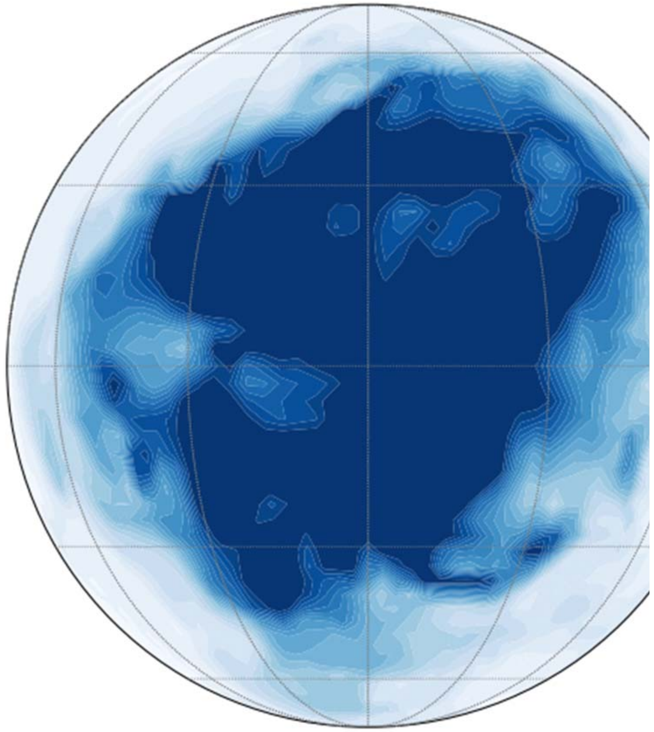
Modélisation des Environnements planétaires et de l'habitabilité: *de la Terre primitive aux exoplanètes*

<u>François Forget</u>*, Jeremy Leconte, Benjamin Charnay, Robin Wordsworth, Ehouarn Millour, Aymeric Spiga Franck.Selsis, et al. …

***CNRS, Institut Pierre Simon Laplace,**
Lab. de Météorologie Dynamique, Paris



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

Objectif de ma présentation:

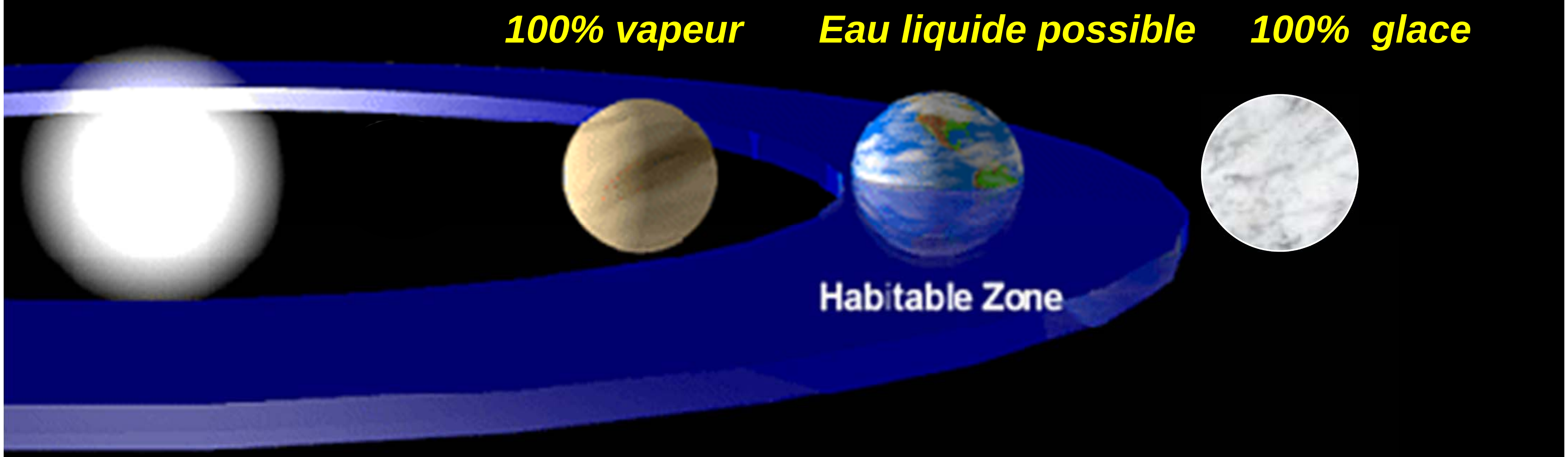
Comment modéliser climats et environnements sur des planètes que nous ne pouvons pas observer ? :

- Exoplanètes telluriques
- Climats passés

⇨Un fil rouge exobiologique: l'**Habitabilité**

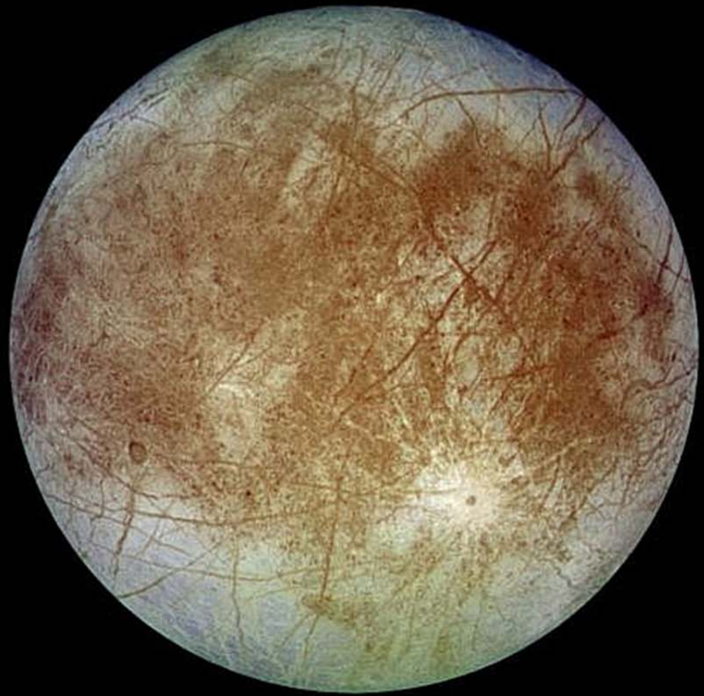
La zone habitable : Eau liquide possible à la surface des planètes

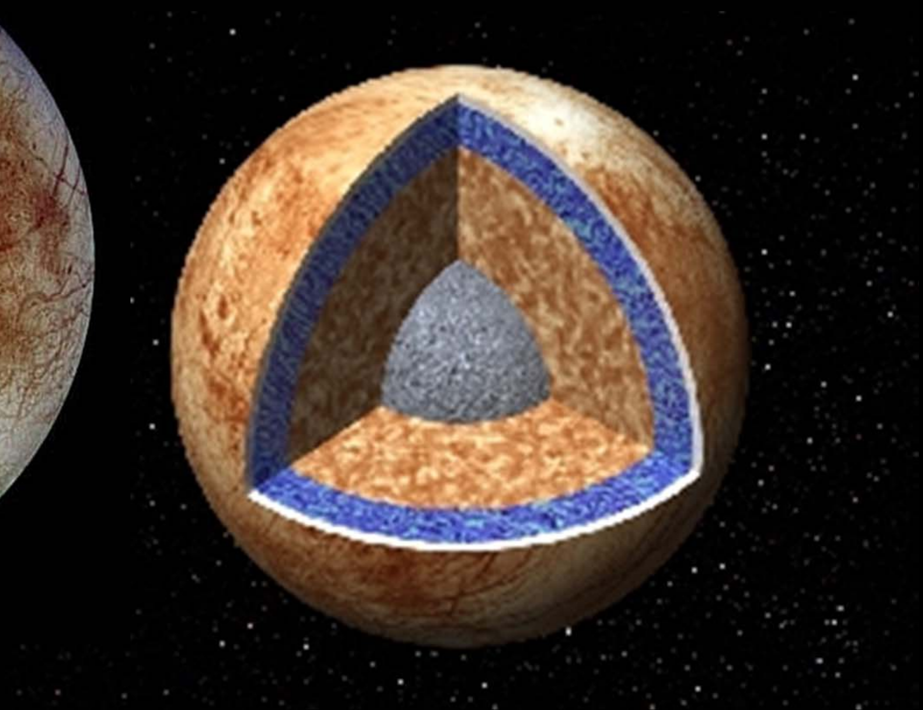
Eg. Kasting et al. 1993
Forget 2013



Quid de l’eau liquide éventuellement présente sous la surface (cf. présentation précédente ?)

(Dans le système solaire: Mars, Europa, Enceladus Ganymede, Callisto, Titan etc.)



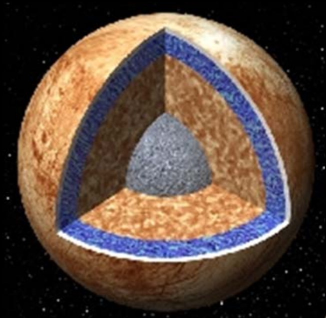


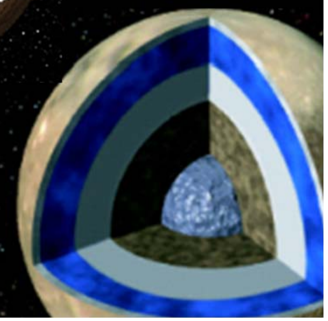
Europe, satellite de Jupiter

Suggestion: 4 types d' « habitabilité »

(Lammer et al. 2009, Forget 2013)

- **Classe I:** Planète avec de l'eau liquide permanente en surface: *comme la Terre*
- **Classe II :** Planète temporairement propice à l'eau liquide en surface, mais qui ont perdues cette capacité (perte de l'atmosphère, perte de l'eau, effet de Serre divergent) : *Mars, Vénus ?*
- **Classe III :** Corps avec un océan sous la surface en interaction avec un manteau rocheux *(Europe)*
- **Classe IV :** Corps avec un océan sous la surface entre deux couche de glace *(Ganymede, Callisto)*

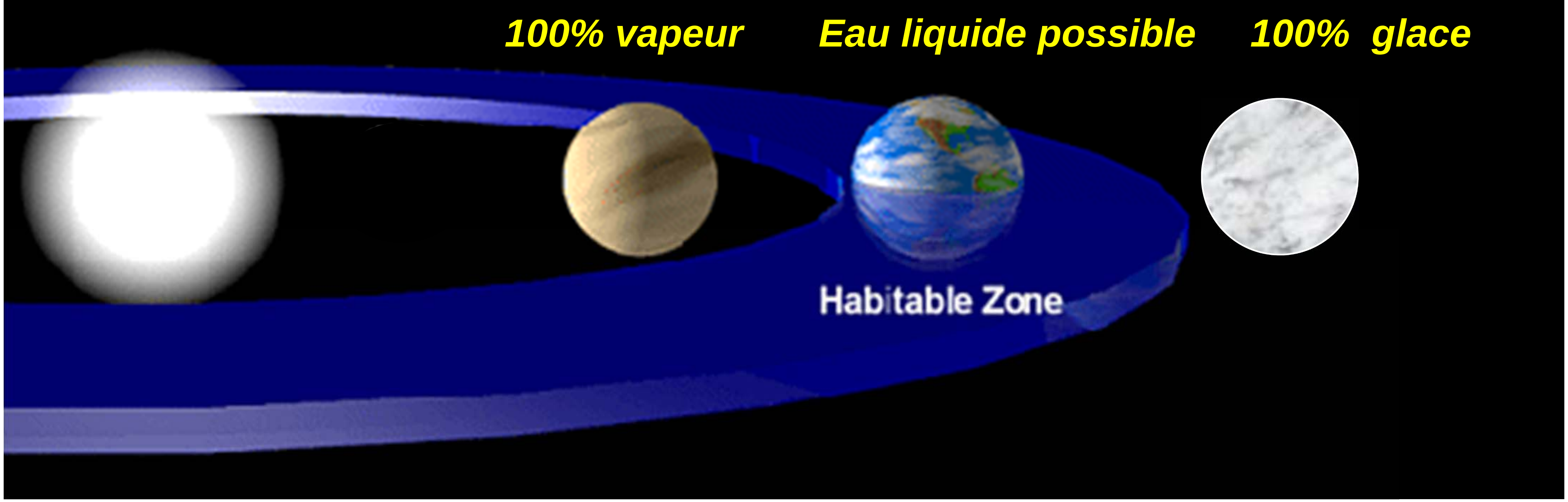




La zone habitable : Eau liquide possible à la surface des planètes

⇨ **Un problème de climat**

Eg. Kasting et al. 1993
Forget 2013



Key parameters controlling the climate on a terrestrial planet:

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

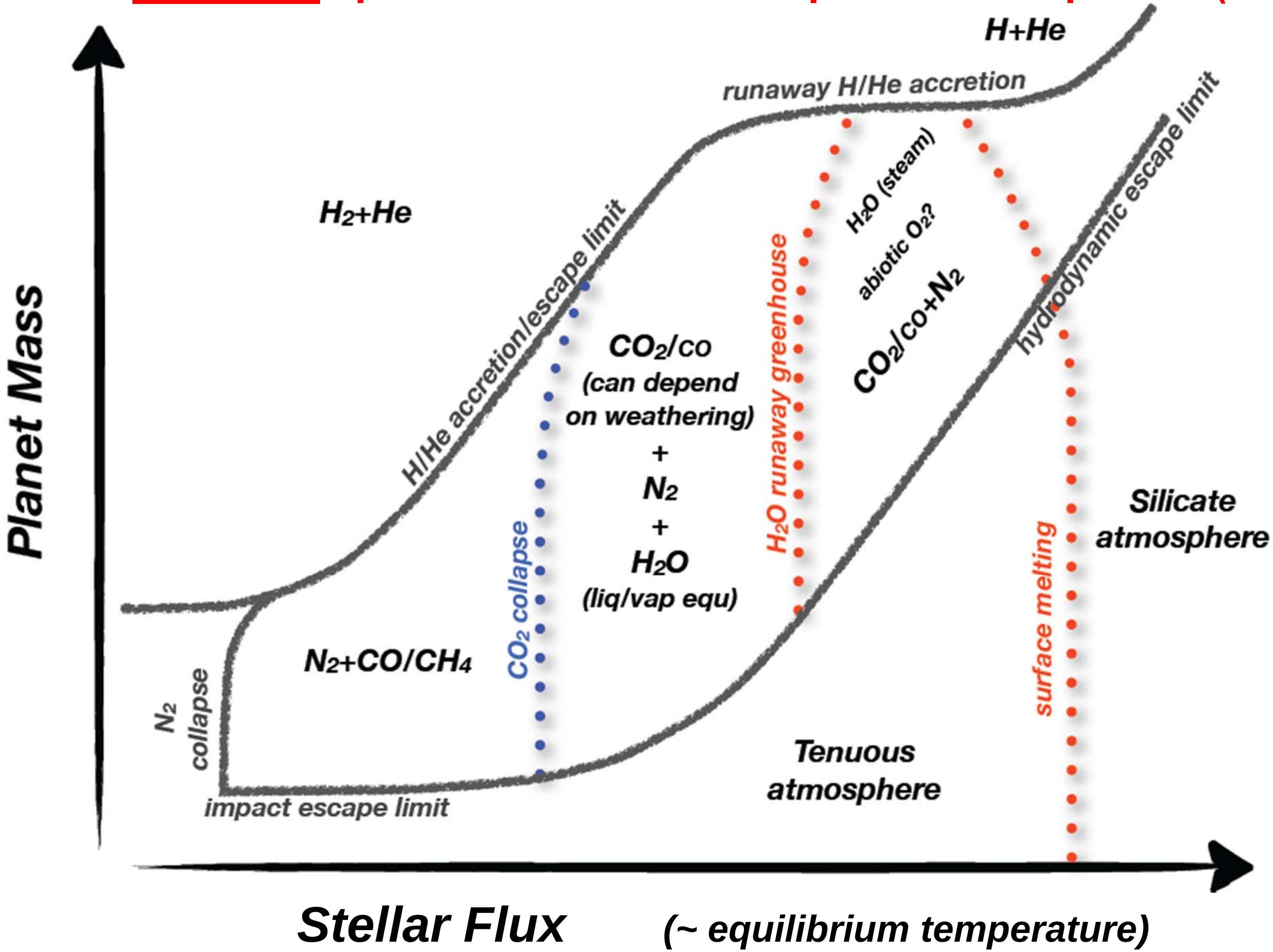
Climate

Atmospheric composition and surface volatile inventory ?

- Our experience in the solar system is not sufficient.
- 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 and interaction with surface)
  - Long term photochemistry …

⇨ **But let's speculate**

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**)

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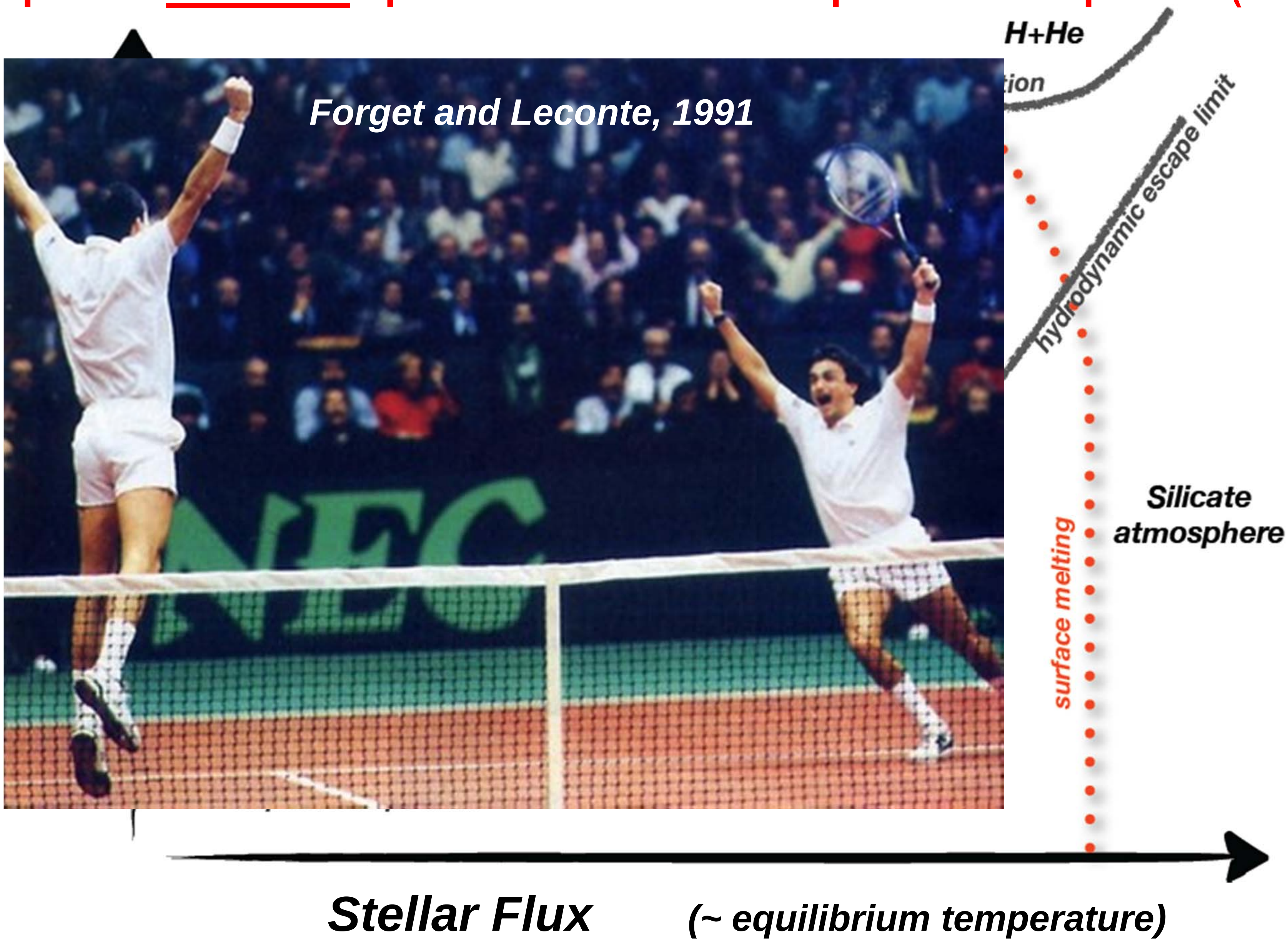

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  and surface volatile inventory
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Climate

Planetary rotation & climate

1) Govern the distribution of insolation
2) Controls circulation and heat transport.

Two "end members" :

- "Free" Planets, which seems to originally rotates "fast" (P < 100 hrs) : Mars, ~Earth, Jupiter, Saturn, Uranus, Neptune… (theory? see *Miguel and Brunini, 2010*)
- Tidally evolved bodies
  - Planets: obliquity →0° ; slow rotation or even locking (Mercury, Venus)
  - Satellites : slow rotation (Titan, Triton)

Key parameters controlling the climate on a terrestrial planet:

- **Stellar insolation**
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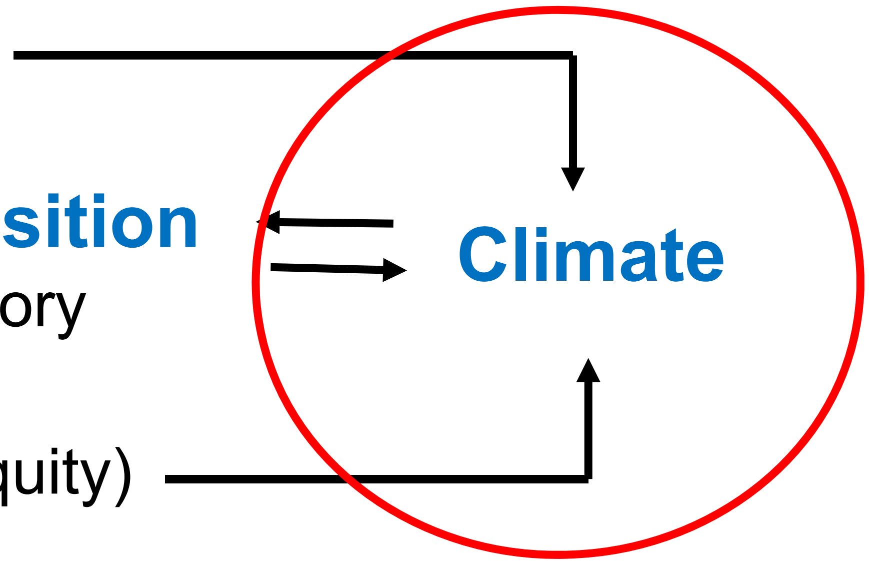
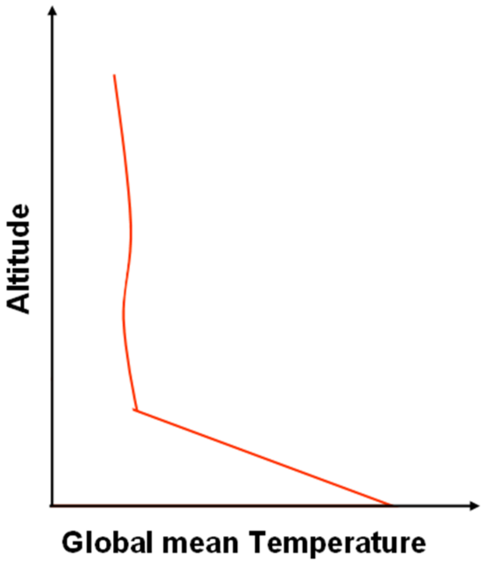
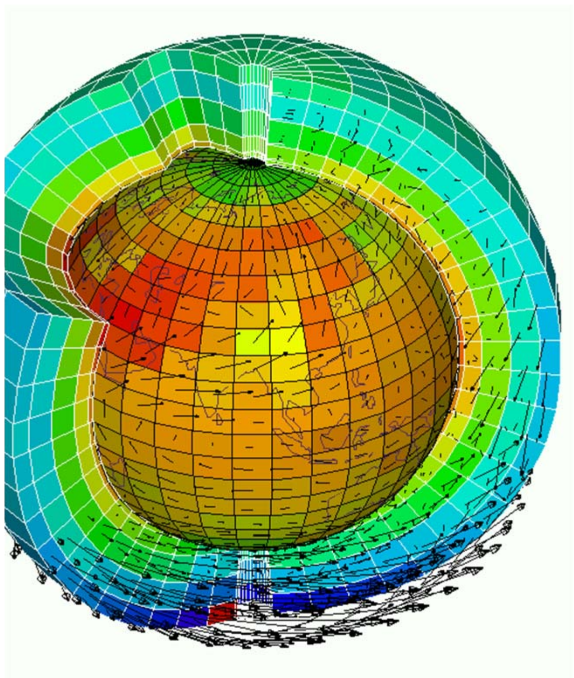


Climate models

A hierarchy of models for planetary climatology





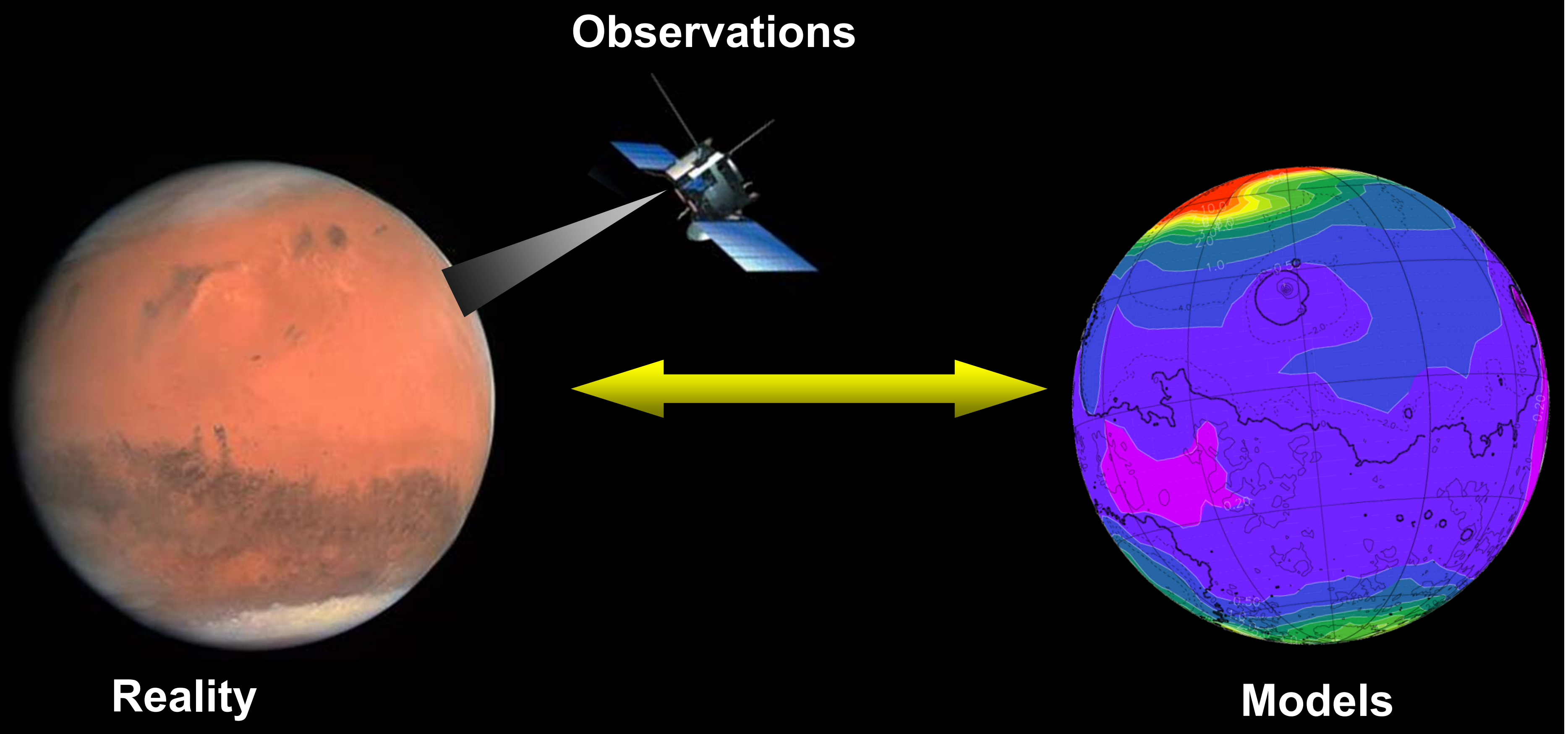
1. 1D global radiative convective models
⇨ Great to explore exoplanetary climates; still define the classical Habitable Zone *(e.g. Kasting et al. 1993)*

2. 2D Energy balance models…

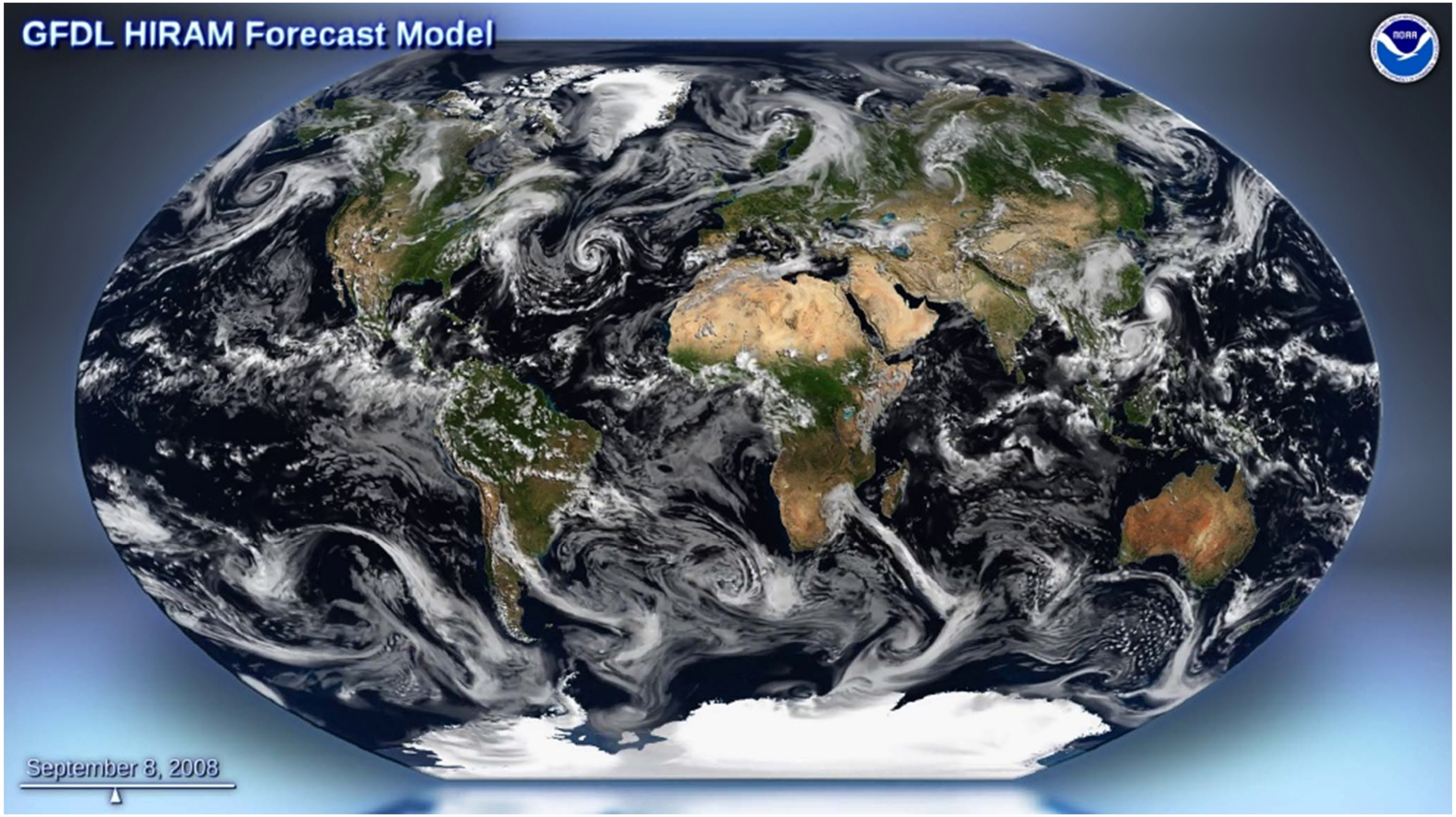
3. Theoretical 3D General Circulation model with simplified forcing: used to explore and analyse the possible atmospheric circulation regime (*see Read 2011, Showman et al. 2013, etc)*

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

Ambitious Global Climate models : Building “virtual” planets behaving like the real ones, on the basis of universal equations

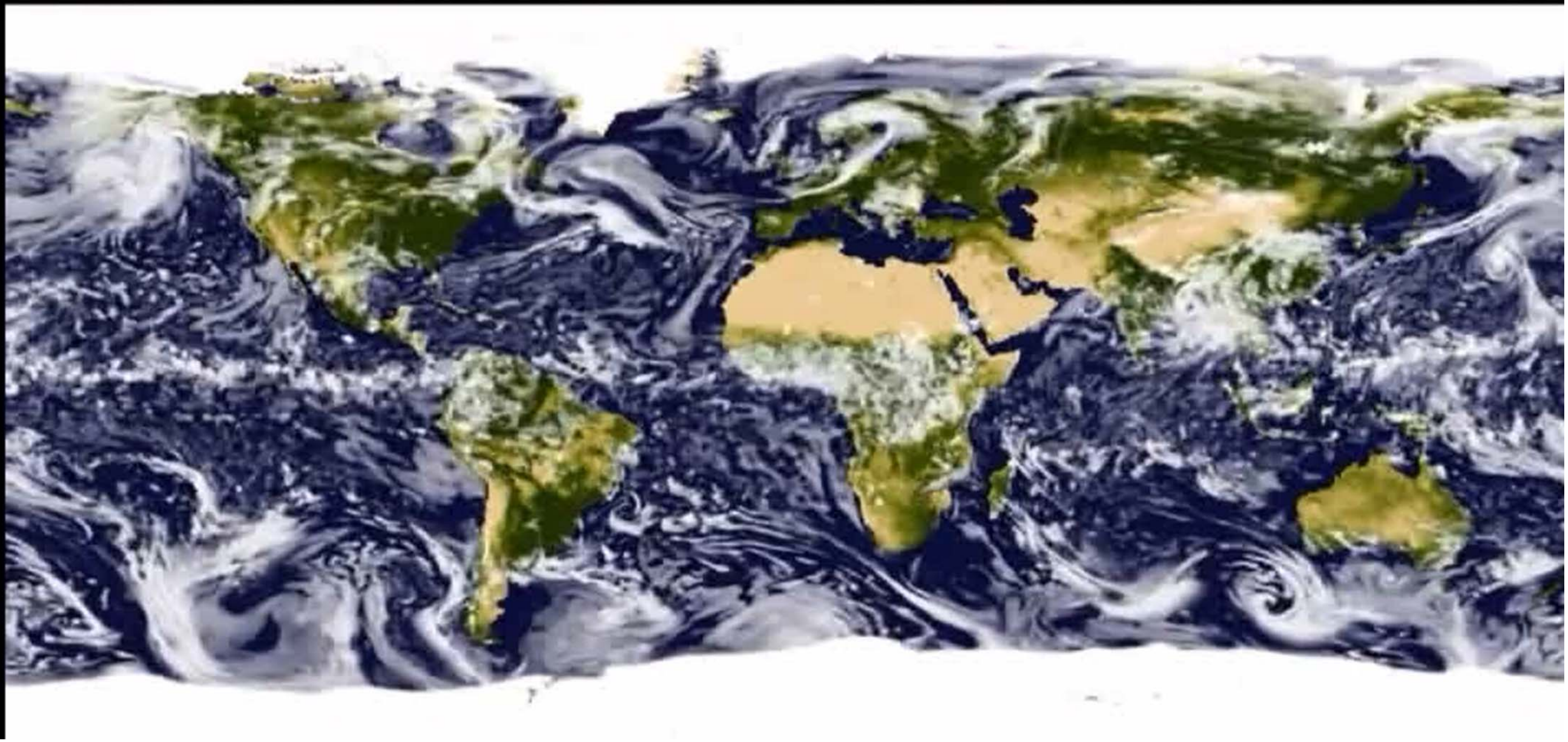


How to build a full Global Climate Simulator ?



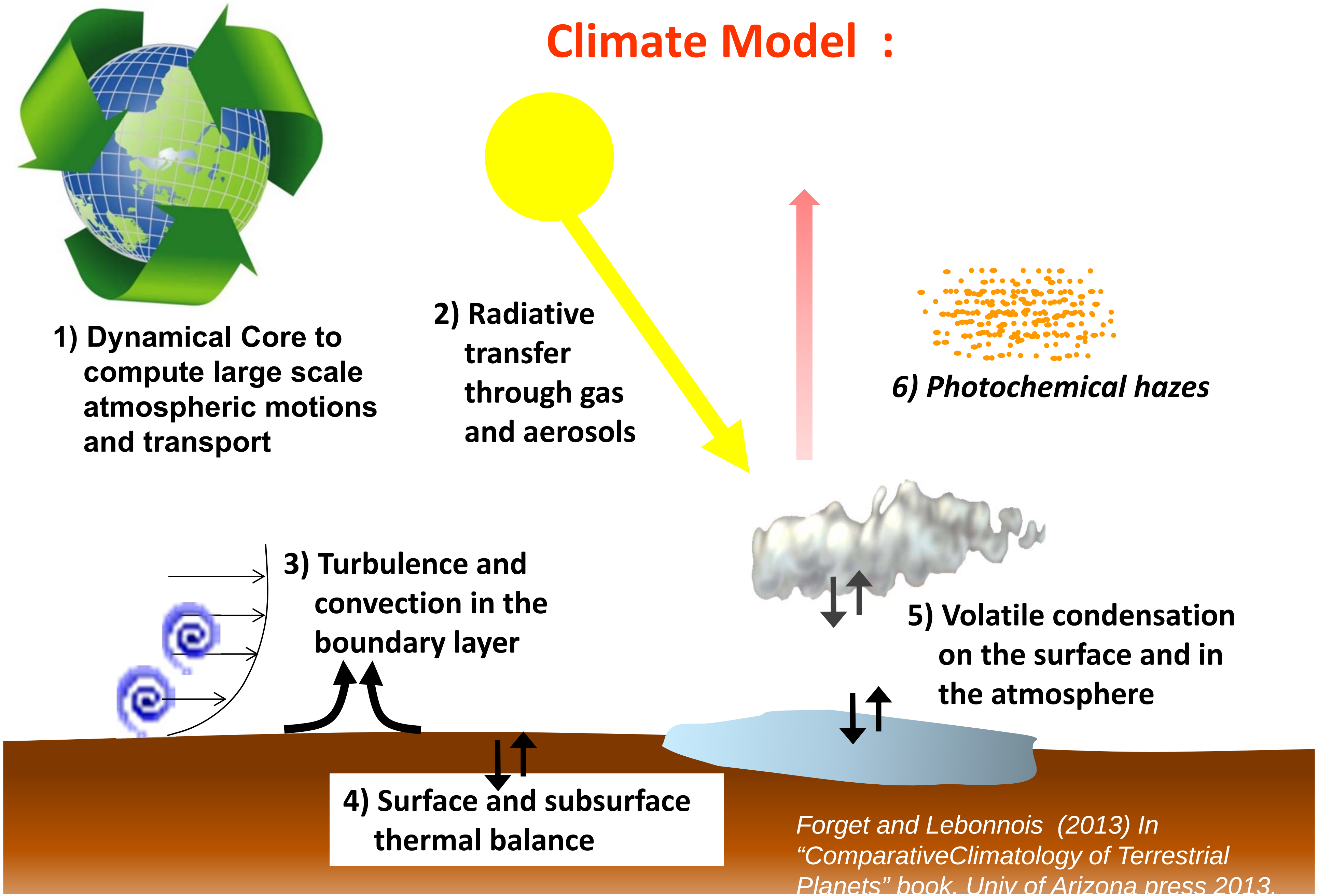
How to build a full Global Climate Simulator ?

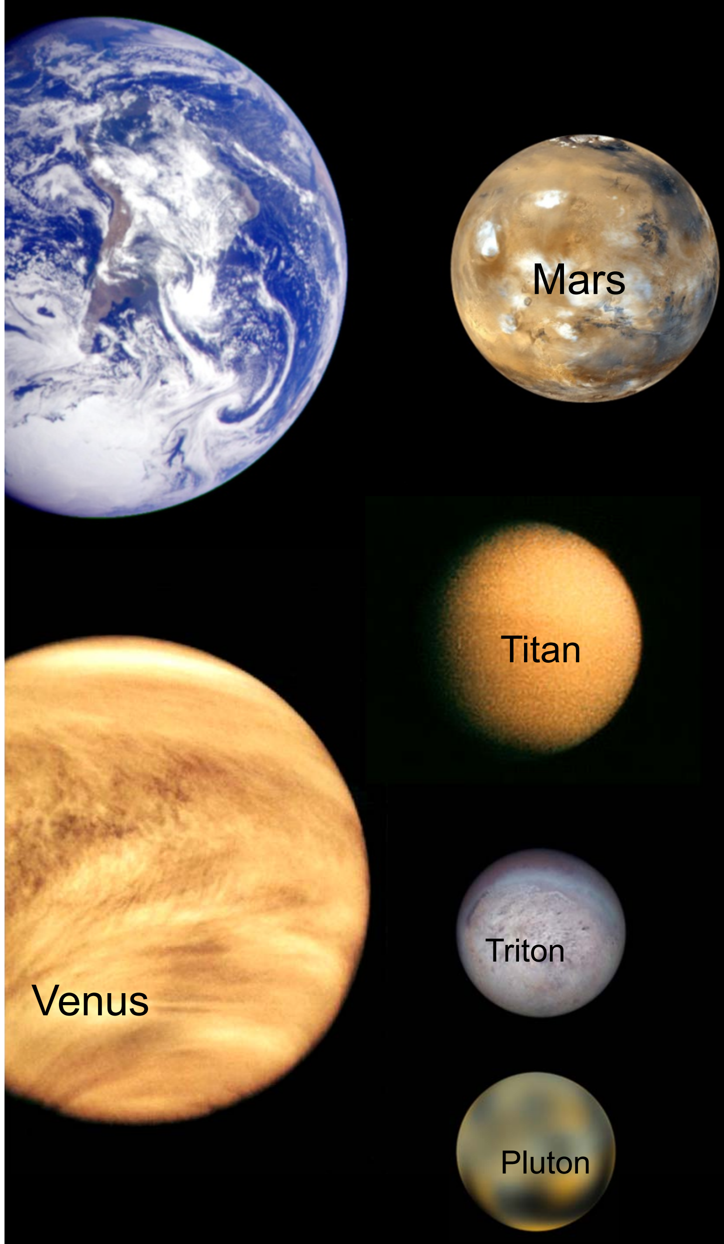
Community Earth System Model (CESM), NCAR:



How to build a full Global Climate Simulator :

How to build a full Global Climate Model :





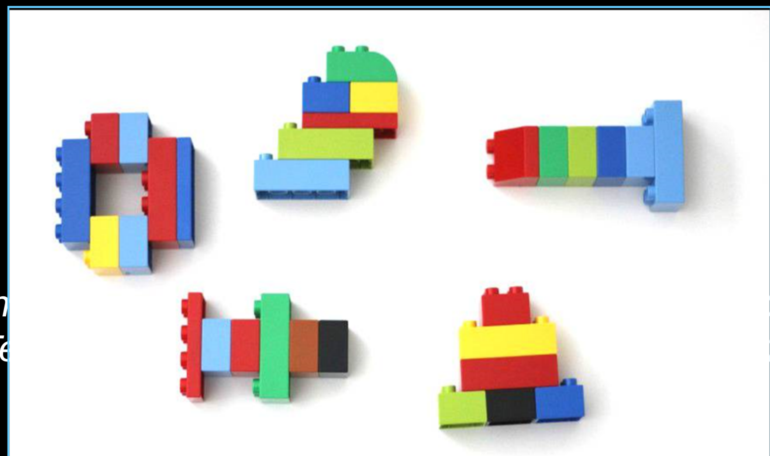
Lessons from Climate Models in the solar system

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.

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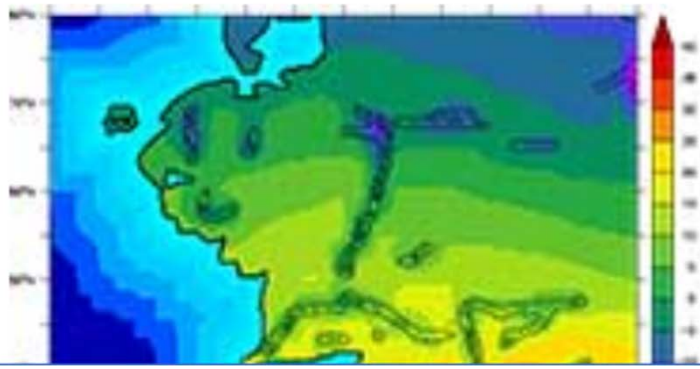
Scientists simulate the climate of Tolkien's Middle Earth

Press release issued: 6 December 2013

Ever wondered what the weather and climate was like in Middle Earth, the land of hobbits, dwarves, elves and orcs, from J.R.R. Tolkien's *The Hobbit* and *The Lord of the Rings*? Climate scientists from the University of Bristol, UK have used a climate model, similar to those used in the recent Intergovernmental Panel on Climate Change (IPCC) report, to simulate and investigate the climate of



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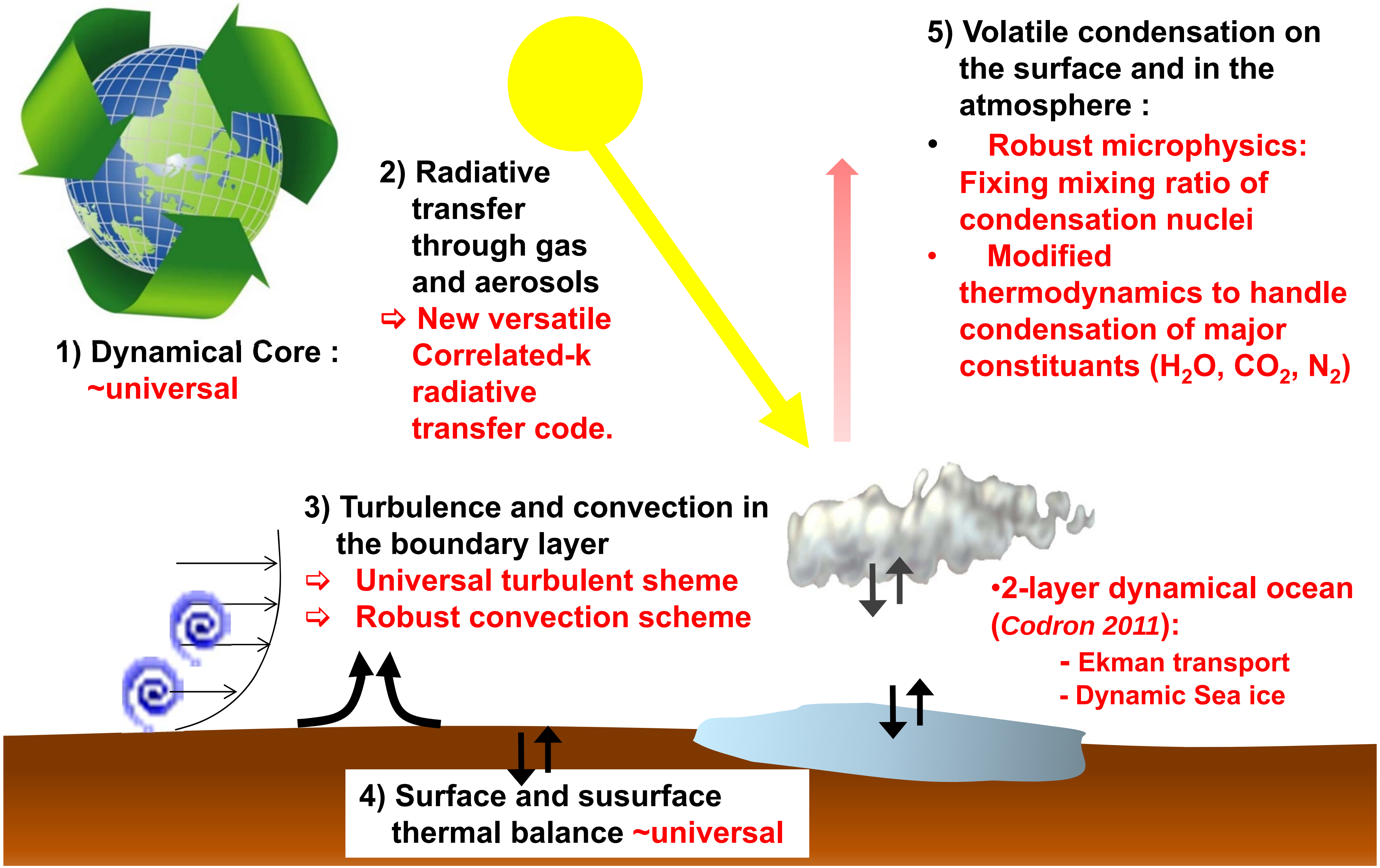
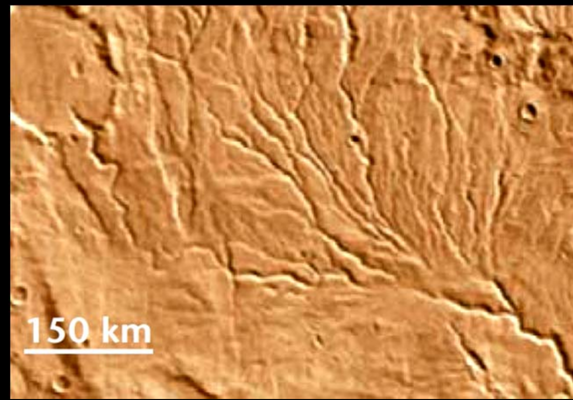
One Model to simulate
them all

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



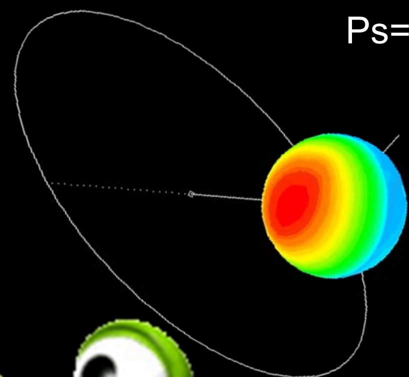
A “Generic” LMD GCM for all terrestrial atmospheres: *Why simulate the unobservable ?*

- **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)*



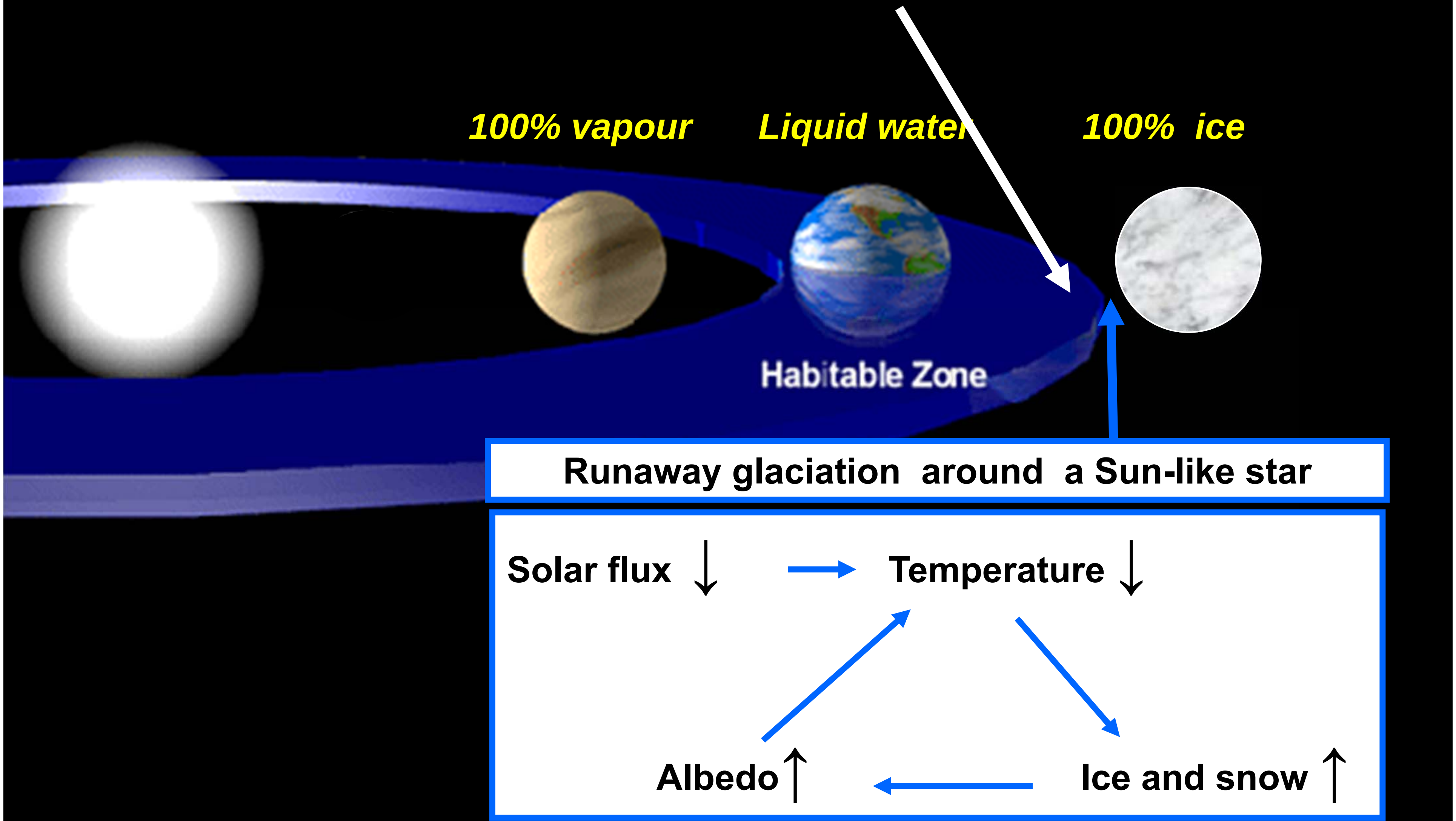
- **To simulate planets around other star to design future telescopic measurements**
  - Exoplanet Thermal phase curves (*Selsis et al. 2011)*
  - Constraining hot superEarth with JWST (*Samuel et al., 2014*)

View at 8.67 µm
Ps= 1bar



- **To adress key scientific questions regarding habitability:**

Outer Edge of the Habitable Zone ?

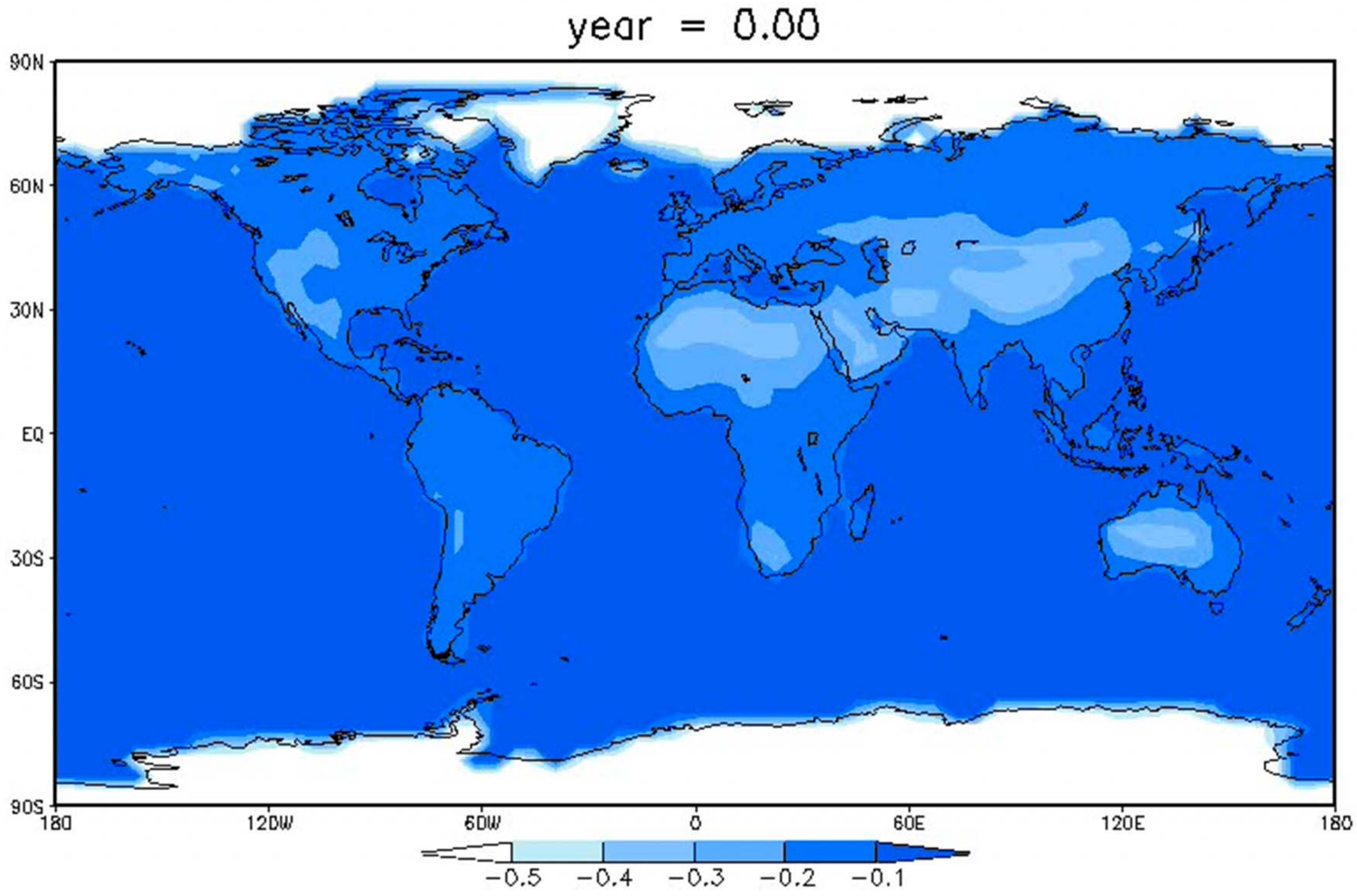


Climate Modelling: the Earth suddenly moved out by 12%

(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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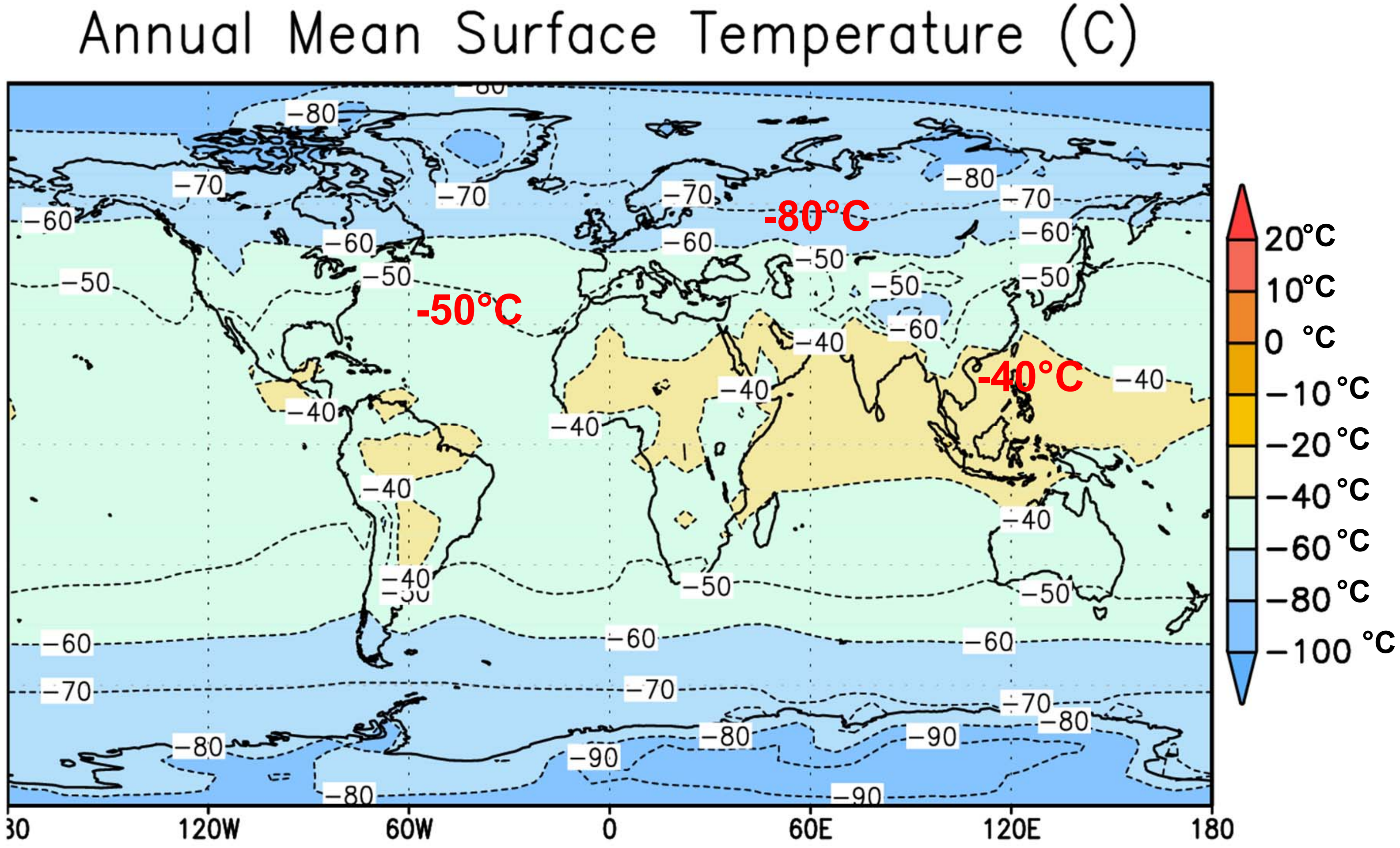
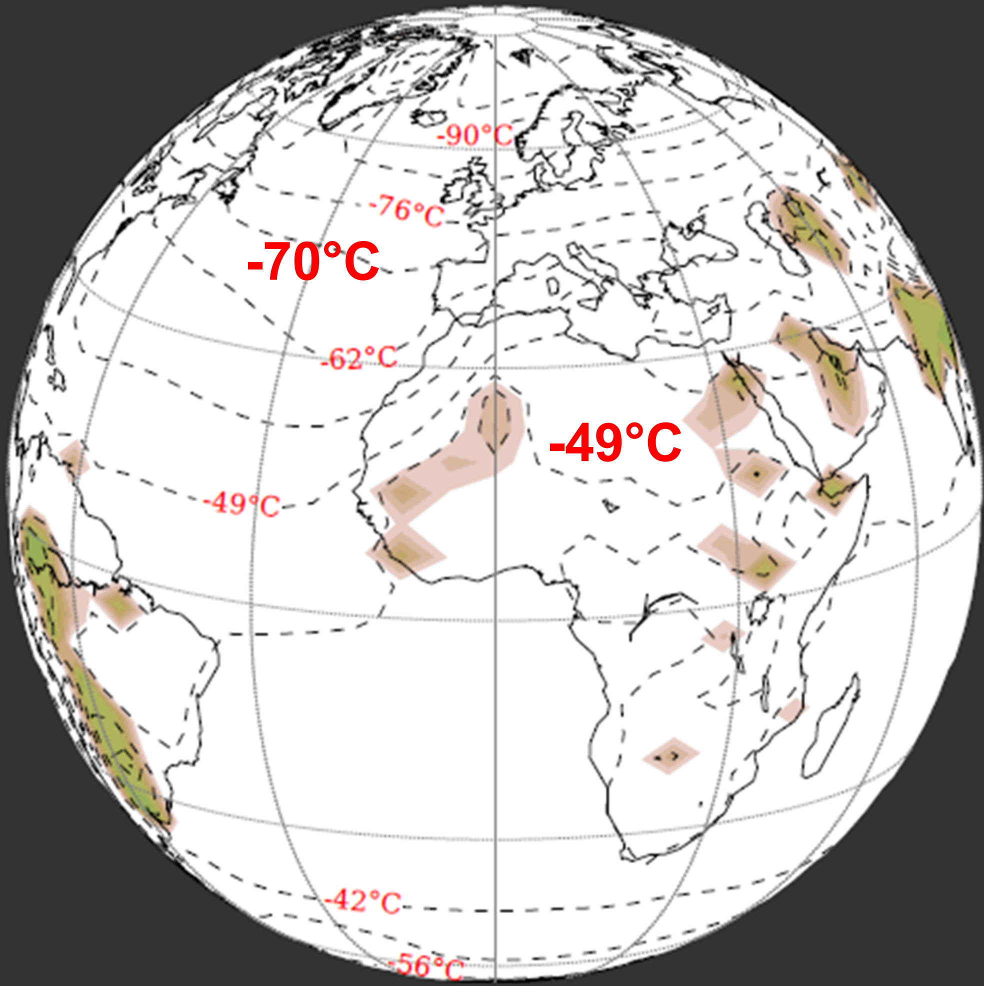


Out of glaciation: greenhouse effect

Flux = 80% present
(~1.12 AU)

Present
Earth atmosphere



Charnay et al., Exploring the faint young Sun problem and the possible climates of the Archean Earth with a 3-D GCM JGR (2013)

Out of glaciation: greenhouse effect

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$[CO_2] \times 2.5$

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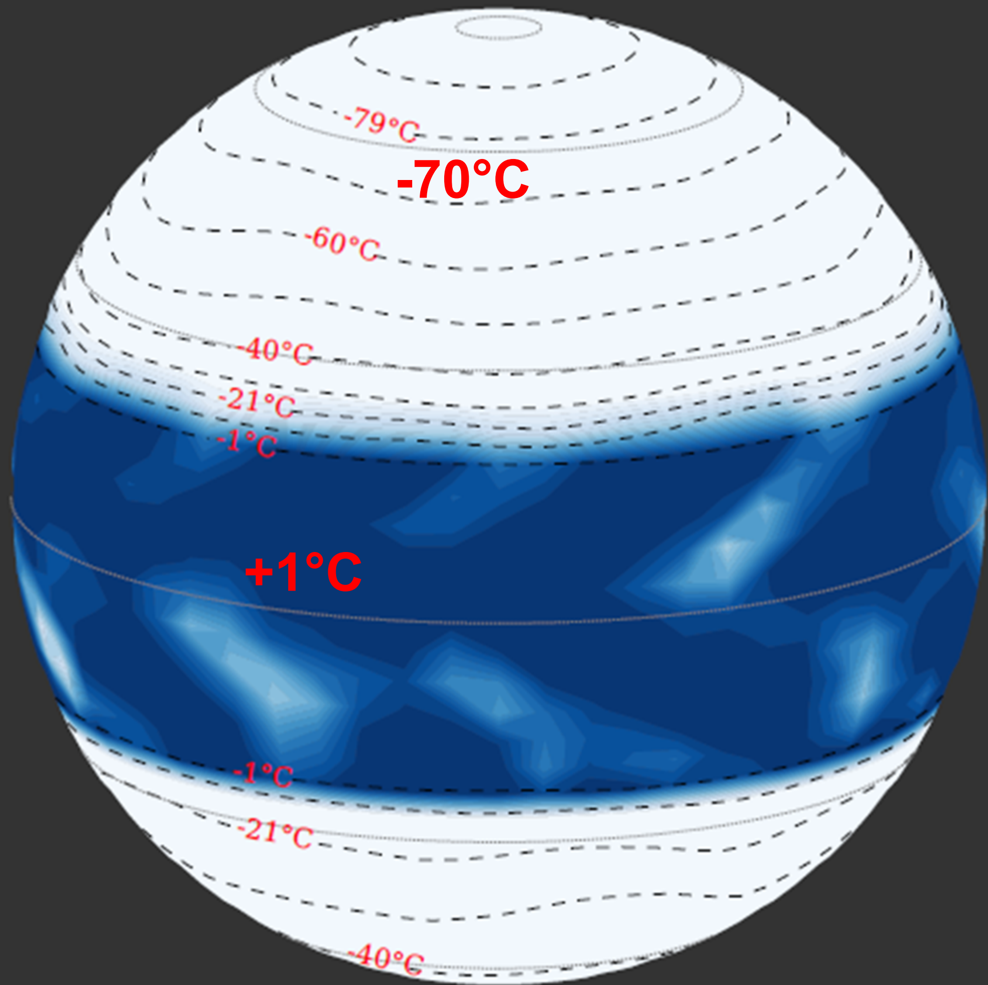

Out of glaciation: greenhouse effect

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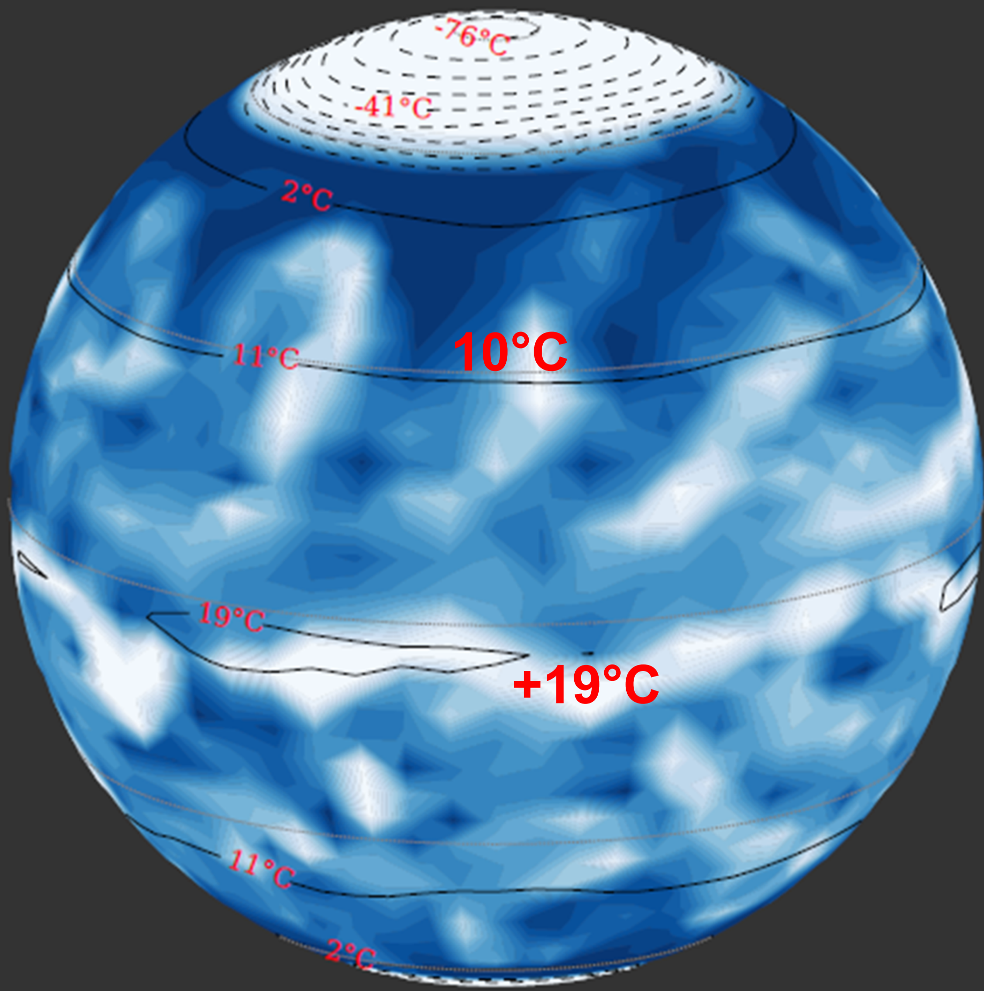
$[CO_2]$ x 250
[CH4] x 1000



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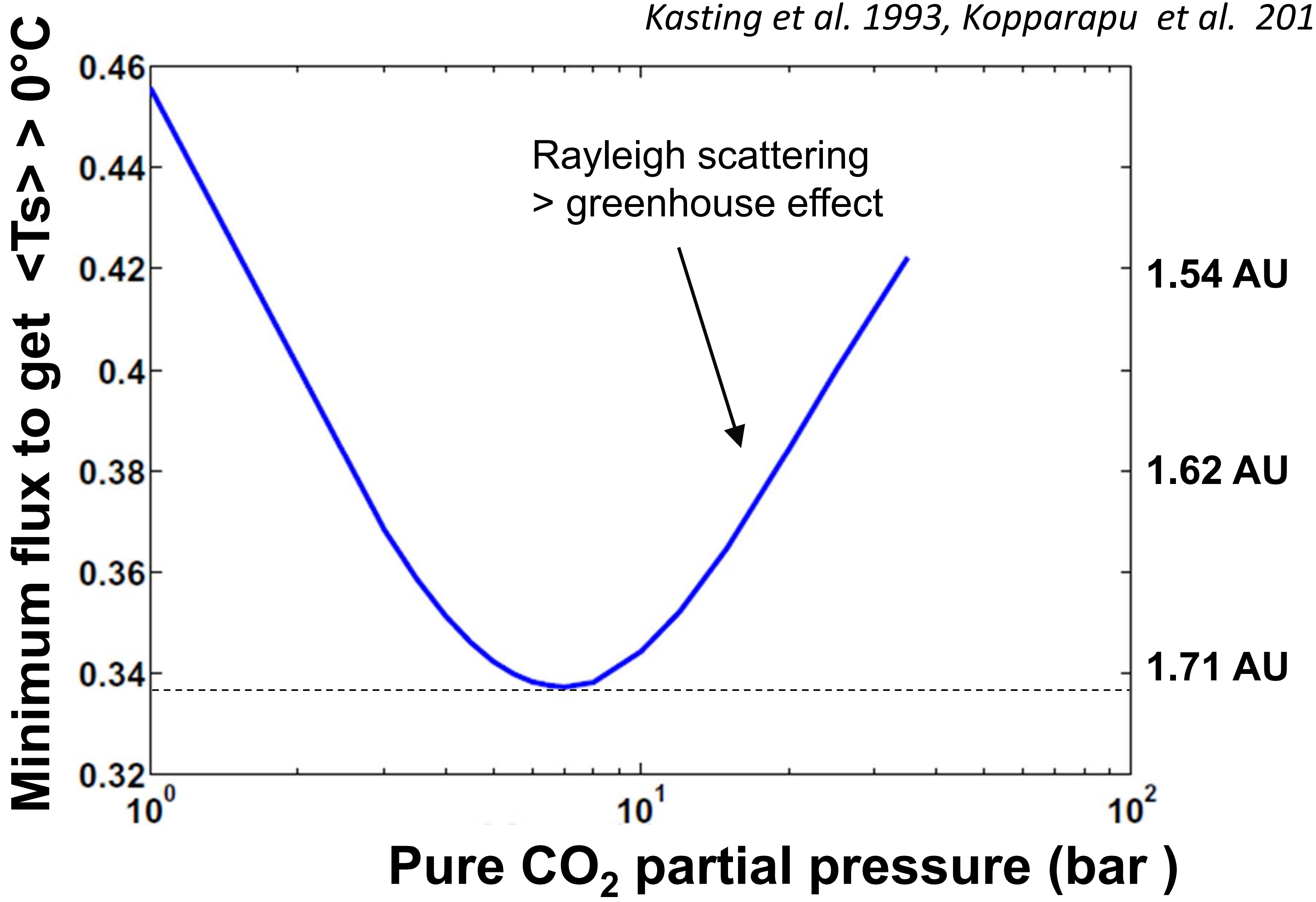
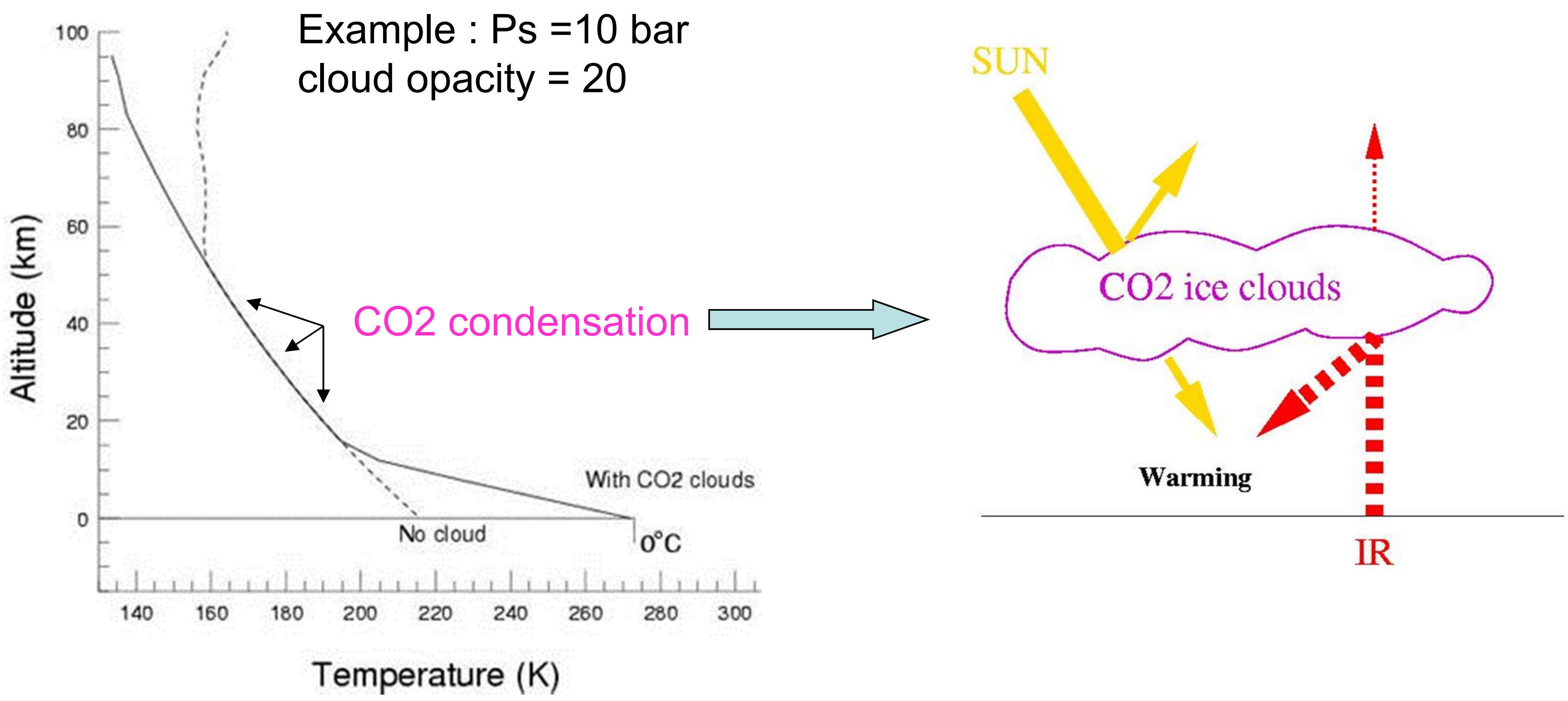
How far can greenhouse effect can keep a planet warm around a sun-like star?

Kasting et al. 1993, Kopparapu et al. 2013

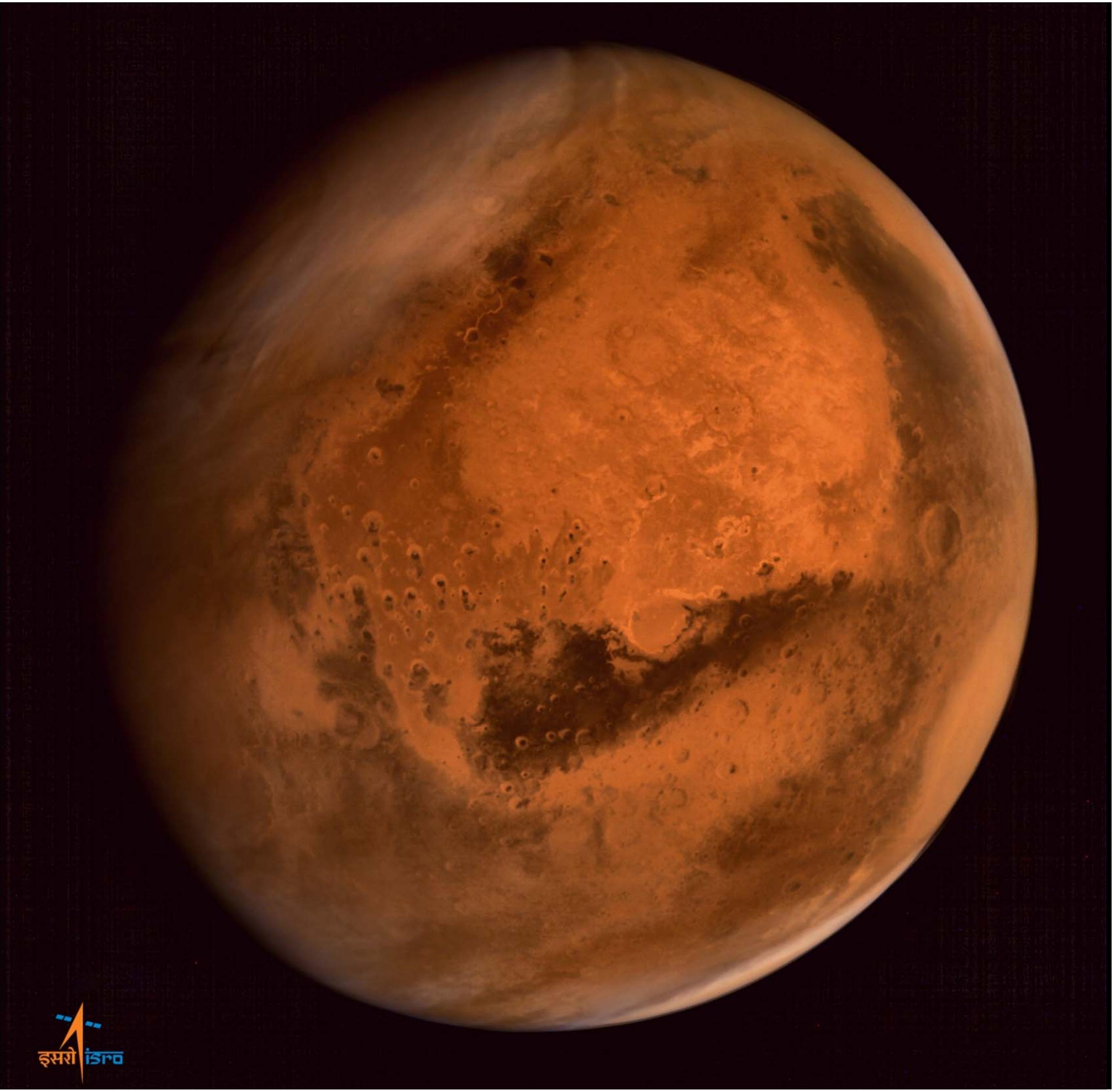


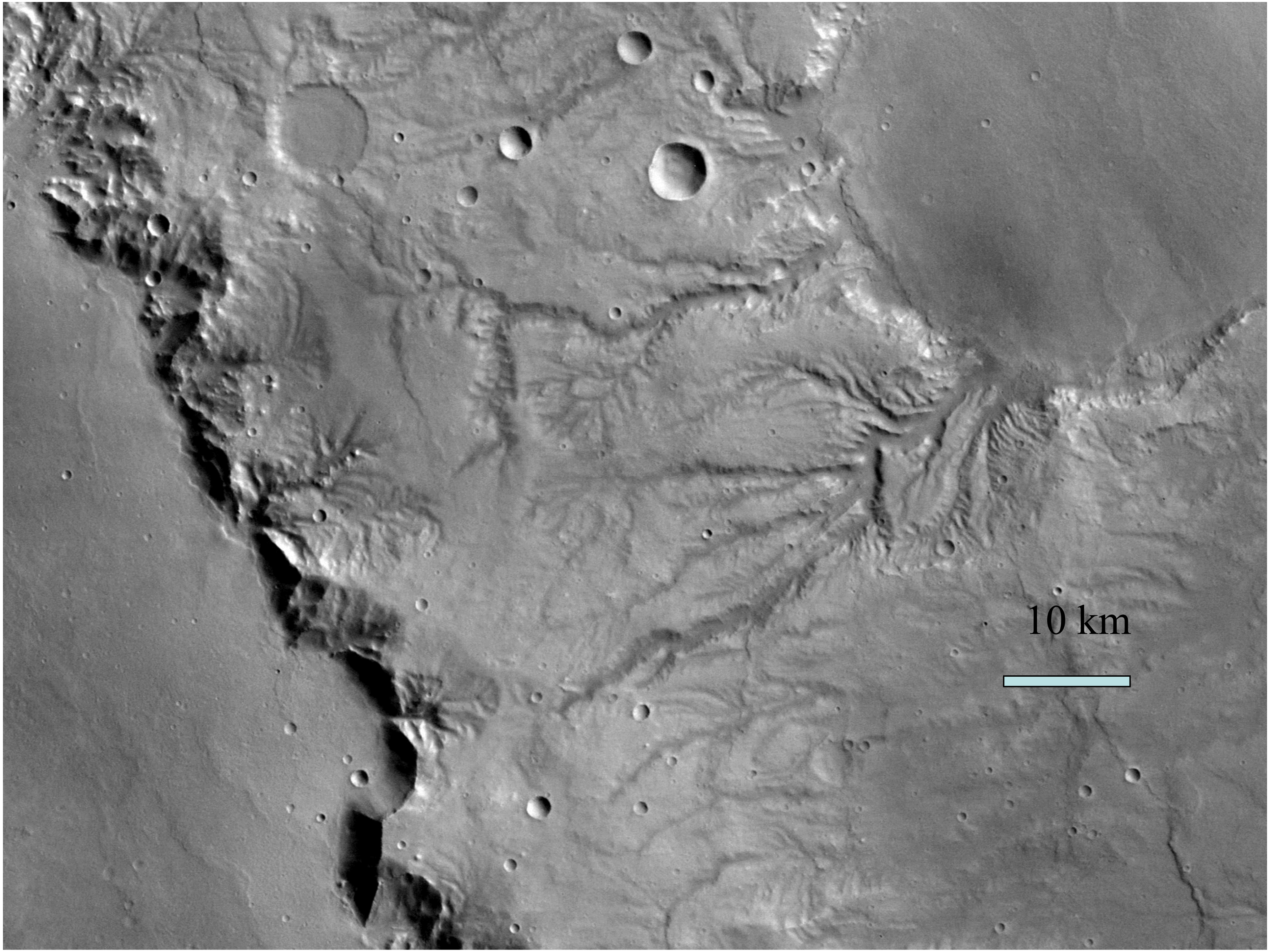
Scattering Greenhouse effect of CO_2 ice clouds
⇨ 0°C as far as 2.5 AU from the Sun ?

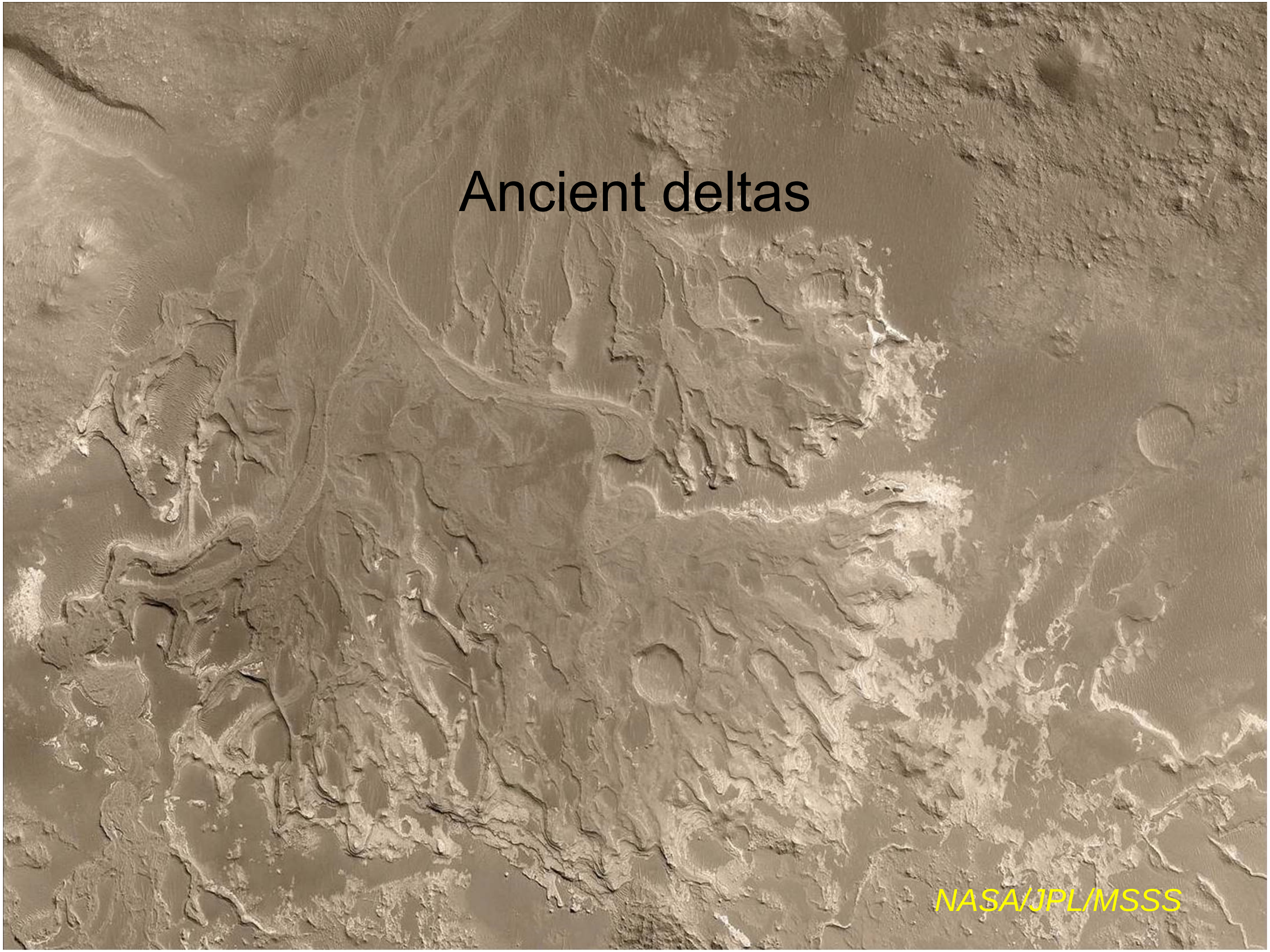
Forget and Pierrehumbert (1997)



MARS




10 km

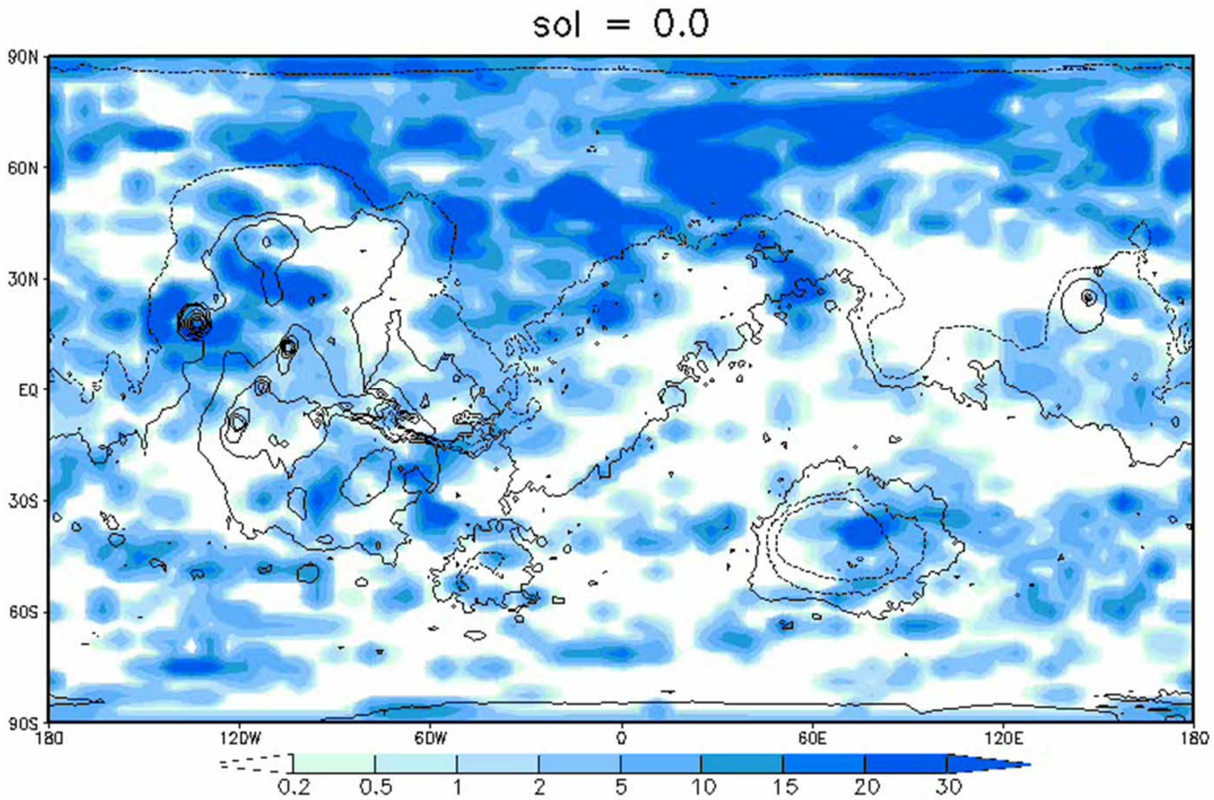

Ancient deltas
NASA/JPL/MSSS

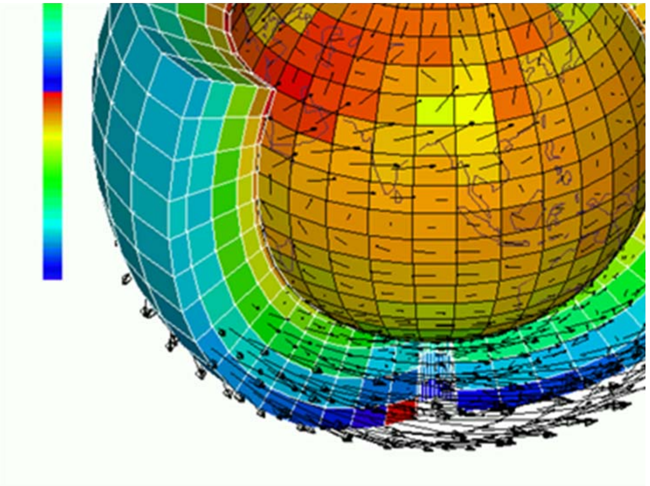
Mars 4 billions years ago ?

(distance to the Sun equivalent to 1.75 UA ; 34% Earth flux)

3D Global climate simulations of Early Mars

(distance equivalent to 1.75 UA)



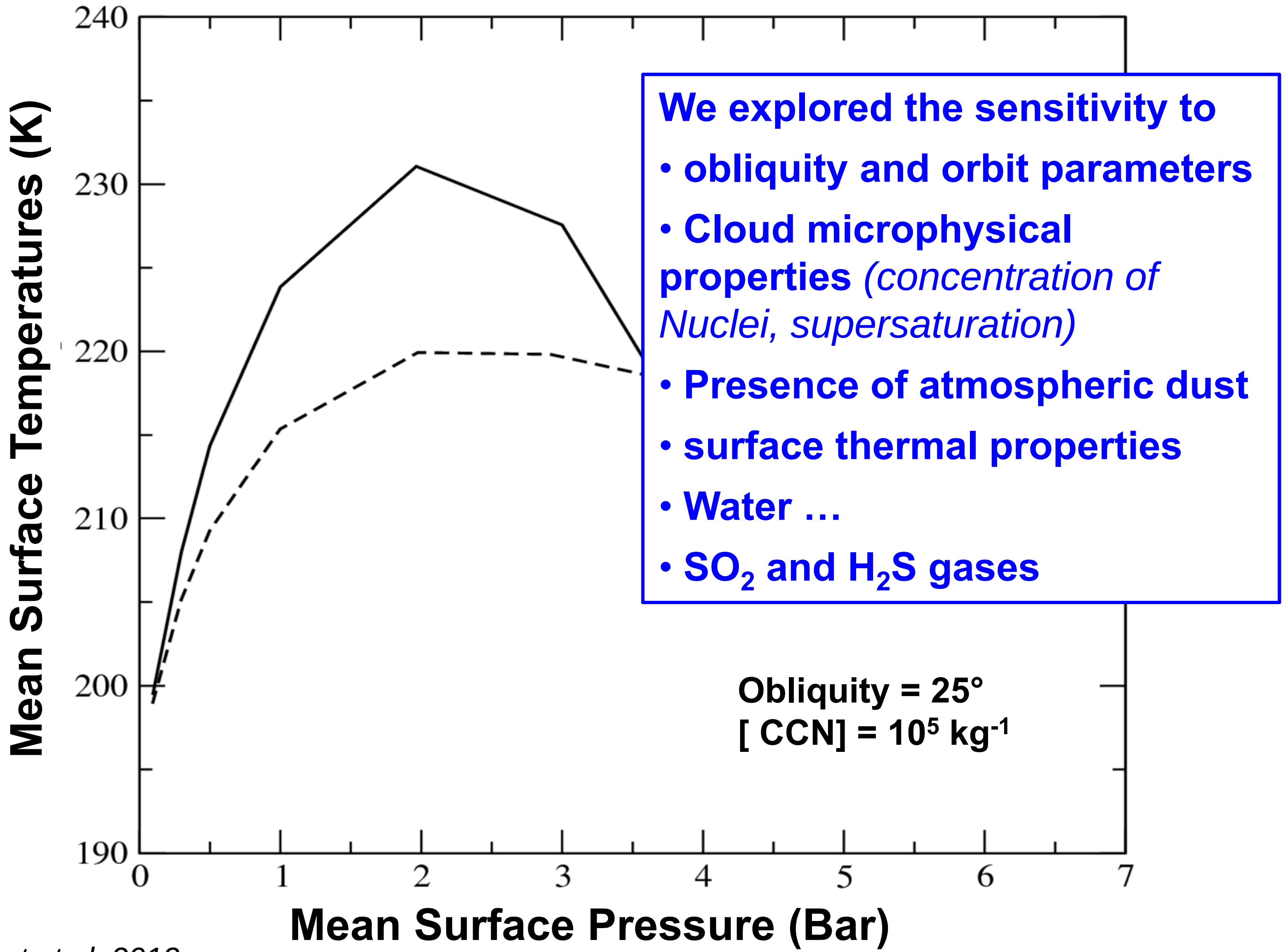


Forget and Pierrehumbert 1997

CO2 ice Cloud optical depth

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

Simulated Global mean surface temperature (K)

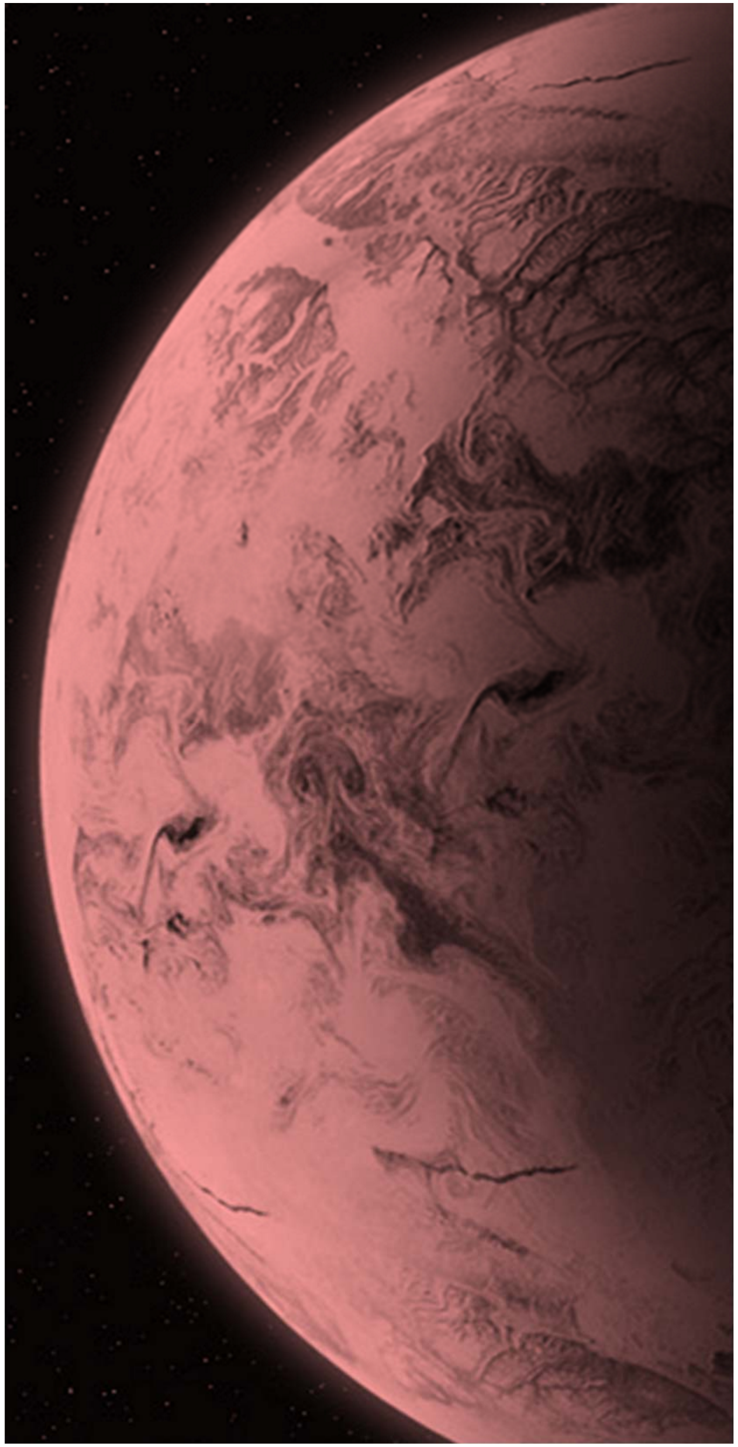


Forget et al. 2013

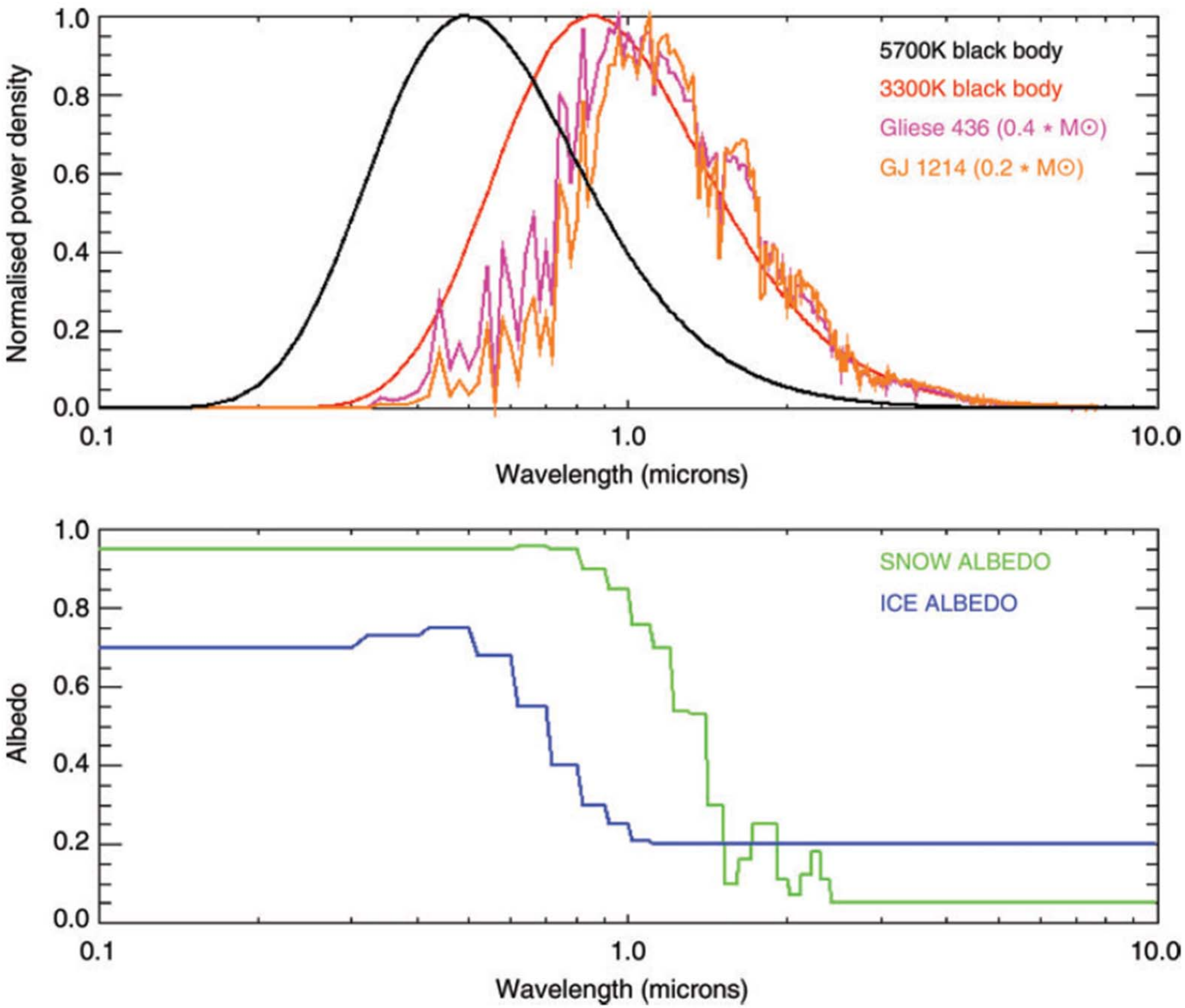
Glaciation around K & M dwarf stars:

Redder stellar spectrum

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



Snow and ice albedo vs Stellar spectra



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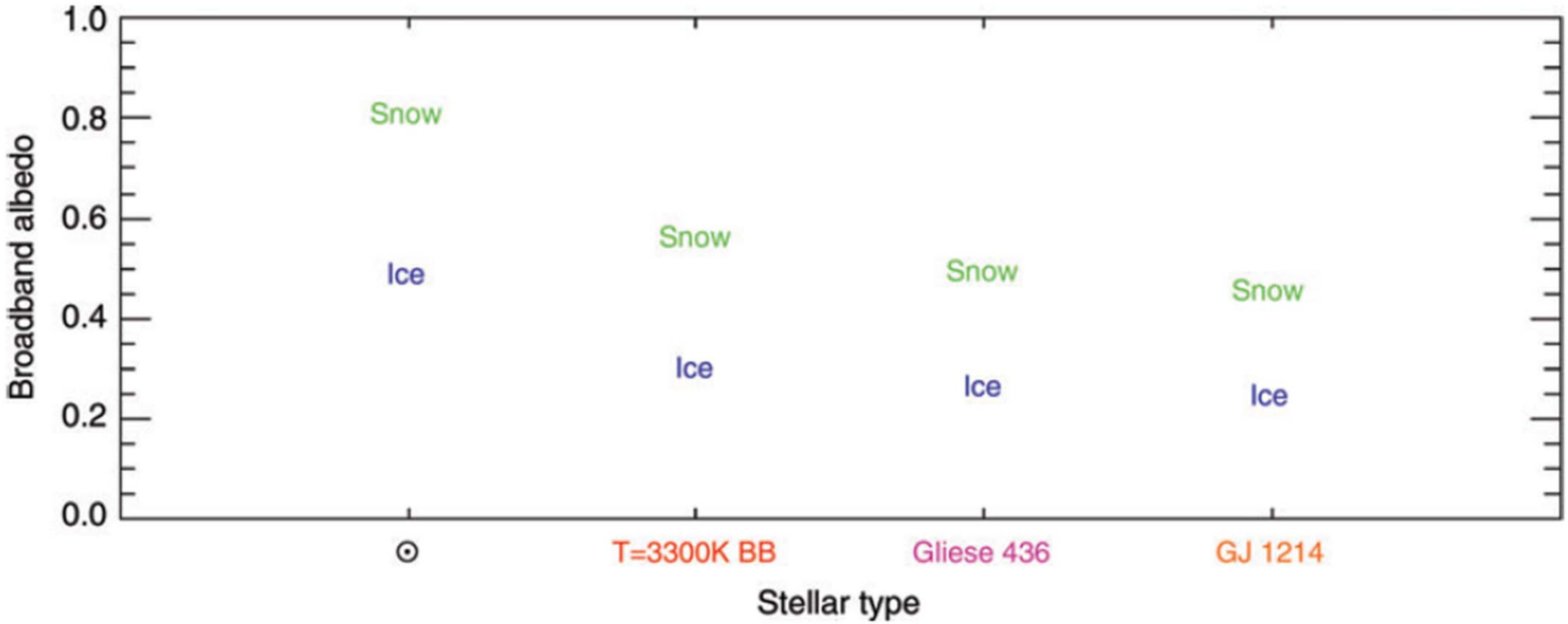

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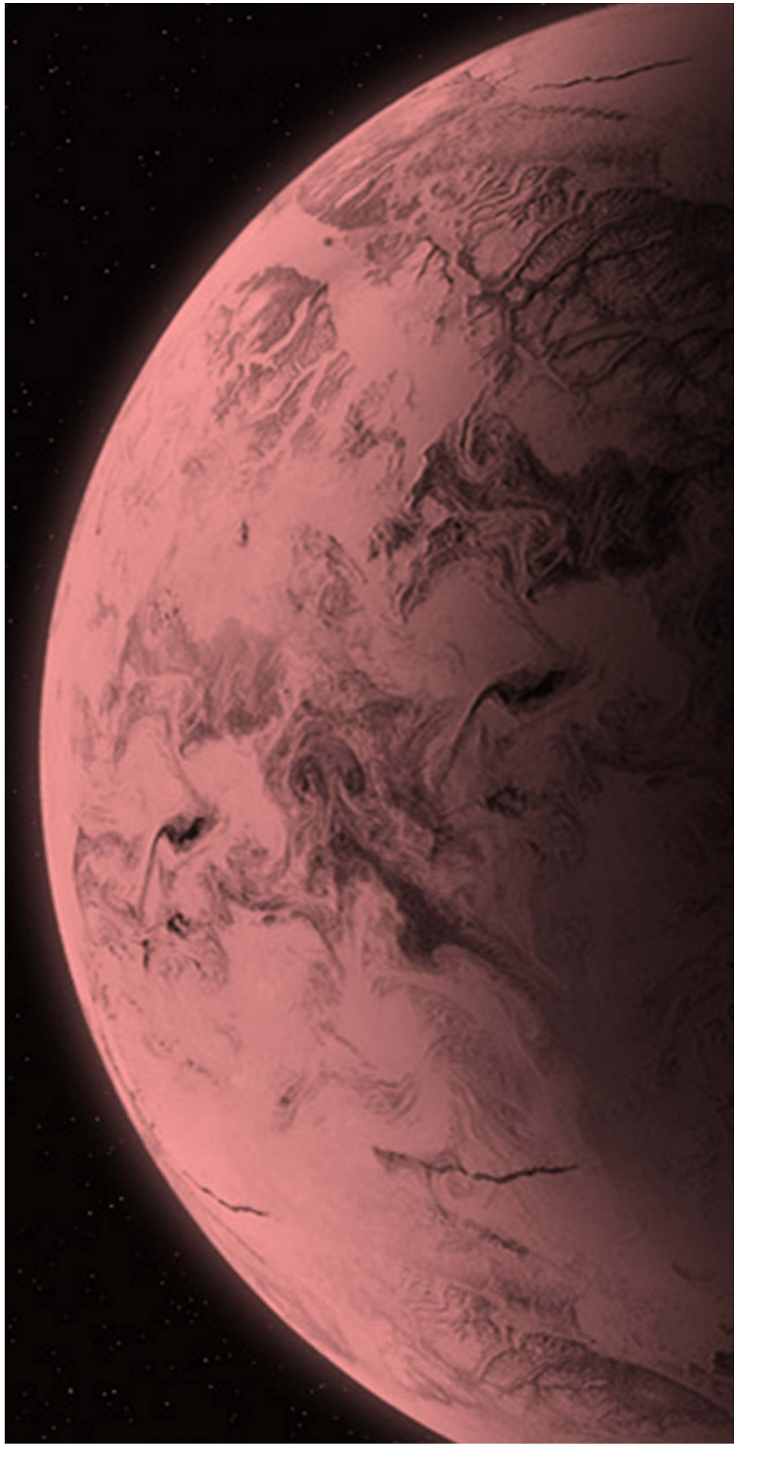
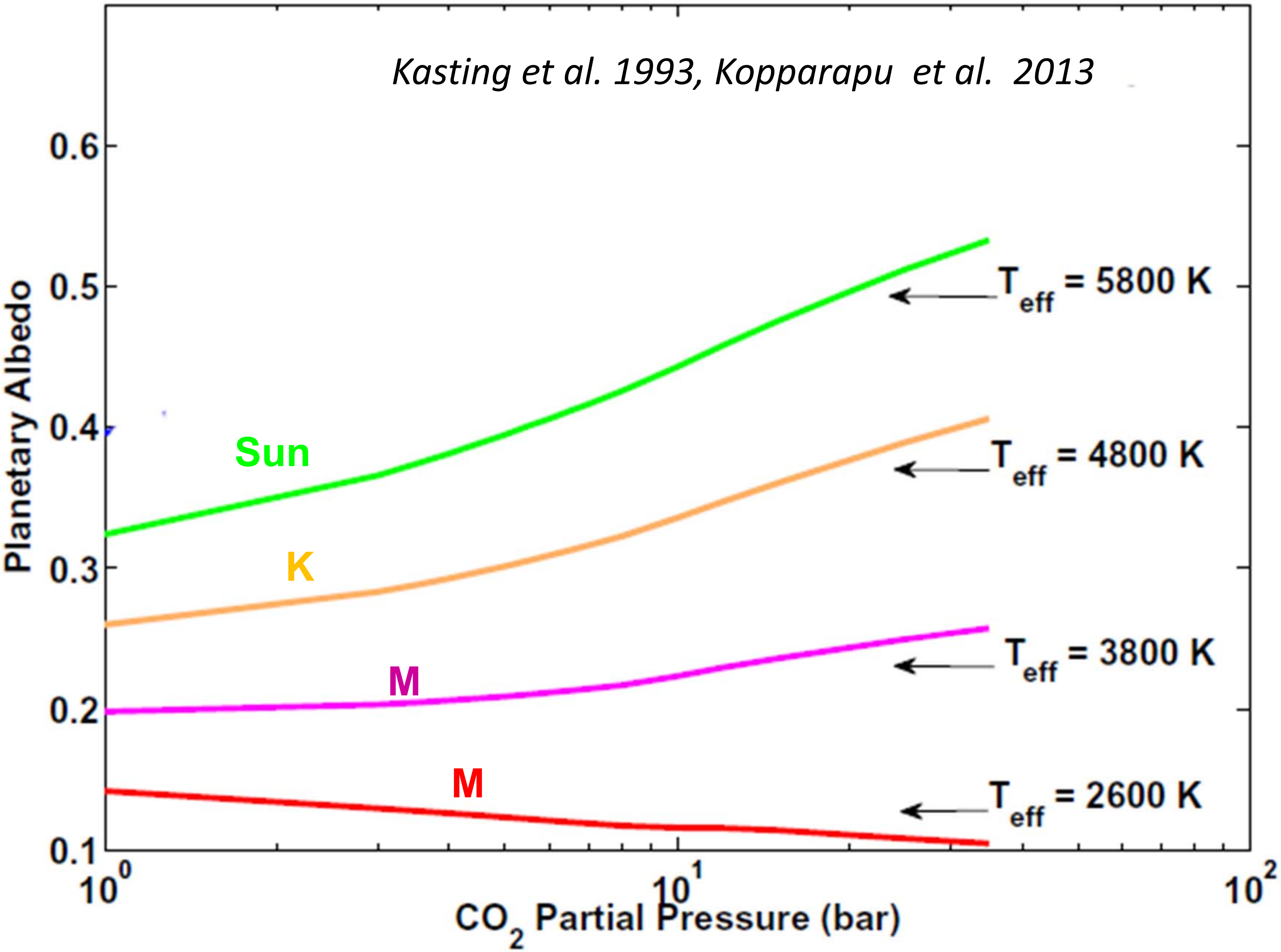
- Weak atmospheric Rayleigh Scaterring

  ⇨ lower albedo

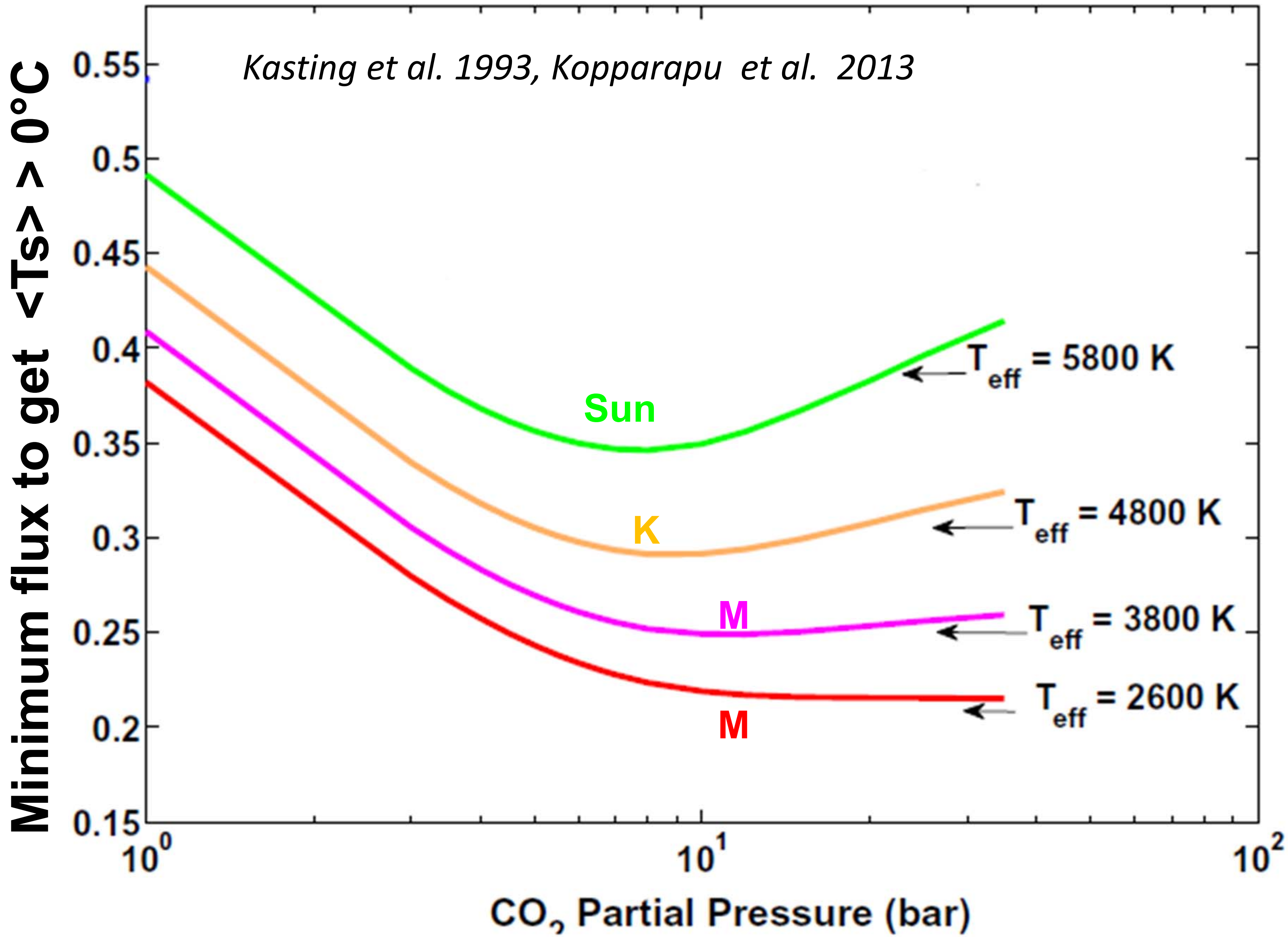
  ⇨ Enhanced high pressure CO2 greenhouse effect



Planetary Albedo around G, K, M stars
(with Rayleigh Scaterring of CO2 gas)



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



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Redder stellar spectrum

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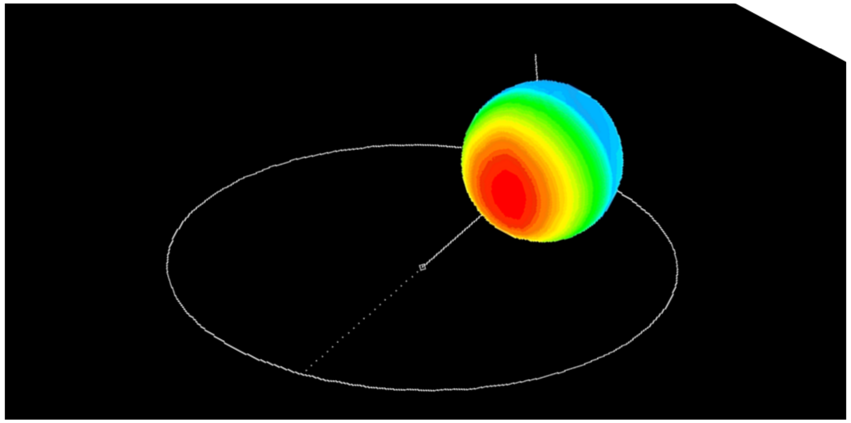
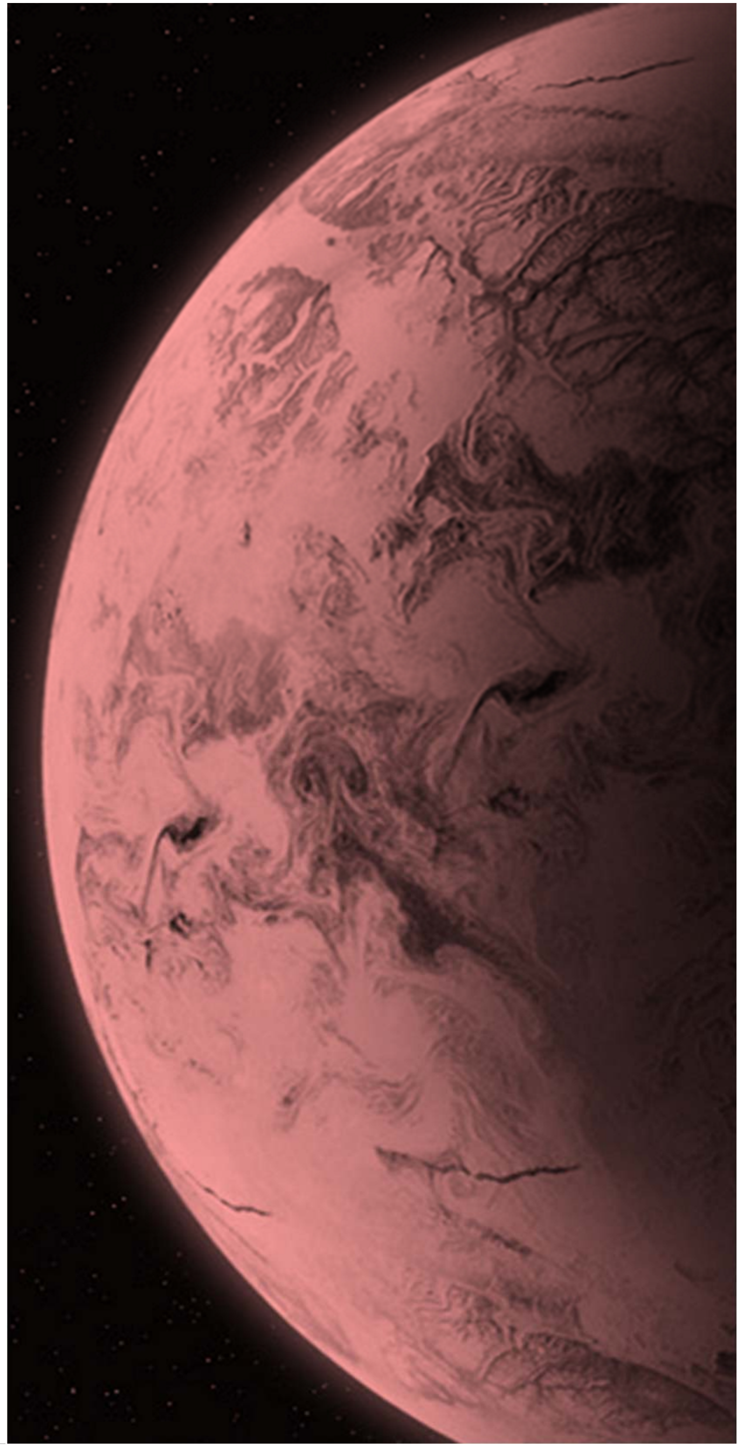
But : Effect of tides on rotation:

- Resonant rotation with zero obliquity

⇨ No insolation at the pole

⇨ Possible Locking with permanent night side



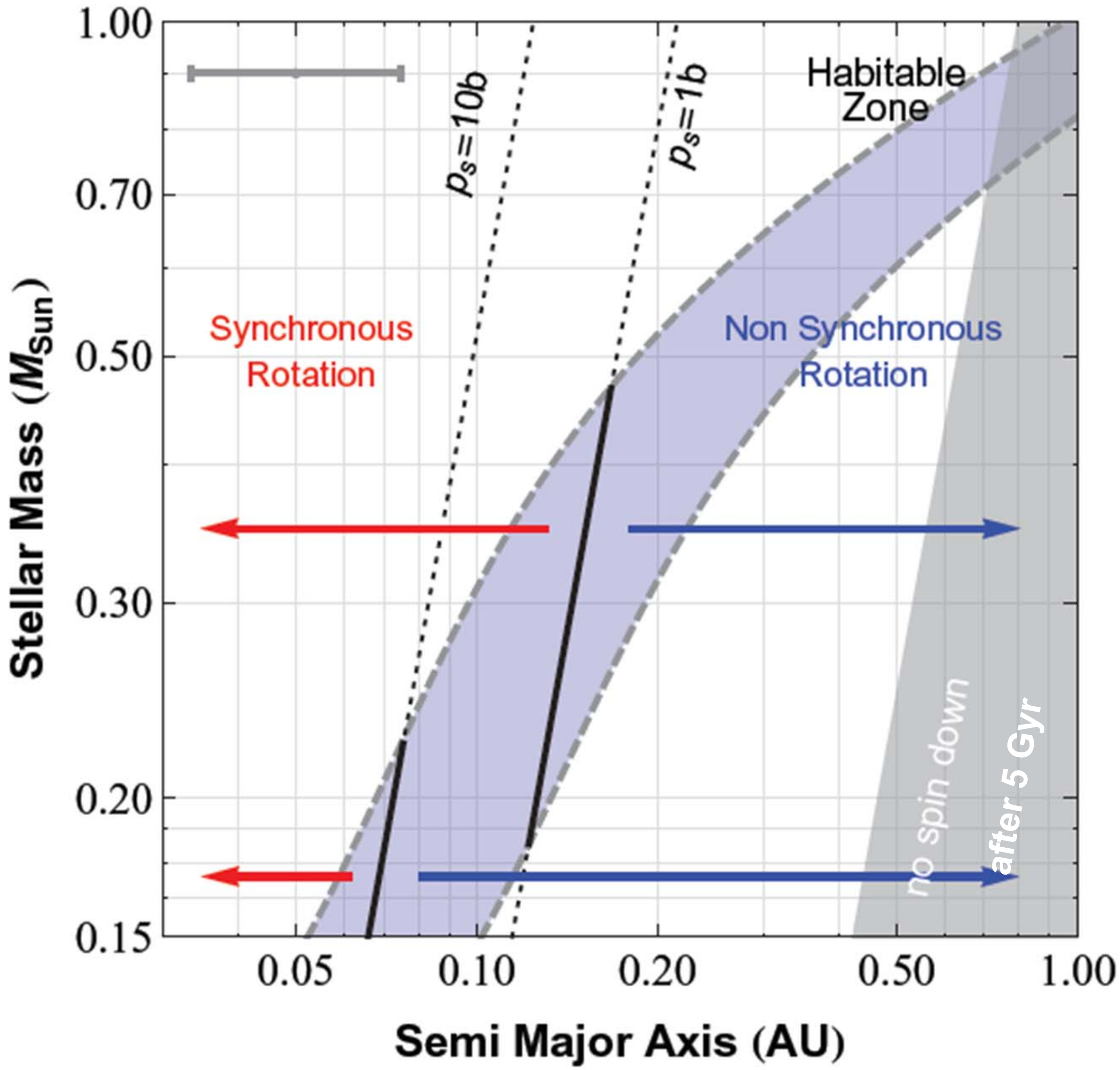


Side Question: Are terrestrial planets in M star habitable zone tidally locked ?

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]*

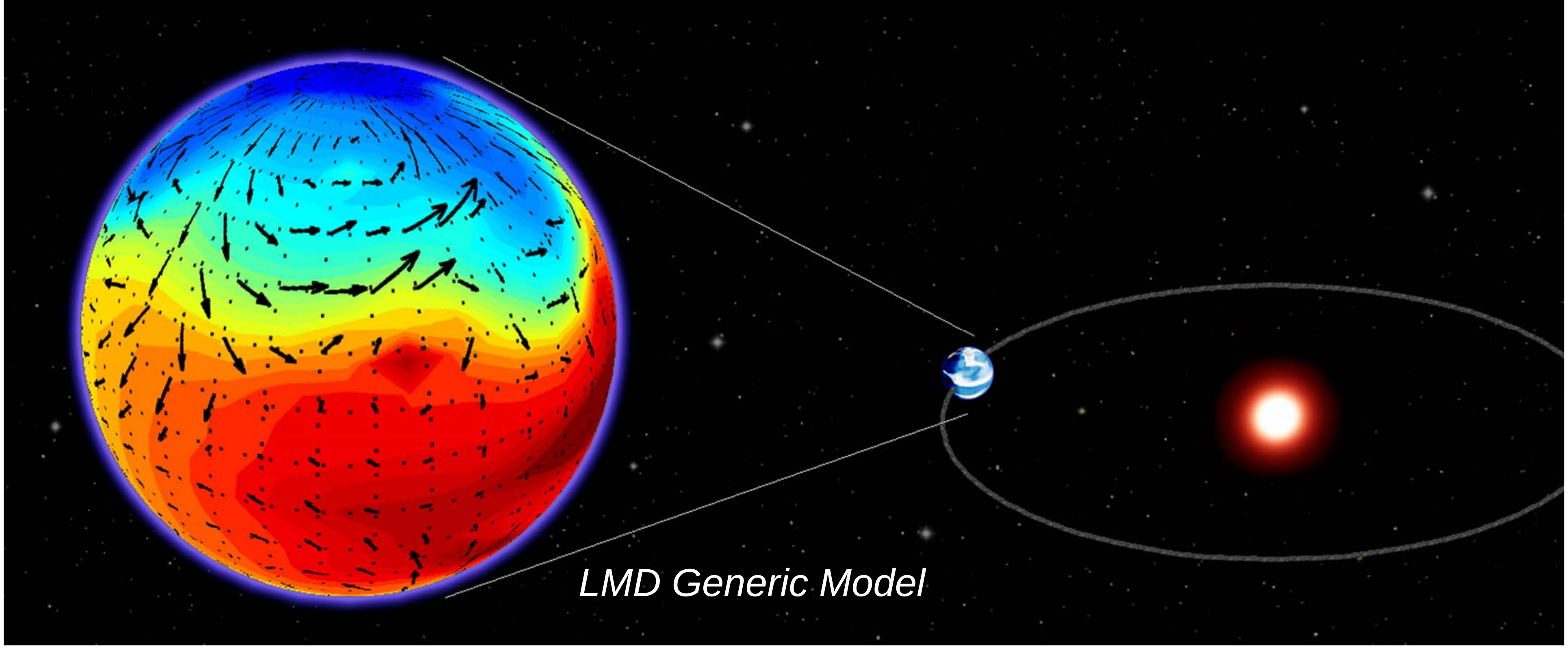
Leconte et al. 2014, in revision



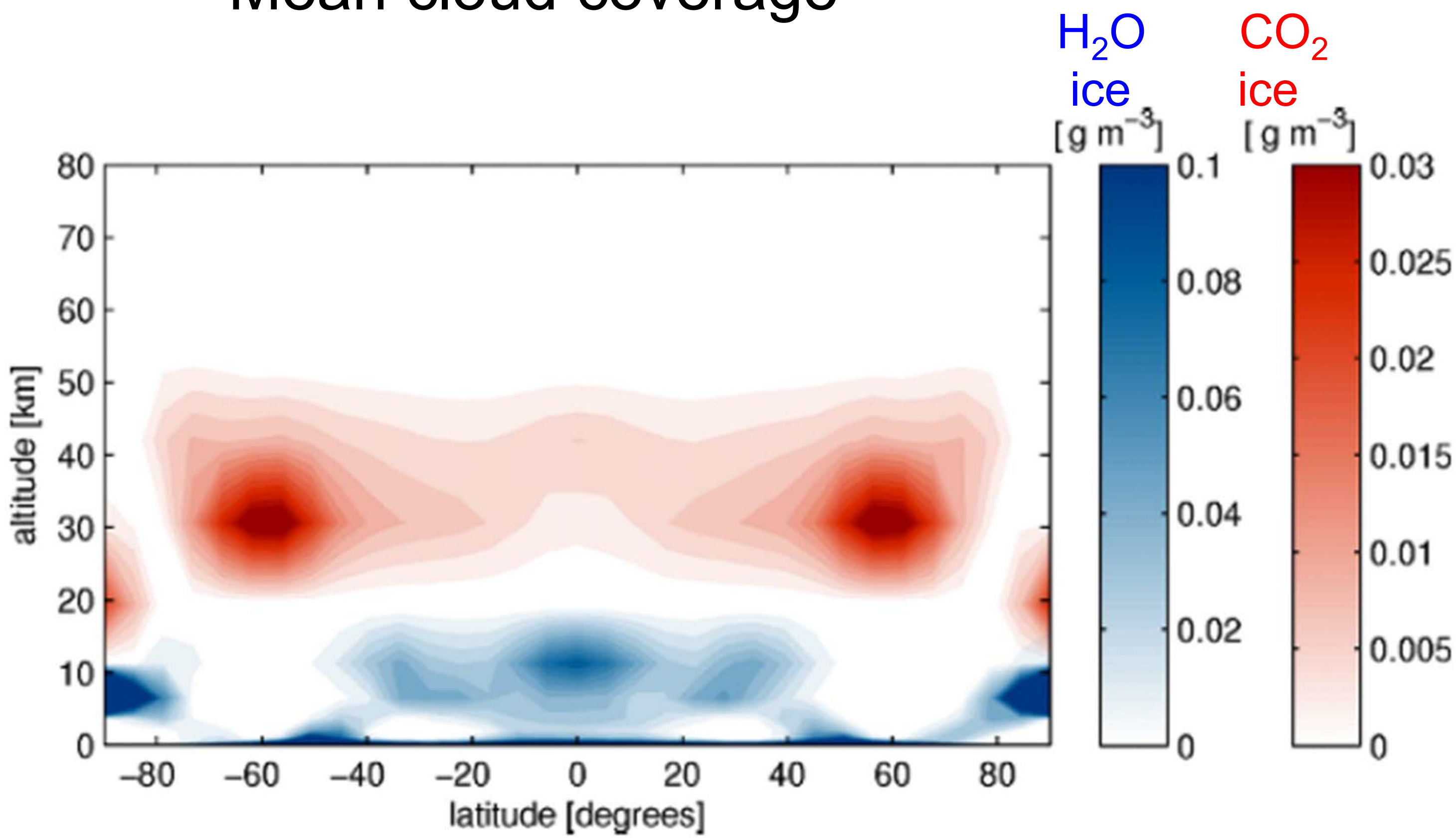
Example: simulating the climate on Exoplanet Gliese 581d

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!)



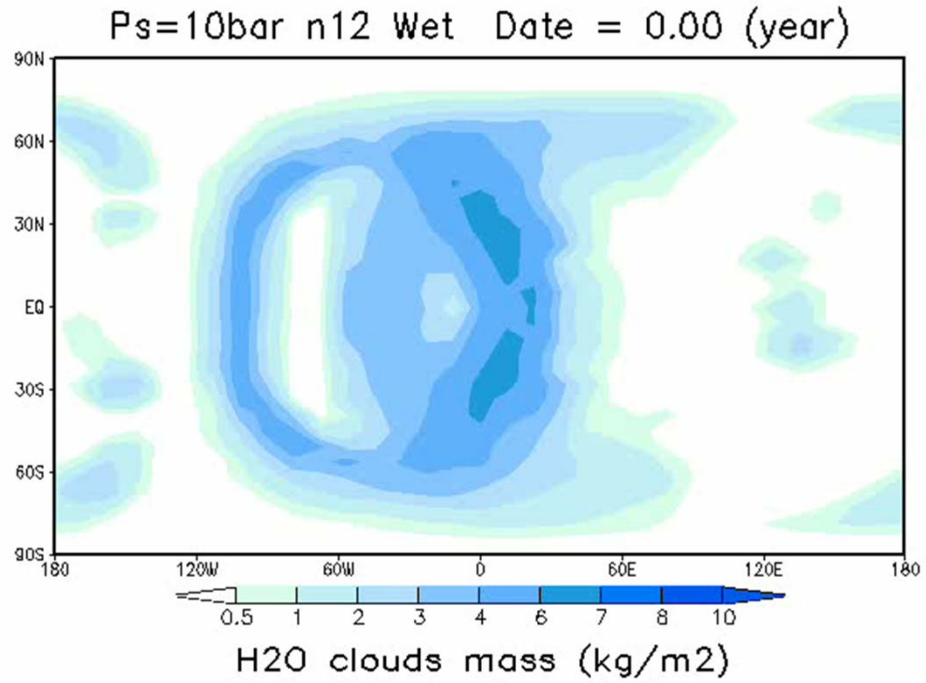
Gliese 581d
Ocean planet Case (no oceanic transport)
Mean cloud coverage



Wordsworth et al. 2011

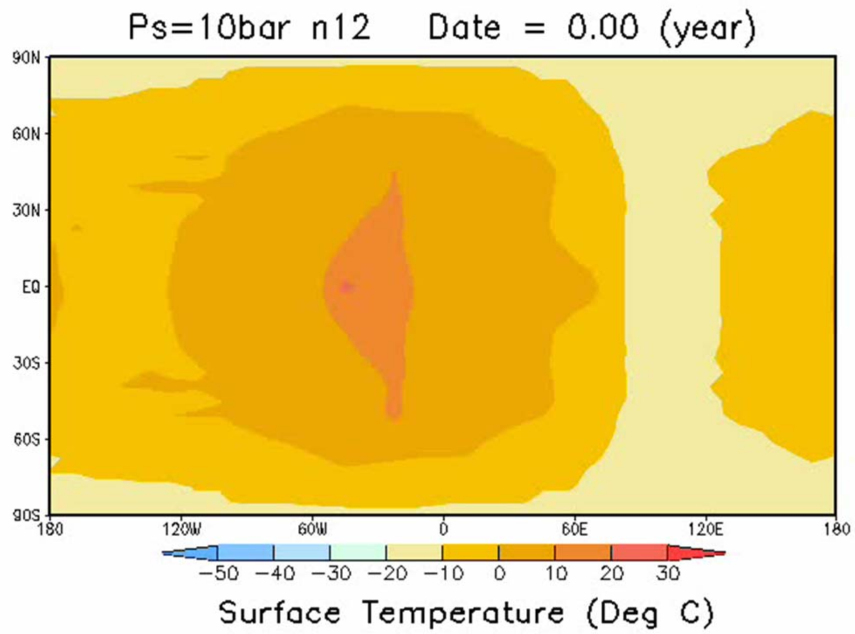
Gliese 581D

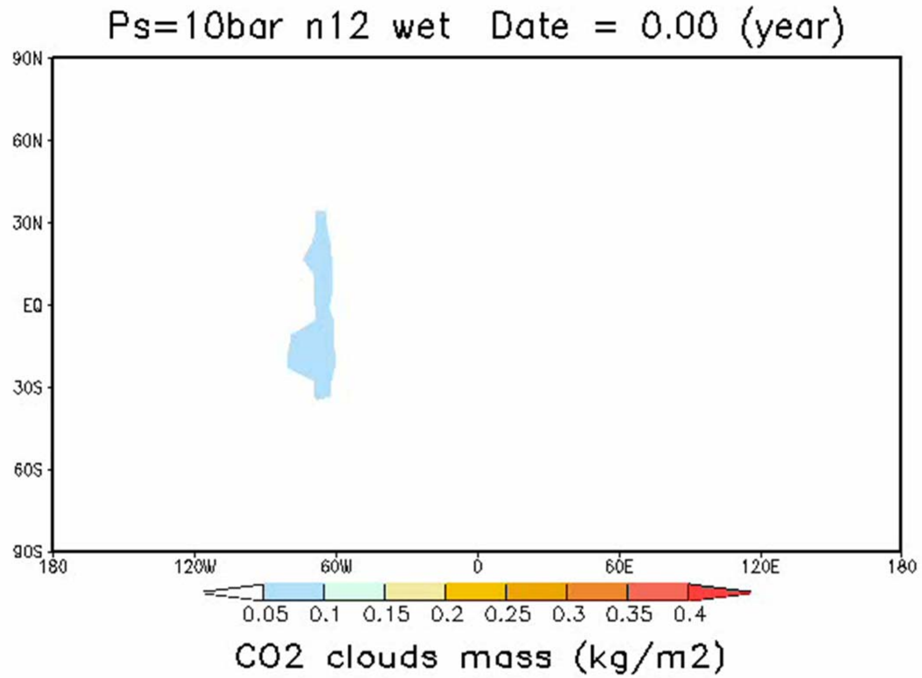
Water clouds



CO2 ice clouds

Surface temperature (K)



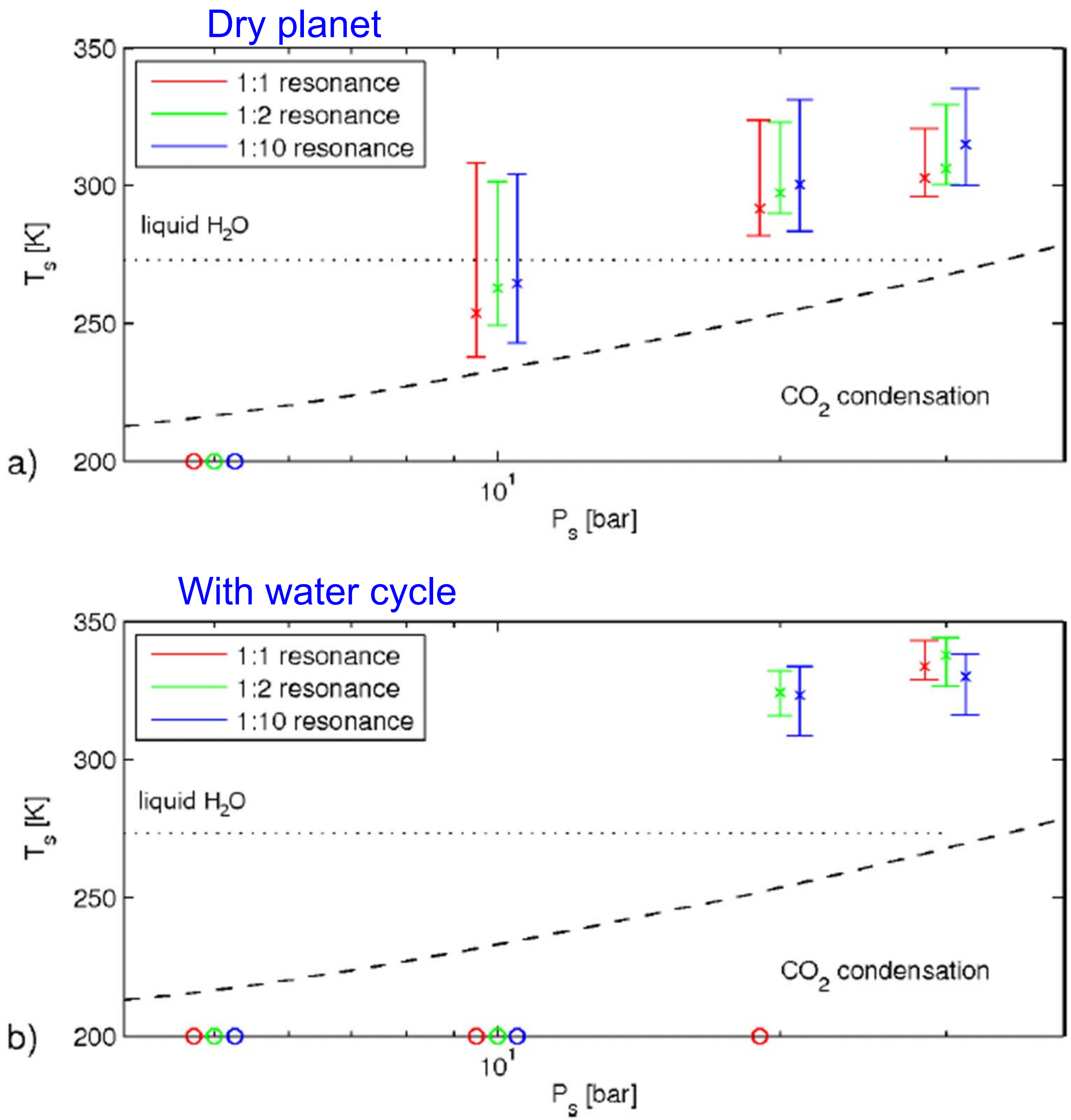


Gliese 581d: conclusions

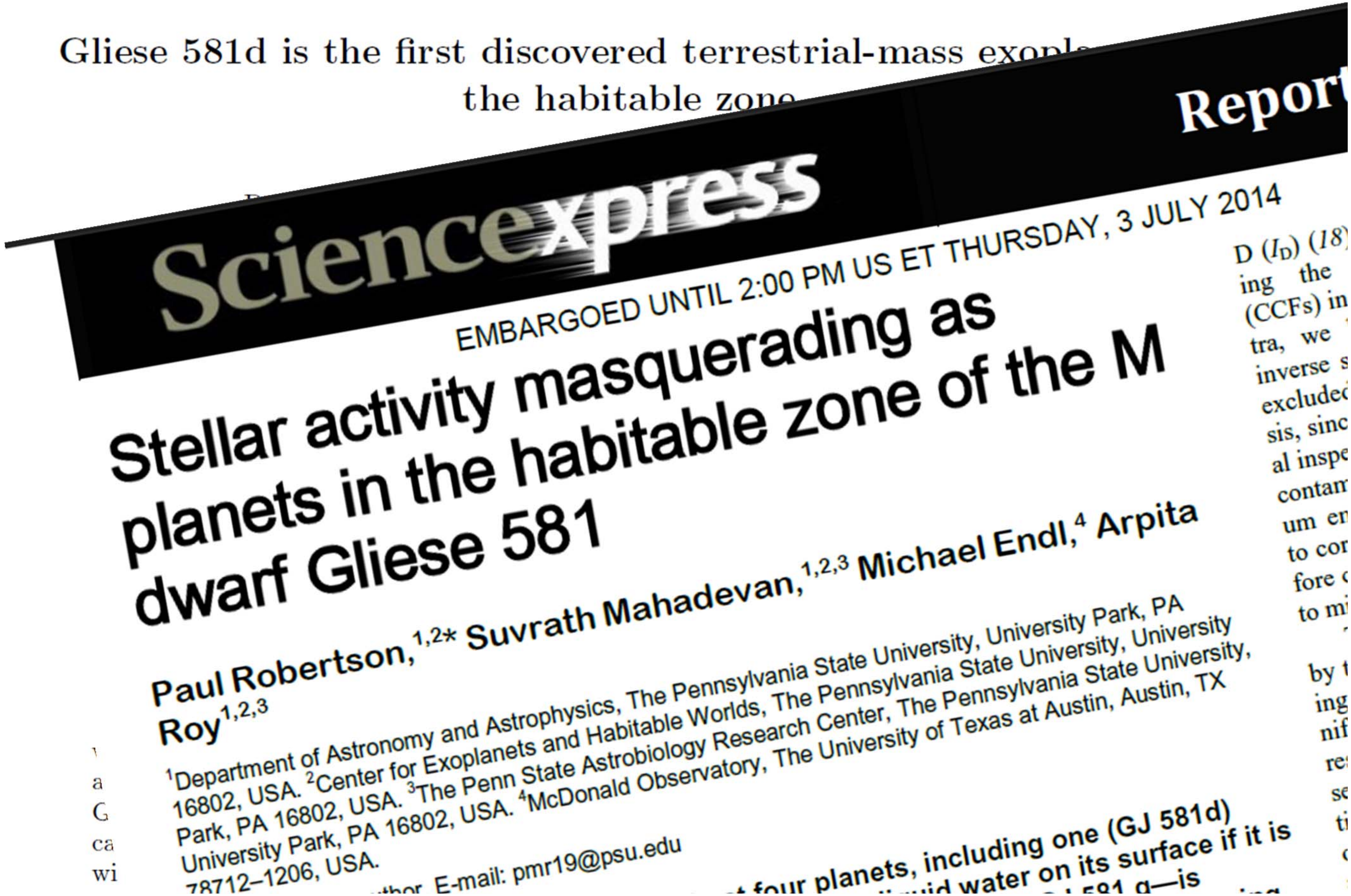
Assuming enough CO2 and H2O (which is not unlikely), Gliese 581d WOULD be habitable.

The first discovered planet in the Habitable zone!

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

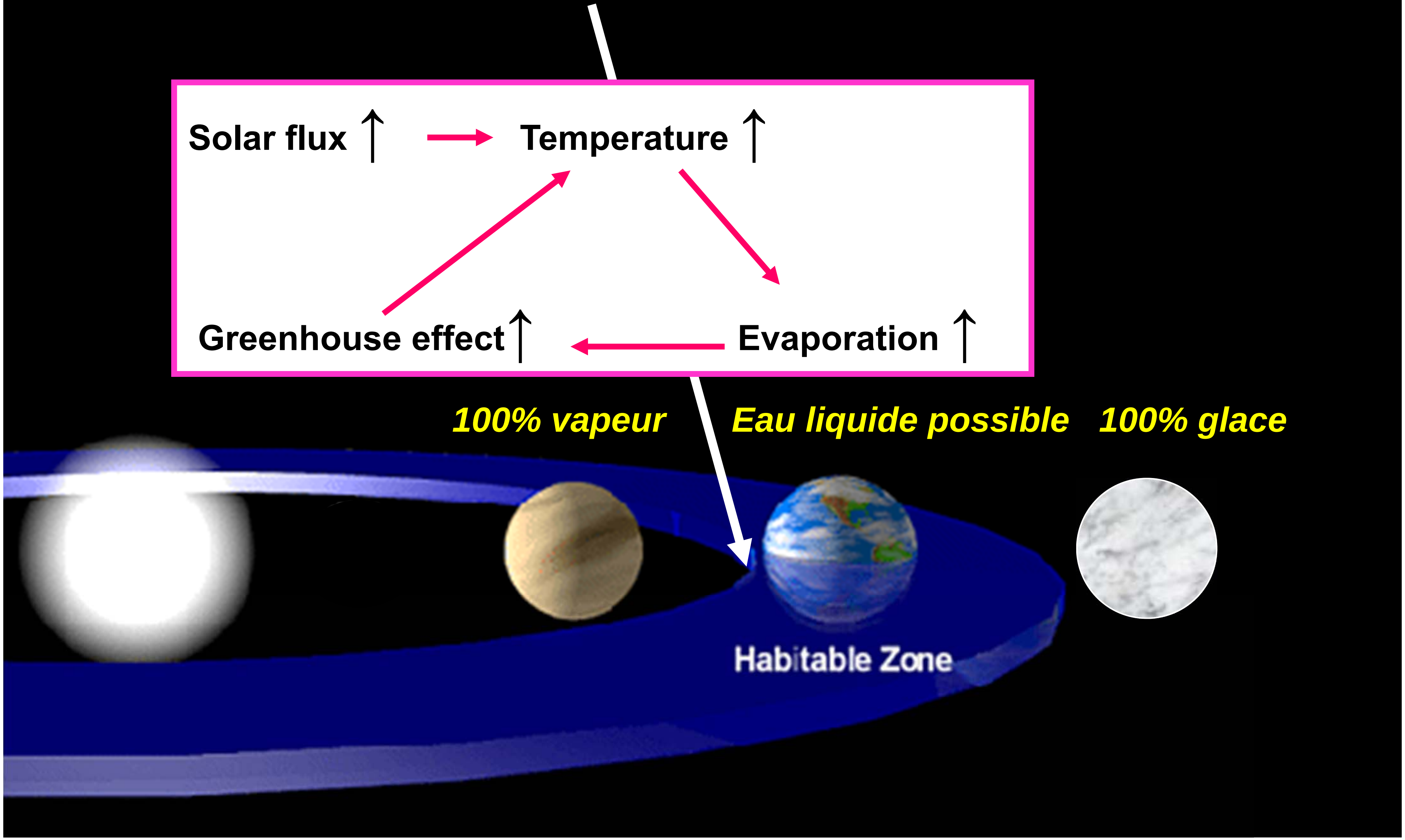
Paul Robertson,[1,2]* Suvrath Mahadevan,[1,2,3] Michael Endl,[4] Arpita Roy[1,2,3]

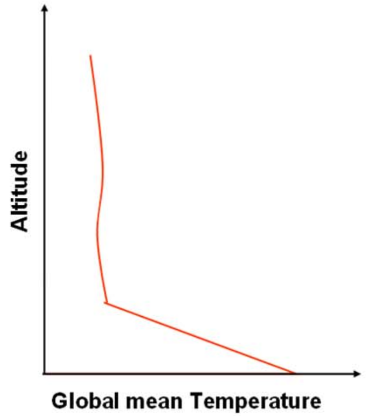
[1]Department of Astronomy and Astrophysics, The Pennsylvania State University, University Park, PA 16802, USA. [2]Center for Exoplanets and Habitable Worlds, The Pennsylvania State University, University Park, PA 16802, USA. [3]The Penn State Astrobiology Research Center, The Pennsylvania State University,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

...thor. E-mail: pmr19@psu.edu

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

Inner Edge of the Habitable Zone ?

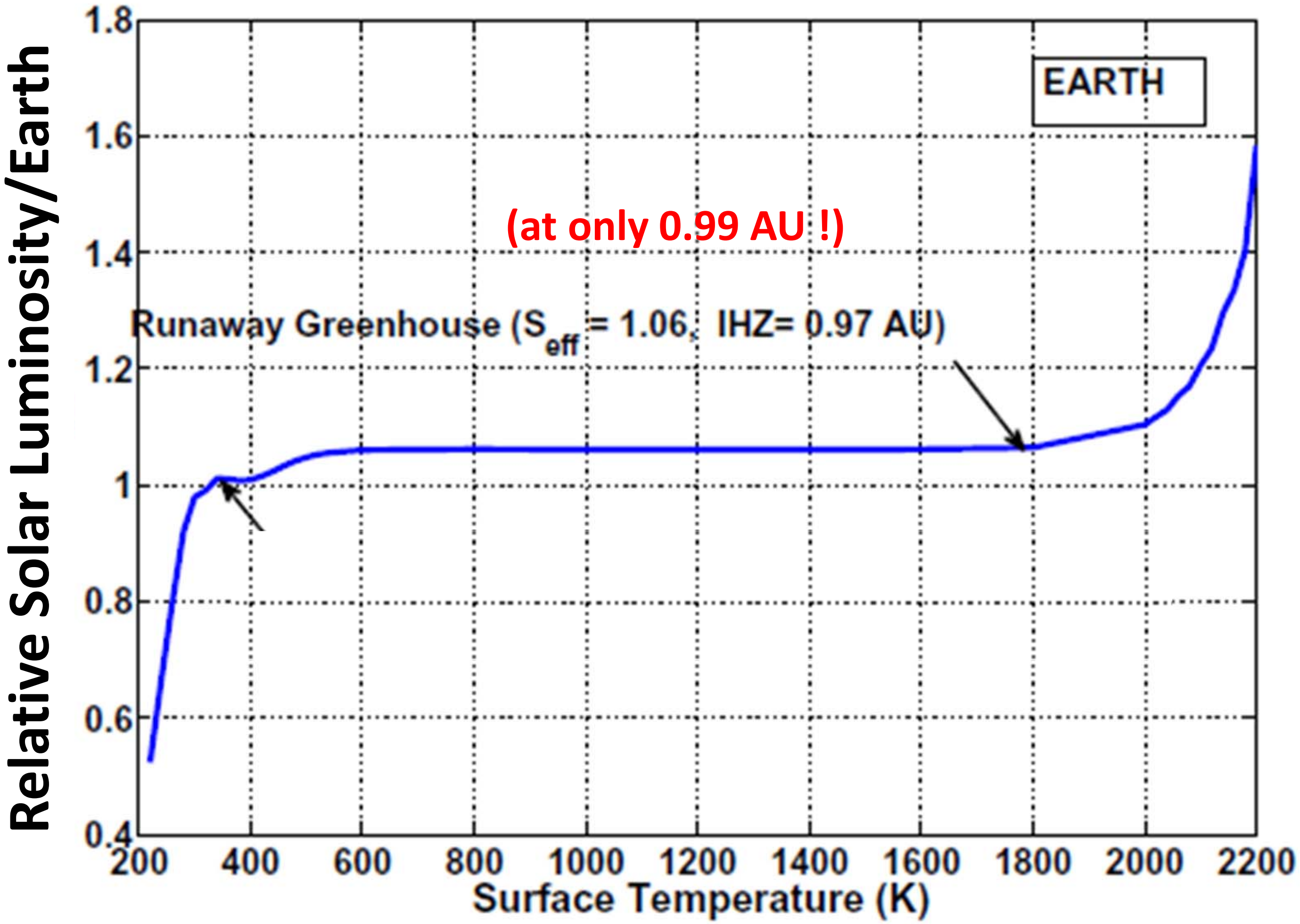




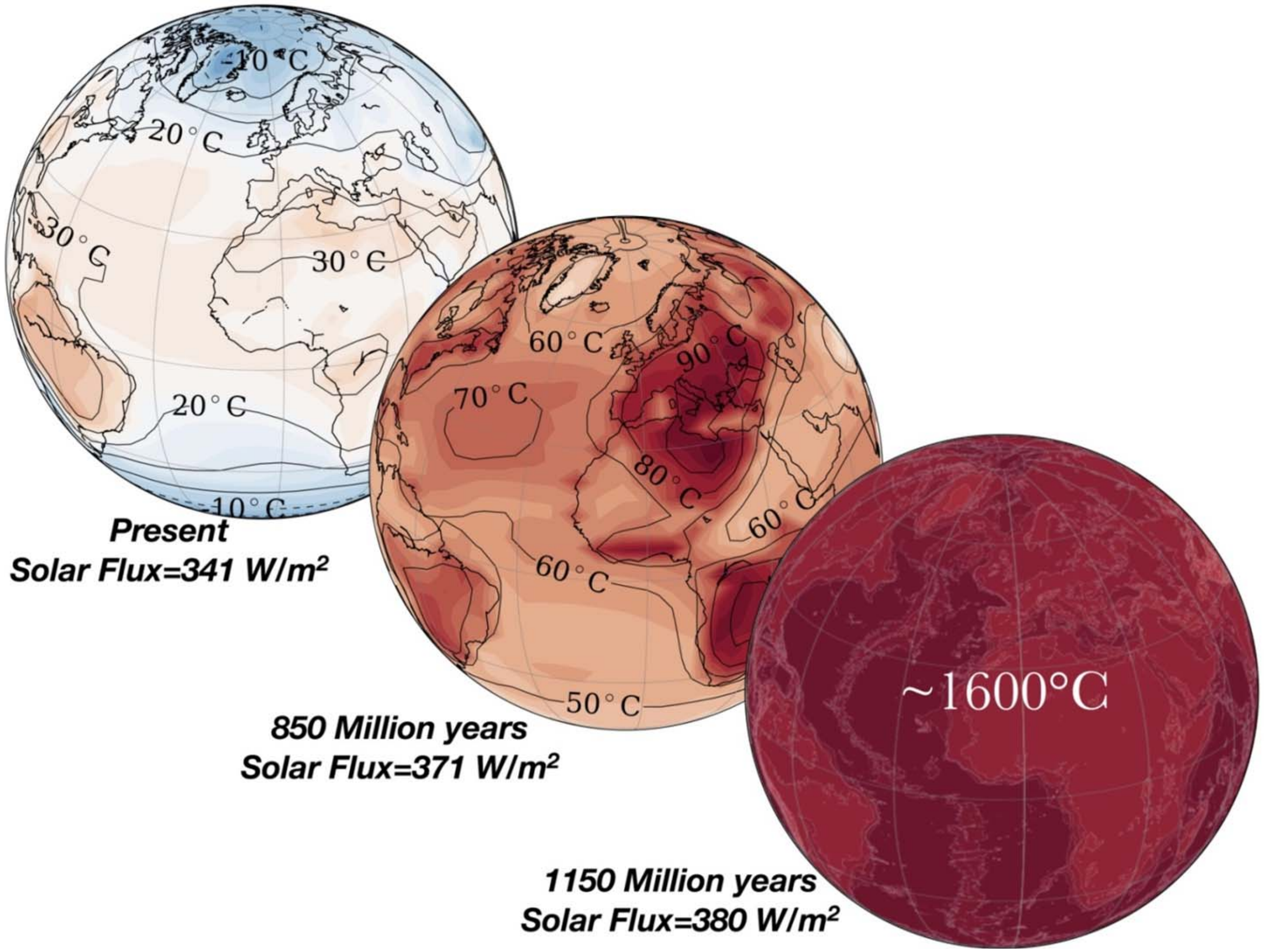
Runaway Greenhouse effect in 1D models

(for an Earth-like planet around a sun)

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



Runaway Greenhouse effect in a complete 3D Global Climate model



Present
Solar Flux=341 W/m²

850 Million years
Solar Flux=371 W/m²

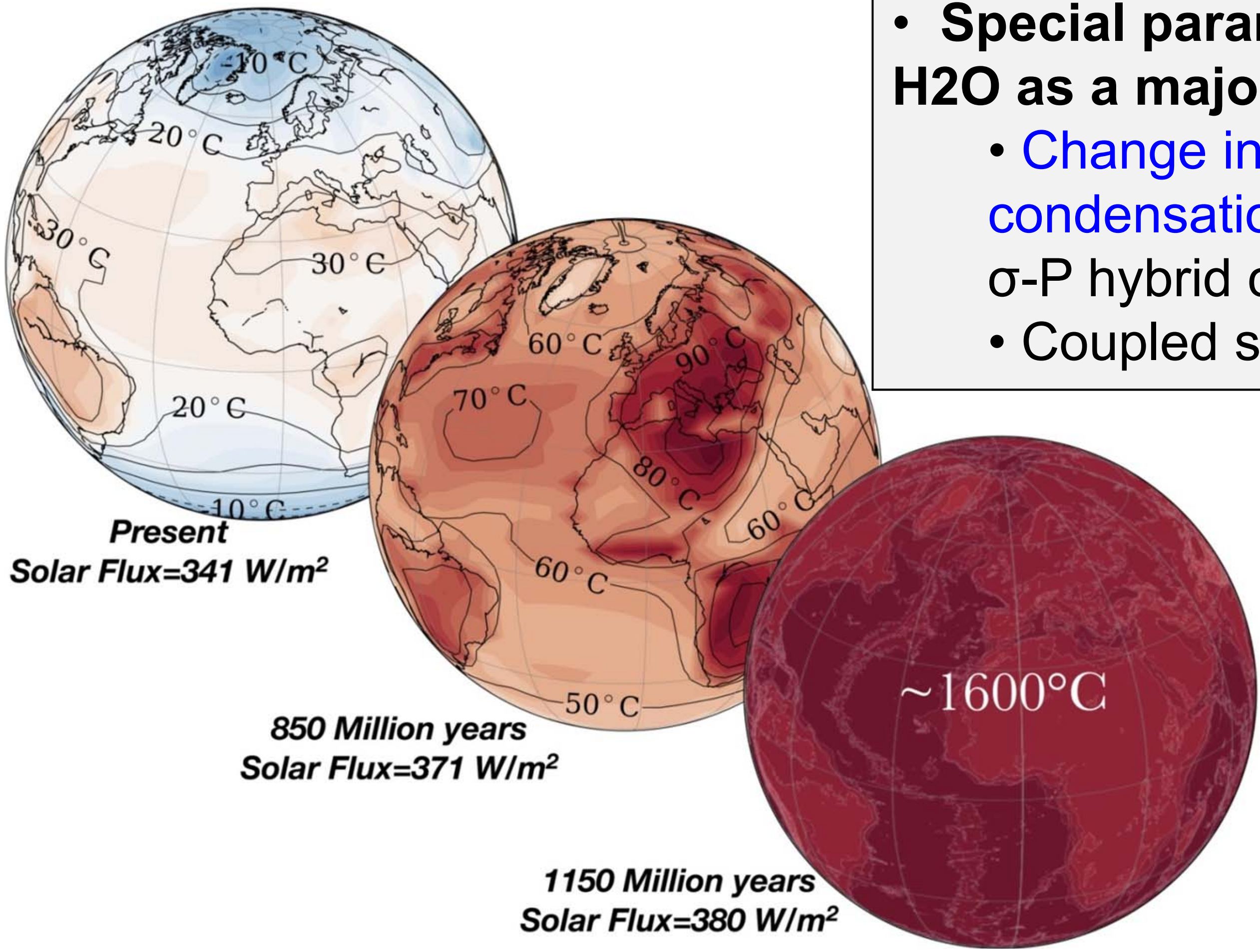
1150 Million years
Solar Flux=380 W/m²

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

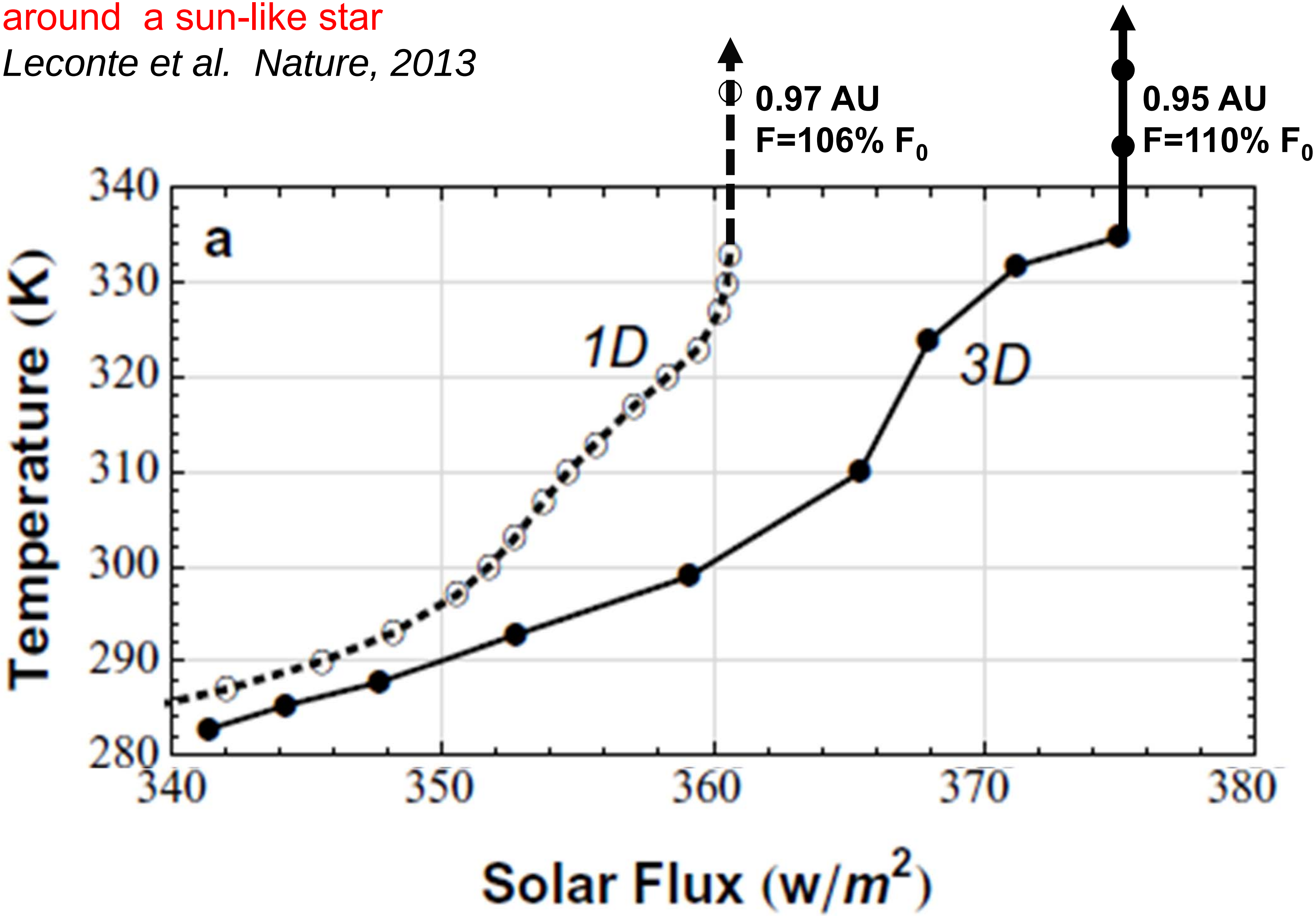
LMD 3D Generic Climate Model

- Earth like planet
- 64x48x30 resolution
- Radiative transfer (correlated k)
  - 19 IR bands
  - 18 solar bands

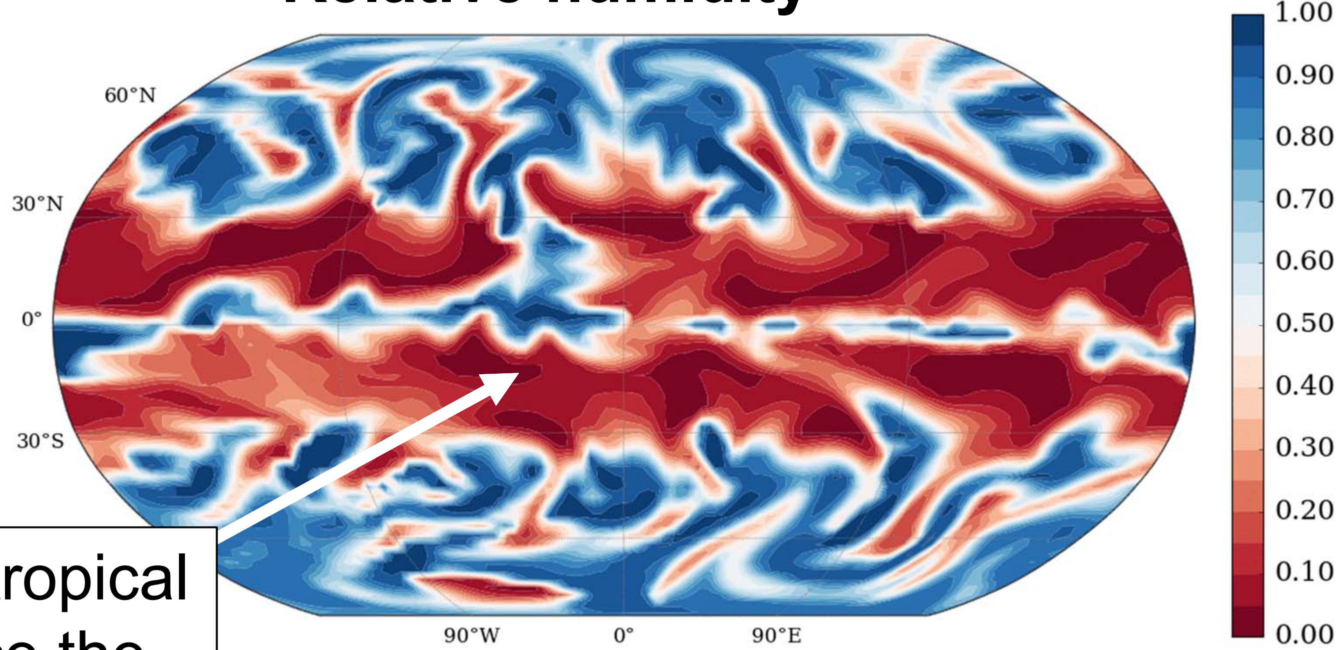
- **Special parametrization to handle H2O as a major constituant :**
  - Change in Ps with condensation/evaporation ⇨ case of σ-P hybrid coordinates.
  - Coupled system [H2O]+T+Ps



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



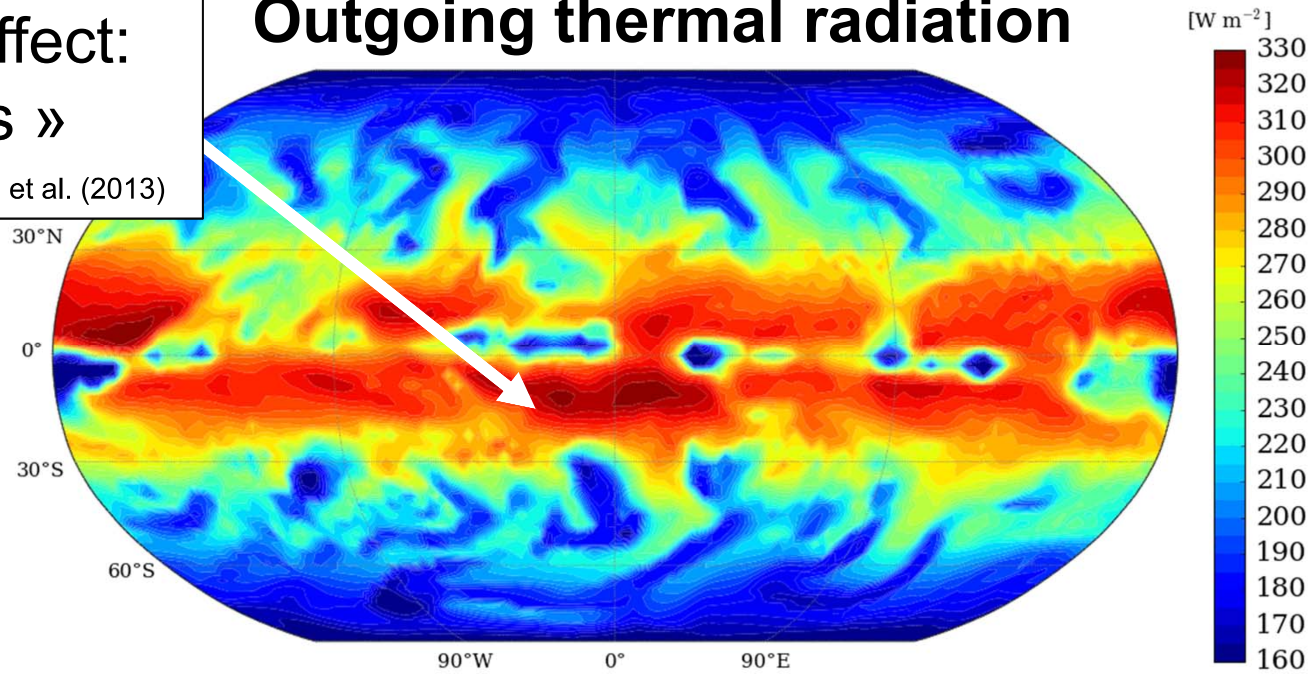
Relative humidity



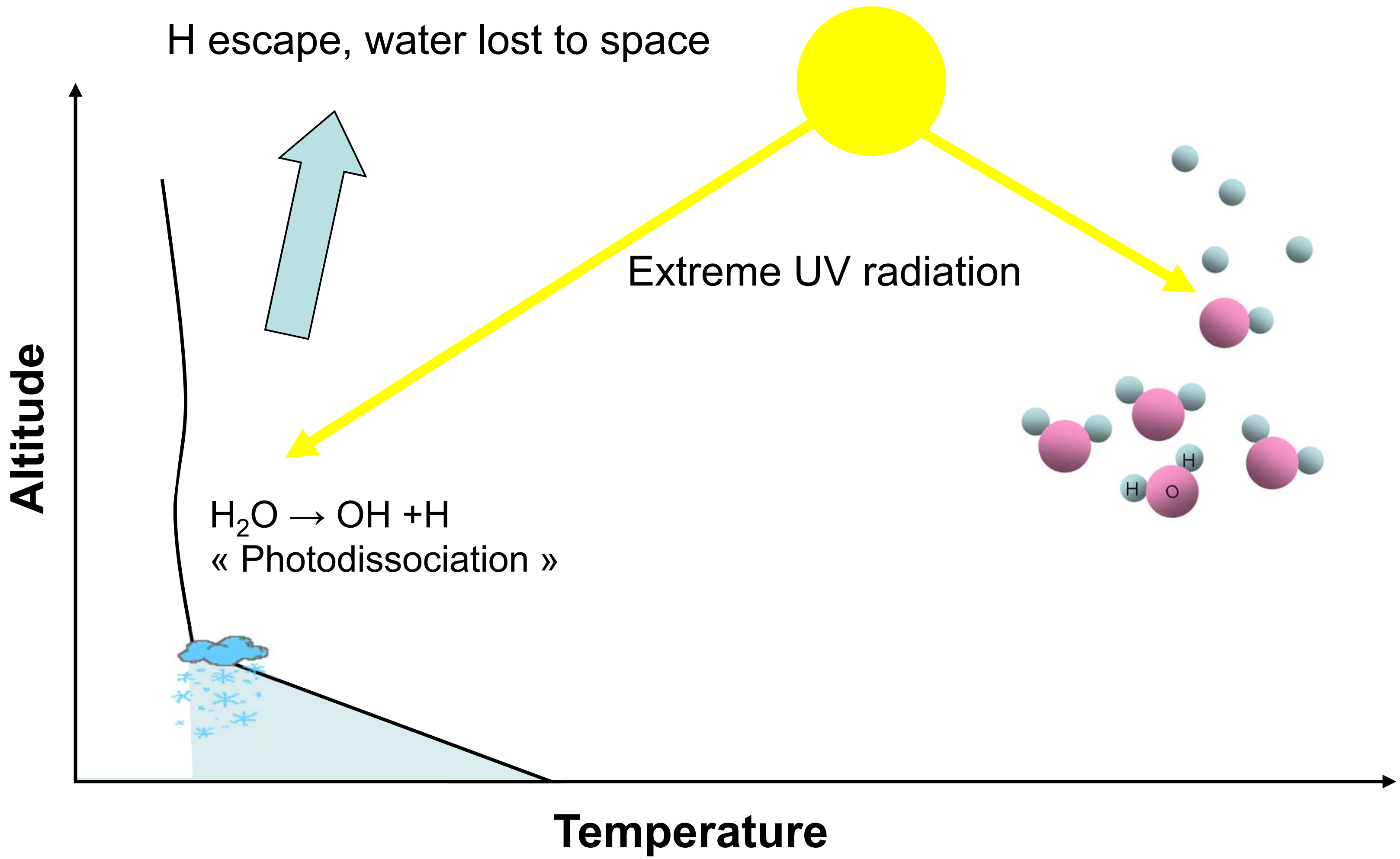
Unsaturated tropical regions reduce the greenhouse effect: « radiative fins »

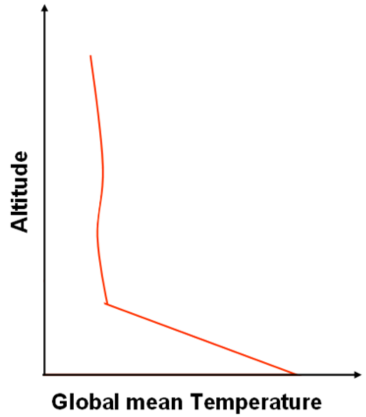
Pierrehumbert (1995), Leconte et al. (2013)

Outgoing thermal radiation



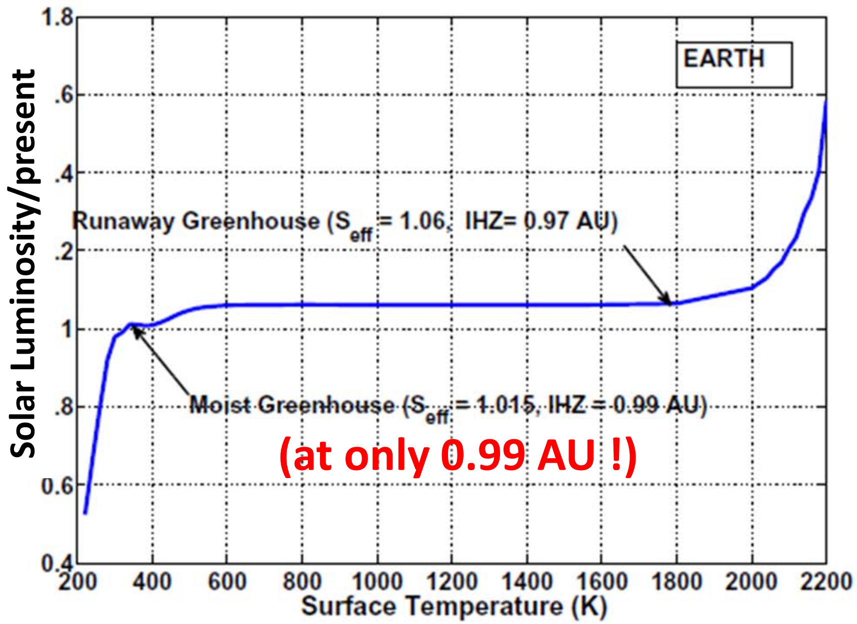
Impact of temperature increase on water vapor distribution and escape: the « water loss limit »… at only 0.99 AU from the Sun (*Kopparapu, Kasting et al. 2013*)

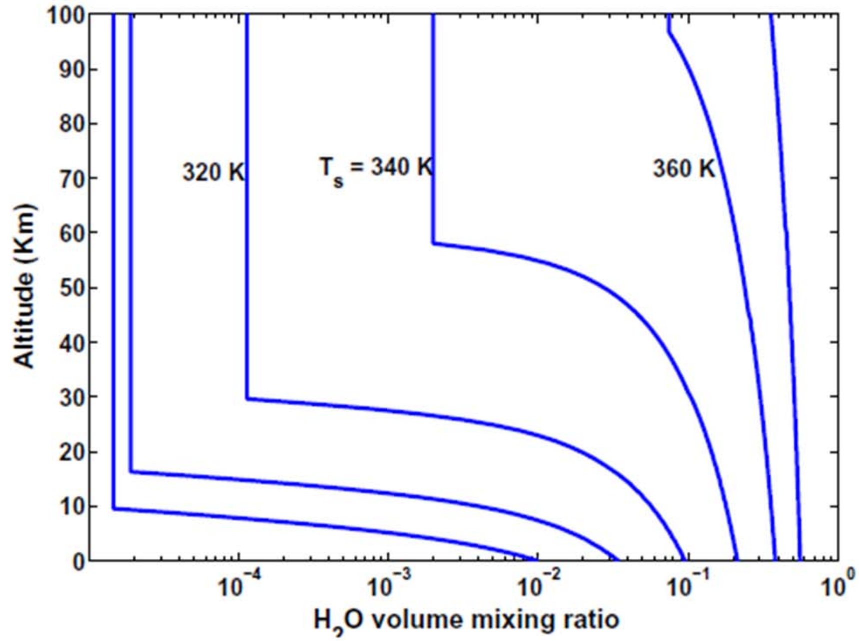




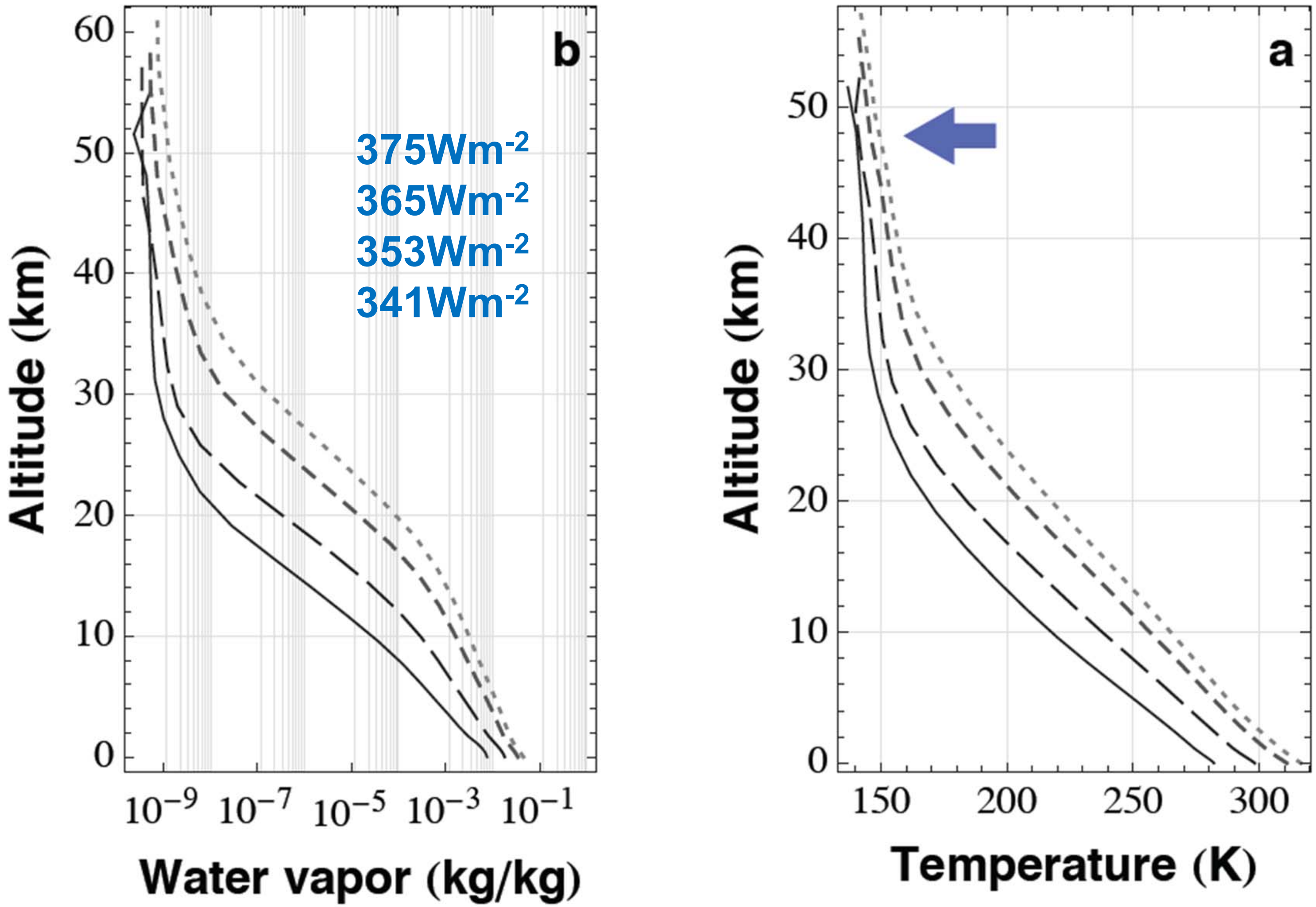
« Water loss limit » in 1D models

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





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



Leconte et al. (Nature; 2013)

Runaway greenhouse effect around K and M dwarf star

Redder stellar spectrum

• Weak atmospheric Rayleigh Scaterring

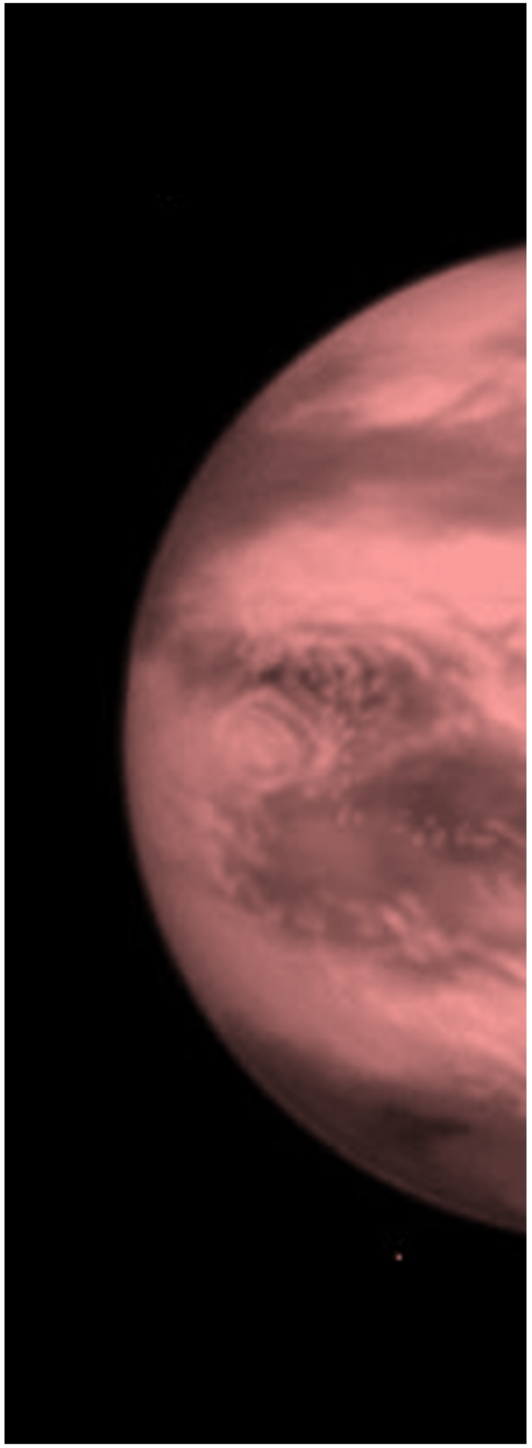
⇨ lower planetary albedo

Effect of tides:

• Resonnant rotation with zero obliquity

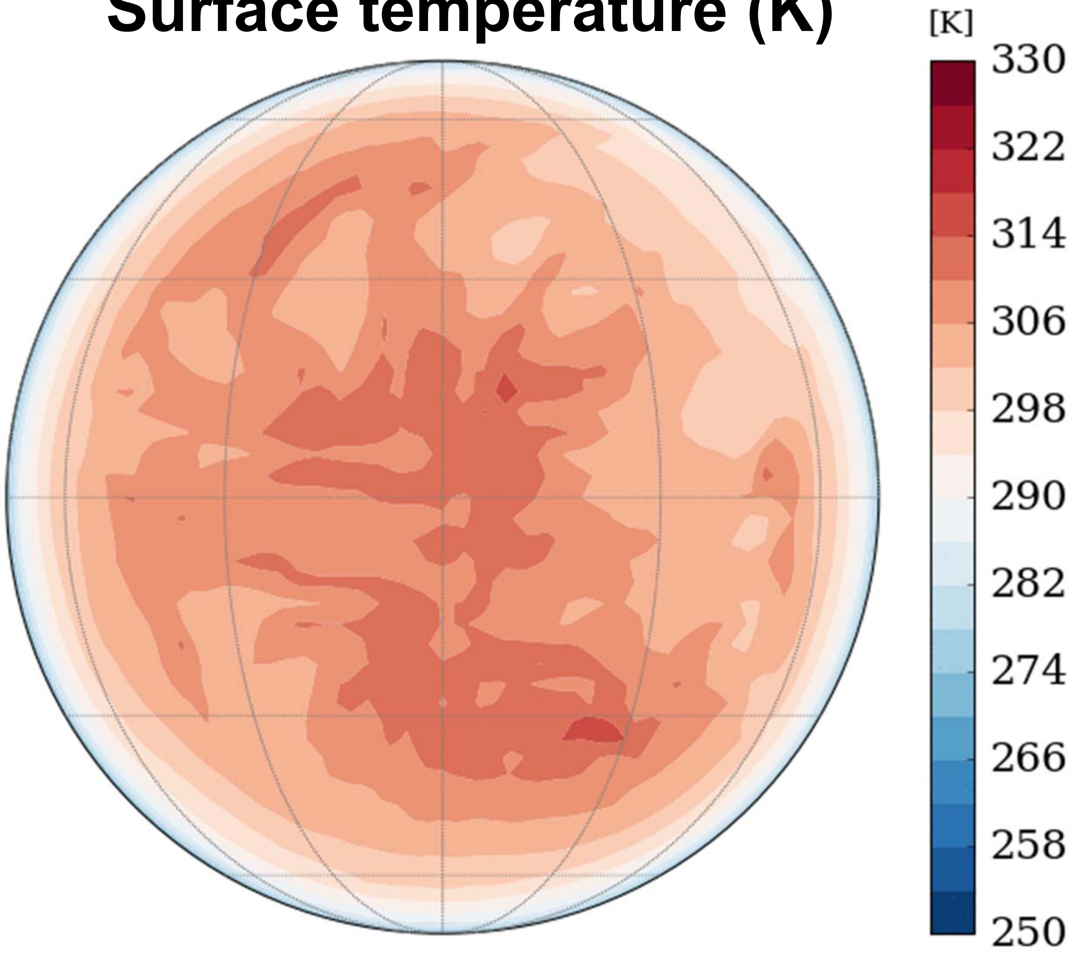
⇨ Possible Locking with permanent night side

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



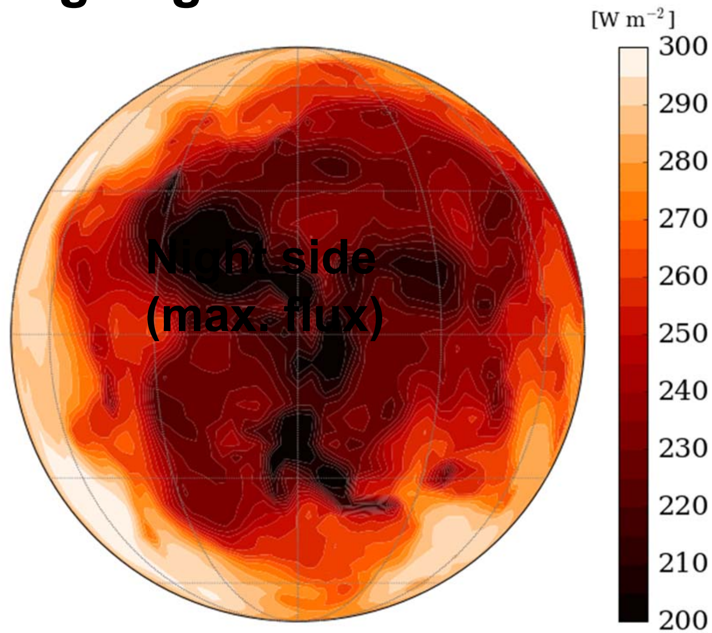
Simulation of aTidal-locked planet with surface liquid water around an Mdwarf
(Jeremy Leconte, LMD climate model)

Surface temperature (K)

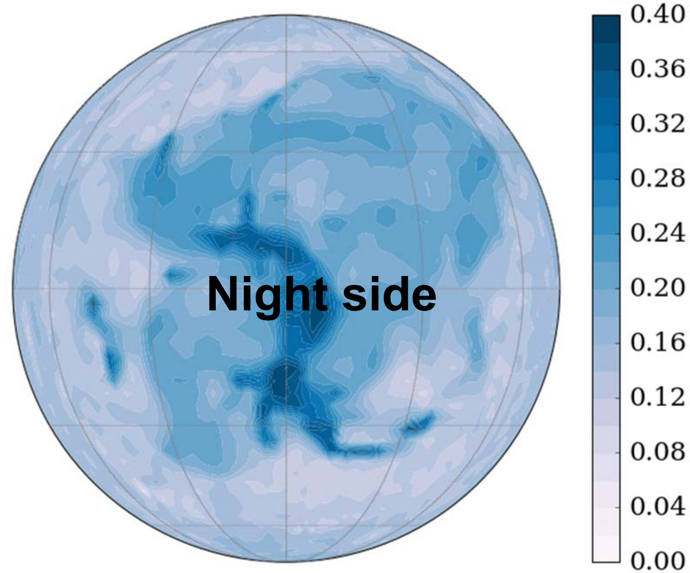


View from a distant point throughout the orbit

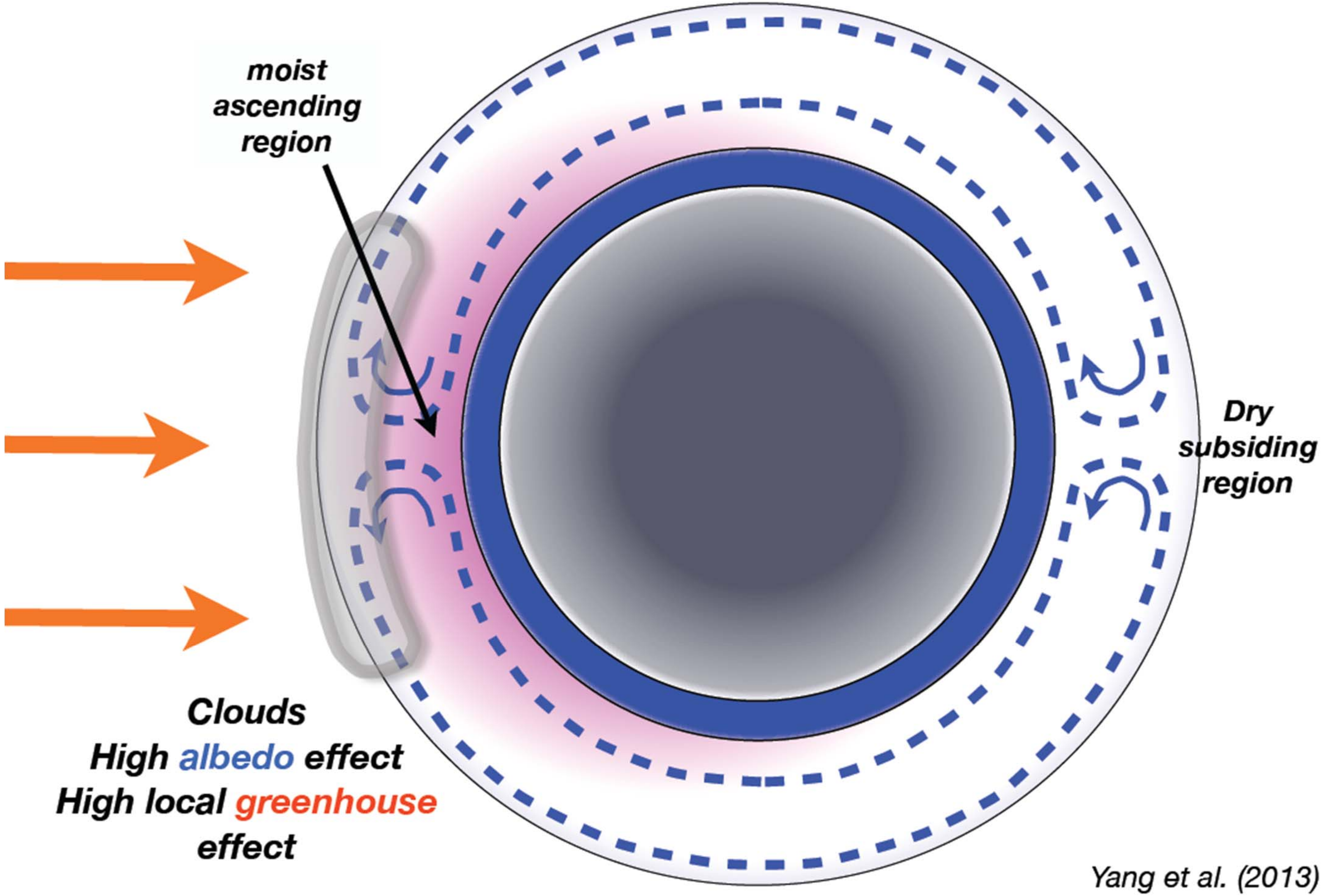
Outgoing Thermal radiation



Planetary Albedo



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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Draft version June 28, 2013

ABSTRACT

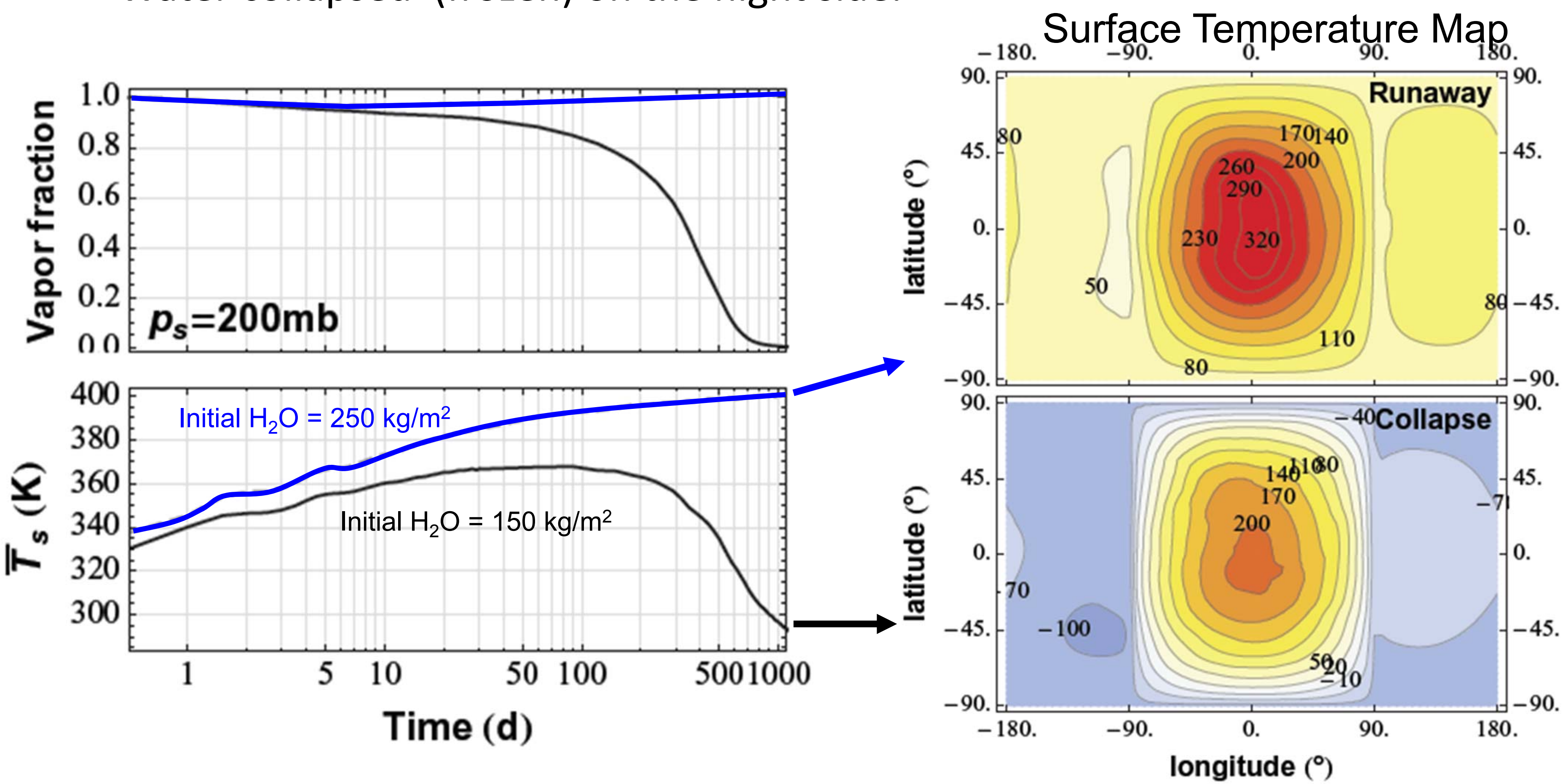
The Habitable Zone (HZ) is the circumstellar region where a planet can sustain surface liquid water. Searching for terrestrial planets in the HZ of nearby stars is the stated goal of ongoing and planned extrasolar planet surveys. Previous estimates of the inner edge of the HZ were based on one dimensional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



Tidally locked hot planet: the case of Gliese 581c

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

- A bistable climate
  - Planet in "runaway greenhouse state" : with all water vapor in the atmosphere : super-hot climate
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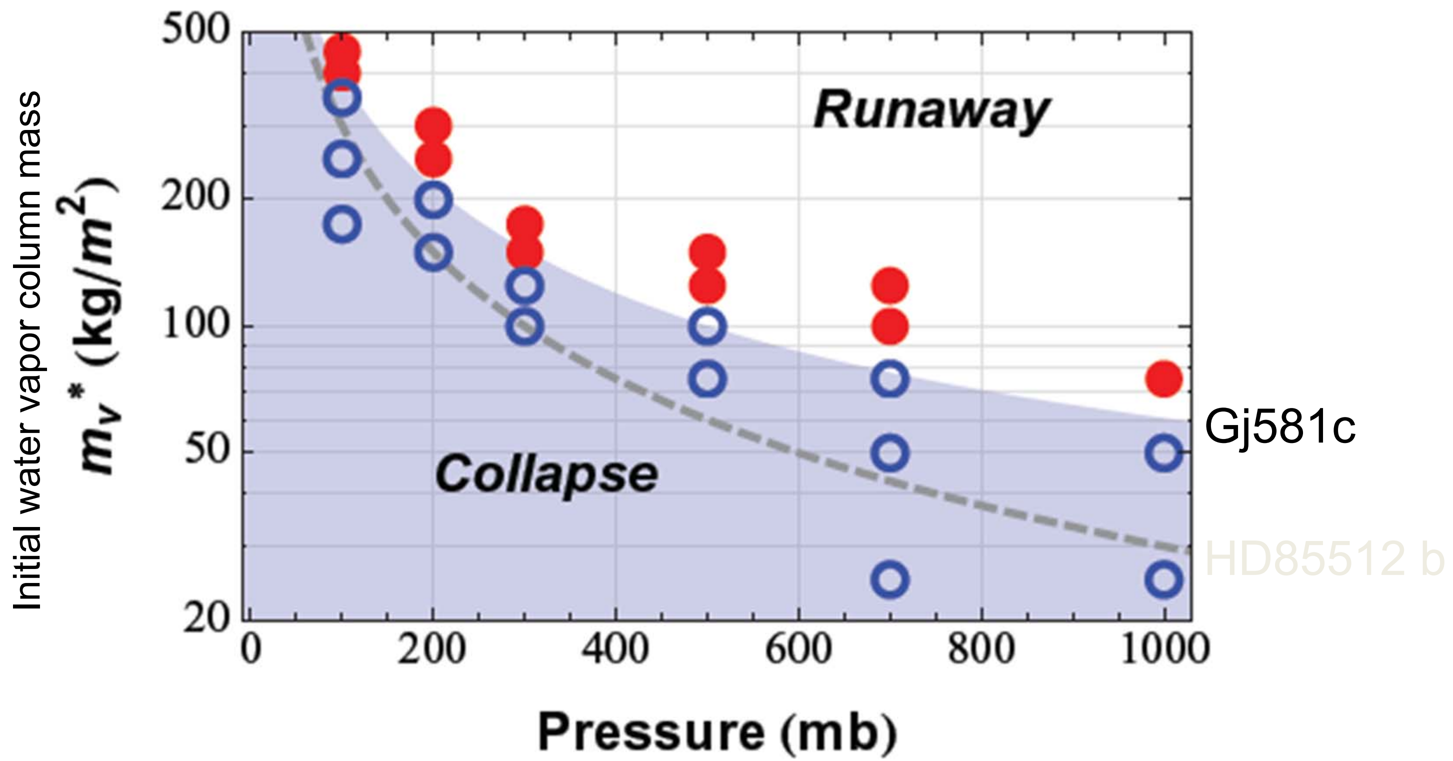
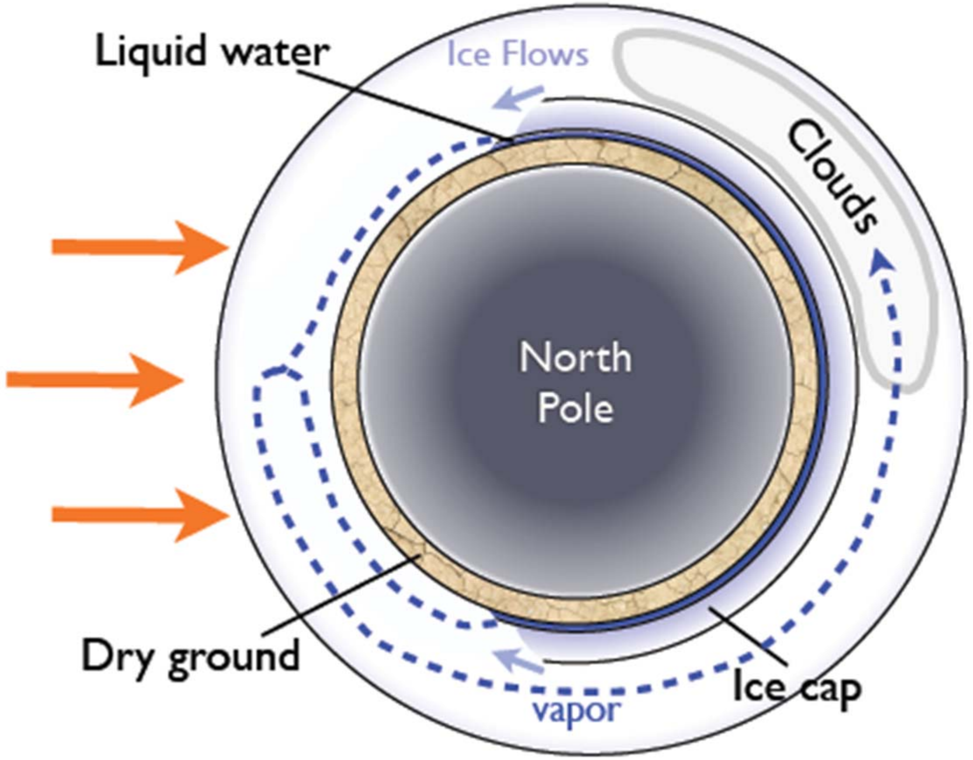
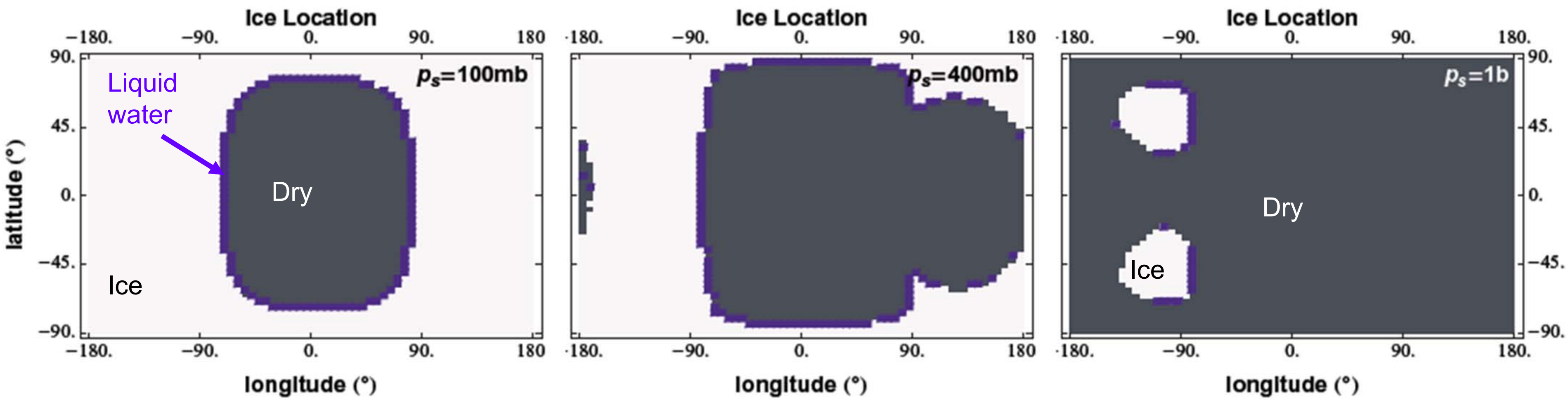
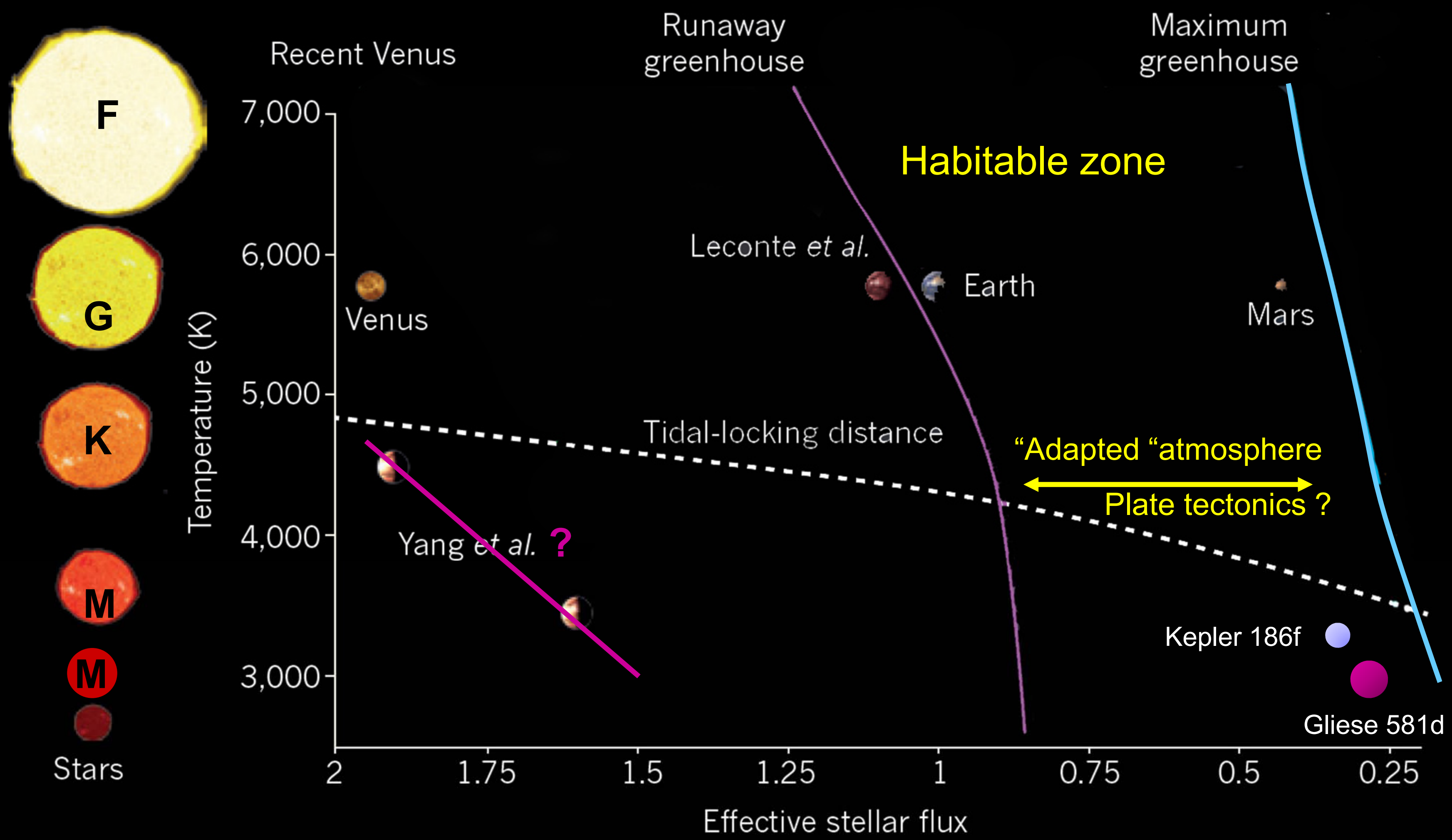


Possibility of liquid water on tidally locked hot planet *(Leconte et al. A&A 2013)*





The habitable zone with full climate models…



Adapted and modified from Kasting and Harman (2013)

Some Conclusions

- Assuming atmosphere/ocean compositions, 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.

- The Key scientific problem remains our understanding of the zoology of atmospheric composition, controlled by even more complex processes :
  - Formation of planets and origin of terrestrial atmospheres
  - Escape to space
  - Interaction with the surface (e.g. plate tectonic)
  - Photochemical evolution

⇨ **We need observations of atmospheres**

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

Forget F. *« on the probability of habitable planets » International Journal of Astrobiology (2013)*
Forget and Leconte (2013)*, « Possible climate on terrestrial exoplanets » Phil. Trans. Royal Society. A. (2014)* (arXiv:1311.3101)

- Backup slide

Other issues with M stars

- M star evolve slowly in the long term, BUT
- Relatively Strong EUV and X ray flux

- Exposition to dense stellar plasma fluxes ejected by coronal mass ejections (CMEs)

  ⇨ **Atmospheric escape to space ?**

  ⇨ **At the surface: high exposure to energetic particles?**