Linking Sub-Neptune Atmospheres to Molten Rocky Interiors

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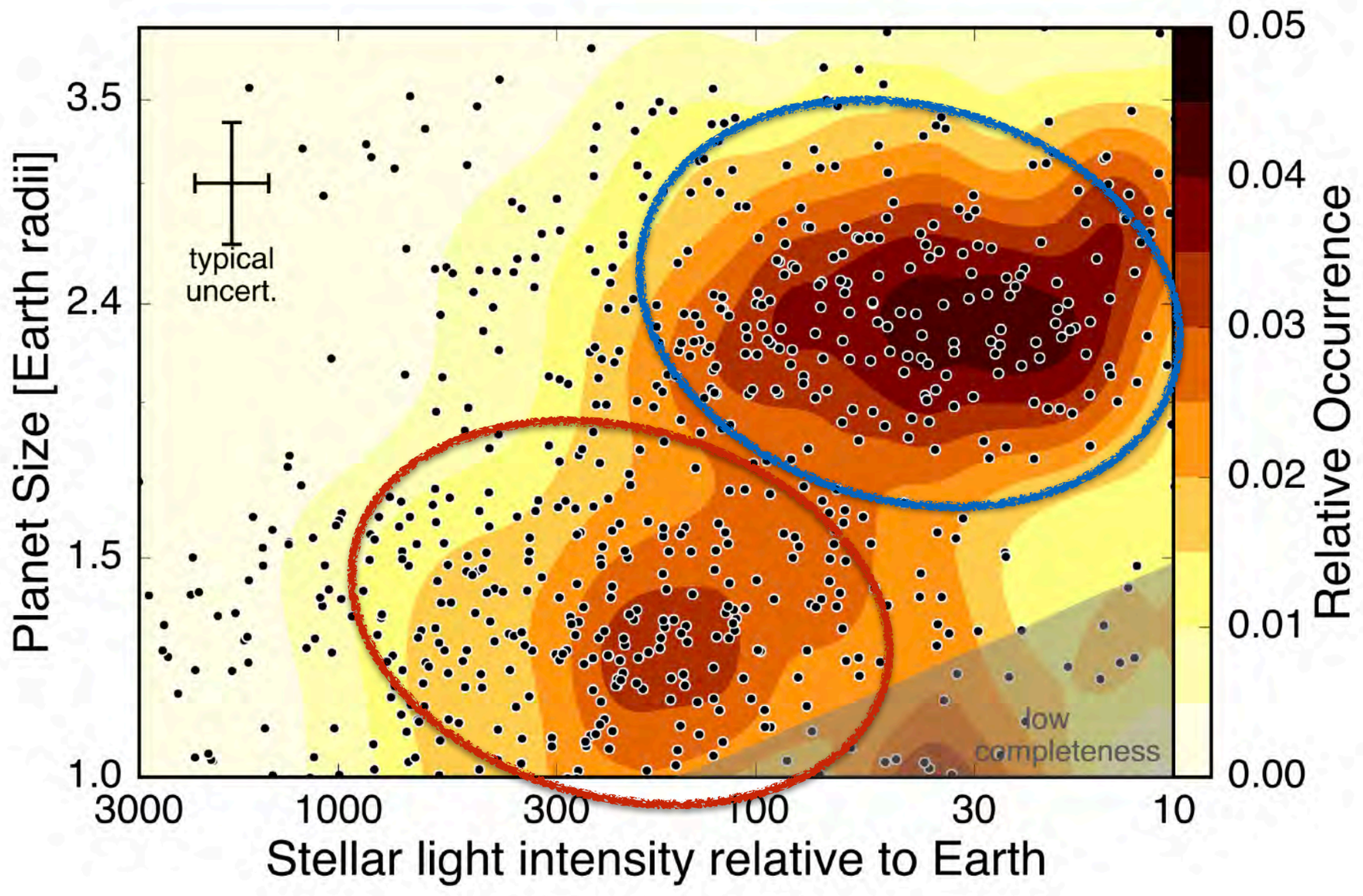
11th of Dec, Niigata, EAMA 11

Pic ref: NASA

Two major classes: Sub-Neptunes and Super-Earths

Exoplanet occurence rate

(Fulton et al., 2017)

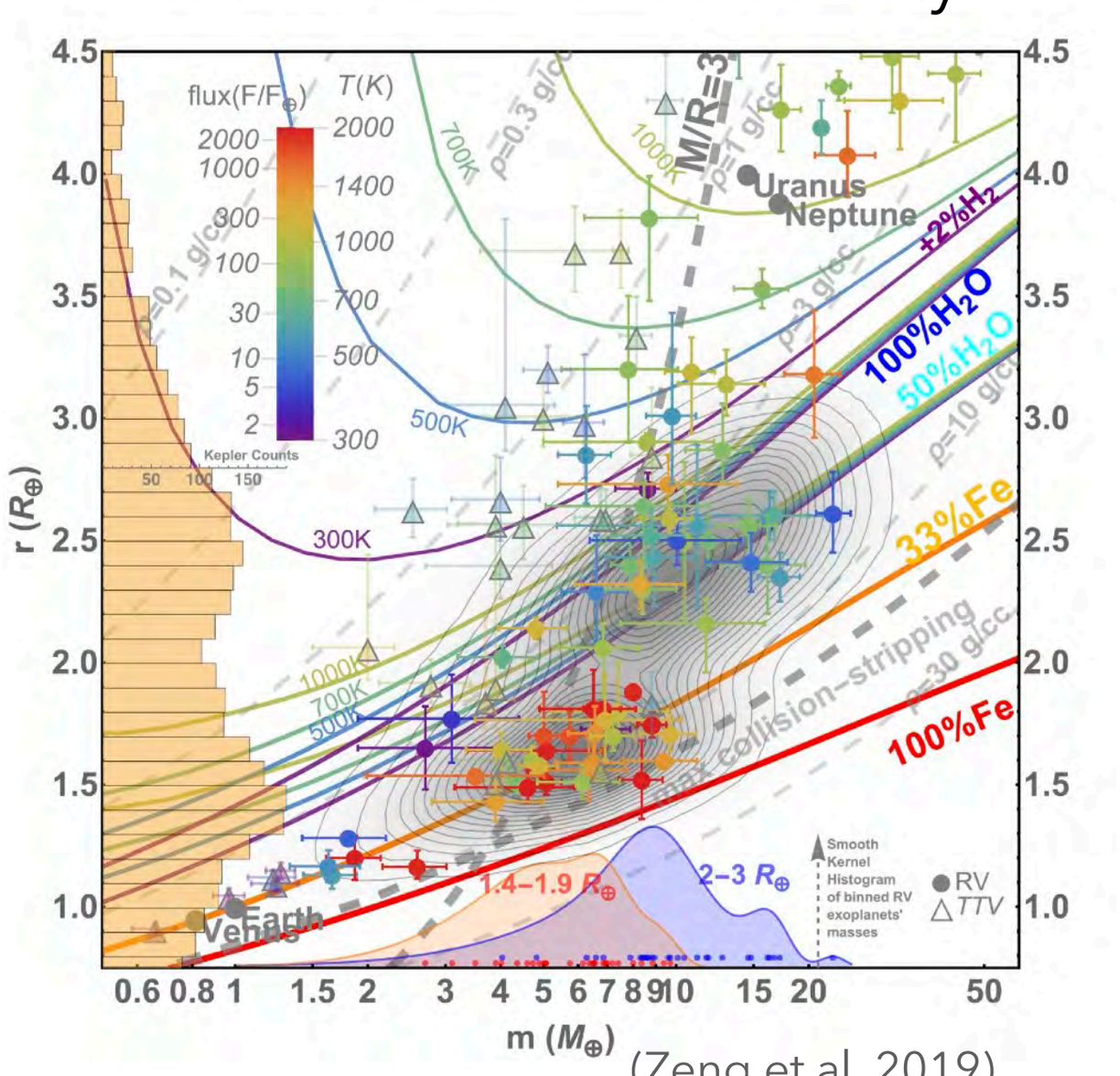


1, Sub-Neptunes

2, Super-Earths

Degeneracy in bulk composition of sub-Neptunes

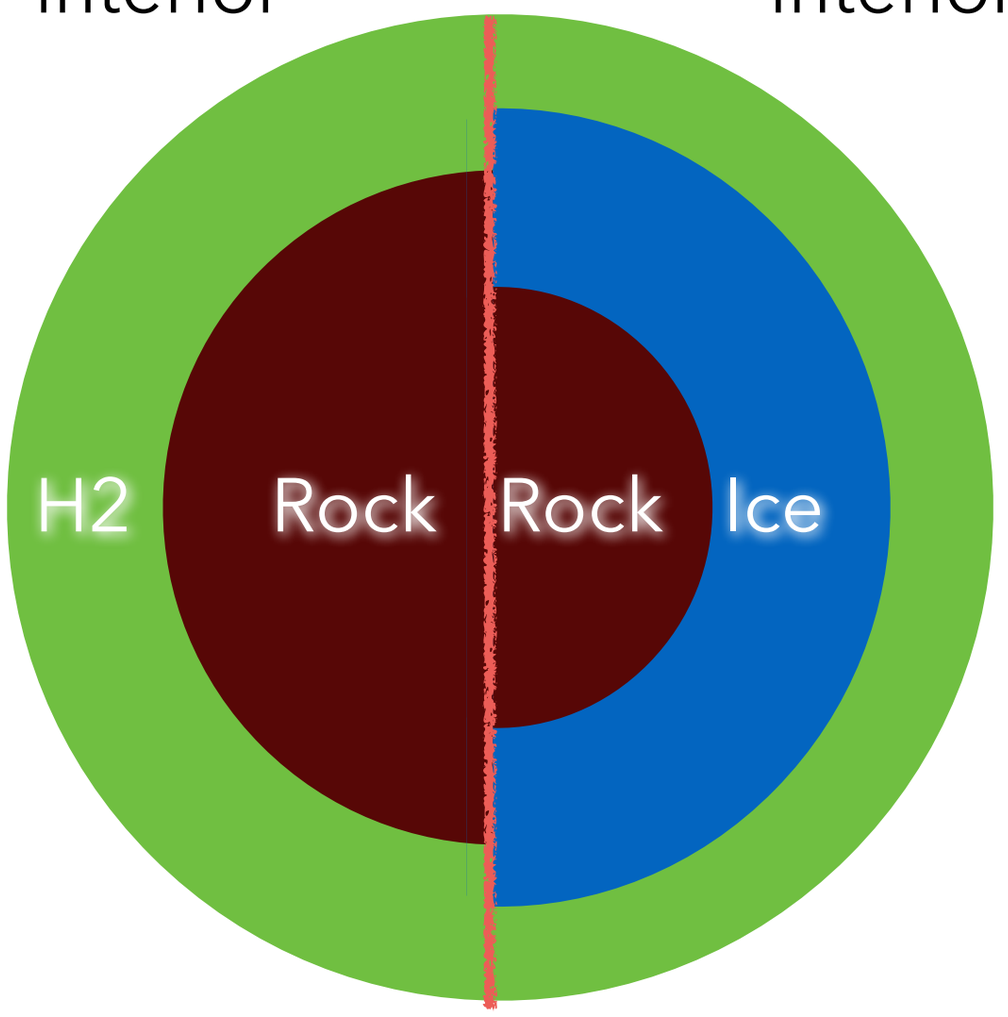
Problem for sub-Neptunes:
Degeneracy in bulk composition
with mass and radius only



(Zeng et al. 2019)

Rocky interior

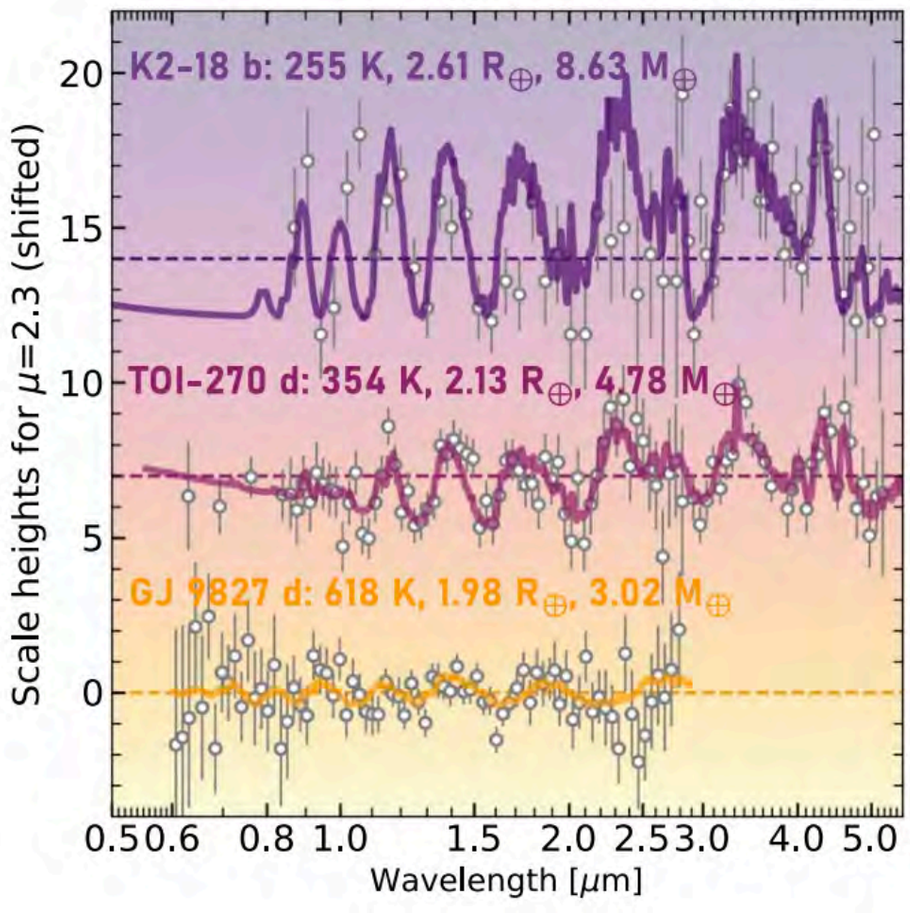
Icy interior



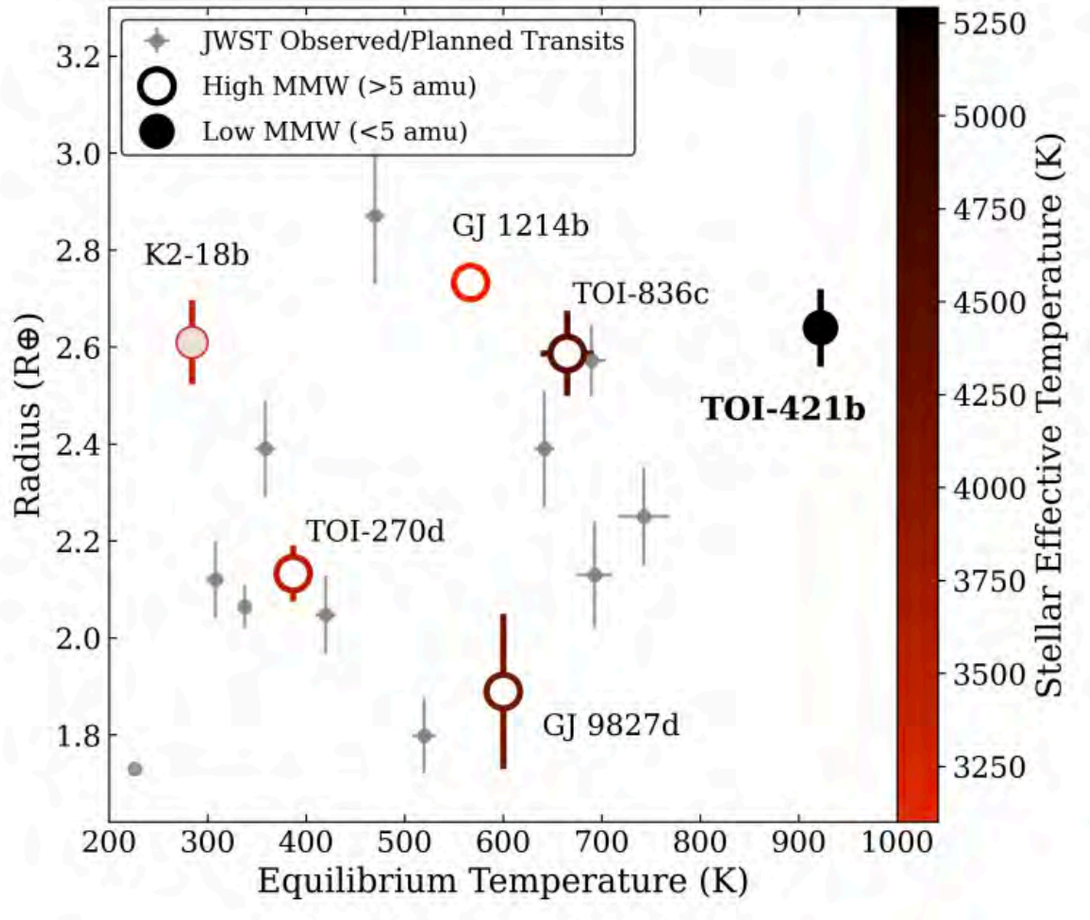
Sub-Neptune atmospheres

Atmospheric observations enable to understand sub-Neptunes more, suggesting **hydrogen-dominated but metal-rich atmospheres**

Atmospheric spectra observed with JWST



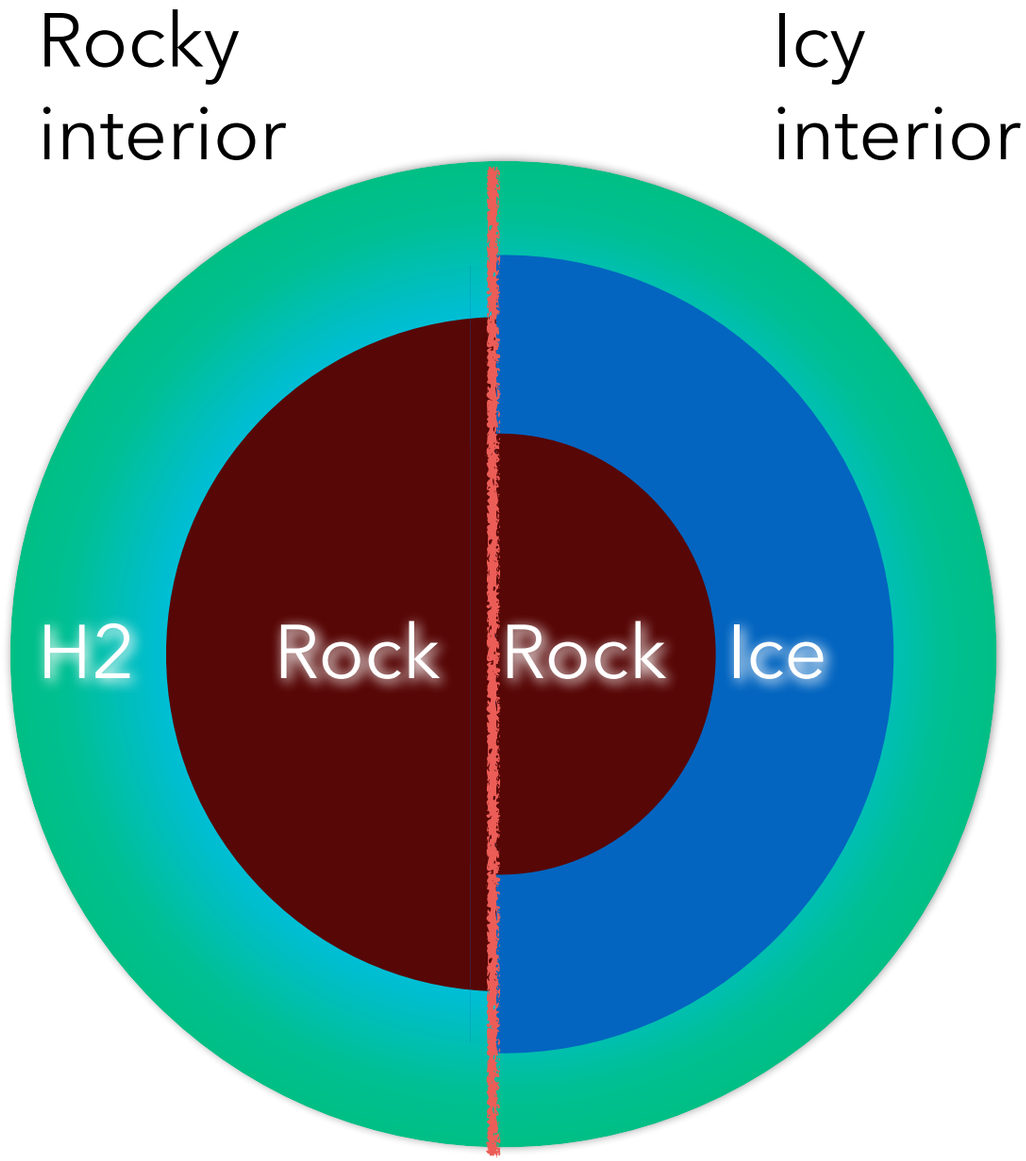
Inferred mean molecular weight



(e.g., Madhusudhan+2023, BenneKe+2024, Piaulet-Ghorayeb+2024, Davenport+2024)

One possible cause to make metal-rich atmosphere

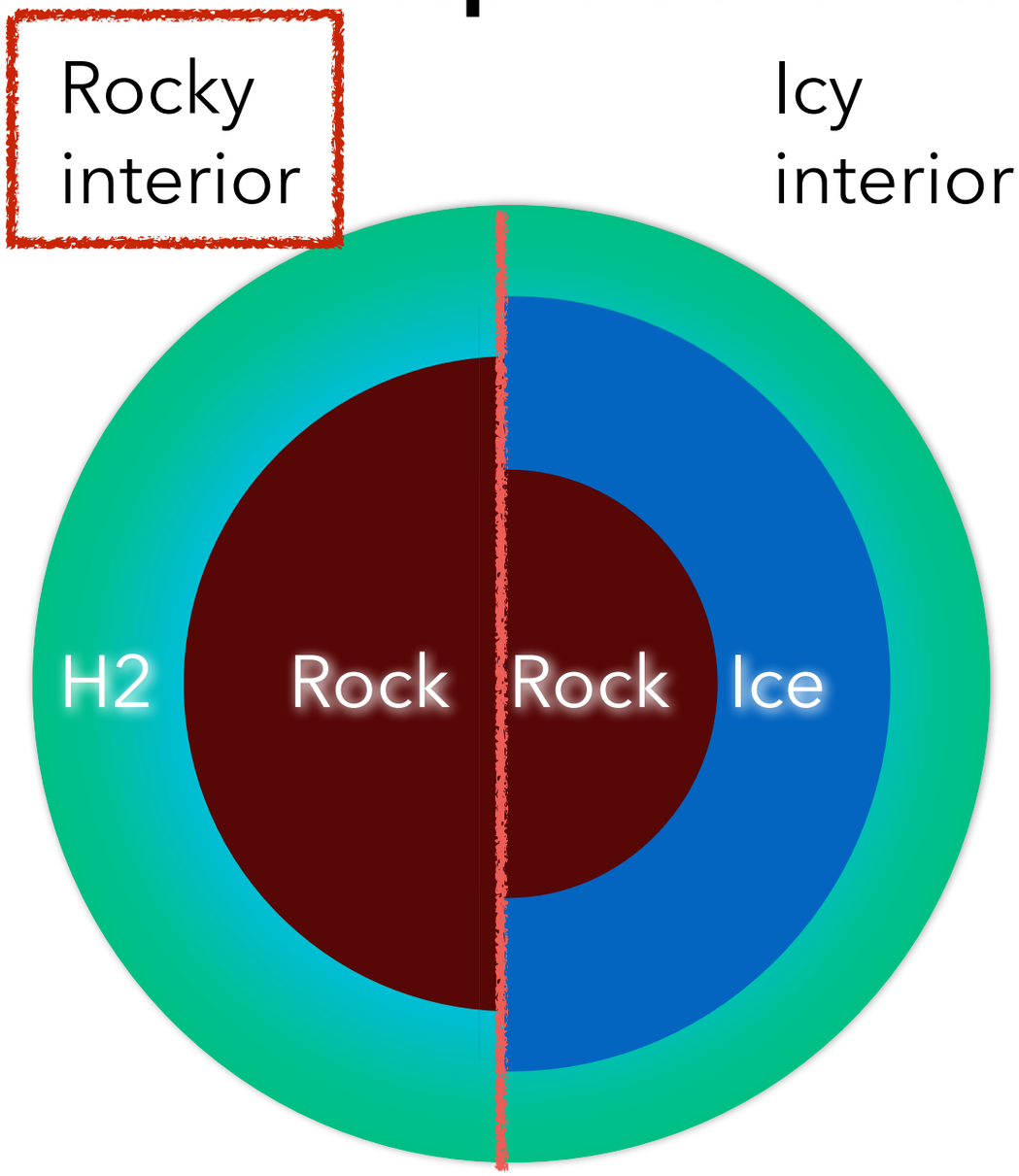
Chemical interaction
(e.g., dissolution and vaporization)
between H2-atmosphere and interior



If the interaction depends on interior comp, we can infer it from Atm

One possible cause to make metal-rich atmosphere

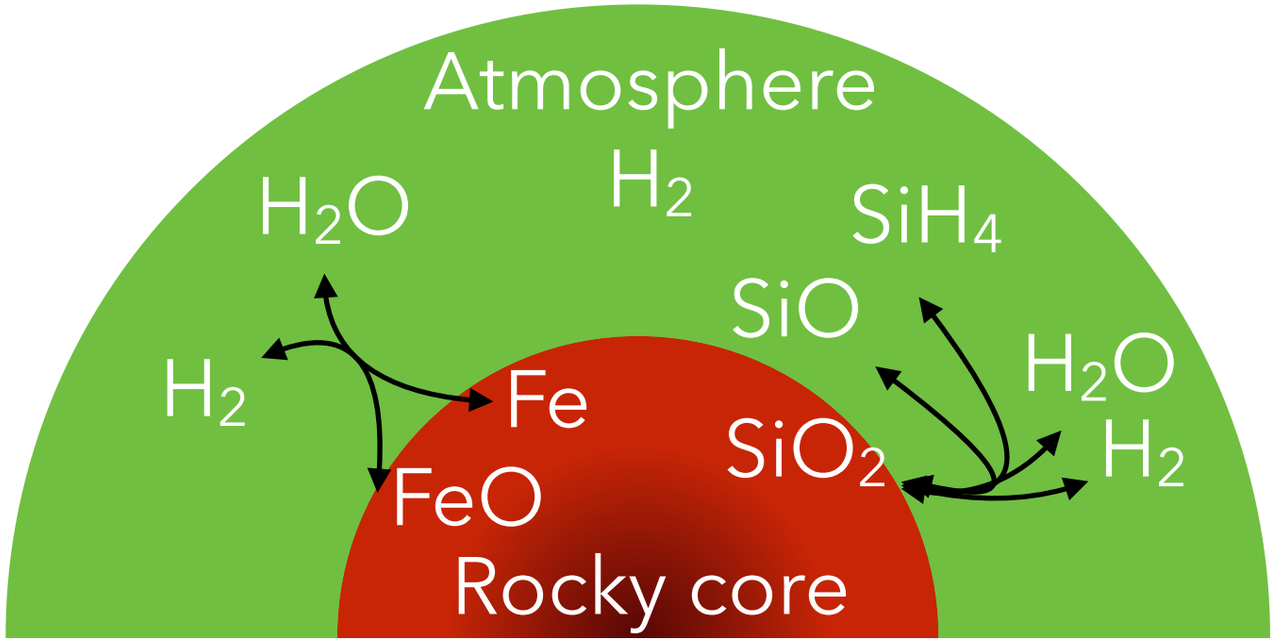
Chemical interaction
(e.g., dissolution and vaporization)
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Overview of atm-rock interaction model prediction

Chemical interaction between rock and H_2 atmosphere



(FeO-rich)
Oxidized

Redox state of rock

(FeO-free)
Reduced

high-H_2O/H_2, high-CO_2/CO, high-O/H, low-C/O

(Kite et al.2020; Tian & Heng 2024; Seo et al. 2024; Werlen et al. 2025)

high-SiH_4/H_2

(Ito et al. 2025)

low-O/H, low-N/H

(Shorttle et al. 2024; Tian & Heng 2024)

*Redox state of inner solar system rocks spans 10 orders of magnitude in vaporized oxygen

(Righter et al. 2016)

Chemical interaction between H2-atmosphere and rocky interior

Chemistry in
Hydrogen-rich Atmosphere

H_2
green house effect

Magma ocean

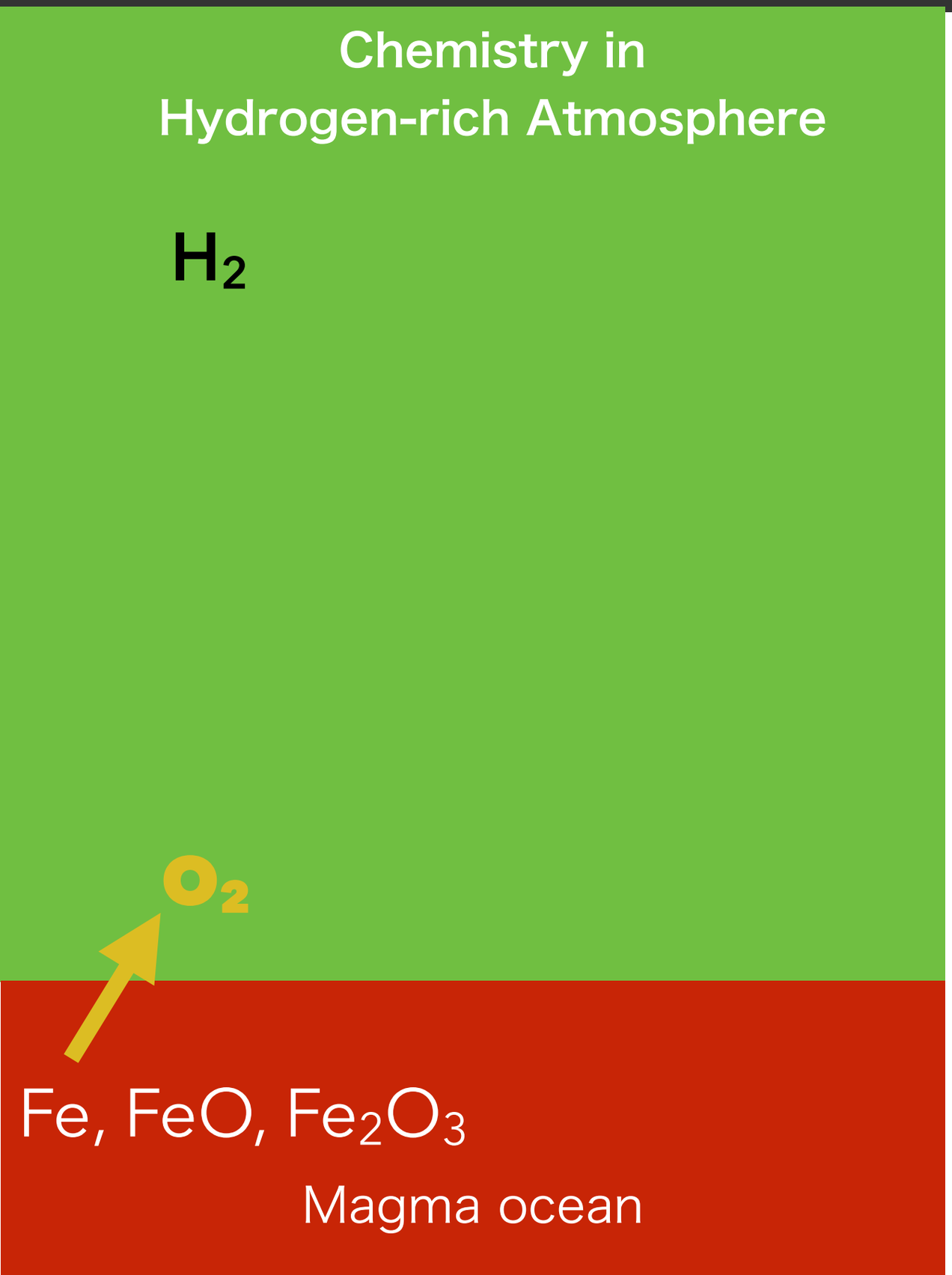
For sub-Neptunes w/ rocky cores

- **Molten rocky interior (magma ocean)**
  sustained by H_2-atmosphere
  (e.g., Vazan et al. 2018, Kite et al. 2020)



(Ref.: NASA)

Chemical interaction between H2-atmosphere and rocky interior



For sub-Neptunes w/ rocky cores

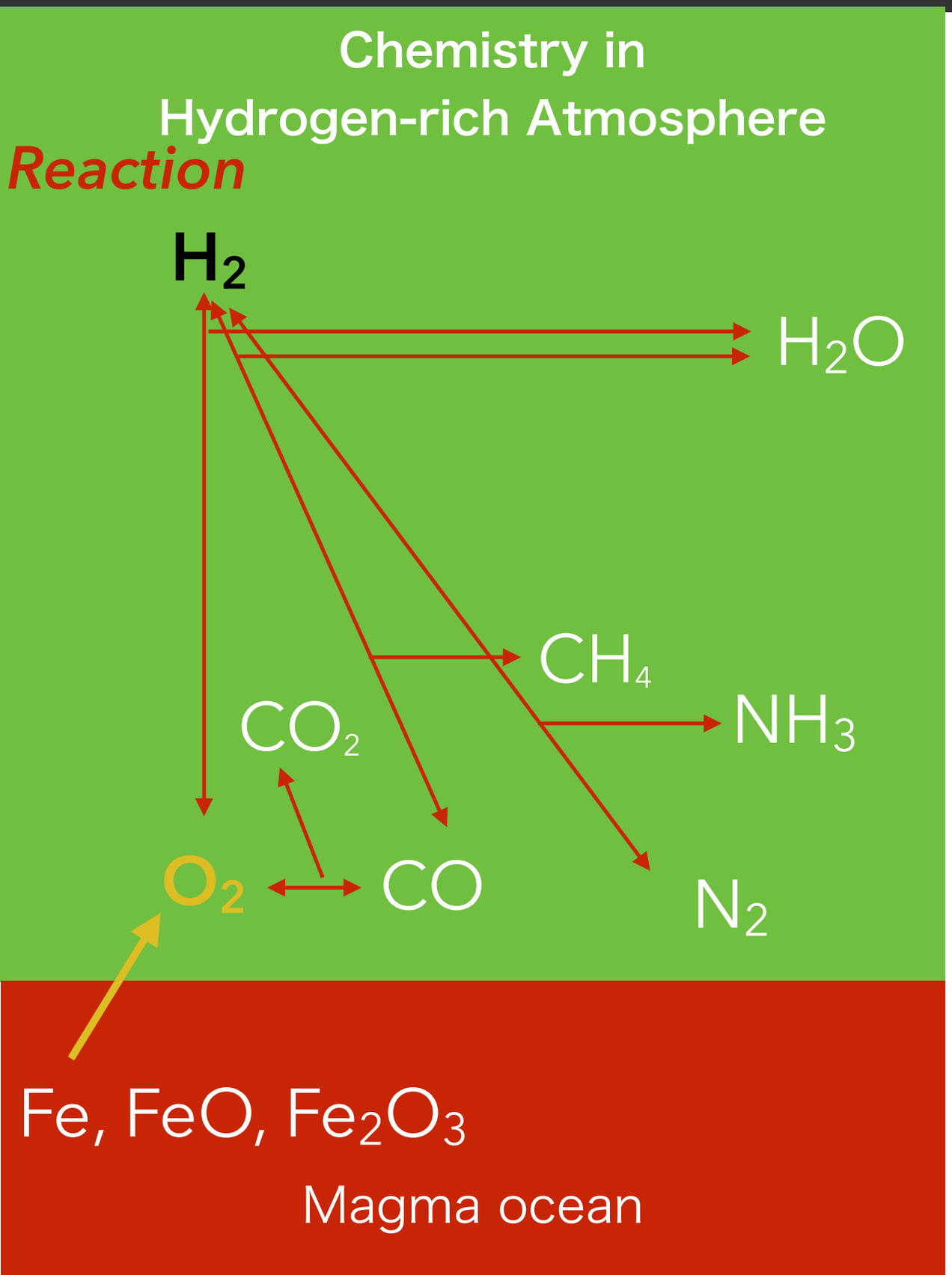
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  (e.g., Vazan et al. 2018, Kite et al. 2020)
- **O_2 controlled by Fe-oxides**

$2FeO(l) \rightleftarrows 2Fe(l) + O_2$

$2Fe_2O_3(l) \rightleftarrows 4FeO(l) + O_2$

(e.g., Frost et al. 2004; Wade & Wood 2005)

Chemical interaction between H2-atmosphere and rocky interior



For sub-Neptunes w/ rocky cores

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- **Redox reactions (w/ H_2 & O_2)**

  $\mathbf{H_2 + 0.5O_2 \rightleftarrows H_2O}$

  $CO + 0.5O_2 \rightleftarrows CO_2$

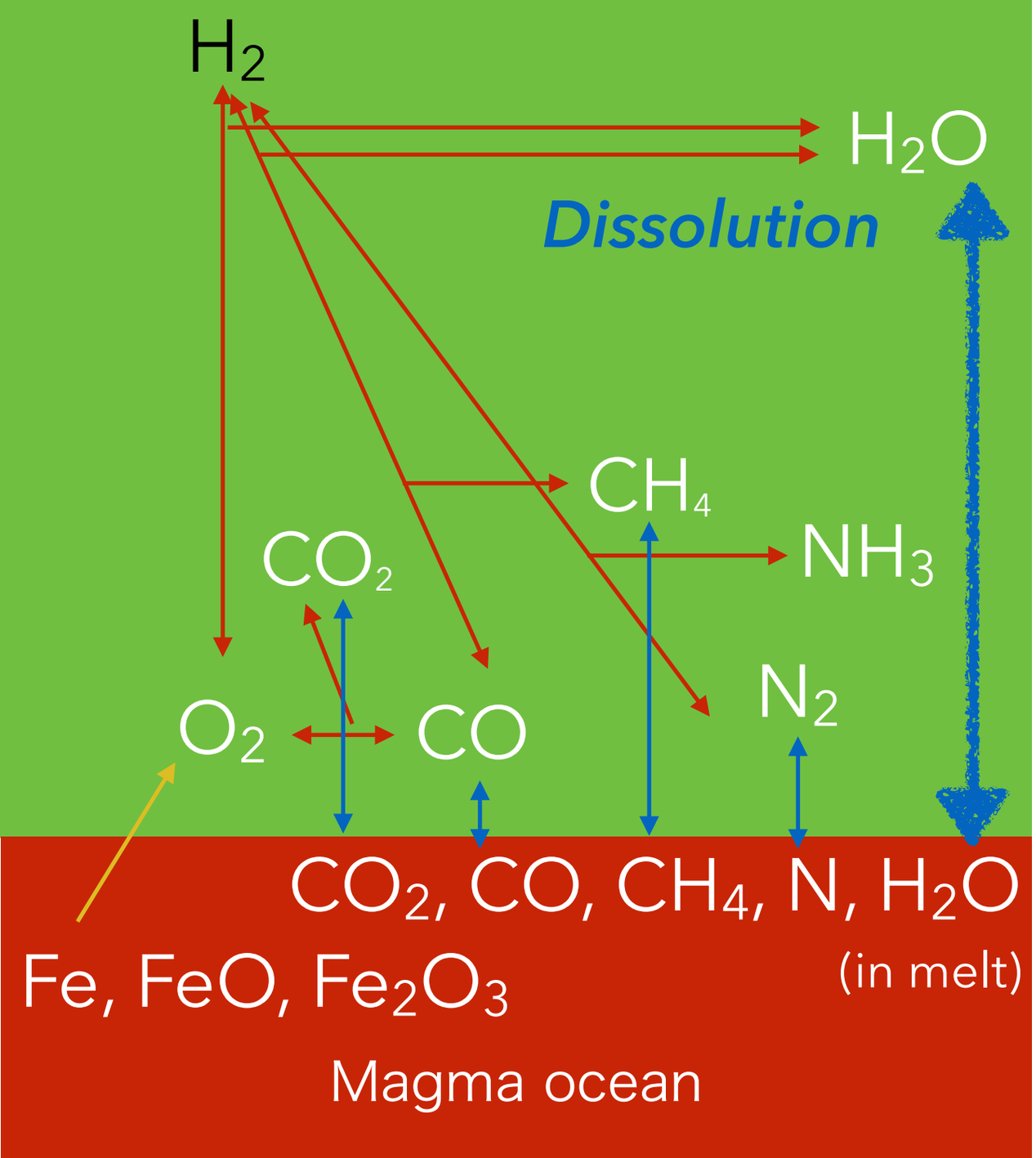
  $CH_4 + O_2 \rightleftarrows CO + 2H_2O$

  $N_2 + 3H_2 \rightleftarrows 2NH_3$

Chemical interaction between H2-atmosphere and rocky interior

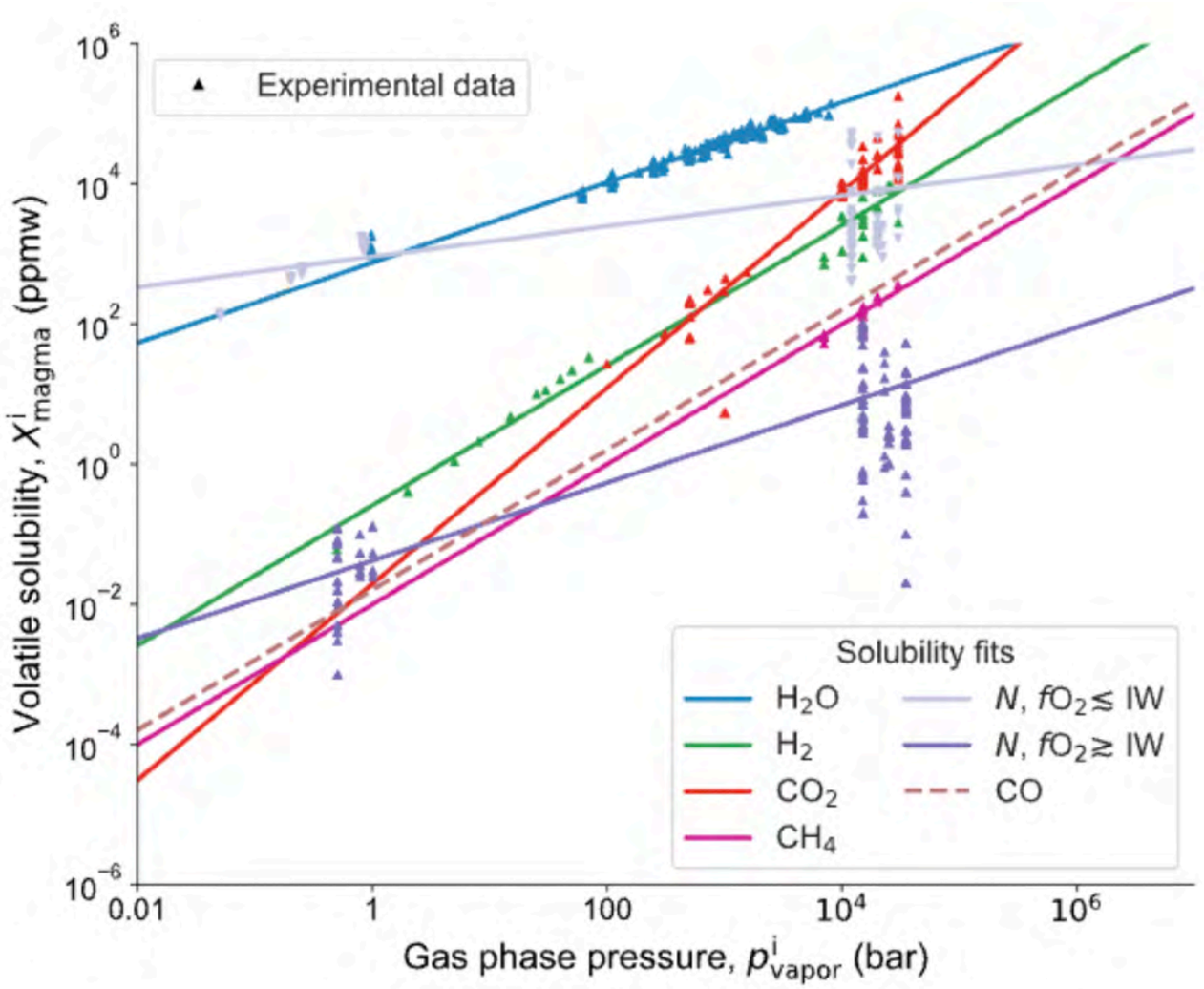
Chemistry in
Hydrogen-rich Atmosphere

Reaction



- **Dissolution of Volatile into Magma ocean**

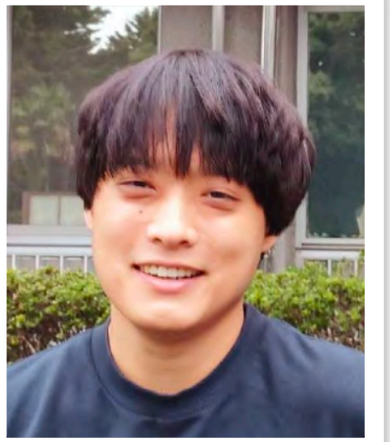
Solubility of volatiles
(summarised by Lichtenberg et al. 2021)



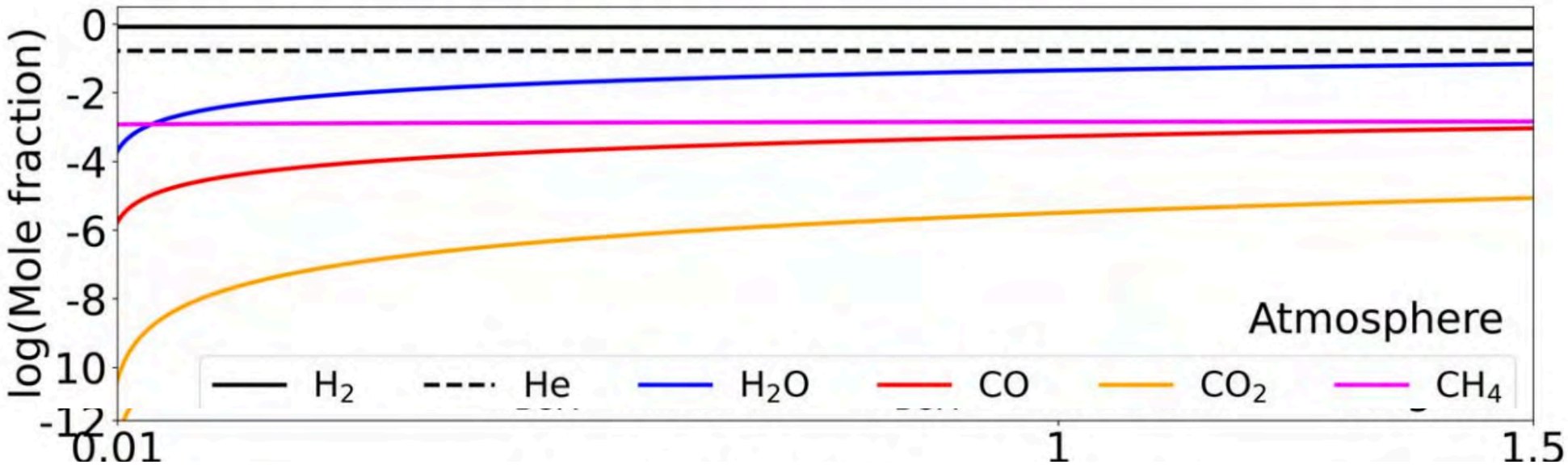
Atmosphere on oxidized (FeO-rich) magma

Atmospheric H-O-C composition equilibrating with magma ocean

at T=3000K, P=1GPa



Chanoul Seo
Ph.D. in NAOJ



$FeO+1.5xFe_2O_3$/ all Fe in magma

(Seo, Ito et al. 2024)

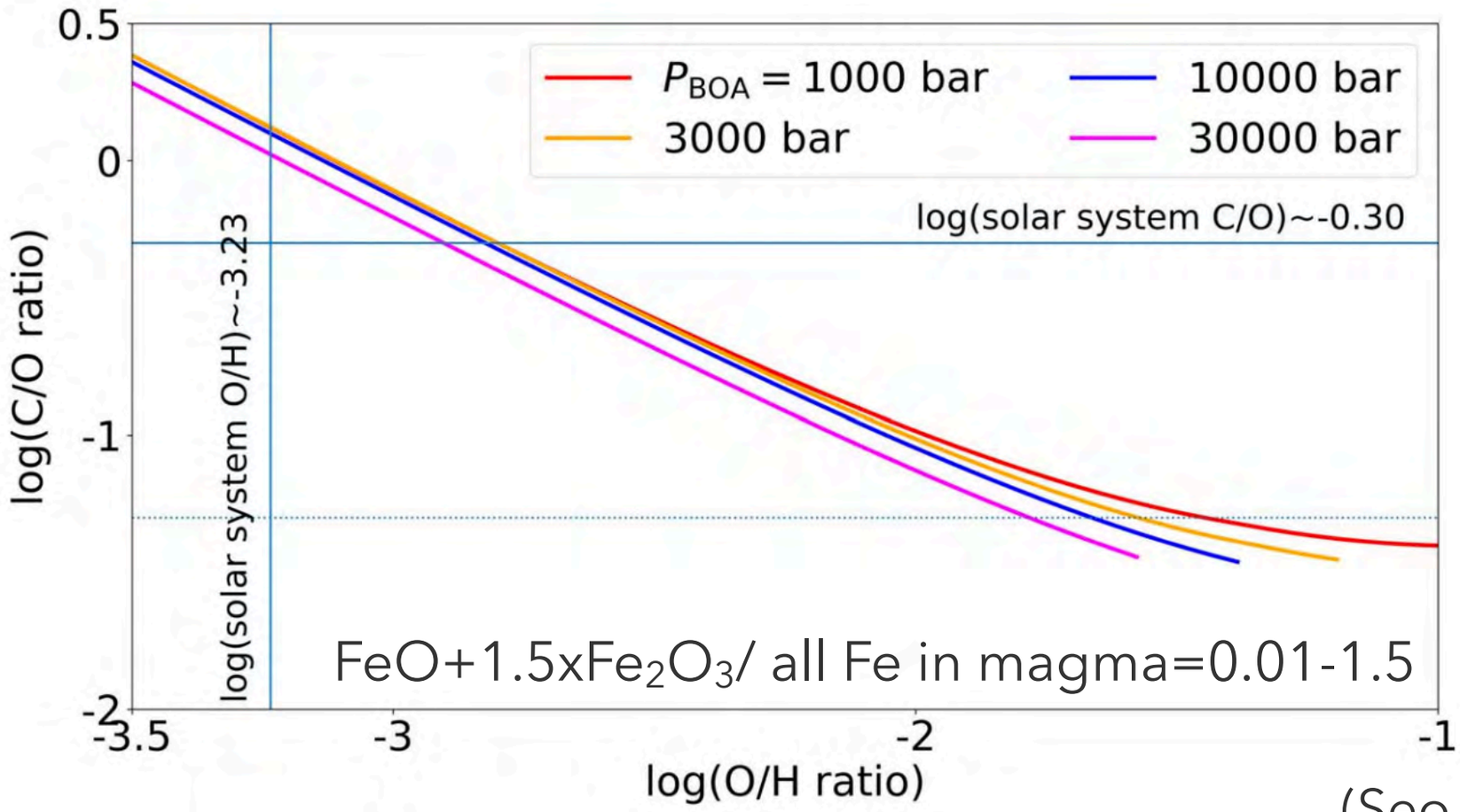
On more oxidized (FeO-rich) magma ocean

higher H_2O/H_2 (Kite et al. 2020), **higher CO_2/CO** (Tian & Heng 2024)

higher O/H & lower C/O (Seo et al. 2024, Werlen et al. 2025)

Atmosphere on oxidized (FeO-rich) magma

Atmospheric element ratio equilibrating with magma ocean



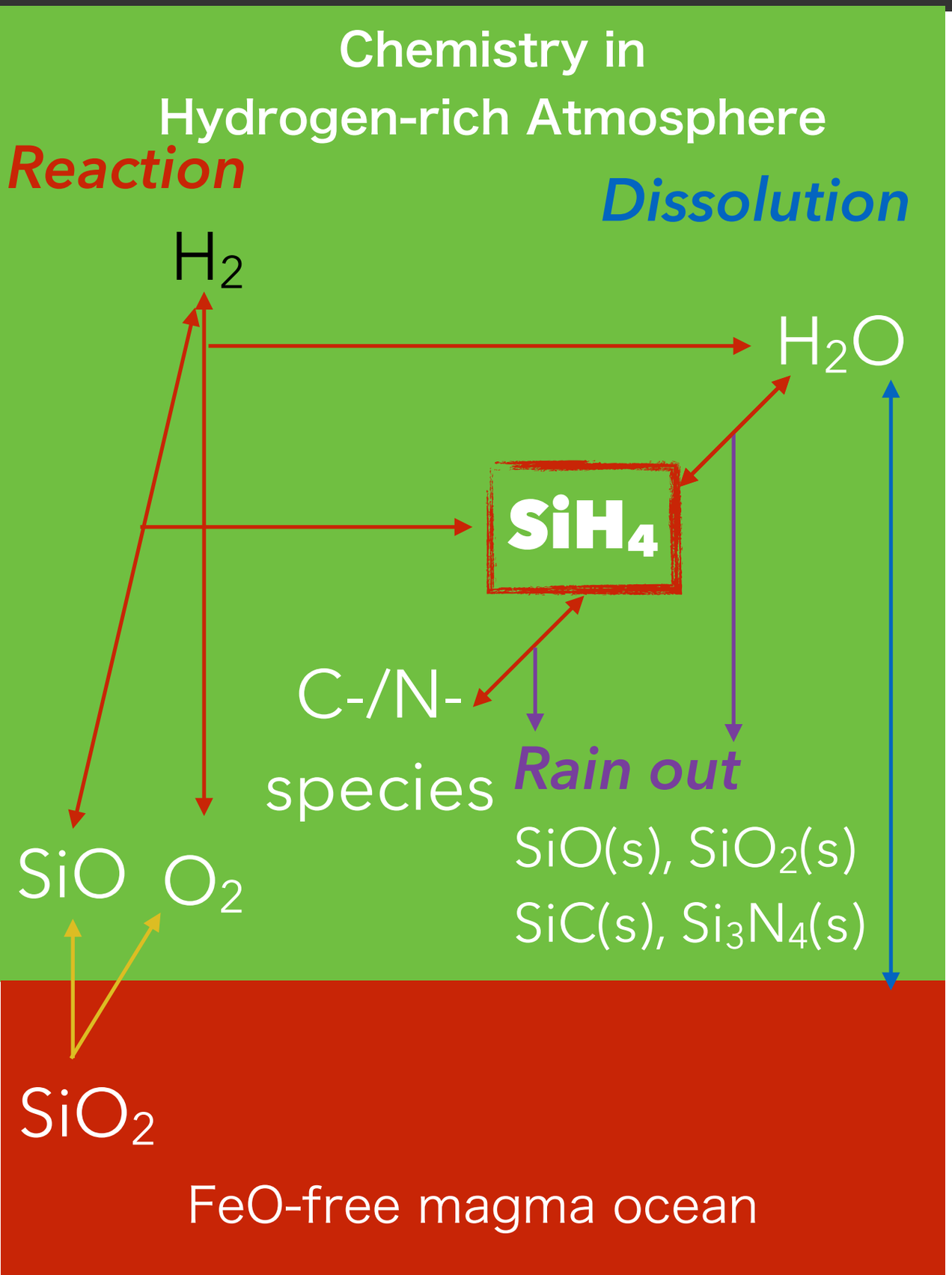
(Seo, Ito et al. 2024)

On more oxidized (FeO-rich) magma ocean

higher H_2O/H_2 (Kite et al. 2020), higher CO_2/CO (Tian & Heng 2024)

higher O/H & lower C/O (Seo et al. 2024, Werlen et al. 2025)

Chemical interaction between H2-atmosphere and rocky interior

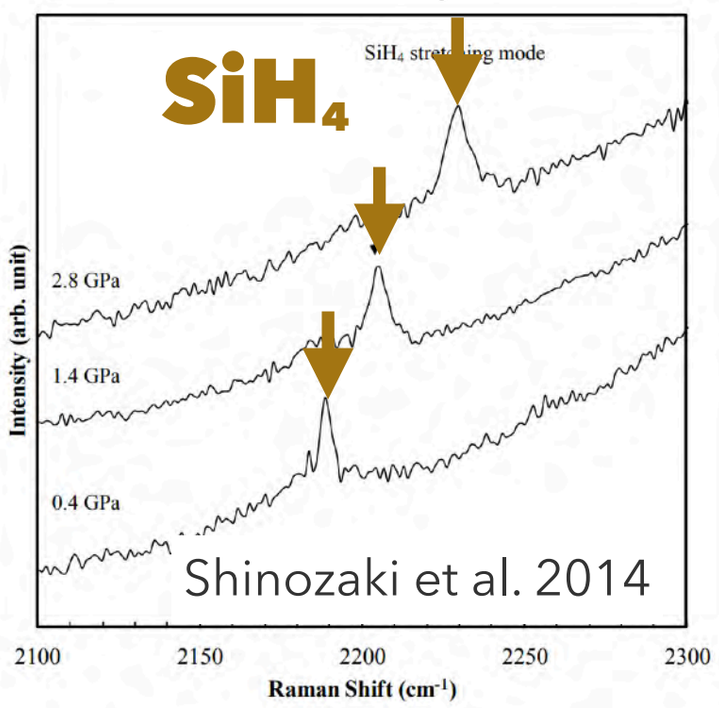


- **On reduced (FeO-free) magma ocean, rocky-element hydrides is expected to be generated**

SiH_4 is the dominant hydride in chemical equilibrium model
(Charnoz et al. 2023)

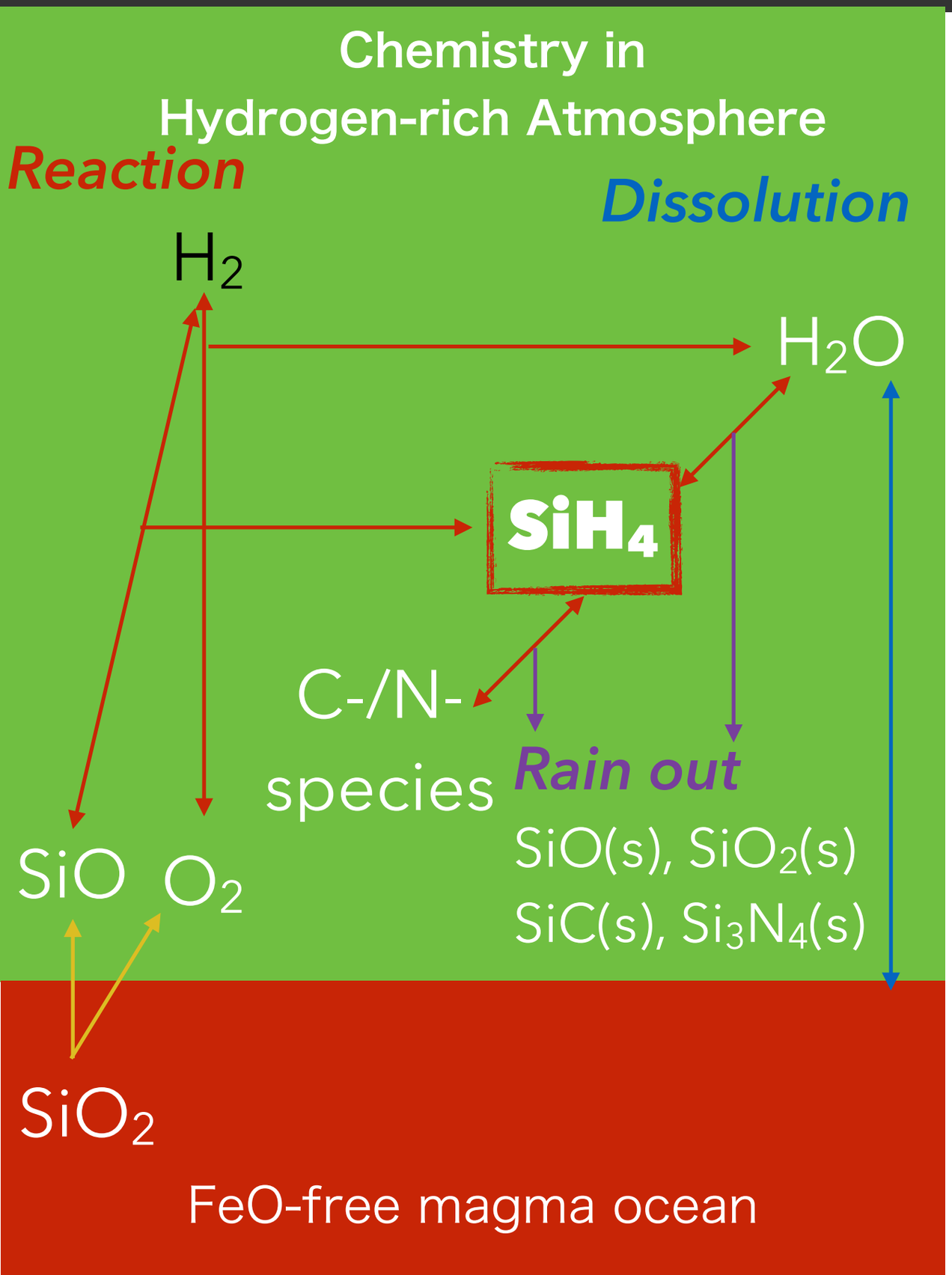
High T & P lab. measurements

in H_2-SiO_2 system



Shinozaki et al. 2014

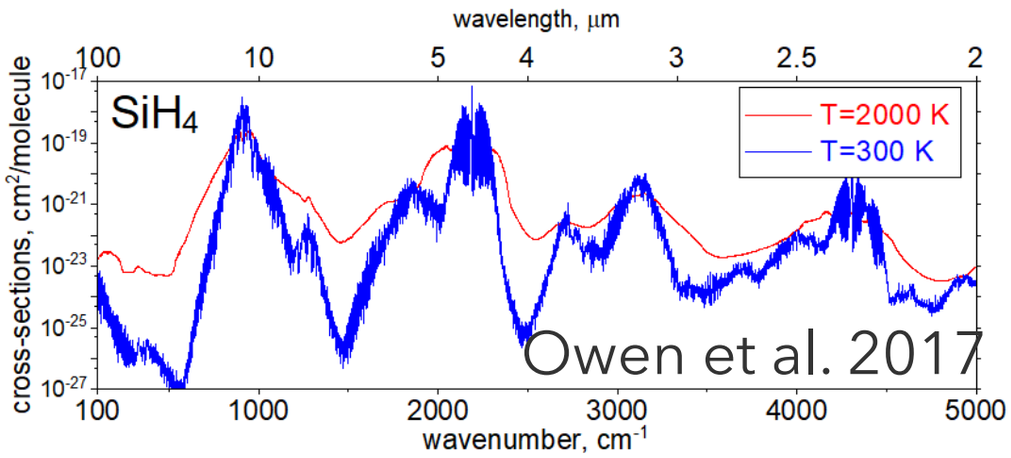
Chemical interaction between H2-atmosphere and rocky interior



- In case of reduced (FeO-free) magma ocean, rocky element hydrides generated

Monosilane, SiH_4, has nice characters in spectroscopy among rocky element hydrides

- **Strong infrared spectrum**



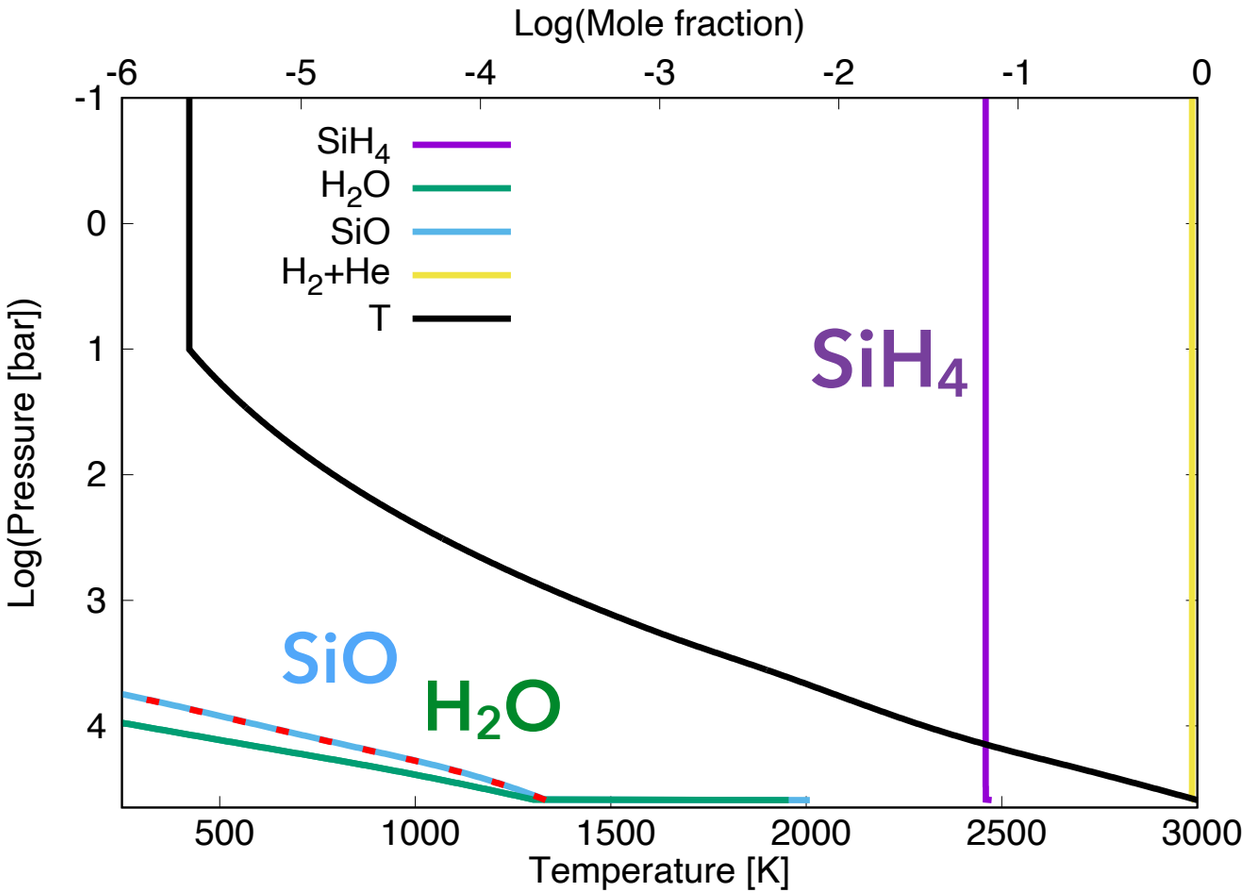
- **Low condensation temp.(161K)**
- **Highly reactive with O, C, N**

Atmosphere on reduced (FeO-free) magma

(Ito et al. 2025: Si-O-H atmospheric model considering FeO-free magma ocean)

Atmospheric composition

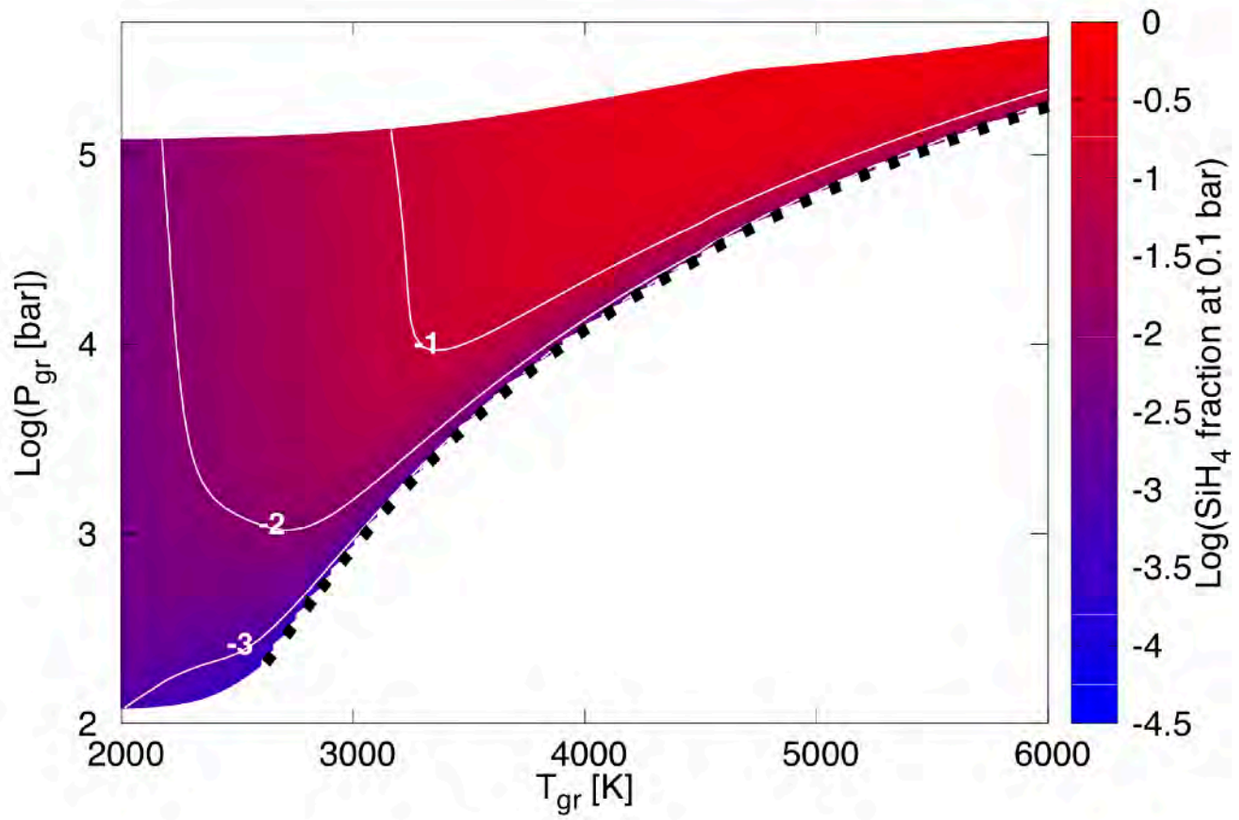
for T_{gr}=3000K, $P_{H2,gr}$=3GPa



Monosilane fraction

at 0.1 bar

for different surface T & P

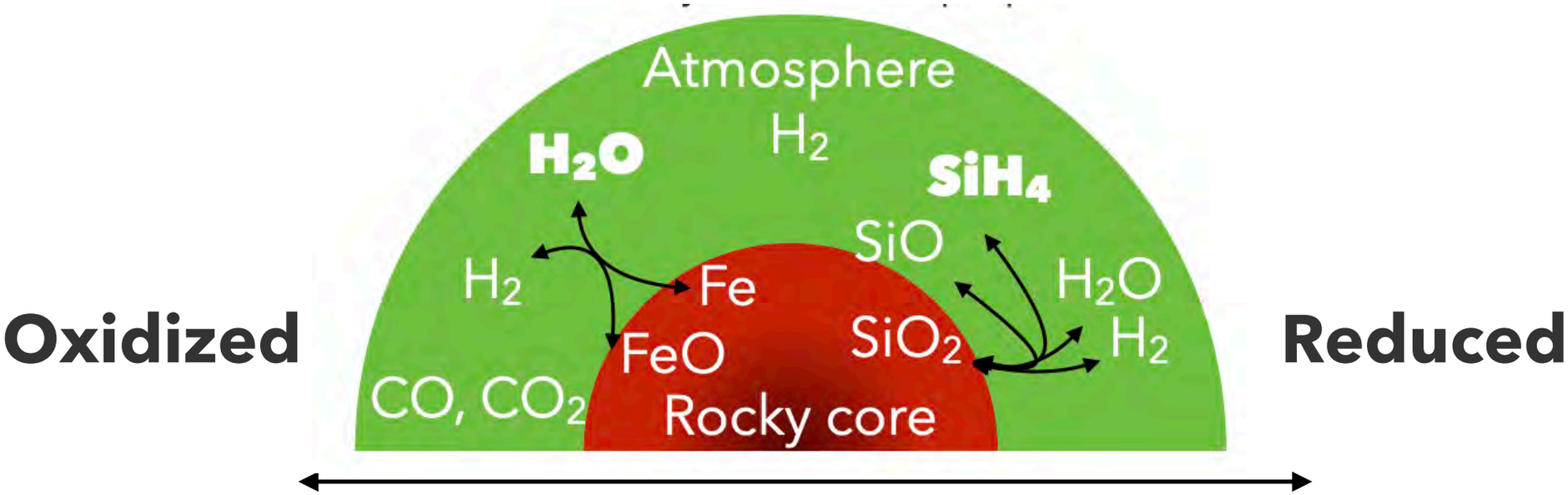


SiH_4 becomes the major species on reduced magma ocean

This can be explained by chemical relation: $X_{SiH4} \propto X_{H2O}^{-2} P_{H2}$

(H_2O↓$\rightleftarrows H_2 + 1/2\ O_2$↓, $SiO_{2,\ liquid} \rightleftarrows SiO$↑$+ 1/2 O_2$↓, ***$SiH_4$***↑↑$+ H_2O$↓, $\rightleftarrows 3H_2 + SiO$↑)

Disc: Atmospheric tracer of rock's redox state in spectra

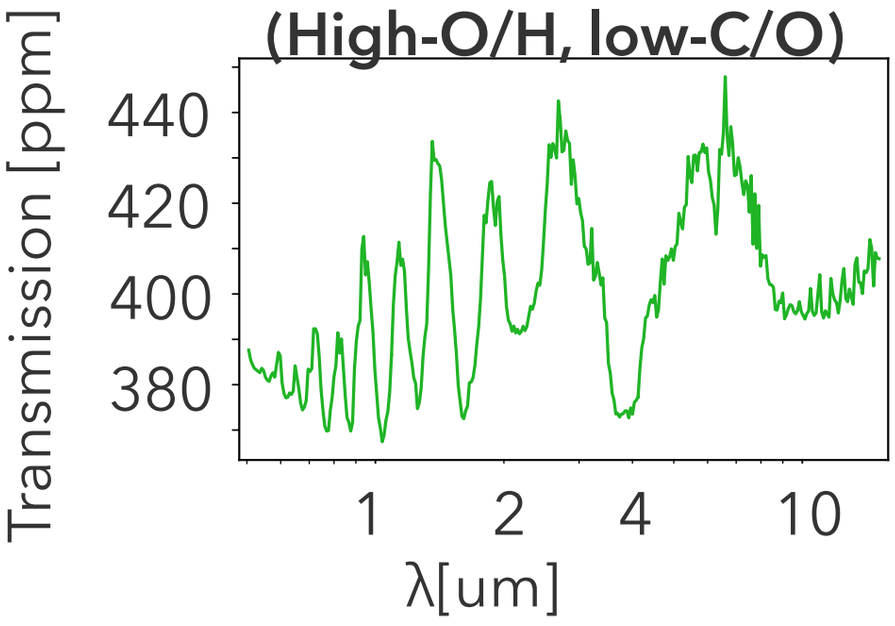


Oxidized **Reduced**

Redox state of magma

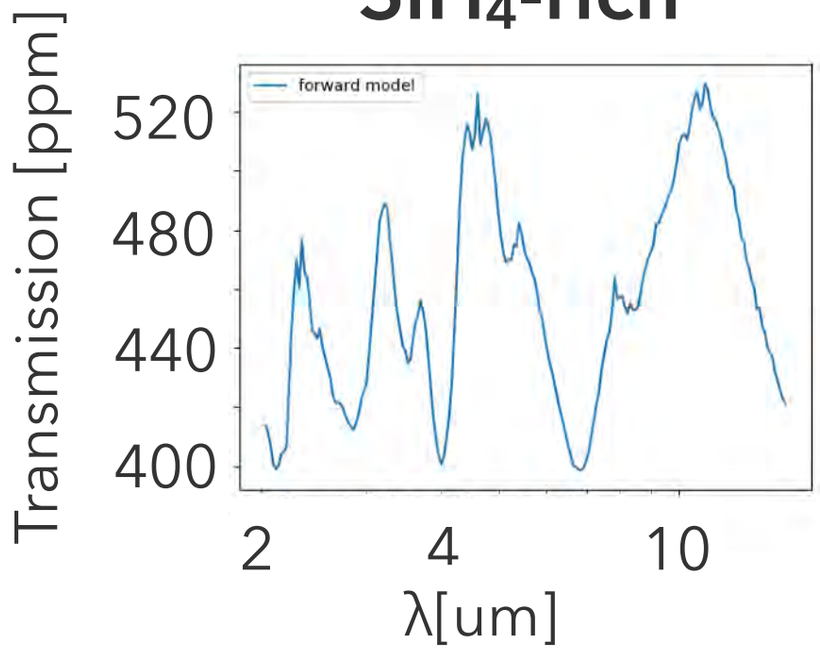
H_2O-rich

(High-O/H, low-C/O)



Spectra examples:
sub-Neptune
around Sun-like star
500K, 5M⊕, 2R⊕

SiH_4-rich



Ongoing/future characterisation with JWST, Ariel, or ELTs would offer opportunities to assess the presence & redox state of a rocky core

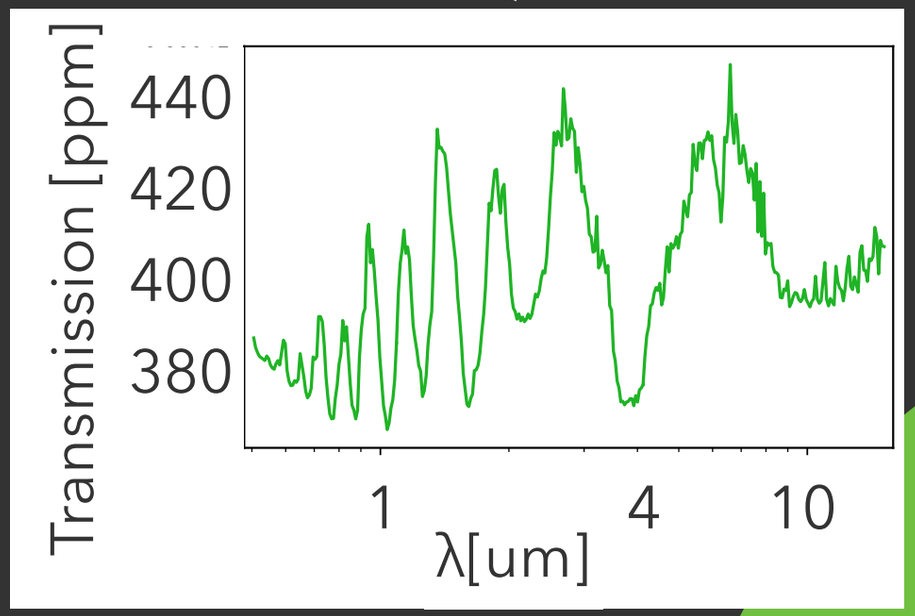
Summary

Background:Bulk composition of sub-Neptune cannot be determined from mass and radius alone, but sub-Neptune's H_2-atmosphere may be altered by rocky cores

<u>Prediction from our & previous magma-atmosphere models</u>

The presence & redox state of rocky core for sub-Neptune are expected to be revealed by ongoing/near-future obs.

Oxidized Redox state of magma **Reduced**



Ex. Planets
around Sun-like star
(500K, 5M⊕, 2R⊕)

