# Mercury's thermo-chemical evolution from numerical models constrained by MESSENGER observations


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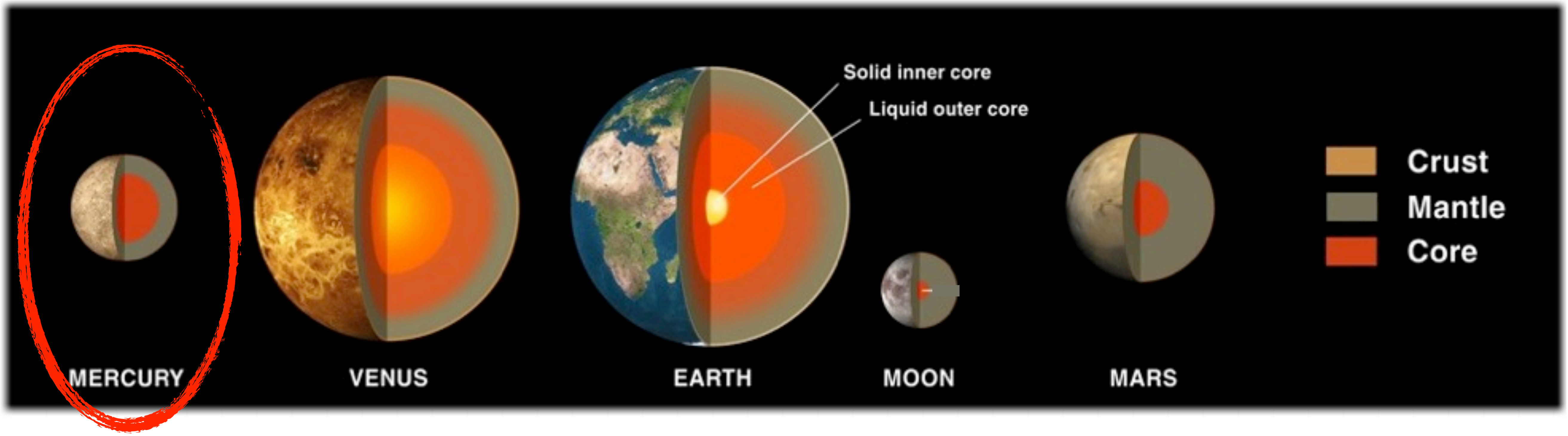
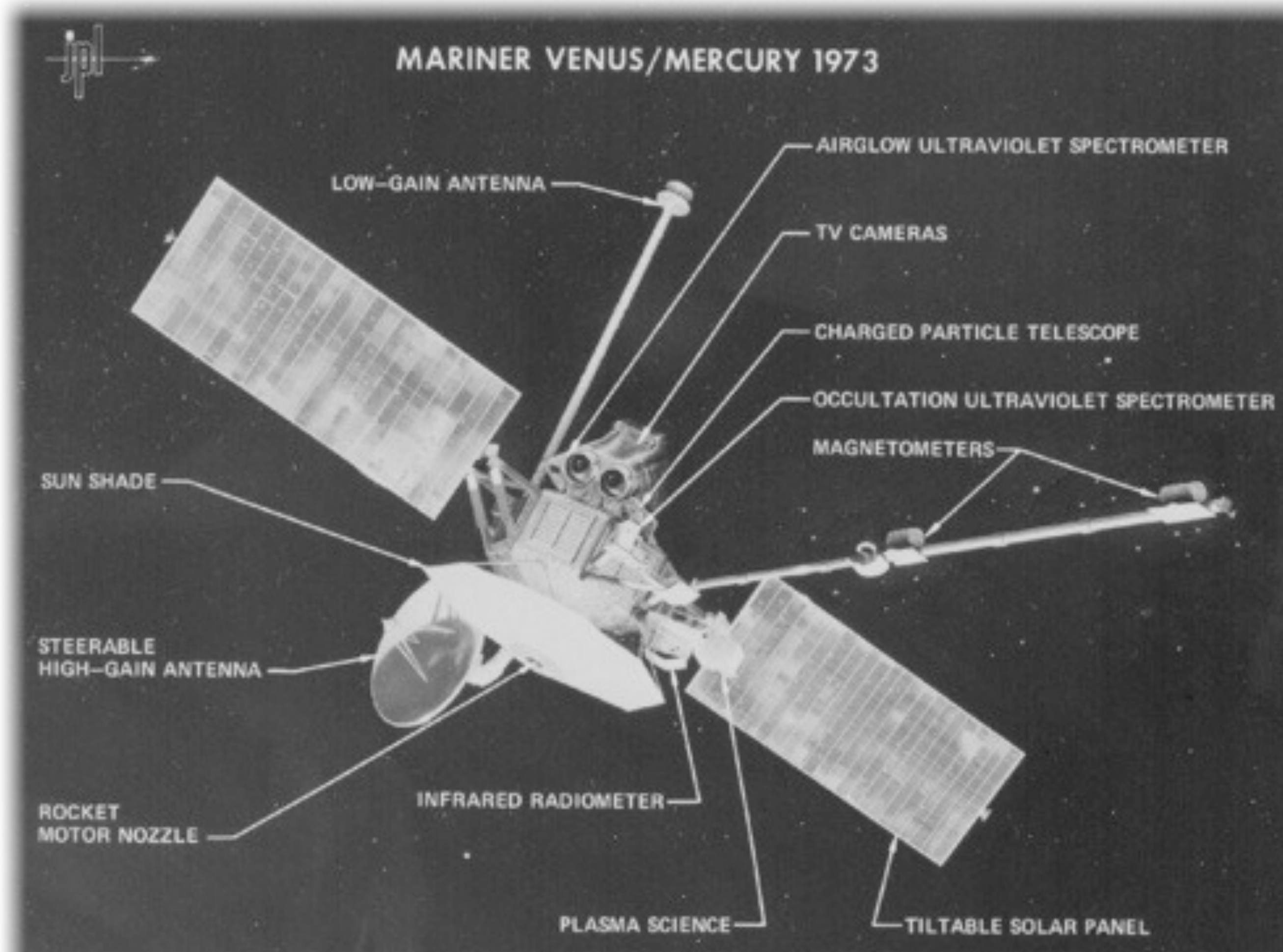
# Basics facts about Mercury




- Semi-major axis: 0.39 AU
- 3:2 spin-orbit resonance
- Radius: 2440 km
- Surface gravity: 3.7 m $s^{-2}$ (like Mars!)
- Mean bulk density: 5.43 g $cm^{-3}$ (like Earth!)
- Black body temperature: 440 K

# Exploration of Mercury

## Mariner10




- First spacecraft to use gravitational slingshot as proposed by Giuseppe Colombo
- 1 Venus and 3 Mercury flybys between 1974 and 1975
- Imaged ~45% of the surface
- Important findings:
  - heavily cratered surface similar to the that of Moon with peculiar tectonic features
  - tenuous atmosphere composed mainly by H, He and O
  - weak (~300 nT) dipolar magnetic field

# Exploration of Mercury

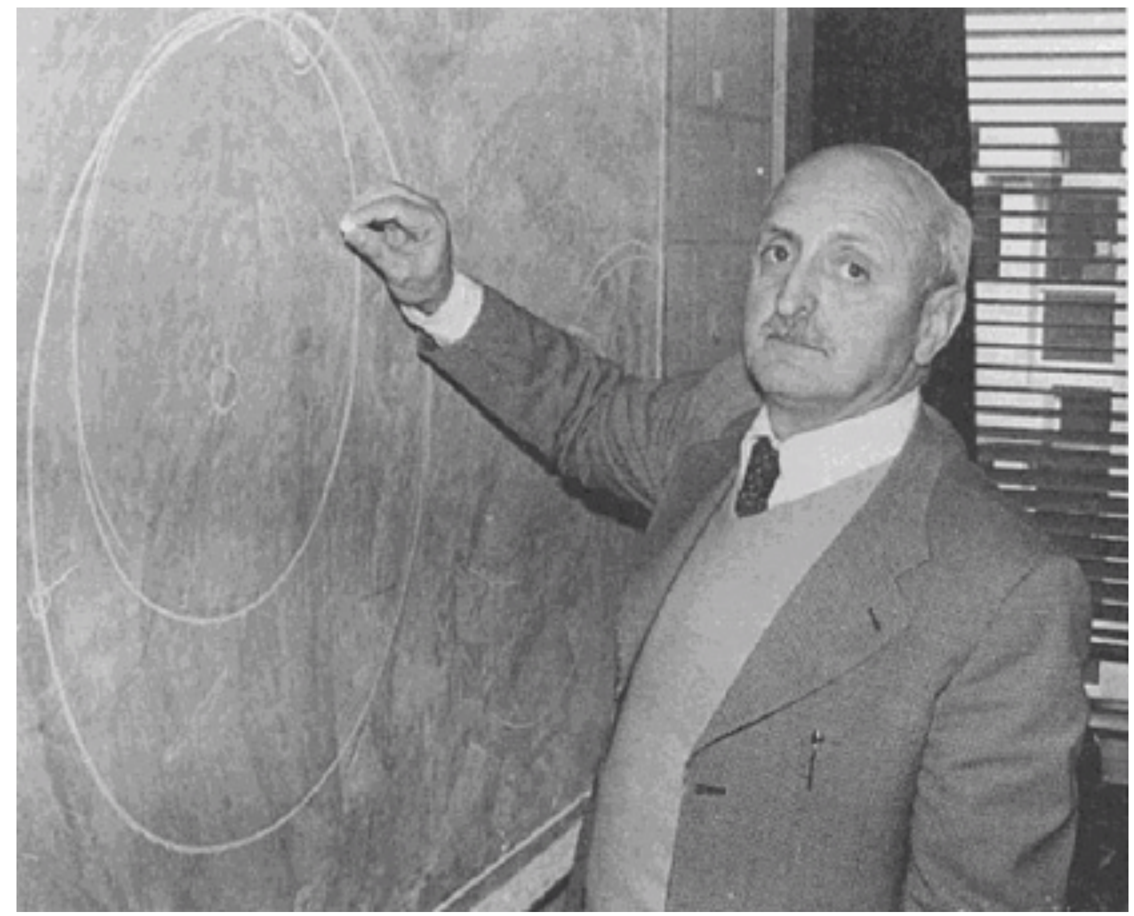

## MESSENGER

MErcury Surface, Space ENvironment, GEochemistry, and Ranging

- First spacecraft to orbit Mercury
- 1 Earth, 2 Venus and 3 Mercury flybys between 2005 and 2011
- Orbit insertion on March 18th 2011
- Highly elliptic, near-polar, 12-hours orbit (~200-15000 km altitude)
- 7 instruments for imaging, atmospheric and surface composition, magnetic field and magnetosphere, topography and gravity

# Exploration of Mercury


## BepiColombo

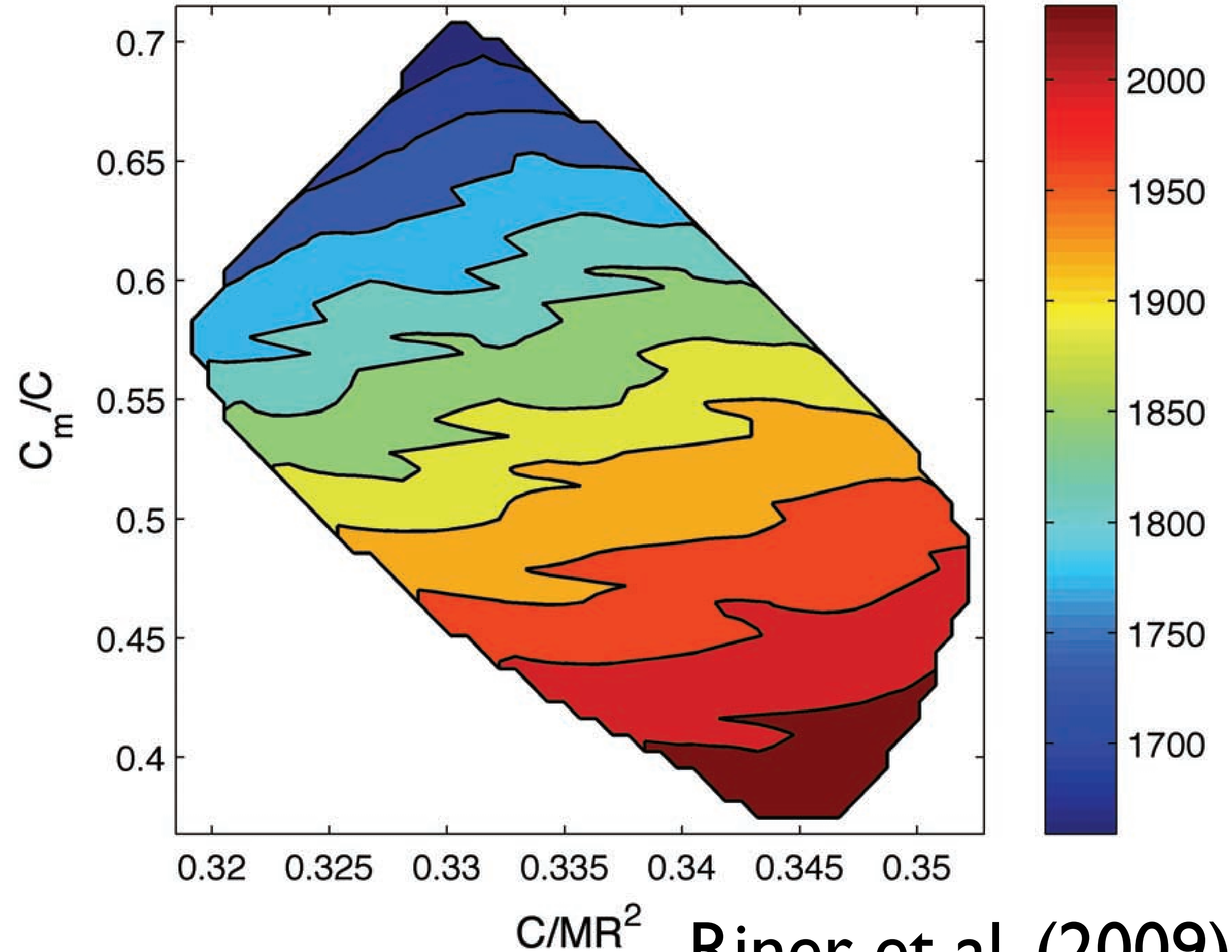


- Joint ESA-JAXA mission due to launch in 2015
- In orbit by 2022 after 1 Earth, 2 Venus and 4 Mercury flybys

# Interior structure and core state

- Pre-MESSENGER interior models (e.g. Riner et al., 2009) constrained by density only ⇒ wide range of plausible core radii: ~1700-2100 km
- ⇒ need for accurate estimates of the moments of inertia *$C/MR^2$ and $C_m/C$*

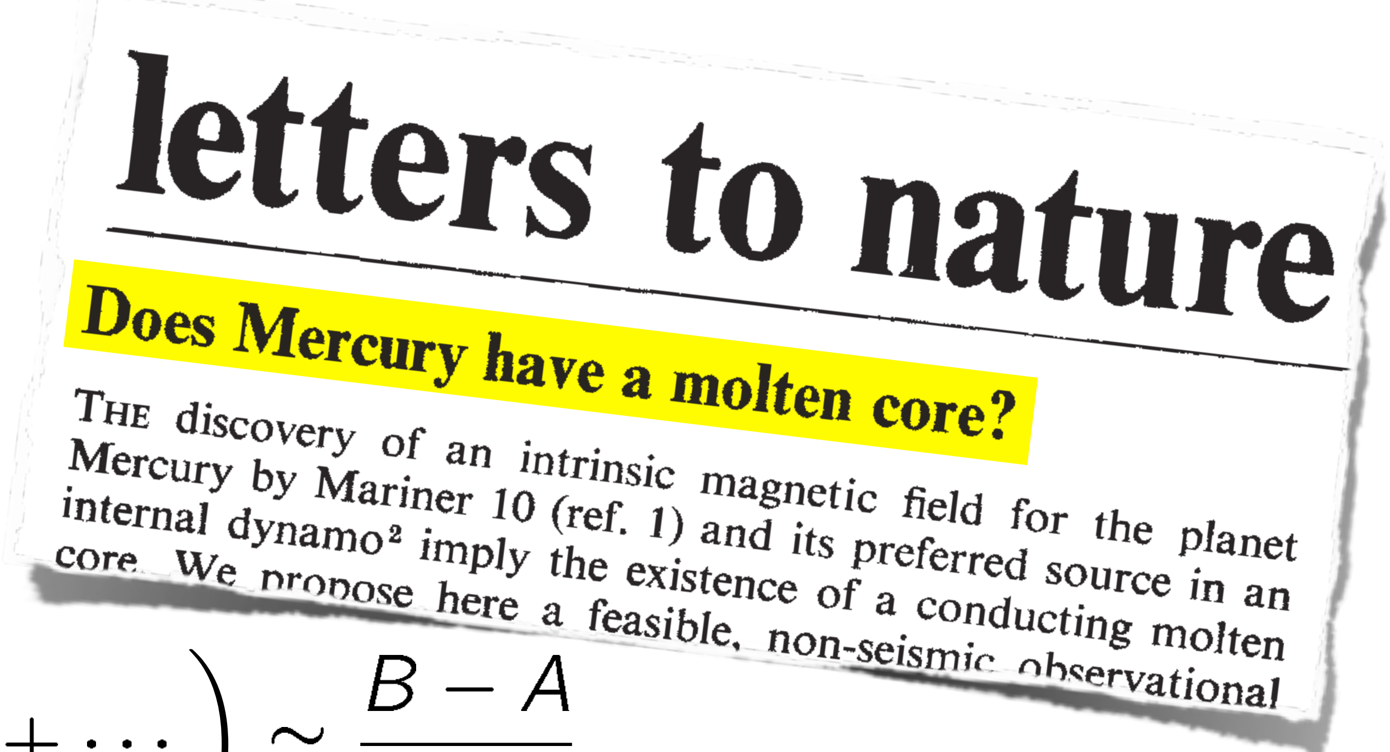
Core radius




Riner et al. (2009)

- Magnetic field ⇒ dynamo ⇒ fluid core ⇒ light alloying element (sulfur?) to prevent complete freezing
- ⇒ accurate knowledge of the core size and state is crucial for structure-, dynamo- and convection models

# “Peale’s experiment”


letters to nature

**Does Mercury have a molten core?**

THE discovery of an intrinsic magnetic field for the planet Mercury by Mariner 10 (ref. 1) and its preferred source in an internal dynamo[2] imply the existence of a conducting molten core. We propose here a feasible, non-seismic observational

Amplitude of the forced librations in longitude with period of 88 days:

$$\Phi = \frac{3}{2}\left(\frac{B-A}{C_m}\right)\left(1 - 11e^2 + \frac{959}{48}e^4 + \cdots\right) \simeq \frac{B-A}{C_m}$$

Peale (1976)

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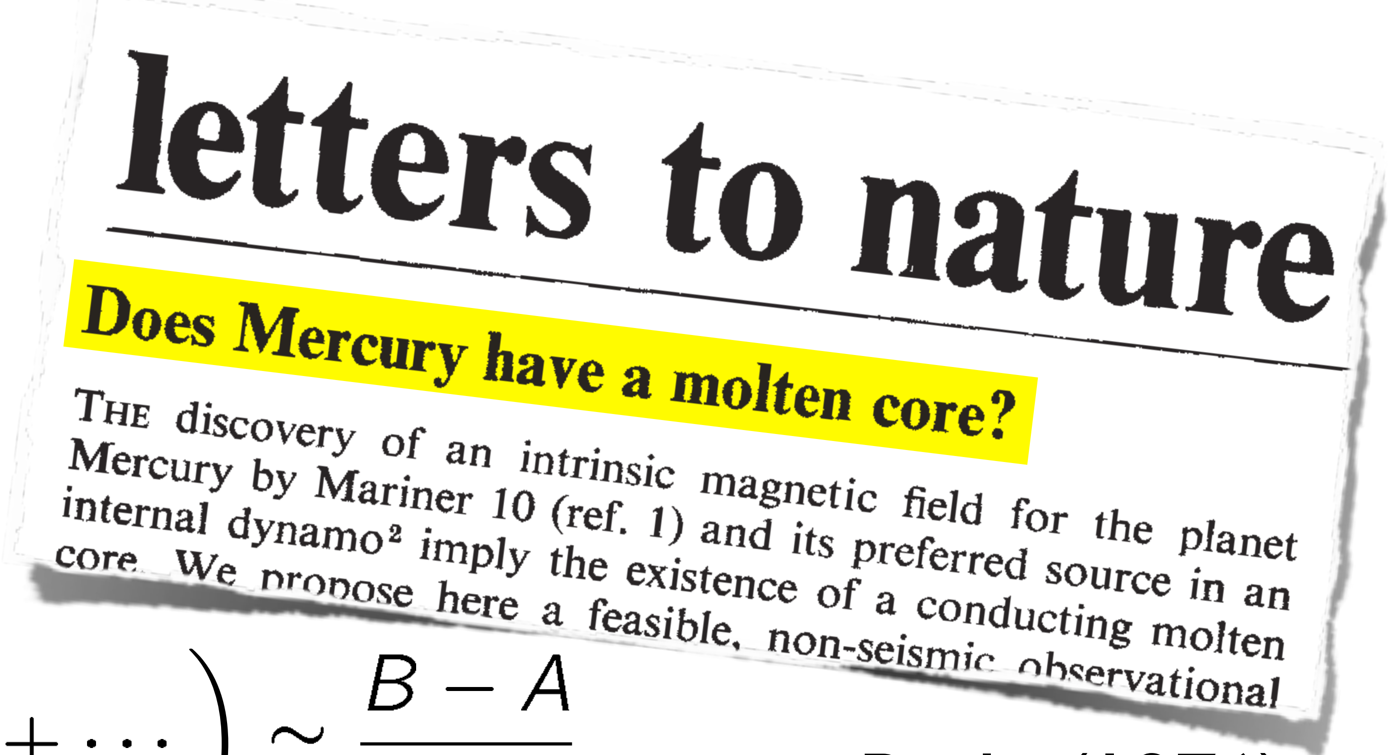

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If Mercury occupies a “Cassini state”:

$$K_1(\vartheta)\left(\frac{C-A}{C}\right) + K_2(\vartheta)\left(\frac{B-A}{C}\right) = K_3(\vartheta)$$

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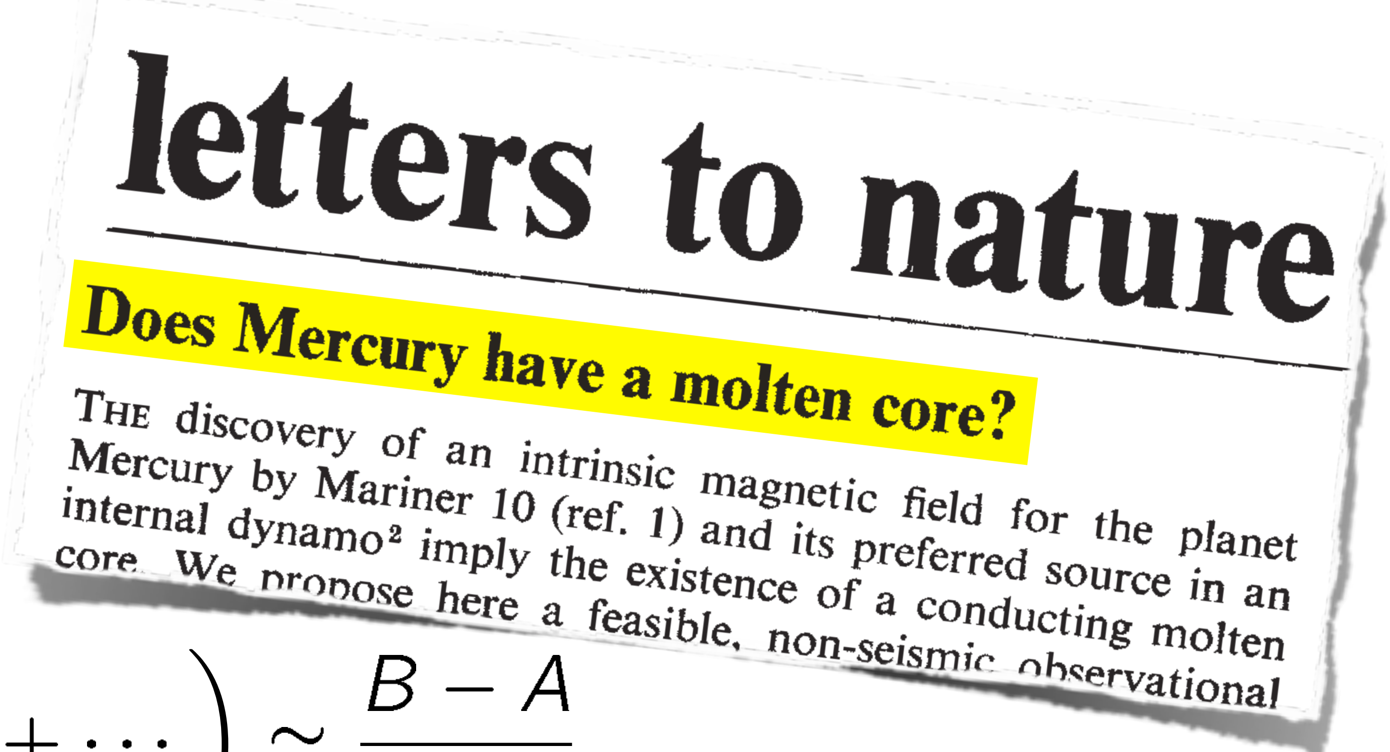
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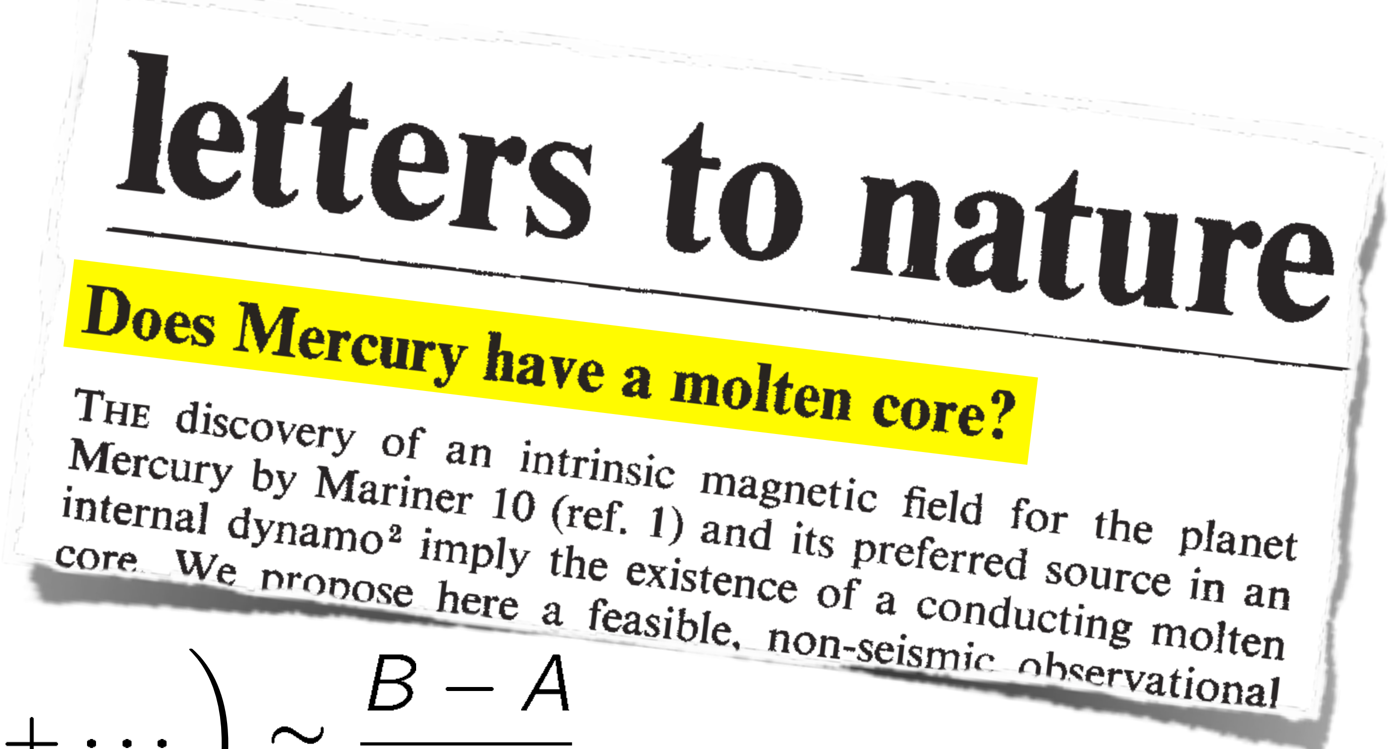
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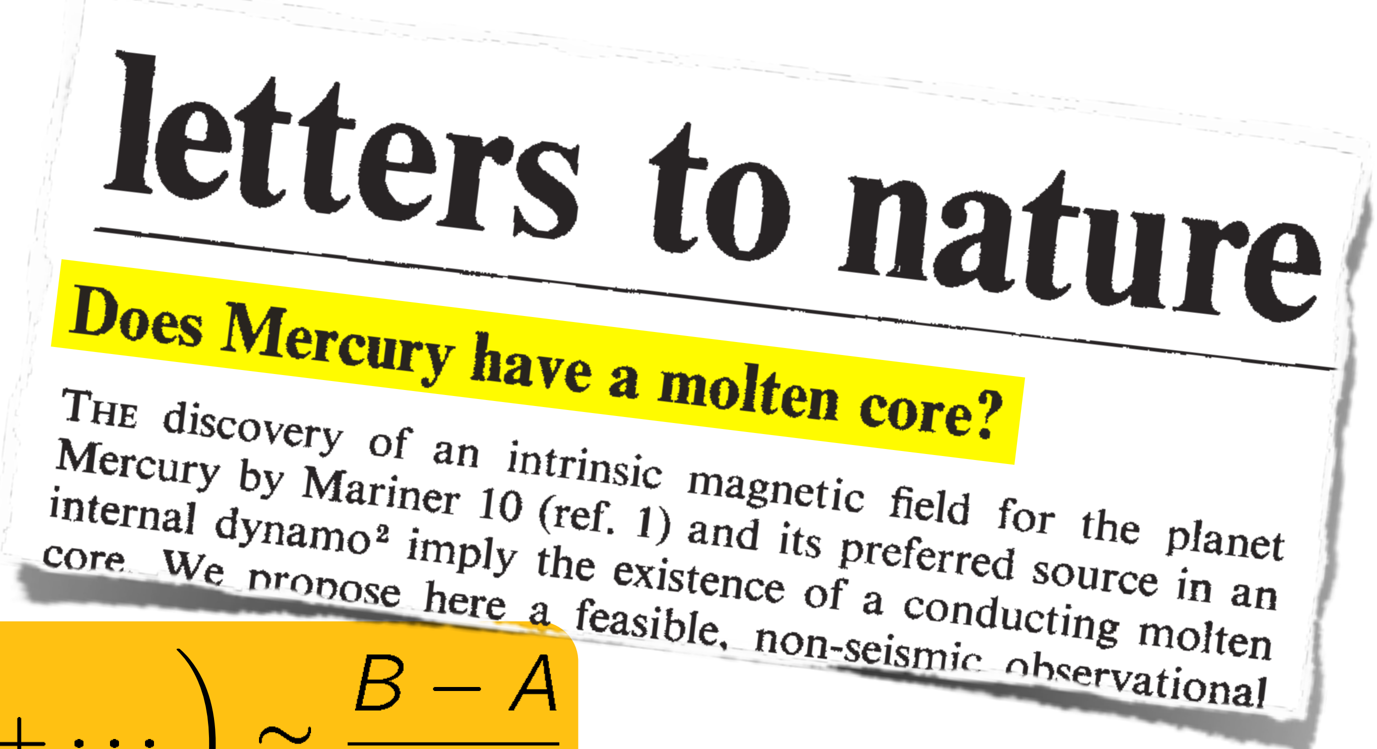
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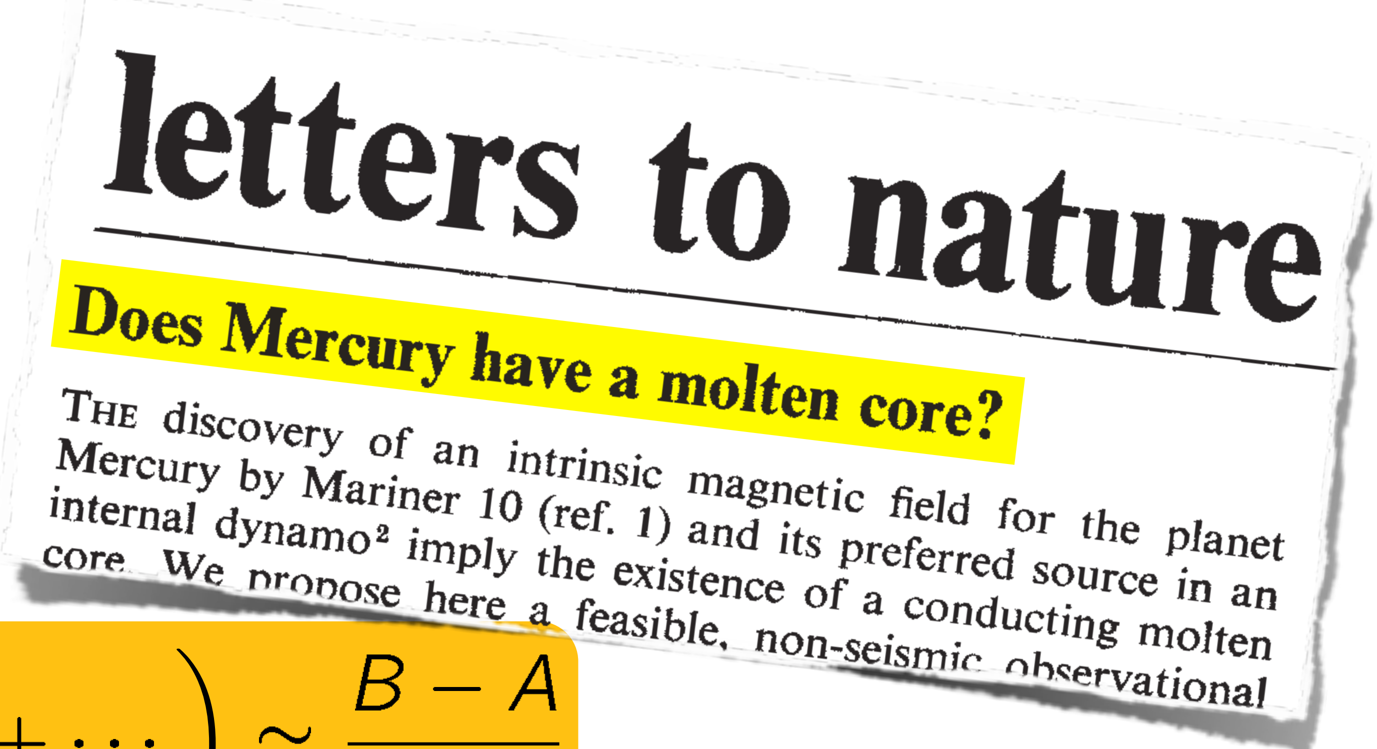

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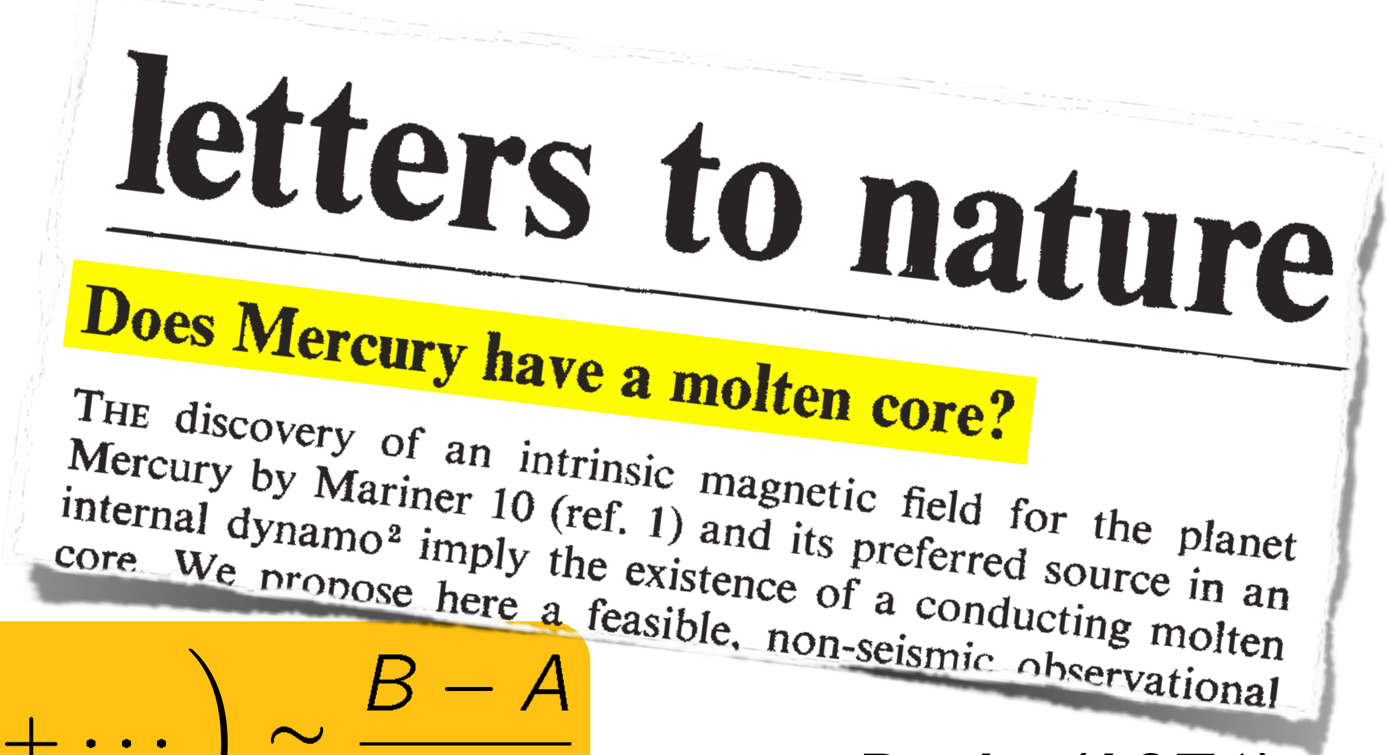
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For a liquid core: $\frac{C_m}{C} \leq 0.5$ and $\Phi^{\text{liquid}} \sim \frac{B-A}{C_m}$ then $\Phi^{\text{liquid}} > \Phi^{\text{solid}}$

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Earth-based high-precision radar measurements of Mercury's spin state and obliquity:

$\Phi = 35.8 \pm 2$ arc sec

$\vartheta = 2.11 \pm 0.1$ arc min

Margot et al. (2007)

**Large Longitude Libration of Mercury Reveals a Molten Core**

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From interior structure models:

$19 \leq \Phi^{\text{solid}} \leq 22$ arc sec

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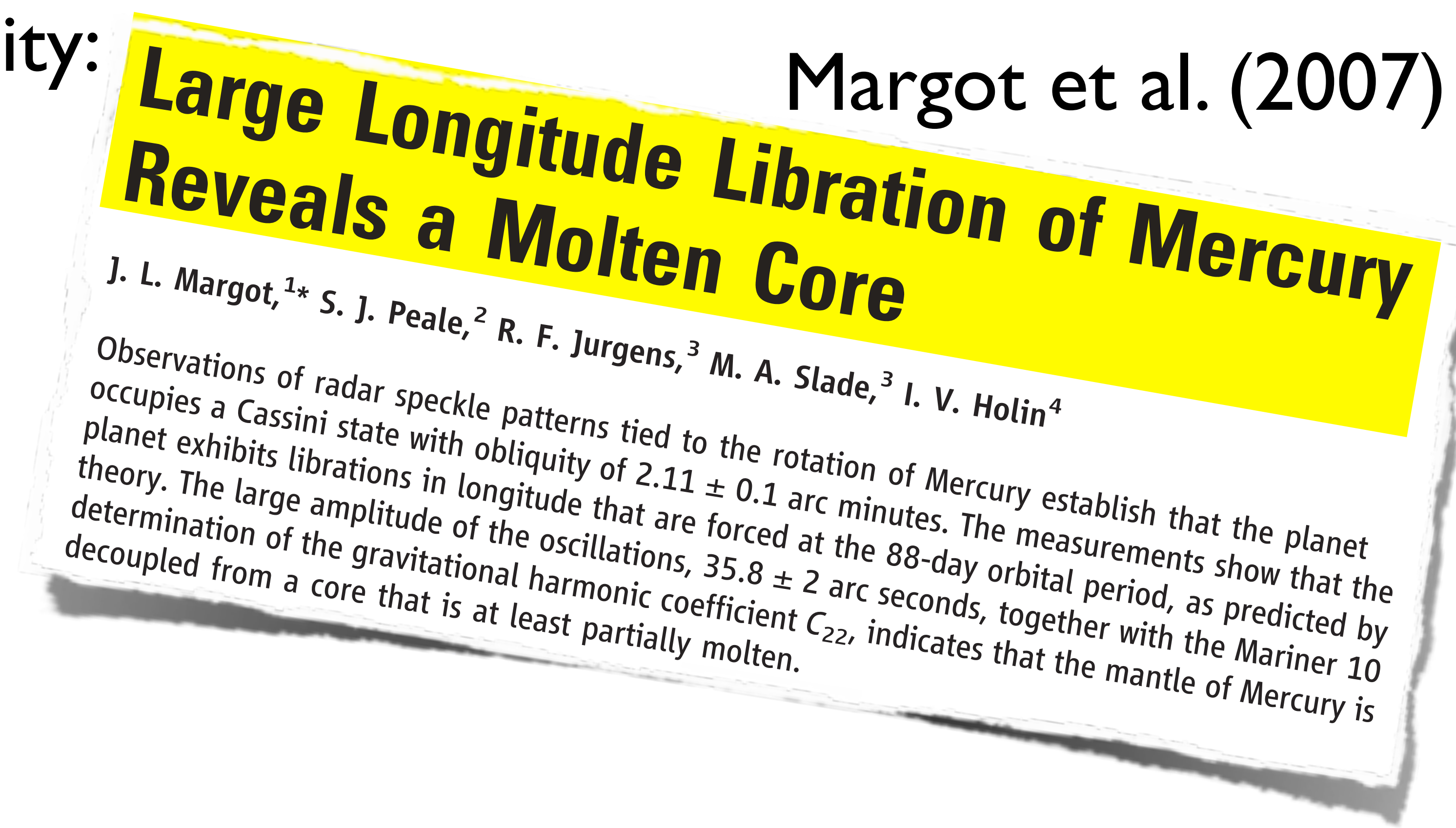
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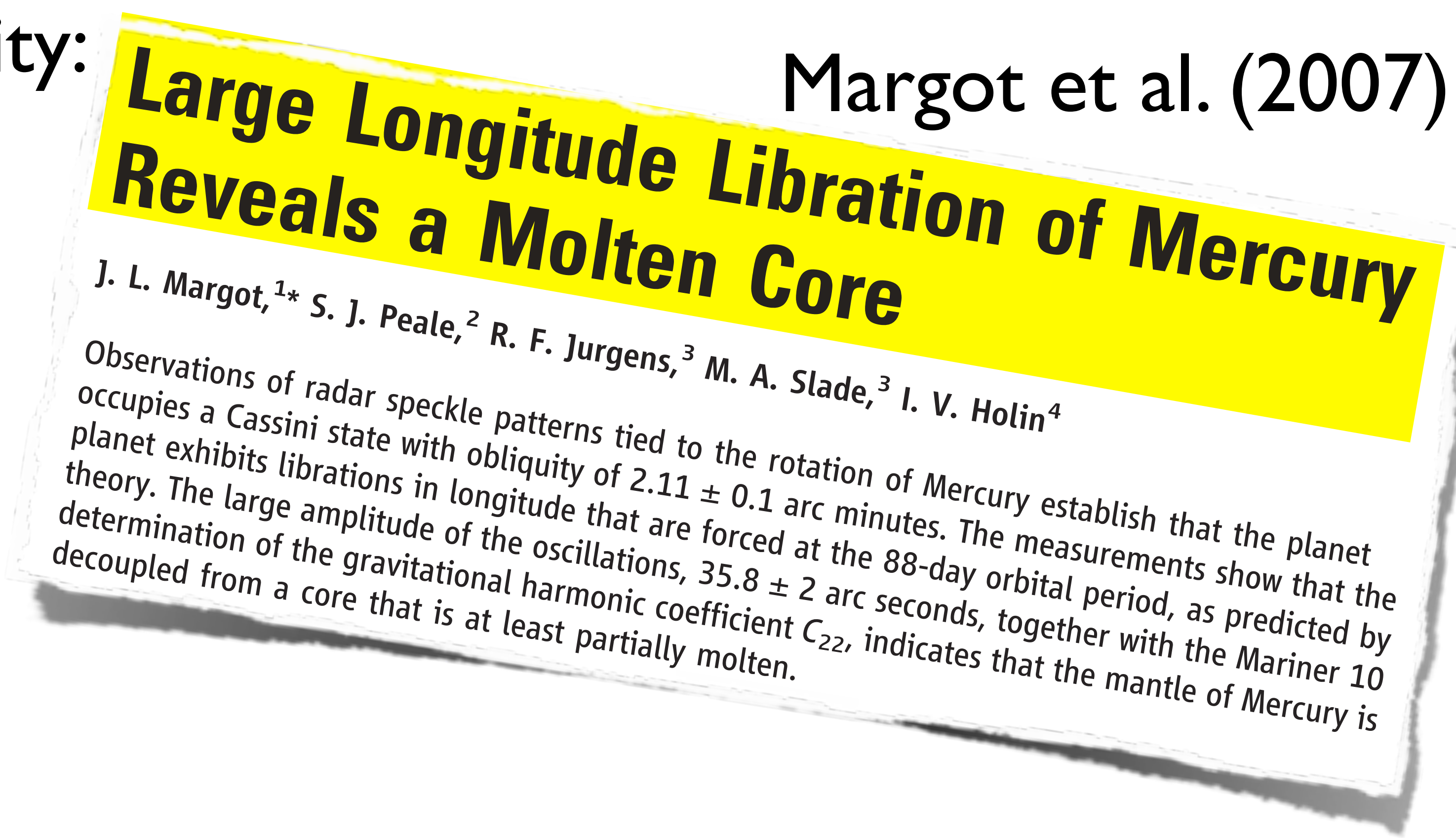

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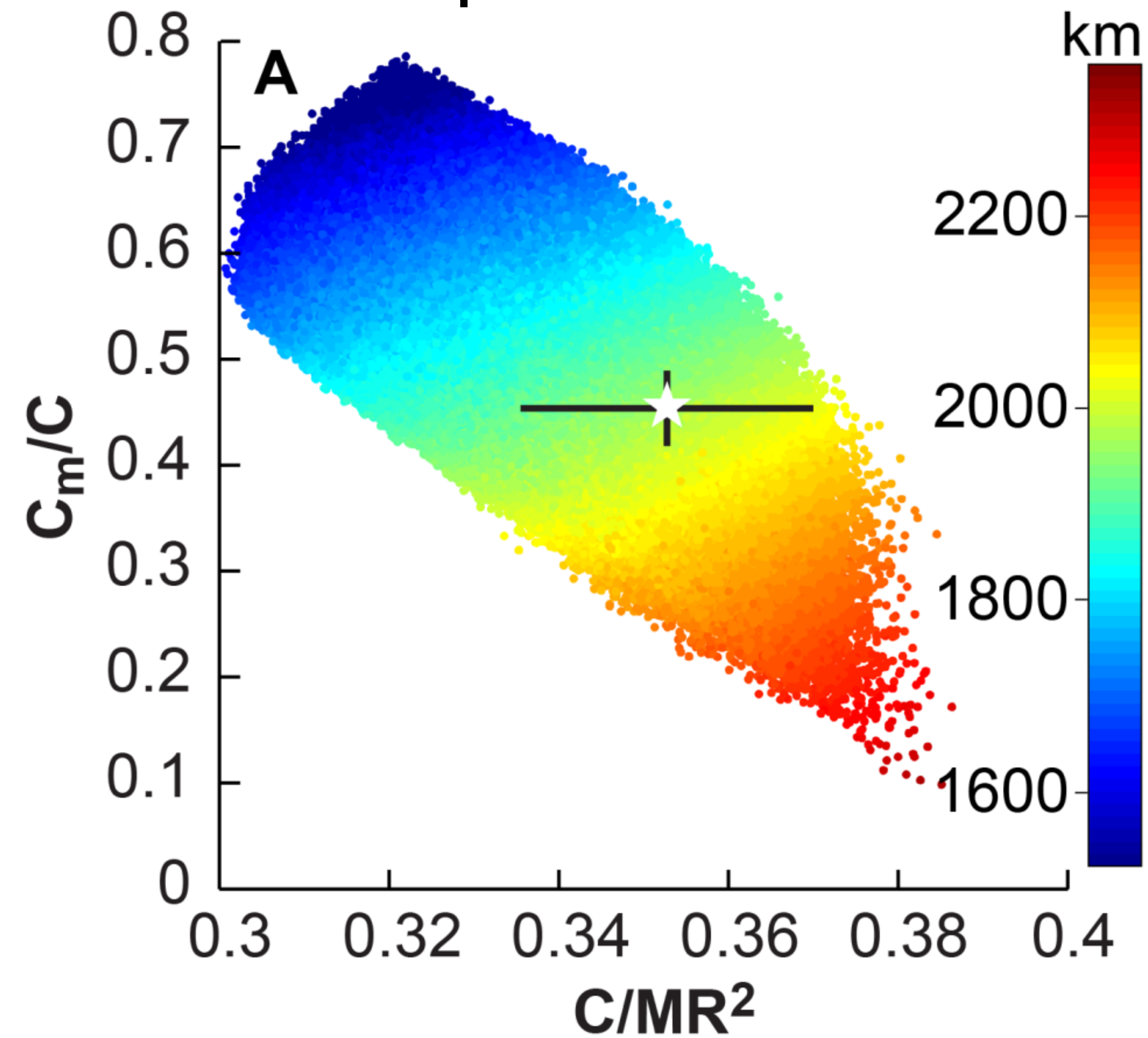
**Mercury’s core must be (at least partially) liquid**

# MESSENGER constraints on core size

- Improved estimates of $C_{20}$ and $C_{22}$ coefficients together with obliquity and spin state measurements yield:
  $C/MR^2 = 0.353 \pm 0.017$
  $C_m/C = 0.452 \pm 0.035$
- Interior structure models predict a core radius of ~2000 km (significantly larger than previously assumed)

Liquid core radius

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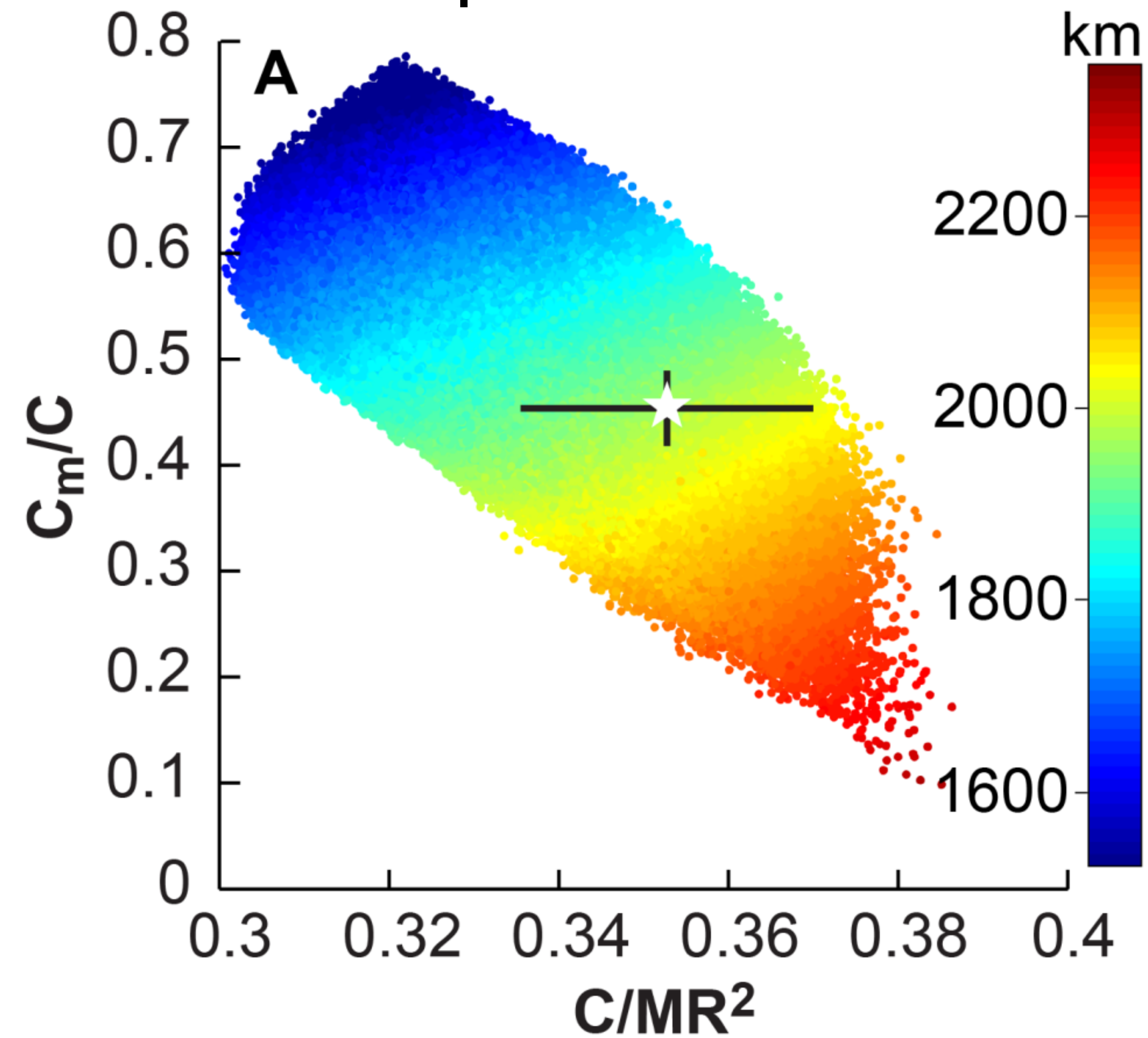


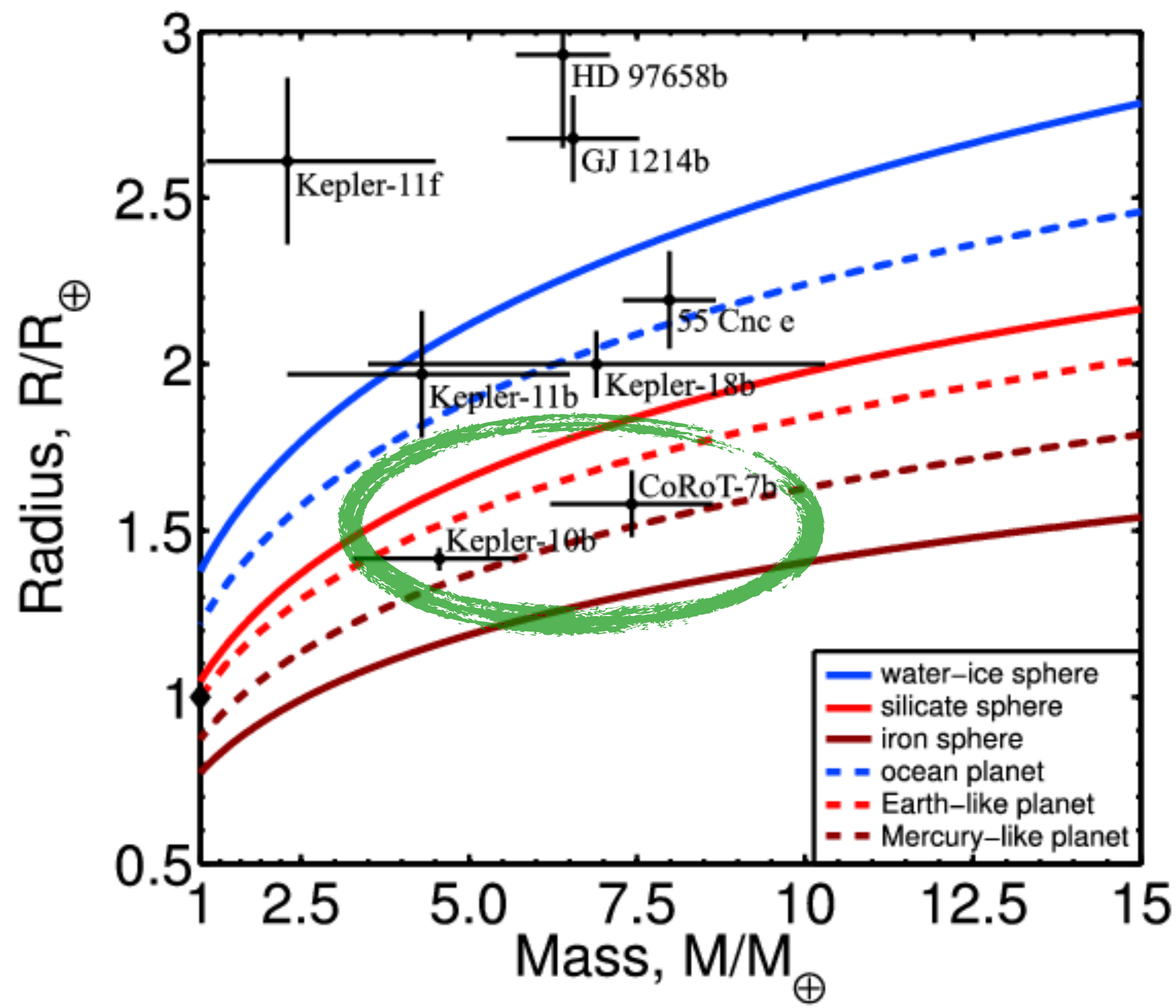

Hauck et al. (2012)

Mercury's silicate shell is only ~400 km thick

# "Super Mercuries"?

Iron-rich planets may not be so unusual

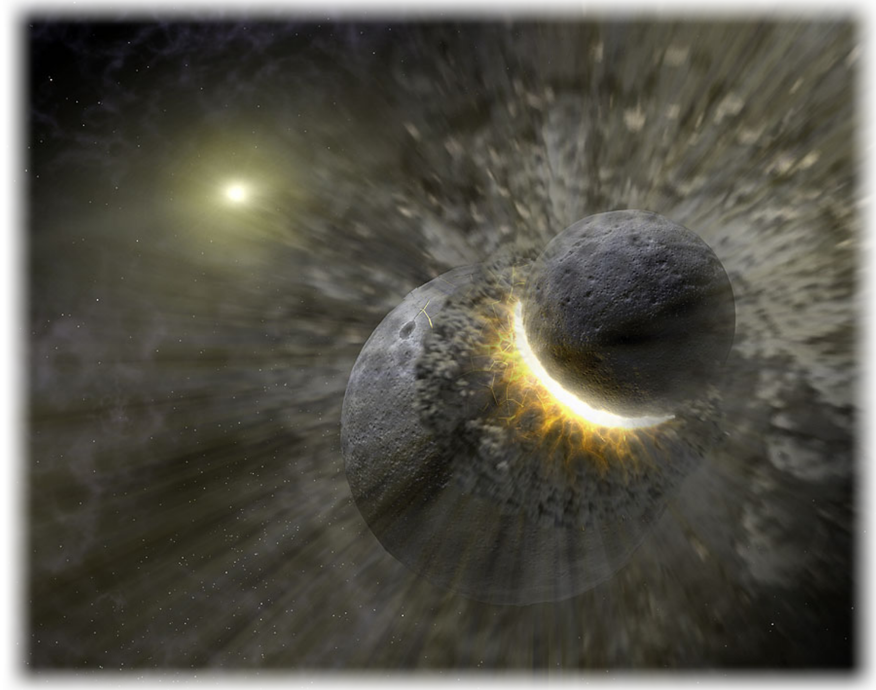
- CoRoT-7b and Kepler10b are the smallest extrasolar planets with measured mass and radius
- They possess a relatively large mean density and are expected to have large iron cores comprising ~60-70 wt-% of the planet

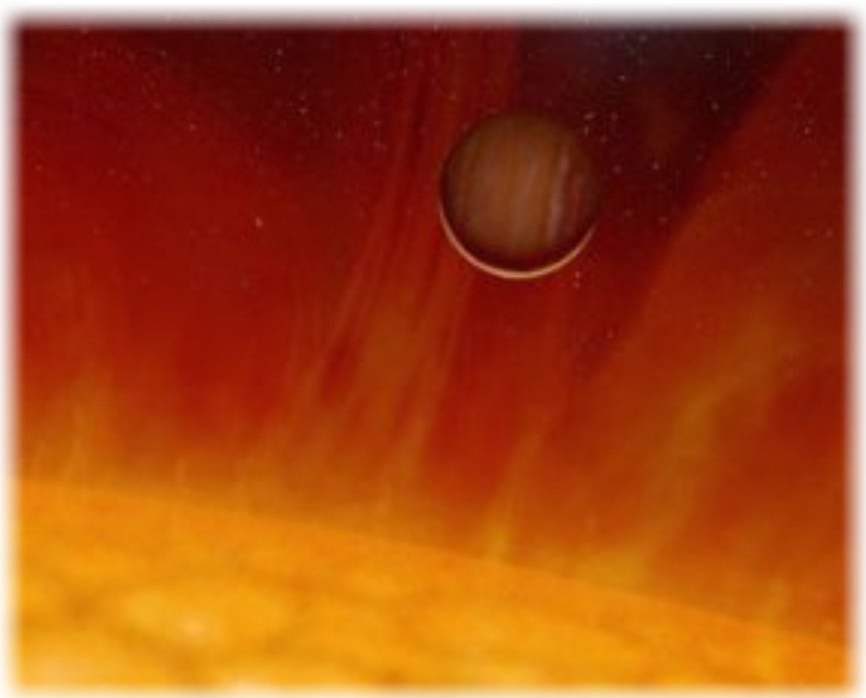



Wagner et al. (2012)

# Mercury's formation scenarios

- Evaporation model (Fegley & Cameron, 1987): vaporization of outer silicate shell in a high temperature (2500-3000 K) solar nebula
- Giant impact hypothesis: removal of early crust and upper mantle by one or more large impacts (Benz et al., 1988)

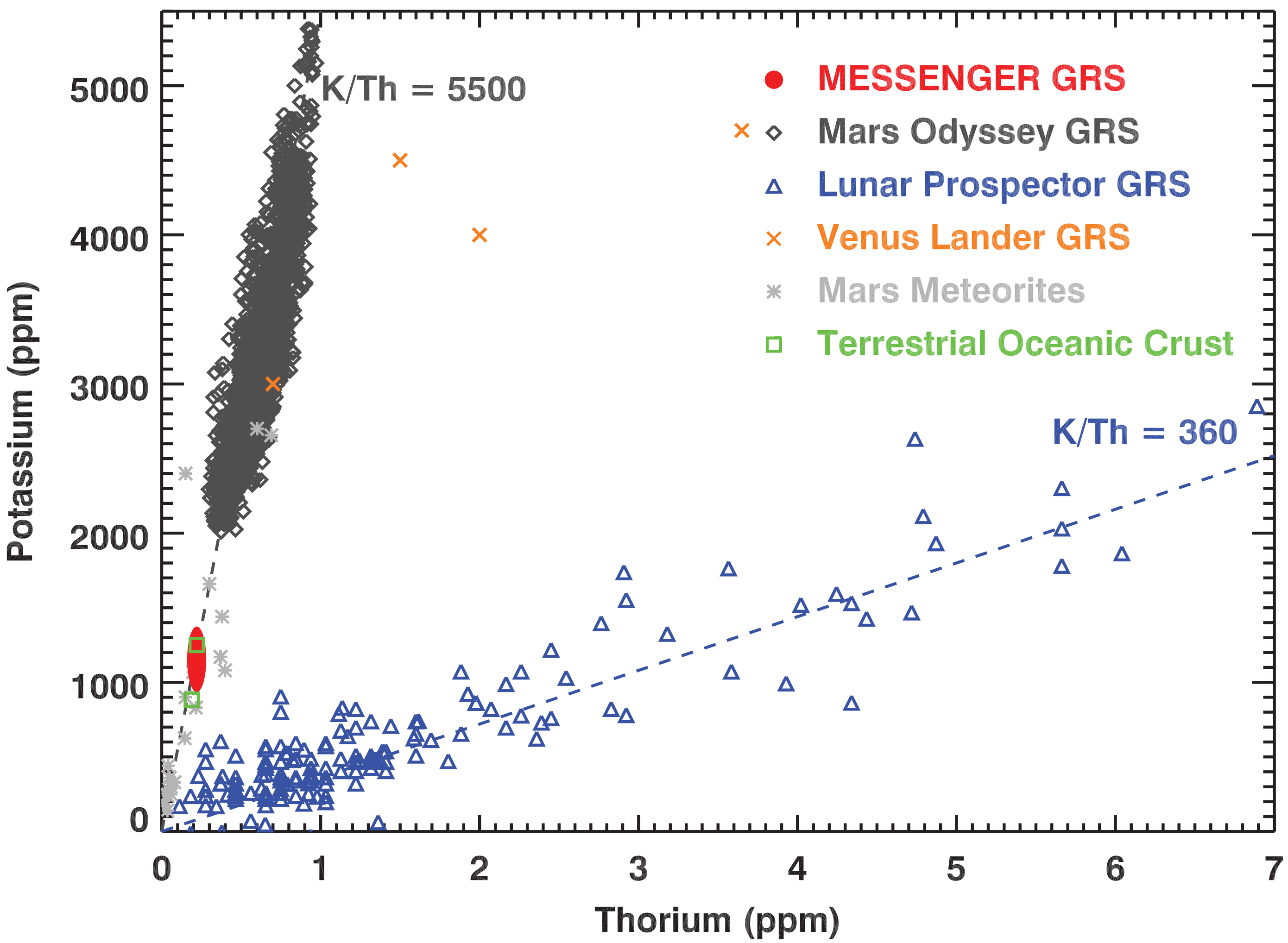




- Formation from high temperature condensates with all iron in metallic state rather than oxidized in FeO (Lewis, 1972)

# MESSENGER constraints on mantle composition

Evaporation, giant impact and high temperature condensate models all predict refractory compositions (rich in Th) and a nearly complete loss of volatiles




Peplowski et al. (2011)

Gamma-ray spectrometer measured the average surface abundances of radioactive elements:

Th: 220 ± 60 ppb

U: 90 ± 20 ppb

K: 1150 ± 220 ppm

Measurements of the X-ray spectrometer revealed a S-enriched surface

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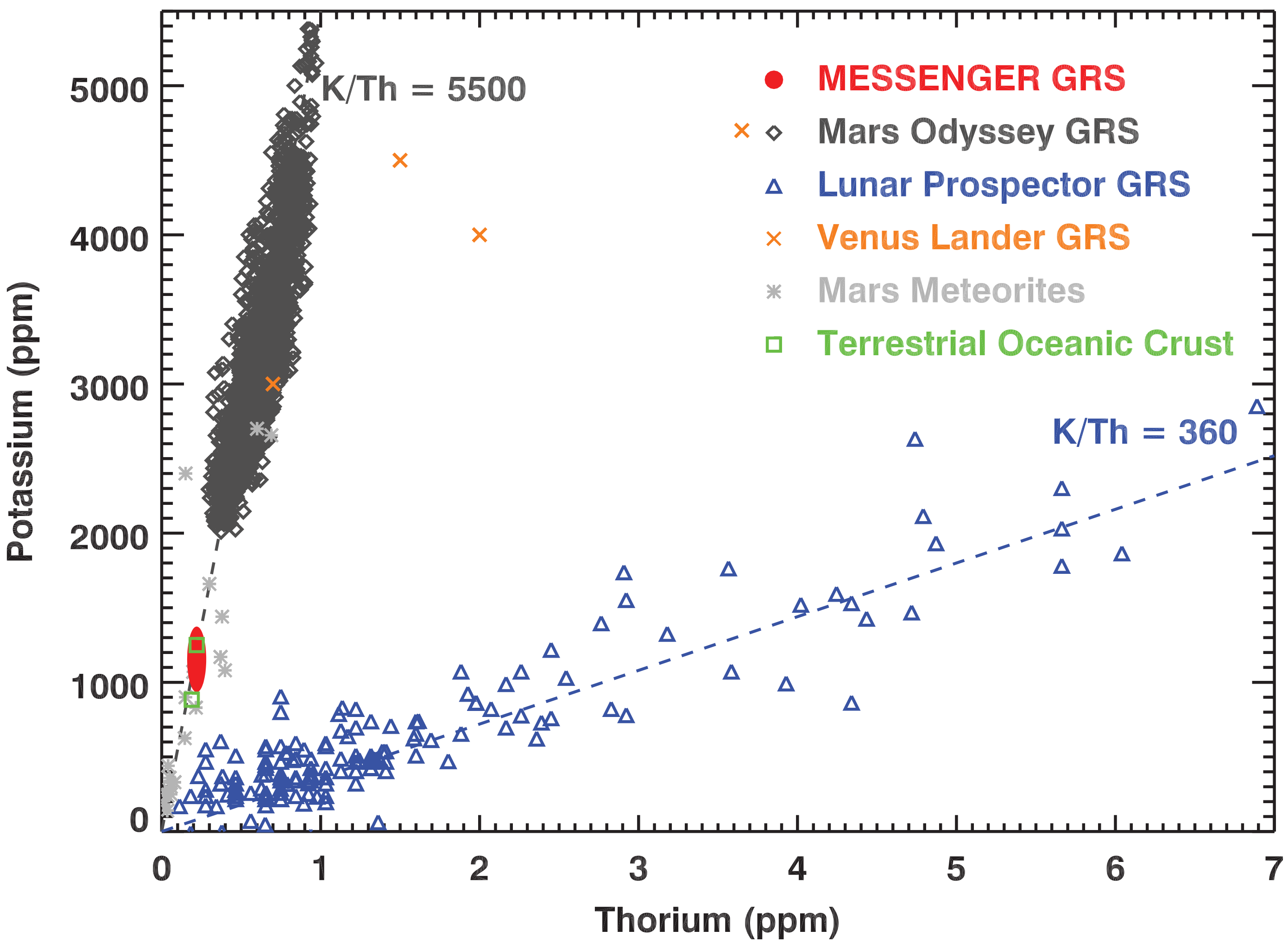


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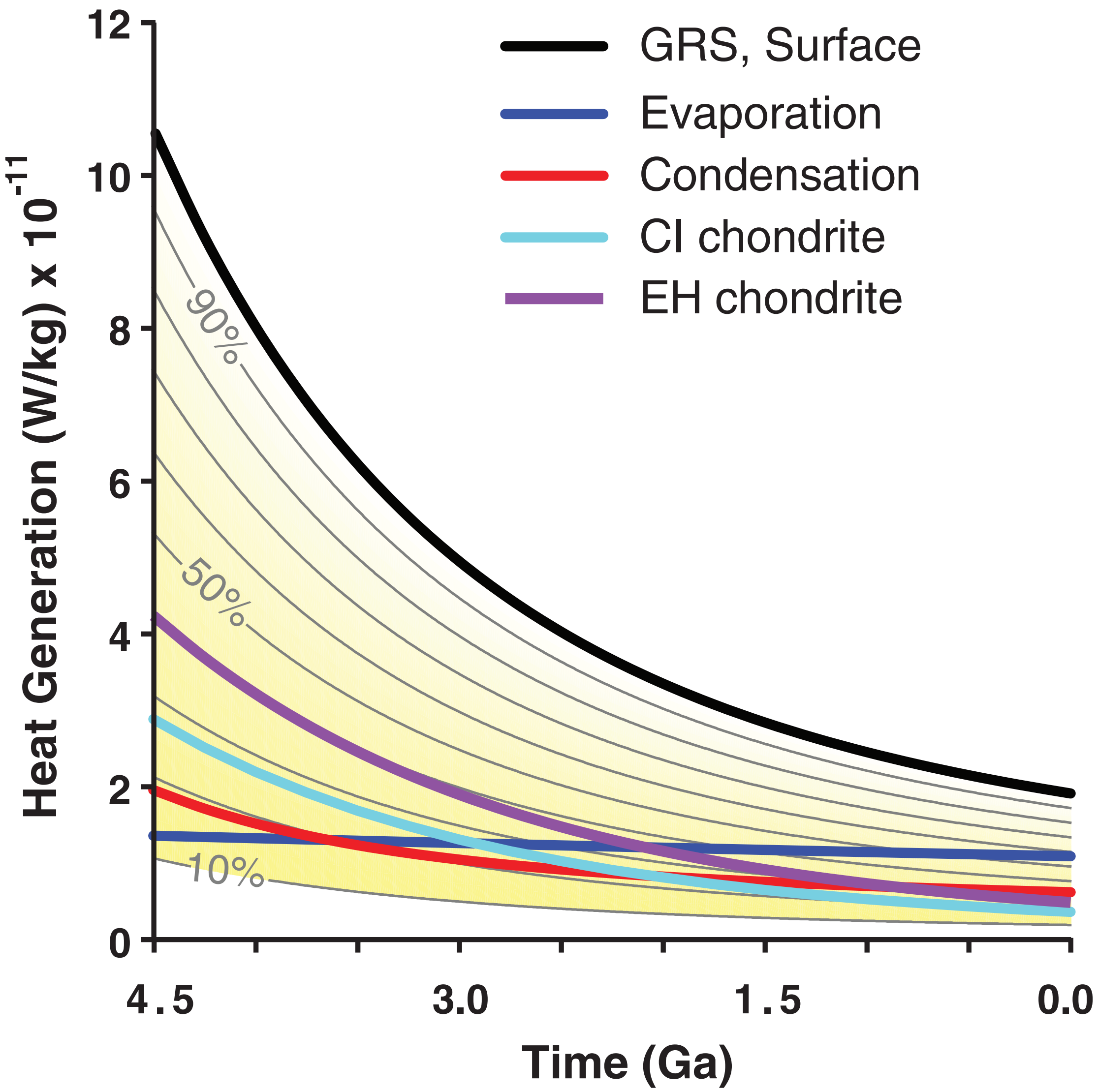
Mercury's mantle contains much more volatiles than previously assumed

# MESSENGER constraints on mantle composition

MESSENGER observations suggest that Mercury formed from particular chondritic minerals with a high metal to silicate ratio

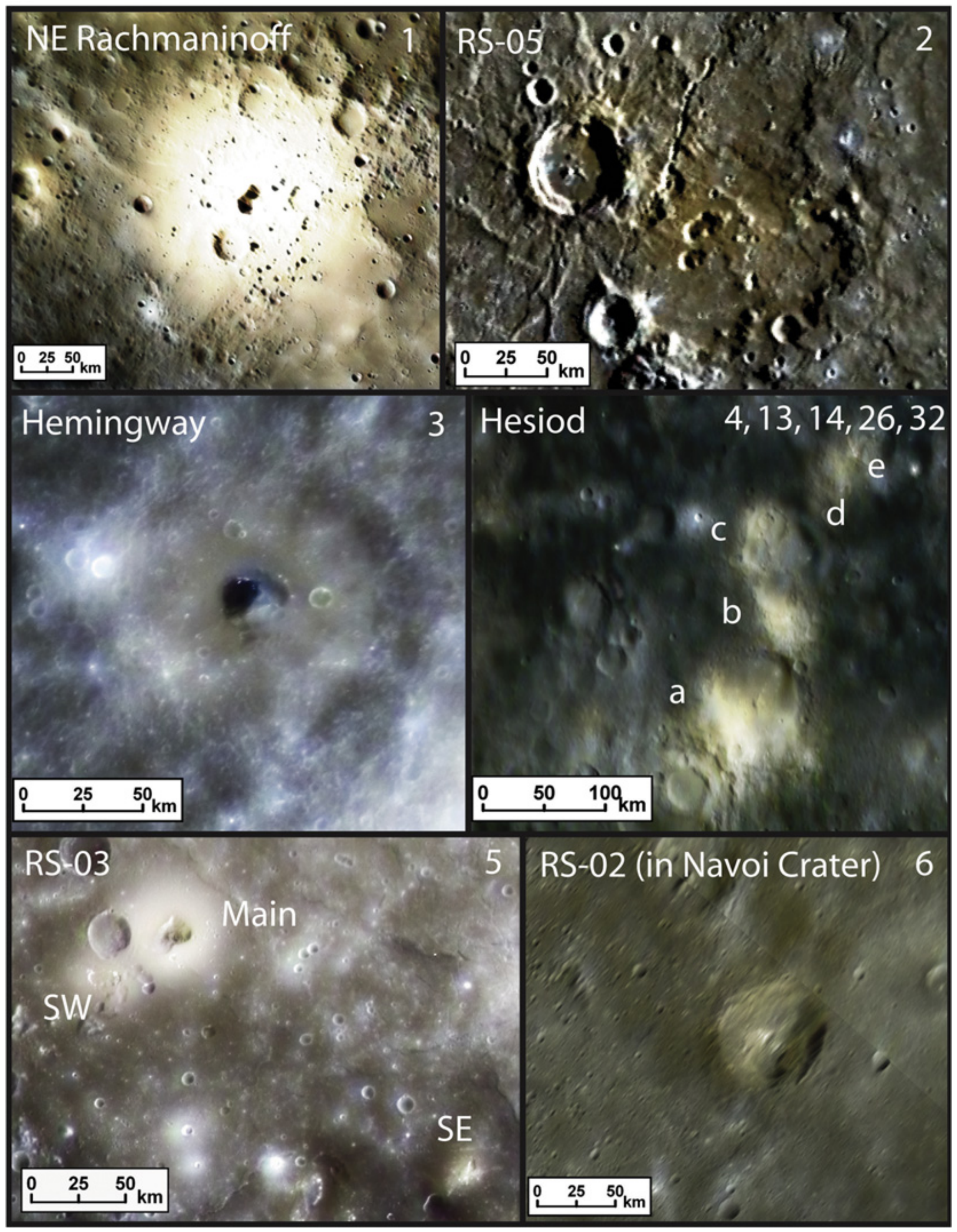



Peplowski et al. (2011)

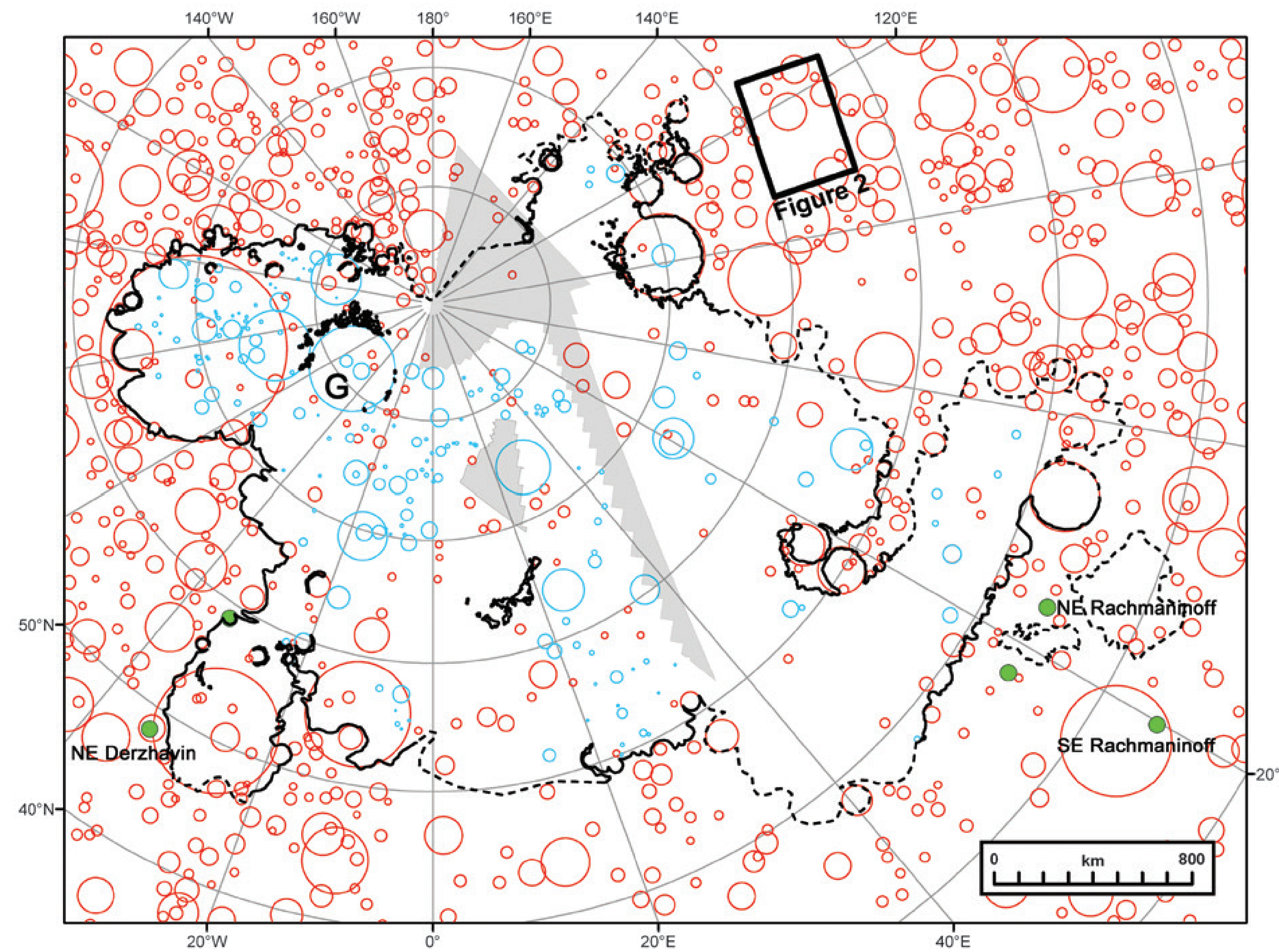
- Decay of heat production with time is consistent with a concentration of volcanic activity relatively early in the planet's history
- The surface abundance of Th, U and K can be used to constrain the relative partitioning of these elements between the bulk of the mantle and crust

# Mercury's volcanic activity

The presence of volatiles is consistent with MESSENGER's observations of widespread pyroclastic deposits all over Mercury's surface and of a vast area of relatively young smooth plains covering the northern hemisphere



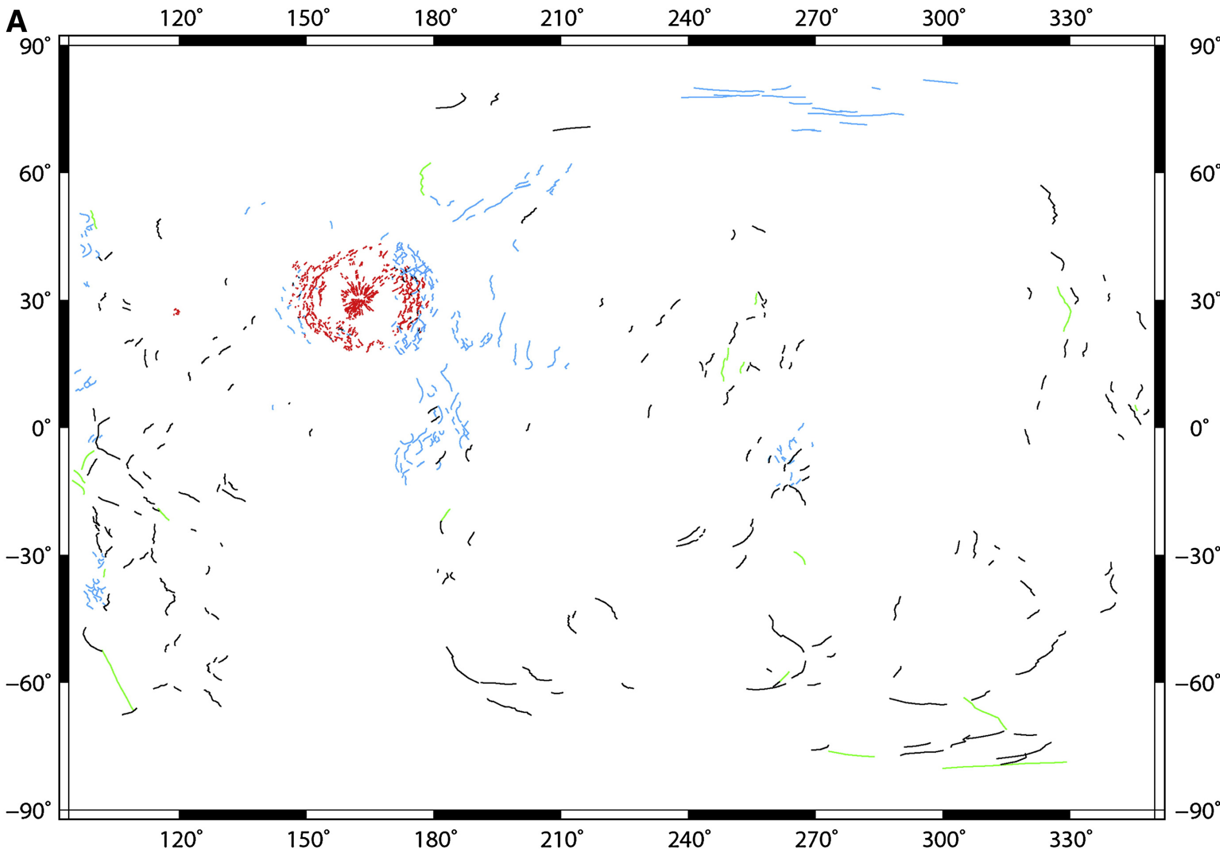

Kerber et al. (2011)



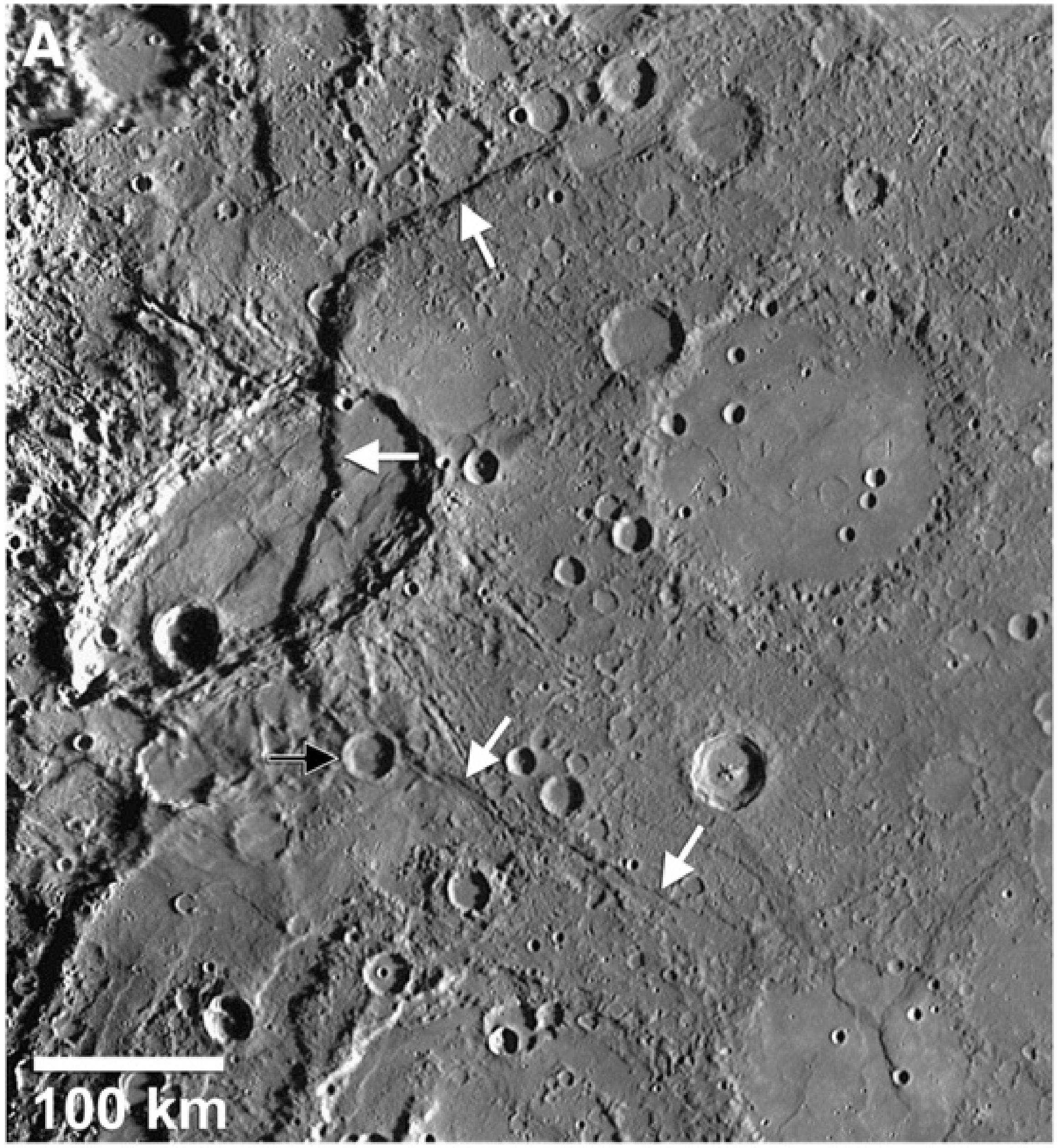

Head et al. (2011)

# Lobate scarps and global contraction

- Most widespread tectonic landform already identified by Mariner 10



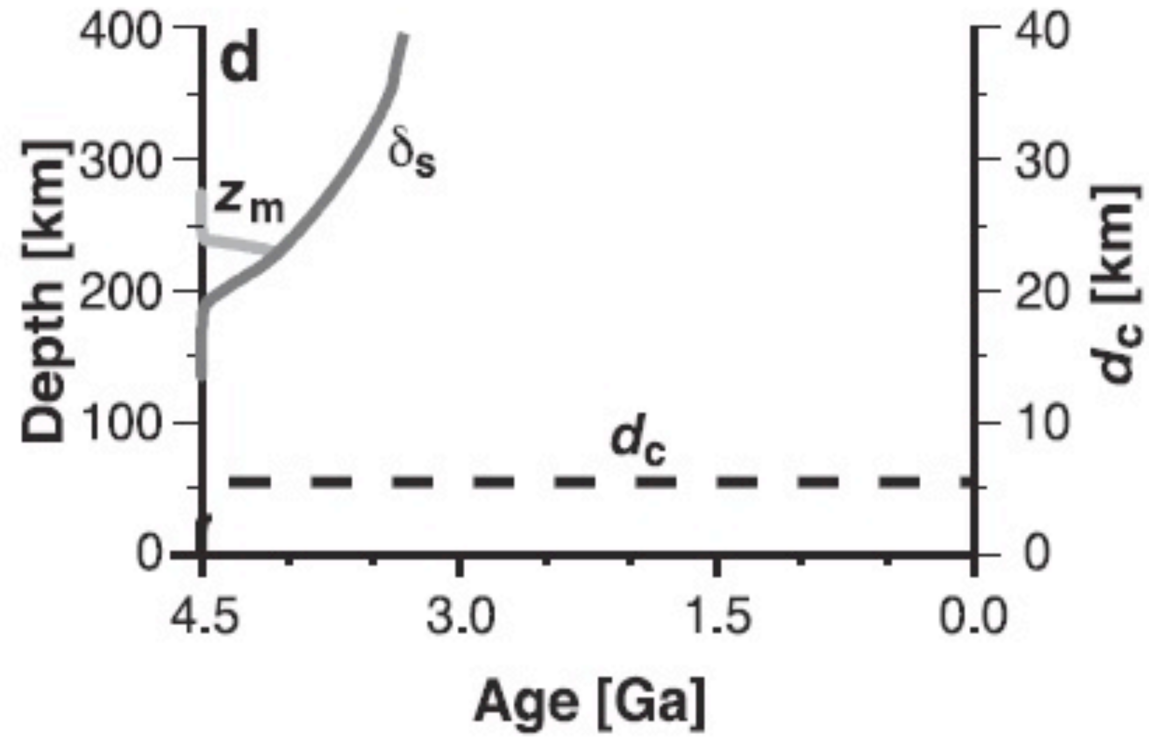

- Surface breaking thrust faults resulting from global contraction: $\Delta R \leq 2$ km (Watters et al., 2009)
- Contraction is attributed to inner core solidification and/or secular cooling (Schubert et al., 1988)



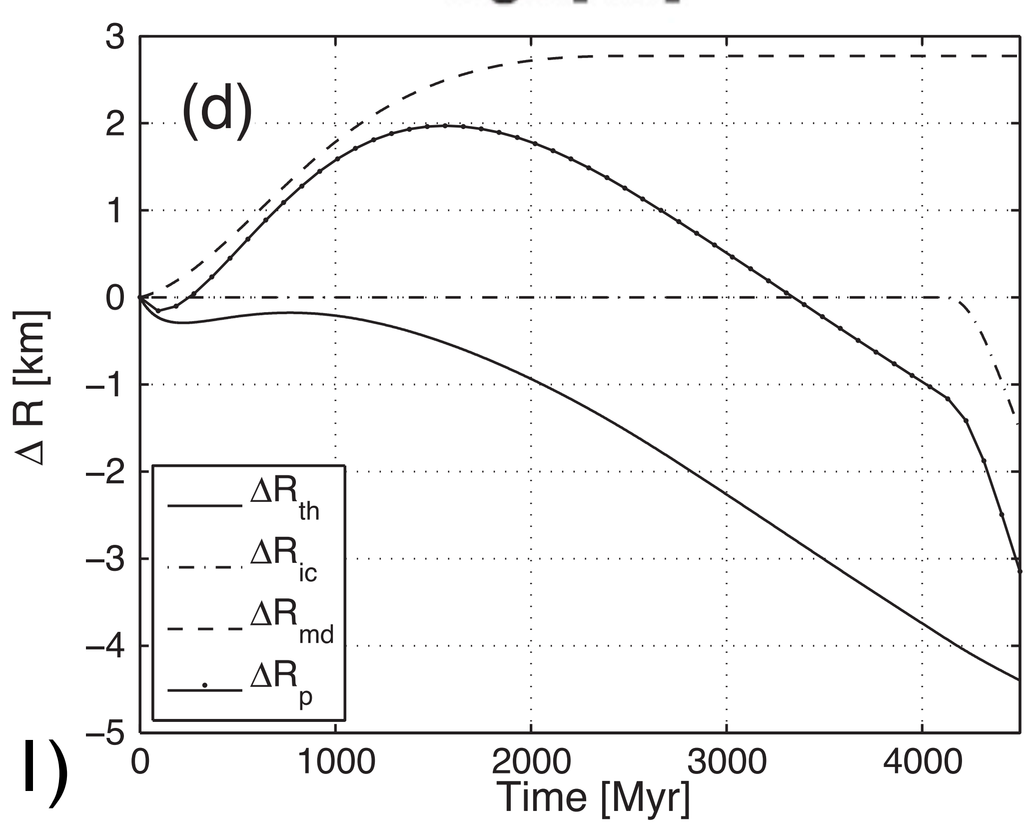

Watters et al. (2009)

# Results from parameterized models

Hauck et al. (2004)




- The small amount of global contraction poses a severe constraint on thermal evolution models
- From earlier parameterized models of thermal evolution (Hauck et al., 2004):
  - high sulfur content in the core to reduce the melting temperature and retard core freezing
  - *refractory composition*
  - *negligible volatile content*
  - *short lasting volcanic activity*
- More recent models (Grott et al., 2011) are compatible with small contraction, the presence of volatiles and long-lasting volcanic activity

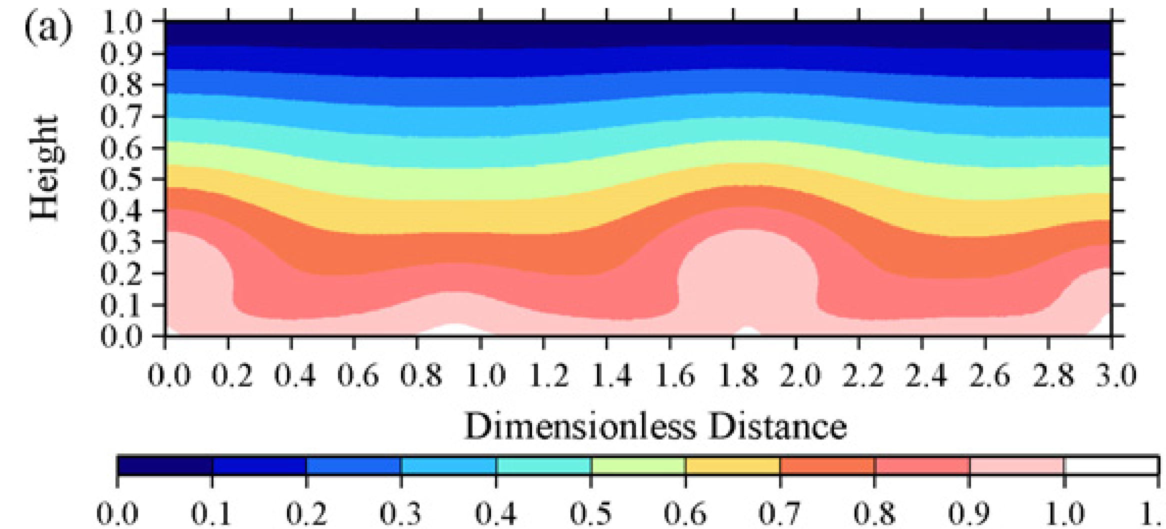



Grott et al. (2011)

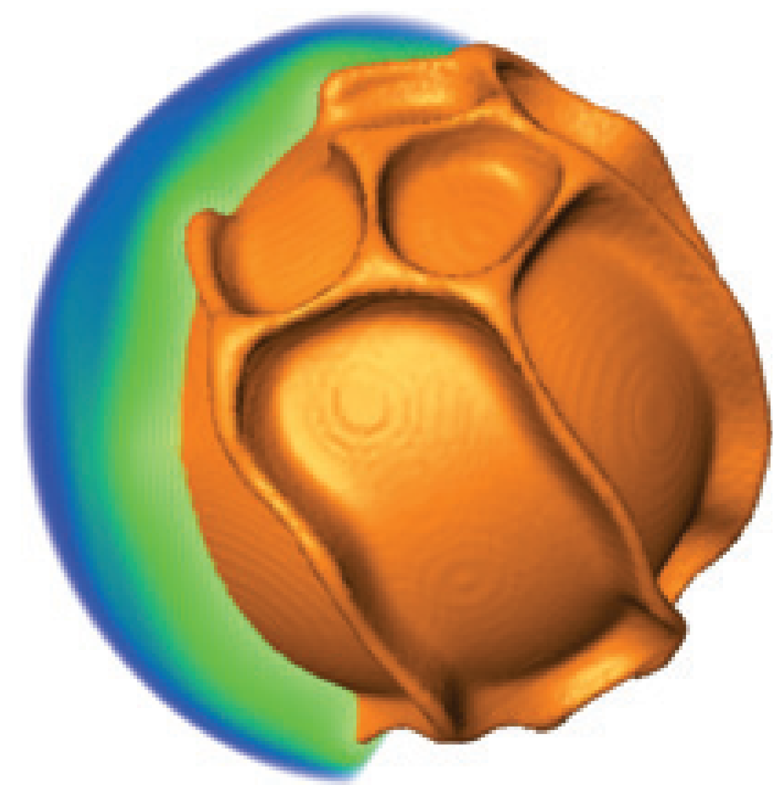
# Results from numerical models

- Limited amount of literature on numerical models of Mercury's mantle convection:
  - Analysis of the conditions that allow convection to persist until present day (Redmond & King, 2007)
  - Attempt at explaining lobate scarps as a result of convective stresses (King, 2008)

All models - both parameterized and numerical - assume a mantle thickness of 600 km, at odds with the latest estimates of the moments of inertia




Redmond & King (2007)



King (2008)

# Thermo-chemical evolution

Use the latest MESSENGER constraints in numerical models of Mercury's thermo-chemical evolution

Conservation equations of thermo-chemical convection with melt extraction, decaying heat sources and cooling boundary conditions:

$$\frac{\partial u_i}{\partial x_i} = 0$$

$$-\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_i}\left(\eta(T)\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{x_i}\right)\right) = (Ra\,T + Rb\,\Phi)\delta_{ir}$$

$$\frac{DT}{Dt} = \frac{\partial}{\partial x_i}\left(\kappa\frac{\partial T}{\partial x_i}\right) + \frac{Ra_H(t,\Phi)}{Ra} - (T + T_0)\frac{\Delta S}{c_p} f(\Phi, T)$$

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change of melt fraction

# Melt parametrization

- Fractional melting model
- Crustal production is calculated locally according to the melt fraction

$$\Phi = \frac{T - T^{\mathrm{sol}}}{T^{\mathrm{liq}} - T^{\mathrm{sol}}}$$

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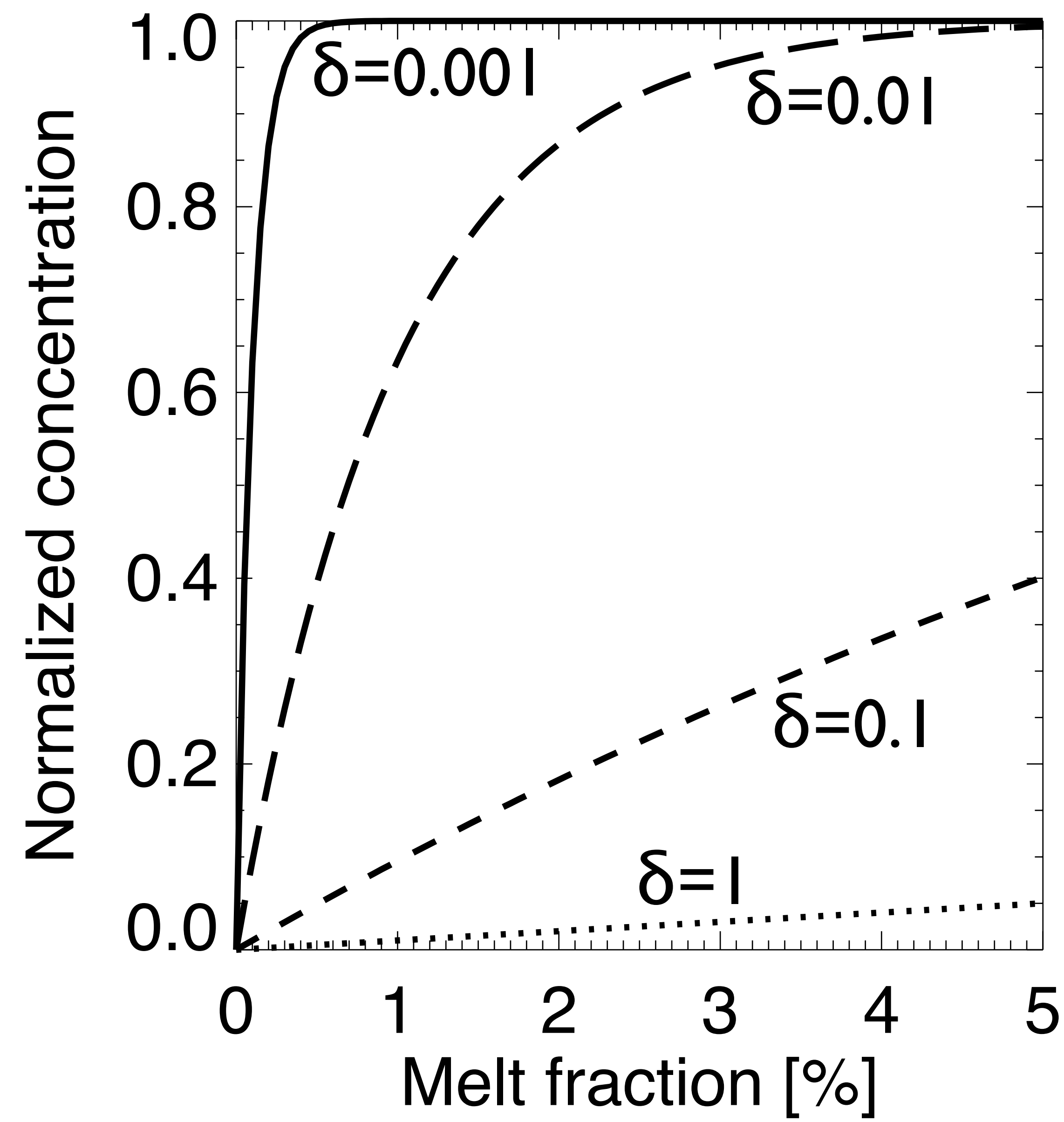
$$\frac{C_{\mathrm{melt}}}{C_0} = \frac{1}{\Phi}\left(1 - (1 - \Phi)^{1/\delta}\right)$$



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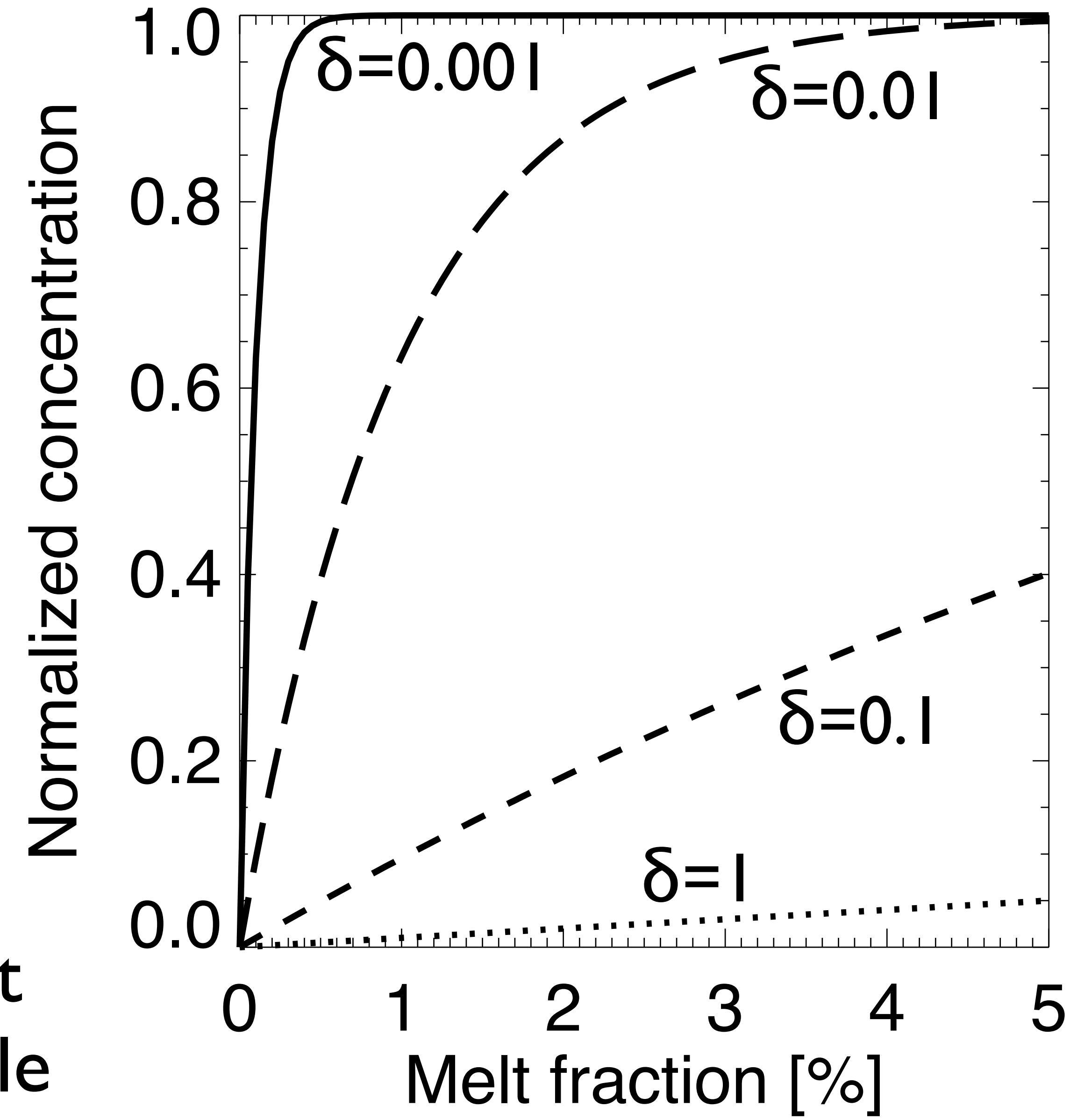
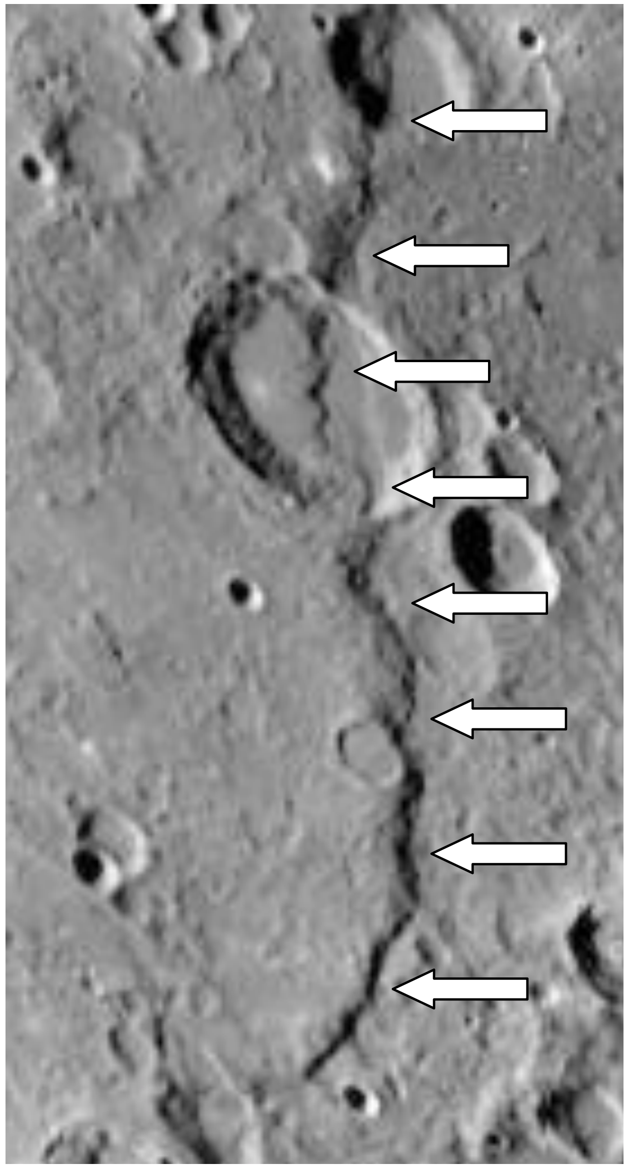
- Upon melting:
  - the solidus increases
  - depleted mantle and newly formed crust are more buoyant than primordial mantle
  - the crust is assigned a lower thermal conductivity



# Global radial contraction



Calculated a posteriori from the history of the mantle temperature profile and evolution of the crustal thickness

Volume changes due to thermal expansion/contraction:

$$\frac{\partial \Delta V_{\mathrm{th}}}{\partial t} = \int_V \alpha(r) \frac{\partial T(r,t)}{\partial t}\, dV$$

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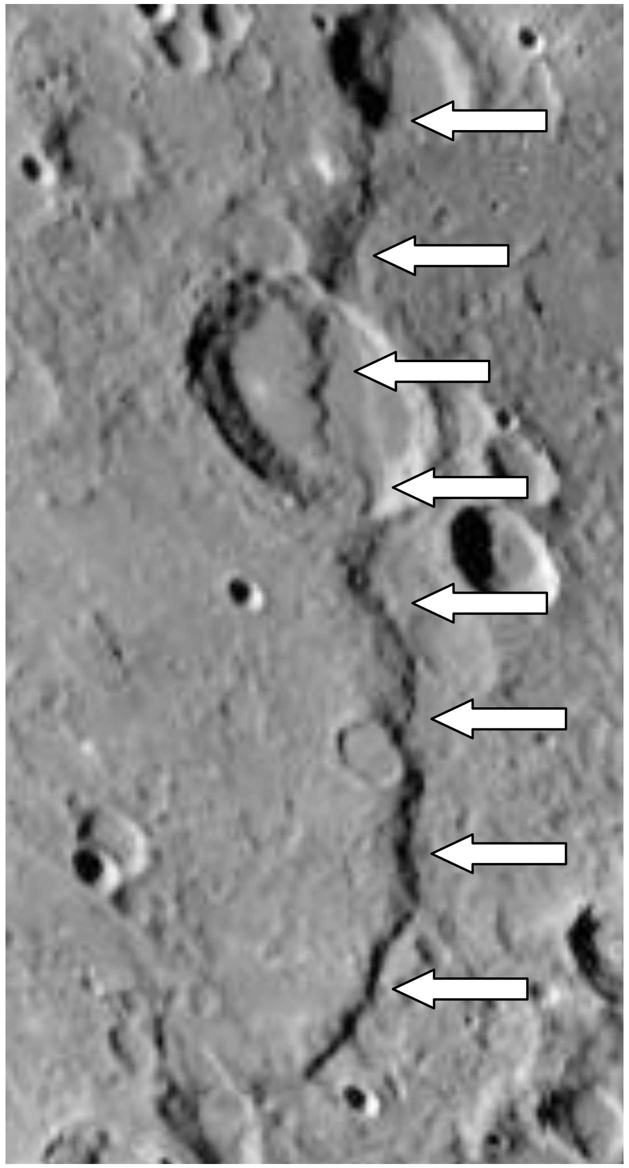

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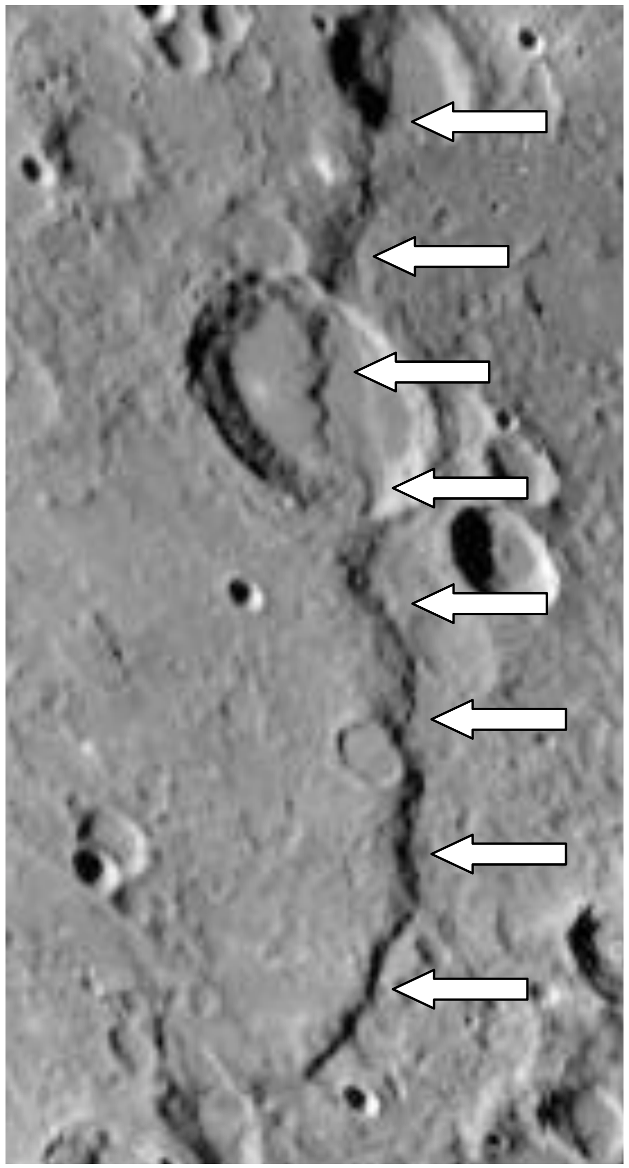

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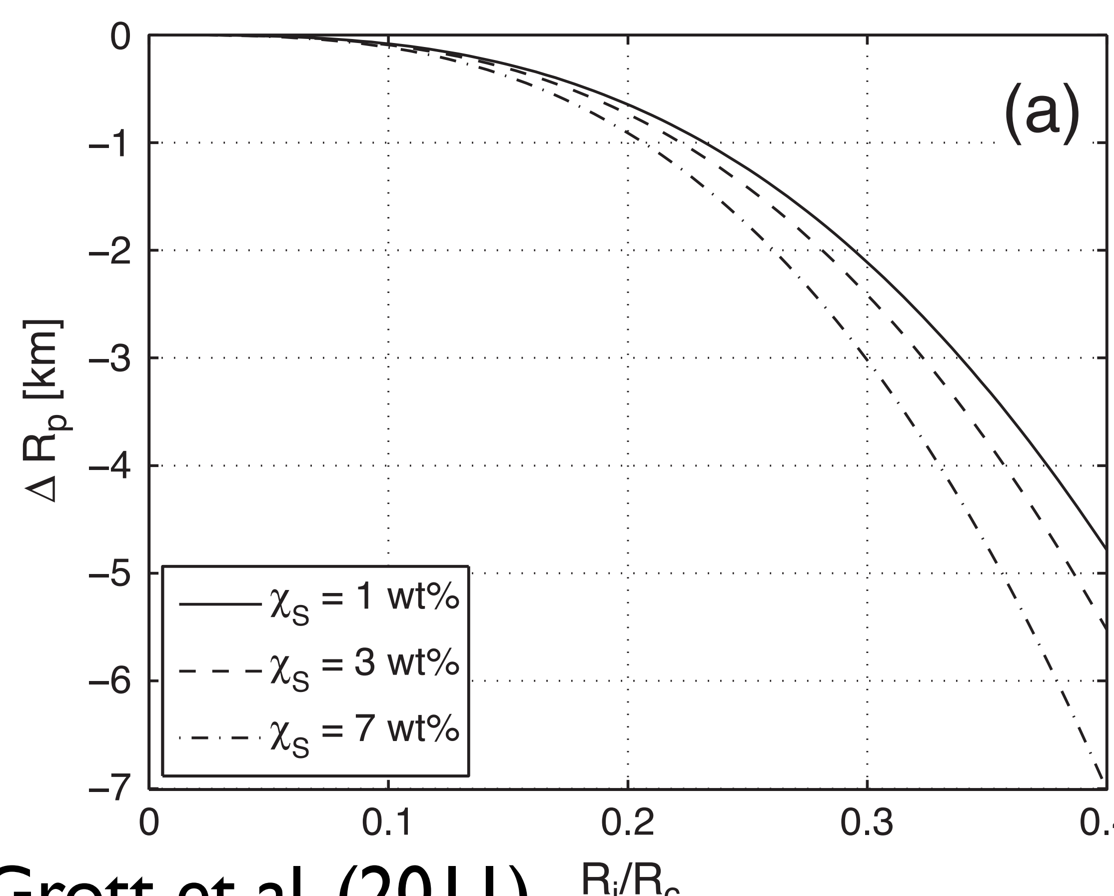
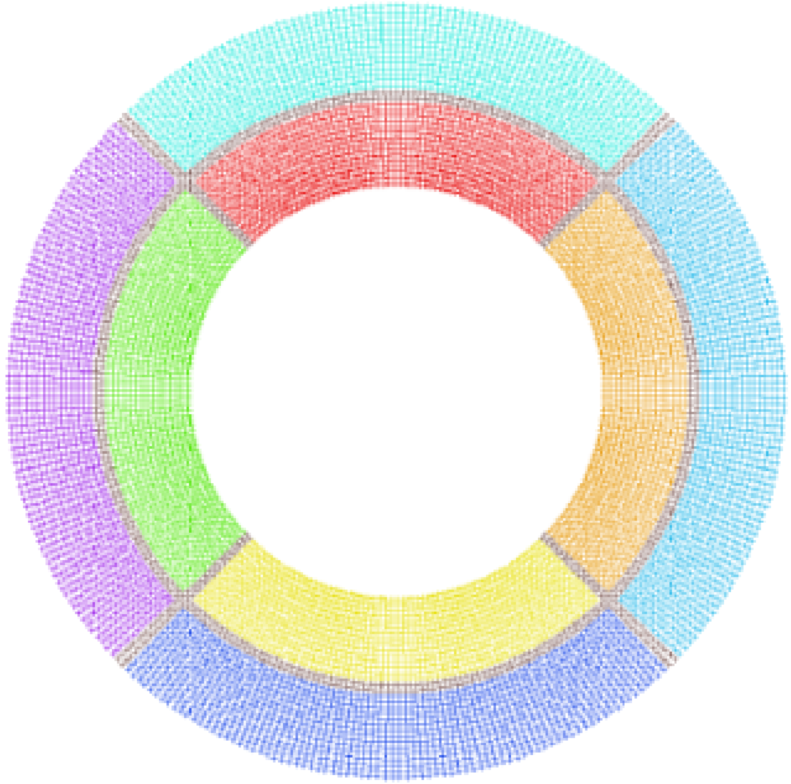
Contraction due to core freezing is neglected in first approximation and a small solid inner core is assumed

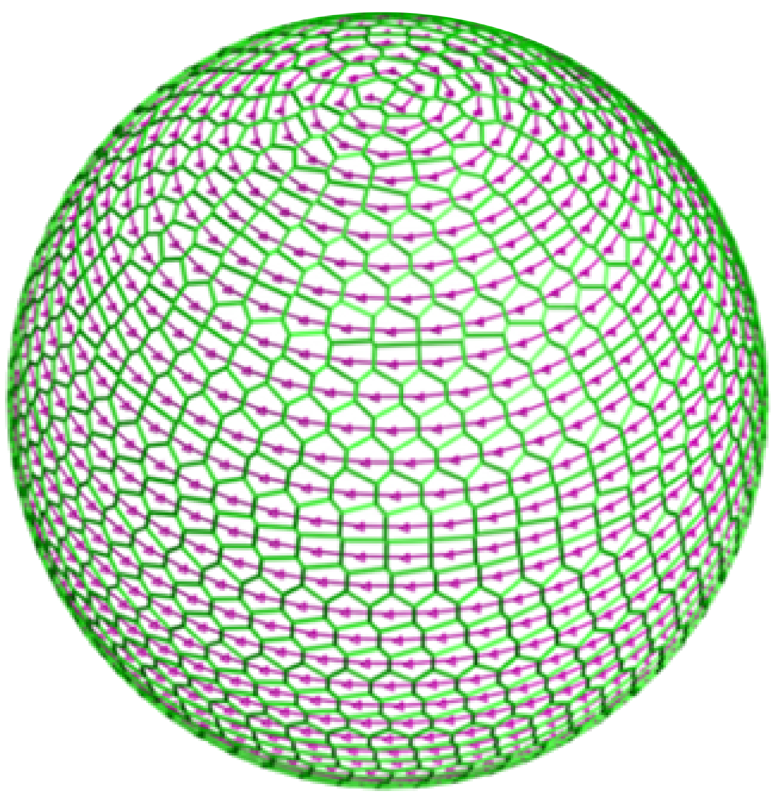



Grott et al. (2011)

# Numerical code

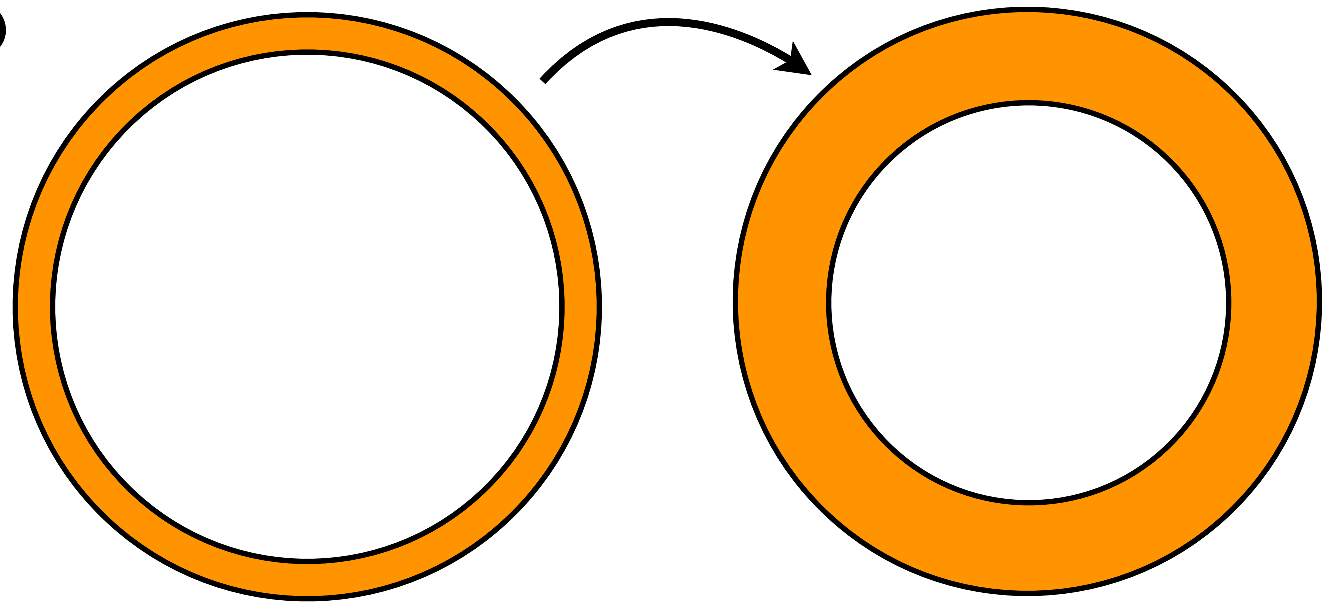
- 2D cylindrical / 3D spherical code Gaia (Hüttig & Stemmer, 2008)
- Structured mesh in 2D, structured or unstructured mesh in 3D
- Primitive variables, finite-volume formulation
- SIMPLE algorithm (Patankar, 1980) to enforce incompressibility
- Tracers to track compositional fields and model crustal growth
- Parallelized via domain decomposition
- Linear scaling up to a few hundreds cores





# Model setup

- Mostly 2D cylindrical models with 3D corrected inner-outer radius ratio (van Keken, 2001)



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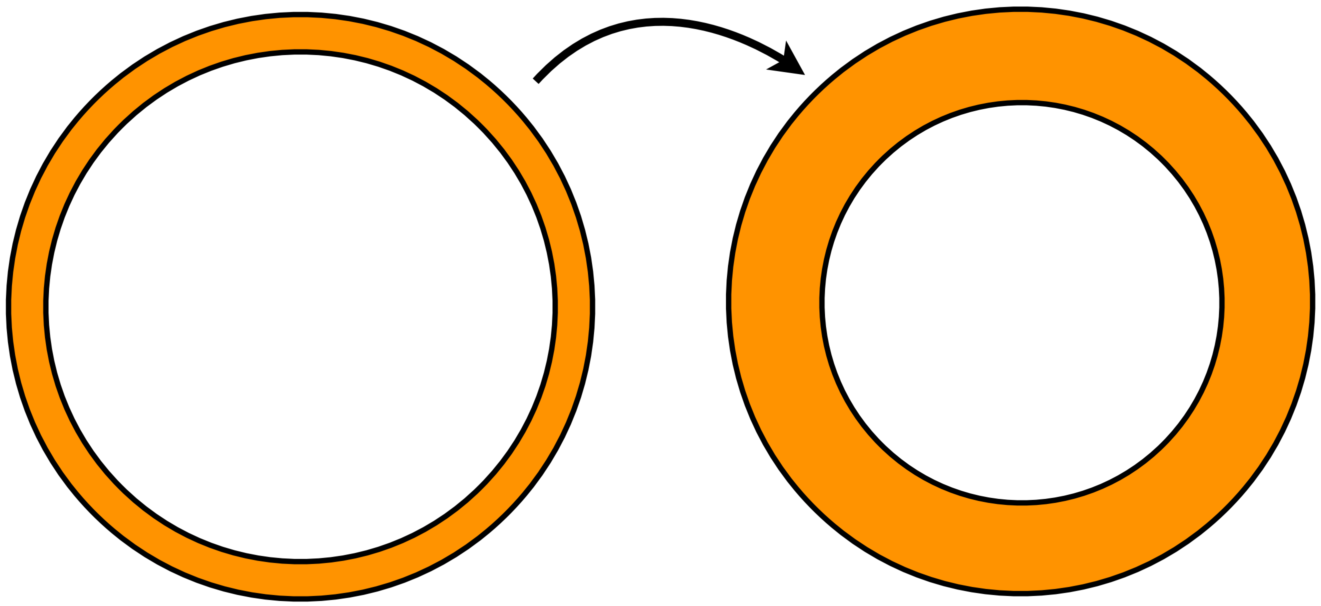

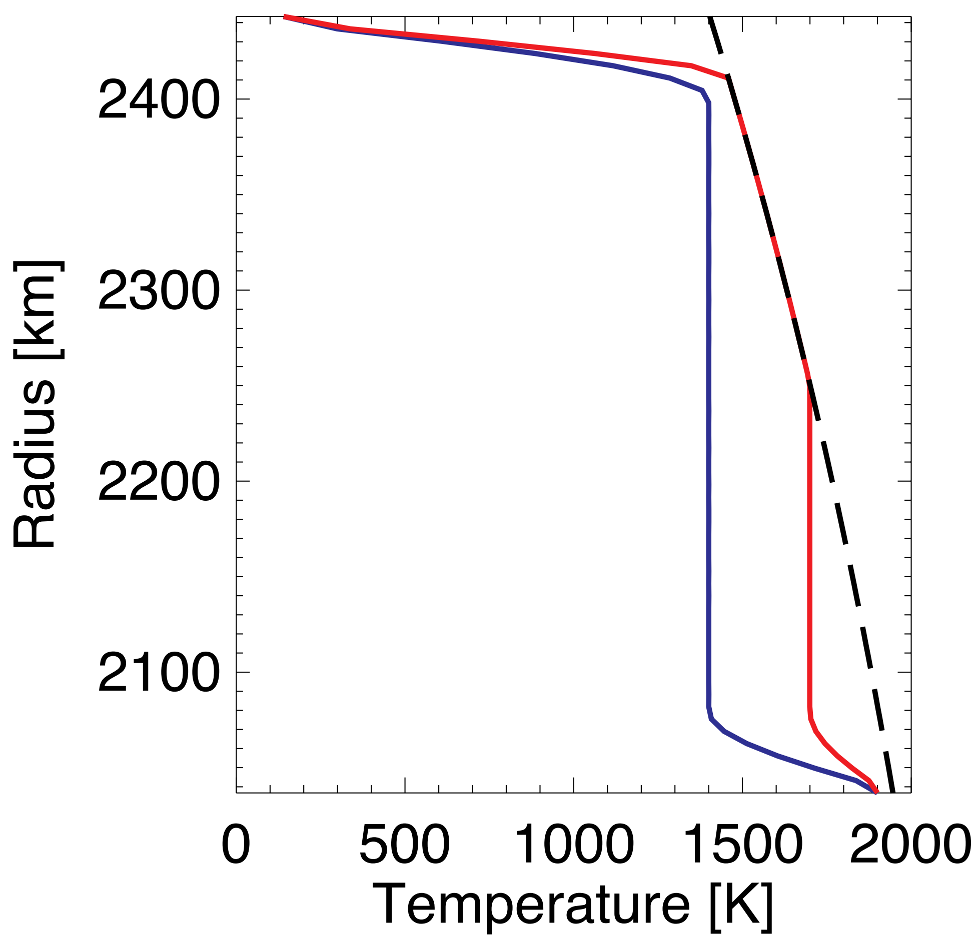

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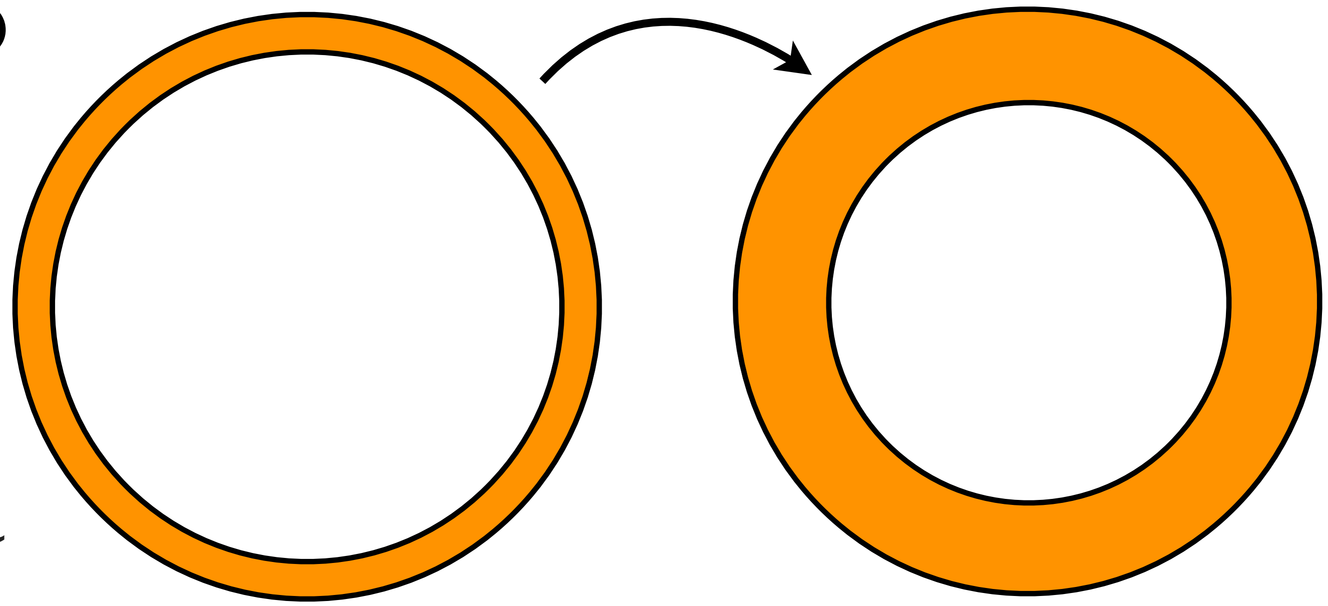

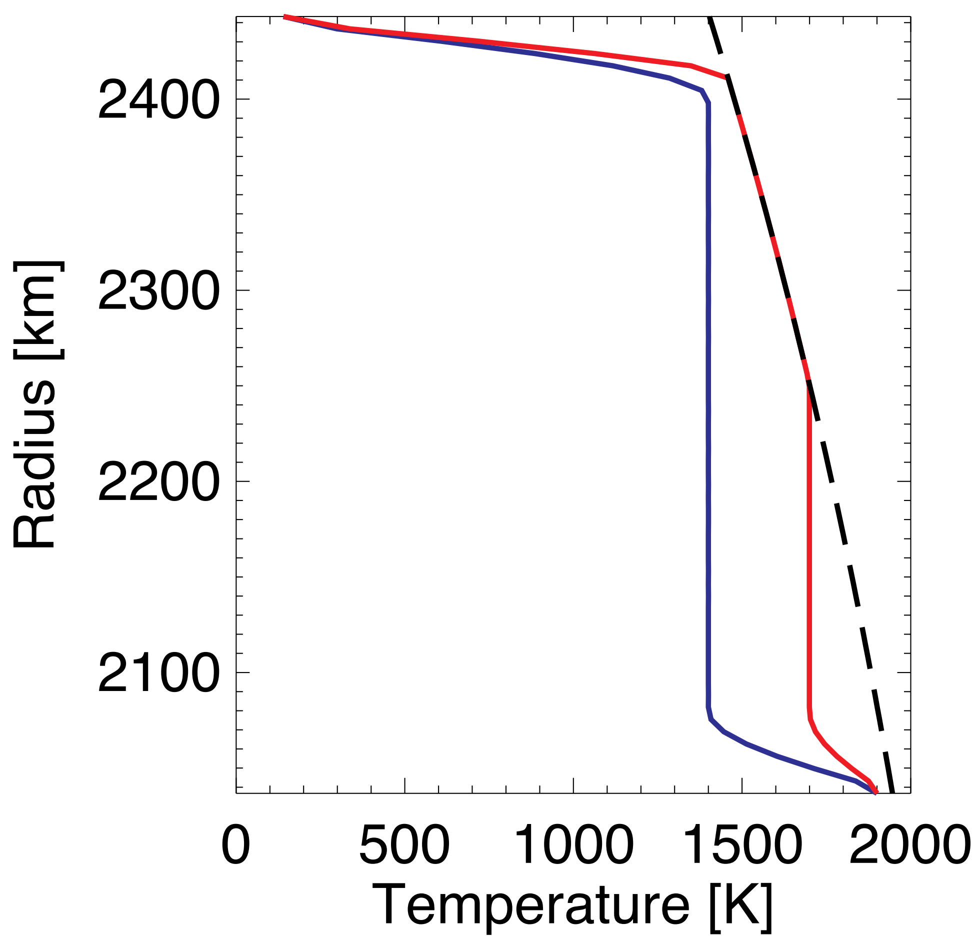

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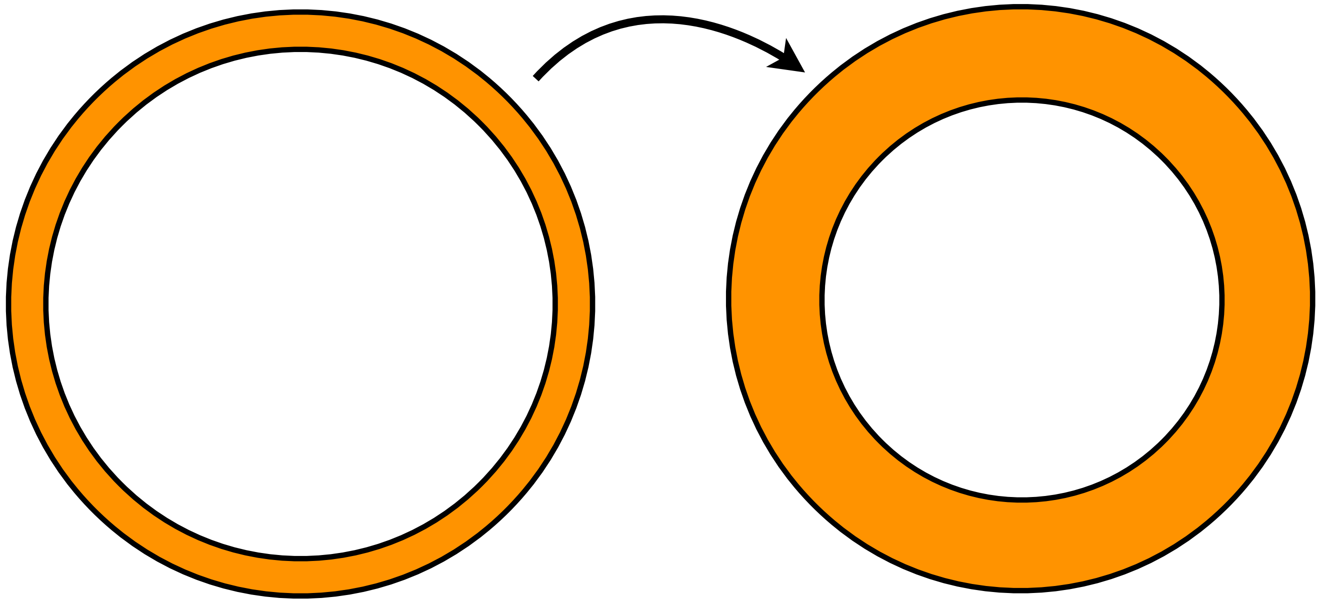

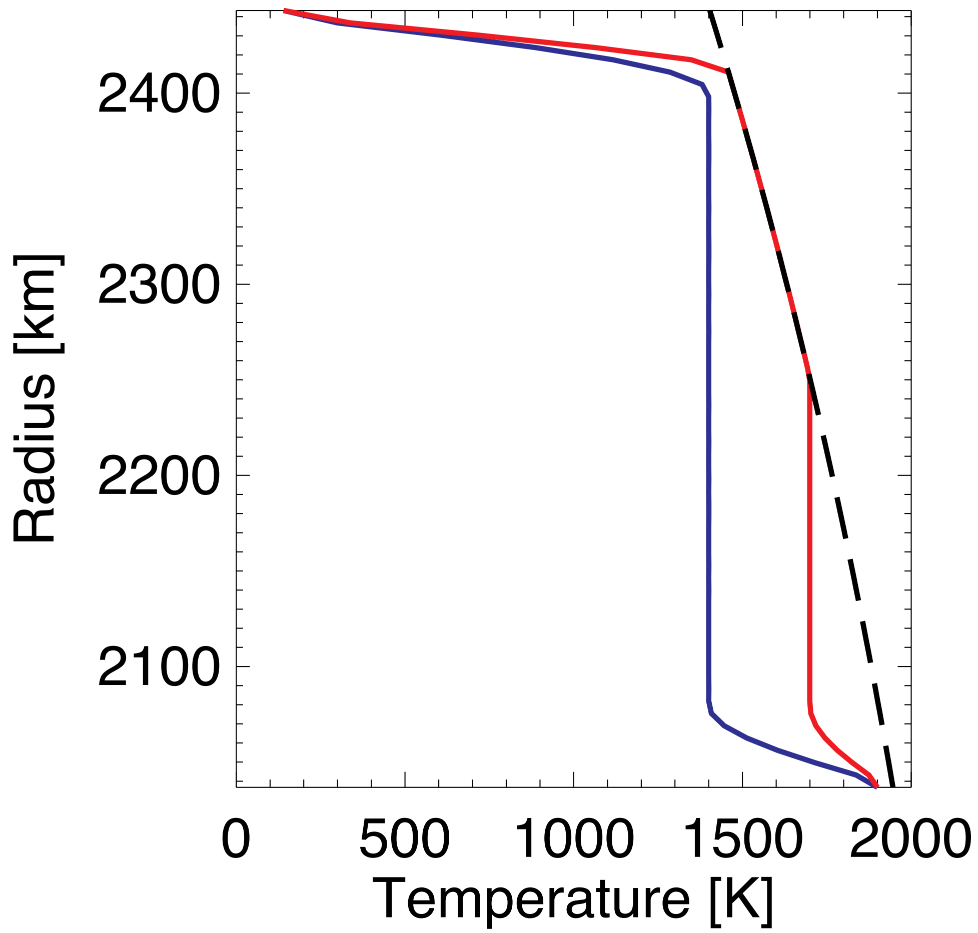

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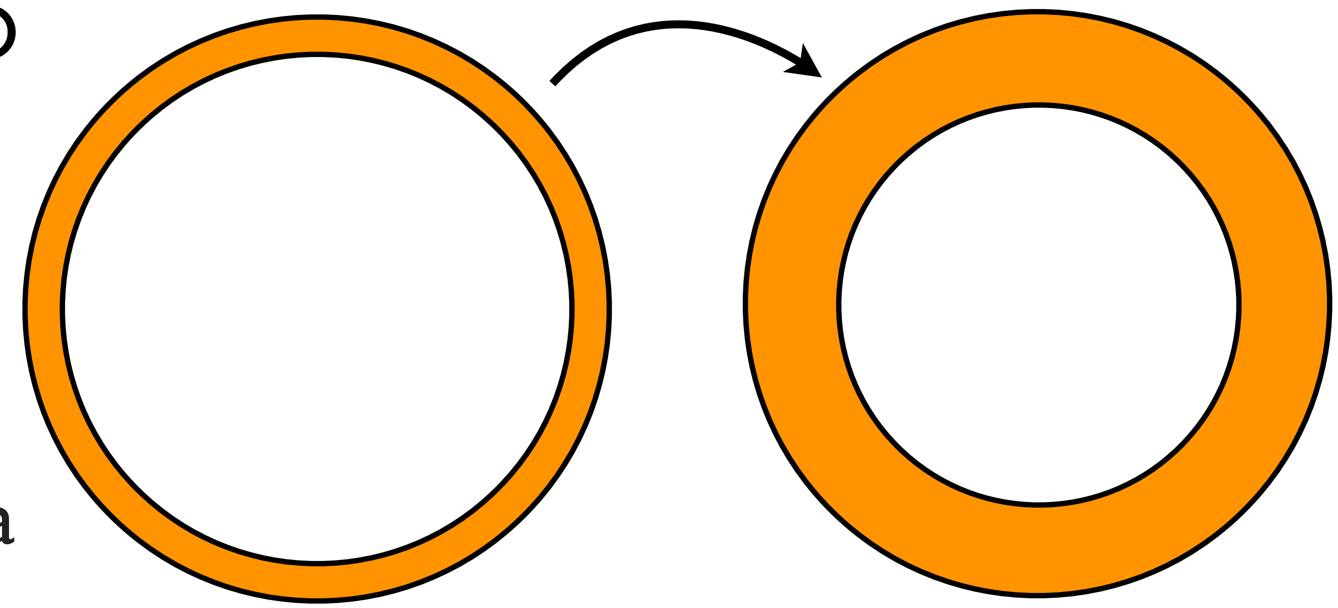
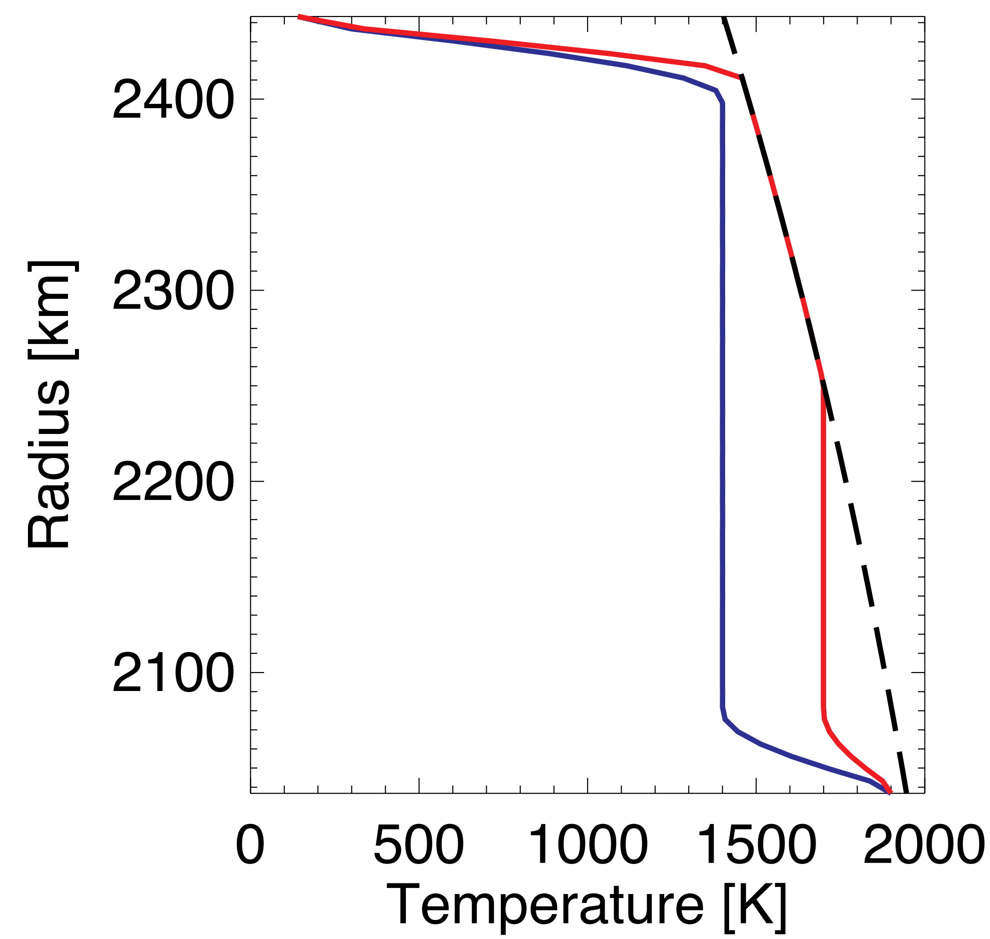
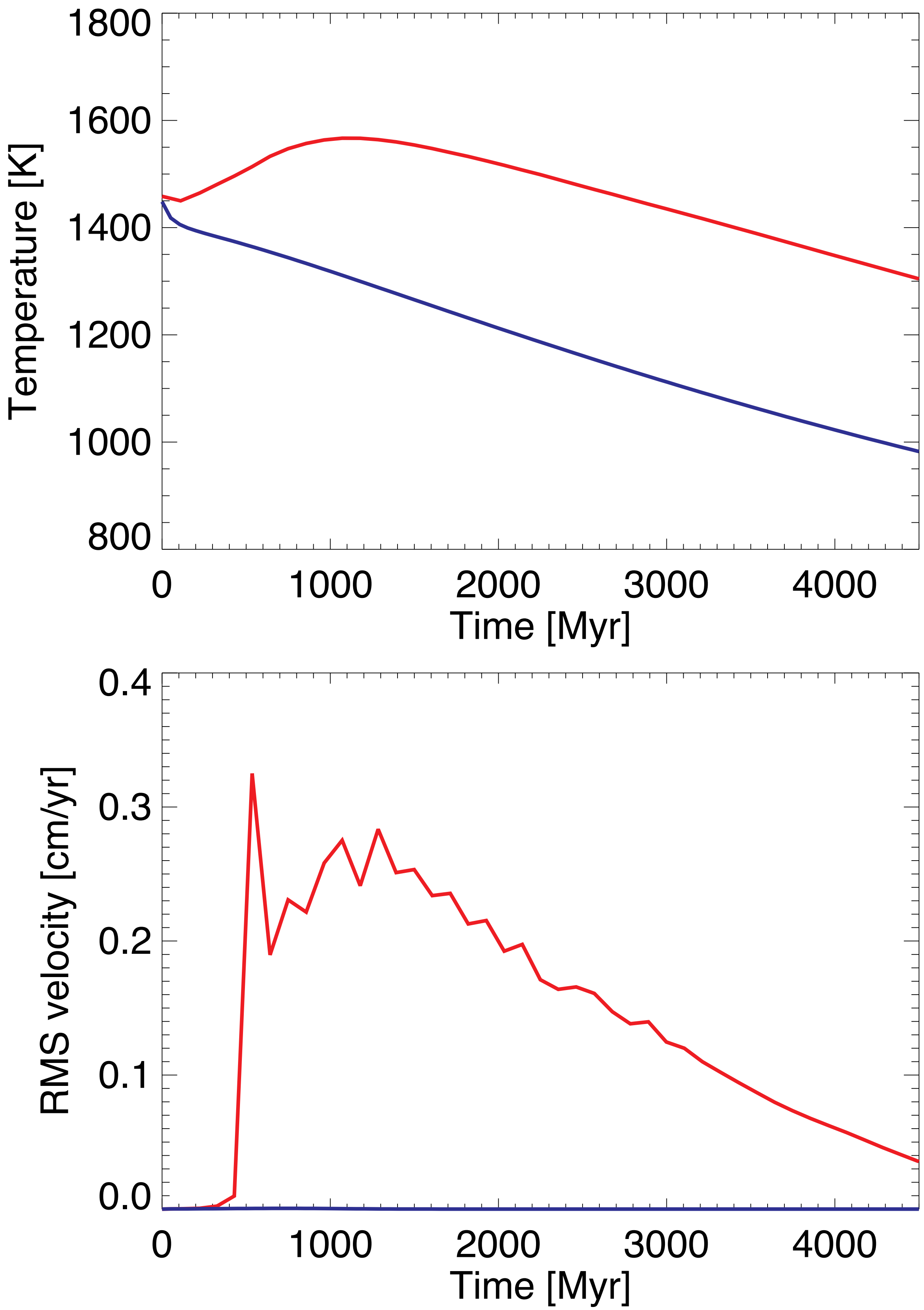
- Surface temperature: either constant at 440 K or variable from 140 K at the poles to 440 K at the equator





# Influence of mantle thickness



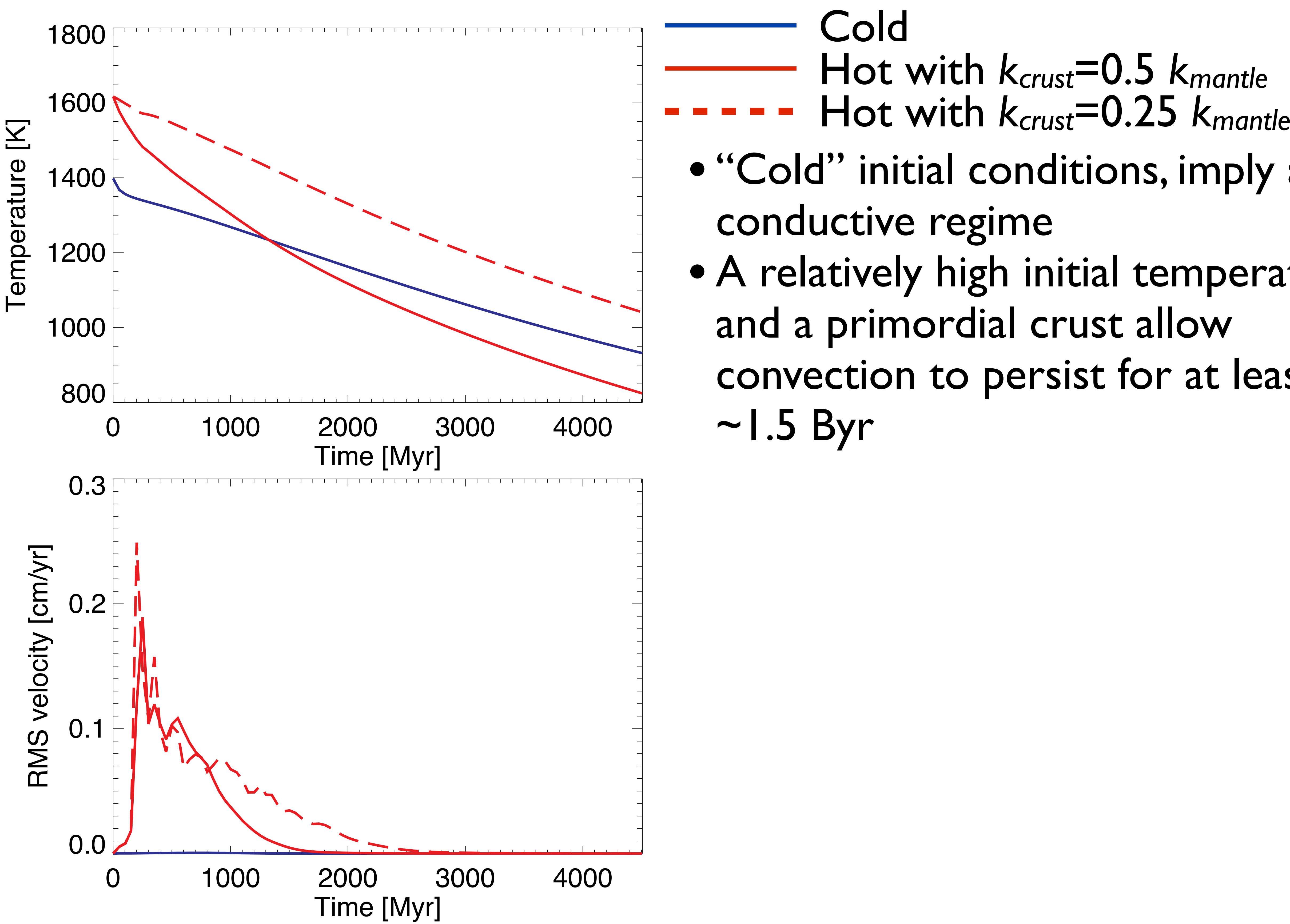

Initially "cold" mantle, 25% of surface heat sources abundance

— $D$=400 km ⇒ $Ra$=2.5 x $10^4$

— $D$=600 km ⇒ $Ra$=8.6 x $10^4$

The thermal Rayleigh number with $D$=600 km is ~3.3 times larger than with $D$=400 km ⇒ it can determine the transition from subcritical to supercritical conditions for the onset of thermal convection

# Results for $H_0$=25% $H_{surface}$




- "Cold" initial conditions, imply a conductive regime
- A relatively high initial temperature and a primordial crust allow convection to persist for at least ~1.5 Byr

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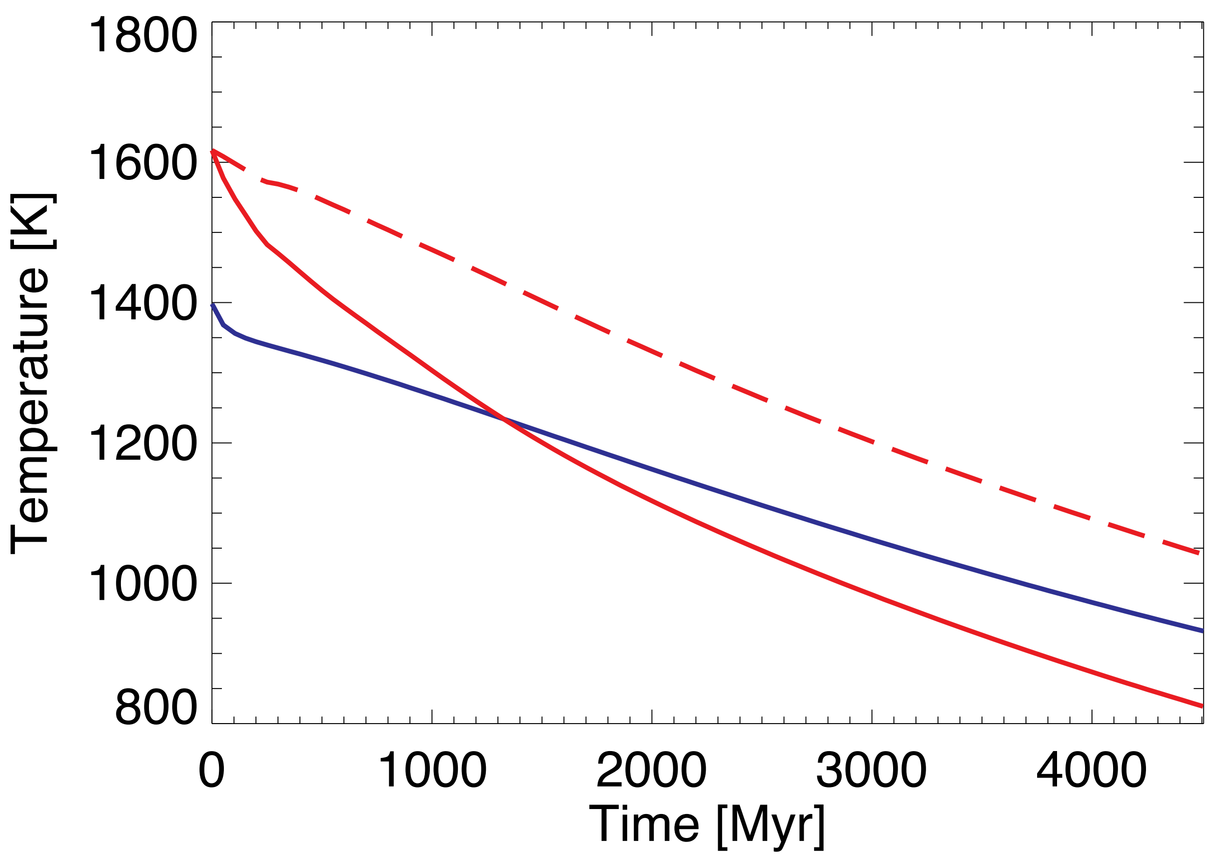


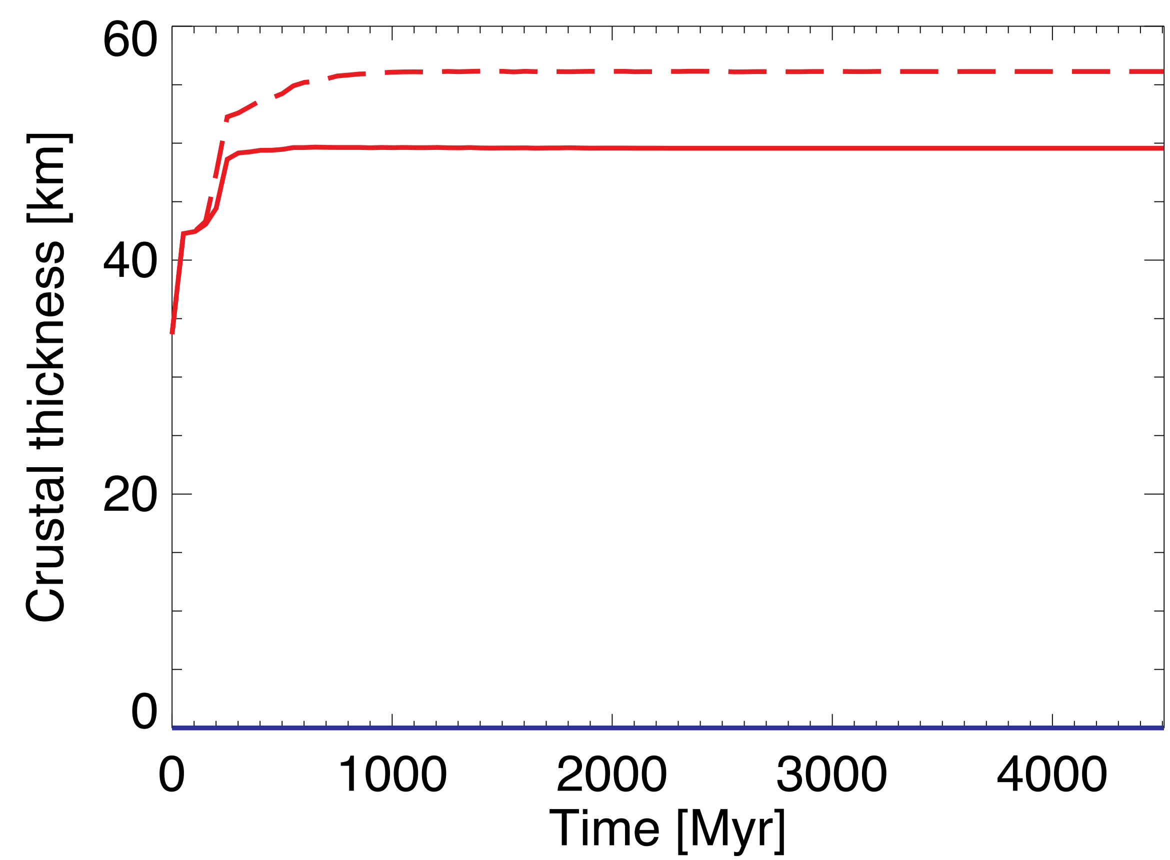

Cold

Hot with $k_{crust}$=0.5 $k_{mantle}$

Hot with $k_{crust}$=0.25 $k_{mantle}$

- "Cold" initial conditions, imply a conductive regime
- A relatively high initial temperature and a primordial crust allow convection to persist for at least ~1.5 Byr

- Crustal production is concentrated in the first part of the evolution



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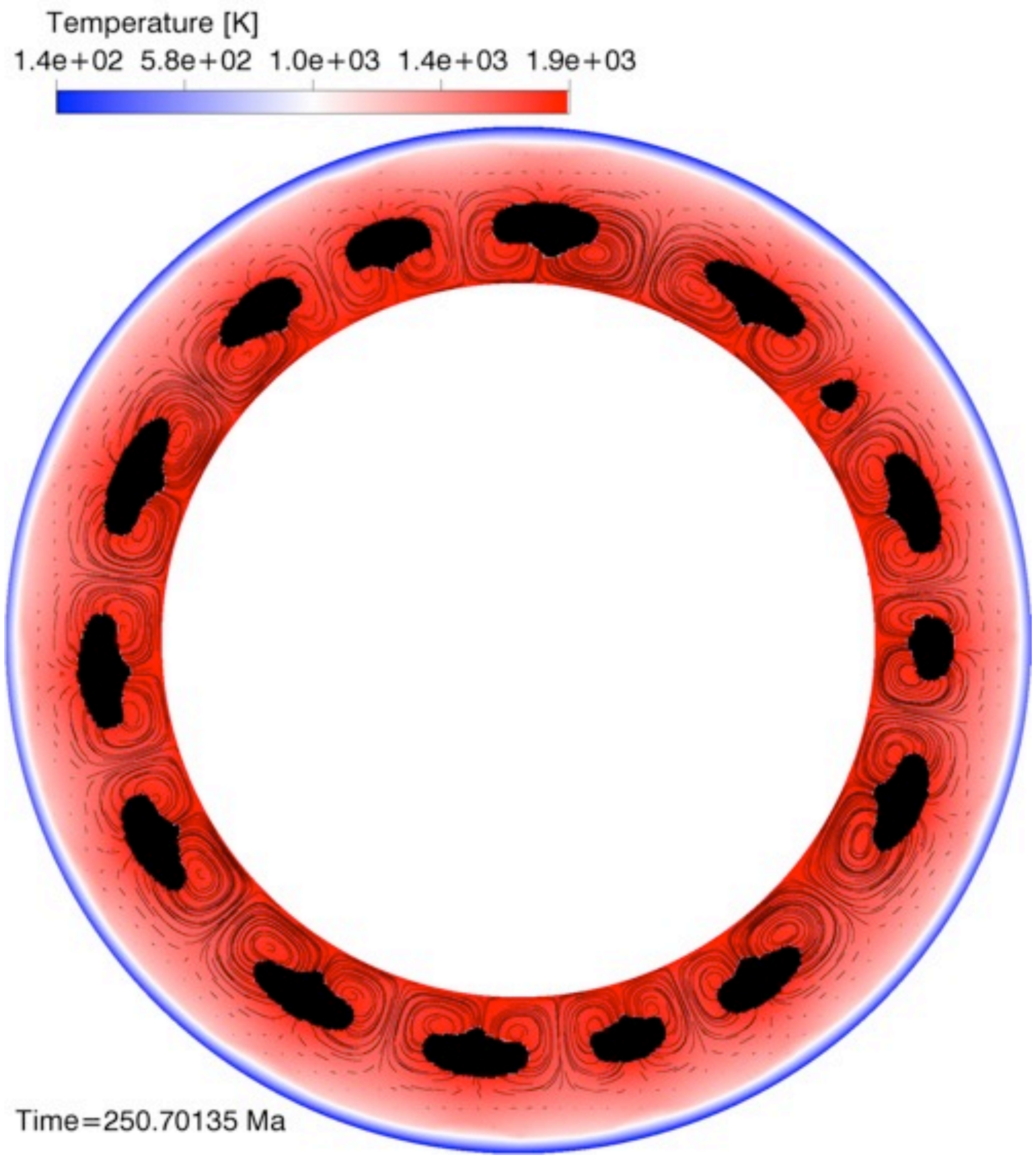

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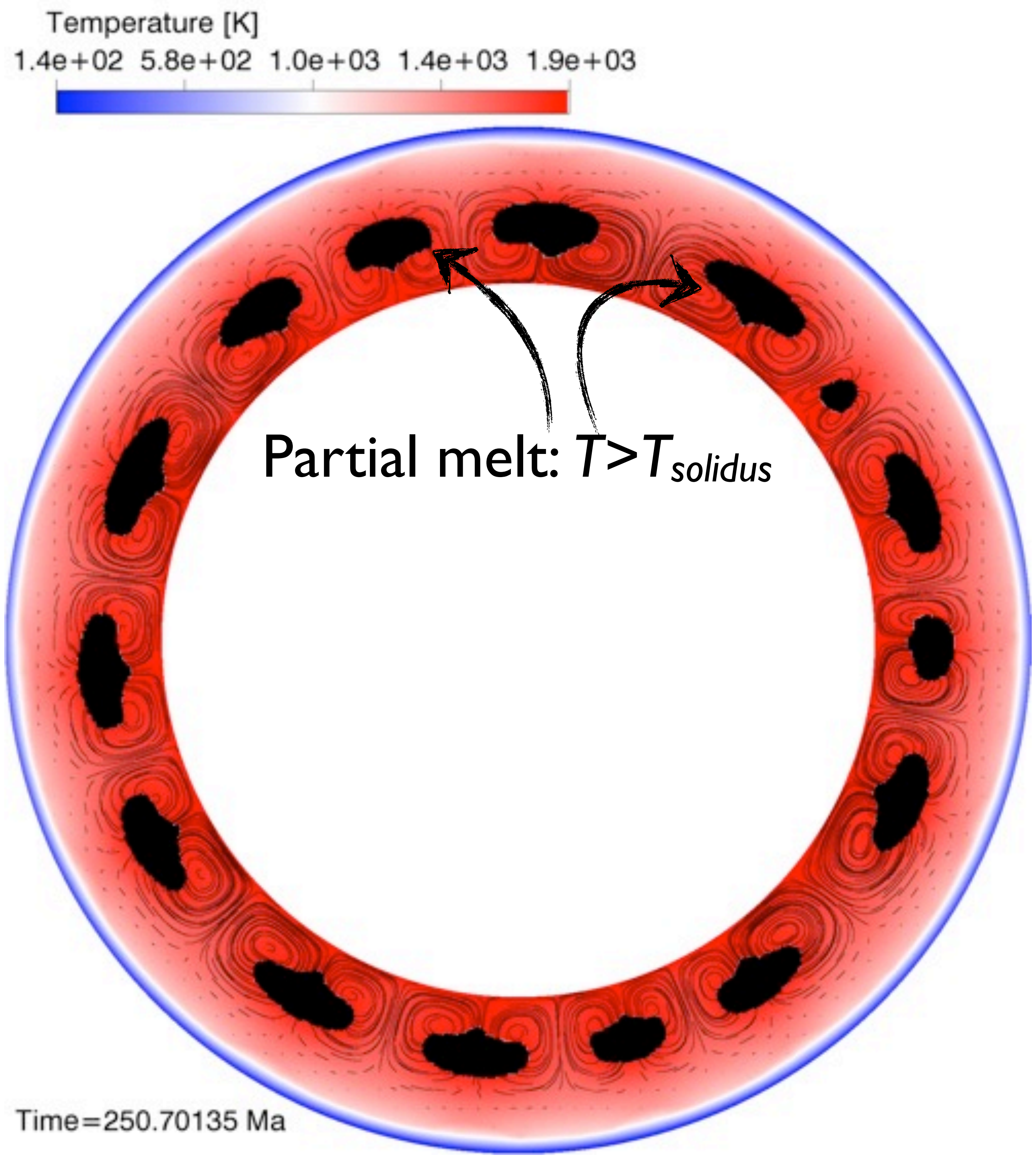

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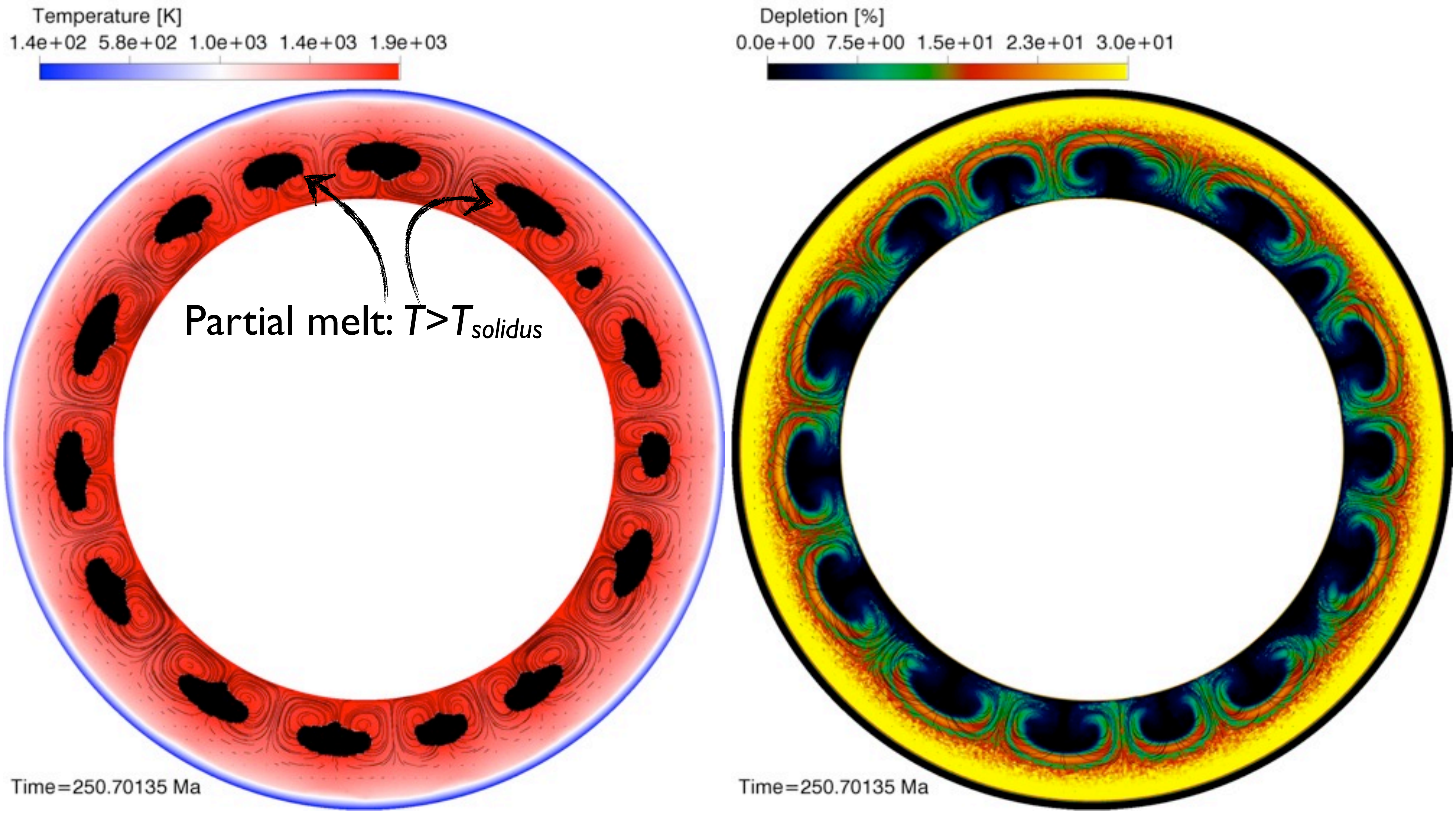

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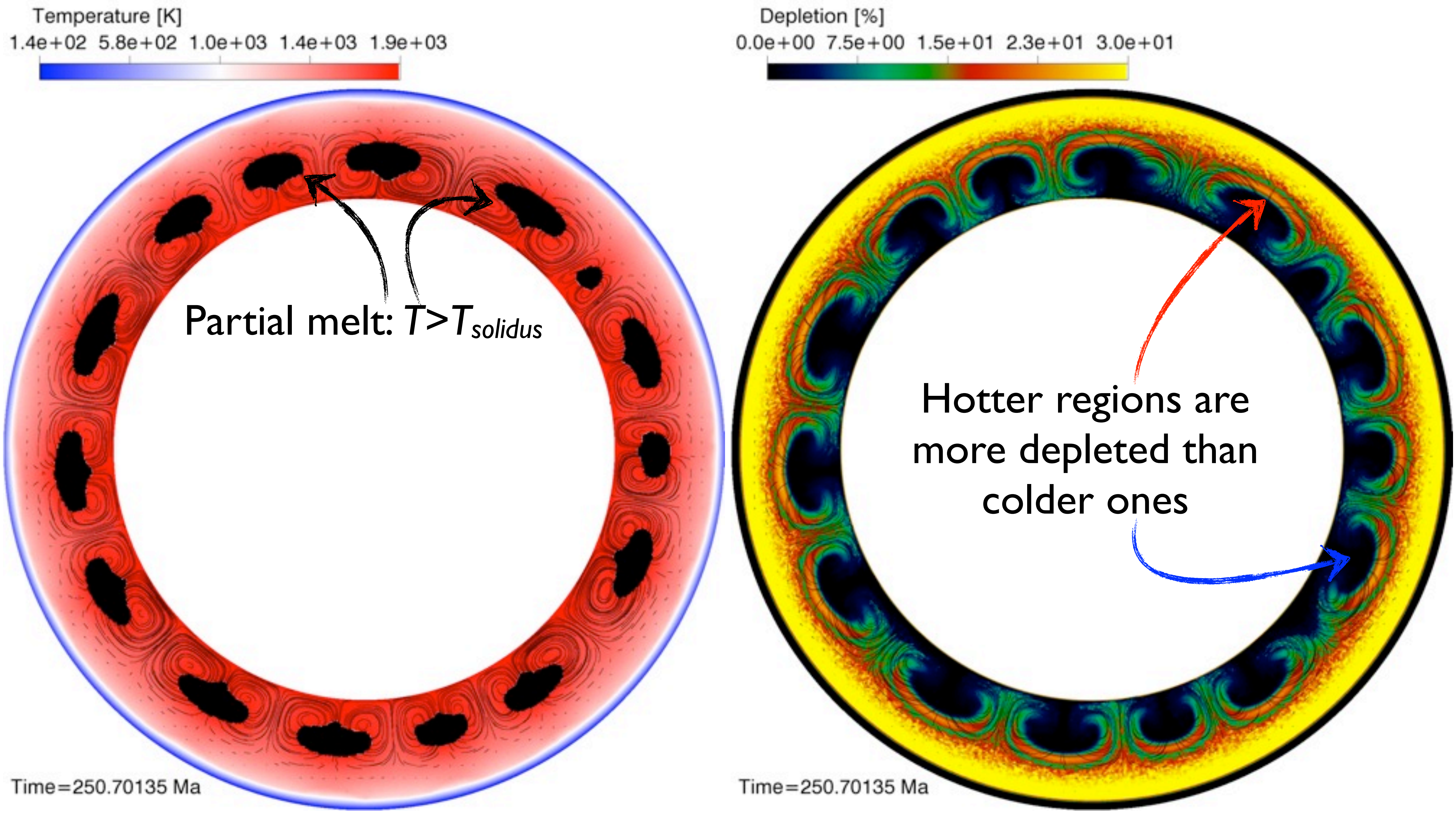

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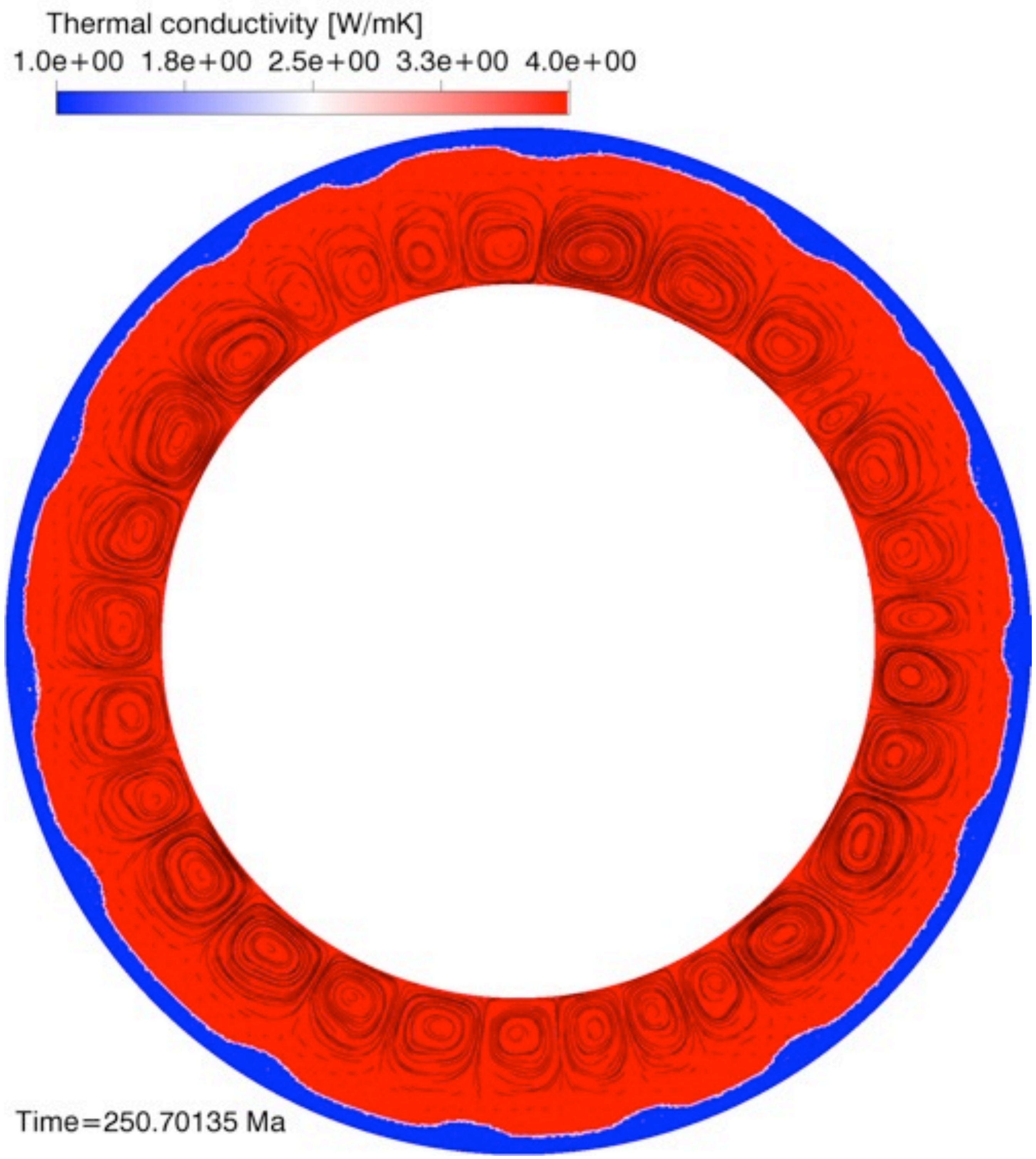

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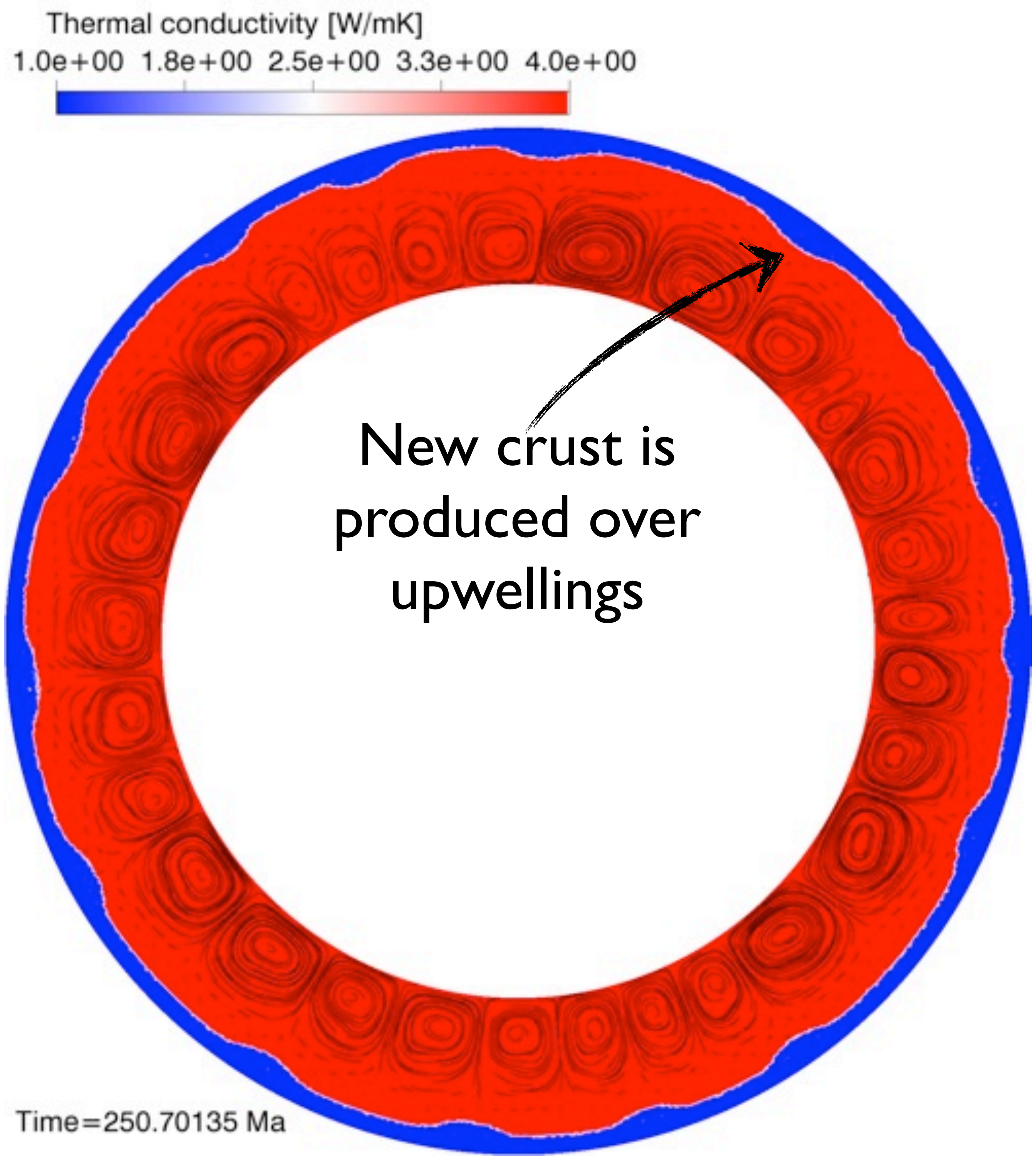

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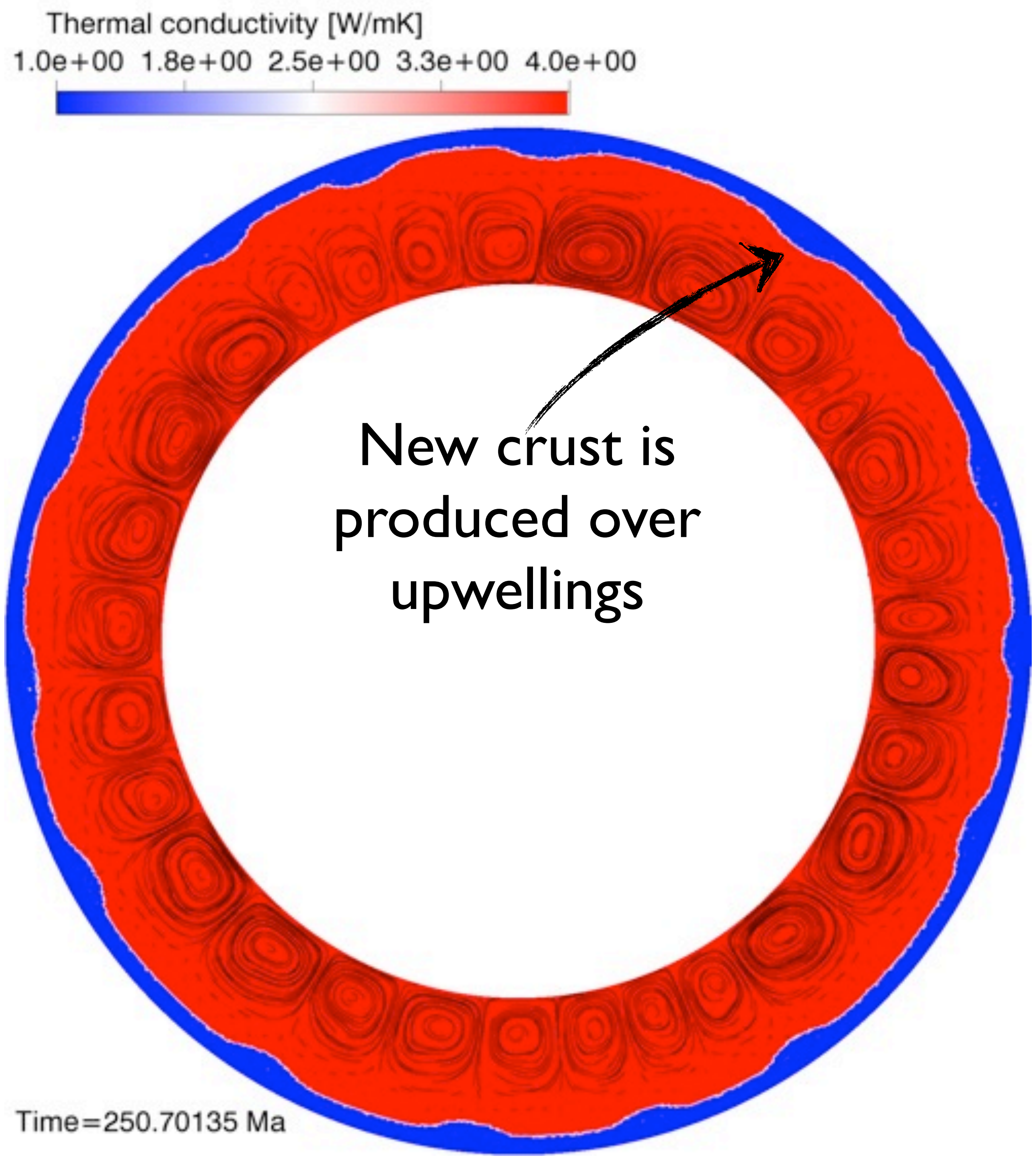


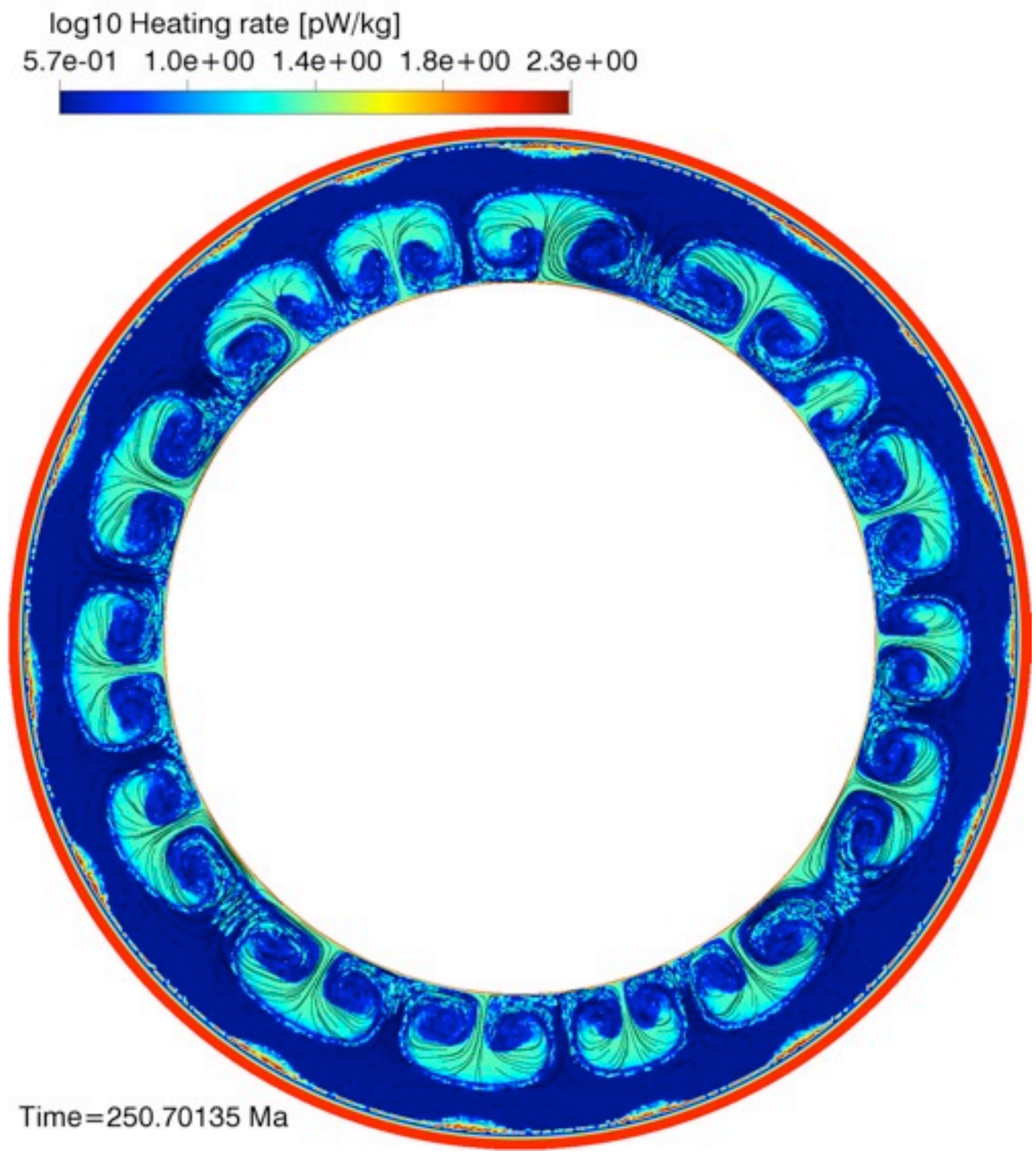

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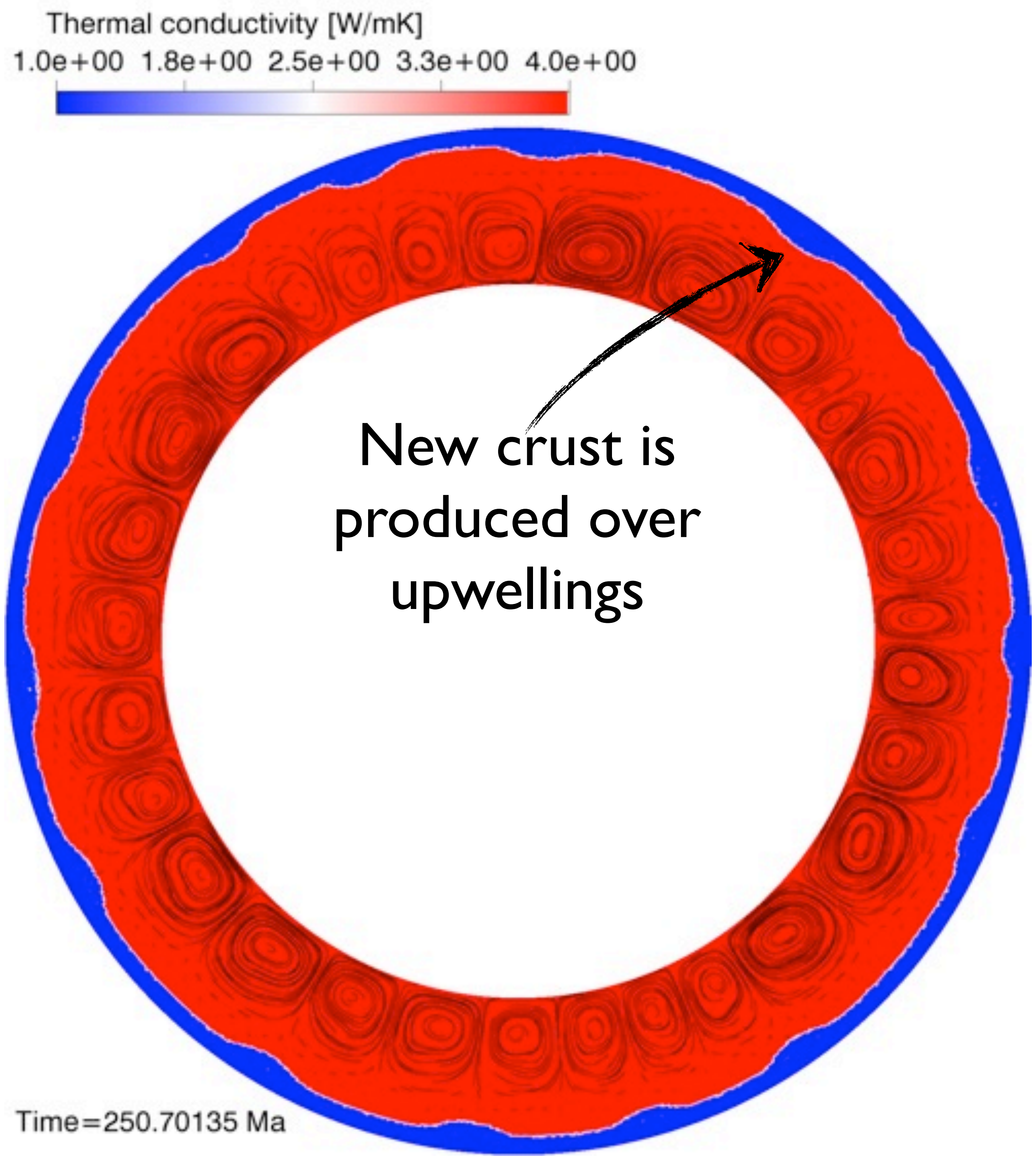


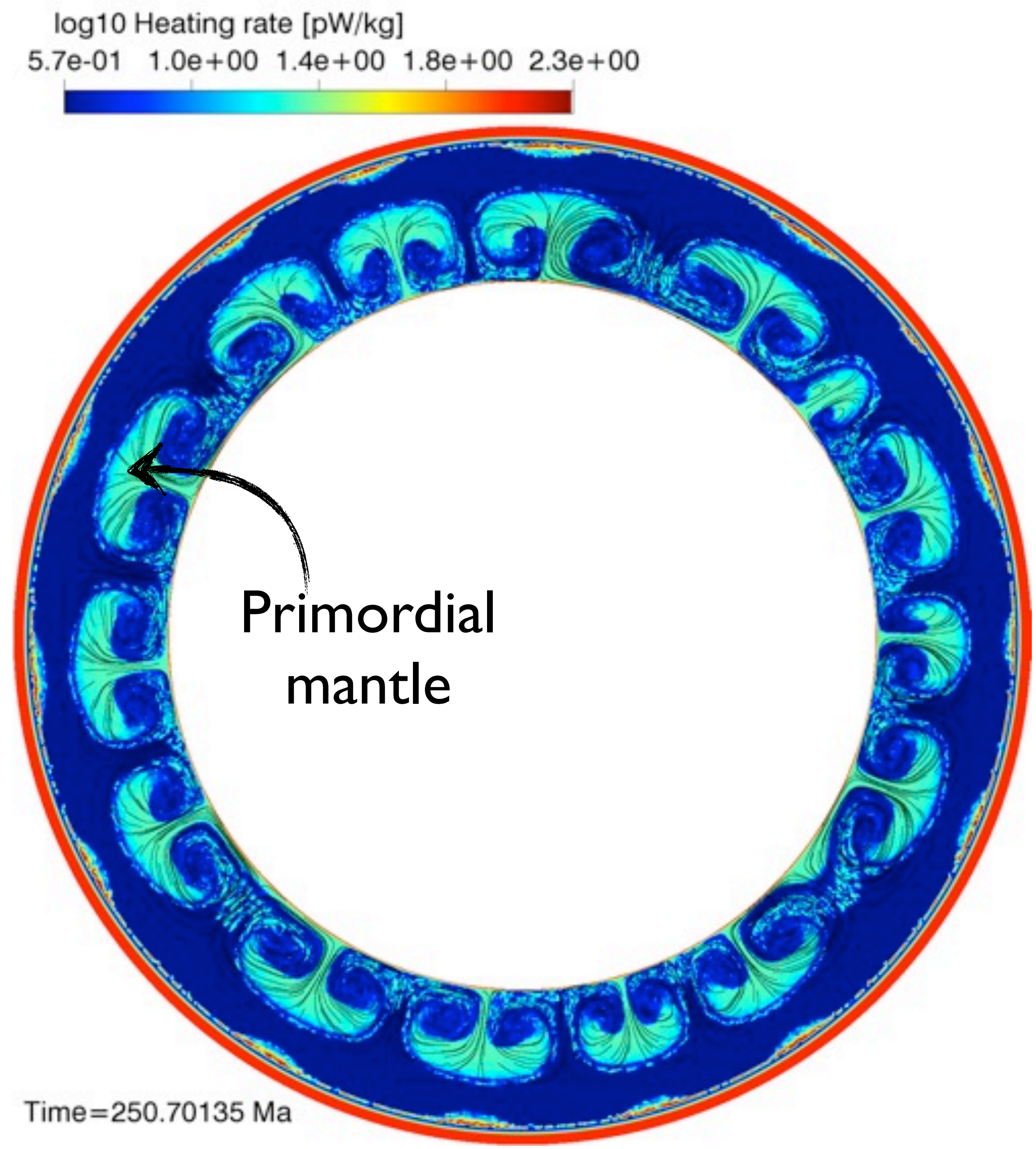

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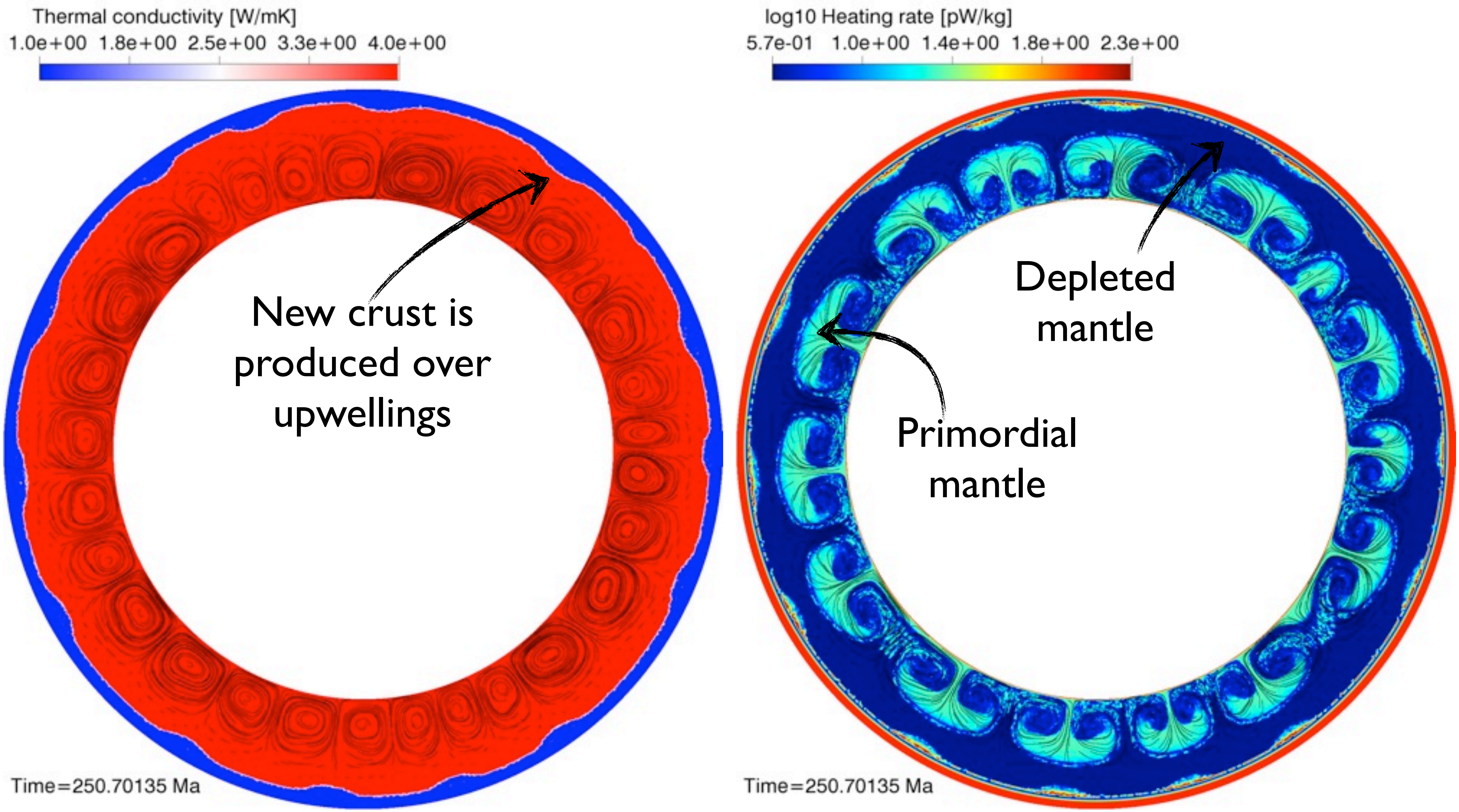

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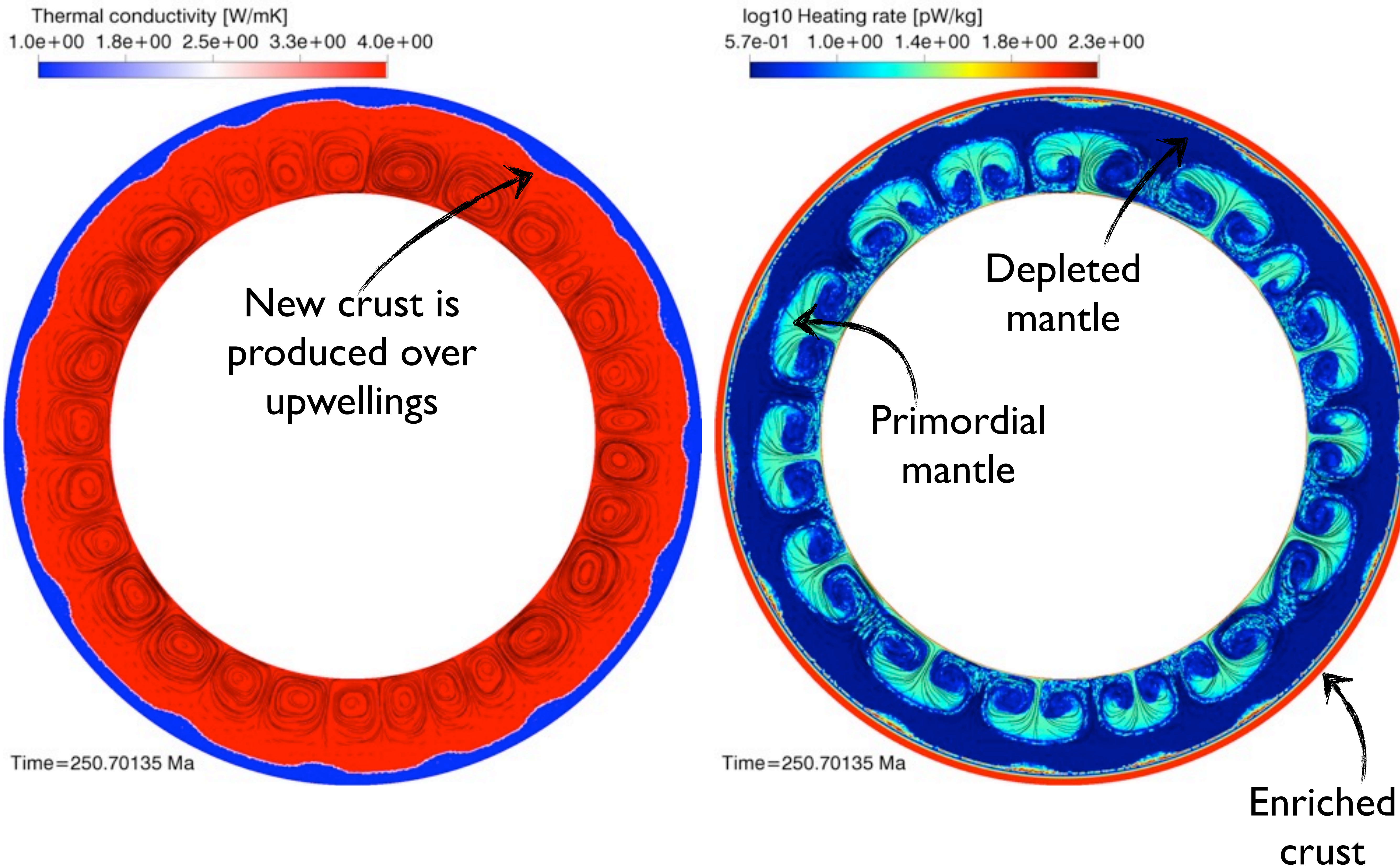
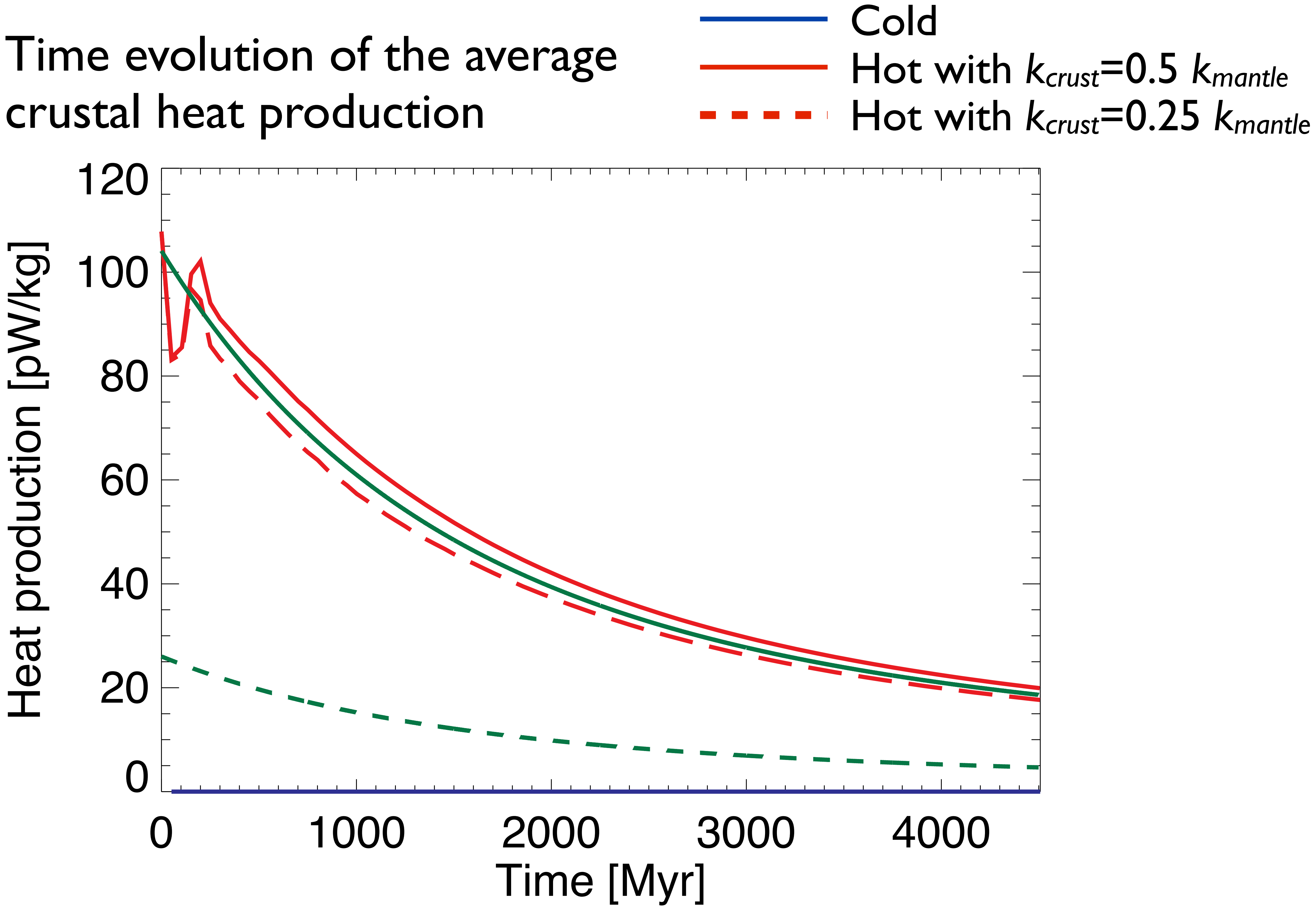


# Results for $H_0$=25% $H_{surface}$

Time evolution of the average crustal heat production



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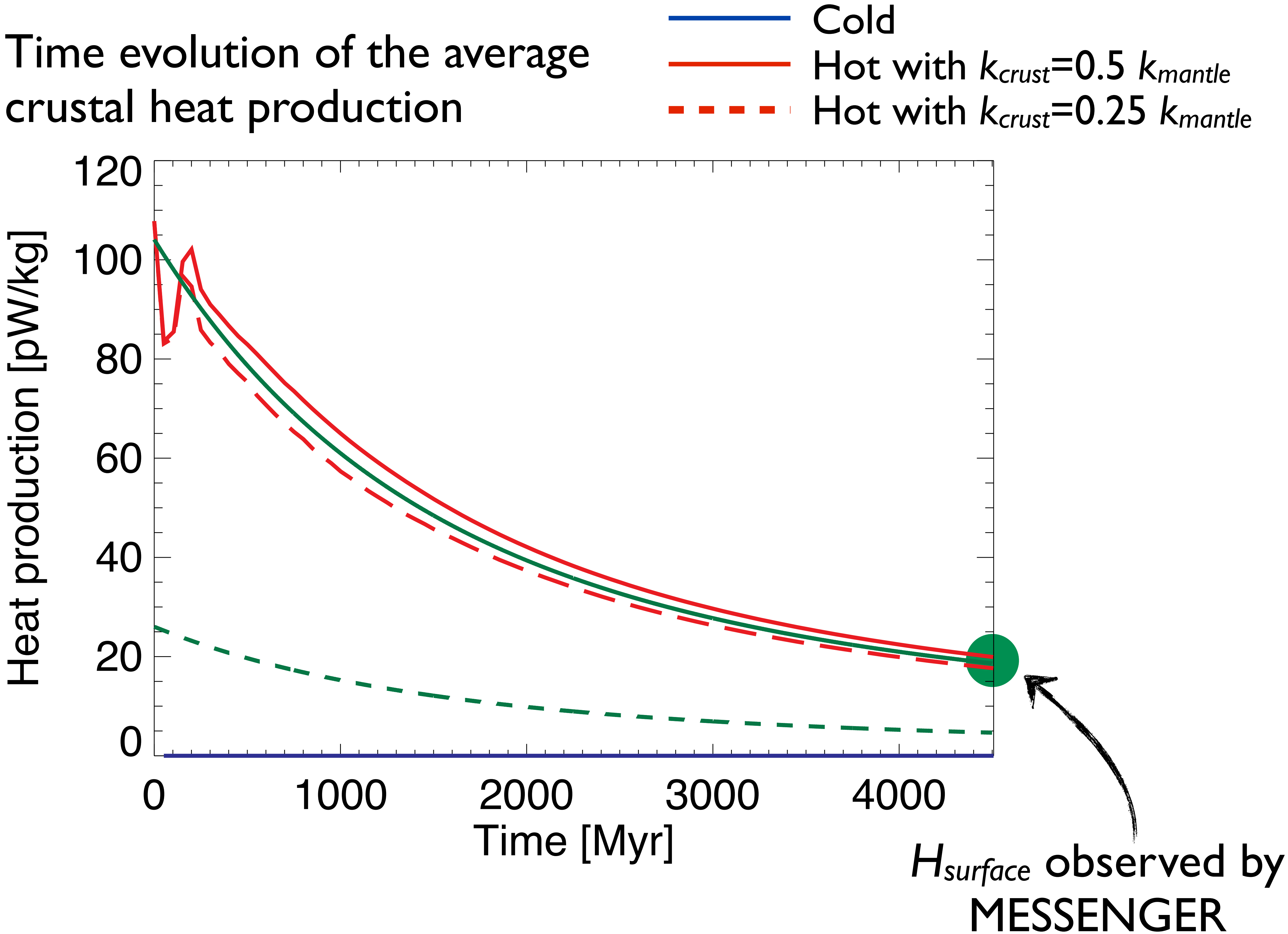

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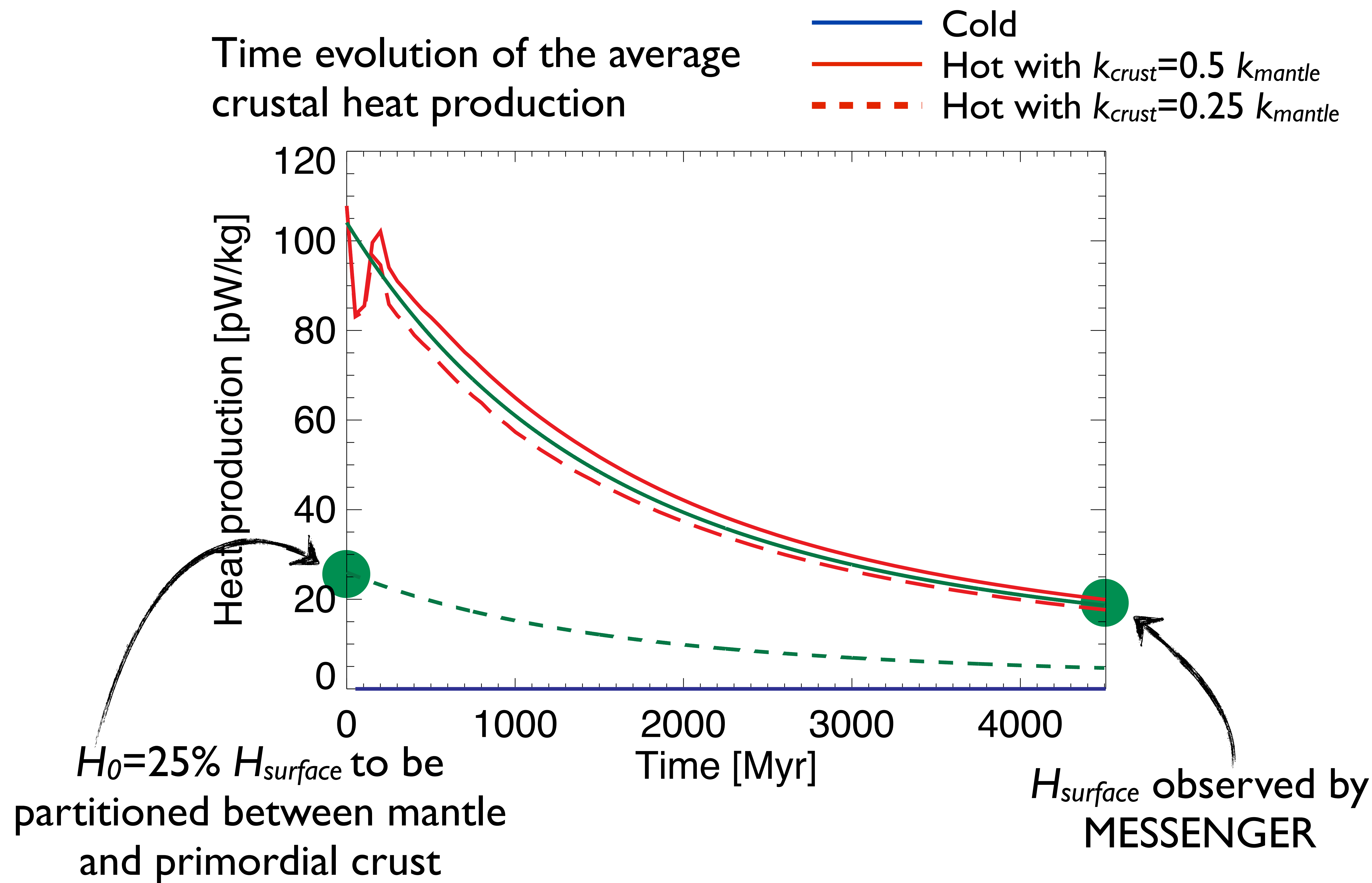

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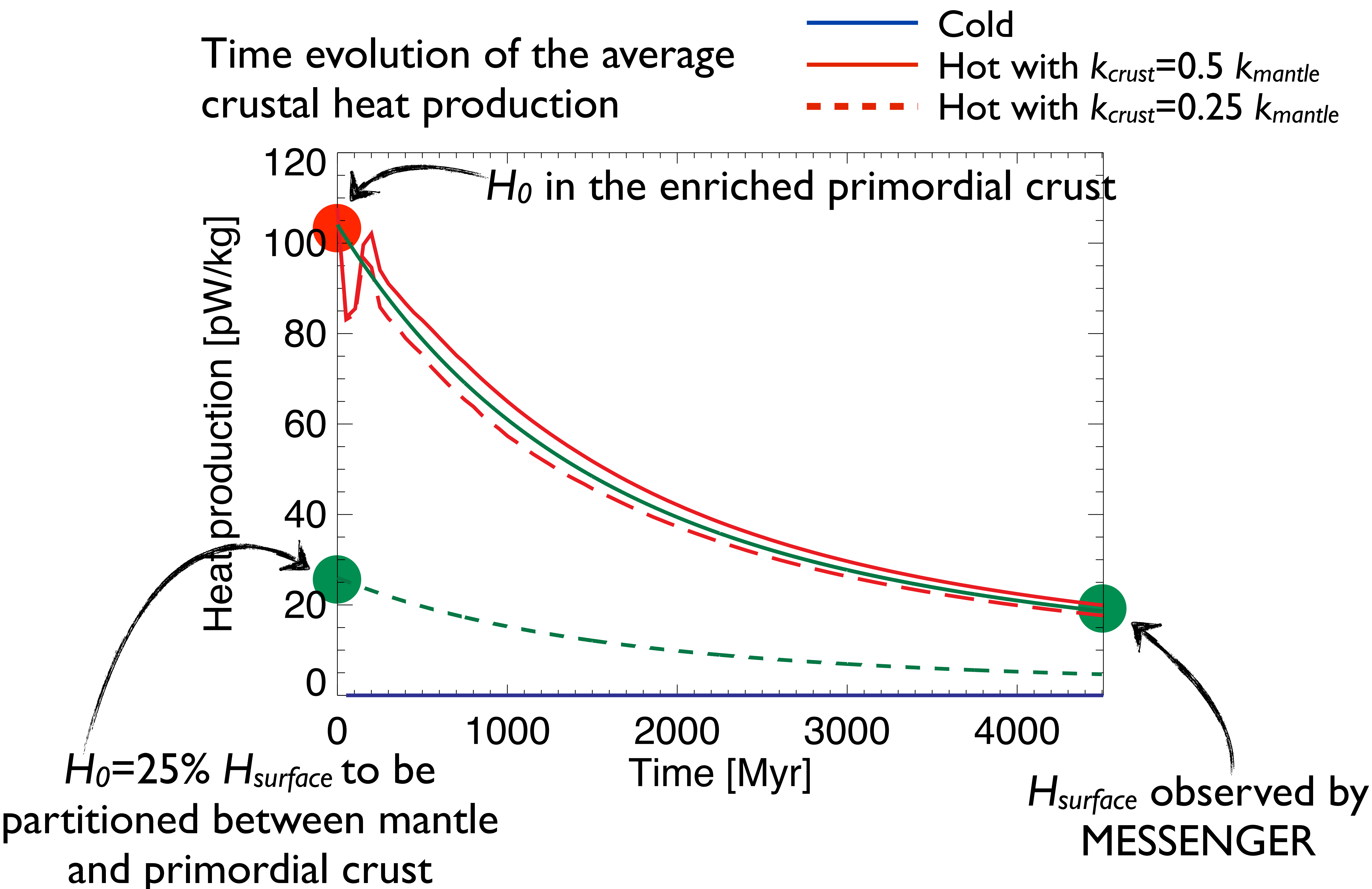

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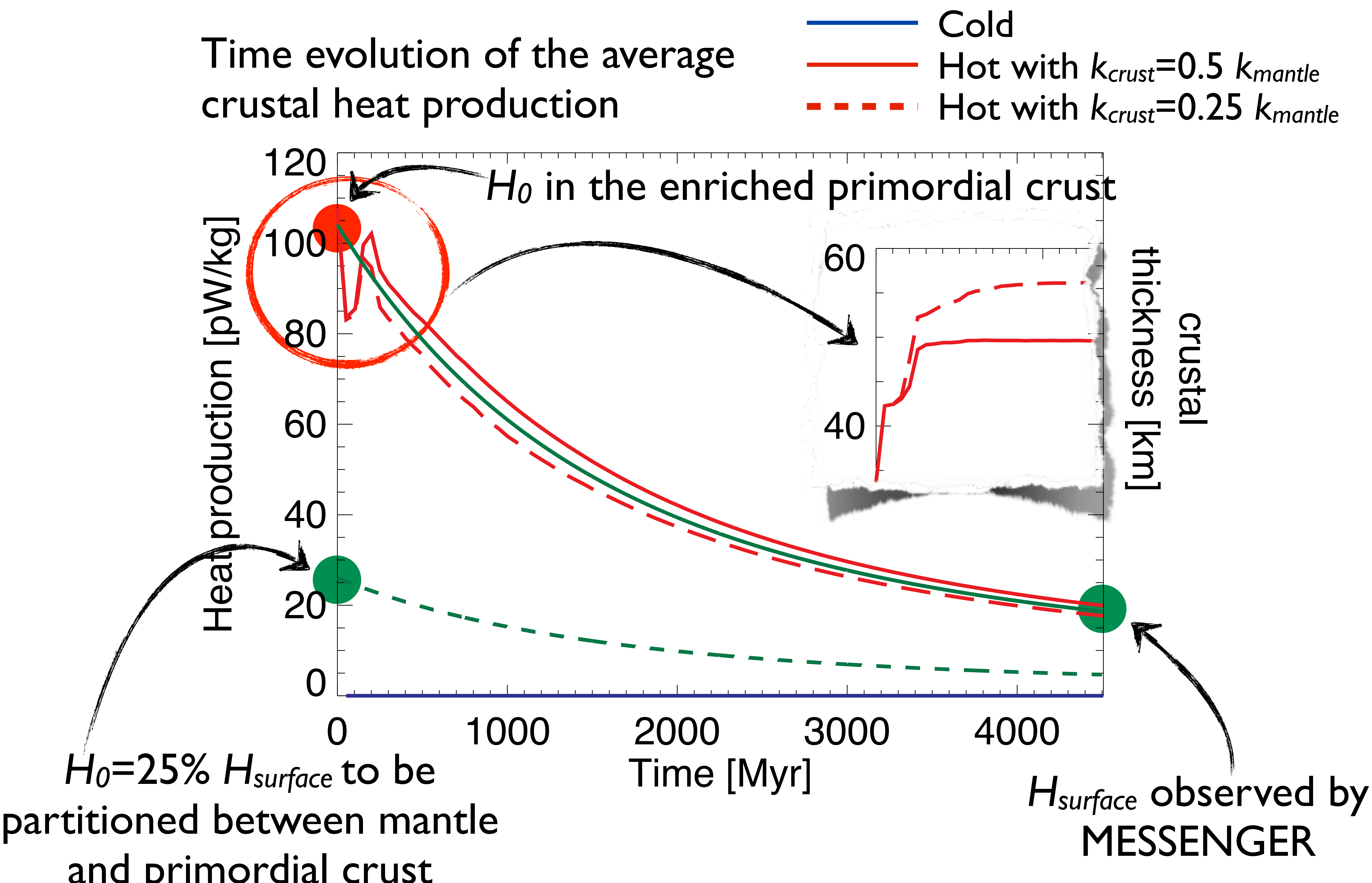

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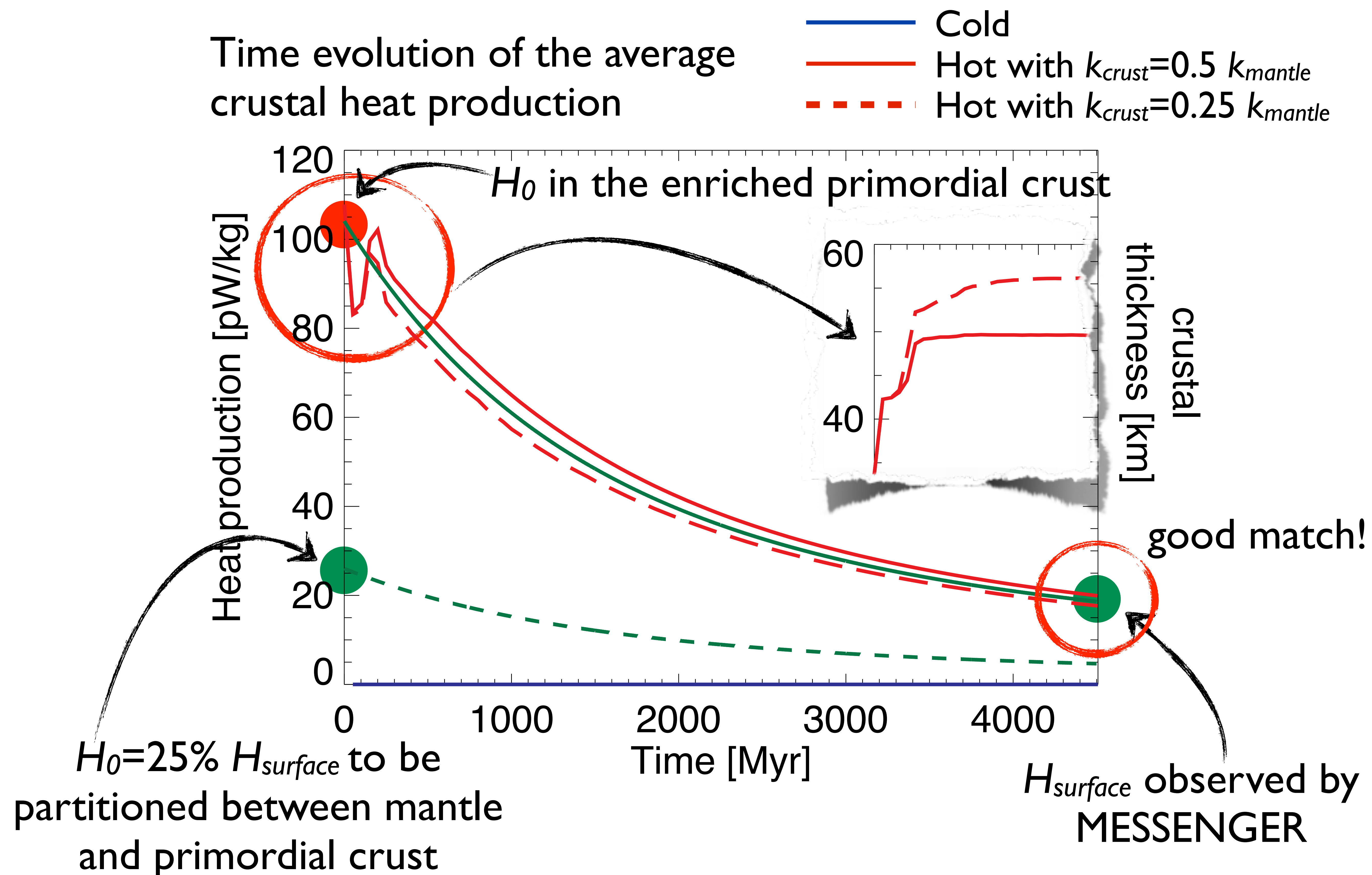
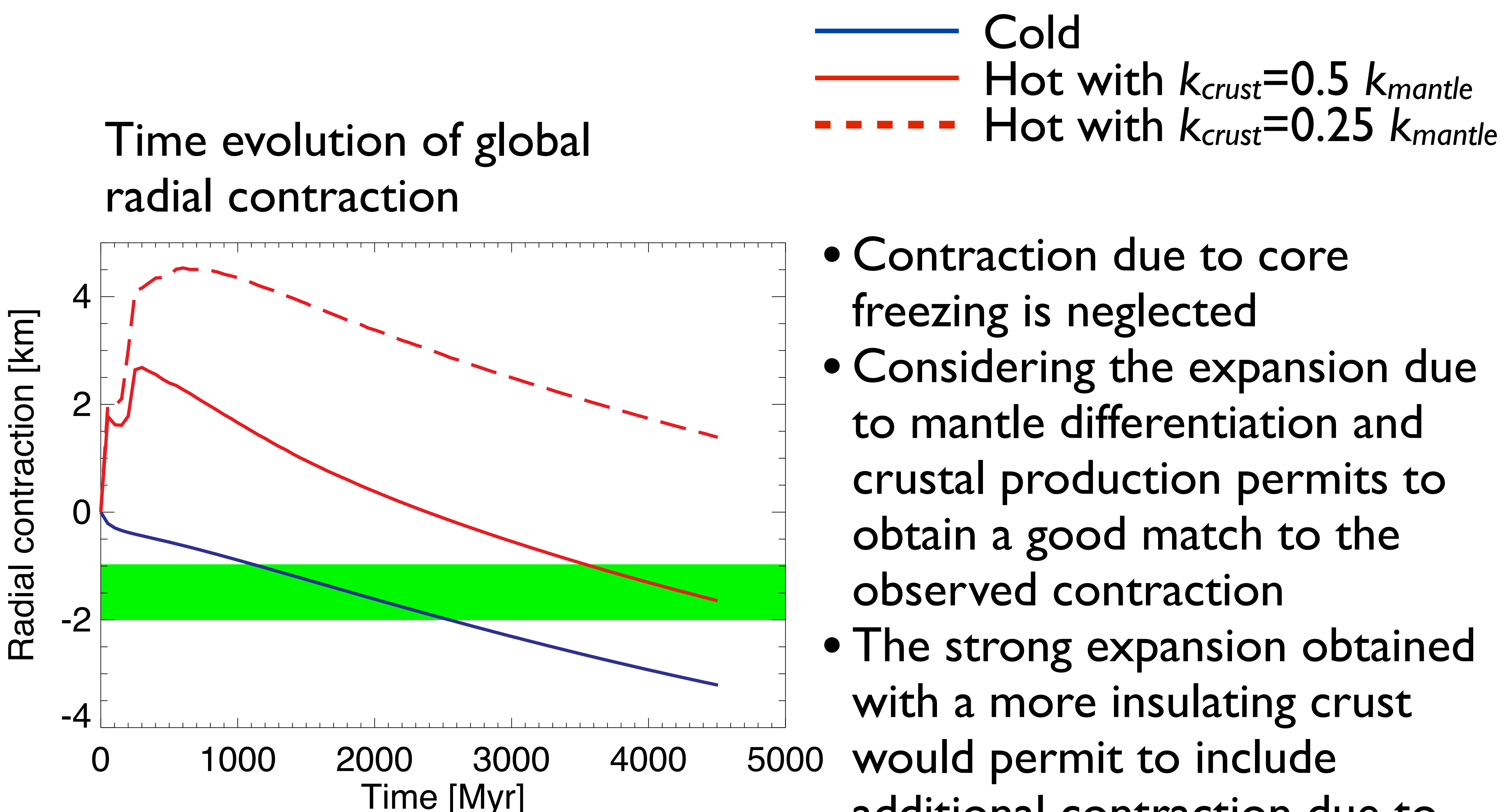


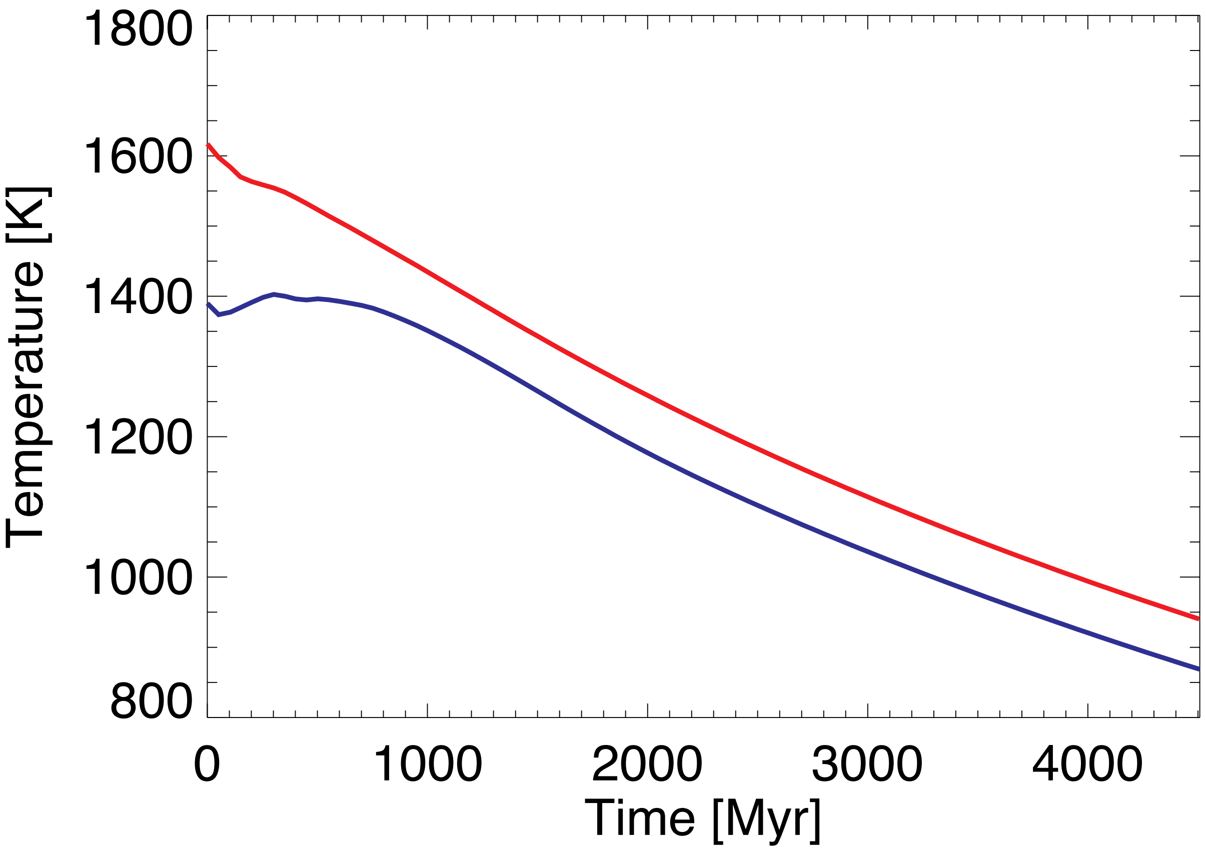
# Results for $H_0$=25% $H_{surface}$

Time evolution of global radial contraction



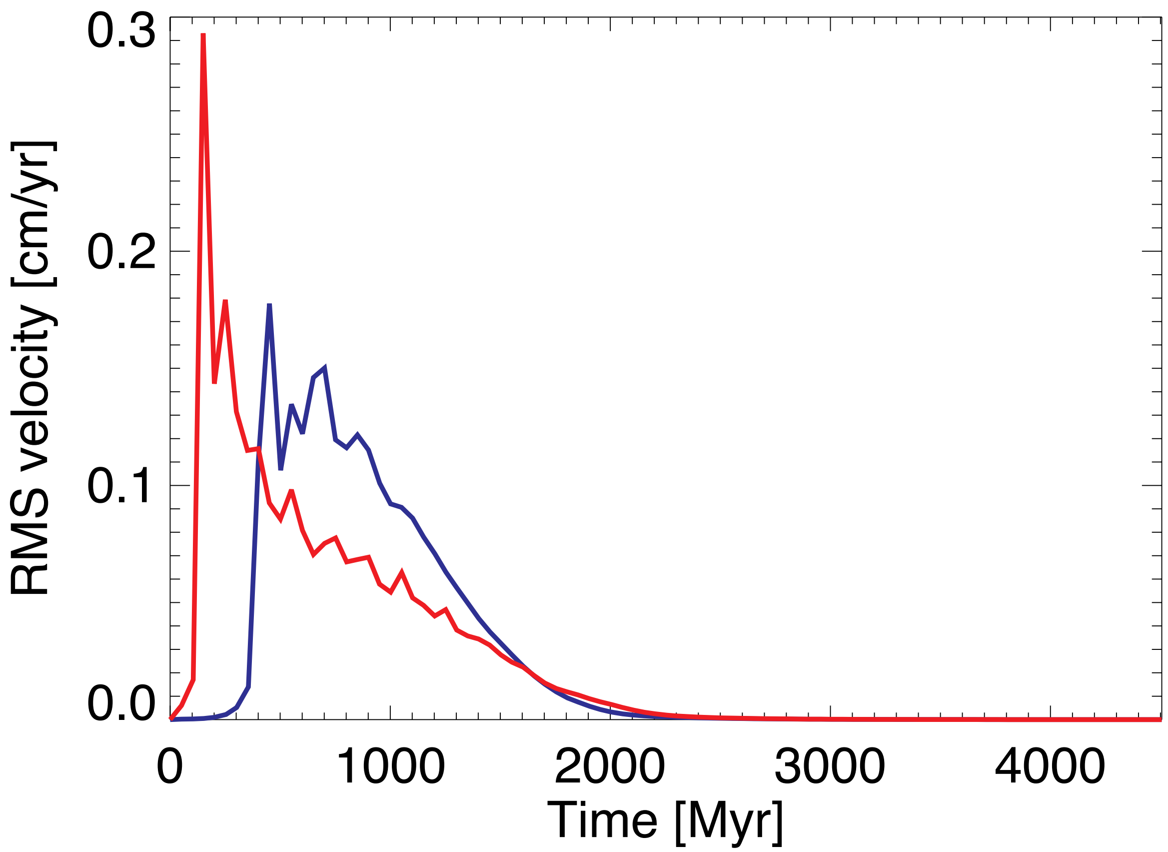

- Contraction due to core freezing is neglected
- Considering the expansion due to mantle differentiation and crustal production permits to obtain a good match to the observed contraction
- The strong expansion obtained with a more insulating crust would permit to include additional contraction due to core freezing

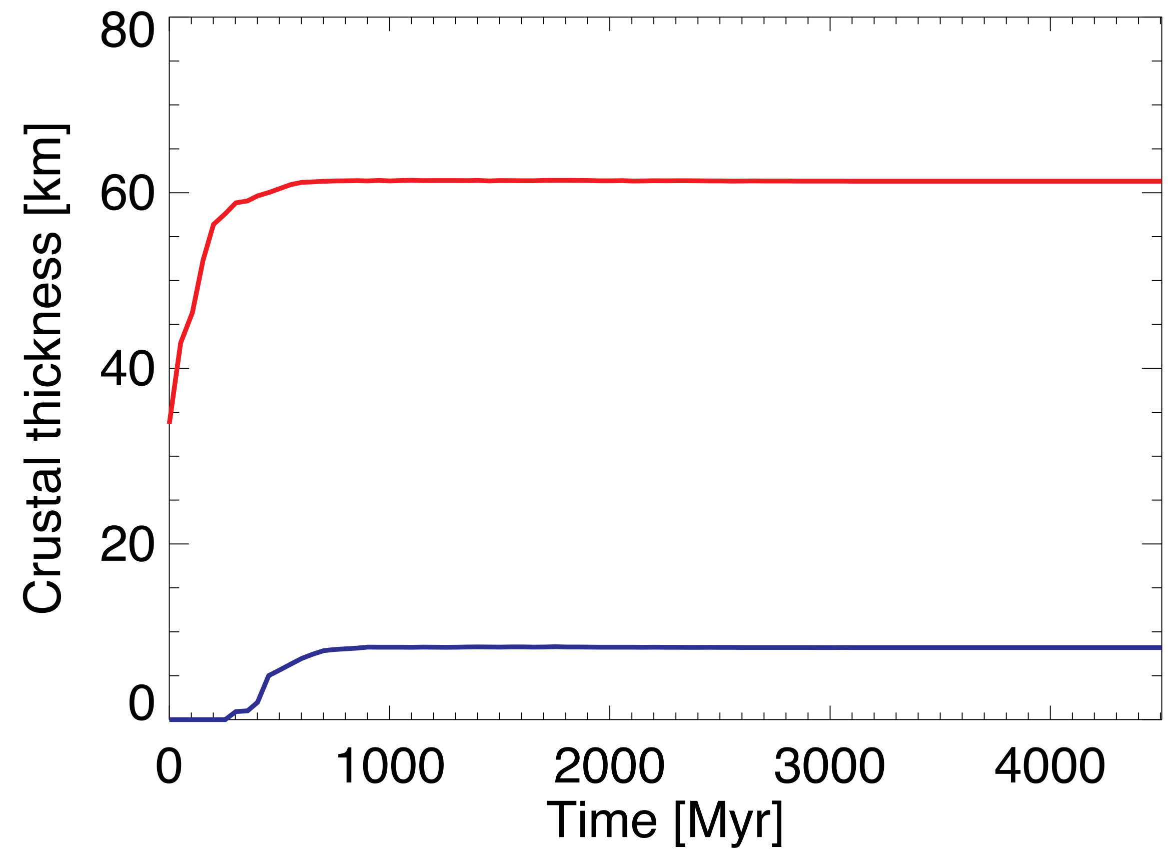
# Results for $H_0$=50% $H_{surface}$



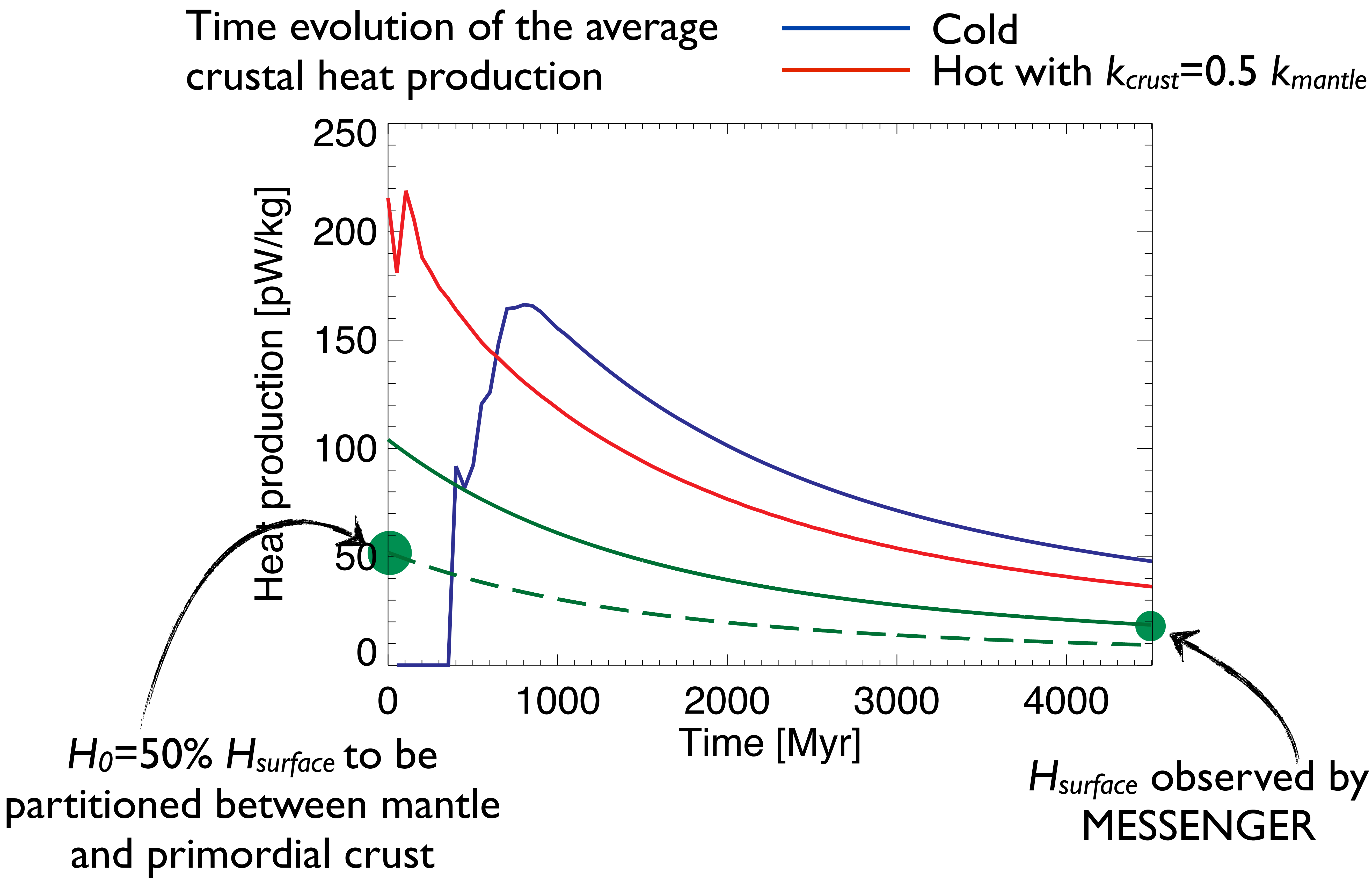

Cold
Hot with $k_{crust}$=0.5 $k_{mantle}$

- “Cold” initial conditions but a high concentration of heat sources allow convection to persist for ~2 Byr ...
- ... but produce a tiny amount of crust

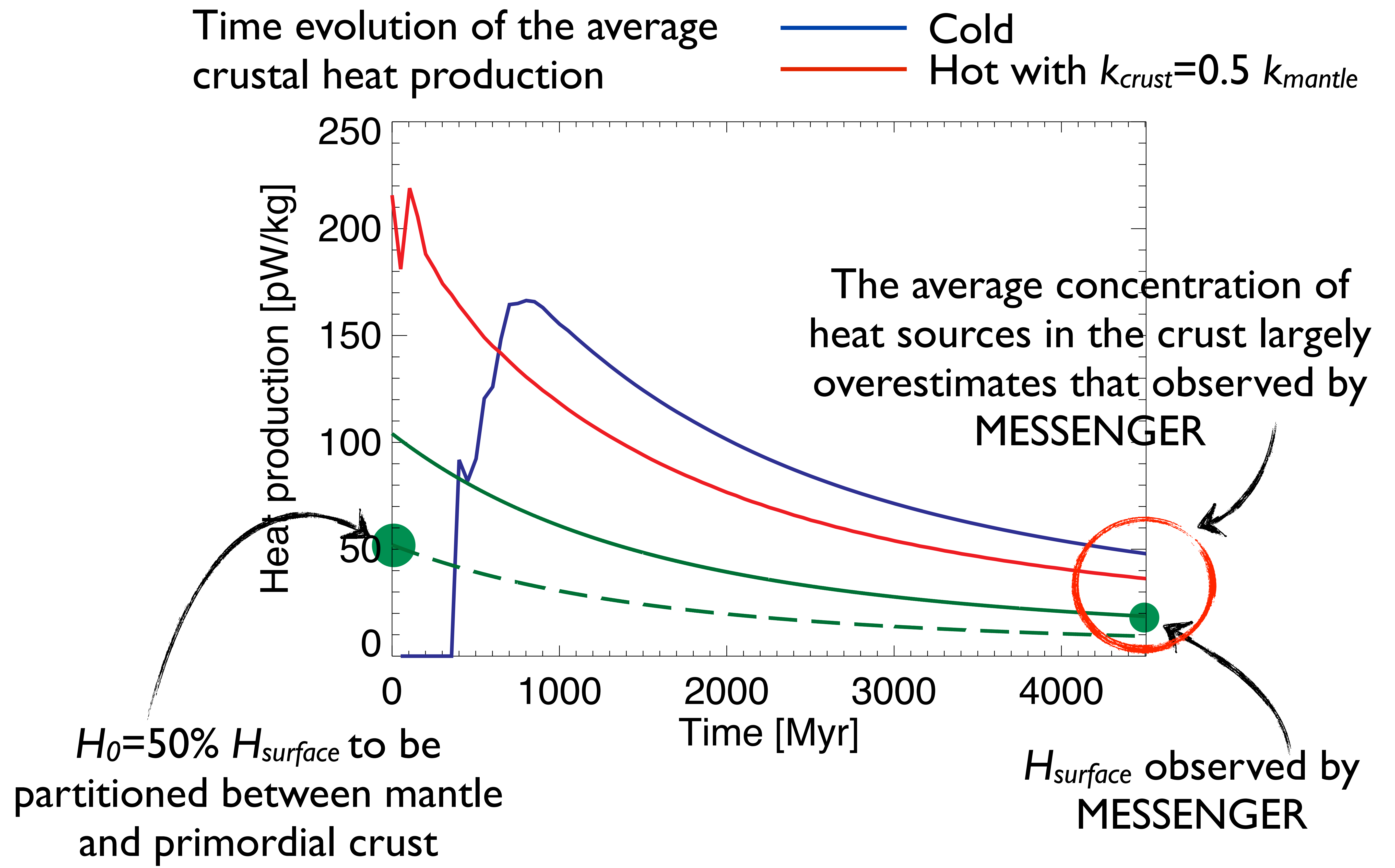


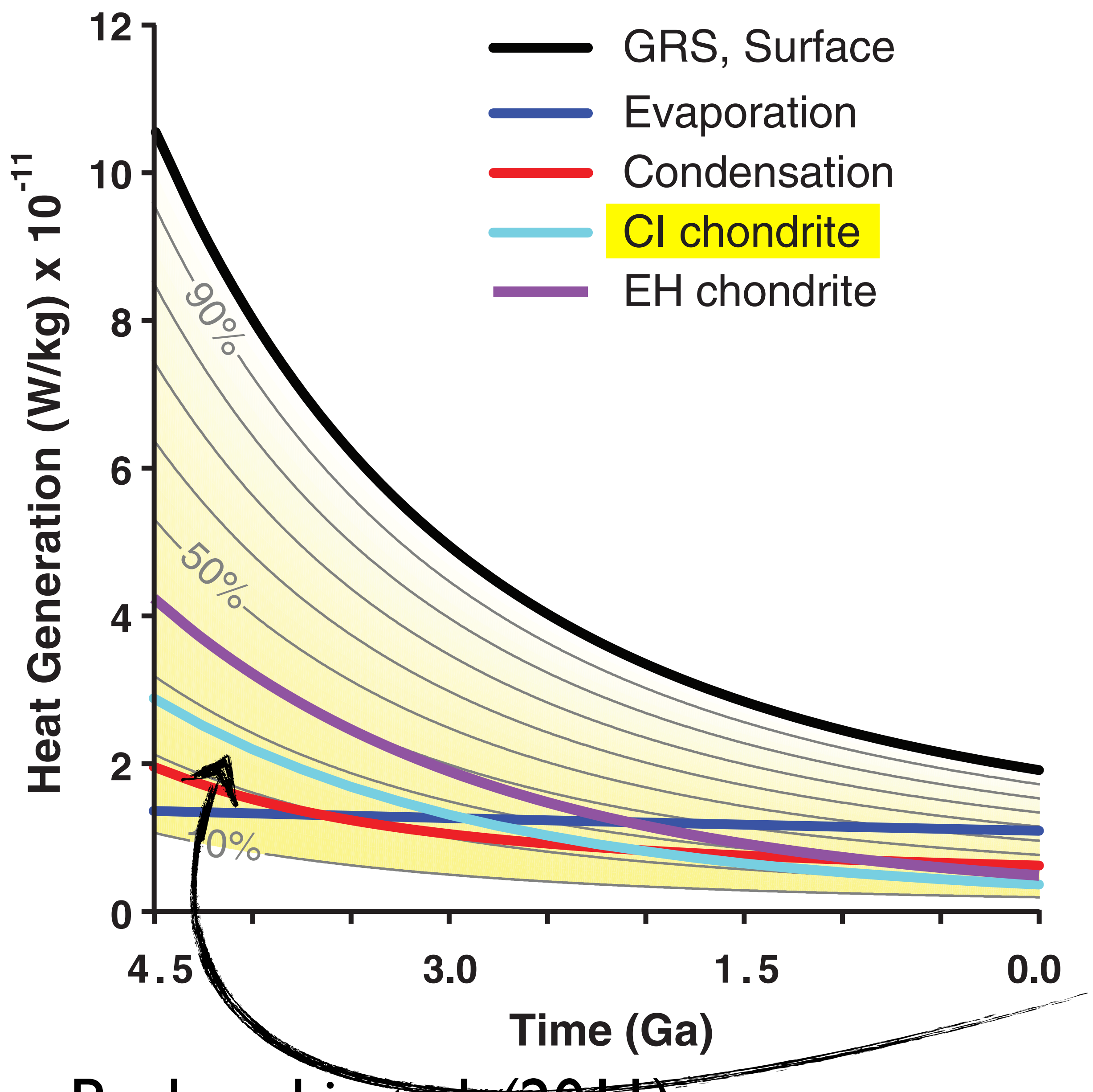
# Results for $H_0$=50% $H_{surface}$



# Results for $H_0$=50% $H_{surface}$



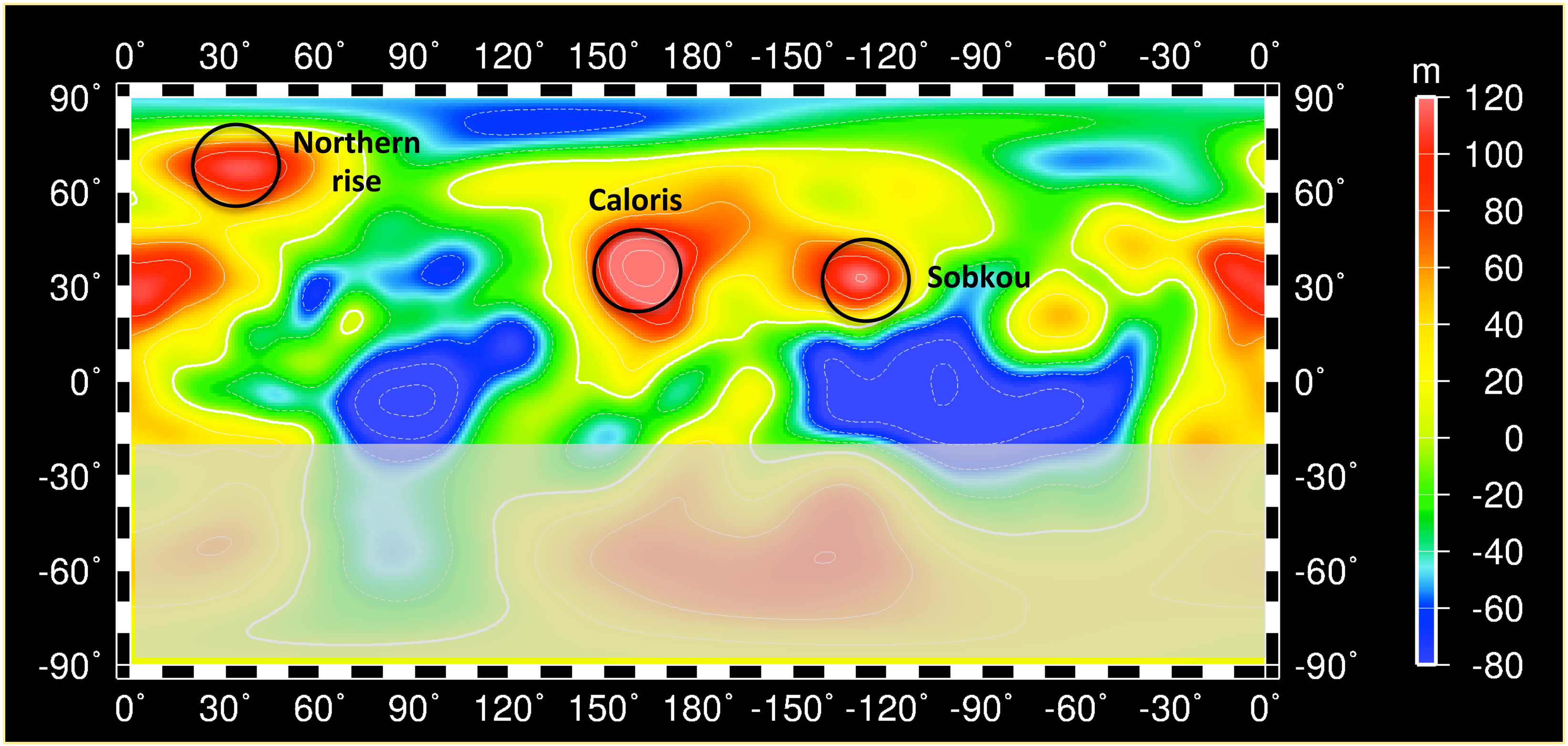
# Quick summary




Peplowski et al. (2011)

- Subsoliuds initial temperatures and $H_0$=25% $H_{surface}$ do not allow convection to start
- With a higher initial temperature and a primordial crust, a good match to the observed surface enrichment can be obtained
- Using $H_0$=50% $H_{surface}$ convection sets in also for "cold" intial conditions but the observed crustal enrichment is largely overestimated
- The decay of heat production corresponding to $H_0$=25% $H_{surface}$ is close to that of some chondrites

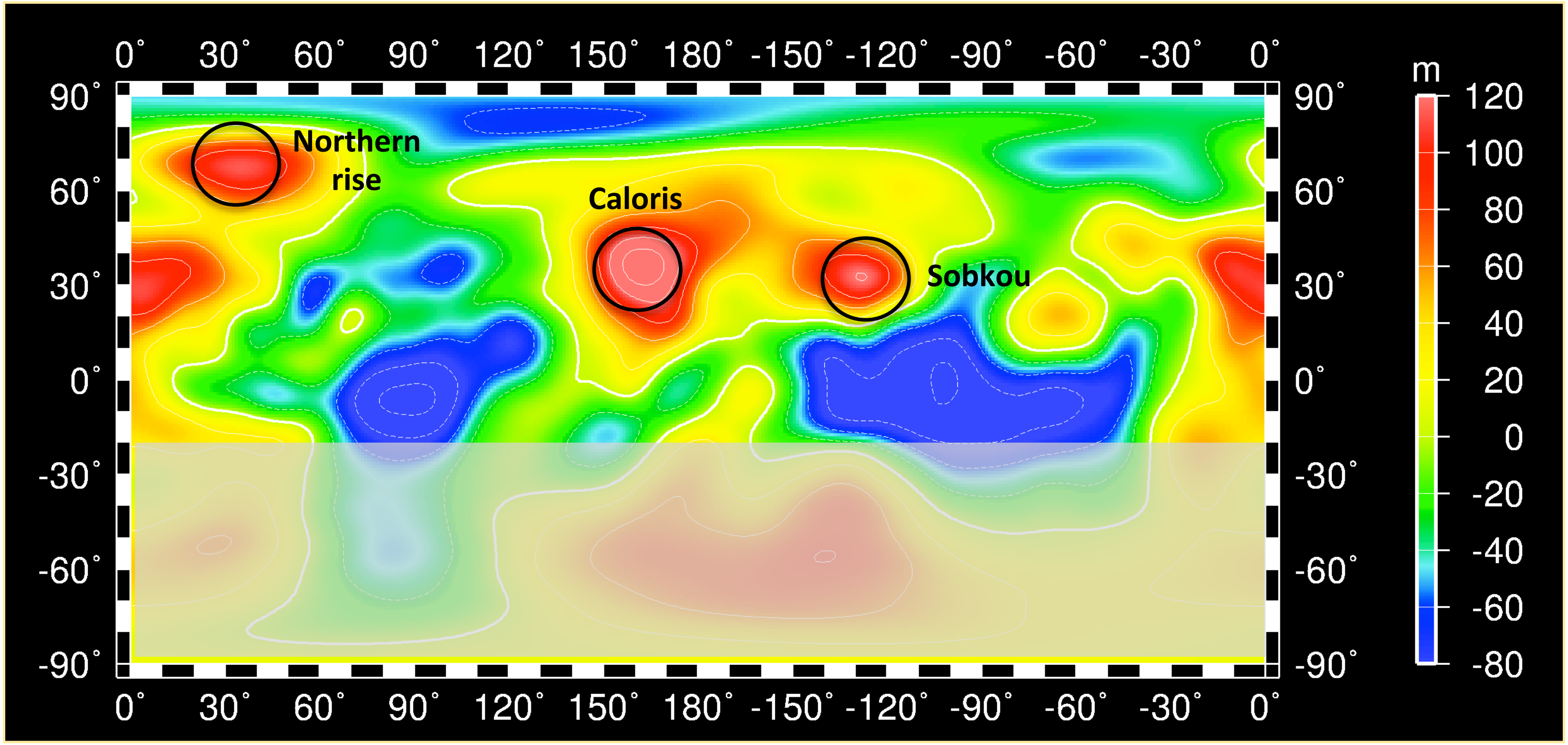
# Dynamic geoid from 3D spherical models




Smith et al. (2011)

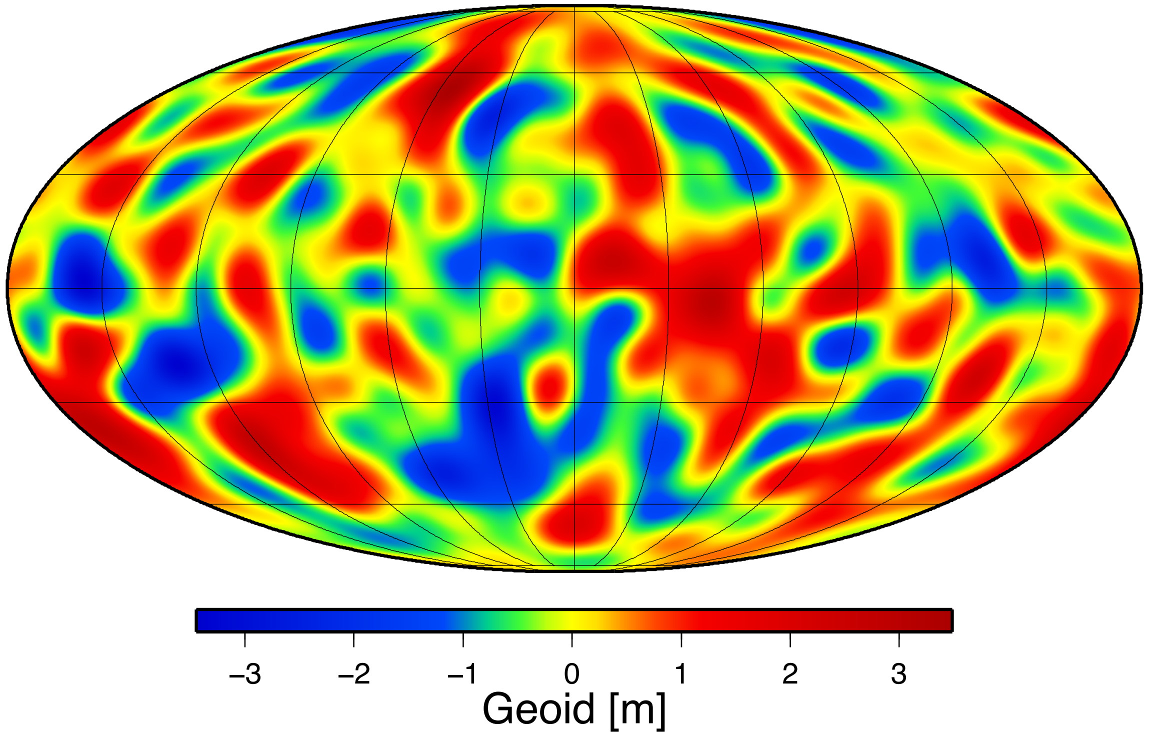
First MESSENGER geoid model up to degree and order 20: peak to peak amplitude of ~200 m

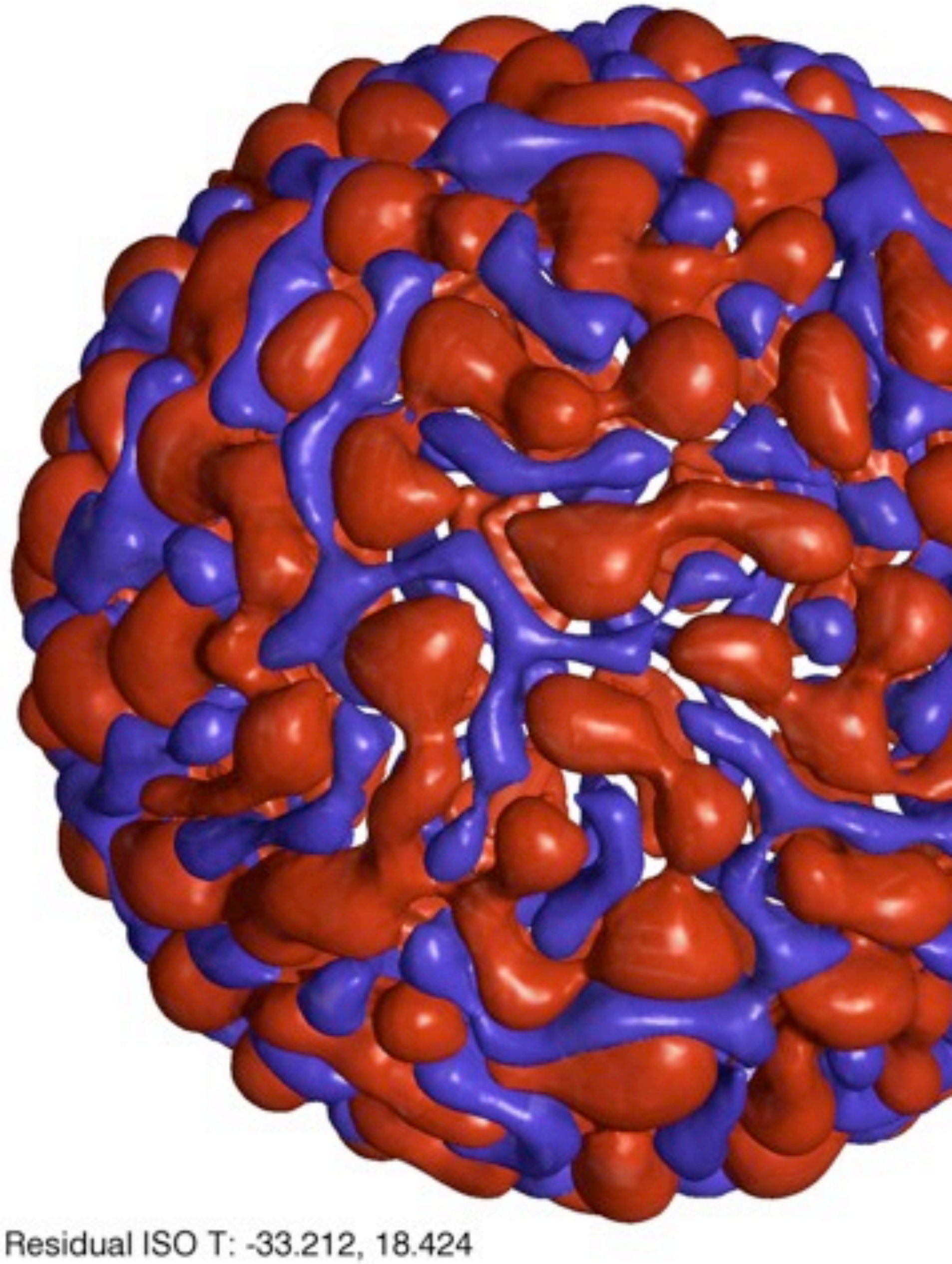
# Dynamic geoid from 3D spherical models




First MESSENGER geoid model up to degree and order 20: peak to peak amplitude of ~200 m

Smith et al. (2011)



# Conclusions

- After 3 flybys and 1 year in orbit, MESSENGER observations have changed quite dramatically the understanding of Mercury. In particular, Mercury
  - has a large(er), at least partially, fluid core and a very thin mantle
  - a significant volatile content
  - experienced stages of intense volcanic activity
- These new pieces of information require models of thermo-chemical evolution to be significantly revised