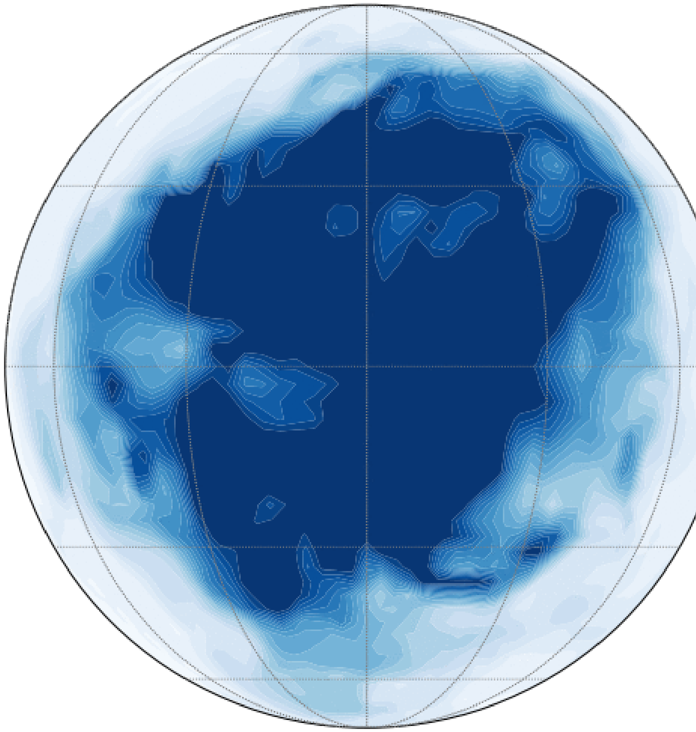
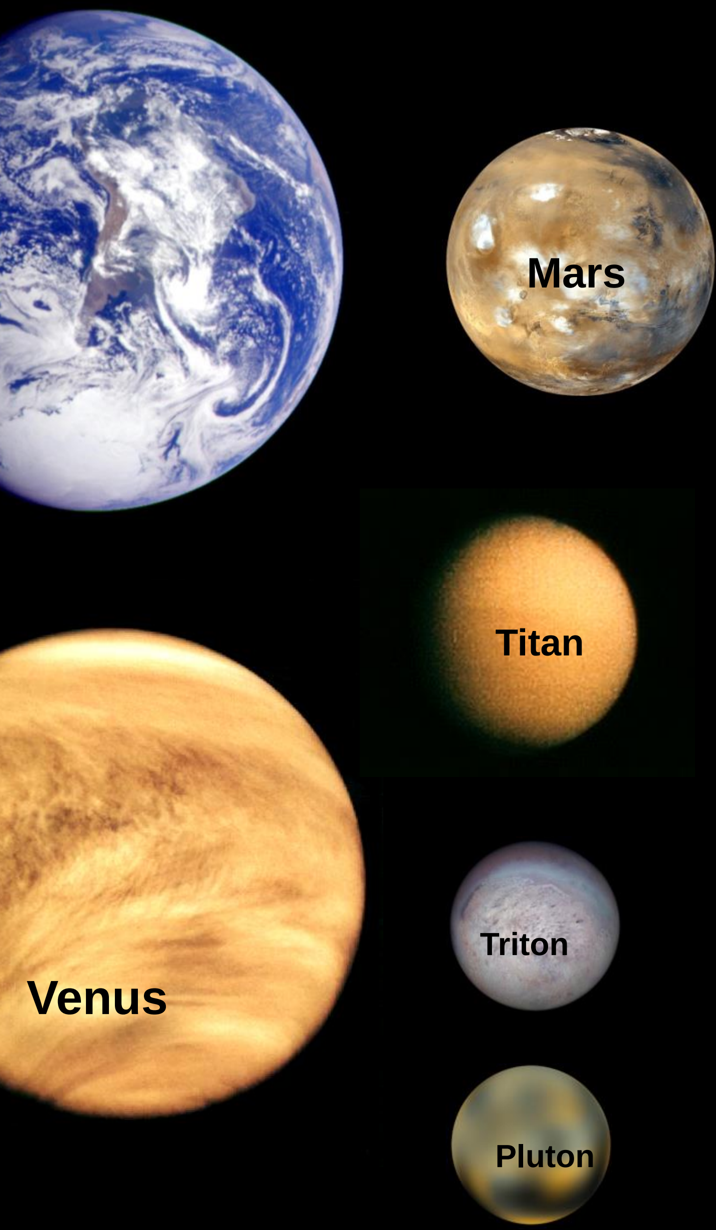
The LMD "Generic" Global Climate Model: Application to exoplanets

François Forget, Jeremy Leconte, Benjamin Charnay, Robin Wordsworth, Ehouarn Millour, Aymeric Spiga Franck Selsis et al. …

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



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



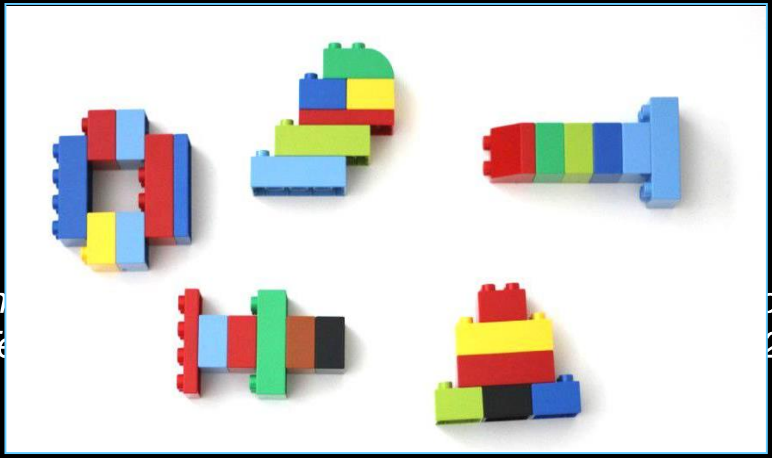
Climate Models in the solar system
What have we learned?

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 an … ogy of
Te … 2013.

A 3D "generic" Global climate model designed to simulate any atmosphere on any terrestrial planet around any star.

1) Dynamical Core : ~universal

2) Radiative transfer through gas and aerosols
⇨ New versatile Correlated-k radiative transfer code.

5) Volatile condensation on the surface and in the atmosphere :

- Robust microphysics: Fixing mixing ratio of condensation nuclei
- Modified thermodynamics to handle condensation of major constituants (H_2O, CO_2, N_2)

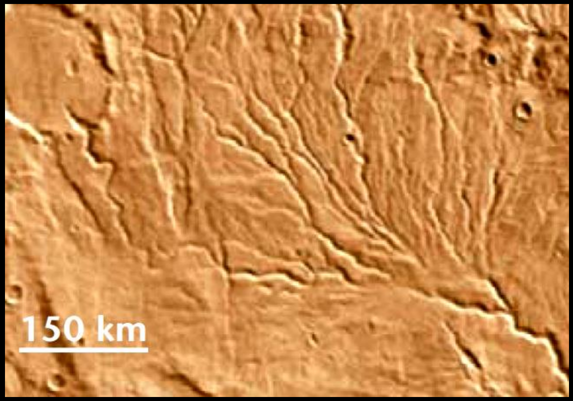
3) Turbulence and convection in the boundary layer
⇨ Universal turbulent sheme
⇨ Robust convection scheme

•2-layer dynamical ocean (*Codron 2011*):
- Ekman transport
- Dynamic Sea ice

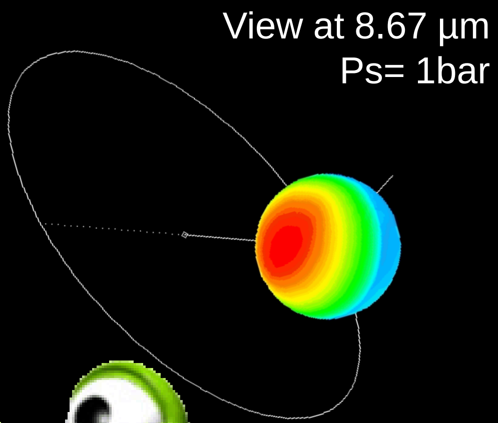
4) Surface and susurface thermal balance ~universal

A "Generic" LMD GCM for all terrestrial atmospheres:
Why simulate planets where no observations are available ?

- **To Model ancient climates to understand geological records**
  - The faint young sun paradox on early Earth *(Charnay et al. 2013)*
  - Early Mars *(Forget et al. 2013, Wordsworth et al. 2013, Kerber et al 2014,*
  - Ancient Titan *(Charnay et al. 2014)*



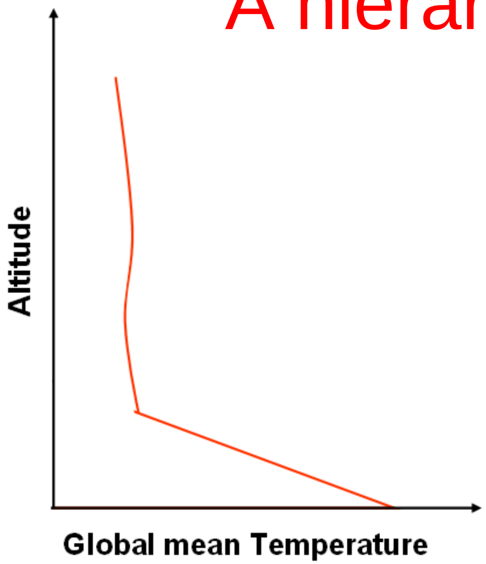
- **To simulate planets around other star to design future telescopic measurements**
  - Exoplanet Thermal phase curves (*Selsis et al. 2011)*
  - Constraining hot superEarth with JWST (*Samuel et al., 2014)*

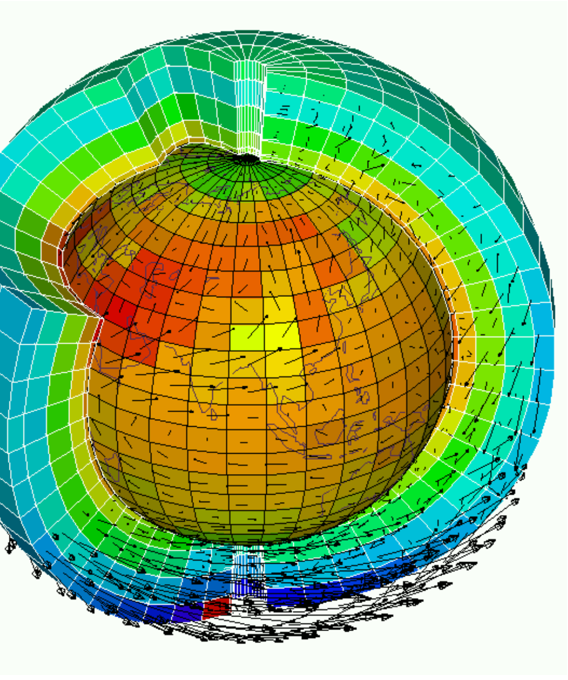


- **To adress key scientific questions regarding habitability:**
  - Define the habitable zone
  - What is the probability of habitable planet in the galaxy ?

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 and energy transport *(previous Talk by Y-Y Hayashi, see Read 2011, Showman et al. 2013, etc)*

4. Full Global Climate Models aiming at building “virtual” planets.

Climate, Surface liquid water and life

100% vapour ***Liquid water*** ***100% ice***

Climate instability : Runaway glaciation

Solar flux ↓ → **Temperature** ↓

Temperature ↓ → **Ice and snow** ↑

Ice and snow ↑ → **Albedo** ↑

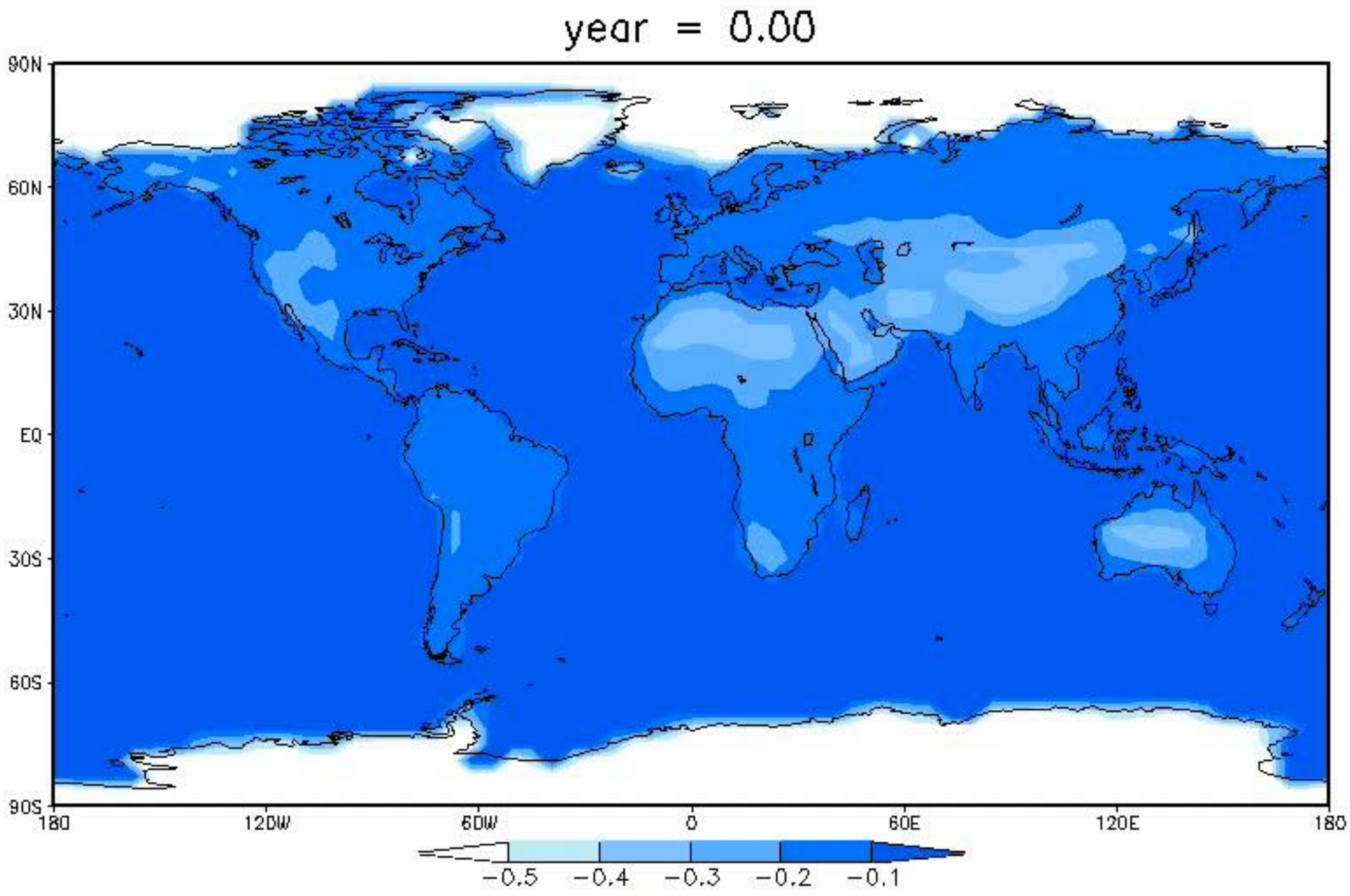
Albedo ↑ → **Temperature** ↓

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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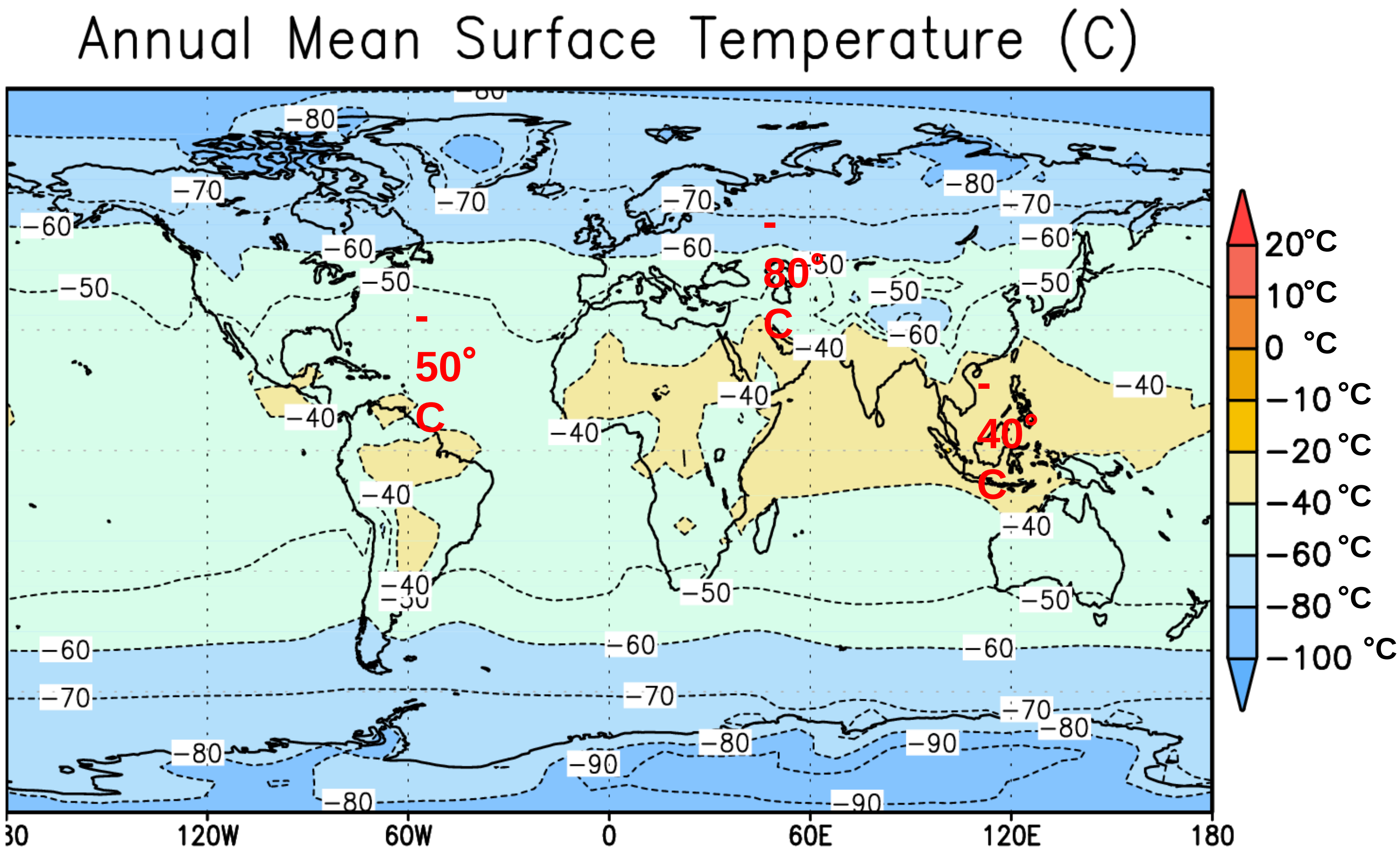
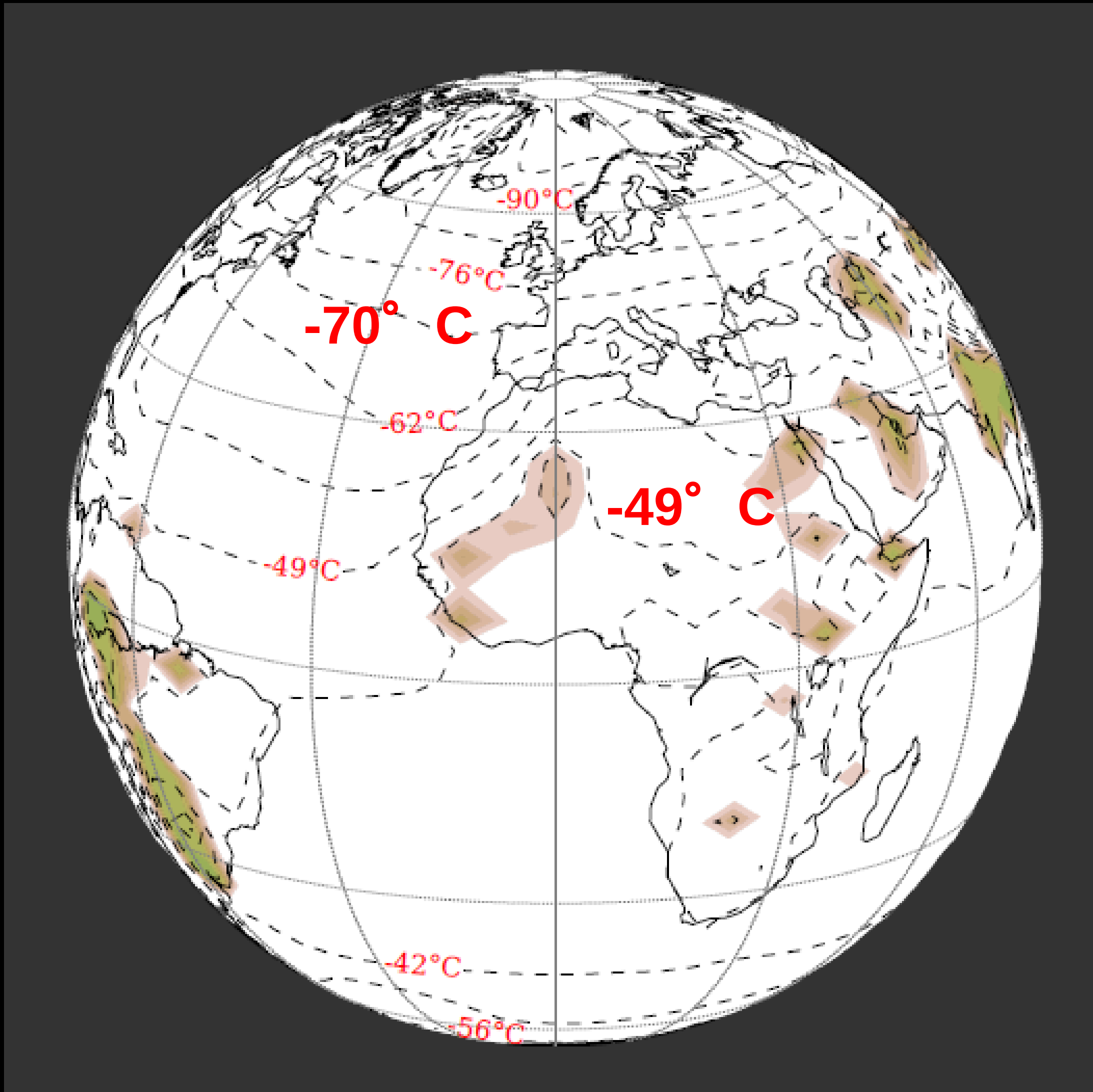


Out of glaciation: greenhouse effect

Flux = 80% present
(~1.12 AU)

Present
Earth atmosphere

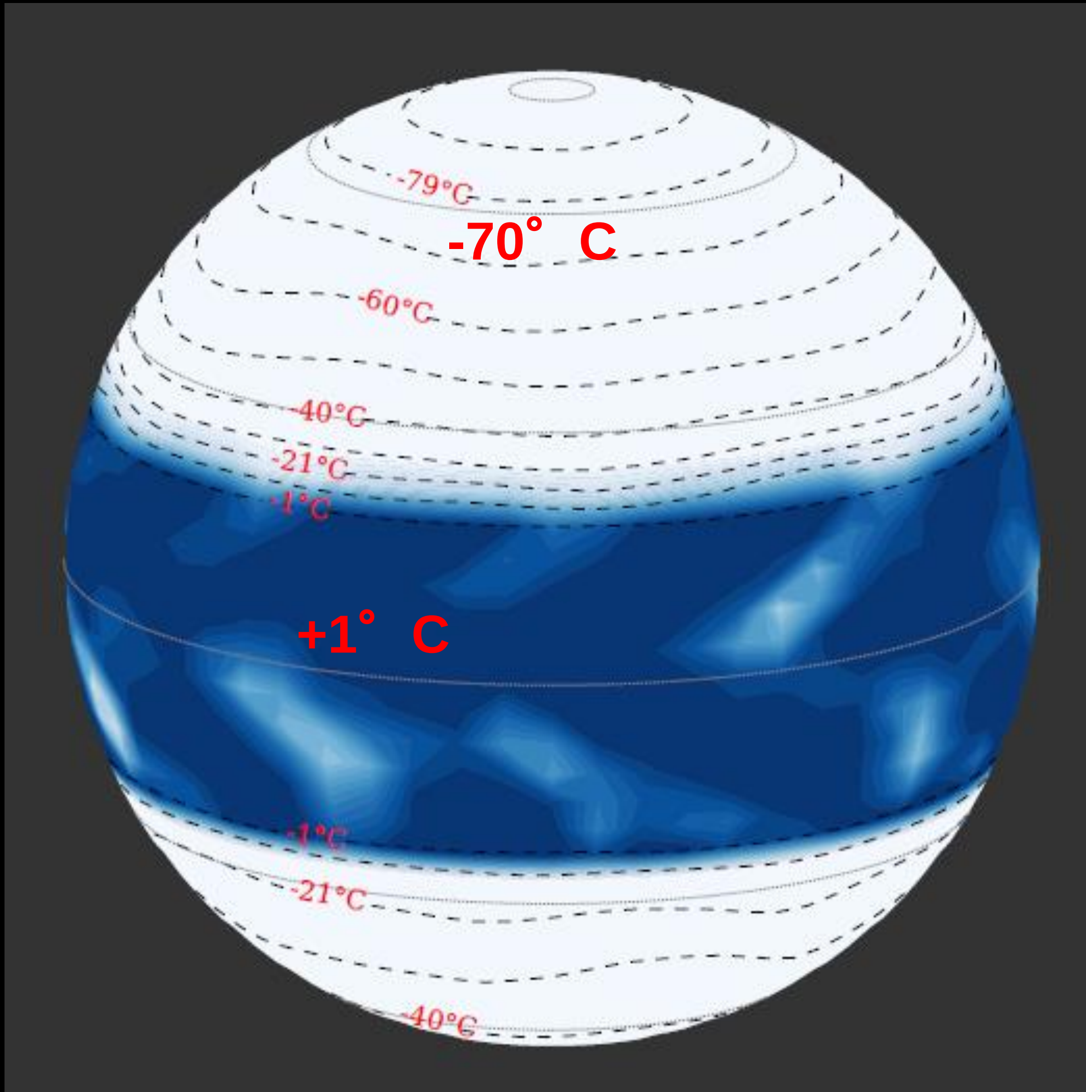


Charnay et al., JGR 2013

Out of glaciation: greenhouse effect

Flux = 80% present
(~1.12 AU)

$[CO_2] \times 2.5$

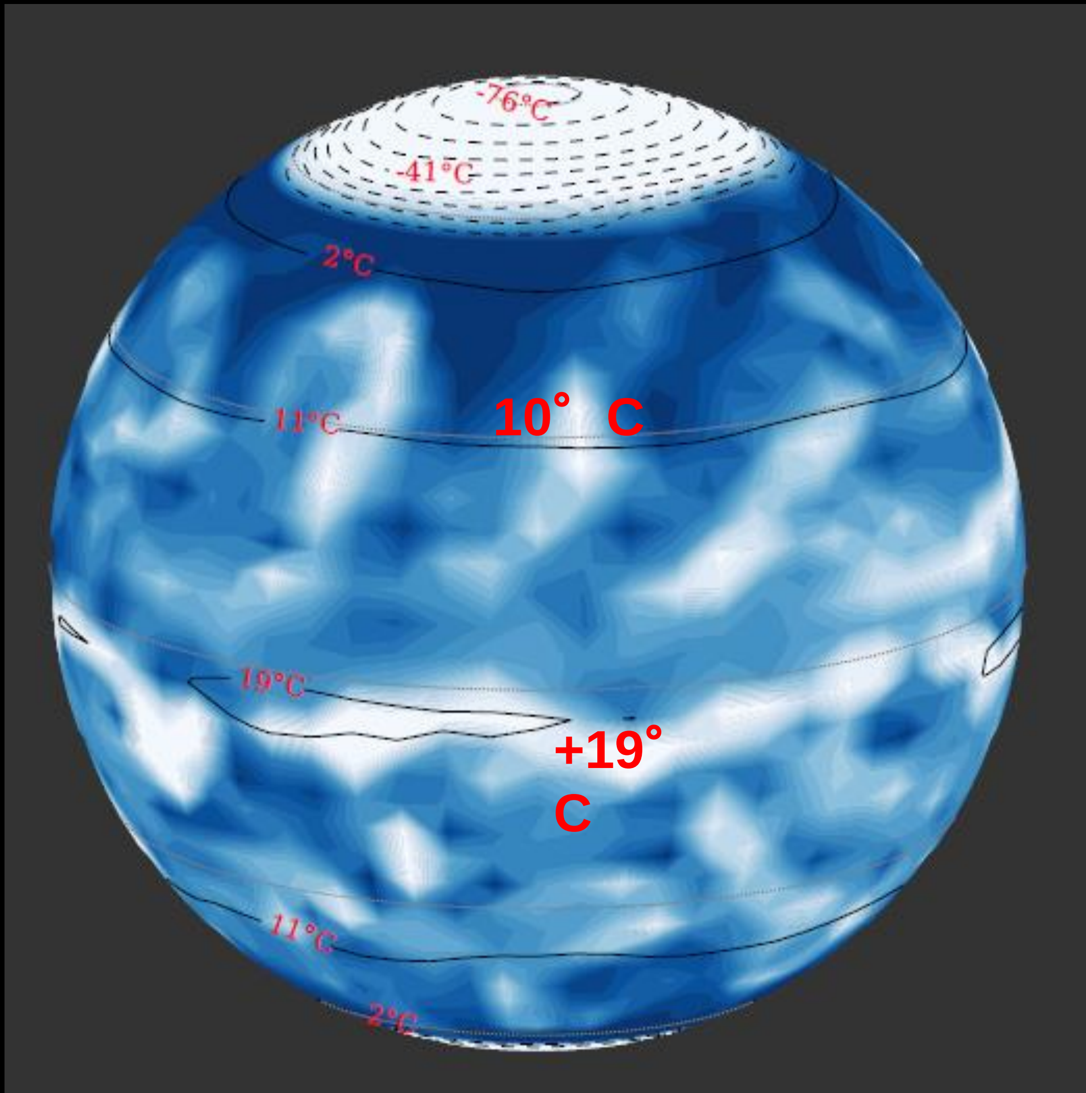


Charnay et al., JGR 2013

Out of glaciation: greenhouse effect

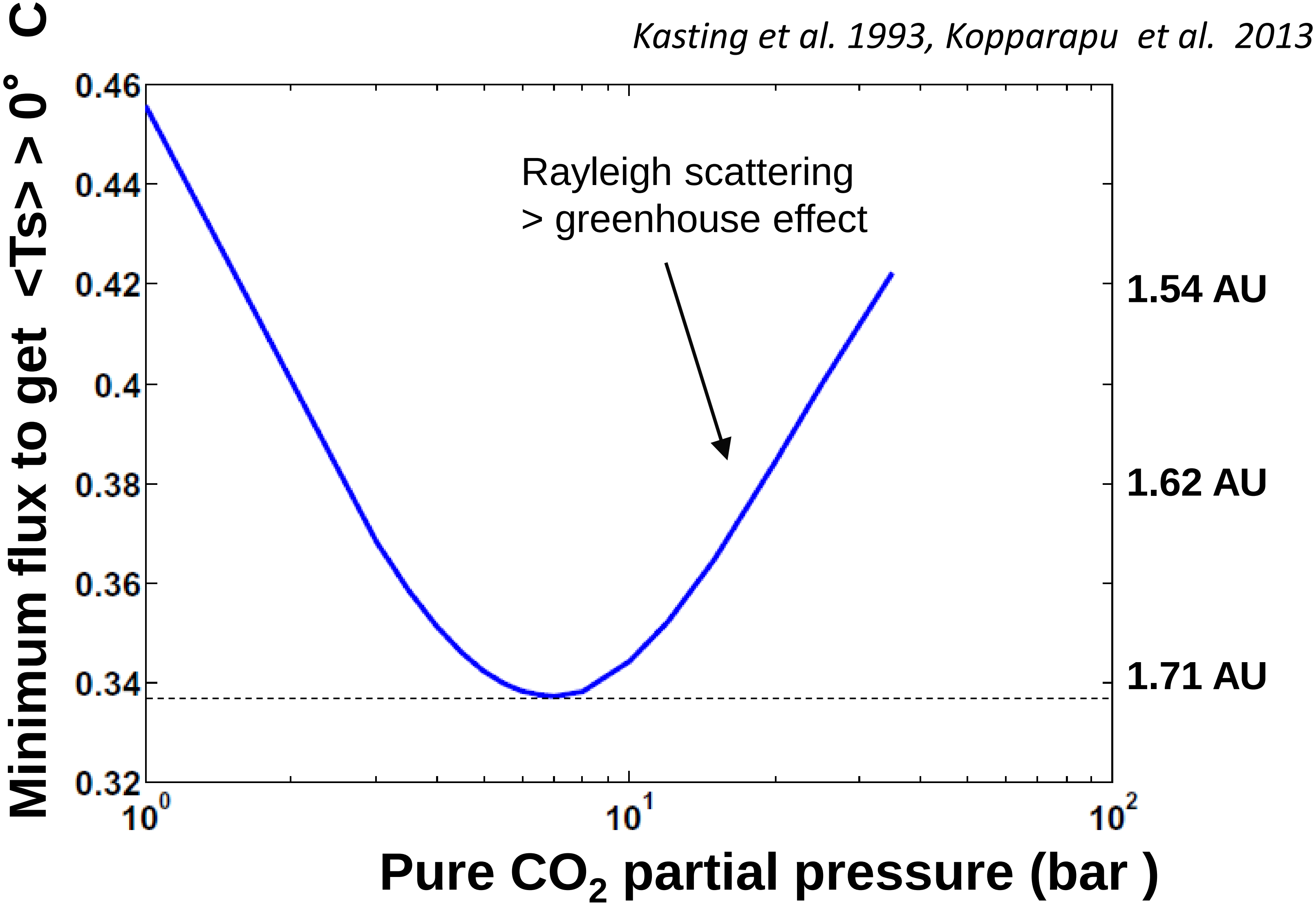
Flux = 80% present
(~1.12 AU)

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



Charnay et al., JGR 2013

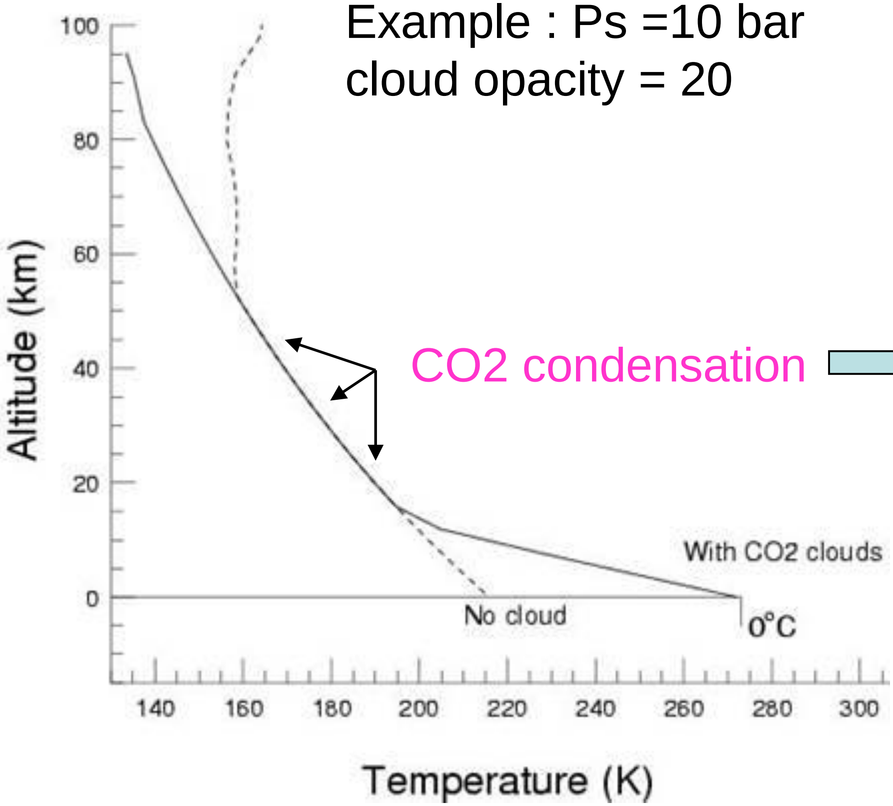
How far can greenhouse effect can keep a planet warm?



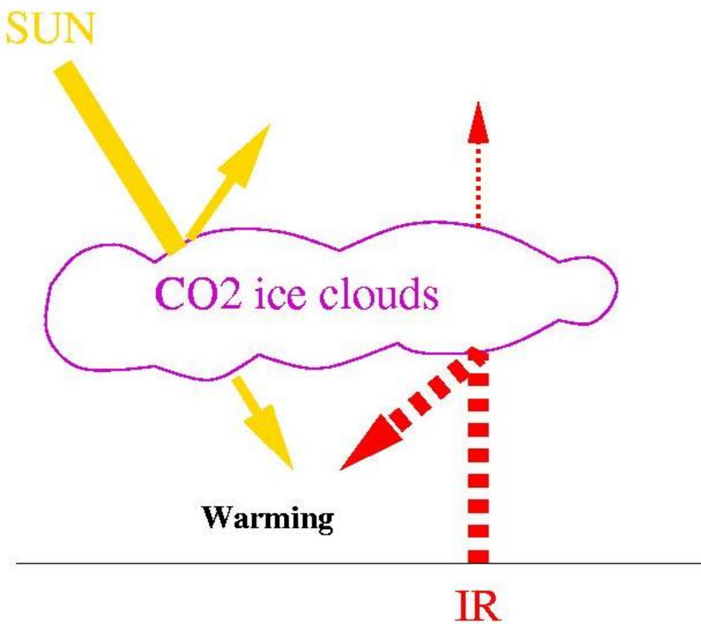
Scattering Greenhouse effect of CO_2 ice clouds
⇨ 0°C as far as 2.5 AU from the Sun ?

Forget and Pierrehumbert (1997)

Example : Ps =10 bar
cloud opacity = 20

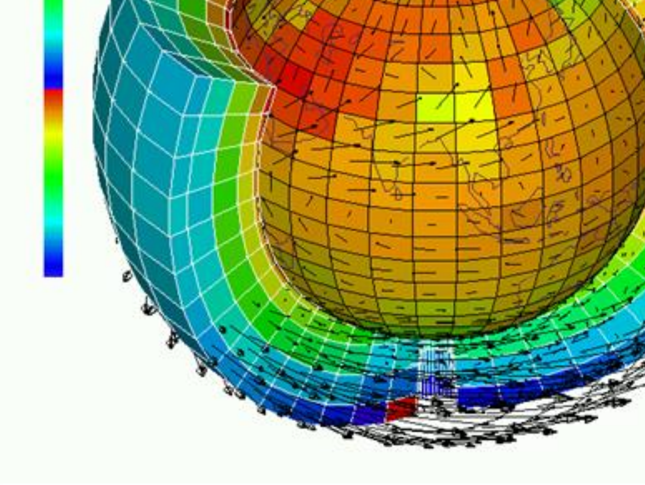


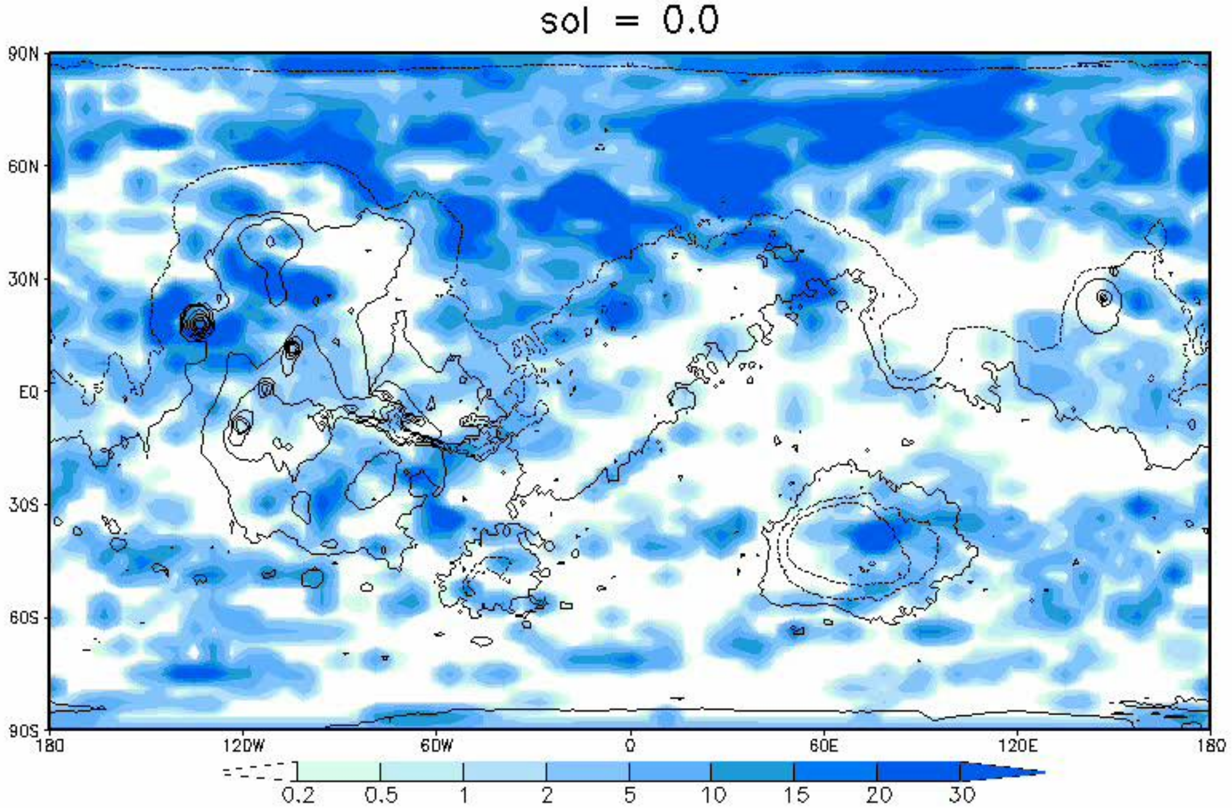
CO2 condensation



3D Global climate simulations of a cold CO2 atmosphere

("Early Mars Case" distance equivalent to 1.75





Max Warming = + 15 K

(uncomplete cloud coverage)

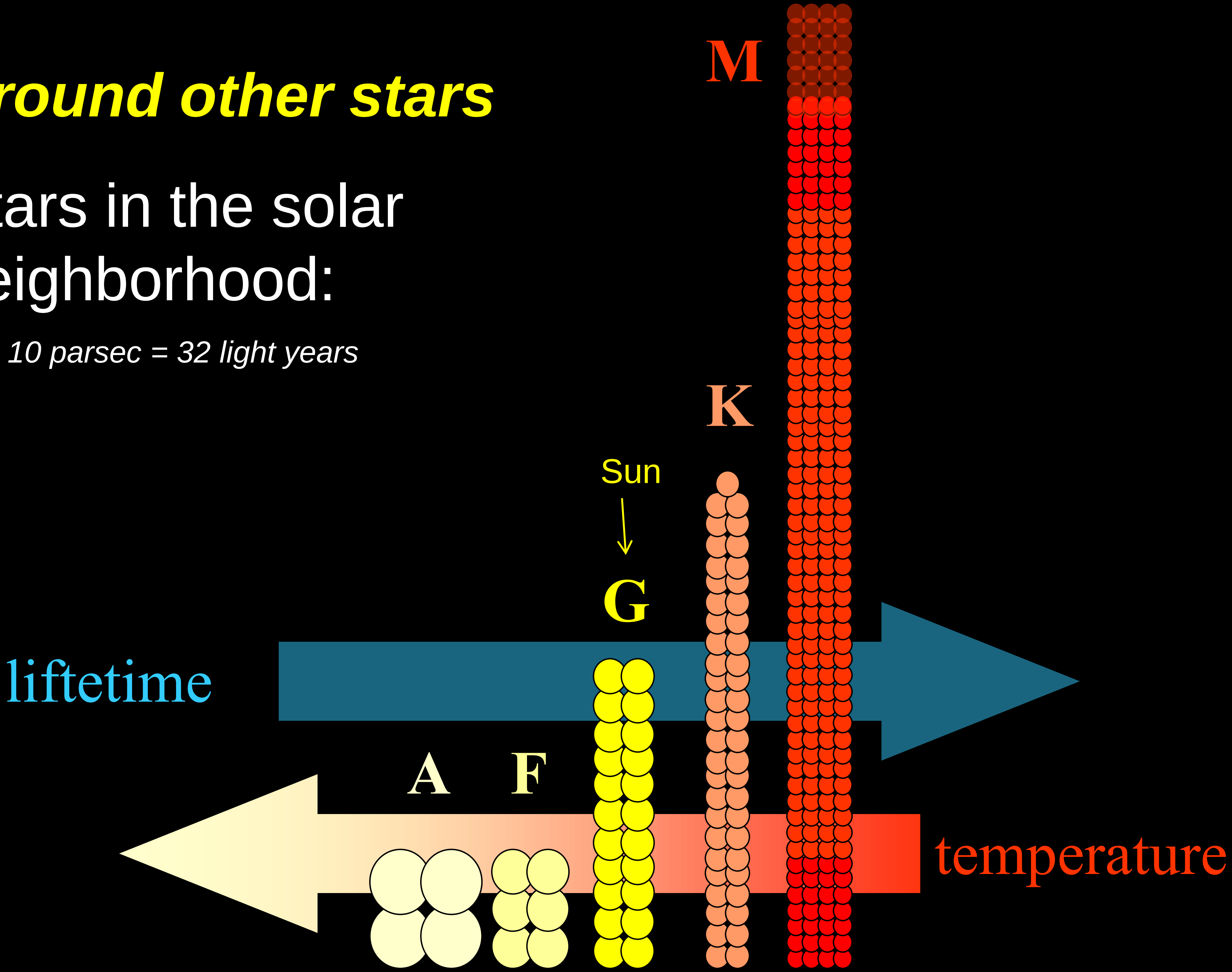
CO2 ice Cloud optical depth

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

Around other stars

Stars in the solar neighborhood:

(d < 10 parsec = 32 light years



Glaciation around K & M dwarf stars:

Redder stellar spectrum

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

    ⇨ higher albedo

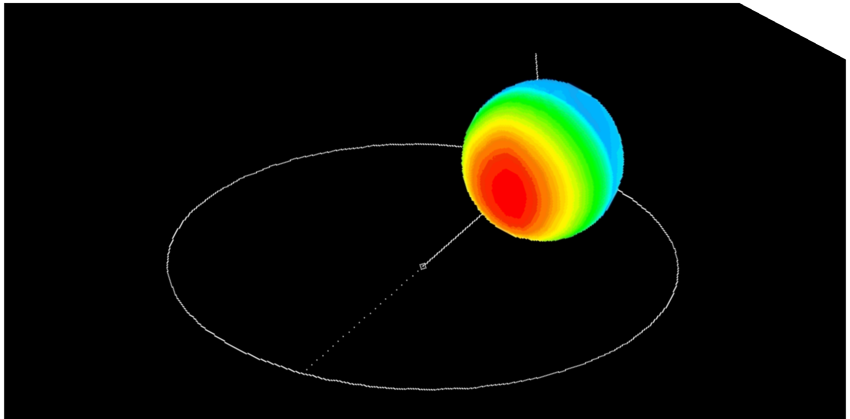
    ⇨ Enhanced high pressure CO2 greenhouse effect

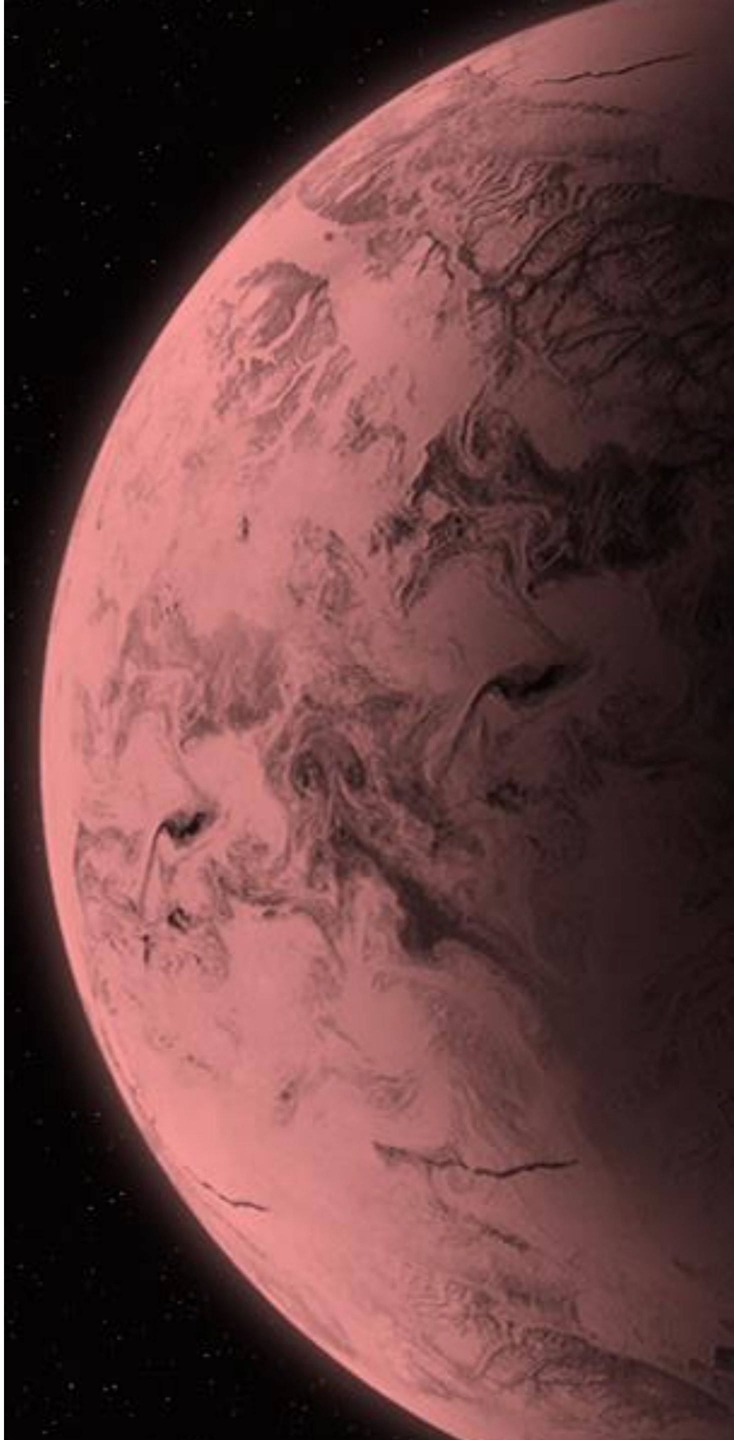
But : Effect of tides on rotation:

- Resonnant rotation with zero obliquity

⇨ No insolation at the pole

⇨ Possible Locking with permanent night side



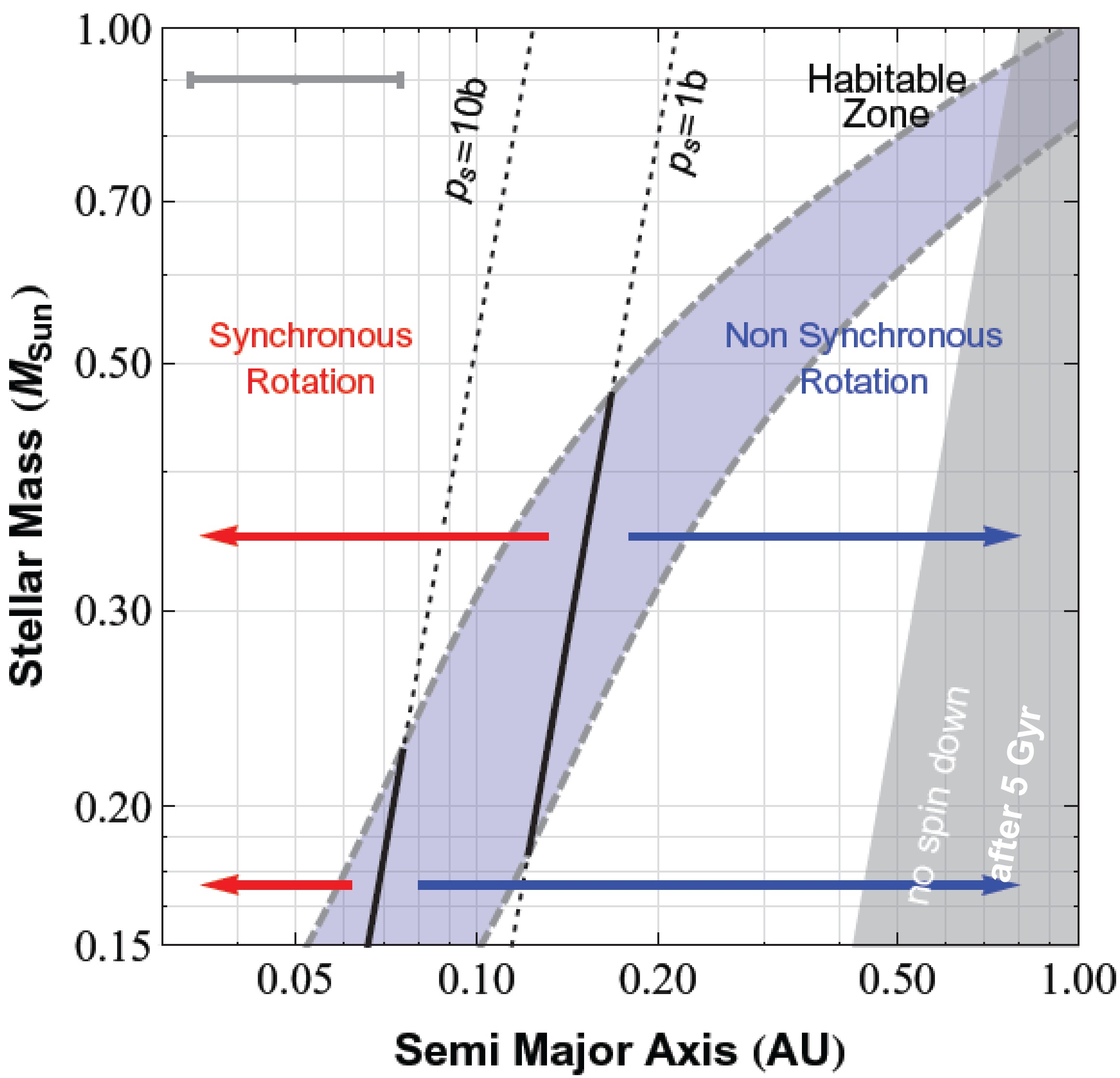


Side Question: Are terrestrial planets in M star habitable zone always tidally locked ?

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. Science 2014,

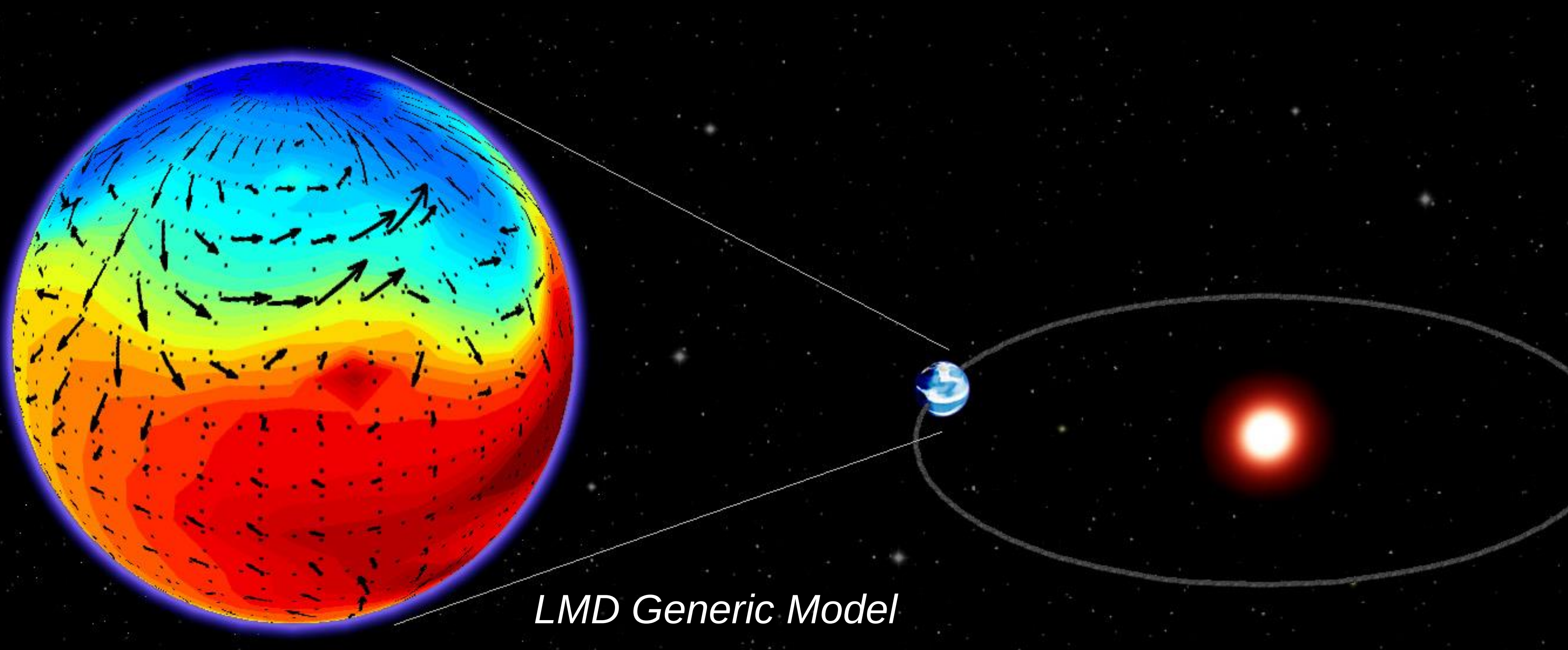


Example: simulating the climate on Exoplanet Gliese 581d

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

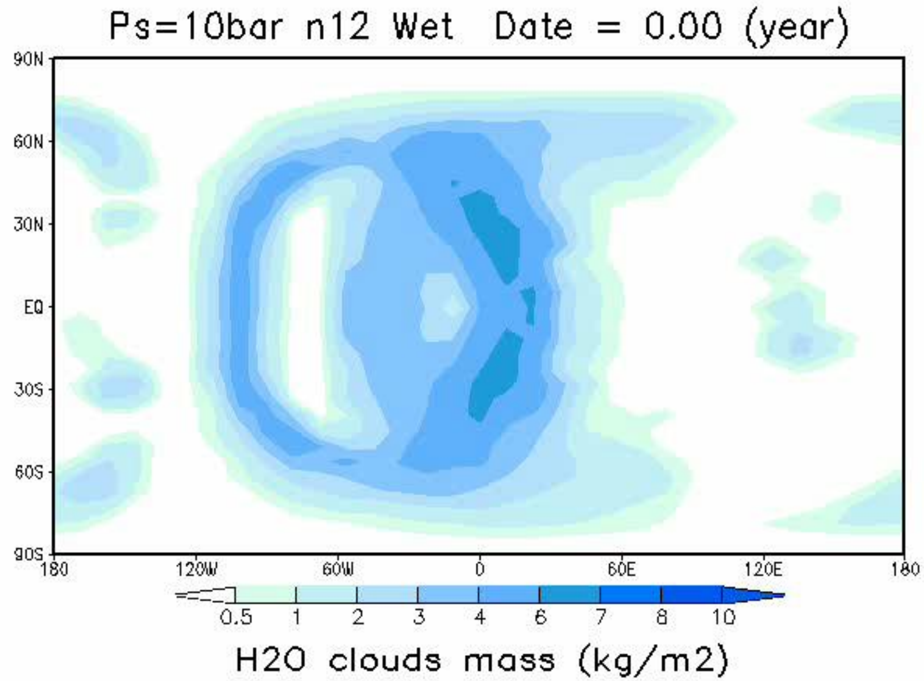
Incident Stellar flux = 27% flux on Earth (less than Early Mars!)

Obliquity = 0° , possibly tidally locked ?



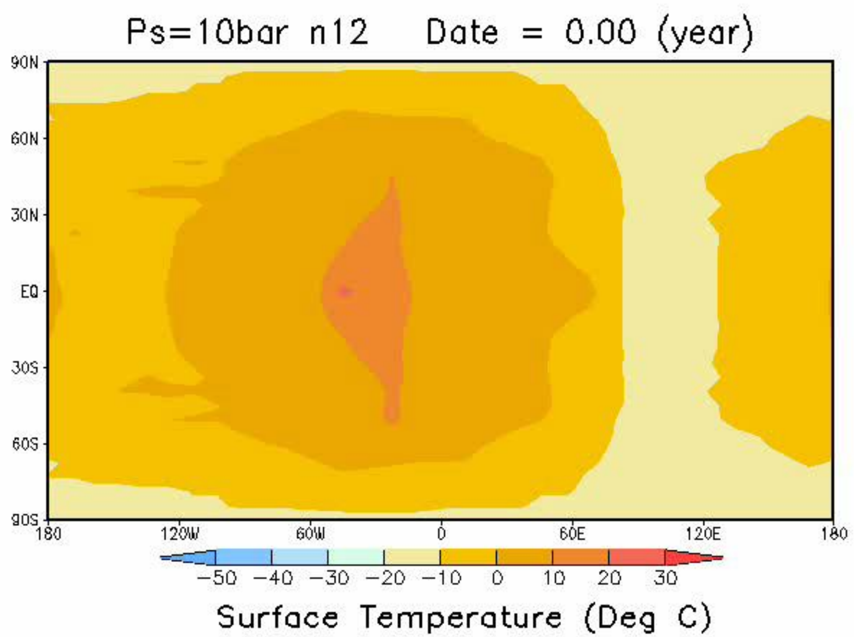
Gliese 581D

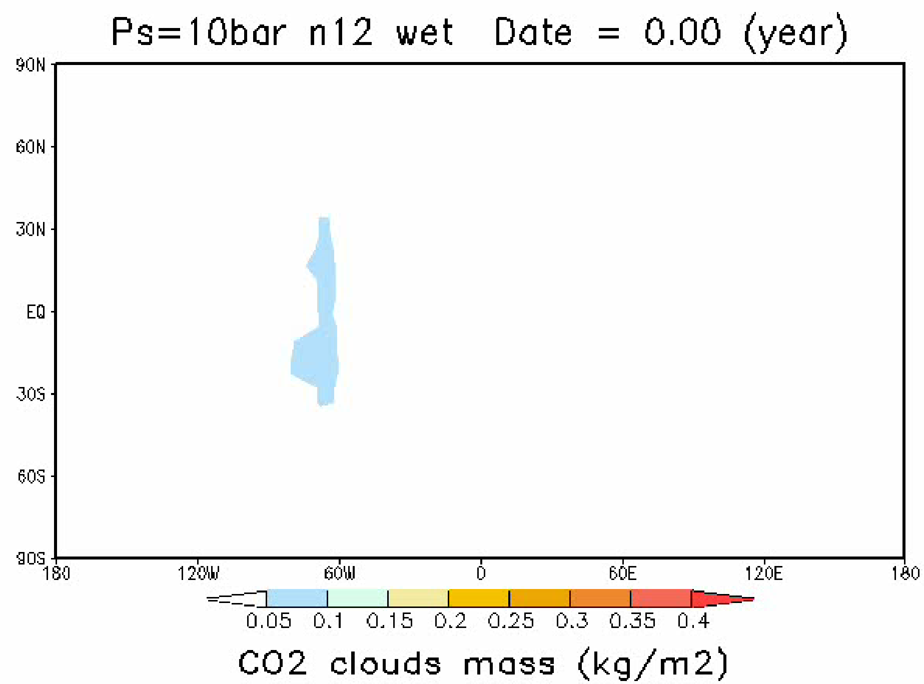
Water clouds



CO2 ice clouds

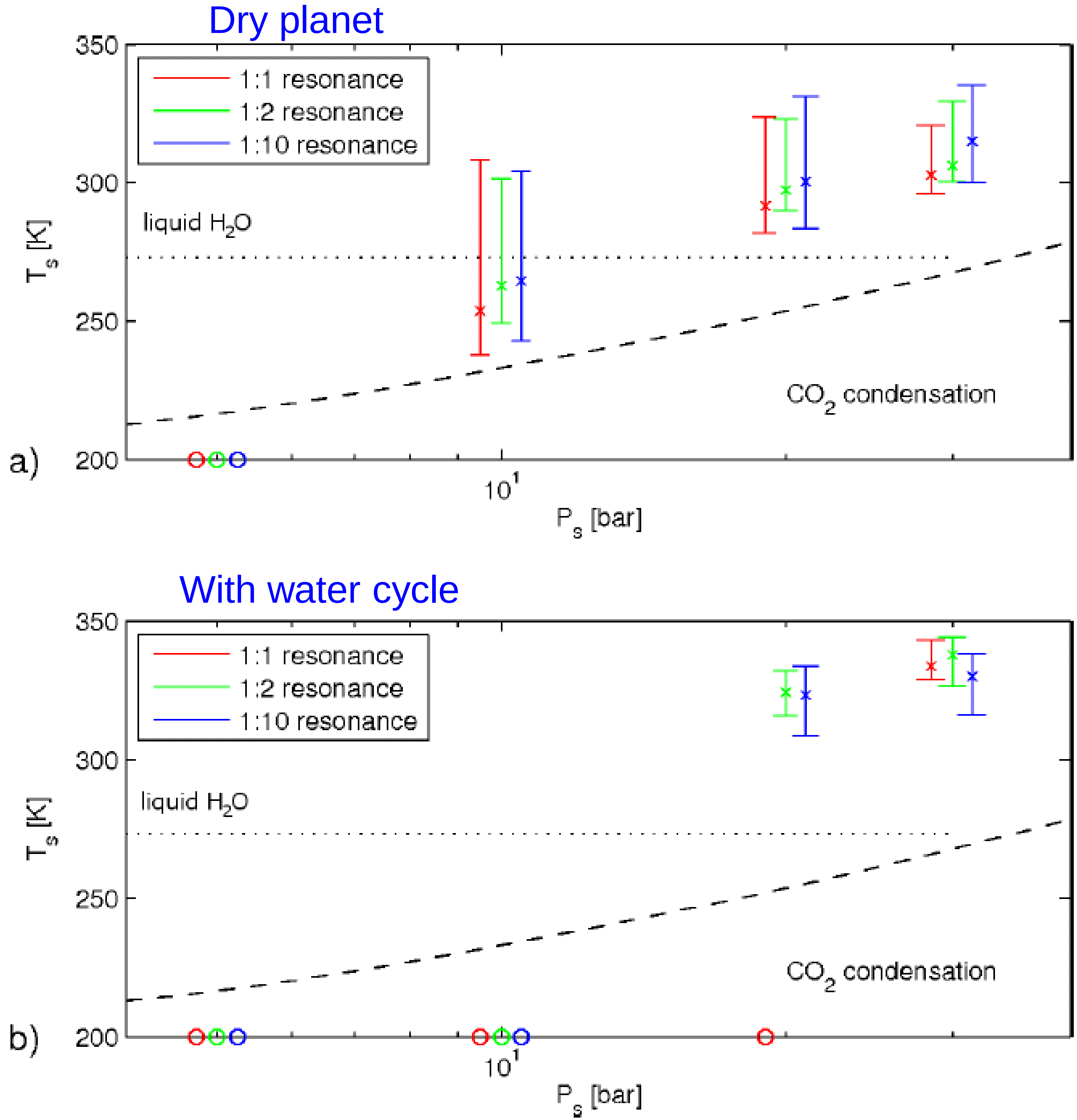
Surface temperature (K)





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

the habit

Report

Science express

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

Stellar activity masquerading as

in the habitable zone of the M

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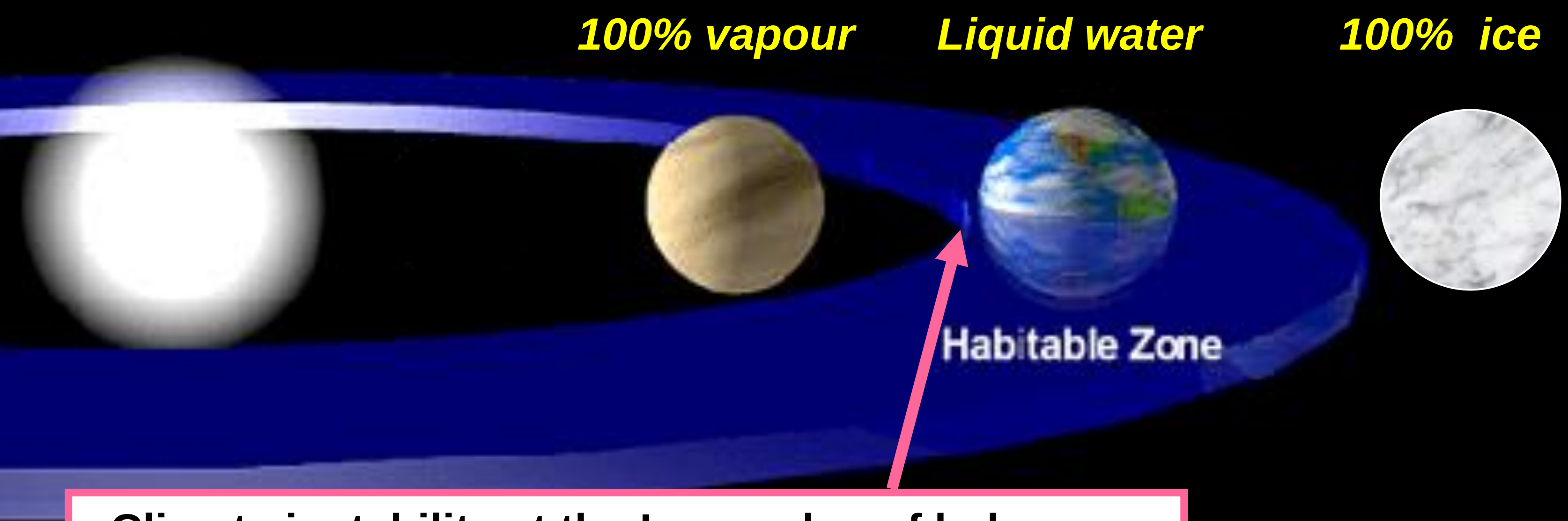
Comment on "Stellar activity
masquerading as plan

Response to Comment on "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]

Anglada-Escudé and Tuomi question the statistical rigor of our analysis
stellar activity aspects that we present. Although we agree that
velocity (RV) modeling are necessary for
we raised were not

Climate, Surface liquid water and life



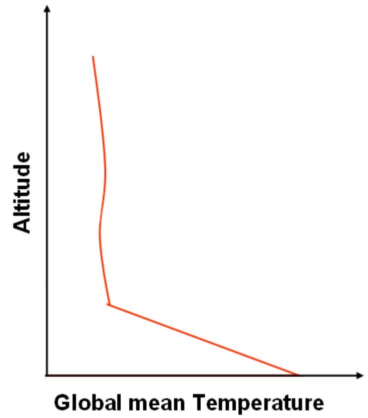
Climate instability at the Inner edge of hab. zone

Solar flux ↑ → Temperature ↑

Temperature ↑ → Evaporation ↑

Evaporation ↑ → Greenhouse effect ↑

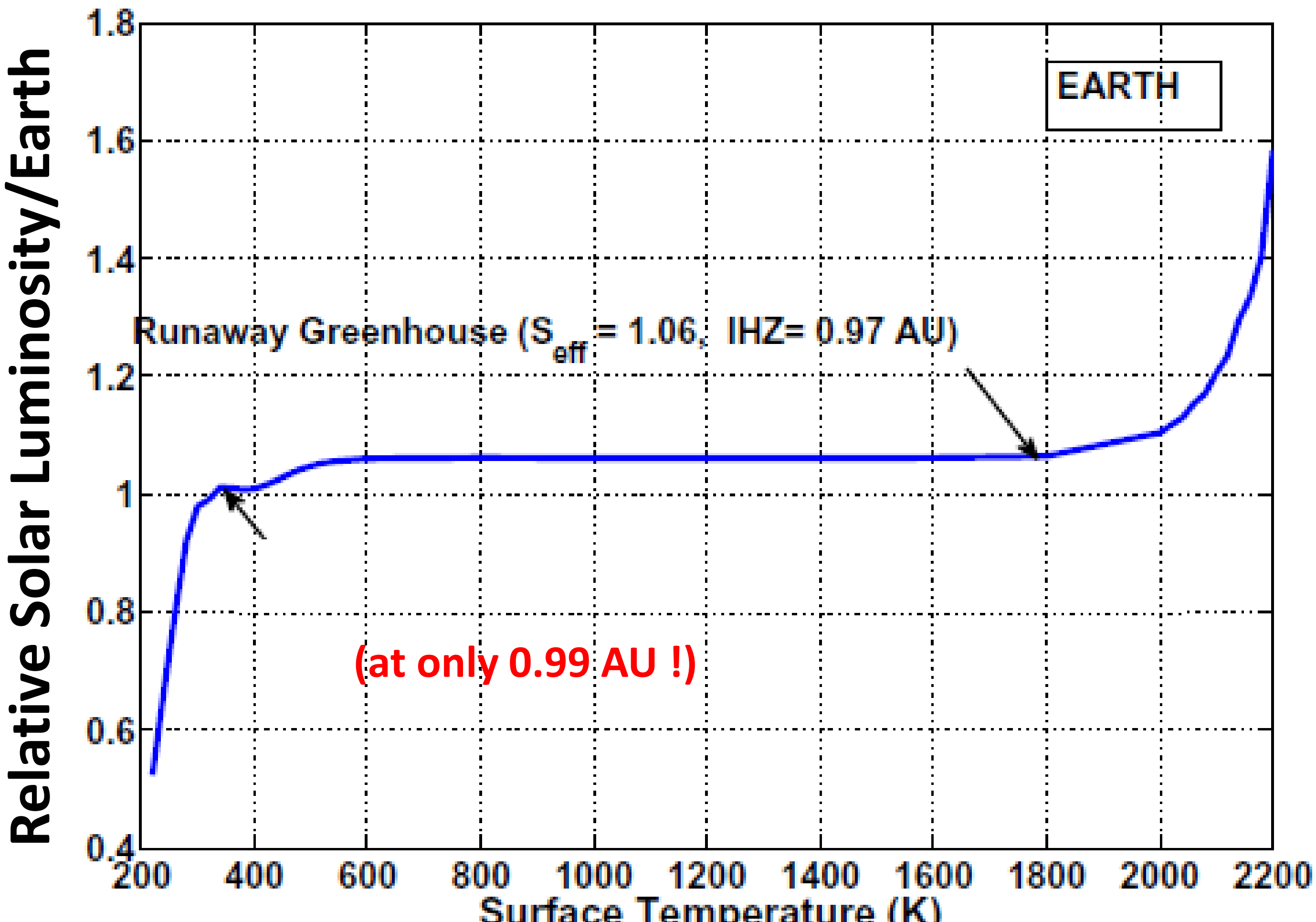
Greenhouse effect ↑ → Temperature ↑



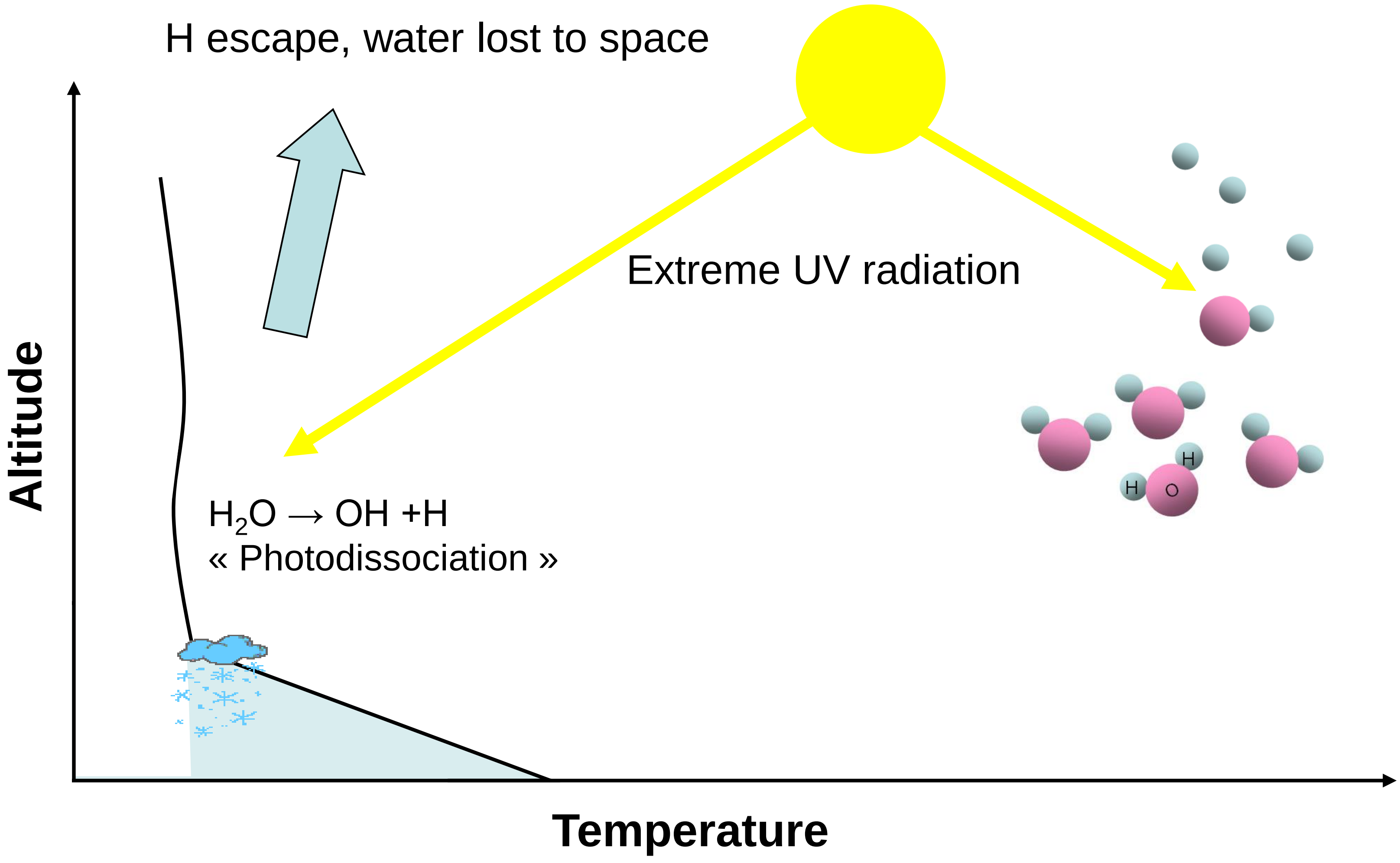
Runaway Greenhouse effect in 1D models

(for an Earth-like planet around a sun)

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

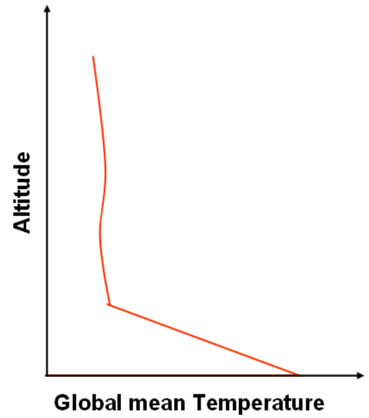


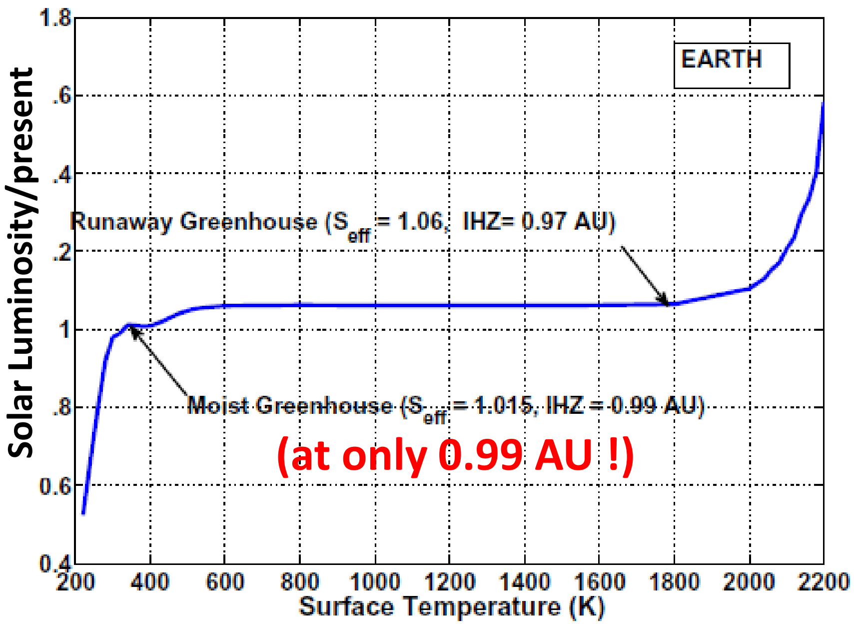
Impact of temperature increase on water vapor distribution and escape: the « water loss limit »… at only 0.99 AU from the Sun (*Kopparapu, Kasting et al. 2013*)

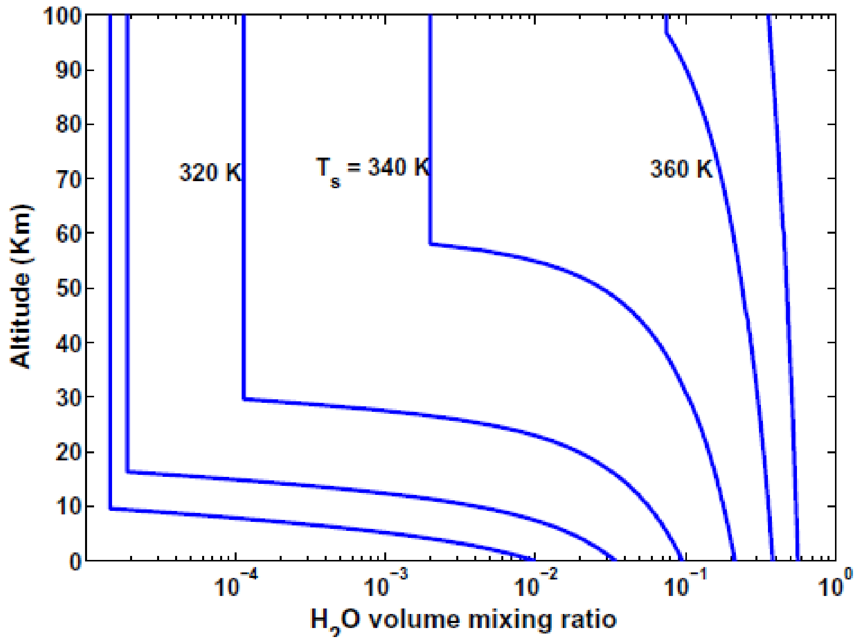


« Water loss limit » in 1D models

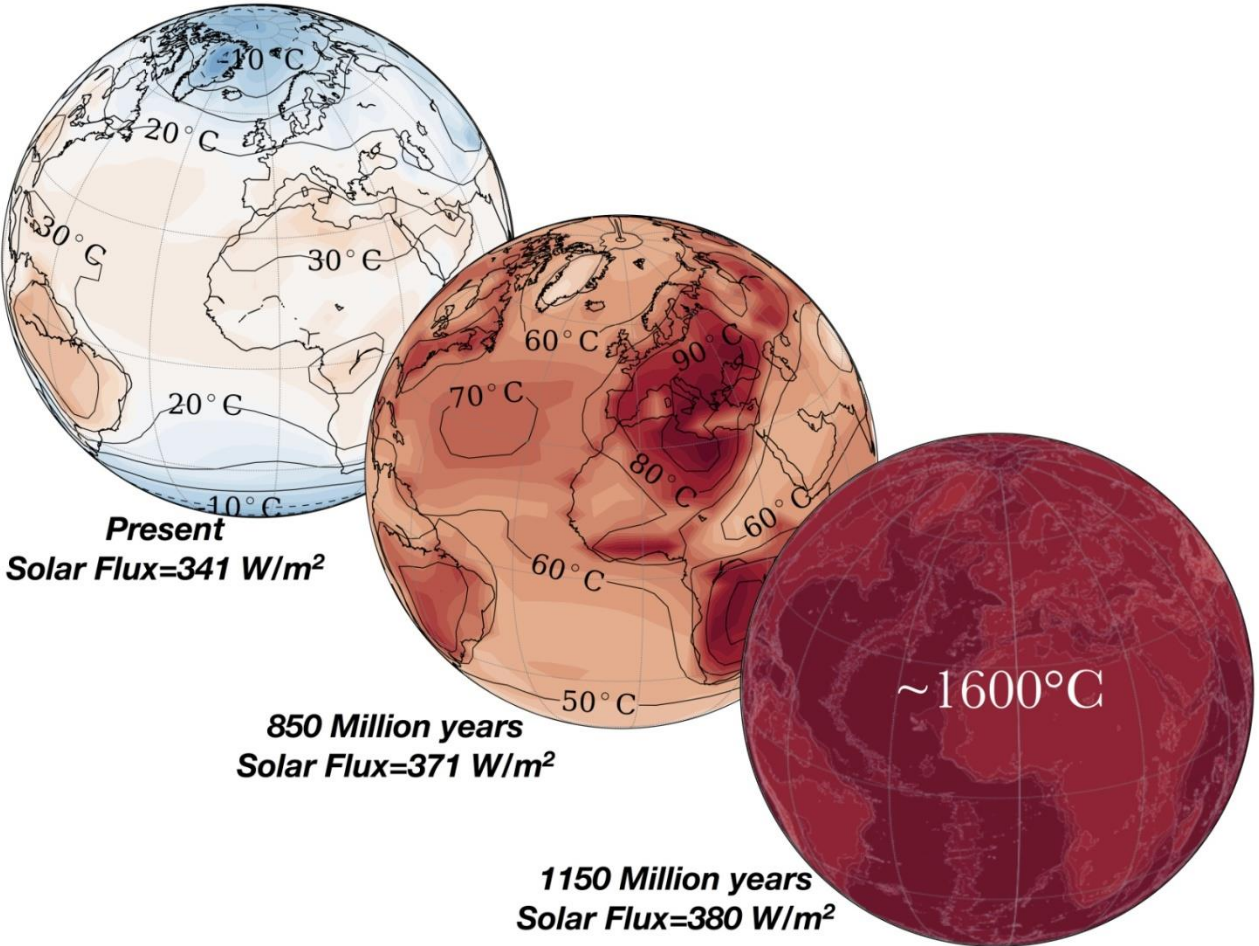
(*Ingersoll 1969, Kasting 1988, Kasting et al. 1993, Kopparapu et al. 2013*)







Runaway Greenhouse effect in a complete 3D Global Climate model



Present
Solar Flux=341 W/m²

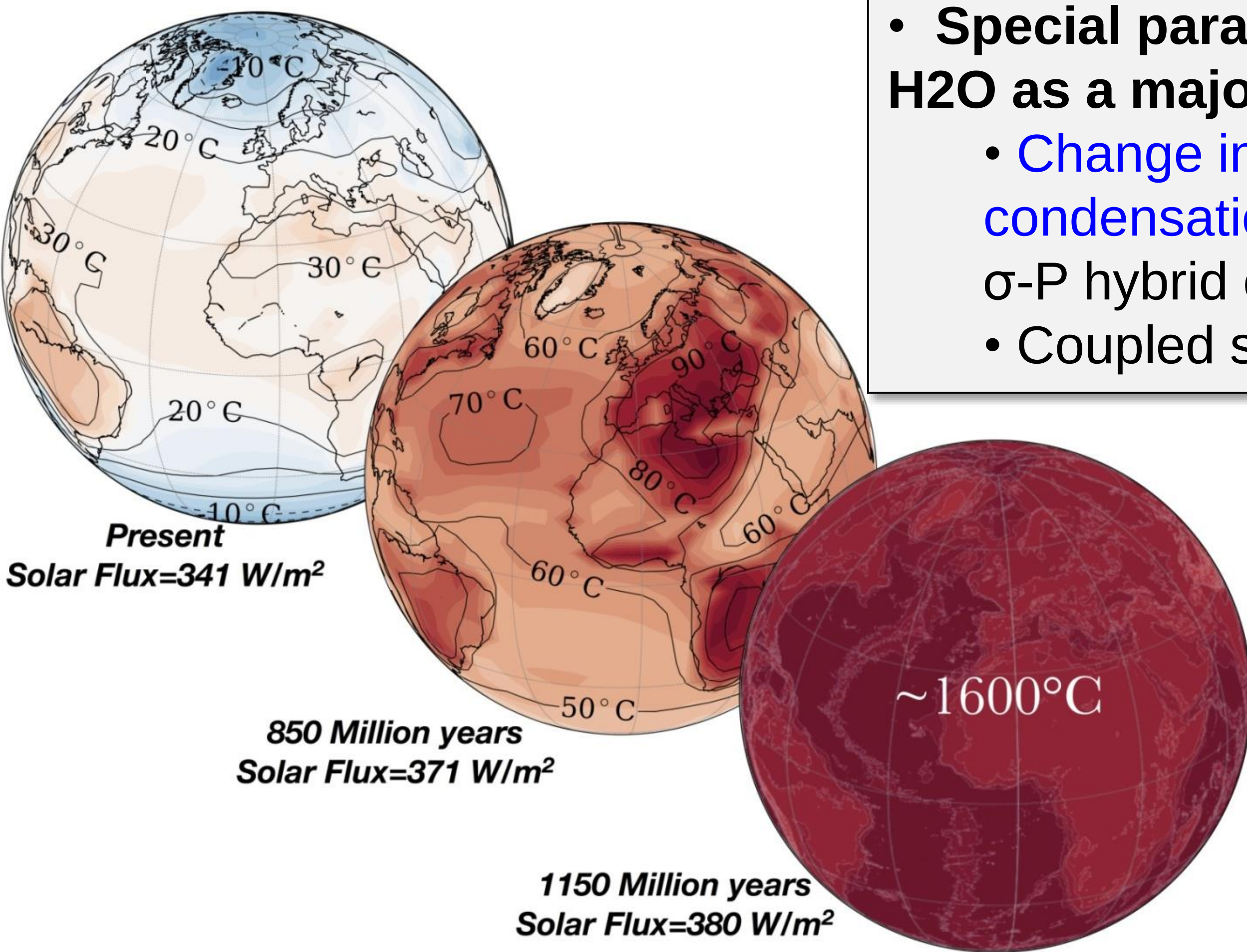
850 Million years
Solar Flux=371 W/m²

1150 Million years
Solar Flux=380 W/m²

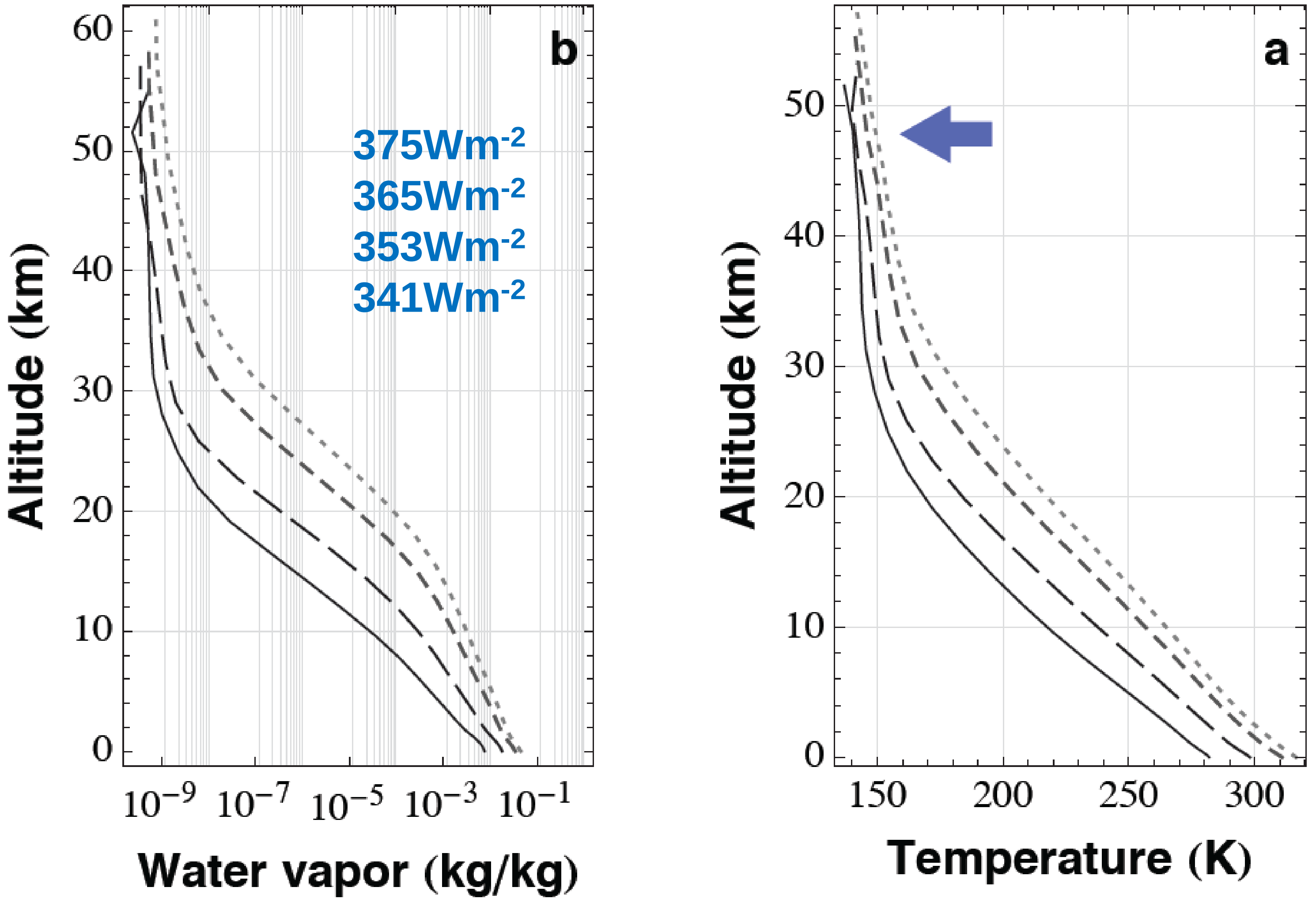
Leconte et al. « *3D Increased insolation threshold for runaway greenhouse processes on Earth like planets*". Nature, 2013

LMD 3D Generic Climate Model

- Earth like planet
- 64x48x30 resolution
- Radiative transfer (correlated k)
  - 19 IR bands
  - 18 solar bands
- **Special parametrization to handle H_2O as a major constituant :**
  - Change in Ps with condensation/evaporation ⇨ case of σ-P hybrid coordinates.
  - Coupled system [H_2O]+T+Ps



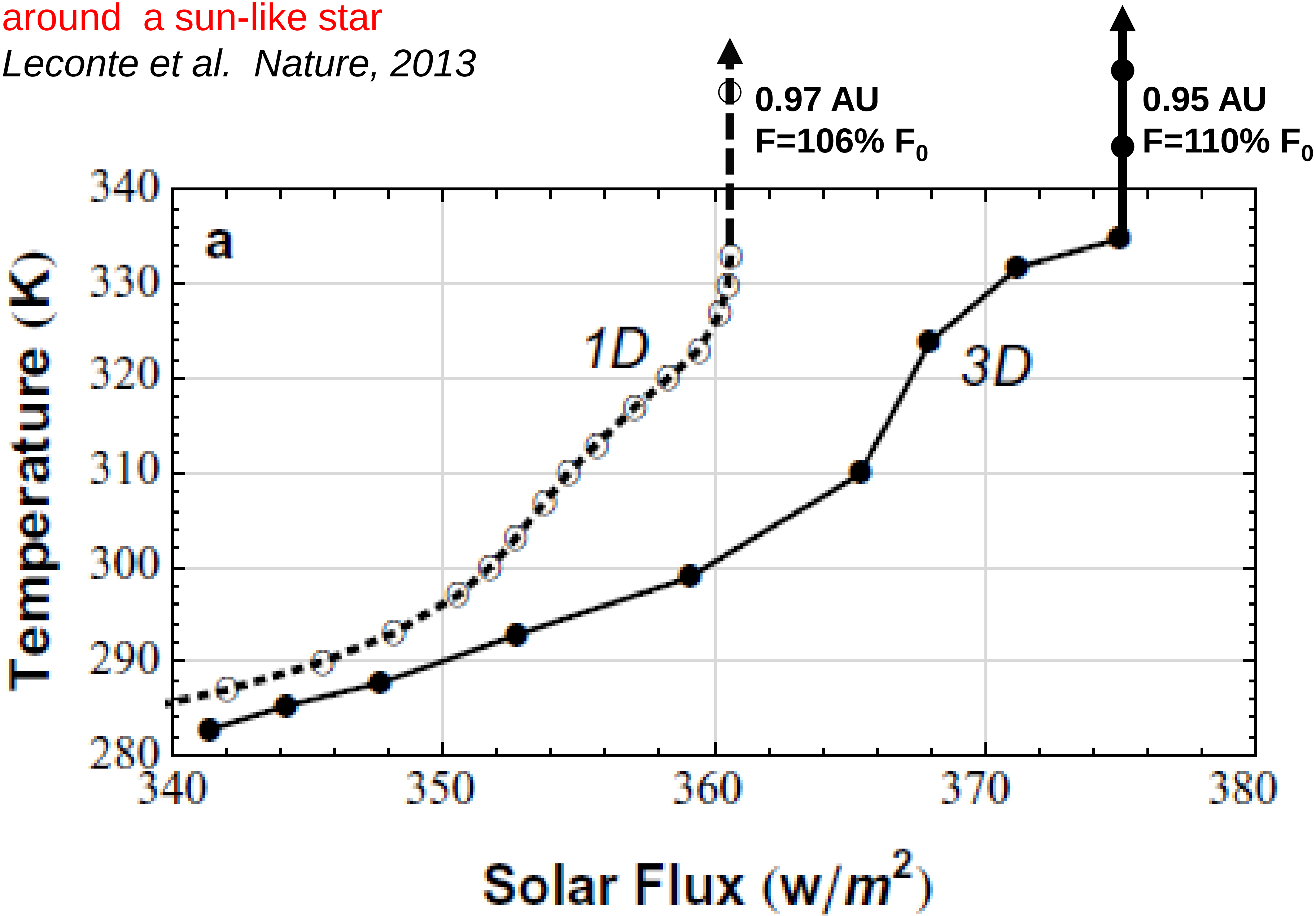
Earth like Simulation with detailed radiative transfer in the upper atmosphere: no water loss limit !



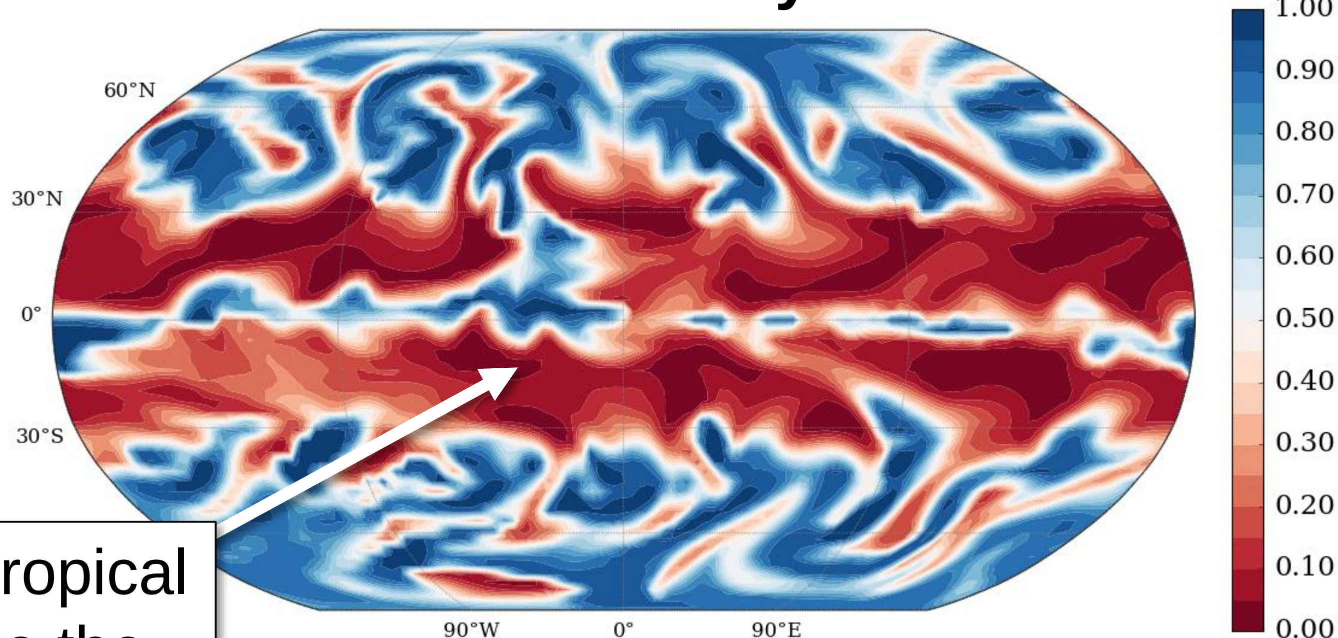
Leconte et al. (Nature; 2013)

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

Leconte et al. Nature, 2013



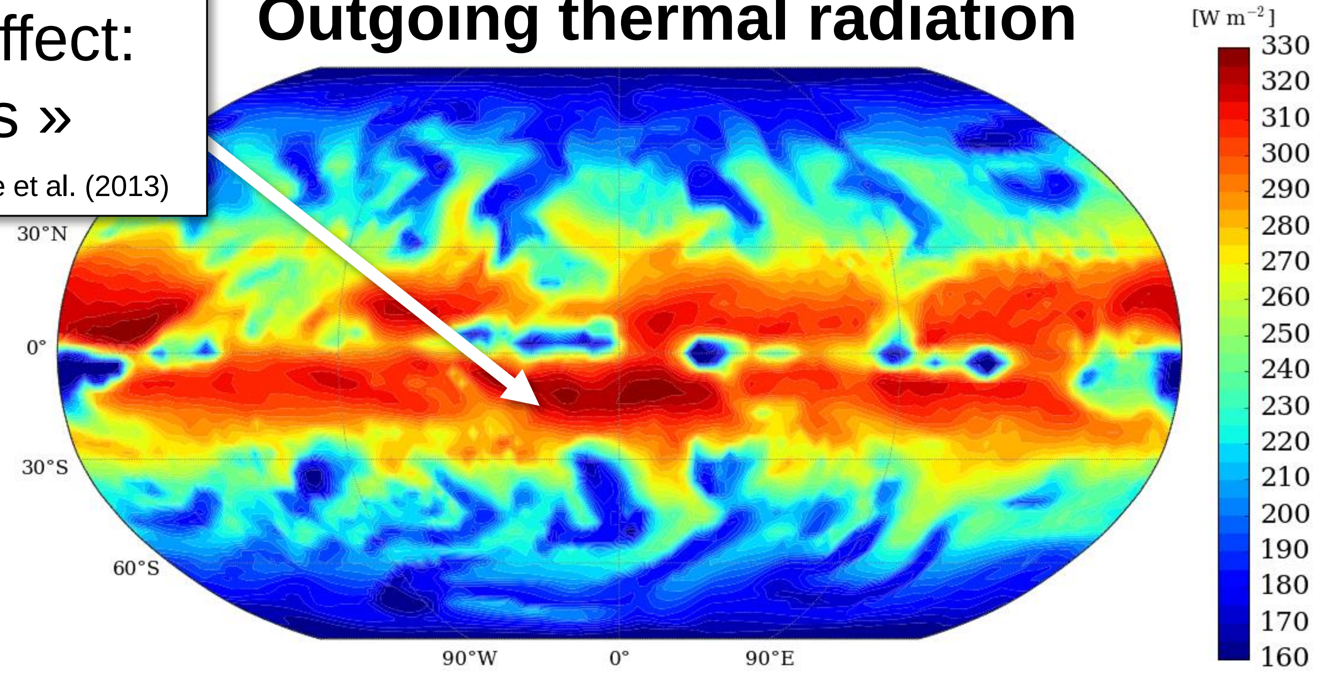
Relative humidity



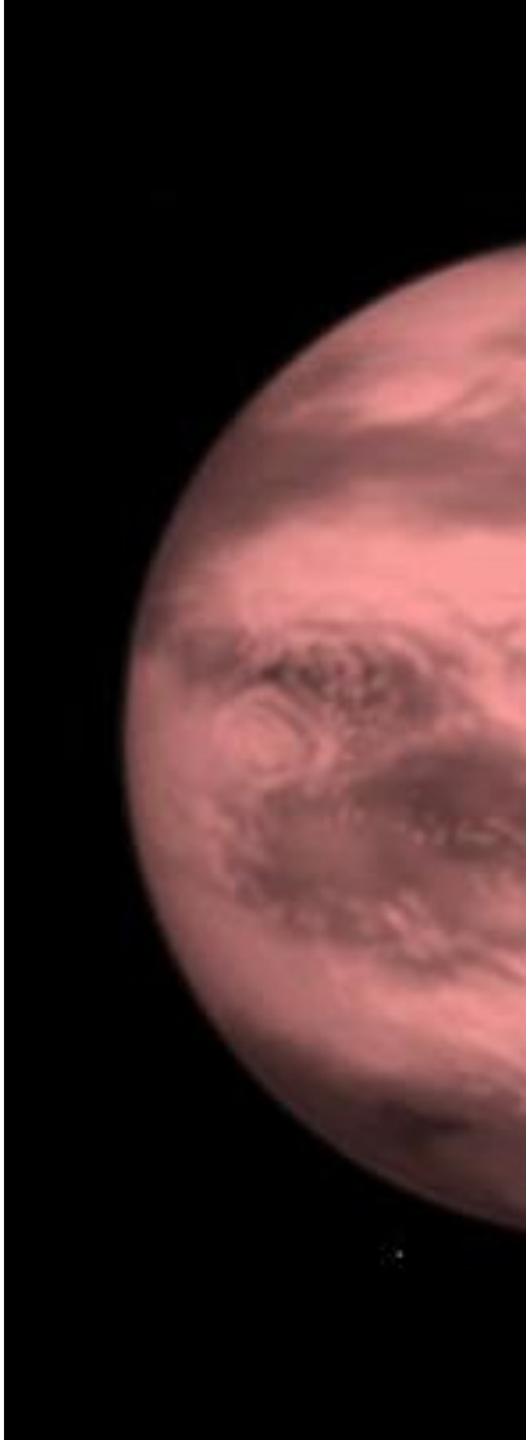
Unsaturated tropical regions reduce the greenhouse effect: « radiative fins »

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

Outgoing thermal radiation



Runaway greenhouse effect around K and M dwarf stars



Redder stellar spectrum

• Weak atmospheric Rayleigh Scaterring

⇨ lower planetary albedo

Effect of tides:

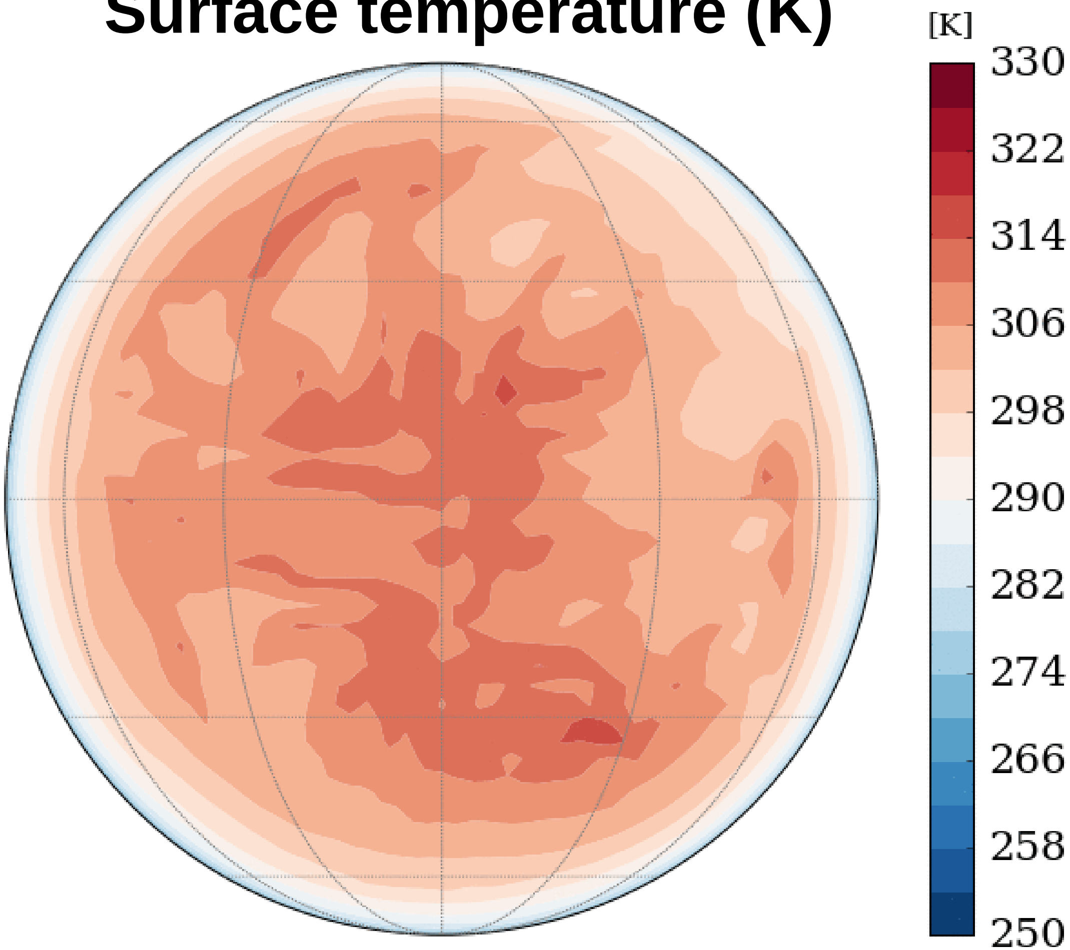
• Resonnant rotation with zero obliquity

⇨ Possible Locking with permanent night side

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

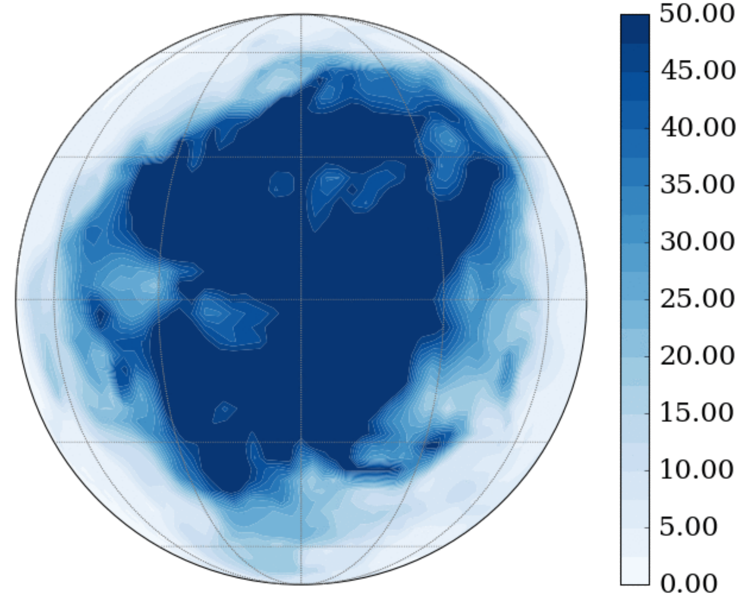
Simulation of aTidal-locked planet with surface liquid water around an Mdwarf
(Jeremy Leconte, LMD climate model)

Surface temperature (K)

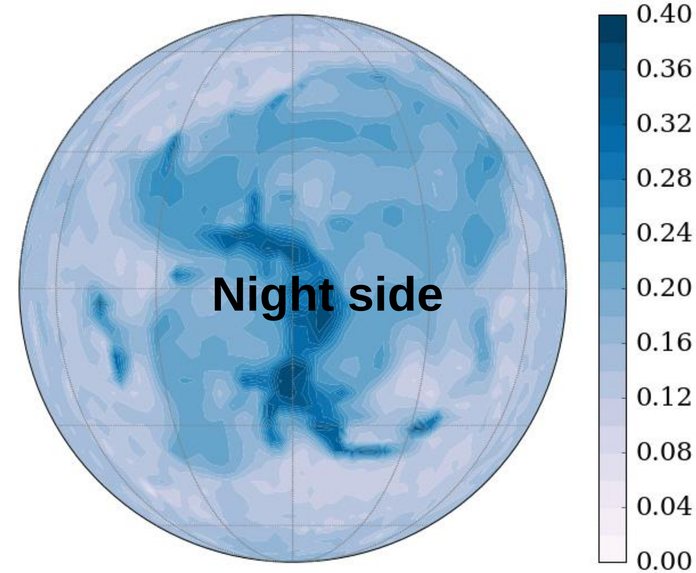


View from a distant point throughout the orbit

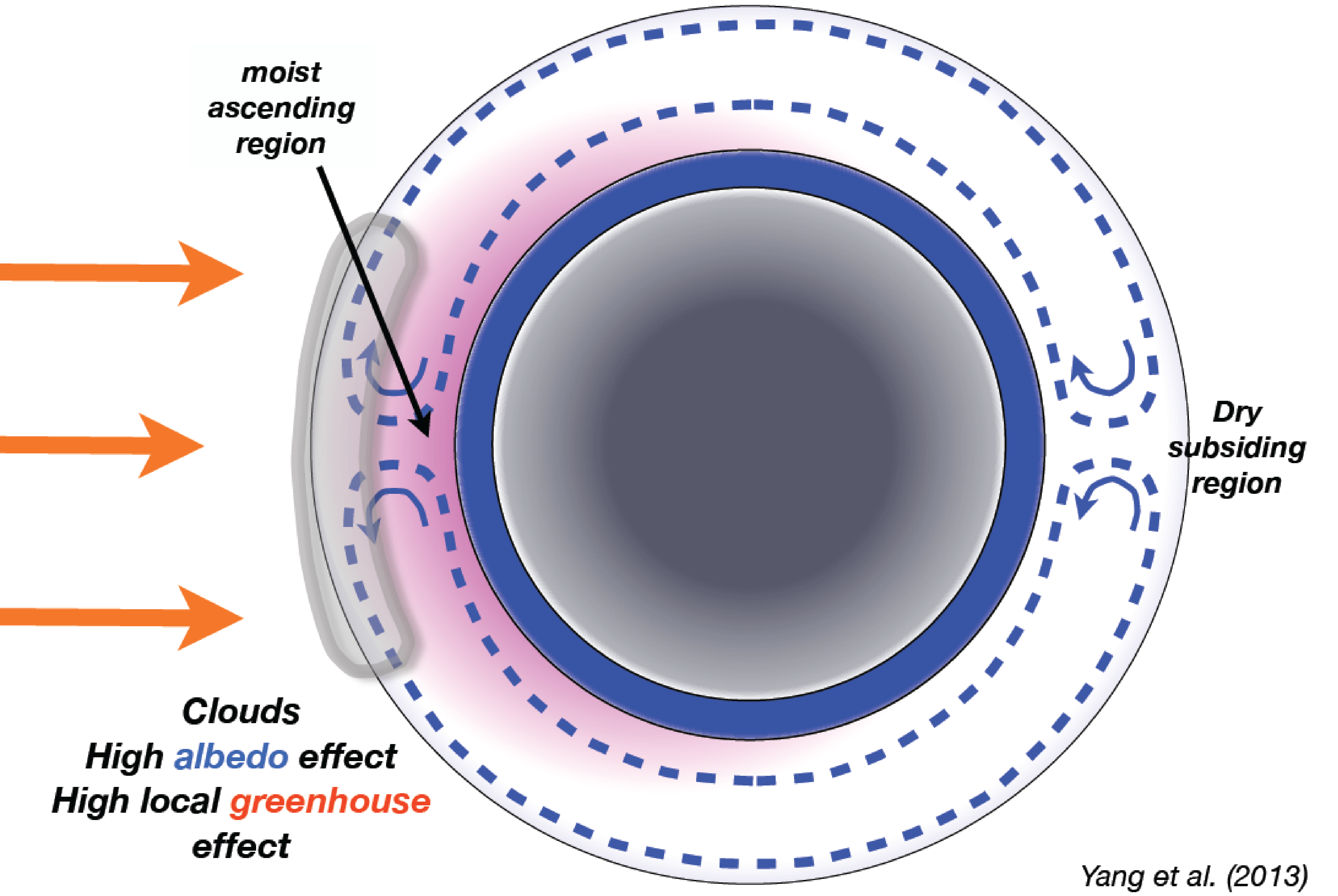
Cloud opacity



Planetary Albedo



Large scale cloud pattern on tidally locked planets



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

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

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Draft version June 28, 2013

ABSTRACT

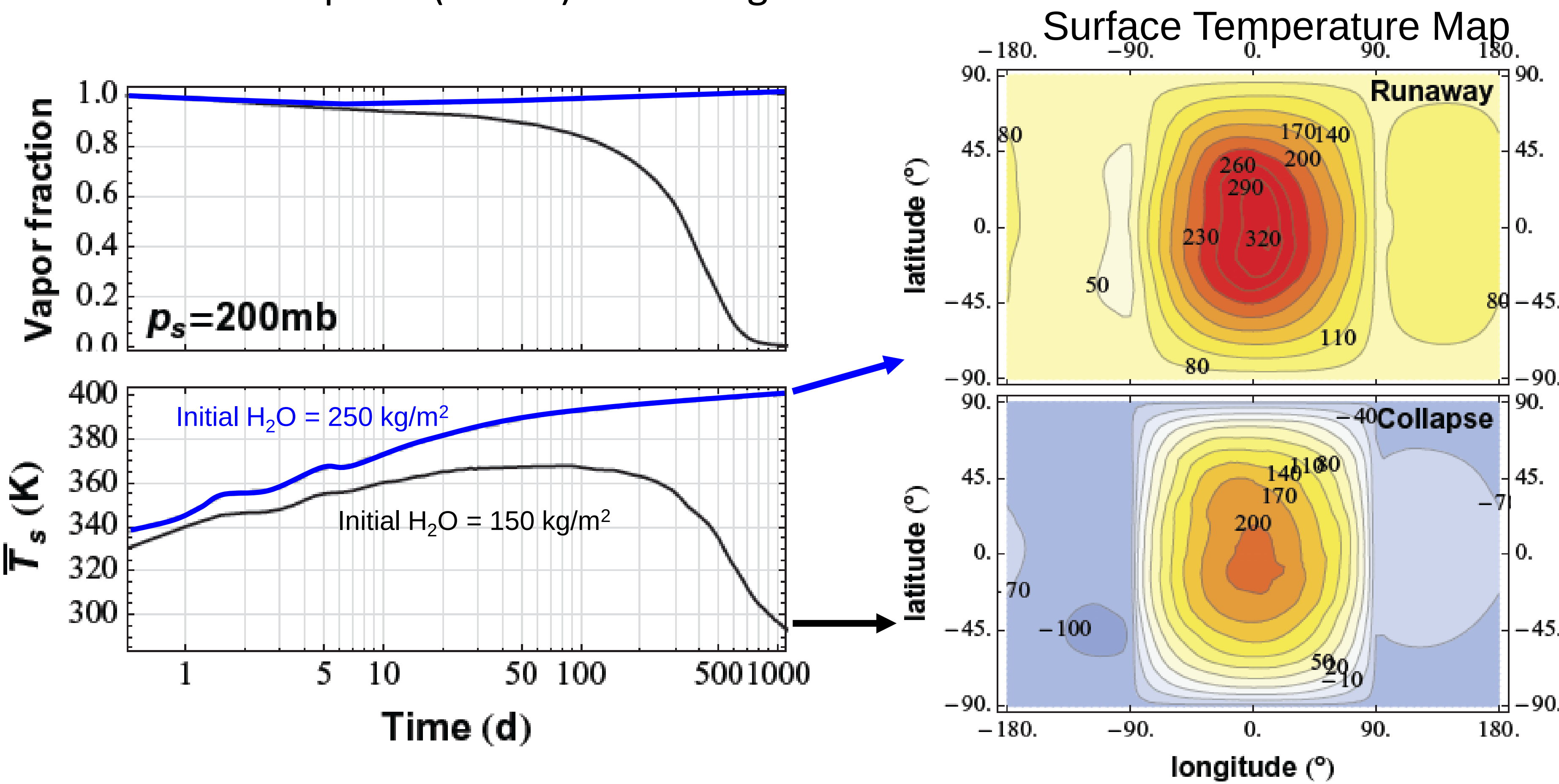
The Habitable Zone (HZ) is the circumstellar region where a planet can sustain surface liquid water. Searching for terrestrial planets in the HZ of nearby stars is the stated goal of ongoing and planned extrasolar planet surveys. Previous estimates of the inner edge of the HZ were based on one dimensional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

Tidally locked hot planets

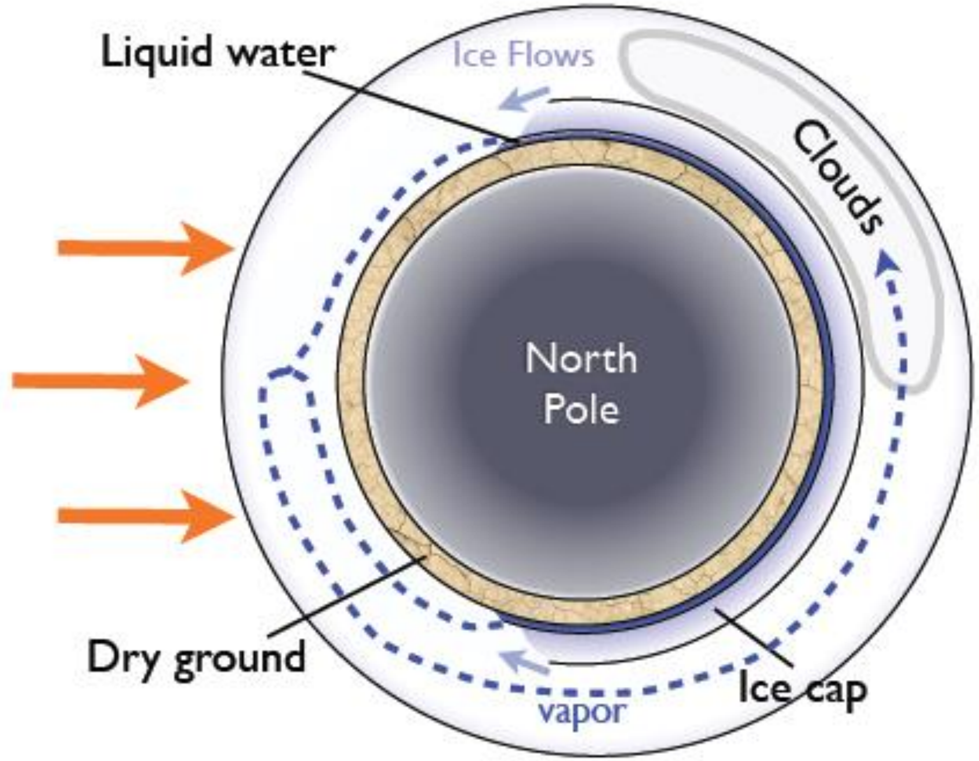
Tidally locked hot planet: Modeling of Gliese 581c and HD85512b

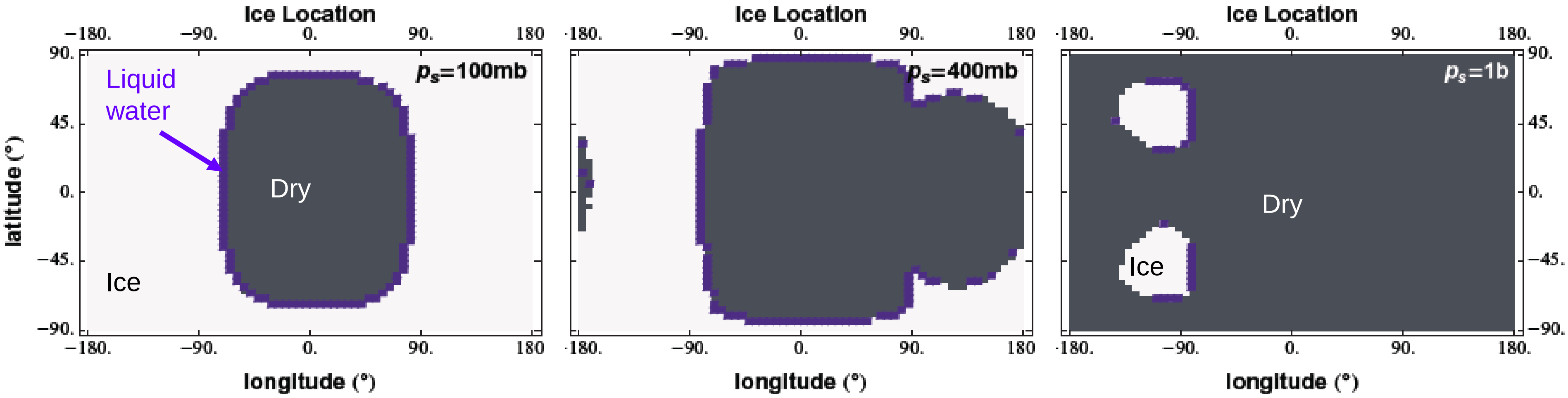
S/4=860 W/m^2 (**250% Earth flux!**) (*Leconte et al. A&A 2013)*

- **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.

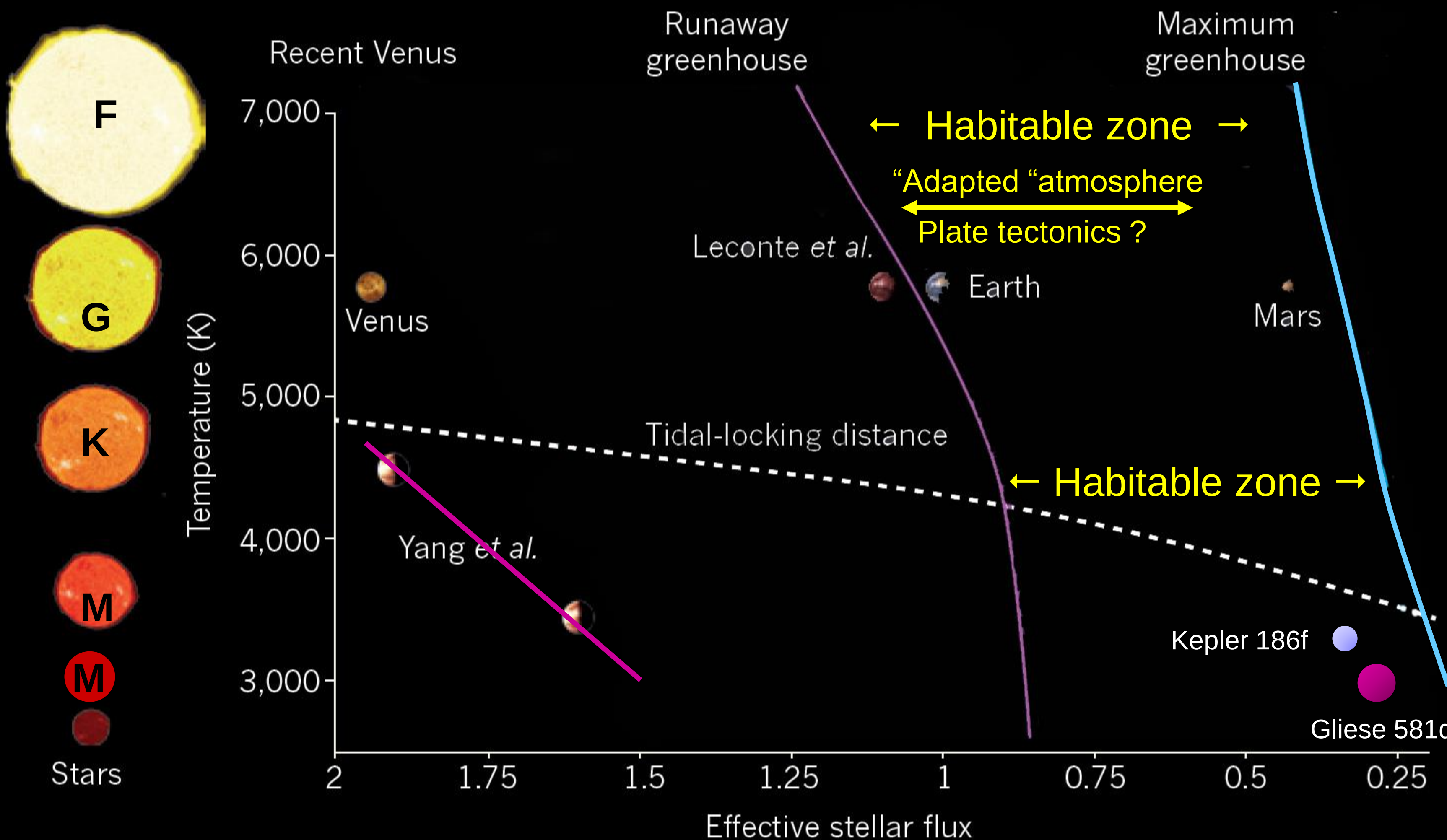


Possibility of liquid water on tidally locked hot planet *(Leconte et al. A&A 2013)*





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 (1/2)

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

Climate → **Habitability**

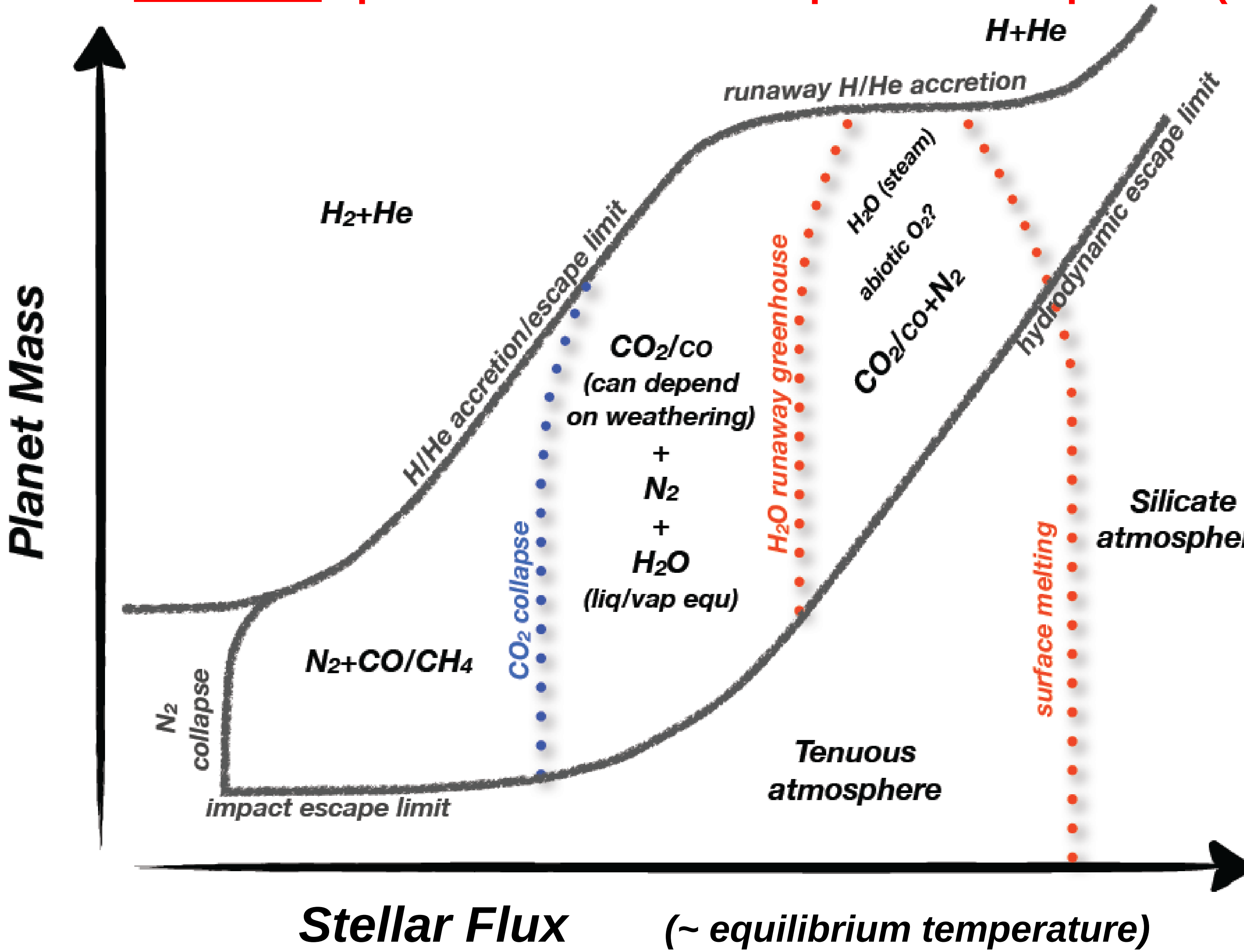
<u>Key problem</u>: understanding of the zoology of **atmospheric composition**, controlled by complex processes :

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

Can we already speculate?

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)

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)**

Conclusions: Atmospheres, Climate and Habitability (2/2)

- **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
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- 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)

ありがとう　ございます