Sven Kiefer

Cloud formation in 3D exoplanet atmospheres

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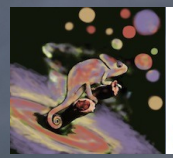
Paul Palmer

Chair: Patrick Wagner

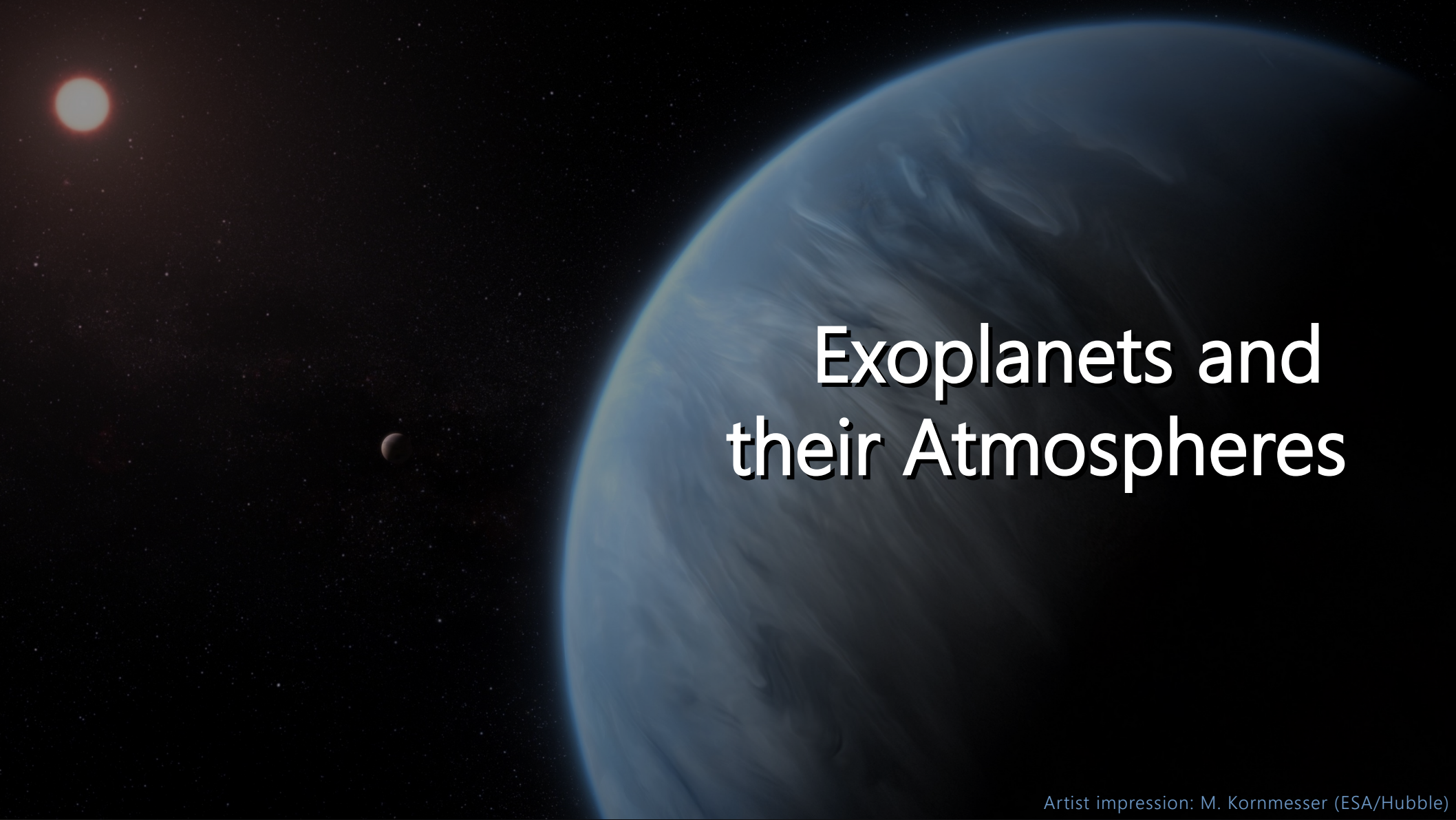


This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Sklodowska-Curie grant agreement no. 860470

The Importance of Clouds in Exoplanet Atmospheres

- Exoplanets and their Atmospheres
- PART I – Clouds and their Environment
- PART II – Optical Properties of Cloud particles
- PART III – The Climate of Warm Saturns
- Summary

Exoplanets and their Atmospheres



Artist impression: M. Kornmesser (ESA/Hubble)

Where can we find clouds?

Where can we find clouds?

Credit: NASA/JPL

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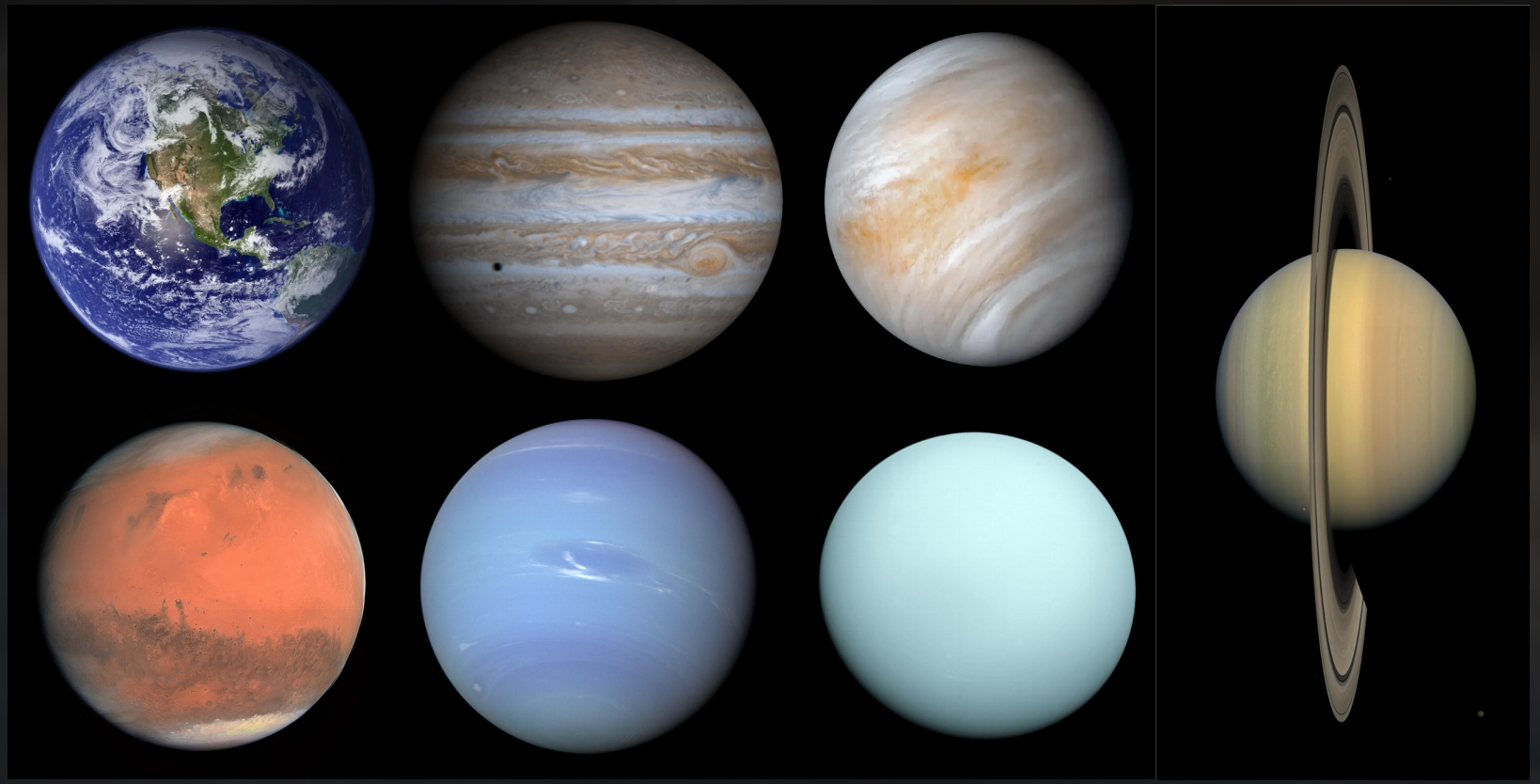

Credit: NASA/JPL

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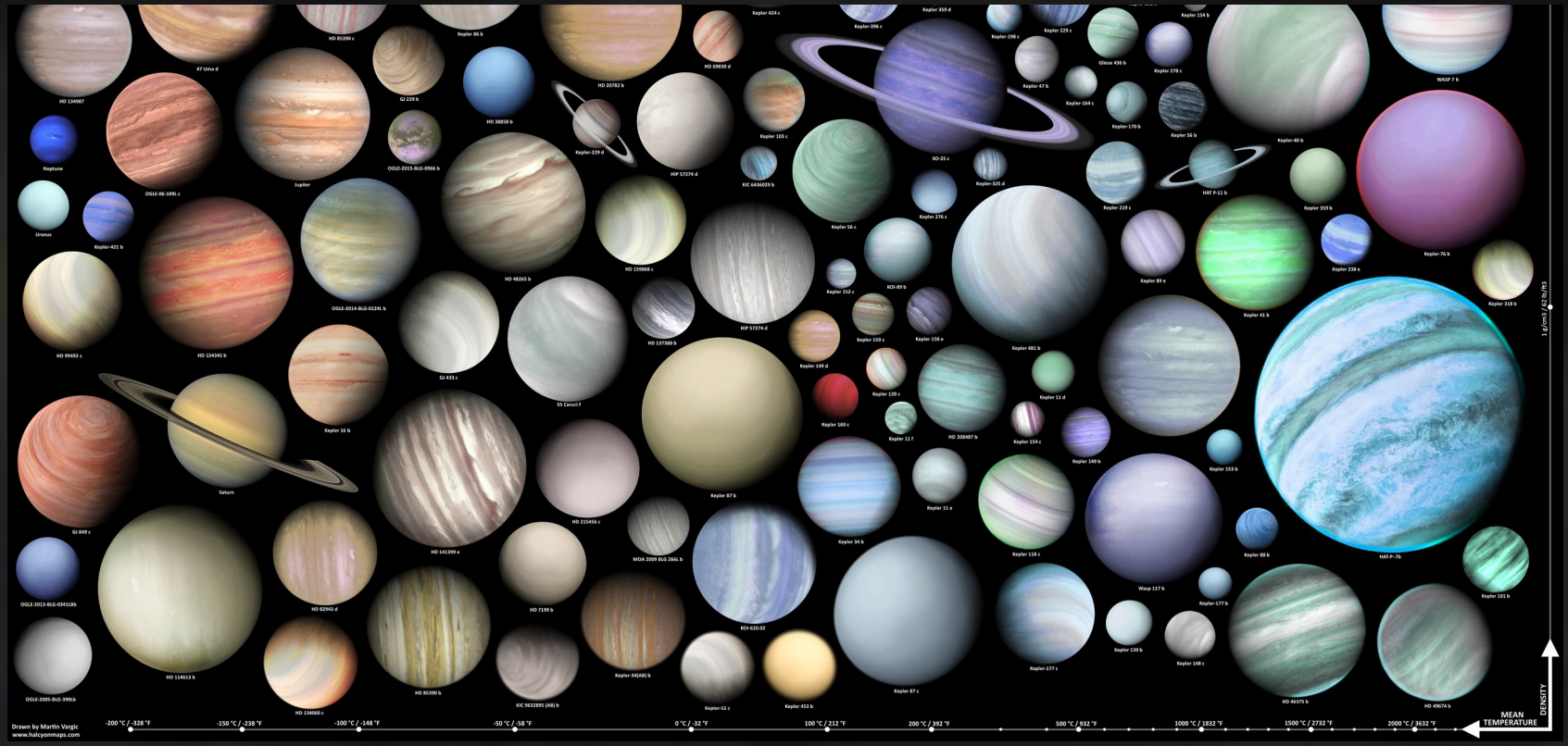
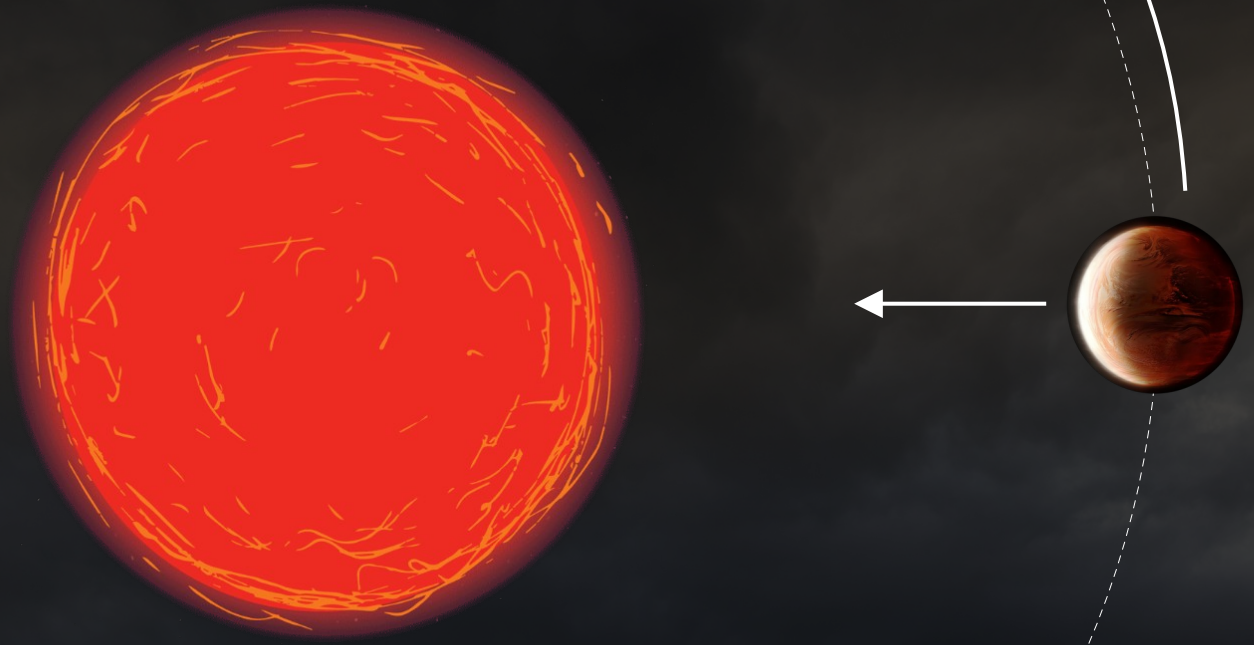


Artist impression: Martin Vargic

What is a hot Jupiter?



Hot Jupiters:

- Radius ~ Jupiter
- Mass ~ Jupiter
- Temperature ~ 1500 K
- Orbit ~ days
- Permanent day side

Artist impression: ESA

How do clouds form? - Let’s start with Earth!

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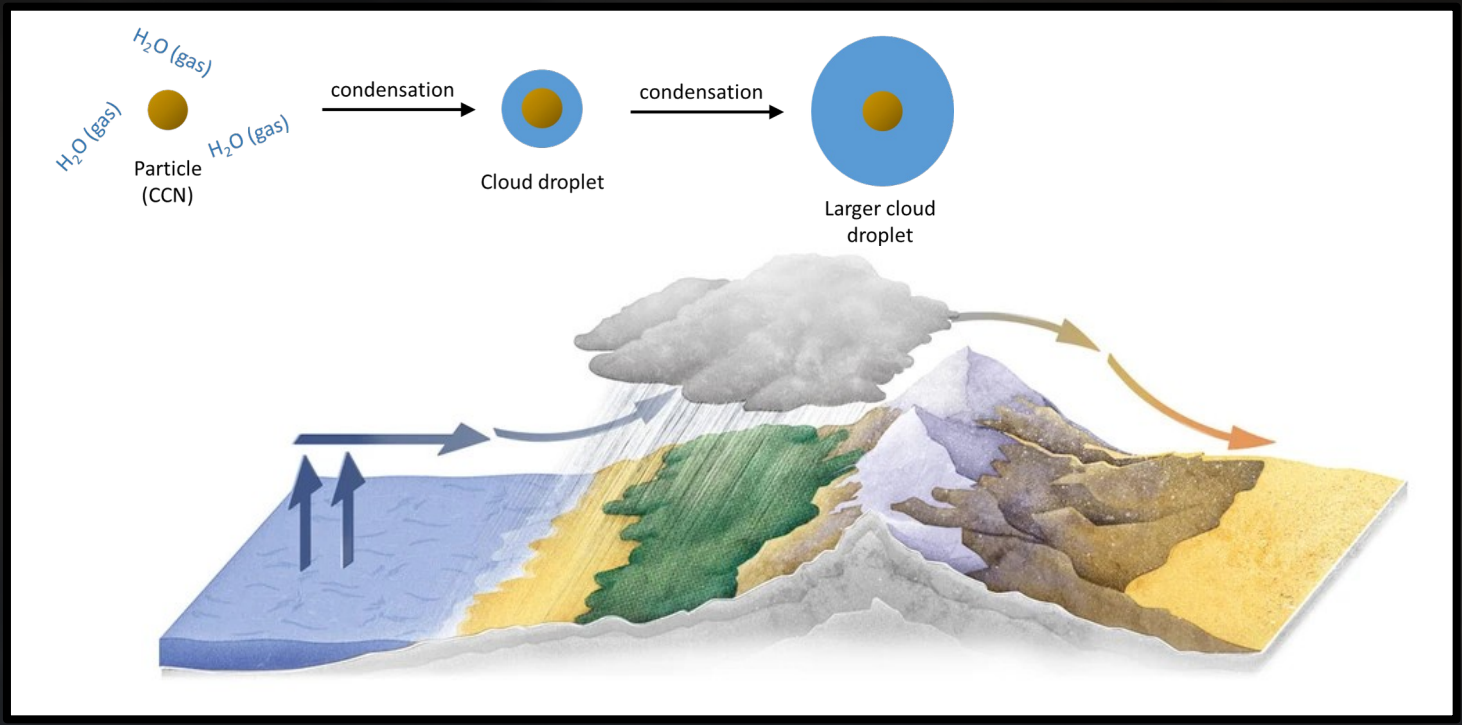


Top Image: Aerosols Department Of Physics And Astronomy Uppsala
Bottom Image: BBC science focus, Alexandra Franklin-Cheung

How do clouds form in gaseous planets?

Image altered from Helling (2018)

How do clouds form in gaseous planets?

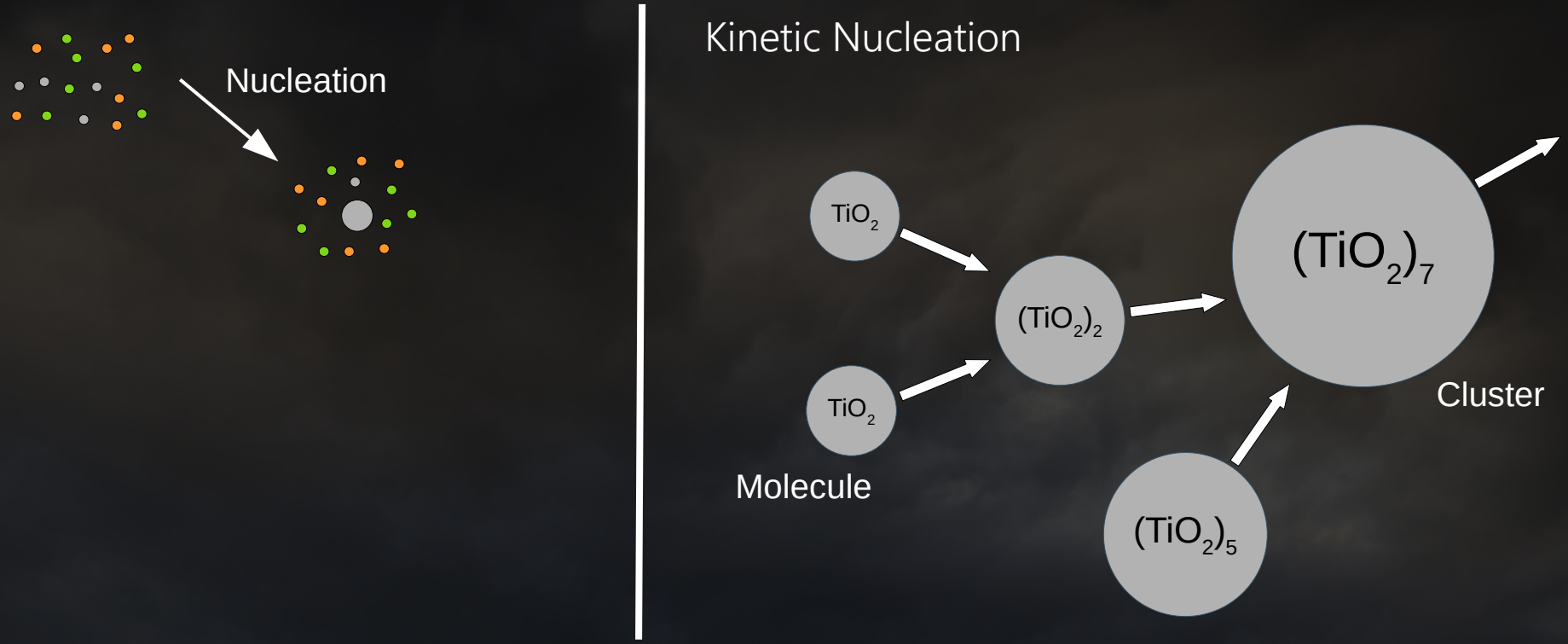
Kinetic Chemistry

What we consider:
→ N, C, H, O
→ Ti, Si
→ 69 species
→ 780 reactions

$NH + H2O \rightarrow NH2 + OH$

Image altered from Helling (2018)

How do clouds form in gaseous planets?



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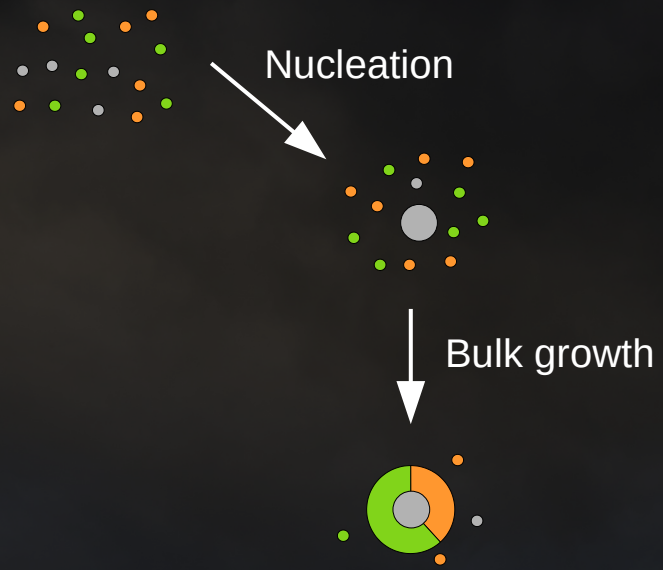
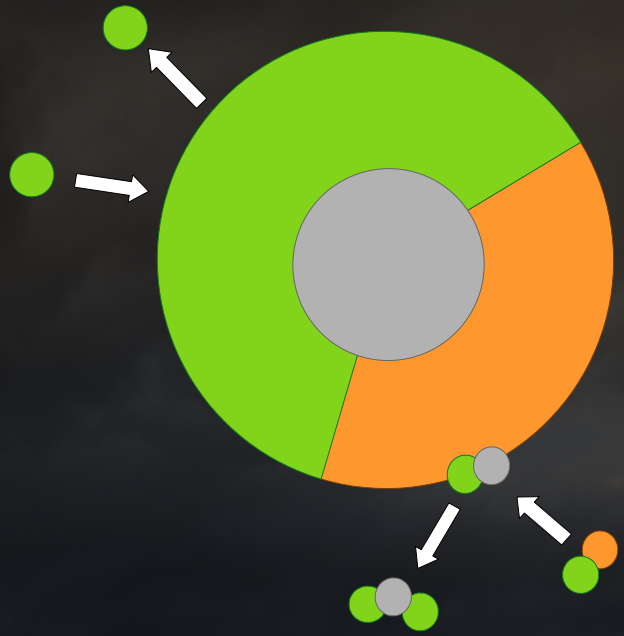


Image altered from Helling (2018)

Bulk Growth



Cloud materials like:

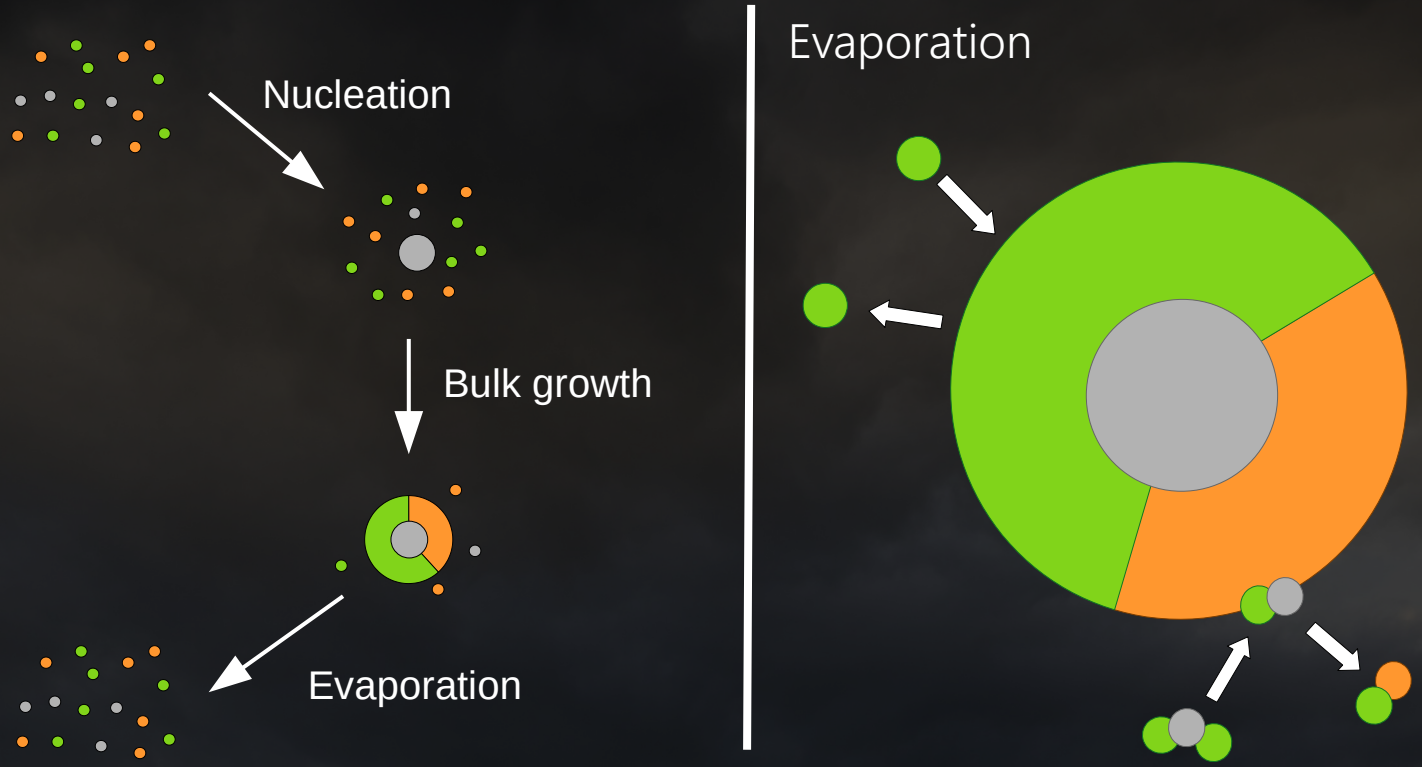
→ SiO, SiO_2

→ Mg_2SiO_4

→ FeO, Fe_2O_3, Fe

→ Total: 16 species

How do clouds form in gaseous planets?



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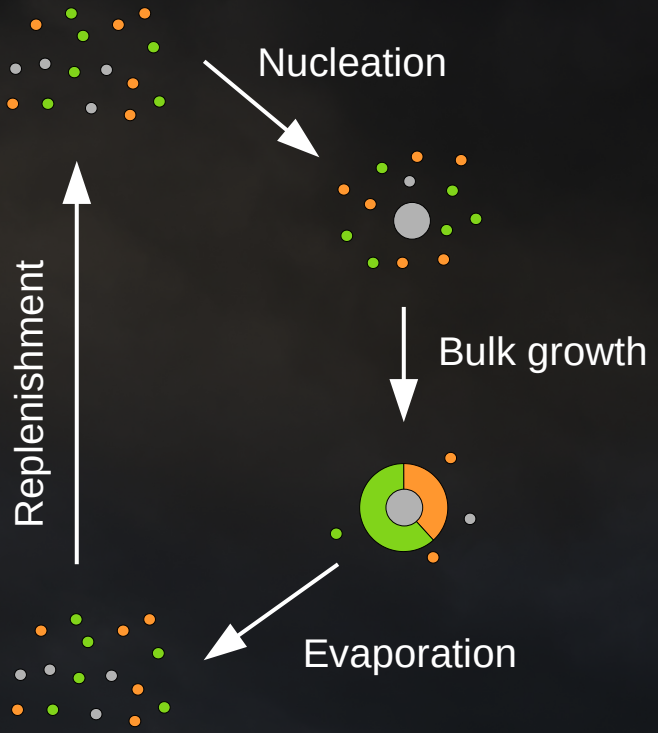

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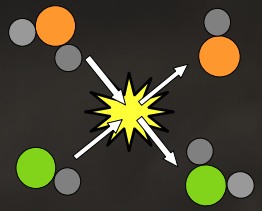
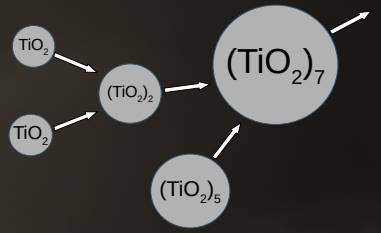


Kinetic Nucleation



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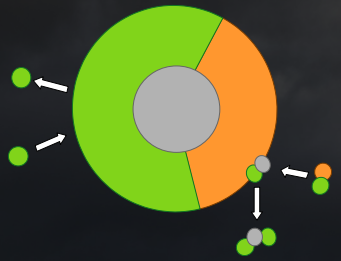
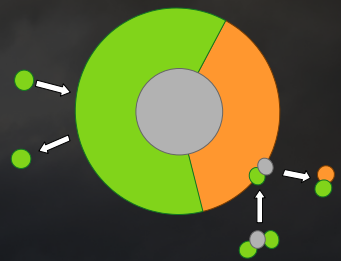


Evaporation



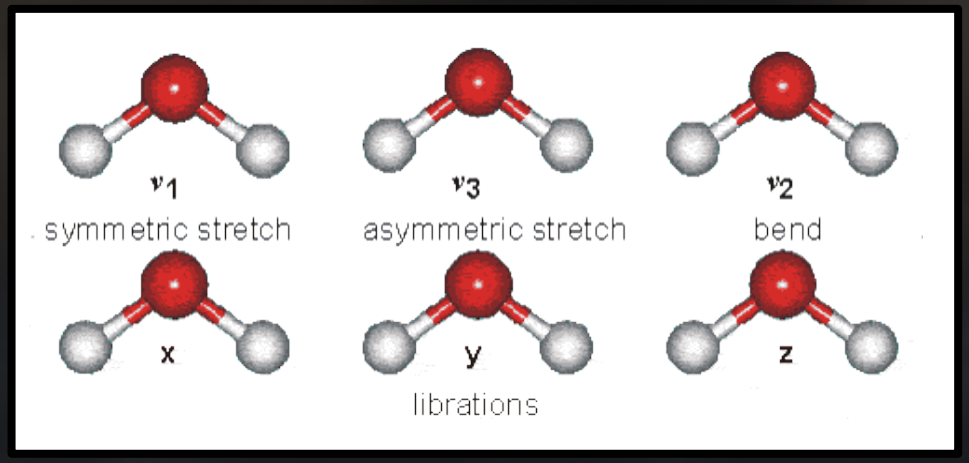
PART I
Clouds and their Environment

Artist impression: M. Kornmesser (ESA/Hubble)

The importance of temperatures

The importance of temperatures

Temperature moves the molecules …



Left Gif: Joachim Gruber (London South Bank University)

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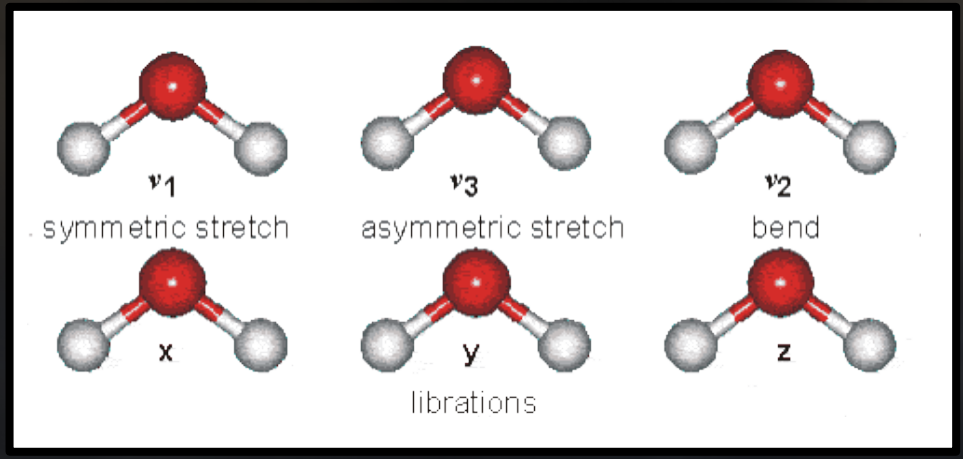
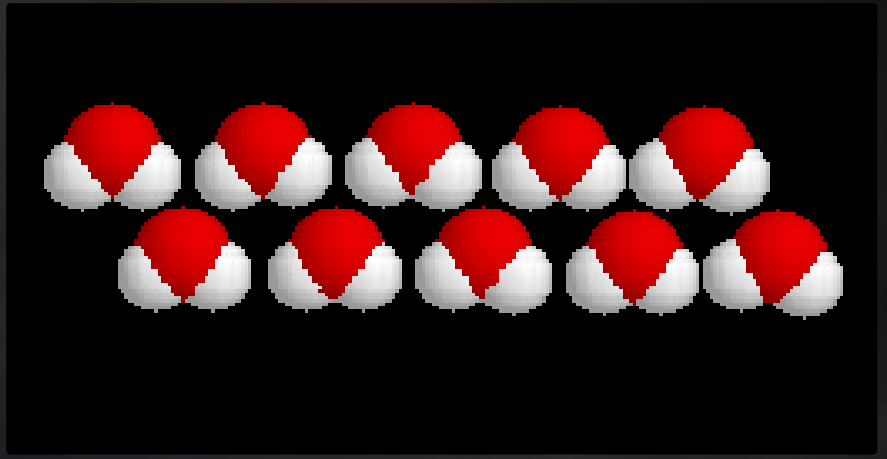
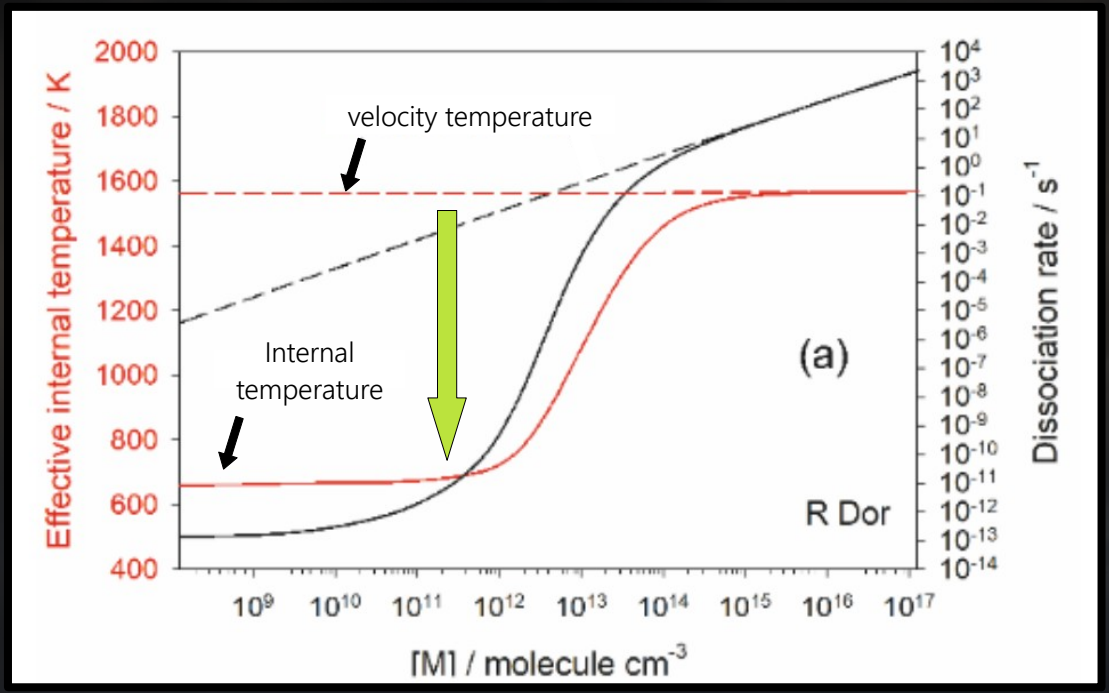


… which determines how they grow.



Left Gif: Joachim Gruber (London South Bank University)
Right Gif: Eric Martz (Atlas of Macromolecules)

The importance of temperatures



Plane & Robertson (2022)

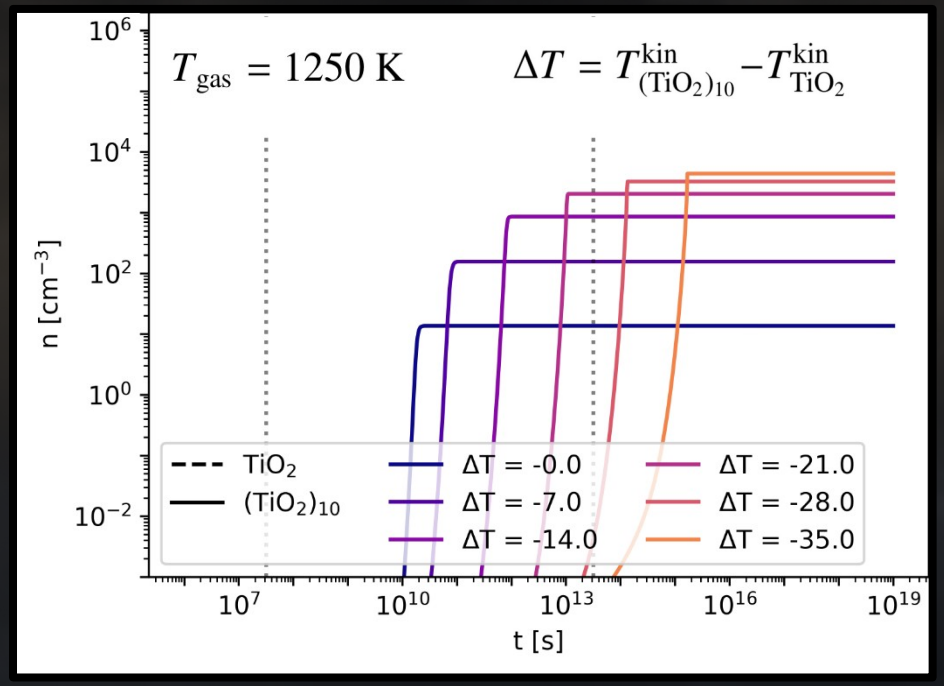
Plane and Robertson 2022:

- Outflows of AGB stars
- Dissociation of $OSi(OH)_2$
- Internal cooling via optical lines

Observational evidence:

- Fonfria et al. 2008, 2017, 2021

The importance of temperatures



Kiefer et al. (2023)

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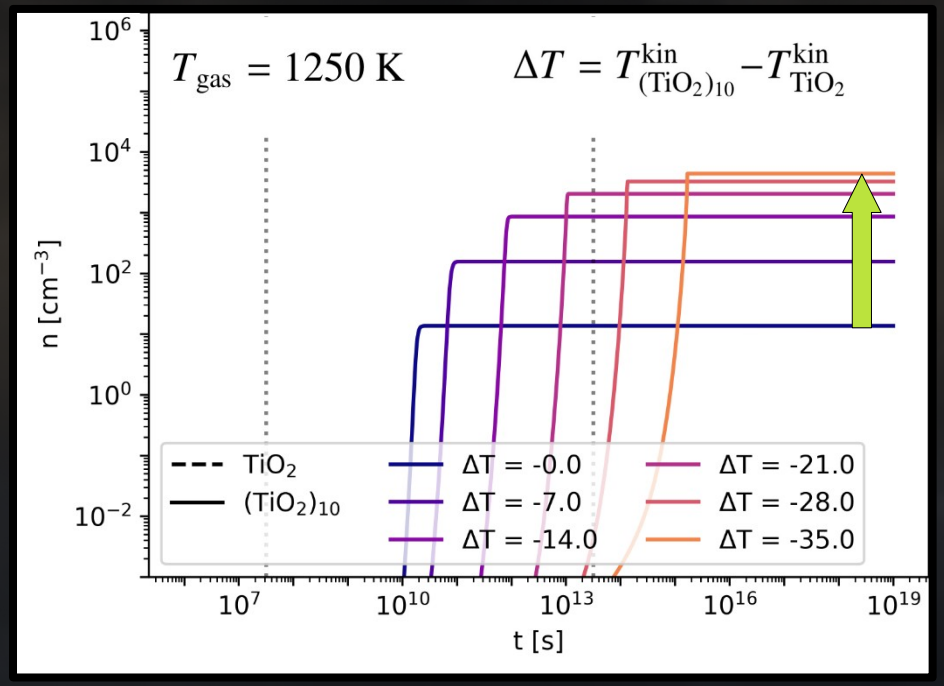
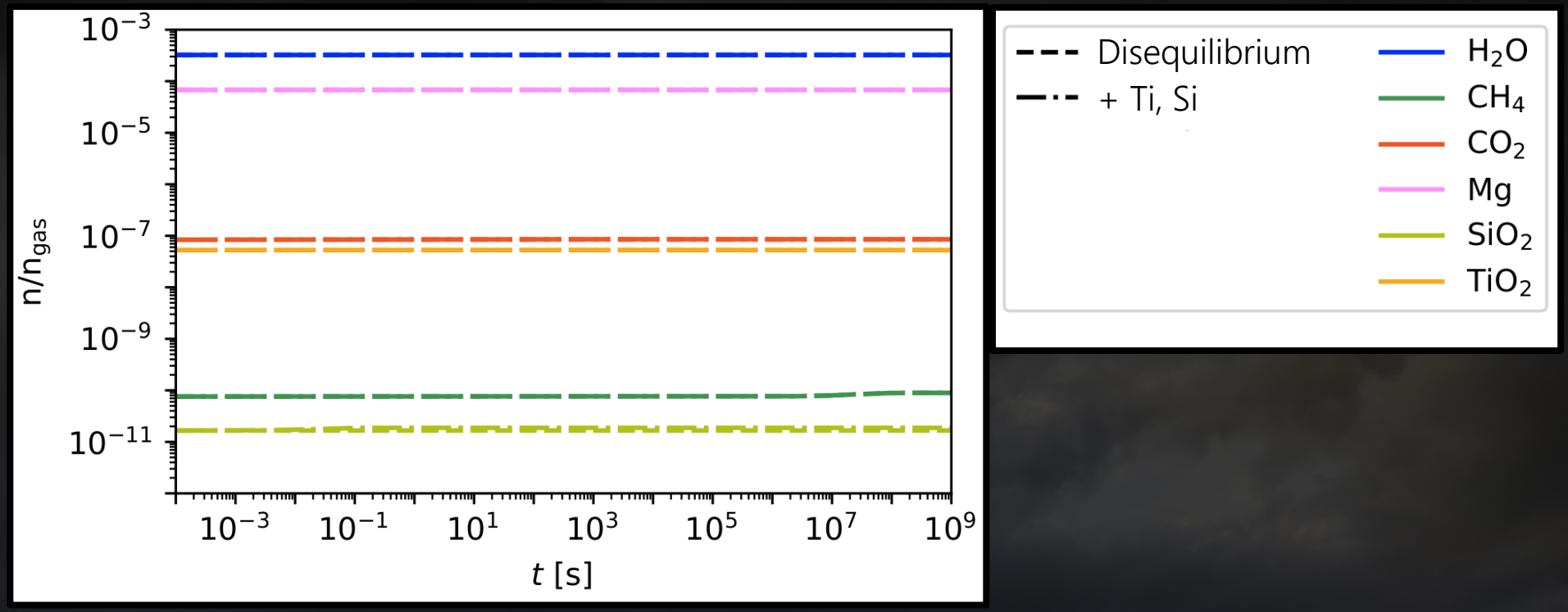


Kiefer et al. (2023)

If larger clusters move slower then more larger clusters can form.

If larger clusters move faster then fewer larger clusters can form.

How clouds affect the gas-phase chemistry



Kiefer et al. (2024a)

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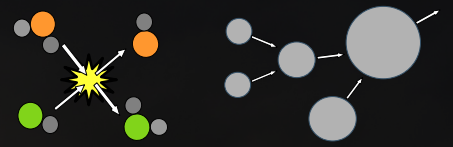

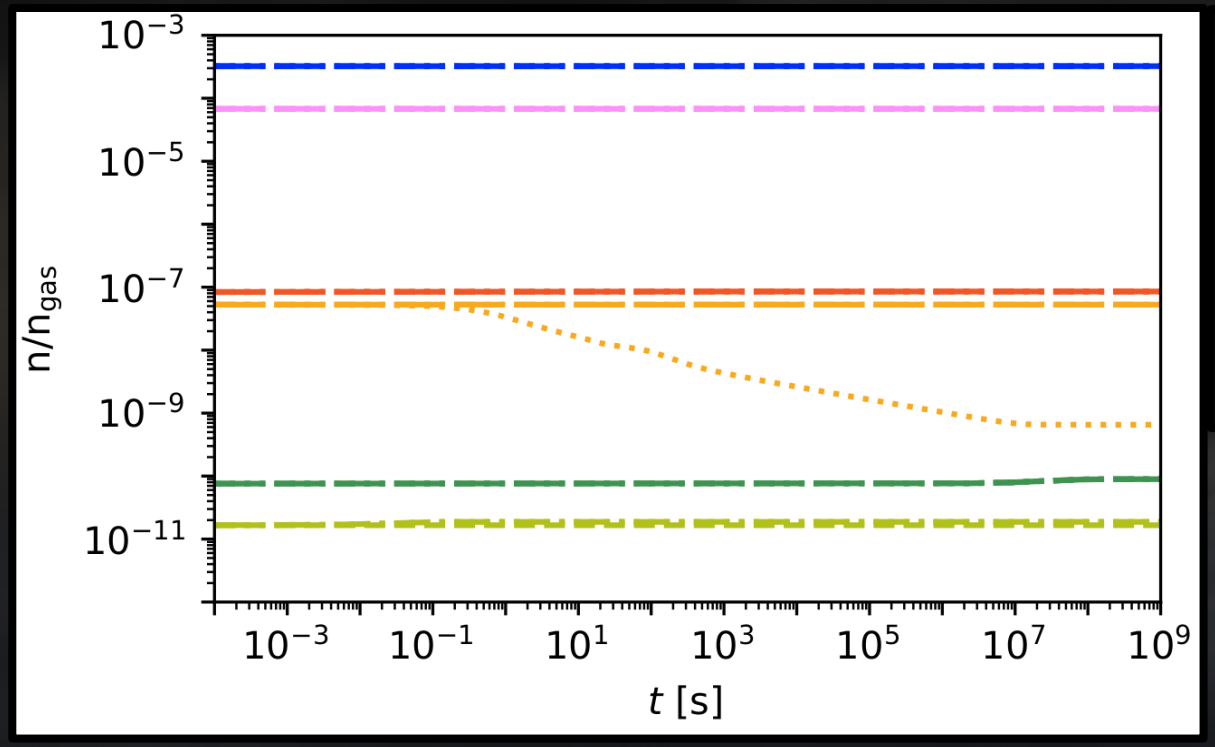

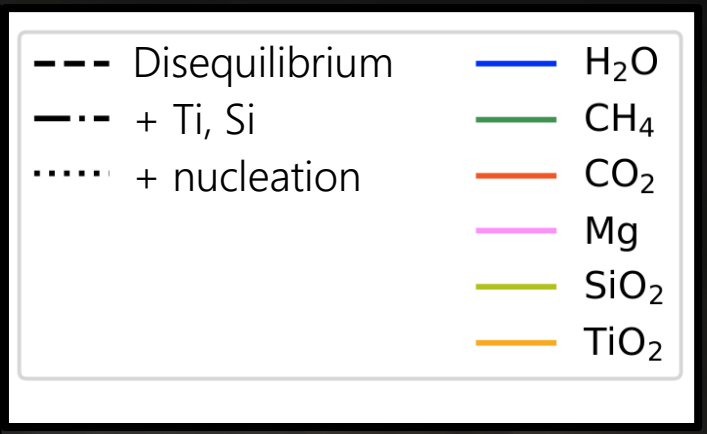

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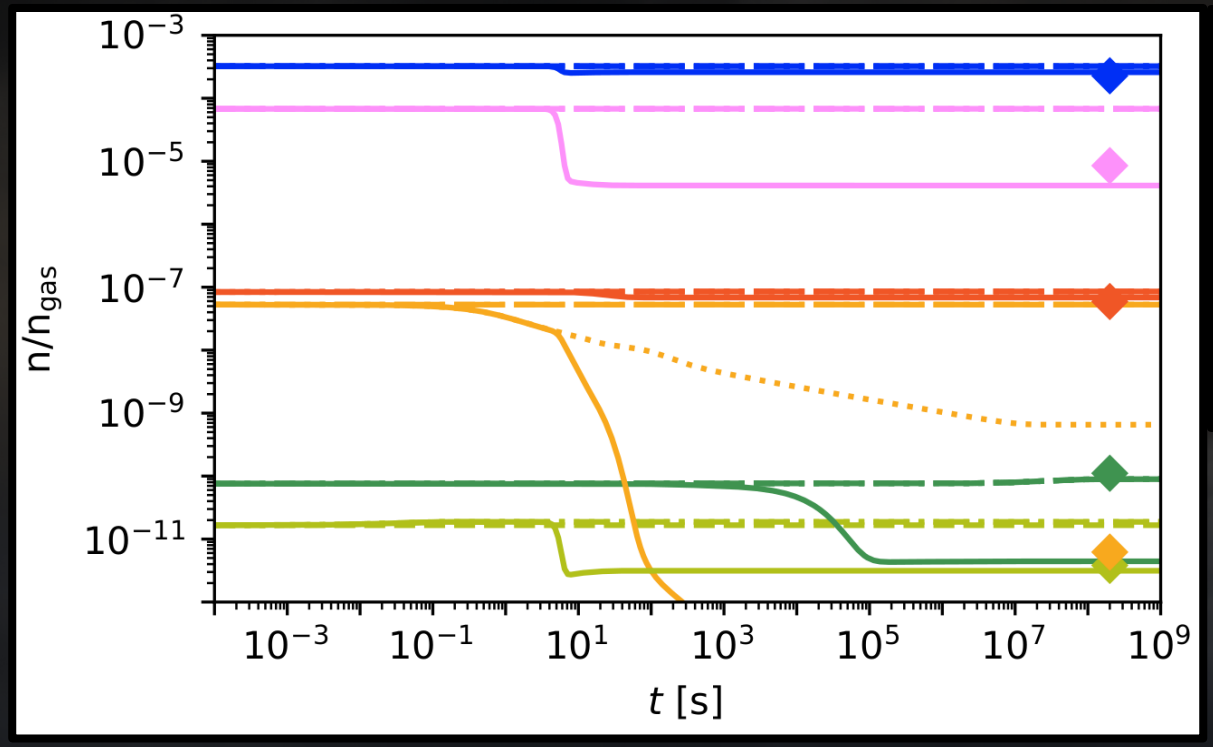


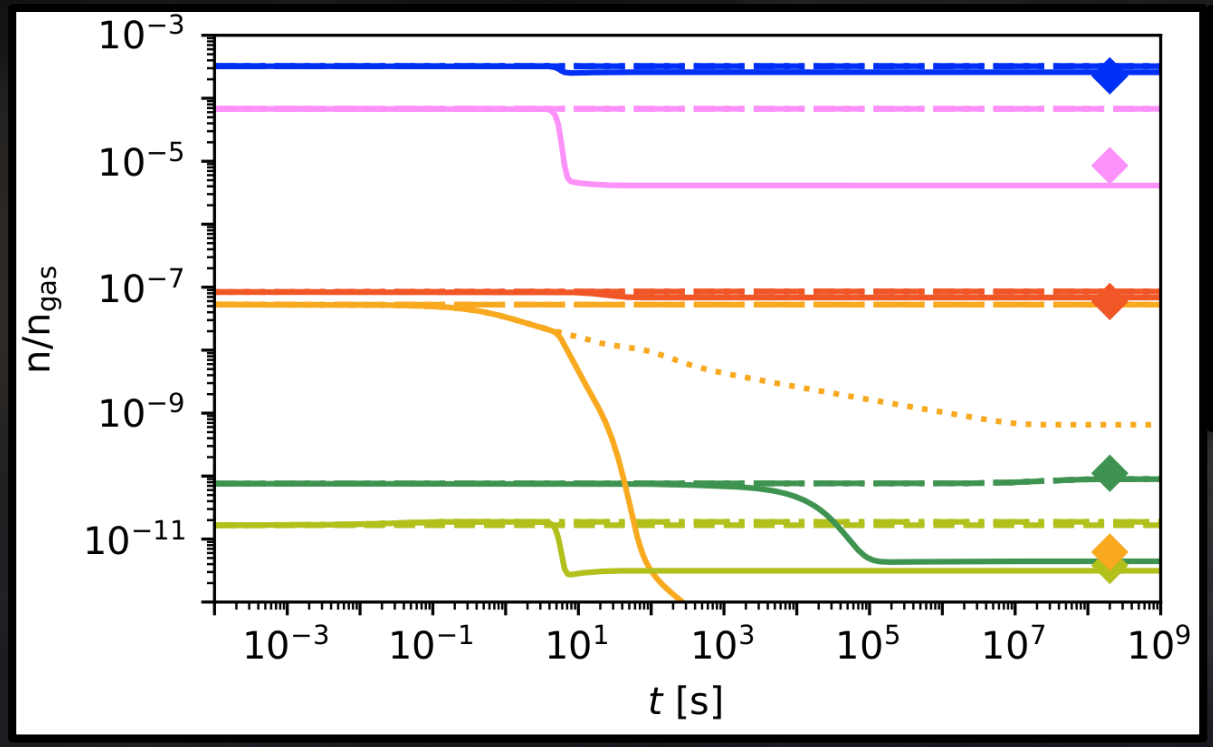
Kiefer et al. (2024a)

Disequilibrium
+ Ti, Si
+ nucleation
+ bulk growth
Equilibrium

H_2O
CH_4
CO_2
Mg
SiO_2
TiO_2

Effect of clouds:

How clouds affect the gas-phase chemistry



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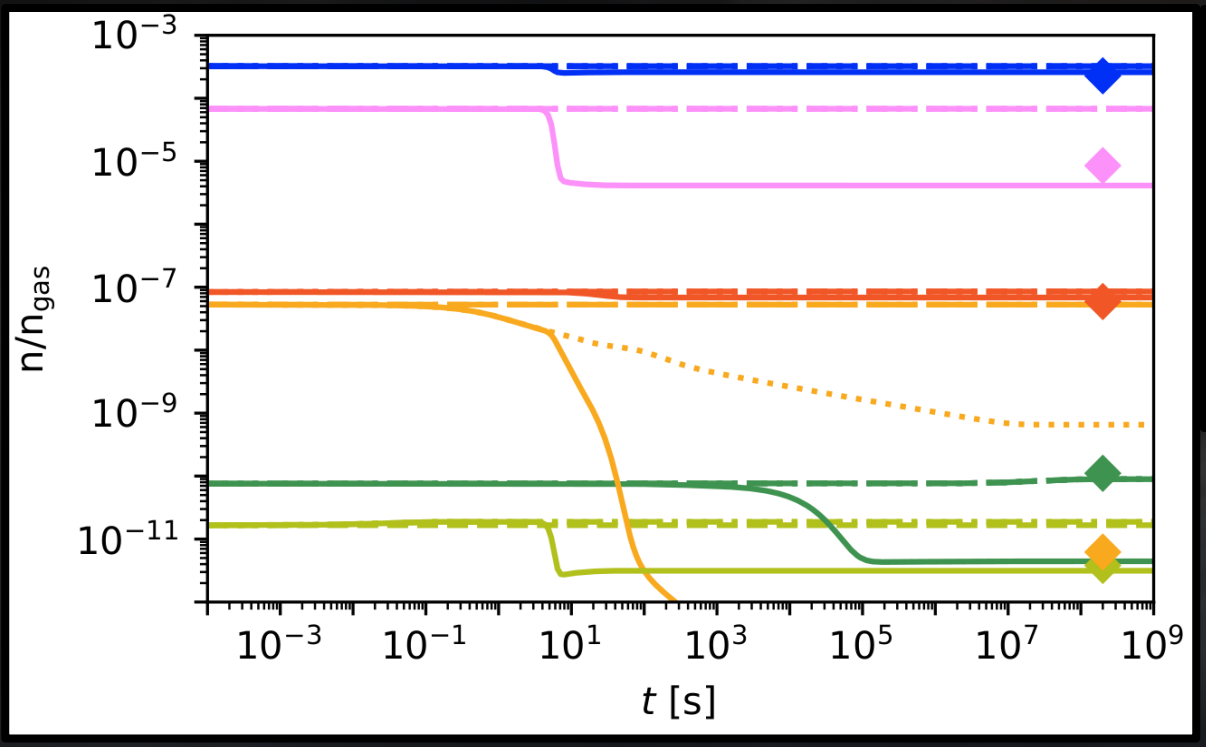

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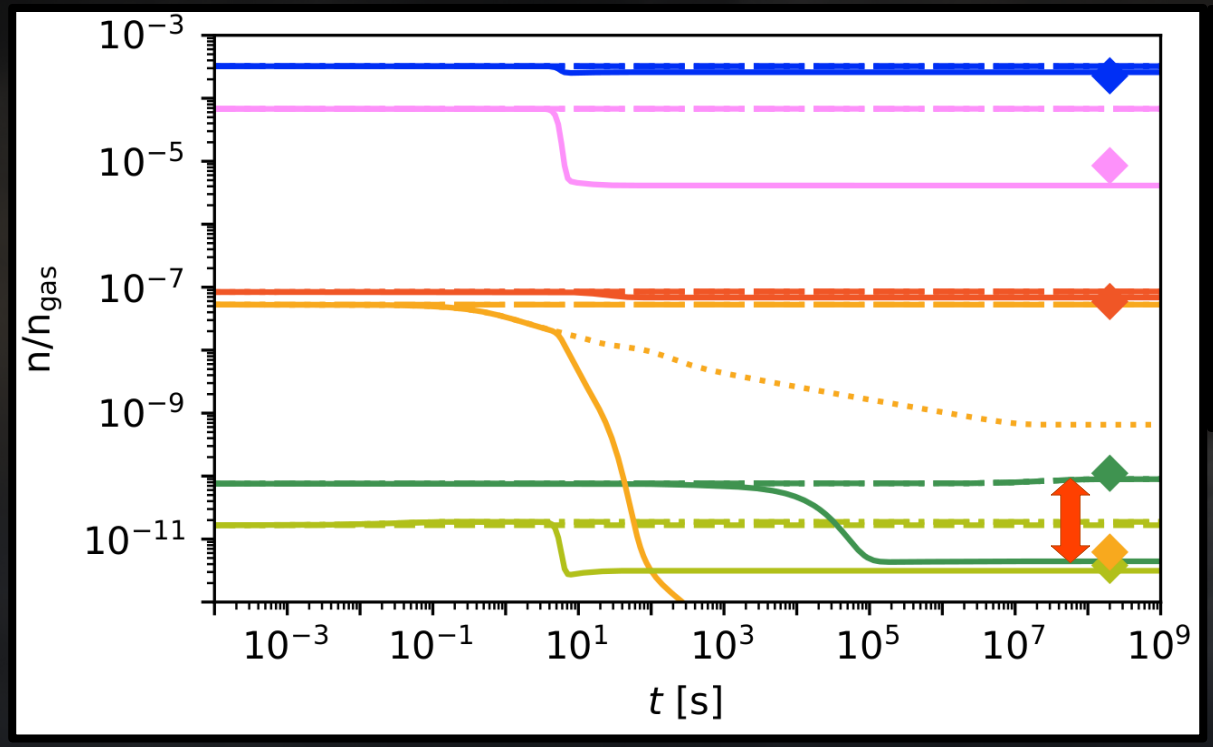

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Equilibrium

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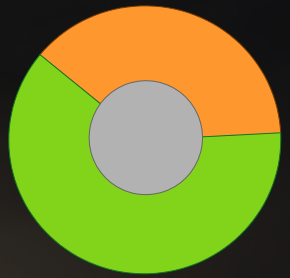
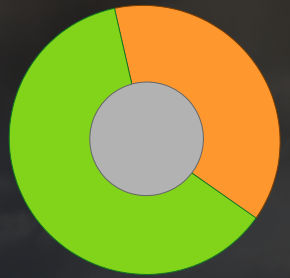
CH_4
CO_2
Mg
SiO_2
TiO_2

Effect of clouds:

1) Depletion of e.g. Mg, Si, Ti
2) Depletion of oxygen
3) What happens to CH_4?

Discovering the SiO-SiO_2 cycle

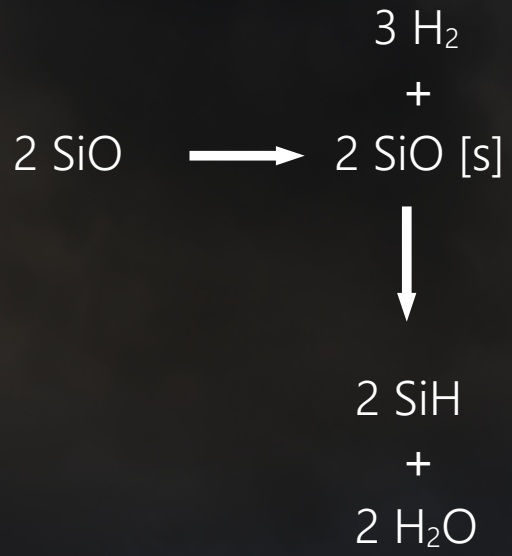


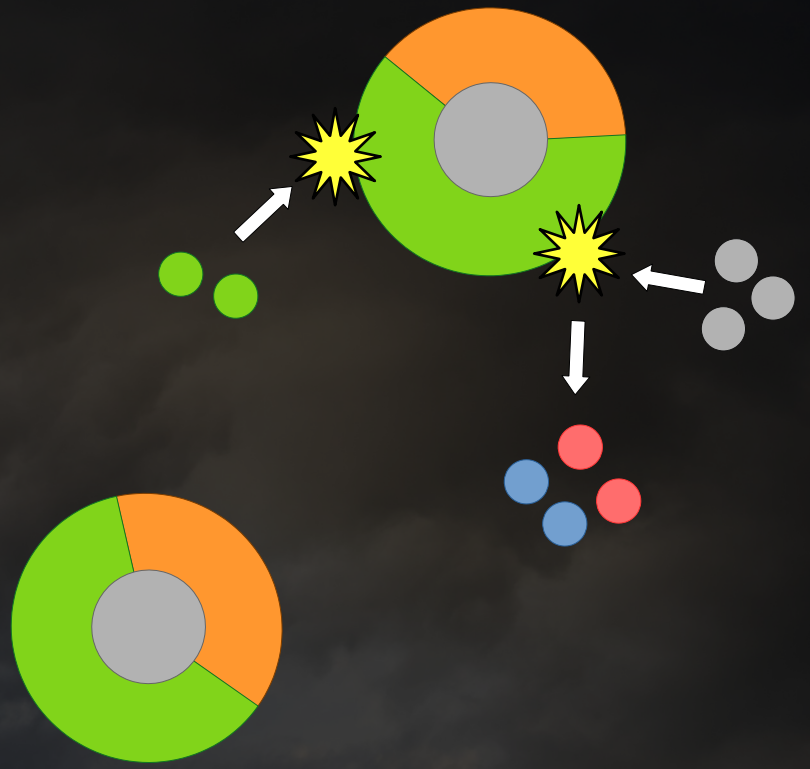


Discovering the SiO-SiO_2 cycle

$$2\ SiO \longrightarrow 2\ SiO\ [s]$$

Discovering the SiO-SiO_2 cycle





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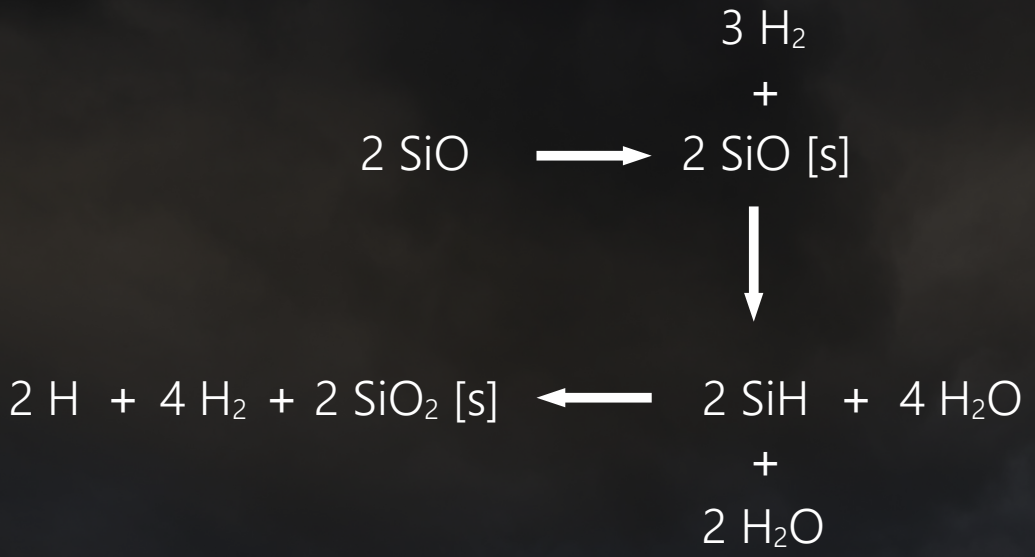

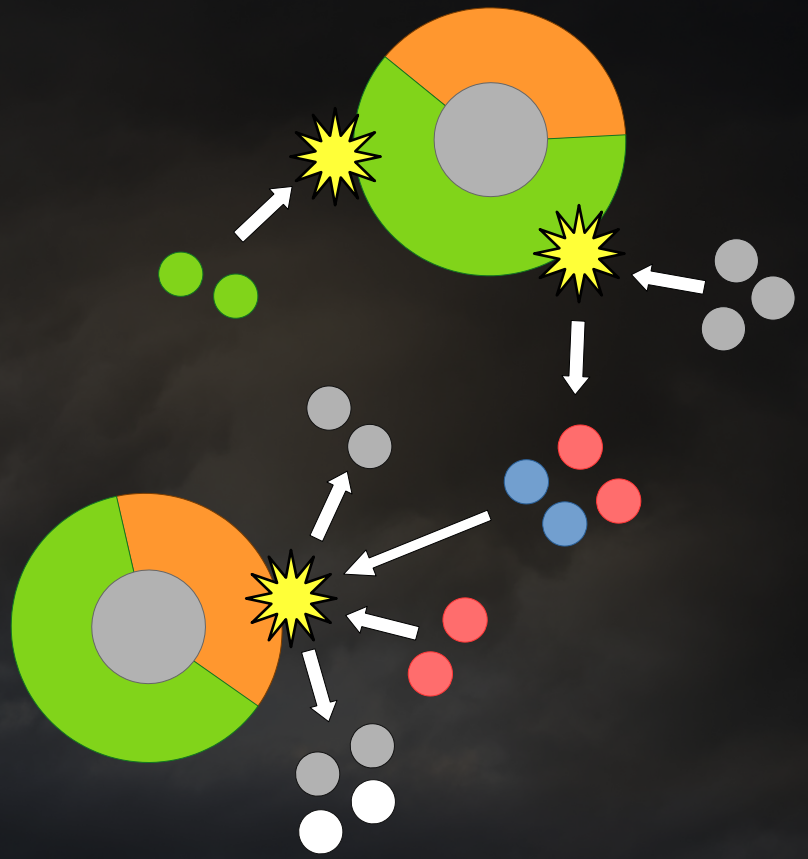

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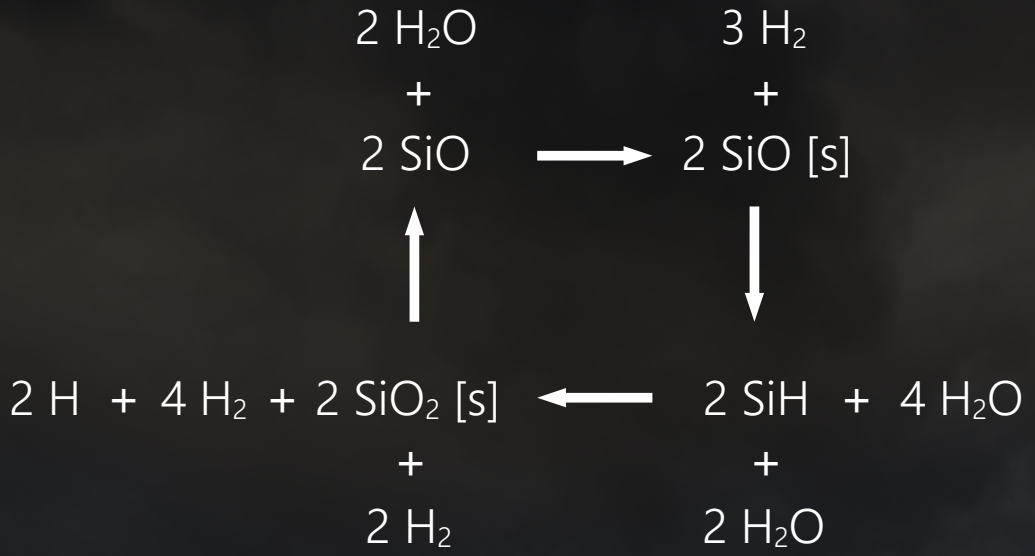

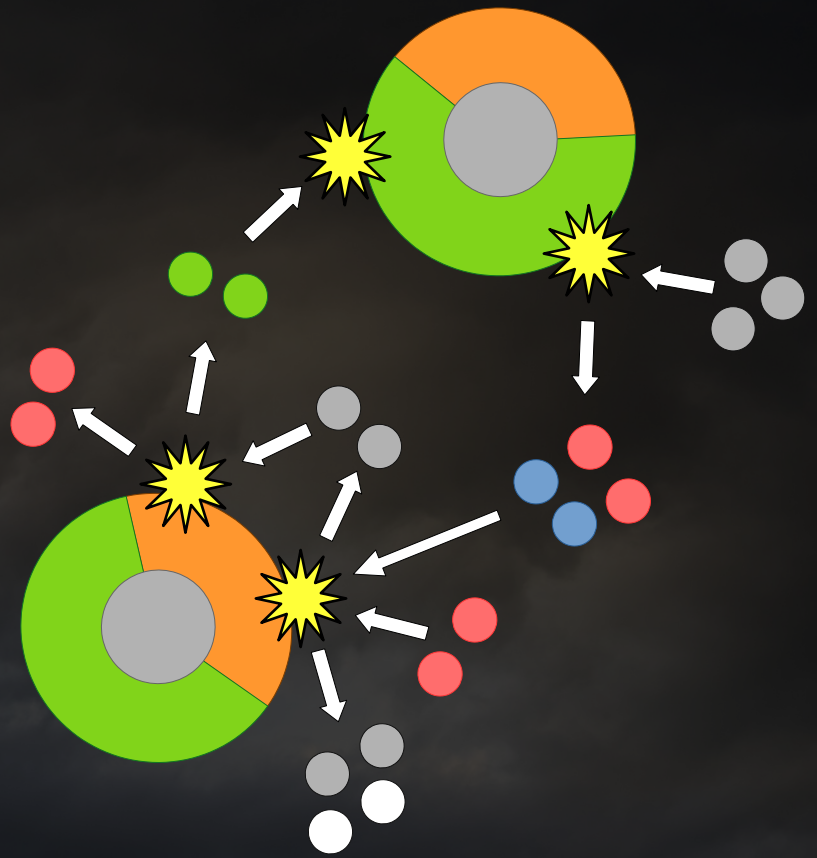

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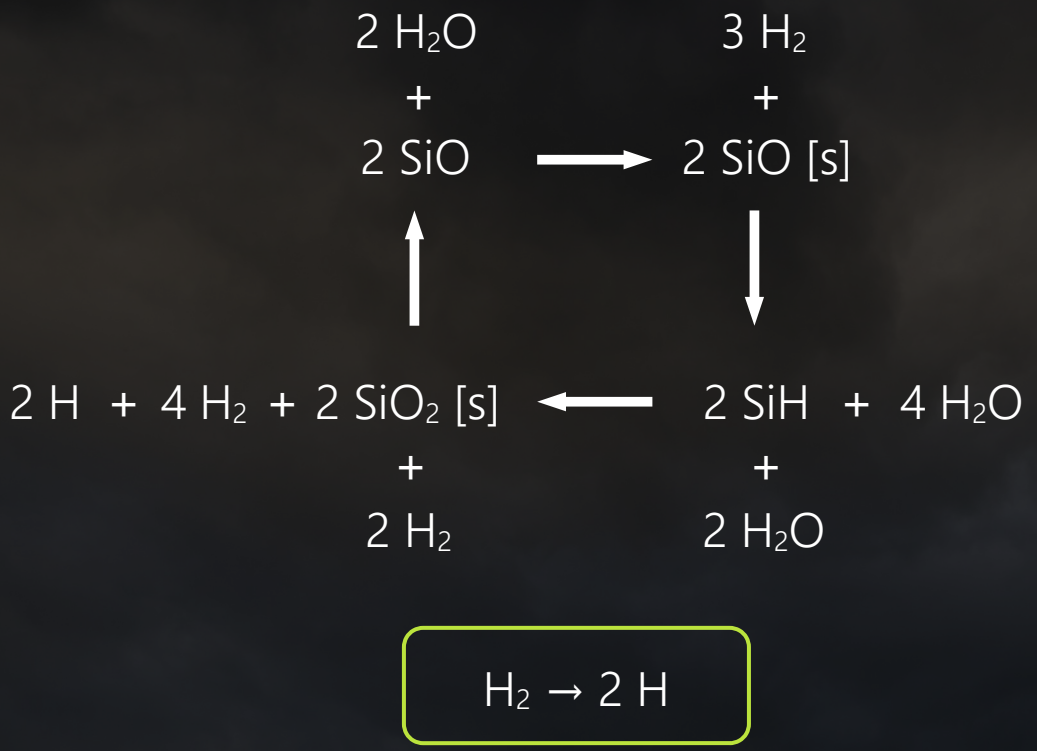

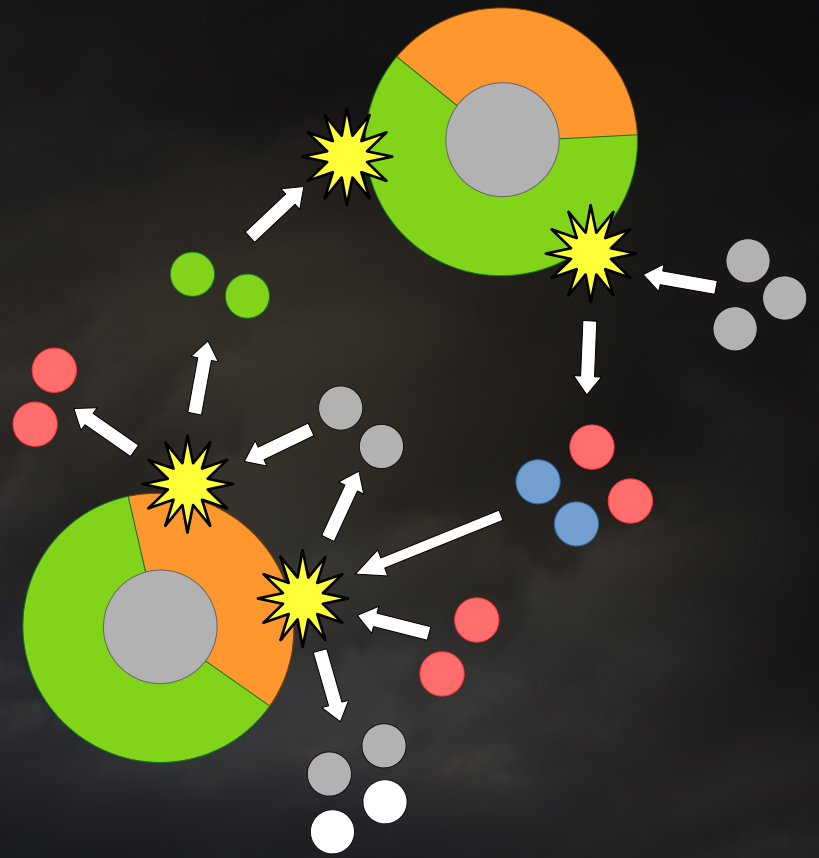

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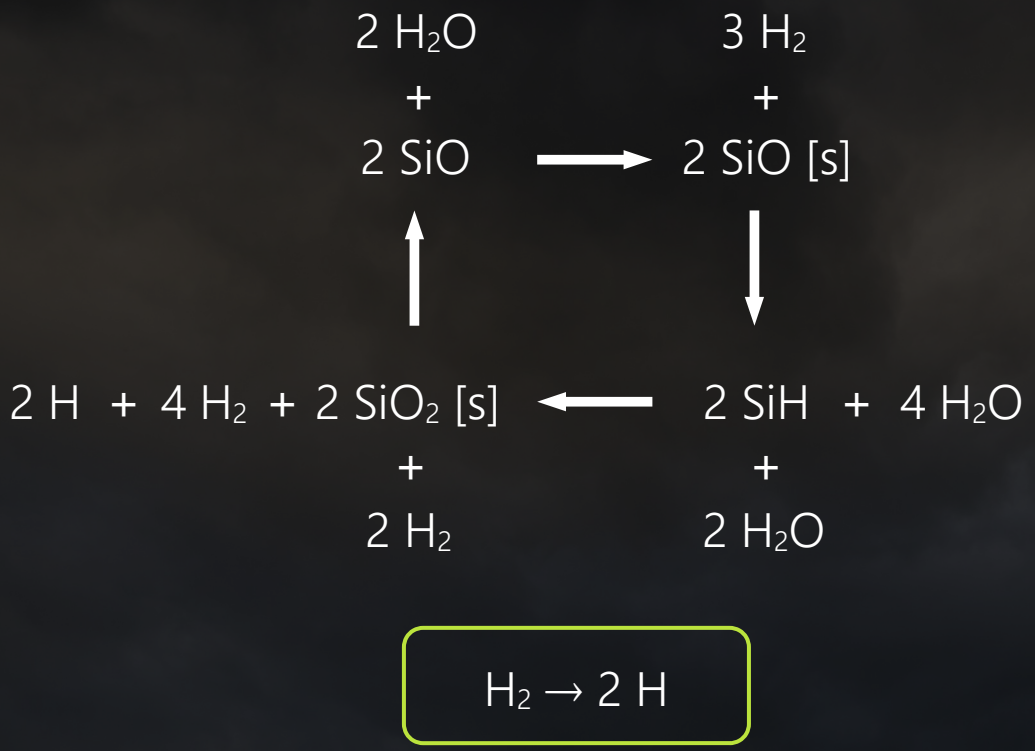

$H_2 \rightarrow 2\ H$

$CH_4 + H \rightarrow CH_3 + H_2$

$CH_3 + H \rightarrow CH_2 + H_2$

$CH_2 + H \rightarrow CH + H_2$

$CH + H_2O \rightarrow H_2CO + H$

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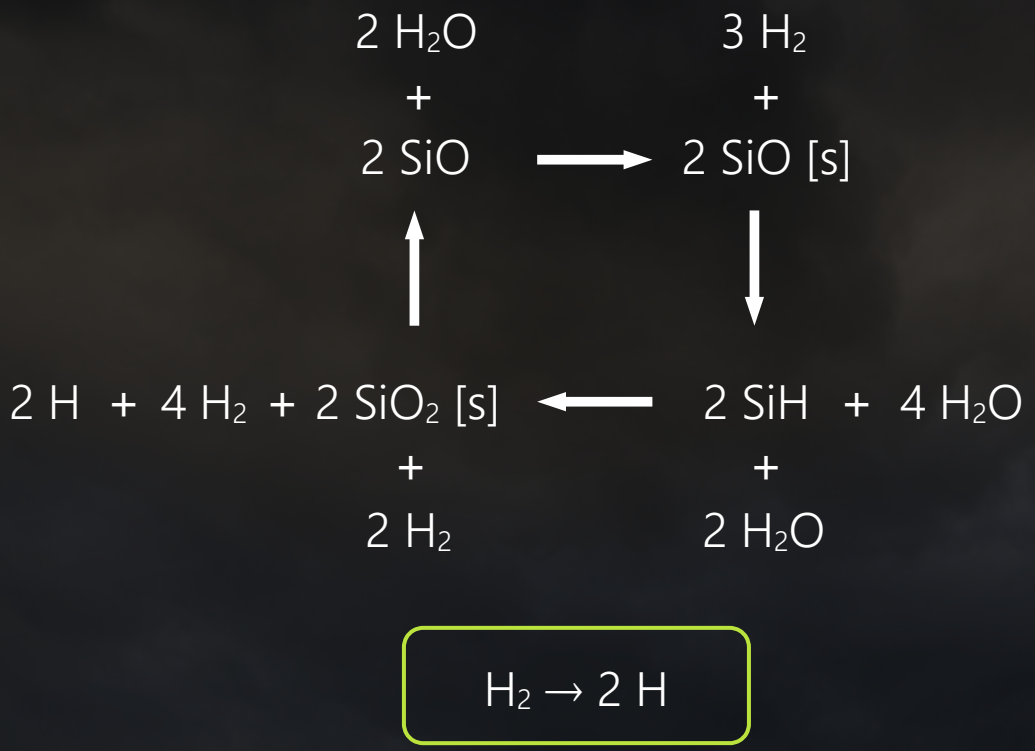

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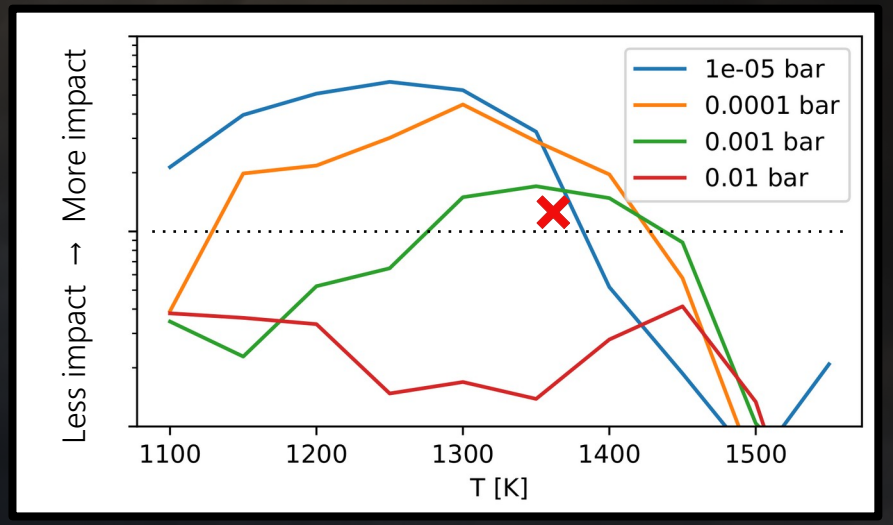
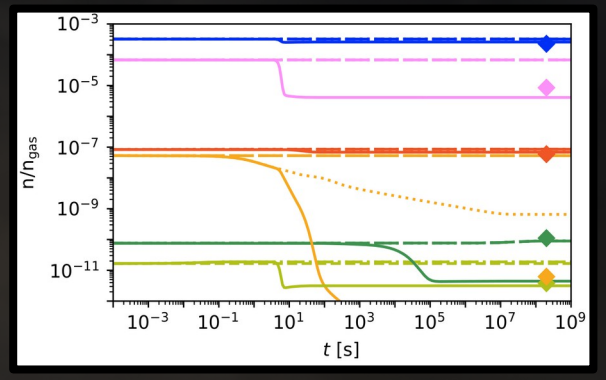
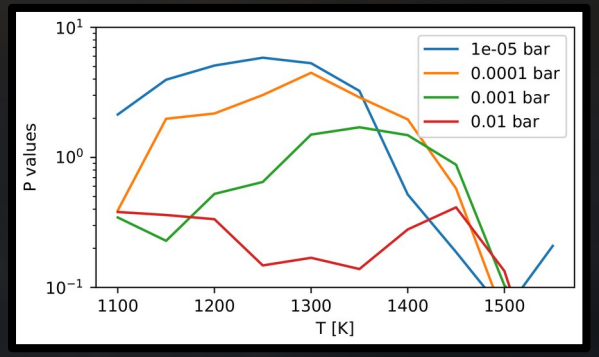


How do clouds interact with their environment?





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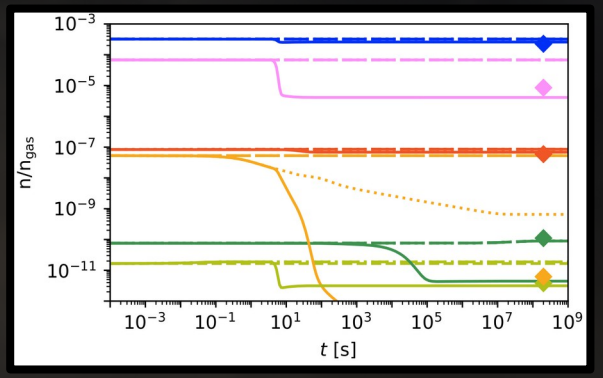

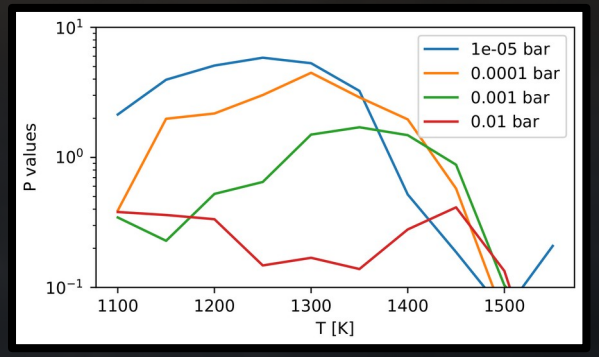

- Temperature differences can impact the formation of larger clusters.

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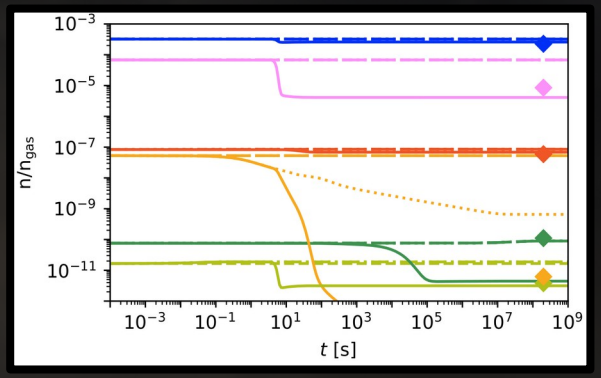
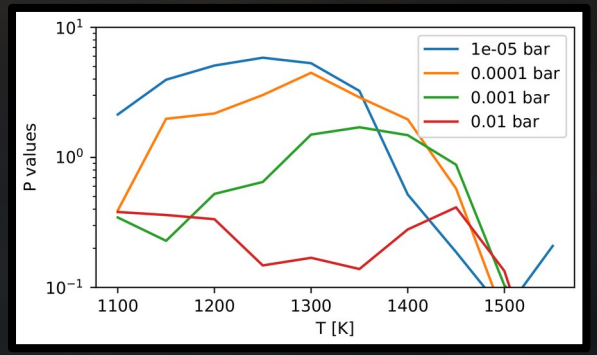
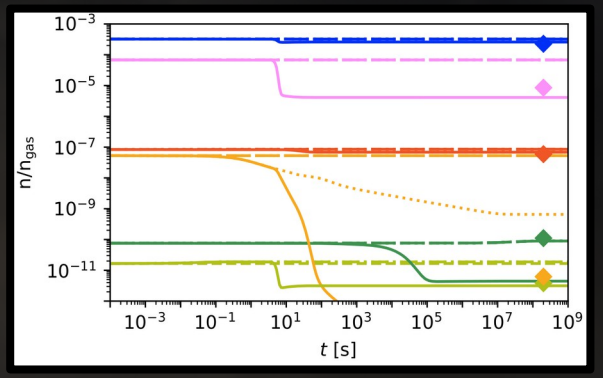
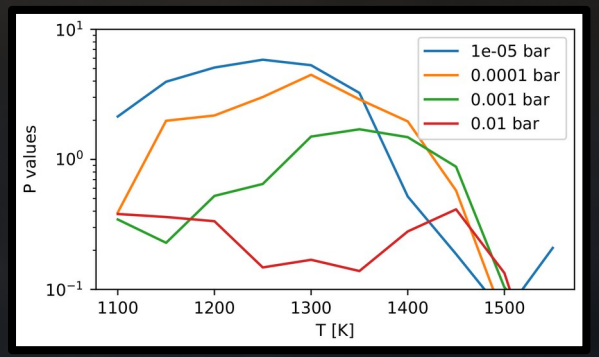




- Temperature differences can impact the formation of larger clusters.
- Cloud formation depletes the gas-phase of cloud forming elements (e.g. Mg, Si, Fe) and oxygen.

How do clouds interact with their environment?





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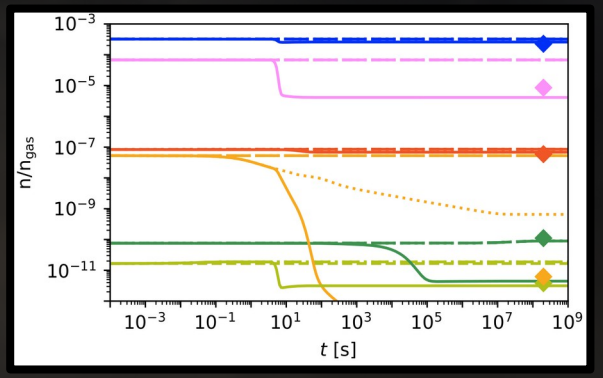
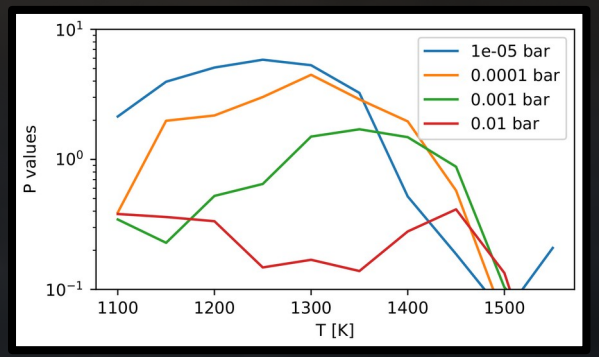
- Cloud formation depletes the gas-phase of cloud forming elements (e.g. Mg, Si, Fe) and oxygen.
- Surface reactions of cloud particles can lead to catalytic cycles.

How do clouds interact with their environment?





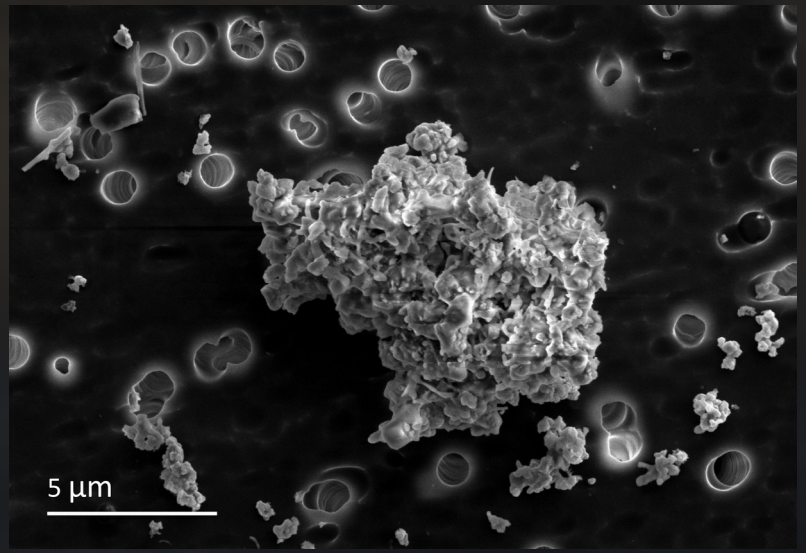
- Temperature differences can impact the formation of larger clusters.
- Cloud formation depletes the gas-phase of cloud forming elements (e.g. Mg, Si, Fe) and oxygen.
- Surface reactions of cloud particles can lead to catalytic cycles.
- Low pressure environments are affected more by non-equilibrium effects.

PART II
Optical Properties of Cloud particles

Real image of Jupiter: SWRI/NASA

The complex nature of cloud particles

Interstellar dust particle (Real image)

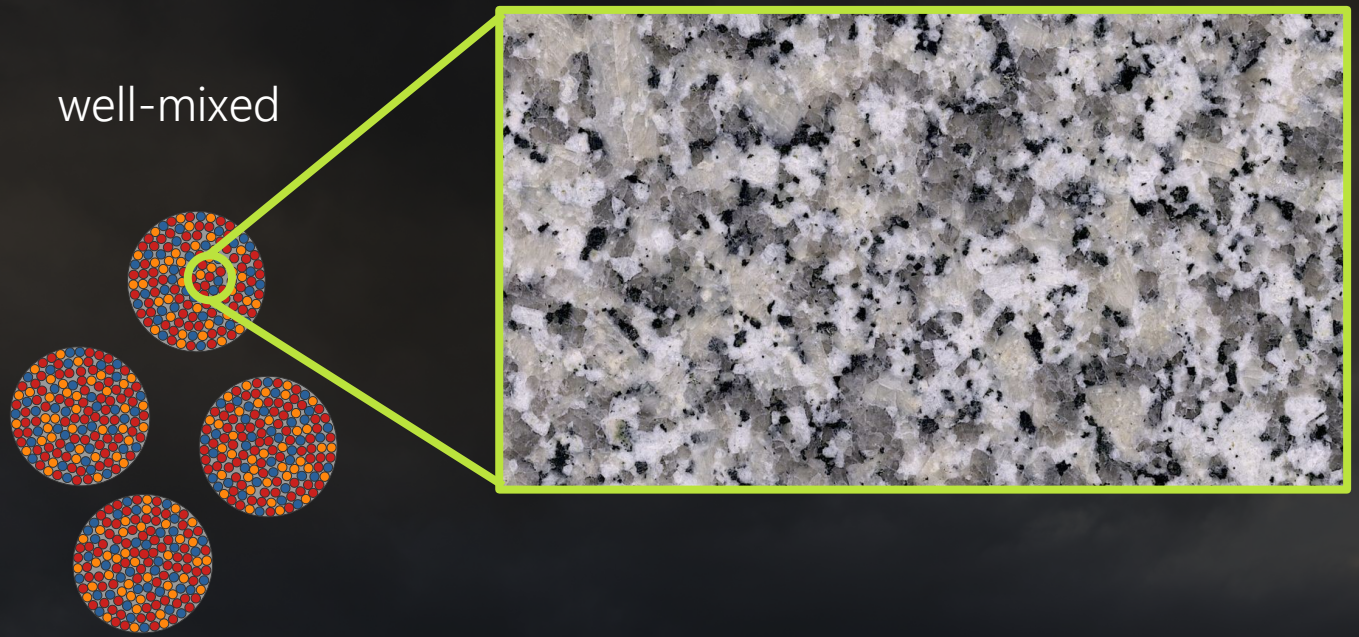


Exoplanet cloud particle (Artist Impression)

Left image: Hope Ishii, University of Hawai'i
Right image: Dr. D.B.S.Samra

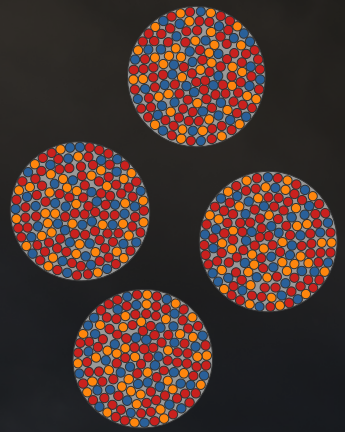
The complex nature of cloud particles – Let's simplify it!

The complex nature of cloud particles – Let's simplify it!



The complex nature of cloud particles – Let's simplify it!

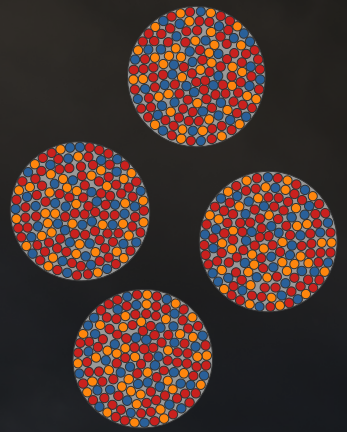
well-mixed



core-shell

The complex nature of cloud particles – Let's simplify it!

well-mixed

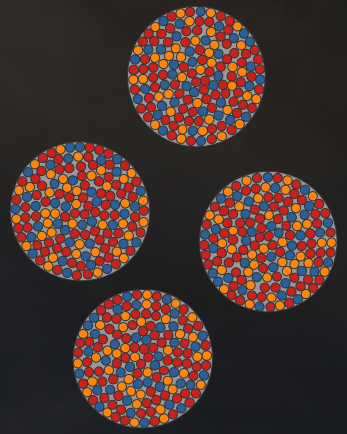


core-shell

batches (BAS)

The complex nature of cloud particles – Let's simplify it!

well-mixed

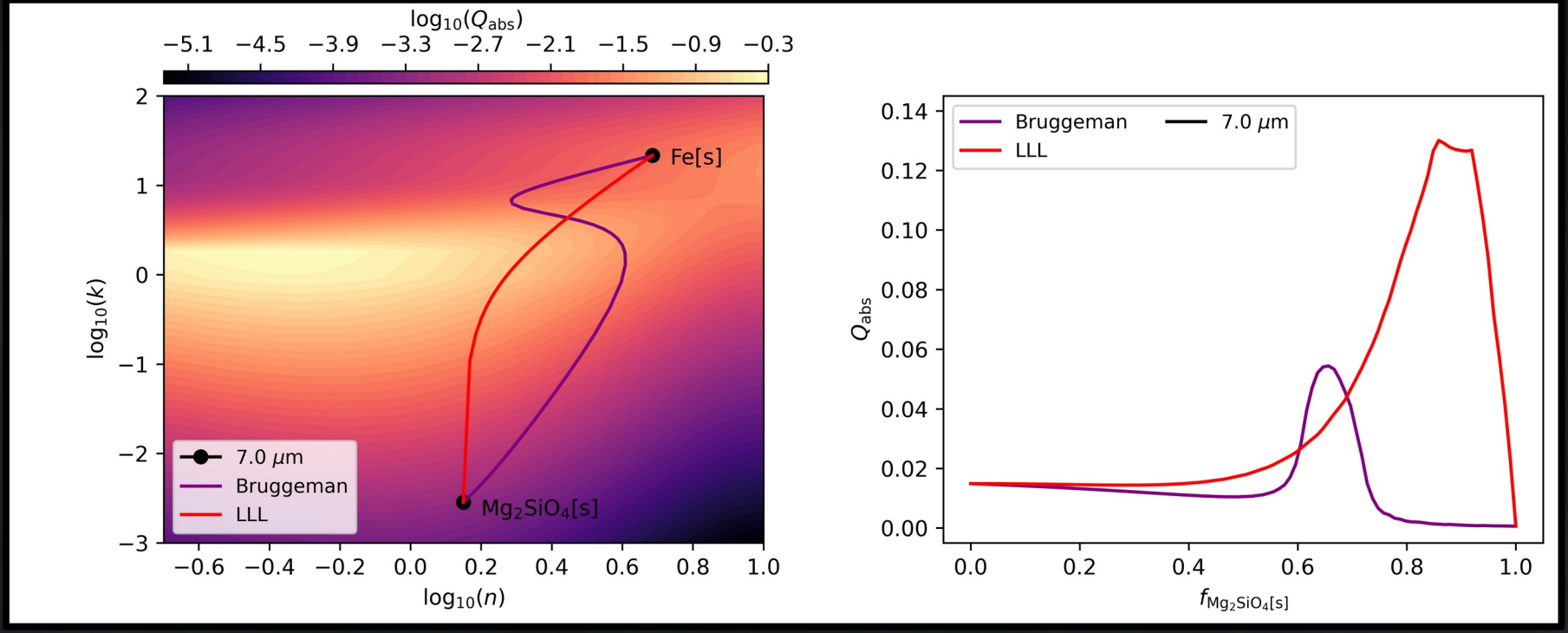


core-shell

batches (BAS)

single (SSA)

What are the differences for well-mixed particles?



Kiefer et al. (2024b)

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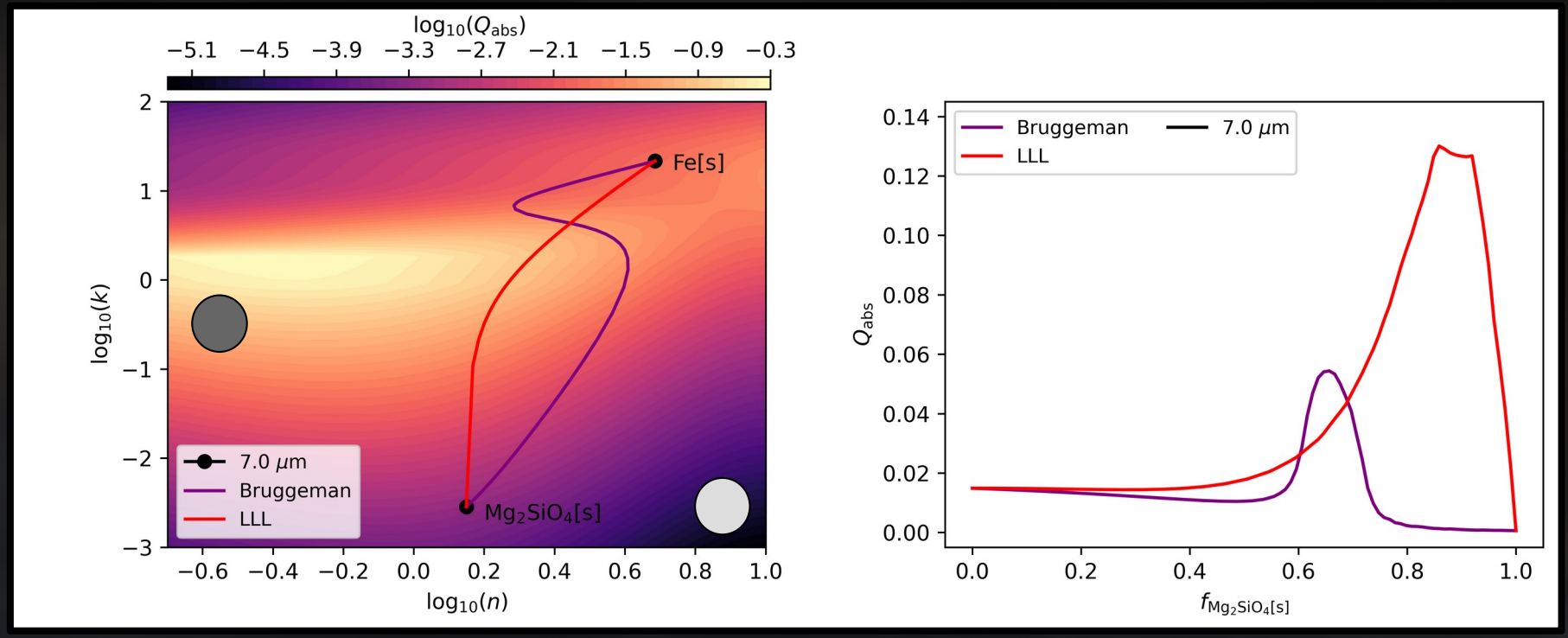

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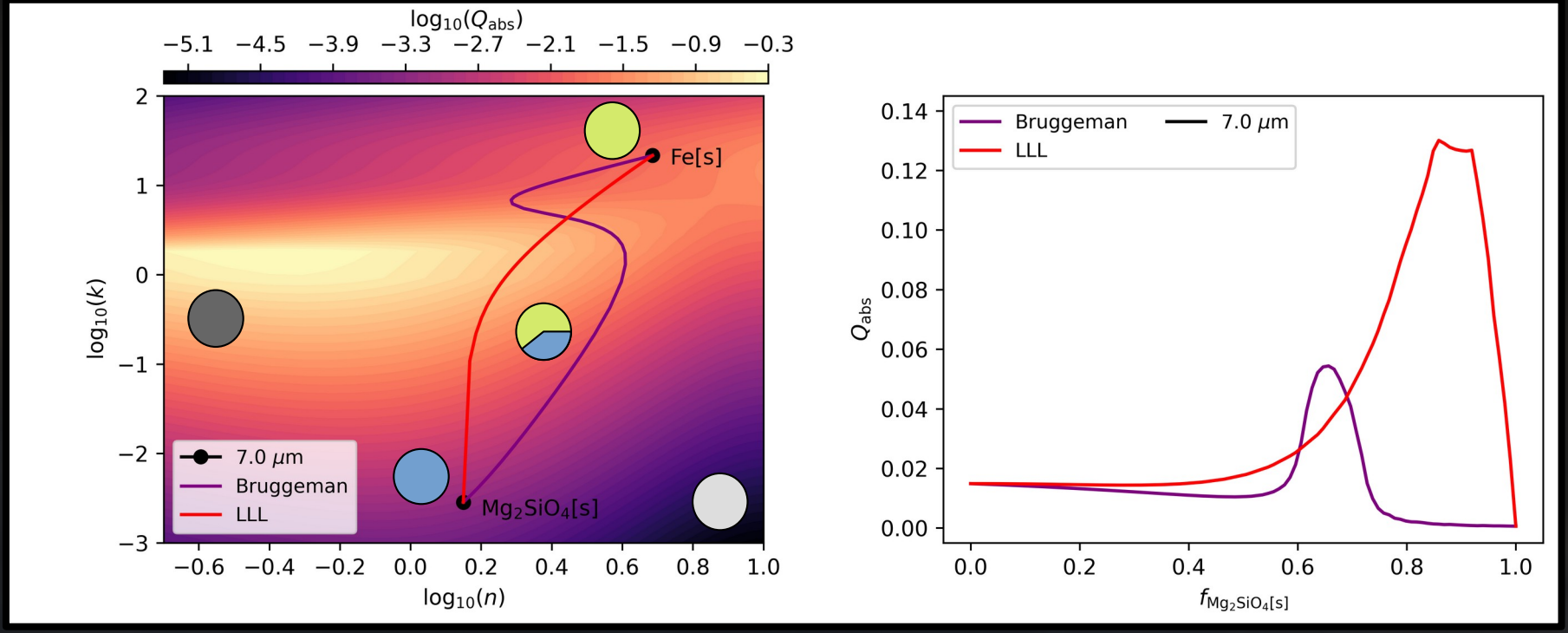

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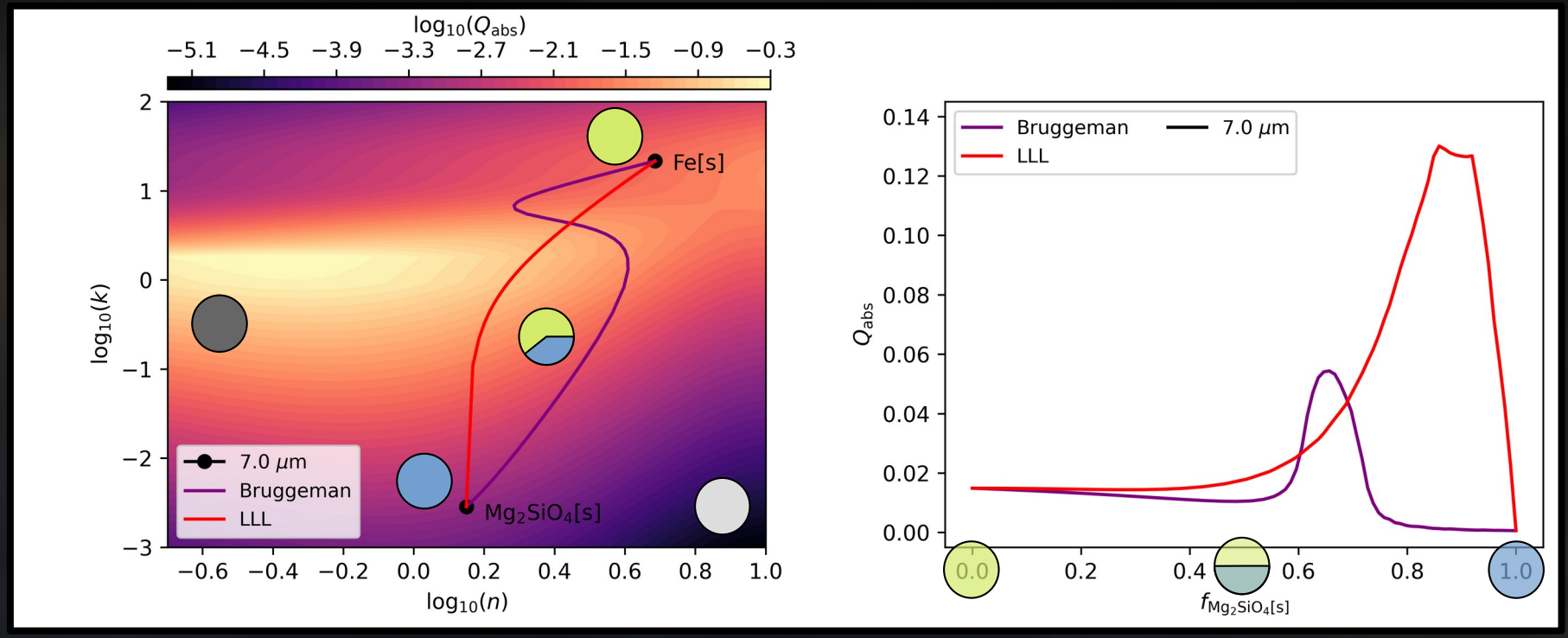

Kiefer et al. (2024b)

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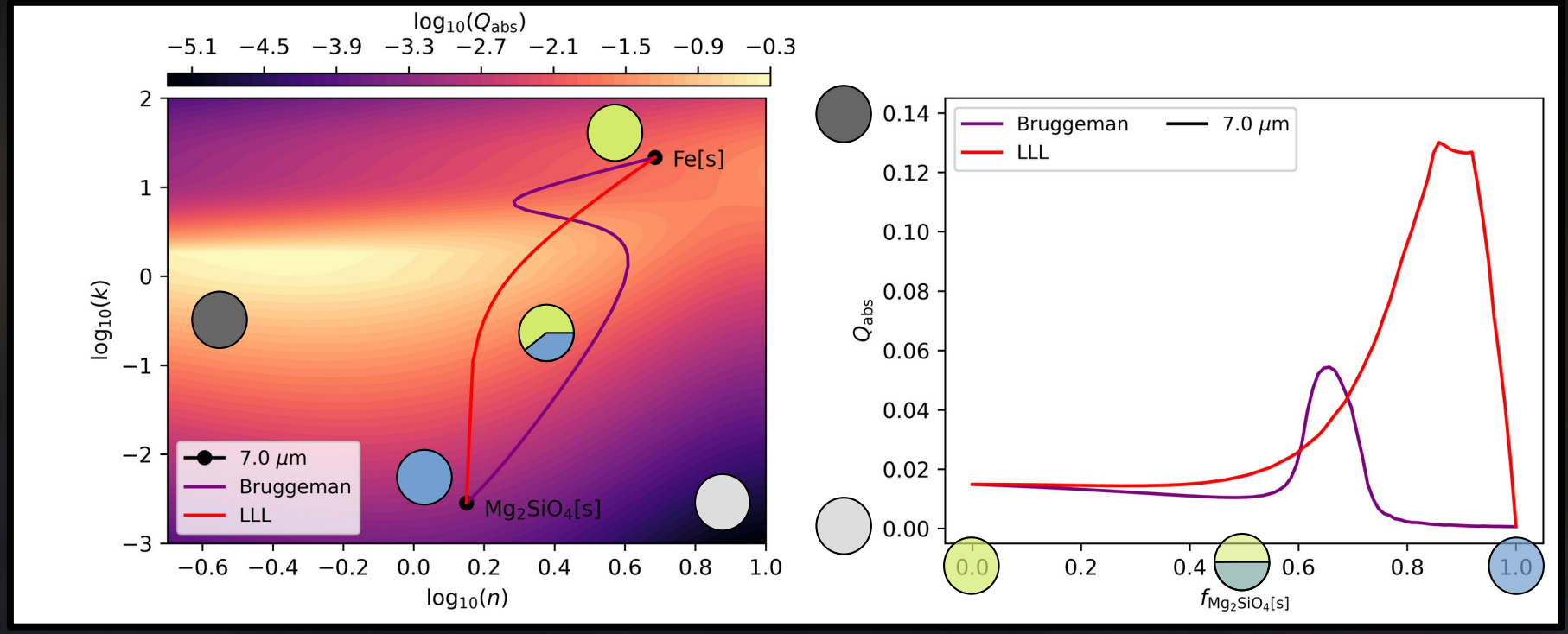

Kiefer et al. (2024b)

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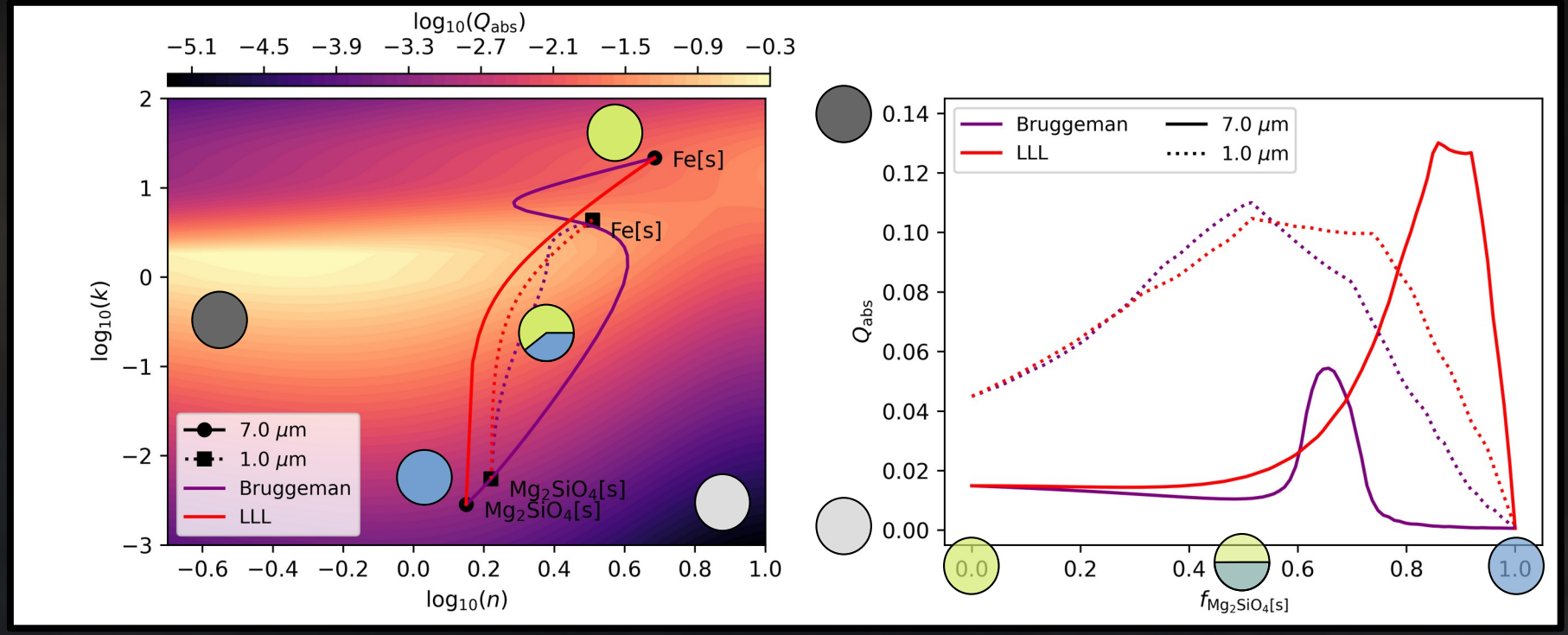

Kiefer et al. (2024b)

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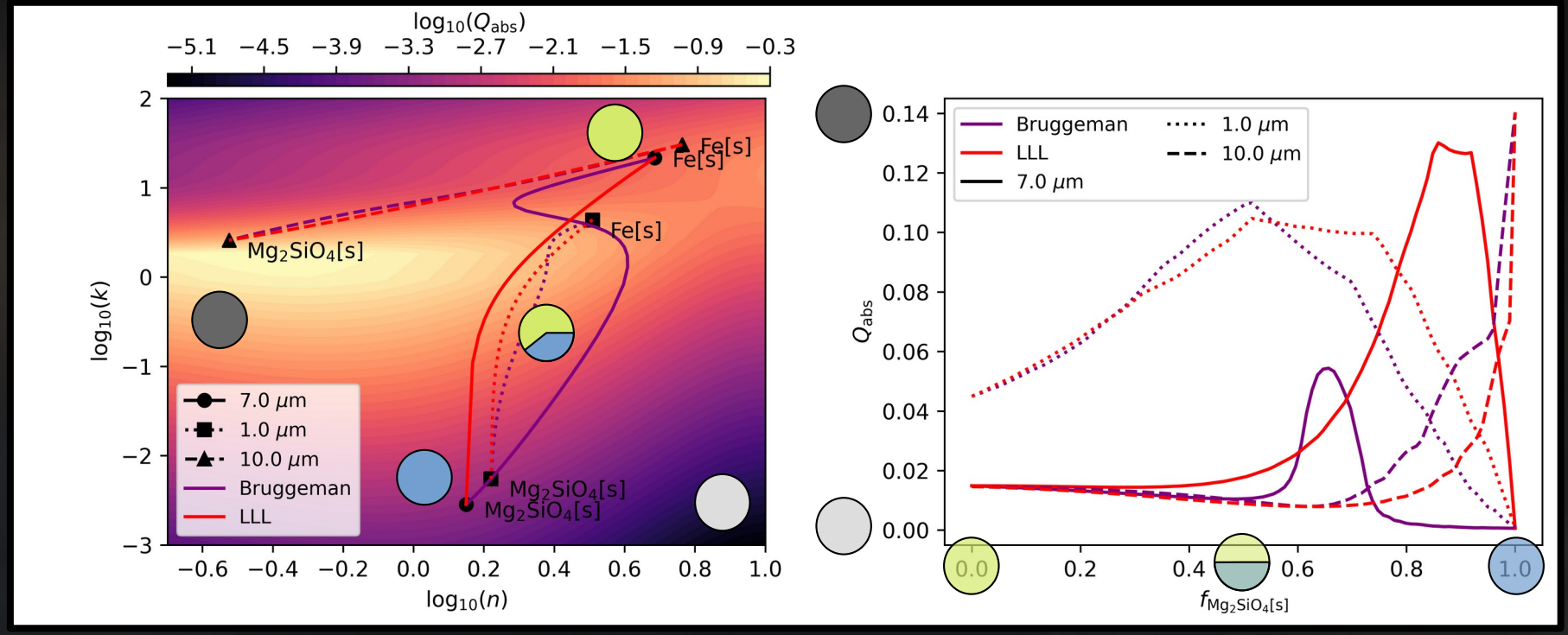


Kiefer et al. (2024b)

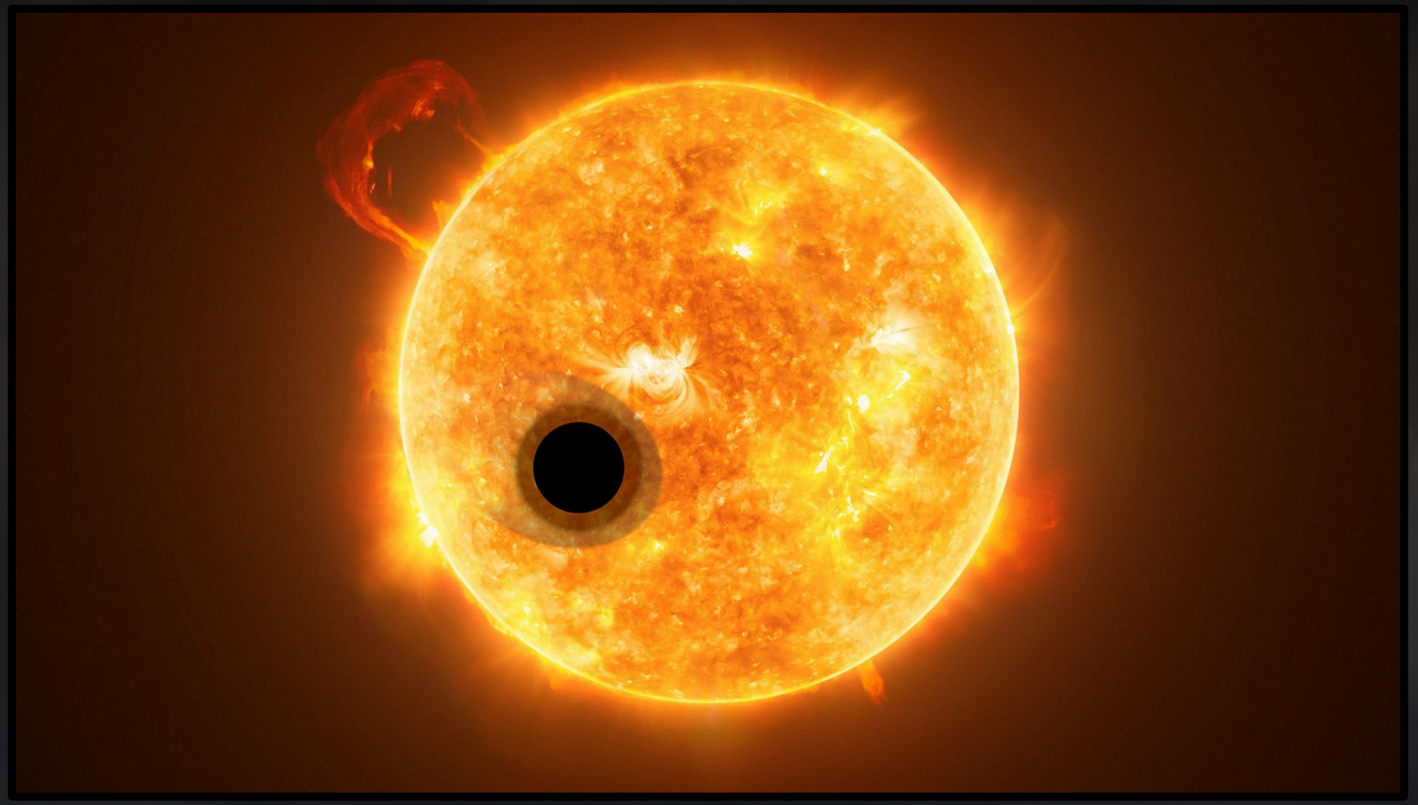
Observing Exoplanets

Observing Exoplanets

Credit: NASA/JPL-Caltech/MSSS/Texas A&M Univ.

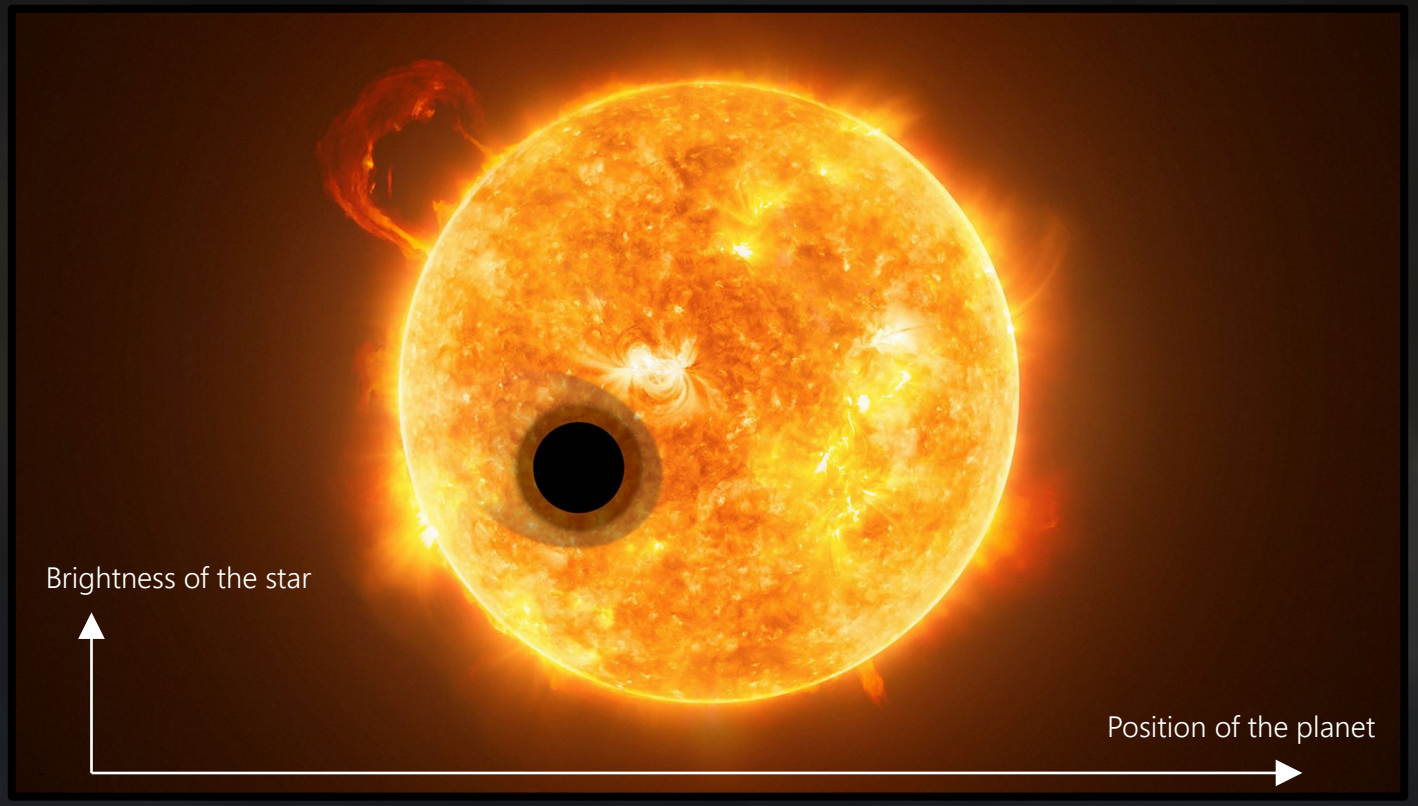
Credit: BBC Weather Watchers – Lindsey Fernandes

Observing Exoplanets



Artist impression:
ESA/Hubble

Observing Exoplanets



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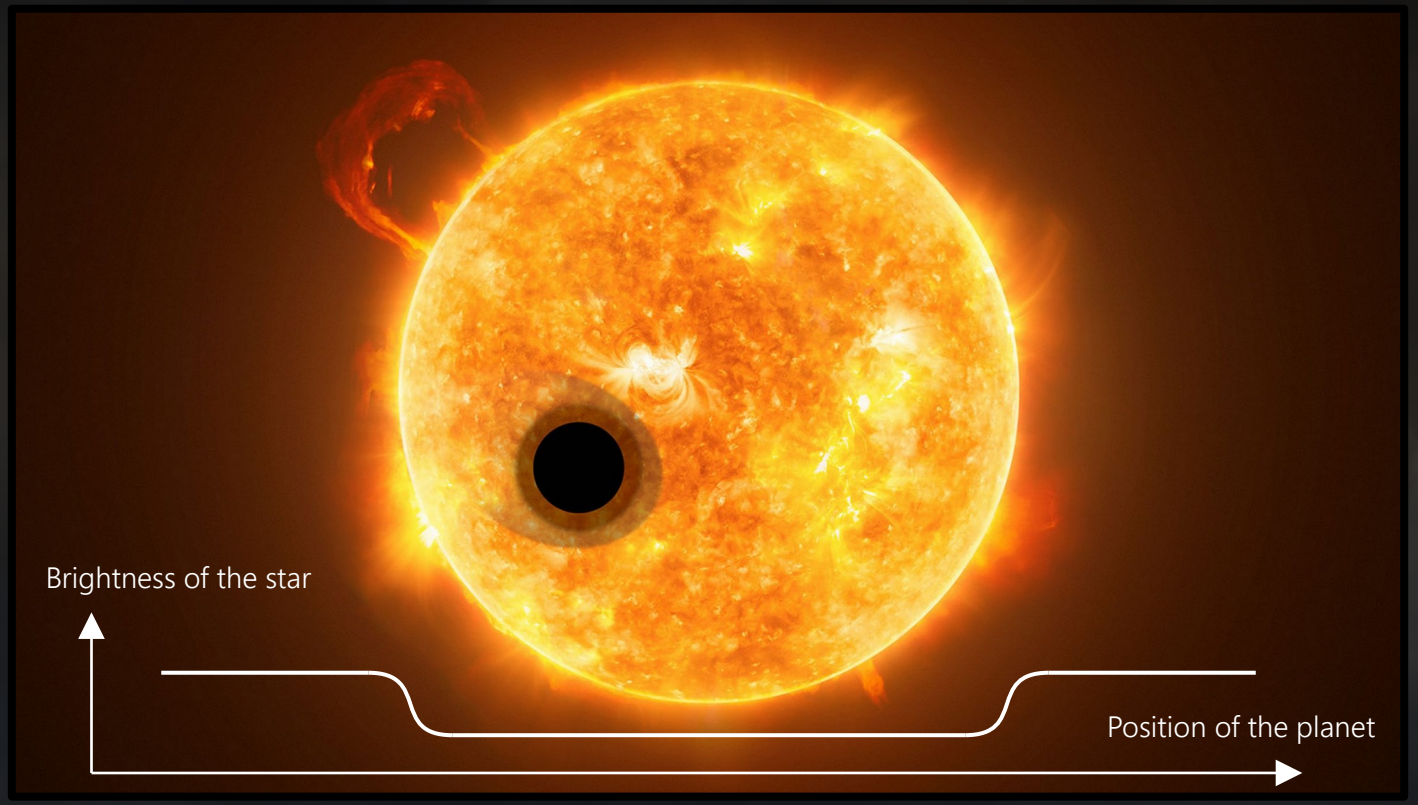
Observing Exoplanets



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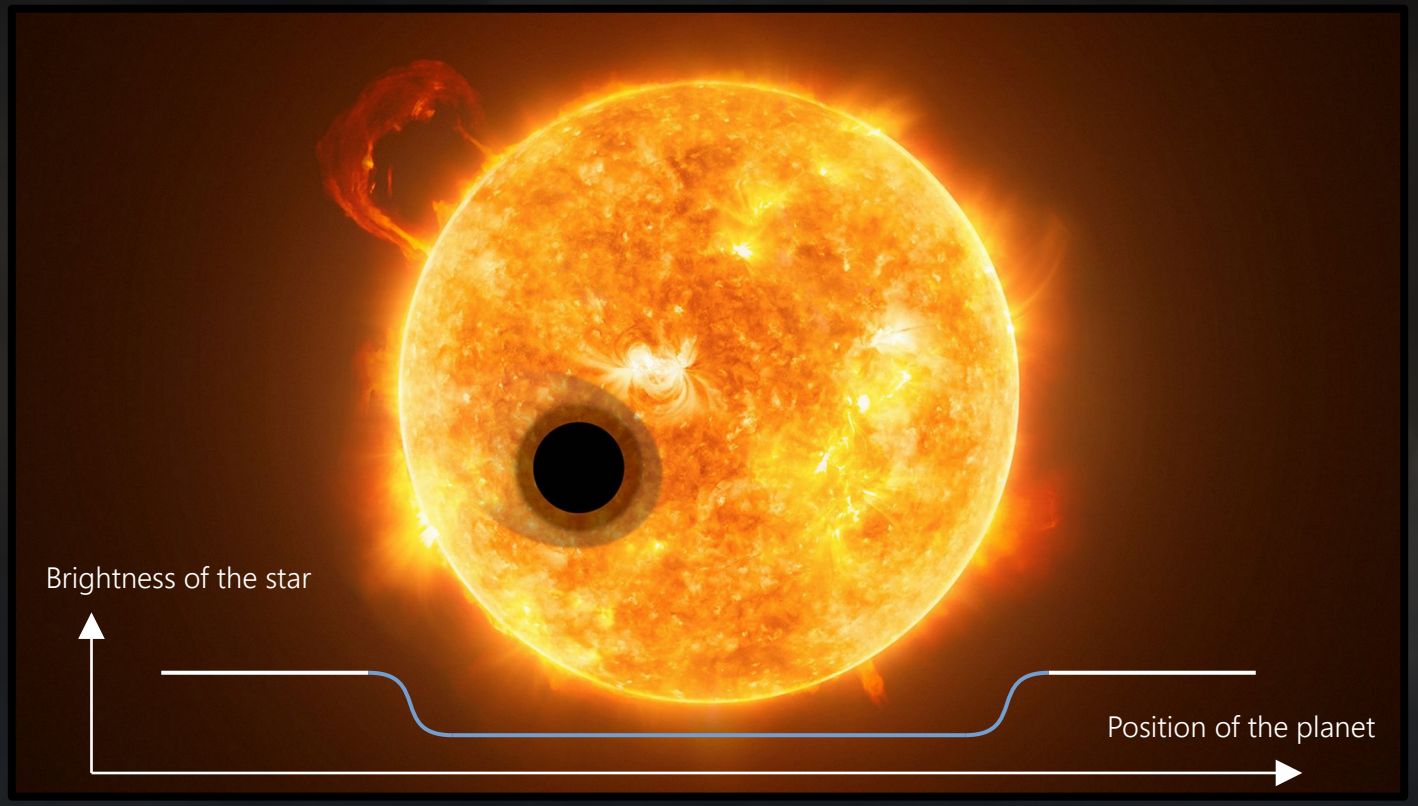

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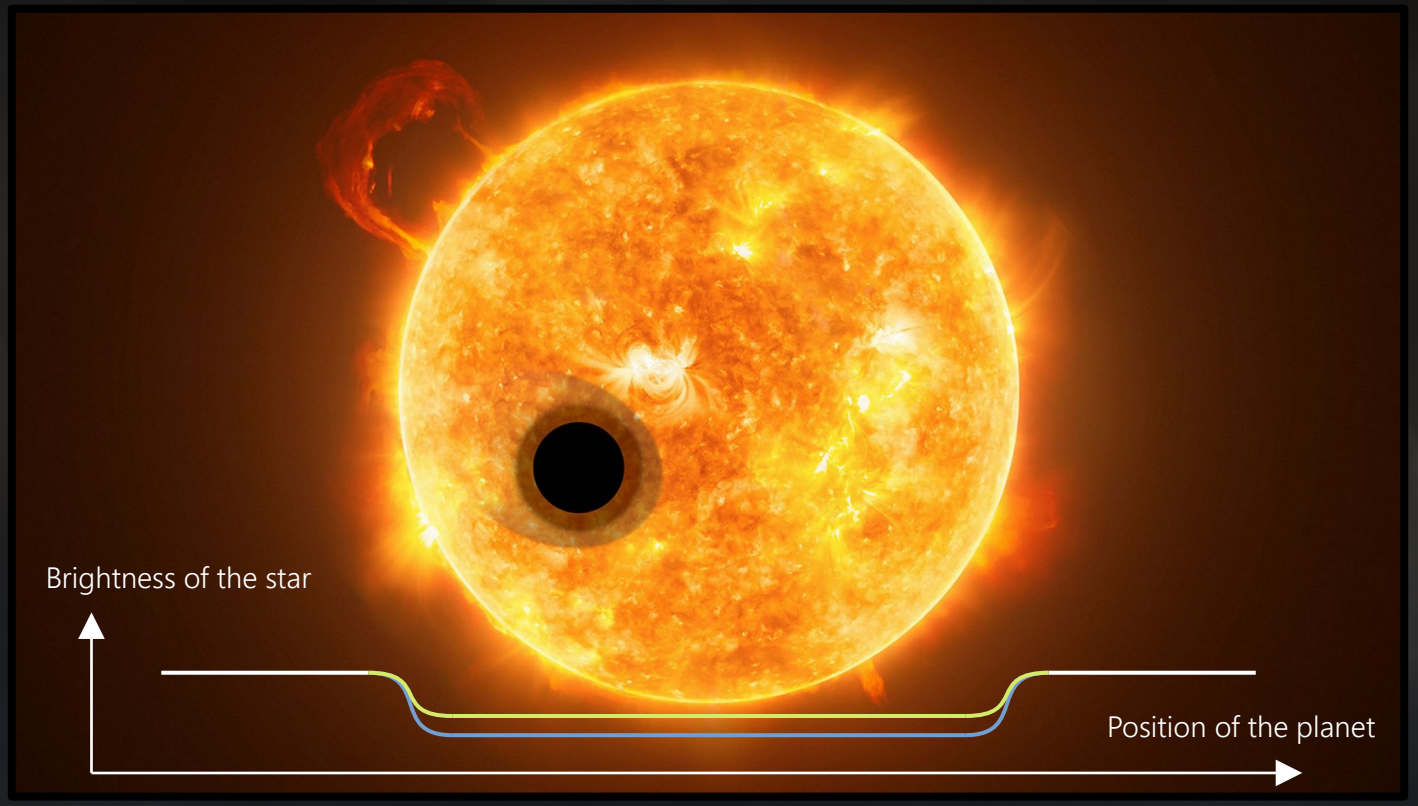
Observing Exoplanets



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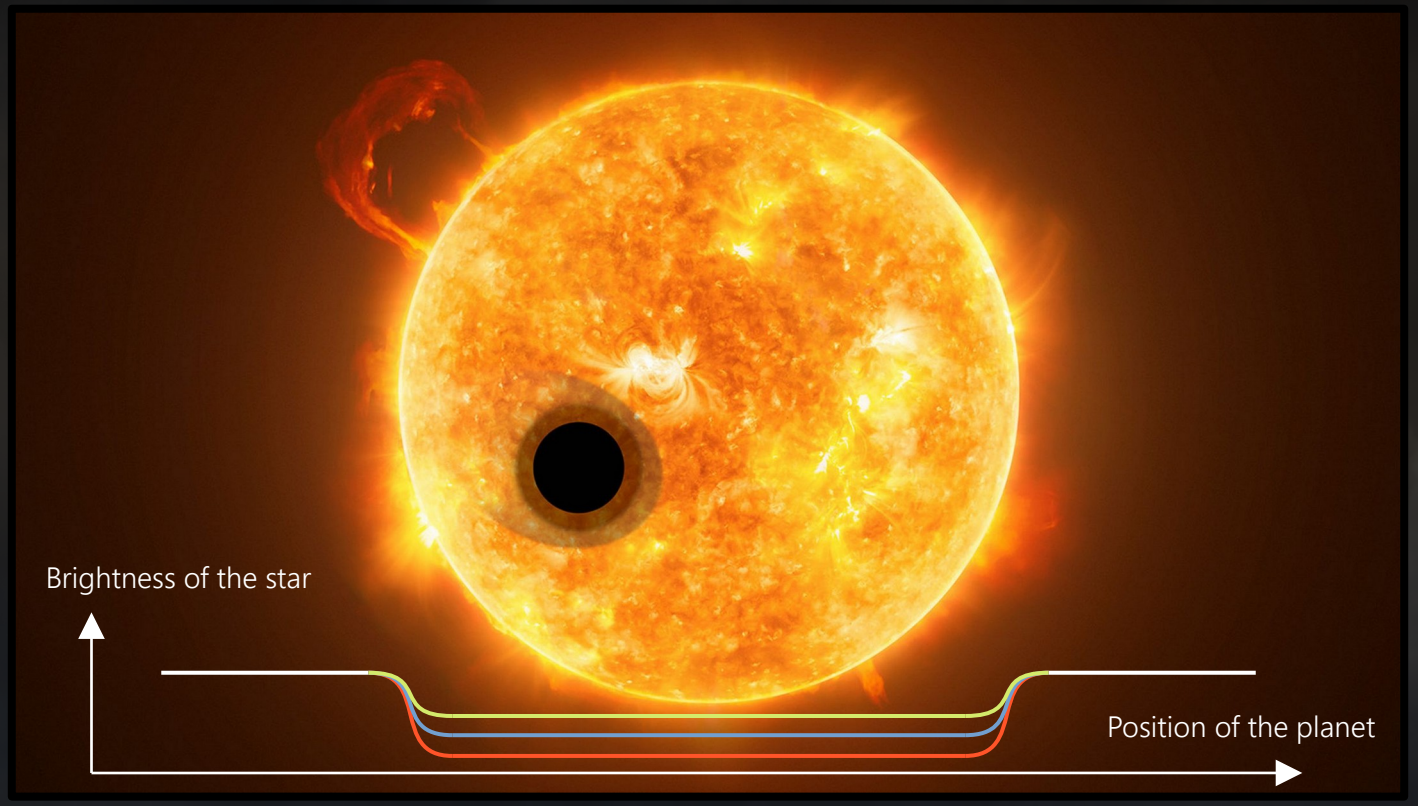

Artist impression:
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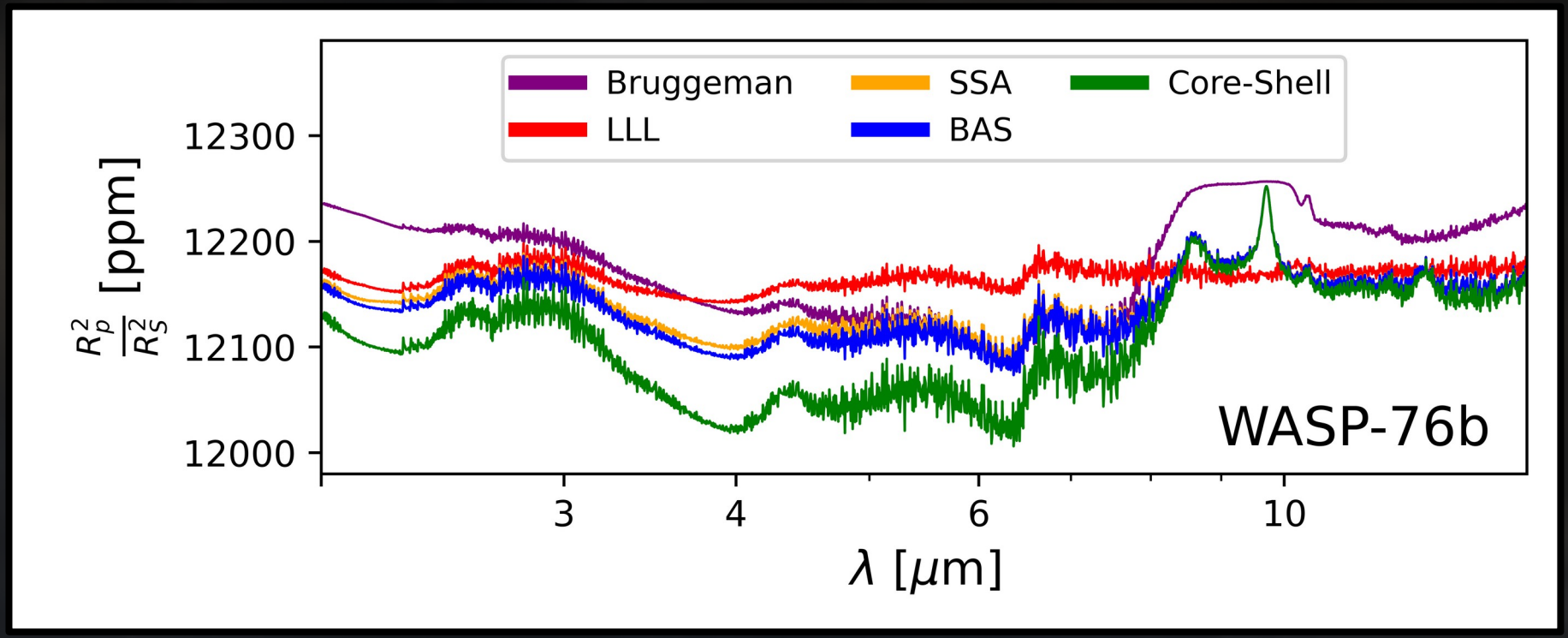
How does the spectra look?



Kiefer et al. (2024b)

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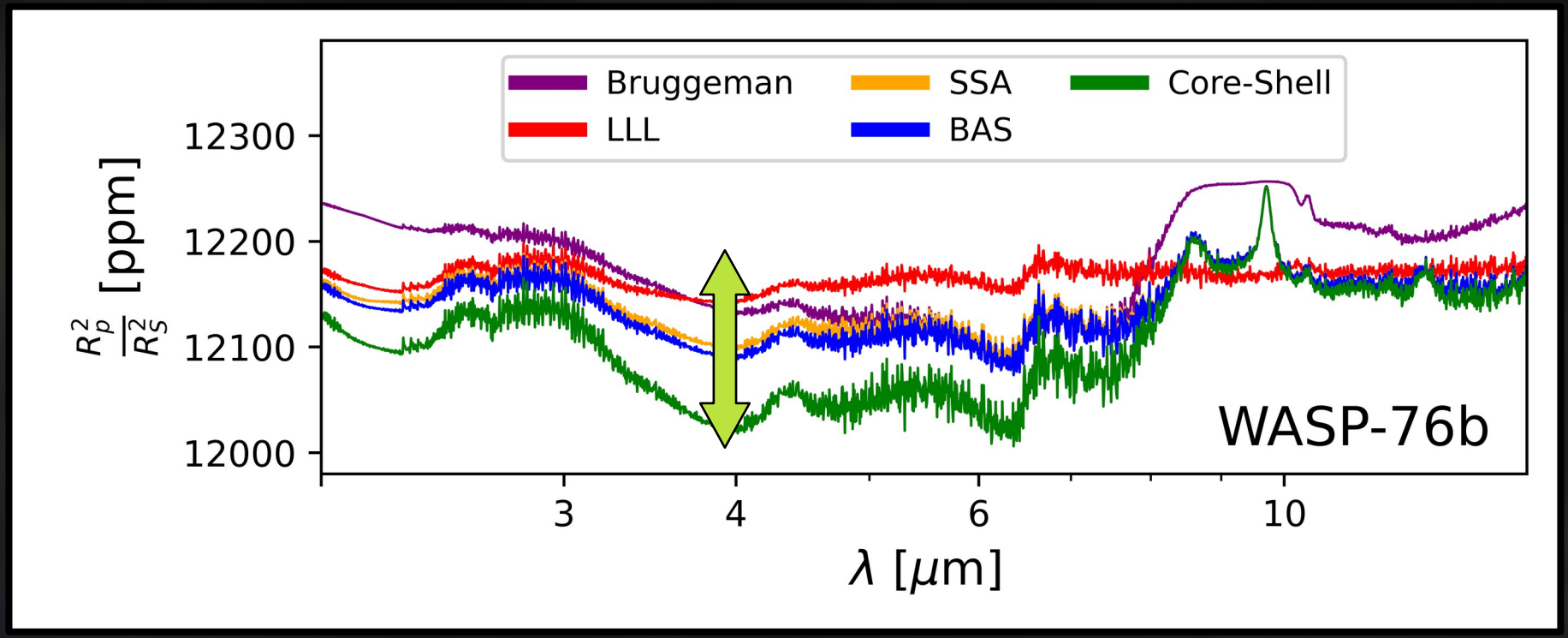

Kiefer et al. (2024b)

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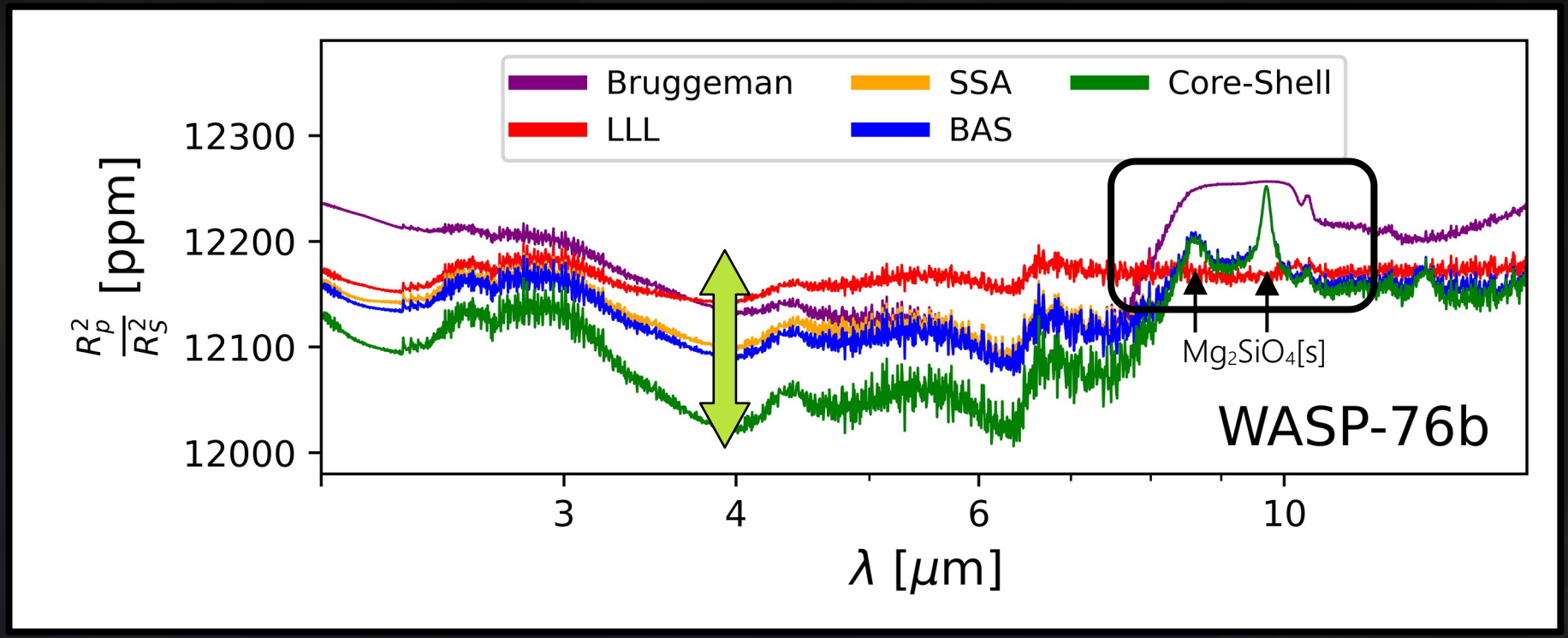
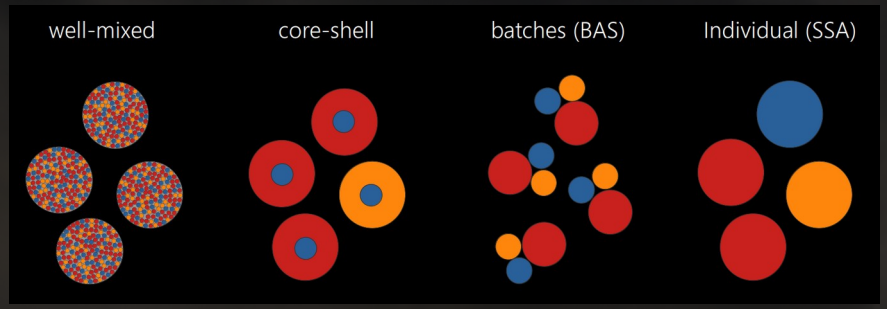
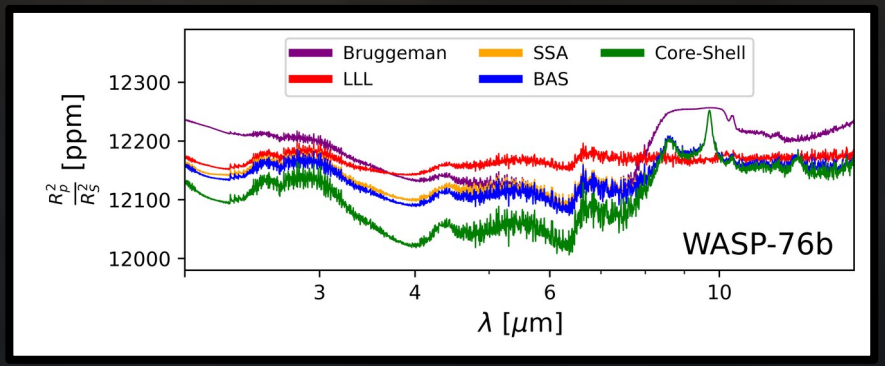


Kiefer et al. (2024b)

Can we observe cloud particle properties?





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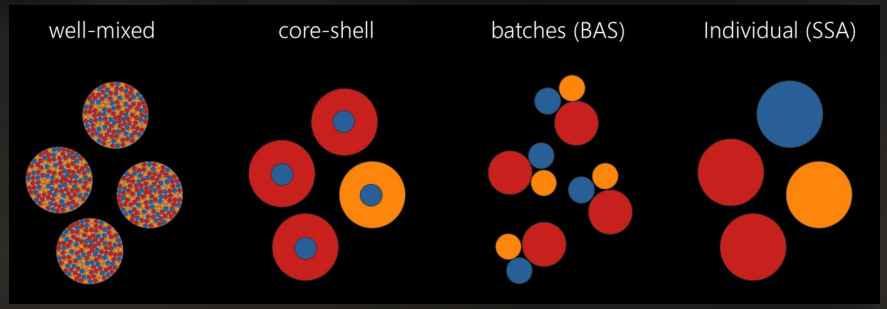
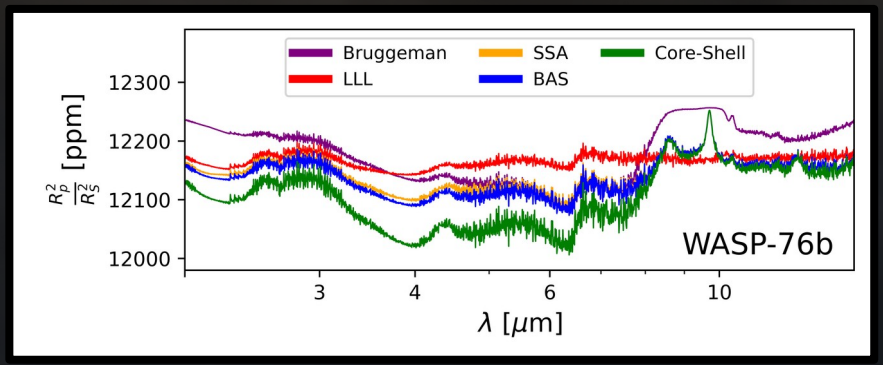
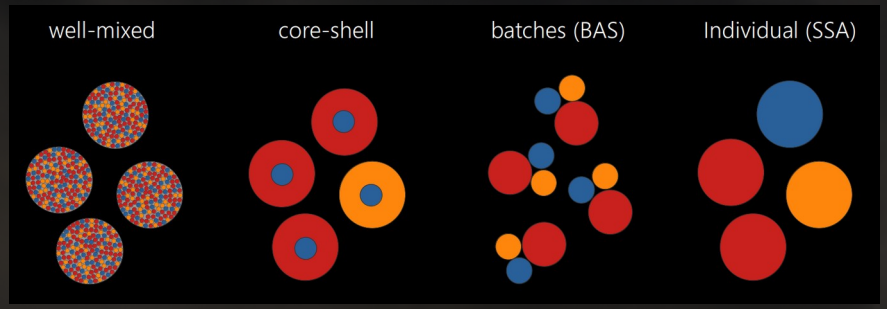
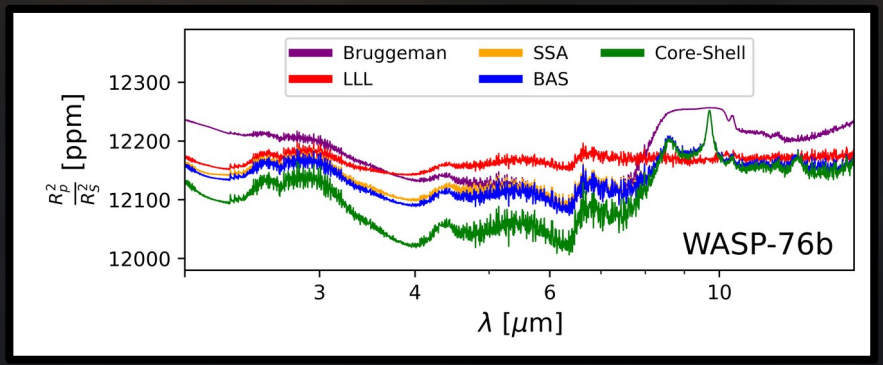




- Non-mixed particles can keep the spectral properties of individual cloud particle materials.

Can we observe cloud particle properties?





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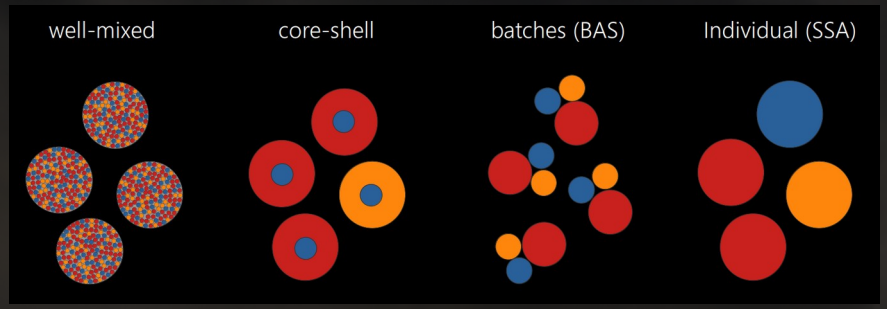
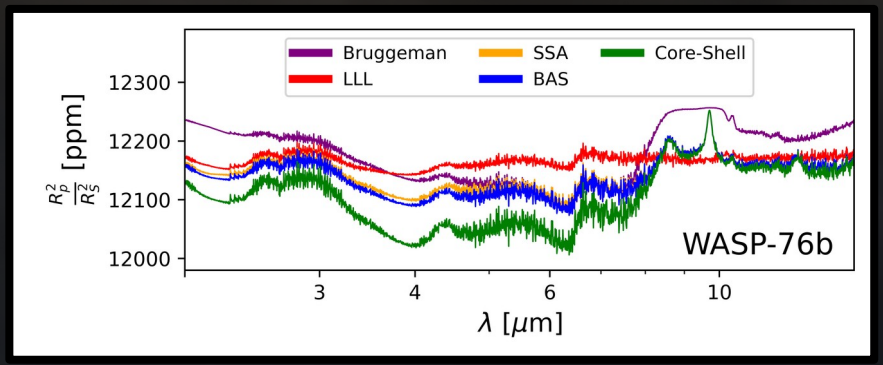
- If cloud particles are well-mixed their spectral features can be complex and broad.

Can we observe cloud particle properties?





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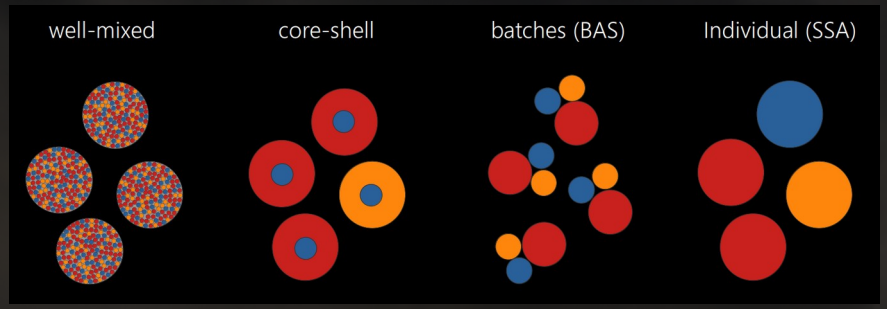
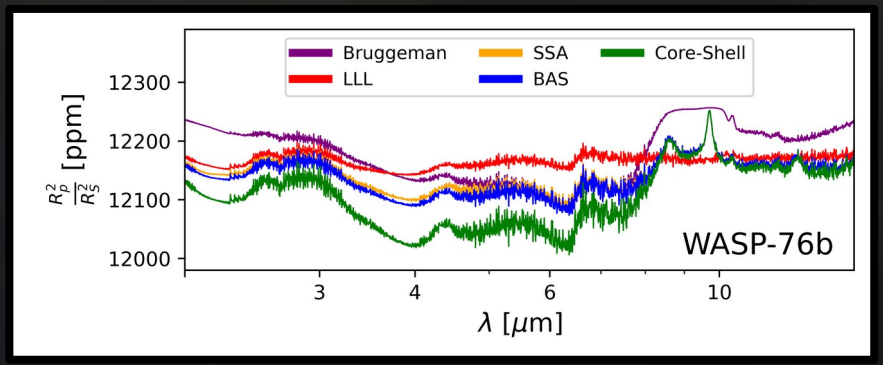
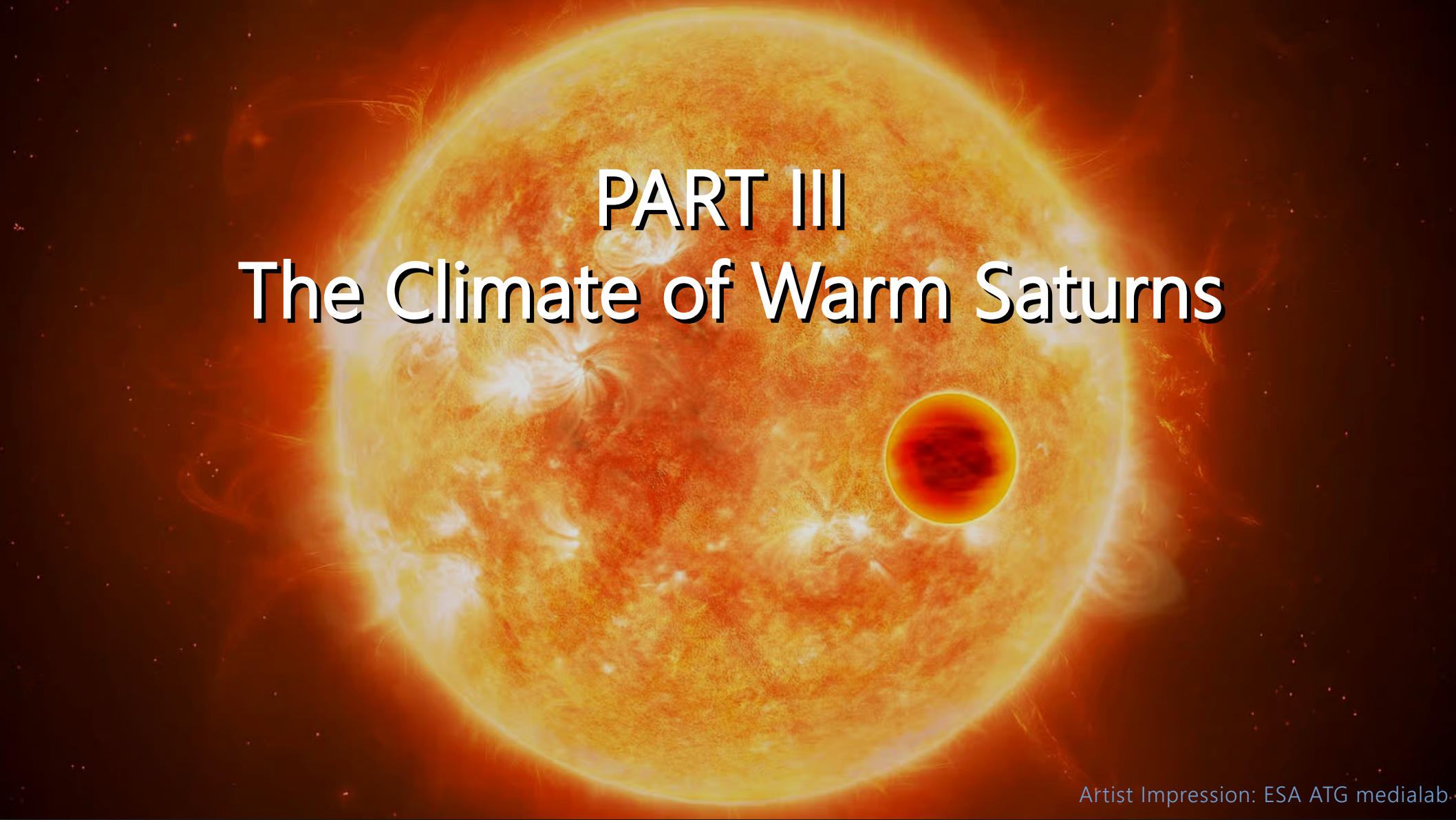




- Non-mixed particles can keep the spectral properties of individual cloud particle materials.
- If cloud particles are well-mixed their spectral features can be complex and broad.
- Transmission spectra are different if calculated with LLL or Brugemann.
- Iron-bearing cloud particle species and carbon can dominate the optical properties even when their inclusions make up less than 1%.

PART III
The Climate of Warm Saturns



Artist Impression: ESA ATG medialab

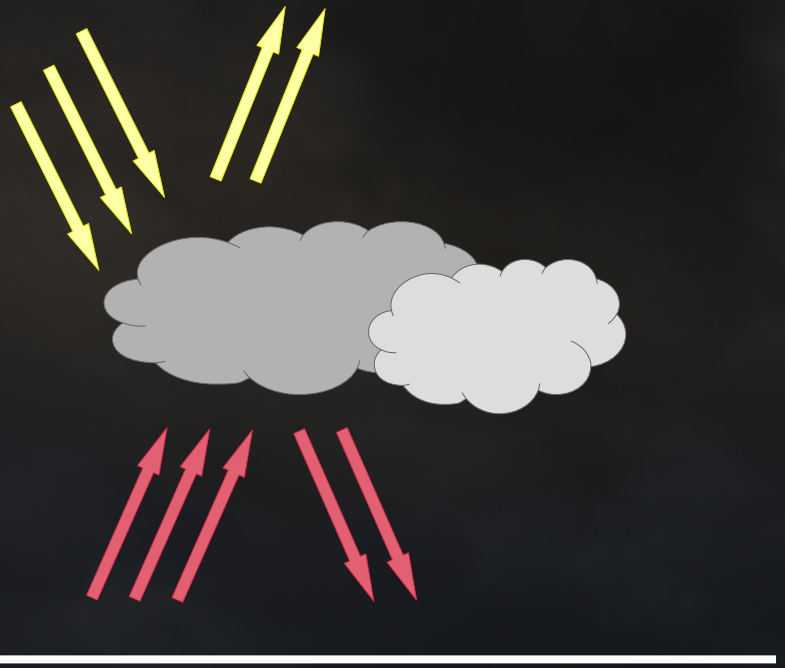
Clouds are three dimensional

Credit: NASA/JPL

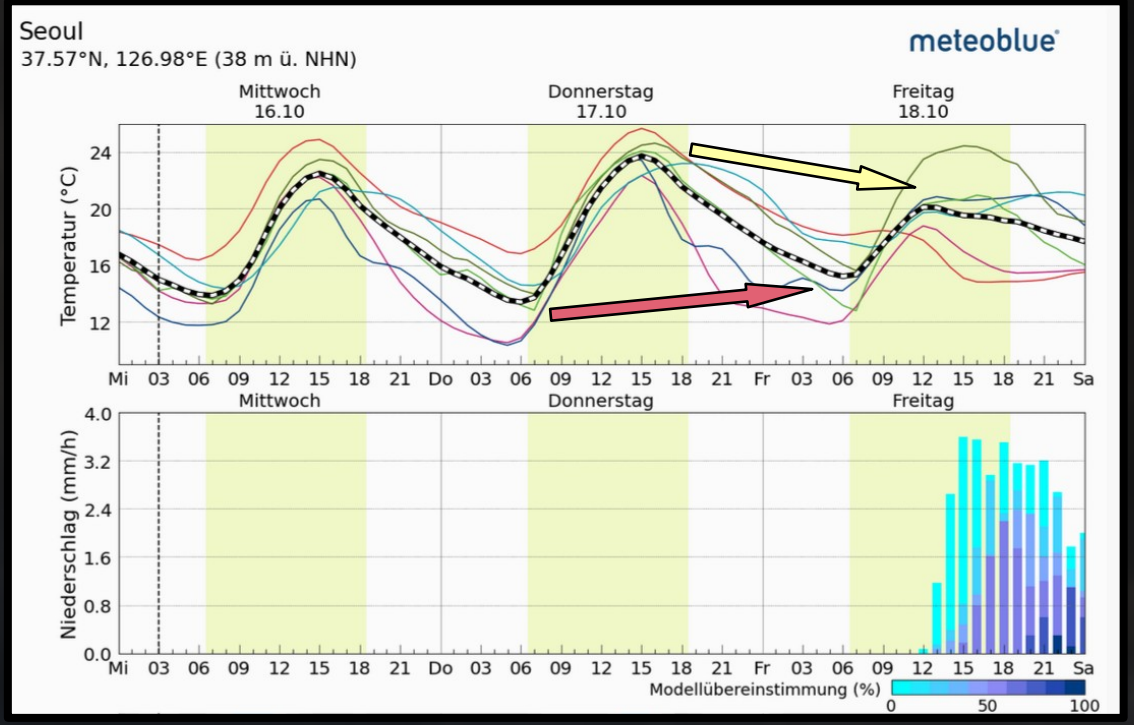
Why are clouds important

Why are clouds important

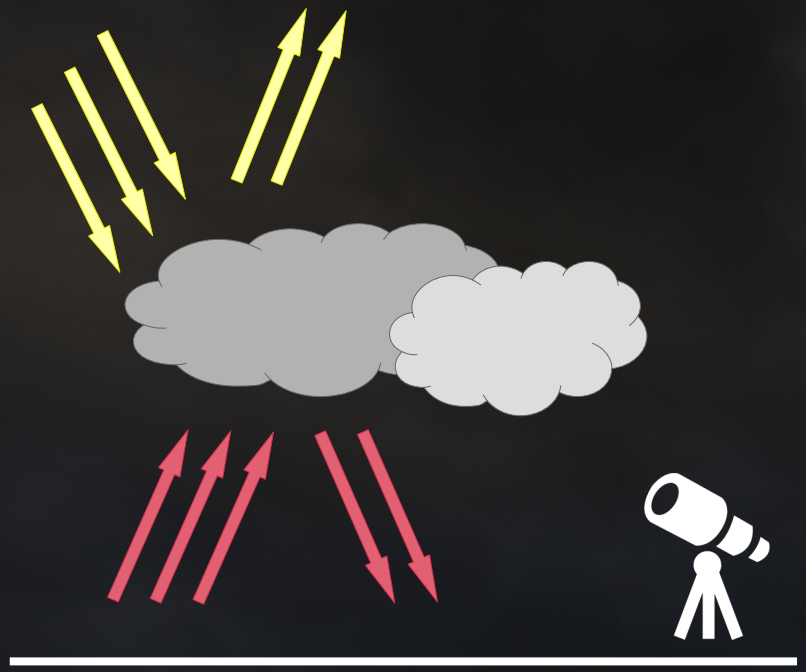
Why are clouds important

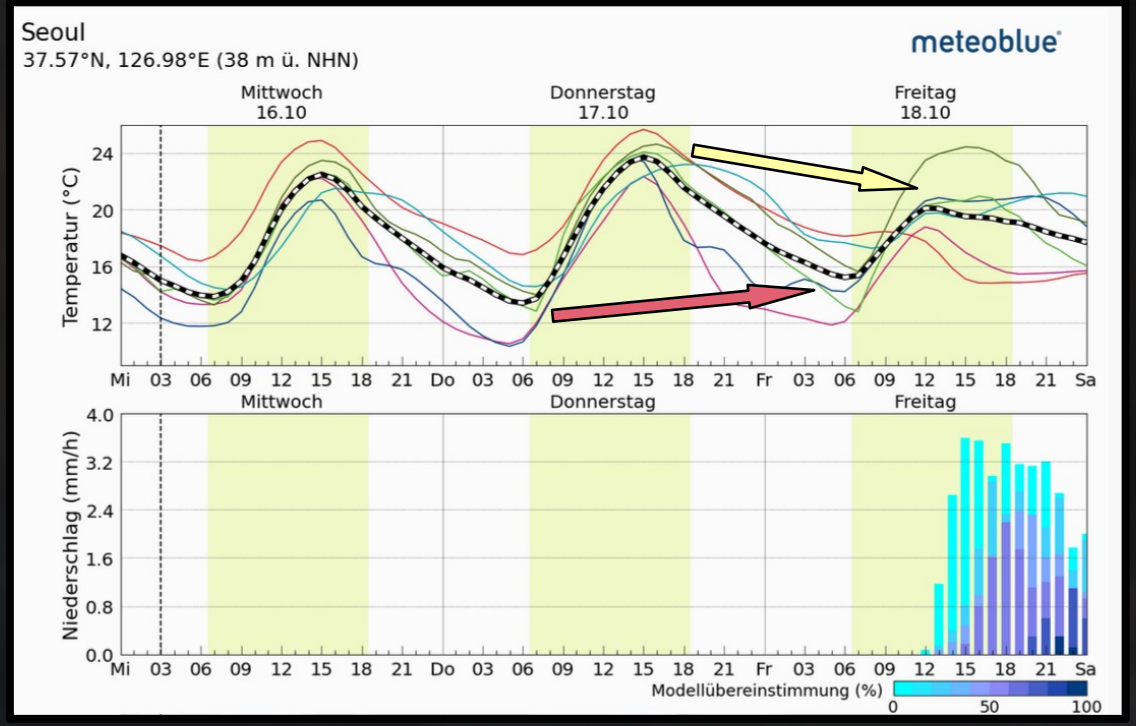


Why are clouds important



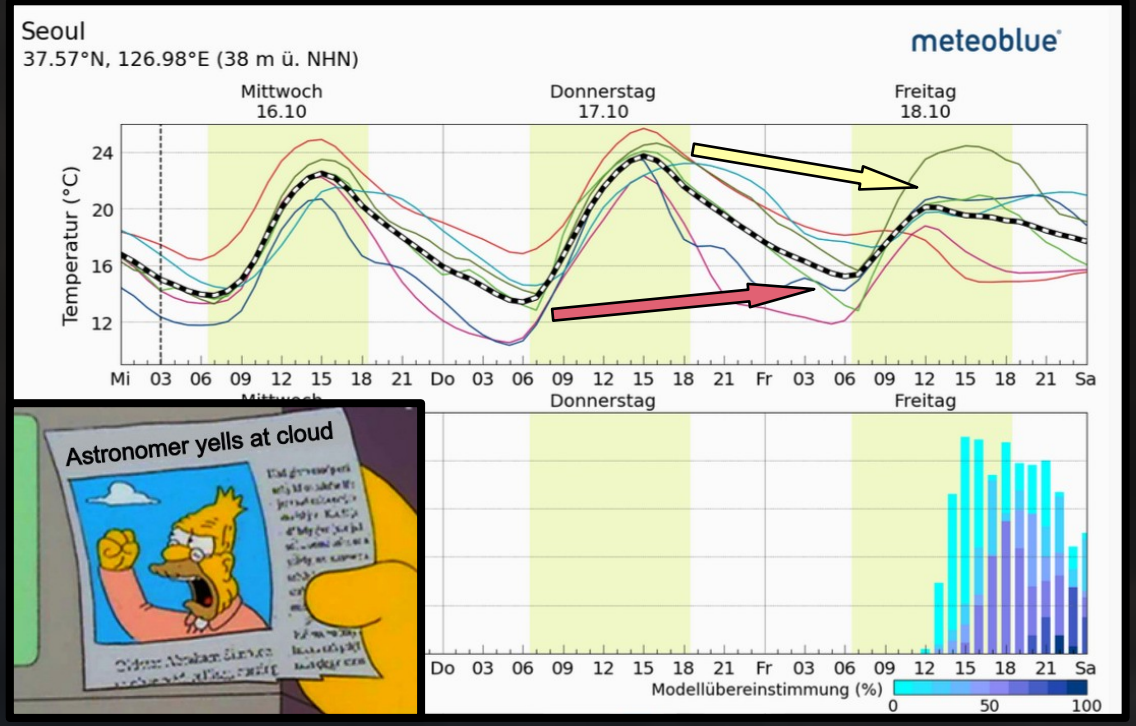
Why are clouds important





PART III – The Climate of Warm Saturns

Why are clouds important



The warm Saturn HATS-6b

HATS-6

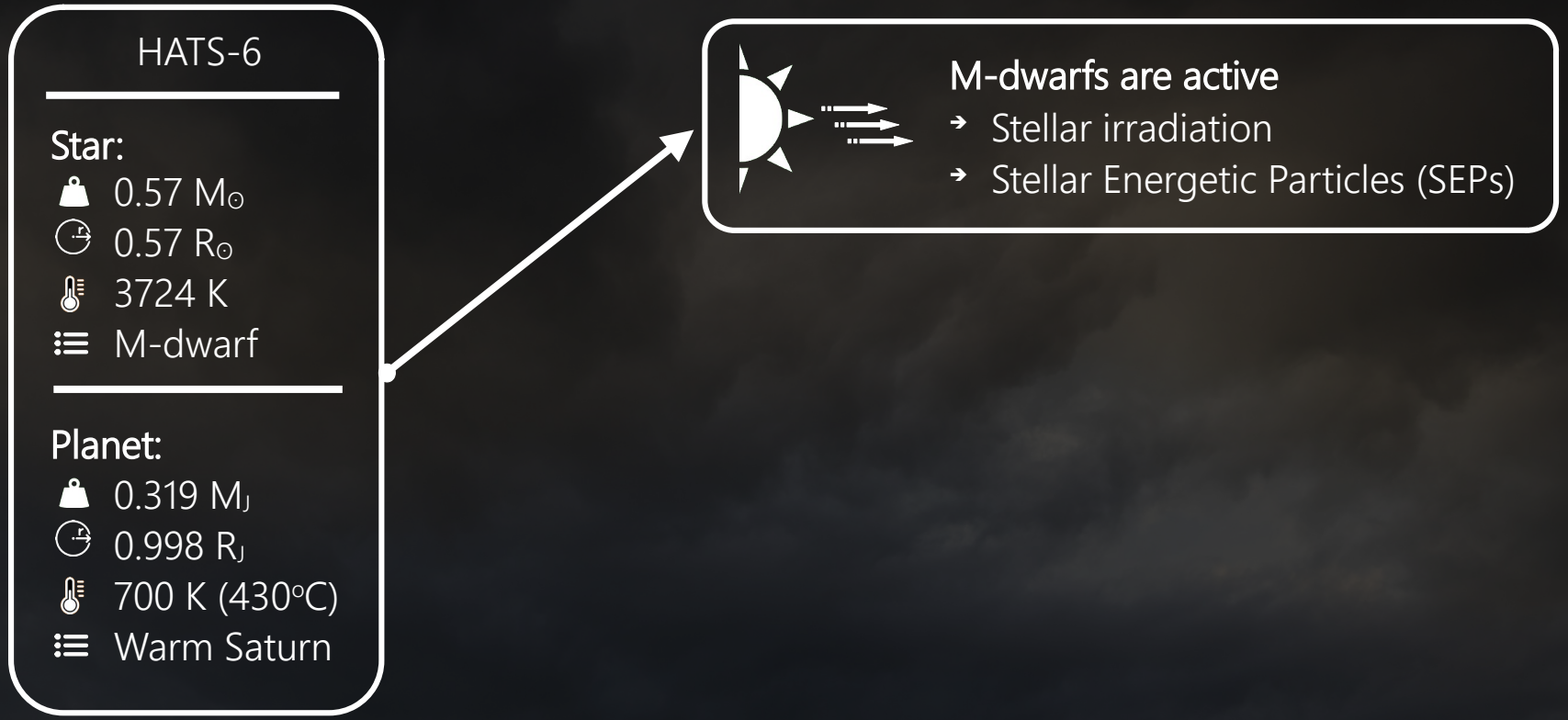
Star:

- 0.57 $M_{\odot}$
- 0.57 $R_{\odot}$
- 3724 K
- M-dwarf

Planet:

- 0.319 M_{J}
- 0.998 R_{J}
- 700 K (430°C)
- Warm Saturn

The warm Saturn HATS-6b



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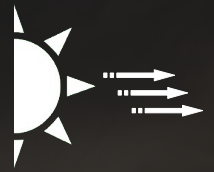

M-dwarfs are active
- Stellar irradiation
- Stellar Energetic Particles (SEPs)

M-dwarfs are small
- Large transit depths (3.2%)
- Questions about formation

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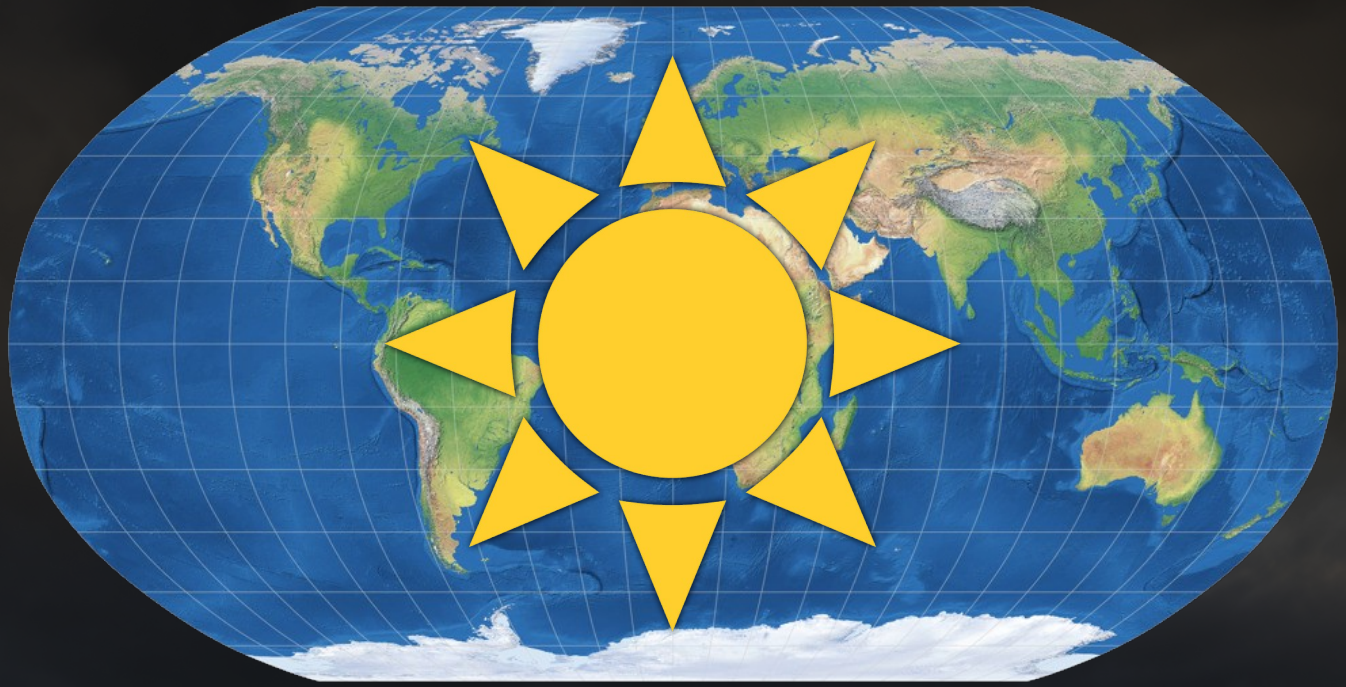
HATS-6b is temperate
- Effective Temperature ~700 K
- Global cloud coverage

The climate of the warm Saturn HATS-6b

The climate of the warm Saturn HATS-6b



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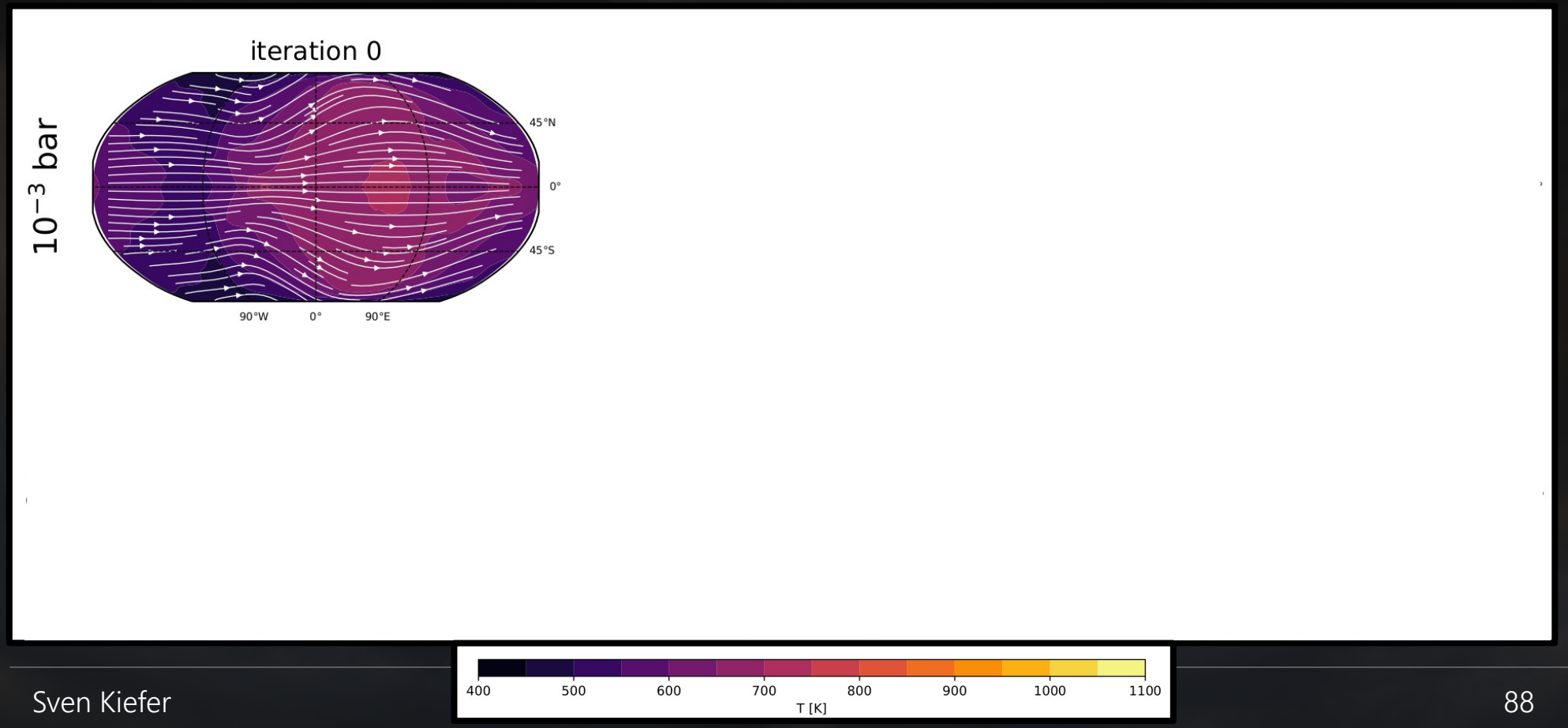
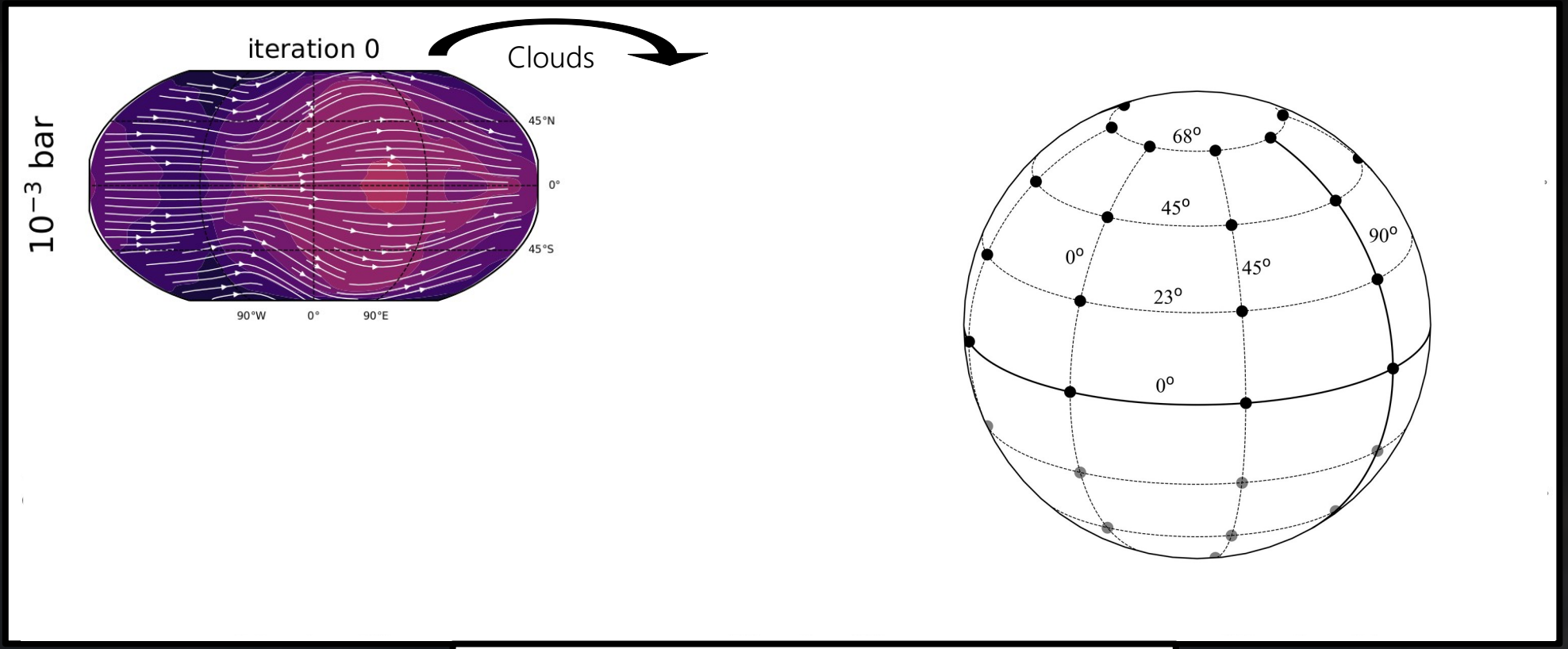


The climate of the warm Saturn HATS-6b



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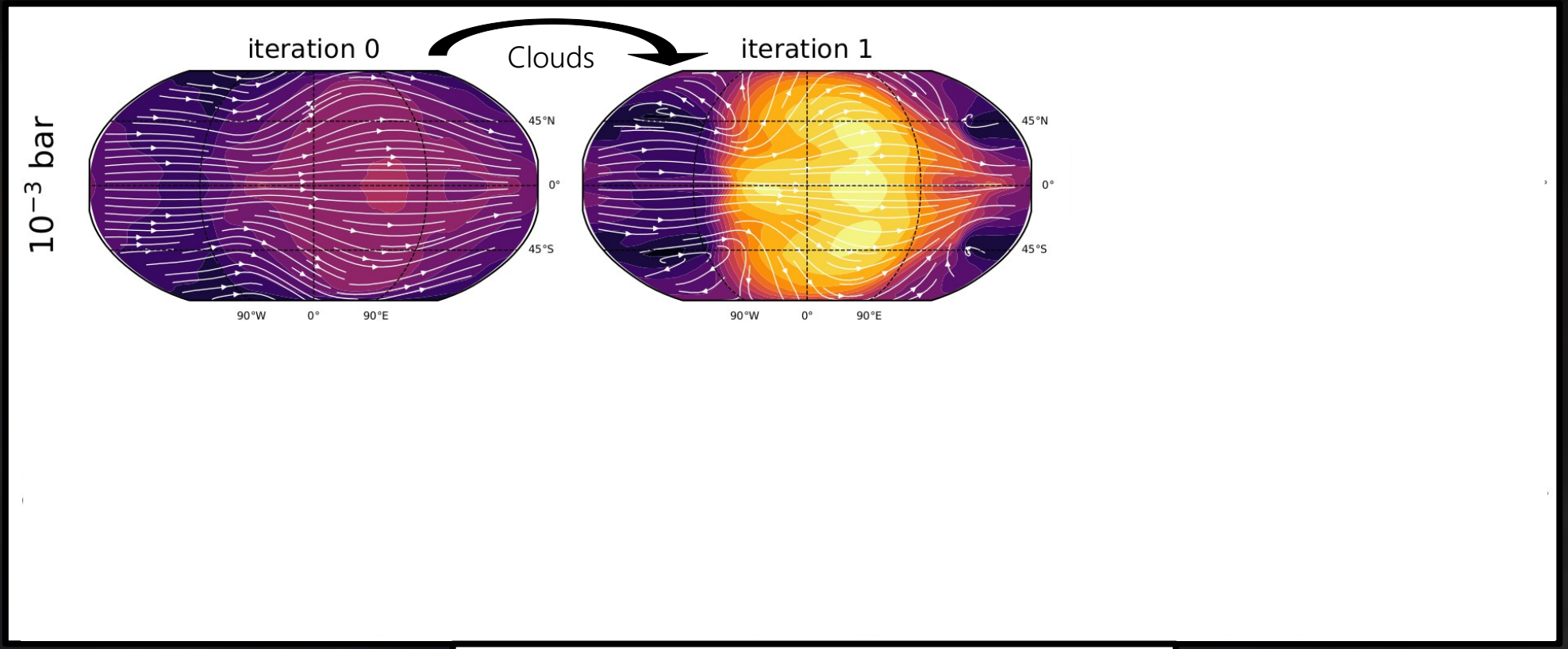

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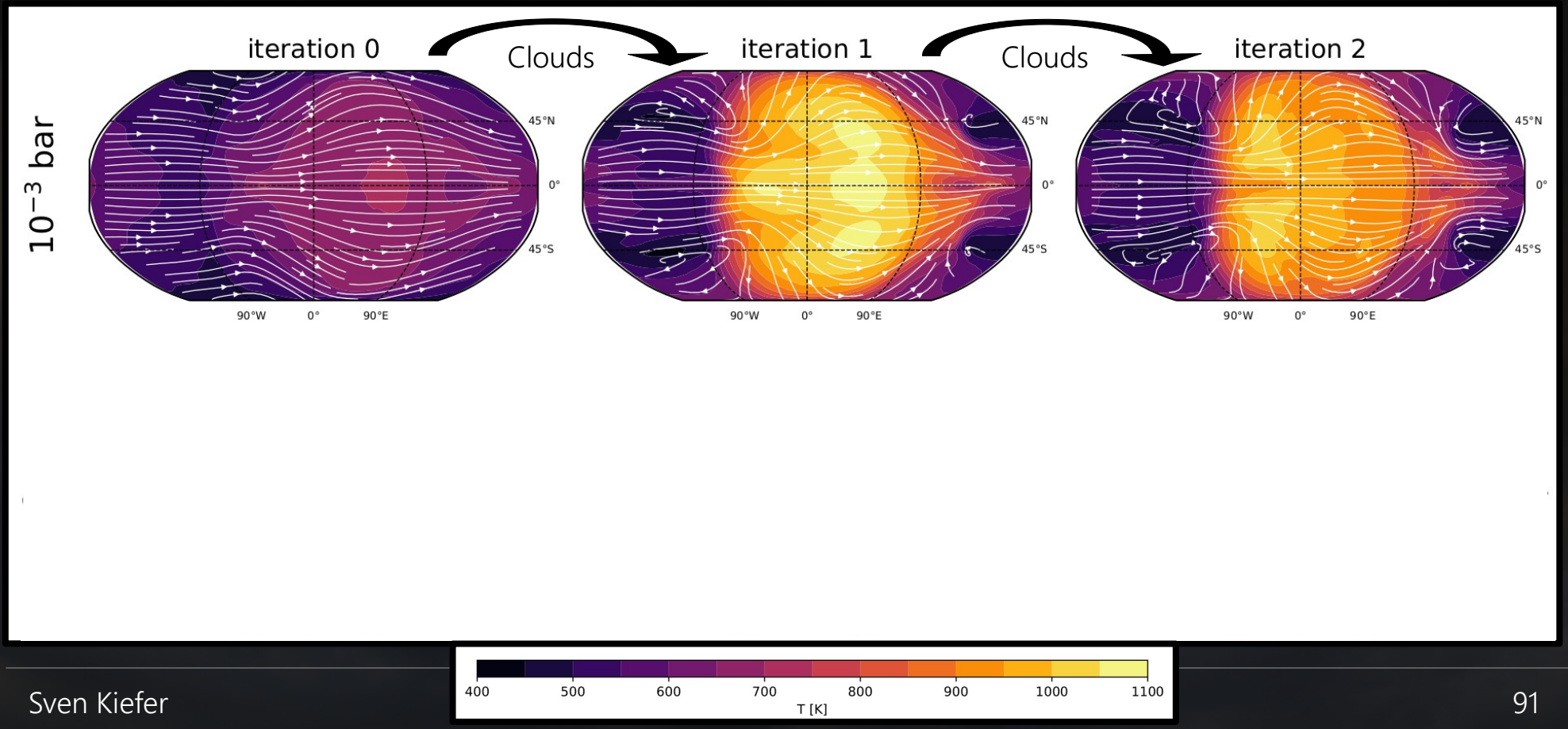

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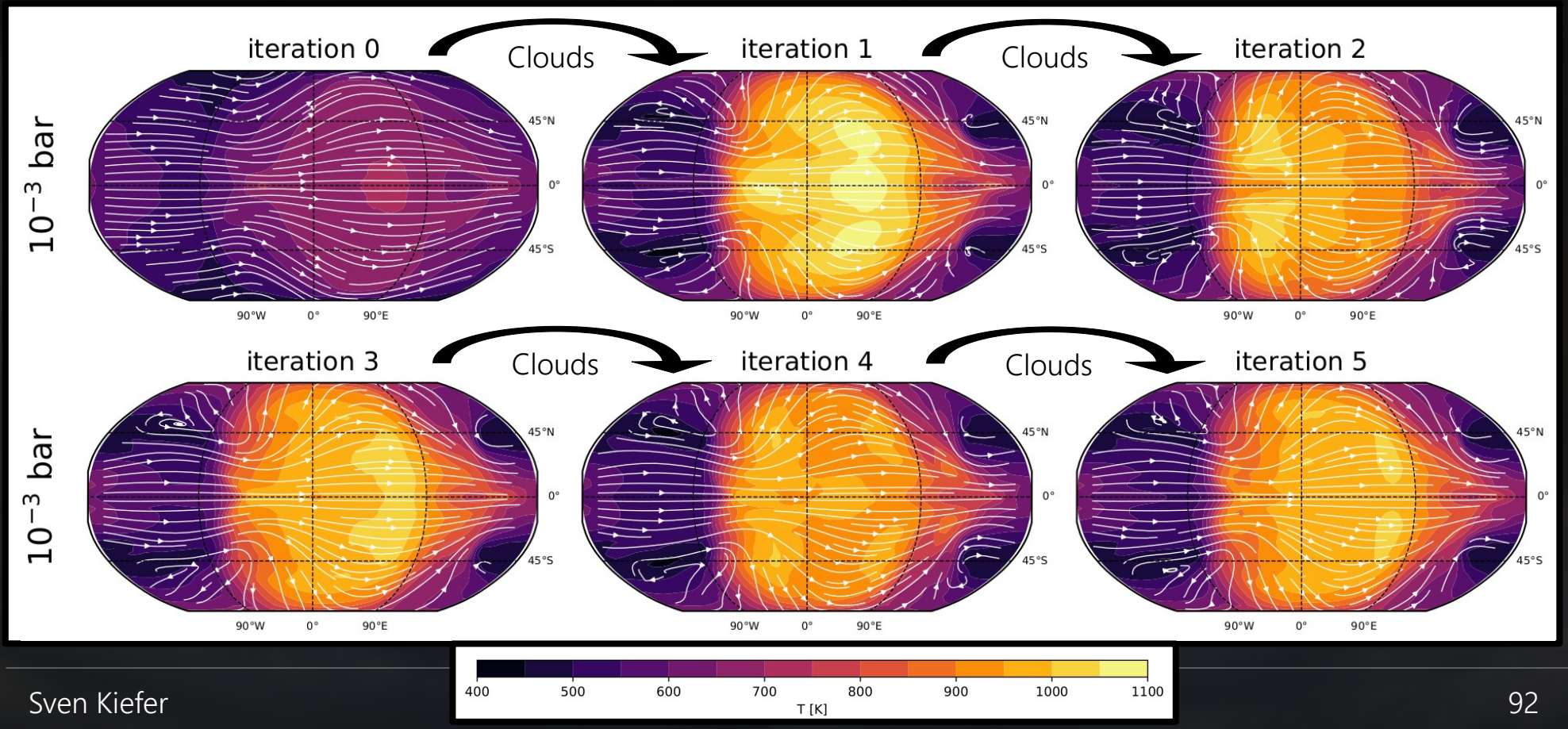

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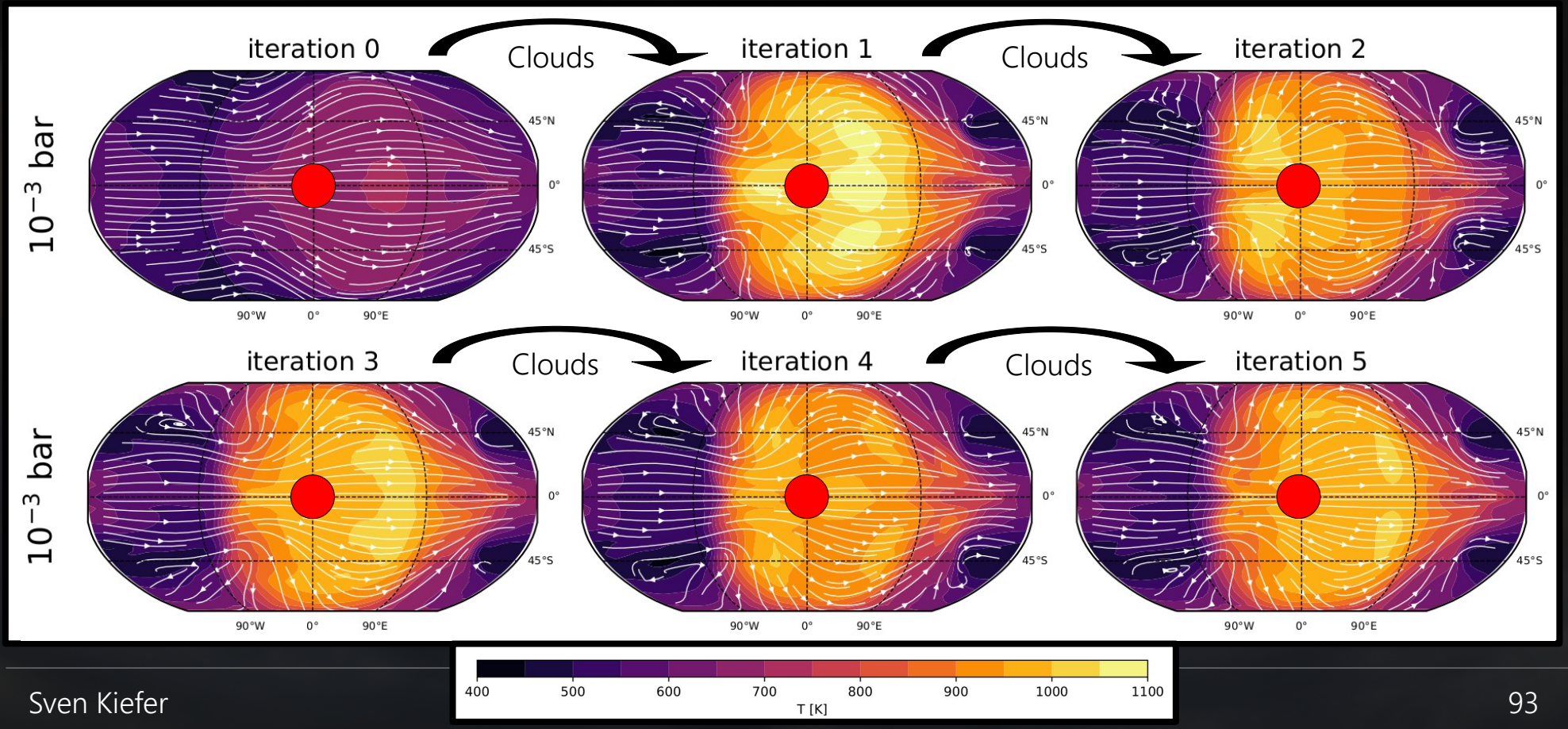

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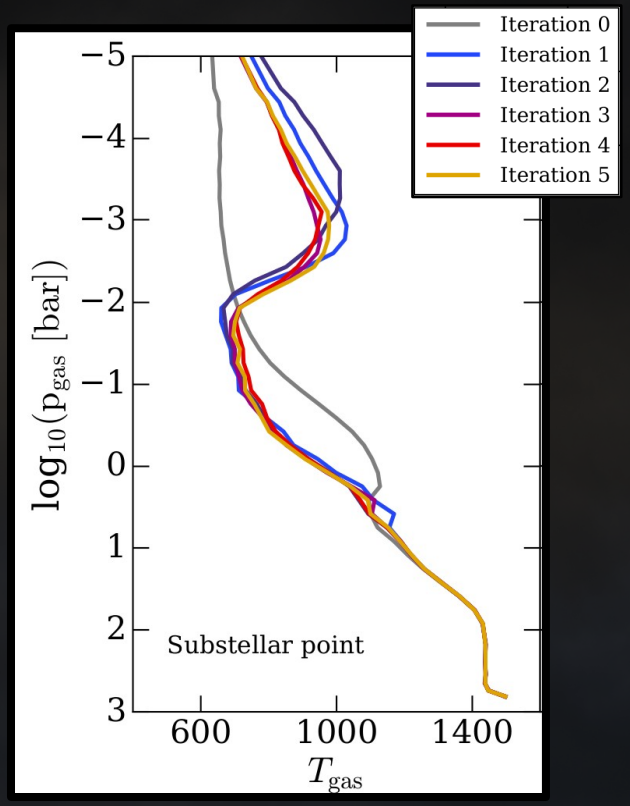
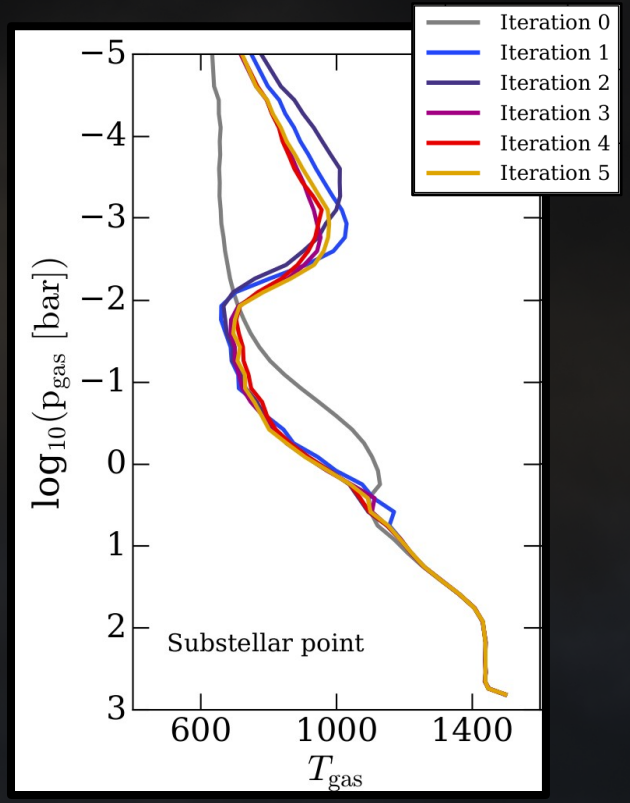
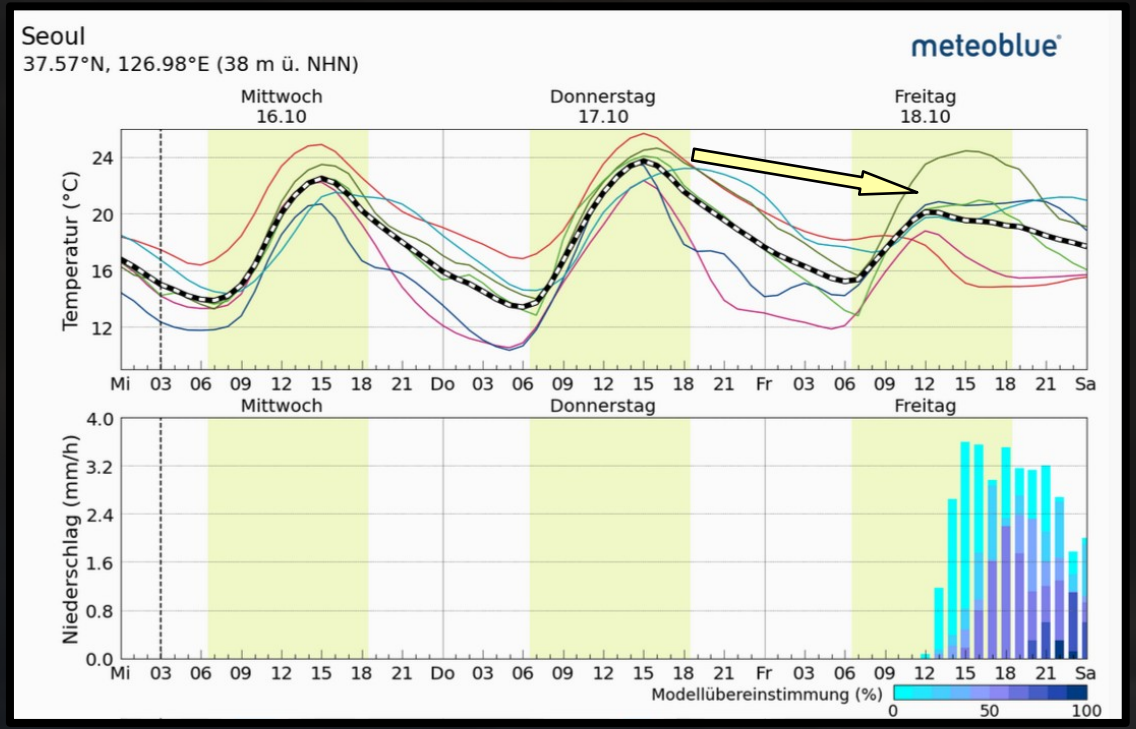
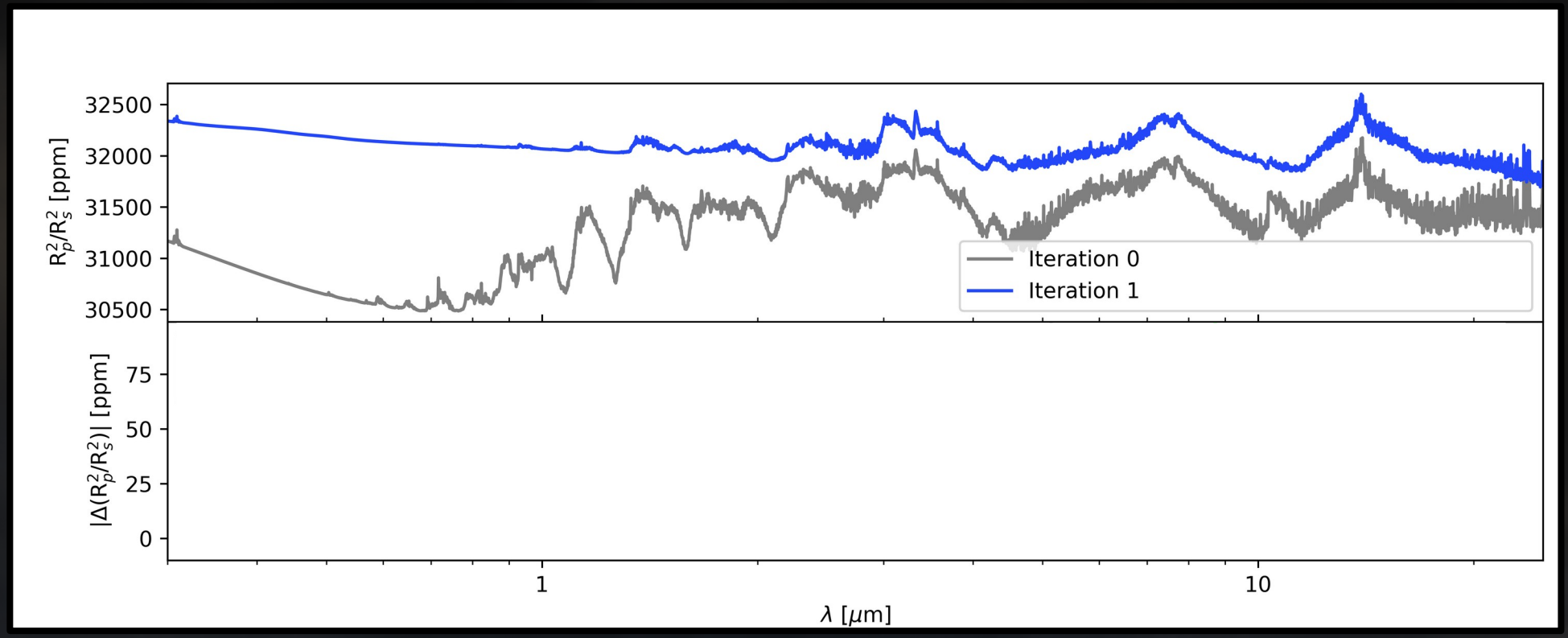


The climate of the warm Saturn HATS-6b





Are the differences observable?



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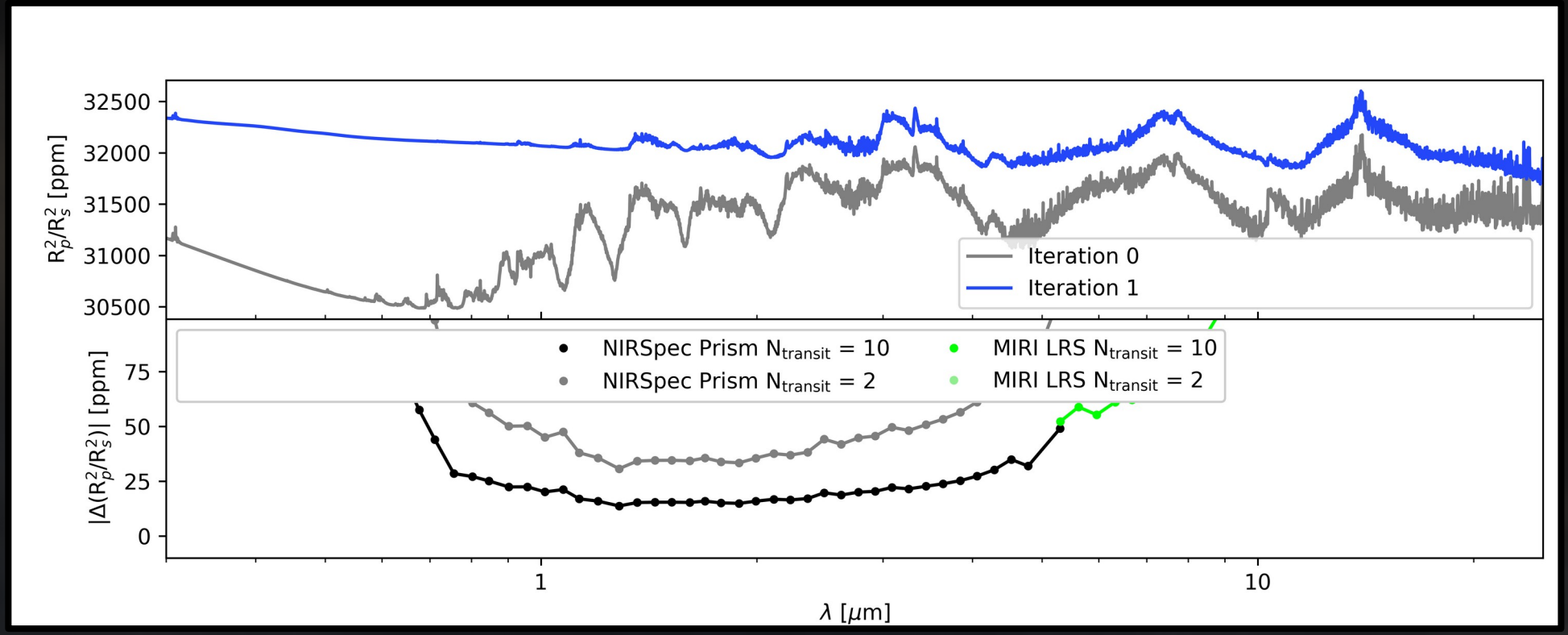

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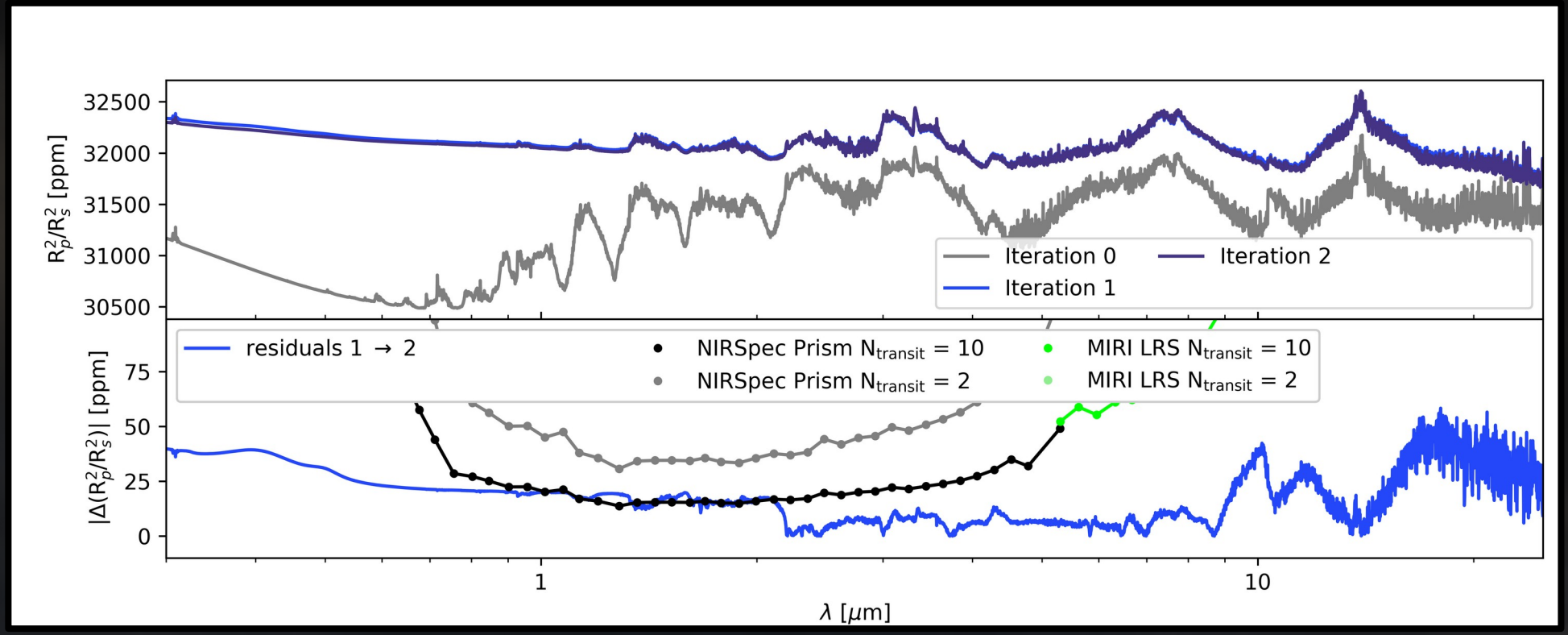

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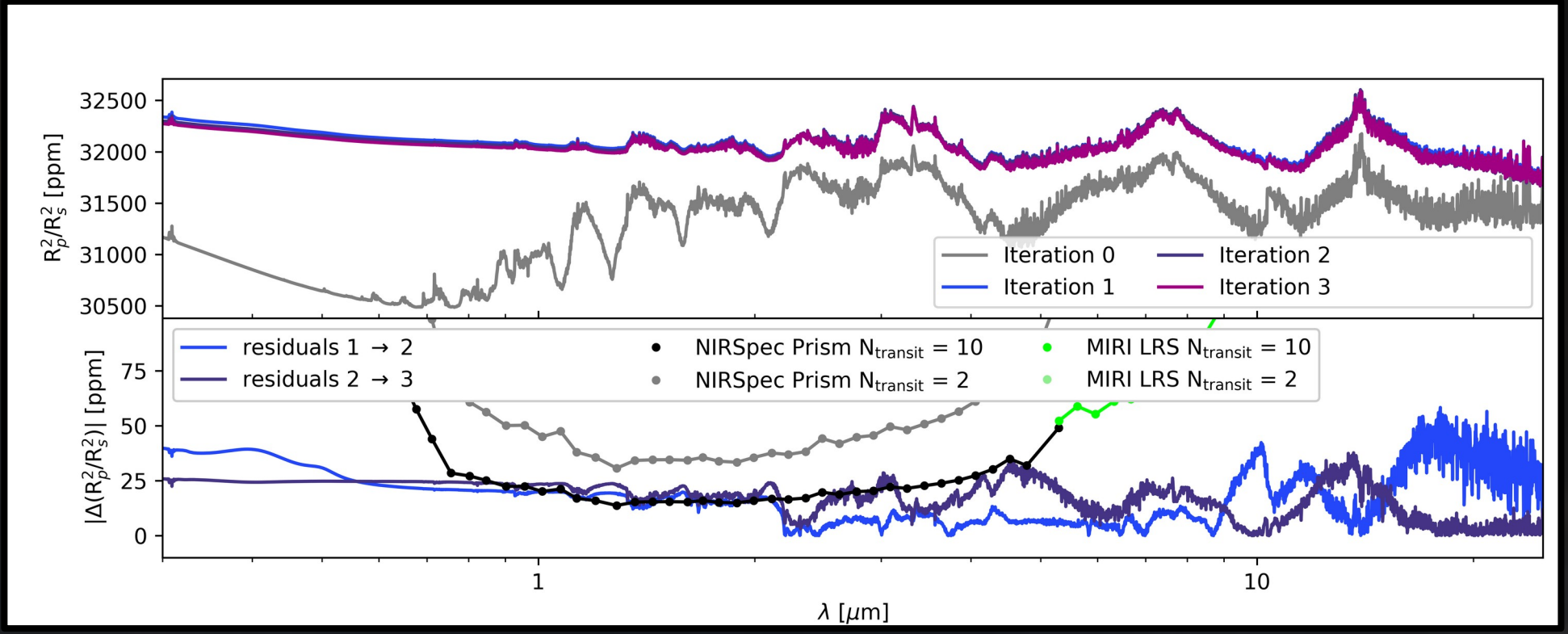

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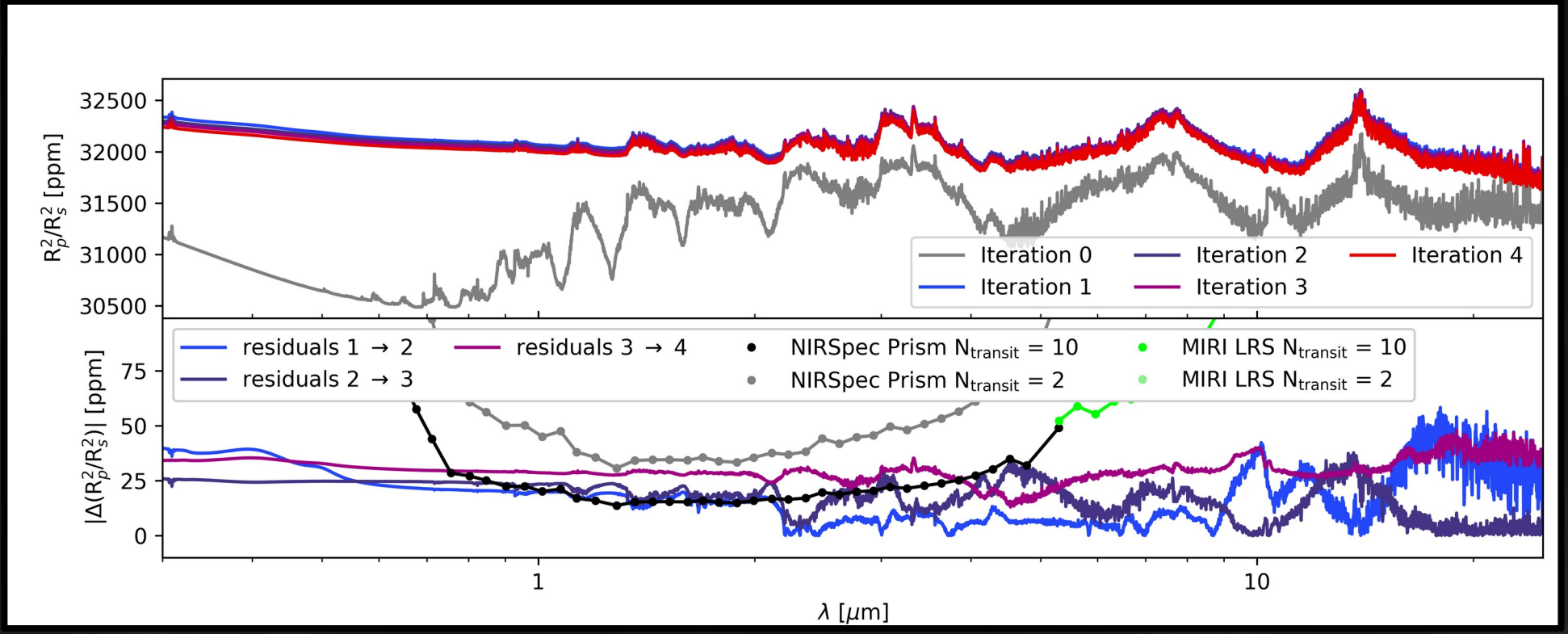

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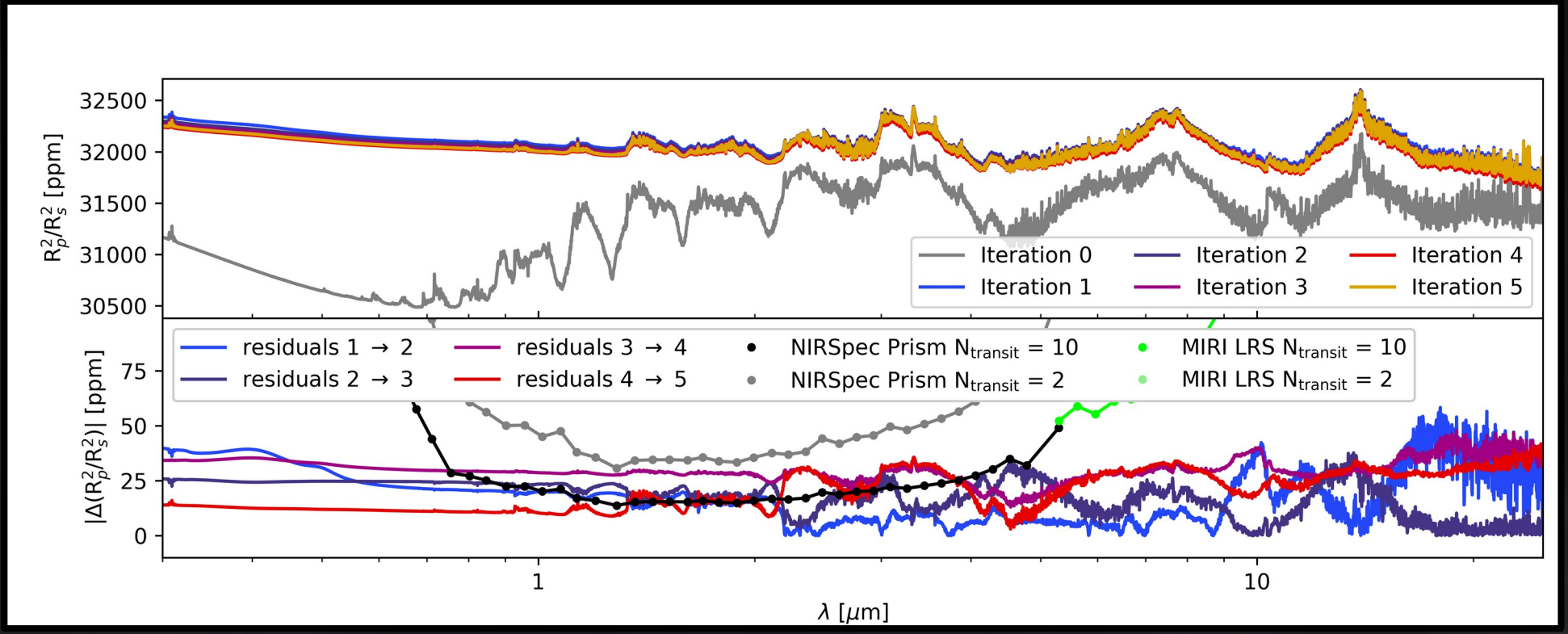

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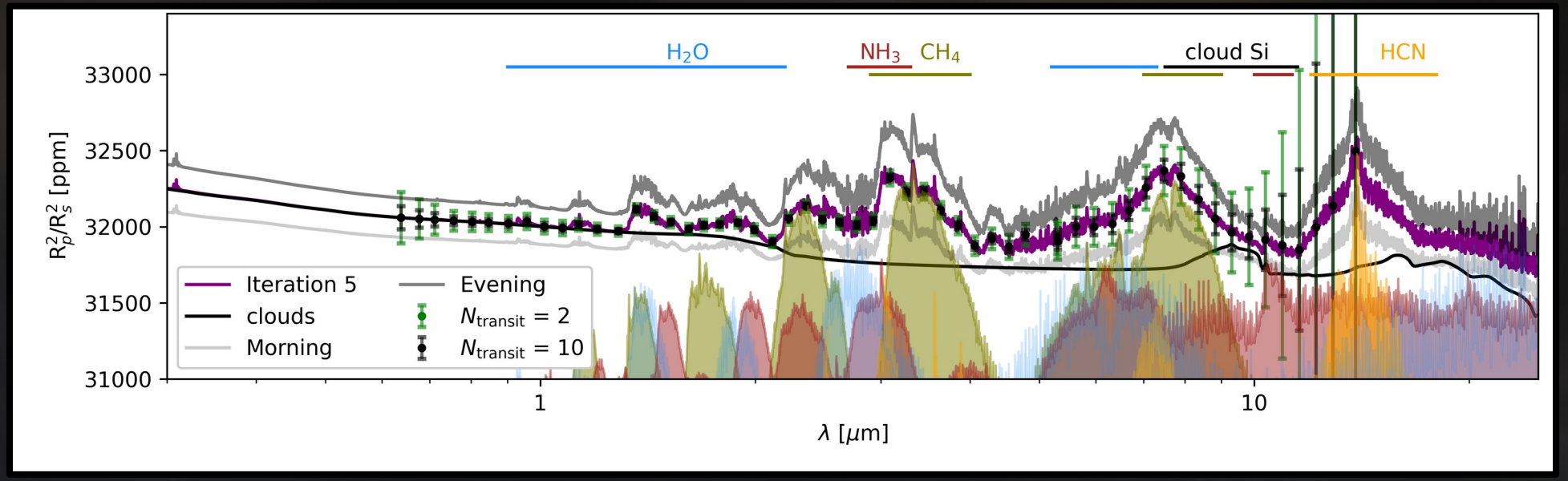

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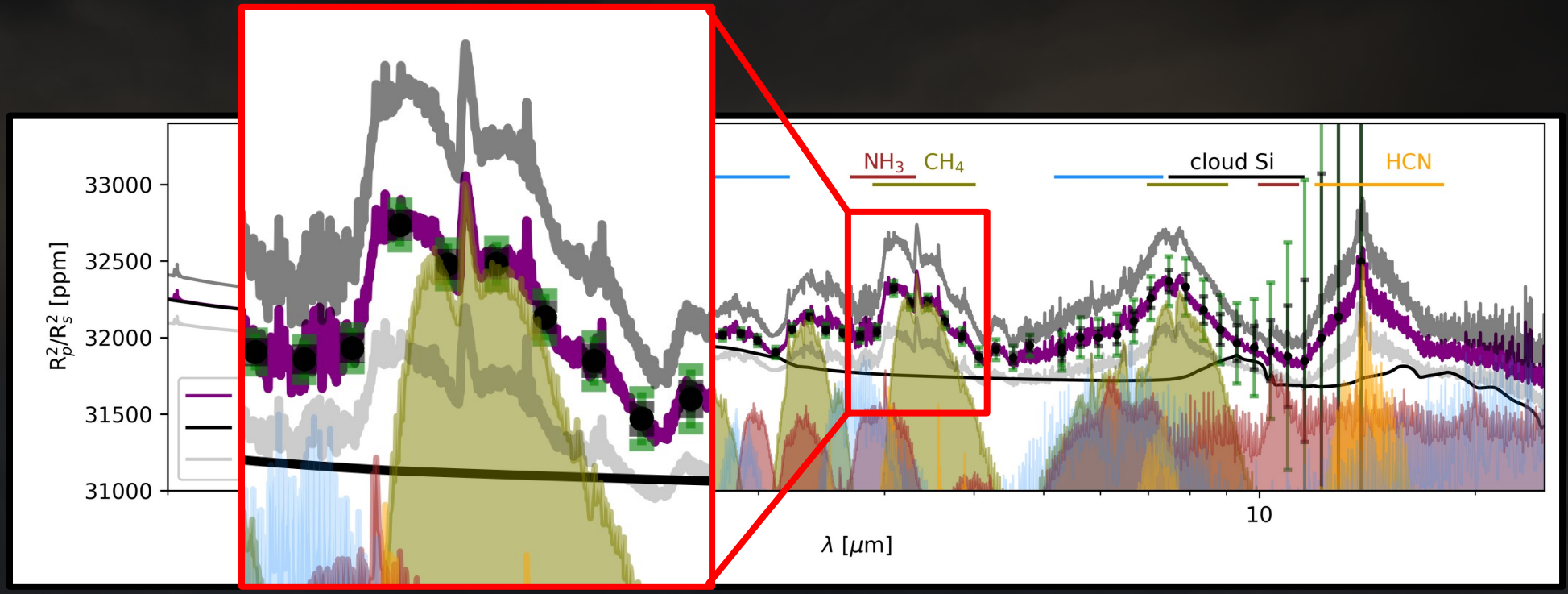

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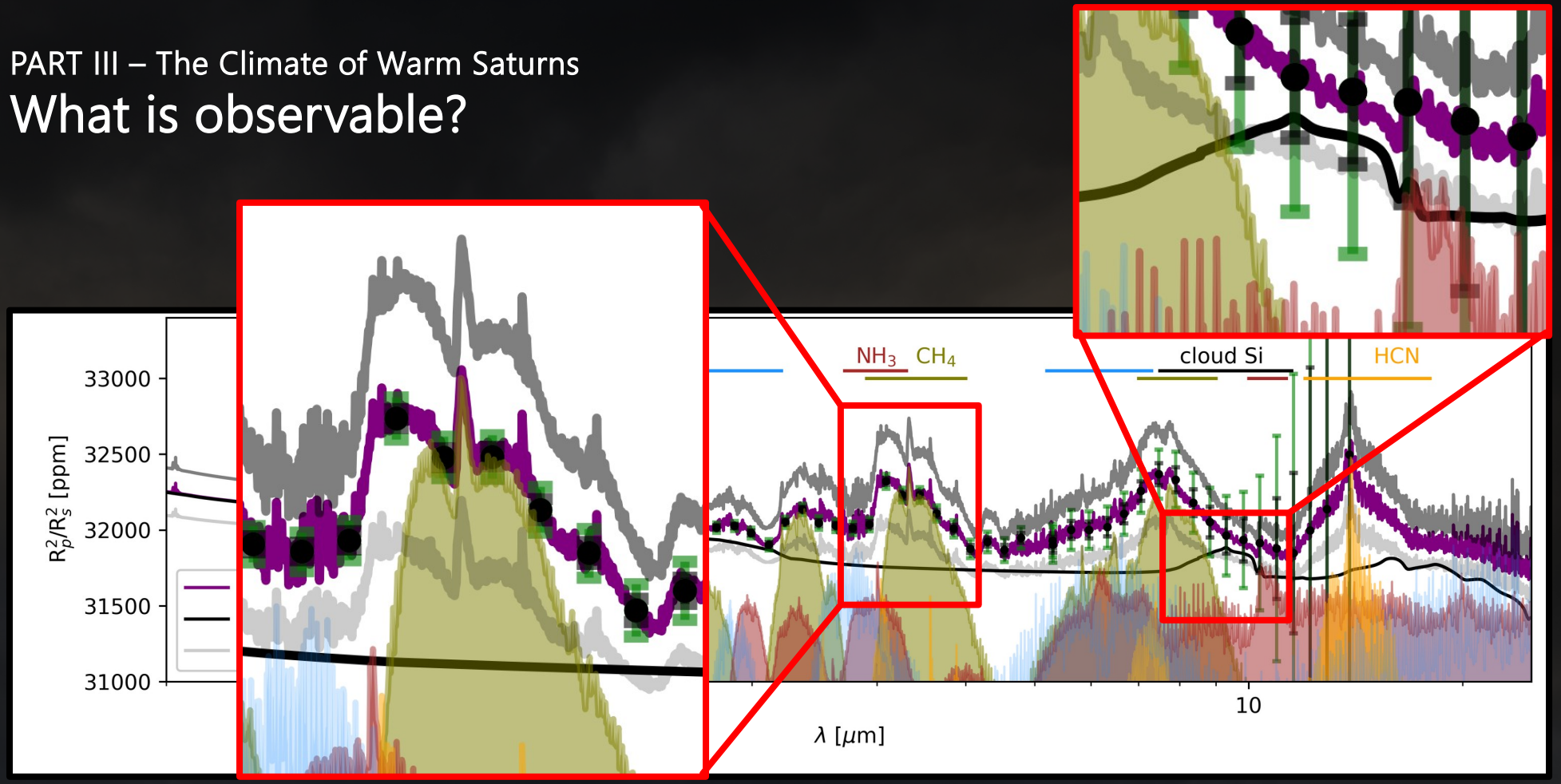
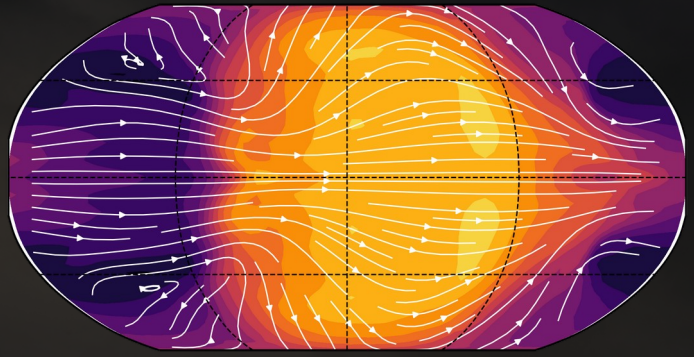
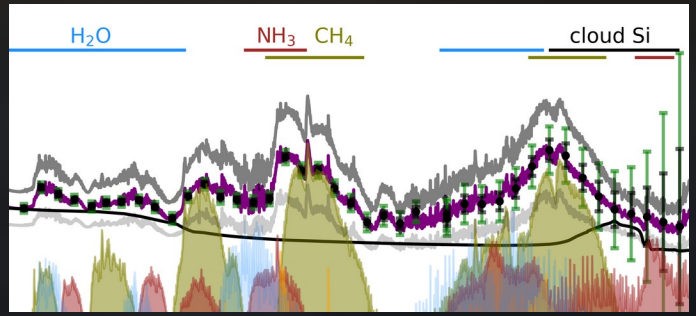


How do clouds affect the climate of warm Saturns?





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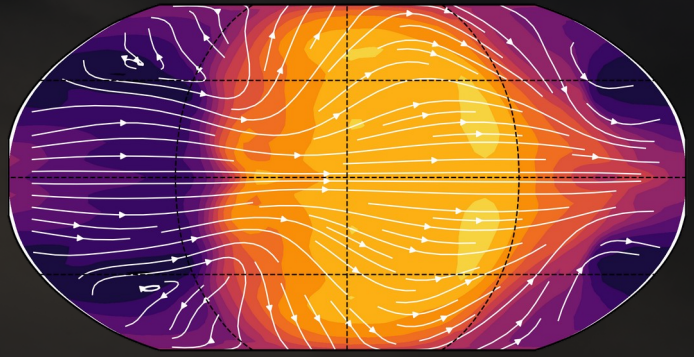

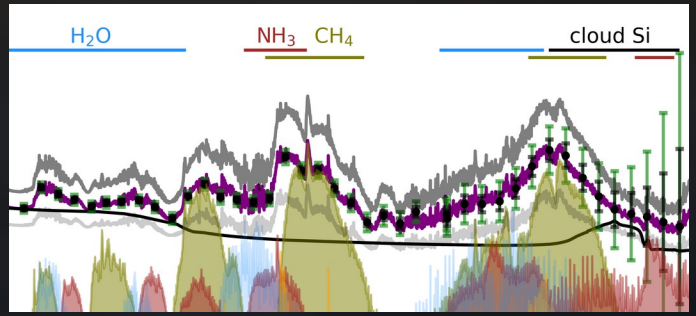

- Iterating between cloud and climate models enables to model exoplanets in their full complexity.

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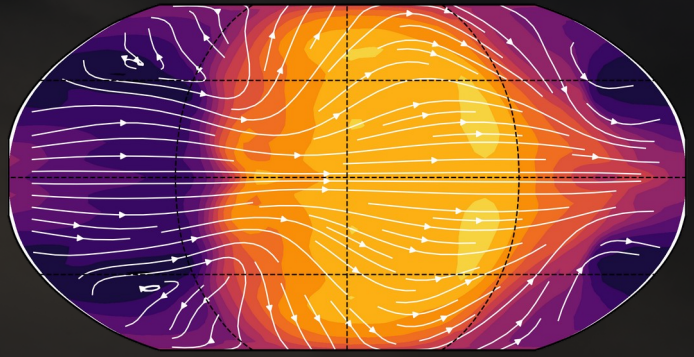

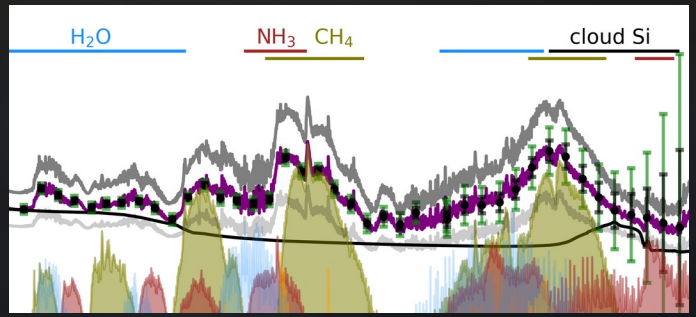

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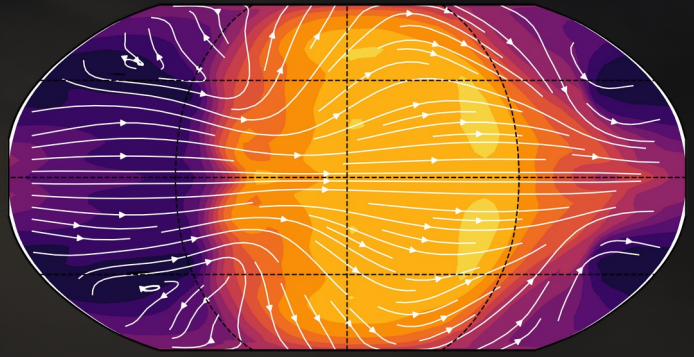

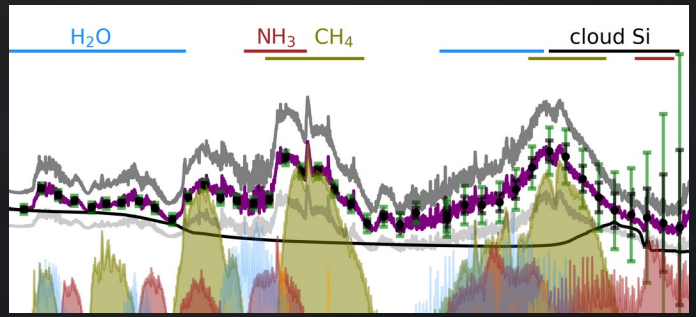

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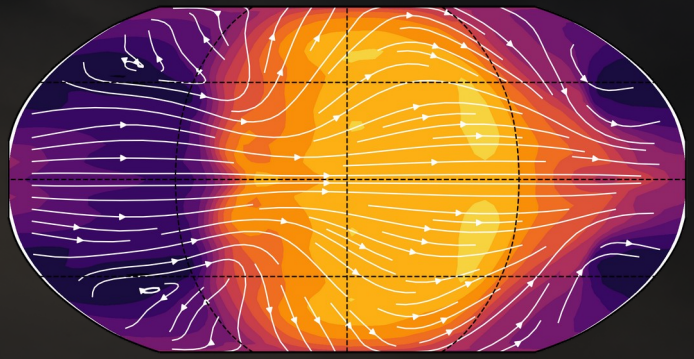

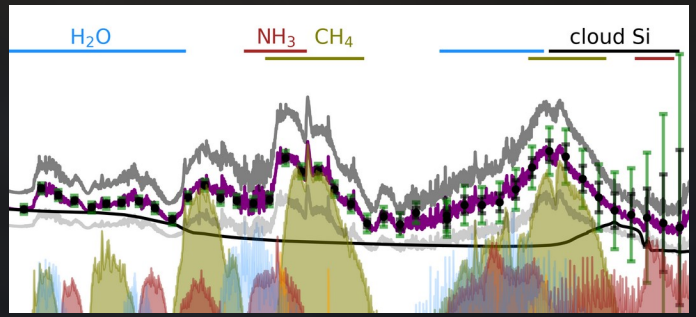

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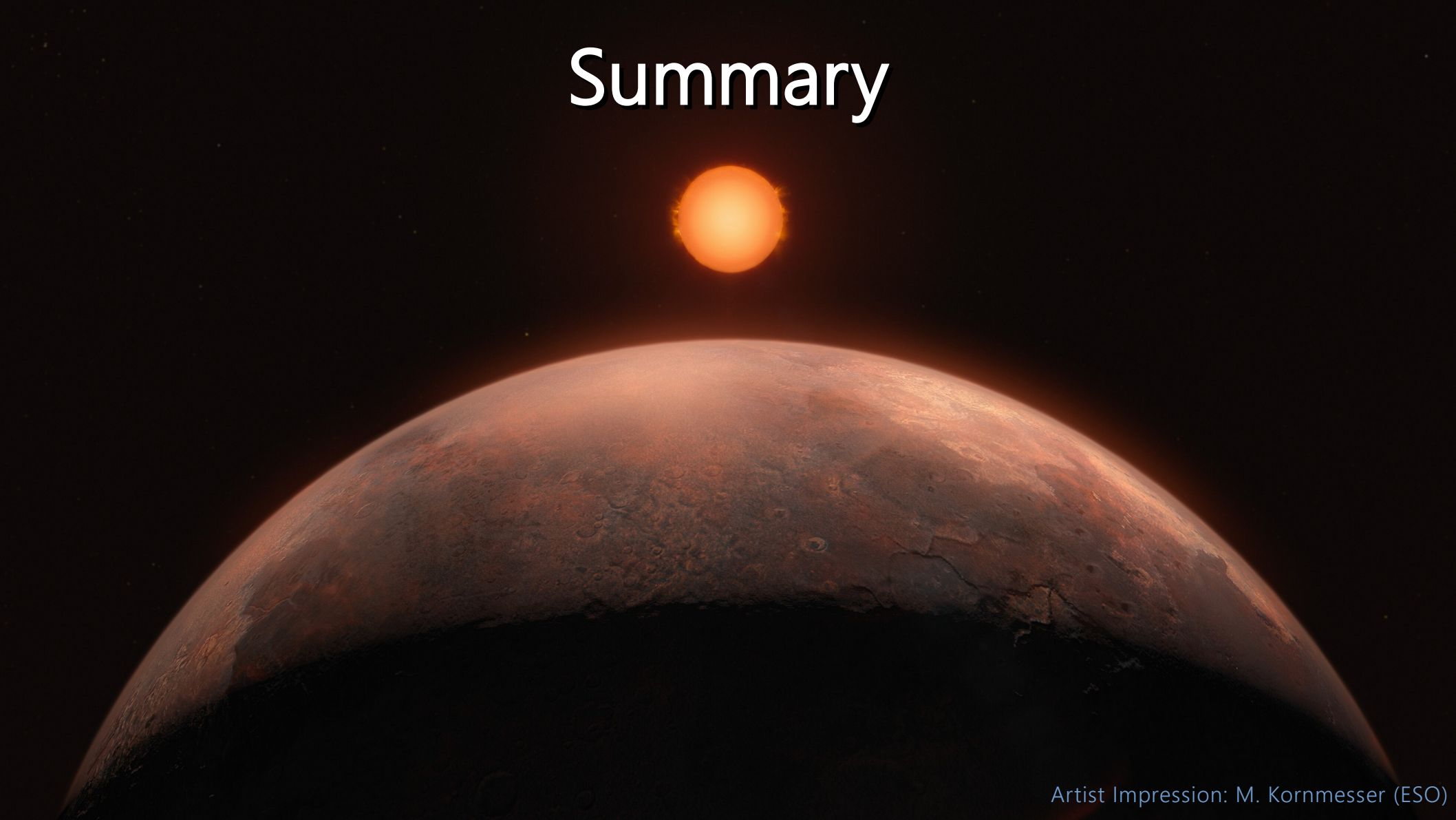
- Clouds can cause a temperature inversion in the upper and cooling in the lower atmosphere.
- The effect of the clouds on the temperature leads to a narrower and faster equatorial wind jet.
- HATS-6b has a favorable transit depth enabling the potential detection of CH_4 and silicate clouds.

Summary



Artist Impression: M. Kornmesser (ESO)

Summary

Cloud formation in 3D Exoplanet Atmospheres

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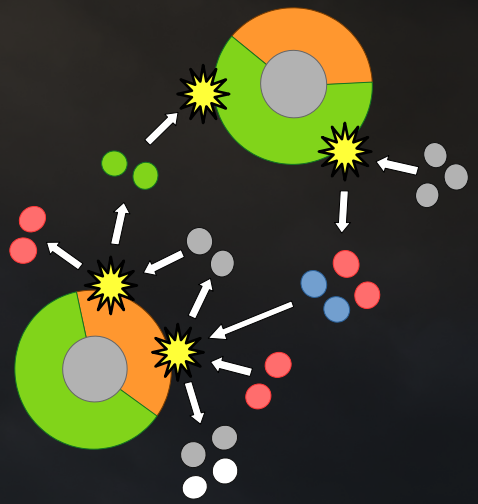
Cloud formation in 3D Exoplanet Atmospheres

Clouds affect and are affected by their environment



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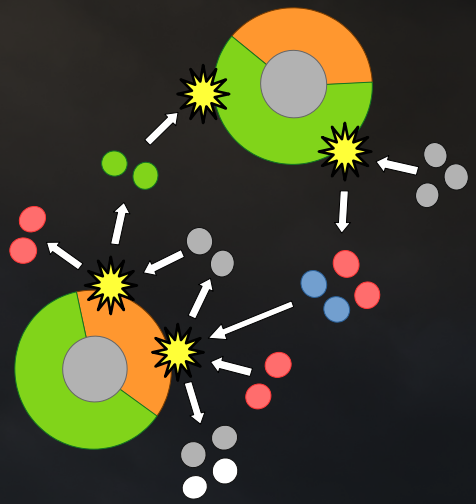
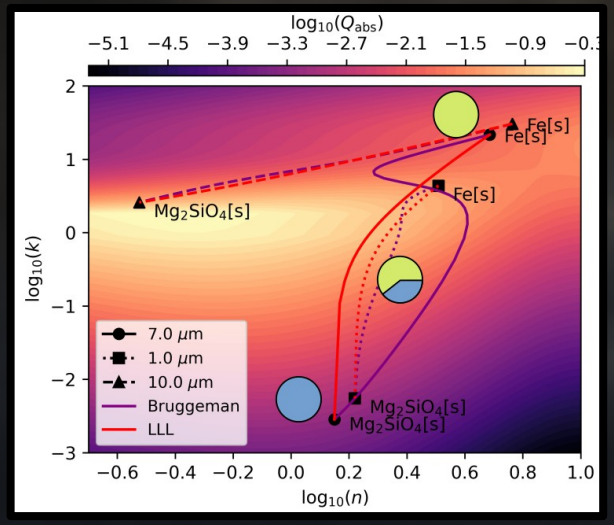


Optical properties of cloud particles are complex



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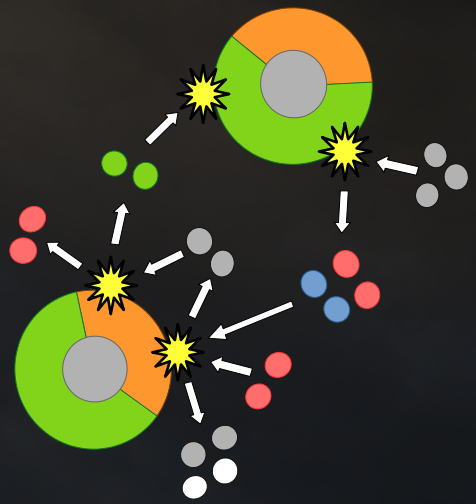

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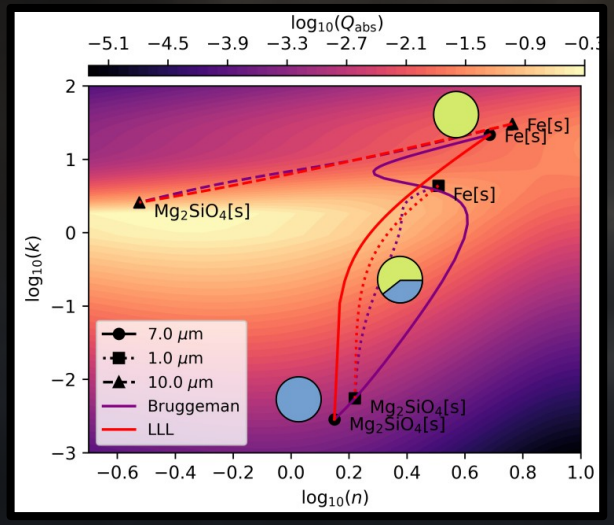

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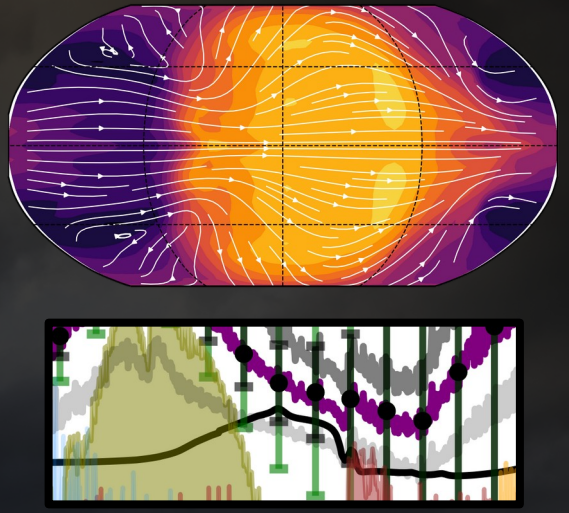

Thank you to everyone!

And especially to ....

Thank you to …

My Supervisors

Leen Decin

Christiane Helling

Ludmila Carone

David Gobrecht

Thank you to …

All the people at the IvS and the IWF

Thank you to …

A network that became family

Thank you to …

A family that has always been family