GLOBAL CLIMATE MODELS AND EXTREME HABITABILITY

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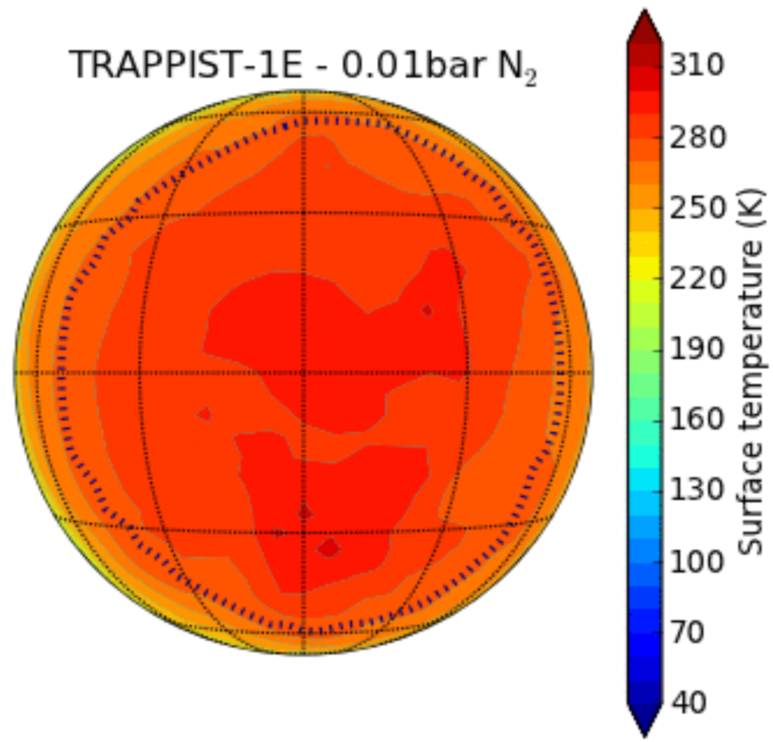


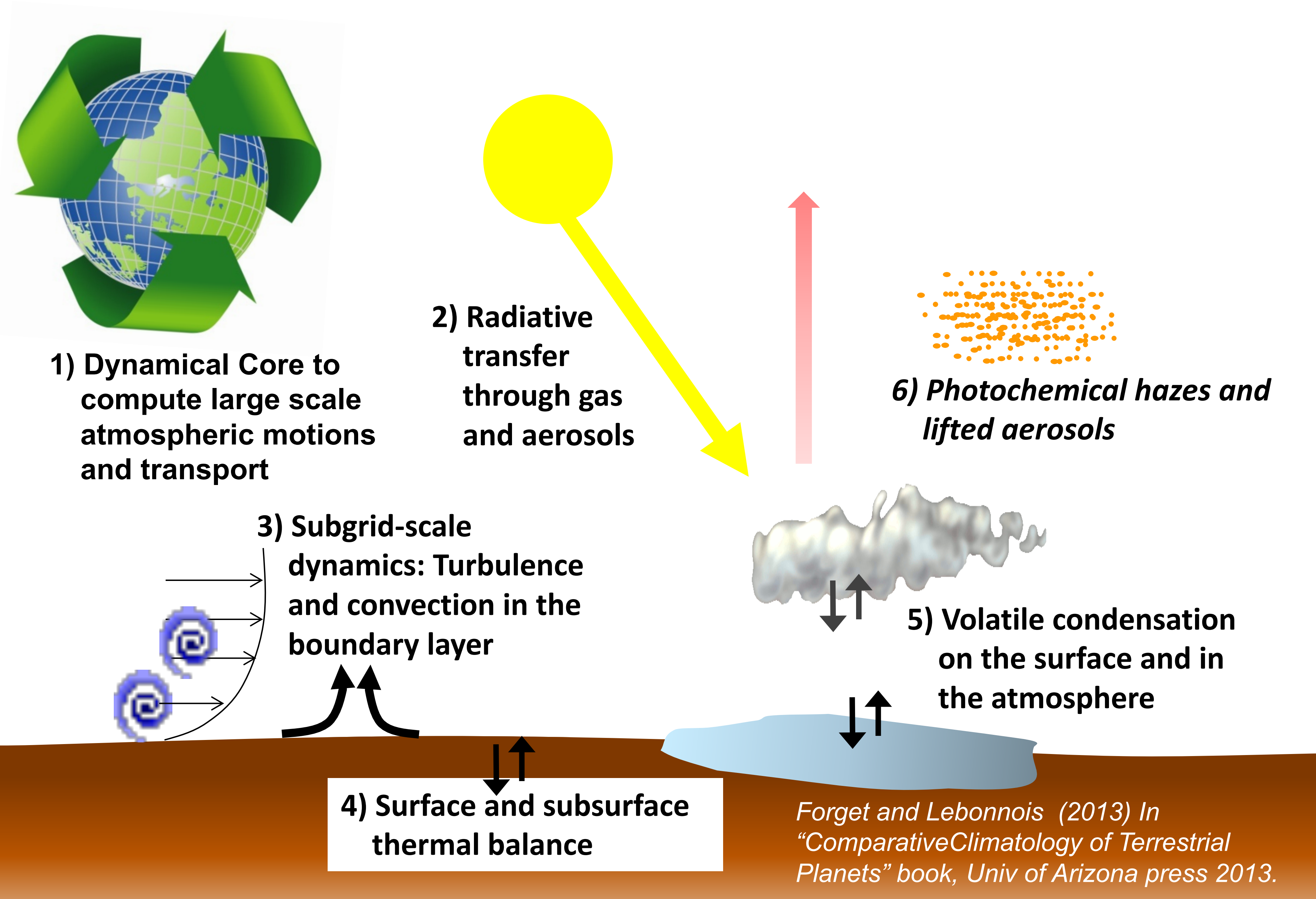
Modelled surface temperatures on tidally locked planets around TRAPPIST-1 with the LMD-G GCM

51st eslab symposium "extreme habitable worlds"
04 - 08 december 2017
European Space Agency

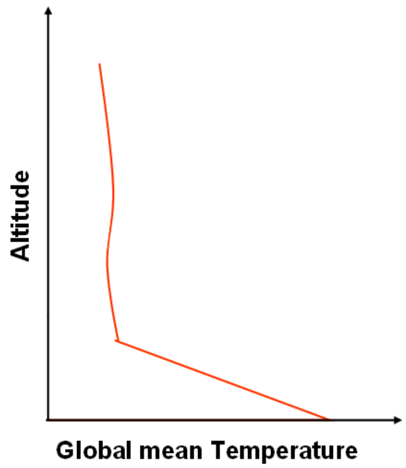
How to build a full Global Climate Simulator ?

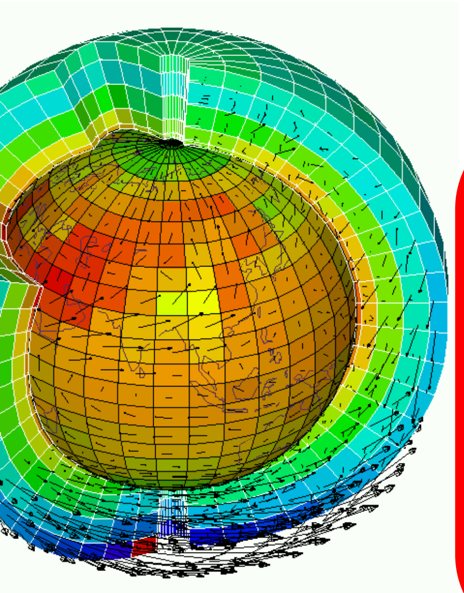
GEOS-5, NASA Goddard GCM

How to build a full Global Climate Simulator ?



Which climate on (extra-solar) planets ?
A hierarchy of models for planetary climatology





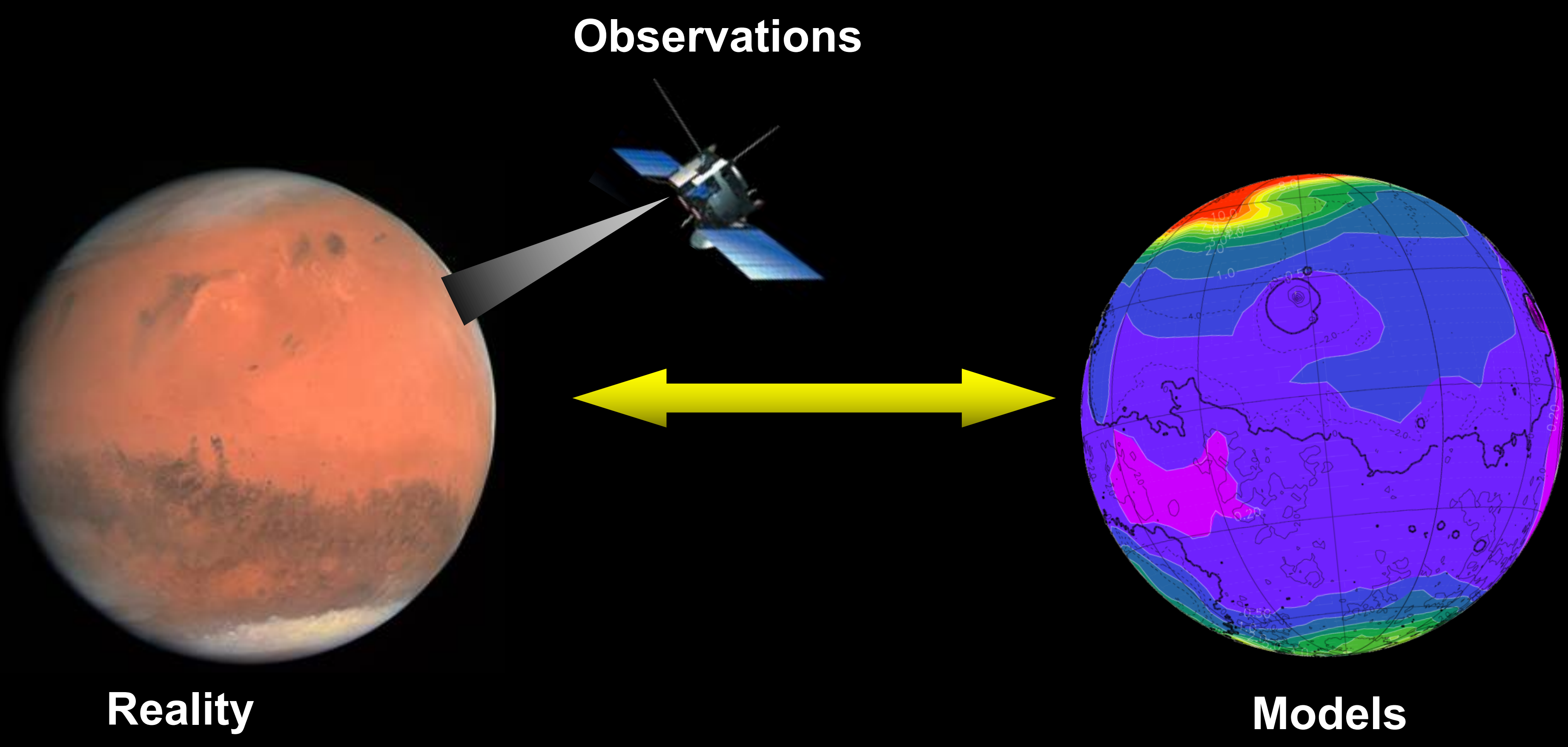
1. **1D global radiative convective models**
   ⇨ Great to explore exoplanetary climates; still define the classical Habitable Zone
2. **2D Energy balance models…**
3. **Theoretical 3D General Circulation Models with simplified forcing**: to explore possible atmospheric circulation regime
4. **Earth Global Climate Models** to simulate 'Earth-like' planets in exotic conditions (different obliquity, insolation, etc.)
5. **Full 3D Global Climate Models** including "all" key climate processes (Rad. Transfer, transport, clouds, rain, snow, etc.)
6. **Full 3D Global Climate Models with**

(1) **an ocean circulation model**

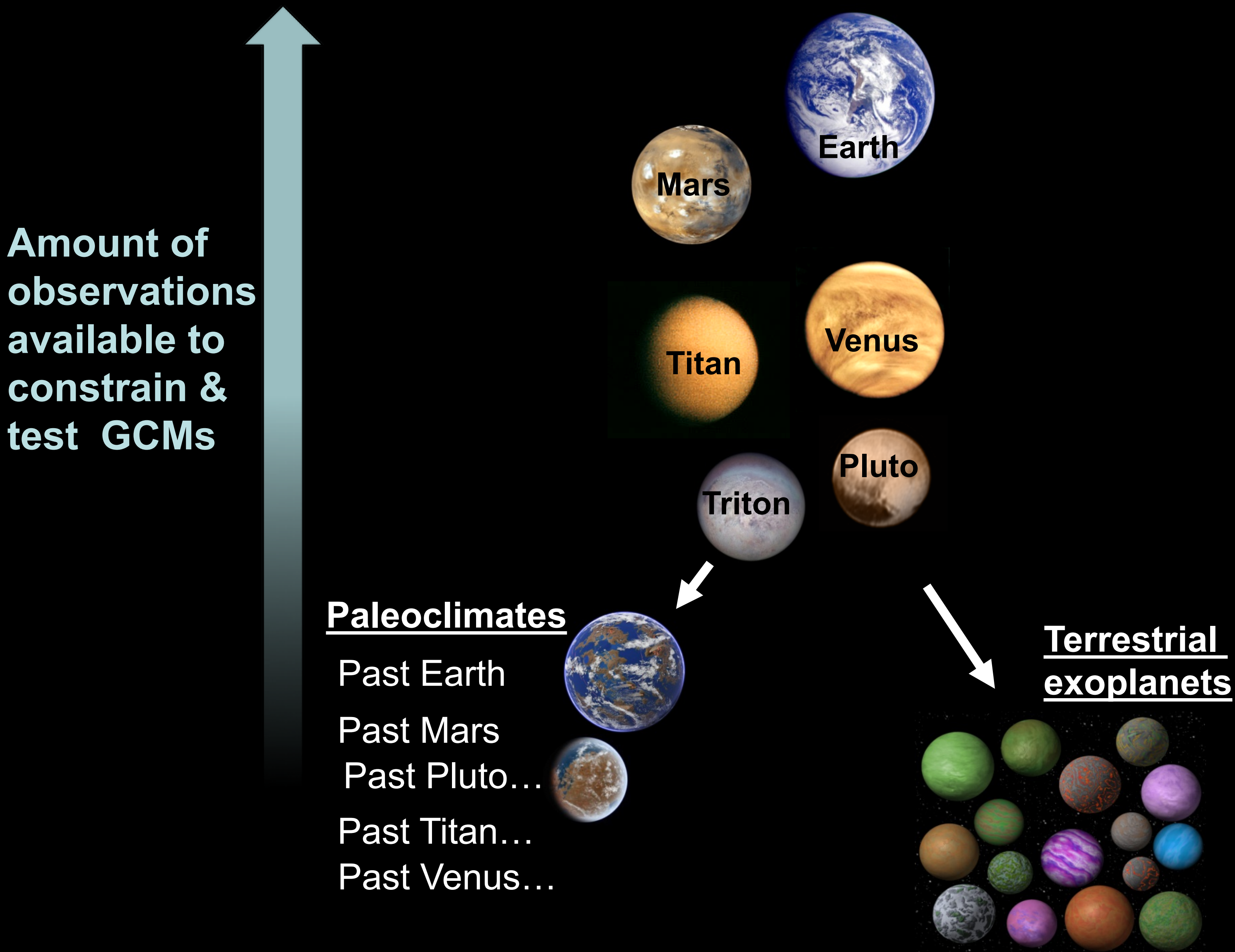
(2) **a converged water cycle to simulate the effect of limited surface water reservoir** (water tends to accumulate in cold trap, not where it is liquid)

Ambitious Global Climate models :

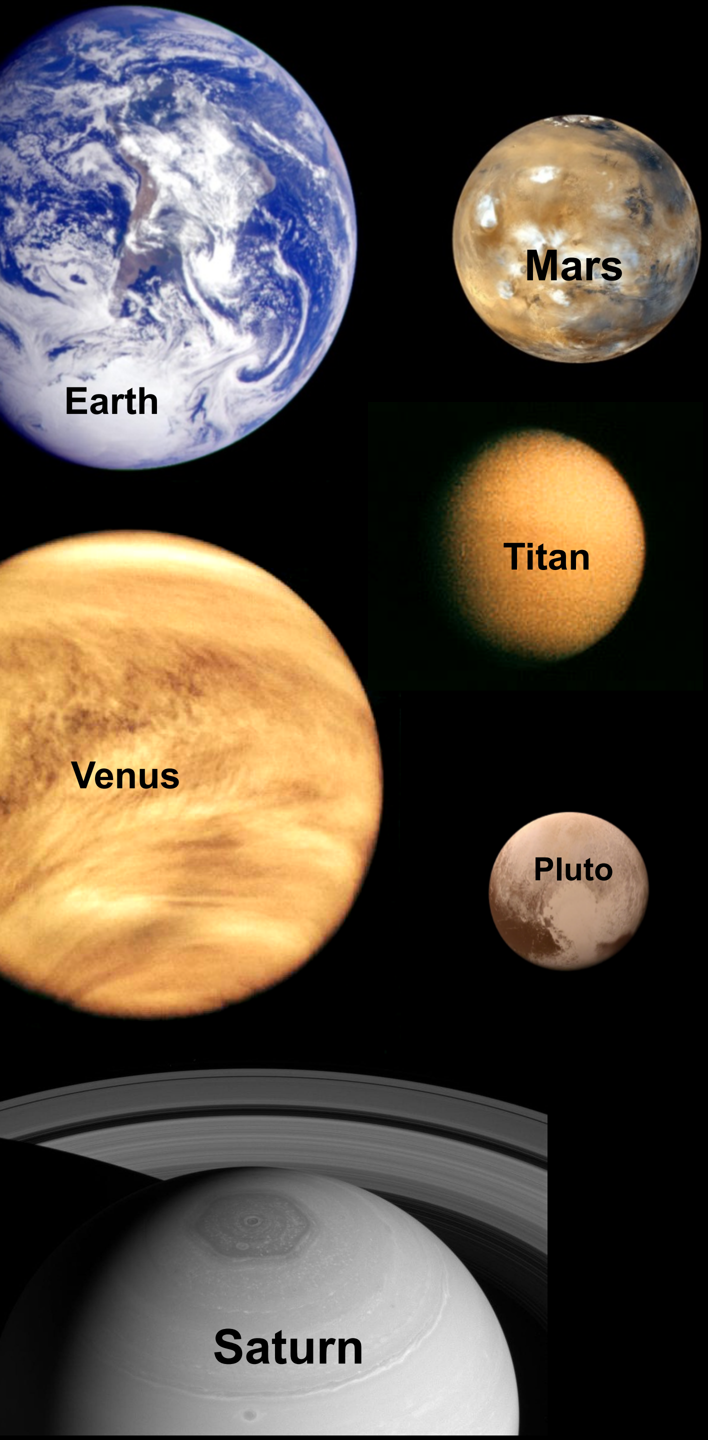
Building “virtual” planets behaving like the real ones, on the basis of universal equations



Terrestrial atmospheres to model



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…)

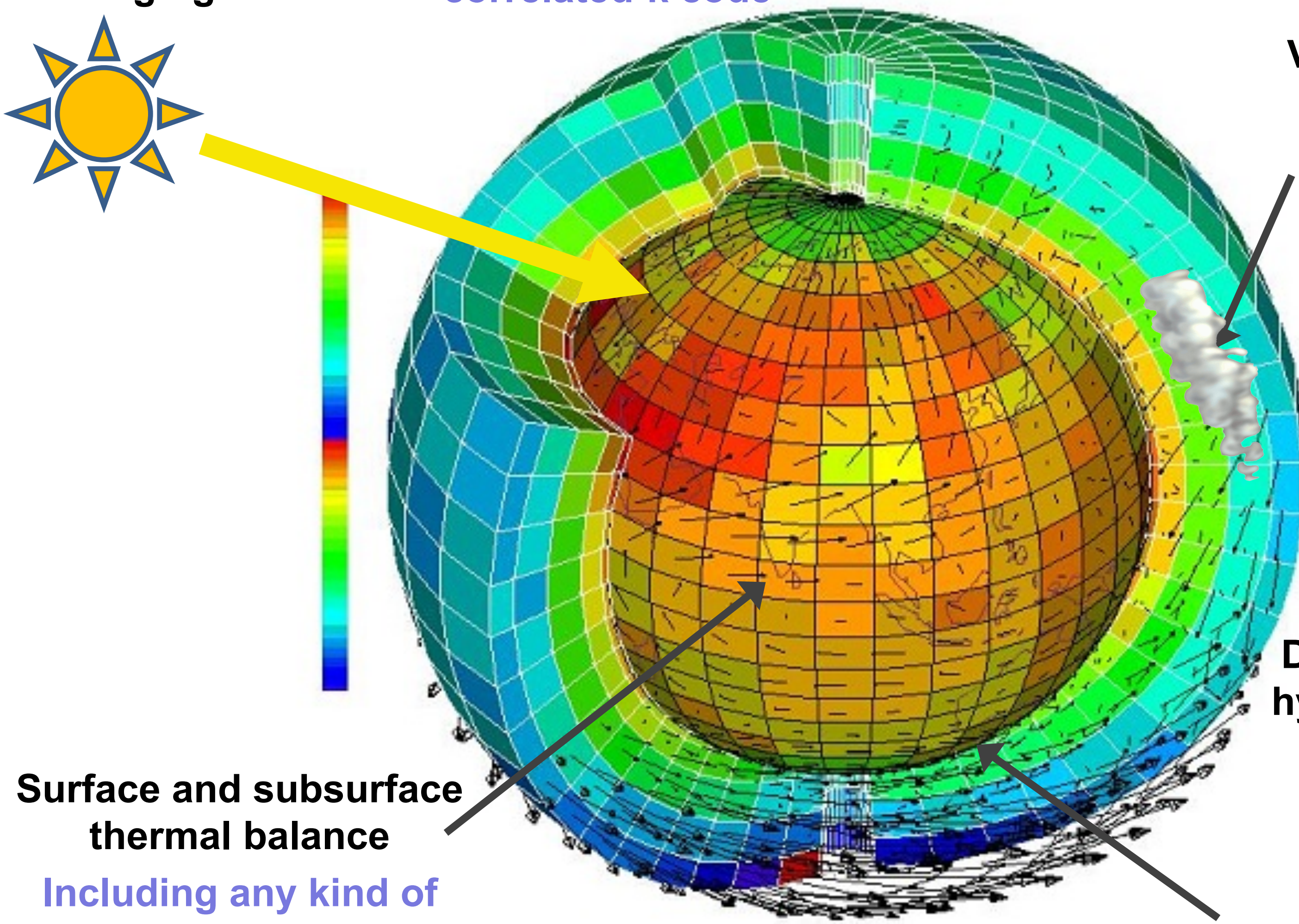
Lesson # 3 Climate model components can be applied without major changes to most terrestrial planets **and thus to explore habitability in extreme conditions**.

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

One model to simulate them all

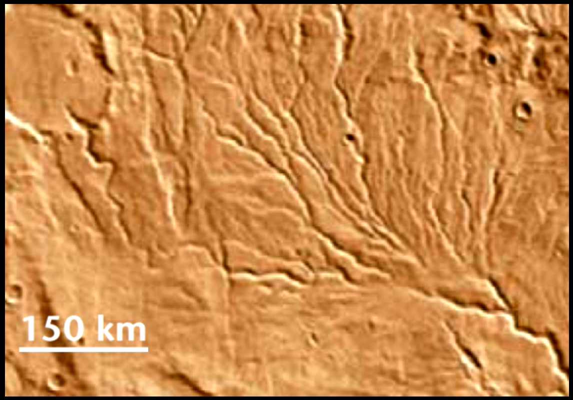
The 3-D LMD "Generic" Global Climate Model

One model to simulate them all



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

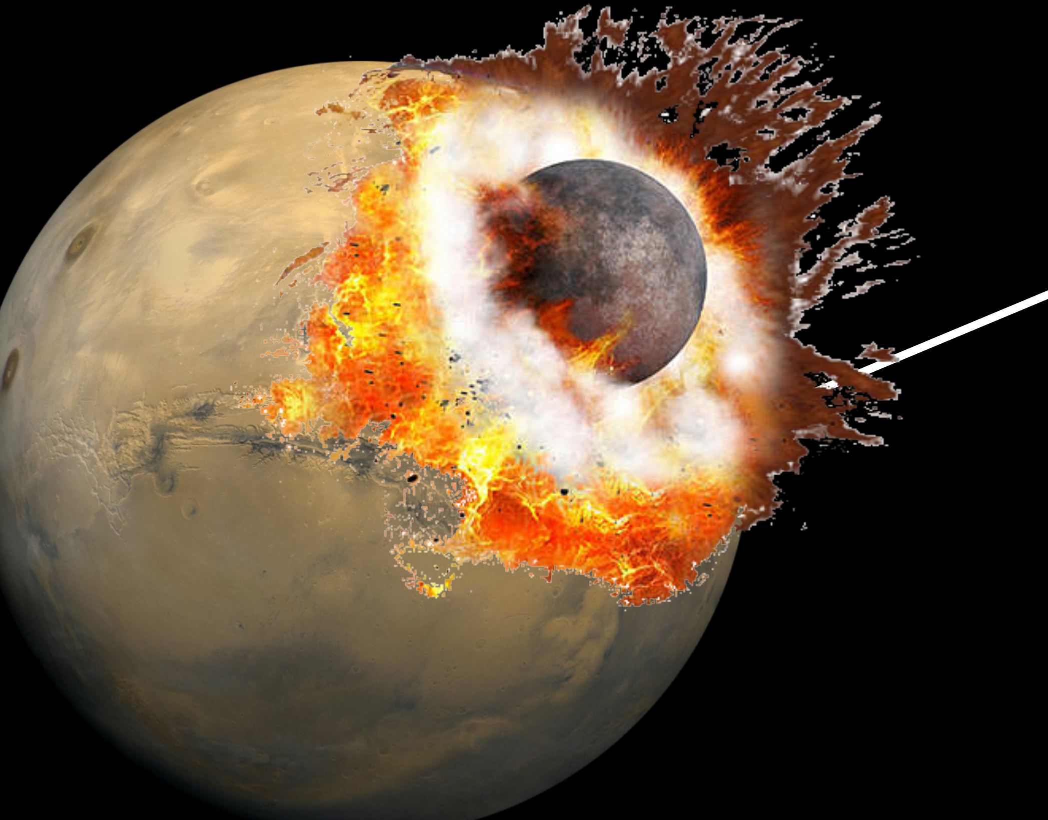
- **To Model ancient climates to understand geological records**
  - The faint young sun paradox on early Earth
    (Charnay et al. 2013, 2017)
  - Early Mars
    (Forget et al. 2013, Wordsworth et al. 2013, 2015, Kerber et al 2015, Bouley et al. 2016, Turbet et al. 2017a, 2018a)
  - Ancient Titan *(Charnay et al. 2014)*

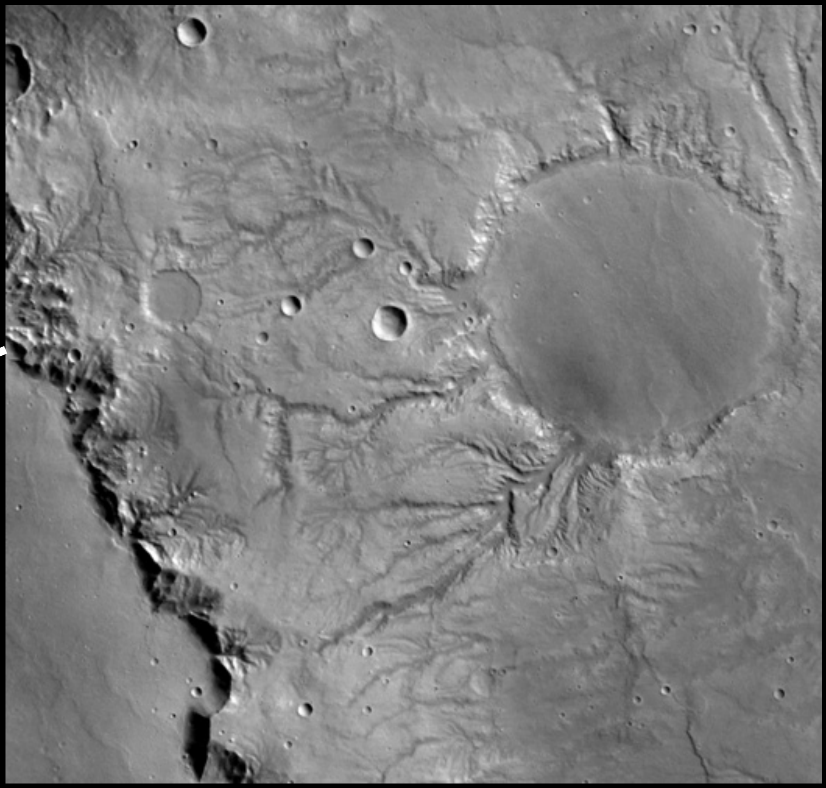


#1 The early Mars enigma

Climate models show that Mars cannot be warmed with CO_2/H_2O only

Wordsworth et al. 2013
Forget et al. 2013



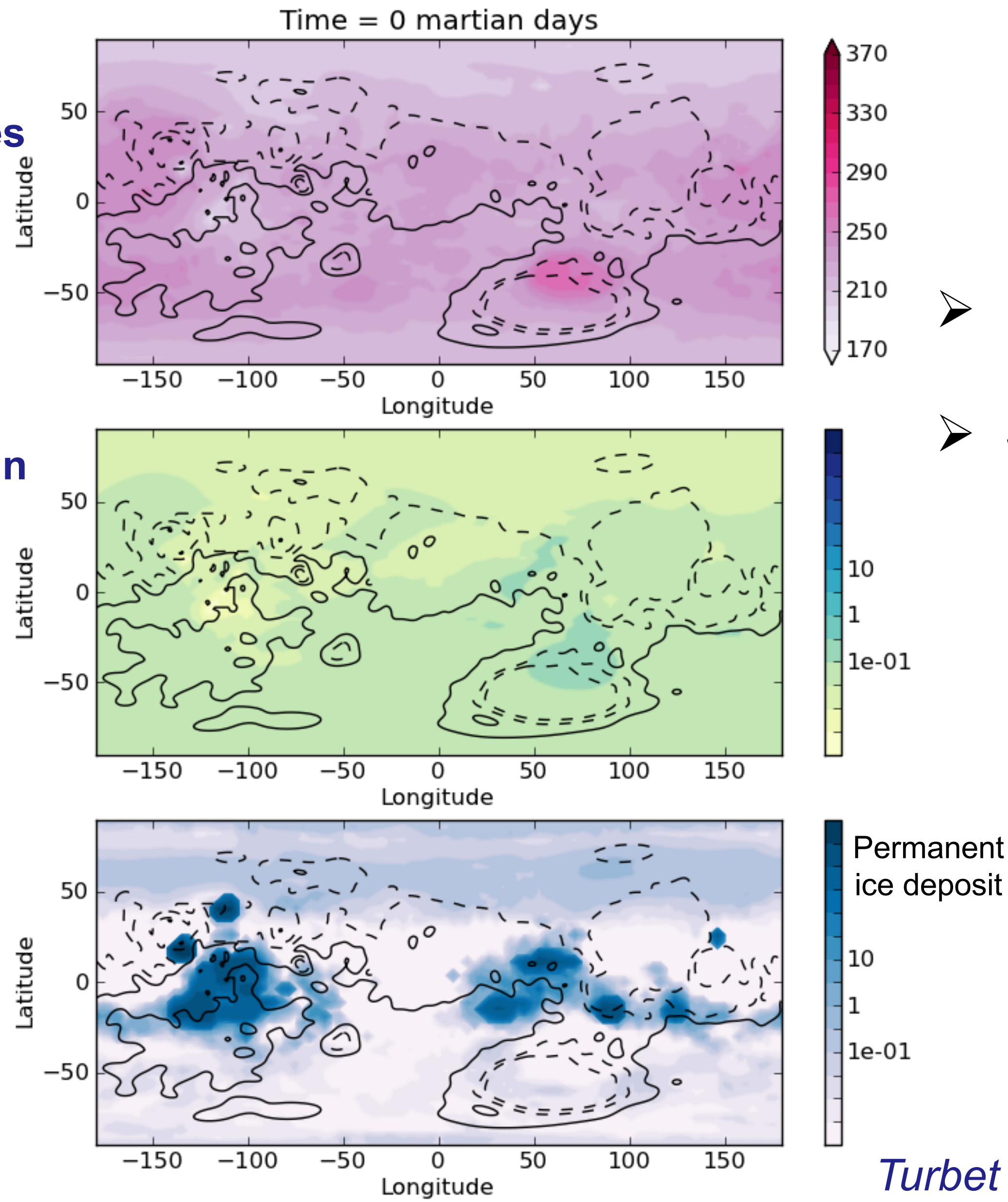


Results of 3-D Global Climate Modeling

Surface Temperatures (K)

Vapor column (kg/m²)

Surface ice deposits (mm)



Initial state:

- 1bar CO_2 atmosphere
- Stabilized surface ice reservoirs

Turbet et al. 2017, Icarus
Turbet et al. 2018, in prep

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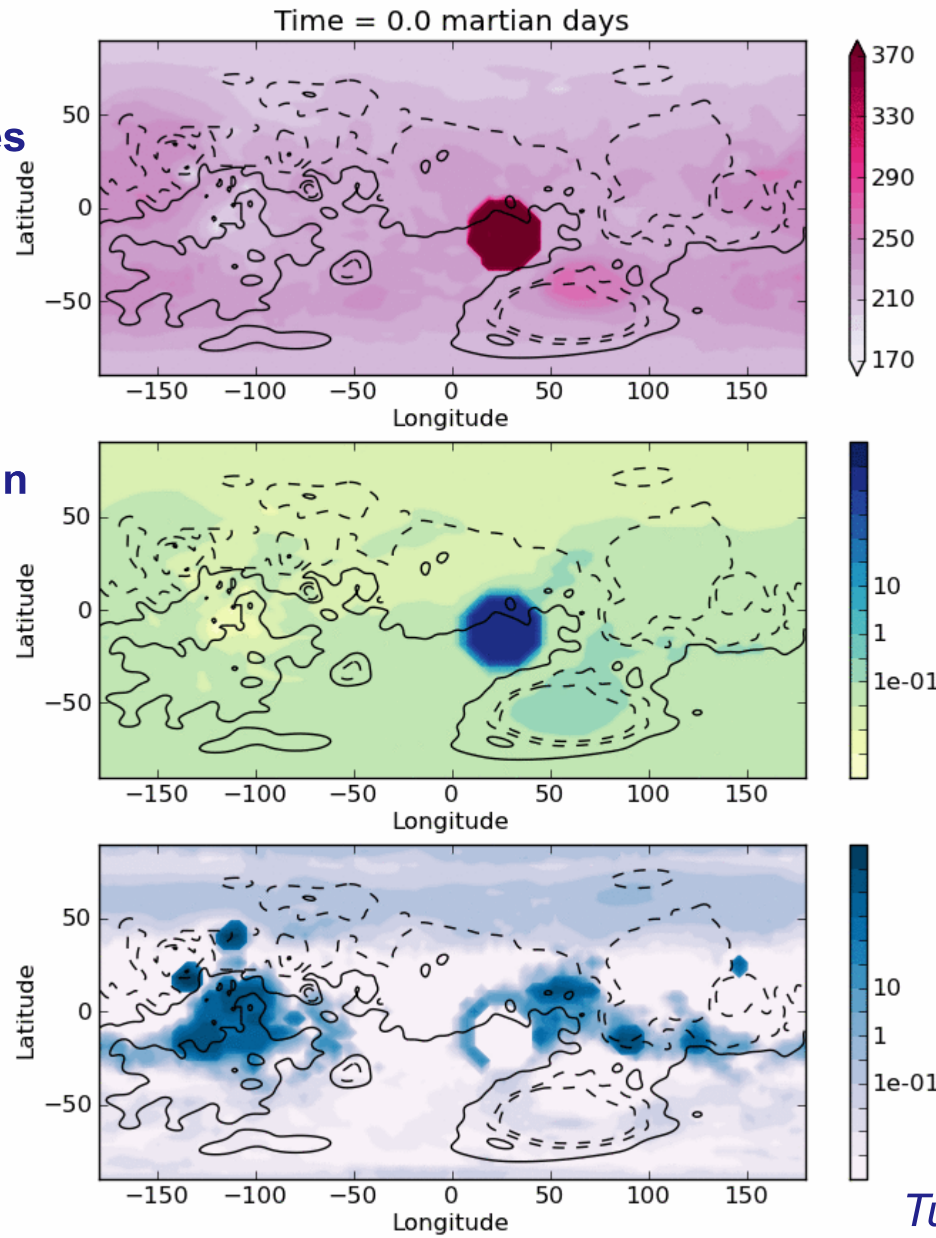


15-km diameter comet hitting the surface of Mars

- ➢ **Hot thermal plume**
- ➢ **Hot ejecta layer deposited on the surface**
- ➢ **Sublimation of the ices:**

1) from surface reservoir
2) from impactor

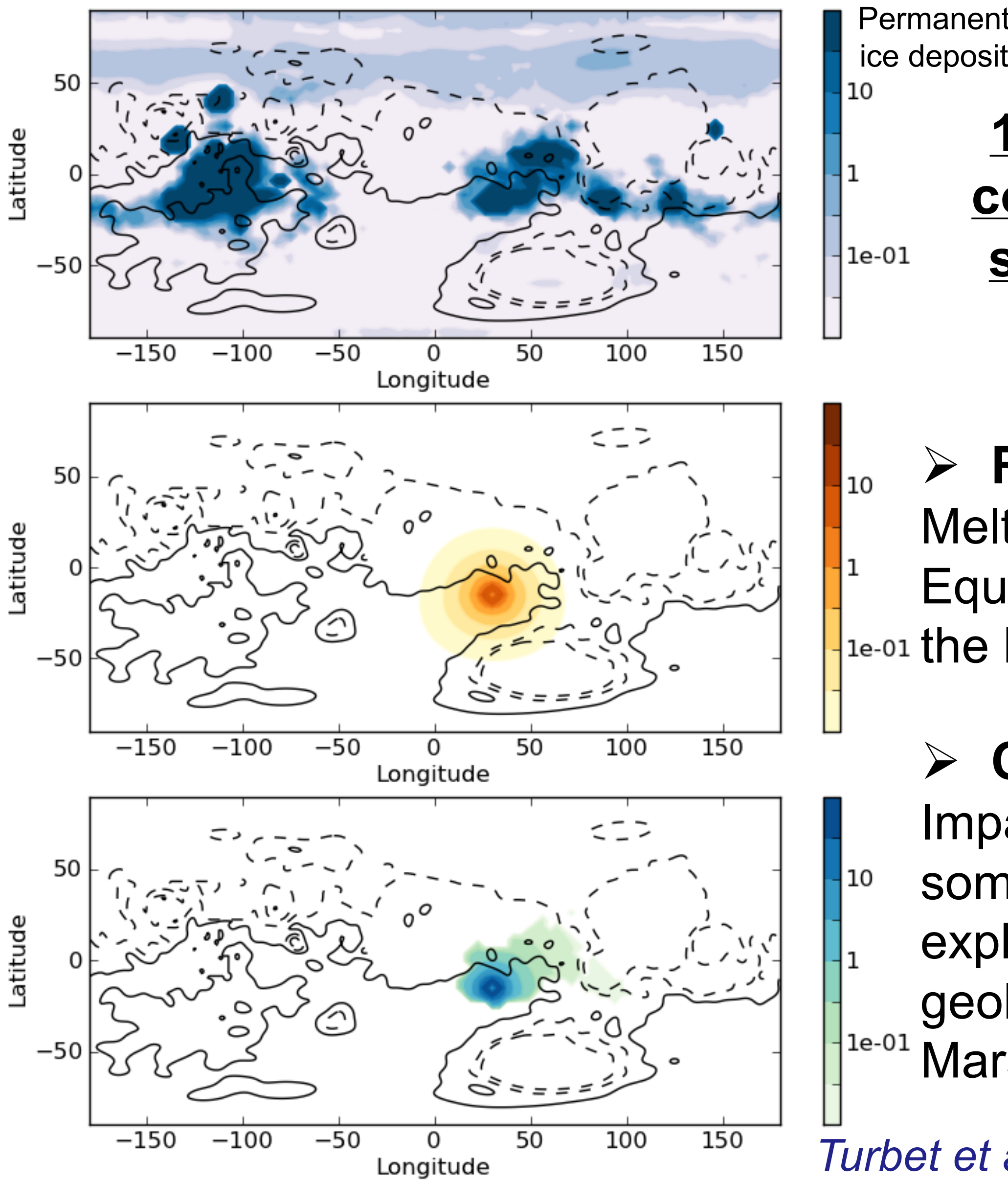
Turbet et al. 2017, Icarus
Turbet et al. 2018, in prep

Results of 3-D Global Climate Modeling

Surface ice deposits (mm)

Thickness of the ejecta (in m)

Production of liquid water from melting (in m)



15-km diameter comet hitting the surface of Mars

- **Results:**
  Melting of 10 cm Global Equivalent Layer (GEL) in the best case scenario

- **Conclusion:**
  Impact events did cause some erosion but cannot explain alone all the geology and mineralogy on Mars.

Turbet et al. 2017, Icarus
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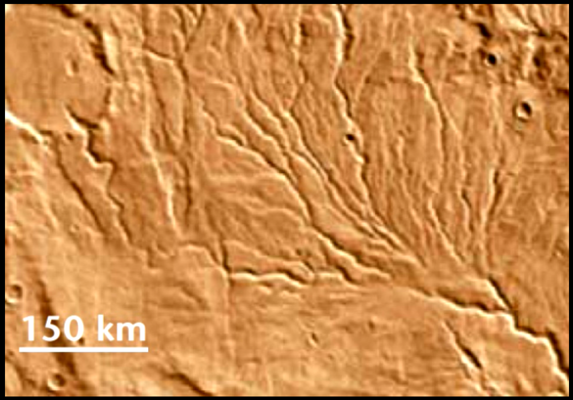


- **To adress key scientific questions regarding habitability:**
  - Define the habitable zone: runaway greenhouse effect (*Leconte et al. 2011, 2014),* Glaciation *(Turbet et al. 2017b)*
  - What is the probability of habitable planet in the galaxy ?
  - Study specific cases: Gliese 581d, Proxima b, Trappist 1 *(Turbet al. 2016, 2018b)*

#2 Runaway Greenhouse on tidally-locked planets

Climate models predict the formation of a thick substellar water cloud

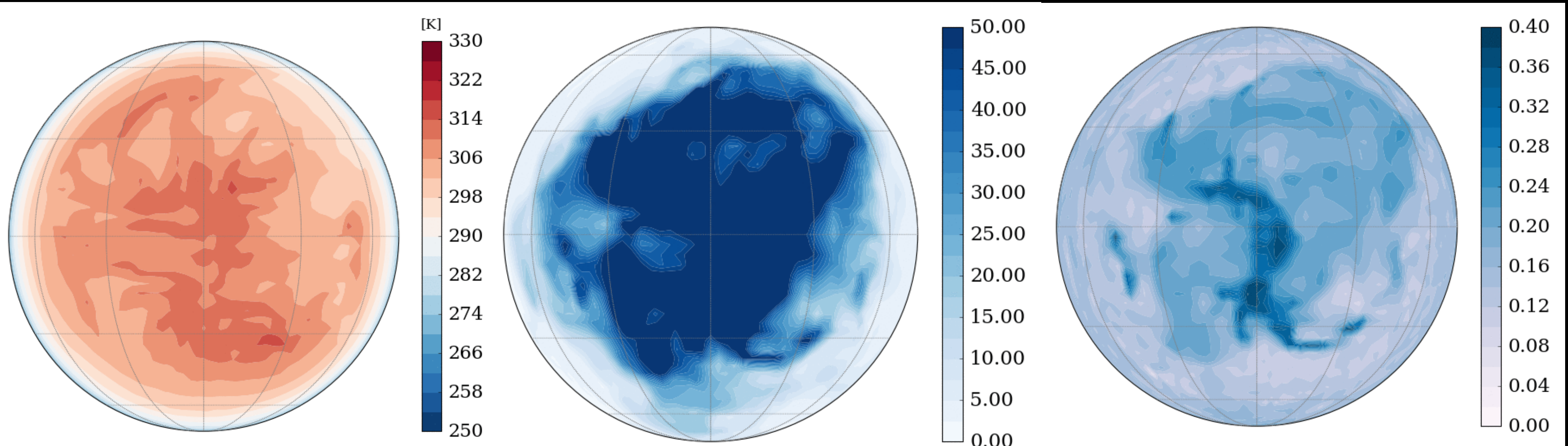
Leconte et al. 2013
Yang et al. 2013

View from a distant point throughout the orbit (Credit: J. Leconte)

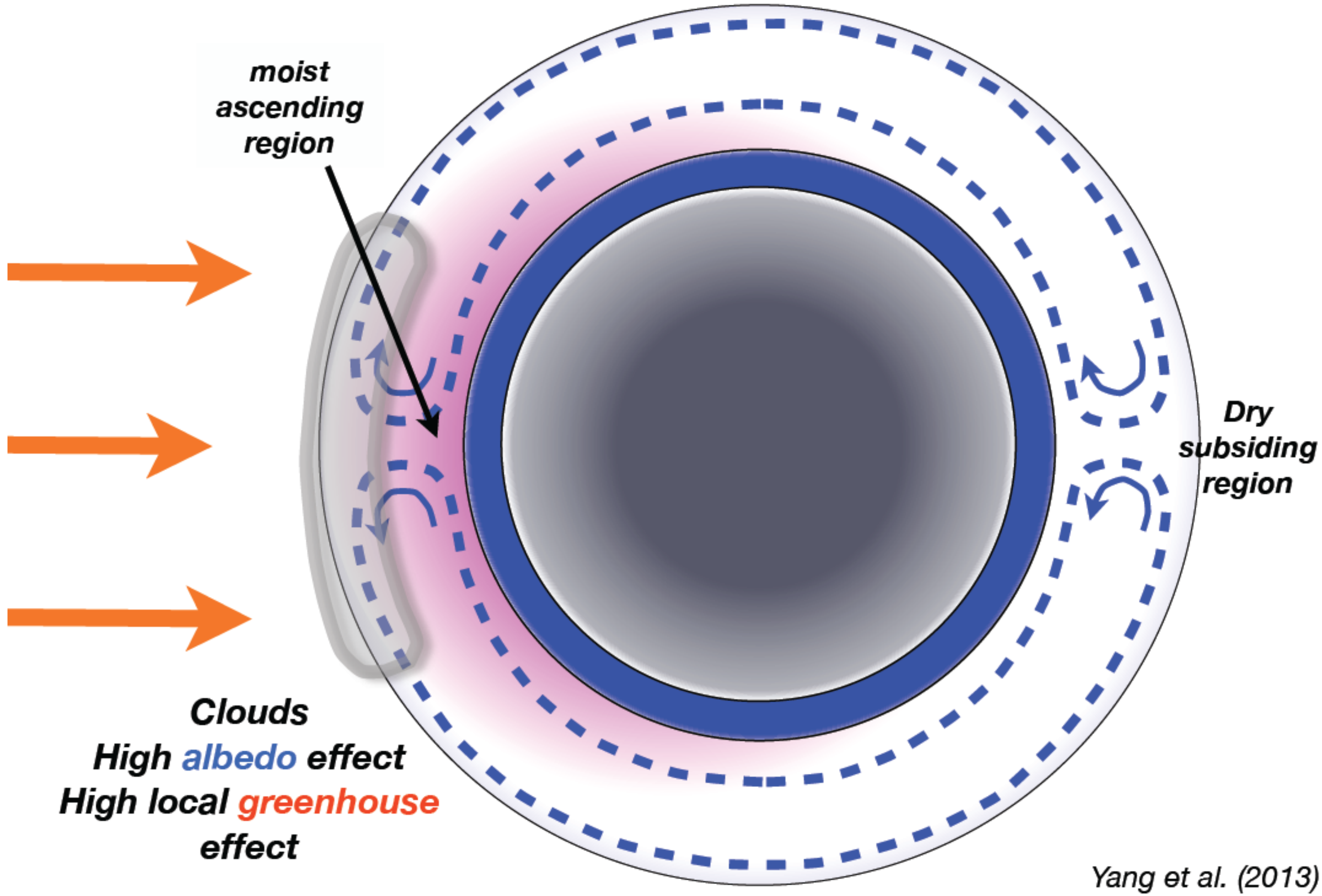
Surface temperatures (K)

Cloud opacity

Planetary albedo



Large scale cloud pattern on tidally locked planets



Courtesy of J. Leconte

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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Center for Interdisciplinary Exploration and Research in Astrophysics (CIERA) and Department of Physics and Astronomy, Northwestern University, 2131 Tech Drive, Evanston, IL 60208, USA

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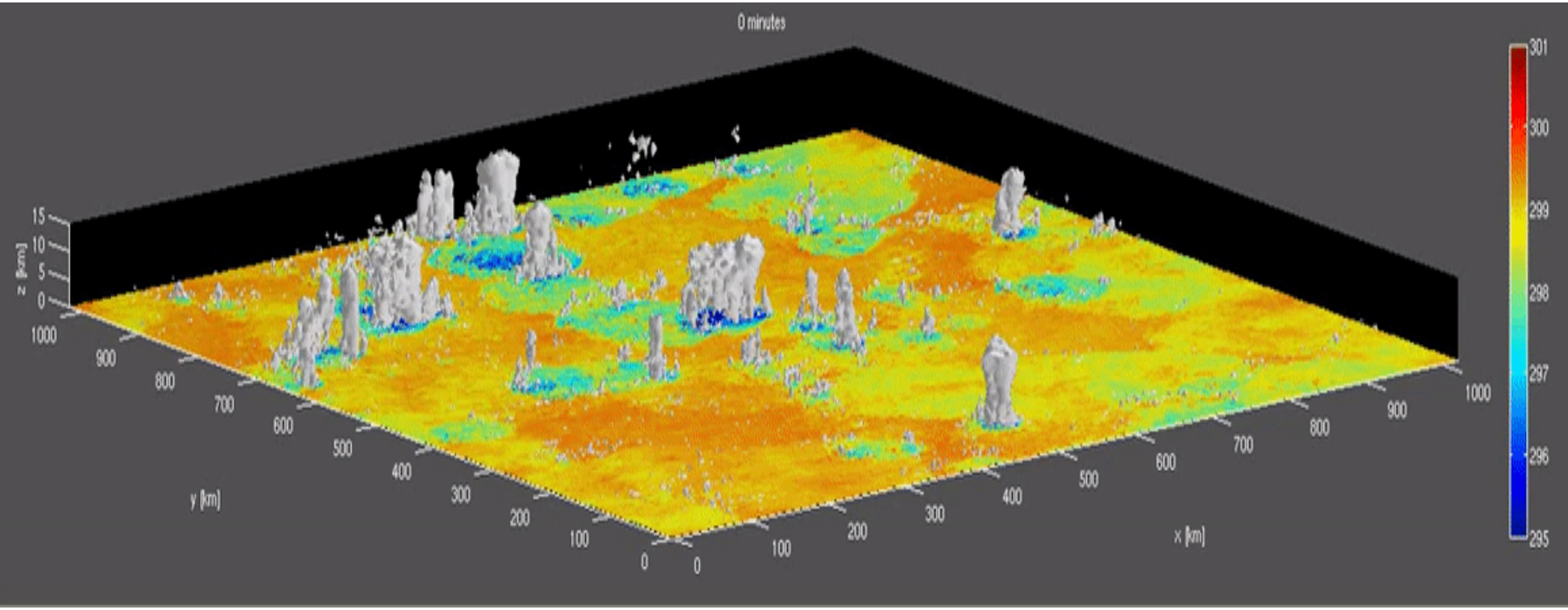
Draft version June 28, 2013

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.

Toward a new generation of climate models

The Cloud Resolving Models (CRM)



Credit: Caroline Muller (LMD)

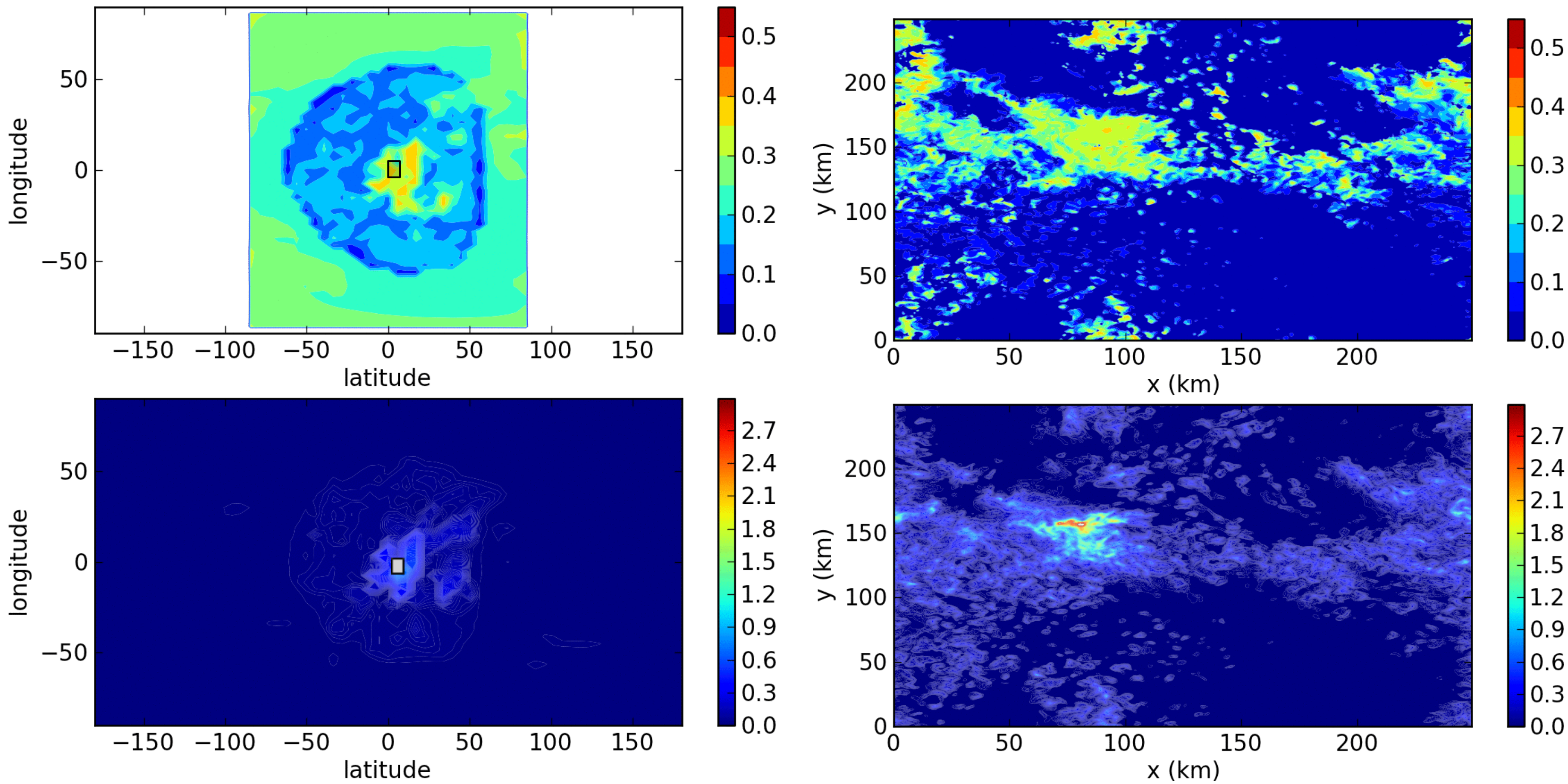
Revisiting the convection at the substellar point with Cloud Resolving Models

For TRAPPIST-1e

Global Climate Model (LMD) | **Cloud Resolving Model (WRF+LMD)**

Planetary albedo

Water ice column (kg/m²)



M. Lefèvre & M. Turbet (LMD), in prep

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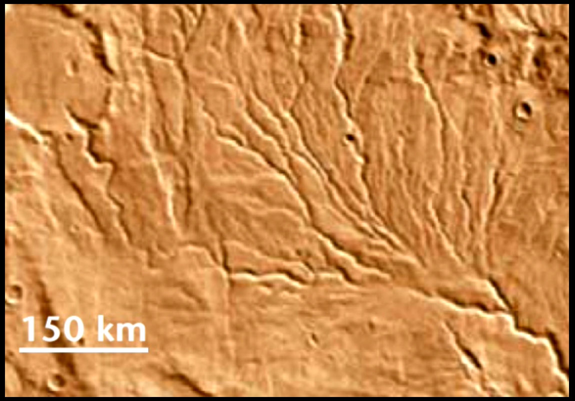

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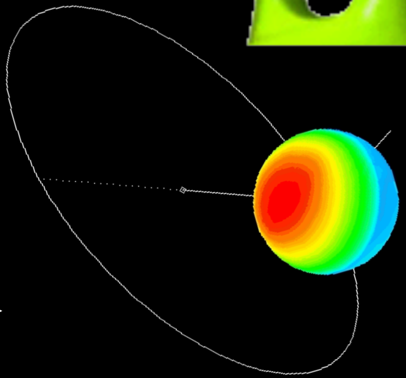
- **To simulate planets around other star to design future telescopic measurements**
  - Exoplanet Thermal phase curves (*Selsis et al. 2011, Turbet et al. 2016, Samuel et al., 2014, etc…)*
  - Spectra simulations (*Charnay et al. 2015, Turbet et al. 2016)*



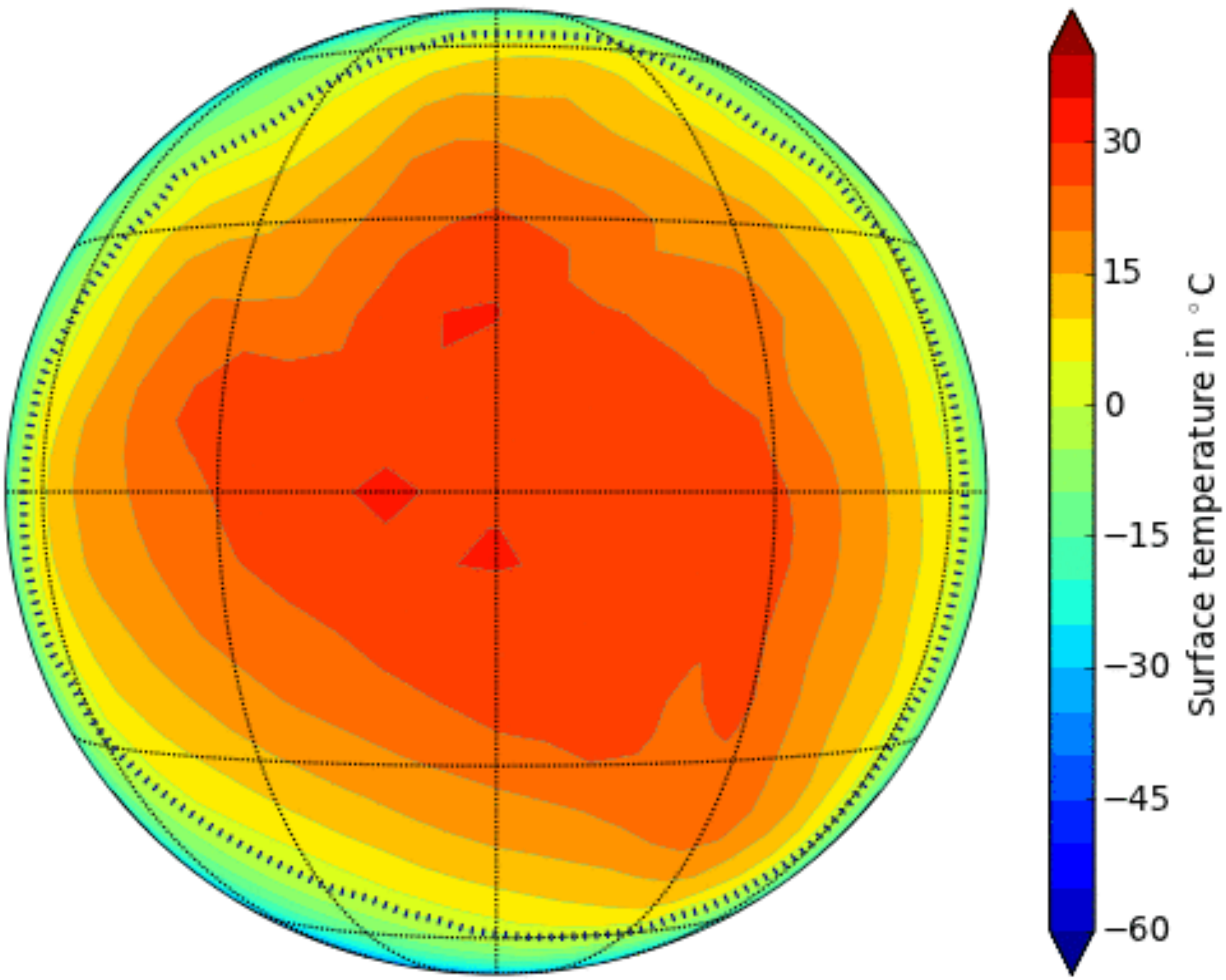
View at 8.67 µm Ps= 1bar

#3 Preparing future ground-based observations of Proxima Cen b

Climate models predict the observational features that can be observed by the next generation of astronomical facilities (JWST, ELT, etc)

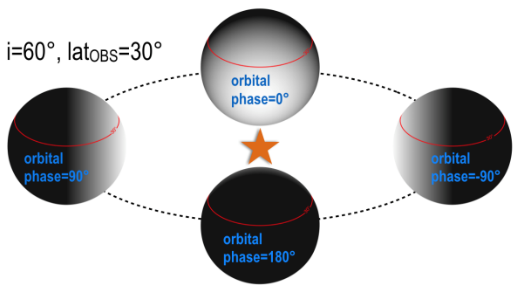
Turbet et al. 2016
Boutle et al. 2017

Proxima b with a global ocean, an Earth-like atmosphere and a synchronous rotation



Turbet et al. 2016, *A&A*

Synthetic spectra for direct imaging with E-ELT



→ Angular separation between 0 and **38 mas**

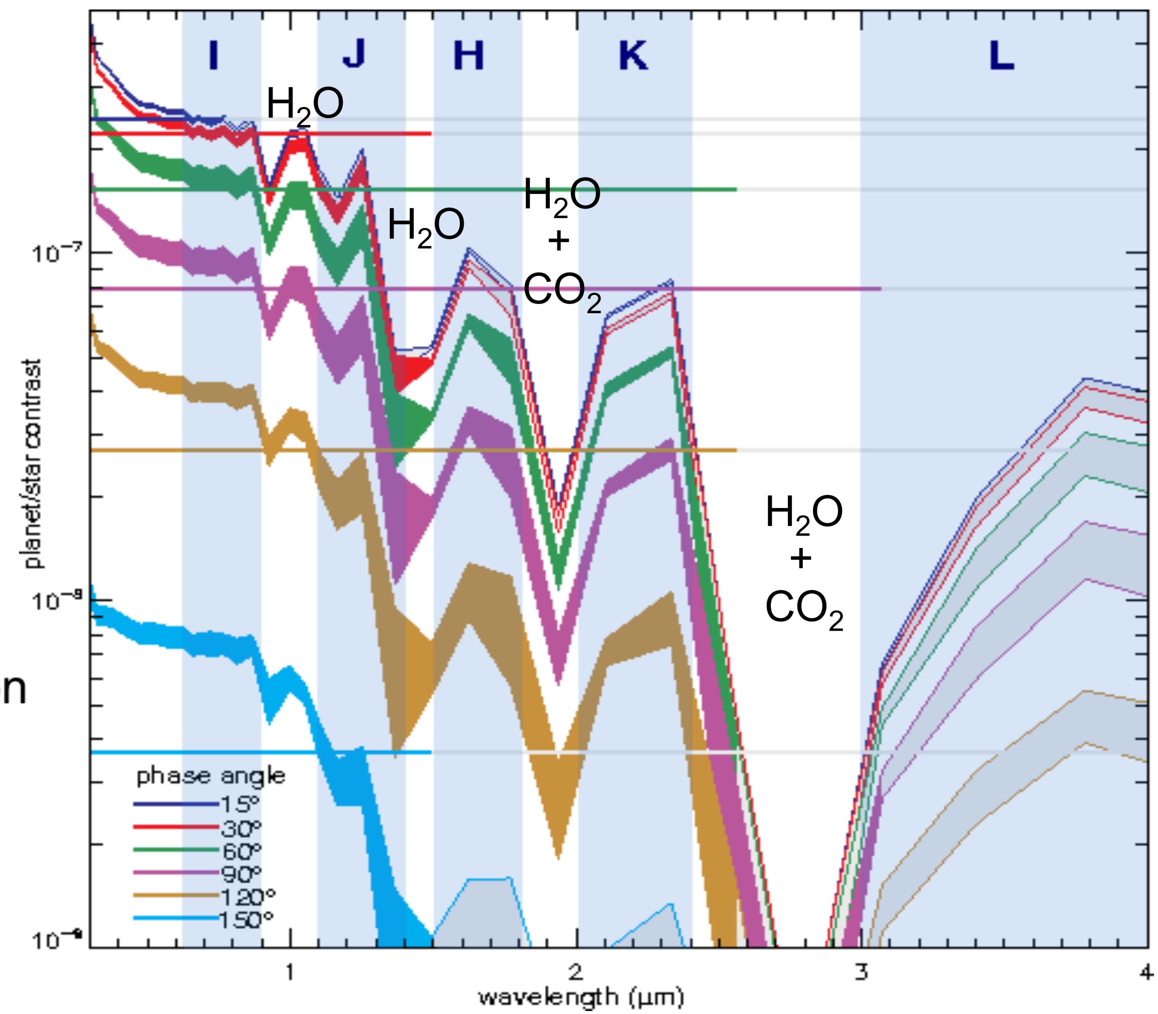
→ **7 $\frac{\lambda}{D}$ at 1 µm** with 39m ELT

→ **J band** seems the best option

→ **Aims:**

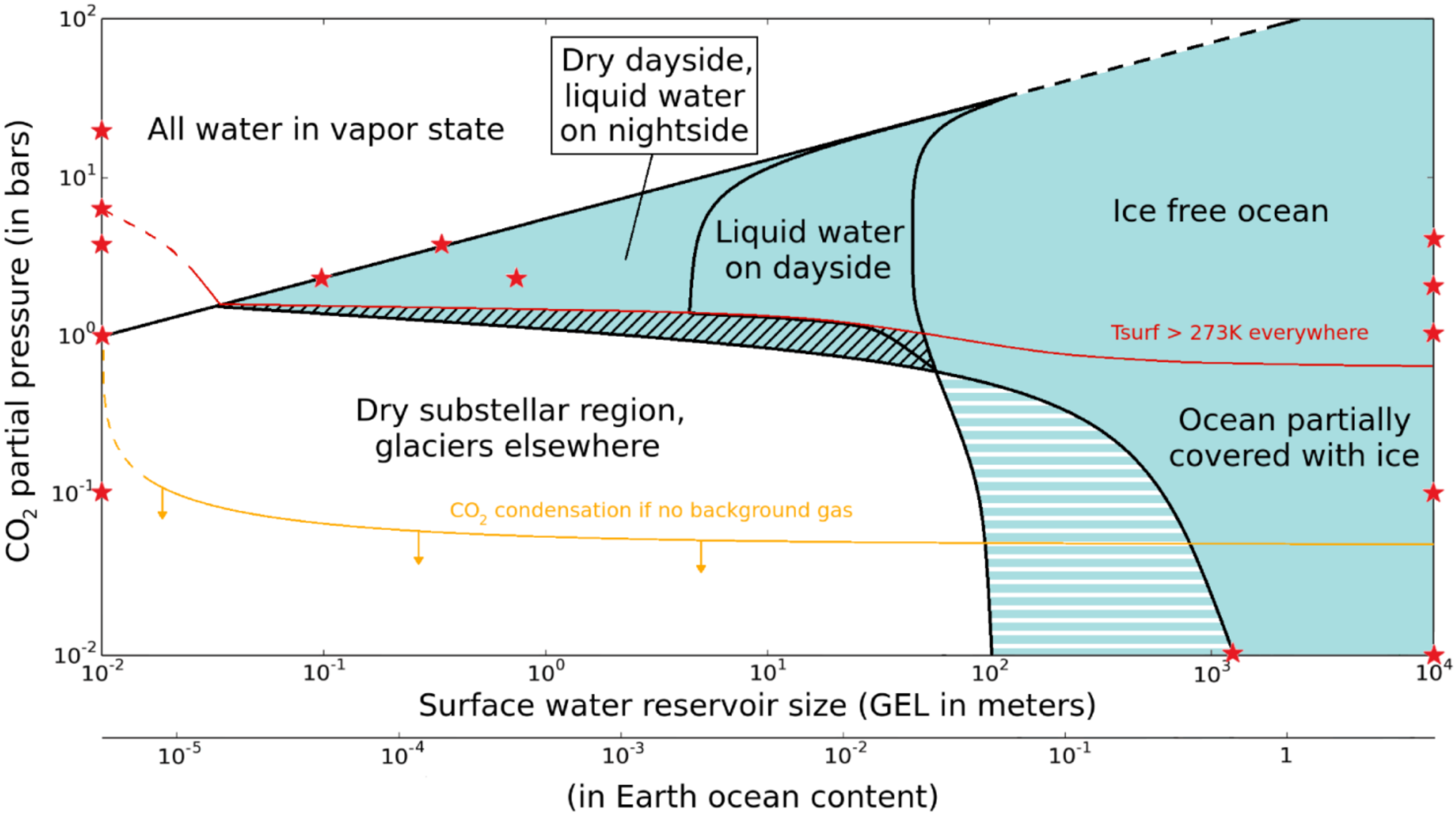
- high resolution spectroscopy
- reflexion phase curves
- …

Synchronous rotation mode and
Earth-like oceans/atmosphere



Turbet et al. 2016, *A&A*

Synchronous rotation: Possible climates



based on multiple 3-D
Global Climate Model (GCM) simulations

Turbet et al. 2016, *A&A*

Conclusions:

Atmospheres, Climate and Habitability

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

Climate → **Habitability**

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)

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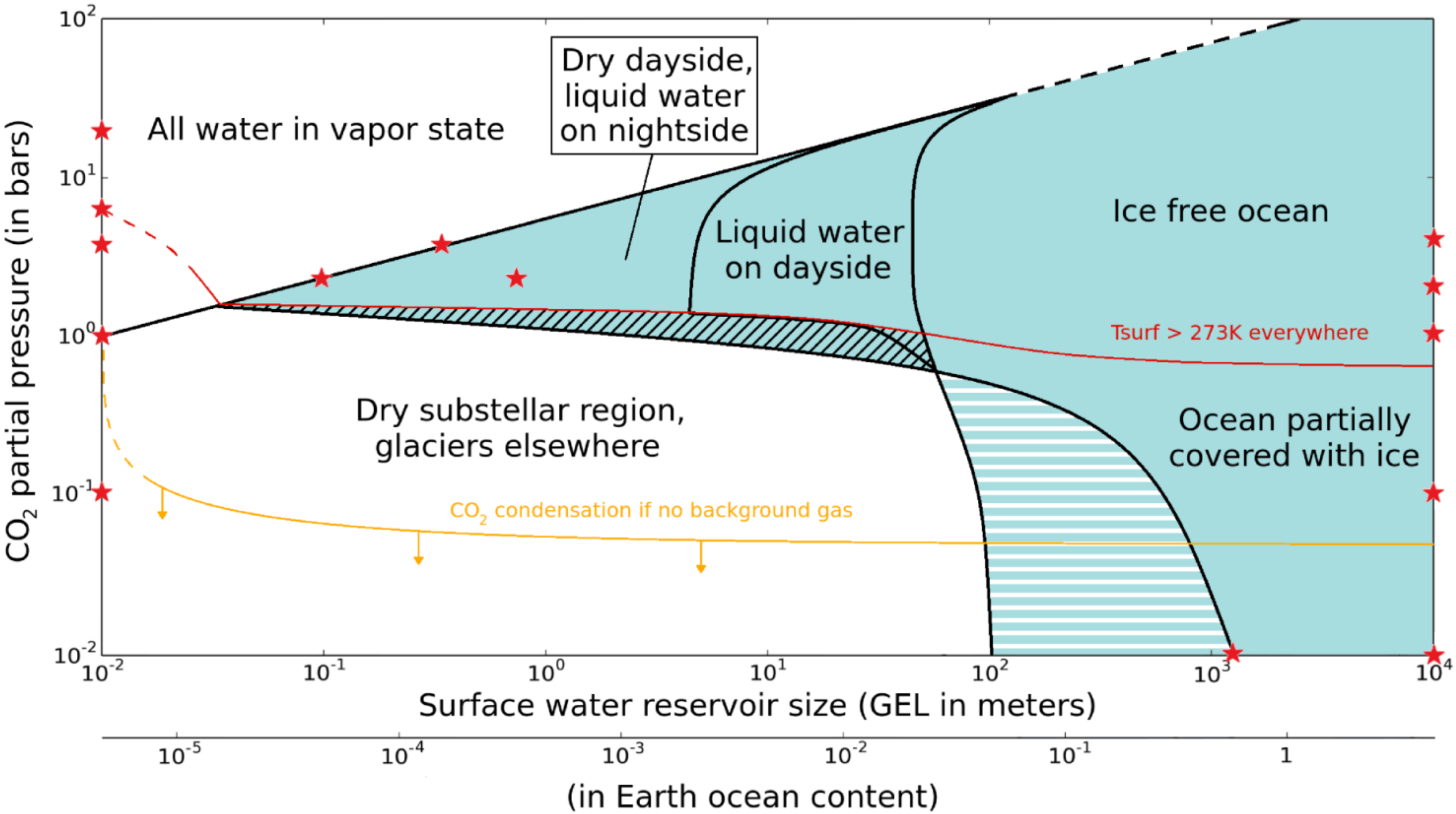

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THANK YOU