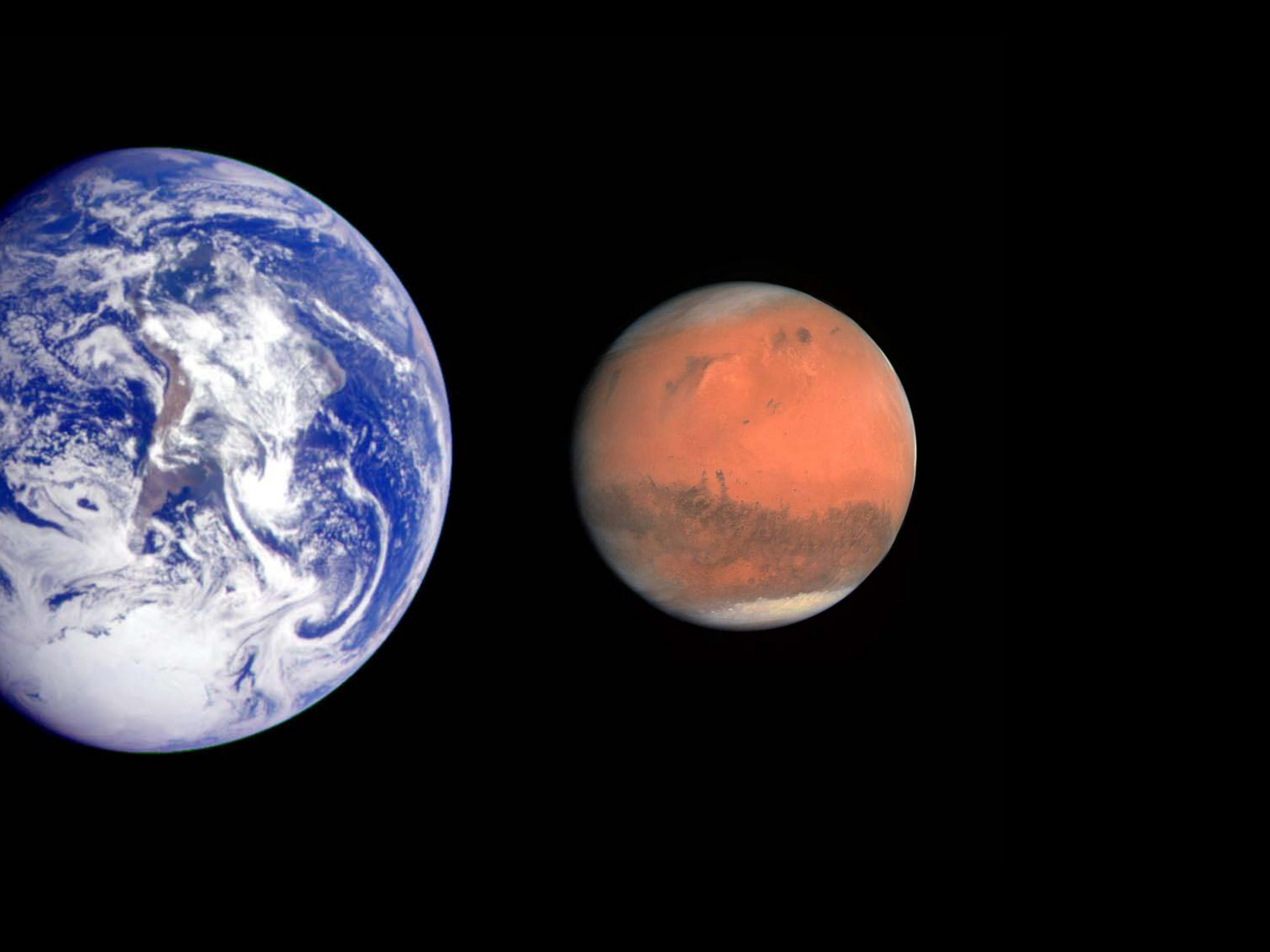
The climates of planet Mars controlled by a chaotic obliquity

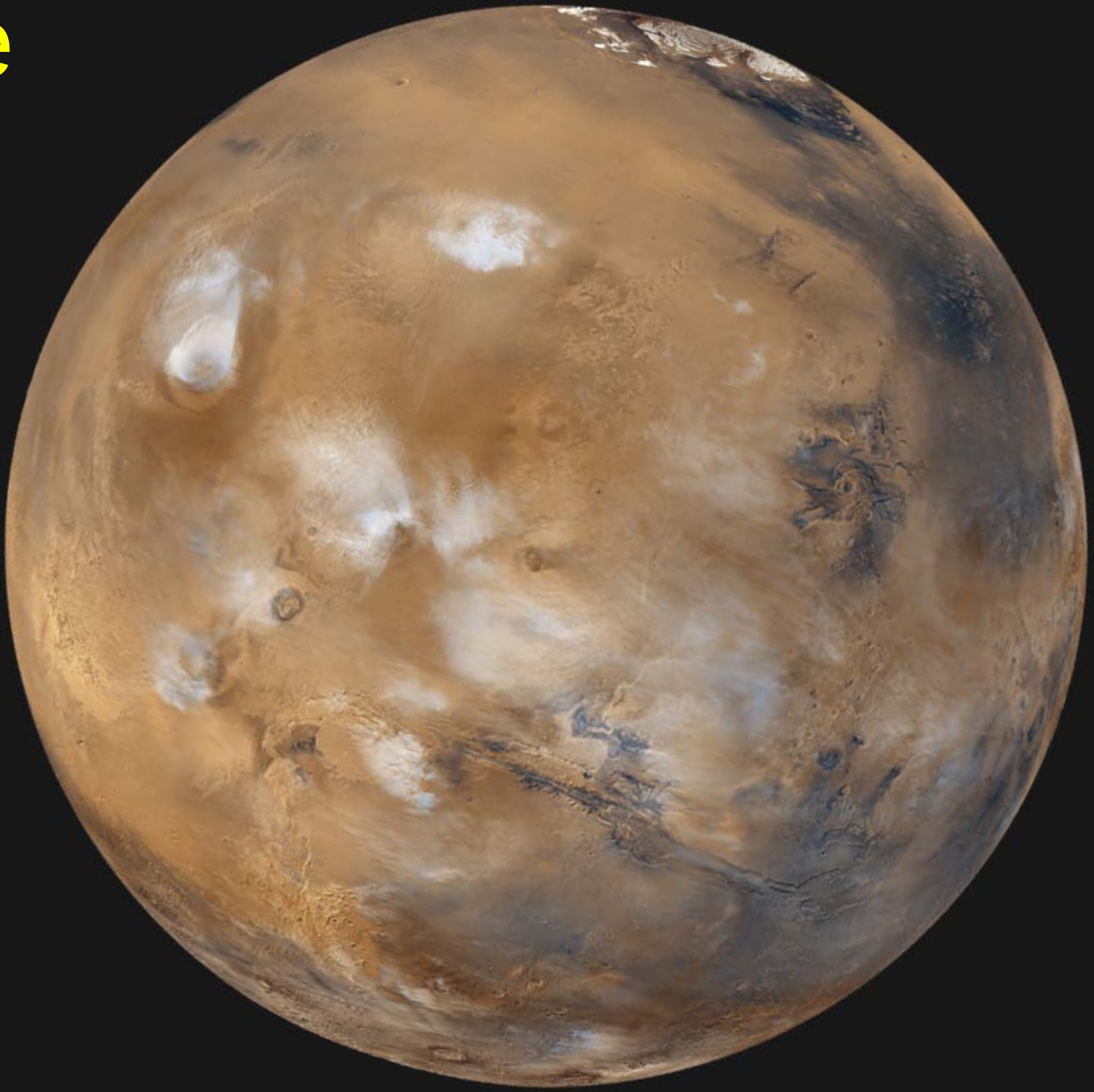
François Forget

(and many others… including Jacques Laskar)

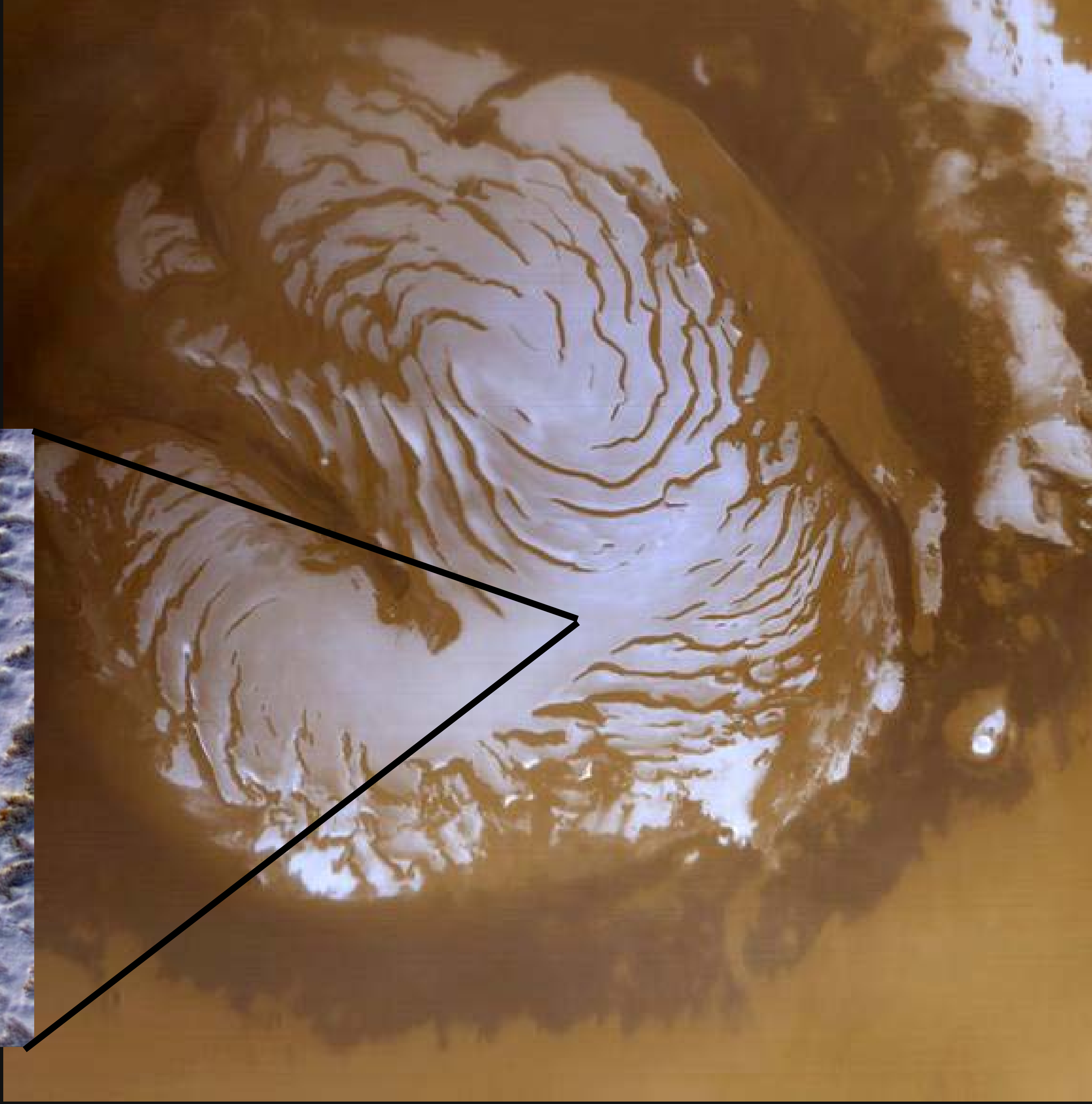
CNRS, Institut Pierre Simon Laplace, Laboratoire de Météorologie Dynamique, Paris

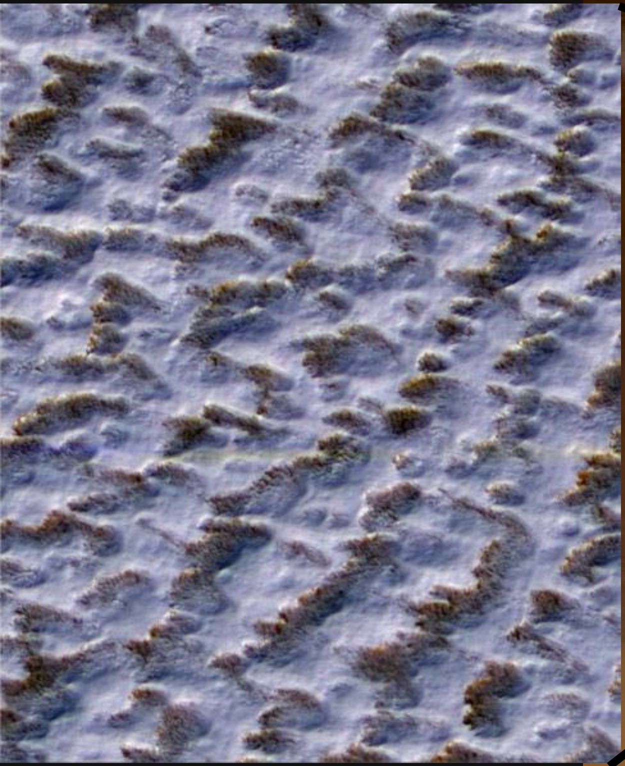


Mars water cycle



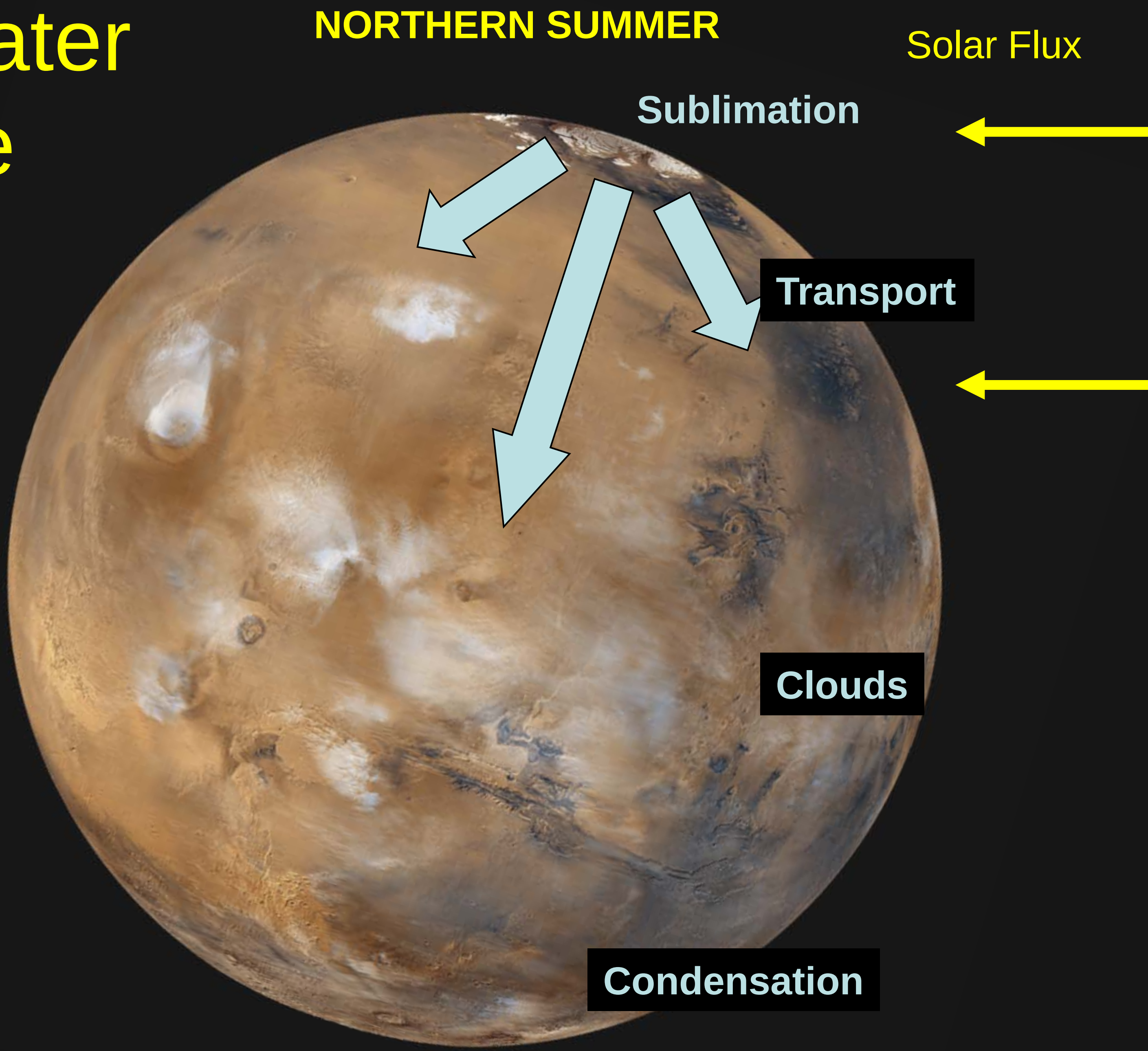
Around North Pole : a relatively fresh and pure water ice layer interacting with the atmosphere (diameter : 1000 km)





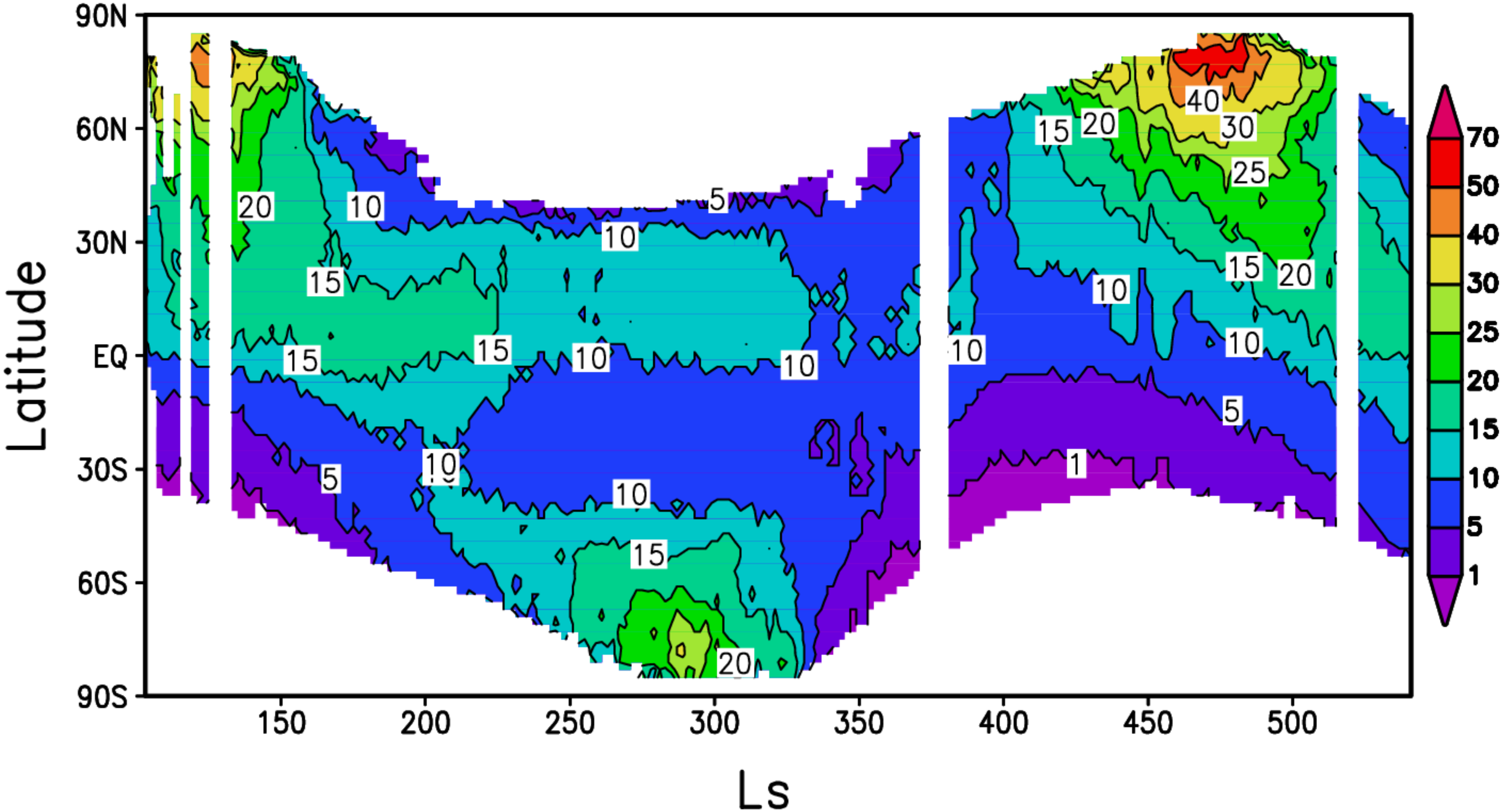
MRO Hirise

Mars water cycle

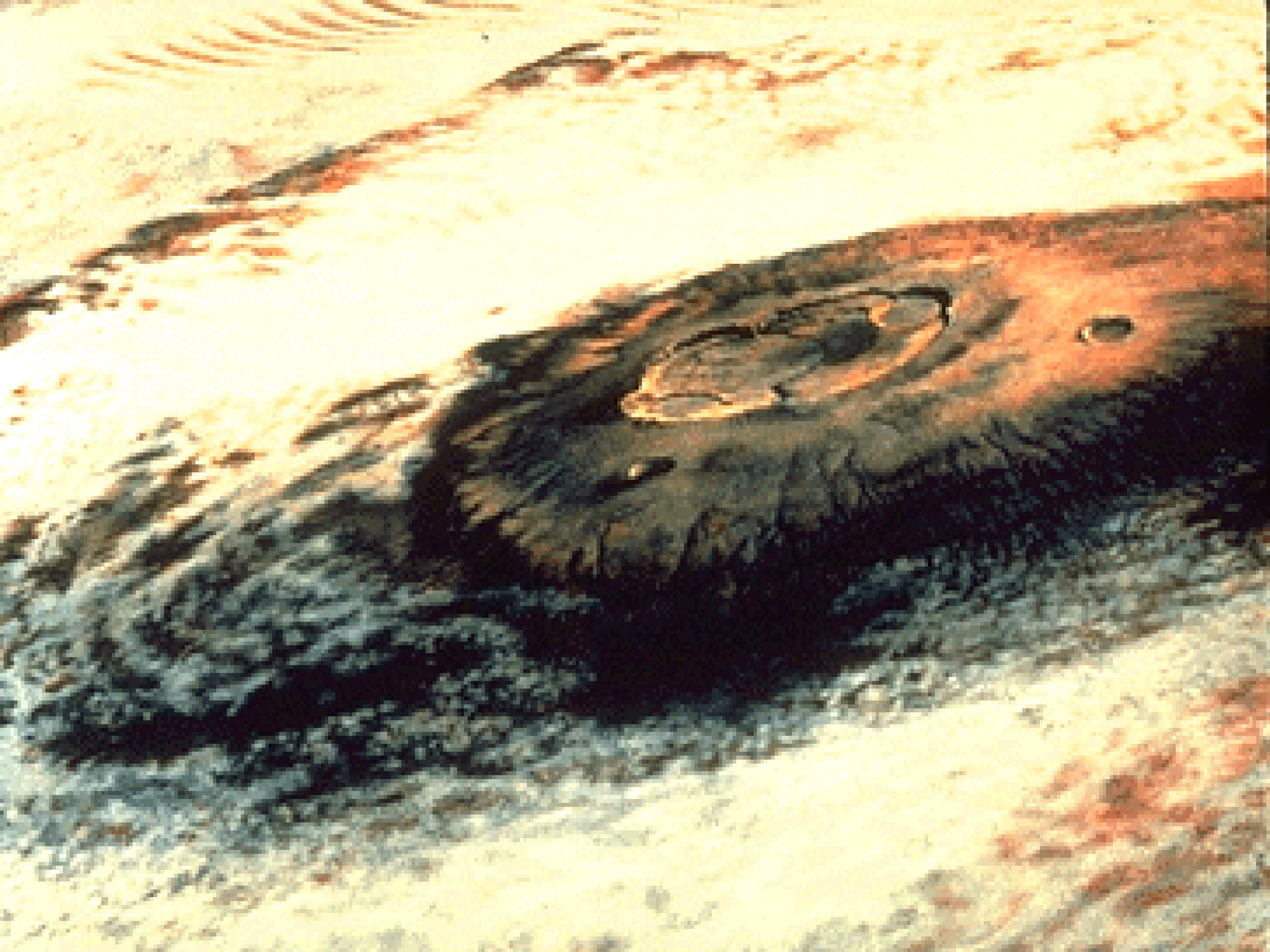


Mars water cycle

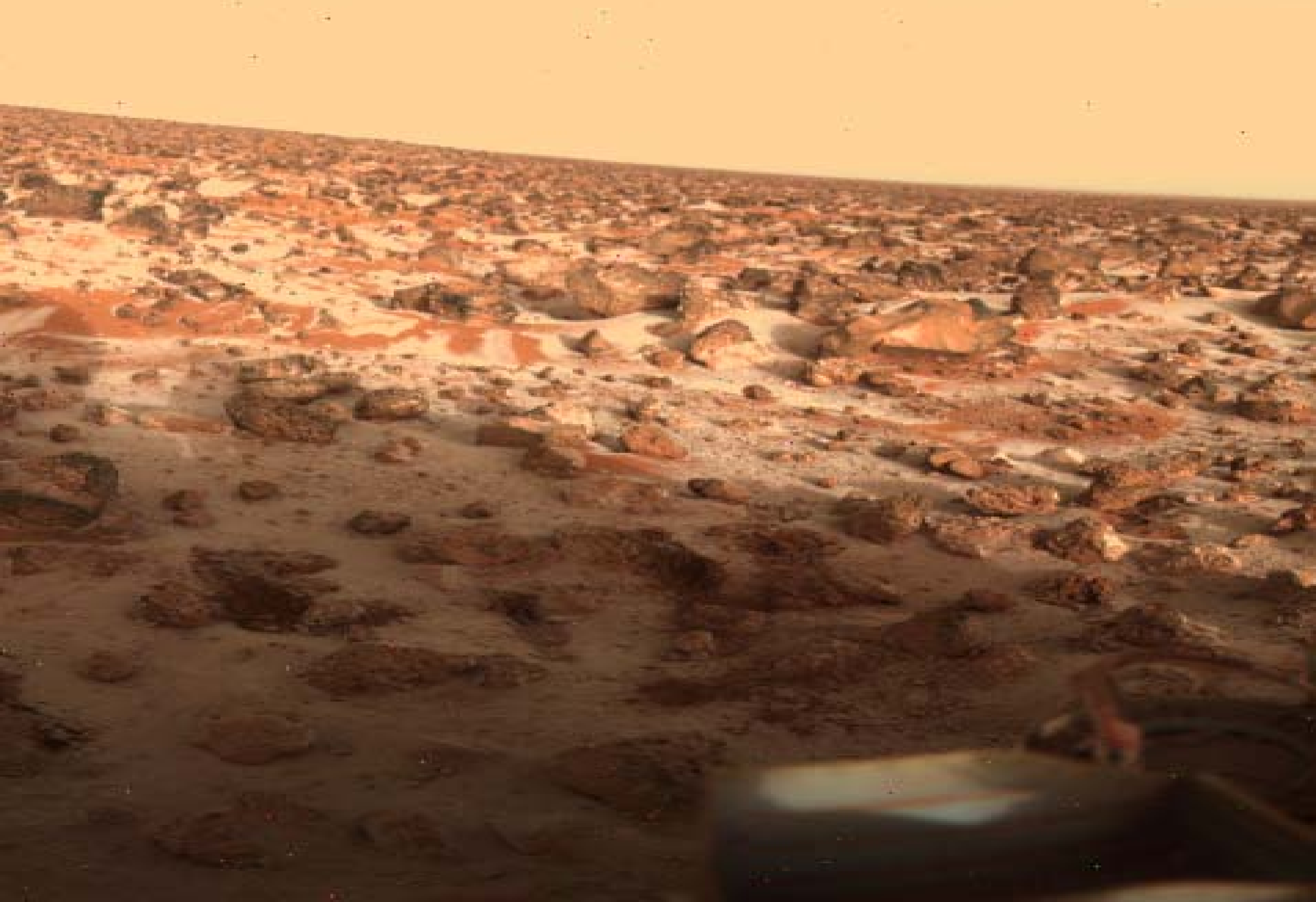
Atmospheric column of water vapor (précipitable microns)
(TES NASA Mars Global Surveyor data)



N Summer Fall Winter Spring Summer

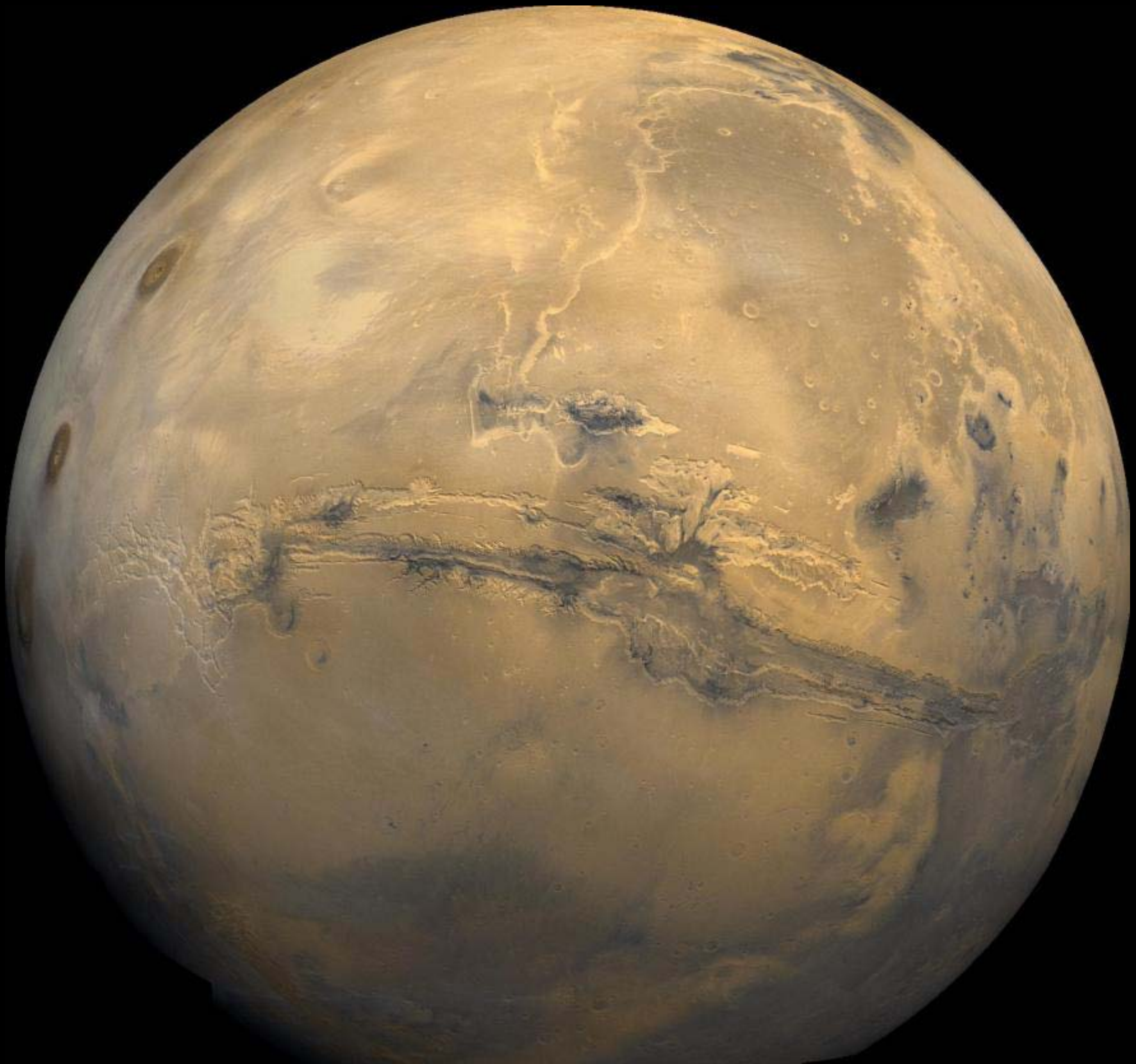


Surface frost, Viking Lander 2 (48°N) in winter

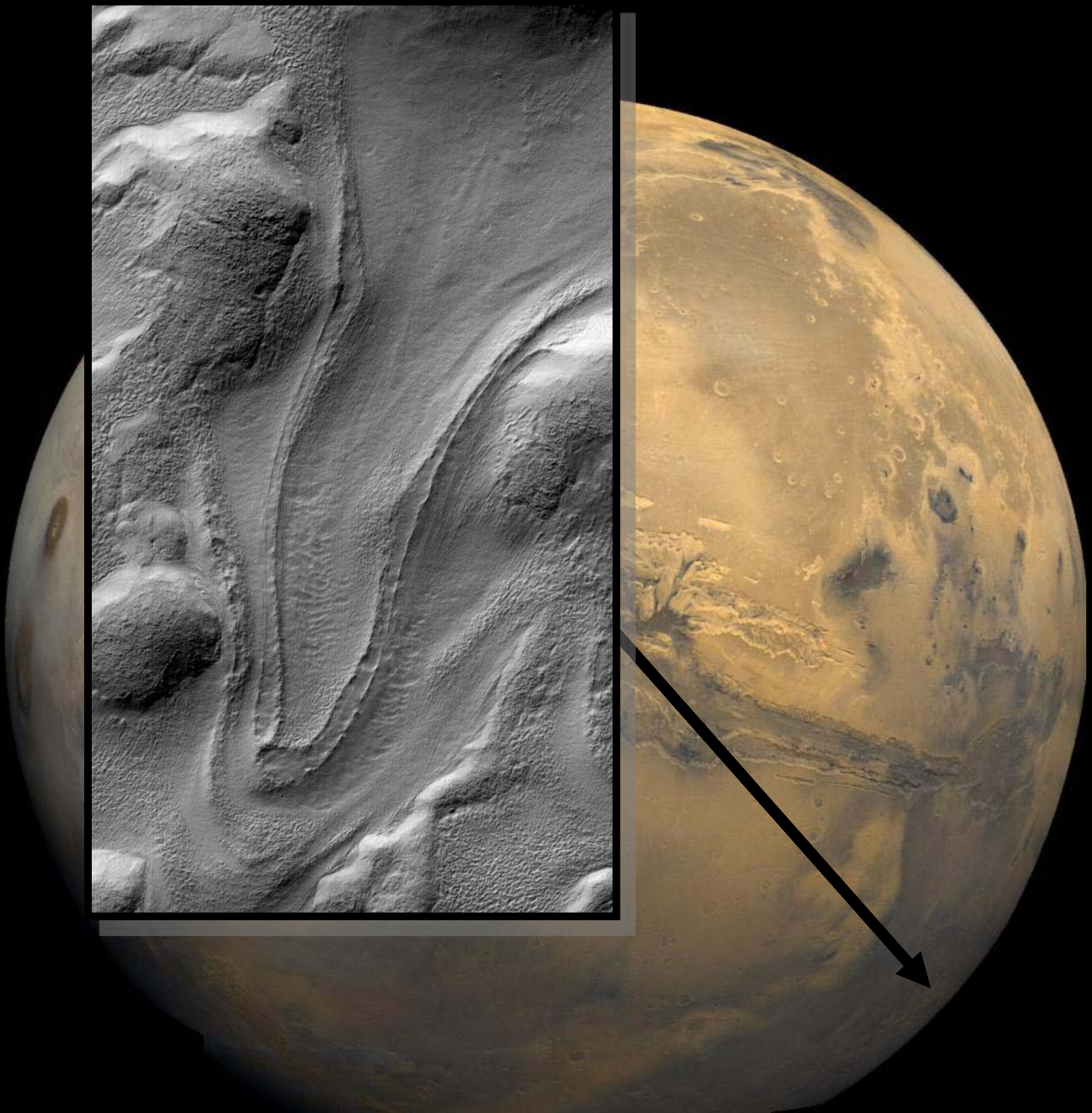


Mars Today: no permanent ice outside the polar regions

No detection by spectrometer (Omega, Crism , etc), as confirmed by climate models



<u>Mid-latitudes</u>: Burried geolofically recent rock glaciers in specific locations



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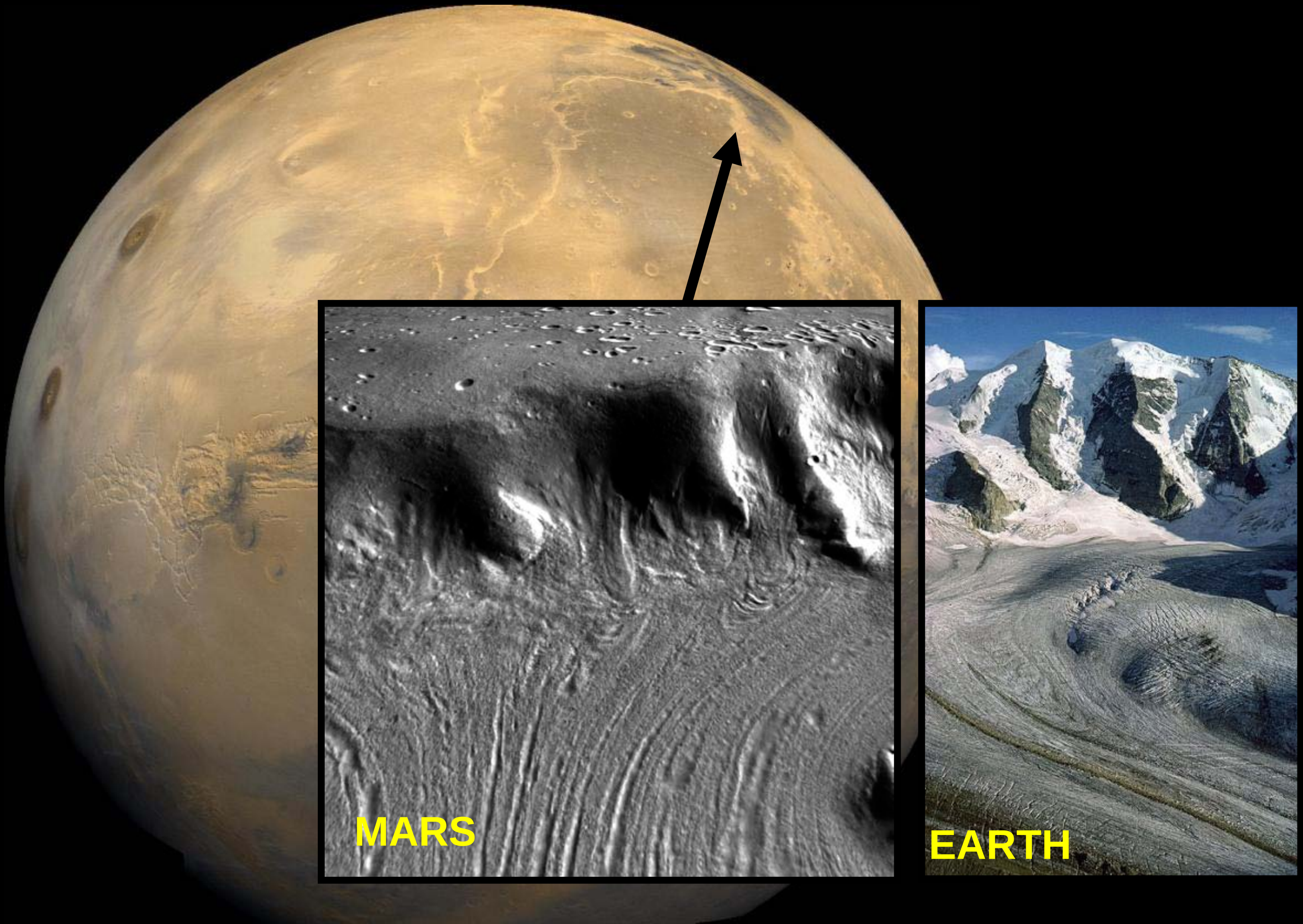
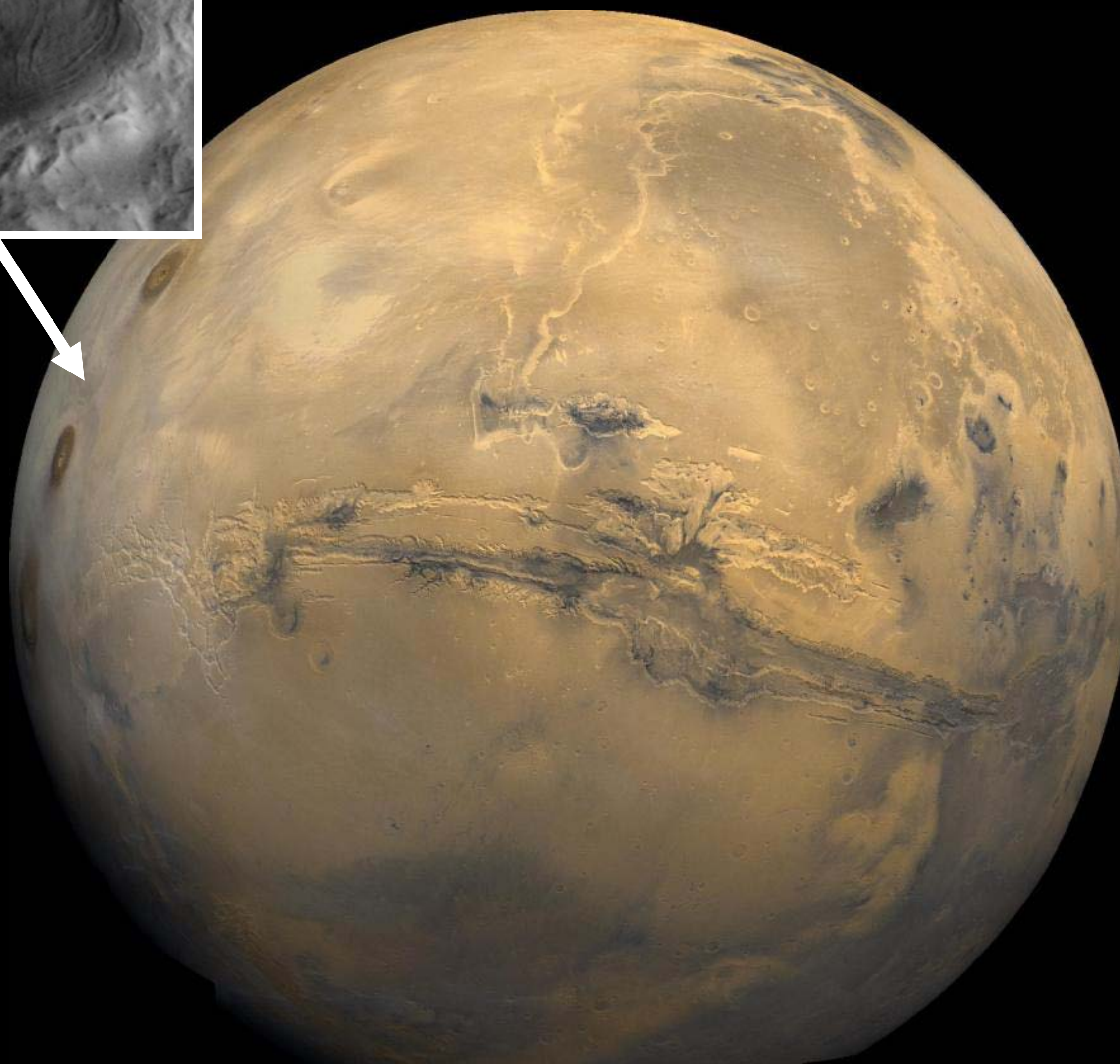


Tropics: Glaciers remnants on the western flanks of the giant Tharsis volcanoes



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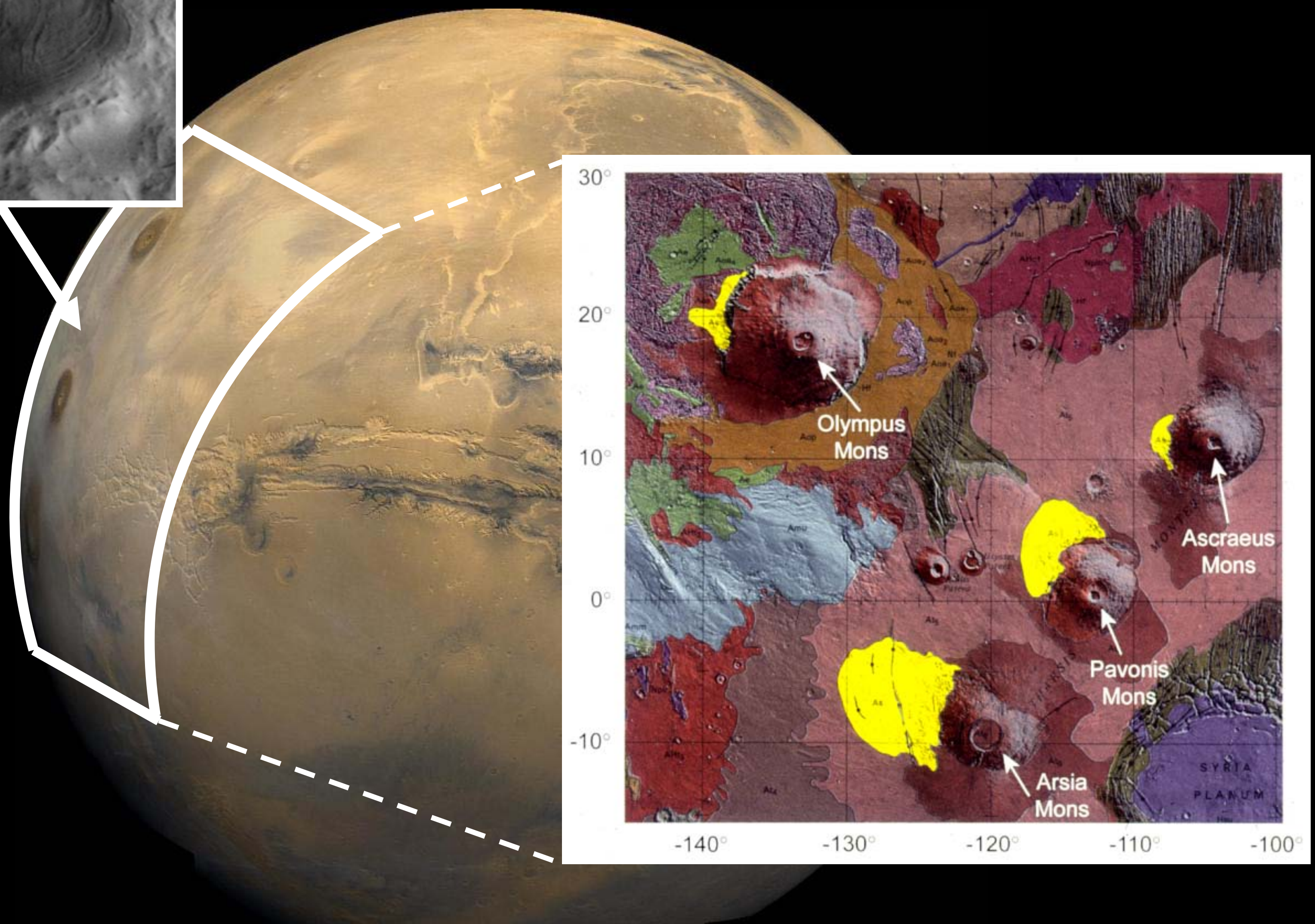
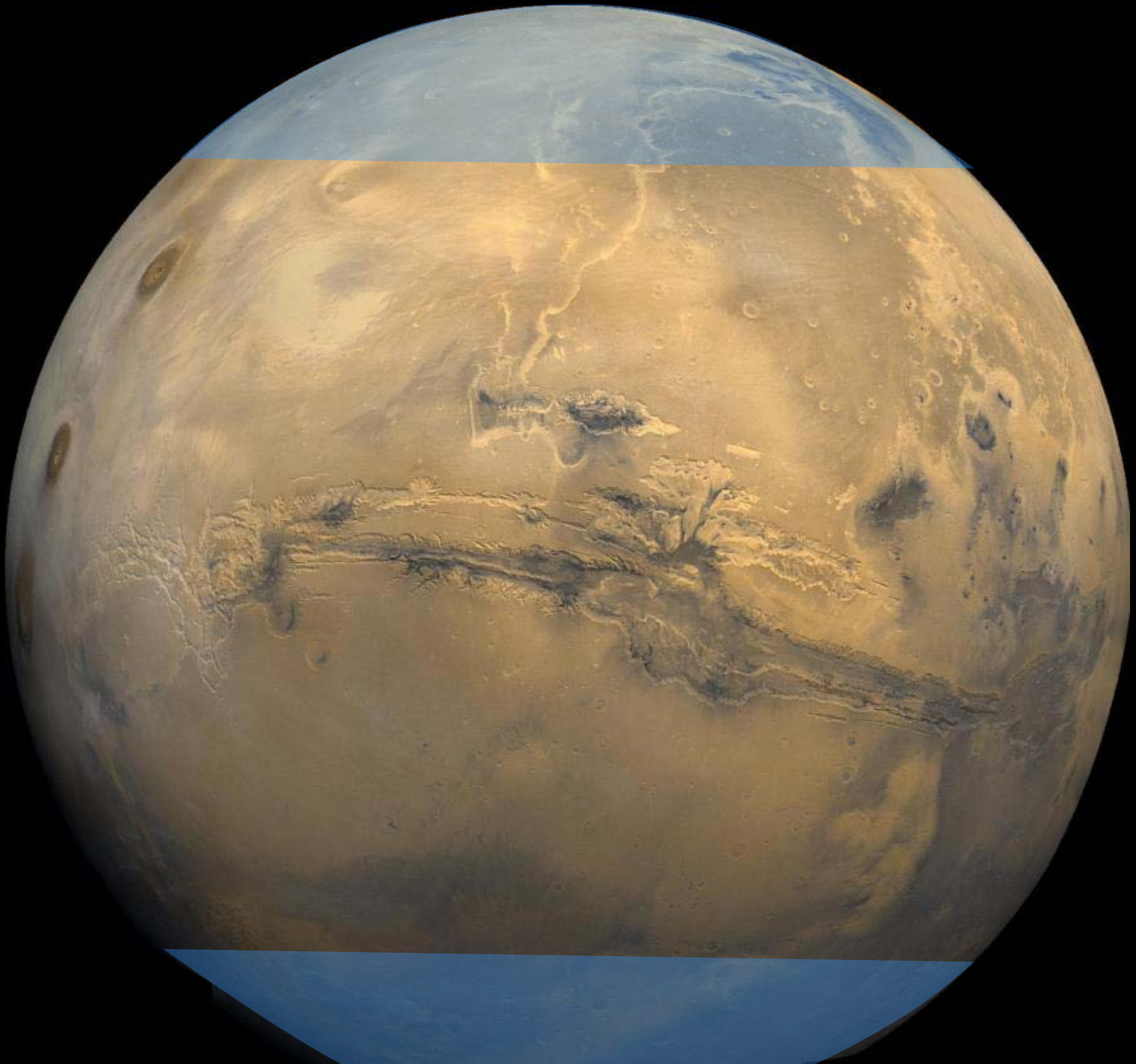
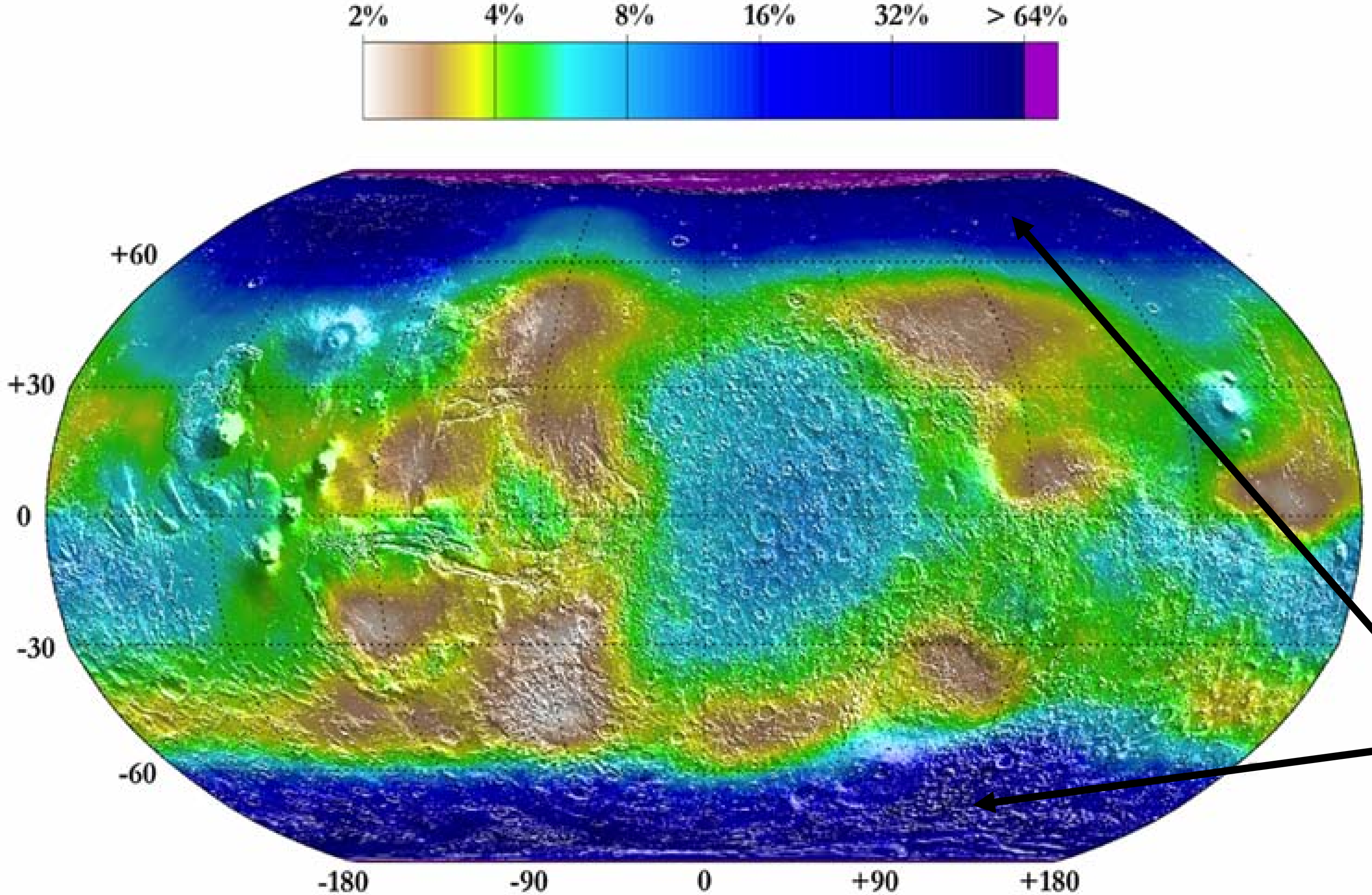


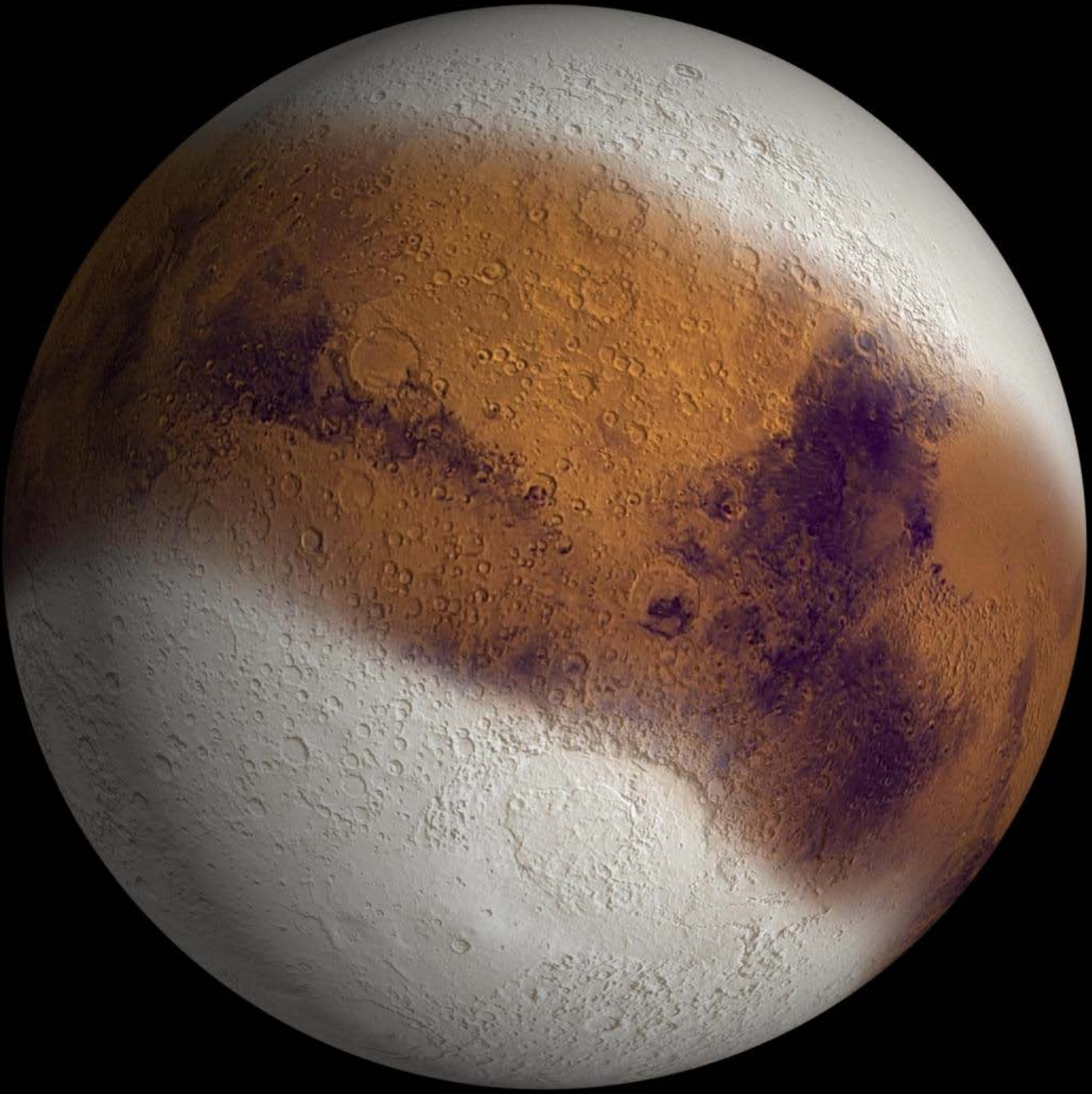
<u>High latitudes</u> (> 50°): covered by a mantle of ice isolated from the atmospheres by a few centimers of dry sand..



An ice-rich layer discovered by Mars Oddyssey below a few cm of dry sediments

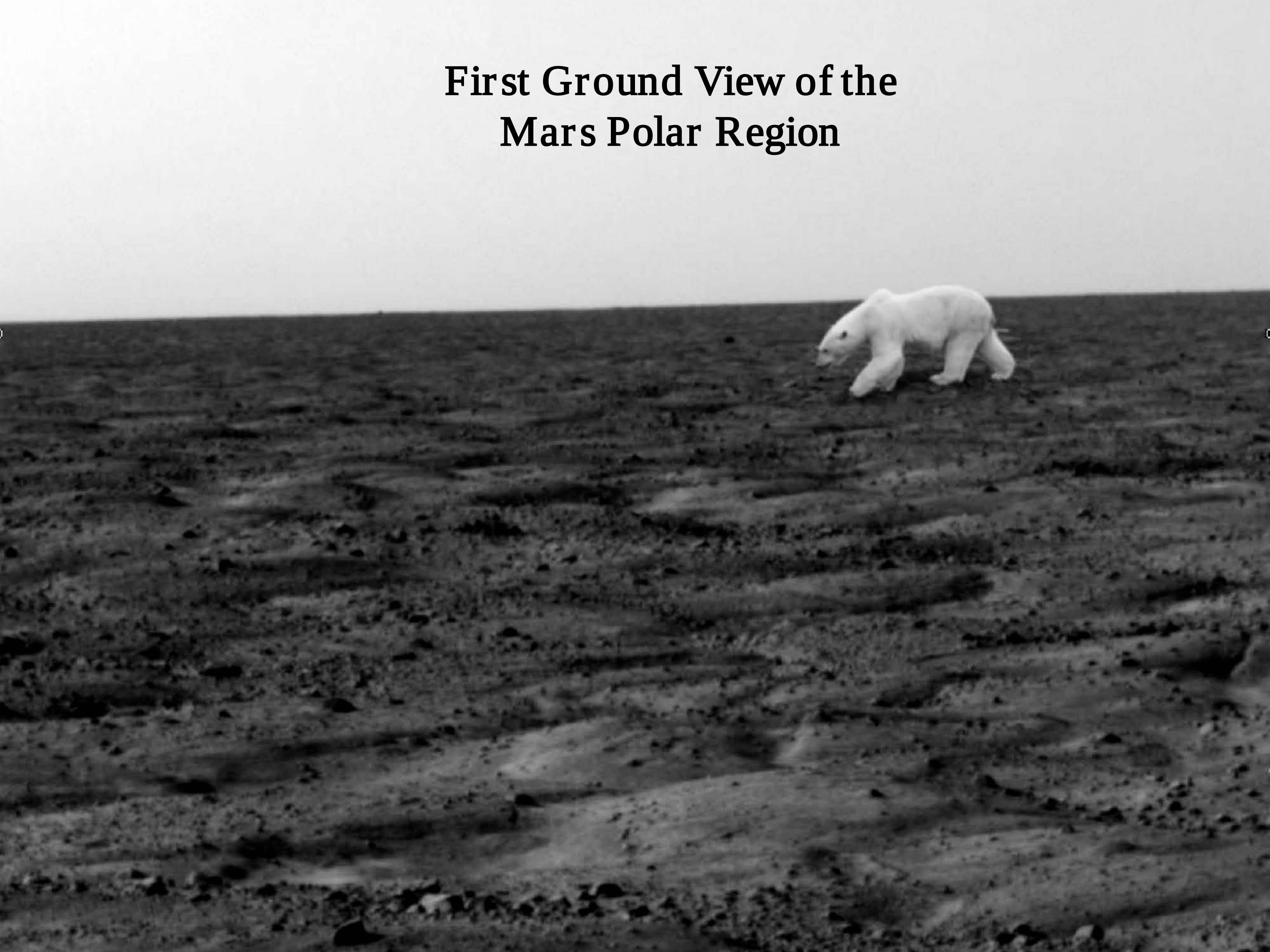
Minimum water equivalent hydrogen abundance (weight percent) deduced from Neutron flux
(Boynton et al. 2002 , Feldman et al. 2004)



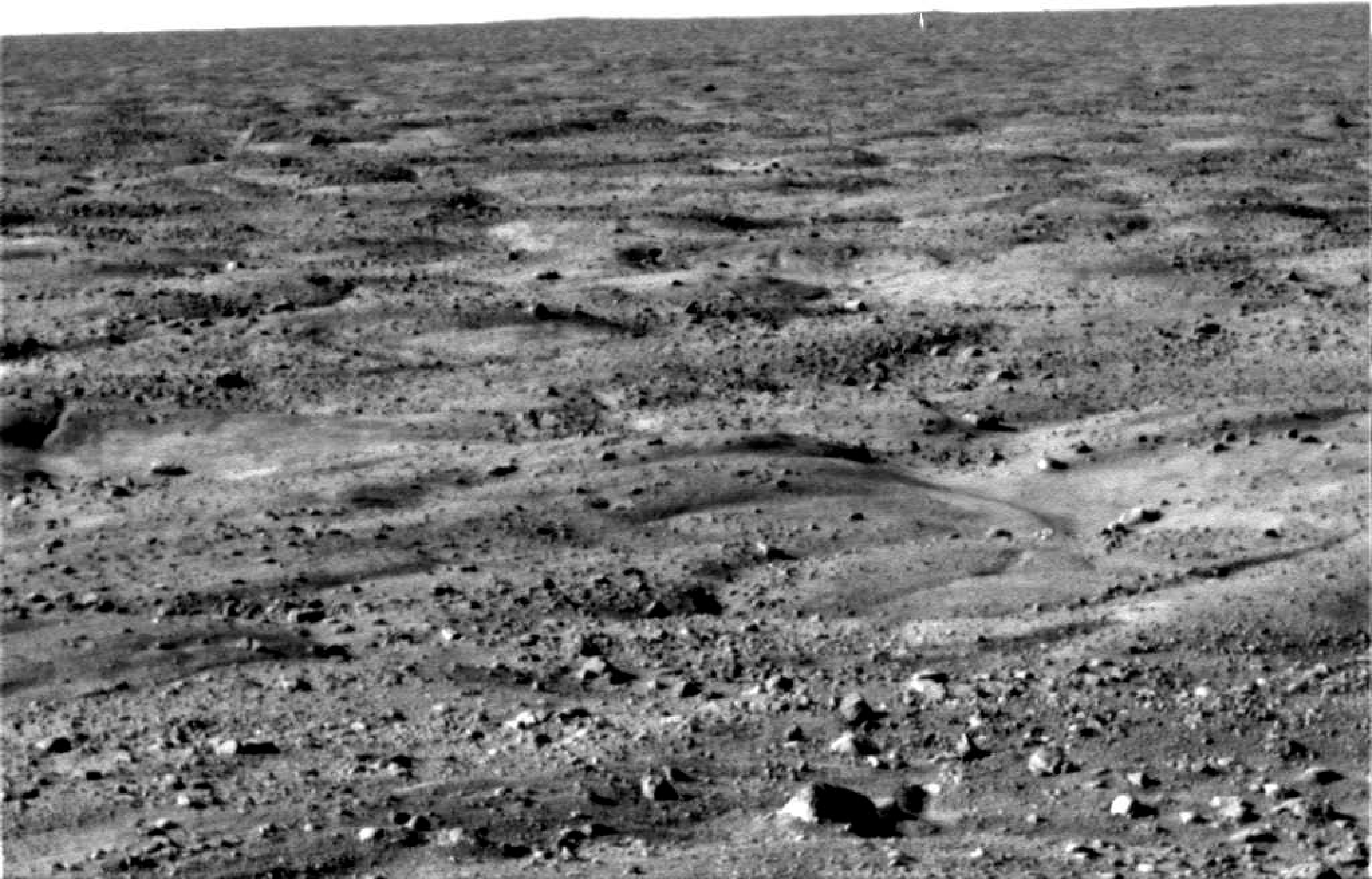


?

Phoenix: May 25, 2008   68°N


First Ground View of the
Mars Polar Region

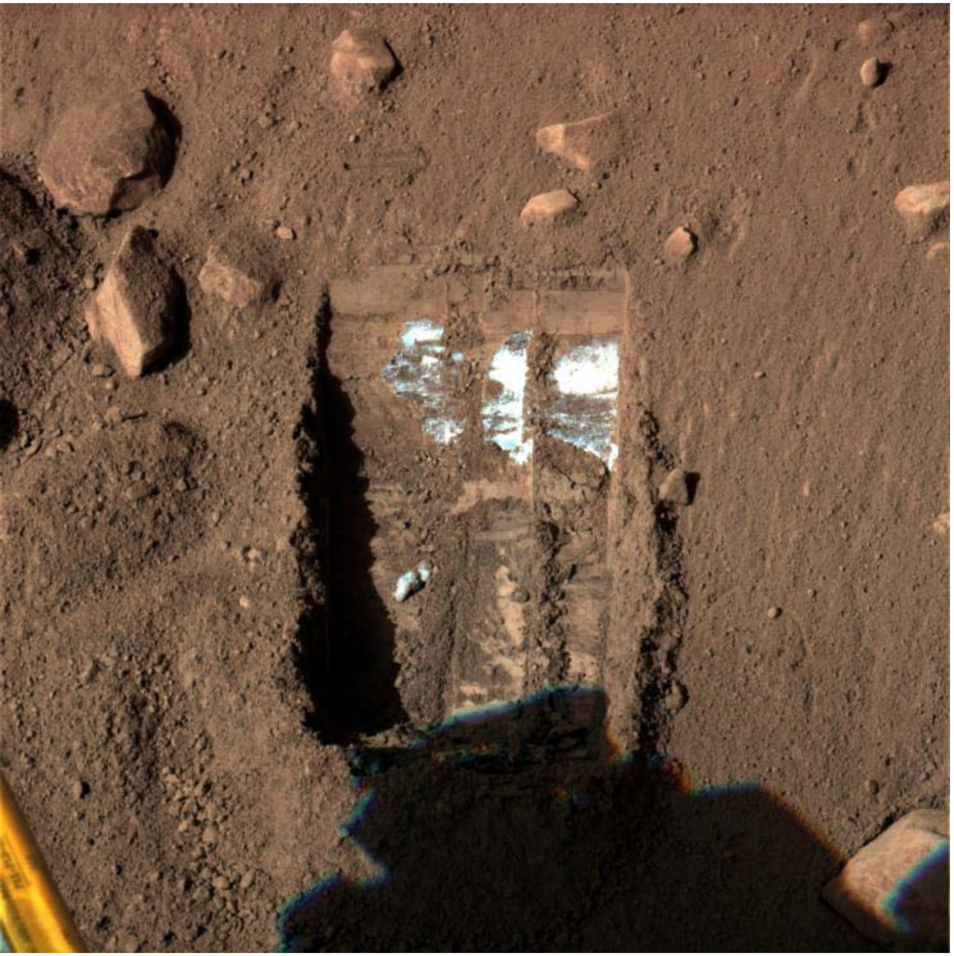
1st image Phoenix, may 2008




Antarctica

Below Phoenix : ice exposed by landing thrusters

Phoenix Ice-Bottomed Trenches



Dodo-Goldilocks

Snow White

Head et al. 2003

ARTICLES

1993

The chaotic obliquity of the planets

J. Laskar & P. Robutel

Astronomie et Systèmes Dynamiques, Bureau des Longitudes, 77 Avenue Denfert-Rochereau, F-75014 Paris, France

Numerical study of the global stability of the spin-axis orientation (
secular orbital perturbations shows that all of the terre
chaotic variations in obliquity at some time i
chaotic region, ranging from 0° to 60°
and the Earth may have been stab
planets can therefore be conside

THE problem of the origin of the obliquities
is, the orientation of their spin axis) is import
obliquities are primordial, they could provide
constraints on the formation of the Solar Sys
investigated how long-term perturbations by oth
he obliquities and precession rates of all major
olar System, and demonstrate that none of the
Mercury, Venus, the Earth and Mars) can be
ave primordial obliquities. Any of these planet
rted with nearly zero obliquity, in a prograde s
aotic behaviour of their obliquity could have dri
ir current value. If their primordial spin rate was h
rcury and Venus could have undergone large a
nges of obliquity from 0° to ~90°, before dissipat
nately drove them to their current obliquity. Th
uity of the Earth may have been reached during a
before the capture of the Moon[5]. The obliquity of
ic at present, with possible variations from 0° to ~6
ities of the outer planets are stable, but may hav
h a similar process in an earlier stage of the Solar Sys
ion.

ds

tion of the Solar System were quasiperiodic
ssion could be modelled

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2004

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Long term evolution and chaotic diffusion of the insolation quantities of Mars

J. Laskar [a,*], A.C.M. Correia [a,b,c], M. Gastineau [a], F. Joutel [a], B. Levrard [a], P. Robutel [a]

[a] *Astronomie et Systèmes Dynamiques, IMCCE-CNRS UMR8028, 77 Av. Denfert-Rochereau, 75014 Paris, France*
[b] *Observatoire de Genève, 51 chemin des Maillettes, 1290 Sauverny, Switzerland*
[c] *Departamento de Física da Universidade de Aveiro, Campus Universitário de Santiago, 3810-193 Aveiro, Portugal*

Received 21 November 2003; revised 26 March 2004

Available online 2 June 2004

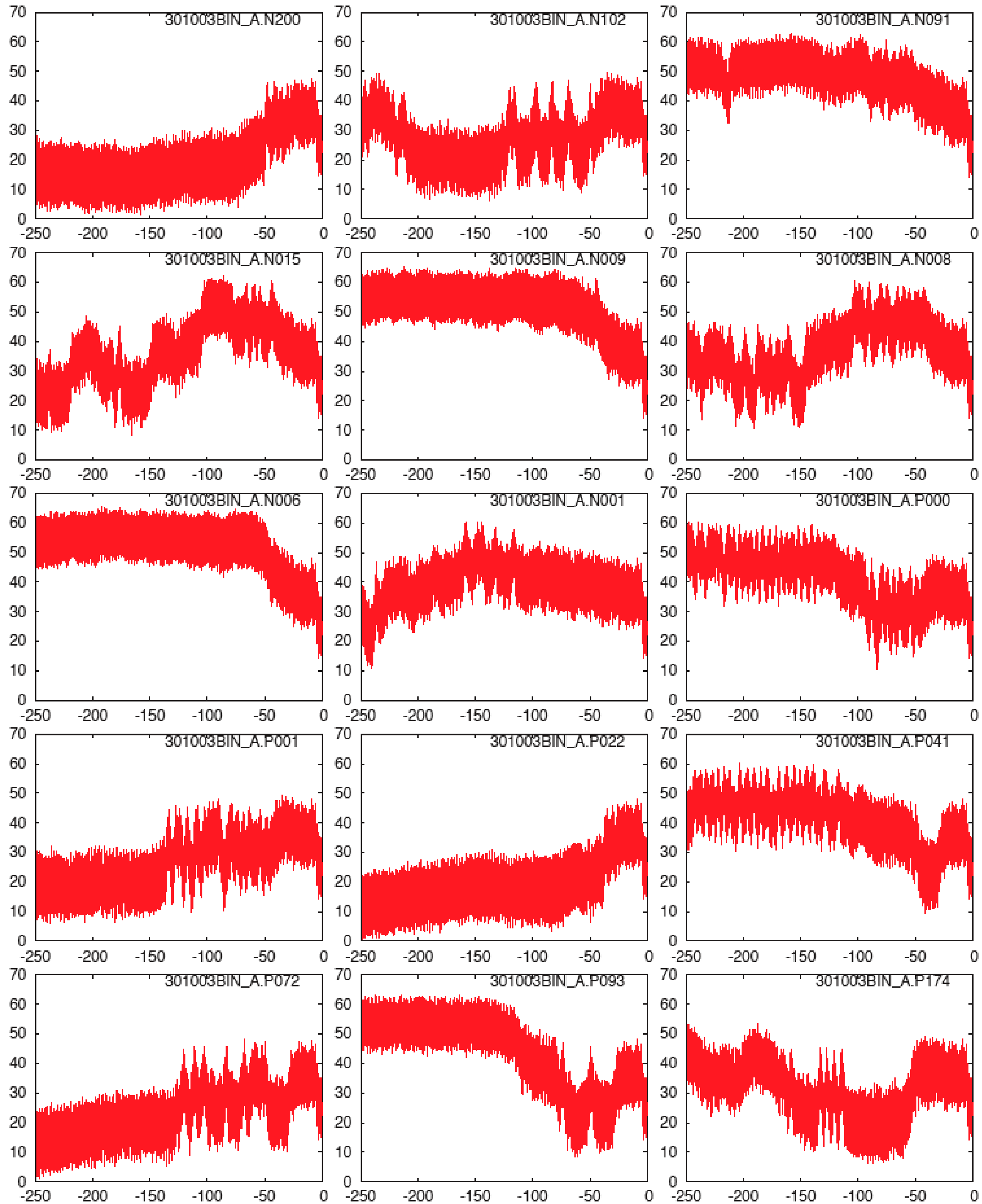
- 250 Myr – Now :

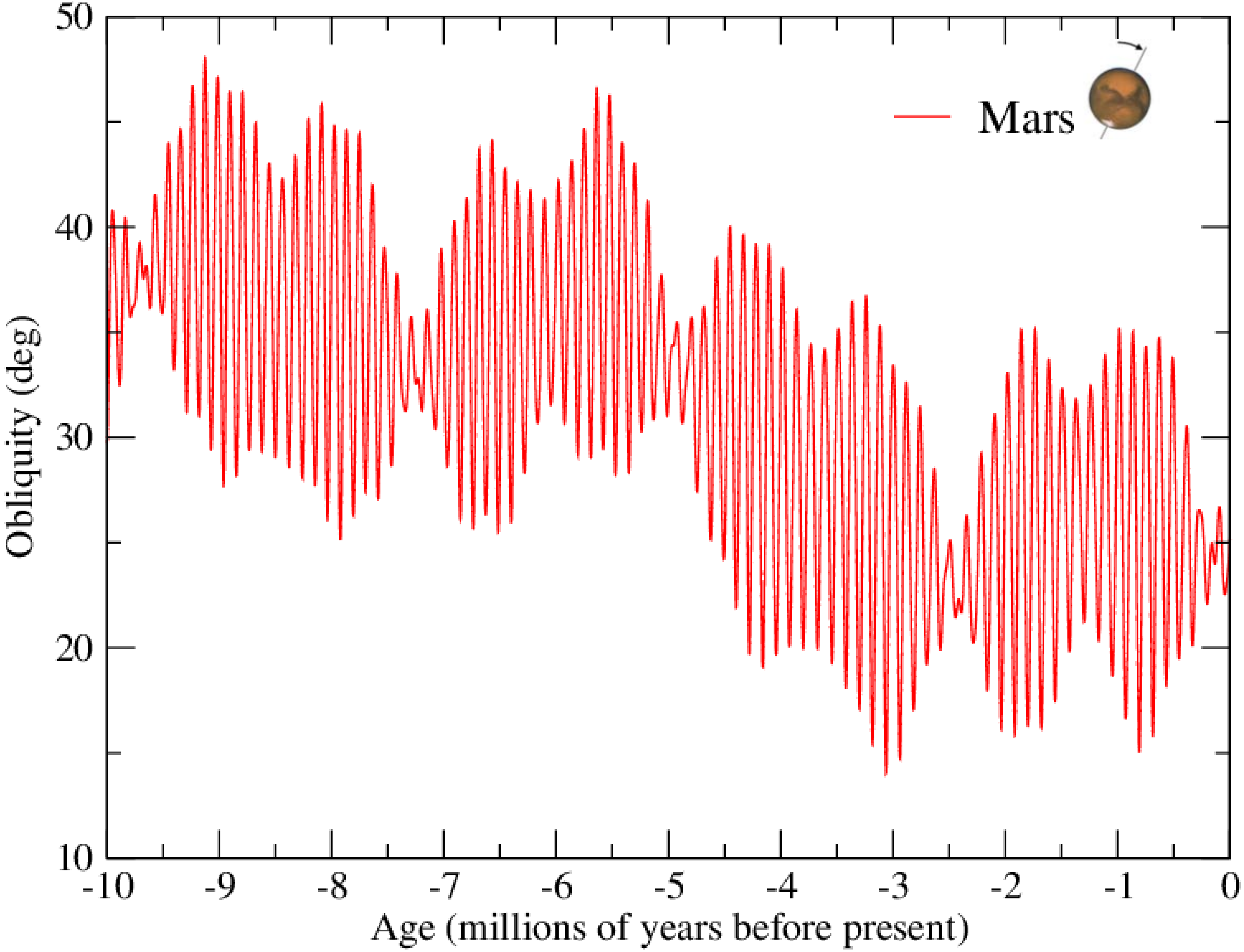
• Chaos : past evolution unknown before -10 Myr

•Possible variations of obliquity

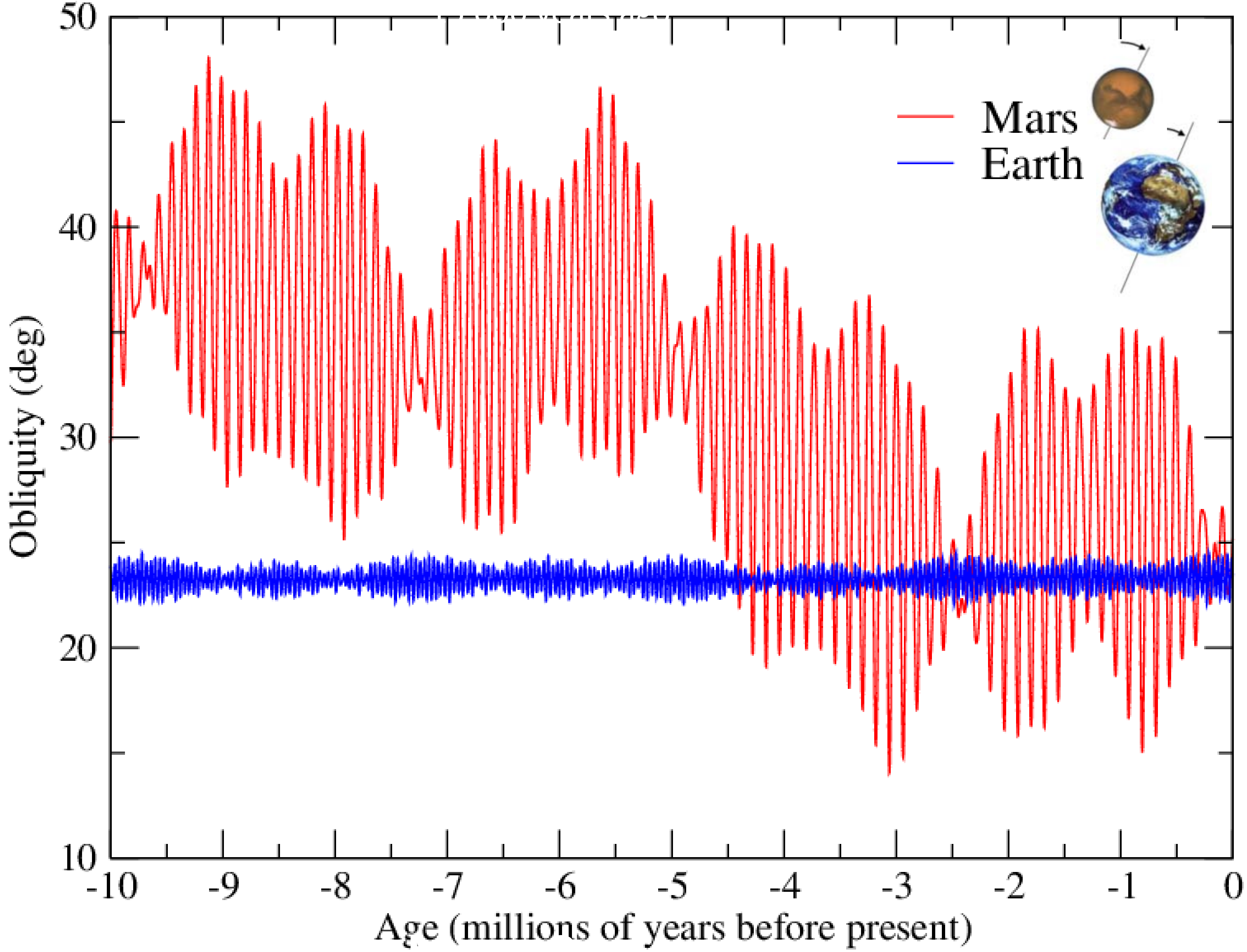
(Laskar et al. 2004) :

⇨ Most likely obliquity was 42º.





Laskar and Robutel (1993), Touma and Wisdom (1993), Laskar (2004)



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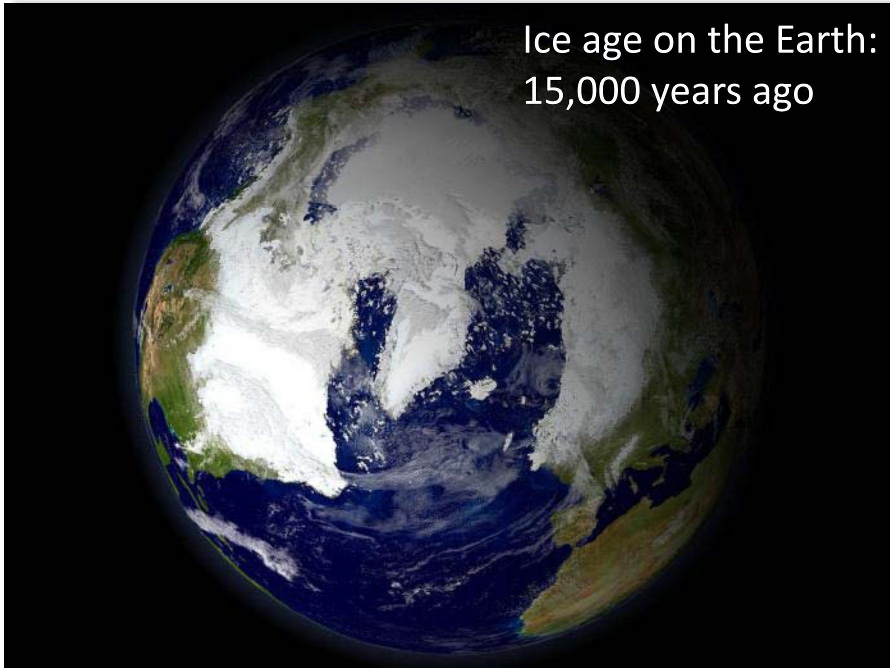
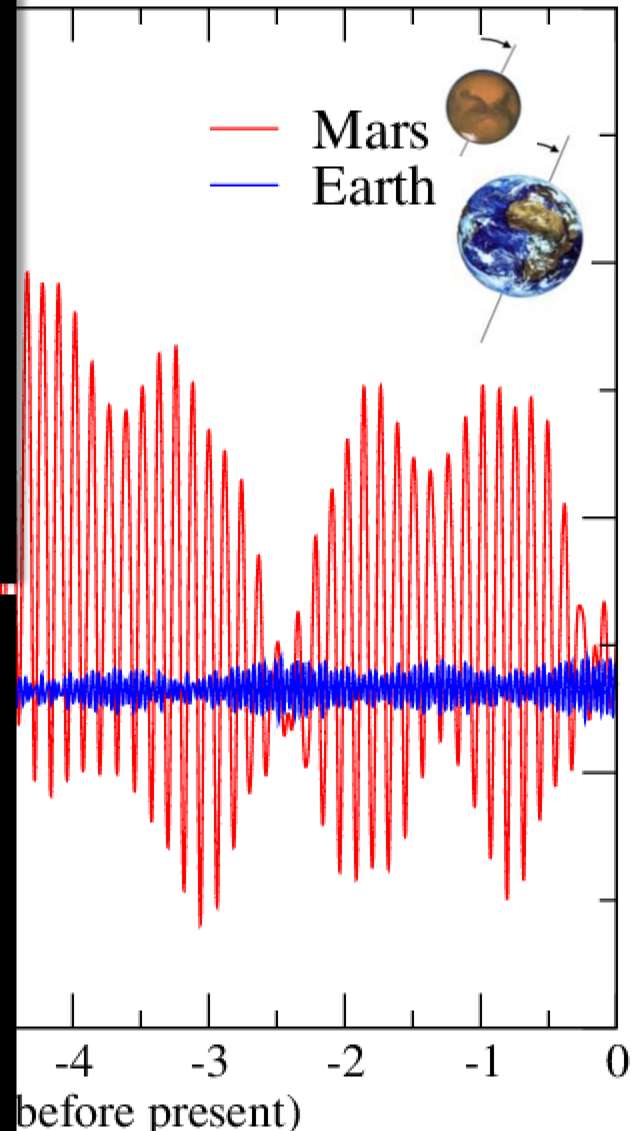
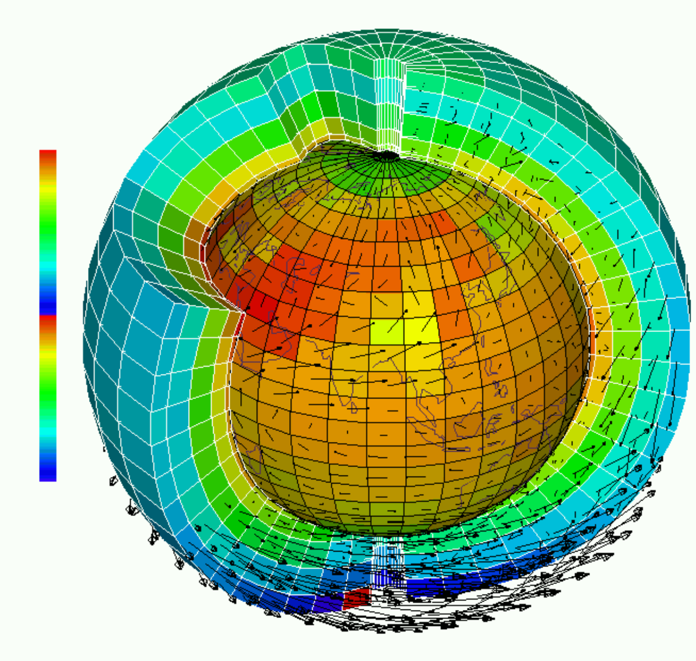


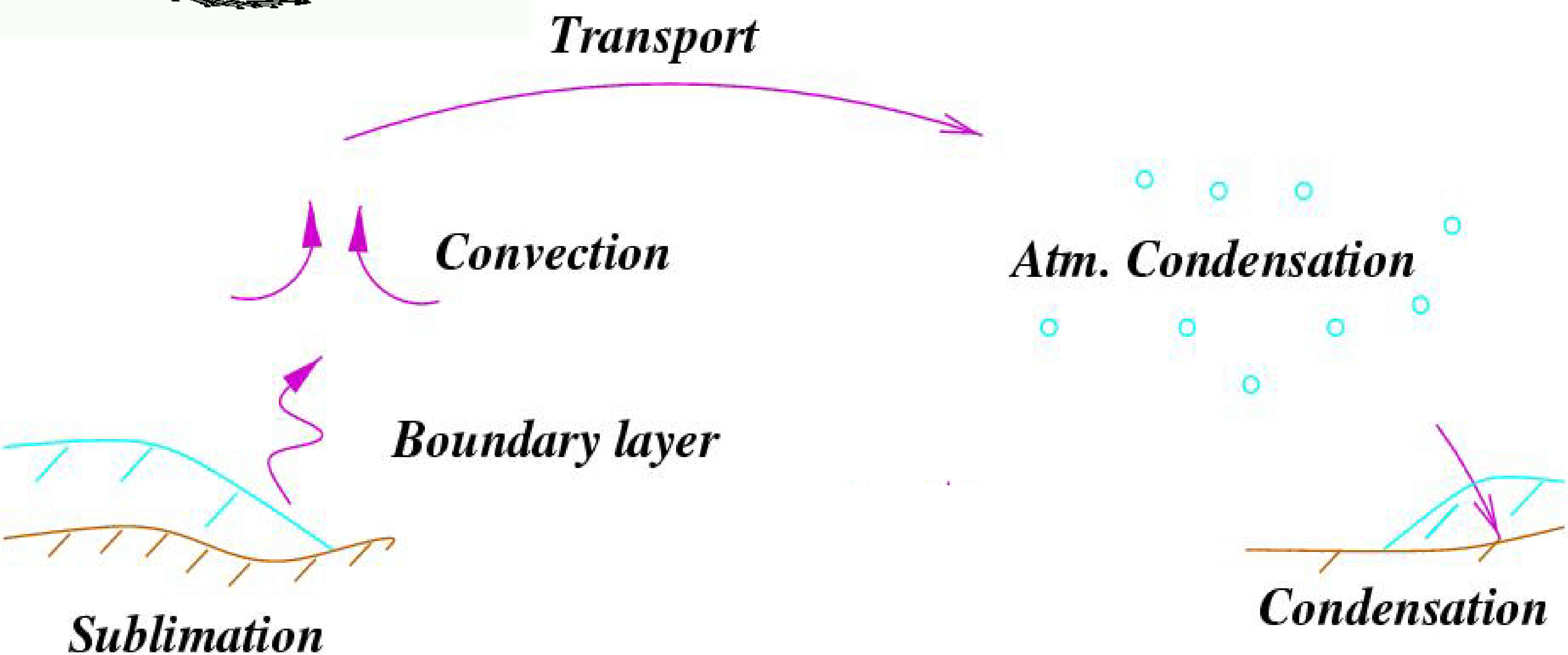


Laskar and Robutel (1993), Touma and Wisdom (1993), Laskar (2004)



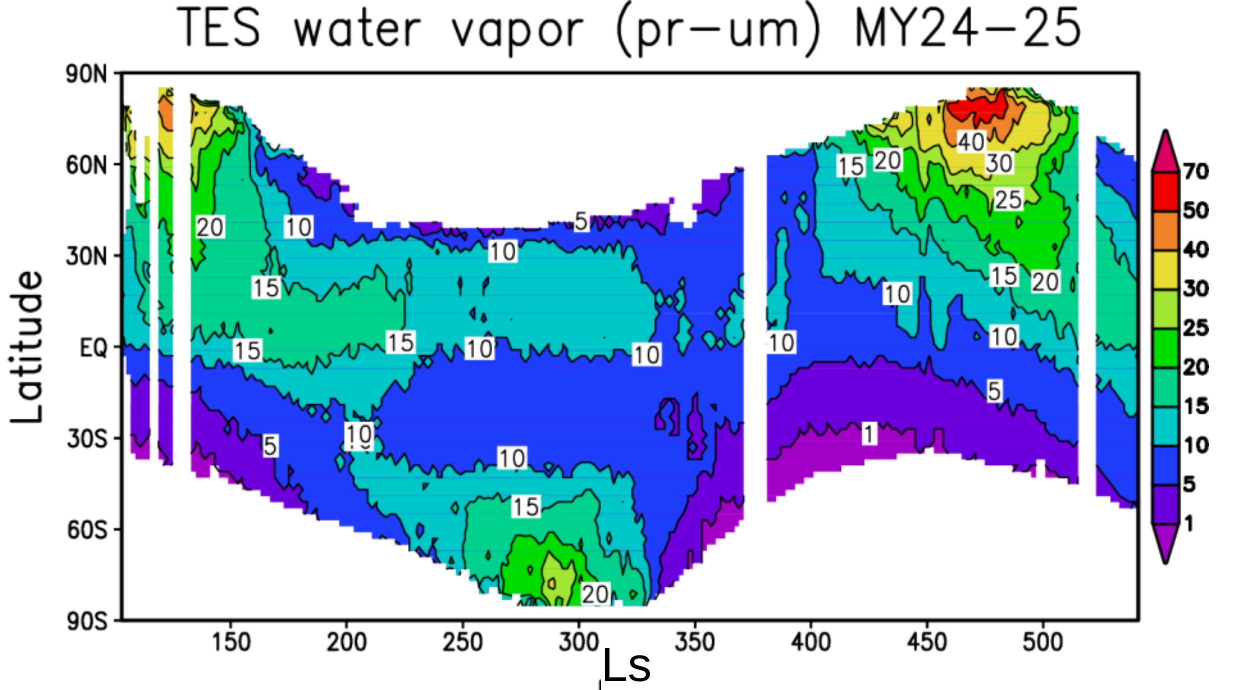
Modelling Mars water cycle with the LMD Mars Global Climate Model

Forget et al. 1999, Montmessin et al. 2004, Forget et al. 2008

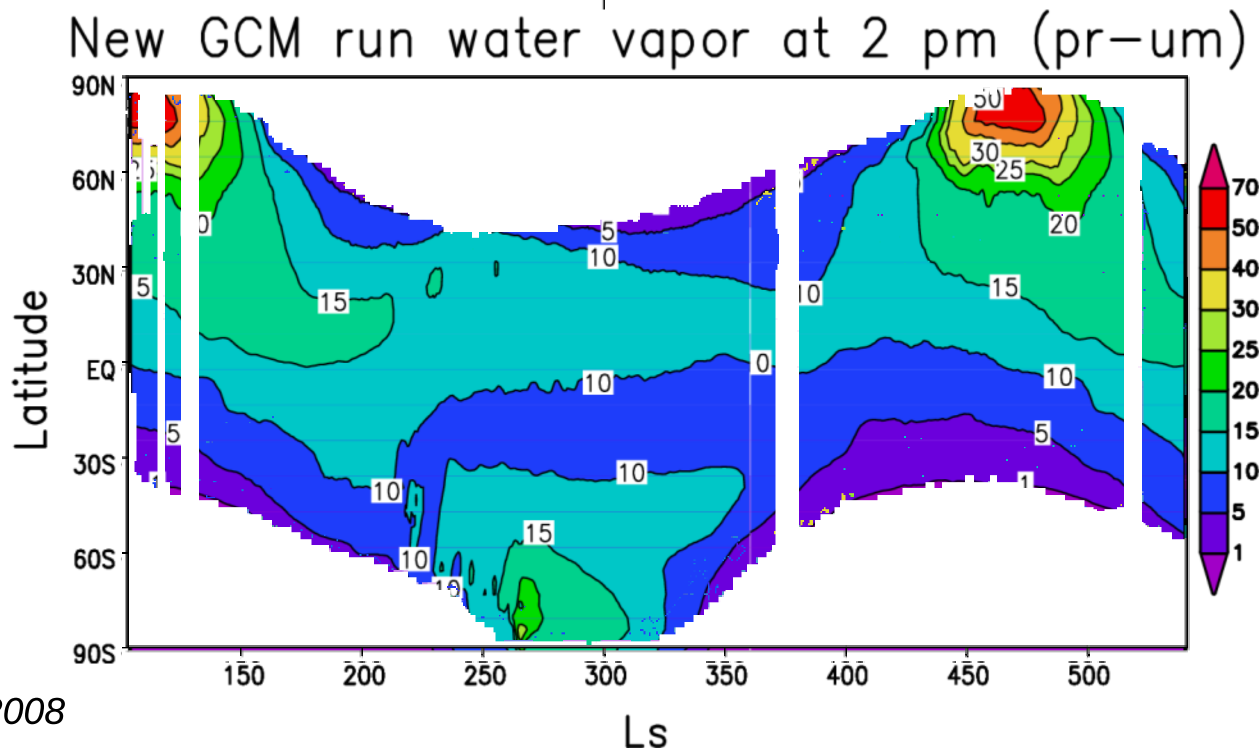


SEASONAL WATER CYCLE

OBSERVATIONS



MODEL



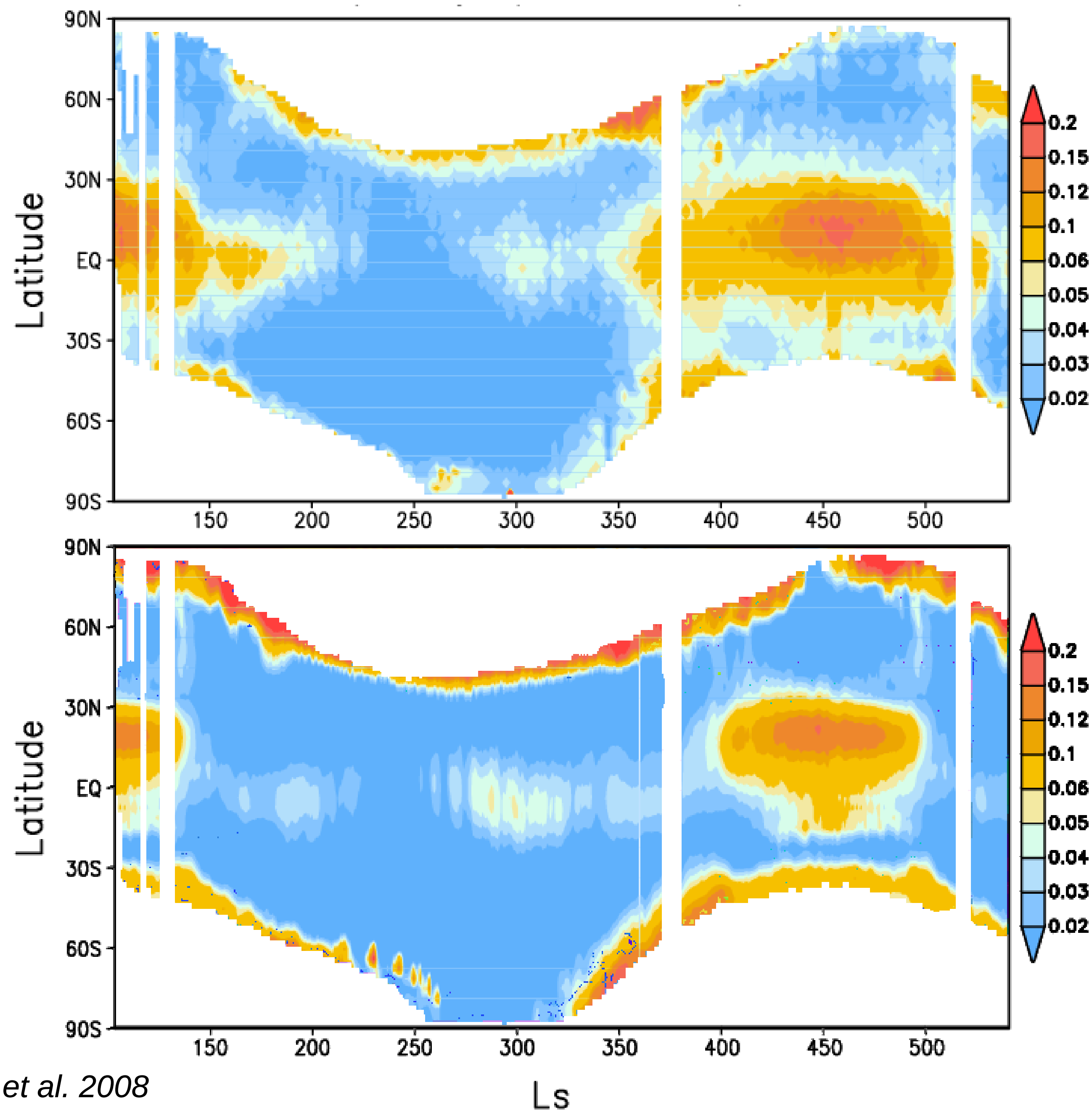
Montmessin et al. 2004, Forget et al. 2008

SEASONAL CLOUD CYCLE

OBSERVATIONS

MODEL

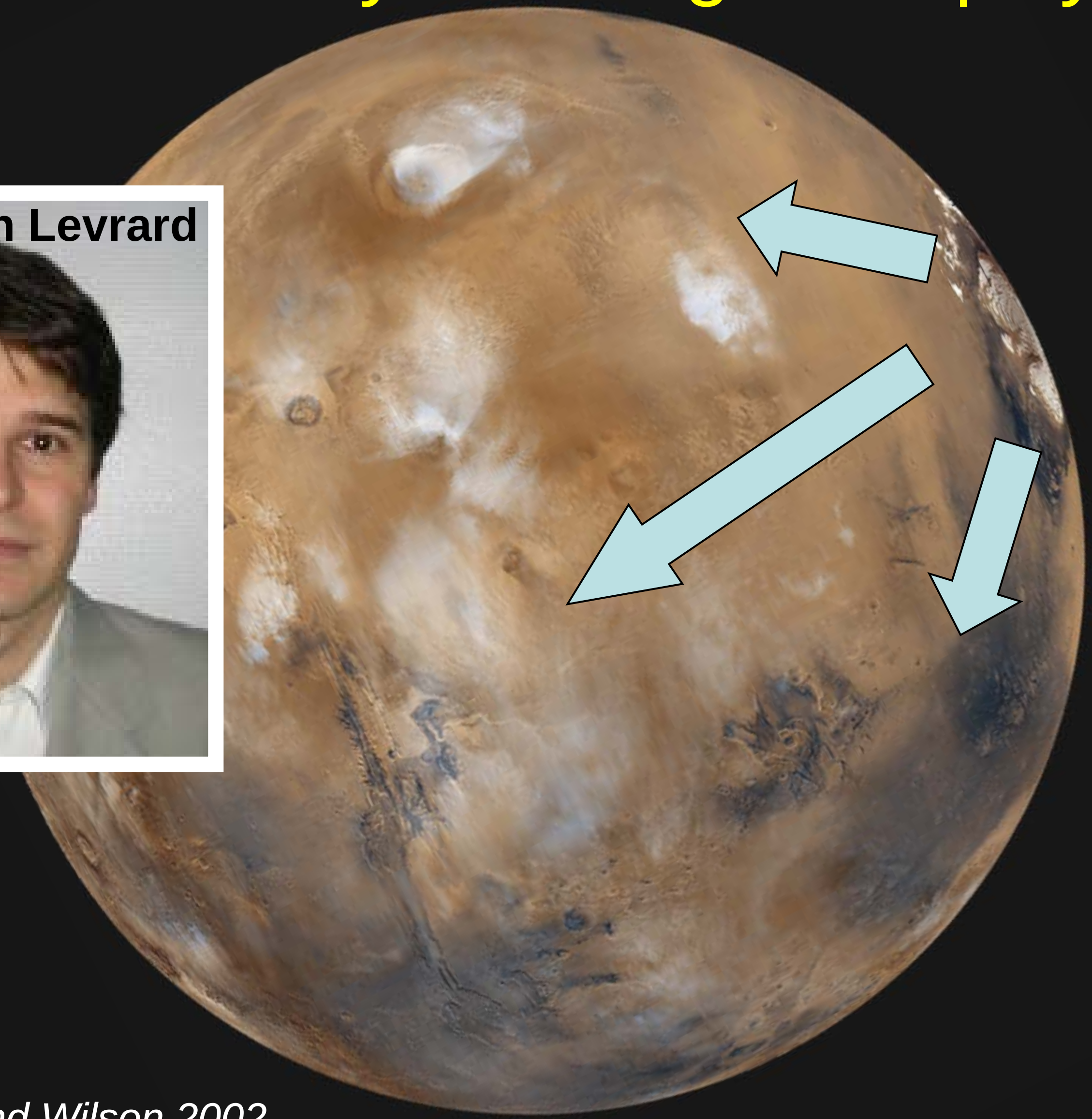
H_2O ice absorption opacity at 2pm ($825\ cm^{-1}$) MY24-25



Montmessin et al. 2004, Forget et al. 2008

Mars water cycle at high obliquity

Solar flux



Richardson and Wilson 2002
Mischna et al. 2003
Levrard et al., 2004
Mischna and Richardson 2005

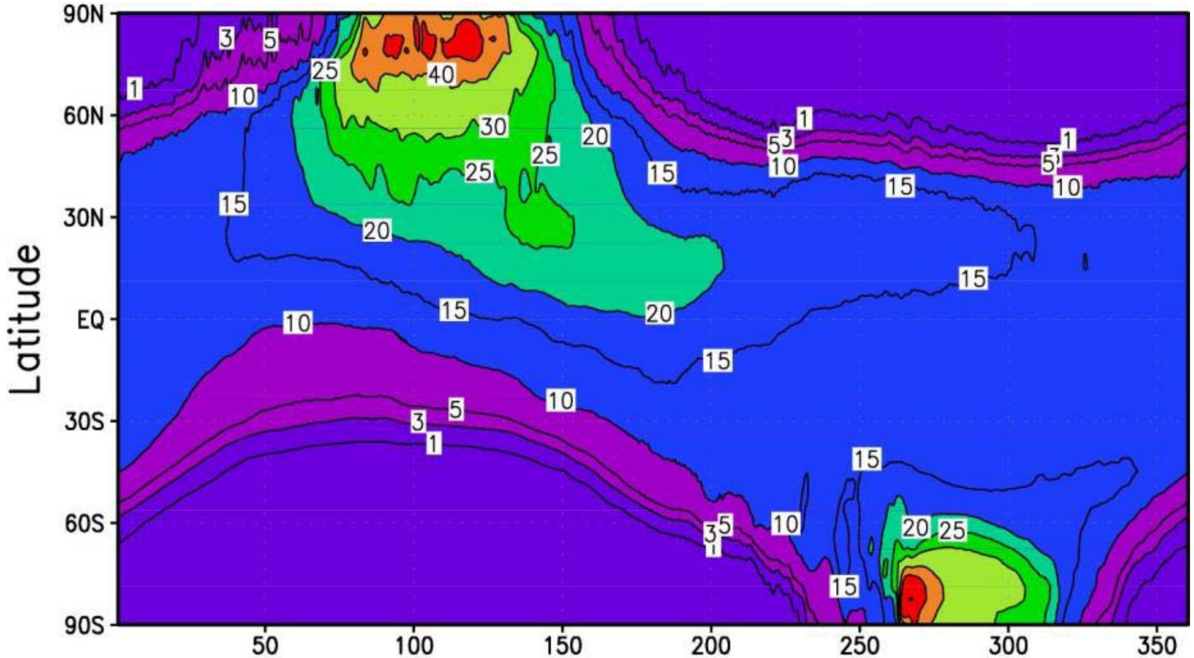
Forget et al., 2006
Madeleine et al., 2009, 2014
Levrard et al. 2007

LMD GCM Simulations:

Water vapor column

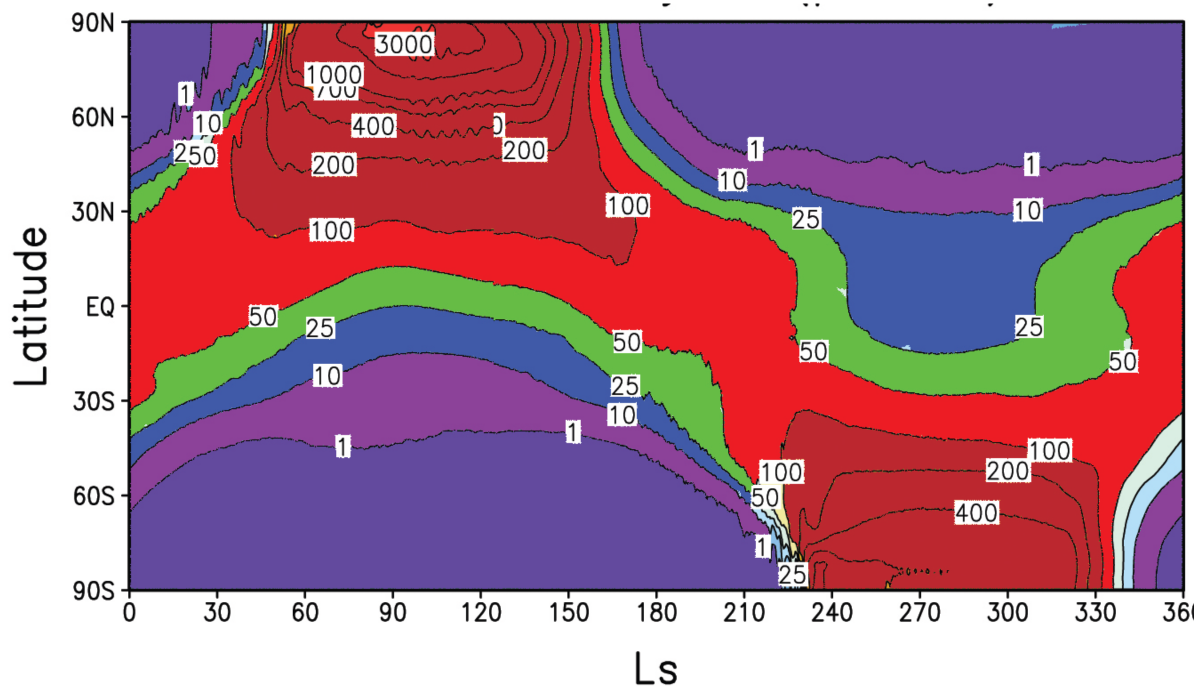
(*precipitable –microns*)

On present-day Mars :



Same, but 45° Obliquity

(Circular orbit)

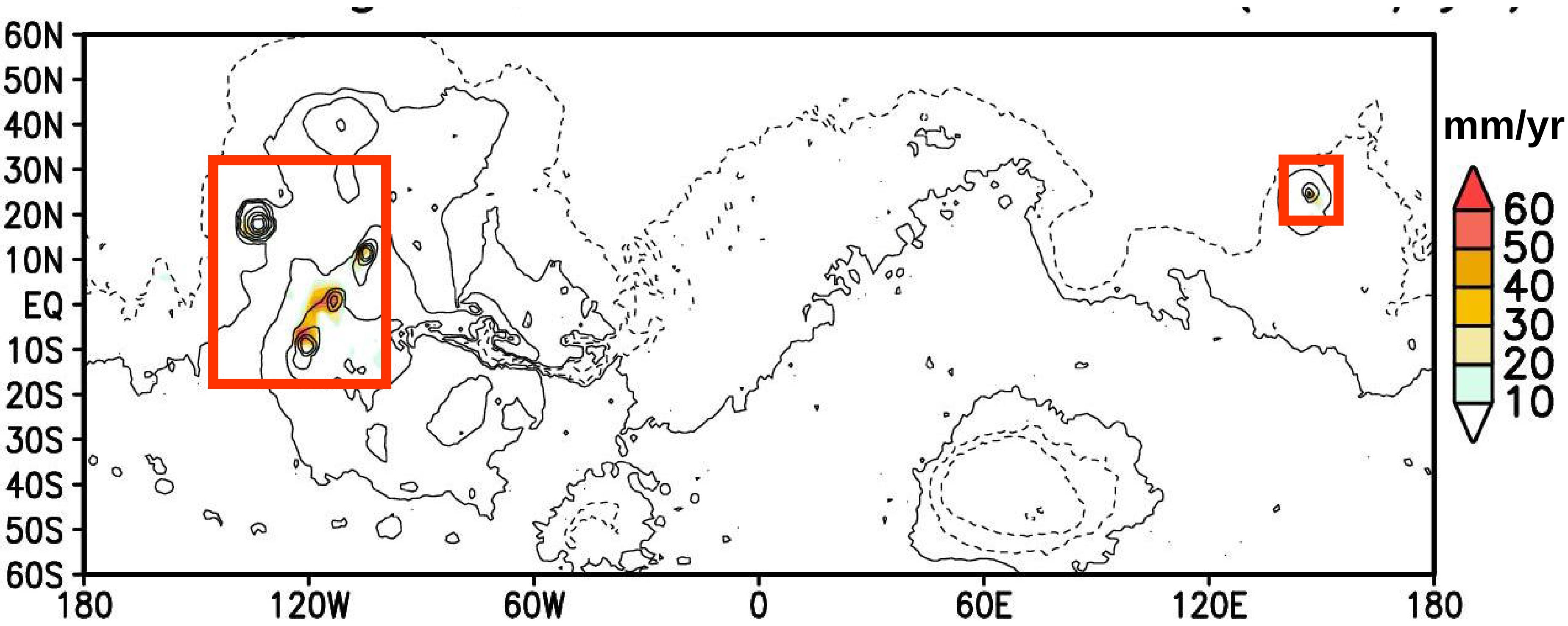


Ice accumulation rate (mm/yr)

high resolution simulation (2°x2°)

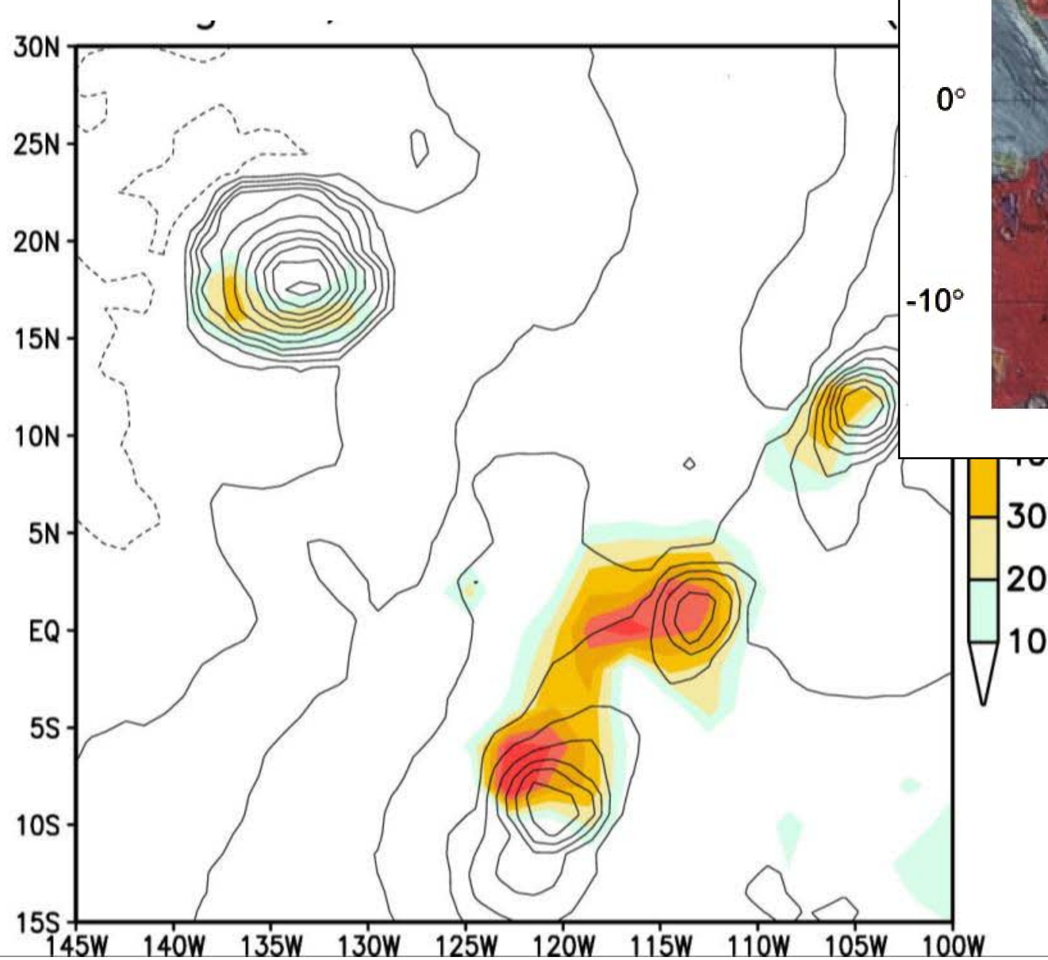
Obliquity = 45° , Excentricity = 0, Dust Opacity =0.2

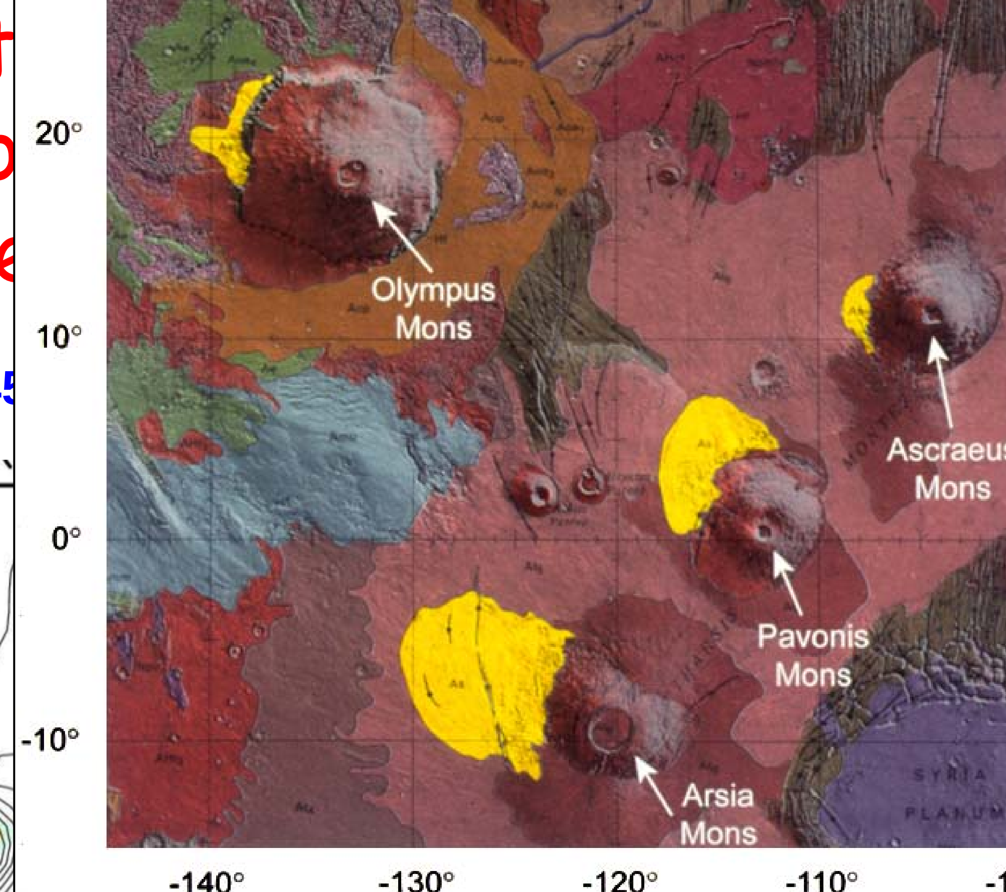
Forget et al. Science 311, p368, 2006



The format
accumulatio
very high re

Forget et al. 2006: Obliquity = 45



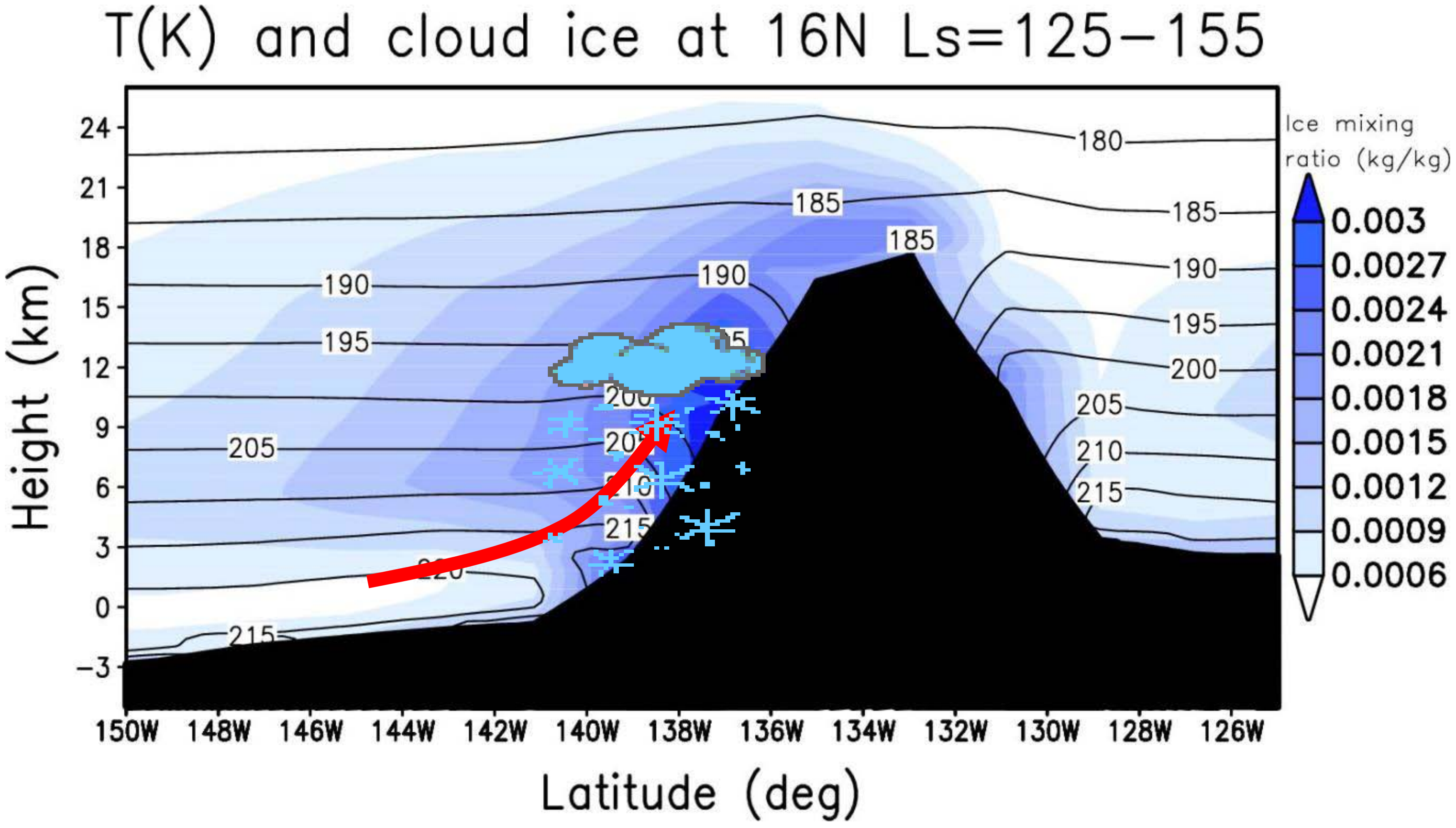


•Fan shaped deposits, drop moraines characteristic of cold based glaciers.

•Rock glaciers

Lucchitta 1981, Head et al. 2003, Shean et al. 2005, 2007, Head et al. 2005, Kadish et al. 2008, Schon and Head 2012

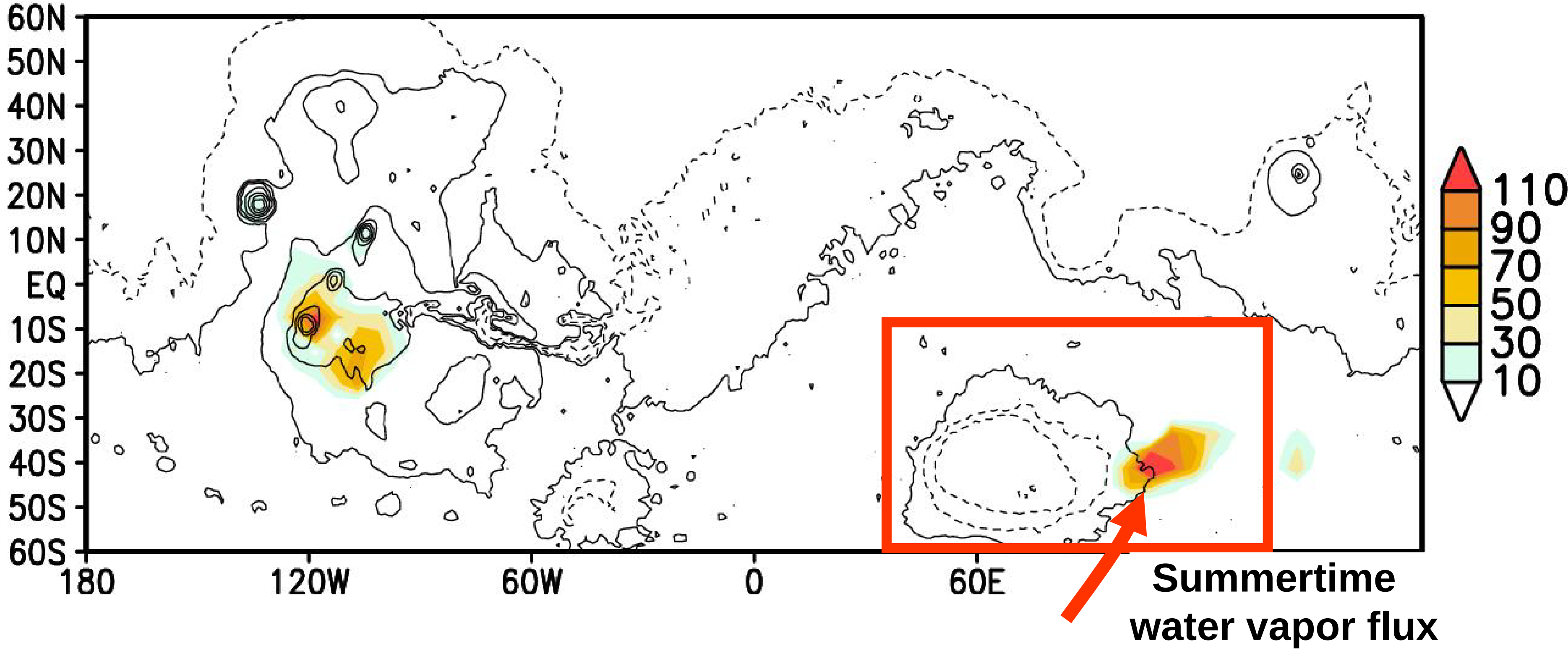
At high obliquity: Ice accumulation by ice precipitation on windward slope

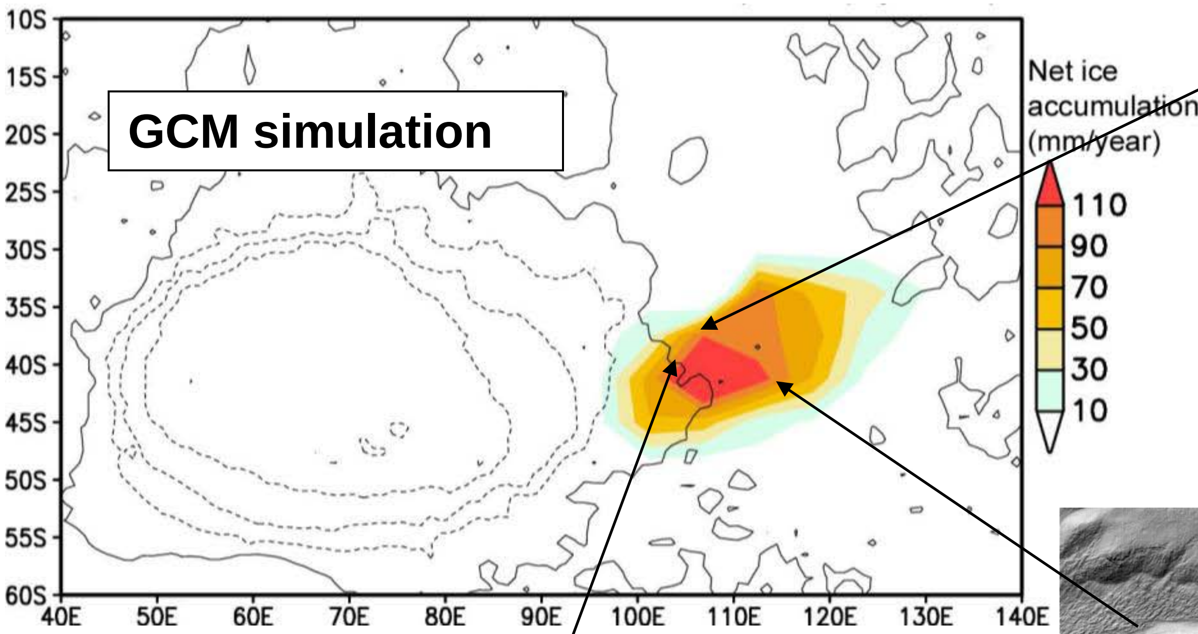


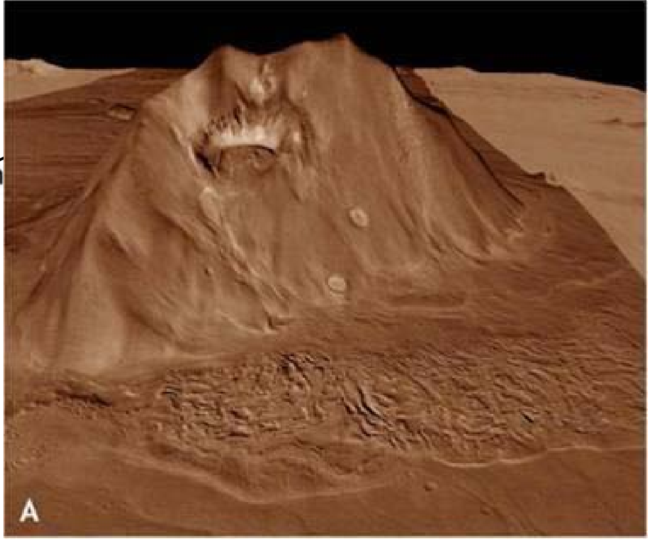
High Obliquity Simulation with a water ice cap **at the south pole**

(Forget et al. 2006)

Yearly accumulation rate (mm/year) (1Oth year simulation)

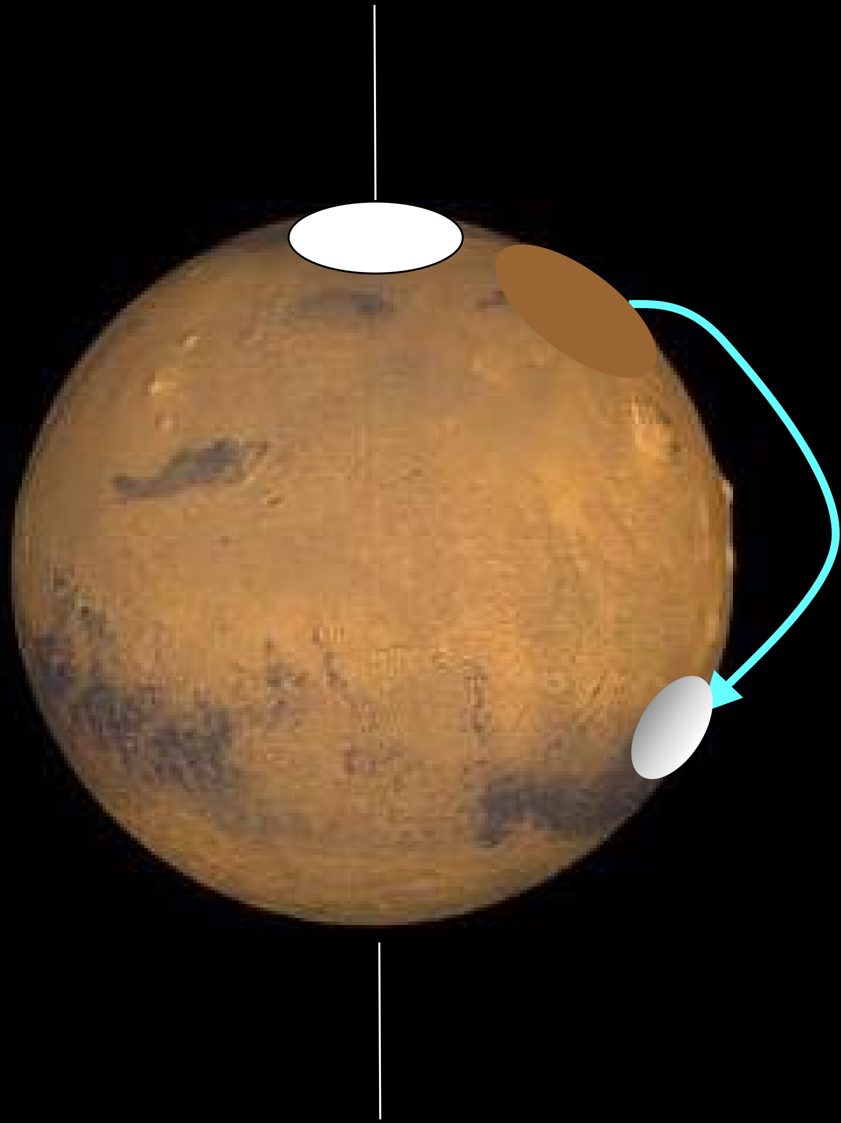






Head et al.
Hartmann et al.
Crown et al.
Etc…

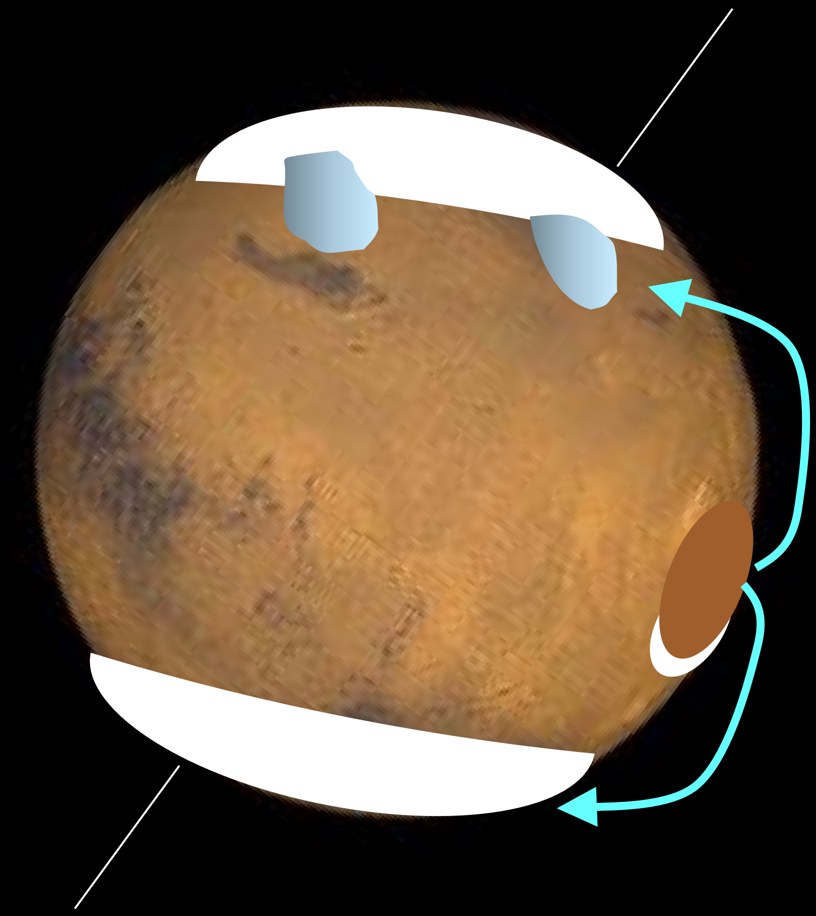
From low to high obliquity
(LMD Mars Global Climate model)

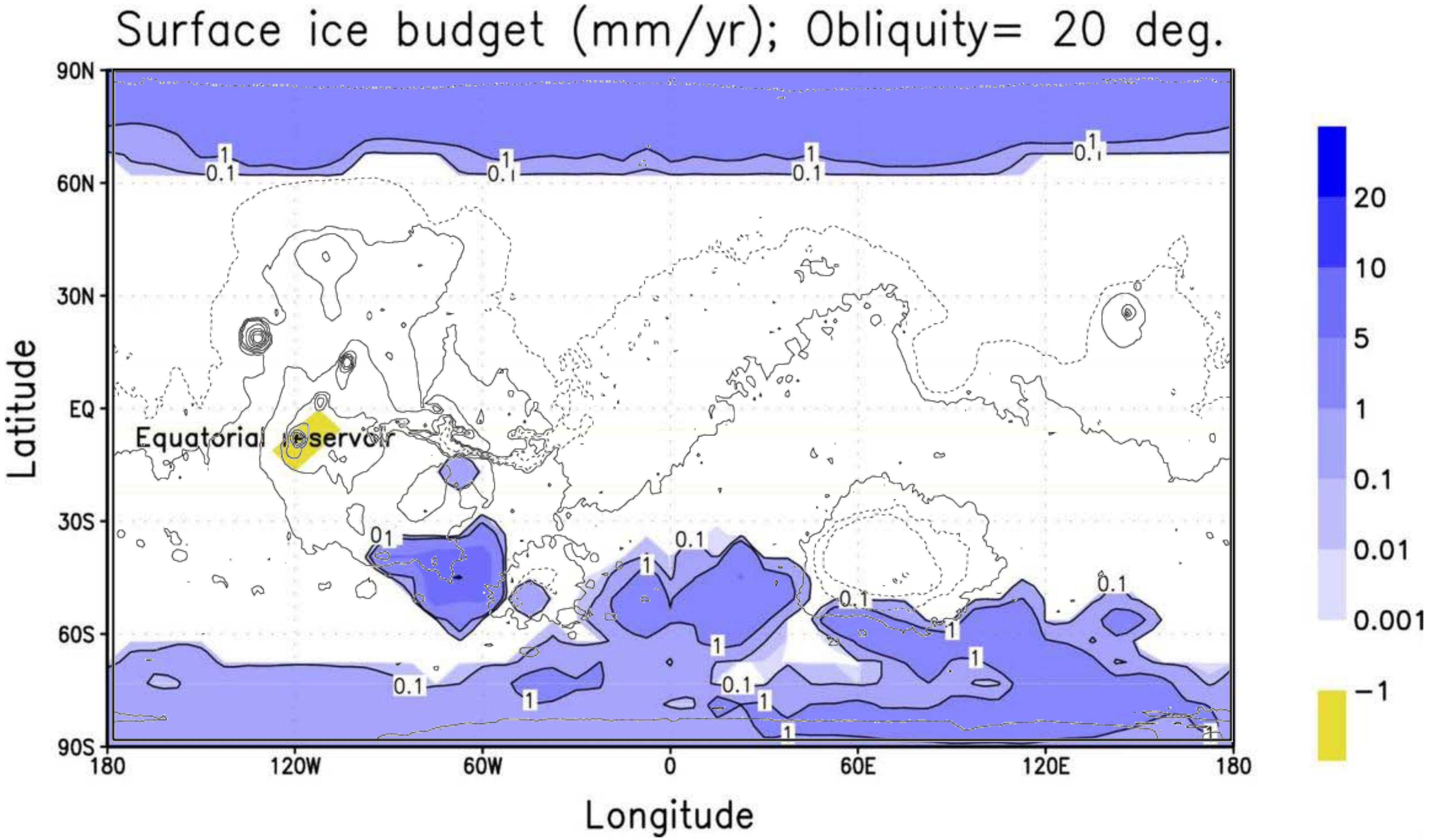


Forget et al., Science, 2006
Levrard et al., Nature, 2004

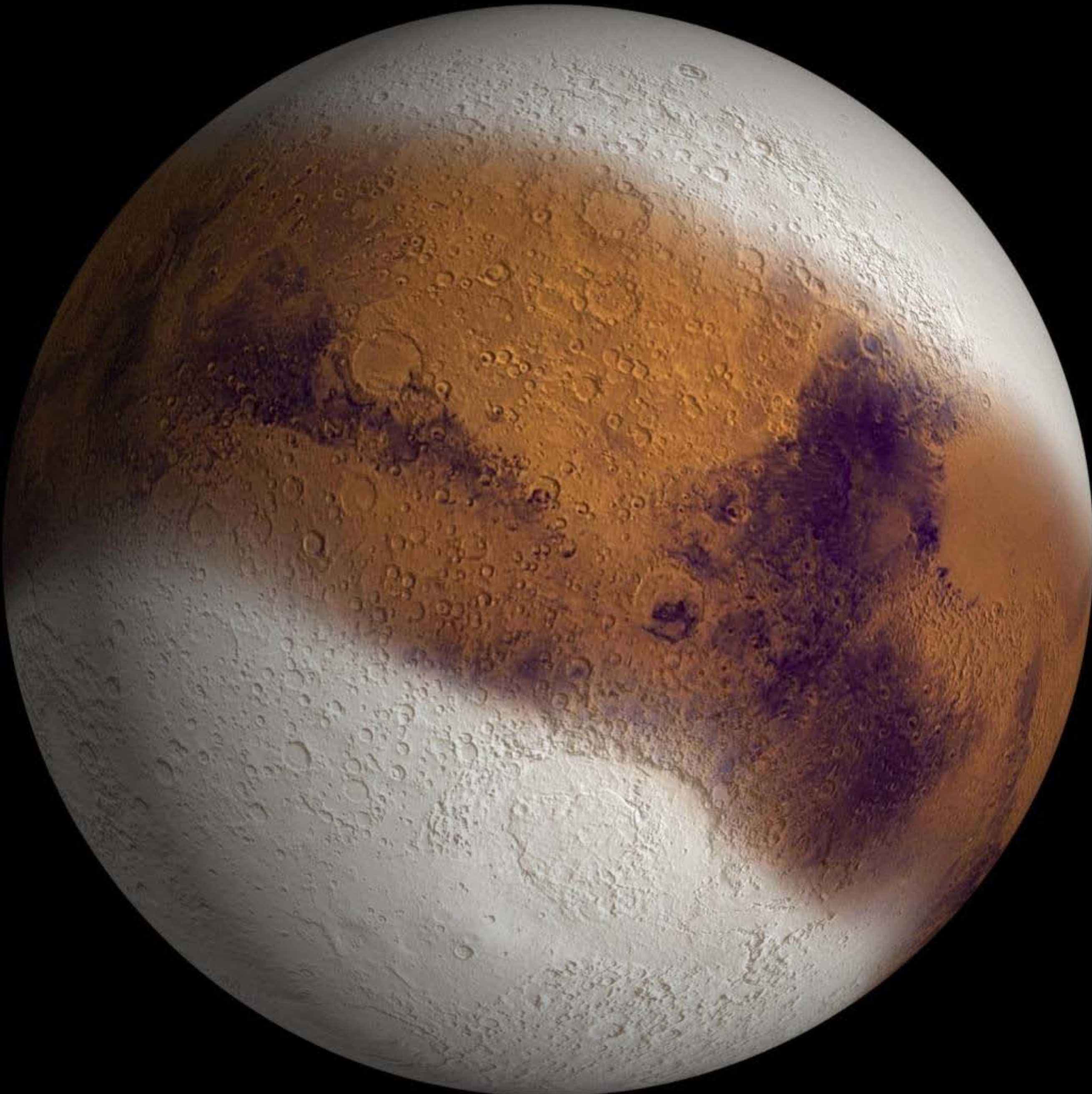
Back from high obliquity to low obliquity

Levrard et al. (2004) Madeleine et al.   (2009)



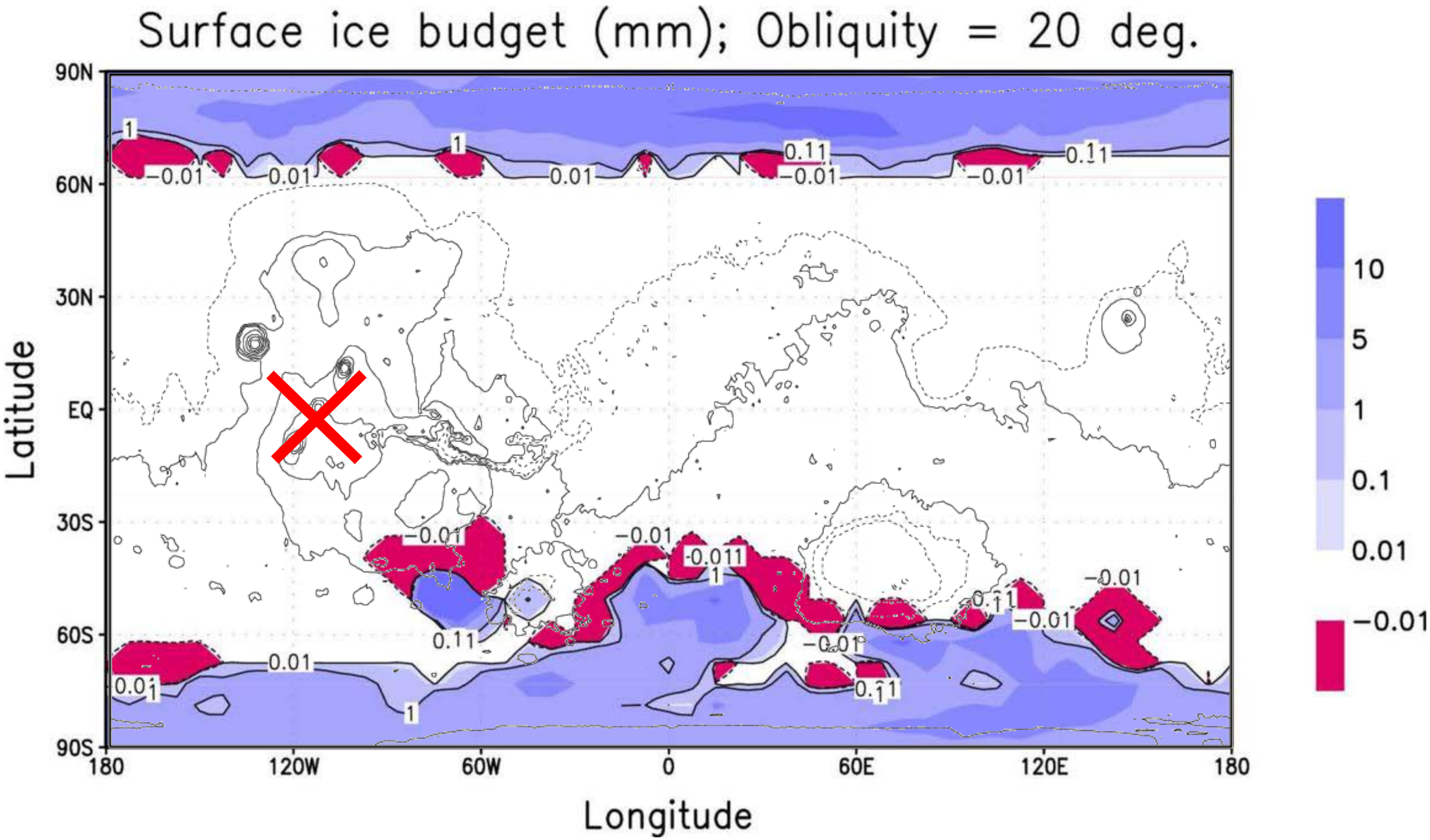


Levrard et al. Nature (2004)

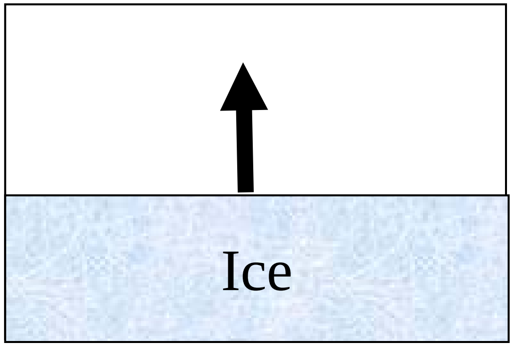


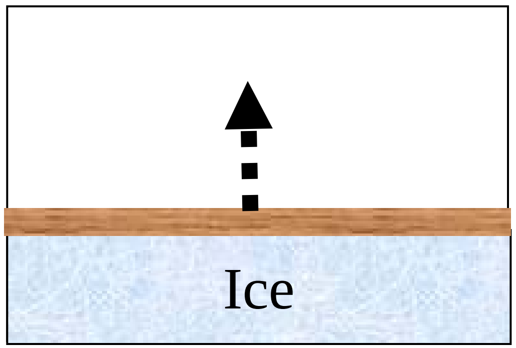

nature
Mars in an ice age
The red planet before the present interglacial

?

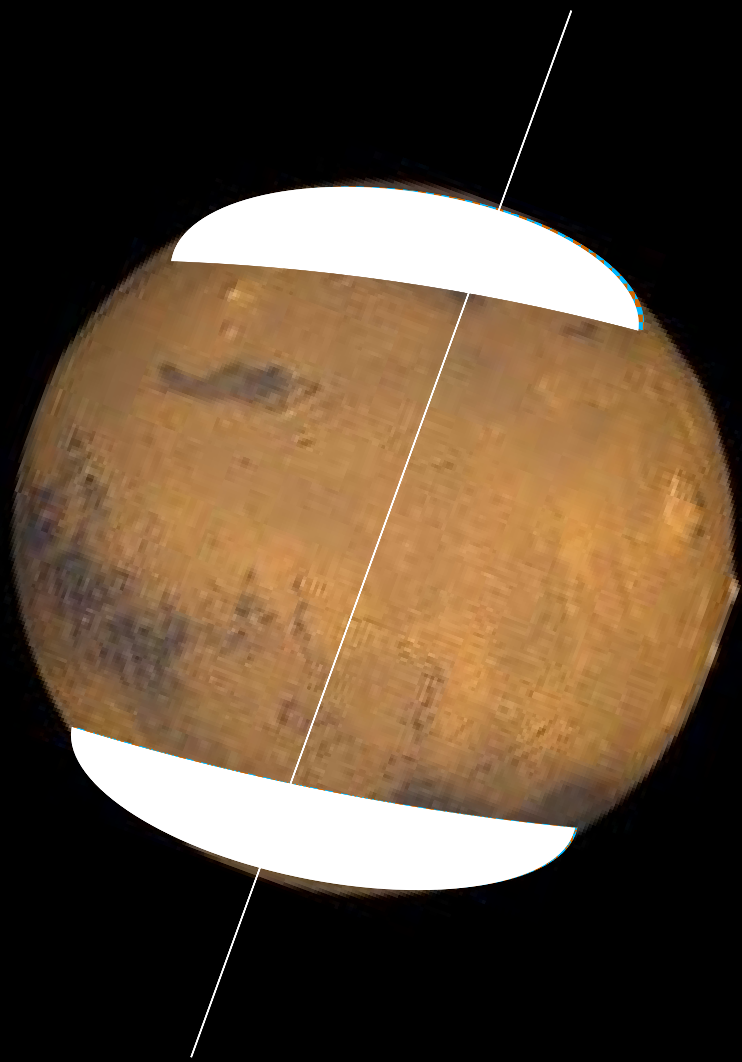


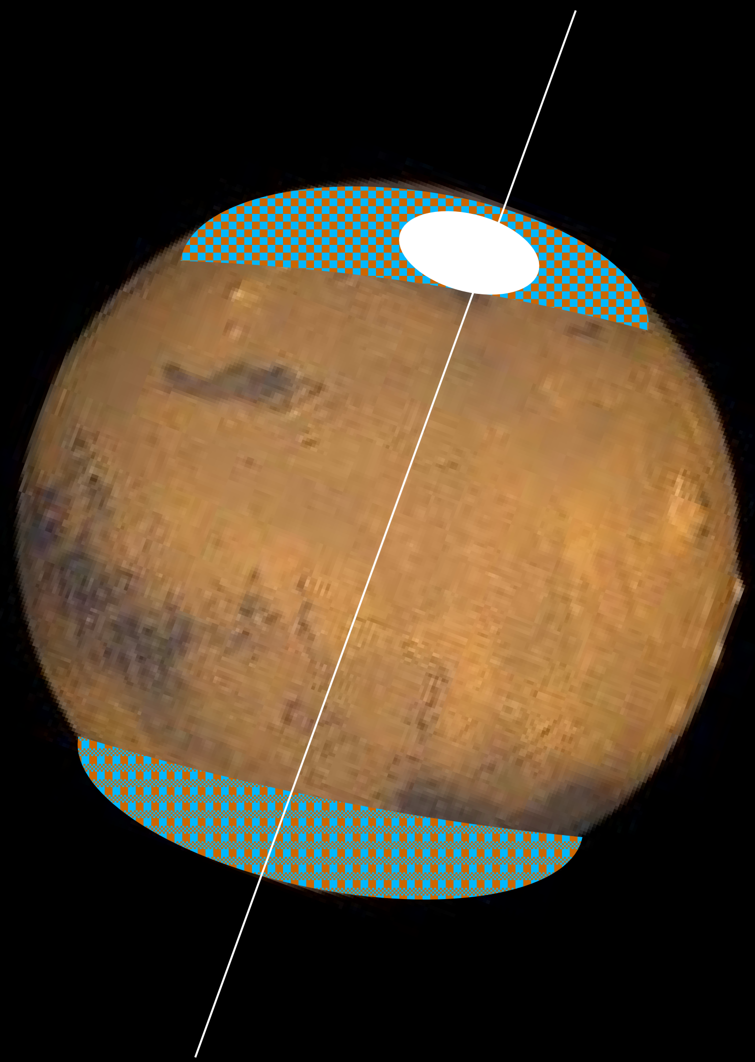
Levrard et al. Nature (2004)


Ice



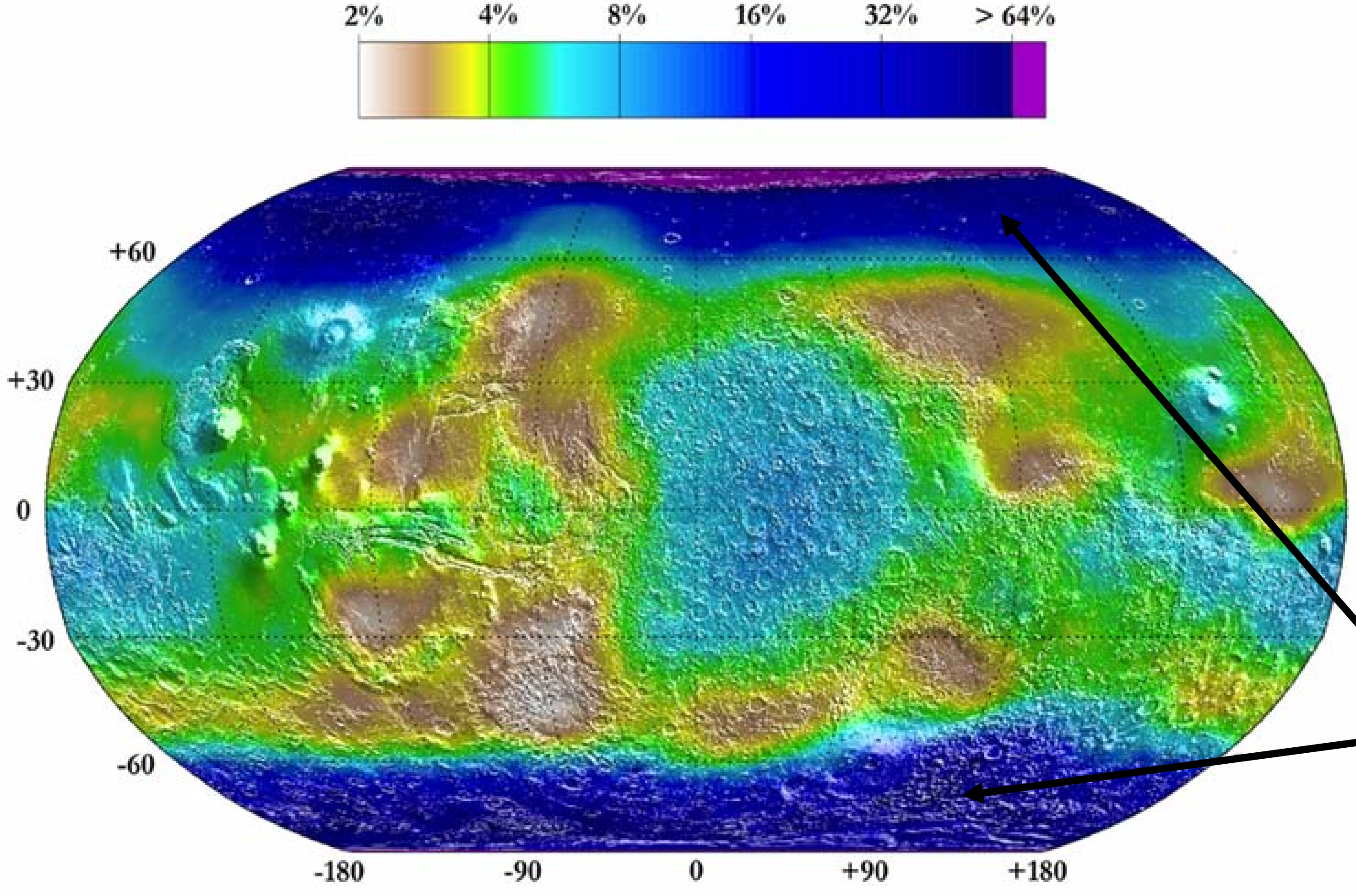
Mischna et al. 2003



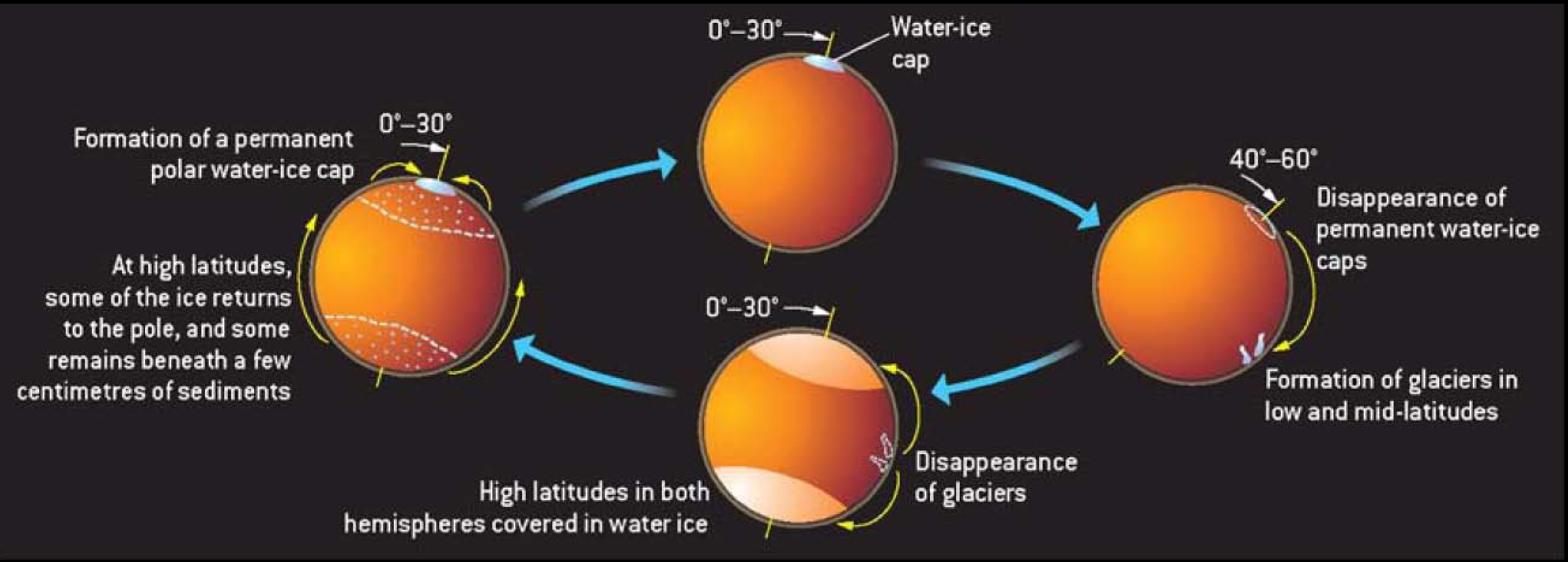


An ice-rich layer discovered by Mars Oddyssey below a few cm of dry sediments

Minimum water equivalent hydrogen abundance (weight percent) deduced from Neutron flux
(Boynton et al. 2002 , Feldman et al. 2004)



The climates of planet Mars controlled by a chaotic obliquity

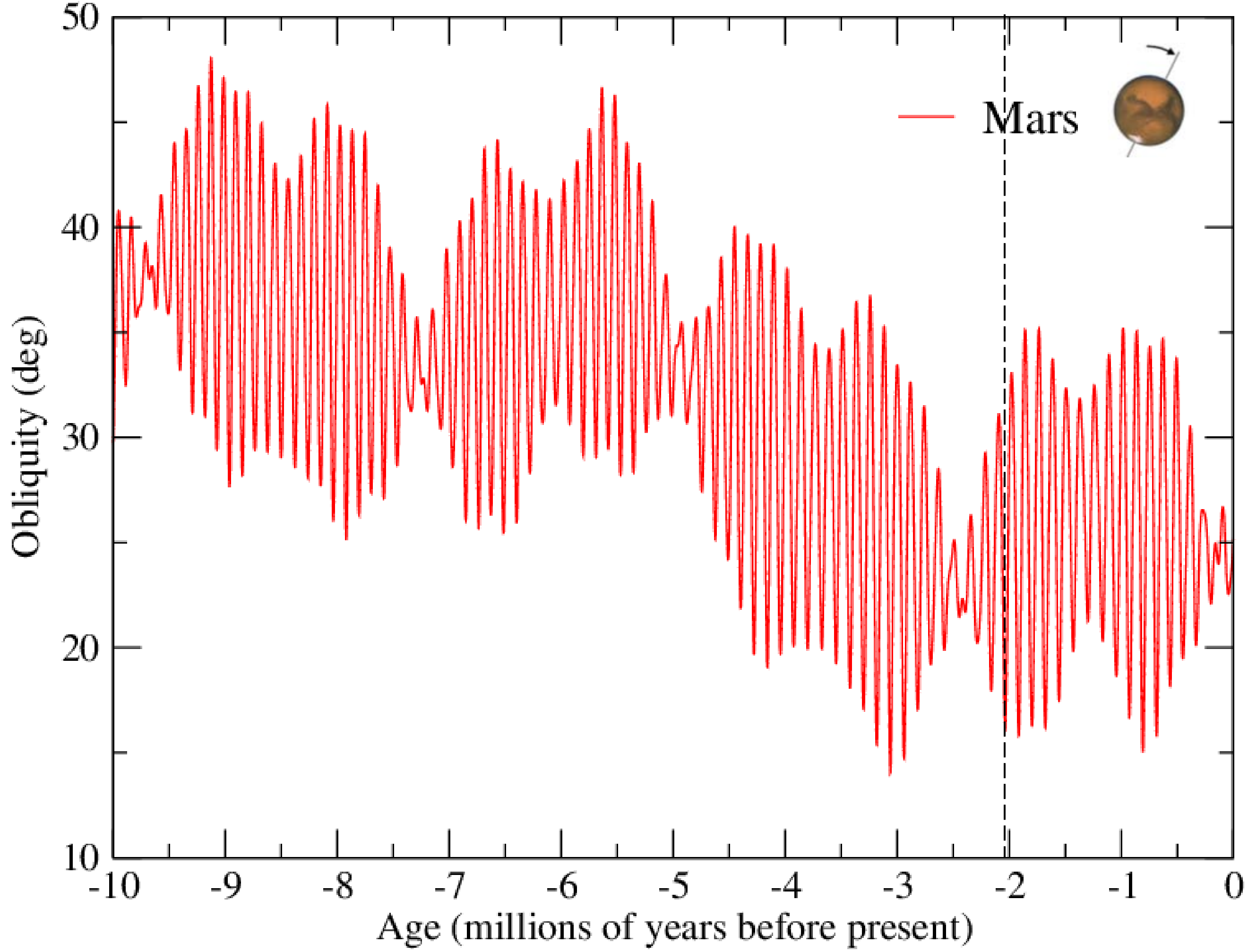


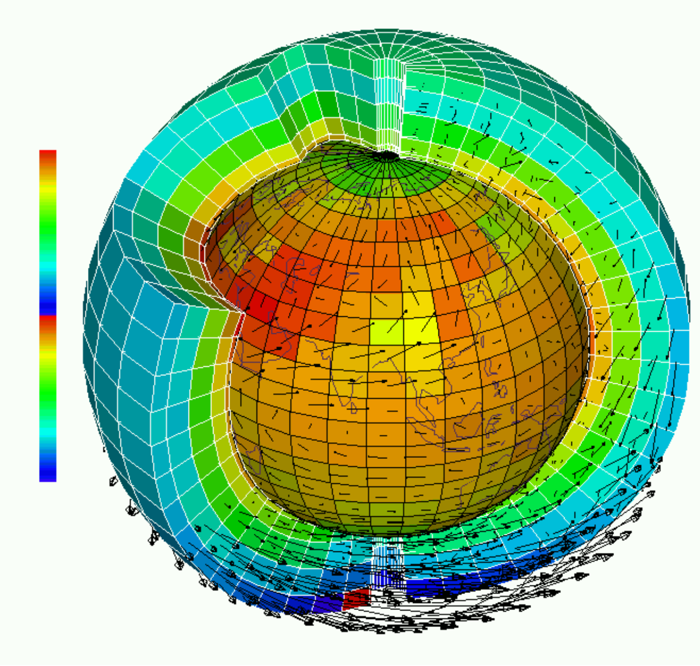
Forget et al. 2008

High Latitude
Ice Mantle

Ice sheets & Pedestal craters, Glaciers …

1 Gyr 100 Myr 10 Myr

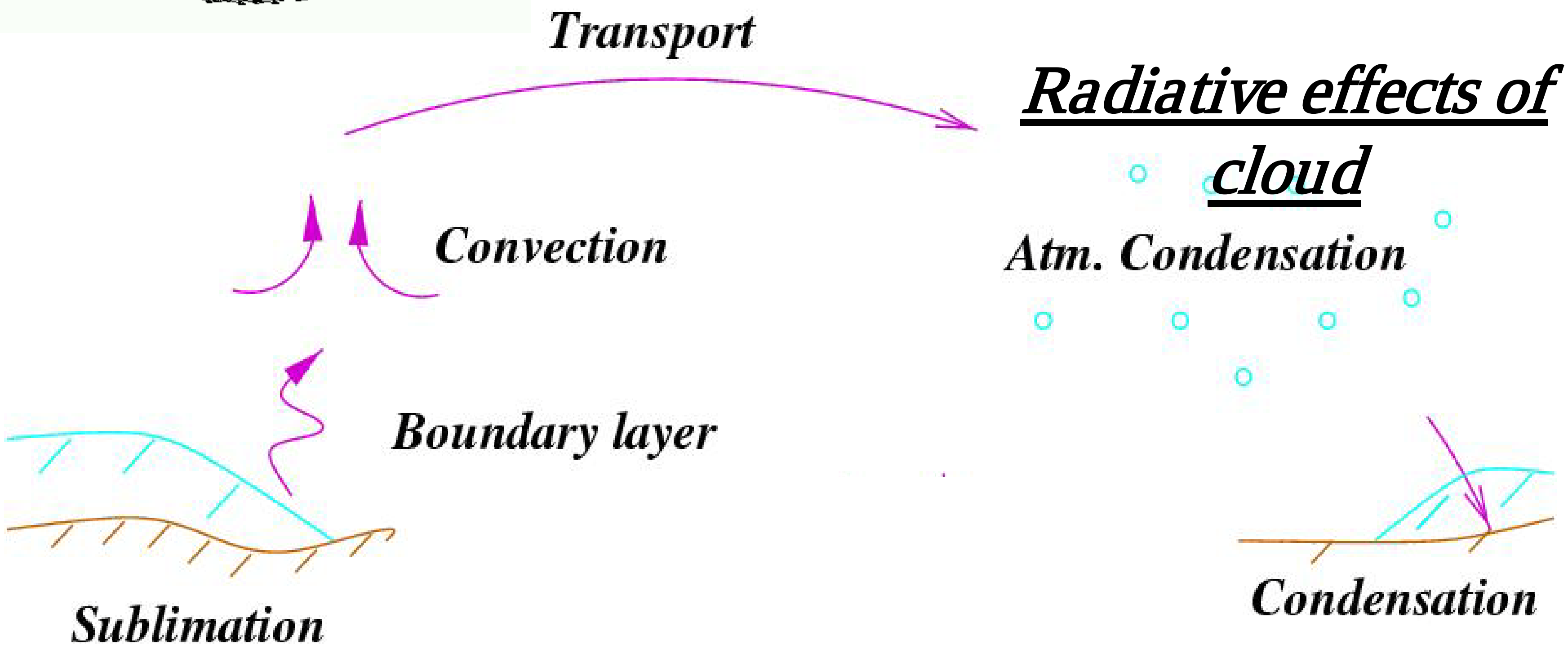




Modelling Mars water cycle with the LMD Mars Global Climate Model

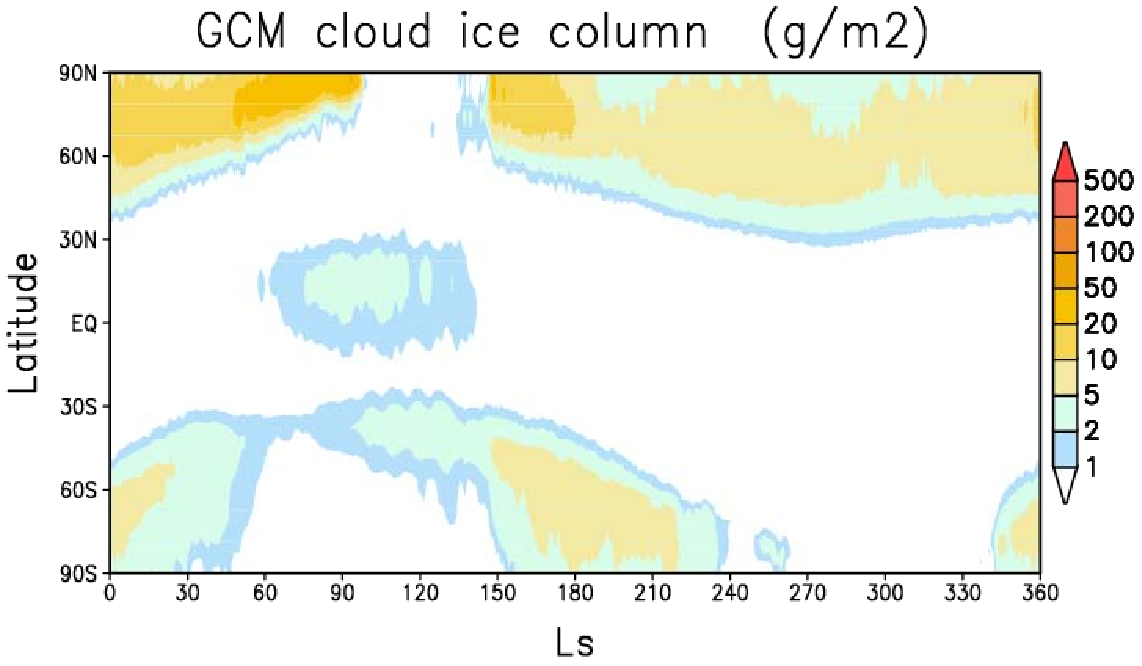
Forget et al. 1999, ontmessin et al. 2004, Forget et al. 2008

Madeleine et al. 2012, Navarro et al. 2014

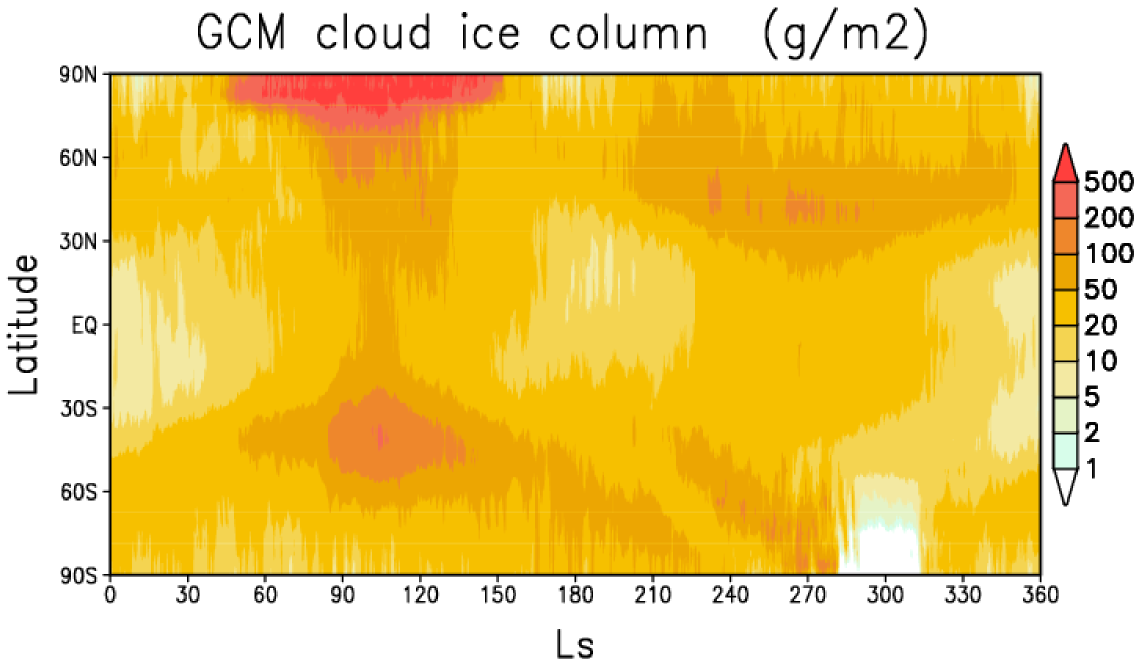


LMD GCM
(with radiatively active clouds)

Present day Mars
(obliquity = 25.2°)

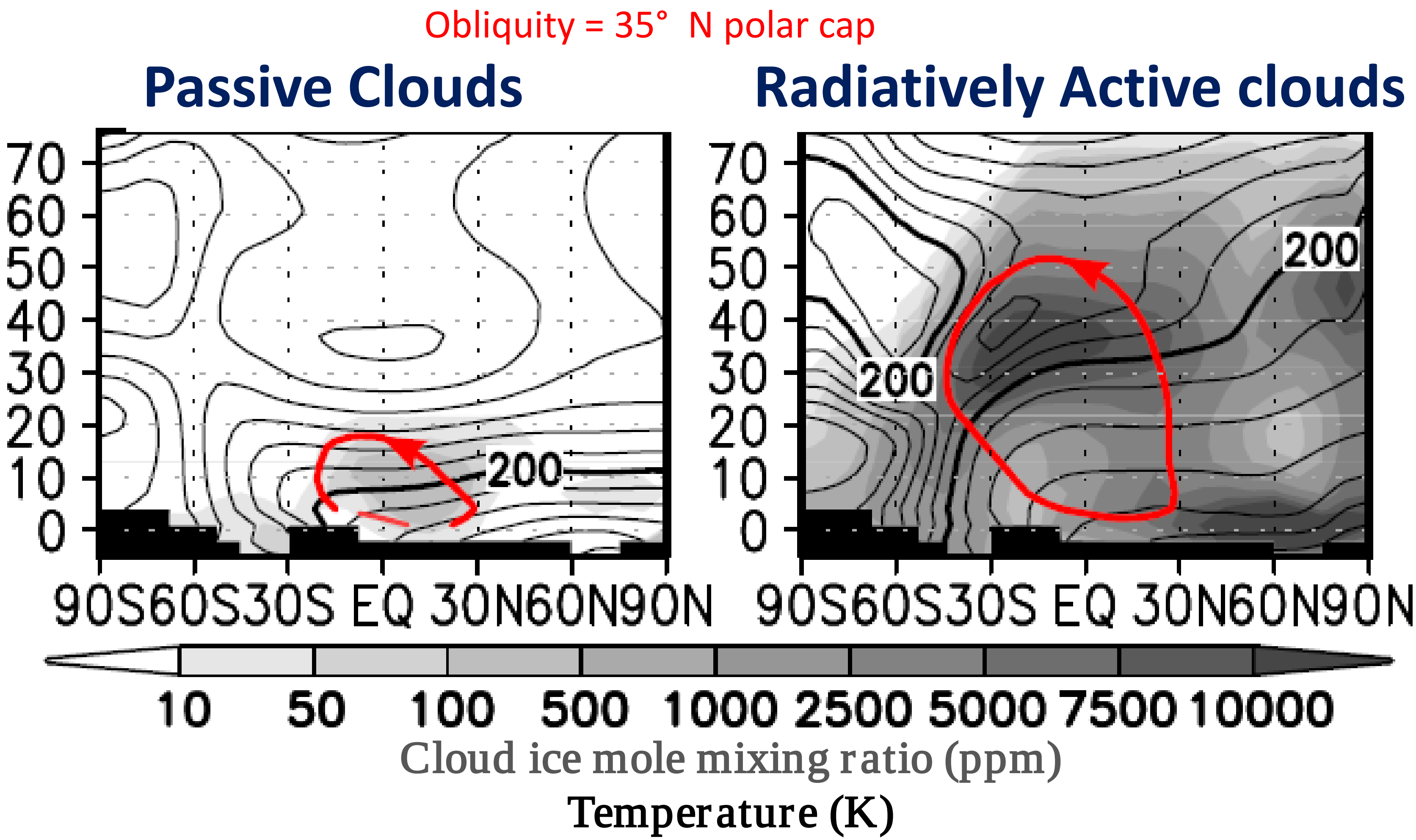


Same Mars but with obliquity = 35°



Radiatively active clouds warm the atmosphere

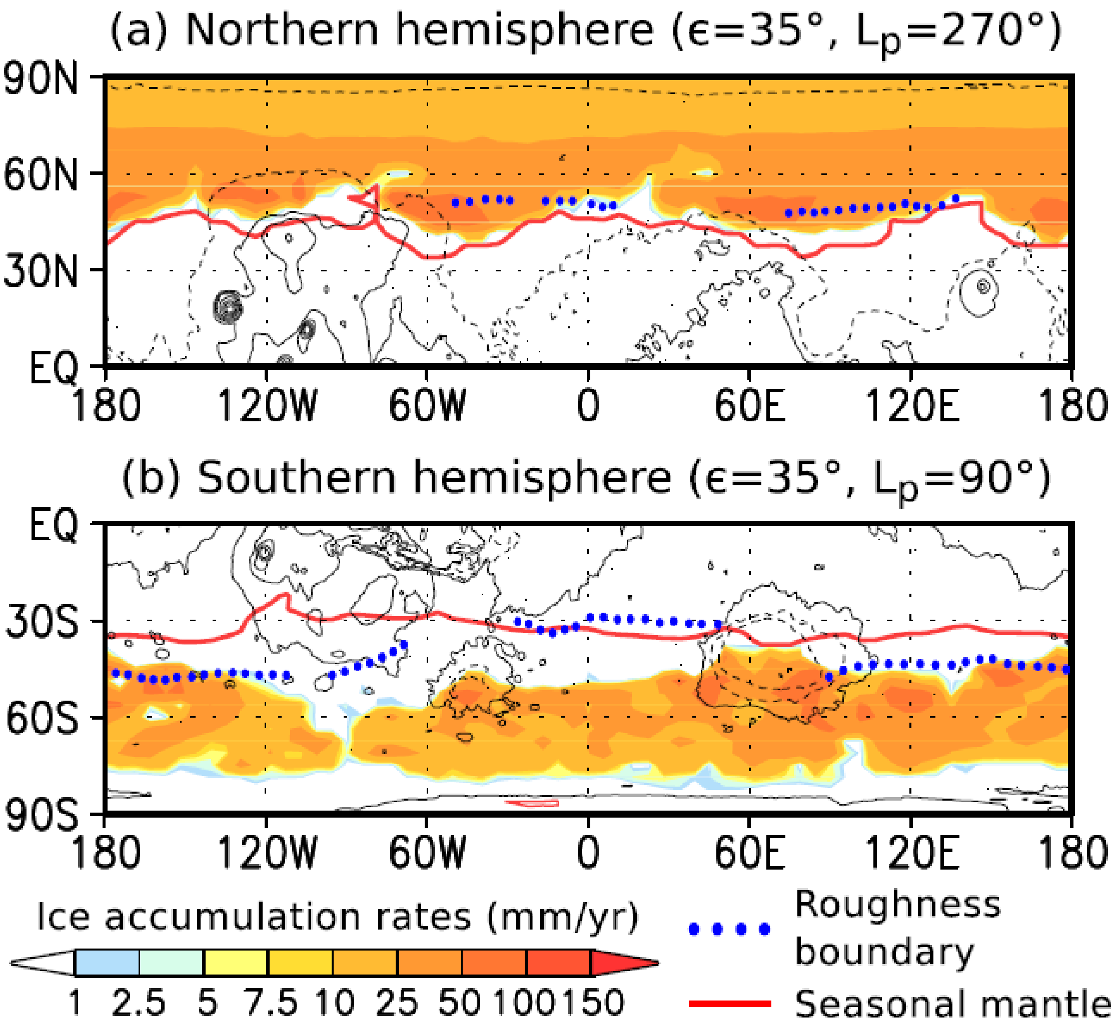
⇨ Much more intense water cycle (more water vapor)
⇨ More clouds (positive feedback)
⇨ More precipitations !



Madeleine et al. GRL 2014

Radiatively active clouds simulations, obliquity = 35°, excentricity = 0.1

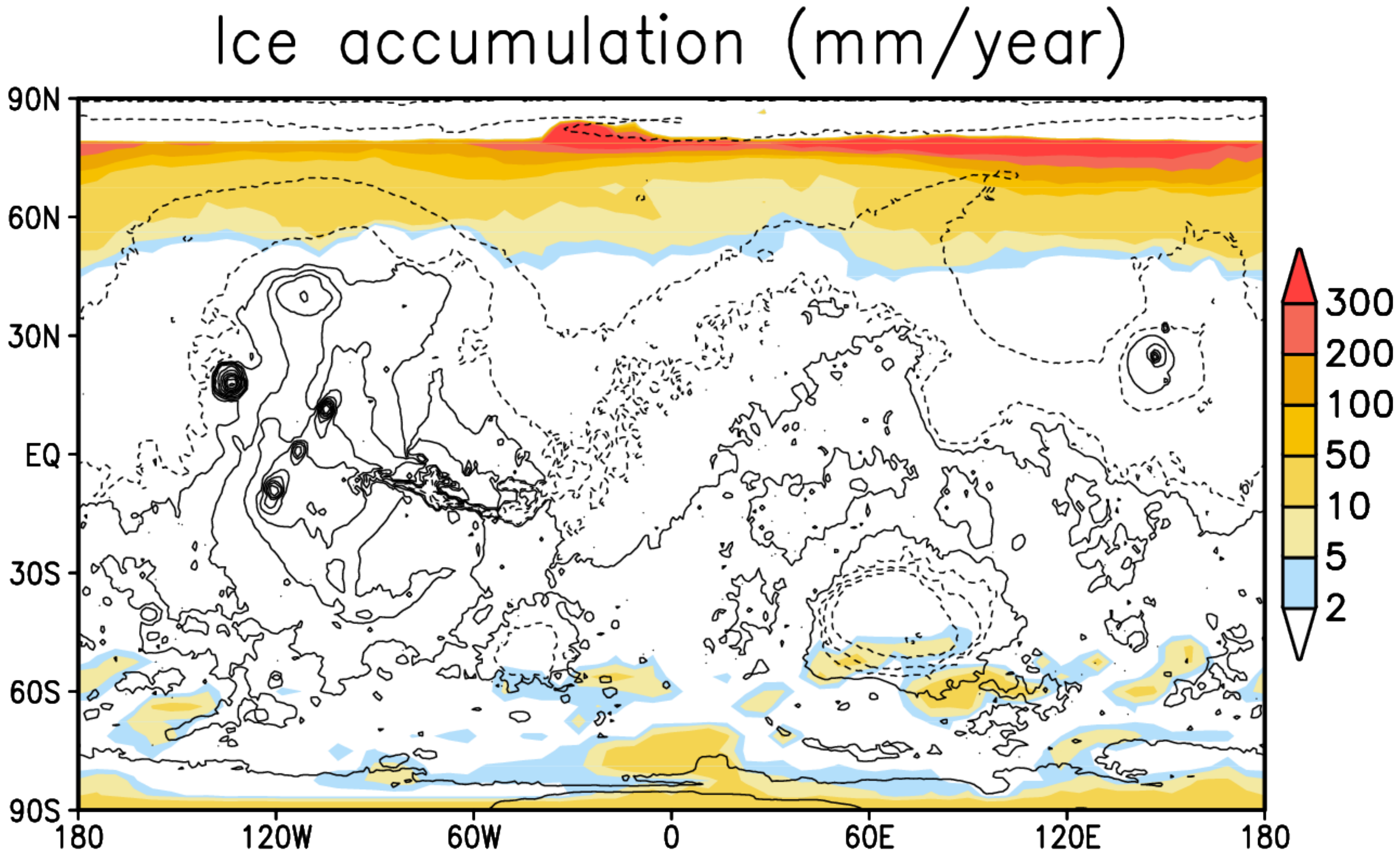
Low snow albedo = 0.4, but dust storm during summer



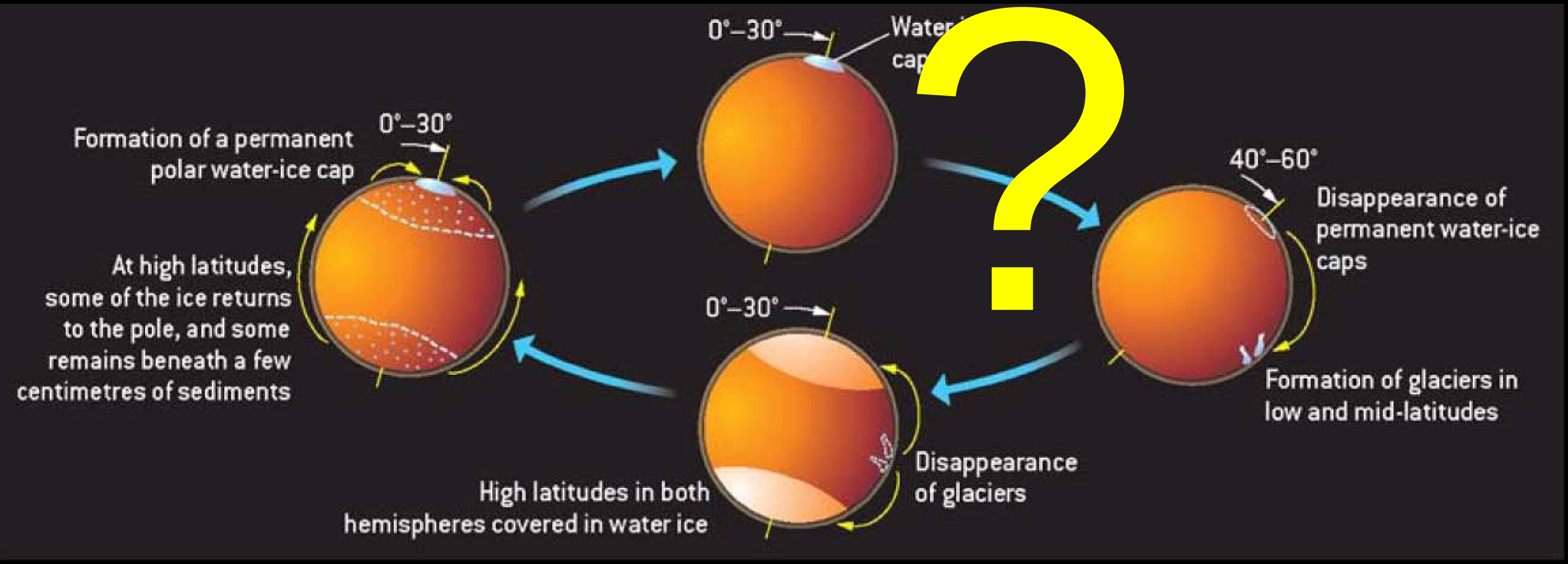
Madeleine et al. GRL 2014

Radiatively active cloud simulations, obliquity = 35°, excentricity = 0

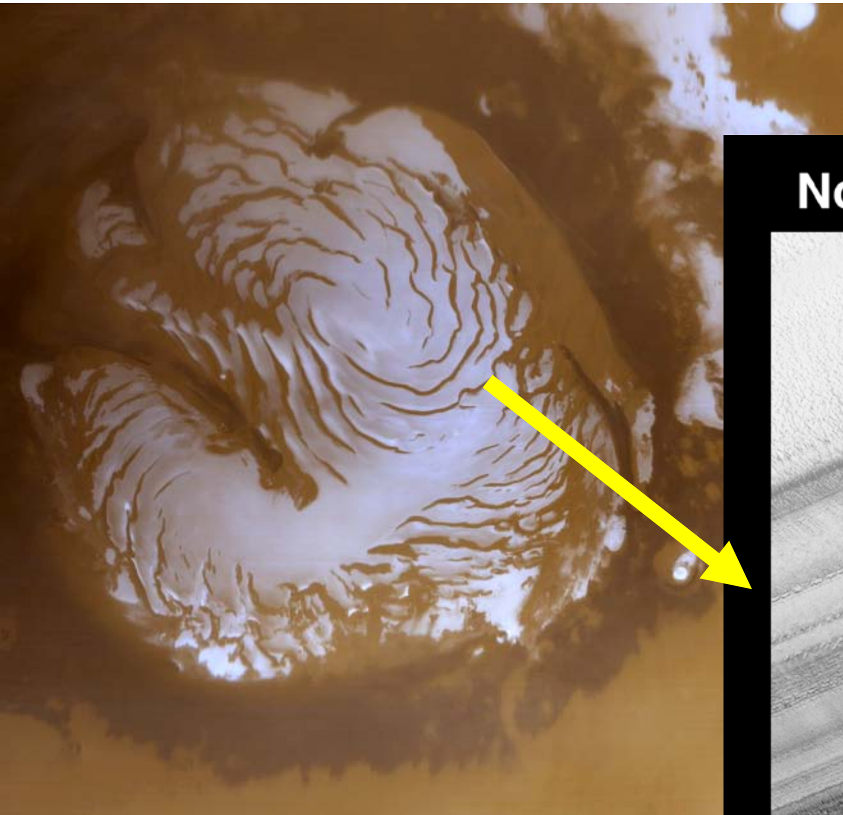
Clear atmosphere, but high snow albedo = 0.7

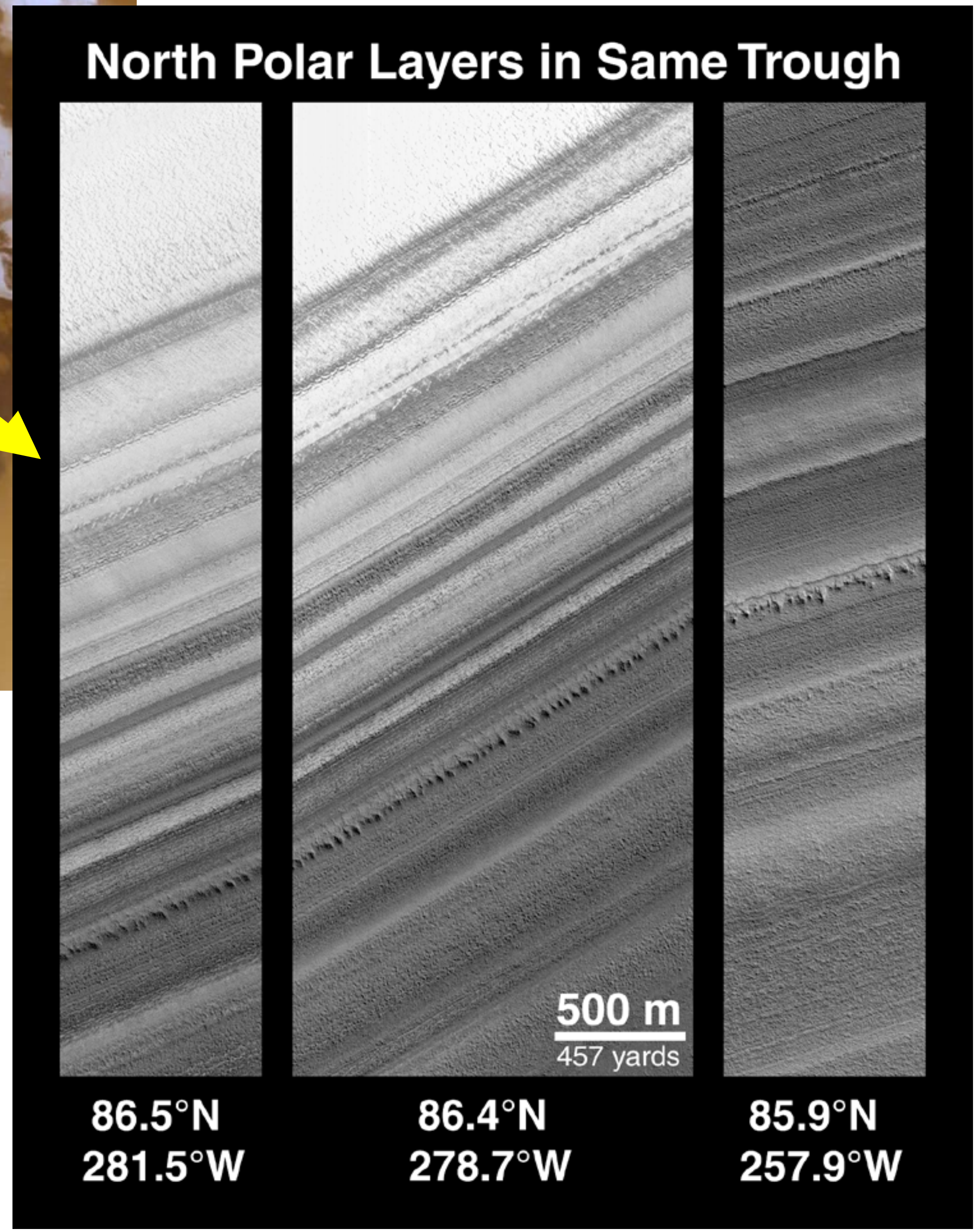


The climates of planet Mars controlled by a chaotic obliquity



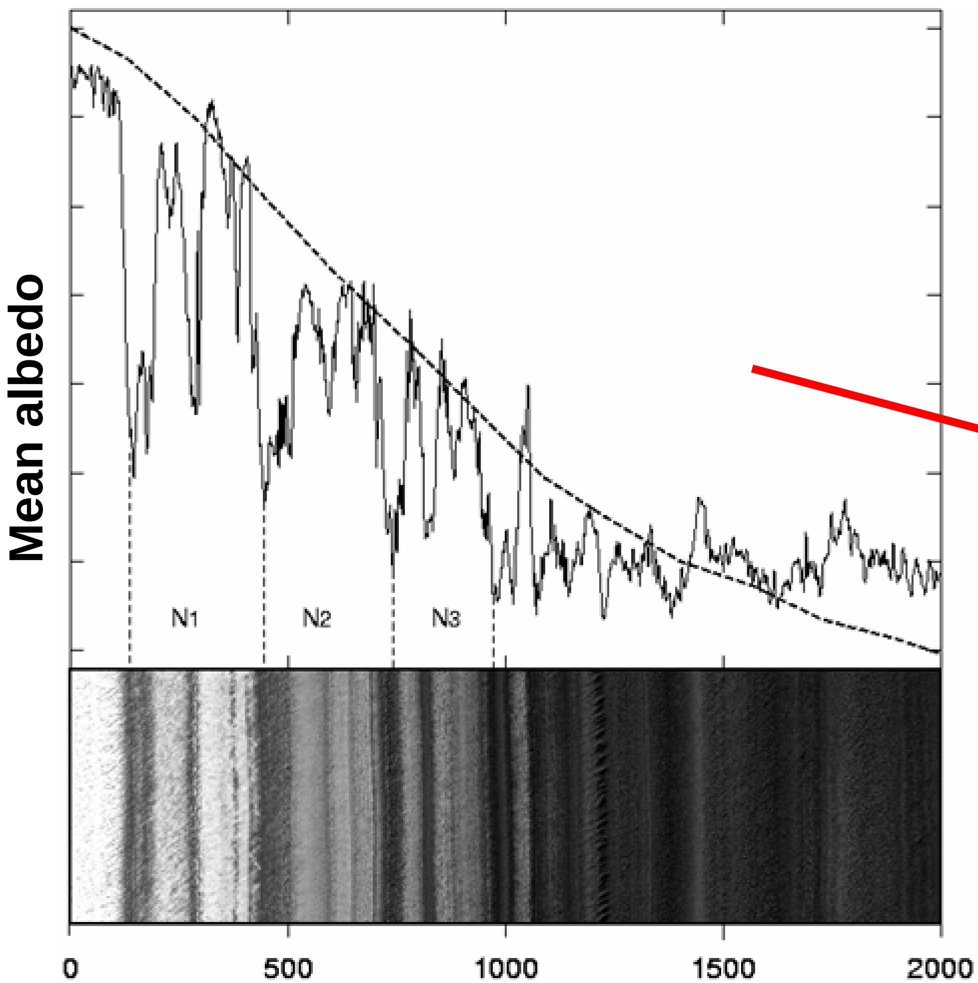
Forget et al. 2008

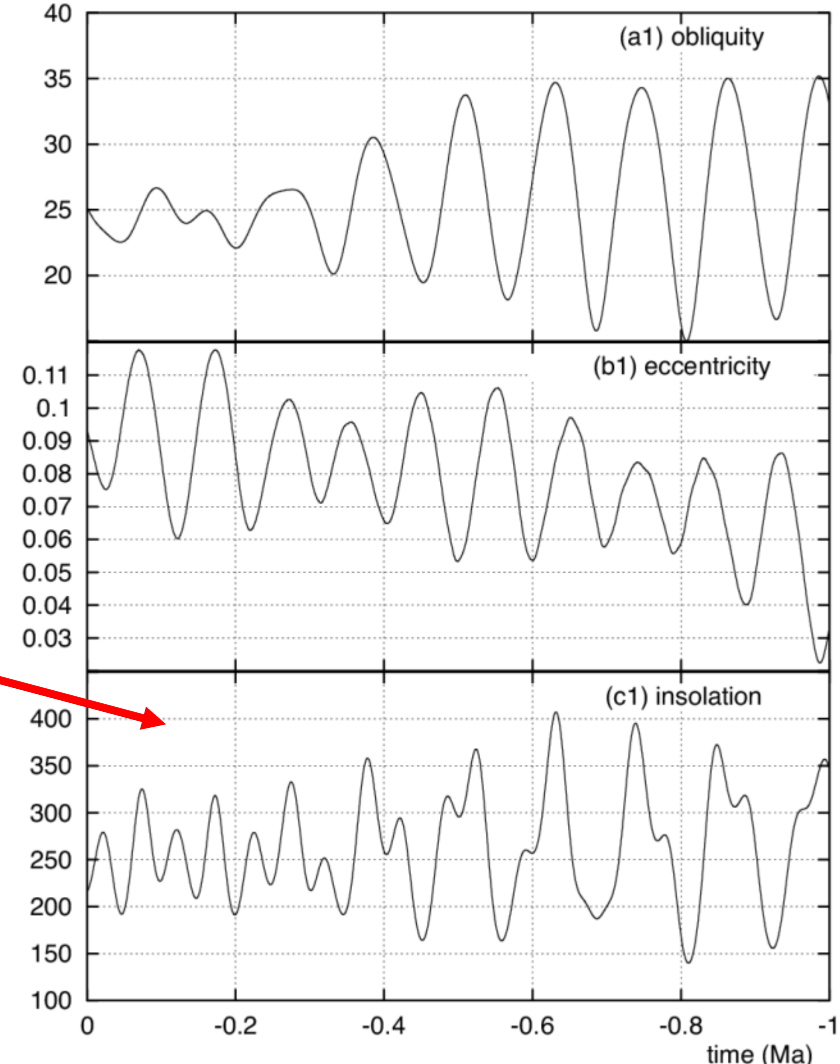




Record of climate variations in the polar layered terrain?

Correlation between polar stratification and insolation
(Laskar, Levrard and Mustard, 2002)

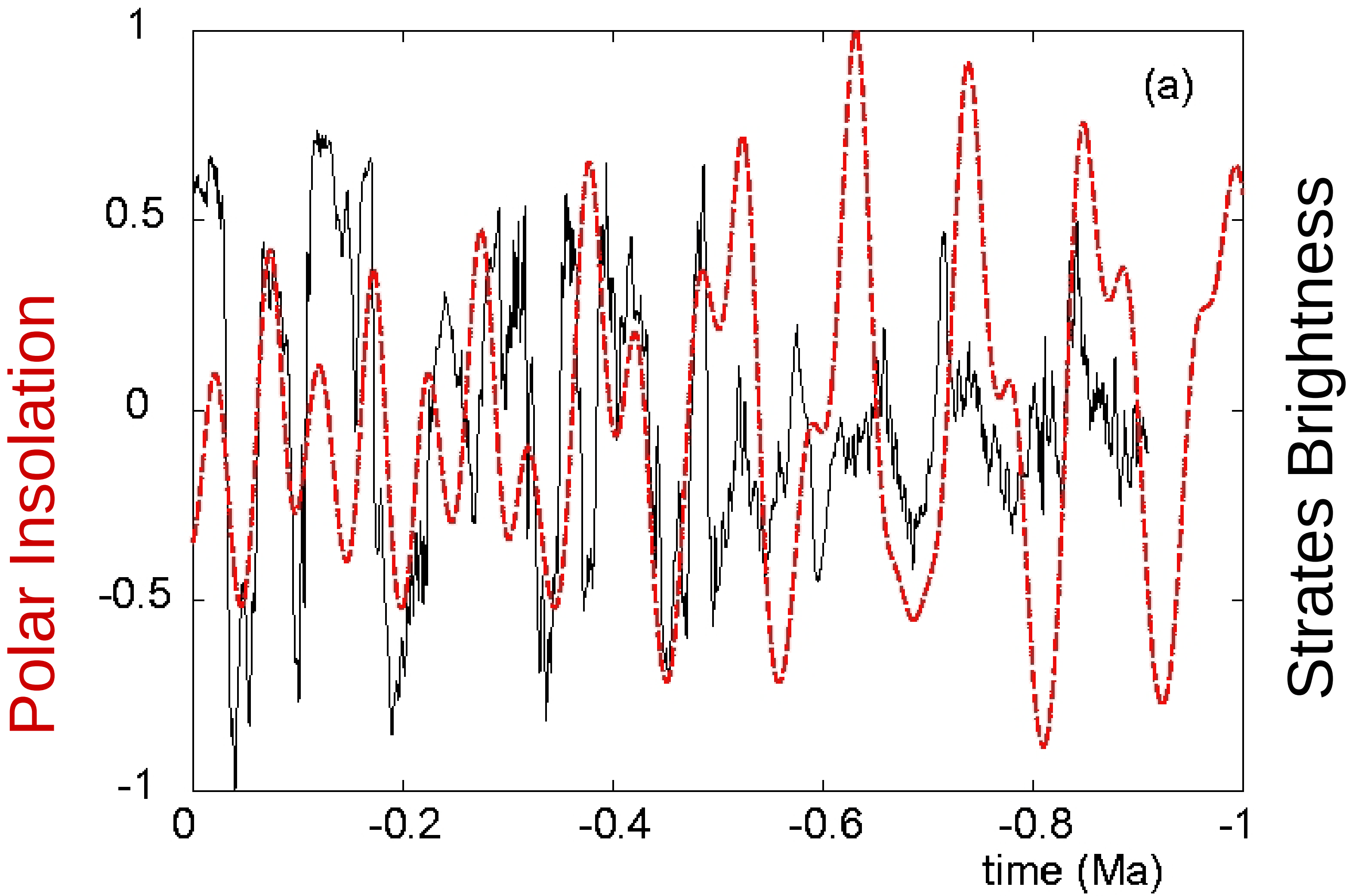




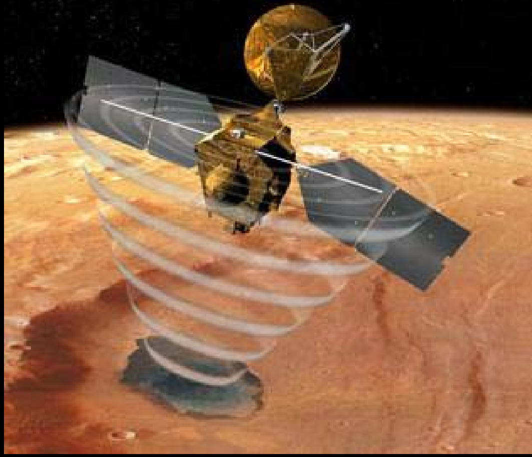
Orbital parameters variations

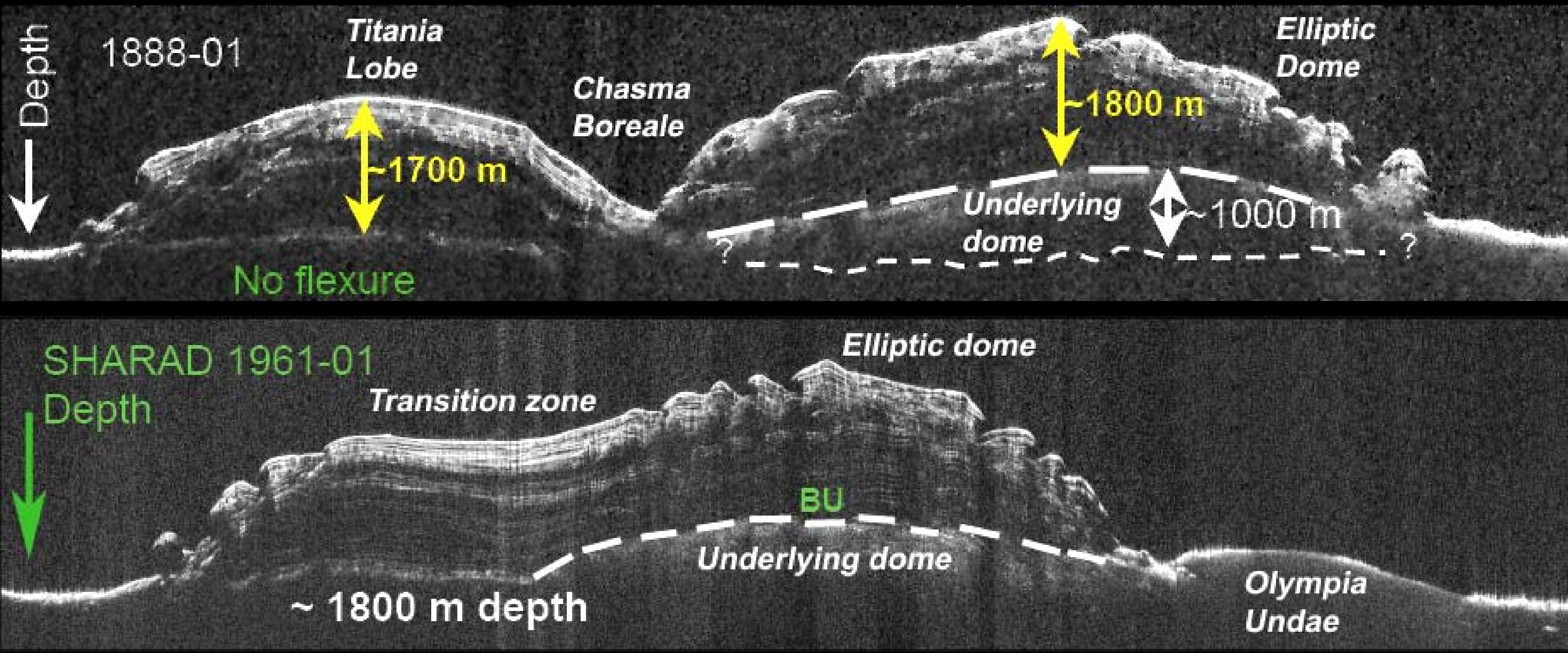
Correlation between polar stratification and insolation

(Laskar, Ievrard and Mustard, 2002)



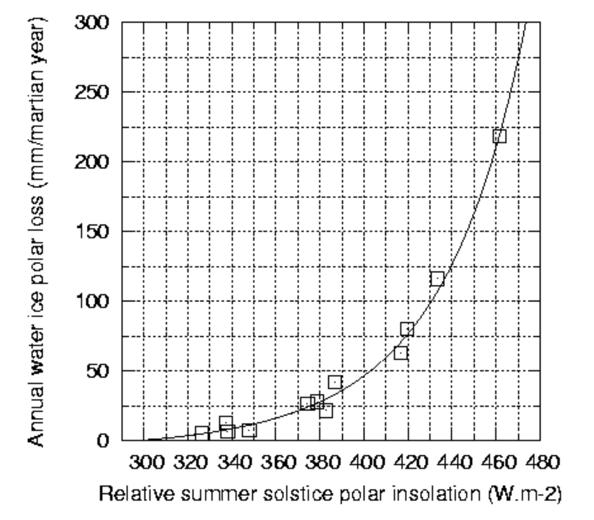
North Polar layered Deposits sounding with radar SHARAD aboard Mars Reconnaissance Orbiter

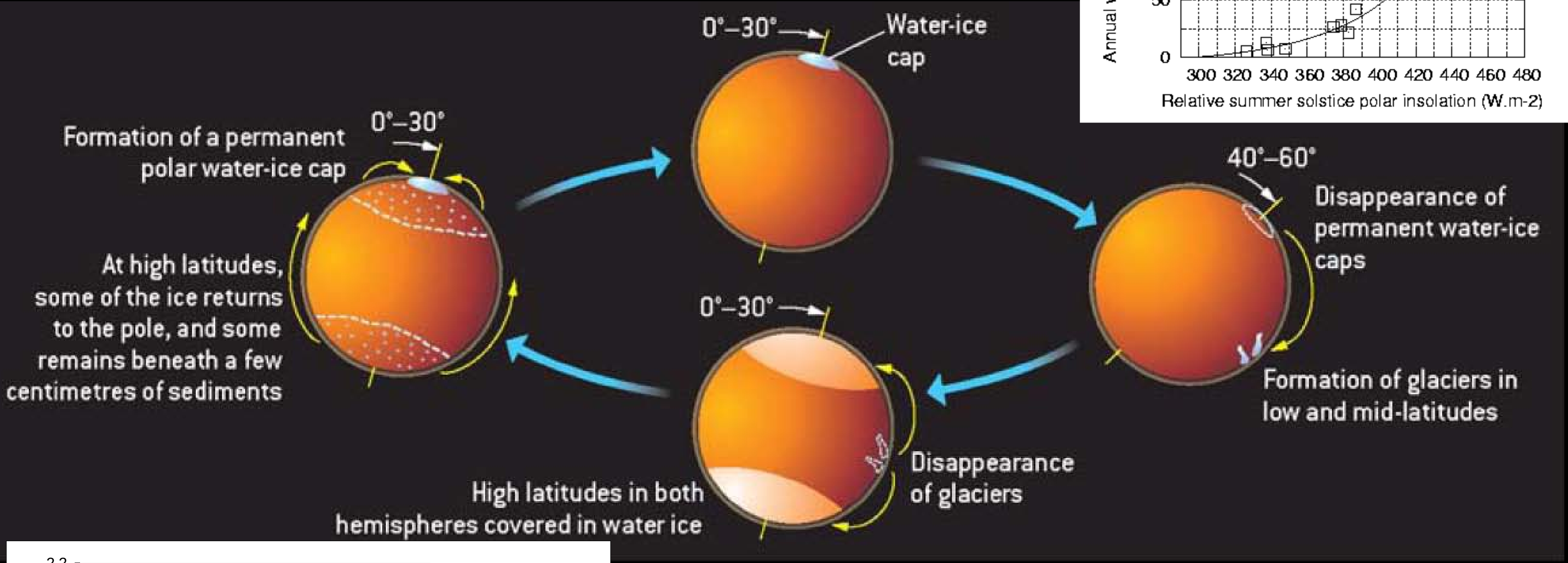


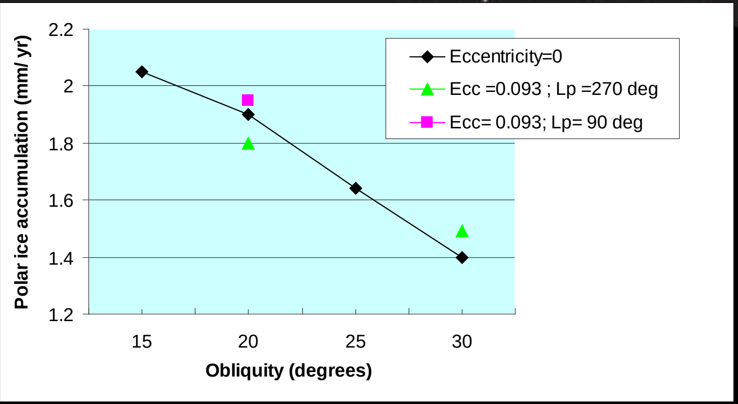


Modelling polar cap building using the LMD Mars Global Climate model

(*Levrard et al., JGR, 2007*)

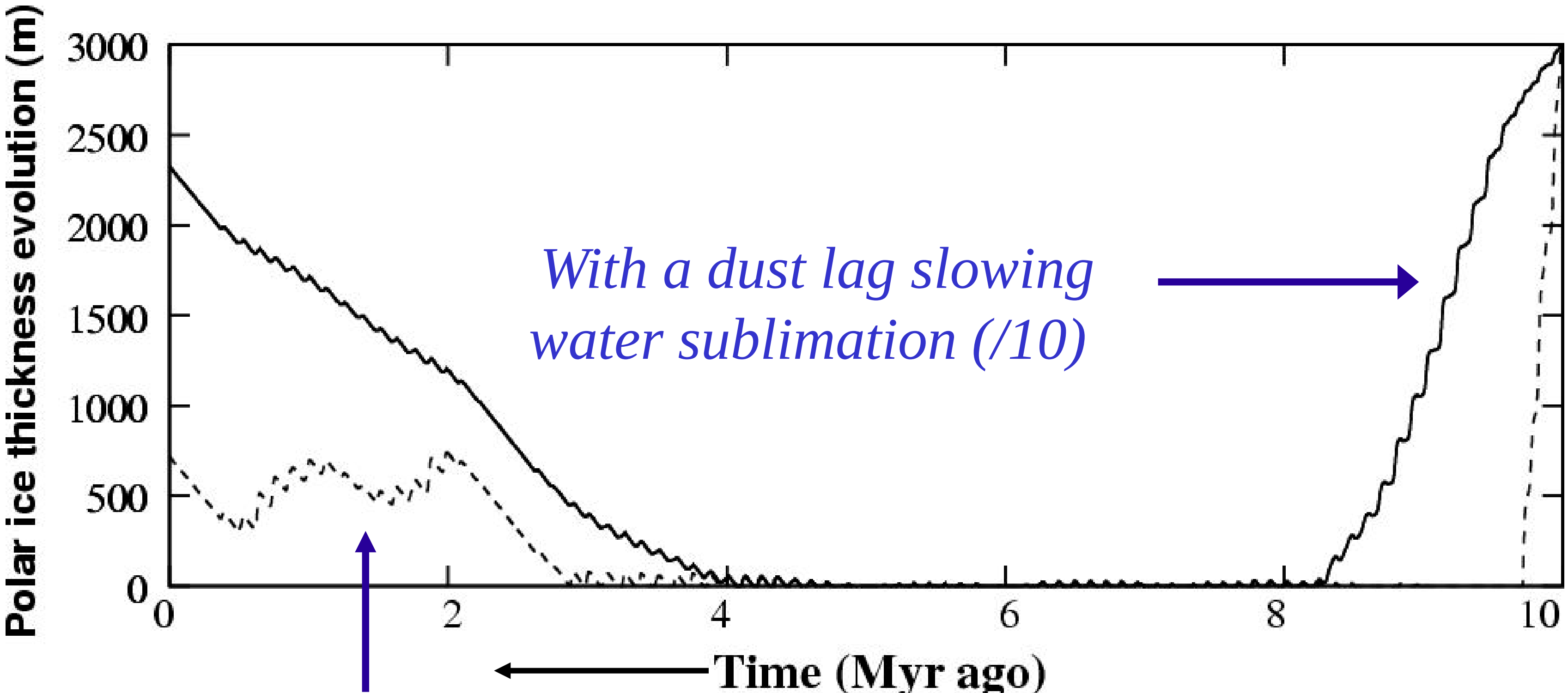






Simulation of the NLD based on LMD GCM simulations and the obliquity & orbital variations since 10 Myr

(*Levrard et al., JGR, 2007*)



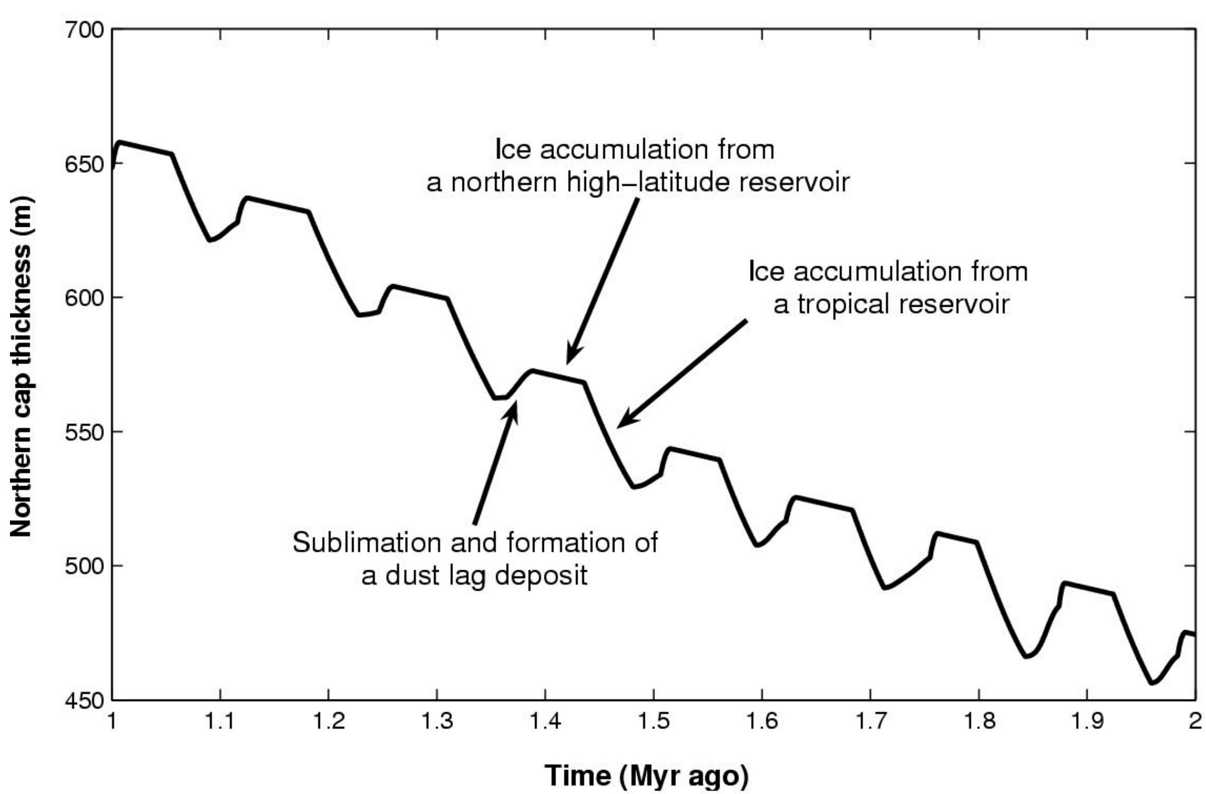
With a dust lag slowing water sublimation (/10)

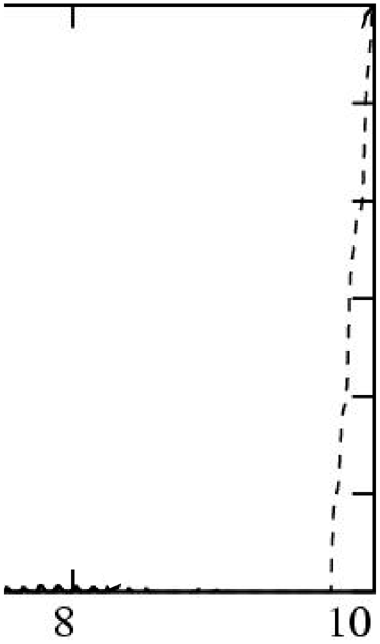
Assuming pure ice

Simulation of the NLD based on LMD GCM simulations and the obliquity & orbital variations since 10 Myr

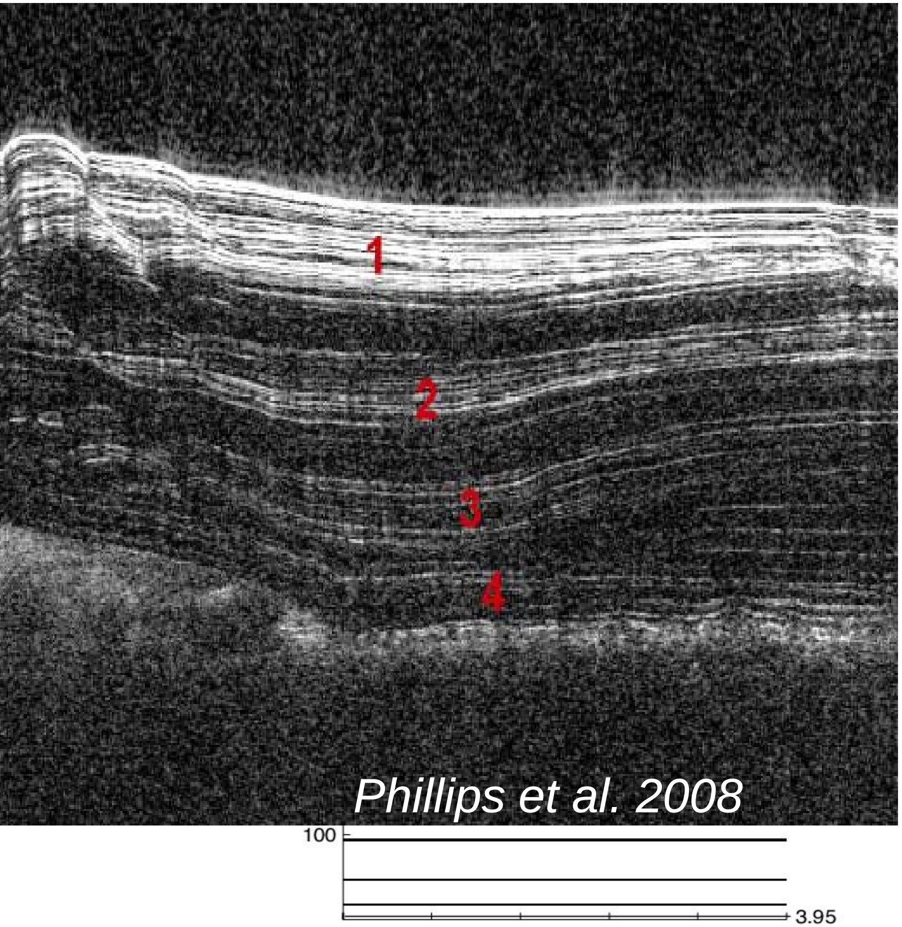
(*Levrard et al., JGR, 2007*)

Polar ice thickness evolution (m)

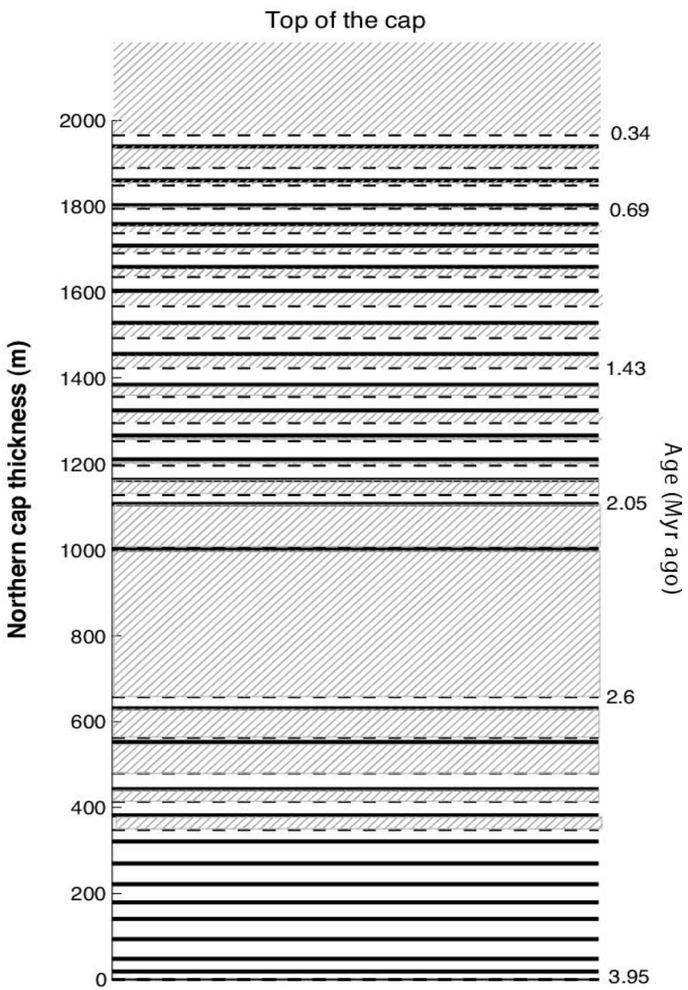




Structure of the modeled present day polar cap with a 3 reservoirs system : Northern PLD ; Tropics ; mid-latitudes (*Levrard et al., JGR, 2007*)



Case 1 : slow accumulation from mid-lat reservoirs : 0.17 mm/yr

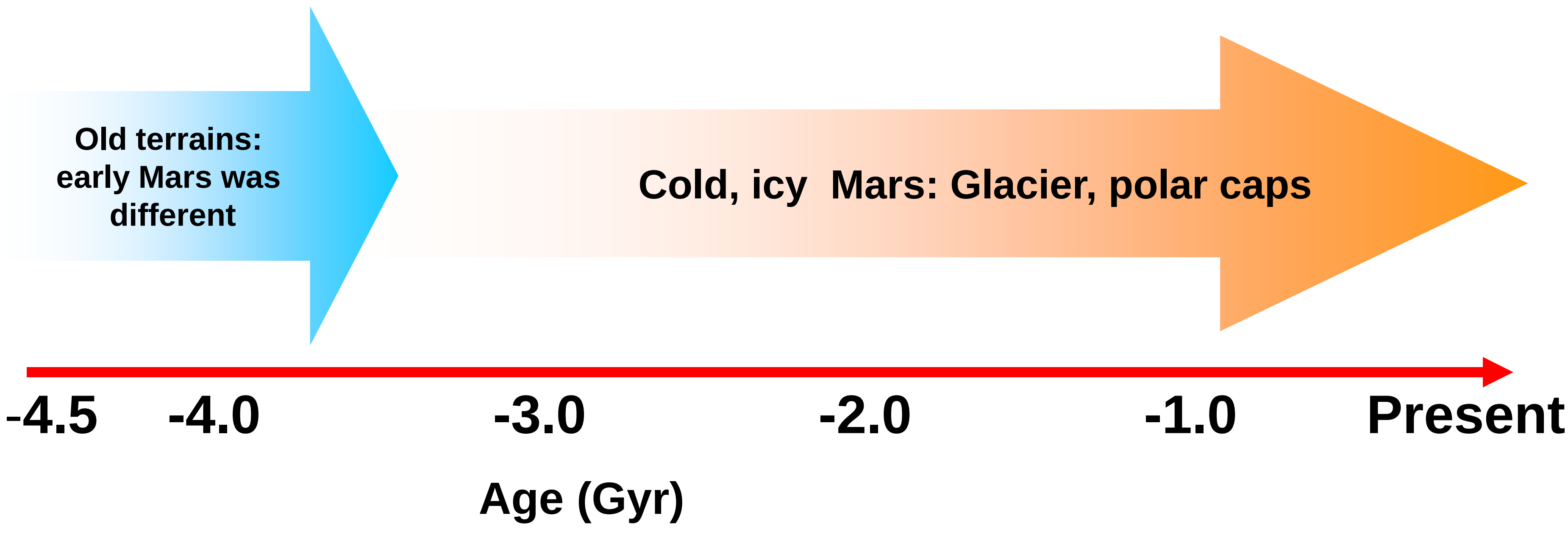


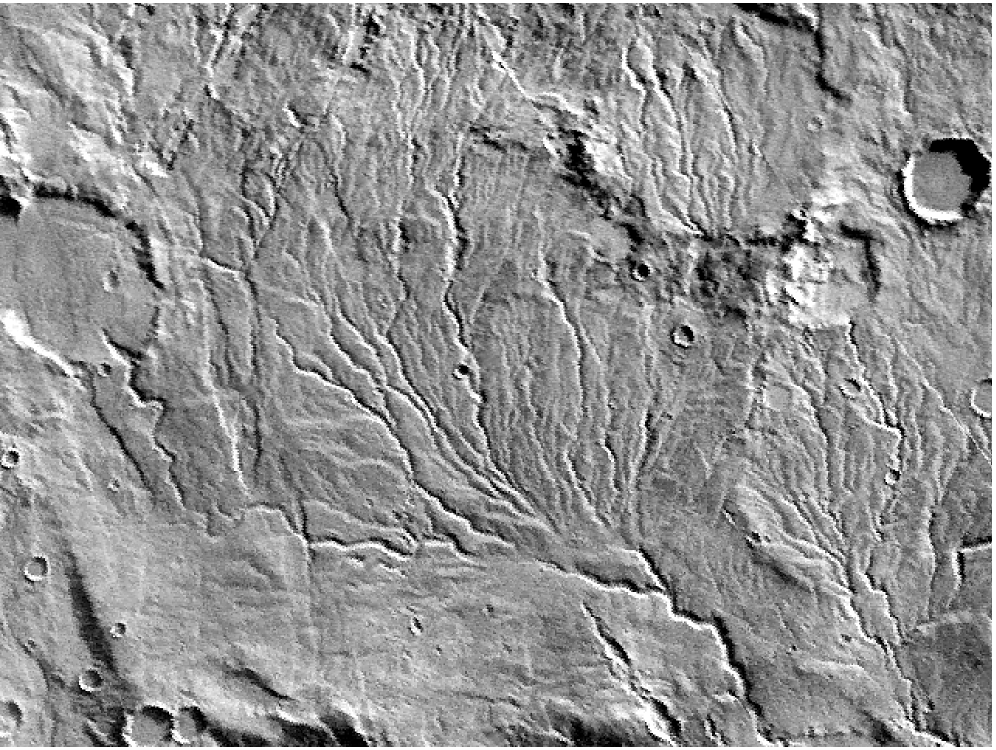
Case 2 : fast accumulation from mid-lat reservoirs : 1.7 mm/yr

CONCLUSIONS

- Due to the variations of Mars orbital / rotational parameters, the **current** Mars climate system have mobilized large amount of water to form glaciers, ice caps until recently and in the future.
- Several **robust** mechanisms have been simulated by the Global Climate Models.
- A new result: the radiative effect of thick clouds could lead to major environmental changes.
  - ⇨ mid latitude ice mantle accumulation are now predicted at longitude < 35° in agreement with the observed mantle age
- What about Mars Billions of years ago ?

Evolution of the Martian Climate



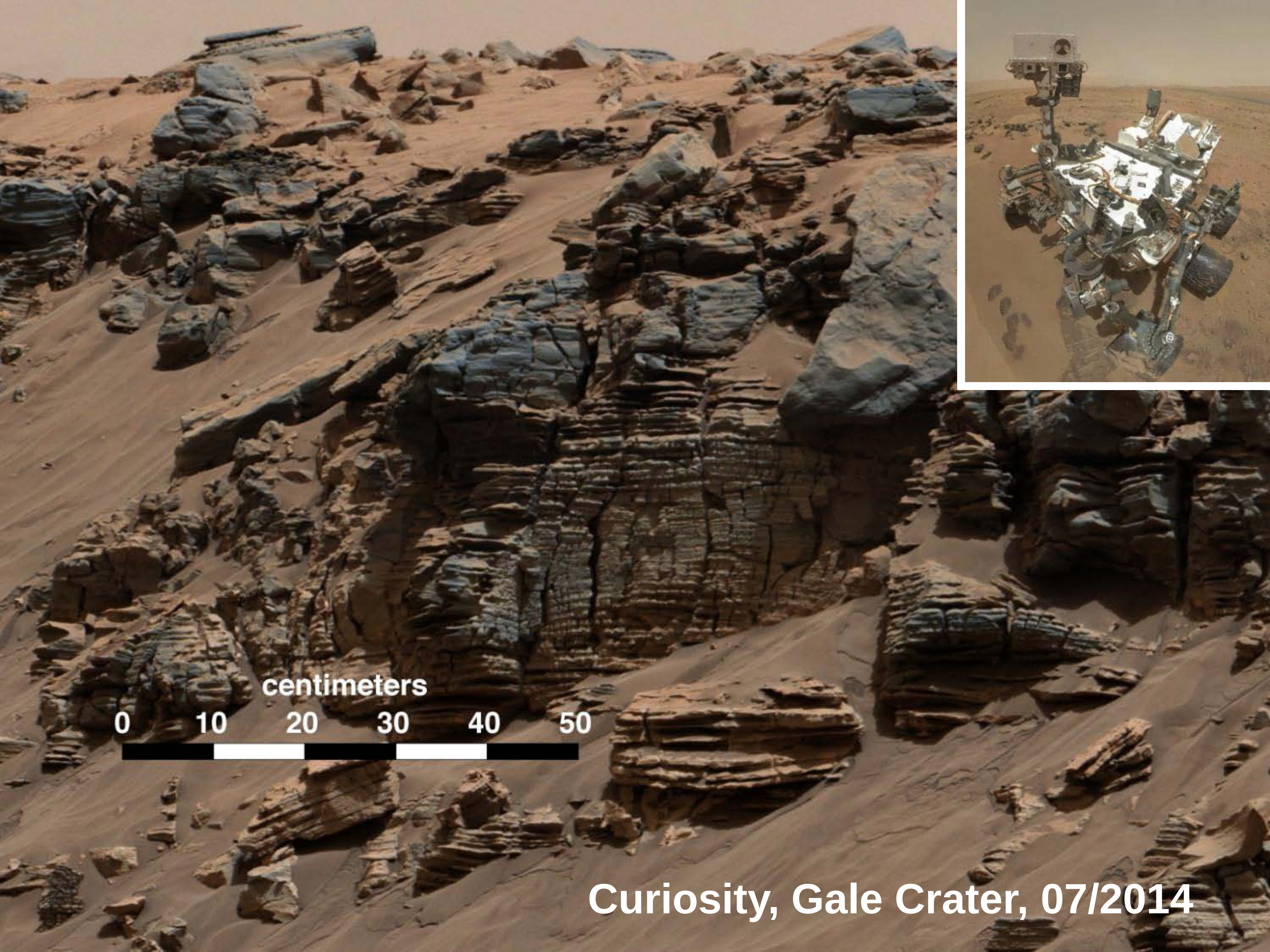


MARS : Warrego Vallis

150 km

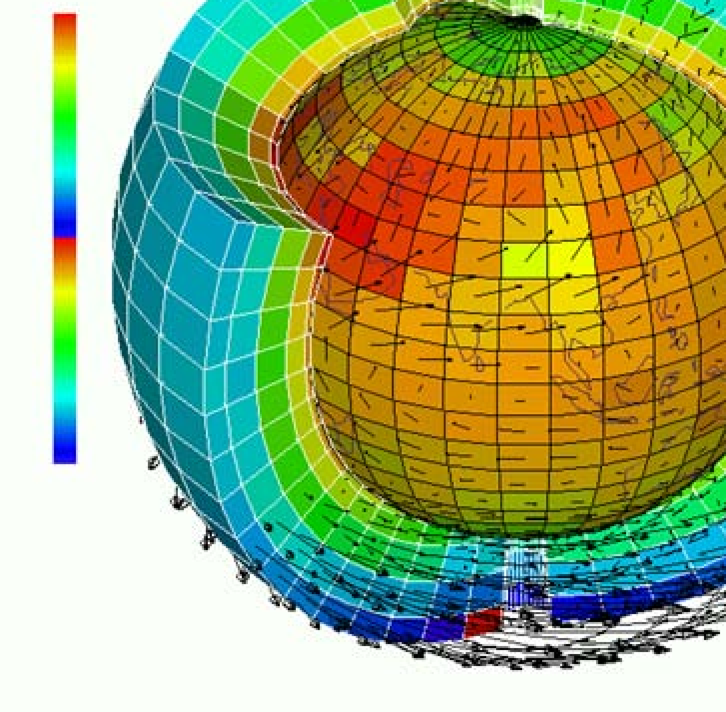
EARTH

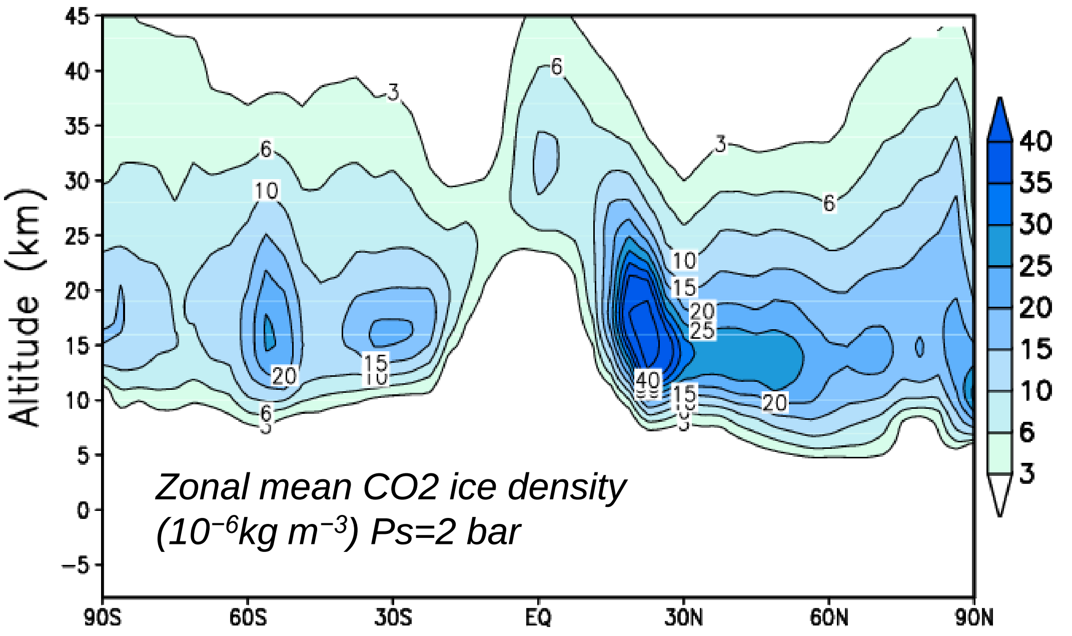
(Yemen ; same scale)


centimeters
0 10 20 30 40 50
Curiosity, Gale Crater, 07/2014

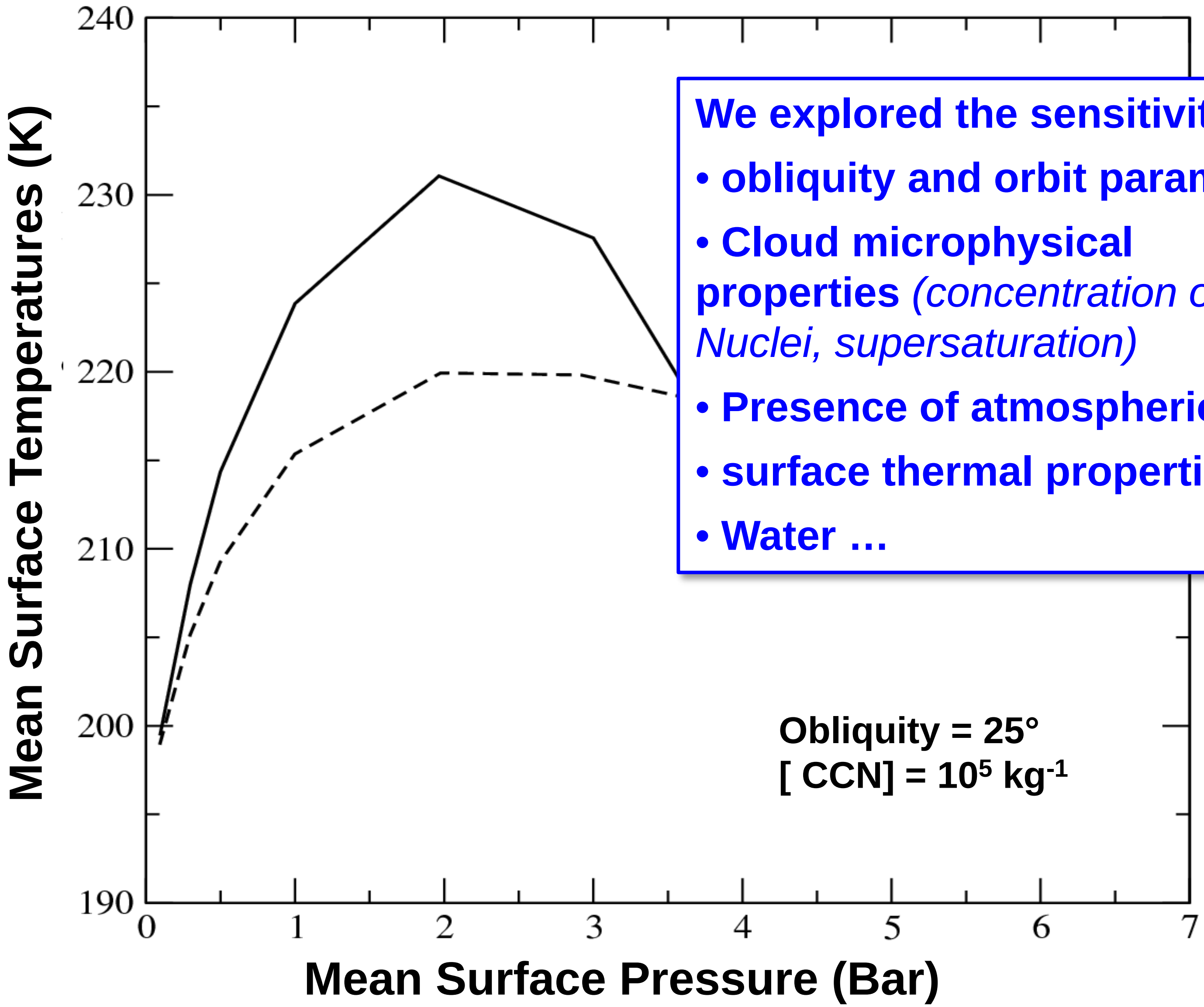
A 3D Global Climate Model (GCM) for early Mars

- **LMDZ grid point dynamical core,**
  - o 64x48 or 32x32 grid points
  - o 15 layers
- **New radiative transfer core:**
  - o Correlated-k for the gaseous absorption
  - o Toon et al. (1989) two-stream method for the aerosols
- **Simple parametrisation of CO_2 cloud microphysics** : condensation, nucleation, transport, sedimentation
  (fixed CCN distribution, but variable mean cloud particle sizes)





Global mean surface temperature (K)



We explored the sensitivity to

- **obliquity and orbit parameters**
- **Cloud microphysical properties** *(concentration of Nuclei, supersaturation)*
- **Presence of atmospheric dust**
- **surface thermal properties**
- **Water …**

Forget et al. 2012, Wordswoth et al. 2013, Kerber et al. 2014


Mars 4 billions
years ago ???
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