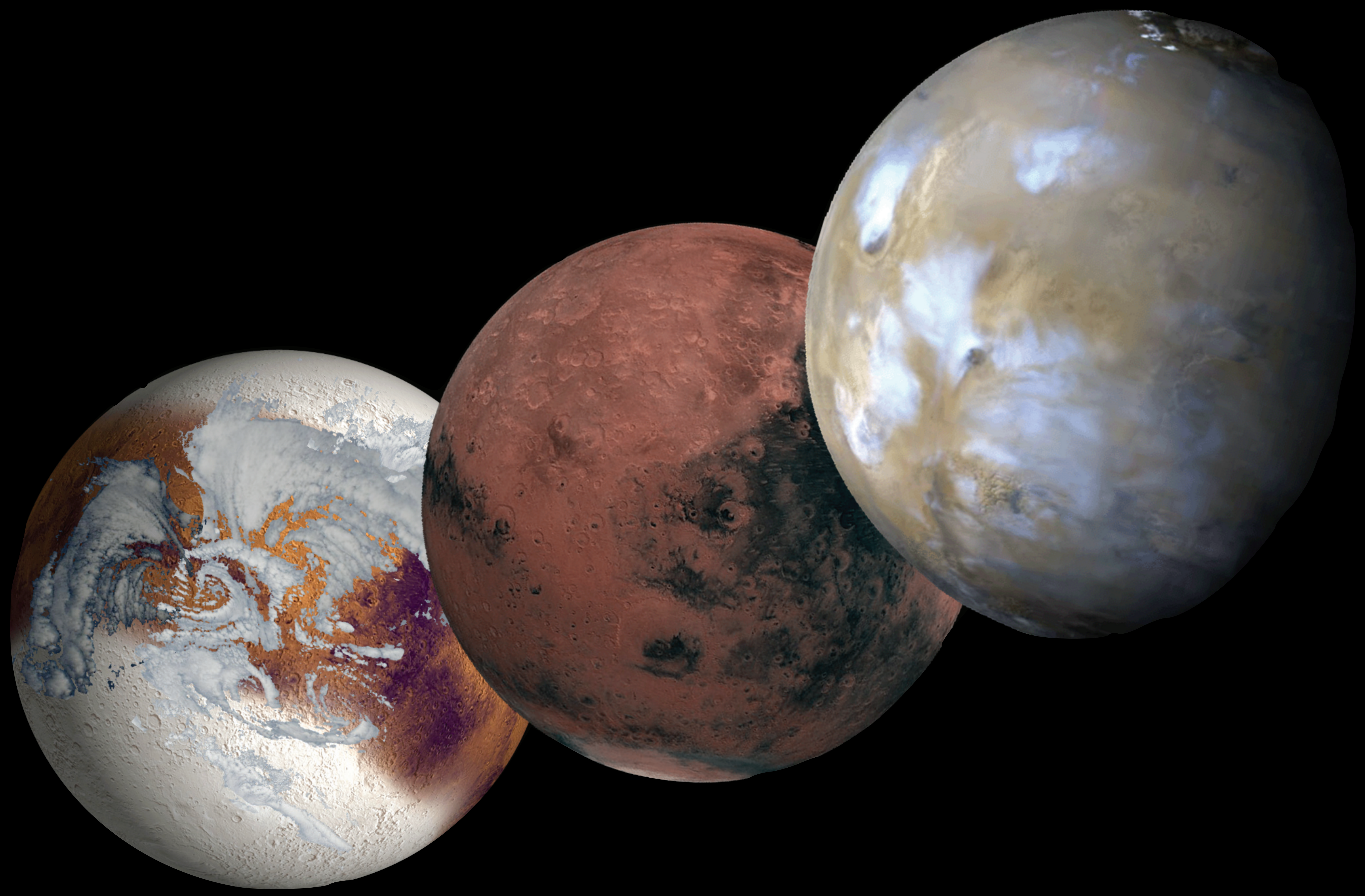
# The Many Faces of Mars During Its Recent Past

*DIX Planetary Science Seminar - 17/02/2026*

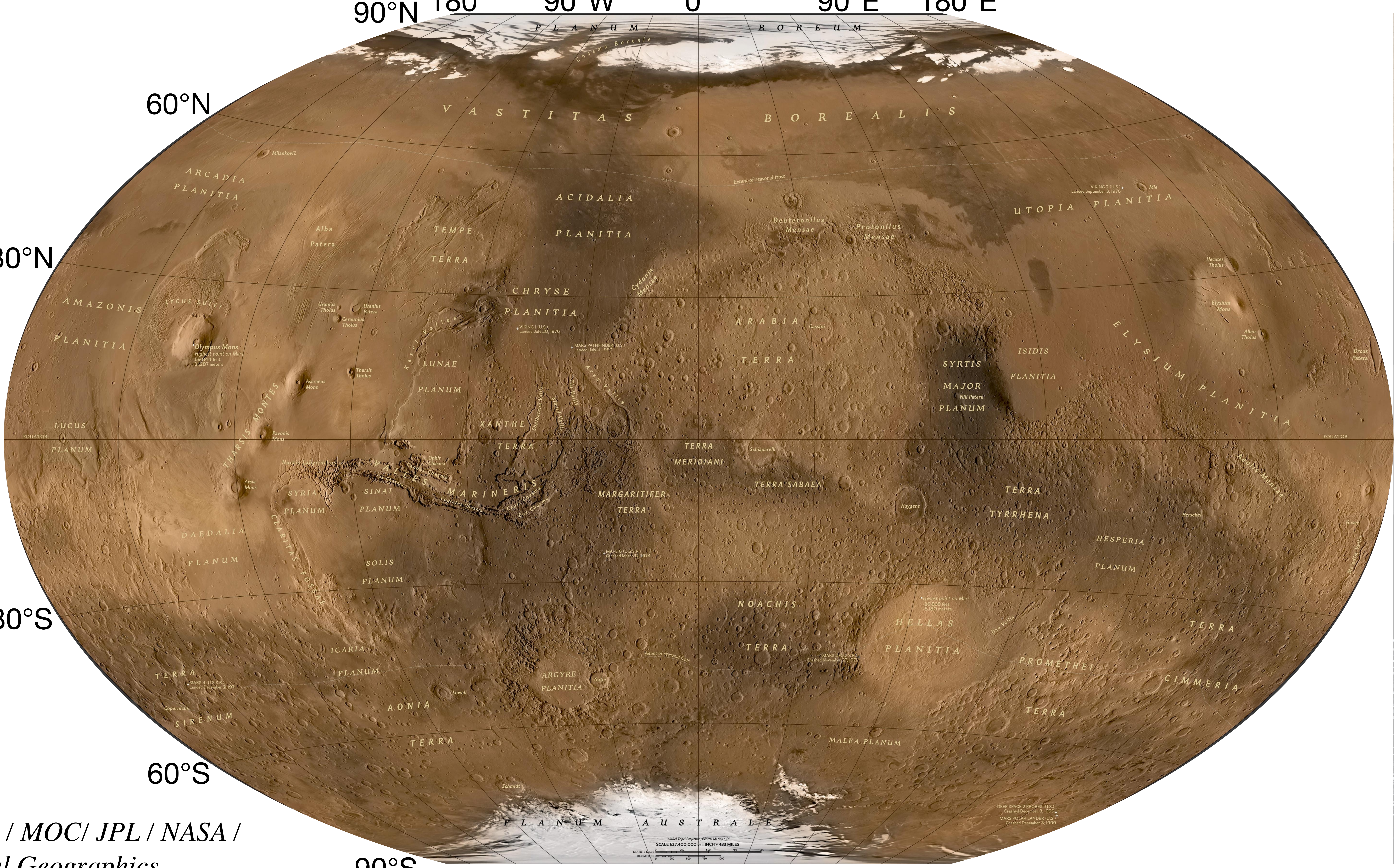

**Lucas Lange, on behalf of the Mars Through Time Team**

*lucas.lange@jpl.nasa.gov*


*PhD @ Laboratoire de Météorologie Dynamique, now NPP @ JPL*

# Some Characteristics of Mars




*Credits : MSSS / MOC/ JPL / NASA / National Geographics*

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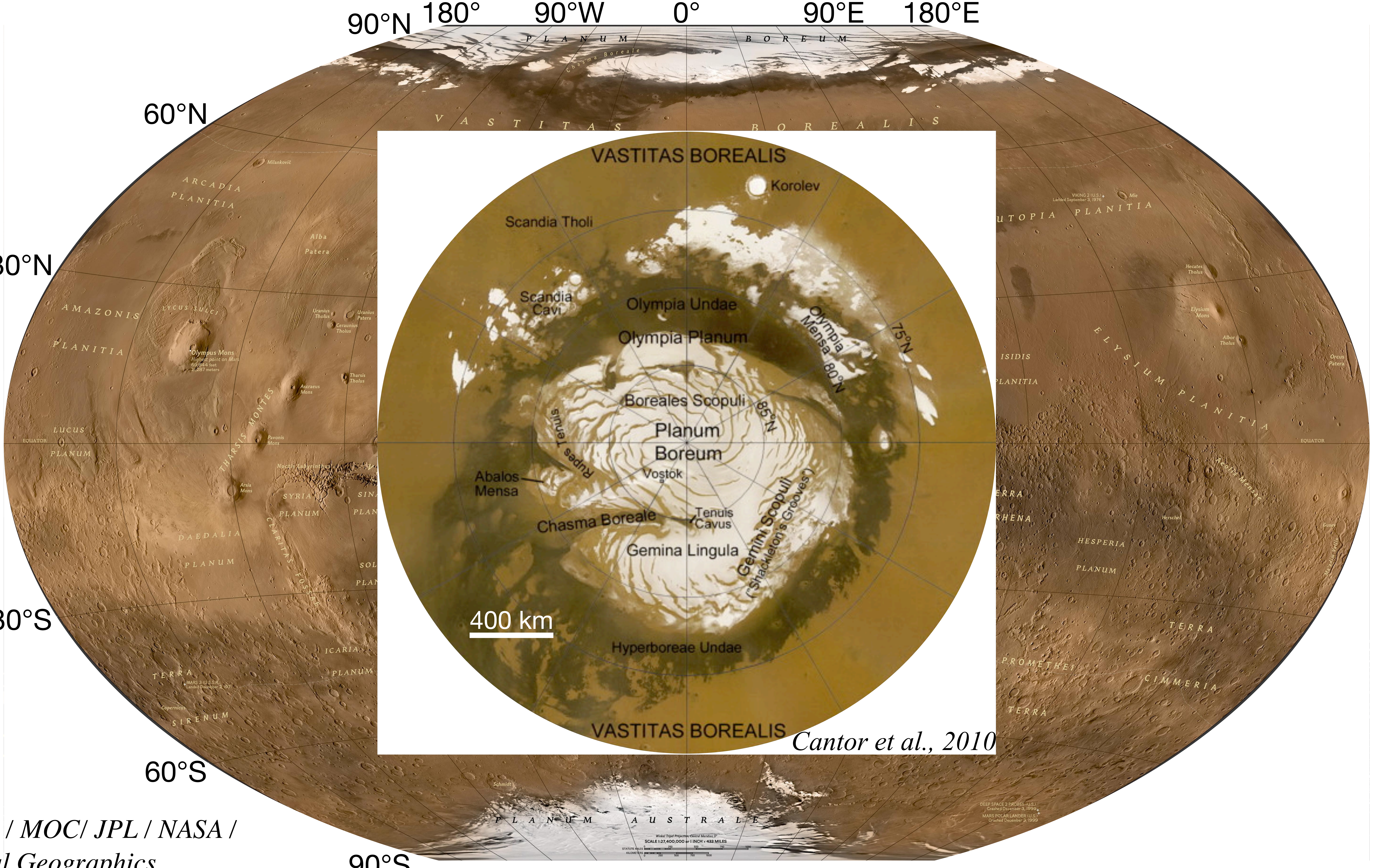


*Cantor et al., 2010*

*Credits : MSSS / MOC/ JPL / NASA / National Geographics*

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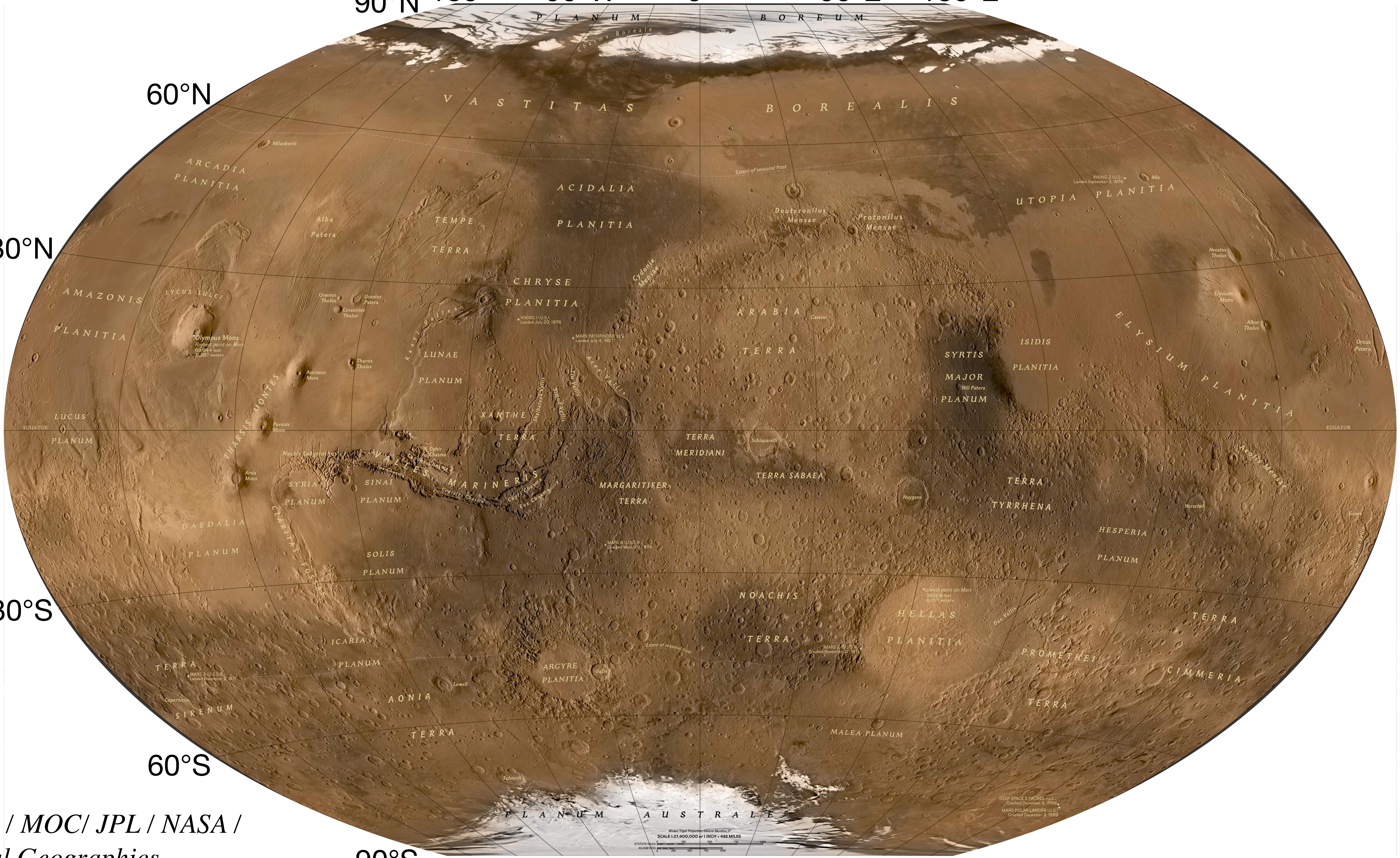


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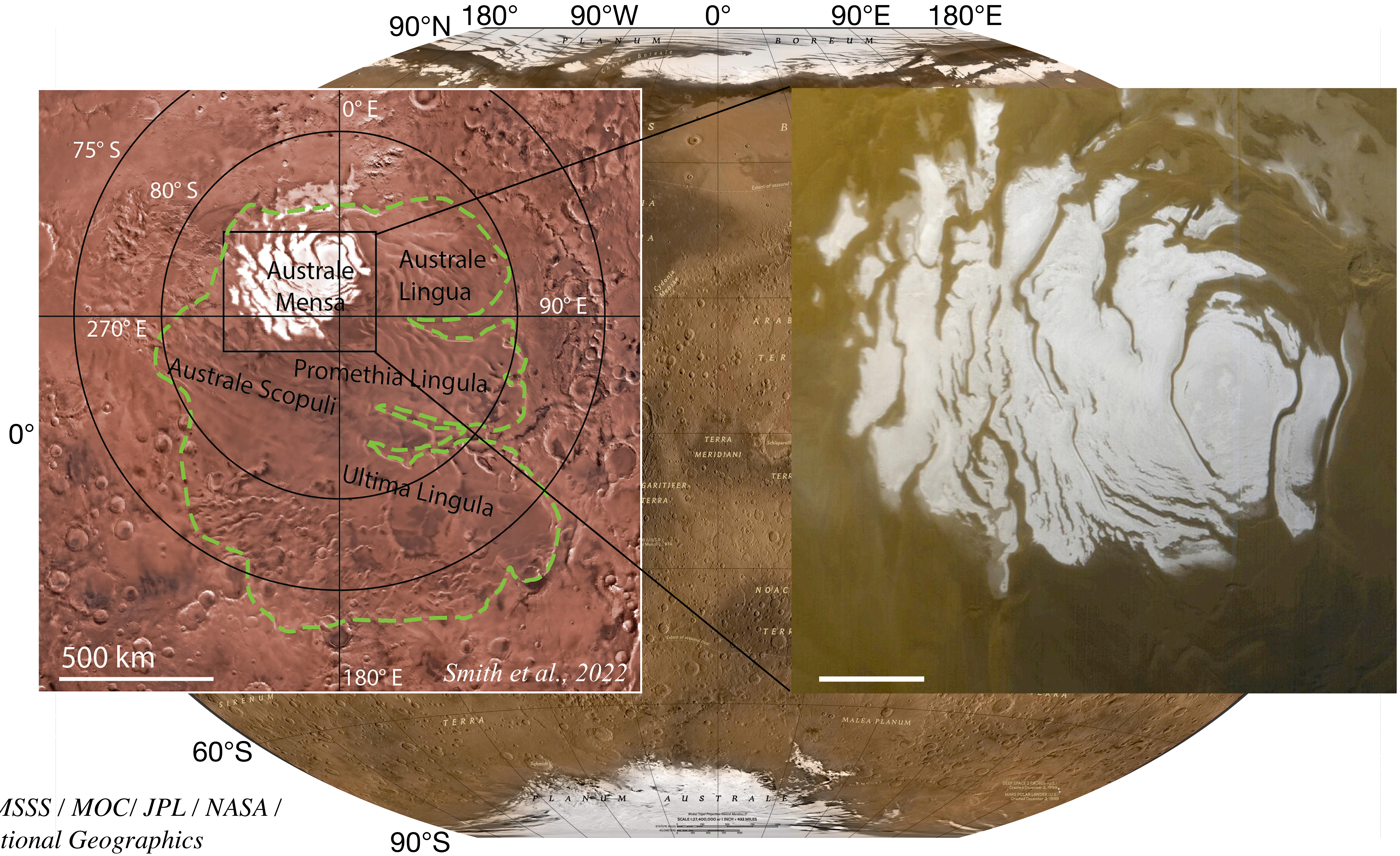


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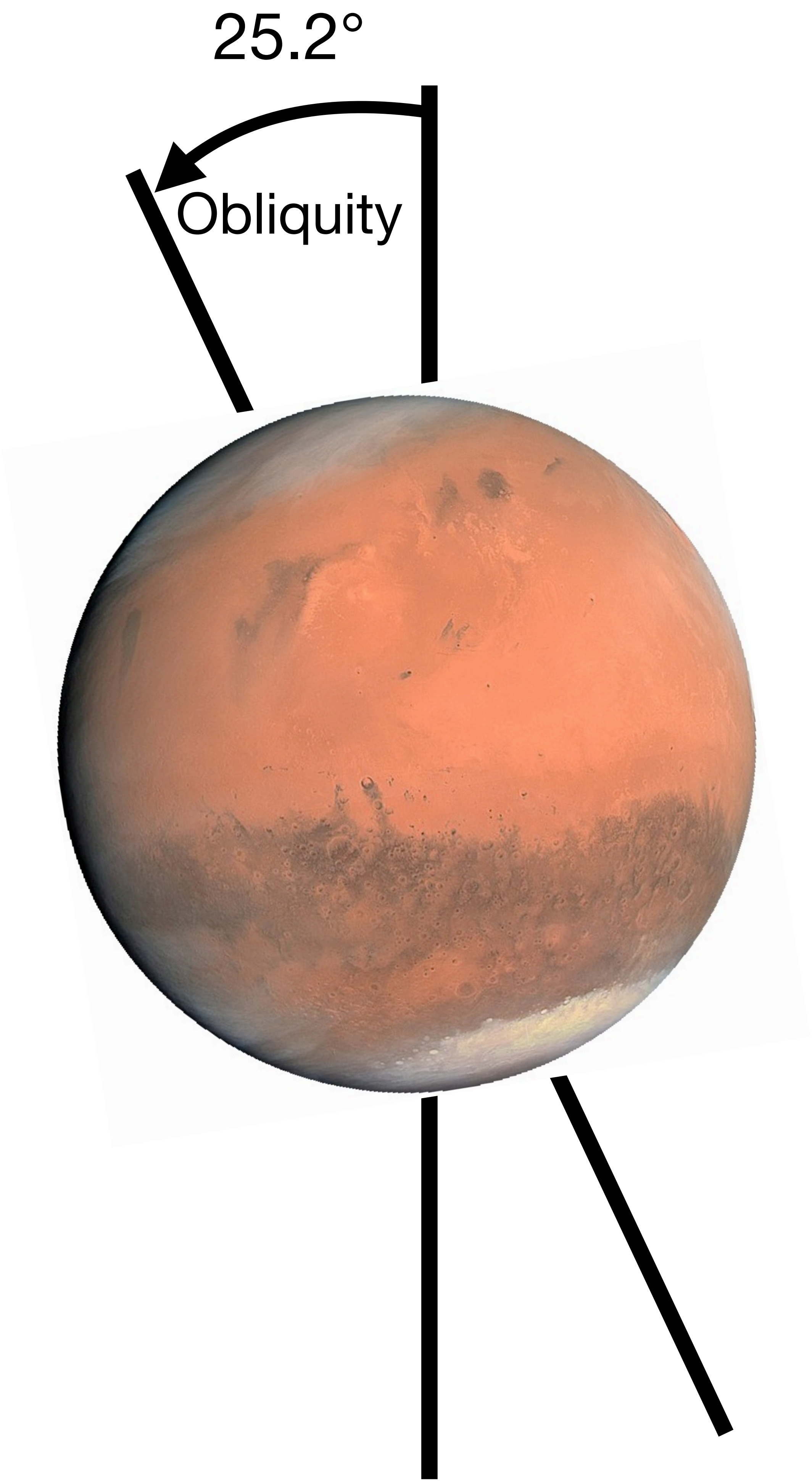
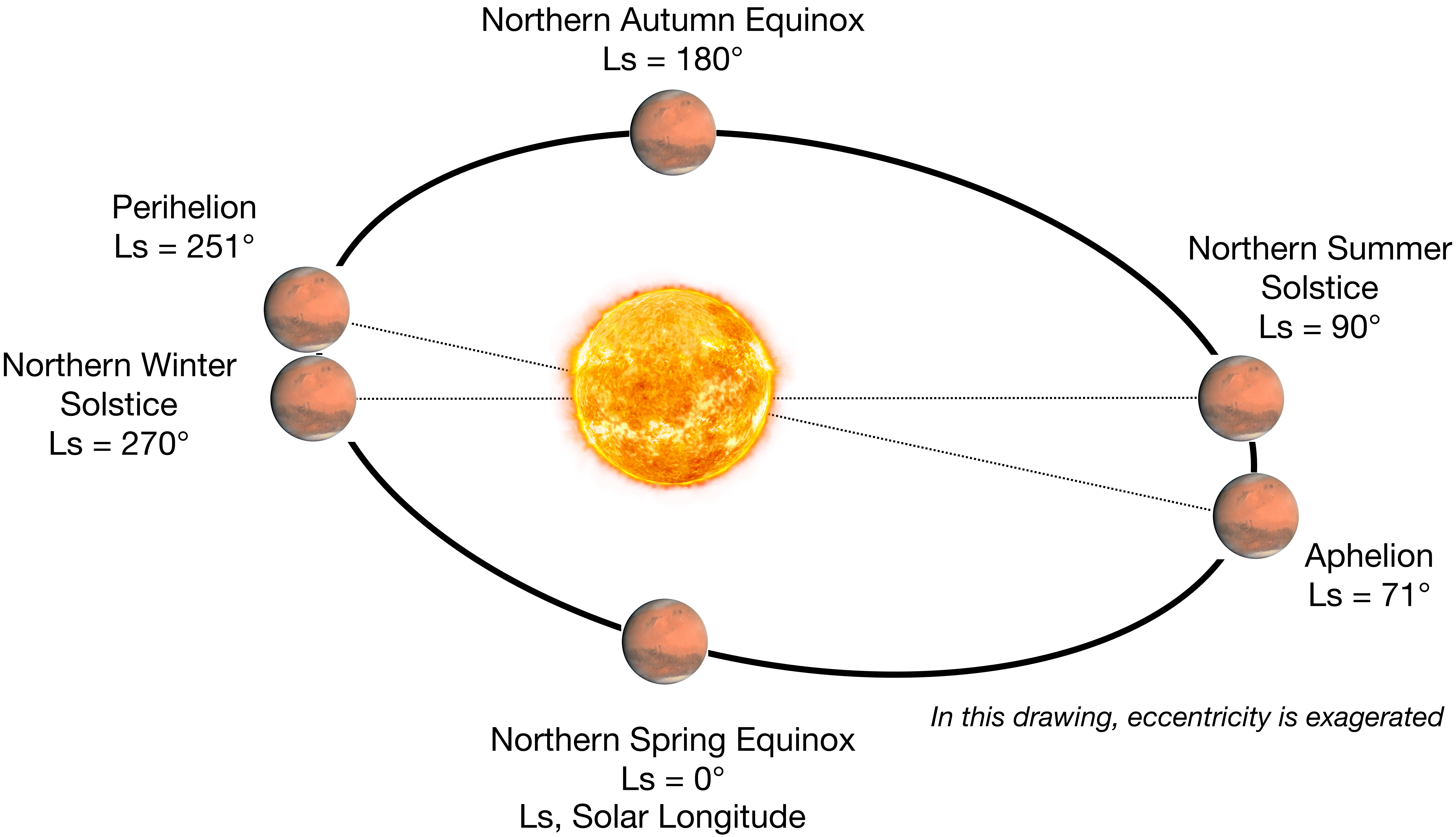
# The Seasons on Mars



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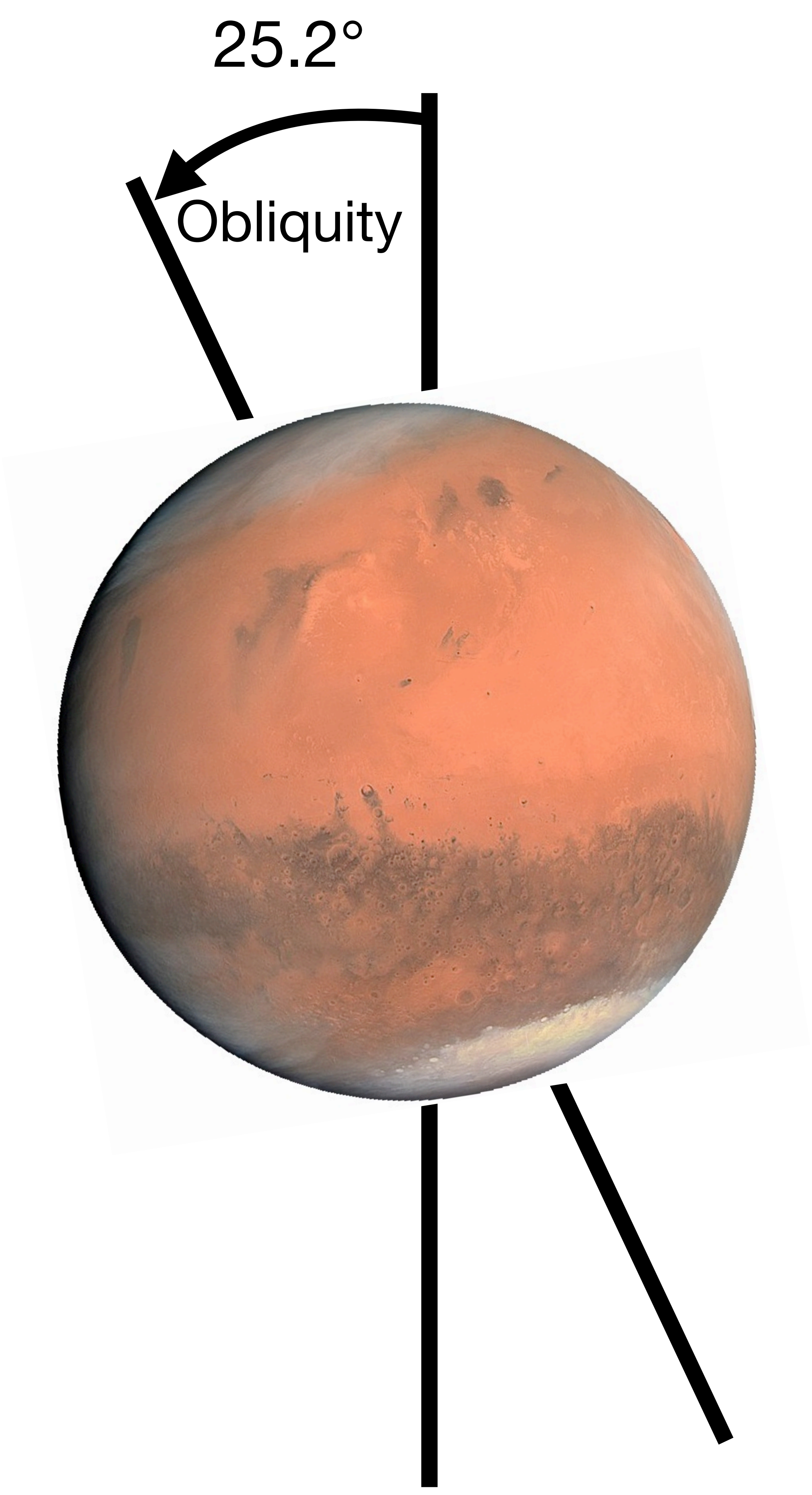
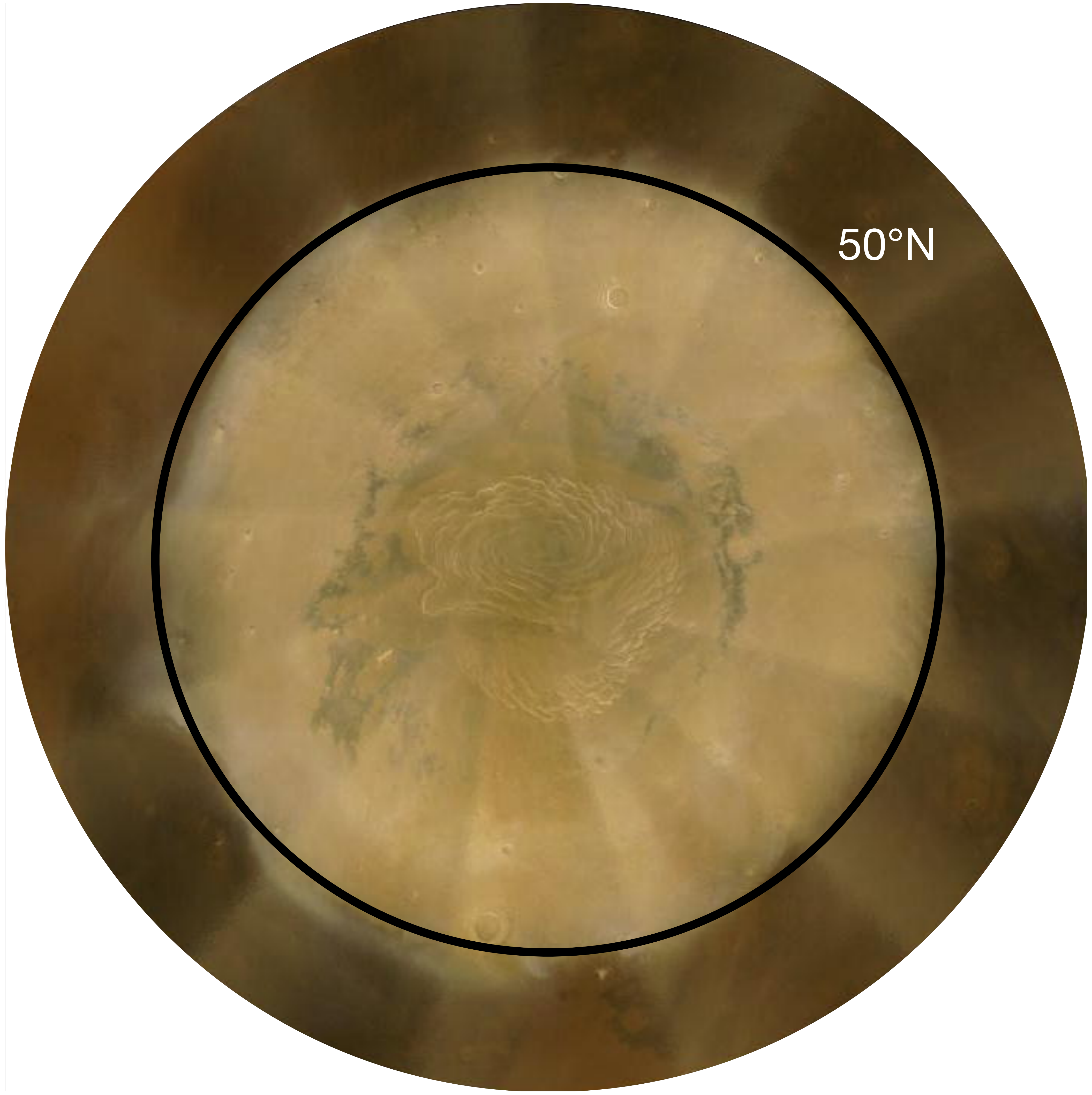
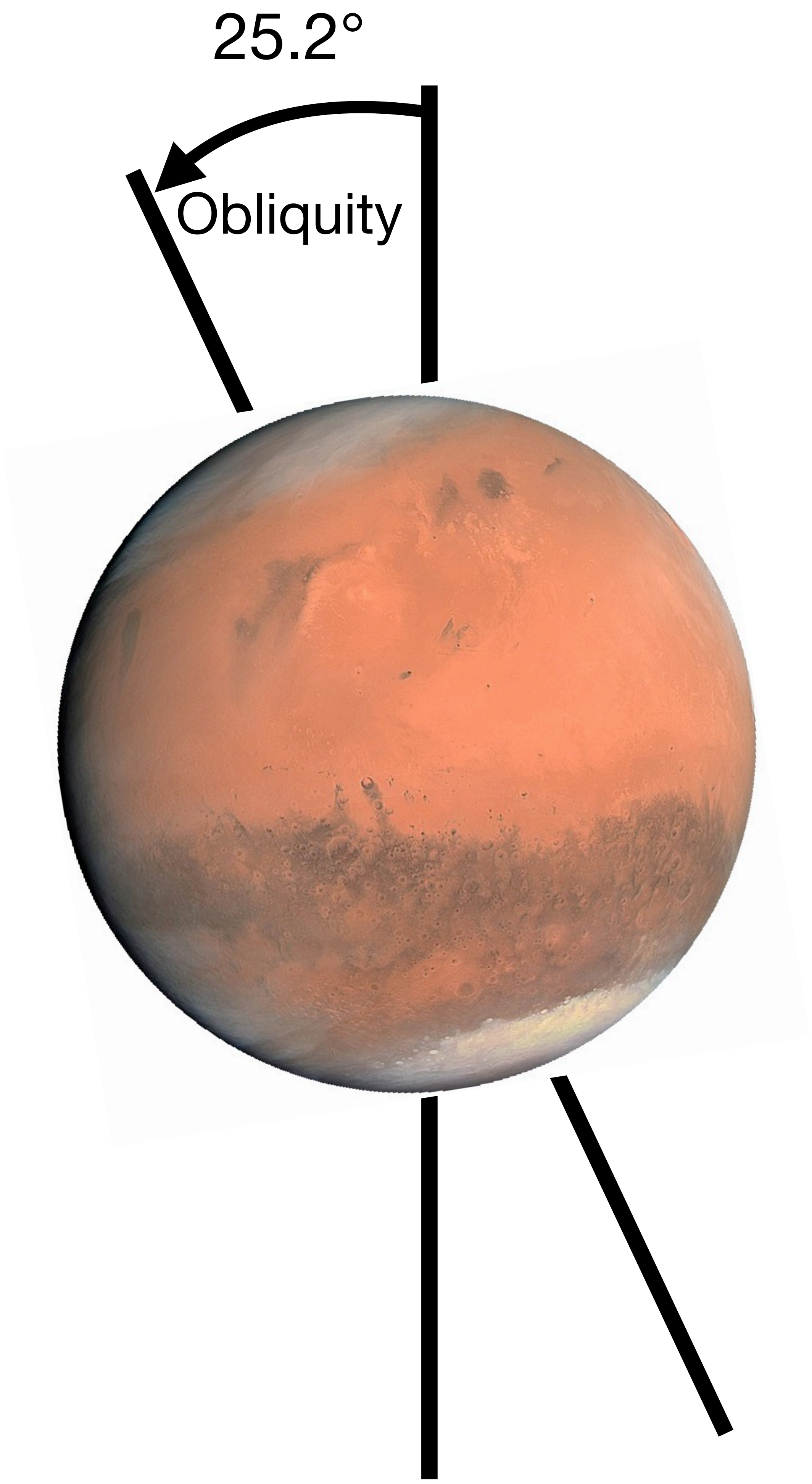



*Calvin et al., 2015*

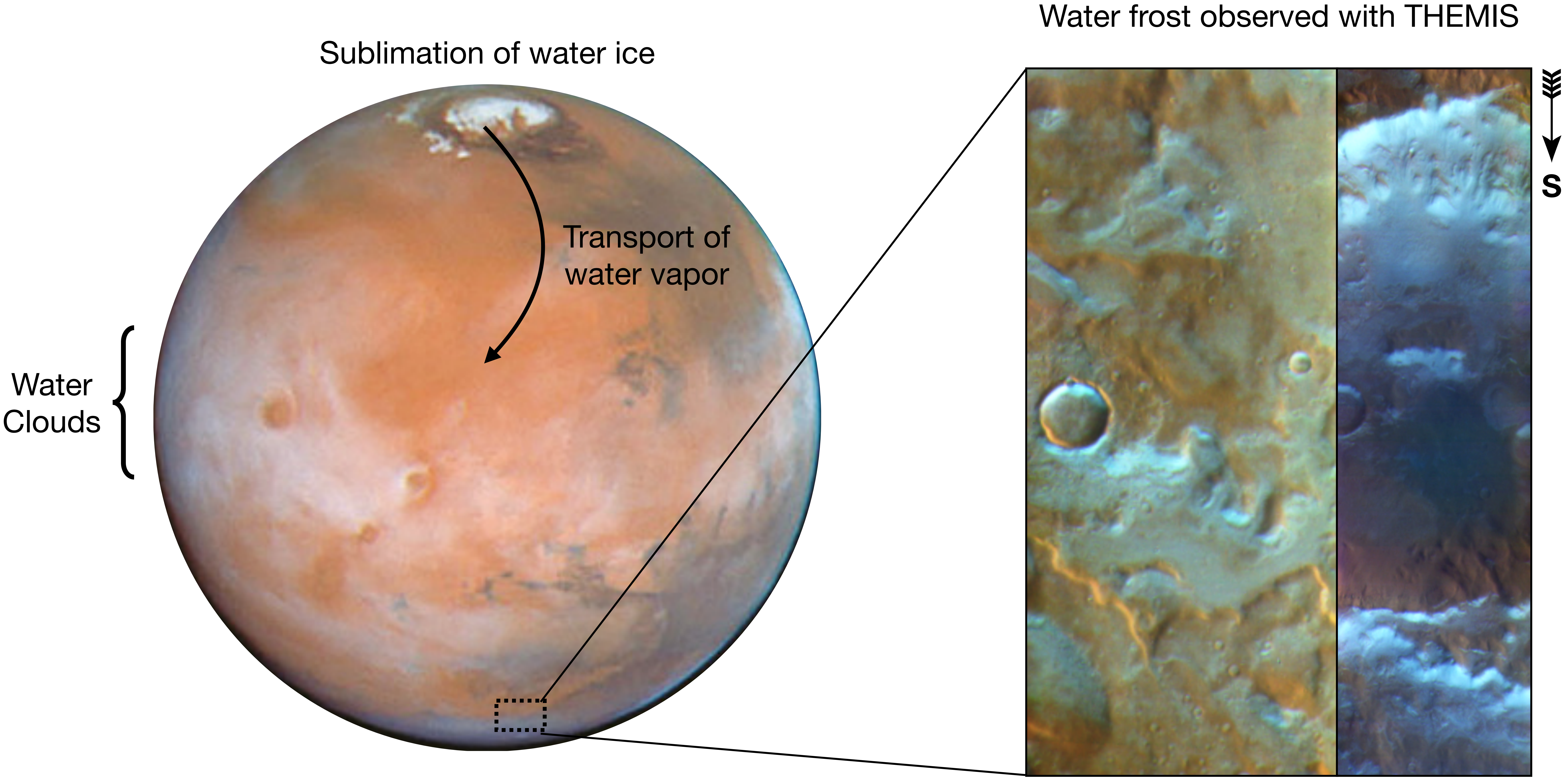
- - 30% of the global surface pressure
- Seasonal ice cap forms down to 50°, with a thickness from mm at mid latitudes to ~m at the pole

# The Seasons on Mars




*Calvin et al., 2015*

# The Seasons on Mars - Water cycle




*Credits : NASA / ESA*

*Lange et al. 2024*

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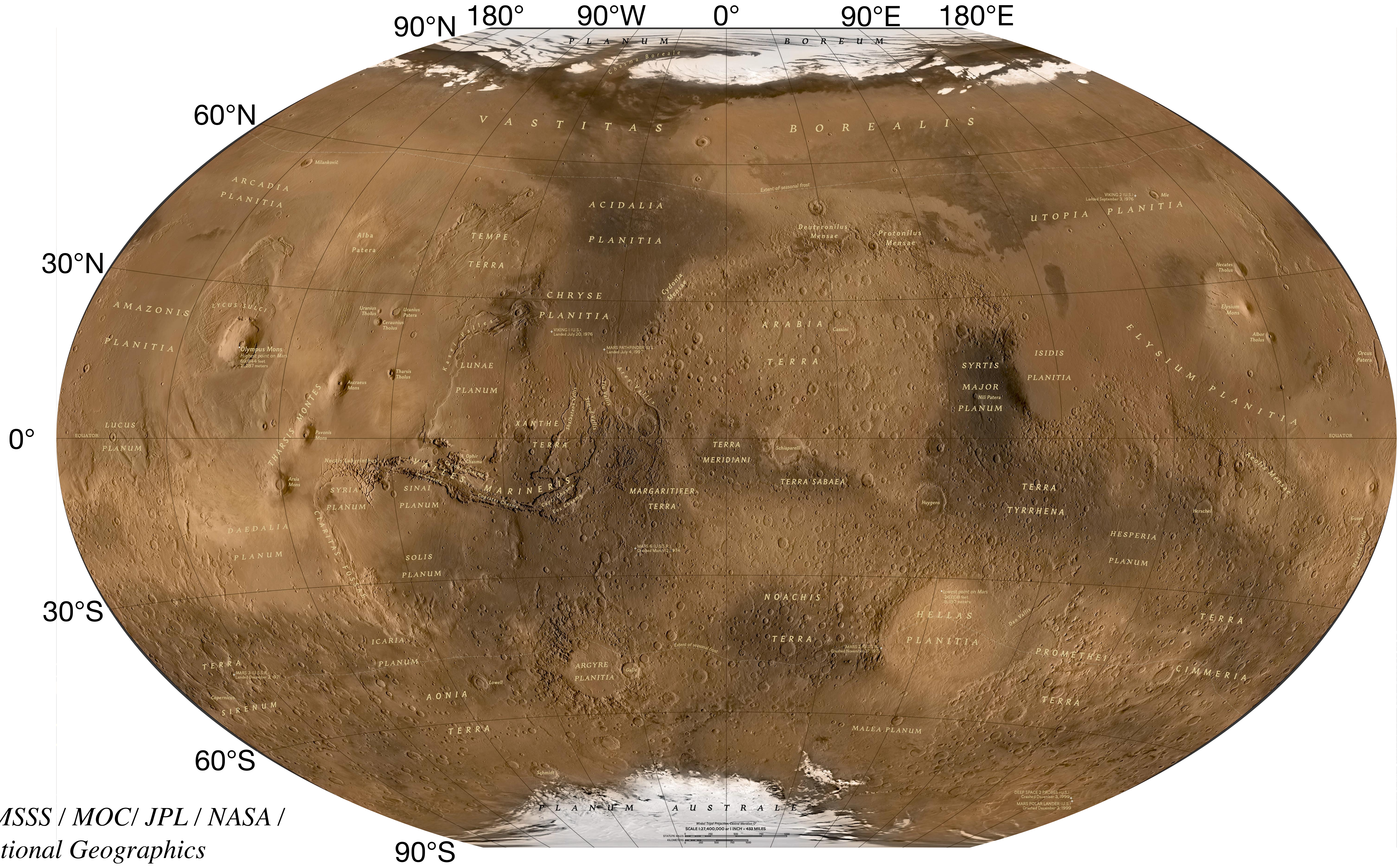


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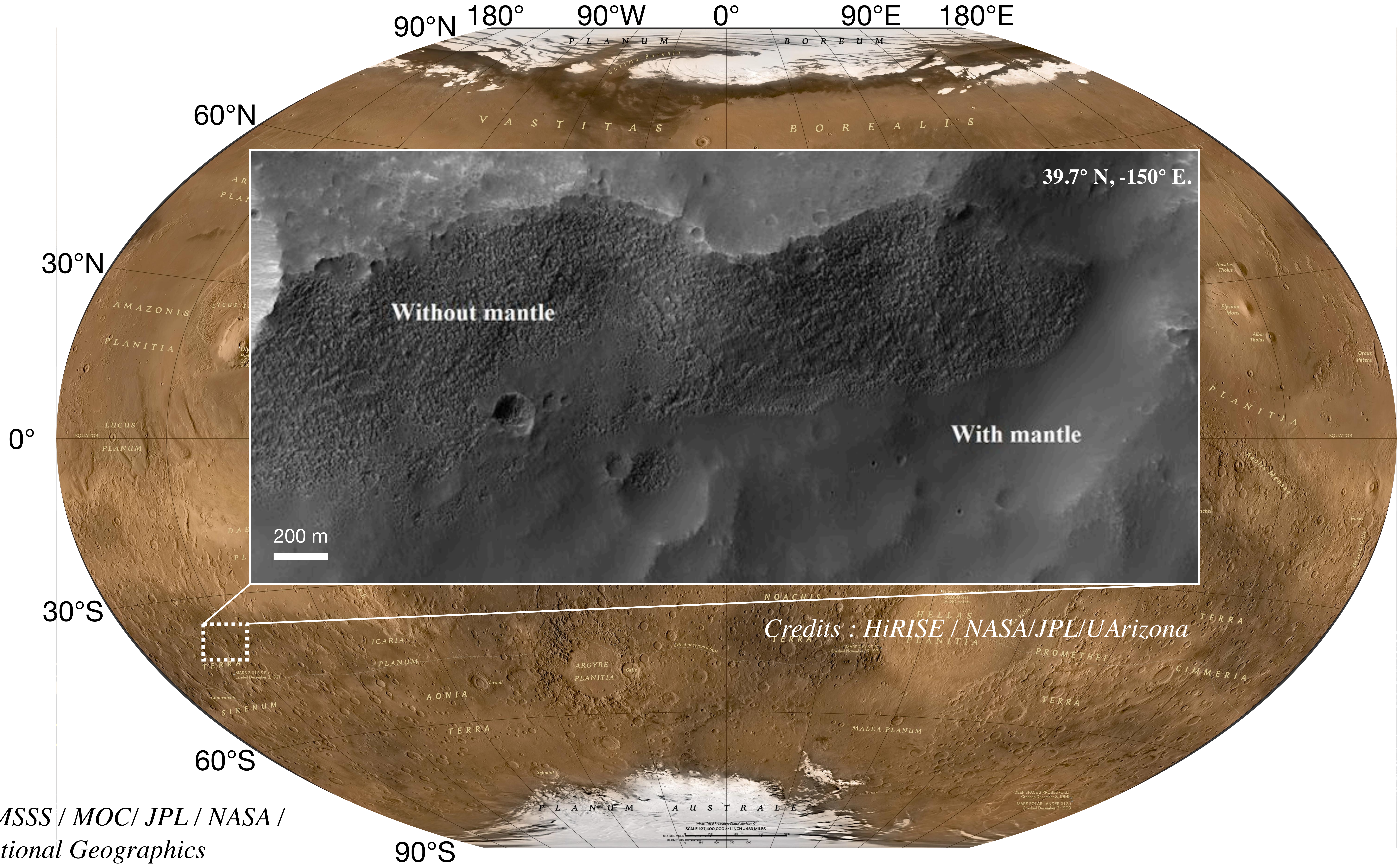


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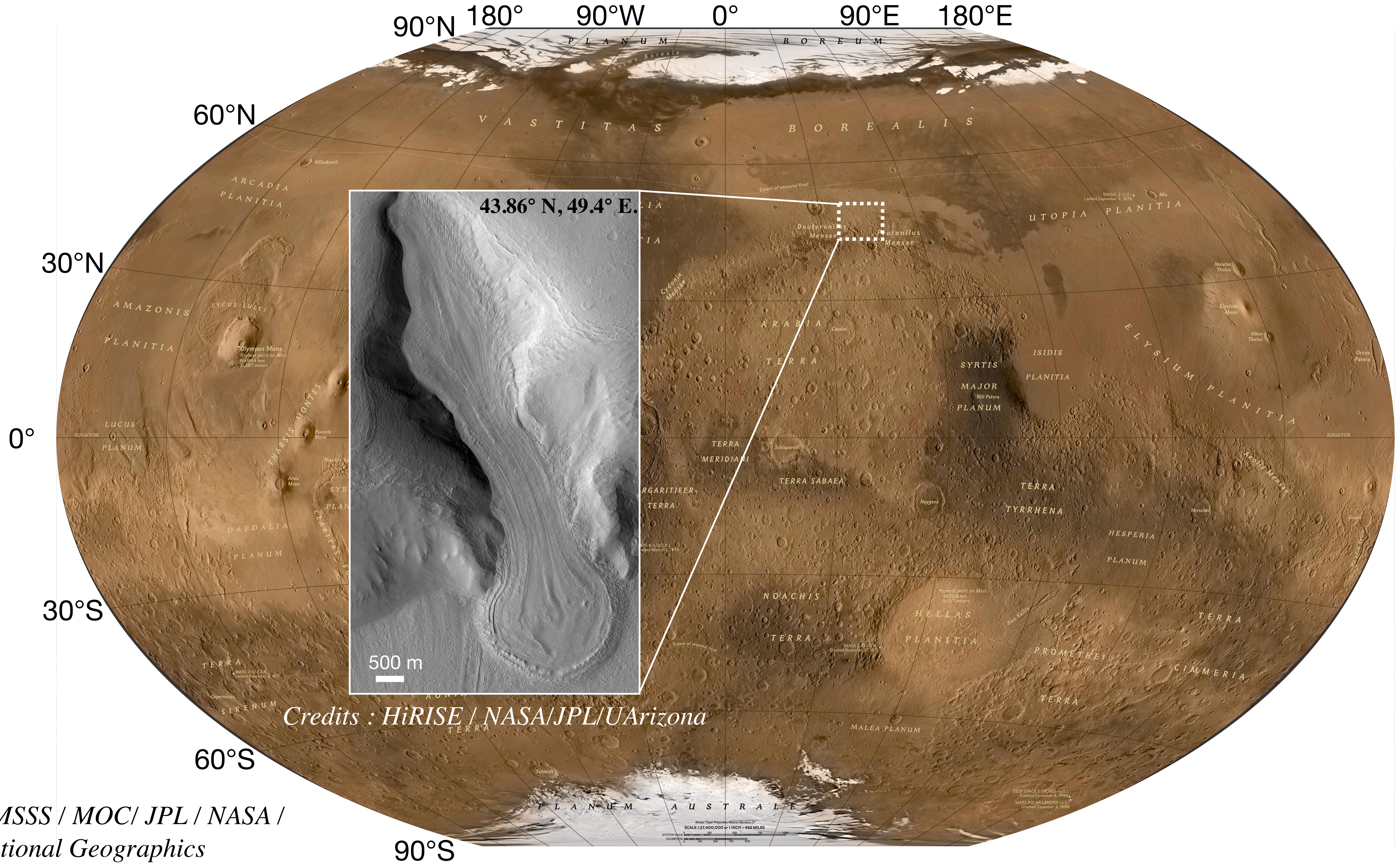
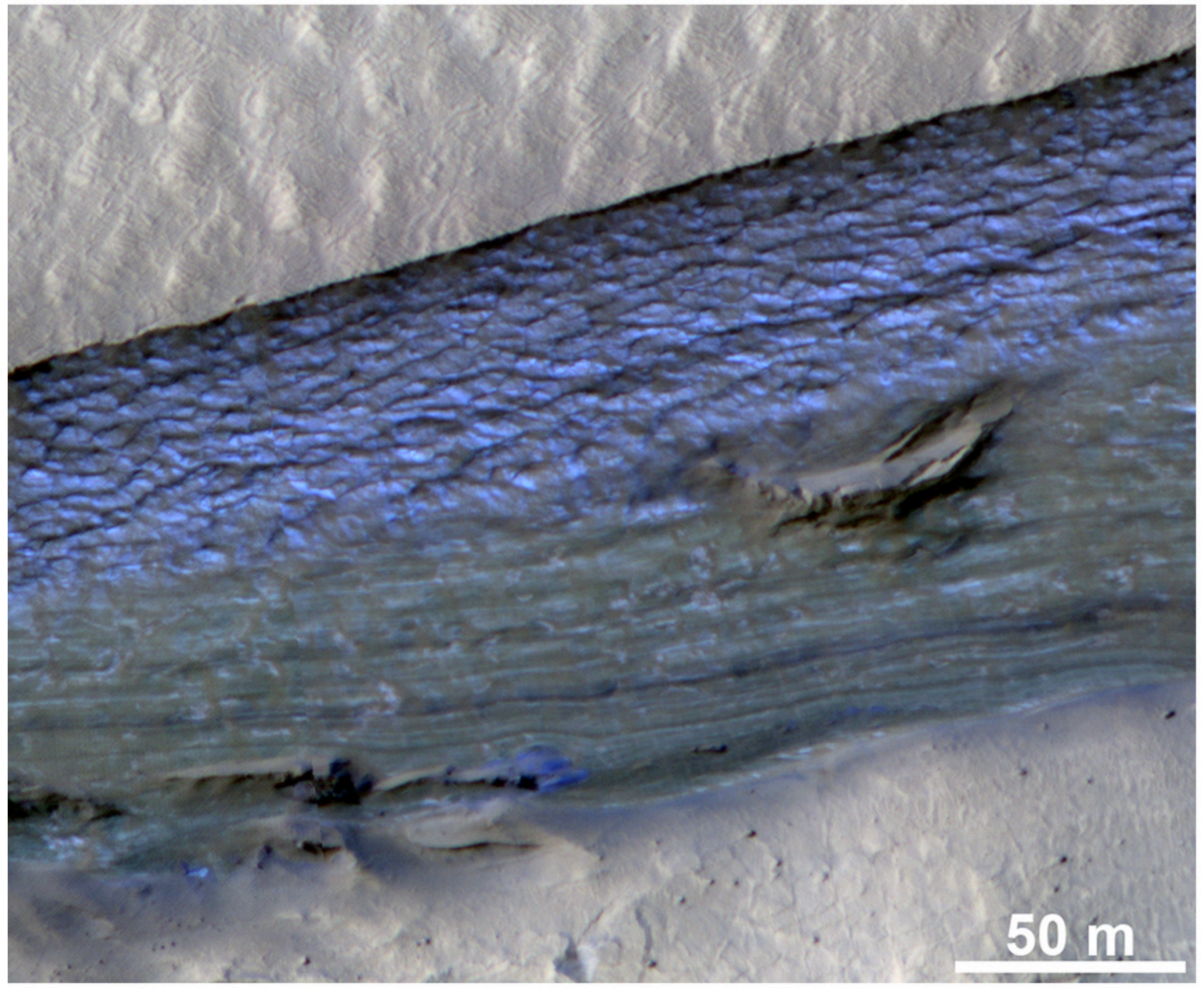



*Credits : MSSS / MOC/ JPL / NASA / National Geographics*

# The Martian Puzzle

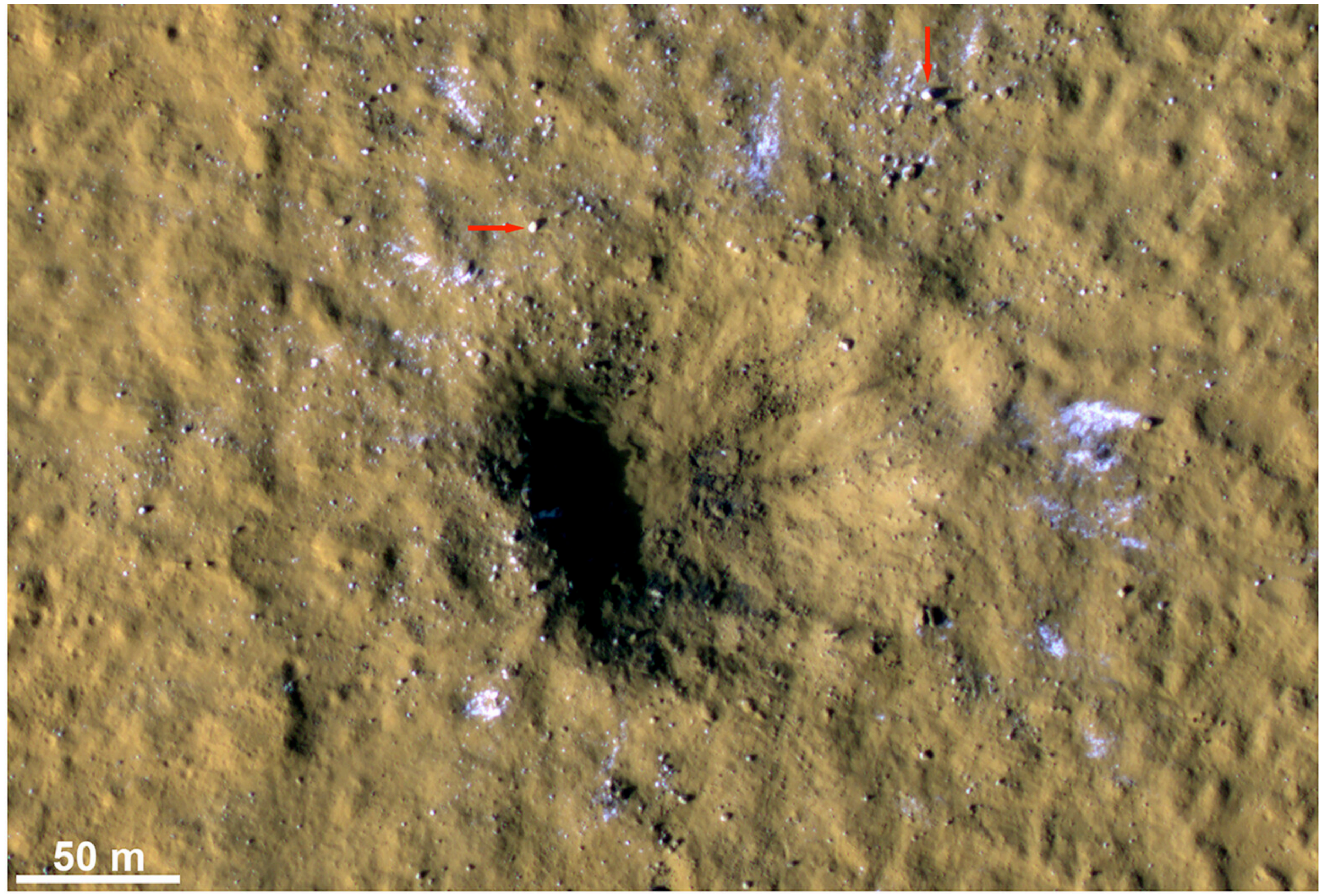
There are multiple evidences of the widespread presence of subsurface water ice on Mars

Subsurface ice exposed on scarp at 58°S




*Dundas et al., 2021*

Impact crater excavating ice at 35°N

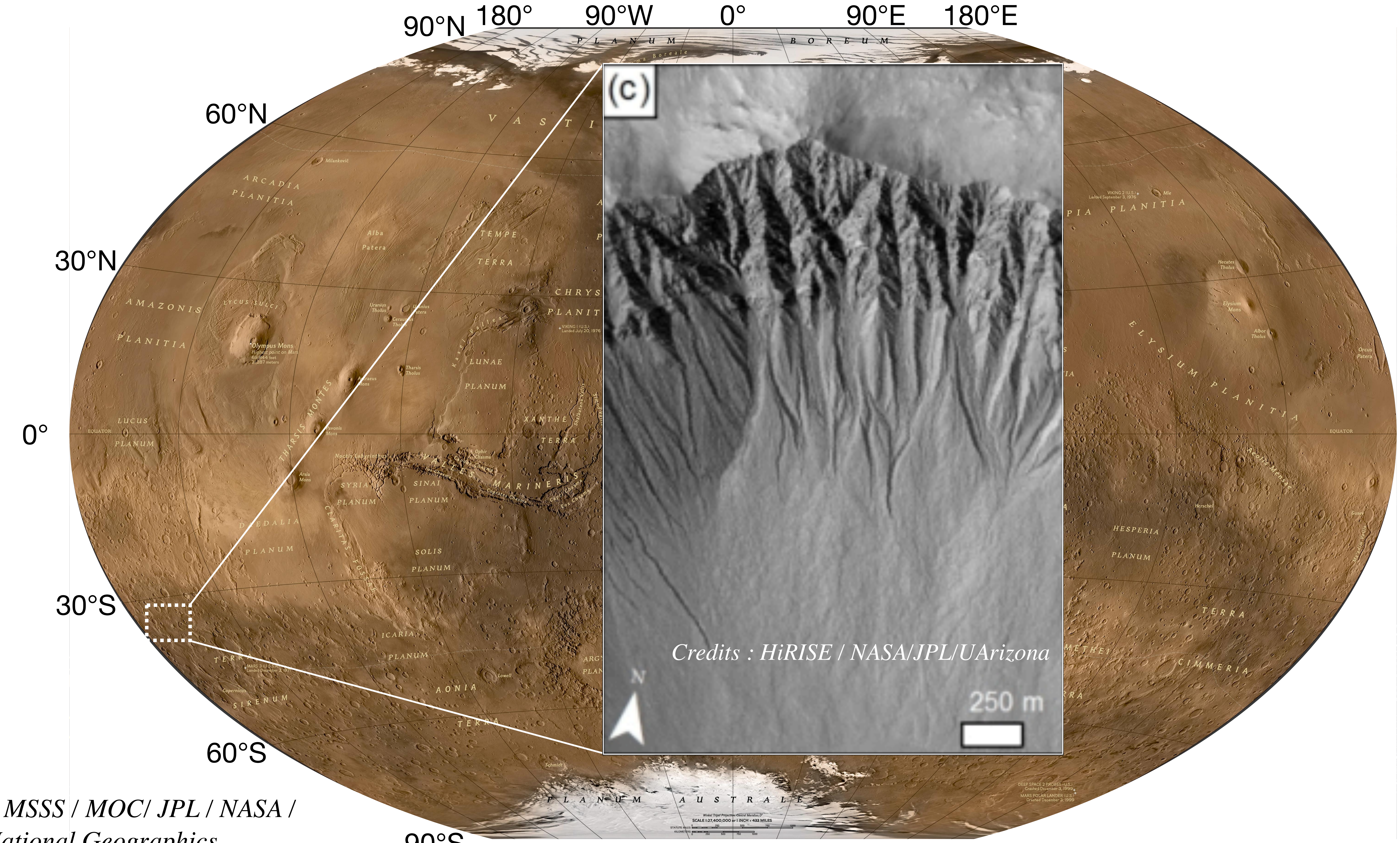



*Dundas et al., 2023*

Ice at Phoenix landing site (61°N)

*Credits: NASA*

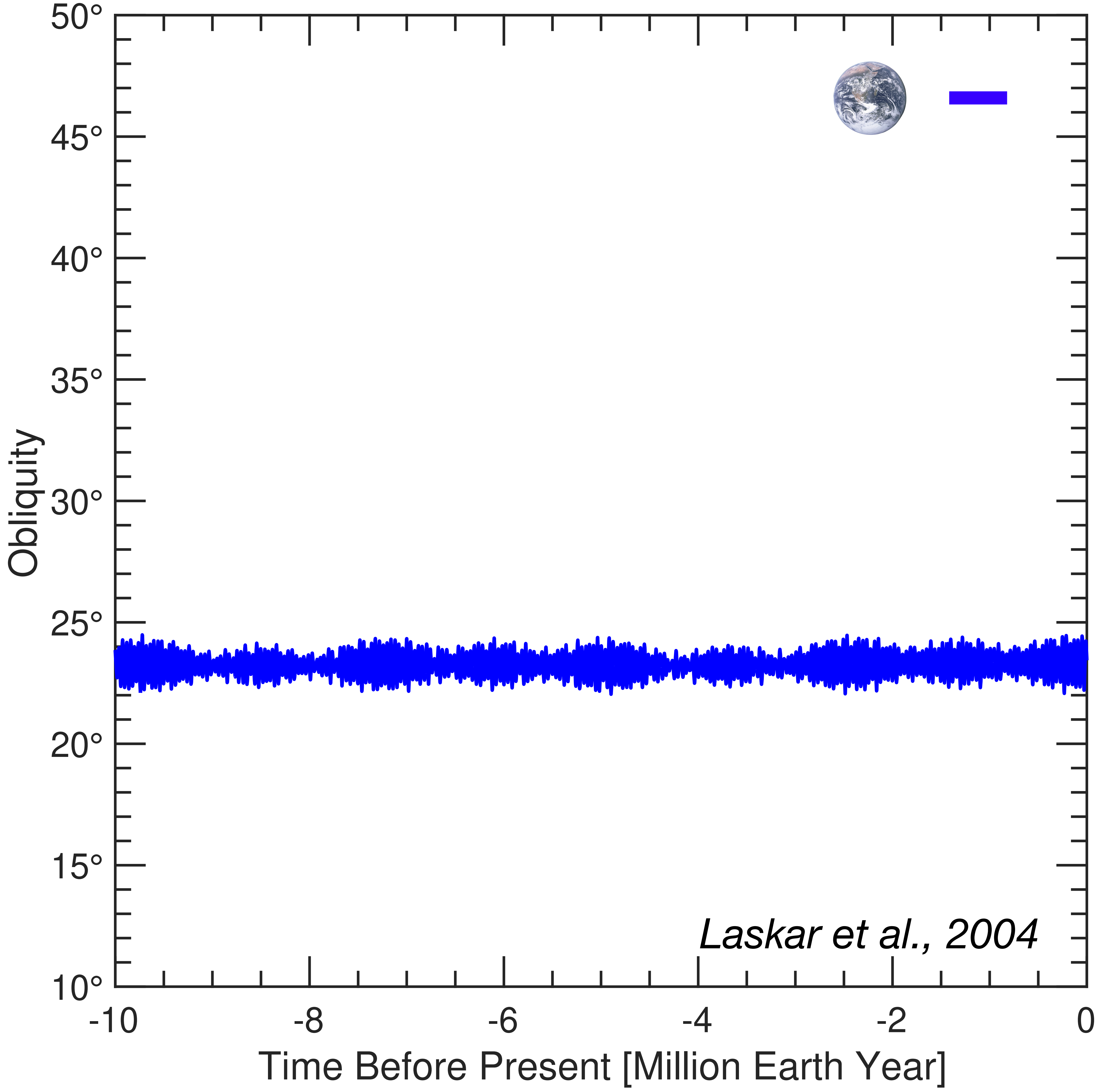
# Some Characteristics of Mars




*Credits : MSSS / MOC/ JPL / NASA / National Geographics*

# The Martian Puzzle

Evolution of the orbital parameters during the last 10 Million years




- The obliquity of Earth has **slightly** varied by < 2° during the recent past.

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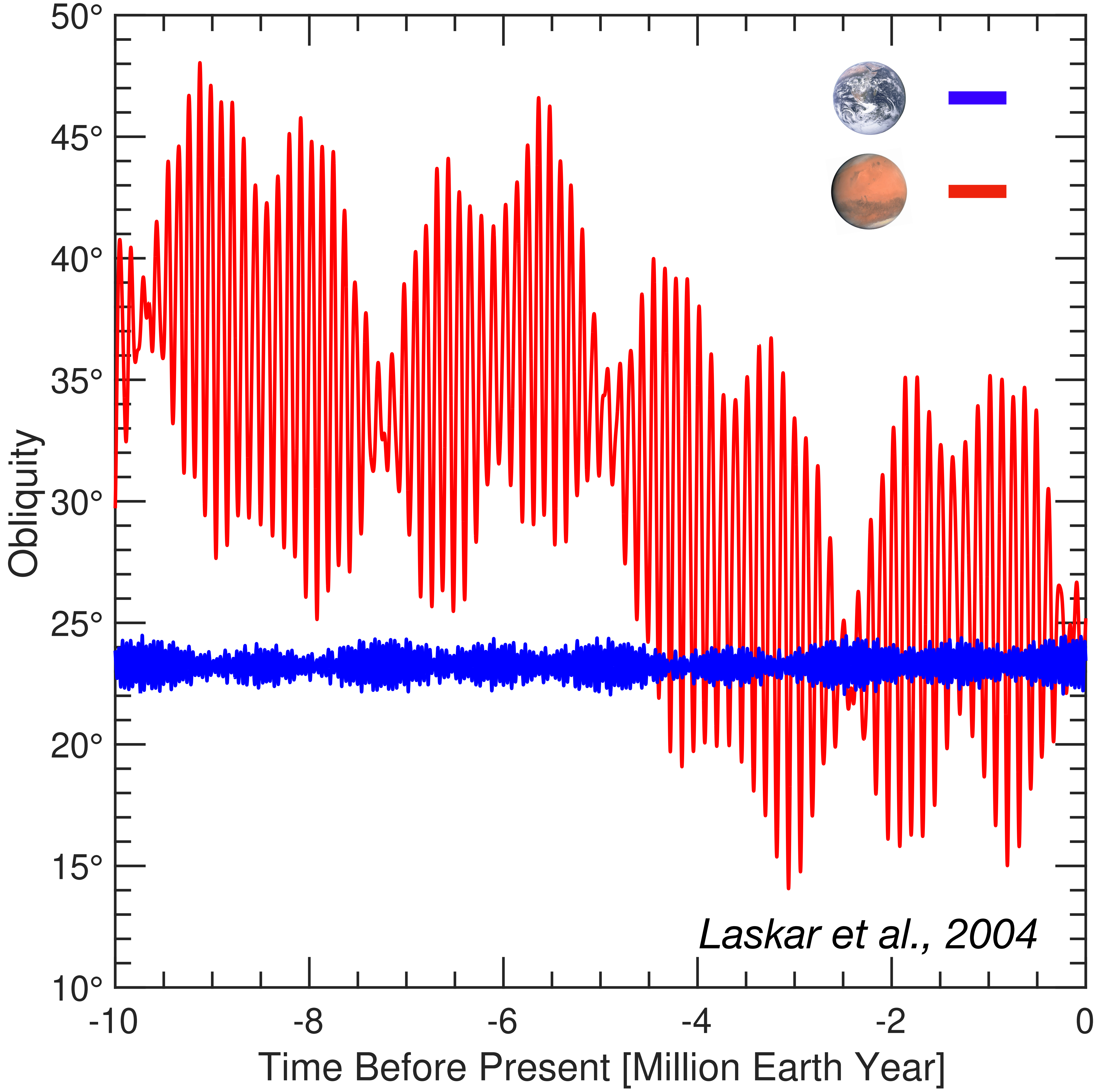


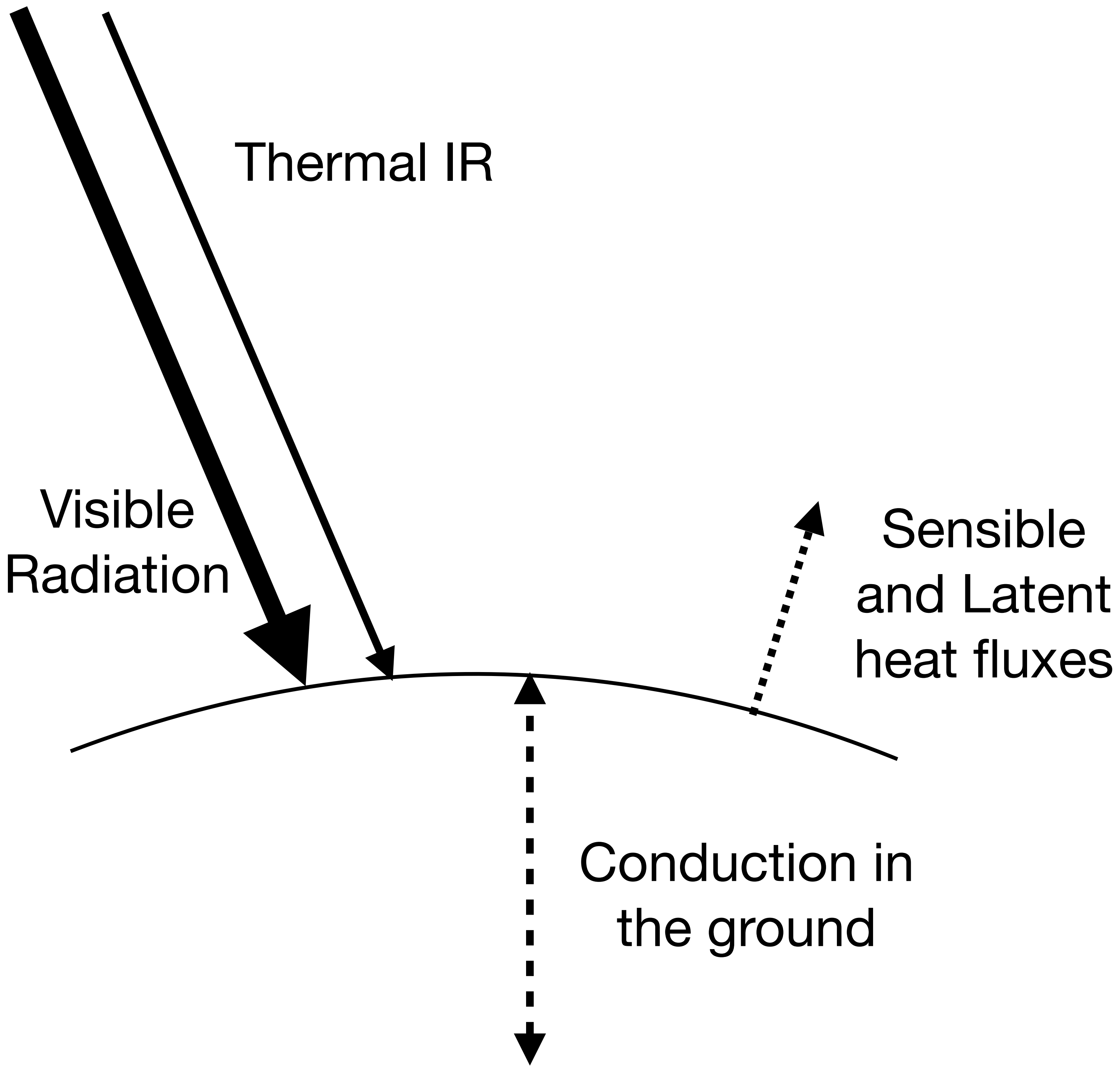

- The obliquity of Earth has **slightly** varied by < 2° during the recent past.
- The obliquity of Mars has **strongly** varied by > 15° during the recent past, leading to significant changes on the planet.

# The Martian Puzzle

Hierarchy of models and what we learn

**Model's Complexity**
(and computation time)

Surface Energy
Balance Models



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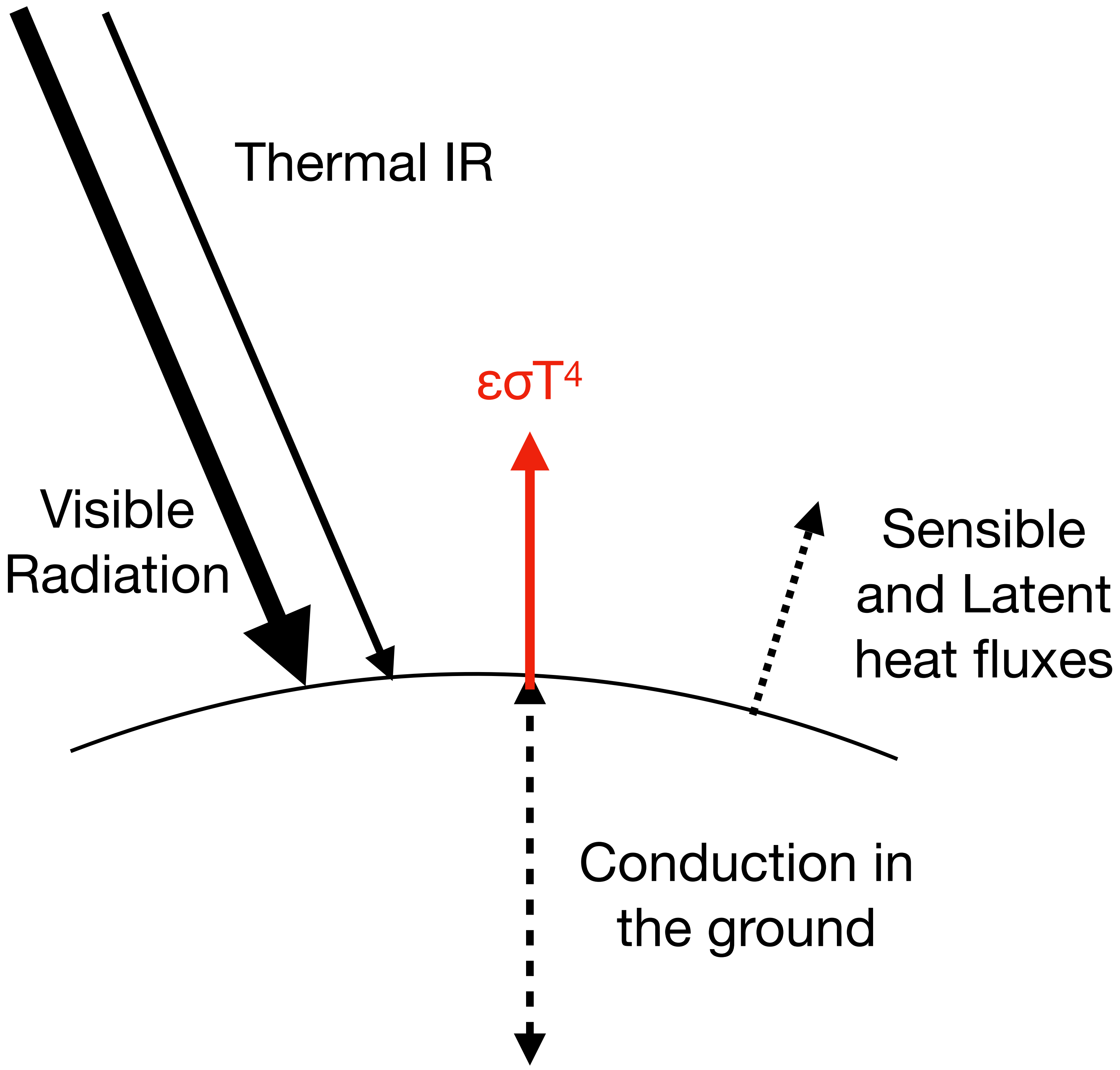

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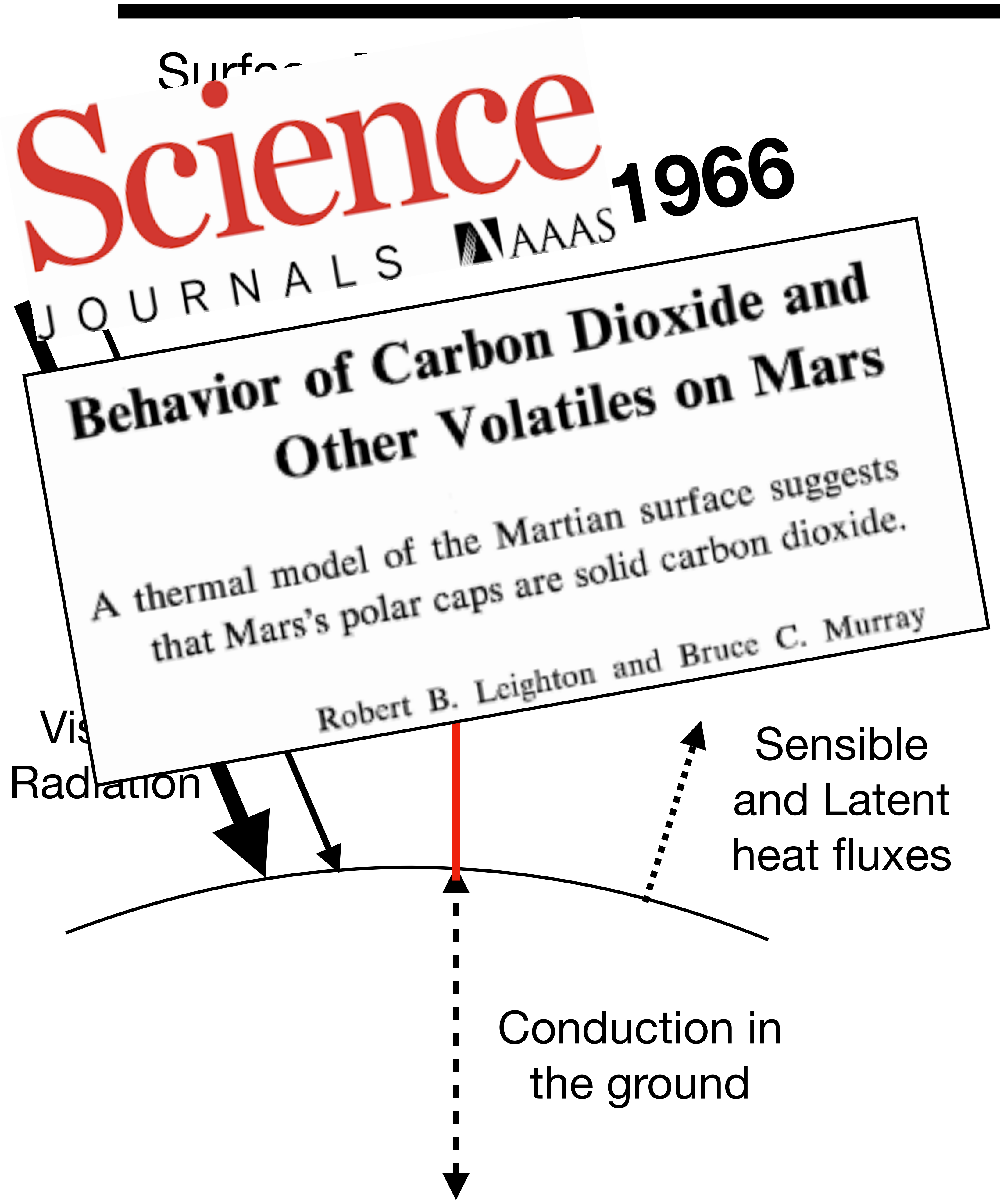

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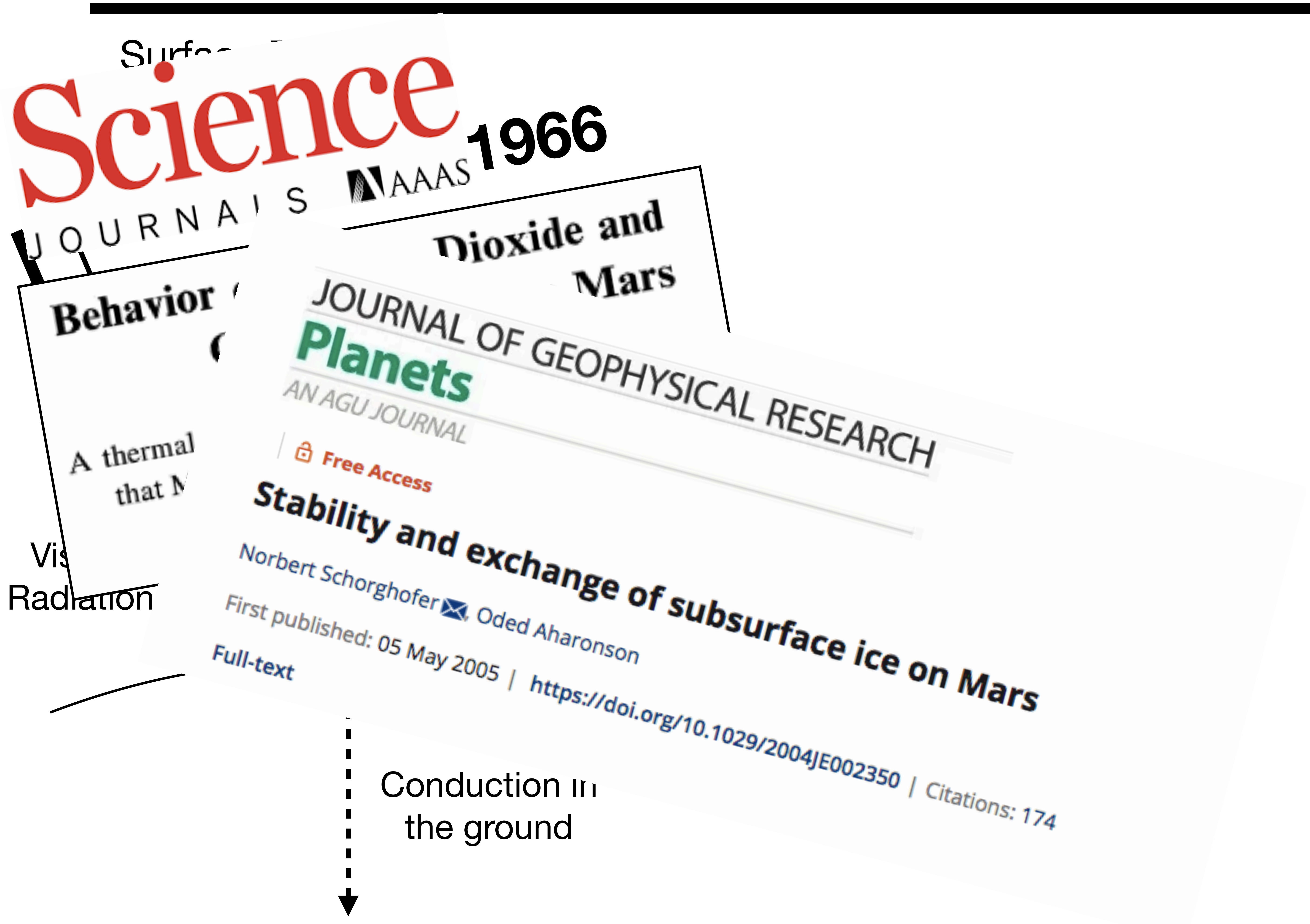

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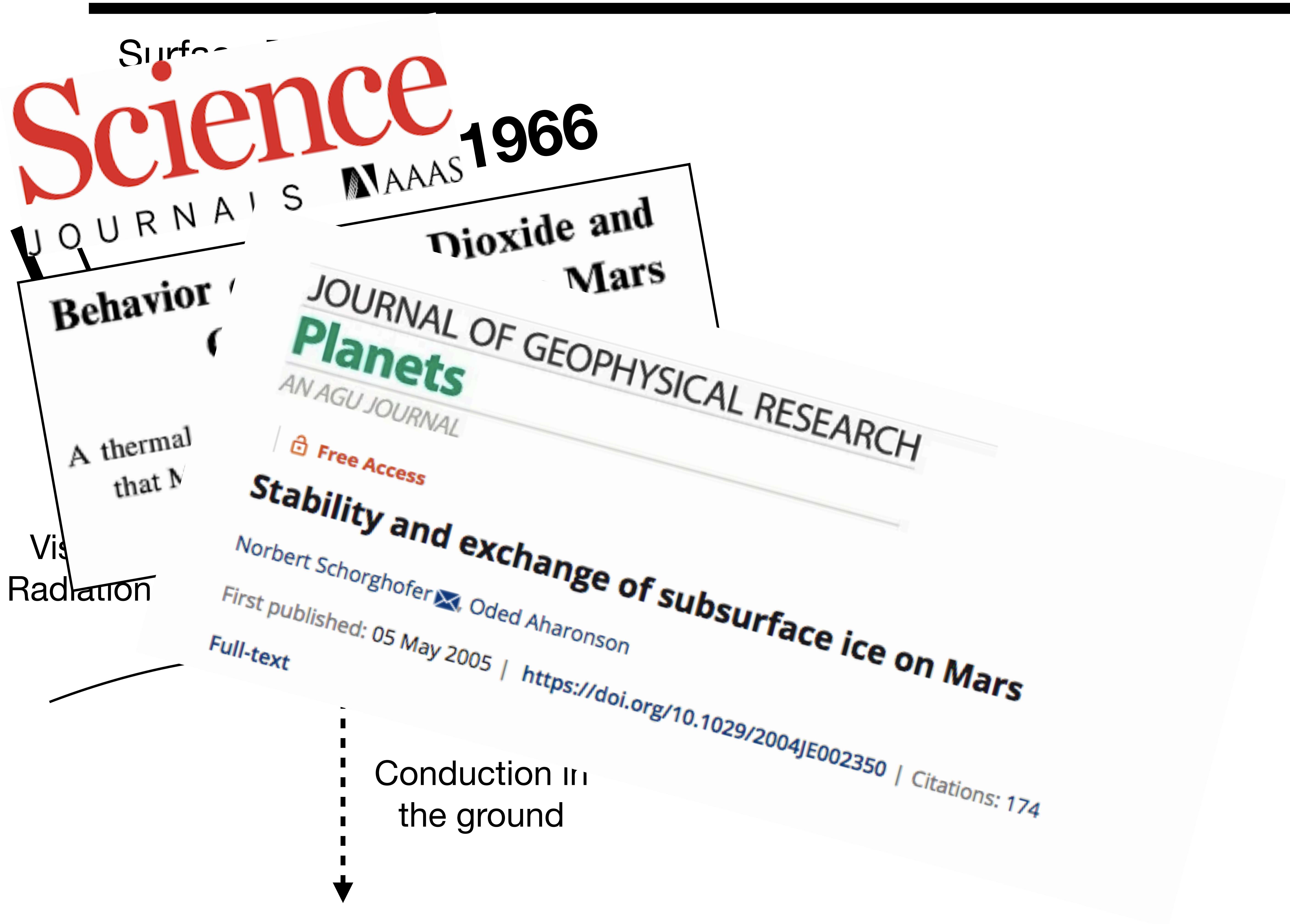
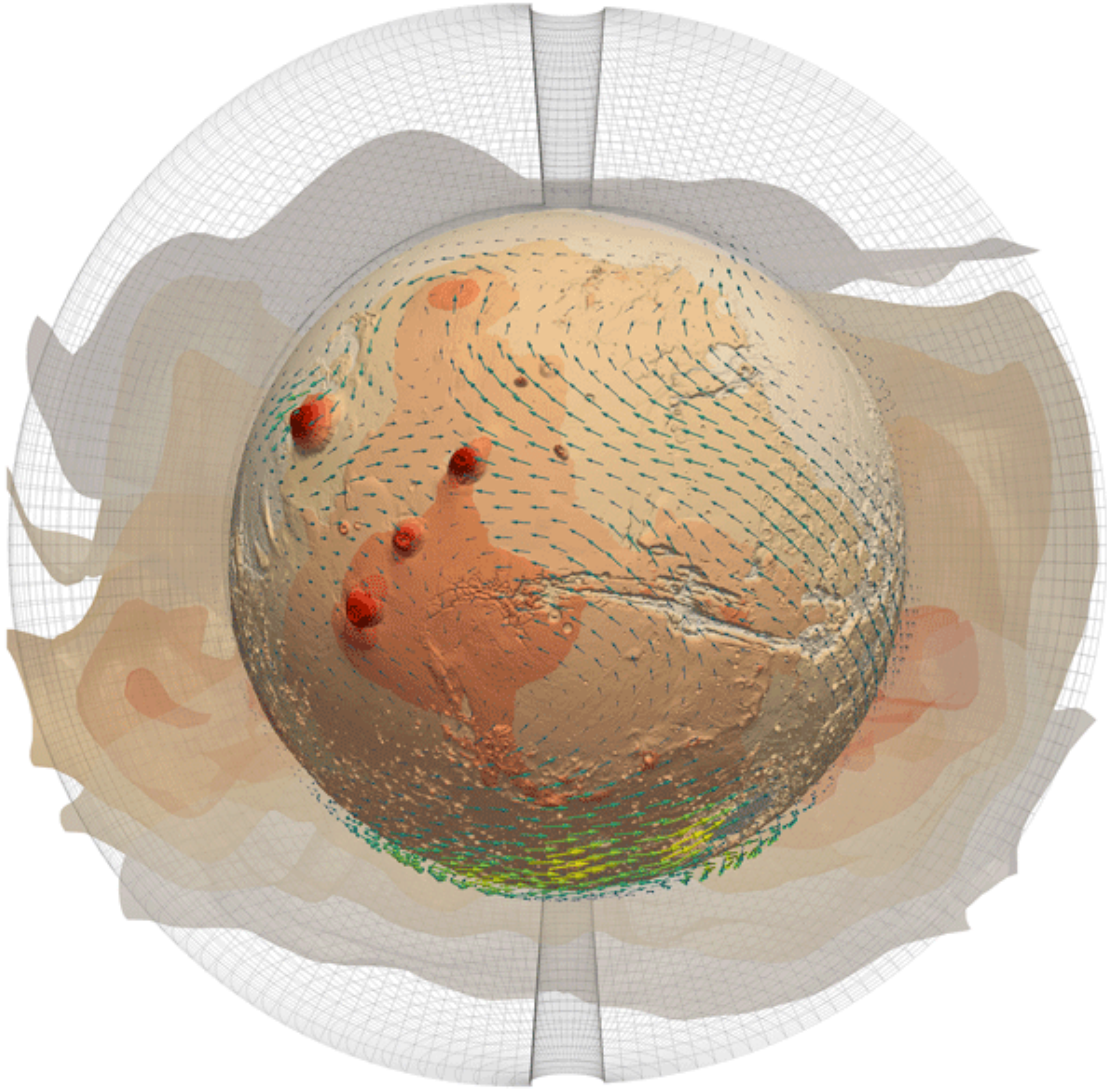
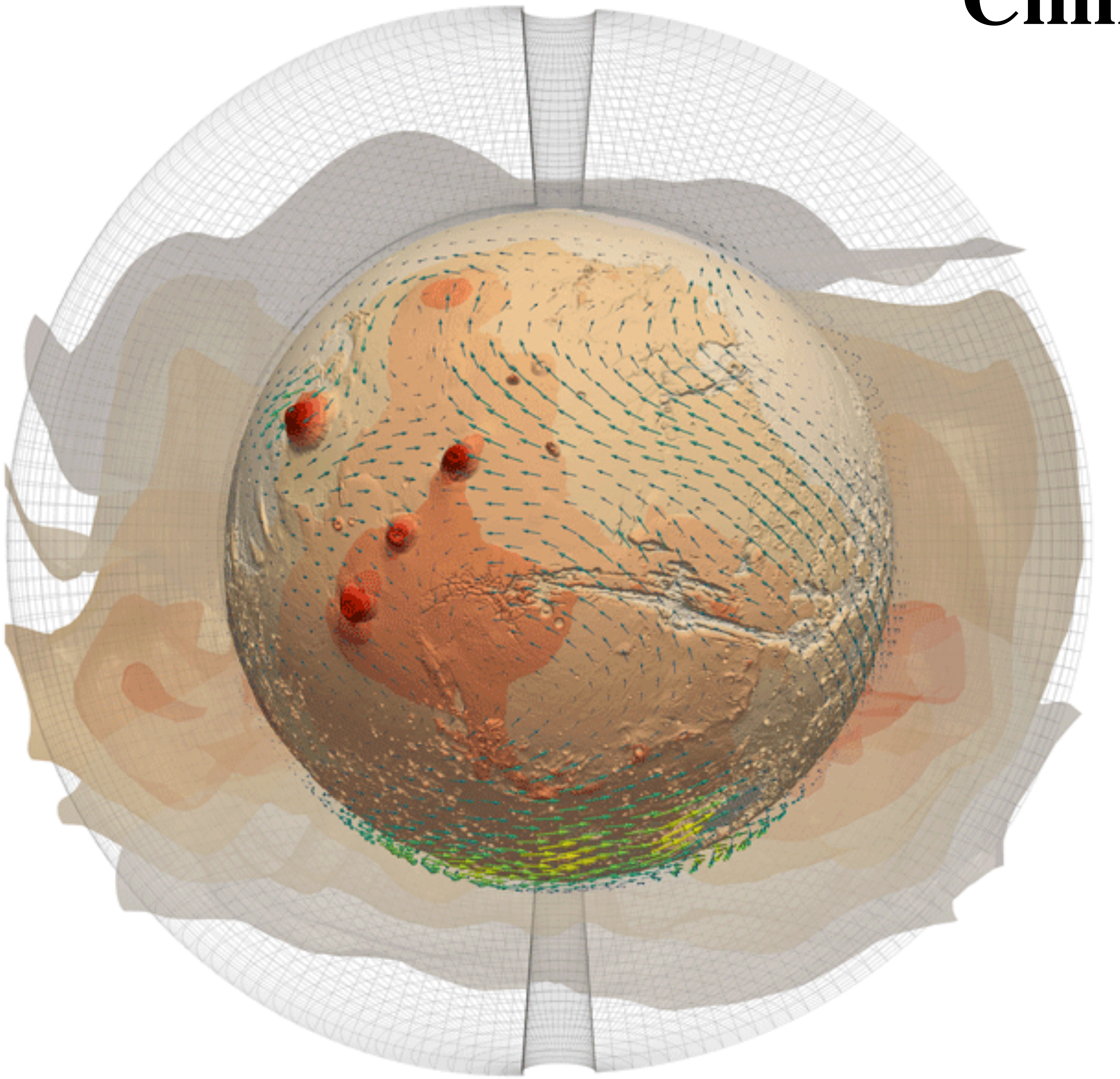



Global Climate Models



# Modeling Past Climates with the Mars Planetary Climate Model

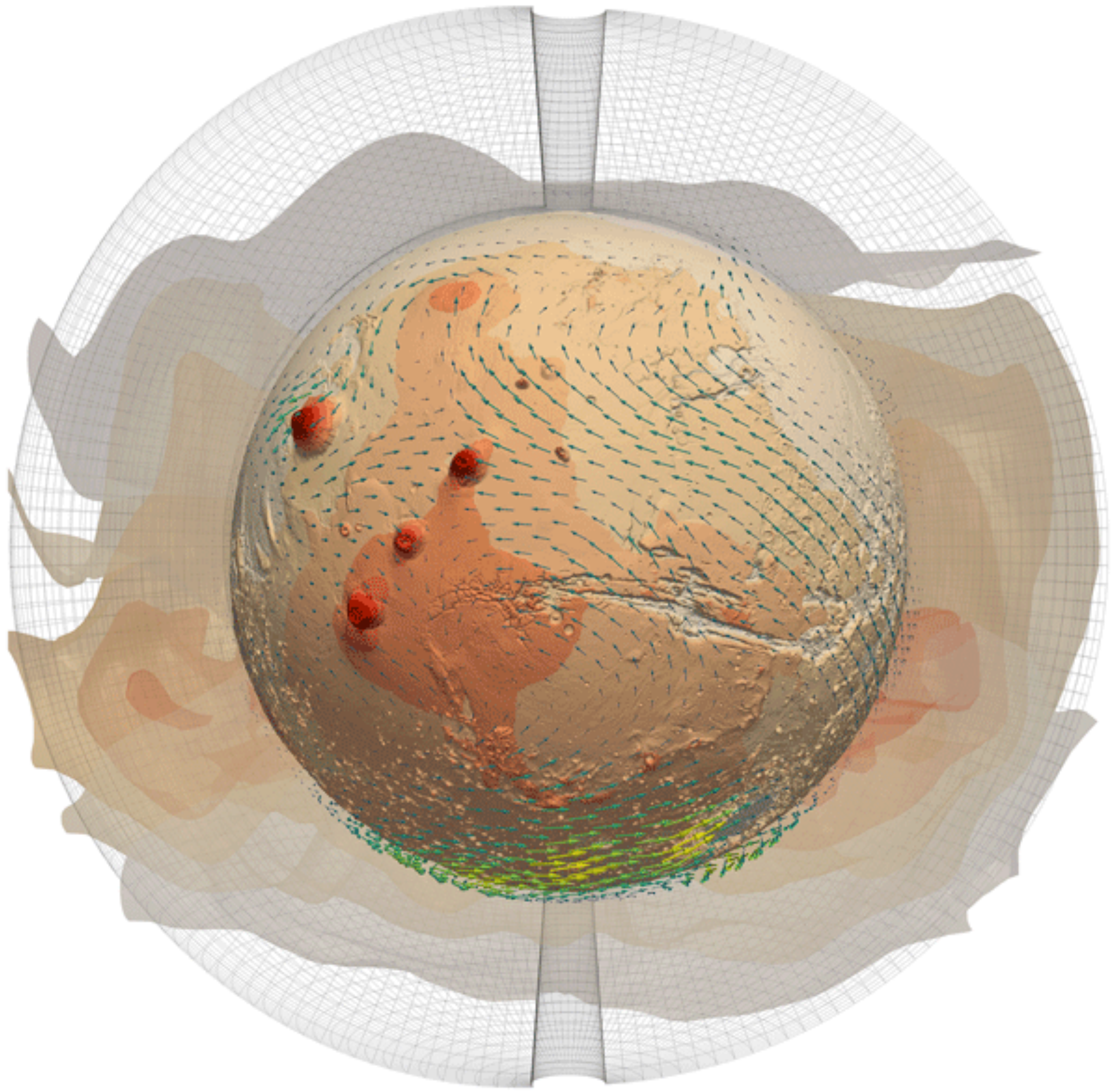


The planet is divided into rectangular grid meshes (300 x 200 km at the Equator).

Hybrid coordinates on the vertical axis, ranging from ~4 m above the surface to > 120 km).

Integration with a timestep of ~ min.

# Modeling Subsurface Ice Equilibrium with the Mars Planetary Climate Model



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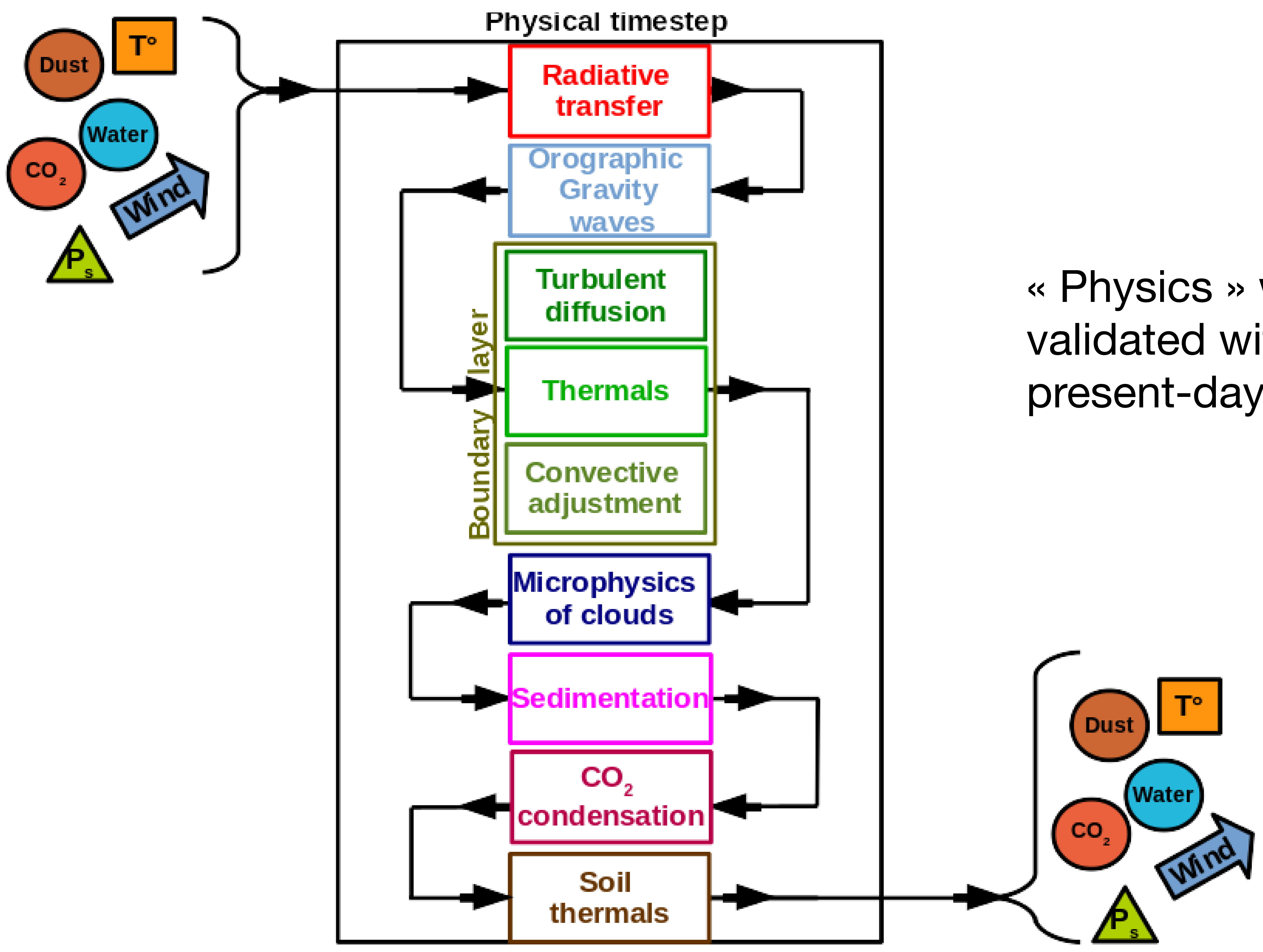


*M.Vals,2019*

« Physics » which has been validated with comparison with present-day observations.

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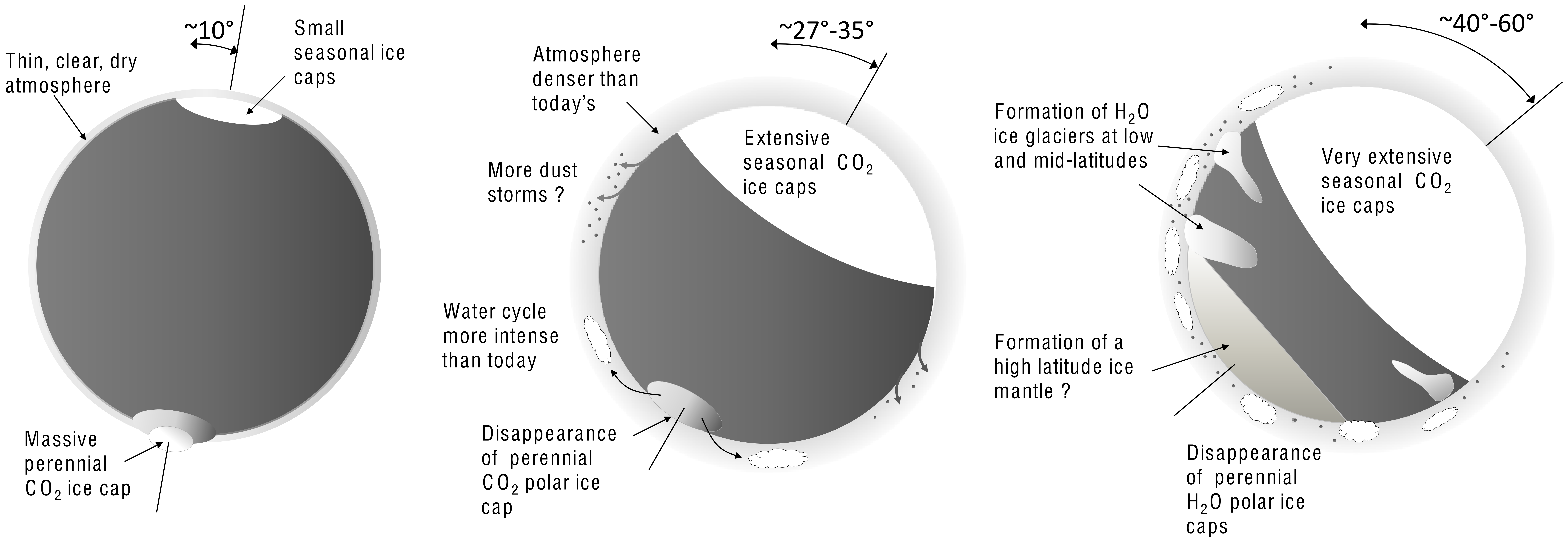
Effect of changing the obliquity on the Martian Climate from previous climate studies: current view




*Forget et al., 2017*

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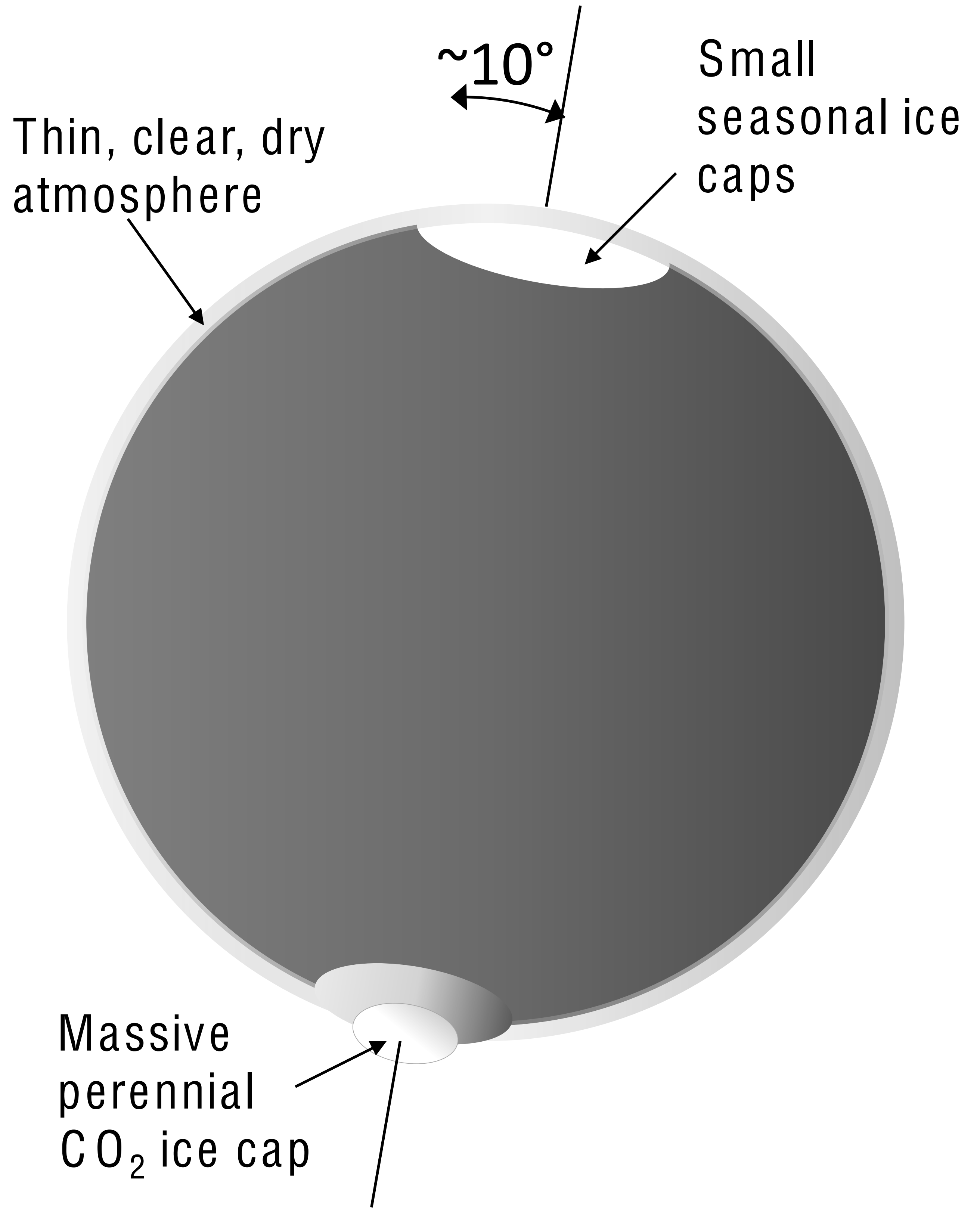


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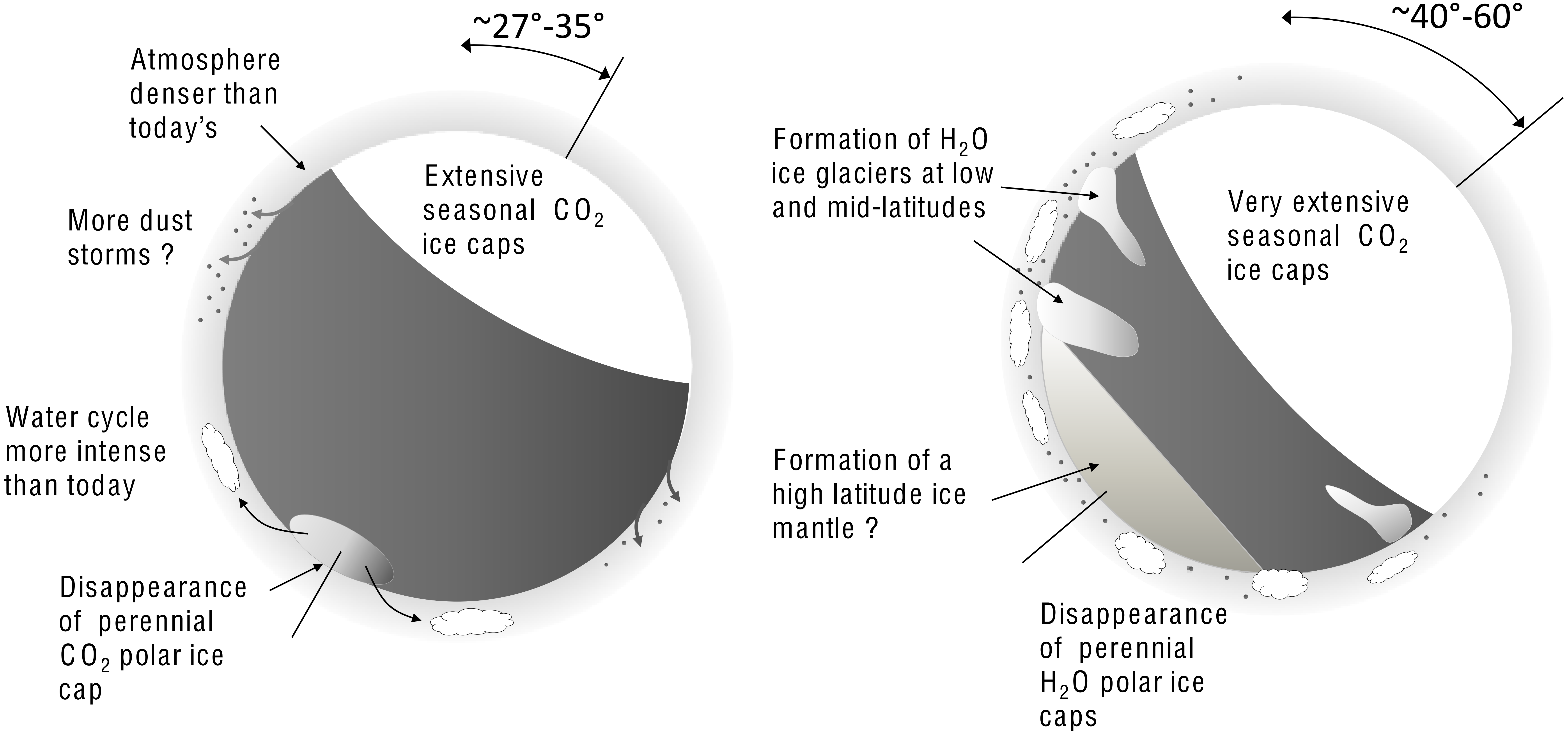


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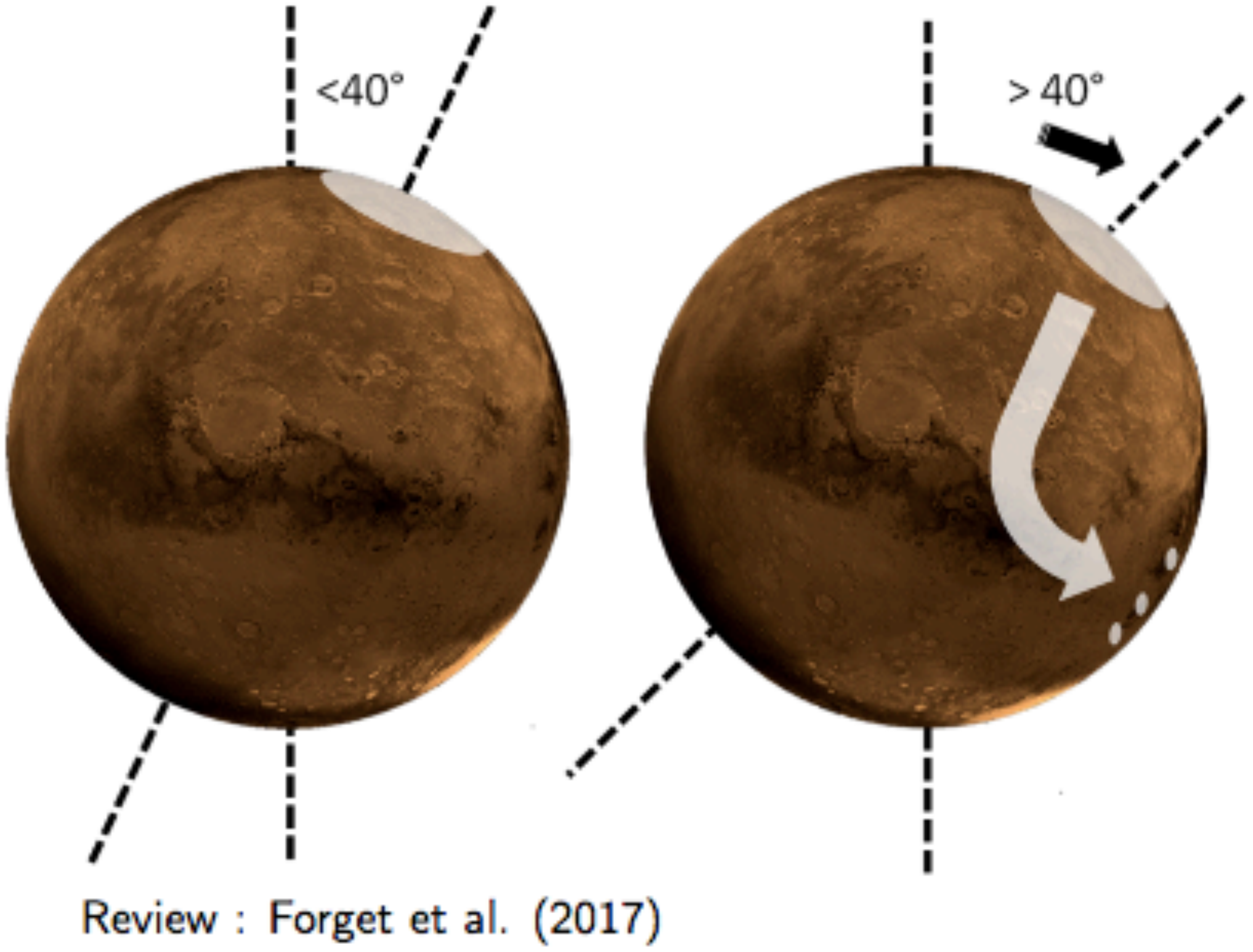


Naar 2024

# Outline

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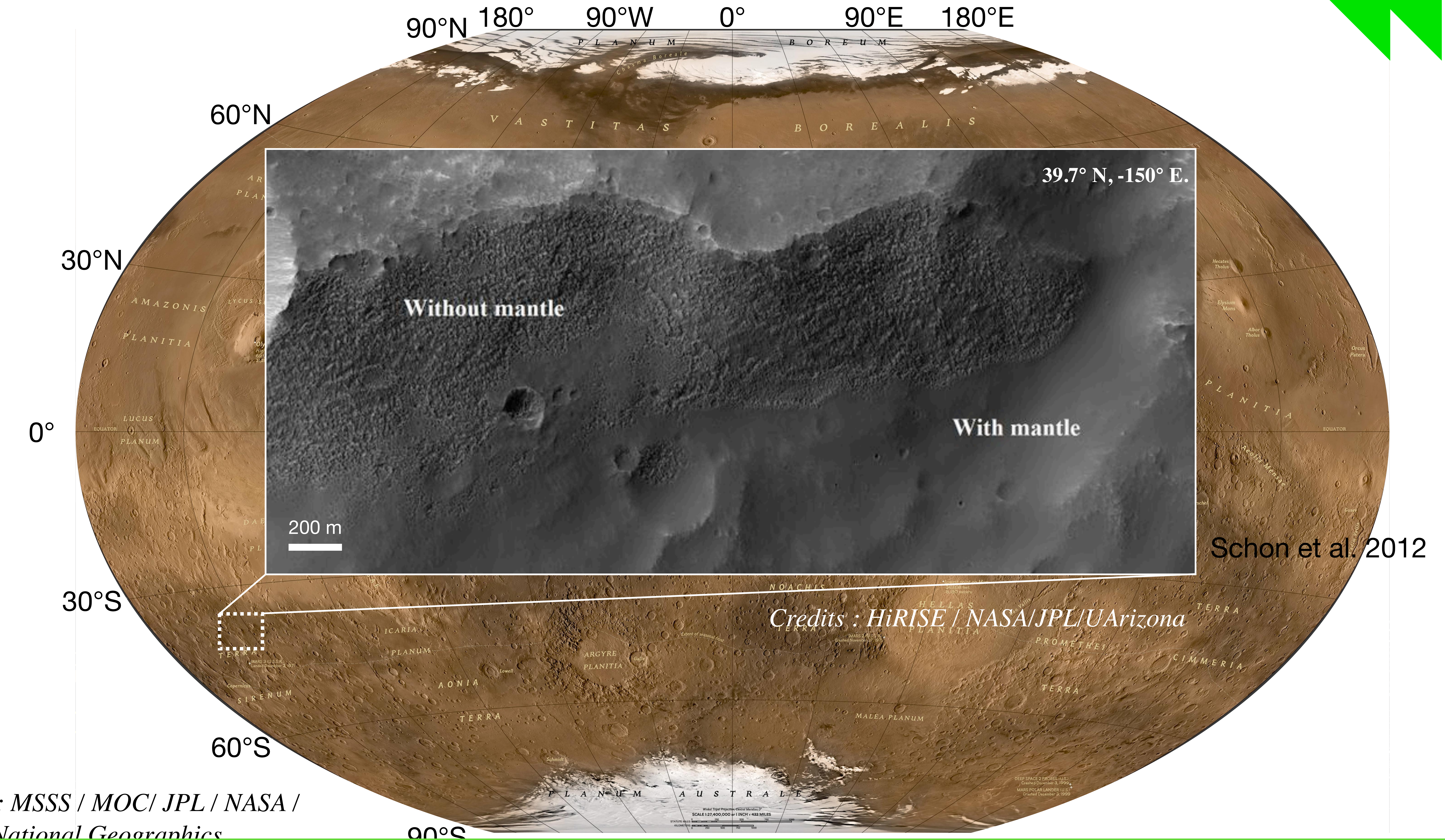
# Some Characteristics of Mars

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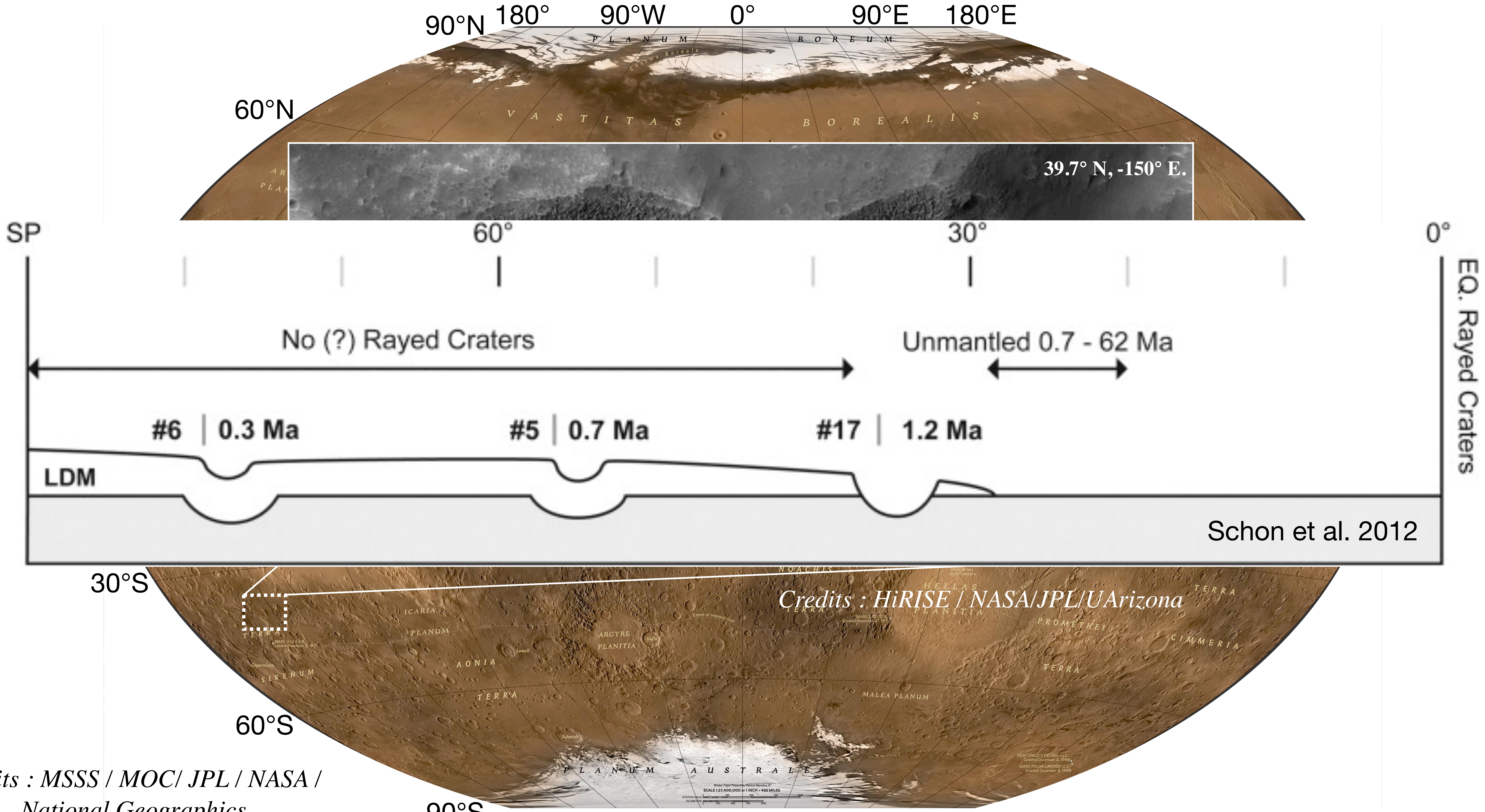


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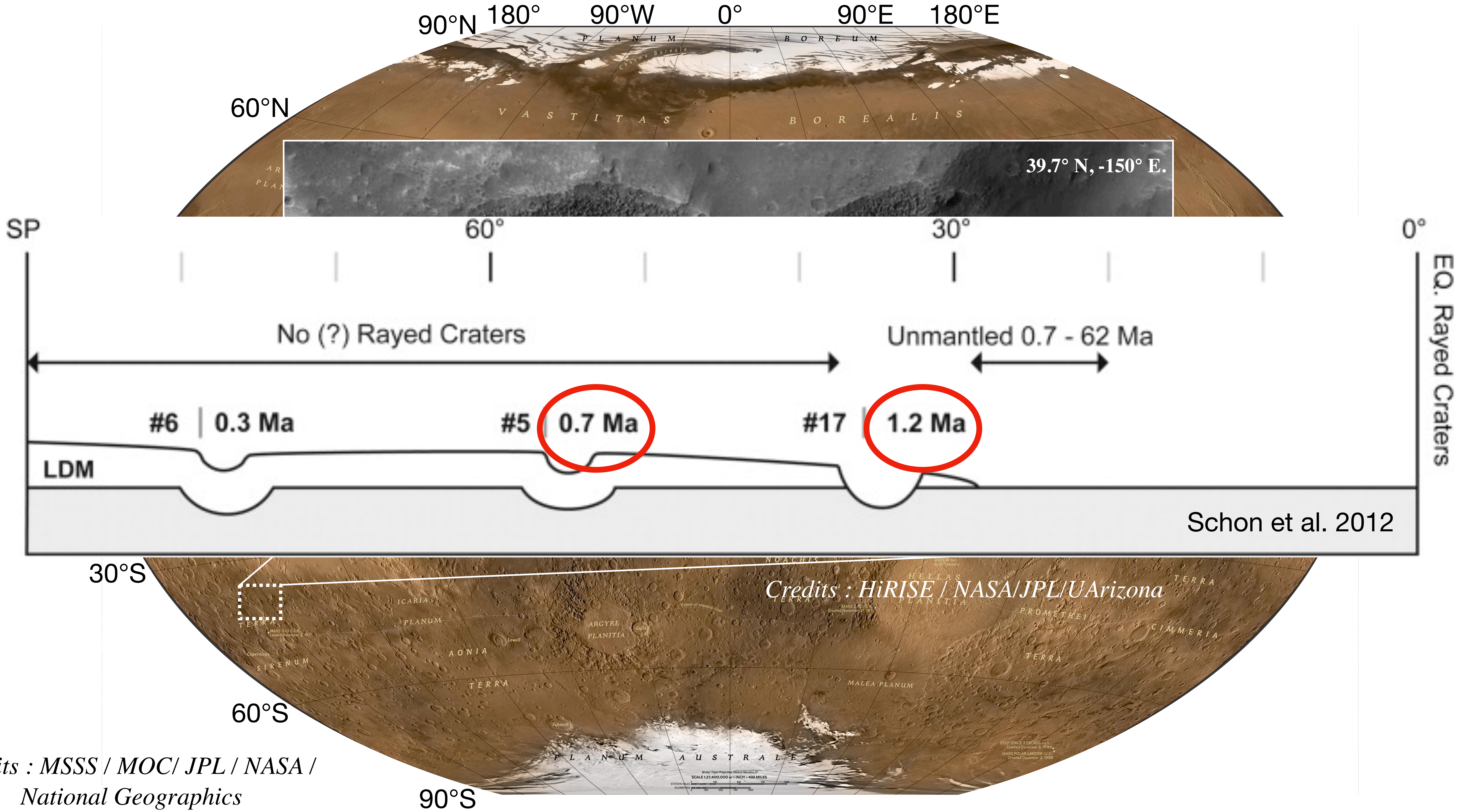


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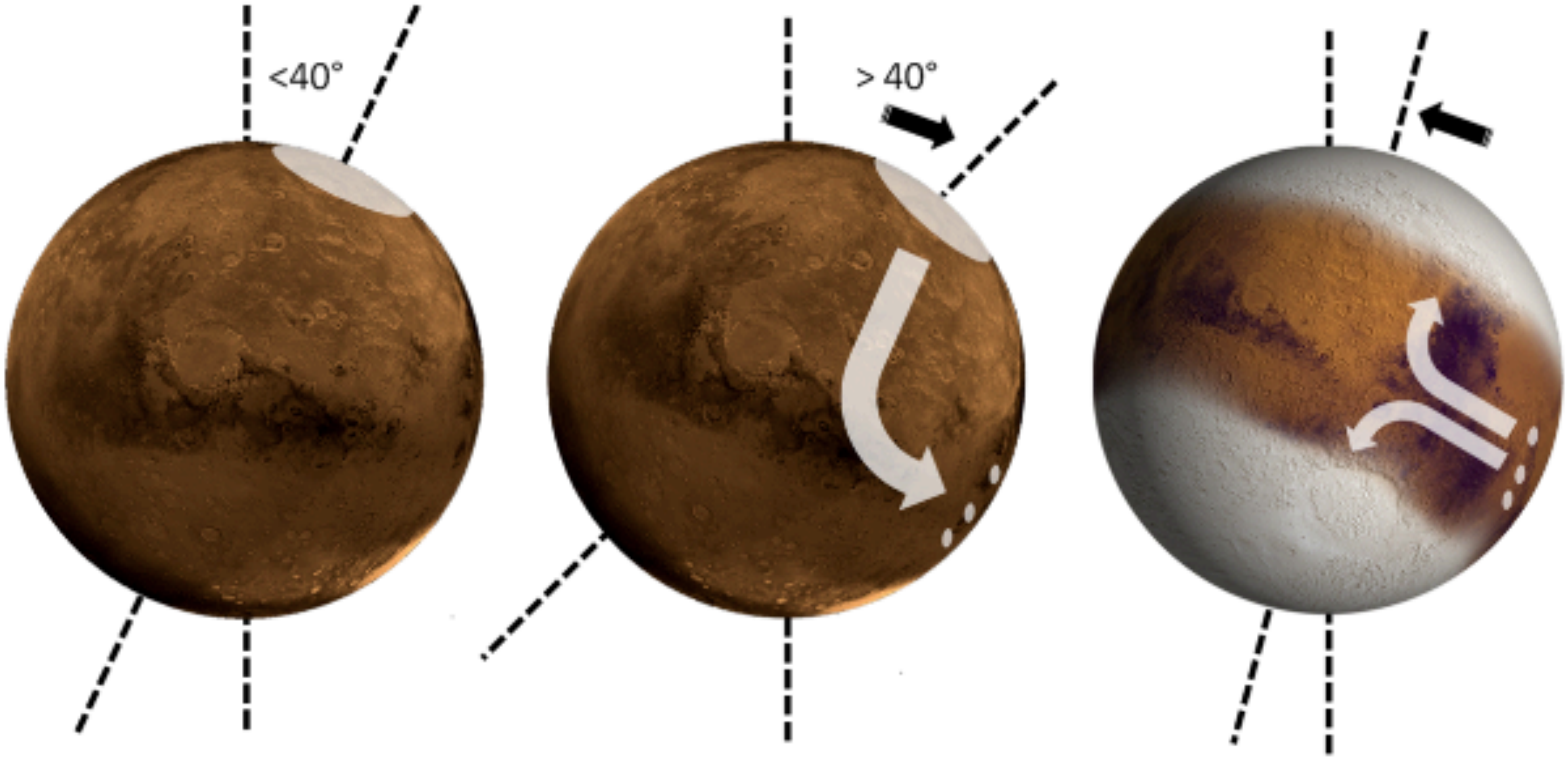


Review : Forget et al. (2017)

Naar 2024

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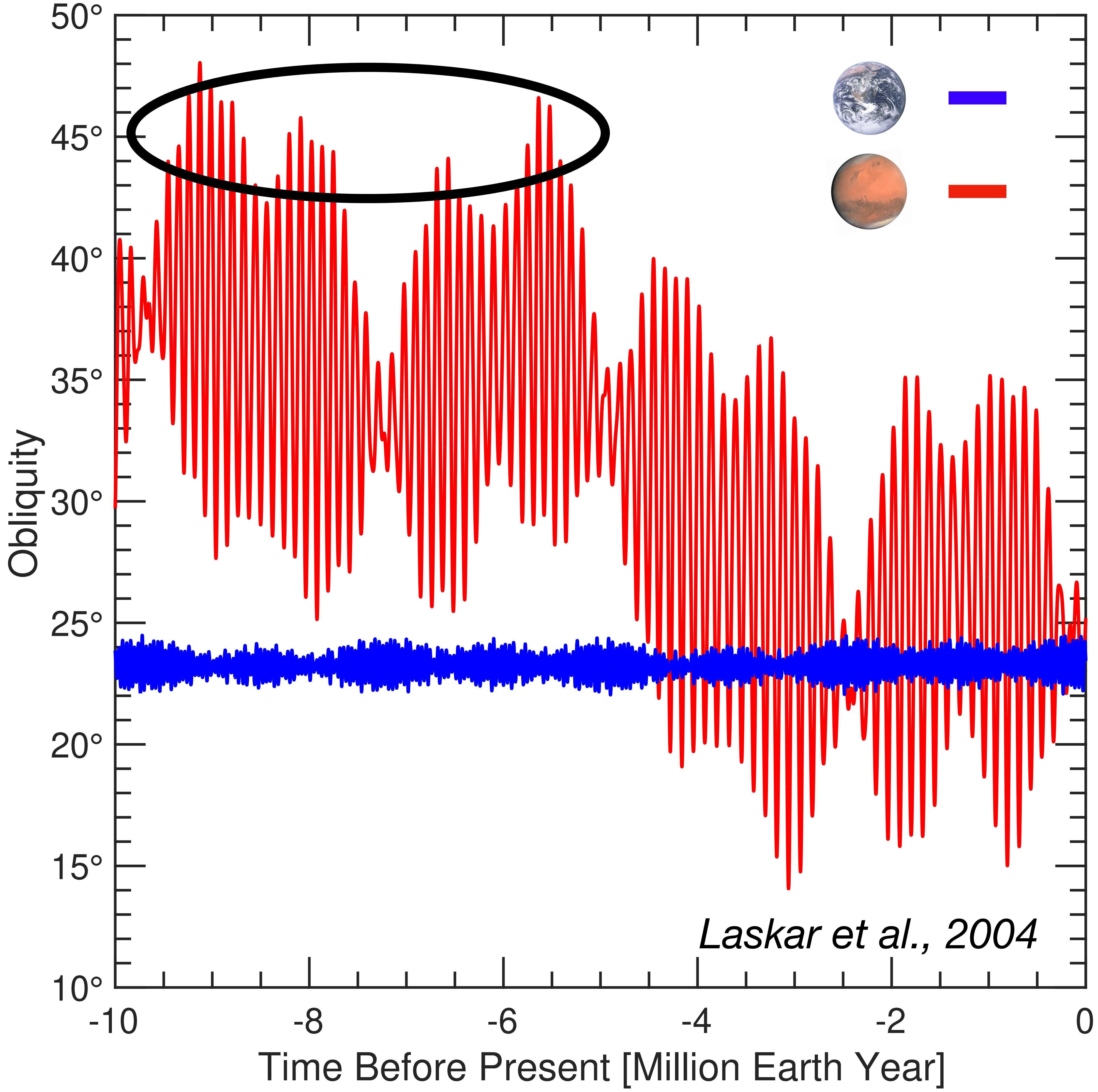


- The obliquity of Earth has **slightly** varied by < 2° during the recent past. This is because of the presence of the Moon which stabilizes the Earth's obliquity

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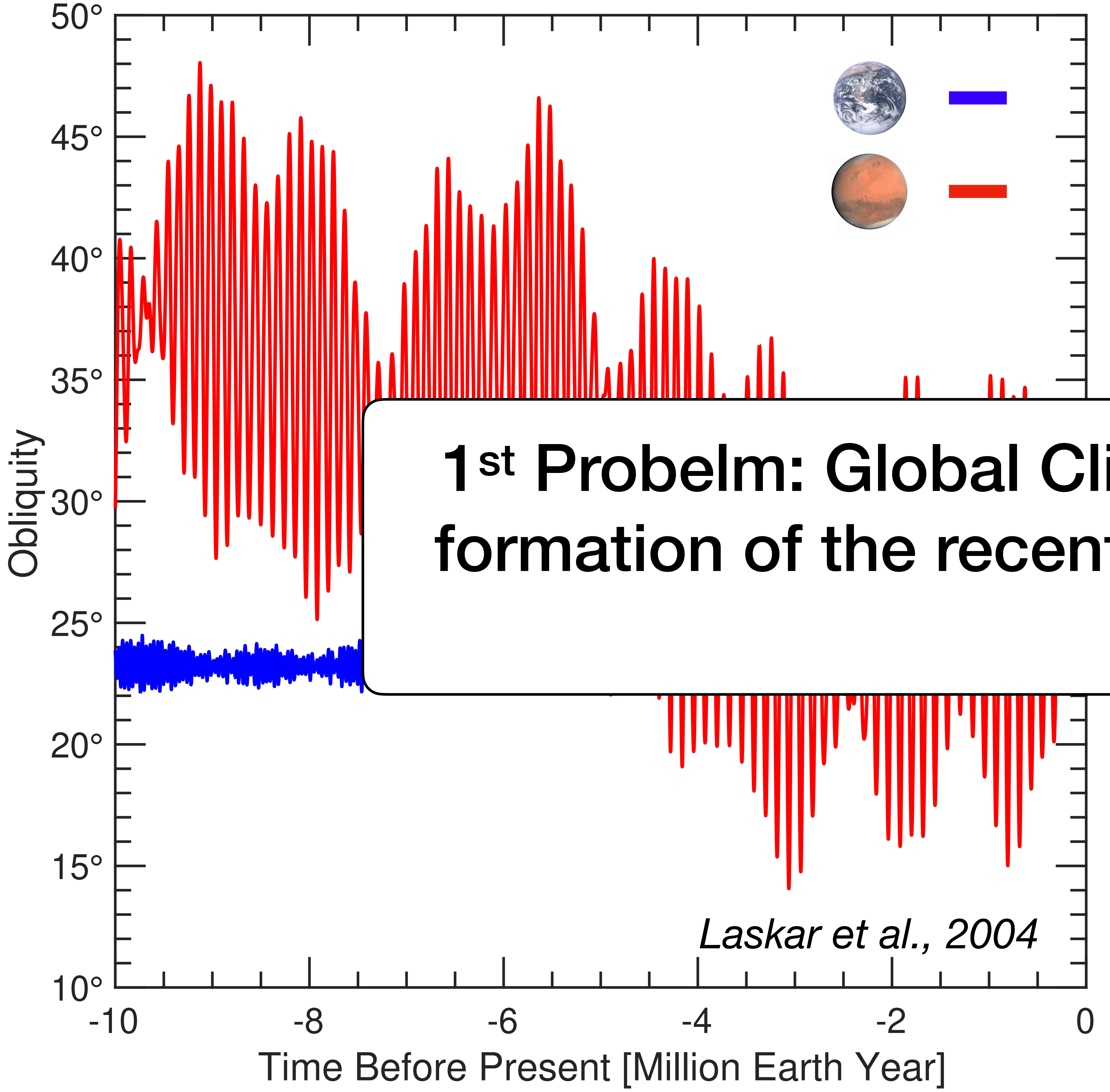


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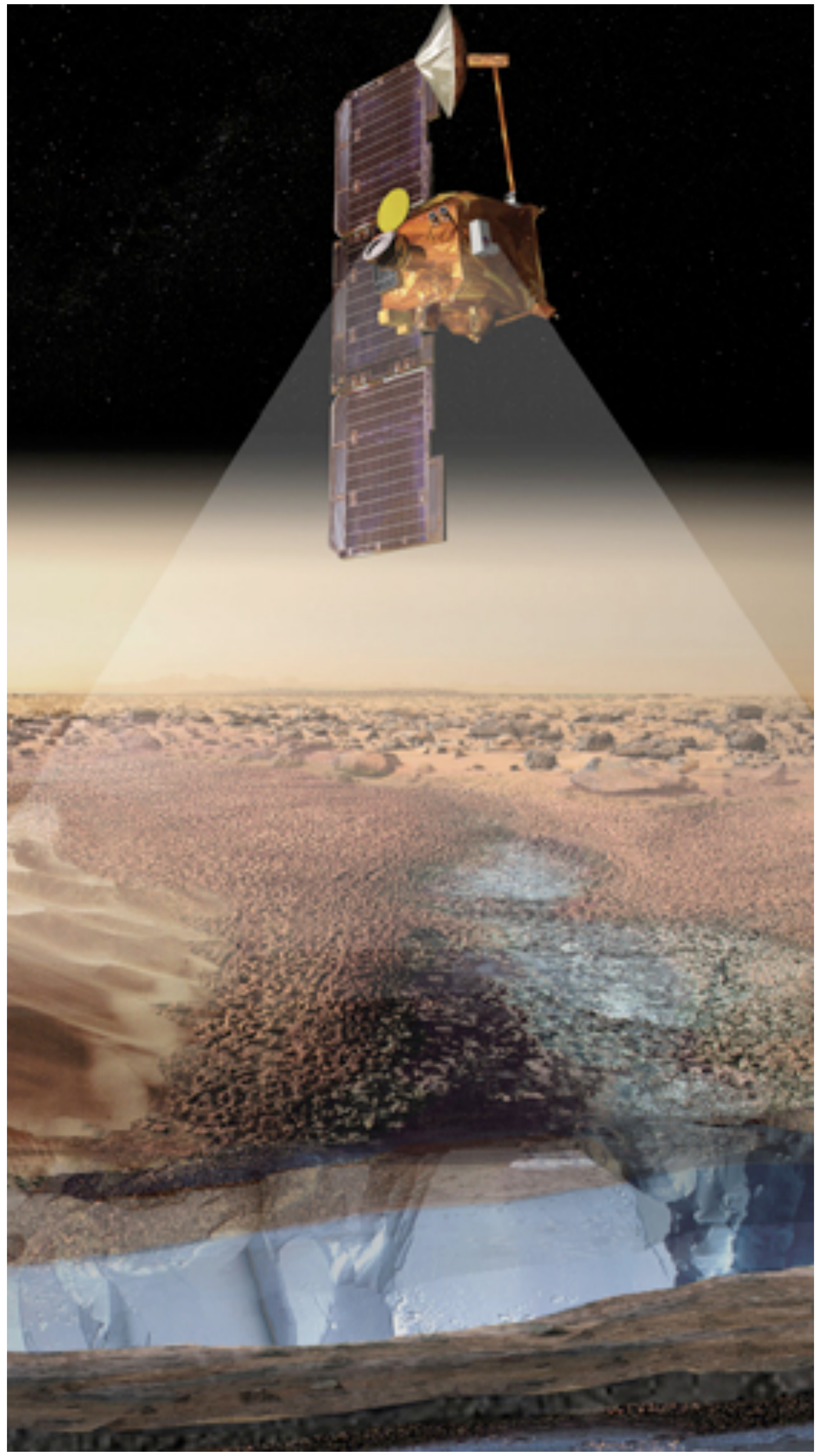
5° during the
e planet.

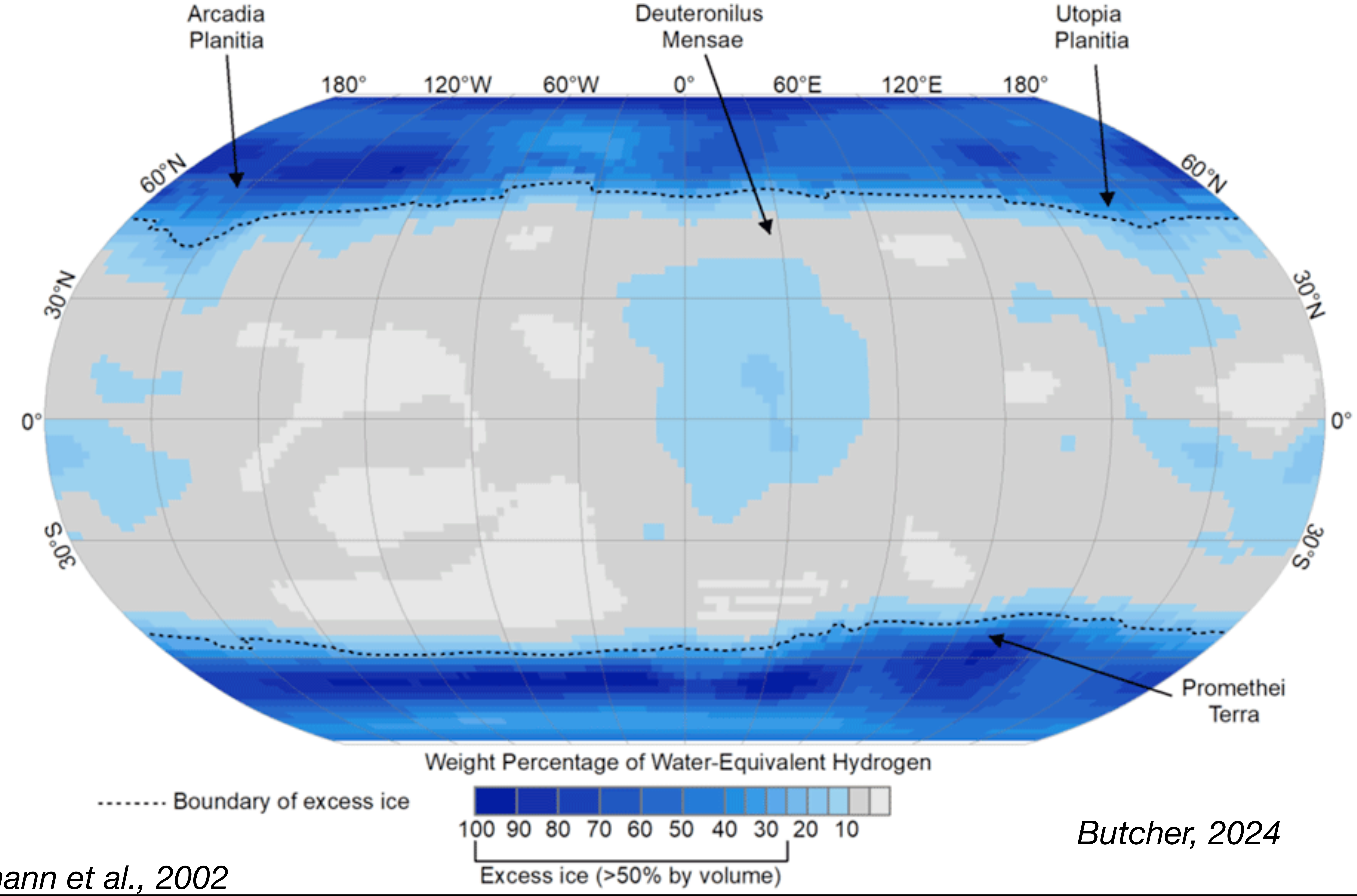
**1st Probelm: Global Climate Model do not predict the formation of the recent ice mantle at mid-latitudes on Mars**

# Water Ice in the Subsurface Detected by MONS



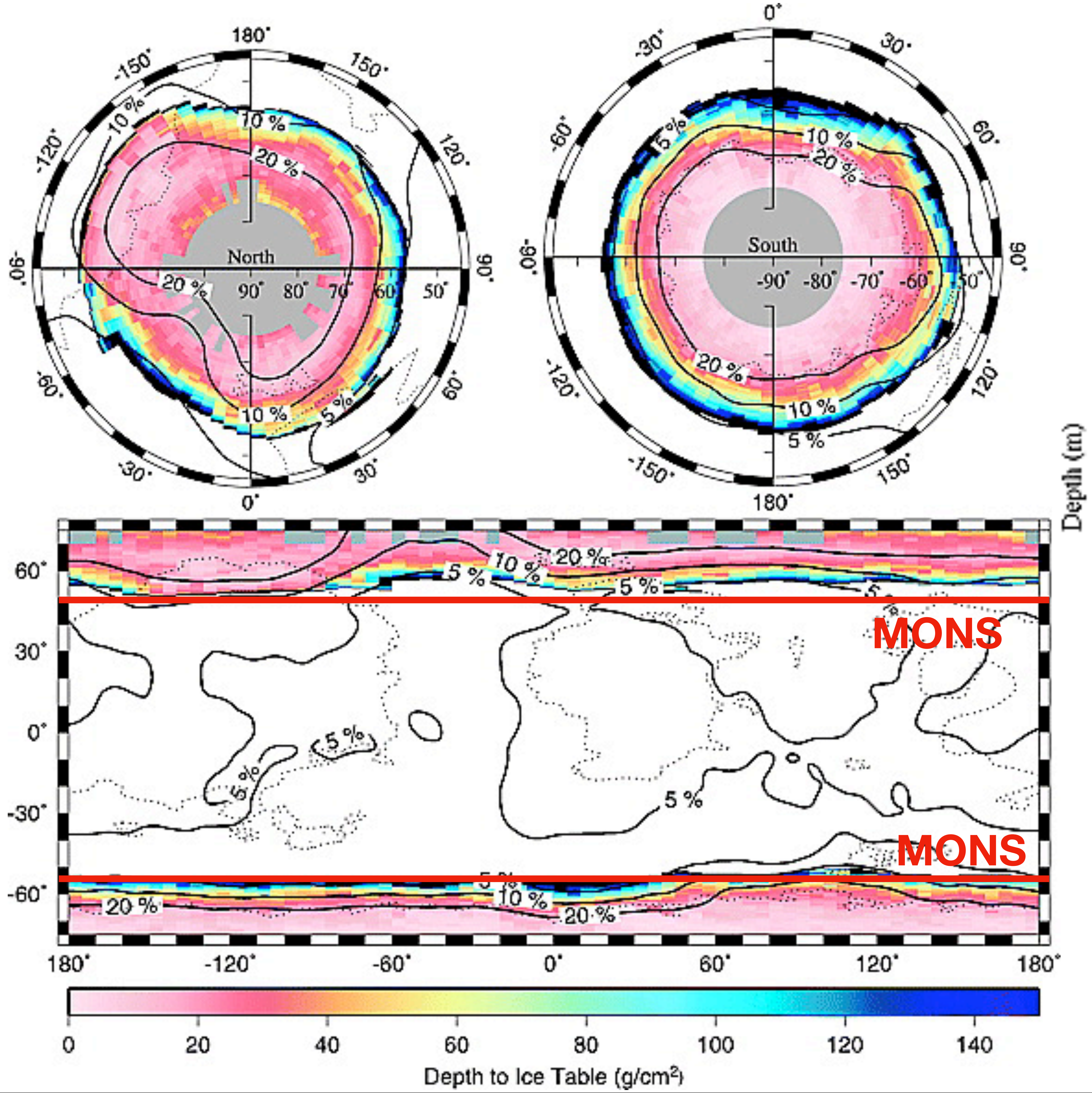
*Credits : NASA*

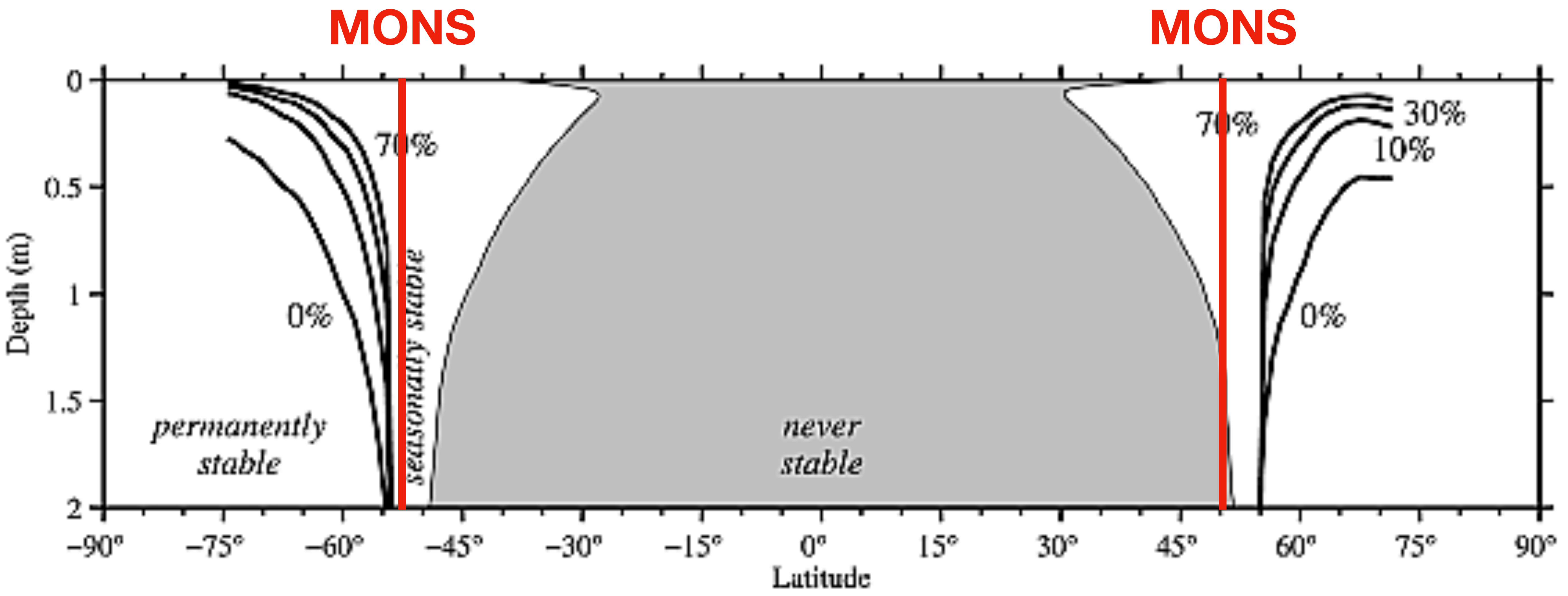
*Boynton et al., Feldmann et al., 2002*




*Butcher, 2024*

# Discovery of Subsurface Ice Excavated by Impacts at Mid-Latitudes




Schorghofer et al., 2005

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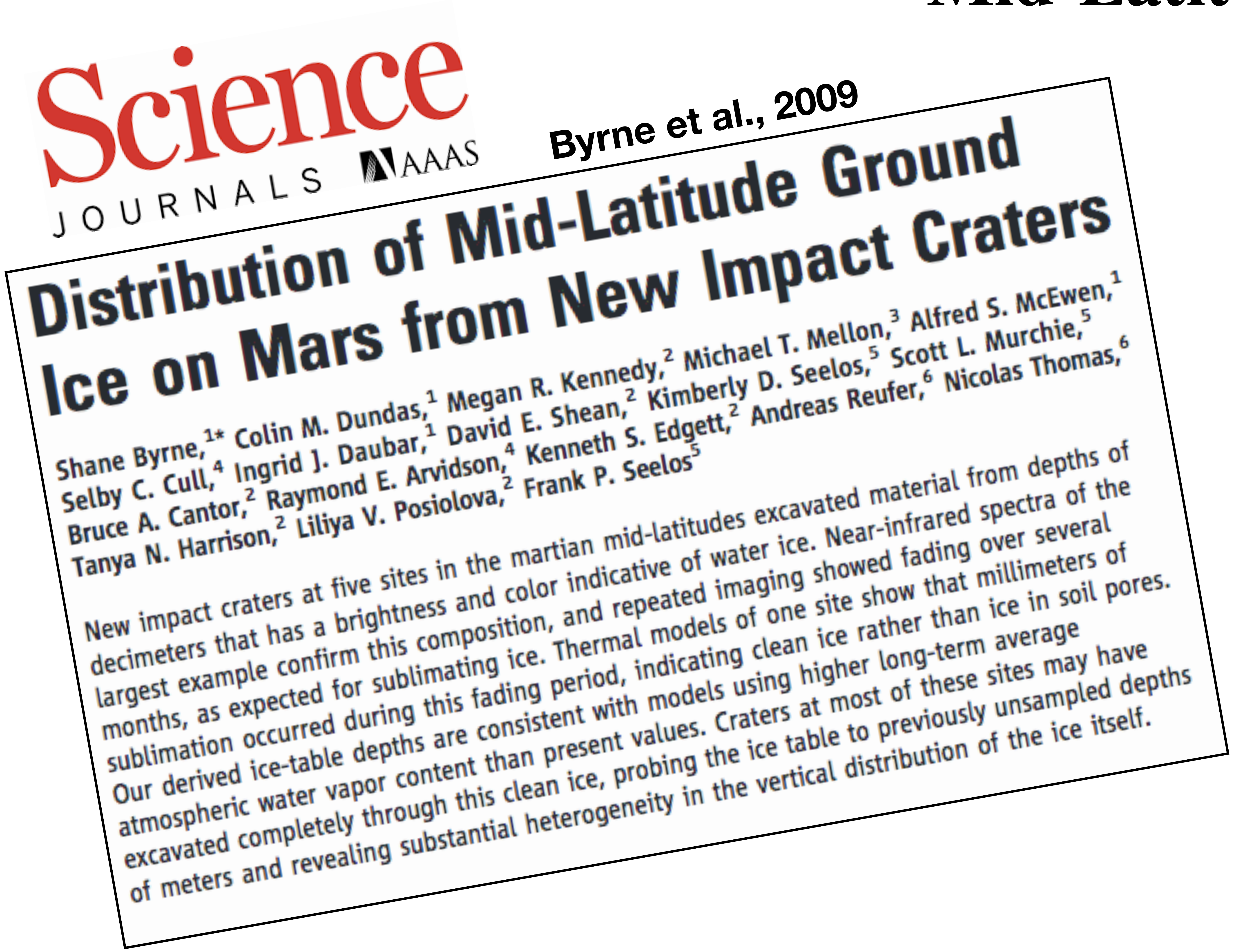
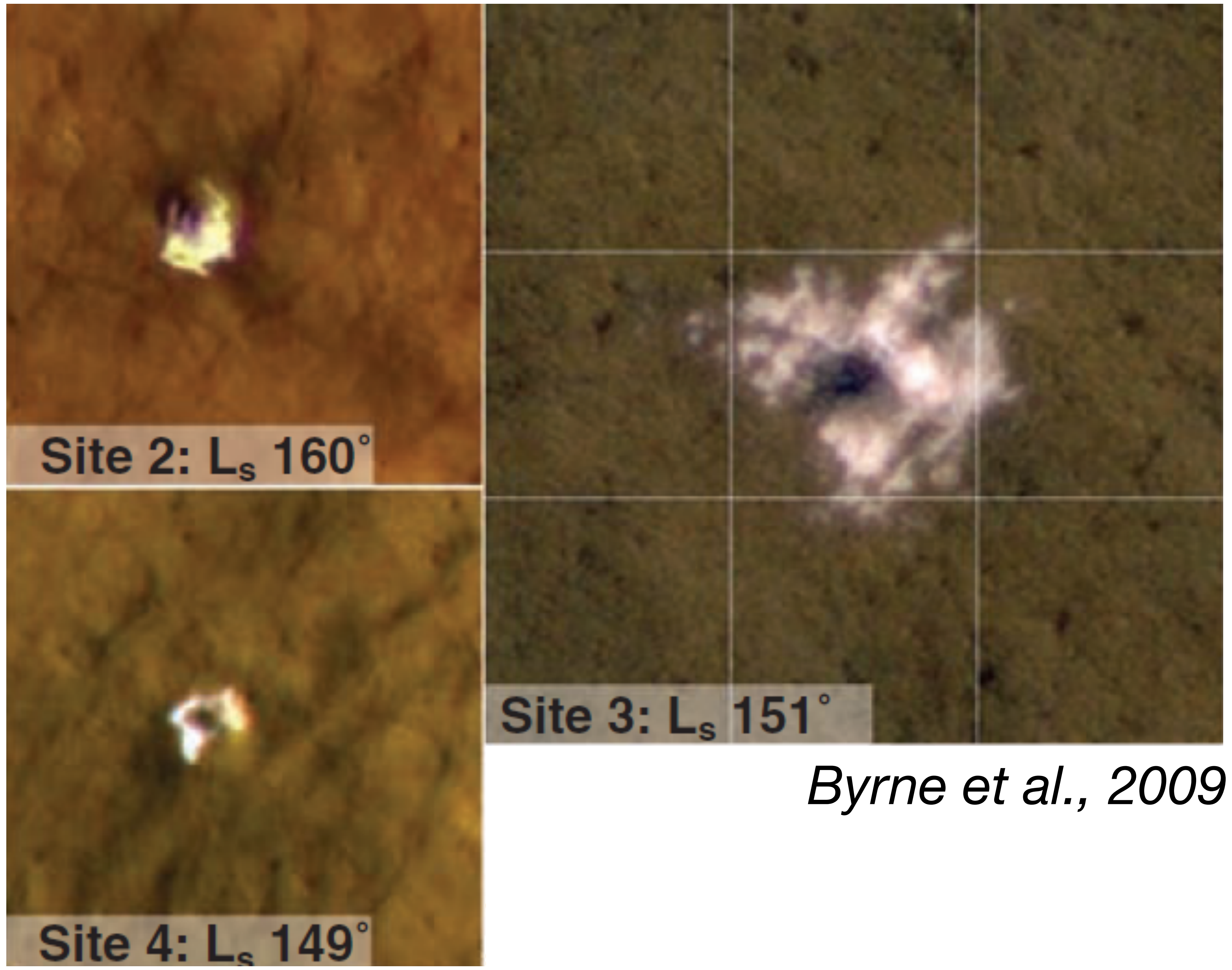
Byrne et al., 2009




## Distribution of Mid-Latitude Ground Ice on Mars from New Impact Craters

Shane Byrne,[1*] Colin M. Dundas,[1] Megan R. Kennedy,[2] Michael T. Mellon,[3] Alfred S. McEwen,[1] Selby C. Cull,[4] Ingrid J. Daubar,[1] David E. Shean,[2] Kimberly D. Seelos,[5] Scott L. Murchie,[5] Bruce A. Cantor,[2] Raymond E. Arvidson,[4] Kenneth S. Edgett,[2] Andreas Reufer,[6] Nicolas Thomas,[6] Tanya N. Harrison,[2] Liliya V. Posiolova,[2] Frank P. Seelos[5]

New impact craters at five sites in the martian mid-latitudes excavated material from depths of decimeters that has a brightness and color indicative of water ice. Near-infrared spectra of the largest example confirm this composition, and repeated imaging showed fading over several months, as expected for sublimating ice. Thermal models of one site show that millimeters of sublimation occurred during this fading period, indicating clean ice rather than ice in soil pores. Our derived ice-table depths are consistent with models using higher long-term average atmospheric water vapor content than present values. Craters at most of these sites may have excavated completely through this clean ice, probing the ice table to previously unsampled depths of meters and revealing substantial heterogeneity in the vertical distribution of the ice itself.

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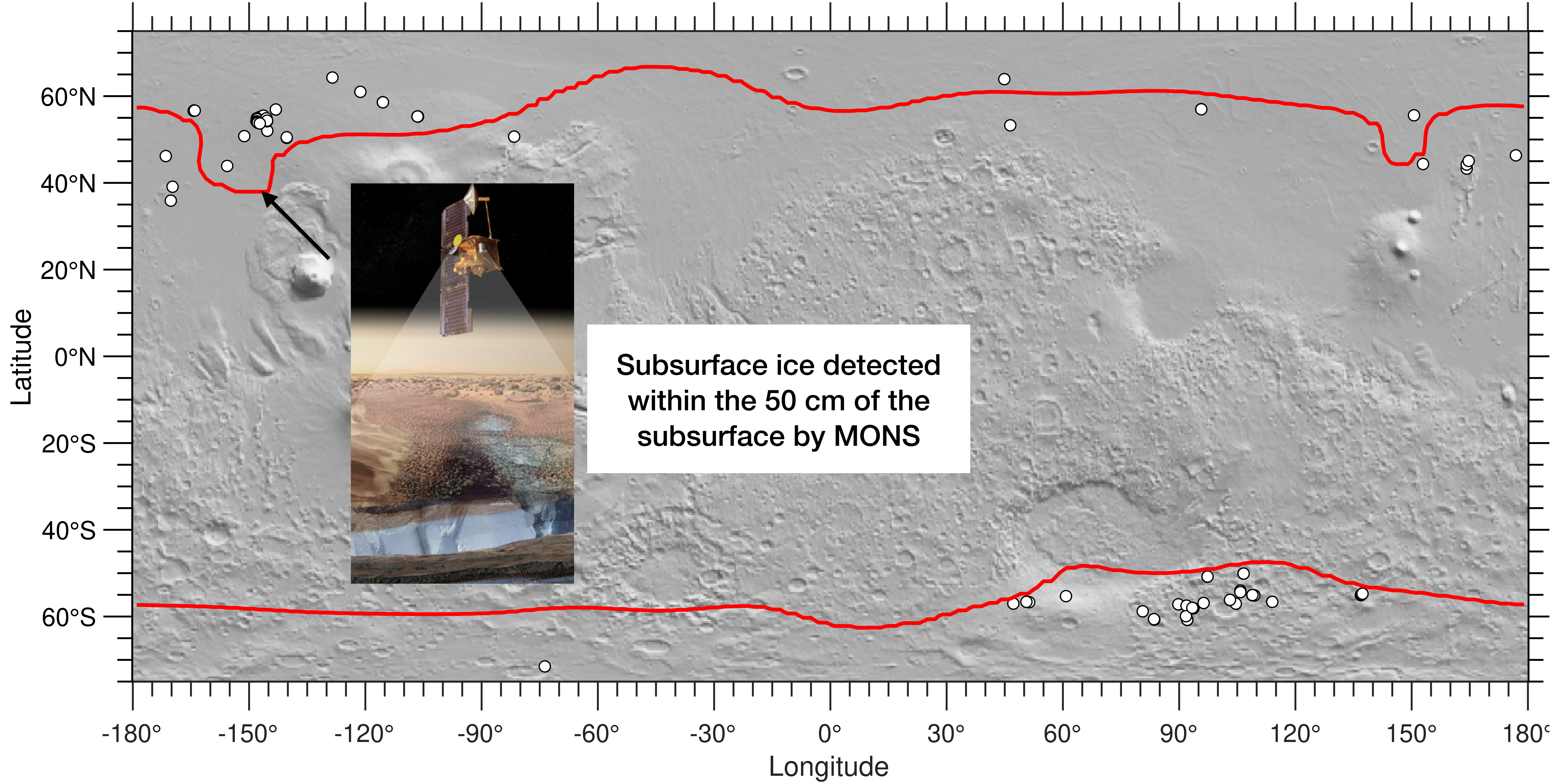

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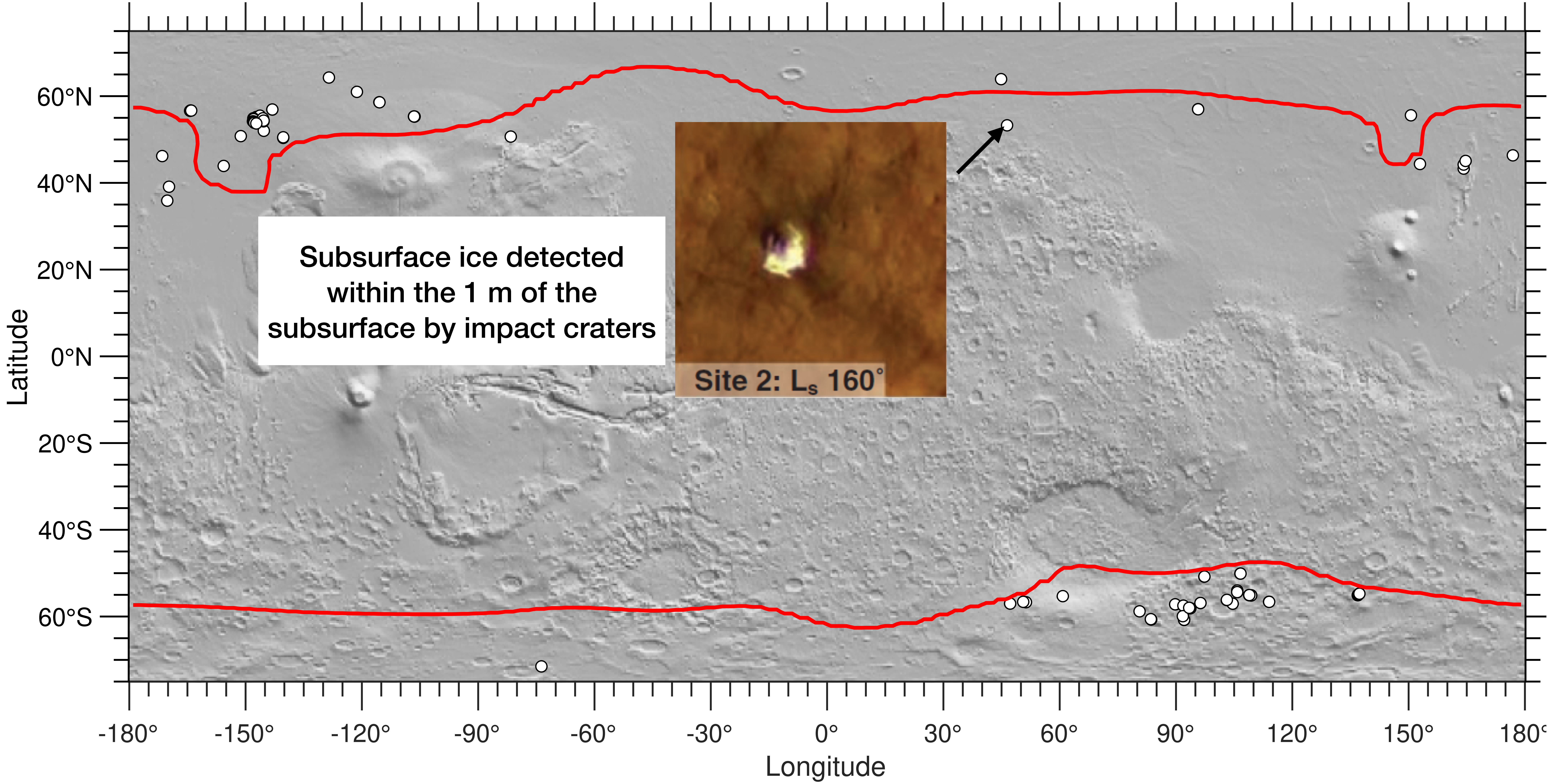

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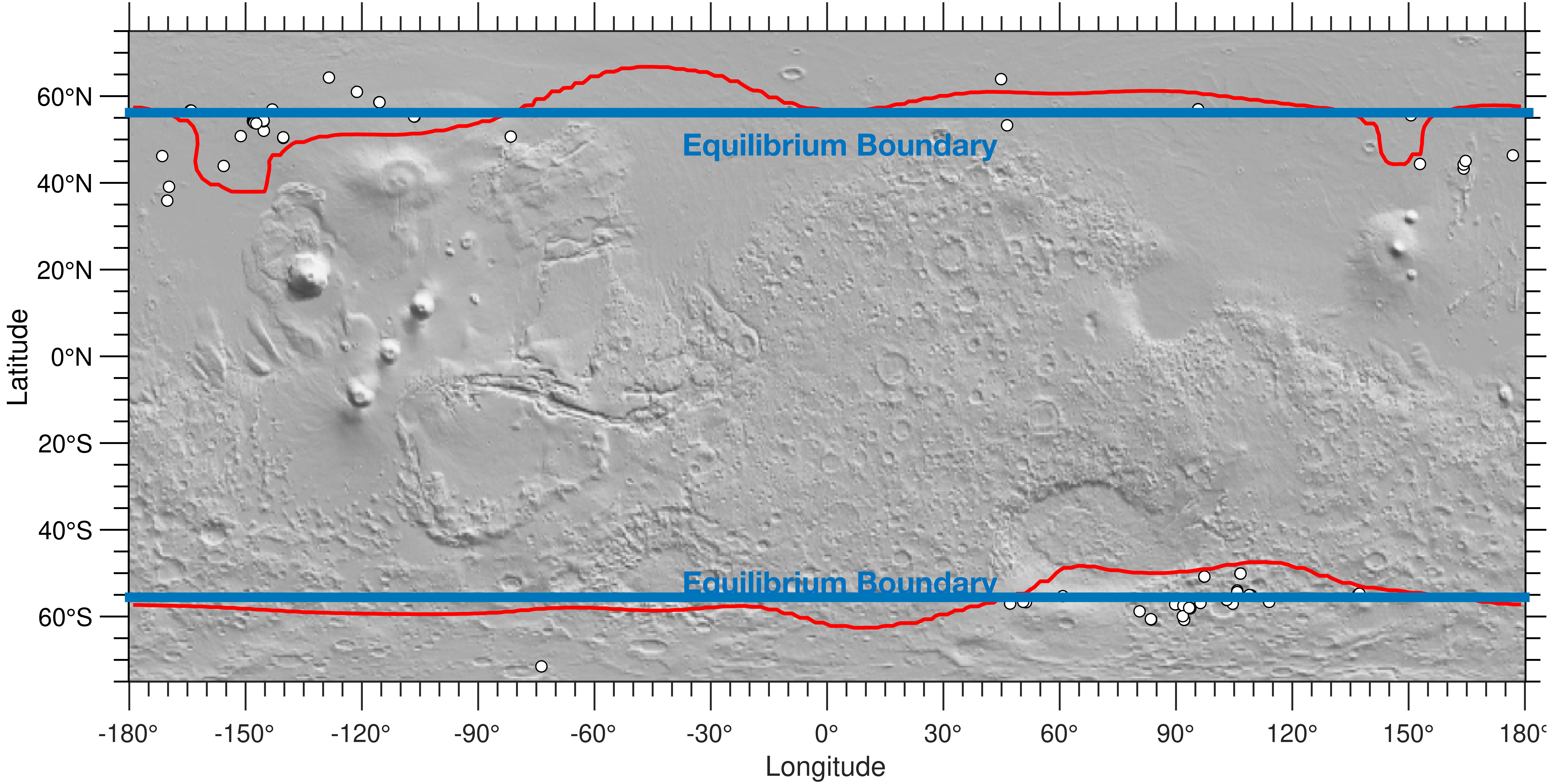

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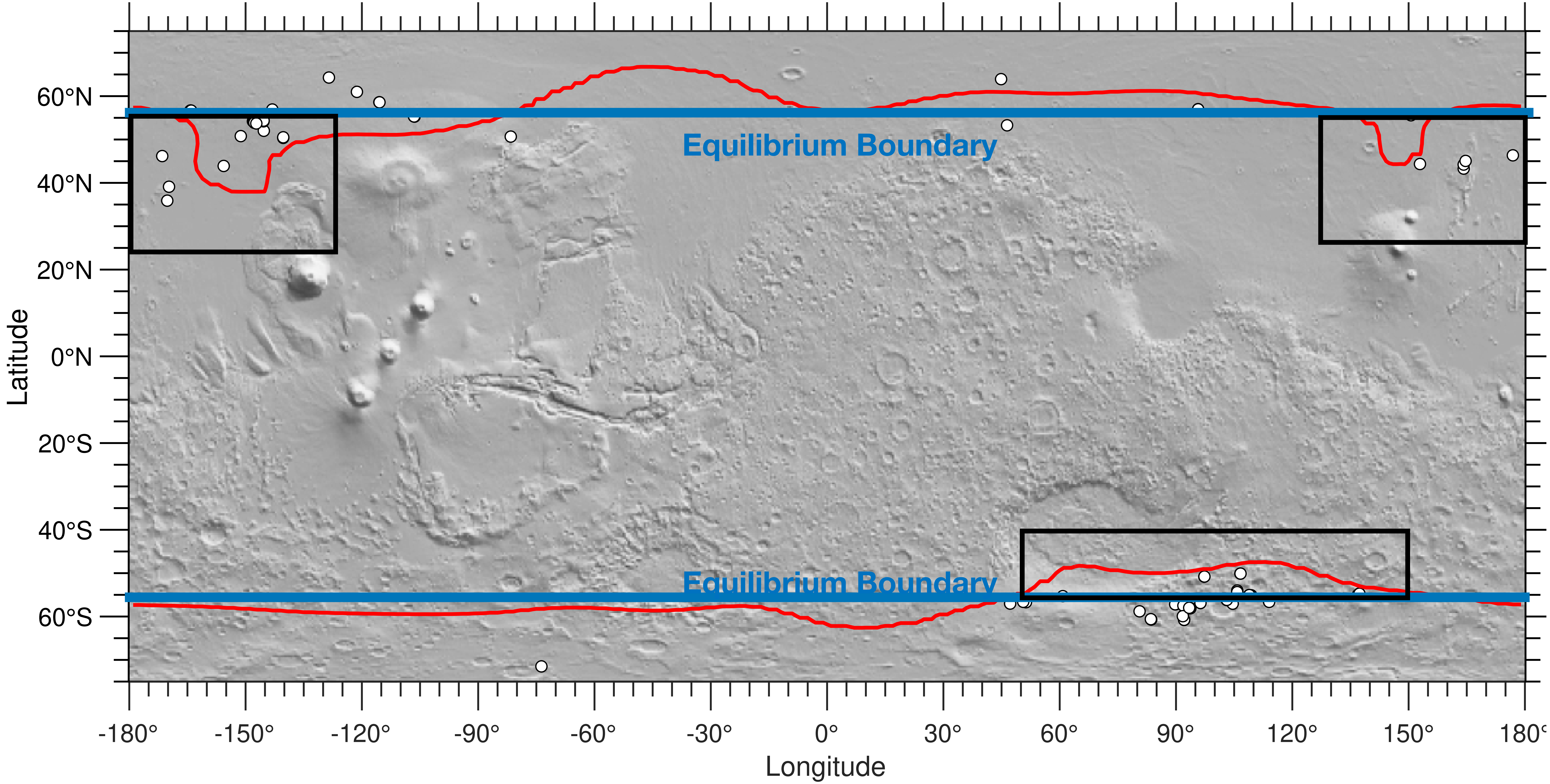

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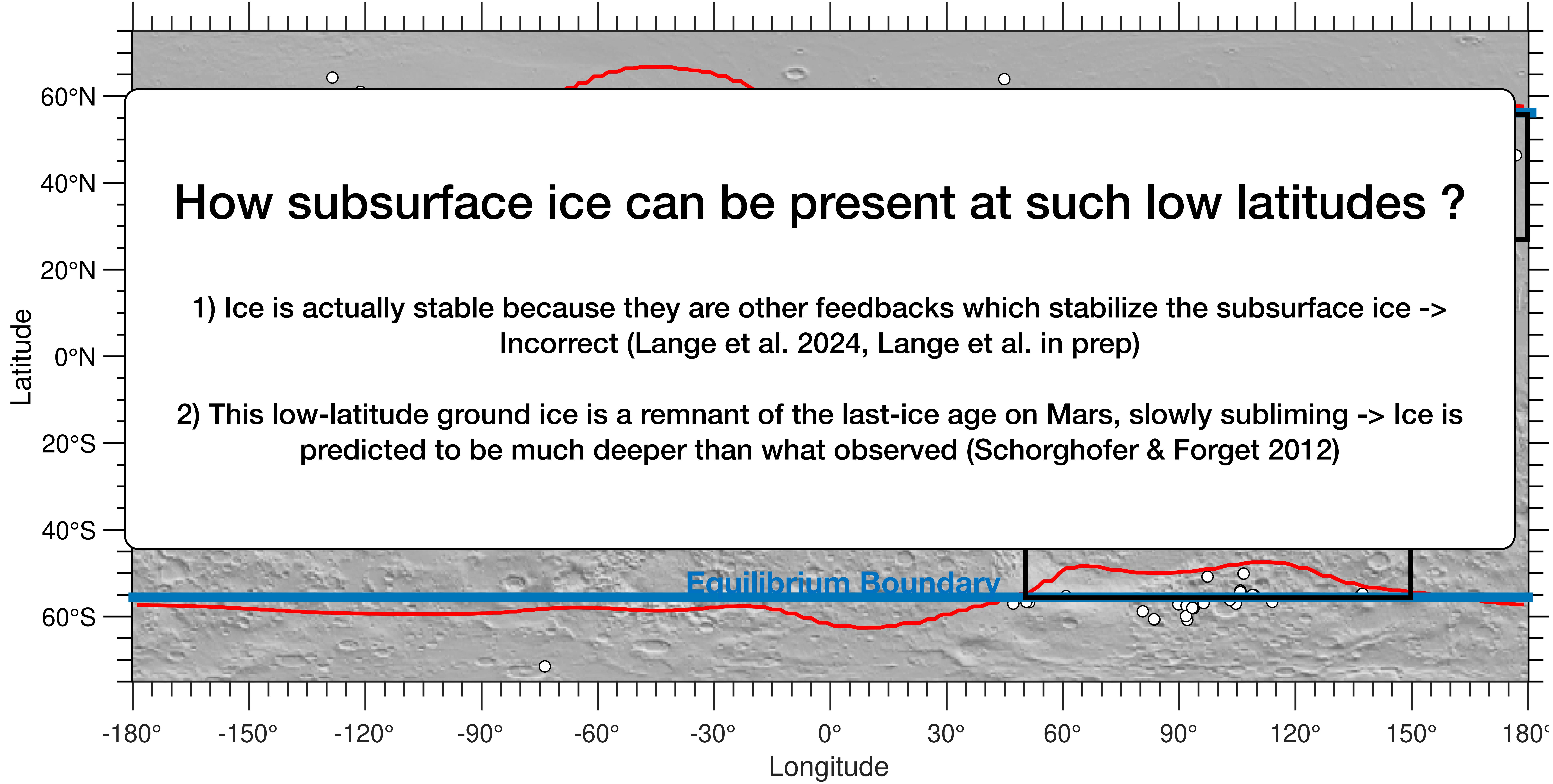
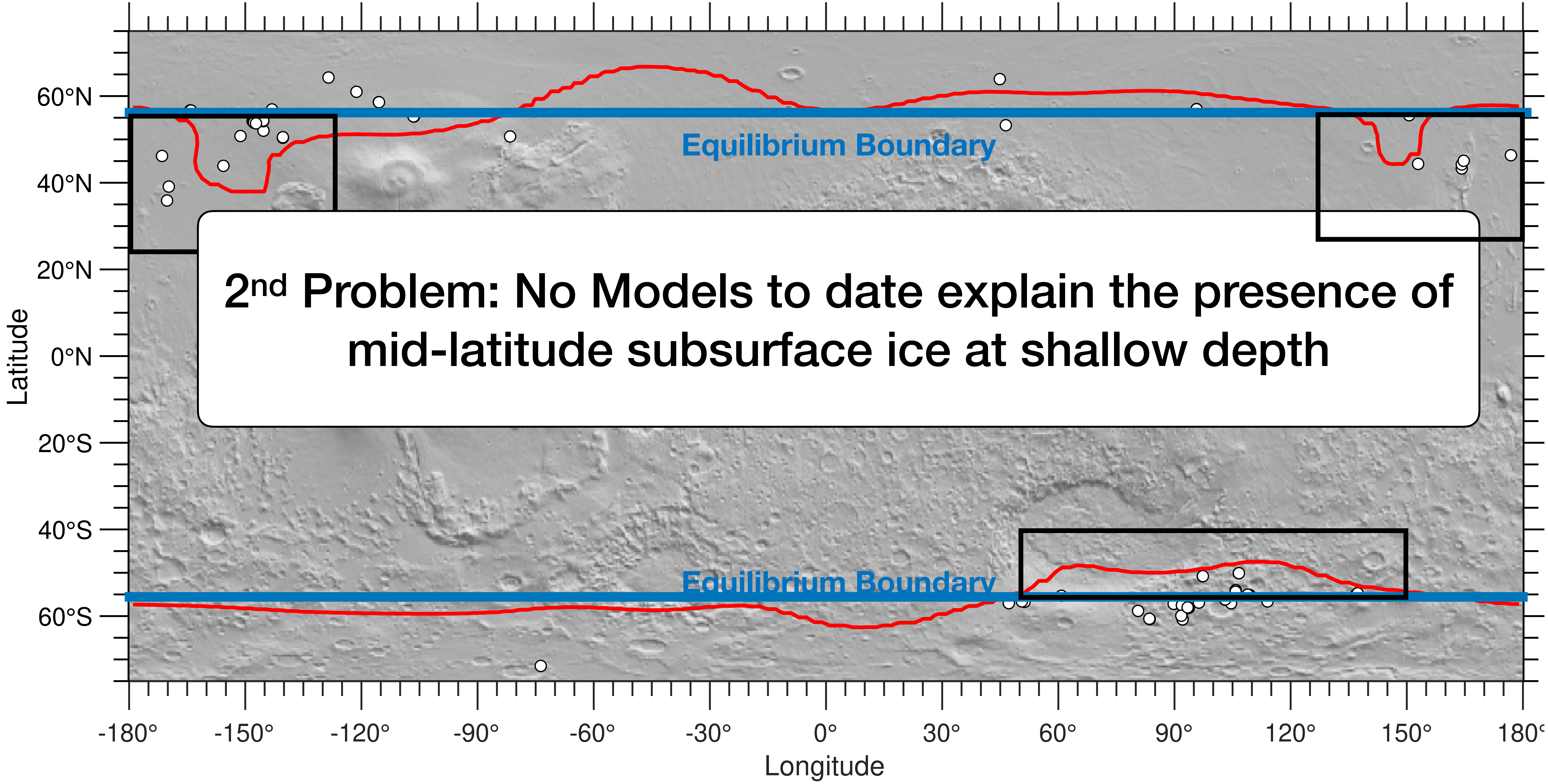



## How subsurface ice can be present at such low latitudes ?

1) Ice is actually stable because they are other feedbacks which stabilize the subsurface ice -> Incorrect (Lange et al. 2024, Lange et al. in prep)

2) This low-latitude ground ice is a remnant of the last-ice age on Mars, slowly subliming -> Ice is predicted to be much deeper than what observed (Schorghofer & Forget 2012)

# Discovery of Subsurface Ice Excavated by Impacts at Mid-Latitudes



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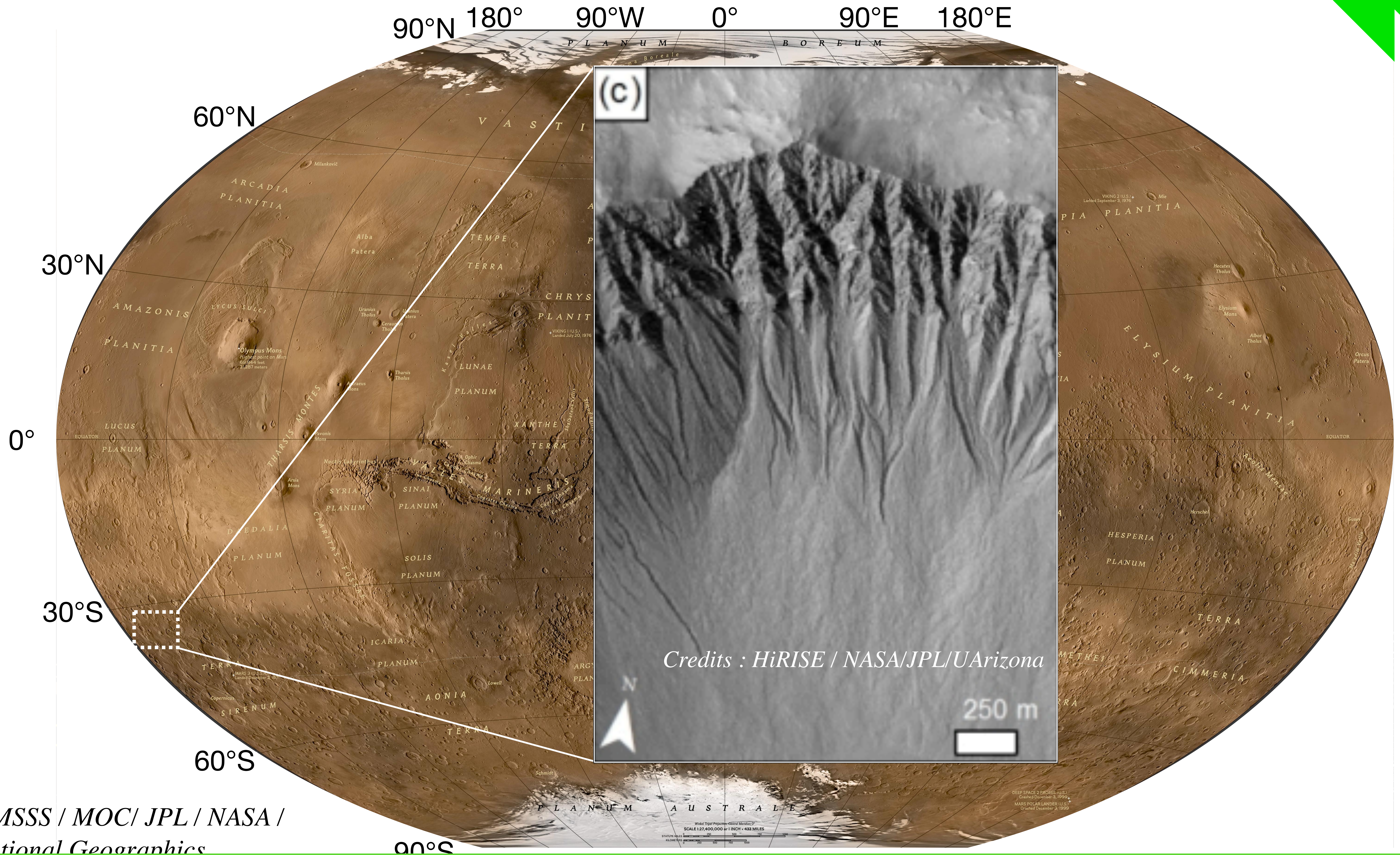


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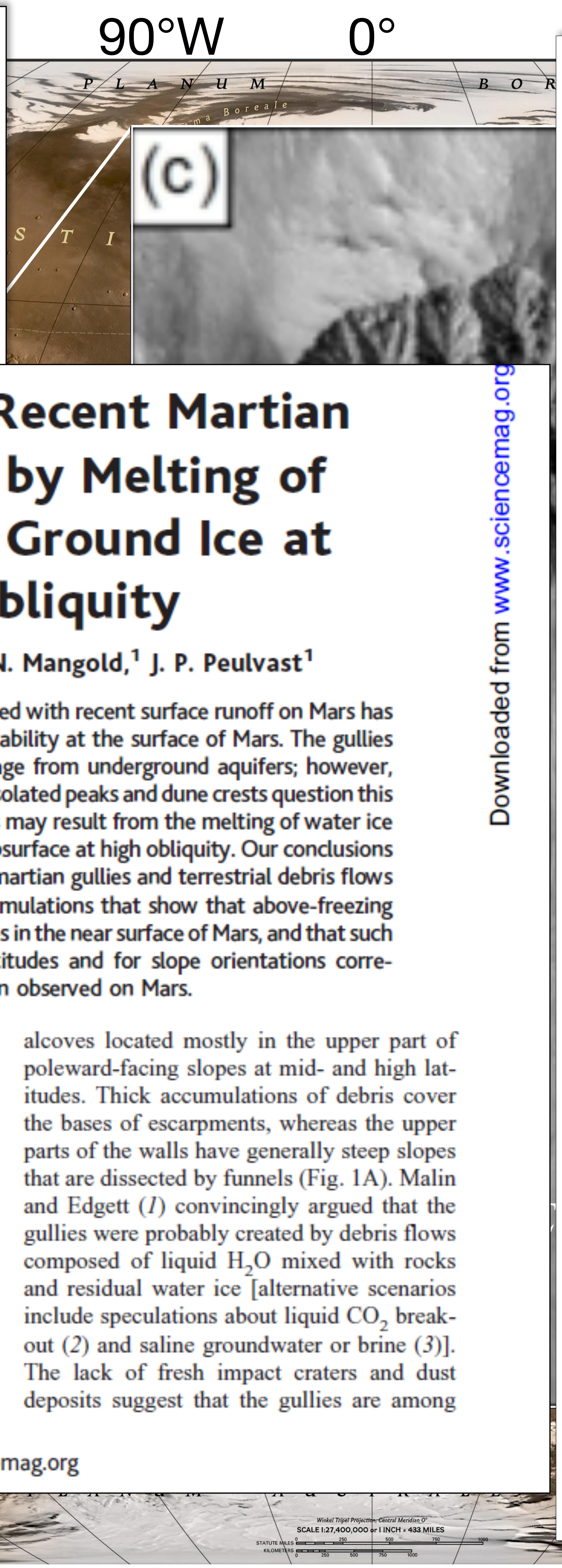


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## Seasonal melting of surface water ice condensing in martian gullies

Konrad J. Kossacki [a,*], Wojciec…
[a] Institute of Geophysics of Warsaw University, Past…
[b] Max-Planck-Institut für Aeronomie, Max-Planck-Str. 2, …

Received 26 May 2003; revised 2…
Available online 14 Augus…

**Abstract**

In this work we consider when and how much liquid water during present … of Mars. These features are usually found on poleward directed slopes. We ana… condenses within the gullies. We follow full annual cycle of condensation an… the heat and mass transport in the soil. During the summer, once the facets of … evaporate. Two mid latitude locations in both hemispheres are considered. The … as the slope of the surface where the gullies appear. It is an extension of the mo… of different sizes, including polygonal features on Mars (Kossacki and Markiew… Sci. 51, 569). We have found, that water ice accumulated during winter can und… of $CO_2$ ice. The amount of liquid water depends on water content in the atmos… to destabilise the slope and cause flow of the surface material. However, eve… important role in surface chemistry, in increasing the cohesive strength of the s… implications.



*Keywords:* Mars; Surface; Water

### 1. Introduction

One of the most intriguing discoveries of the recent high resolution orbiter imaging of the surface of Mars are the numerous gullies on slopes of craters and isolated knobs. The gullies are believed to indicate recent surface flows, presumably of liquid water. Hundreds of these small and young gullies can be found in images of Mars Observer Camera (MOC) aboard Mars Global Surveyor (Malin and Edgett, 2000; Costard et al., 2002). Most recently they have also been imaged by the Mars Odyssey Thermal Emission Imaging System (Christensen, 2003). The gullies are found mostly in mid and high latitudes in both hemispheres. Most of them are found on slopes of craters but they also occur

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doi:10.1016/j.icarus.2004.05.018

## Formation of Recent Martian Debris Flows by Melting of Near-Surface Ground Ice at High Obliquity

F. Costard,[1] F. Forget,[2*] N. Mangold,[1] J. P. Peulvast[1]

**The observation of small gullies associated with recent surface runoff on Mars has renewed the question of liquid water stability at the surface of Mars. The gullies could be formed by groundwater seepage from underground aquifers; however, observations of gullies originating from isolated peaks and dune crests question this scenario. We show that these landforms may result from the melting of water ice in the top few meters of the martian subsurface at high obliquity. Our conclusions are based on the analogy between the martian gullies and terrestrial debris flows observed in Greenland and numerical simulations that show that above-freezing temperatures can occur at high obliquities in the near surface of Mars, and that such temperatures are only predicted at latitudes and for slope orientations corresponding to where the gullies have been observed on Mars.**

The observation of small gullies on Mars was one of the more unexpected discoveries of the Mars Observer Camera (MOC) aboard the Mars Global Surveyor spacecraft (*1*). The characteristics of these landforms suggest the local occurrence of a fluid emanating from alcoves located mostly in the upper part of poleward-facing slopes at mid- and high latitudes. Thick accumulations of debris cover the bases of escarpments, whereas the upper parts of the walls have generally steep slopes that are dissected by funnels (Fig. 1A). Malin and Edgett (*1*) convincingly argued that the gullies were probably created by debris flows composed of liquid $H_2O$ mixed with rocks and residual water ice [alternative scenarios include speculations about liquid $CO_2$ break-out (*2*) and saline groundwater or brine (*3*)]. The lack of fresh impact craters and dust deposits suggest that the gullies are among

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MARTIAN GEOLOGY

## Gullies on Mars could have formed by melting of water ice during periods of high obliquity

J. L. Dickson[*1,2], A. M. Palumbo[2], J. W. Head[2], L. Kerber[3], C. I. Fassett[4]†, M. A. Kreslavsky[5]

Gullies on Mars resemble water-carved channels on Earth, but they are mostly at elevations where liquid water is not expected under current climate conditions. It has been suggested that sublimation of carbon dioxide ice alone could have formed Martian gullies. We used a general circulation model to show that the highest-elevation Martian gullies coincide with the boundary of terrain that experienced pressures above the triple point of water when Mars' rotational axis tilt reached 35°. Those conditions have occurred repeatedly over the past several million years, most recently ~630,000 years ago. Surface water ice, if present at these locations, could have melted when temperatures rose >273 kelvin. We propose a dual gully formation scenario that is driven by melting of water ice followed by carbon dioxide ice sublimation.

Gullies on Mars resemble $H_2O$-carved channels on Earth (*1*). Their concentration at Mars' midlatitudes, where near-surface ice is stable (*1–3*), is consistent with an $H_2O$-melting model for their formation. However, the observed distribution includes elevations where present-day atmospheric pressure is always below the triple point of $H_2O$ (*2, 4*), so solid $H_2O$ ice is expected to sublimate to form vapor rather than melt to form liquid. The seasonal timing of contemporary mobilization of surface material within gullies is consistent with sublimation of solid $CO_2$ (*5, 6*), so it is possible that gullies formed from $CO_2$-mediated processes alone (*7*). However, the mechanism of such a $CO_2$-only process is uncertain and lacks an Earth analog. Repeat orbital imaging shows that present-day erosion of gullies is rare. Although examples have been documented (*5, 6*), erosion of gully channels is minor (Fig. 1A) and infrequent. At high latitudes (>70°), where solid $CO_2$ ice is emplaced and removed every year, ~98.3% of gullies show no activity and none experience channel erosion (*8*).

An alternative possibility is that gullies were incised by small amounts of liquid $H_2O$ during earlier climate conditions that were more conducive to melting of $H_2O$ ice. This scenario would be consistent with the stratigraphy of gully fans (*9, 10*), which indicates cycles of emplacement of fan sediment, fracturing (Fig. 1B), and incision. Mars' axial tilt (obliquity) is known to vary over hundreds of thousands of years (*11*), so earlier periods of higher obliquity could have provided more-favorable climates for liquid $H_2O$. Previous studies have shown that at 35° obliquity, $H_2O$ ice accumulated on midlatitude (30° to 45° in each hemisphere), pole-facing slopes (*11–15*), locations that … contain gullies (*14, 15*). Meanwhile, large … of $CO_2$ ice (currently sequestered in the southern polar ice cap) sublimated (*16*), producing an atmosphere with double its current pressure (*17*). The extent of terrain that experienced conditions capable of hosting liquid $H_2O$ would have been greater at that time than in the present.

### General circulation models

We tested the hypothesis that liquid $H_2O$ was involved in the formation of gullies by investigating whether the mapped locations of gullies (*3*) correlate with the locations of terrain that could host liquid $H_2O$ when Mars experienced 35° obliquity. We used a three-dimensional general circulation model (GCM) of Mars (*13, 18*) to simulate climatic conditions at three obliquities and associated pressures (*16, 17*) that occurred in the past million

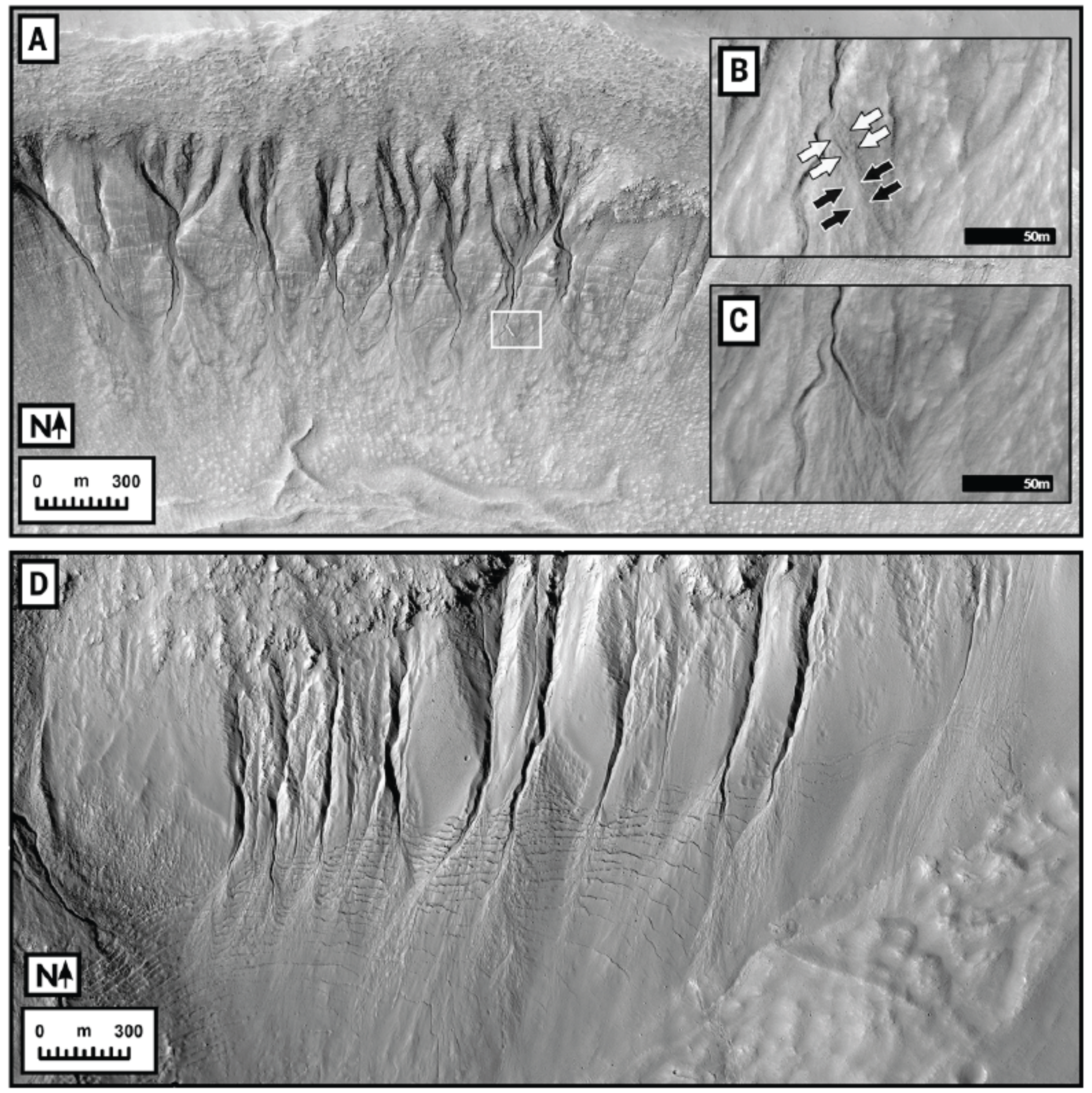


**Fig. 1. Active gullies and gully stratigraphy on Mars.** (A) Orbital image of Terra Sirenum (37.45°S, –137.05°E) showing a gully channel–forming event (*5*). The image was taken with the High Resolution Imaging Science Experiment

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*Credits : MSSS / MOC/ JPL / NASA / National Geographics*

# Some Characteristics of Mars

Science
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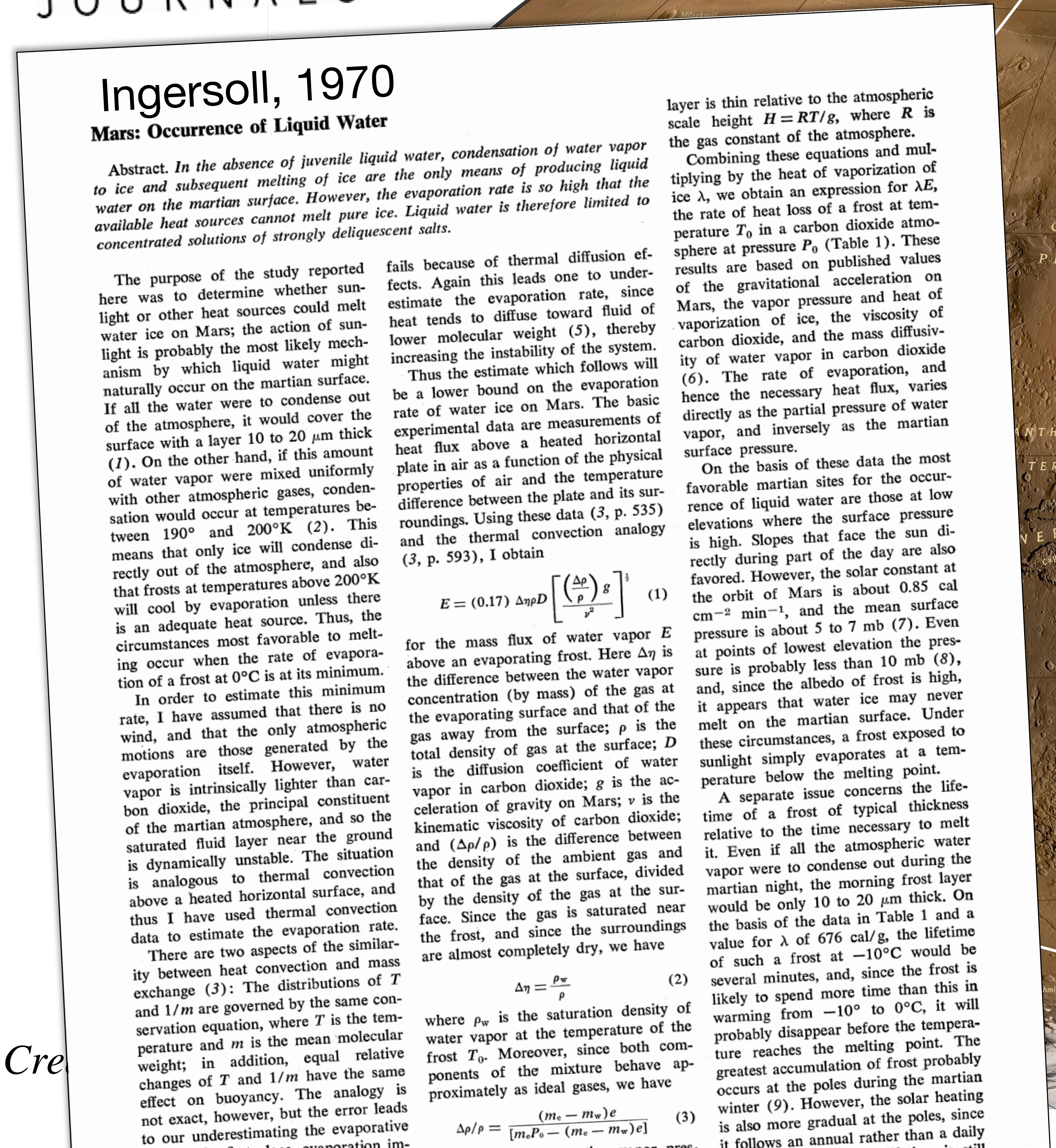

Ingersoll, 1970

**Mars: Occurrence of Liquid Water**

Abstract. *In the absence of juvenile liquid water, condensation of water vapor to ice and subsequent melting of ice are the only means of producing liquid water on the martian surface. However, the evaporation rate is so high that the available heat sources cannot melt pure ice. Liquid water is therefore limited to concentrated solutions of strongly deliquescent salts.*

The purpose of the study reported here was to determine whether sunlight or other heat sources could melt water ice on Mars; the action of sunlight is probably the most likely mechanism by which liquid water might naturally occur on the martian surface. If all the water were to condense out of the atmosphere, it would cover the surface with a layer 10 to 20 μm thick (*1*). On the other hand, if this amount of water vapor were mixed uniformly with other atmospheric gases, condensation would occur at temperatures between 190° and 200°K (*2*). This means that only ice will condense directly out of the atmosphere, and also that frosts at temperatures above 200°K will cool by evaporation unless there is an adequate heat source. Thus, the circumstances most favorable to melting occur when the rate of evaporation of a frost at 0°C is at its minimum.

In order to estimate this minimum rate, I have assumed that there is no wind, and that the only atmospheric motions are those generated by the evaporation itself. However, water vapor is intrinsically lighter than carbon dioxide, the principal constituent of the martian atmosphere, and so the saturated fluid layer near the ground is dynamically unstable. The situation is analogous to thermal convection above a heated horizontal surface, and thus I have used thermal convection data to estimate the evaporation rate.

There are two aspects of the similarity between heat convection and mass exchange (*3*): The distributions of $T$ and $1/m$ are governed by the same conservation equation, where $T$ is the temperature and $m$ is the mean molecular weight; in addition, equal relative changes of $T$ and $1/m$ have the same effect on buoyancy. The analogy is not exact, however, but the error leads to our underestimating the evaporative

fails because of thermal diffusion effects. Again this leads one to underestimate the evaporation rate, since heat tends to diffuse toward fluid of lower molecular weight (*5*), thereby increasing the instability of the system.

Thus the estimate which follows will be a lower bound on the evaporation rate of water ice on Mars. The basic experimental data are measurements of heat flux above a heated horizontal plate in air as a function of the physical properties of air and the temperature difference between the plate and its surroundings. Using these data (*3*, p. 535) and the thermal convection analogy (*3*, p. 593), I obtain

$$E = (0.17)\ \Delta\eta\rho D\left[\frac{\left(\frac{\Delta\rho}{\rho}\right)g}{\nu^2}\right]^{1/3} \quad (1)$$

for the mass flux of water vapor $E$ above an evaporating frost. Here $\Delta\eta$ is the difference between the water vapor concentration (by mass) of the gas at the evaporating surface and that of the gas away from the surface; $\rho$ is the total density of gas at the surface; $D$ is the diffusion coefficient of water vapor in carbon dioxide; $g$ is the acceleration of gravity on Mars; $\nu$ is the kinematic viscosity of carbon dioxide; and $(\Delta\rho/\rho)$ is the difference between the density of the ambient gas and that of the gas at the surface, divided by the density of the gas at the surface. Since the gas is saturated near the frost, and since the surroundings are almost completely dry, we have

$$\Delta\eta = \frac{\rho_w}{\rho} \quad (2)$$

where $\rho_w$ is the saturation density of water vapor at the temperature of the frost $T_0$. Moreover, since both components of the mixture behave approximately as ideal gases, we have

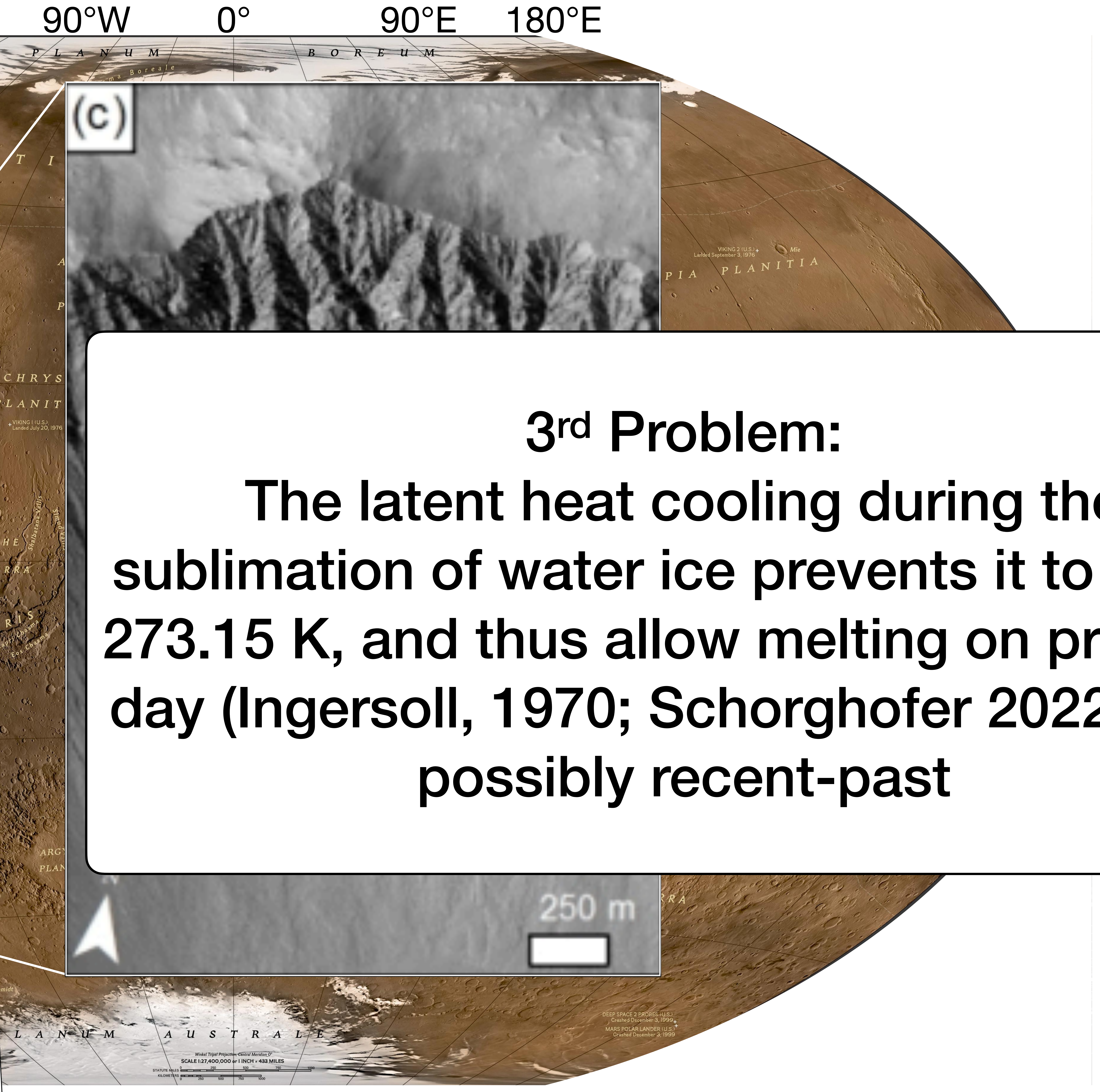
$$\Delta\rho/\rho = \frac{(m_c - m_w)e}{[m_cP_0 - (m_c - m_w)e]} \quad (3)$$

layer is thin relative to the atmospheric scale height $H = RT/g$, where $R$ is the gas constant of the atmosphere.

Combining these equations and multiplying by the heat of vaporization of ice $\lambda$, we obtain an expression for $\lambda E$, the rate of heat loss of a frost at temperature $T_0$ in a carbon dioxide atmosphere at pressure $P_0$ (Table 1). These results are based on published values of the gravitational acceleration on Mars, the vapor pressure and heat of vaporization of ice, the viscosity of carbon dioxide, and the mass diffusivity of water vapor in carbon dioxide (*6*). The rate of evaporation, and hence the necessary heat flux, varies directly as the partial pressure of water vapor, and inversely as the martian surface pressure.

On the basis of these data the most favorable martian sites for the occurrence of liquid water are those at low elevations where the surface pressure is high. Slopes that face the sun directly during part of the day are also favored. However, the solar constant at the orbit of Mars is about 0.85 cal $cm^{-2}$ $min^{-1}$, and the mean surface pressure is about 5 to 7 mb (*7*). Even at points of lowest elevation the pressure is probably less than 10 mb (*8*), and, since the albedo of frost is high, it appears that water ice may never melt on the martian surface. Under these circumstances, a frost exposed to sunlight simply evaporates at a temperature below the melting point.

A separate issue concerns the lifetime of a frost of typical thickness relative to the time necessary to melt it. Even if all the atmospheric water vapor were to condense out during the martian night, the morning frost layer would be only 10 to 20 μm thick. On the basis of the data in Table 1 and a value for $\lambda$ of 676 cal/g, the lifetime of such a frost at −10°C would be several minutes, and, since the frost is likely to spend more time than this in warming from −10° to 0°C, it will probably disappear before the temperature reaches the melting point. The greatest accumulation of frost probably occurs at the poles during the martian winter (*9*). However, the solar heating is also more gradual at the poles, since it follows an annual rather than a daily




3rd Problem:
The latent heat cooling during the sublimation of water ice prevents it to reach 273.15 K, and thus allow melting on present-day (Ingersoll, 1970; Schorghofer 2022), and possibly recent-past

*Cre*

# Outline

# What can explain the discrepeancies between the models and the observations?

1. **Some key mechanisms are missing**

2. **The models can not capture some microclimates conductive to ice accumulation/melting**

3. **???**

*Credits : HiRISE / NASA/JPL/UArizona*

# Key mechanisms are missing: the effect of water ice cloud

Geophysical Research Letters

Research Letter | Free Access

**Recent Ice Ages on Mars: The role of radiatively active clouds and cloud microphysics**

J.-B. Madeleine, J. W. Head, F. Forget, T. Navarro, E. Millour, A. Spiga, A. Colaïtis, A. Määttänen, F. Montmessin, J. L. Dickson

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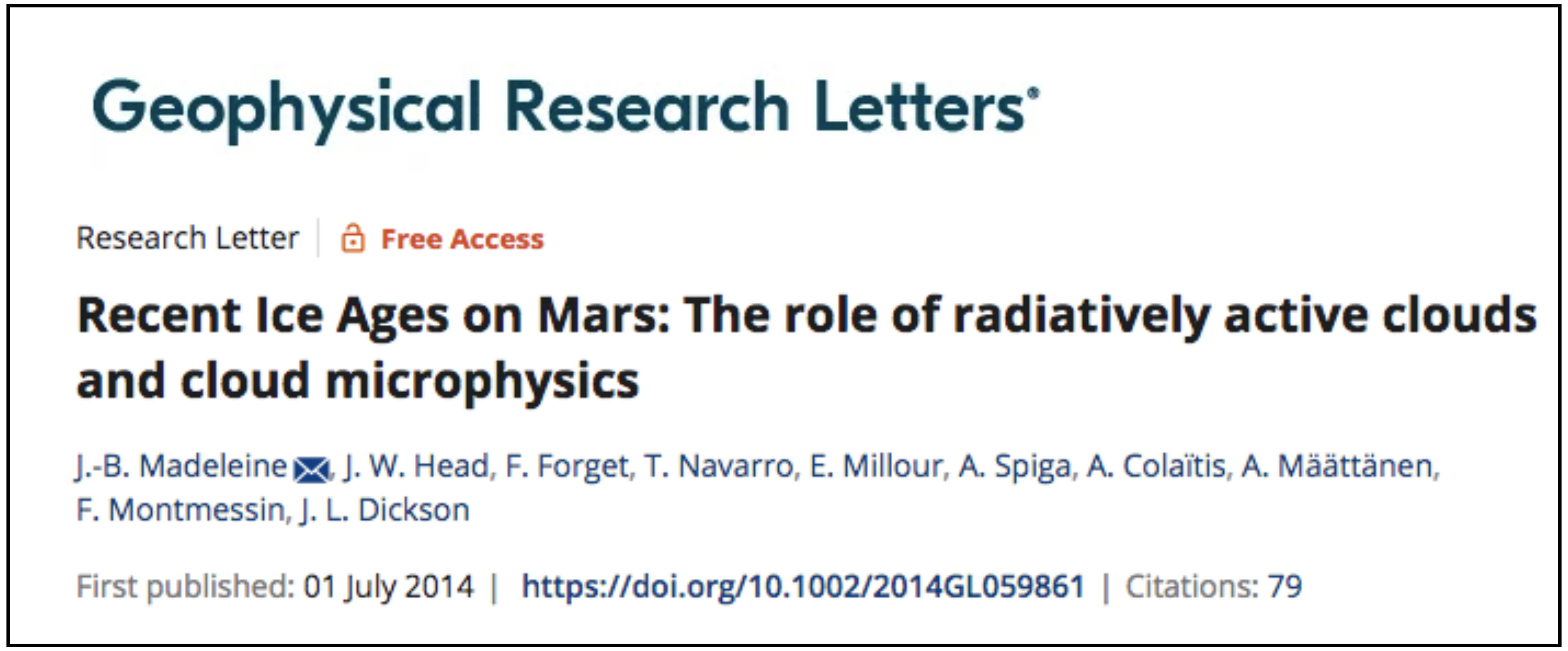
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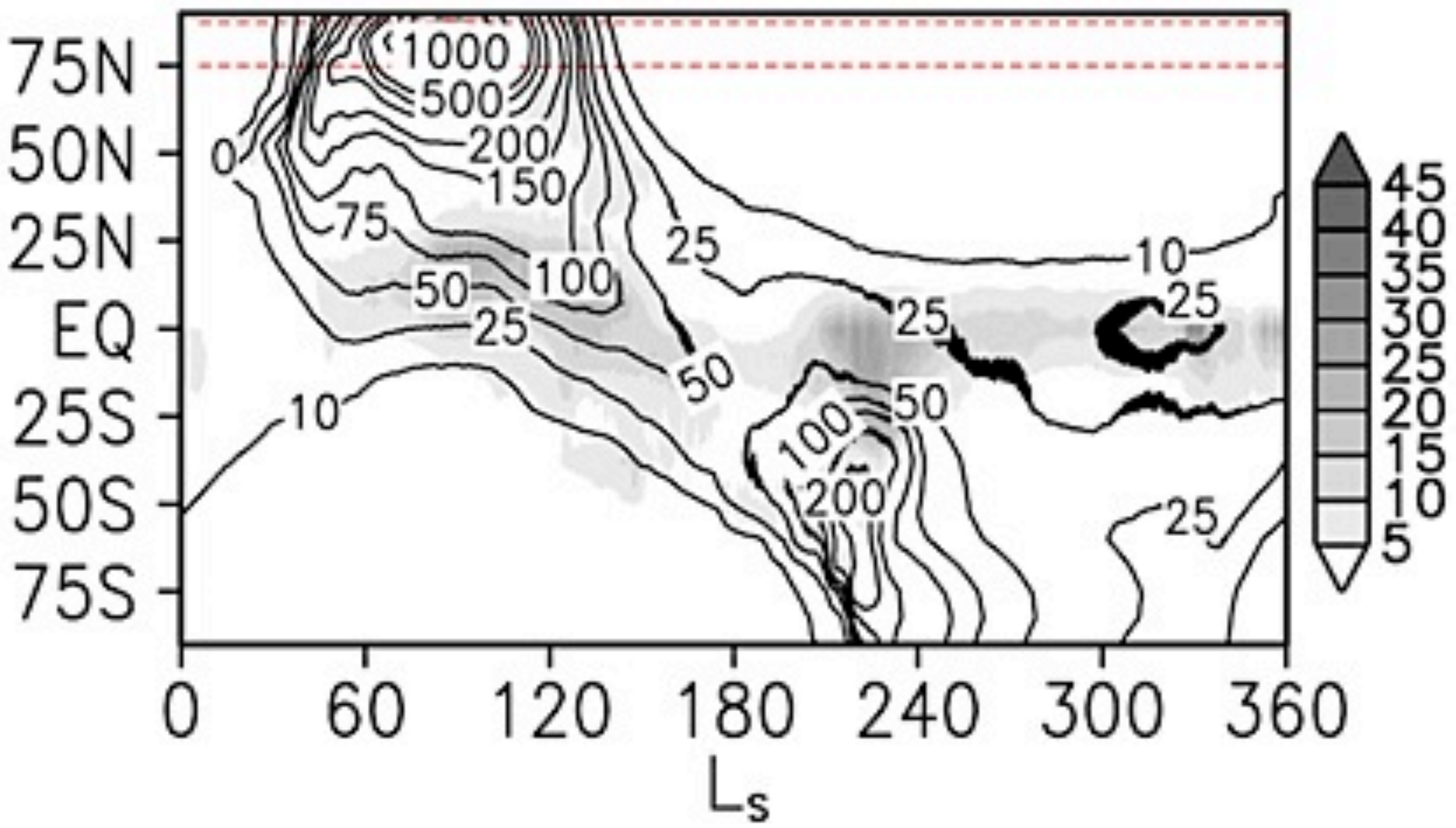


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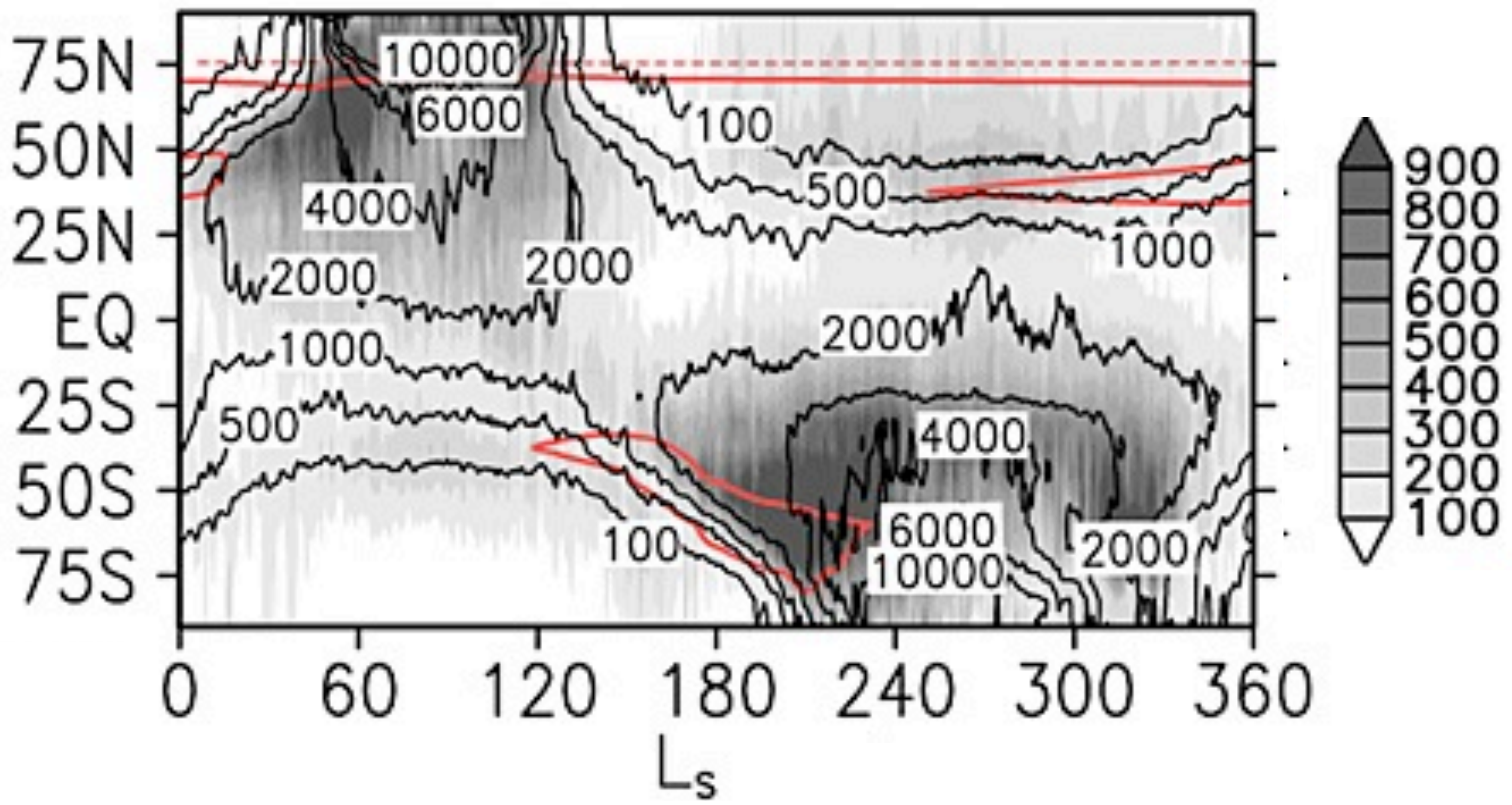

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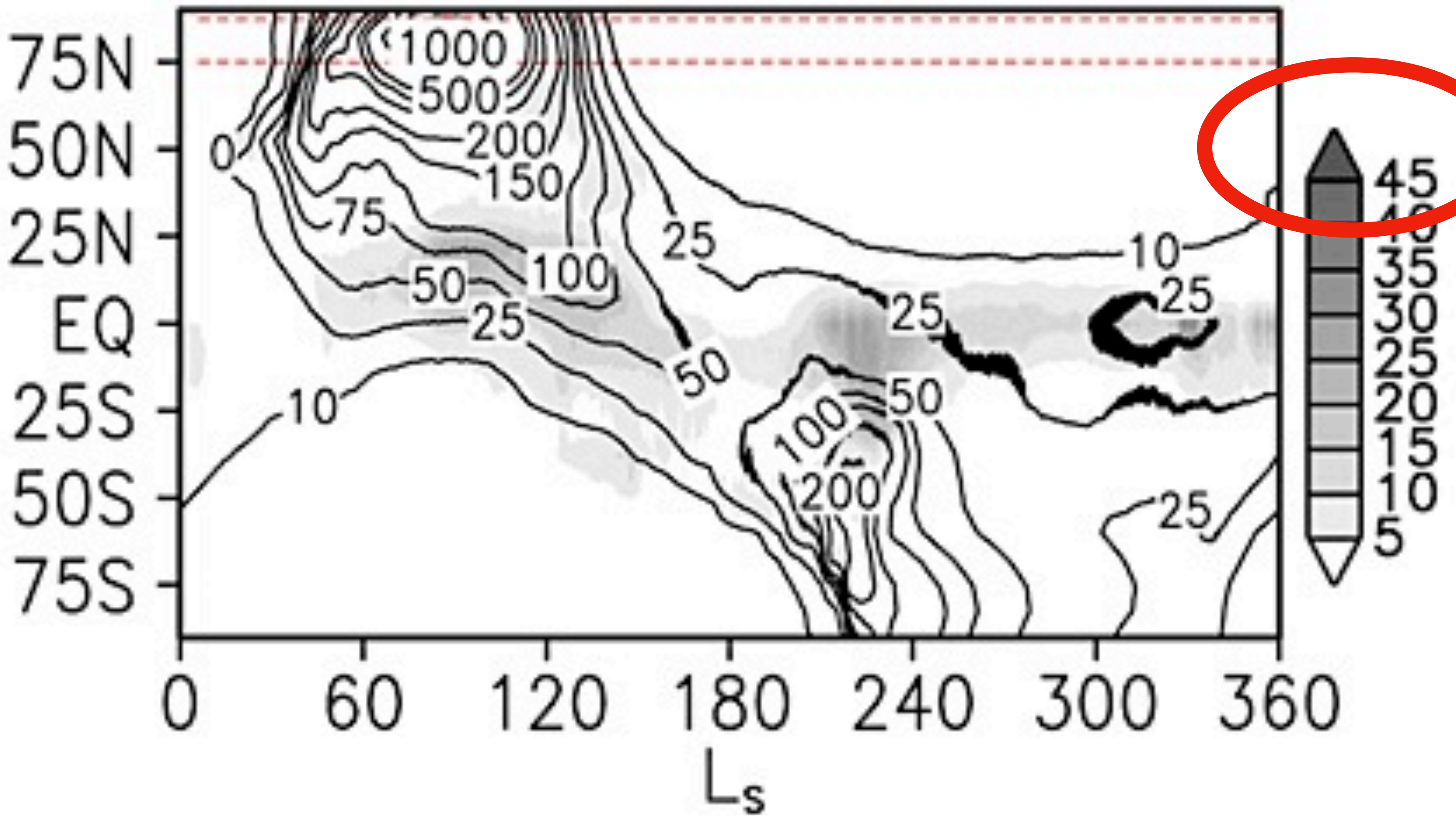


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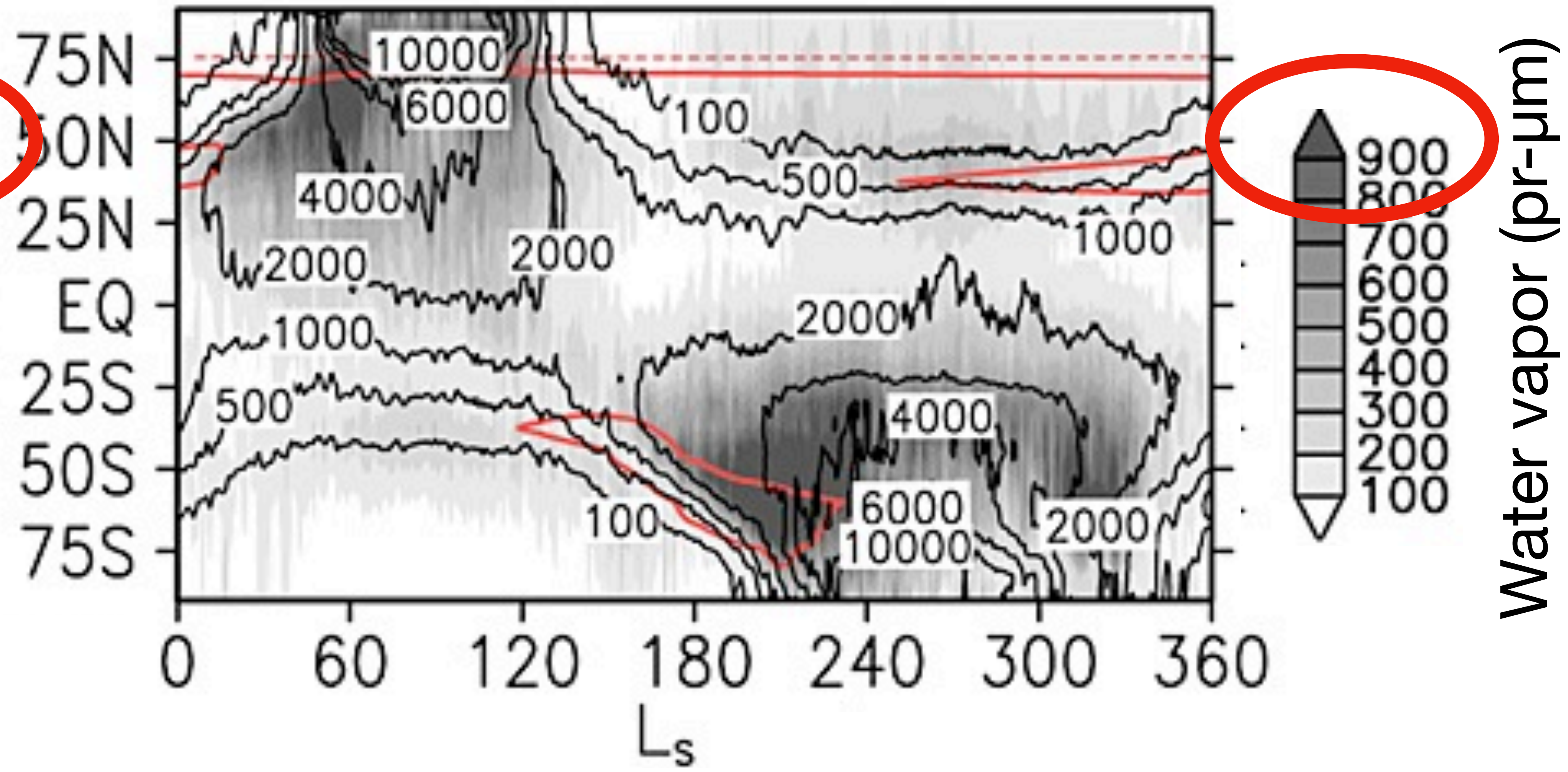
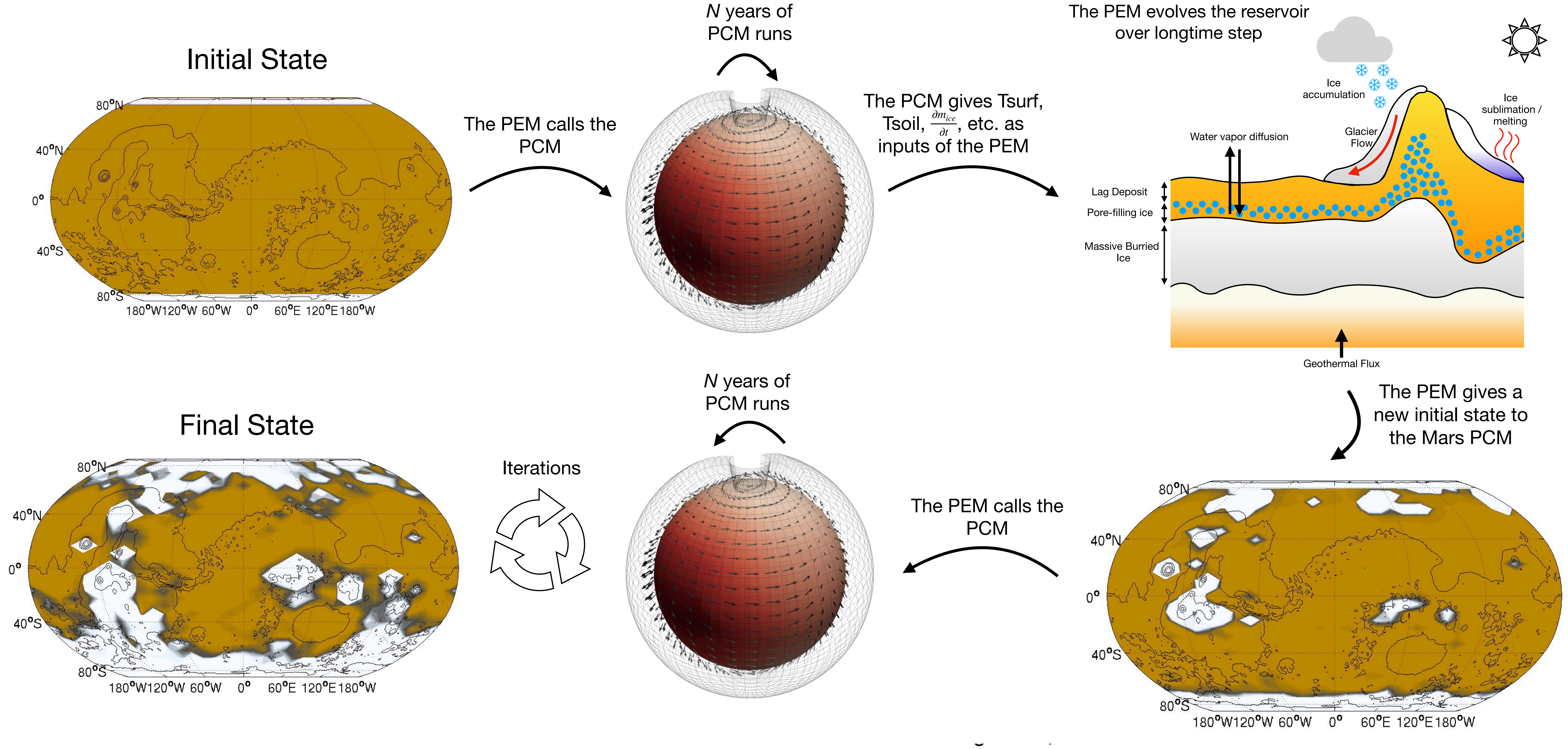


# Modeling Martian Paleoclimates: The Planetary Evolution Model (PEM)



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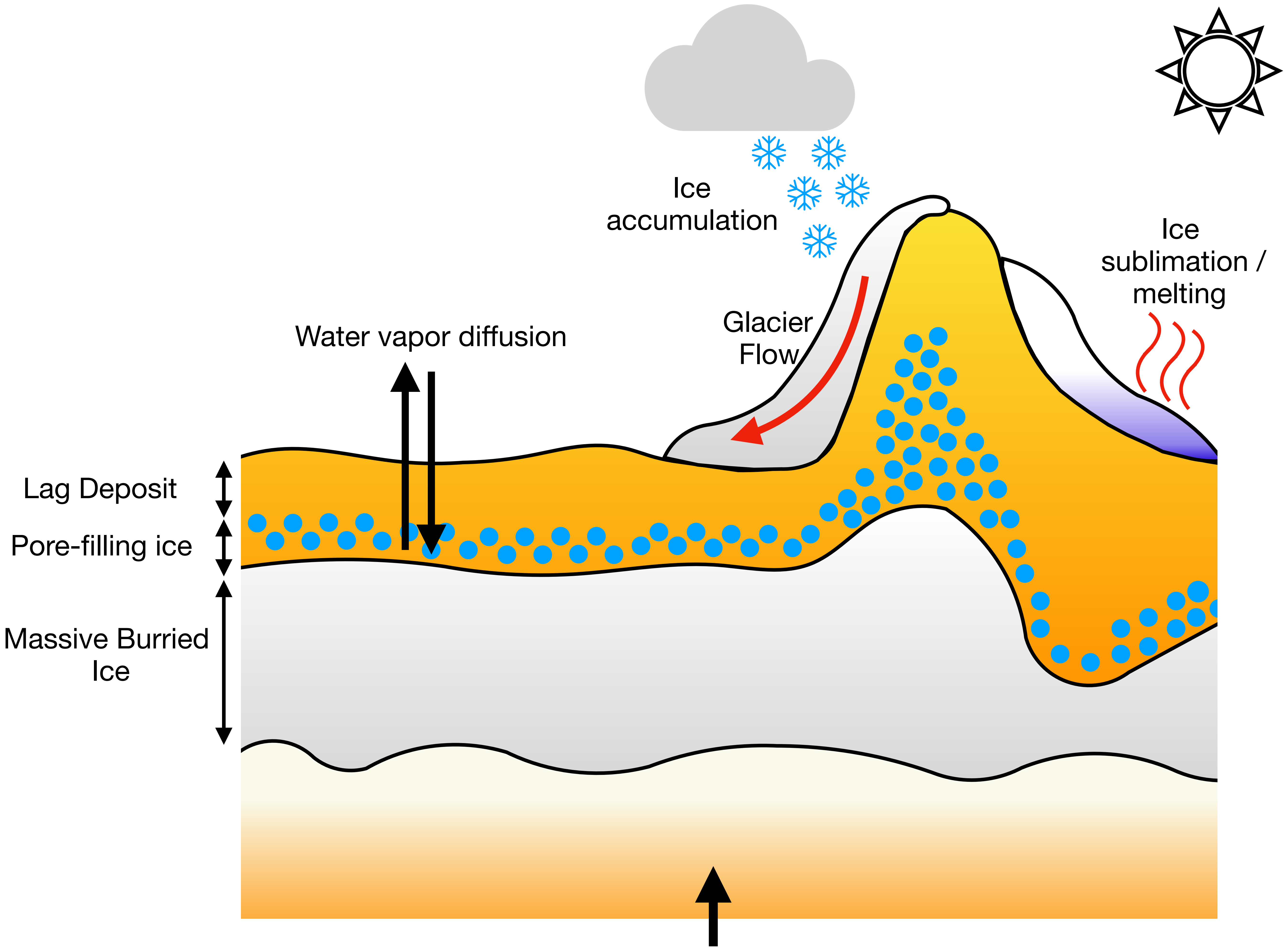

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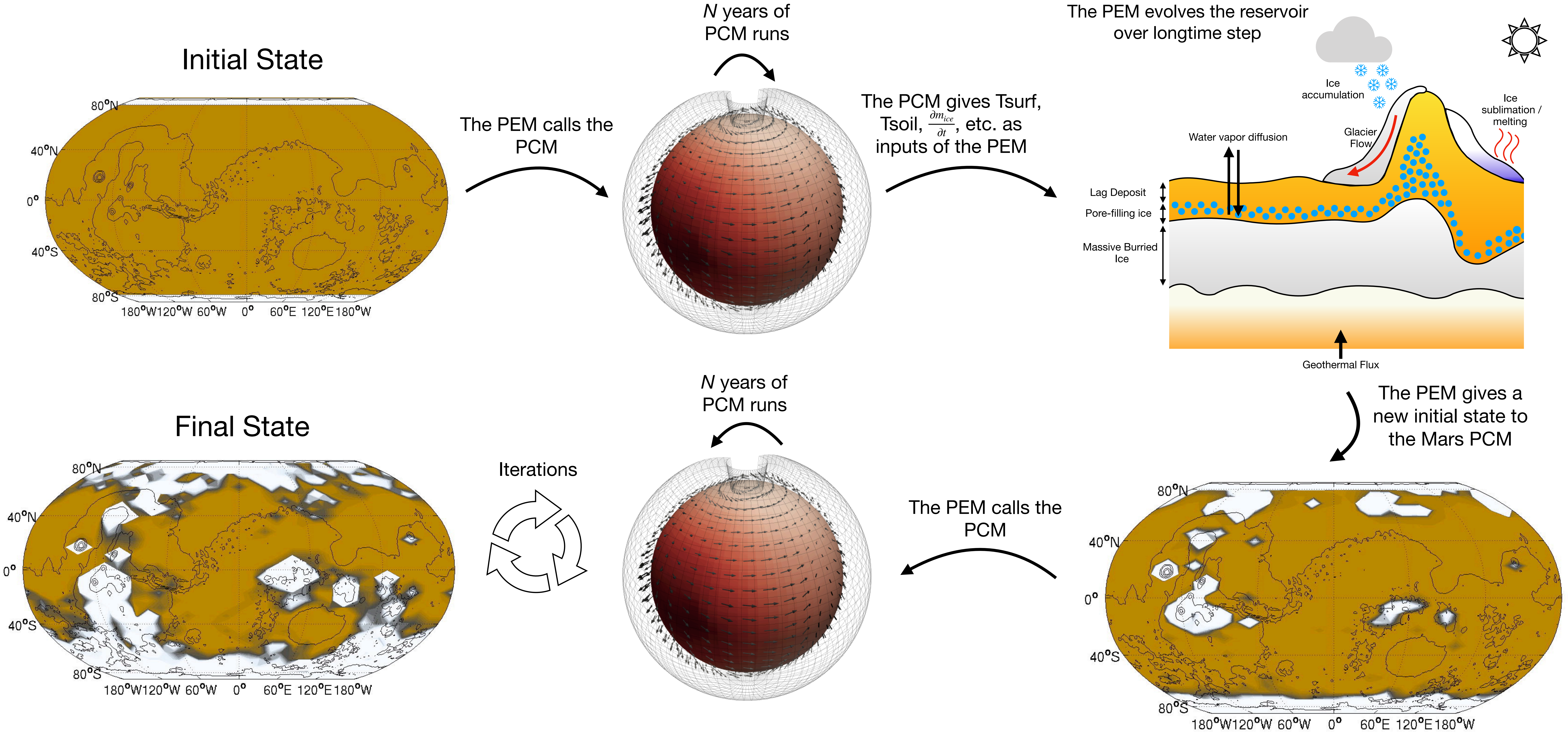
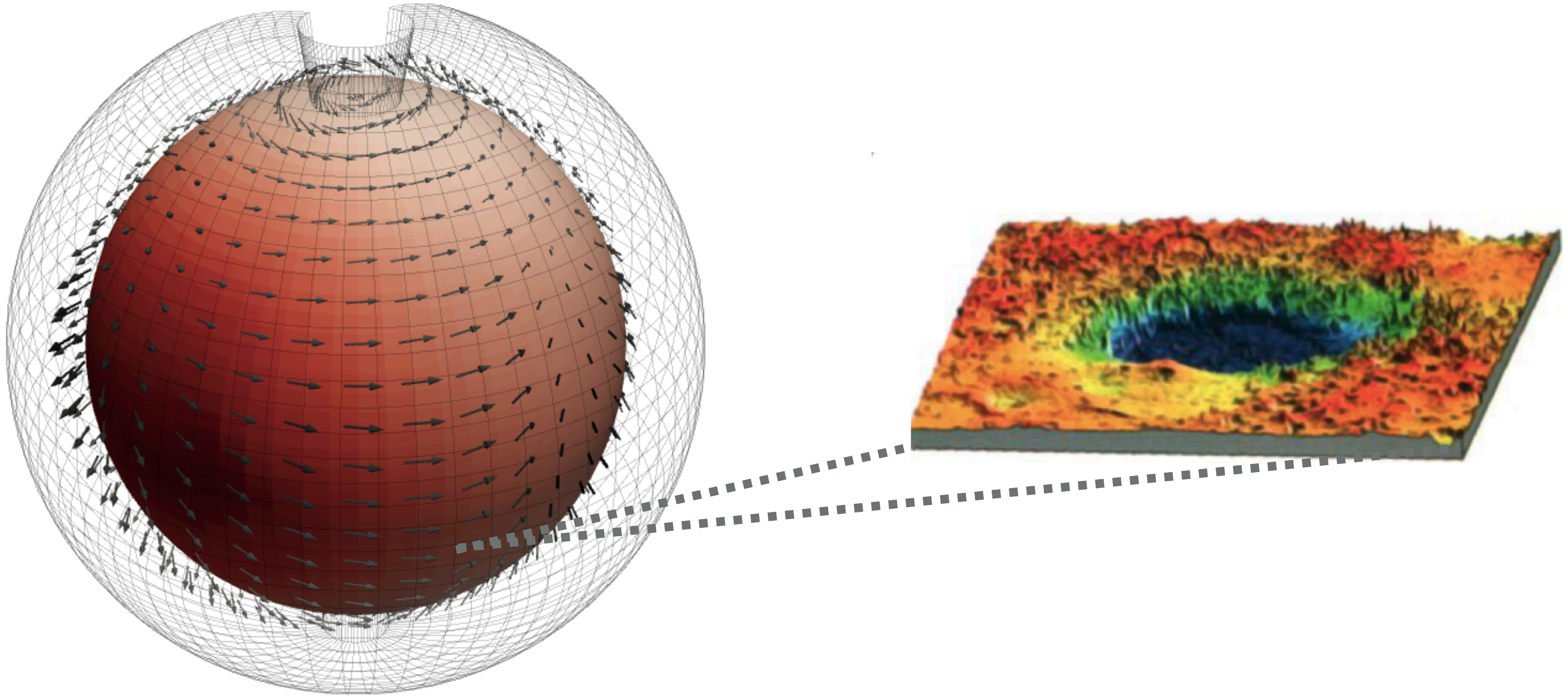


# Modeling Slope Microclimates in a coarse global Climate Model



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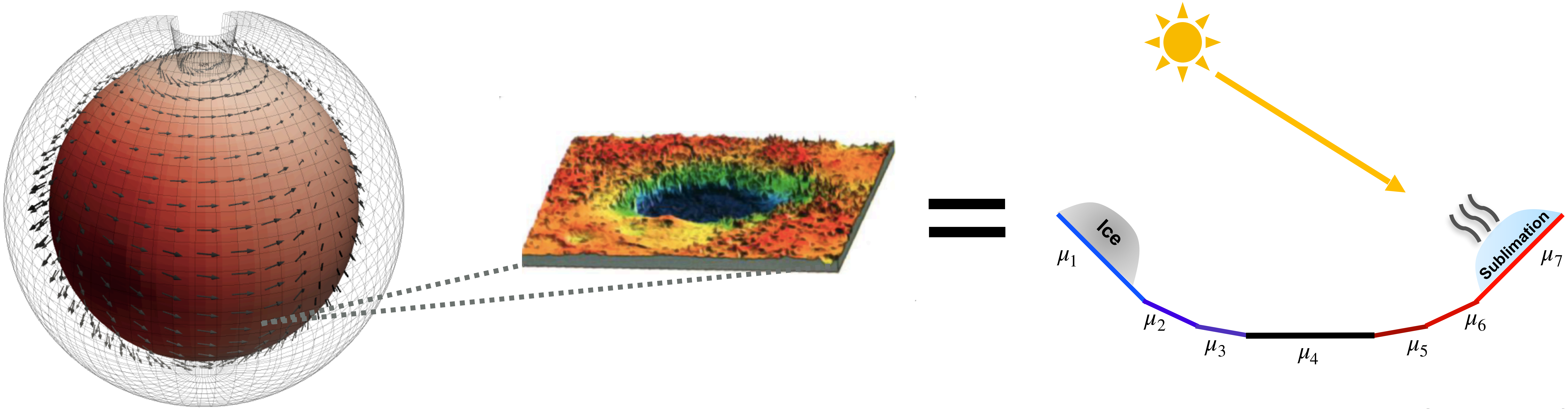
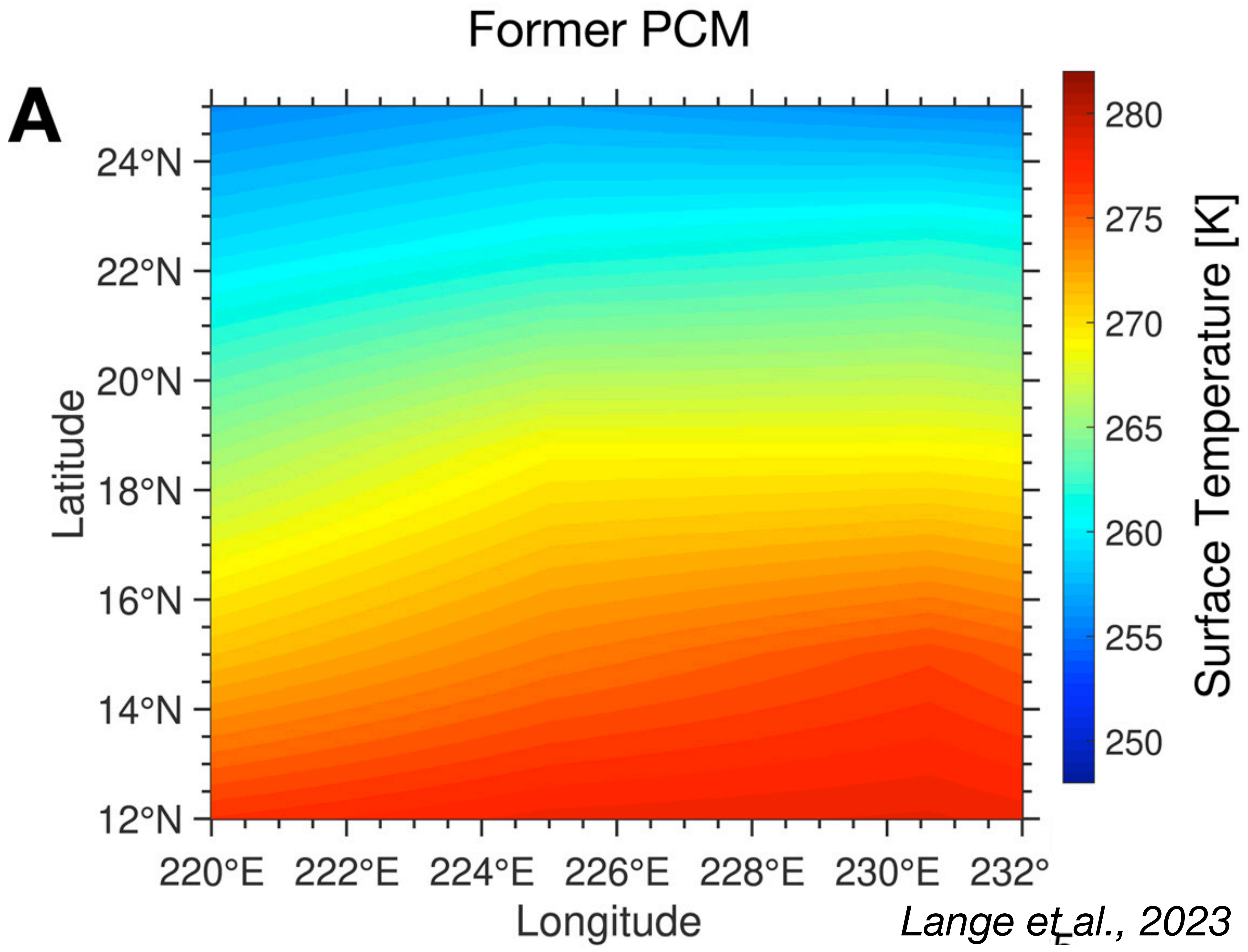



*Lange et al., 2023*

- Each slopes on Mars can be represented on average by an equivalent North/South facing slopes.
- On each sub-grid surface, we compute the surface energy budget, update temperature, ice amount, etc. The atmosphere sees an average of these sub-grid fields.

# Modeling Slope Microclimates in a coarse global Climate Model




*Lange et al., 2023*

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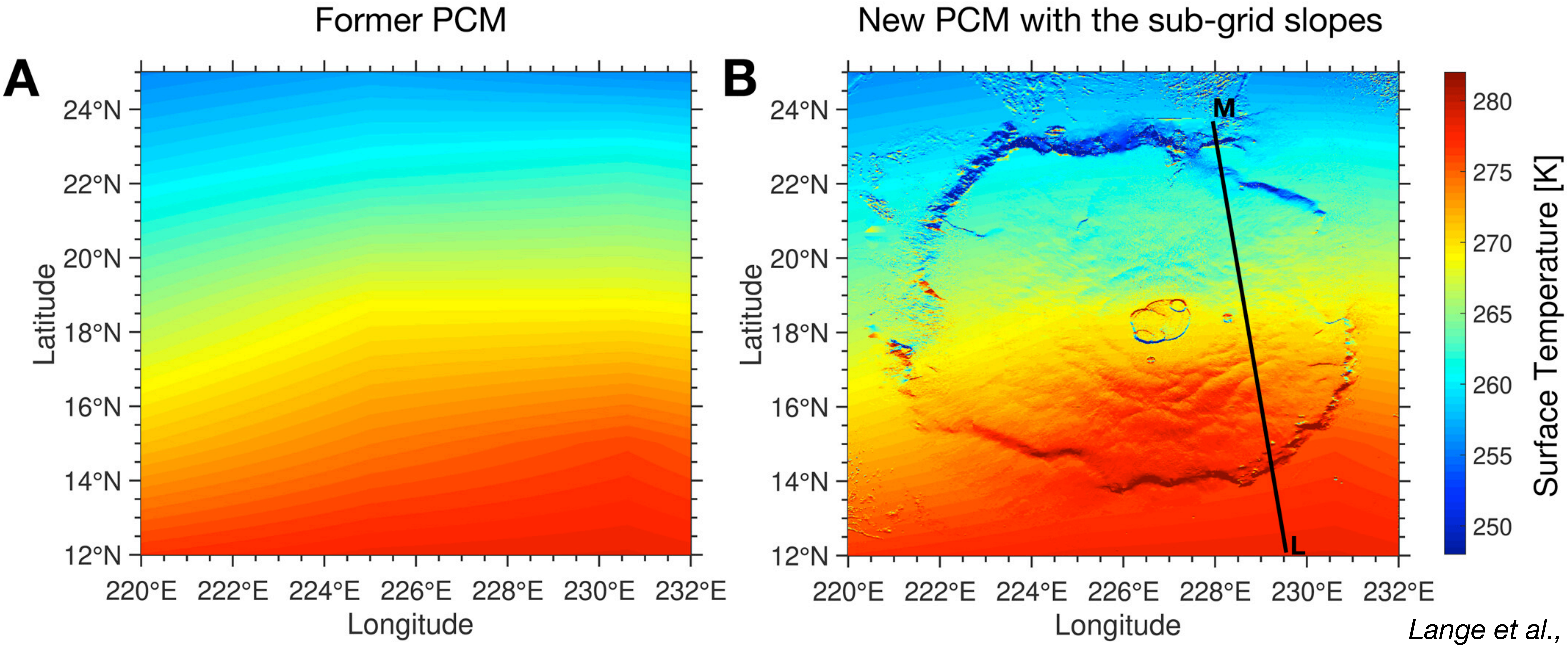



*Lange et al., 2023*

# What can explain the discrepeancies between the models and the observations?

1. **Some key mechanisms are missing**
   -> Radiative effect of clouds, (sub)surface-atmosphere interactions

2. **The models can not capture some microclimates conductive to ice accumulation/melting**
   -> slope parameterization

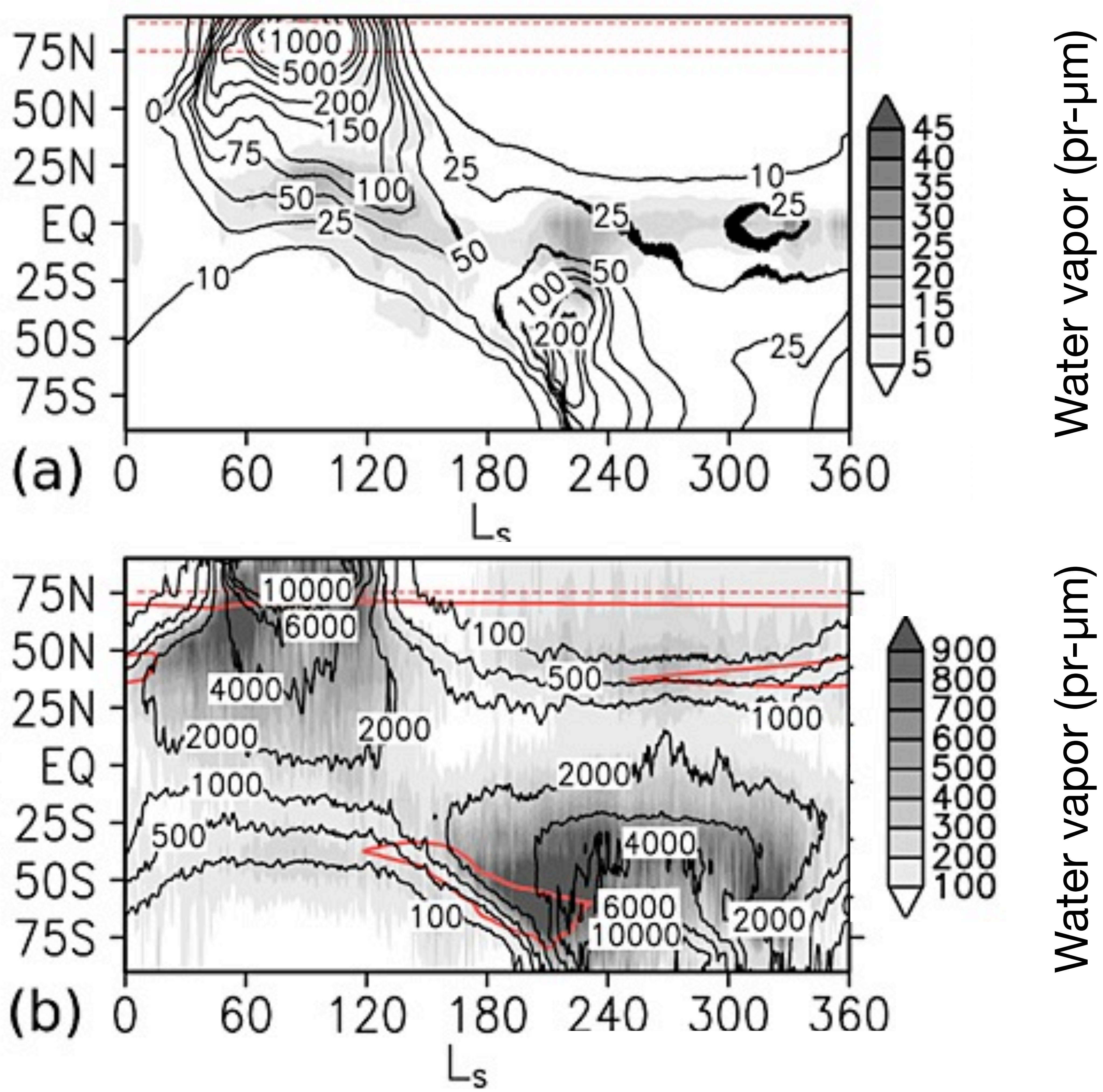
3. **???**

*Credits : HiRISE / NASA/JPL/UArizona*

# Outline



# The Mysterious presence of Mid-Latitudes Subsurface Ice



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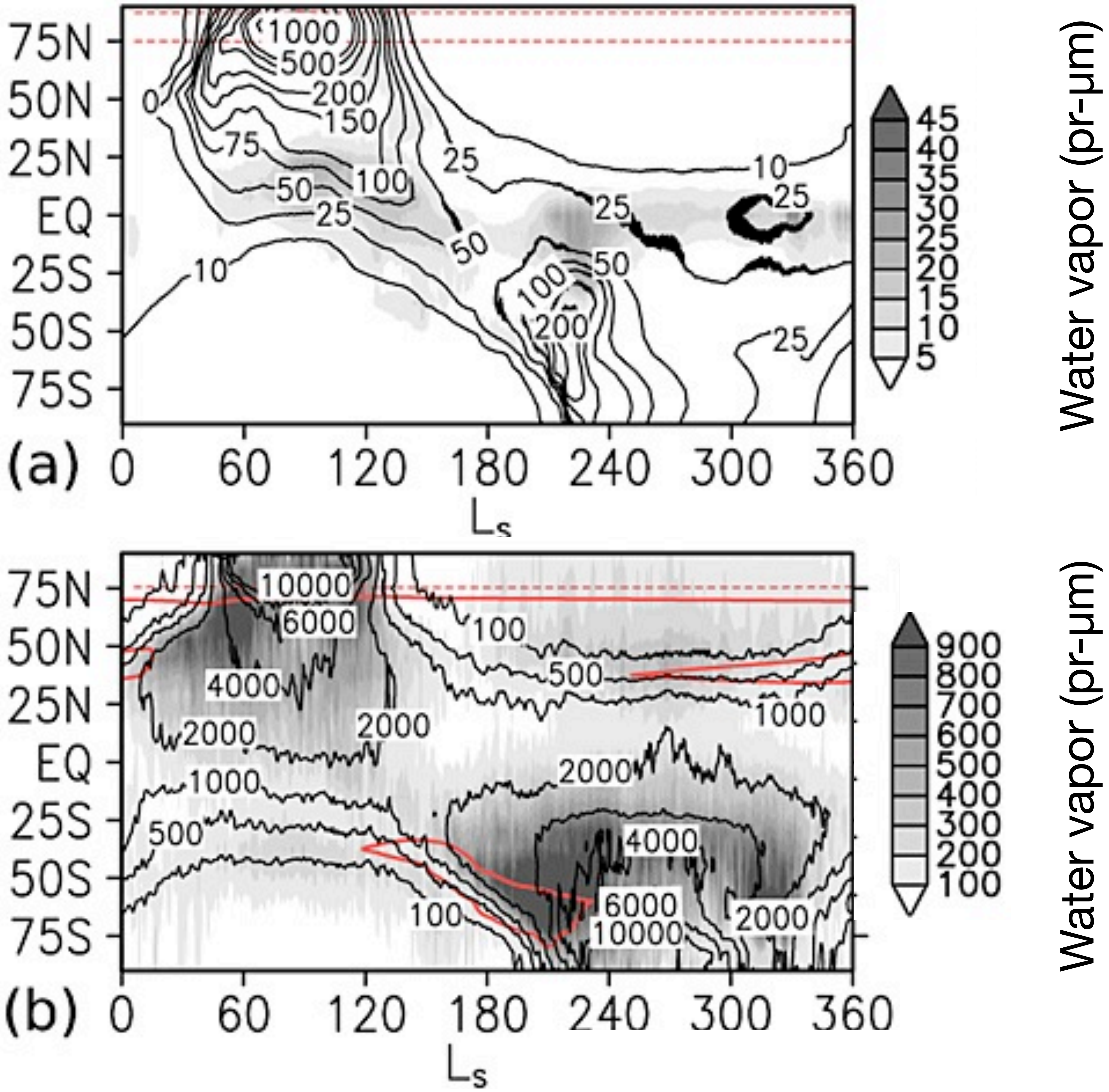
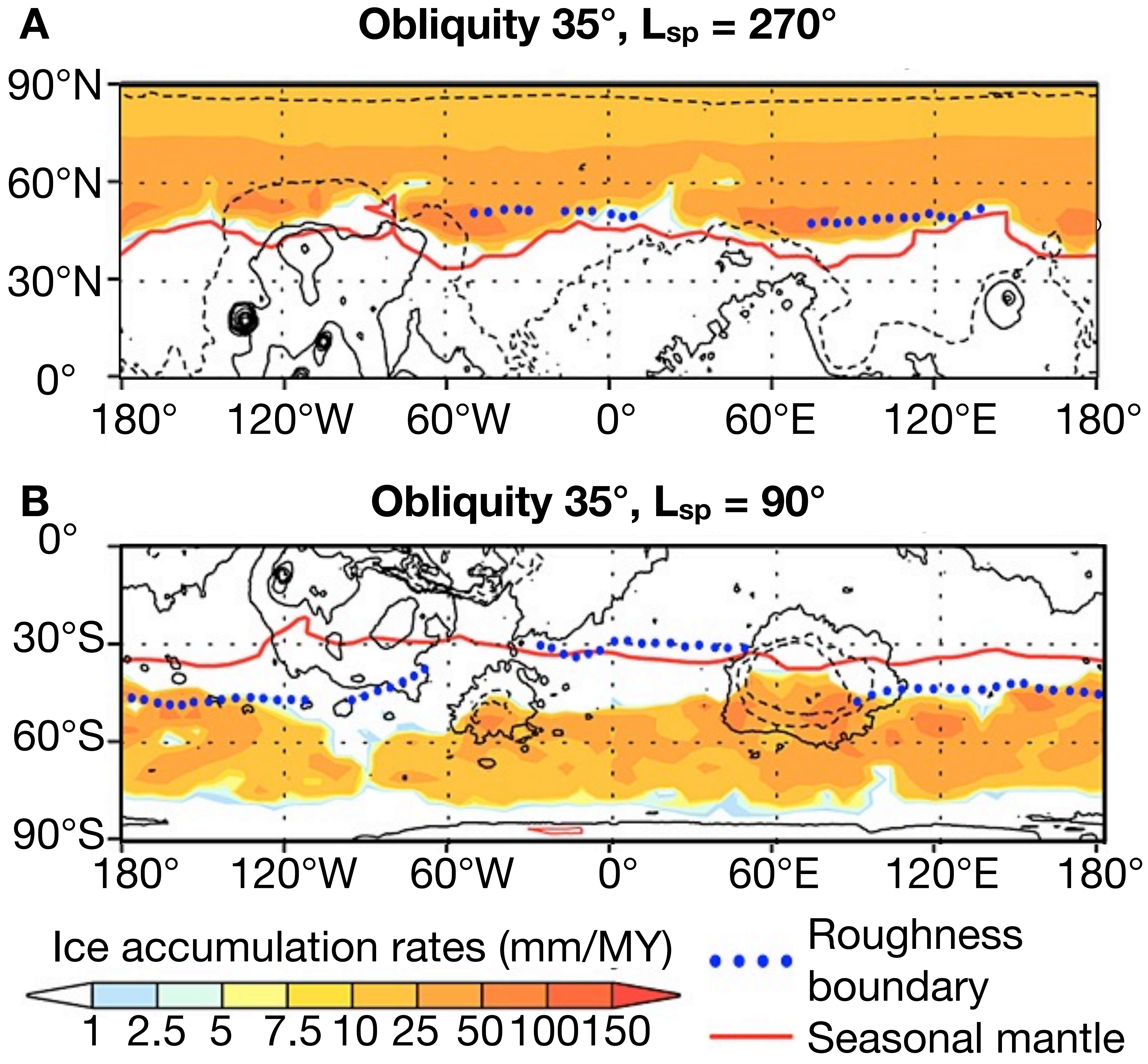
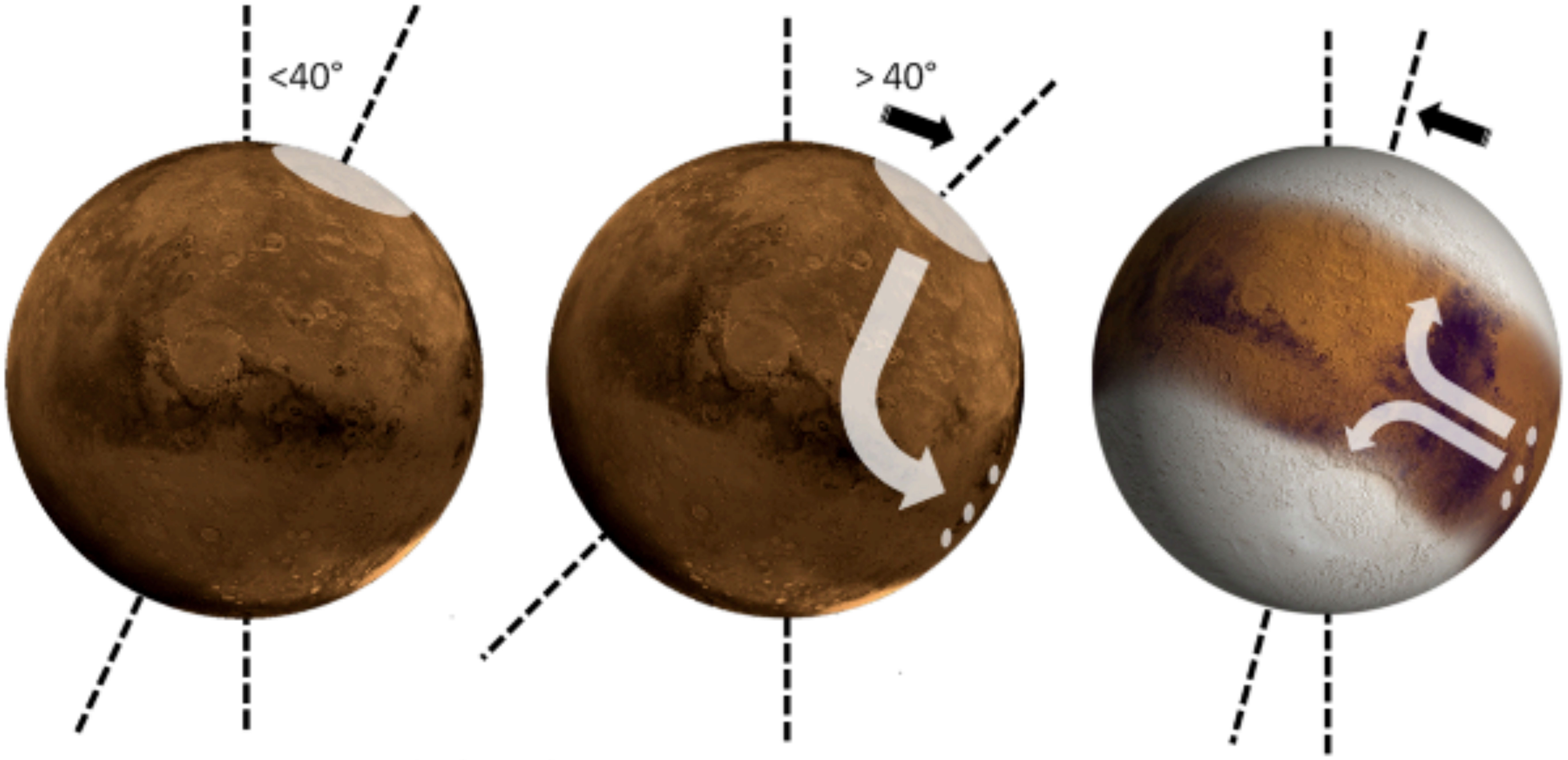



*Adapted from Madeleine et al., 2014, Naar 2023*

# The Martian Puzzle

Effect of changing the obliquity on the Martian Climate from previous climate studies




Review : Forget et al. (2017)

Forget & Naar, in prep.

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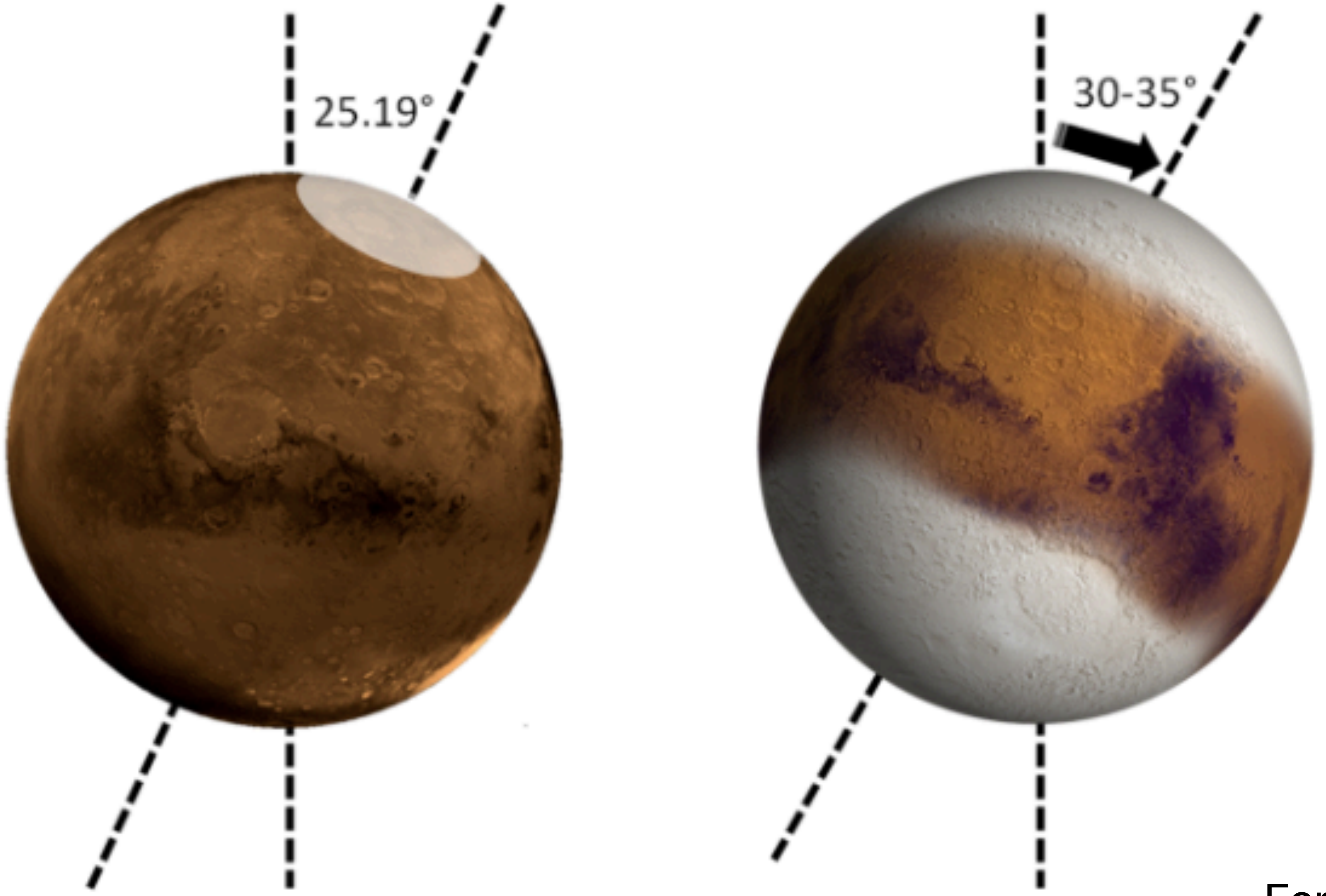


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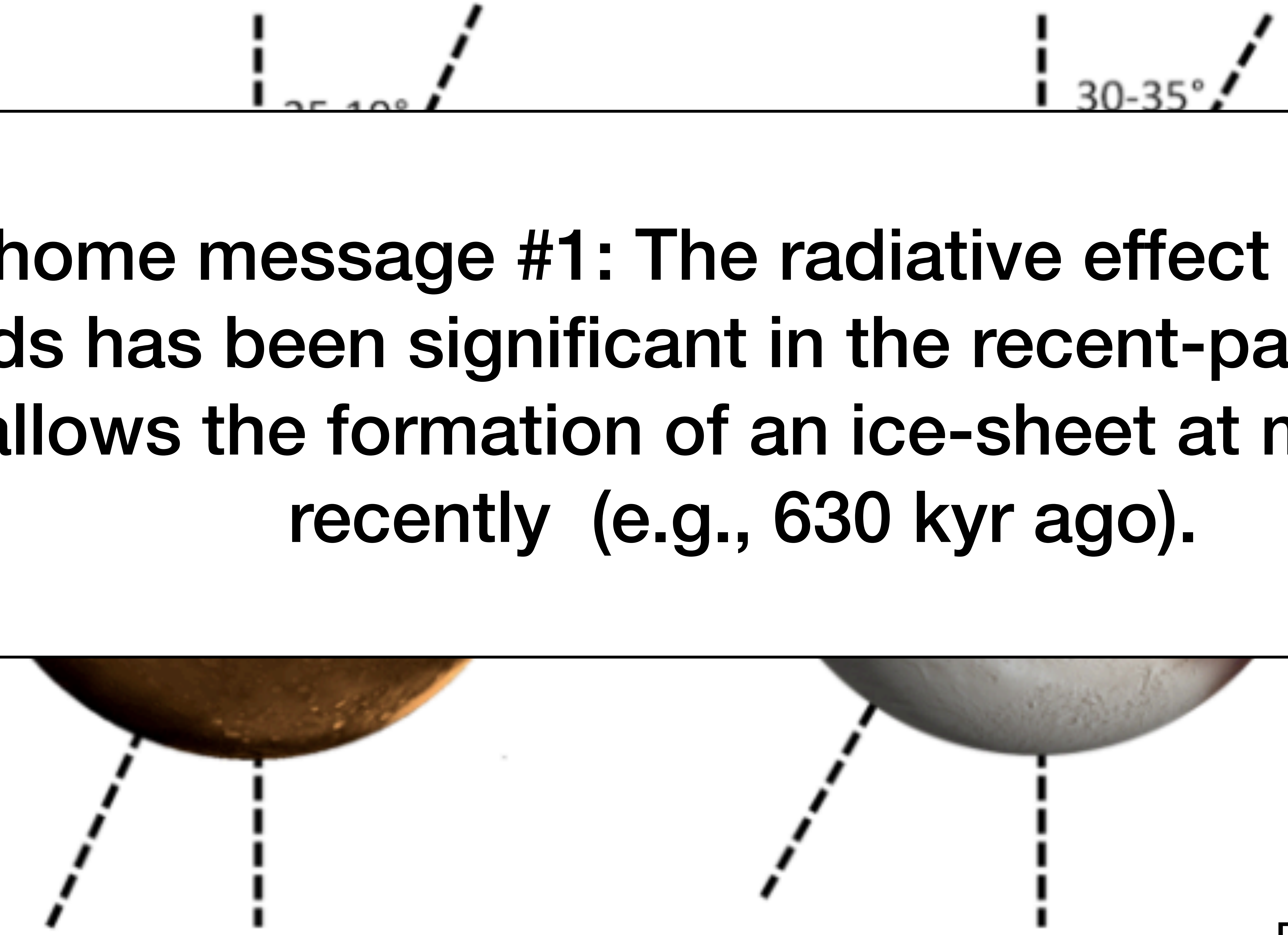
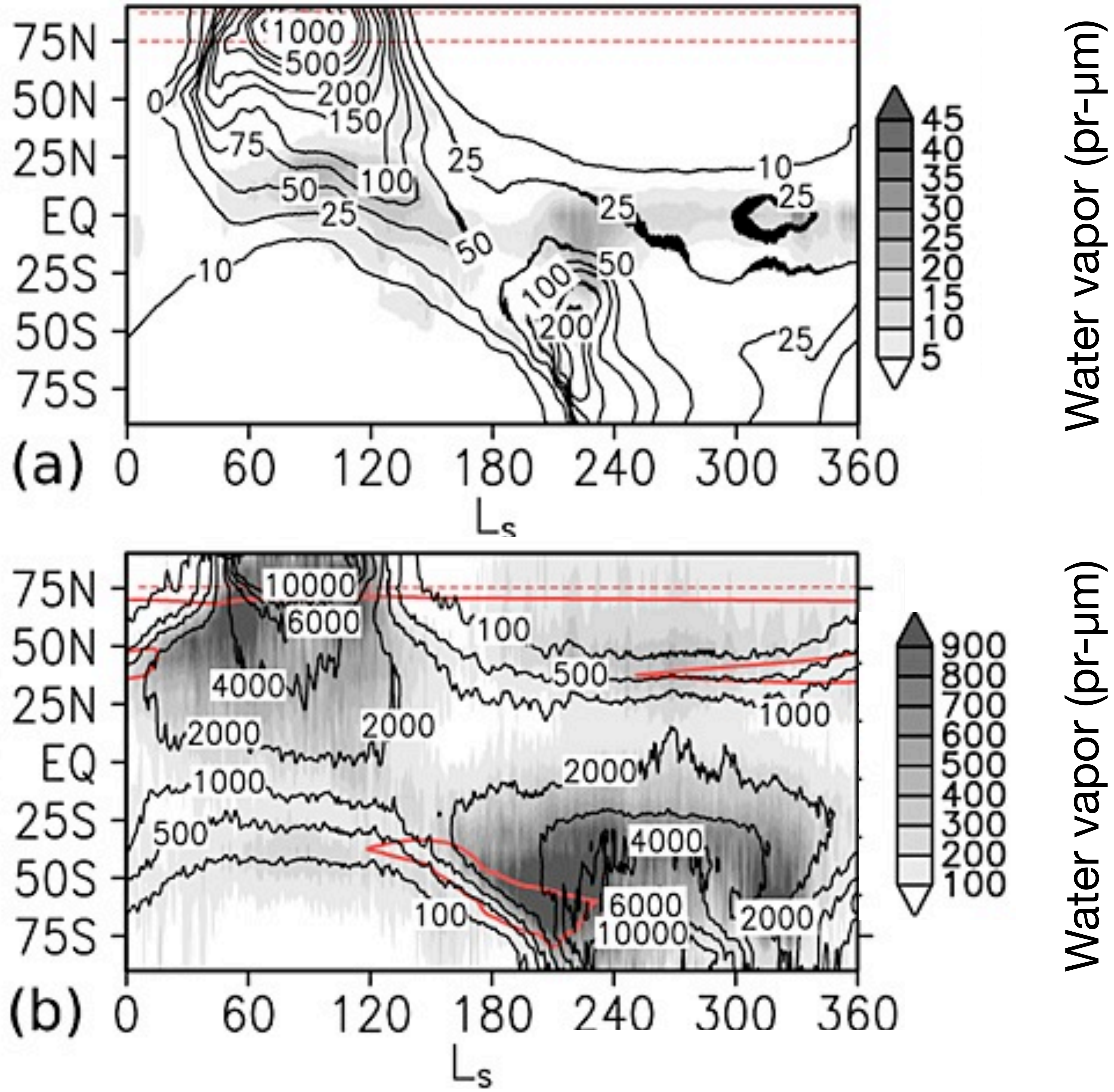
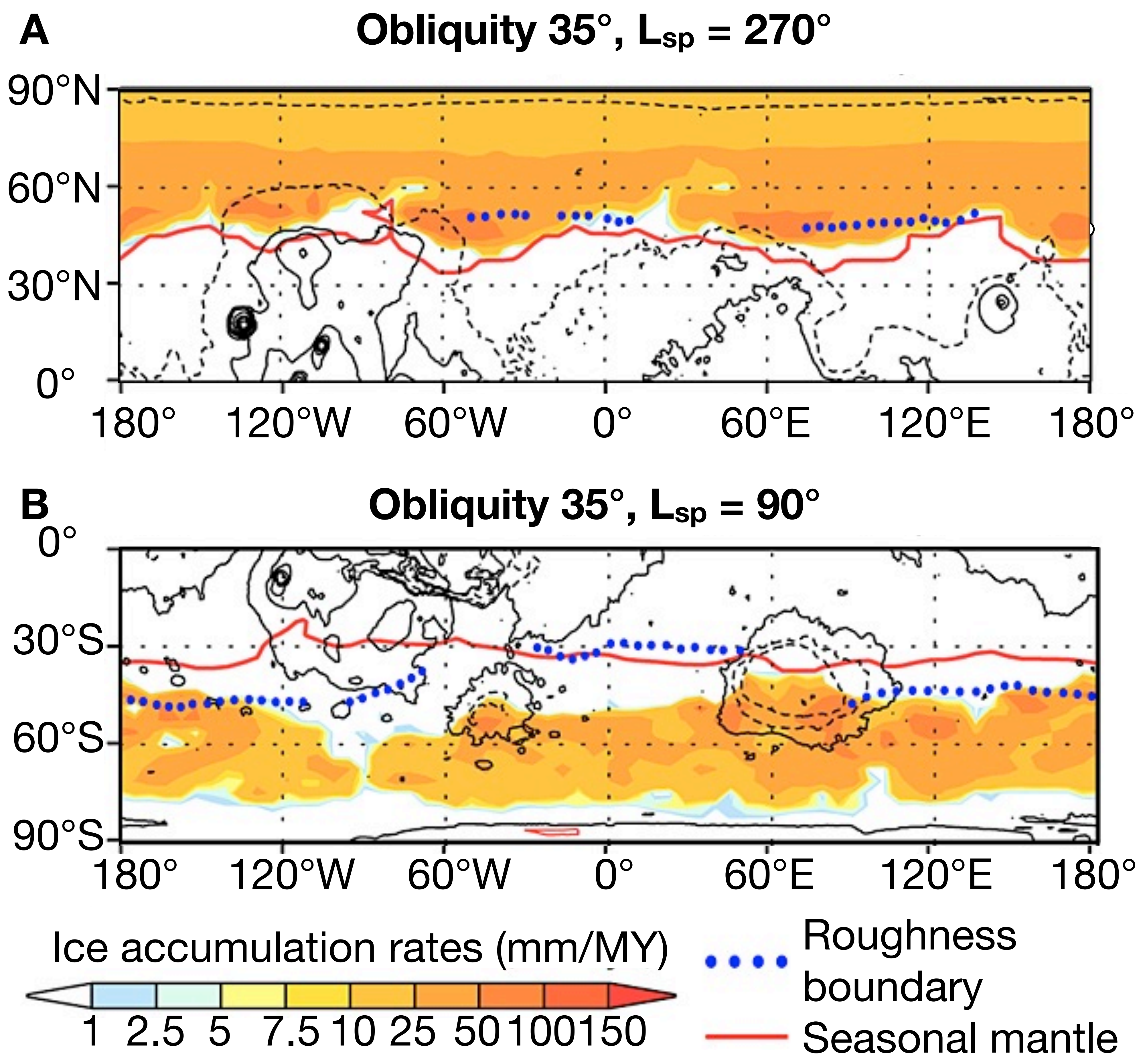



**Take-home message #1: The radiative effect of water ice clouds has been significant in the recent-past of Mars, and allows the formation of an ice-sheet at mid-latitude recently (e.g., 630 kyr ago).**

Forget & Naar, in prep.

# The Mysterious presence of Mid-Latitudes Subsurface Ice

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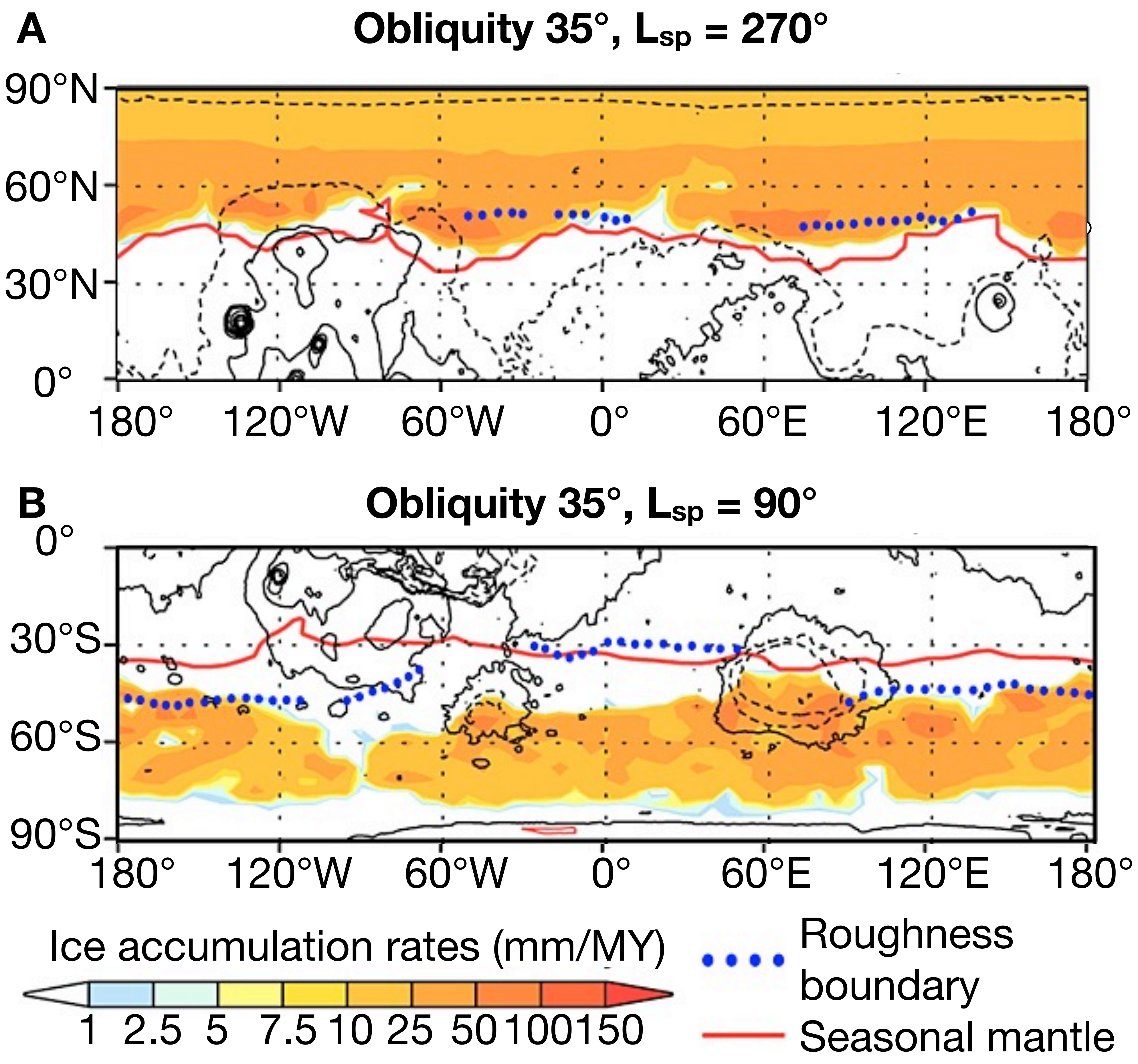


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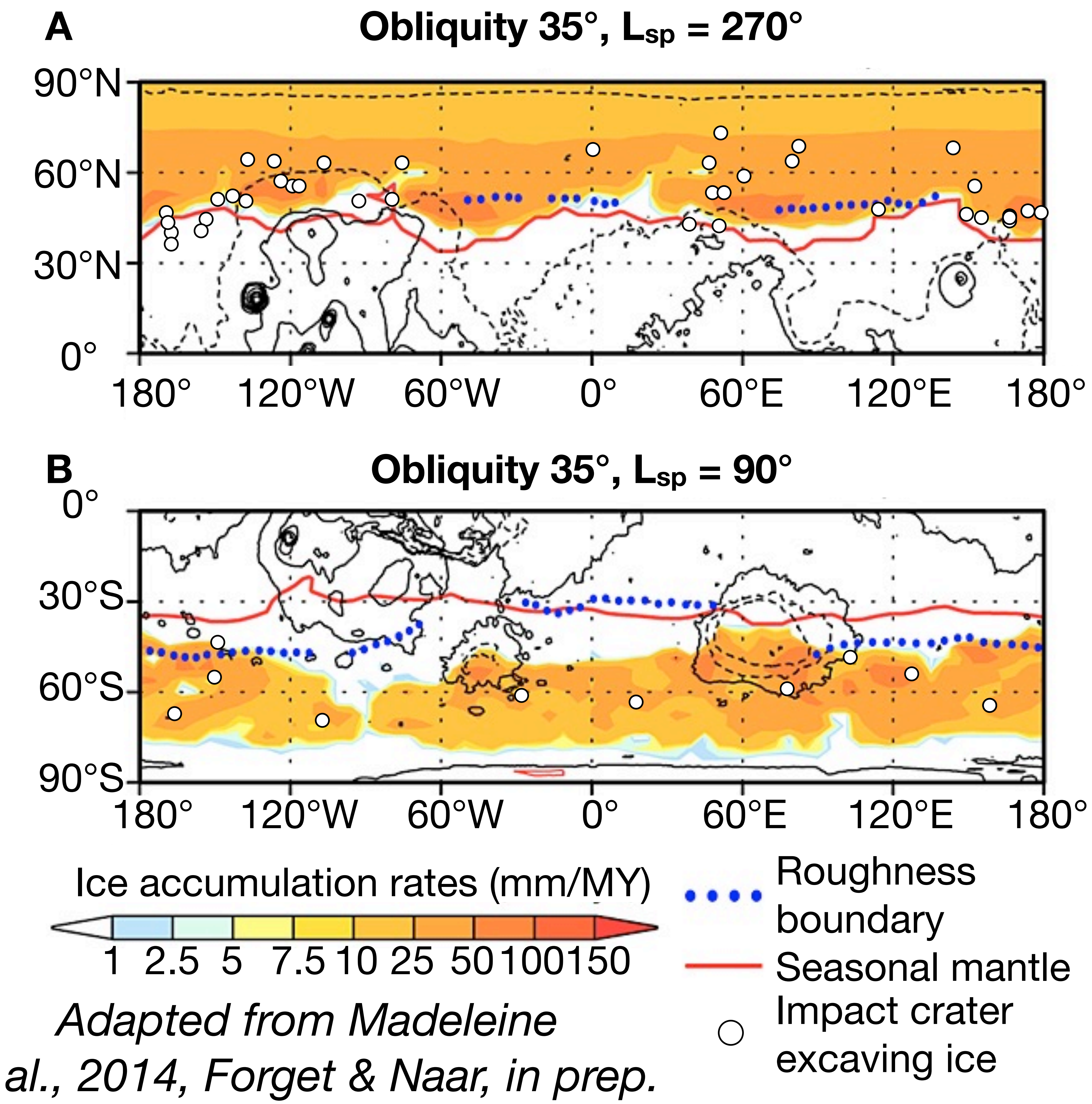


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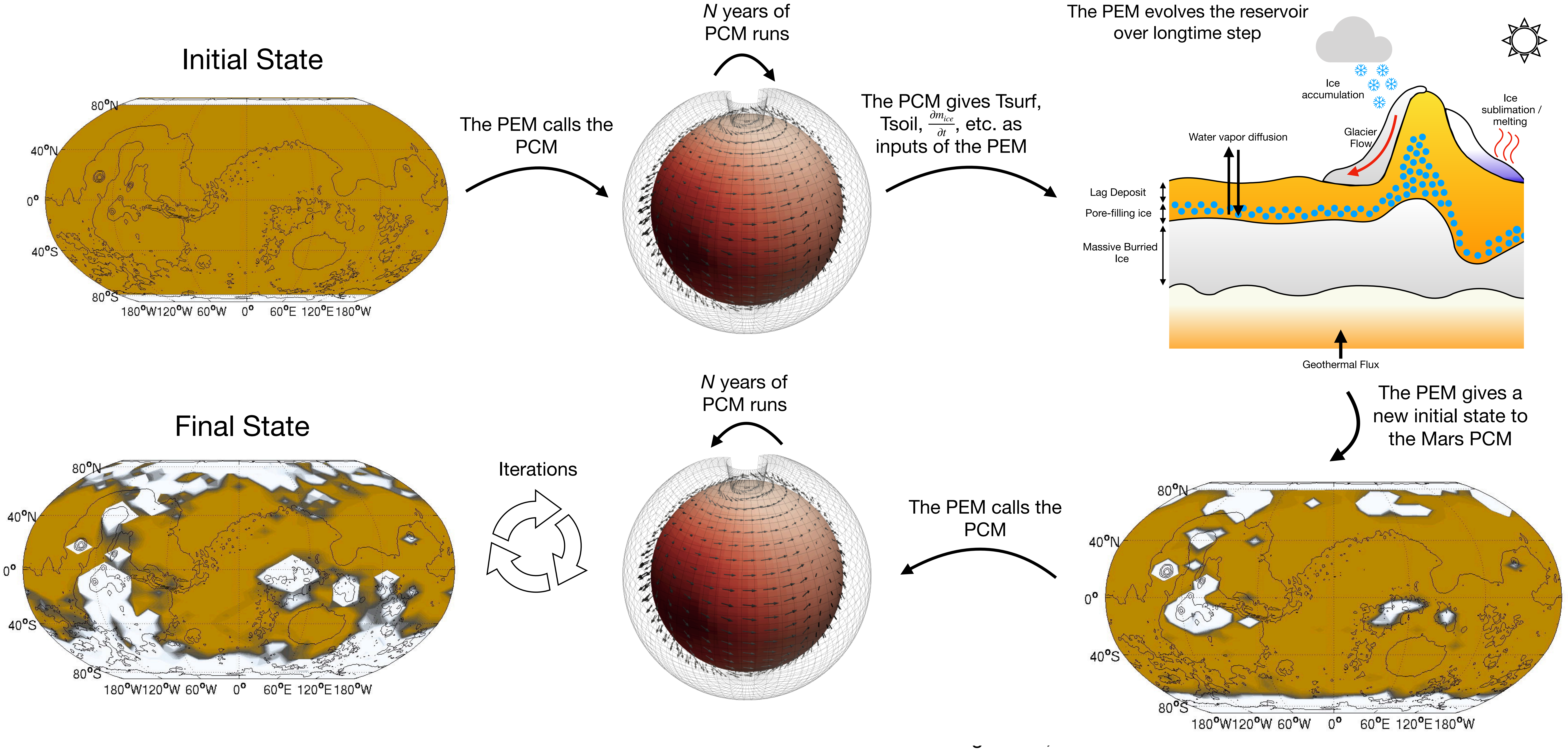

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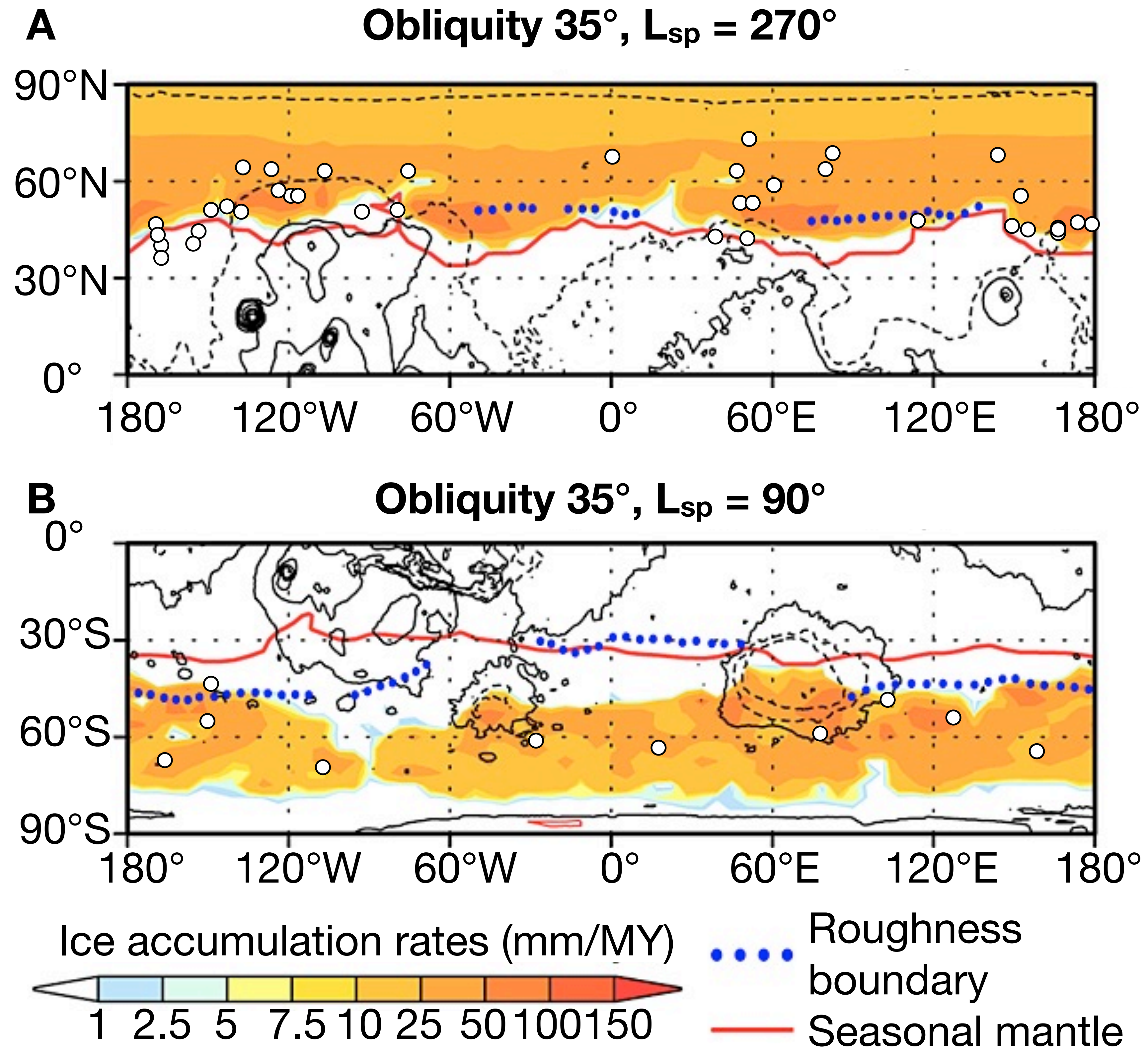


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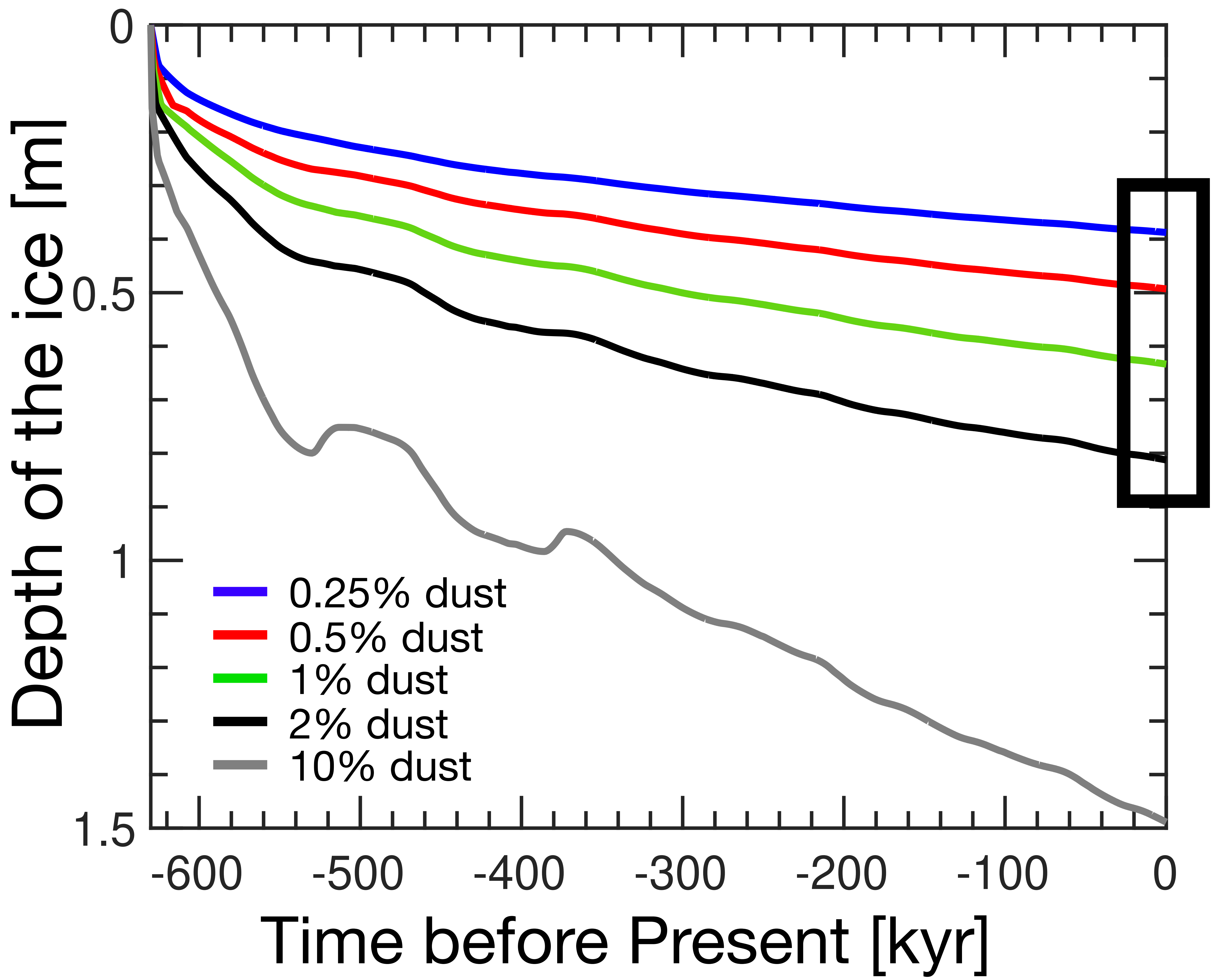


Range of depth (30-80 cm) where ice is excavated by impacts (*Dundas et al., 2014, 2018*).

*Vos et al., in prep*

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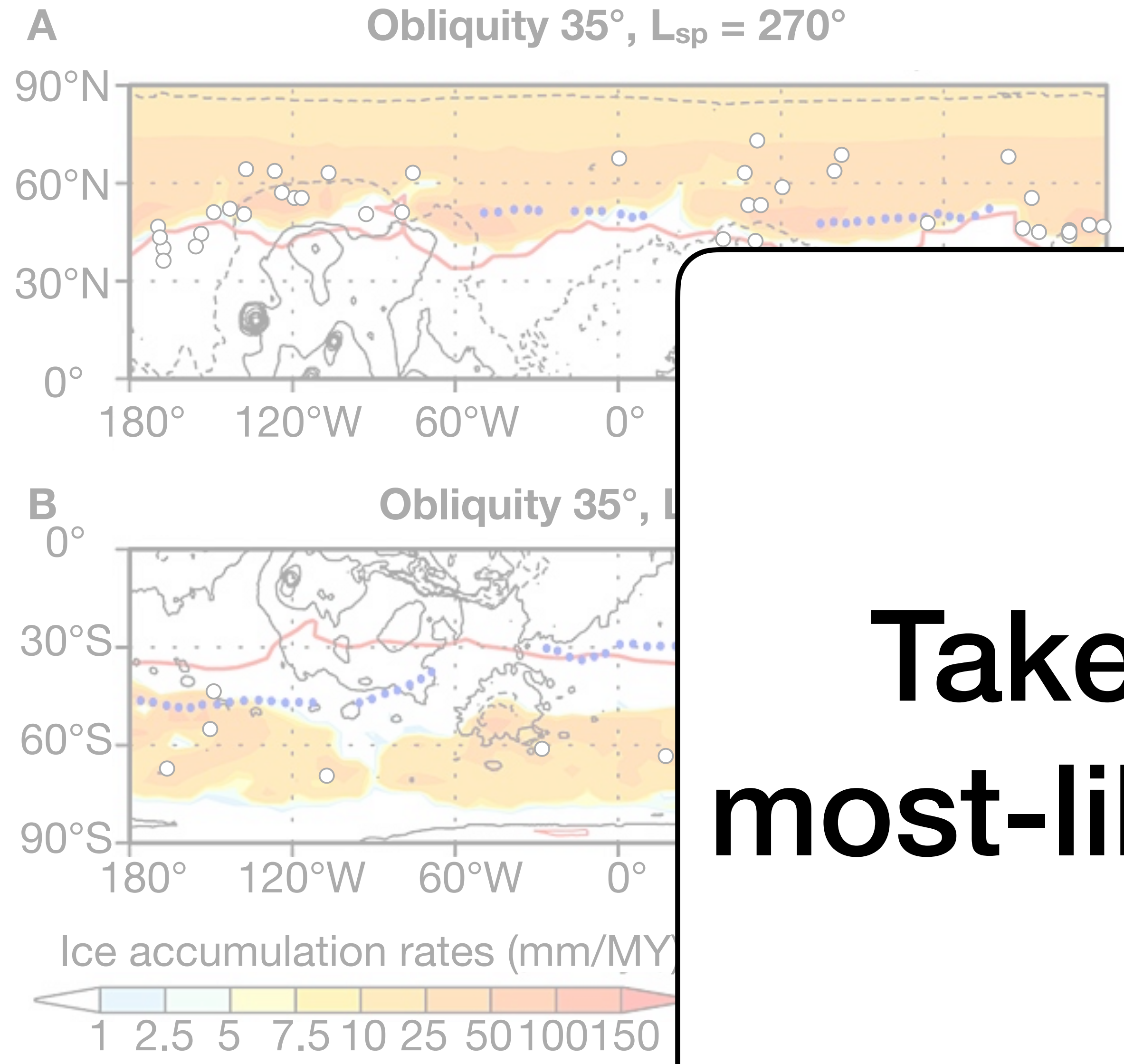
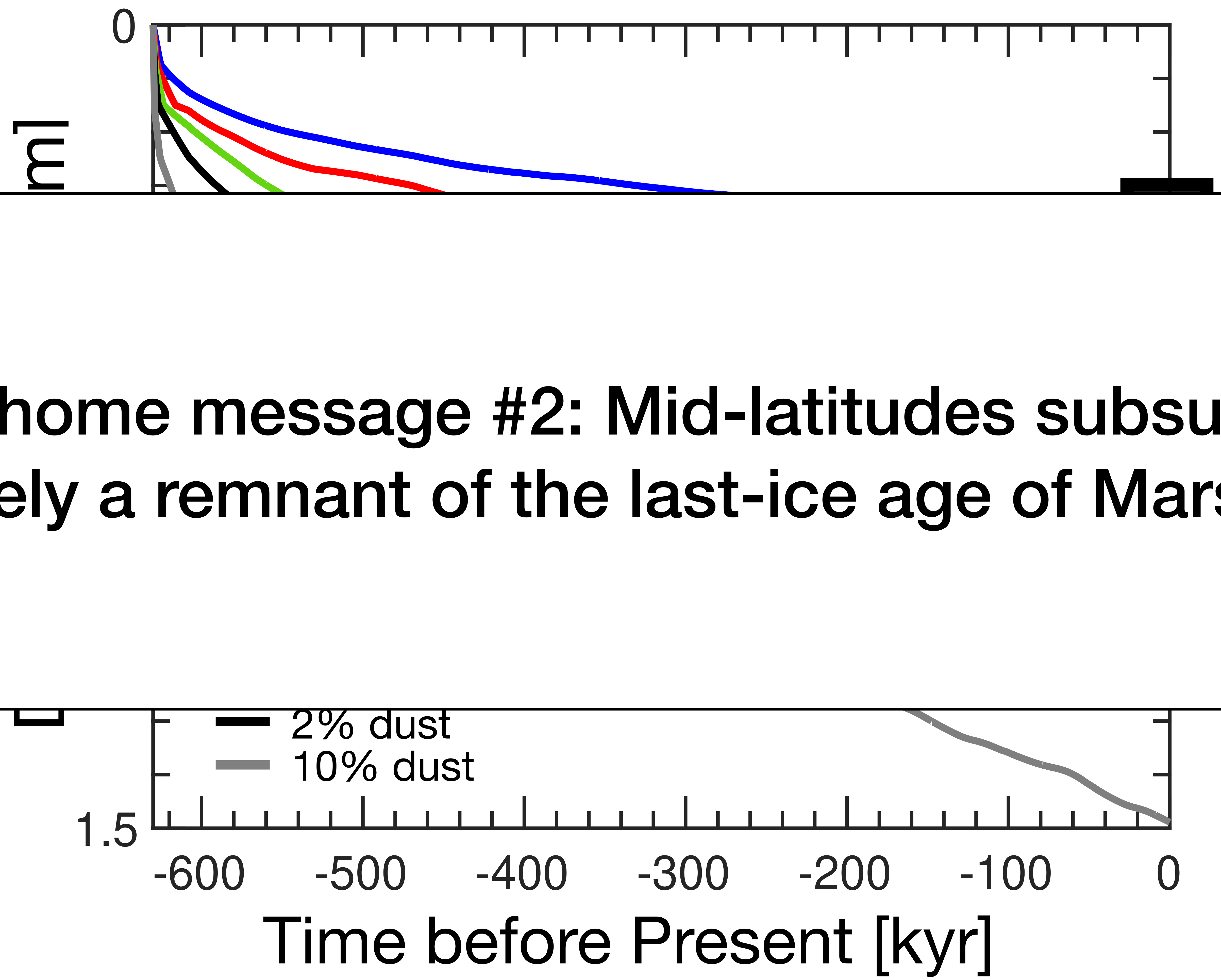



0 cm) where
impacts
4, 2018).

**Take-home message #2: Mid-latitudes subsurface ice is most-likely a remnant of the last-ice age of Mars, 630 kyr ago**

*Vos et al., in prep*

# The formation of Gullies on Mars

RESEARCH

MARTIAN GEOLOGY

## Gullies on Mars could have formed by melting of water ice during periods of high obliquity

J. L. Dickson*[1,2], A. M. Palumbo[2], J. W. Head[2], L. Kerber[3], C. I. Fassett[4]†, M. A. Kreslavsky[5]

Gullies on Mars resemble water-carved channels on Earth, but they are mostly at elevations where liquid water is not expected under current climate conditions. It has been suggested that sublimation of carbon dioxide ice alone could have formed Martian gullies. We used a general circulation model to show that the highest-elevation Martian gullies coincide with the boundary of terrain that experienced pressures above the triple point of water when Mars' rotational axis tilt reached 35°. Those conditions have occurred repeatedly over the past several million years, most recently ~630,000 years ago. Surface water ice, if present at these locations, could have melted when temperatures rose >273 kelvin. We propose a dual gully formation scenario that is driven by melting of water ice followed by carbon dioxide ice sublimation.

Gullies on Mars resemble $H_2O$-carved channels on Earth (1). Their concentration at Mars' midlatitudes, where near-surface ice is stable (1–3), is consistent with an $H_2O$-melting model for their formation. However, the observed distribution includes elevations where present-day atmospheric pressure is always below the triple point of $H_2O$ (2, 4), so solid $H_2O$ ice is expected to sublimate to form vapor rather than melt to form liquid. The seasonal timing of contemporary mobilization of surface material within gullies is consistent with sublimation of solid $CO_2$ (5, 6), so it is possible that gullies formed from $CO_2$-mediated processes alone (7). However, the mechanism of such a $CO_2$-only process is uncertain and lacks an Earth analog. Repeat orbital imaging shows that present-day erosion of gullies is rare. Although examples have been documented (5, 6), erosion of gully channels is minor (Fig. 1A) and infrequent. At high latitudes (>70°), where solid $CO_2$ ice is emplaced and removed every year, ~98.3% of gullies show no activity and none experience channel erosion (8).

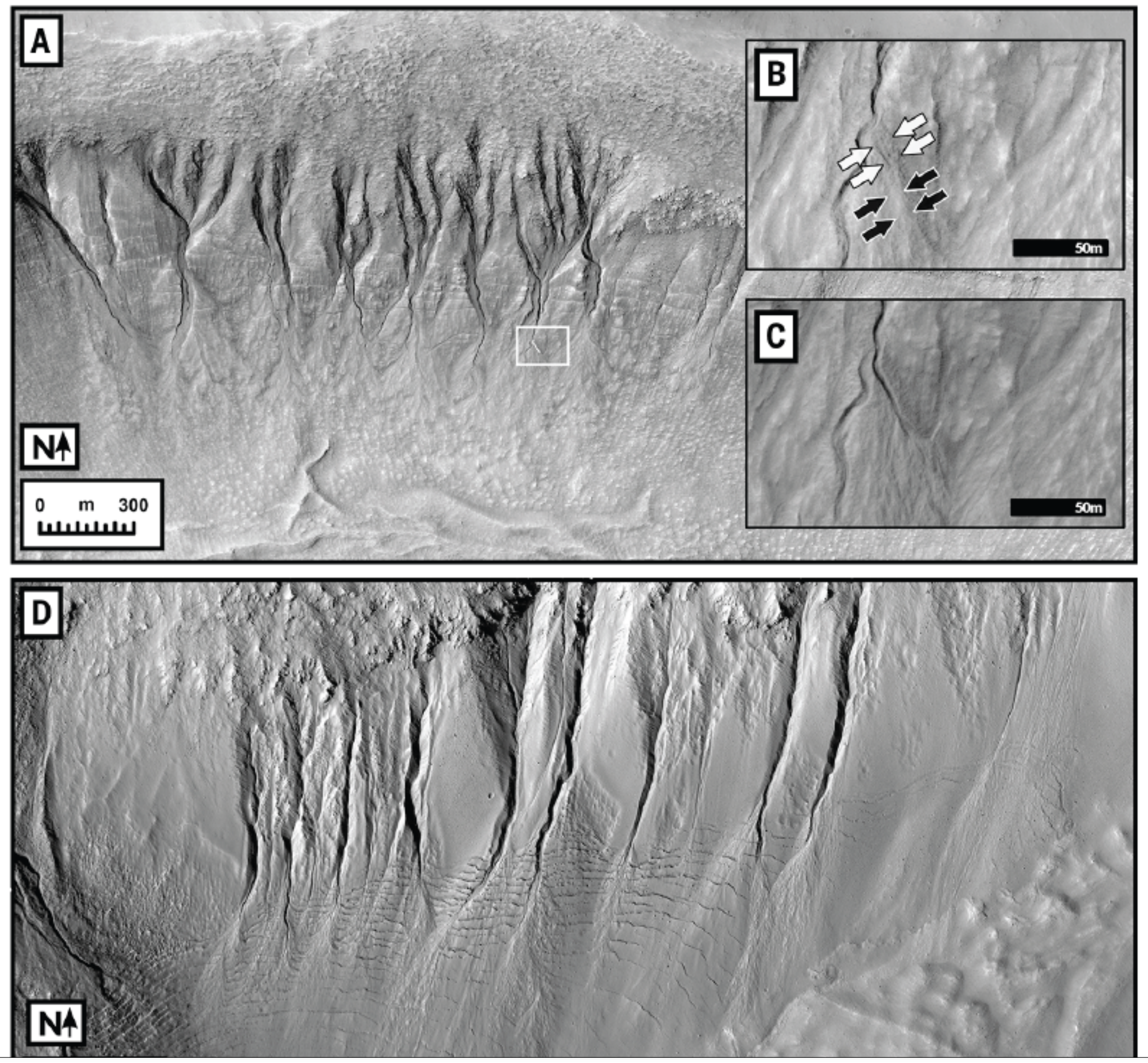
An alternative possibility is that gullies were incised by small amounts of liquid $H_2O$ during earlier climate conditions that were more conducive to melting of $H_2O$ ice. This scenario would be consistent with the stratigraphy of gully fans (9, 10), which indicates cycles of emplacement of fan sediment, fracturing (Fig. 1B), and incision. Mars' axial tilt (obliquity) is known to vary over hundreds of thousands of years (11), so earlier periods of higher obliquity could

uid $H_2O$. Previous studies have shown that at 35° obliquity, $H_2O$ ice accumulated on midlatitude (30° to 45° in each hemisphere),

pole-facing slopes (11–15), locations that contain gullies (14, 15). Meanwhile, large s... of $CO_2$ ice (currently sequestered in the southern polar ice cap) sublimated (16), producing an atmosphere with double its current pressure (17). The extent of terrain that experienced conditions capable of hosting liquid $H_2O$ would have been greater at that time than in the present.

### General circulation models

We tested the hypothesis that liquid $H_2O$ was involved in the formation of gullies by investigating whether the mapped locations of gullies (3) correlate with the locations of terrain that could host liquid $H_2O$ when Mars experienced 35° obliquity. We used a three-dimensional general circulation model (GCM) of Mars (13, 18) to simulate climatic conditions at three obliquities and associated pressures (16, 17) that occurred in the past million

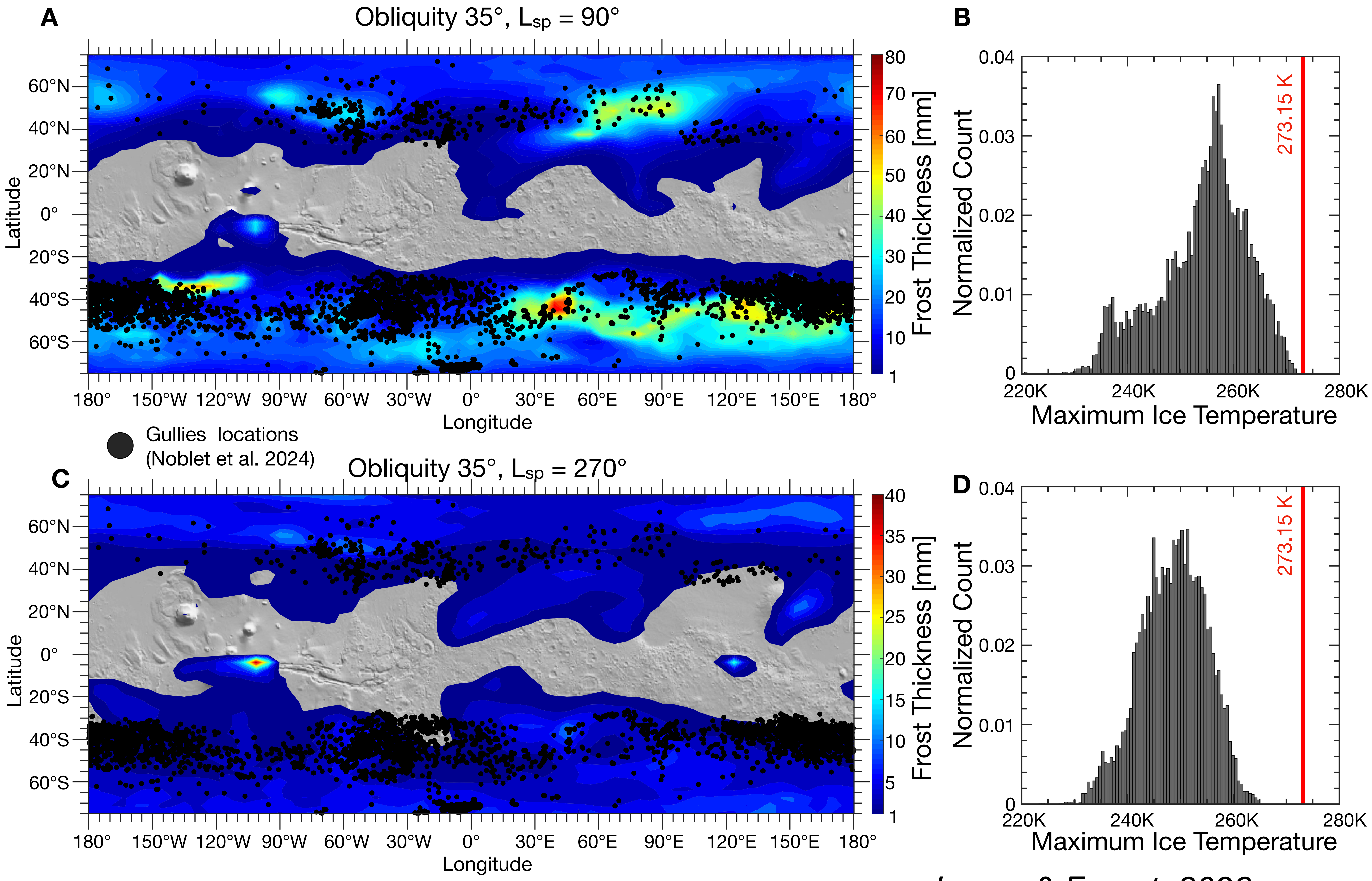







- Ingersoll (1970) demonstrates that the sublimation cooling prevents the melting of water ice on present-day Mars
- This cooling is proportional to the difference of humidity between the atmosphere and the surface.
- The cooling might be reduced at high obliquity, when the atmosphere is wetter?

# The formation of Gullies on Mars



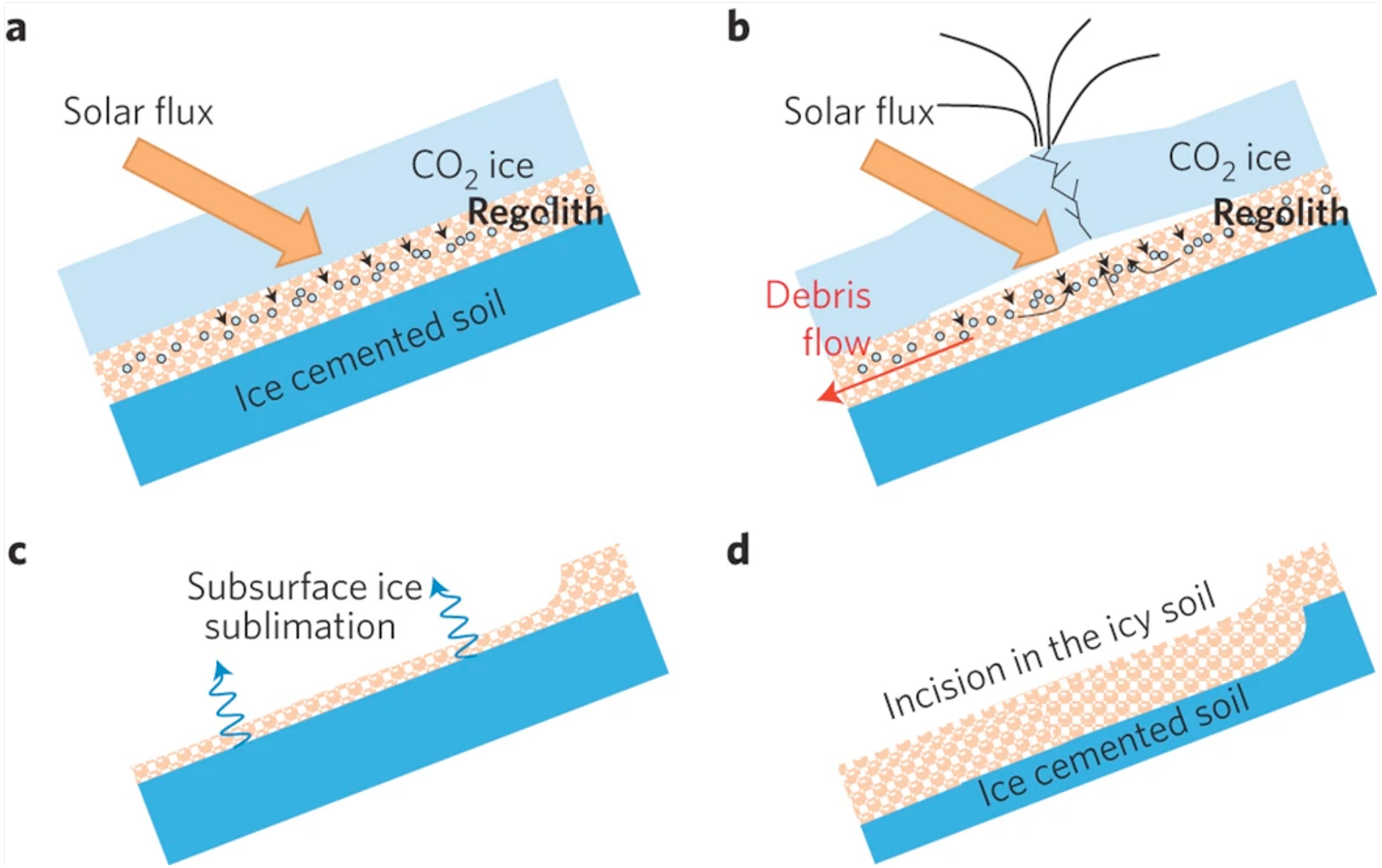

Even with a 10-10 times wetter atmosphere, the significant sublimation cooling prevents melting at high obliquity

-> other mechanisms have created gullies ? (e.g., $CO_2$ ice sublimation)

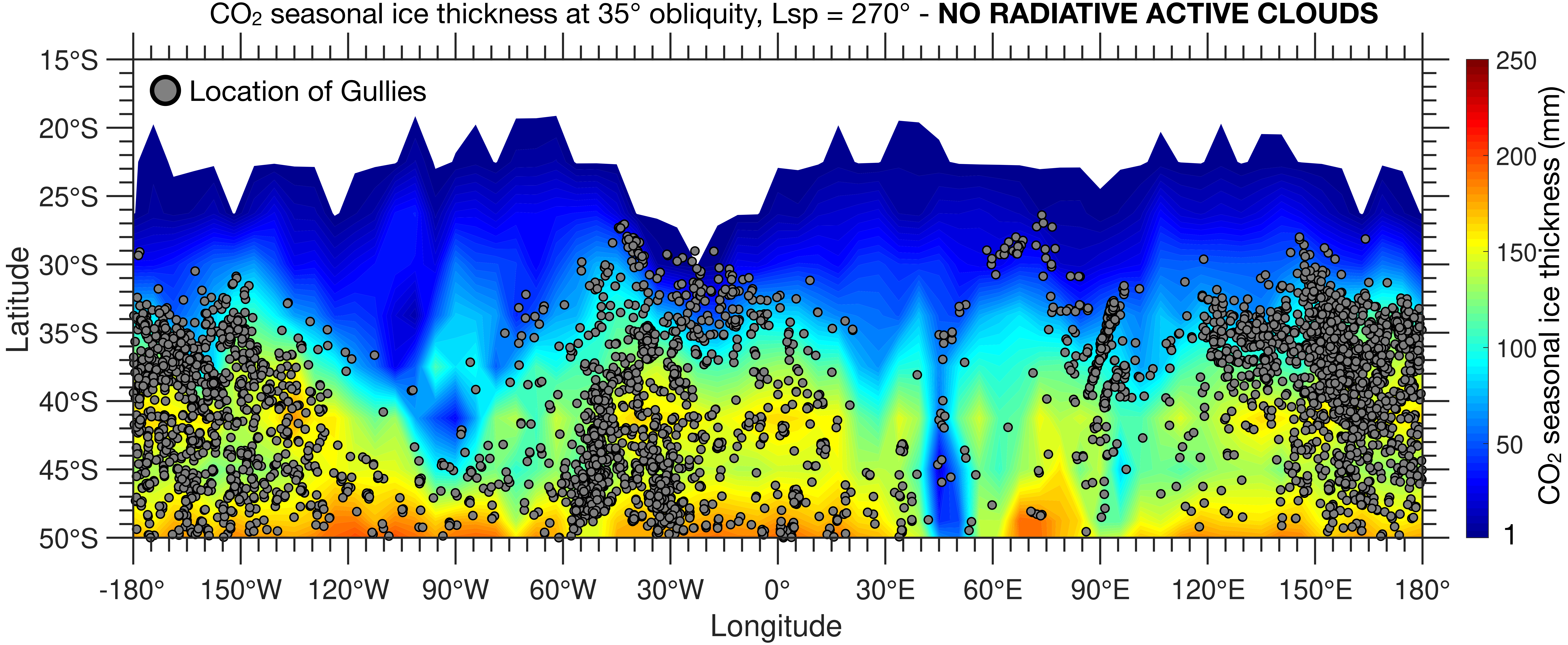
*Lange & Forget, 2026*

# The formation of Gullies on Mars

**Example of process : Gas fluidized debris flow**
(*Pilorget and Forget, Nature G. 2016*)

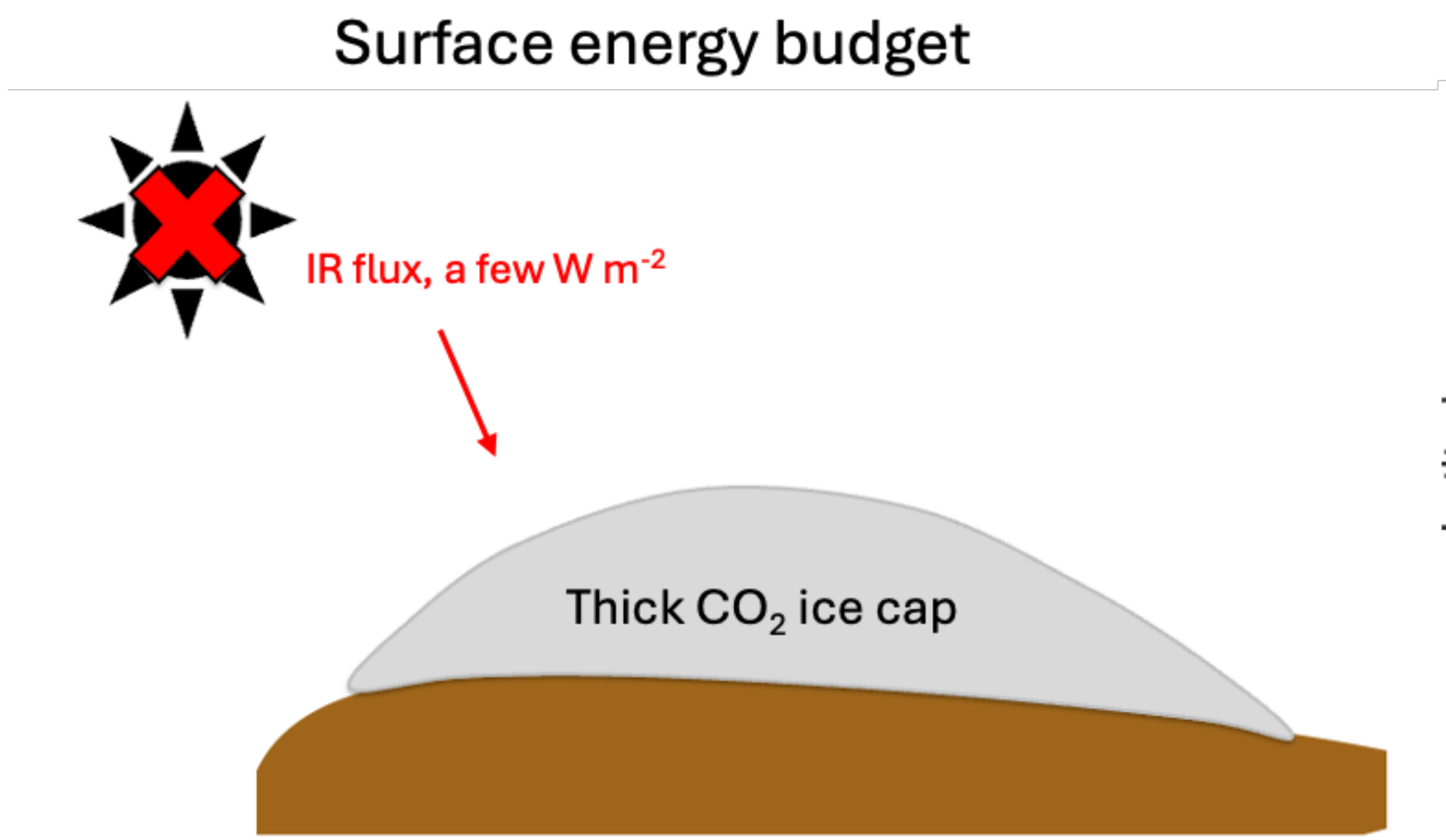


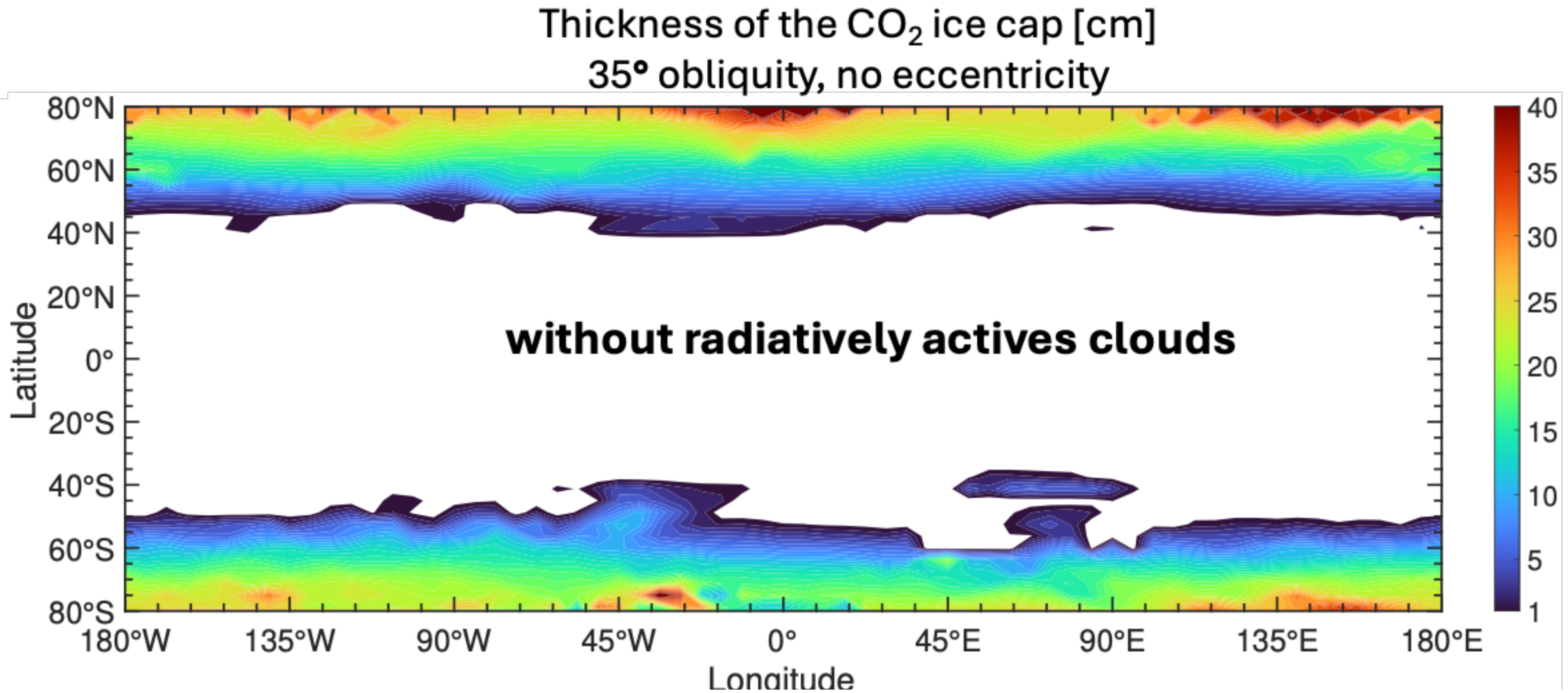
# The formation of Gullies on Mars




*Lange et al., in prep*

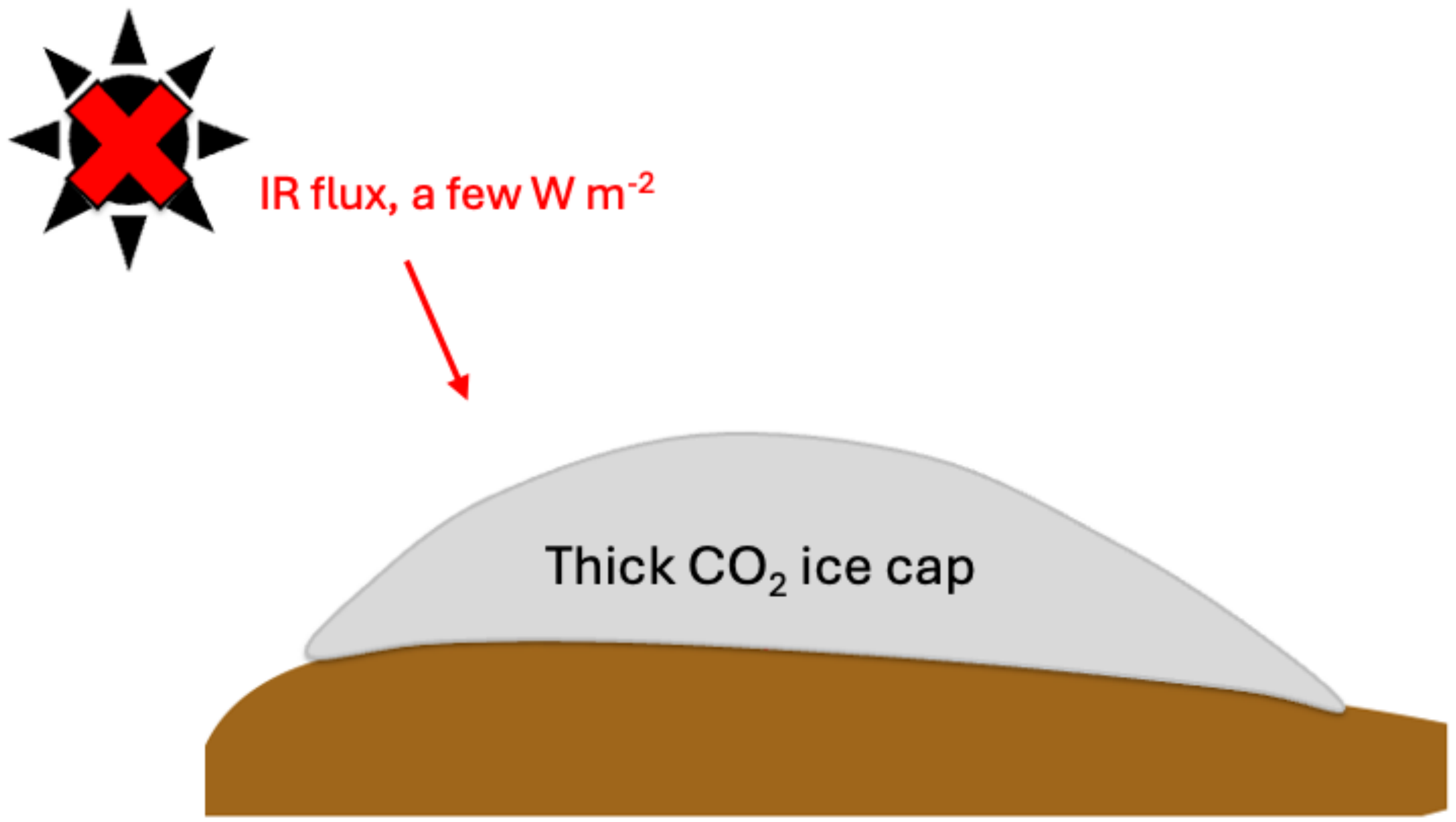
# The formation of Gullies on Mars



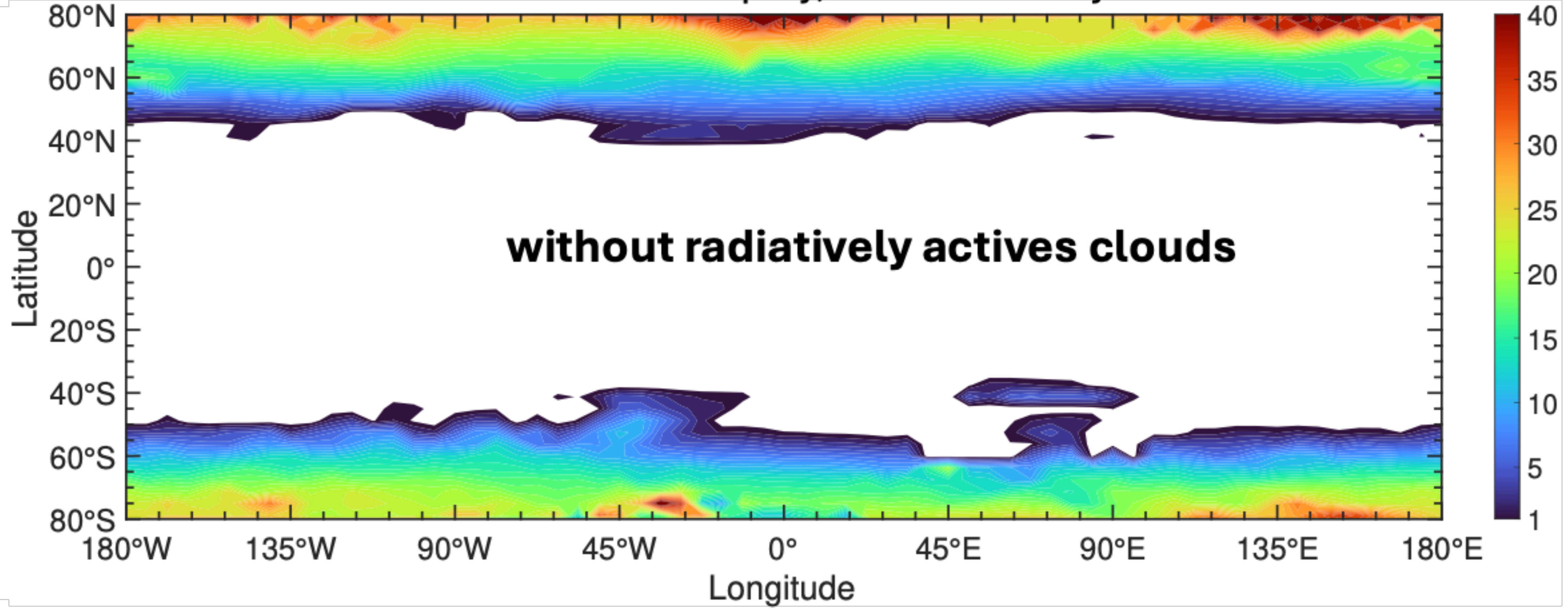



# The formation of Gullies on Mars

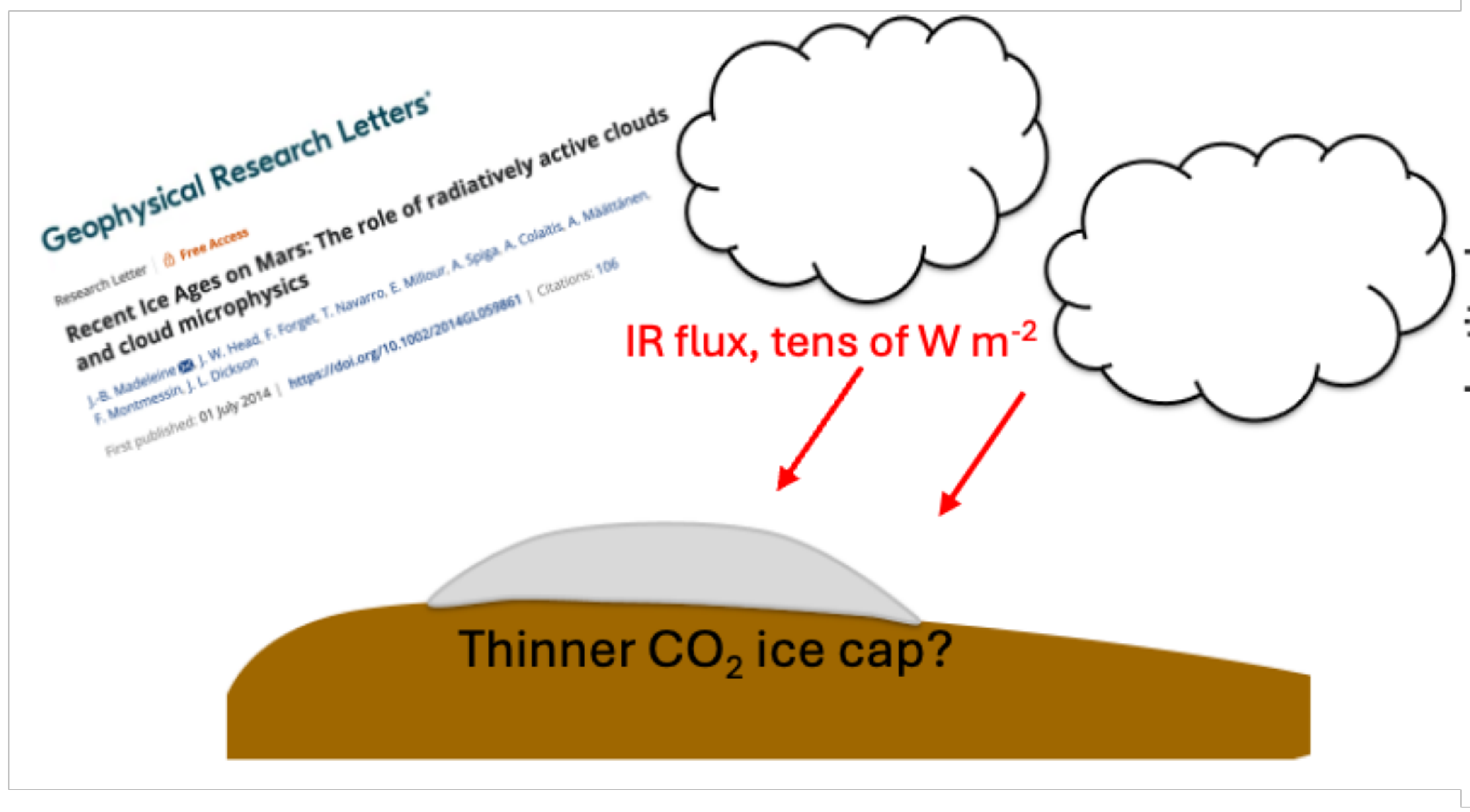
## Surface energy budget

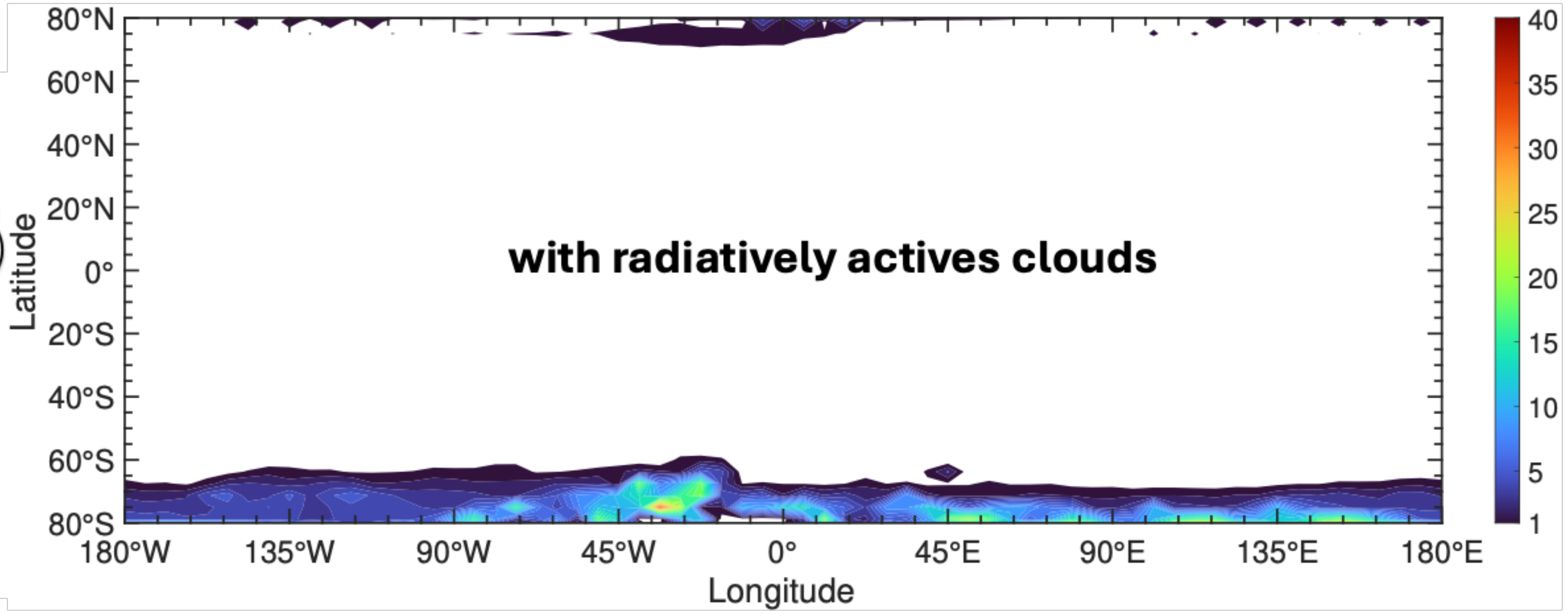



Thickness of the $CO_2$ ice cap [cm]
35° obliquity, no eccentricity




## **REVISED** Surface energy budget



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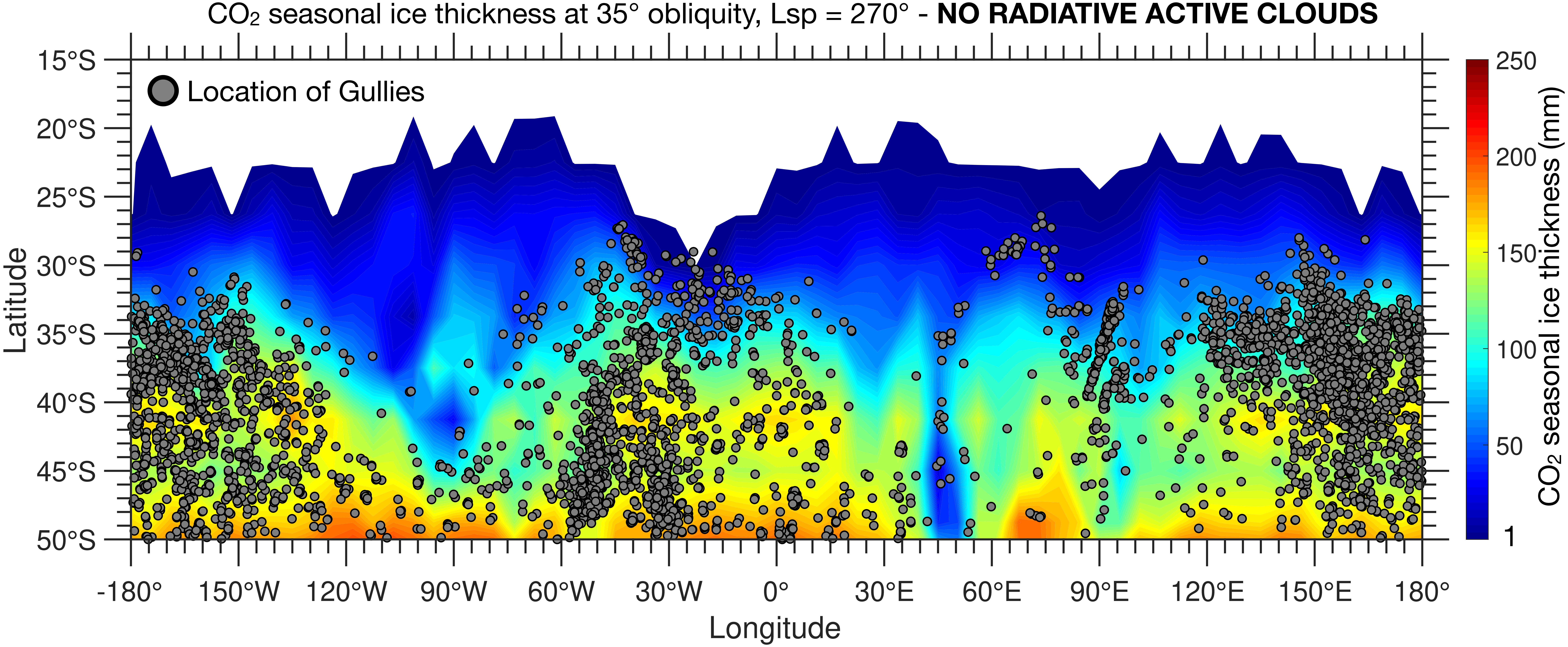


*Lange et al., in prep*

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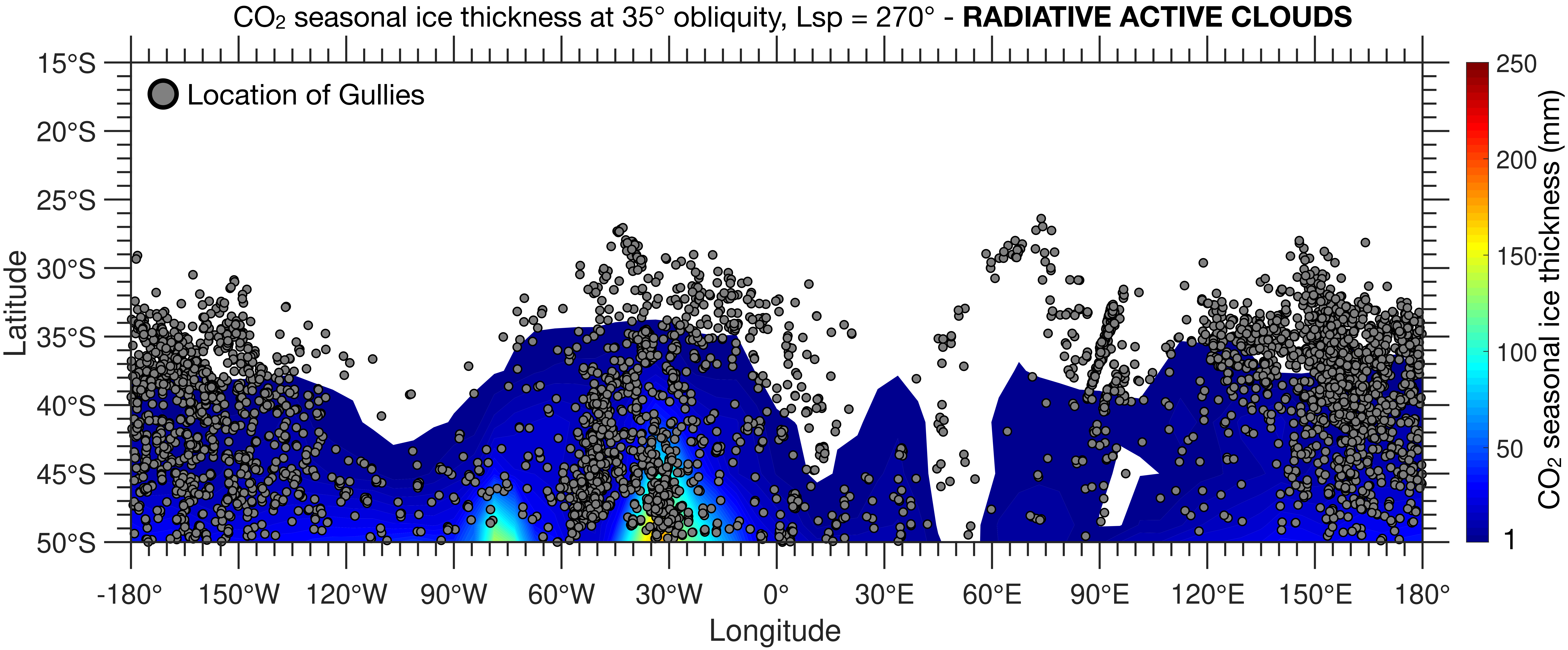


*Lange et al., in prep*

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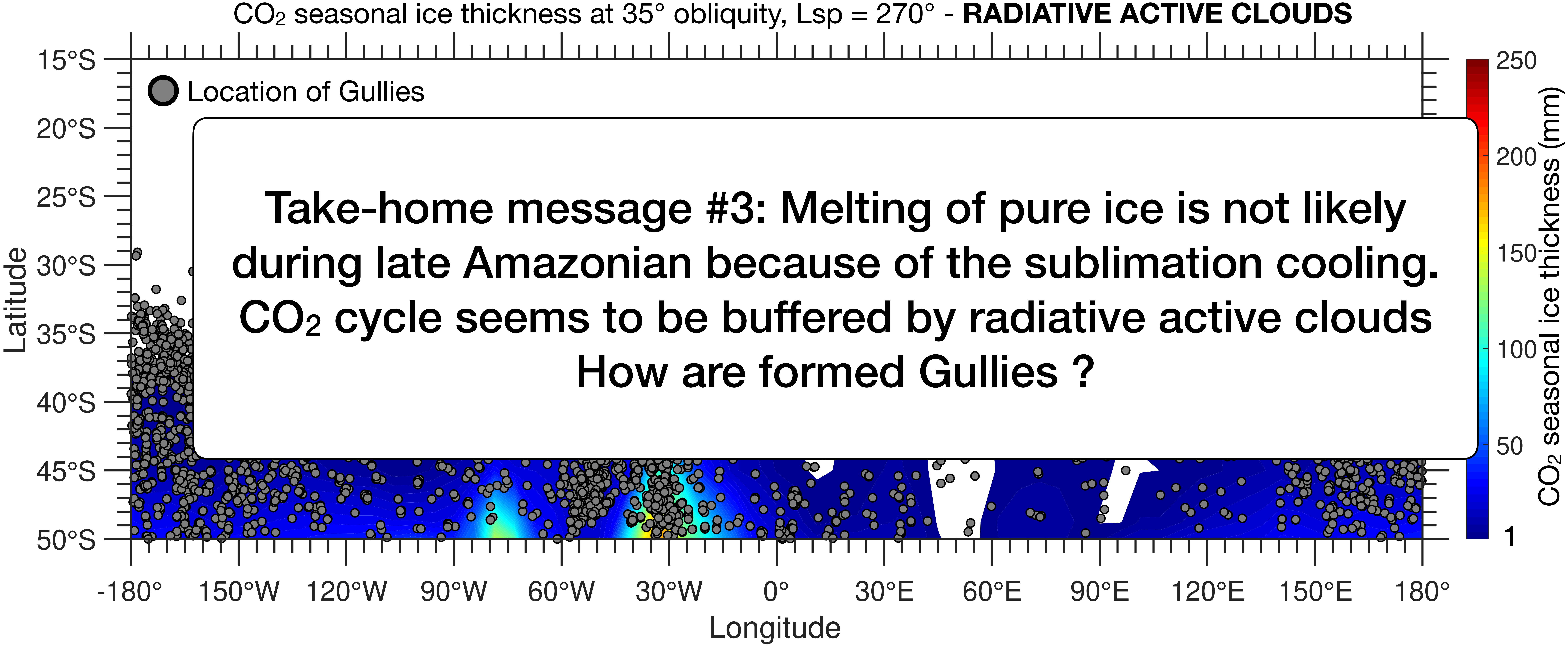



**Take-home message #3: Melting of pure ice is not likely during late Amazonian because of the sublimation cooling. $CO_2$ cycle seems to be buffered by radiative active clouds How are formed Gullies ?**

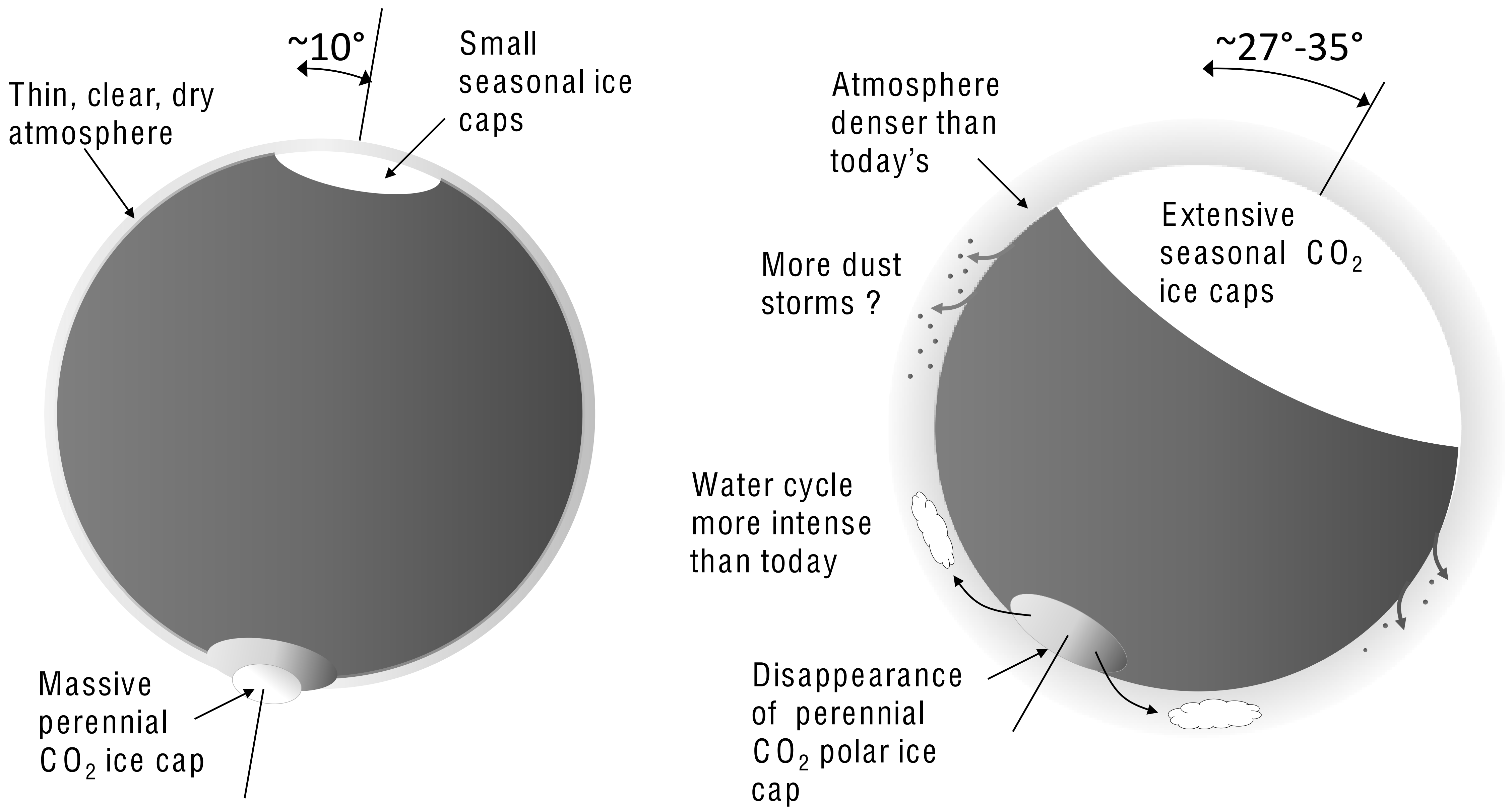
*Lange et al., in prep*

# Outline

# The Martian Puzzle

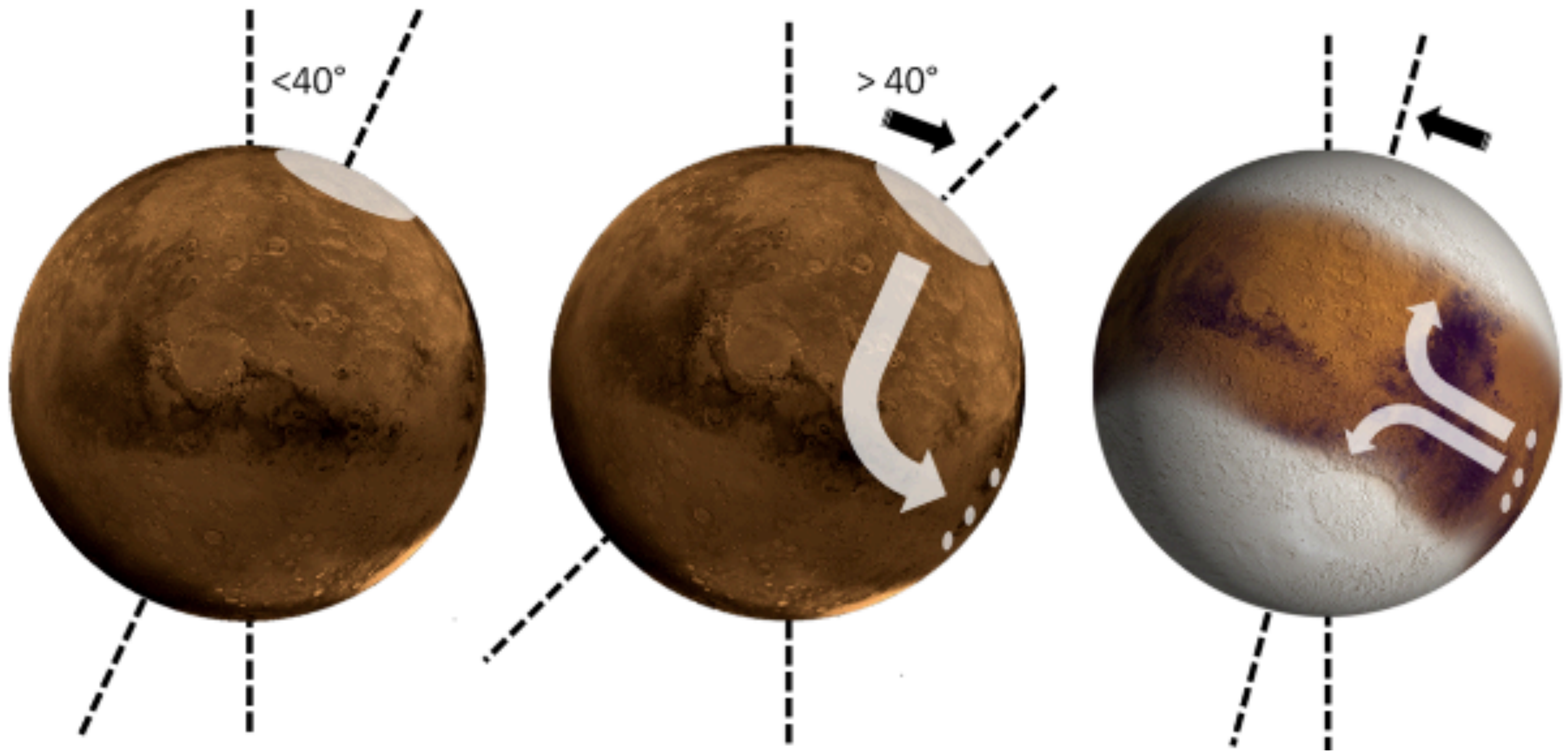
Effect of changing the obliquity on the Martian Climate from previous climate studies: current view

$CO_2$ ice




*Forget et al., 2017*

Water ice




*Forget et al., 2017*

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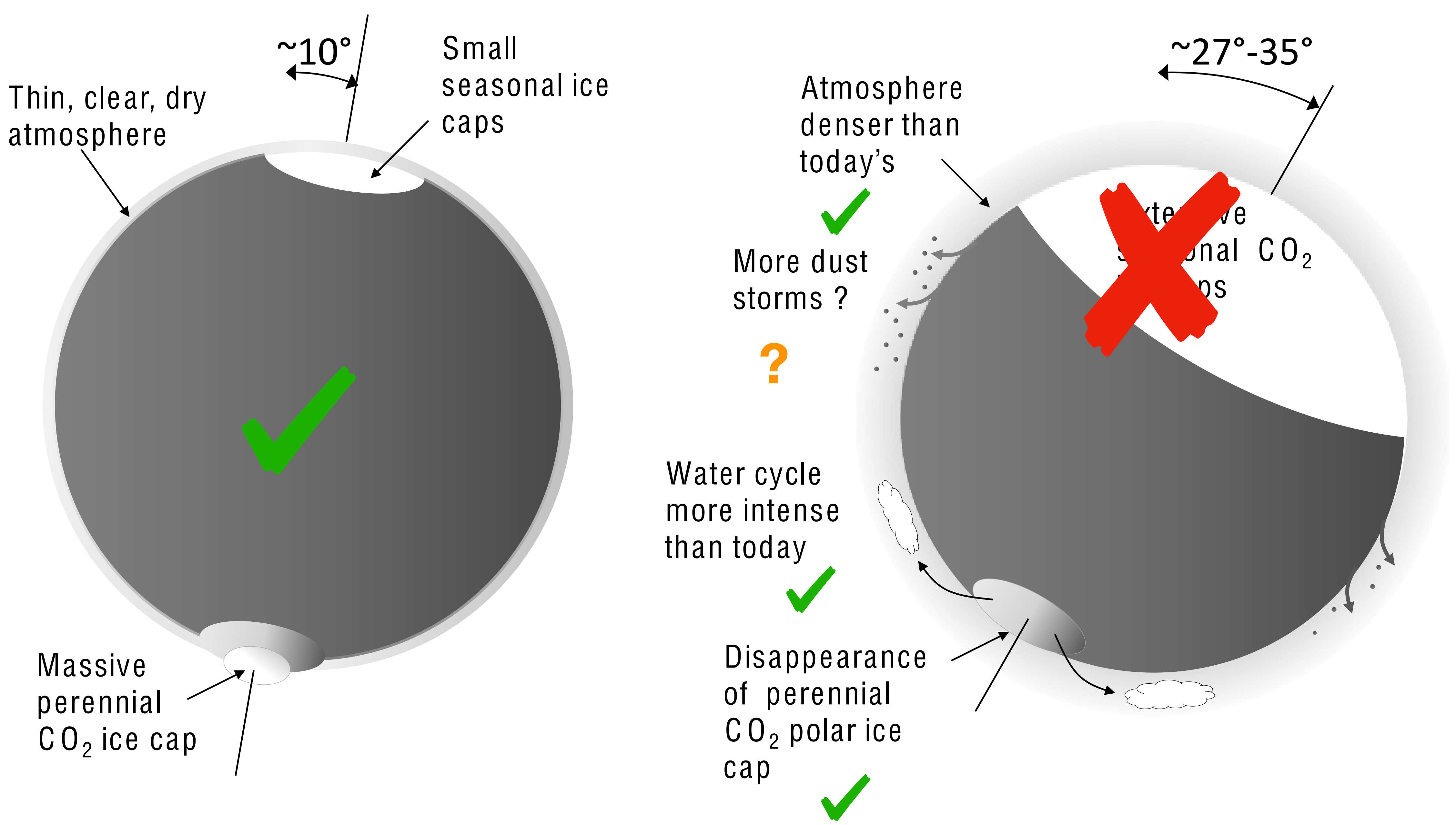
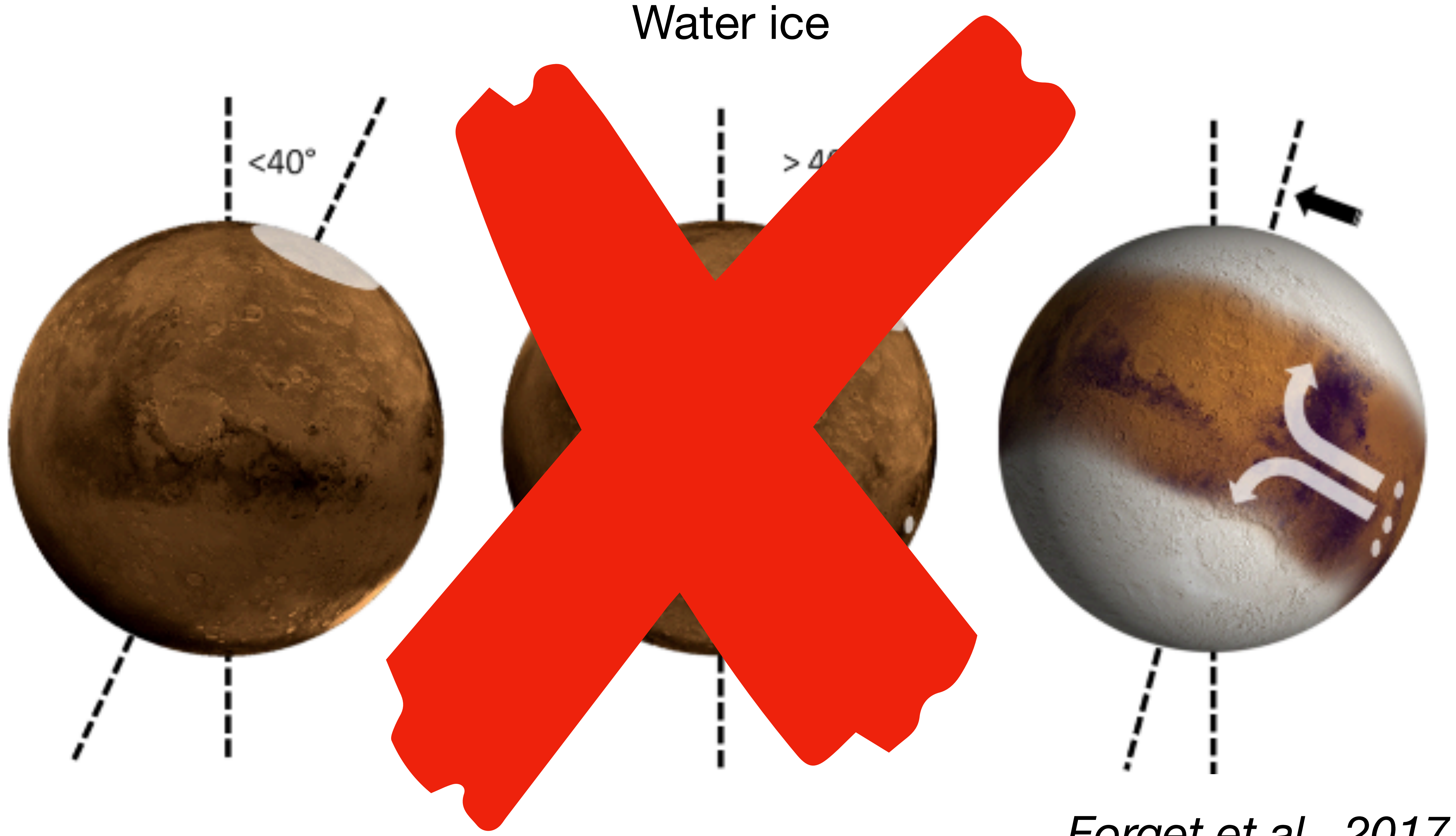



*Lange et al., in prep.*

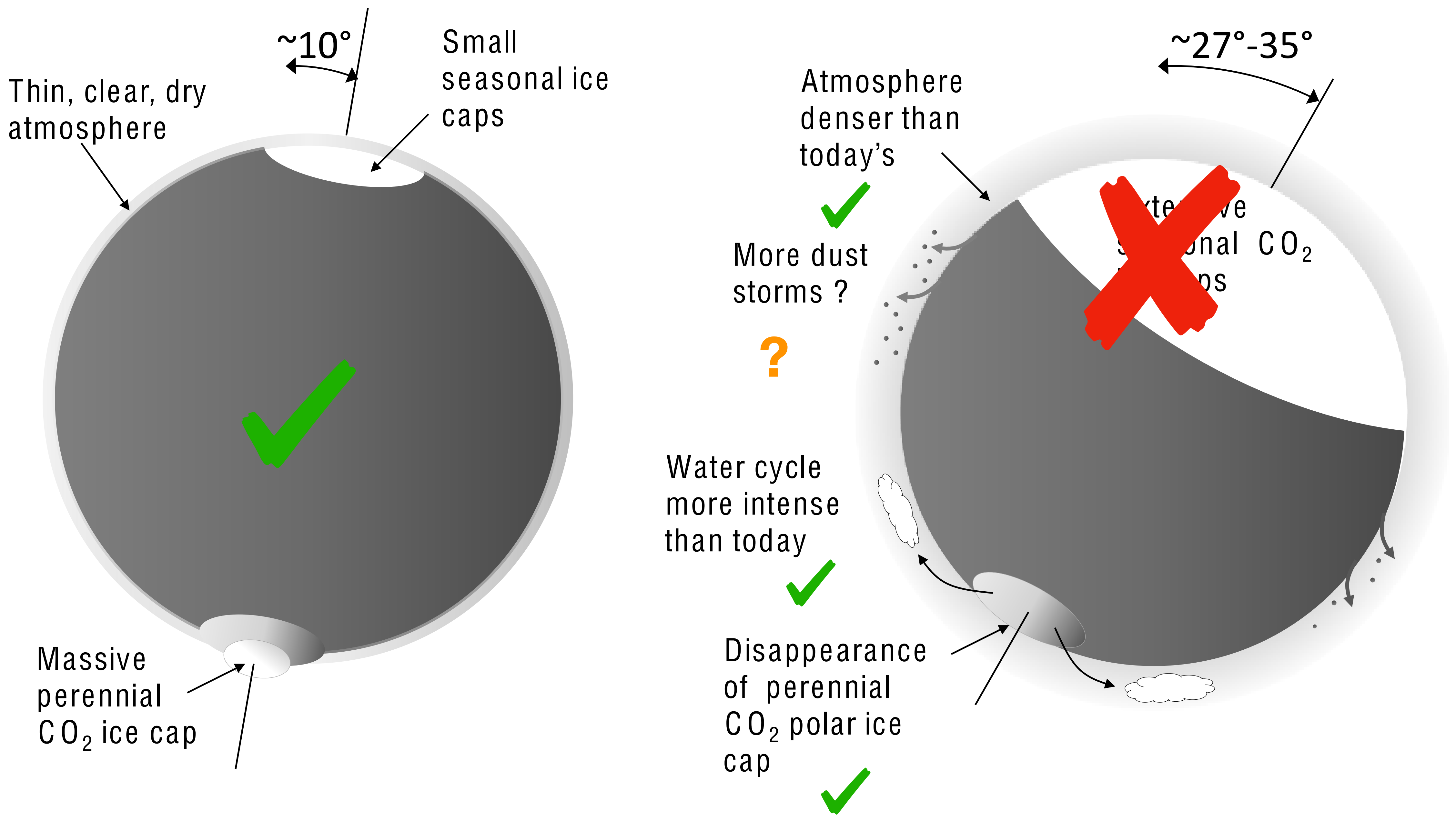



*Forget et al., 2017*

# The Martian Puzzle

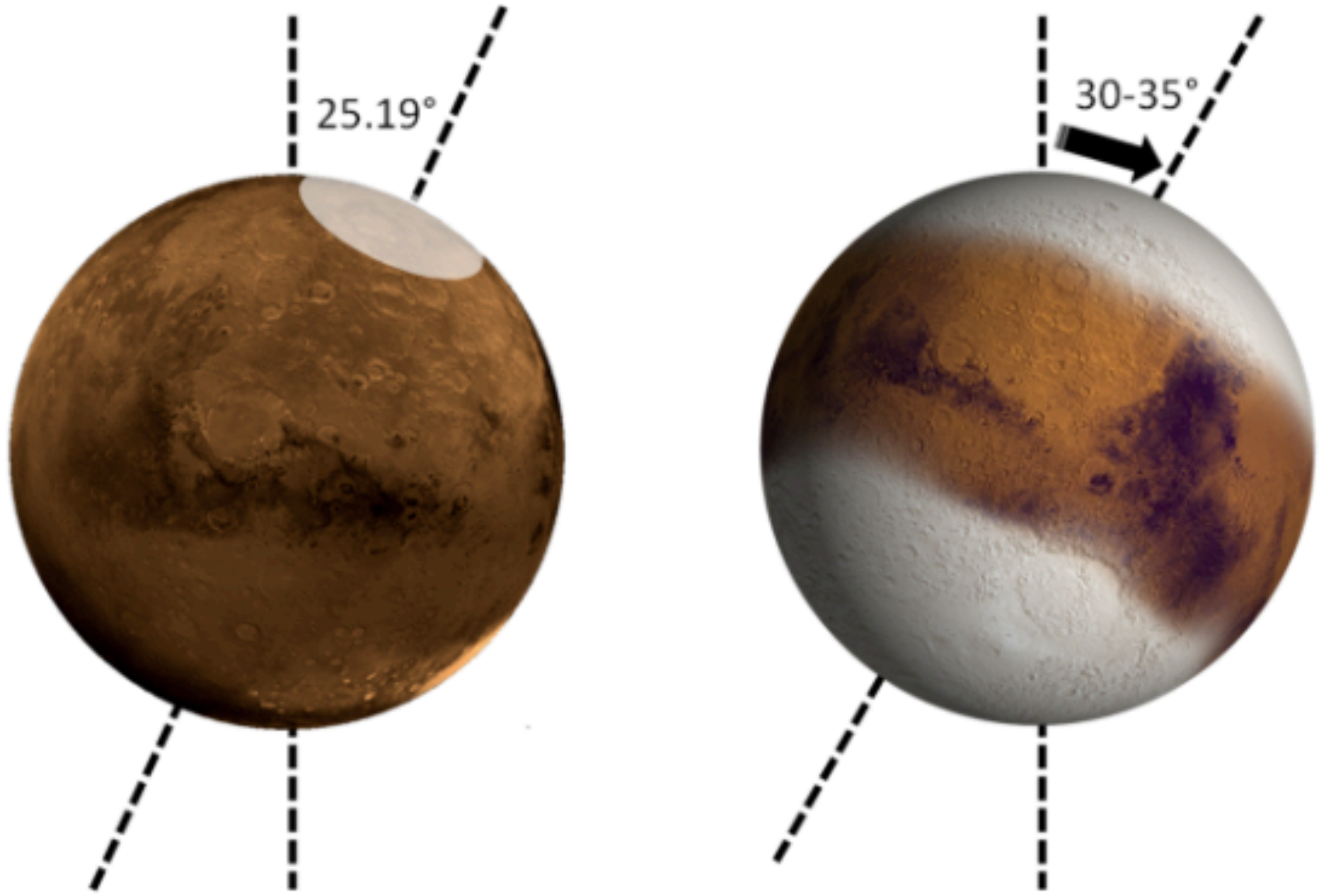
Effect of changing the obliquity on the Martian Climate from previous climate studies: current view

## $CO_2$ ice




*Lange et al., in prep.*

## Water ice




*Naar 2024, Forget & Naar, in prep.*

1. Despite a significant amount of studies on the Martian Paleoclimates, most models fail to explain the observations of recent ice features on Mars

2. The radiative effect of water ice clouds has been significant in the recent-past of Mars, and allows the formation of an ice-sheet at mid-latitude recently (e.g., 630 kyr ago).

3. Mid-latitudes subsurface ice is most-likely a remnant of this Recent Past of Mars, 630 kyr ago

4. Melting of pure water ice is not possible in the last millions years. $CO_2$ cycle seems to be buffered by the radiative effect of clouds. What could have triggered the formation of gullies?

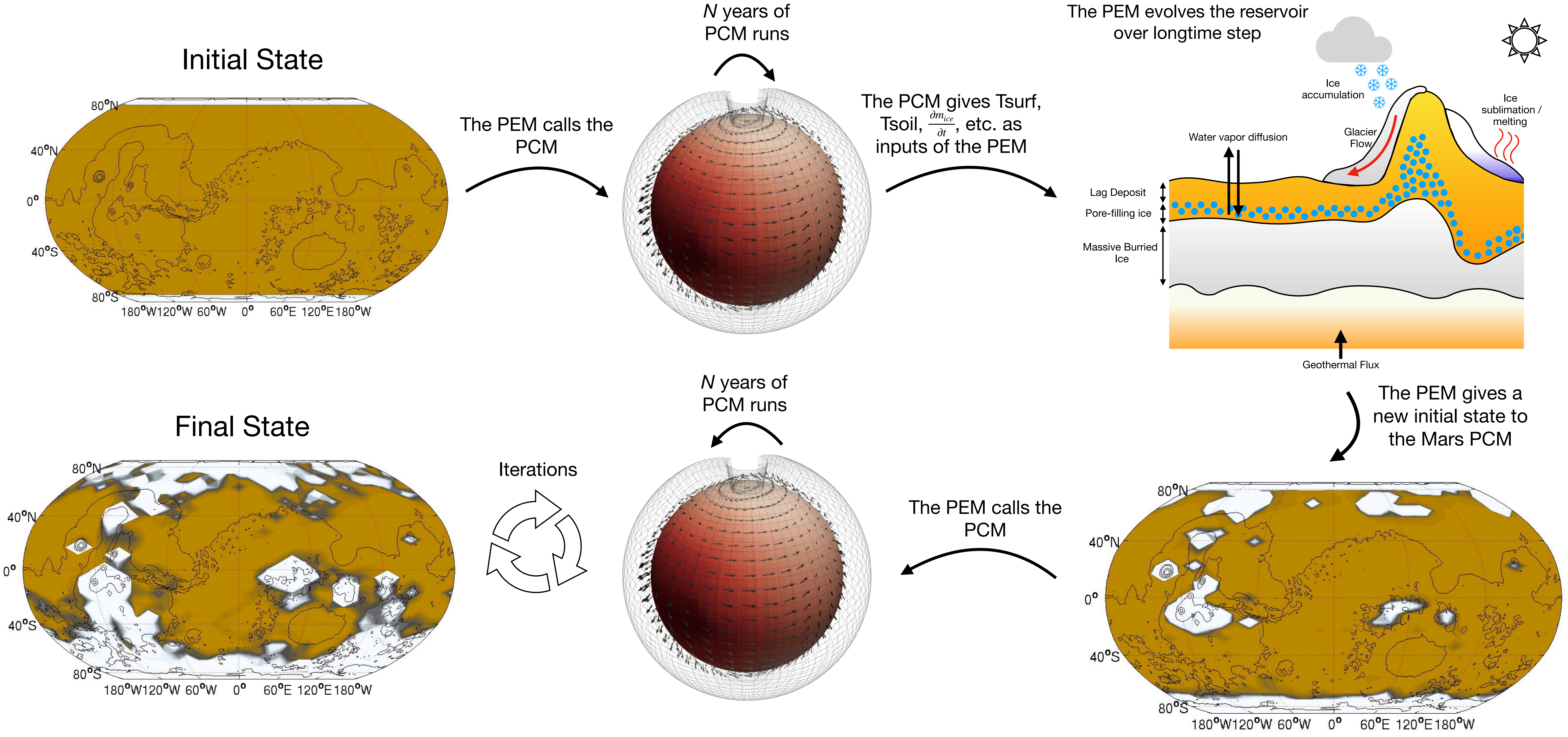
# Future works:

- Model the penetration of solar radiation into dusty ice to check wheter melting is possible (or not?) - snowpack model -> former JPL's postdoc A.Khuller-
- Have an interactive dust cycle
- Model the formation of the layered deposits

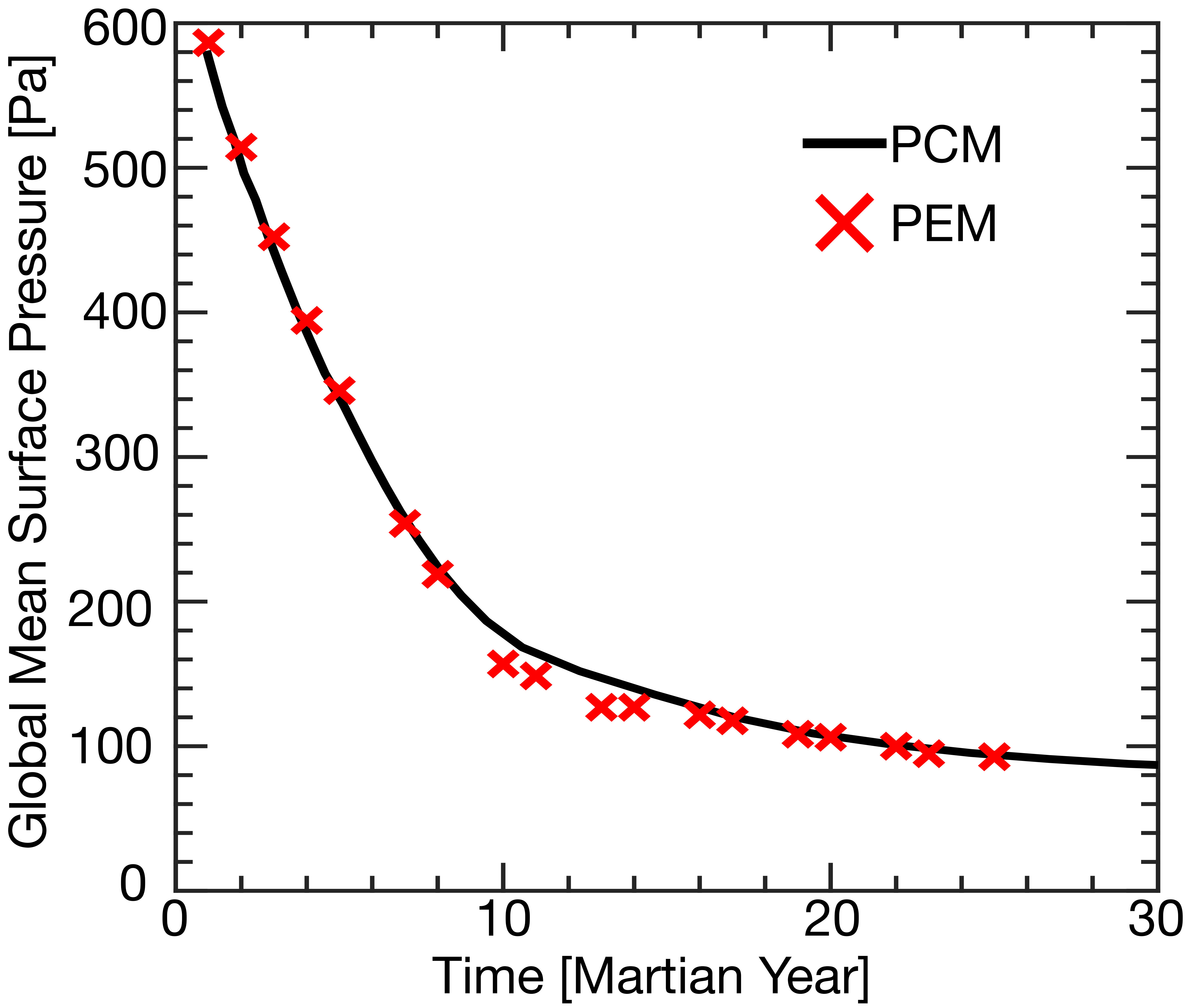
**Thank you !**


Back-up
15 km
Credits: ESA/DLR/FU Berlin

# Modeling Martian Paleoclimates: The Planetary Evolution Model (PEM)

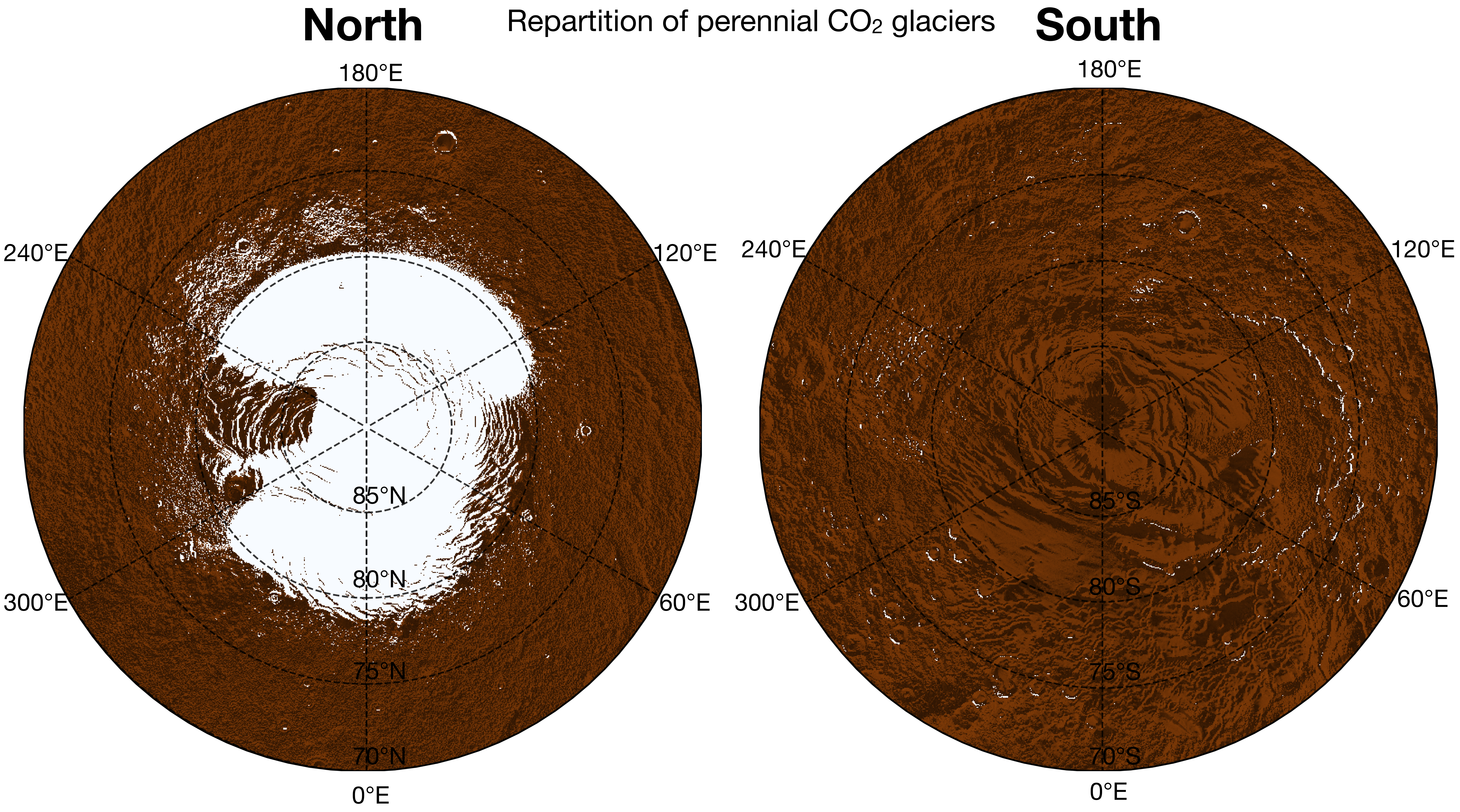


# Mars at Low Obliquity (5°)



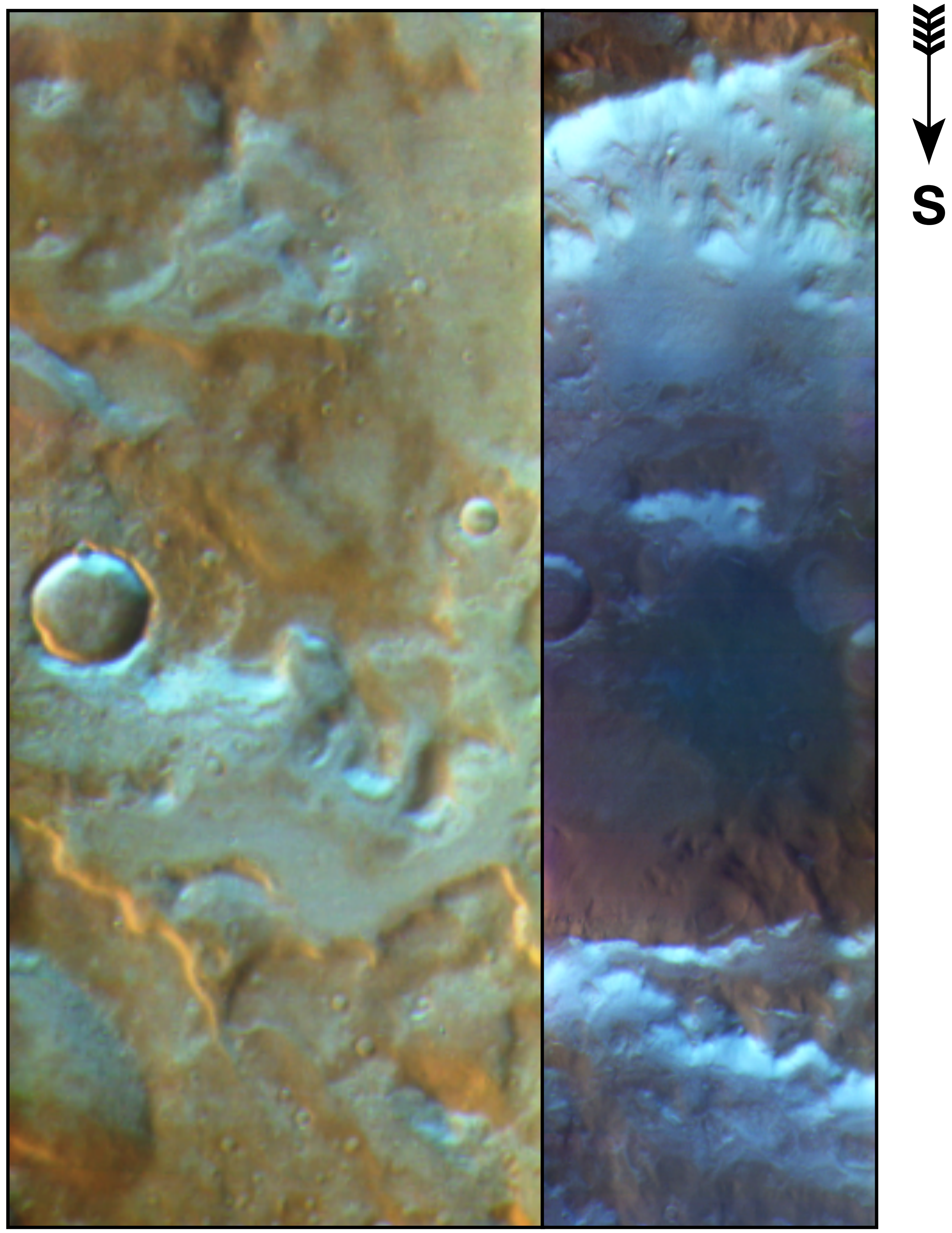

- At 5° obliquity, the pressure drops to 60 Pa, with an atmosphere mainly composed of $Ar/N_2$.
- Mars's surface pressure at 15° obliquity is ~ 260 Pa, with an atmosphere that is still composed of 90% $CO_2$.

# Mars at Low Obliquity (15°)



# Melting water ice on the surface of Mars

Water frost observed with THEMIS




*Lange et al. 2024*

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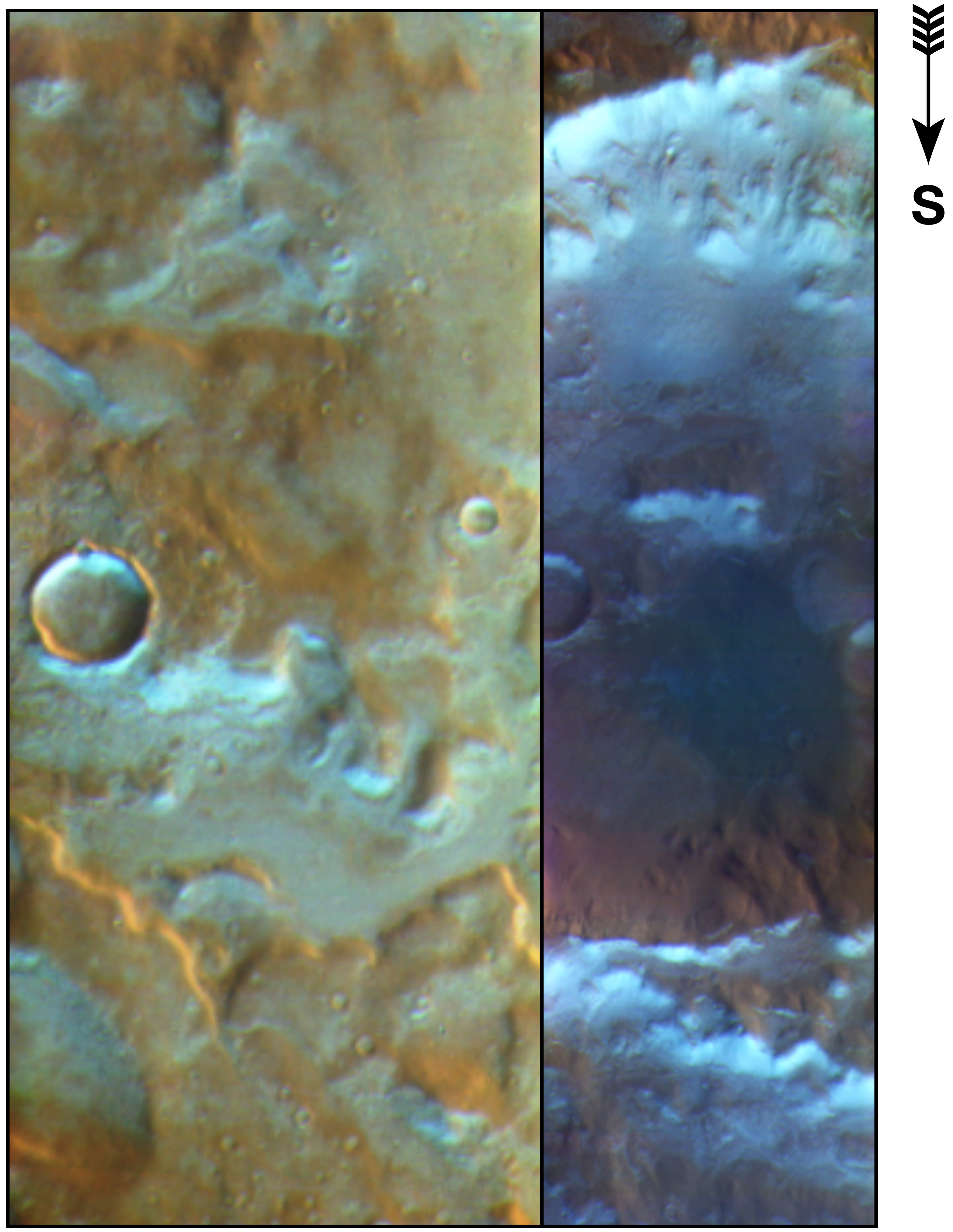
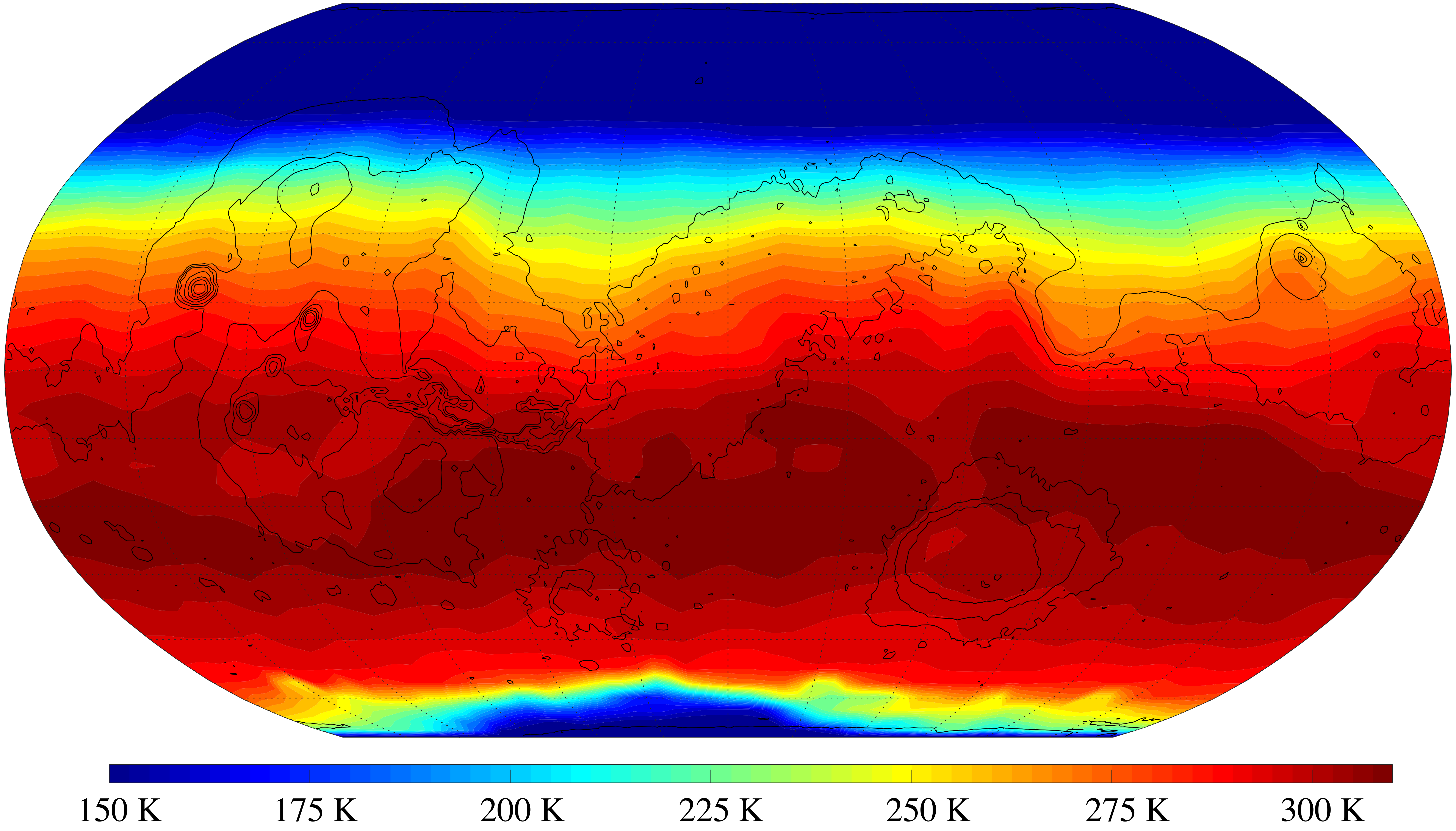



*Lange et al. 2024*

Modeled surface temperatures at 1 pm, Ls = 270°



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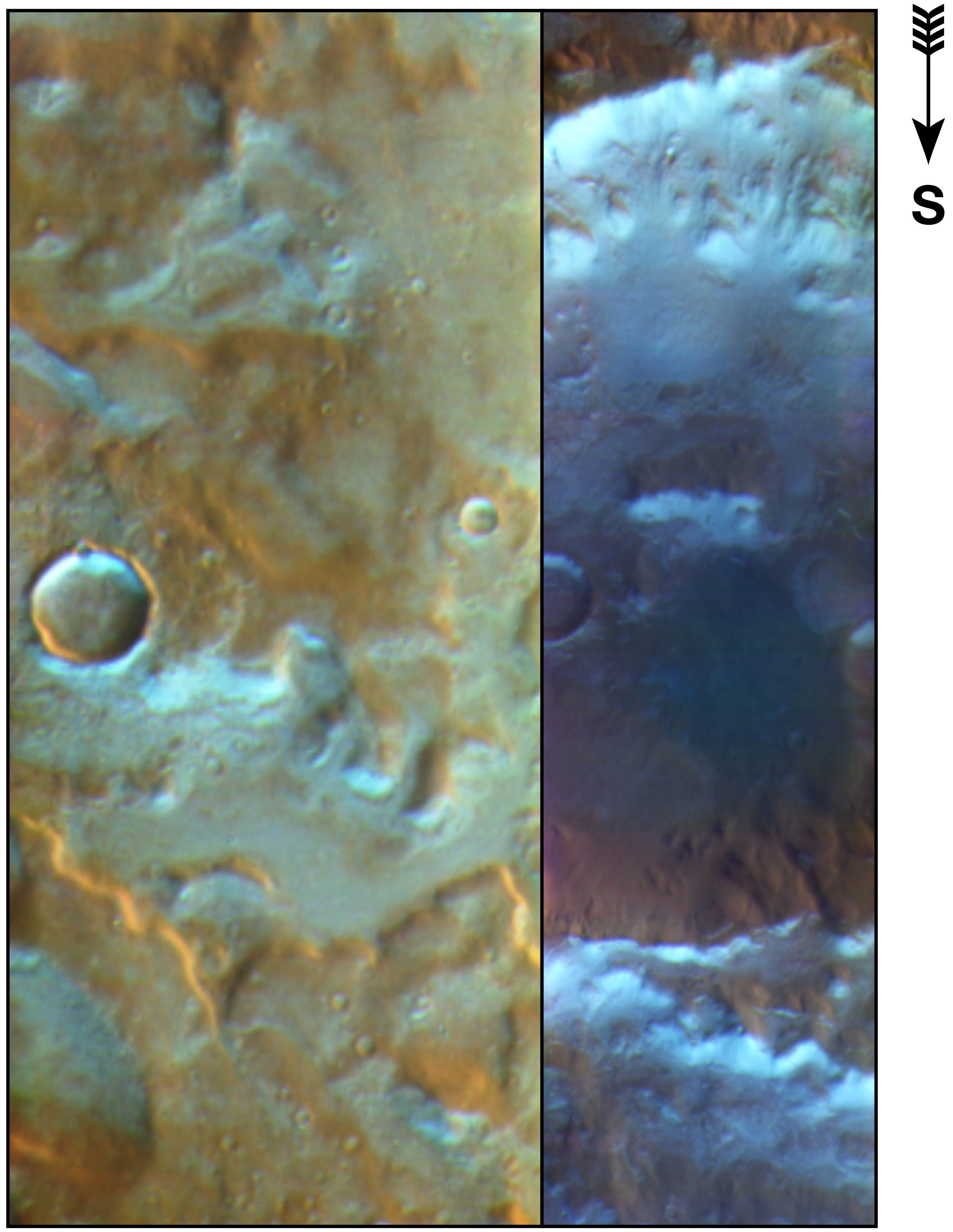


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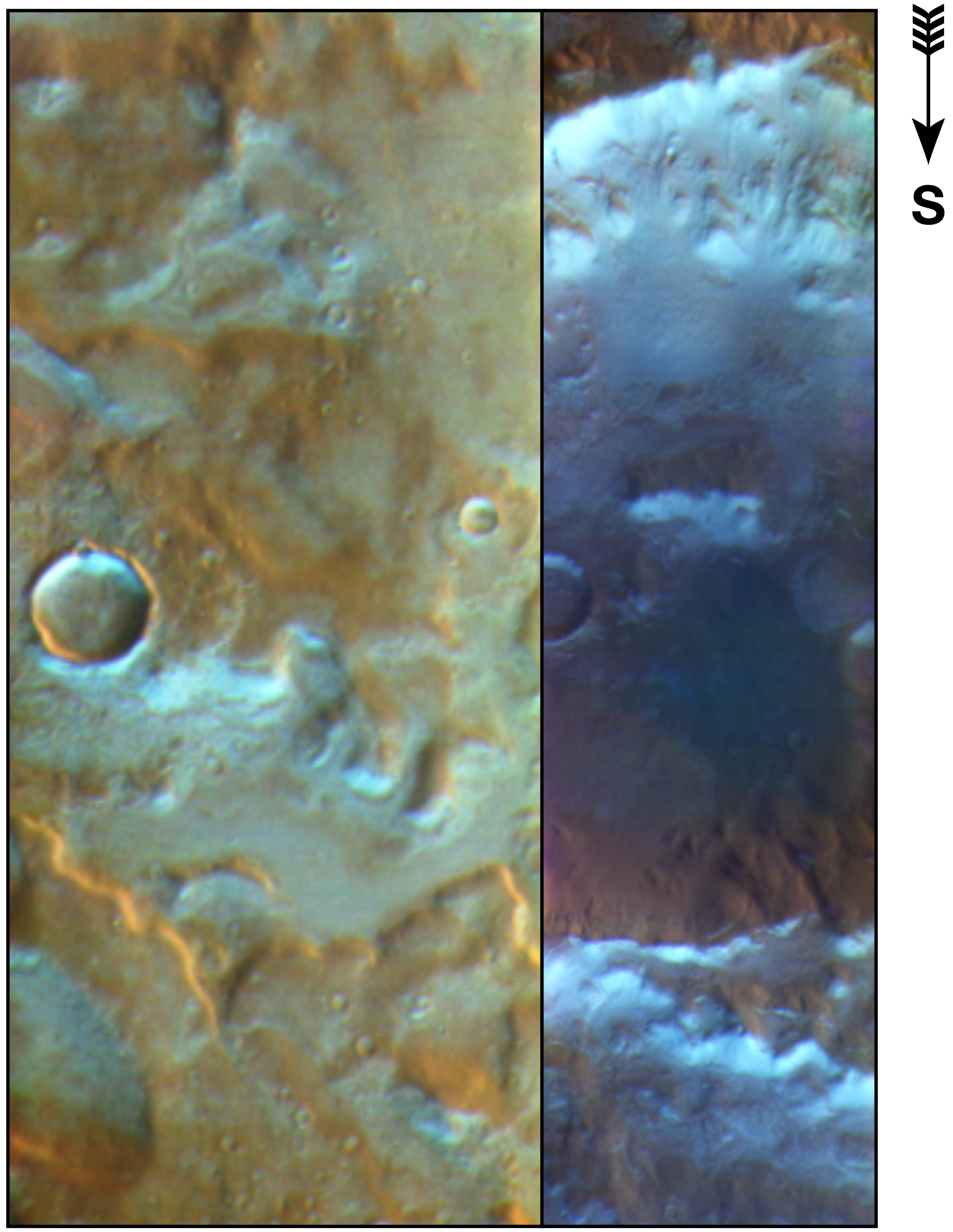
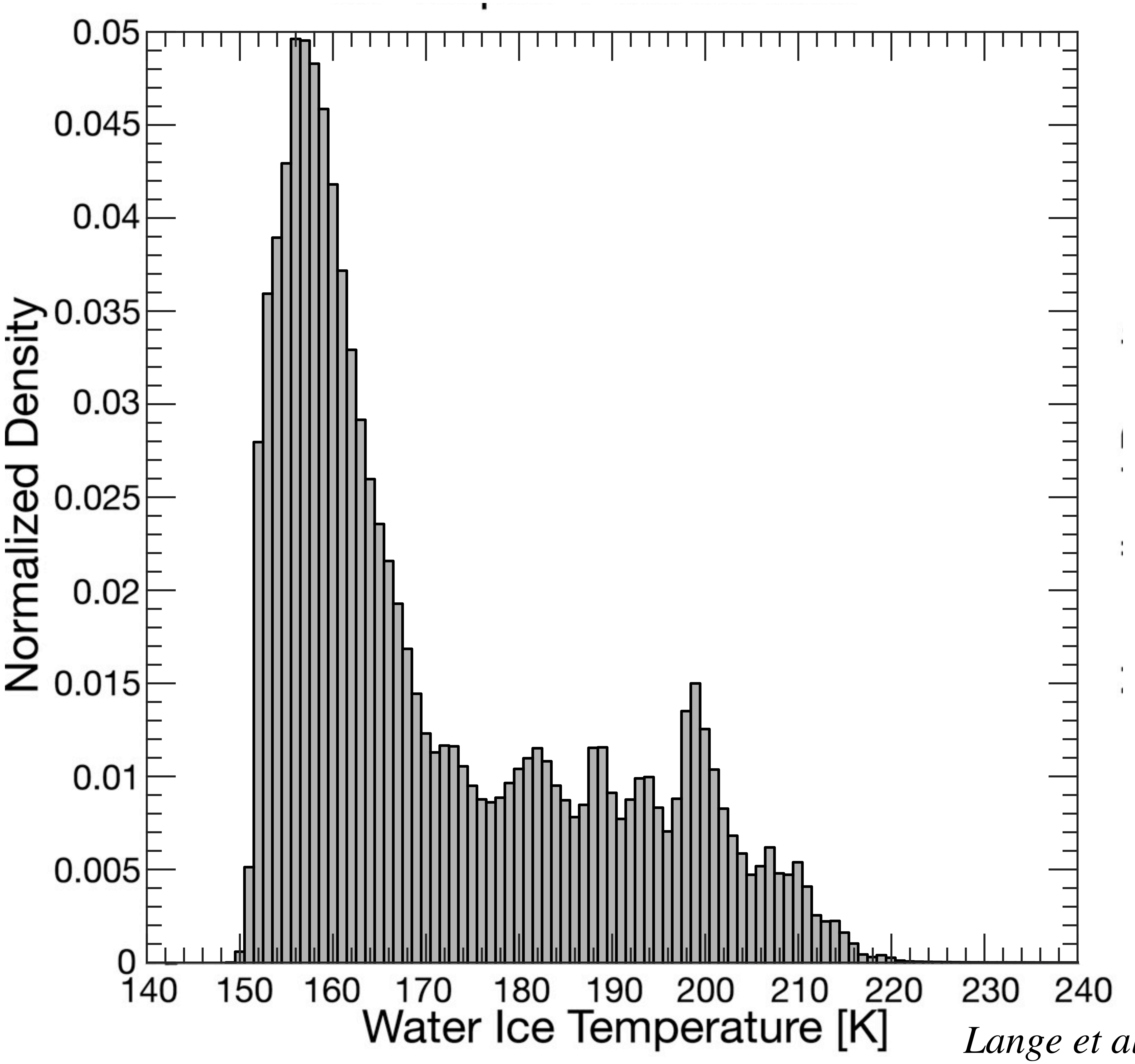



*Lange et al. 2024*

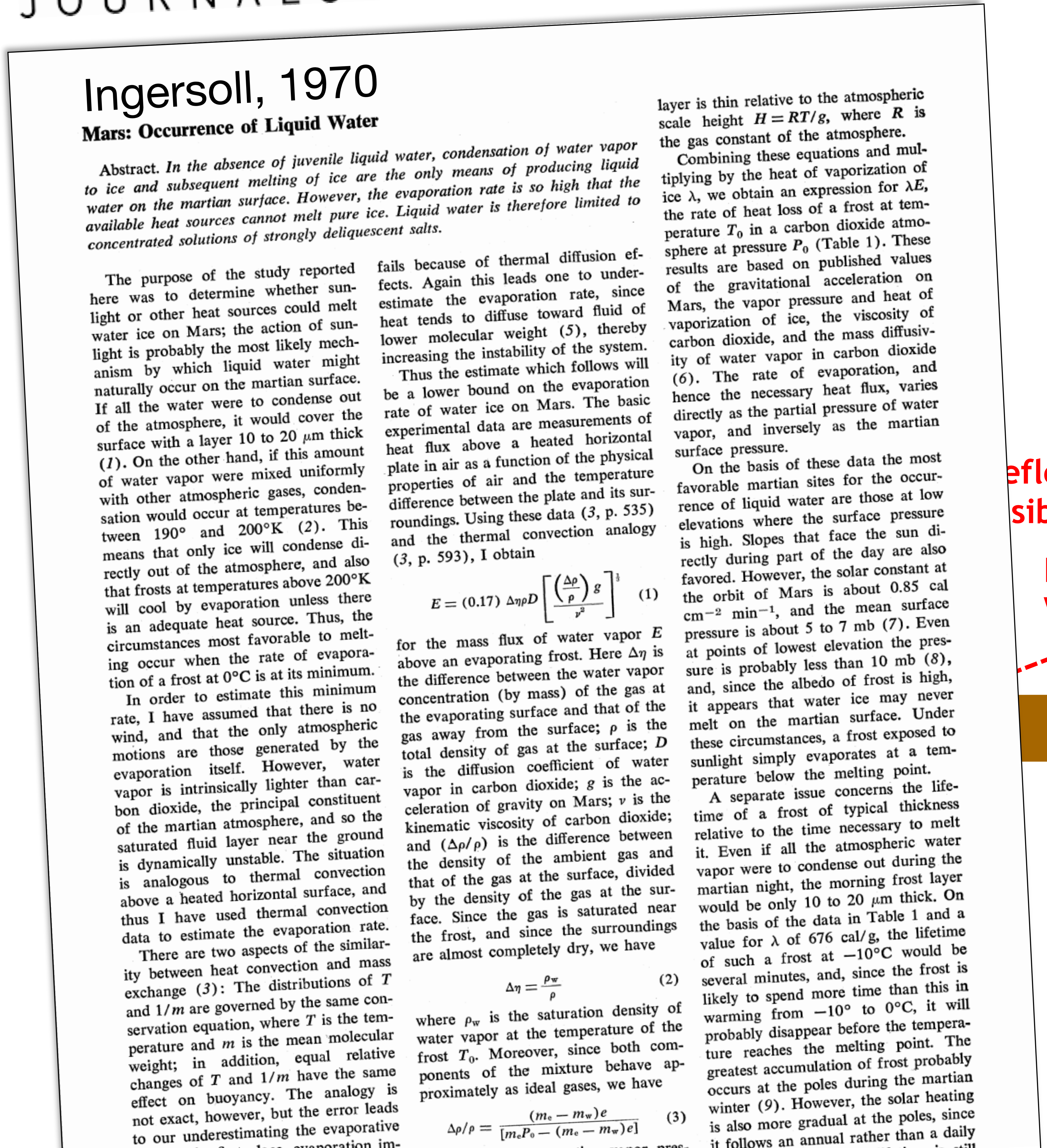
Water frost temperature measured with THEMIS




*Lange et al. 2024*

# The Key Effect of the Sublimation Cooling by Latent Heat

Science
JOURNALS AAAS



Ingersoll, 1970

## Mars: Occurrence of Liquid Water

Abstract. *In the absence of juvenile liquid water, condensation of water vapor to ice and subsequent melting of ice are the only means of producing liquid water on the martian surface. However, the evaporation rate is so high that the available heat sources cannot melt pure ice. Liquid water is therefore limited to concentrated solutions of strongly deliquescent salts.*

The purpose of the study reported here was to determine whether sunlight or other heat sources could melt water ice on Mars; the action of sunlight is probably the most likely mechanism by which liquid water might naturally occur on the martian surface. If all the water were to condense out of the atmosphere, it would cover the surface with a layer 10 to 20 μm thick (*1*). On the other hand, if this amount of water vapor were mixed uniformly with other atmospheric gases, condensation would occur at temperatures between 190° and 200°K (*2*). This means that only ice will condense directly out of the atmosphere, and also that frosts at temperatures above 200°K will cool by evaporation unless there is an adequate heat source. Thus, the circumstances most favorable to melting occur when the rate of evaporation of a frost at 0°C is at its minimum.

In order to estimate this minimum rate, I have assumed that there is no wind, and that the only atmospheric motions are those generated by the evaporation itself. However, water vapor is intrinsically lighter than carbon dioxide, the principal constituent of the martian atmosphere, and so the saturated fluid layer near the ground is dynamically unstable. The situation is analogous to thermal convection above a heated horizontal surface, and thus I have used thermal convection data to estimate the evaporation rate.

There are two aspects of the similarity between heat convection and mass exchange (*3*): The distributions of $T$ and $1/m$ are governed by the same conservation equation, where $T$ is the temperature and $m$ is the mean molecular weight; in addition, equal relative changes of $T$ and $1/m$ have the same effect on buoyancy. The analogy is not exact, however, but the error leads to our underestimating the evaporative

fails because of thermal diffusion effects. Again this leads one to underestimate the evaporation rate, since heat tends to diffuse toward fluid of lower molecular weight (*5*), thereby increasing the instability of the system.

Thus the estimate which follows will be a lower bound on the evaporation rate of water ice on Mars. The basic experimental data are measurements of heat flux above a heated horizontal plate in air as a function of the physical properties of air and the temperature difference between the plate and its surroundings. Using these data (*3*, p. 535) and the thermal convection analogy (*3*, p. 593), I obtain

$$E = (0.17)\ \Delta\eta\rho D \left[\frac{\left(\frac{\Delta\rho}{\rho}\right) g}{\nu^2}\right]^{\frac{1}{3}} \quad (1)$$

for the mass flux of water vapor $E$ above an evaporating frost. Here $\Delta\eta$ is the difference between the water vapor concentration (by mass) of the gas at the evaporating surface and that of the gas away from the surface; $\rho$ is the total density of gas at the surface; $D$ is the diffusion coefficient of water vapor in carbon dioxide; $g$ is the acceleration of gravity on Mars; $\nu$ is the kinematic viscosity of carbon dioxide; and $(\Delta\rho/\rho)$ is the difference between the density of the ambient gas and that of the gas at the surface, divided by the density of the gas at the surface. Since the gas is saturated near the frost, and since the surroundings are almost completely dry, we have

$$\Delta\eta = \frac{\rho_w}{\rho} \quad (2)$$

where $\rho_w$ is the saturation density of water vapor at the temperature of the frost $T_0$. Moreover, since both components of the mixture behave approximately as ideal gases, we have

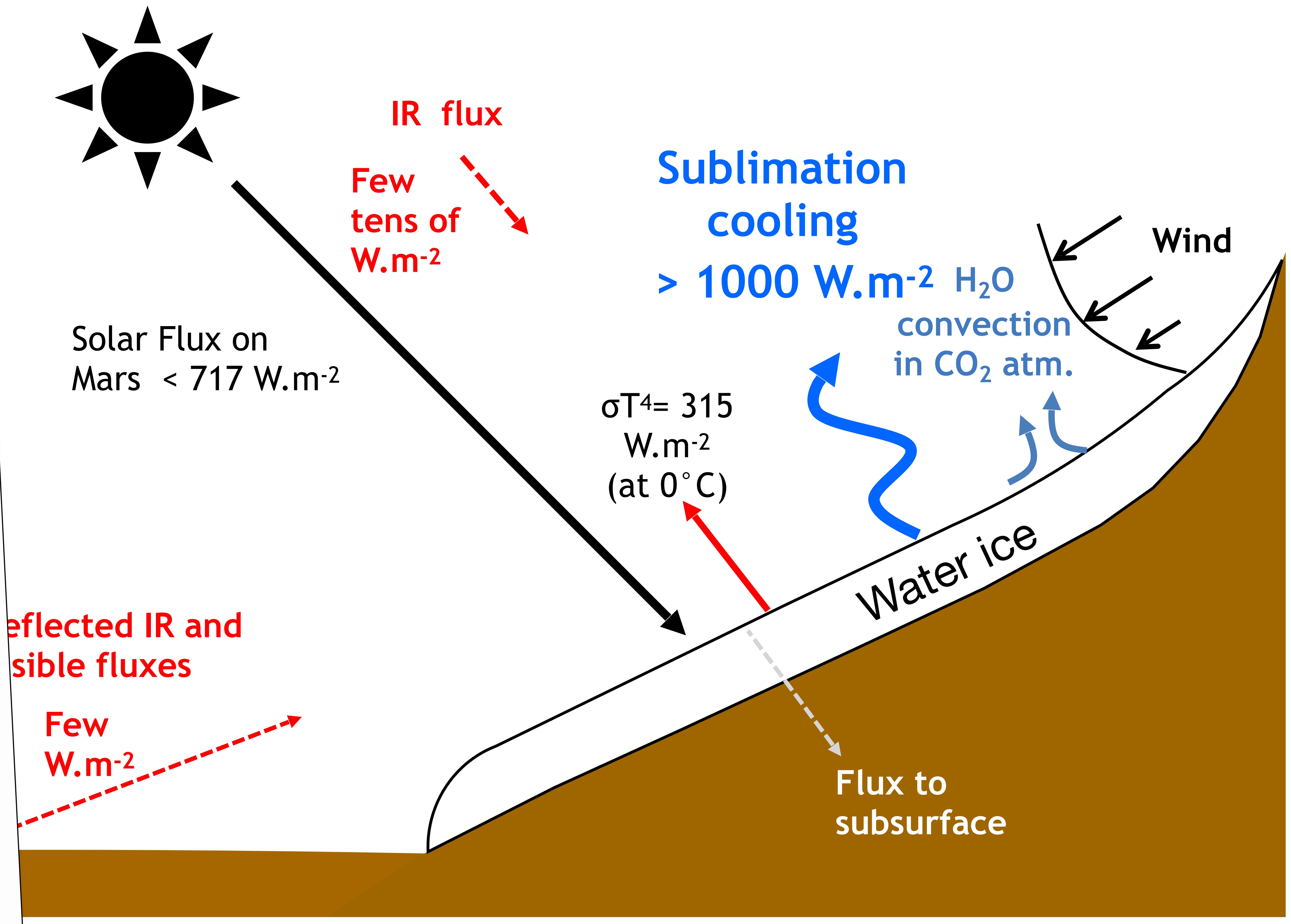
$$\Delta\rho/\rho = \frac{(m_c - m_w)e}{[m_c P_0 - (m_c - m_w)e]} \quad (3)$$

layer is thin relative to the atmospheric scale height $H = RT/g$, where $R$ is the gas constant of the atmosphere.

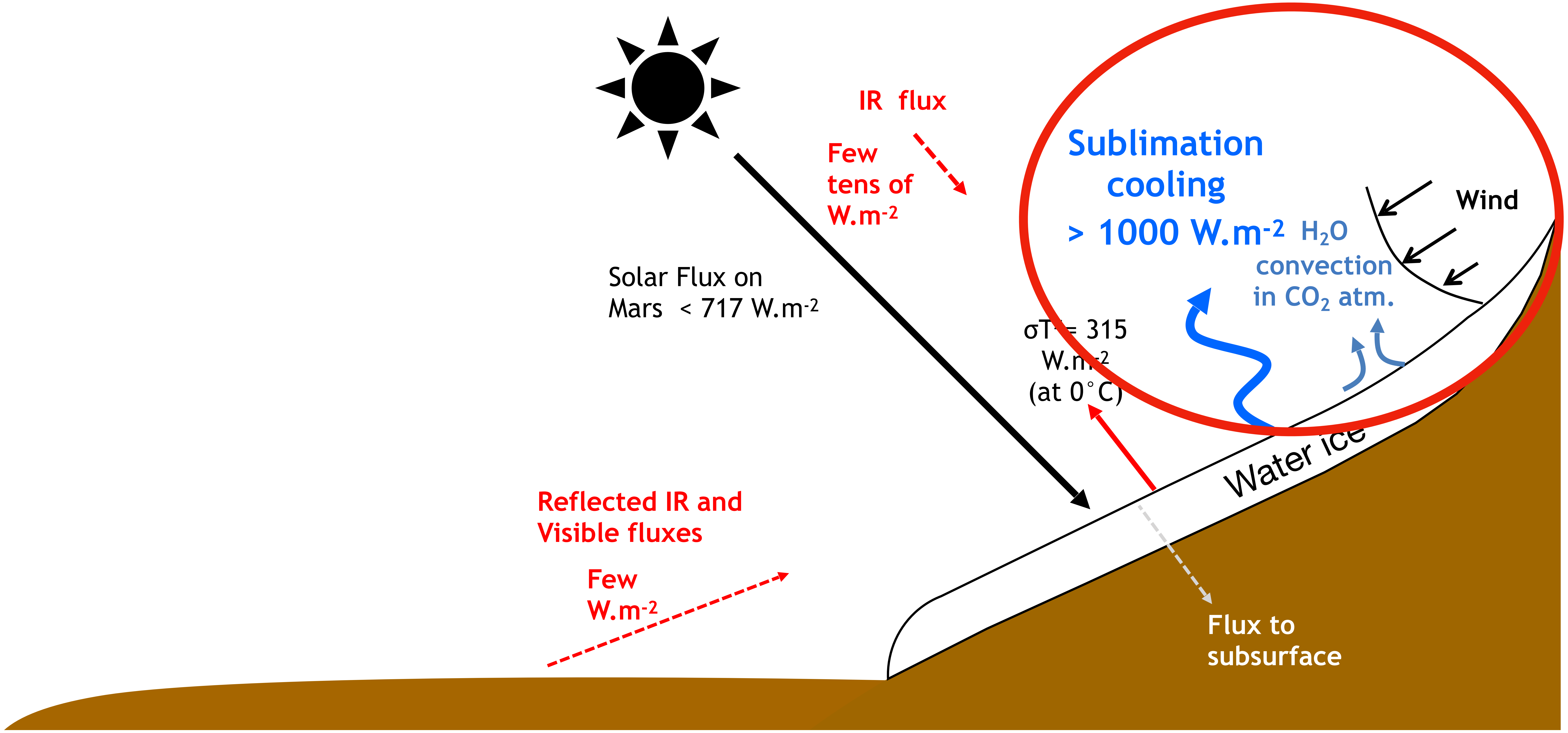
Combining these equations and multiplying by the heat of vaporization of ice λ, we obtain an expression for λ$E$, the rate of heat loss of a frost at temperature $T_0$ in a carbon dioxide atmosphere at pressure $P_0$ (Table 1). These results are based on published values of the gravitational acceleration on Mars, the vapor pressure and heat of vaporization of ice, the viscosity of carbon dioxide, and the mass diffusivity of water vapor in carbon dioxide (*6*). The rate of evaporation, and hence the necessary heat flux, varies directly as the partial pressure of water vapor, and inversely as the martian surface pressure.

On the basis of these data the most favorable martian sites for the occurrence of liquid water are those at low elevations where the surface pressure is high. Slopes that face the sun directly during part of the day are also favored. However, the solar constant at the orbit of Mars is about 0.85 cal cm$^{-2}$ min$^{-1}$, and the mean surface pressure is about 5 to 7 mb (*7*). Even at points of lowest elevation the pressure is probably less than 10 mb (*8*), and, since the albedo of frost is high, it appears that water ice may never melt on the martian surface. Under these circumstances, a frost exposed to sunlight simply evaporates at a temperature below the melting point.

A separate issue concerns the lifetime of a frost of typical thickness relative to the time necessary to melt it. Even if all the atmospheric water vapor were to condense out during the martian night, the morning frost layer would be only 10 to 20 μm thick. On the basis of the data in Table 1 and a value for λ of 676 cal/g, the lifetime of such a frost at −10°C would be several minutes, and, since the frost is likely to spend more time than this in warming from −10° to 0°C, it will probably disappear before the temperature reaches the melting point. The greatest accumulation of frost probably occurs at the poles during the martian winter (*9*). However, the solar heating is also more gradual at the poles, since it follows an annual rather than a daily

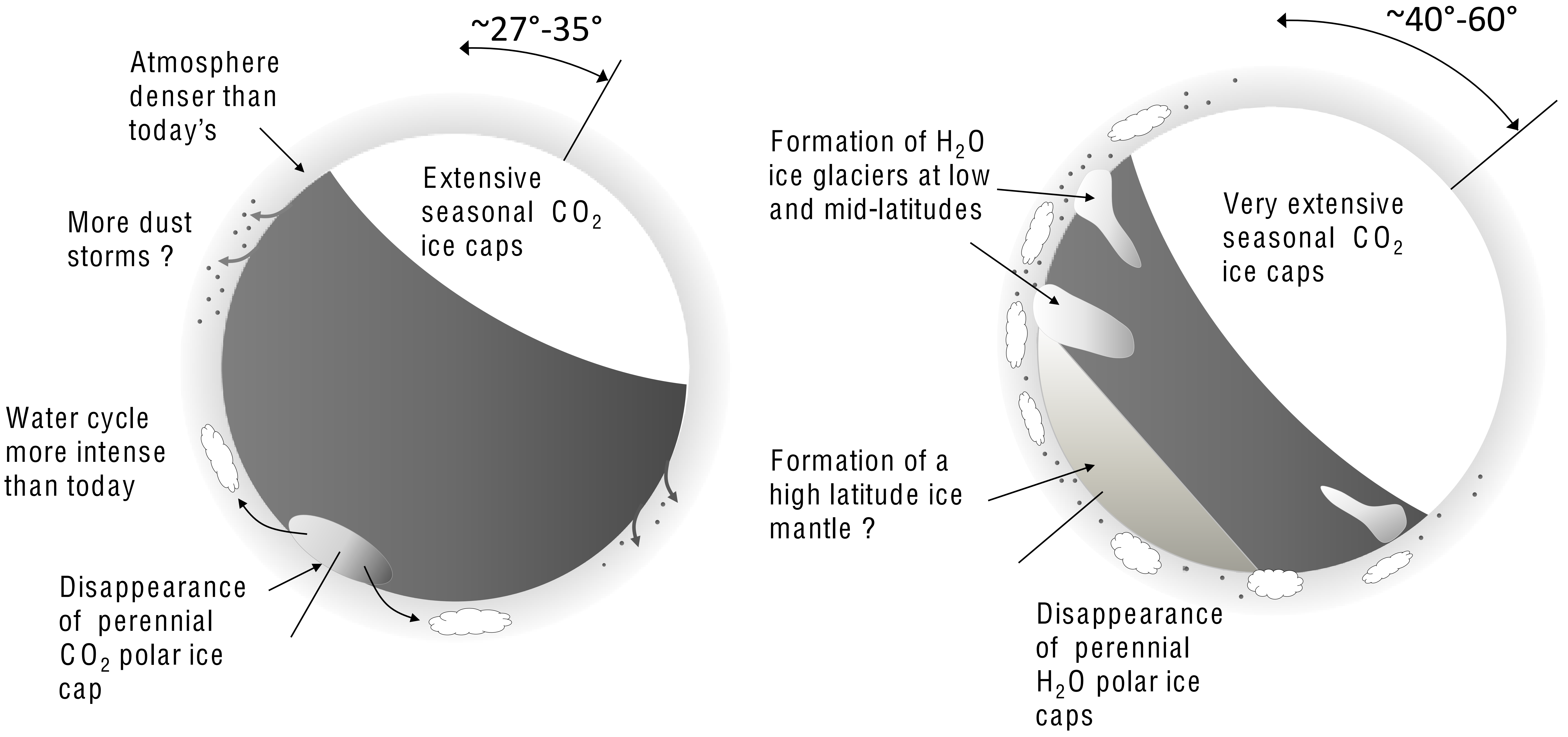


# The Key Effect of the Sublimation Cooling by Latent Heat



# The Martian Puzzle

Effect of changing the obliquity on the Martian Climate from previous climate studies




*Forget et al., 2017*

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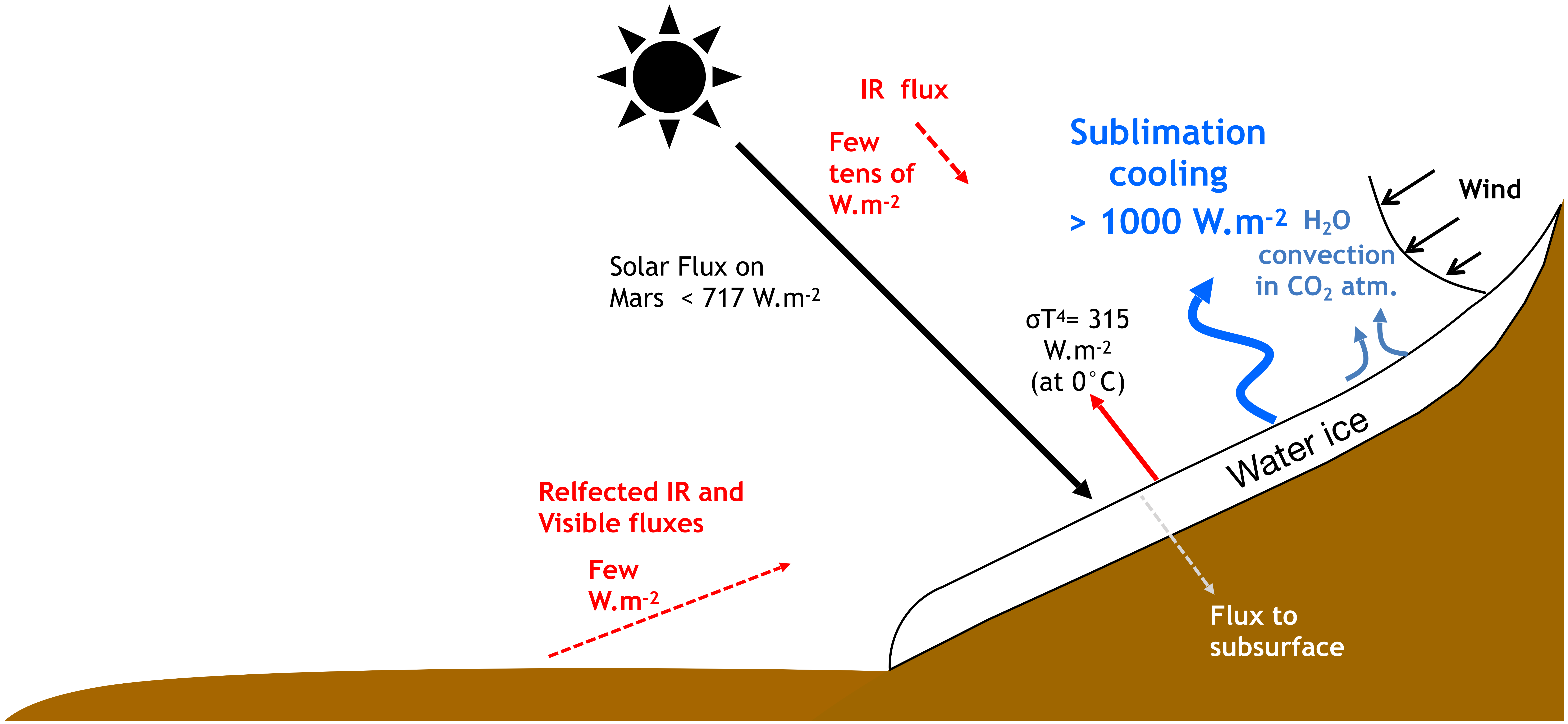

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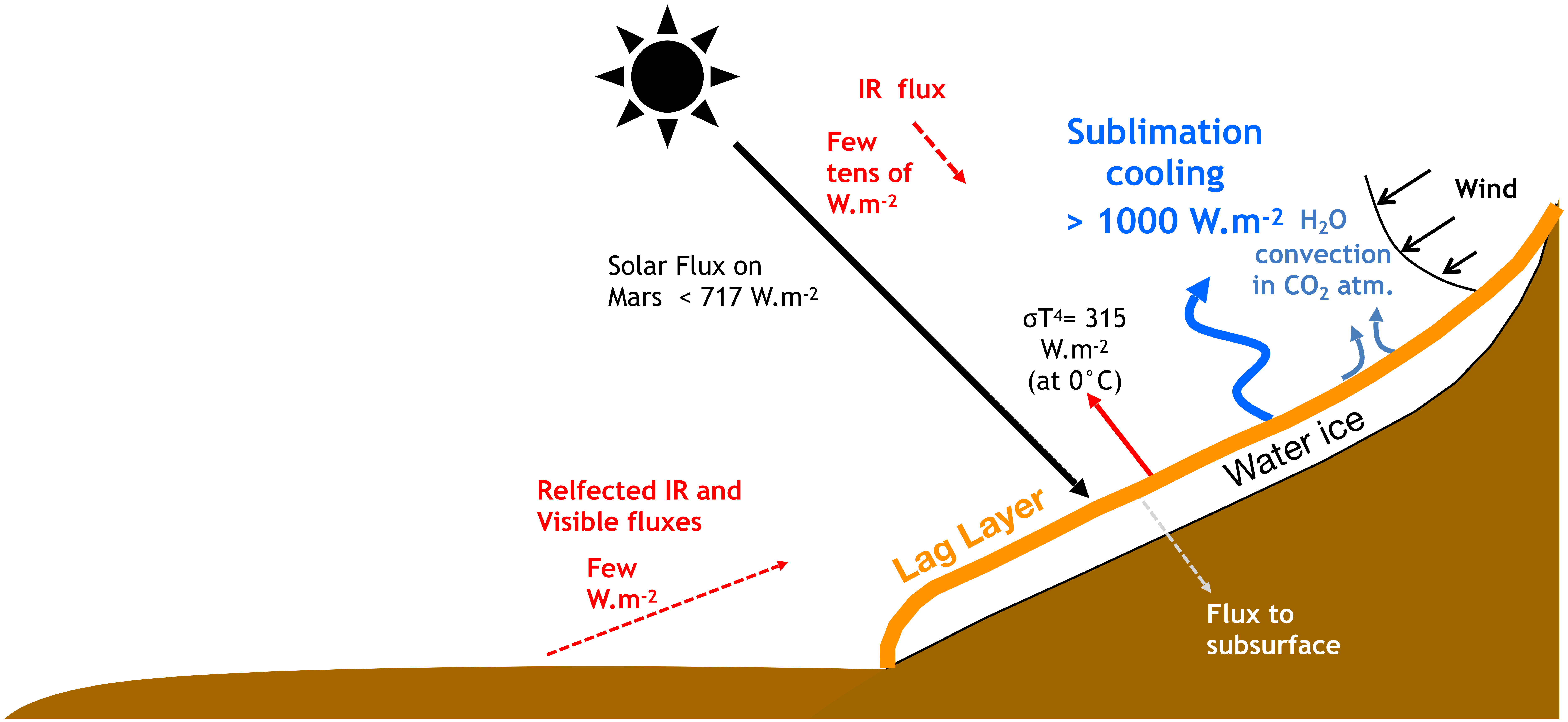

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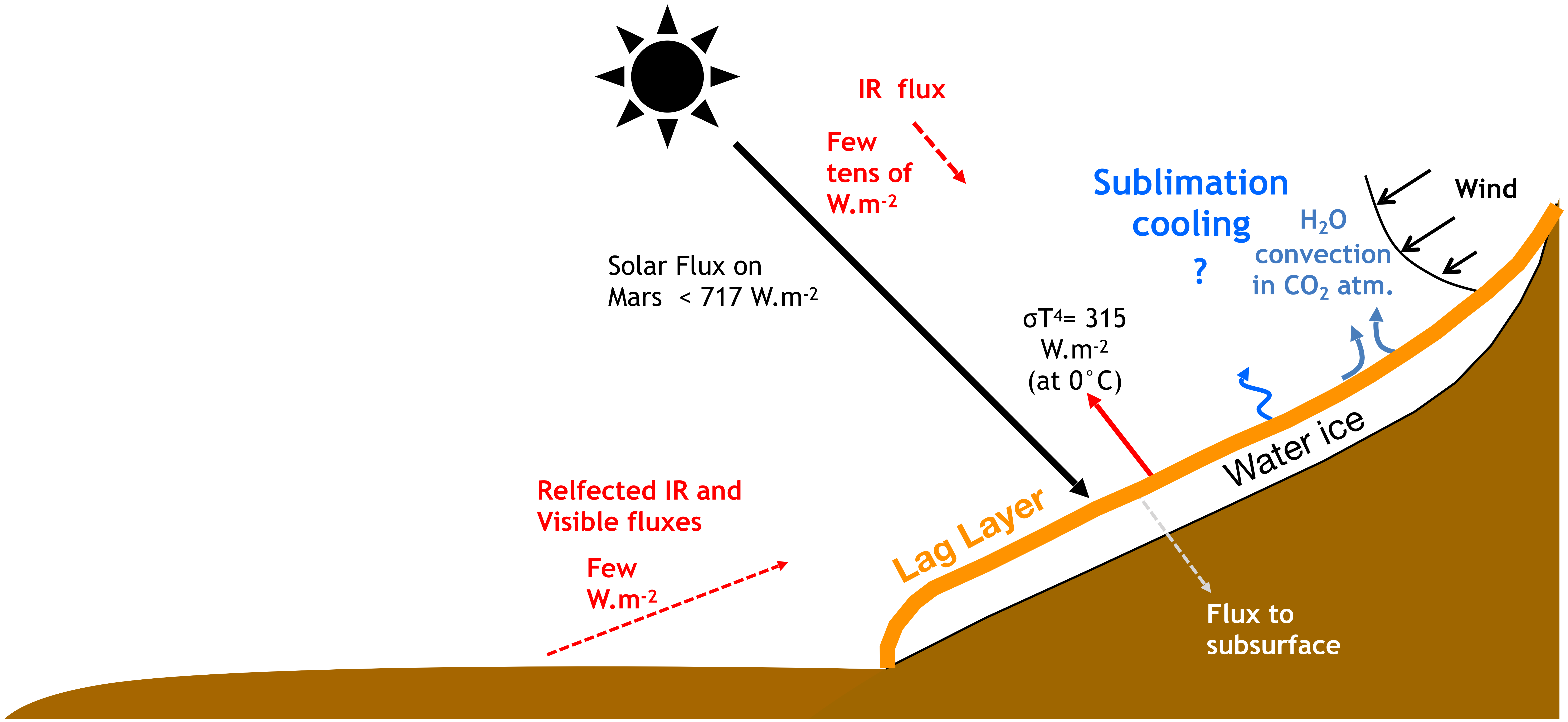
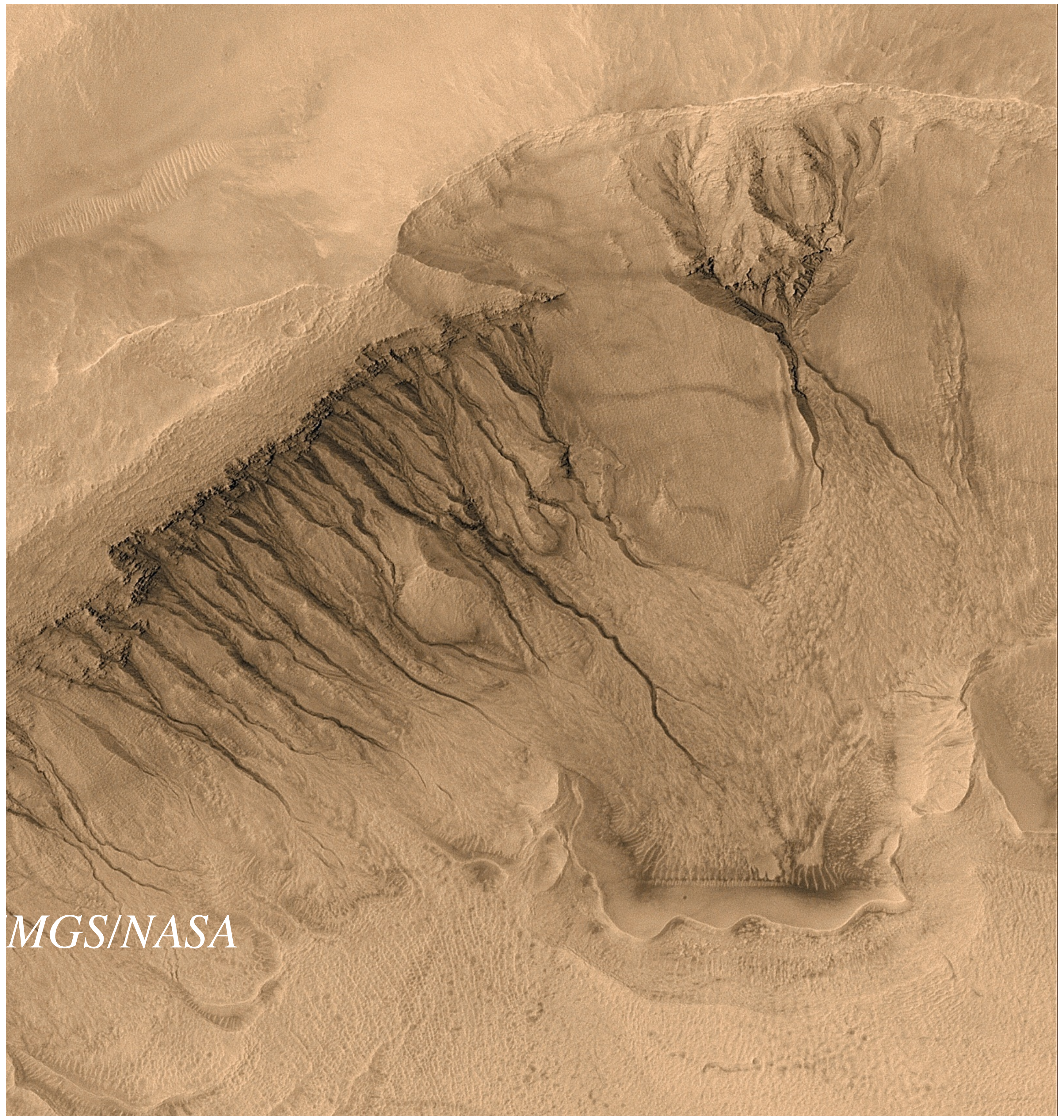


# Destabilization of Subsurface Water Ice by $CO_2$ sublimation

Gullies on Mars at 39.1°S, 166.1°W



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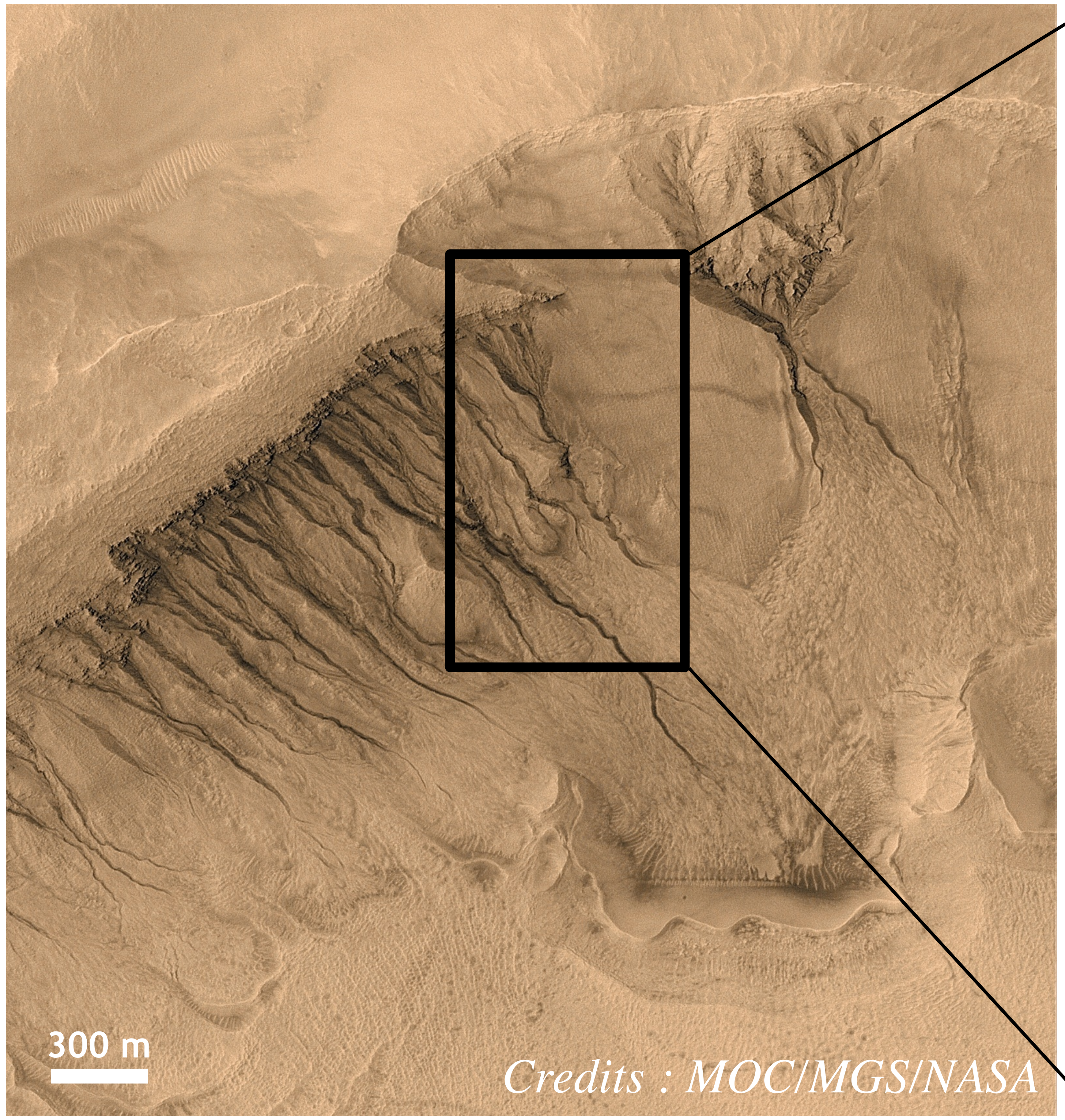
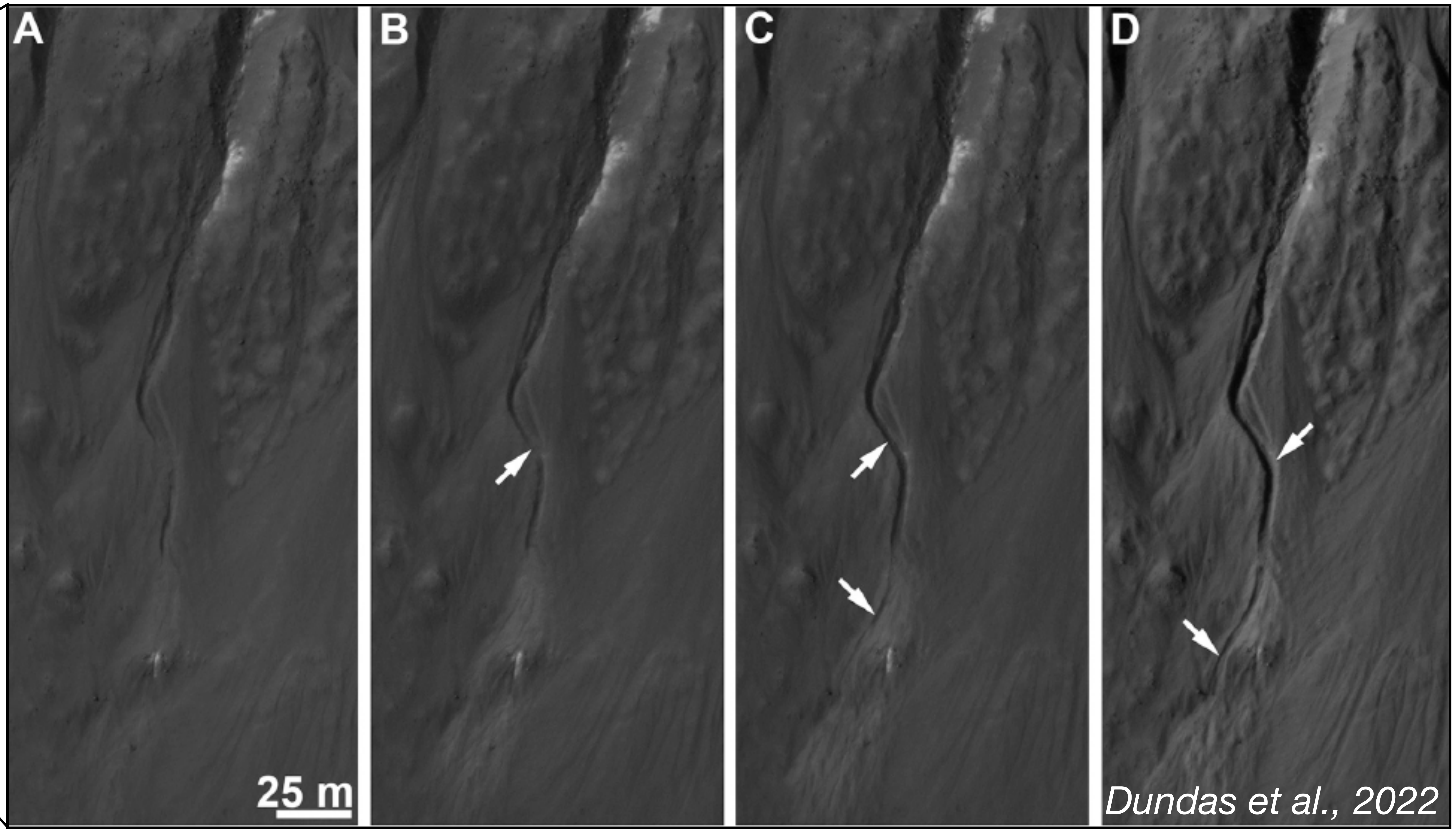
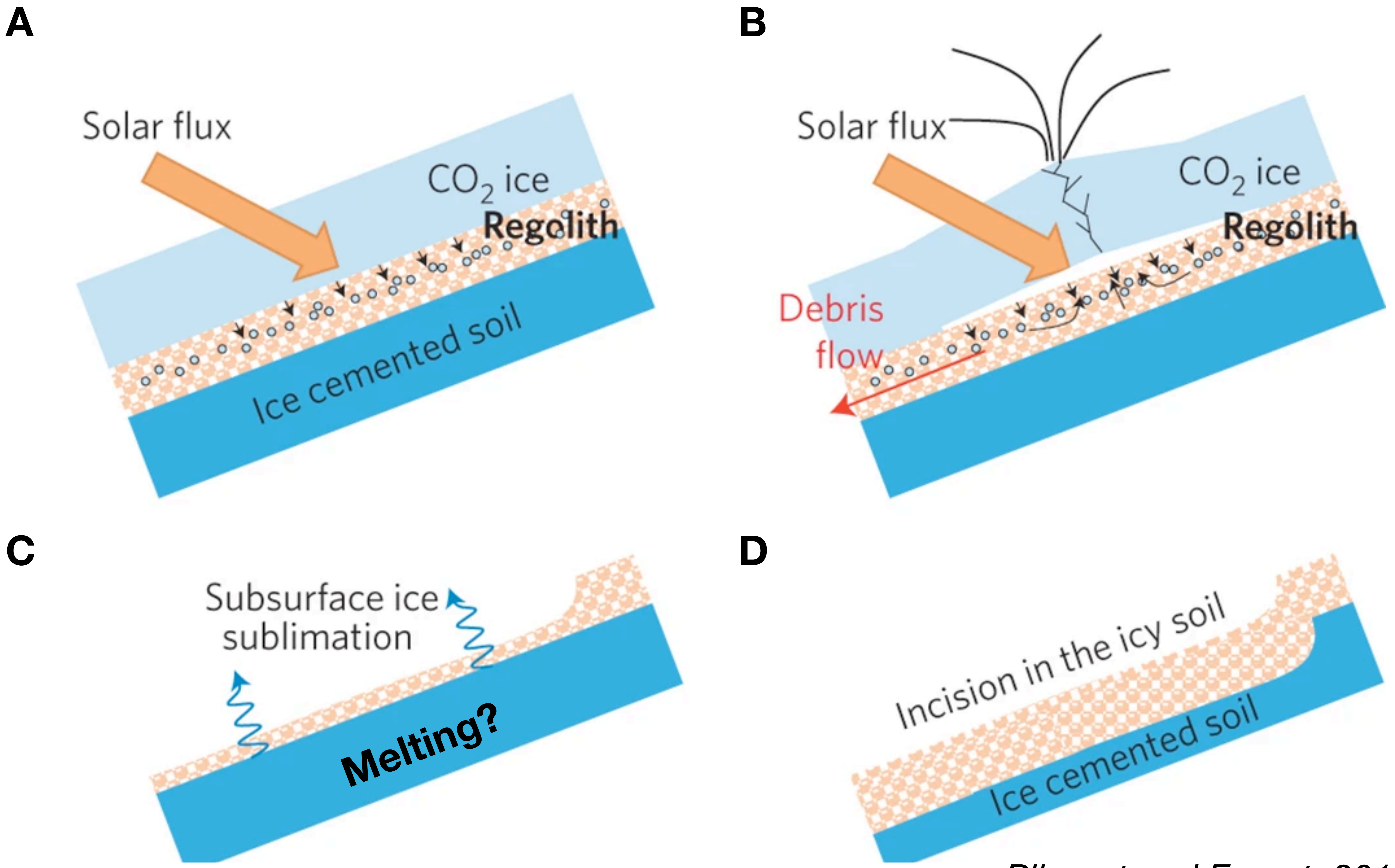



Gullies activity



# The Best Way to Melt Subsurface Ice: Destabilize Subsurface Ice




*Pilorget and Forget, 2016*

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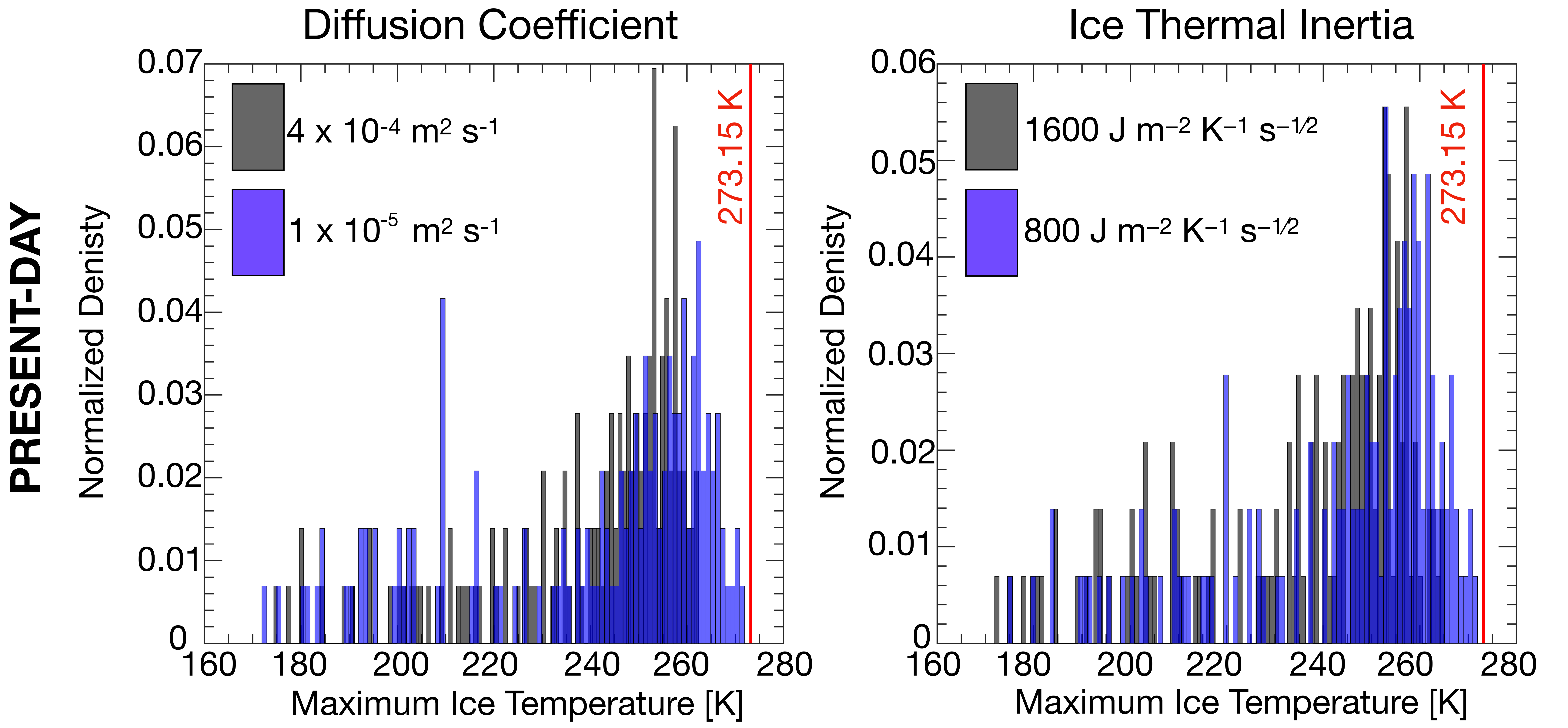
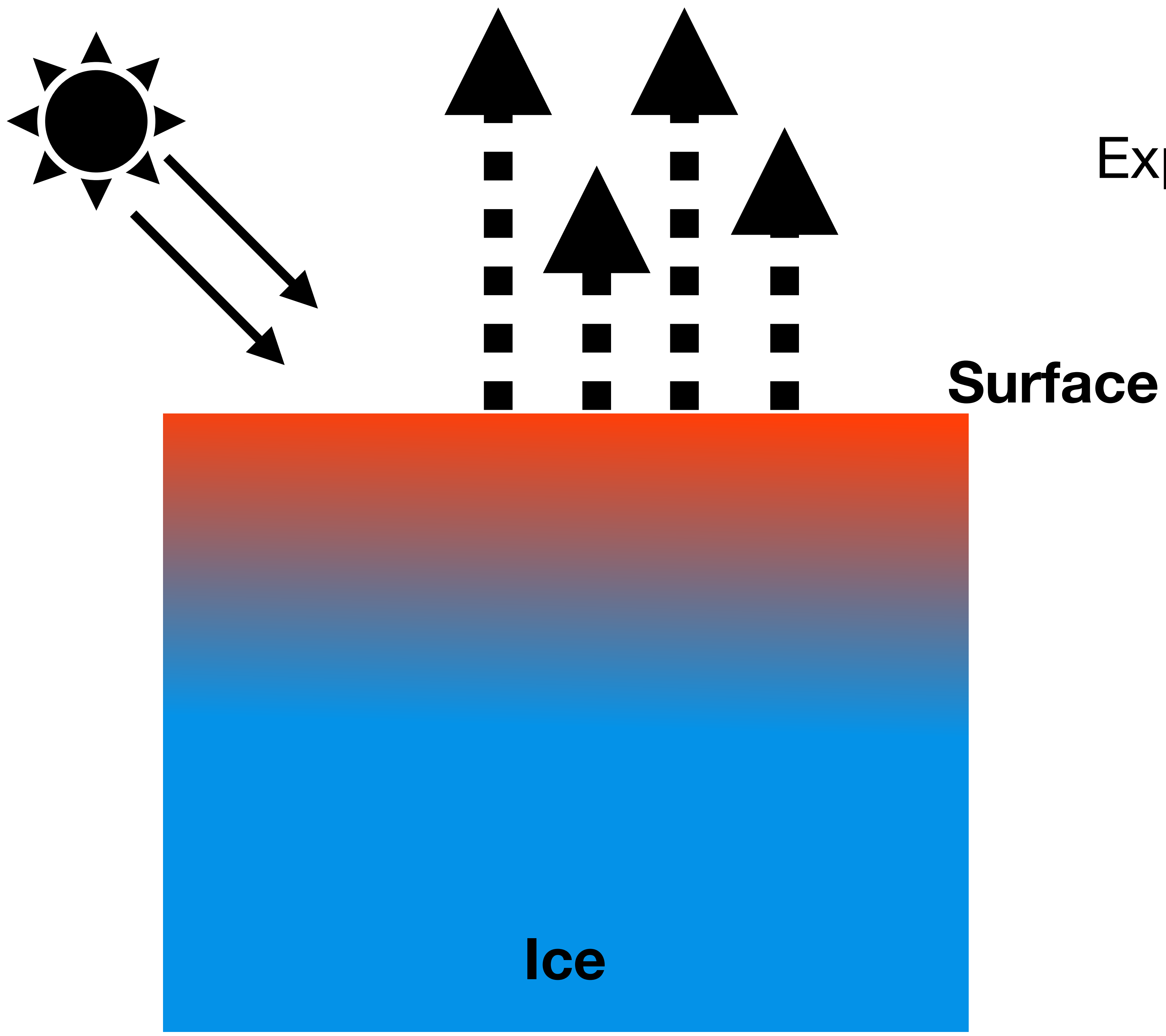



Melting of destabilized subsurface ice impossible on present-day Mars, and very unlikely at high obliquity

# Equilibrium Condition

**Strong sublimation** $\propto (\rho_{\mathrm{vap,atm}} - \rho_{\mathrm{sat,ice}}(T_{\mathrm{ice}}))$

Exponential dependance to $T_{\mathrm{ice}}$




Ice exposed to the atmosphere warms and sublimes quickly.

# Equilibrium Condition

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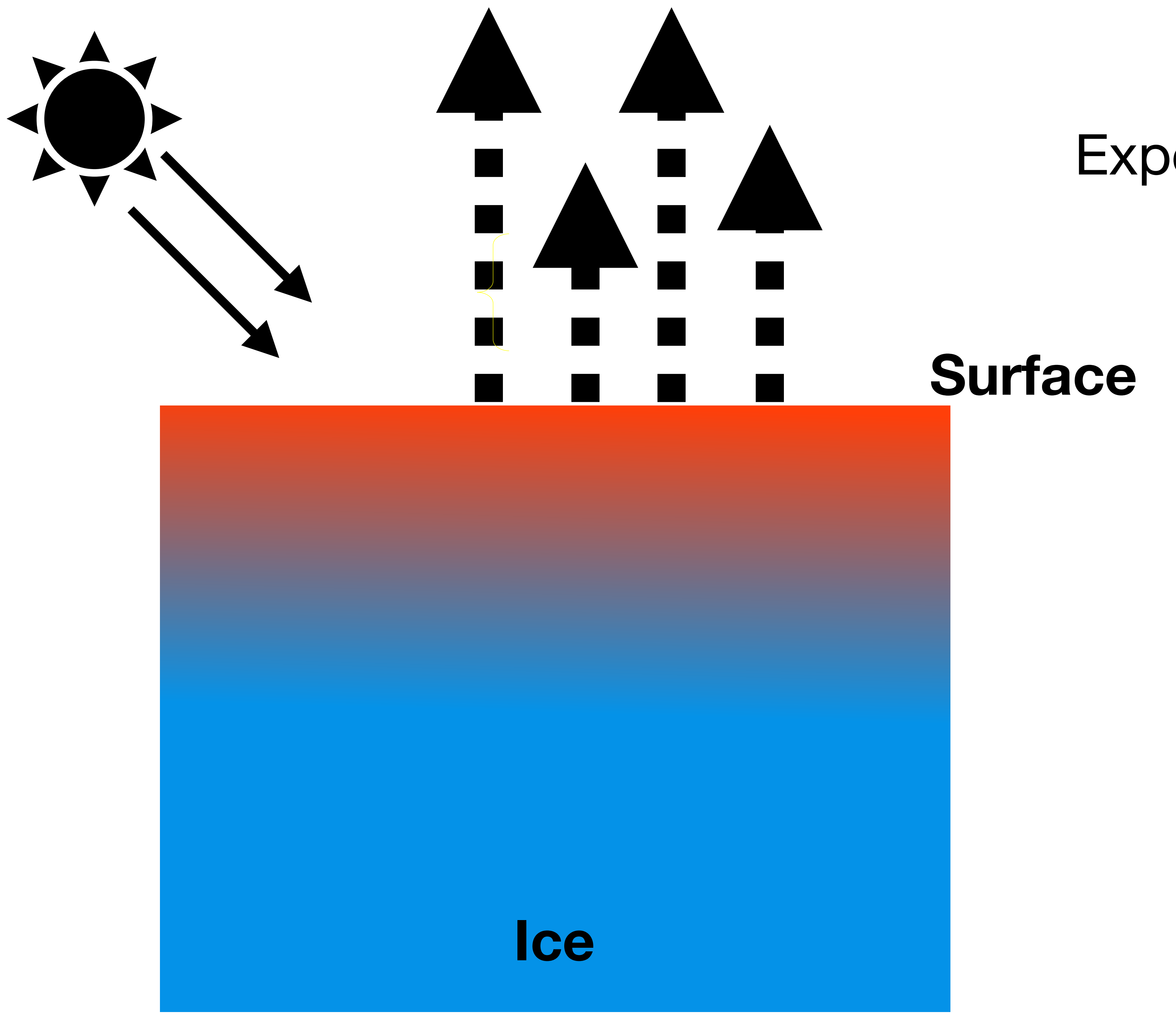
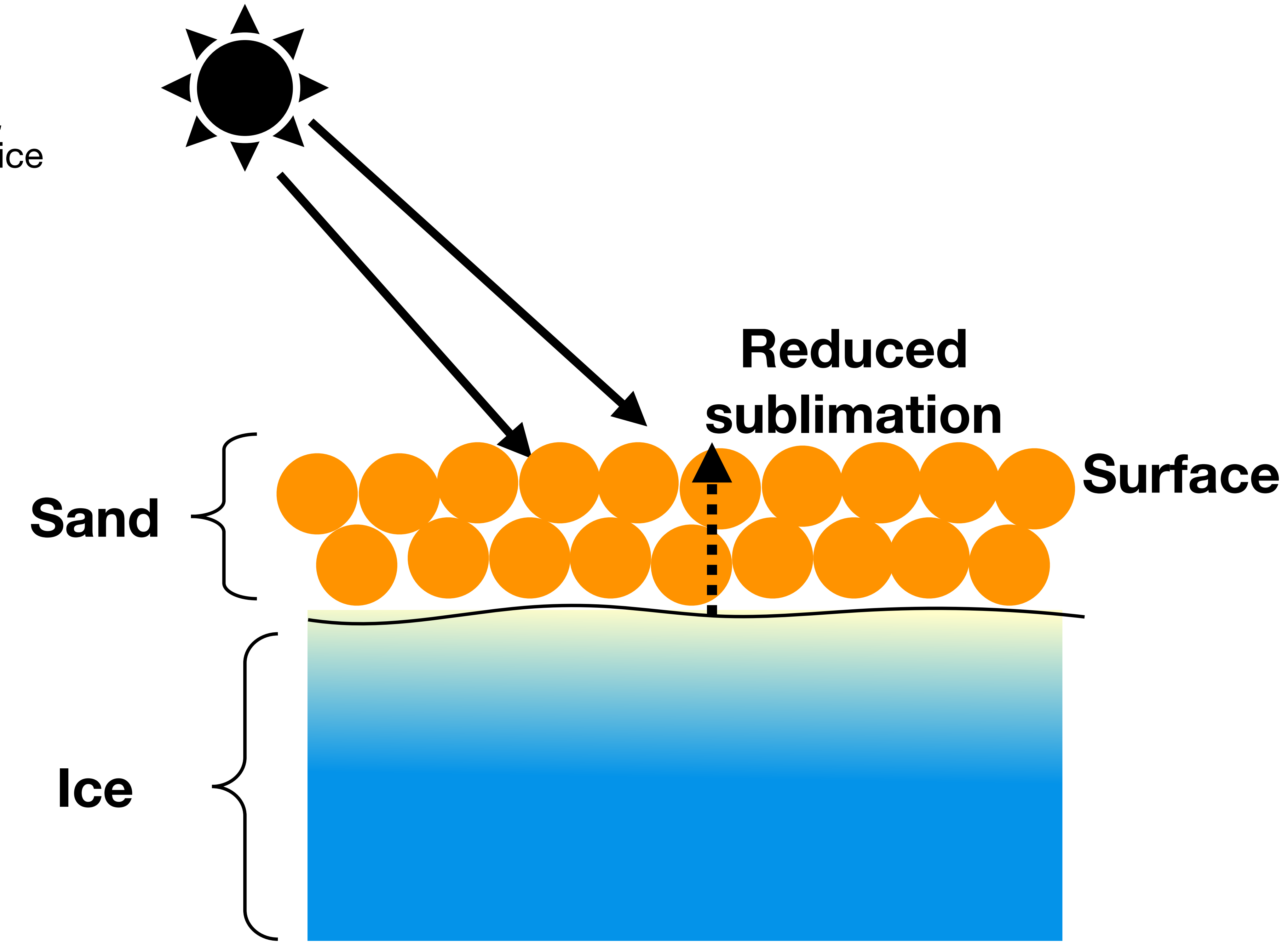
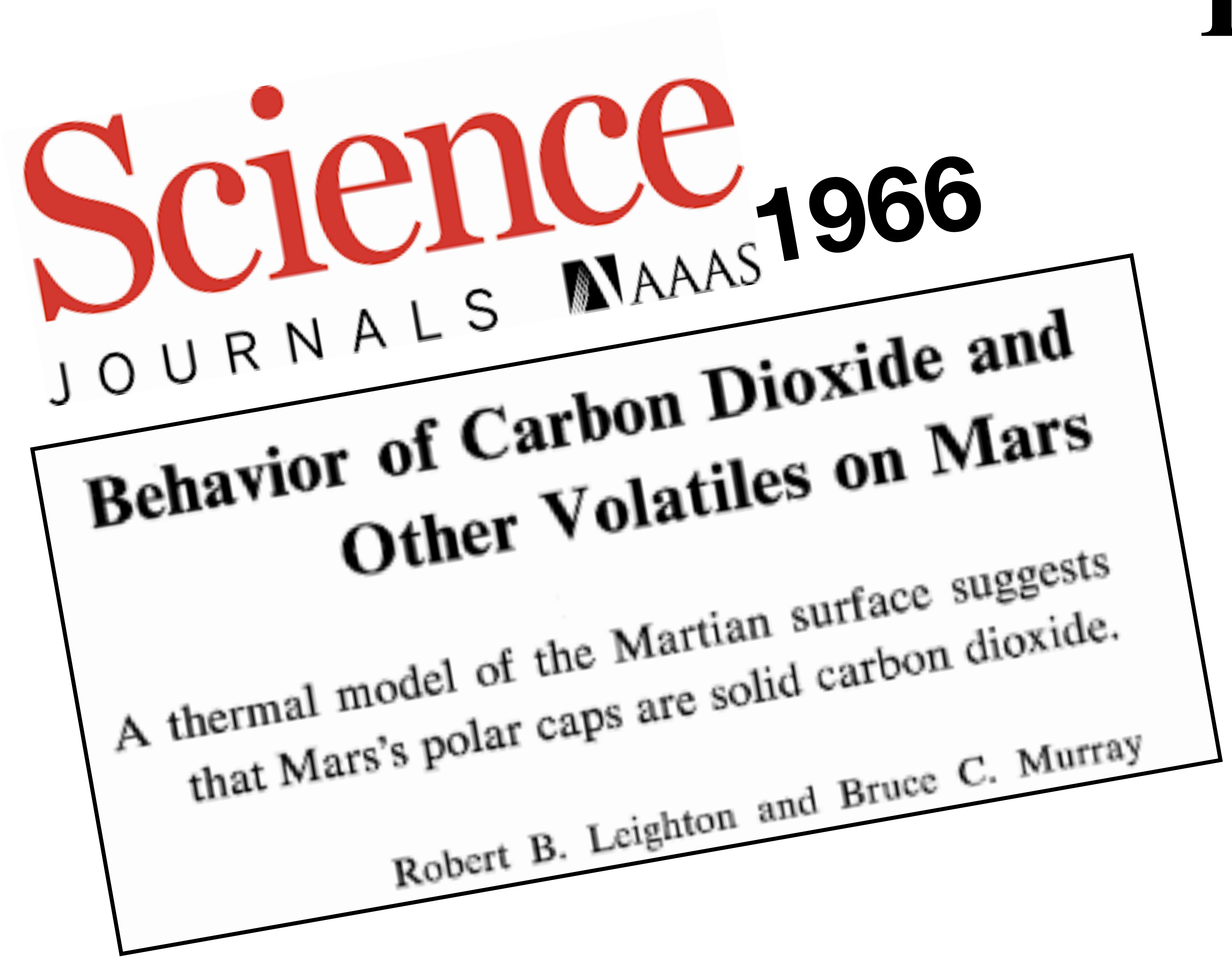



Ice exposed to the atmosphere warms and sublimes quickly.




When ice is covered by a layer of regolith, it is protected from the sun. Ice is colder and can be stable.

# Equilibrium Condition


Science JOURNALS AAAS 1966

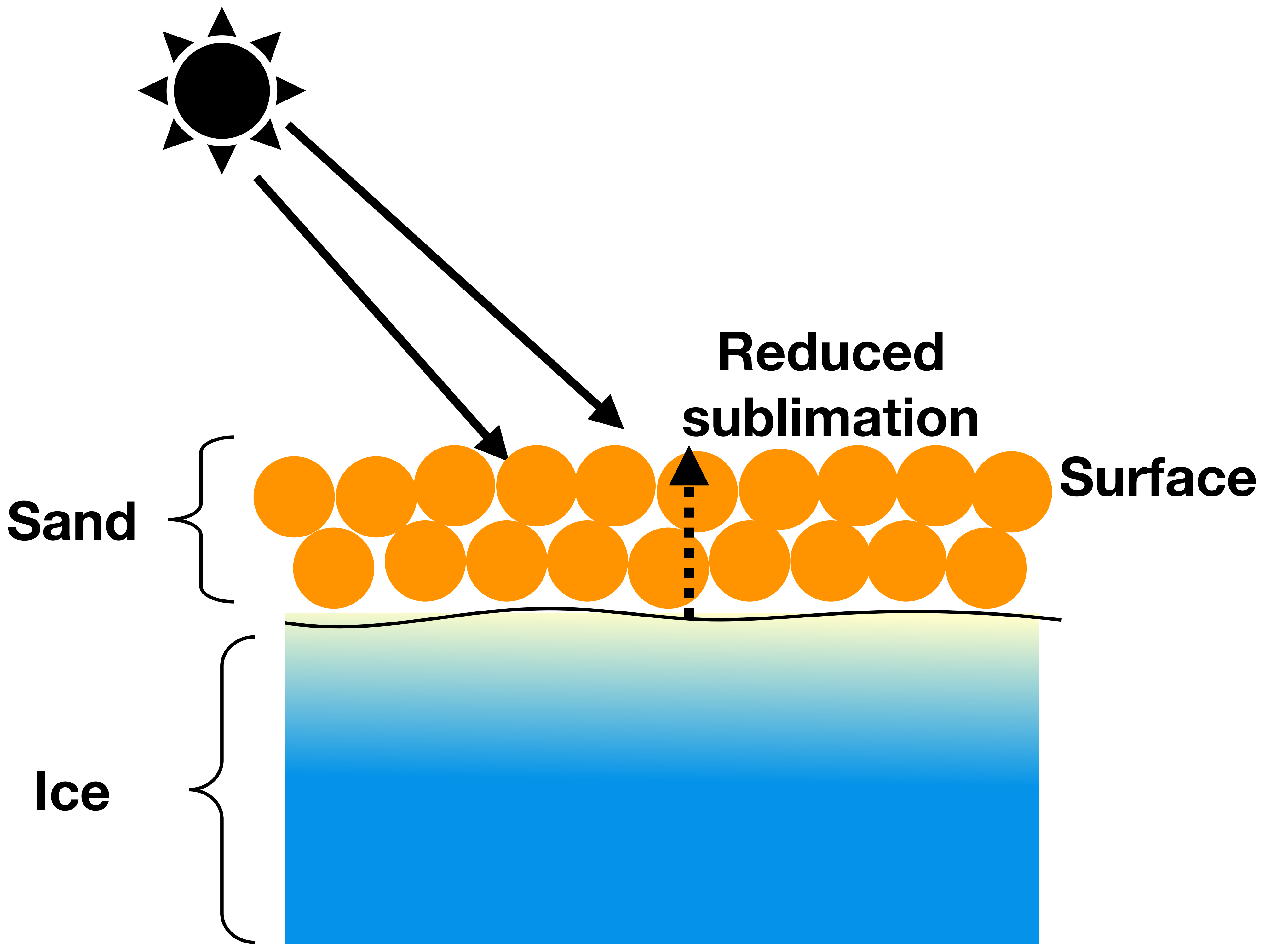
**Behavior of Carbon Dioxide and Other Volatiles on Mars**

A thermal model of the Martian surface suggests that Mars's polar caps are solid carbon dioxide.

Robert B. Leighton and Bruce C. Murray

Subsurface water ice is stable at depth $z_{ice}$ if:

$$\overline{\left(\frac{p_{vap,surf}}{T_{surf}}\right)} = \overline{\left(\frac{p_{sv}(T_{soil}(z_{ice}))}{T_{soil}(z_{ice})}\right)}$$

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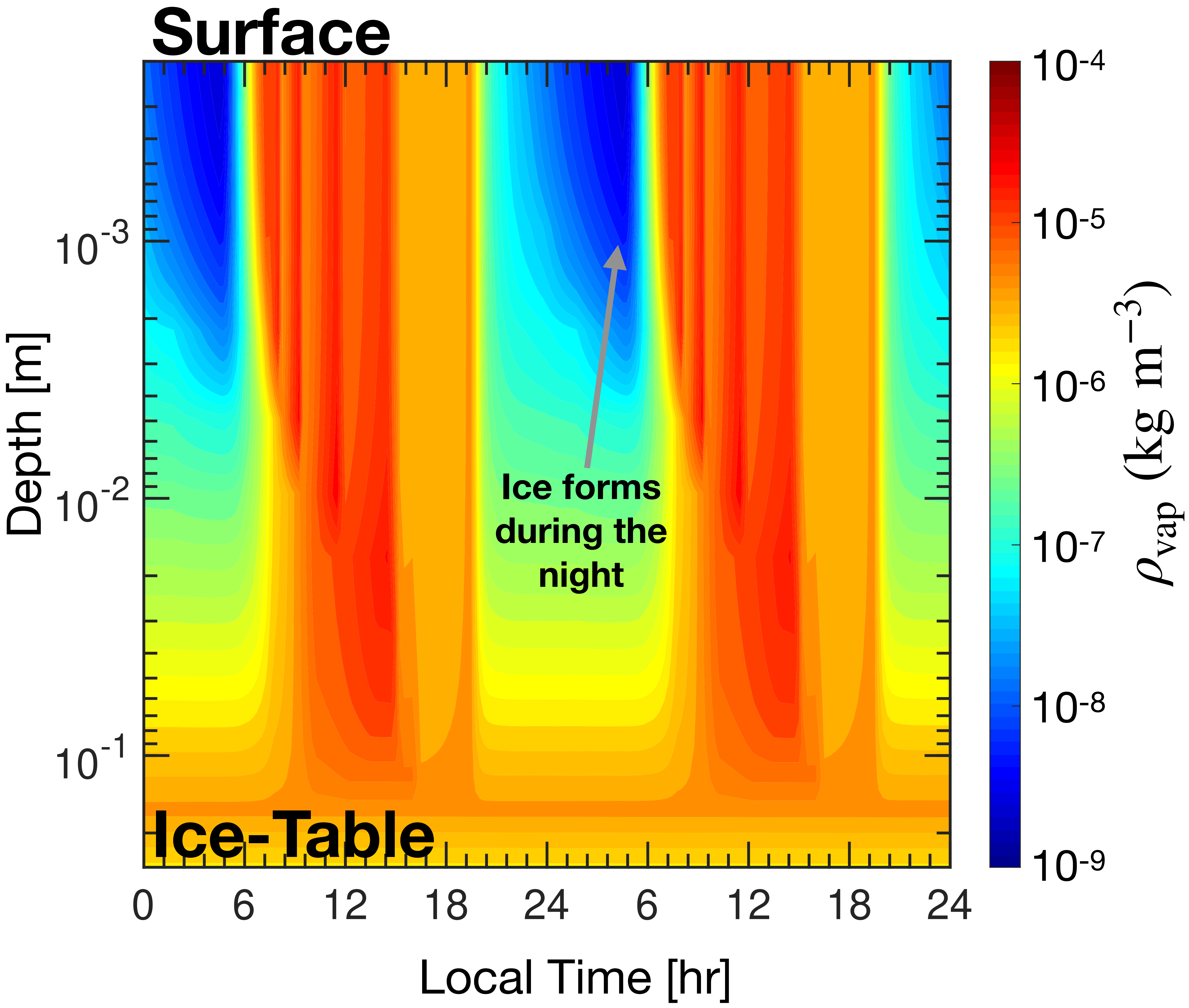
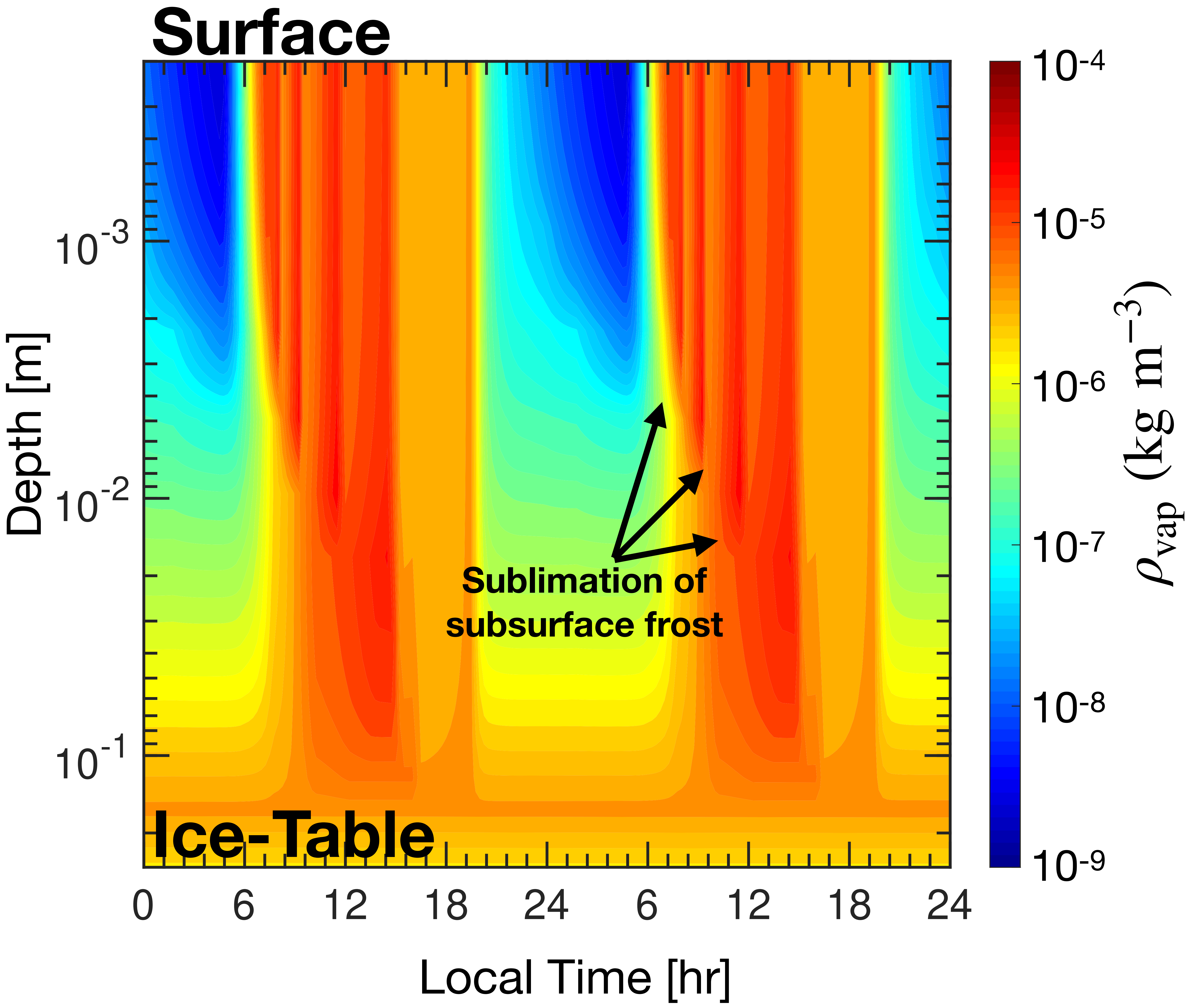
# Physical Improvement in the Subsurface Ice-Atmosphere Exchanges




- When subsurface frost is subliming, there is a strong flux of water vapor upward.
- The vapor mixing through the surface layer is not efficient in removing all of this water vapor.
- Vapor remains in the subsurface, stabilizing ground ice.

# Physical Improvement in the Subsurface Ice-Atmosphere Exchanges

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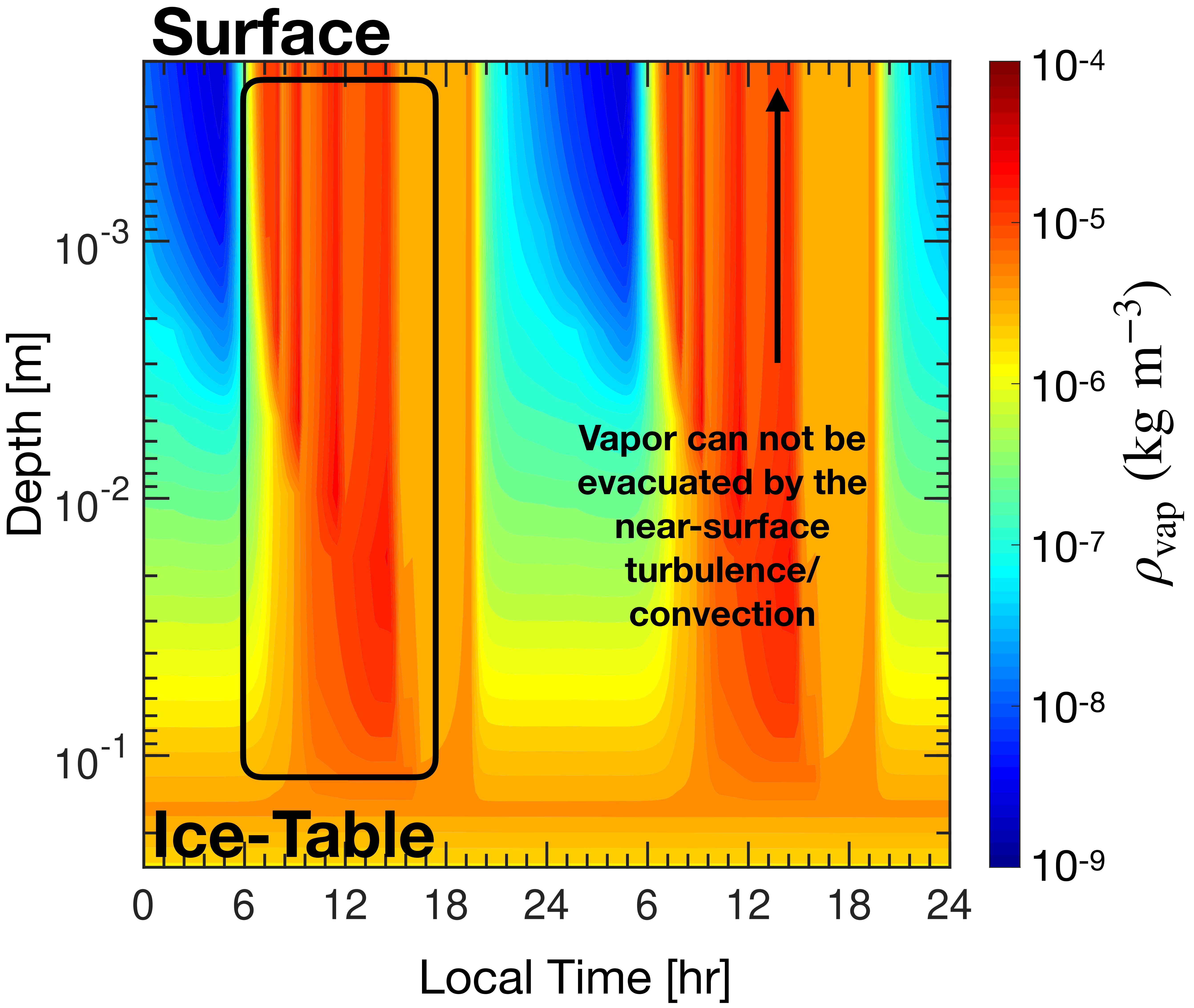


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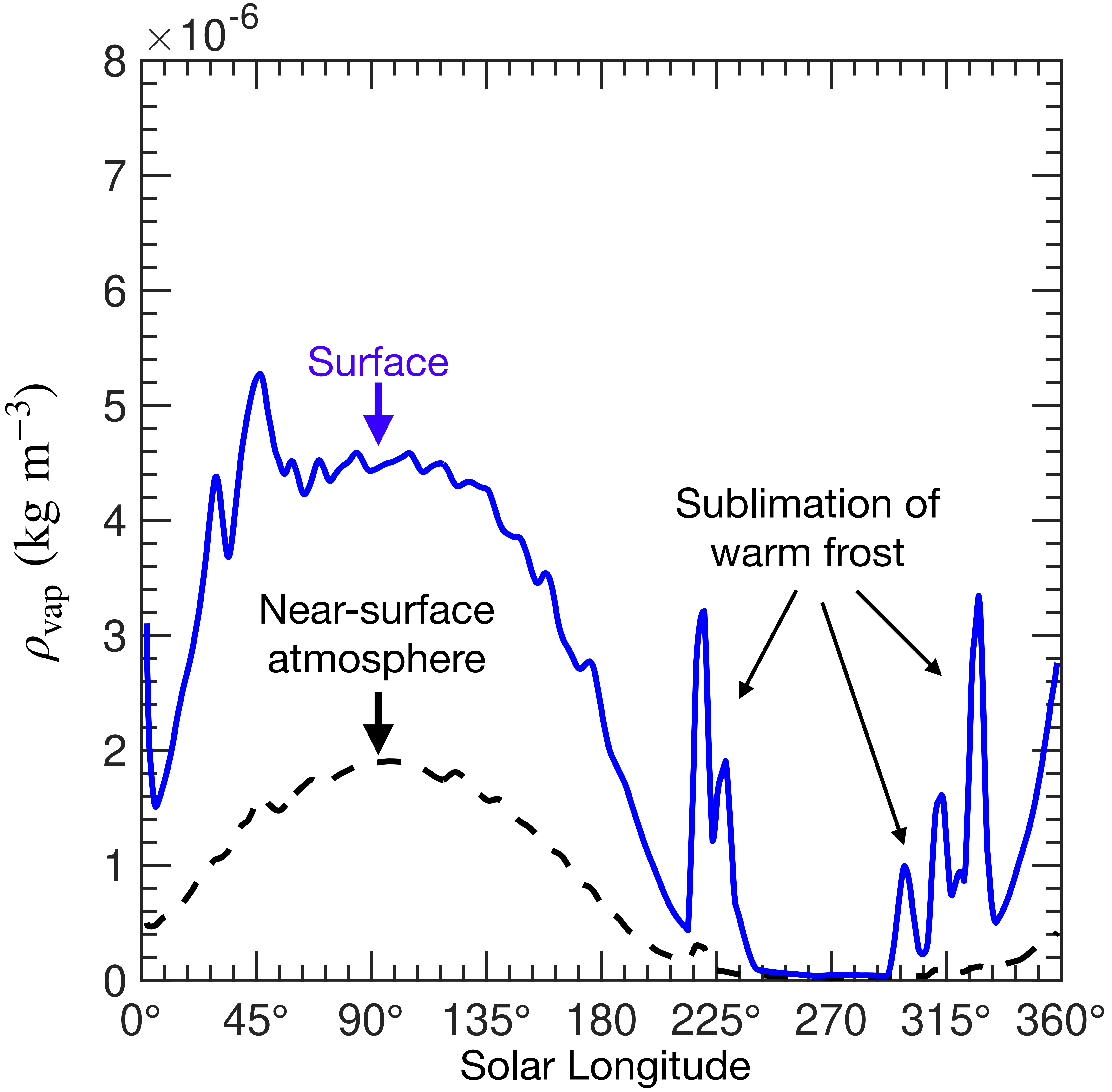
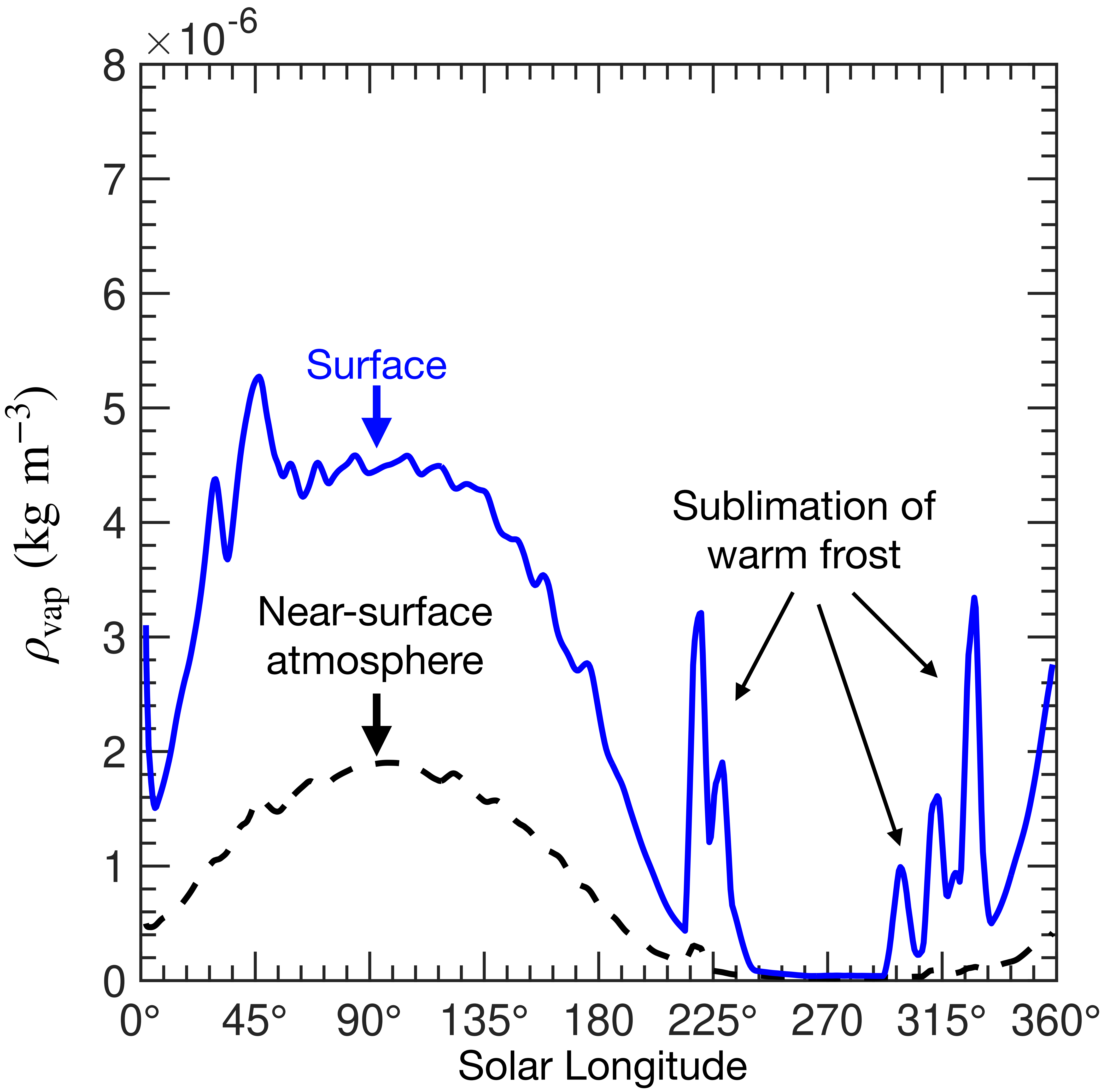
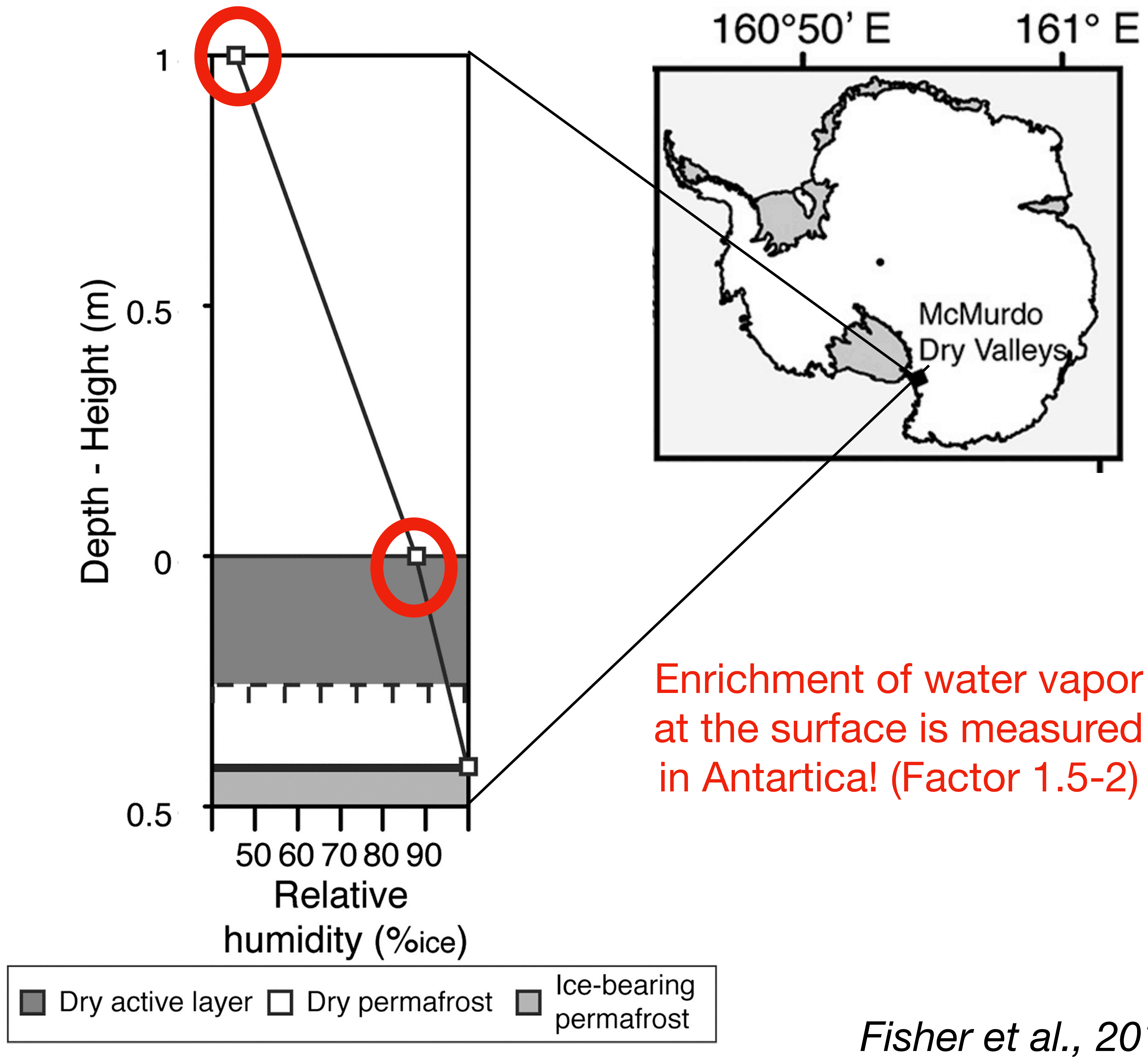



- Near-subsurface water vapor could be 1.5-3 higher than the near-surface atmospheric vapor.
- Strong sensitivity to the soil properties (thermal inertia).
- Further improvements are needed to include the effect of advection.

# Physical Improvement in the Subsurface Ice-Atmosphere Exchanges

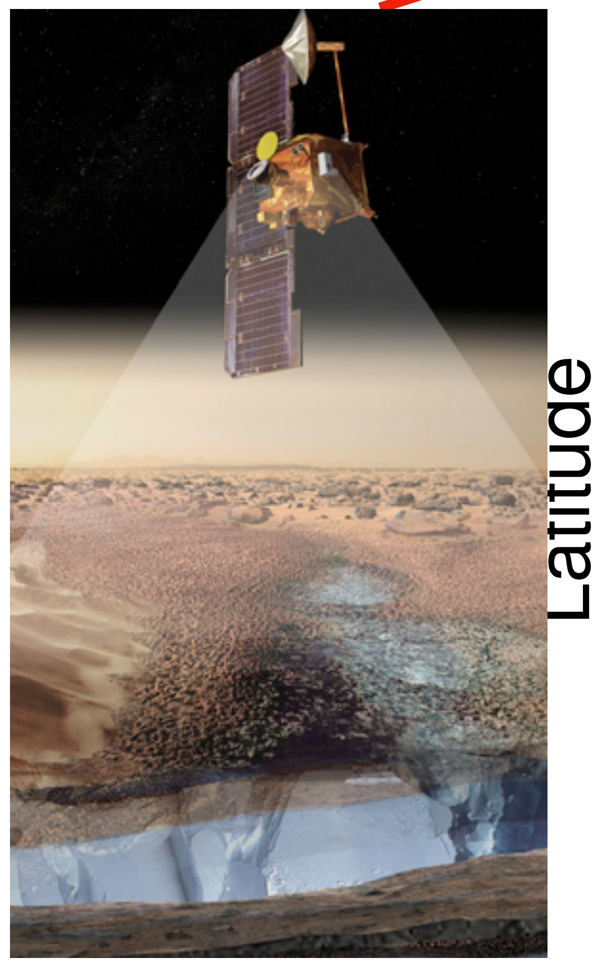


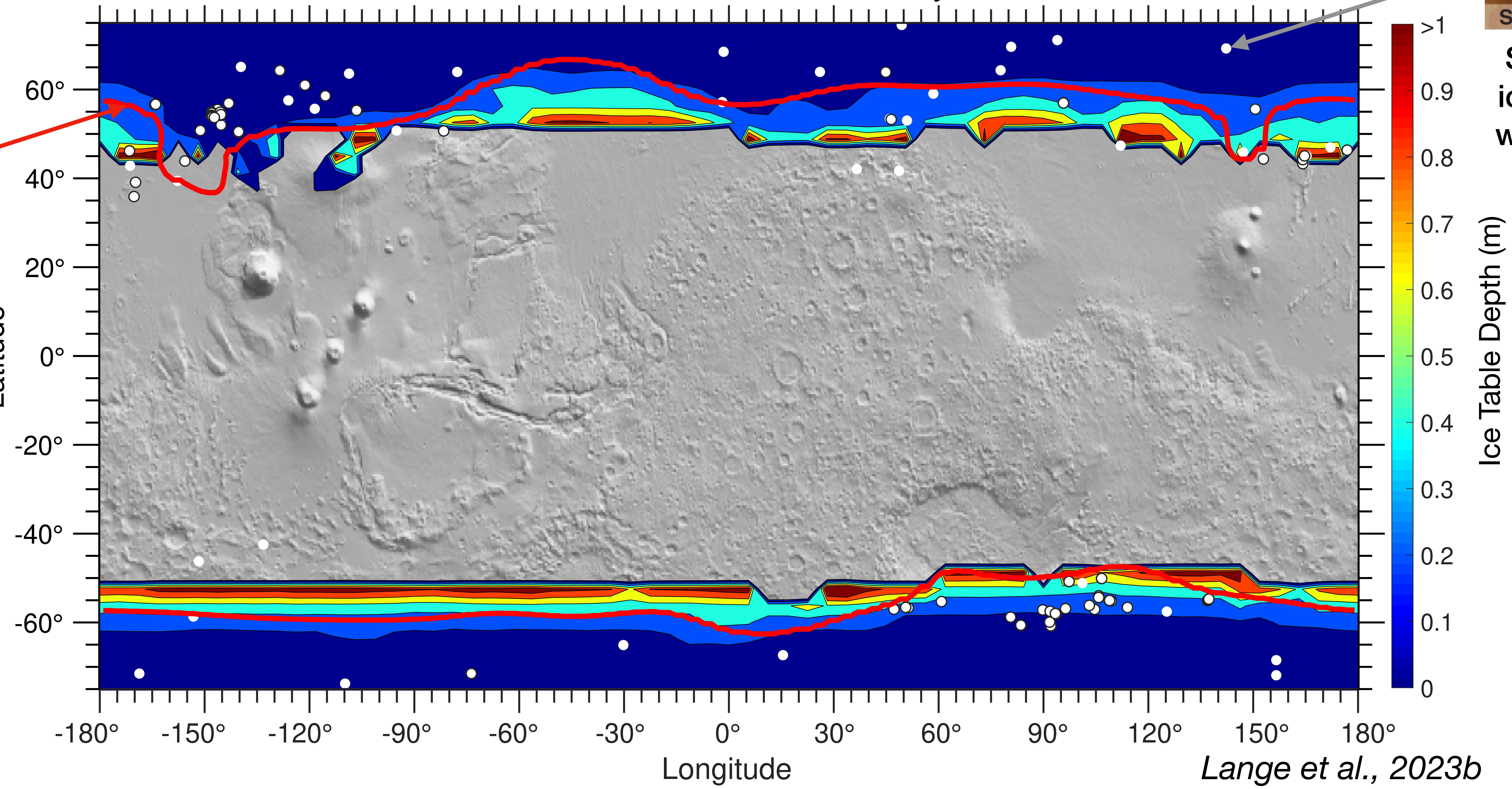

Enrichment of water vapor at the surface is measured in Antartica! (Factor 1.5-2)

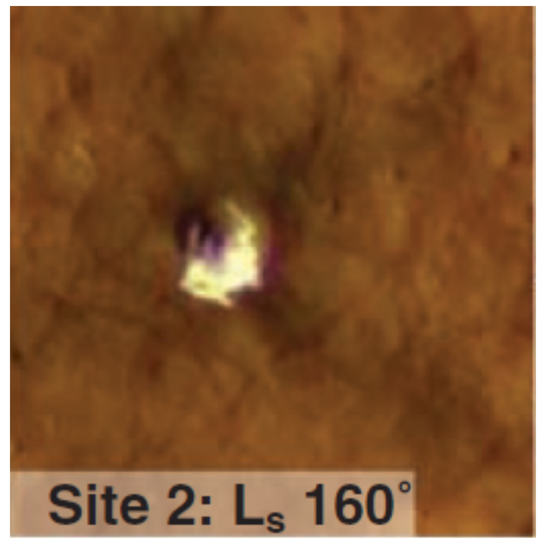
*Fisher et al., 2016*

# Modeling Subsurface Ice Equilibrium with the Mars Planetary Climate Model



Subsurface ice detected within the 50 cm




Subsurface ice detected within 1 m of the soil

*Lange et al., 2023b*