Understanding habitability on the pathways to habitable planets

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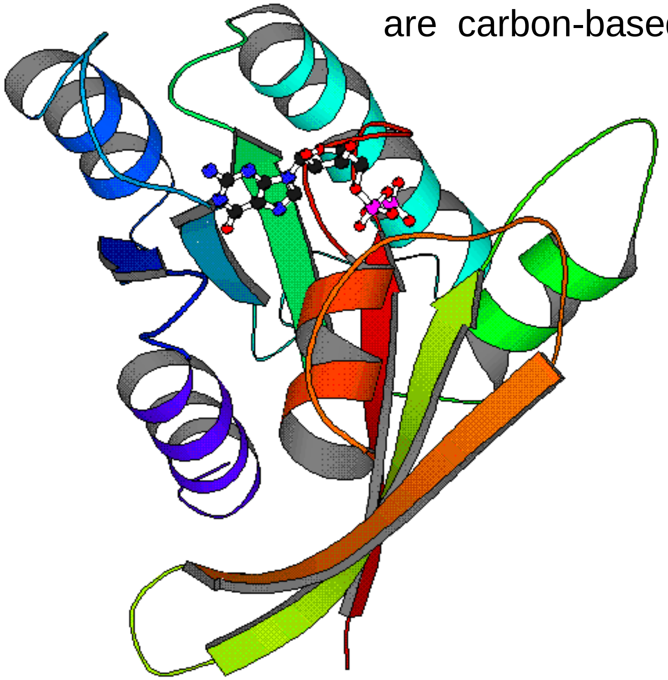
Habitability: What is life ?
What's needed for Life ?

- **??**

⇨ Carbon-based chemistry
… in liquid water

- **Carbon life without liquid water is**
  - **difficult to imagine**
  - **difficult to recognize and detect**

~95% of known chemical compounds are carbon-based

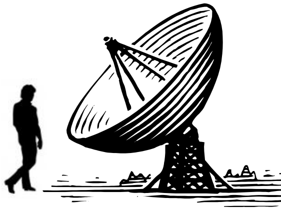


Hypothesis: Habitability = liquid water available

Habitability = liquid water available

⇨ Some habitables planets are « more habitable » than others

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



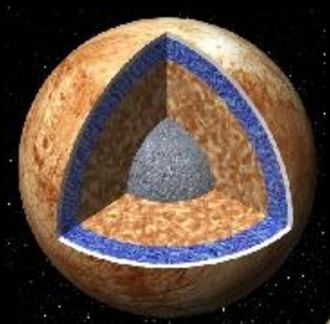
- **Quality of habitability**: Active, evolved (and detectable) life requires energy (light) and chemical species

4 kinds of « habitability »

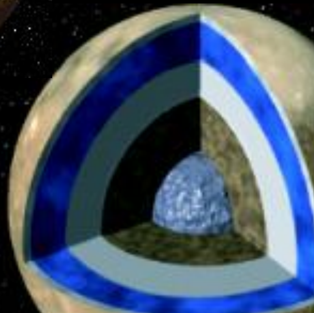
(Lammer et al. Astron Astrophys Rev 2009; Forget 2013)

- **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) : *Early Mars, early Venus ?*



- **Class III :** Bodies with subsurface ocean which interact with silicate mantle *(Europa*)



- **Class IV :** Bodies with subsurface ocean between two ice layers *(Ganymede)*

4 kinds of « habitability »

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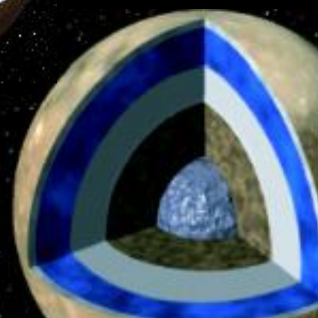
- **Cla**
whic

Surface liquid water allows photosynthetic life, able to modify its environment

⇨ **Traditional Habitable Zone** *(J.Kasting)* or the « *Hunting Zone* » (*F. Selsis*)

- **Class IV :** Bodies with subsurface ocean between two ice layers *(Ganymede)*

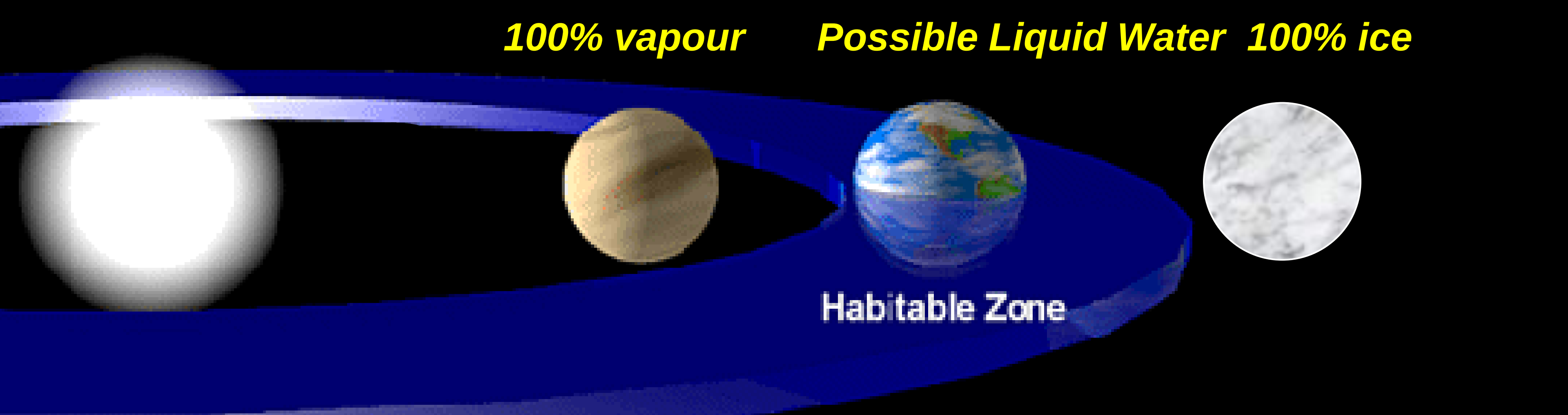


The« Habitable Zone» : liquid water possible on the <u>surface</u> of planets

Eg. Kasting et al. 1993
Forget 2013

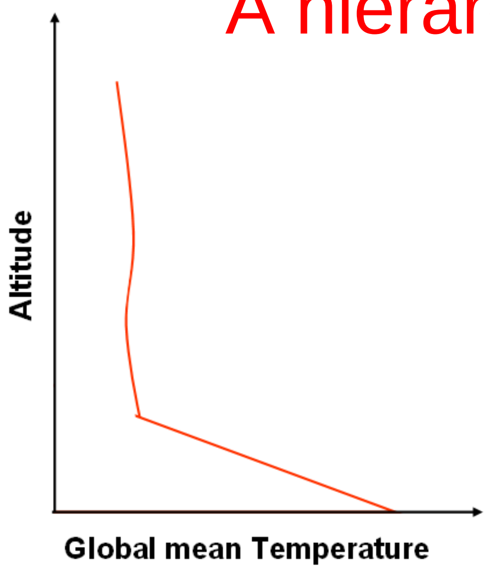
i.e. the region outside which it is <u>impossible</u> for a rocky planet to maintain liquid water on its surface

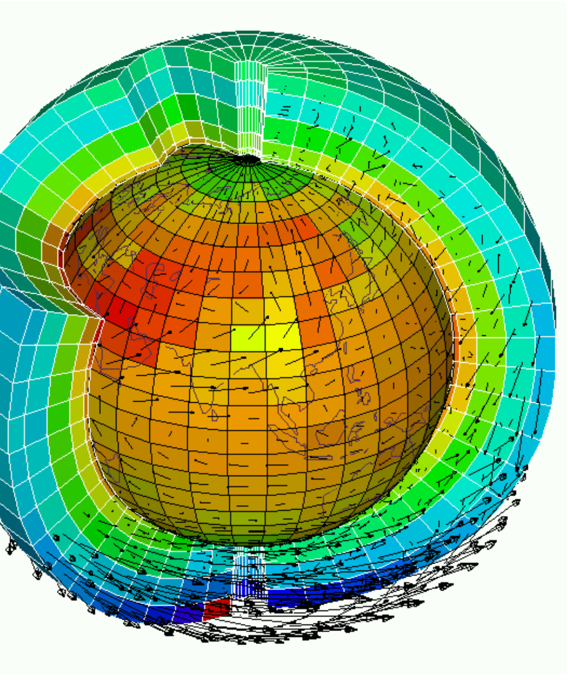
⇨ A problem of climate and atmosphere



Which climate on extra-solar planets ?

A hierarchy of models for planetary climatology





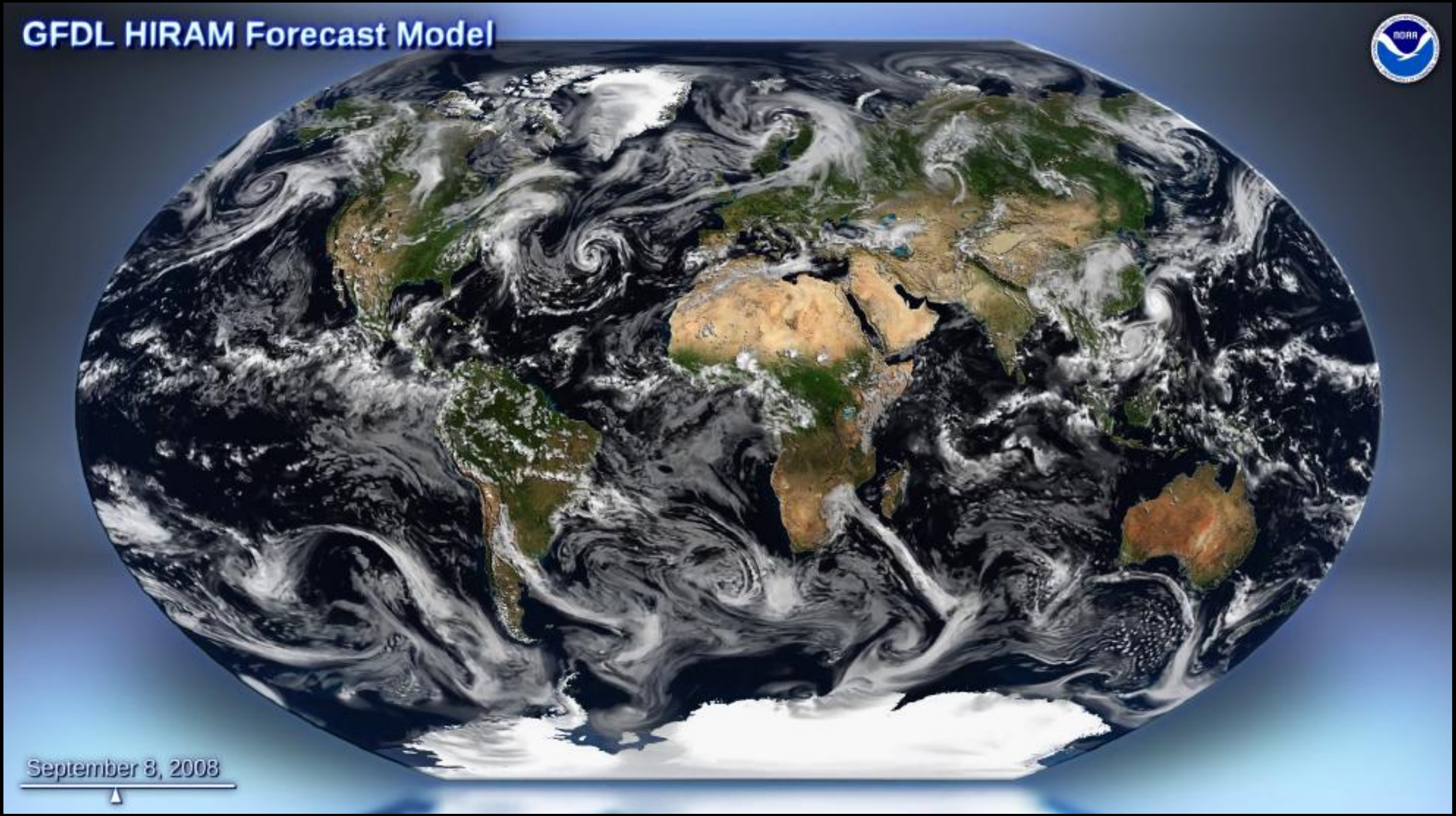
1. 1D global radiative convective models
⇨ Great to explore exoplanetary climates; still define the classical Habitable Zone
(e.g. Kasting et al. 1993, Kopparapu et al. 2013)

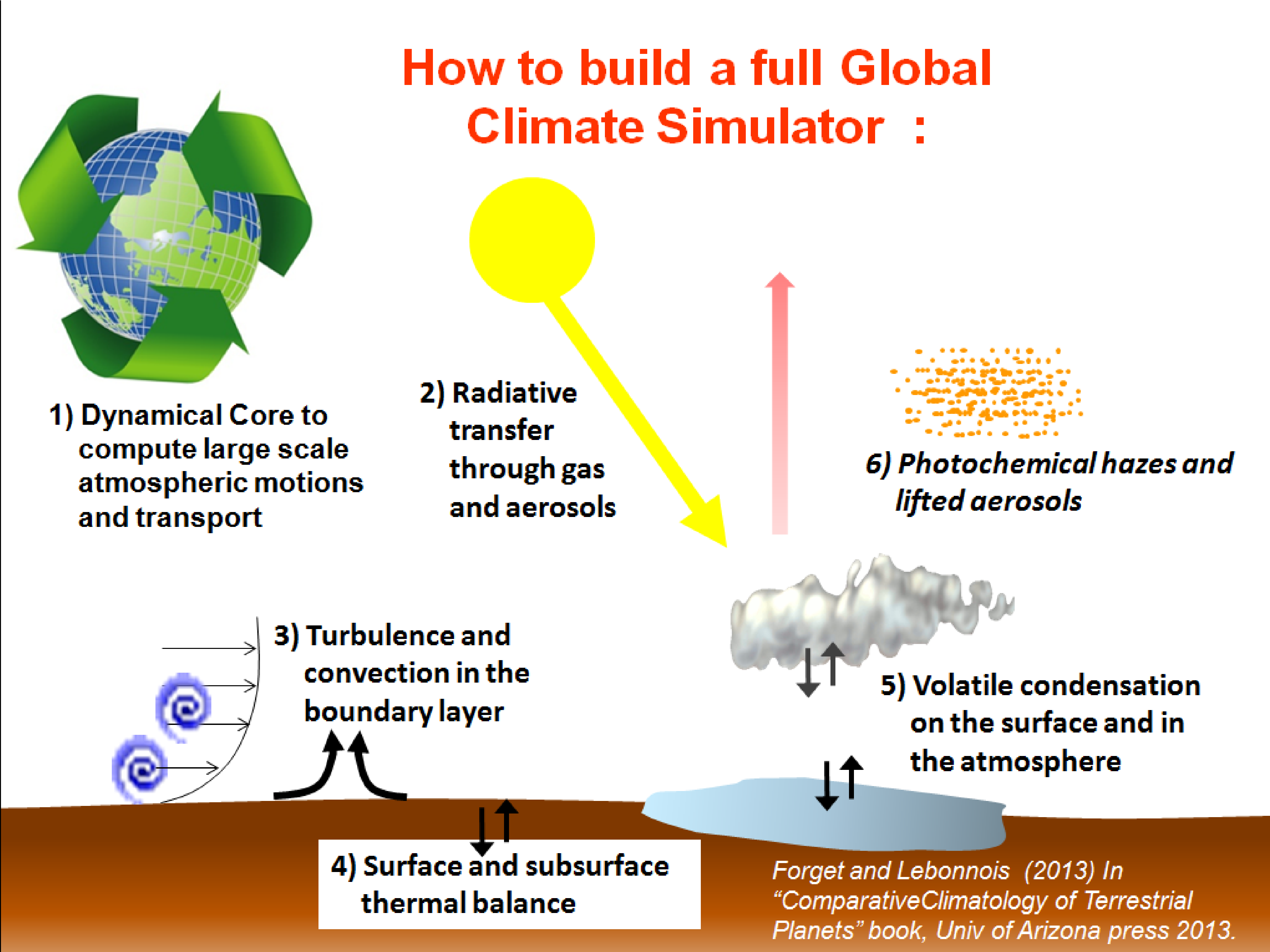
2. 2D Energy balance models…

3. Theoretical 3D General Circulation model with simplified forcing: used to explore and analyse the possible atmospheric circulation regime
(see Read 2011, Showman et al. 2013, etc)

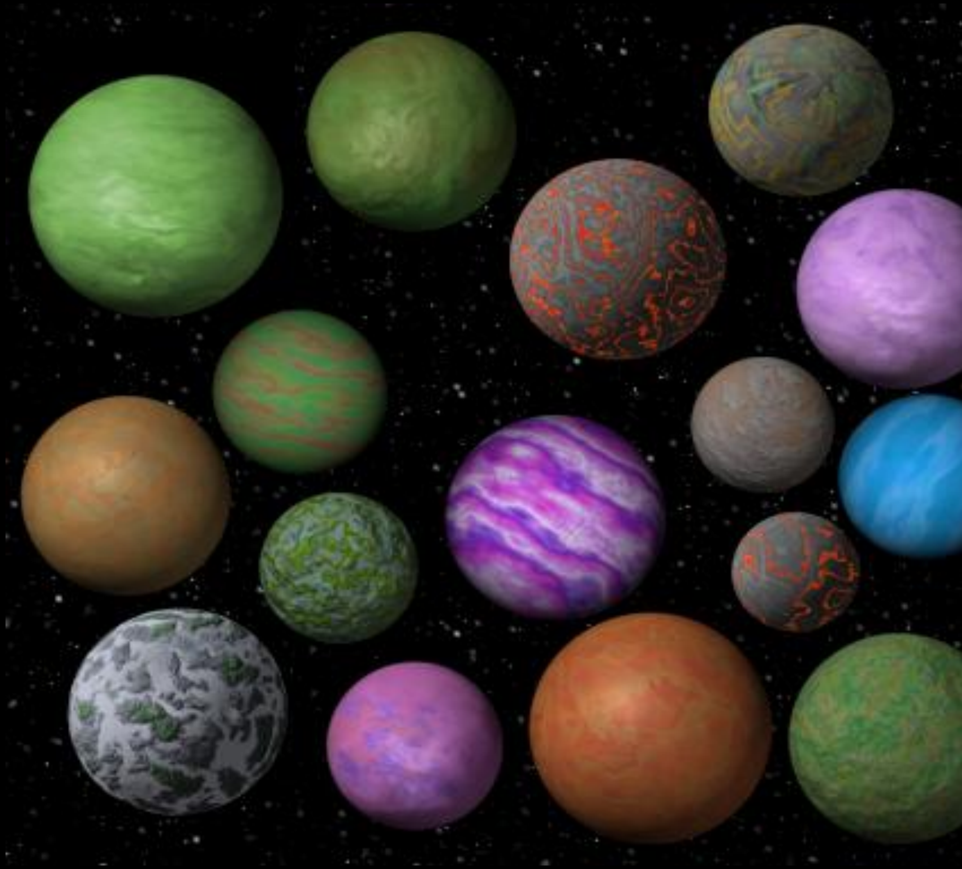
4. Full 3D Global Climate Models aiming at building "virtual" planets.

How to build a Global Climate Simulator ?




How to build a full Global Climate Simulator :
1) Dynamical Core to compute large scale atmospheric motions and transport
2) Radiative transfer through gas and aerosols
6) Photochemical hazes and lifted aerosols
3) Turbulence and convection in the boundary layer
5) Volatile condensation on the surface and in the atmosphere
4) Surface and subsurface thermal balance
Forget and Lebonnois (2013) In "ComparativeClimatology of Terrestrial Planets" book, Univ of Arizona press 2013.

From observed planets Global Climate Modelling to extrasolar planets climatology



Key parameters controlling the climate on a terrestrial planet:

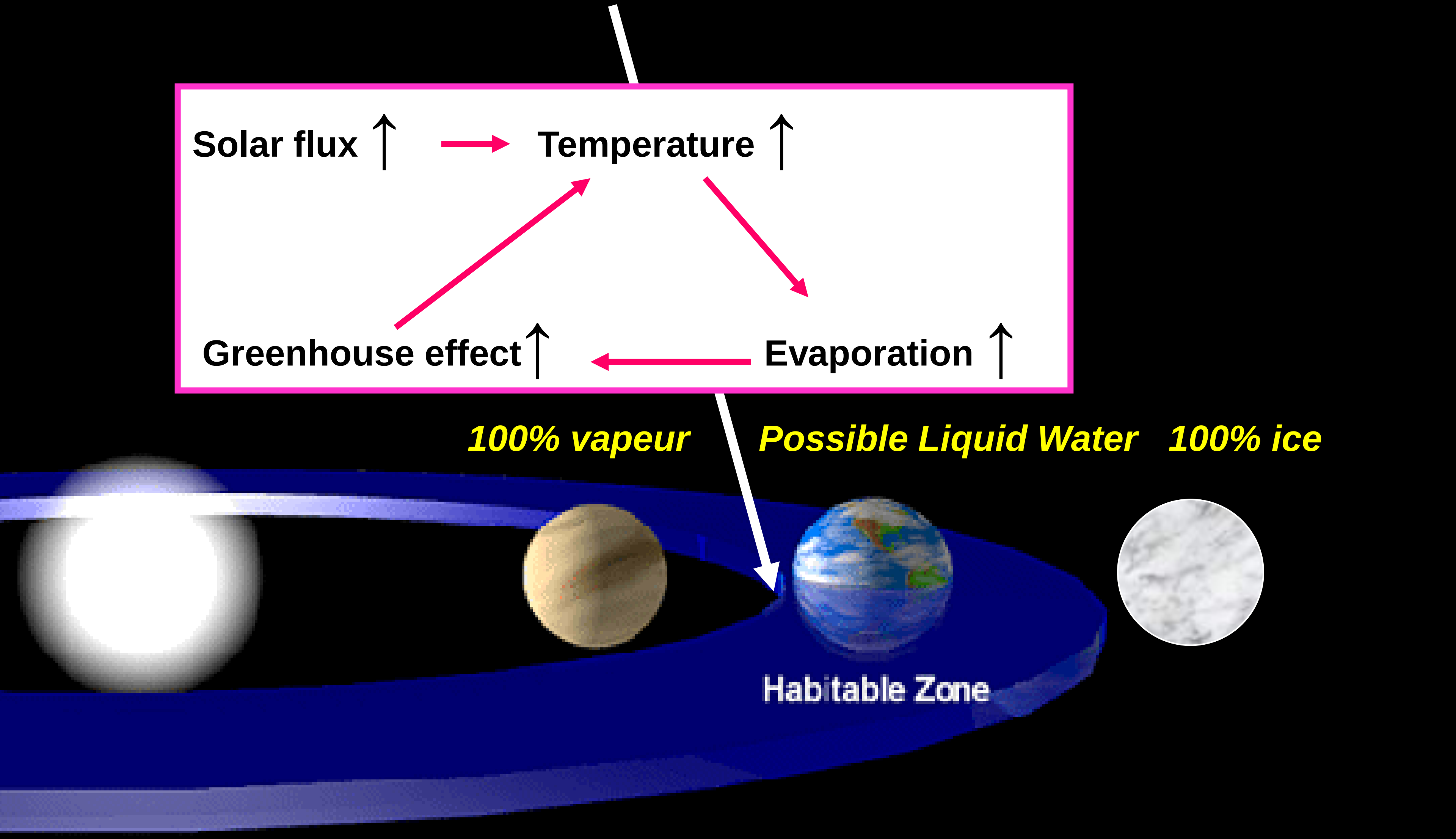
Climate models

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

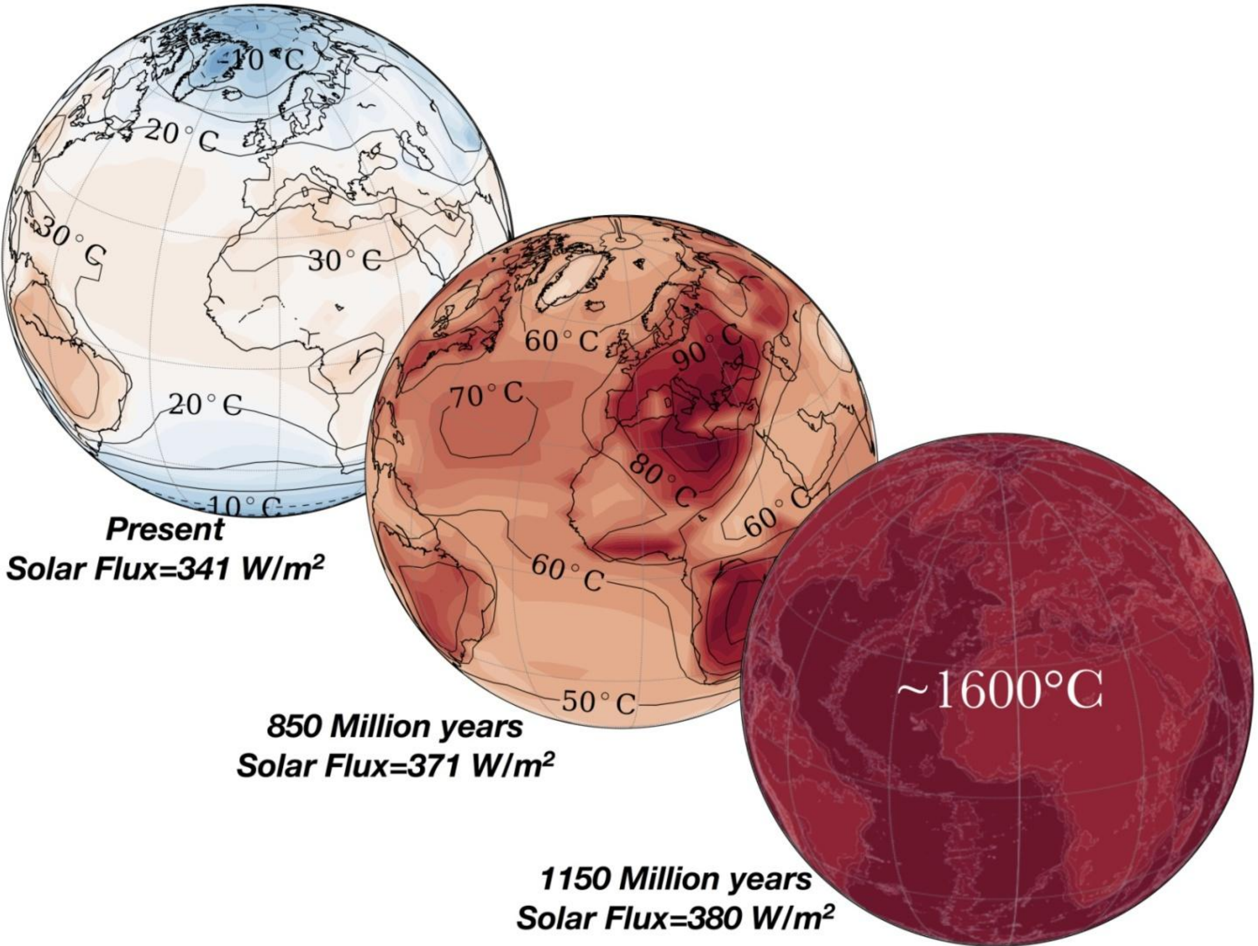
Climate

Habitability of planets

Inner Edge of the Habitable Zone ?



Runaway Greenhouse effect in a complete 3D Global Climate model

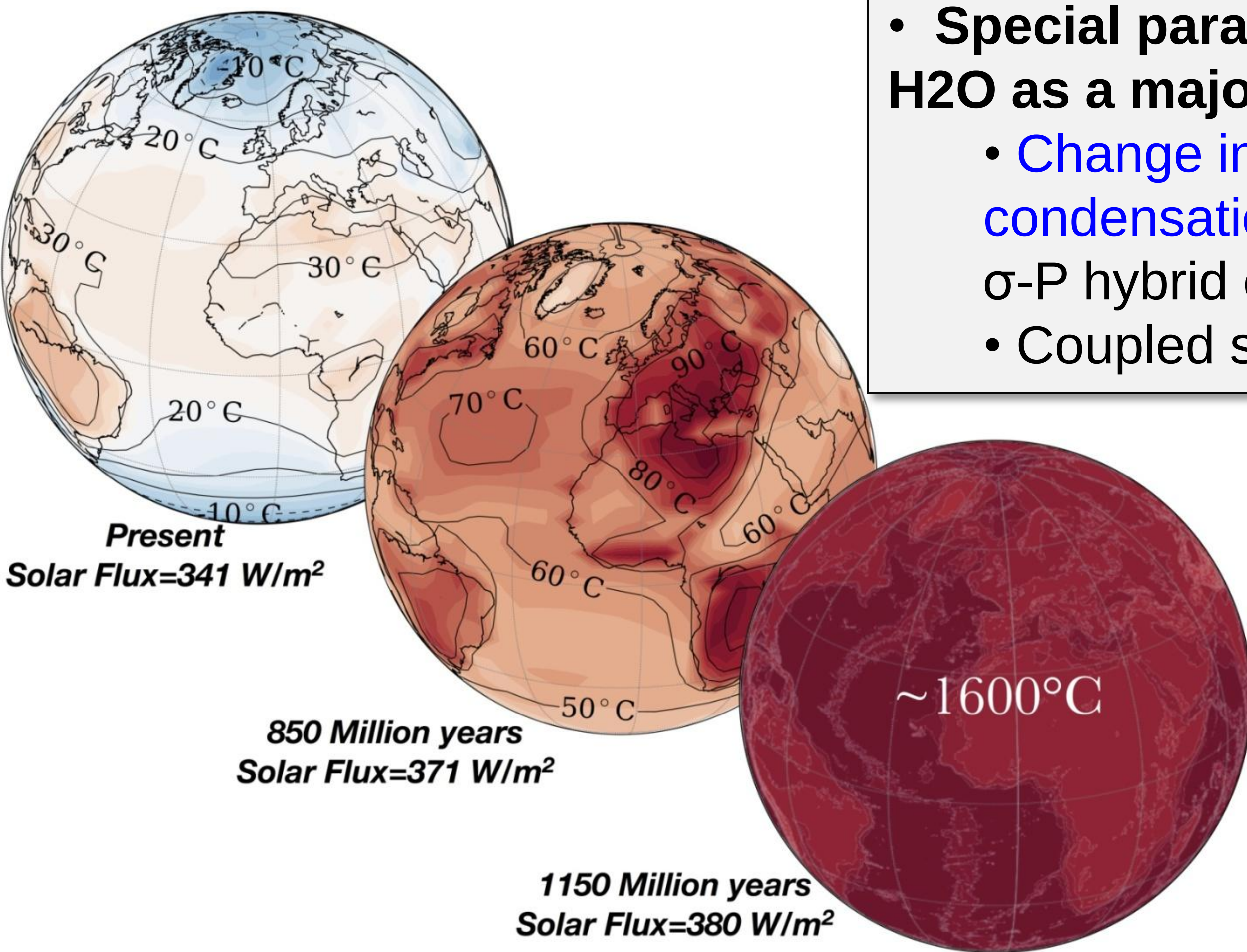


Leconte et al. 2013
Wolf and Toon 2014
Yang et al. 2013, 2014

Leconte et al. « *3D Increased insolation threshold for runaway greenhouse processes on Earth like planets*". Nature, 2013

LMD 3D Generic Climate Model

- Earth like planet
- 64x48x30 resolution
- Radiative transfer (correlated k)
  - 19 IR bands
  - 18 solar bands
- **Special parametrization to handle H2O as a major constituant :**
  - Change in Ps with condensation/evaporation ➪ case of σ-P hybrid coordinates.
  - Coupled system [H2O]+T+Ps

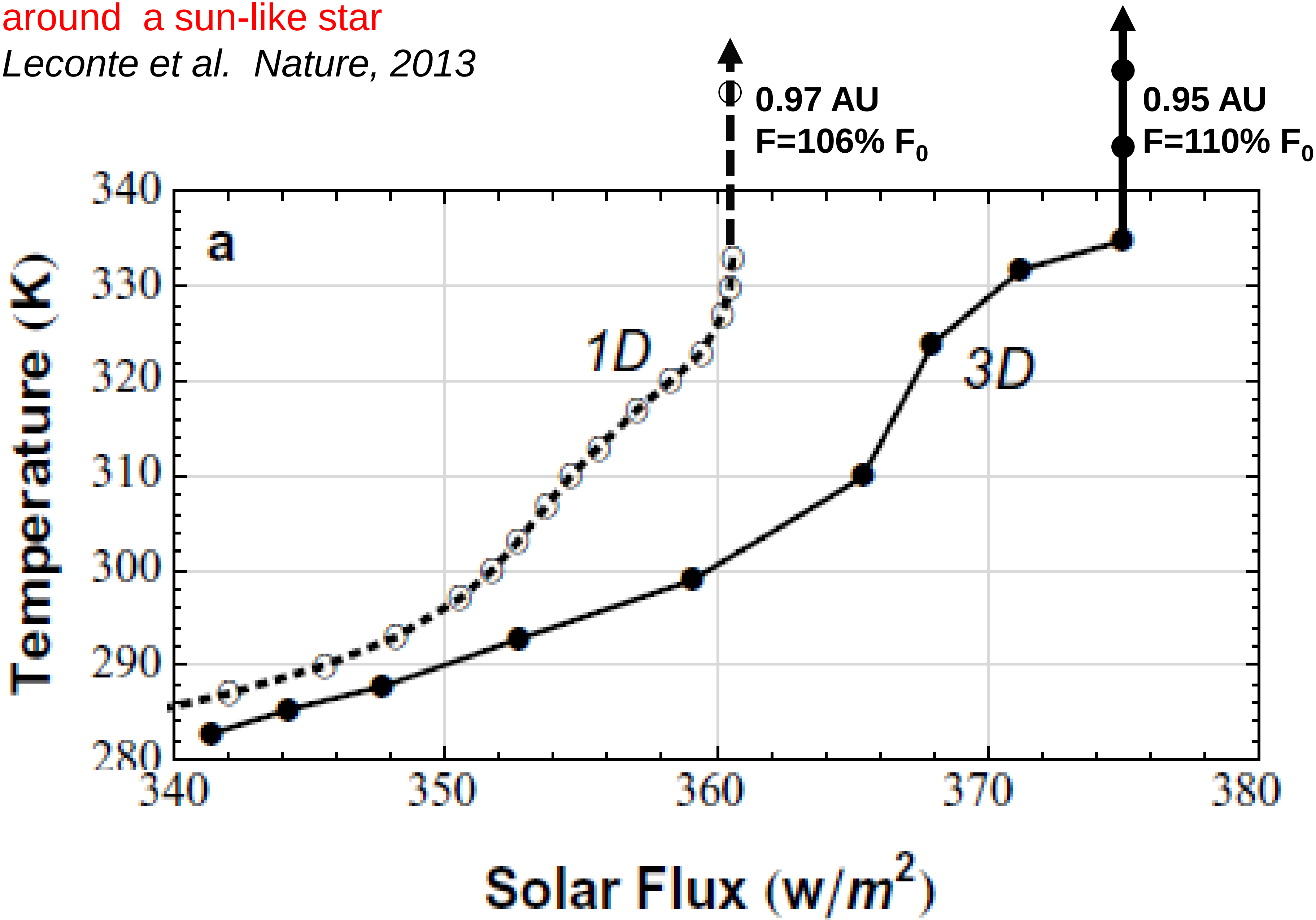


Present
Solar Flux=341 W/m²

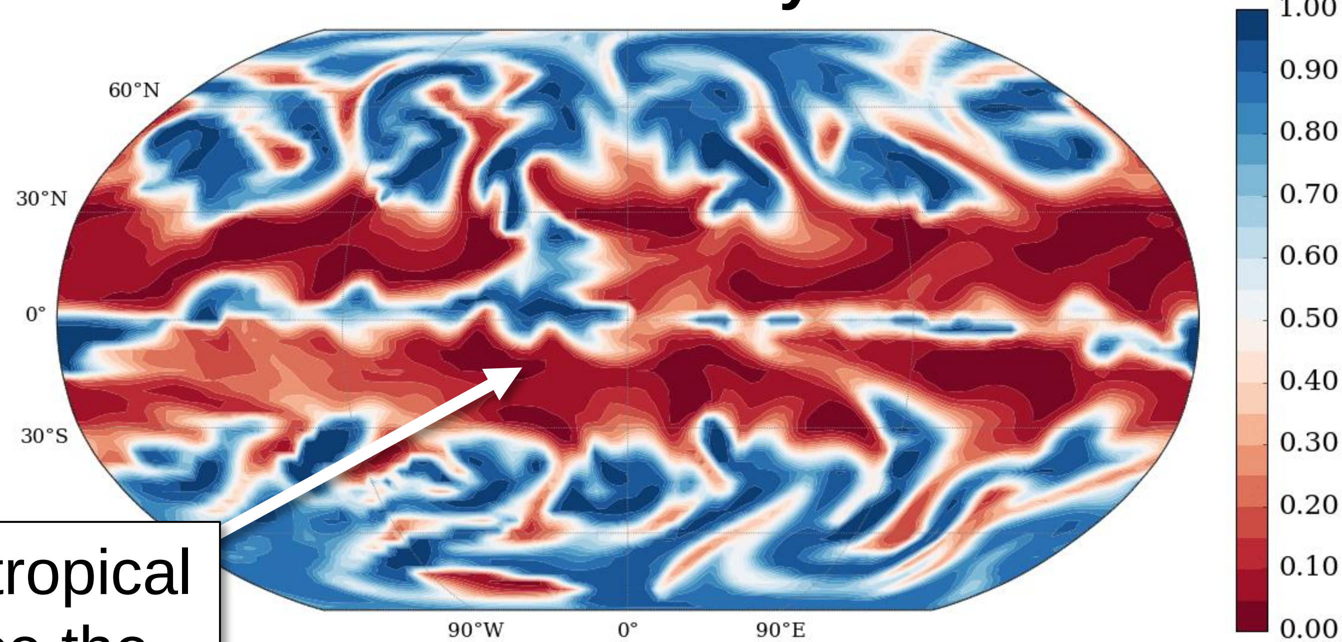
850 Million years
Solar Flux=371 W/m²

1150 Million years
Solar Flux=380 W/m²

LMD Model : Earth like planet
around a sun-like star
Leconte et al. Nature, 2013



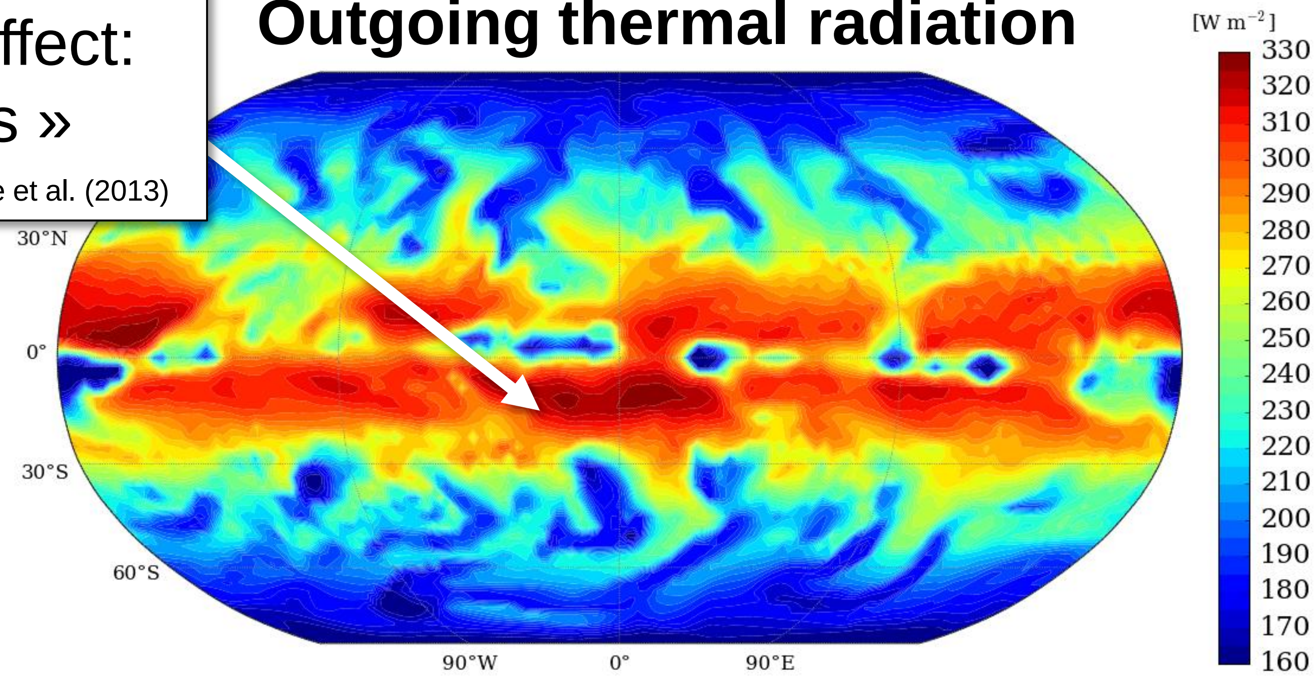
Relative humidity



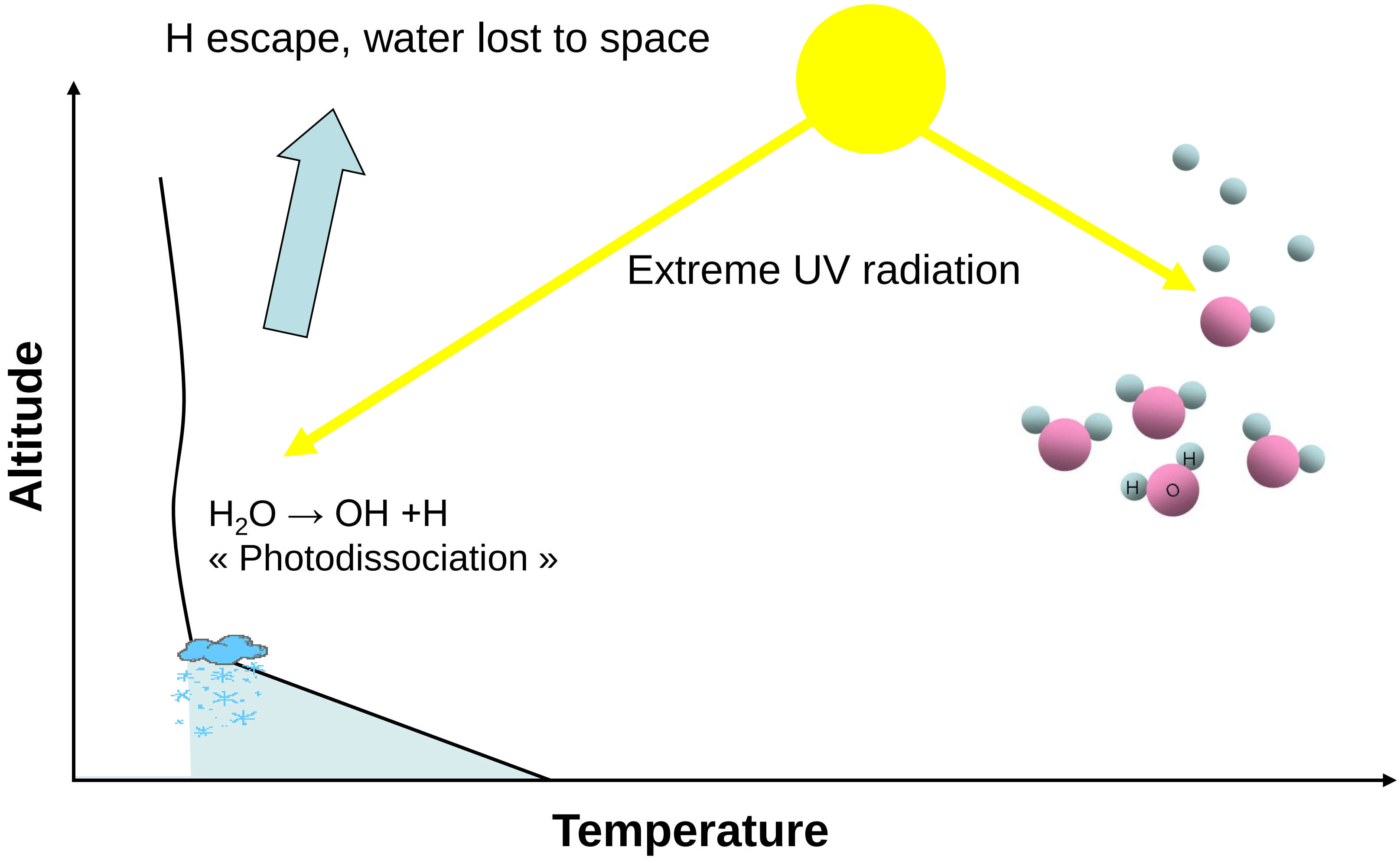
Unsaturated tropical regions reduce the greenhouse effect: « radiative fins »

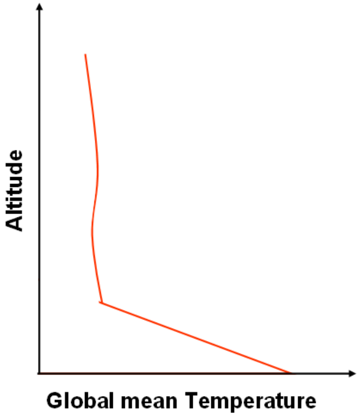
Pierrehumbert (1995), Leconte et al. (2013)

Outgoing thermal radiation



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*)

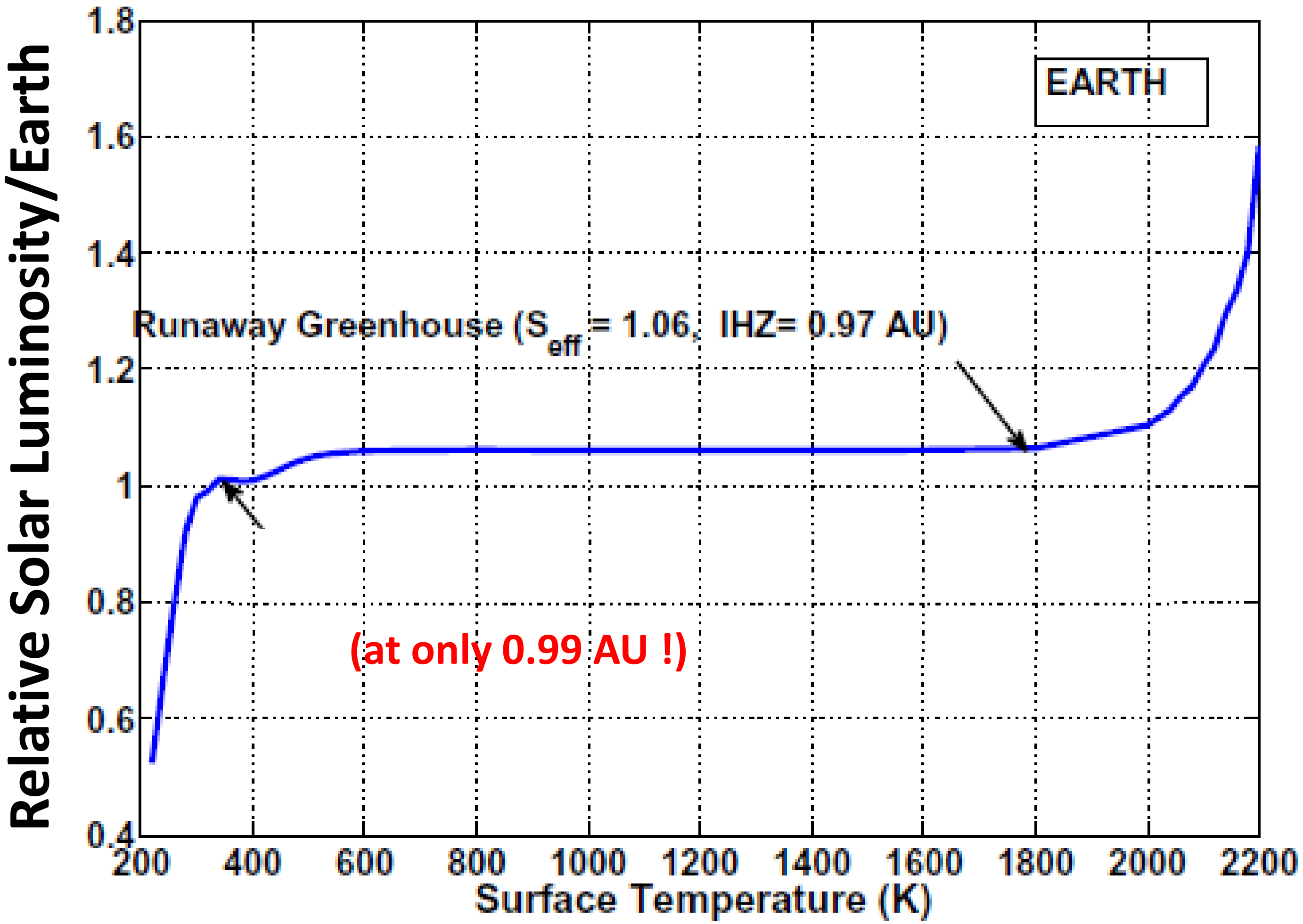


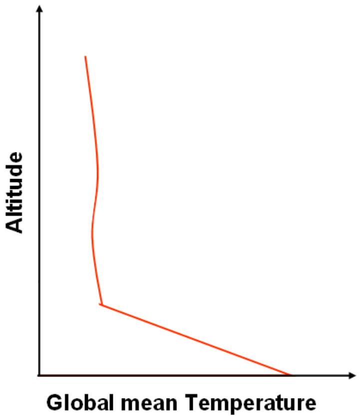


Runaway Greenhouse effect in 1D models

(for an Earth-like planet around a sun)

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





« Water loss limit » in 1D models

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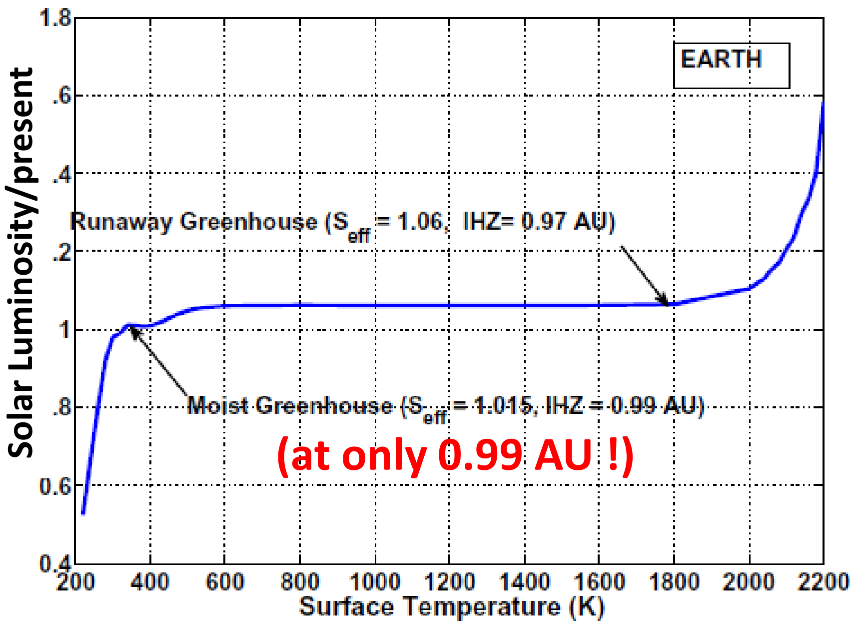
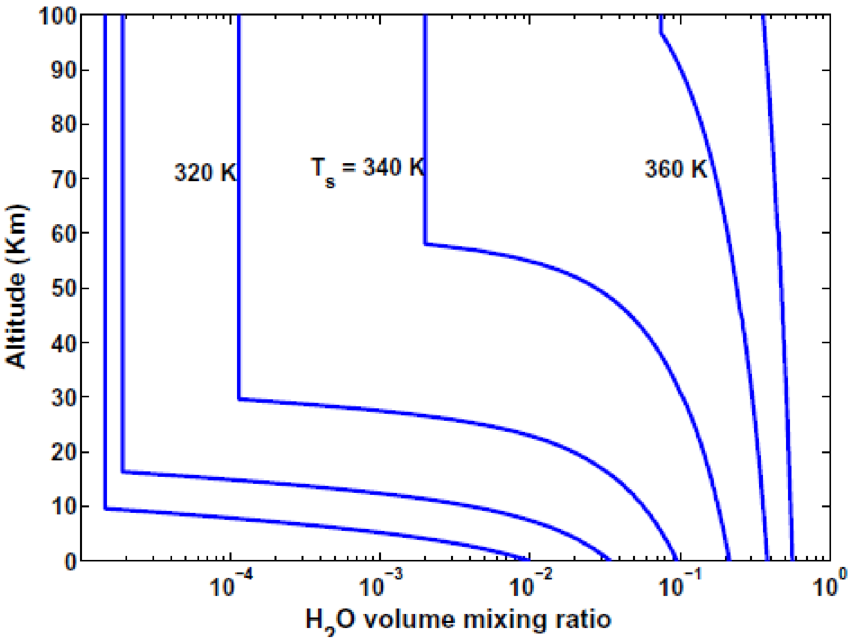
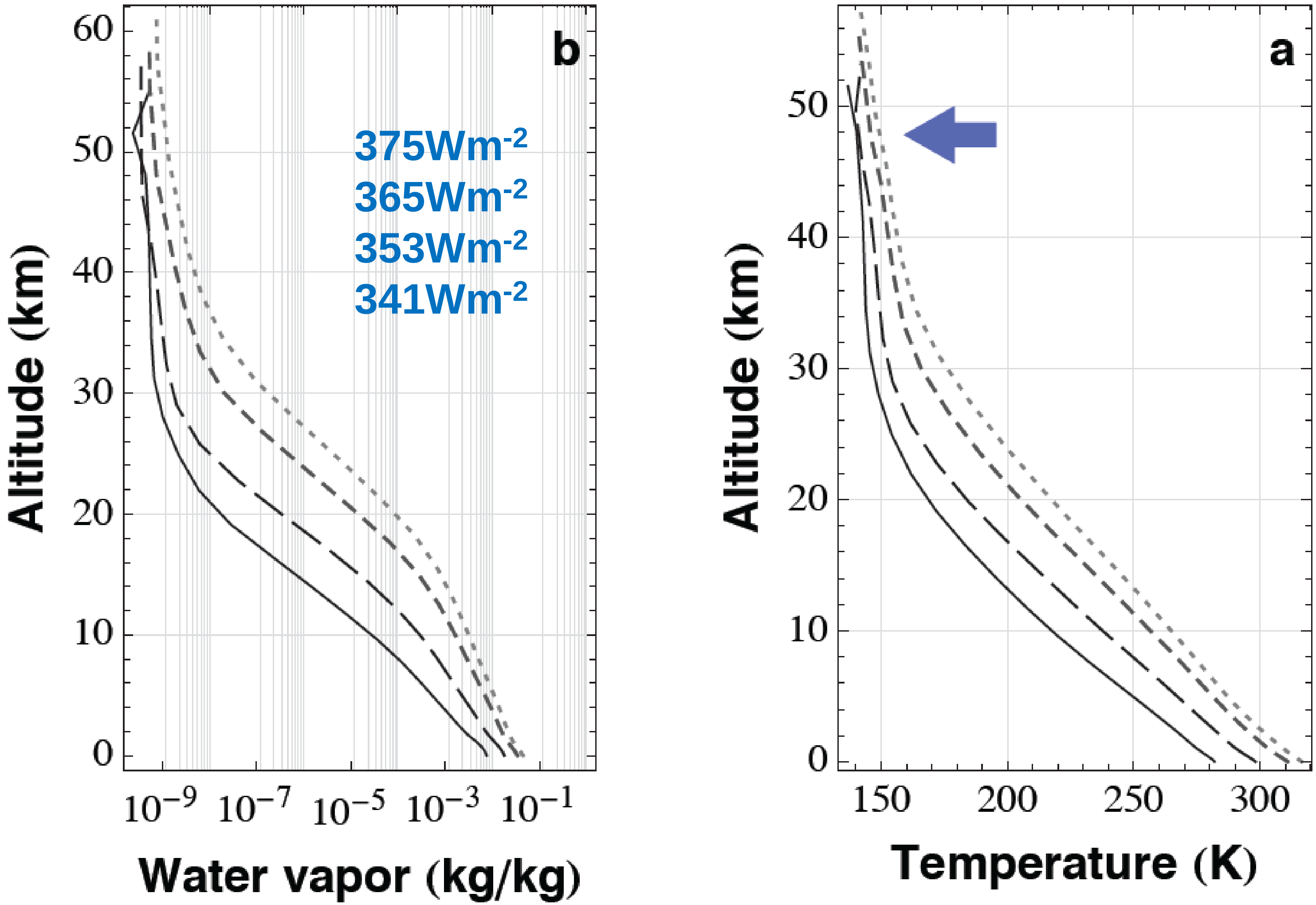


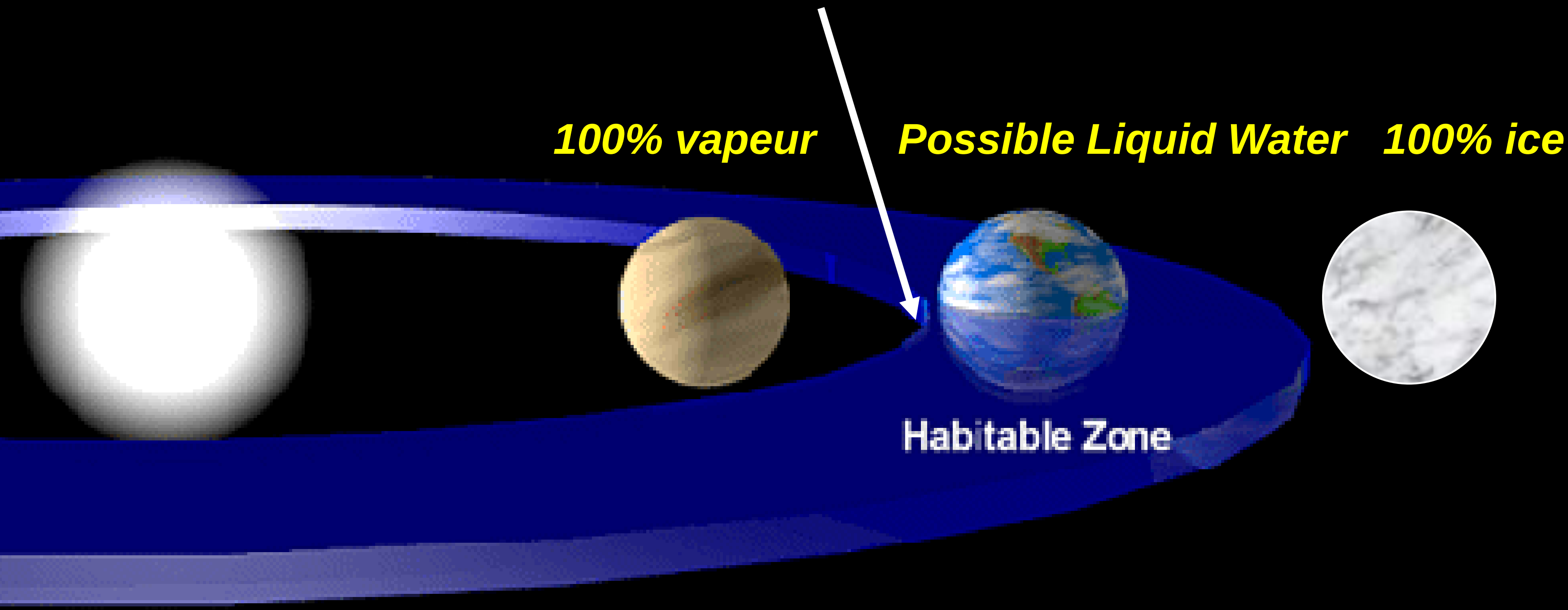


Earth like Simulation with detailed radiative transfer in the upper atmosphere: no water loss limit !



Leconte et al. (Nature; 2013)

Inner Edge of the Habitable Zone

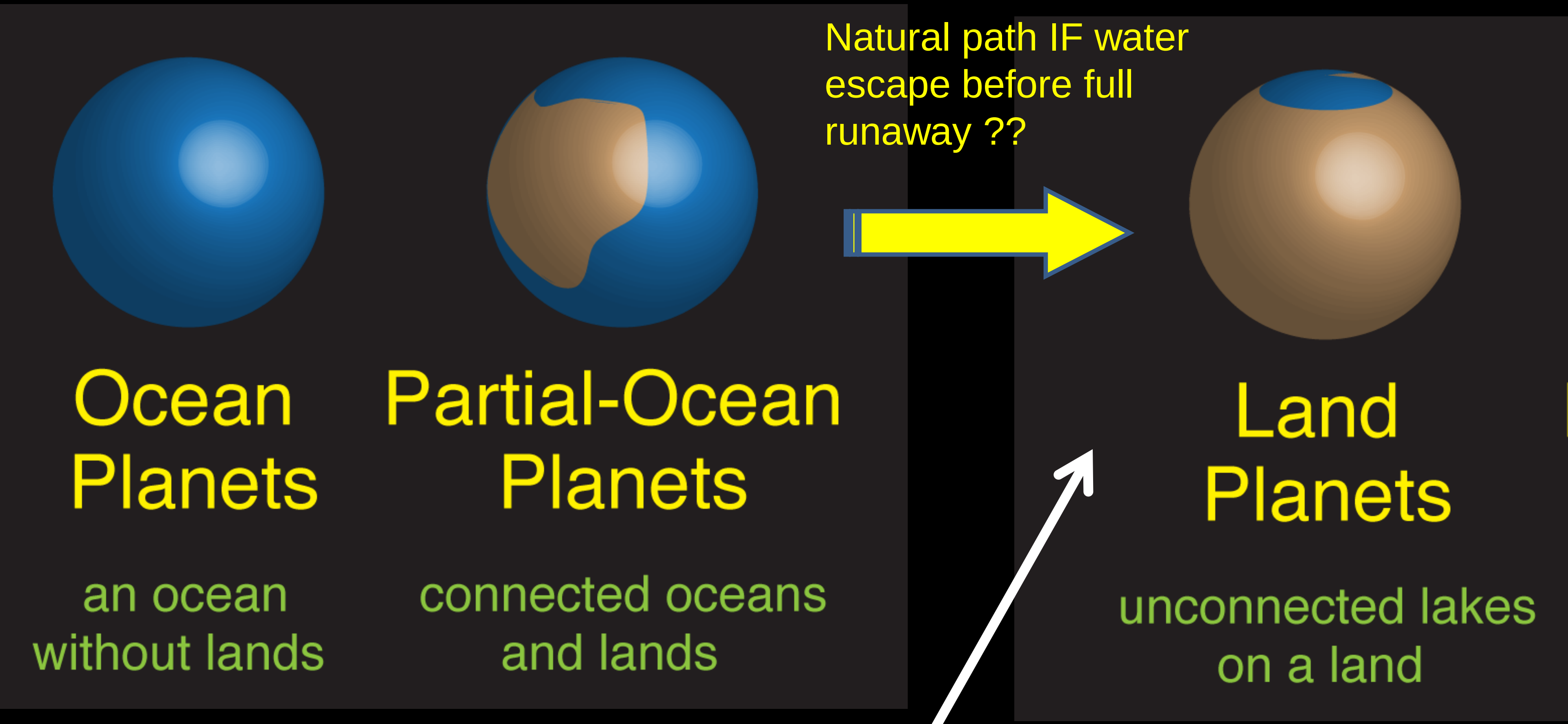


Around a given star, the exact location of the inner edge also depends on

- The water inventory (case of « dune » planet)
- The rotation rate and clouds

Climate depends on the amount of available water

(e.g. Abe et al. 2011)



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

Runaway greenhouse effect around K and M dwarf stars

Redder stellar spectrum

• Weak atmospheric Rayleigh Scaterring

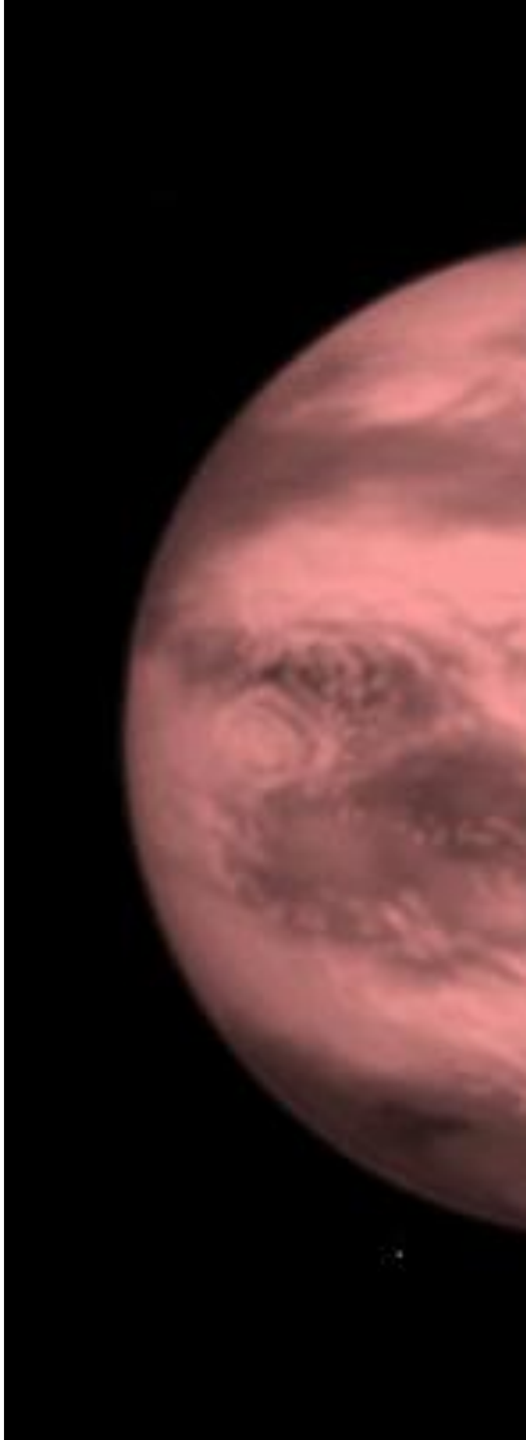
⇨ lower planetary albedo

Effect of tides:

• Resonnant rotation with zero obliquity

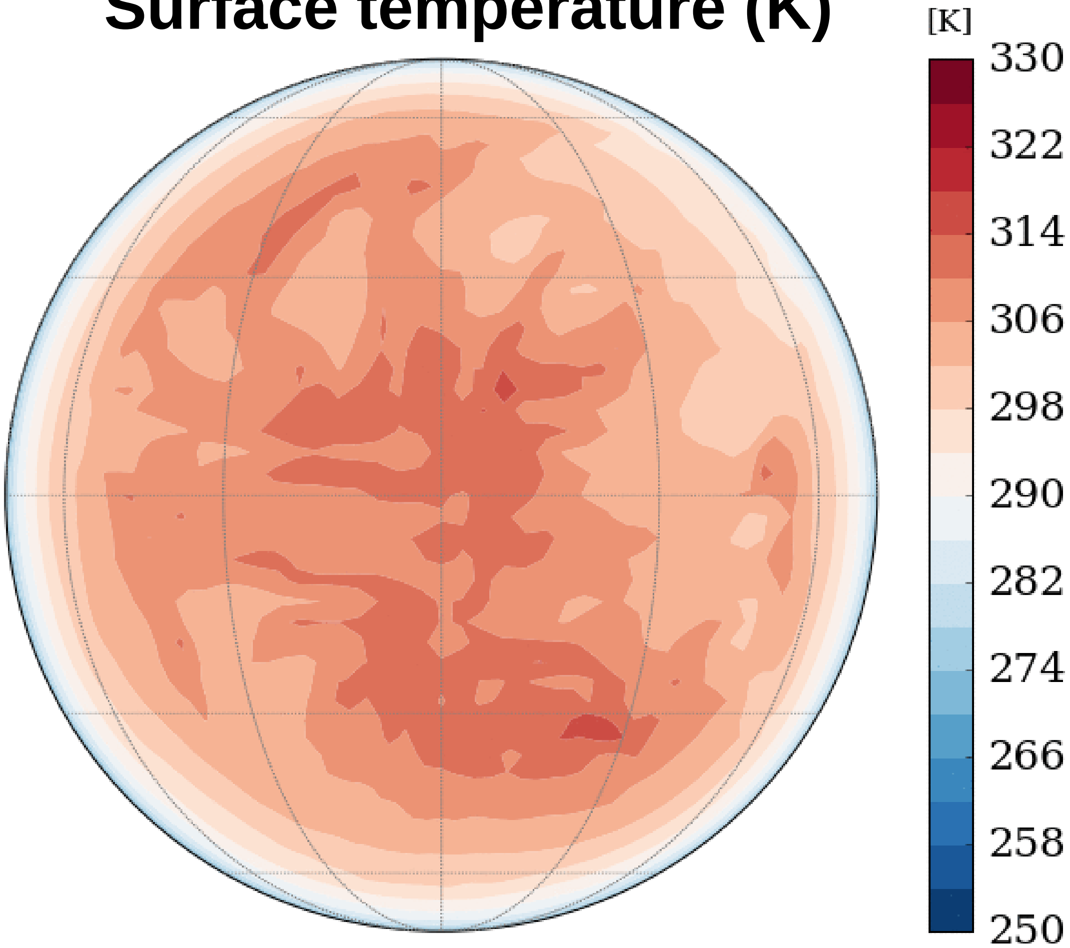
⇨ Possible Locking with permanent night side

(see Leconte et al. A&A 2013, Yang et al. ApJL2013, 2014)



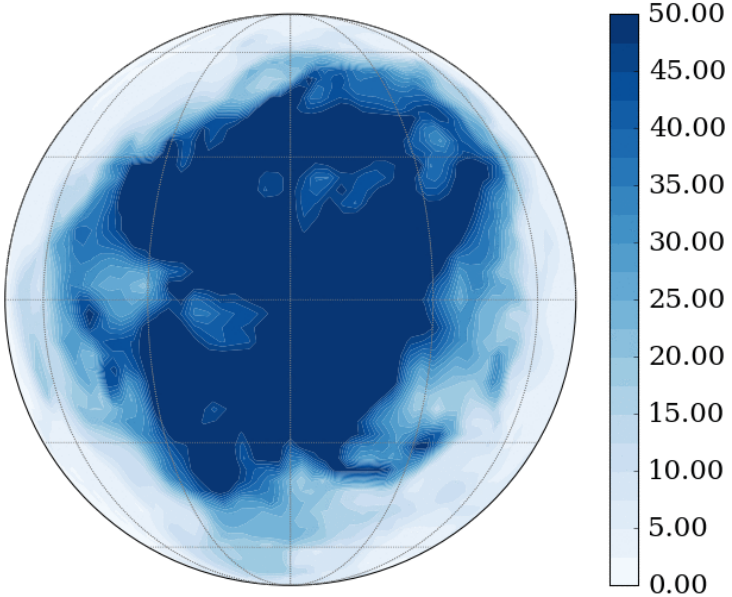
Simulation of aTidal-locked planet with surface liquid water around an Mdwarf
(Jeremy Leconte, LMD climate model)

Surface temperature (K)

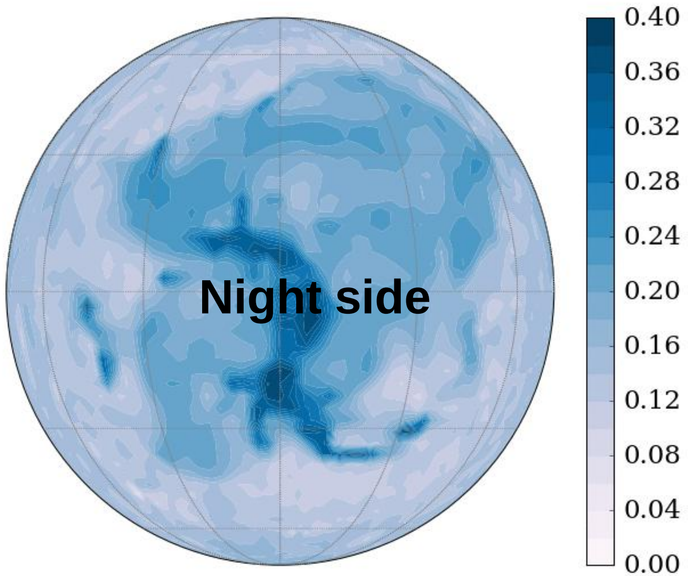


View from a distant point throughout the orbit

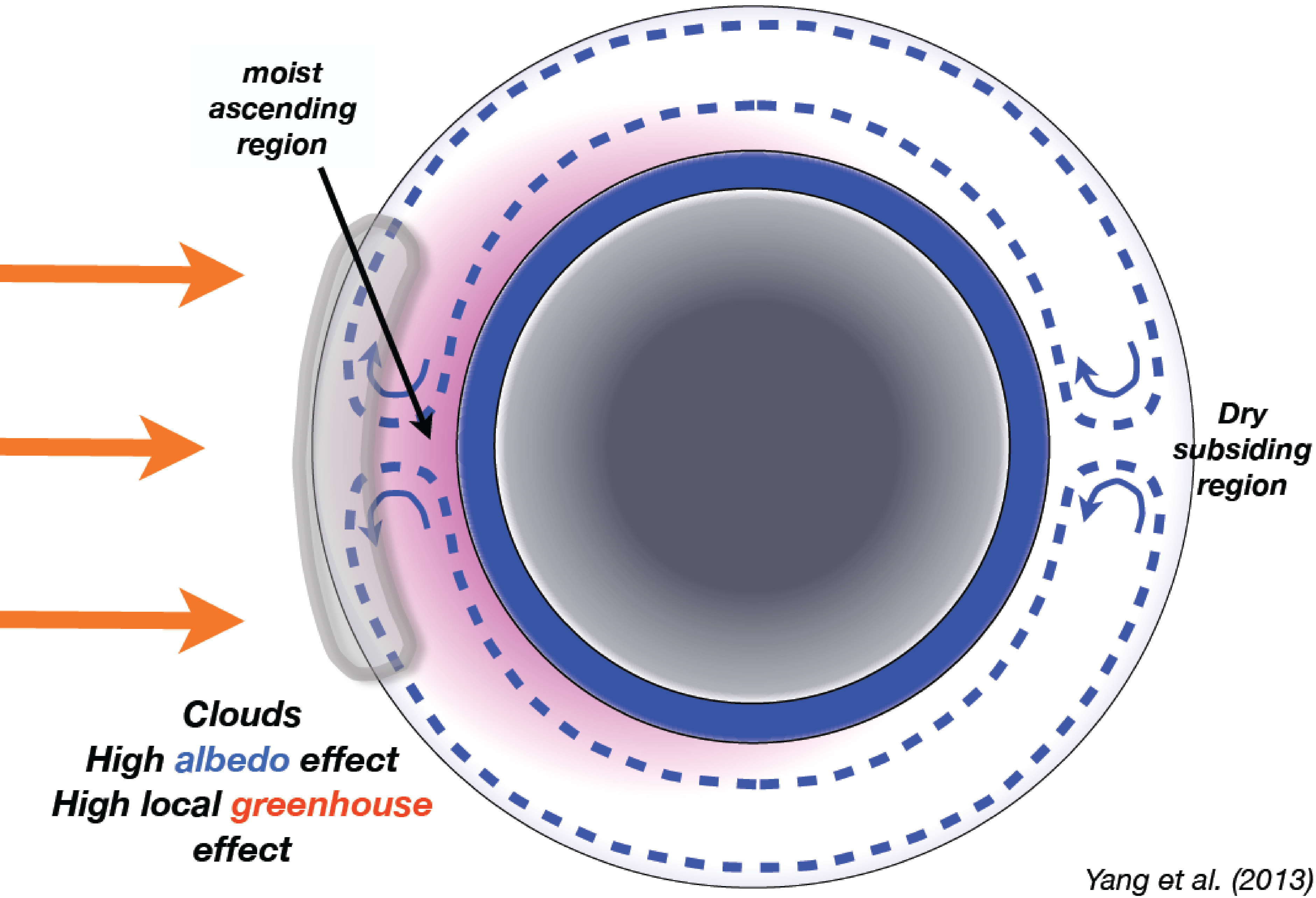
Cloud opacity



Planetary Albedo



Large scale cloud pattern on tidally locked planets



The Astrophysical Journal Letters, Volume 771, Issue 2, article id. L45, 6 pp. (2013)
See also Yang et al. . Astrophysical Journal Letters, Volume 787 (2014)

STABILIZING CLOUD FEEDBACK DRAMATICALLY EXPANDS THE HABITABLE ZONE OF TIDALLY LOCKED PLANETS

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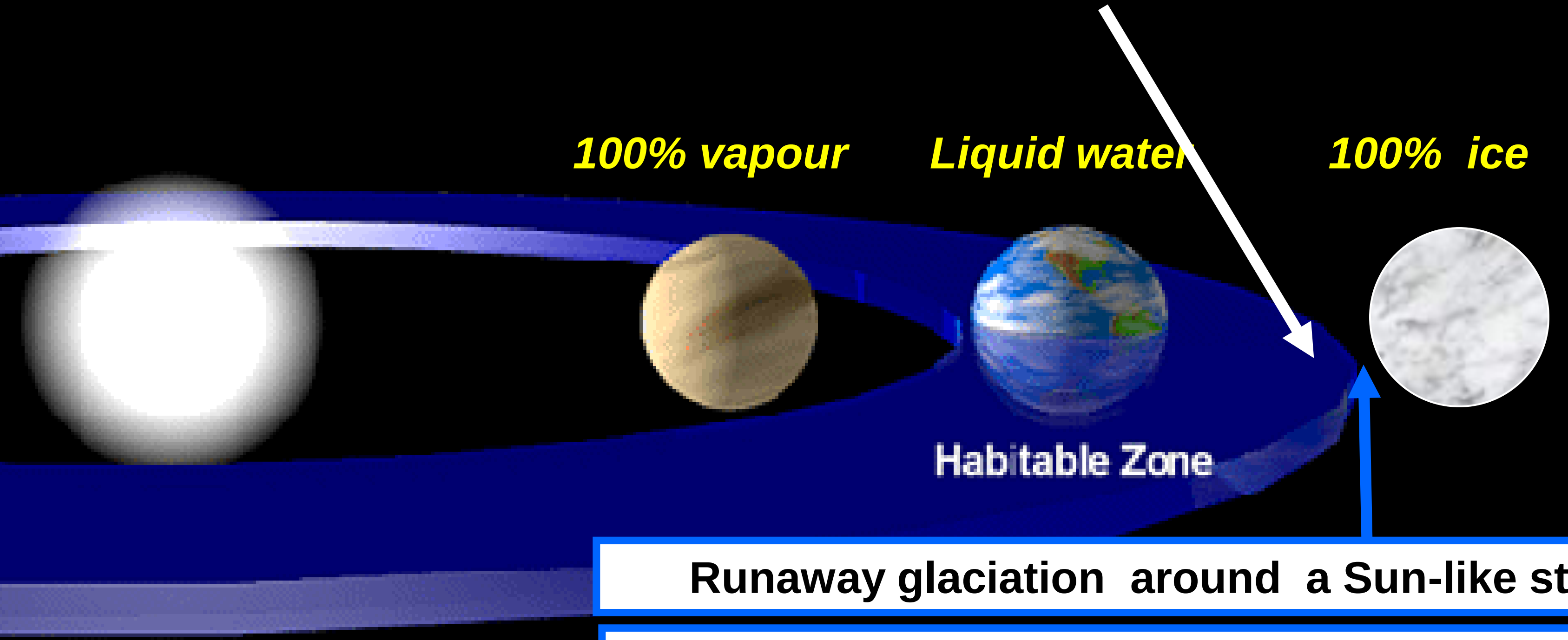
Draft version June 28, 2013

ABSTRACT

The Habitable Zone (HZ) is the circumstellar region where a planet can sustain surface liquid water. Searching for terrestrial planets in the HZ of nearby stars is the stated goal of ongoing and planned extrasolar planet surveys. Previous estimates of the inner edge of the HZ were based on one dimensional radiative–convective models. The most serious limitation of these models is the inability to predict cloud behavior. Here we use global climate models with sophisticated cloud schemes to show that due to a stabilizing cloud feedback, tidally locked planets can be habitable at twice the stellar flux found by previous studies. This dramatically expands the HZ and roughly doubles the frequency of habitable planets orbiting red dwarf stars. At high stellar flux, strong convection produces thick water clouds near the substellar location that greatly increase the planetary albedo and reduce surface temperatures. Higher insolation produces stronger substellar convection and therefore higher albedo, making this phenomenon a stabilizing climate feedback. Substellar clouds also effectively block outgoing radiation from the surface, reducing or even completely reversing the thermal emission contrast between dayside and nightside. The presence of substellar water clouds and the resulting clement surface conditions will therefore be detectable with the James Webb Space Telescope.

Outer Edge of the Habitable Zone ?



Runaway glaciation around a Sun-like star

Solar flux ↓ → Temperature ↓

Temperature ↓ → Ice and snow ↑

Ice and snow ↑ → Albedo ↑

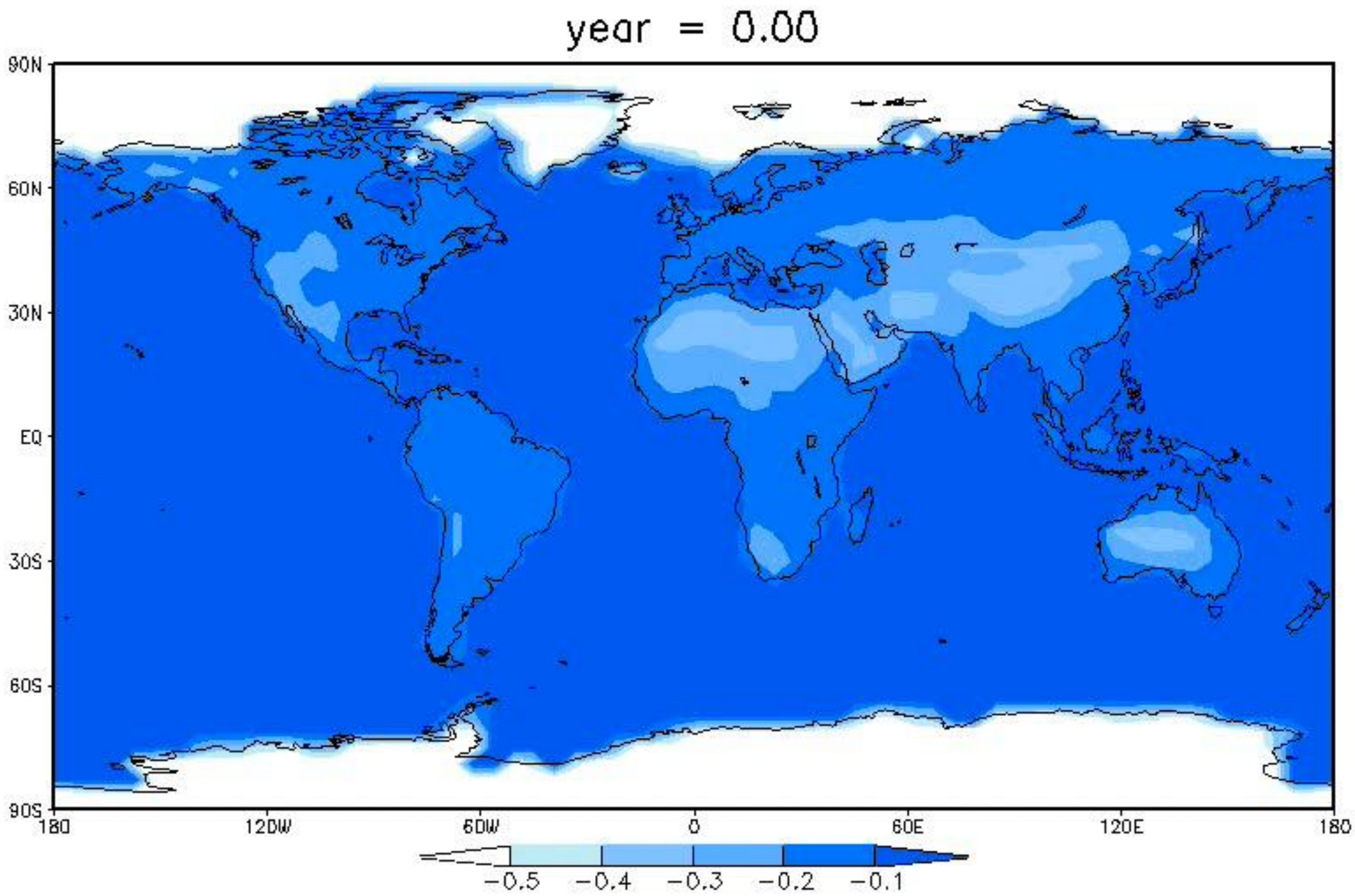
Albedo ↑ → Temperature ↓

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:



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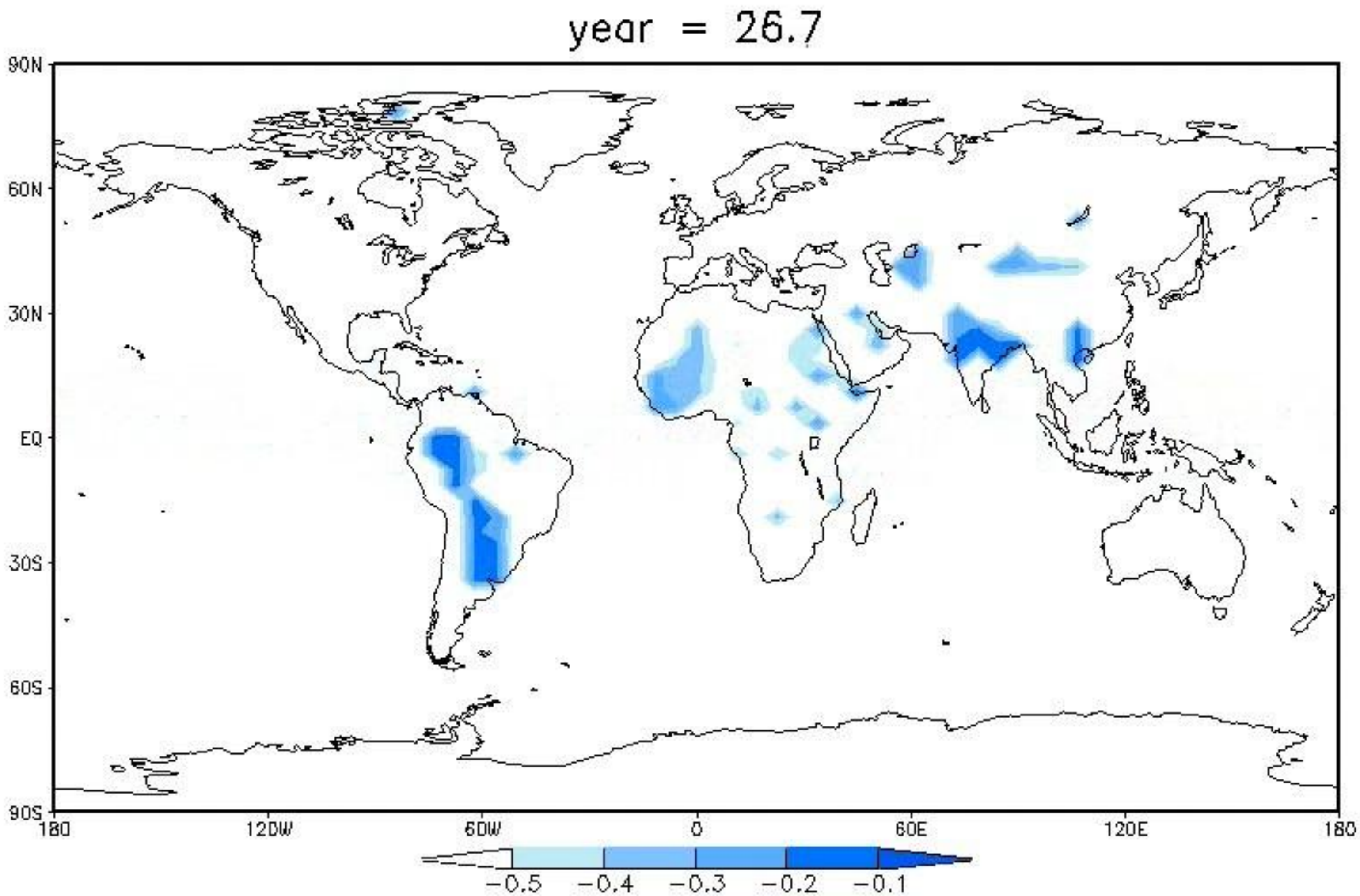

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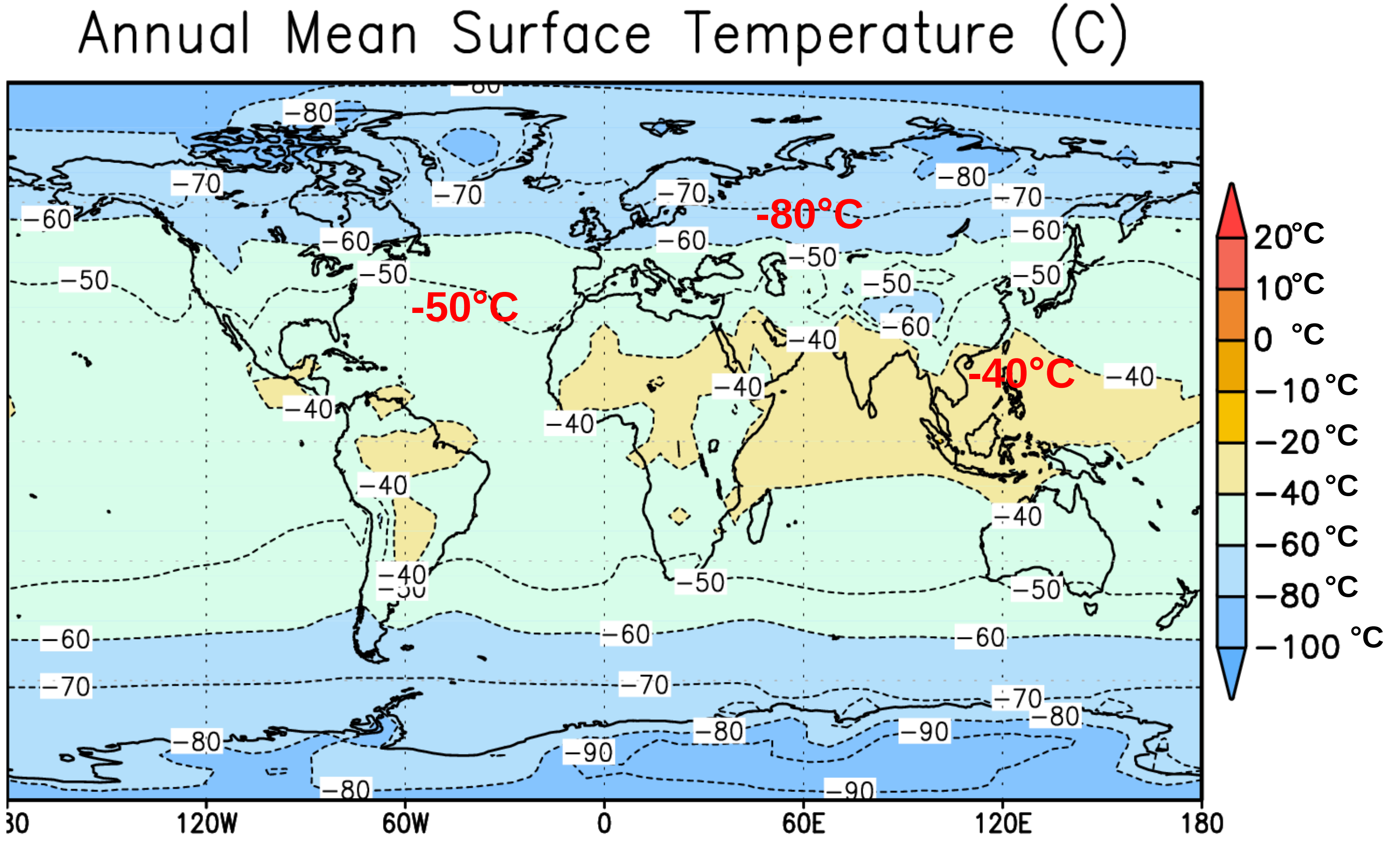
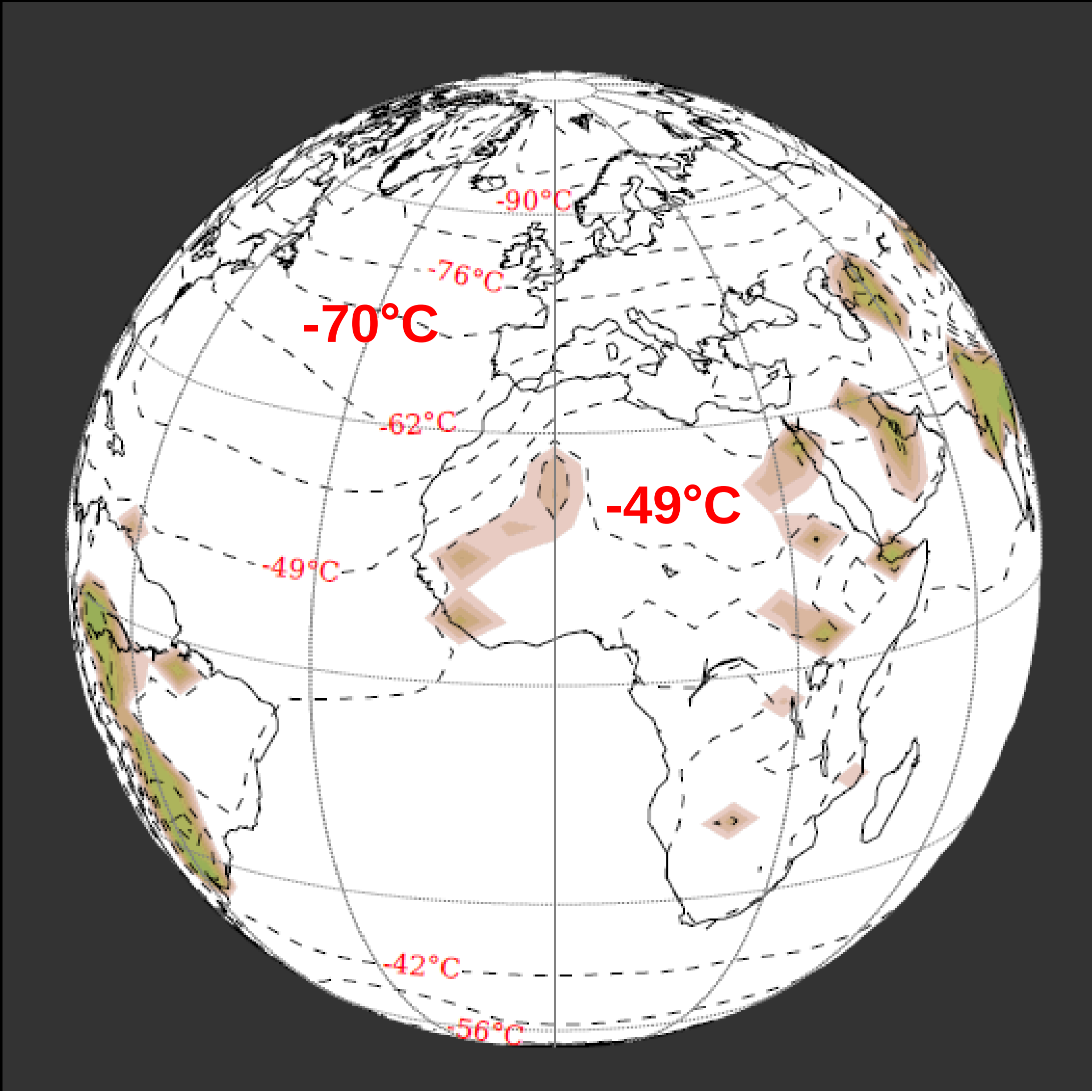


Out of glaciation: greenhouse effect

Flux = 80% present
(~1.12 AU)

Present
Earth atmosphere

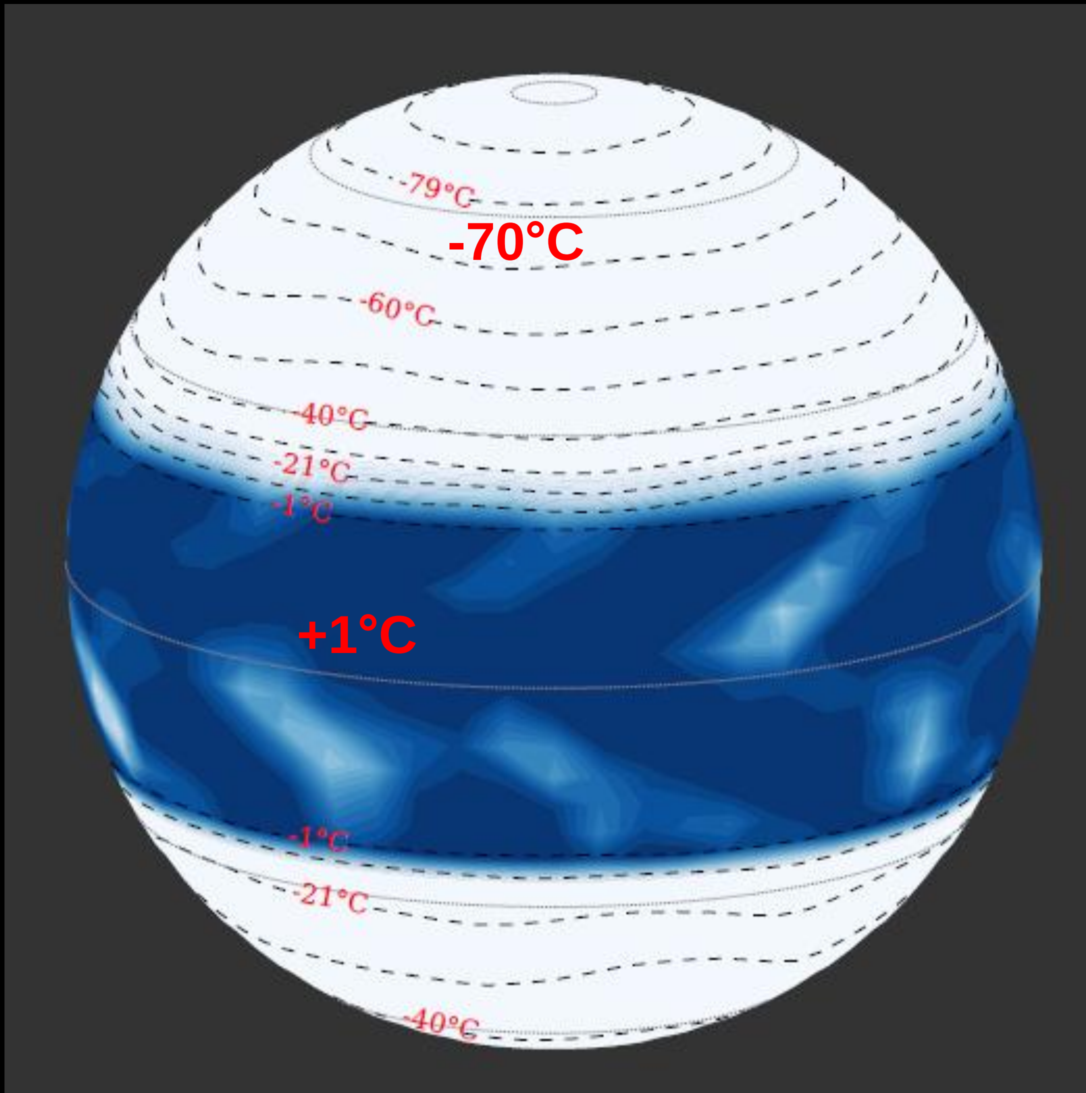


Charnay et al., JGR 2013

Out of glaciation: greenhouse effect

Flux = 80% present
(~1.12 AU)

$[CO_2] \times 2.5$

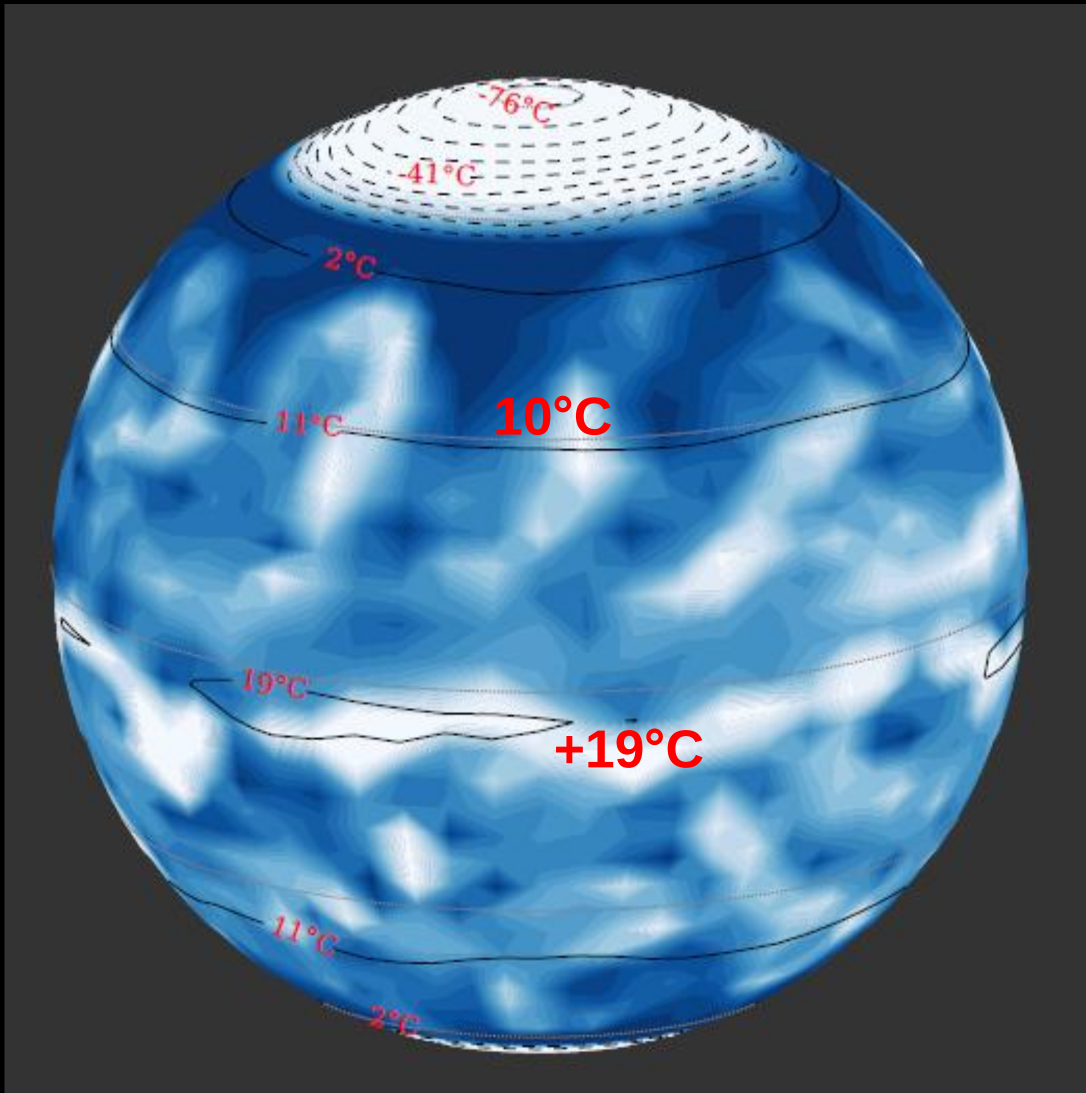


Charnay et al., JGR 2013

Out of glaciation: greenhouse effect

Flux = 80% present
(~1.12 AU)

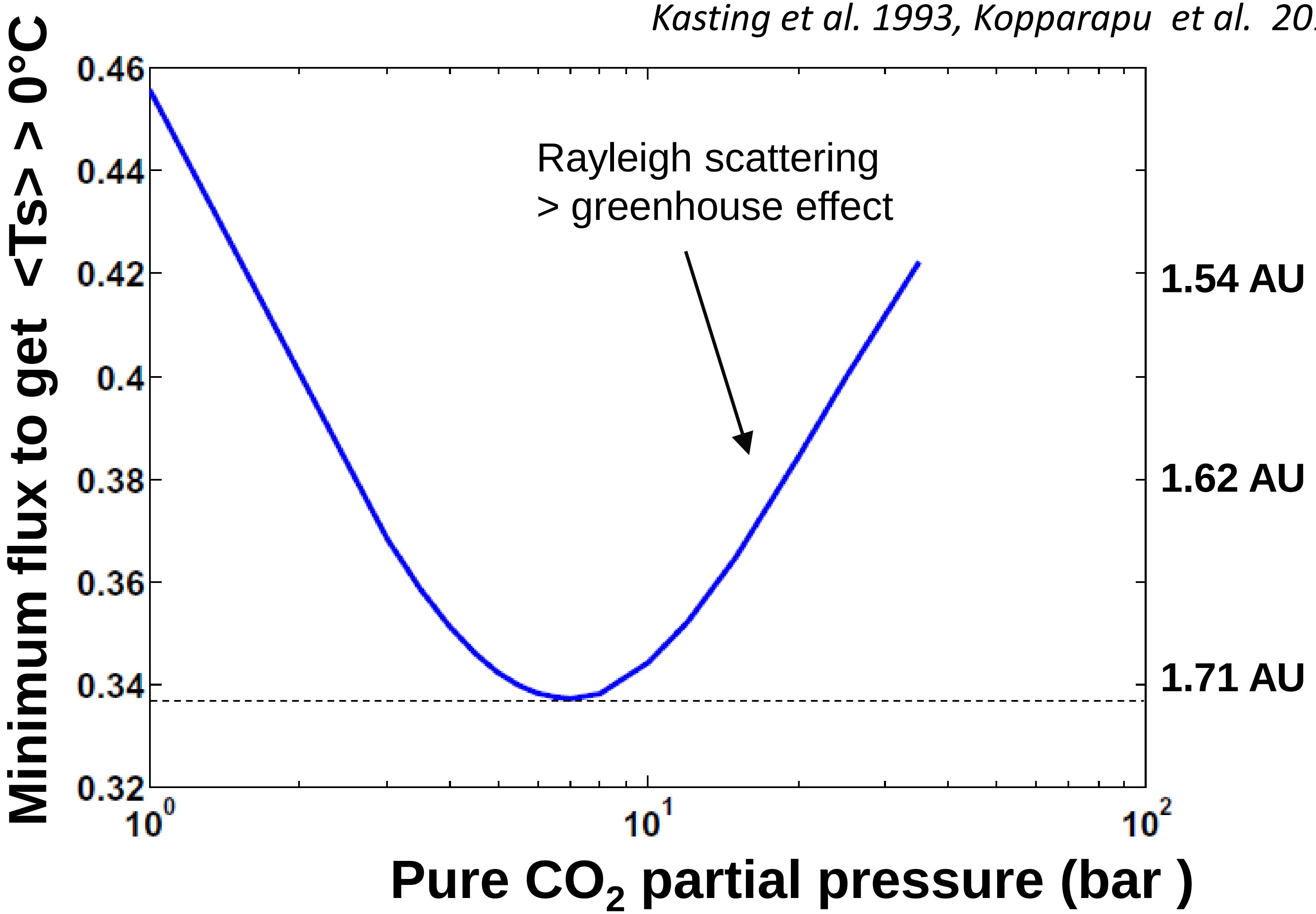
$[CO_2]$ x 250
[CH4] x 1000



Charnay et al., JGR 2013

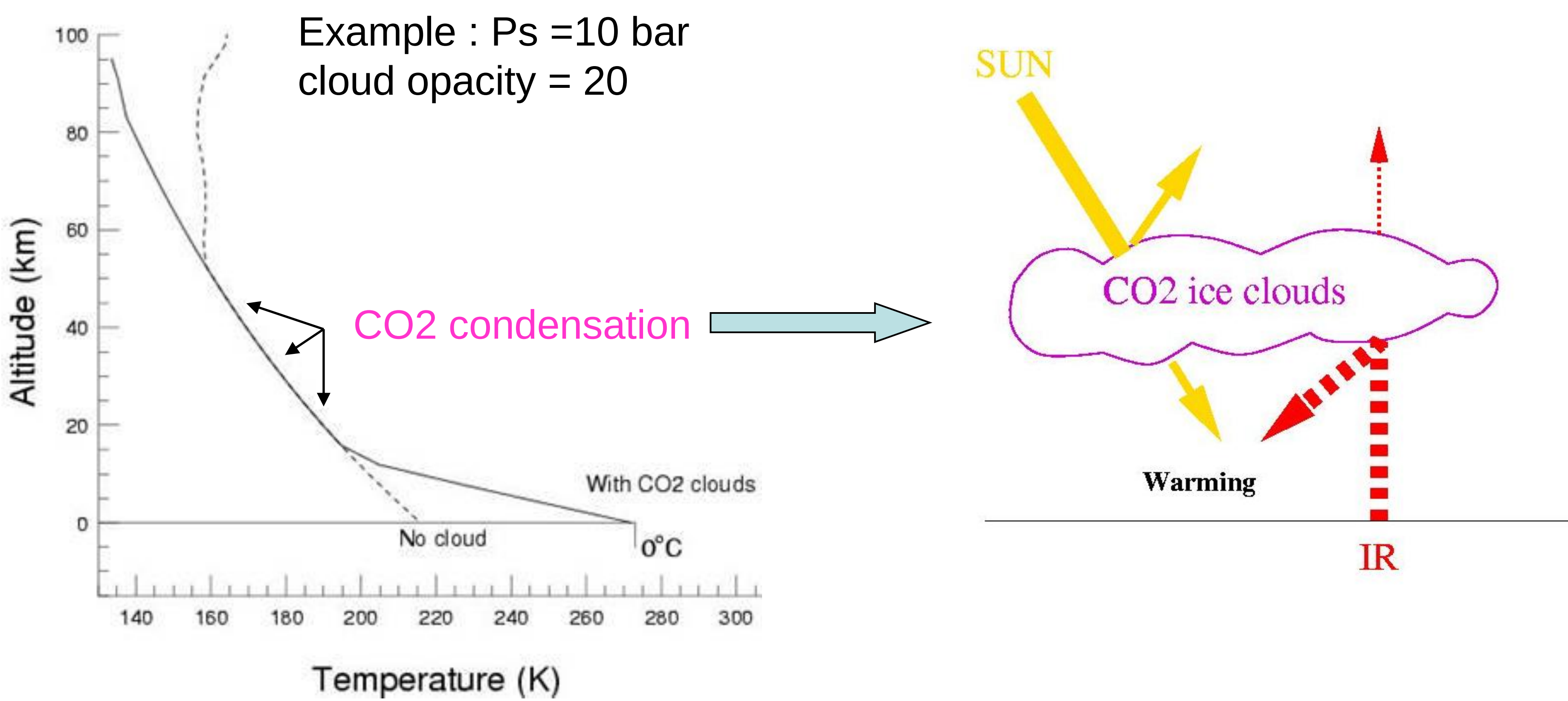
How far can greenhouse effect can keep a planet warm around a sun-like star?

Kasting et al. 1993, Kopparapu et al. 2013



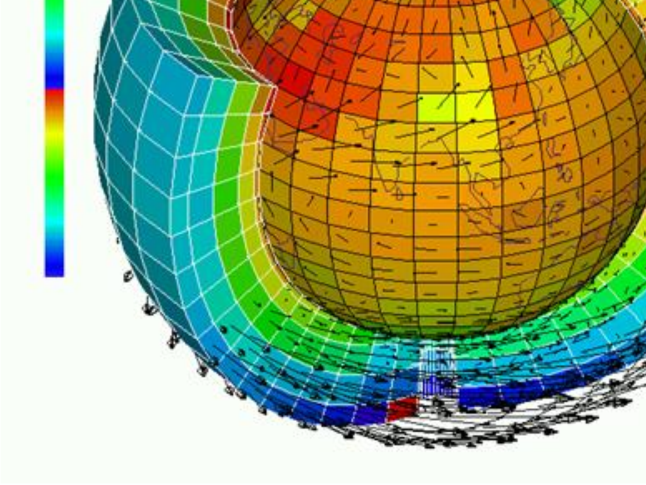
Scattering Greenhouse effect of CO_2 ice clouds
⇨ 0°C as far as 2.5 AU from the Sun ?

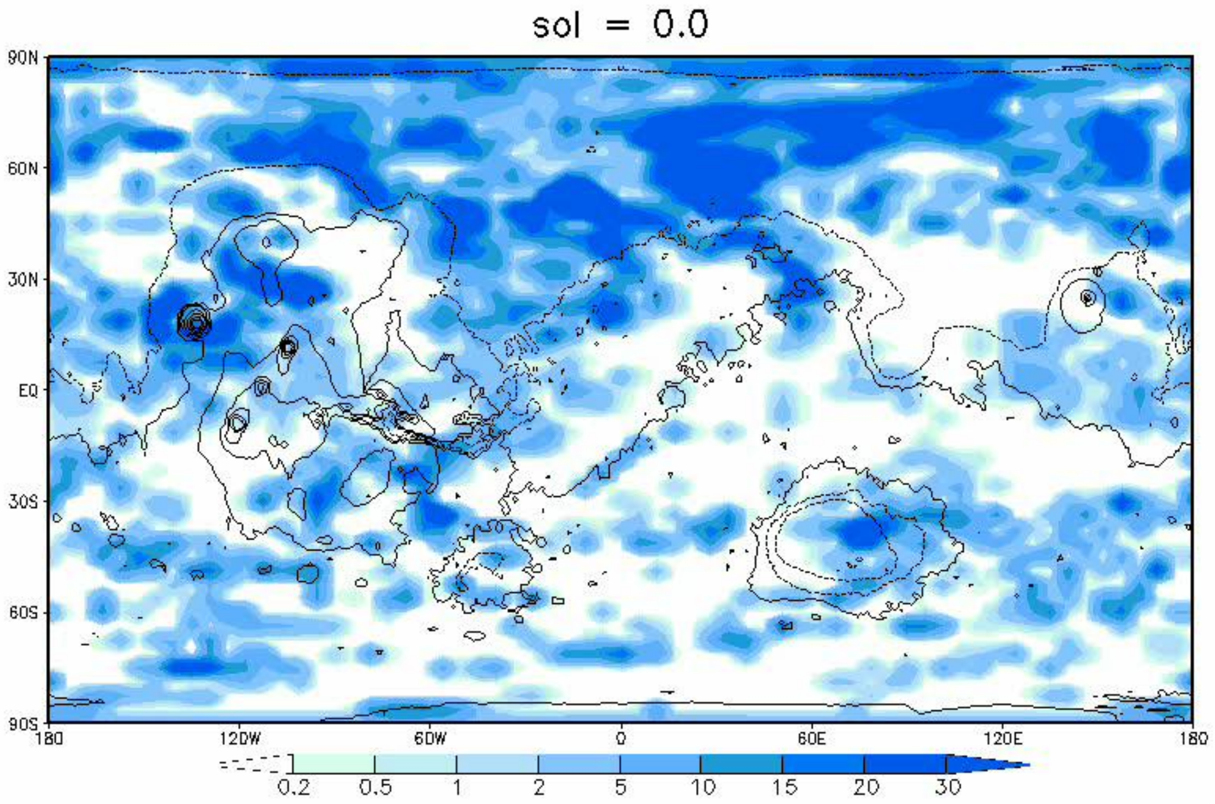
Forget and Pierrehumbert (1997)



3D Global climate simulations of a cold CO_2 atmosphere

("Early Mars Case" distance equivalent to 1.75





Max Warming = + 15 K

(uncomplete cloud coverage)

CO_2 ice Cloud optical depth

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

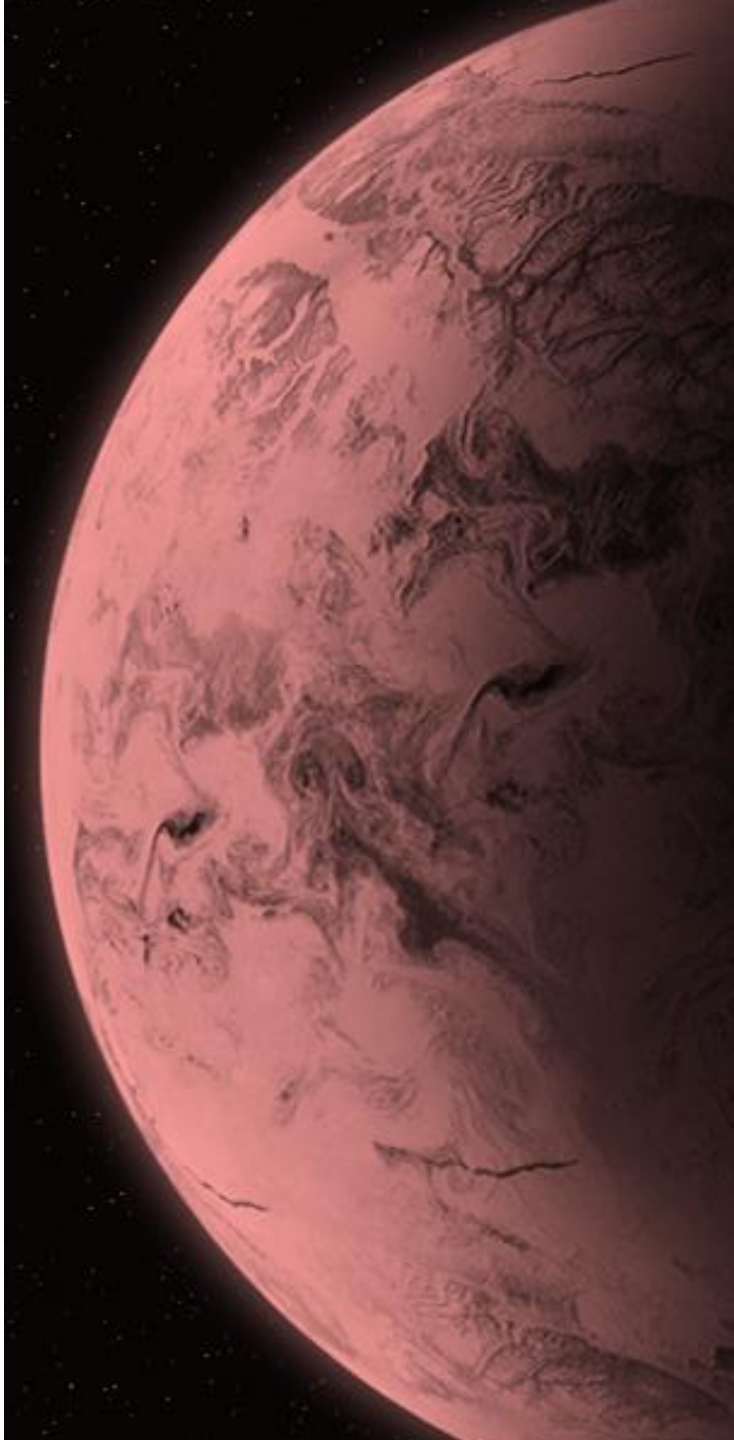
Glaciation around K & M dwarf stars:

Redder stellar spectrum

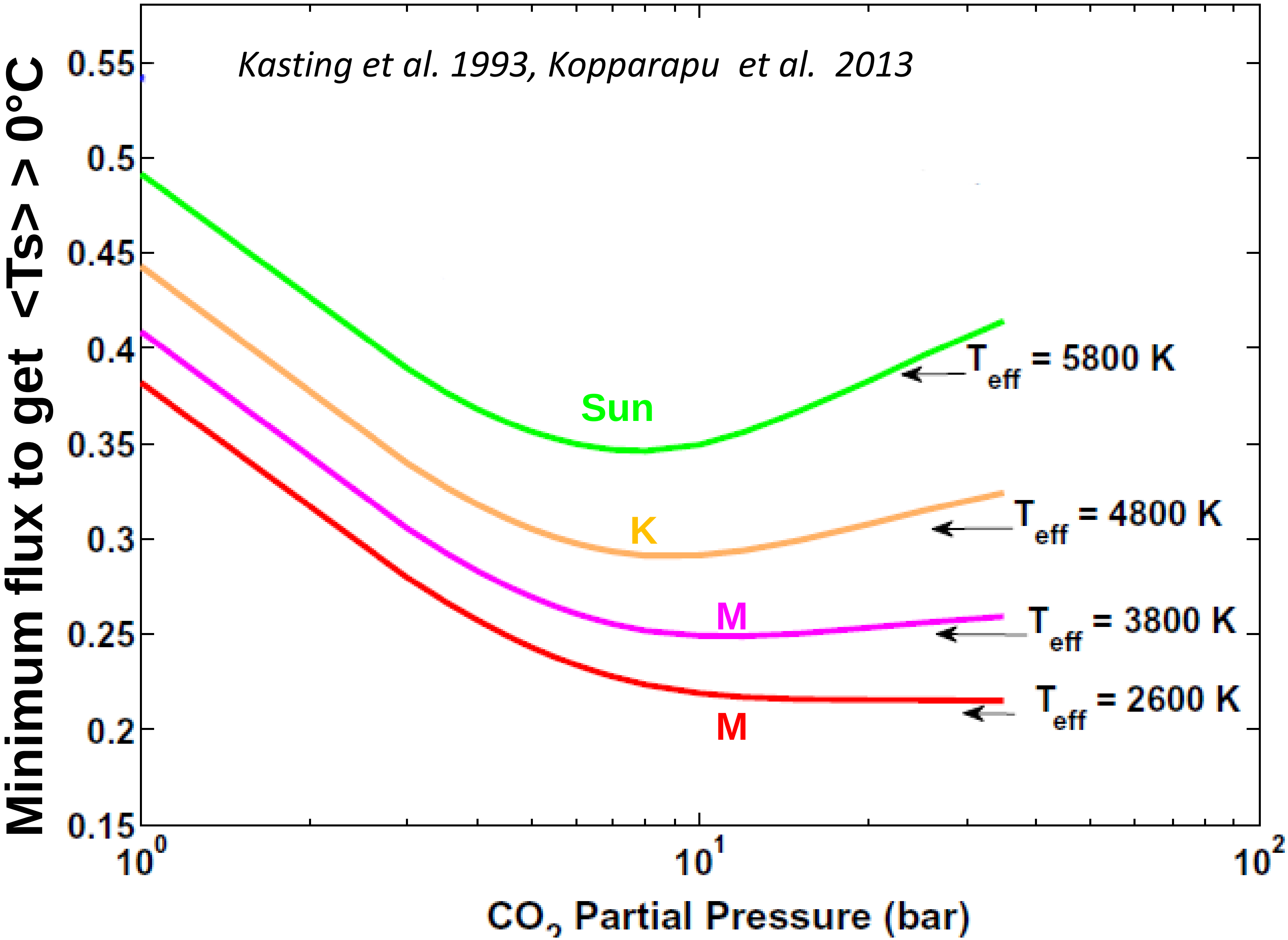
- No albedo water ice feedback *(Joshi and haberle, 2012)*
- Weak atmospheric Rayleigh Scaterring

  ⇨ lower albedo

  ⇨ Enhanced high pressure CO2 greenhouse effect

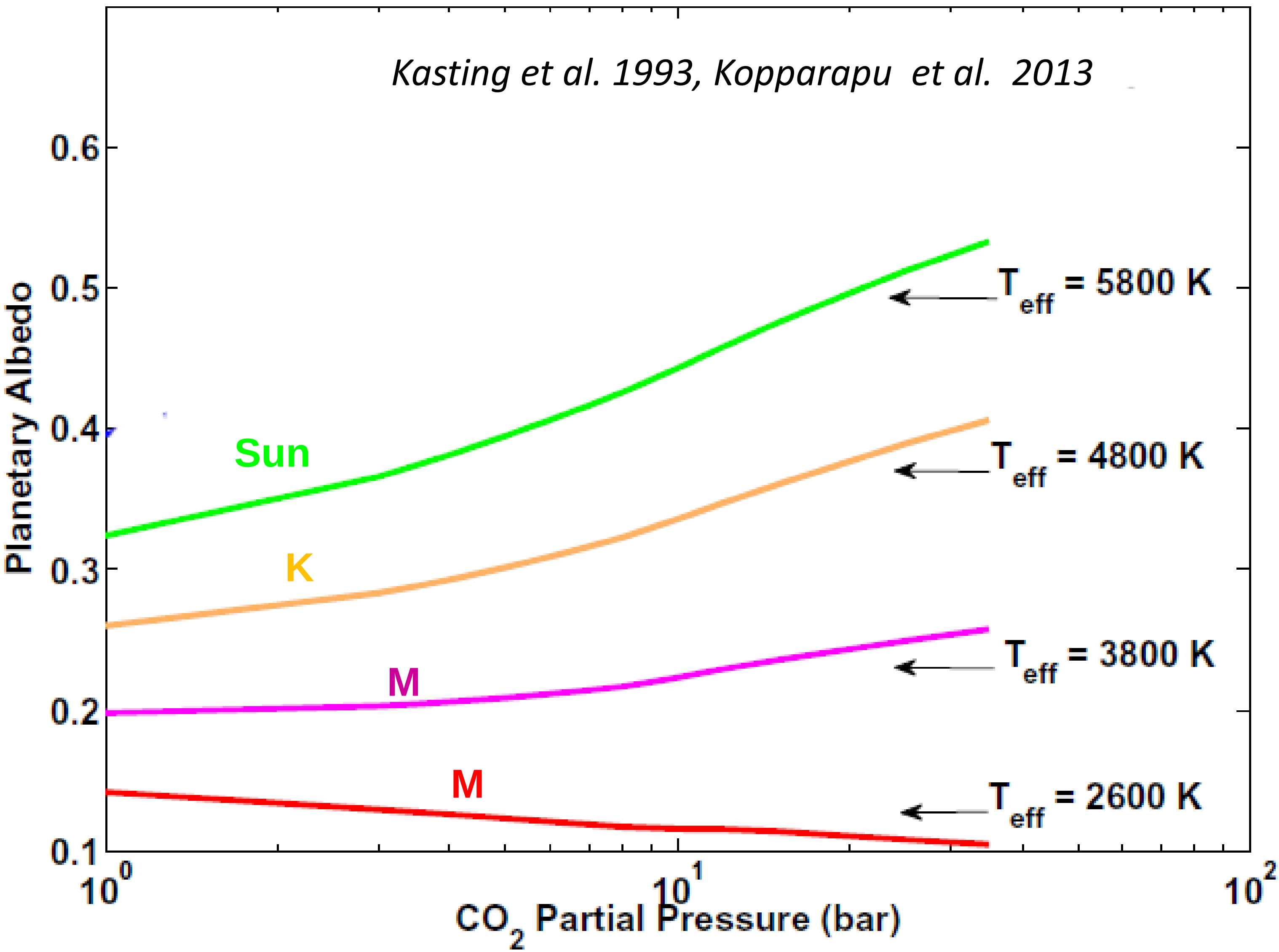


How far can greenhouse effect can keep a planet warm around various stars?



Planetary Albedo around G, K, M stars

(with Rayleigh Scaterring of CO2 gas)



Glaciation around K & M dwarf stars:

Redder stellar spectrum

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

  ⇨ lower albedo

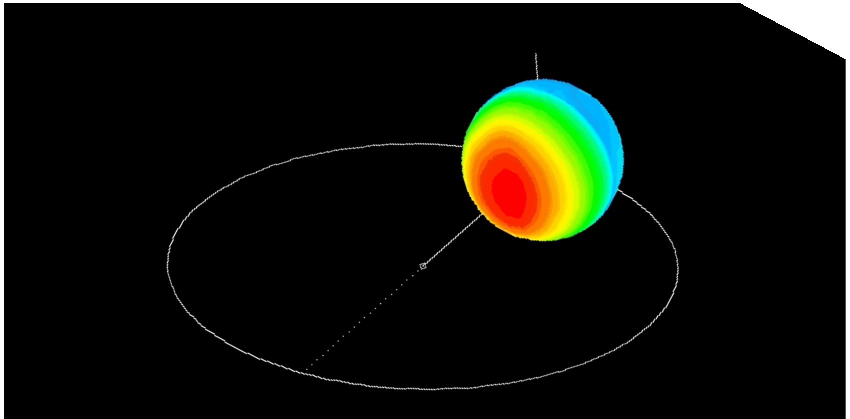
  ⇨ Enhanced high pressure CO_2 greenhouse effect

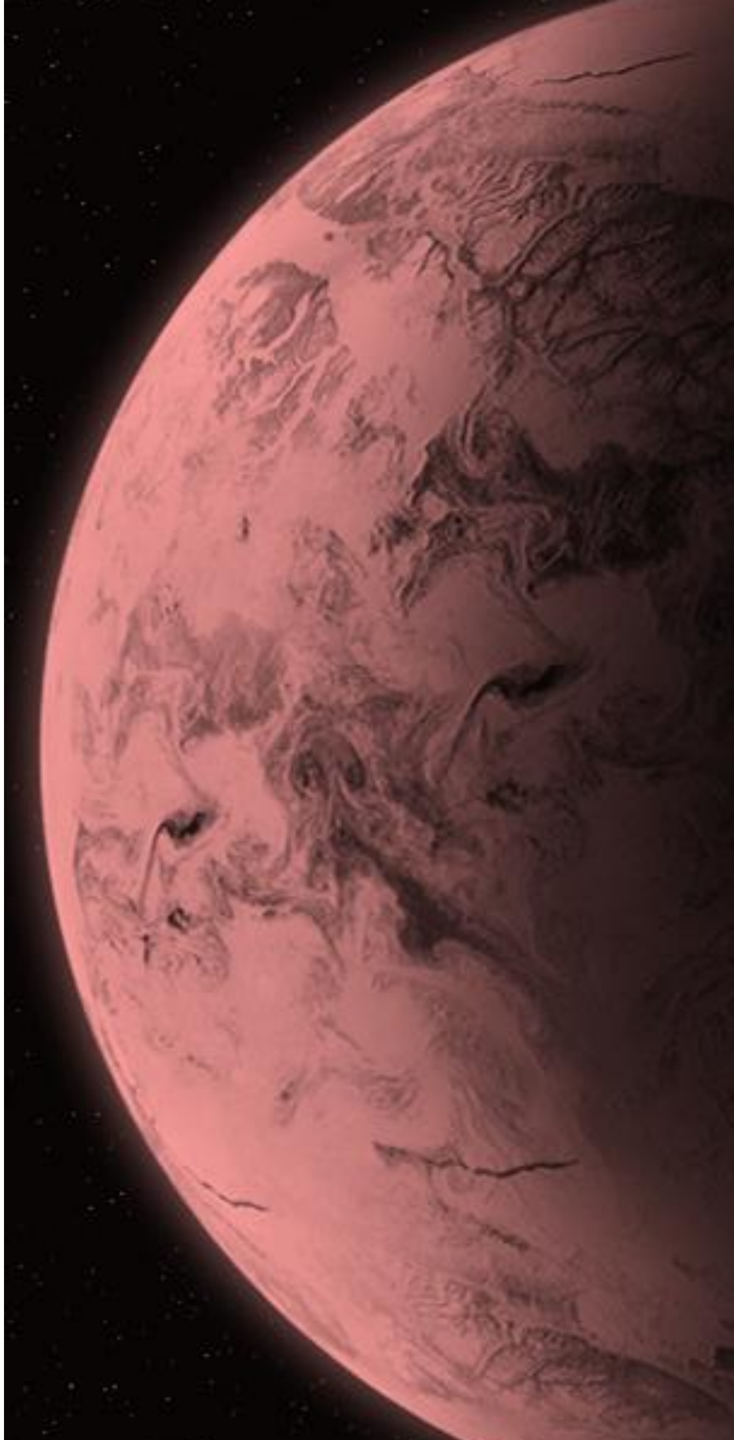
But : Effect of tides on rotation:

- Resonant rotation with zero obliquity

⇨ No insolation at the pole

⇨ Possible Locking with permanent night side?





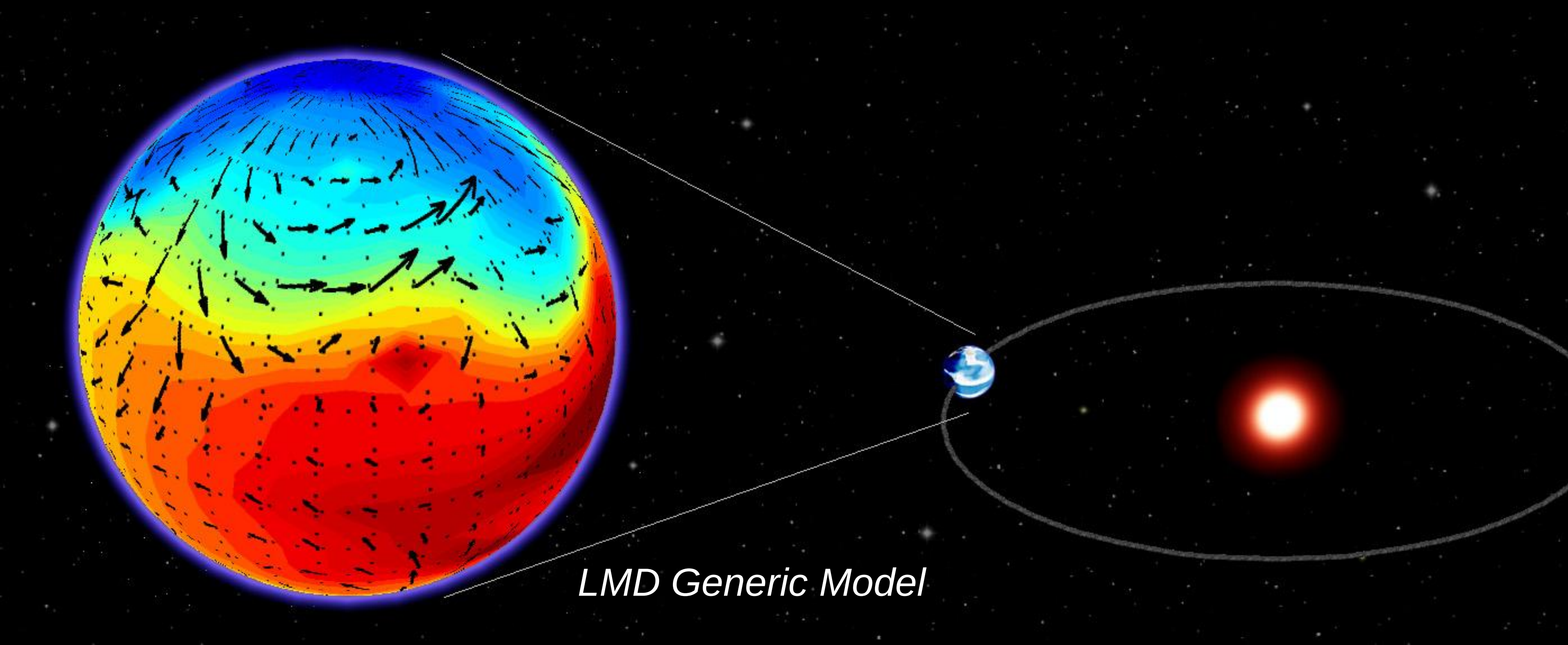
Example: simulating the climate on Exoplanet Gliese 581d (*Wordsworth et al. 2011*)

Super-Earth? : M sin*i* $\approx$ 7 M_{Earh} around Mdwarf (0.31 Msun)

Incident Stellar flux = 27% flux on Earth (less than Early Mars!)

Obliquity = 0°, possibly tidally locked ?

Udry et al. 2007, Mayor et al. 2009:



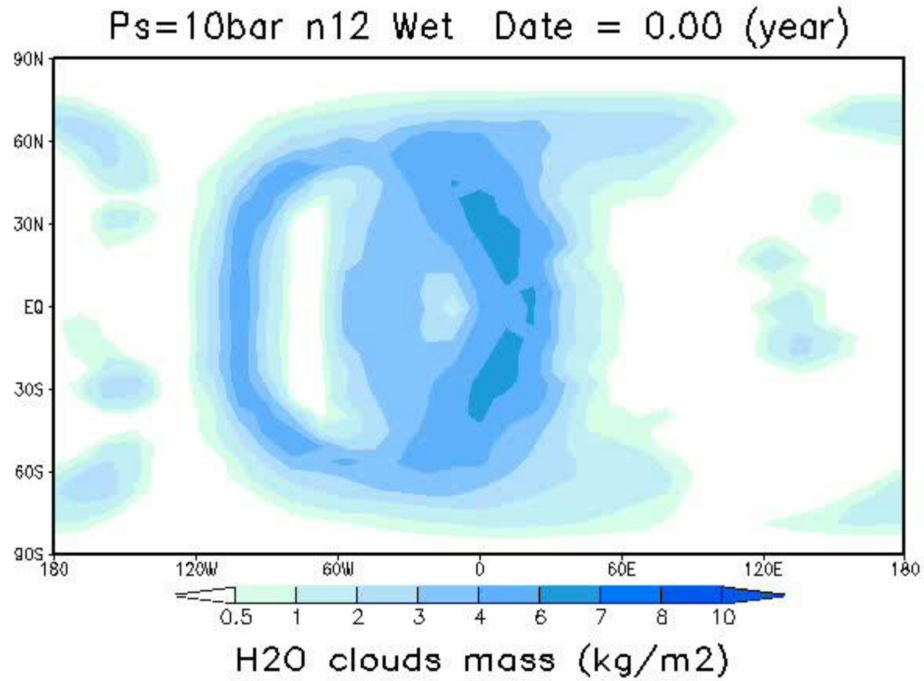
Gliese 581D
With P(CO2)=10bar

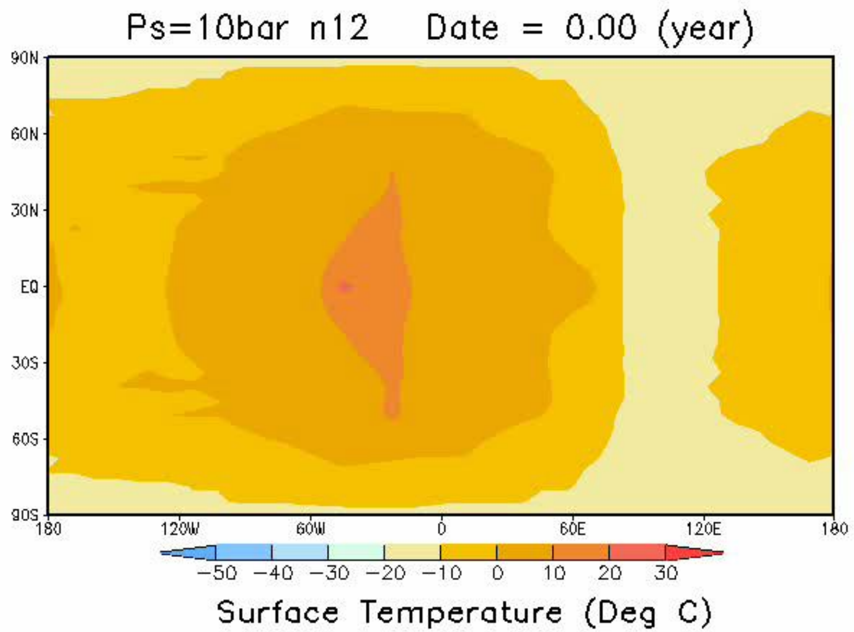
(*Wordsworth et al. 2011*)

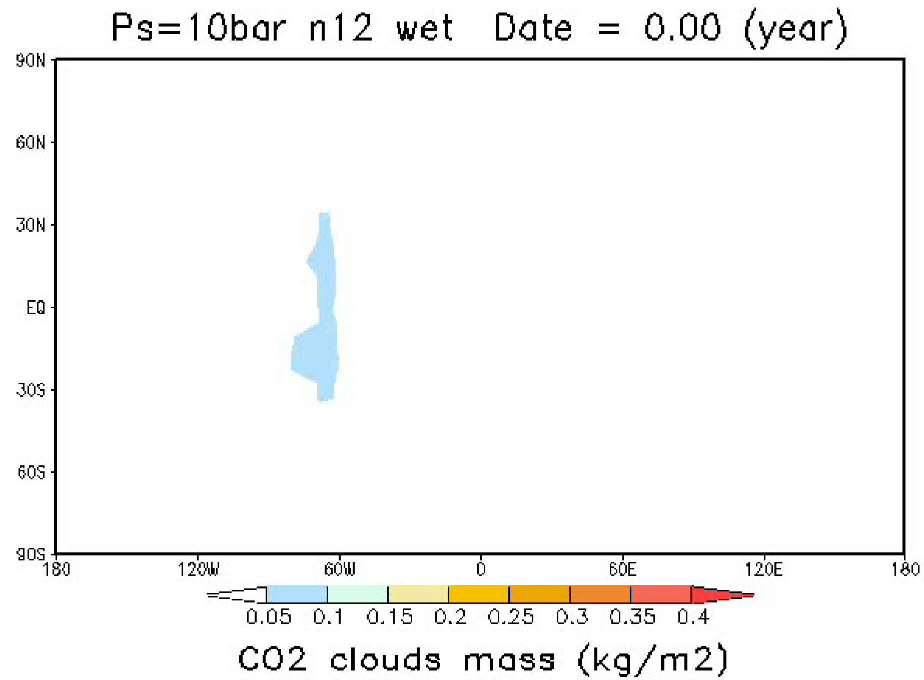
Water clouds

CO2 ice clouds

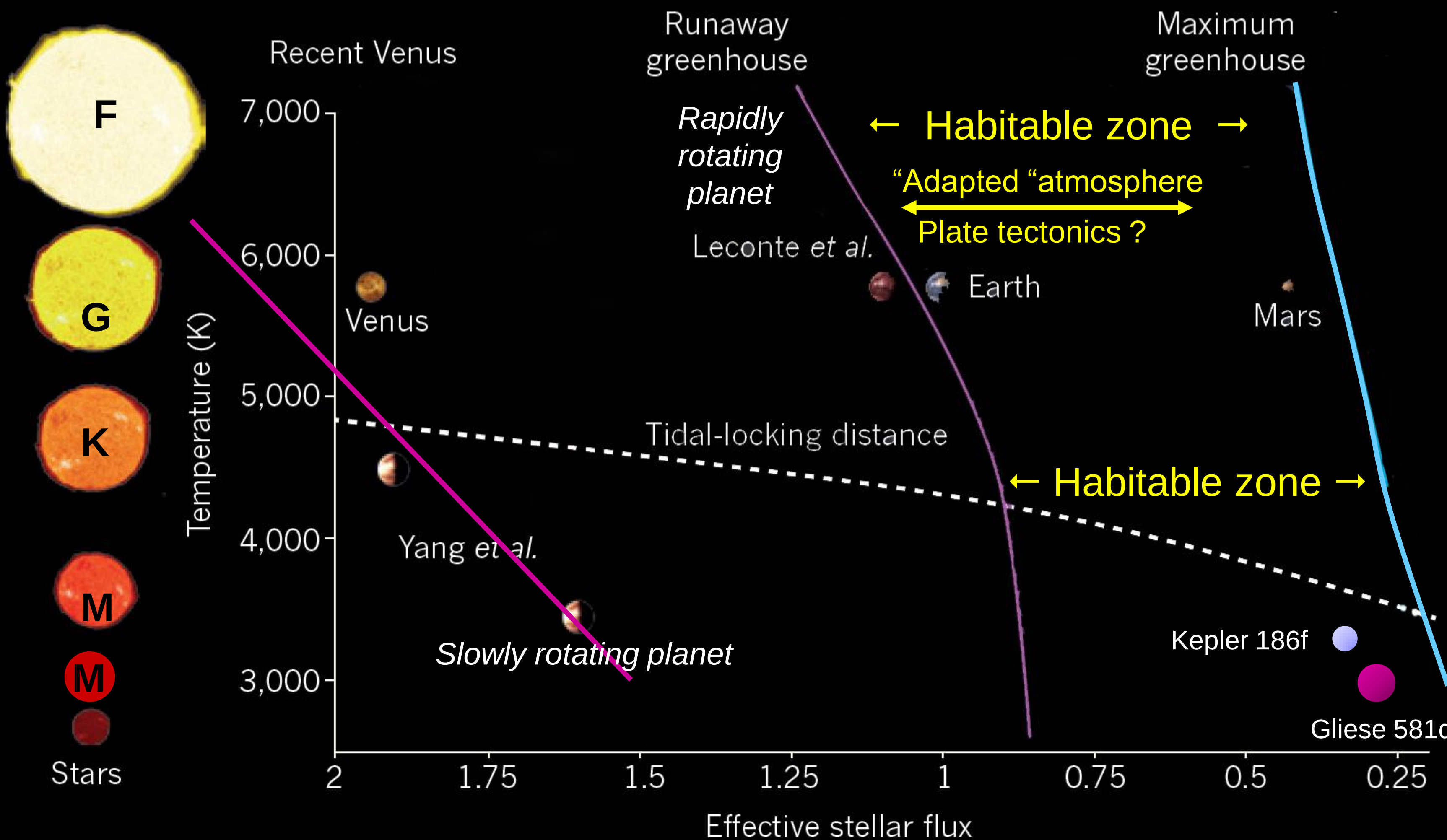
Surface temperature (K)







The traditional Habitable zone with N2-CO2-H2O atmospheres-…



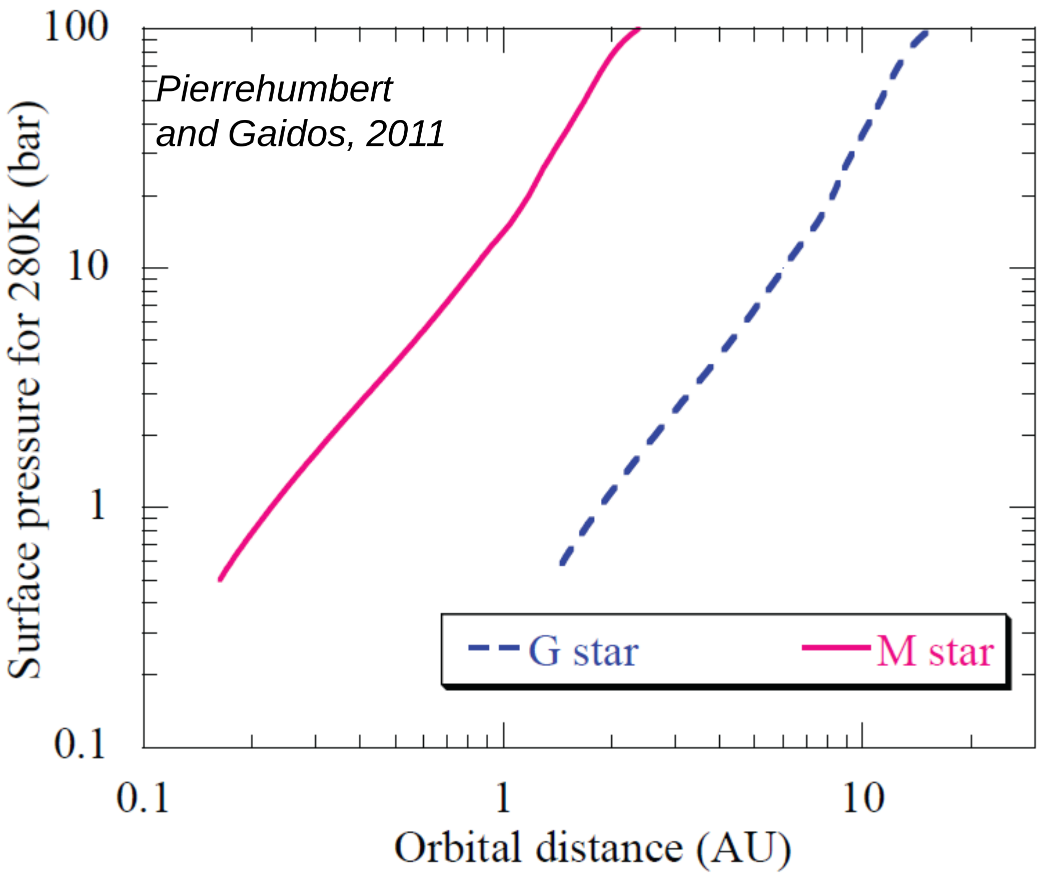
Adapted and modified from Kasting and Harman (2013)

The case of Hydrogen-rich primordial 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)
- However primordial atmosphere tends to escape to space and not last long:

⇨« Cold » planets near the outer edge of the habitable zone may pass throughtransient periods with surface oceans *(Wordsworth 2012)*

Are H_2-rich terrestrial atmospheres possible?



Atmospheres, Climate and Habitability

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

Climate → **Habitability**

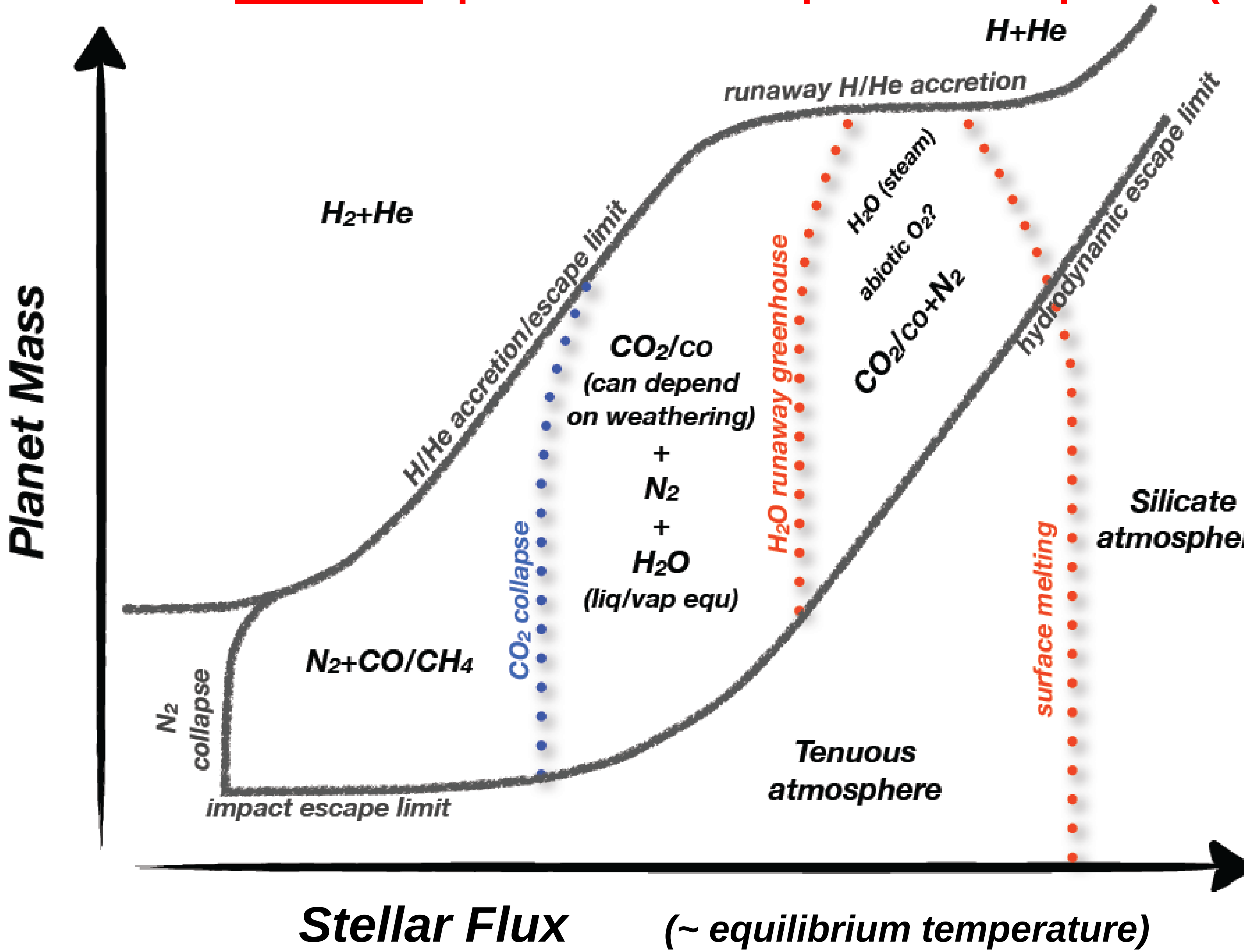
Key problem: understanding of the zoology of **atmospheric composition**, controlled by complex processes :

- Formation of planets and atmospheres
- Escape to space
- Interaction with the surface & interior
- Photochemical evolution

⇨ **Our experience in the solar system is not sufficient**

For given parameters and atmospheres, **Global Climate Models** are fit to explore the climate and habitability of terrestrial exoplanets. However, whatever the quality of the model, heavy study of model sensitivity to parameters will always be necessary (climate instabilities)

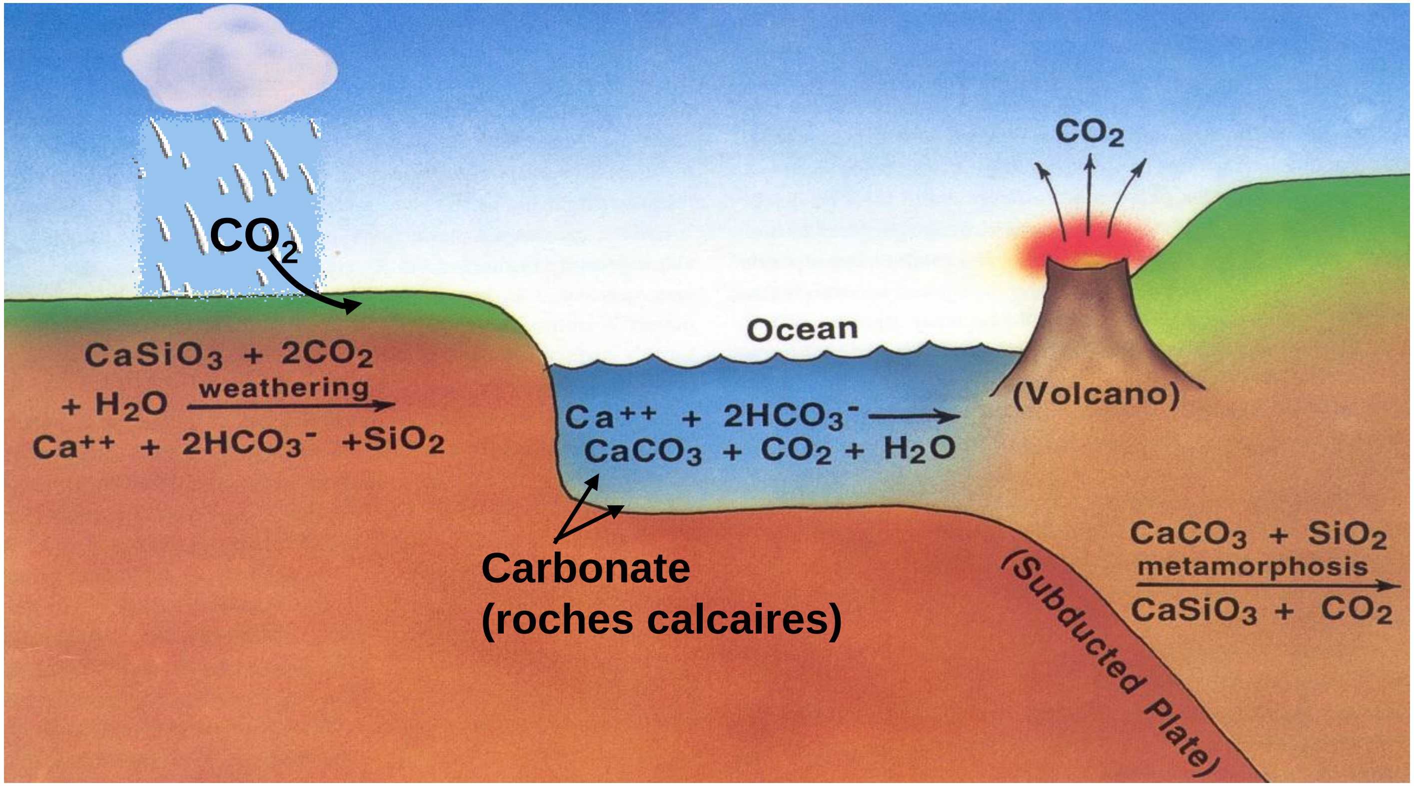
SPECULATION: <u>dominant</u> species terrestrial planet atmospheres (abiotic)



***Forget and Leconte (2013)**, « Possible climate on terrestrial exoplanets »*
Phil. Trans. Royal Society. A. (2014) (**arXiv:1311.3101)**

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

Walker et al. 1981



Temperature ↓ ⇒ Water cycle ↓ ⇒ Weathering ↓

⇓

Temperature ↑ ⇐ Greenhouse effect ⇐ P_{CO2} ↑

Conclusions

- **Some habitable planets (with liquid water) are more "habitable" than others** (duration of habitability, availability of light and chemicals, etc.)
- The "**Habitable zone**" could be defined as the zone outside which it is surface liquid water is impossible: little hope to find a detectable biosignature.
- **The key open question: what does it take for a planet in the habitable zone to be and remain habitable:**
  - getting & keeping the right atmosphere (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 need observations of atmospheres !**

⇨ **We can learn a lot from atmospheres well outside the Habitable zone**