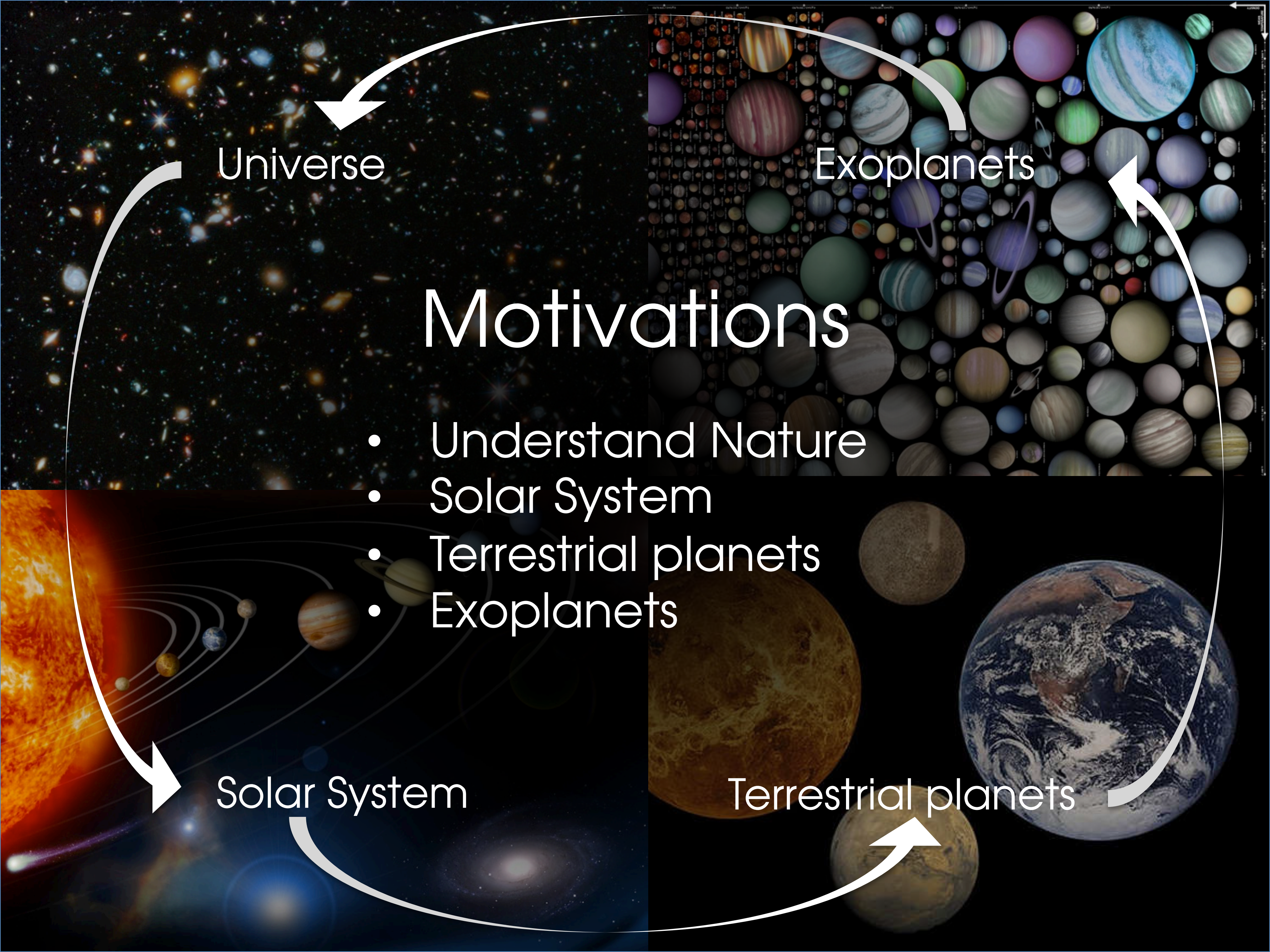
A Few Topics on the Interior Structure and Evolution of Mercury

Sebastiano Padovan
German Aerospace Center (DLR)

Russian-German Seminar
June 1st, 2016
Berlin

Motivations

- Understand Nature
- Solar System
- Terrestrial planets
- Exoplanets



What does interior structure mean?

- In this talk it means the broad features of a terrestrial planet. i.e., density, state, temperature at the present time.

What does evolution mean?

- How does the interior structure changes over time, and how did the body end up the way it is?

Interior Structure: Constraints

- Mean density
- Moment of Inertia
- Moment of Inertia (take 2)
- Crustal thickness
- Tides

Mean Density

$$\rho = \frac{1}{V}\int_M dm \propto \frac{M}{R^3}$$

- Mean density bears on the bulk abundance of elements in the interior of a body.

Example: Mercury and Earth

Earth: 5515 kg/m^3

Mercury: 5427 kg/m^3

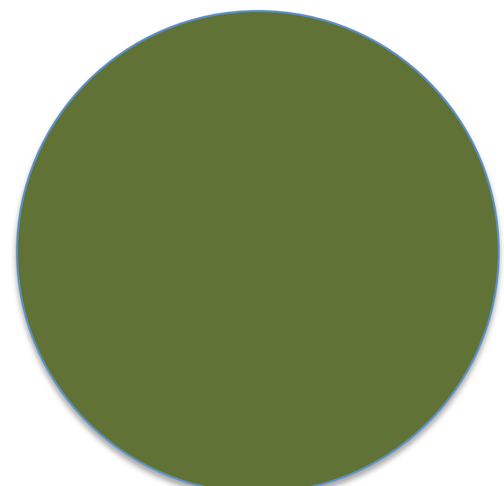
Uncompressed densities

Earth: 4000 kg/m^3

Mercury: 5300 kg/m^3

Implications

Mercury has more metals



References: NASA NSSDC

Moment of Inertia $C = \int_M r_\perp^2 \, dm = \alpha M R^2$

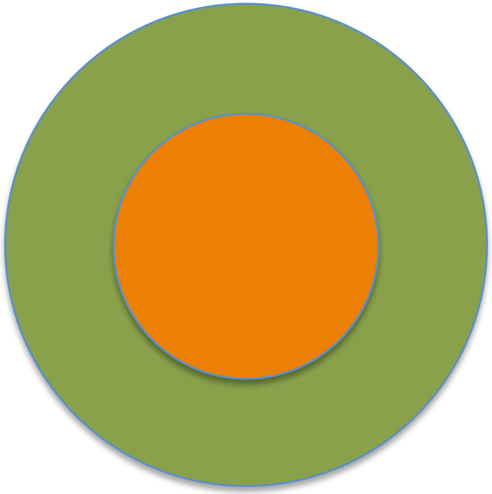
- Moment of Inertia bears on the radial distribution of mass.

Moment of Inertia $C = \int_M r_\perp^2 \, dm = \alpha M R^2$

- Moment of Inertia bears on the radial distribution of mass.

Values of α

Point mass:	0.
Earth:	0.330
Mercury:	0.346
Mars:	0.364
Moon:	0.393
Uniform density:	0.4

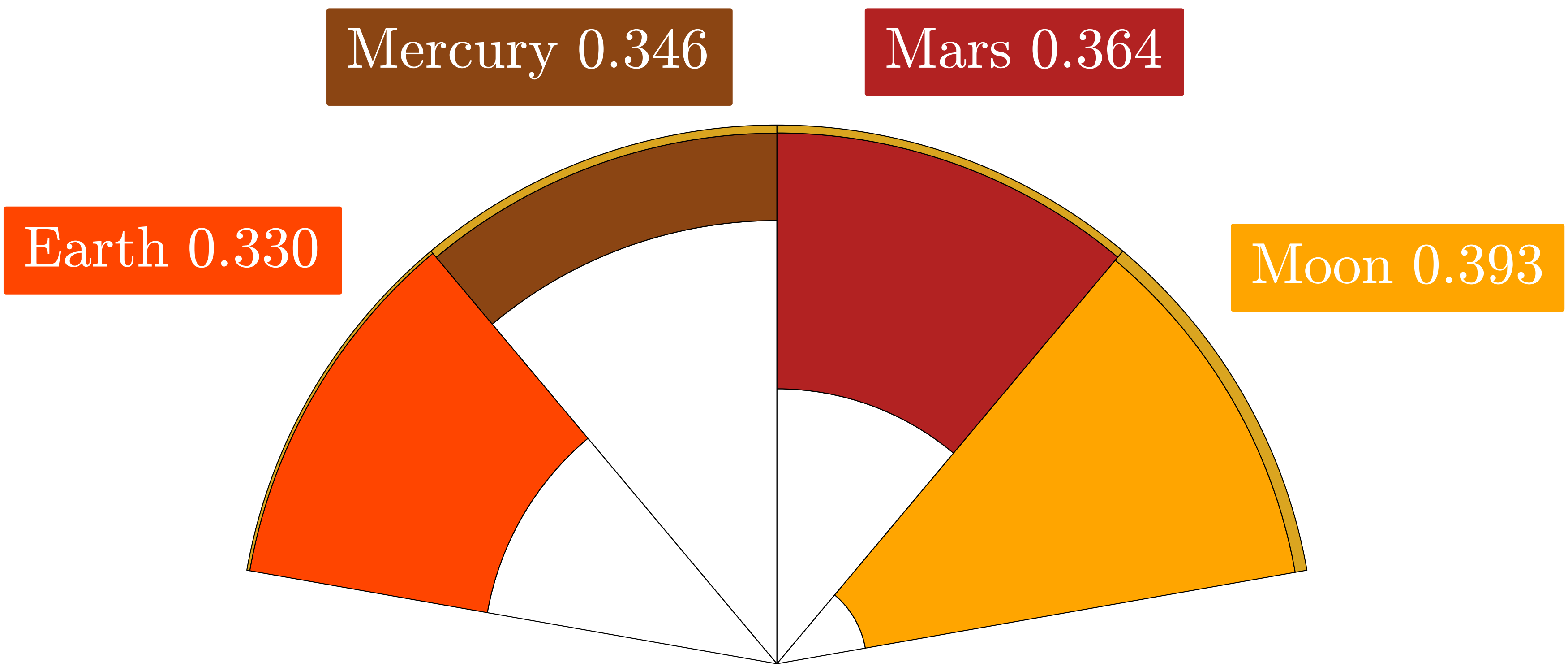


References: Williams et al., 2014; Konopliv et al., 2011; Margot et al., 2012; NASA NSSDC

Moment of Inertia

$$C = \int_M r_\perp^2 \, dm = \alpha M R^2$$

- Moment of Inertia bears on the radial distribution of mass.

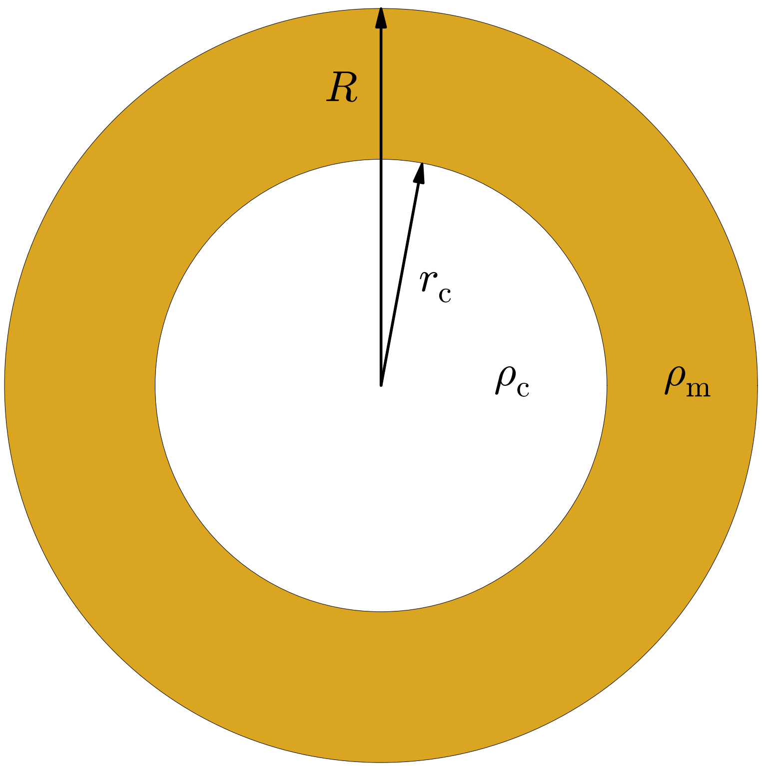


References: Williams et al., 2014; Konopliv et al., 2011; Margot et al., 2012; NASA NSSDC

Two-layer model

Unknowns: r_c, ρ_c, ρ_m
Observables: ρ

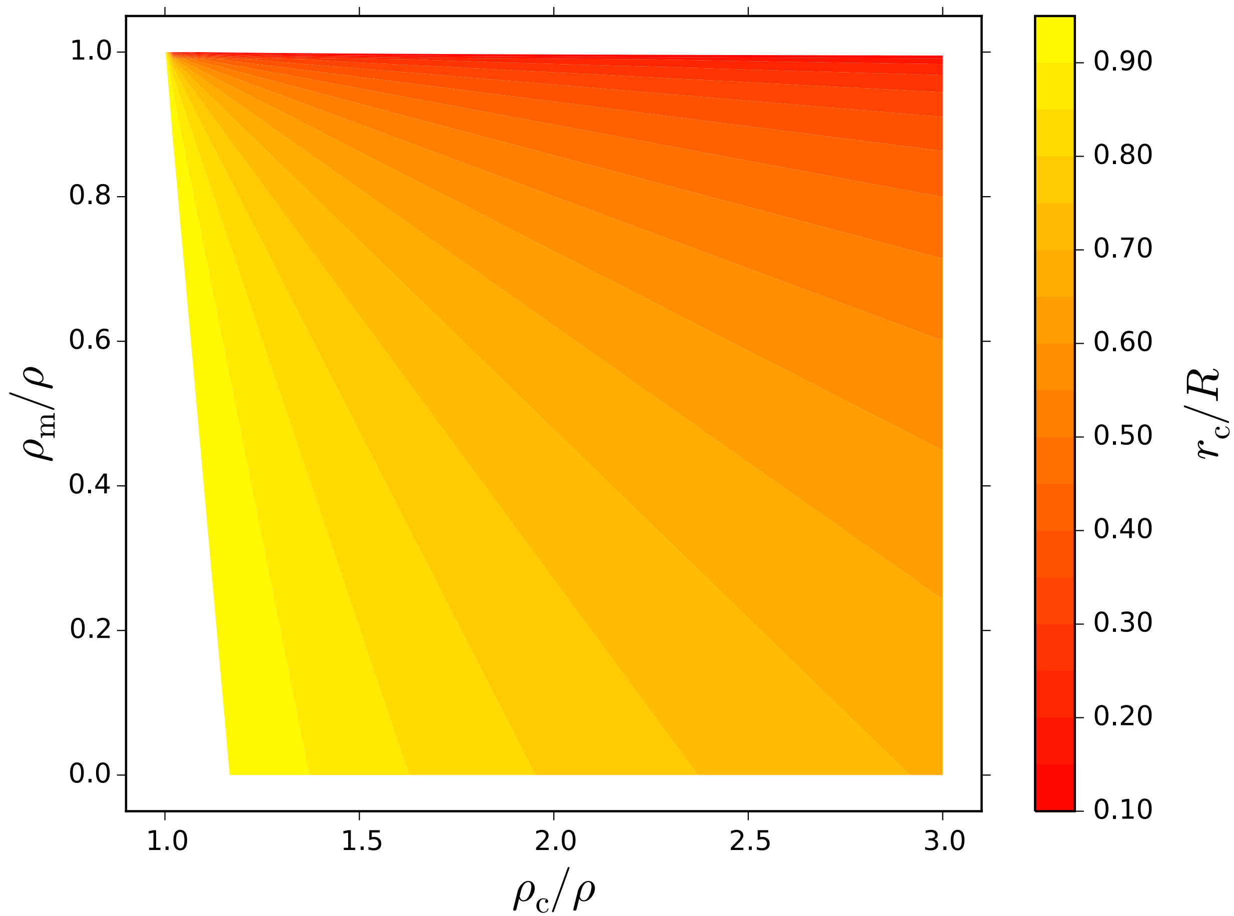
$$\rho = \rho_c \frac{r_c^3}{R^3} + \rho_m \left(1 - \frac{r_c^3}{R^3}\right)$$



Two-layer model

Unknowns: r_c, ρ_c, ρ_m
Observables: ρ

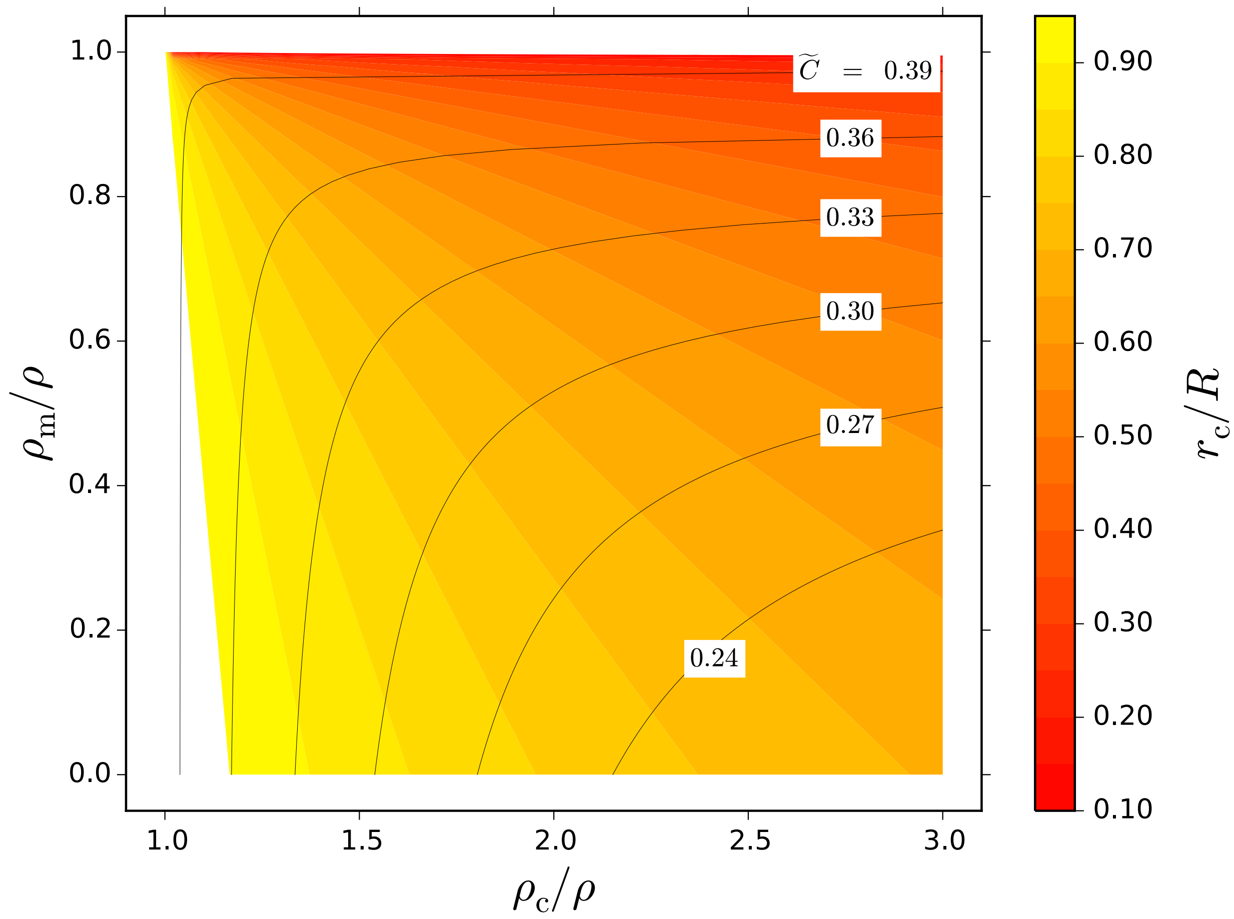
$$\rho = \rho_c \frac{r_c^3}{R^3} + \rho_m \left(1 - \frac{r_c^3}{R^3}\right)$$



Two-layer model

Unknowns: r_c, ρ_c, ρ_m
Observables: ρ, C

$$\rho = \rho_c \frac{r_c^3}{R^3} + \rho_m \left(1 - \frac{r_c^3}{R^3}\right); \qquad \frac{C}{MR^2} = 0.4 \left\{ \frac{\rho_c}{\rho}\left(\frac{r_c}{R}\right)^5 + \frac{\rho_m}{\rho}\left[1 - \left(\frac{r_c}{R}\right)^5\right] \right\}$$



Moment of Inertia
Outer Solid Shell

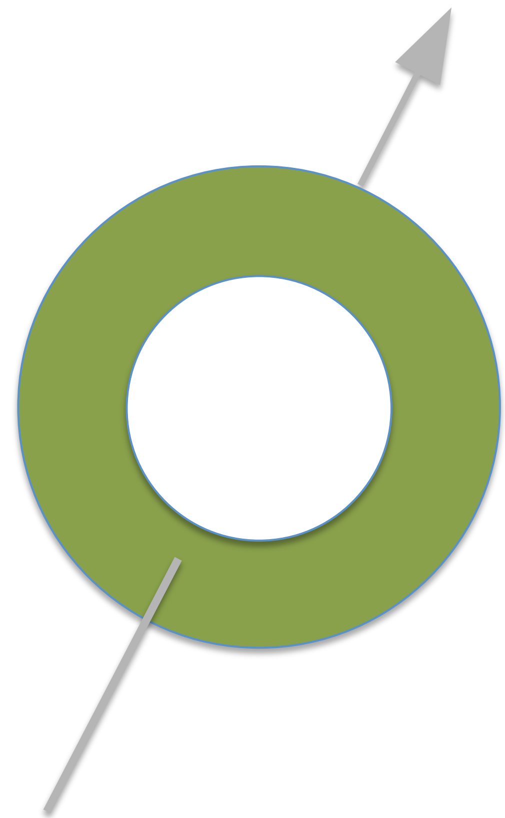
$$C_m = \int_m r_\perp^2 \, dm'$$

- Possible to measure remotely for Mercury for its dynamical configuration

- The fact that

$$C_m < C$$

implies that the core of Mercury is liquid.

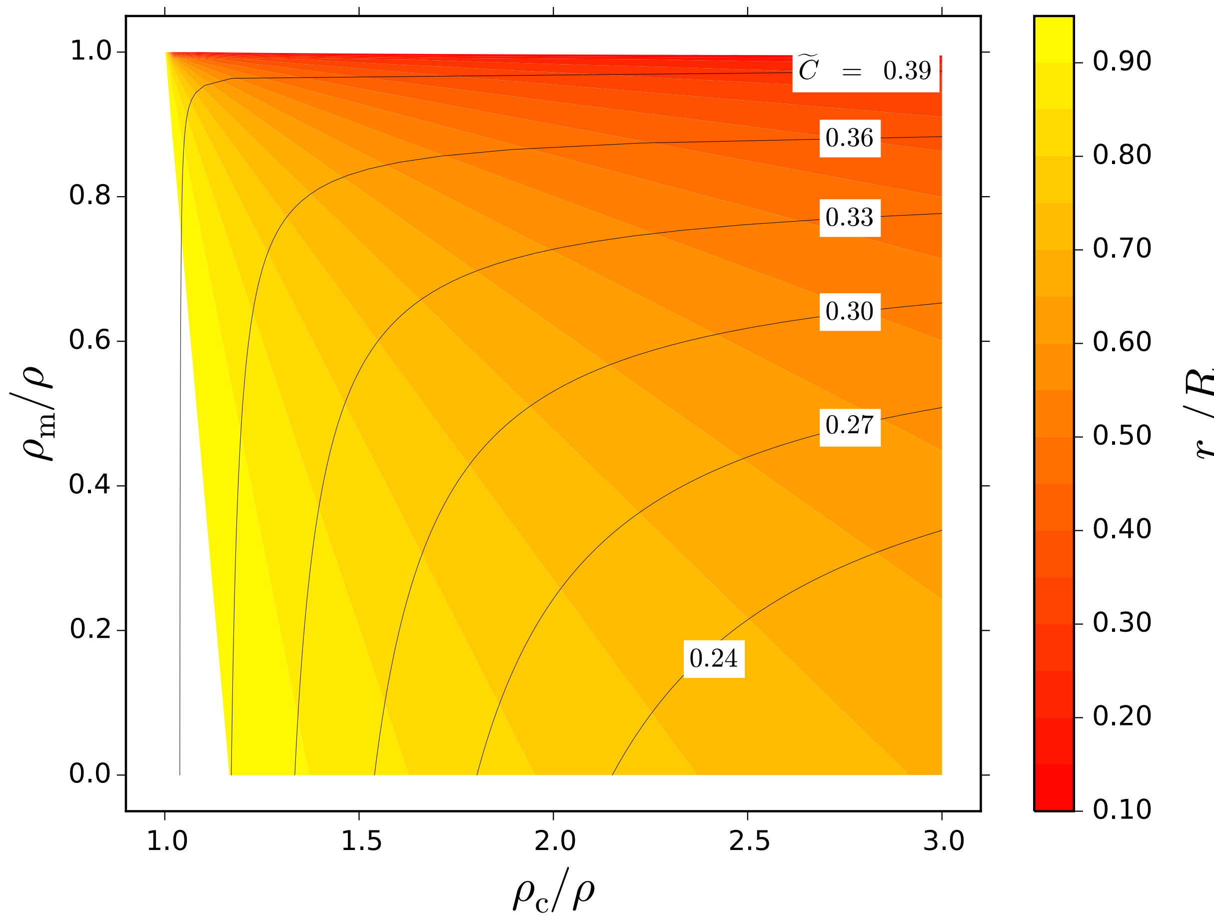


References: Peale 1976.

Two-layer model

Unknowns: r_c, ρ_c, ρ_m
Observables: ρ, C

$$\rho = \rho_c \frac{r_c^3}{R^3} + \rho_m \left(1 - \frac{r_c^3}{R^3}\right); \qquad \frac{C}{MR^2} = 0.4\left\{\frac{\rho_c}{\rho}\left(\frac{r_c}{R}\right)^5 + \frac{\rho_m}{\rho}\left[1 - \left(\frac{r_c}{R}\right)^5\right]\right\}$$

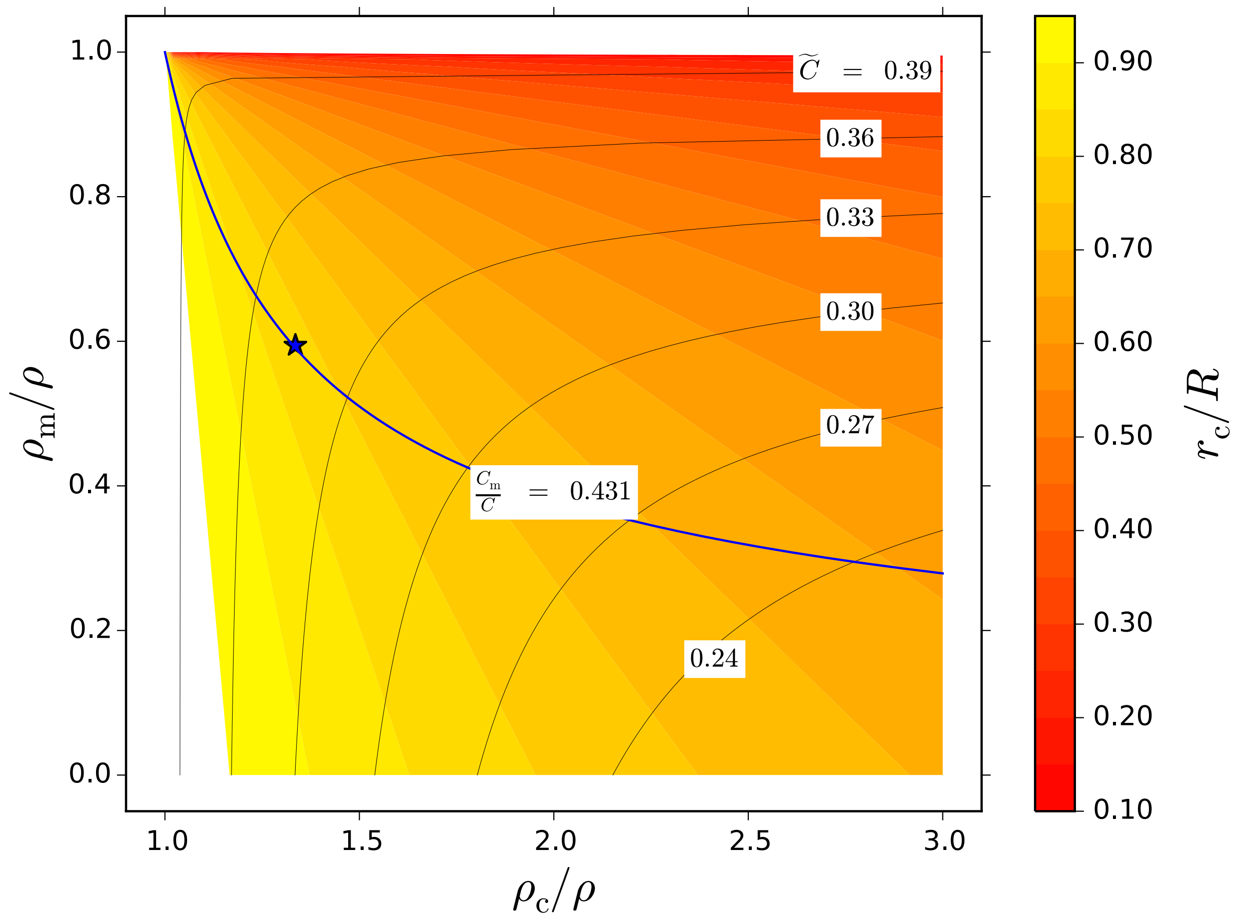


Two-layer model

Unknowns: r_c, ρ_c, ρ_m
Observables: ρ, C, C_m

$$\rho = \rho_c \frac{r_c^3}{R^3} + \rho_m \left(1 - \frac{r_c^3}{R^3}\right); \qquad \frac{C}{MR^2} = 0.4\left\{\frac{\rho_c}{\rho}\left(\frac{r_c}{R}\right)^5 + \frac{\rho_m}{\rho}\left[1 - \left(\frac{r_c}{R}\right)^5\right]\right\};$$

$$\frac{C_m}{MR^2} = 0.4\,\frac{\rho_m}{\rho}\left(1 - \frac{r_c^5}{R^5}\right)$$



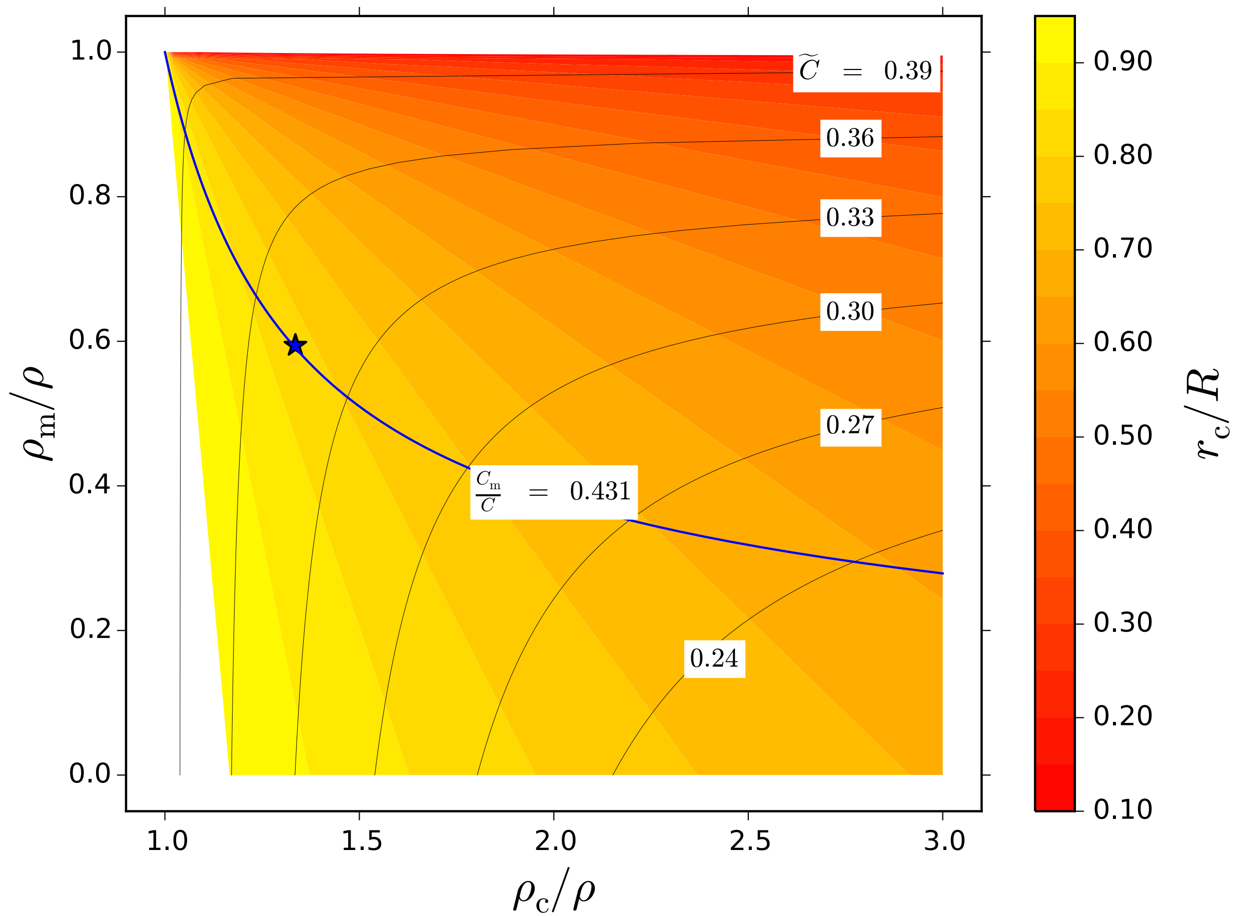
Two-layer model

Unknowns: r_c, ρ_c, ρ_m
Observables: ρ, C, C_m

$$\rho = \rho_c \frac{r_c^3}{R^3} + \rho_m \left(1 - \frac{r_c^3}{R^3}\right); \qquad \frac{C}{MR^2} = 0.4 \left\{ \frac{\rho_c}{\rho}\left(\frac{r_c}{R}\right)^5 + \frac{\rho_m}{\rho}\left[1 - \left(\frac{r_c}{R}\right)^5\right]\right\};$$

$$\frac{C_m}{MR^2} = 0.4 \frac{\rho_m}{\rho}\left(1 - \frac{r_c^5}{R^5}\right)$$

$$\rho_c = 7256 \text{ kg/m}^3$$
$$\rho_m = 3204 \text{ kg/m}^3$$
$$r_c = 1998 \text{ km}$$



Two-layer model

Unknowns: r_c, ρ_c, ρ_m
Observables: ρ, C, C_m

Simplifications of a 2-layer model:

No constant density
More than 2 layers (inner core, crust)

Comparison with accurate models:

Two-Layer Model	Accurate Modeling (Hauck et al., 2013)
$\rho_c = 7256 \text{ kg/m}^3$	$\rho_c = 6980 \pm 280 \text{ kg/m}^3$
$\rho_m = 3204 \text{ kg/m}^3$	$\rho_m = 3380 \pm 200 \text{ kg/m}^3$
$r_c = 1998 \text{ km}$	$r_c = 2020 \pm 30 \text{ km}$

References: Hauck et al., 2013.

Two-layer model

Unknowns: r_c, ρ_c, ρ_m
Observables: ρ, C, C_m

Accurate Modeling (Hauck et al., 2013)

Two-Layer Model

$$\rho_c = 7256 \text{ kg/m}^3$$
$$\rho_m = 3204 \text{ kg/m}^3$$
$$r_c = 1998 \text{ km}$$

Accurate Modeling (Hauck et al., 2013)

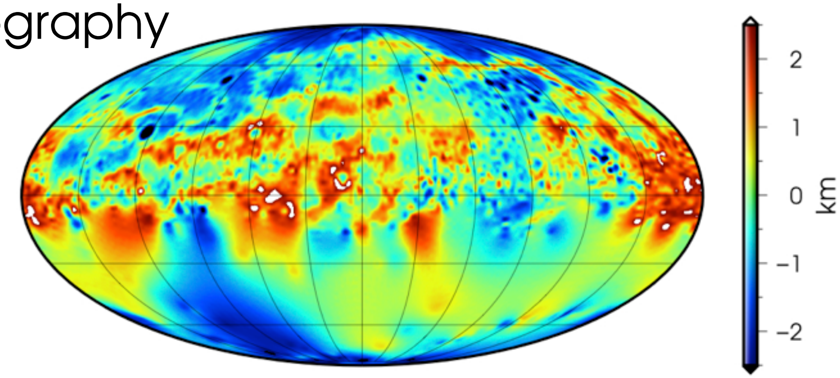
$$\rho_c = 6980 \pm 280 \text{ kg/m}^3$$
$$\rho_m = 3380 \pm 200 \text{ kg/m}^3$$
$$r_c = 2020 \pm 30 \text{ km}$$

References: Hauck et al., 2013.

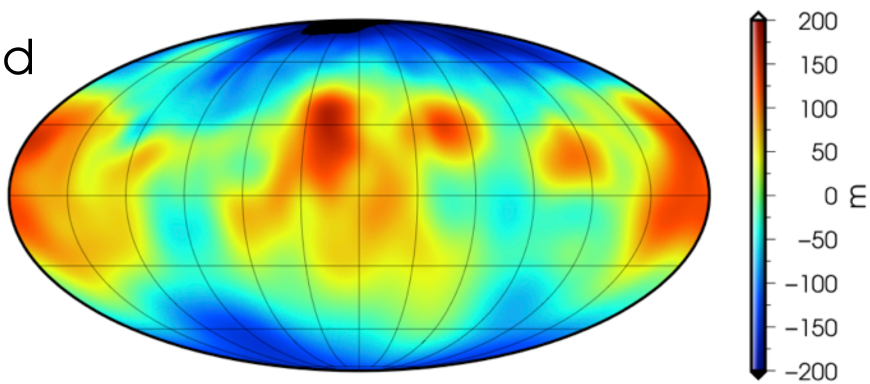
Crustal thickness

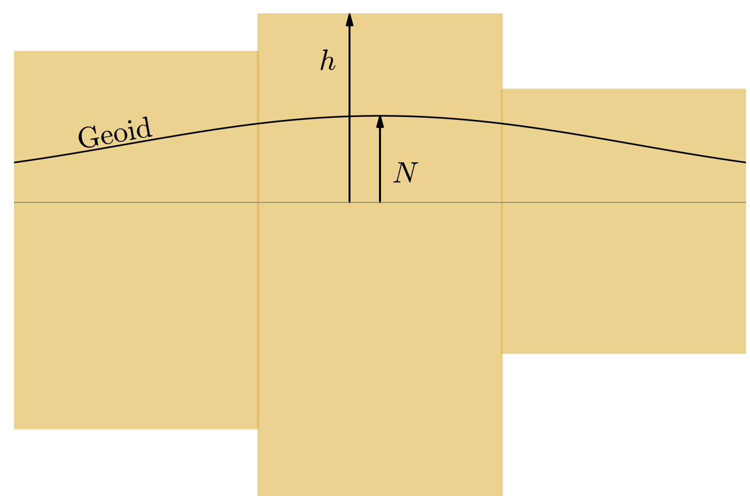
- Using gravity (measured) and topography (measured), one can estimate the crustal thickness by assuming a compensation model.

Topography



Geoid

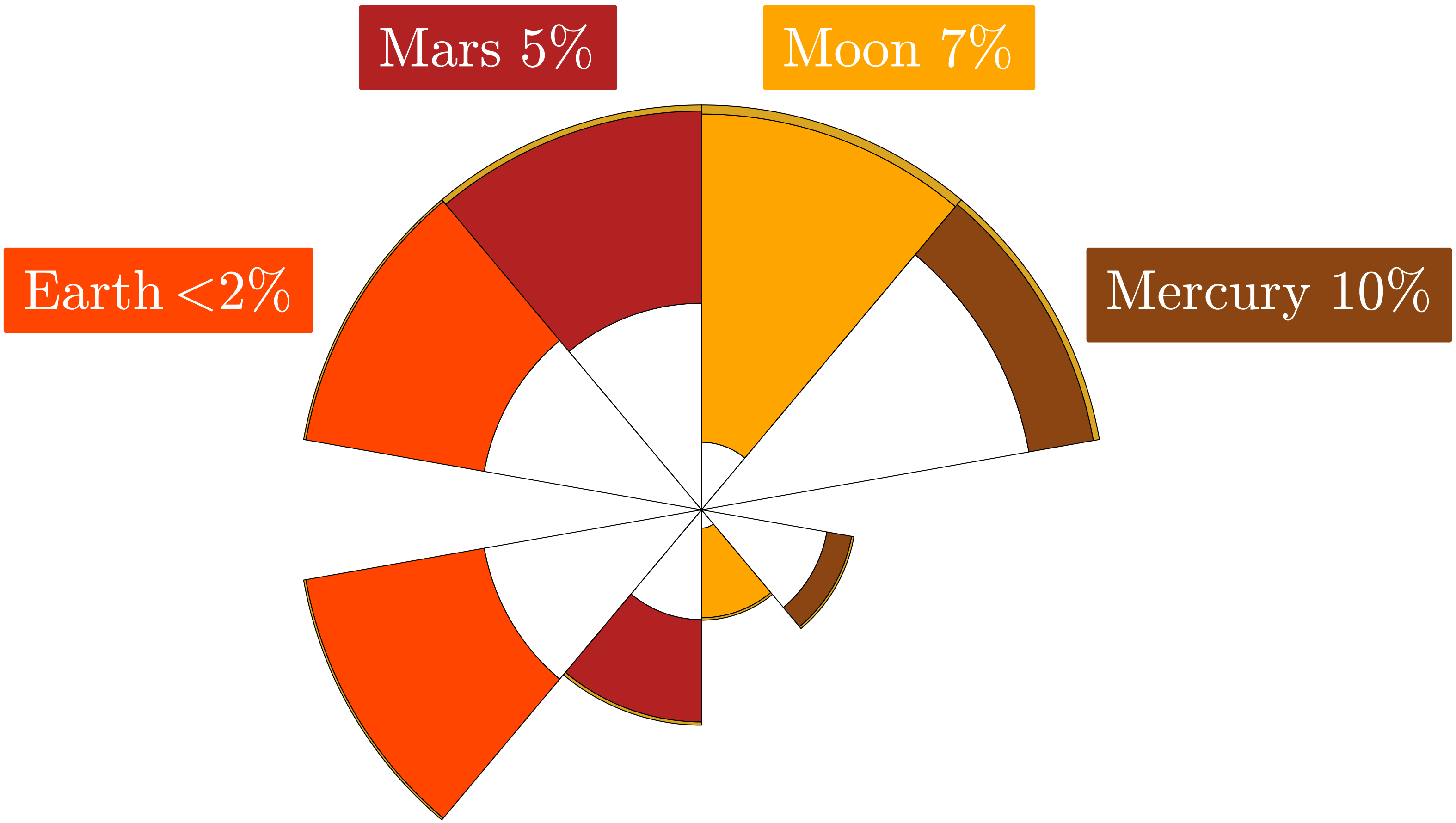




Compensation Model

Crustal thickness: 35 ±18 km (Padovan et al., 2015)

- Mercury has the highest efficiency of crustal production



Interior structure of Mercury

- State of the core
- Mean density of the core
- Radius of the core
- Mean density of the outer shell

Constant thoroughout evolution

- Large amount of melt produced
- Cold mantle at present

Time dependent

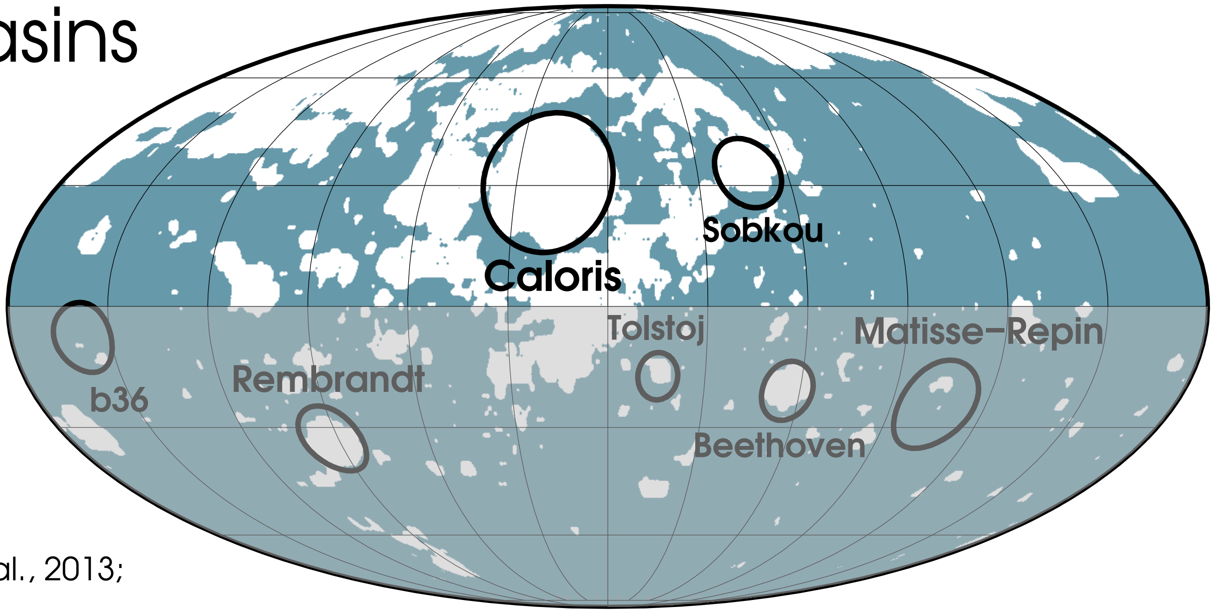
Evolution of Mercury

Questions:

- How did Mercury cooled during its evolution?
- When and how did the crust form?

Observables:

- Timing of the major volcanic eruptions
- Big impact basins



References: Fassett et al., 2012; Denevi et al., 2013; Padovan et al. ,2015.

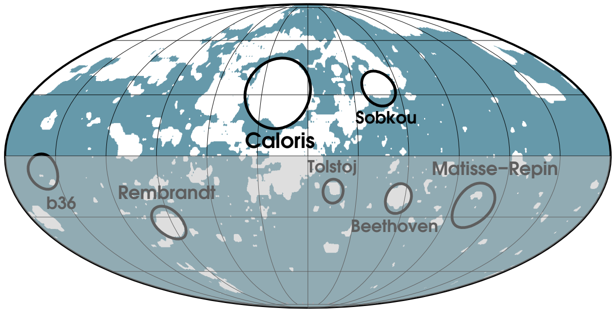
Evolution of Mercury

Questions:

- How did Mercury cooled during its evolution?
- When and how did the crust form?

Observables:

- Timing of the major volcanic eruptions
- Big impact basins

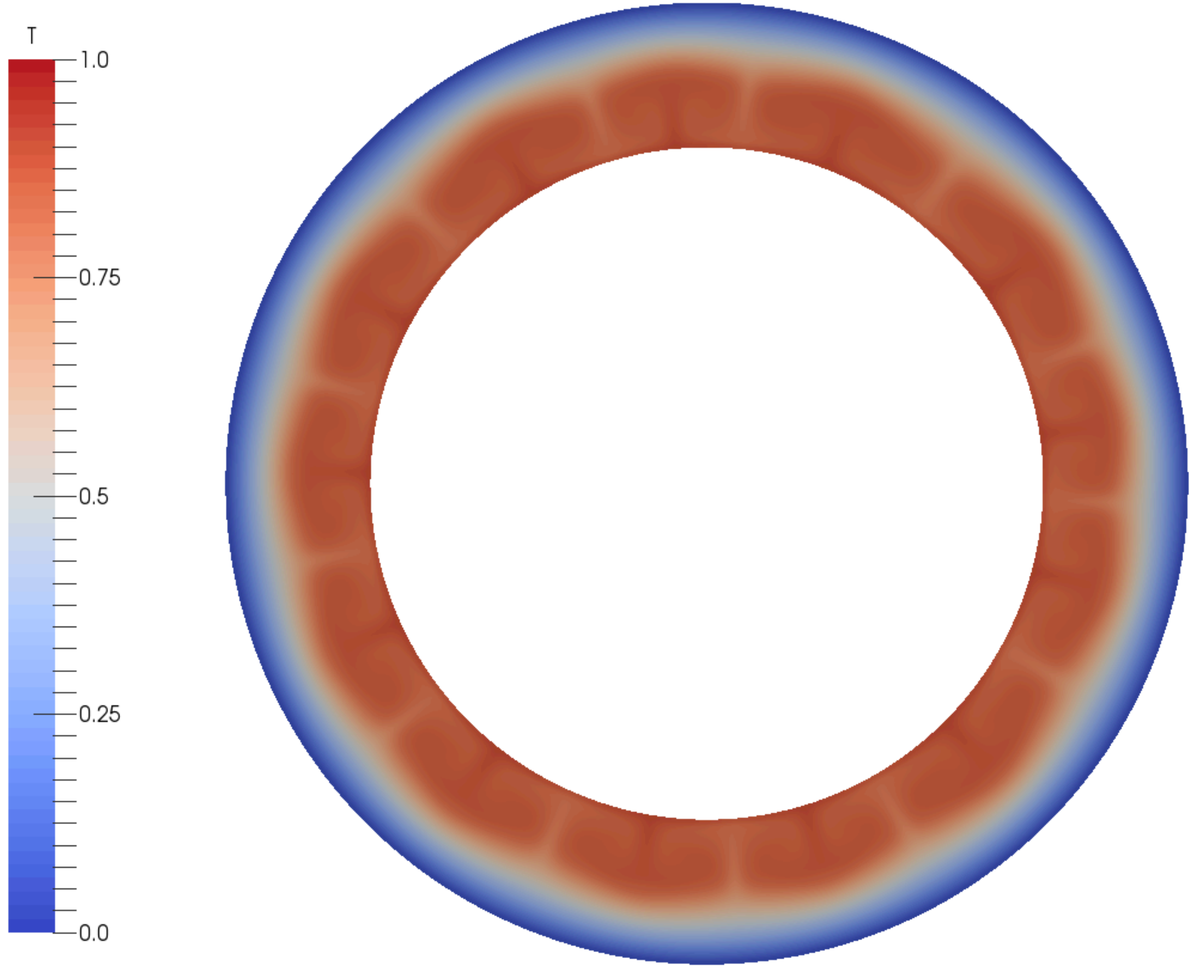


Models:

- Endogenic processes (mantle convection driven by decay of radioactive sources)
- Exogenic processes (impacts)

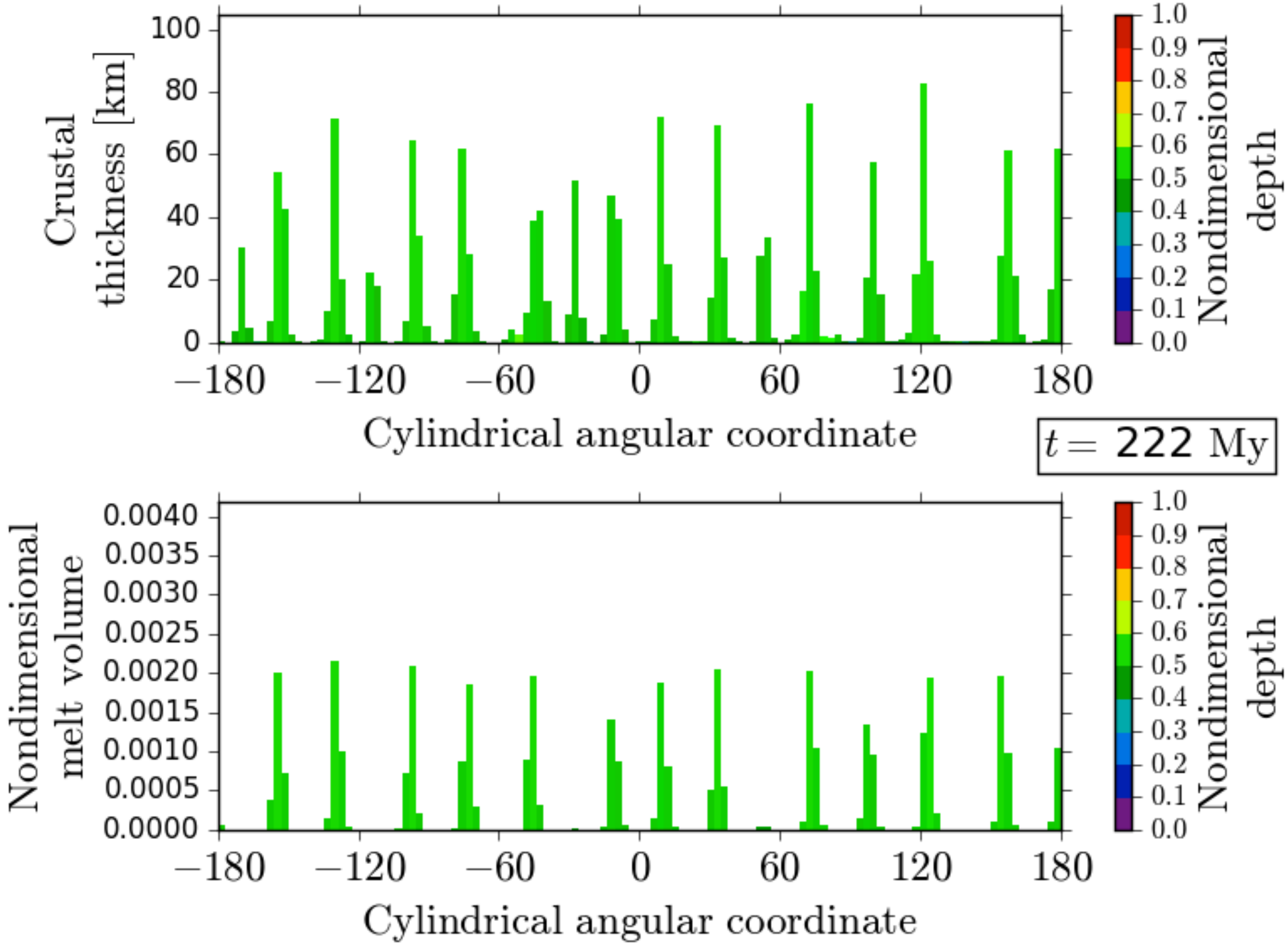
Evolution of Mercury

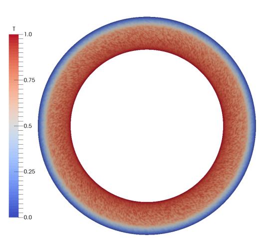
Convection



Evolution of Mercury

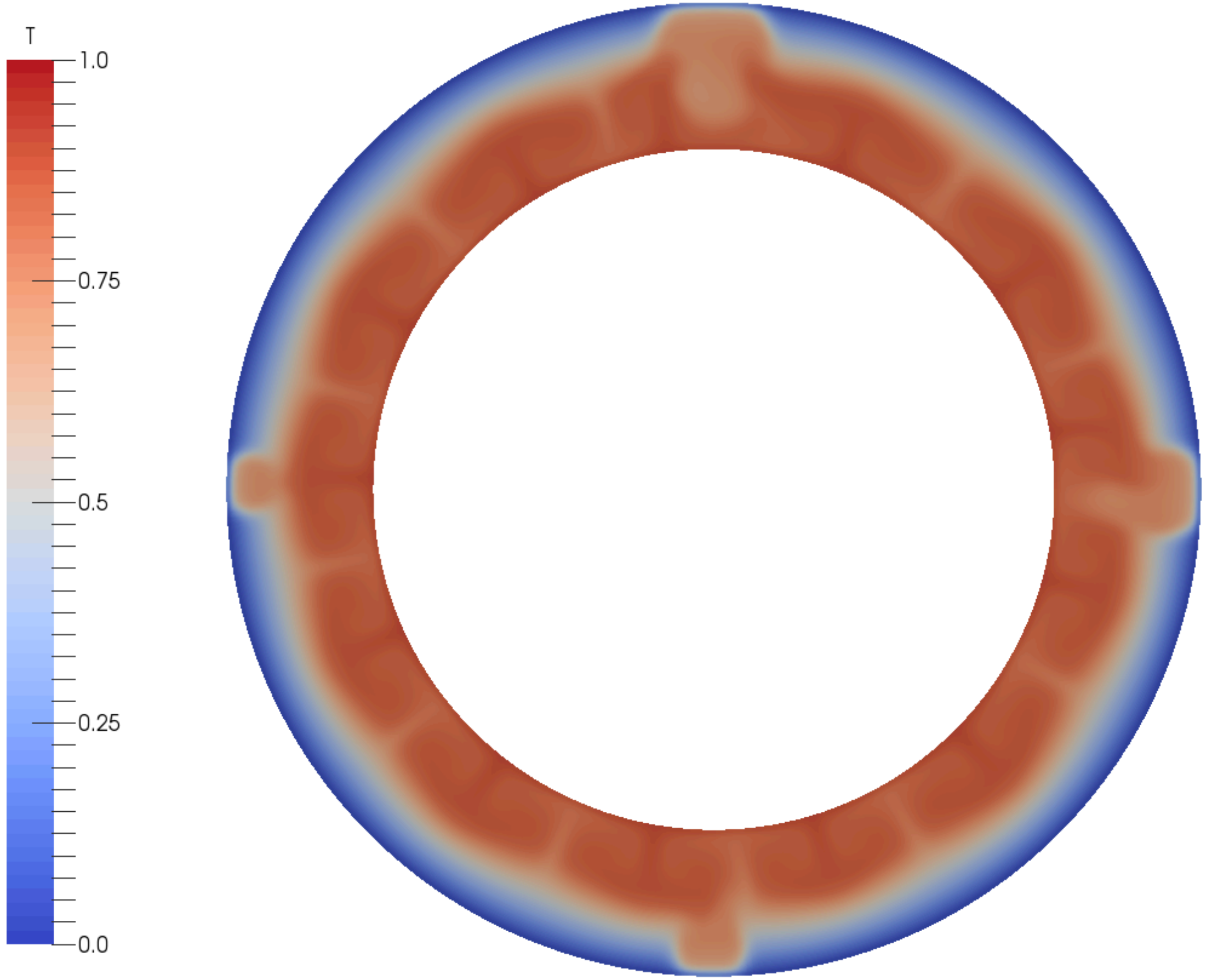
Melt Production from Convection





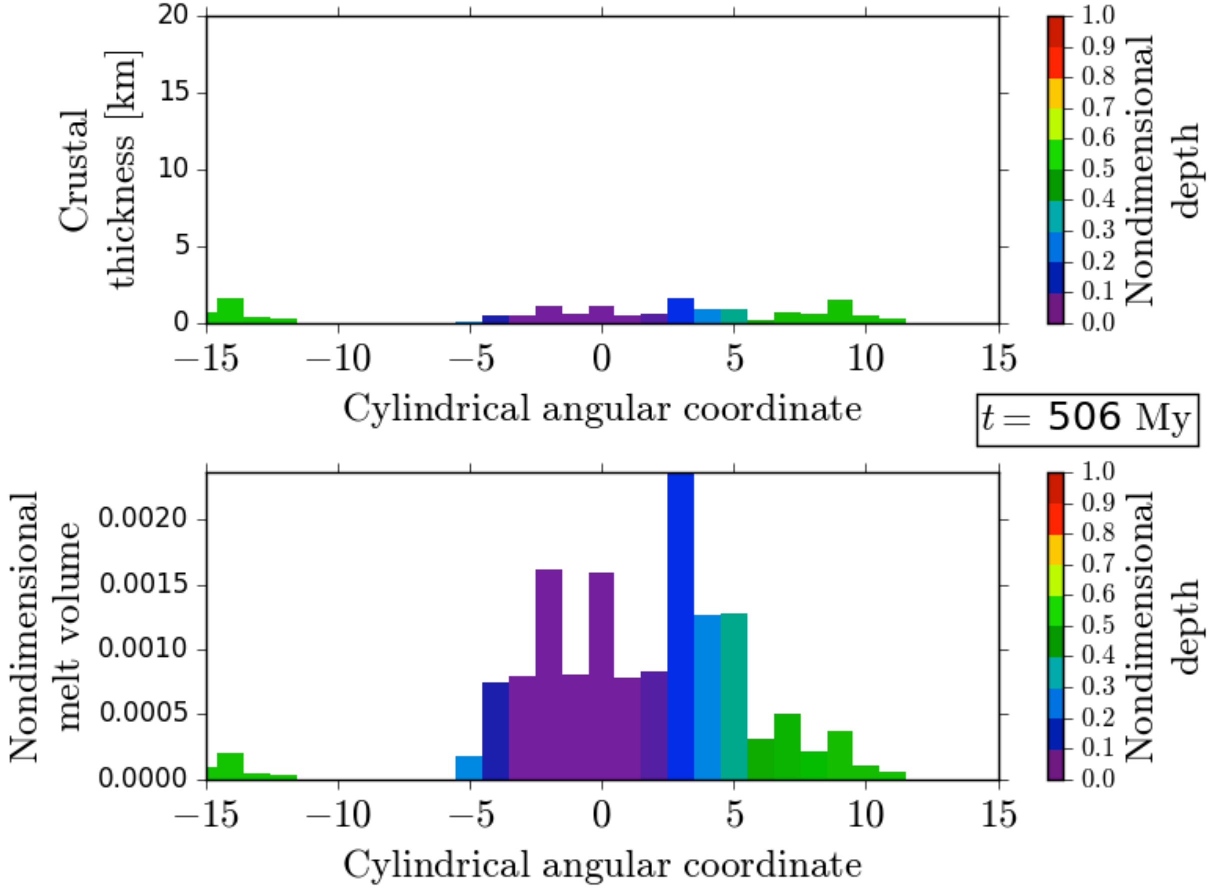
Evolution of Mercury

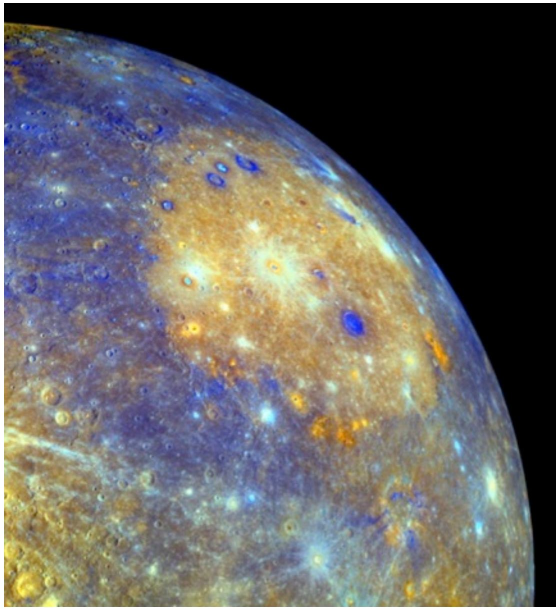
Convection + Impacts



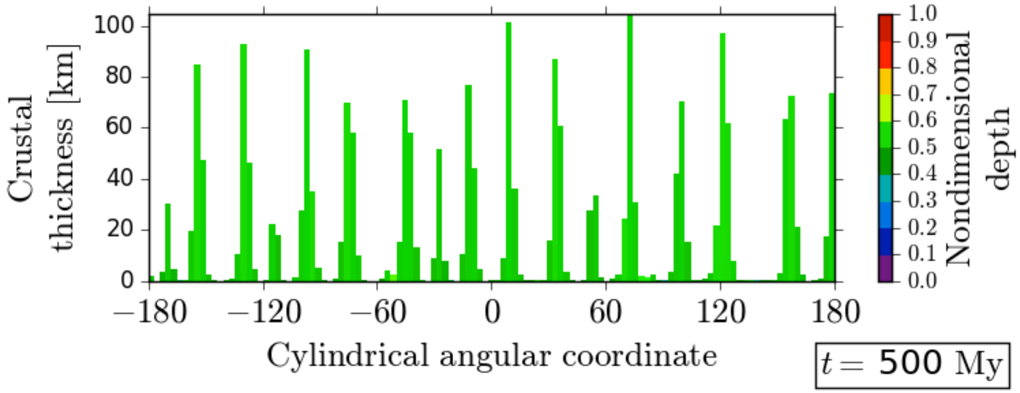
Evolution of Mercury

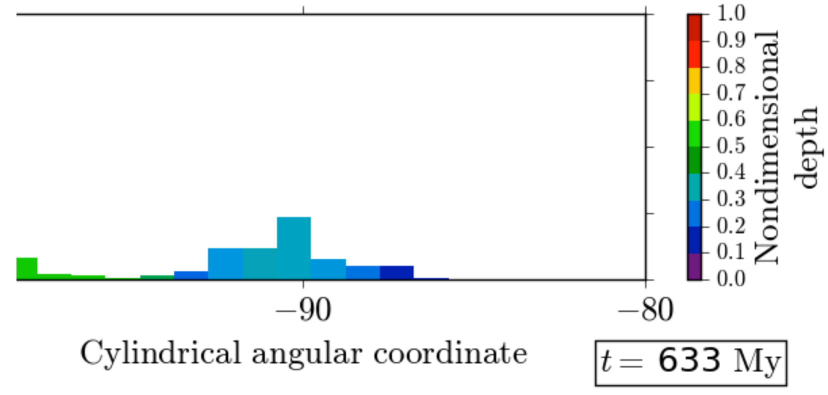
Post-impact Melt (Caloris basin)





Evolution of Mercury





- Around the impact site, the thermal anomalies induce melting at shallower depths with respect to the convection-only case
- The post-basin melt sheet is a few kilometers thick. This is compatible with estimates of the thickness of the upper layer of Caloris interior plains

References: Ernst et al., 2014.

Summary

The interior structure of Mercury is relatively well known:

- State of the outer core (liquid)
- Radius of the core
- Density of the core
- Density of the outer solid shell
- Crustal thickness
- Temperature of the CMB

Decreasing Precision

Current research:

- How did the present crust accumulate?
- How well can we tie the geological record to the thermal evolution?

Outlook

In a wider perspective, a few important things to be addressed are:

- What can we learn from just mean density?
- What does stellar composition tell about the interior of the planets?
- We should incorporate atmosphere production with interior modeling, given that atmosphere composition is probably the next information we will get from exoplanets.