



Limits on Silicate Weathering and Their Impact on the Habitability of Wet, Rocky Worlds

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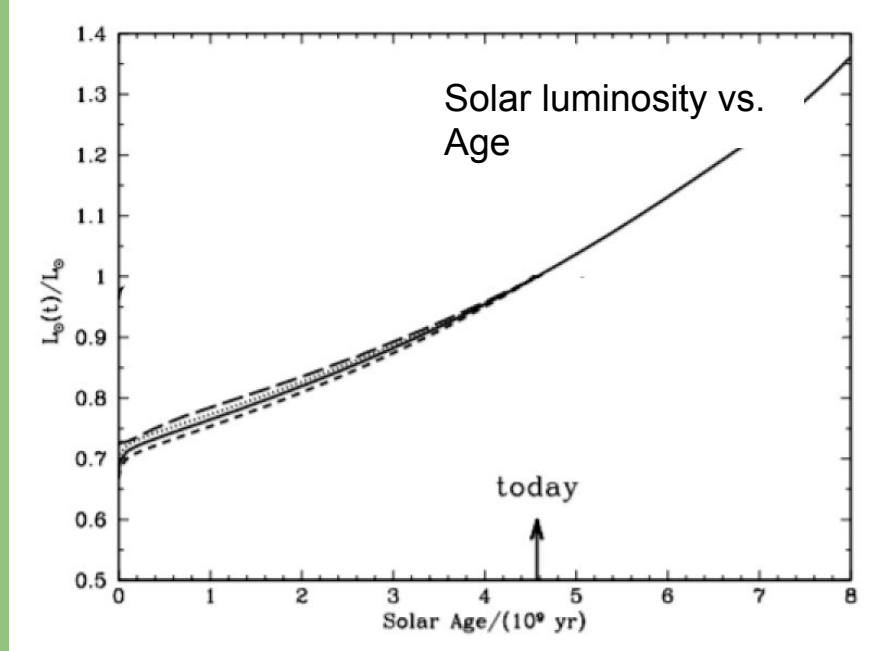
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Outline

1. Background on the silicate weathering feedback and its proposed influence on climate and planetary habitability
2. How thermodynamics limits silicate weathering
3. How energetic input limits silicate weathering

The sun has brightened by ~32% over its lifetime, but the Earth has maintained a (relatively) stable climate...What's going on here?



(modified from
Bahcall et al 2001)

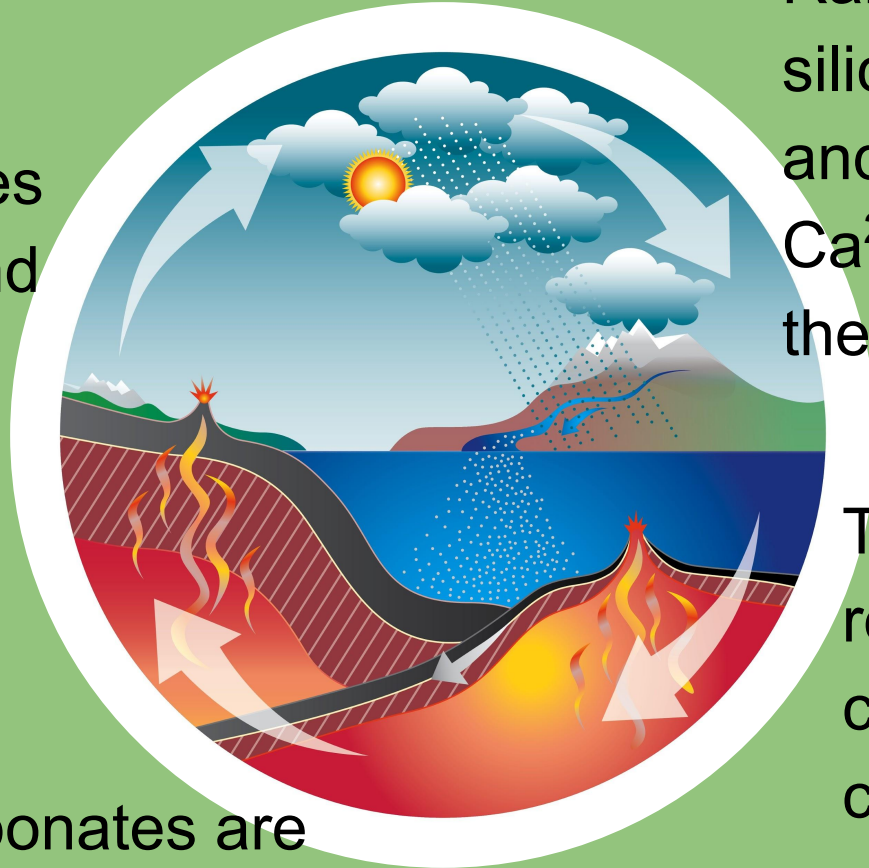
The Carbonate - Silicate Cycle



Image credit: Jenny Leibundgut

The carbonates are cooked and the CO_2 is released from volcanoes

The carbonates are subducted



Rain dissolves silicate minerals and carries the $\text{Ca}^{2+}/\text{Mg}^{2+}$ ions to the ocean

The dissolved ions react with ocean carbon, forming carbonate rocks

Image credit: Jenny Leibundgut

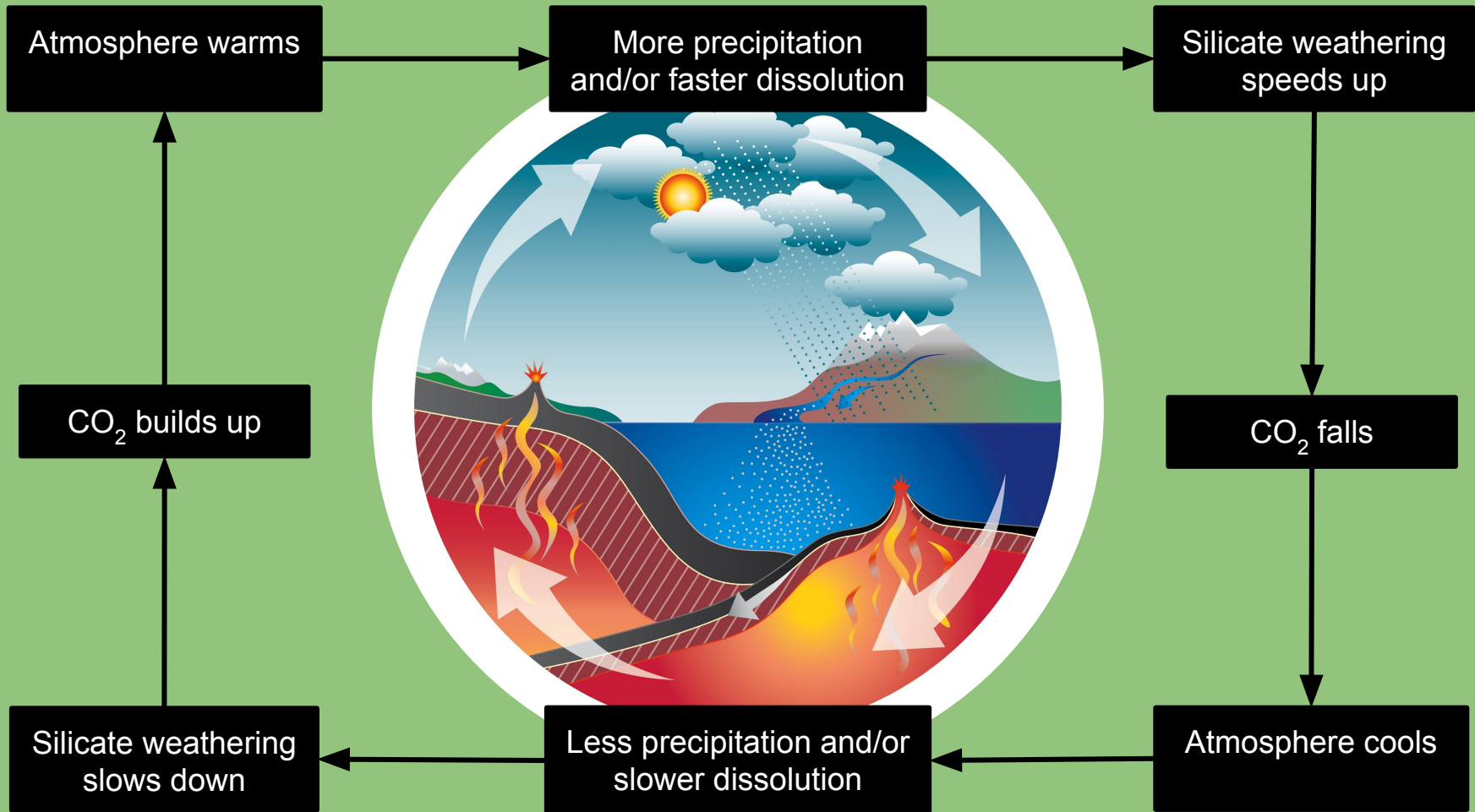
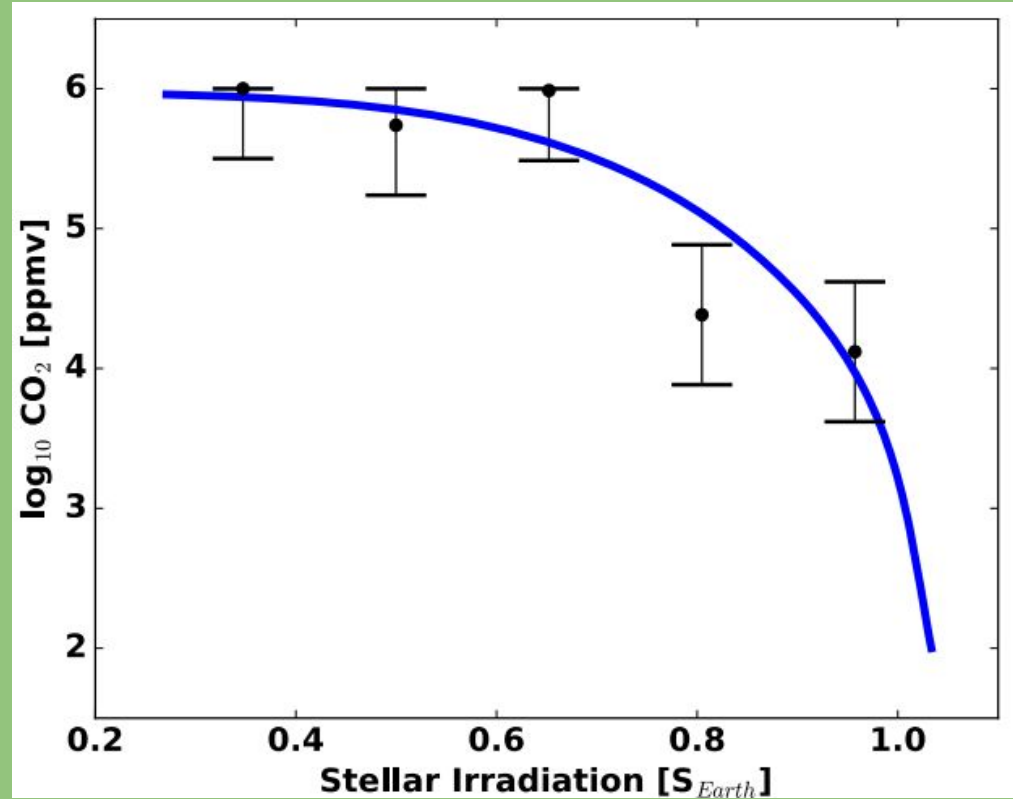
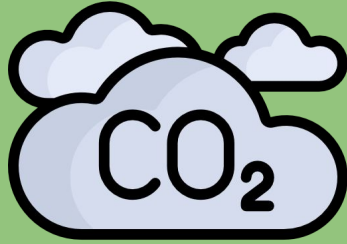


Image credit: Jenny Leibundgut

Hypothesis that underlies the concept of “habitable zone”:
Exoplanets with land & oceans will have higher CO₂ at lower instellation due to the silicate weathering feedback



(from Bean et al 2017)



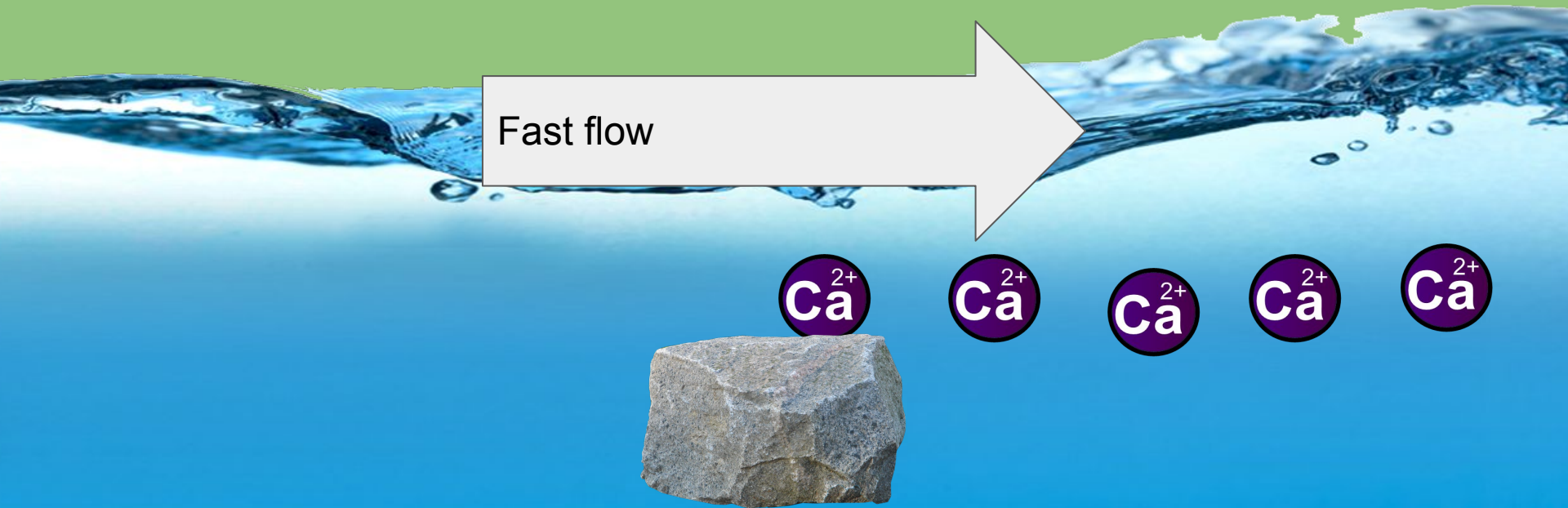
But how should silicate weathering
be modeled to best predict
relationships between temperature,
 CO_2 , and instellation on rocky
worlds?



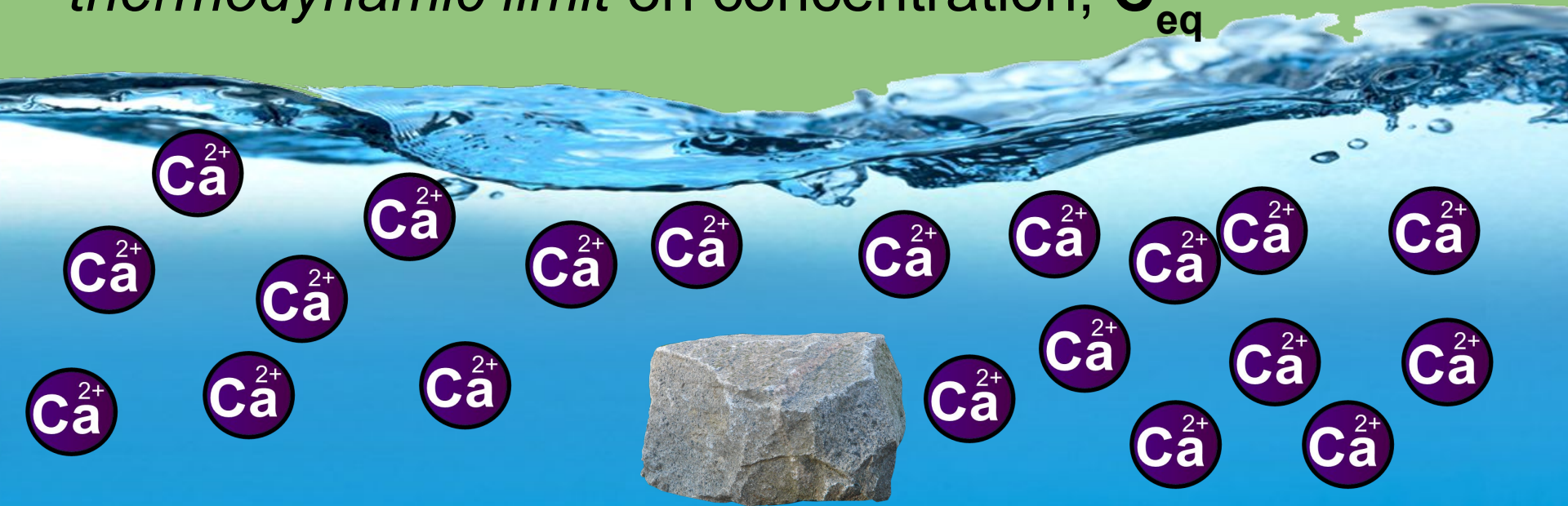
Imagine a silicate rock in a stream, or, better yet,
look several inches below these words



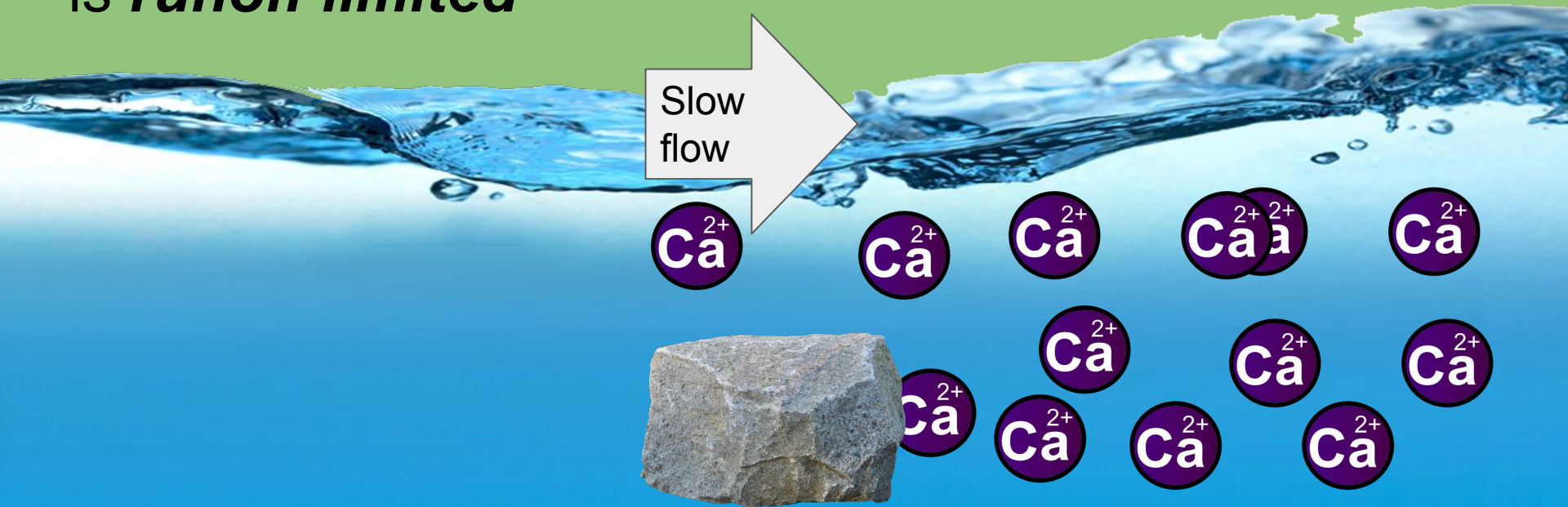
With a high enough flow rate, the water carries away cations as soon as they are produced -- this is ***kinetically limited*** weathering




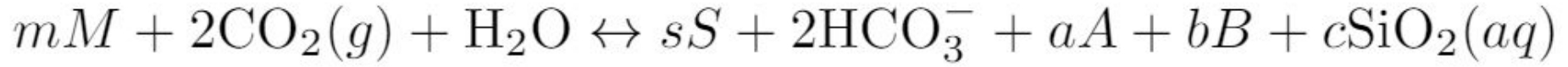
In stagnant water, the rock will dissolve until the system reaches equilibrium between dissolving and precipitating minerals. The ions reach a *thermodynamic limit* on concentration, C_{eq}




With just a little flow, if rock dissolution happens faster than ions are carried away, the solution stays at its maximum concentration (C_{eq}) and weathering is ***runoff limited***



What controls the thermodynamic limit on solute concentration (C_{eq})? Clay (in part)!




Primary
silicate
mineral



Carbon
dioxide




Water




Secondary
mineral
(clay)



Bicarbonate



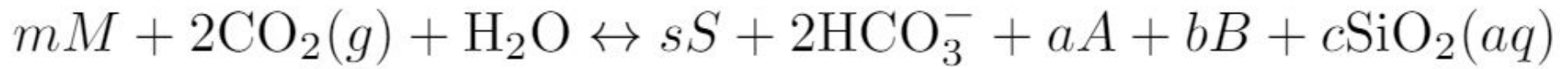
Divalent
cations
(e.g. Ca^{2+})



Monovalent
cations (e.g.
 Na^+)



Silica



$$K = \frac{[\text{HCO}_3^-]^2 [A]^a [B]^b [C]^c}{(\text{pCO}_2)^2}$$

$$= \frac{r[A]^{2+a+b+c}}{(\text{pCO}_2)^2}$$

$$[A] = C_{eq} = \left(\frac{K}{r}\right)^{\frac{1}{2+a+b+c}} (\text{pCO}_2)^{\frac{2}{2+a+b+c}}$$

$$C_{eq} = \Lambda (\text{pCO}_2)^n$$

C_{eq} is controlled by equilibrium between silicate dissolution and clay precipitation reactions, leading to a strong pCO_2 dependence
(Winnick & Maher, 2018)

Previous rocky exoplanet silicate weathering models have implicitly assumed *kinetic limitation*! (WHAK)

$$w_w = w_{w,mod} \frac{\gamma p}{\gamma_{mod} p_{mod}} \exp\left(\frac{T - T_{mod}}{T_e}\right) \left(\frac{p\text{CO}_2}{p\text{CO}_{2,mod}}\right)^\beta$$

(based on Walker, Hays, and Kasting, 1981)

But what if we explicitly allow for the possibility of *runoff limitation* via *thermodynamic limitation*? (MAC)

$$w_m = \gamma \frac{\alpha}{[k_{eff,ref} \exp\left(\frac{T - T_{mod}}{T_e}\right) \left(\frac{p\text{CO}_2}{p\text{CO}_{2,mod}}\right)^\beta]^{-1} + m A t_s + \alpha [q \Lambda (p\text{CO}_2)^n]^{-1}}$$

(based on Maher & Chamberlain 2014 and Winnick & Maher 2018)

We coupled simple 0-dimensional climate & weathering models to find planetary CO_2 and temperature as a function of insolation with these constraints:

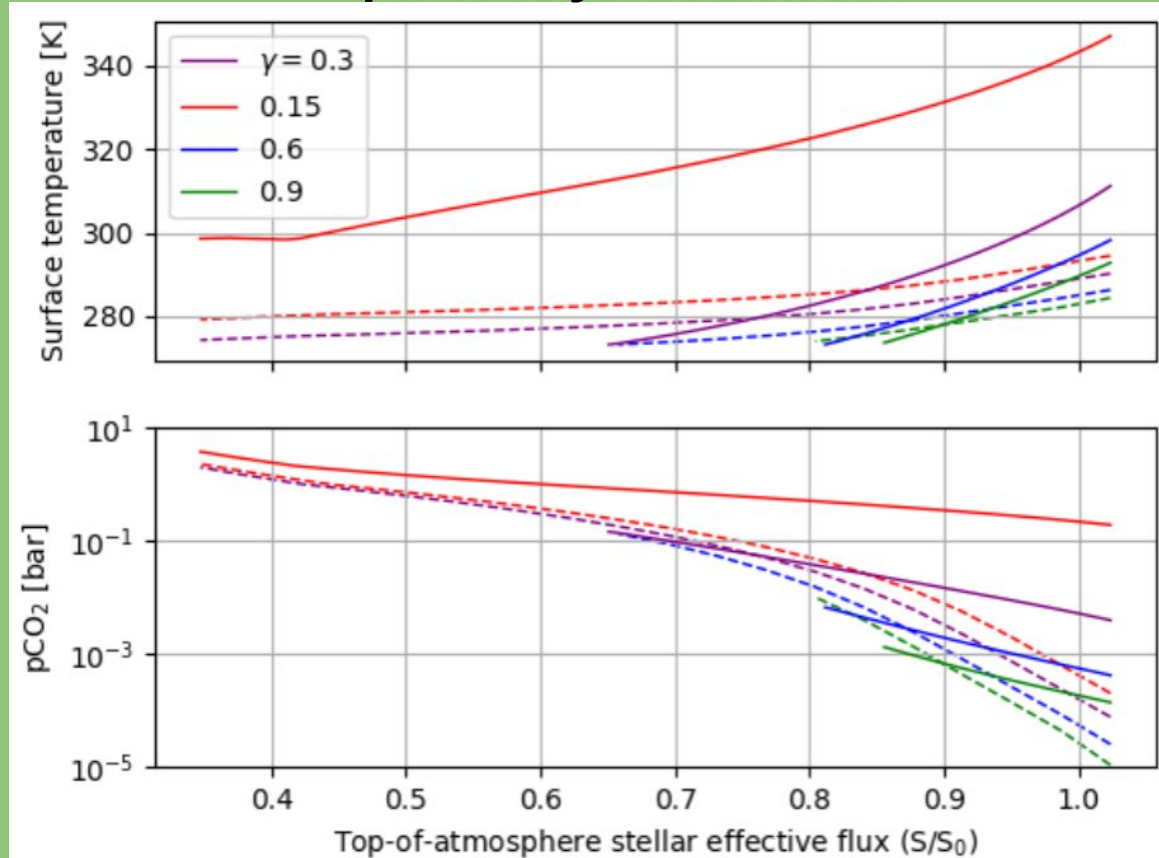
Outgoing longwave radiation = net insolation
(energy balance)

CO_2 drawdown by weathering = CO_2 outgassing
(CO_2 balance)

We define the “effective outer edge” of the habitable zone as the instellation where planetary temperature reaches 273.15 K for a given set of weathering parameter choices



The different models of weathering lead to different climates as a function of instellation and planetary land fraction

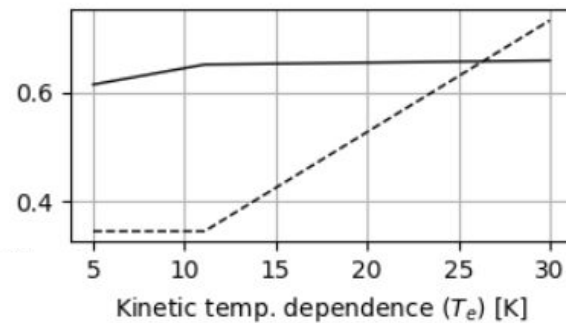
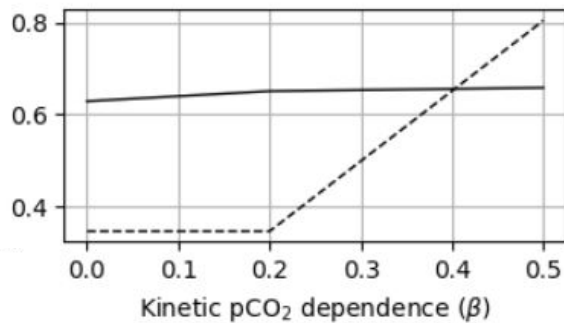
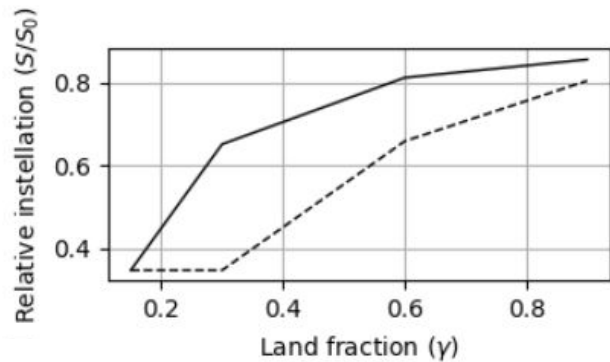


Dashed curves:
WHAK model

Solid curves:
MAC model

Colors:
Purple \rightarrow Land fraction 0.3
Red \rightarrow 0.15
Blue \rightarrow 0.6
Green \rightarrow 0.9

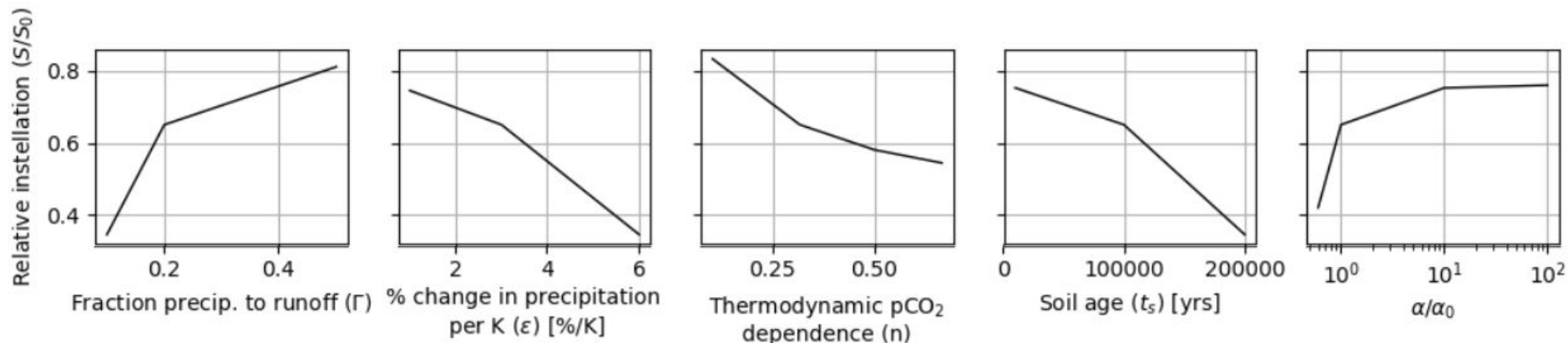
With MAC weathering, the effective outer edge of the habitable zone is *more sensitive to land fraction* but *less sensitive to silicate dissolution kinetics* than in simulations with WHAK weathering



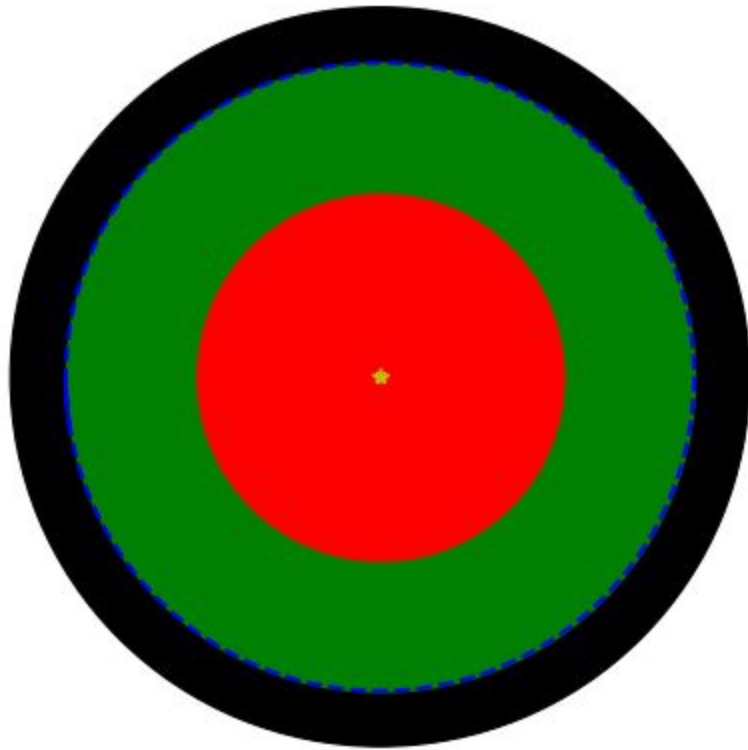
Dashed curves:
WHAK model

Solid curves:
MAC model

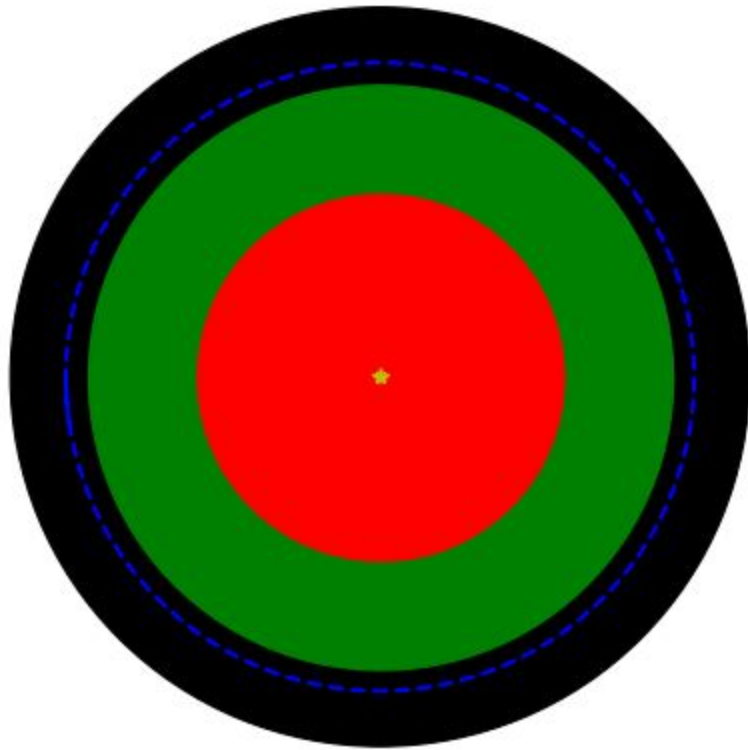
With MAC weathering, the effective outer edge of the habitable zone is very *sensitive to hydrology, weathering thermodynamics, and surface soil properties*



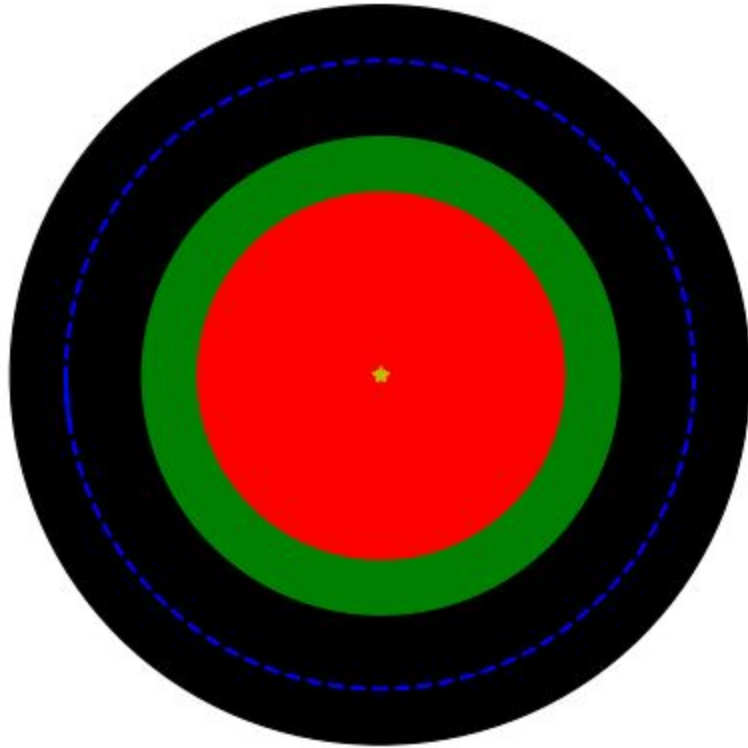
Classical habitable zone outer edge



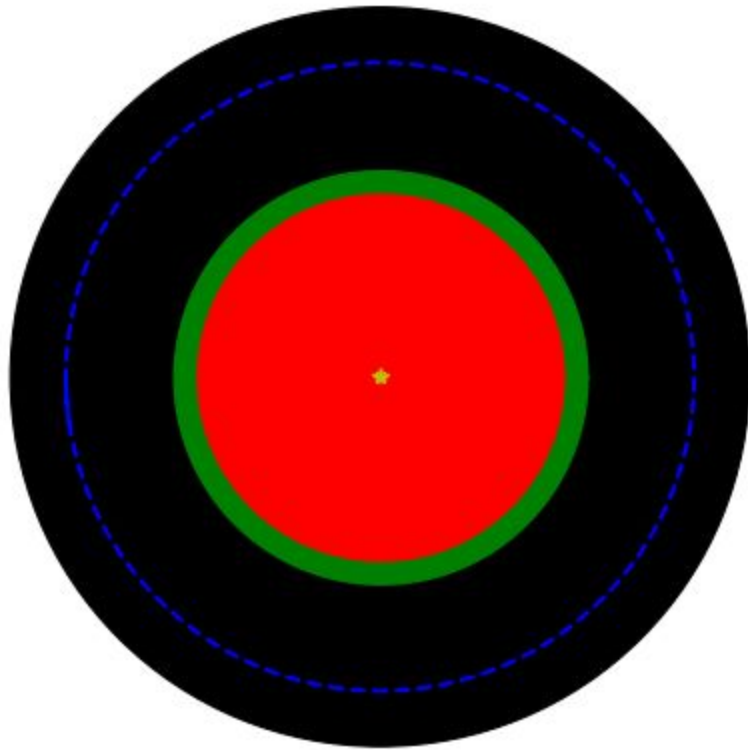
Habitable zone with outer edge at $S/S_0 = 0.4$



Habitable zone with outer edge at $S/S_0 = 0.6$



Habitable zone with outer edge at $S/S_0 = 0.8$



One more limit to think about:



An **energetic limit** on precipitation



At steady-state, evaporation = precipitation

Evaporation requires energy (latent heat)

This energy comes from sunshine, so
absorbed insolation sets an upper limit on
global precipitation



This energetic limit on precipitation is approximately:

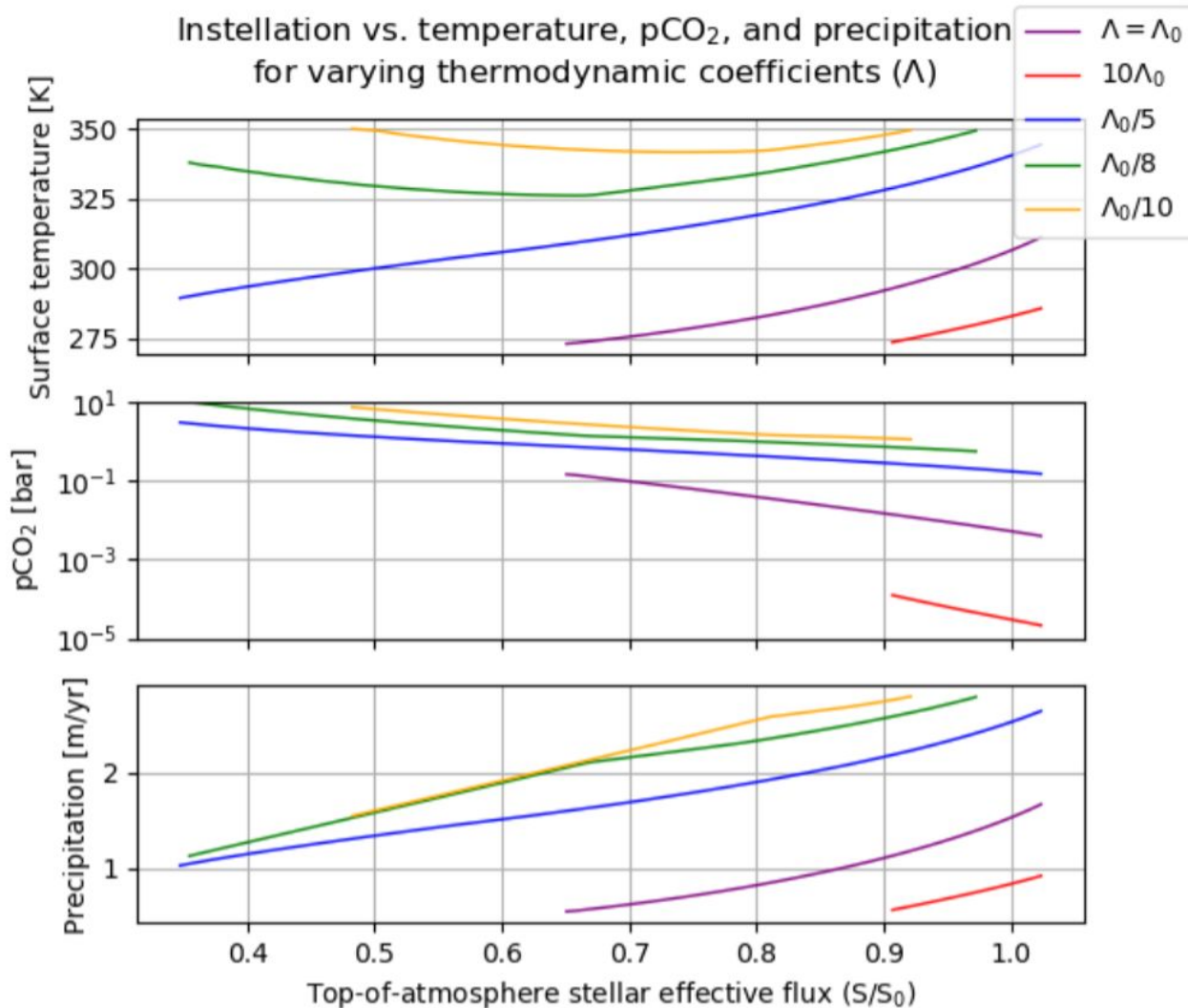
$$p_{max} = \frac{S_{eff}}{L(T)}$$

$$L(T) = 1.918 \times 10^6 \left(\frac{T}{T - 33.91} \right)^2$$

where $L(T)$ is given by the Henderson-Sellers equation.

Can this limit be reached?

Instellation vs. temperature, pCO₂, and precipitation
for varying thermodynamic coefficients (Λ)



The temperature curves that increase as instellation decreases are in an *energetically - limited* precipitation regime

Reminder:

$$C_{eq} = \Lambda(p\text{CO}_2)^n$$

The silicate weathering feedback is fundamentally different on planets with energetically-limited precipitation because precipitation is decoupled from temperature

1. Including thermodynamic and energetic limits on silicate weathering strongly impacts planetary climate and weathering behavior.
2. MAC weathering: sensitive to land fraction, but insensitive to the kinetics of silicate dissolution.
3. Hydrology, lithology, weathering thermodynamics, and surface properties dramatically impact the width of the habitable zone.
4. Energetically-limited precipitation can lead to hot climates in the outer reaches of the habitable zone.

Take-home message?

When we model rocky exoplanet climates, how we represent silicate weathering has a strong impact on the width of the habitable zone and the behavior of planets within that zone! We need to keep thinking hard about this topic!