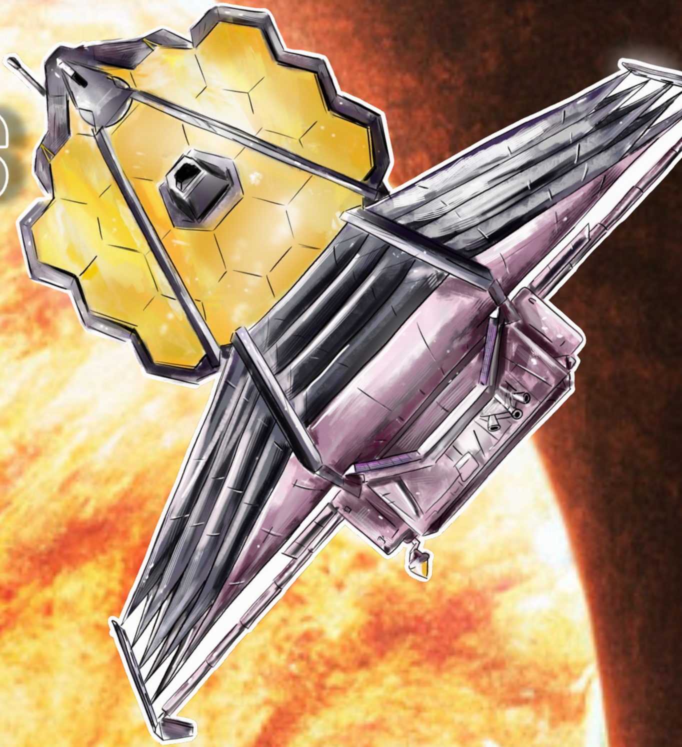
SAGAN SUMMER WORKSHOP

JULY 2023

# Rocky exoplanets: Formation and Links to Present-day Atmospheres




Yamila Miguel

Leiden Observatory

SRON


Graphic by DALL-E

# SAGAN SUMMER WORKSHOP 2009

# WHY STUDY ROCKY PLANETS?

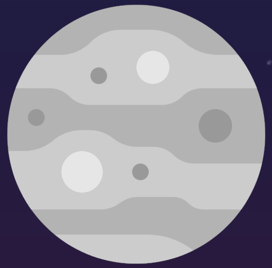
We want to understand how the Earth was formed

The diversity of worlds observed show a full range of evolutionary snapshots

We want to know how unique are the rocky planets in our solar system

The diversity of atmospheres provide extreme scenarios and test the chemical origins of life and the distinction between potentially habitable and lifeless worlds

Lava planets open observational windows into global geodynamic and climate regimes inaccessible in the present Solar System



Atmosphere-less planets open observational windows into the study of surfaces and geology of alien worlds

Icons created by Freepik - Flaticon

YAMILA MIGUEL - Leiden Observatory - SRON

How do we explain the diversity of rocky planets (including differences in our own solar system)?

Do rocky exoplanets (around M stars) have an atmosphere?

What is the atmosphere made of?

Can we learn about their interiors from atmospheric observations?

# HOW DO THE ATMOSPHERES OF ROCKY PLANETS FORM?

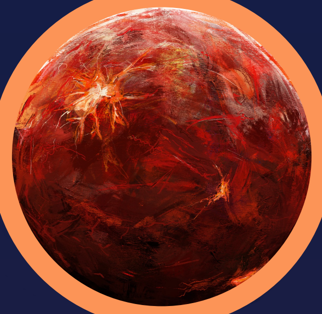
## PRIMARY ATMOSPHERES ACCRETED FROM THE PRIMORDIAL NEBULA

Ormel et al. 2015b,a; Lambrechts & Lega 2017; Moldenhauer et al. 2021, 2022

## EVAPORATION OF THE PRIMARY ATMOSPHERES

Ikoma & Hori 2012b; Liu et al. 2015b; Lammer et al. 2018; Ginzburg et al. 2018; Gupta & Schlichting 2019; Biersteker & Schlichting 2019; Kegerreis et al. 2020; Denman et al. 2020; Chance et al. 2022;

## SECONDARY ATMOSPHERES OUTGASSED FROM THE INTERIOR



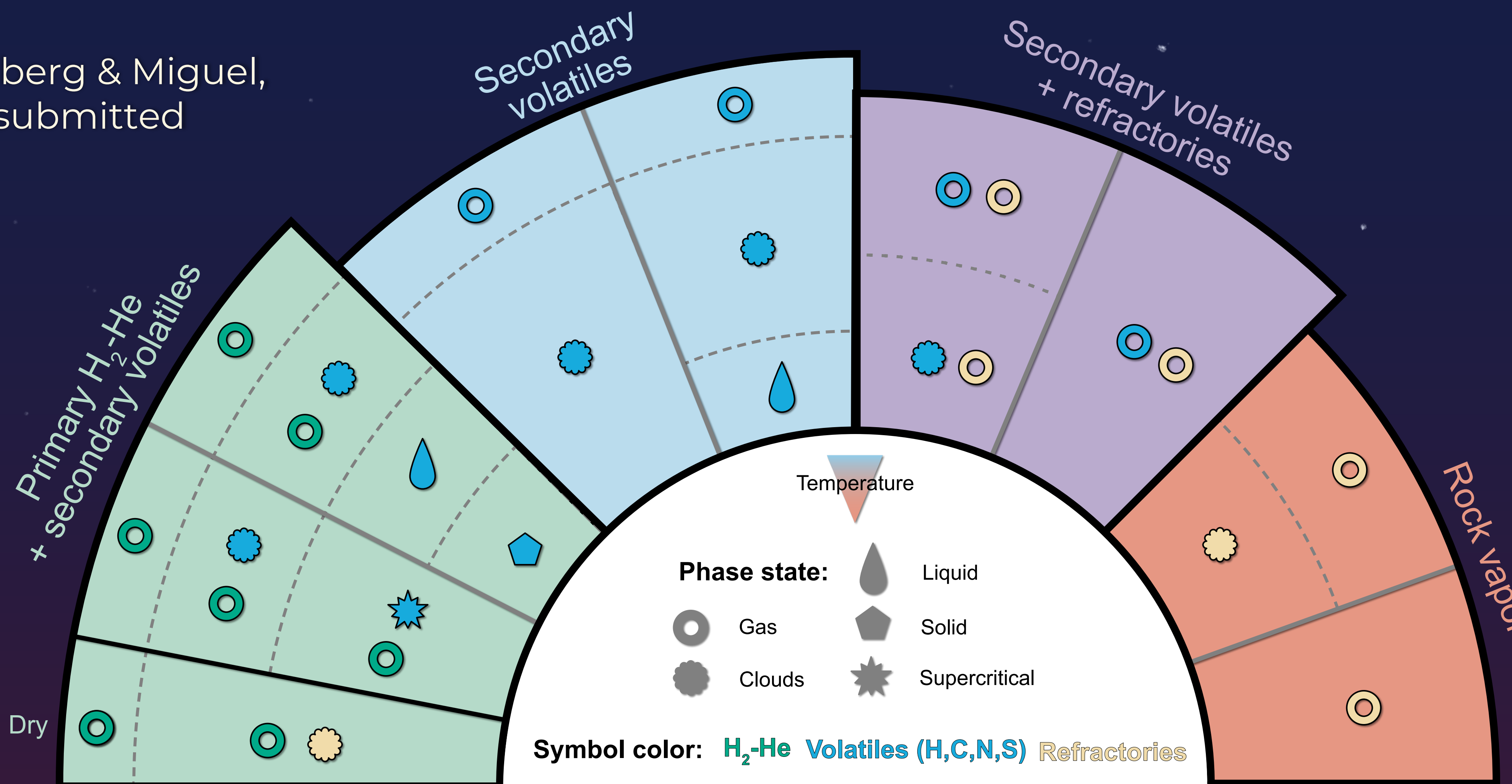
Elkins-Tanton 2008; Elkins-Tanton & Seager 2008; Gaillard & Scaillet 2014; Schaefer & Fegley 2011; 2017; Ortenzi et al. 2020; Guimond et al. 2021; Gaillard 499 et al. 2021; Wordsworth & Kreidberg 2022; Baumeister et al. 2023;

YAMILA MIGUEL - Leiden Observatory - SRON

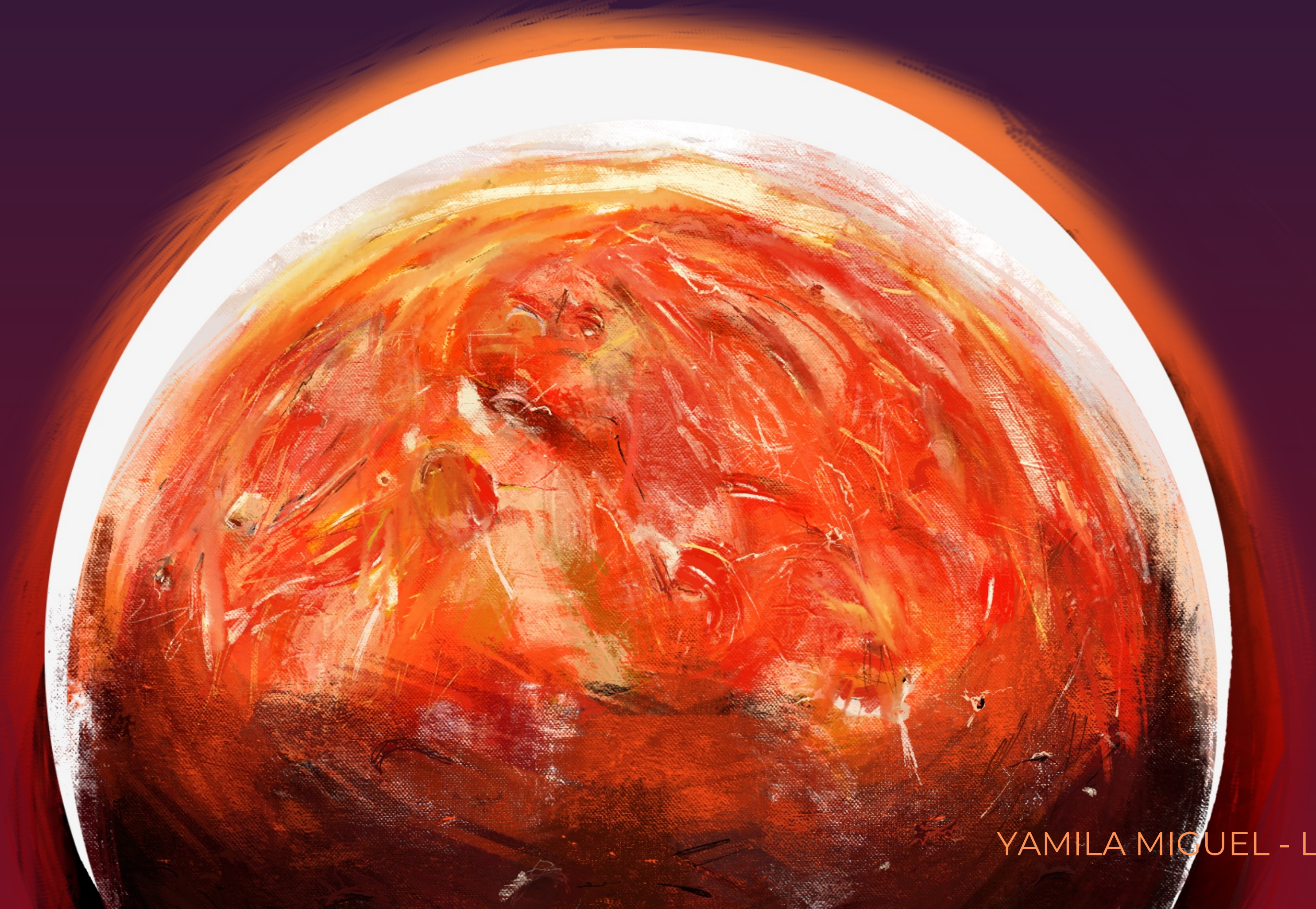
YAMILA MIGUEL - Leiden Observatory - SRON

# DIFFERENT TYPES OF ROCKY EXOPLANET ATMOSPHERES

Lichtenberg & Miguel, review submitted

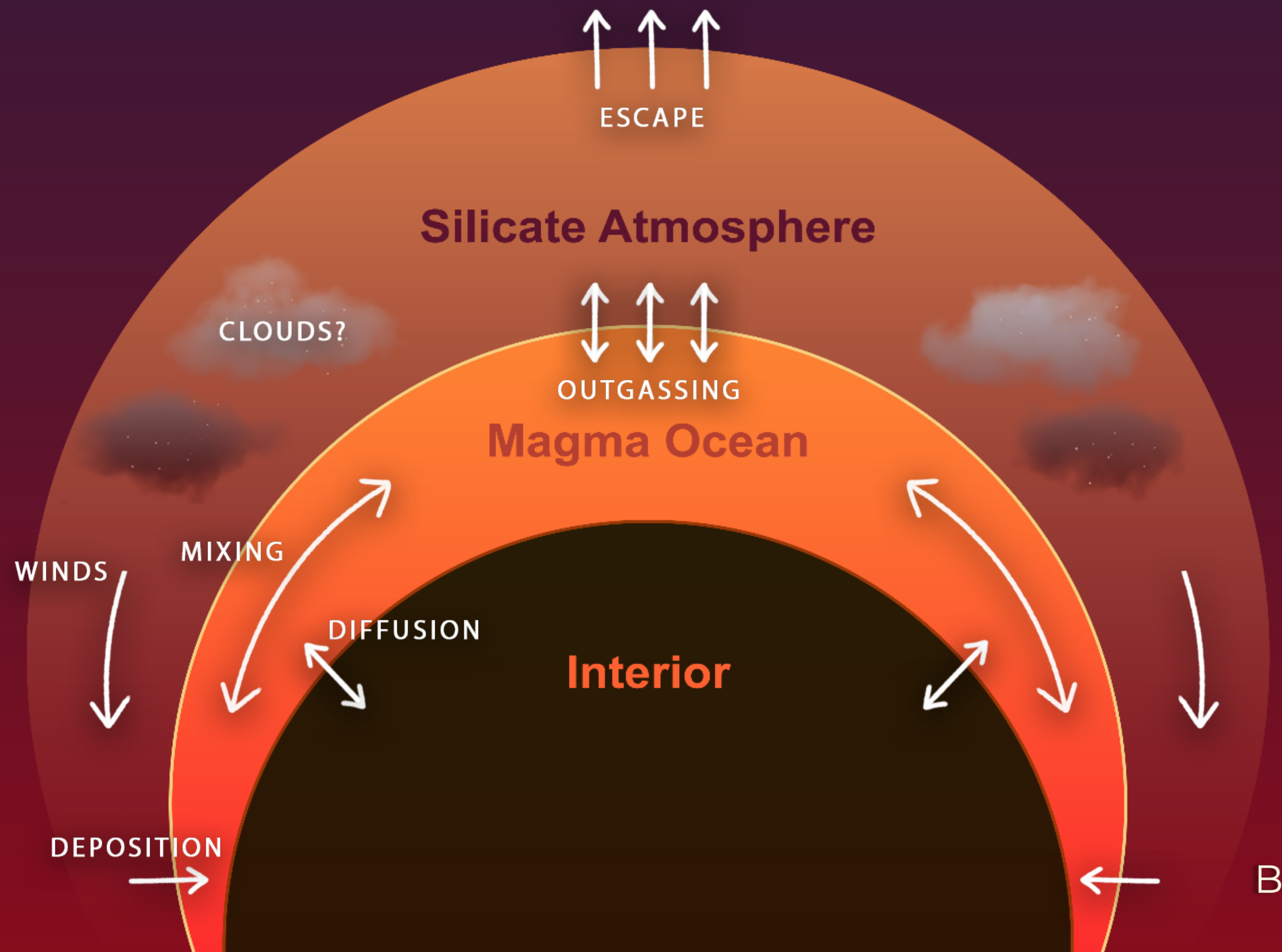


# LAVA WORLDS



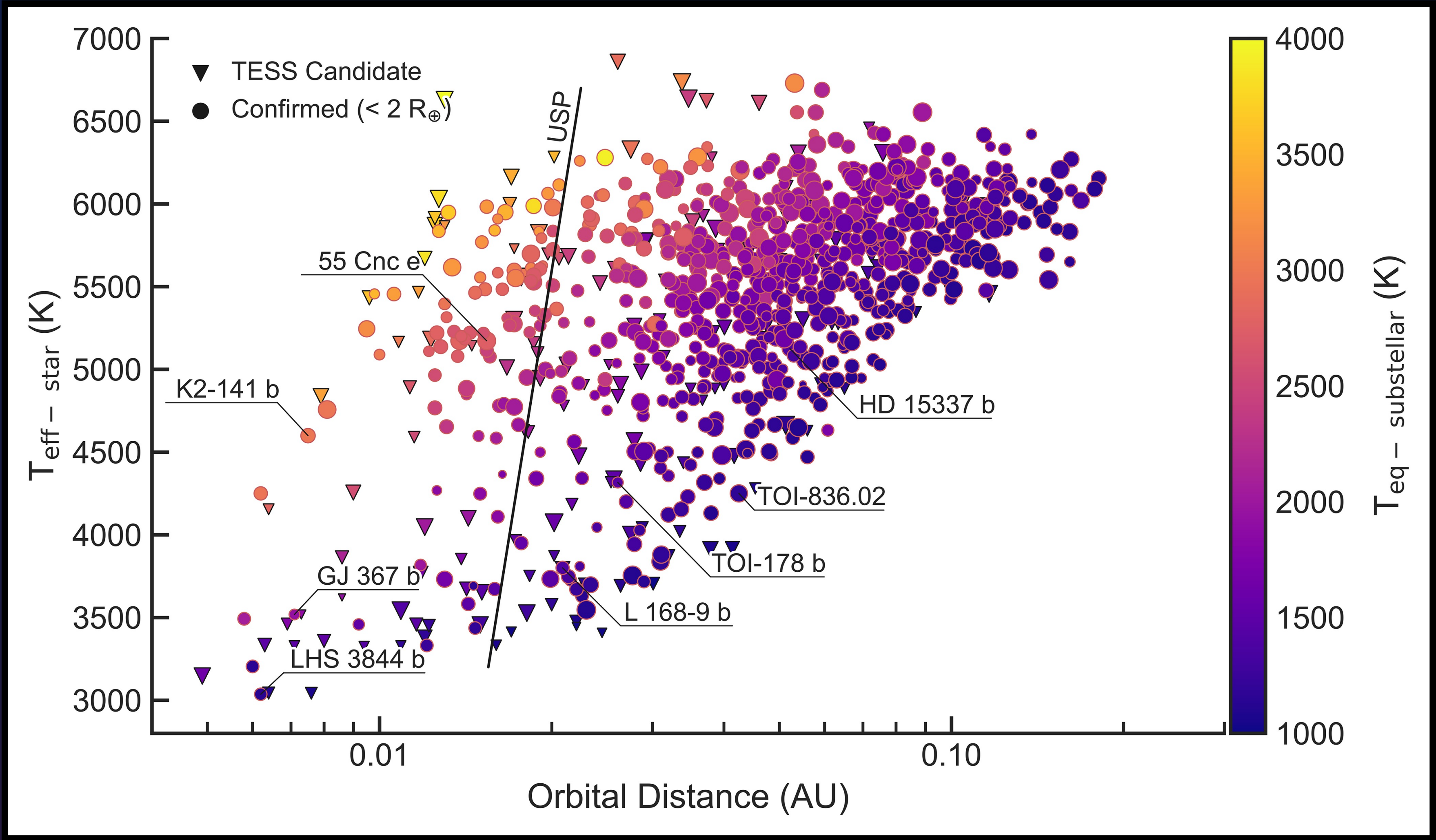
YAMILA MIGUEL - Leiden Observatory - SRON

YAMILA MIGUEL - Leiden Observatory - SRON



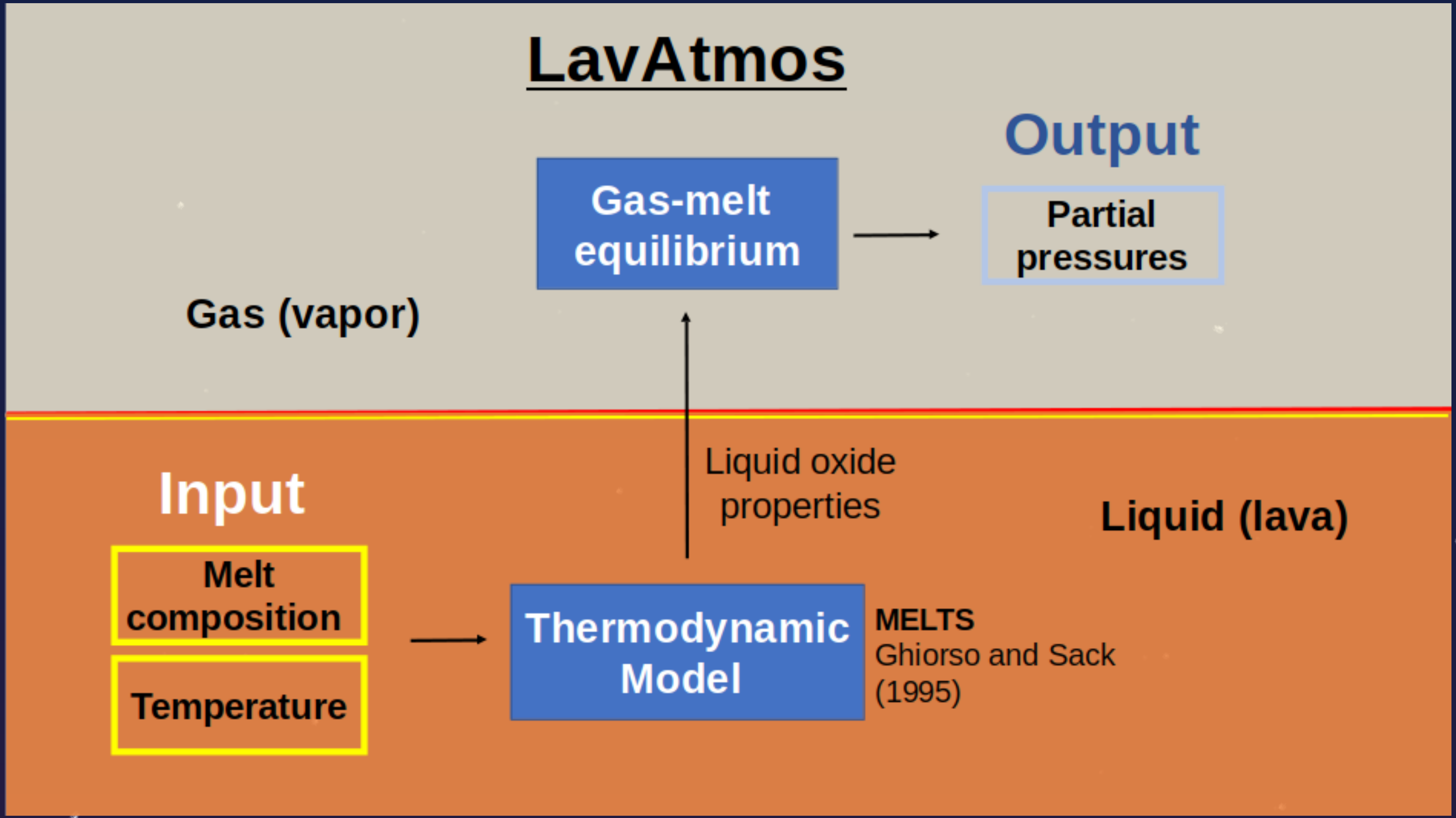

Based on Kite et al. 2016

# HOT ROCKY EXOPLANETS WITH T>1000K



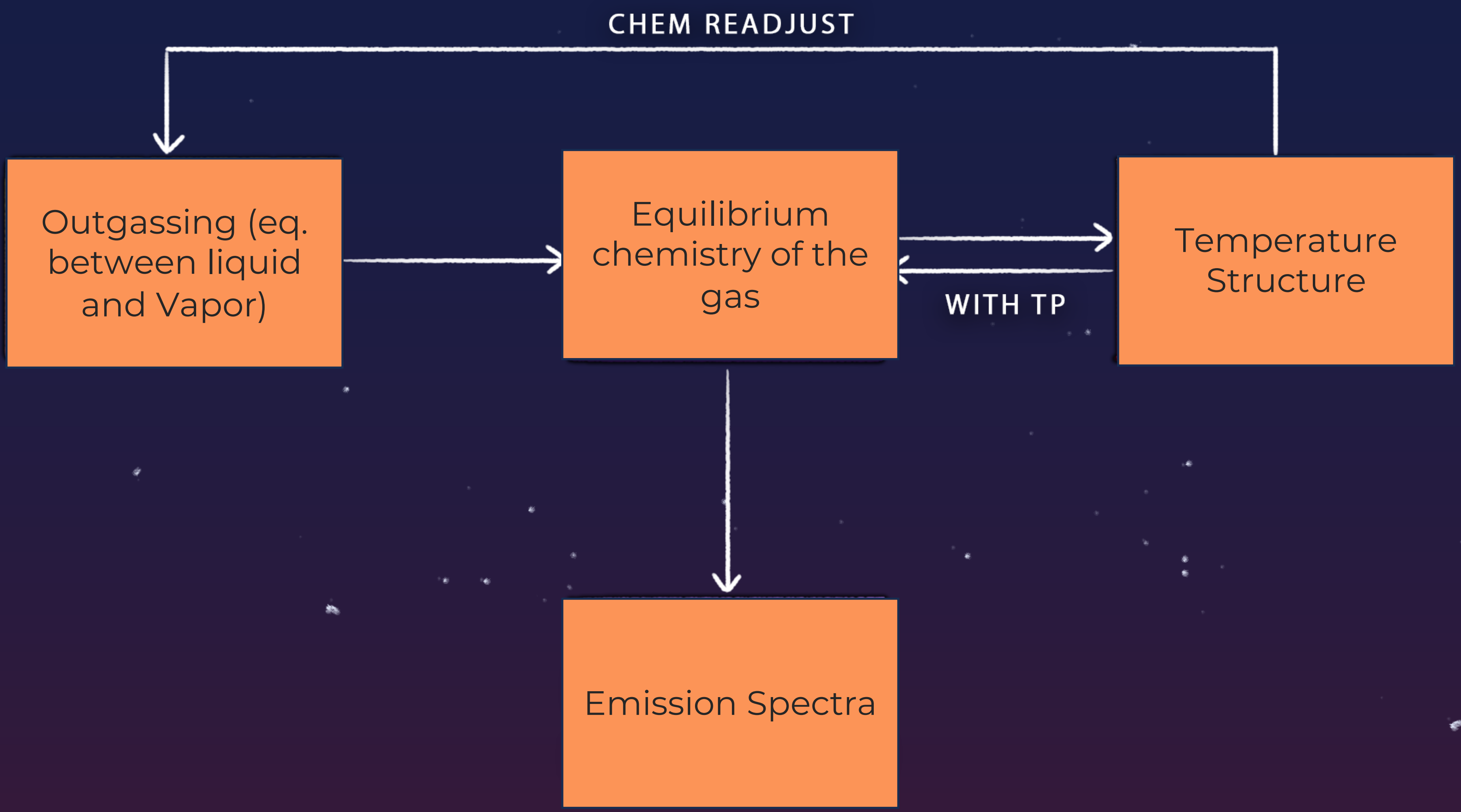

Zilinskas et al. (2022)

# MODELLING THE OUTGASSING FROM THE MAGMA

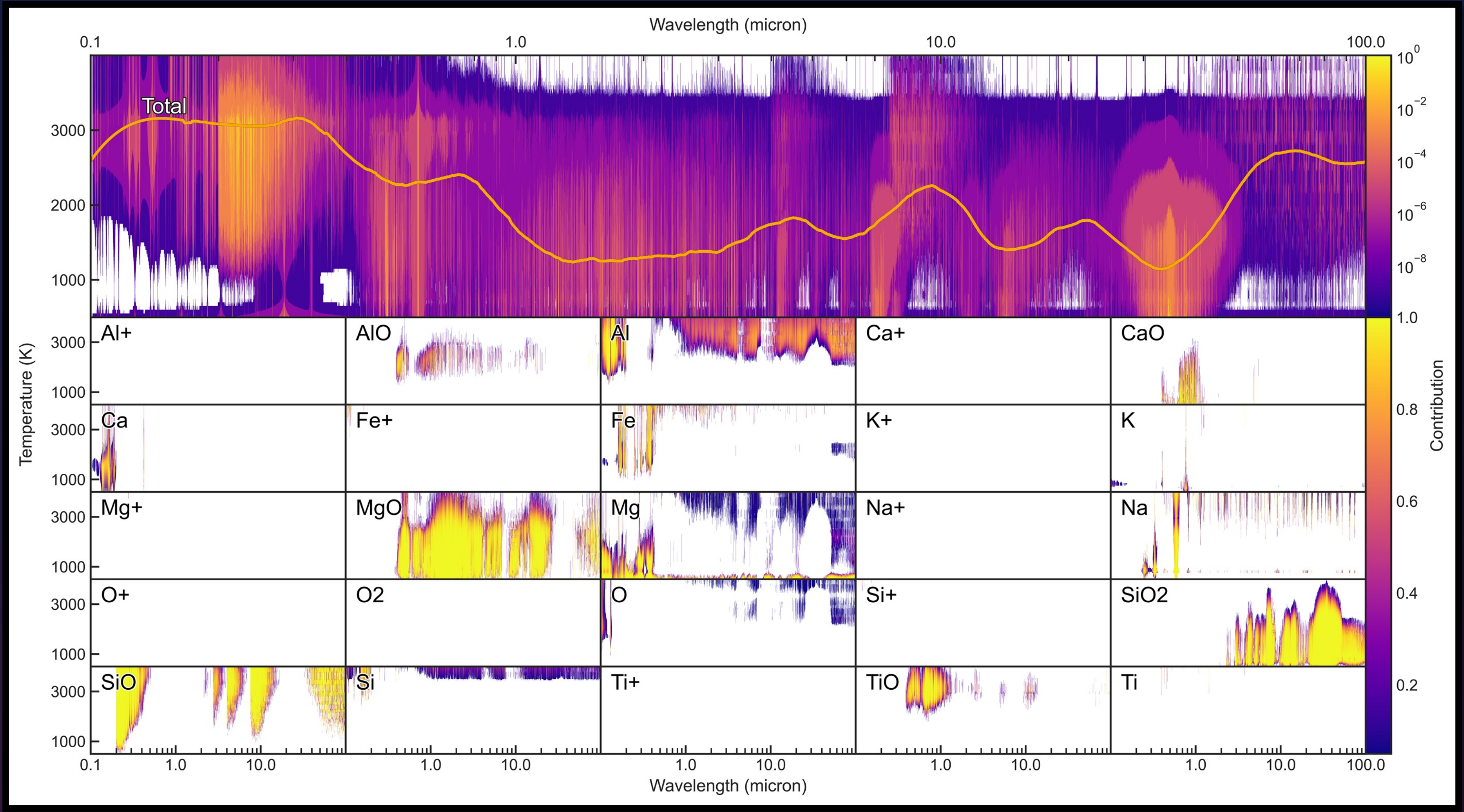



van Buchem, Miguel, et al. (2023)
**https://github.com/cvbuchem/LavAtmos**
Other codes for ougassing: MAGMA (Fegley+); VapoRock (Wolf et al. 2022)

# Methodology

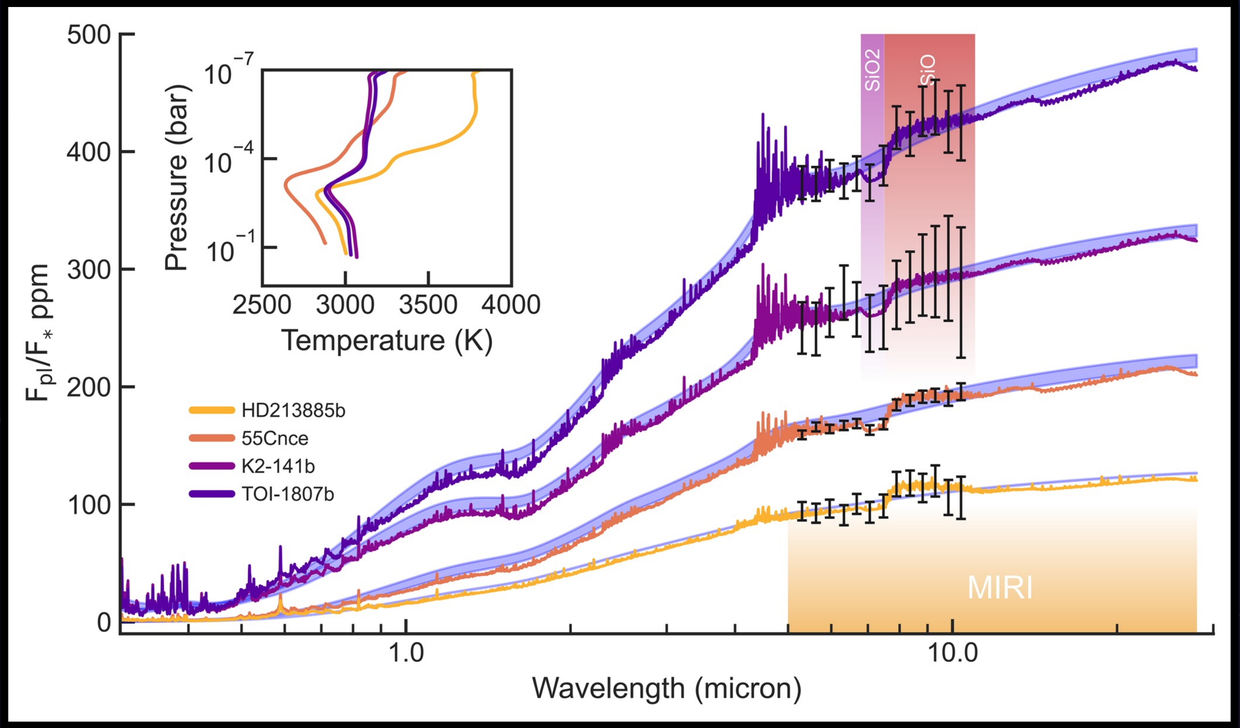


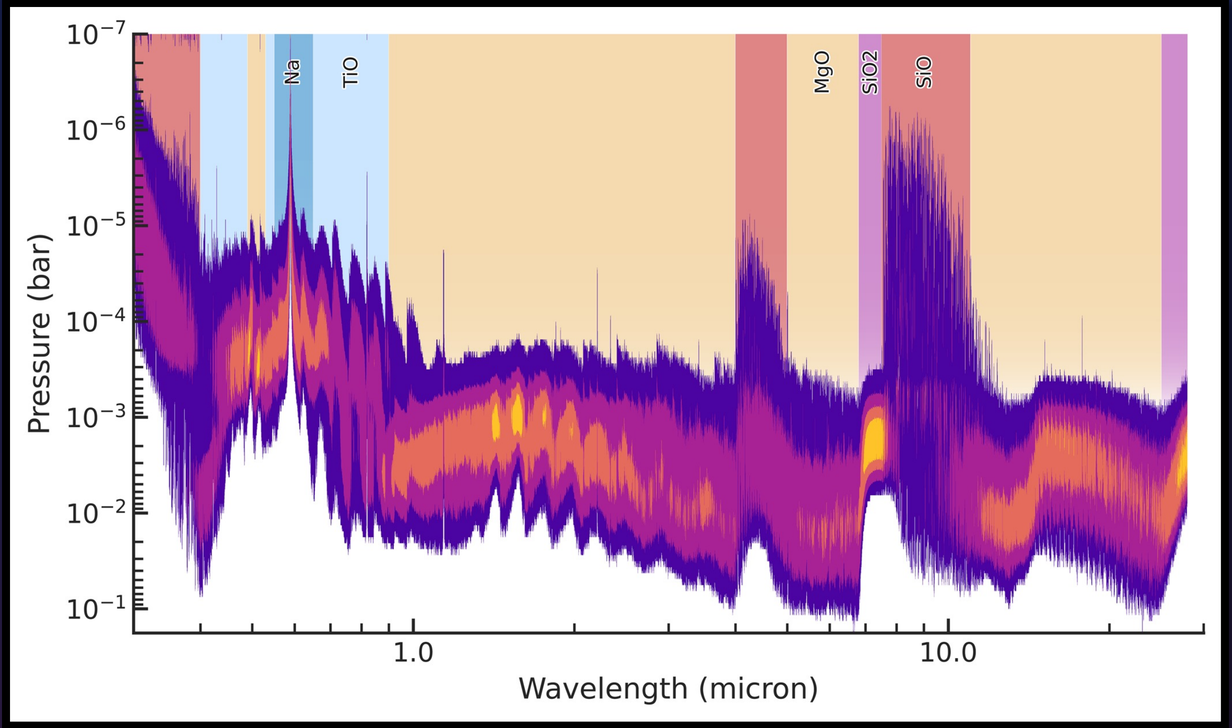
# OPACITIES OF SILICATE ATMOSPHERES




Zilinskas et al. (2022)

# EMISSION OBSERVABILITY USING MIRI LRS

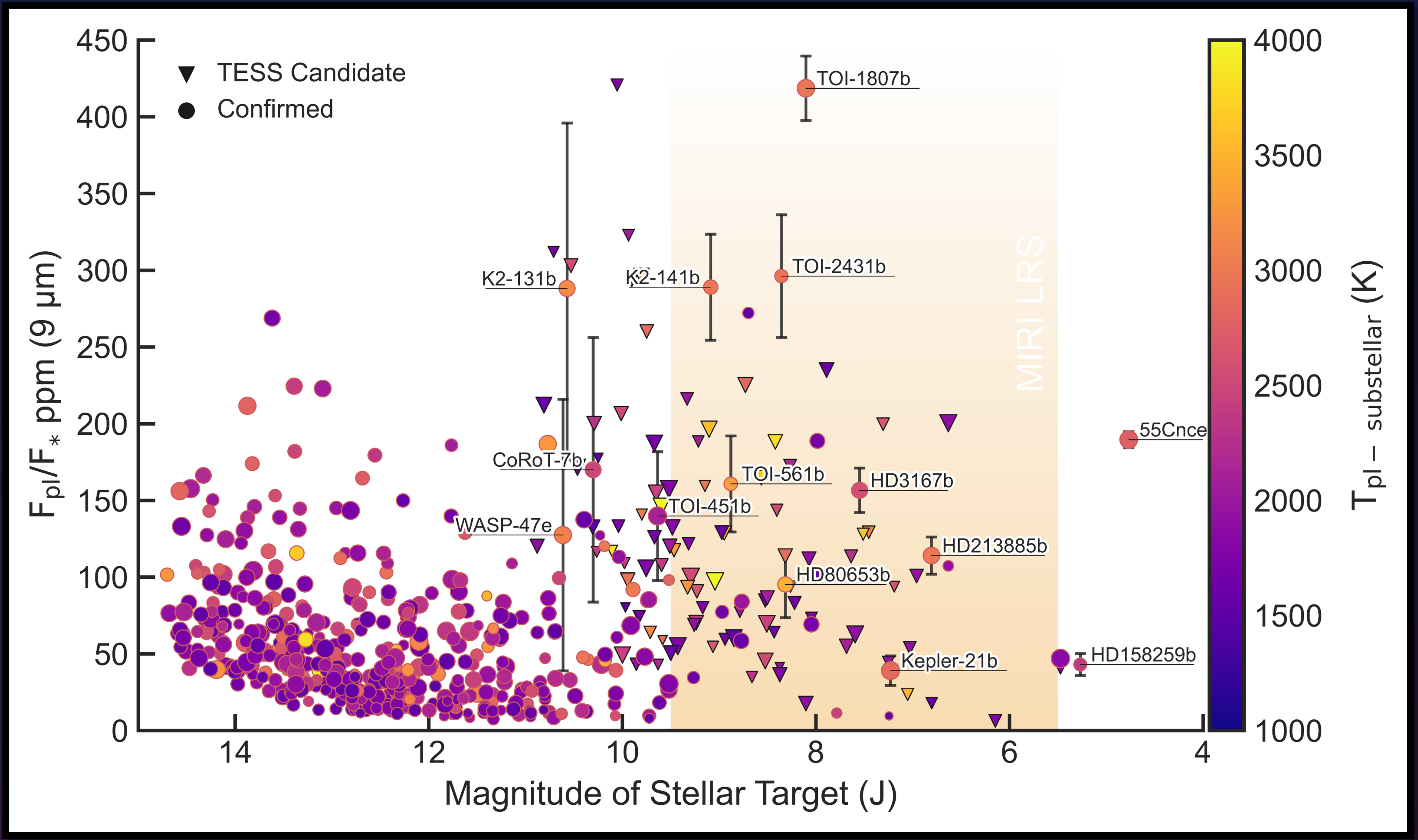



Zilinskas et al. (2022)

Other papers on chemistry and observability of these planets: Schaefer & Fegley 2009; Miguel et al. 2011; Ito et al. 2015; Kite et al. 2016; Nguyen et al. 2020, 2022

# EMISSION OBSERVABILITY USING MIRI LRS

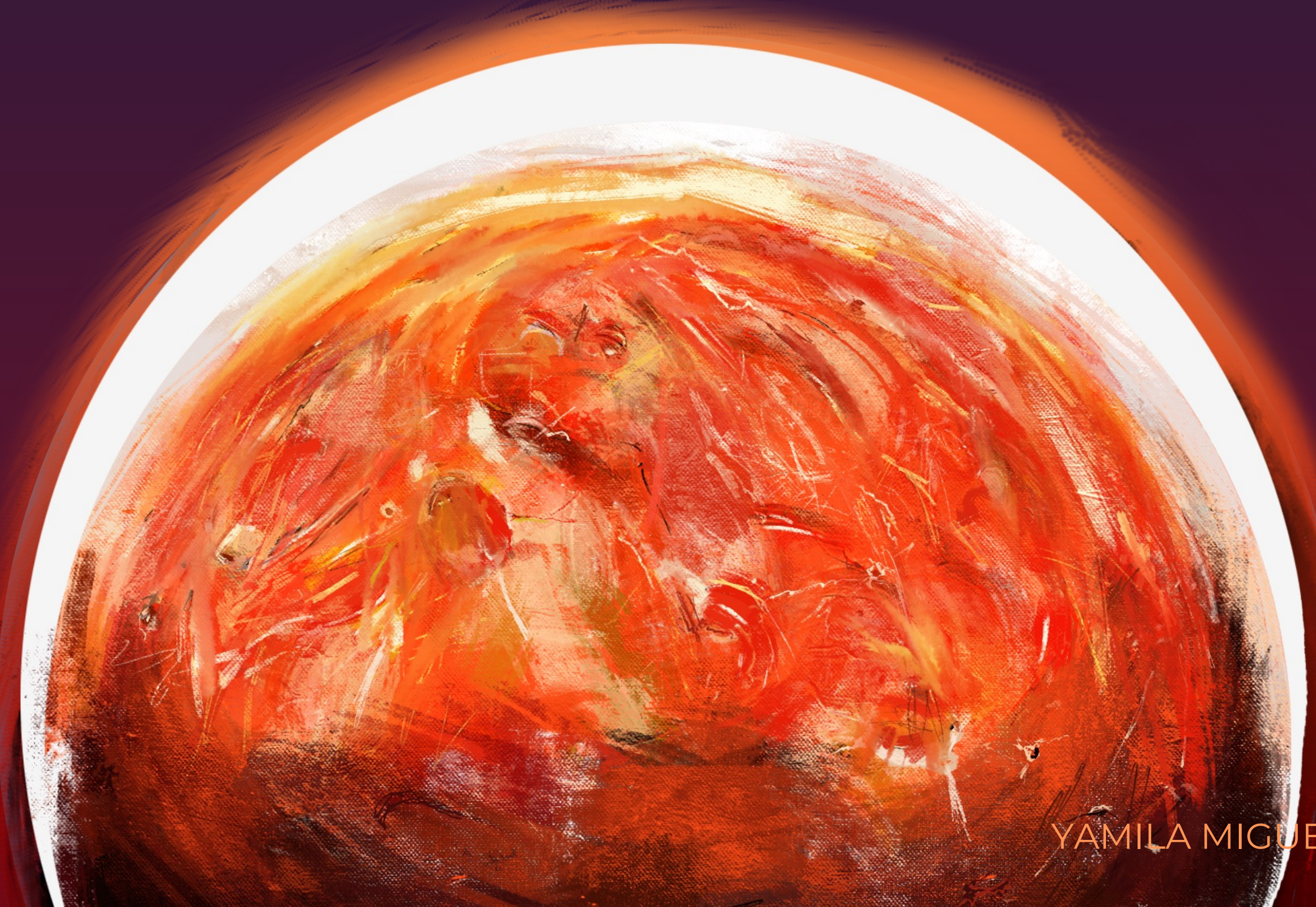



Zilinskas et al. (2022)

# LAVA WORLDS

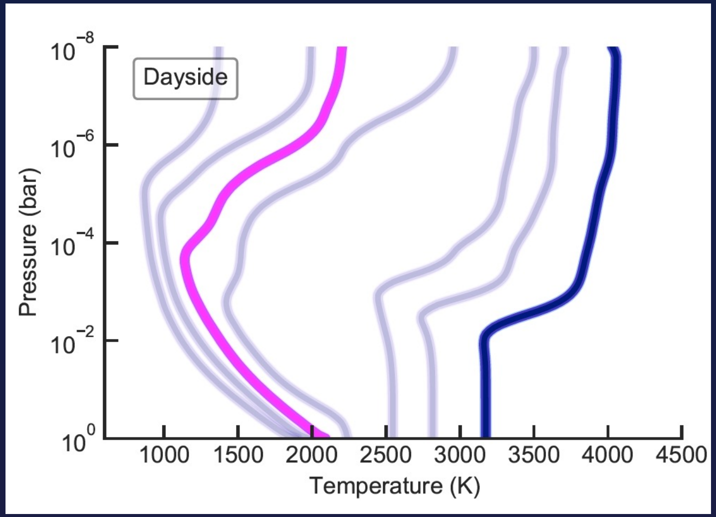
## with a volatile atmospheres

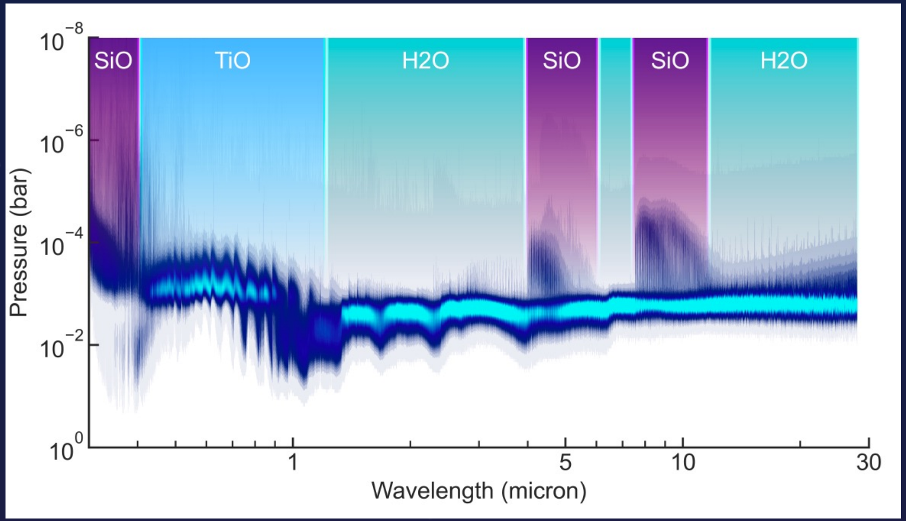
Schaefer and Fegley 2012, Miguel 2018, Herbort et al. 2020, 2021; Kite & Schaefer 2021; Misener & Schlichting 2022, 2023; **Piette et al. 2023**; **Zilinskas et al.** 2020; 2021, **2023**

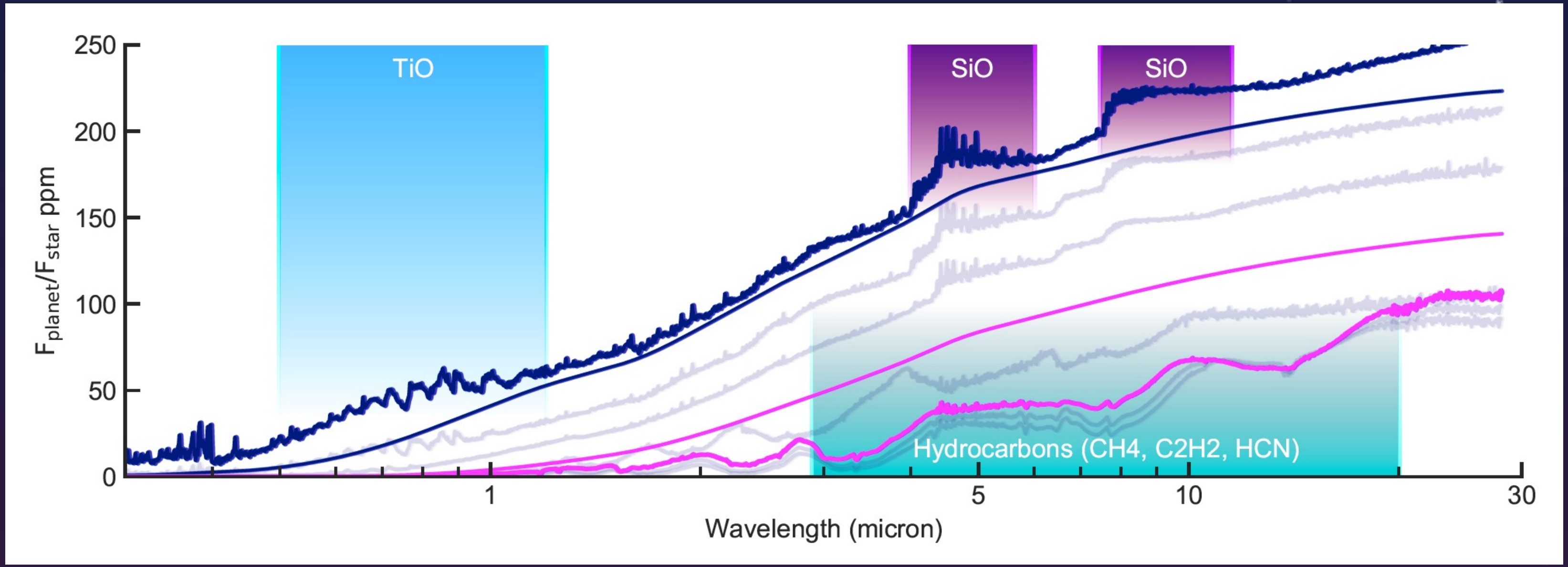


YAMILA MIGUEL - Leiden Observatory - SRON

# EMISSION OBSERVABILITY (LAVA+H2 DOMINATED)

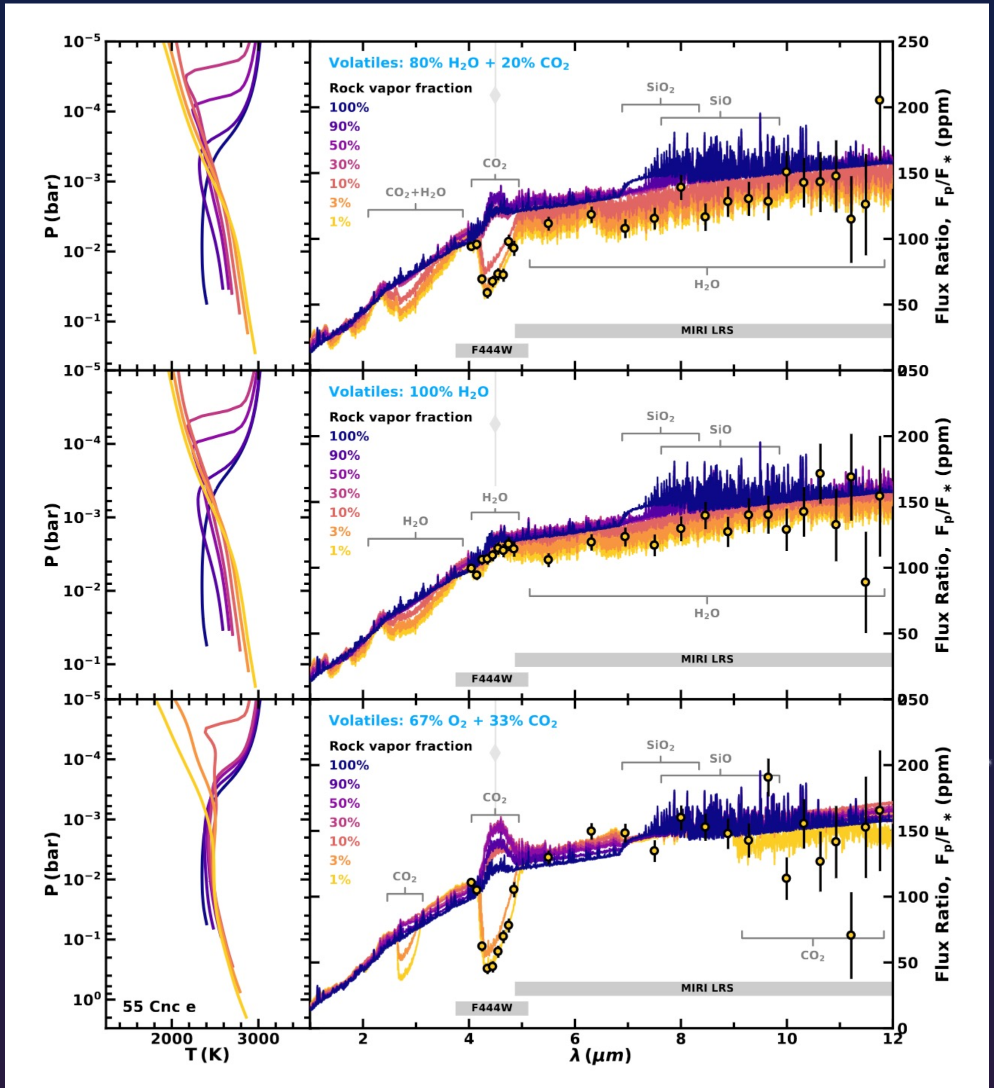



Zilinskas et al. 2023

# EMISSION OBSERVABILITY (LAVA+H2O+CO2+O2)




Piette et al. 2023

also Zilinskas et al. 2021 for more on T inversions and N2-dominated atm.

YAMILA MIGUEL - Leiden Observatory - SRON

# IN SHORT

YAMILA MIGUEL - Leiden Observatory – SRON
@AstroYamila –www.YamilaMiguel.com

## ROCKY PLANET ATMOSPHERES

Atmospheres reflect the formation and evolution of the planet, but links are difficult

## LAVA PLANETS

Amazing planets that reflect their interior composition!

Infrared features of SiO, $SiO_2$ are the best features to detect that indicate the presence of a magma ocean

Na, MgO, TiO are other potential absorbers to keep an eye on

## LAVA PLANETS + VOLATILE ATMOSPHERE

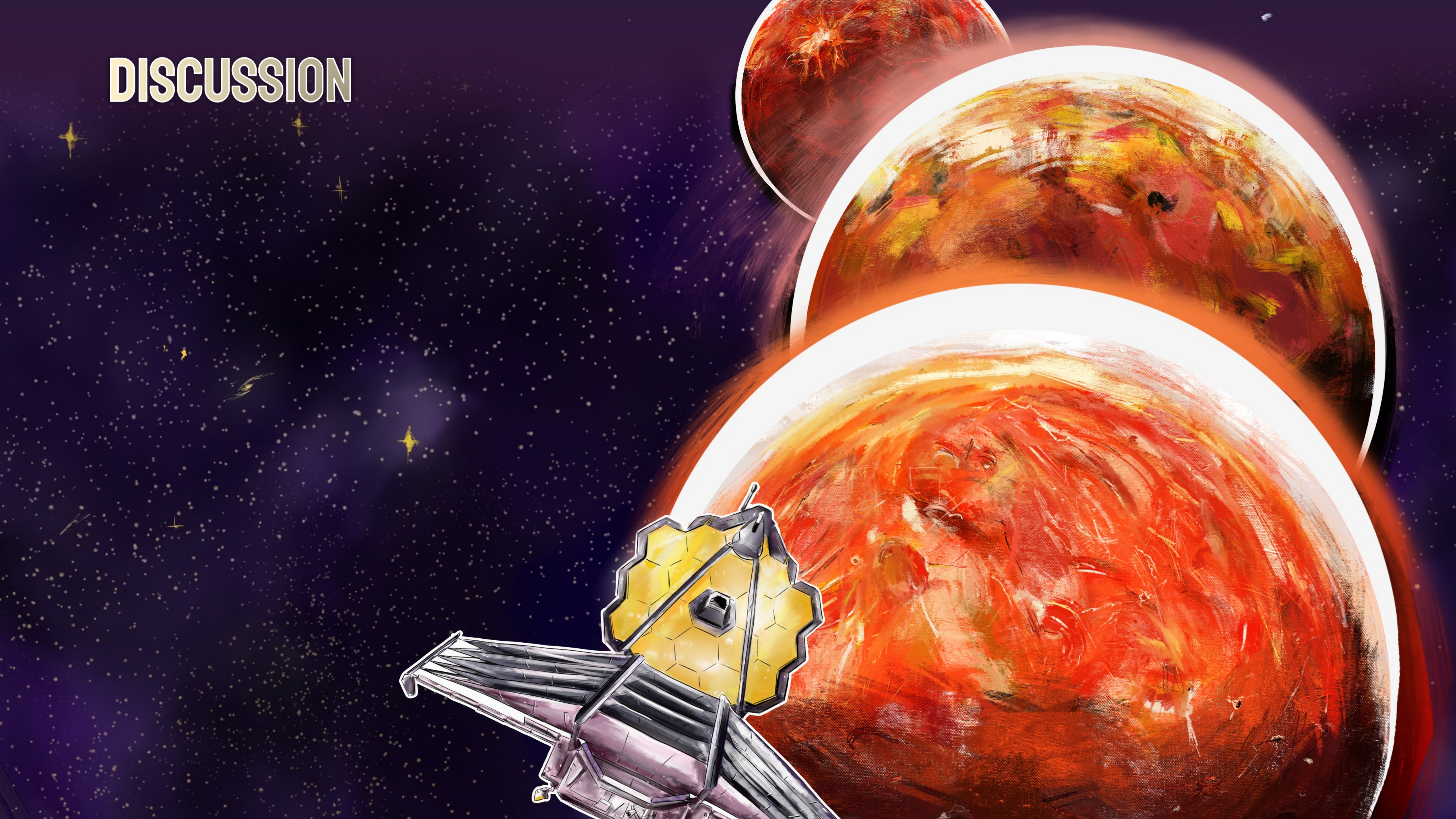
SiO, $SiO_2$ and TiO might indicate the presence of a magma ocean on the planet's surface

Temperature inversions are giving us information of the abundance of volatiles vs. refractories

LavAtmos – Silicate Outgassing
https://github.com/cvbuchem/LavAtmos

If you want to know more:
Lichtenberg & Miguel (Review to appear in to the new decadal edition of the Treatise on Geochemistry)

# DISCUSSION



# ROCKY PLANET FORMATION

## CLASSIC THEORY: PLANETESIMAL ACCRETION

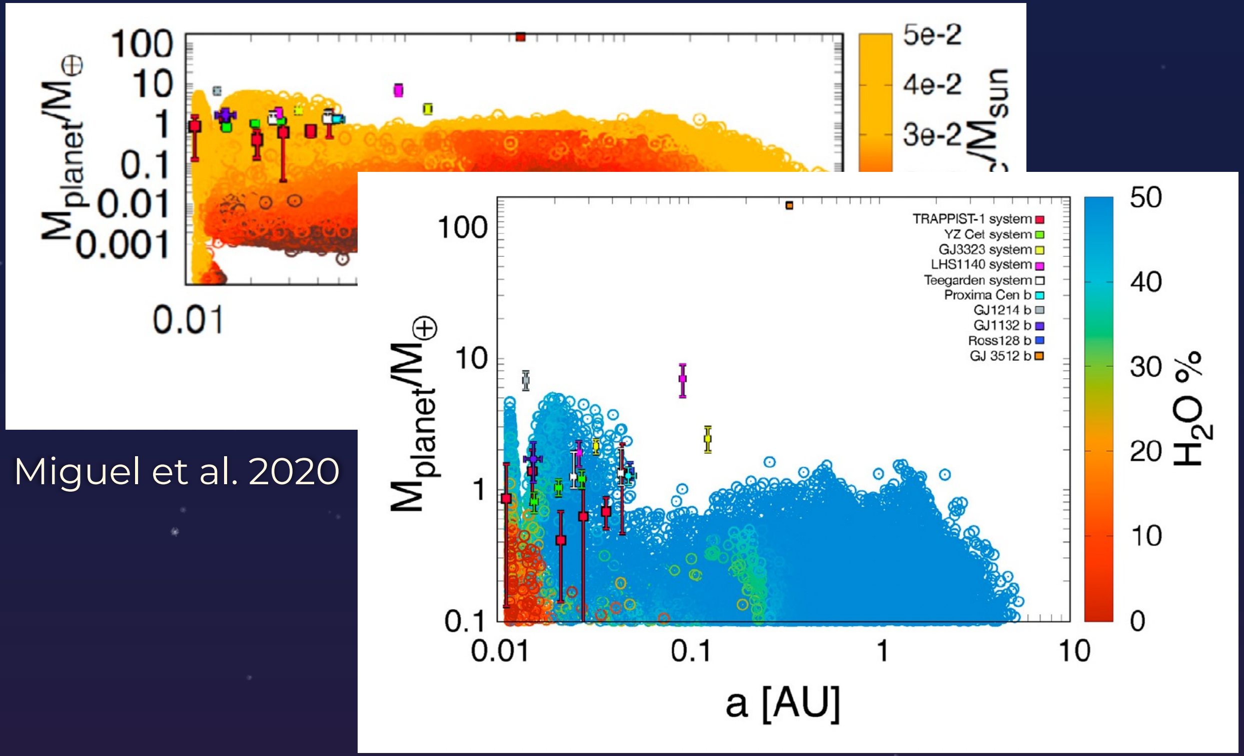
- Planets grow by accreting km-sized planetesimals. Timescales of 1e6 years (Raymond et al. 2020; Batygin & Morbidelli 2023)
- Followed by a phase of giant impacts that can last 1e8 yr (Raymond et al. 2014)

## PEBBLE ACCRETION

- Formation through the direct accretion of mm- to cm-sized pebbles. Timescales of XXXXXXXX (Levison et al. 2015; Johansen et al. 2021)
- Followed by a phase of giant impacts that can last 1e8 years (Levison et al. 2015; Izidoro et al. 2021)

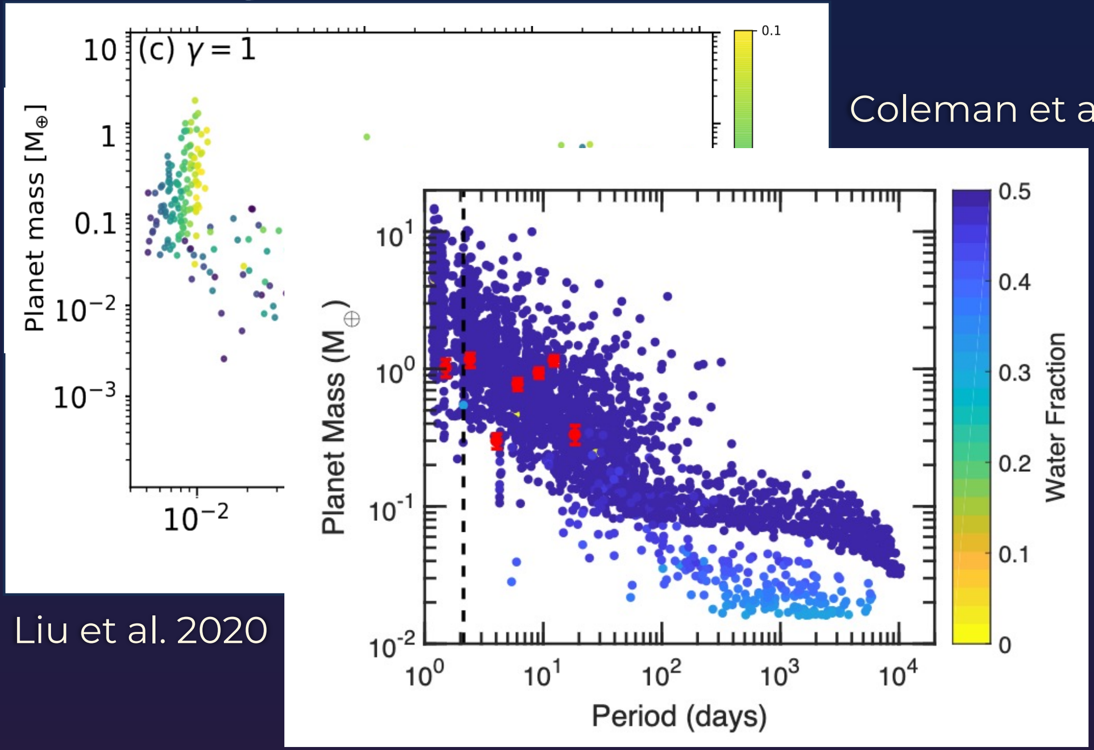
# PLANET FORMATION AROUND M STARS

## CLASSIC THEORY: PLANETESIMAL ACCRETION




Miguel et al. 2020

## PEBBLE ACCRETION

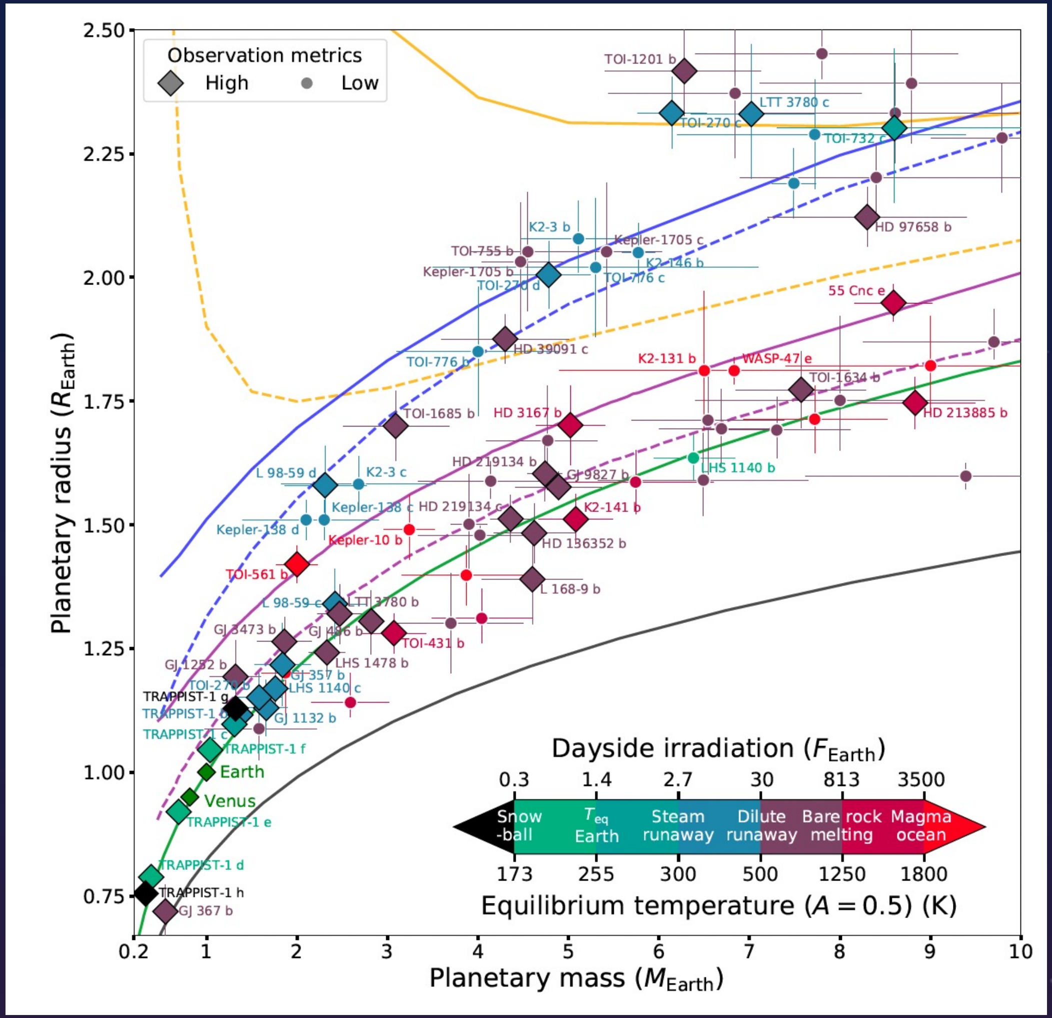



Coleman et al. 2019

Liu et al. 2020

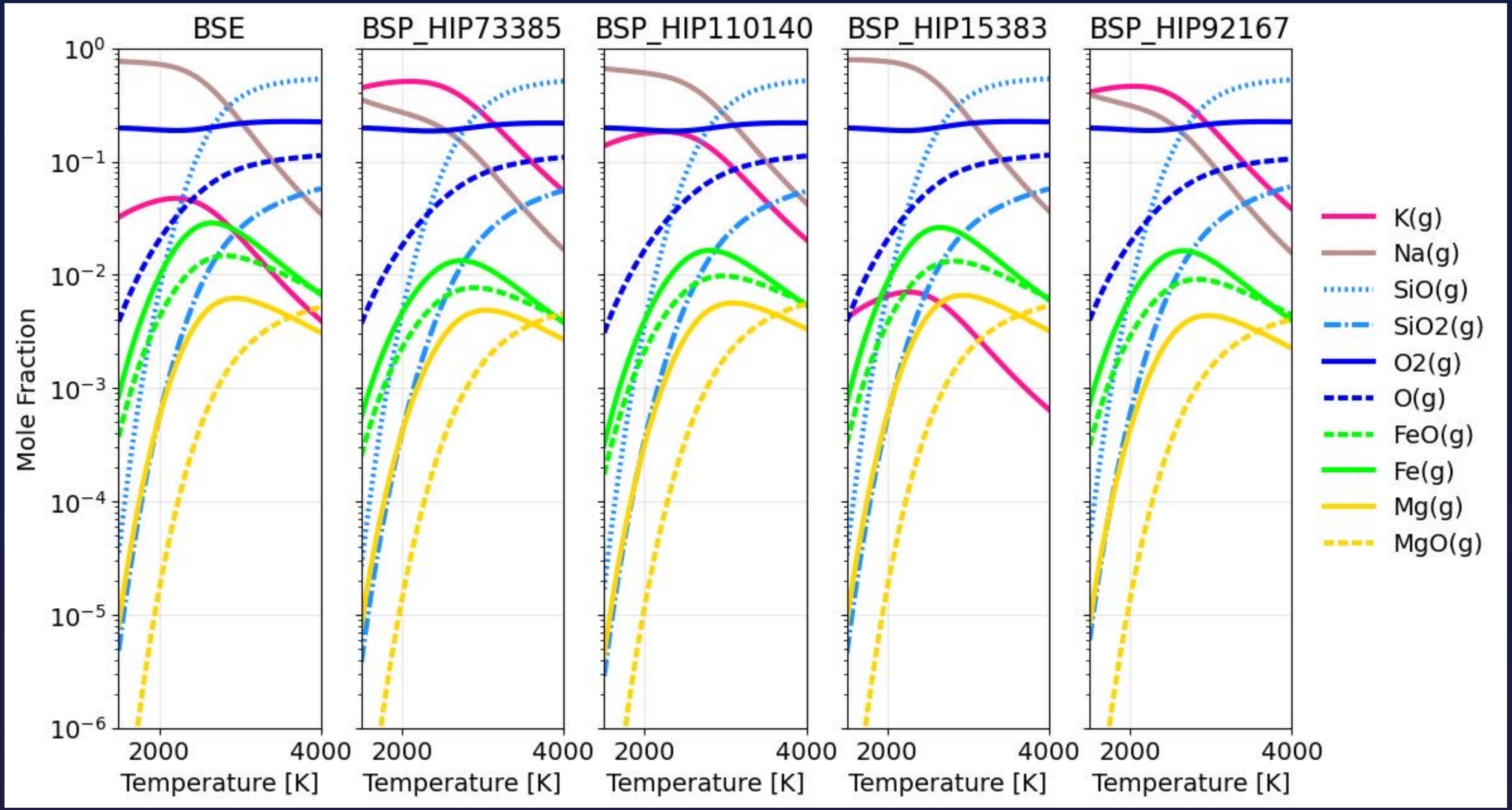
Ogihara & Ida 2009; Ronco & de Elía 2014; Alibert & Benz 2017; Coleman et al. 2019; Schoonenberg et al. 2019; Miguel et al. 2020; Dash & Miguel 2020; Liu et al. 2020; Ormel et al. 2017; Burn et al. 2021; Zawadzki et al. 2021; Sánchez et al. 2022; Clement et al. 2022; Pan et al. 2022; Ogihara et al. 2022; Lichtenberg & Clement 2022.

# LEARNING ABOUT PLANET FORMATIONI: MASS VS RADIUS




Lichtenberg & Miguel, review submitted

# ABUNDANCES OF LAVA PLANETS' ATMOSPHERES

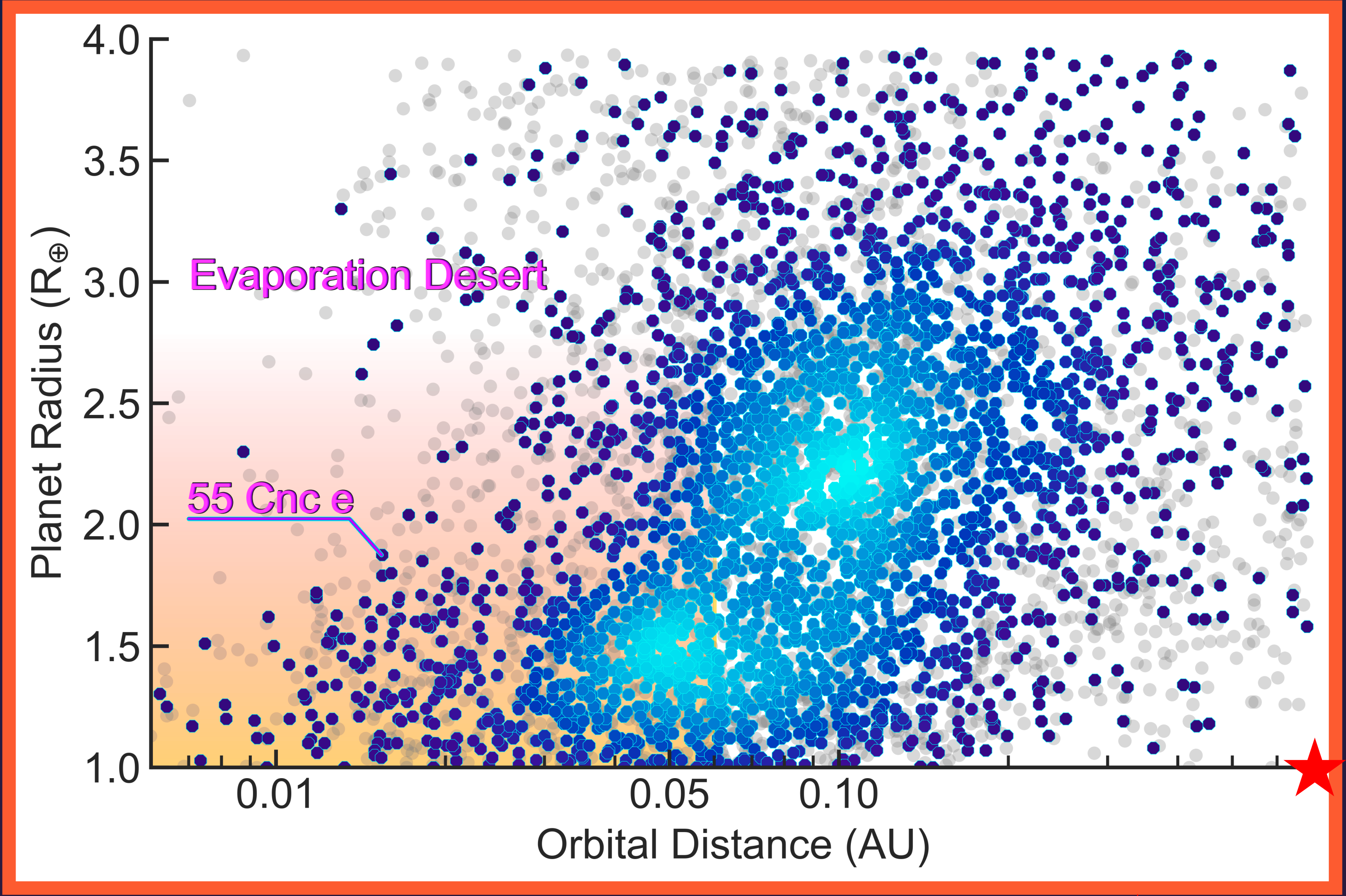



van Buchem, Miguel, et al. (2023), Buddhacharya, van Buchem, Miguel in prep.

Relation between the stars and crust composition:
Putirka and Rarick 2019

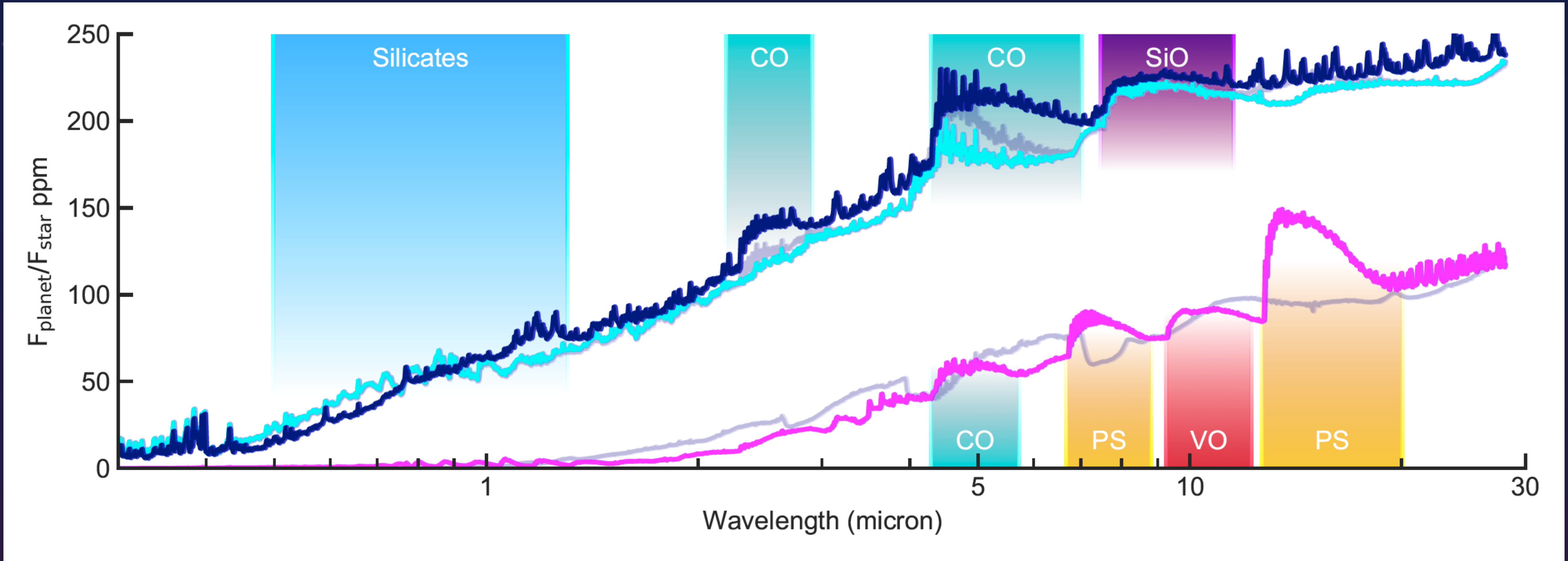
# CONFIRMED SHORT PERIOD EXOPLANETS

(Rocky and Rocky+volatile atmospheres)




Zilinskas et al. 2023

# Emission Observability H-depleted




Zilinskas et al. 2023