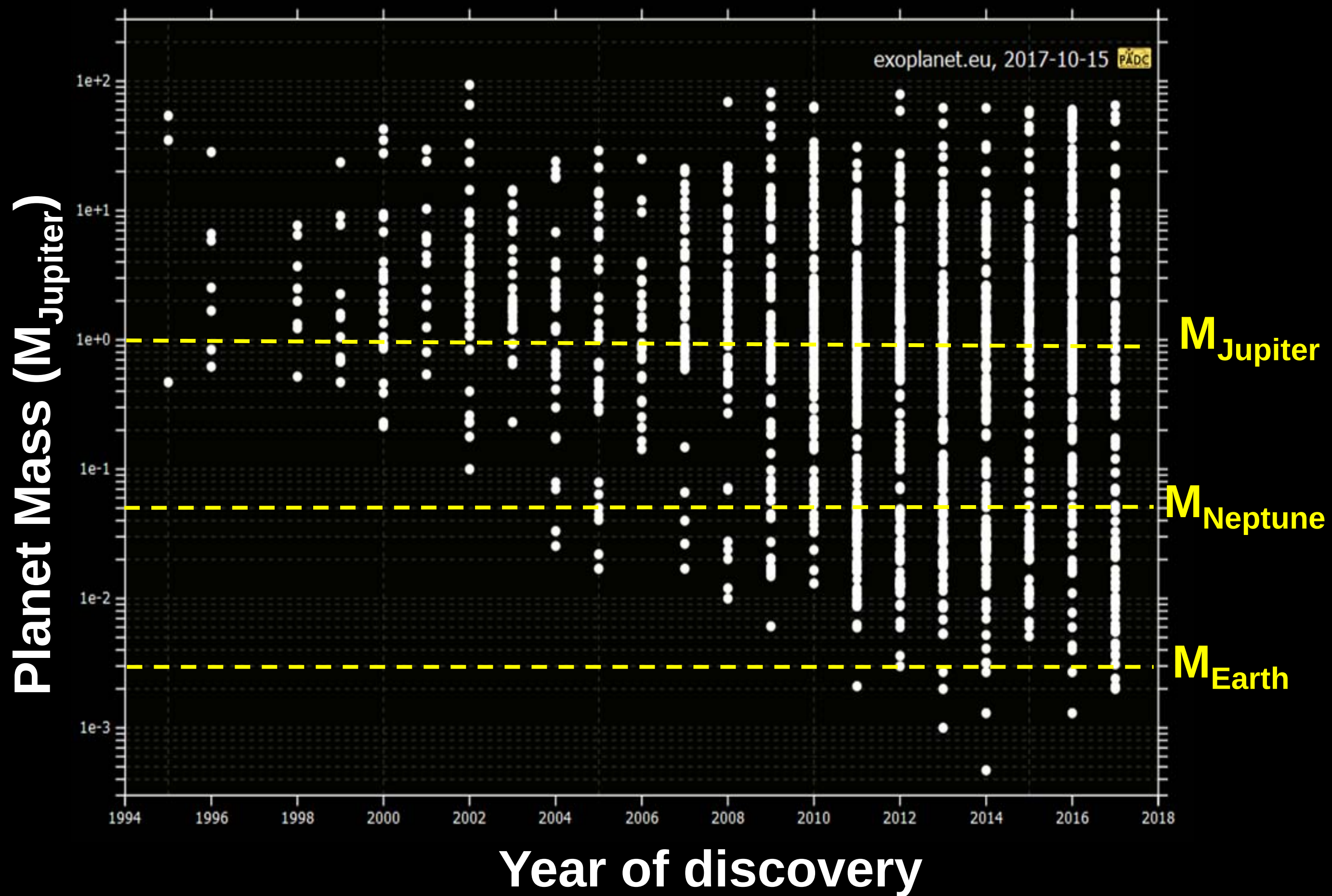
Habitability of Exoplanets

François Forget

CNRS, Institut Pierre Simon Laplace, Laboratoire de Météorologie Dynamique, Paris, France

September 21, 2022: 5179 planets discovered in 3819 planetary systems



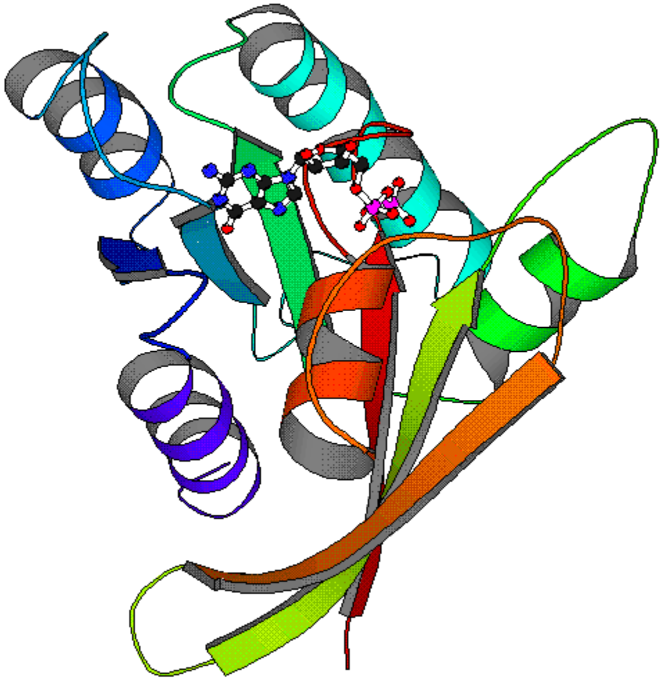
- The solar system is not at all typical !
- Most stars host rocky planets

⇨ Which planets are suitable for life ? Where are they ?

<u>Habitability</u>: What is life ? What's needed for Life ?

~95% of known chemical compounds are carbon-based

- **??**
- Life : "*chemical system capable of Darwinian evolution*" (NASA Pannel, 1996)
- **What we know ⇨ Carbon-based chemistry … in liquid water**



Why liquid Water ?

- H_2O - liquid state in the appropriate temperature range for organic reactions
- Hydrogen bonding - can form bonds with other water molecules
- Bipolar character - good electrical conductor + **good solvent** for various organic molecules
- Essential in the cytoplasm and other cellular compartments where biochemical reactions take place - transport of metabolites

UDIES

Planetary

Keck

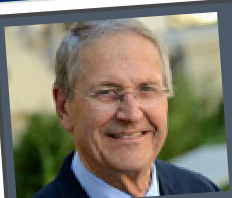
Astrophysics

Enginee

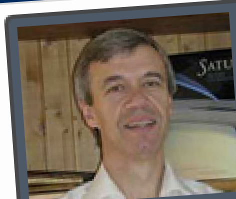
Don't Follow (Just) the Water: Does Life Occur in Non-Aqueous Media?

July 6-10, 2015
California Institute of Technology - Pasadena, CA 91125

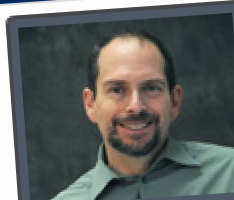
Team Leads



Jack Beauchamp
California Institute of Technology



Christophe Sotin
Jet Propulsion Laboratory



Jonathan Lunine
Cornell University

Description

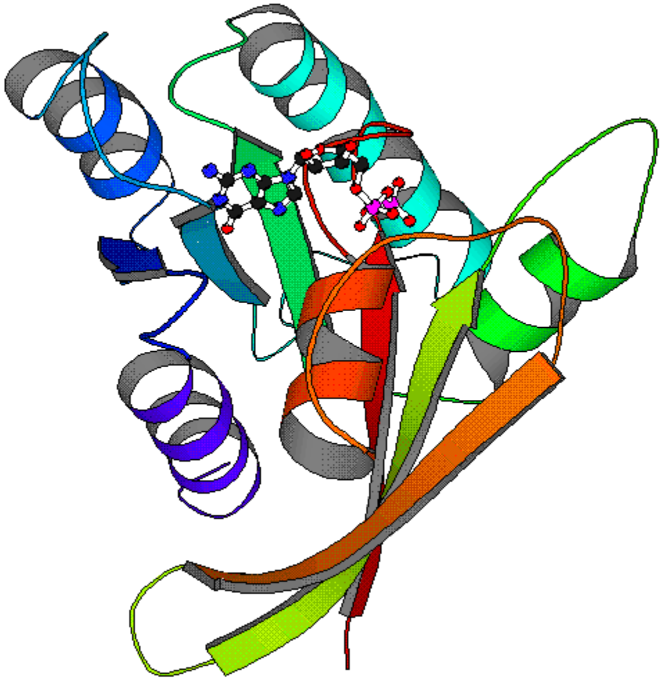
Workshop Overview:

Is the origin of life a common or even inevitable outcome of the general evolution of structure in the cosmos? Determining the ubiquity of life in the cosmos requires understanding the range of environments within which chemical self-organization and self- ... liquid water is the medium that allows molecules to interact and assemble the machinery ... Discovering that self-organization and self-

Habitability: What is life ? What's needed for Life ?

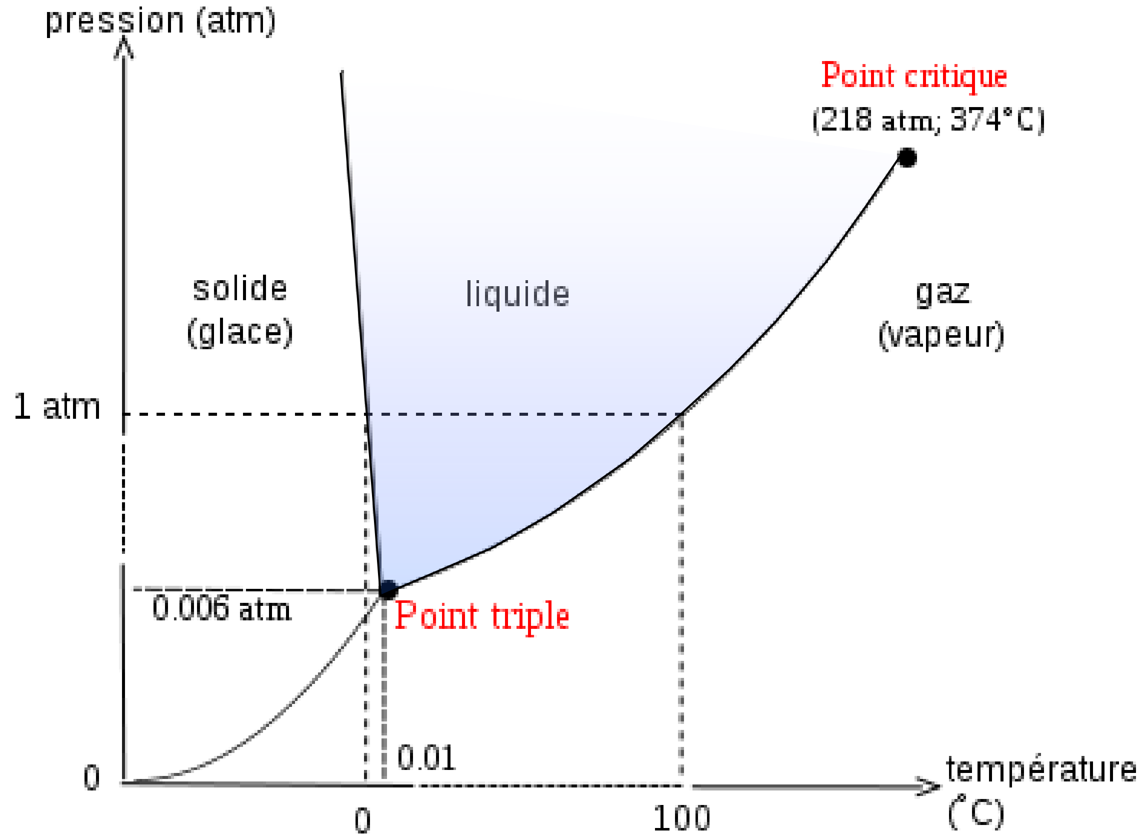
~95% of known chemical compounds are carbon-based

- **??**
- **What we know ⇨ Carbon-based chemistry … in liquid water**
- **Carbon life without liquid water is**
  - **difficult to imagine**
  - **probably difficult to recognize and detect**



Hypothesis: Habitability = liquid water available

To get liquid water



H_2O should be generally an abundant condensate in the outer planetary nebulaes. But to get it liquid:

- 6,1 mb < Pressure < ~5 kb – 100 kb (HP ice, depends on T)
- Above freezing temperature: T >~0°C
- Below boiling temperature (Depends on abs. pressure):

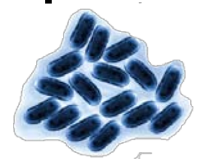
  T < 1°C to 374°C (or more ?)

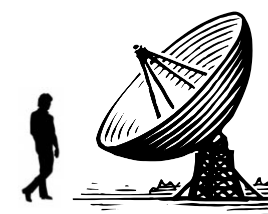
\- *Note : Earth's life exist for -15°C < T < 122°C*

Habitable = liquid water available

⇨ Some habitable environments are nevertheless « more habitable » than others

- **Duration of habitability**:Time is required for life to emerge (maybe) and evolve





  ⇨ “*Continuous habitability*”

- **Quality of habitability**:

Active, evolved (and detectable) life requires

  – **Other chemical species**

    (On Earth: N, P, S, Na, etc)

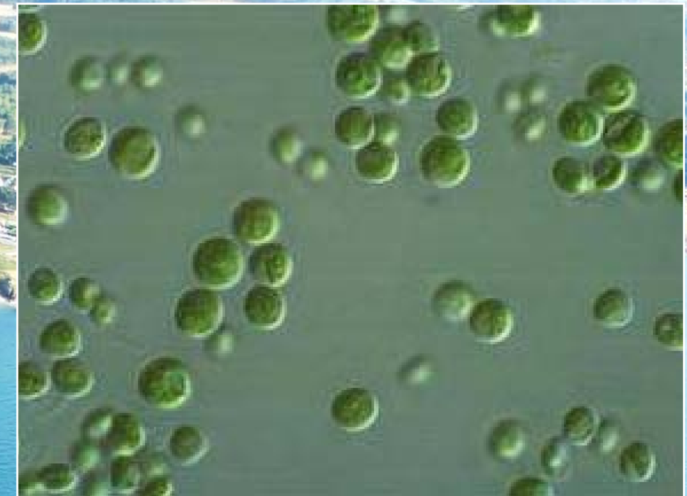
  – **Energy**

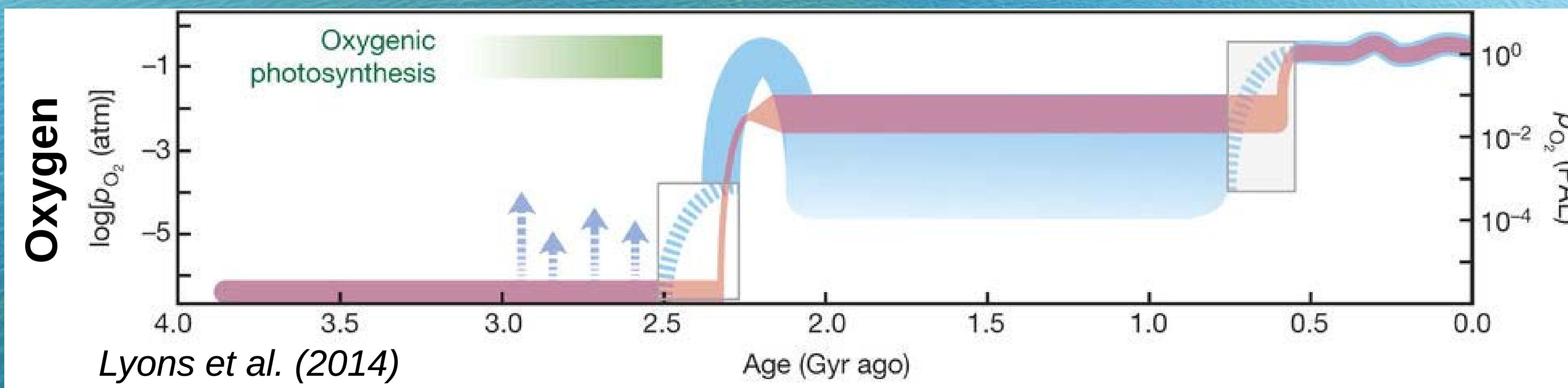
    (<u>Light</u>, possibly Chemical energy

    (e..g., $H_2 + CO_2$ • $CH_4 + H_2O$)

On the Earth: Photosynthesis on the surface

⇨ Modification of the environment





Liquid water in the solar system

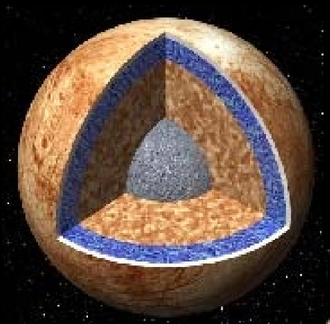

Ocean Worlds?
ice
water
rock
metal
Europa
Ganymede
Callisto
Titan
Eris
Pluto
Sedna
Enceladus
Triton
Titania
Oberon
Rhea
Earth

4 kinds of « habitability »

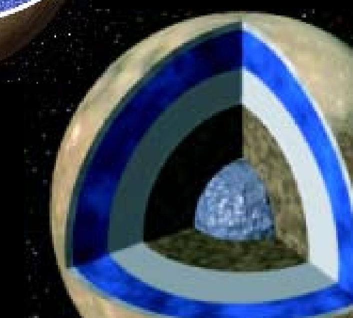
(Lammer et al. Astron Astrophys Rev 2009; Forget 2013)

- **Class I:** Planets with permanent surface liquid water: *like Earth*

- **Class II :** Planet temporally able to sustain surface liquid water but which lose this ability (loss of atmosphere, loss of water, wrong greenhouse effect) : *Mars, Venus ?*



- **Class III :** Bodies with subsurface liquid water which interact with silicate mantle *(e.g. Europa, Enceladus)*



- **Class IV :** Bodies with subsurface ocean between two ice layers *(e.g. Ganymede, Callisto)*

4 kinds of « habitability »

(Lammer et al. Astron Astrophys Rev 2009; Forget 2013)

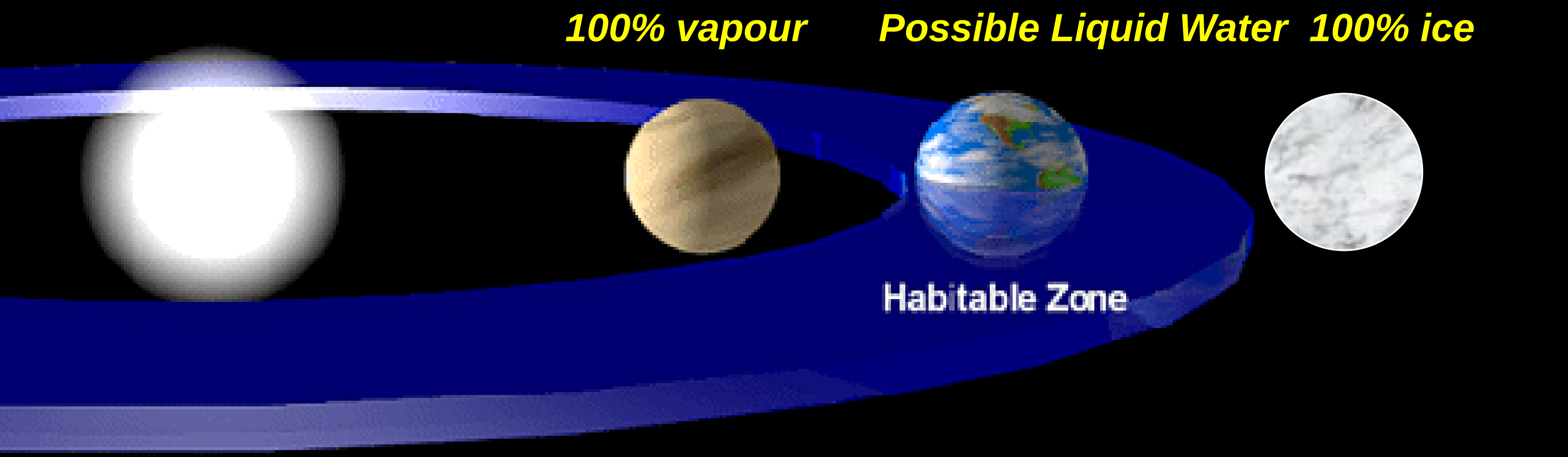
- **Class I:** Planets with permanent surface liquid water: *like Earth*

- **Class II :** Planet temporally able to sustain surface liquid water but which lose this ability (loss of atmosphere, loss of water, wrong greenhouse effect) : *Mars, Venus ?*
- Surface liquid water allows photosynthetic life, able to modify its environment *(and more complex life ?)*

- **Class IV :** Bodies with subsurface ocean between two ice layers *(e.g. Ganymede, Callisto)*

The “Habitable Zone” (HZ): *liquid water possible on the surface of planets*

Eg. Kasting et al. 1993



- **Originally** : Habitable zone defined to represent the conditions that Earth enjoys
- **Today**: Habitable zone concept designed to prepare observations, for astronomers looking for detectable life (photosynthesis required ?)

  ⇨ **HZ = “Hunting zone”**

Habitable Zone

- HZ: The region outside which it is <u>not possible</u> for a rocky planet to maintain liquid water on its surface

- Of course being in the habitable zone does not mean that a world is habitable *(e.g.… the Moon)*

- The Habitable zone does not depend on the planet (*Don't say "the Moon is not in the habitable zone because it has no atmosphere"*).

- Nevertheless different kind of habitable zones can be defined depending of the considered type of atmospheres (see below) …

Characterizing the "Habitable Zone":

⇨ A problem of climate and atmospheres

100% vapour *Possible Liquid Water* *100% ice*

Key parameters controlling the climate on a terrestrial planet:

Climate model

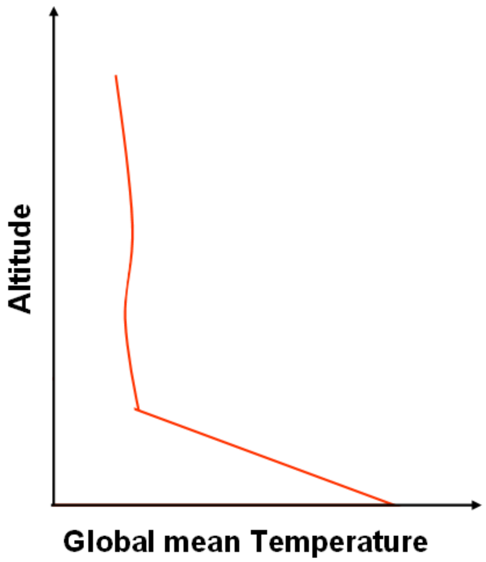
- **Stellar insolation**
- **Atmospheric composition** and surface volatile inventory
- **Rotation** (rate and obliquity)

Climate

Surface Habitability of Planets

(Forget and Leconte 2013)

A hierarchy of models for planetary climates



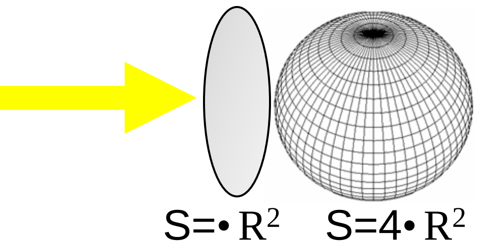
1. 1D global "radiative convective models"

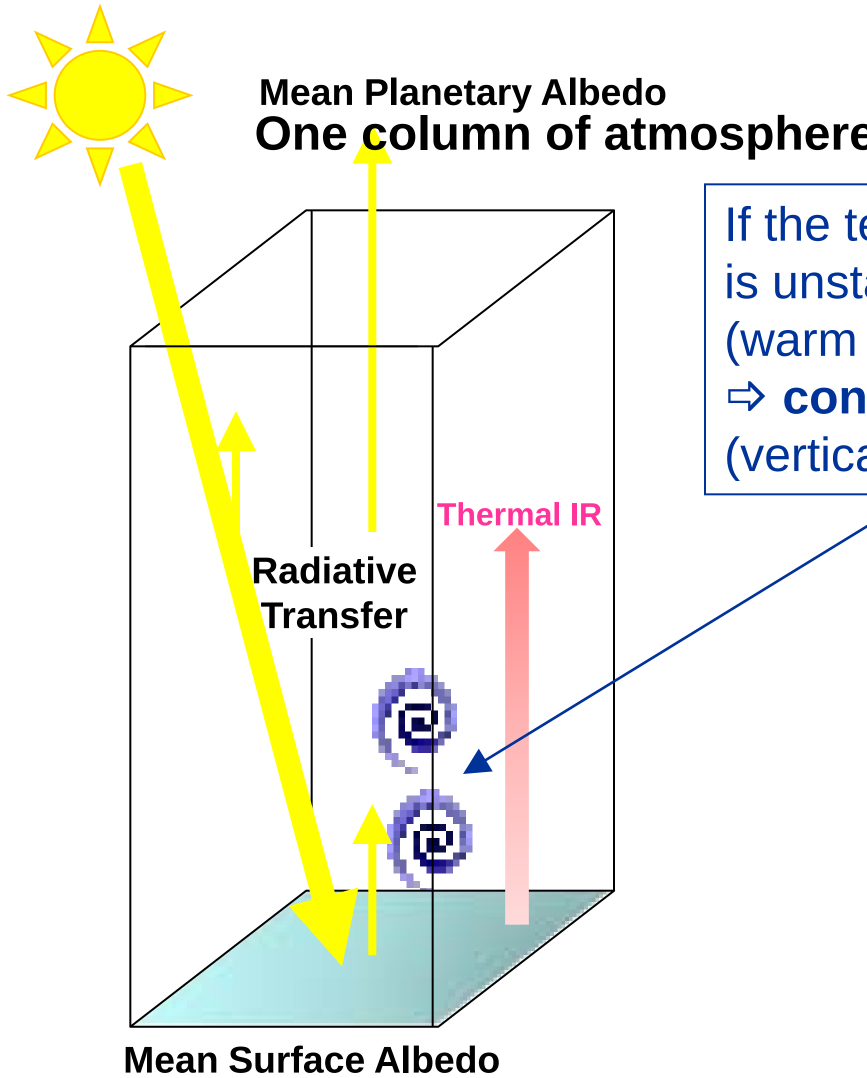
⇨ Great to explore a wide range of possible climates; *(e.g. Kasting et al. 1993 , Kopparapu et al. 2013, 2014)*

1D « radiative convective models »

Mean Insolation at the top of the atmosphere :

- Incident angle = 60°
- Mean Incident flux =
  flux from star (W m^{-2}) / 4





If the temperature profile is unstable
(warm air below cold air
⇨ **convection**
(vertical mixing)

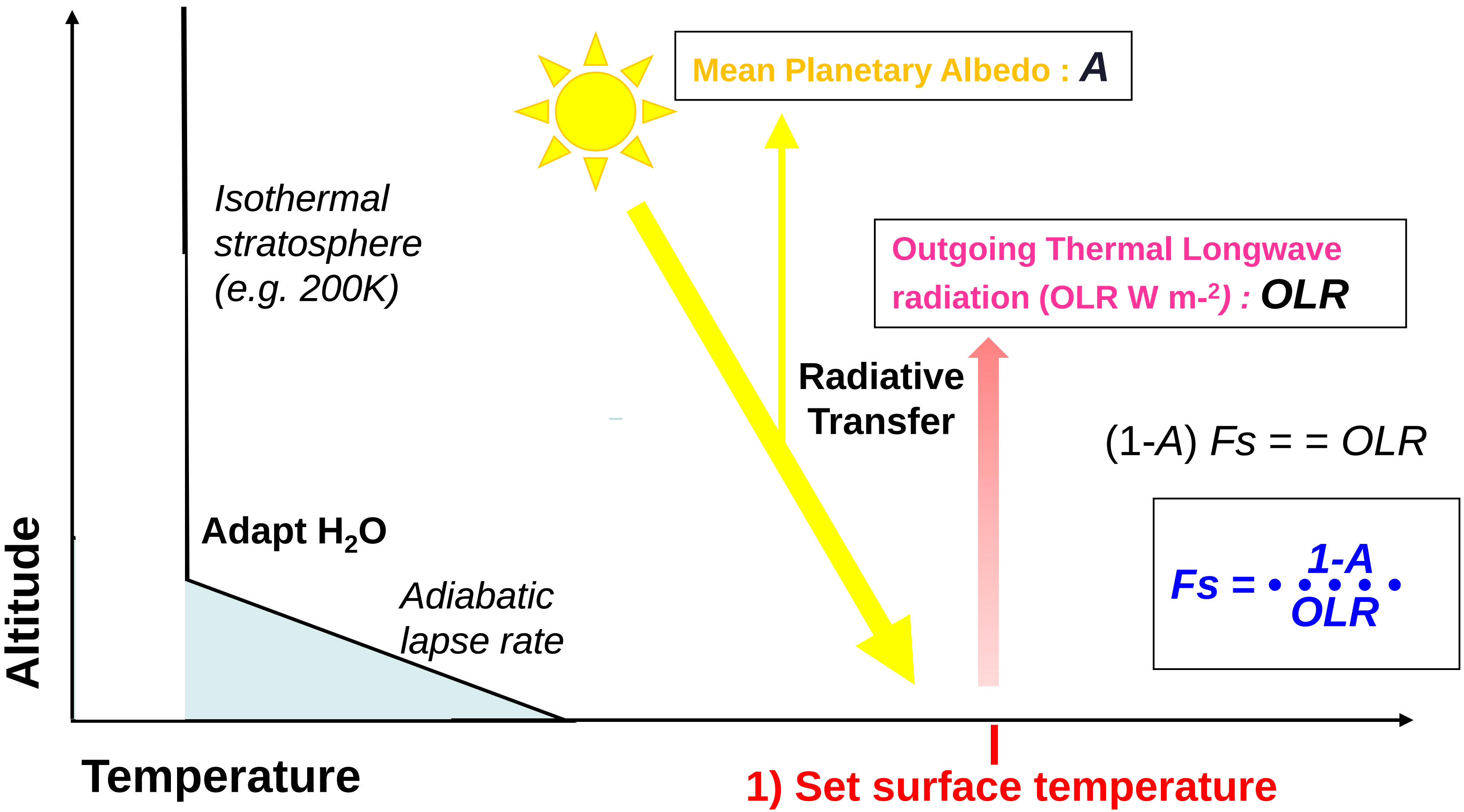
How to compute the radiative profiles from radiative convective calculations ?

- **“Time marching model”**
  - from an abitrary initial state, let the model converge to equilibrium.
  - Example: http://laps.lmd.jussieu.fr
- **“inverse climate modeling”**
  - Famous method used by Kasting and many other studies (see next slide).

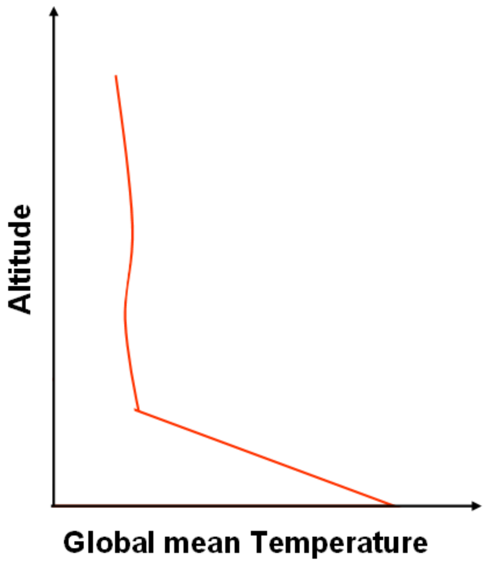
"Inverse climate modeling"

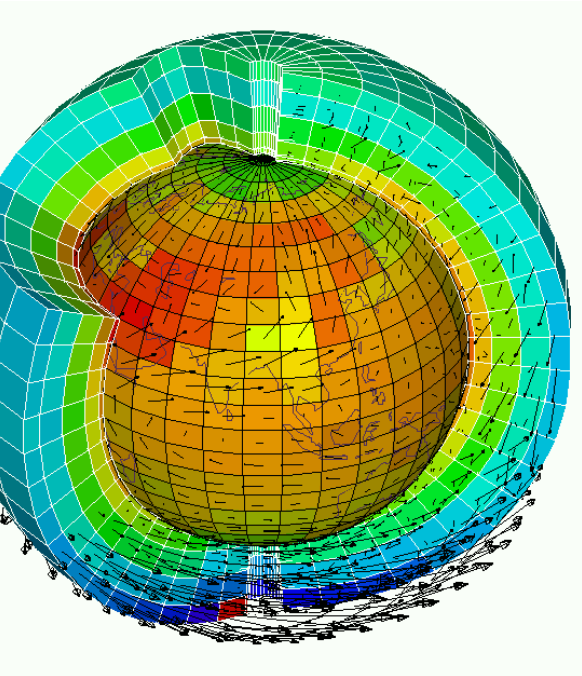
(*Kasting et al.*, *Kopparapu, etc.*)

⇨ Design to compute the solar flux ***Fs* needed** to achieve a **given** surface temperature



A hierarchy of models for planetary climates





1. 1D global radiative convective models
➩ Great to explore a wide range of possible climates; *(e.g. Kasting et al. 1993 , Kopparapu et al. 2013, 2014)*

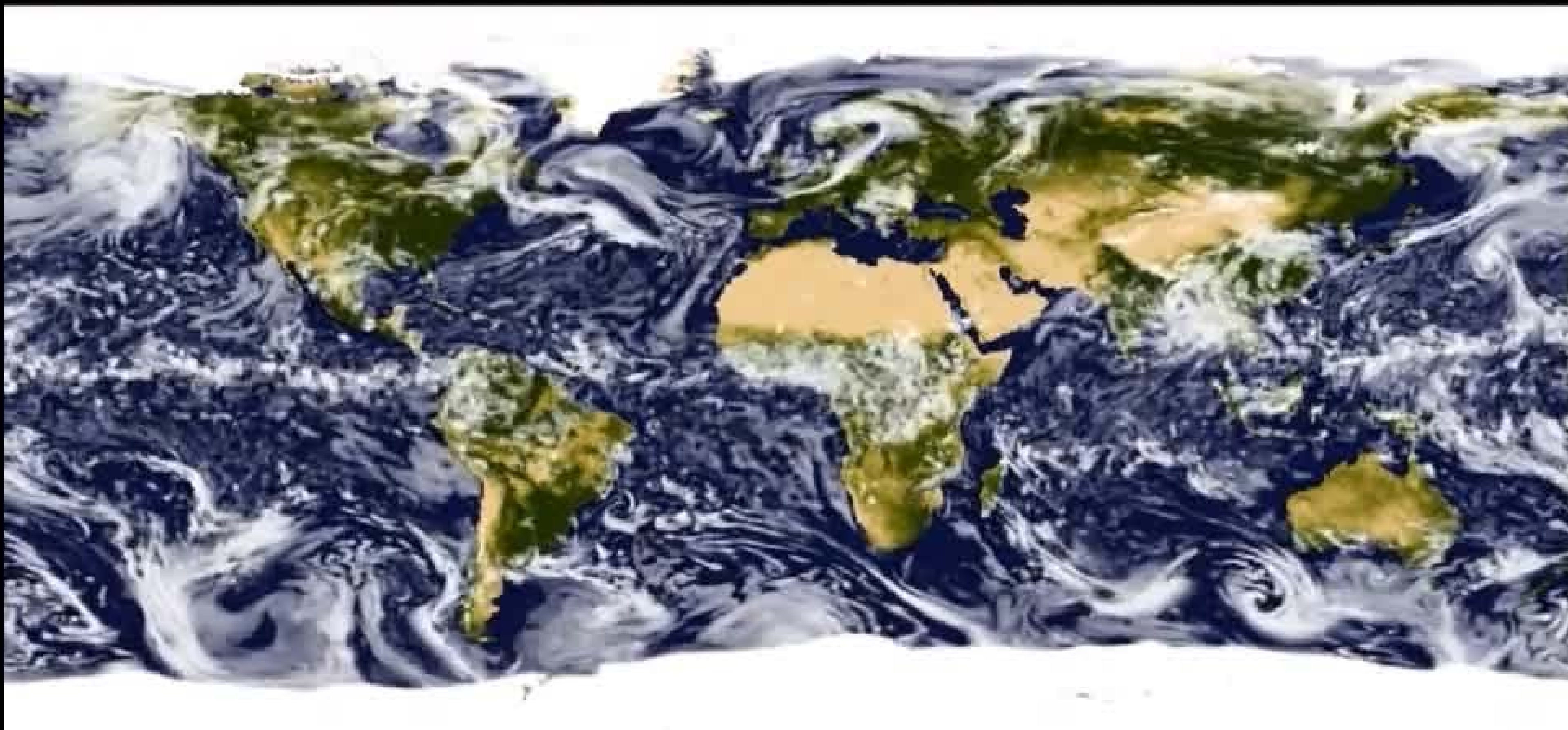
2. 2D Energy balance models…

3. Theoretical 3D General Circulation model with simplified forcing: used to explore and analyse the possible atmospheric circulation regime *(e.g. Read 2011, Kaspi & Showman 2015, etc)*

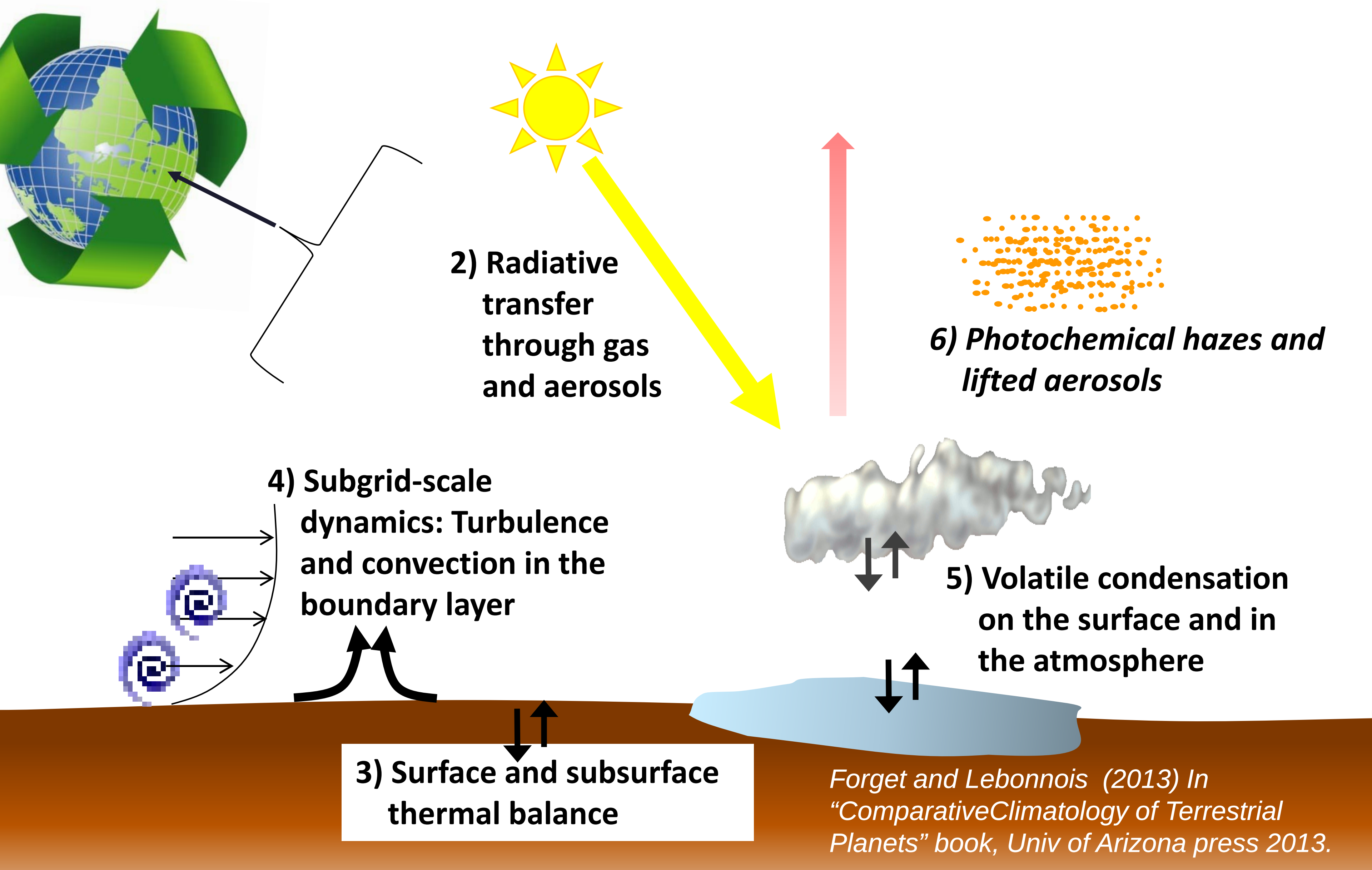
4. Full Global Climate Models aiming at building "virtual" planets.

How to build a full Global Climate Simulator ?

Community Earth System Model (CESM), NCAR (Boulder)

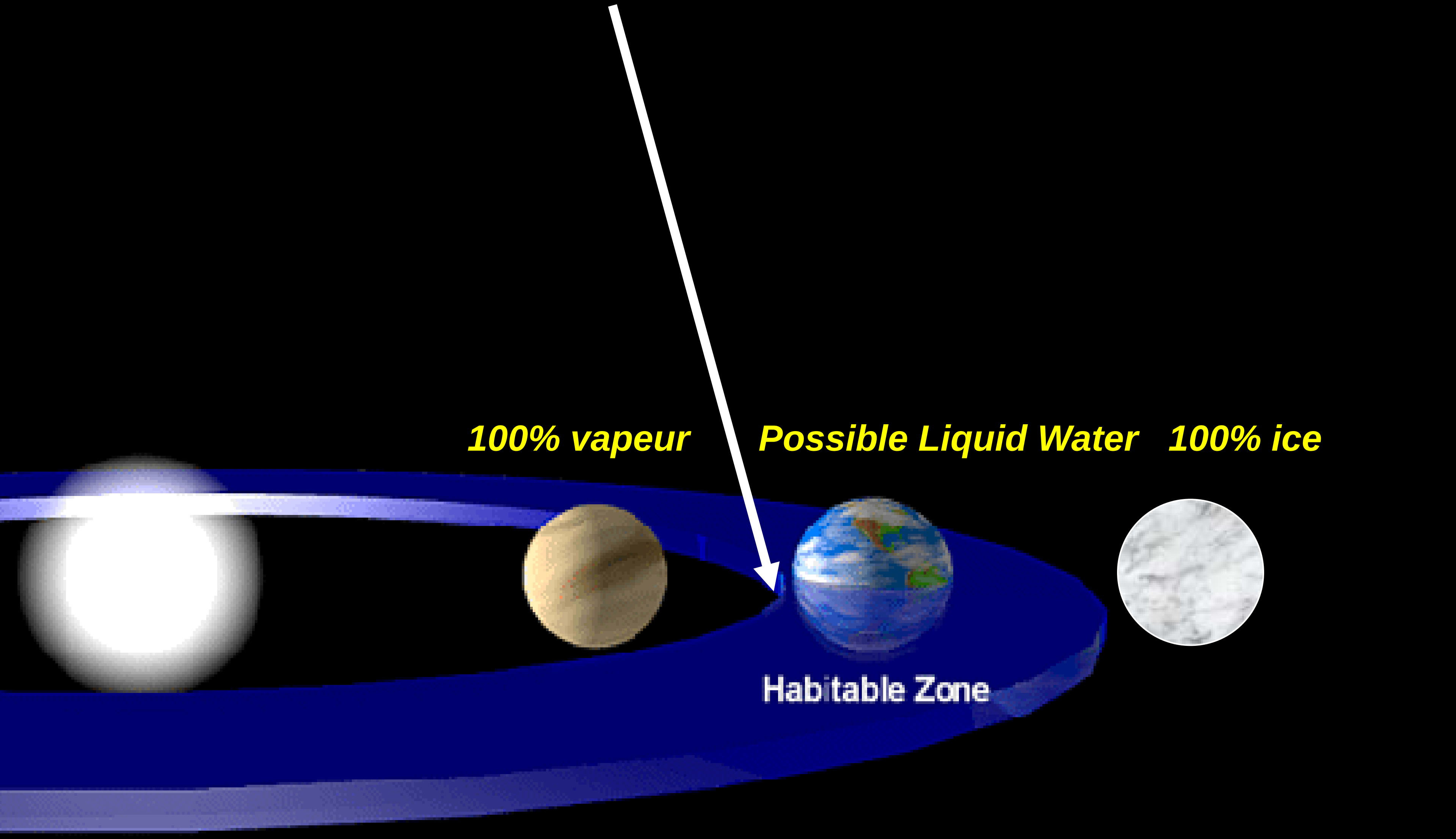


How to build a full Global Climate Simulator ?

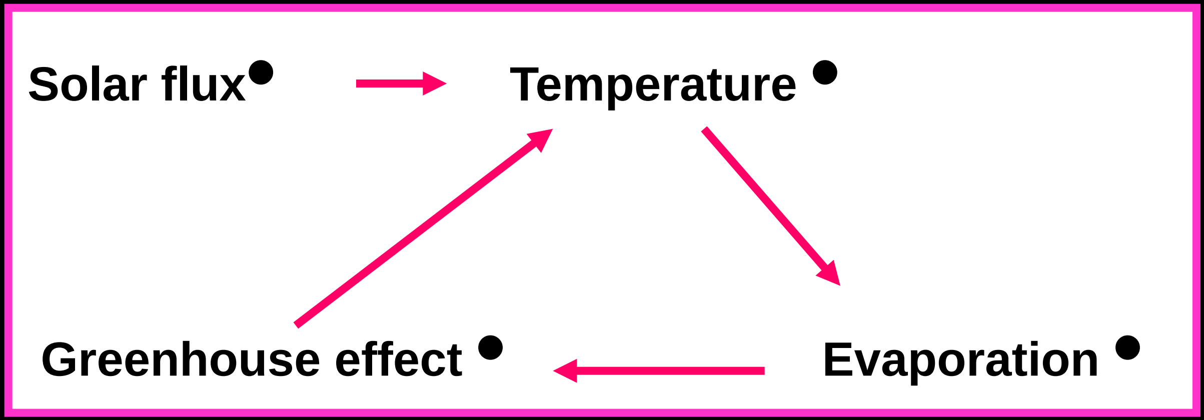


Forget and Lebonnois (2013) In "ComparativeClimatology of Terrestrial Planets" book, Univ of Arizona press 2013.

Surface habitability on warm planets: The Inner Edge of the Habitable Zone ?



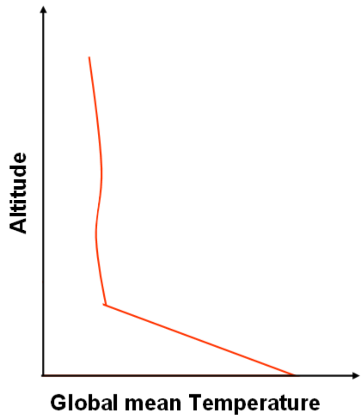
Inner limit of the Habitable zone
How close can one get to a sun-like star?

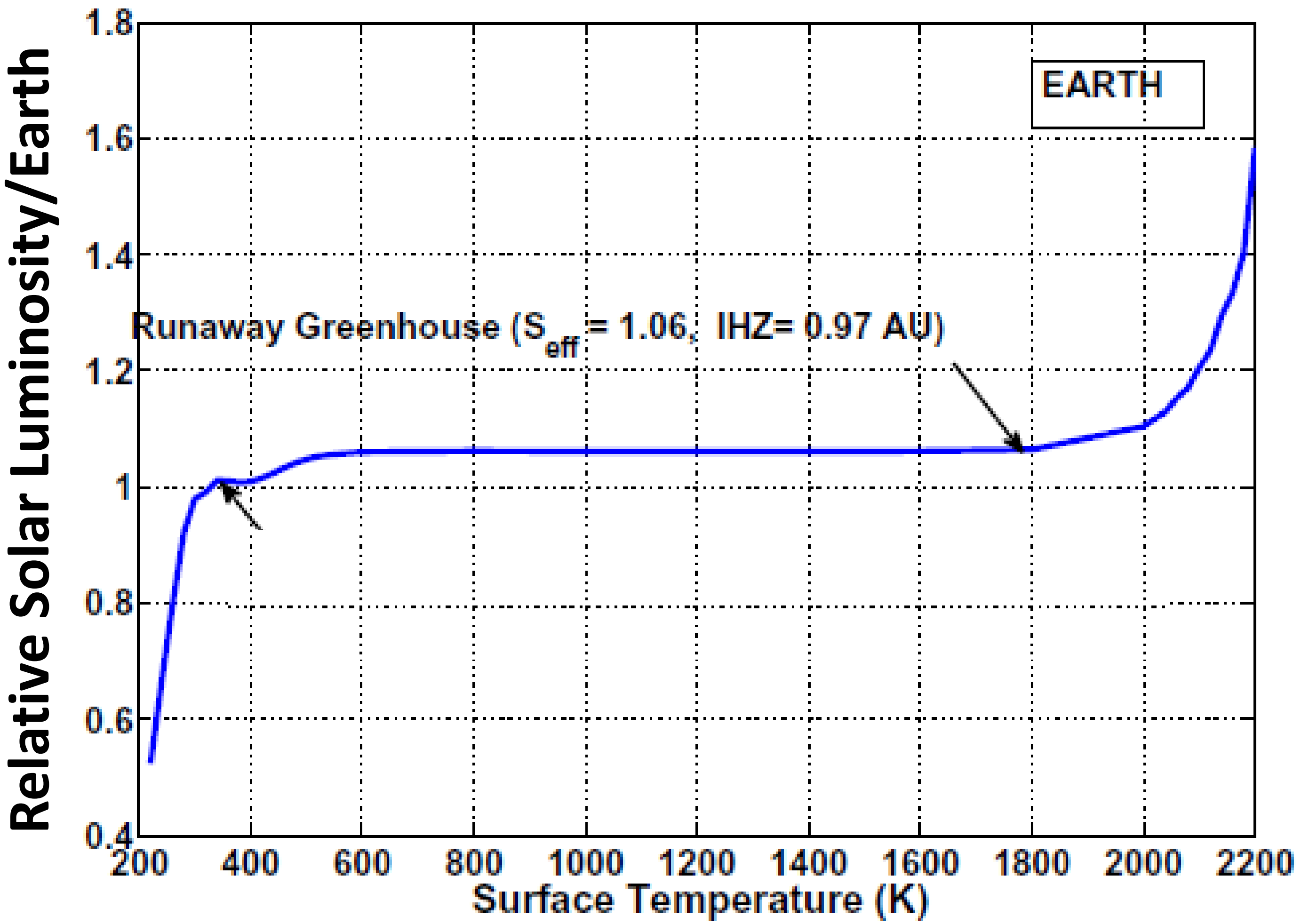


Runaway Greenhouse effect in 1D models

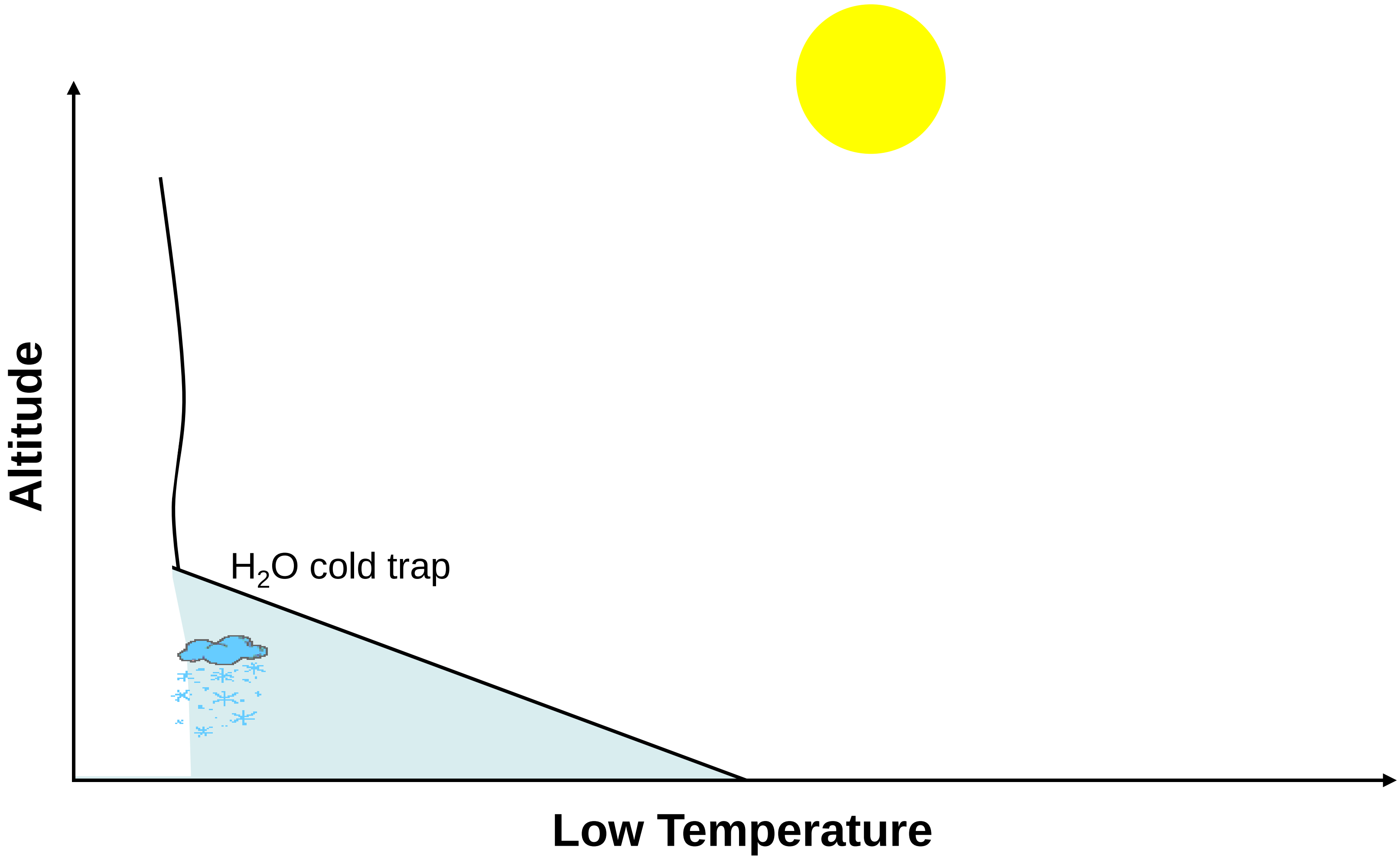
(for an Earth-like planet around a sun)

(*Ingersoll 1969, Kasting 1988, Kasting et al. 1993, Goldblatt et al. 2013, Kopparapu et al. 2013*)

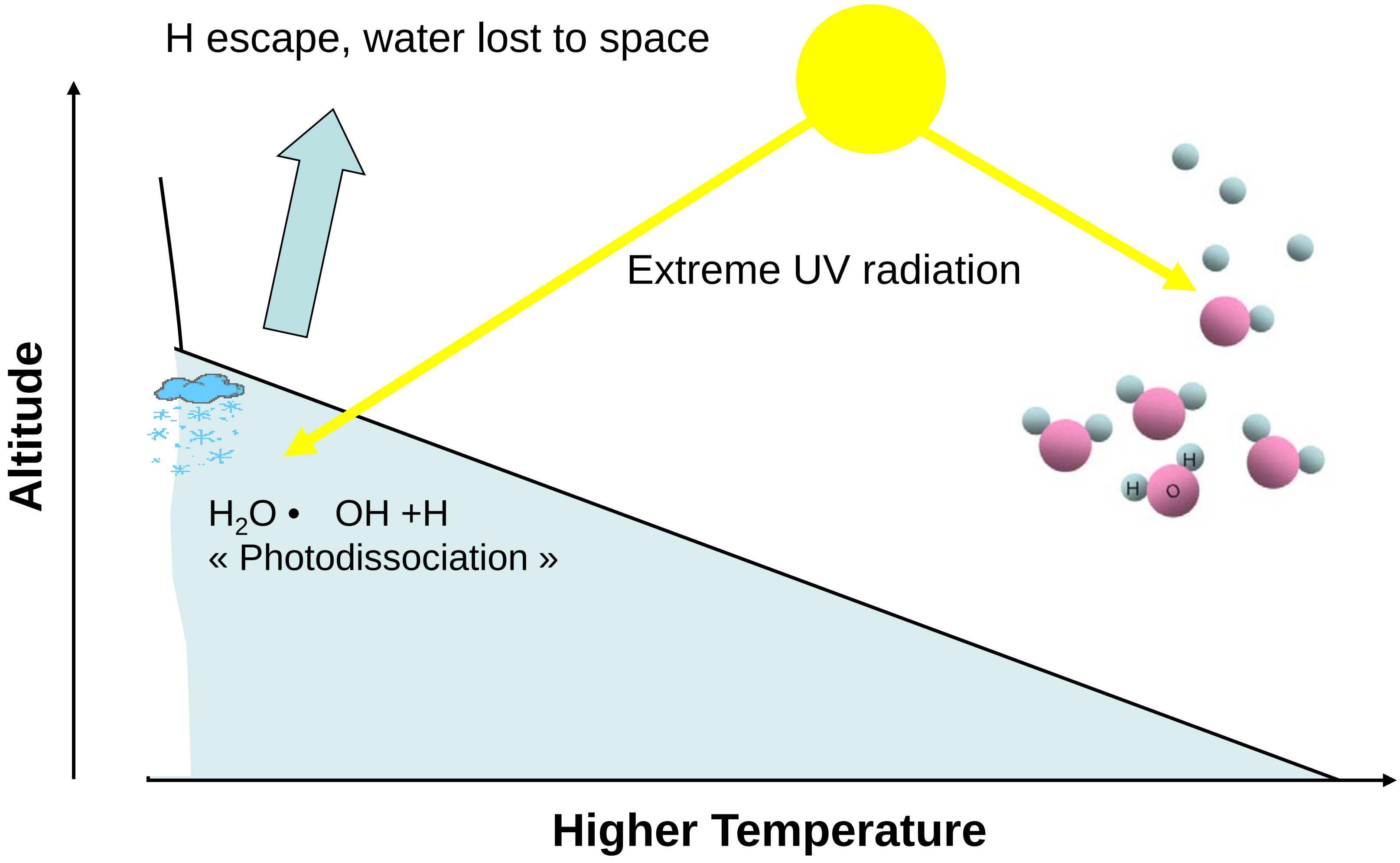


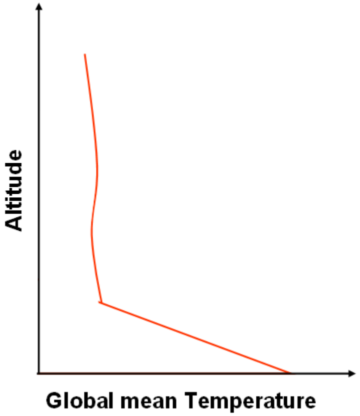


Impact of temperature increase on water vapor distribution and escape: the « water loss limit »… at only 0.99 AU from the Sun (*Kopparapu, Kasting et al. 2013*)



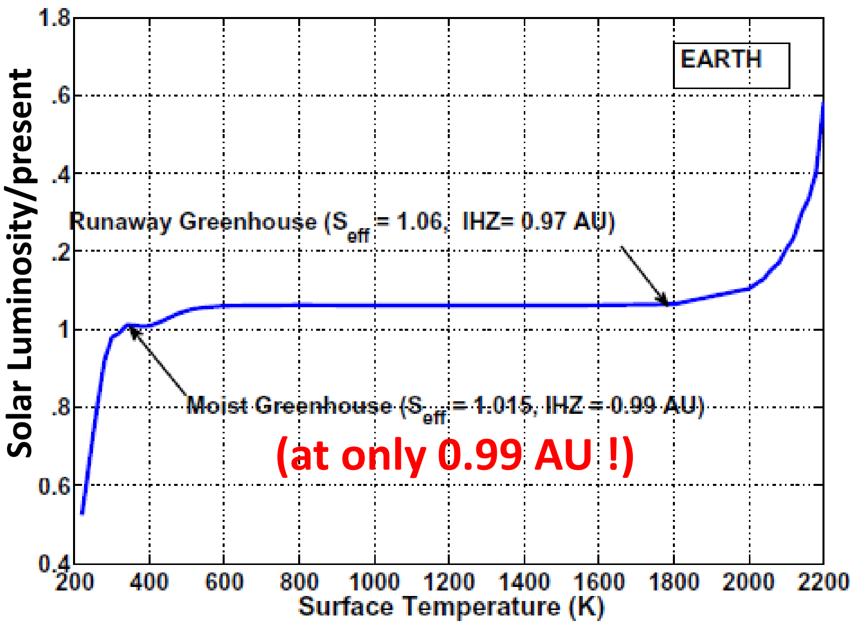
Impact of temperature increase on water vapor distribution and escape: the « water loss limit »… at only 0.99 AU from the Sun (*Kopparapu, Kasting et al. 2013*)

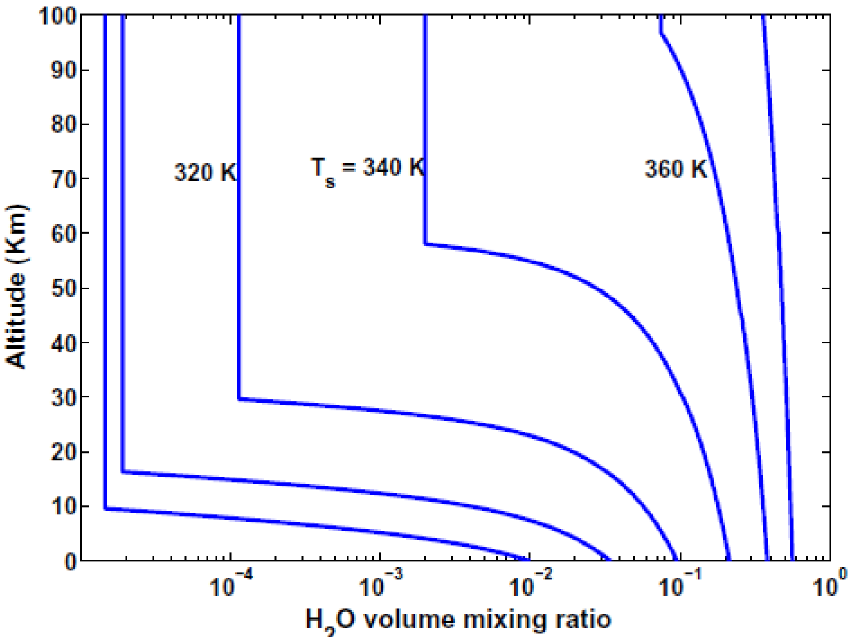


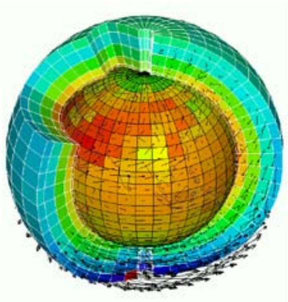


« Water loss limit » in 1D models

(*Ingersoll 1969, Kasting 1988, Kasting et al. 1993, Kopparapu et al. 2013*)



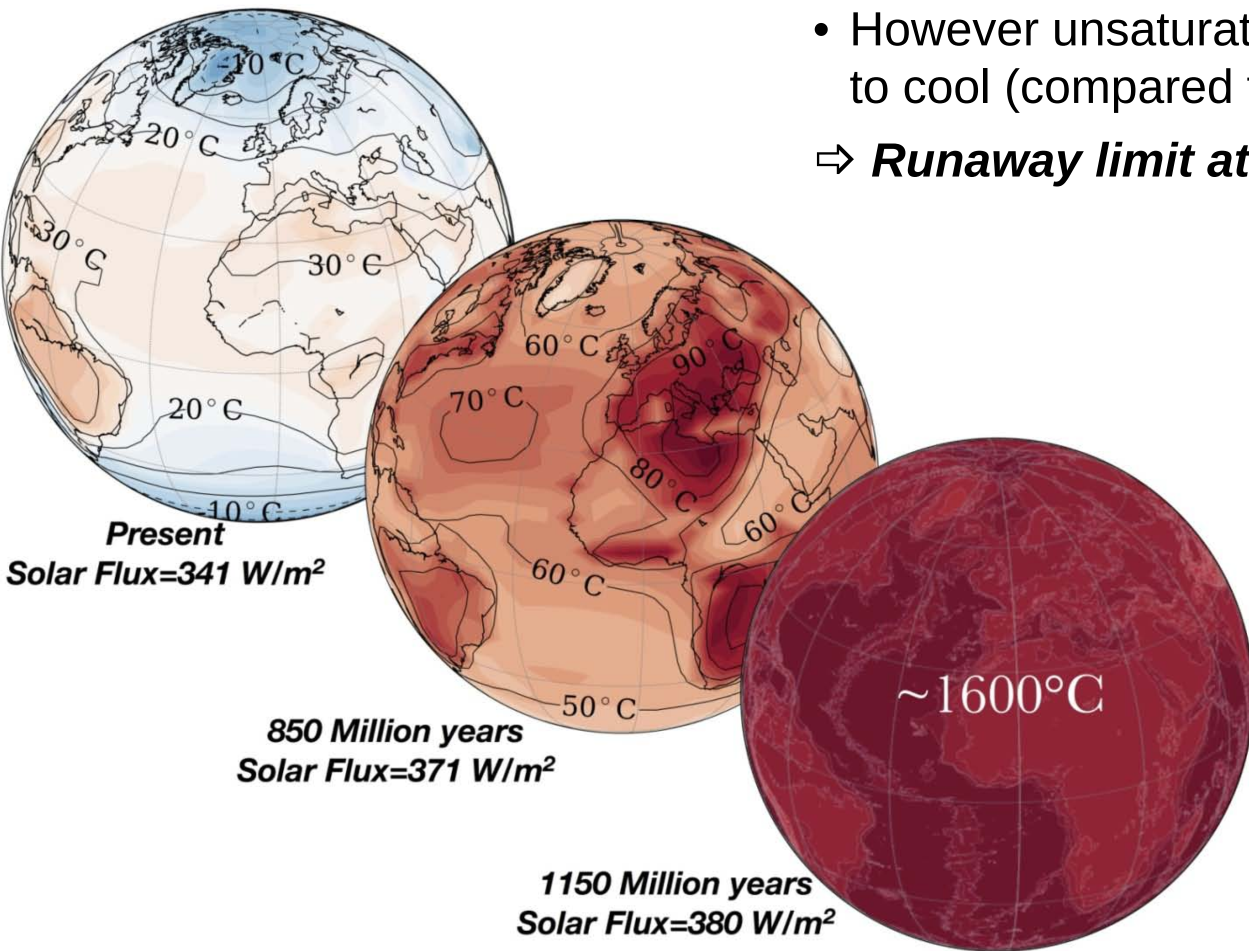




Runaway Greenhouse effect around the Sun in a complete 3D Global Climate model

- Complex processes with water vapor as a dominant gases
- On Earth-like planet clouds **warm** the surface
- However unsaturated regions allows the planet to cool (compared to 1D models)

⇨ ***Runaway limit at 0.95 AU***



Present
Solar Flux=341 W/m²

850 Million years
Solar Flux=371 W/m²

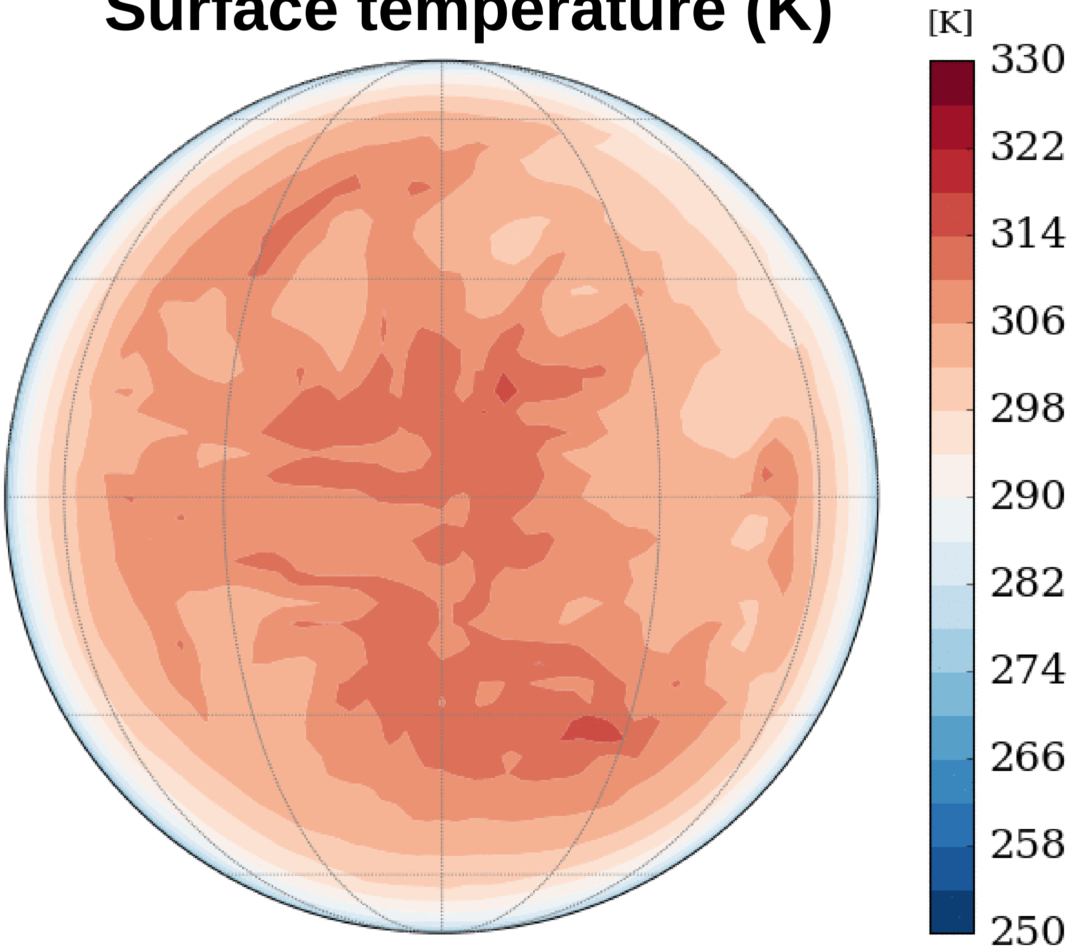
1150 Million years
Solar Flux=380 W/m²

- Leconte et al. « *3D Increased insolation threshold for runaway greenhouse processes on Earth like planets". **Nature,** 2013*
- Wolf and Toon *2014, 2015*
- Yang et al. 2013, *2014*

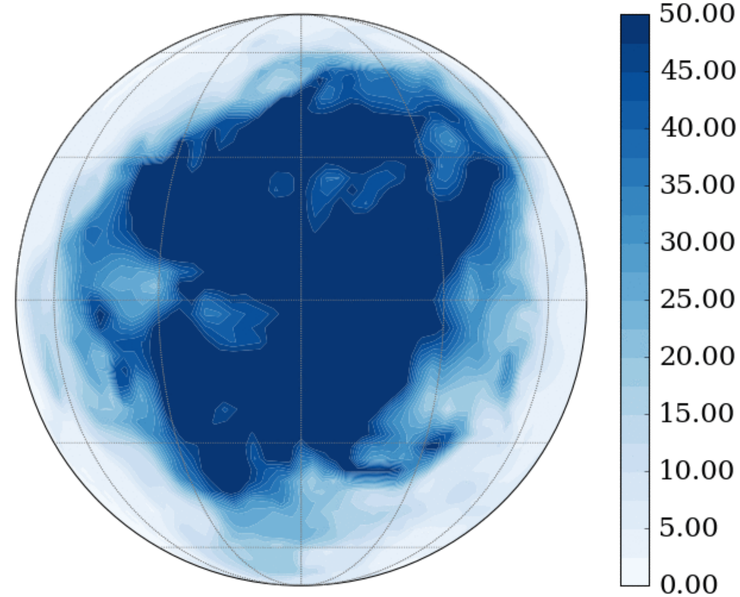
Runaway greenhouse effect on a slowly rotating planet…

(Simulation Jeremy Leconte, LMD climate model)

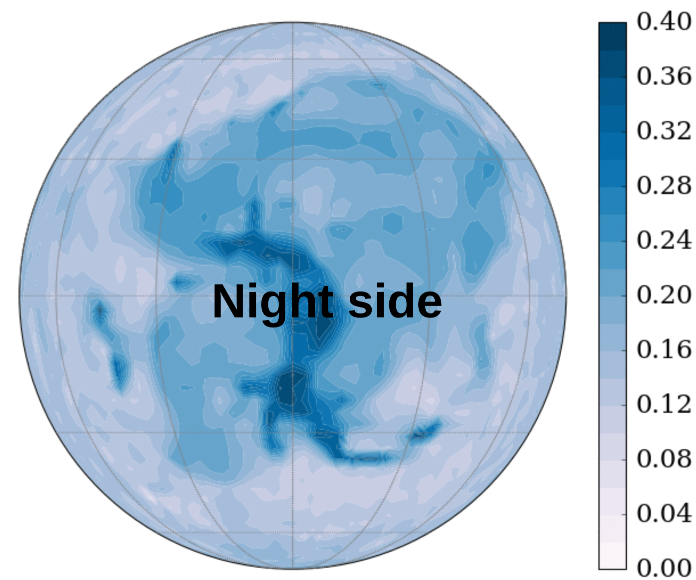
Surface temperature (K)



Cloud opacity



Planetary Albedo



Runaway greenhouse effect on a slowly rotating planet…

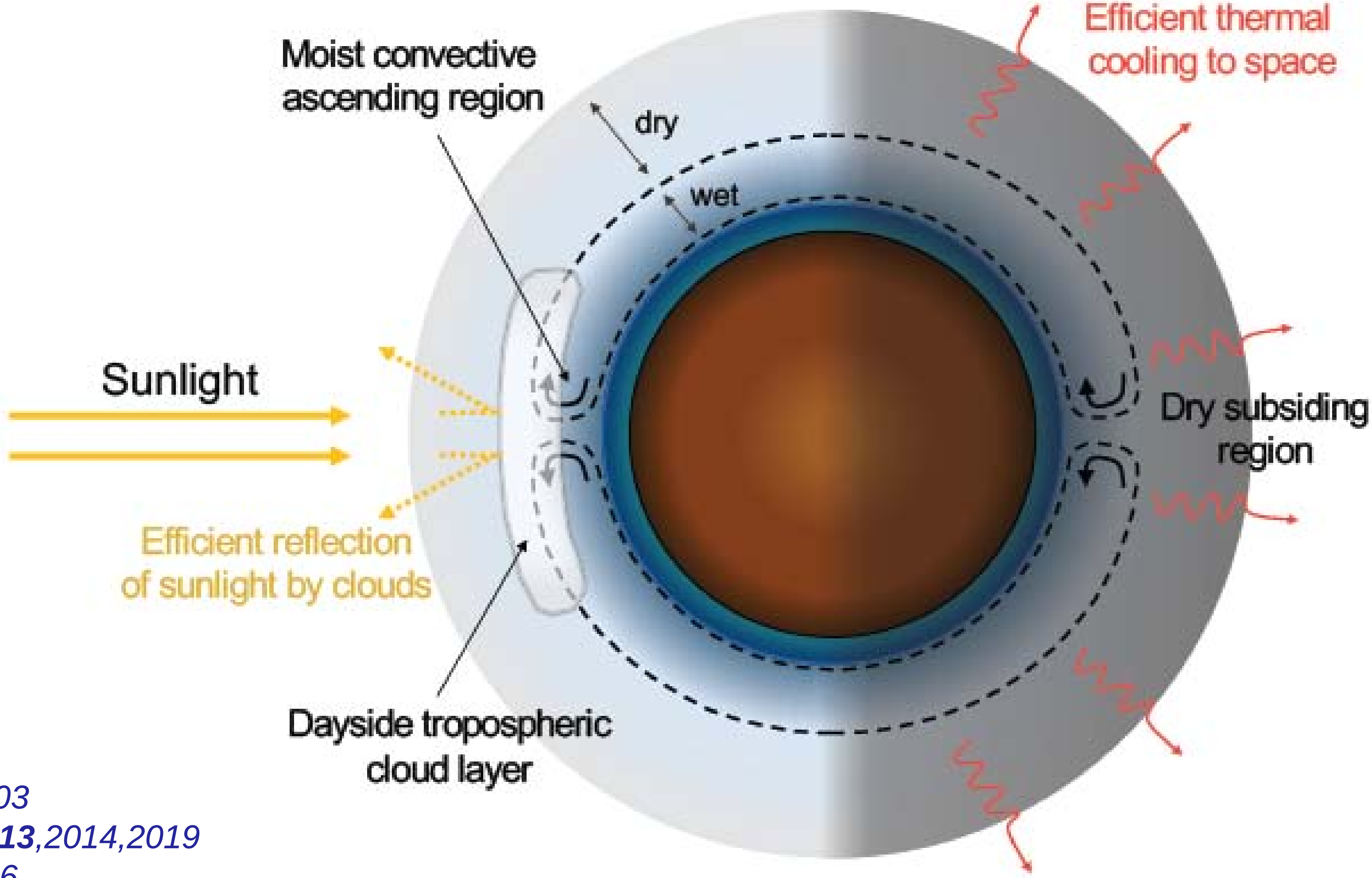
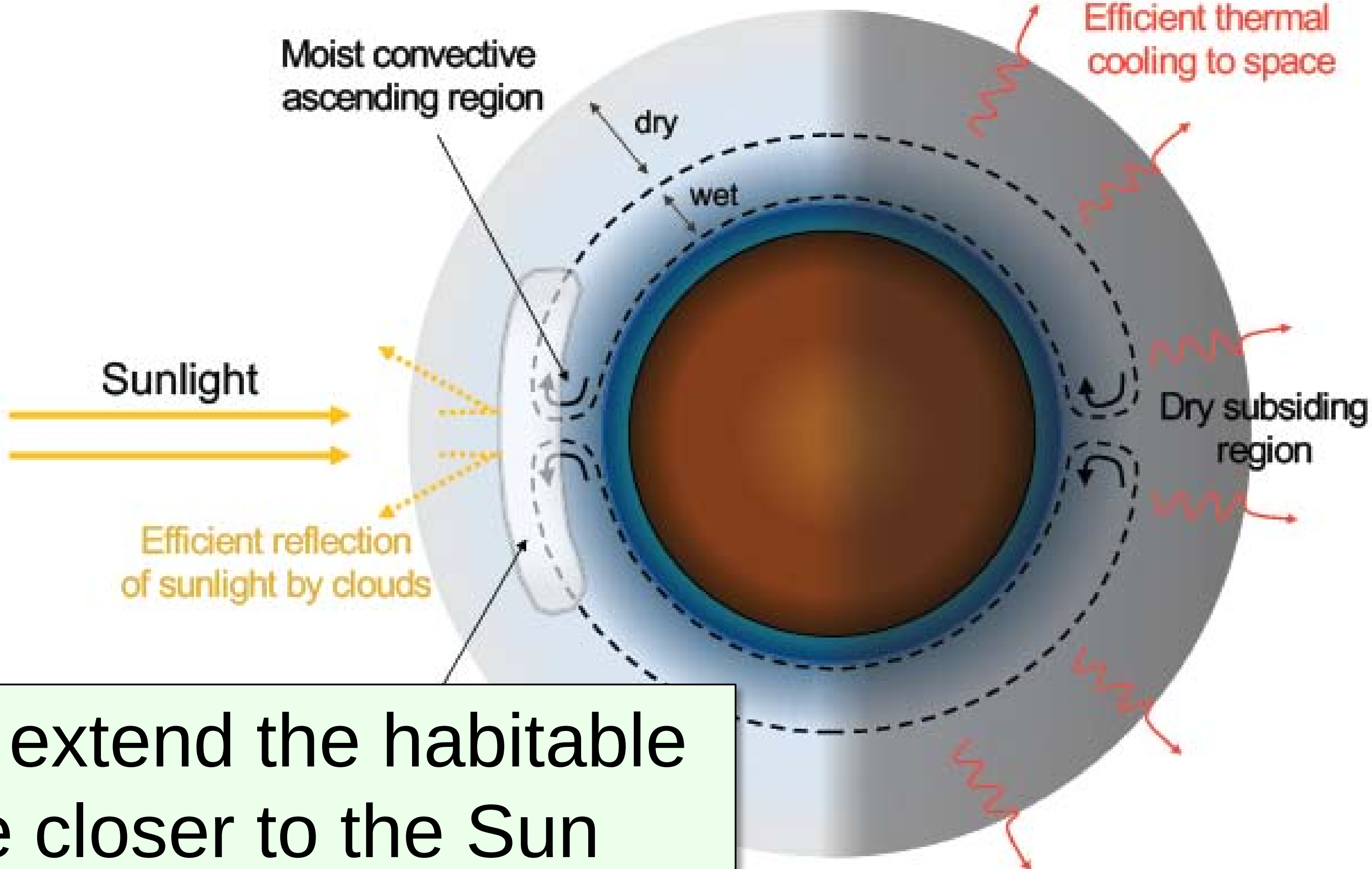


Figure from Turbet et al. (2021)

Joshi et al. 2003
***Yang et al. 2013**,2014,2019*
Way et al. 2016
Way & Del Genio 2020
Kopparapu et al. 2016
Fauchez et al. 2020
Sergeev et al. 2020, 2021

Runaway greenhouse effect on a slowly rotating planet…

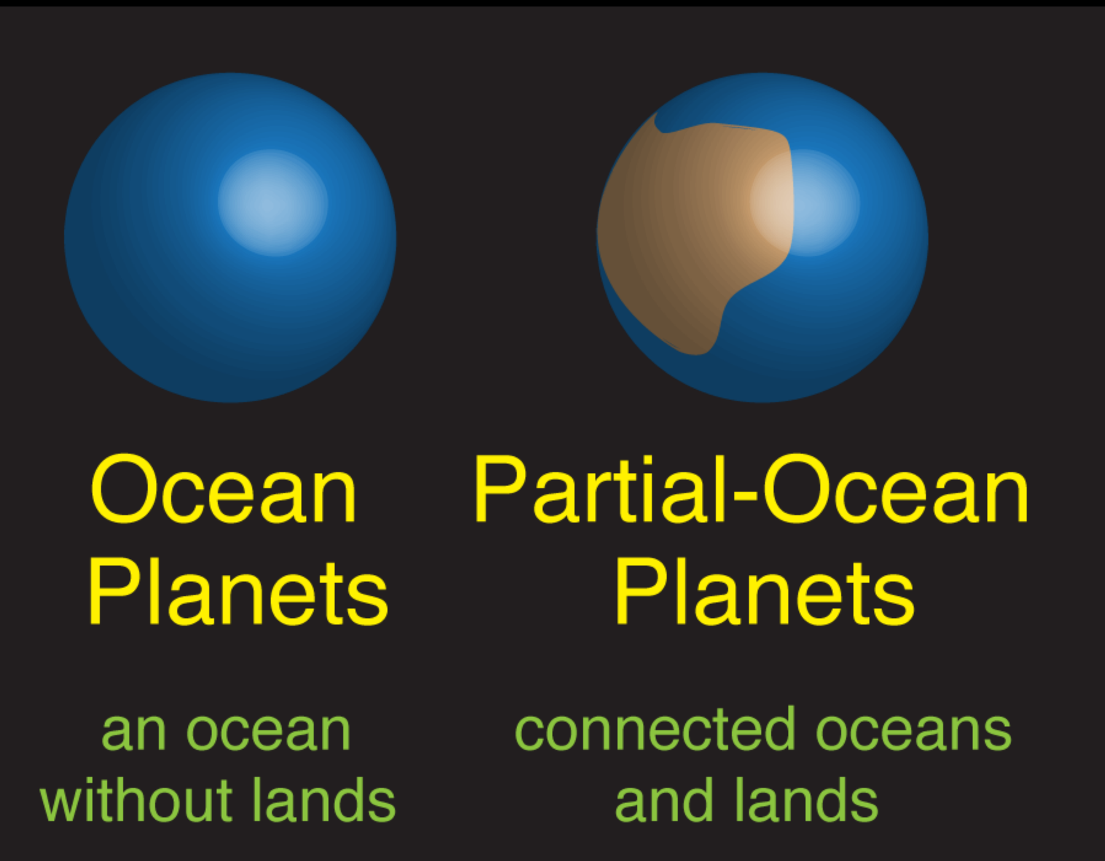


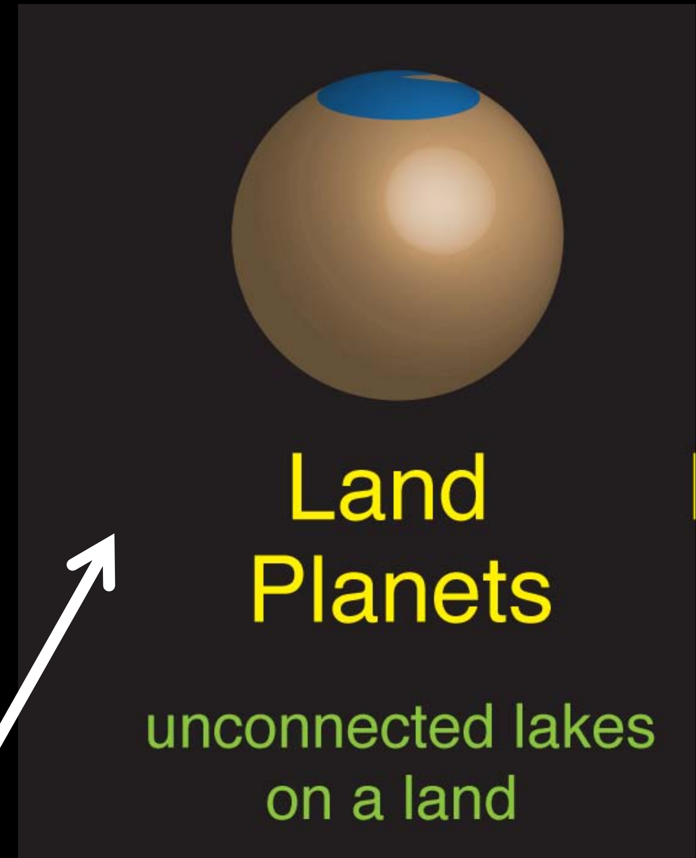
Can extend the habitable zone closer to the Sun down to 0.7 or 0.5 AU

Figure from Turbet et al. (2021)

Climate also depends on the amount of available water

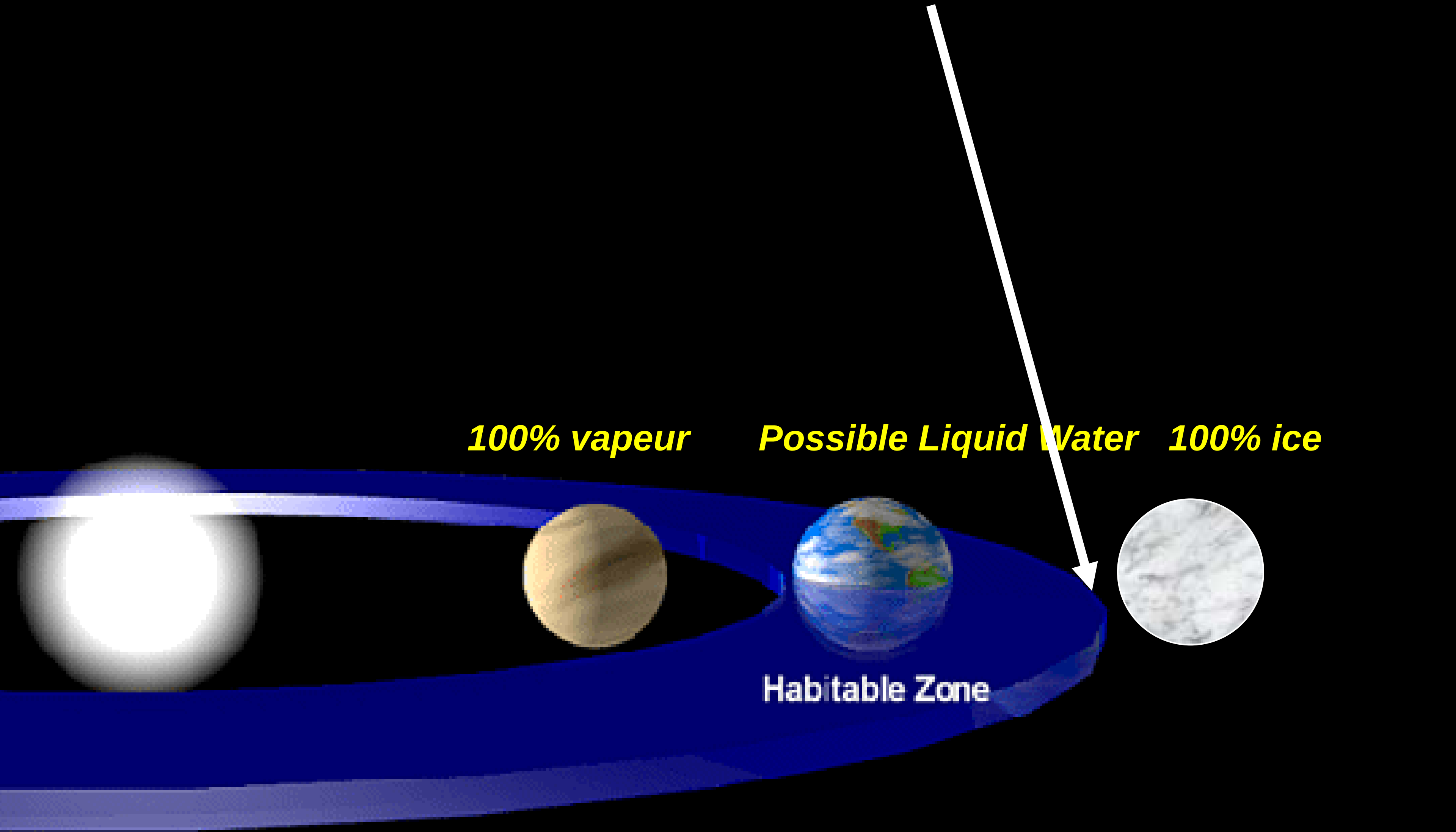
(e.g. Abe et al. 2011, Kodama et al. 2015, 2019)



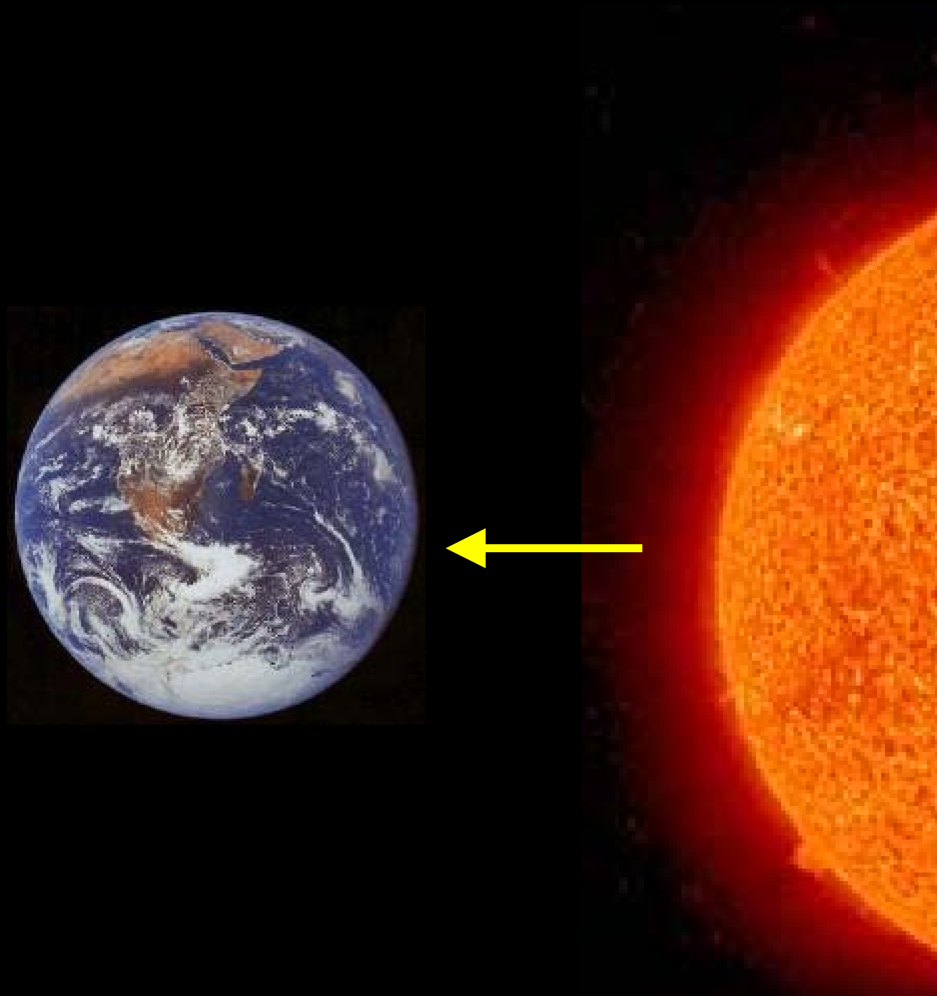


- Runaway greenhouse depends on mean insolation at the edge of the polar sea (cold trap)
- « Runaway limit significantly extended »

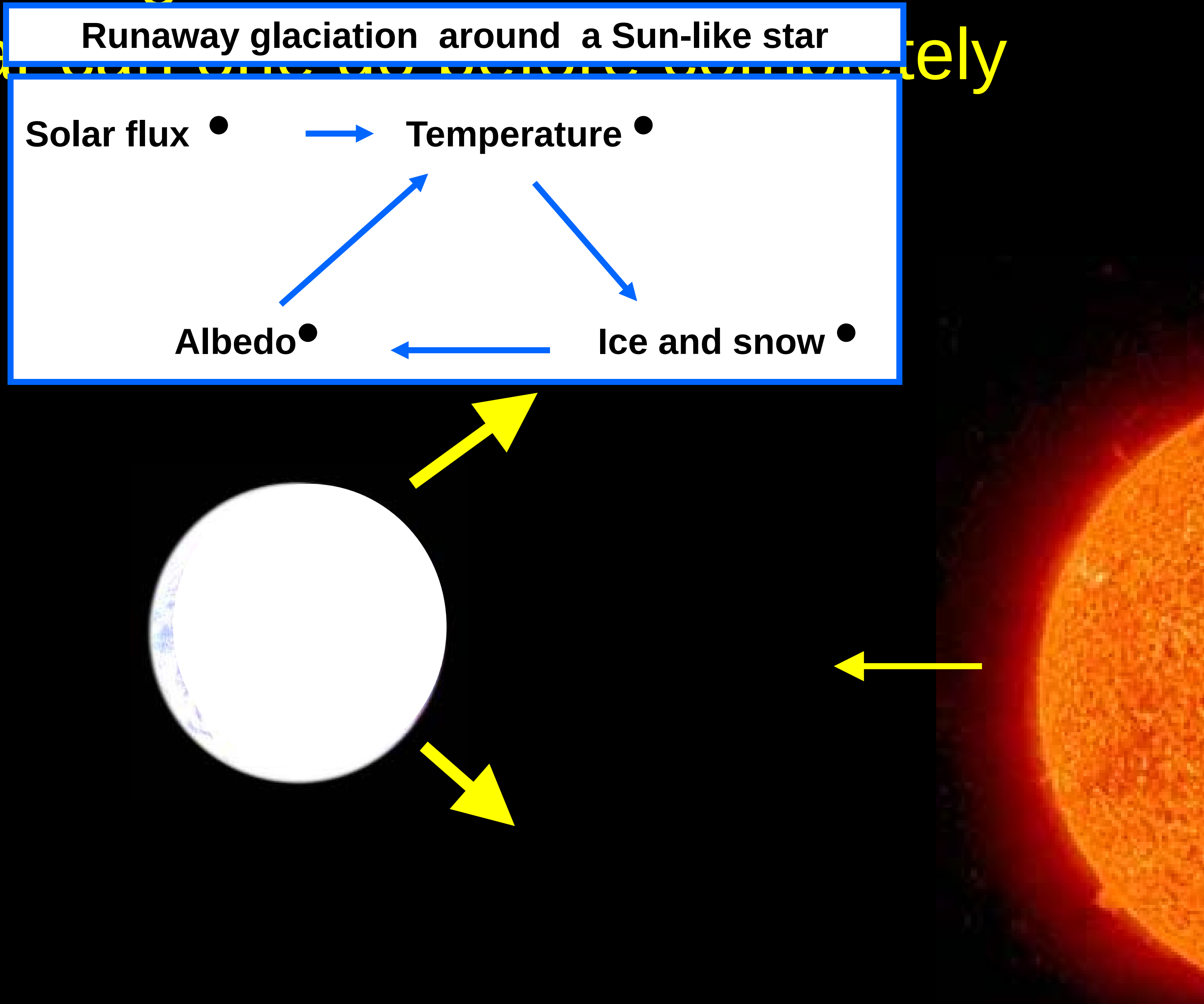
Habitability on cold planets
Outer Edge of the Habitable Zone ?



Outer edge of the habitable zone : how far can one go before completely freezing the planet ?



Outer edge of the habitable zone : how fa… tely

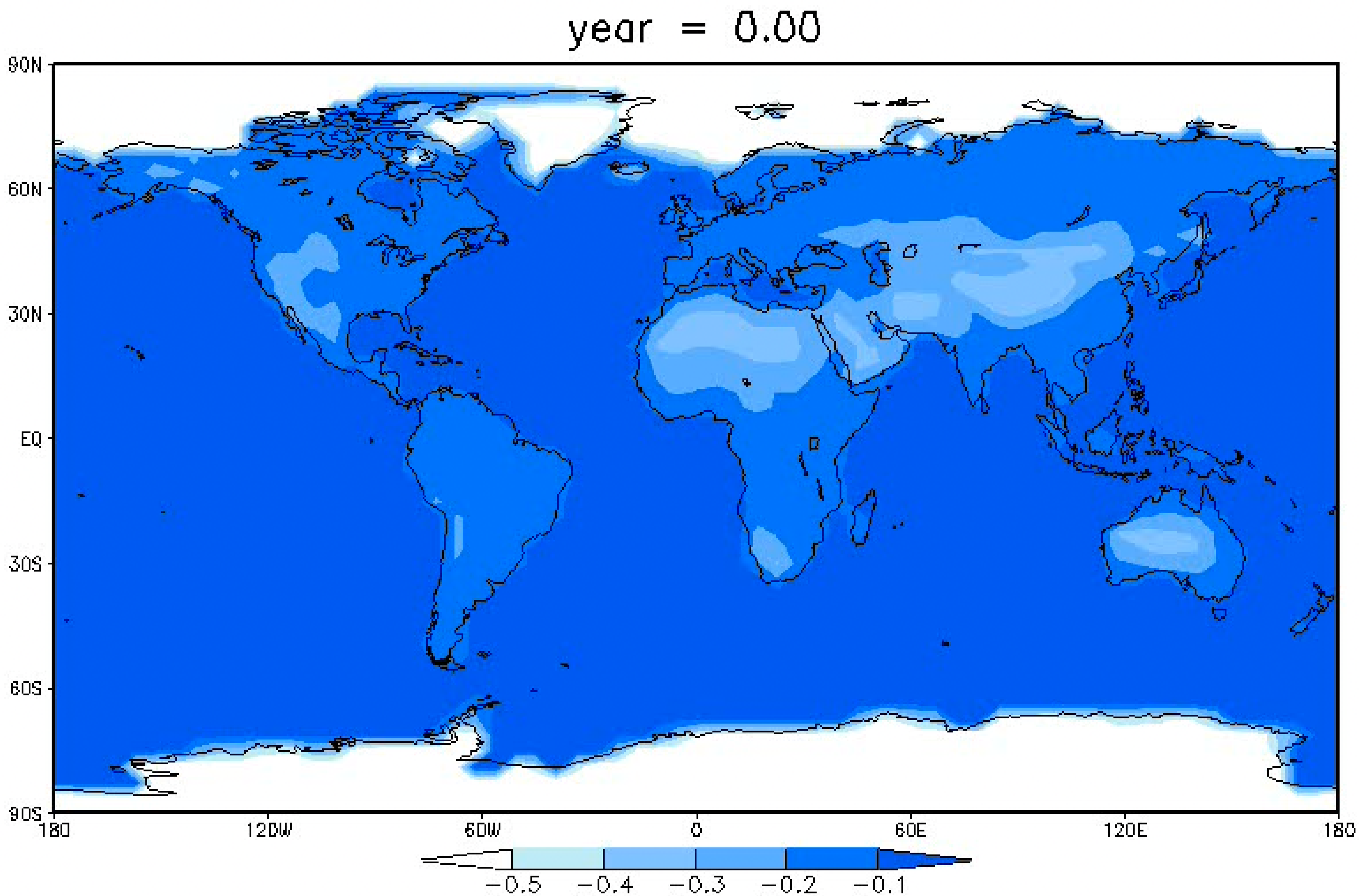


Climate Modelling: the Earth suddenly moved out by 12%

(79% current insolation = the Earth 3 billions years ago)

LMD Generic Climate model, with a "dynamical slab Ocean" (*Benjamin Charnay et al. JGR 2013)*

ALBEDO:

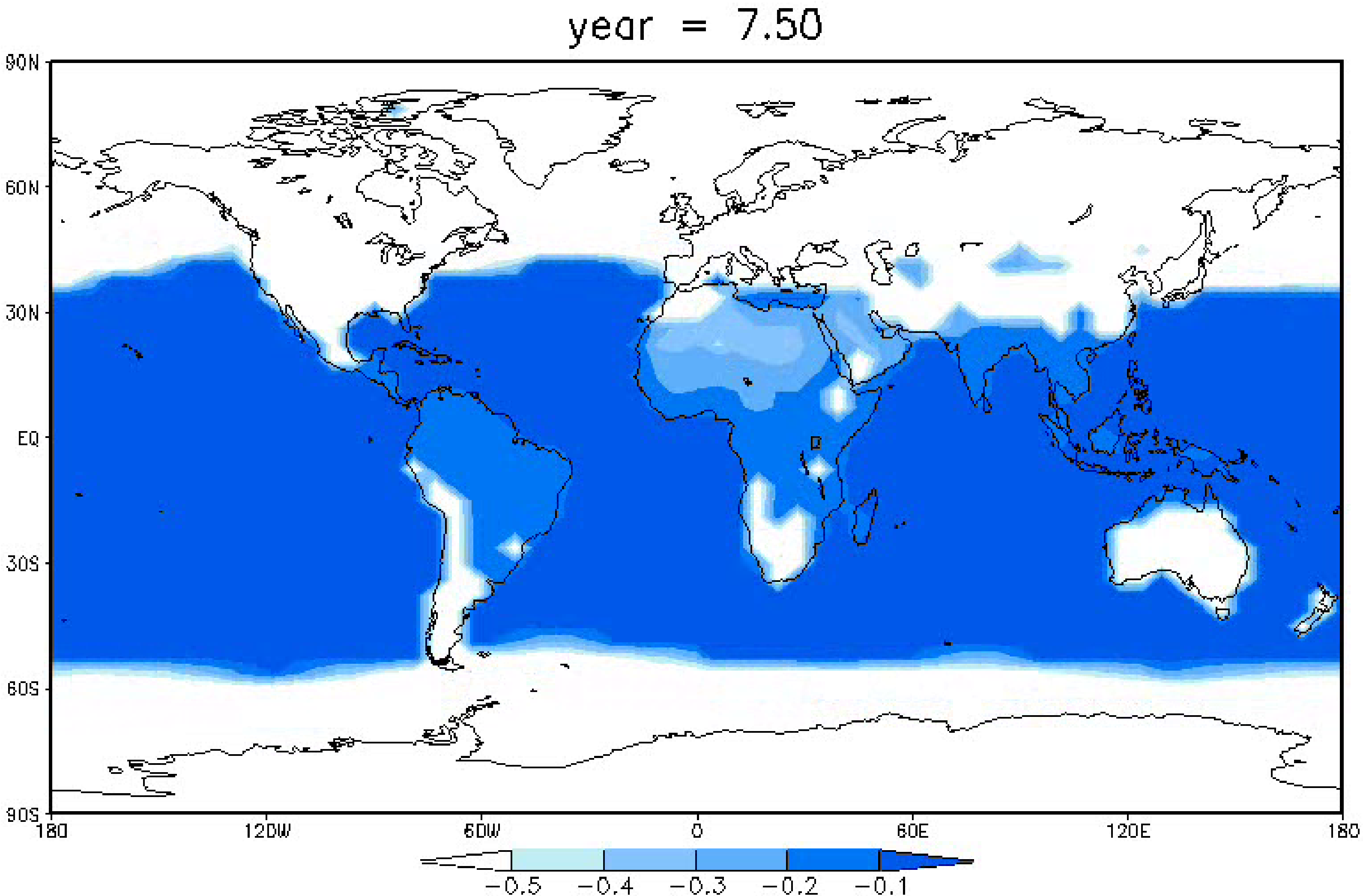


Climate Modelling: the Earth suddenly moved out by 12%

(79% current insolation = the Earth 3 billions years ago)

LMD Generic Climate model, with a "dynamical slab Ocean" (*Benjamin Charnay et al. JGR 2013)*

ALBEDO:

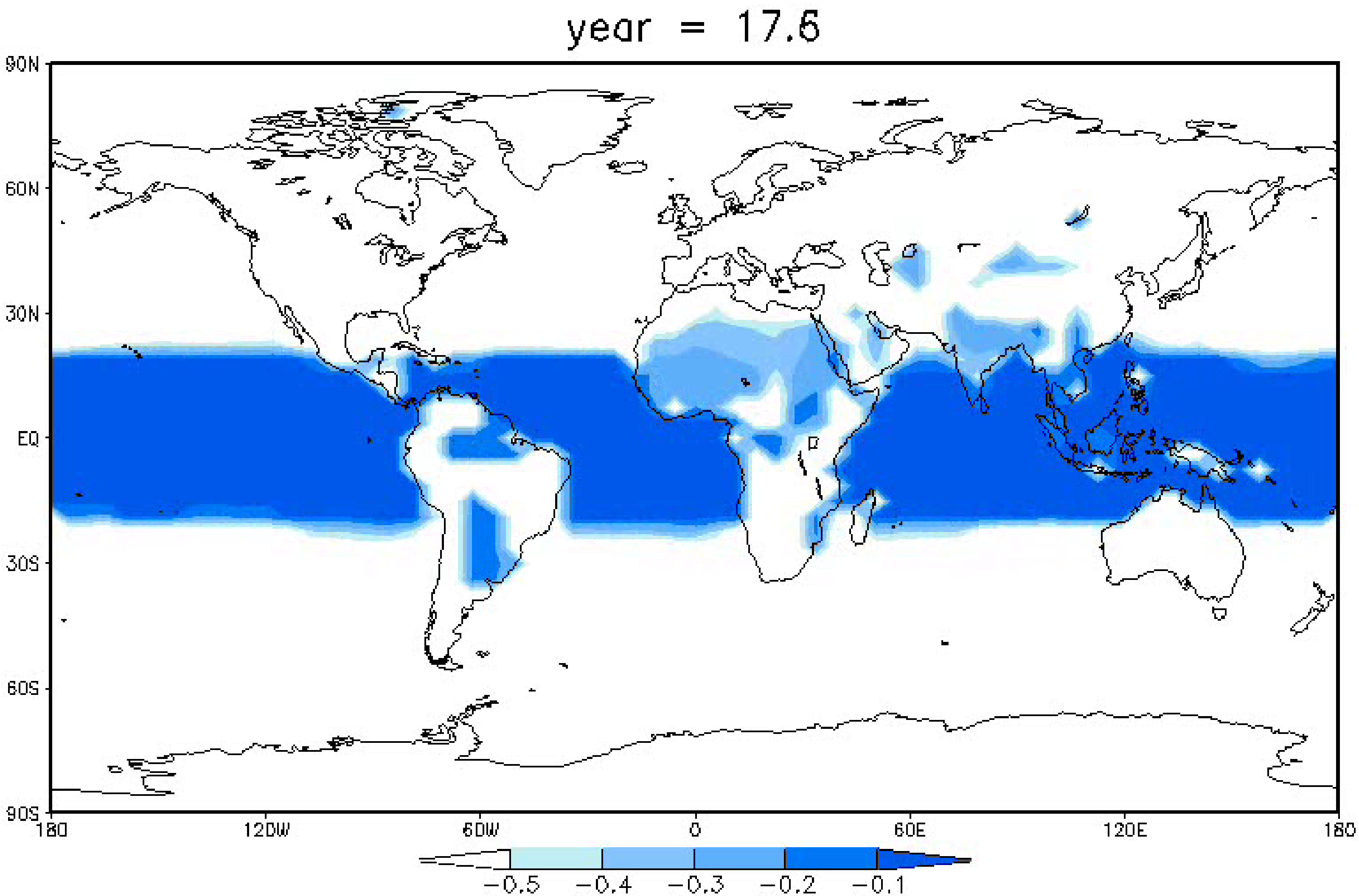


Climate Modelling: the Earth suddenly moved out by 12%

(79% current insolation = the Earth 3 billions years ago)

LMD Generic Climate model, with a "dynamical slab Ocean" (*Benjamin Charnay et al. JGR 2013)*

ALBEDO:

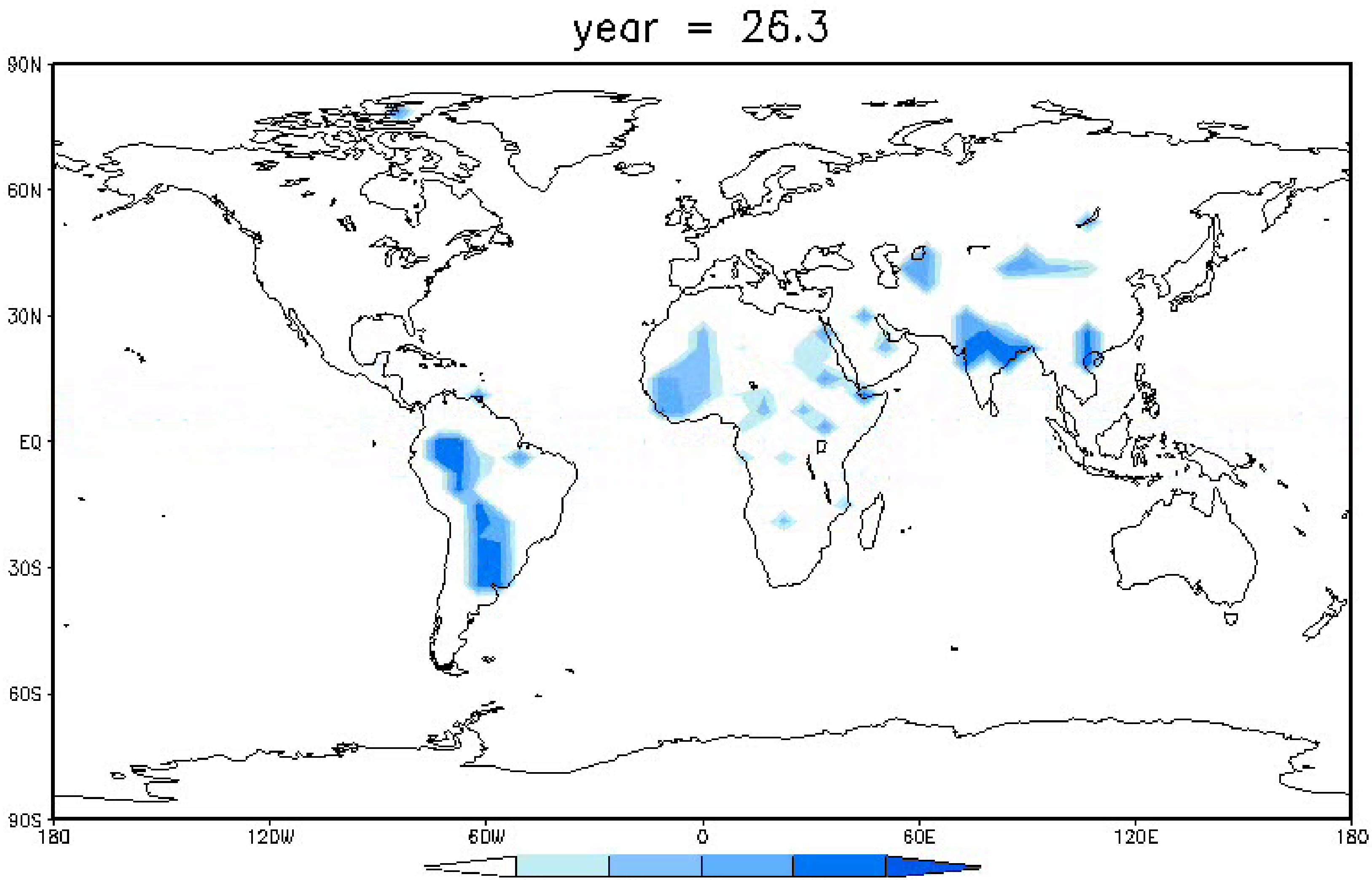


Climate Modelling: the Earth suddenly moved out by 12%

(79% current insolation = the Earth 3 billions years ago)

LMD Generic Climate model, with a "dynamical slab Ocean" (*Benjamin Charnay et al. JGR 2013)*

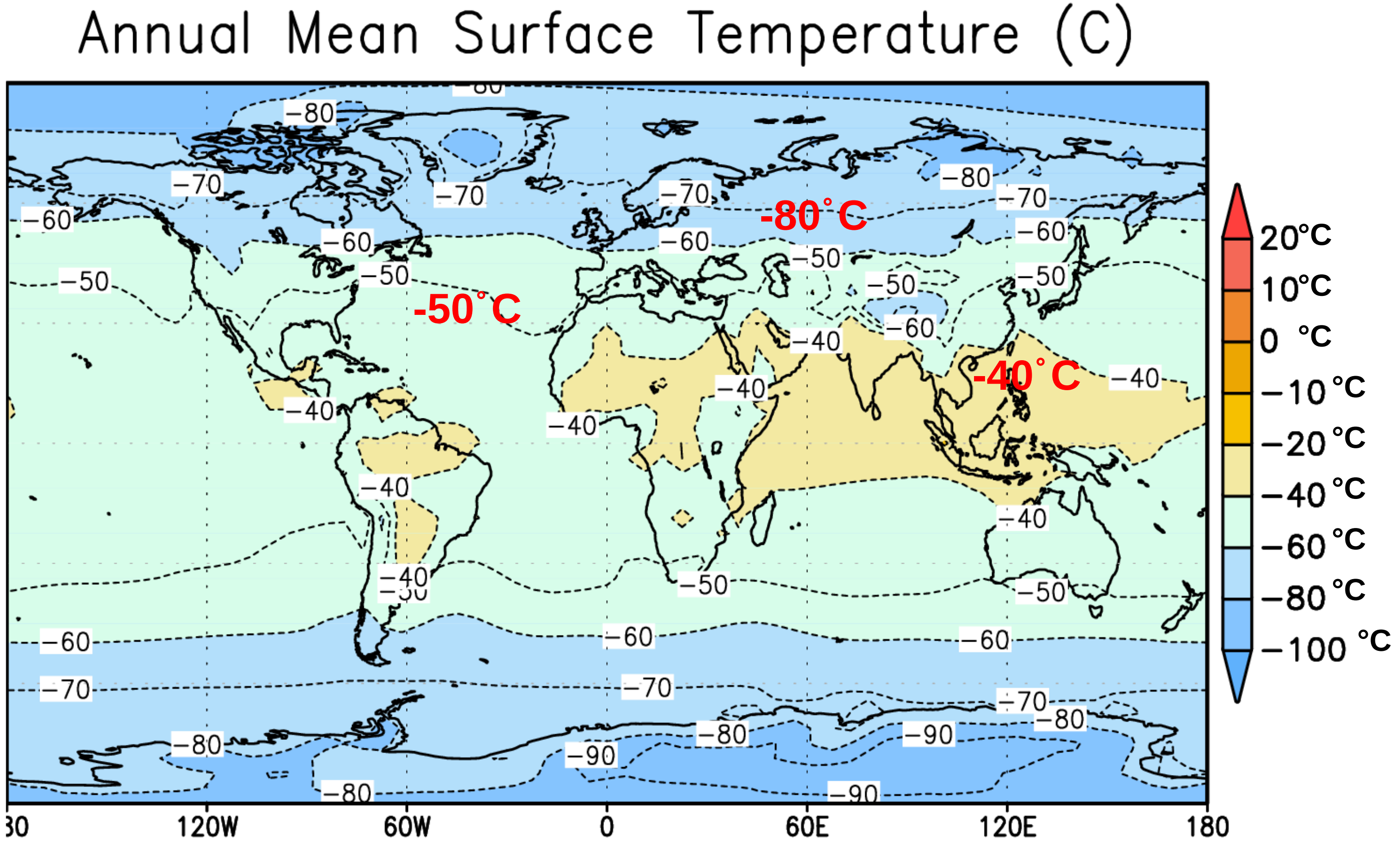
ALBEDO:



Climate Modelling: the Earth suddenly moved by 12%

(79% current insolation = the Earth 3 billions years ago)

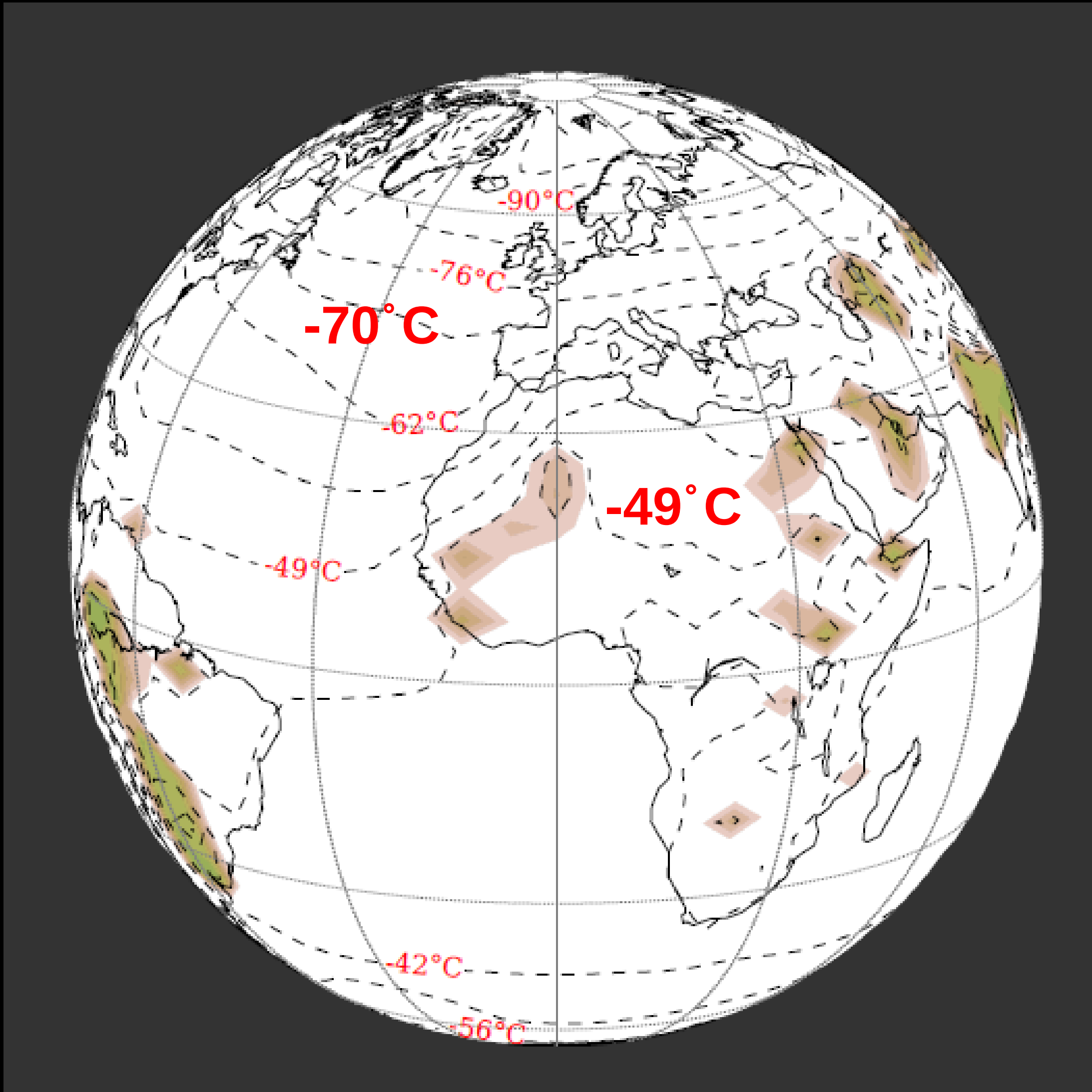
LMD Generic Climate model, with a "dynamical slab Ocean" (*Benjamin Charnay et al. JGR 2013)*



Out of glaciation: greenhouse effect

Flux = 80% present
(~1.12 AU)

Present
Earth atmosphere

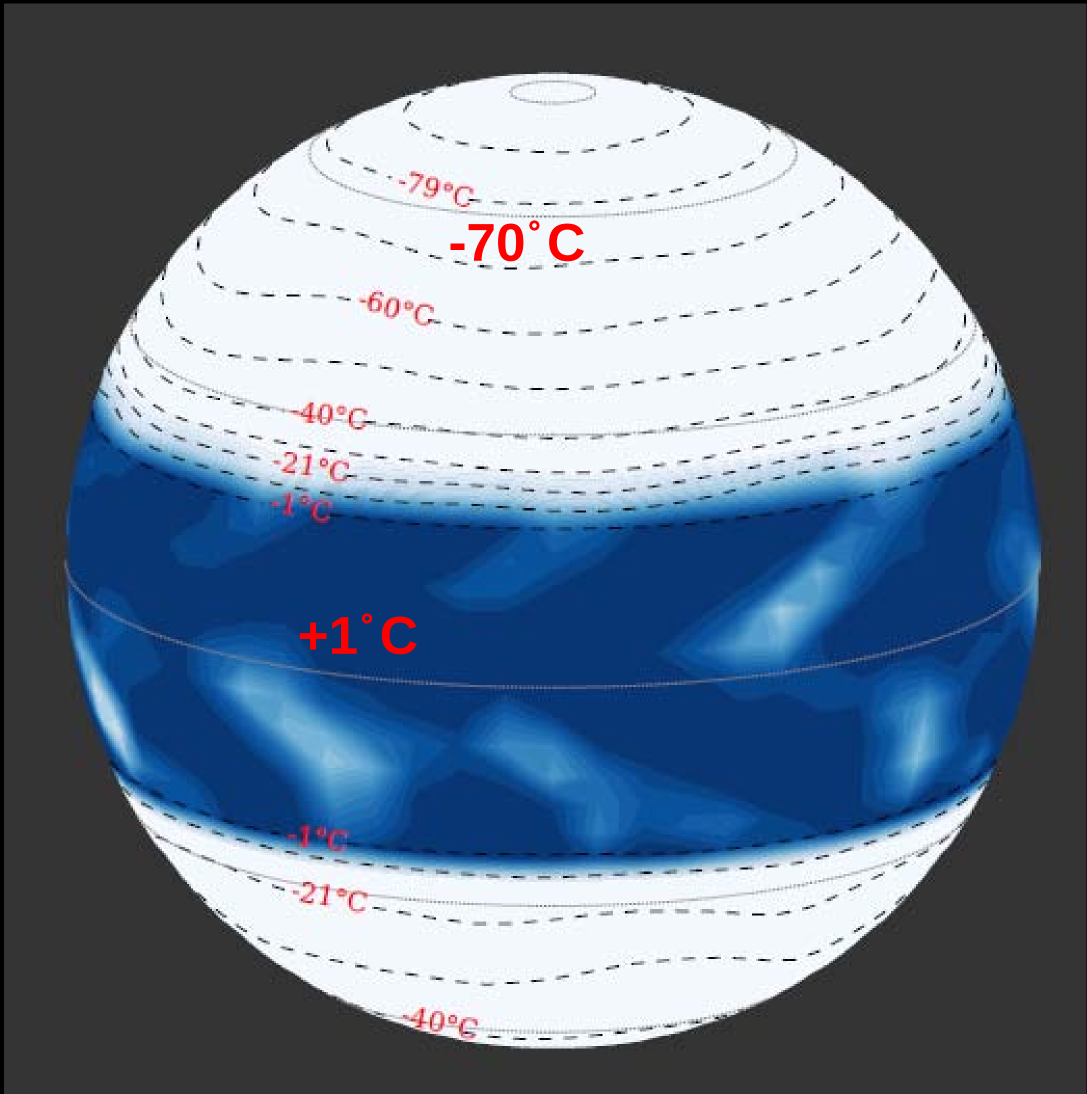


Charnay et al., JGR 2013

Out of glaciation: greenhouse effect

Flux = 80% present
(~1.12 AU)

$[CO_2] \times 2.5$

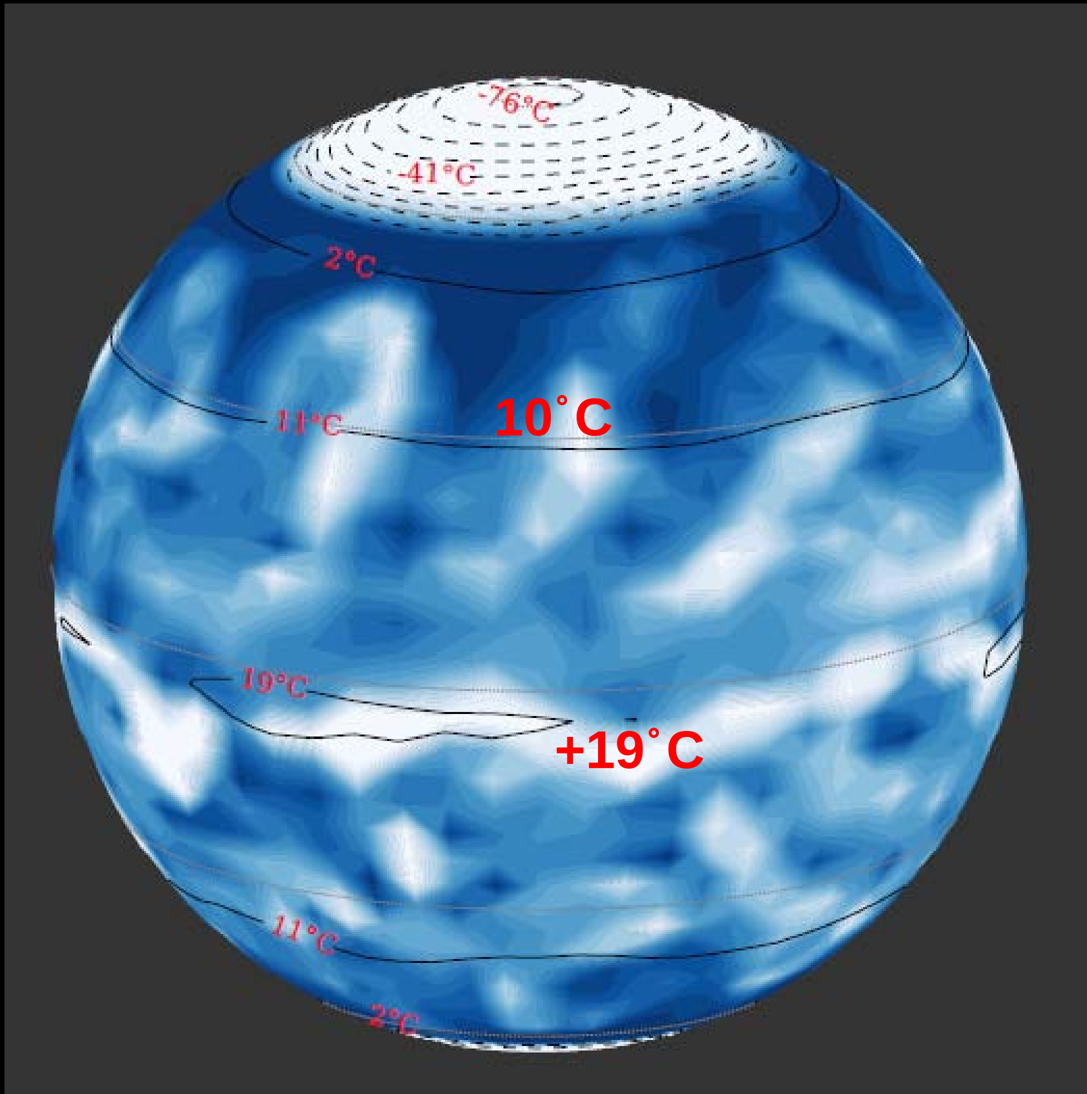


Charnay et al., JGR 2013

Out of glaciation: greenhouse effect

Flux = 80% present
(~1.12 AU)

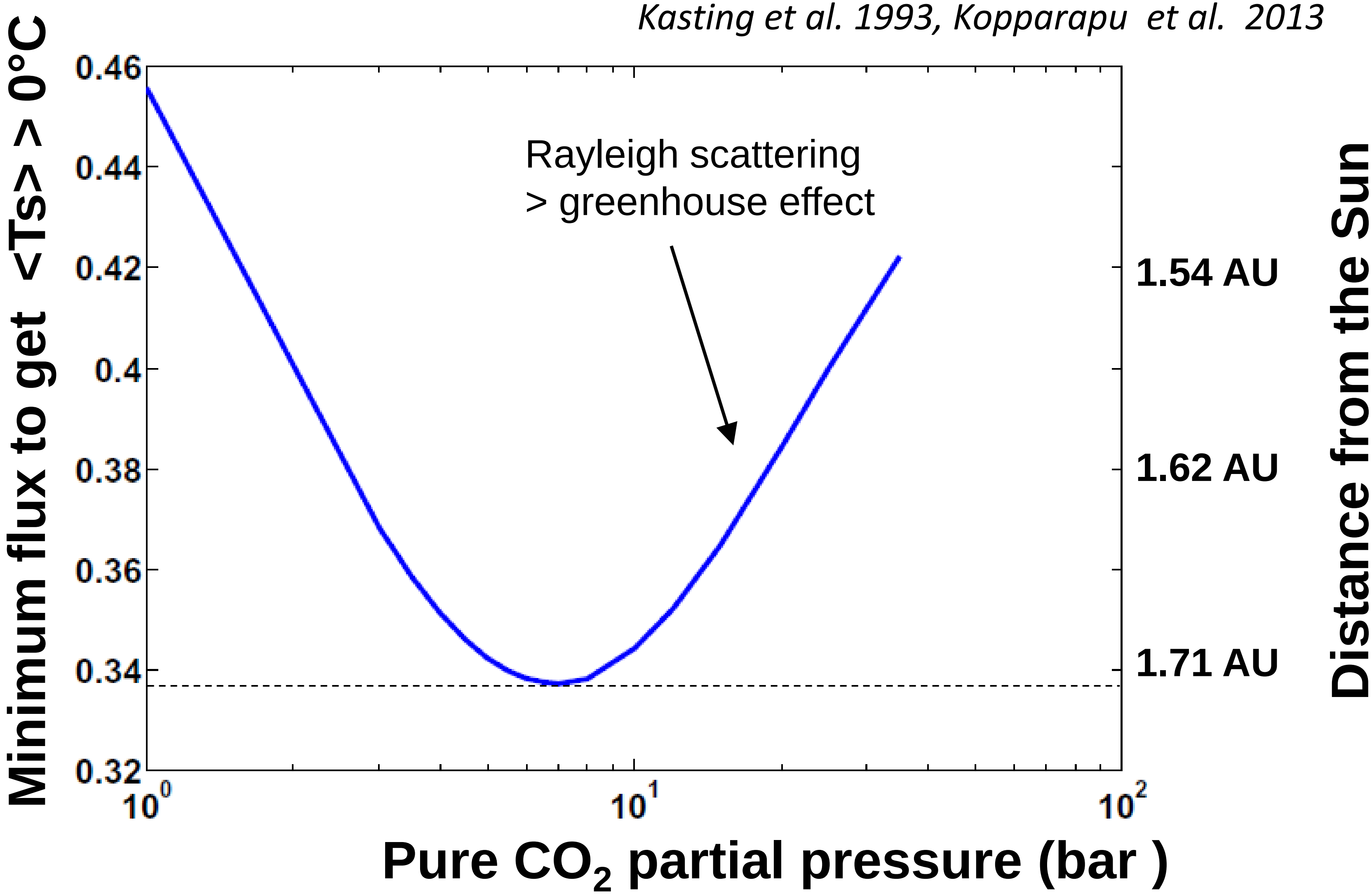
$[CO_2]$ x 250
[CH4] x 1000



Charnay et al., JGR 2013

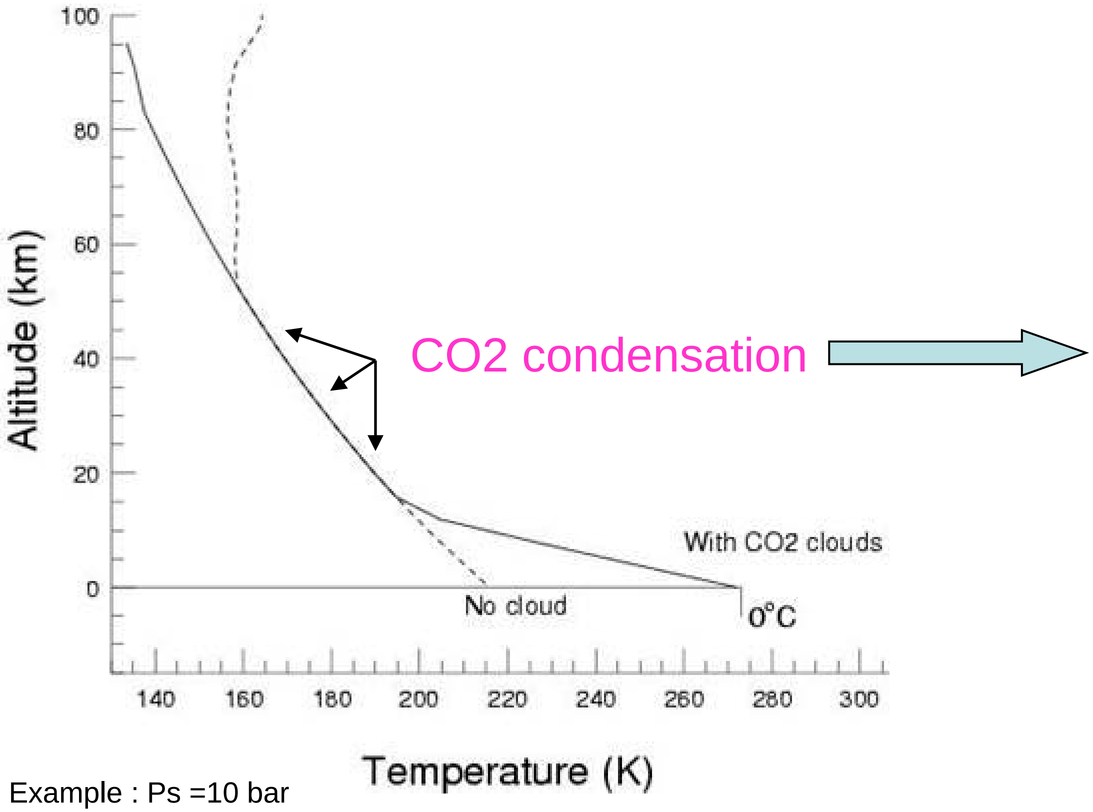
How far can greenhouse effect can keep a planet warm around a sun-like star?

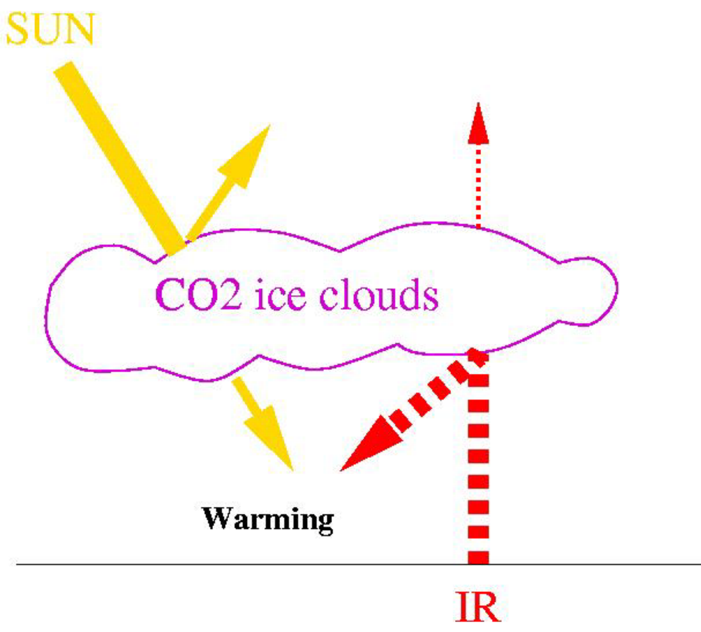
Kasting et al. 1993, Kopparapu et al. 2013



Scattering Greenhouse effect of CO_2 ice clouds ⇨ 0°C as far as 2.5 AU from the Sun ??

Forget and Pierrehumbert (1997)

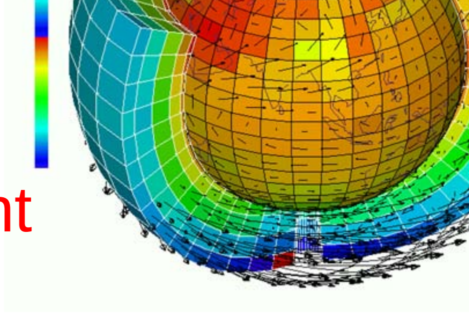




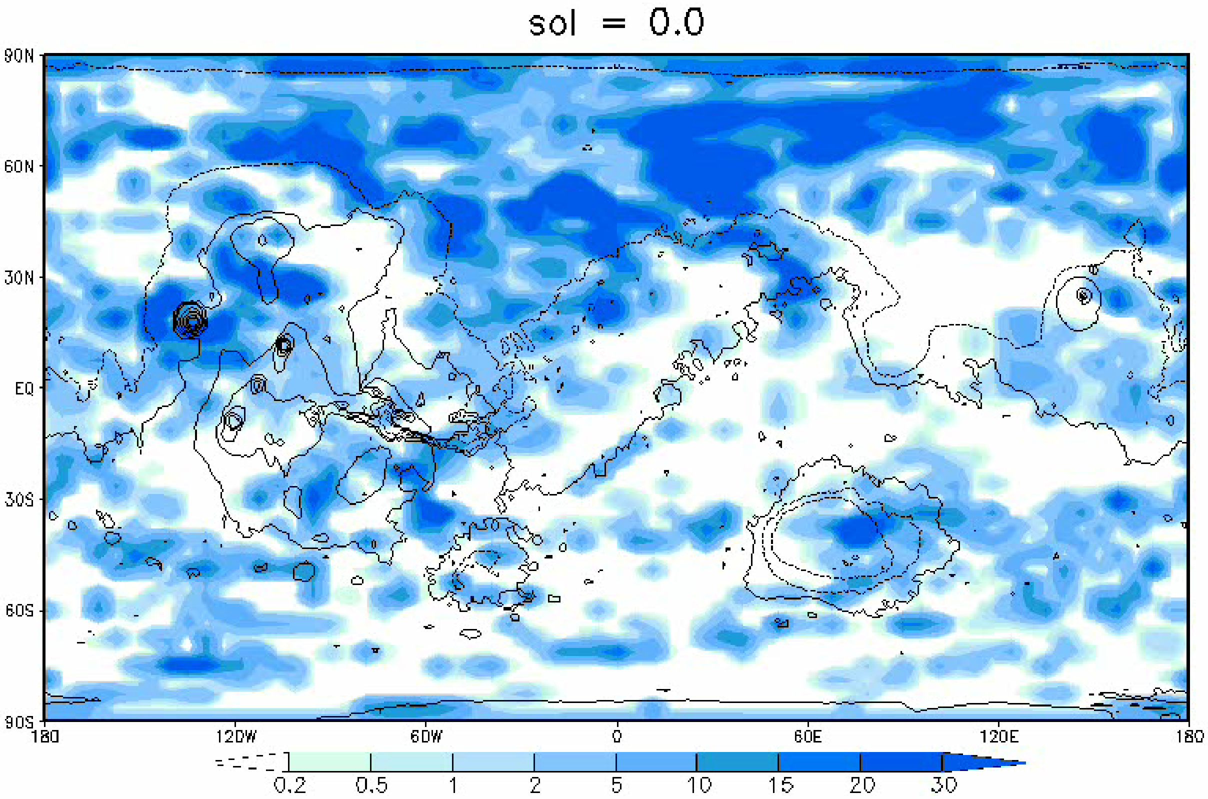
Example : Ps =10 bar
cloud opacity = 20

See also *Kitzmann et al. (2013, 2016, 2017)*

3D Global climate simulations of a cold CO_2 atmosphere => CO_2 ice clouds are not very efficient



("Early Mars Case" distance equivalent to 1.75 AU)



CO2 ice Cloud optical depth

Max Warming = + 15 K

(because of uncomplete cloud coverage)

Forget et al. Icarus 2013, Wordsworth et al. Icarus 2013

The case of CO_2, N_2 + volcanic H_2 atmosphere

⇨Collision induced absorption at high pressure

Ramirez et al., 2014, ; Ramirez and Kaltenegger 2017 Wordsworth et al., 2017; Turbet et al., 2019

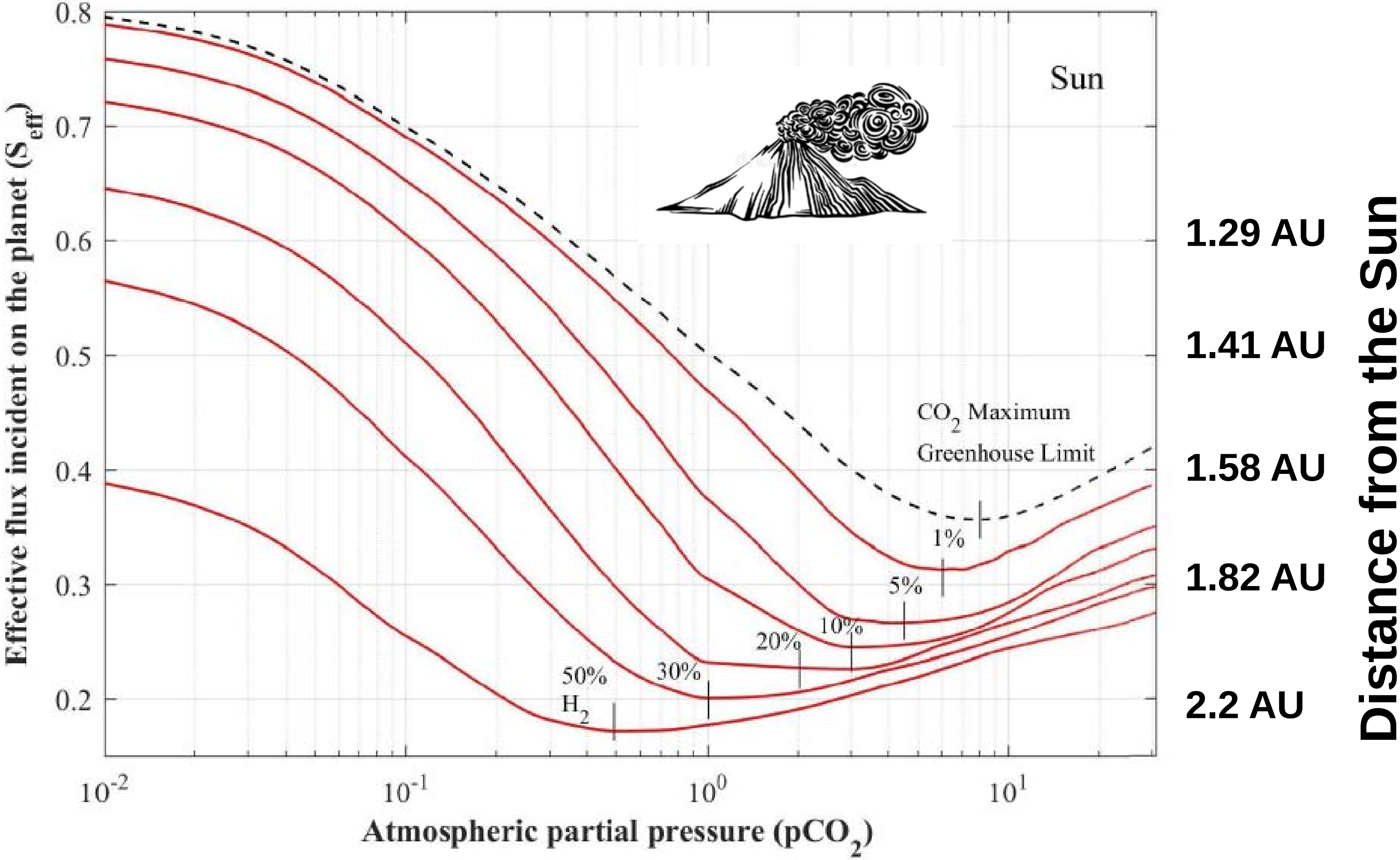
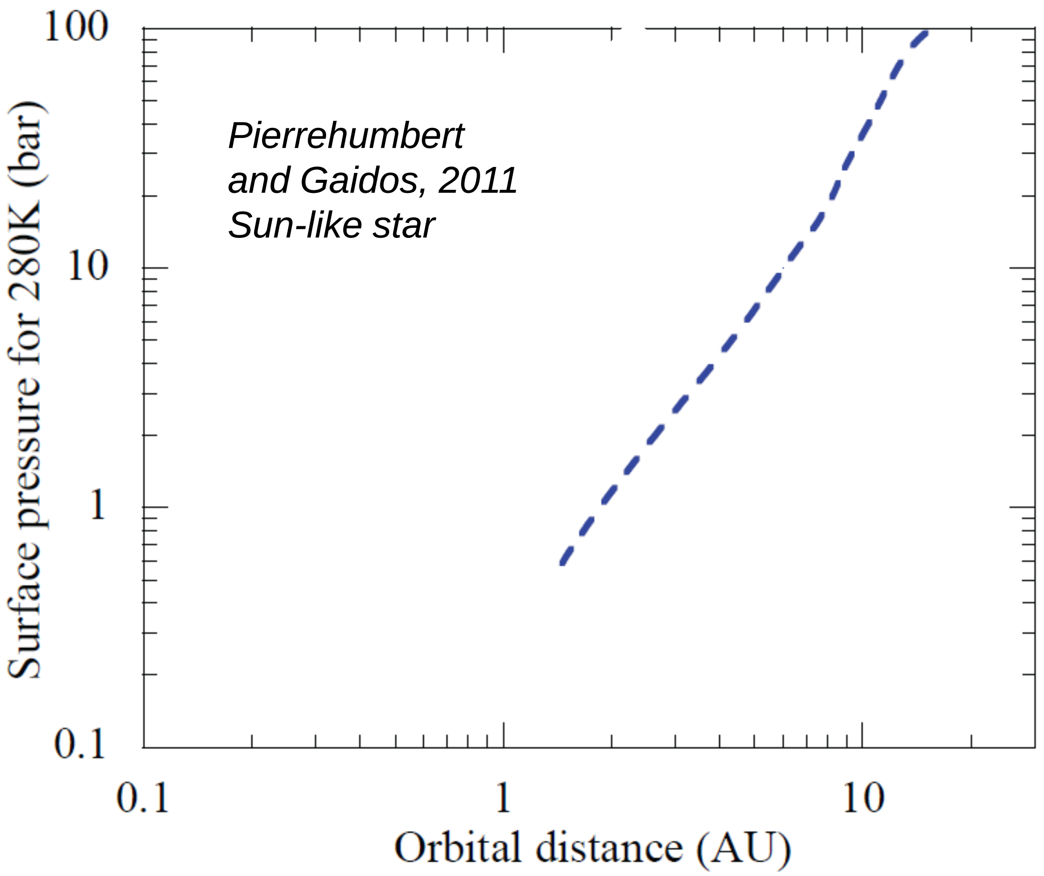


Figure from Ramirez and Kaltenegger 2017

The case of Hydrogen-rich atmosphere:

- High pressure H_2 is a good, non-condensable **greenhouse gas** thanks to collision-induced absorption
  (Stevenson 1999, Pierrehumbert and Gaidos, 2011, Wordsworth 2012, Madhusudhan et al. 2021, *Mol-Lous 2022)*



Stevenson et al. Nature (1999)

Life-sustaining planets in interstellar space?

During planet formation, rock and ice embryos of the order of Earth's mass may be formed, some of which may be ejected from the Solar System as they scatter gravitationally from proto-giant planets. These bodies can retain atmospheres rich in molecular hydrogen which, upon cooling, can have basal pressures of 10^2 to 10^4 bars. Pressure-induced far-infrared opacity of H_2 may prevent these bodies from eliminating internal radioactive heat except by developing an extensive adiabatic (with no loss or gain of heat) convective atmosphere. This means that, although the effective temperature of the body is around 30 K, its surface temperature can exceed the melting point of water. Such bodies may therefore have water oceans whose surface pressure and temperature are like those found at the base of Earth's oceans. Such potential homes for life will be difficult to detect.

Planet formation is imperfectly understood, but many models involve the accumulation of solid bodies of up to several Earth masses while the hydrogen-rich solar increasingly likely at greater distances, especially once the atmosphere has cooled (so that the photosphere is no longer large compared with the solid body). The atmospheric escape time can be as short as a million years at one astronomical unit early in the Solar System[1], but longer than the age of the Solar System in the interstellar medium. Sputtering (collision with interstellar molecular or atomic hydrogen at tens to hundreds of kilometres per second) can be important if denser interstellar regions are encountered, but the column density of hydrogen in the case of $M_{atm}/M \approx 0.001$ to 0.01 is so large that removing such an atmosphere would correspond to much more mass being sputtered per unit area than the total mass per unit area of a comet in the Oort cloud.

At the present epoch (assumed to be around 4.6 Gyr after formation), an interstellar planet would have a luminosity derived from long-lived radionuclides of around $4\times10^{20}\,\chi$ erg s^{-1} if it is like Earth[8], where χ is the planet mass in units of Earth masses. Assuming a thin atmosphere and an Earth-like density, the effective temperature T_e of the planet is given by $T_e \approx 34\,\chi^{1/12}$ K. From hydrostatic equilibrium, the surface pressure $P_s \approx 10^6 \times M_{atm}/M$ bars. However, optical-depth unity at relevant infrared wavelengths (about 100 μm) is possibility of non-thermal radio emission, they will be very difficult to detect.

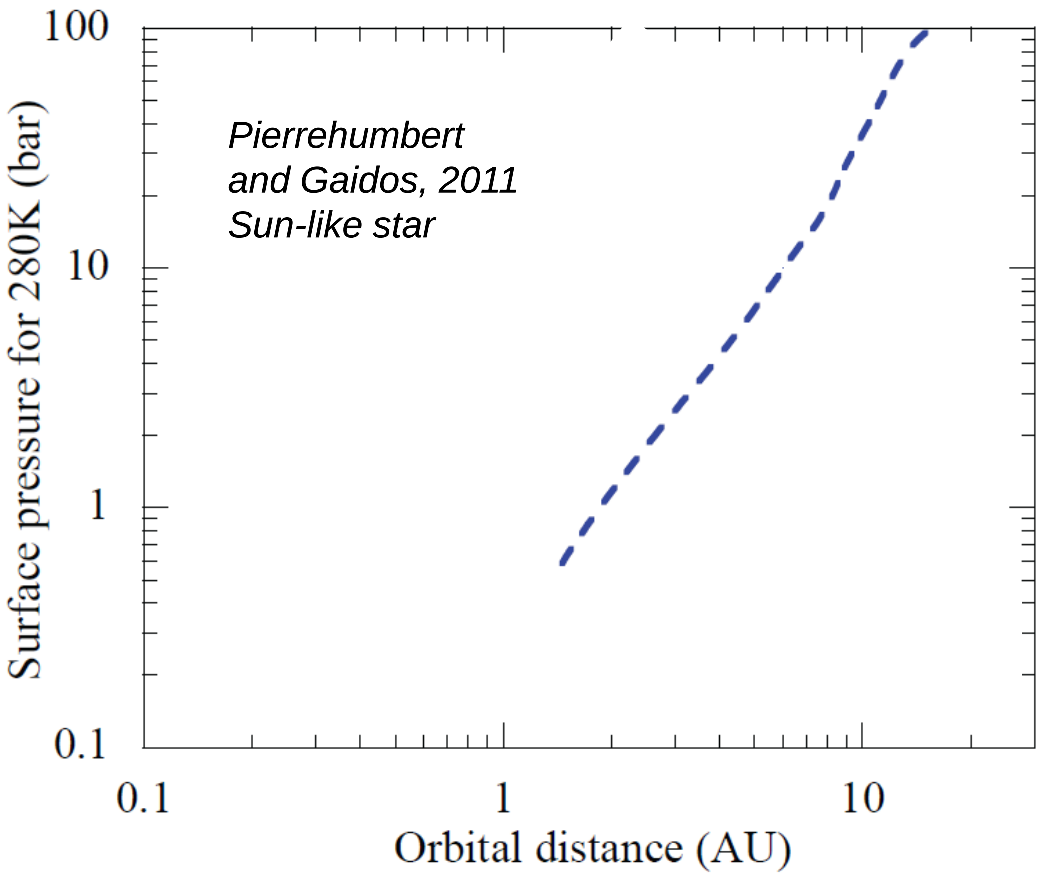
If life can develop and be sustained without sunlight (but with other energy sources, plausibly volcanism or lightning in this instance), these bodies may provide a long-lived, stable environment for life (albeit one where the temperatures slowly decline on a billion-year timescale). The complexity and biomass may be low because the energy source will be small, but it is conceivable that these are the most common sites of life in the Universe. Details of the above results are available from the author.

David J. Stevenson
Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, California 91125, USA
e-mail: djs@gps.caltech.edu

1. Hayashi, C., Nakazawa, K. & Nakagawa, Y. in *Protostars and Planets II* (eds Black, D. C. & Matthews, M. S.) 1100–1153 (Univ. Arizona Press, Tucson, 1985).
2. Lissauer, J. J. *Icarus* **69,** 249–265 (1987).
3. Levison, H. F., Lissauer, J. J. & Duncan, M. J. *Astron. J.* **116,** 1998–2014 (1998).
4. Cameron, A. G. W. *Meteoritics* **30,** 133–161 (1995).
5. Boss, A. P. *Science* **276,** 1836–1839 (1997).
6. Birnbaum, G., Borysow, A. & Orton, G. S. *Icarus* **123,** 4–22 (1996).
7. Stevenson, D. J. *Planet. Space Sci.* **30,** 755–764 (1982).
8. Stacey, F. D. *Physics of the Earth* 3rd edn (Brookfield, Brisbane, 1992).
9. Conrath, B. J. *et al.* in *Uranus* (eds Bergstrahl, J. T., Miner, E. T. & Matthews, M. S.) 204–252 (Univ. Arizona Press, Tucson, 1991).

The case of Hydrogen-rich atmosphere:

- High pressure H_2 is a good, non-condensable **greenhouse gas** thanks to collision-induced absorption
  (Stevenson 1999, Pierrehumbert and Gaidos, 2011, Wordsworth 2012, Madhusudhan et al. 2021, *Mol-Lous 2022)*
- However primordial H_2-rich atmosphere tends to escape to space and not last long for Earth-size planets.

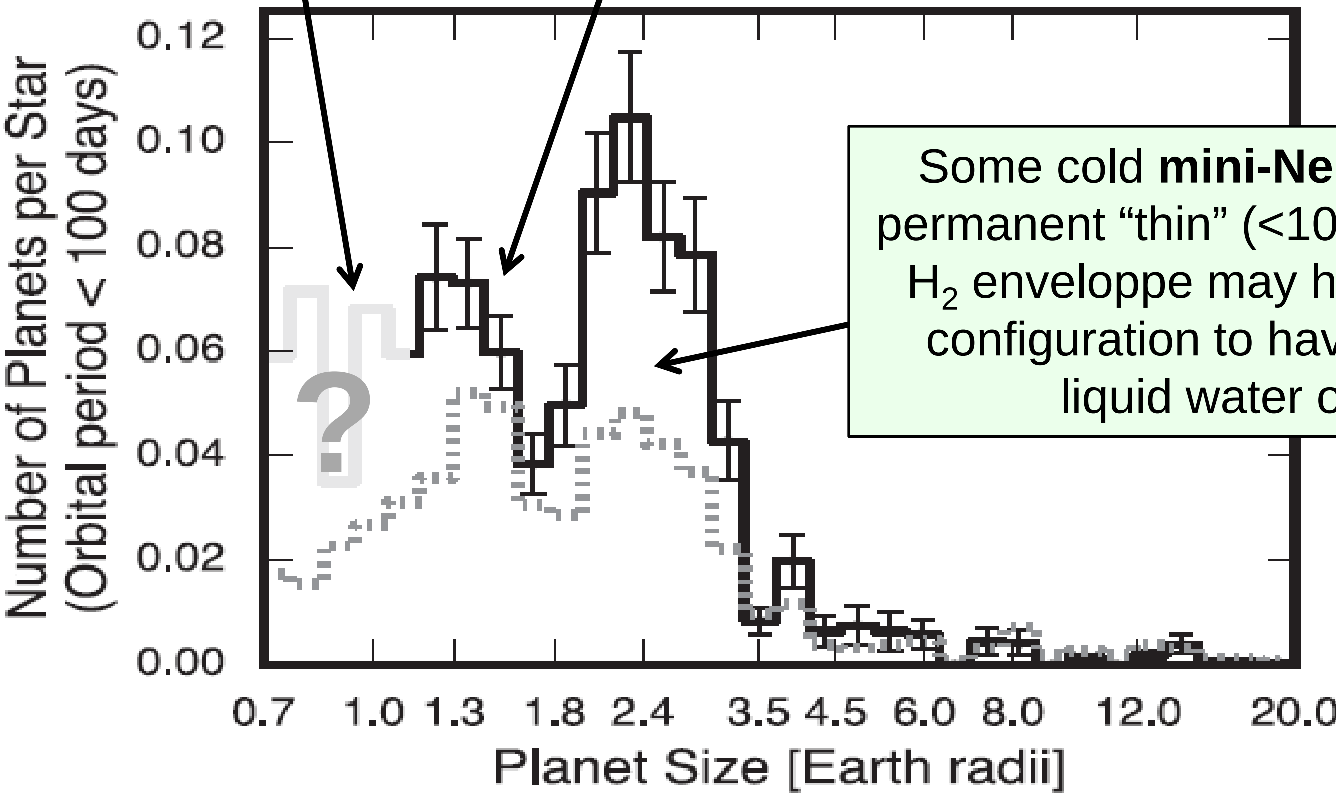


Observations : possibly many "habitable" Ocean planets with thick H_2 –He atmosphere ? *(Pierrehumbert and Gaidos 2011 , Wordsworth 2012 , Madhusudhan et al. 2020, 2021, Mol-Lous 2022)*

Cold **Earth-Size planet** with H_2 atm. may pass through transient periods with surface oceans

Cold **super-Earth** may keep a slighty evolving H_2 primordial atmosphere and be habitable for billions of tears

Some cold **mini-Neptunes** with permanent "thin" (<10000 bars) He-H_2 enveloppe may have the right configuration to have a surface liquid water ocean



Fulton and Petigura (2017): Statistics on Kepler's planets

“Hycean worlds” : with oceans underlying H2-rich atmospheres

seem exotic, but could be very common in the Galaxy…

However: same problems than with Europa-like icy ocean worlds :

- No photosynthesis ?
- High -ressure ice at the bottom ?
- **Undetectable biosignature ?**

⇨ Not in the “Hunting Zone”

Summary: Habitable zone around a Sun-like star

Sun | *0.5 AU* | *0.95 AU* | *1.7 AU* | *2.5 AU*

← **Likely** →

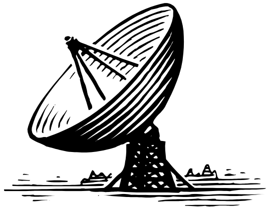
⟵ **Maximum possible extension ?** ⟶

Special case of H_2
-rich atmospheres ⟶

Habitability trough time:

Time is necessary to life to arise and evolve :

- - 4,5 Ga : Earth formation
- Before -3,8 -3,5 Ga : Life
- -1.4 Ga : Multi-cellular life
- - 0.6 Ga : First animals
- ± 0 : Intelligence

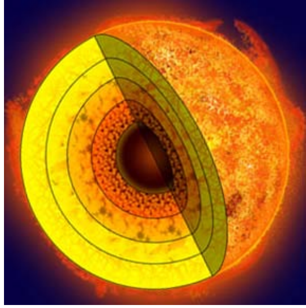


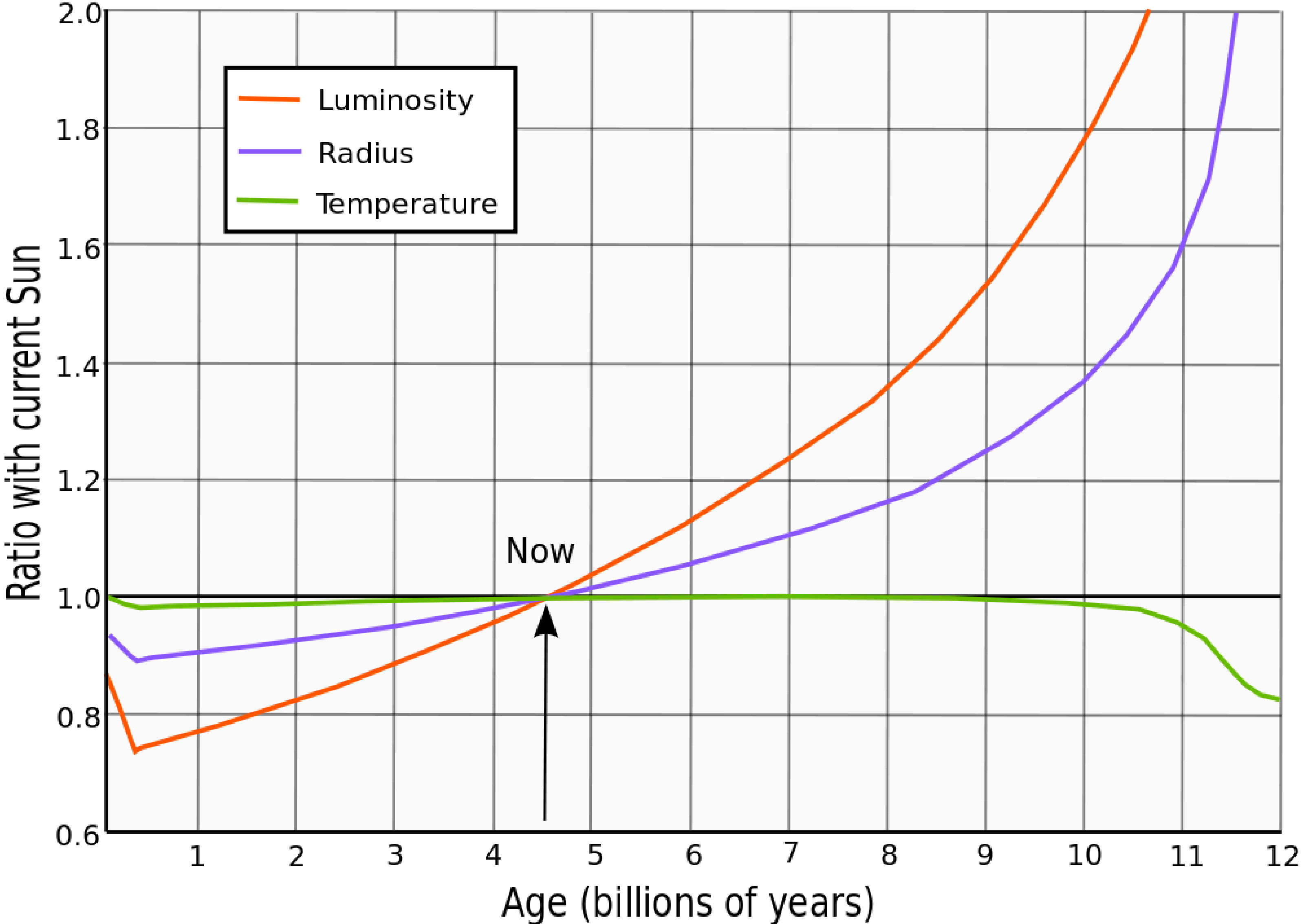
Problem :

- Evolution of stars

Evolution of the Sun

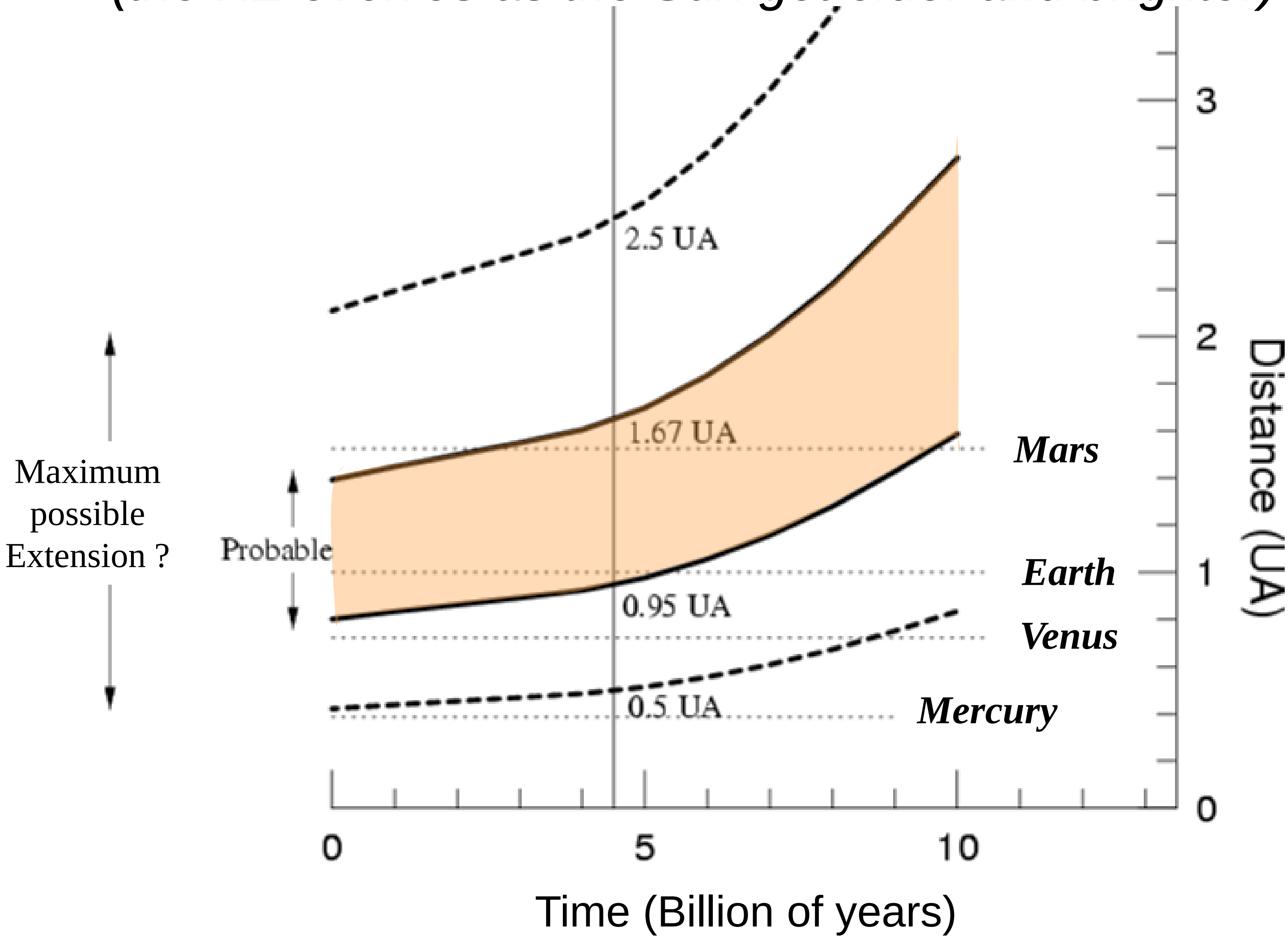
(due to increasing density in the Sun as H is converted into He)





The solar system habitable zone through time

(the HZ evolves as the Sun get older and brighter)

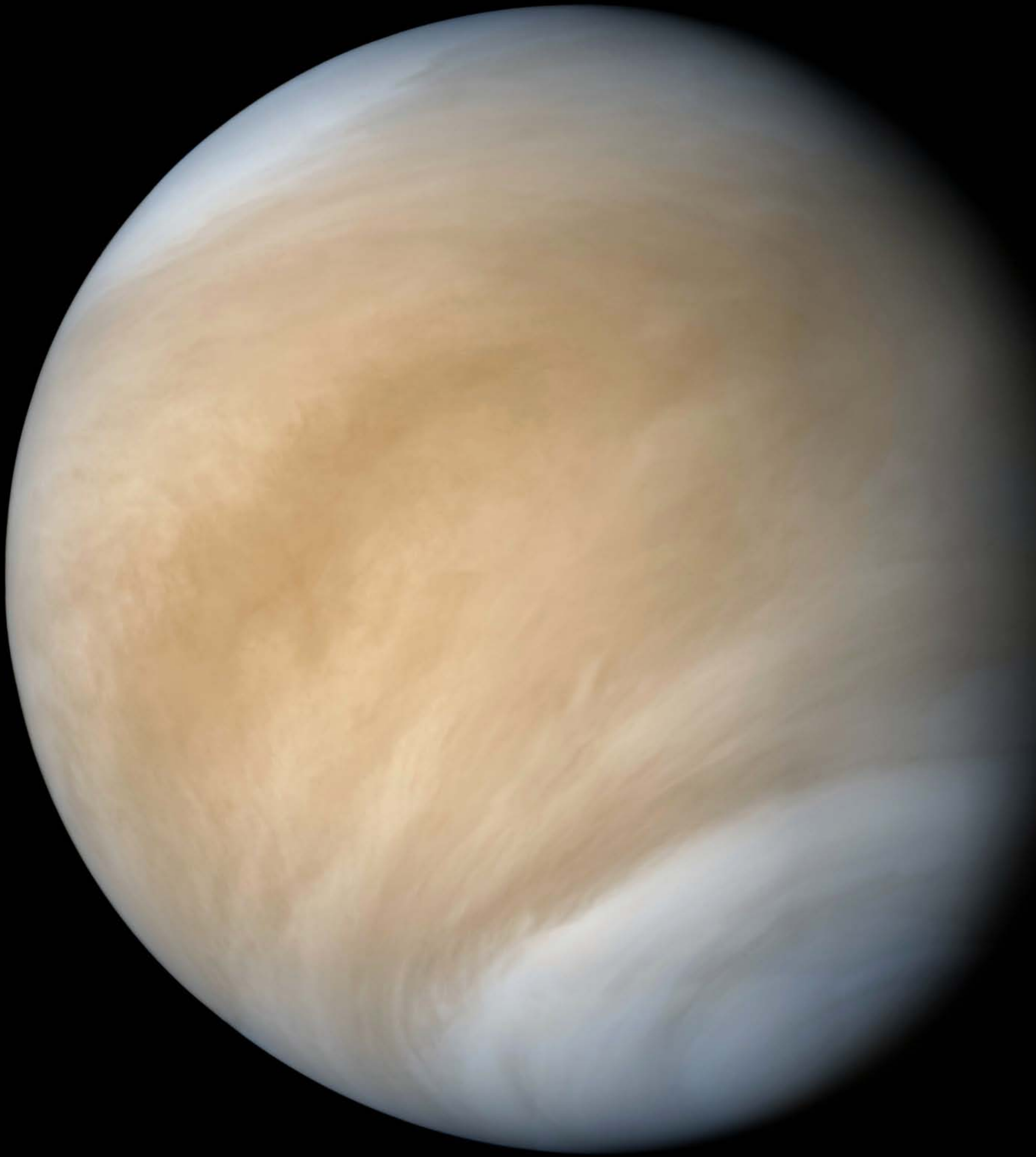


Forget 1998

VENUS

Massive atmosphere of CO_2

- *Greenhouse effect*
- *Surface : T > 460° C*



Early Evolution of Venus:

Scenario #1: Wet Early Venus

1) Venus and Earth start with the same ingredients.
2) An ocean condenses, Early Venus Habitable (e.g. Way et al. 2016)
3) Brighter Sun: Evaporation of oceans
4) Loss of H_2O to space
5) No more water cycle:

⇨Accumulation of CO_2 in the atmosphere *(on the Earth liquid water dissolves CO_2 and transforms it into carbonate)*

1) Present day Venus : on the surface
   - Pressure ~ 90 bars (CO2)
   - Température > 400˚C

Runaway greenhouse effect on Venus rotating more and more slowly

(Yang et al. 2013, Way et al. 2016, 2018) Way & Del Genio (2020)

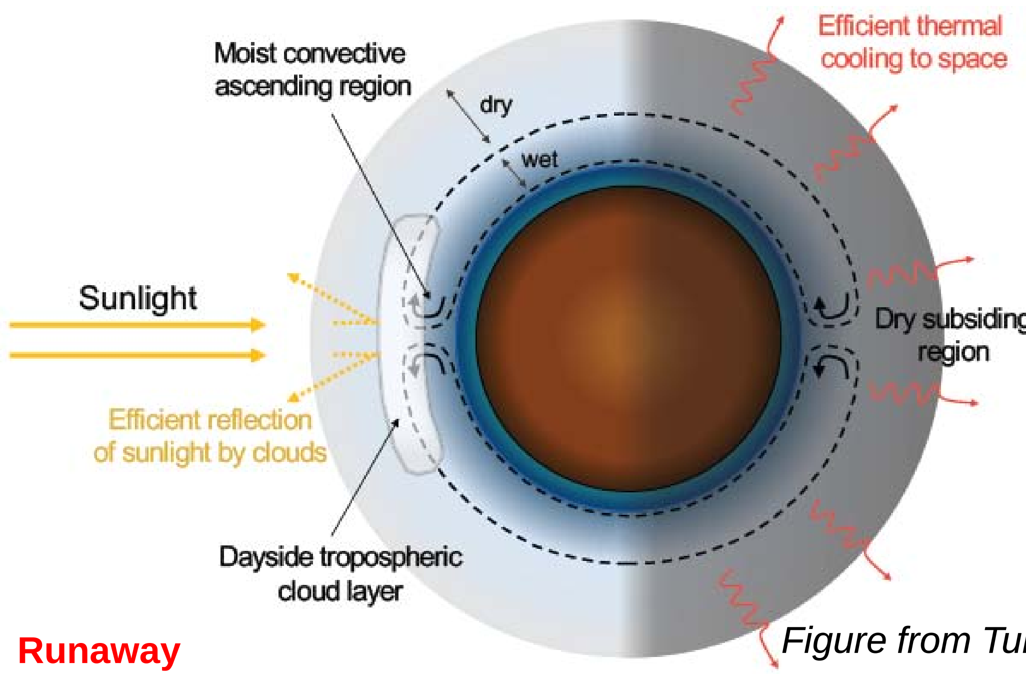
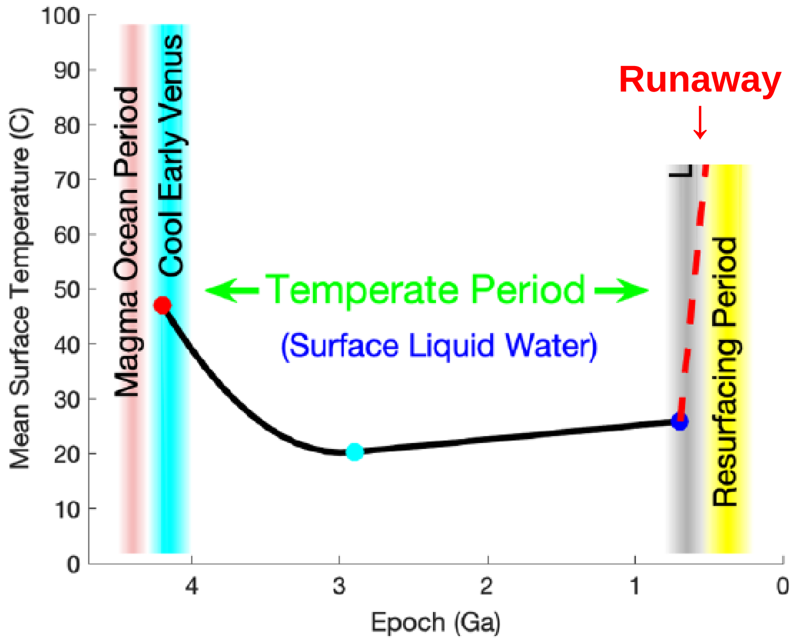


Figure from Turbet et al. (2021)



A possible history of Venus according to *Way & Del Genio (2020)*

Early Evolution of Venus:

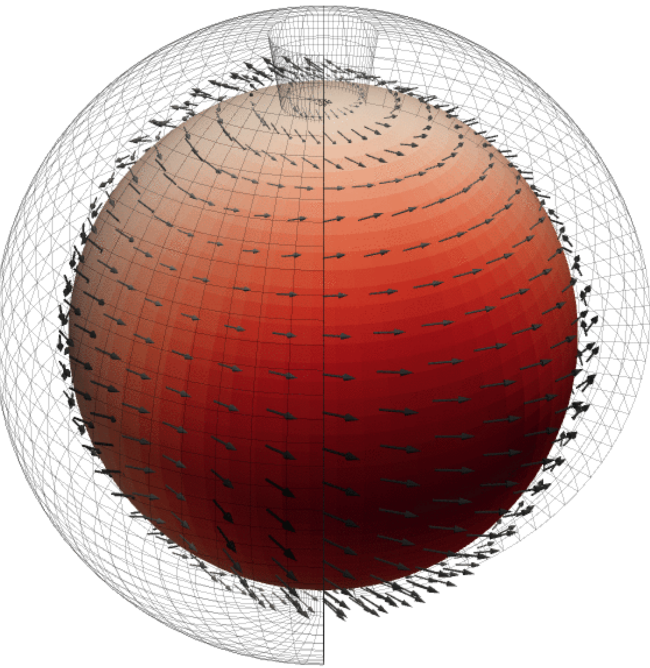
Scenario #1: Wet Early Venus

1) An Ocean condenses, Early Venus Habitable (e.g. Way et al. 2016)
2) Brighter Sun: Evaporation of oceans
3) Loss of H_2O to space
4) No more water cycle: Accumulation of CO_2 in the atmosphere
5) Present day Venus : on the surface
    - Pressure ~ 90 bars (CO2)
    - Température > 400˚C

Alternative Scenario #2: Never-wet Venus

- Water never condensed and escaped to space during the early Steam Atmosphere Period

Gilmannet al., EPSL 2009; Wordsworth, EPSL 2016; Lebrun et al. 2013; Hamano et al. 2013 ; Massol et al. 2016; Salvador et al. 2017, Turbet et al. (2021)



nature

Article

Day–night cloud asymmetry prevents early oceans on Venus but not on Earth

https://doi.org/10.1038/s41586-021-03873-w

Received: 31 March 2021

Accepted: 3 August 2021

Published online: 13 October 2021

Check for updates

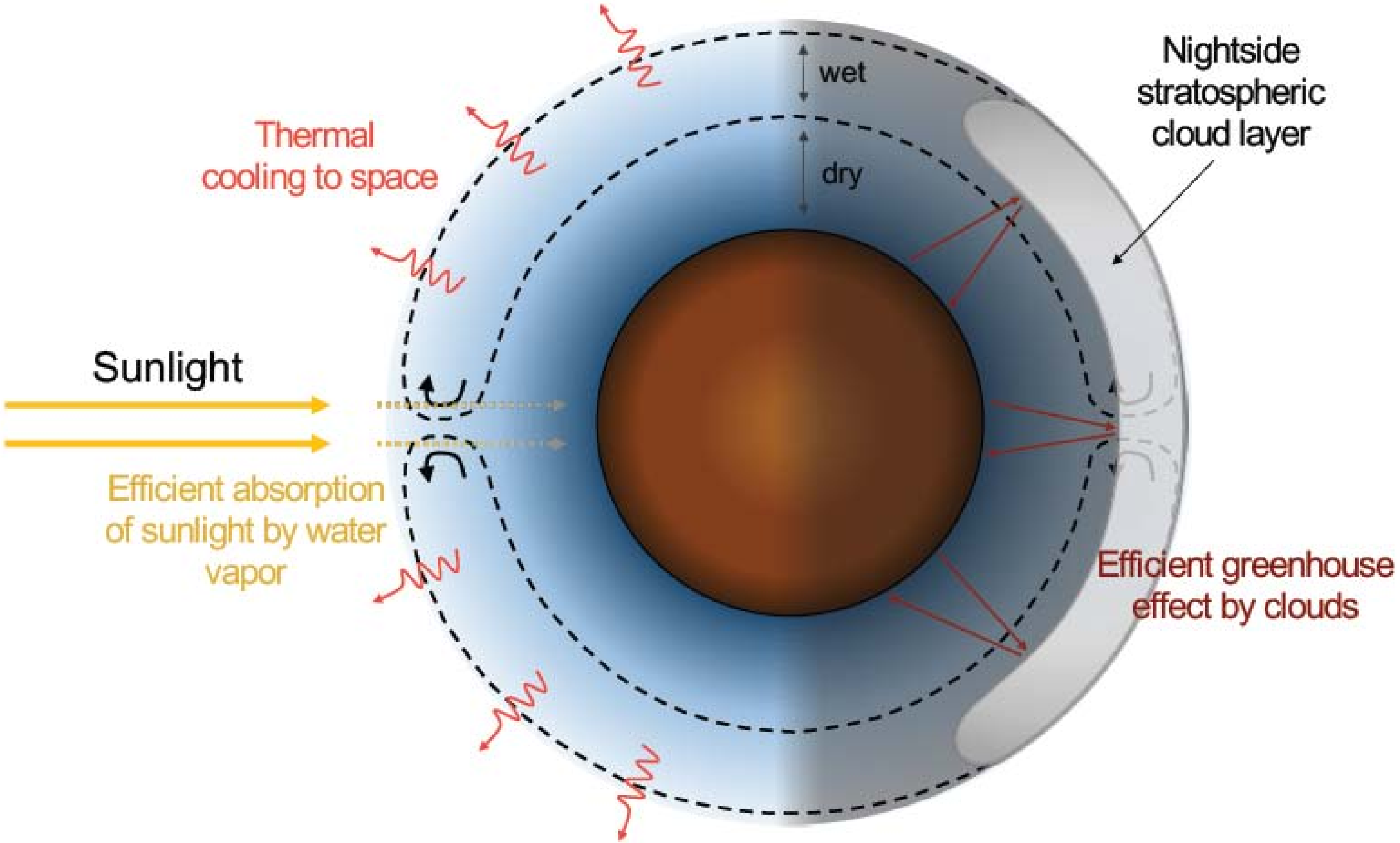
Martin Turbet[1]✉, Emeline Bolmont[1], Guillaume Chaverot[1], David Ehrenreich[1], Jérémy Leconte[2] & Emmanuel Marcq[3]

Earth has had oceans for nearly four billion years[1] and Mars had lakes and rivers 3.5–3.8 billion years ago[2]. However, it is still unknown whether water has ever condensed on the surface of Venus[3,4] because the planet—now completely dry[5]—has undergone global resurfacing events that obscure most of its history[6,7]. The conditions required for water to have initially condensed on the surface of Solar System terrestrial planets are highly uncertain, as they have so far only been studied with one-dimensional numerical climate models[3] that cannot account for the effects of atmospheric circulation and clouds, which are key climate stabilizers. Here we show using three-dimensional global climate model simulations of early Venus and Earth that water clouds—which preferentially form on the nightside, owing to the strong subsolar water vapour absorption—have a strong net warming effect that inhibits surface water condensation even at modest insolations (down to 325 watts per square metre, that is, 0.95 times the Earth solar constant). This shows that water never condensed and that, consequently, oceans never formed on the surface of Venus. Furthermore, this shows that the formation of Earth's oceans required much lower insolation than today, which was made possible by the faint young Sun. This also implies the existence of another stability state for present-day Earth: the 'steam Earth', with all the water from the oceans evaporated into the atmosphere.

Most numerical studies that seek to identify the conditions that allow terrestrial planets to have surface liquid water (in the form of lakes, seas or oceans) assume that surface liquid water was present in the first place. Studies of Mars have focused on finding the conditions necessary to prevent complete glaciation[8], in an attempt to explain widespread evidence of past intermittent hydrological activities[2,9,10]. Studies of Venus have focused on finding the conditions necessary to delay complete evaporation[4,11]. Deuterium/hydrogen (D/H) isotopic ratio measurements[12,13] (about 10^2 times higher than on Earth) suggest indeed that the early Venus superficial water reservoir ranged from roughly 4 m to 500 m global equivalent layer[4] (GEL; that is, the thickness of the liquid water layer if spread evenly across the surface), but could have been even higher as the D/H fractionation factor during (hydrodynamic) escape of hydrogen can be close to unity[14]. The early Venus superficial water reservoir was thus much higher than today[5] (about (Fig. 1a). On fast-rotating planets like Earth, atmospheric dynamics produce dry regions (in the descending branches of atmospheric cells, for example, Hadley cells) that would increase thermal emission to space, cooling and thus stabilizing oceans[19,22].

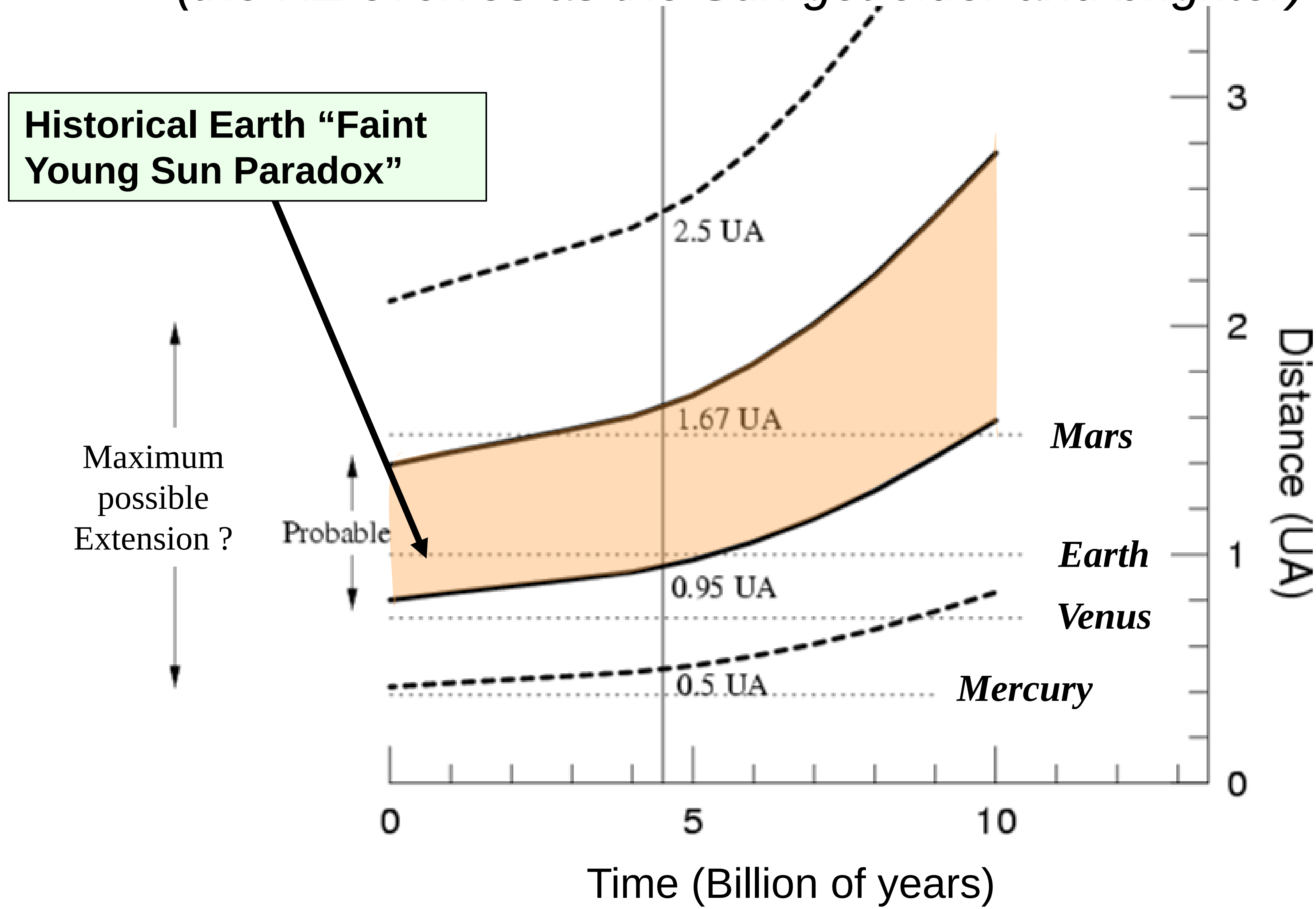
However, even before the question of the conditions for maintaining a surface liquid water ocean arises, water initially present in the young and warm planetary atmosphere must be able to condense on the surface. Planets are indeed expected to form hot due to their initial accretion energy, and thus to cross a magma ocean stage[3,16,23,24]—where superficial water is present only in the form of vapour—before evolving towards their final state. The conditions leading to the condensation of a water ocean after the magma ocean phase have so far been studied with only one-dimensional (1D) numerical climate models[3,24], which neglect the effects of atmospheric dynamics and clouds. Hot, water-vapour-dominated atmospheres are indeed notoriously difficult[19]

Turbet et al. 2021 : 3D modelling of the thick water vapour atmosphere after its formation : oceans cannot condense because of night clouds greenhouse effect



The solar system habitable zone through time

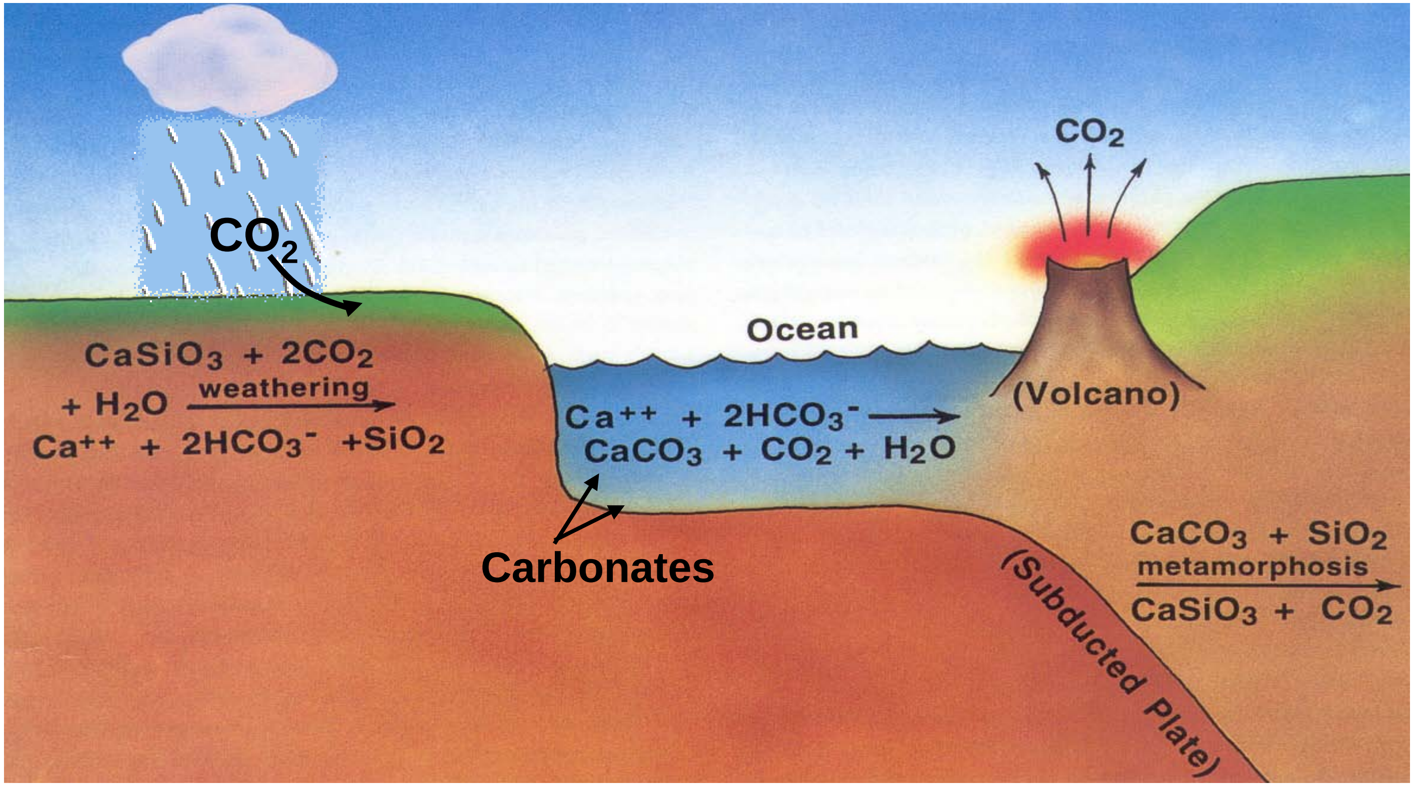
(the HZ evolves as the Sun get older and brighter)



Forget 1998

On the Earth: the right greenhouse effect over 4 Byr with the carbonate – Silicate cycle

Walker et al. 1981



Temperature • → Water cycle• → Weathering •

↓

Temperature • ← Greenhouse effect ← P_{CO2} •

“Carbonate-silicate cycle predictions of Earth-like planetary climates and testing the habitable zone concept” *Lehmer , Catling and Krissansen-Totton (2020)*

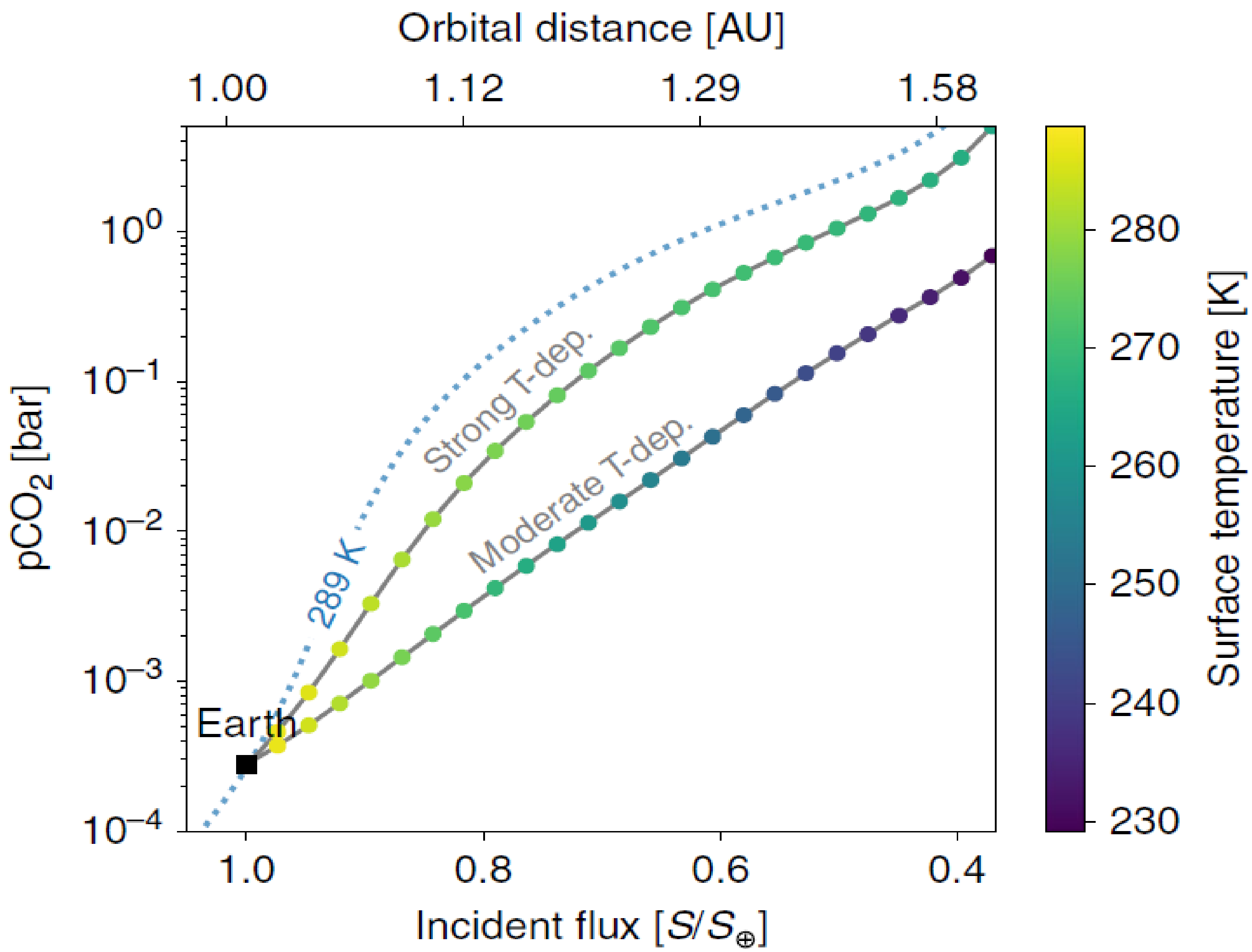


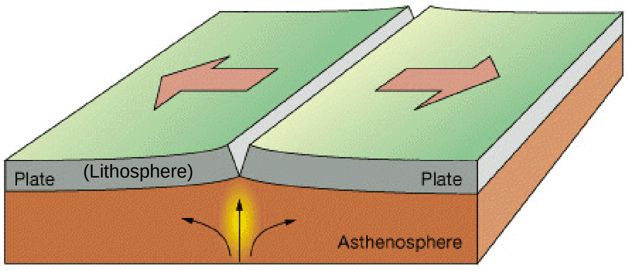
Fig. 2 The relationship between incident flux and atmospheric CO_2 for Earth-like planets regulated by a carbonate–silicate weathering cycle.

Is plate tectonic likely on other terrestrial planets ?

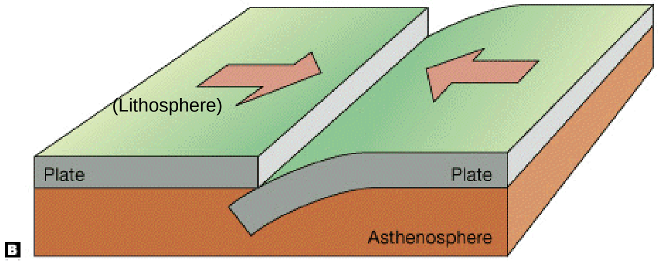
By default, planets could have a single « stagnant lid » lithosphere and no efficient surface recycling process.

To enable plate tectonics one need :

- Mantle Convective stress > lithospheric resistance
  ⇨ lithospheric failure



- Plate denser (e.g. cold) than asthenosphere, enough to drive subduction (currently control the horizontal motion).

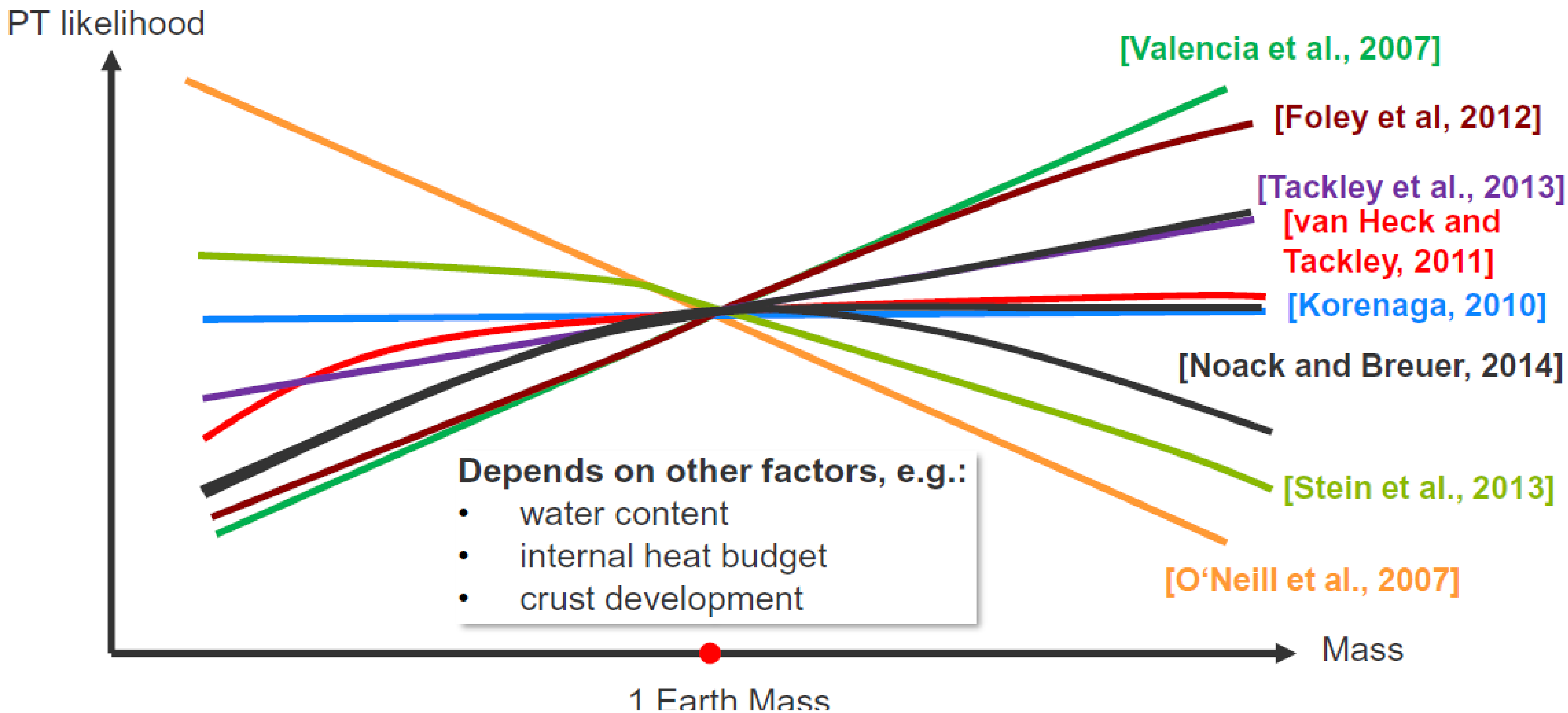


Is plate tectonic likely on other terrestrial planets ?

- **On small planets** (e.g. Mars) : rapid interior cooling : weak convection stress, thick lithosphere ⇨ no long term plate tectonic
- **On large planets** (e.g. super-Earth) : different views :
  - **To first order** : More vigorous convection ⇨ stronger convective stress & thinner lithosphere (e.g. *Valencia et al. 2007*)
  - **However**, some models predict that the increase in mantle depth mitigate the convective stress (O'Neil and Lenardic, 2007):

    « supersized Earth are likely to be in an episodic or stagnant lid regime »
  - **Moreover,** In super-Earth, very high pressure increase the viscosity near the core-mantle boundary (*Noack, Breuer et al. ..*)
  - **Role of water in the mantle ?** (explain why no plate tectonic on Venus)
  - Role of surface temperature

Is plate tectonic likely on other terrestrial planets ?

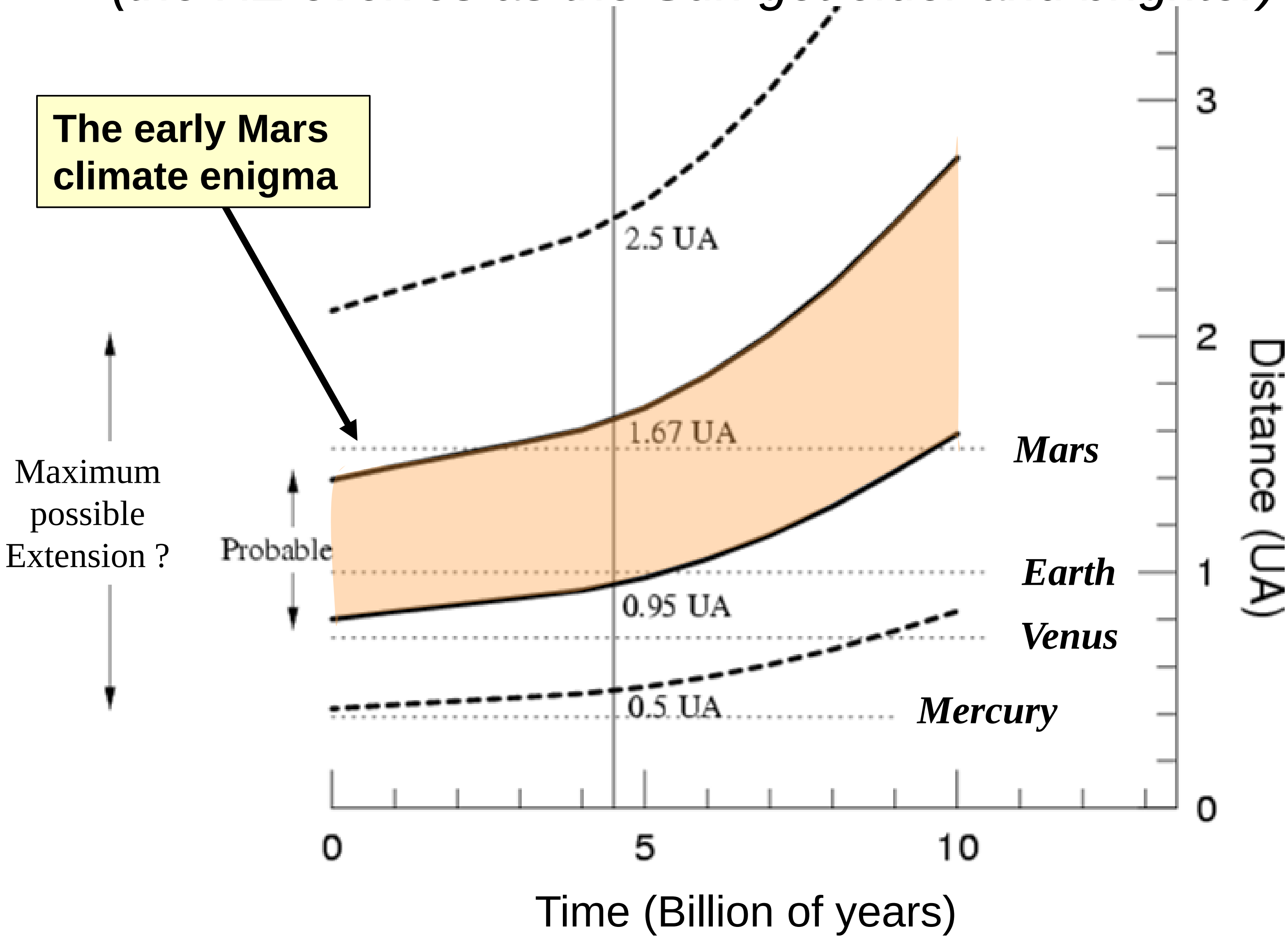


Noack et al. 2020

⇨The Earth could be just at the right size to enable plate tectonics, and with the right water budget…

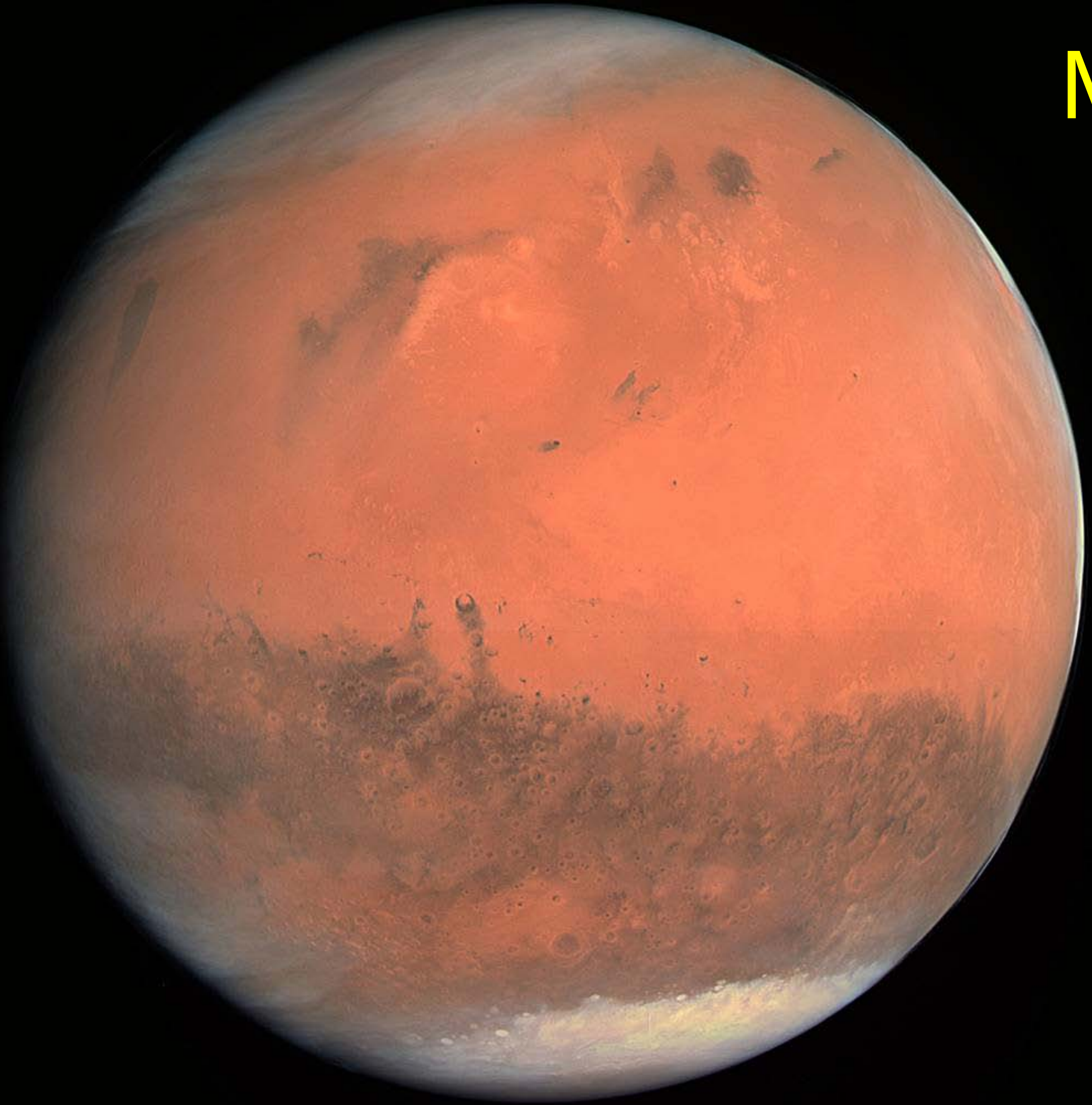
The solar system habitable zone through time

(the HZ evolves as the Sun get older and brighter)



Forget 1998

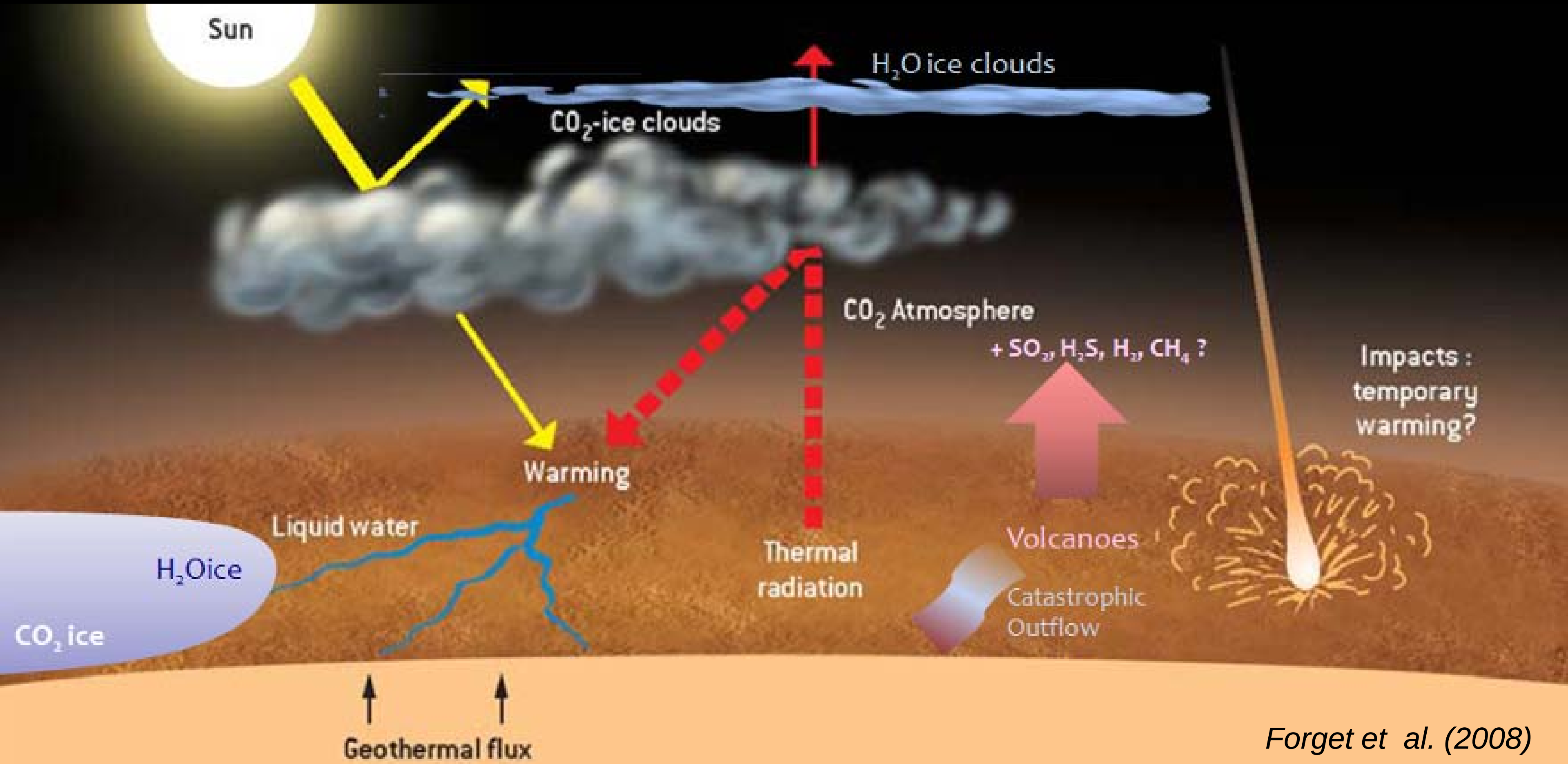
Mars




Mars 3 - 4 Ga?
© copyright kees

The Early Mars Climate Enigma

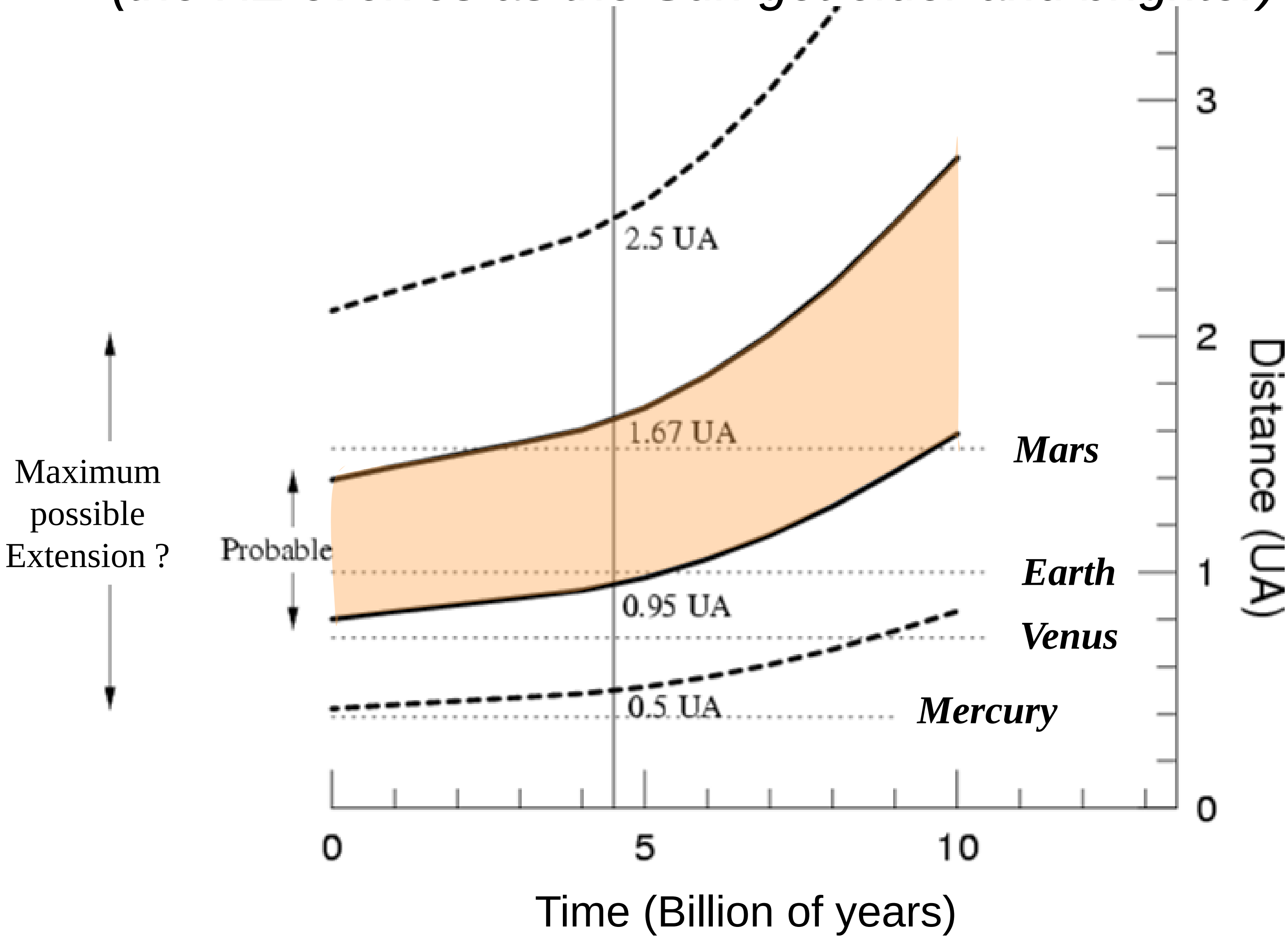
Mars 4 to 3 Ga was different than what it was later, with apparently liquid water at the surface. How was that possible ?



Forget et al. (2008)

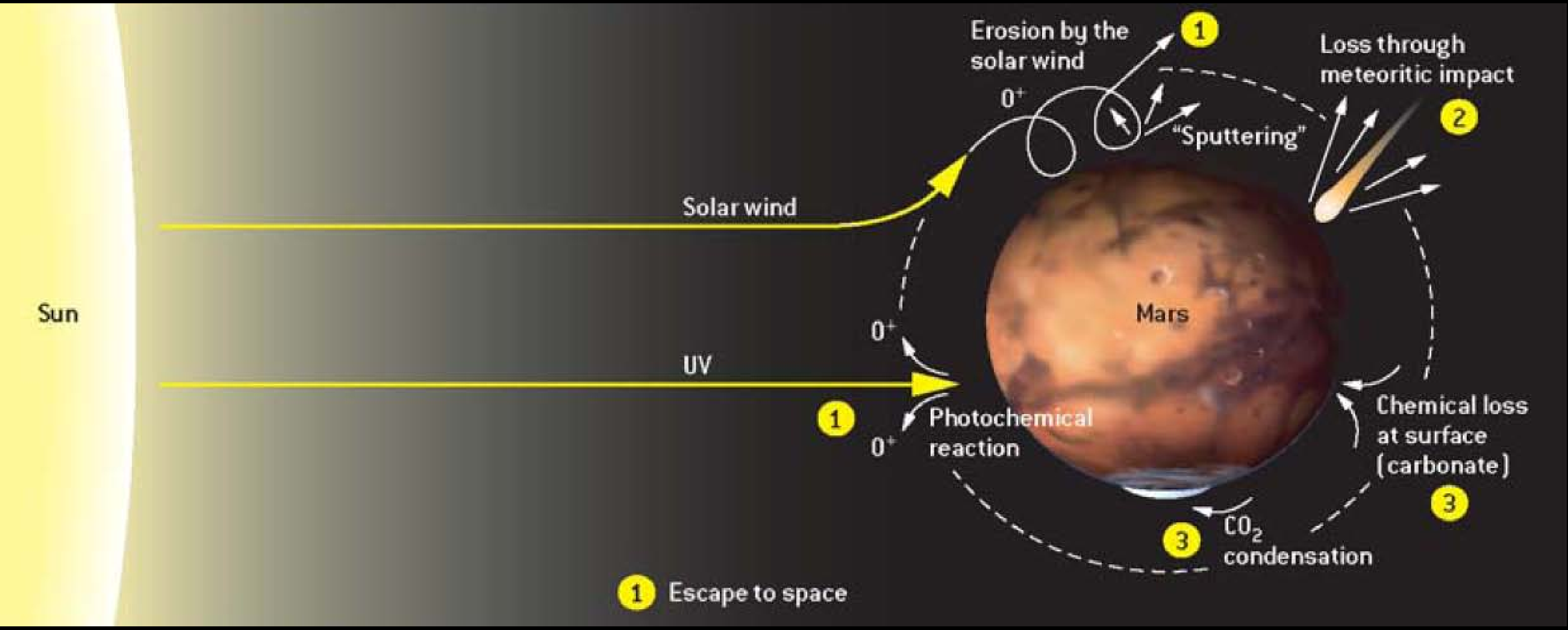
The solar system habitable zone through time

(the HZ evolves as the Sun get older and brighter)

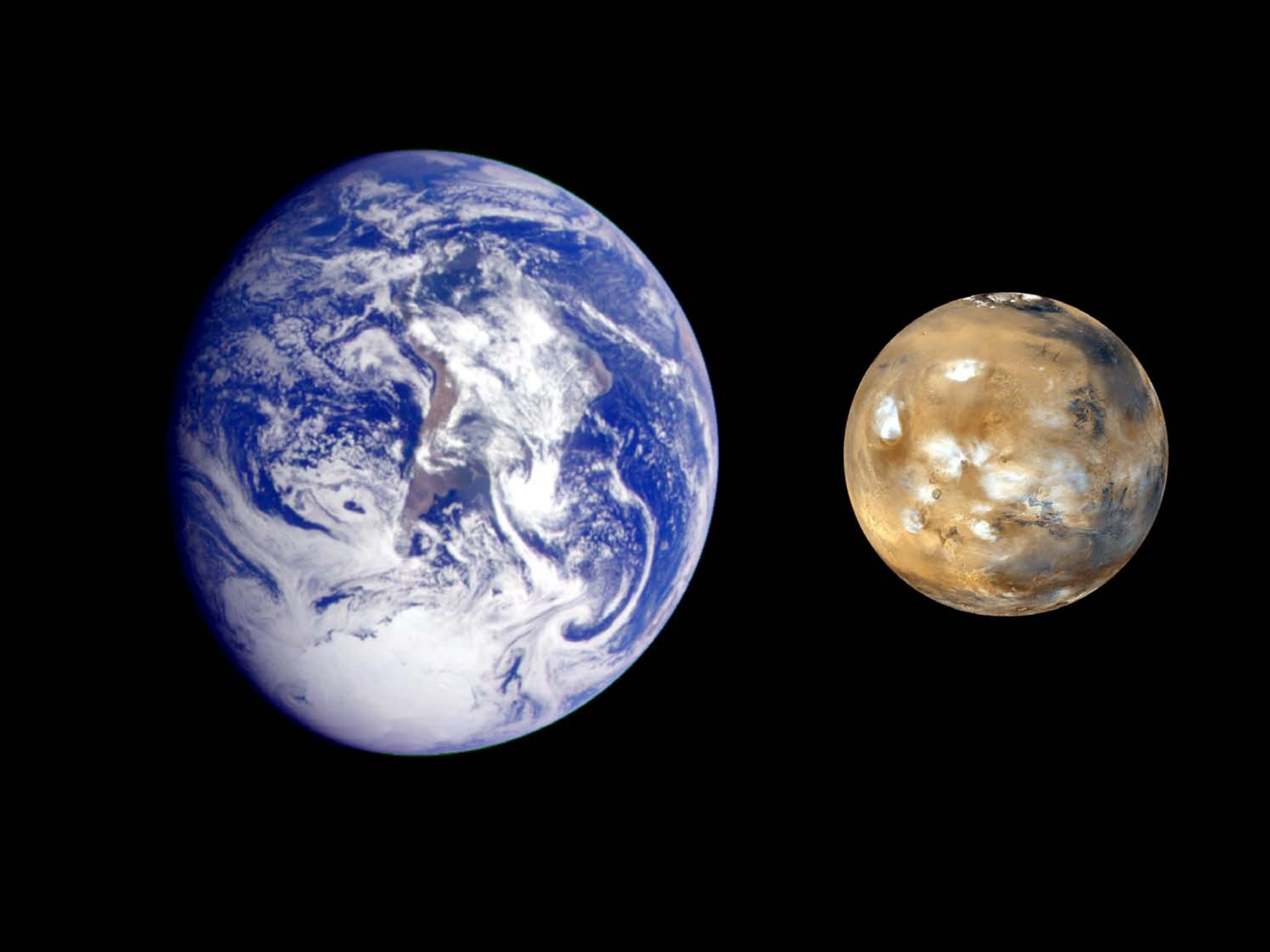


Forget 1998

Why did Mars lose its atmosphere ?



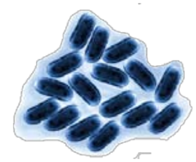
Forget et al. (2008)



Habitability trough time:

Time is necessary to life to arise and evolve :

- - 4,5 Ga : Earth formation
- Before -3,8 -3,5 Ga : Life
- -1.4 Ga : Multi-cellular life
- - 0.6 Ga : First animals
- ± 0 : Intelligence



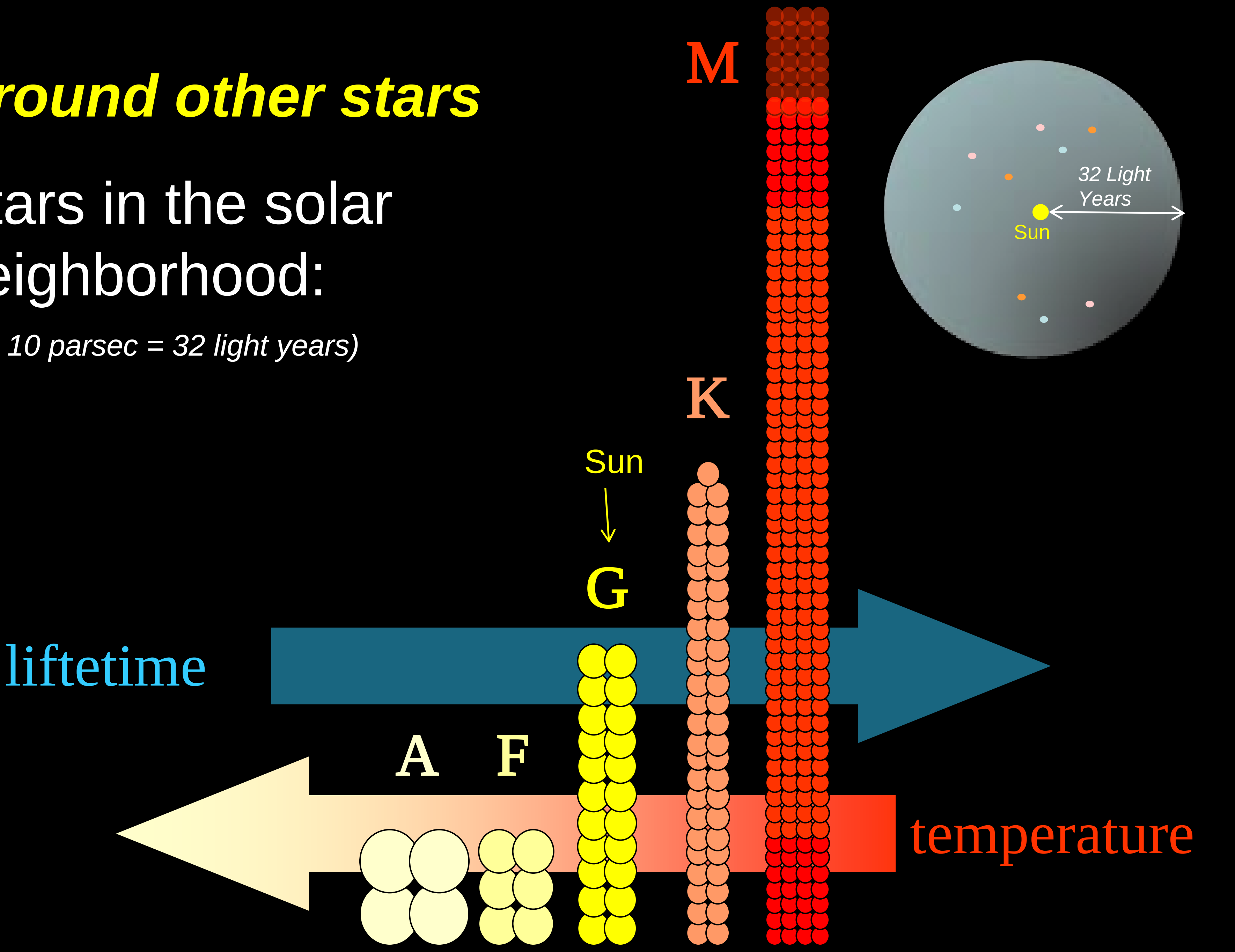
Problem :

- Evolution of stars
- Conservation of the atmosphere and climate stability : that may requires
  - Gravity (Mars) : *Planet mass should be > ~0.5 Earth mass ?*
  - A magnetic field ??? (Mars)
  - Plate tectonic ?
  - Life ?
  - Climate stability : is a moon necessary ?

Around other stars

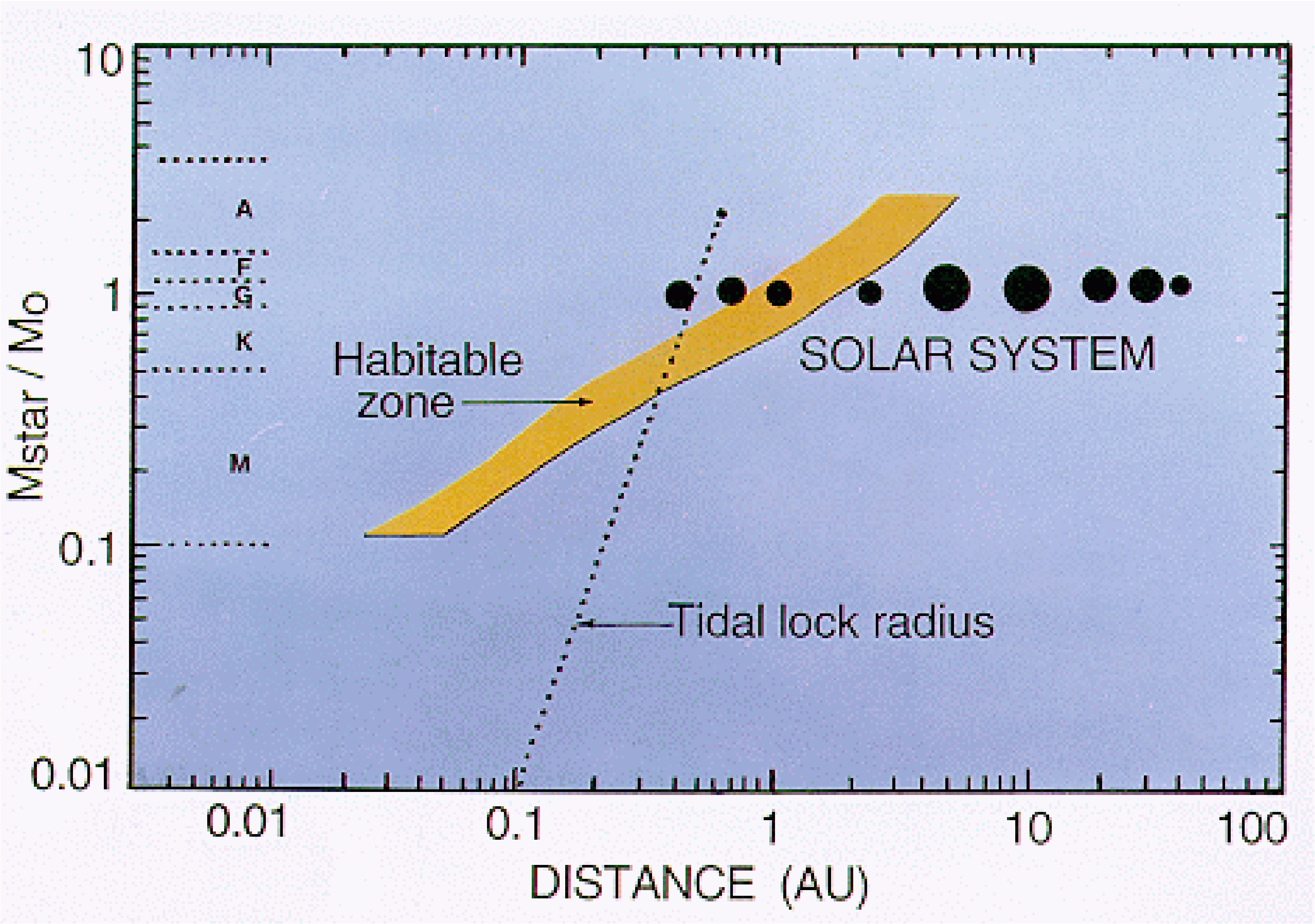
Stars in the solar neighborhood:

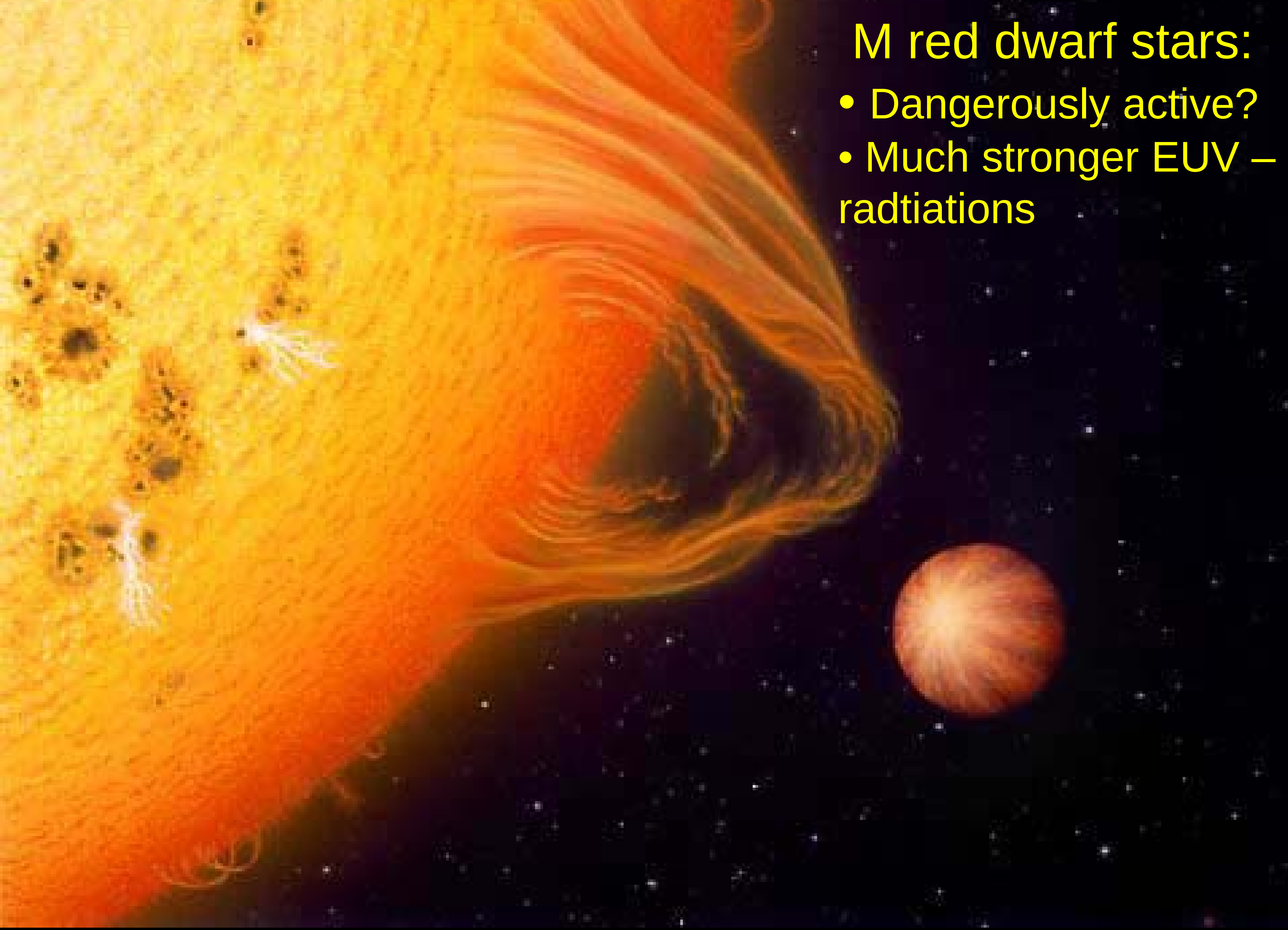
(d < 10 parsec = 32 light years)



Habitable Zone around other stars

(Kasting et al. 1993)



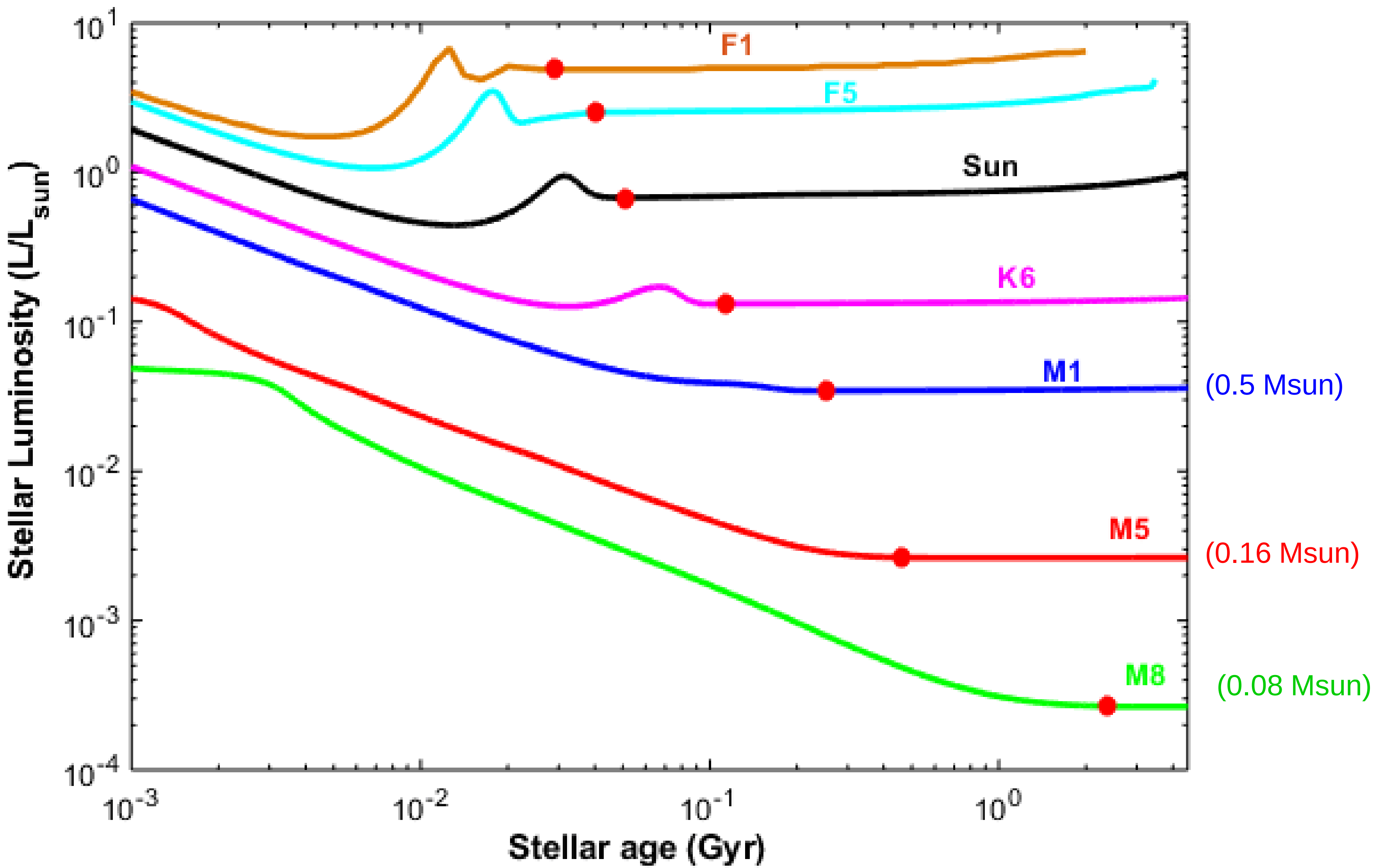


M red dwarf stars:

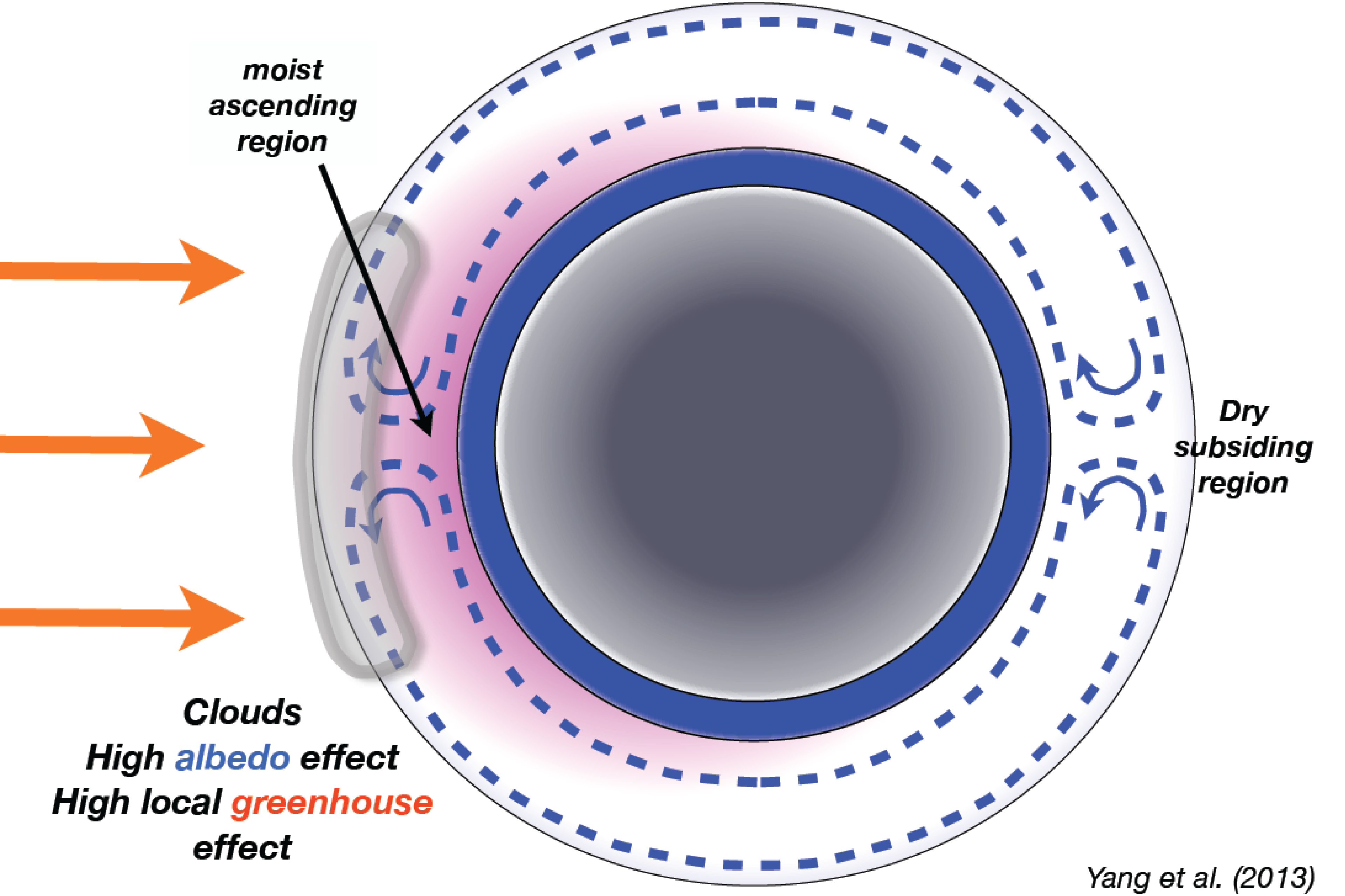
- Dangerously active?
- Much stronger EUV – radtiations

Small stars "cool" slowly before stabilizing their luminosity

Their planets have time to lose a lot of water to space before condensing their oceans…



Large scale cloud pattern on tidally locked planets



Glaciation around K & M dwarf stars:

Redder stellar spectrum

- No albedo water ice feedback *(Joshi and haberle, 2012)*
- Weak atmospheric Rayleigh Scaterring

  ⇨ lower albedo

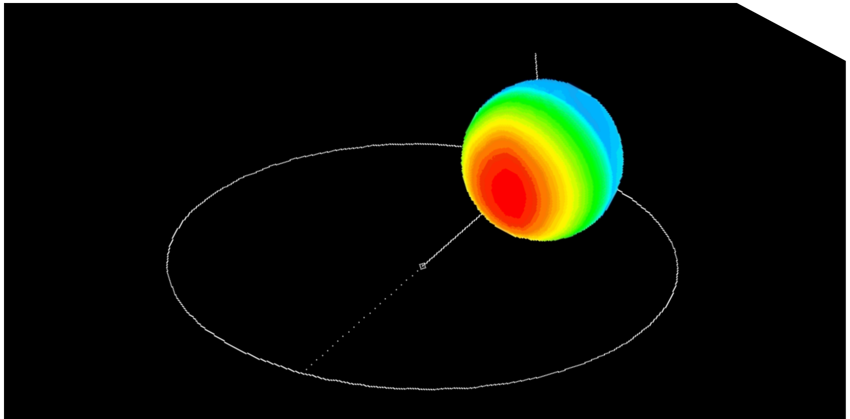
  ⇨ Enhanced high pressure CO2 greenhouse effect

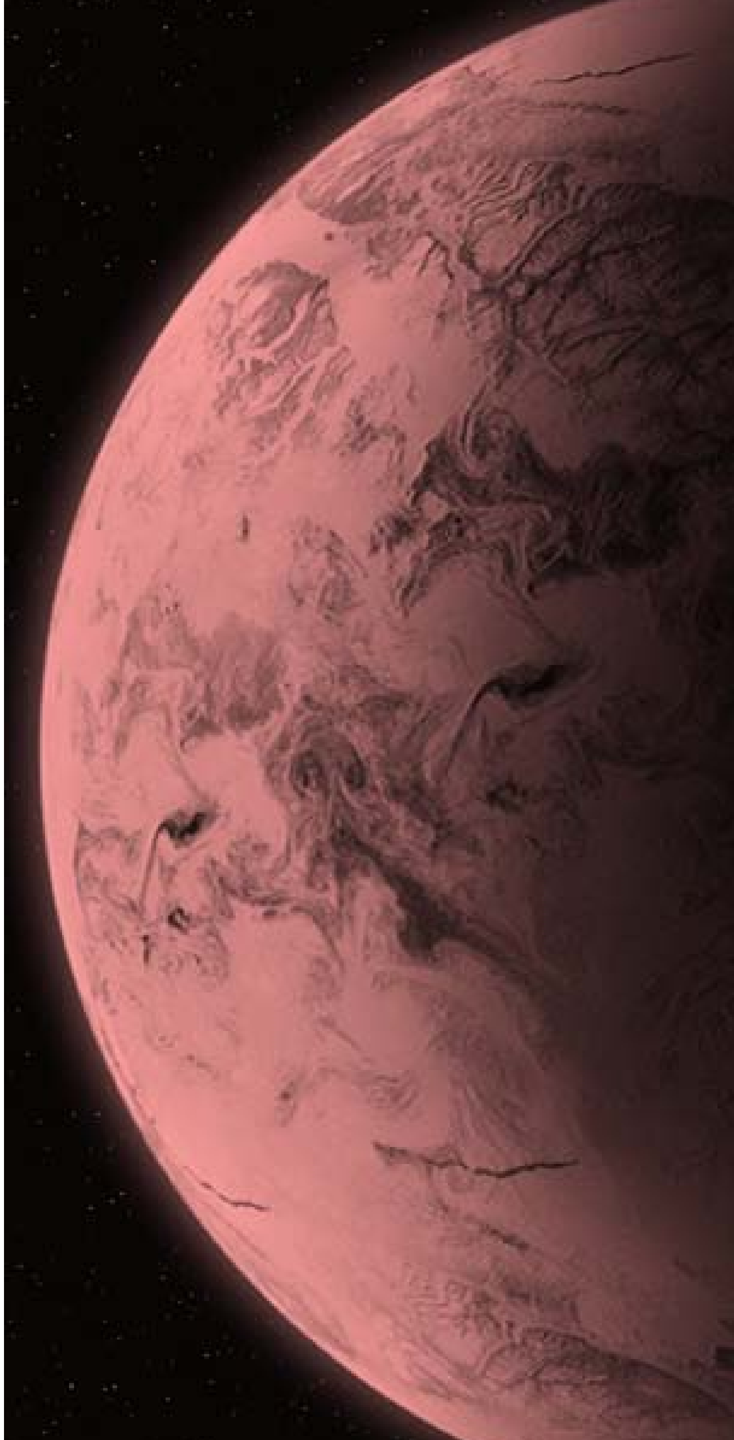
But : Effect of tides on rotation:

- Resonant rotation with zero obliquity

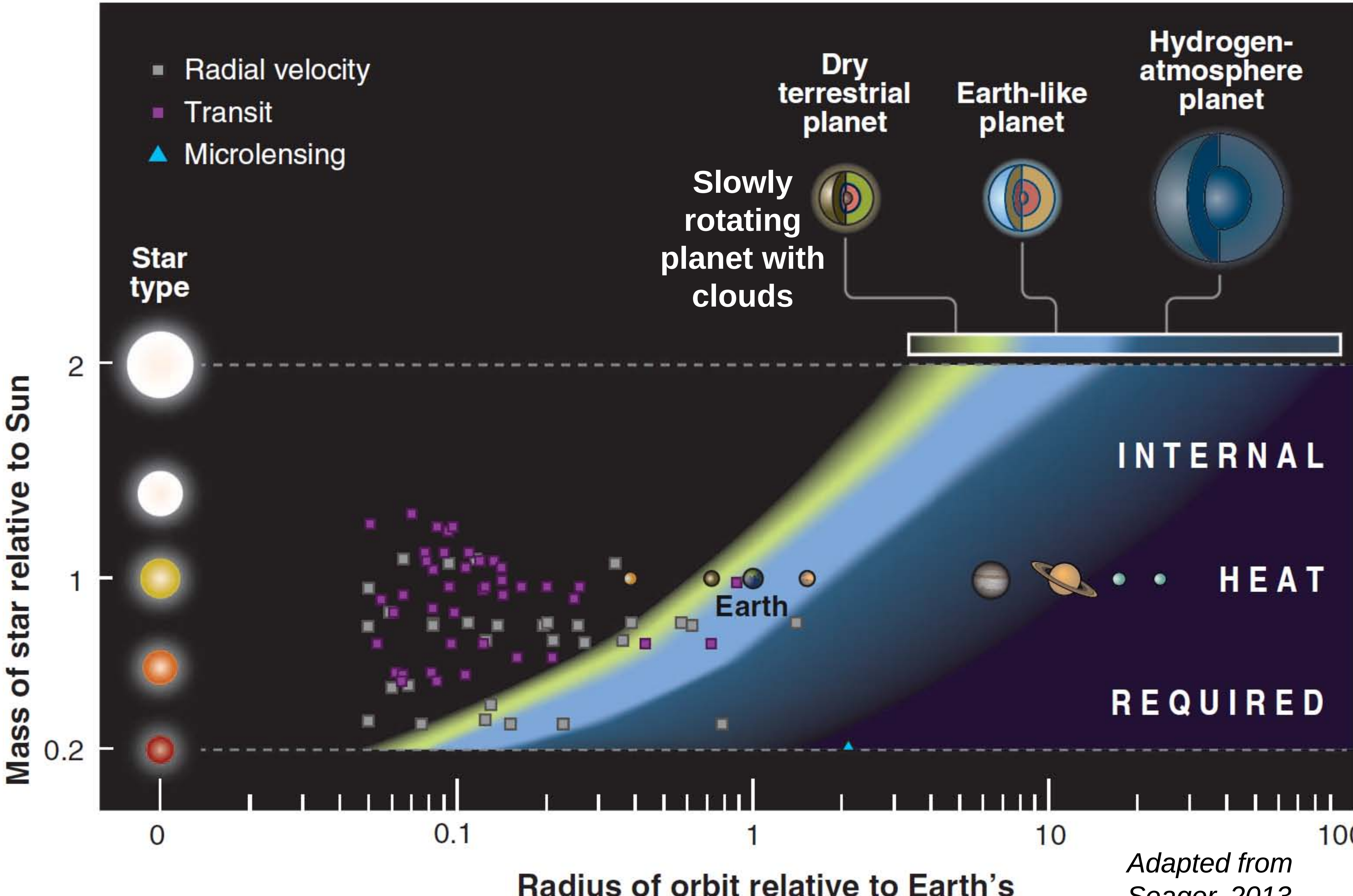
⇨ No insolation at the pole

⇨ Possible Locking with permanent night side?



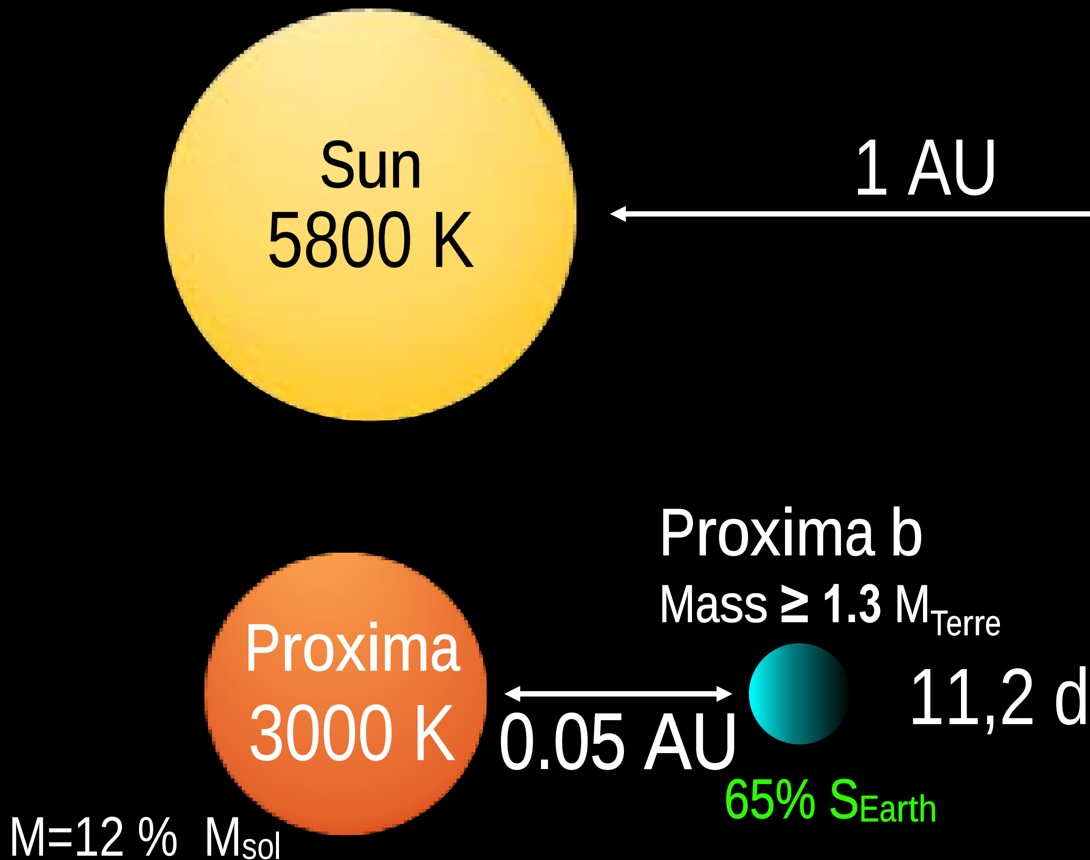


Summary : The surface liquid water habitable zone



Adapted from Seager, 2013,

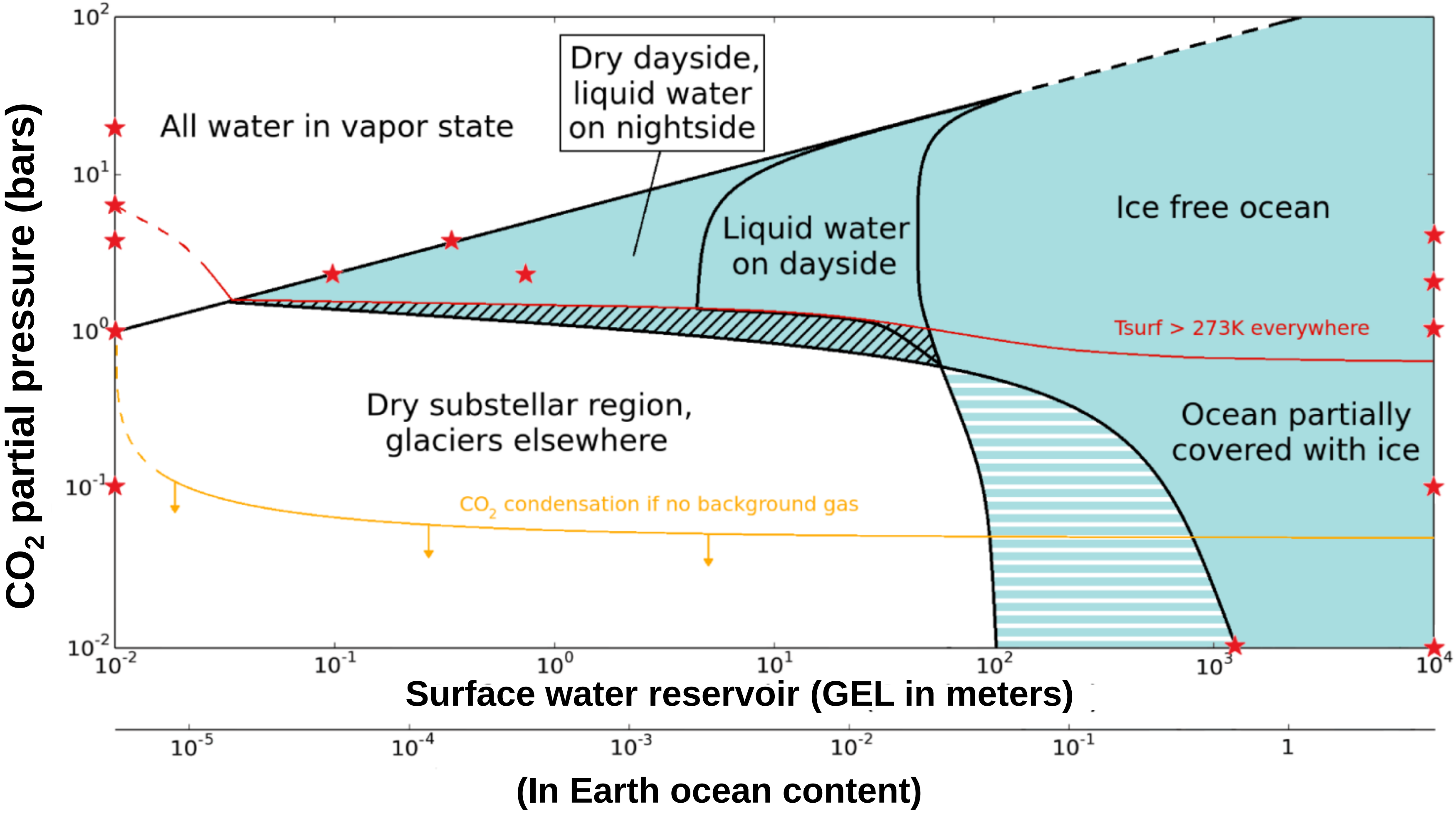
An exemple of habitability study
Proxima b: an exoplanet around the closest star to the Sun



⇨ Which environment on Proxima b ?

Possible climates on Proxima b

(Synchronous rotation)



based on multiple 3-D ★
Global Climate Model (GCM) simulations

Turbet et al. 2016, *A&A*

Conclusions on habitability

- **Some habitable planets (with liquid water) are more "habitable" than others** (duration of habitability, availability of light and chemicals, etc.)

- The "**Habitable zone**" can be defined as the orbit range outside which surface liquid water is impossible ⇨ Outside there is little hope to find a detectable biosignature for Astronomers.

- **The key open question**: what does it take for a planet in the habitable zone to be and remain suitable for surface liquid water
  - getting & keeping the right atmosphere & water inventory (impacts, escapes…)
  - adapting its atmosphere & greenhouse effect to star evolution and other sources of unstability

⇨ **On the Earth, our understanding is biased *("Anthropic principle")***

- We have learned climatology, geophysics, astrophysics, etc. from a system that have "worked"

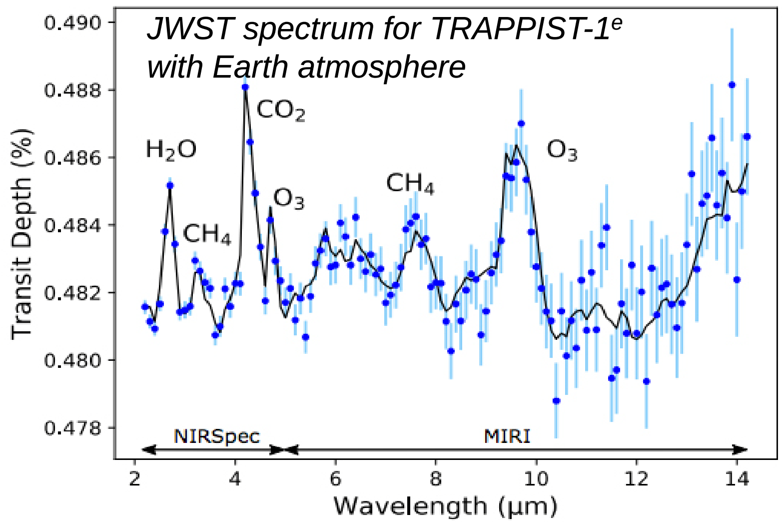
- The Earth could be exceptional : it is difficult to realize this and it is not a lucky coincidence that we are on it.

Conclusion 2: how to investigate the likelyness of extraterrestrial life ?

Ongoing : a step by step investigation:

1) Are there rocky exoplanets in the HZ ? Yes ✓
2) What kind of atmospheres on exoplanets ?
   - Upcoming soon : JWST, Giant ground based telescopes, Ariel, “Habex – Luvoir”
   - We can learn a lot from atmosphere even outside the habitable zone
3) Are exo-oceans common ? *More difficult to detect*
4) In parallel : Does “life” start easily in liquid water environment ? ⇨ *Investigation in the solar system*

The lucky Shortcut:
Remote detection of “bio-signatures” on a nearby exoplanet →



Thank you