Large-scale Numerical Simulations of Planetary Interiors

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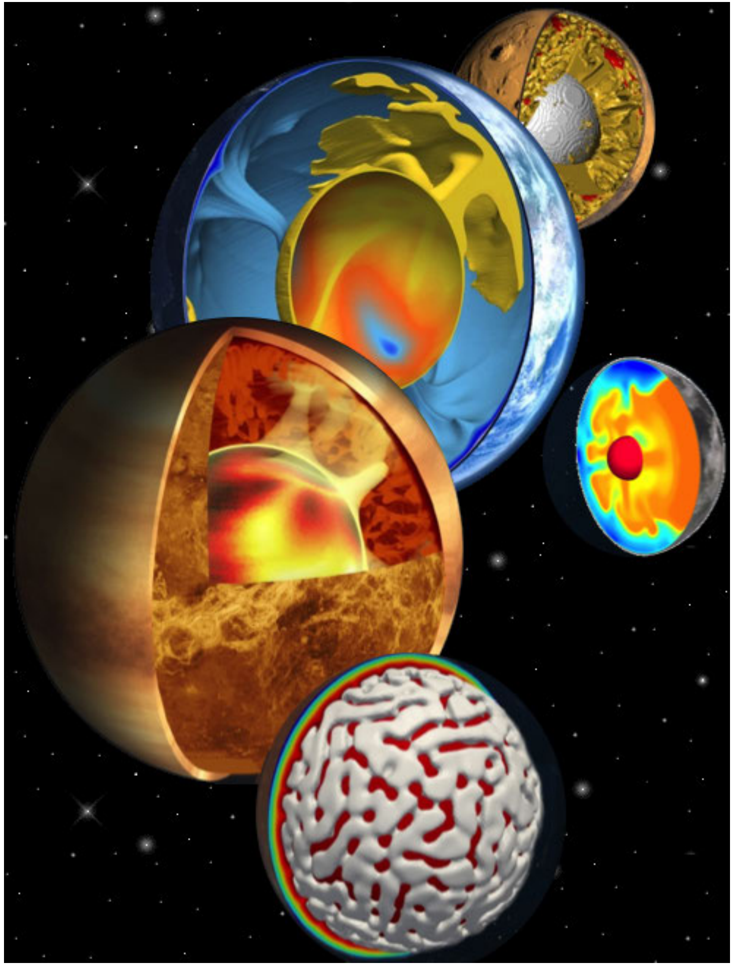
The interior of terrestrial planets

- The interiors of the planets in the Solar System are essentially heat engines.
- The available energy budget determines the amount of volcanic and tectonic activity a planet can experience.
- Large-scale numerical simulations of interior dynamics together with observational constraints can help to understand planetary evolution.



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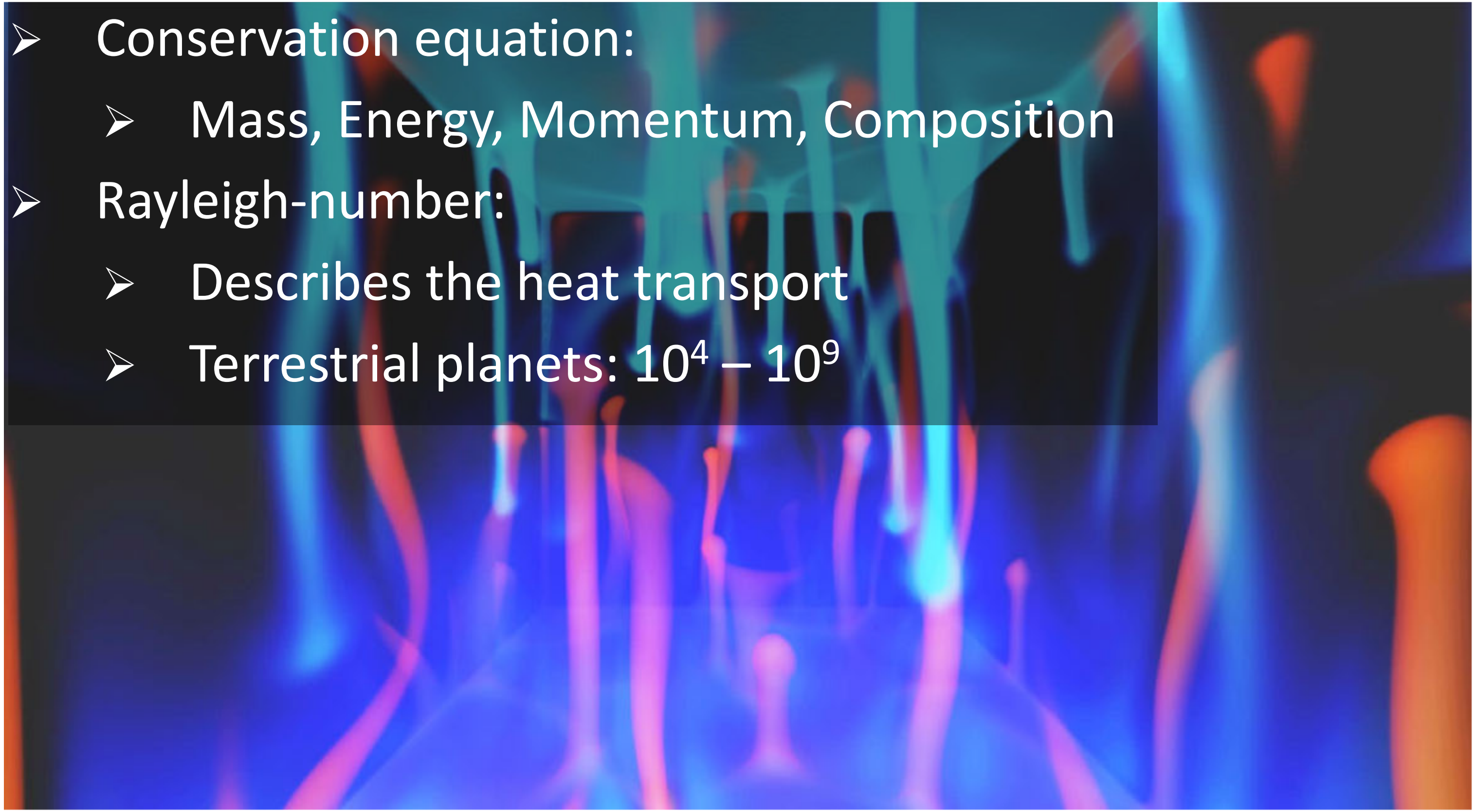
Modeling mantle convection

- Conservation equation:
  - Mass, Energy, Momentum, Composition
- Rayleigh-number:
  - Describes the heat transport
  - Terrestrial planets: $10^4 – 10^9$



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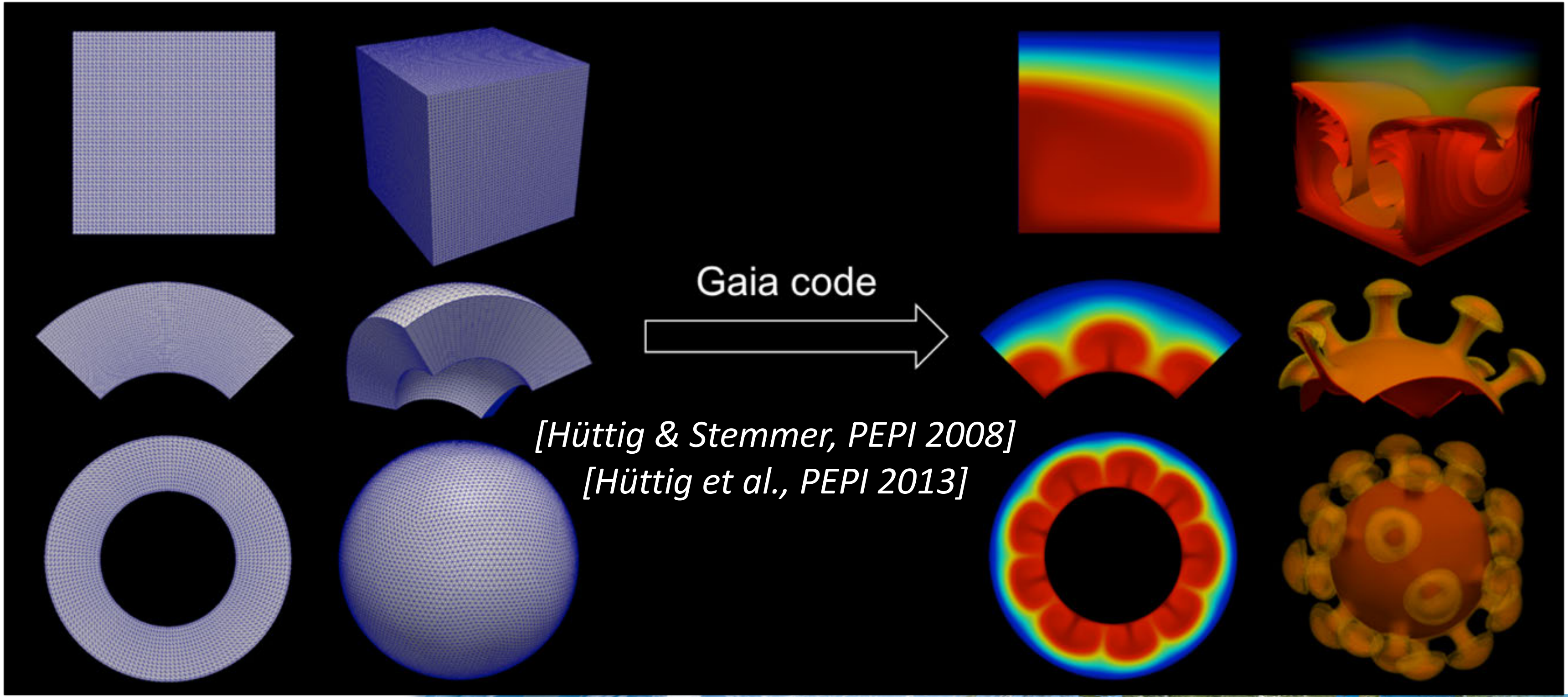
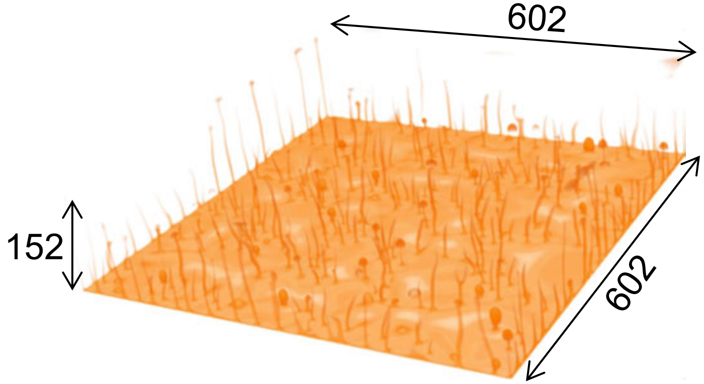
Gaia code for modeling mantle convection

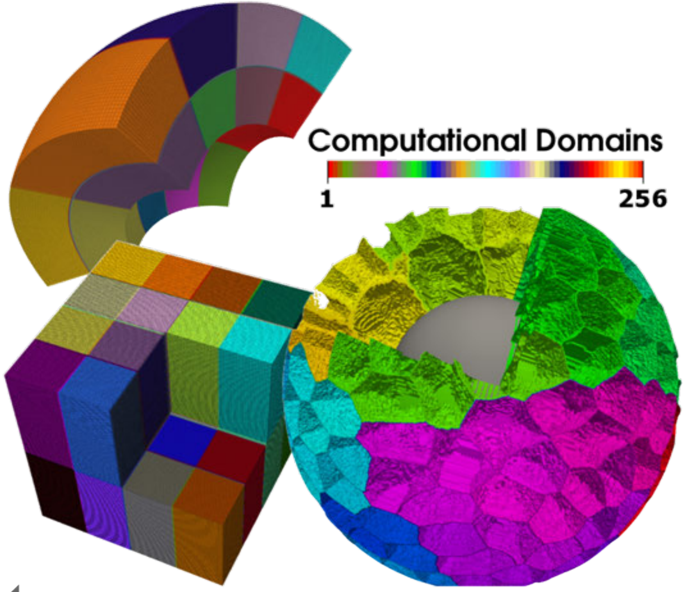
- Developed and maintained at the Institute of Planetary Research (DLR)

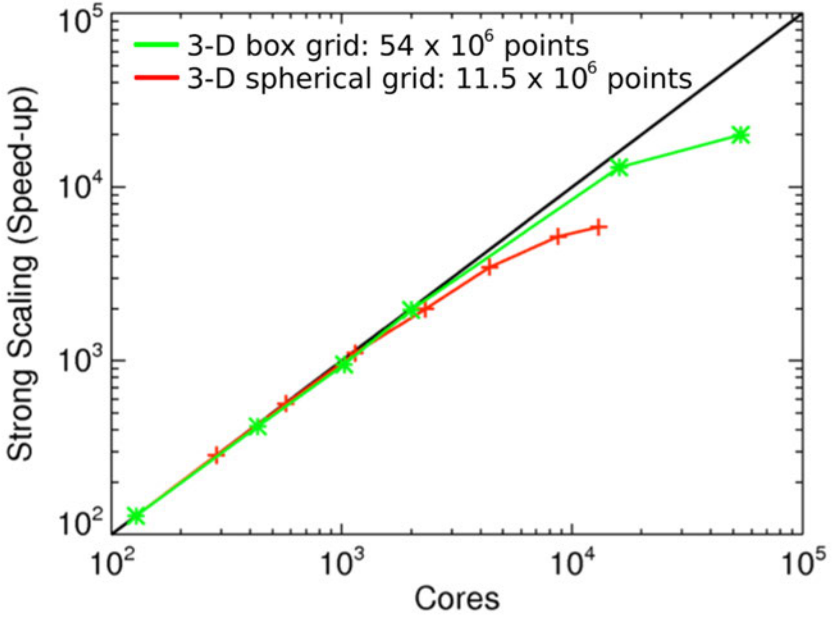


Gaia code performance

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







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HPC Centers

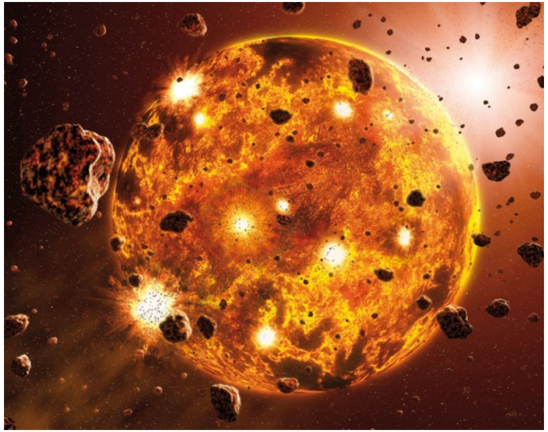
- Large scale simulations:
  - Hundreds of processes
  - Duration: Day(s) – Week(s)
- Large amount of data:
  - Typically in TB range
  - Sophisticated handling and post-processing

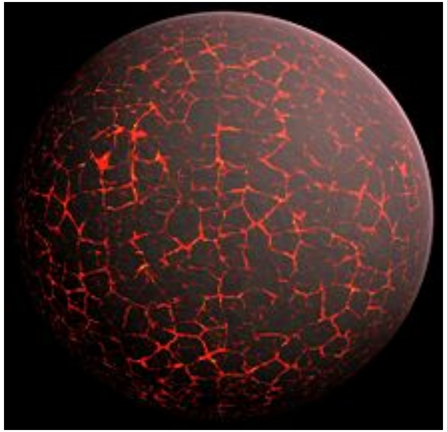
HLRS Stuttgart: Rank 19 of the Top 500 HPC Systems worldwide (Nov. 2017)

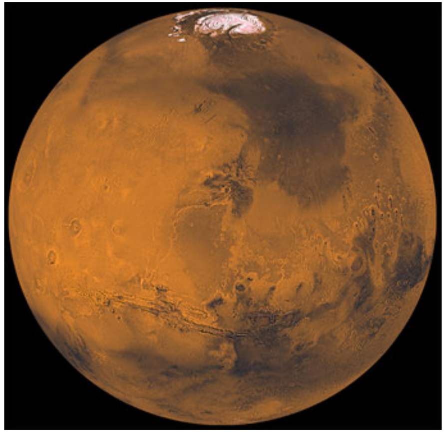
HLRN Berlin + Hannover: Rank 182 of the Top 500 HPC Systems worldwide (Nov. 2017)

Planetary evolution

4.5 Gyr ago —— time ——> Present day







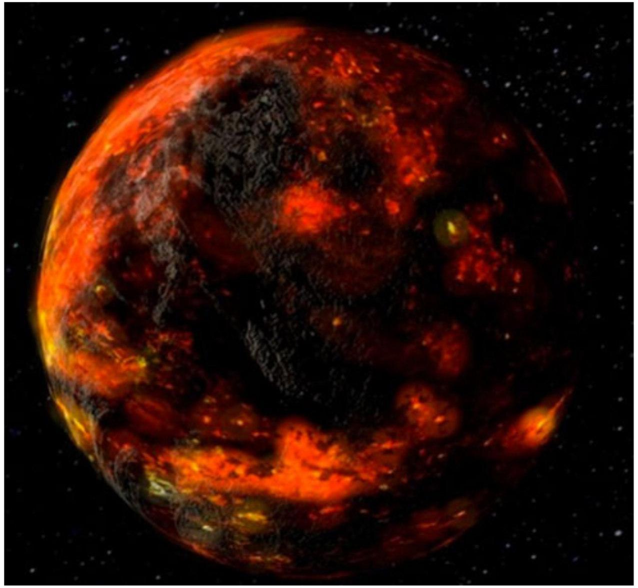
- Planets accrete hot and store formation energy in their interior.
- Most likely all terrestrial planets experienced local or even global magma oceans during their early evolution.
- Present-day interior dynamics are the result of long term thermal history.

Crystallization of a liquid magma ocean

- Large amounts of heat available during the early history may lead to the formation of a global magma ocean.

- Main heat sources:
  - Accretion and core formation
  - Radiogenic elements
  - Tidal dissipation

- Crystallization of the liquid magma ocean sets the stage for the subsequent planetary evolution.



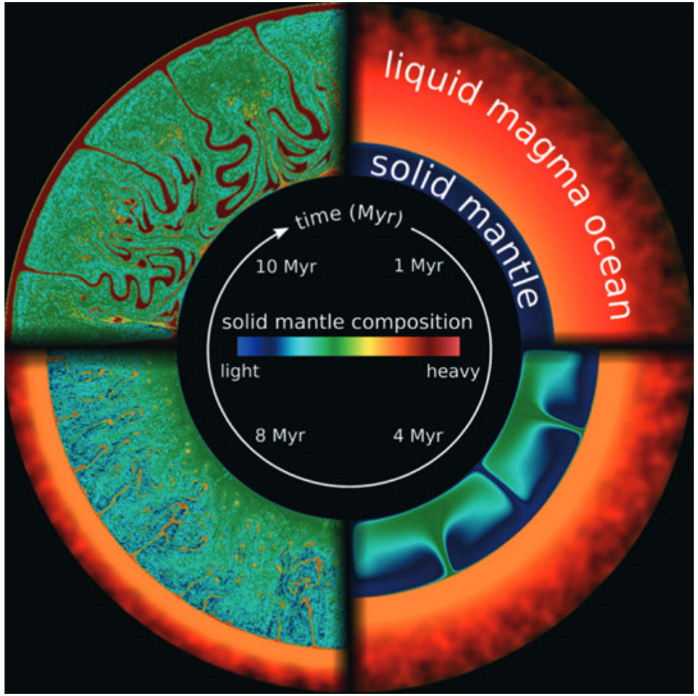
Credit: NASA/GFSC

Mixing during the magma ocean crystallization

- Onset of solid state convection may occur if the crystallization time is longer than 1 Myr.

- Mixing of chemical heterogenities may take place during the magma ocean crystallization.

- Chemical heterogeneities may be reduced or even erased during the crystallization phase.



[Maurice et al., JGR 2017]

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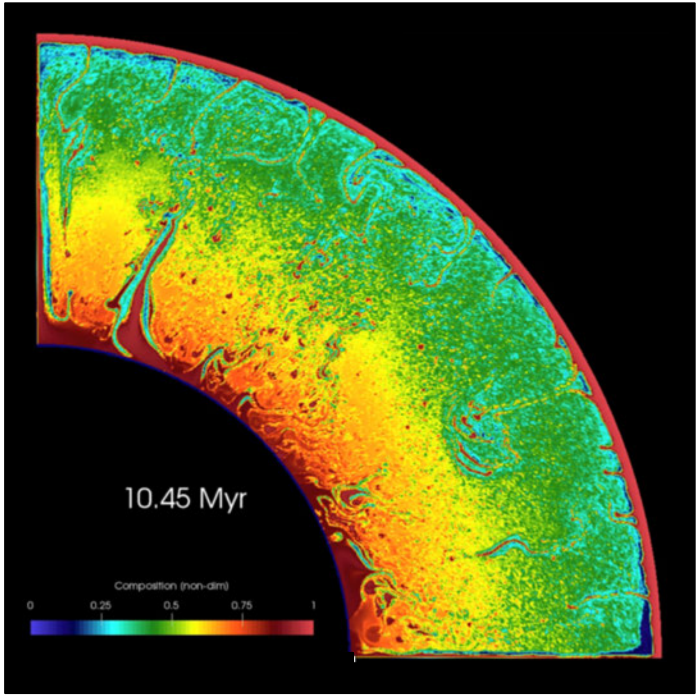
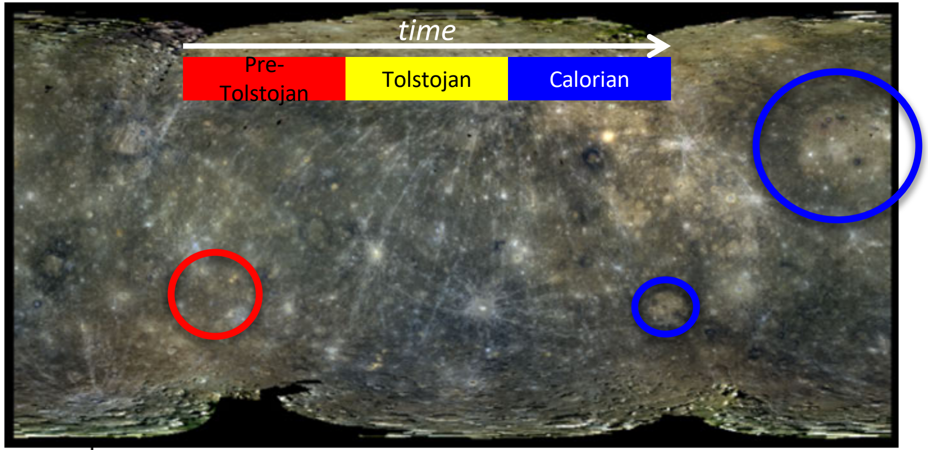


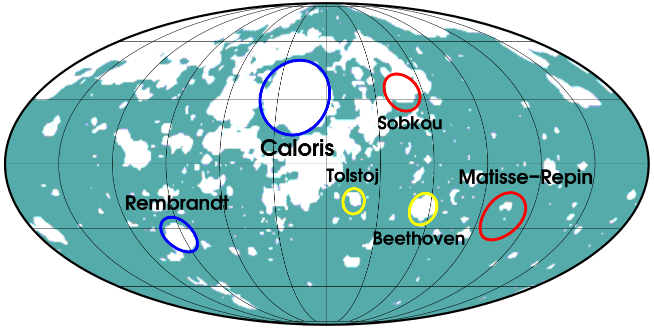
[Maurice et al., JGR 2017]

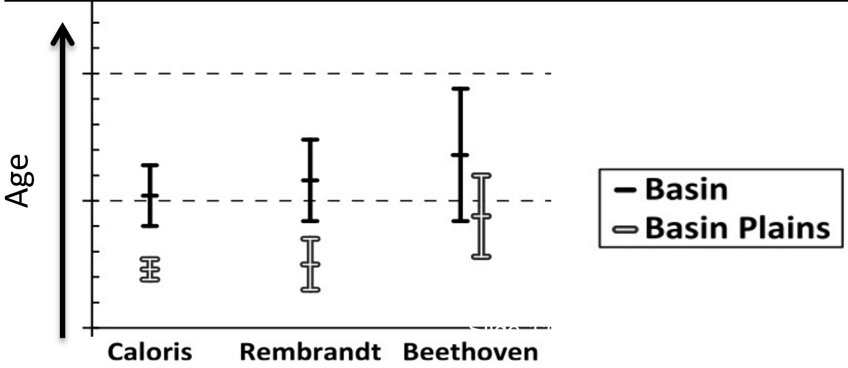
Large impacts and the thermal evolution of Mercury

- Young large basins on the surface of Mercury are compositionally distinct.

- Smooth volcanic material in their interior has been emplaced after the basin formation.

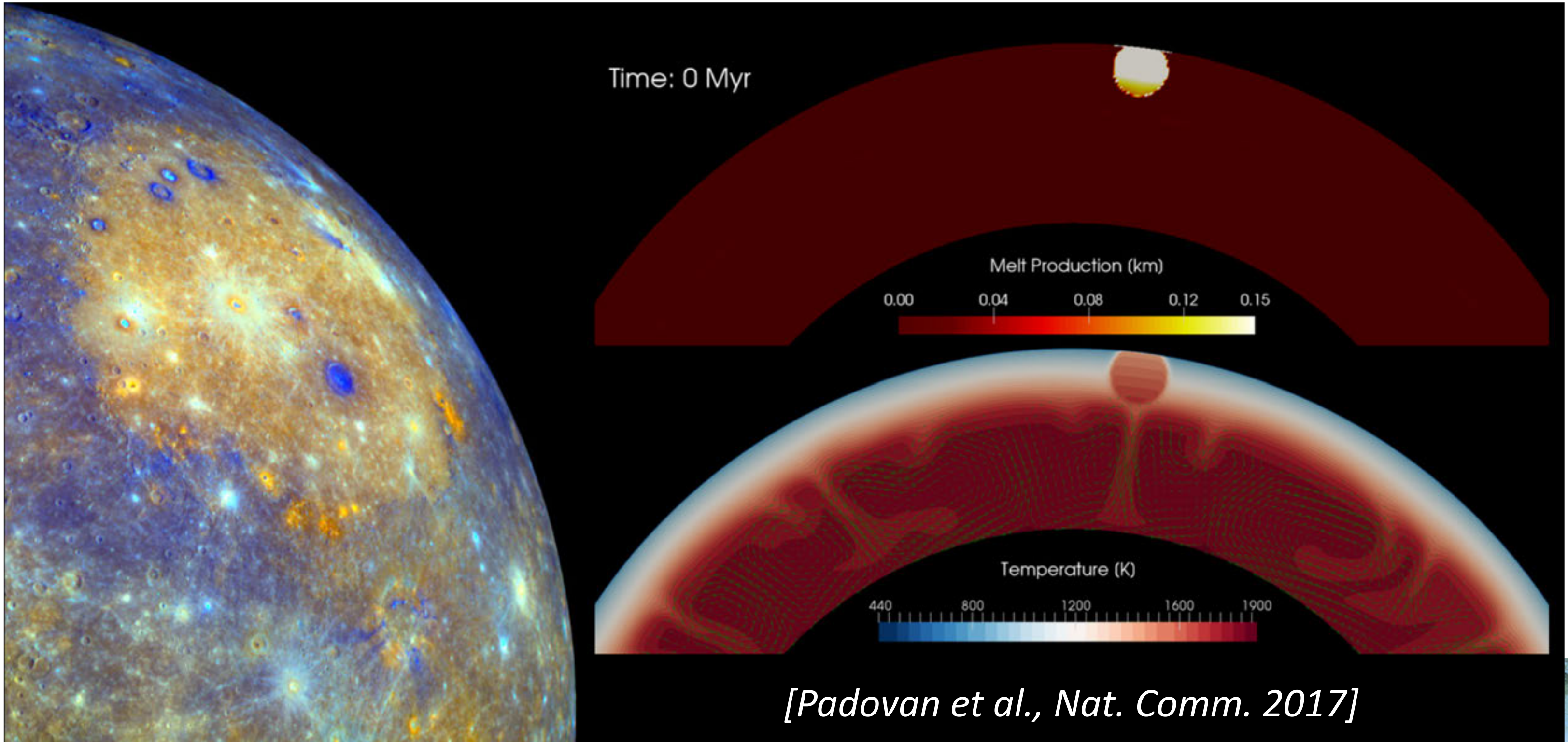






Large impacts and the thermal evolution of Mercury

- Volcanic material within young large basins originates in the stagnant lid.
- Thus, it contains partial melt of potentially pristine mantle material.



[Padovan et al., Nat. Comm. 2017]

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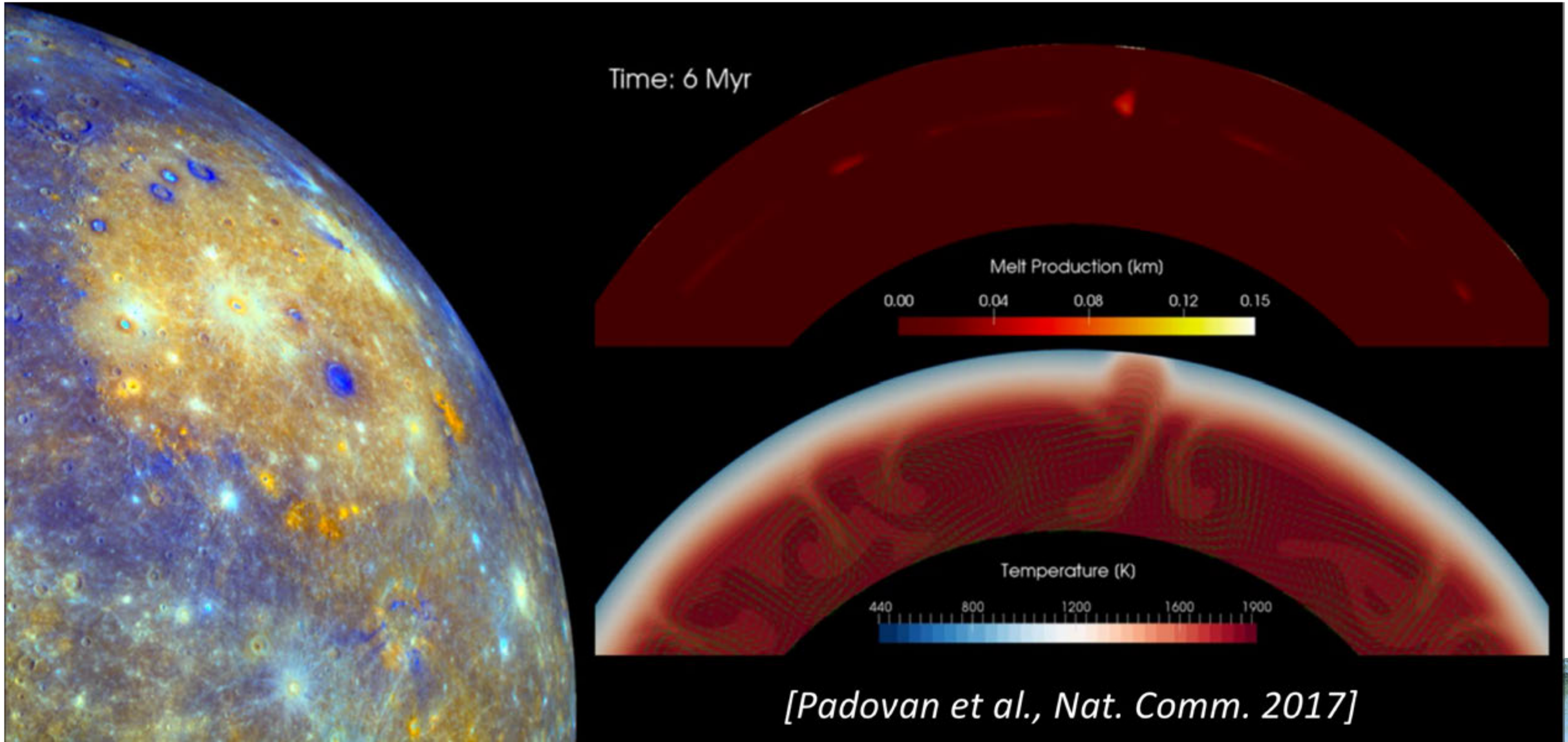
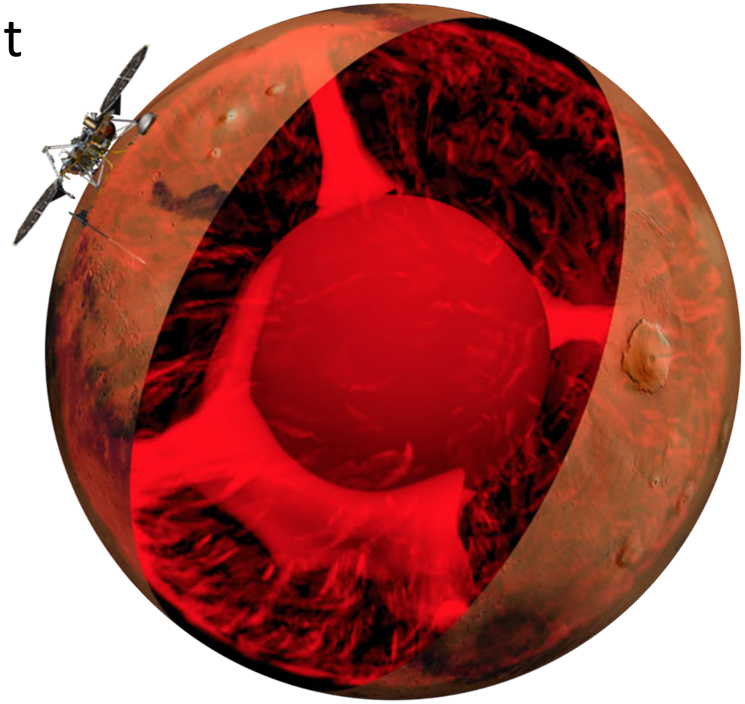


[Padovan et al., Nat. Comm. 2017]

Thermal evolution and present-day state of Mars

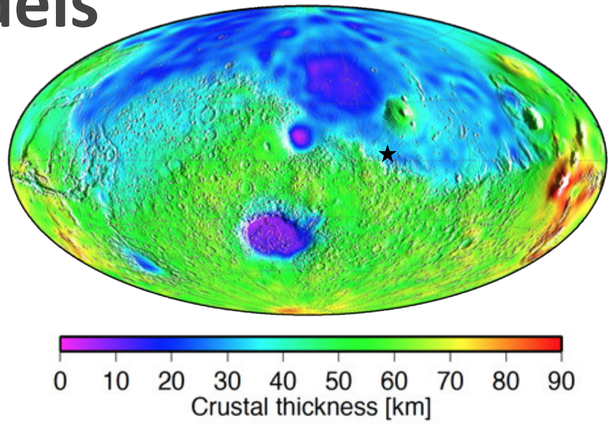
- Mars has been volcanically active throughout its entire evolution up to the recent past.
- Gravity and topography data can be used to construct crustal thickness models.
- GRS measurements indicate that the crust contains a large amount of radiogenic elements.
- The upcoming InSight mission will perform in-situ heat flow and seismic measurements on Mars.



Credit: NASA/JPL-Caltech/DLR

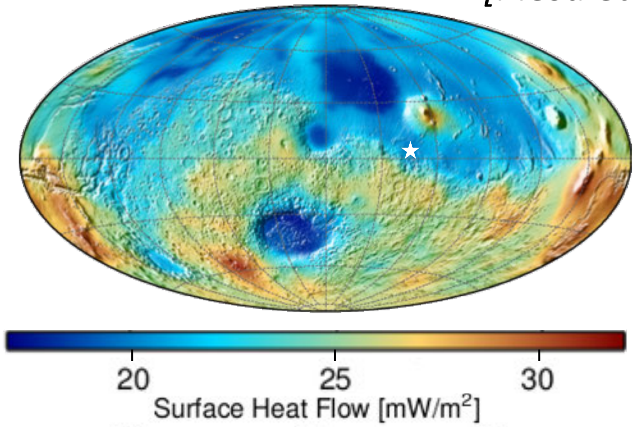
Surface heat flow and seismicity models

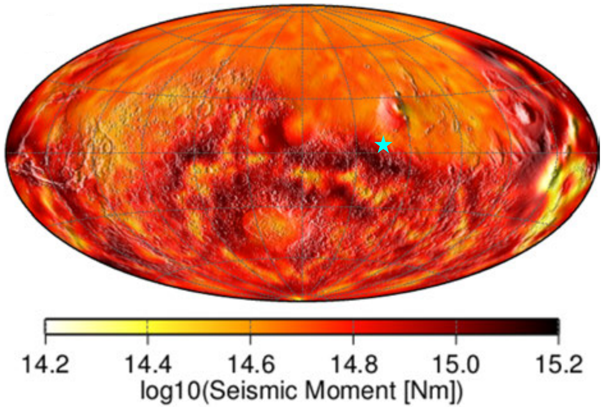
- Models predict a heat flow distribution that correlates with crustal thickness and crustal heat source distribution.
- Models predict a more homogeneous distribution of seismicity, with all areas being seismically active.



★ InSight Landing Site

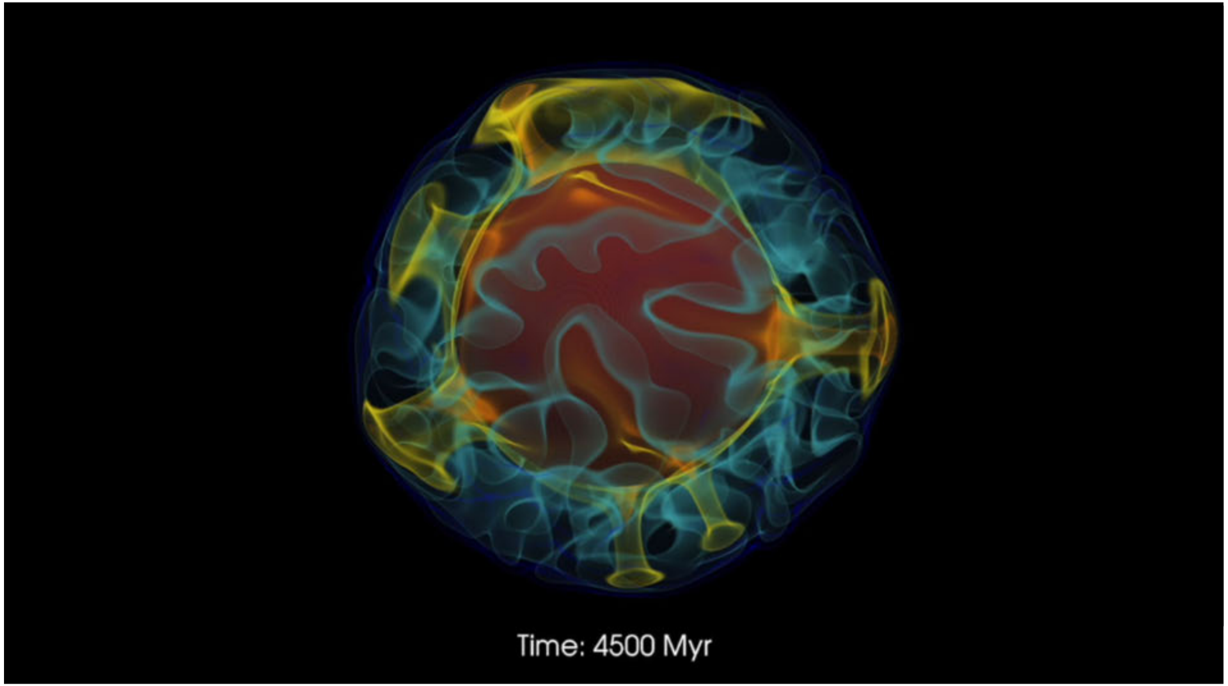
[Plesa et al., JGR 2016, GRL 2018]





Mars' thermal evolution

- Models indicate that mantle plumes may be present today underneath large volcanic provinces on Mars.



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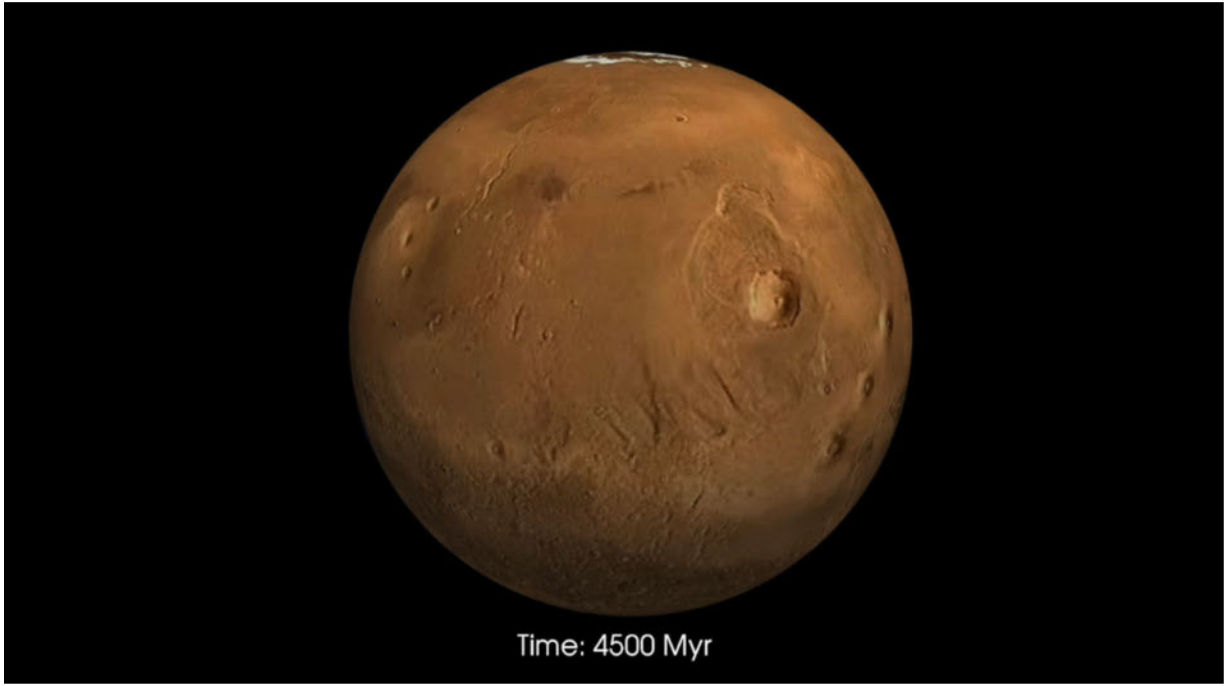

Conclusions

- Numerical models can help interpreting various mission data (e.g., surface composition, heat flow and seismic measurements).
- Models suggest that chemical heterogeneities may be reduced or even erased during the magma ocean crystallization.
- Volcanic material within young large basins on Mercury may sample pristine mantle material.
- Mantle plumes may still be present today underneath large volcanic provinces on Mars.