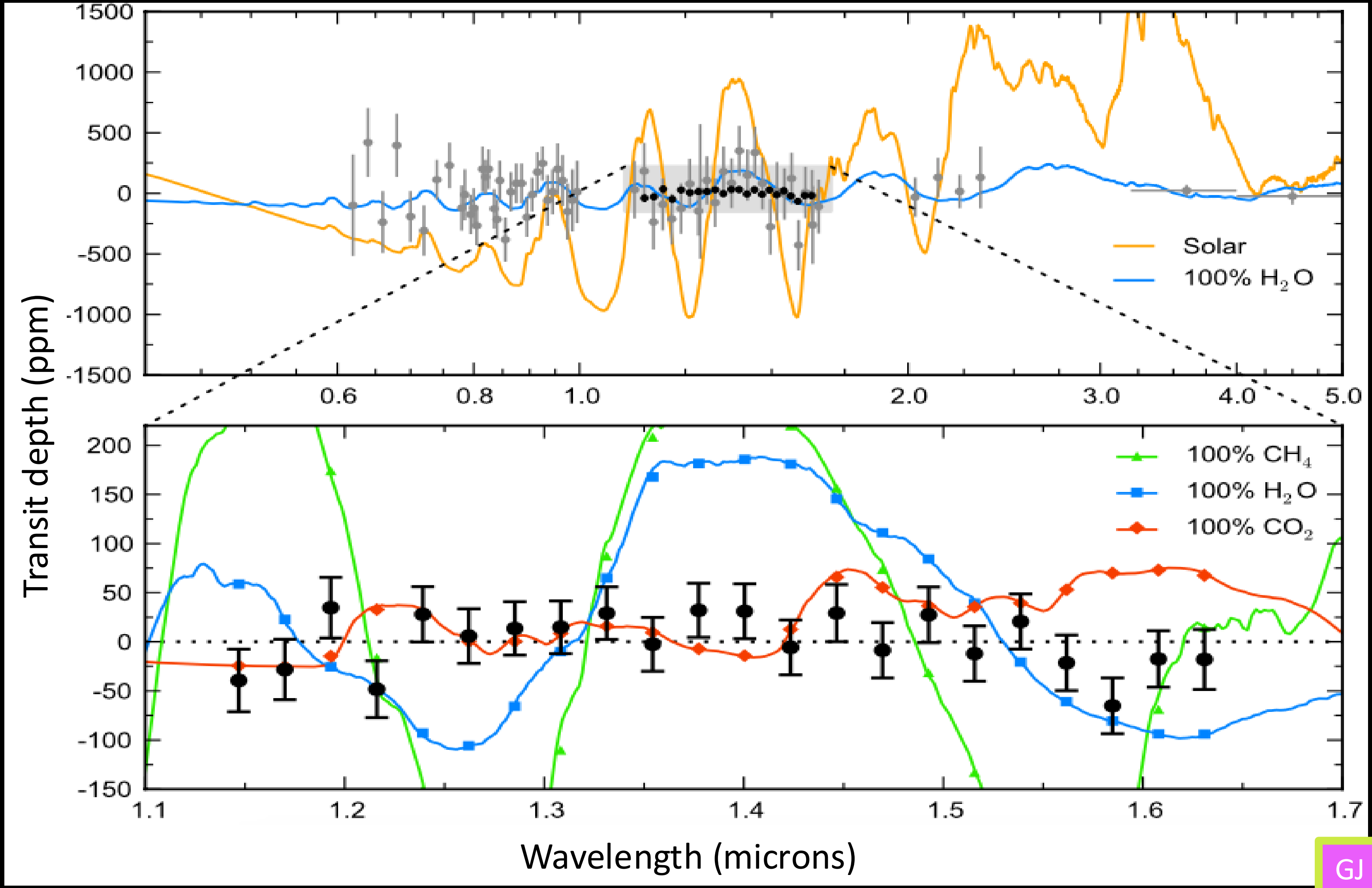
"Quenched", i.e., condensed and supercooled **rapidly**



Crystallized, i.e., condensed and cooled **slowly**

Cushing et al., *ApJ*, 2006

Clouds or hazes are some of the possibilities for our inability to see anything in some exoplanet atmosphere observations with telescope observations…



Kreidberg et al., *Nature*, 2014

GJ 1214b – a warm sub-Neptune (500K; 2.7 $R_\oplus$)

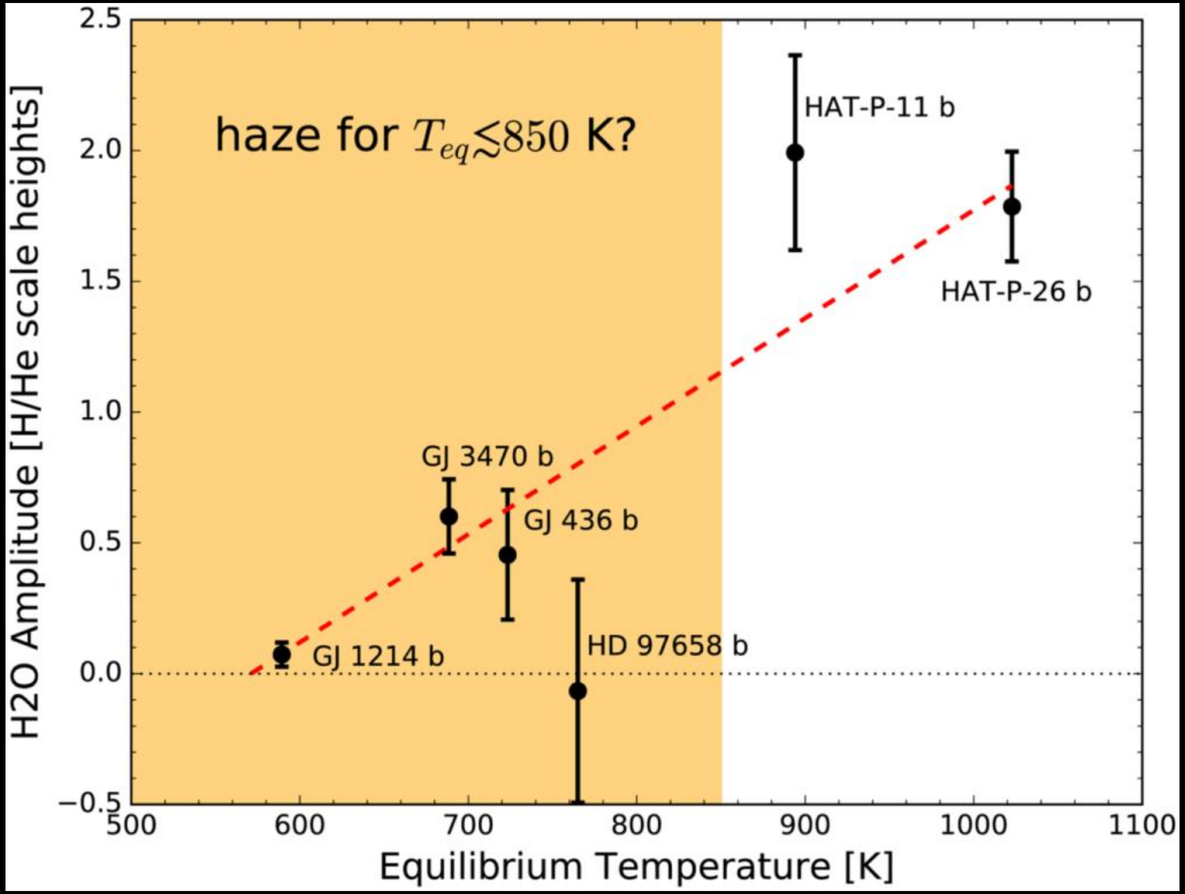
Both haze and cloud **chemistry** and **morphology** can be constrained in the lab, which feeds into models, which is how we interpret observations

Haze

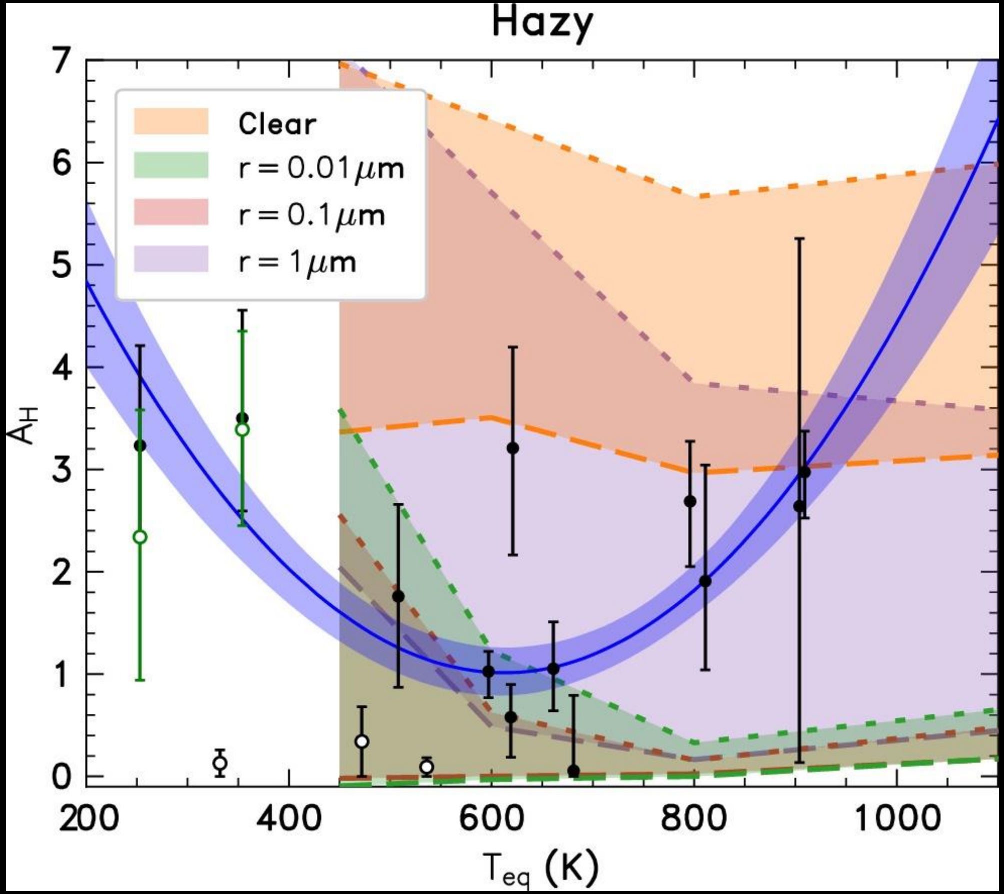
Clouds

Haze:
Chemistry

The shift to a haze-dominated regime *might* be due to methane being the major carbon reservoir at cooler temperatures

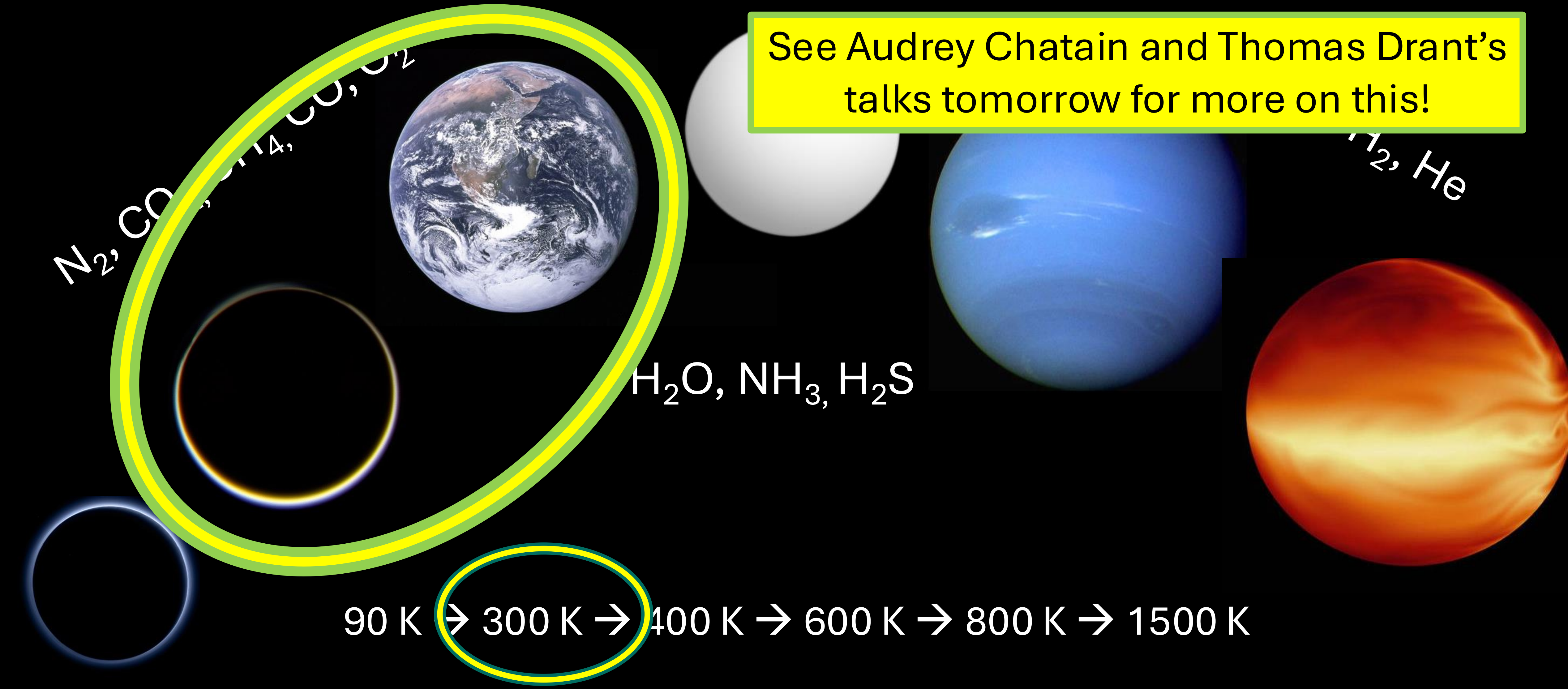


Crossfield & Kreidberg, *AJ,* 2017



Brande et al., *ApJL,* 2024

solar system lab studies and exoplanet lab studies are *complementary*

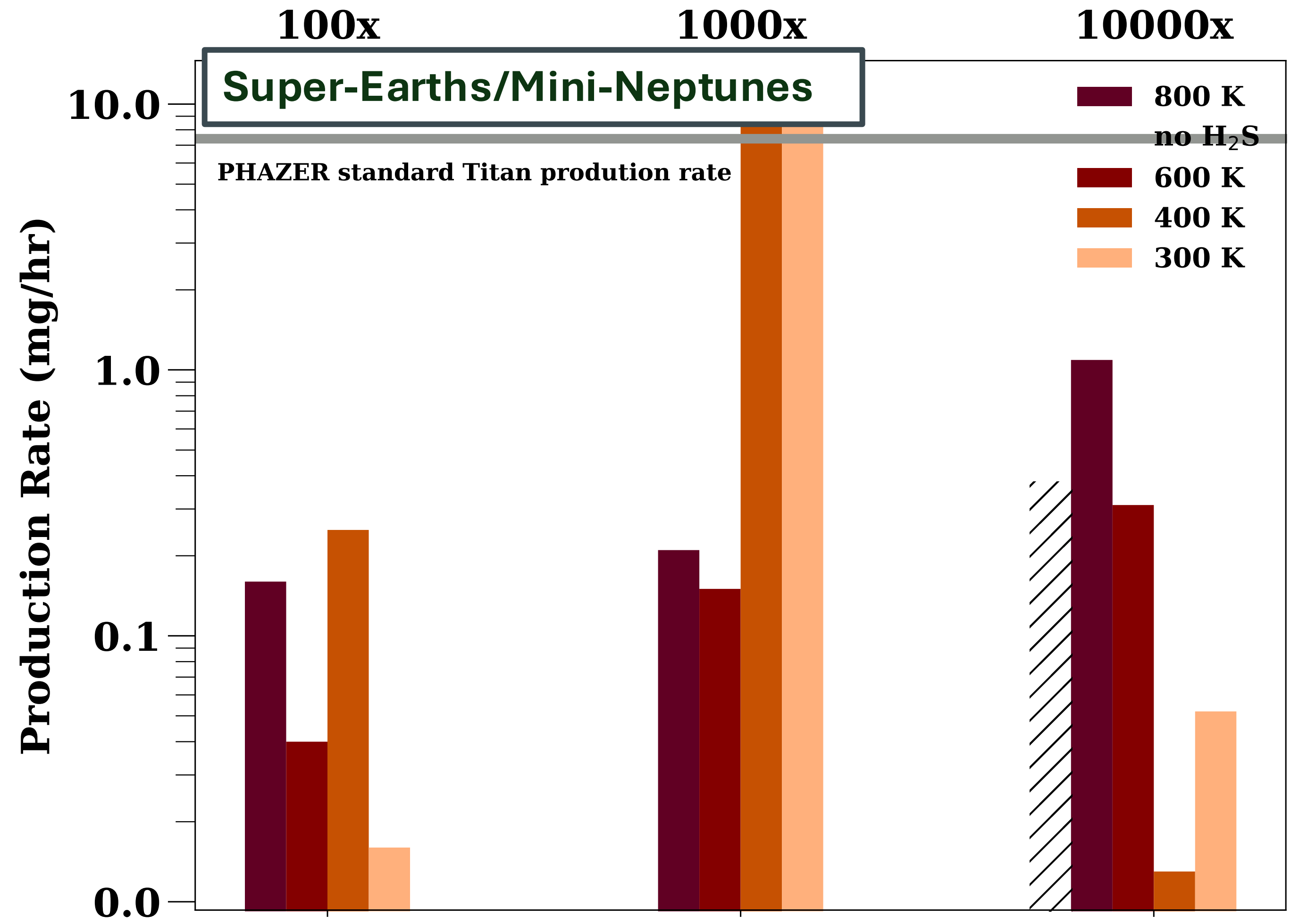


NASA/JHU APL/SWRI

NASA/JPL-Caltech/SSI/CICLOPS/Kevin M. Gill

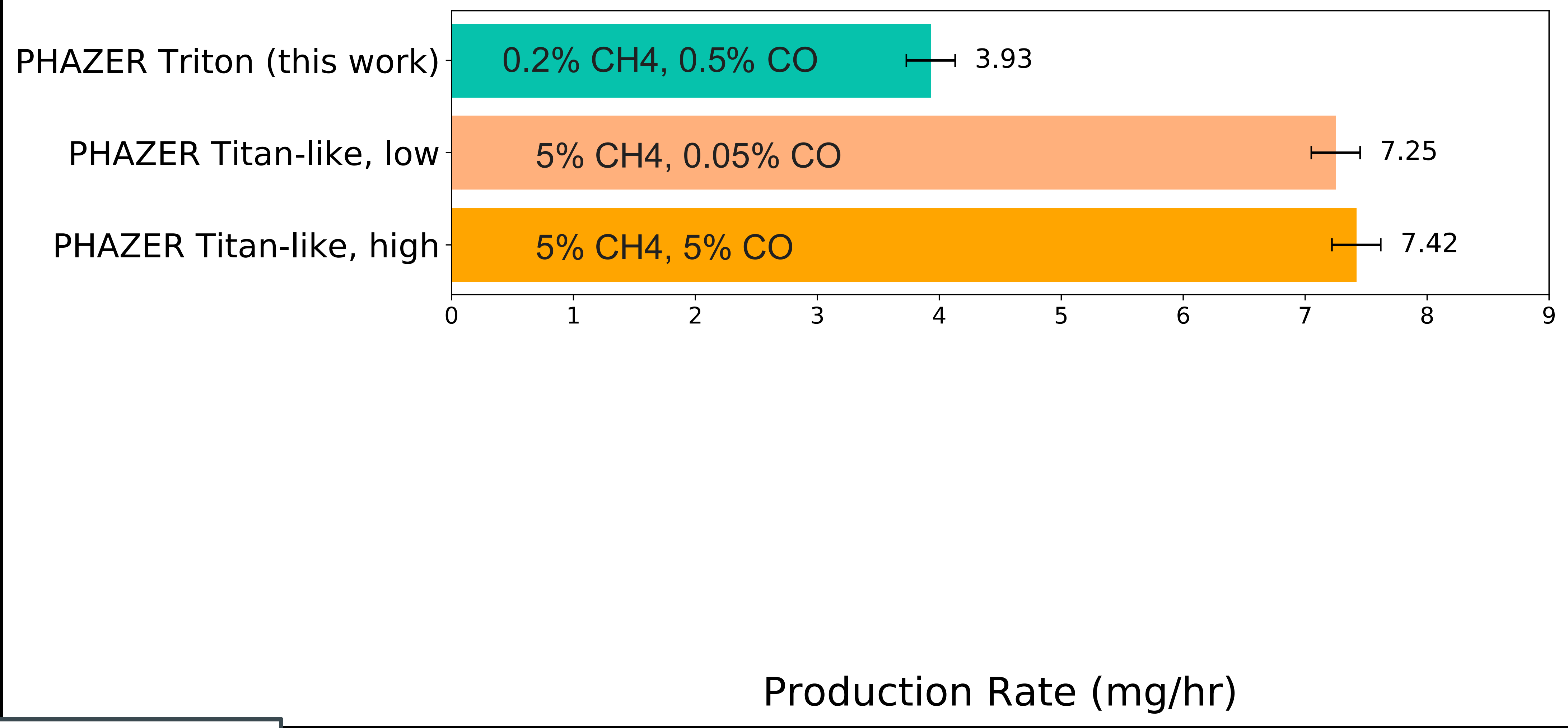
NASA/JPL/Caltech

The amount of haze produced varies by composition



Hörst et al., 2018 and updates from He et al., 2020

CH_4 drives haze formation, but it's *not* the only formation pathway

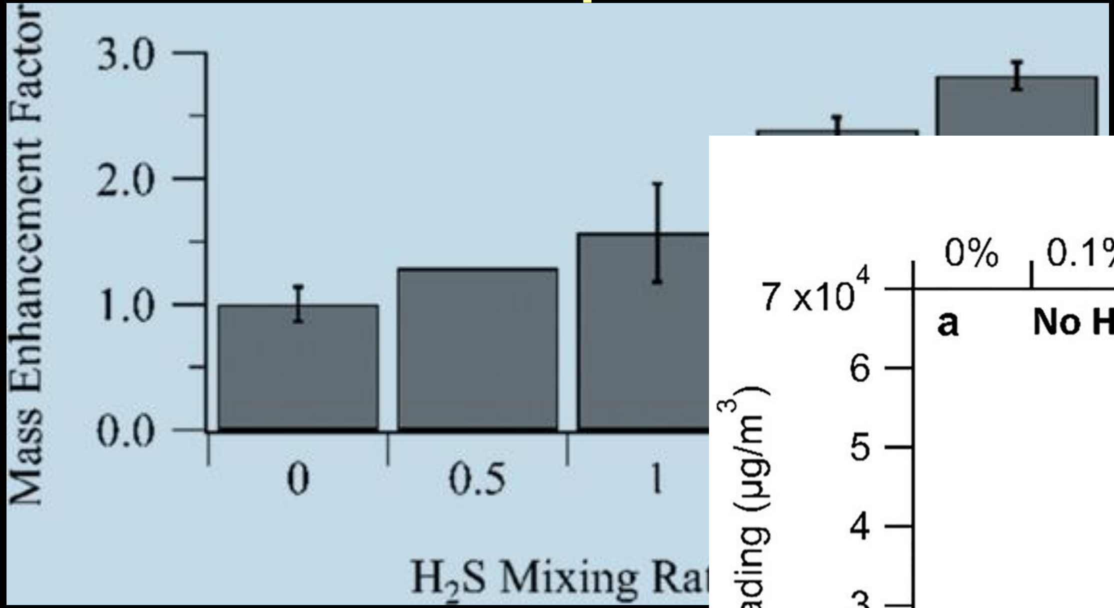


Moran et al., *JGR - Planets*, 2022

Titan, Triton, and Pluto

Hydrogen sulfide increases haze production in diverse atmospheres

N2/CH4/H2S Atmospheres

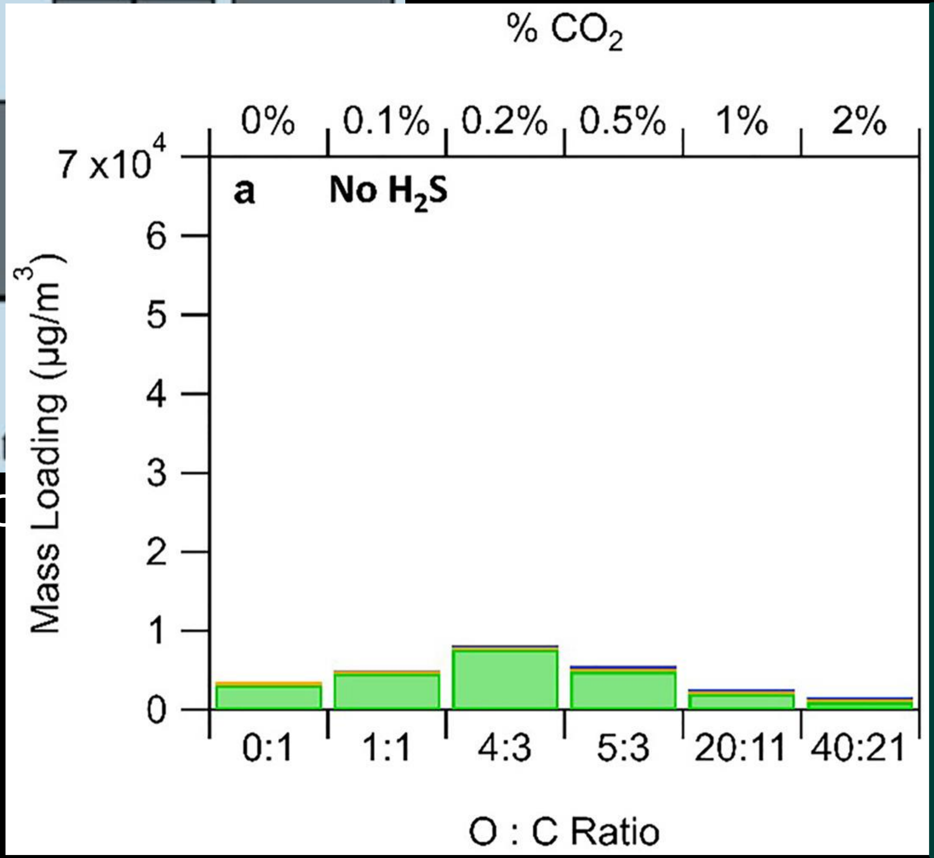


Reed et al., ACS Earth and Space C

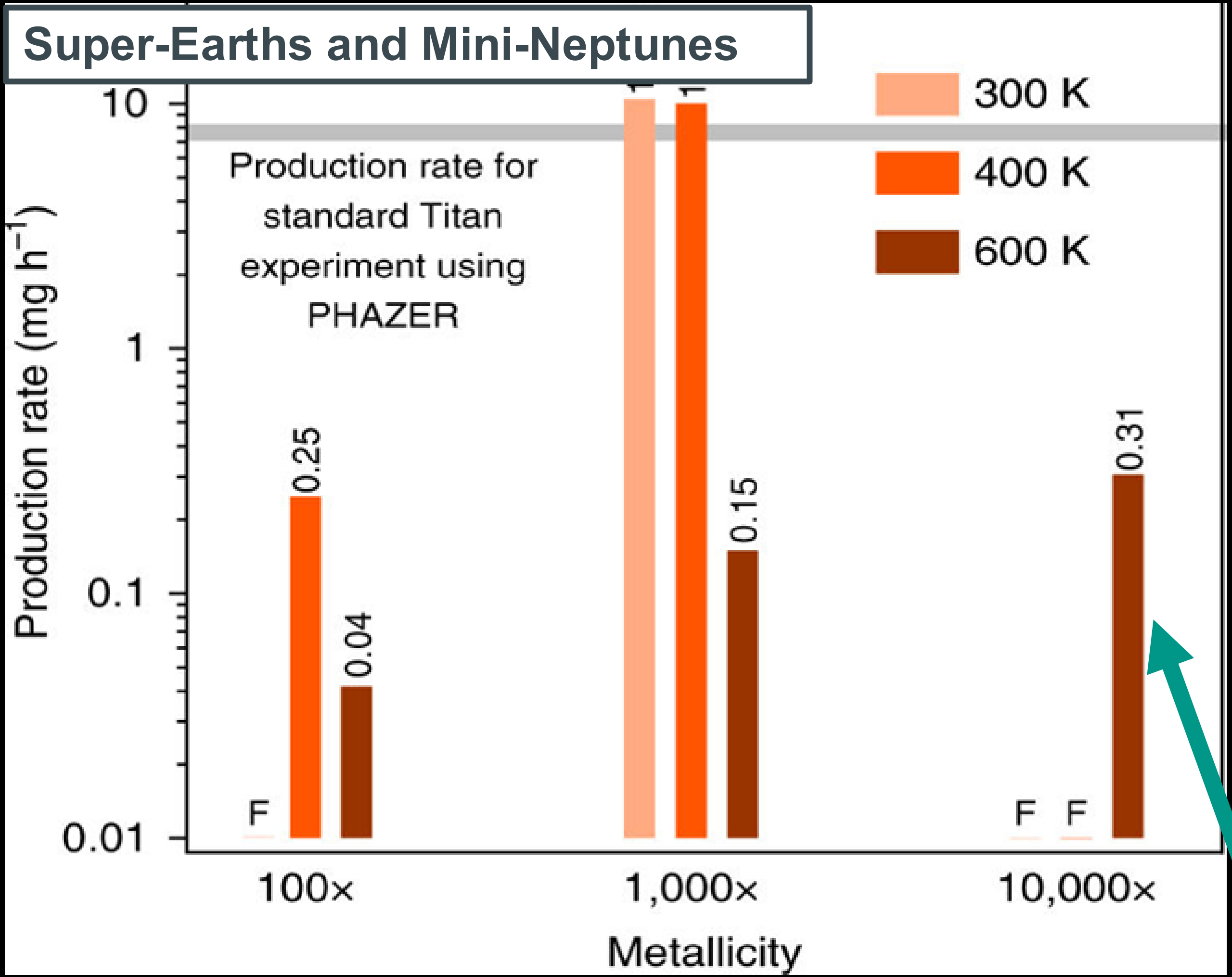
Early Earth atmospheres

(Adapted from) Reed et al., GRL, 2022

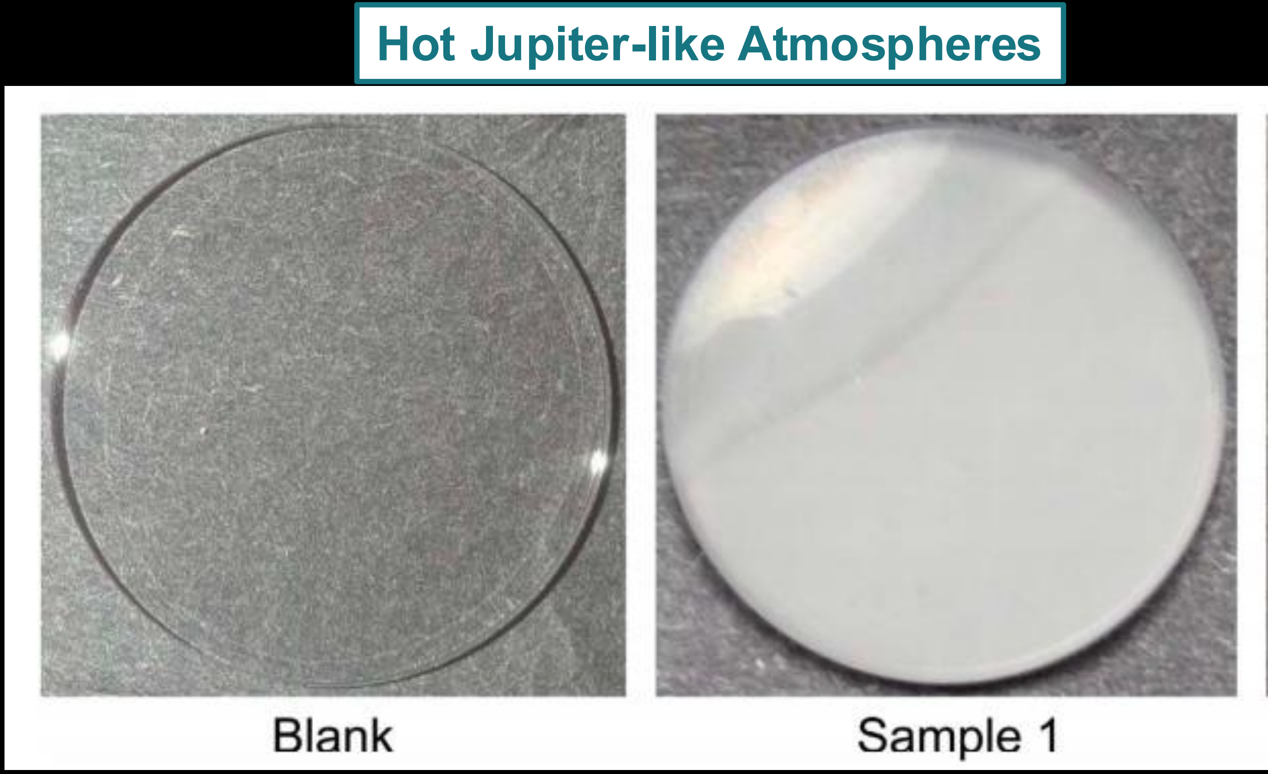
N2/CH4/CO2/H2S Atmospheres



Exoplanet lab haze studies show us that methane doesn't need to be present to drive haze formation



Hörst et al., *Nature Astronomy*, 2018

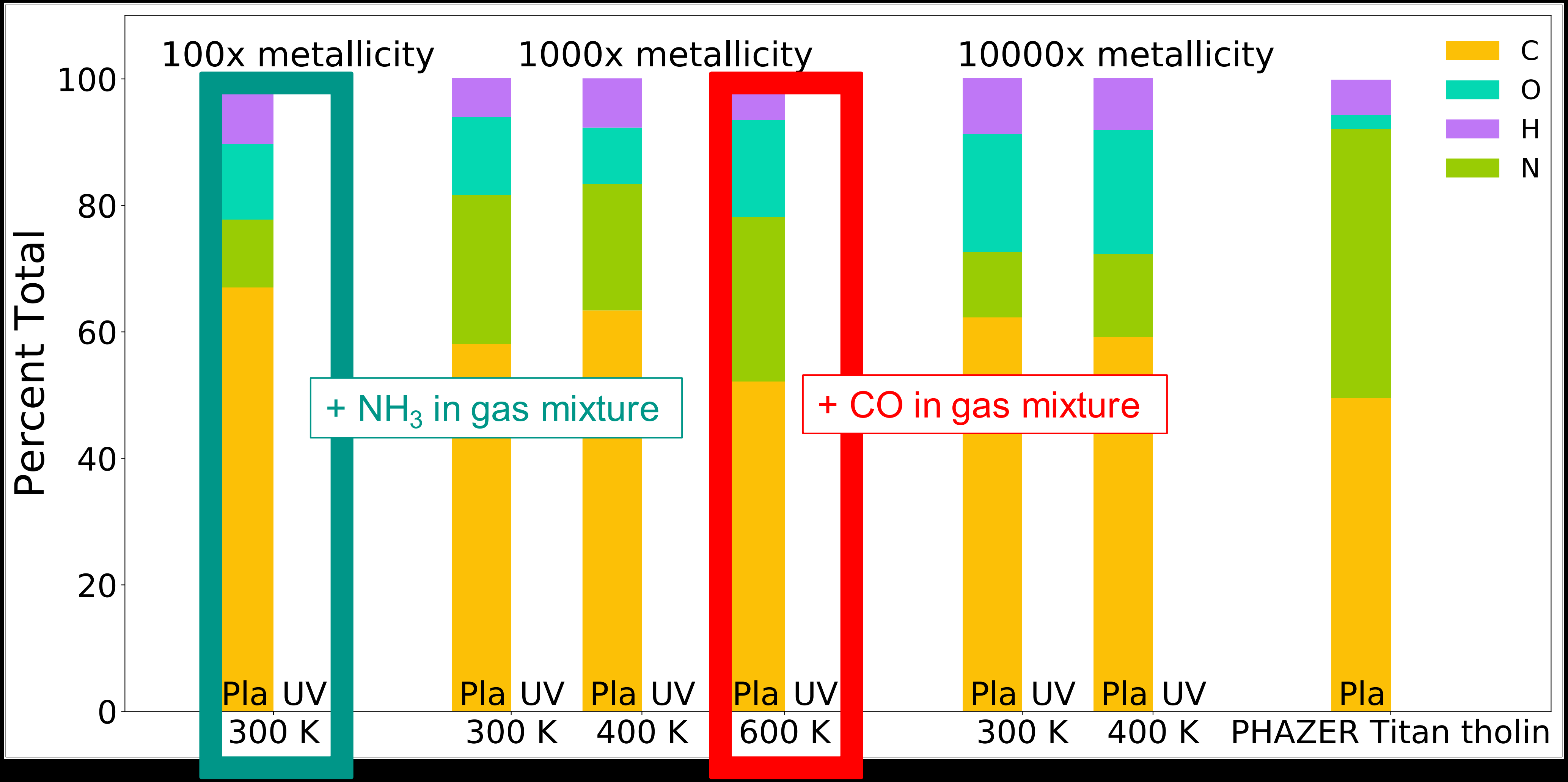


1473 K, H2/CO gas mix (99.7%/0.3%) under Ly-alpha

Fleury et al., *ApJ*, 2019

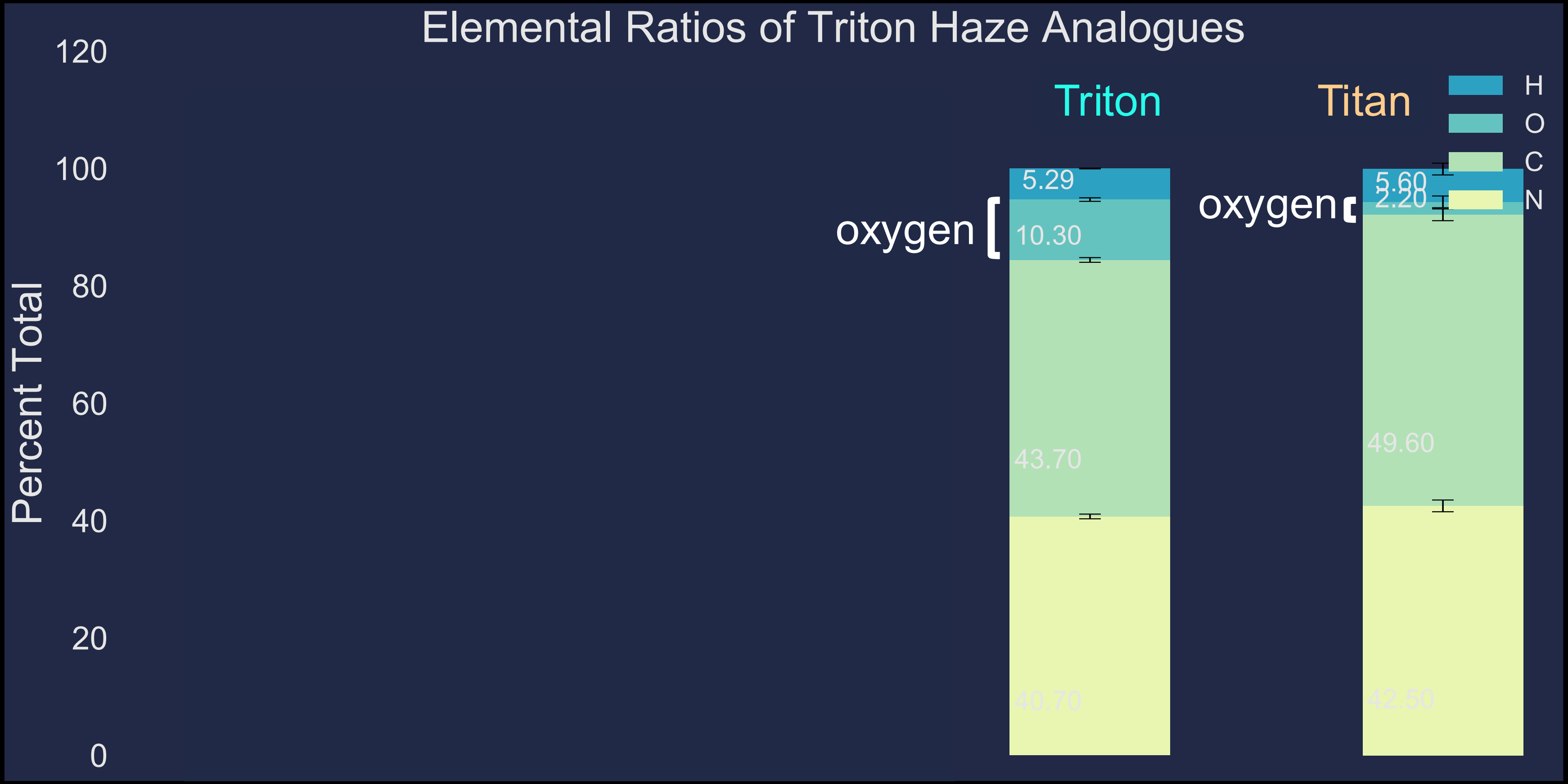
Only contained CO not CH_4!

Composition of the solid is not straightforward – tiny changes in the amount and kind of molecule participating in haze formation matters



Moran et al., *PSJ*, 2020

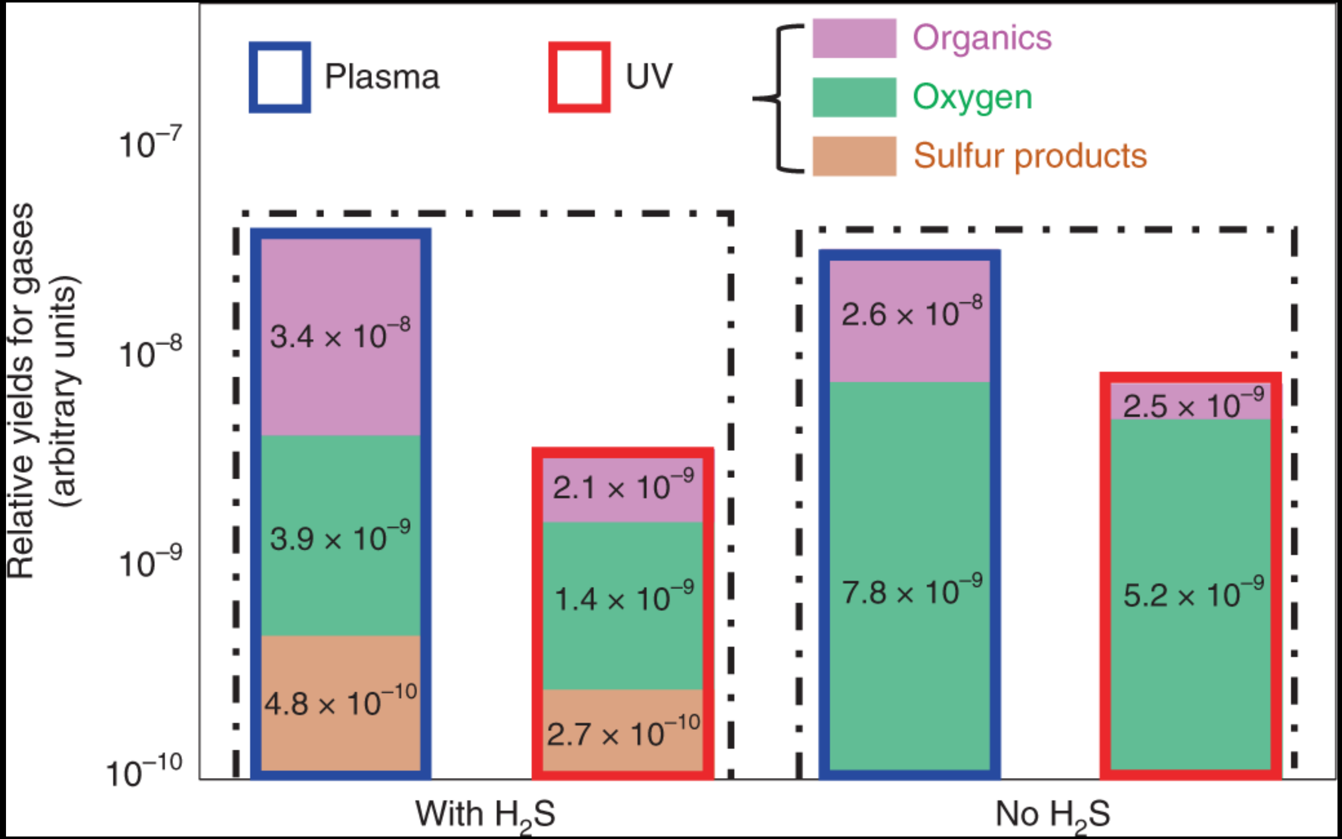
When CO > CH_4, oxygen is much more strongly incorporated to the solid particles



Moran et al., *JGR– Planets*, 2022

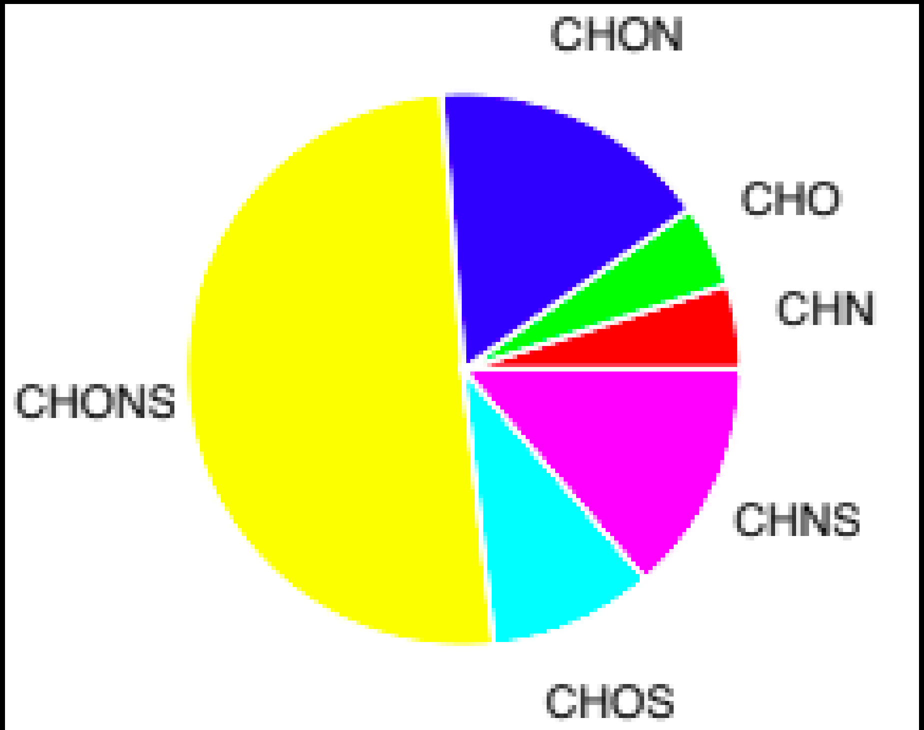
Trace species reactants in the gas phase are critical for ultimate haze composition

Gas Phase Products, measured with RGA



He et al., *Nature Astronomy*, 2020

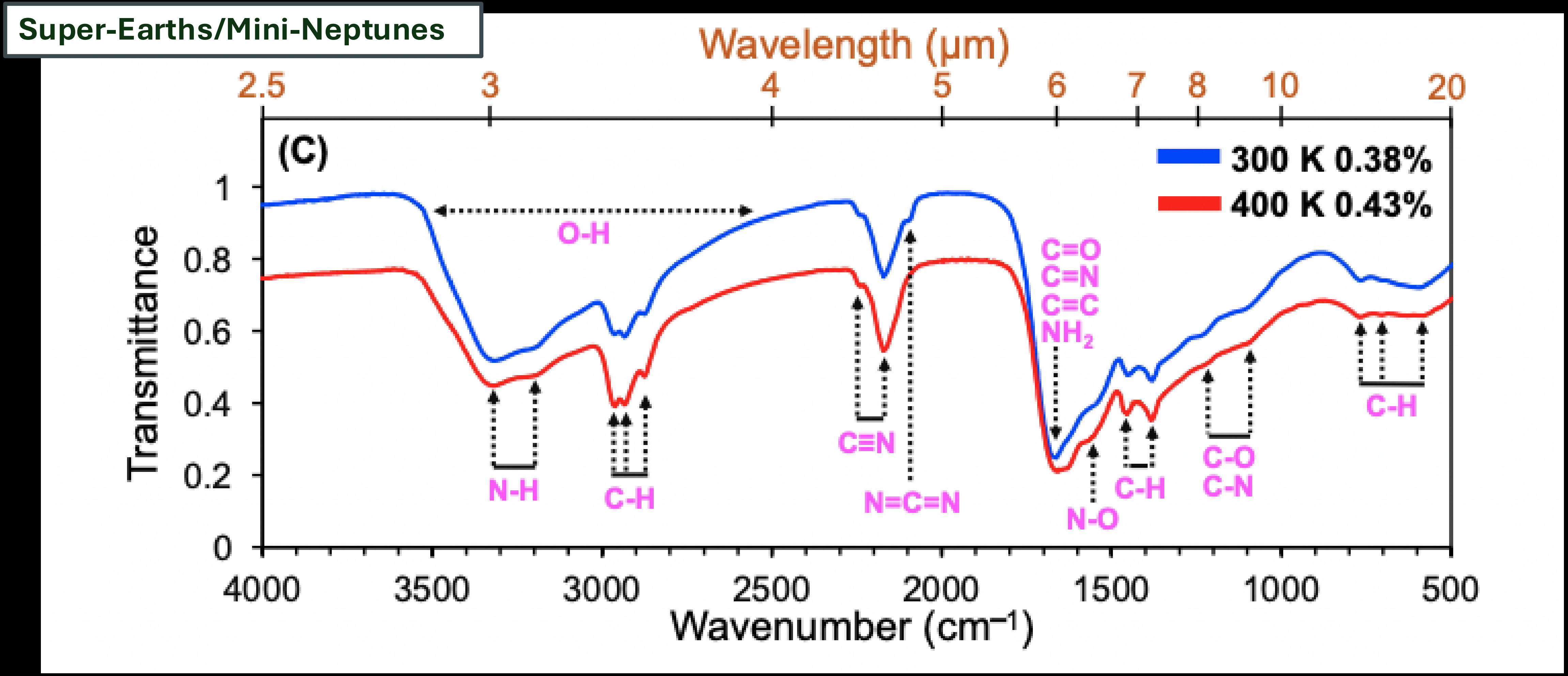
Solid Products, measured with MS



Vuitton, Moran et al., *PSJ*, 2021

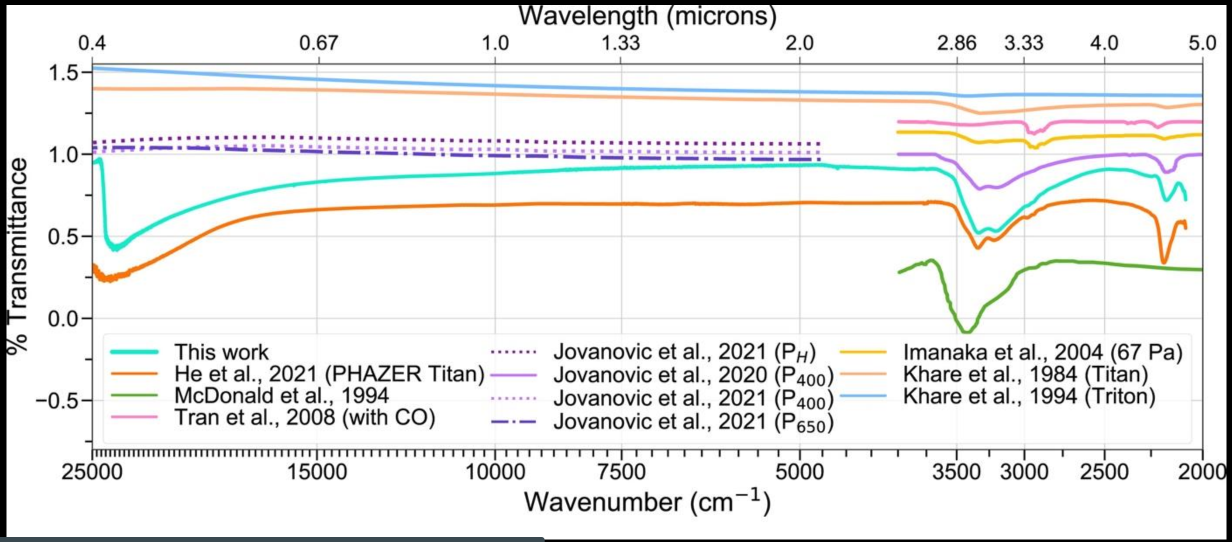
*Both **oxygen** and **sulfur** are readily incorporated into the haze solids!*

NIR-MIR spectroscopy corroborates mass spectrometry results on the functional groups that make up the haze particles

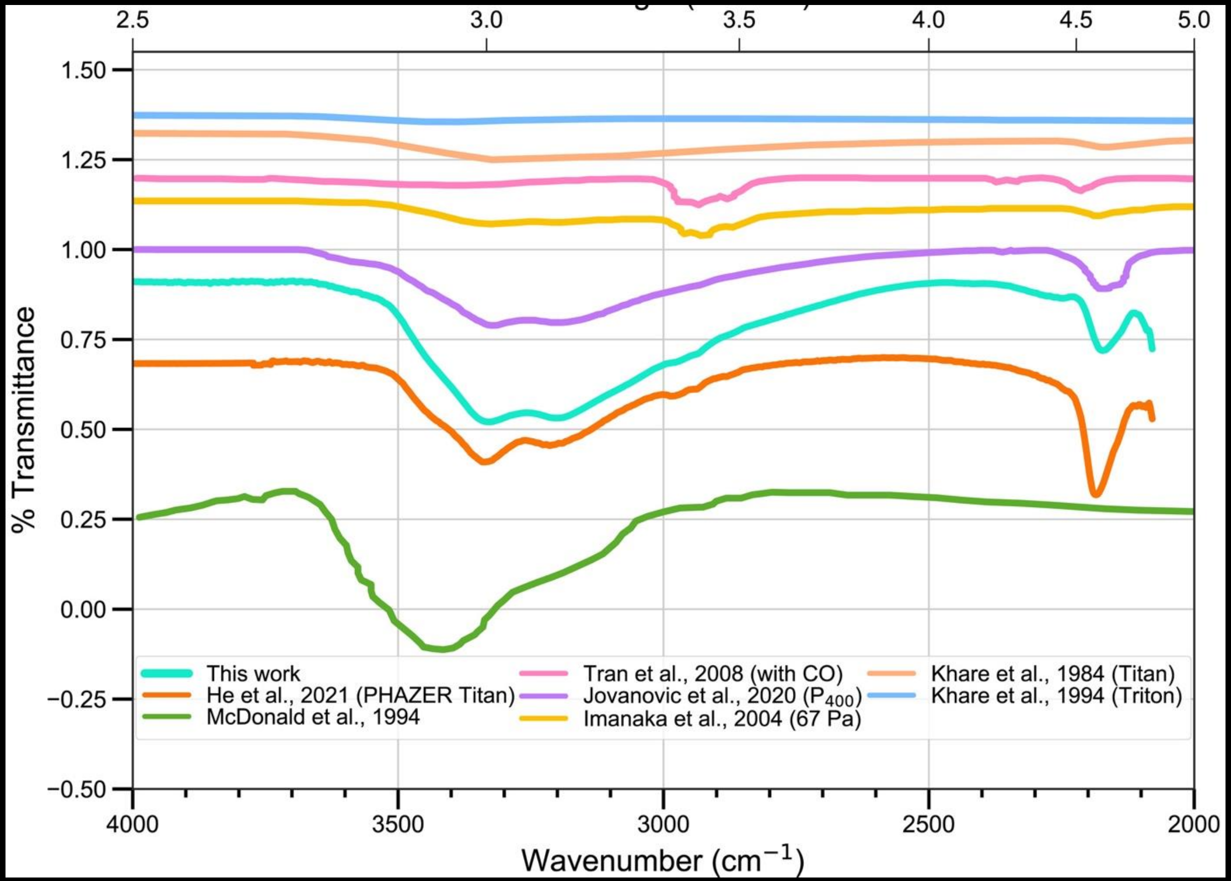


He, Radke, Moran, et al., *Nature Astronomy*, 2024

NIR-MIR spectroscopy corroborates mass spectrometry results on the functional groups that make up the haze particles



Titan, **Triton**, and **Pluto**

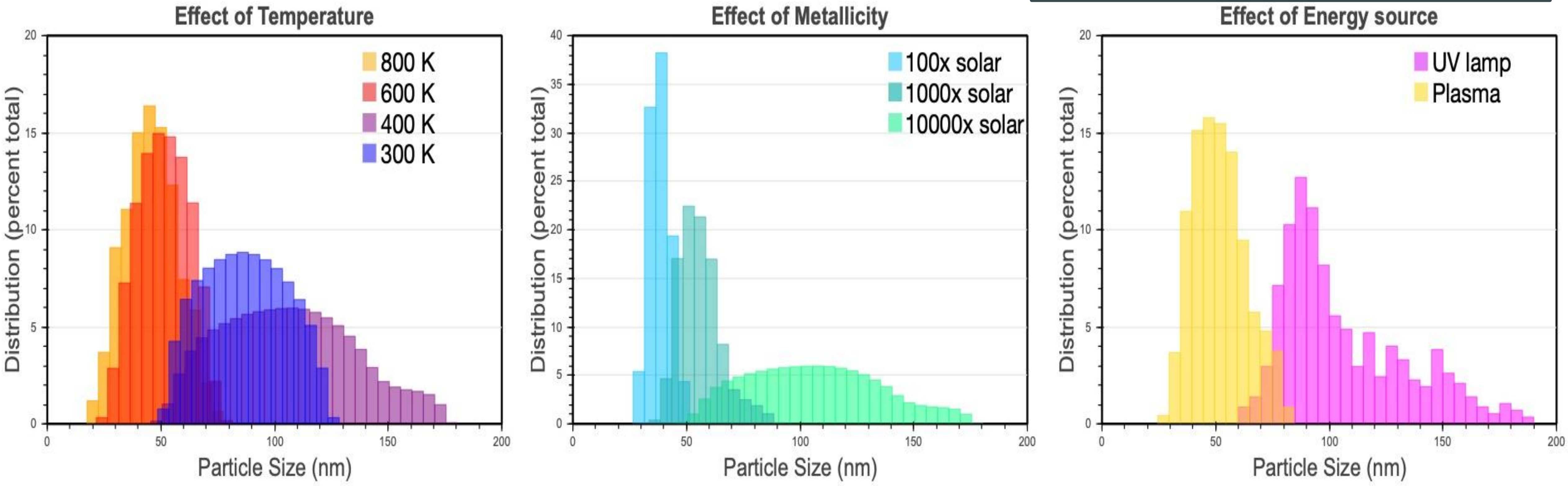


Moran et al., *JGR - Planets*, 2022

Haze:
Morphology

Haze particle sizes from the lab vary, but they're all small enough for Rayleigh scattering…

Super-Earths and Mini-Neptunes

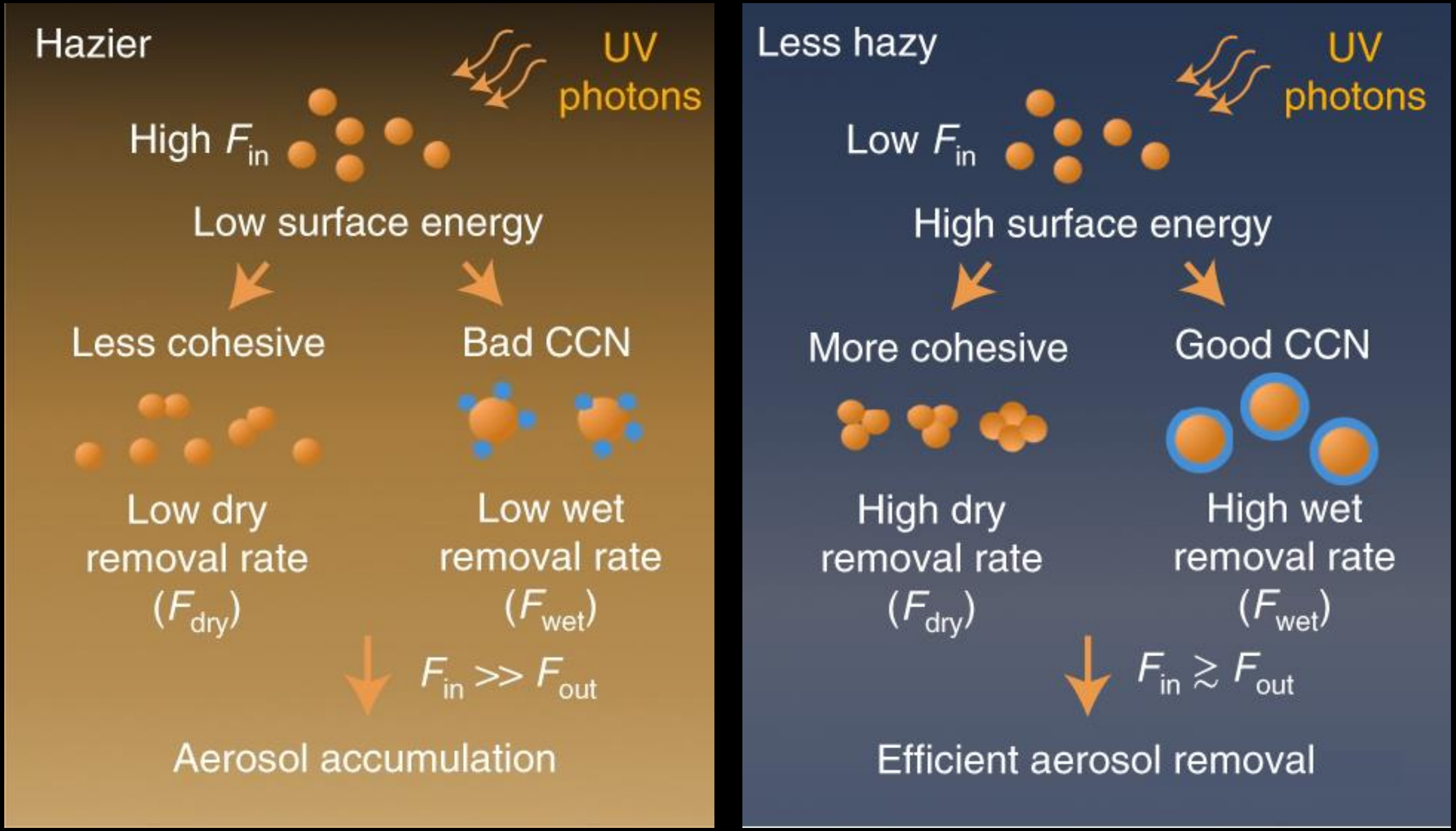


Gao, Wakeford, Moran & Parmentier, *JGR – Planets*, 2021
(summarizing He et al., 2018a, 2018b, 2020a)

Material properties affect how aerosols evolve through the atmosphere: particles can be quite sticky and cohesive, which means they can easily get act as cloud condensation nuclei and/or conglomerate

see also Pesciotta et al., *ApJ*, 2026; Huseby et al., *PSJ*, 2026

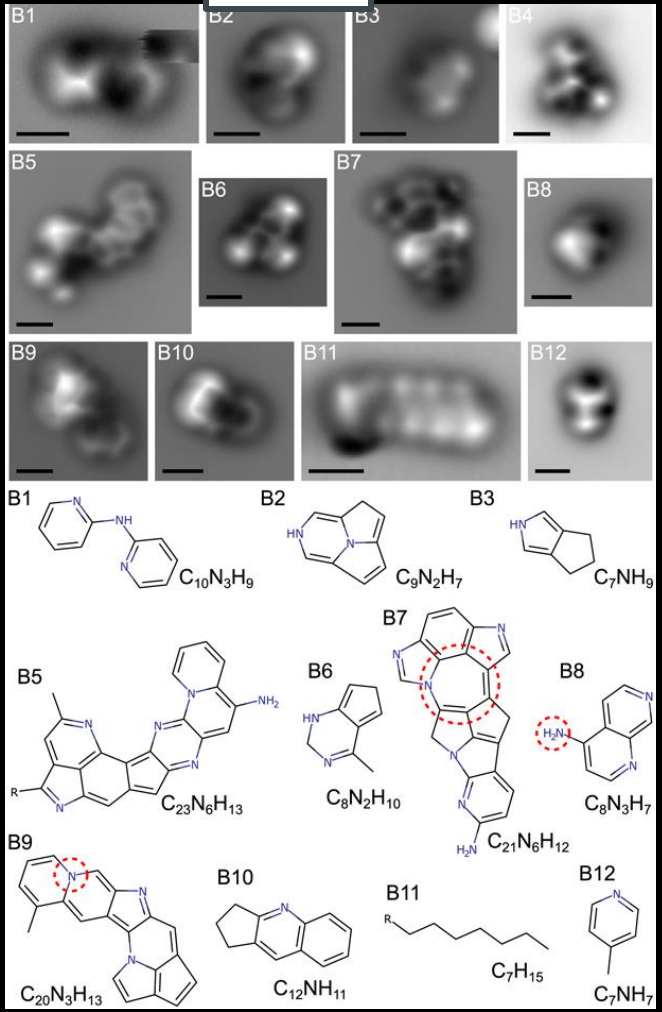
Super-Earths and Mini-Neptunes



Yu et al., *Nature Astronomy*, 2021

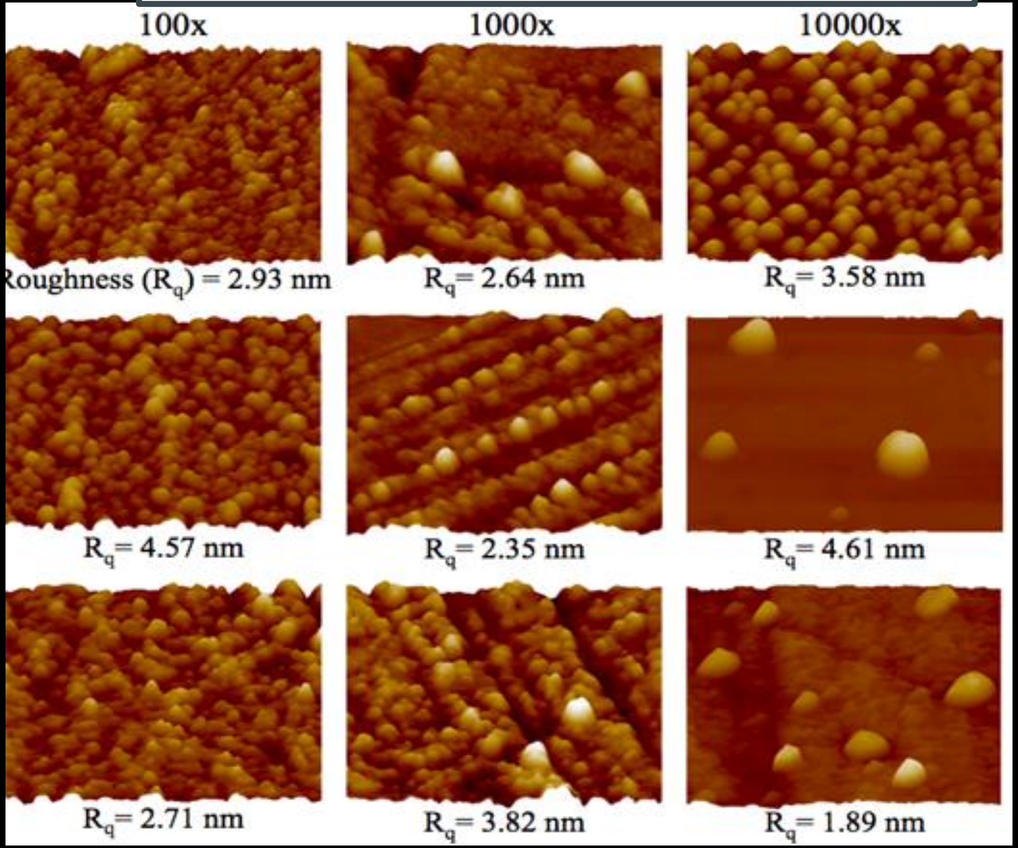
These material properties controlling particle size and shape often result in *non-spherical particles*

Titan



Schulz et al., ApJL, 2021

Super-Earths and Mini-Neptunes

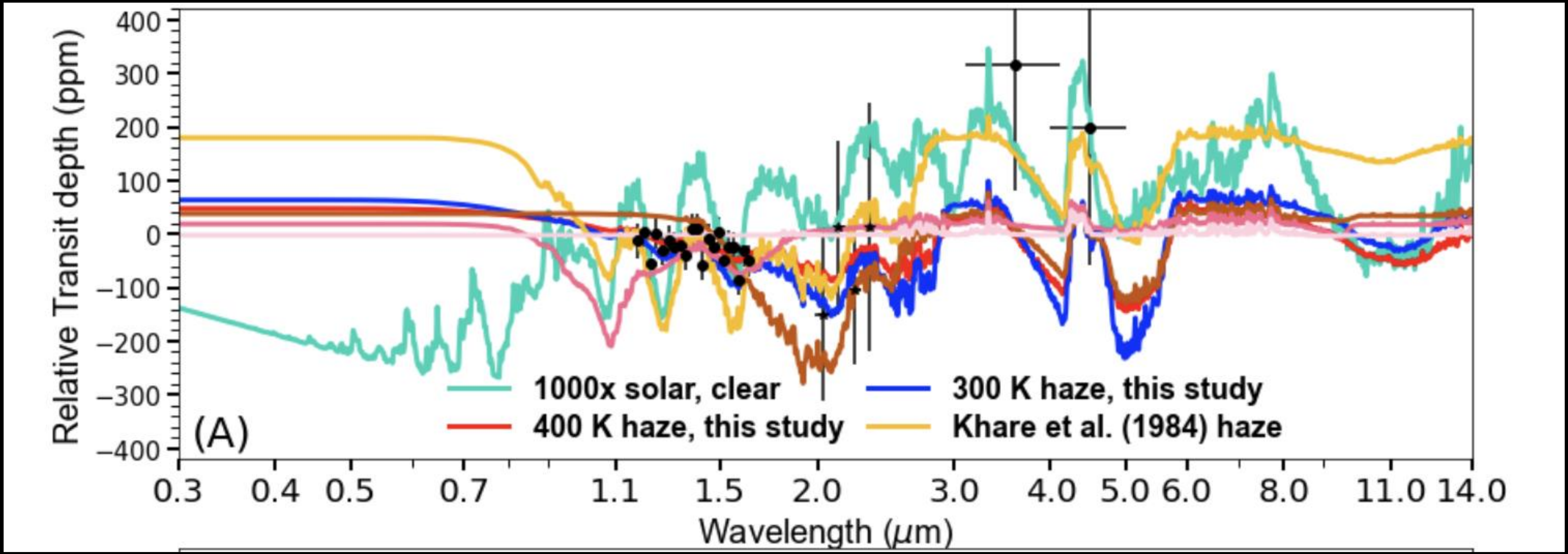


He et al., AJ, 2018

Haze:

Composition & Morphology → Remote Sensing

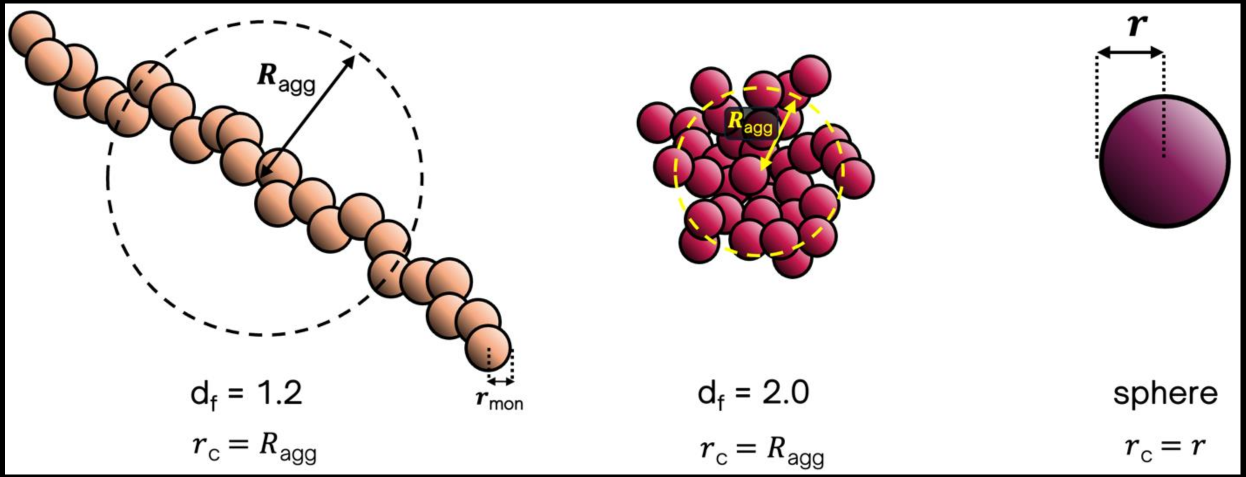
Composition via optical properties and particle sizes (via production and growth) are both needed to produce atmospheric spectral models to compare to observations

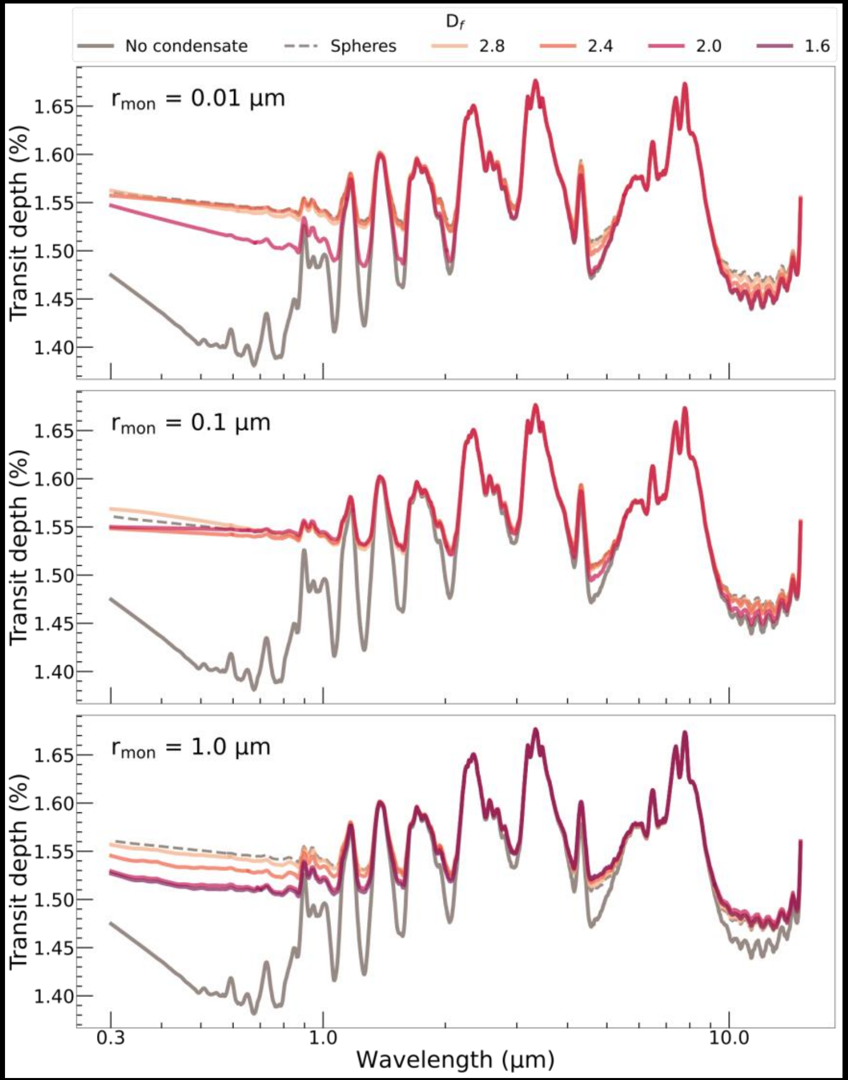


Mie theory!
only spherical
particles

He, Radke, Moran, et al., *Nature Astronomy,* 2024
(along with results of Corrales et al., *ApJL,* 2023 in pink colors)
also more now out from Thomas Drant, talking tomorrow! ☺

Hazes' size and shape can be better modeled by *fractal aggregates* in atmospheric spectral models to compare to observations

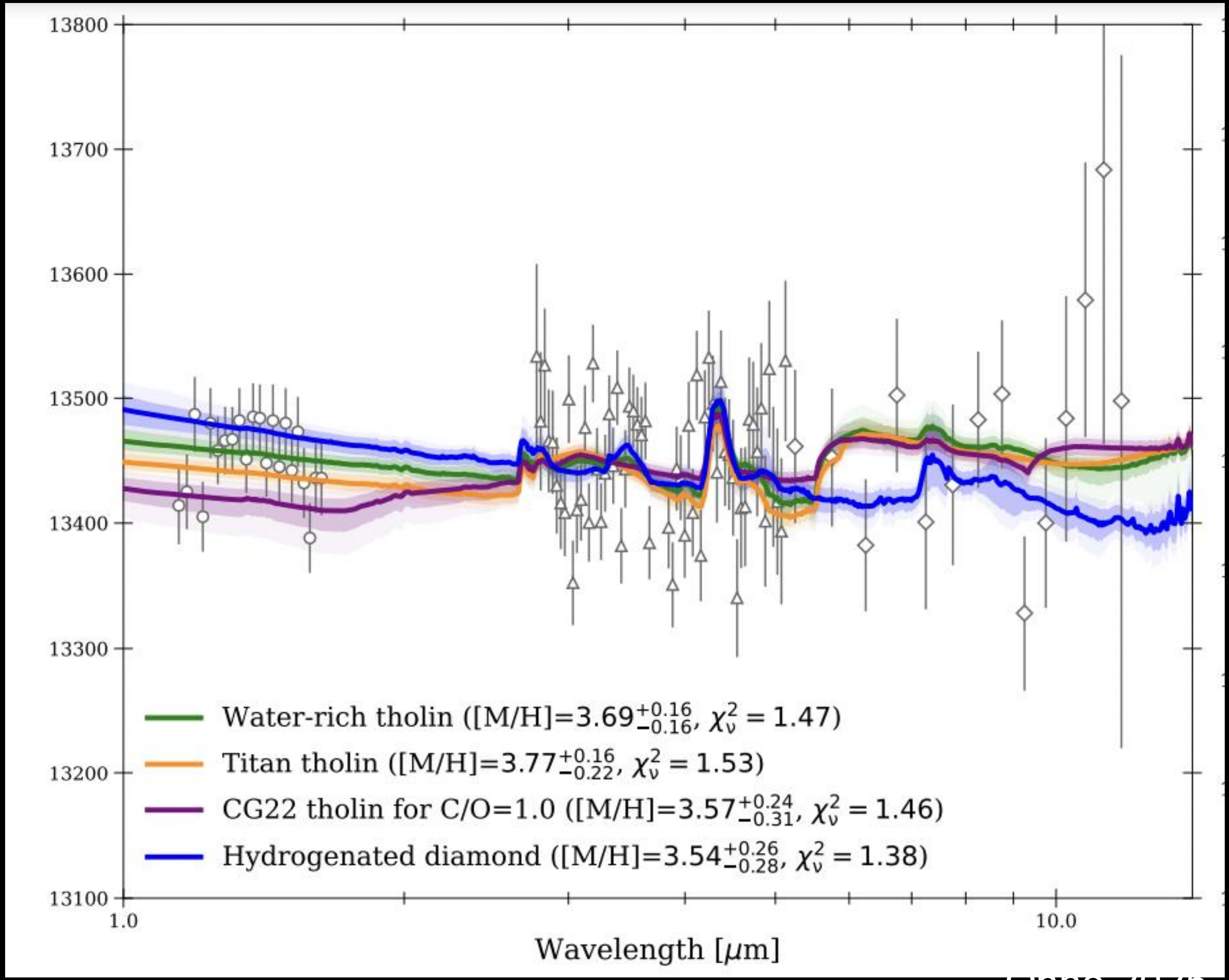




Moran & Lodge et al, *ApJ*, 2025
Lodge & Moran et al, *ApJ*, 2026

see also Ohno et al 2020; Samra et al 2022, Vahidinia et al 2024

JWST NIRSpec seems to break through the haze. Very high metallicity atmosphere –haze features are suppressed and high SNR needed

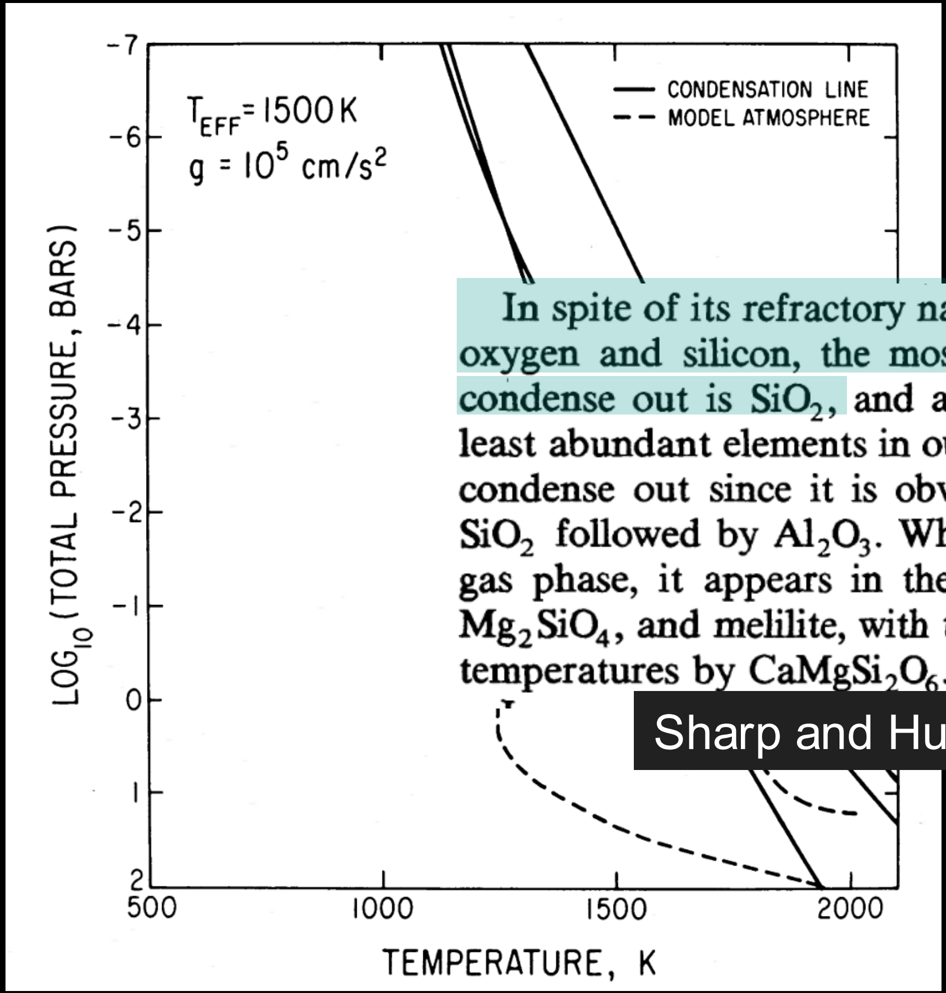


Ohno 2025

see also Ohno et al., 2024; Schlawin et al., 2024


Clouds:
Chemistry

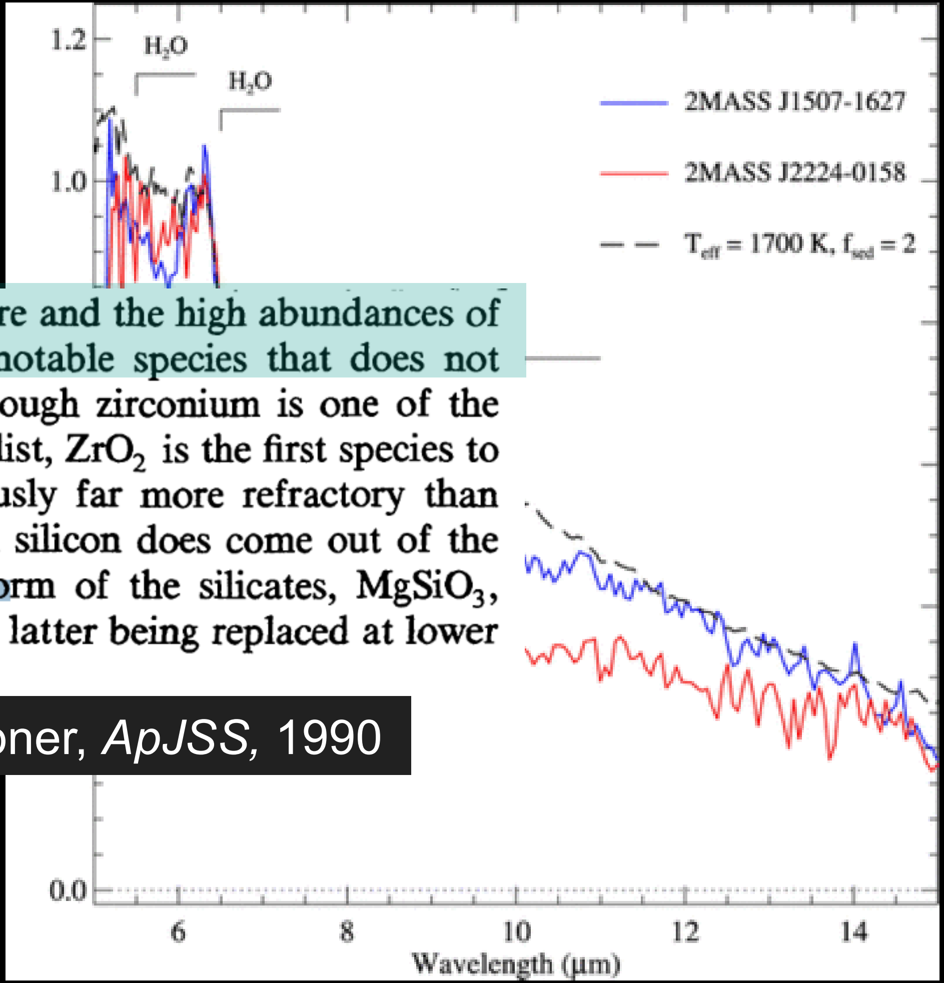
Spitzer provided *observational* confirmation that L-dwarf clouds were likely composed of silicates, long expected by theory



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

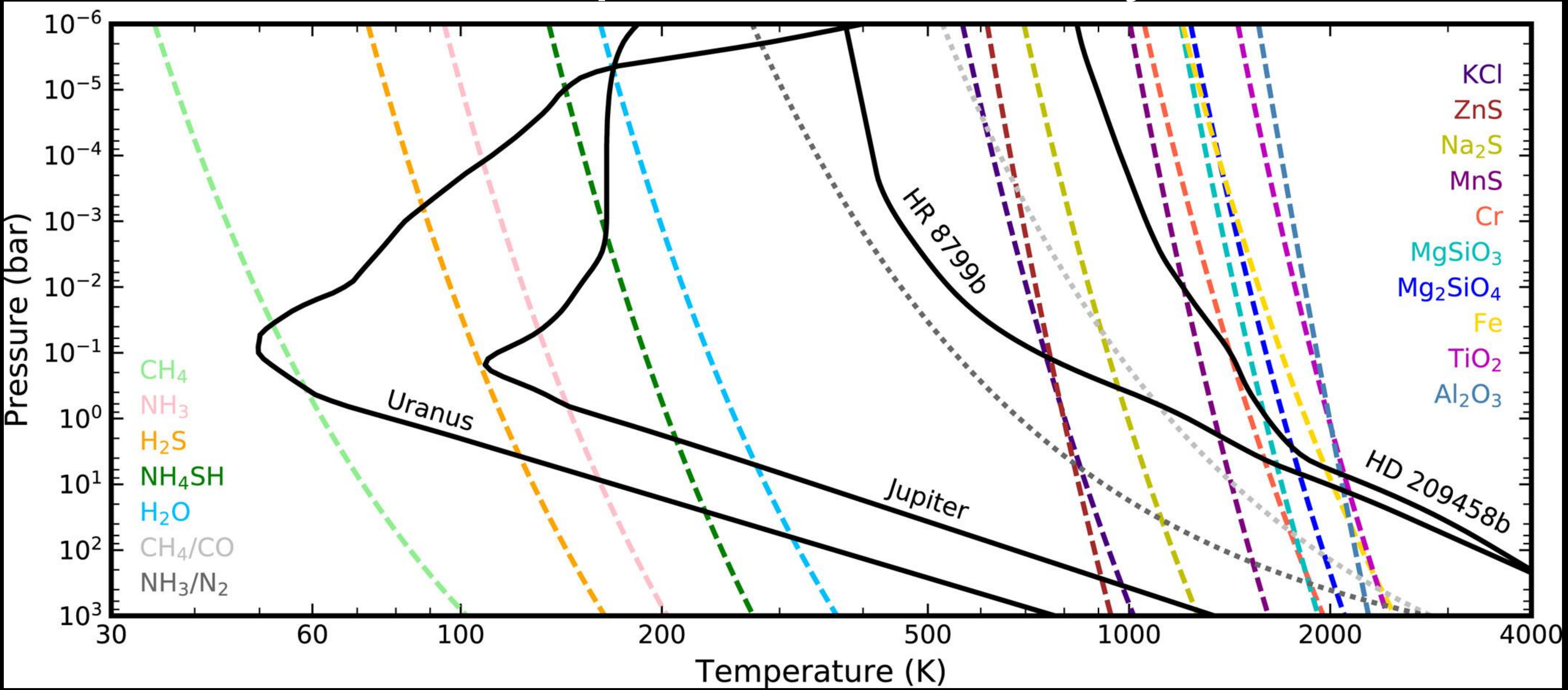
In spite of its refractory nature and the high abundances of oxygen and silicon, the most notable species that does not condense out is SiO_2, and although zirconium is one of the least abundant elements in our list, ZrO_2 is the first species to condense out since it is obviously far more refractory than SiO_2 followed by Al_2O_3. When silicon does come out of the gas phase, it appears in the form of the silicates, $MgSiO_3$, Mg_2SiO_4, and melilite, with the latter being replaced at lower temperatures by $CaMgSi_2O_6$.

Sharp and Huebner, *ApJSS*, 1990



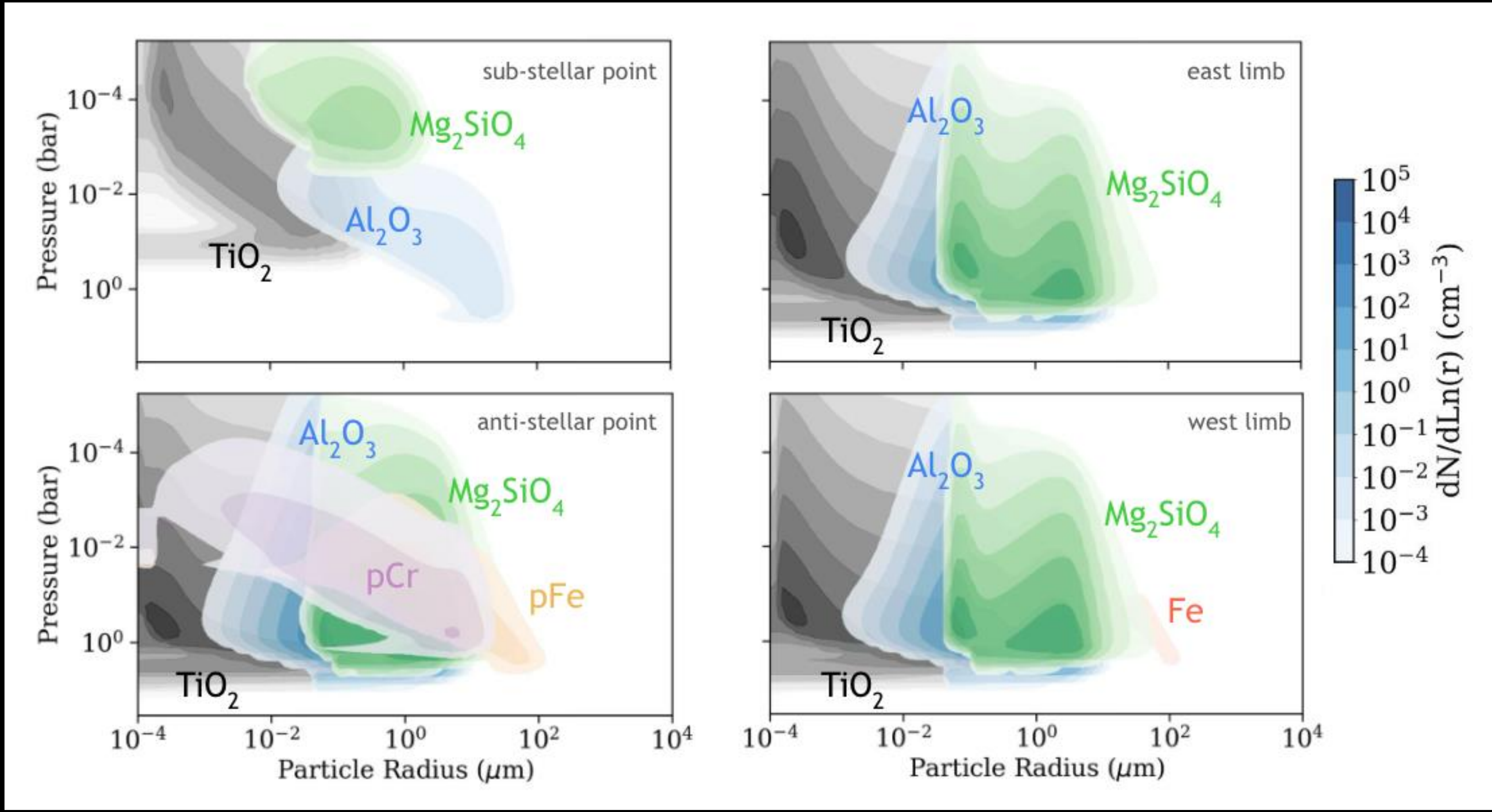
Burgasser et al., *ApJ*, 2008

Cloud condensation chemistry is highly diverse
~~but simpler than haze chemistry~~



Gao, Wakeford, Moran & Parmentier, *JGR – Planets*, 2021

Cloud condensation chemistry is highly diverse: heterogenous nucleation and metallicity dependent compositions



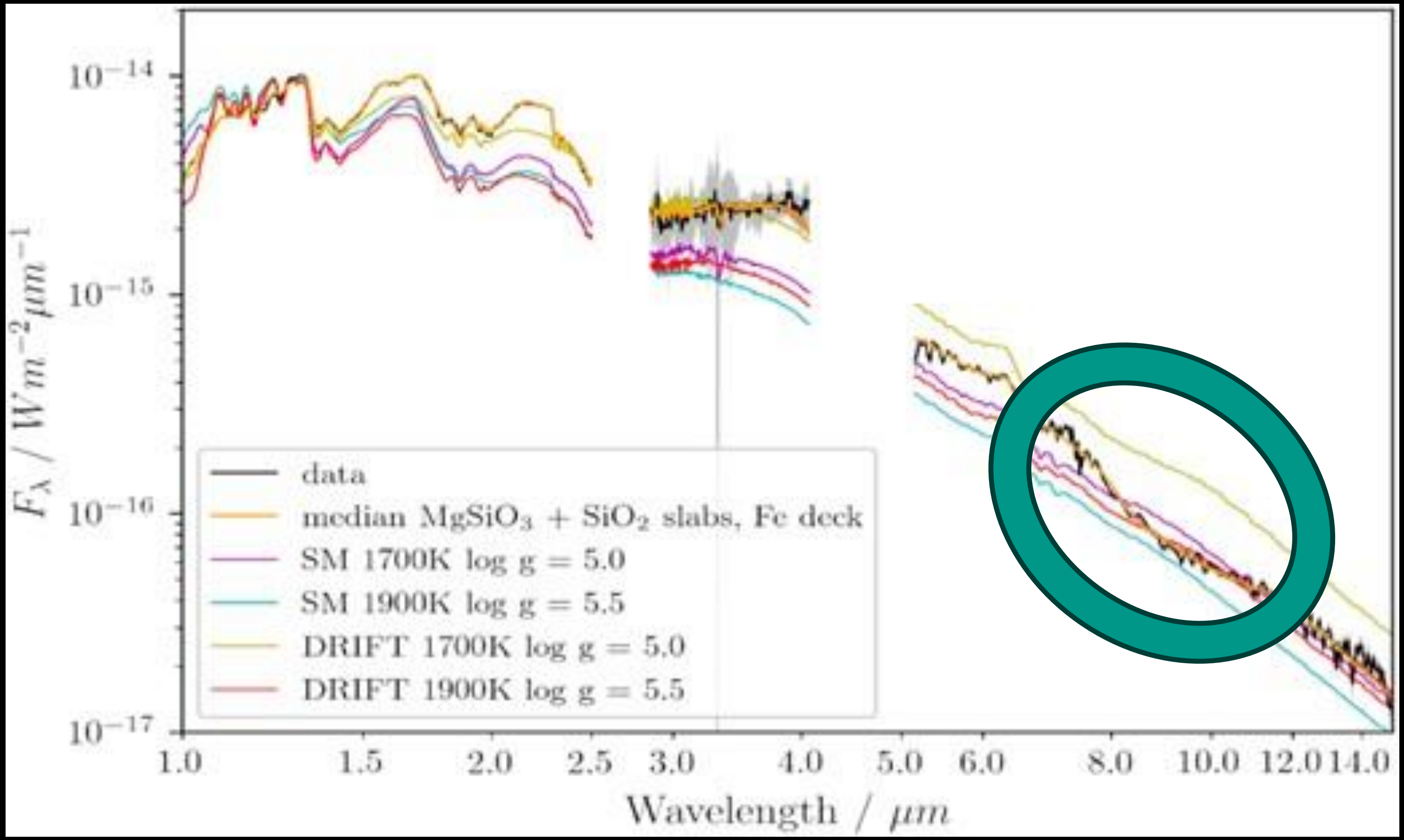
Fromont et al, AAS Journals, submitted

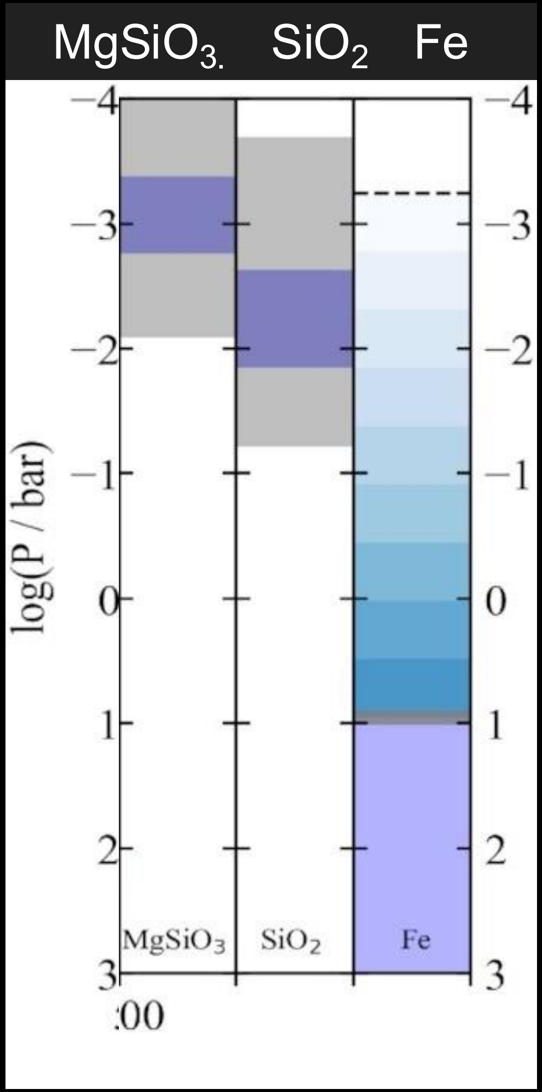
Table 1. Relative Cloud Masses and Condensation Temperatures for $P_T = 0.1$ bar and [Fe/H] = 0.0, after Lodders (2002).

Name	Formula	Relative Cloud Mass†	Condensation Temperature (K)
	Initial Al-bearing condensates		
Hibonite	$CaAl_{12}O_{19}$	2091	1914
Grossite	$CaAl_4O_7$	2442	1848‡
Corundum	Al_2O_3	1915	...
	Initial Ti-bearing condensates		
Ca titanate	$Ca_4Ti_3O_{10}$	170	1854
Ca titanate	$Ca_3Ti_2O_7$	180	1818‡
Perovskite	$CaTiO_3$	149	1707‡
	Other condensates		
Gehlenite	$Ca_2Al_2SiO_7$	3678	1796‡
Fe metal	Fe	21032	1682
Spinel	$MgAl_2O_4$	2673	1663‡
Akermanite	$Ca_2Mg_2Si_2O_7$	3657	1626‡
Ti oxide	Ti_3O_5	82	1610‡
Ti oxide	Ti_2O_3	79	1610‡
Forsterite	Mg_2SiO_4	32180	1592
Diopside	$CaMgSi_2O_6$	5809	1560‡
Anorthite	$CaAl_2Si_2O_8$	5227	1513‡
Enstatite	$MgSiO_3$	44585	1508
Cr metal	Cr	303	1416‡
Ti oxide	Ti_4O_7	83	1290‡
Mn sulfide	MnS	360	1271
Na sulfide	Na_2S	≡ 1000	925

Wakeford et al., *MNRAS*, 2017

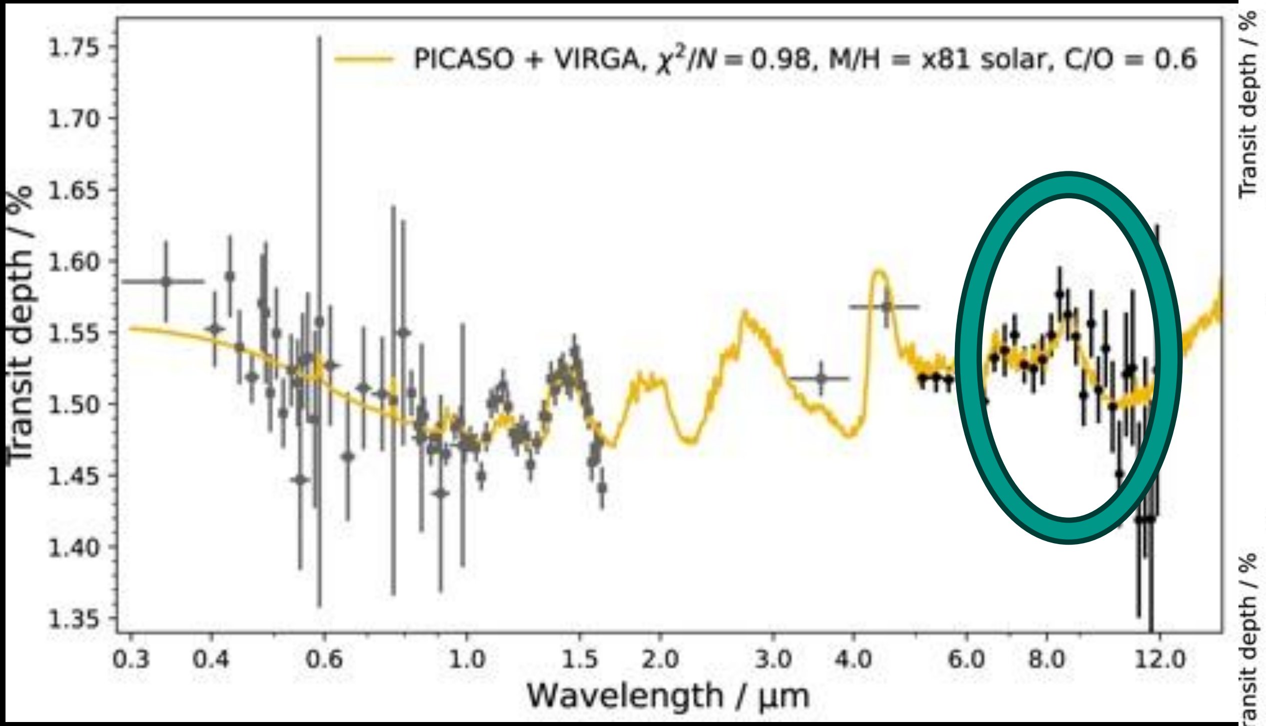
SiO_2, not just $MgSiO_3$ or Mg_2SiO_4, is discovered in an L dwarf….(and it looks amorphous not crystalline)

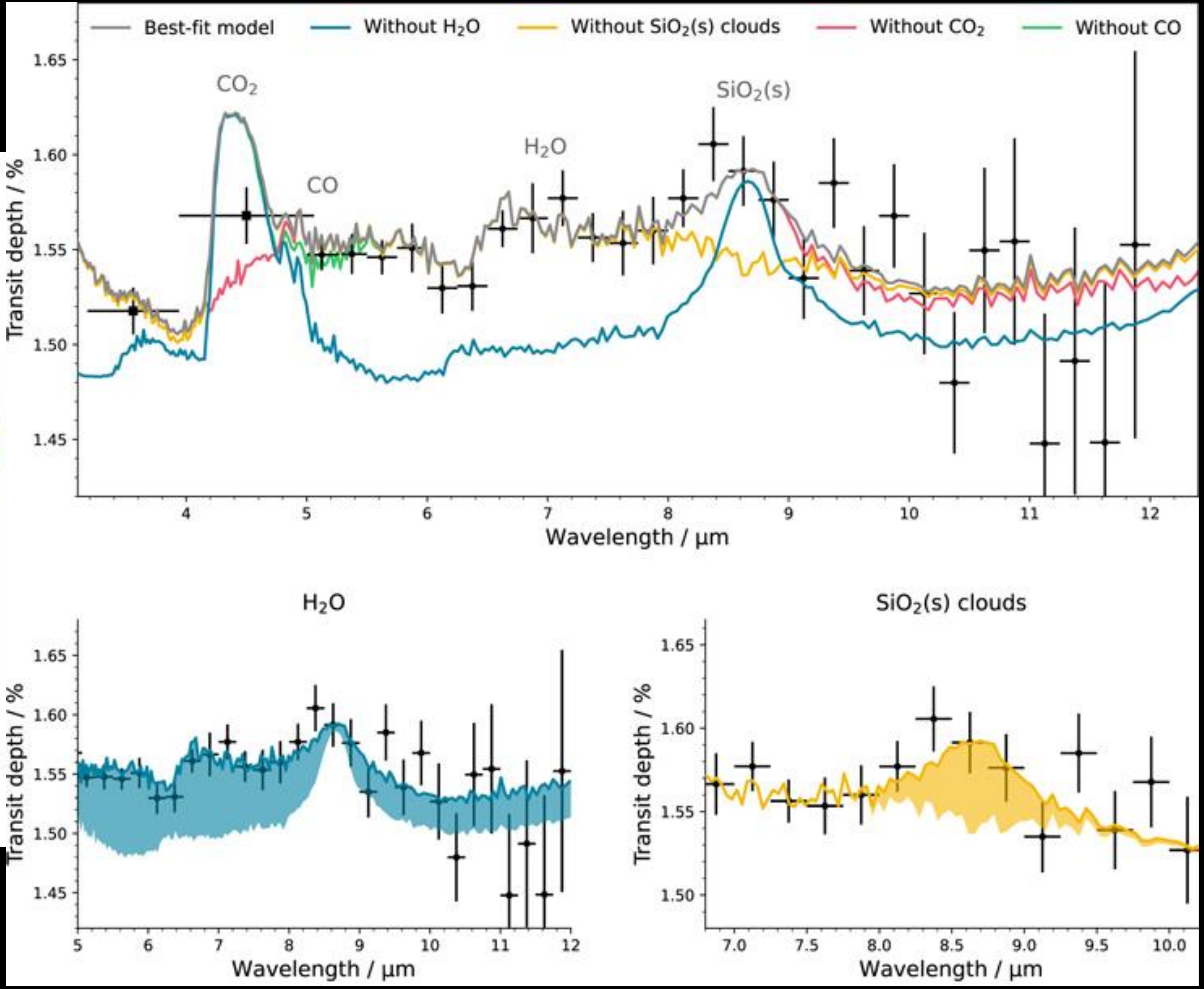




Burningham et al., *MNRAS*, 2021

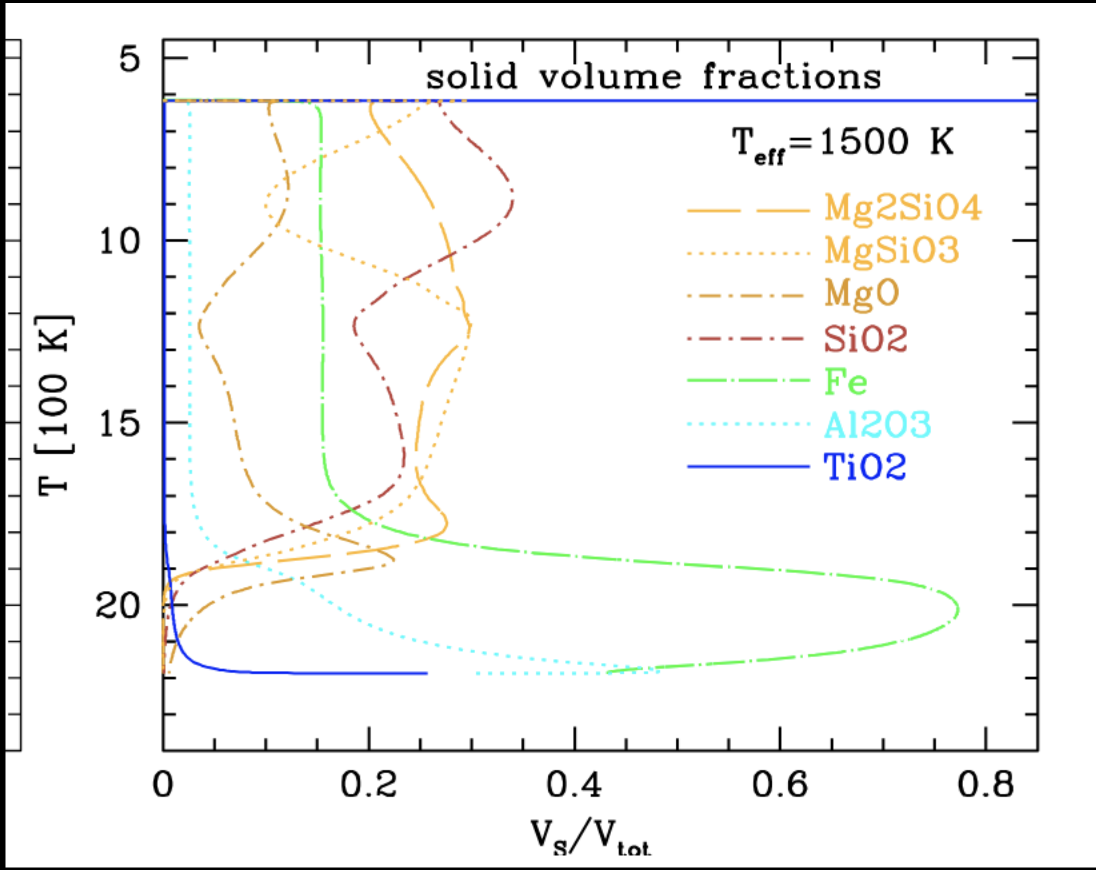
With JWST MIRI LRS, SiO_2 is discovered in the hot Jupiter WASP-17b



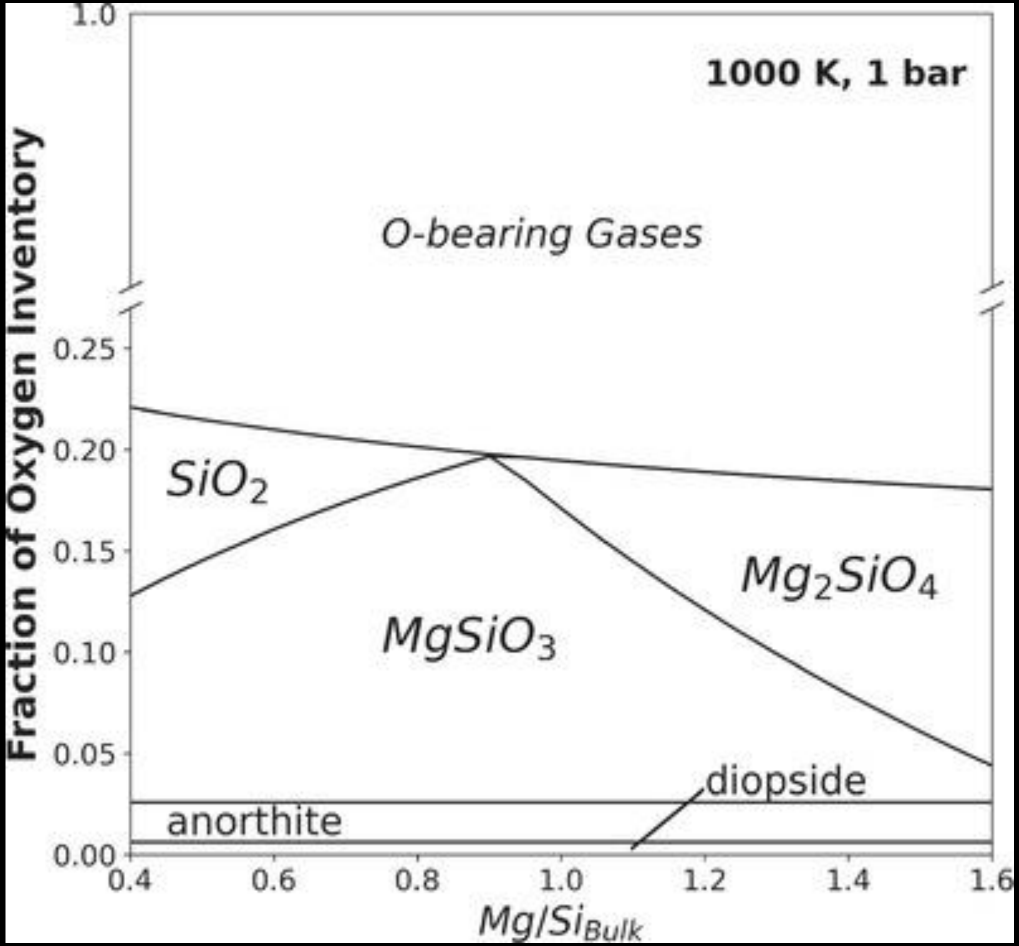


Grant et al., *ApJL* 2023

The cloud condensation sequence (where silicates dominate) and thus **oxygen sequestration** is highly dependent on the bulk chemistry of the atmosphere



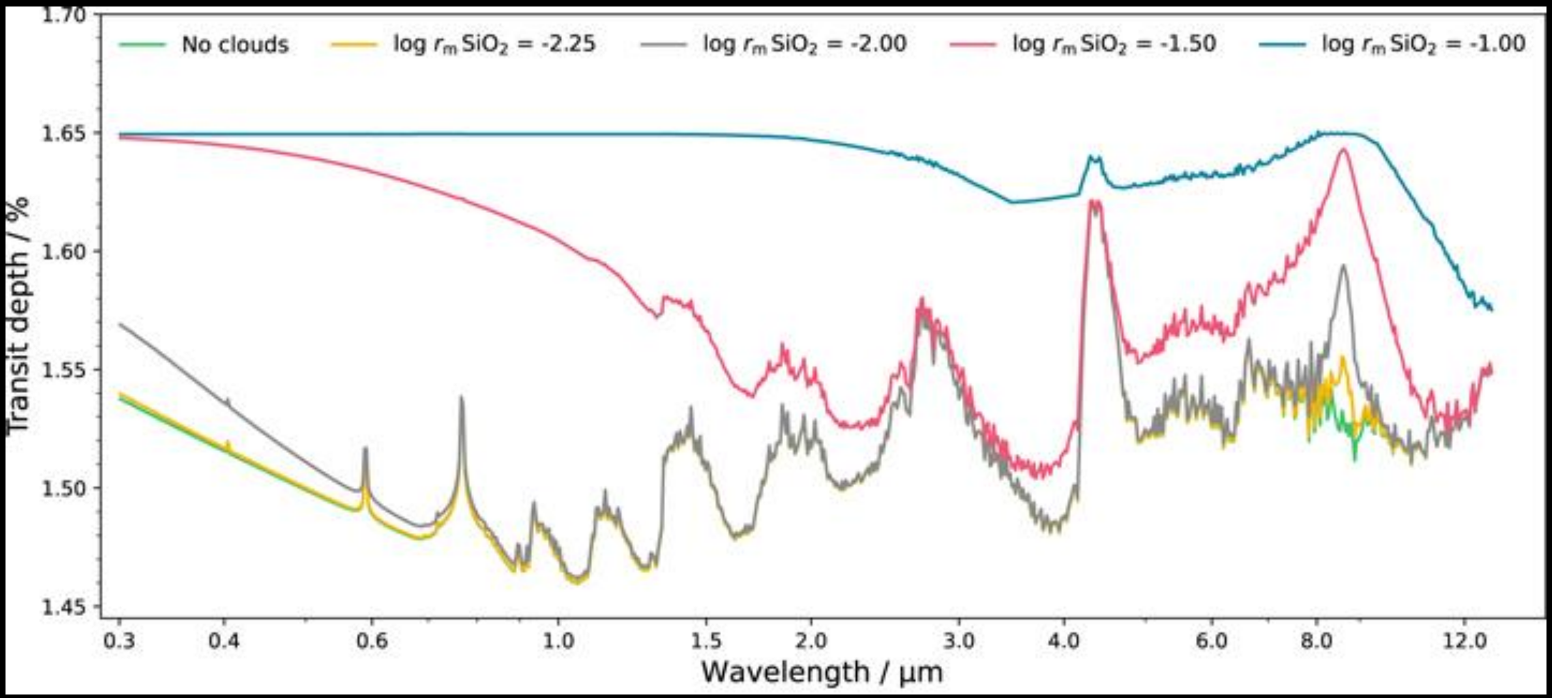
Helling et al., *A&A* 2006

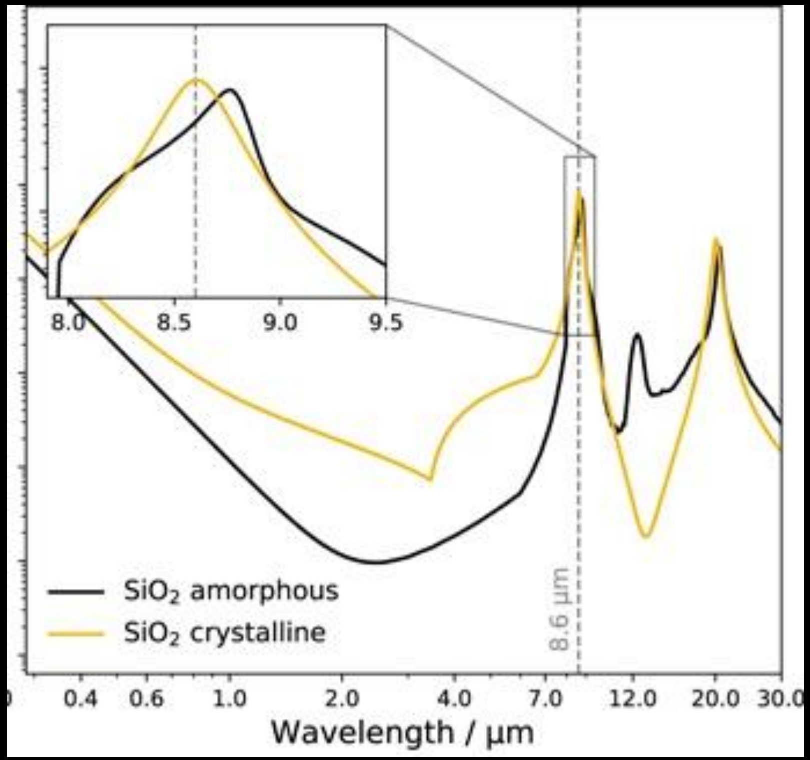


Calamari et al., *ApJ* 2024; Calamari et al., *ApJL*, 2026

Clouds: *Morphology*

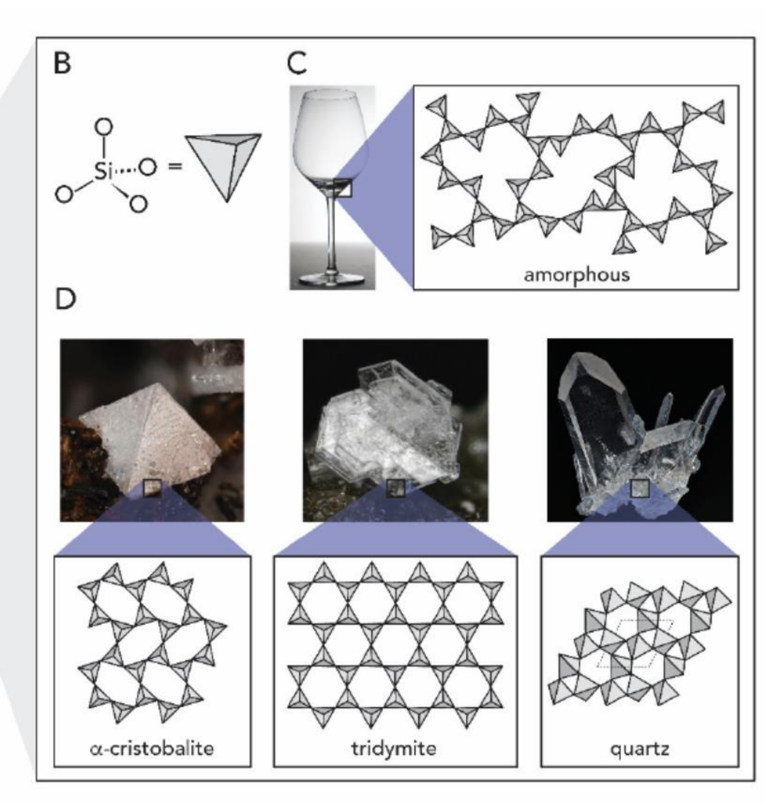
WASP-17b's SiO_2 clouds seem to be crystalline, not amorphous, with sub-micron sized particles



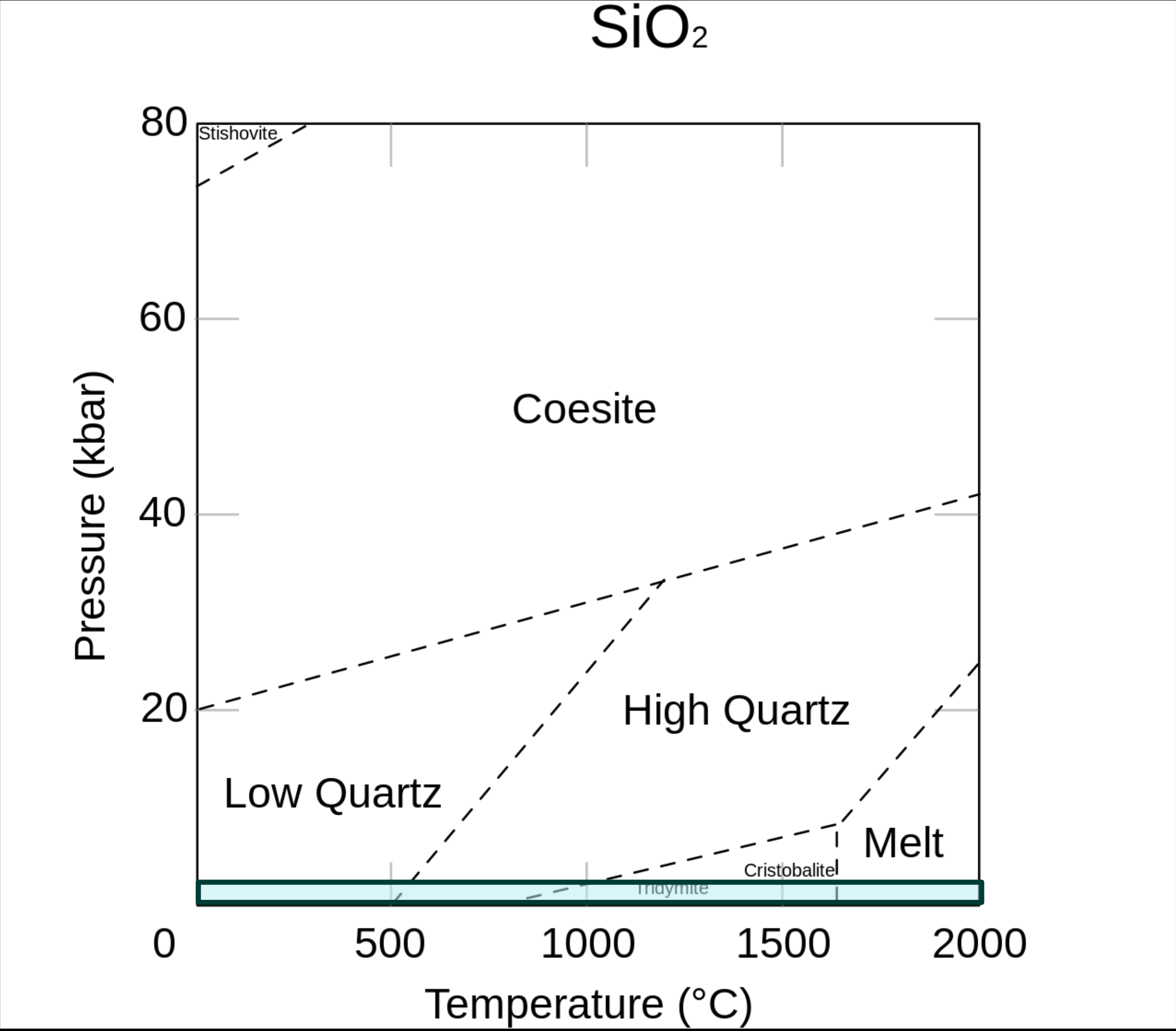


Grant et al., *ApJL* 2023

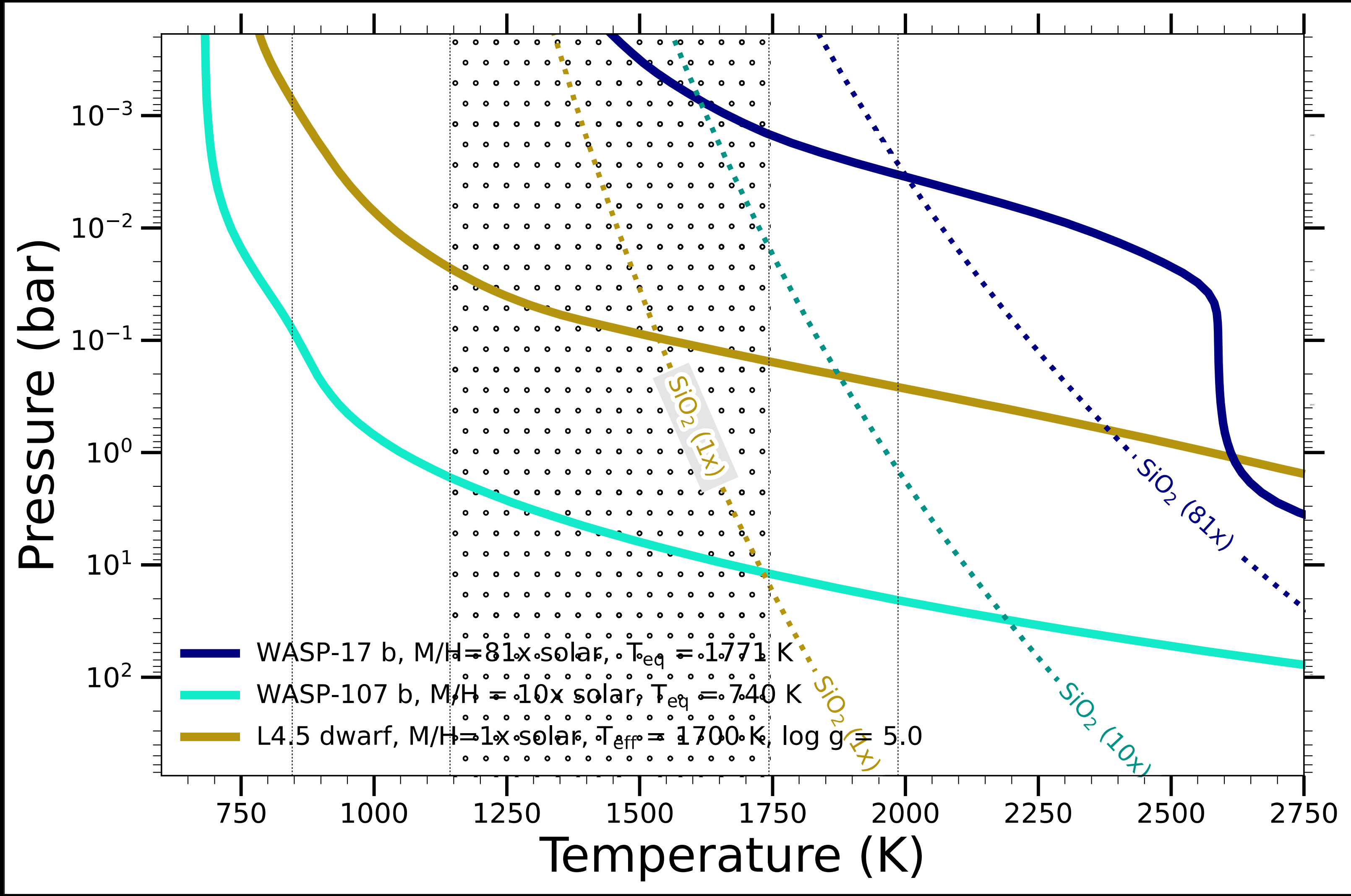
There are multiple stable polymorphs of many minerals – including SiO_2 – at high temperature/low pressure conditions

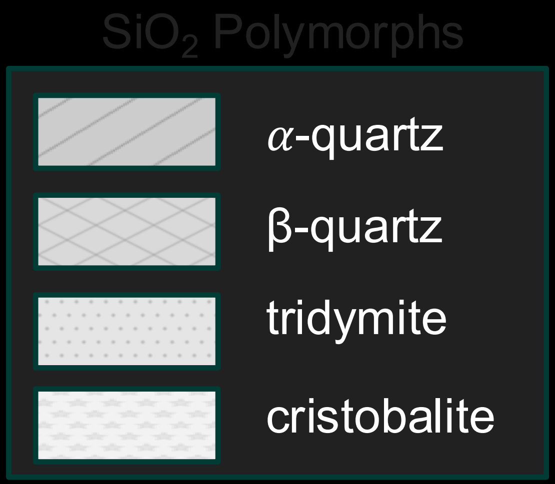


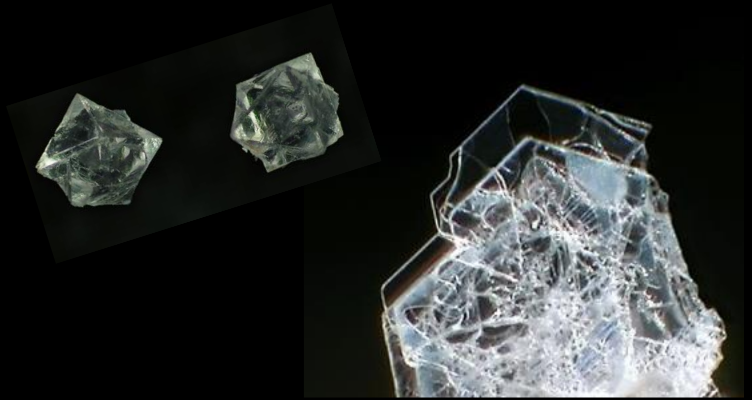
Moura et al., 2020, *Biomimetics*



There are multiple stable polymorphs of SiO_2 at the high temperature/low pressure conditions of substellar atmospheres

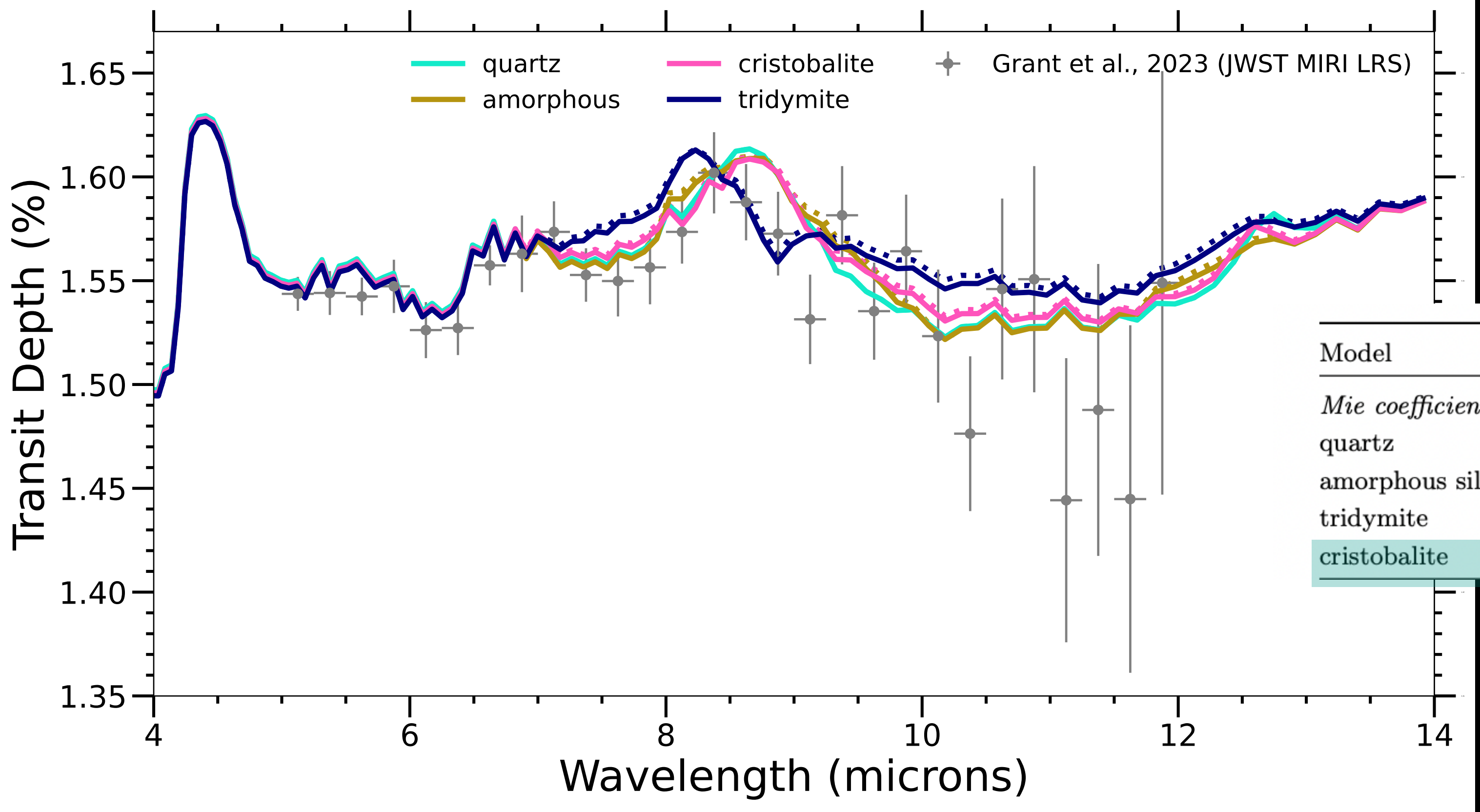






Moran, Marley, & Crossley, *ApJ Letters*, 2024

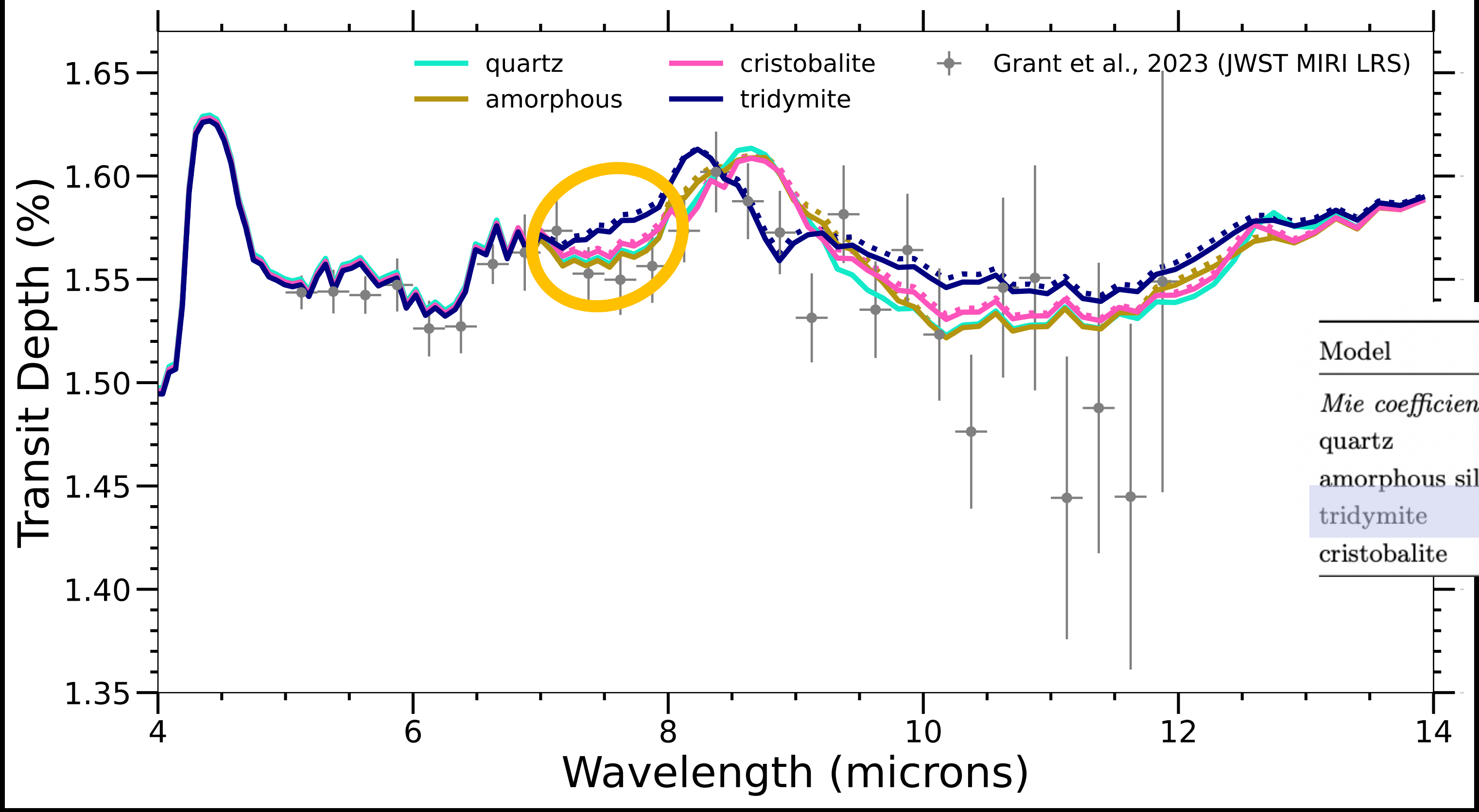
Cristobalite clouds **are a better fit** to the WASP-17 b JWST data compared to either quartz or amorphous silica



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, *ApJ Letters*, 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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tridymite	131.0	1.379**	135.6	5.3
cristobalite	125.7	1.323	130.3	–

**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….

Moran, Marley, Crossley, *ApJ Letters*, 2024

Measurements of tridymite leave something to be desired

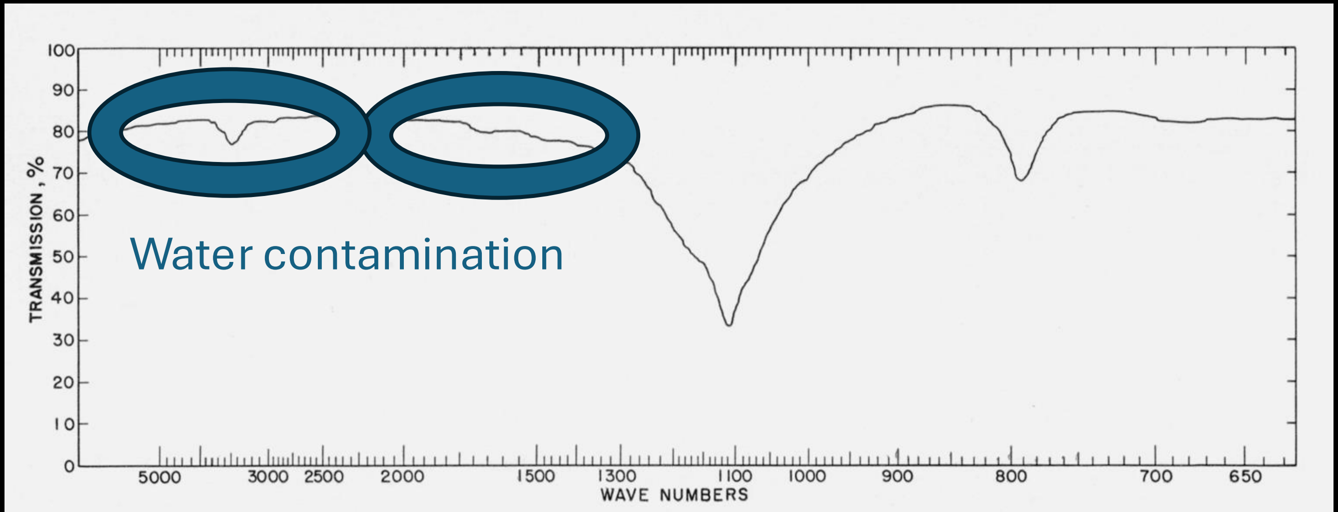
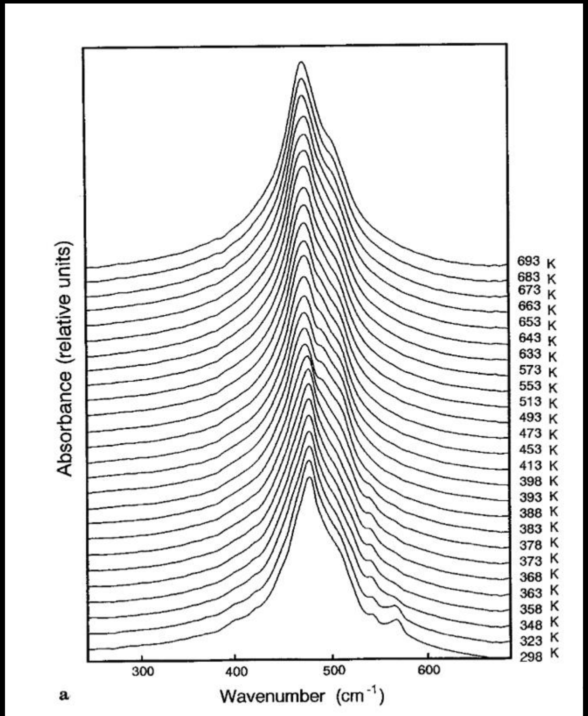


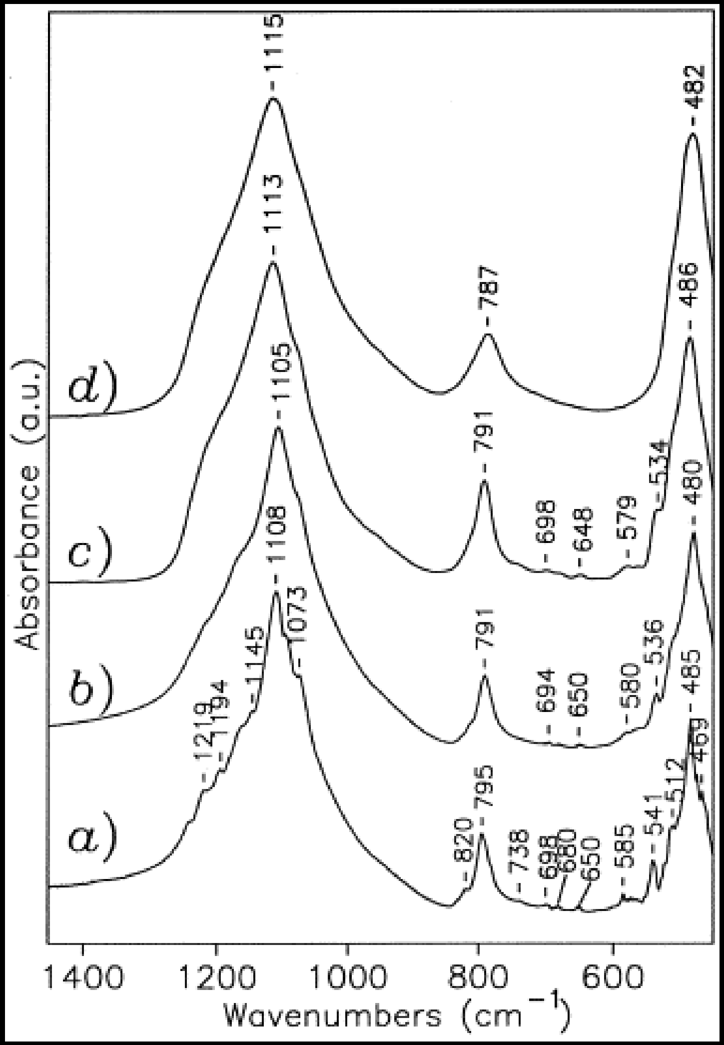
FIGURE 3. *Infrared transmission spectrogram of tridymite.*

Lippincott et al., 1958



Cellai et al., 1995

"Samples were prepared by the standard KBr pellets method."

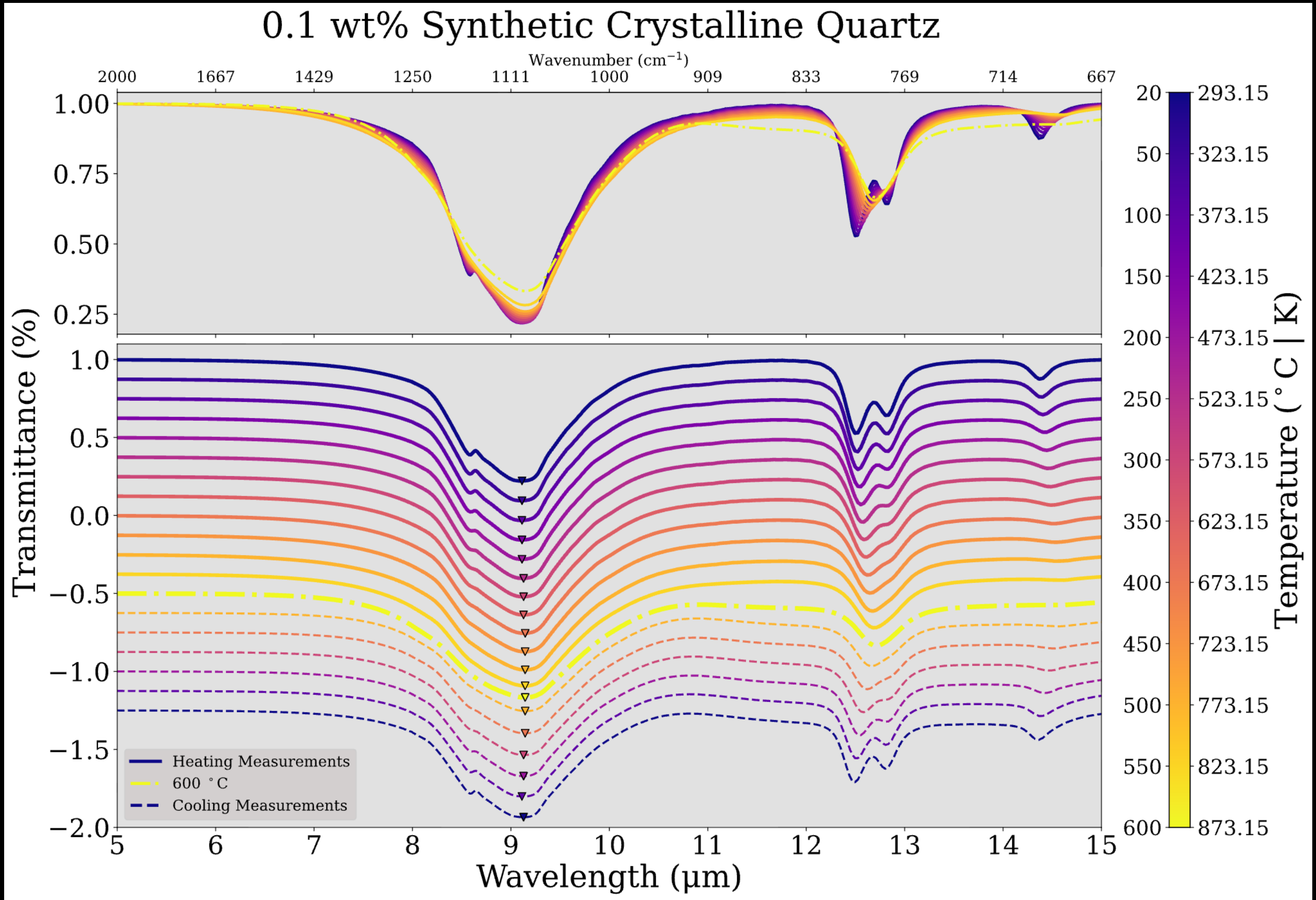


Sitarz et al., 2000

Modern labs can step in to provide new, well-vetted and applicable silicate material laboratory measurements

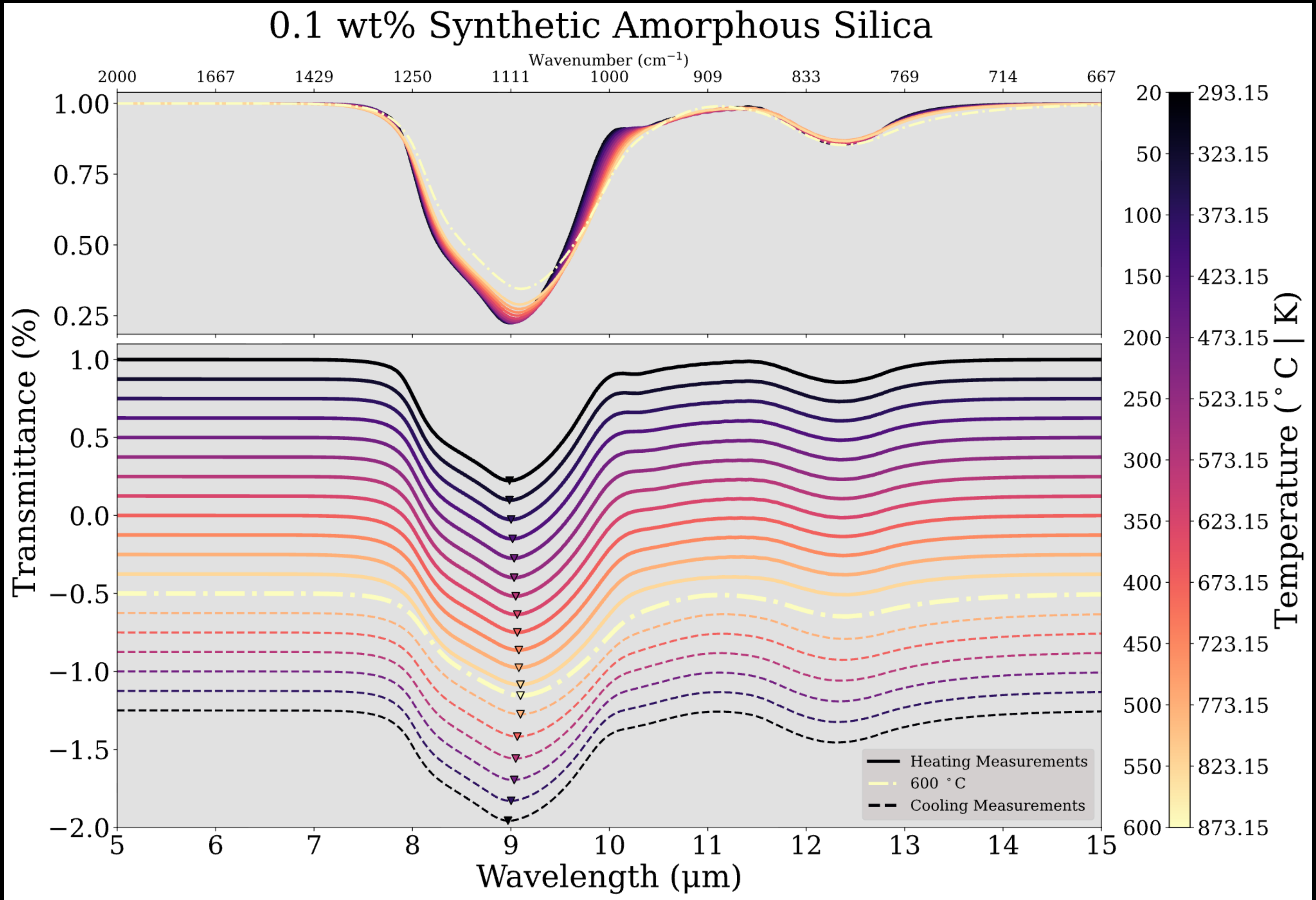
From here on out, many in prep results…
so no photos* or social media please where you see this icon

Quartz absorption shifts near instantaneously, and this transition is *reversible*



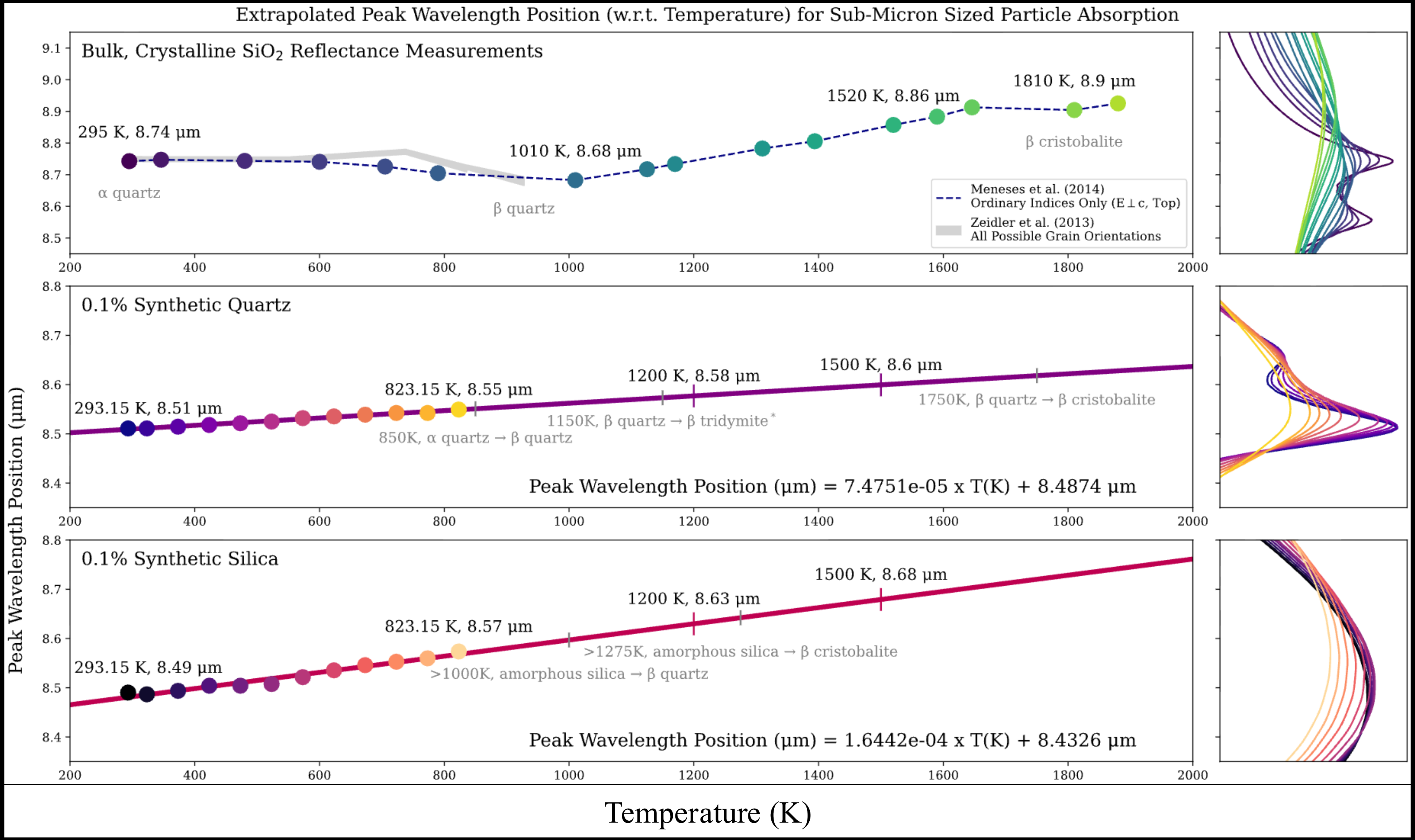
Mullens, Terragni, Moran, et al. submitted

Even *amorphous* SiO_2 absorption shifts near instantaneously, making such clouds a precise probe of atmospheric temperature



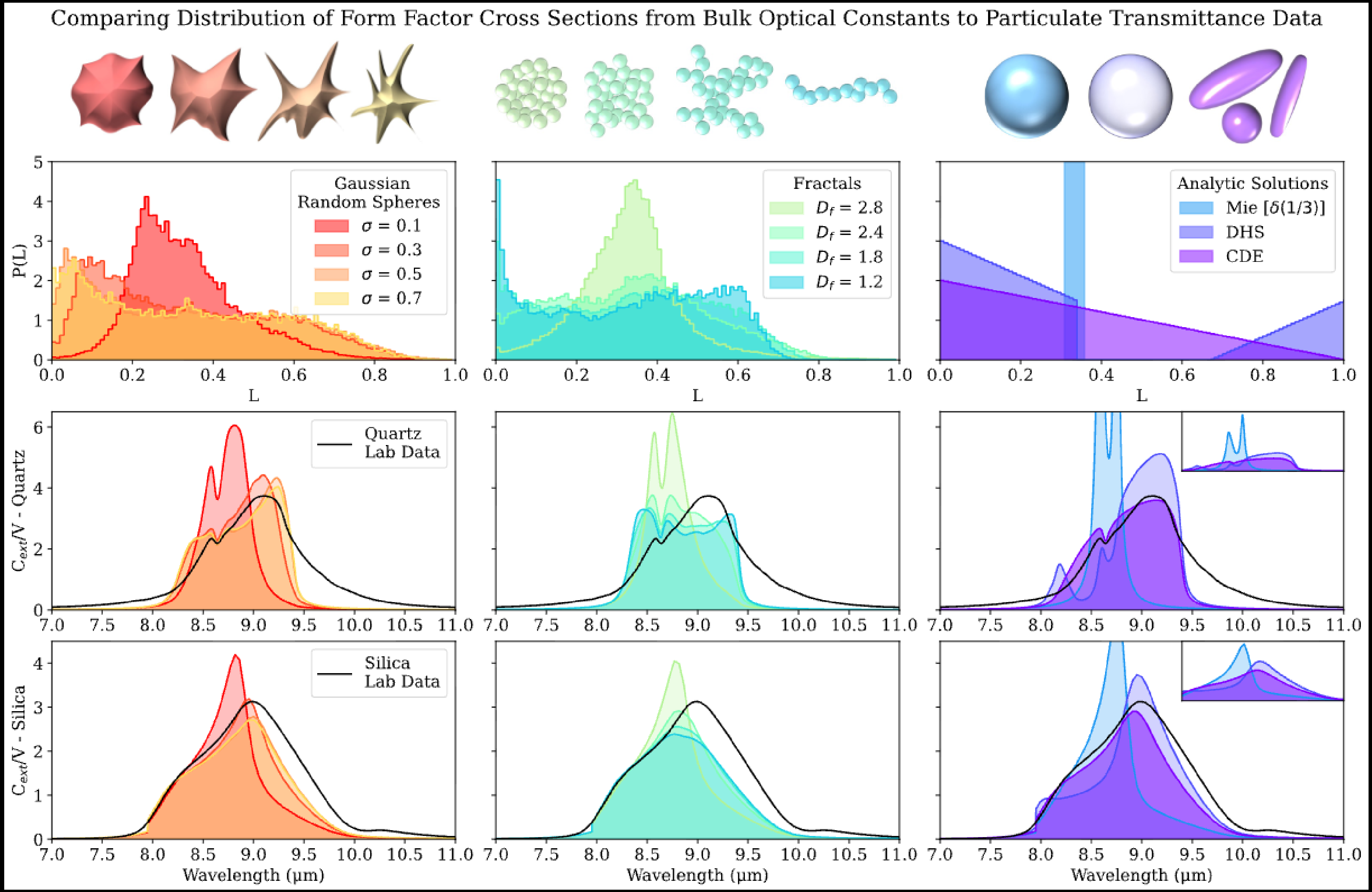
Mullens, Terragni, Moran, et al. submitted

Extrapolating from our (current) lab upper limit to our planets shifts peak wavelength up to 0.3 microns *just for SiO_2*



Mullens, Moran, Terragni, et al. in prep

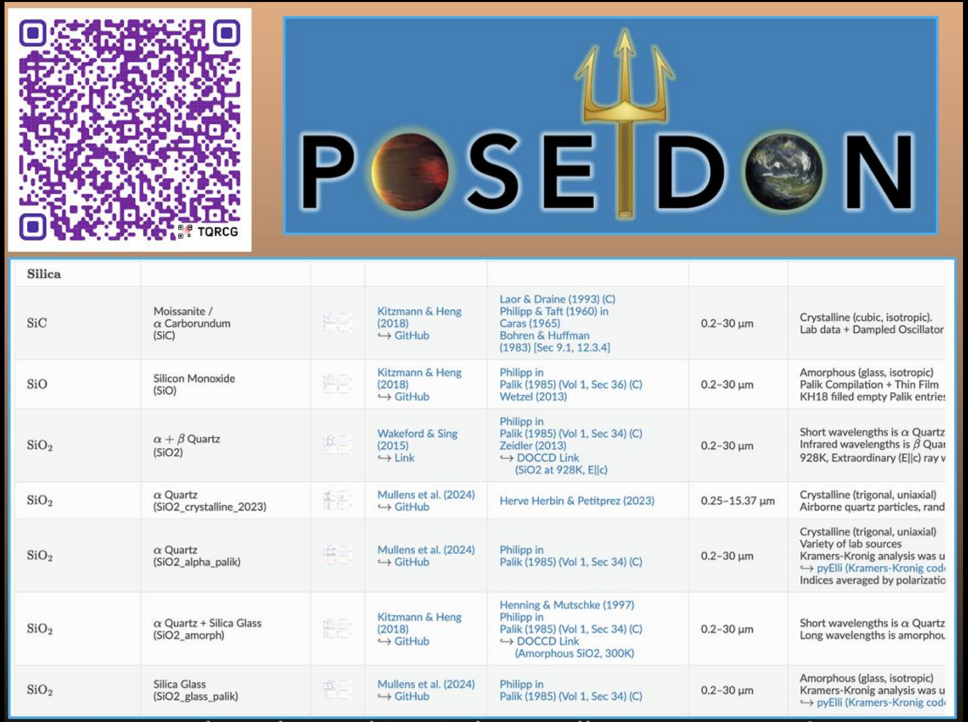
Most optical properties in the literature are from bulk reflectance and then most of us use Mie theory for our models….which is probably biasing our inferences



Mullens, Terragni, Moran, et al. submitted

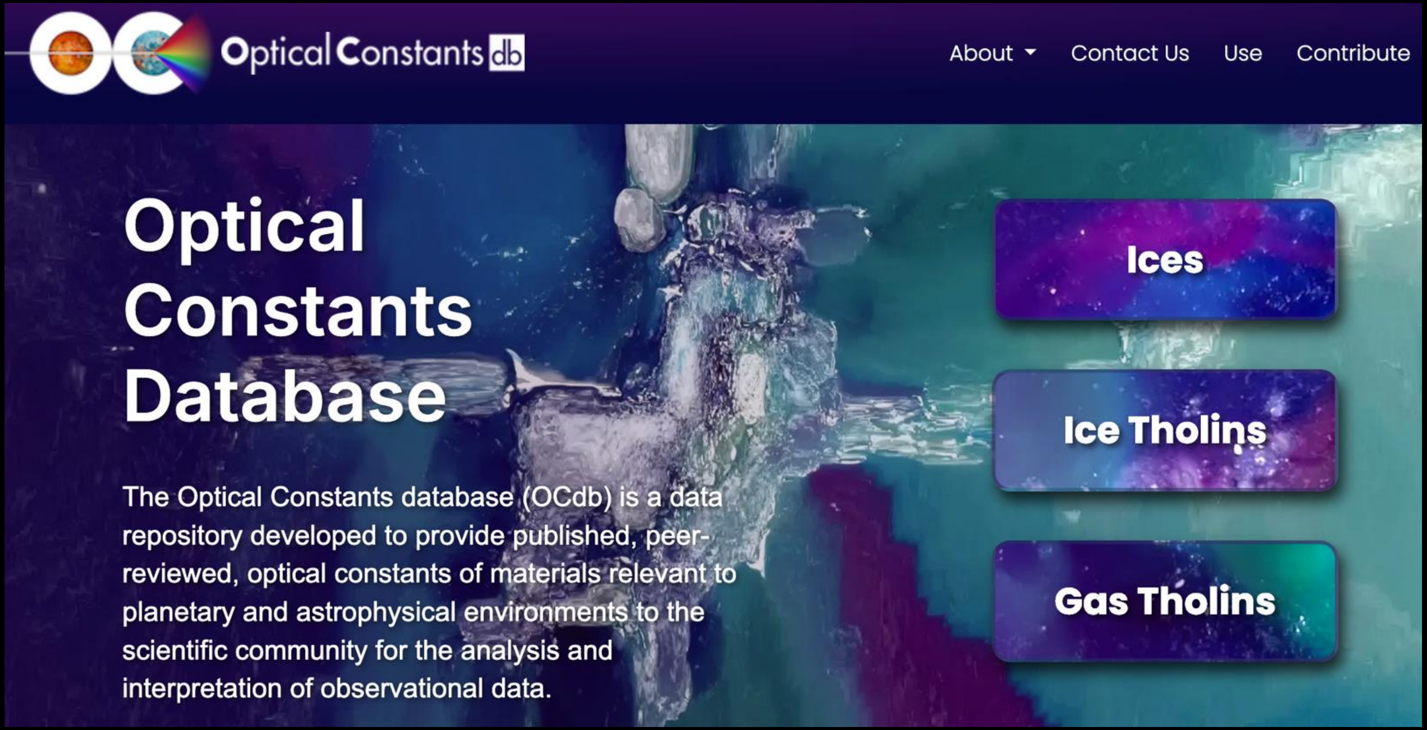
There are some incredible databases of optical properties with extensive docs and some incredible, actively developed models using the newest lab data

Mullens, Lewis & MacDonald, ApJ, 2024



Silica						
SiC	Moissanite / α Carborundum (SiC)		Kitzmann & Heng (2018) ↪ GitHub	Laor & Draine (1993) (C) Philipp & Taft (1960) in Caras (1965) Bohren & Huffman (1983) [Sec 9.1, 12.3.4]	0.2–30 µm	Crystalline (cubic, isotropic). Lab data + Dampled Oscillator
SiO	Silicon Monoxide (SiO)		Kitzmann & Heng (2018) ↪ GitHub	Philipp in Palik (1985) (Vol 1, Sec 36) (C) Wetzel (2013)	0.2–30 µm	Amorphous (glass, isotropic) Palik Compilation + Thin Film KH18 filled empty Palik entries
SiO_2	$\alpha + \beta$ Quartz (SiO2)		Wakeford & Sing (2015) ↪ Link	Philipp in Palik (1985) (Vol 1, Sec 34) (C) Zeidler (2013) ↪ DOCCD Link (SiO2 at 928K, E||c)	0.2–30 µm	Short wavelengths is α Quartz Infrared wavelengths is β Quar 928K, Extraordinary (E||c) ray v
SiO_2	α Quartz (SiO2_crystalline_2023)		Mullens et al. (2024) ↪ GitHub	Herve Herbin & Petitprez (2023)	0.25–15.37 µm	Crystalline (trigonal, uniaxial) Airborne quartz particles, rand
SiO_2	α Quartz (SiO2_alpha_palik)		Mullens et al. (2024) ↪ GitHub	Philipp in Palik (1985) (Vol 1, Sec 34) (C)	0.2–30 µm	Crystalline (trigonal, uniaxial) Variety of lab sources Kramers-Kronig analysis was u ↪ pyElli (Kramers-Kronig cod Indices averaged by polarizatio
SiO_2	α Quartz + Silica Glass (SiO2_amorph)		Kitzmann & Heng (2018) ↪ GitHub	Henning & Mutschke (1997) Philipp in Palik (1985) (Vol 1, Sec 34) (C) ↪ DOCCD Link (Amorphous SiO2, 300K)	0.2–30 µm	Short wavelengths is α Quartz Long wavelengths is amorphou
SiO_2	Silica Glass (SiO2_glass_palik)		Mullens et al. (2024) ↪ GitHub	Philipp in Palik (1985) (Vol 1, Sec 34) (C)	0.2–30 µm	Amorphous (glass, isotropic) Kramers-Kronig analysis was u ↪ pyElli (Kramers-Kronig cod

~70 rocks, salts, and ices in base collection, out now!
In depth readme file on how lab data was taken.



managed by Ella Sciamma-O'Brien at NASA Ames

e.g., Lodge & Moran et al., ApJ, 2026

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Takeaways

Hazes readily incorporate **oxygen and sulfur as well as carbon.**
They are probably **fractal aggregates.**

Clouds can be both minerals and organics & therefore depend on **bulk planet chemistry**,
For minerals, **polymorphs** matter. For organics, **fractal aggregates** matter.

These differences are observable existing telescopes, and thus
clouds and hazes *are tracers* of atmospheric condition via remote sensing

We require high accuracy, high precision laboratory data to be folded into the models used to interpret observational data