Modelling Exoplanetary climates and Habitability

François Forget*,

Jeremy Leconte, Benjamin Charnay, Robin Wordsworth, Ehouarn Millour, Franck Selsis et al.
…

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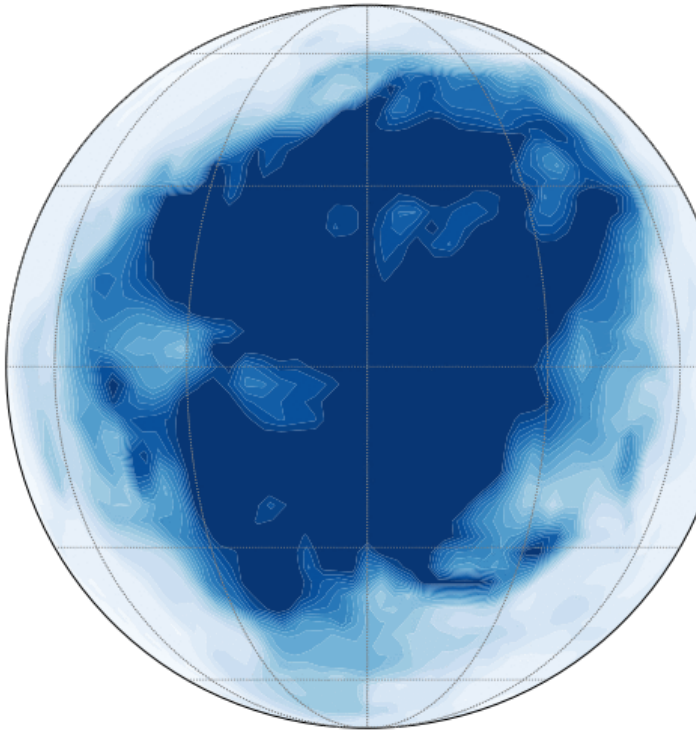
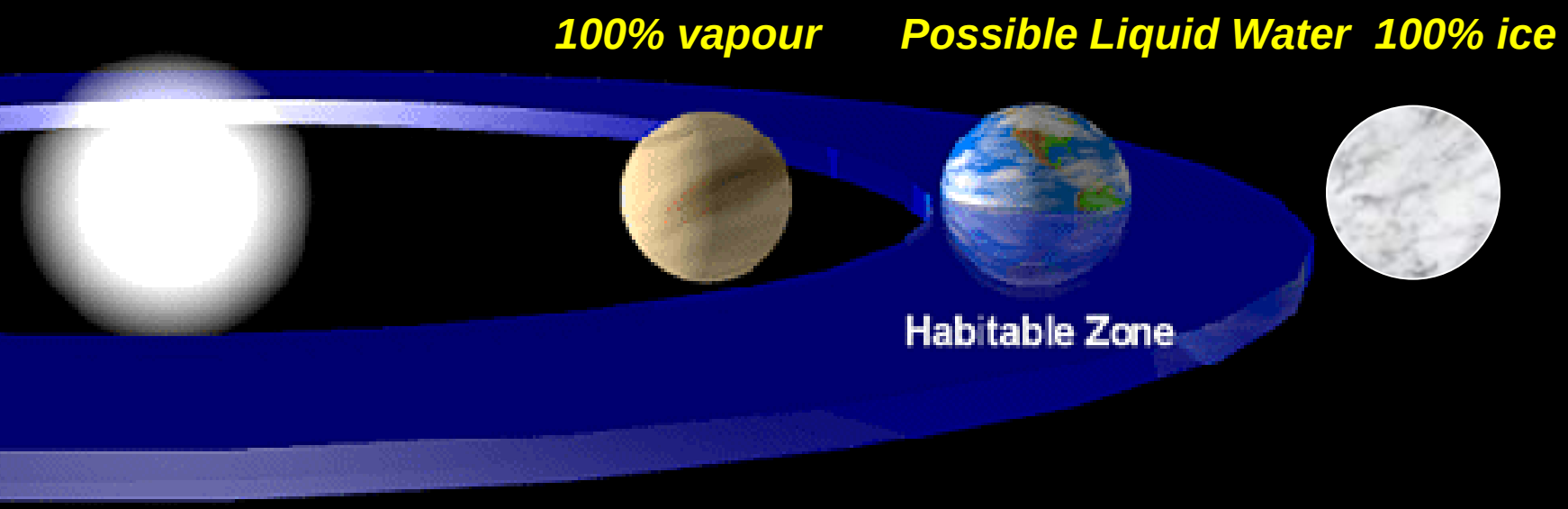


Modeled Cloud pattern on a tidally locked planet around a M dwarf star
LMD GCM. J. Leconte

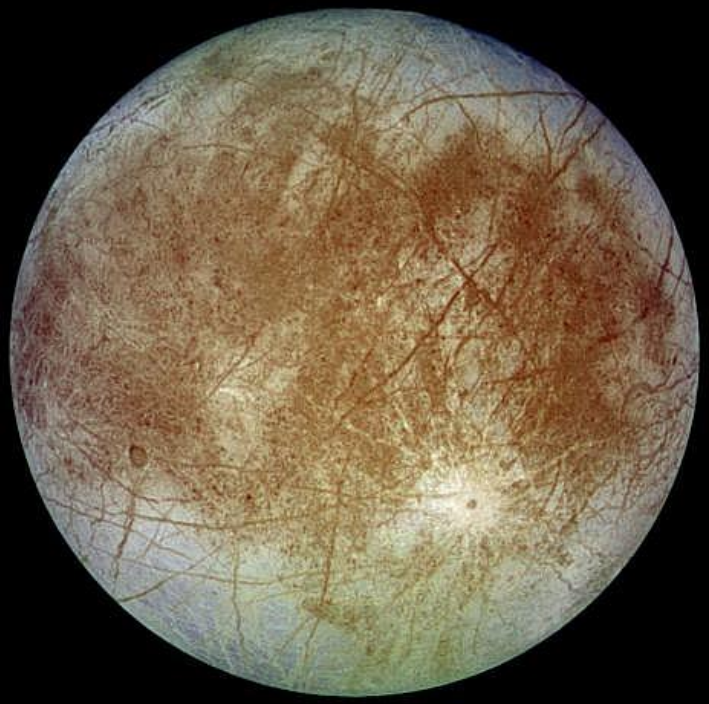
The« Habitable Zone» : liquid water possible on the <u>surface</u> of planets

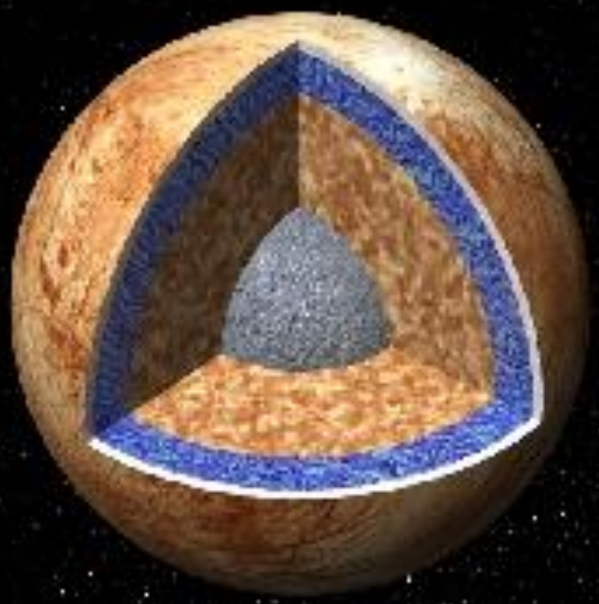
Eg. Kasting et al. 1993
Forget 2013



So what about underground liquid water reservoir <u>below the surface</u> ?

(In the solar system: Mars, Europa, Enceladus Ganymede, Callisto, Titan etc.)





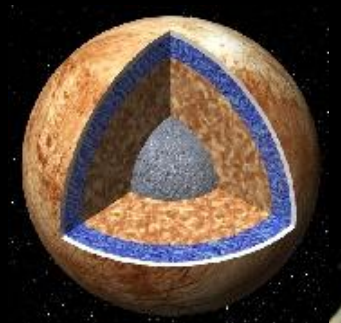
Europa, satellite of Jupiter

4 kinds of « habitability »

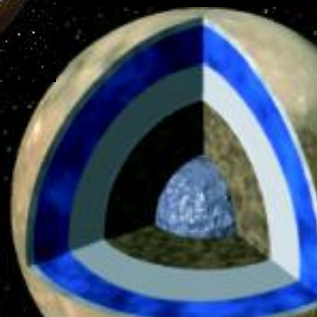
(Lammer et al. Astron Astrophys Rev 2009; Forget 2013)

- **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)*

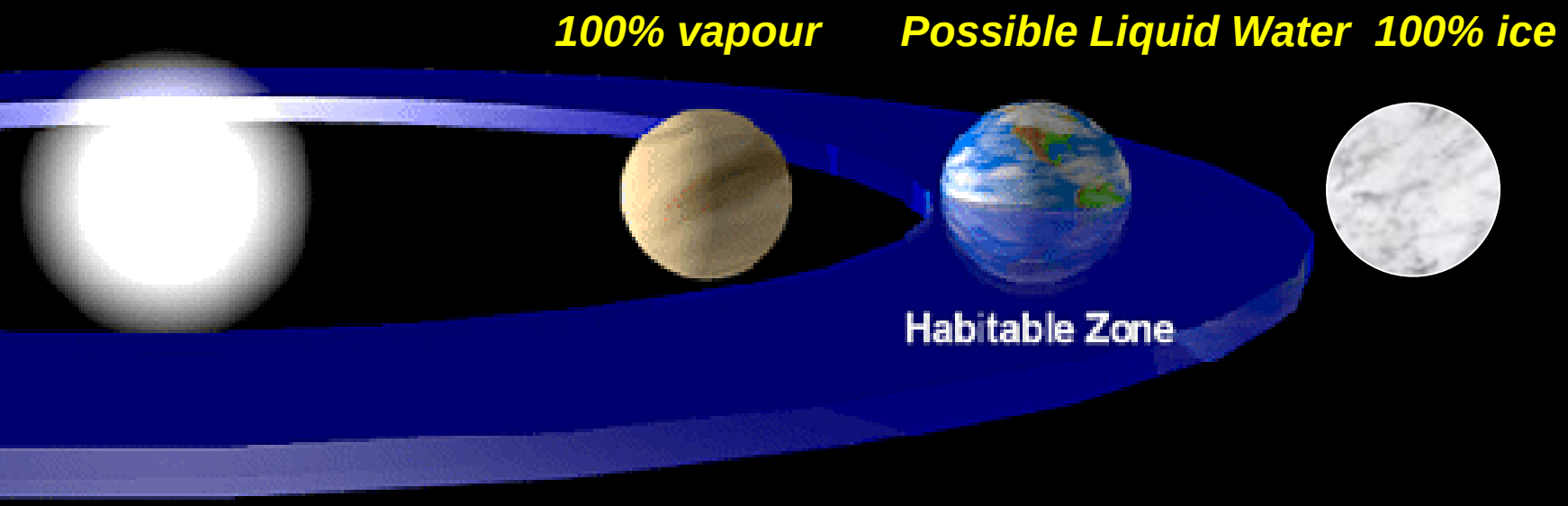


- **Class IV :** Bodies with subsurface ocean between two ice layers *(Ganymede)*

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

⇨ A problem of climate and atmosphere

Eg. Kasting et al. 1993
Forget 2013



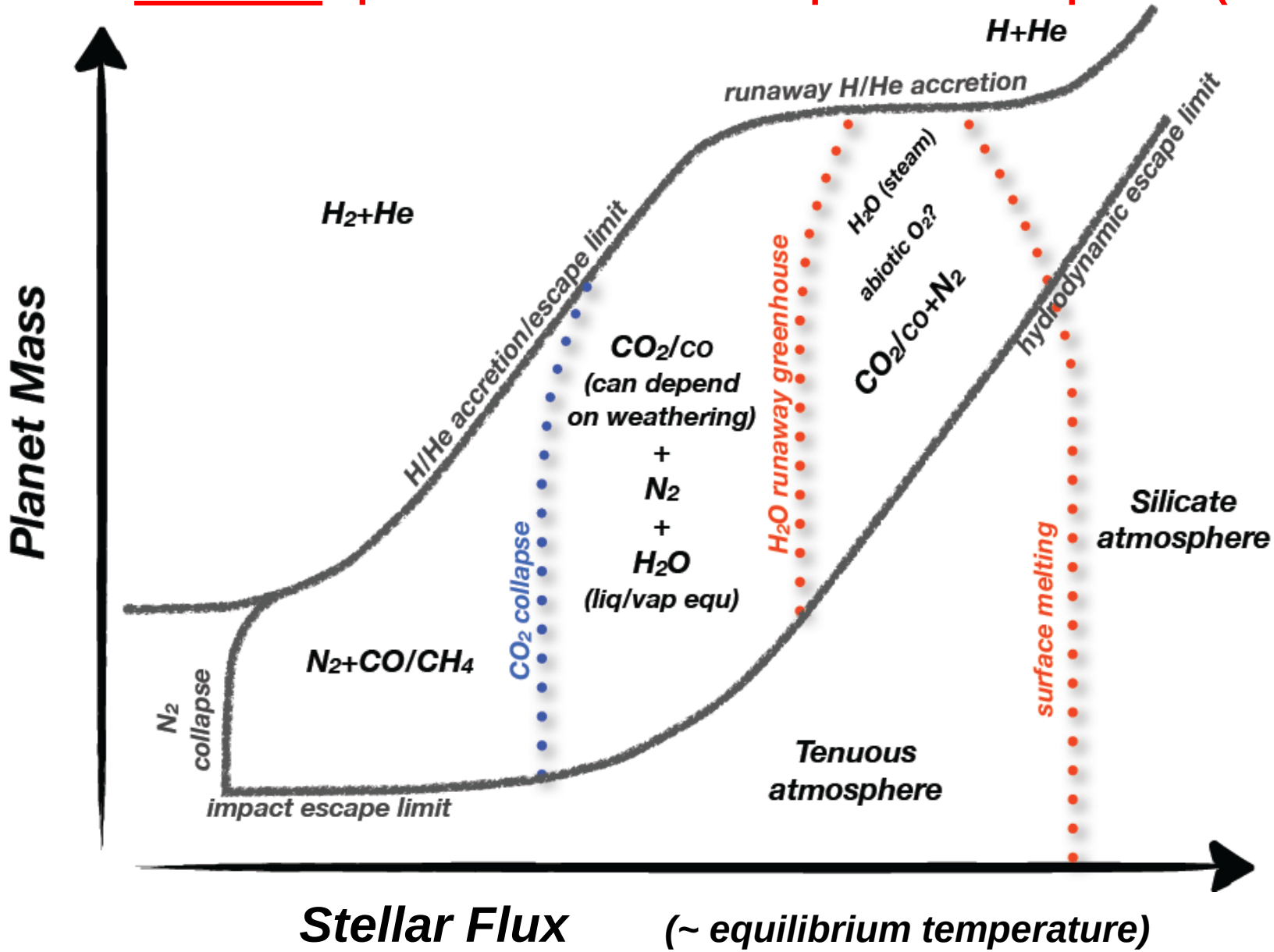
Which atmosphere on terrestrial planets around other stars ?

- The nature of terrestrial atmospheres depends on complex processes difficult to model:
  - Planetary formation and origins of volatiles
  - Atmospheric escape (thermal, impacts, non-thermal)
  - Geochemistry (degassing, interaction with surface, recycling)
  - Long term photochemistry …
- Our experience in the solar system is not sufficient.

⇨We usually assume a planetary volatile inventory composed of N_2, CO_2, H_2O

(see e.g. Forget and Leconte *Phil. Trans. Royal Society. A. , 2014)*

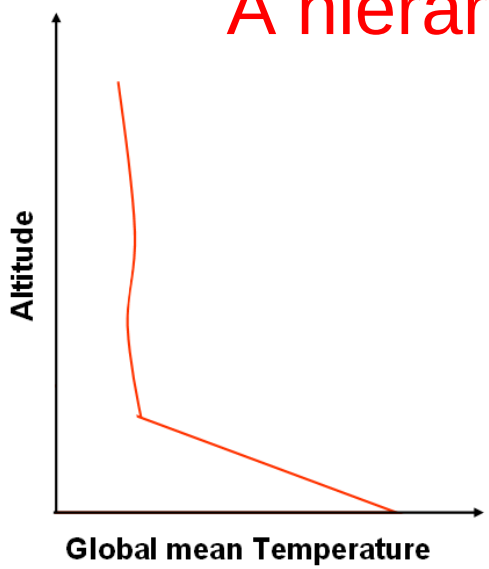
Expected dominant species in an terrestrial planet atmospheres (abiotic)

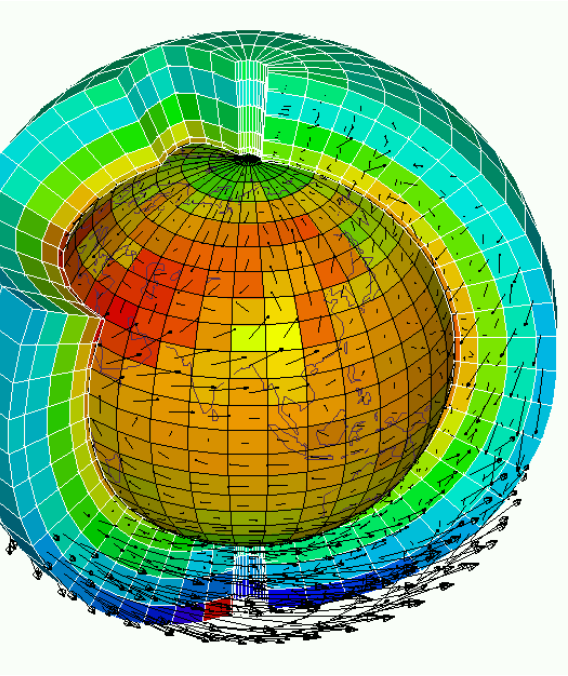


Forget and Leconte (2013), *« Possible climate on terrestrial exoplanets »*
Phil. Trans. Royal Society. A. (2014) (**arXiv:1311.3101)**

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…

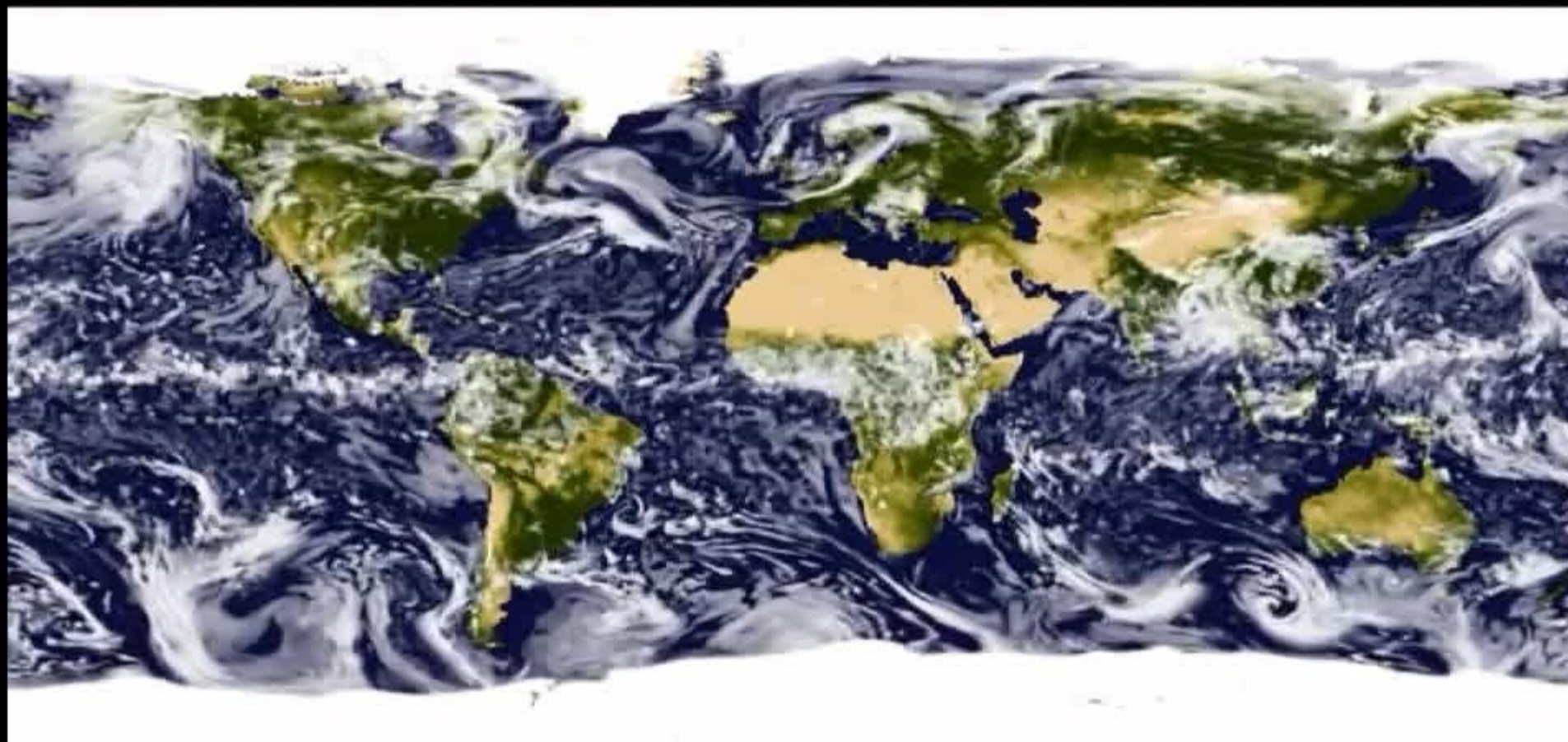
3. Theoretical 3D General Circulation model with simplified forcing: used to explore and analyse the possible atmospheric circulation regime

(*see Read 2011, Showman et al. 2013, etc)*

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

How to build a full Global Climate Simulator ?

Community Earth System Model (CESM), NCAR:



Climate Models in the solar system
What have we learned?

Lesson # 1: By many measures: GCMs work

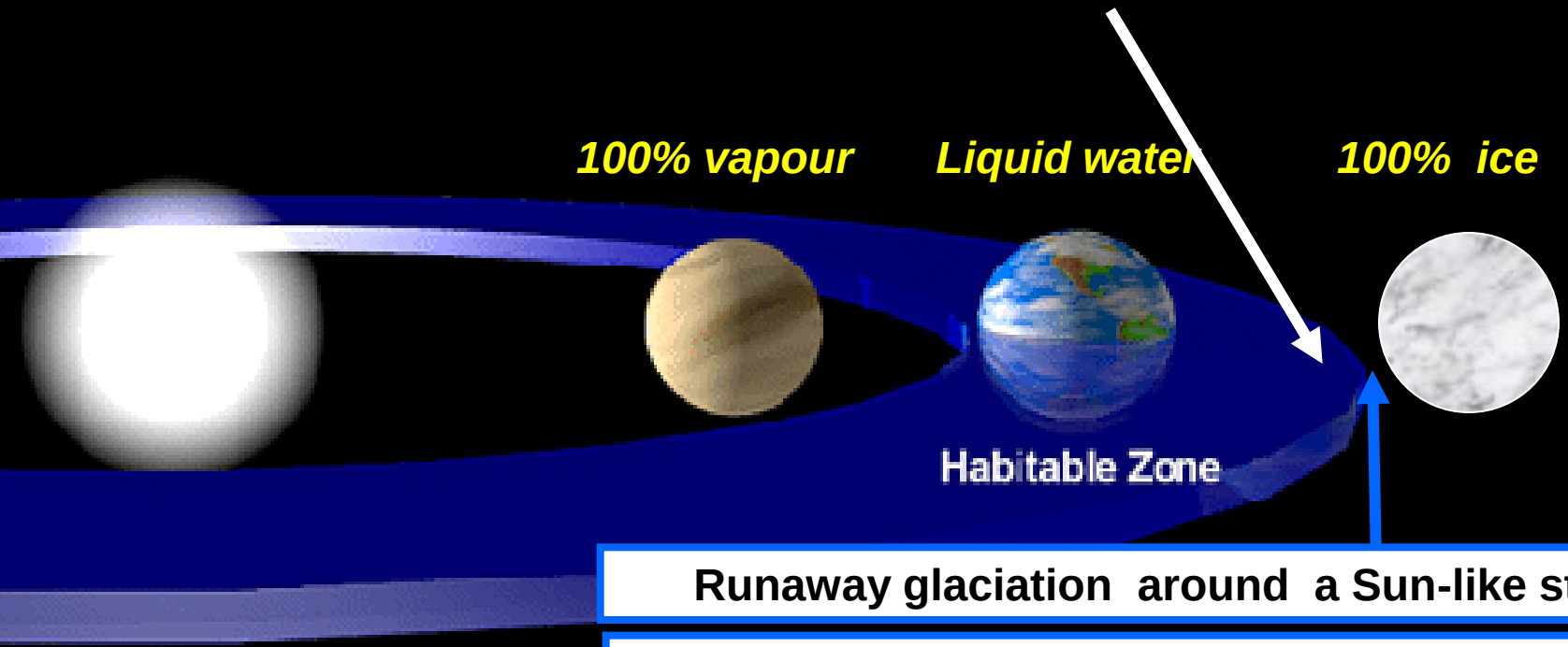
Lesson # 2: Why and when GCMs fail

(missing physical processes, non-linear processes and threshold effects, positive feedbacks and instability, etc…)

Lesson # 3 Climate model components can be applied without major changes to most terrestrial planets.

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

Outer Edge of the Habitable Zone ?



Runaway glaciation around a Sun-like star

Solar flux ↓ → Temperature ↓

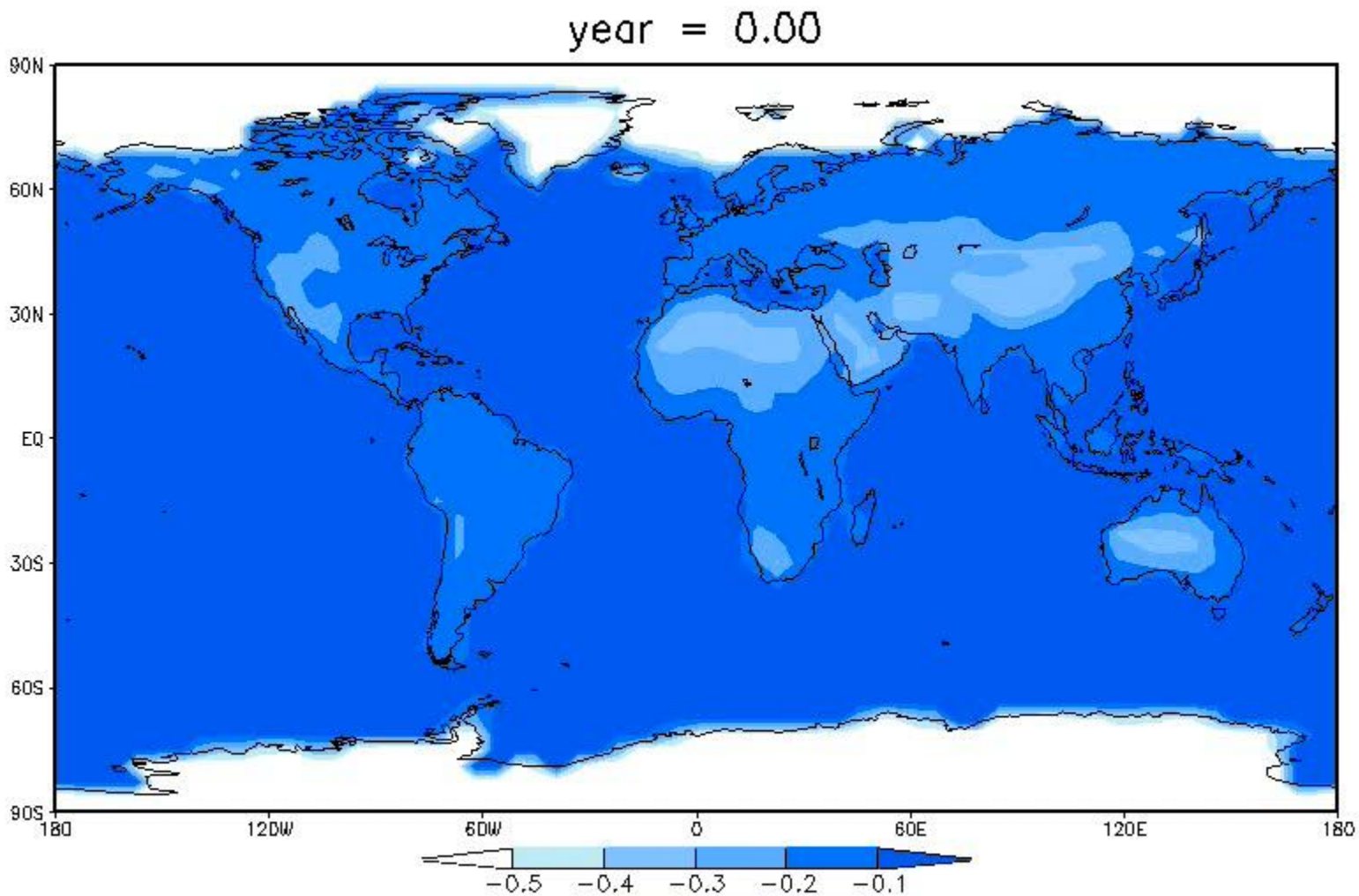
Ice and snow ↑ → Albedo ↑ → Temperature ↓

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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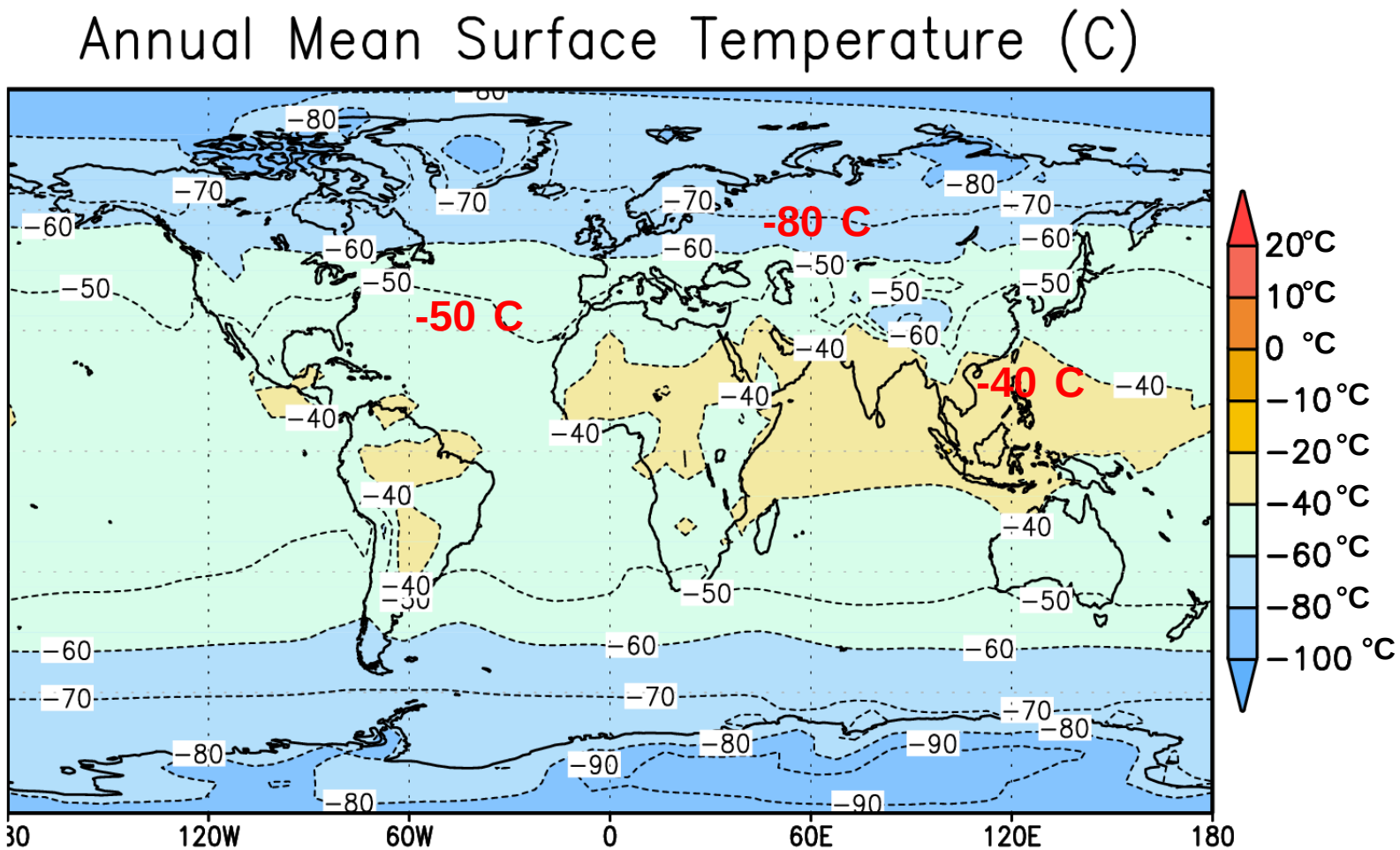
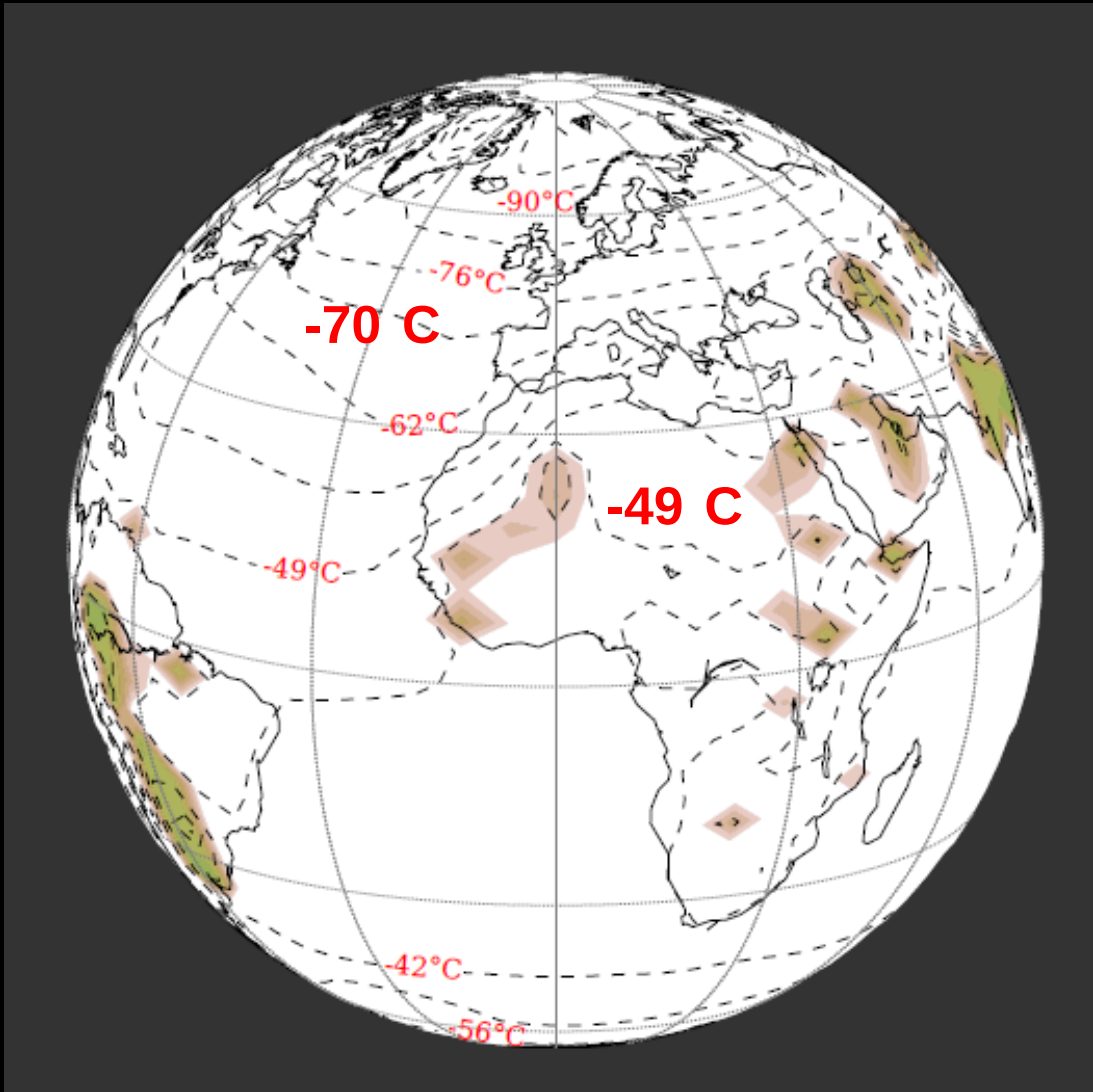


Out of glaciation: greenhouse effect

Flux = 80% present
(~1.12 AU)

Present
Earth atmosphere



Charnay et al., JGR 2013

Out of glaciation: greenhouse effect

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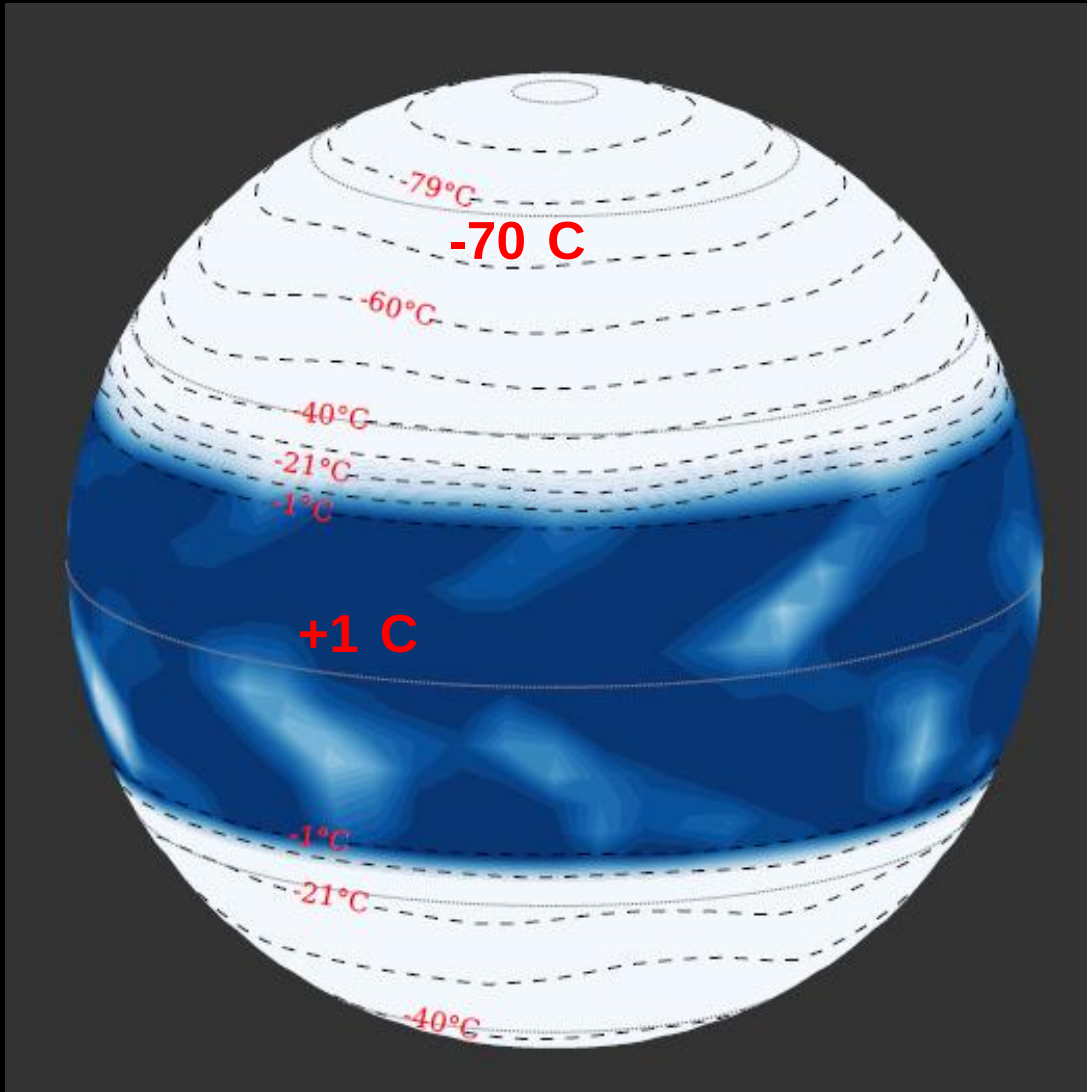
$[CO_2]$ x 2.5

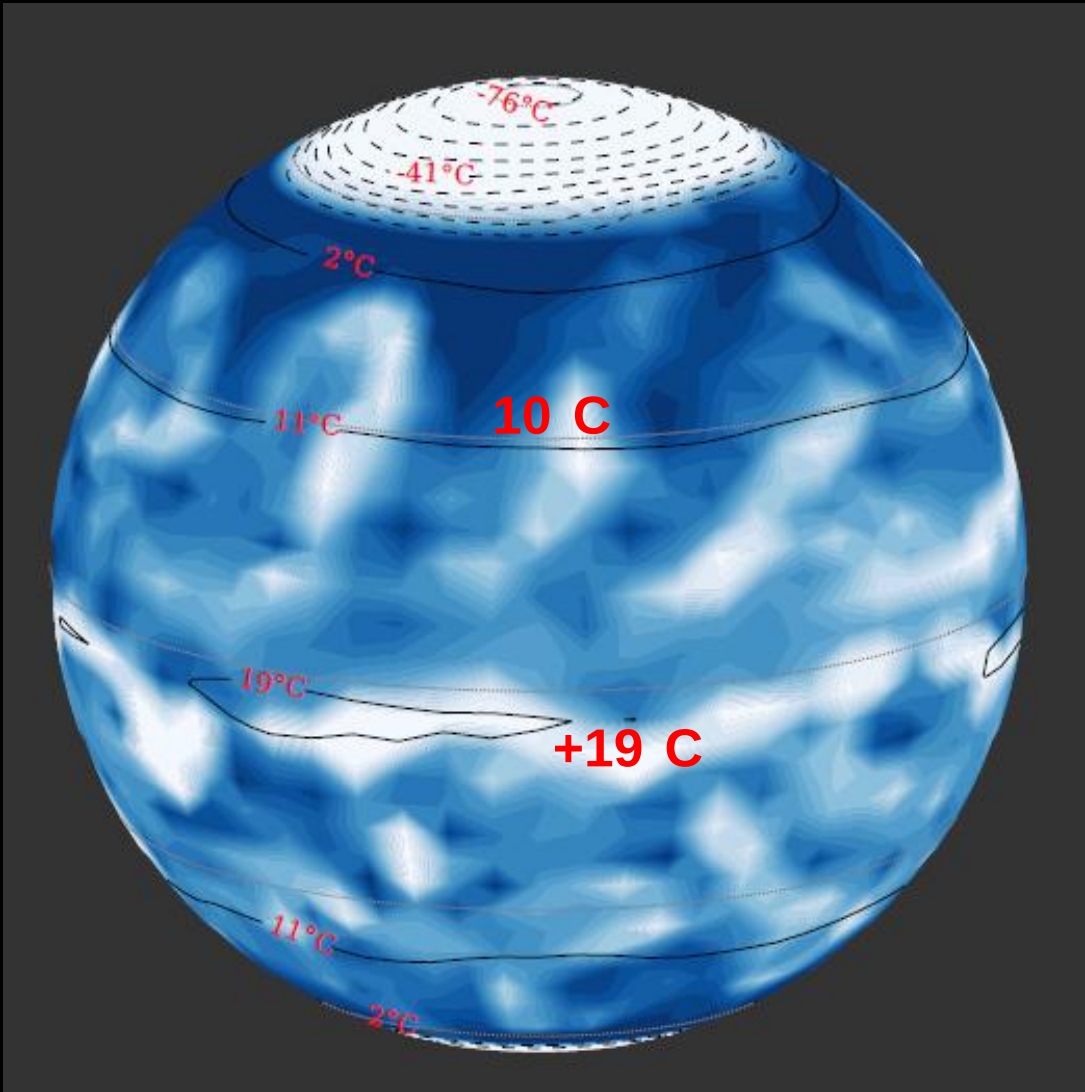


Charnay et al., JGR 2013

Out of glaciation: greenhouse effect

Flux = 80% present
(~1.12 AU)

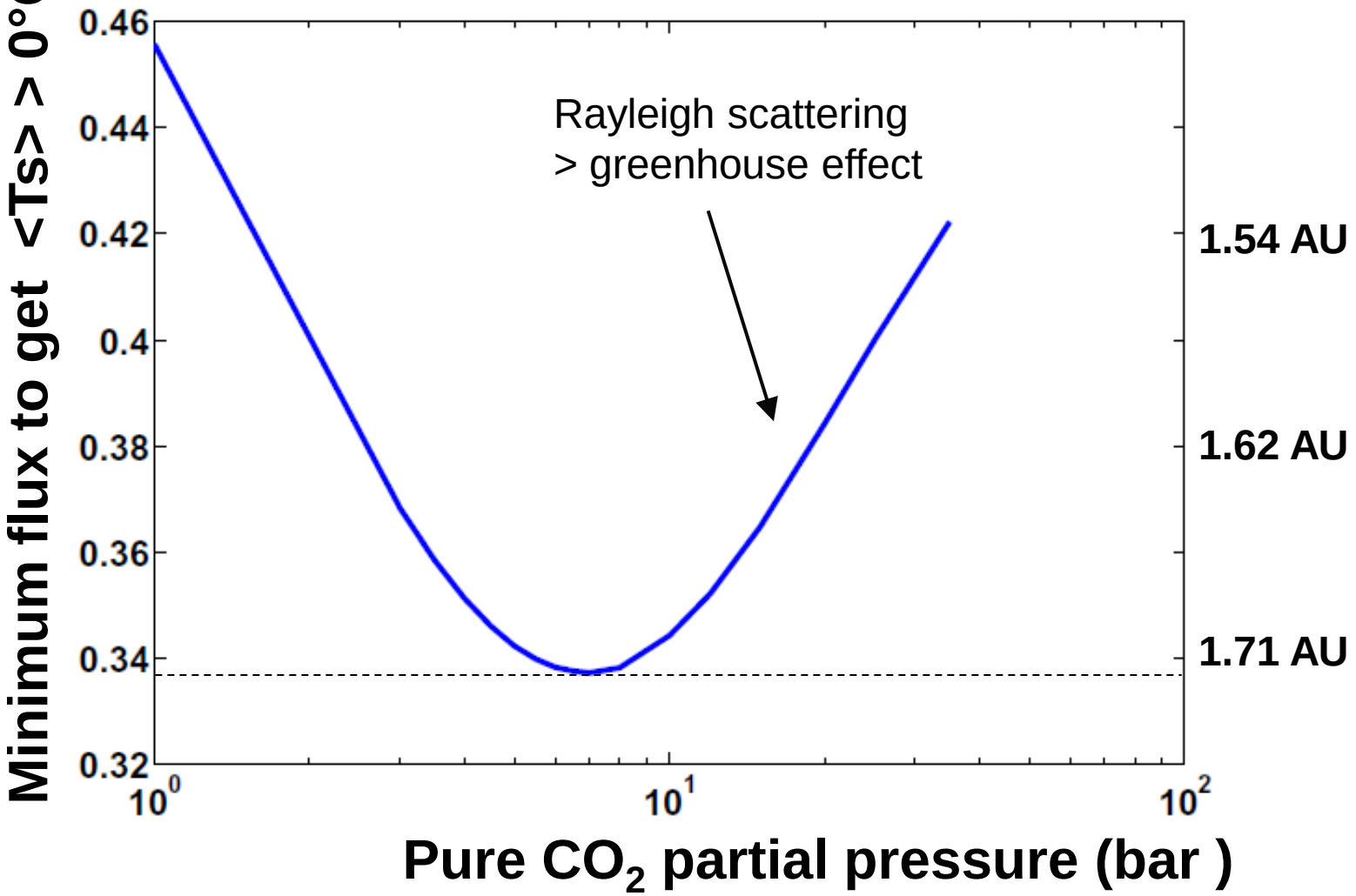
$[CO_2]$ x 250
[CH4] x 1000



Charnay et al., JGR 2013

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

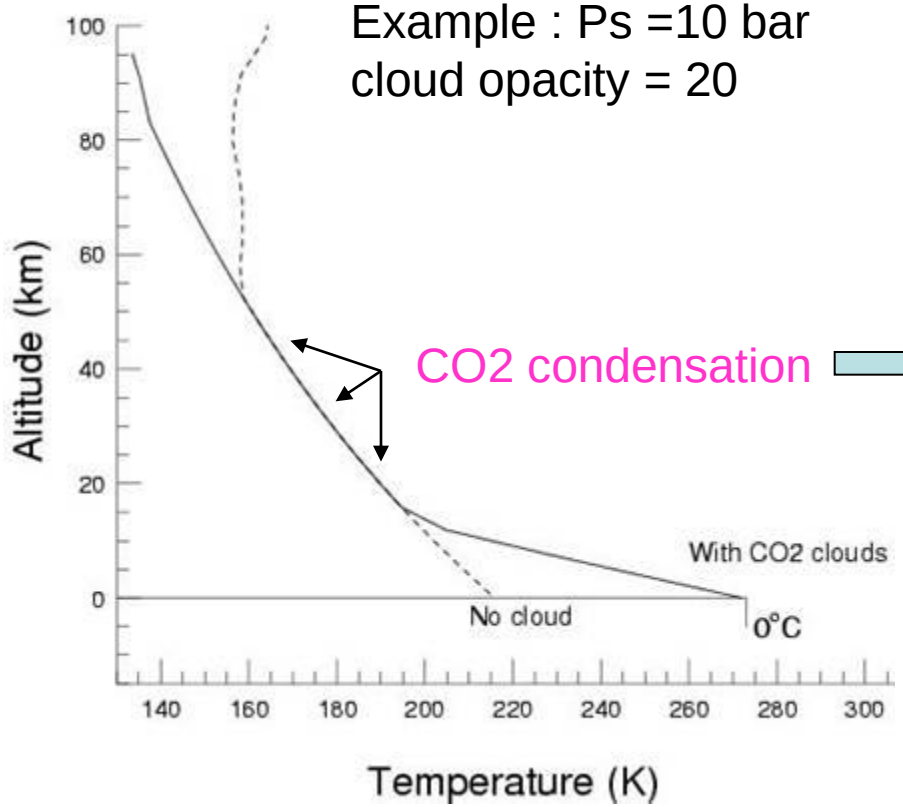
Kasting et al. 1993, Kopparapu et al. 2013

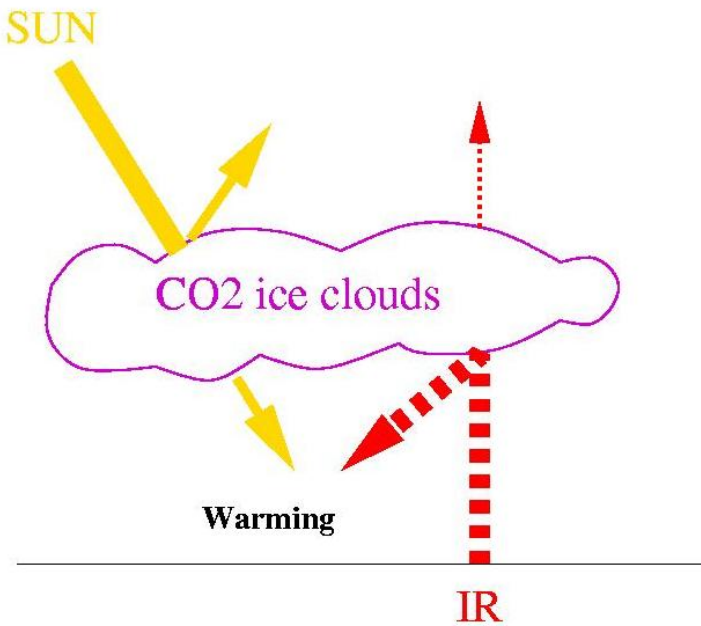


Scattering Greenhouse effect of CO_2 ice clouds
⇨ 0°C as far as 2.5 AU from the Sun ?

Forget and Pierrehumbert (1997)

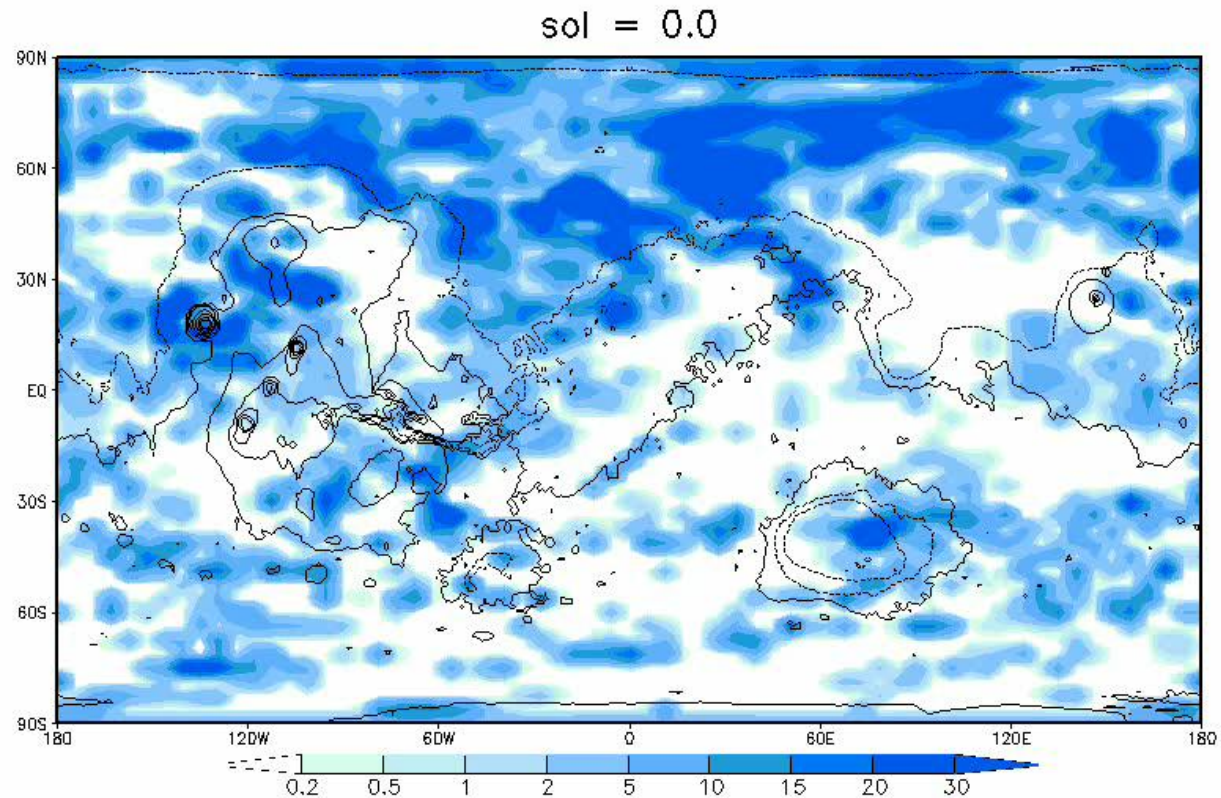
Example : Ps =10 bar
cloud opacity = 20

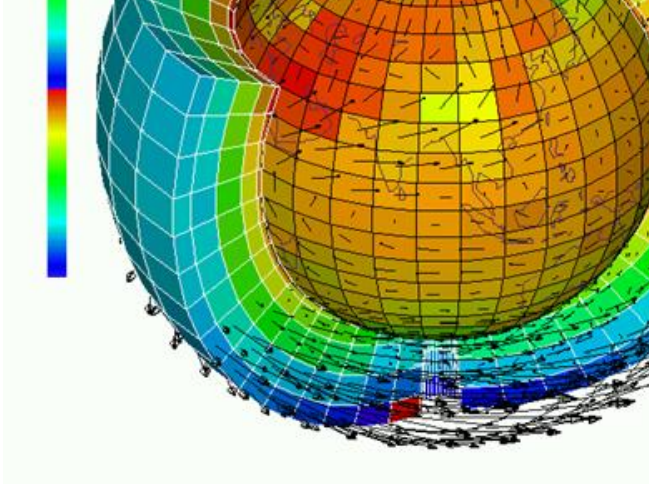




3D Global climate simulations of a cold CO2 atmosphere

(“Early Mars Case” distance equivalent to 1.75





Max Warming = + 15 K

(uncomplete cloud coverage)

CO2 ice Cloud optical depth

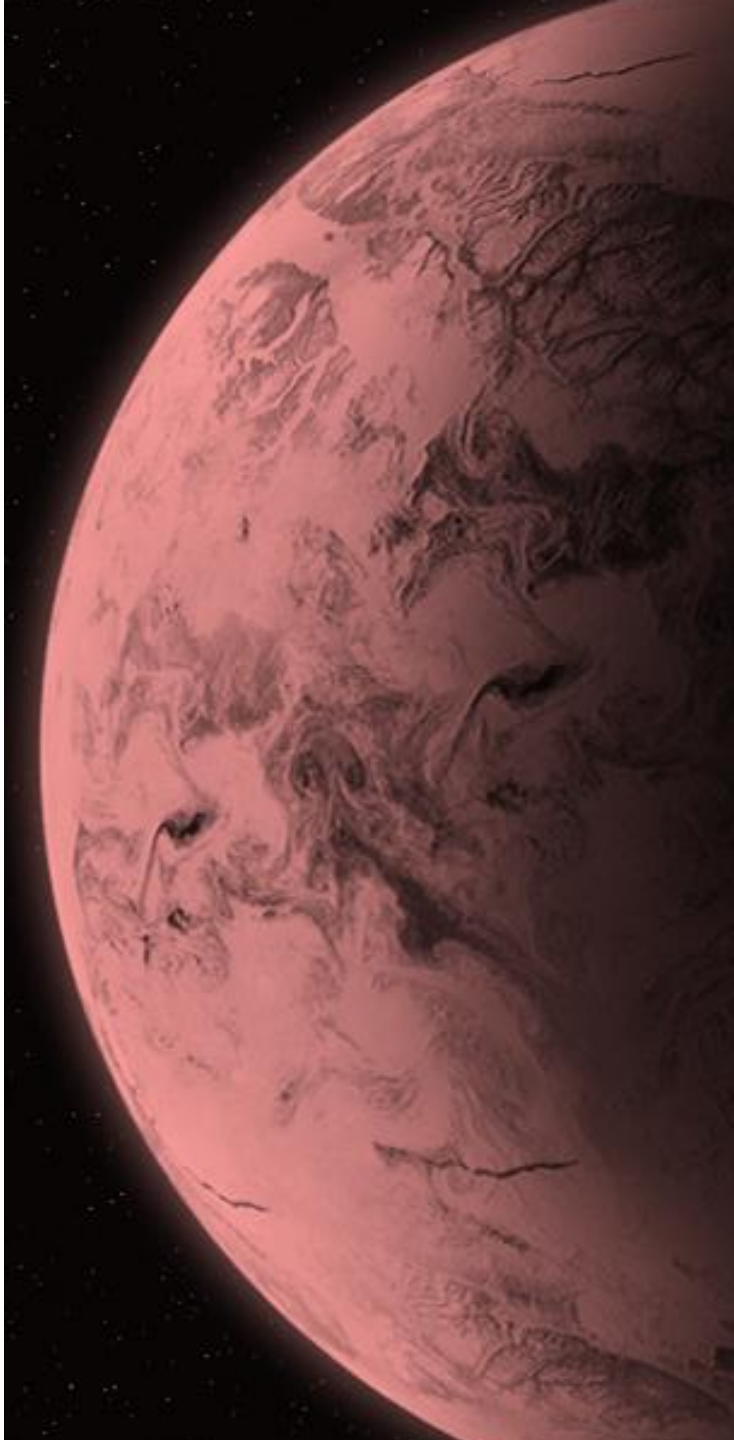
Forget et al. Icarus 2013,
Wordsworth et al. Icarus 2013

Around other stars

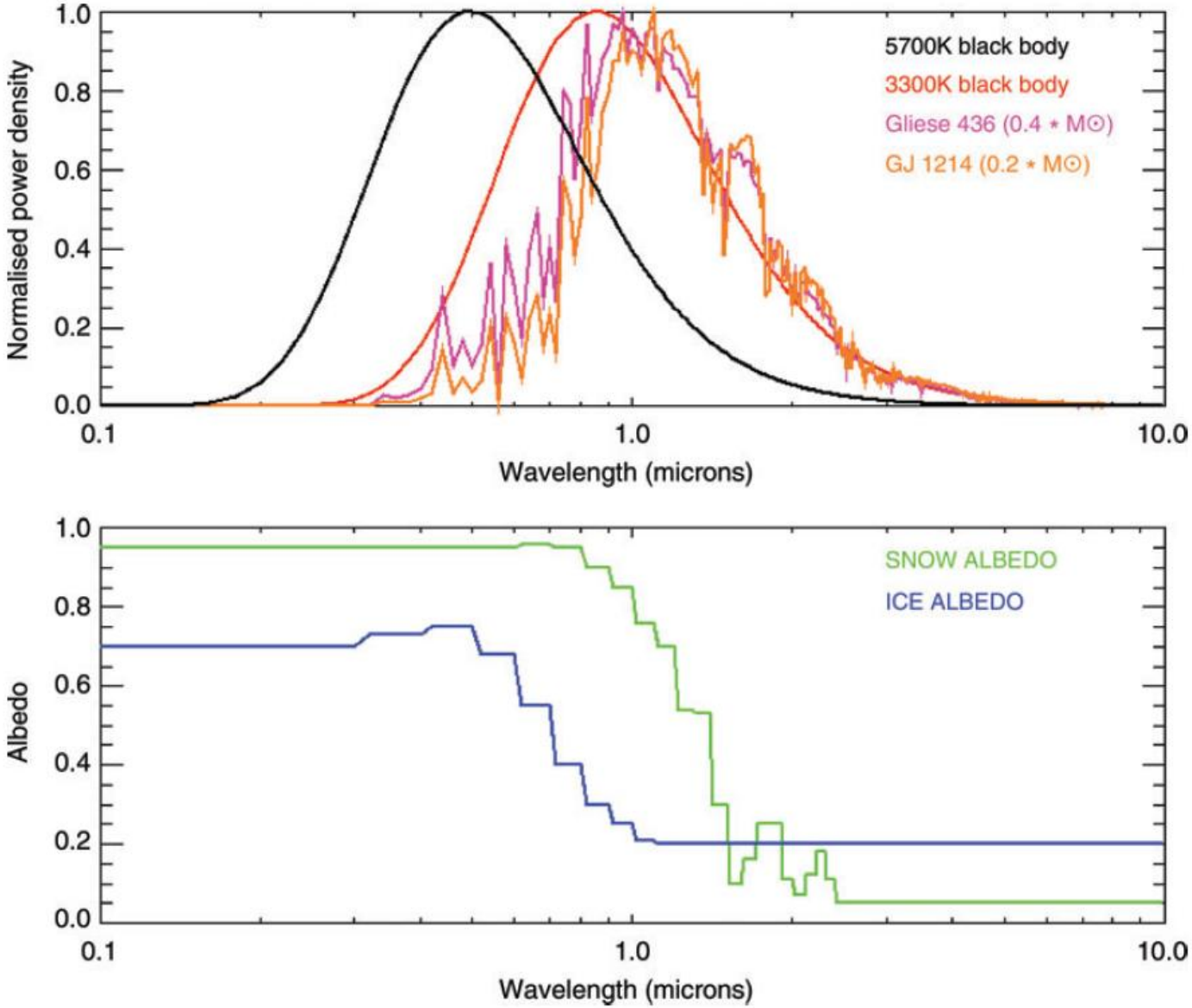
Glaciation around K & M dwarf stars:

Redder stellar spectrum

- No albedo water ice feedback *(Joshi and haberle, 2012)*



Snow and ice albedo vs Stellar spectra



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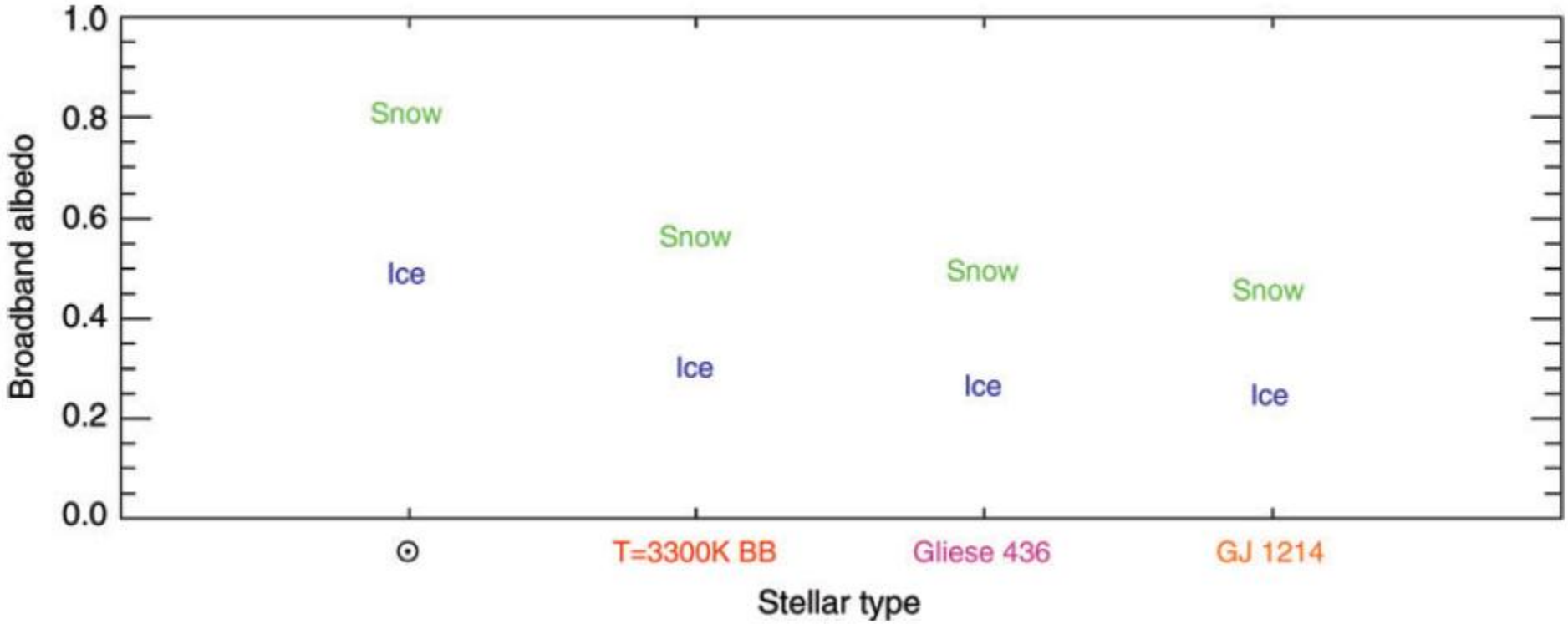


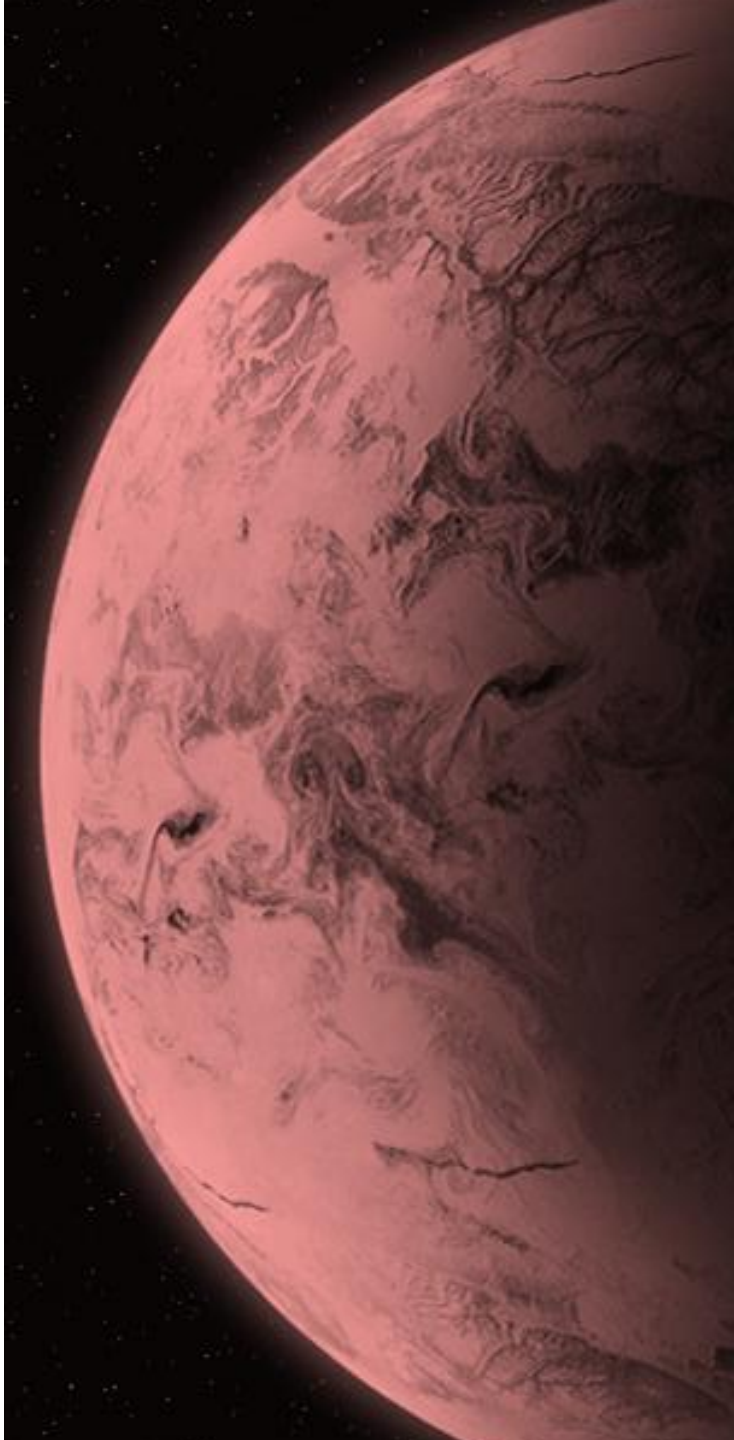
Glaciation around K & M dwarf stars:

Redder stellar spectrum

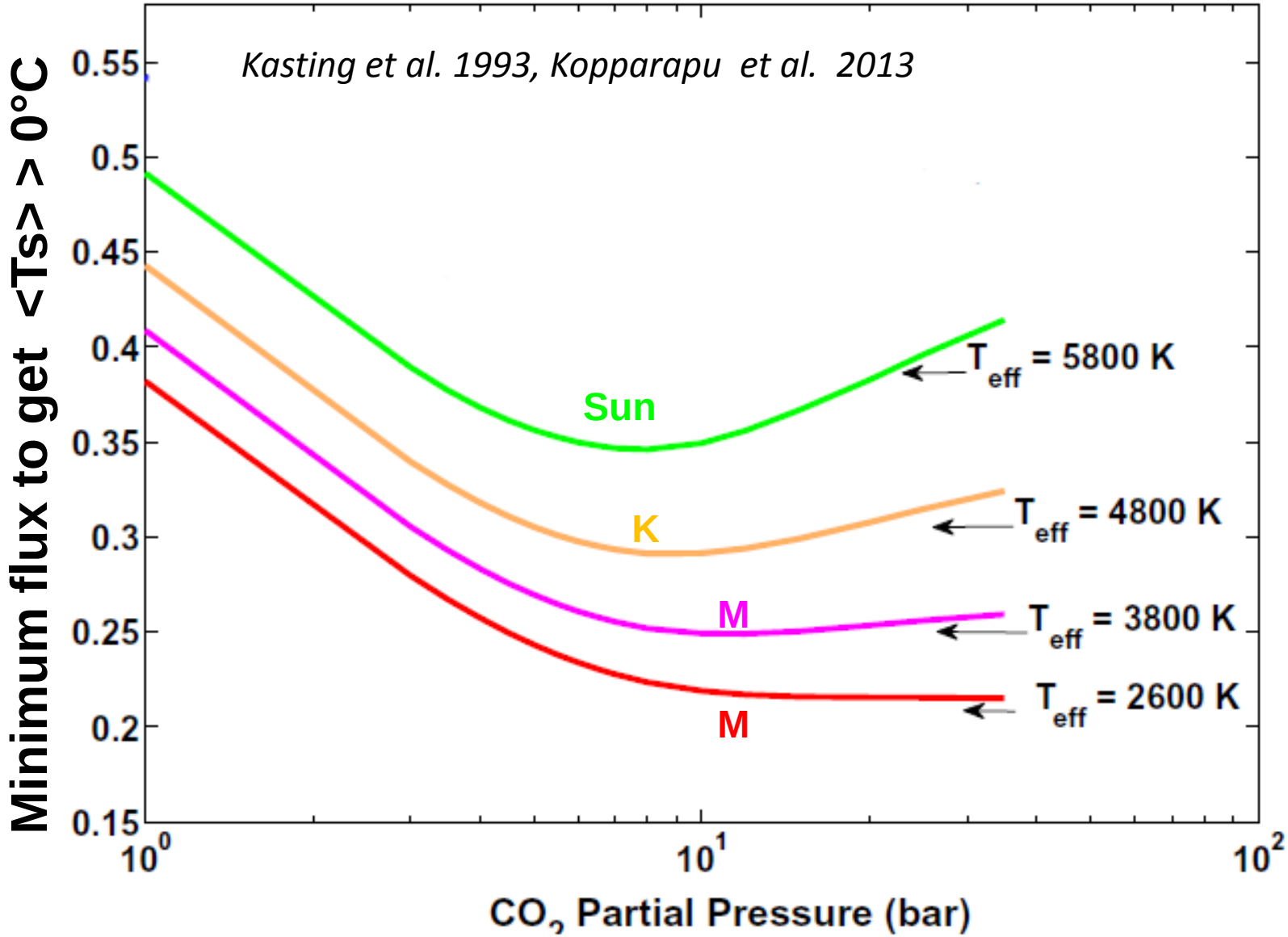
- No albedo water ice feedback *(Joshi and haberle, 2012)*
- Weak atmospheric Rayleigh Scaterring

  ⇨ lower albedo

  ⇨ Enhanced high pressure CO2 greenhouse effect



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



Glaciation around K & M dwarf stars:

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  ⇨ lower albedo

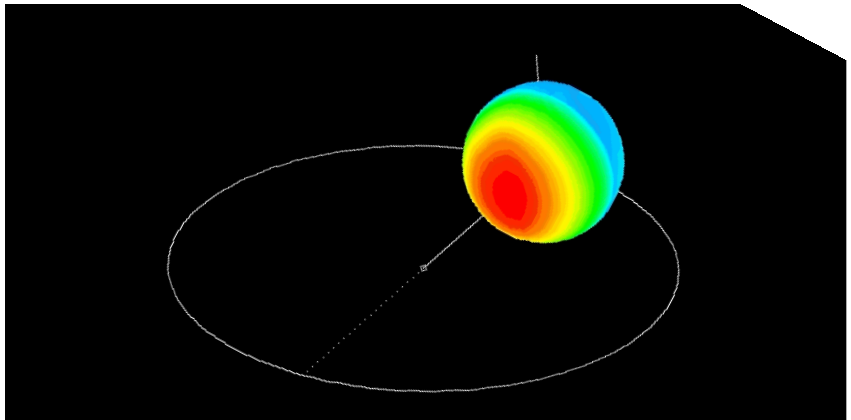
  ⇨ Enhanced high pressure CO2 greenhouse effect

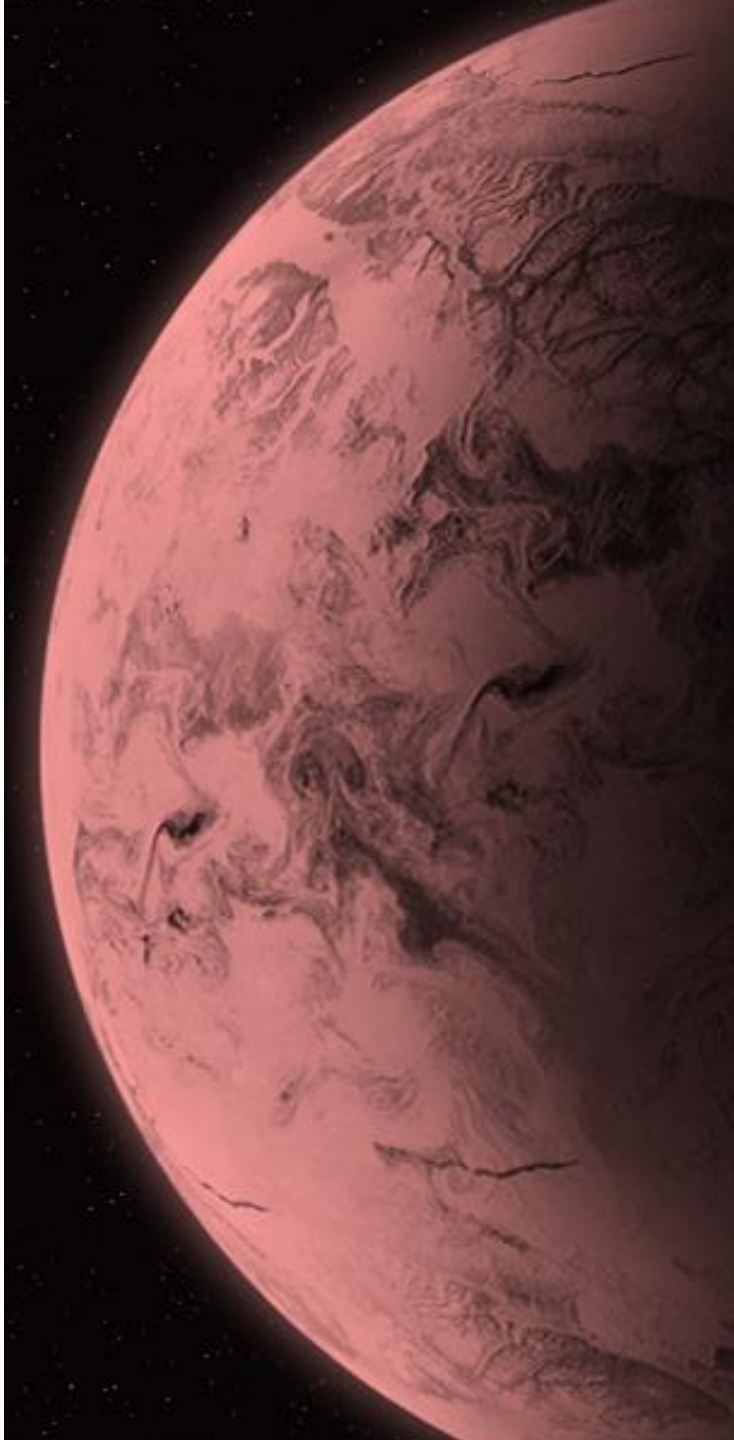
But : Effect of tides on rotation:

- Resonant rotation with zero obliquity

⇨ No insolation at the pole

⇨ Possible Locking with permanent night side



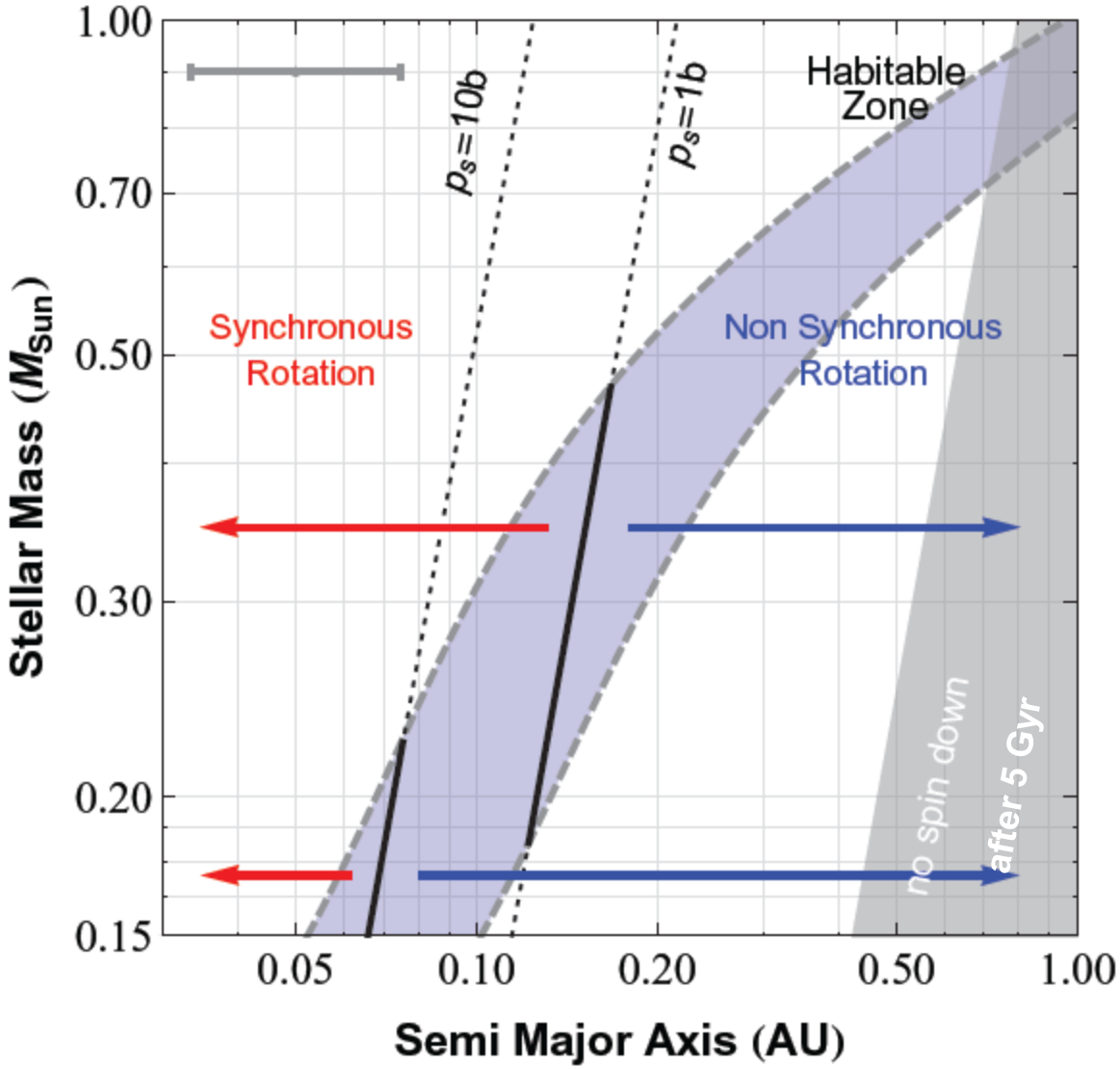


Side Question: Are terrestrial planets in M star habitable zone always tidally locked ?

Rocky planet on circular orbit around M stars should synchronously rotating (*Dole, 1964, Kasting et al. 1993*) after ~1 Gyr. However:

- This does not apply to Giant planet satellites…
- Planets with eccentric orbit are likely to be in other resonance , non-synchronous resonance (like Mercury) [*e.g. Correia et al. 2008*]
- In presence of an atmosphere, thermal tides (resulting from solar heating of the atmosphere) can put the rotation out of synchronicity (like Venus) [*Gold and Stoter, 1969, Correia and Laskar 2003, 2008, Leconte et al. 2014]*

Leconte et al. 2014, in revision

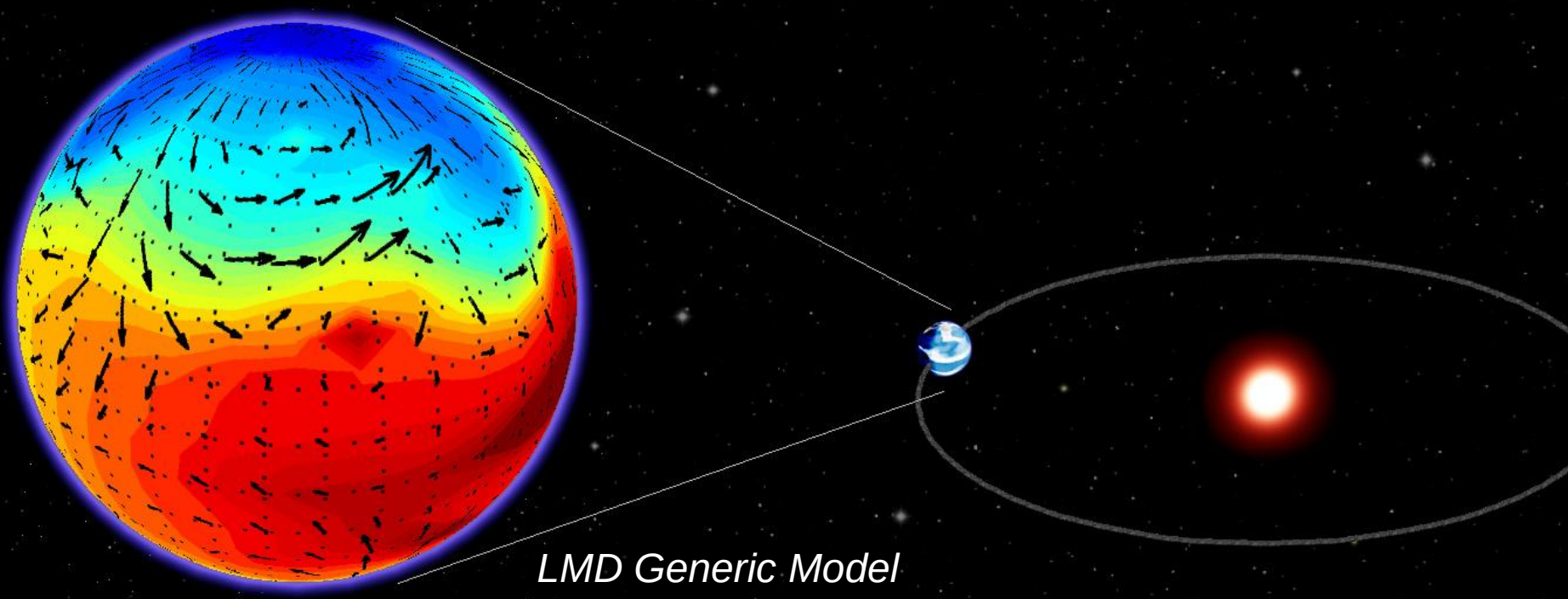


Example: simulating the climate on Exoplanet Gliese 581d

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 ?



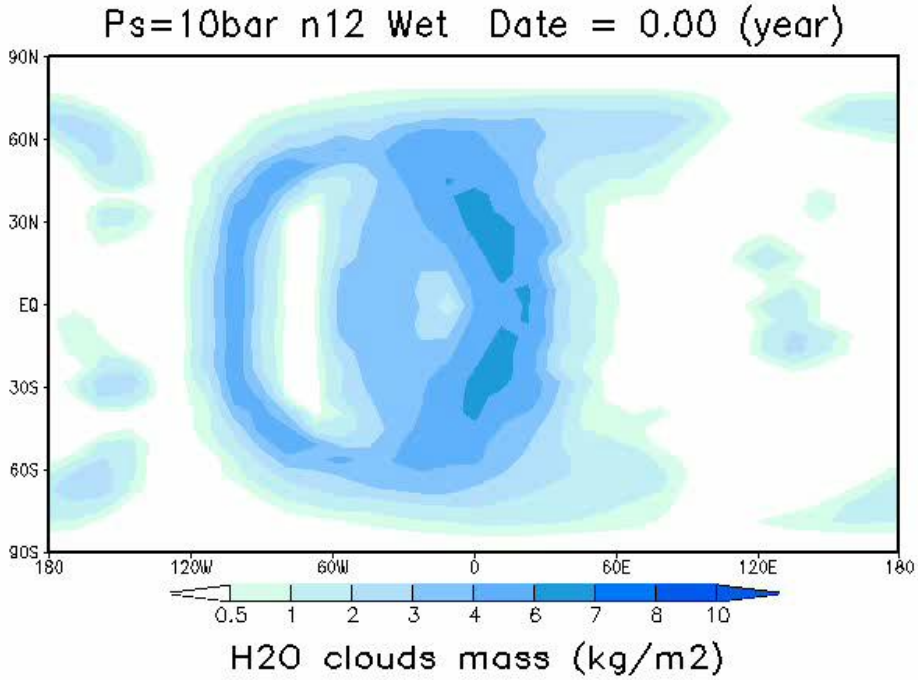
LMD Generic Model

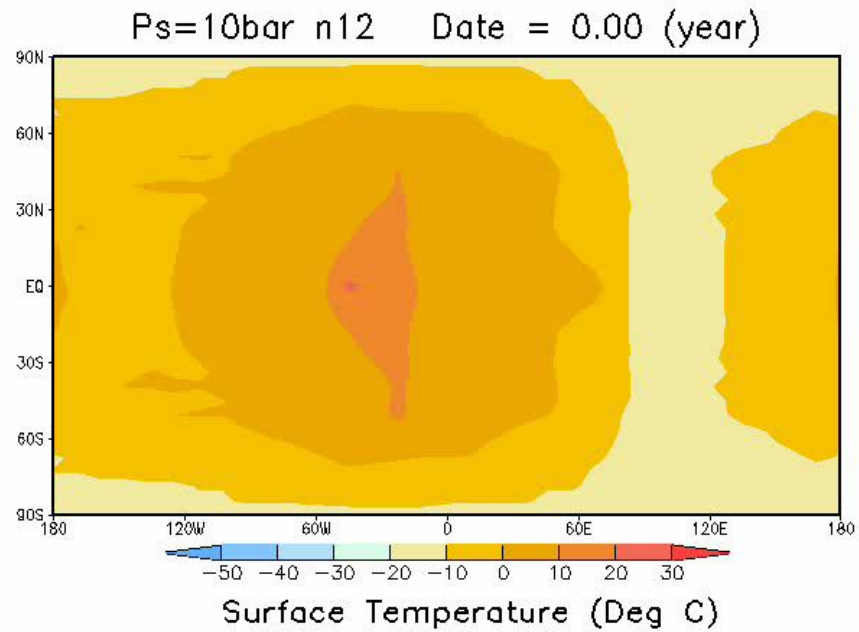
Gliese 581D

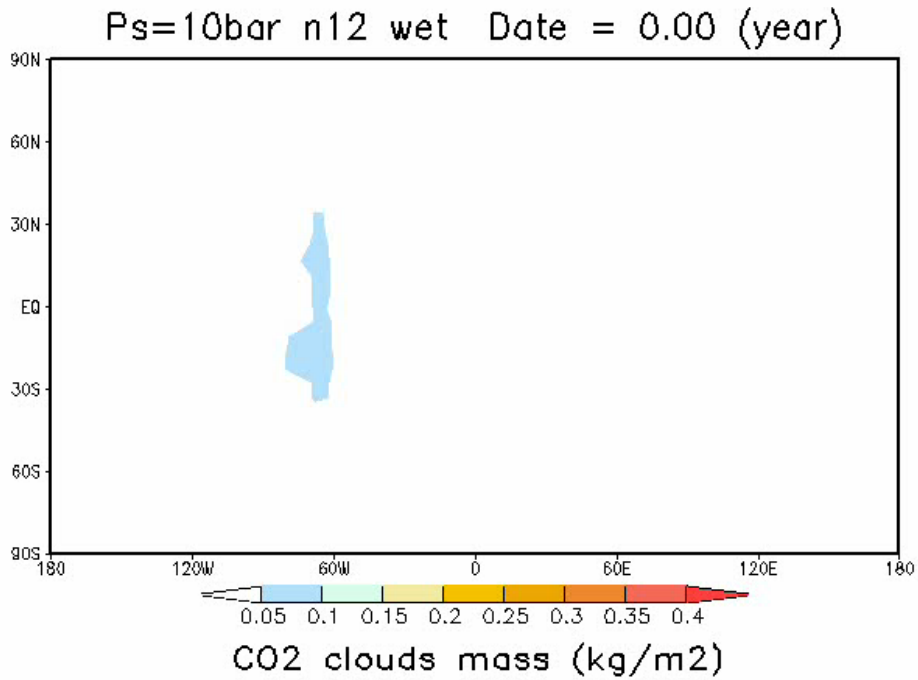
Water clouds

CO2 ice clouds

Surface temperature (K)

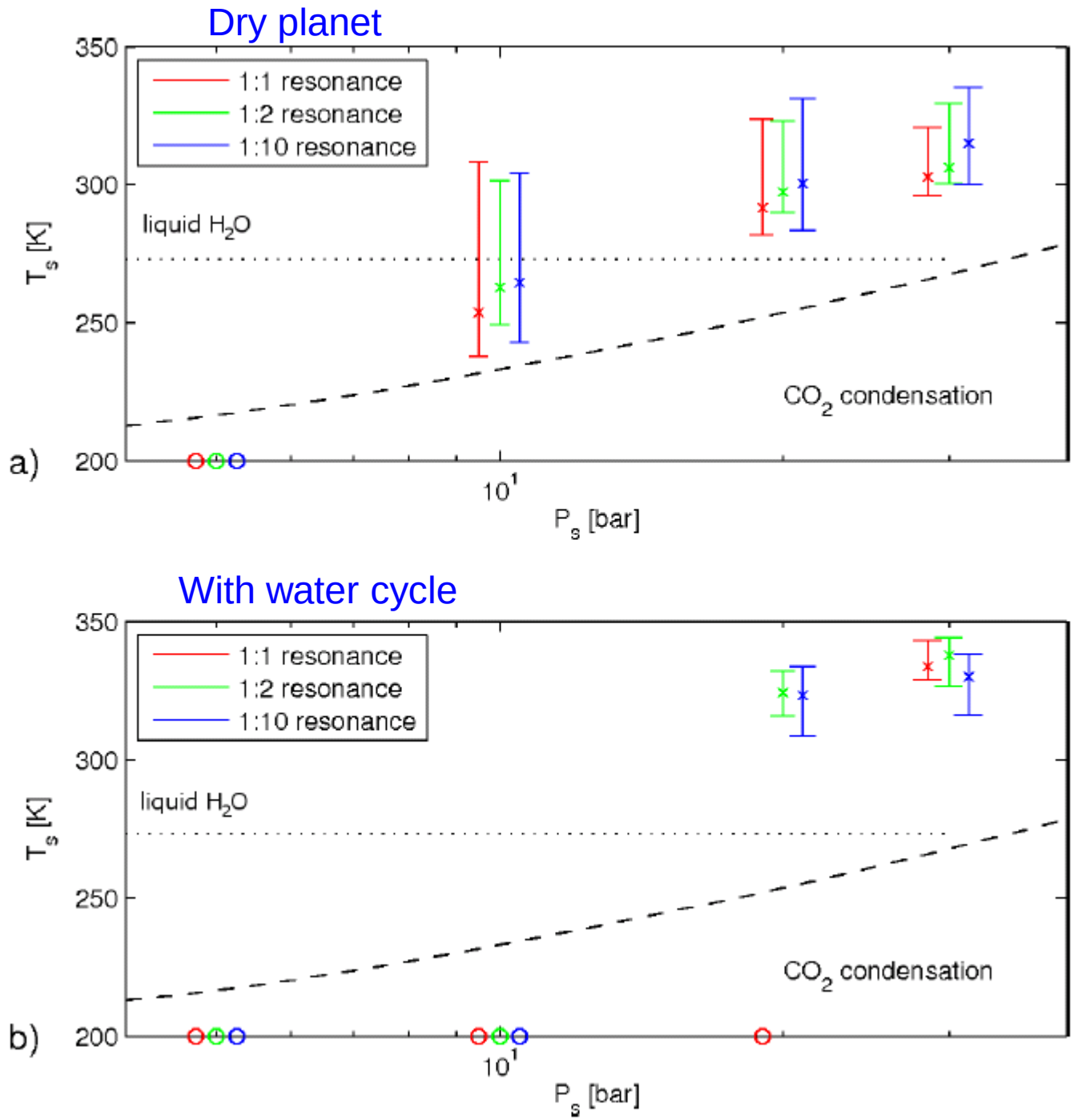






Gliese 581d: conclusions

Assuming enough CO2 and H2O (which is not unlikely), Gliese 581d WOULD be habitable.



Wordsworth et al. 2011

Astrophysical Journal, Wordsworth, Forget et al. 2011

Gliese 581d is the first discovered terrestrial-mass exopl
the habitable zone

Report

Sciencexpress

EMBARGOED UNTIL 2:00 PM US ET THURSDAY, 3 JULY 2014

Stellar activity masquerading as planets in the habitable zone of the M dwarf Gliese 581

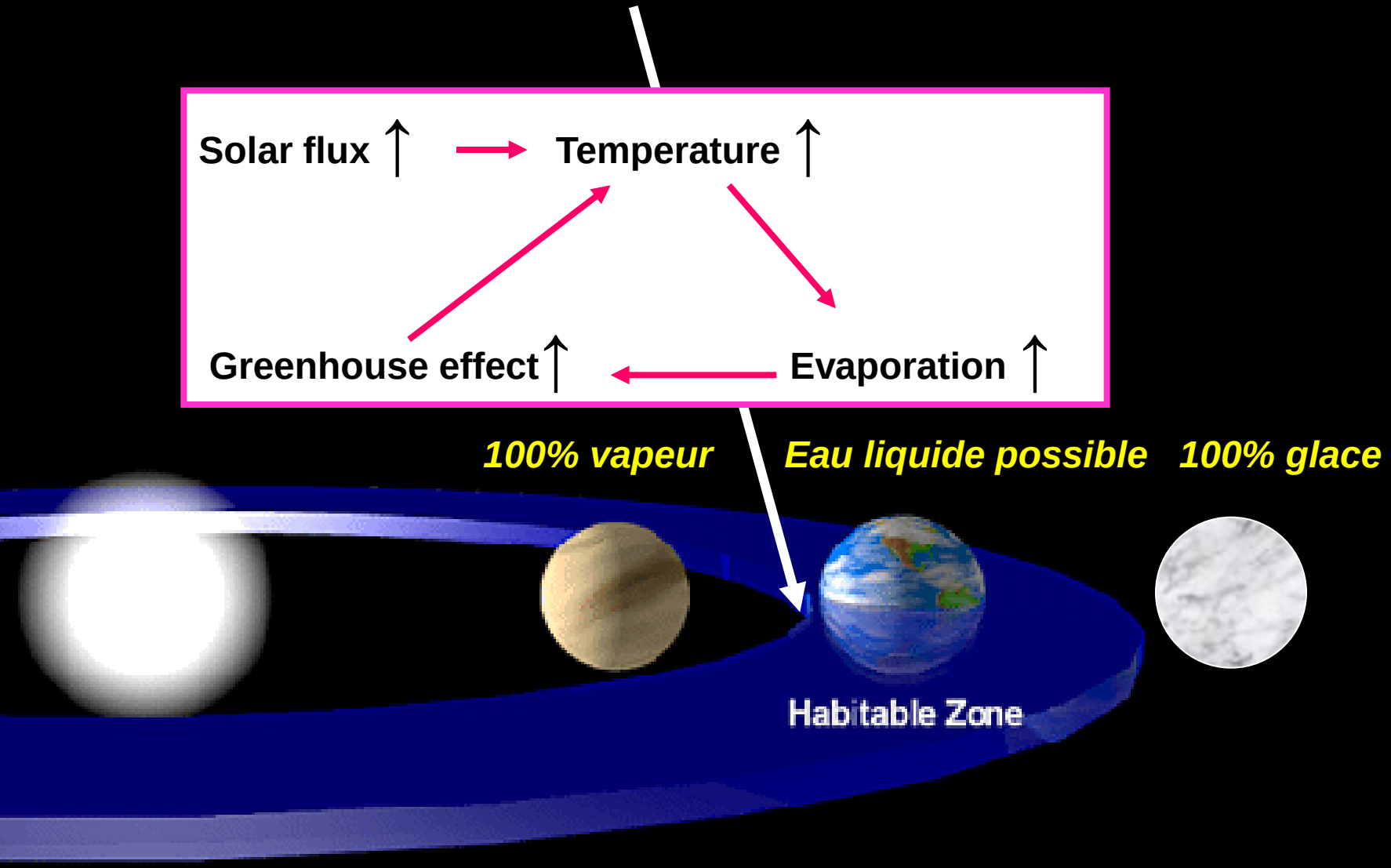
Paul Robertson,[1,2*] Suvrath Mahadevan,[1,2,3] Michael Endl,[4] Arpita Roy[1,2,3]

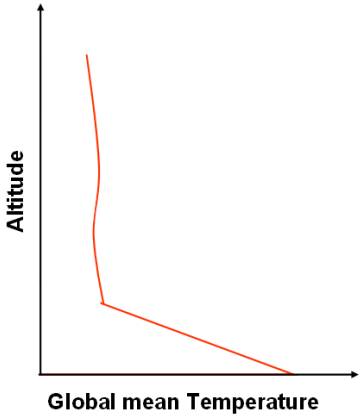
[1]Department of Astronomy and Astrophysics, The Pennsylvania State University, University Park, PA 16802, USA. [2]Center for Exoplanets and Habitable Worlds, The Pennsylvania State University, University Park, PA 16802, USA. [3]The Penn State Astrobiology Research Center, The Pennsylvania State University, University Park, PA 16802, USA. [4]McDonald Observatory, The University of Texas at Austin, Austin, TX 78712–1206, USA.

E-mail: pmr19@psu.edu

four planets, including one (GJ 581d)
water on its surface if it is
581 g—is

Inner Edge of the Habitable Zone ?

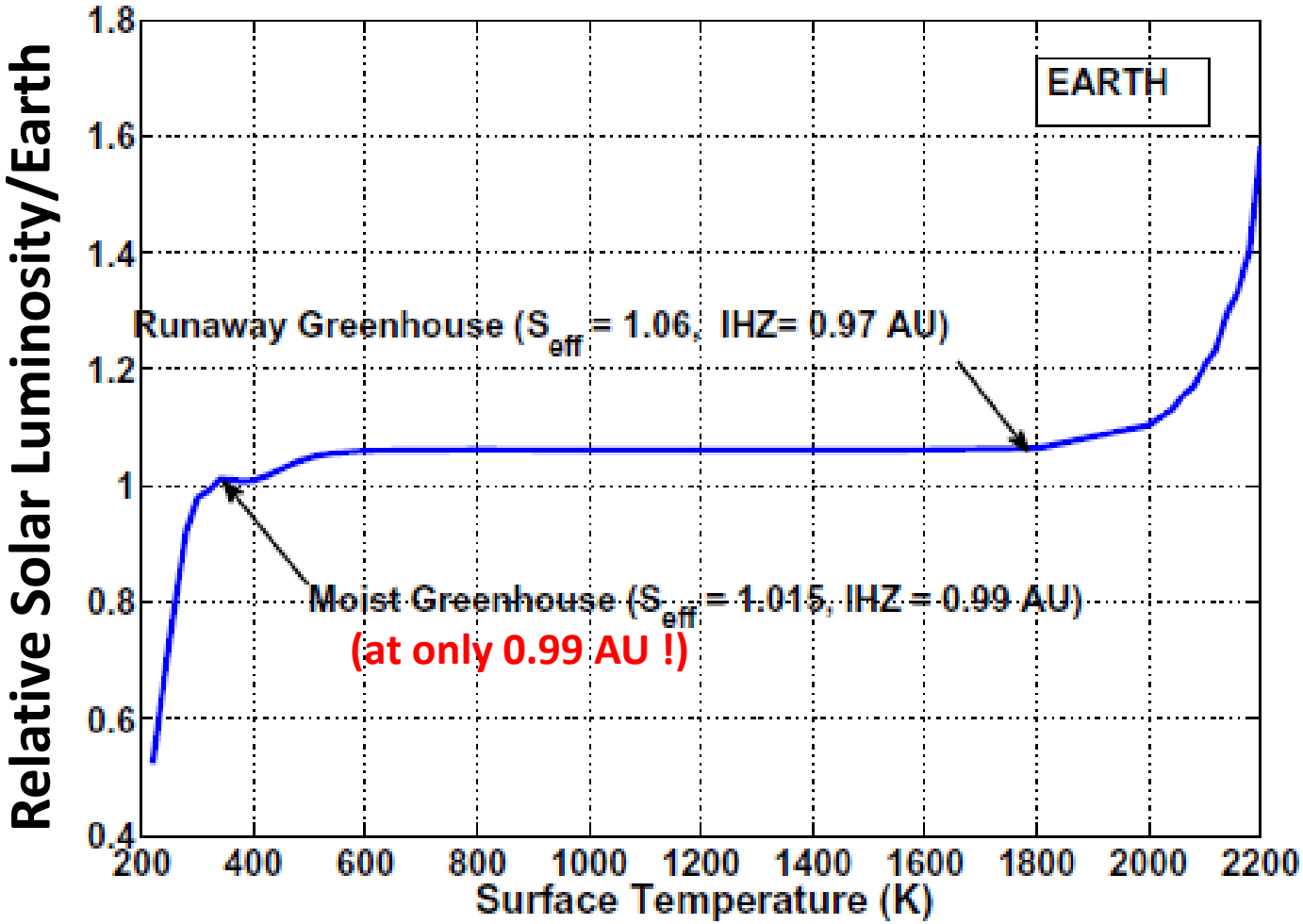




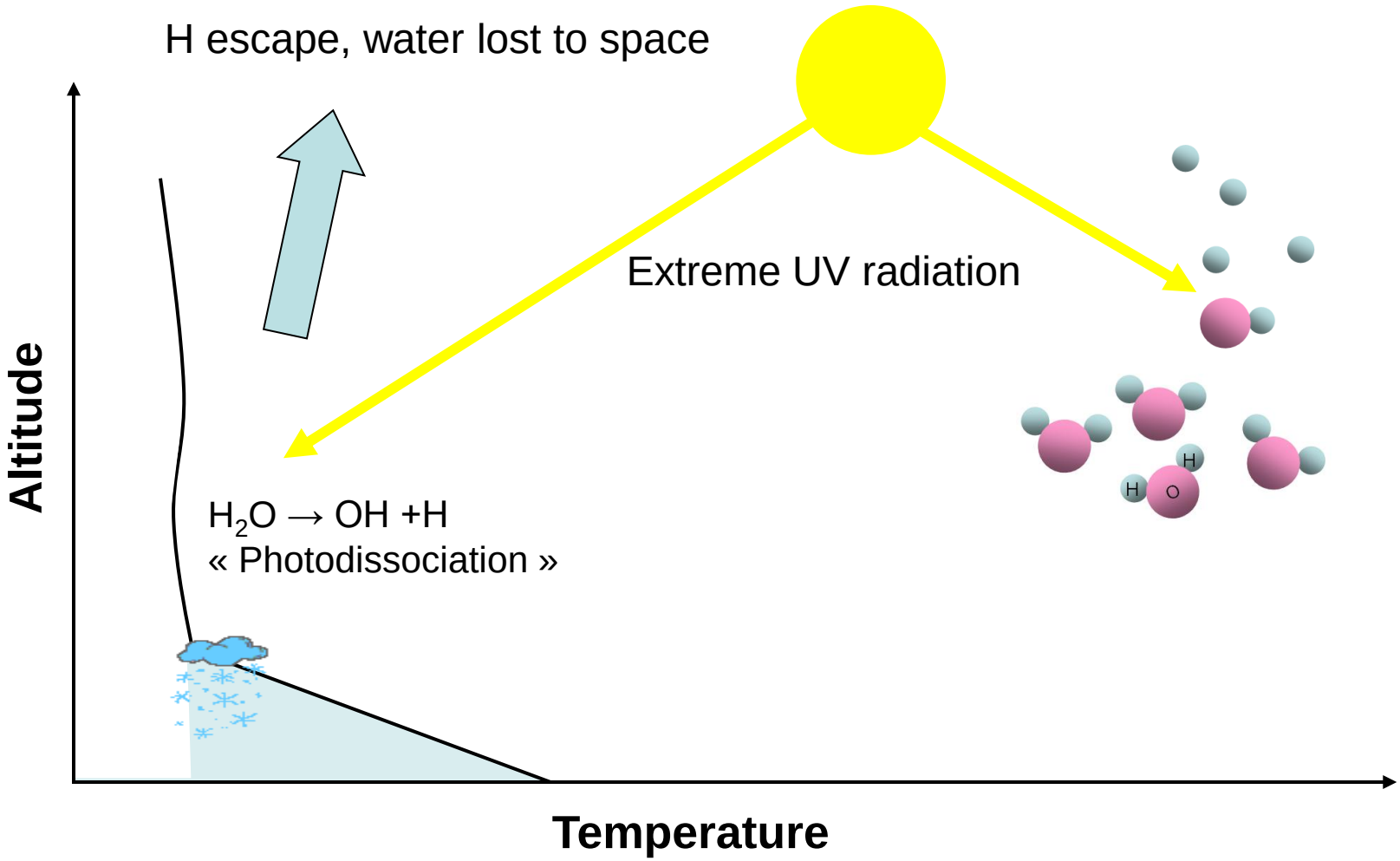
Runaway Greenhouse effect in 1D models

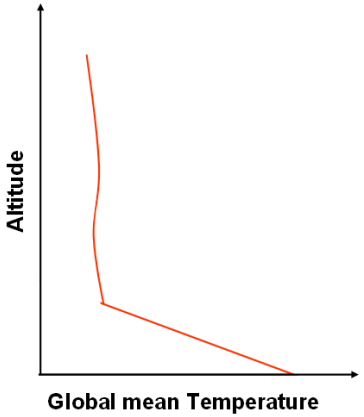
(for an Earth-like planet around a sun)

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



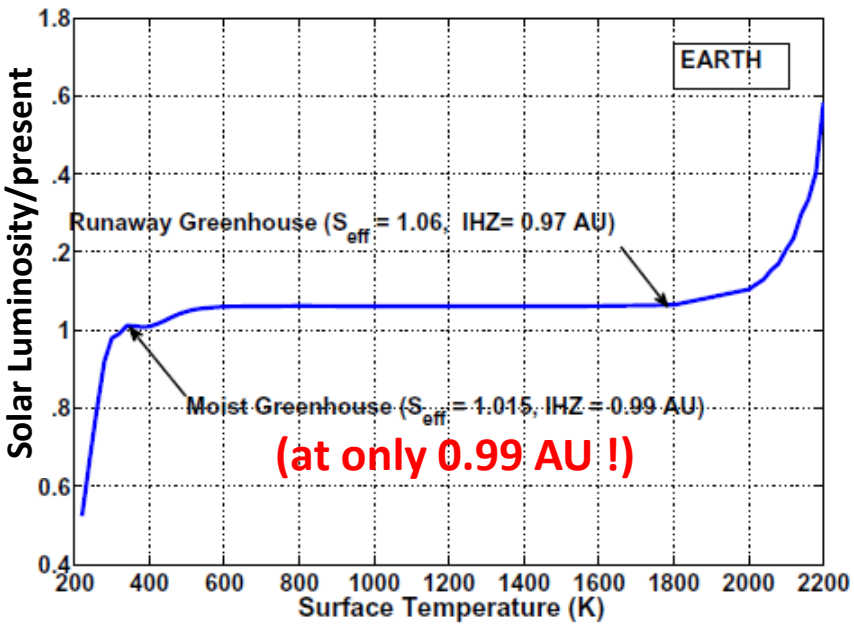
Impact of temperature increase on water vapor distribution and escape: the « water loss limit »… at only 0.99 AU from the Sun (*Kopparapu, Kasting et al. 2013*)

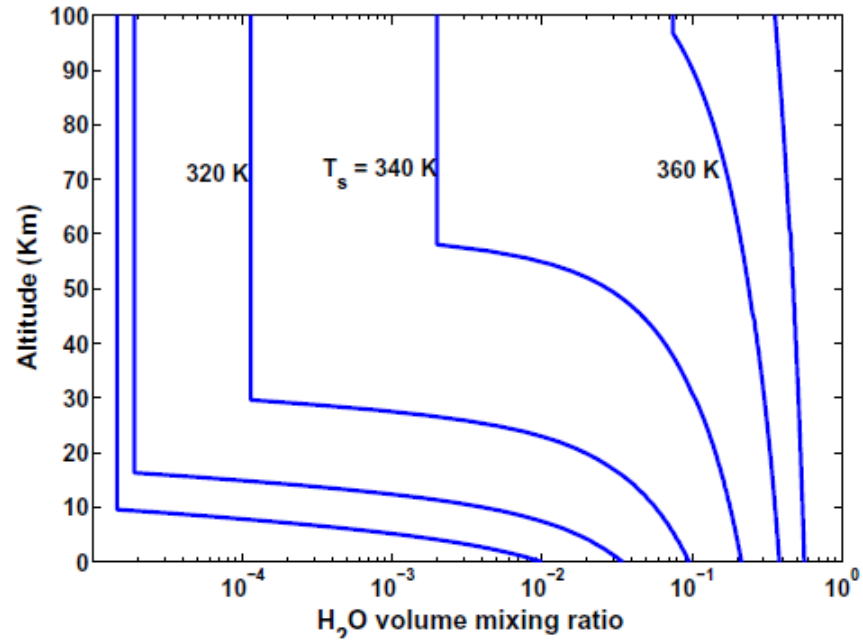




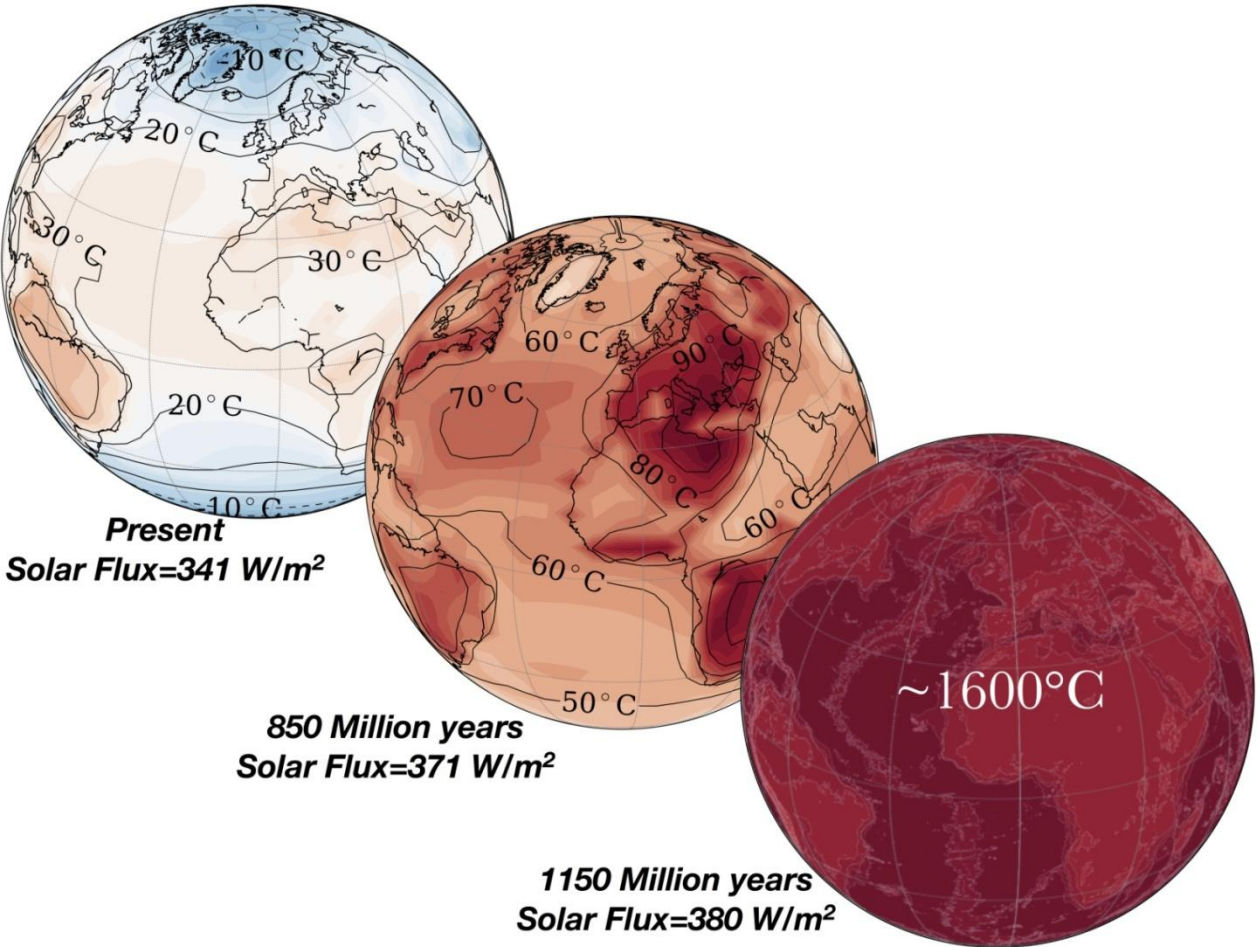
« Water loss limit » in 1D models

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





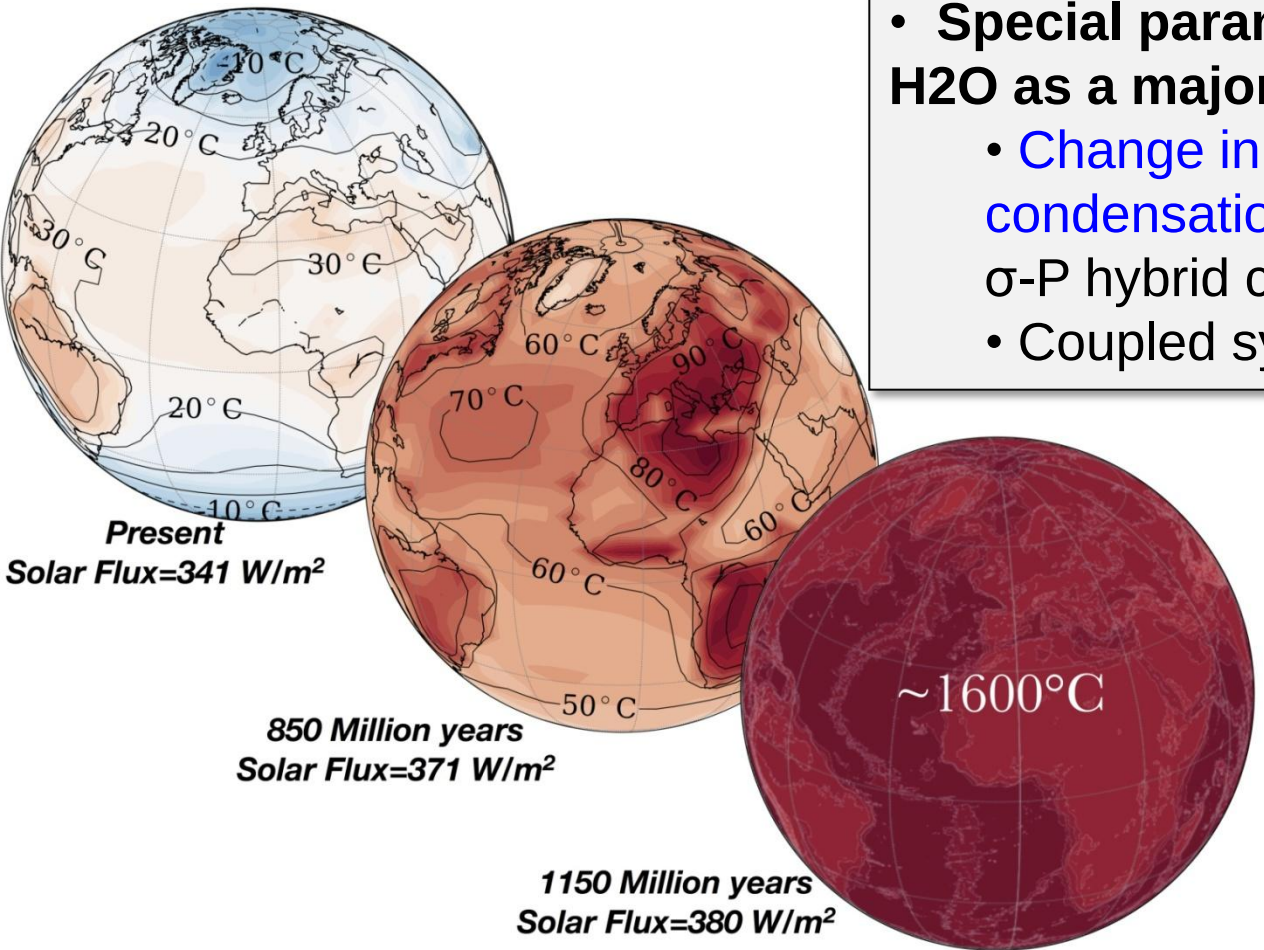
Runaway Greenhouse effect in a complete 3D Global Climate model



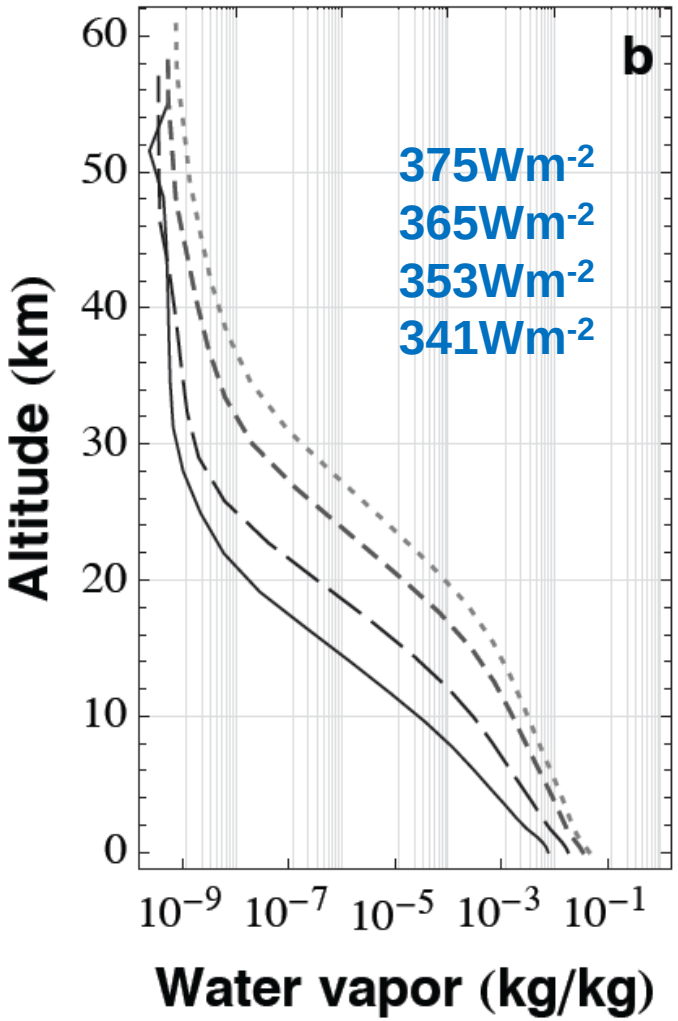
Leconte et al. « *3D Increased insolation threshold for runaway greenhouse processes on Earth like planets*". Nature, 2013

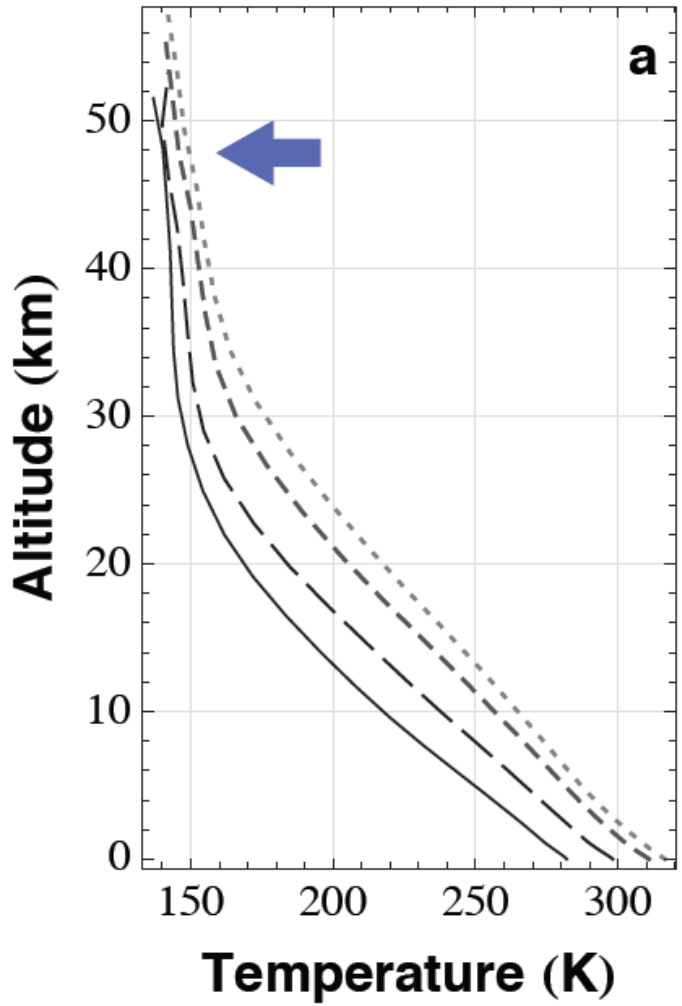
LMD 3D Generic Climate Model

- 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



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

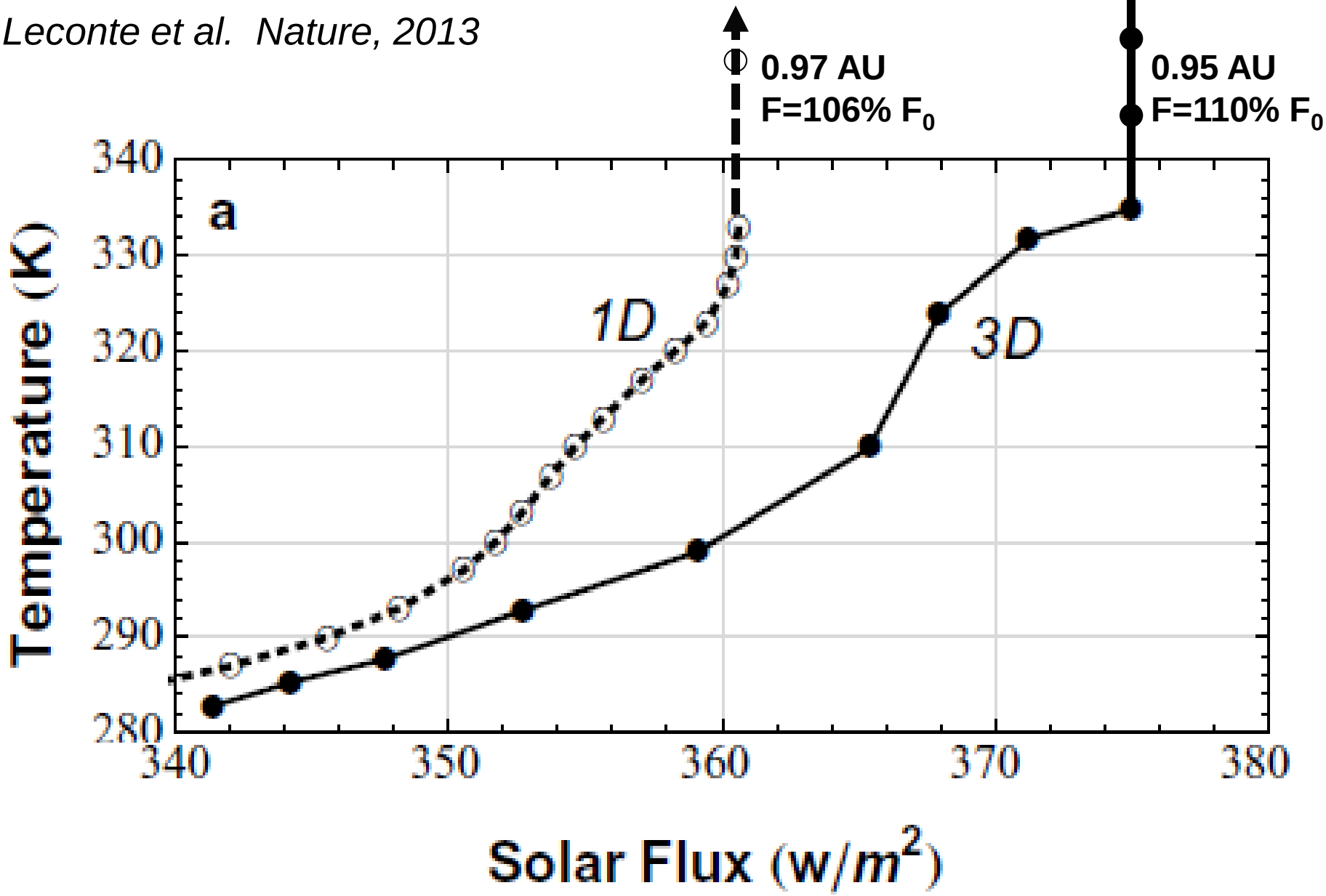




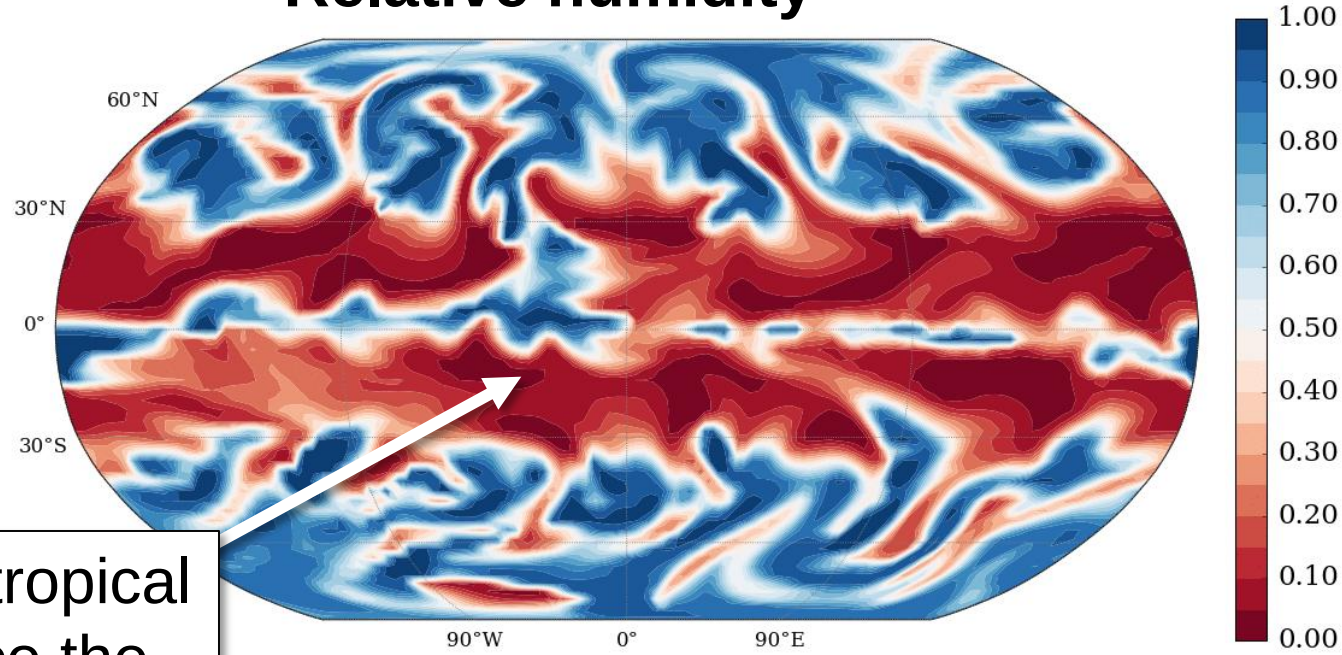
Leconte et al. (Nature; 2013)

LMD Model : Earth like planet around a sun-like star

Leconte et al. Nature, 2013



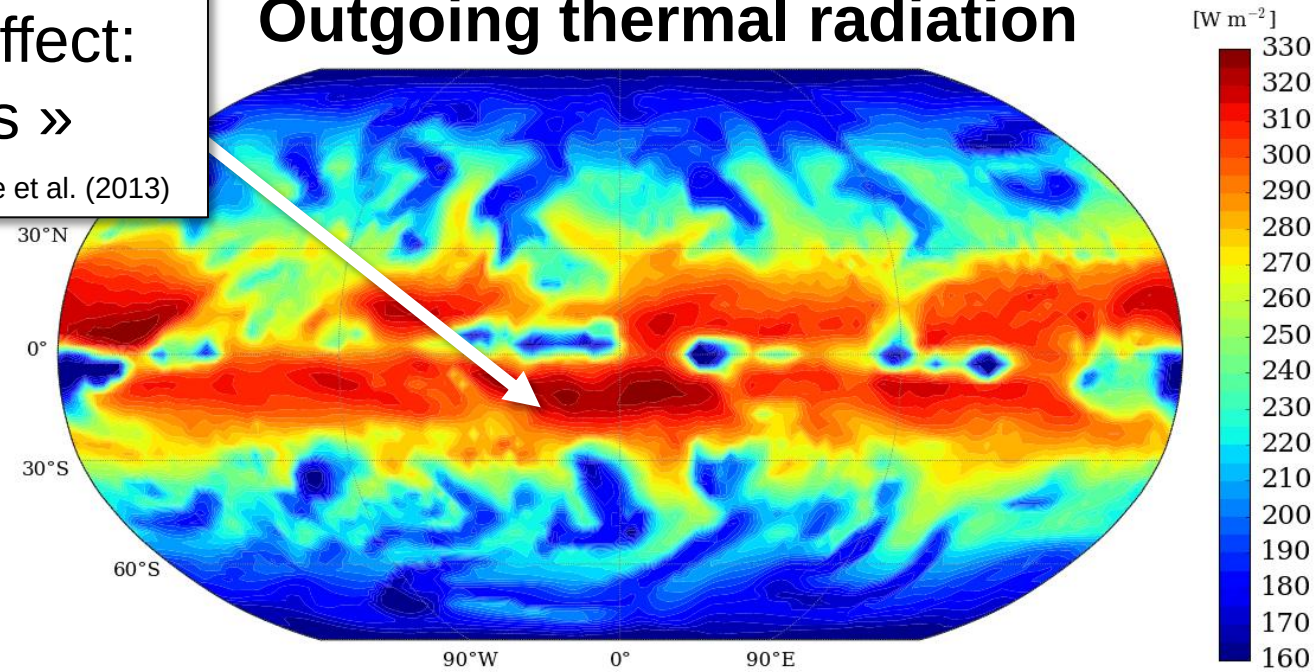
Relative humidity



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

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

Outgoing thermal radiation



Runaway greenhouse effect around K and M dwarf star

Redder stellar spectrum

- Weak atmospheric Rayleigh Scaterring

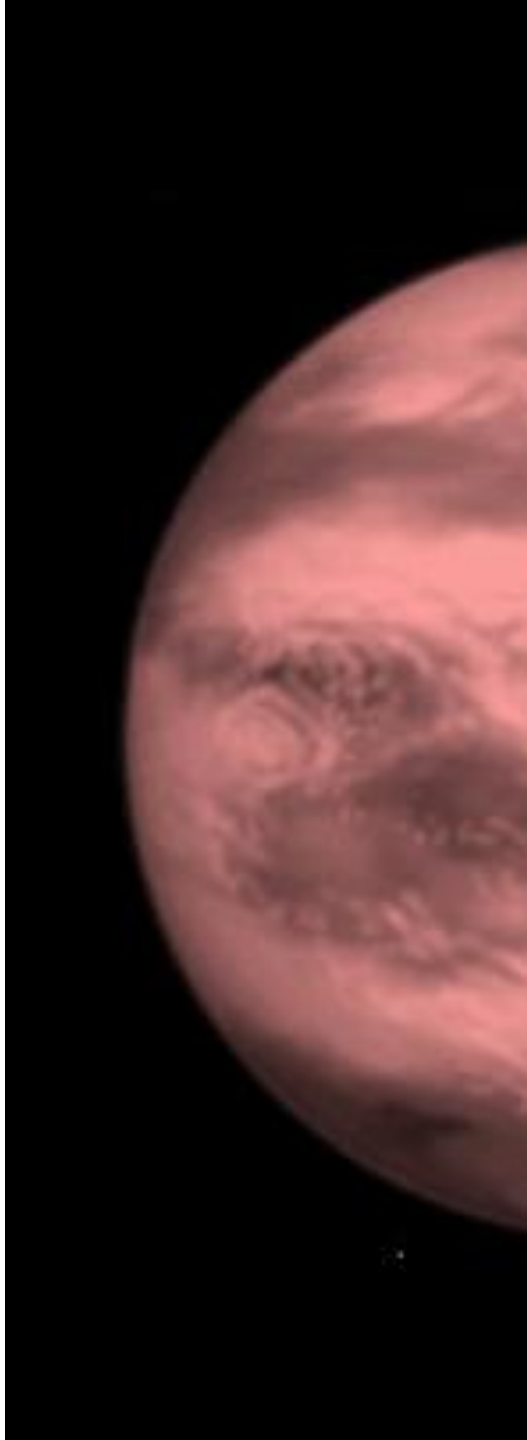
  ⇨ lower planetary albedo

Effect of tides:

- Resonnant rotation with zero obliquity

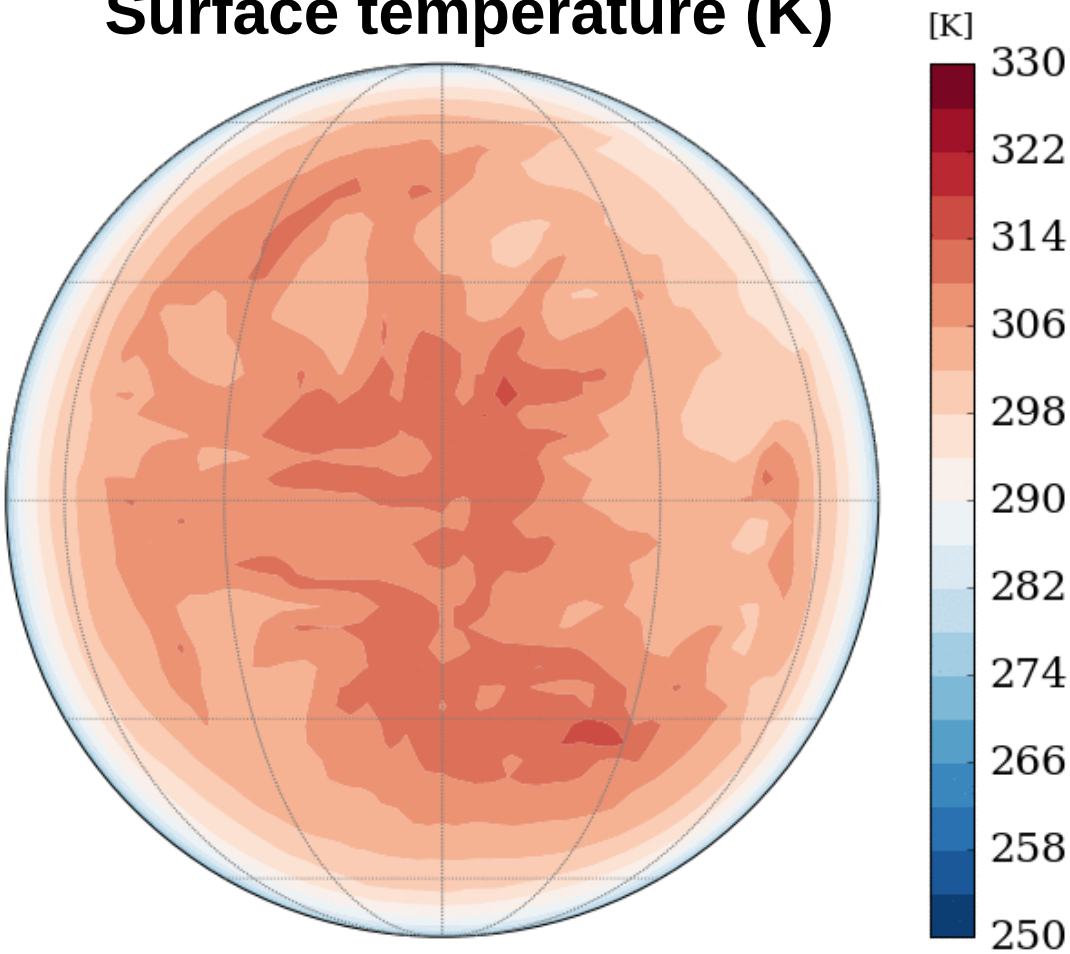
  ⇨ Possible Locking with permanent night side

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

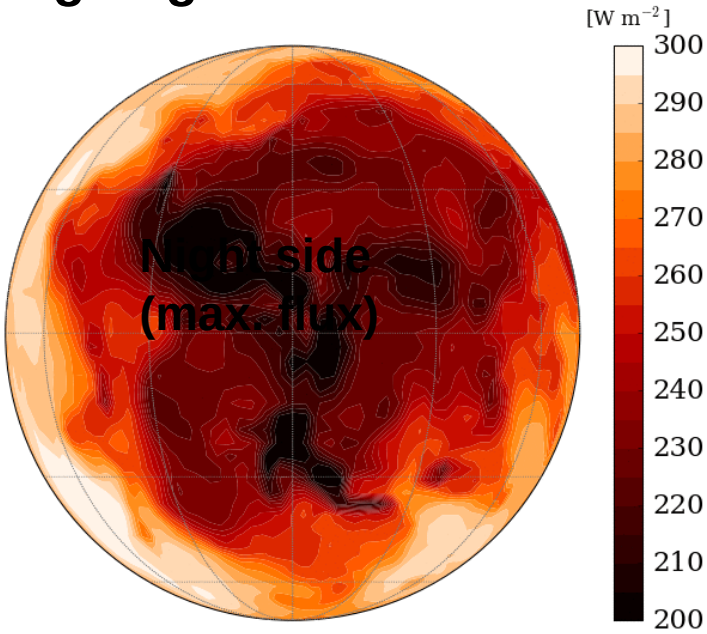


Simulation of aTidal-locked planet with surface liquid water around an Mdwarf
(Jeremy Leconte, LMD climate model)

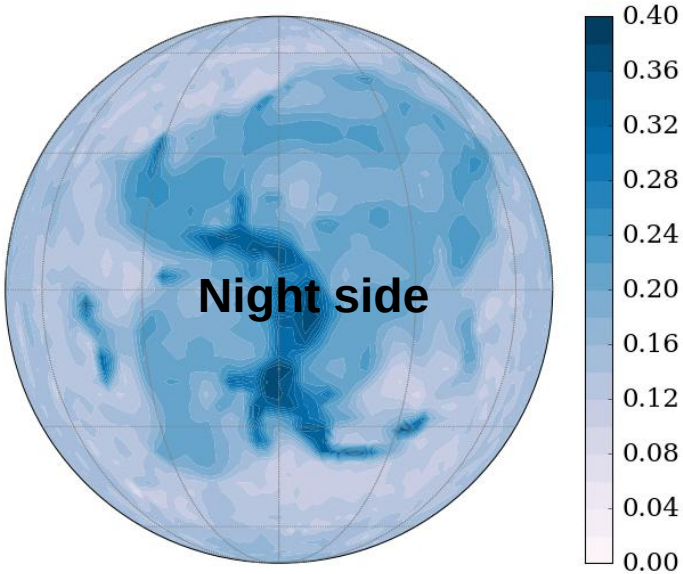
Surface temperature (K)



Outgoing Thermal radiation

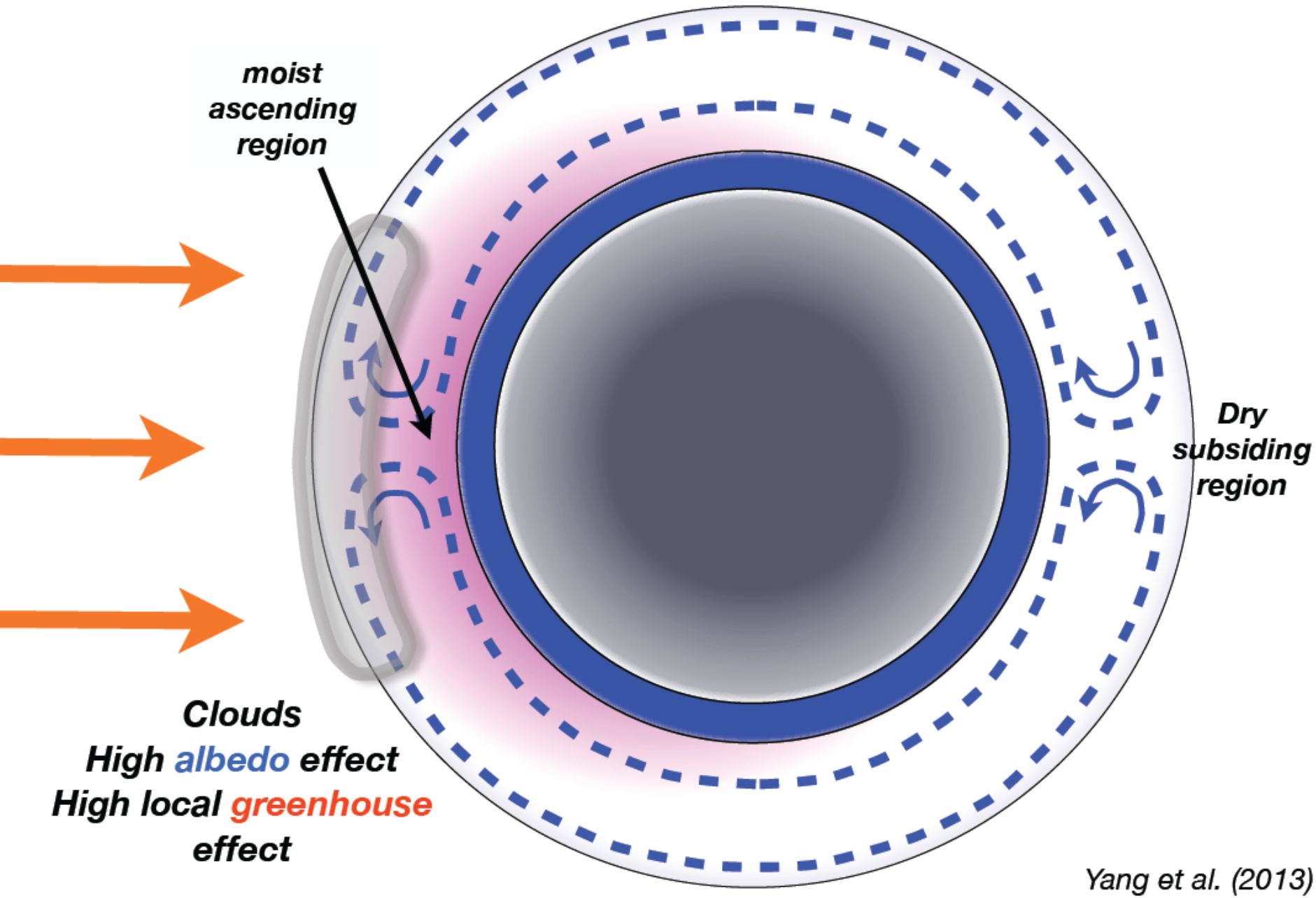


Planetary Albedo



View from a distant point throughout the orbit

Large scale cloud pattern on tidally locked planets



Yang et al. (2013)

The Astrophysical Journal Letters, Volume 771, Issue 2, article id. L45, 6 pp. (2013).

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

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ABSTRACT

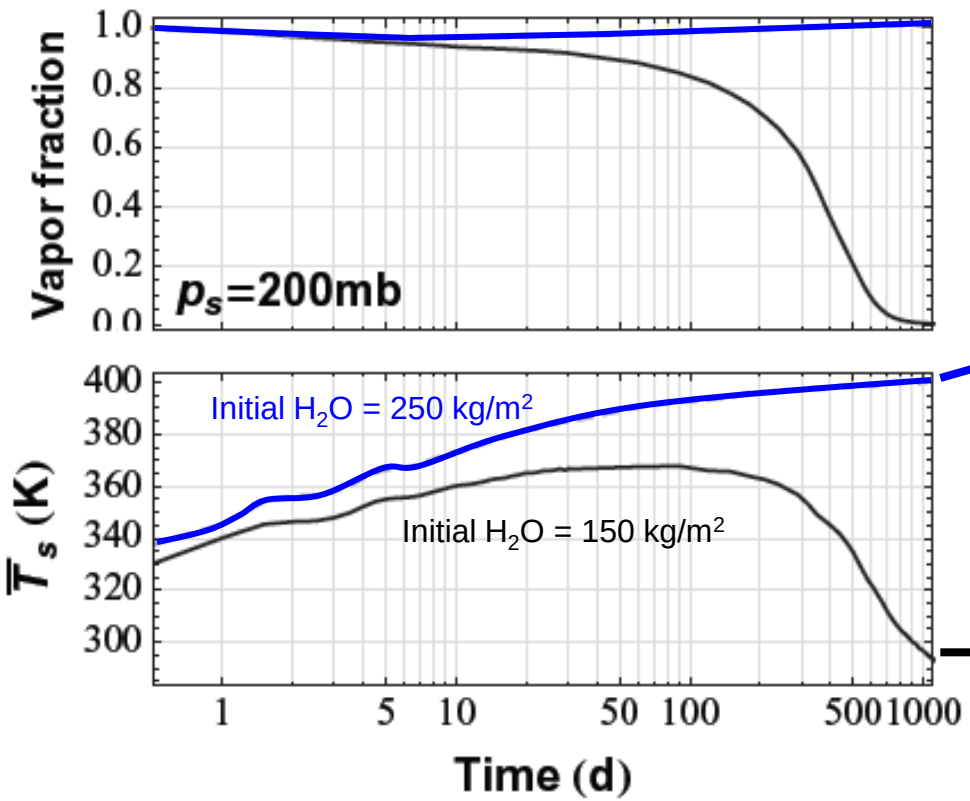
The Habitable Zone (HZ) is the circumstellar region where a planet can sustain surface liquid water. Searching for terrestrial planets in the HZ of nearby stars is the stated goal of ongoing and planned extrasolar planet surveys. Previous estimates of the inner edge of the HZ were based on one dimensional 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.

Tidally locked hot planets

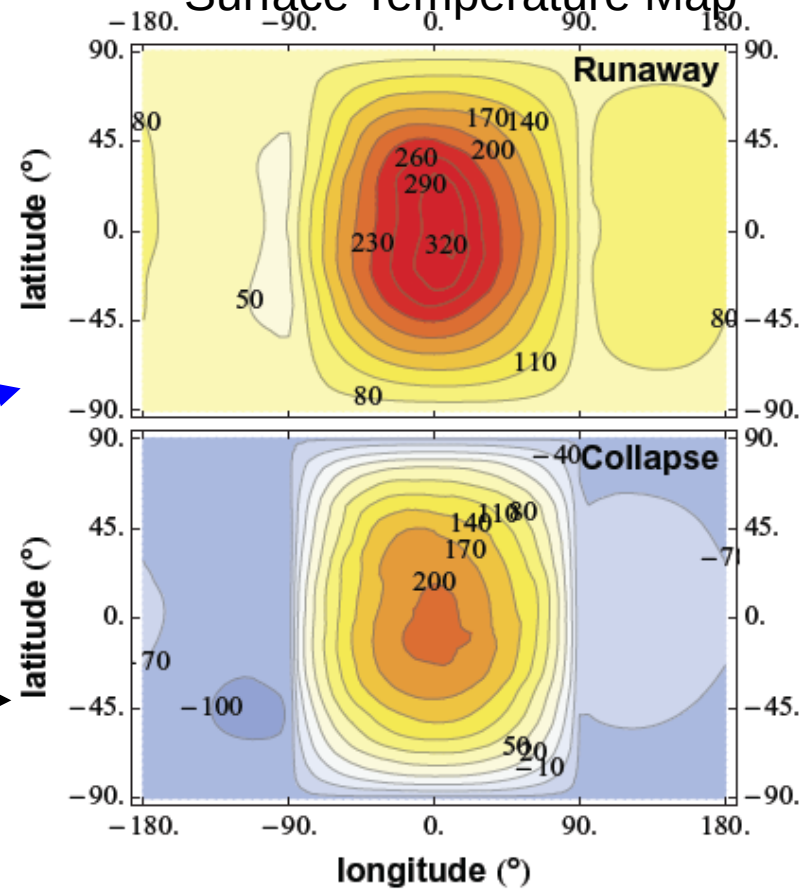
Tidally locked hot planet: Modeling of Gliese 581c and HD85512b

S/4=860 W/m^2 (**250% Earth flux!**) (*Leconte et al. A&A 2013)*

- **A bistable climate**
  - Planet in "runaway greenhouse state" : with all water vapor in the atmosphere : super-hot climate
  - Water collapsed (frozen) on the night side.



Surface Temperature Map



Tidally locked hot planet: the case of Gliese 581c

(Leconte et al. A&A 2013, revised; see also Abe et al. 2011)

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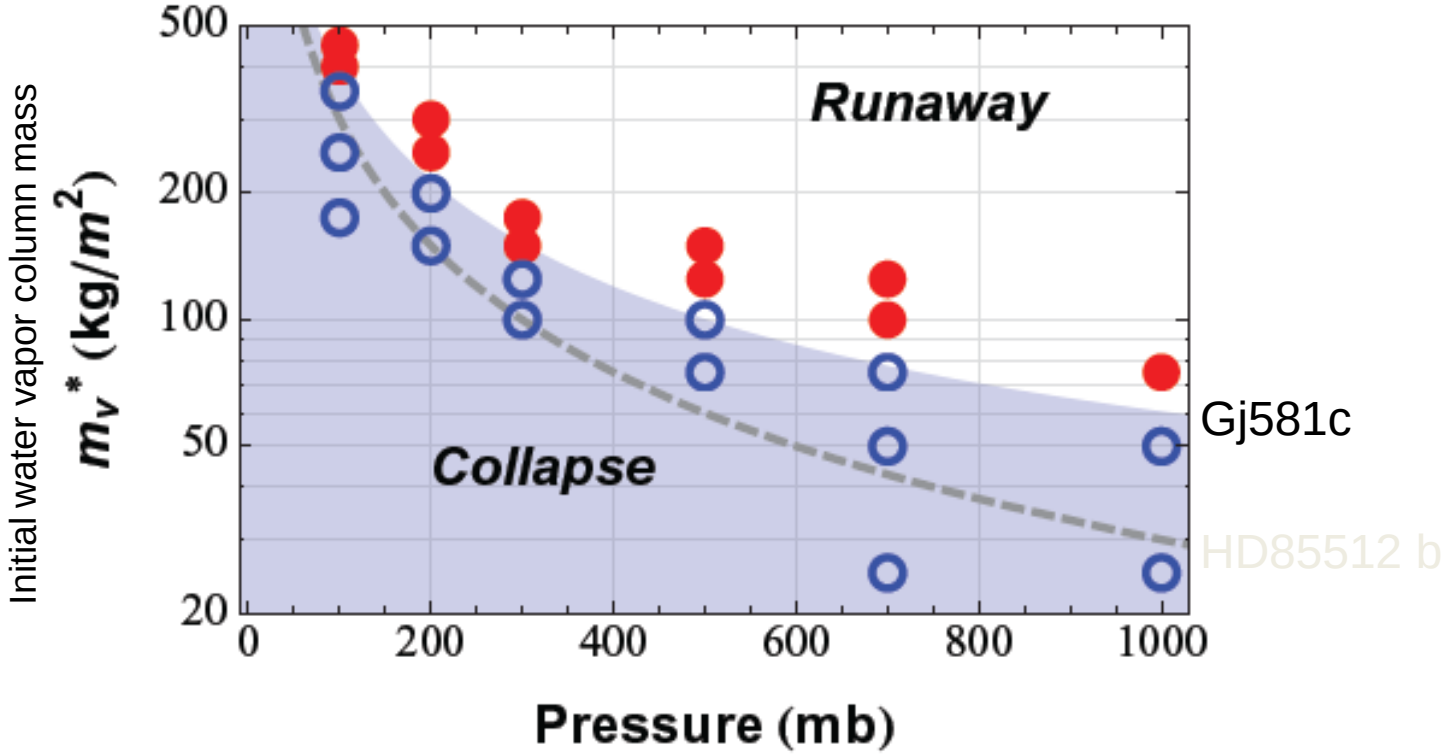
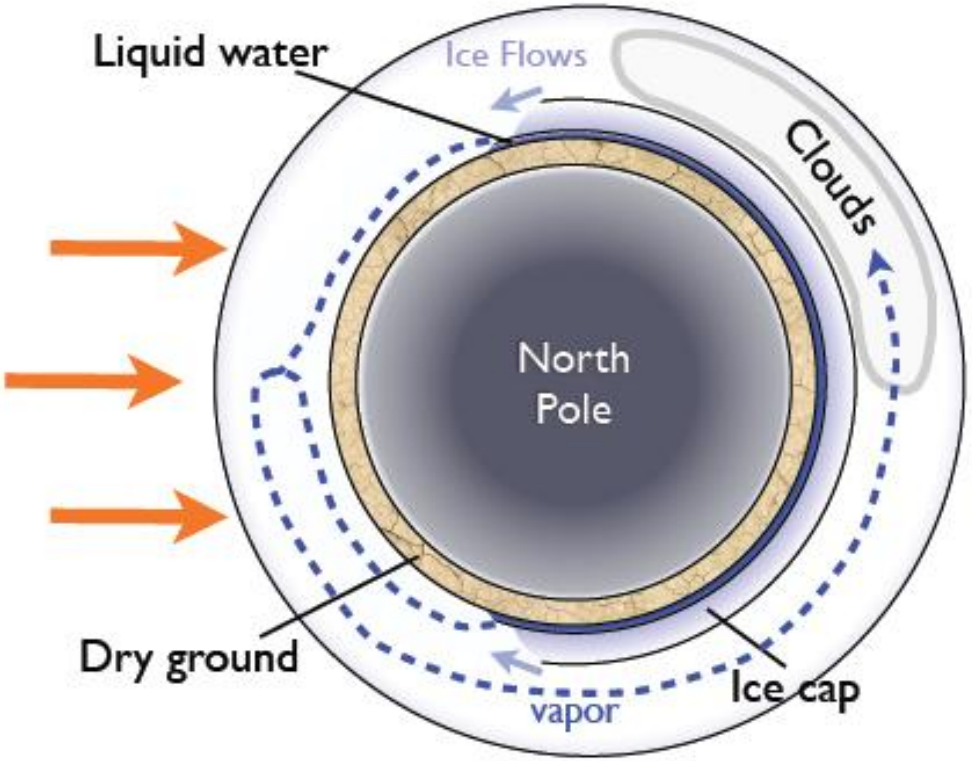
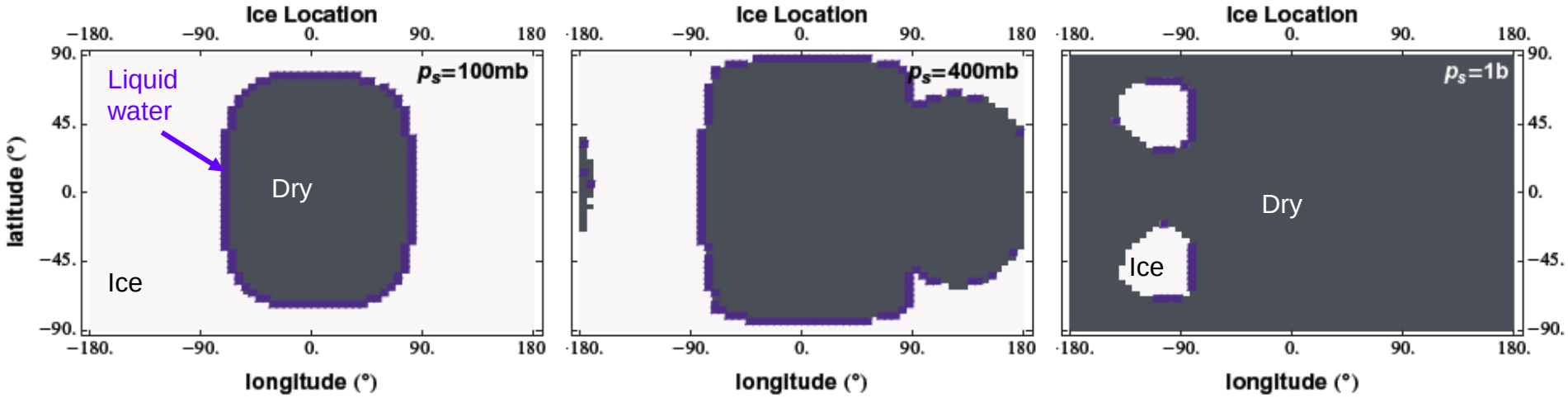
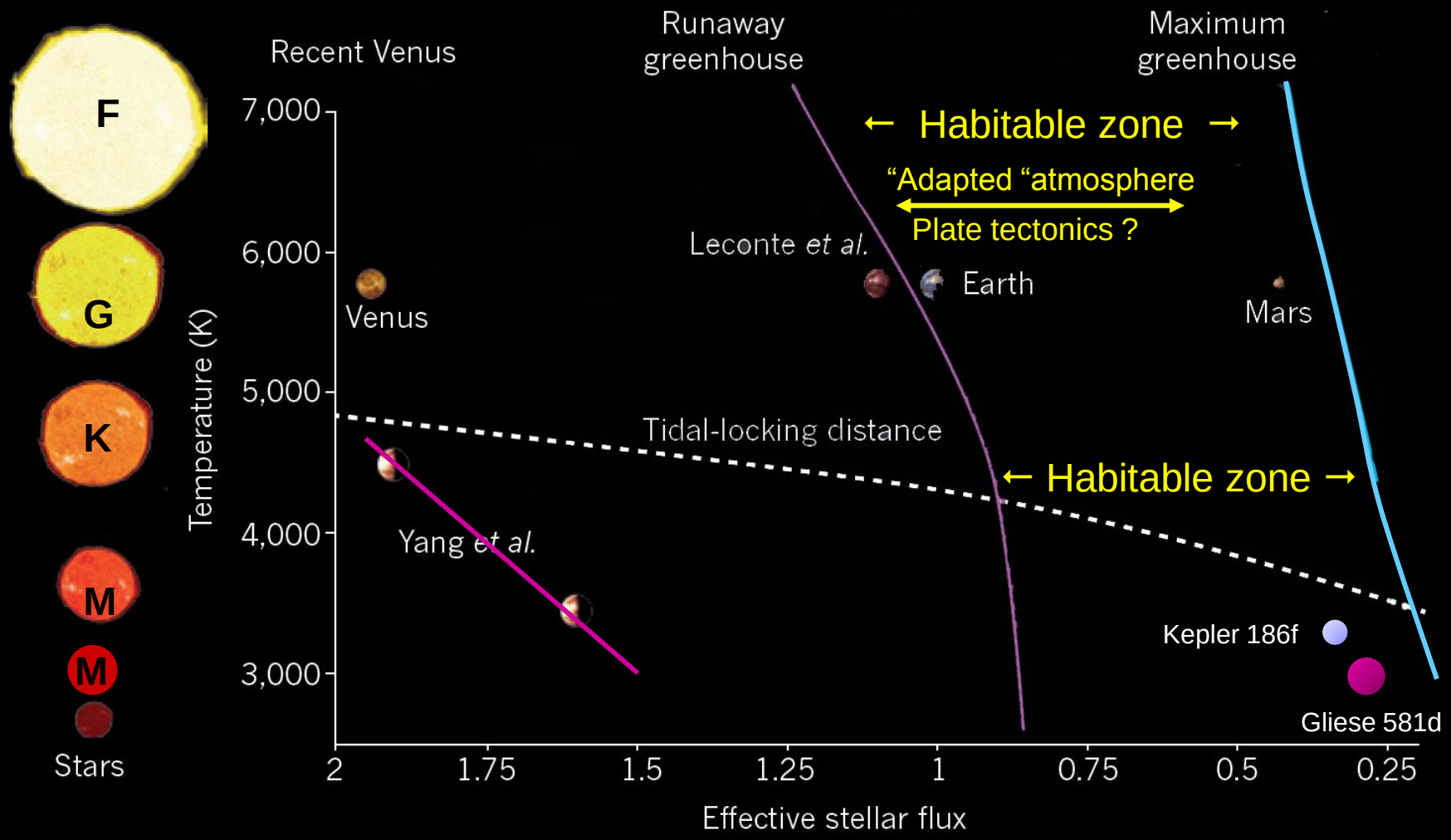


Possibility of liquid water on tidally locked hot planet *(Leconte et al. A&A 2013)*





Toward a better understanding of the habitable zone with full climate models…



Adapted and modified from Kasting and Harman (2013)

Conclusions: 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

⇨ **We need observations !**

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

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)