UNIVERSITÉ DE GENÈVE
FACULTY OF SCIENCE
Department of Astronomy

Les Gustins Summer School 2024

Exoclimate Modelling:

Investigating the Effect of Dynamics on Climate with an Energy Balance Model

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Centre Vie dans l'Univers

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Structure

1. Introduction
   - Habitable zone
   - TRAPPIST-1
   - Tides
2. Methods
   - N-body code
   - Climate model
3. Model validation
   - Insolation
   - Diffusion coefficient
4. Results

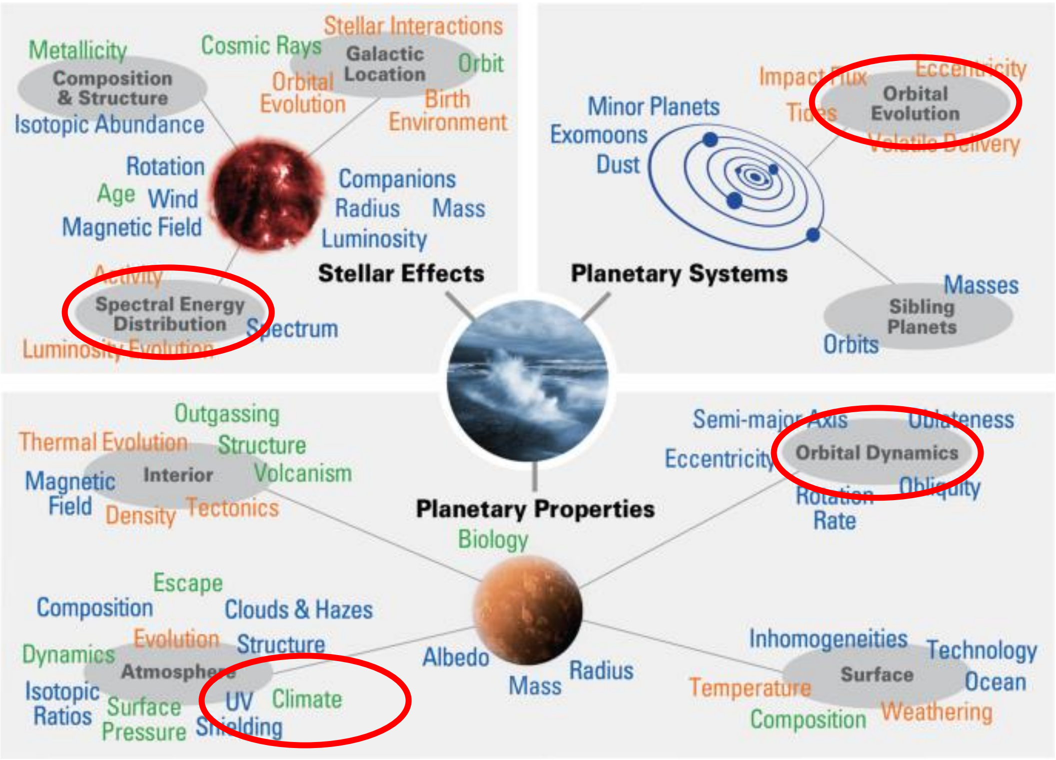
Habitable zone planets

Habitable zone

Range of orbital separations around a star within which liquid water could be sustained on the surface of a planetary body.

Huang, 1959; Kasting et al., 1993

Many elements have an impact on the habitable zone…



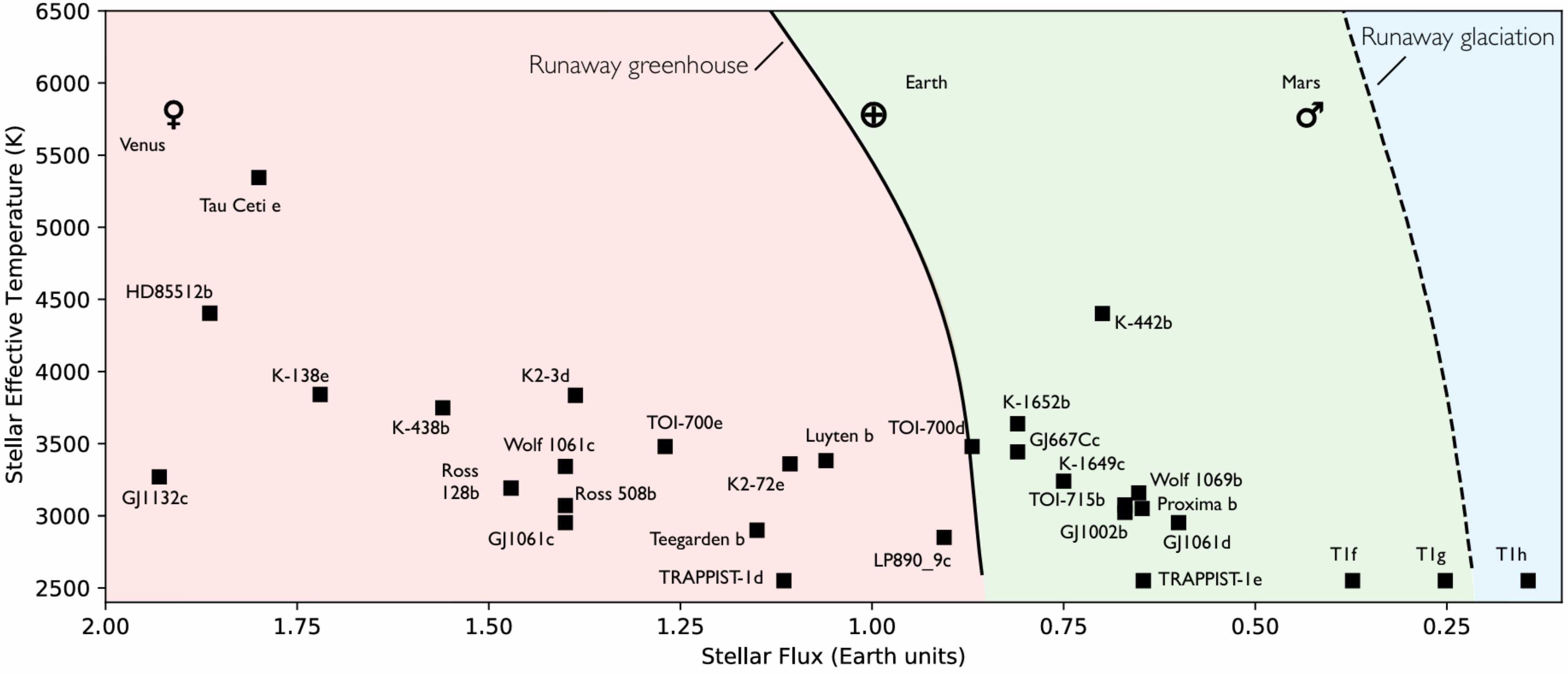
Meadows & Barnes, 2018

Habitable zone planets

Habitable zone

Range of orbital separations around a star within which liquid water could be sustained on the surface of a planetary body.

Huang, 1959; Kasting et al., 1993



Courtesy: E. Bolmont (Kopparapu et al. 2013, Turbet et al. 2023)

Habitable zone planets

Habitable zone

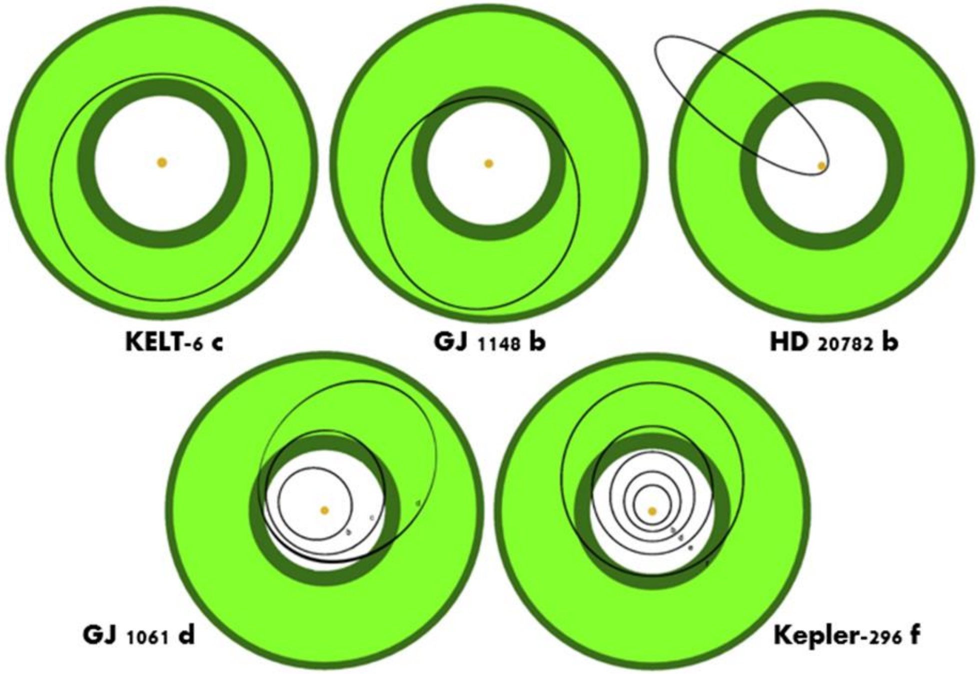
Range of orbital separations around a star within which liquid water could be sustained on the surface of a planetary body.

Huang, 1959; Kasting et al., 1993

Habitable zone planets

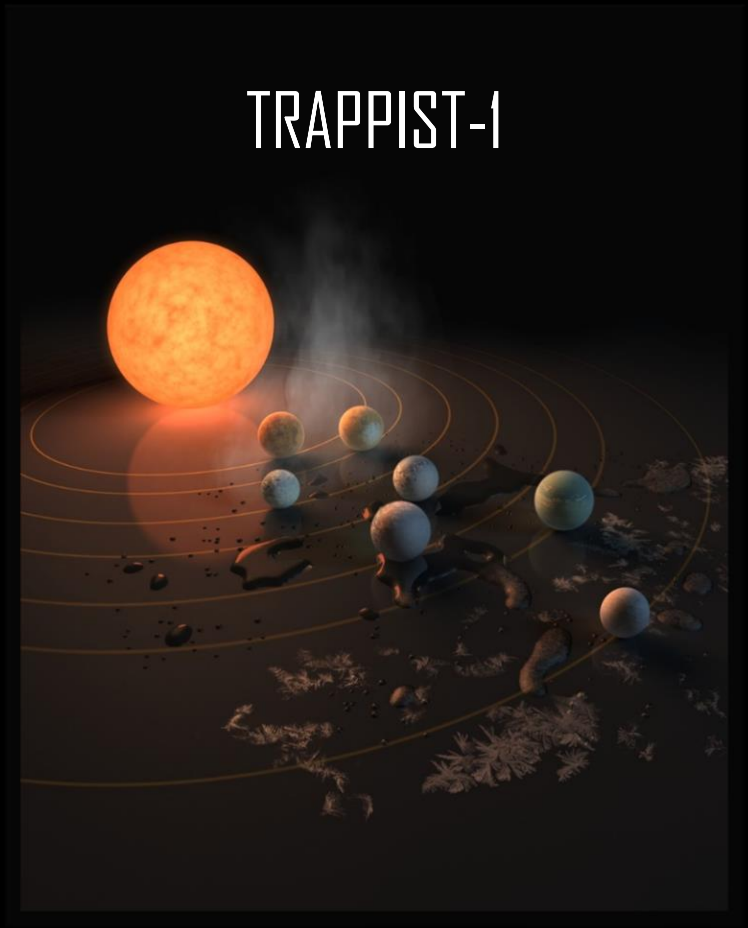
⇎

Permanent surface **liquid** water



Hill et al. 2023

TRAPPIST-1 system



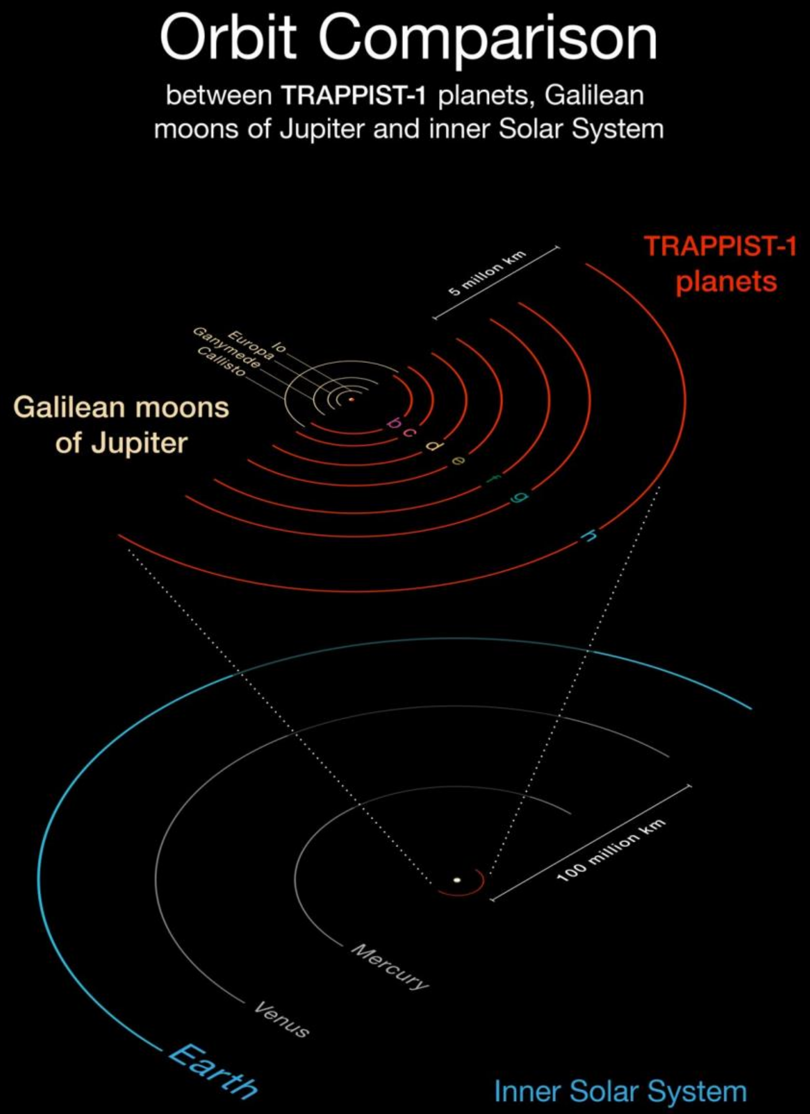
Credit: NASA/JPL-Caltech/R. Hurt (IPAC)

7 **rocky** planets

3 planets in **habitable zone**

M-dwarf host star

Compact system



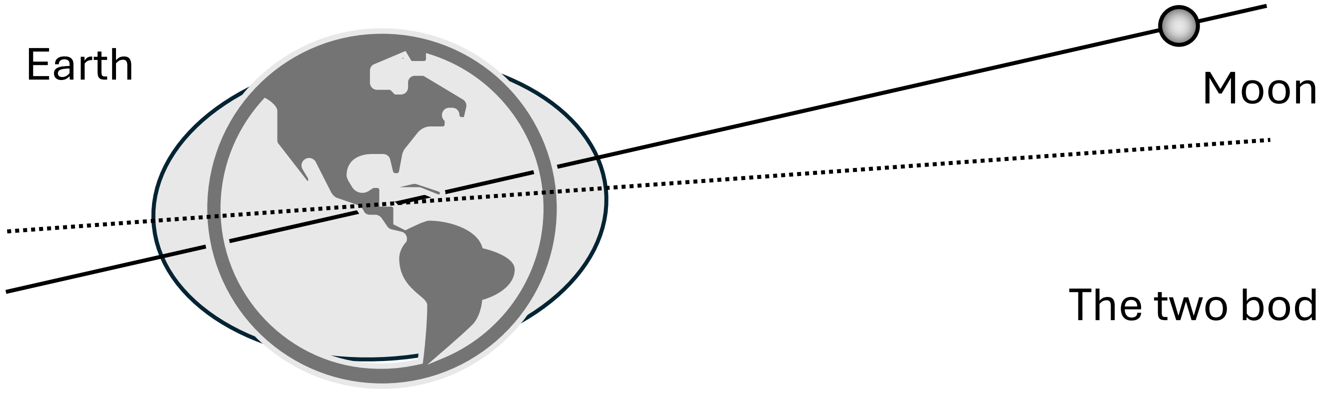
Credit: ESO/O. Furtak

Tidal interactions

Different points of an extended body feel **different gravitational potential**.

The body is **deformed**.

There is a **delay** between the **position of the perturber** and the **position of the tidal bulge**.



The two bodies **exchange angular momentum**.

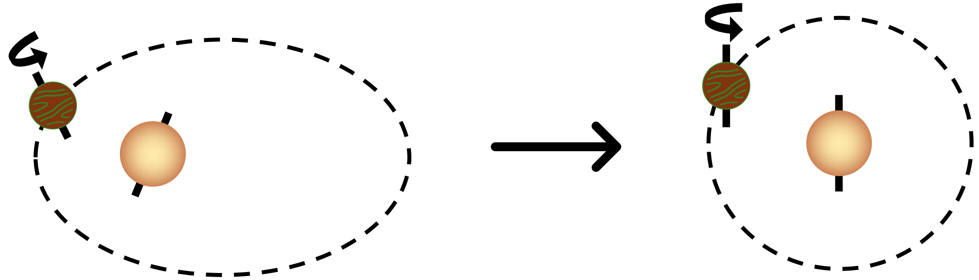
Tidal evolution: End state for close-in planets

One planet orbiting a star

Damping,

Alignment,

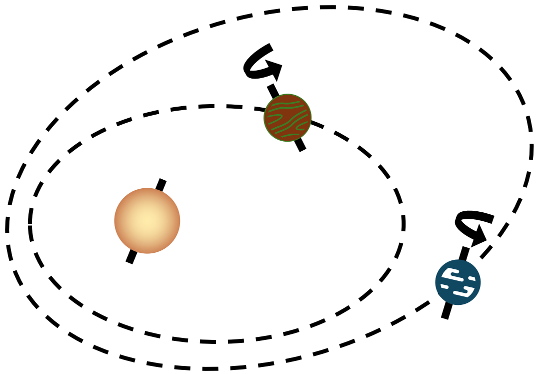
Synchronisation.



Multiple planets orbiting a star

Tidal damping and planet-planet excitation,

Precession.



In both cases

On longer timescales, migration.

Orbital and rotational parameters

evolve with time !

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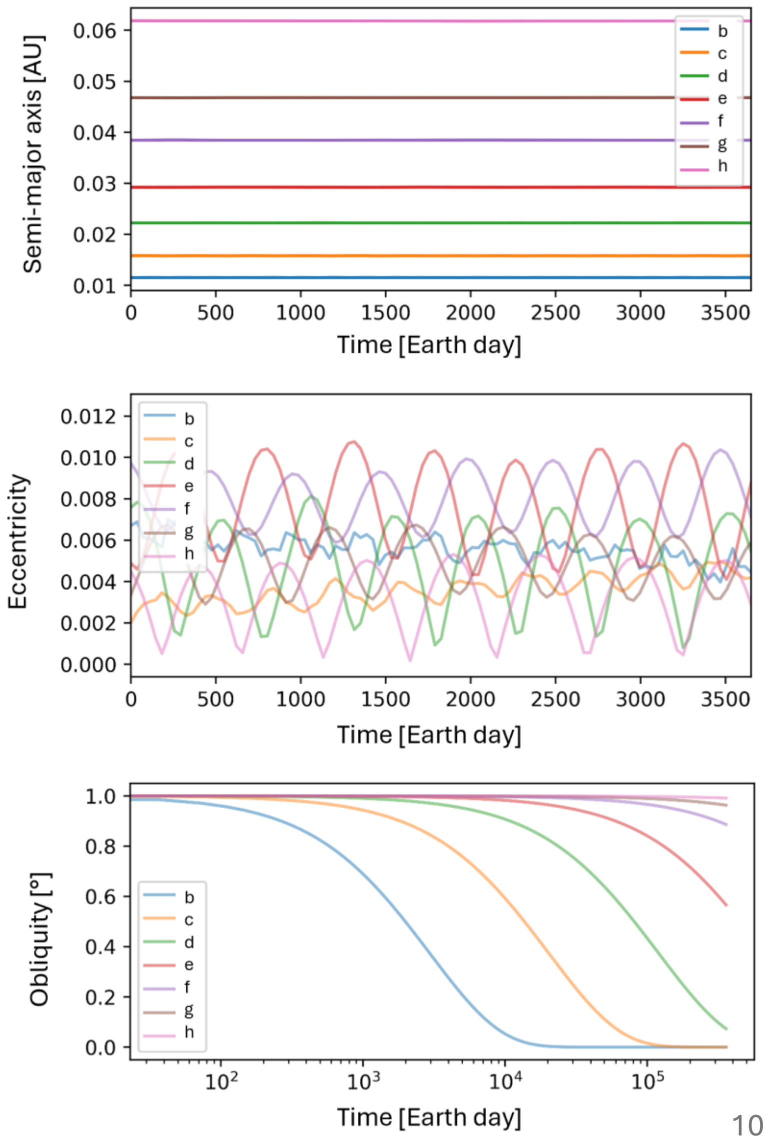
N-body code: *Posidonius*

Blanco-Cuaresma & Bolmont, 2017

Simulation of TRAPPIST-1 system



Describe the **motion** of many **interacting** particles,

Follow the **orbit** of planets, track **orbital parameters**.

Gravitation and tidal forces,

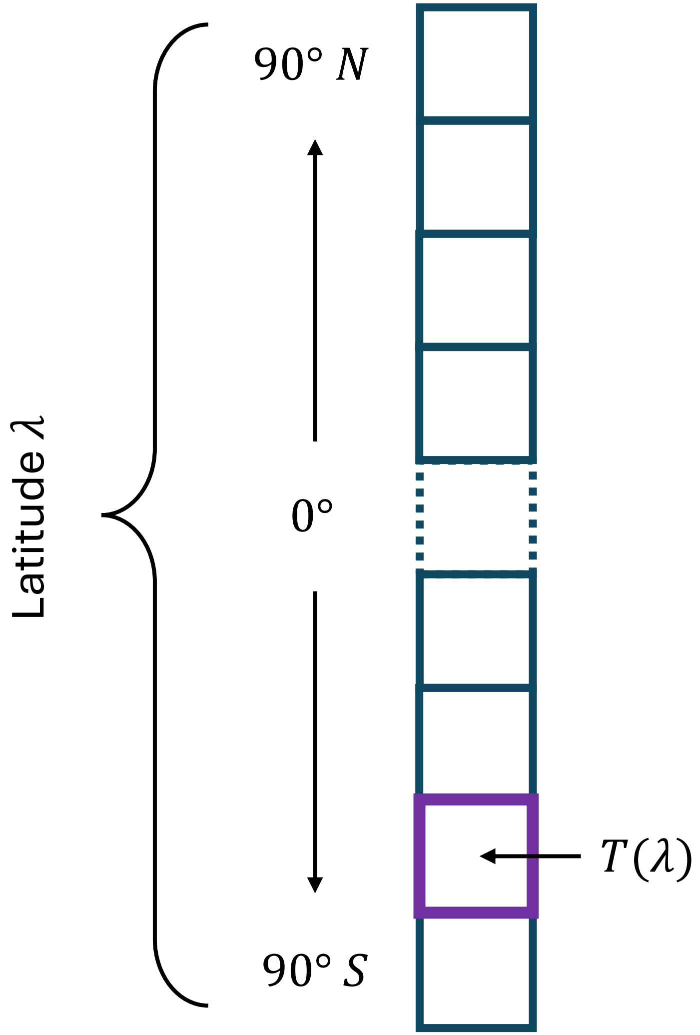
Constant time lag model.

Climate model

Hierarchy of climate models

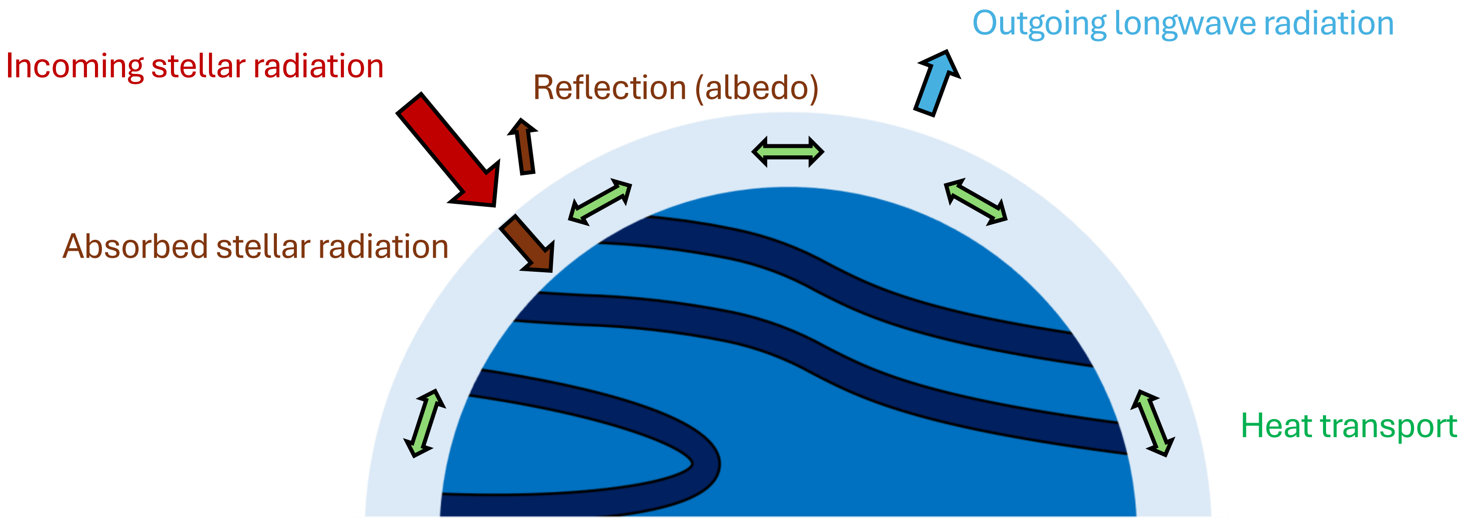
- 0-D Energy Balance Model (= 0-D EBM)
- 1-D Energy Balance Model (= 1-D EBM)
- …
- 3-D Global Climate Model (= 3-D GCM)

For each **latitude**, the model computes the evolution of **temperature** with **time**.



Radiative energy balance

Source of energy	→	Incoming stellar radiation
Sinks of energy	→	Outgoing longwave radiation
Transport of energy	→	Latitudinal heat transport



Aquaplanet

Illustration adapted from E. Bolmont

Radiative energy balance

Source of energy → Incoming stellar radiation

Sinks of energy → Outgoing longwave radiation

Transport of energy → Latitudinal heat transport

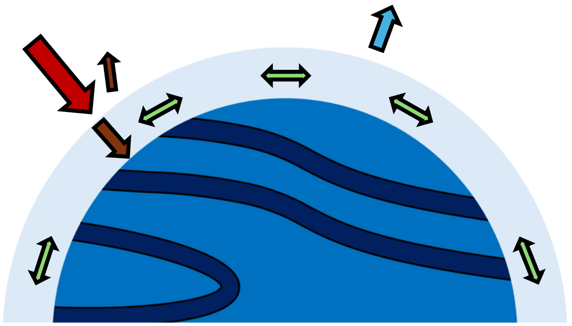
$$\underbrace{C\,\frac{\partial T(x,t)}{\partial t}}_{\text{Surface heat capacity}} - \underbrace{\frac{\partial}{\partial x}\left(D(1-x^2)\frac{\partial T(x,t)}{\partial x}\right)}_{\text{Heat transport}} + \underbrace{I(T)}_{\text{Outgoing longwave radiation}} = \underbrace{S(1-A(T))}_{\text{Absorbed stellar radiation}}$$

Surface heat capacity

Heat transport

Absorbed stellar radiation

Outgoing longwave radiation



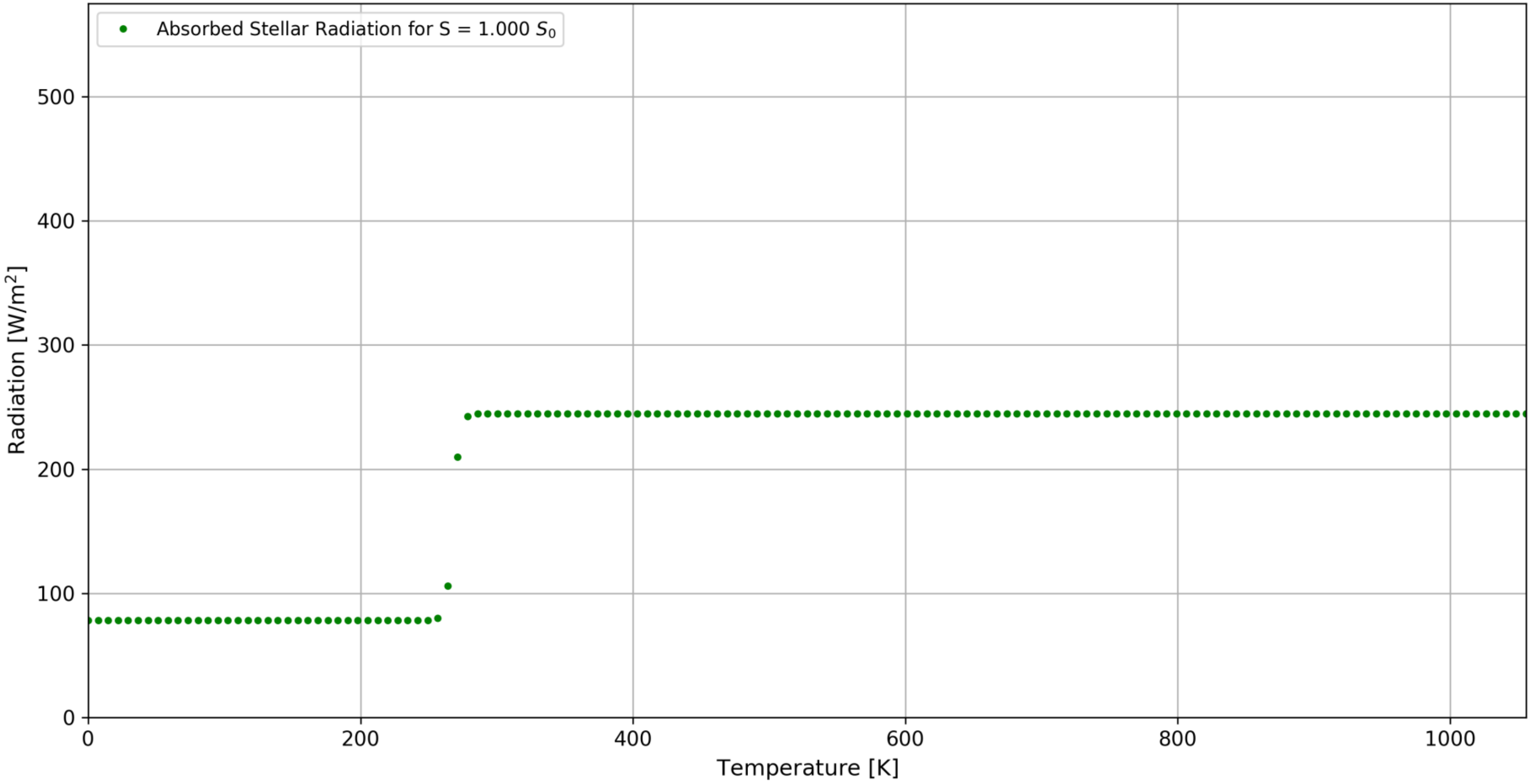
Williams & Kasting 1997; Spiegel et al. 2008; Dressing et al. 2010

Radiative energy balance of an Earth-like planet

$$I(T) = S(1 - A(T))$$

Absorbed stellar radiation

Amount of energy that contributes to the **heating** of the planet.

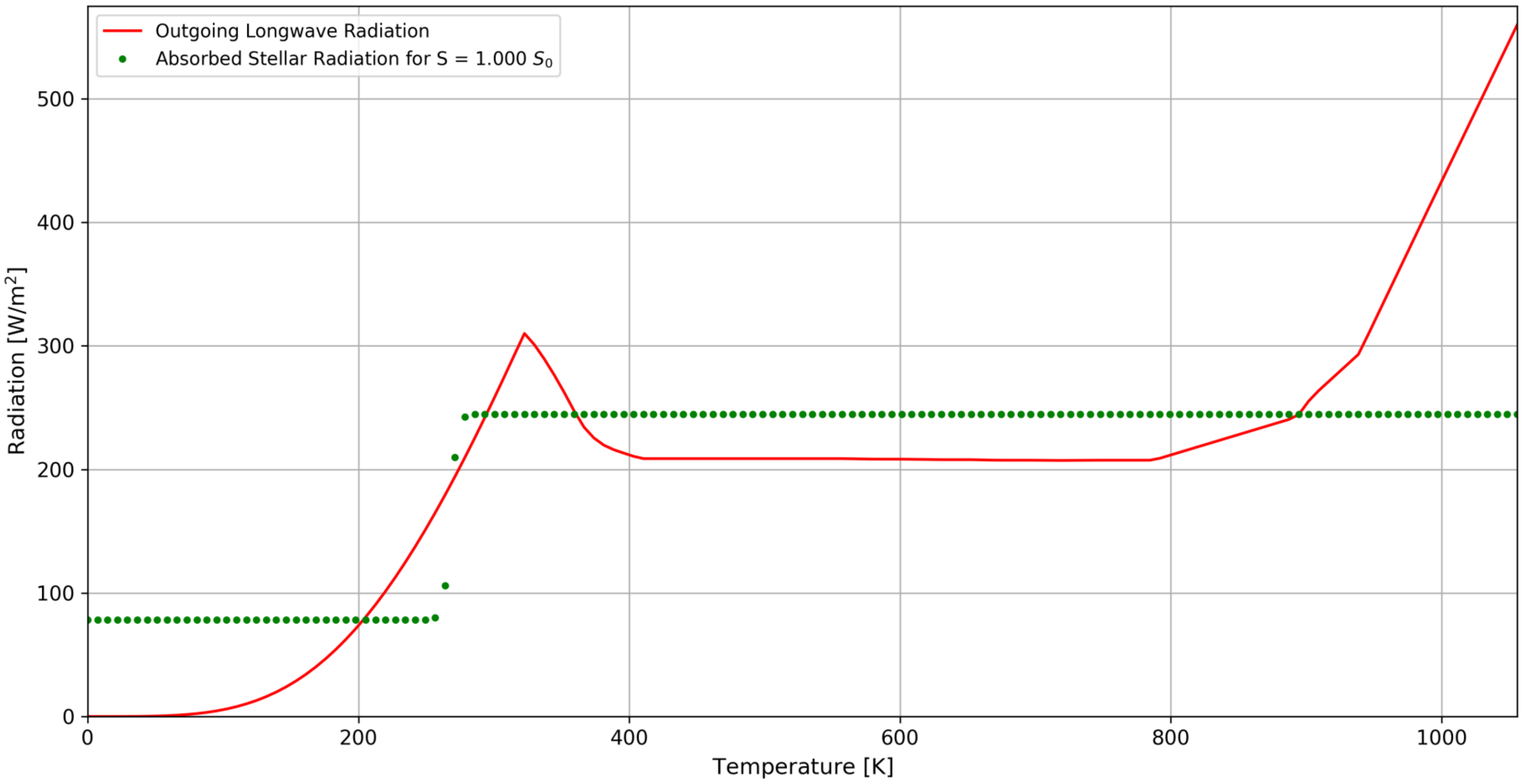


Radiative energy balance of an Earth-like planet

$$I(T) = S(1 - A(T))$$

Outgoing longwave radiation

Amount of energy that is **radiated** away.



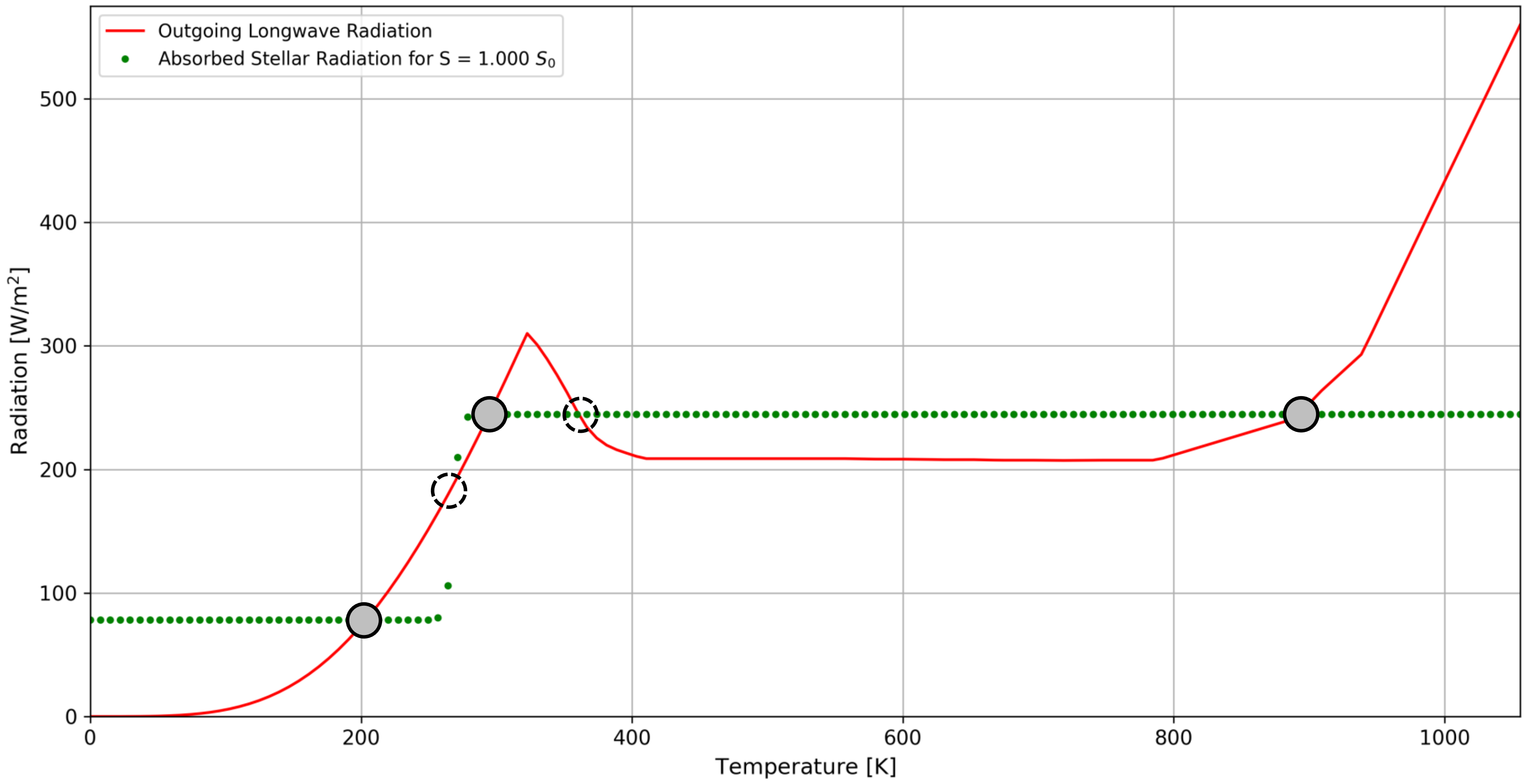
Radiative energy balance of an Earth-like planet

$$I(T) = S(1 - A(T))$$

An **Earth-like** planet with $S = S_0$ has :

3 **stable** states

2 **unstable** states



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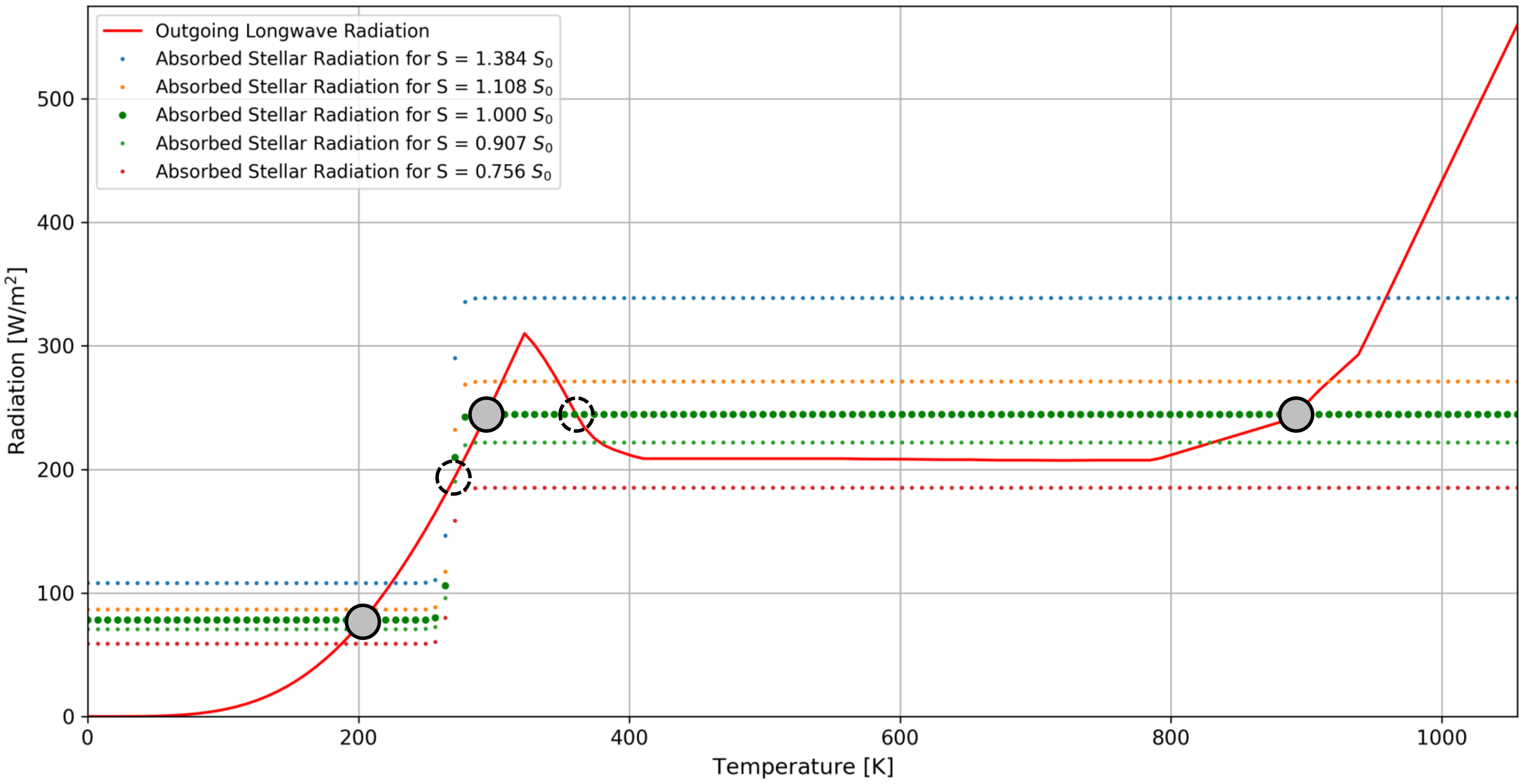


Feedbacks

There is an interplay between various **feedback processes:**

Boltzmann radiative feedback (OLR)

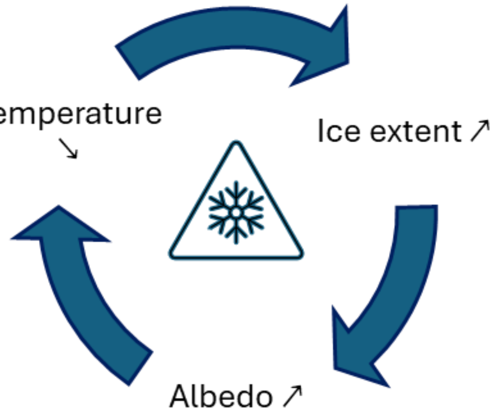
Ice-albedo feedback (ASR)

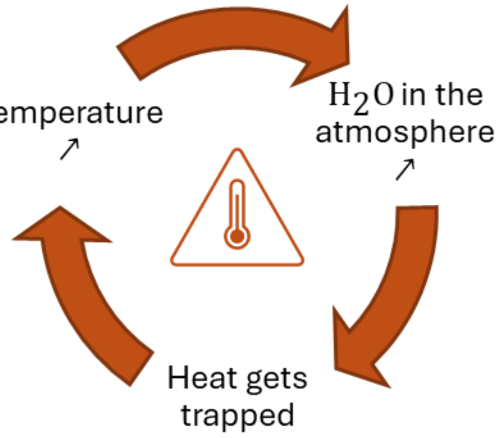
Water vapour feedback (OLR)

Cloud feedback (ASR + OLR)

Positive destabilising feedbacks ⟶ **Runaway glaciation**

Runaway greenhouse





Kasting et al., 1993

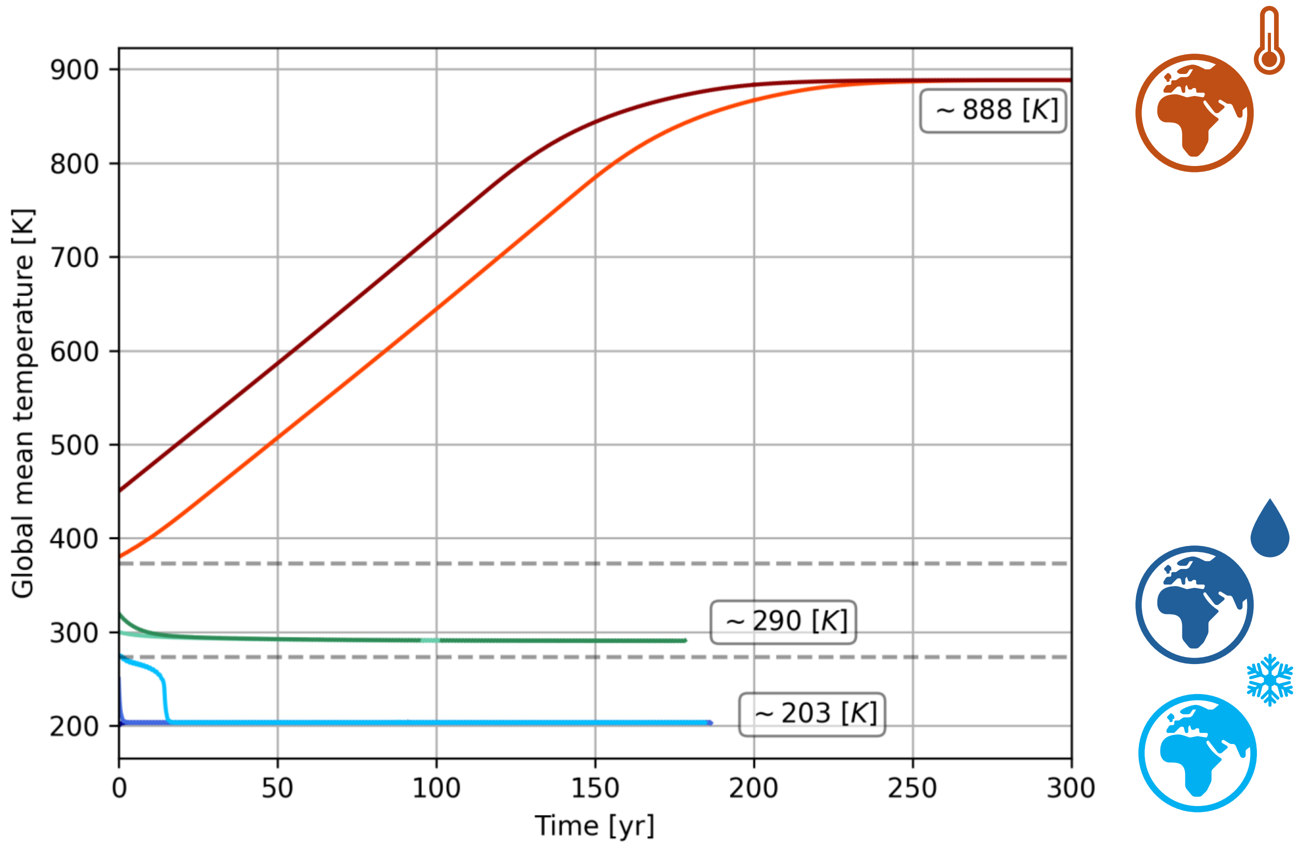
Earth-like aquaplanet

Earth-like aquaplanet

100% ocean

eccentricity = 0.0167

obliquity = 23.5°



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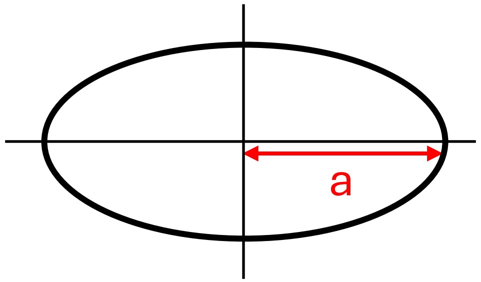
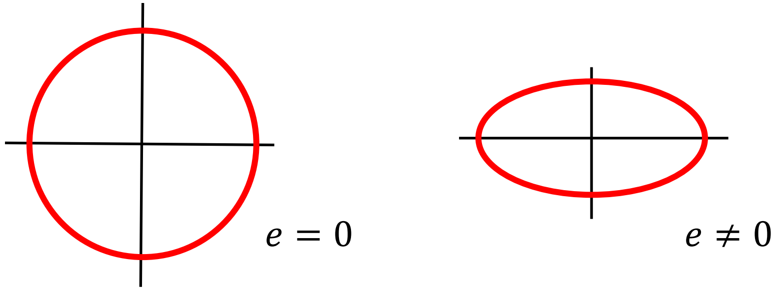
Orbital parameters

The **daily averaged insolation** depends on orbital parameters such as:

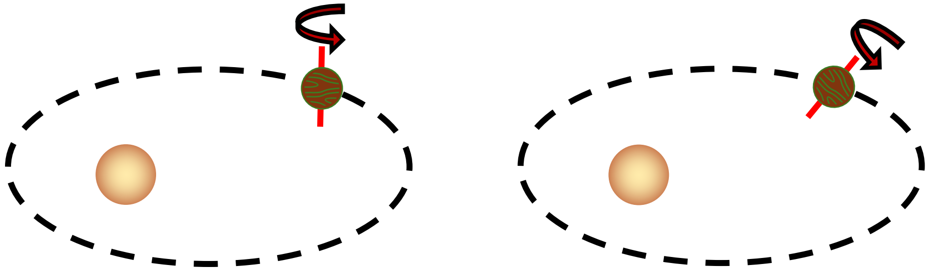
a the **semi-major axis** of the planetary orbit,



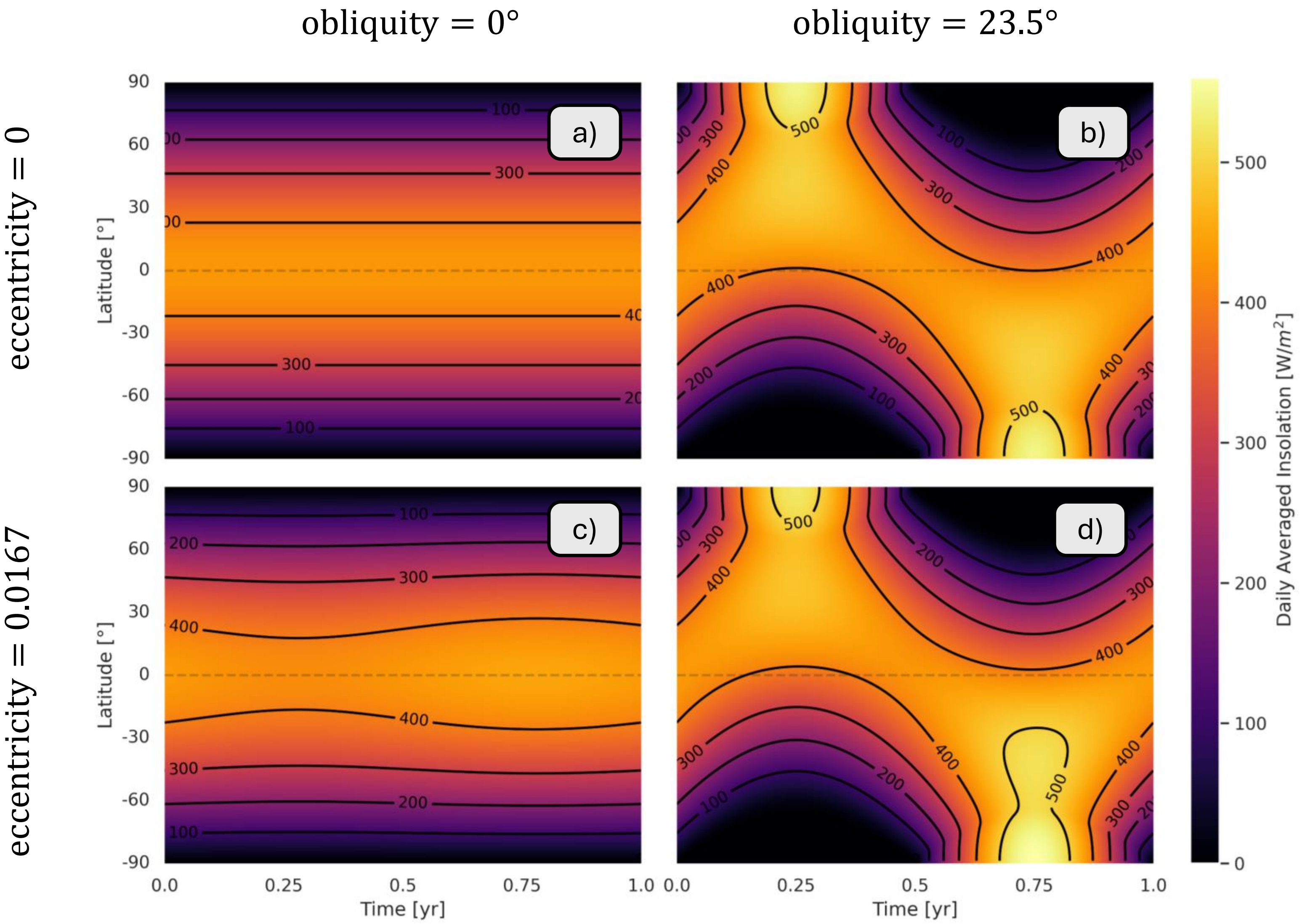
e the **eccentricity** of the planetary orbit,



ε the **obliquity** of the planet rotation axis.



Insolation


obliquity = 0°
obliquity = 23.5°
eccentricity = 0
eccentricity = 0.0167
a)
b)
c)
d)
Latitude [°]
Time [yr]
Daily Averaged Insolation [W/m²]
90
60
30
0
-30
-60
-90
0.0
0.25
0.5
0.75
1.0
100
200
300
400
500

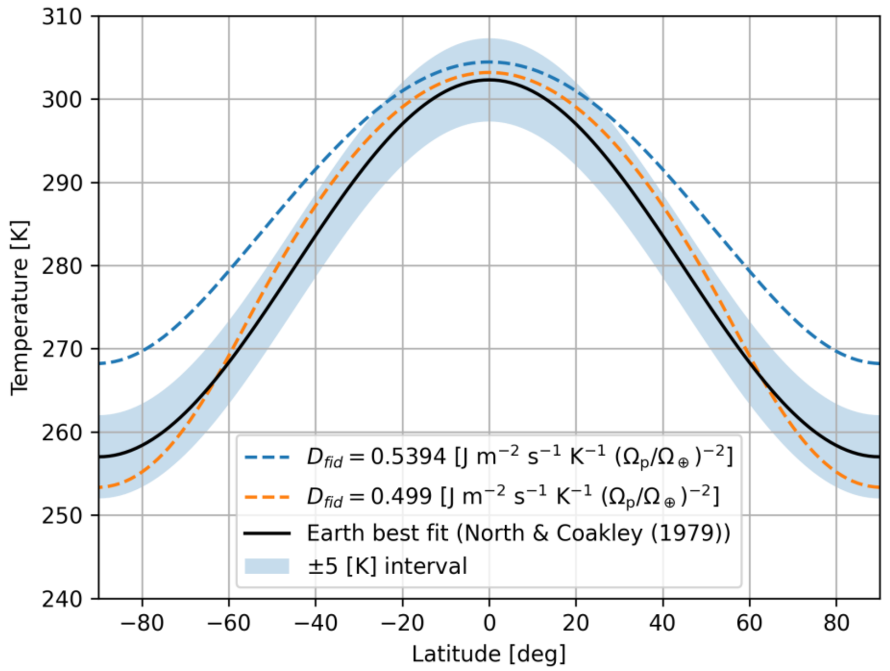
Tuning: diffusion coefficient

Earth-like planet

70% ocean, 30% land

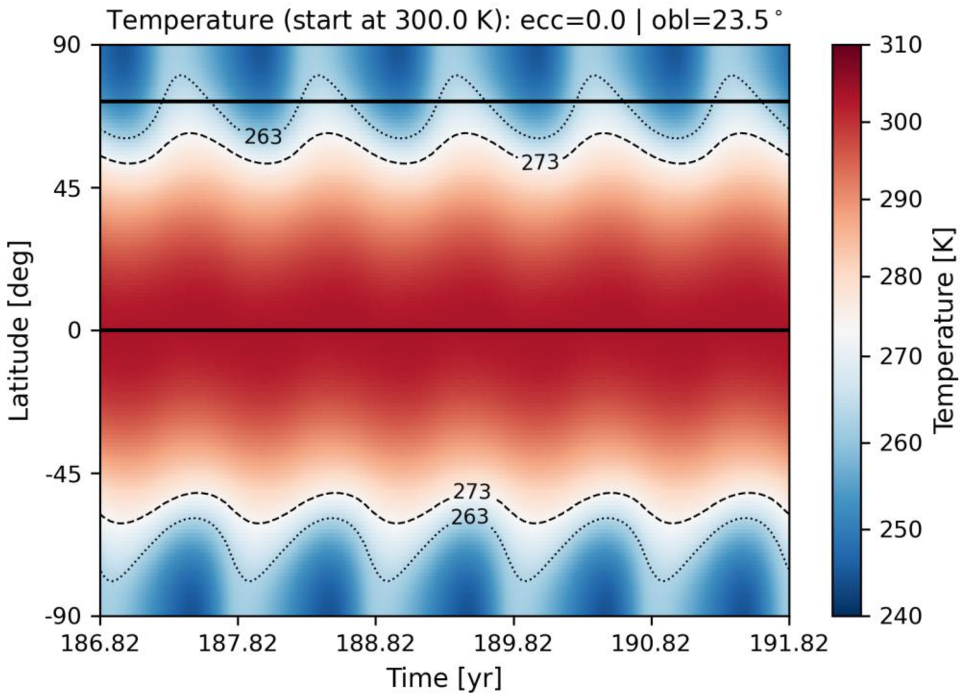
$\text{eccentricity} = 0$

$\text{obliquity} = 23.5°$



Three criteria:

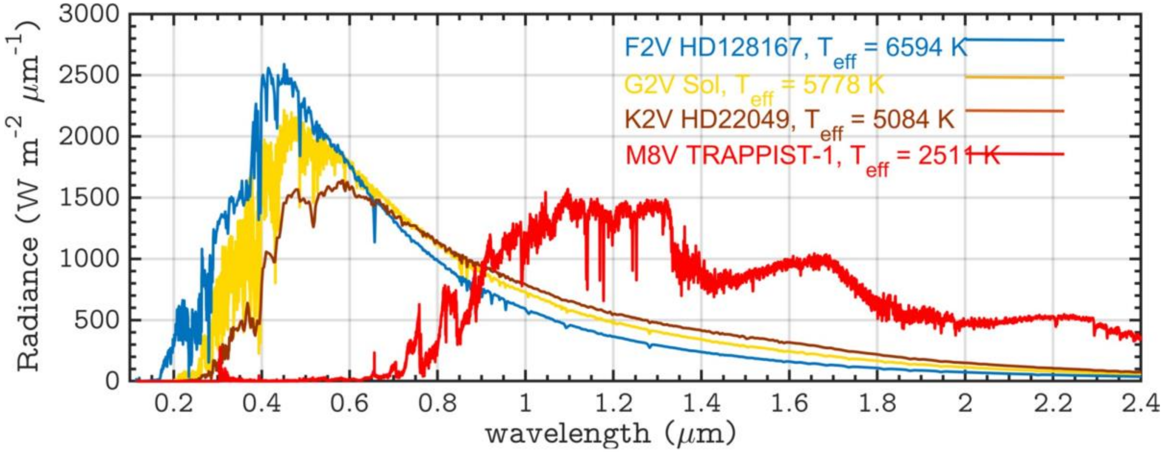
1. Global mean temperature $294\ K \longrightarrow 289\ K$
2. Mean latitudinal temperature profile
3. Mean ice line



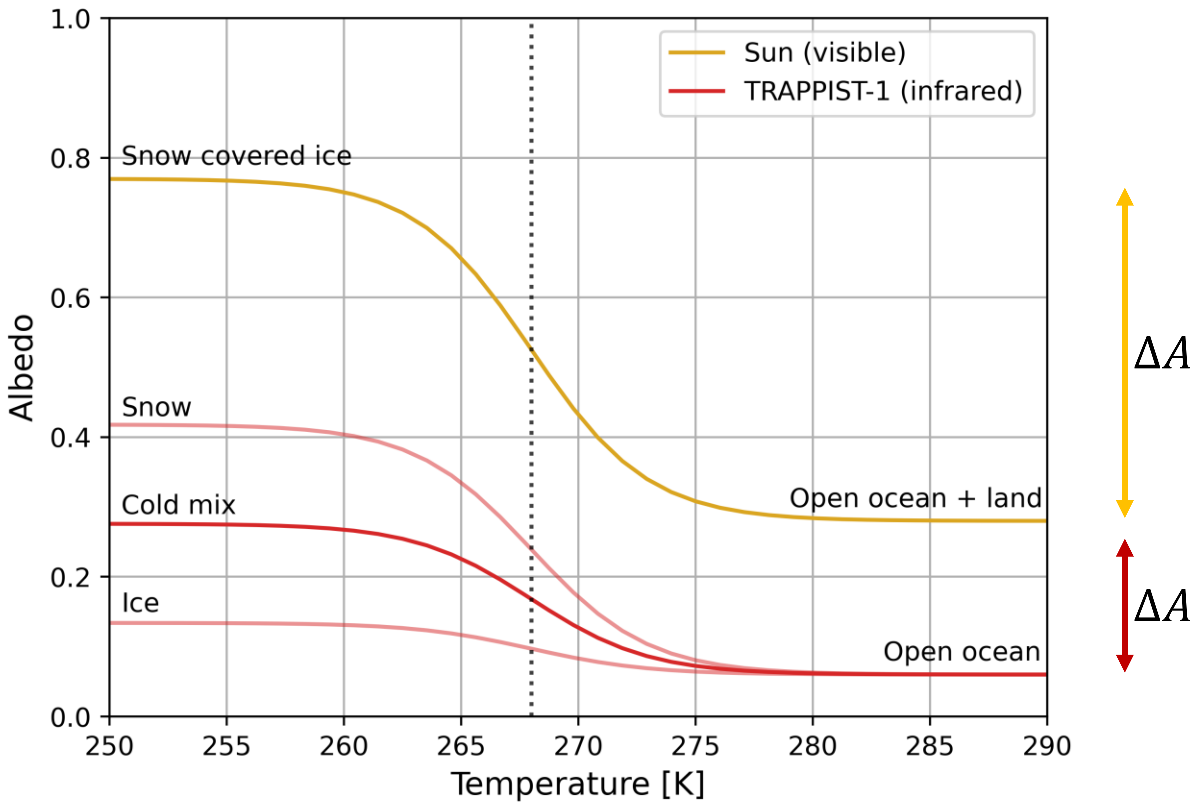
North & Coakley 1979; Williams & Kasting 1997; Spiegel et al., 2008

Structure

Albedo wavelength dependence



Rushby et al. 2020



Gilmore 2014; Rushby et al. 2020; Brandt et al. 2005

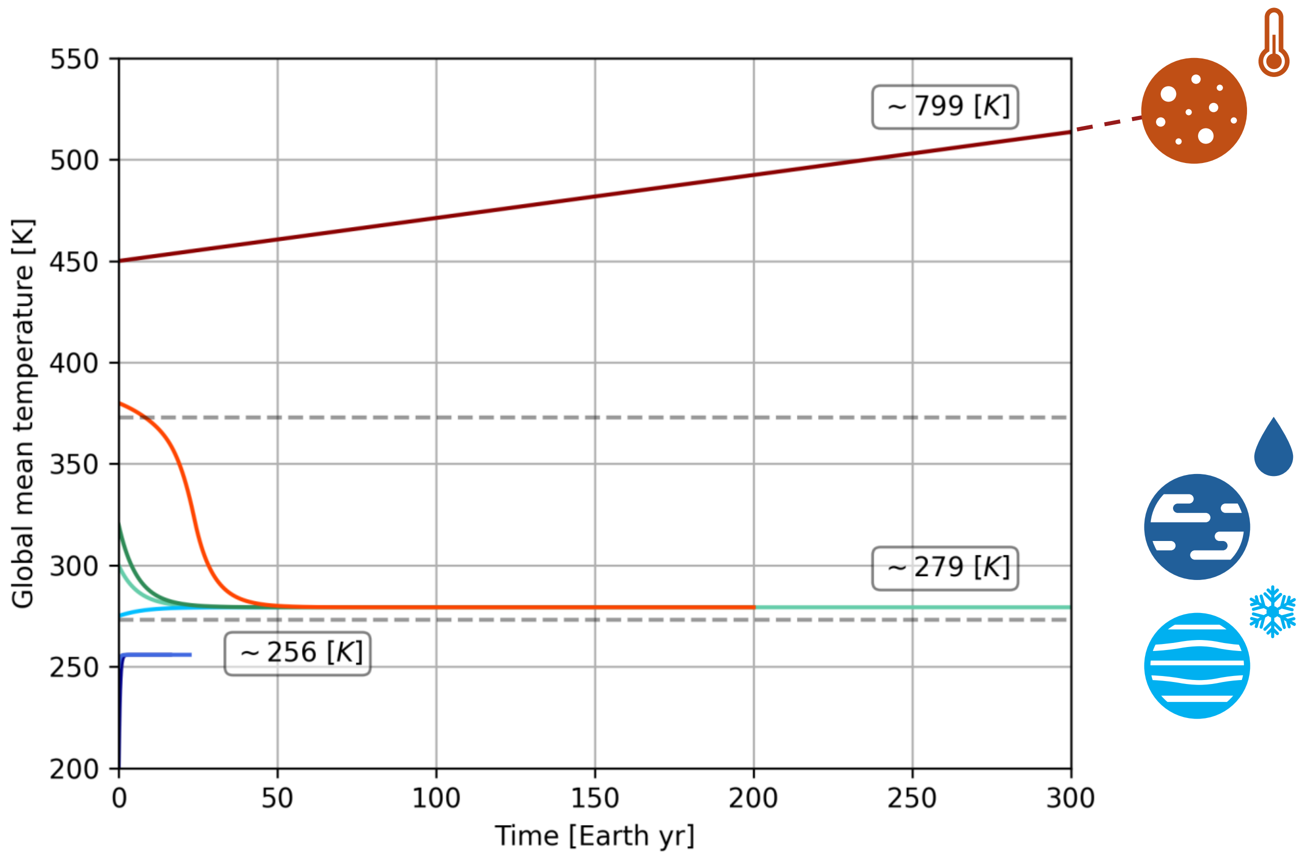
TRAPPIST-1e

TRAPPIST-1e

100% ocean

eccentricity = 0

obliquity = 0°



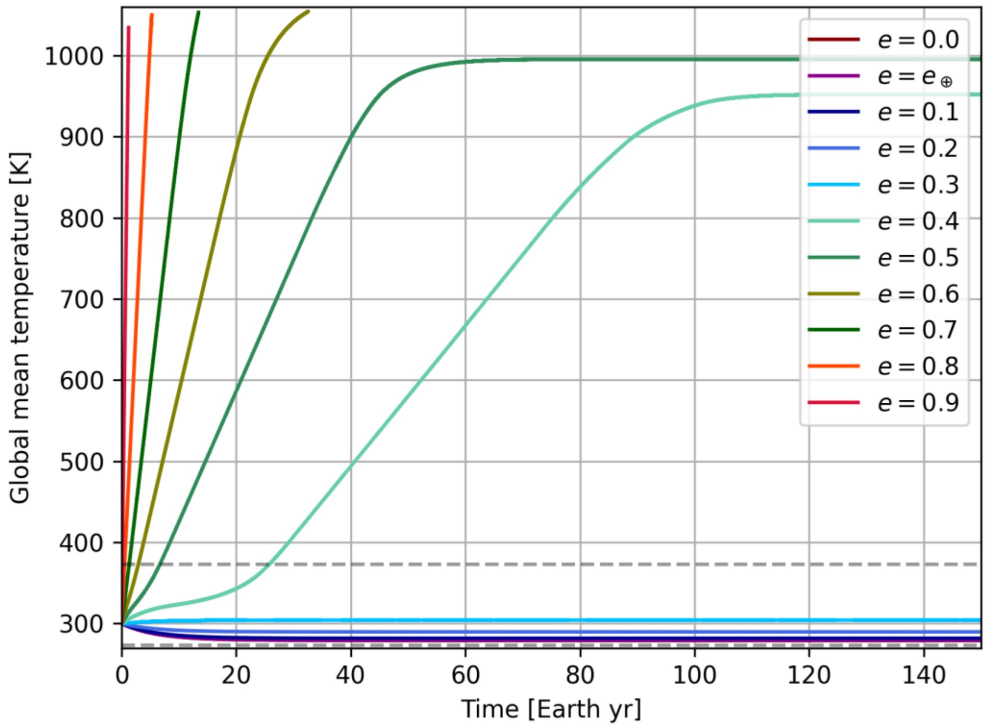
Effect of constant eccentricity

TRAPPIST-1e

100% ocean

eccentricity = e_i

obliquity = 0°



$$F = \frac{L_{star}}{4\pi a^2 \sqrt{1 - e^2}}$$

Bolmont et al. 2016

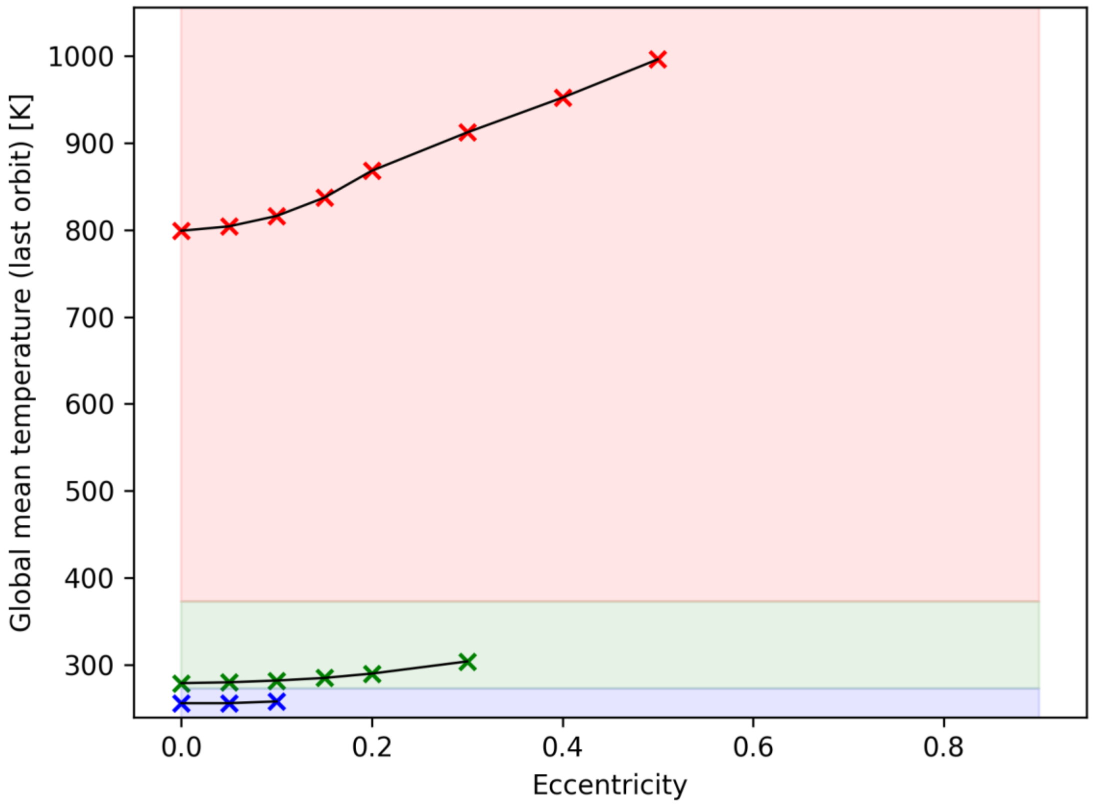
Bifurcation diagram

TRAPPIST-1e

100% ocean

eccentricity = e_i

obliquity = 0°



$T > 373\ K$

$273\ K < T < 373\ K$

$T < 273\ K$

Effect of time-dependent eccentricity

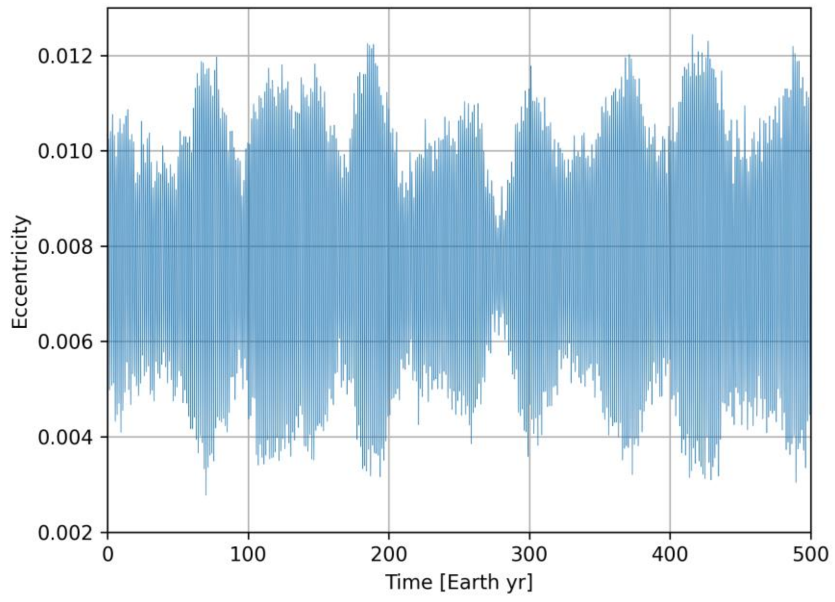
TRAPPIST-1e

100% ocean

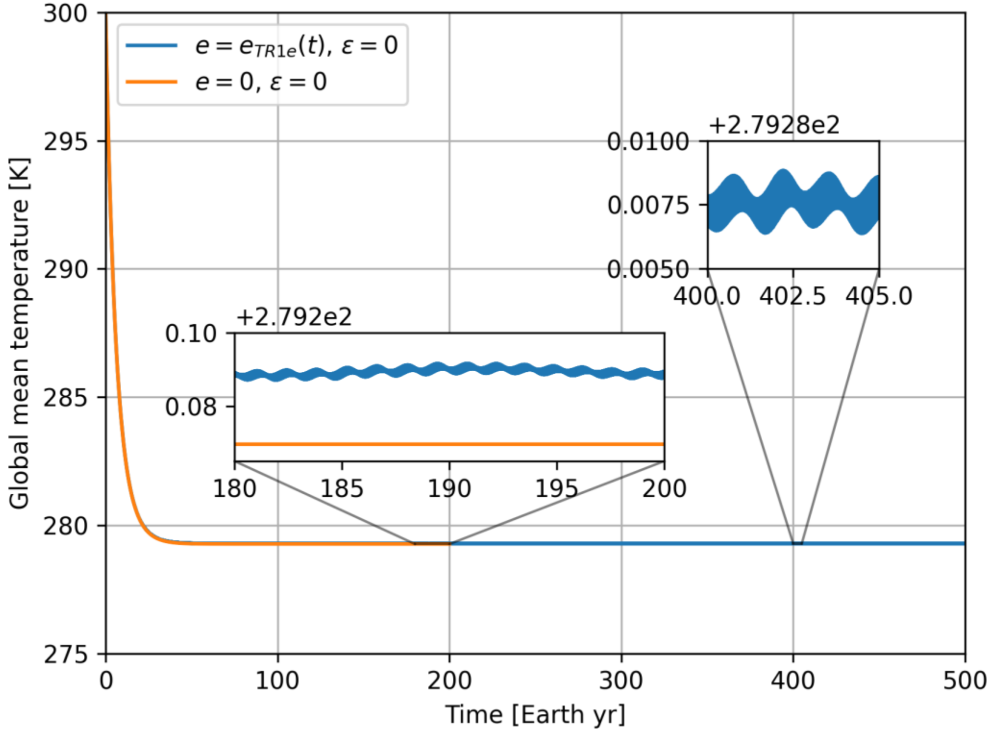
eccentricity $= \{0, e(t)\}$

obliquity $= 0°$

N-body simulation



Climate simulation

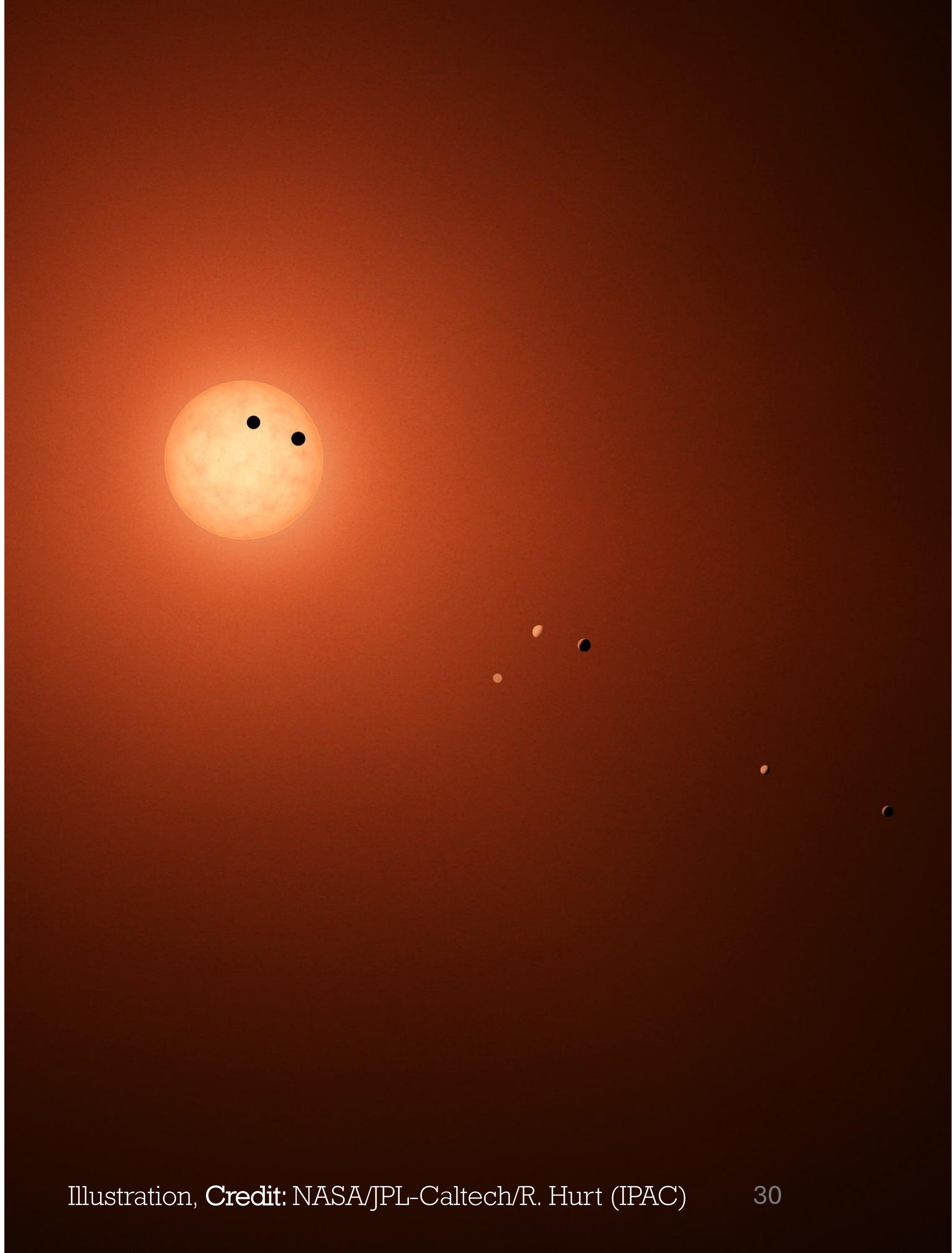


Conclusion

- Slow rotating planets have a very efficient **heat transport**.
- Depending on the external forcing (eccentricity), some **stable states** become **unavailable**.
- Given observational constraints, TRAPPIST-1e would be in a **tristability** regime.
- A realistic description of the **eccentricity evolution** of TRAPPIST-1e **does not** significantly **impact** the climate.

Outlook

- Need of observations to **constrain** our climate model.
- The EBM can be used for studies of other planetary systems (e.g. **more extreme** dynamical cases).



Illustration, **Credit:** NASA/JPL-Caltech/R. Hurt (IPAC)