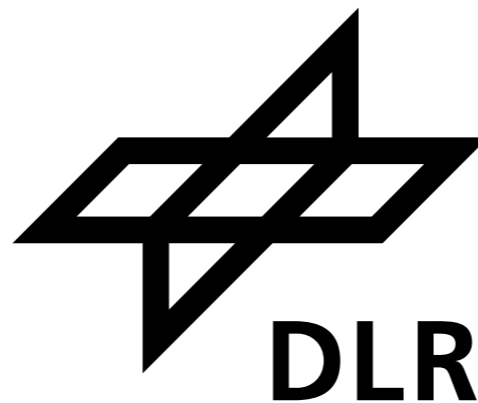


Mercury's thermo-chemical evolution from numerical models constrained by MESSENGER observations

Nicola Tosi^{1,2}

Doris Breuer², Ana Plesa², Frank Wagner², Matthieu Laneuville³

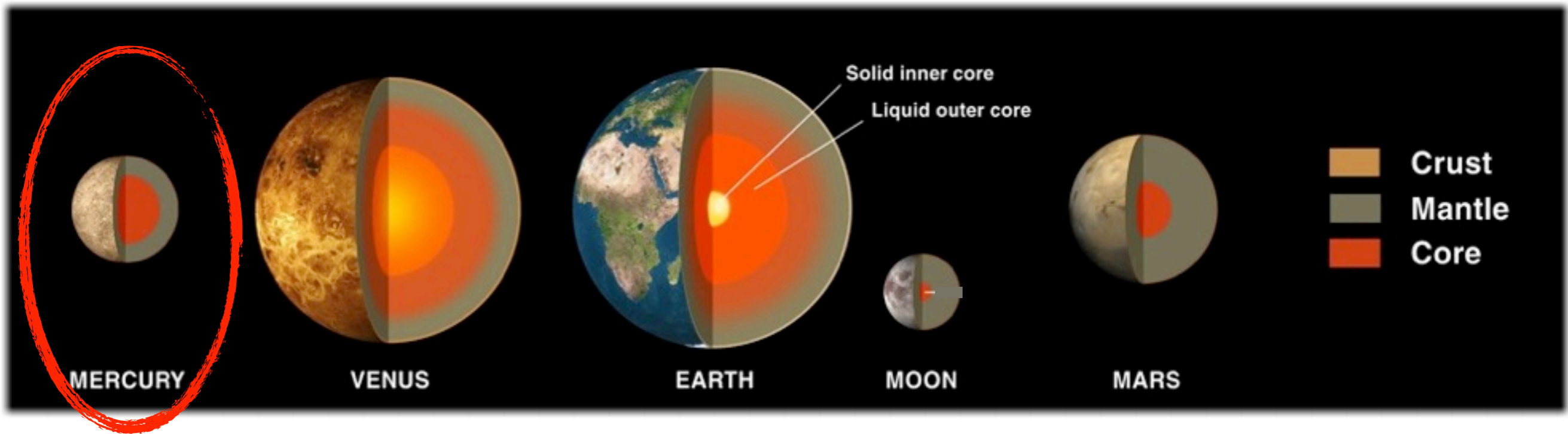


¹ Technische Universität Berlin, Germany

² Deutsches Zentrum für Luft und Raumfahrt, Berlin, Germany

³ Institut de Physique du Globe de Paris, France

Basics facts about Mercury

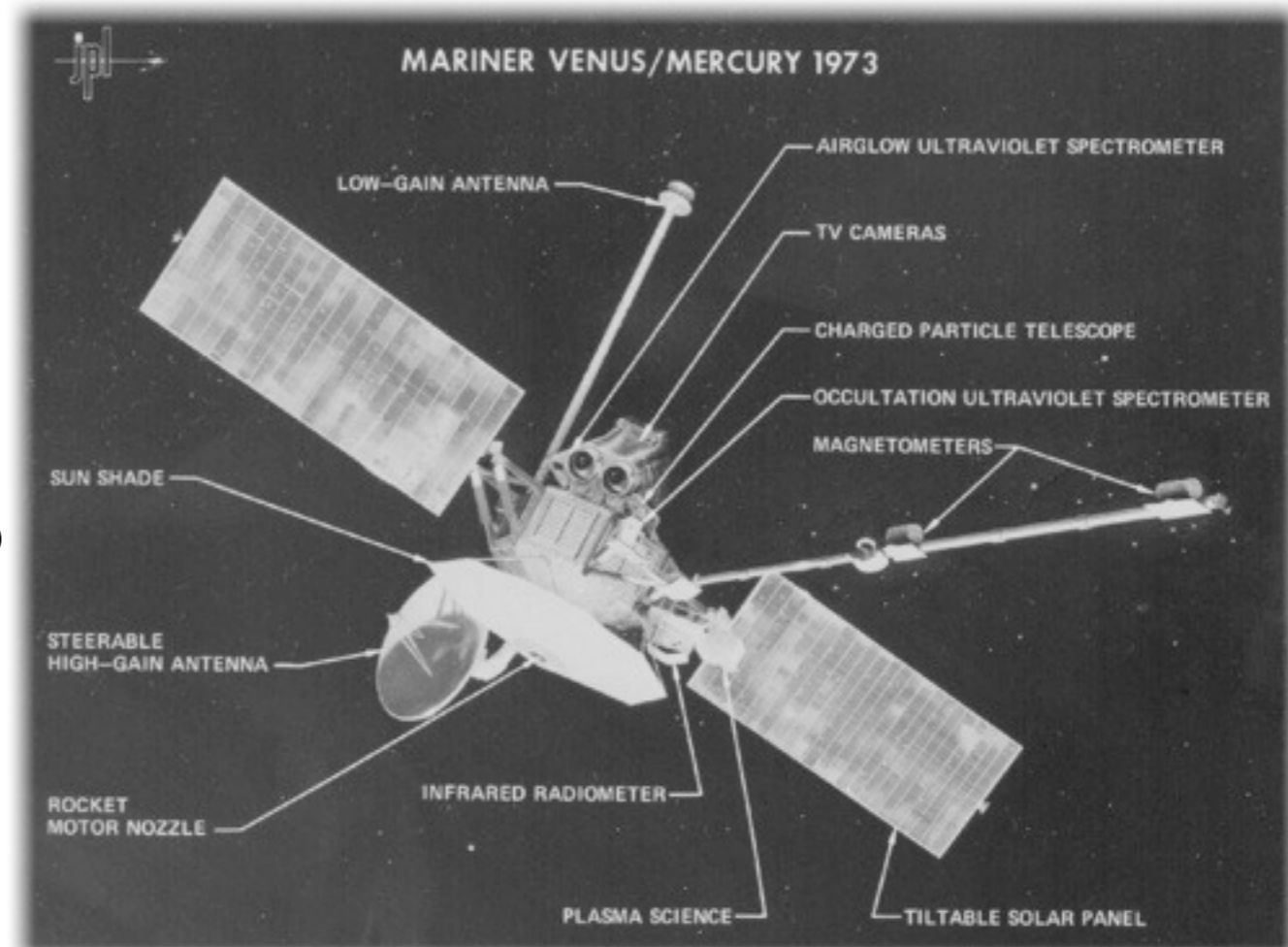


- Semi-major axis: 0.39 AU
- 3:2 spin-orbit resonance
- Radius: 2440 km
- Surface gravity: 3.7 m s^{-2} (like Mars!)
- Mean bulk density: 5.43 g cm^{-3} (like Earth!)
- Black body temperature: 440 K

Exploration of Mercury

Mariner 10

- 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-hour orbit (~200-15000 km altitude)
- 7 instruments for imaging, atmospheric and surface composition, magnetic field and magnetosphere, topography and gravity

Exploration of Mercury



The poster features the ESA logo at the top left and the mission name 'BEPICOLOMBO' in large, stylized letters. Below the name is the subtitle 'Comprehensive exploration of Planet Mercury'. The central image shows the BepiColombo spacecraft in orbit around Mercury, with the planet's surface and a red orbital path visible. Text on the left side provides details about the mission's challenges and objectives.

esa

BEPICOLOMBO

Comprehensive exploration of Planet Mercury

BepiColombo, an ESA mission in cooperation with JAXA, will explore Mercury, the planet closest to the Sun.

Europe's space scientists have identified the mission as one of the most challenging long-term planetary projects because Mercury's proximity to the Sun makes it difficult for a spacecraft to reach and survive in the harsh environment. The scientific return of this mission lies in the need to acquire an accumulation of observations, only achievable in close vicinity of the planet, to better understand Mercury and to enhance our overall understanding of the Solar System.

The mission will consist of two separate spacecraft that will orbit the planet. ESA is building one of the main spacecraft, the Mercury Planetary Orbiter (MPO), and the Japanese space agency JAXA will contribute the other, the Mercury Magnetospheric Orbiter (MIO).

The journey to Mercury will begin with the launch of the BepiColombo spacecraft from Kourou in August 2018. The complementary trajectory requires an enormous amount of braking energy against the Sun's gravity, which increases with proximity to the Sun. BepiColombo will accomplish this by making clever use of the gravity of the Moon, Earth, Venus and Mercury itself and by using the efficient propulsion method with solar electric thrusters, a method proven by ESA's SMART-1 mission.

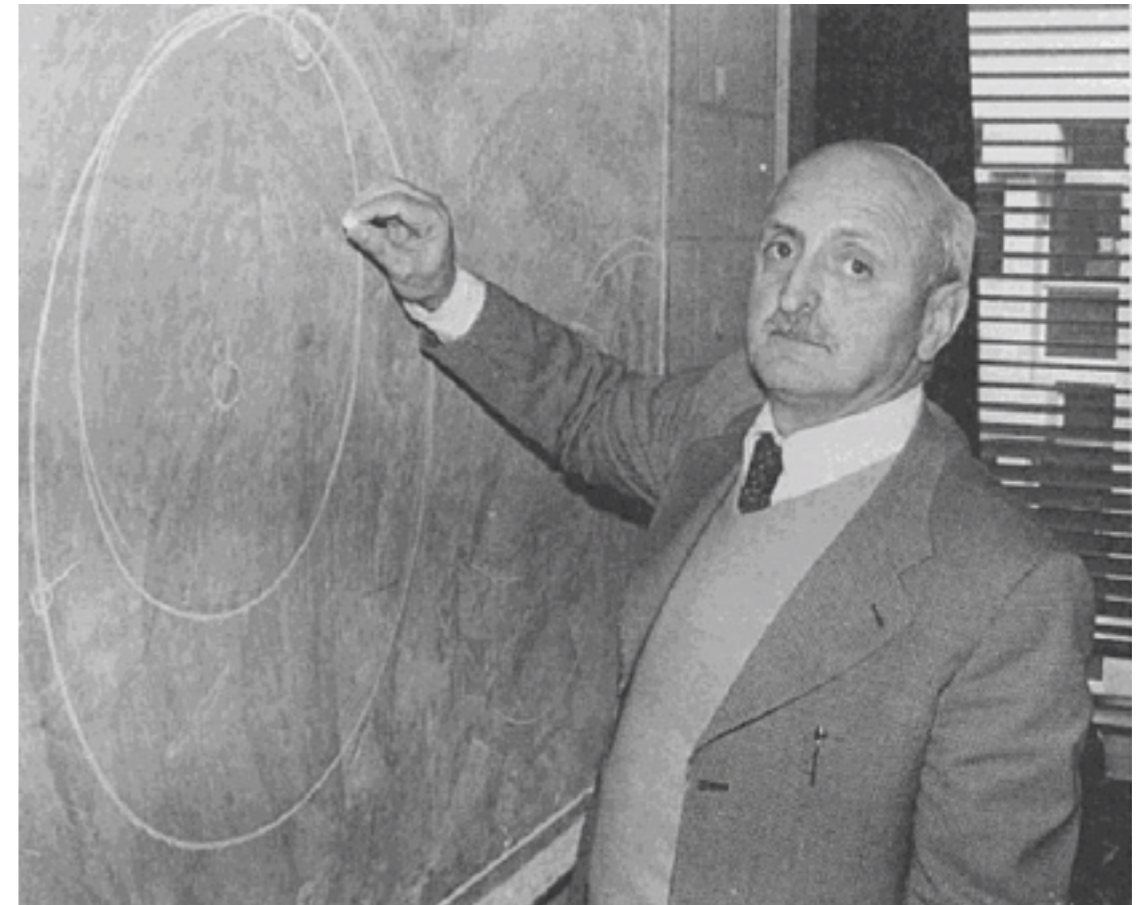
Following arrival at Mercury after a 6-year cruise through space, BepiColombo will begin its time to the mission objectives:

- Origin and evolution of spin-orbit resonances
- Mercury as a planetary form: magnetic moments, geology, composition and history
- Mercury's tenuous atmosphere (exosphere): composition and dynamics
- Mercury's magnetized envelope (magnetosphere): structure and dynamics
- Origin of Mercury's magnetic field
- Test of Einstein's theory of general relativity

European Space Agency
Agency satellite communications

More information can be found at:
<http://www.esa.int/mission/bepicolombo>

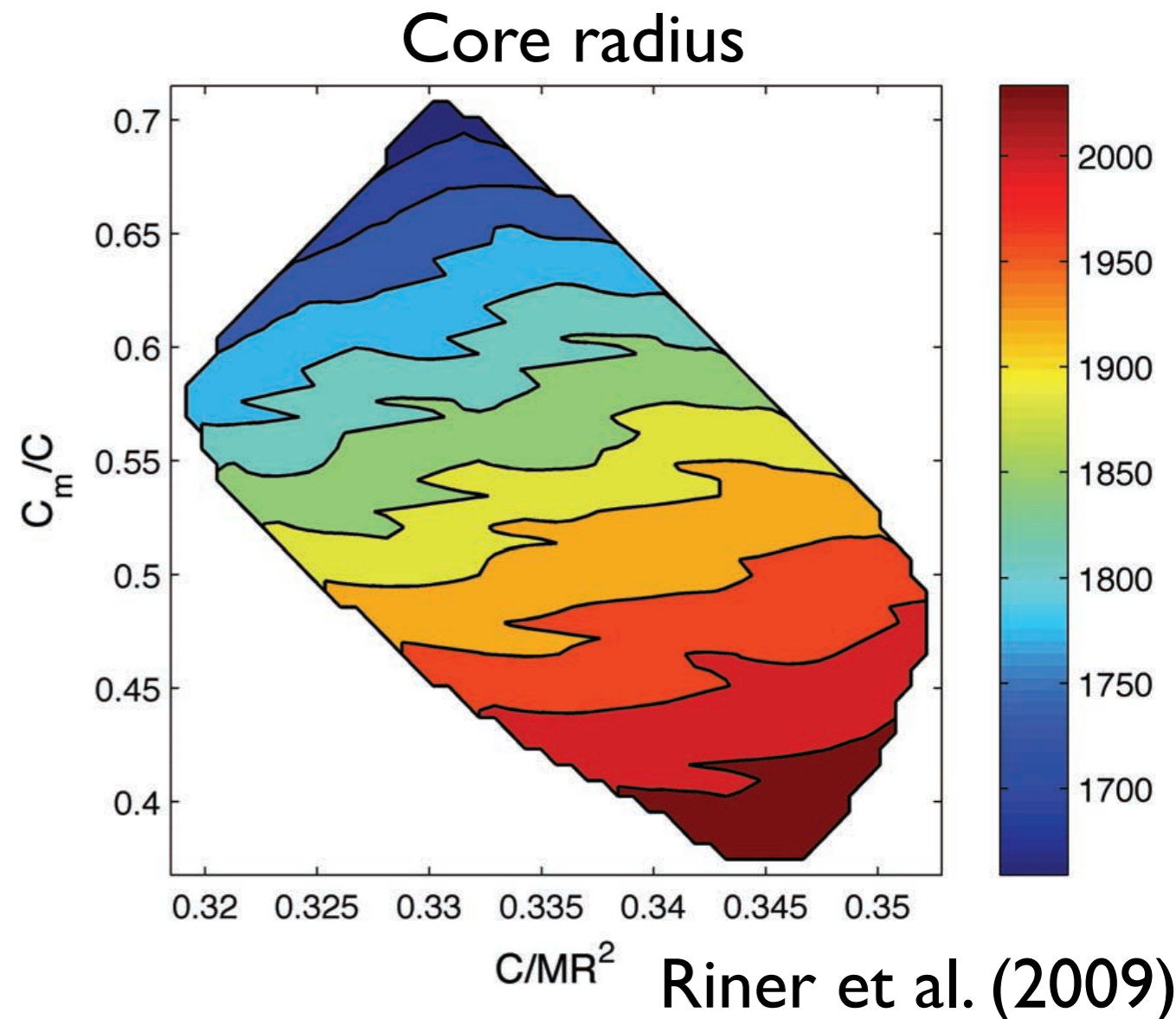
BepiColombo



- 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 \Rightarrow wide range of plausible core radii: ~ 1700 - 2100 km
- \Rightarrow need for accurate estimates of the moments of inertia C/MR^2 and C_m/C



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

“Peale’s experiment”

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

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

Peale (1976)

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 dynamo² imply the existence of a conducting molten core. We propose here a feasible, non-seismic observational

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

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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:

$$\phi = 35.8 \pm 2 \text{ arc sec}$$

$$\vartheta = 2.11 \pm 0.1 \text{ arc min}$$

Margot et al. (2007)

Large Longitude Libration of Mercury Reveals a Molten Core

J. L. Margot,^{1*} S. J. Peale,² R. F. Jurgens,³ M. A. Slade,³ I. V. Holin⁴

Observations of radar speckle patterns tied to the rotation of Mercury establish that the planet occupies a Cassini state with obliquity of 2.11 ± 0.1 arc minutes. The measurements show that the planet exhibits librations in longitude that are forced at the 88-day orbital period, as predicted by theory. The large amplitude of the oscillations, 35.8 ± 2 arc seconds, together with the Mariner 10 determination of the gravitational harmonic coefficient C_{22} , indicates that the mantle of Mercury is decoupled from a core that is at least partially molten.

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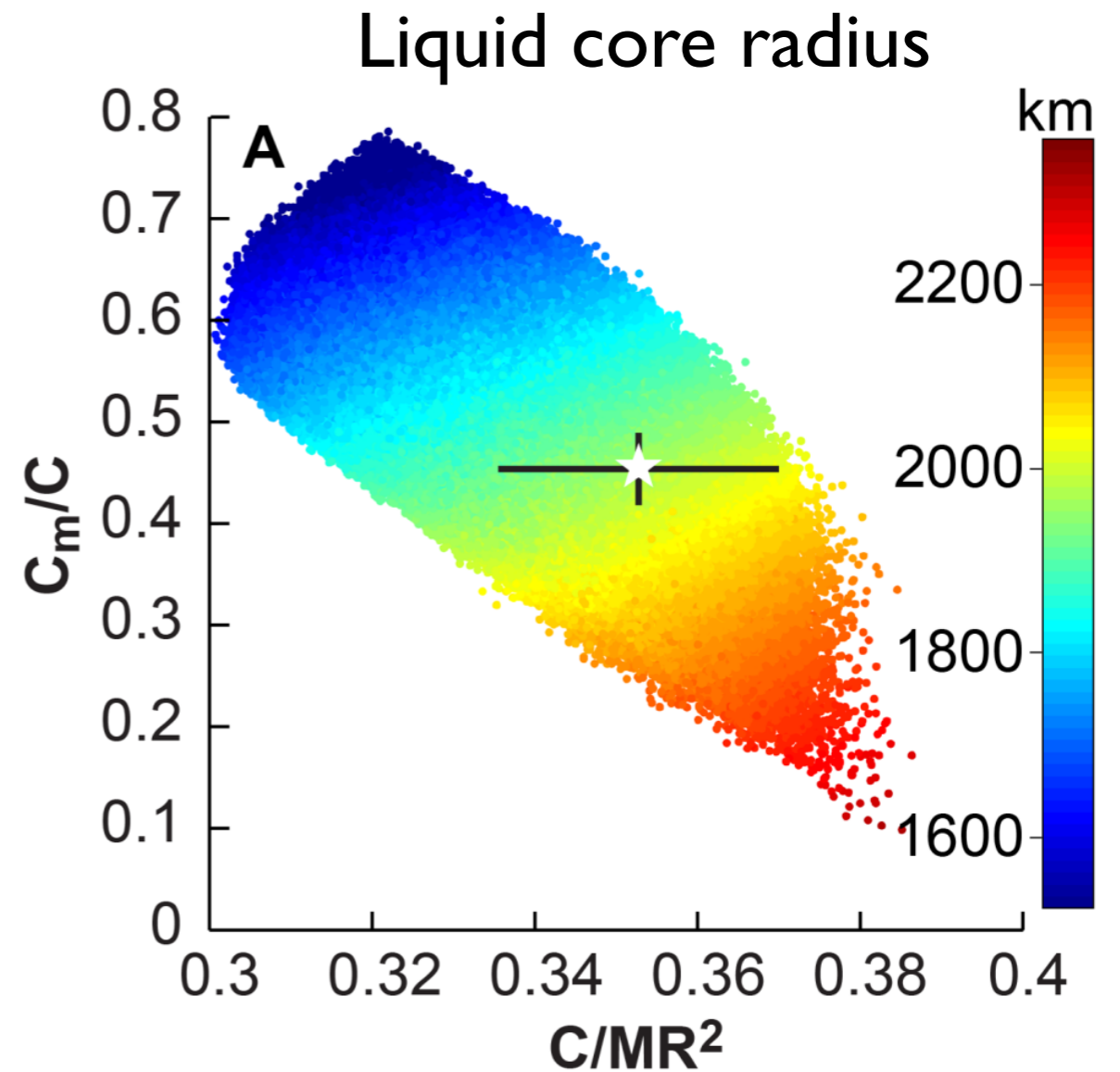
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Mercury’s core must be (at least partially) liquid

MESSENGER constraints on core size

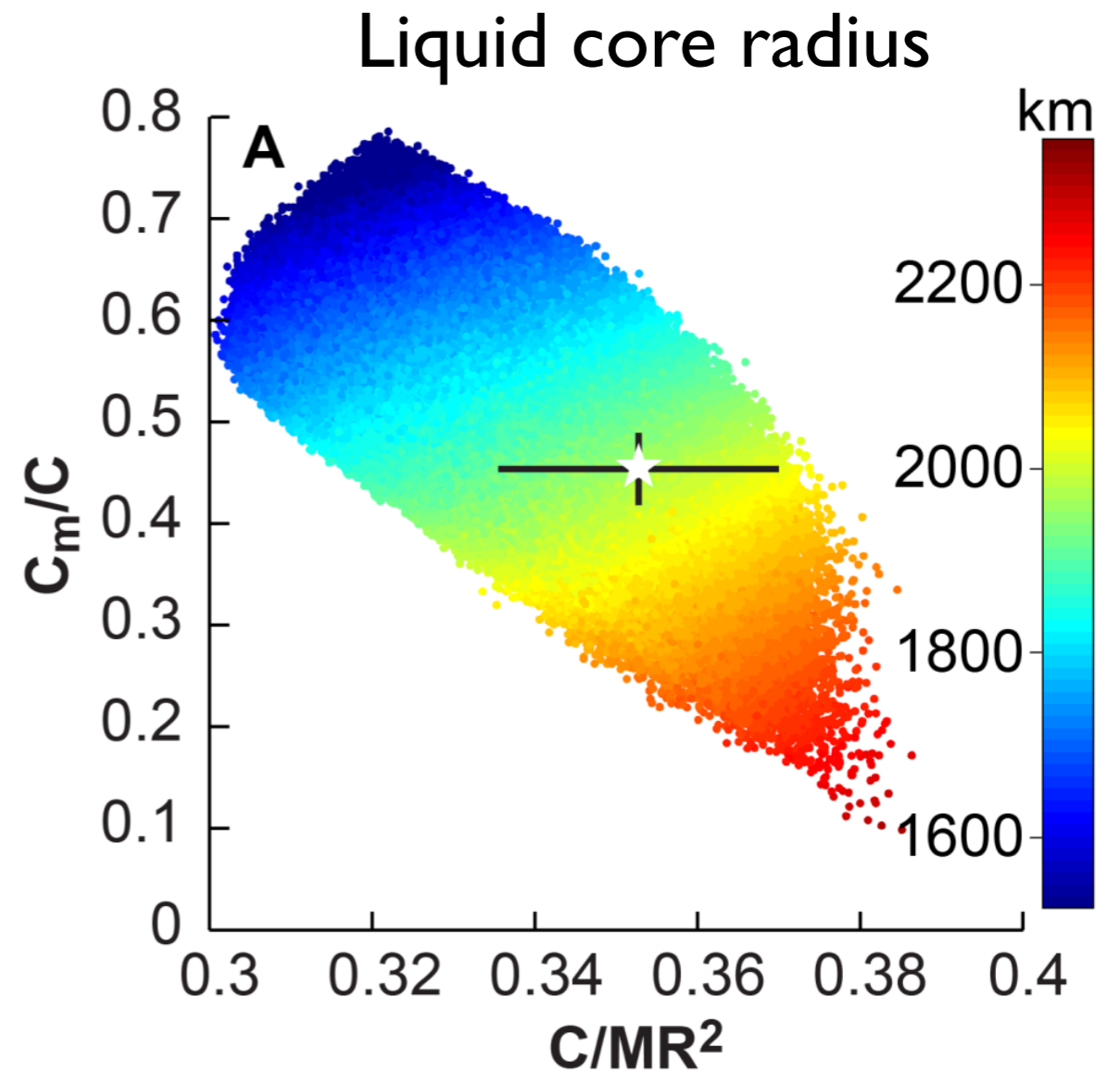
- Improved estimates of C_{20} and C_{22} coefficients together with obliquity and spin state measurements yield:
 $C/MR^2 = 0.353 \pm 0.017$
 $C_m/C = 0.452 \pm 0.035$
- Interior structure models predict a core radius of ~ 2000 km (significantly larger than previously assumed)



Hauck et al. (2012)

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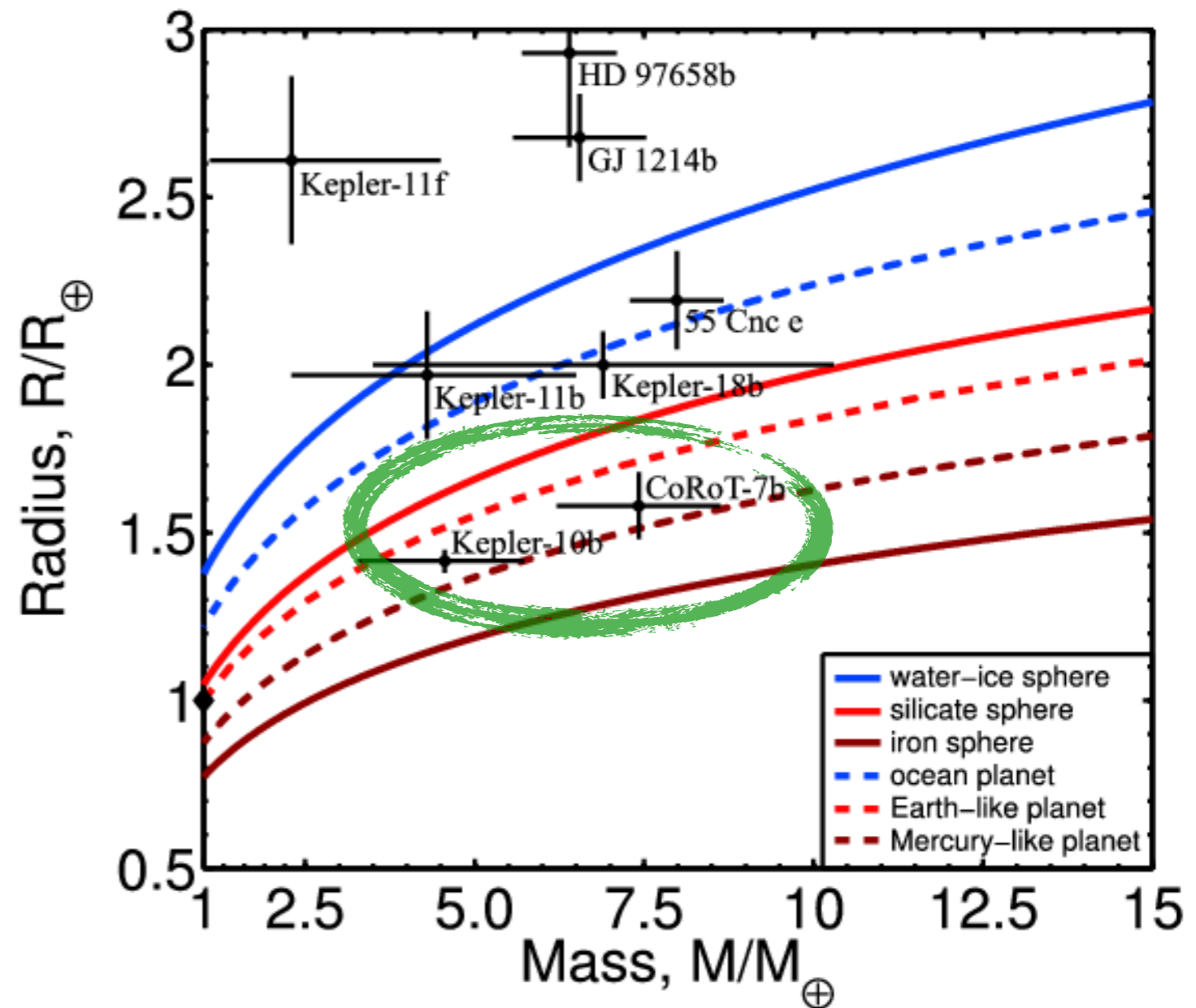
Hauck et al. (2012)

Mercury's silicate shell is only ~ 400 km thick

“Super Mercuries”?

Iron-rich planets may not be so unusual

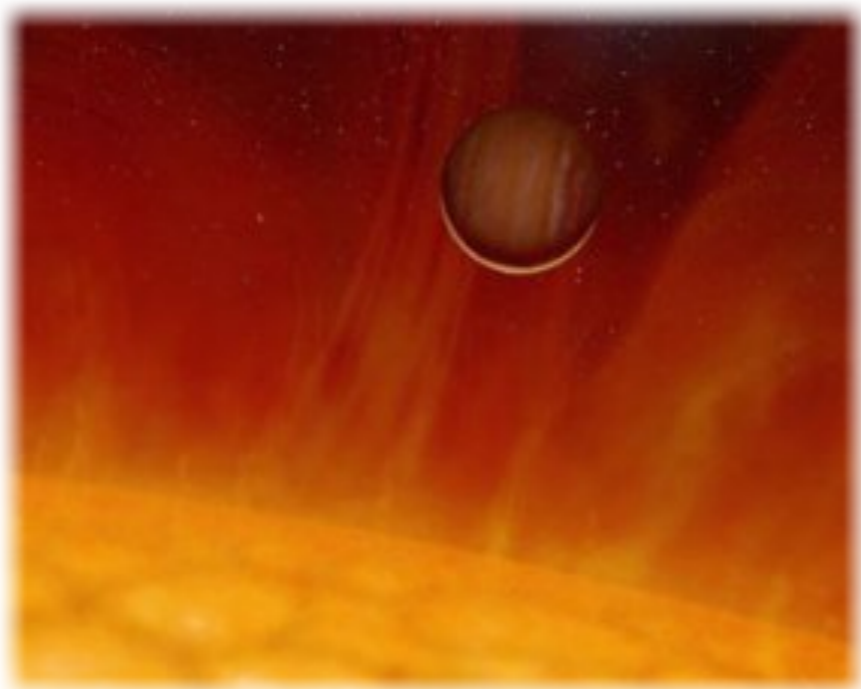
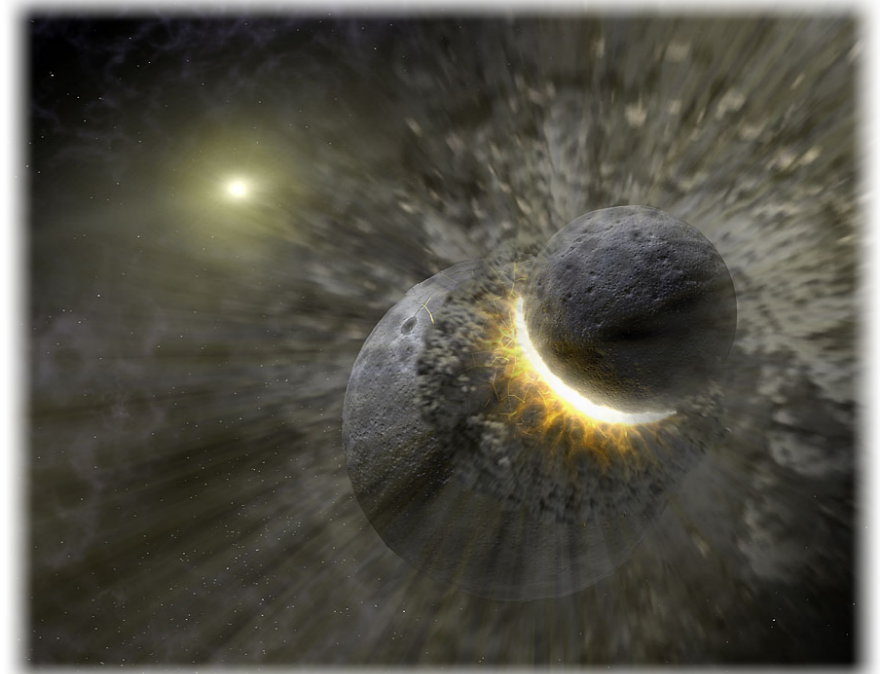
- CoRoT-7b and Kepler 10b are the smallest extrasolar planets with measured mass and radius
- They possess a relatively large mean density and are expected to have large iron cores comprising ~60-70 wt-% of the planet



Wagner et al. (2012)

Mercury's formation scenarios

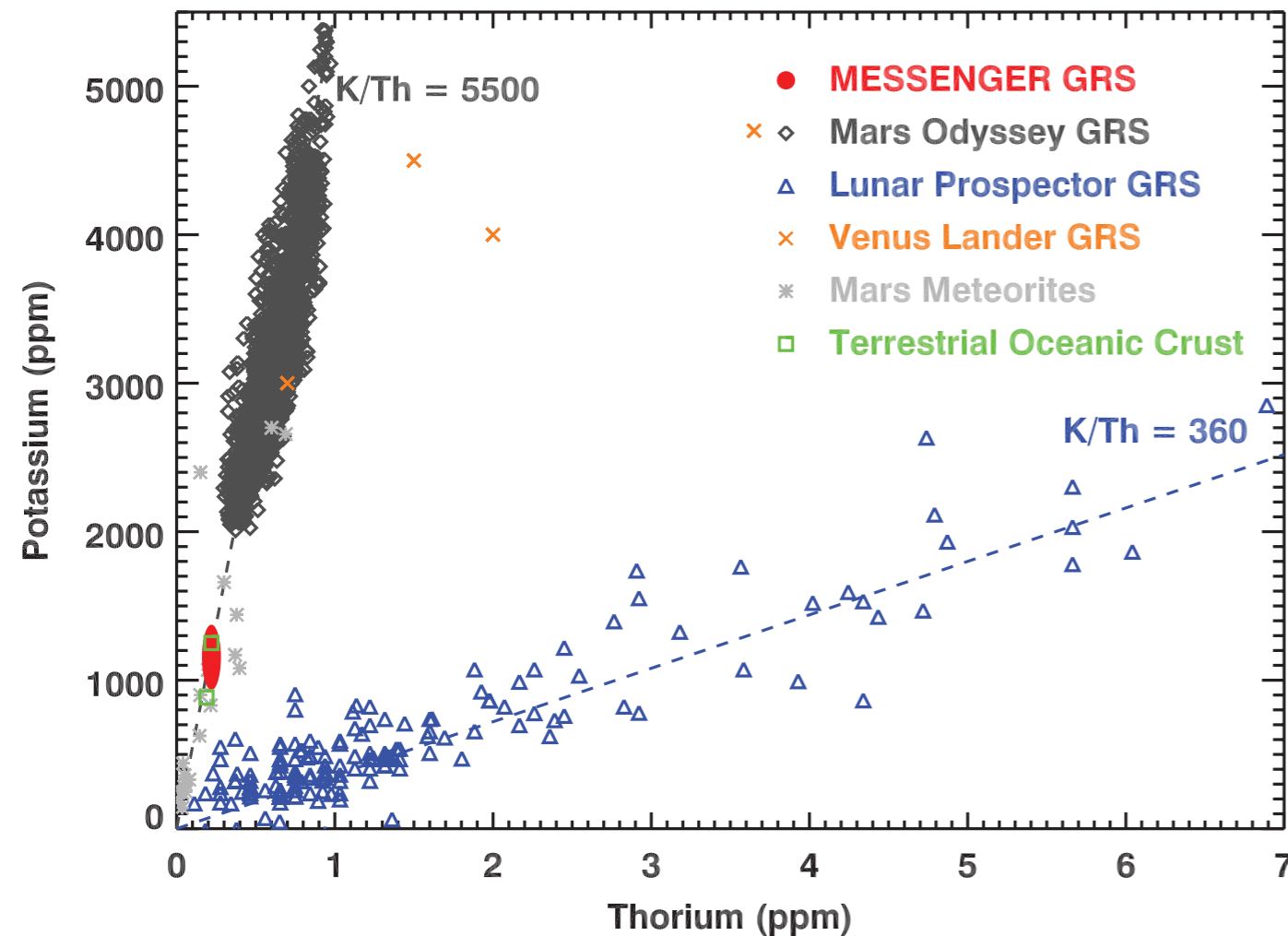
- Evaporation model (Fegley & Cameron, 1987): vaporization of outer silicate shell in a high temperature (2500-3000 K) solar nebula
- Giant impact hypothesis: removal of early crust and upper mantle by one or more large impacts (Benz et al., 1988)



- 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

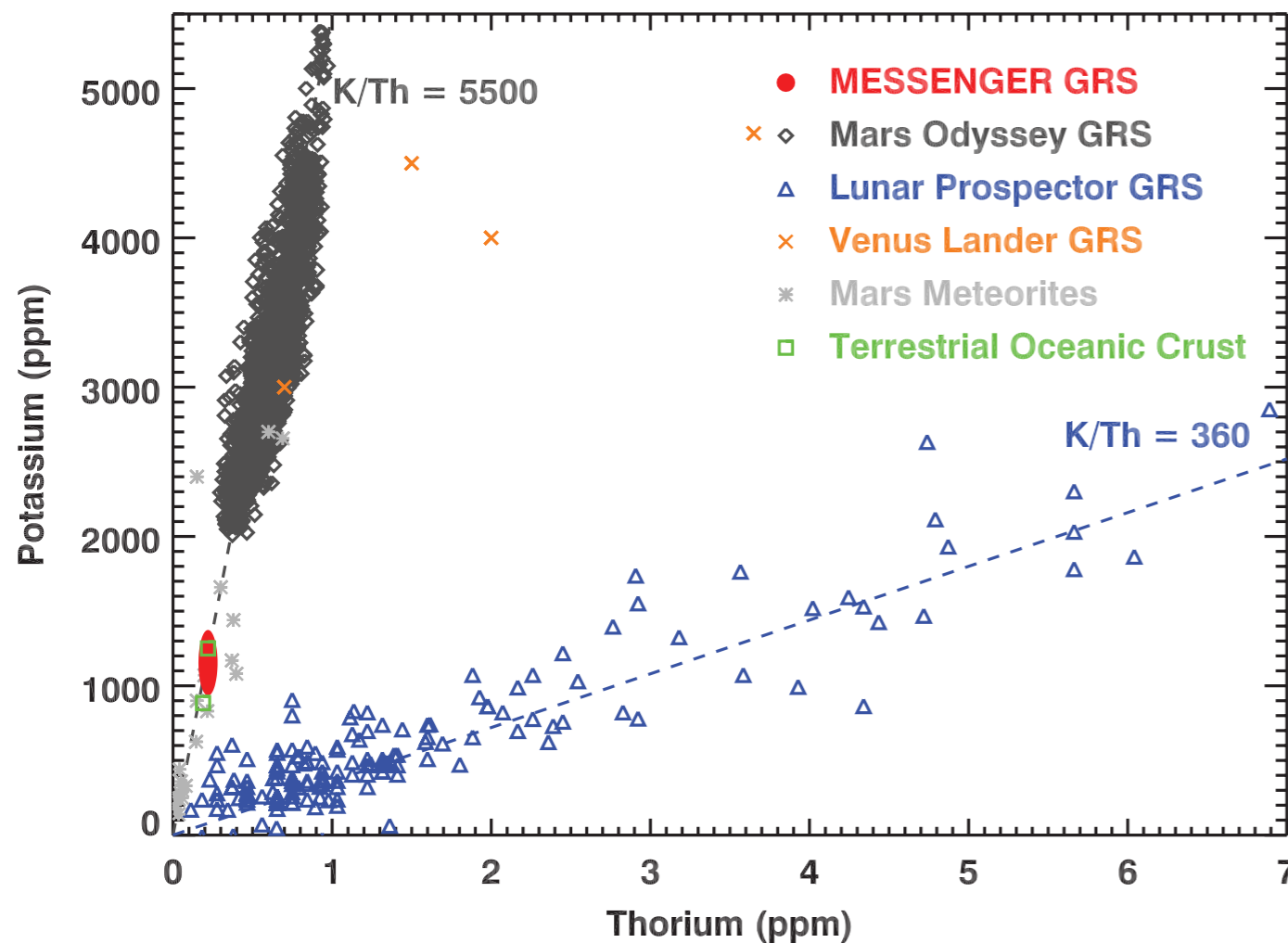
U: 90 ± 20 ppb

K: 1150 ± 220 ppm

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

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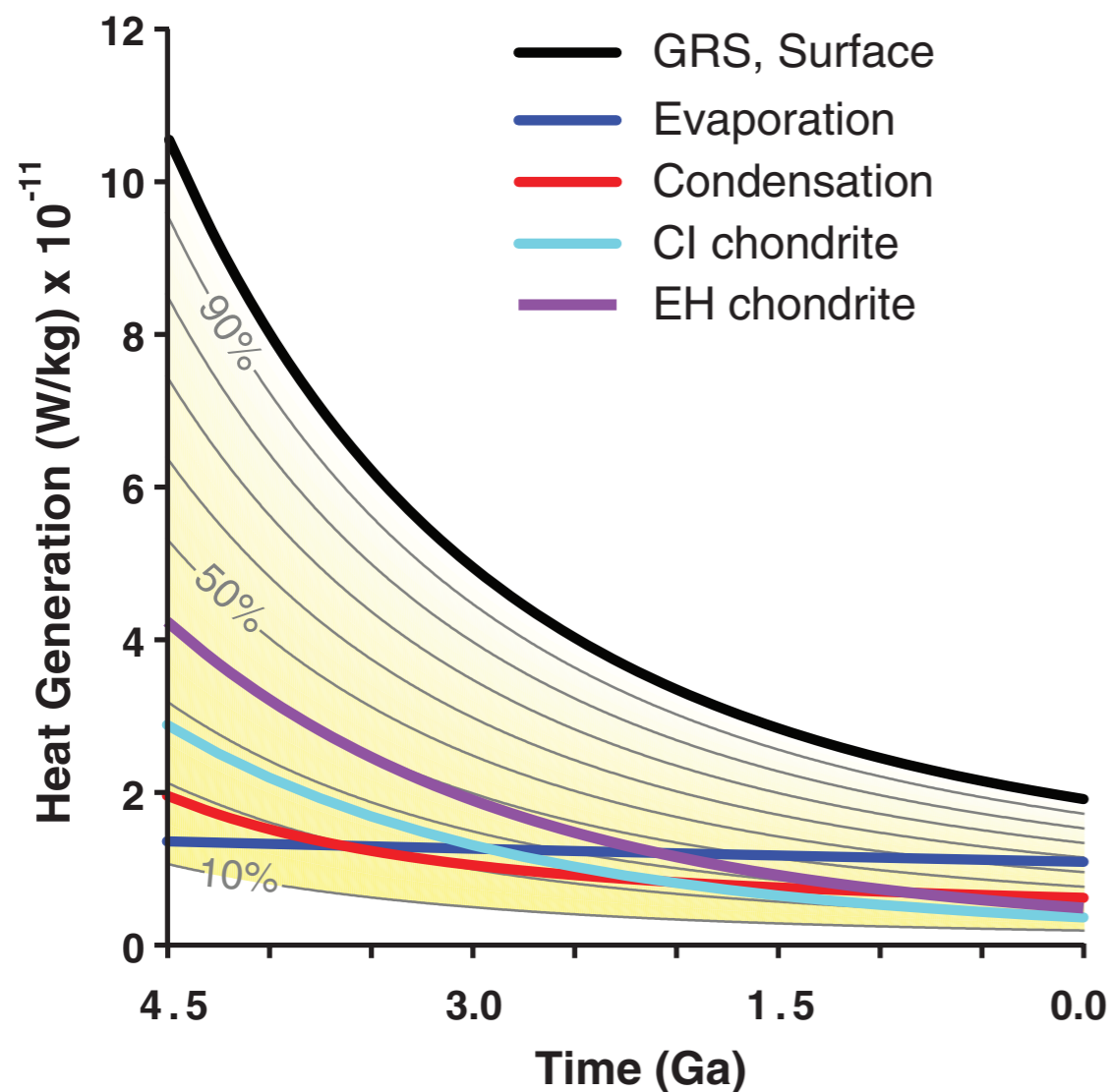
K: 1150 ± 220 ppm

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

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

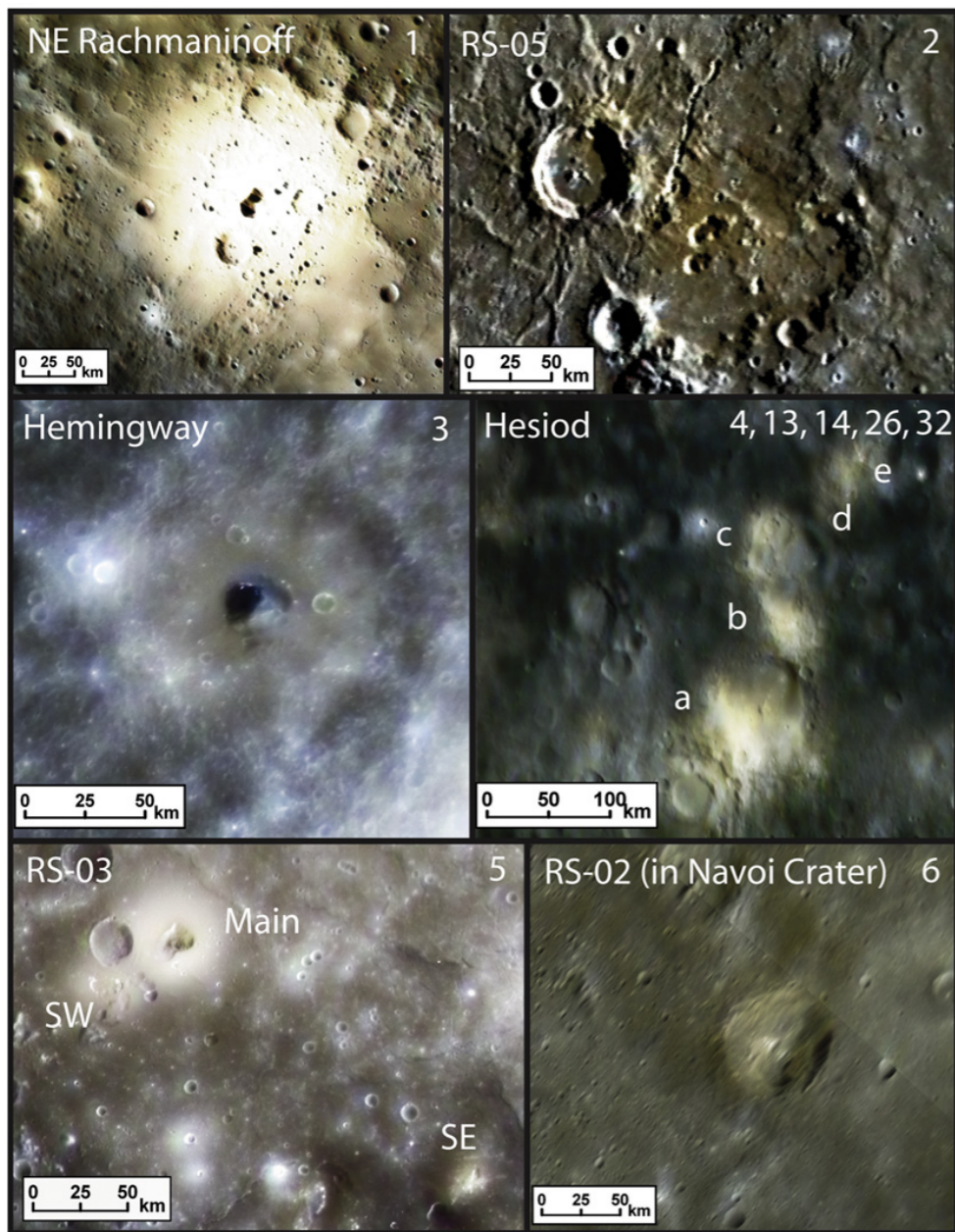


- Decay of heat production with time is consistent with a concentration of volcanic activity relatively early in the planet's history
- The surface abundance of Th, U and K can be used to constrain the relative partitioning of these elements between the bulk of the mantle and crust

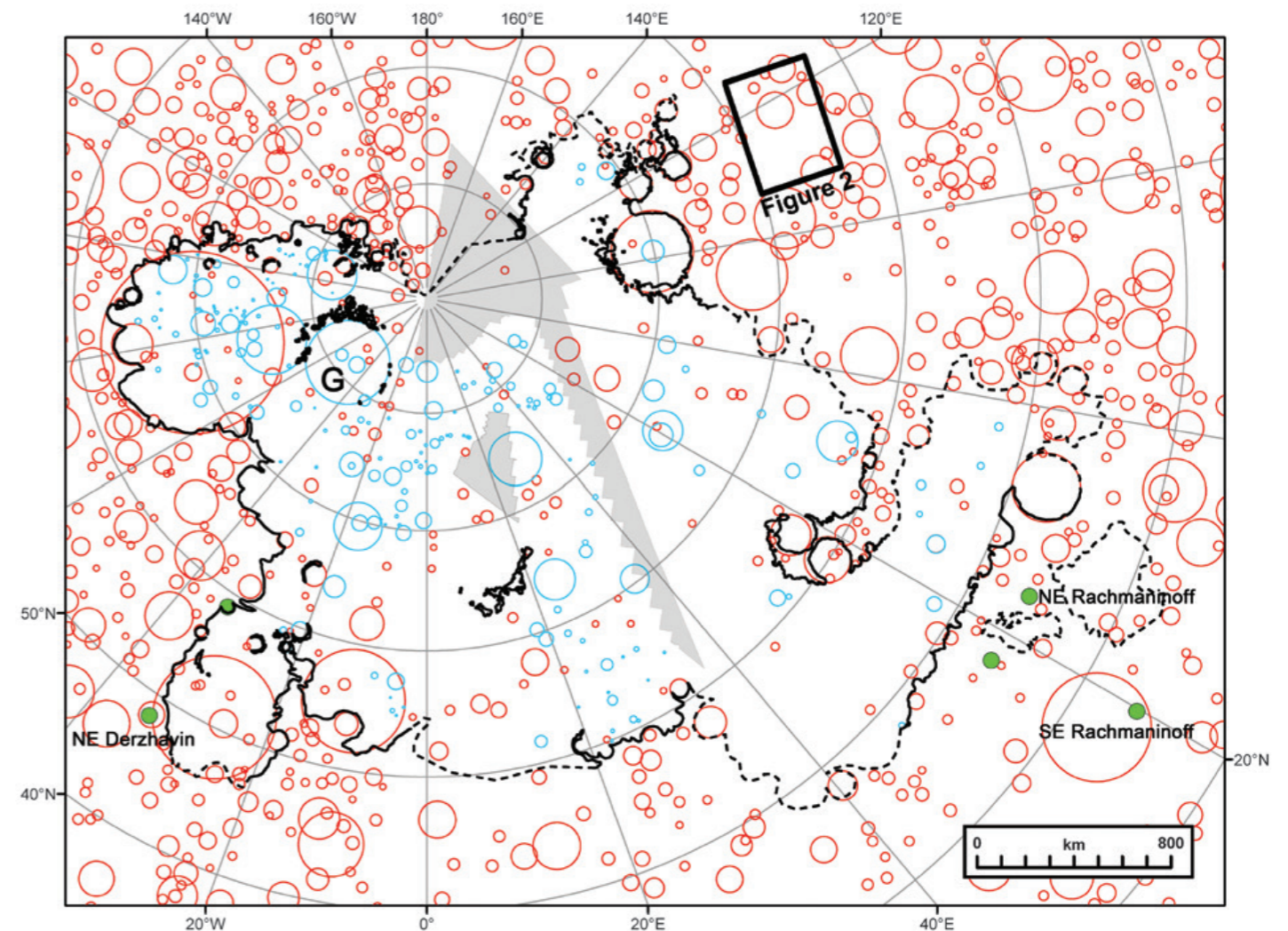
Peplowski et al. (2011)

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



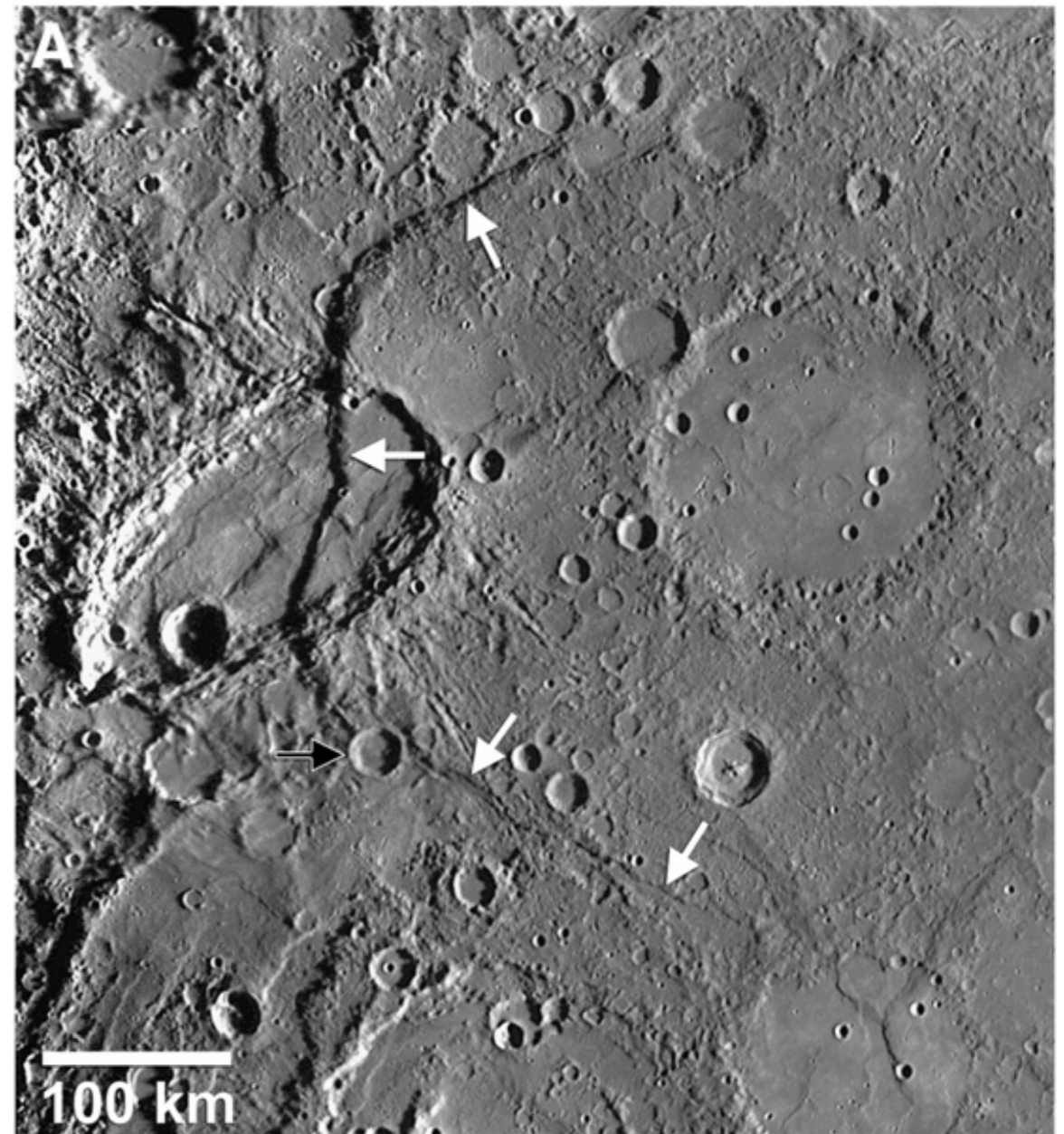
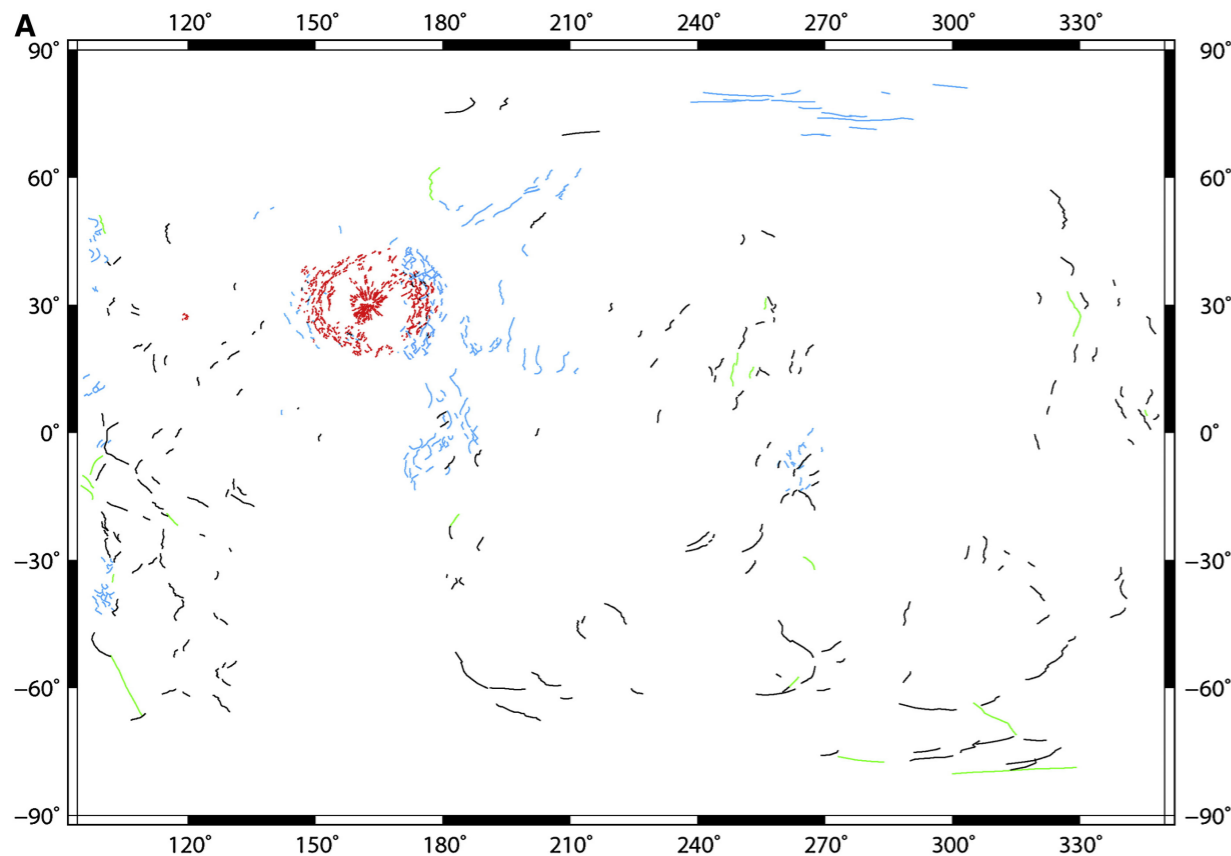
Kerber et al. (2011)



Head et al. (2011)

Lobate scarps and global contraction

- Most widespread tectonic landform already identified by Mariner 10



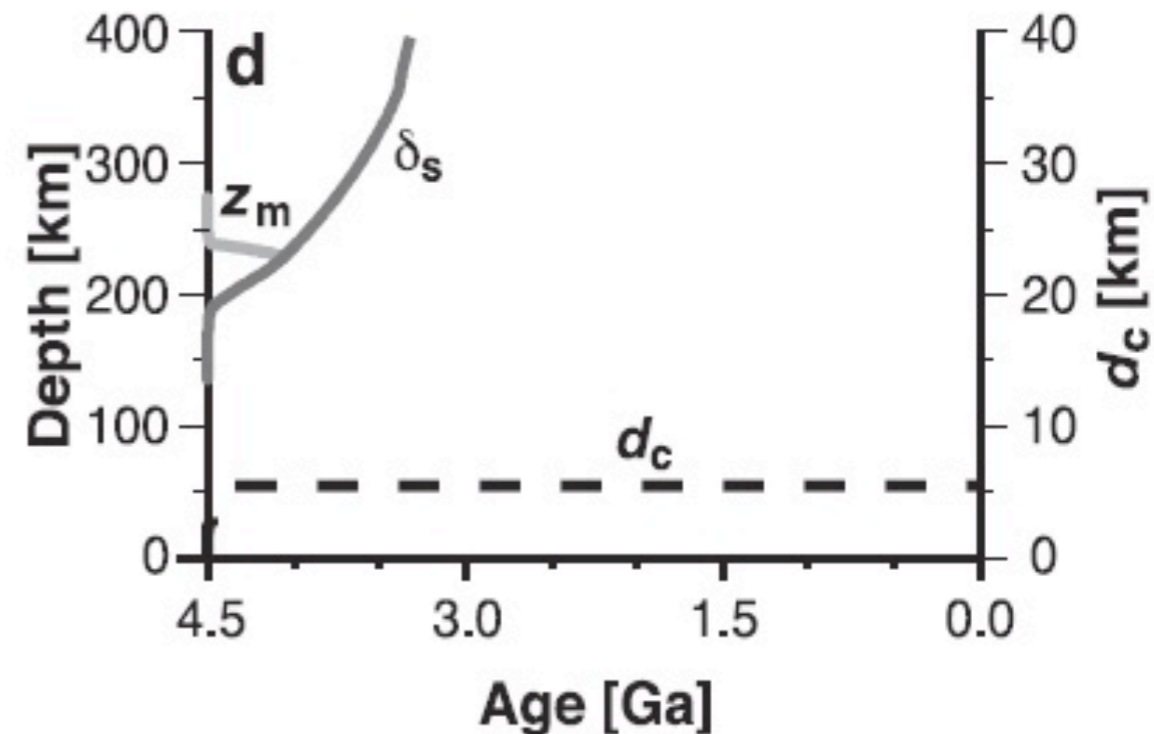
- Surface breaking thrust faults resulting from global contraction: $\Delta R \leq 2$ km (Watters et al., 2009)
- Contraction is attributed to inner core solidification and/or secular cooling (Schubert et al., 1988)

Watters et al. (2009)

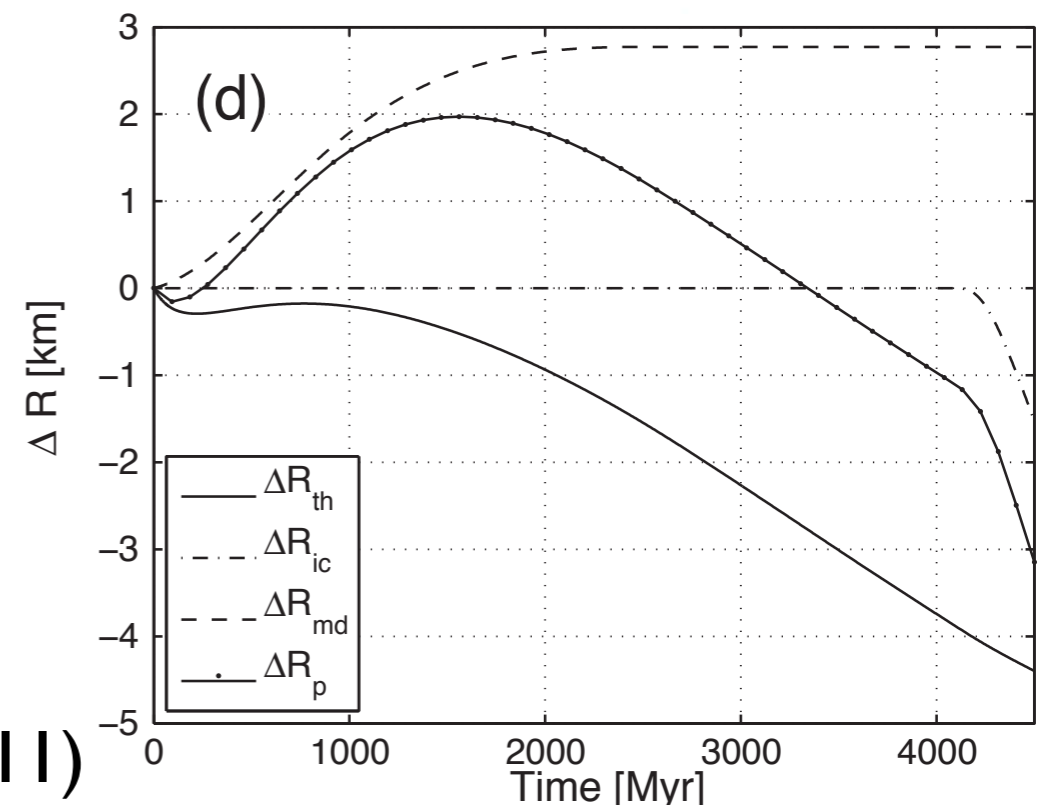
Results from parameterized models

- 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

Hauck et al. (2004)



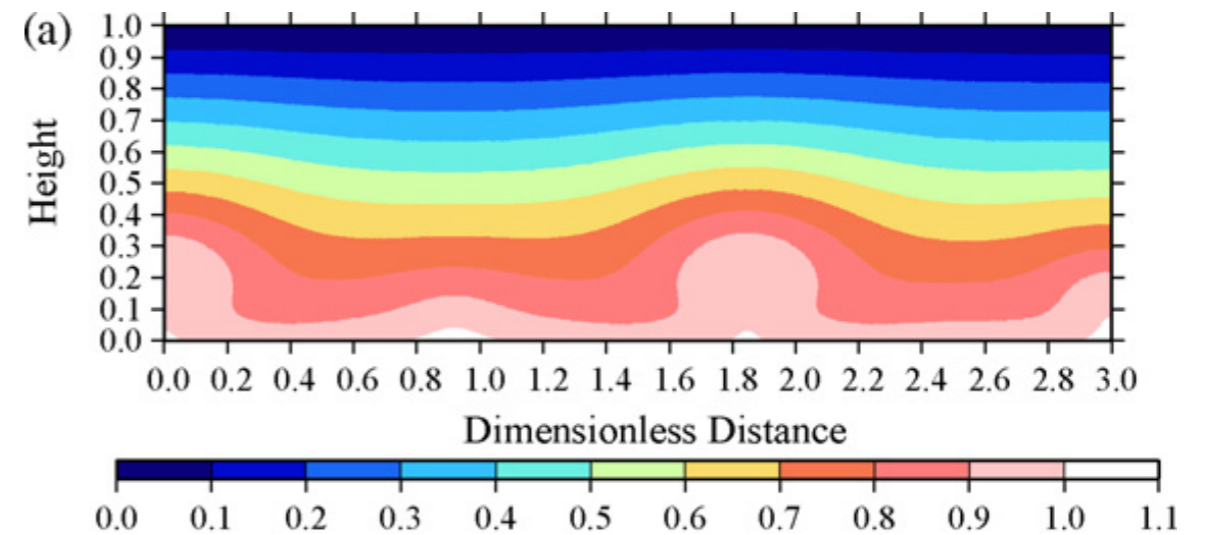
Grott et al. (2011)



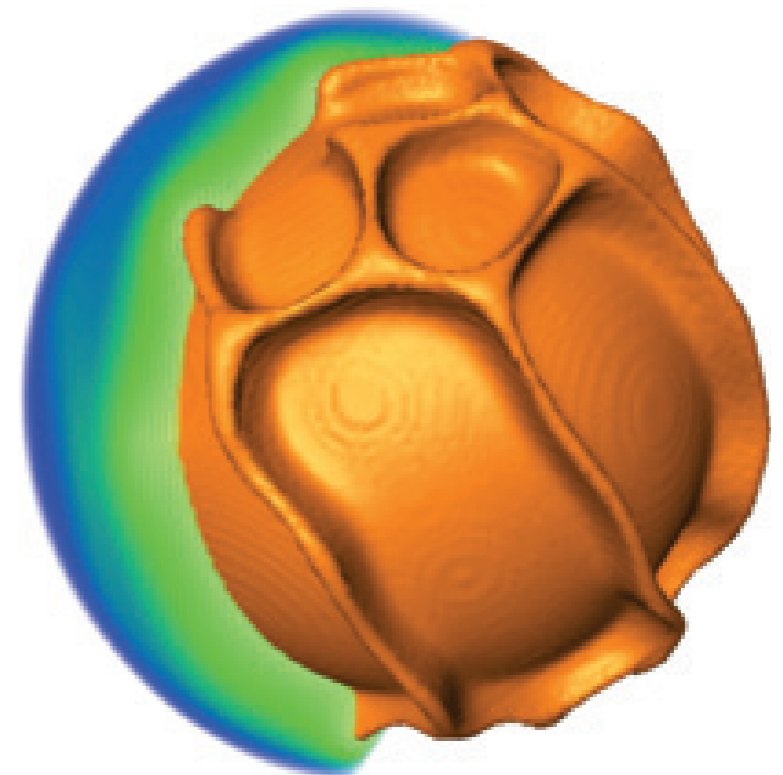
Results from numerical models

- 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:

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

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

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

$$\frac{D\Phi}{Dt} = f(\Phi, T)$$

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

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

$$\frac{D\Phi}{Dt} = f(\Phi, T)$$

compositional
buoyancy of
melt residuum



Thermo-chemical evolution

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

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latent heat

$$\frac{D\Phi}{Dt} = f(\Phi, T)$$

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latent heat

$$\frac{D\Phi}{Dt} = f(\Phi, T)$$

change of melt fraction

Melt parametrization

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

$$\phi = \frac{T - T^{\text{sol}}}{T^{\text{liq}} - T^{\text{sol}}}$$

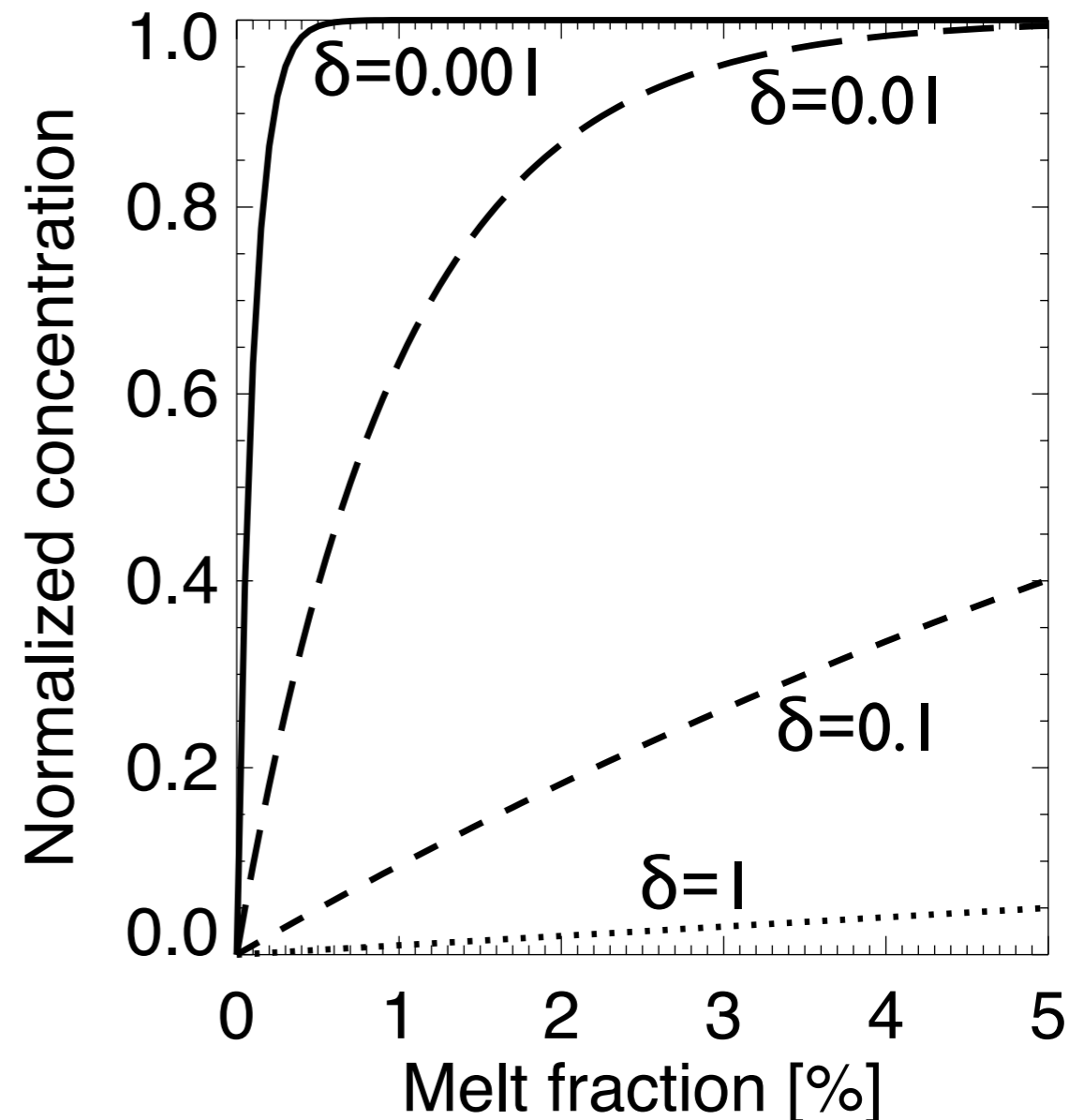
Melt parametrization

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



Melt parametrization

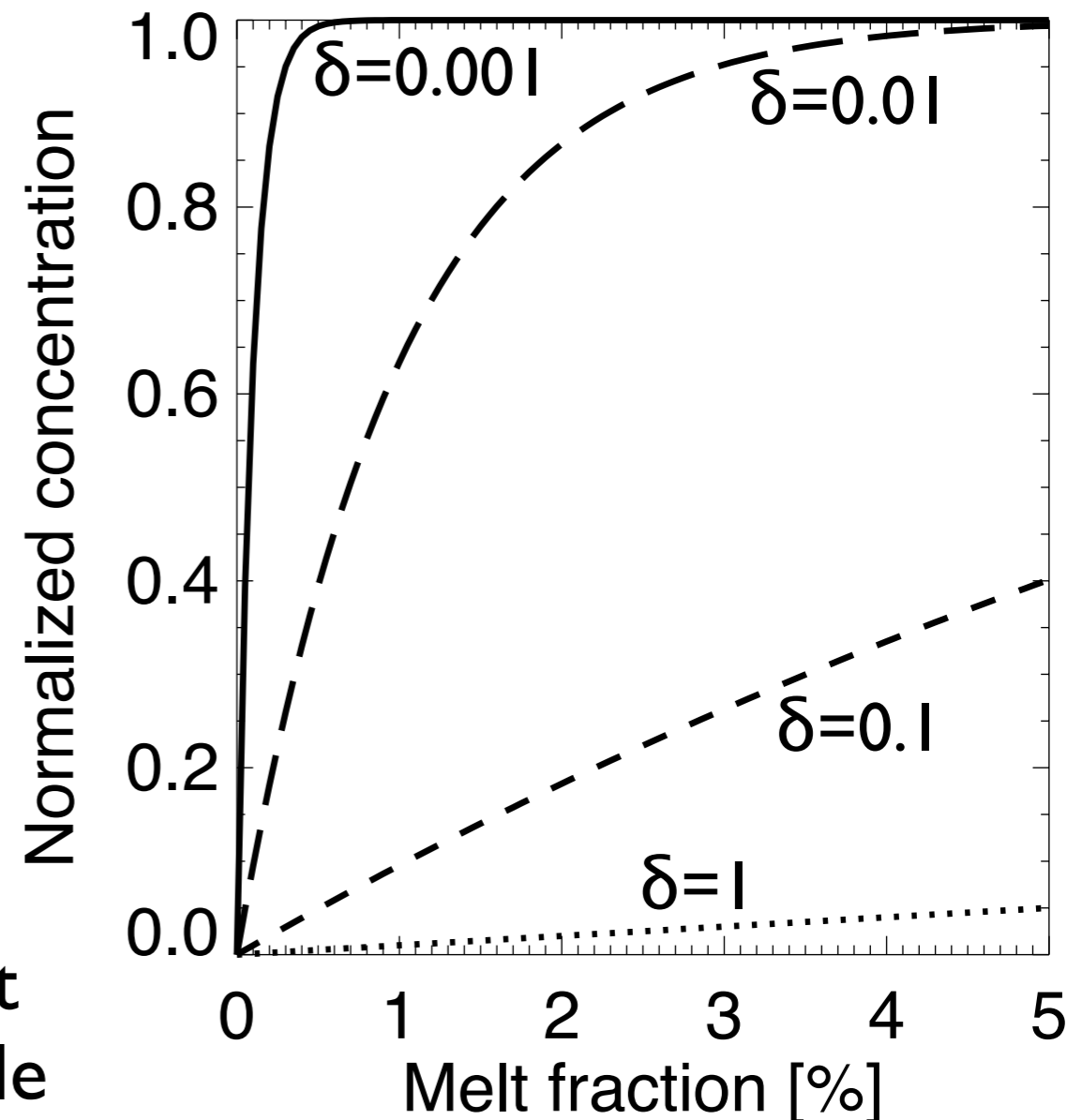
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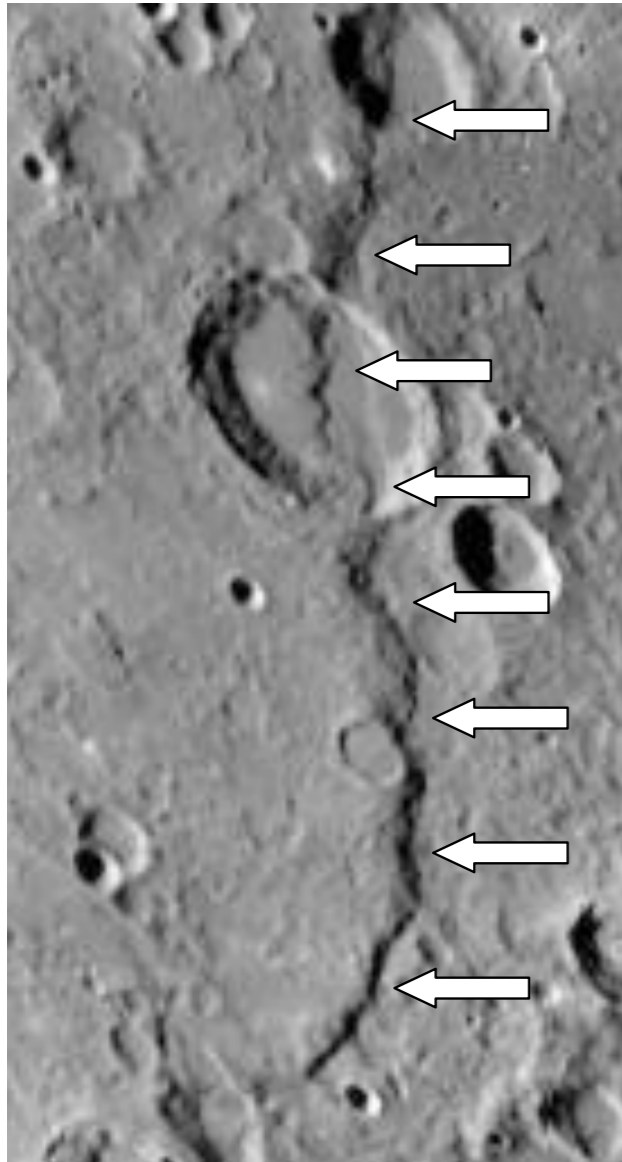
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$$\frac{C_{\text{melt}}}{C_0} = \frac{1}{\phi} \left(1 - (1 - \phi)^{1/\delta} \right)$$

- 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

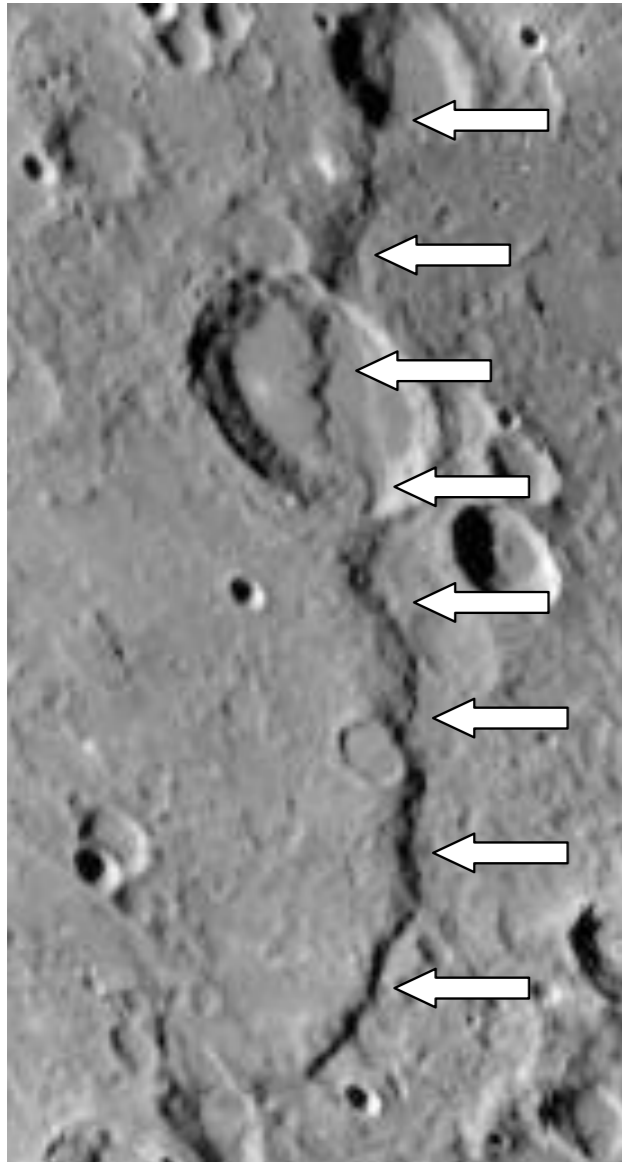


Calculated a posteriori from the history of the mantle temperature profile and evolution of the crustal thickness

Volume changes due to thermal expansion/contraction:

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

Global radial contraction



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

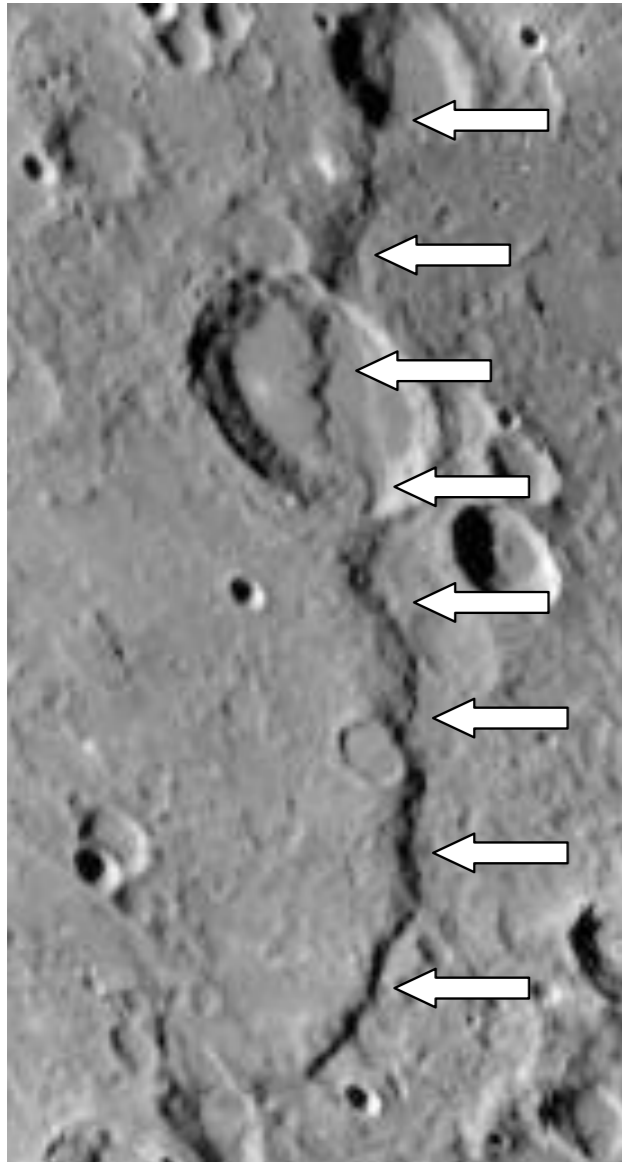
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Volume increase due to mantle differentiation caused by partial melting:

$$\frac{\partial \Delta V_{\text{md}}}{\partial t} = \frac{1}{\phi_{\text{max}}} \frac{\delta V}{V} \frac{\partial V_{\text{cr}}}{\partial t}$$

Global radial contraction



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

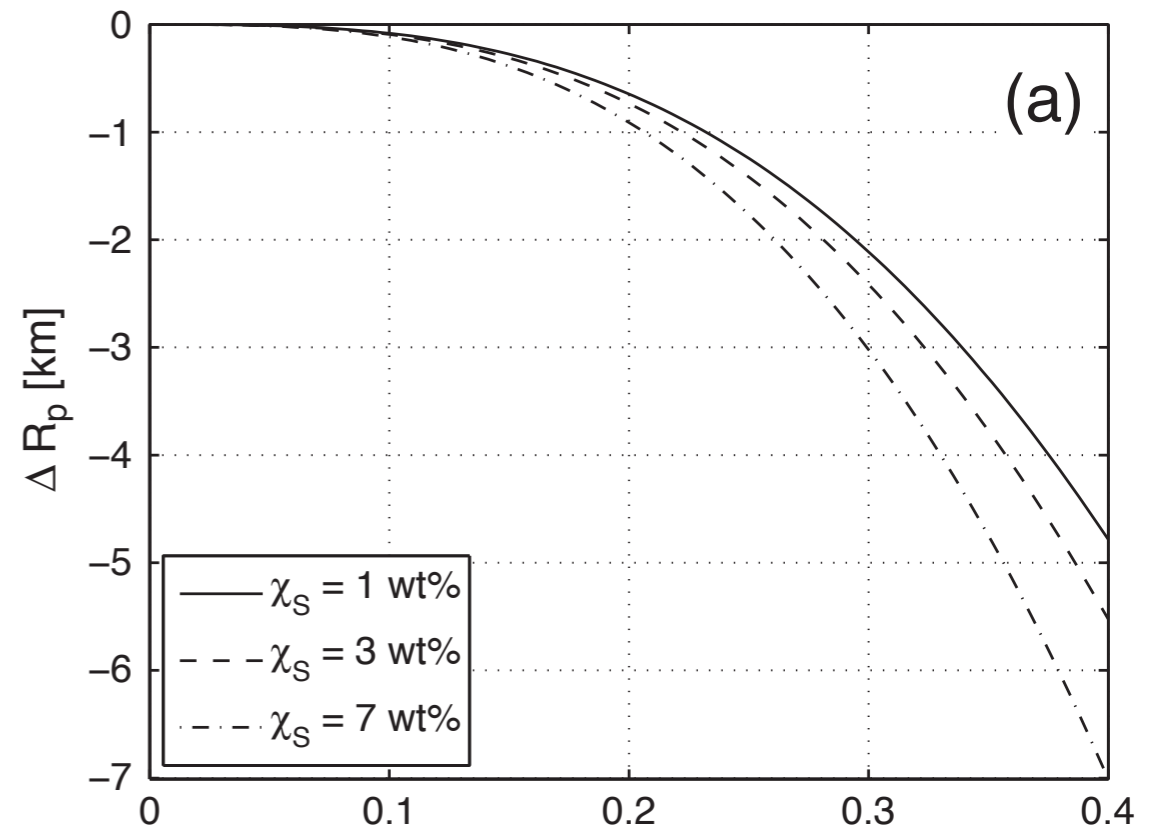
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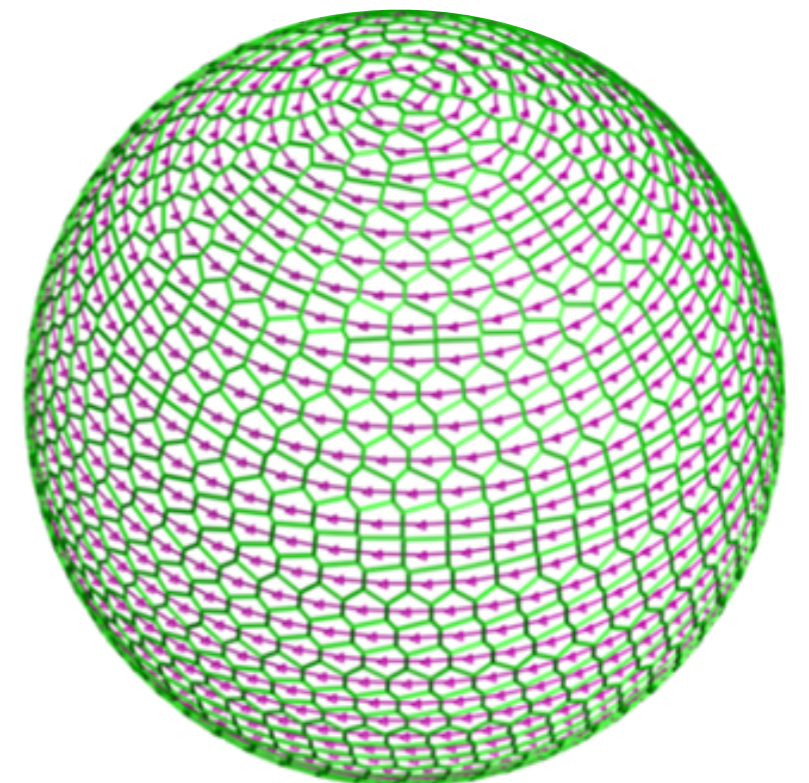
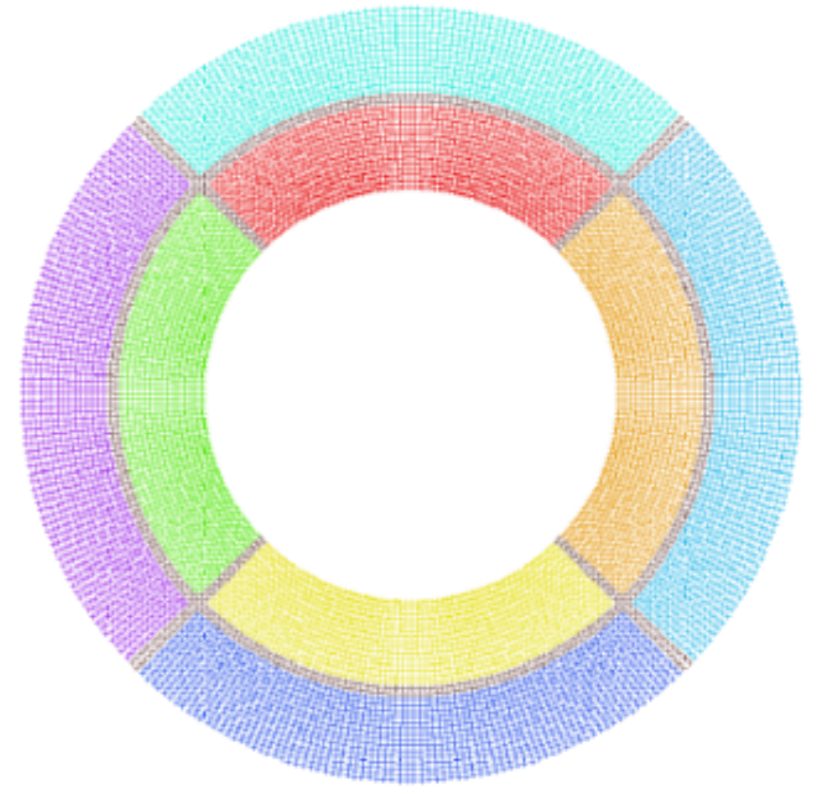
Contraction due to core freezing is neglected in first approximation and a small solid inner core is assumed



Grott et al. (2011) R_i/R_c

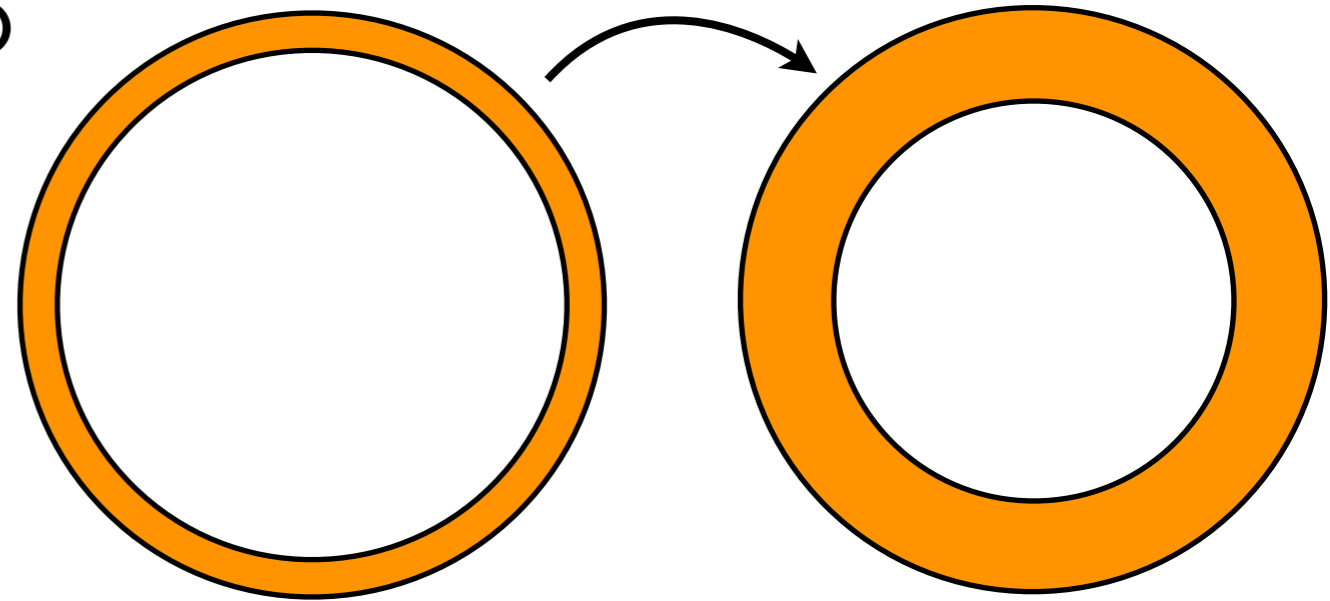
Numerical code

- 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



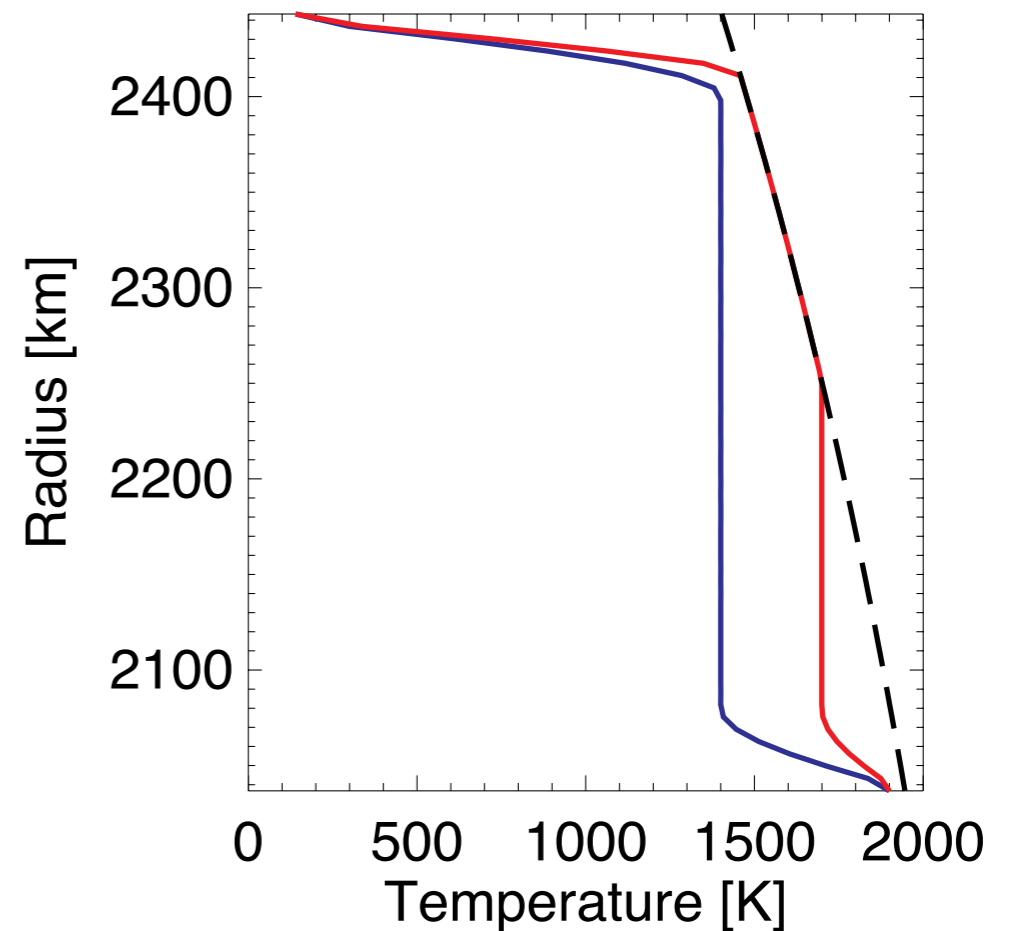
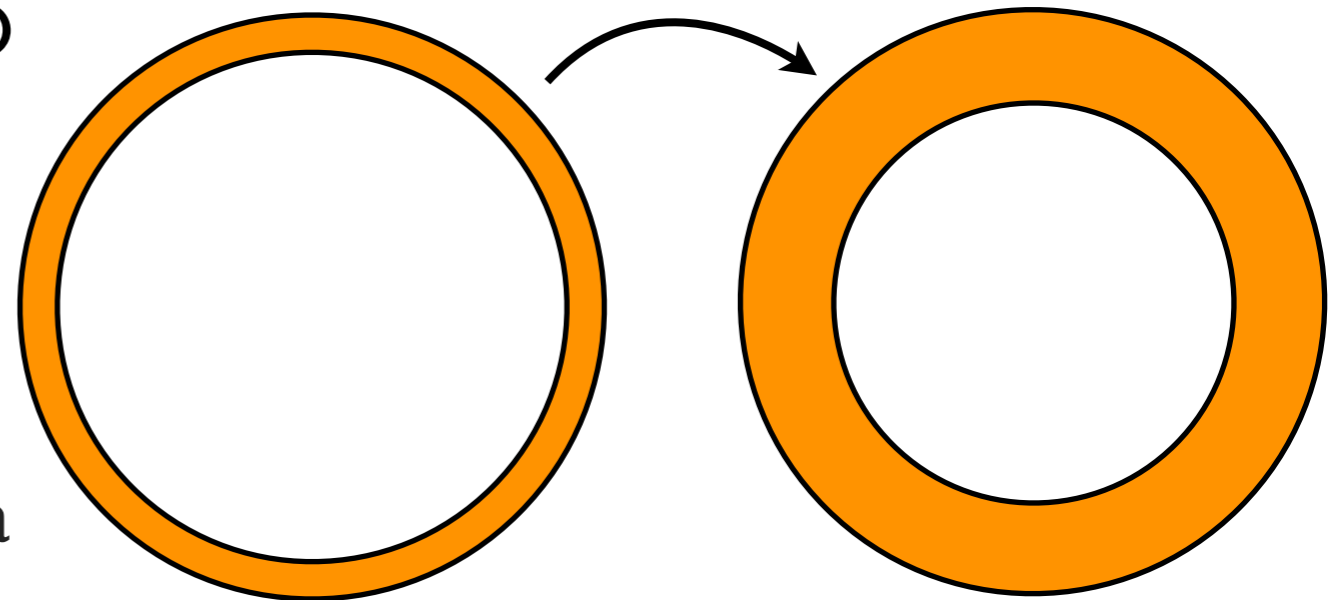
Model setup

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



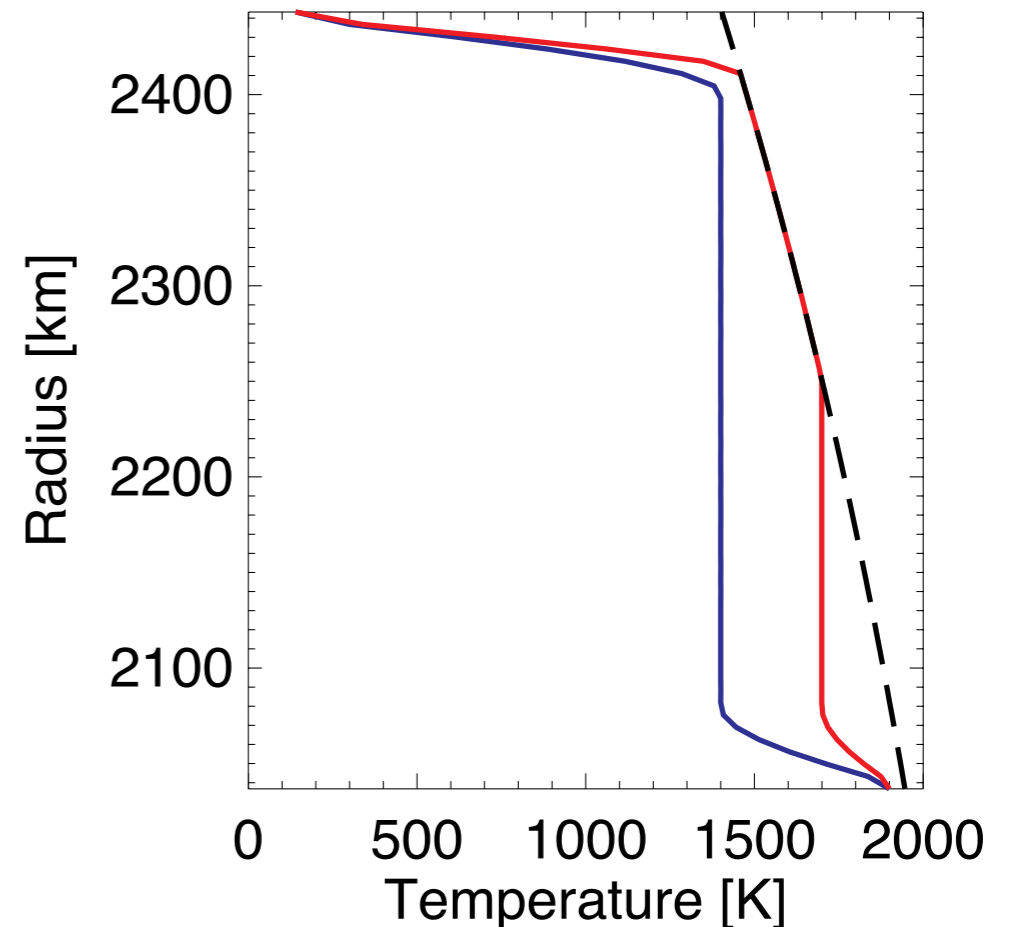
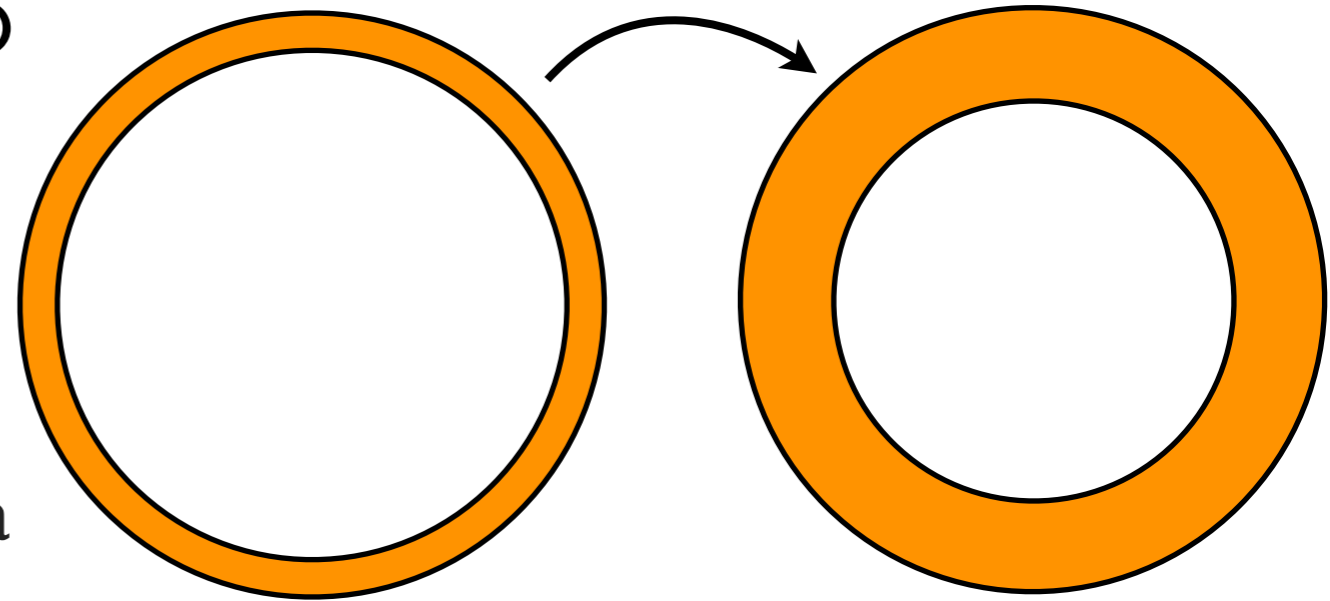
Model setup

- Mostly 2D cylindrical models with 3D corrected inner-outer radius ratio (van Keken, 2001)
- Initial temperature distribution:
 - “cold” subsolids at 1400 K
 - “hot” supersolidus at 1700 K with a primordial crust



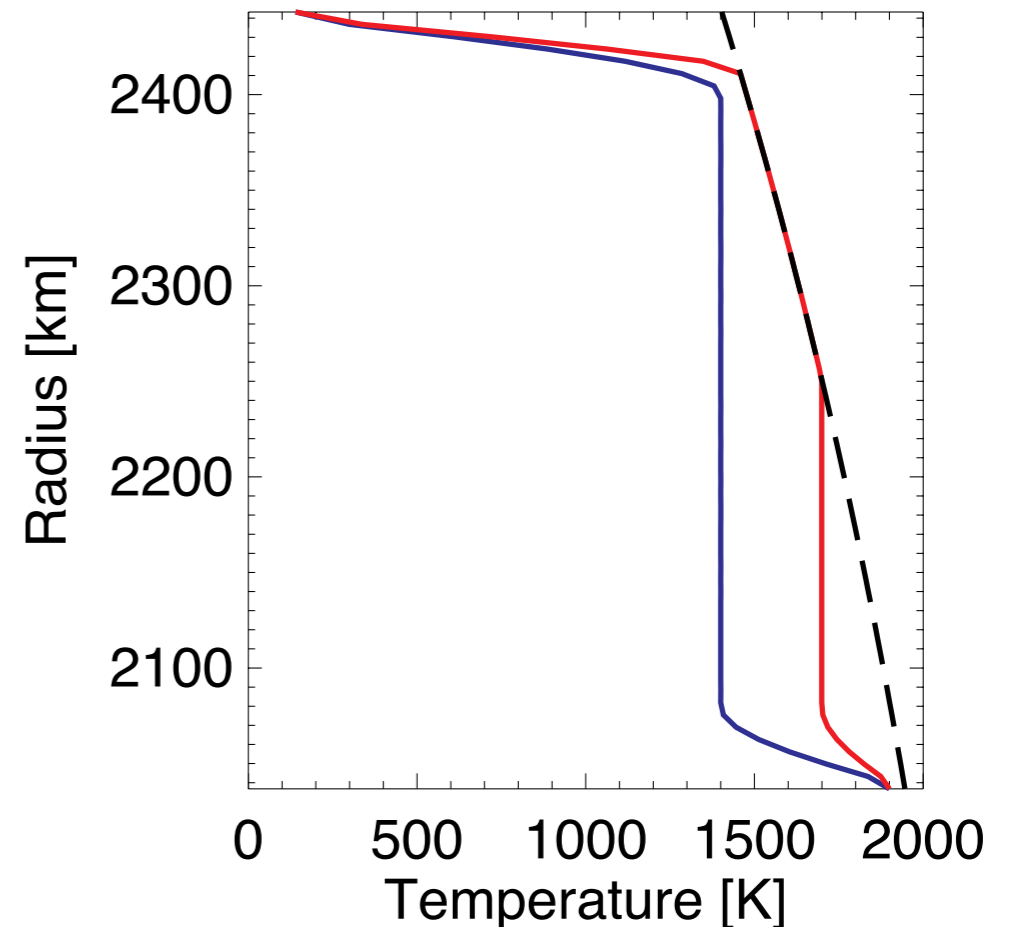
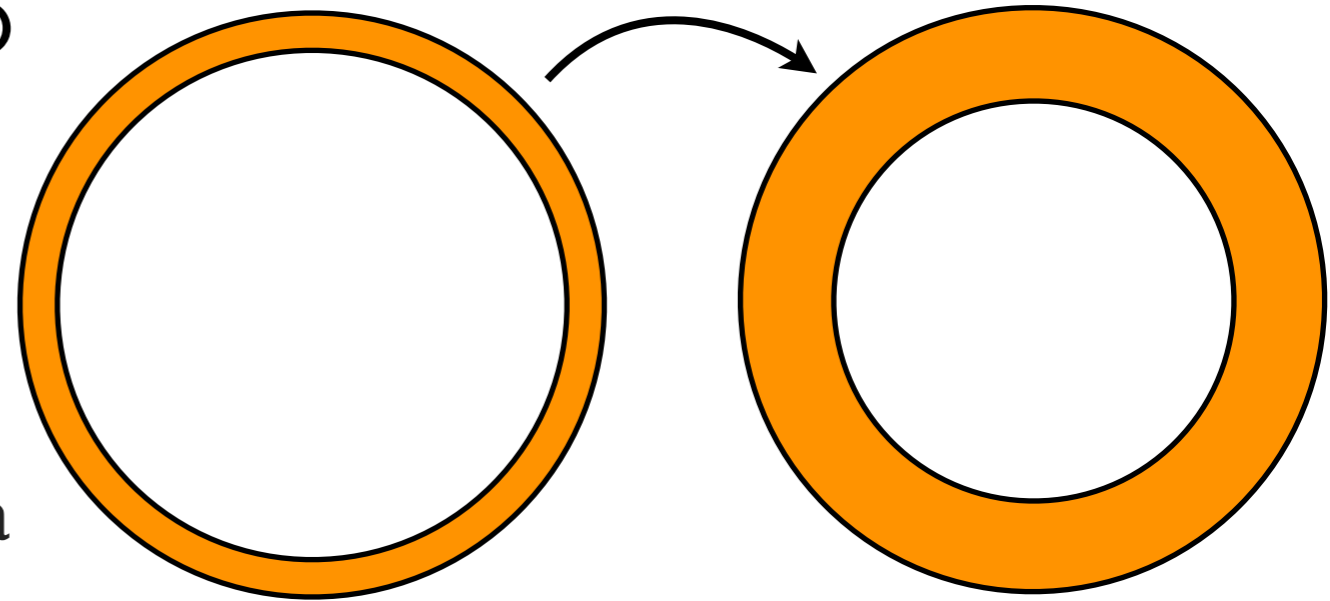
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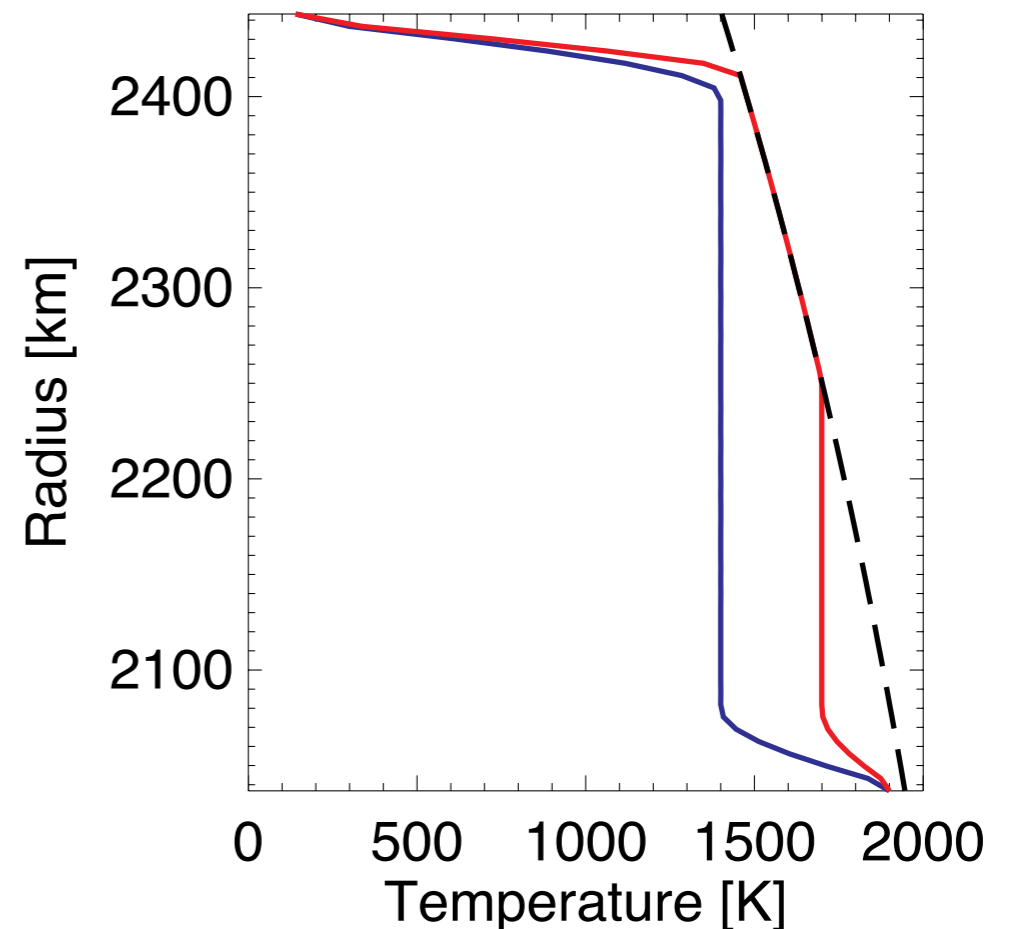
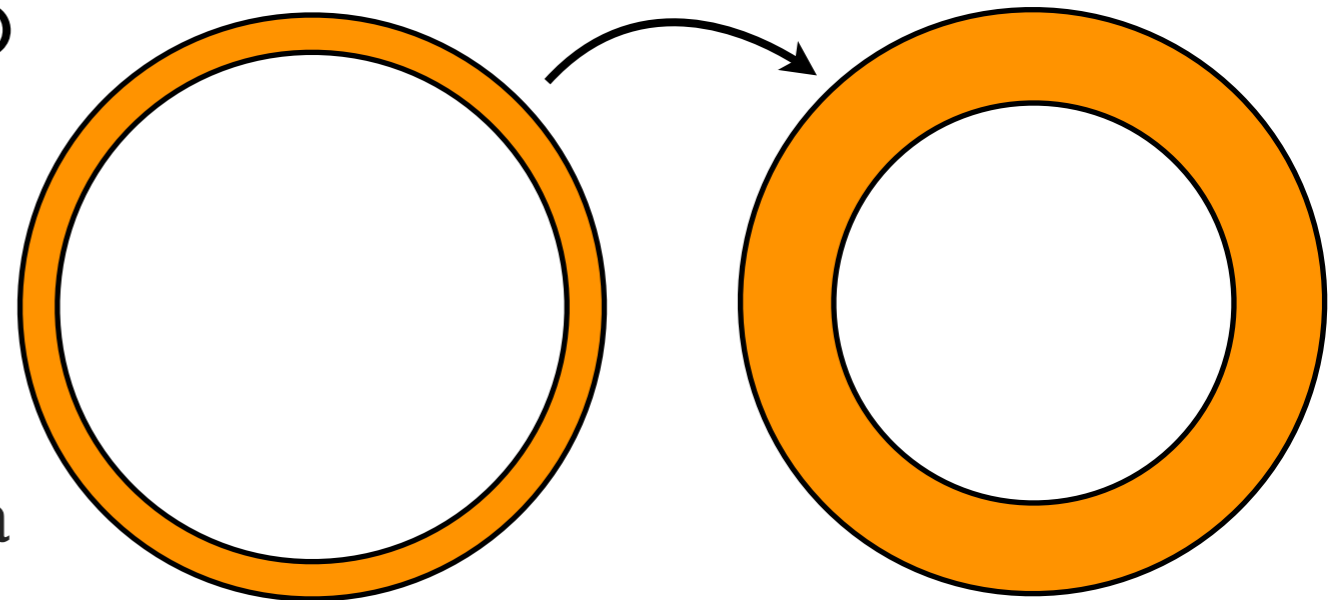
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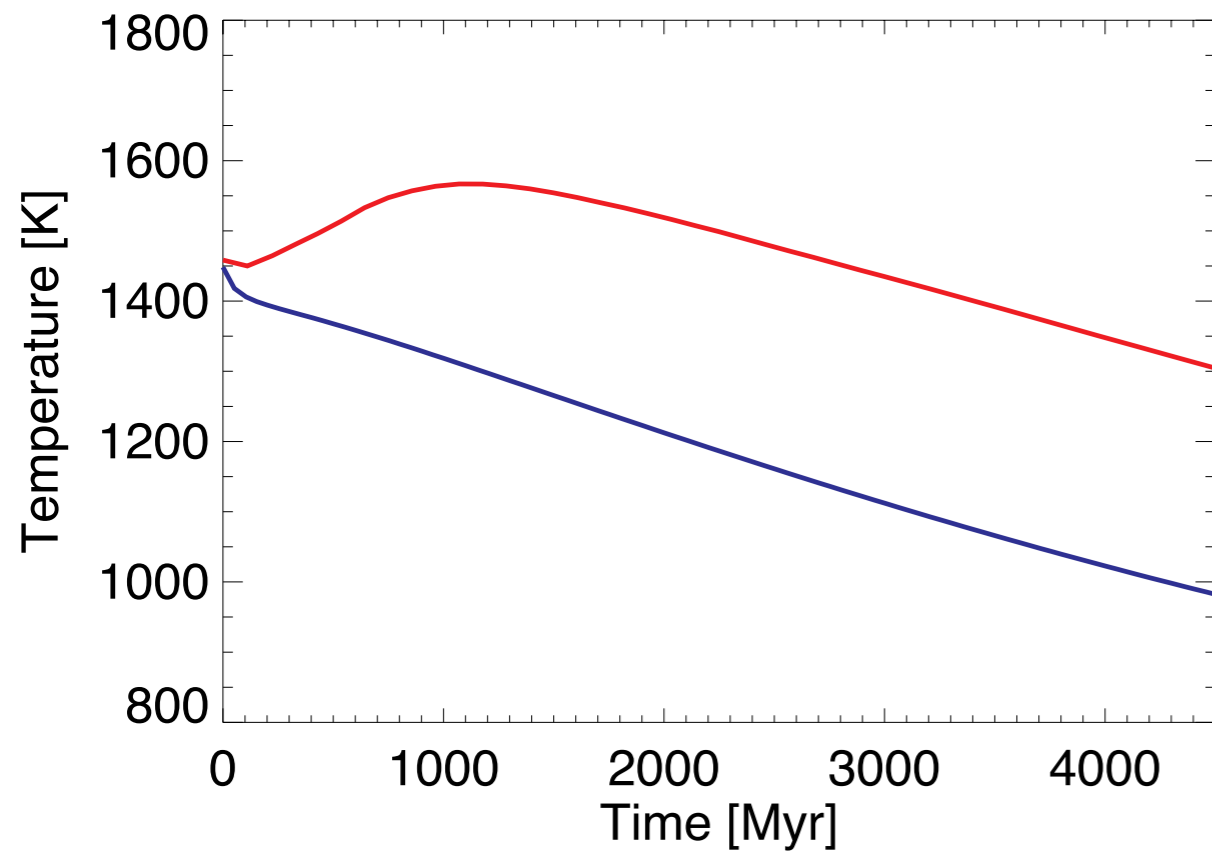


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- Surface temperature: either constant at 440 K or variable from 140 K at the poles to 440 K at the equator



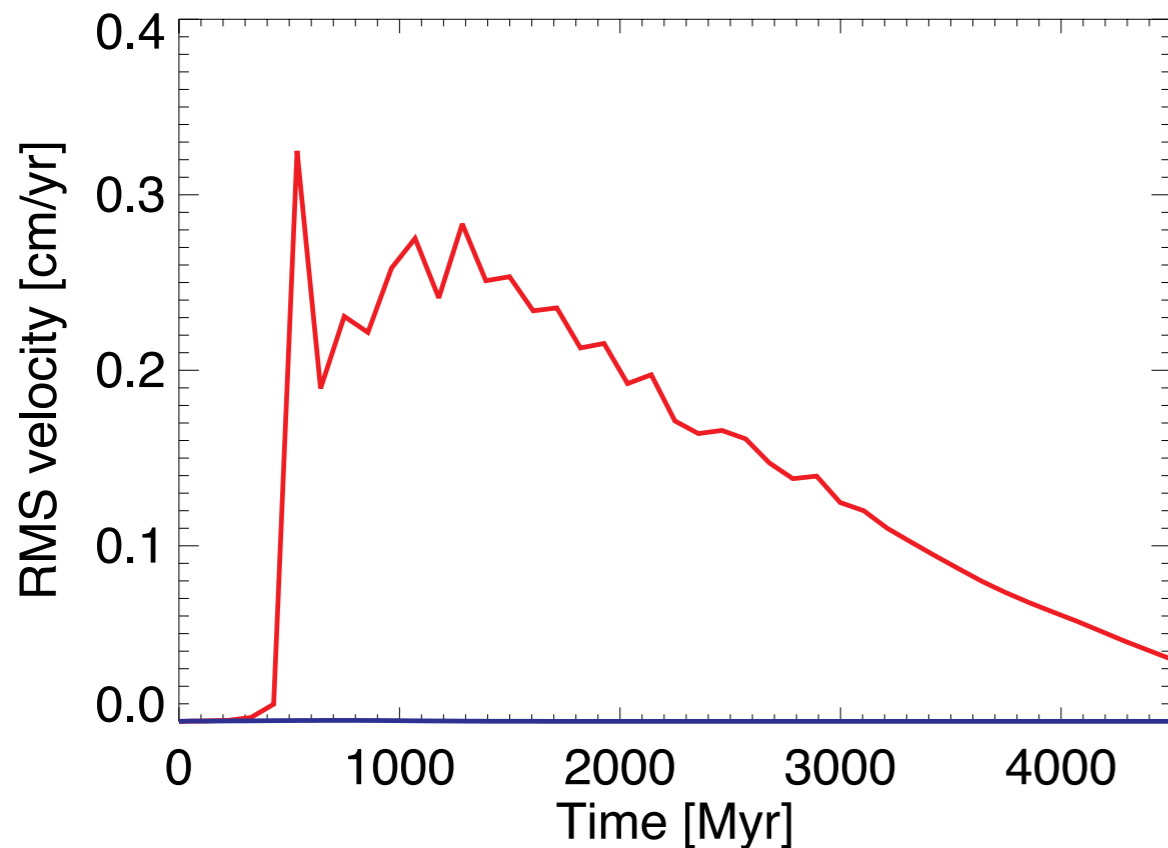
Influence of mantle thickness



Initially “cold” mantle, 25% of surface heat sources abundance

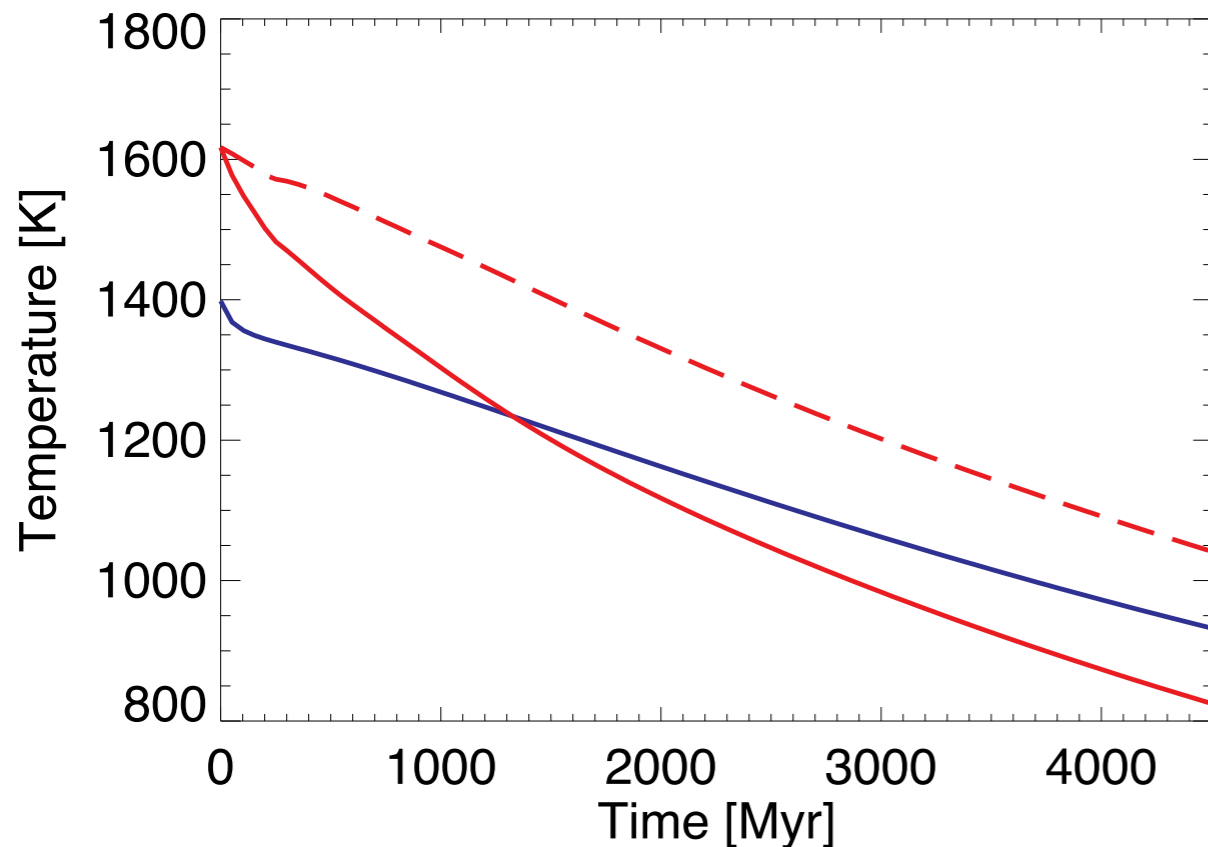
— $D=400$ km $\Rightarrow Ra=2.5 \times 10^4$

— $D=600$ km $\Rightarrow Ra=8.6 \times 10^4$



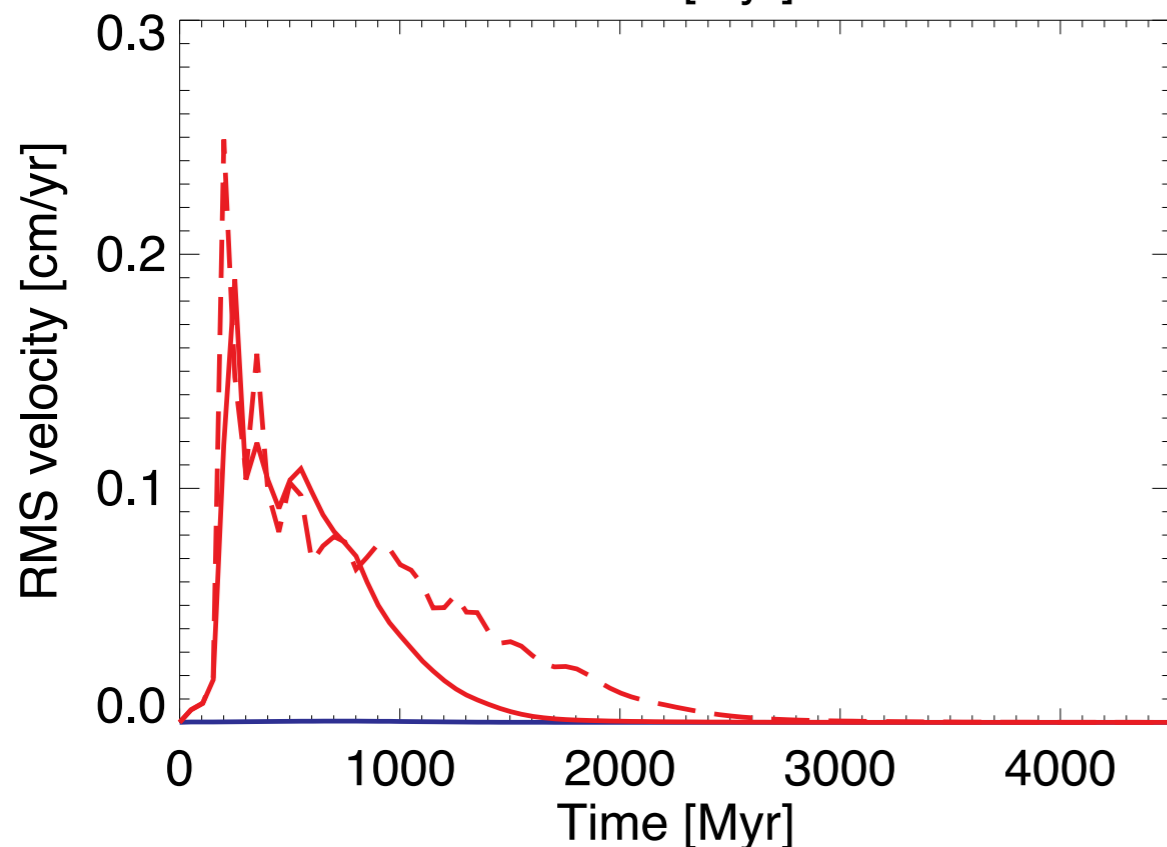
The thermal Rayleigh number with $D=600$ km is ~ 3.3 times larger than with $D=400$ km \Rightarrow it can determine the transition from subcritical to supercritical conditions for the onset of thermal convection

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

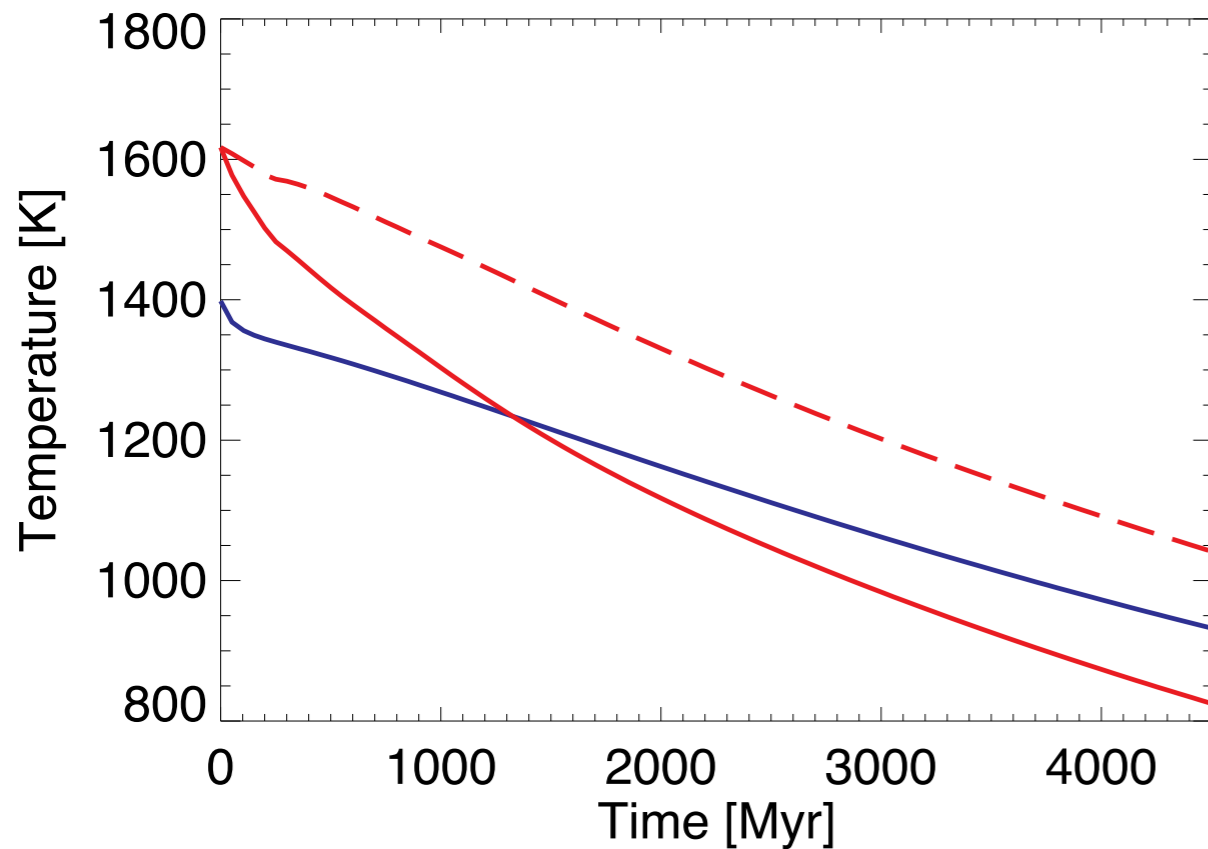


- Cold
- Hot with $k_{crust}=0.5 k_{mantle}$
- - - Hot with $k_{crust}=0.25 k_{mantle}$

- “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



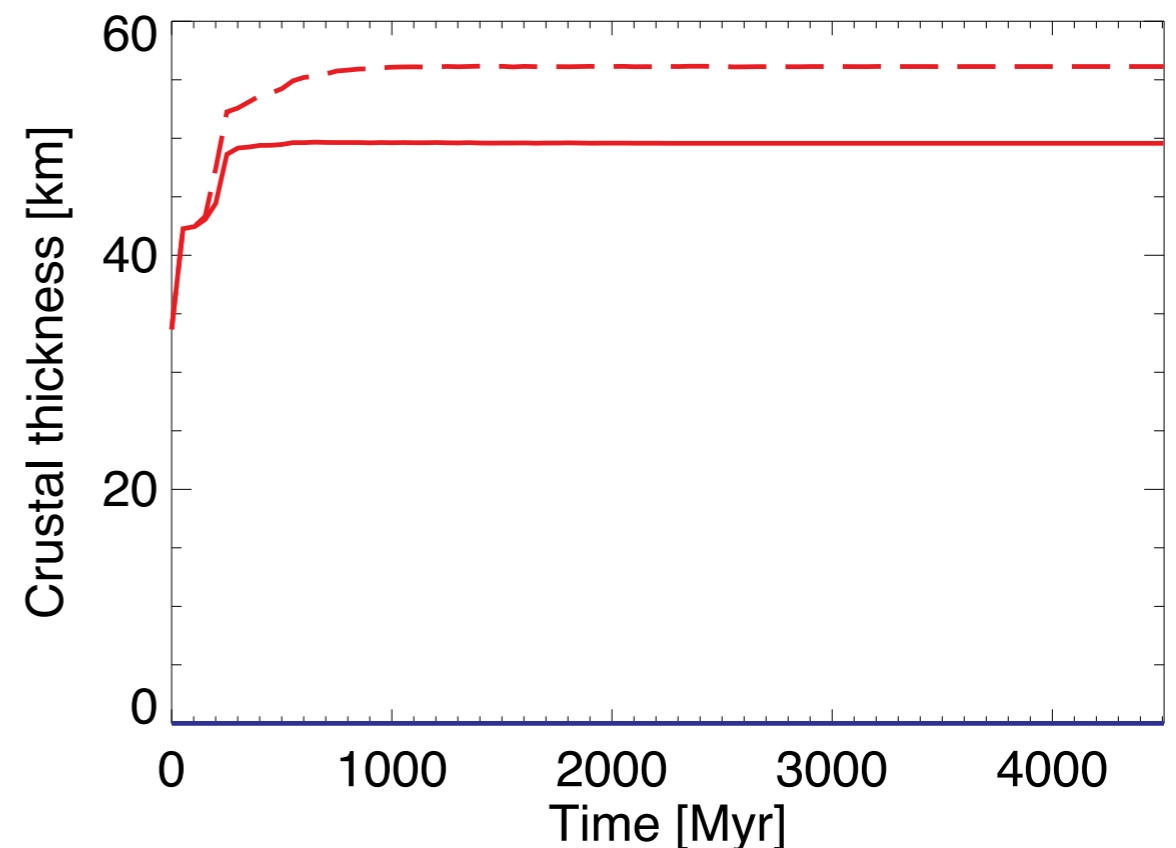
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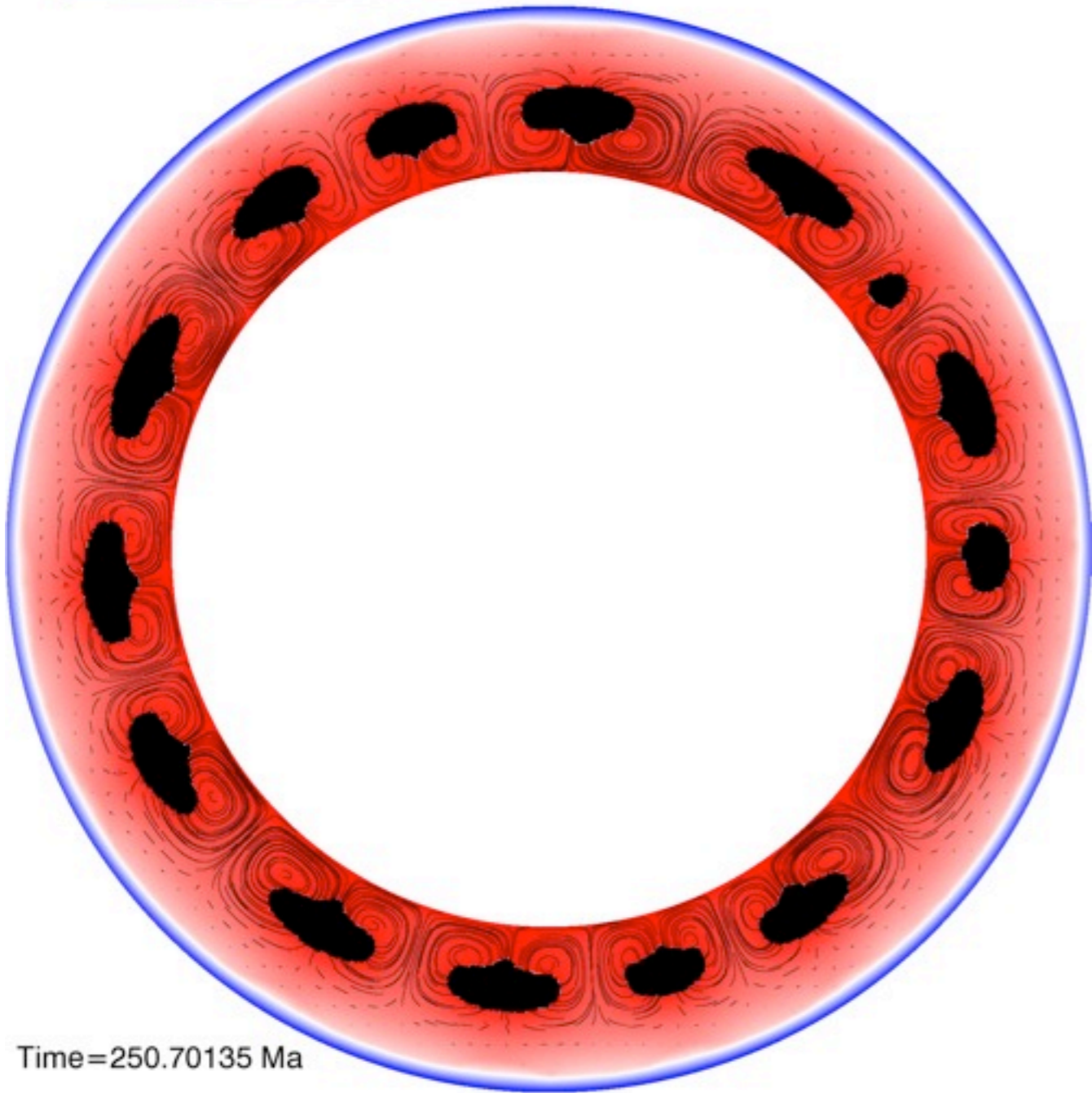
- Crustal production is concentrated in the first part of the evolution



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

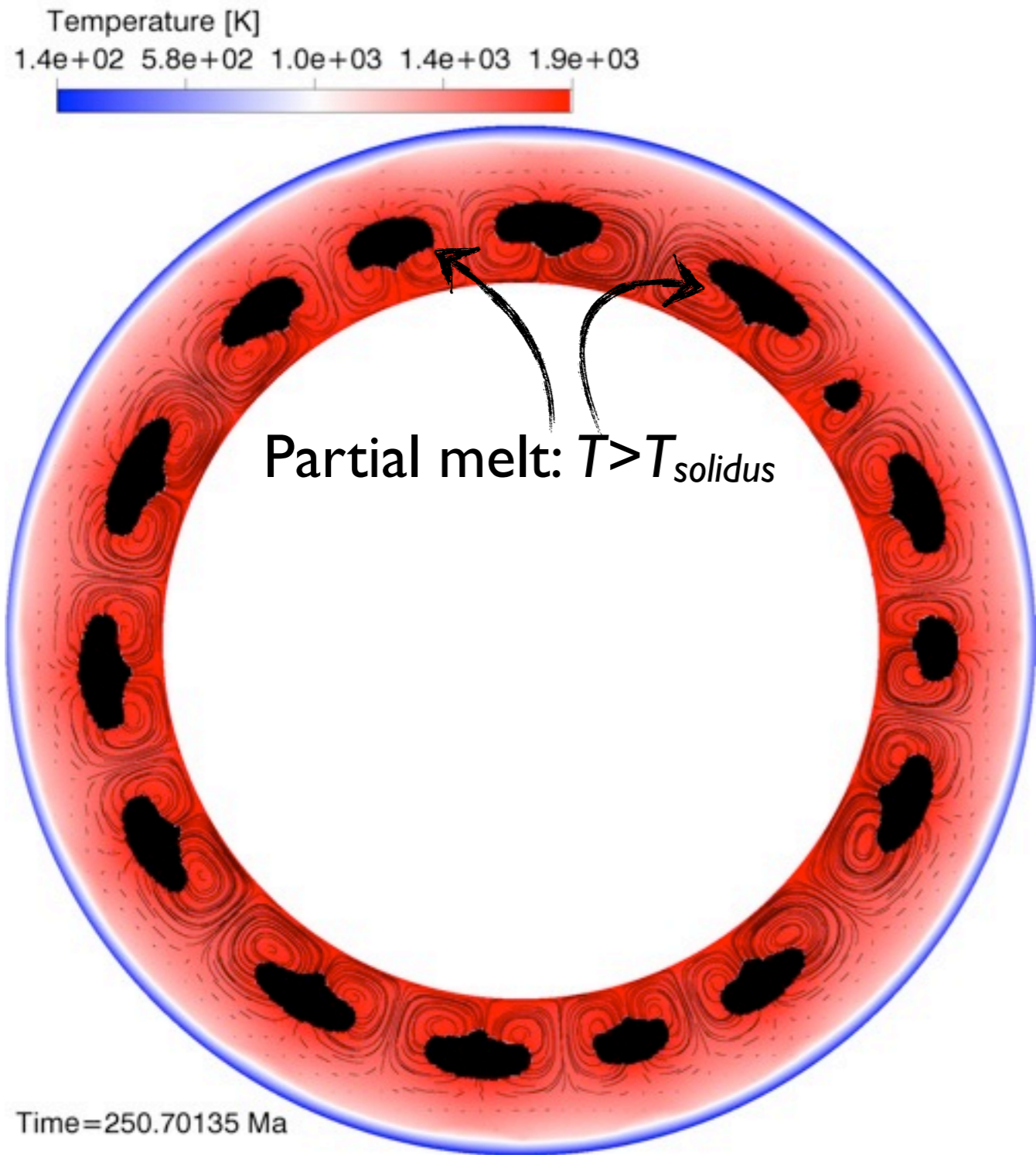
Temperature [K]

1.4e+02 5.8e+02 1.0e+03 1.4e+03 1.9e+03

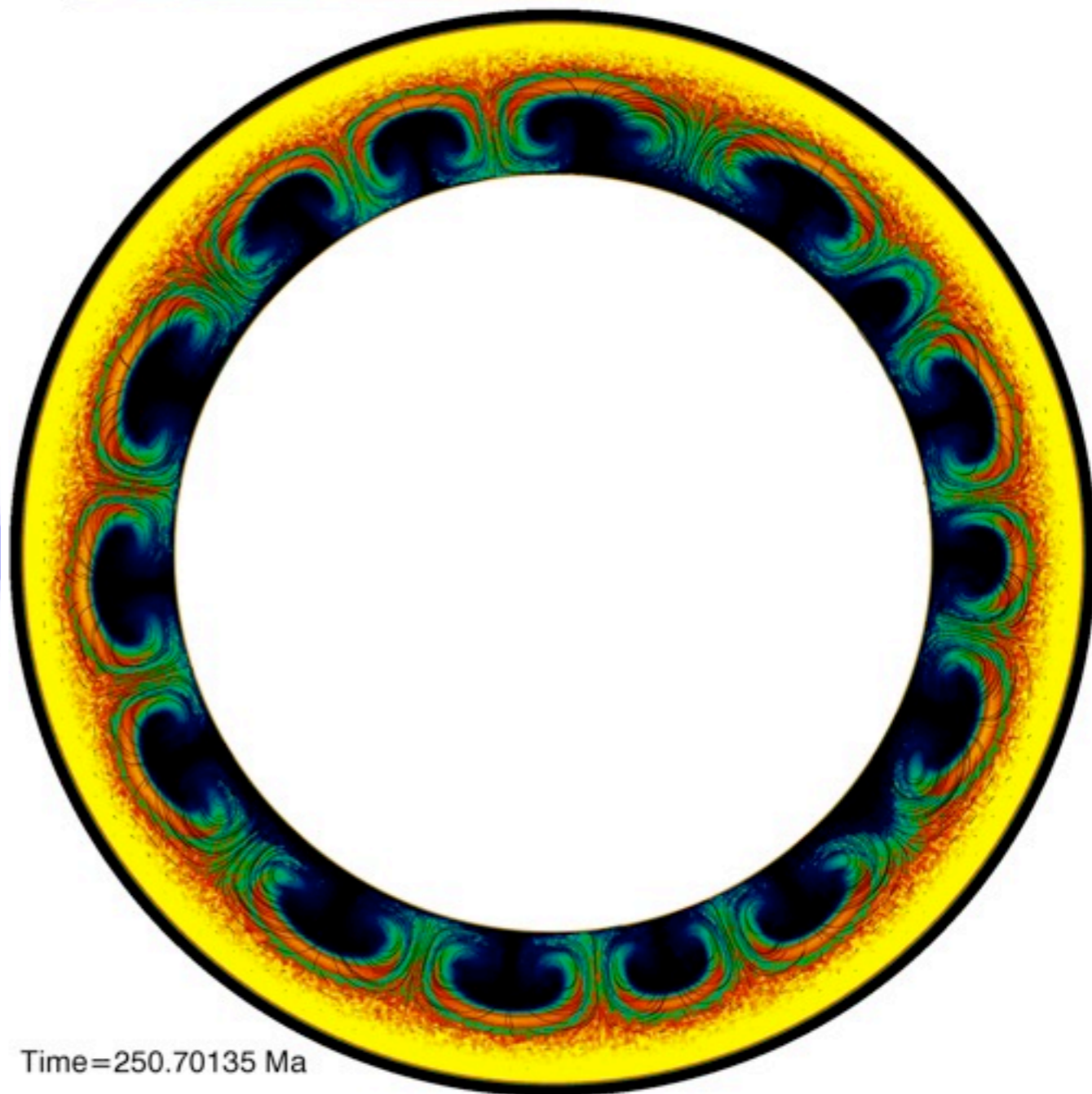
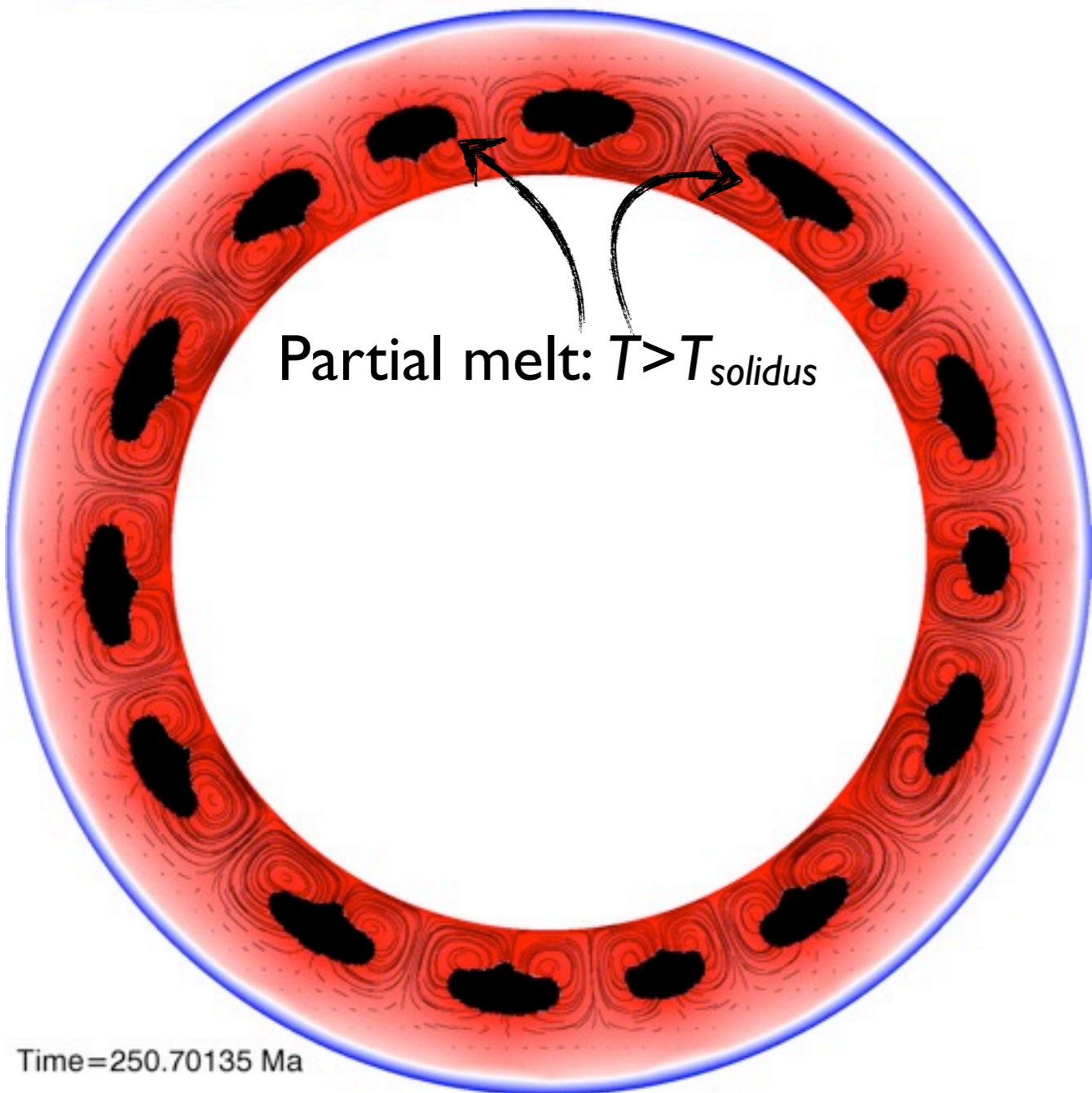


Time=250.70135 Ma

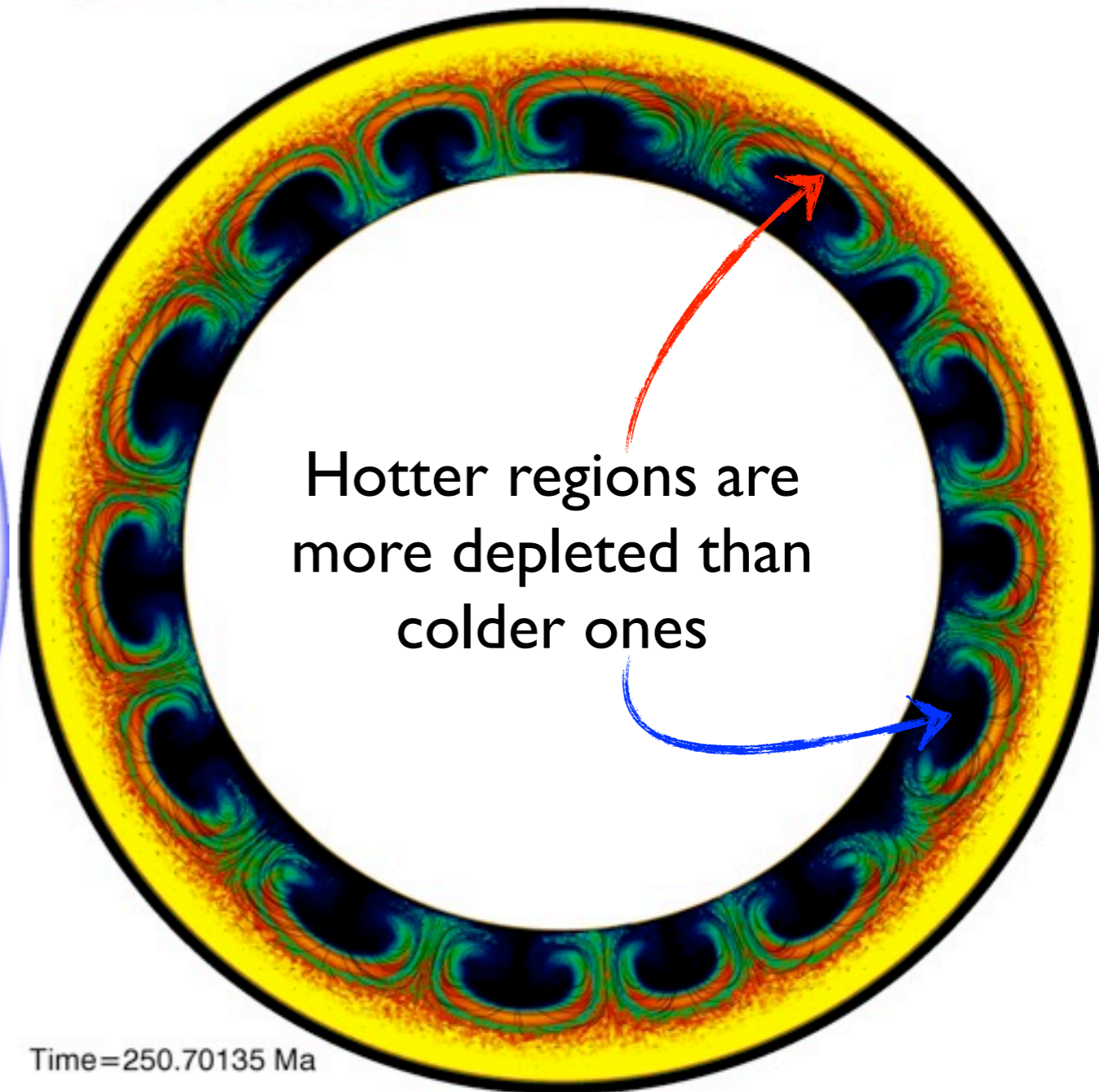
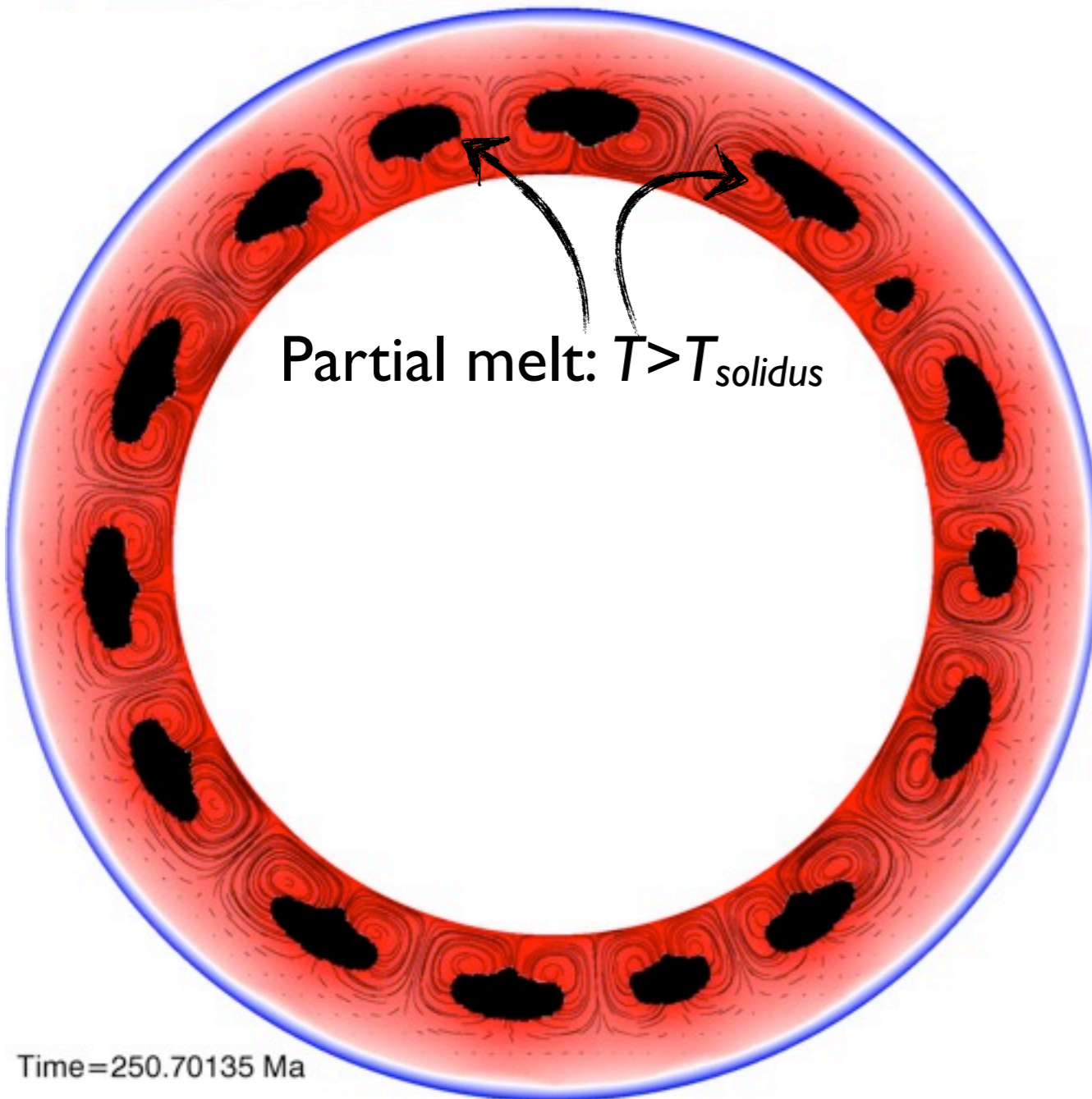
Results for $H_0=25\% H_{surface}$



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



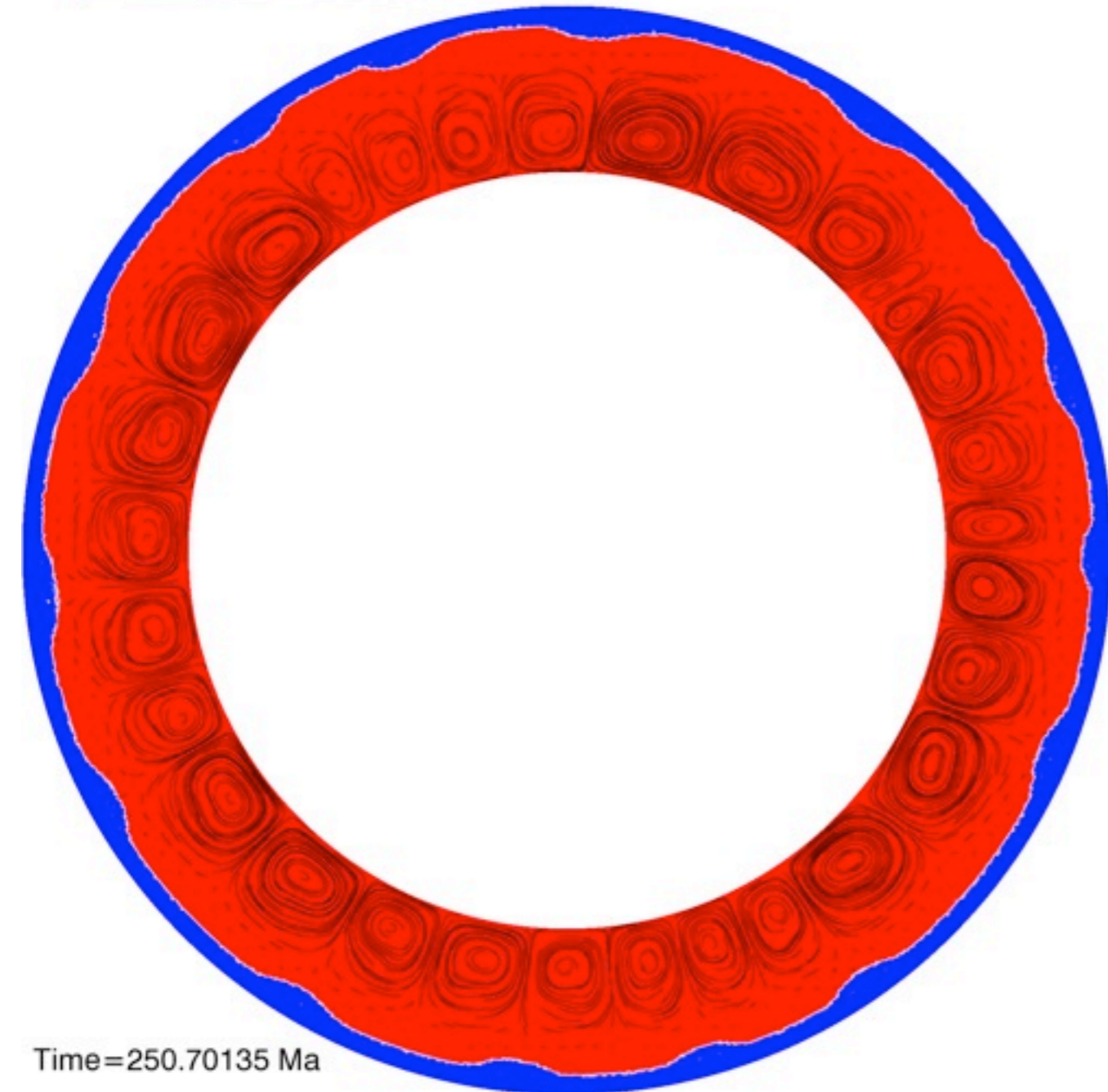
Results for $H_0=25\% H_{surface}$



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

Thermal conductivity [W/mK]

1.0e+00 1.8e+00 2.5e+00 3.3e+00 4.0e+00



Time=250.70135 Ma

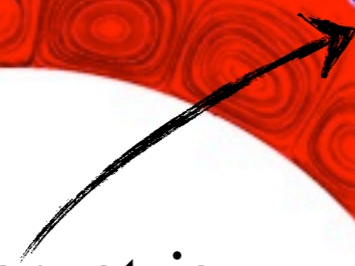
Results for $H_0=25\% H_{surface}$

Thermal conductivity [W/mK]

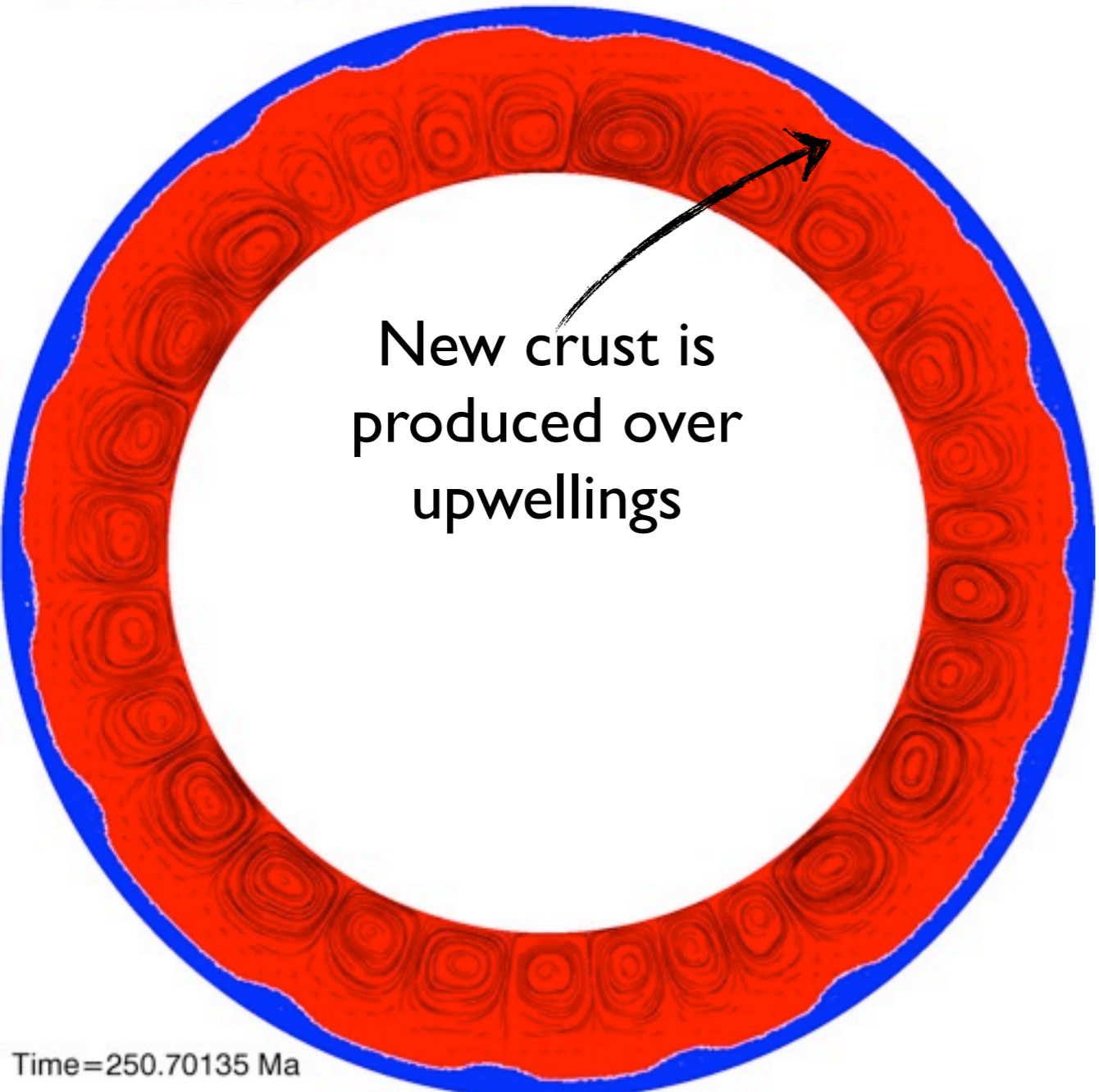
1.0e+00 1.8e+00 2.5e+00 3.3e+00 4.0e+00



New crust is
produced over
upwellings



Time=250.70135 Ma



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

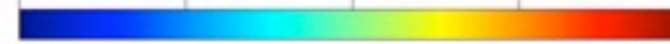
Thermal conductivity [W/mK]

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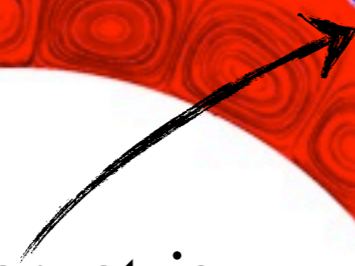


log10 Heating rate [pW/kg]

5.7e-01 1.0e+00 1.4e+00 1.8e+00 2.3e+00



New crust is produced over upwellings



Time=250.70135 Ma

Time=250.70135 Ma

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

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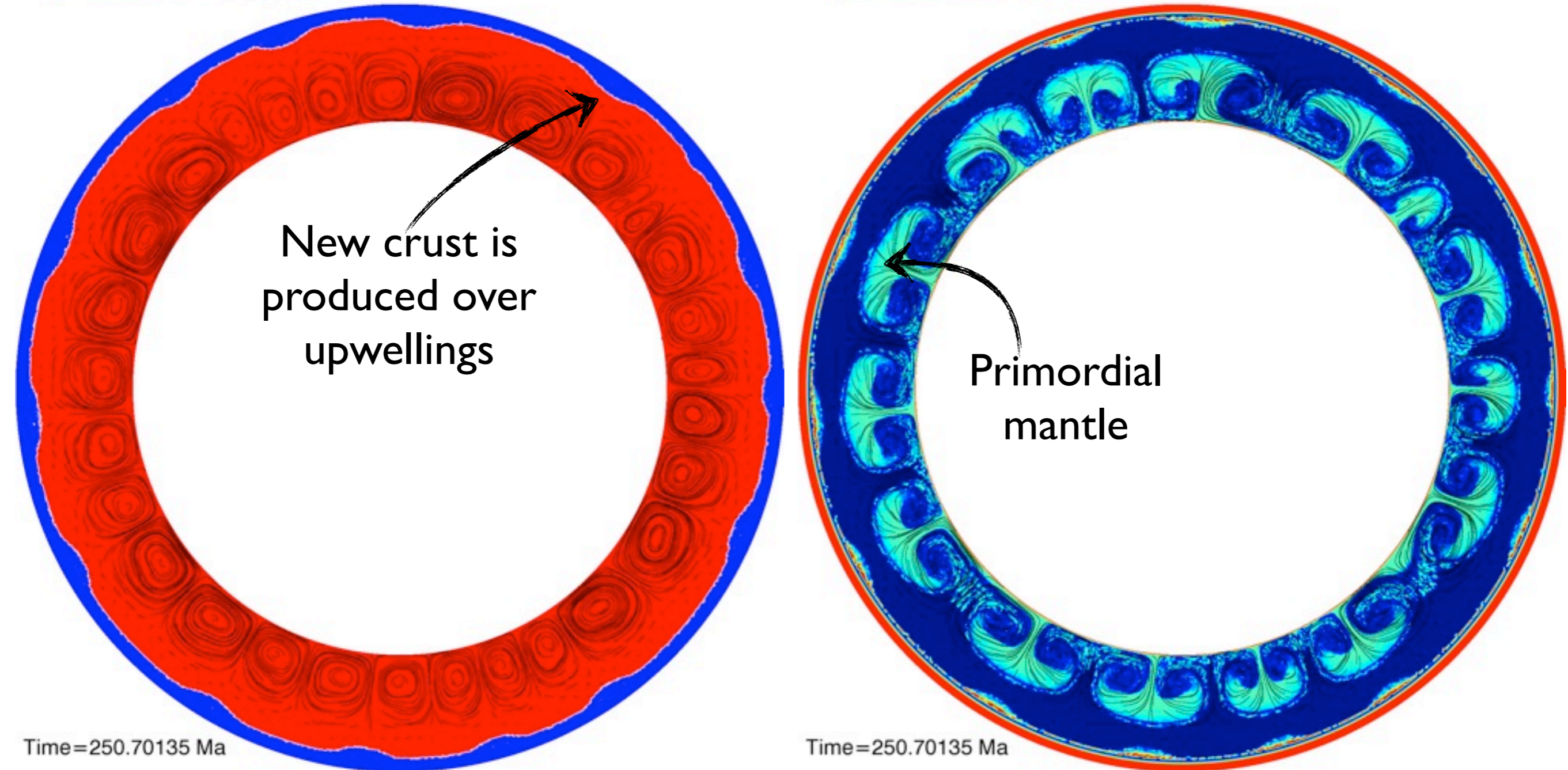
log10 Heating rate [pW/kg]
5.7e-01 1.0e+00 1.4e+00 1.8e+00 2.3e+00

New crust is
produced over
upwellings

Primordial
mantle

Time=250.70135 Ma

Time=250.70135 Ma



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

Thermal conductivity [W/mK]
1.0e+00 1.8e+00 2.5e+00 3.3e+00 4.0e+00

log10 Heating rate [pW/kg]
5.7e-01 1.0e+00 1.4e+00 1.8e+00 2.3e+00

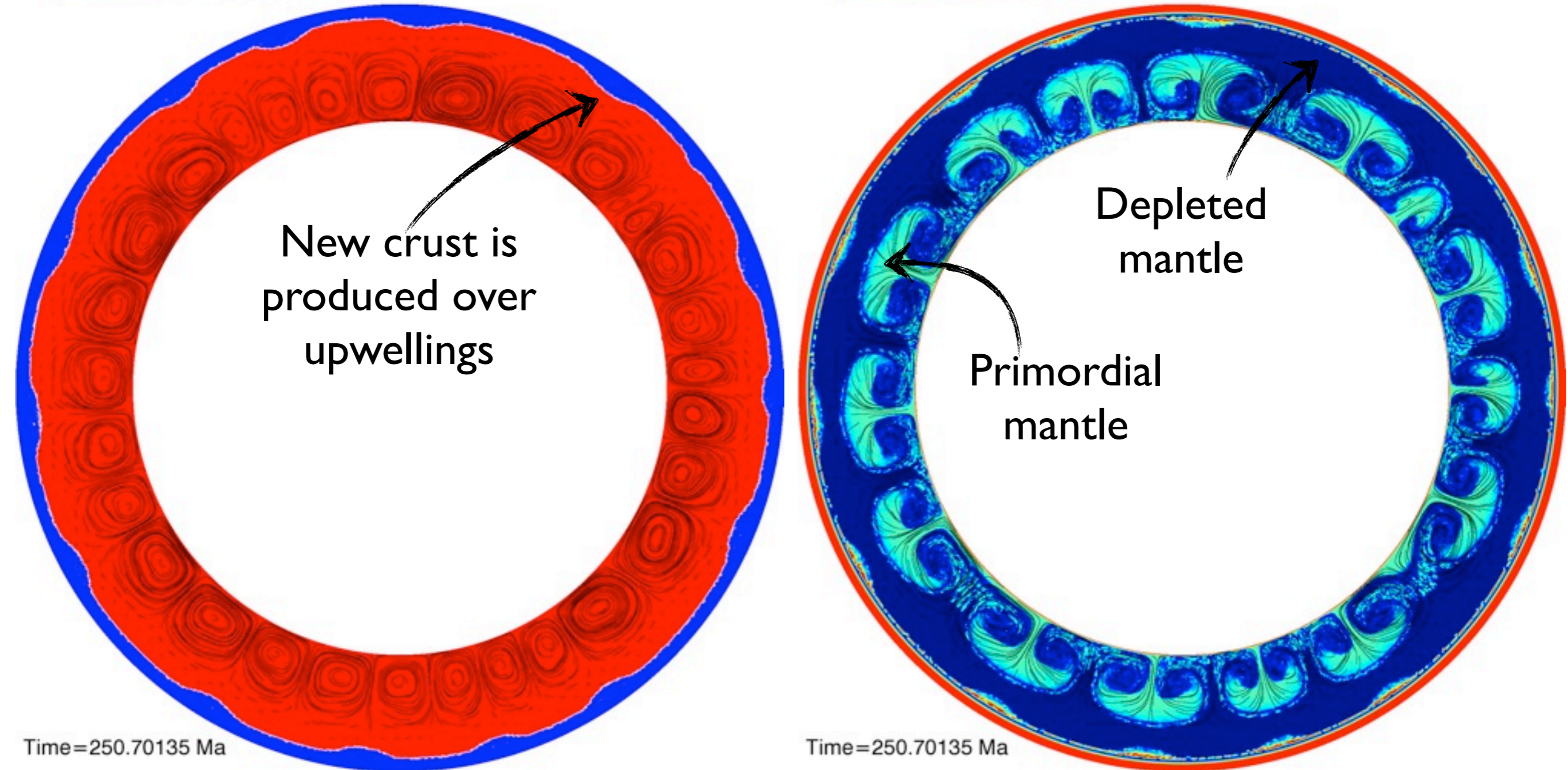
New crust is produced over upwellings

Depleted mantle

Primordial mantle

Time=250.70135 Ma

Time=250.70135 Ma



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

Thermal conductivity [W/mK]
1.0e+00 1.8e+00 2.5e+00 3.3e+00 4.0e+00

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5.7e-01 1.0e+00 1.4e+00 1.8e+00 2.3e+00

New crust is produced over upwellings

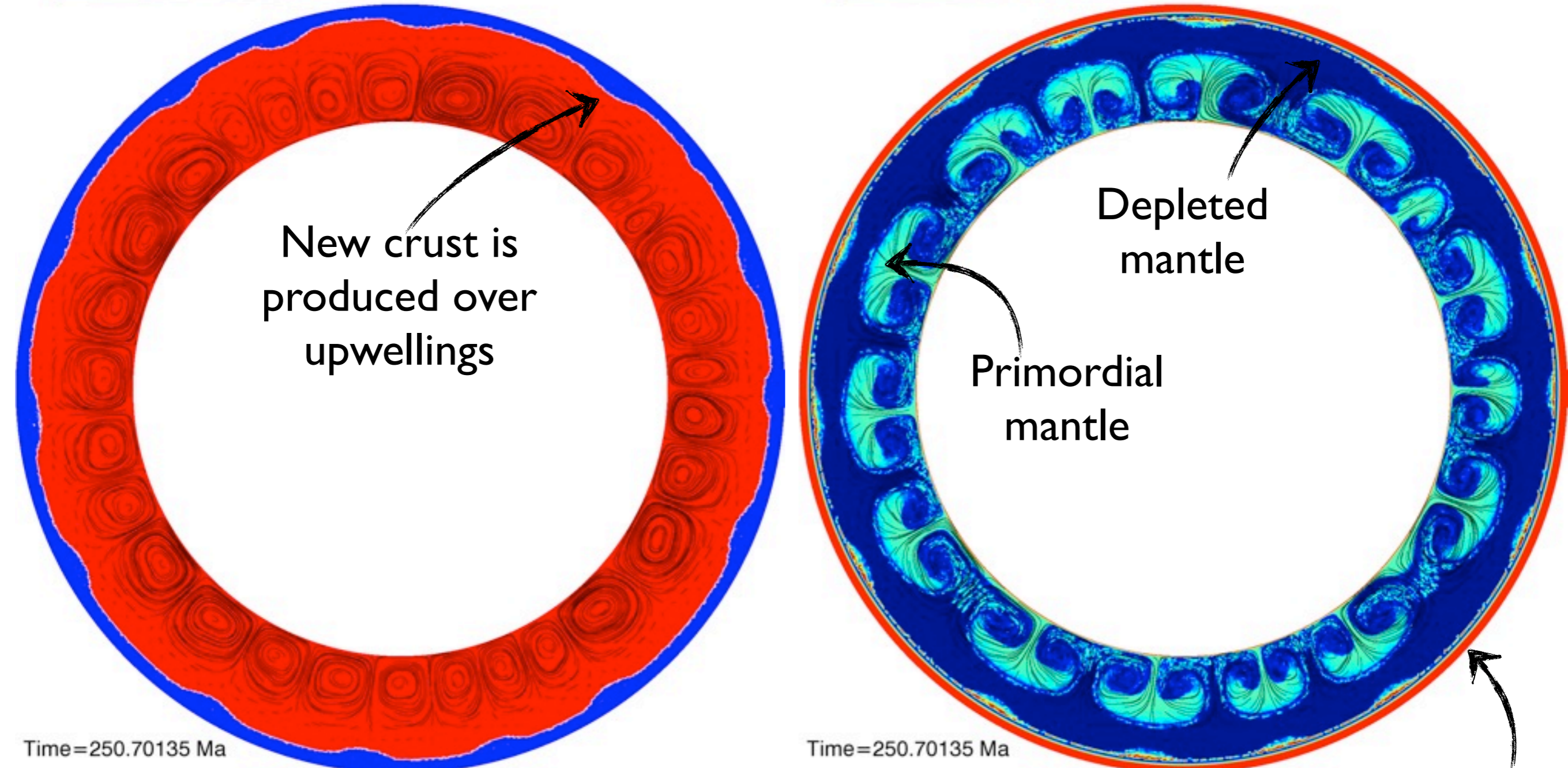
Depleted mantle

Primordial mantle

Enriched crust

Time=250.70135 Ma

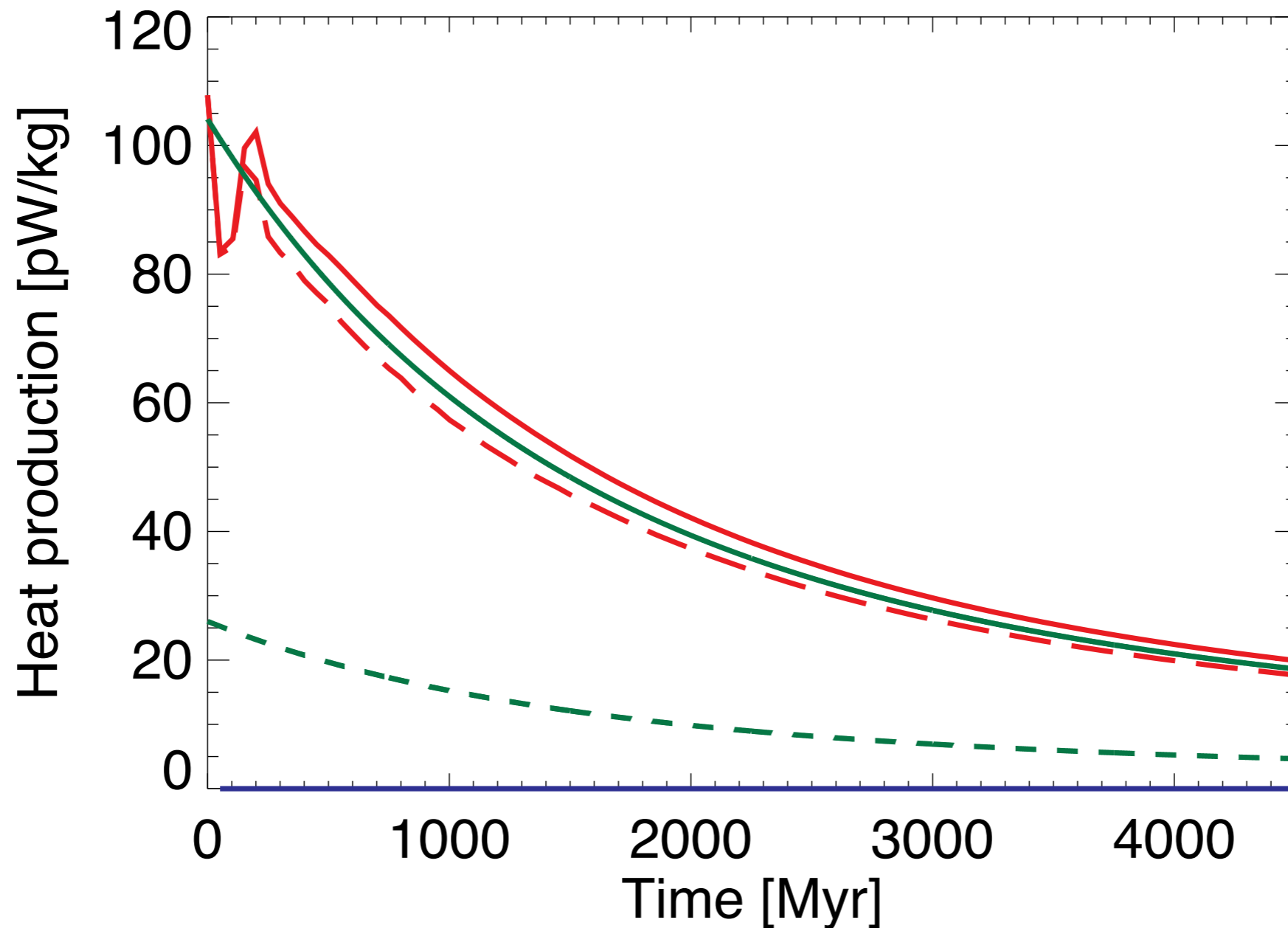
Time=250.70135 Ma



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

Time evolution of the average crustal heat production

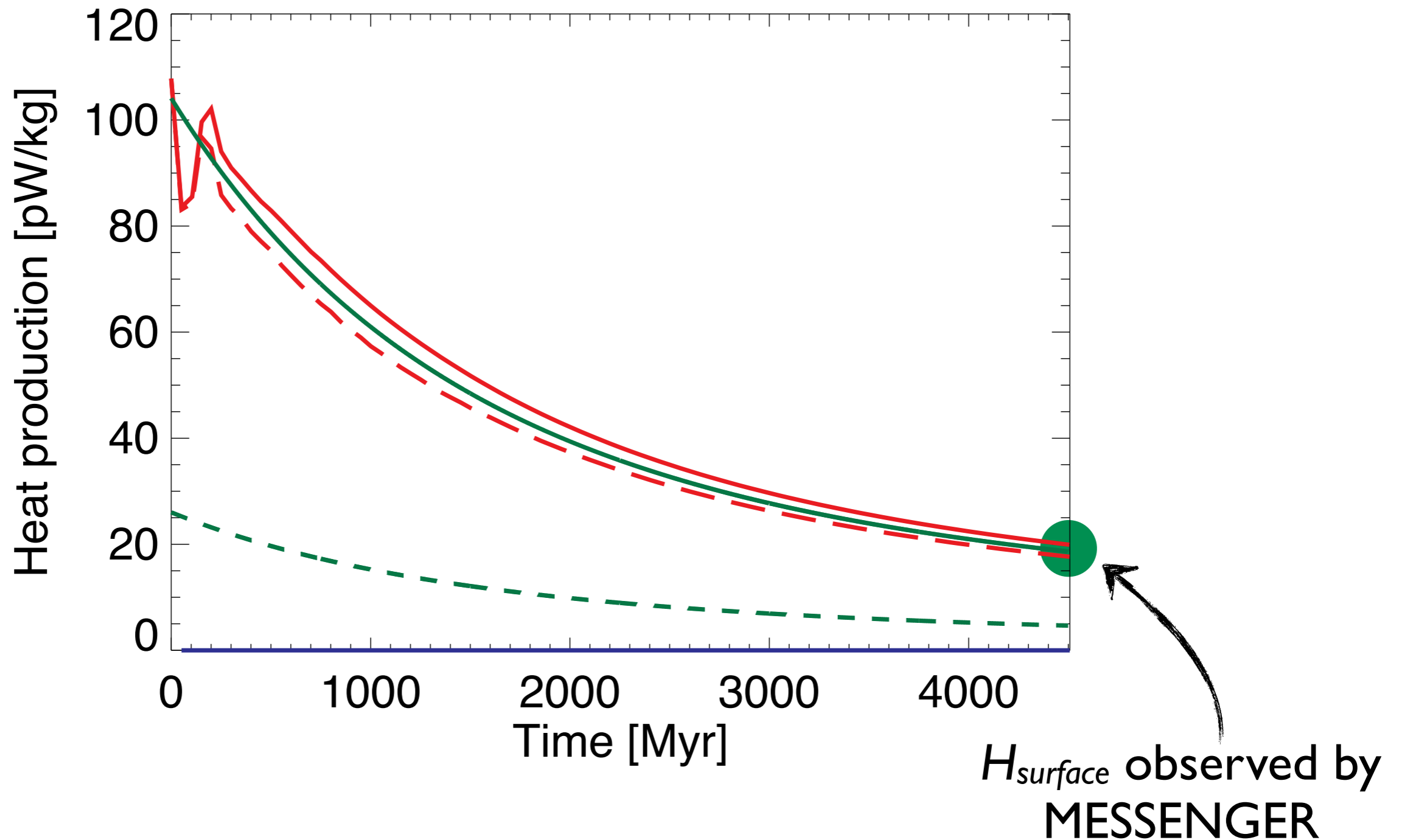
- Cold
- Hot with $k_{crust}=0.5 k_{mantle}$
- - - Hot with $k_{crust}=0.25 k_{mantle}$



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

Time evolution of the average crustal heat production

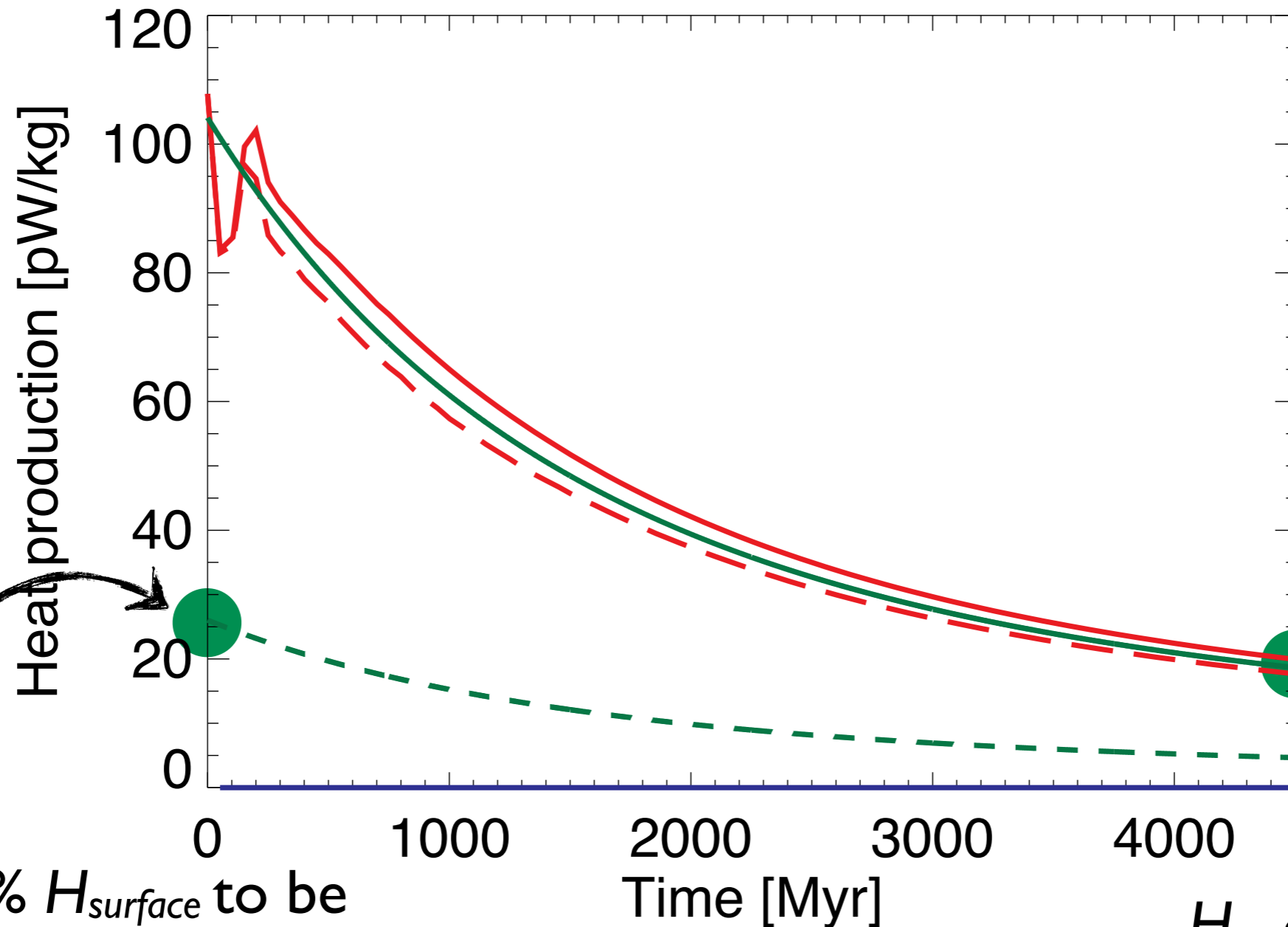
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Time evolution of the average crustal heat production

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



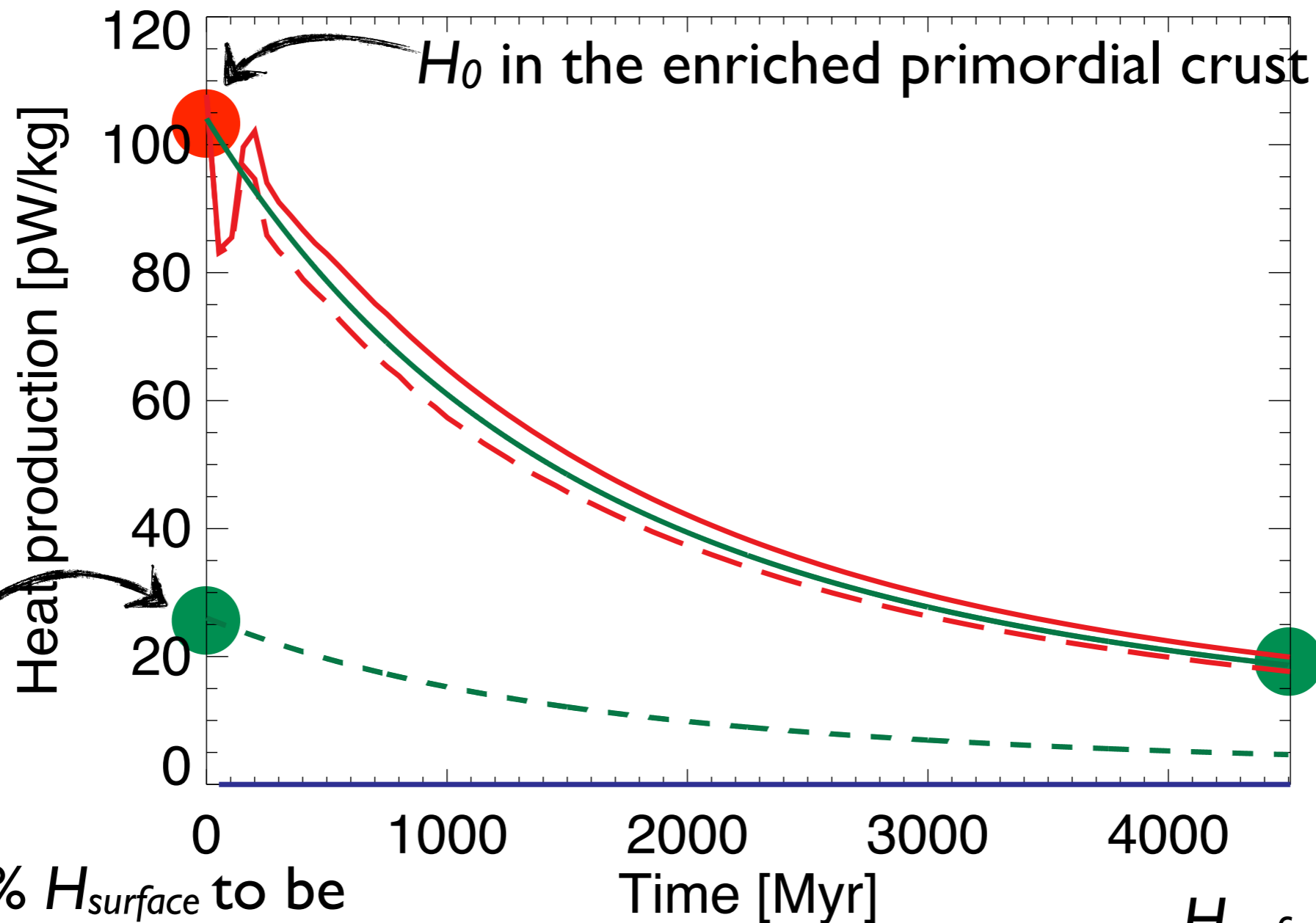
$H_0=25\% H_{surface}$ to be partitioned between mantle and primordial crust

$H_{surface}$ observed by MESSENGER

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

Time evolution of the average crustal heat production

- Cold
- Hot with $k_{crust}=0.5 k_{mantle}$
- - - Hot with $k_{crust}=0.25 k_{mantle}$



H_0 in the enriched primordial crust

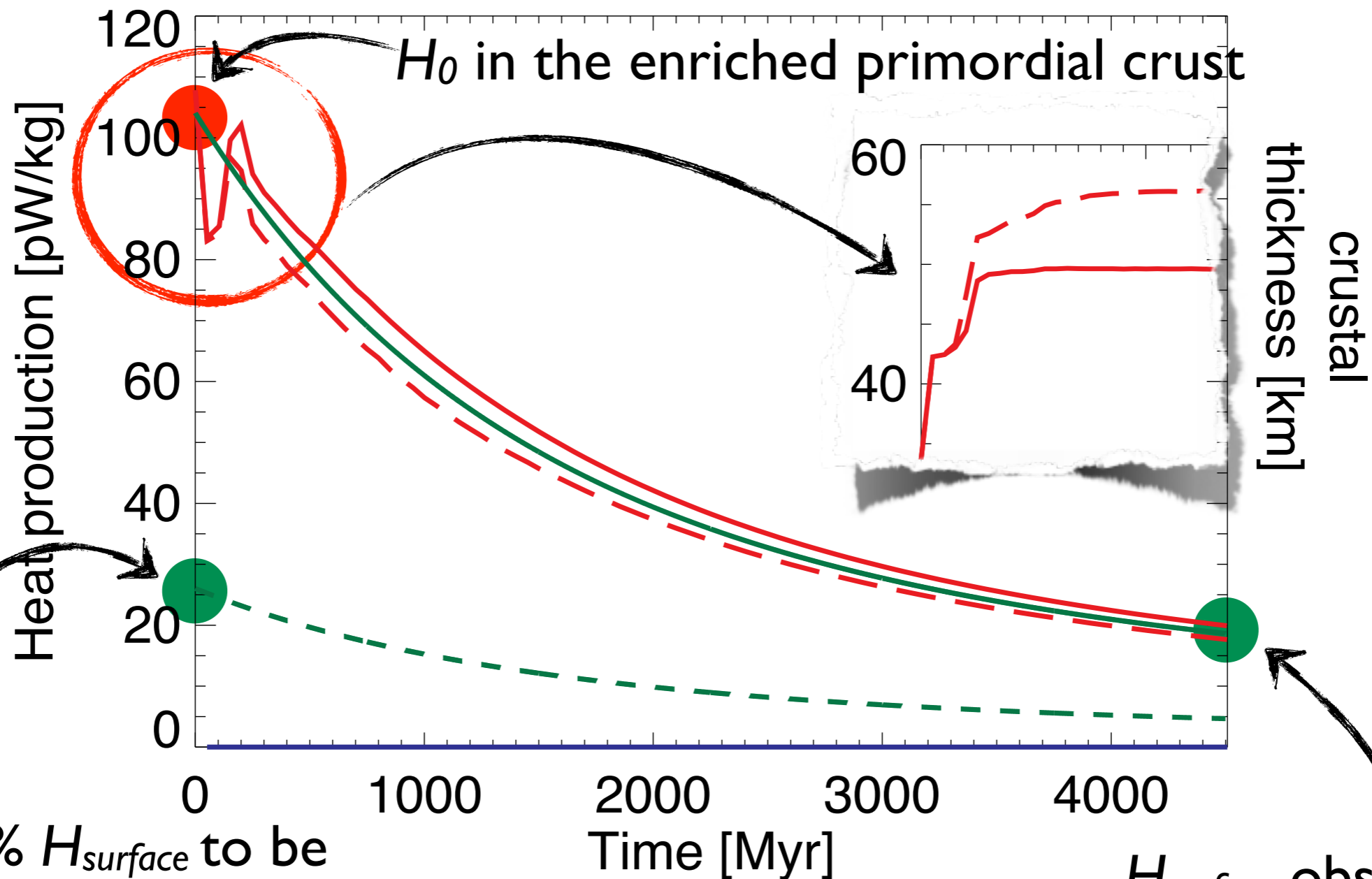
$H_0=25\% H_{surface}$ to be partitioned between mantle and primordial crust

$H_{surface}$ observed by MESSENGER

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

Time evolution of the average crustal heat production

- Cold
- Hot with $k_{crust}=0.5 k_{mantle}$
- - - Hot with $k_{crust}=0.25 k_{mantle}$



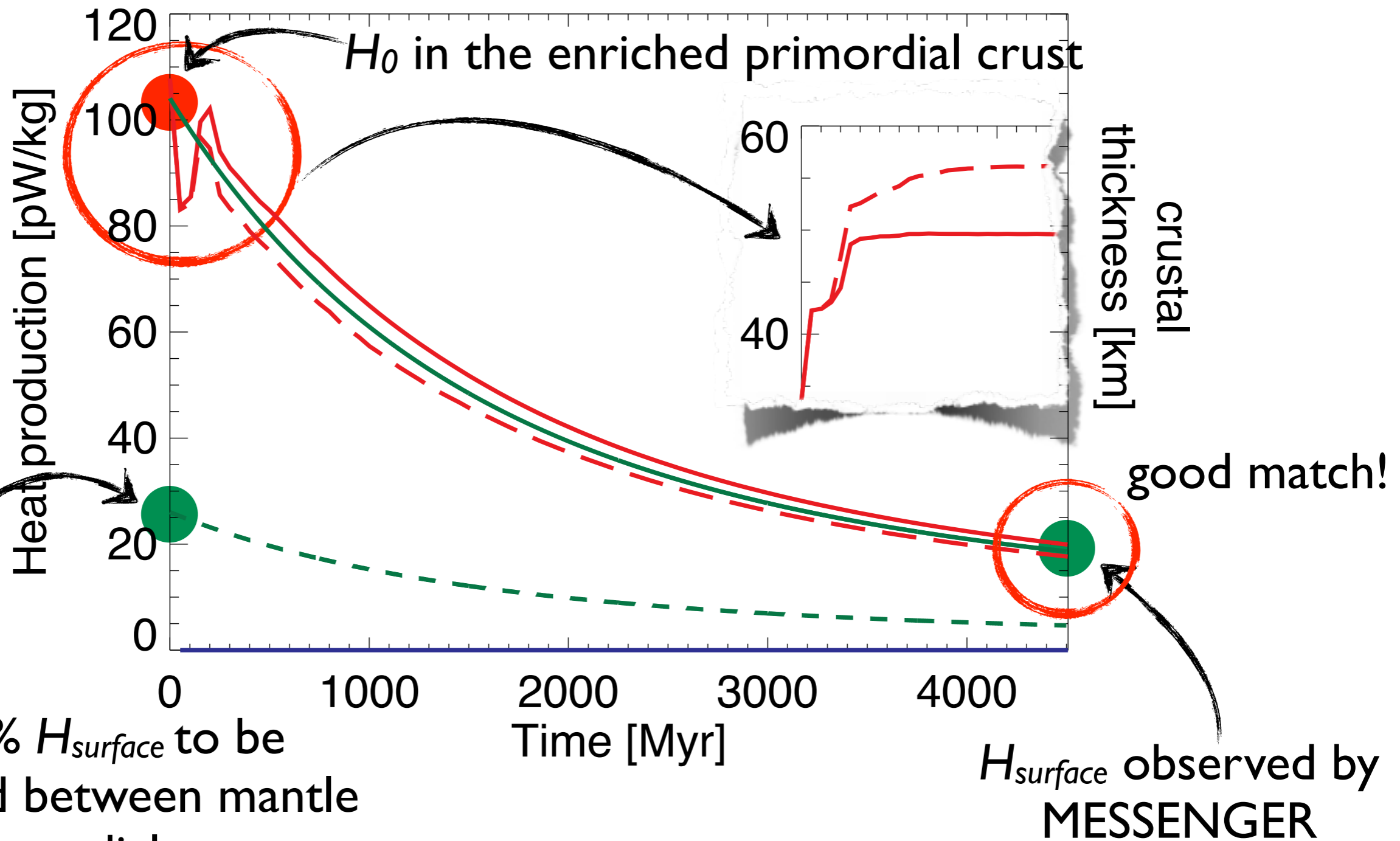
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$H_{surface}$ observed by MESSENGER

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

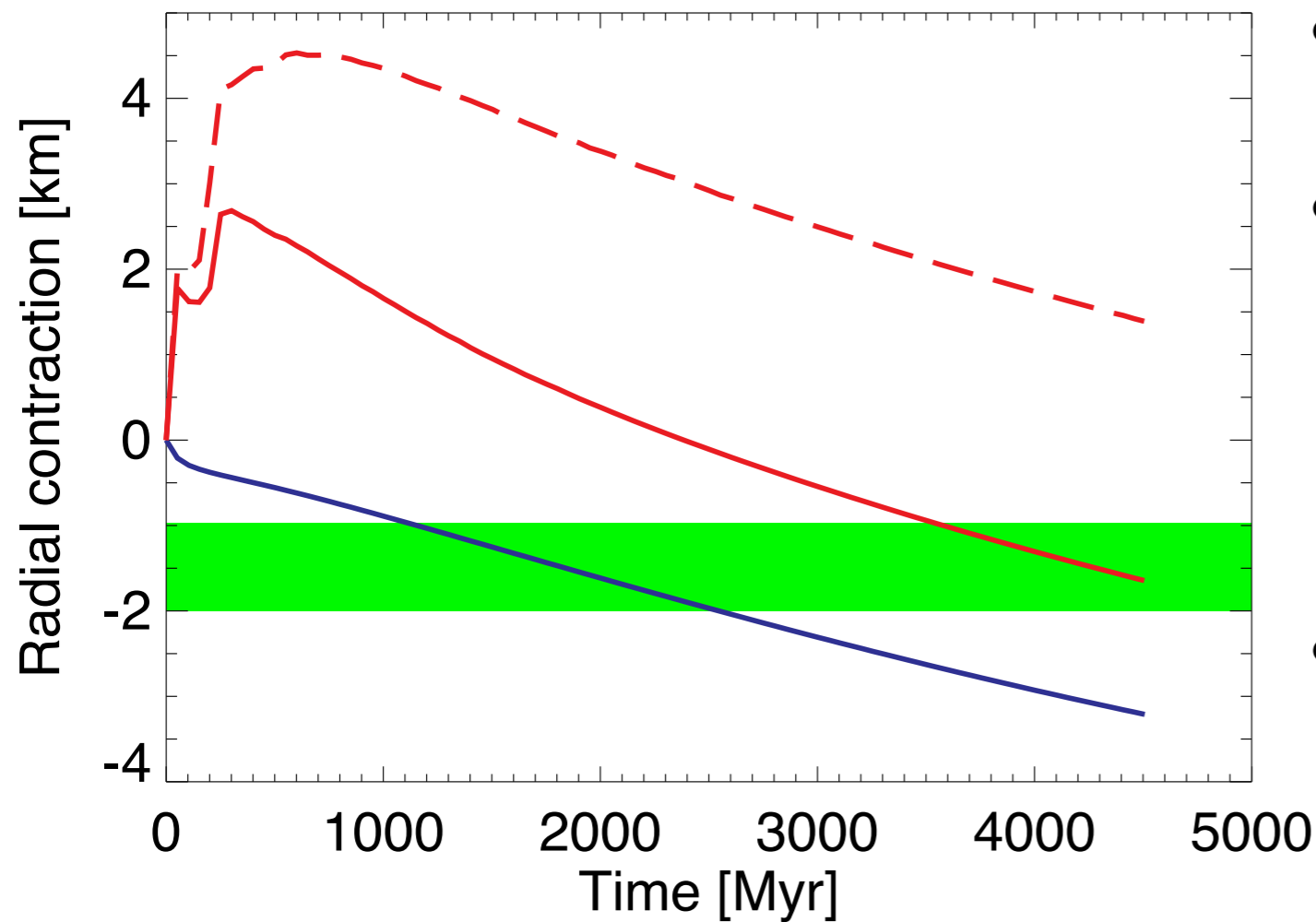
Time evolution of the average crustal heat production

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



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

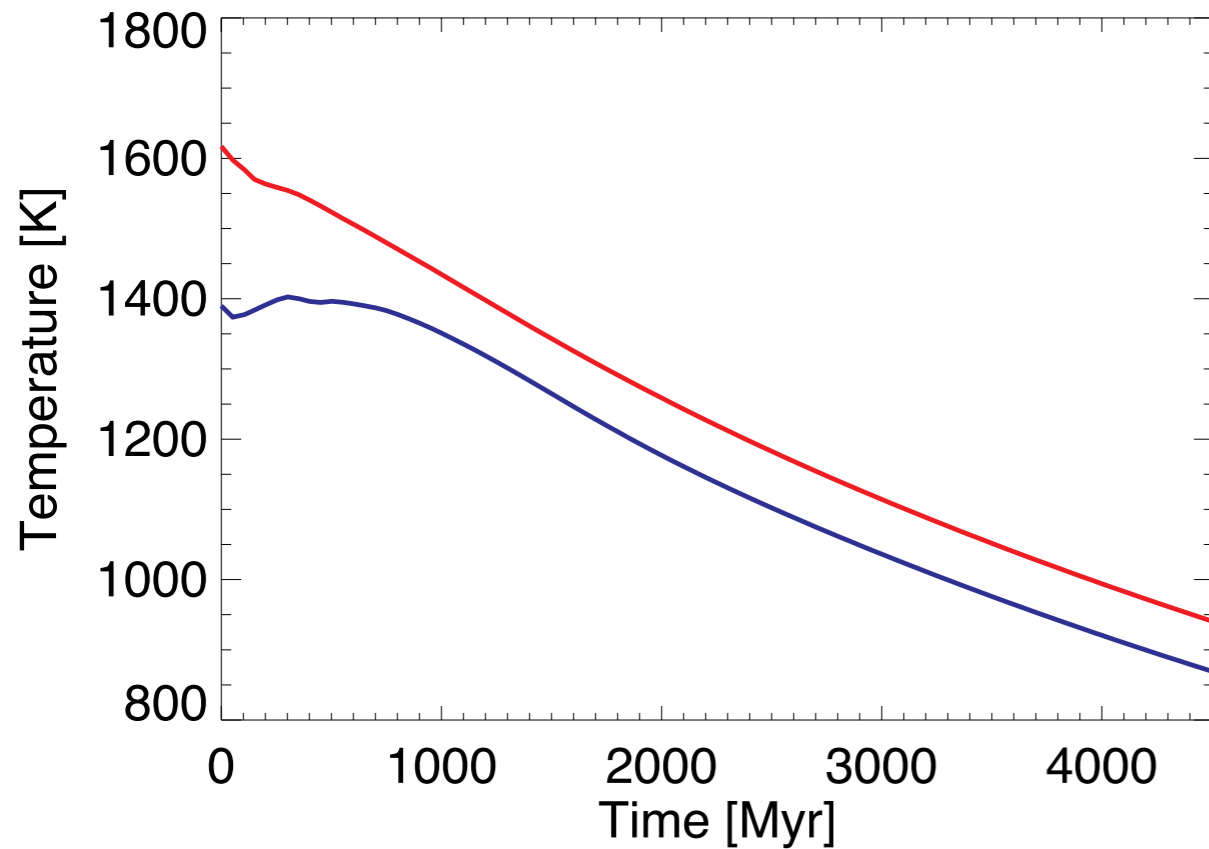
Time evolution of global radial contraction



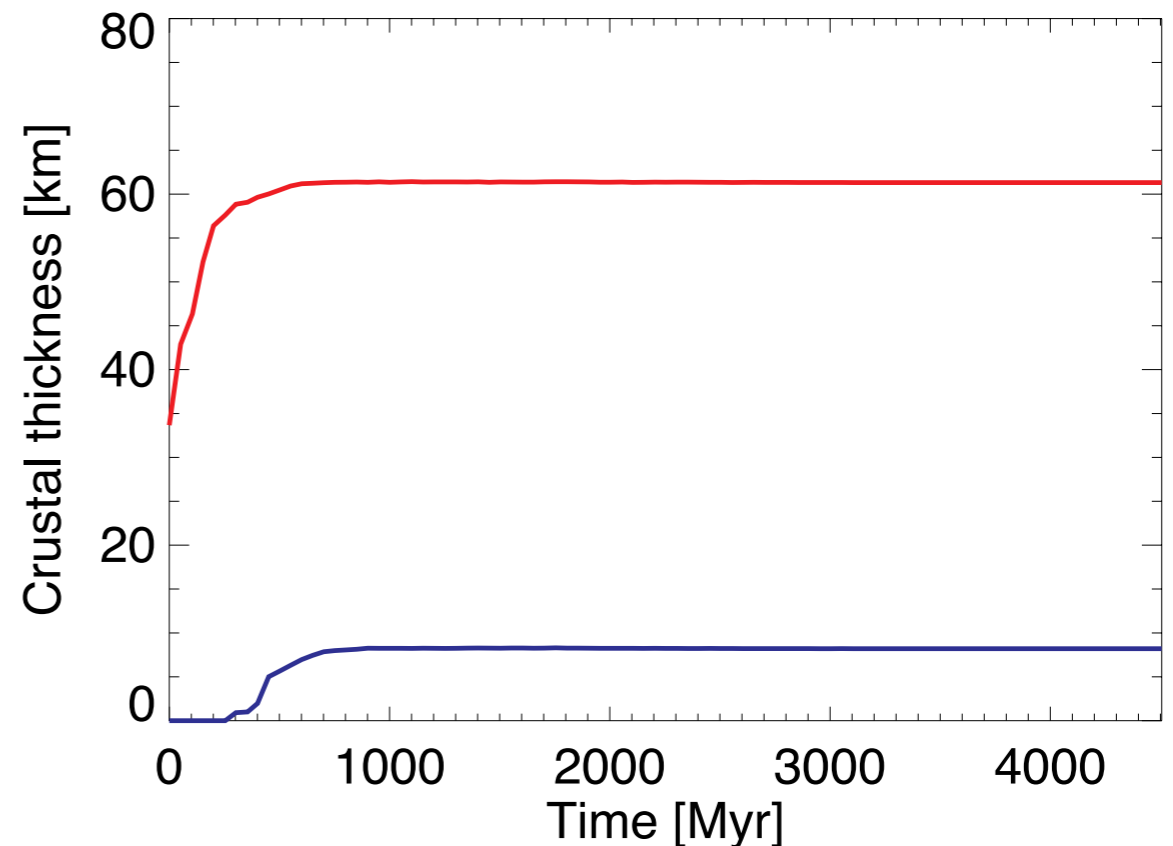
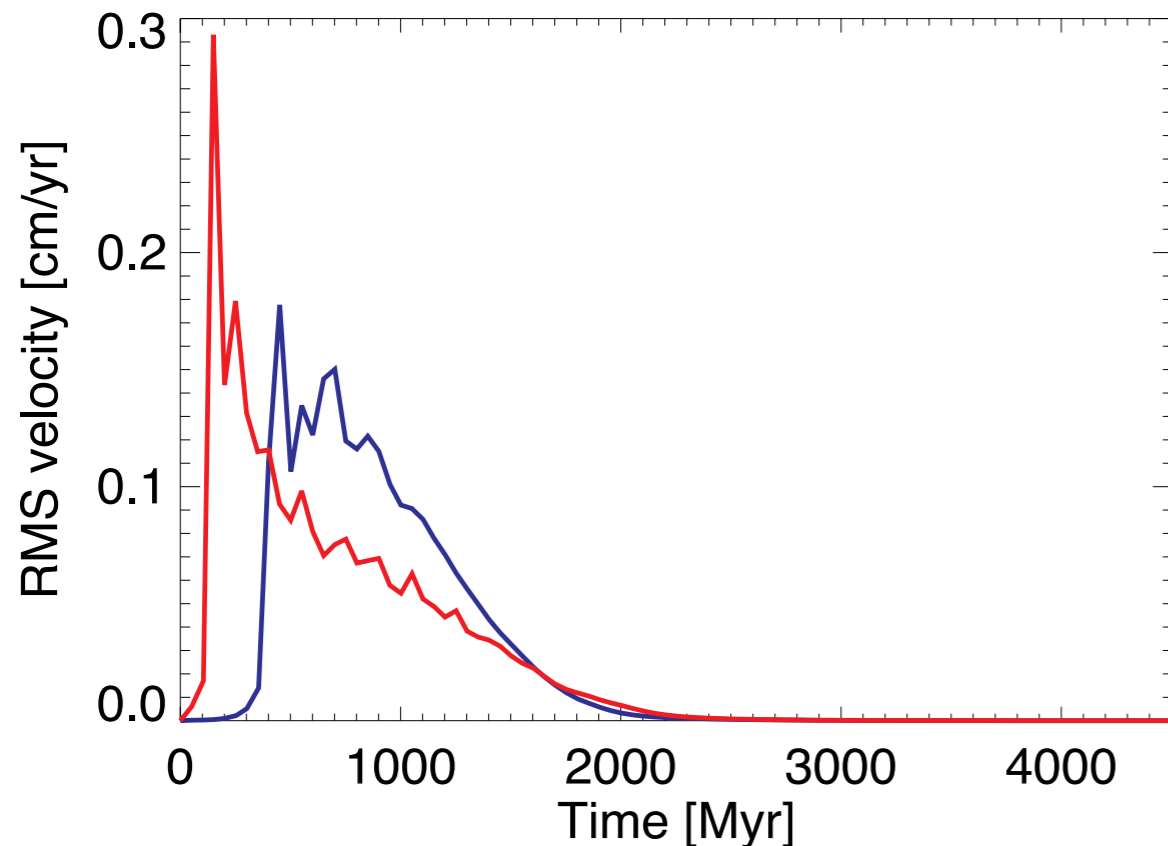
- Cold
- Hot with $k_{crust}=0.5 k_{mantle}$
- - - Hot with $k_{crust}=0.25 k_{mantle}$

- 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 $H_0=50\% H_{surface}$



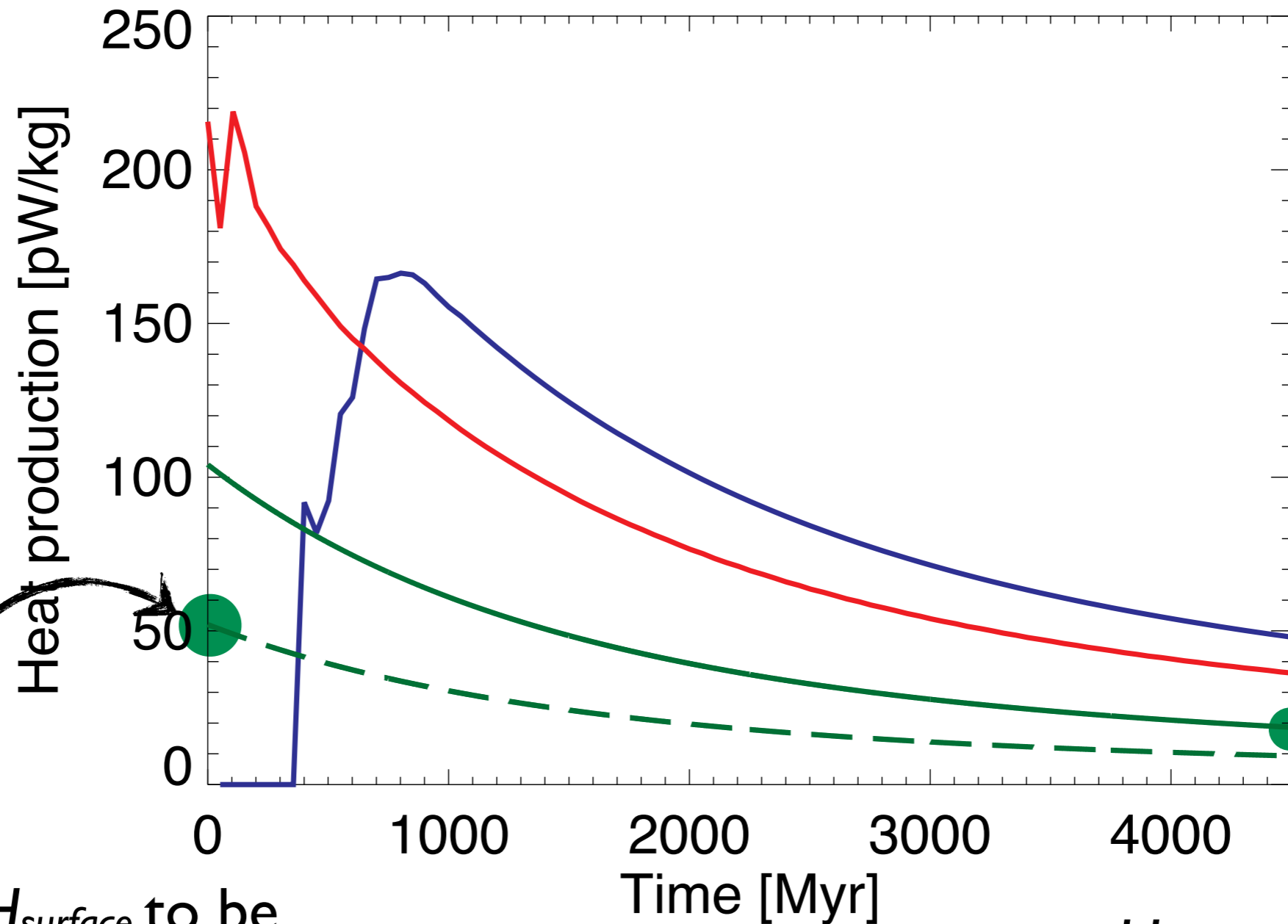
- Cold
- Hot with $k_{crust}=0.5 k_{mantle}$
- “Cold” initial conditions but a high concentration of heat sources allow convection to persist for ~ 2 Byr ...
- ... but produce a tiny amount of crust



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

Time evolution of the average
crustal heat production

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



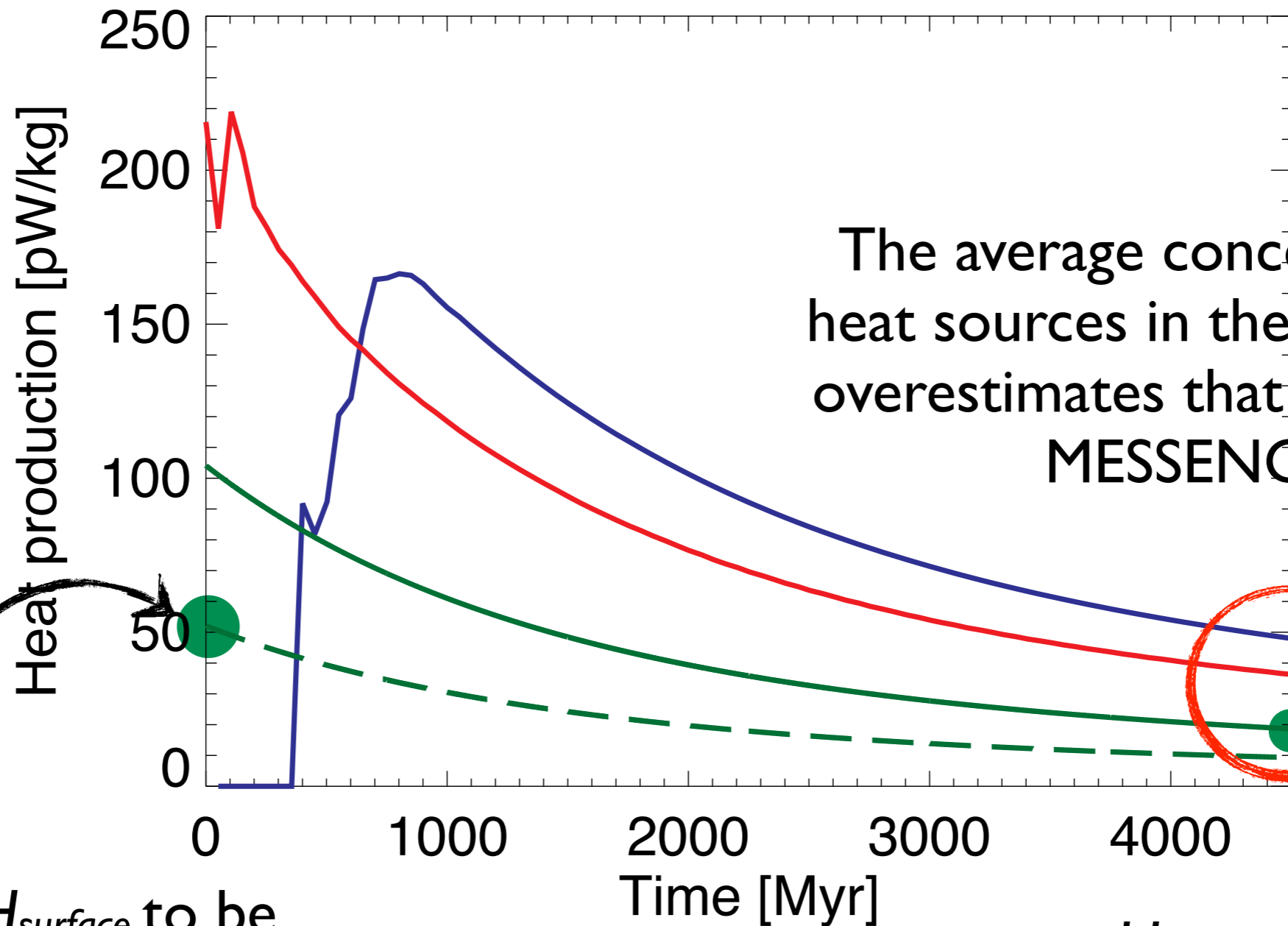
$H_0=50\% H_{surface}$ to be
partitioned between mantle
and primordial crust

$H_{surface}$ observed by
MESSENGER

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

Time evolution of the average crustal heat production

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

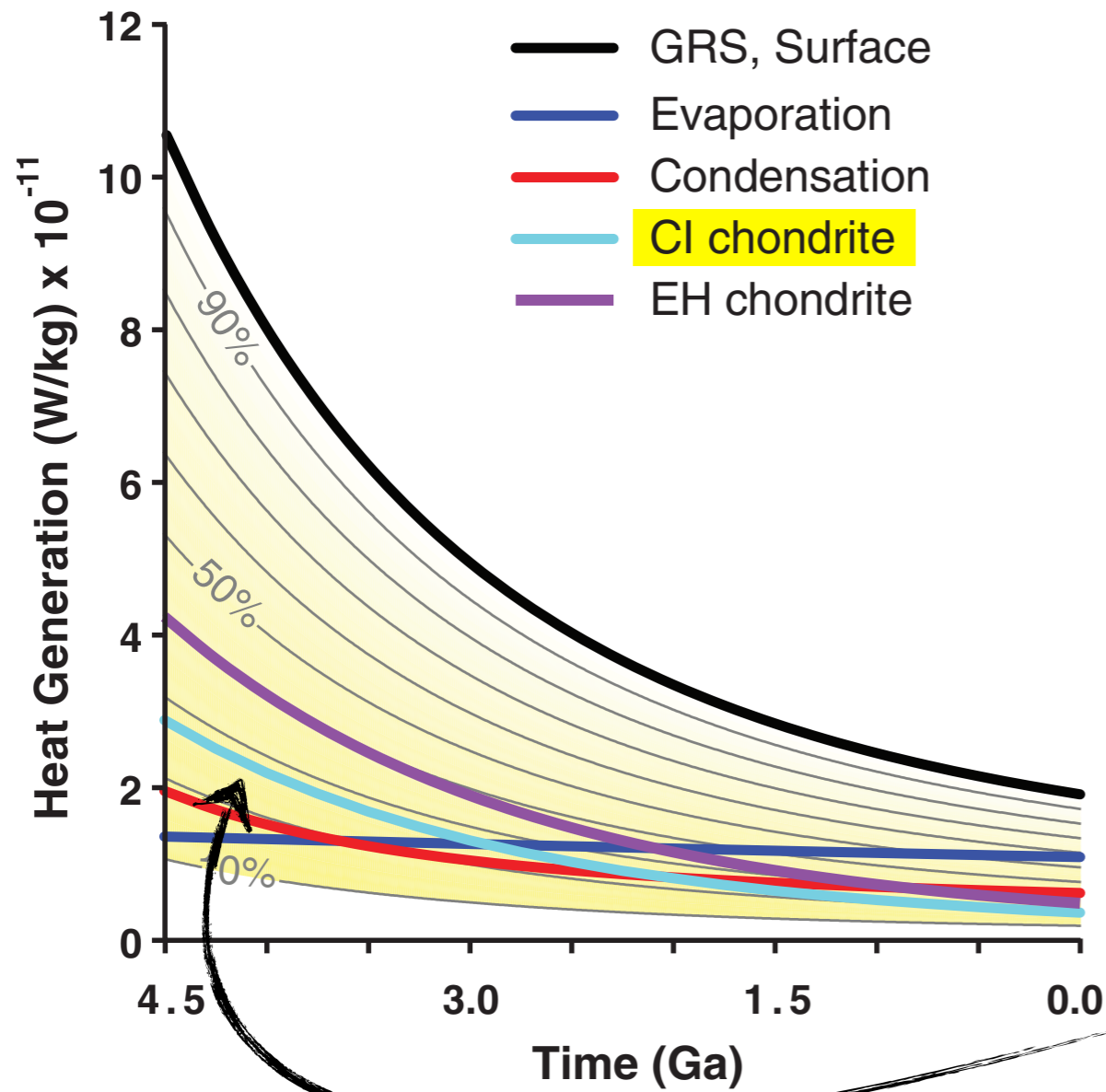


The average concentration of heat sources in the crust largely overestimates that observed by MESSENGER

$H_0=50\% H_{surface}$ to be partitioned between mantle and primordial crust

$H_{surface}$ observed by MESSENGER

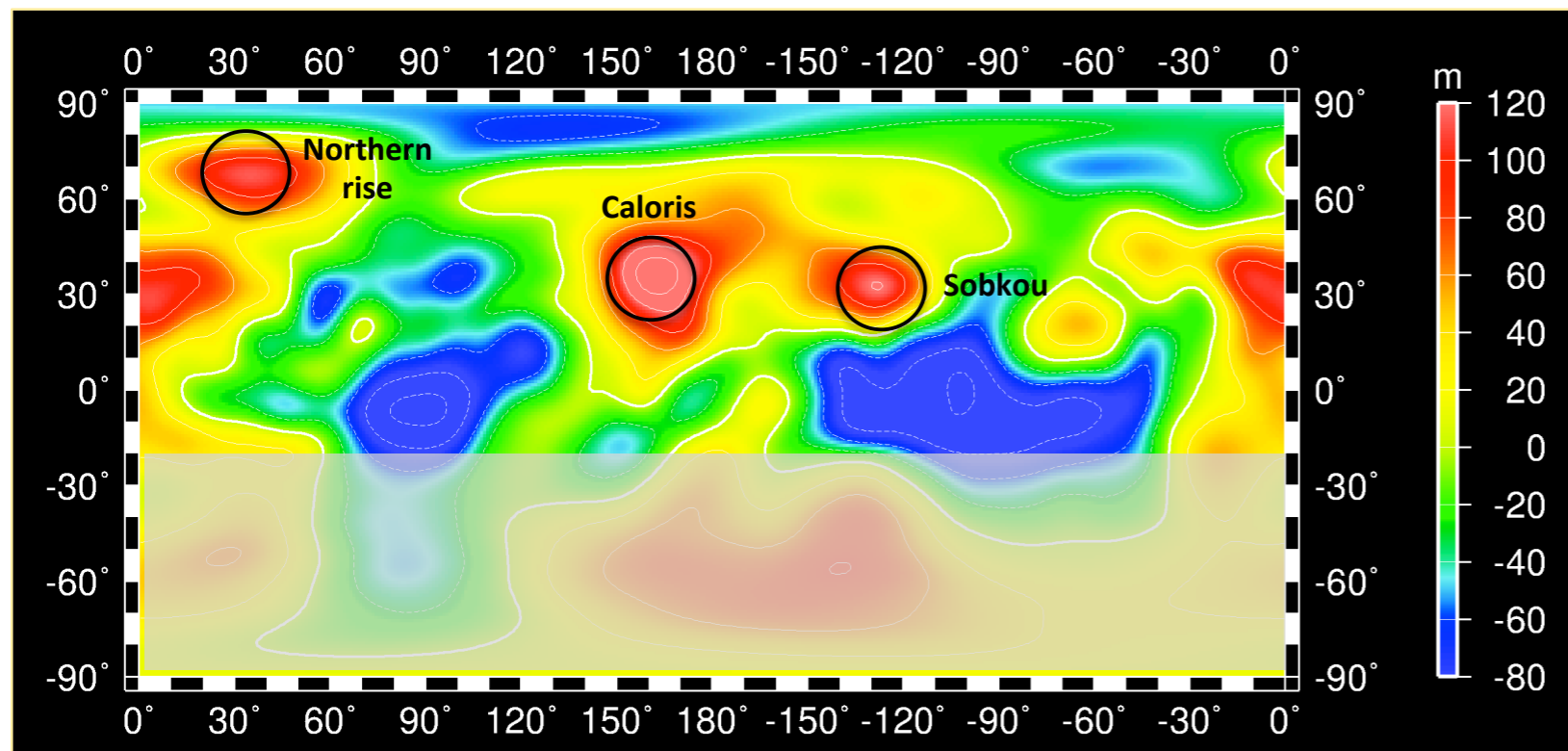
Quick summary



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

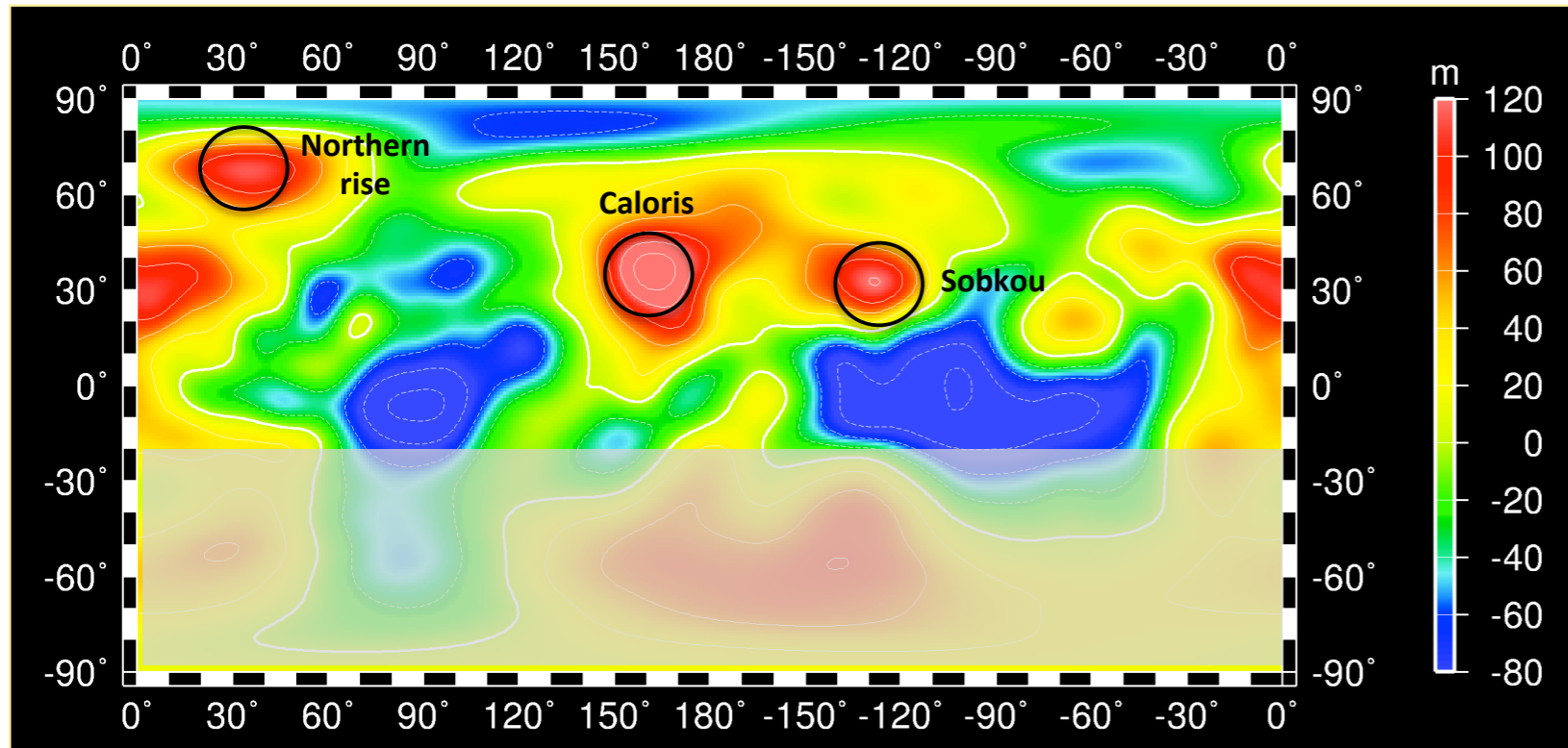
Dynamic geoid from 3D spherical models



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

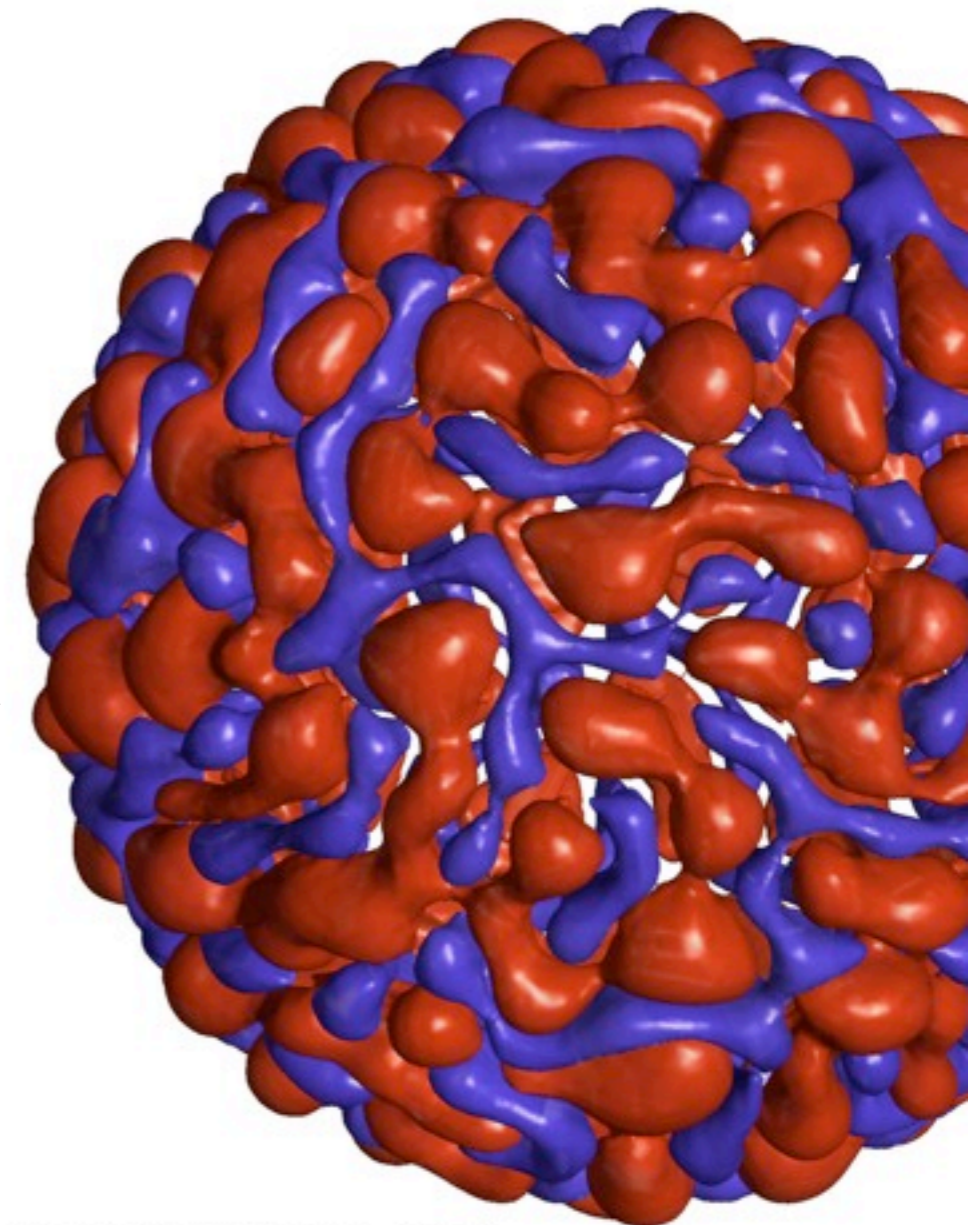
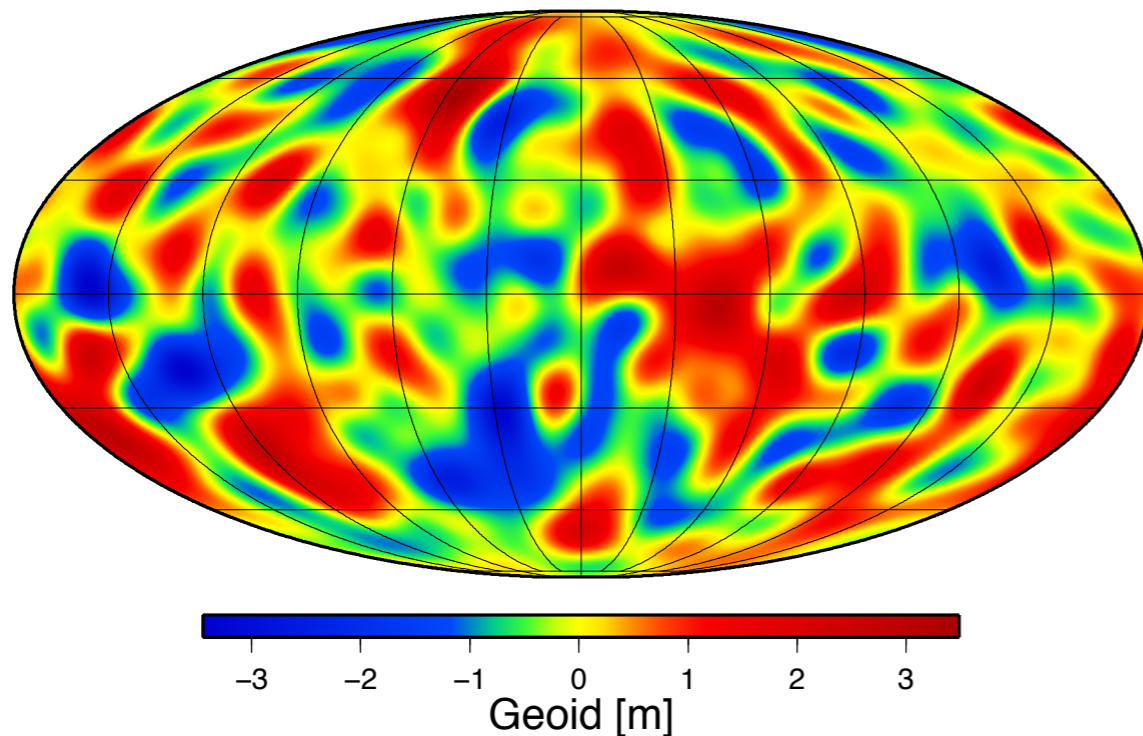
Smith et al. (2011)

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

