Carbon Cycling on the TRAPPIST-1 Planets

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2023 NASA ExoExplorer Series

Johns Hopkins University

Advisor: Prof. Laura Schaefer (Stanford University)

JOHNS HOPKINS KRIEGER SCHOOL of ARTS & SCIENCES

Stanford

CHAMPs

Credit: NASA, ESA, CSA, Joseph Olmstead (STScI)

From Puerto Rico to Maryland

UNIVERSITY OF MARYLAND 18 56

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Our Home: Planet Earth

Image Credit: NASA

Our Home: Planet Earth

Has plate tectonics!

↓

Drive important geological processes occurring such as the carbon cycle

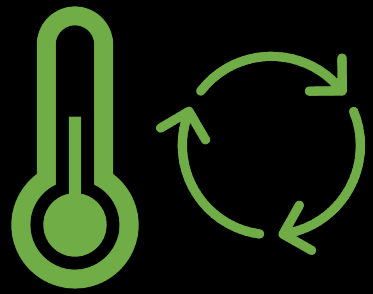
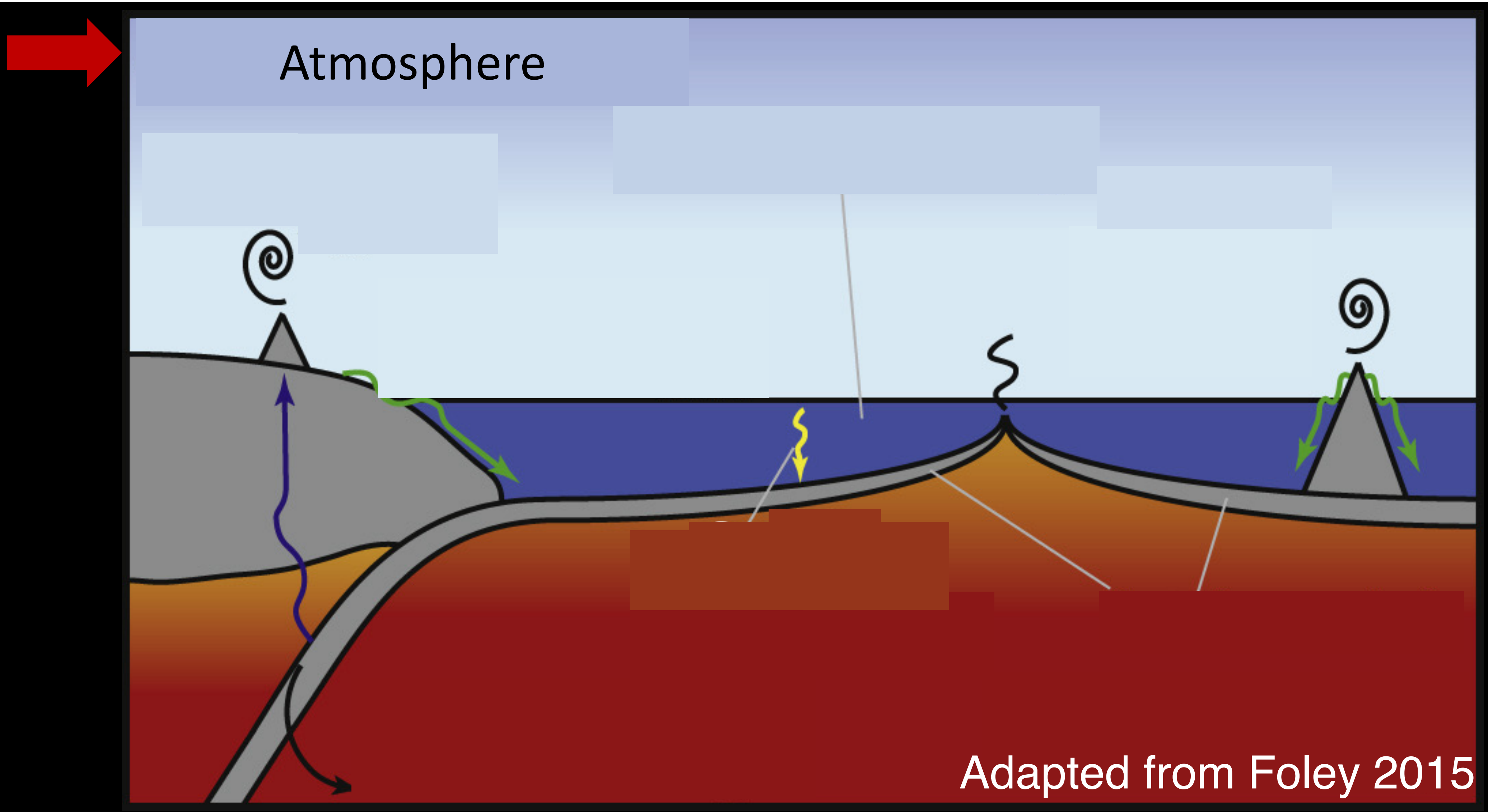


Image Credit: NASA

The carbon cycle regulates the climate of a planet over long timescales



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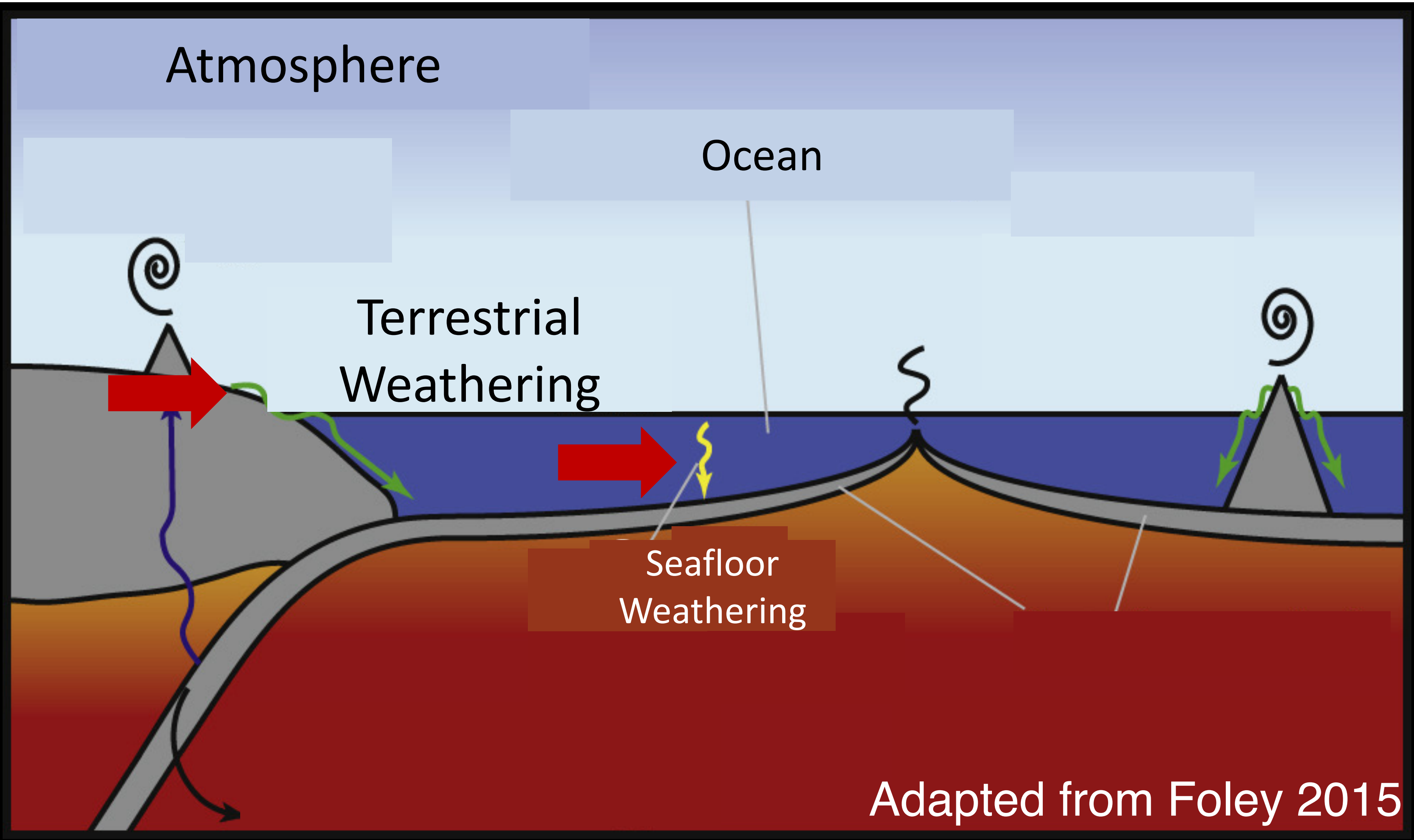

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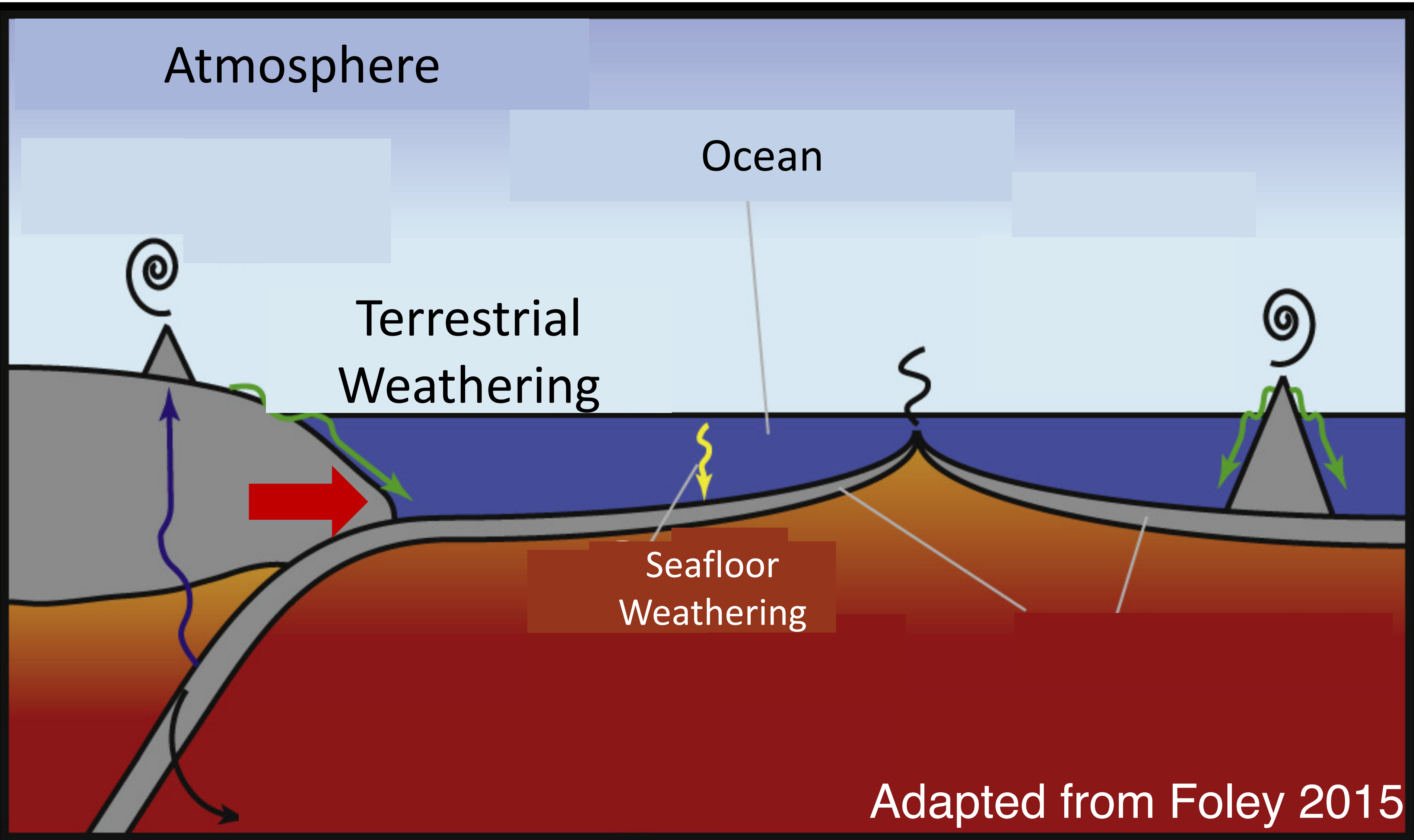

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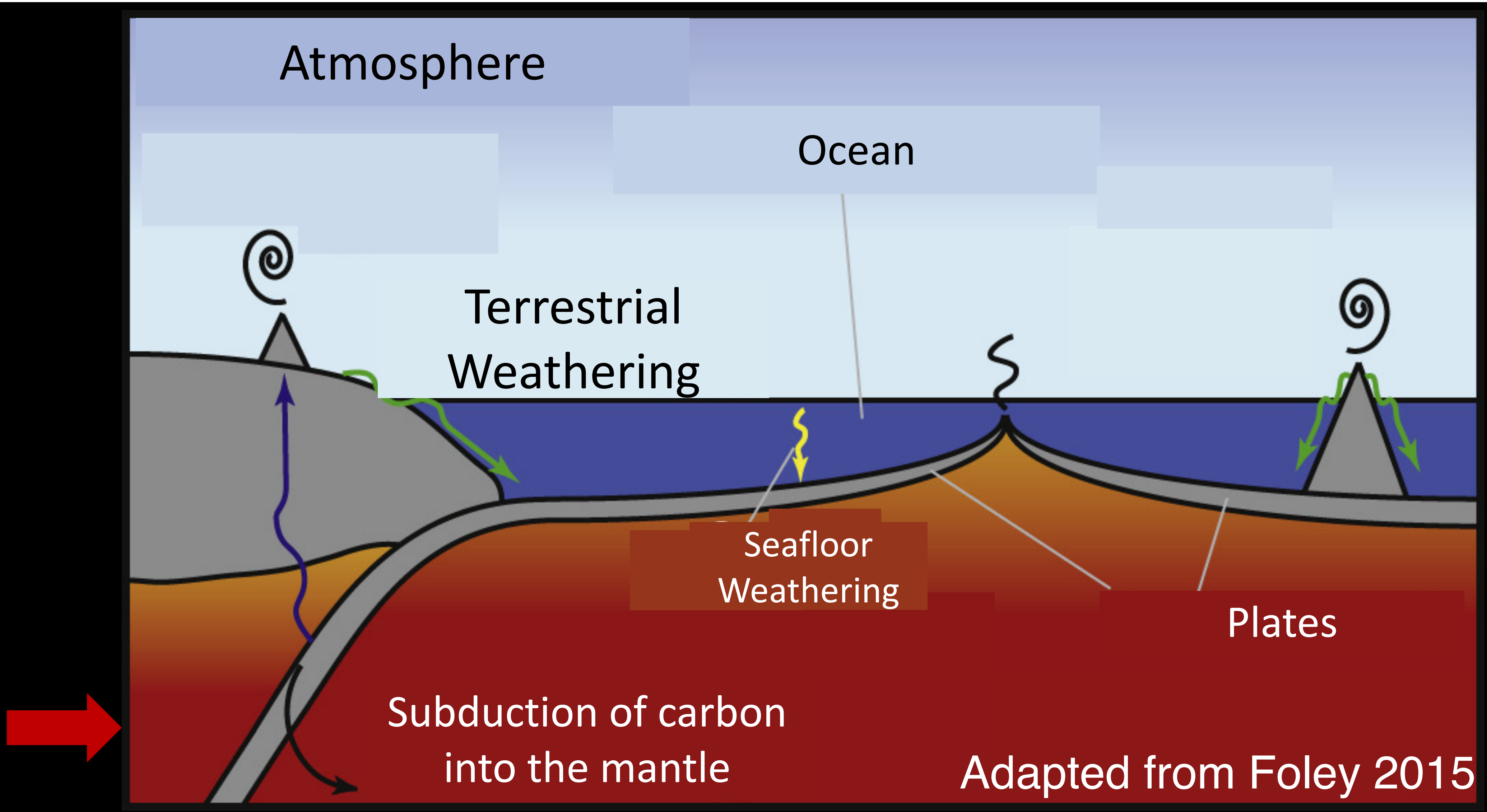
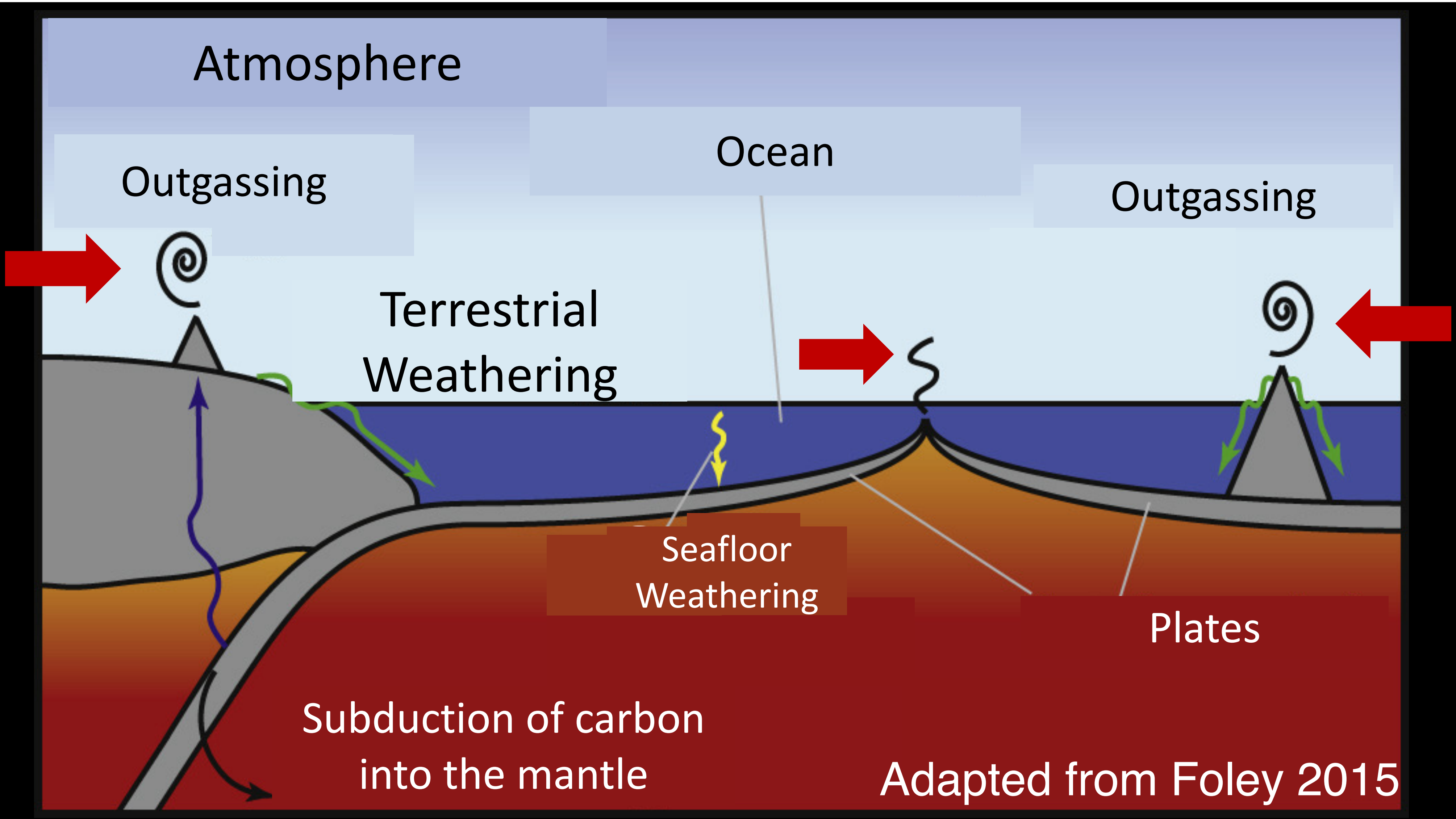
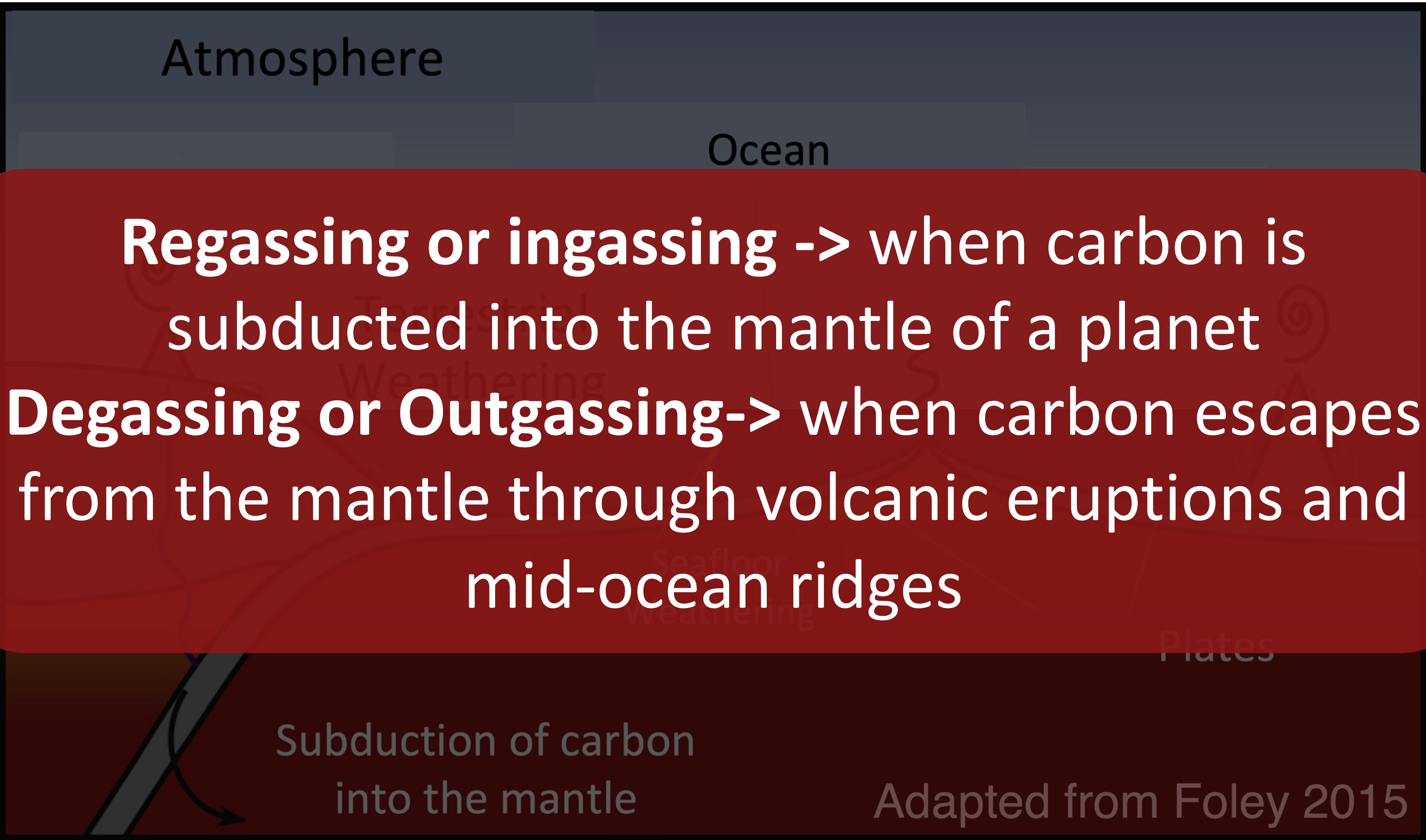


Adapted from Foley 2015

The carbon cycle regulates the climate of a planet over long timescales



The carbon cycle regulates the climate of a planet over long timescales

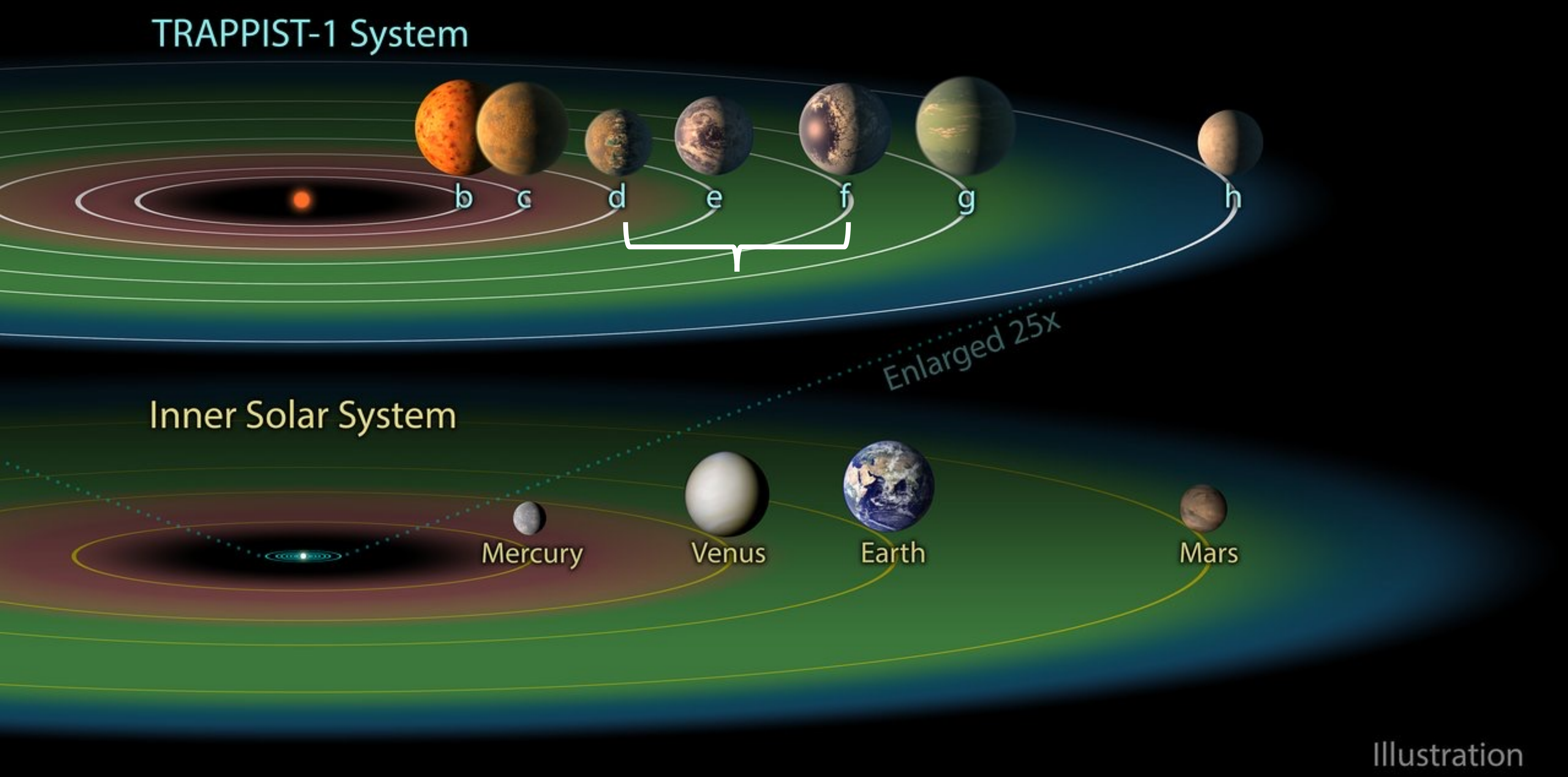


Regassing or ingassing -> when carbon is subducted into the mantle of a planet

Degassing or Outgassing-> when carbon escapes from the mantle through volcanic eruptions and mid-ocean ridges

Adapted from Foley 2015

We mainly obtain atmosphere observations for exoplanets and therefore it is crucial to study their evolution and how interior processes can shape the atmosphere we observe today with telescopes!



Credit: NASA/JPL-Caltech

The TRAPPIST-1 planets have been observed many times since their discovery

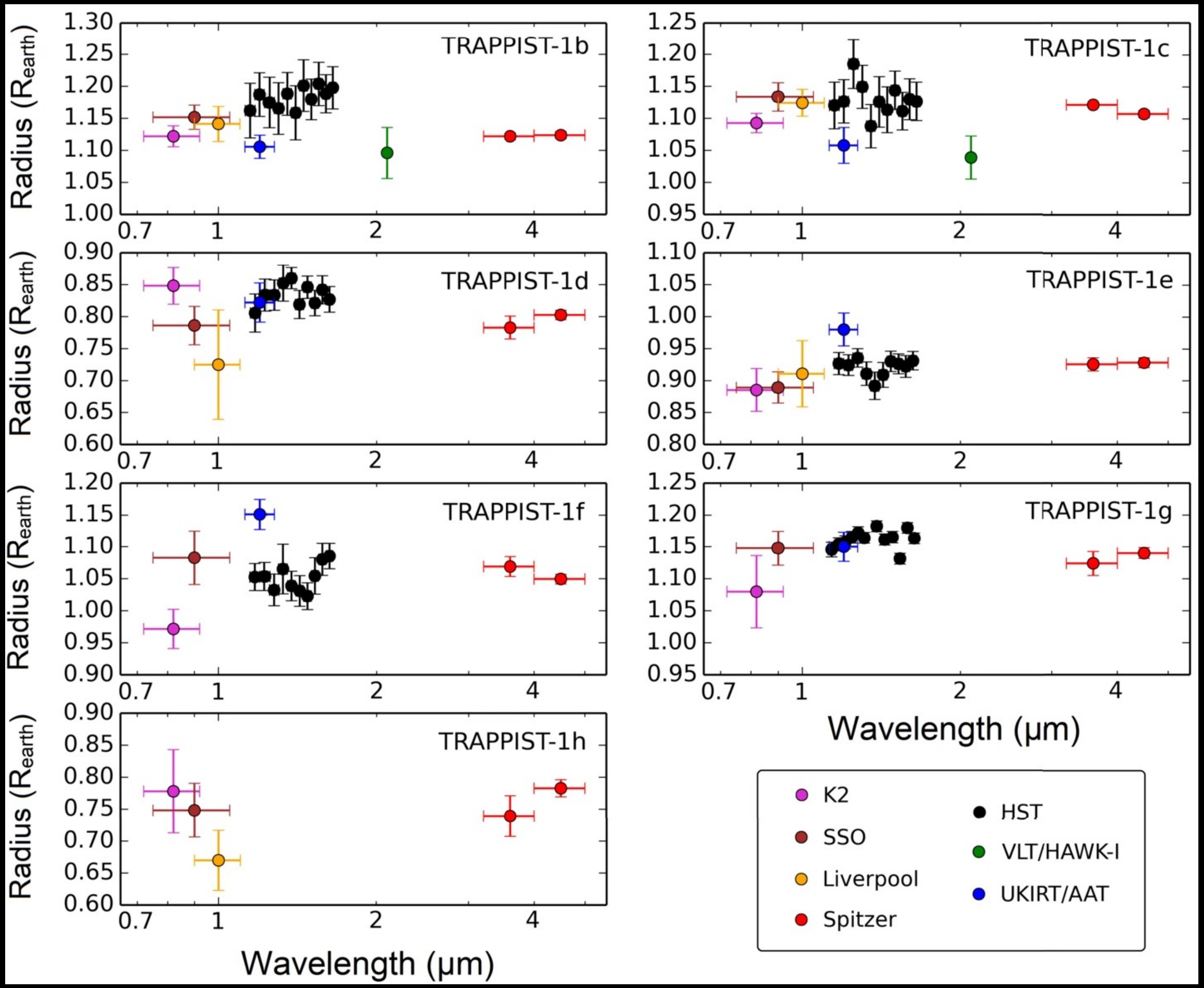


Figure from Turbet et al. 2020

- It is very unlikely that the TRAPPIST-1 planets have hydrogen-dominated atmospheres
- It is expected that these planets either have a high molecular weight atmosphere or no atmosphere at all
- It is also very important to account for stellar contamination in observations!

TRAPPIST-1b was looked at with JWST!

Article | Published: 27 March 2023

Thermal Emission from the Earth-sized Exoplanet TRAPPIST-1 b using JWST

Thomas P. Greene, Taylor J. Bell, Elsa Ducrot, Achrène Dyrek, Pierre-Olivier Lagage & Jonathan J. Fortney

- They looked at the thermal emission from the planet with MIRI: found a dayside temperature of ~500K
- Suggests that it has no significant atmosphere!

GOAL:

To study the role of outgassing in the evolution of the atmospheric composition and planetary climate for TRAPPIST-1 d, e, f

How do we study this?

Outgassing Models

We choose and test a range of oxygen fugacities (fO_2)

→

We model the carbon cycle on the TRAPPIST-1 planets

→

We track the following gas species:

- H_2O
- H_2
- CO
- CO_2

Image Credit: Amanda Smith/University of Cambridge

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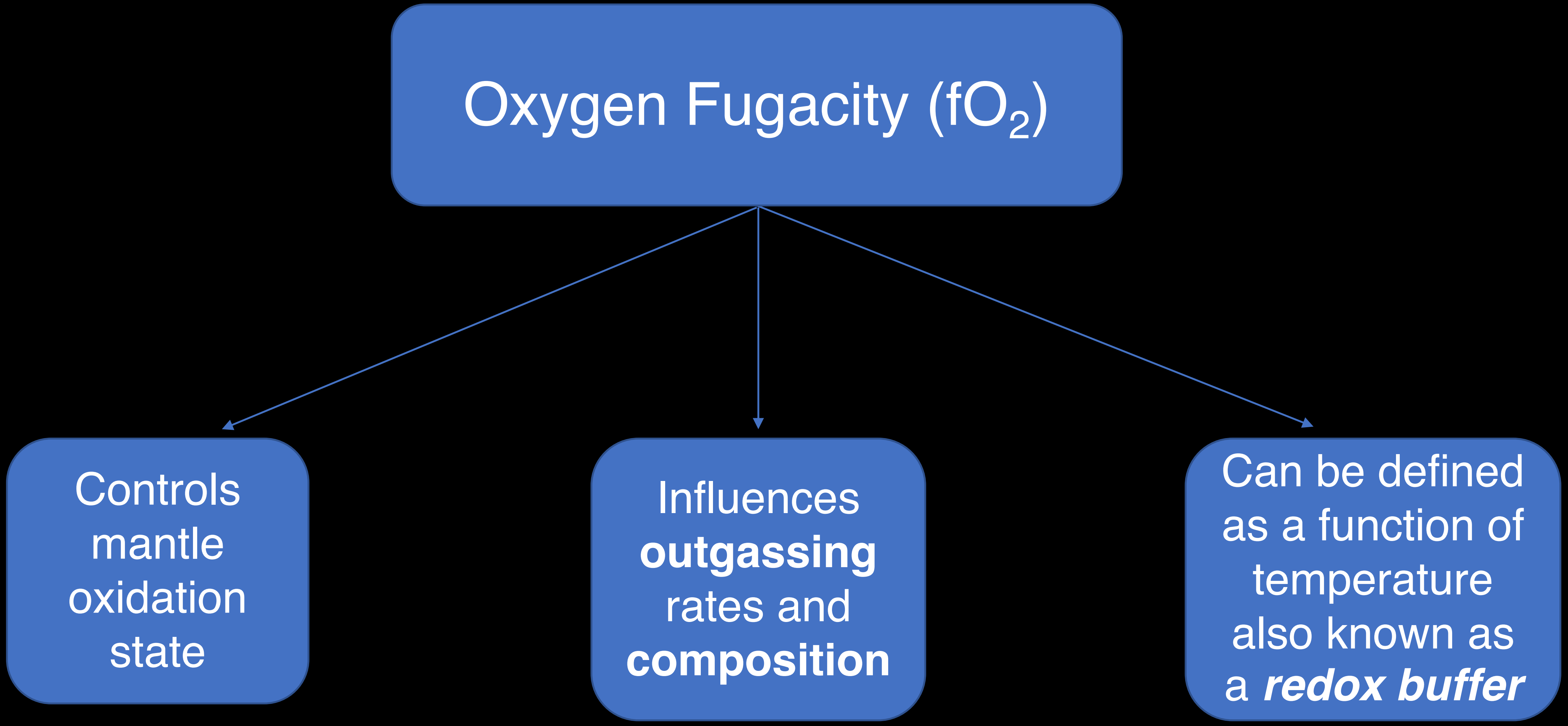
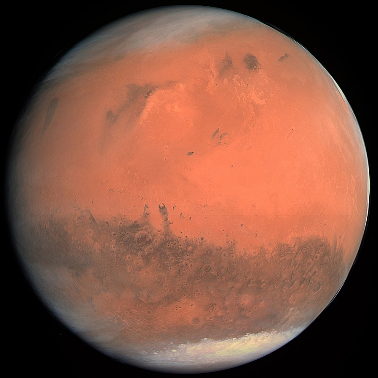

Oxygen Fugacity (fO_2)
Controls mantle oxidation state
Influences **outgassing** rates and **composition**
Can be defined as a function of temperature also known as a ***redox buffer***

We consider a range of oxygen fugacities (fO_2) for TRAPPIST-1 d, e and f

Reduced



Buffer:
IW
(Iron–Wüstite)

Oxidized

Buffer:
IW+4
(Iron–Wüstite + 4)

Oxygen Fugacity (fO_2)

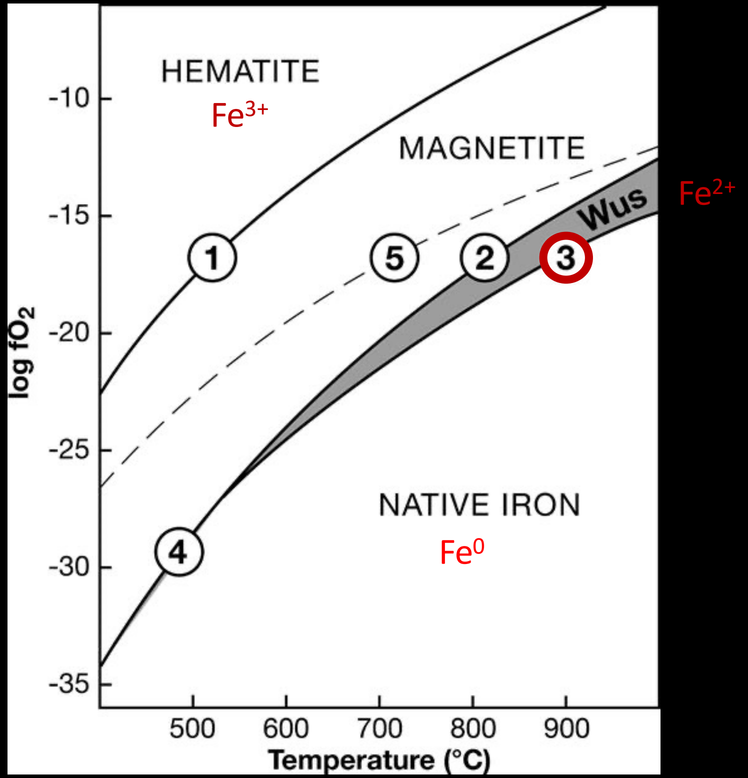
Iron – Wüstite (IW) buffer

$2(1-x)\ Fe + O_2(g) = 2\ Fe_{1-x}O$ (wüstite)

Gas reactions

$H_2(g) + ½\ O_2(g) = H_2O(g)$ ➡ $$\frac{P_{H_2O}}{P_{H_2}} \propto f_{O_2}^{1/2}$$

$CO(g) + ½\ O_2(g) = CO_2(g)$ ➡ $$\frac{P_{CO_2}}{P_{CO}} \propto f_{O_2}^{1/2}$$

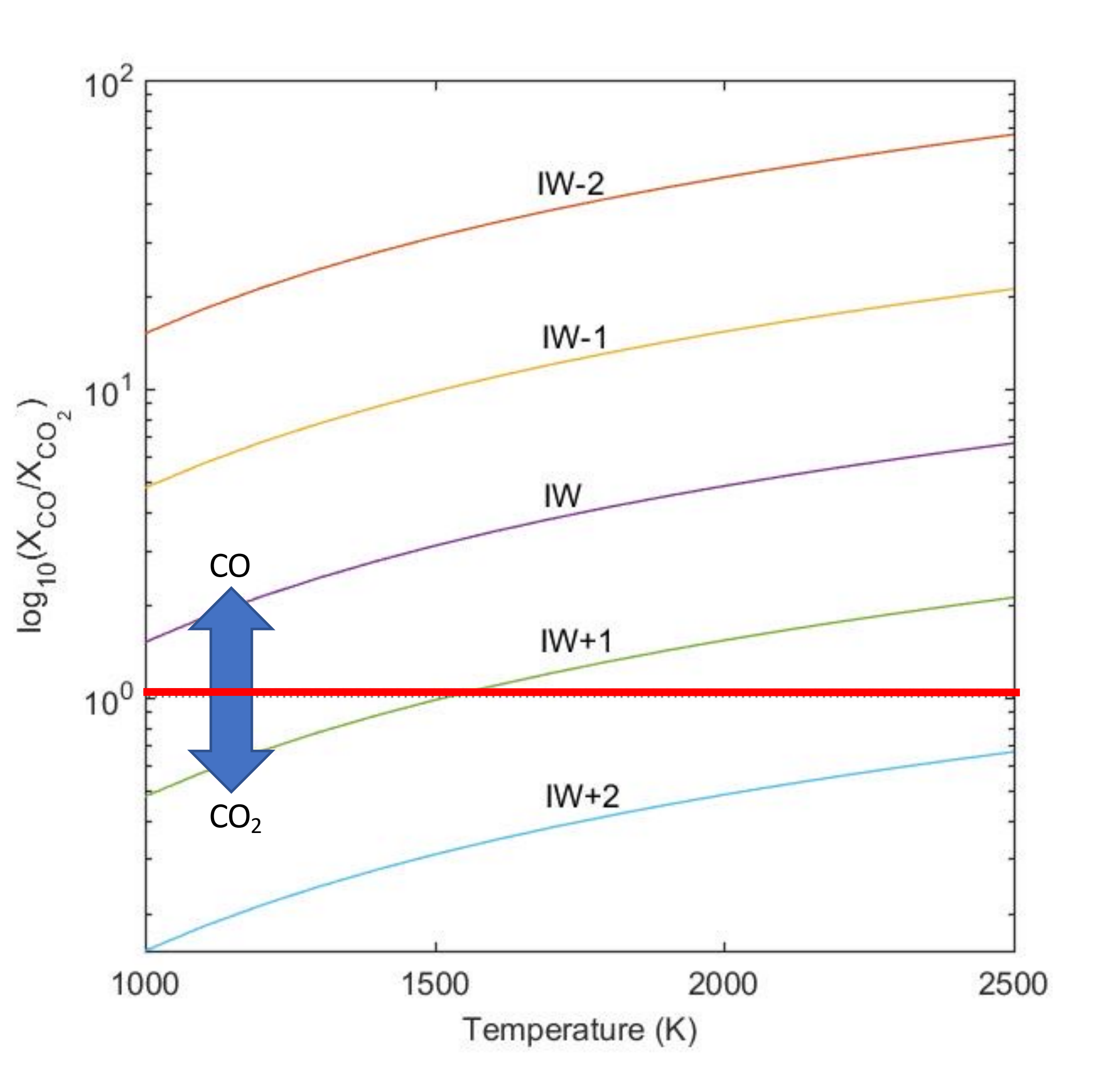


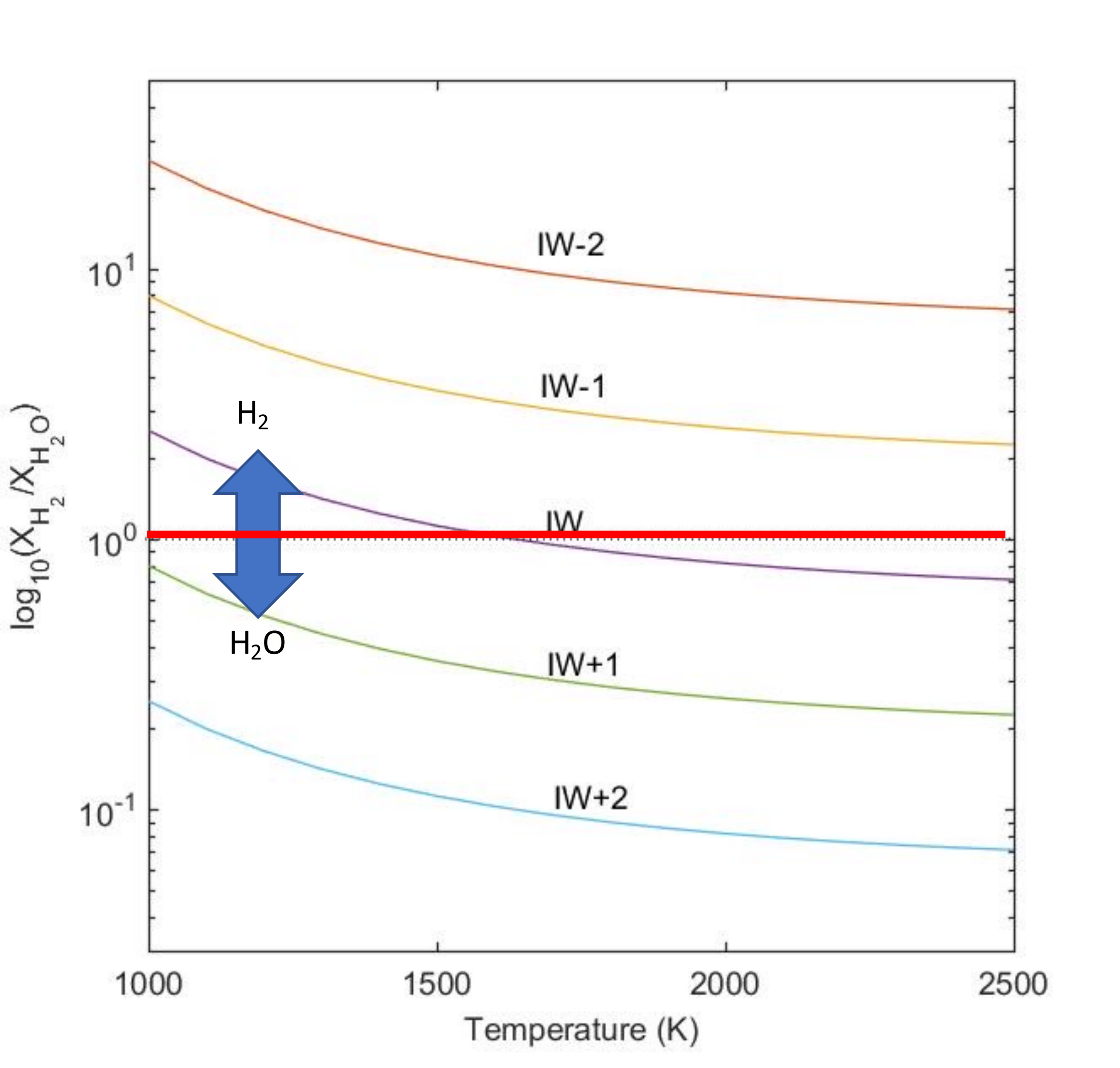
Seifert et al. (2010) Eu. J. Min.

- Controls relative gas abundances (e.g. H_2/H_2O, CO/CO_2).
- Carbon outgassing rates depend on it.

Modified from: Laura Schaefer

Gas Composition at fixed fO_2





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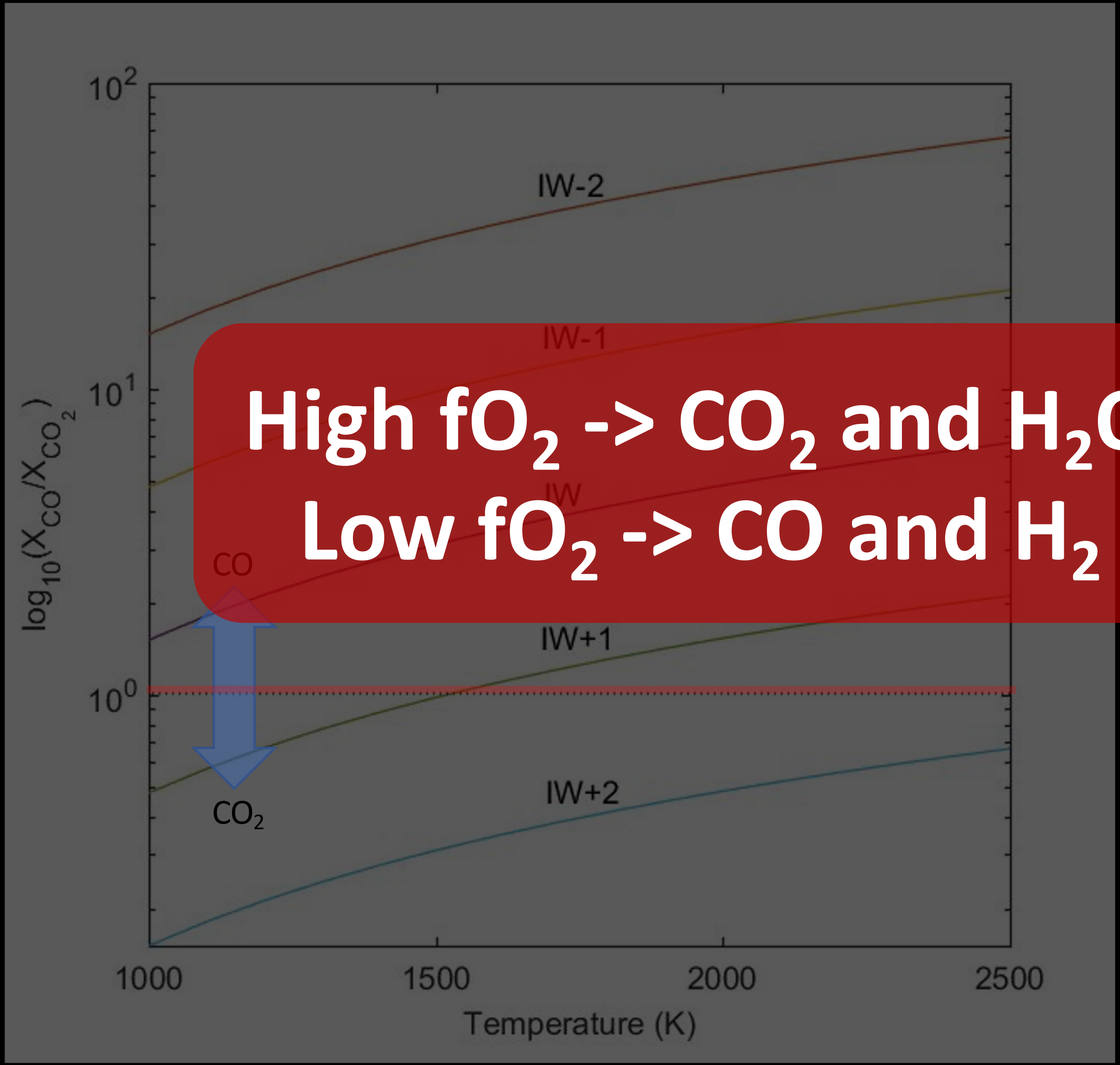

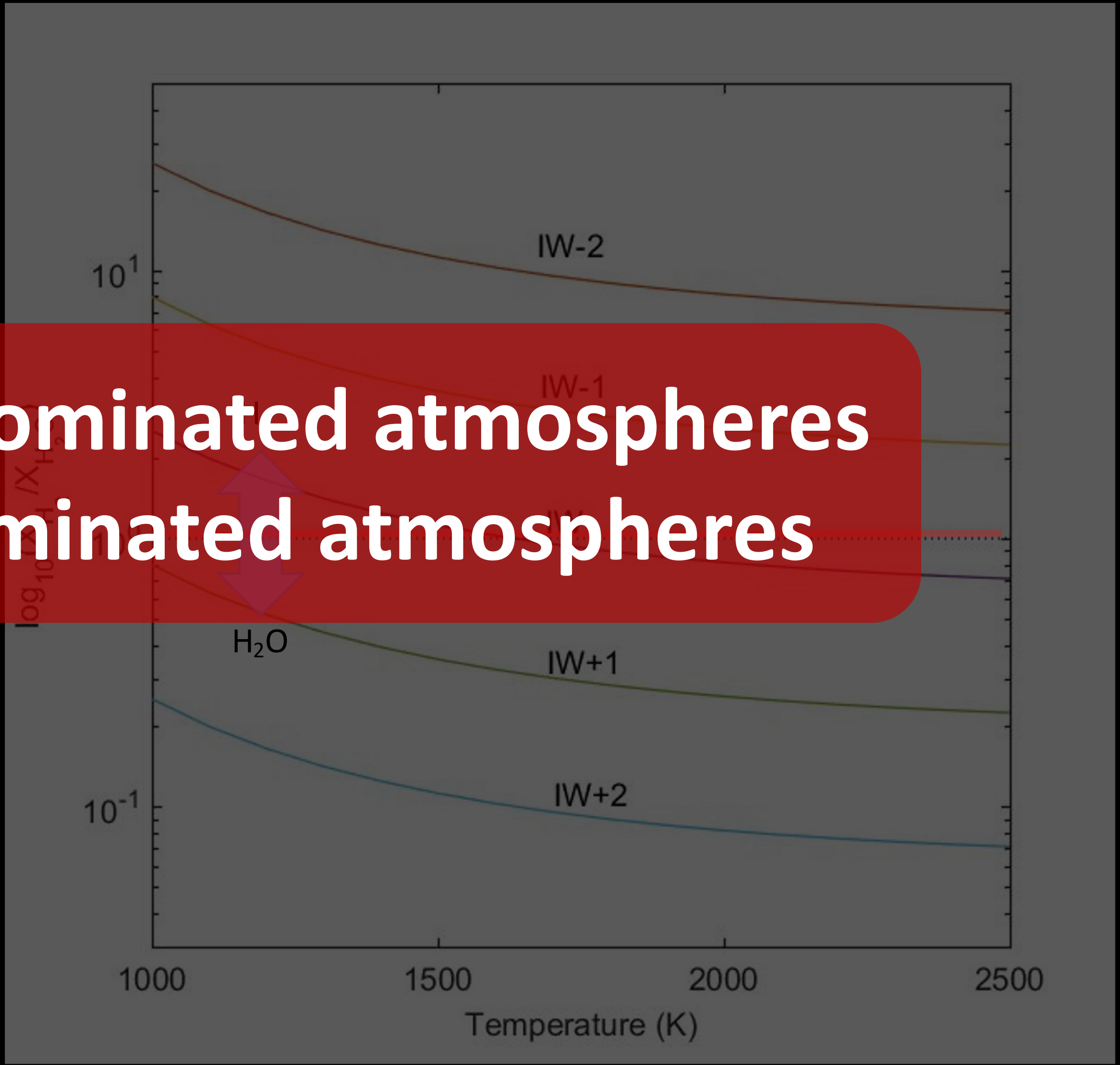

High fO_2 -> CO_2 and H_2O dominated atmospheres
Low fO_2 -> CO and H_2 dominated atmospheres

Modified from: Laura Schaefer

Outgassing Models

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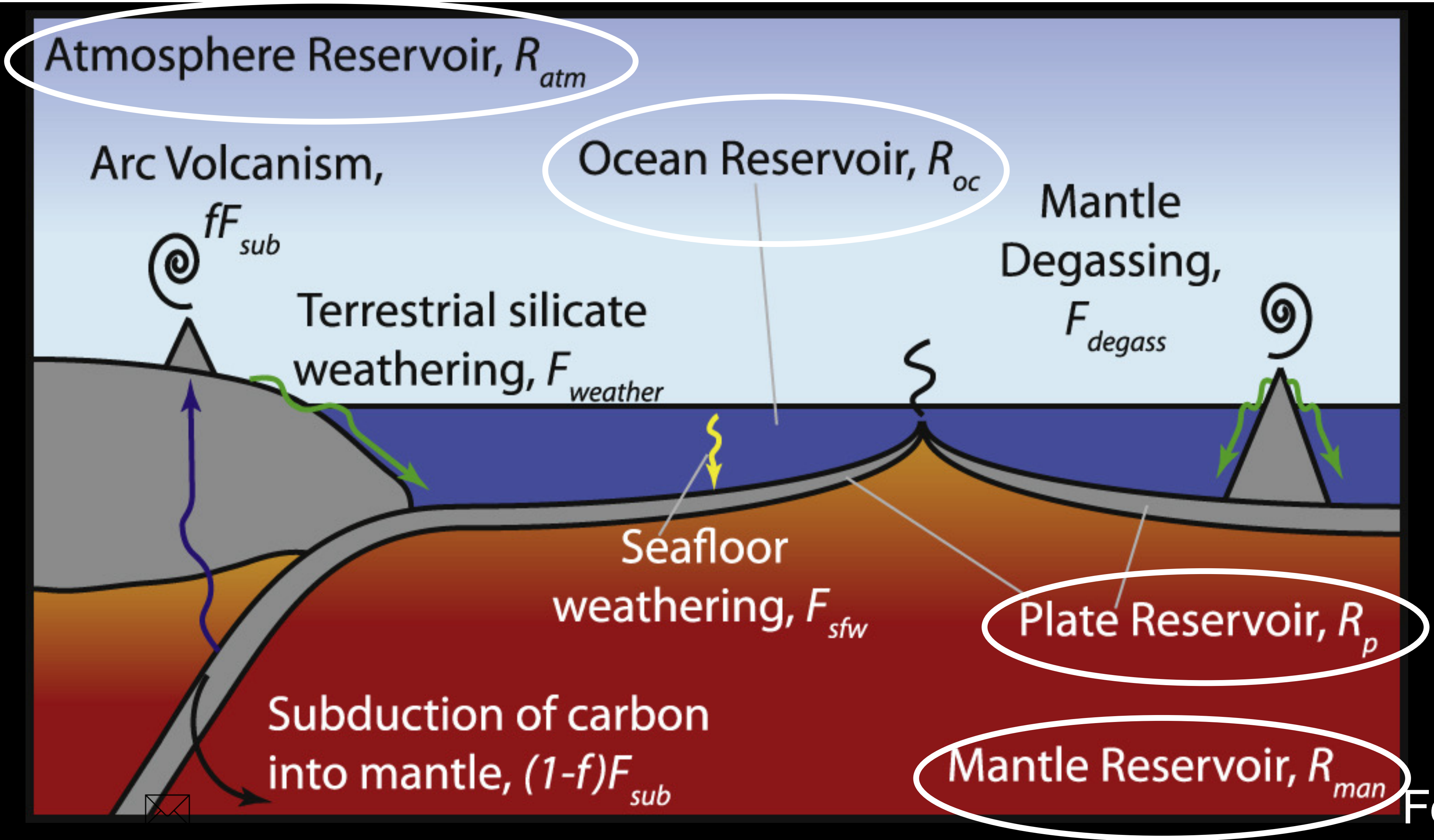
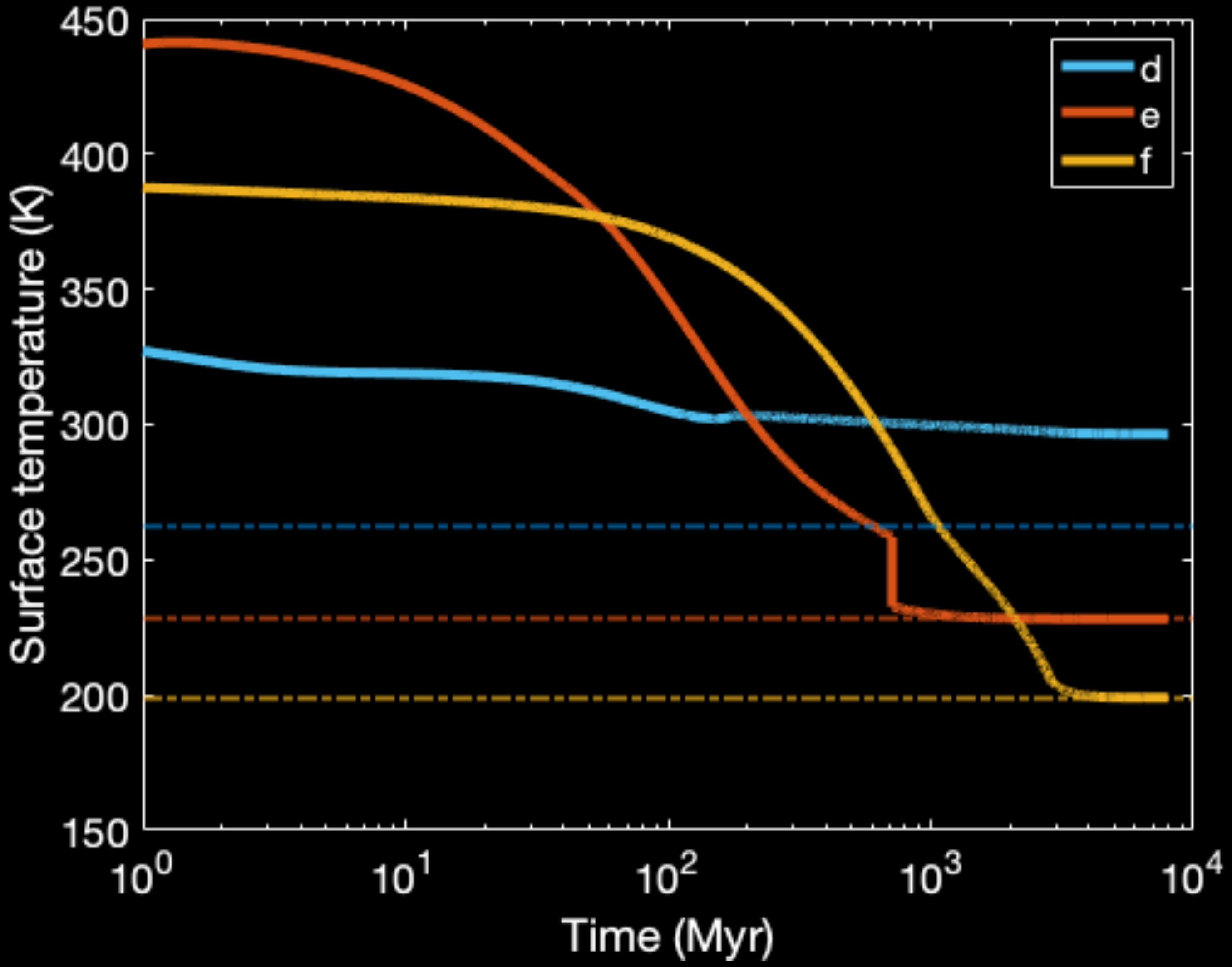
Image Credit: Amanda Smith/University of Cambridge

We model the carbon cycle and incorporate the deep water cycle (Schaefer & Sasselov 2015) to track the gas species



Foley 2015

We use Driscoll & Bercovici 2013 and Foley 2015 to calculate **surface temperatures** for TRAPPIST-1 planets



Driscoll & Bercovici 2013:

$$T_s^4 = T_e^4 \left(1 + \frac{3}{4}\tau_g\right) \text{ where:}$$

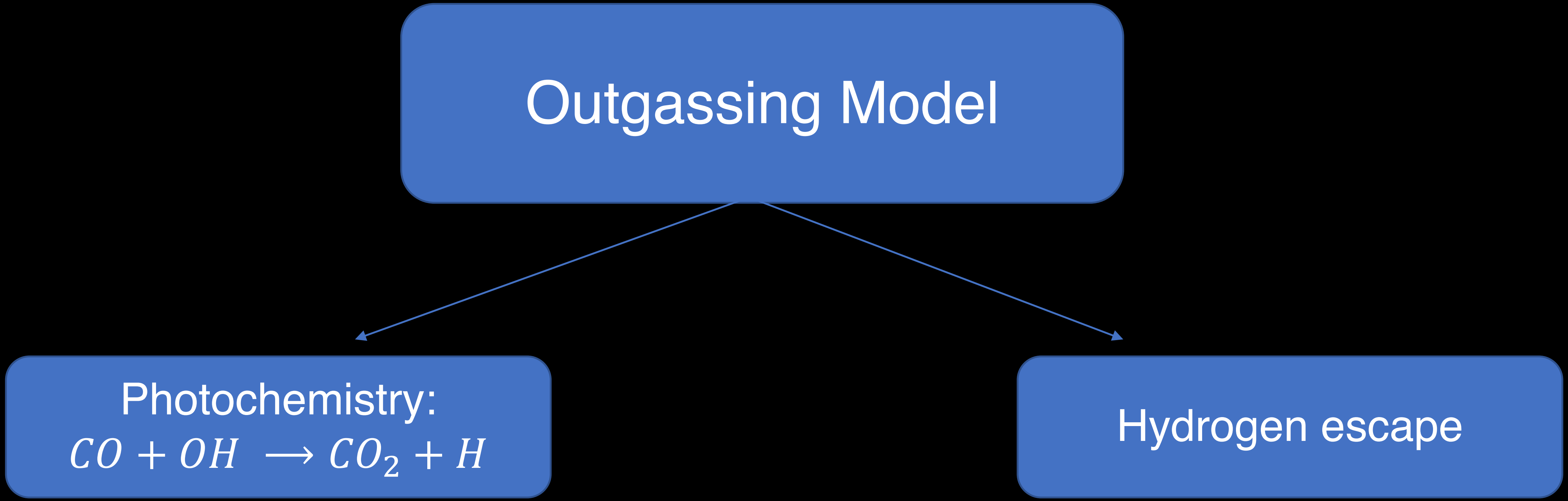
$$\tau_g = \frac{P_w}{P_{k,w}} + \frac{P_c}{P_{k,c}}$$

T_s = surface temperature
T_e = equilibrium temperature
τ_g = optical depth at surface
P_w = water partial pressure
$P_{k,w}$ = water opacity pressure
P_c = carbon dioxide partial pressure
$P_{k,c}$ = carbon dioxide opacity pressure

Foley 2015:

$$T = T^* + 2\,(T_e - T_e^*) + 4.6\left(\frac{P_c}{P_c^*}\right)^{0.346} - 4.6$$

Our model also accounts for photochemistry and atmospheric escape



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We model the carbon cycle on the TRAPPIST-1 planets

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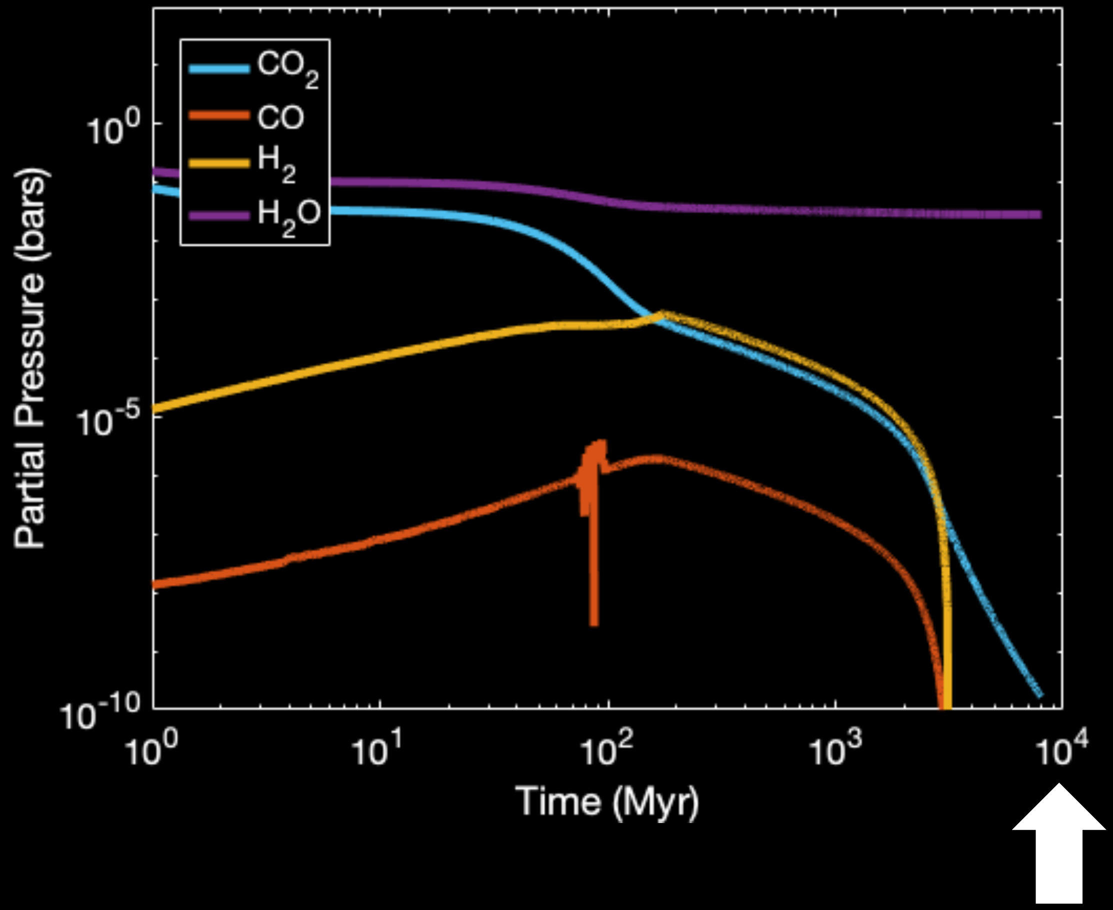
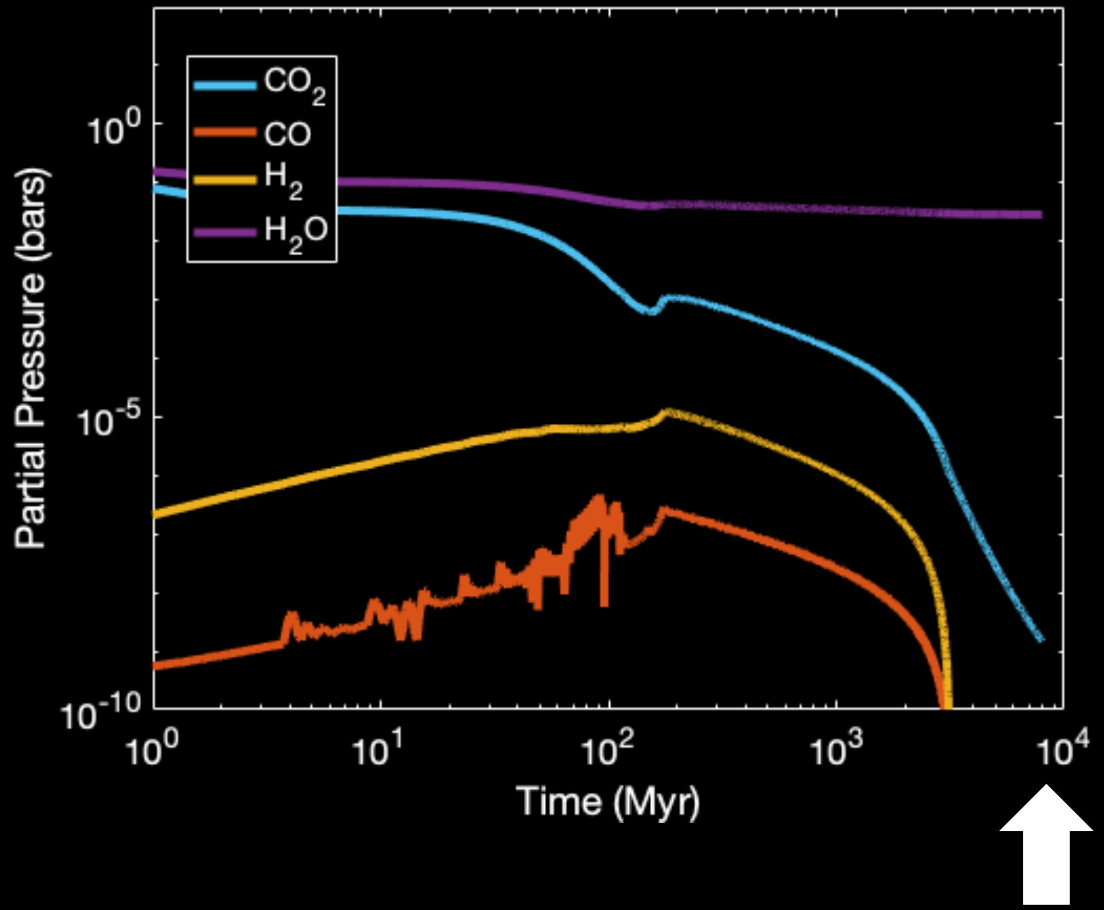
Image Credit: Amanda Smith/University of Cambridge

Atmospheric Composition of TRAPPIST-1 d

Low fO_2 (IW)



High fO_2 (IW + 4)



Gonzalez-Quiles *et al.* 2023 (In Prep)

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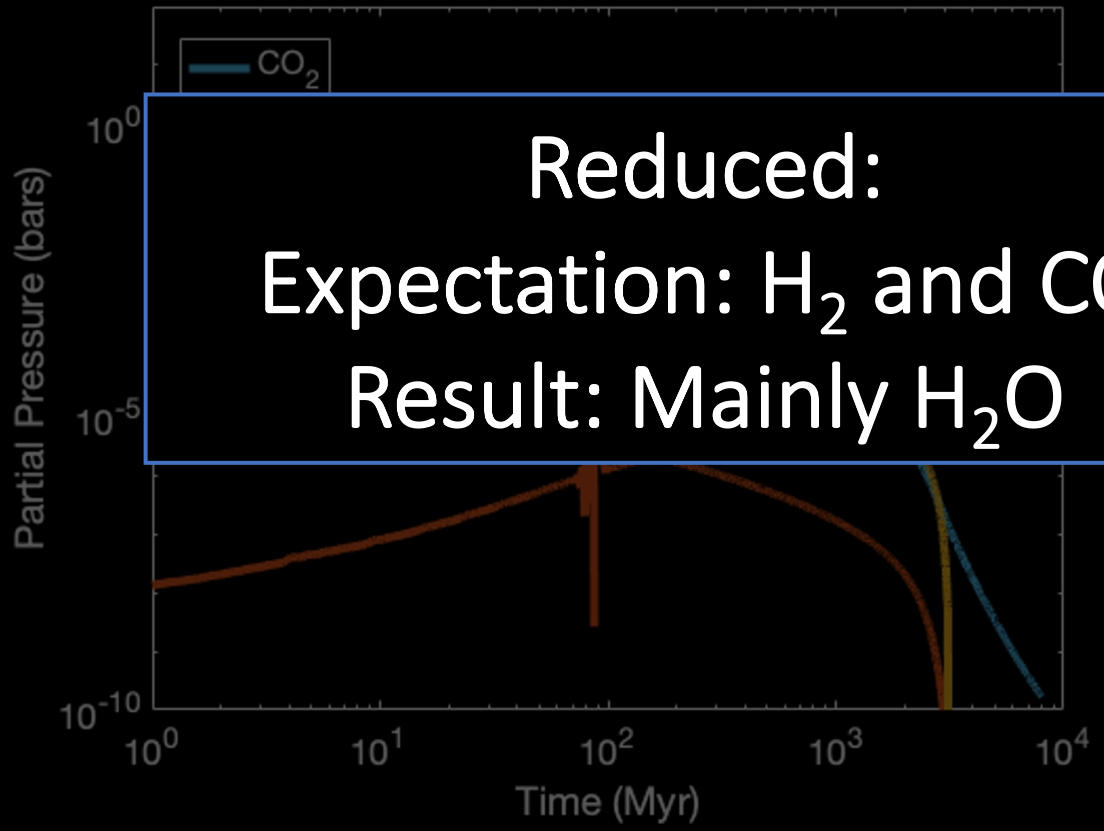

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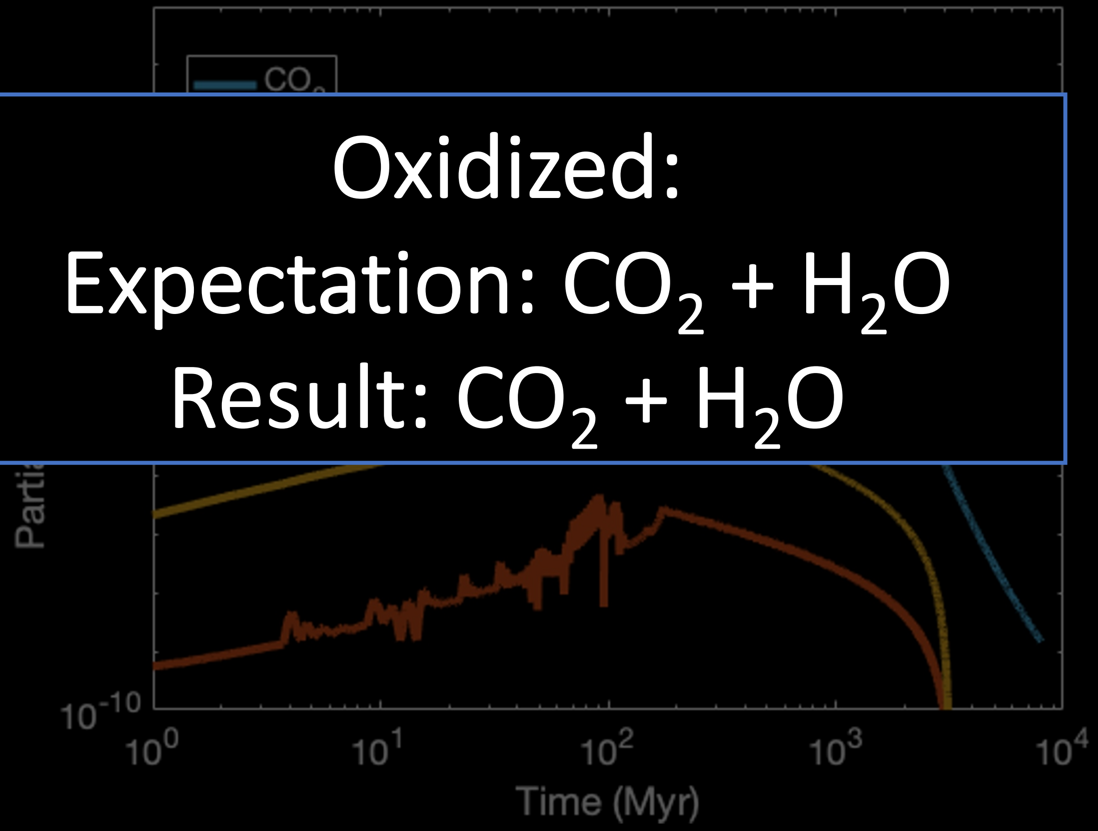


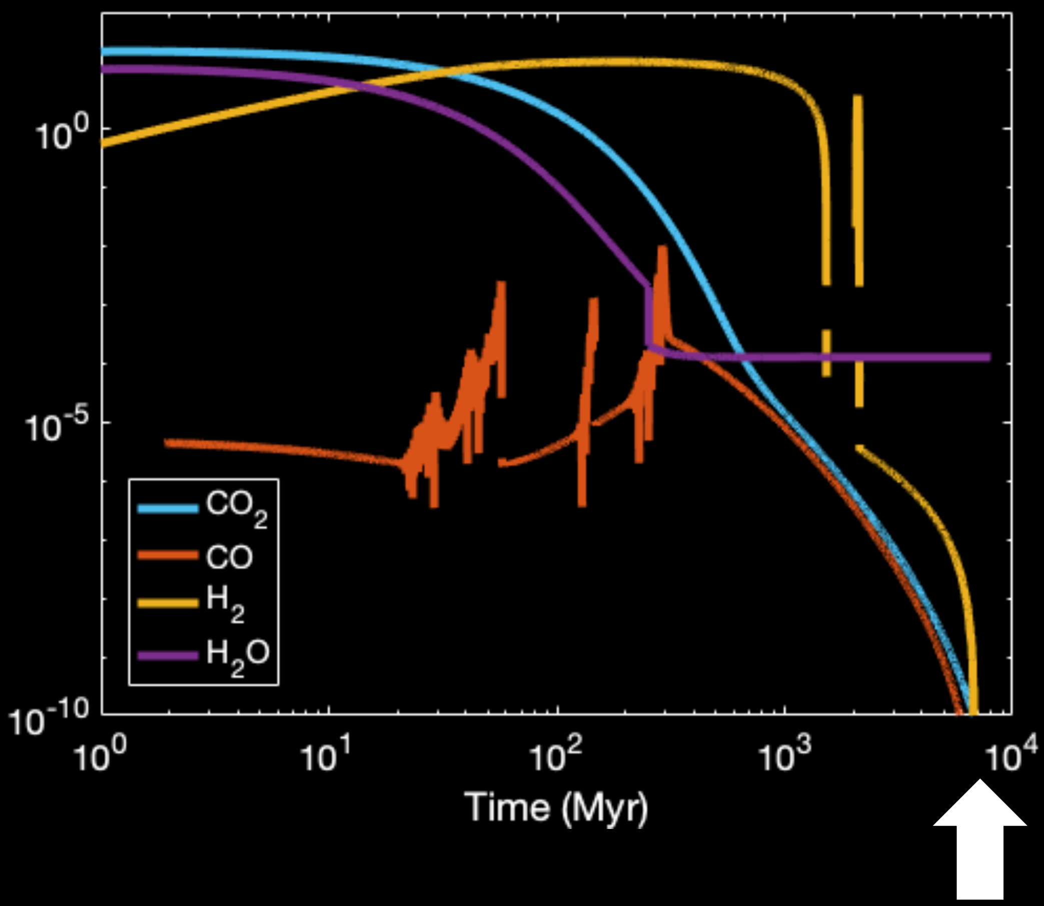
Reduced:
Expectation: H_2 and CO
Result: Mainly H_2O

Oxidized:
Expectation: $CO_2 + H_2O$
Result: $CO_2 + H_2O$

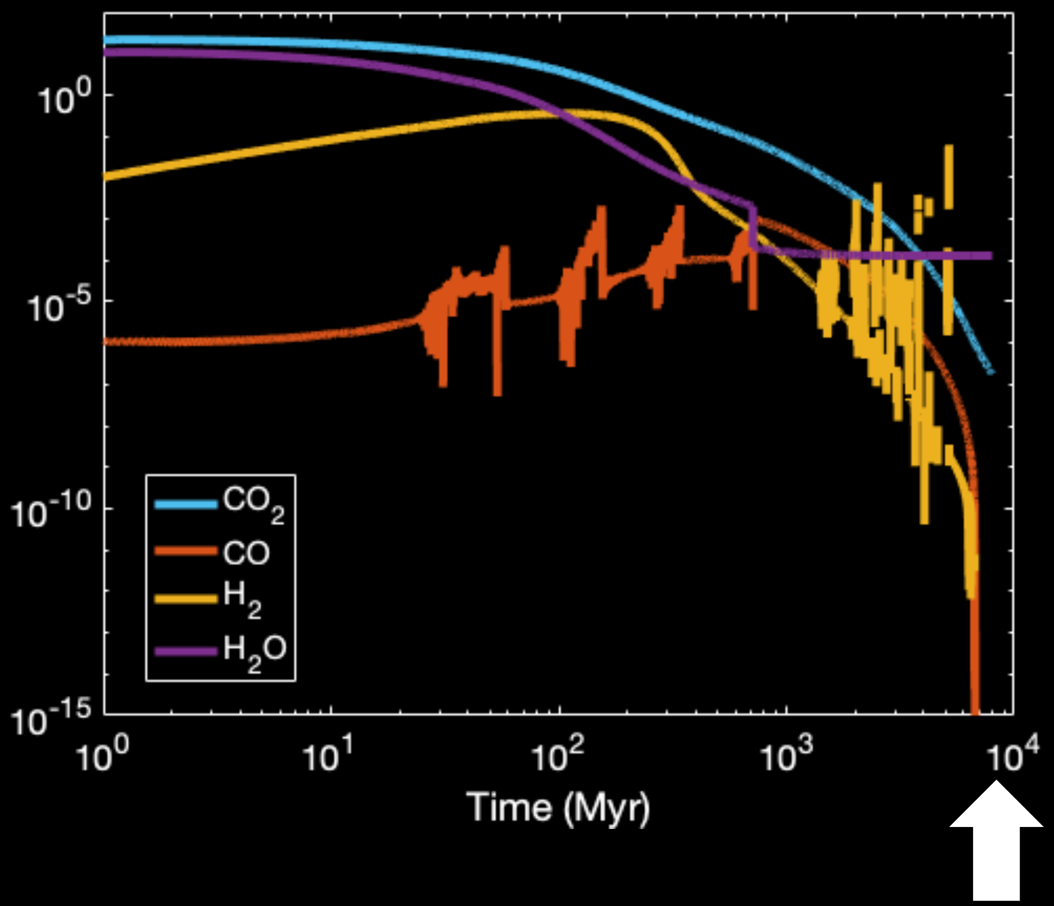
Gonzalez-Quiles *et al.* (In Prep)

Atmospheric Composition of TRAPPIST-1 e

Low fO_2 (IW)



High fO_2 (IW + 4)



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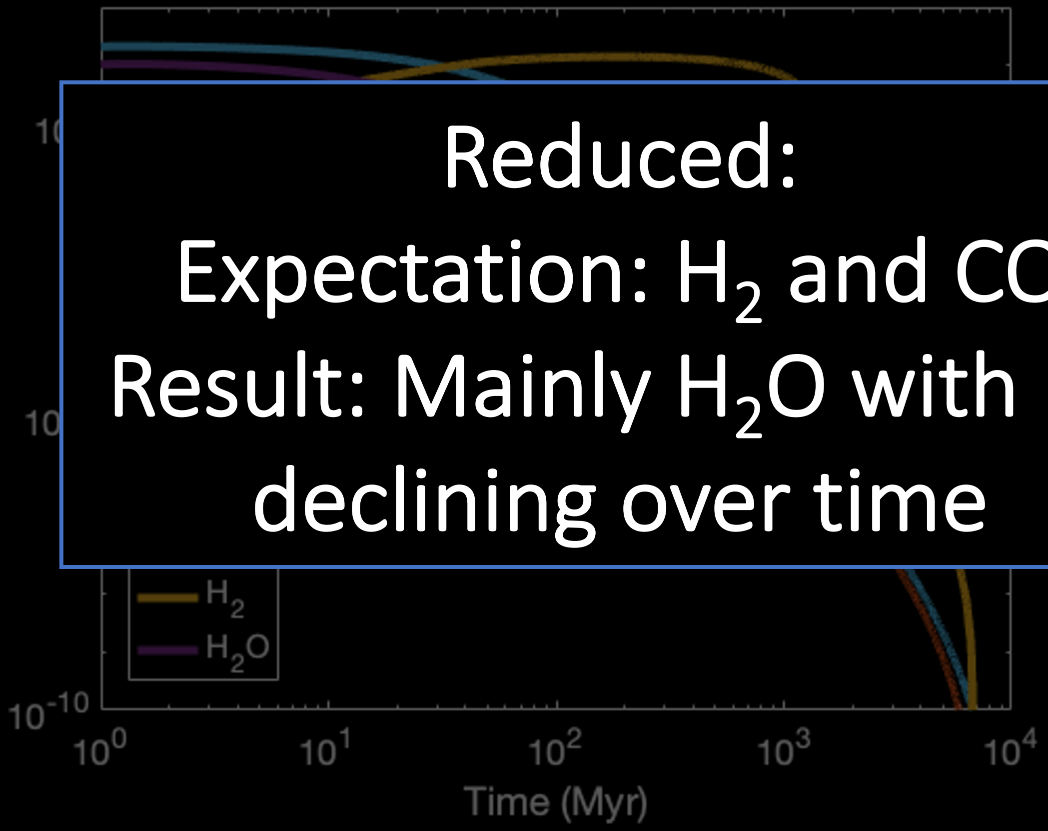
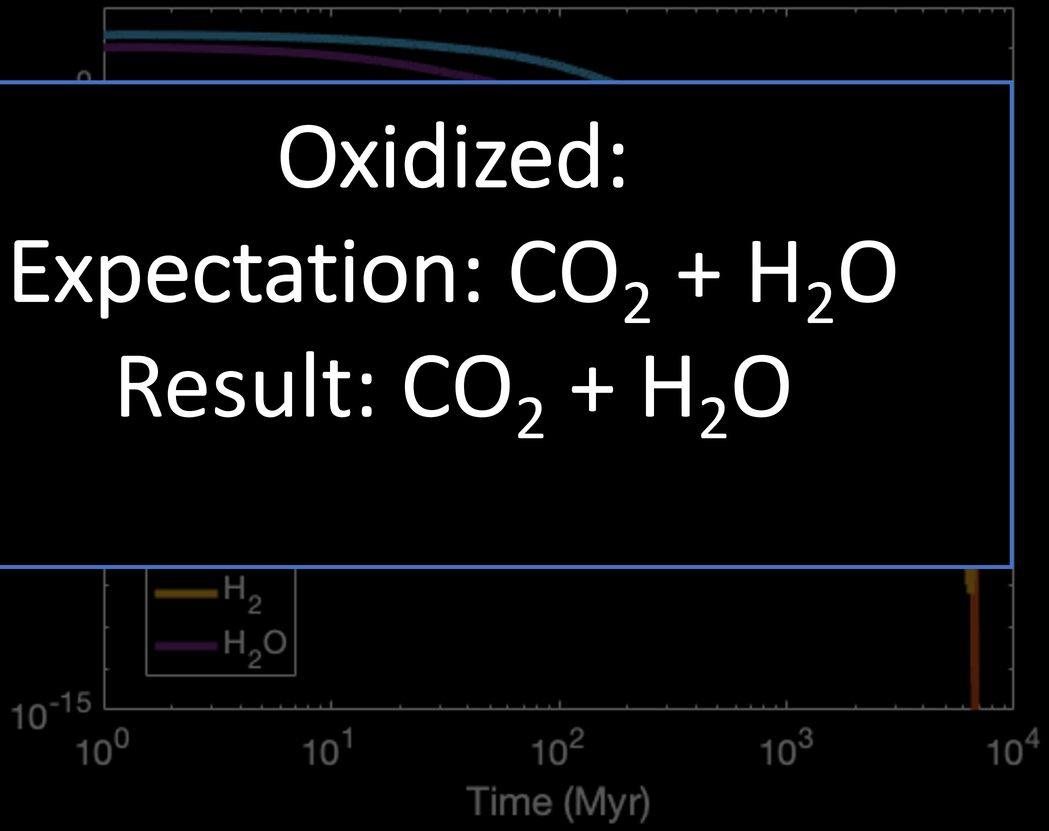
Atmospheric Composition of TRAPPIST-1 e

Low fO_2 (IW)



High fO_2 (IW + 4)

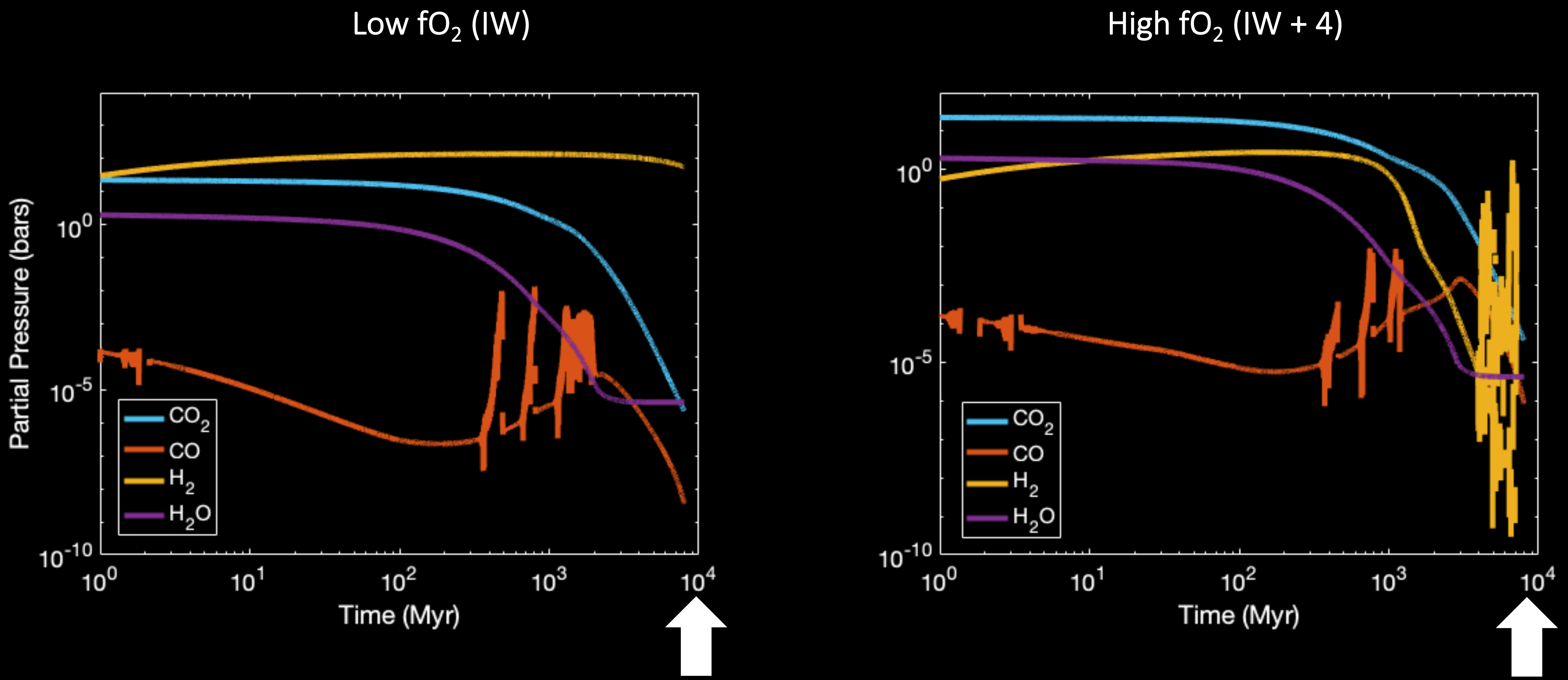


Reduced:
Expectation: H_2 and CO
Result: Mainly H_2O with H_2 declining over time

Oxidized:
Expectation: $CO_2 + H_2O$
Result: $CO_2 + H_2O$

Gonzalez-Quiles *et al.* 2023 (In Prep)

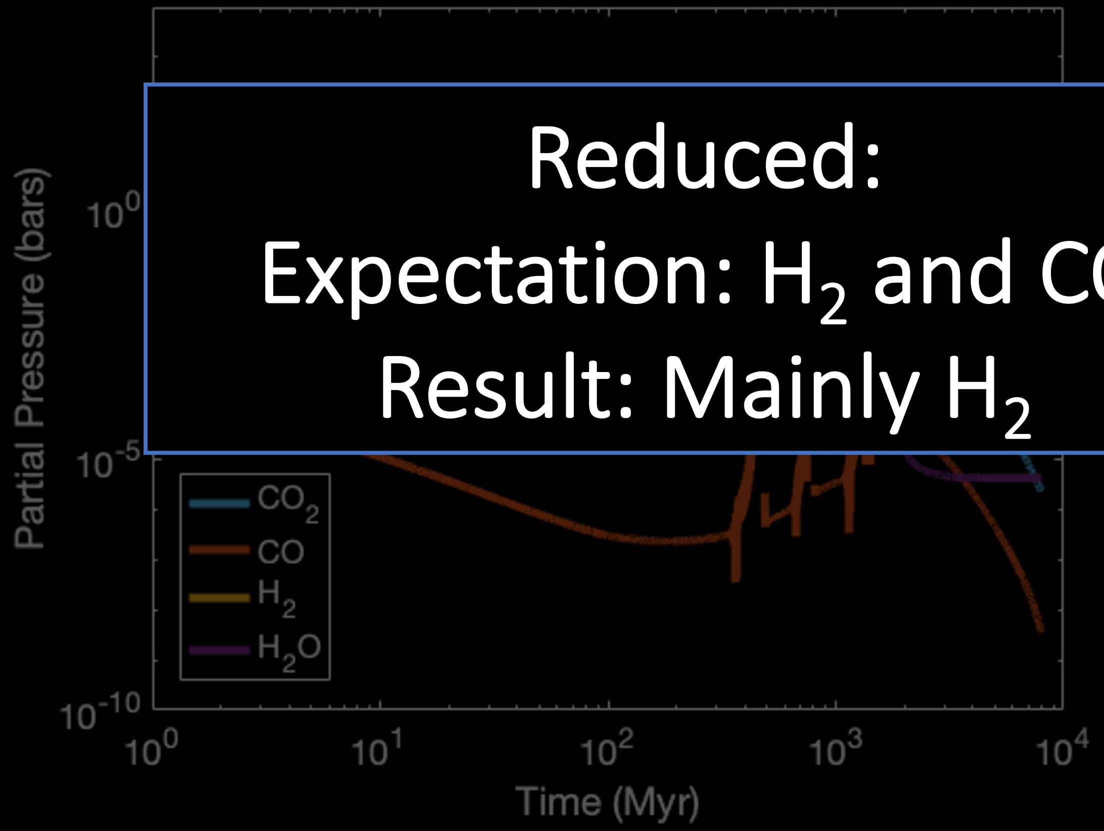
Atmospheric Composition of TRAPPIST-1 f



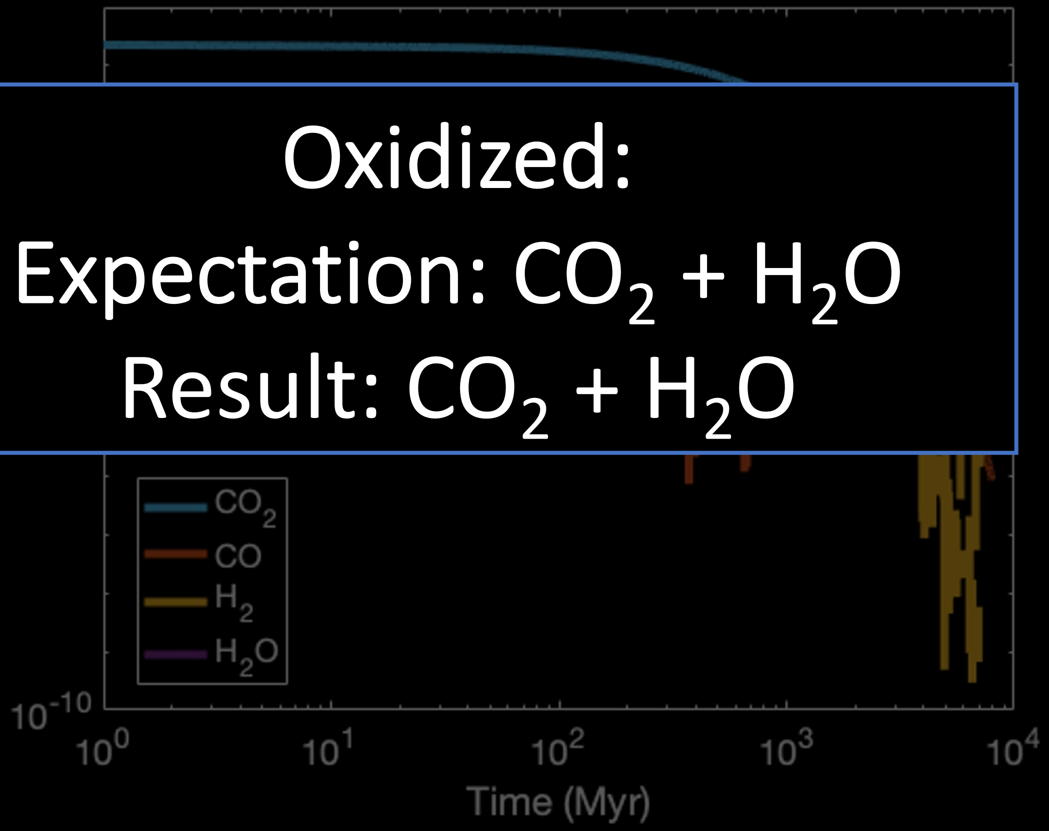
Gonzalez-Quiles *et al.* 2023 (In Prep)

Atmospheric Composition of TRAPPIST-1 f

Low fO_2 (IW)



High fO_2 (IW + 4)



Reduced:
Expectation: H_2 and CO
Result: Mainly H_2

Oxidized:
Expectation: $CO_2 + H_2O$
Result: $CO_2 + H_2O$

Gonzalez-Quiles *et al.* 2023 (In Prep)

Our results suggest that the atmospheric composition of these planets may depend on the oxygen fugacity and outgassing rates, but other important processes can also impact the atmospheric composition of these planets!

What's Up Next?

Add nitrogen and sulfur into our models.

Modify the thermal evolution model to incorporate heat transport from the core to the mantle.

Interested in collaborating, please reach out to me!

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Illustration Credit: NASA Goddard Space Flight Center/Chris Smith

Summary

Modeling the deep water cycle and the carbon cycle is important for understanding interior-surface-atmosphere interactions and their effect on habitability of exoplanets.

Outgassing models were run for TRAPPIST-1 d, e and f for different oxygen fugacities.

Oxygen fugacity can impact outgassing and therefore influence the atmospheric composition of planets.

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Illustration Credit: NASA Goddard Space Flight Center/Chris Smith

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- This work is also supported by the NSF GRFP
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TRAPPIST-1 Parameters

TRAPPIST -1 Planets	Radius (R_{earth})	Mass (M_{earth})	g (g_{Earth})	T_{eq} (K)	Core Mass Fraction (wt %)	Water Mass Fraction (wt %)	R_{core} (R_{earth})
d	0.788	0.388	0.624	262	19.7	10^{-3} (10^{-4}, 2)	0.38
e	0.92	0.692	0.817	228	24.6	0.3 (10^{-4}, 2.1)	0.48
f	1.045	1.039	0.951	199	20.1	1.0 (0.6, 3.4)	0.49

Agol et al. 2021 PSJ 2:1

@JunellieG