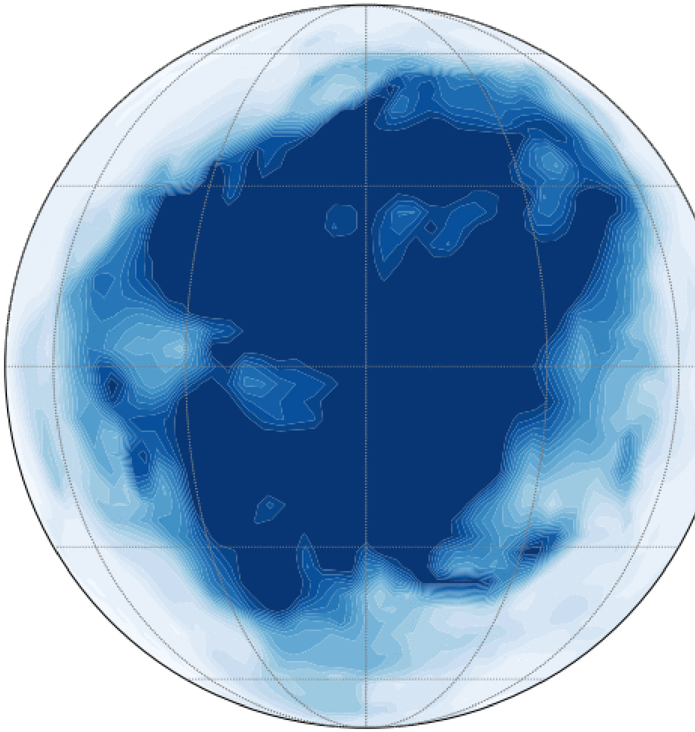
Modélisation des climats possibles sur les planètes extrasolaires telluriques

François Forget*,

with Martin Turbet , Jeremy Leconte, Benjamin Charnay, Robin Wordsworth, Ehouarn Millour, Franck Selsis, Emeline Bolmont , et al. …

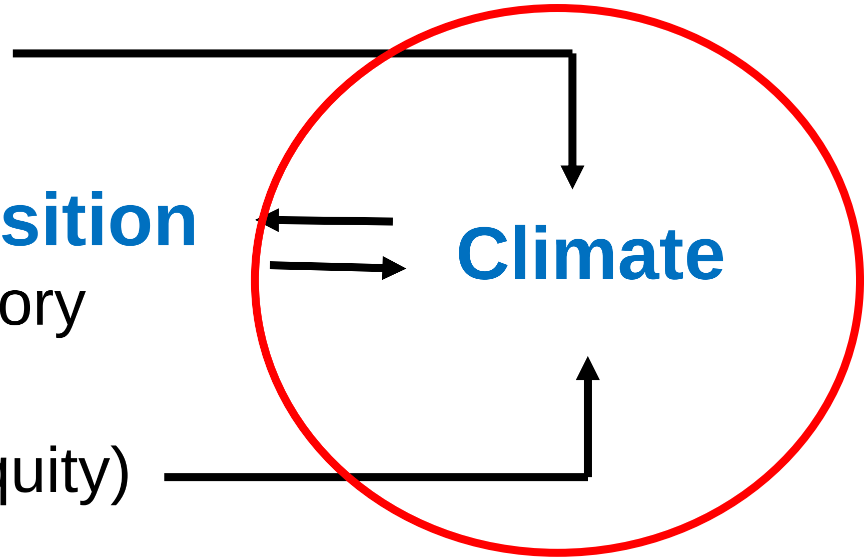
CNRS, Institut Pierre Simon Laplace, Laboratoire de Météorologie Dynamique, Paris



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

Key parameters controlling the climate on a terrestrial planet:

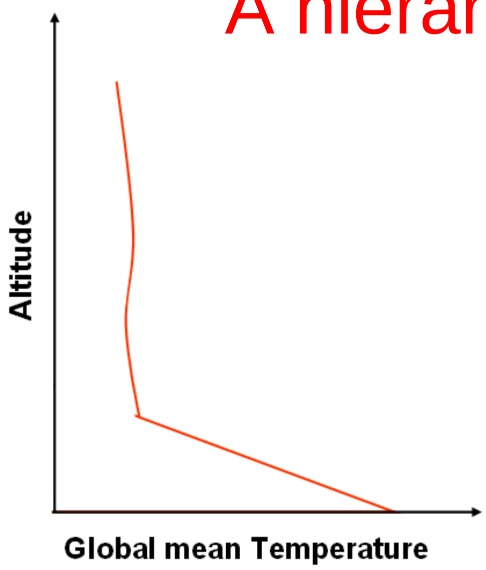
- **Stellar insolation**
- **Atmospheric composition**
  and surface volatile inventory
- **Rotation** (rate and obliquity)

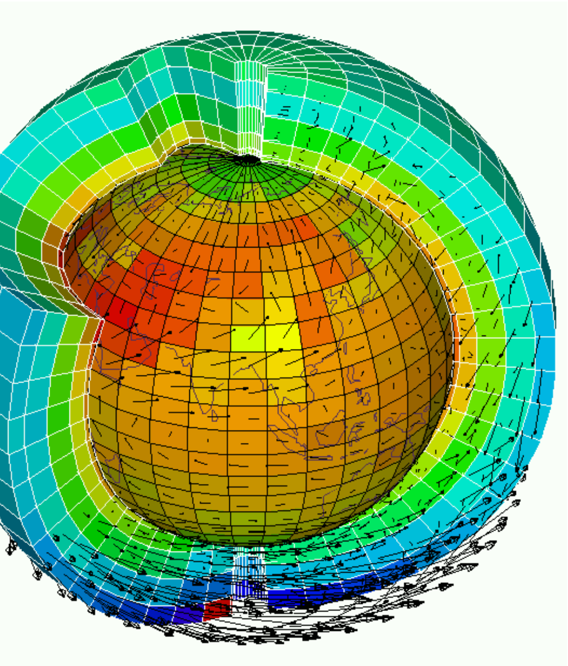


Climate models

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)

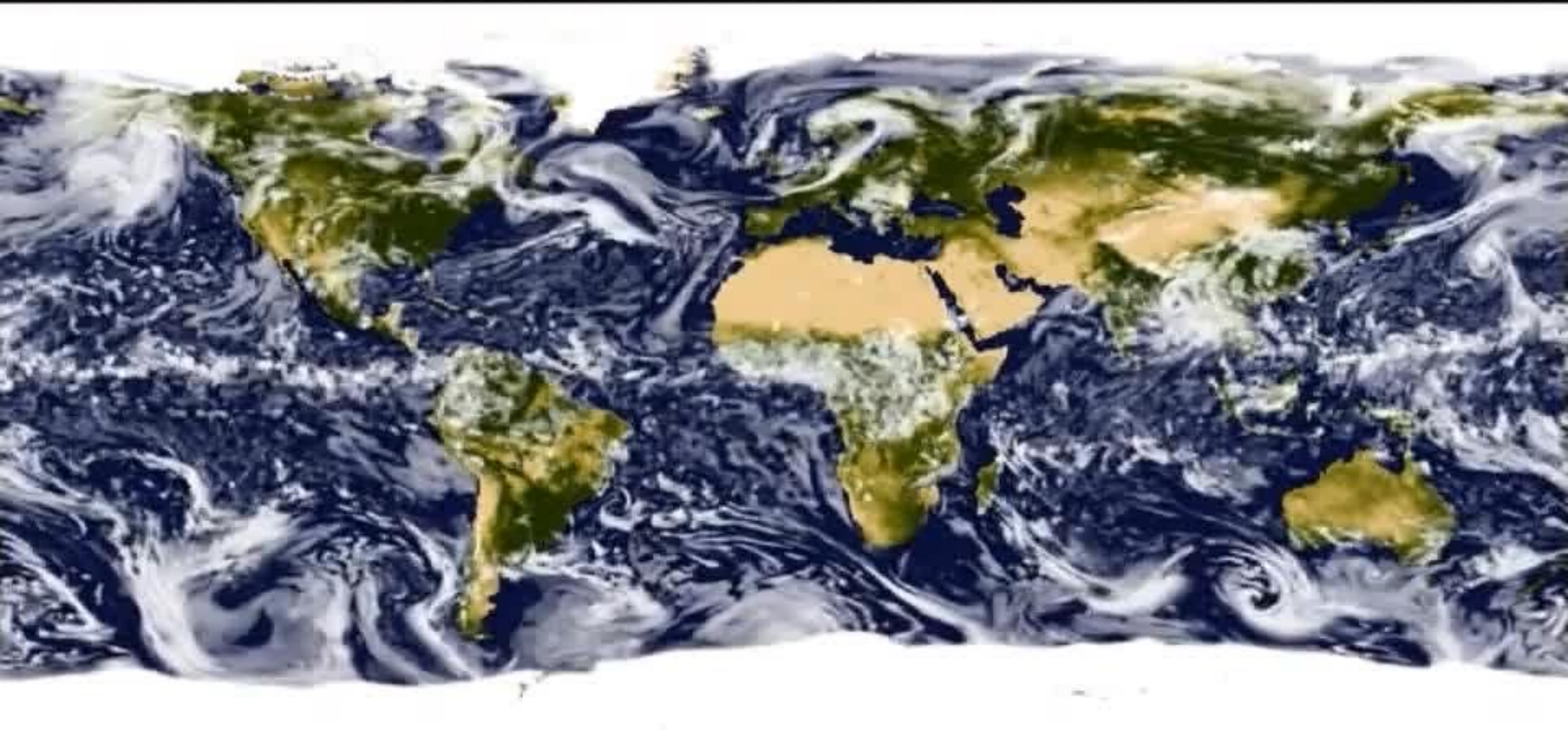
2. 2D Energy balance models…

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

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

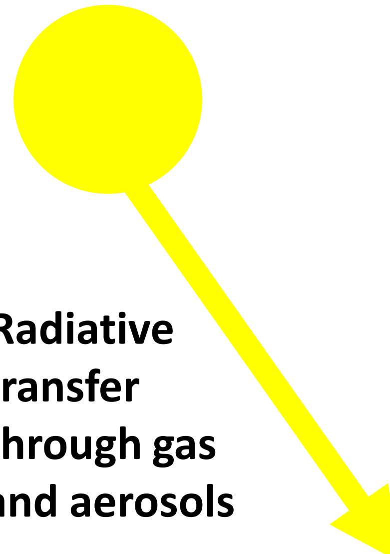
How to build a full Global Climate Simulator ?

Community Earth System Model (CESM), NCAR:

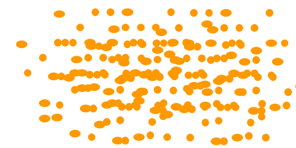


How to build a full Global Climate Simulator :

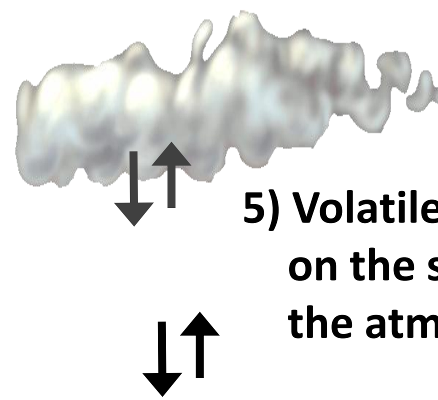
1) Dynamical Core to compute large scale atmospheric motions and transport



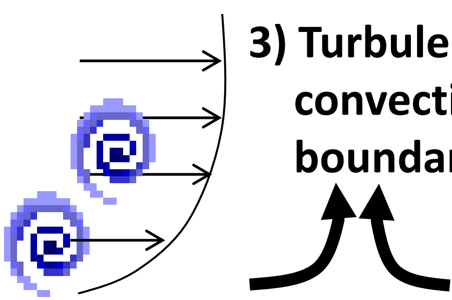
2) Radiative transfer through gas and aerosols



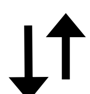
6) Photochemical hazes and lifted aerosols



5) Volatile condensation on the surface and in the atmosphere



3) Turbulence and convection in the boundary layer



4) Surface and subsurface thermal balance

How to build a full Global Climate Simulator :

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.

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

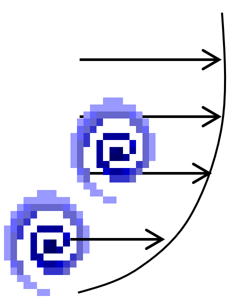
1) Dynamical Core : ~universal

NEW: photo-chemical core

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)



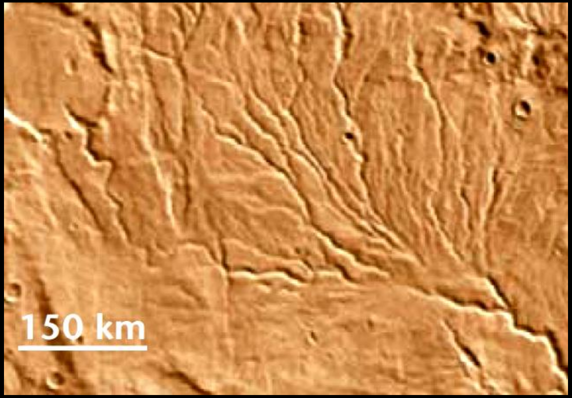
3) Turbulence and convection in the boundary layer
⇨ Universal turbulent sheme
⇨ Robust convection scheme

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

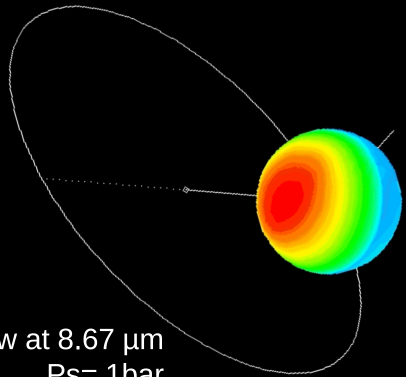
4) Surface and susurface thermal balance ~universal

A "Generic" LMD GCM for all terrestrial atmospheres:
Why model poorly constrained atmospheres ?

- **To Model ancient climates to understand geological records**
  - The faint young sun paradox on early Earth *(Charnay et al. 2013, 2016)*
  - Early Martians
    (Forget et al. 2013, Wordsworth et al. 2013, 2015, Kerber et al 2015, Turbet et al. 2016)
  - Ancient Titan *(Charnay et al. 2014)*



- **To simulate planets around other star to design and interpret telescopic observations**
  - Exoplanet Thermal phase curves (*Selsis et al. 2011, Turbet et al. 2016)*
  - Constraining hot superEarth with JWST (*Samuel et al., 2014)*
  - Modeling of clouds in GJ1214b's atmosphere *(Charnay et al. 2016)*



View at 8.67 µm
Ps= 1bar

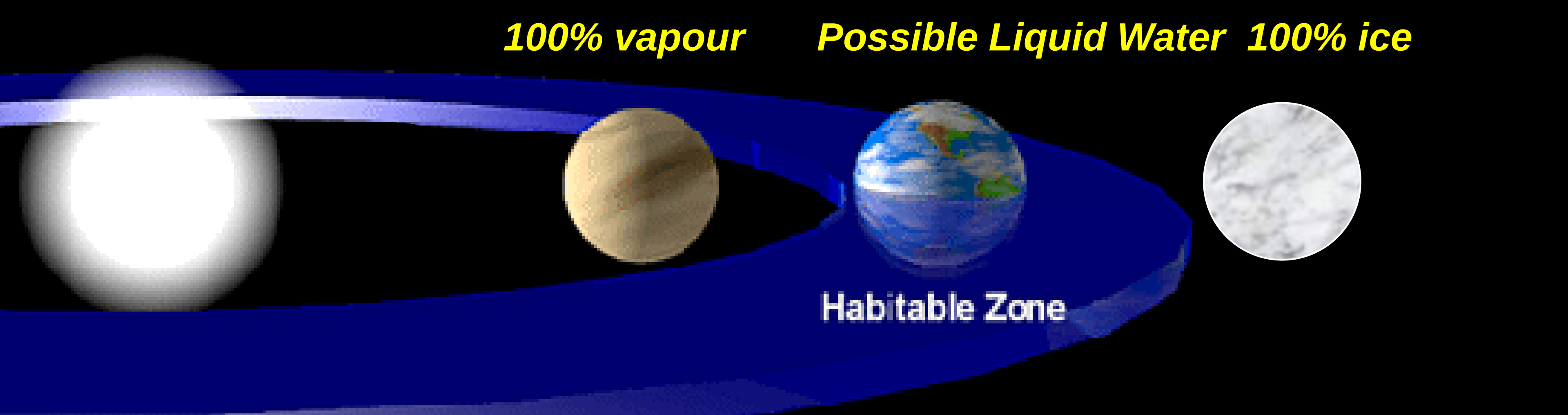
- **To adress key scientific questions regarding habitability:**
  - Define the habitable zone: *Forget (2013), Forget and Leconte (2014) Wordsworrth et al. 2011, 2012, 2013, 2014), Leconte et al. (2014), Bolmont et al. (2016).*
  - What is the probability of habitable planet in the galaxy ?

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

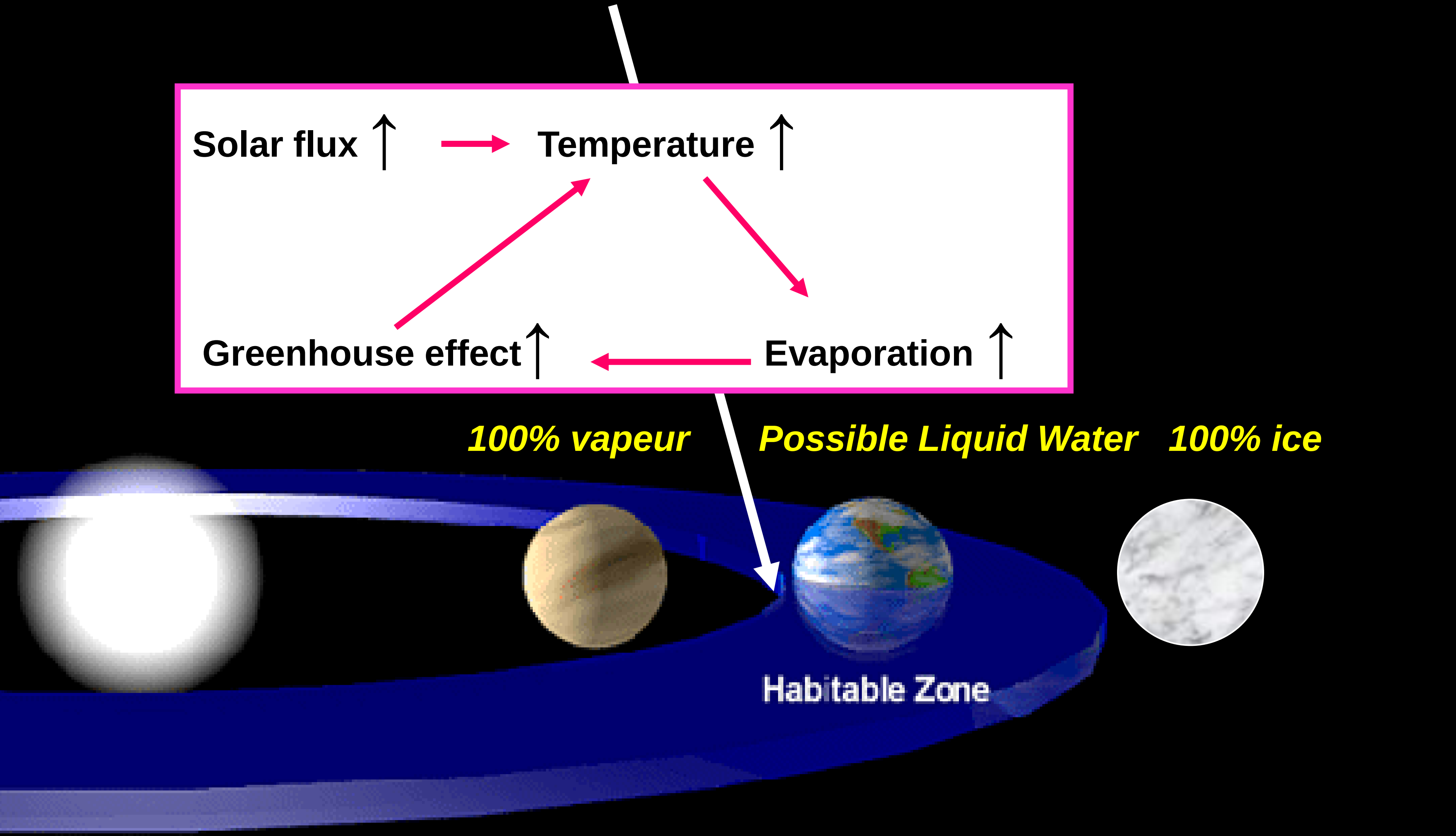
Eg. Kasting et al. 1993
Forget 2013

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

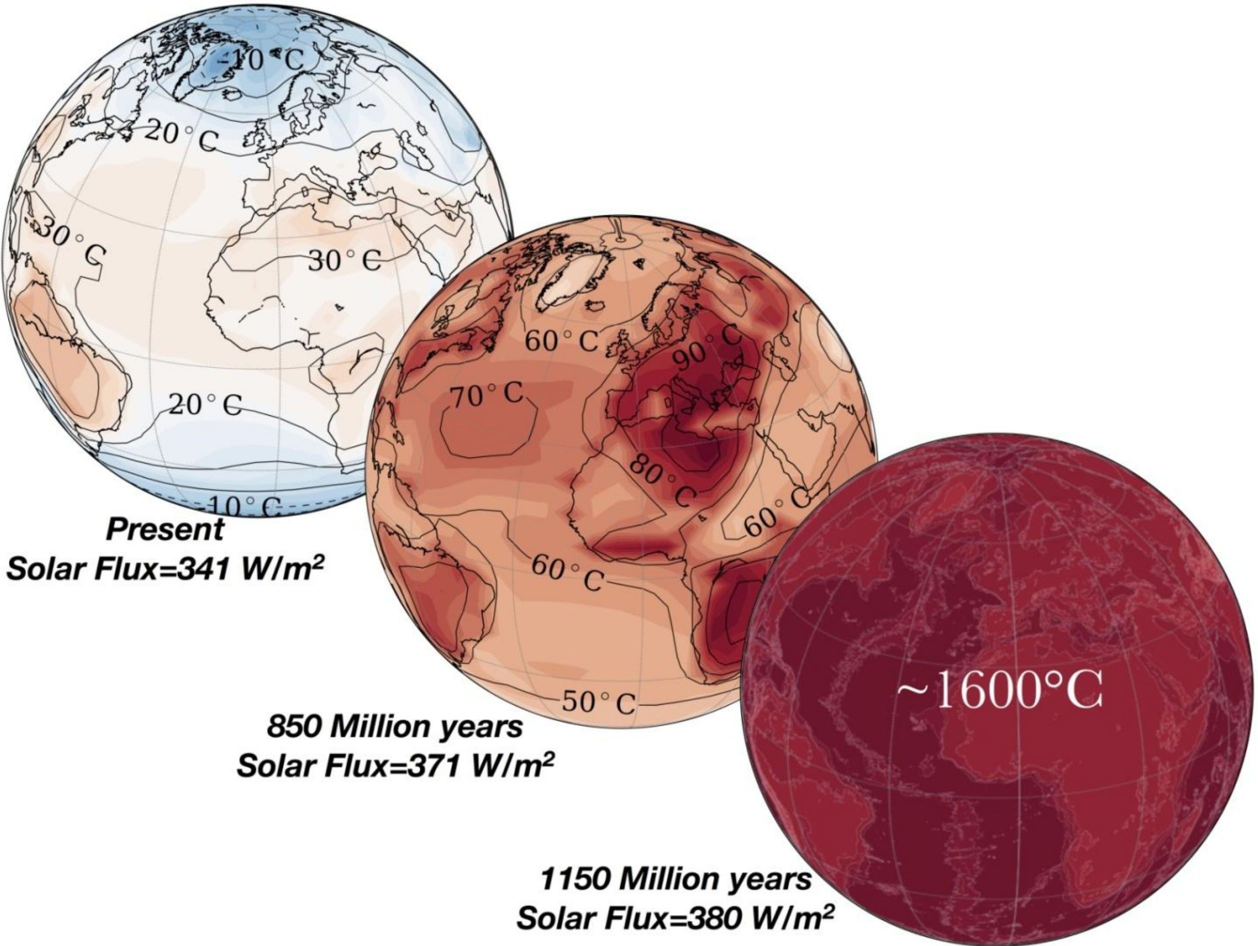
⇨ A problem of climate



Inner Edge of the Habitable Zone ?



Runaway Greenhouse effect in a complete 3D Global Climate model



Present
Solar Flux=341 W/m²

850 Million years
Solar Flux=371 W/m²

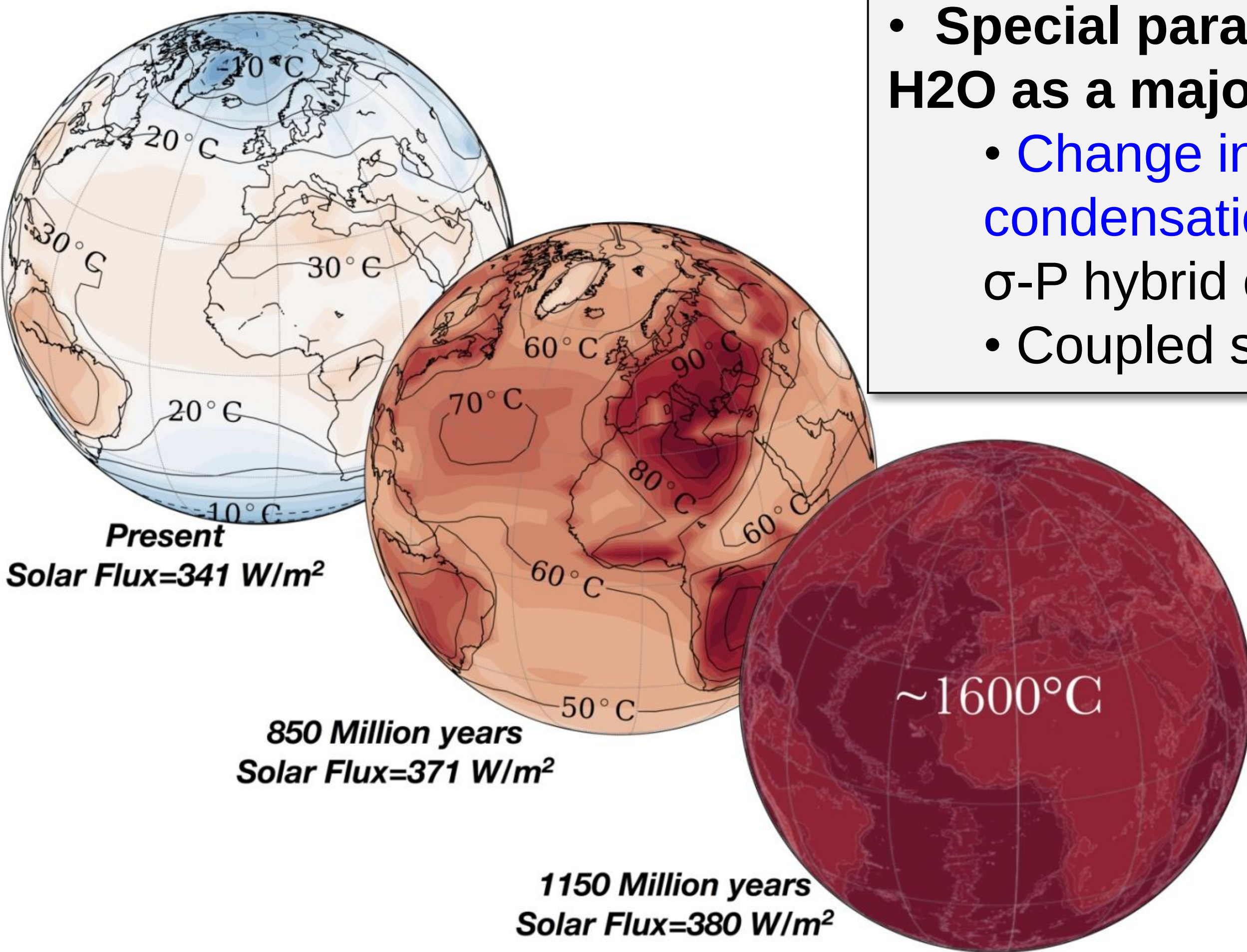
1150 Million years
Solar Flux=380 W/m²

Leconte et al. 2013
Wolf and Toon 2014 , 2015
Yang et al. 2013, 2014

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

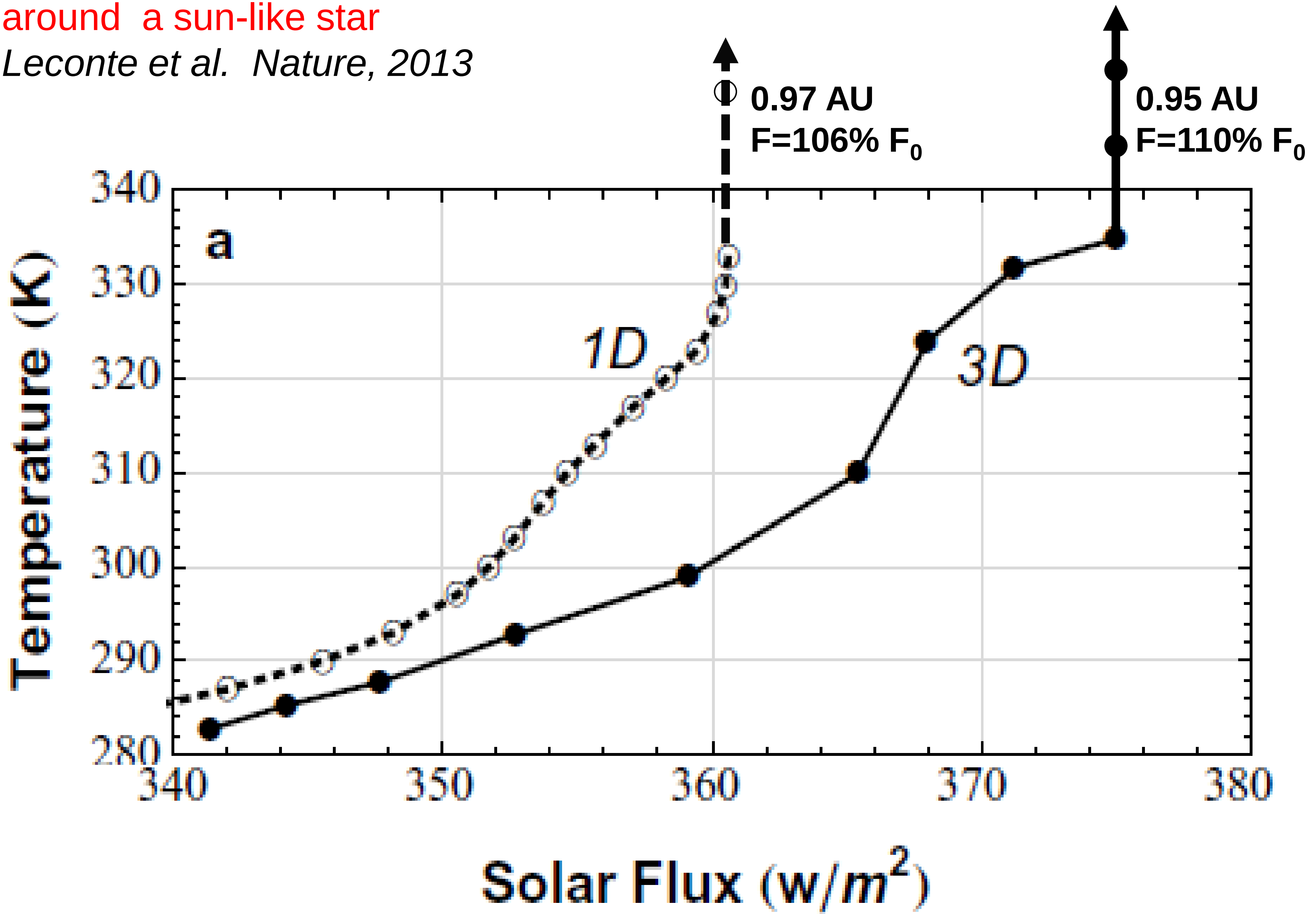
LMD 3D Generic Climate Model

- 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



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

Leconte et al. Nature, 2013



Runaway greenhouse effect around K and M dwarf stars

Redder stellar spectrum

• Weak atmospheric Rayleigh Scaterring

⇨ lower planetary albedo

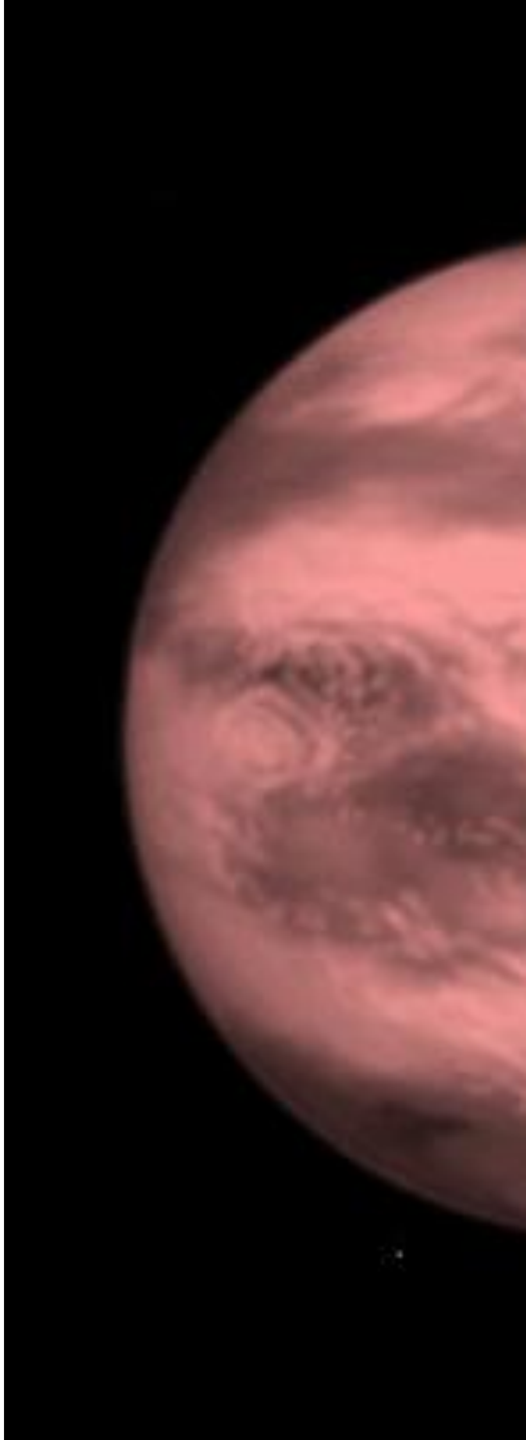
(e.g. Kasting et al., 1993, Shields et al. 2013)

Effect of tides:

• Resonnant rotation with zero obliquity

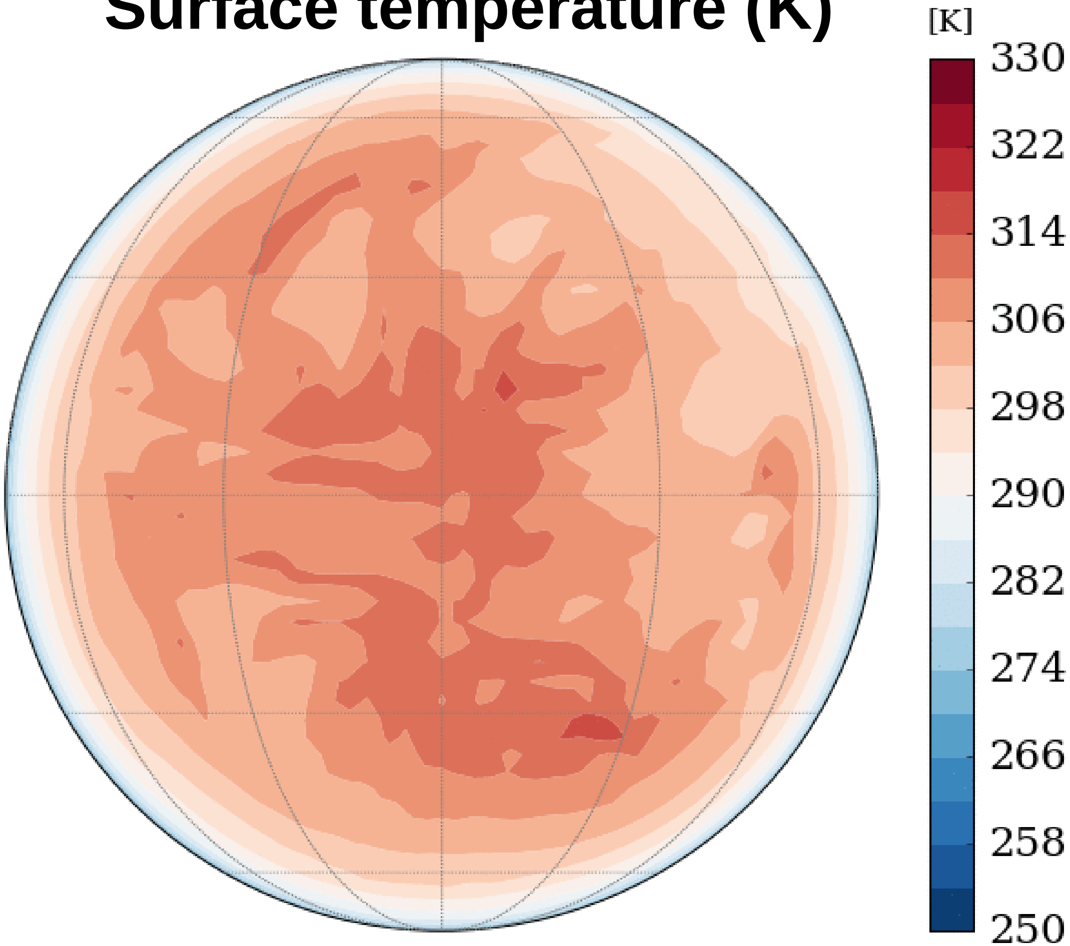
⇨ Possible Locking with permanent night side

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



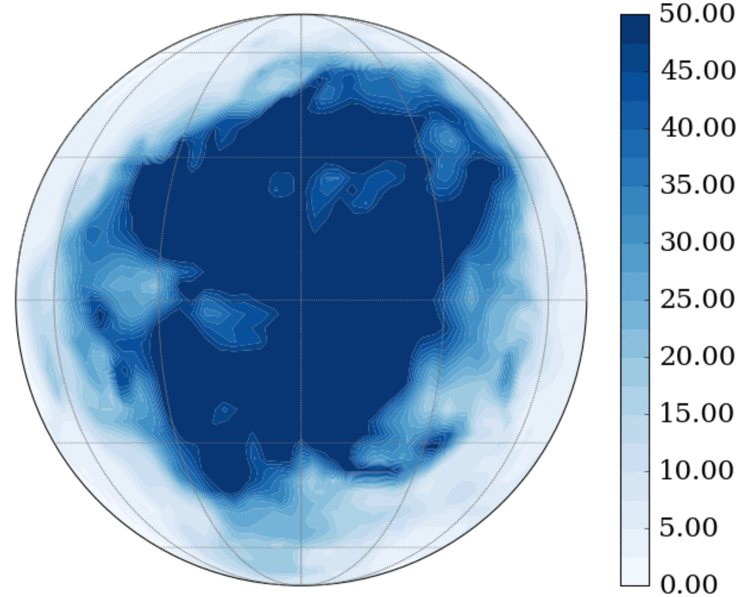
Simulation of aTidal-locked planet with surface liquid water around an Mdwarf
(Jeremy Leconte, LMD climate model)

Surface temperature (K)

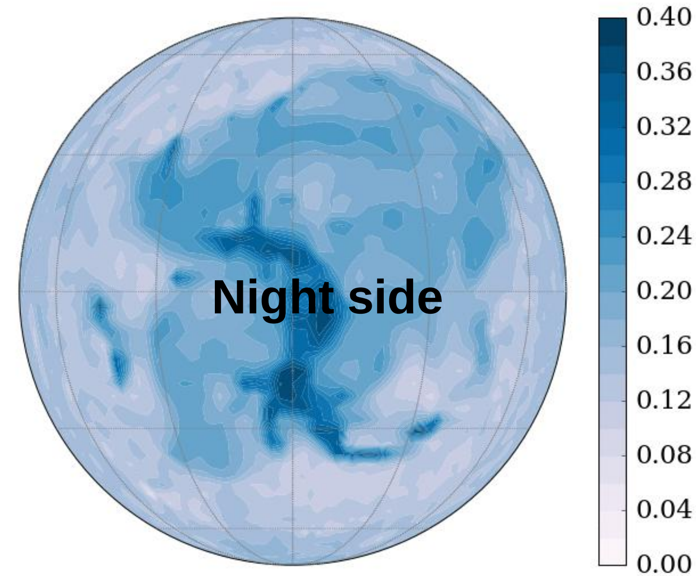


View from a distant point throughout the orbit

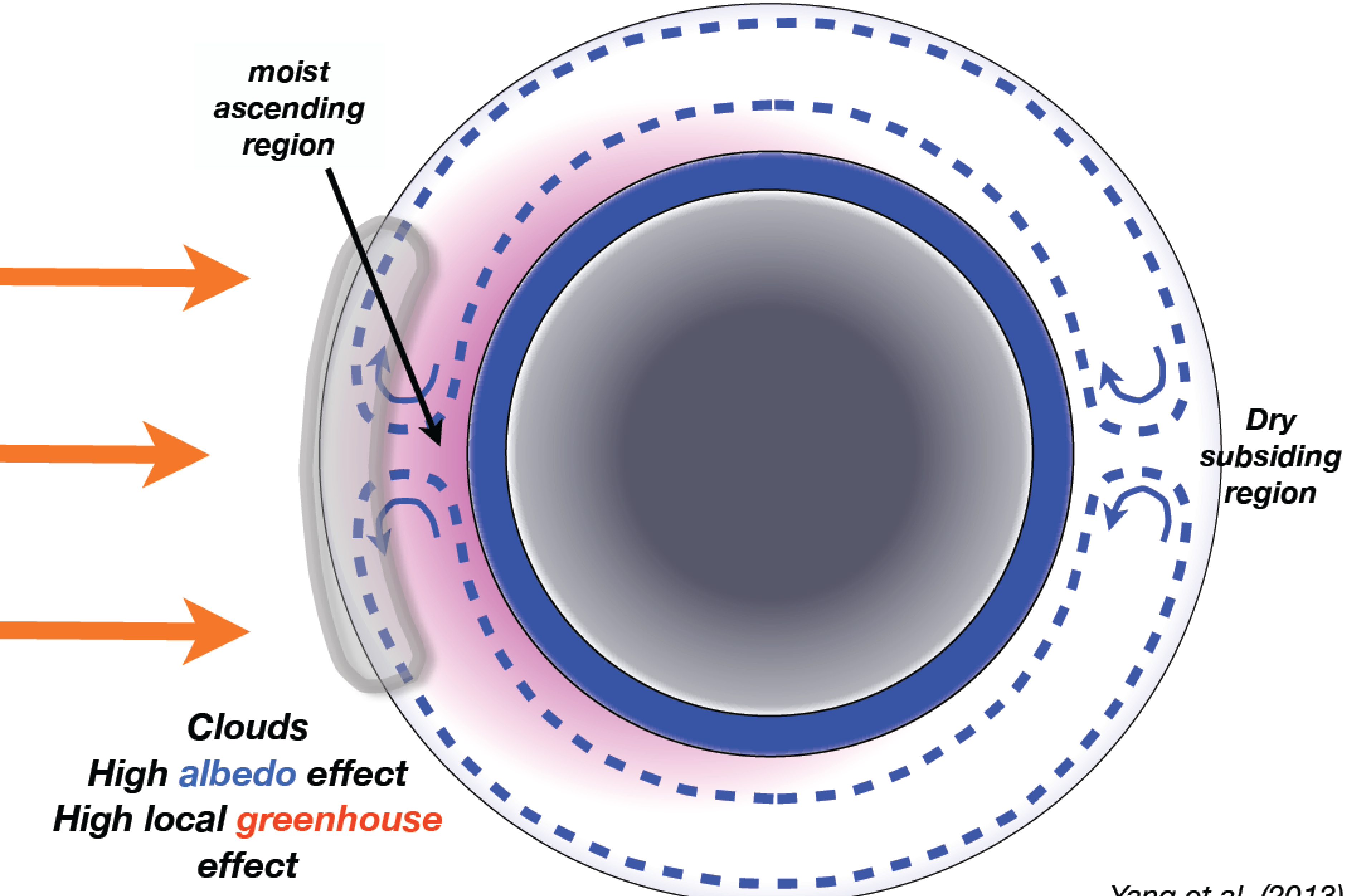
Cloud opacity



Planetary Albedo



Large scale cloud pattern on tidally locked planets



Yang et al. (2013)

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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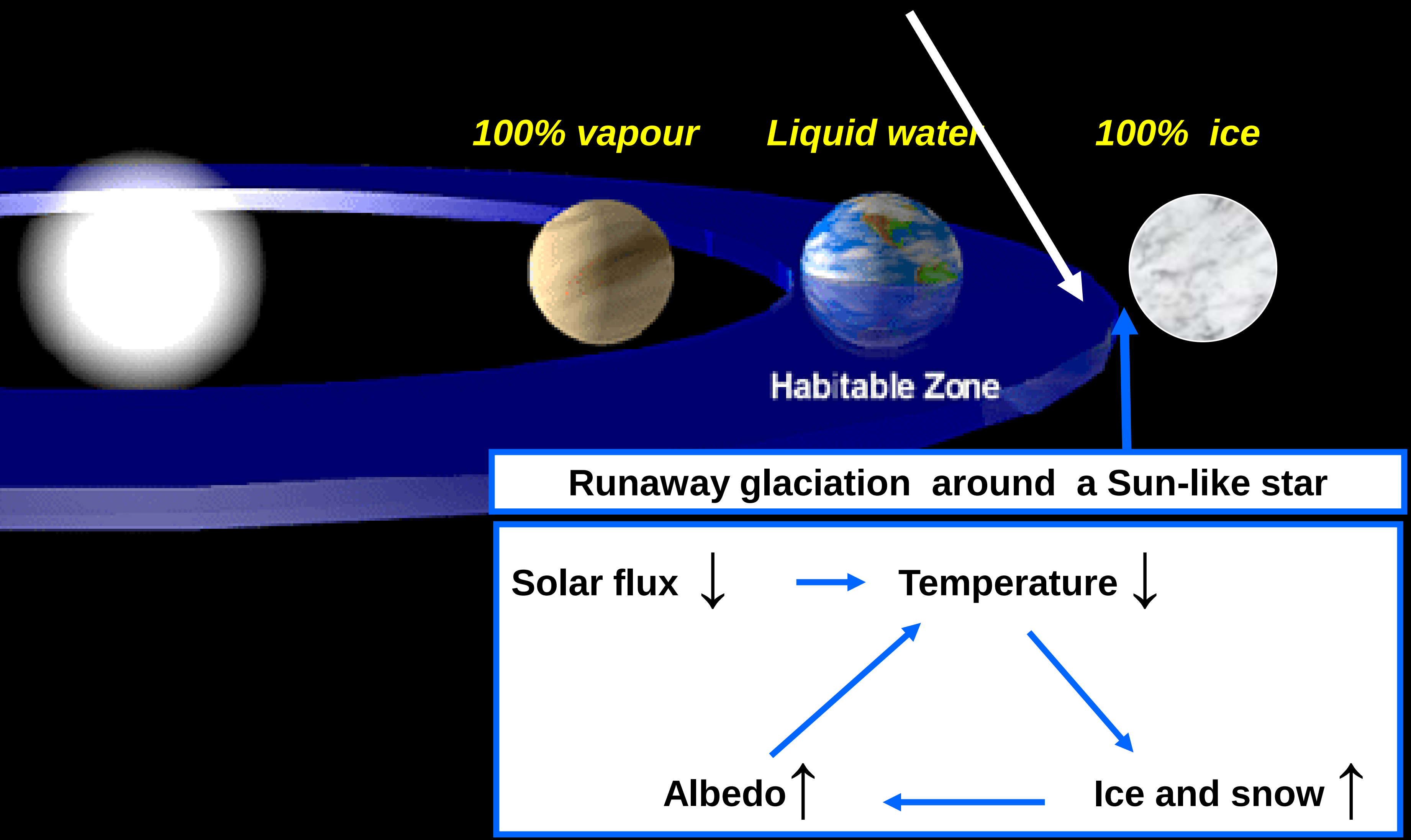
Draft version June 28, 2013

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 ?

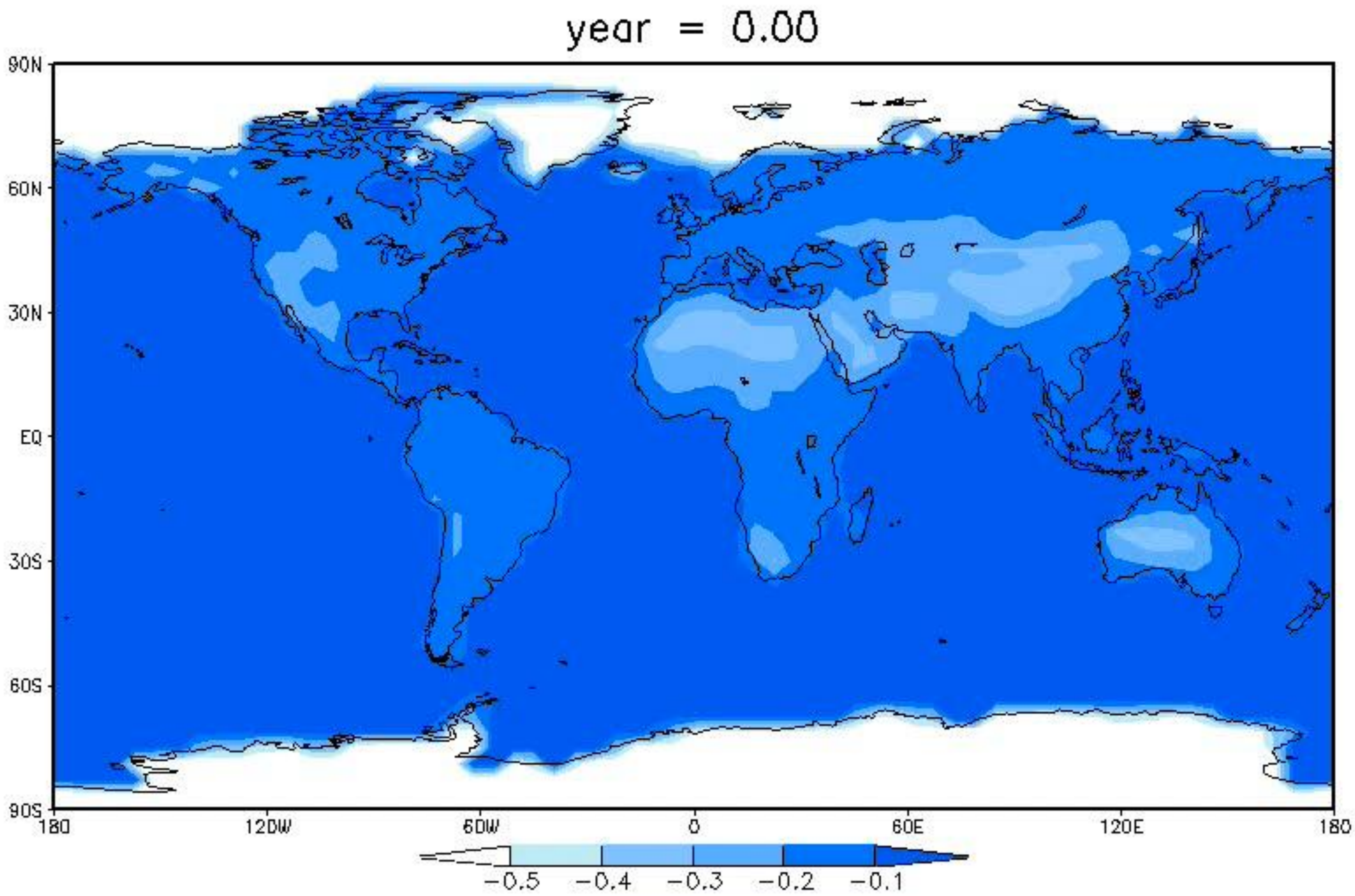


Climate Modelling: the Earth suddenly moved out by 12%

(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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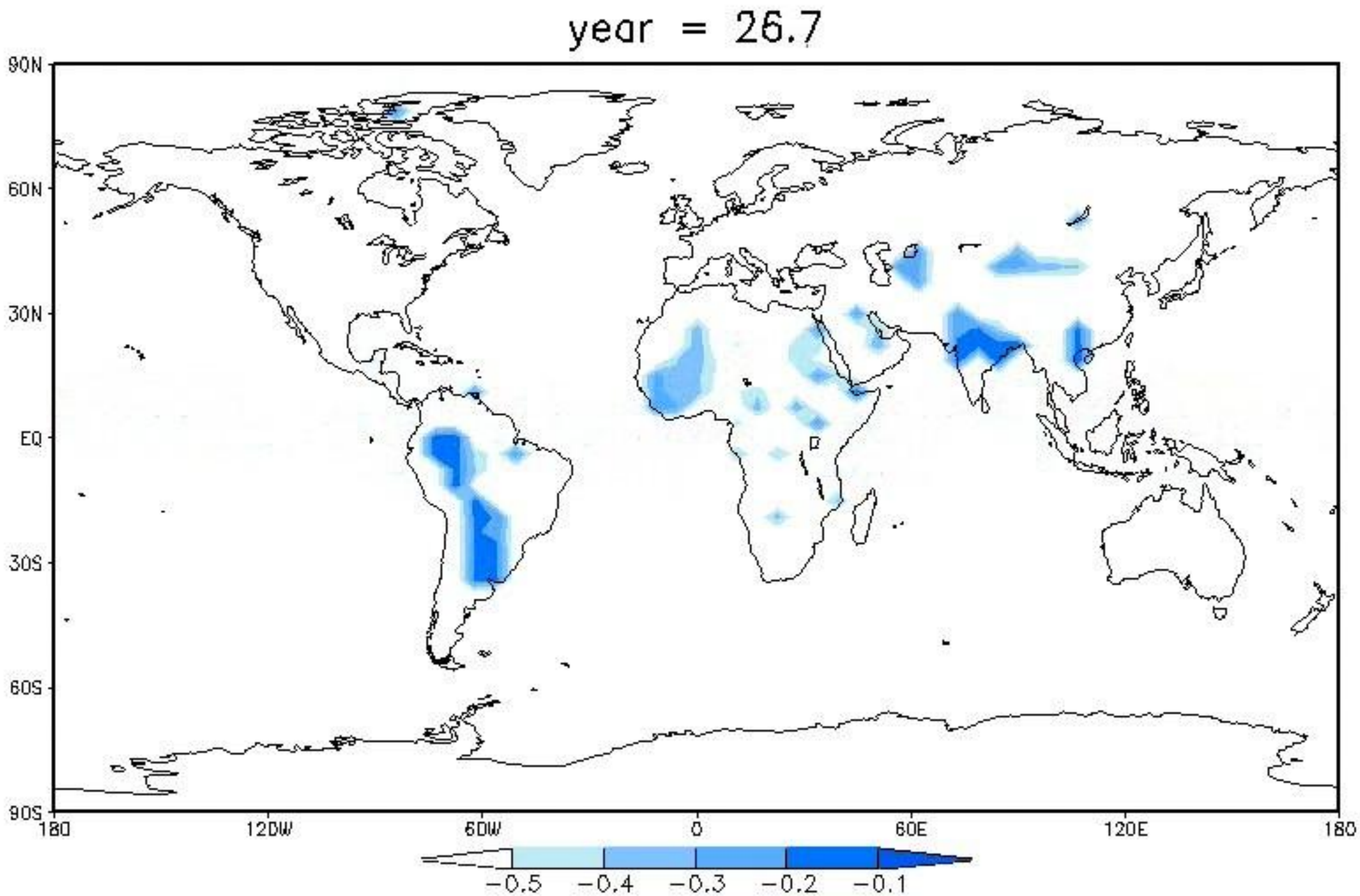

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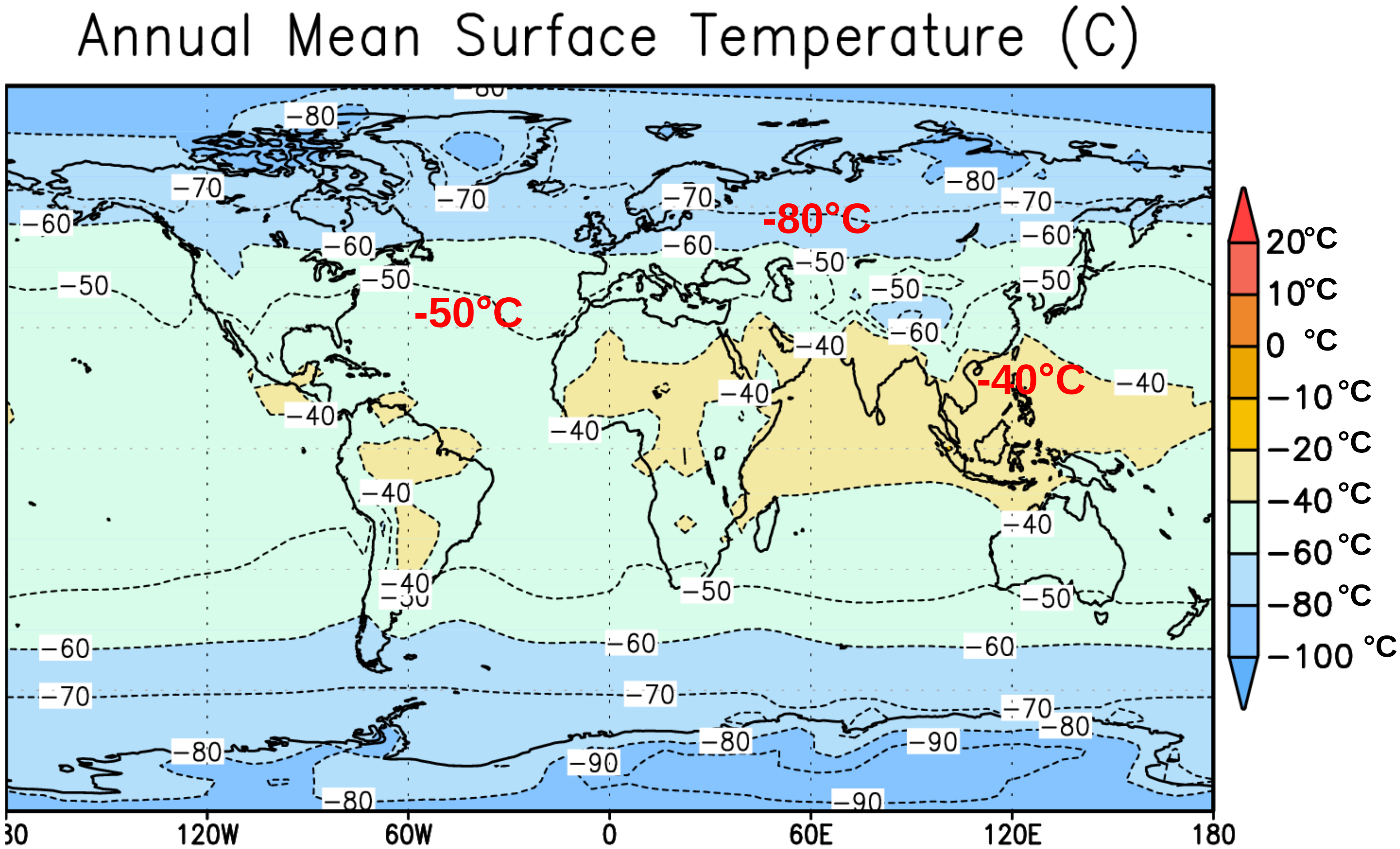
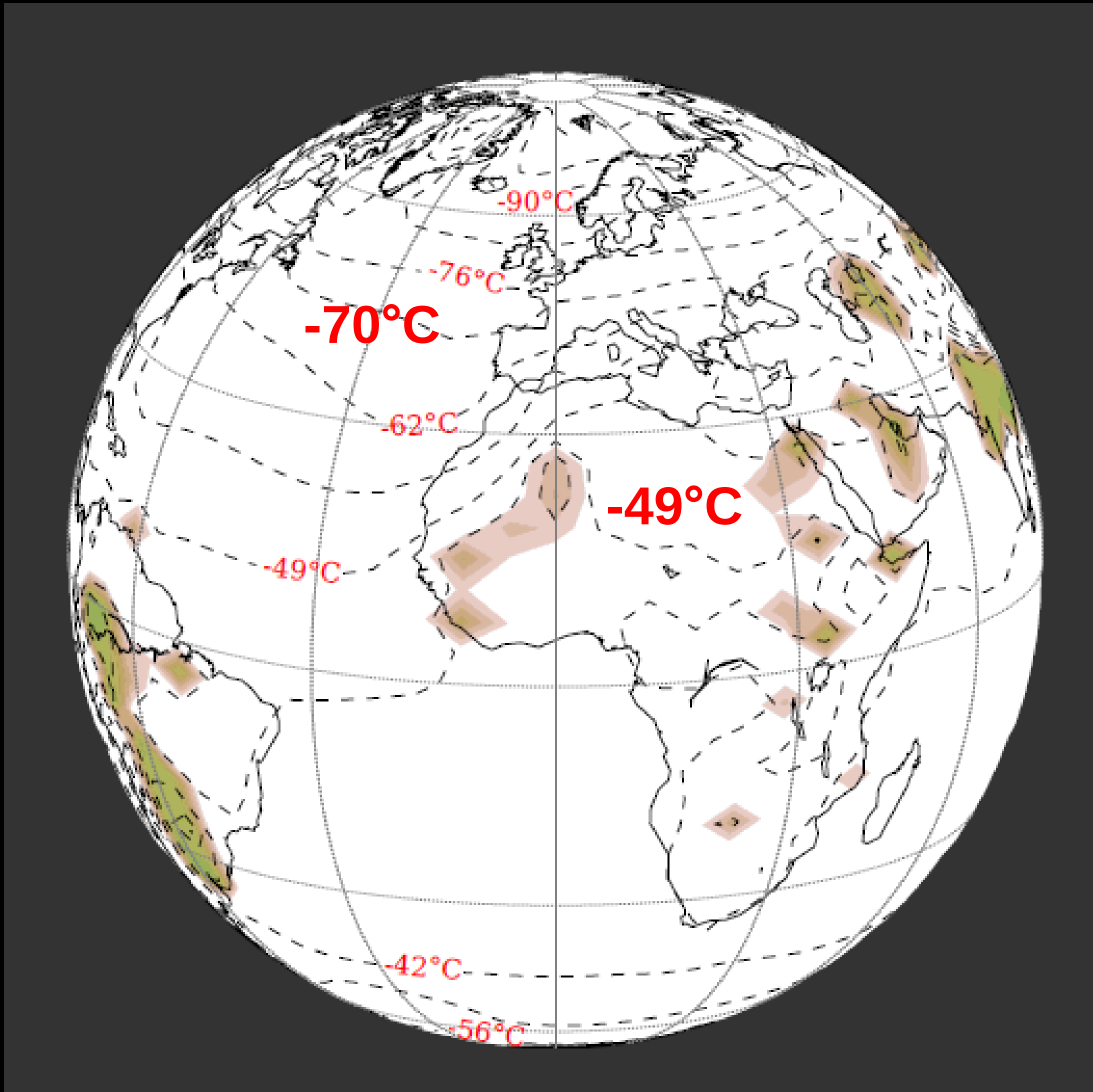


Out of glaciation: greenhouse effect

Flux = 80% present
(~1.12 AU)

Present
Earth atmosphere

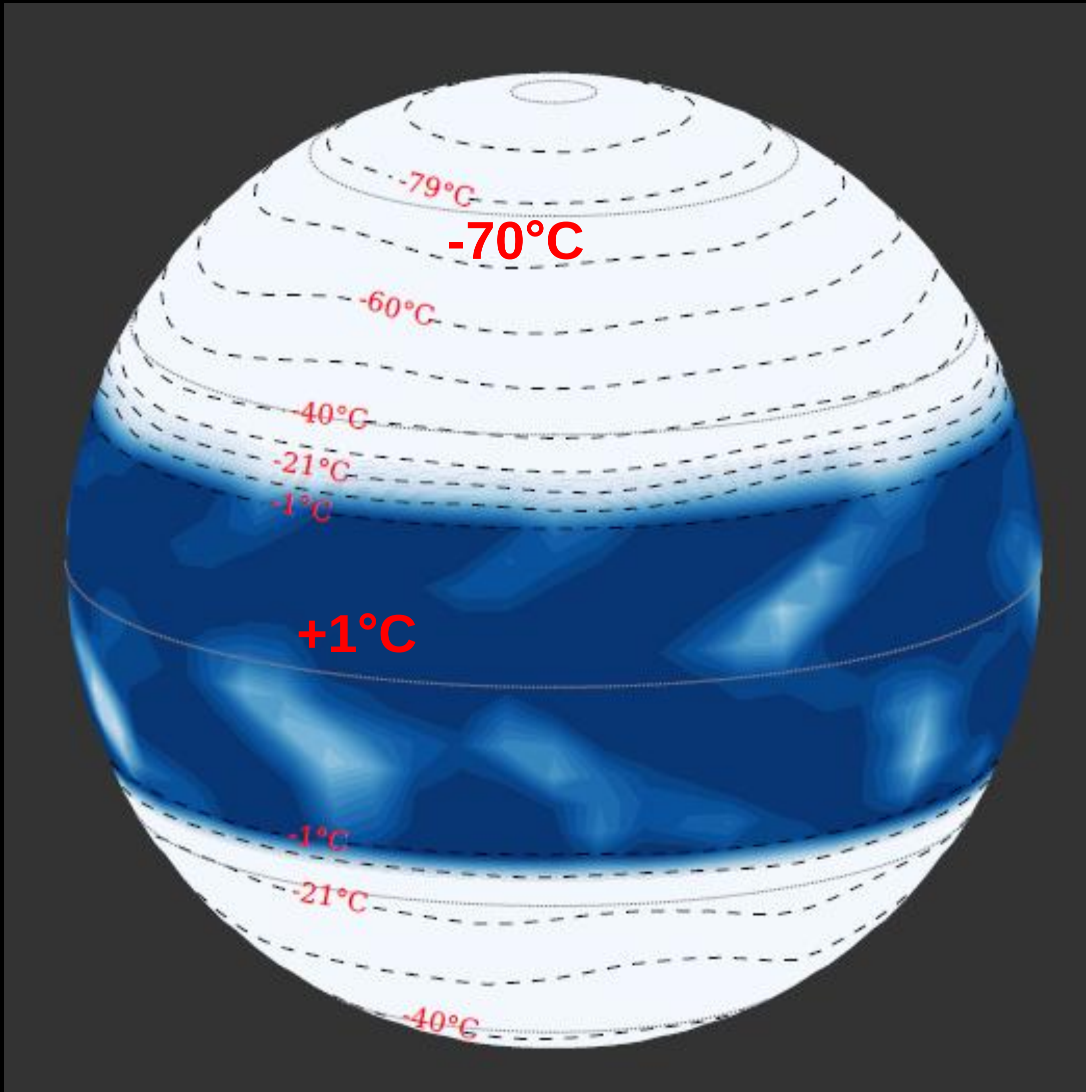


Charnay et al., JGR 2013

Out of glaciation: greenhouse effect

Flux = 80% present
(~1.12 AU)

$[CO_2] \times 2.5$

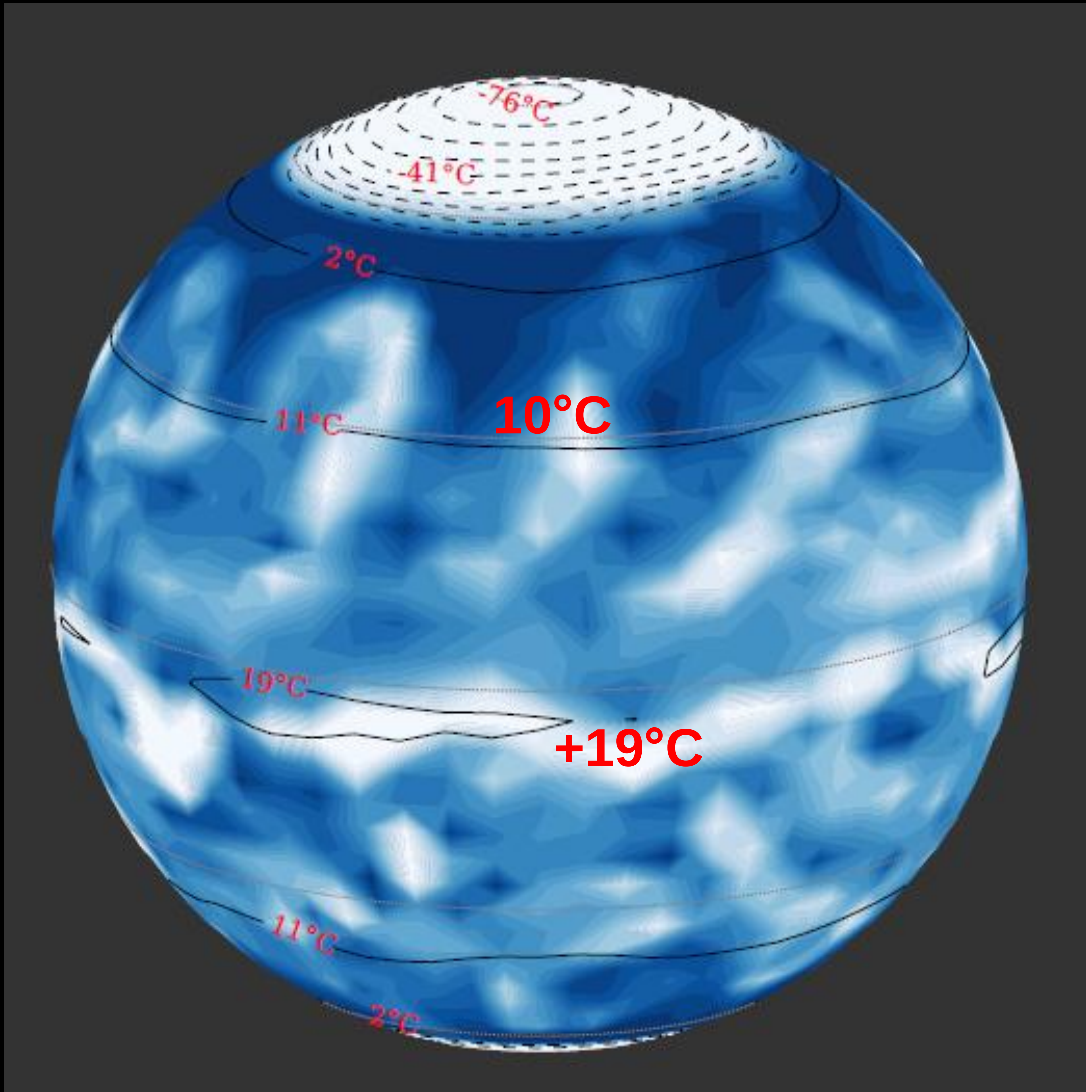


Charnay et al., JGR 2013

Out of glaciation: greenhouse effect

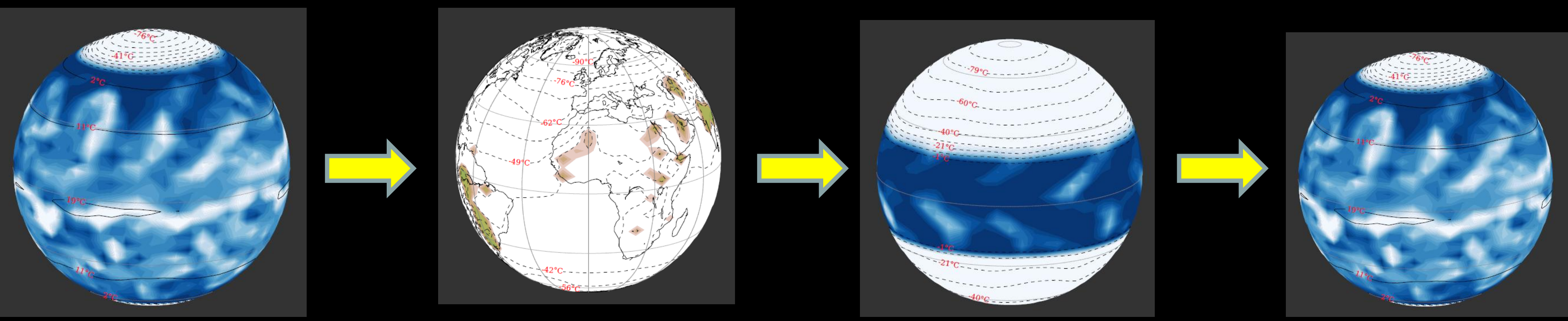
Flux = 80% present
(~1.12 AU)

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



Charnay et al., JGR 2013

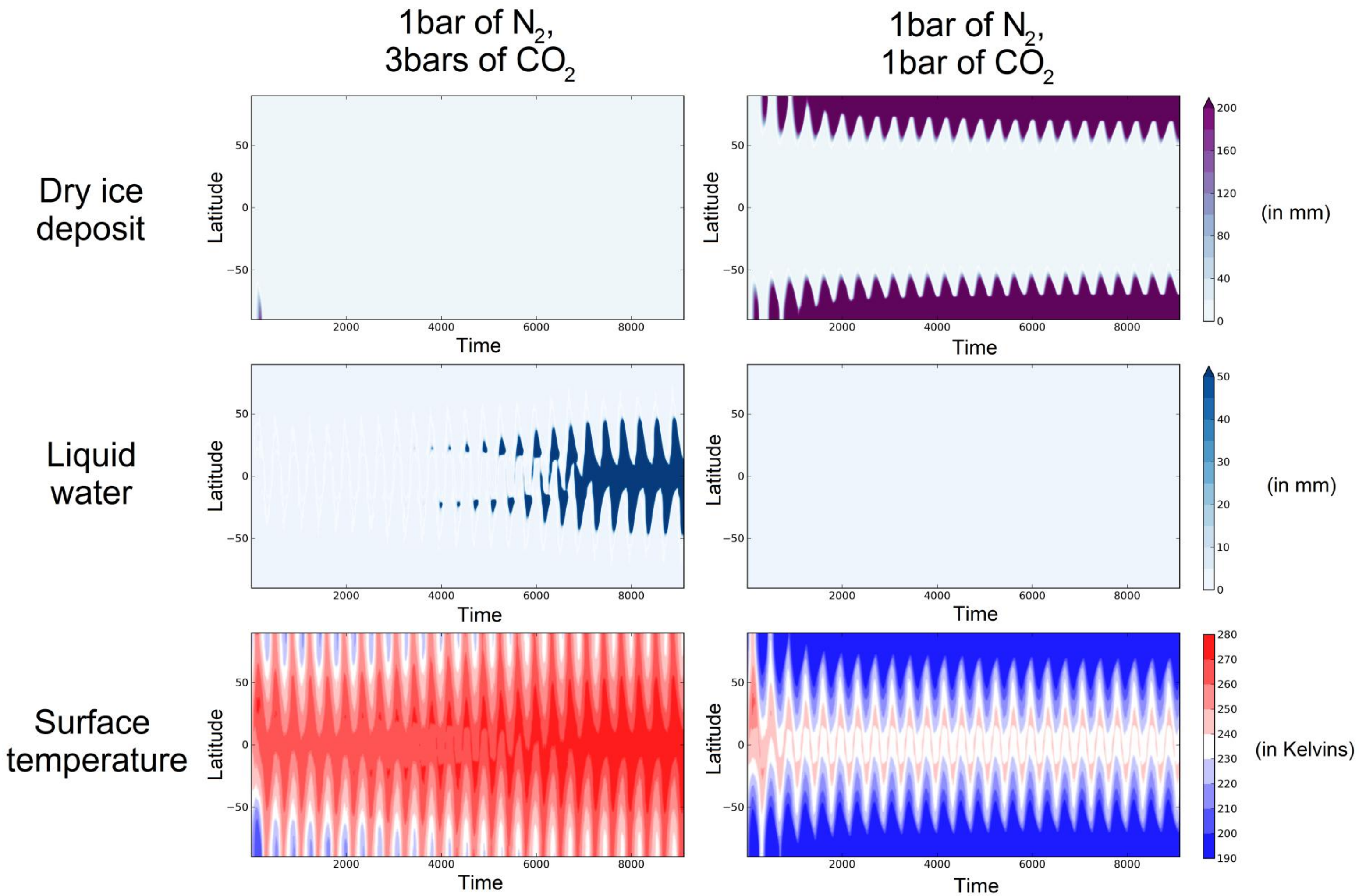
Many issues to explore: Example: How to exit from a glaciation ?



Possible scenarios of glaciation escape

around a Sun-like star (Martin Turbet)

Directly 3bars of CO2: Glaciation escape | **Start from 1 bars of CO2: CO2 polar condensation**



Glaciation around K & M dwarf stars:

Redder stellar spectrum

• No albedo water ice feedback

(Joshi and haberle, 2012, Shields et al. 2013)

• Weak atmospheric Rayleigh Scaterring

⇨ lower albedo

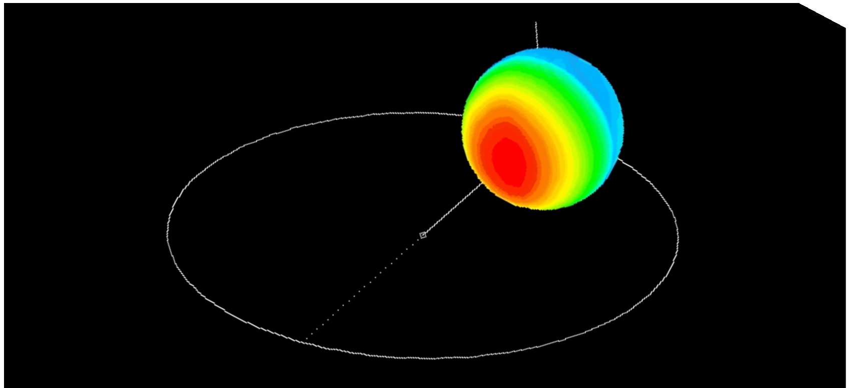
⇨ Enhanced high pressure CO_2 greenhouse effect

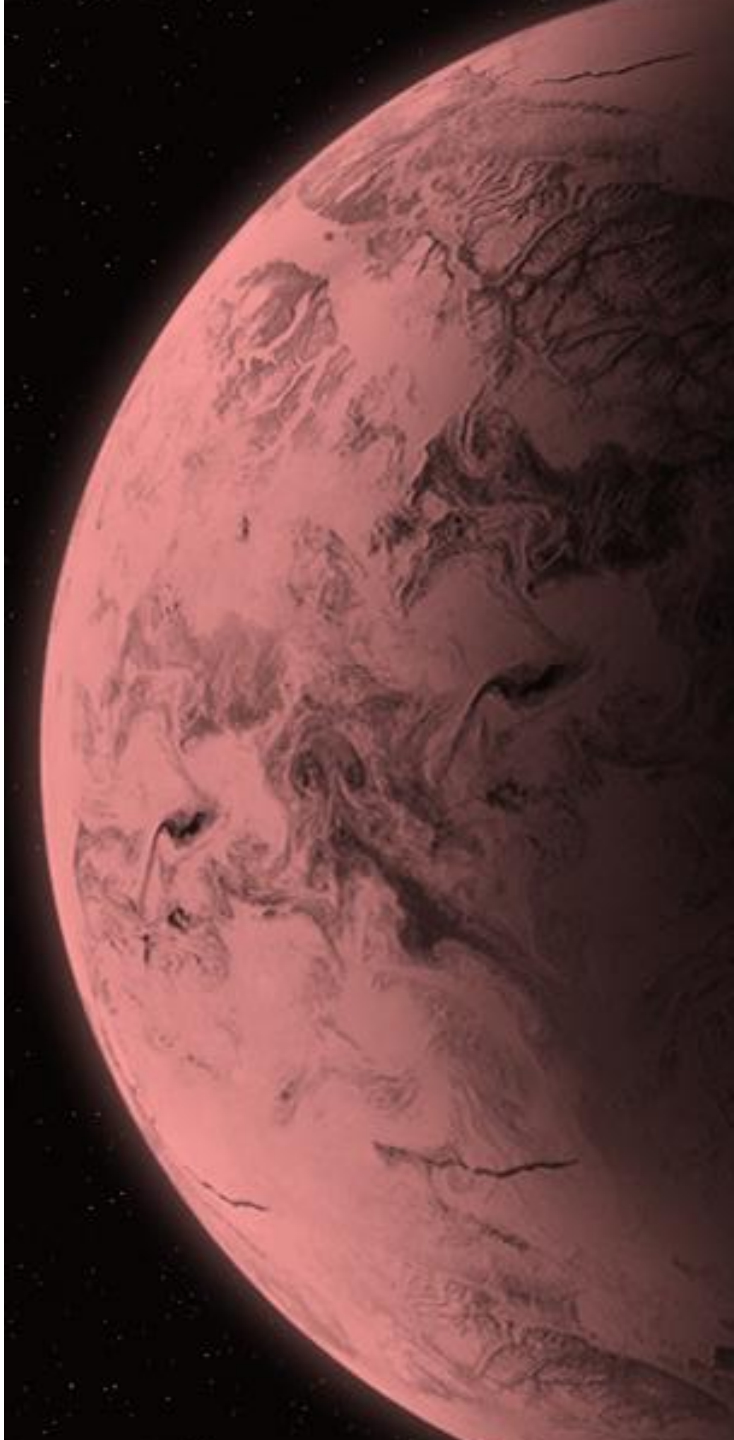
But : Effect of tides on rotation:

• Resonant rotation with zero obliquity

⇨ No insolation at the pole

⇨ Possible Locking with permanent night side?





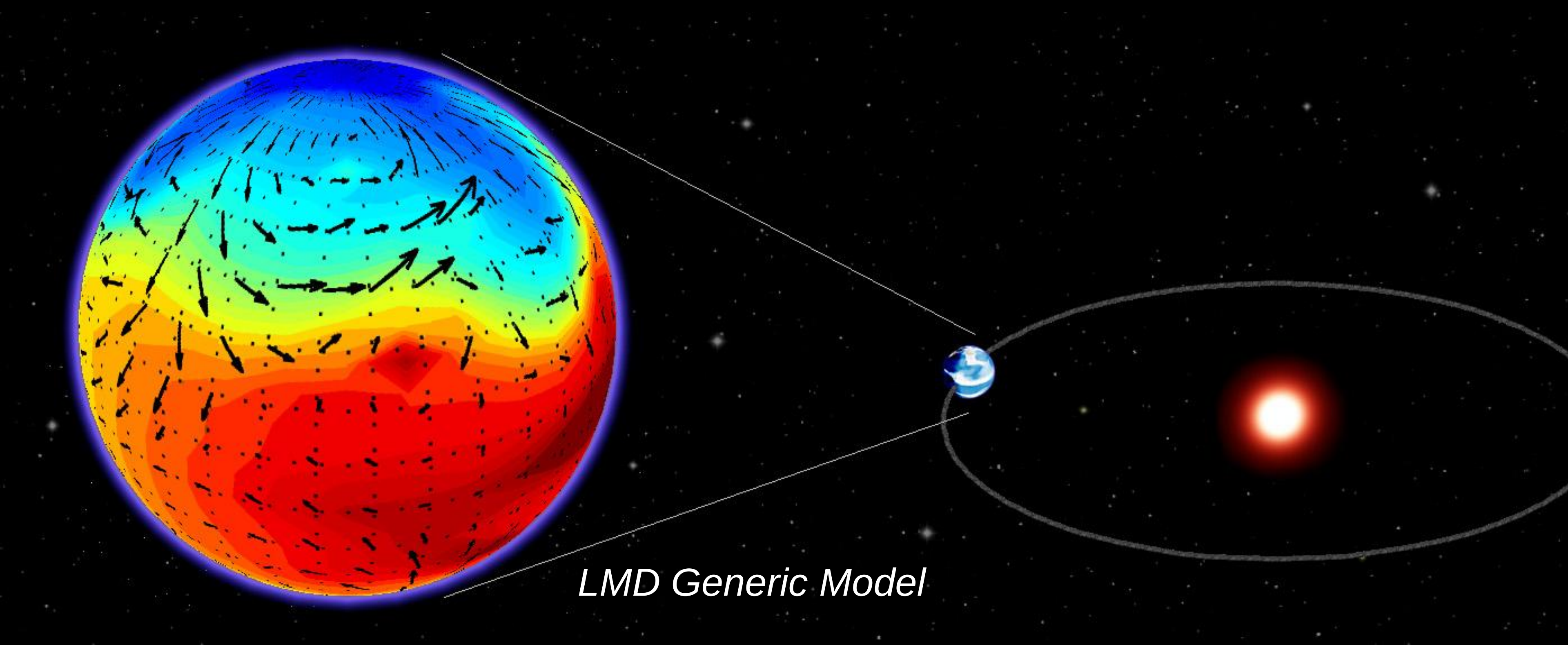
Example: simulating the climate on Exoplanet Gliese 581d (*Wordsworth et al. 2011*)

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 ?

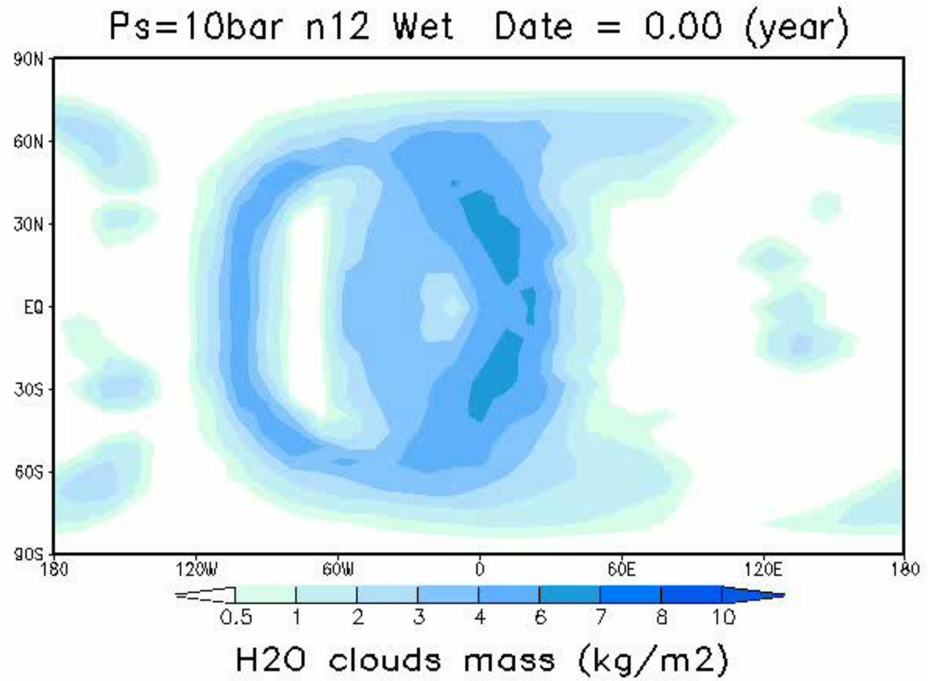
Udry et al. 2007, Mayor et al. 2009:



Gliese 581D
With P(CO_2)=10bar

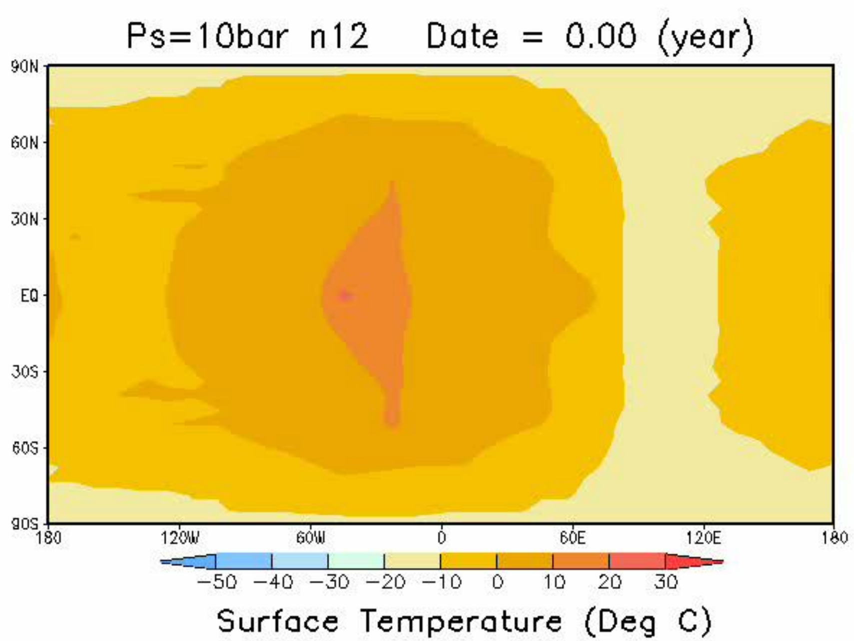
(*Wordsworth et al. 2011*)

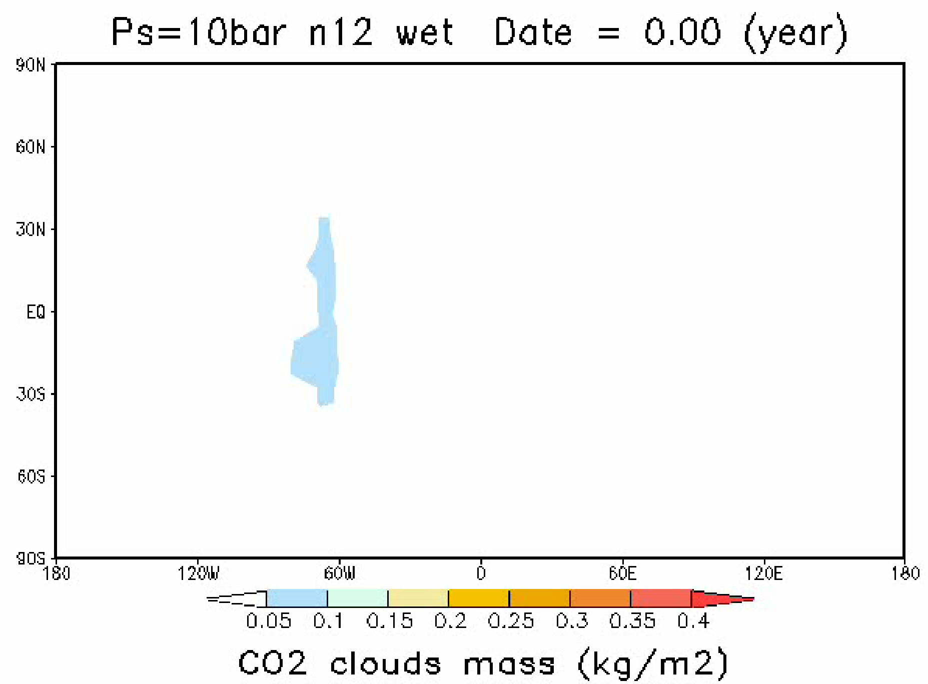
Water clouds



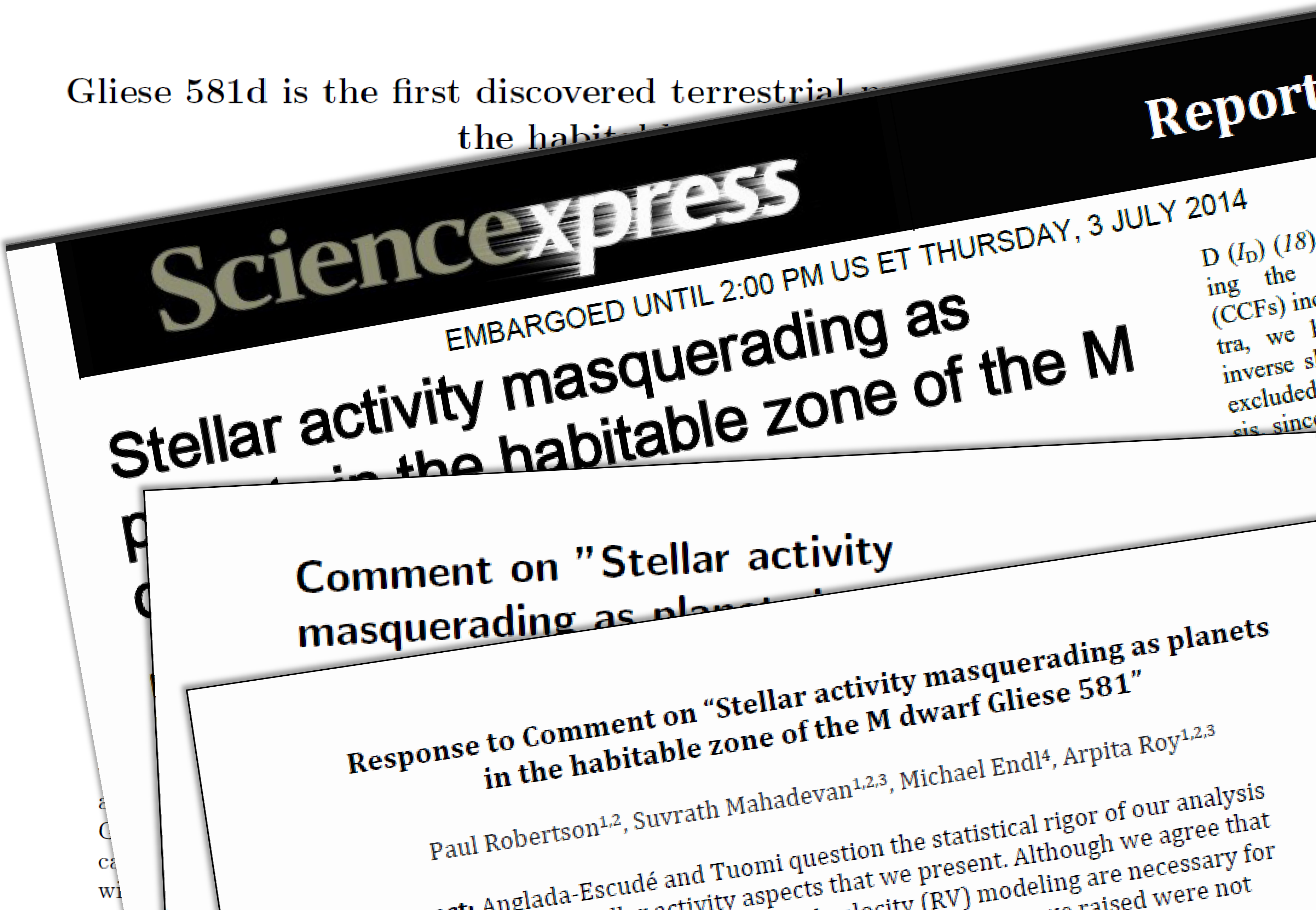
CO2 ice clouds

Surface temperature (K)





Astrophysical Journal, Wordsworth, Forget et al. 2011



Gliese 581d is the first discovered terrestrial ...
the habit...

Science express

Report

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

Stellar activity masquerading as
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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]

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

Astrophysical Journal, Wordsworth, Forget et al. 2011

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

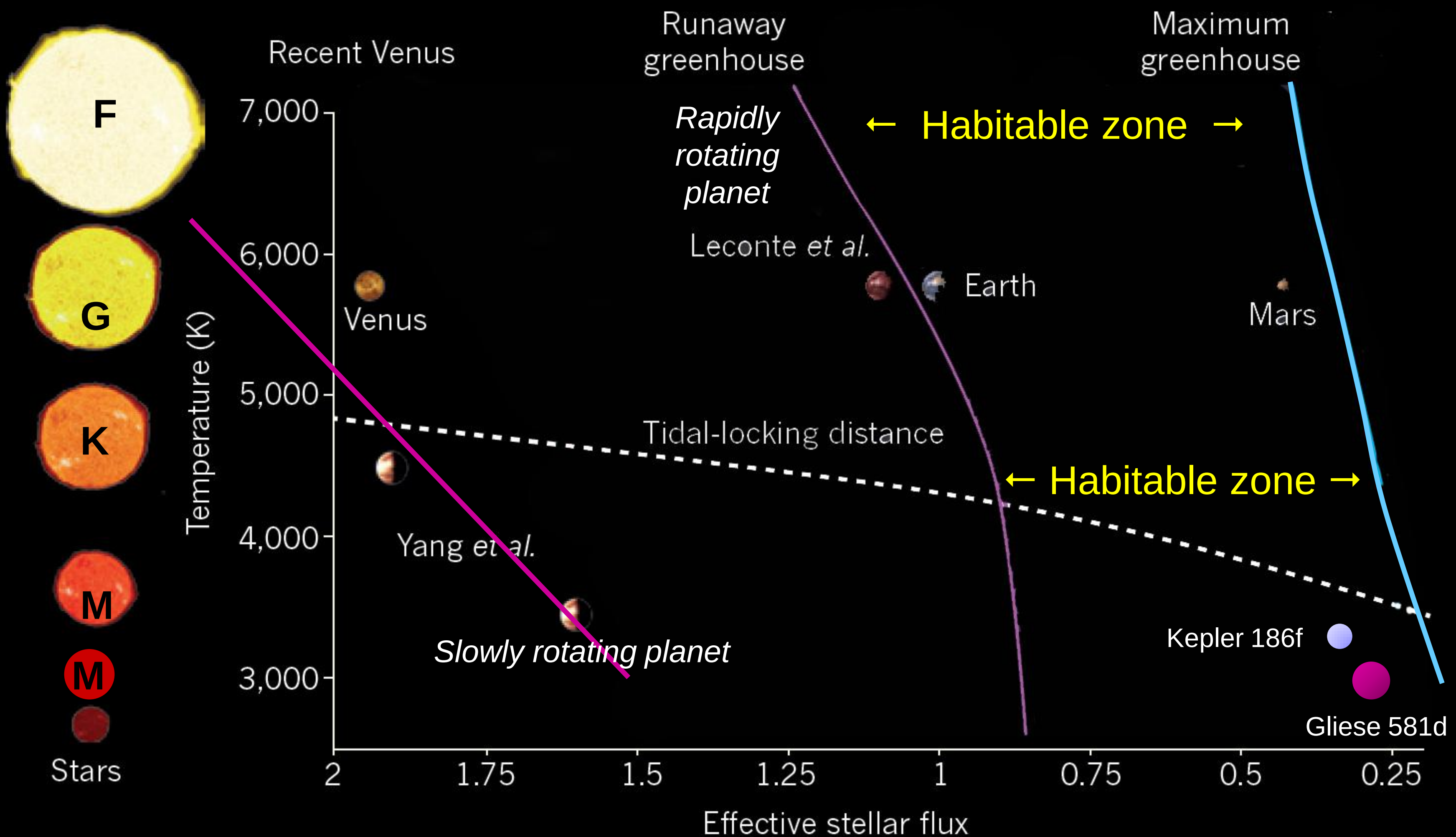
Robin D. Wordsworth,[1*] François Forget,[1] Franck Selsis,[2,3]
Ehouarn Millour,[1] Benjamin Charnay,[1] Jean-Baptiste Madeleine[1]

[1]Laboratoire de Météorologie Dynamique,
Institut Pierre Simon Laplace, Paris, France
[2]CNRS, UMR 5804, Laboratoire d'Astrophysique de Bordeaux,
2 rue de l'Observatoire, BP 89, F-33271 Floirac Cedex, France
[3]Université de Bordeaux, Observatoire Aquitain des Sciences de
l'Univers, 2 rue de l'Observatoire, BP 89, F-33271 Floirac Cedex, France

ABSTRACT

It has been suggested that the recently discovered exoplanet GJ581d might be able to support liquid water due to its relatively low mass and orbital distance. However, GJ581d receives 35% less stellar energy than Mars and is probably locked in tidal resonance, with extremely low insolation at the poles and possibly a permanent night side. Under such conditions, it is unknown whether any habitable climate on the planet would be able to withstand global glaciation and / or atmospheric collapse. Here we present three-dimensional climate simulations that demonstrate GJ581d will have a stable atmosphere and surface liquid water for a wide range of plausible cases, making it the first confirmed super-Earth in the habitable zone. We find that atmospheres with over 10 bar CO_2 and varying amounts of background gas (e.g., N_2) yield global mean

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



Adapted and modified from Kasting and Harman (2013)

Conclusions: Atmospheres, Climate and Habitability (1/3)

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

Climate → **Habitability**

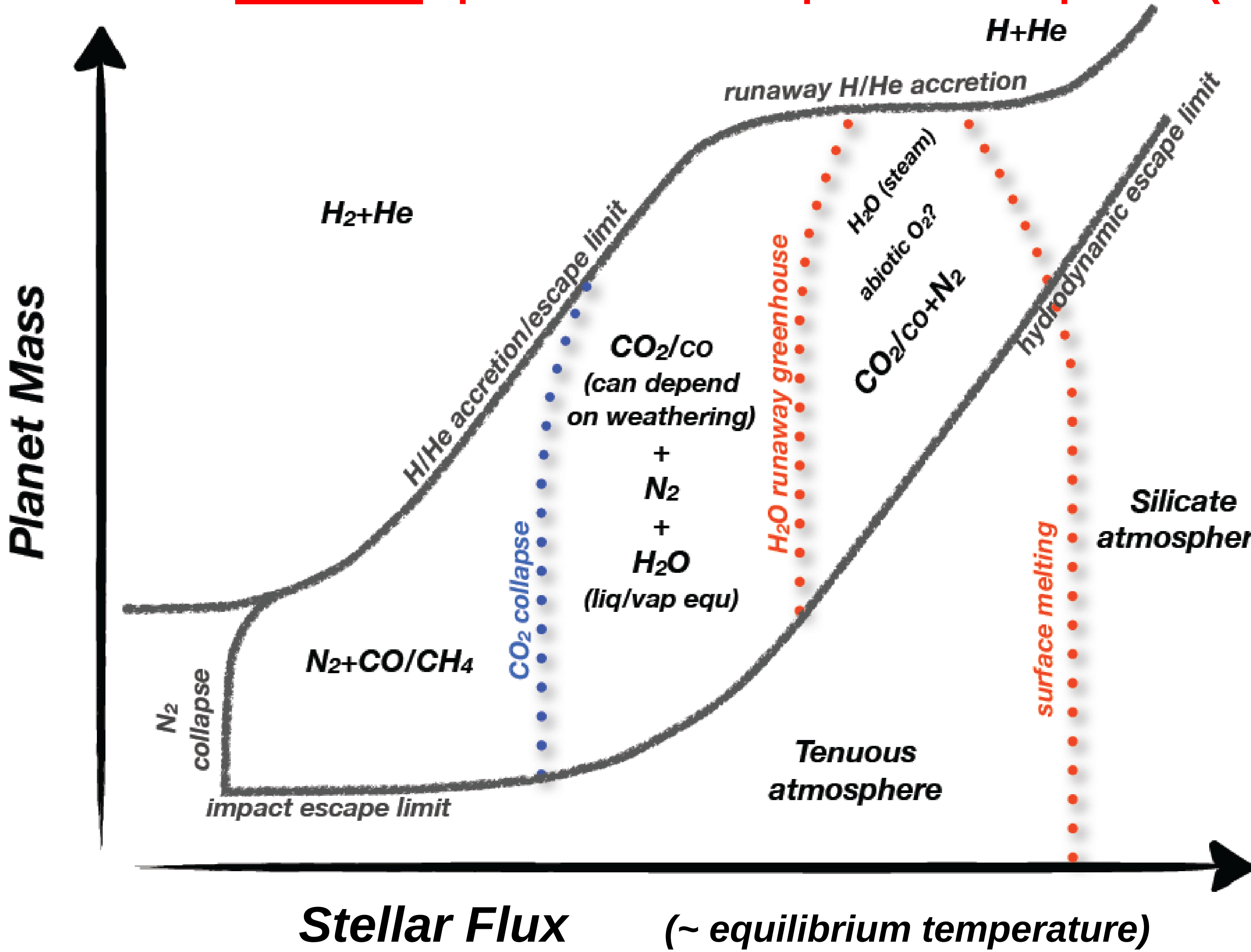
<u>Key problem</u>: understanding of the zoology of **atmospheric composition**, controlled by complex processes :

- 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)

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)**

Conclusions: Atmospheres, Climate and Habitability (2/3)

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- 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)