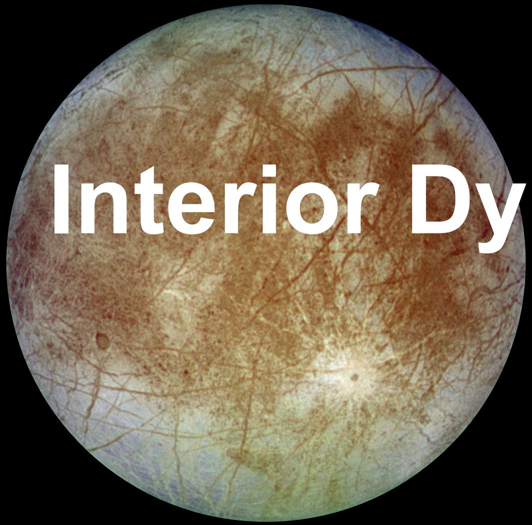

Interior Dynamics of Rocky Planets and Icy Moons: The Case of Mars and Europa

Ana-Catalina Plesa

DLR Institute of Planetary Research

Astronomical Institute of the Romanian Academy, Online Seminar, 25th September 2024

Knowledge for Tomorrow

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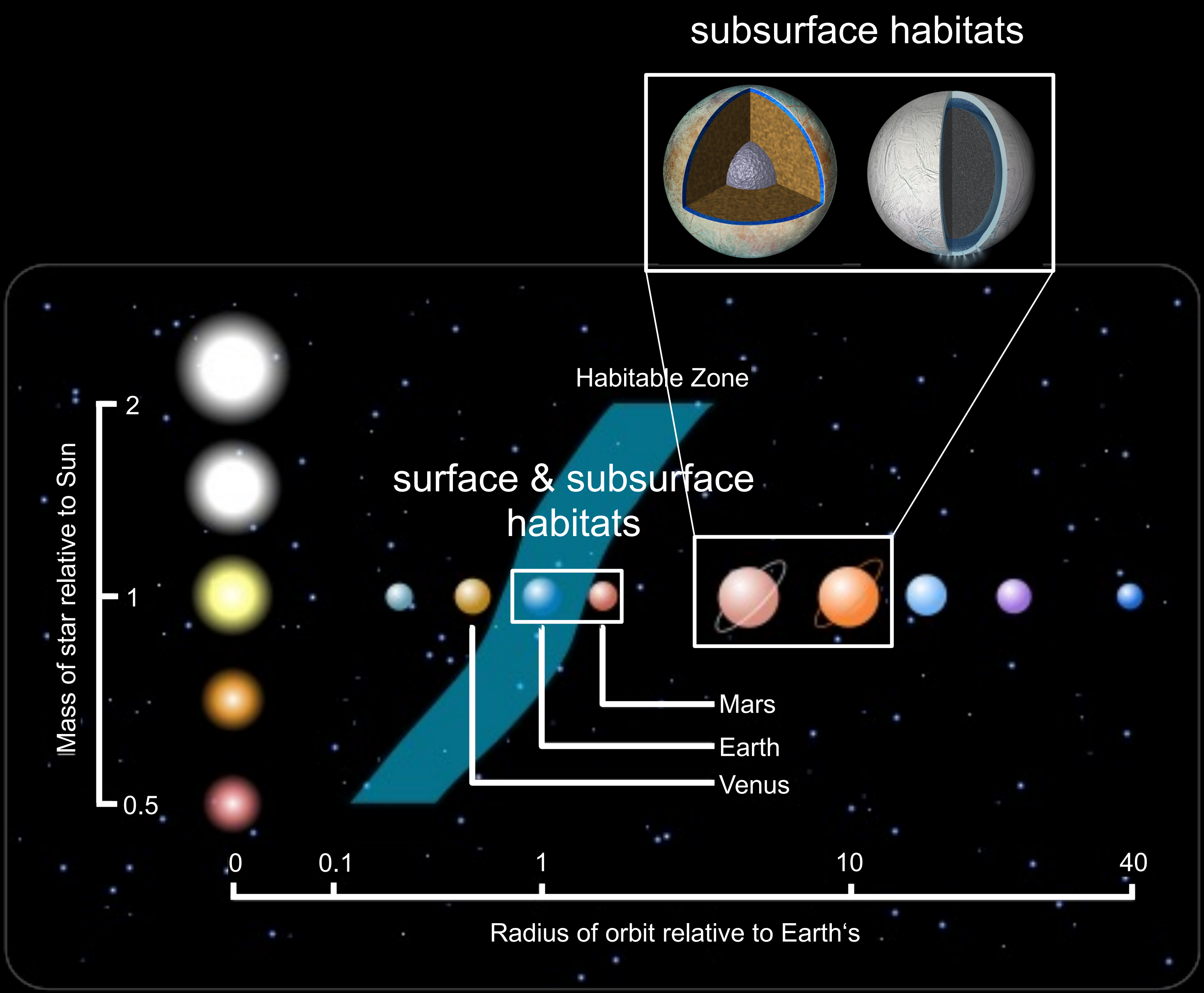
Habitable environments

- **Habitability requirements:**
  - liquid water
  - energy source to drive metabolism
  - chemical compounds as nutrients

- **Habitable Zone (HZ):** the region around a star where an Earth analog can possess liquid water on its surface



Credits: NASA/Astrobiology Magazine

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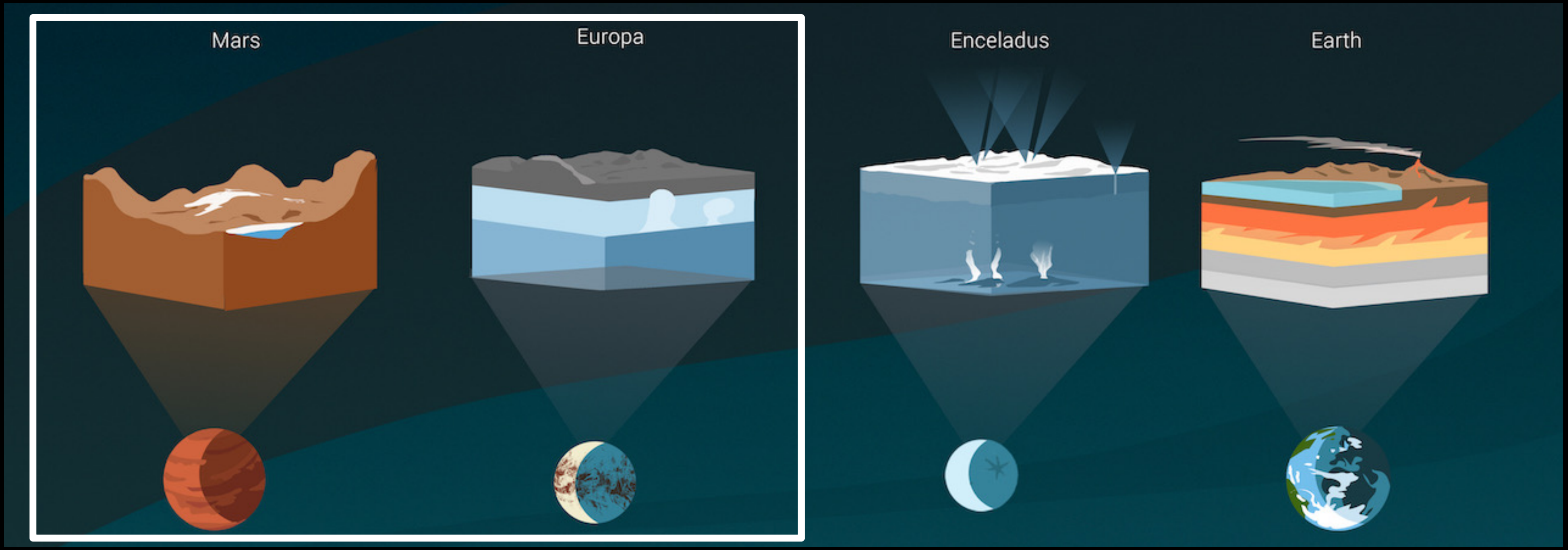
Habitable environments classification

- **Class I:** habitats suitable for the evolution of multi cellular life forms on the surface (classical HZ)
- **Class II:** microbial life may have evolved and habitats in the subsurface, ice/H_2O may have remained (inner & outer edge of the HZ)
- **Class III:** life forms may have evolved and populate subsurface H_2O oceans (beyond the ice-line)

[Lammer et al., 2009]



Credits: NASA/JPL-Caltech/Lizbeth B. De La Torre

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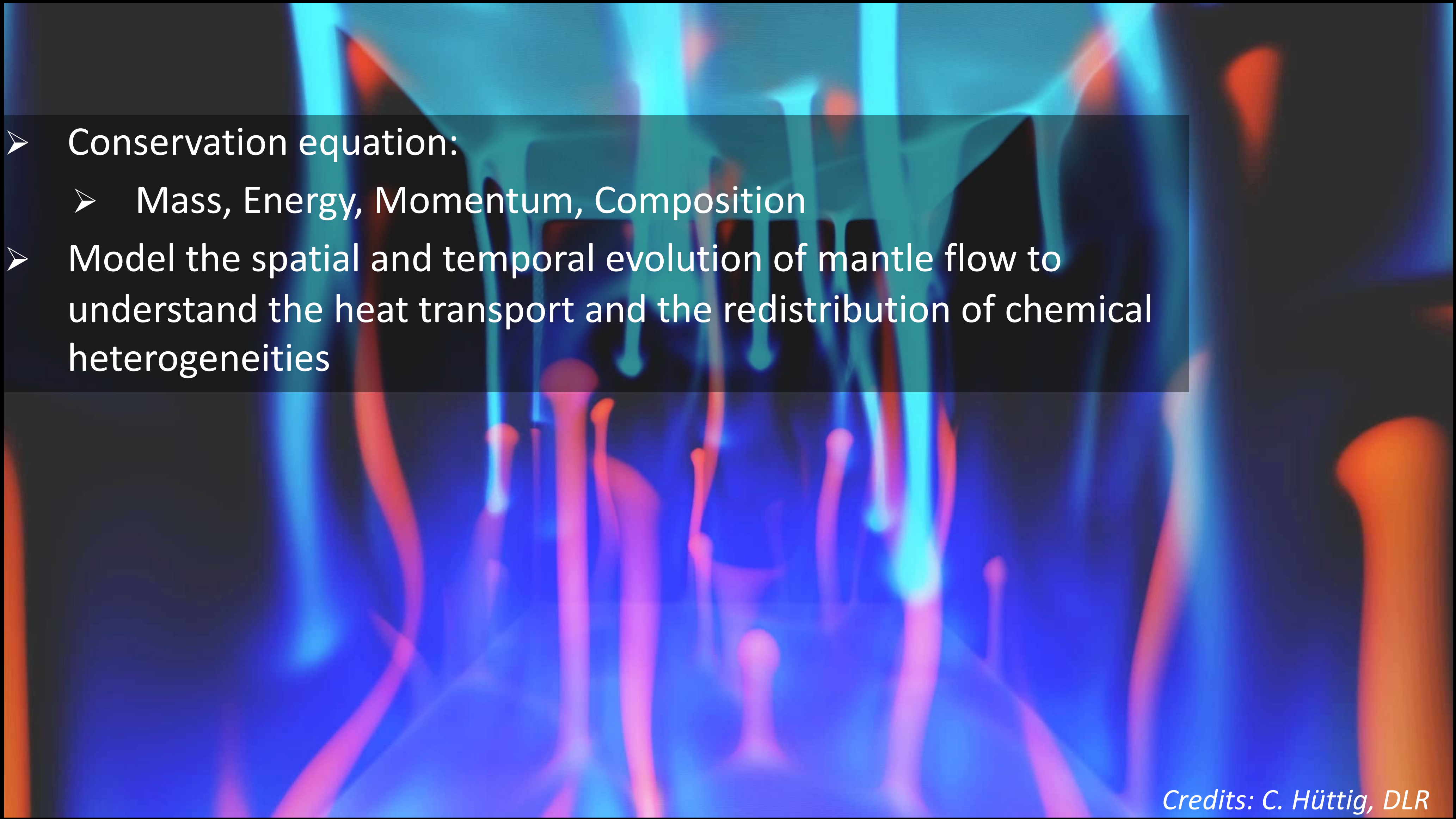
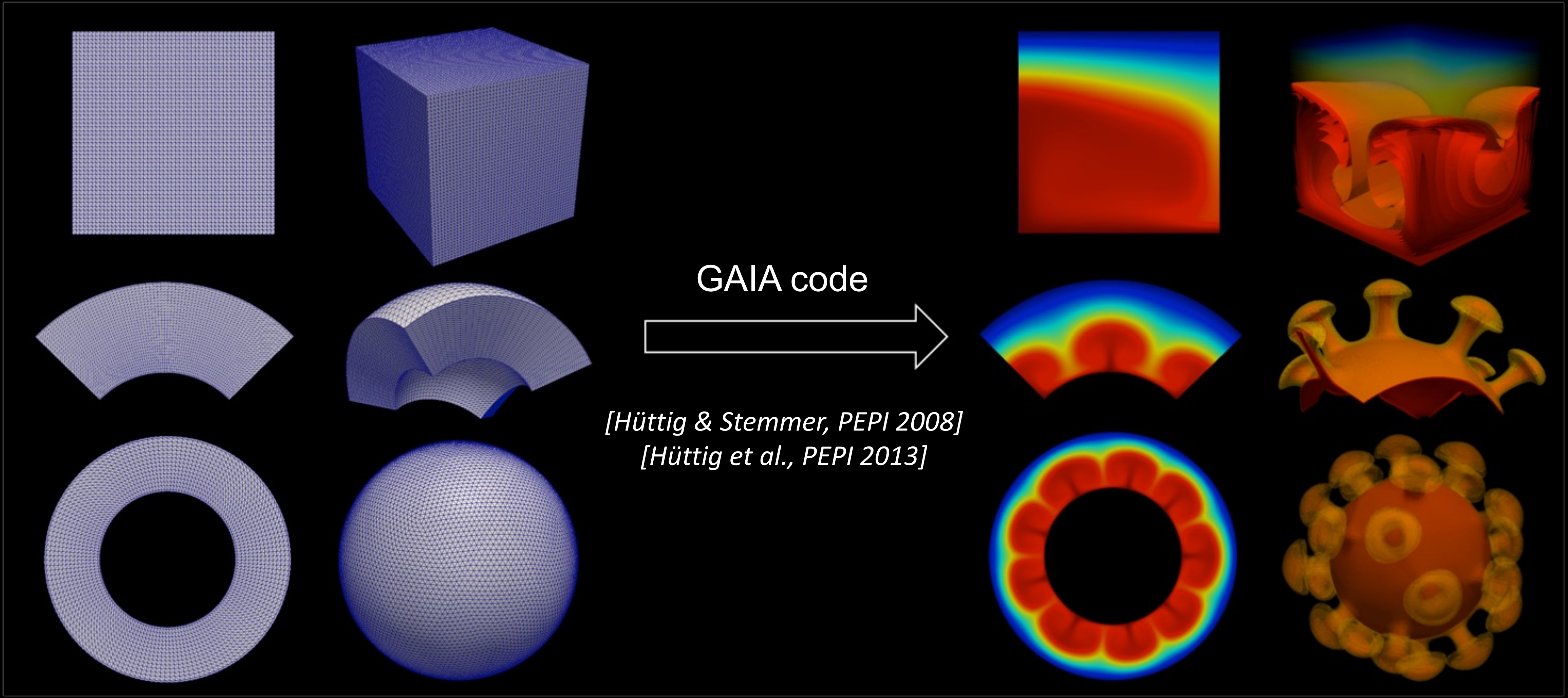
Geodynamical models of rocky planets and icy moons

- Conservation equation:
  - Mass, Energy, Momentum, Composition
- Model the spatial and temporal evolution of mantle flow to understand the heat transport and the redistribution of chemical heterogeneities



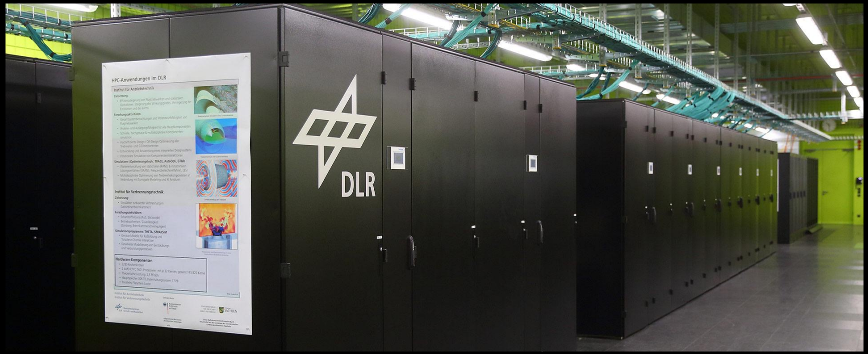
Credits: C. Hüttig, DLR

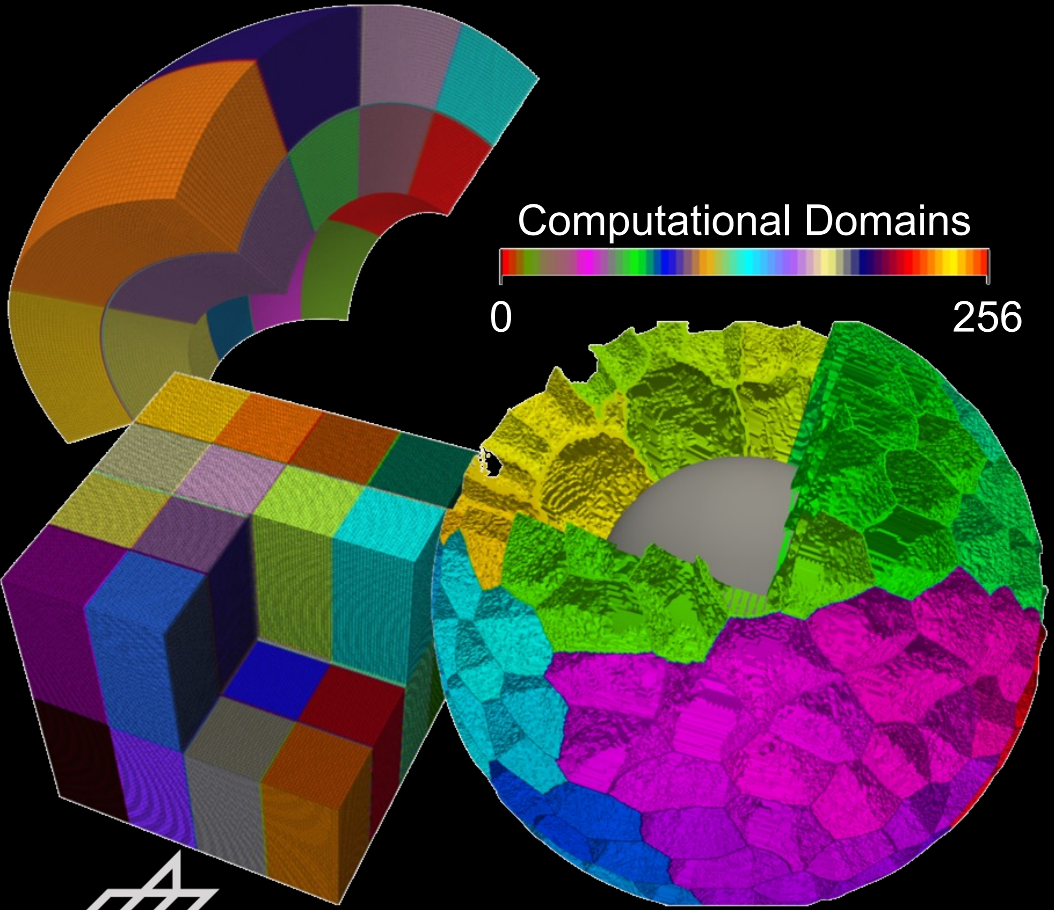
The fluid flow solver GAIA

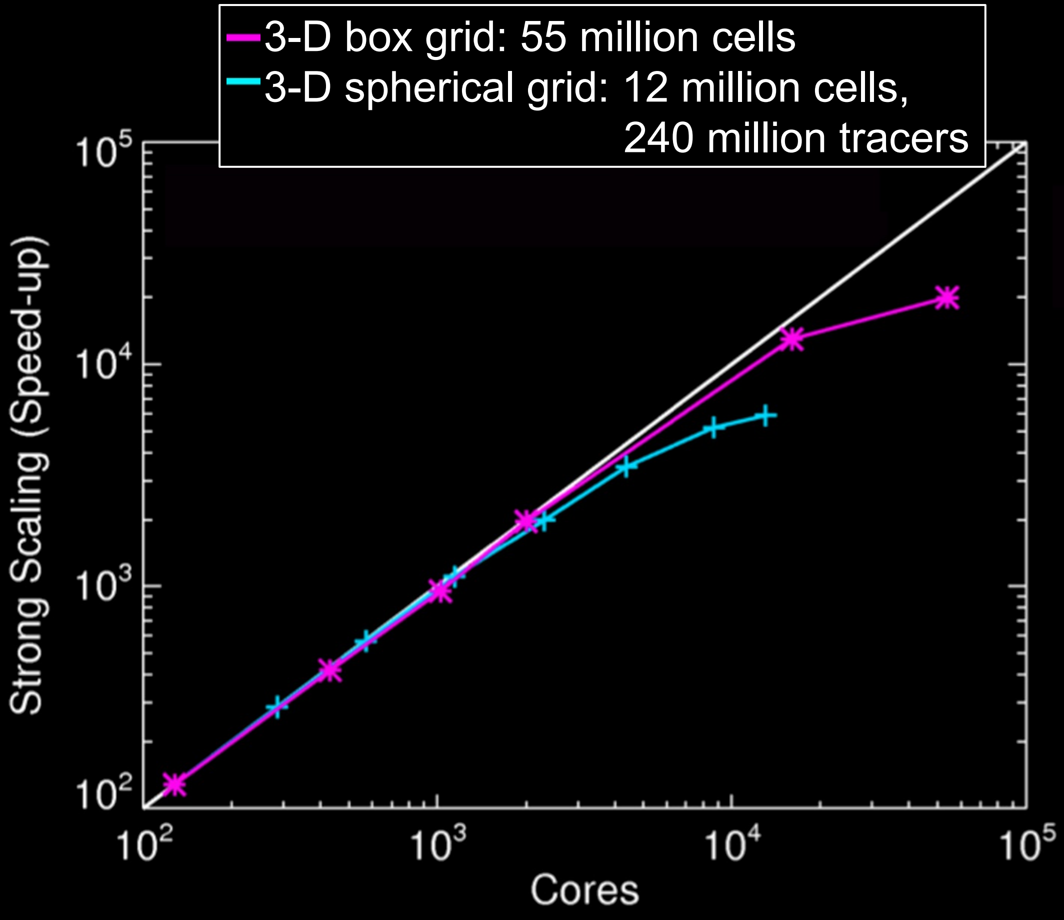


GAIA performance

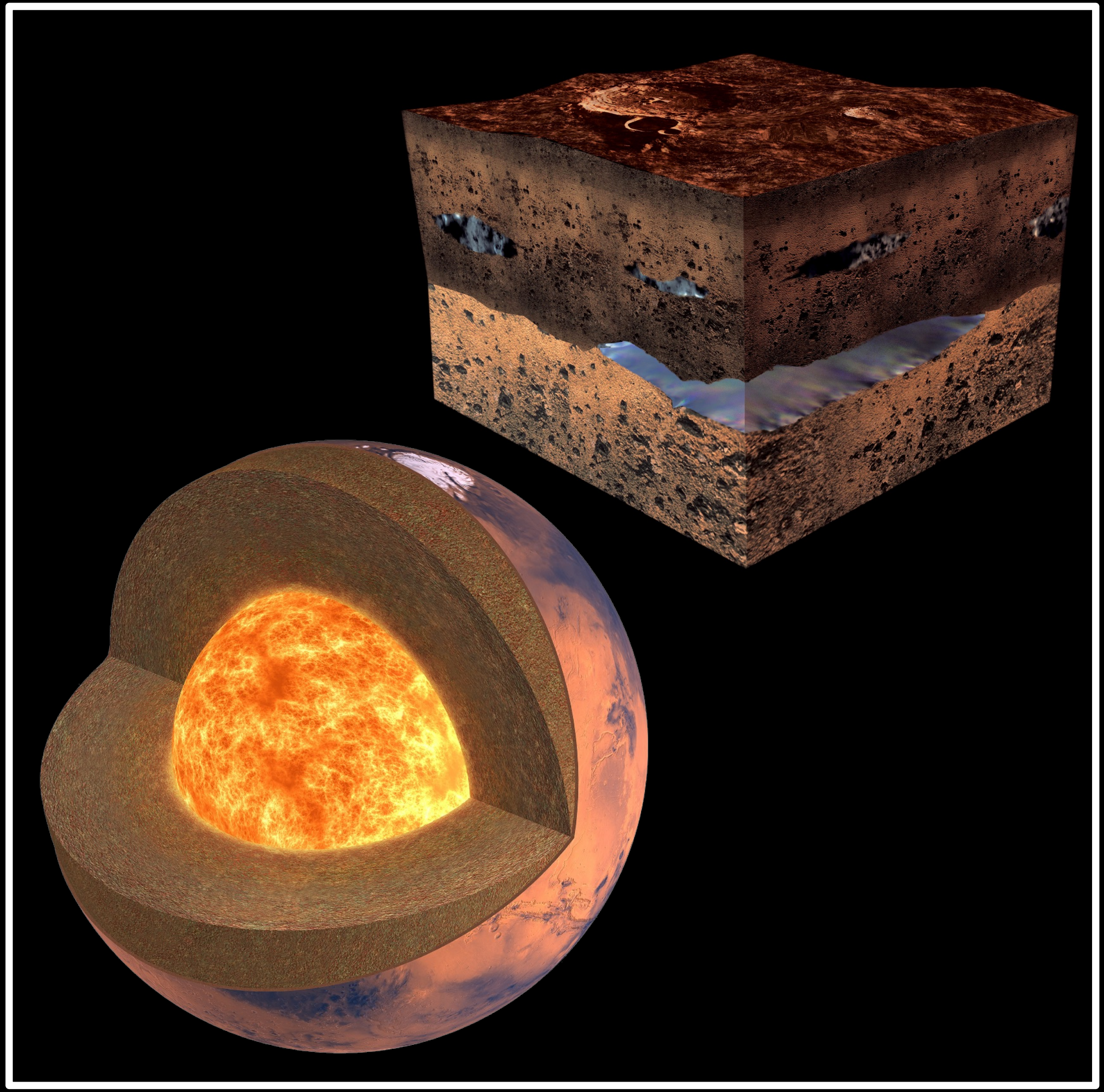
- Written in C++ without the need of using external libraries
- Efficiently parallelized

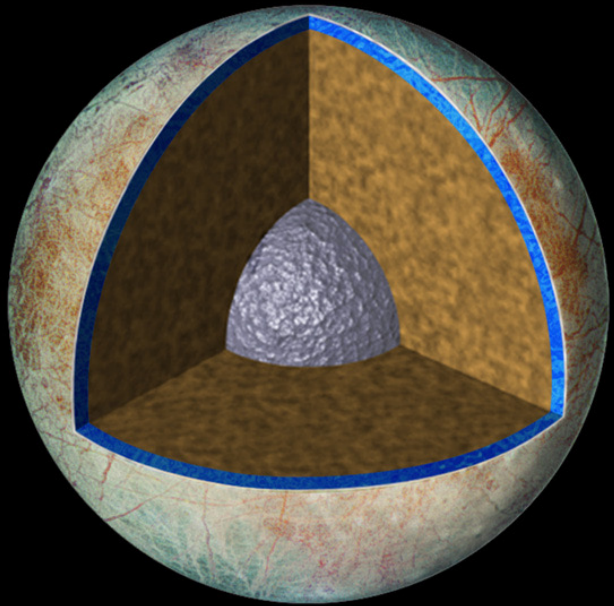






The subsurface environments of Mars and Europa





Credits: ESA/Medialab/IPGP/David Ducros/Astronomy/Roen Kelly/NASA/JPL

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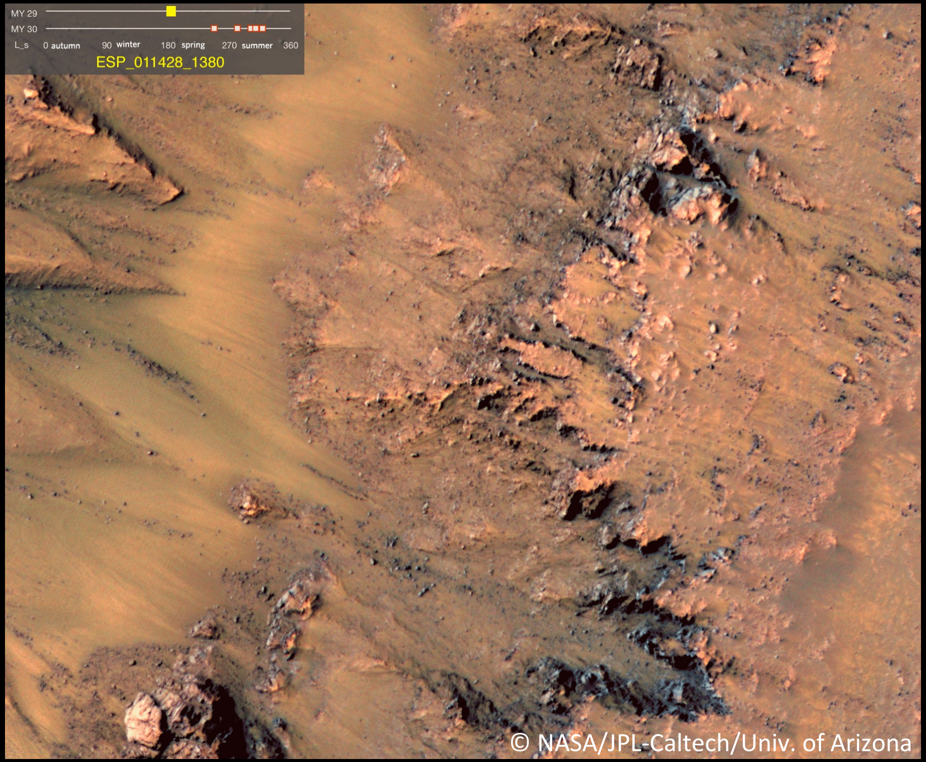
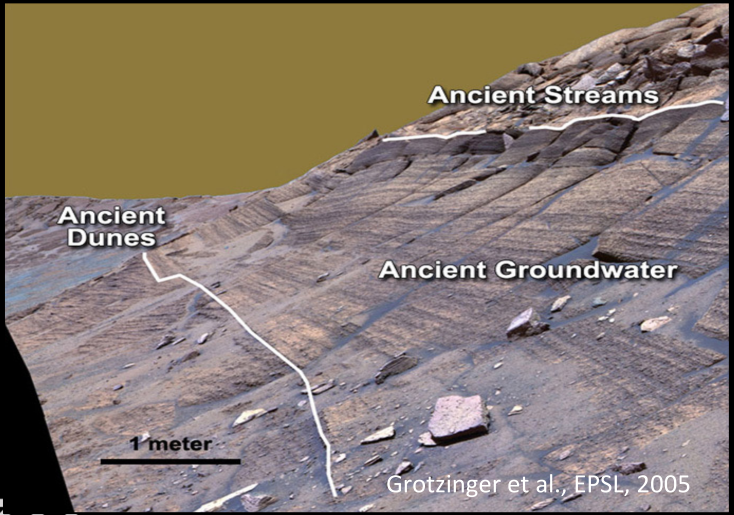
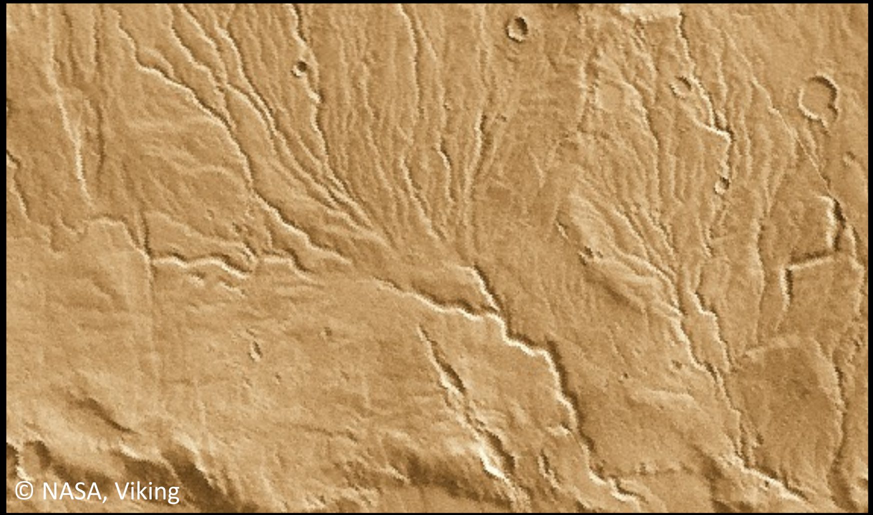
Traces past liquid water

- The surface of Mars has been shaped by liquid water during its planetary evolution.
- Today, liquid water is no longer stable at the surface due to the temperature and pressure conditions, but liquid groundwater may still exist in the Martian subsurface.

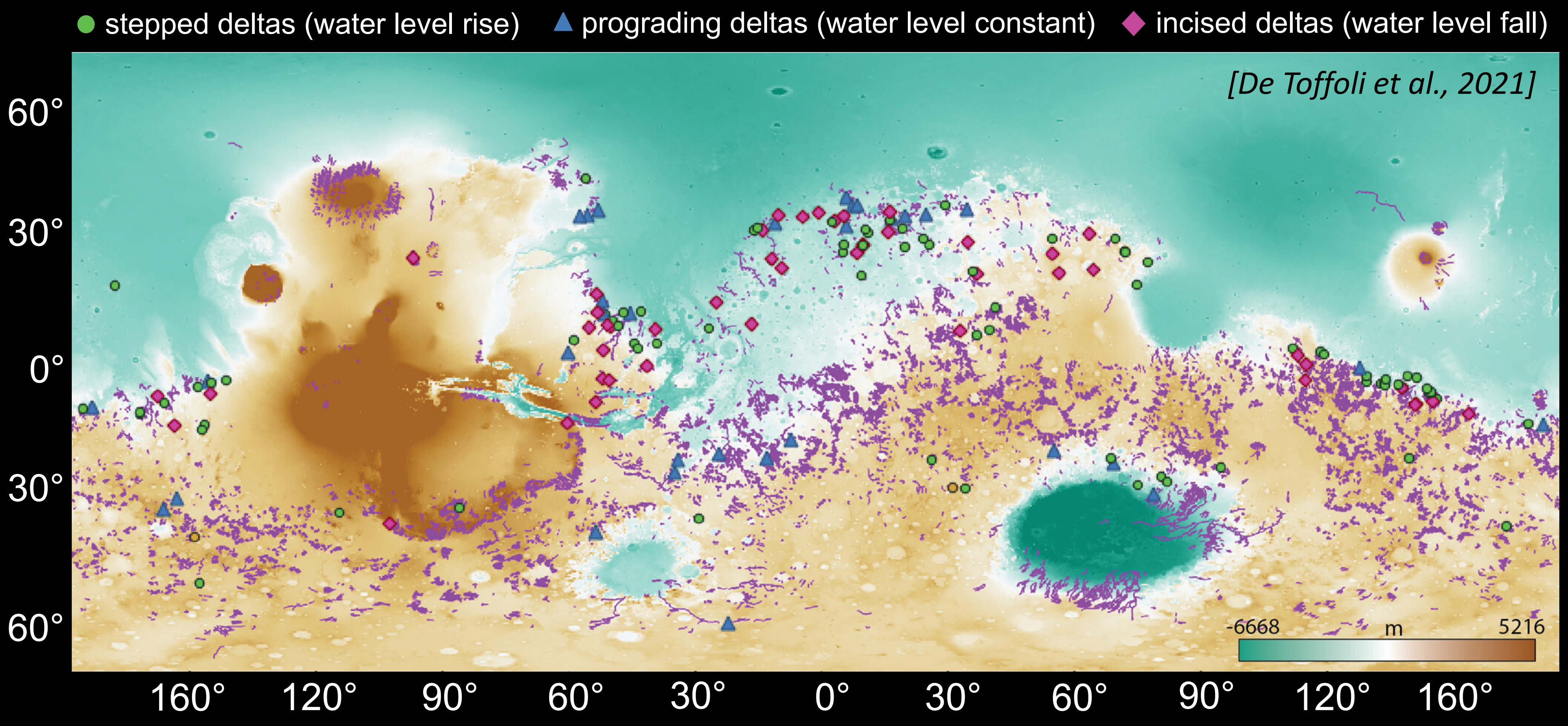






Water on Mars

- Updated global catalog of deltas on Mars characterized in terms of their geomorphology
- Total: 161 deltas, among which 68 were not reported in previous catalogs



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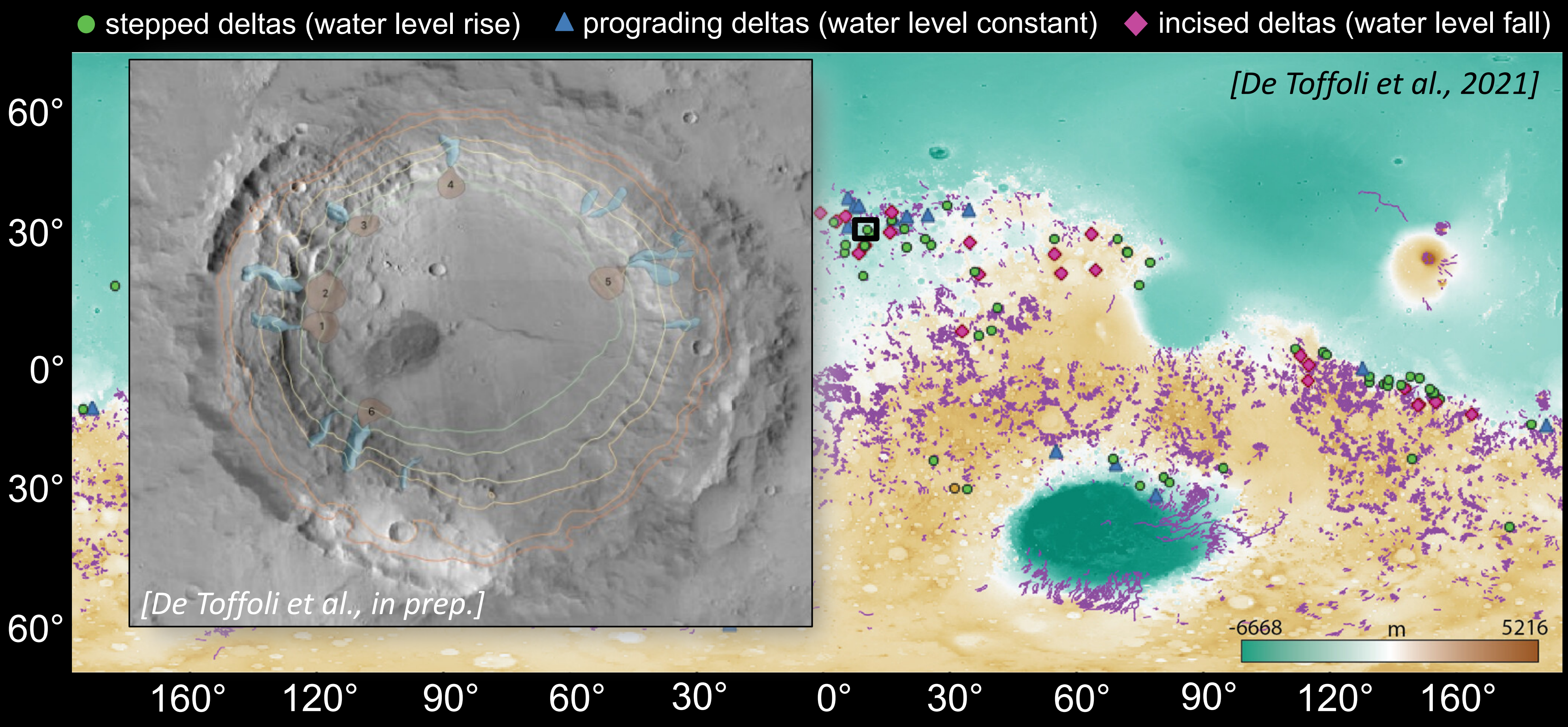
Water on Mars

- Unnamed crater displays numerous water related features
- The crater is missing a connection with large scale fluvial networks: groundwater?



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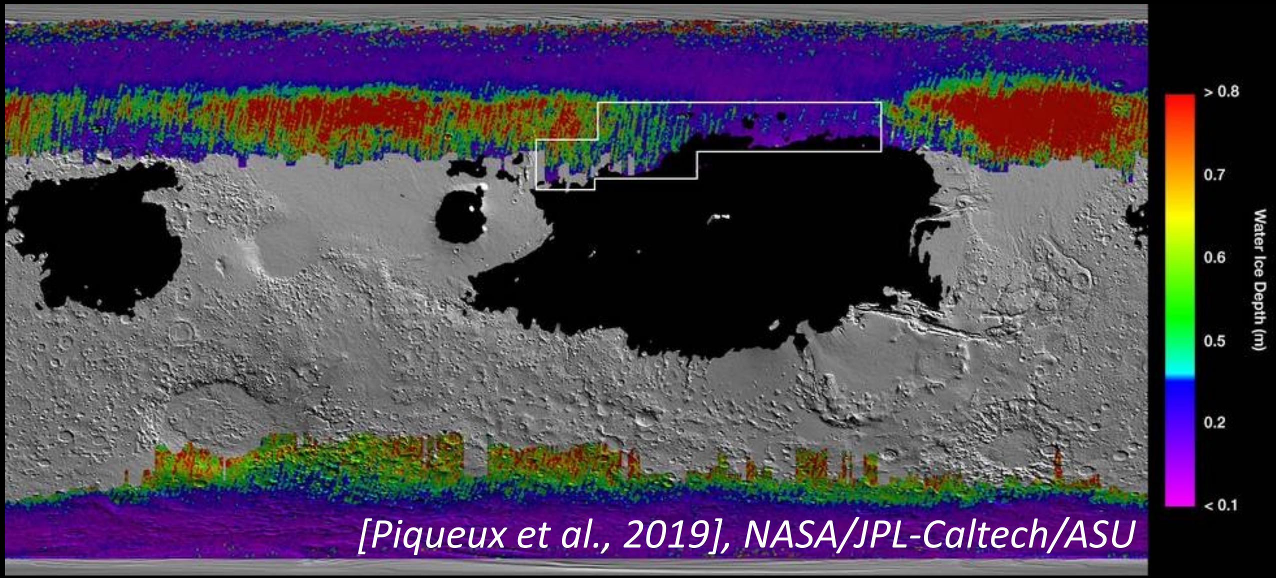
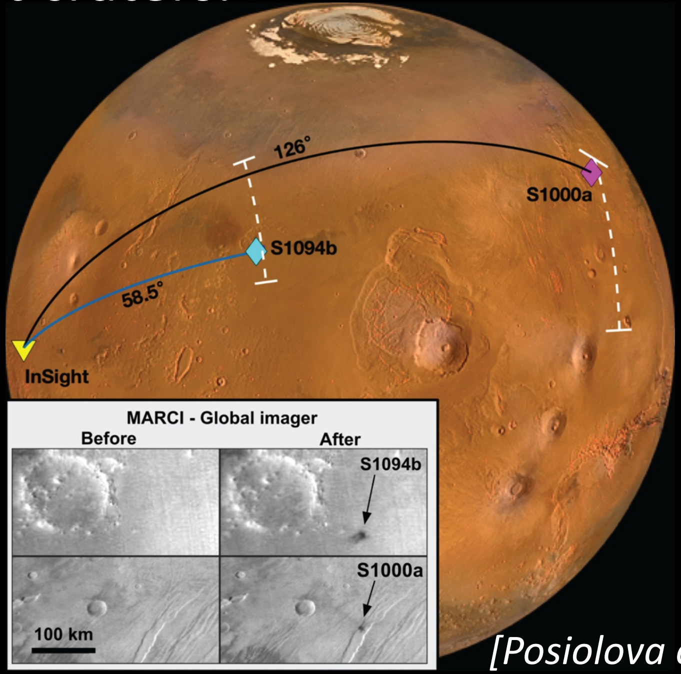
Subsurface ice and water

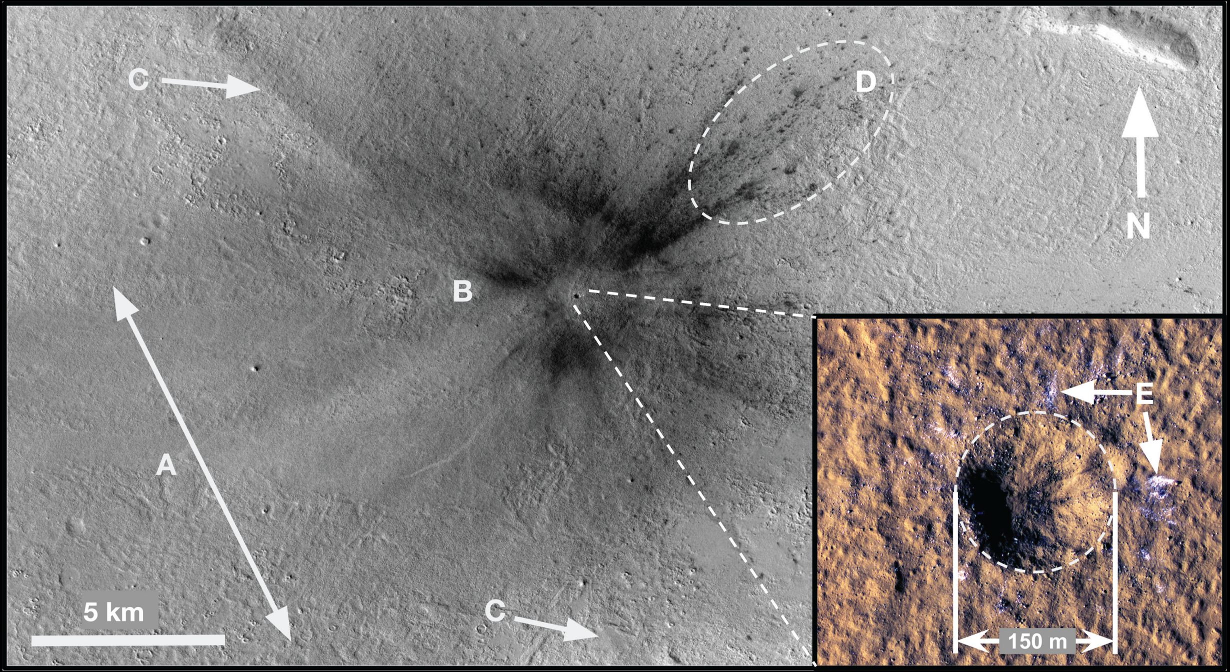
- Ice and groundwater may still be present in the subsurface today.
- Subsurface water ice has been detected at high latitudes from orbit and in fresh impact craters.



[Piqueux et al., 2019], NASA/JPL-Caltech/ASU



[Posiolova et al., 2022]



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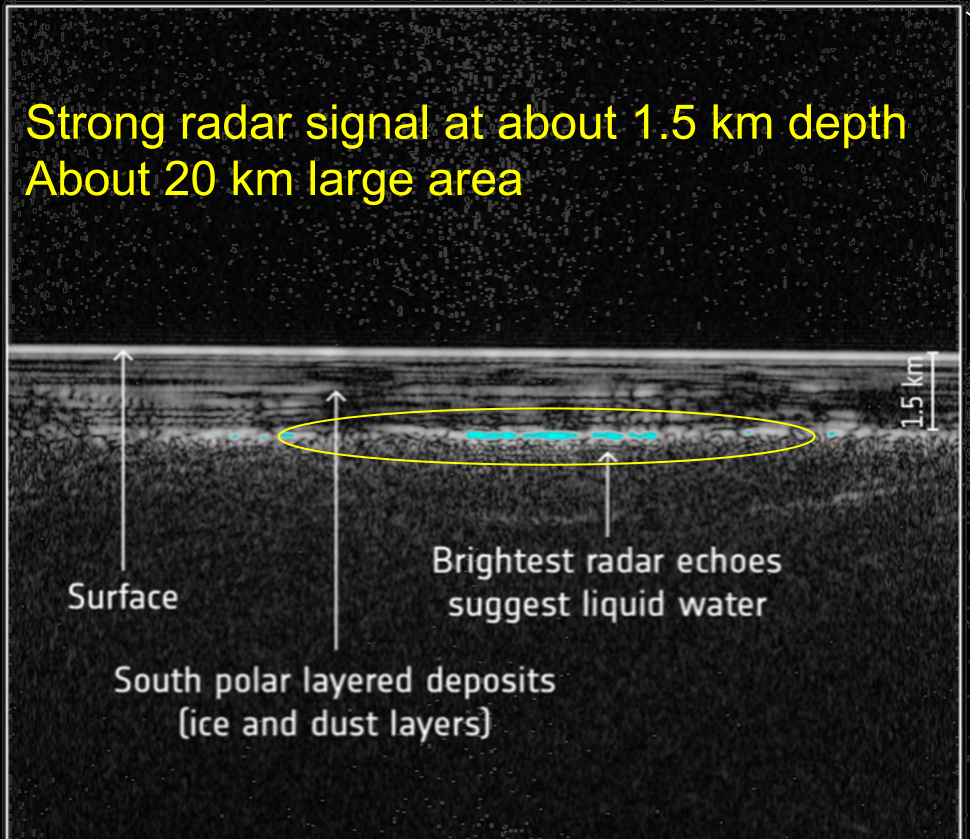
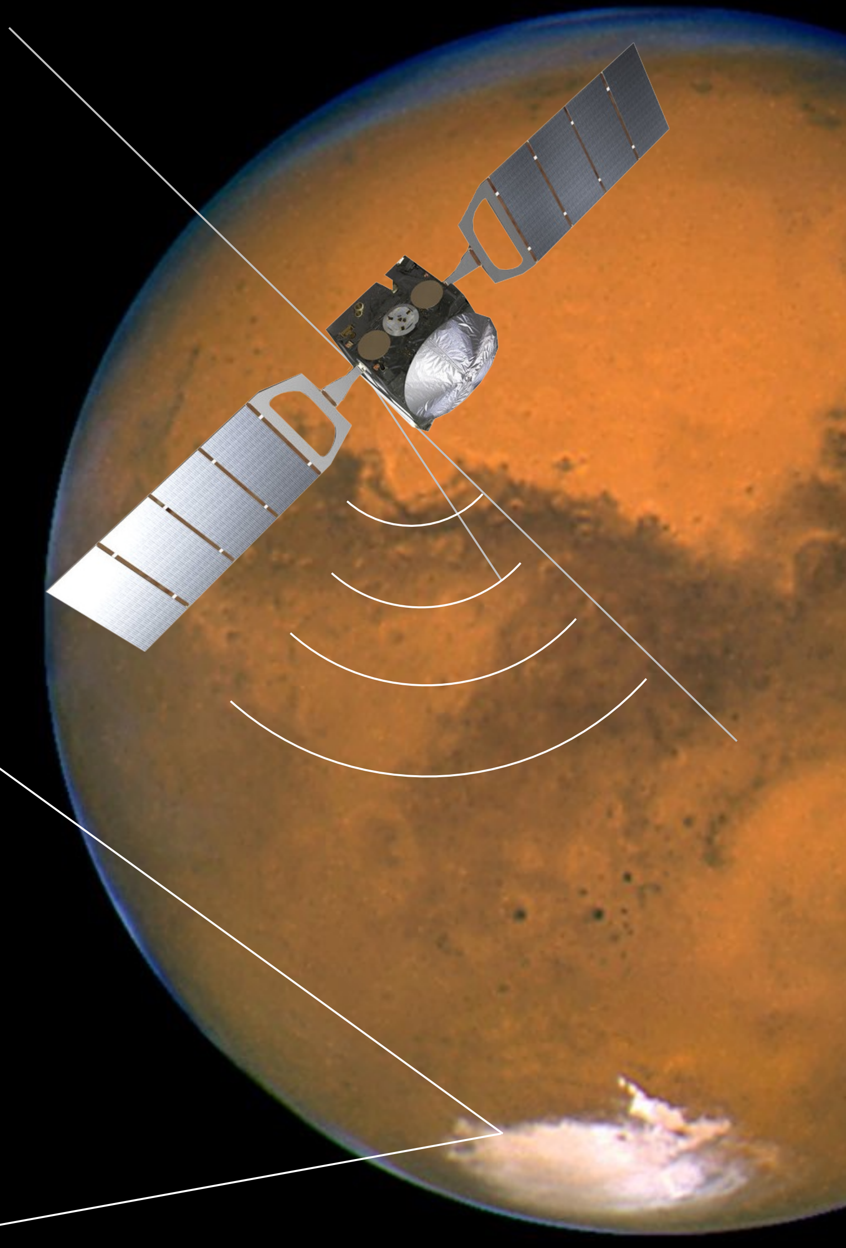
Present day water at the south pole

- Radar observations by MARSIS suggest the presence of a liquid reservoir underneath the south pole.



Credits: ESA/NASA/JPL/ASI/Univ. Rome; Orosei et al. 2018.



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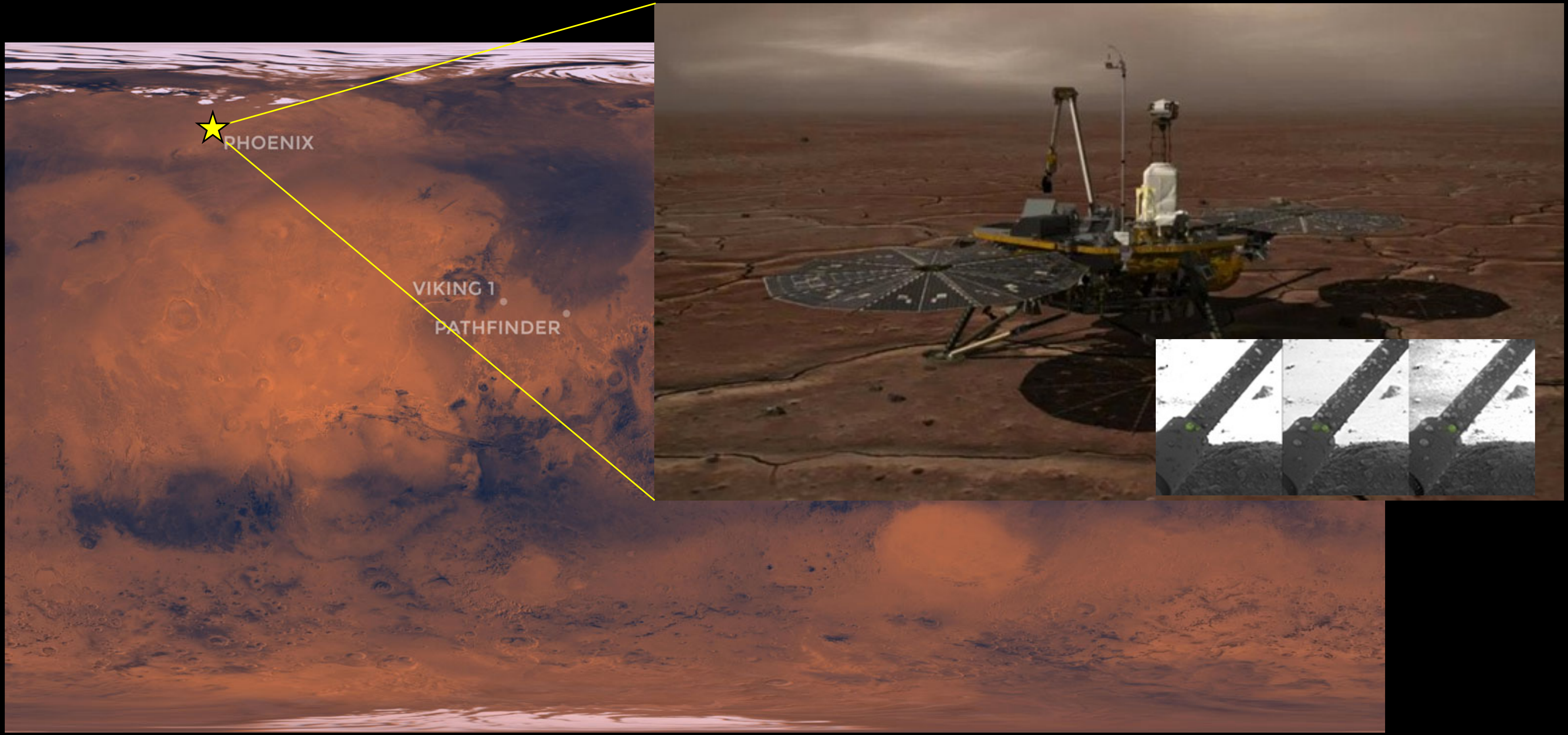
Liquid water and brines on Mars

- If liquid water exists on the surface of Mars it is most likely in form of brines.



Credits: NASA/JPL-Caltech/University of Arizona/Max Planck Institute

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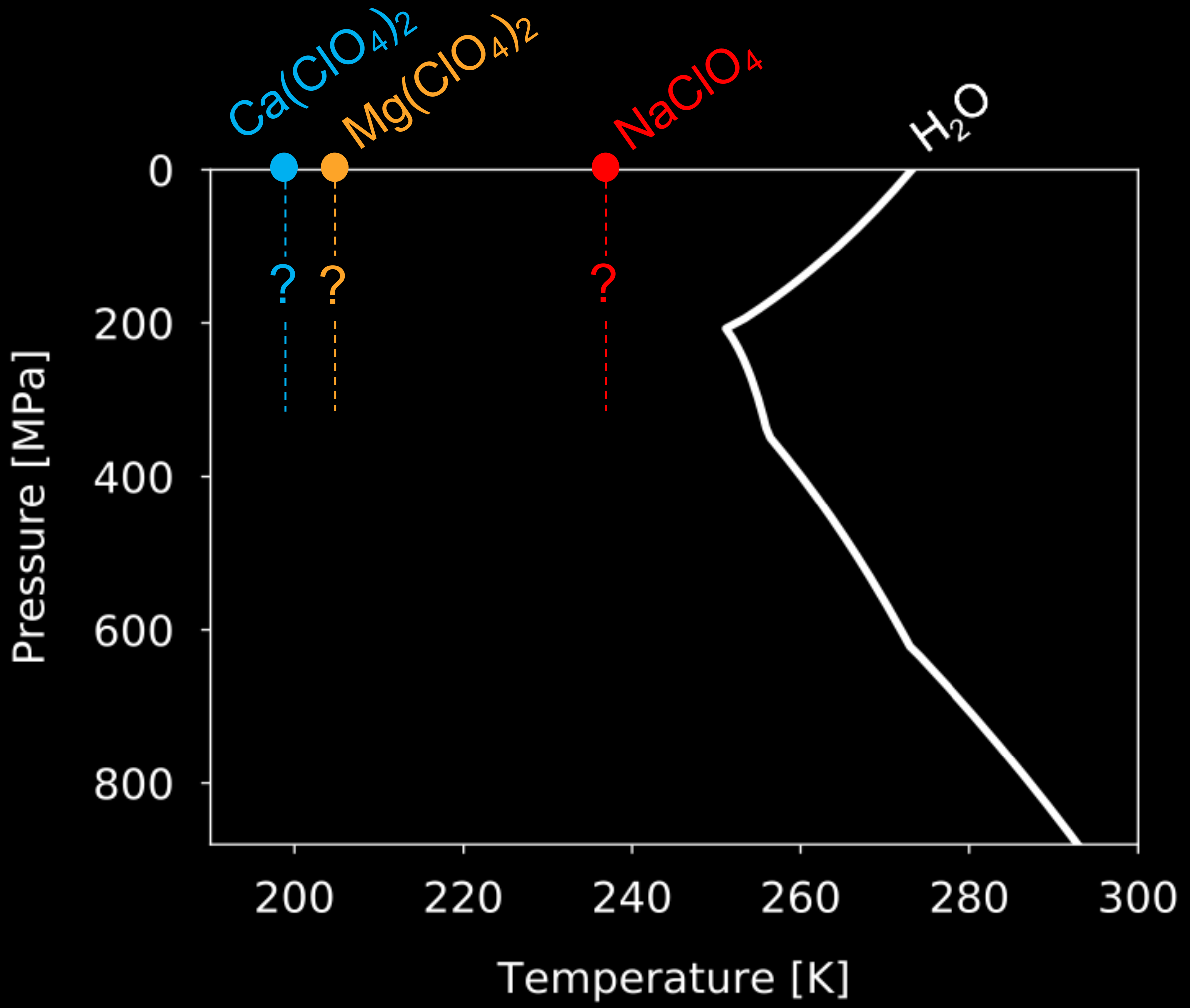
Critical parameters influencing the ‘potential‘ ground water table

- **Near-surface parameters**
  - Melting temperature (amount and distribution of salts)
  - Crustal thickness distribution
  - Thermal conductivity
  - Surface temperature (obliquity variations)



[Chizhov, 1993; Chevrier et al., 2009; Marion et al., 2010]

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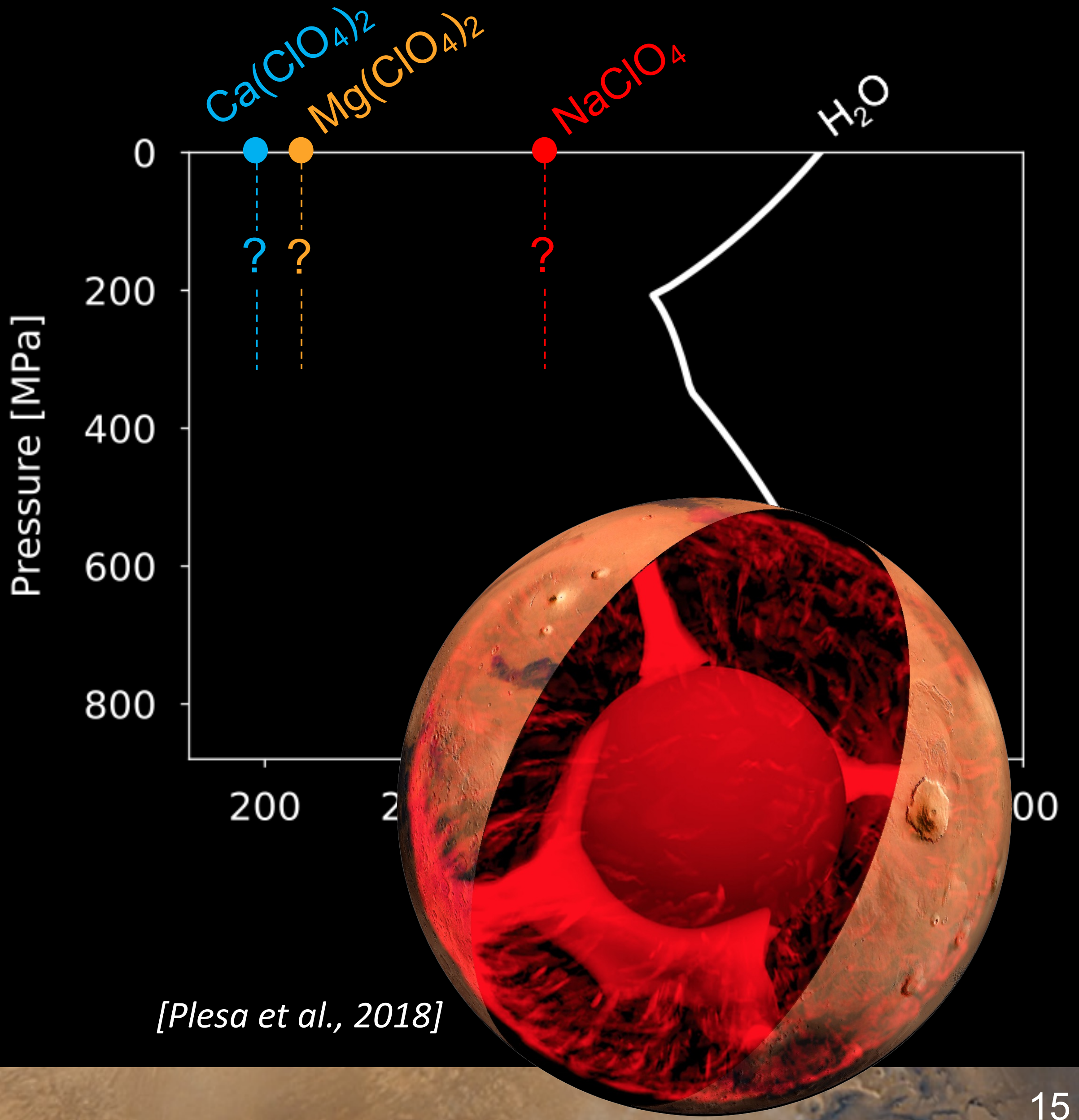
Critical parameters influencing the ‘potential‘ ground water table

- **Near-surface parameters**
  - Melting temperature (amount and distribution of salts)
  - Crustal thickness distribution
  - Thermal conductivity
  - Surface temperature (obliquity variations)

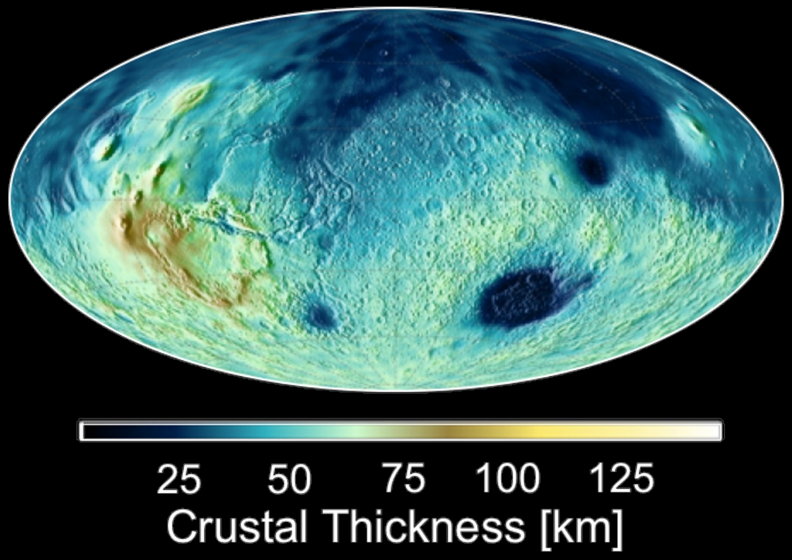
- **Deep-interior parameters**
  - Heat sources (amount and distribution)
  - Convection pattern (size and distribution of mantle plumes)



[Plesa et al., 2018]

Cryosphere depth calculations

- The present-day temperature distribution is obtained from global thermal evolution models.
- The effect of the crustal thickness is mainly evident in basins, along the dichotomy, and in volcanic provinces.
- Variations of the surface temperatures give general water table depth trends with latitude.



[Wieczorek et al., 2013, 2019]

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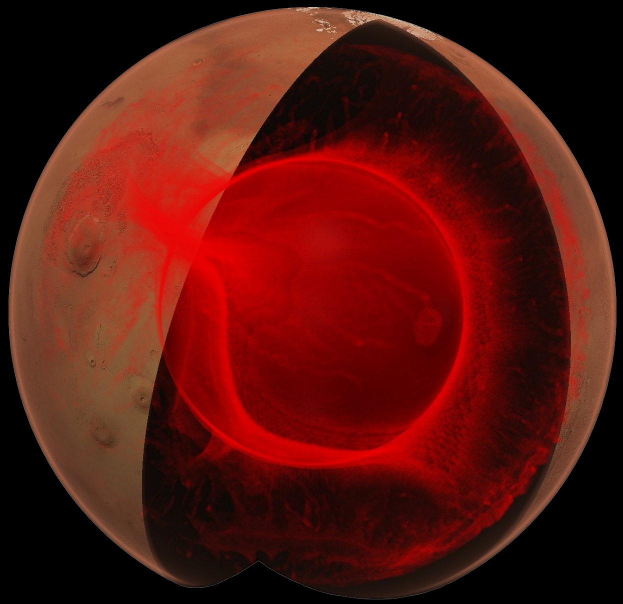

[Plesa et al., 2016, 2018]

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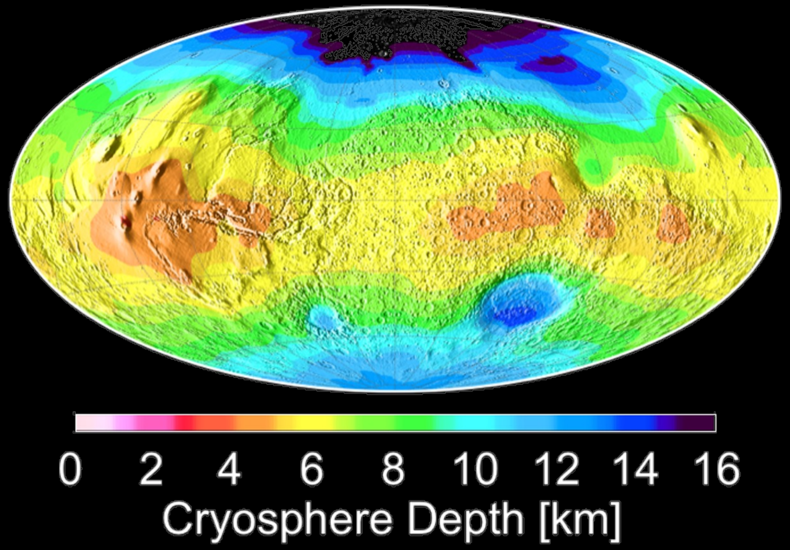
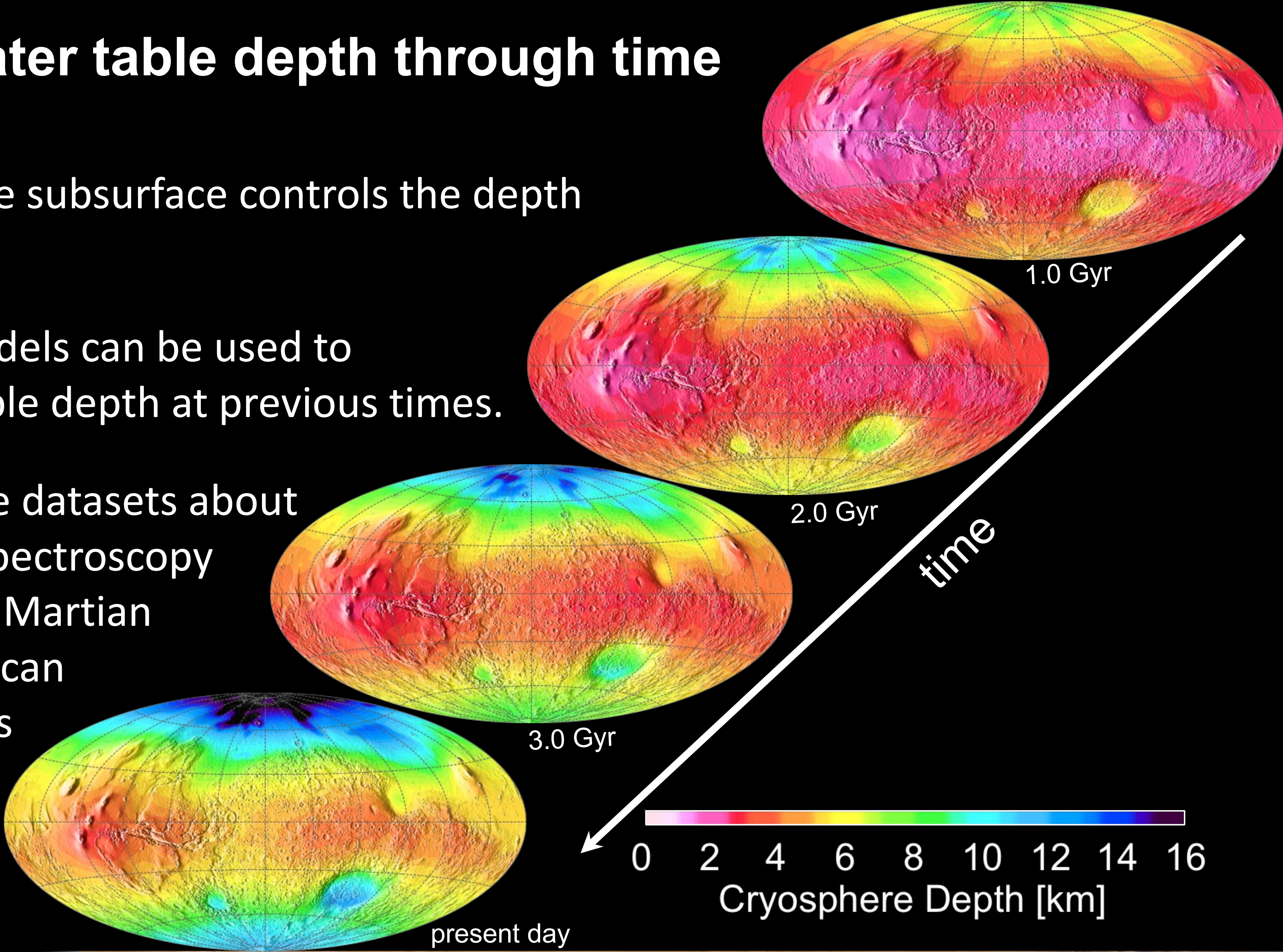


[Plesa et al., Stamenkovic et al., EPSC, 2019, 2020]

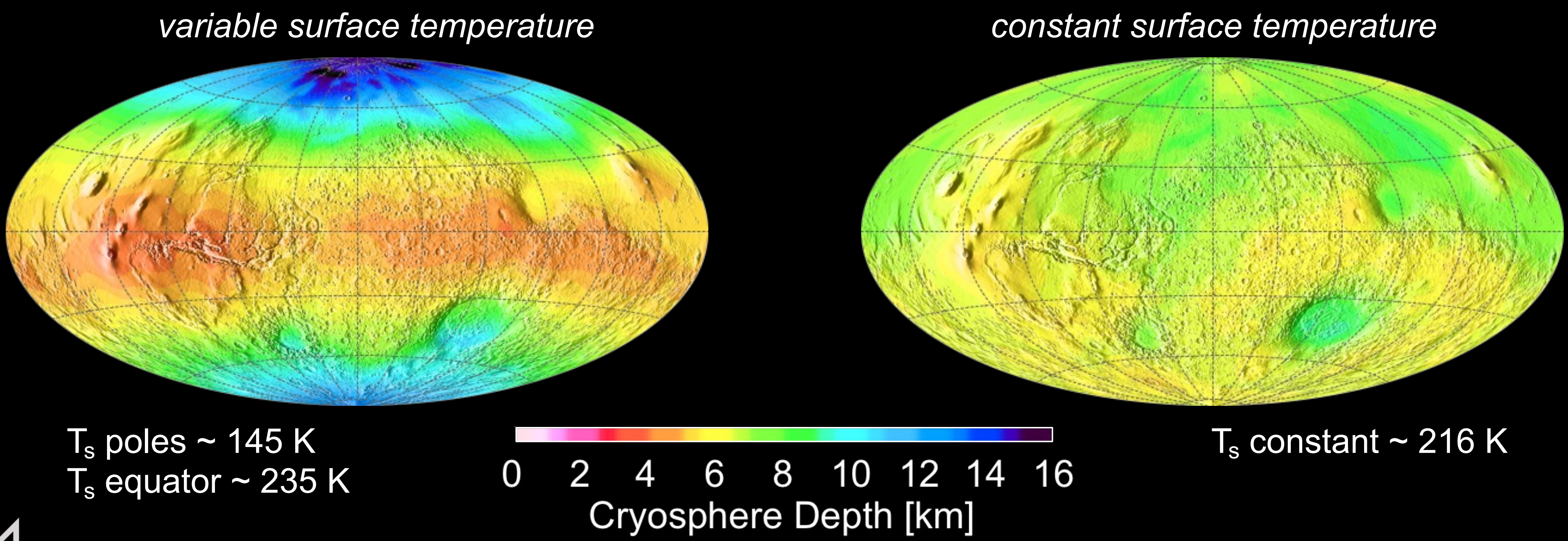
Evolution of the water table depth through time

- The temperature in the subsurface controls the depth of the water table.
- Thermal evolution models can be used to estimate the water table depth at previous times.
- Combined with diverse datasets about the geomorphology, spectroscopy and mineralogy of the Martian surface, these models can help to identify regions where liquid water may be located close to the surface.



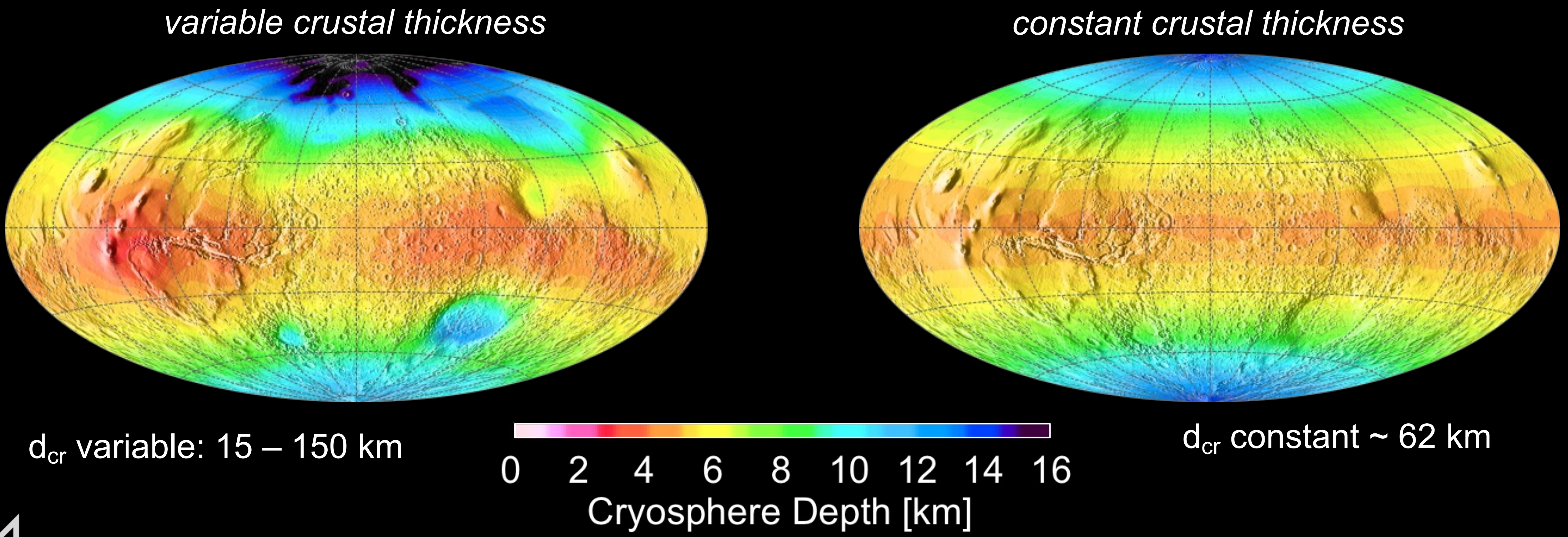
Effects of surface temperature distribution

- The surface temperature controls the distribution of the groundwater depth with latitude.
- If no variations of the surface temperature are present, the groundwater depth distribution follows the crustal thickness pattern.



Effects of crustal thickness

- Crustal thickness variations introduce variations with both latitude and longitude
- If no variations of the crustal thickness are present, the groundwater depth distribution follows the surface temperature pattern.



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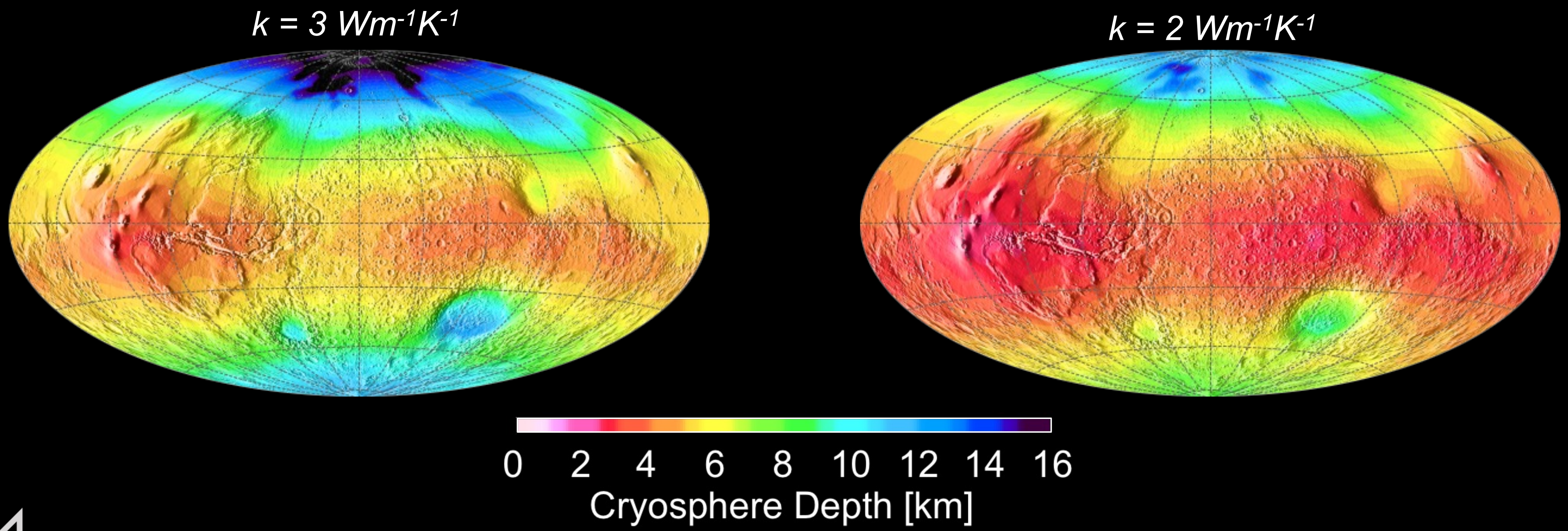
Effects of crustal thermal conductivity

- The thermal conductivity of the crust controls the temperature distribution in the subsurface layers.
- A lower crustal thermal conductivity leads to shallower groundwater table.



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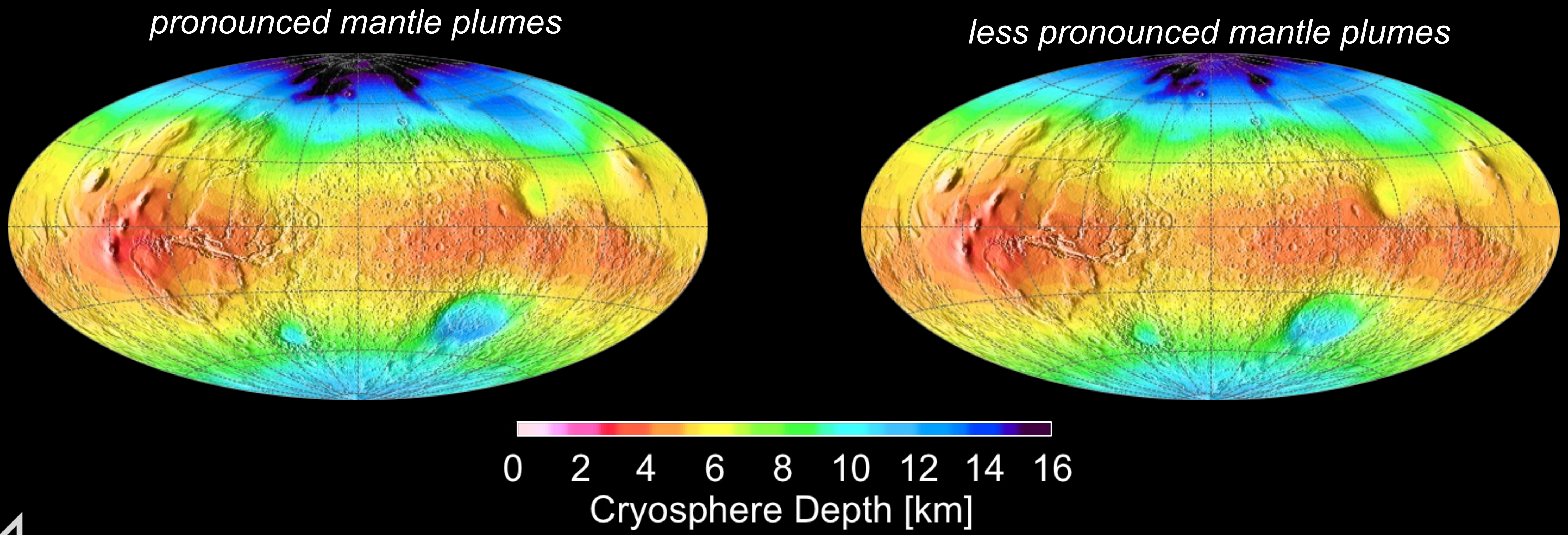
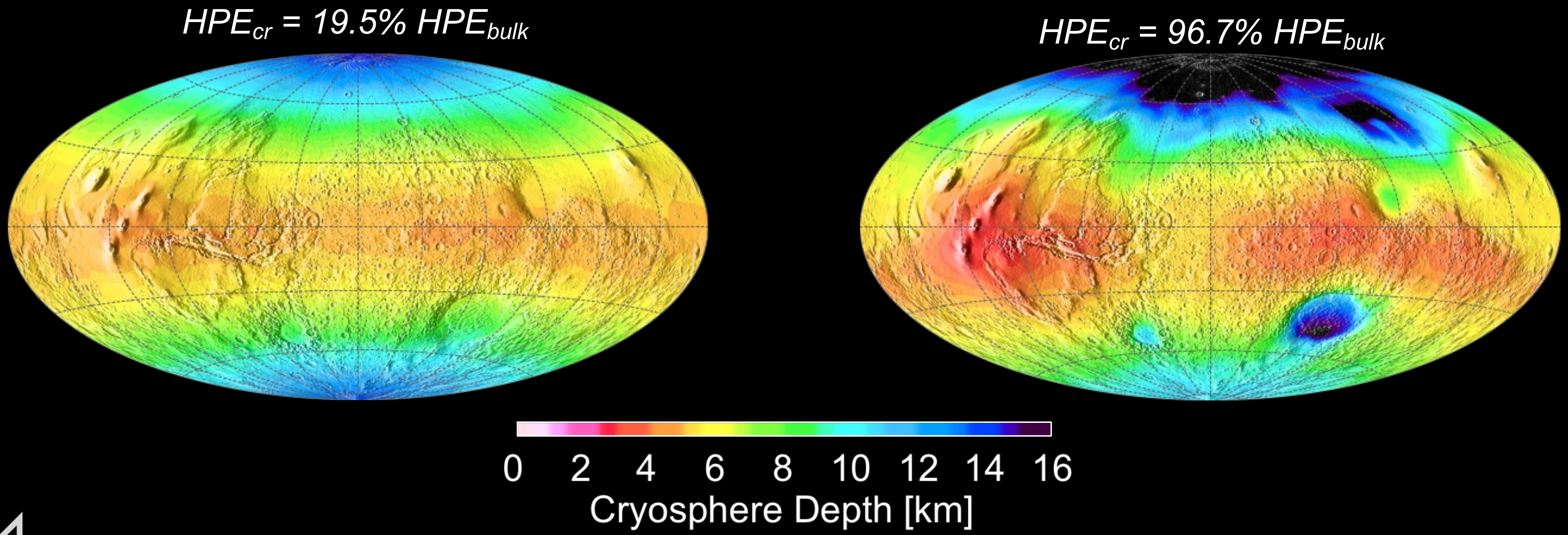
Effects of mantle plumes

- The effects of mantle plumes are minor.
- Slightly larger variations of the depth of the water table are observed for more pronounced mantle plumes.



Effects of heat source distribution

- A low amount of radioactive heat producing elements leads to minor variations of the groundwater depth, while a high amount of HPE in the crust accentuates the variations of the groundwater depth.



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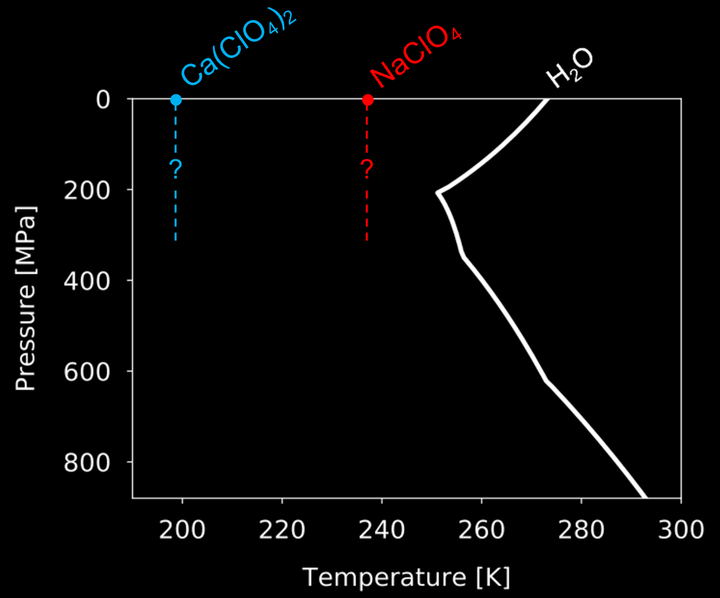
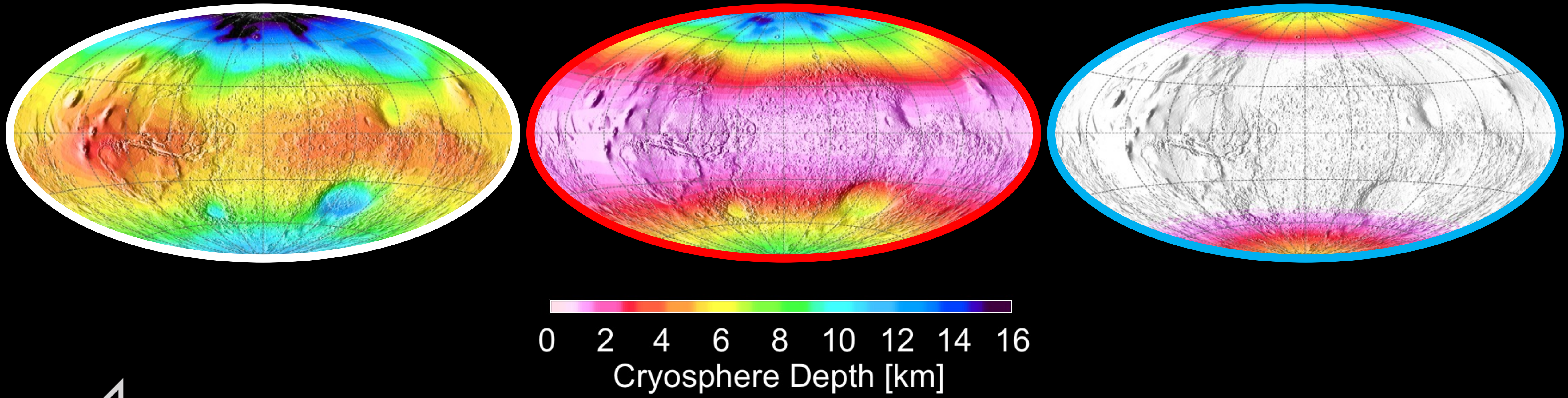
Effects of salts

- The groundwater table shifts closer to the surface if salts (e.g., perchlorates) are present.
- The depth variations of the groundwater table are mainly caused by the surface temperature distribution.





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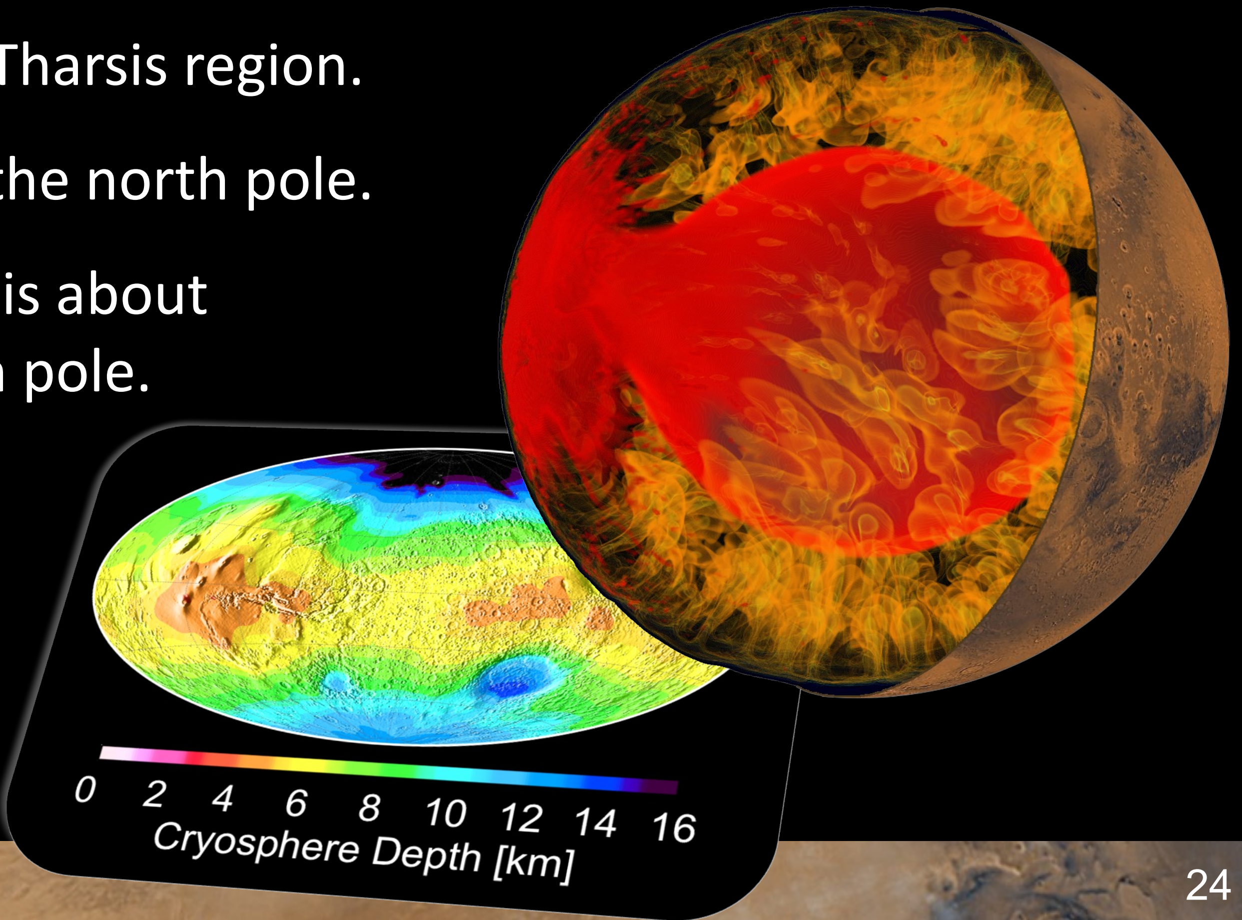
Conclusions: Mars‘ subsurface environment

- **Understanding present-day subsurface conditions of Mars requires the study of its entire evolution.**
- **Cryosphere depth**:
  - Water table lies around 2-5 km depth in Tharsis region.
  - Water table lies around ~20 km close to the north pole.
  - Water table in the northern polar region is about 1.5 times deeper than beneath the south pole.
  - Salts, if in eutectic concentration reduce the depth by 7.5 km on average and up to 13 km locally.



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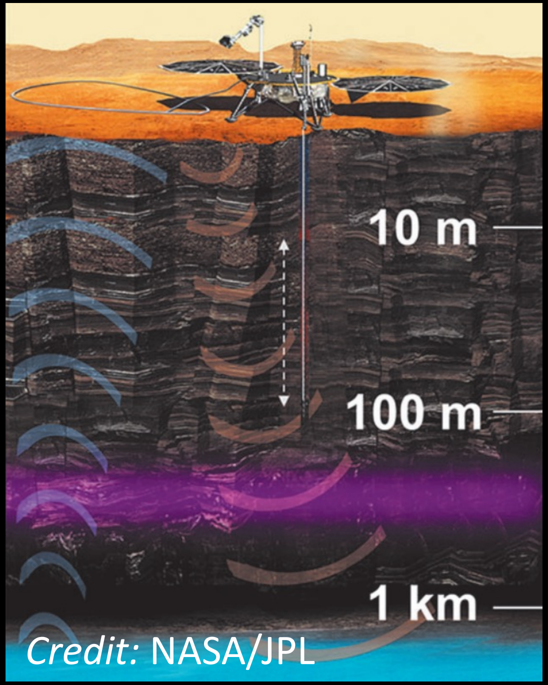
The future of Mars‘ subsurface exploration

- VALKYRIE (Volatiles And Life: KeY Reconnaissance and In situ Exploration) payload concept:
  - a transient electromagnetic sounder capable of detecting the presence of saline liquid to depths of kilometers
  - a drill capable of accessing depths of 10s of meters or more

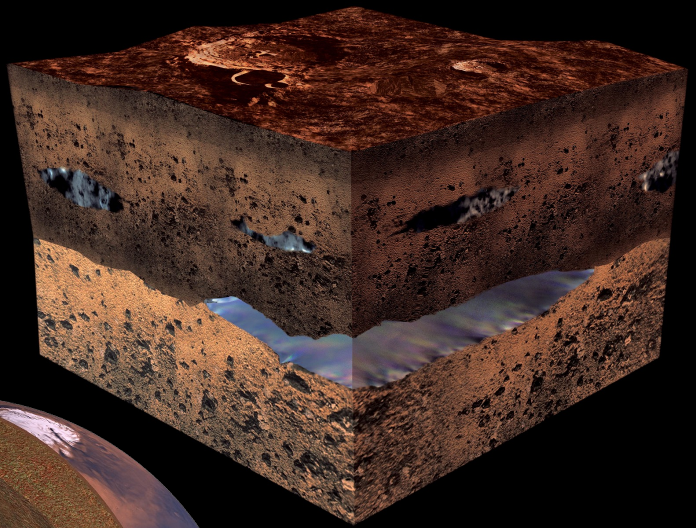


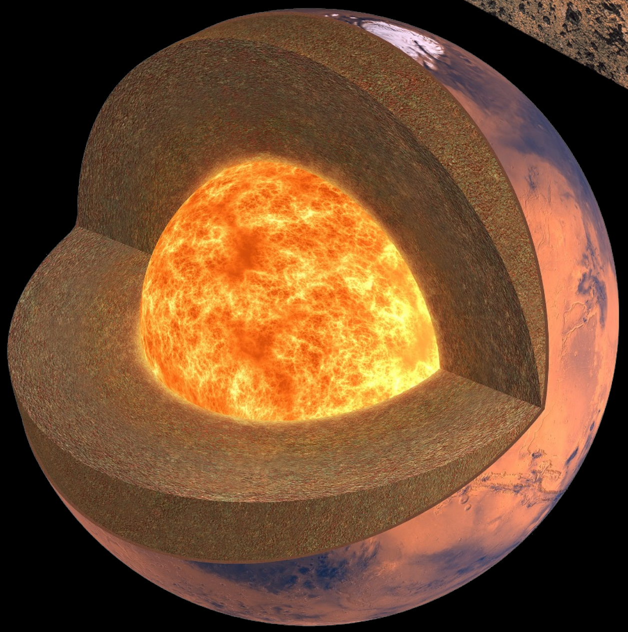
Credit: NASA/JPL

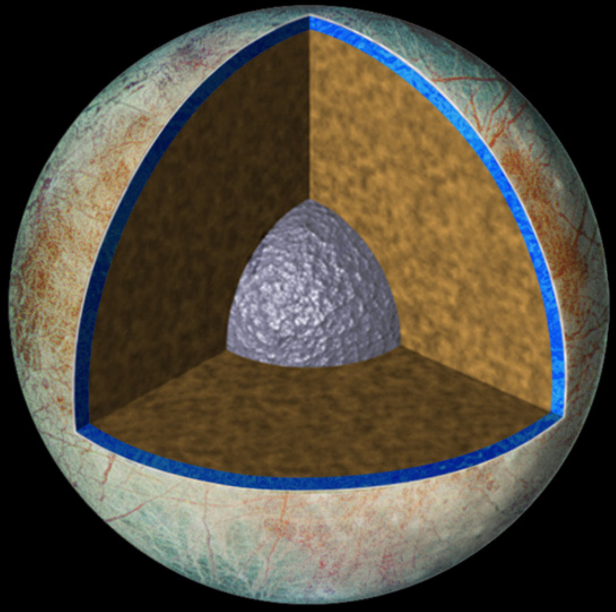
White Papers:

- Stamenkovic et al. ***The Quest for Life Leads Underground: Exploring Modern-Day Subsurface Habitability & Extant Life on Mars***, White Paper ESA Voyage 2050
- Stamenkovic et al. ***DeepTrek: Exploring the Martian Underground***, White Paper in Planetary Science and Astrobiology Decadal Survey 2023 -2032
- Edwards et al. ***Deep Trek: Mission Concepts for Exploring Subsurface Habitability & Life on Mars A Window into Subsurface Life in the Solar System***, White Paper in Planetary Science and Astrobiology Decadal Survey 2023 -2032

The subsurface environments of Mars and Europa







Credits: ESA/Medialab/IPGP/David Ducros/Astronomy/Roen Kelly/NASA/JPL

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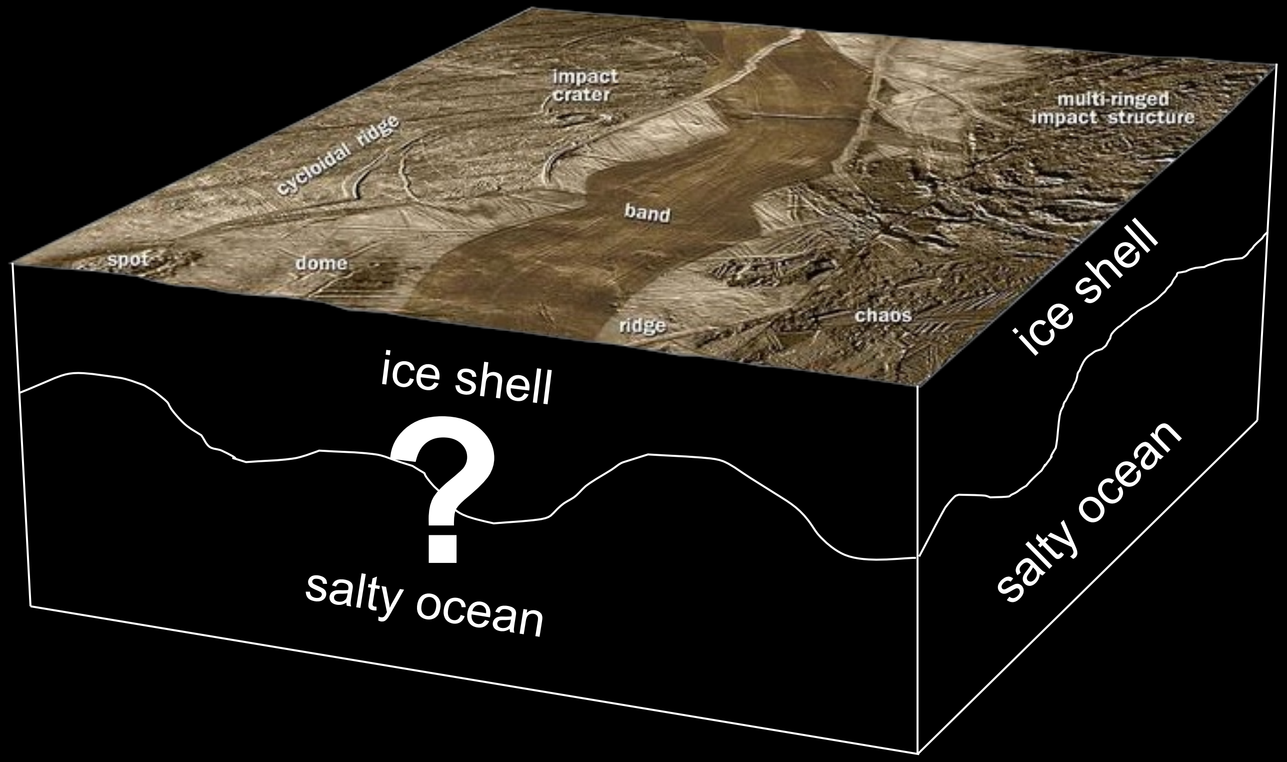
Europa‘s surface and subsurface

- The presence of an ocean underneath an icy shell.
- Variety of geological features at Europa‘s surface hint at processes within the ice shell.
- Both the ocean and at least to some extent the ice shell contain impurities (salts) that may affect the dynamics and hence the surface features.



Credits: modified after NASA/JPL-Caltech

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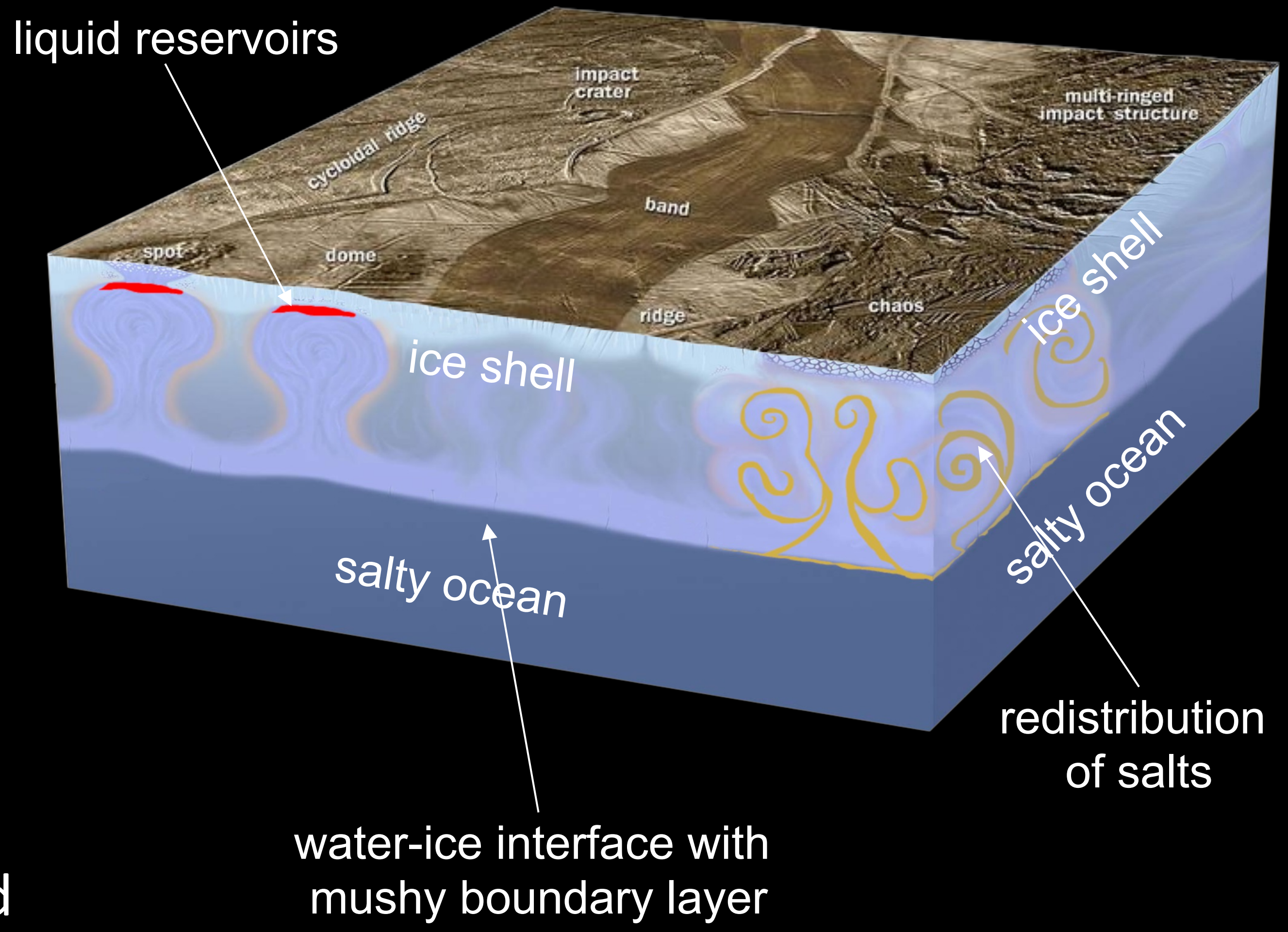

Credits: modified after NASA/JPL-Caltech

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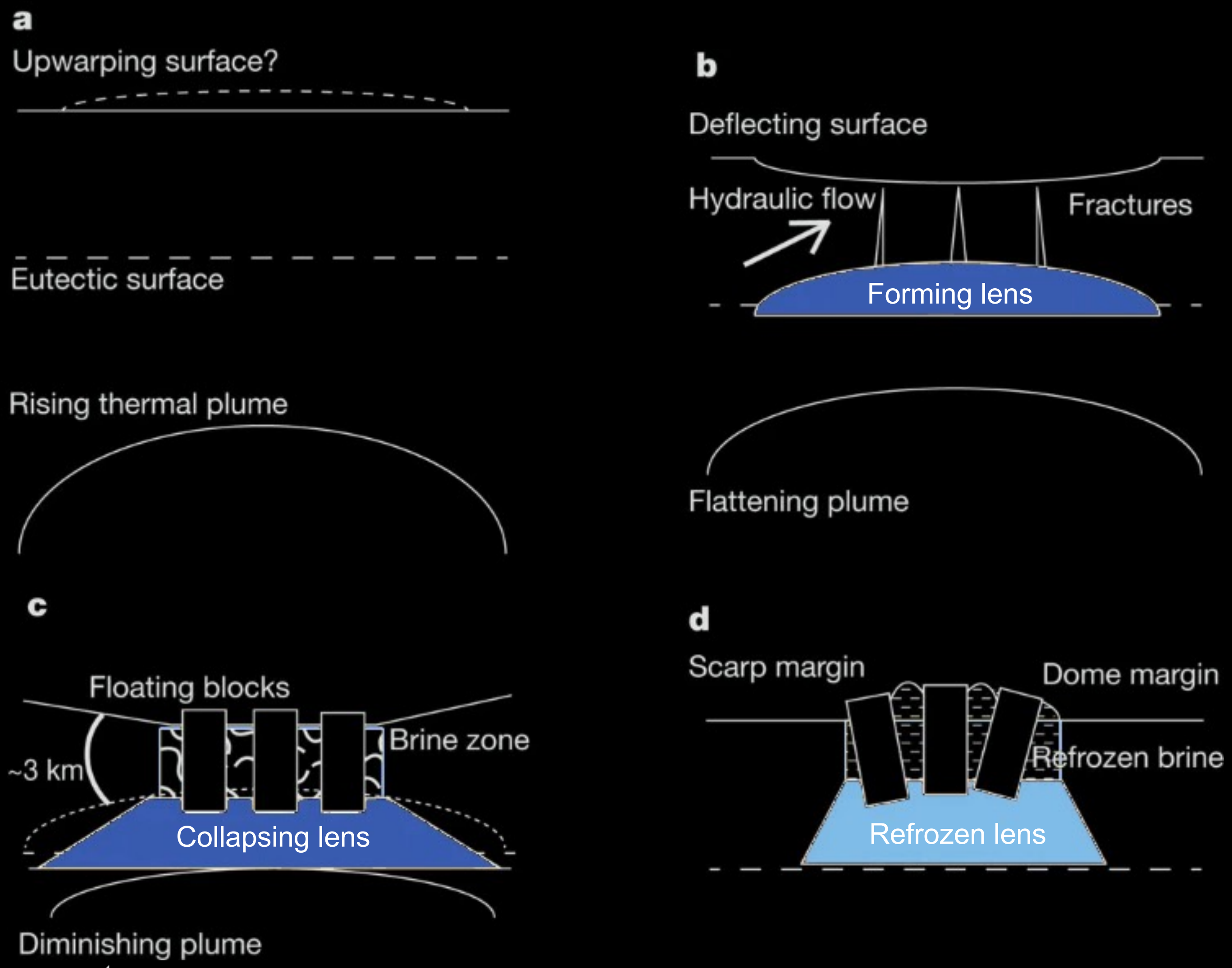
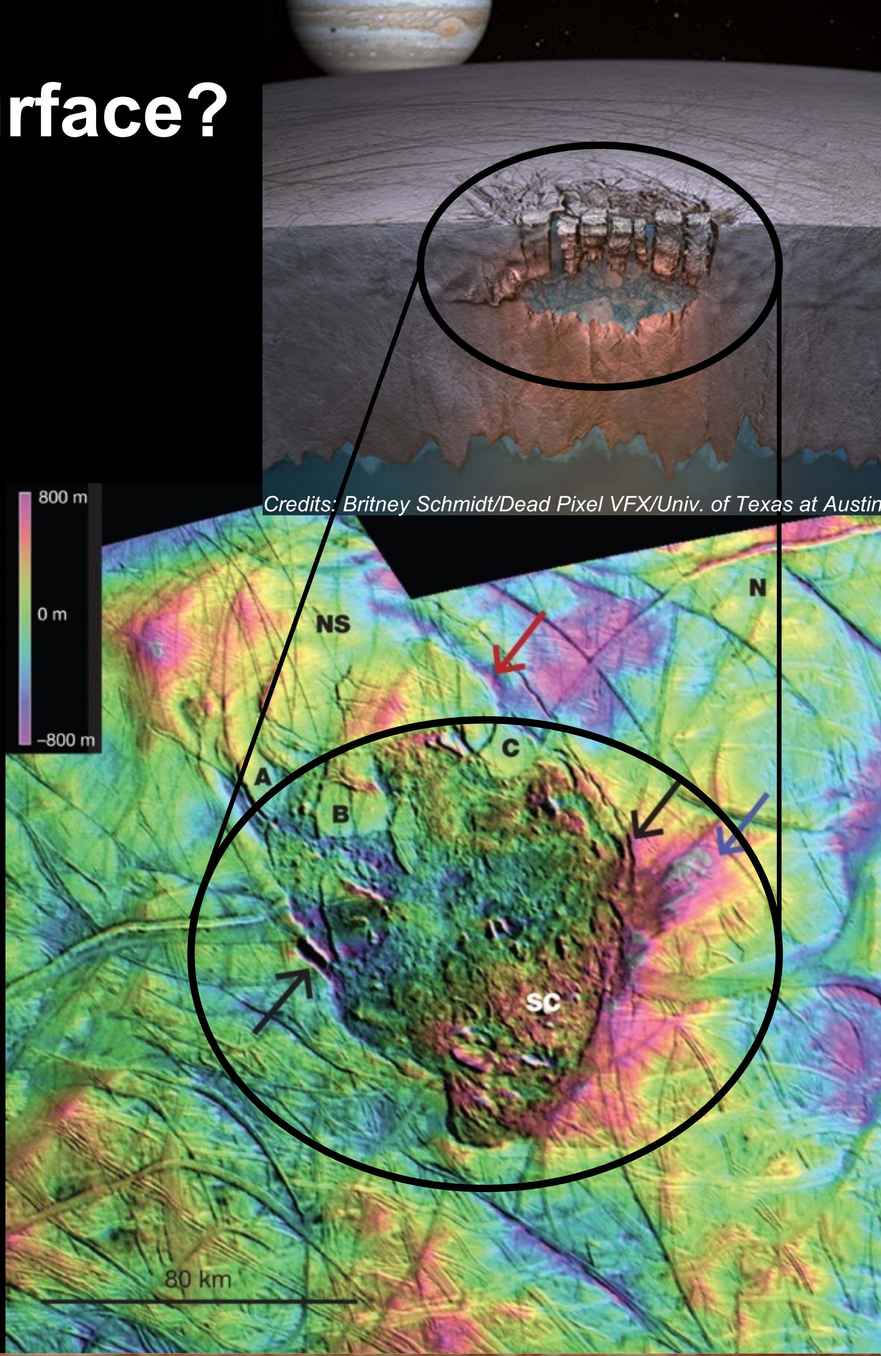
Chaos terrain: liquid reservoirs below the surface?



[Schmidt et al., 2011]



Credits: Britney Schmidt/Dead Pixel VFX/Univ. of Texas at Austin

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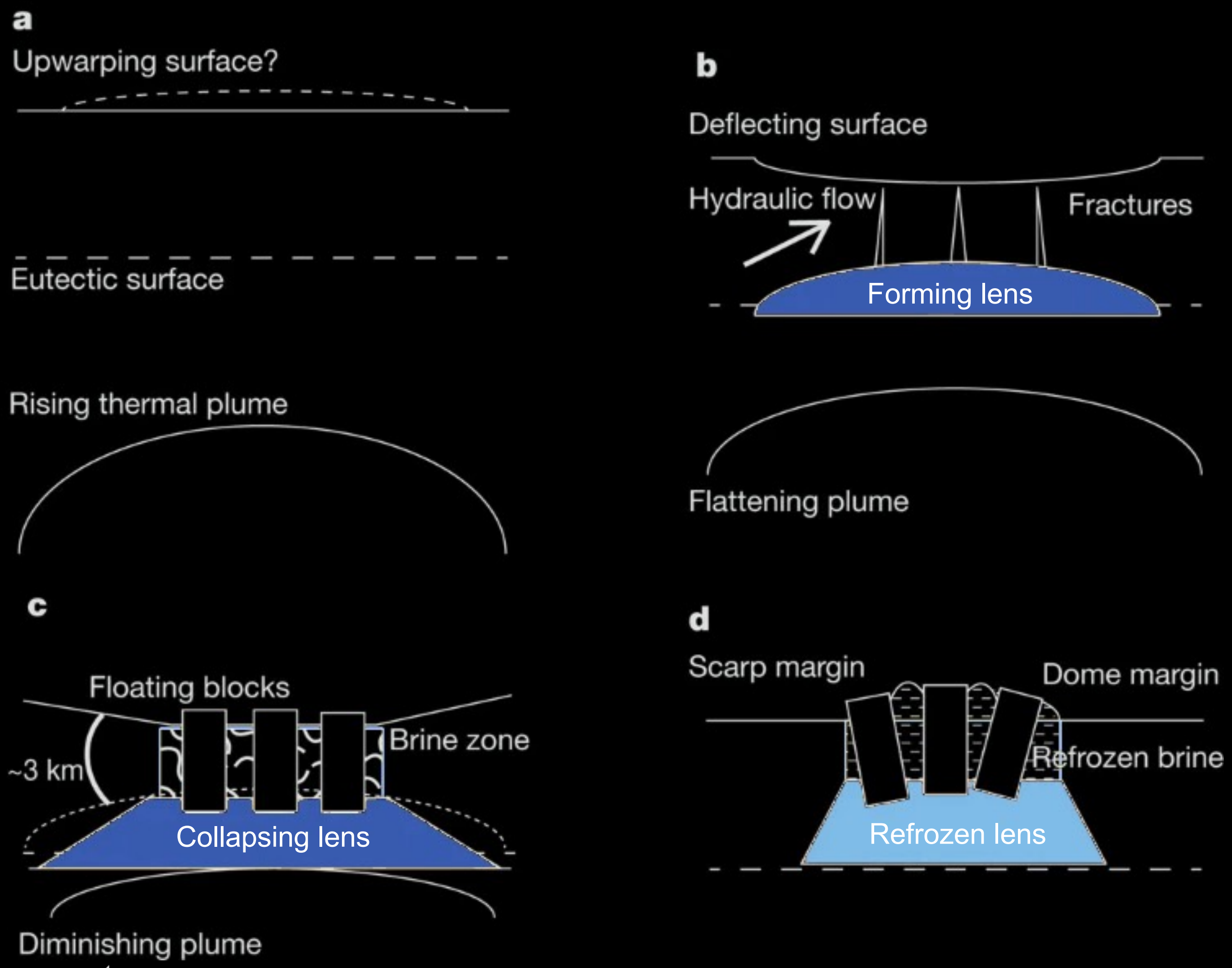

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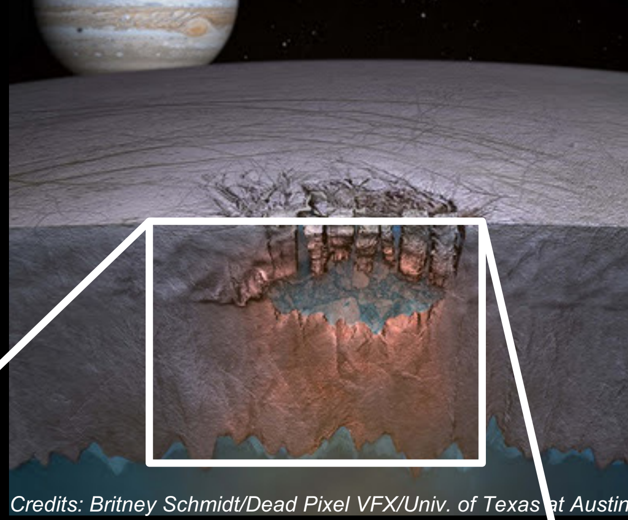
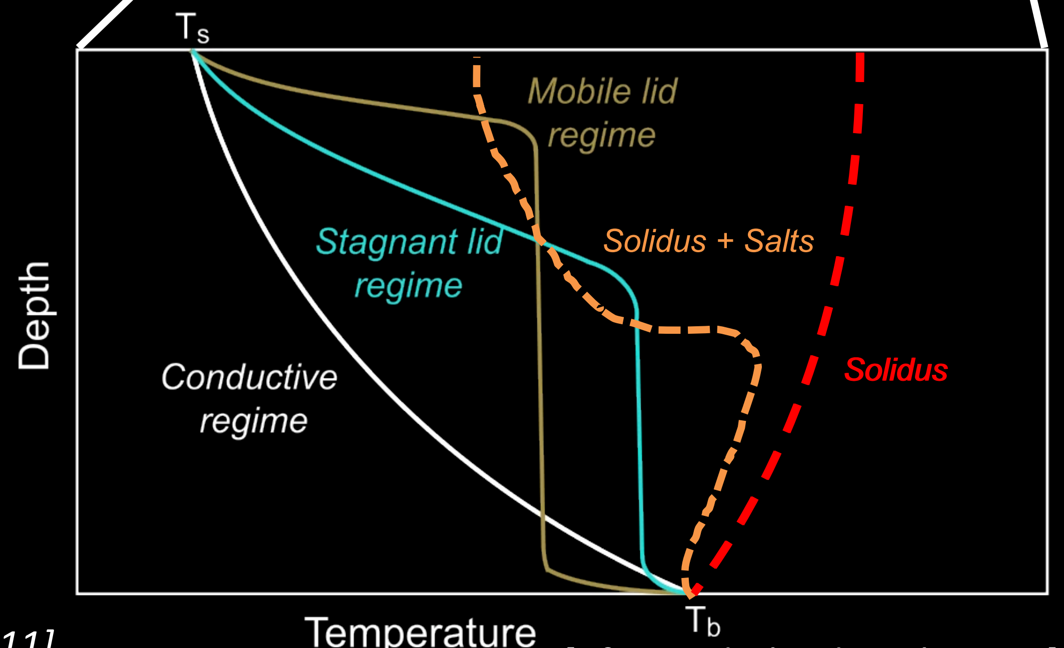




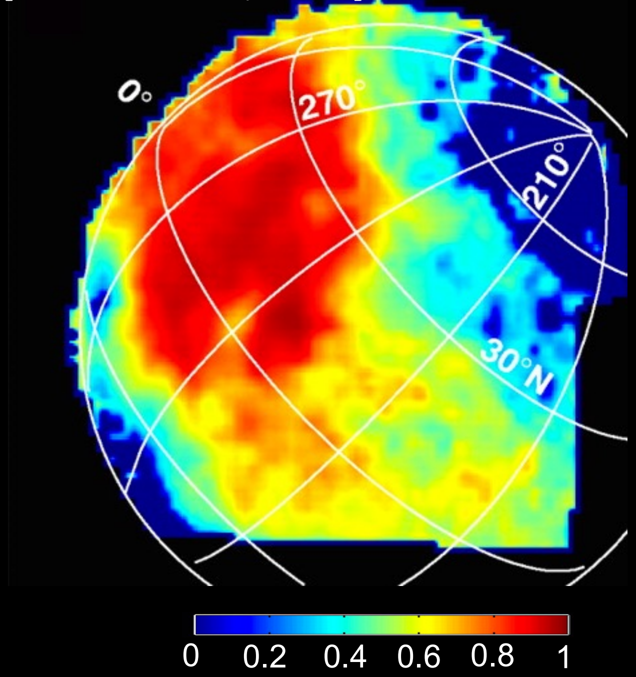
[after Soderlund et al., 2020]

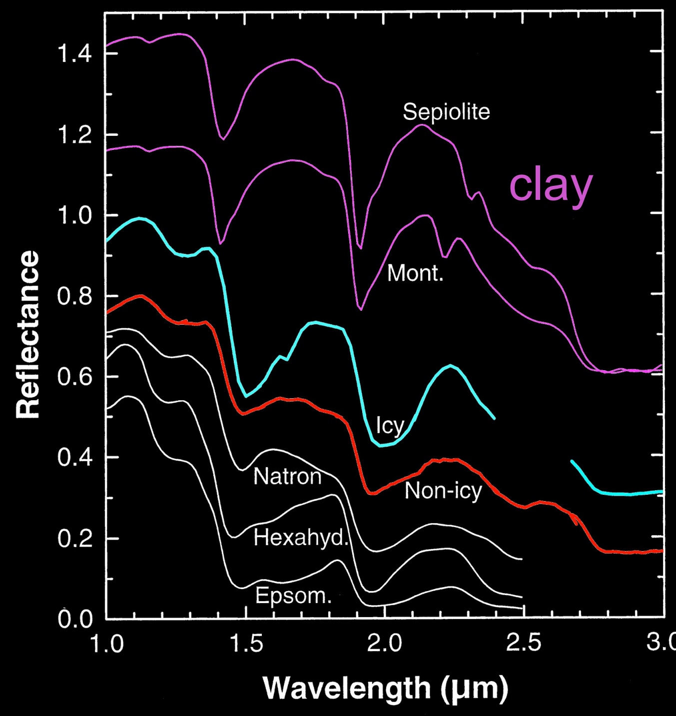
Salts

- Sulfate salts suggested to best explain the spectral signature observed in Galileo NIMS data.

  [e.g., McCord et al. 1998]

[McCord et al., 1998]



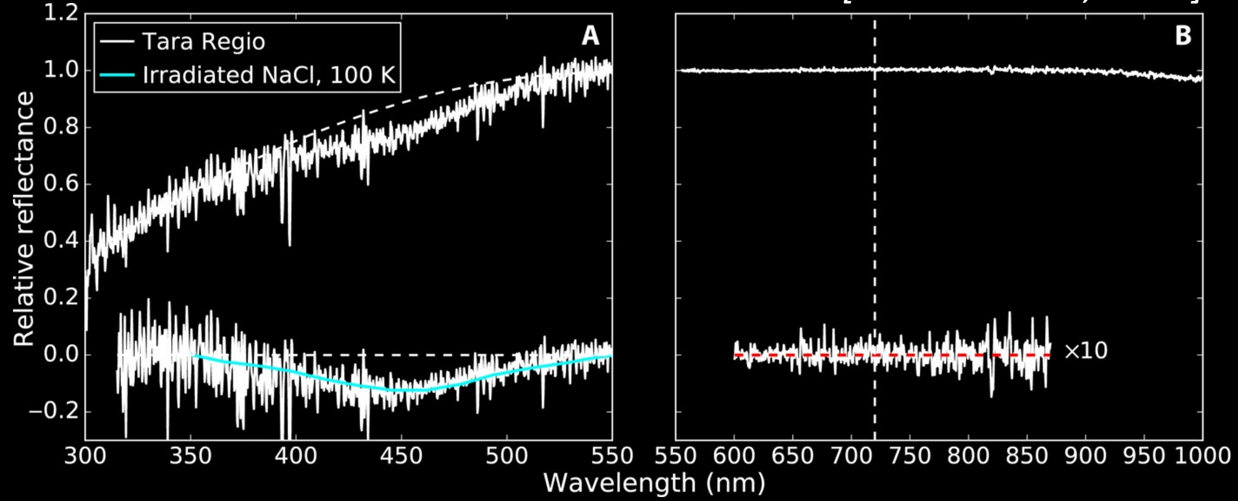


- Iradiated sodium chloride is a best match for higher spectral resolution data from Keck Observatory.

  [Trumbo et al. 2019]

Table salt: NaCl

[Trumbo et al., 2019]



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Salts

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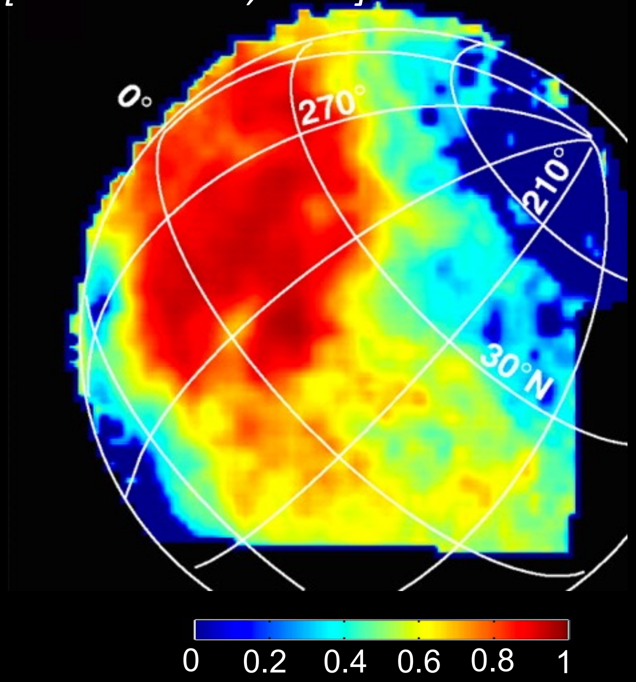
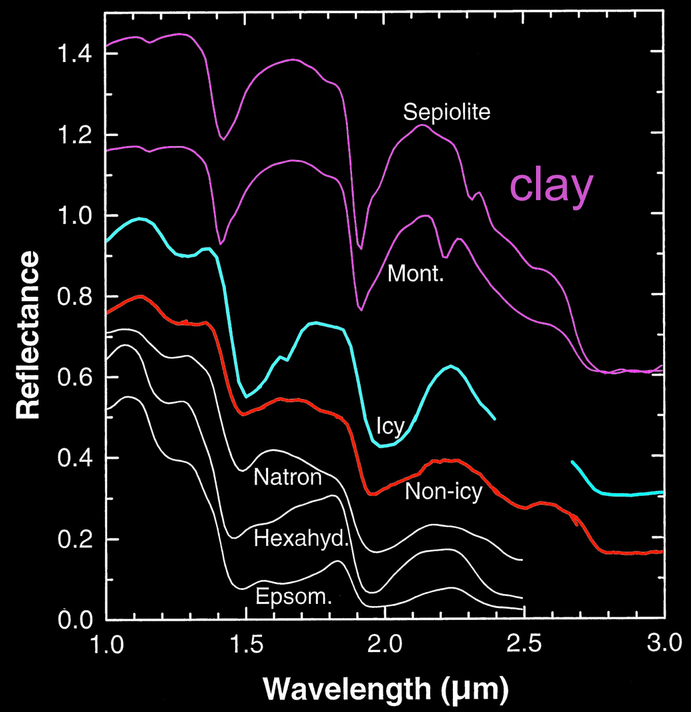
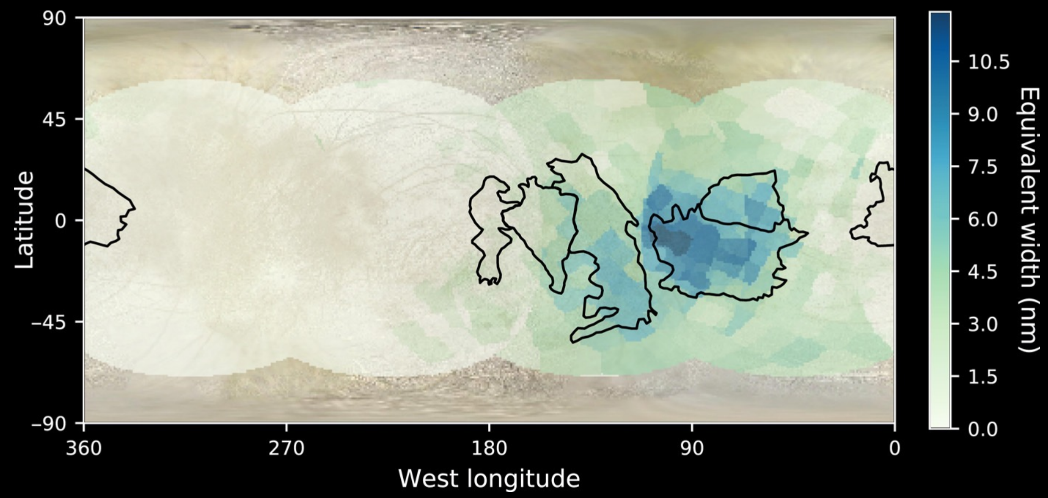
[McCord et al., 1998]





[Trumbo et al., 2019]



Initial distribution of salts

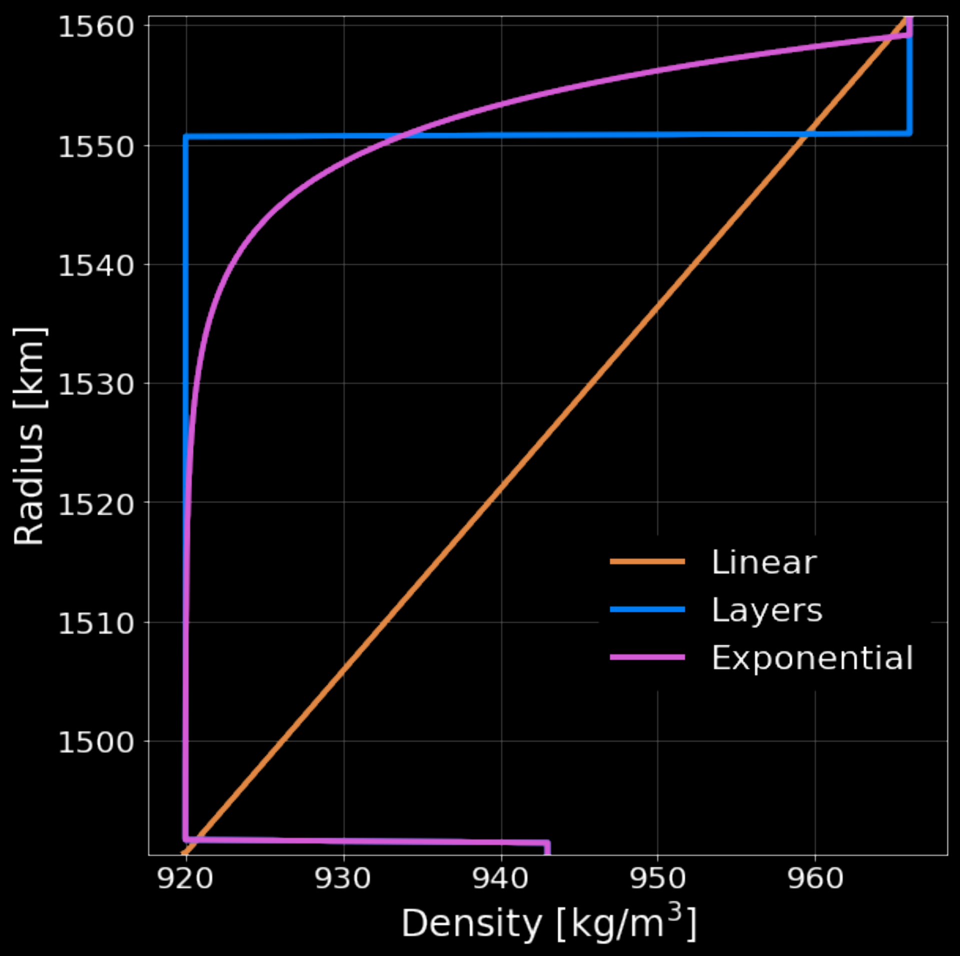
Fast freezing scenario:

- salts are incorporated throughout the ice shell

Initially fast freezing & subsequent moderate freezing rate:

- salts are incorporated mostly during the initial freezing stage
- briny layer may be present at the ice-ocean interface

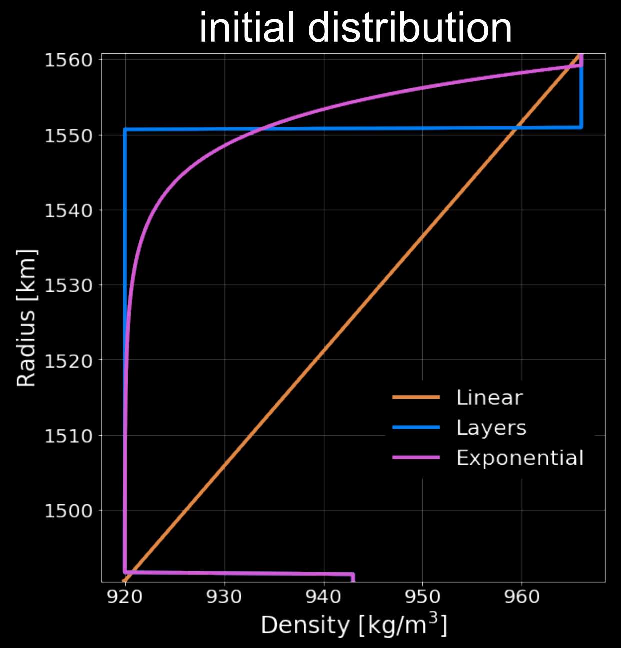
Investigate mixing and spatial distribution of salts in Europa's ice shell using geodynamical models

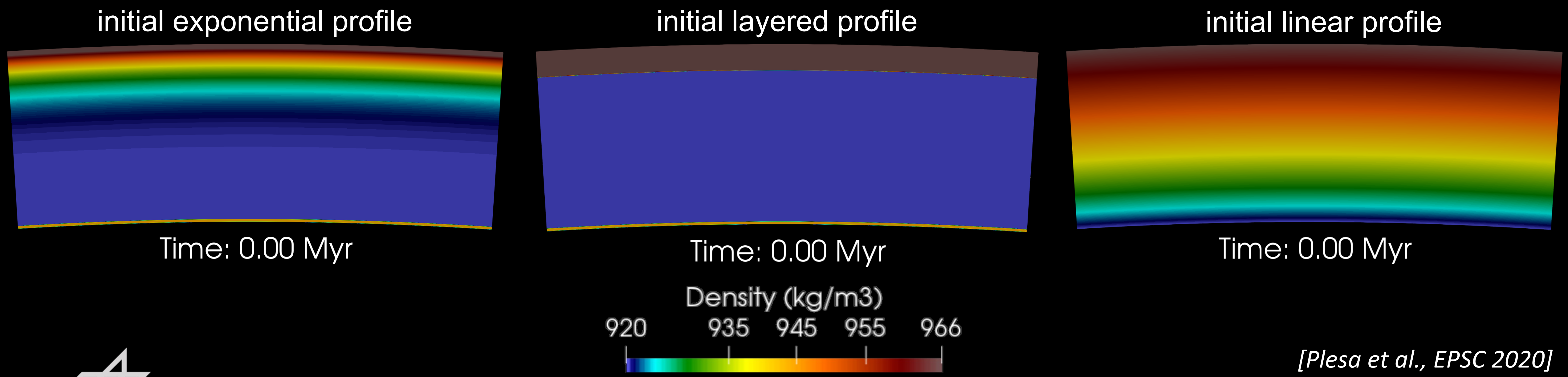


[Plesa et al., EPSC 2020]

Salt redistribution within the ice shell

- Initial unstable density profile due to the salt distribution throughout the ice shell.
- Highest salt concentration located close to the surface.
- Briny layer at the ice-ocean interface



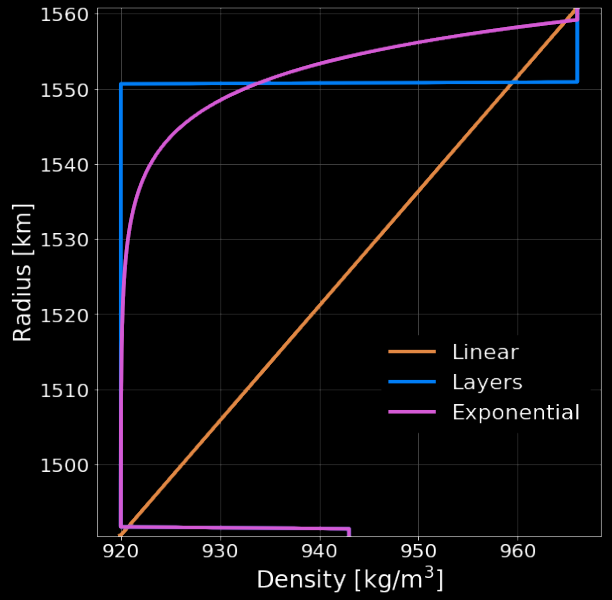


[Plesa et al., EPSC 2020]

DLR

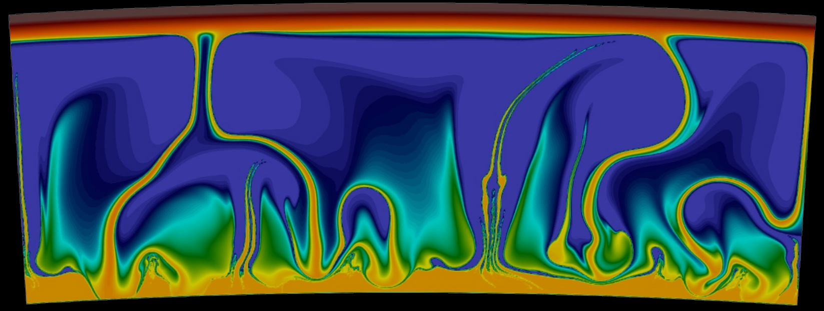
Salt redistribution within the ice shell

initial distribution



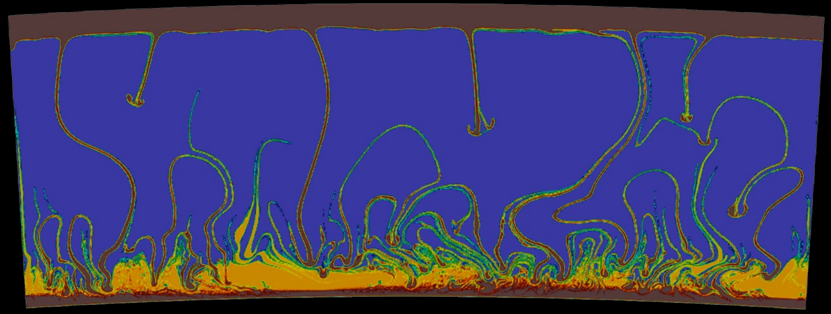
- Overturn of the initially unstable density profile.
- High salt concentrations are transported toward the ice-ocean interface
- Highest salt concentrations are trapped in the stagnant lid (immobile layer that forms due to high viscosity)

initial exponential profile



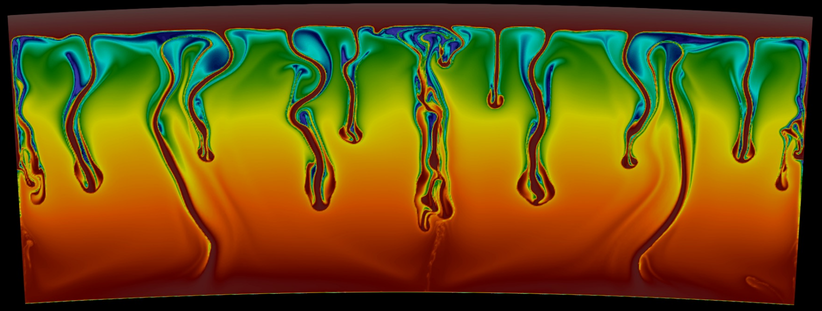
Time: 0.05 Myr

initial layered profile



Time: 0.05 Myr

initial linear profile



Time: 0.05 Myr

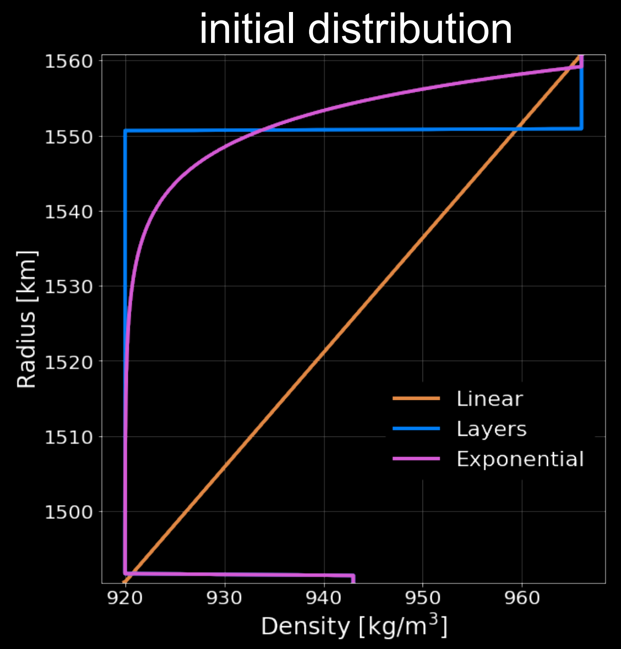
Density (kg/m3)

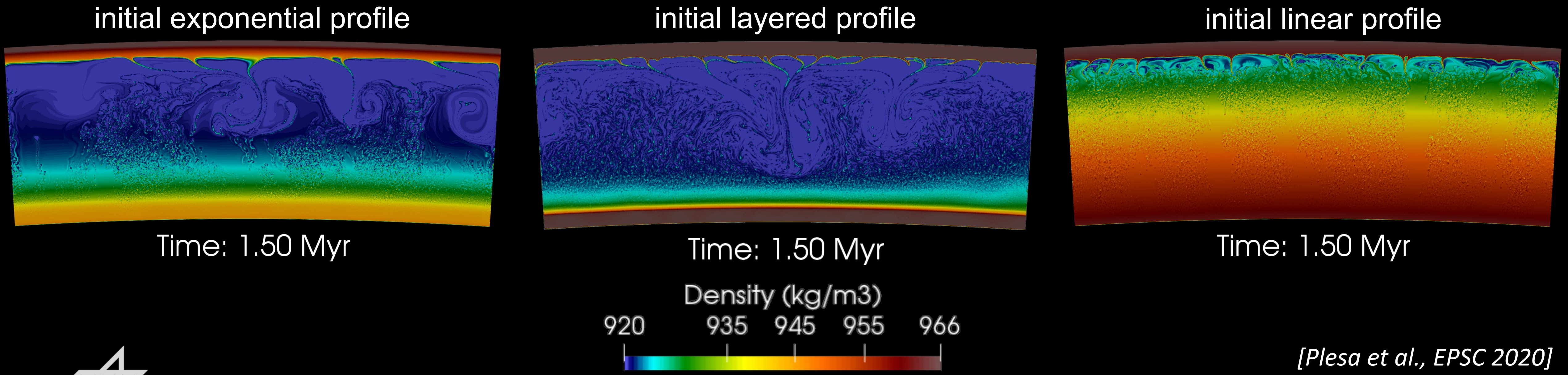
[Plesa et al., EPSC 2020]

DLR

Salt redistribution within the ice shell

- Overturn of the initially unstable density profile.
- High salt concentrations are transported toward the ice-ocean interface
- Highest salt concentrations are trapped in the stagnant lid (immobile layer that forms due to high viscosity)





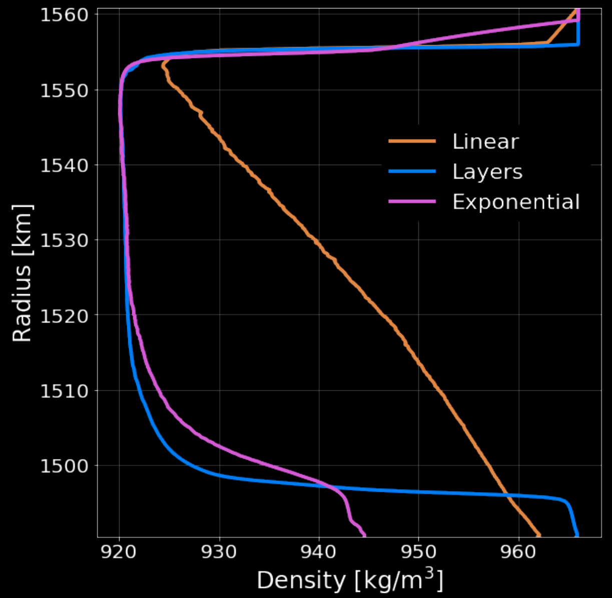
[Plesa et al., EPSC 2020]

DLR

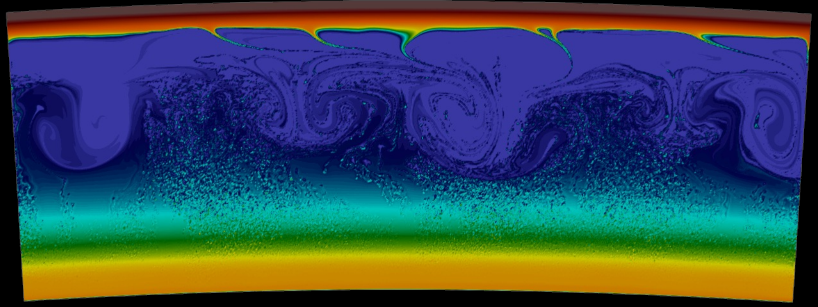
Salt redistribution within the ice shell

- Stable configuration after overturn.
- Highest salt concentrations remain trapped in the stagnant lid (immobile layer that forms due to high viscosity).
- In part salts can become mixed in the ice shell, apart from the initial linear salt distribution.

final distribution

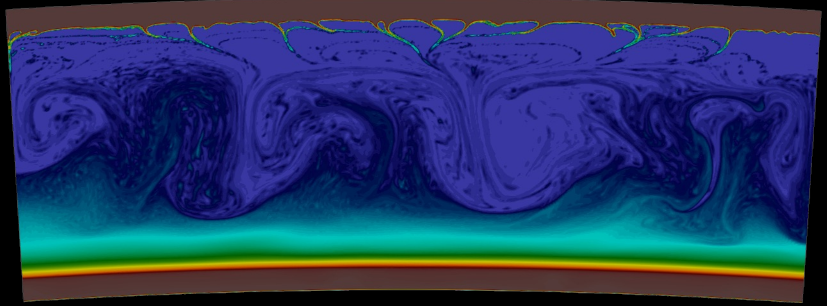


initial exponential profile



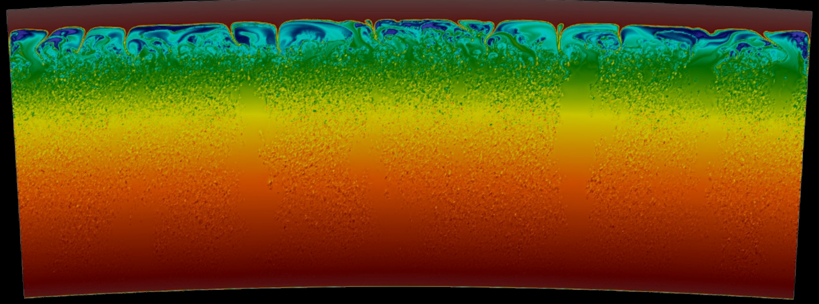
Time: 2.50 Myr

initial layered profile



Time: 2.50 Myr

initial linear profile



Time: 2.50 Myr

[Plesa et al., EPSC 2020]

DLR

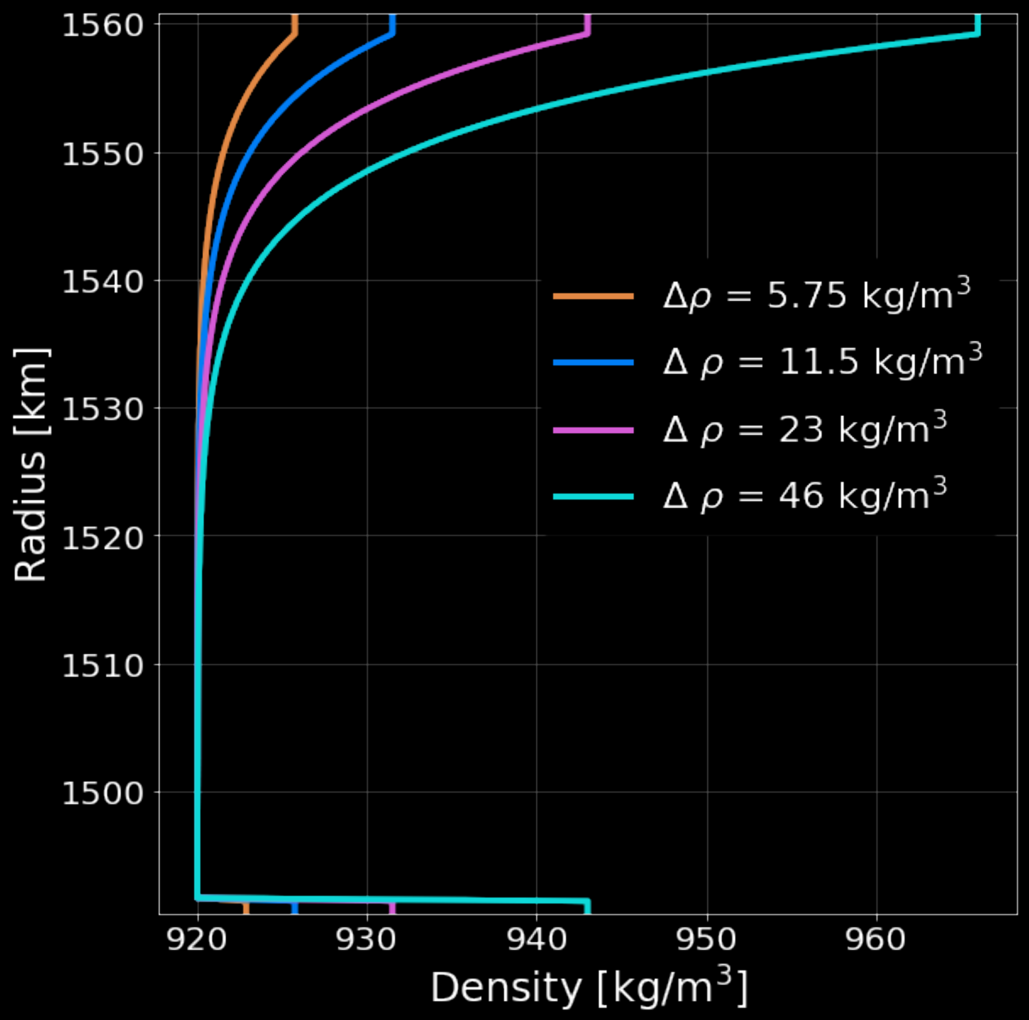
Initial amount of salts within the ice shell

- Density contrasts between salty components and pure water ice in the range of 5.75 – 46 kg/m^3 correspond to 0.6% - 5% compositional density variations due to salinity.

  [Han & Showman, 2004]

- Initial distribution assuming an initial fast freezing rate and subsequently a moderate-slow freezing rate.

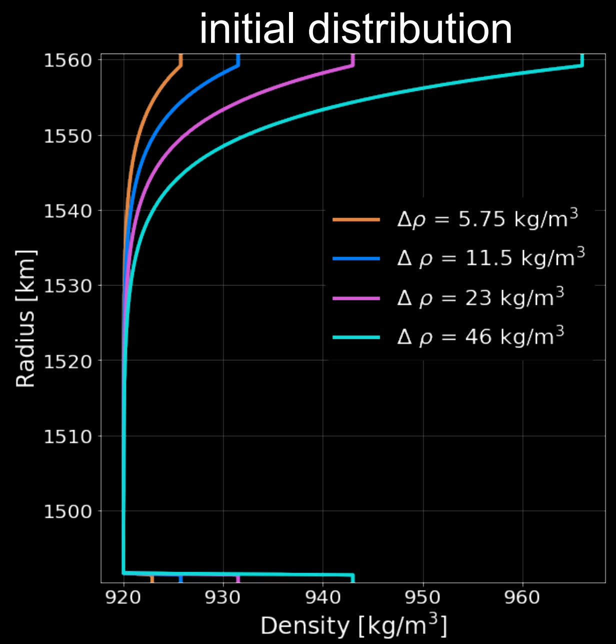
- Briny layer assumed at the ice-ocean interface.



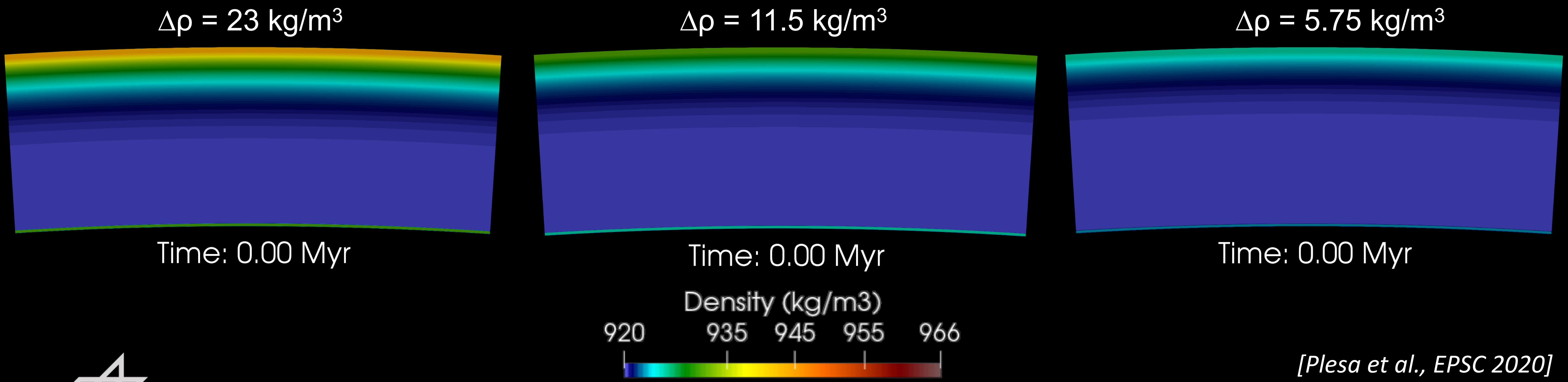
[Plesa et al., EPSC 2020]

DLR

Salt redistribution within the ice shell



- Initial unstable density profile due to the salt distribution throughout the ice shell.
- Highest salt concentration located close to the surface.
- Briny layer at the ice-ocean interface

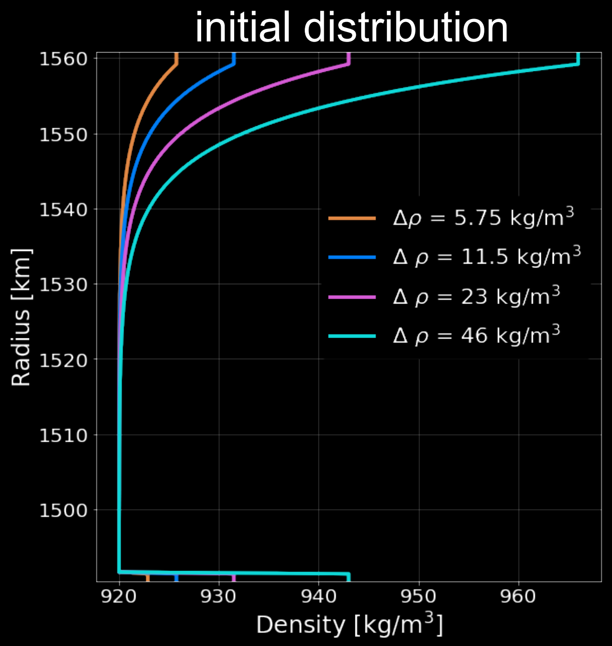


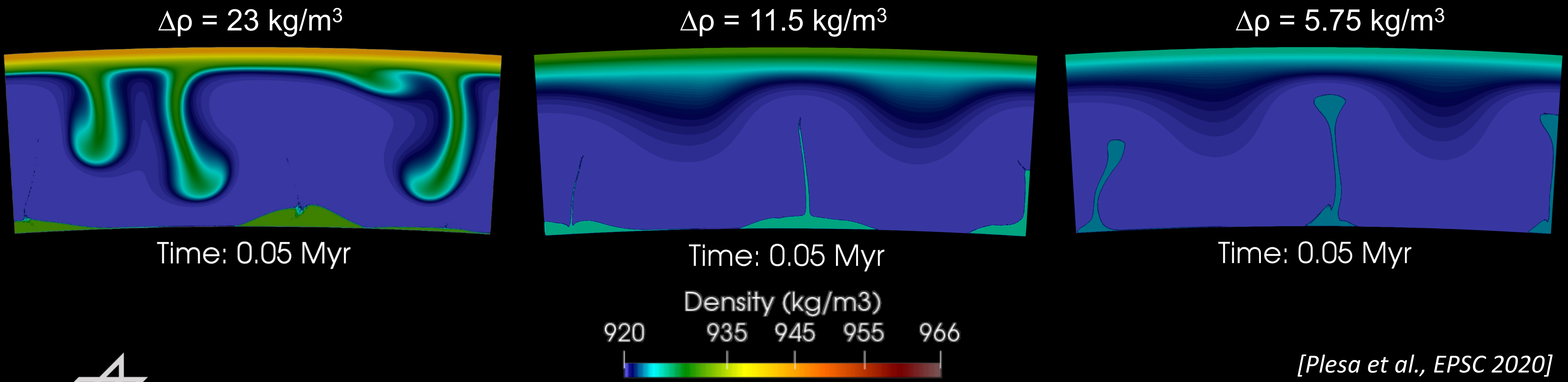
[Plesa et al., EPSC 2020]

DLR

Salt redistribution within the ice shell

- Overturn of the initially unstable density profile.
- High salt concentrations are transported toward the ice-ocean interface
- Highest salt concentrations are trapped in the stagnant lid (immobile layer that forms due to high viscosity)

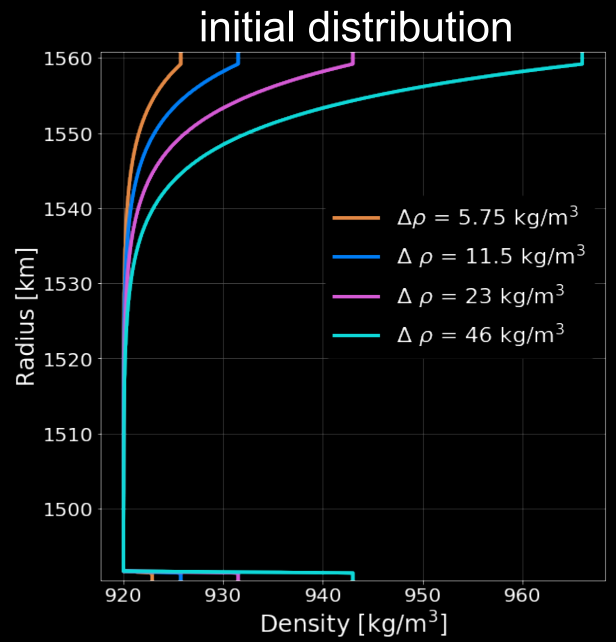




[Plesa et al., EPSC 2020]

DLR

Salt redistribution within the ice shell



- Overturn of the initially unstable density profile.
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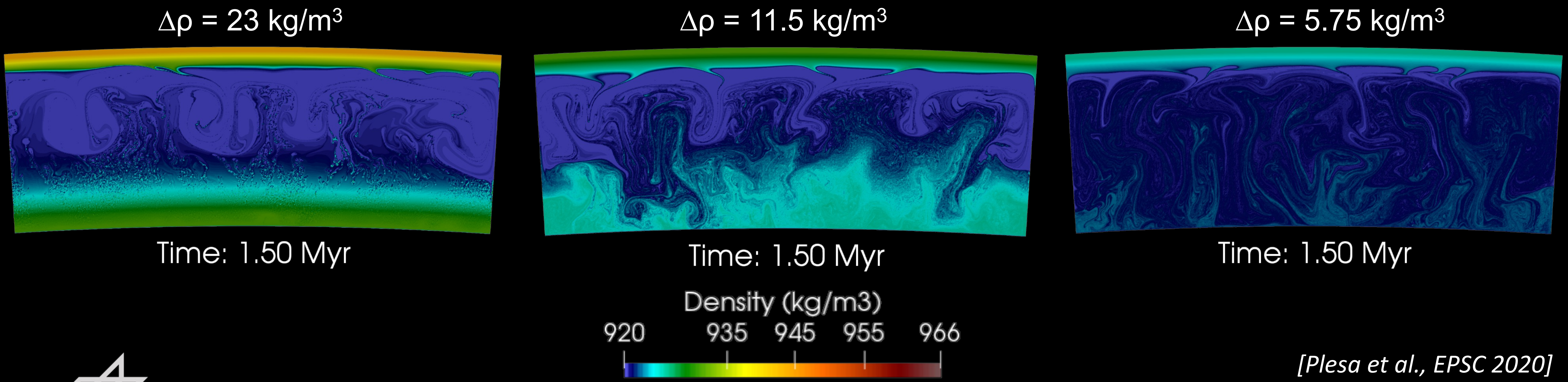
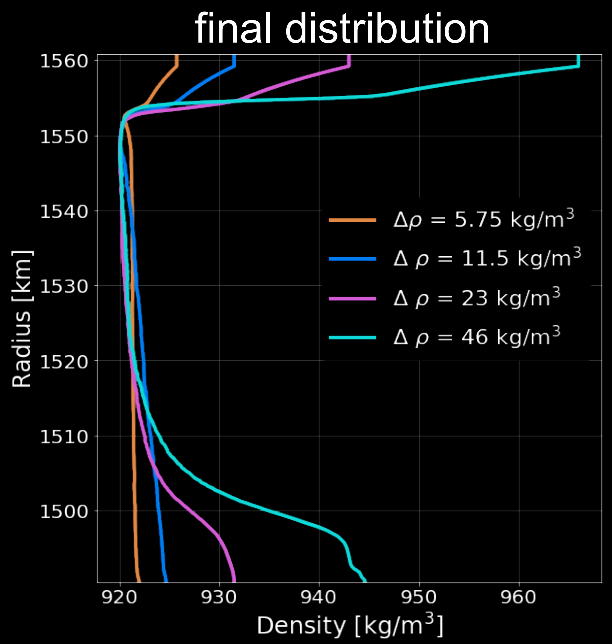


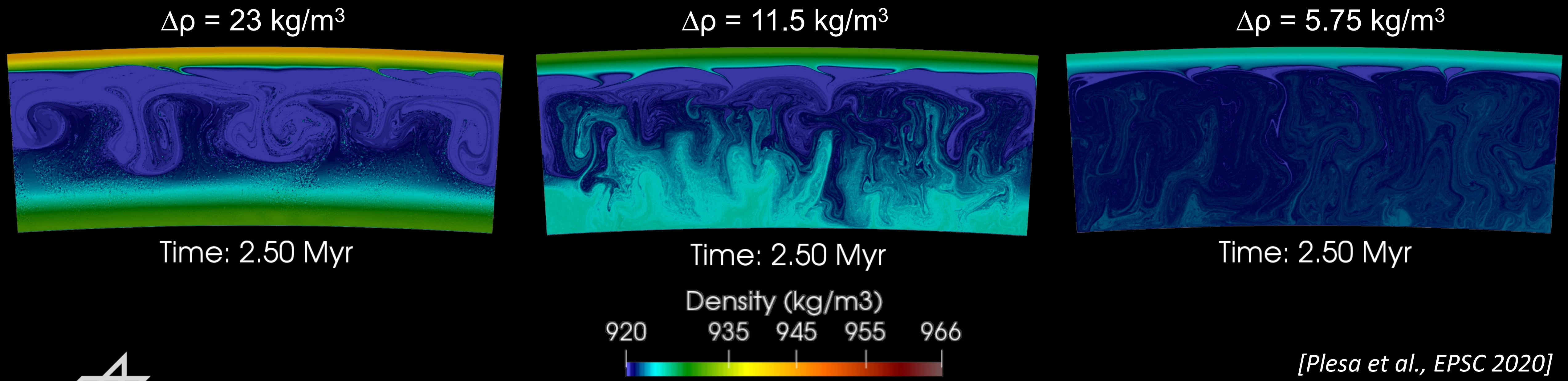
[Plesa et al., EPSC 2020]

DLR

Salt redistribution within the ice shell



- Stable configuration after overturn with large scale mixing for salt concentrations lower than 2.5% density variations due to salinity.
- Highest salt concentrations remain trapped in the stagnant lid (immobile layer that forms due to high viscosity).

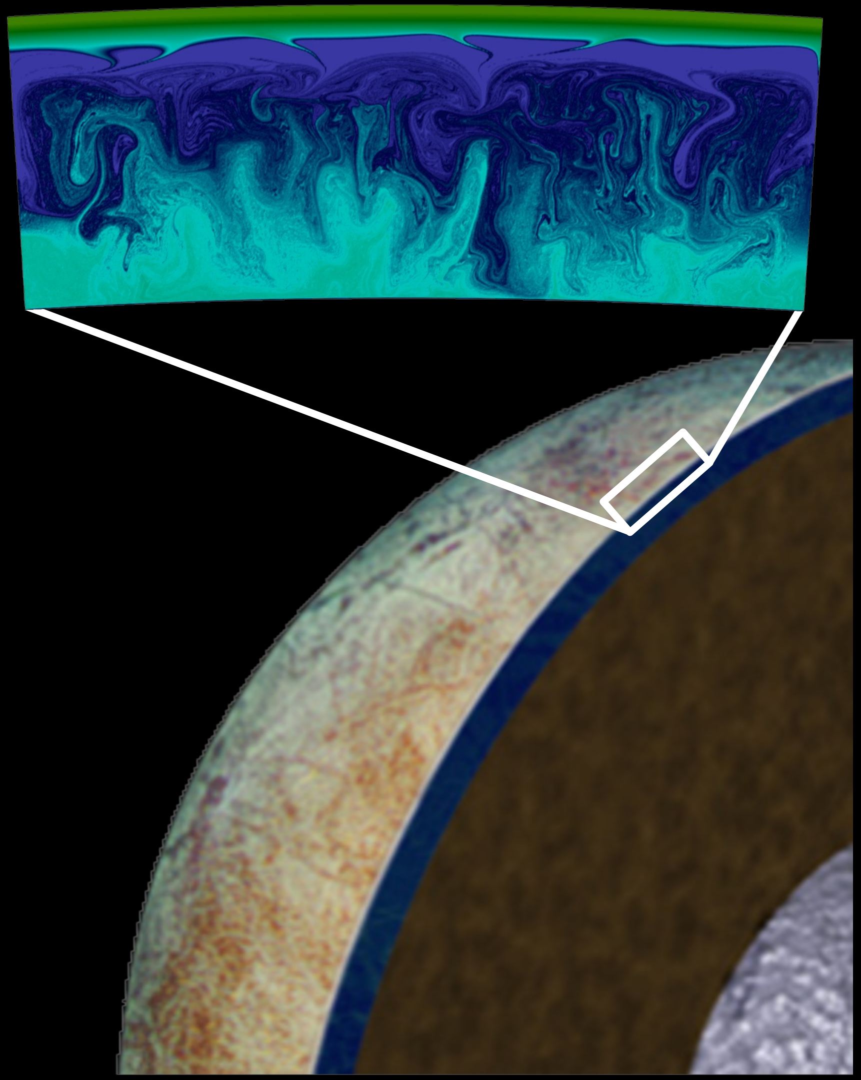


[Plesa et al., EPSC 2020]

DLR

Conclusions: Europa‘s subsurface environment

- In the initial linear distribution with $\Delta\rho = 46\ kg/m^3$ (5% density variations due to salinity) the ice shell becomes conductive with a stable salinity stratification.
- In all other scenarios some degree of mixing takes place, with salts being transported through the ice shell.
- Most of the salty components remain trapped in a stagnant lid close to the surface. Plume induced melting of this heterogeneous layer may lead to the formation of chaos terrain (Schmidt et al., 2001).

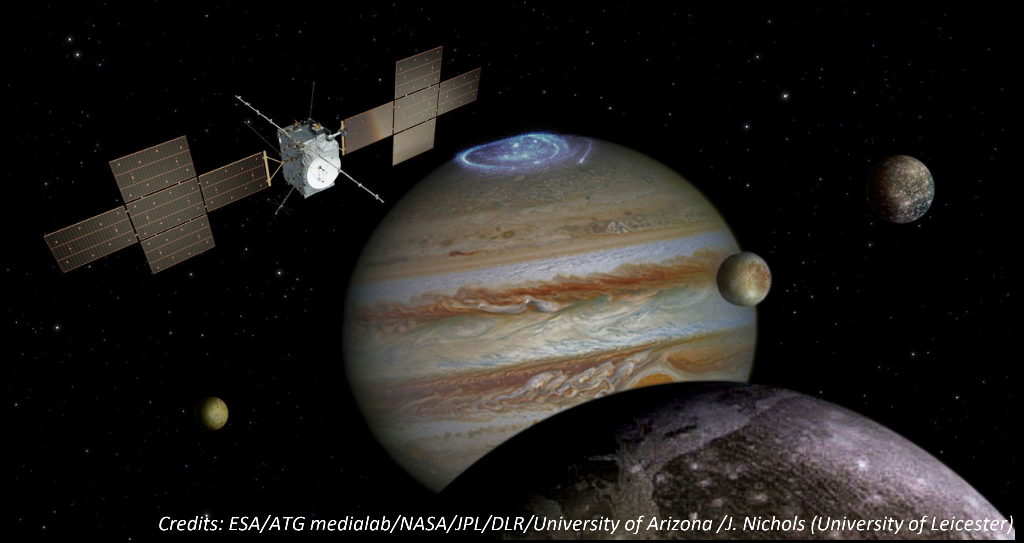


DLR

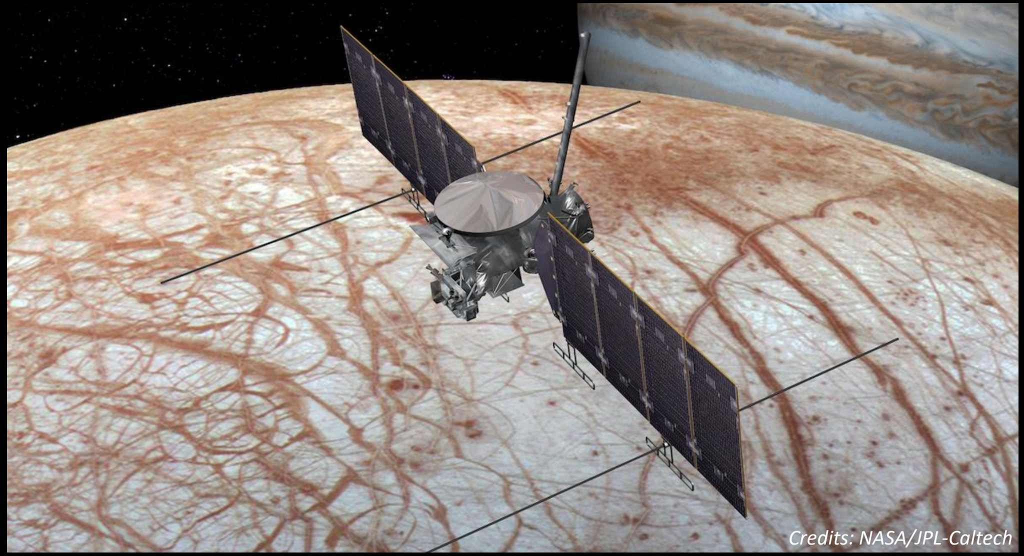
The future subsurface exploration of Europa

- JUICE
  - Mission to the Jupiter system
  - Characterize, Jupiter, Ganymede, Europa, and Callisto
  - 2 Europa flybys, altitude: 400km
  - Launch: 14. April 2023
  - Arrival at Jupiter-system: 2031
  - Orbit around Ganymede: 2034

- Europa Clipper
  - Dedicated mission to Europa
  - Characterize Europa‘s habitability
  - Nearly 50 Europa flybys, altitudes as low as 25 km
  - Most flybys at altitudes below 100 km
  - Launch: 10. October 2024
  - Arrival at Europa: 2030



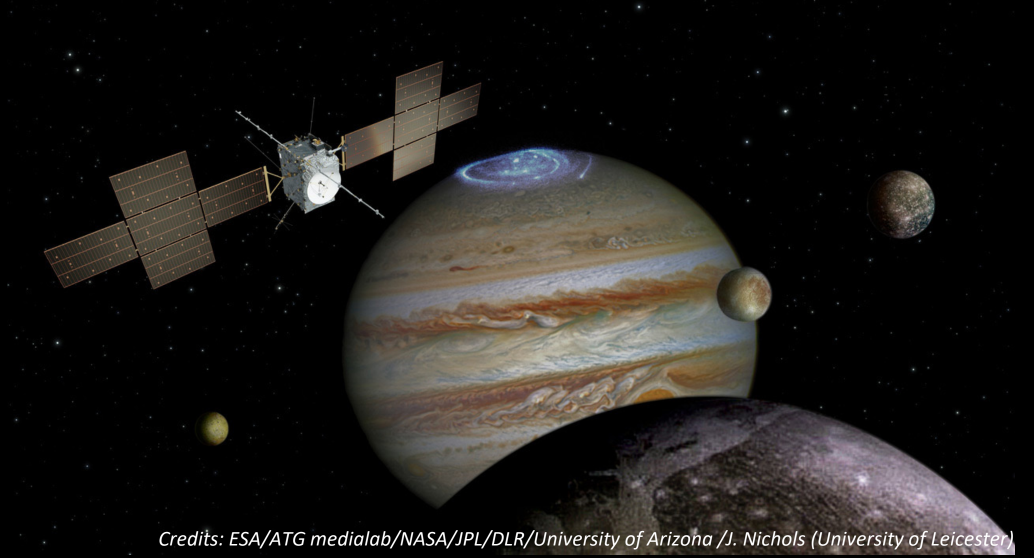
Credits: ESA/ATG medialab/NASA/JPL/DLR/University of Arizona /J. Nichols (University of Leicester)



Credits: NASA/JPL-Caltech

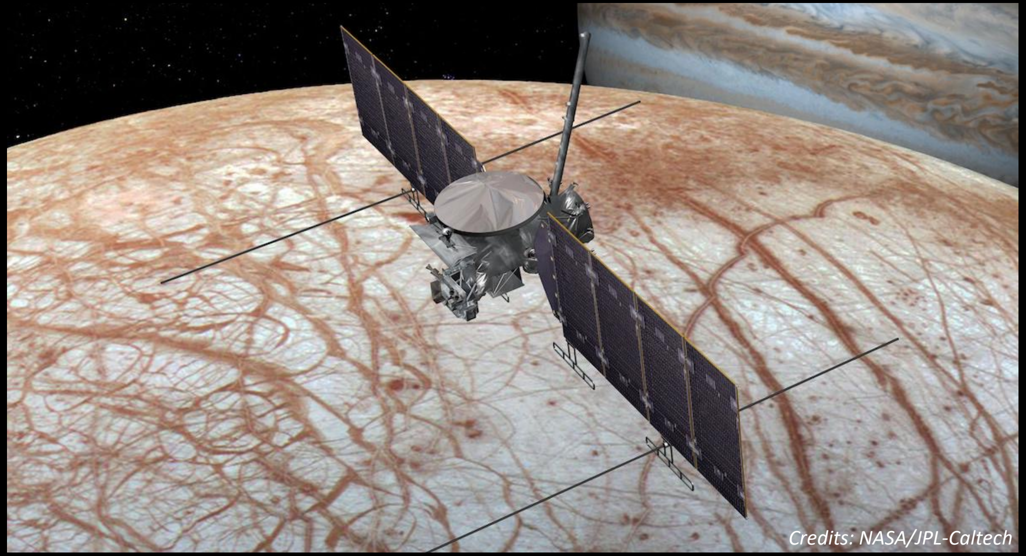
The future subsurface exploration of Europa

- JUICE @ Europa
  - Determine the composition of the non-ice material on the surface, with a focus on substances that relate to potential habitability of the subsurface ocean
  - Search for liquid water below the surface
  - Study the active processes



Credits: ESA/ATG medialab/NASA/JPL/DLR/University of Arizona /J. Nichols (University of Leicester)

- Europa Clipper
  - Characterize the ice shell and any subsurface water
  - Understand the habitability of Europa's ocean through composition and chemistry
  - Understand the formation of surface features, current activity, and characterize high science interest localities



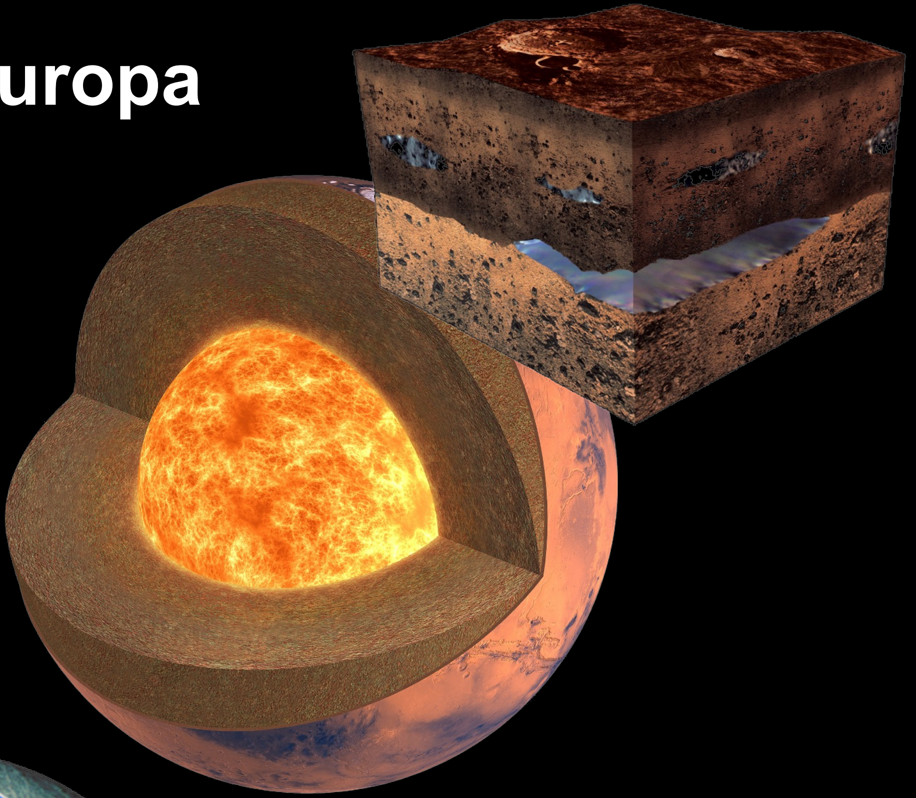
Credits: NASA/JPL-Caltech

DLR

Conclusions: the subsurface of Mars and Europa

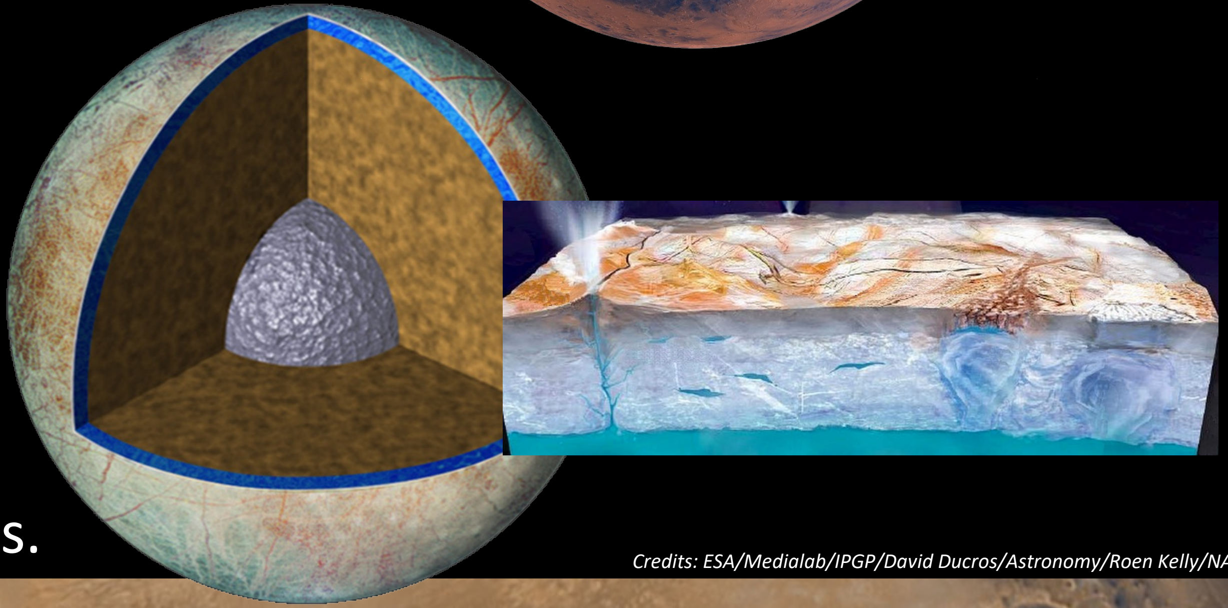
Mars:

- Groundwater table varies significantly across the planet.
- Salts, if in eutectic concentration have a large effect, reducing the groundwater depth by several km.



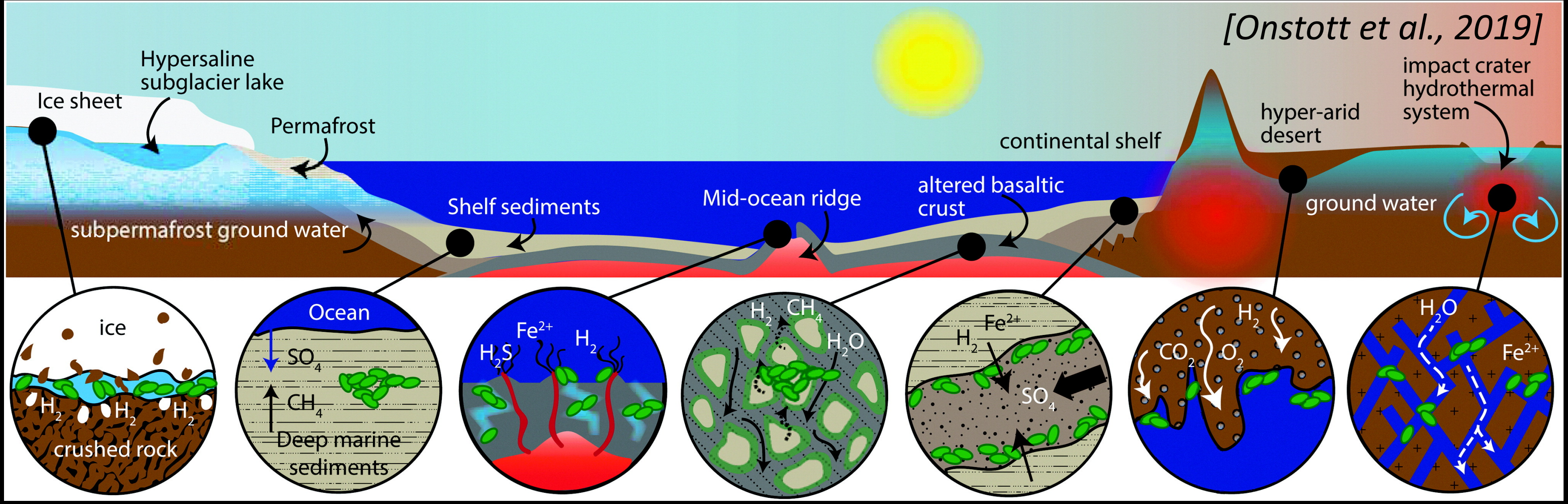
Europa:

- If salts are present in the ice shell, some degree of mixing takes place.
- Plume induced melting of a salty layer trapped in the stagnant lid may lead to the formation of chaos terrain, as suggested in previuos works.

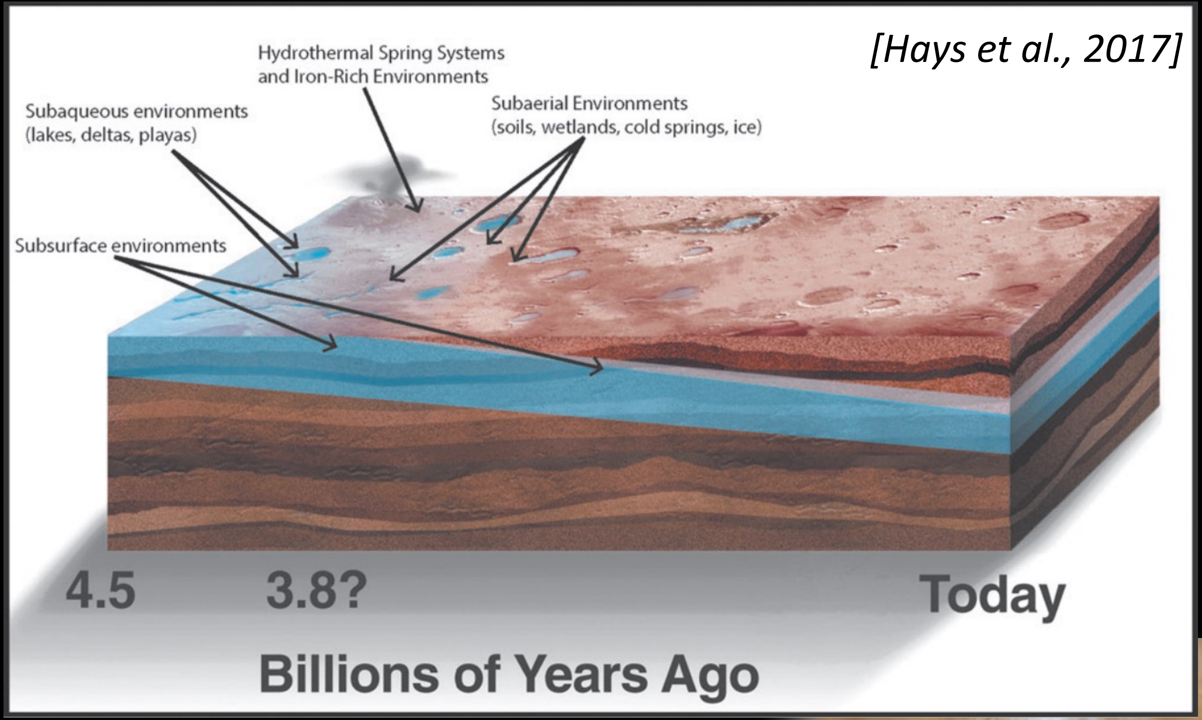


Credits: ESA/Medialab/IPGP/David Ducros/Astronomy/Roen Kelly/NASA/JPL

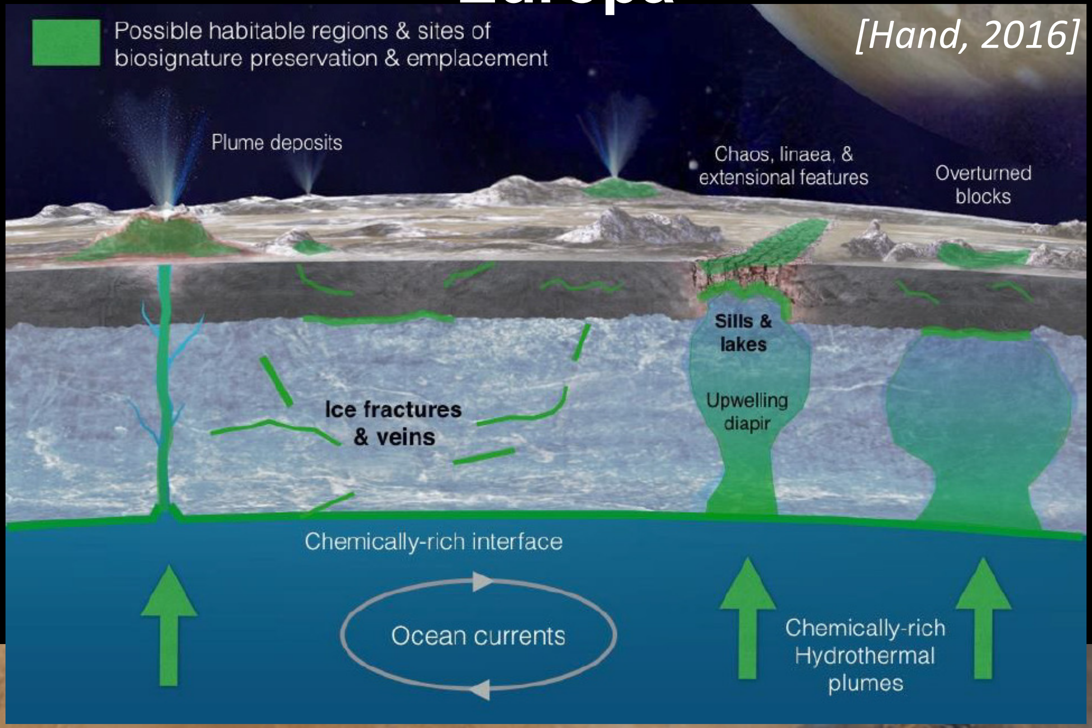
Earth



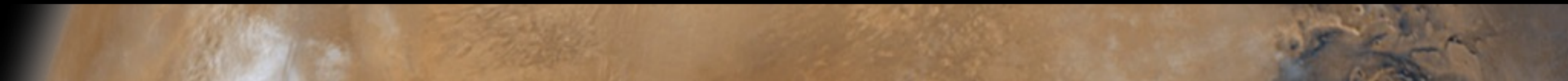
Mars



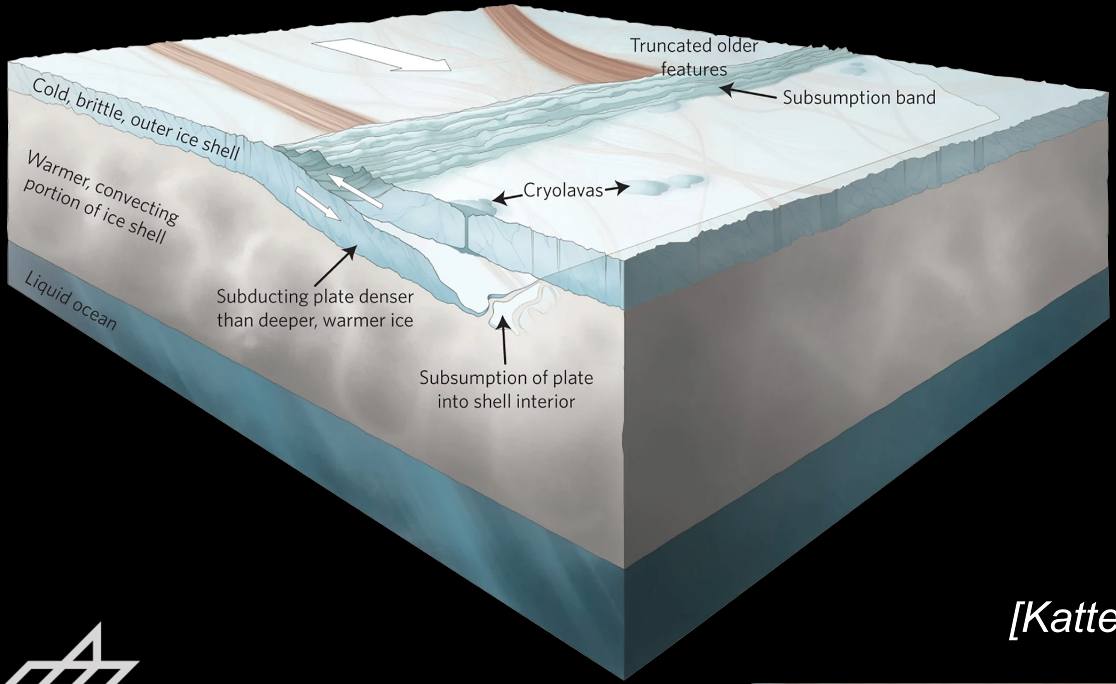
Europa

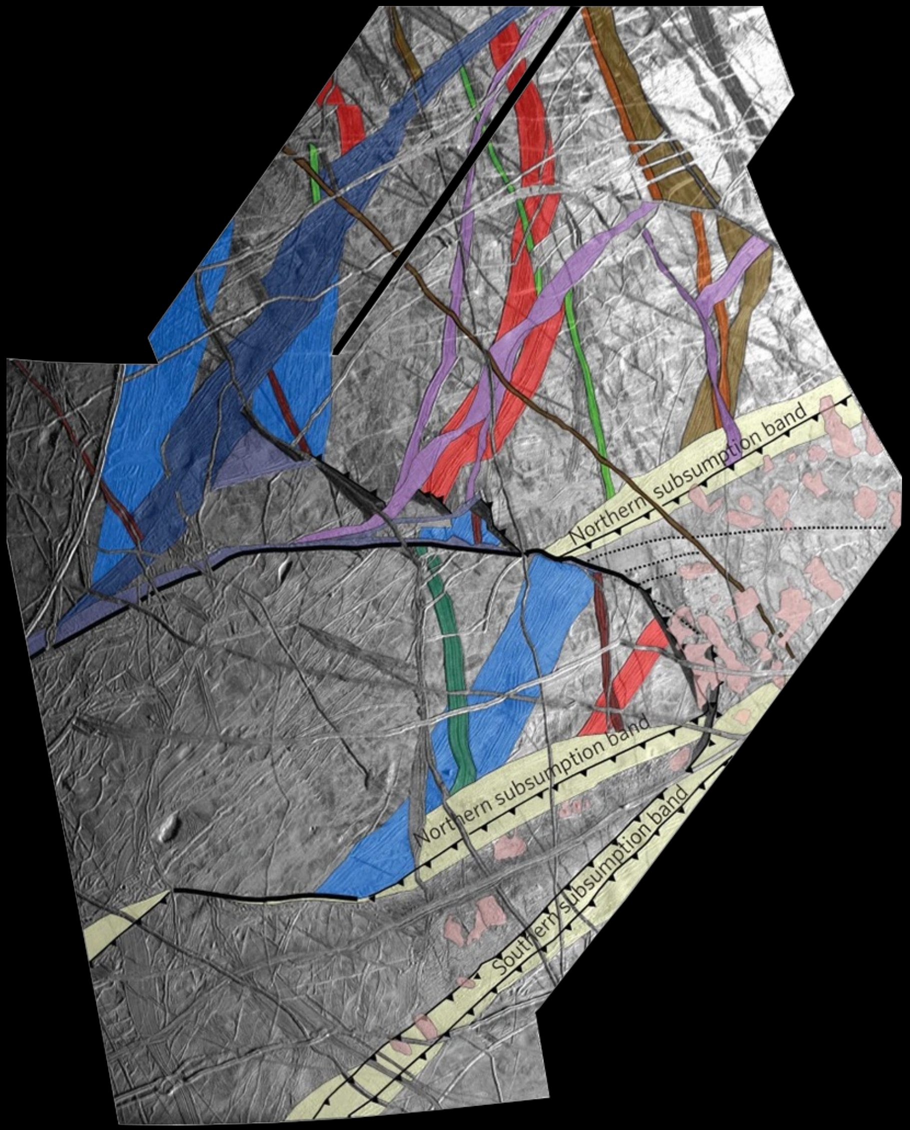


DLR



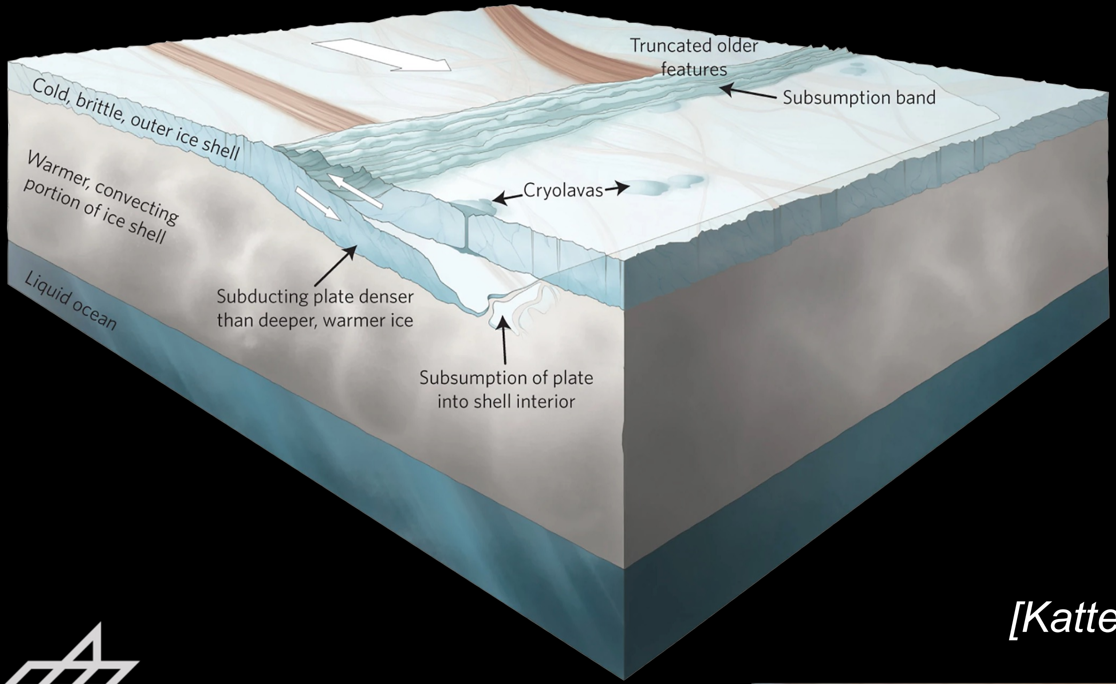
Dilatational bands: subduction?

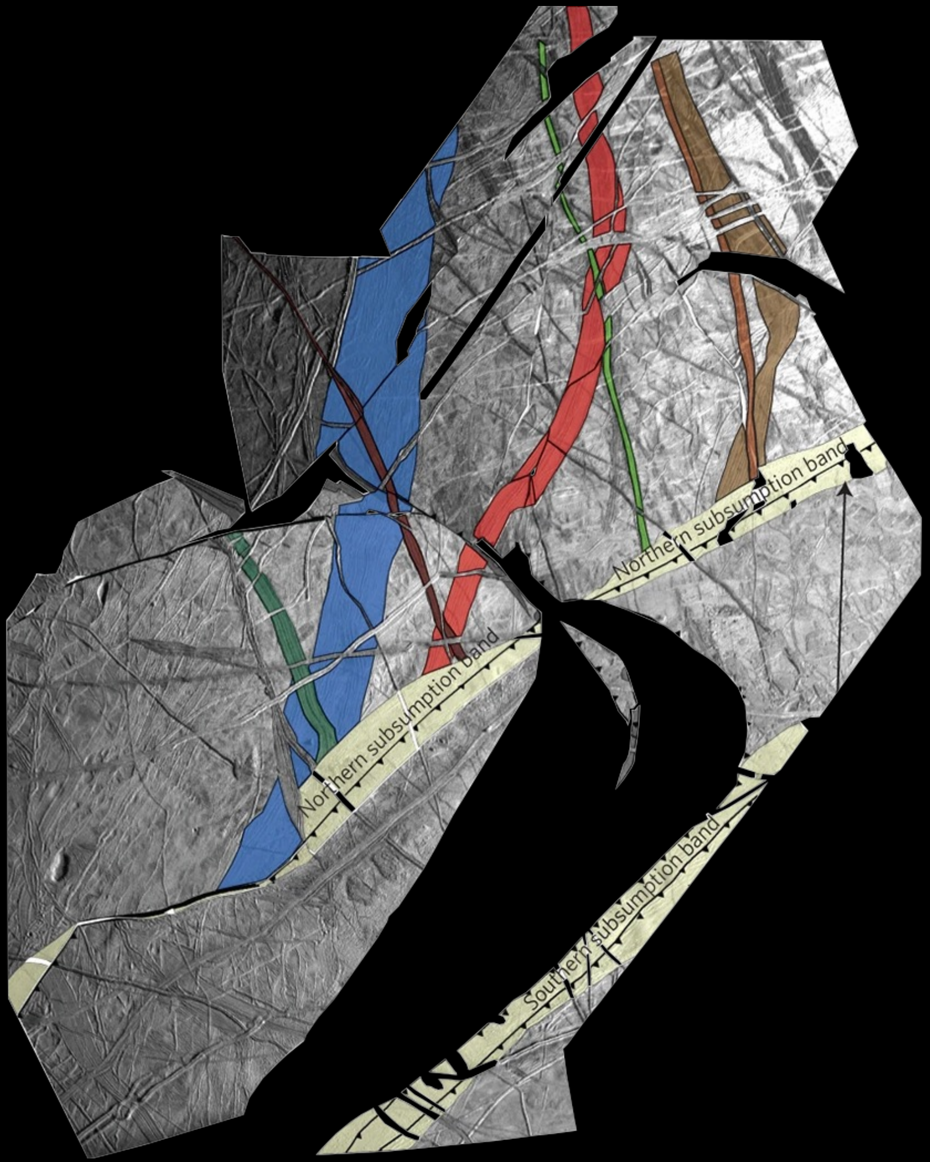




[Kattenhorn and Prockter 2014]

Dilatational bands: subduction?





[Kattenhorn and Prockter 2014]

DLR