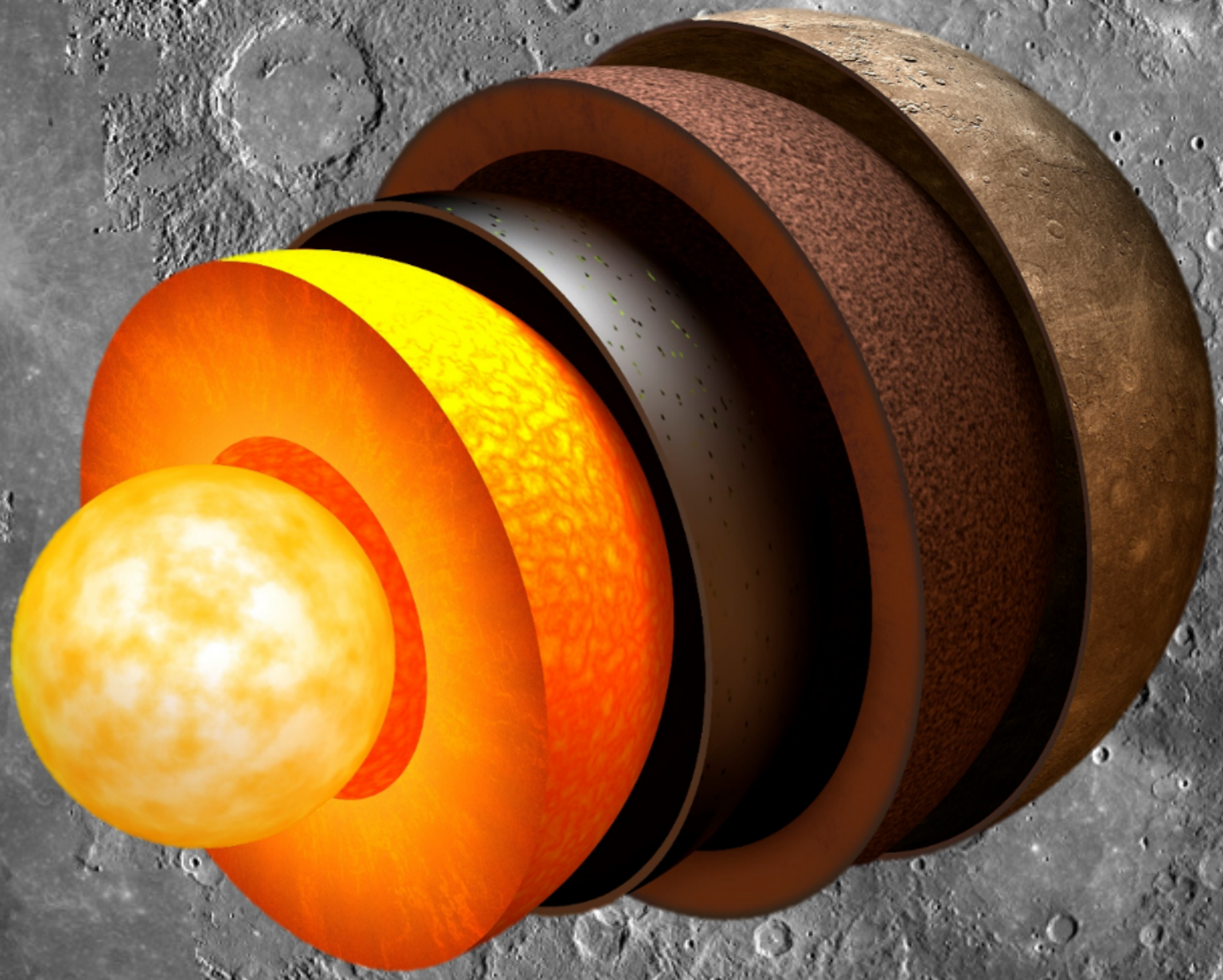
Effect of a thermally stratified layer in the outer core of Mercury on its internally generated magnetic field



ROYAL OBSERVATORY OF BELGIUM

KU LEUVEN

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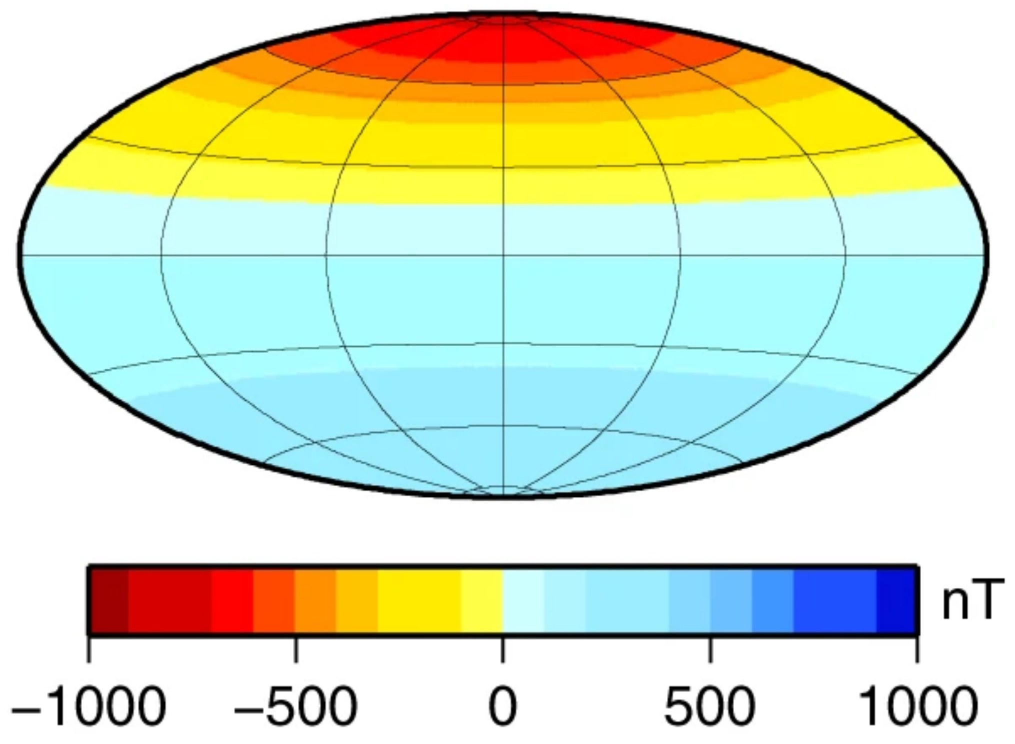
Scope

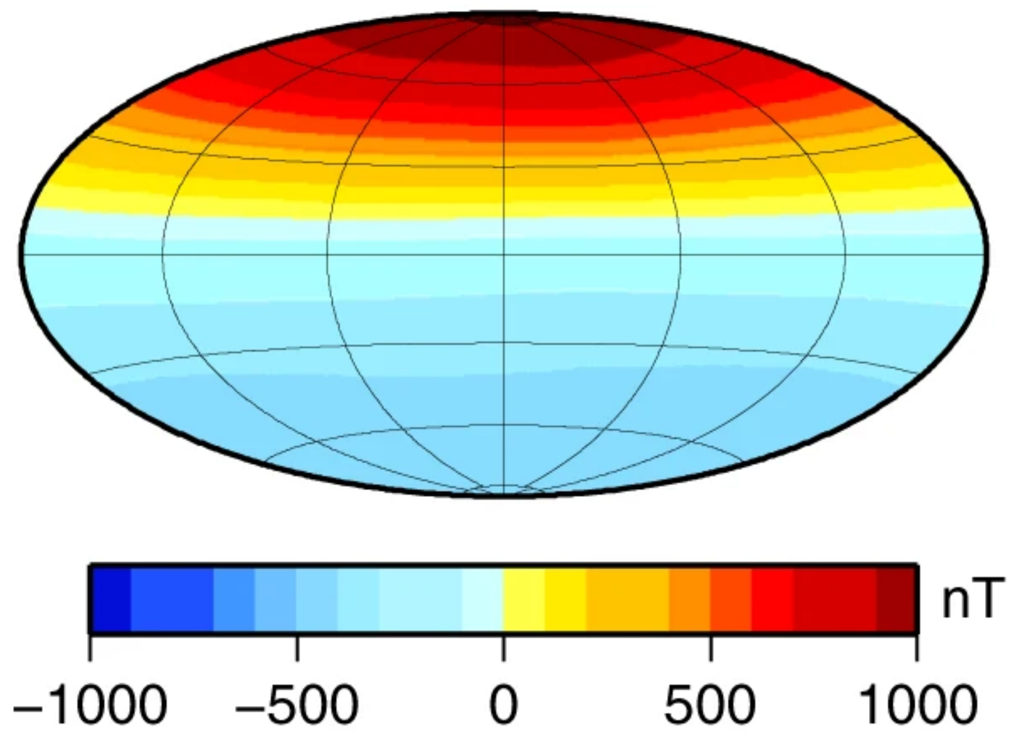
- dynamo: long lived (~3.9 Gyr), surprisingly weak dipole field, axisymmetric, equatorially asymmetric.. (e.g. Johnson 2015)
- dynamo models require a stratified layer to explain the observed magnetic field (e.g. Christensen 2006, Takahashi 2019)
- core-mantle boundary heat flow sub-adiabatic during thermal evolution favour presence of stratified layer (e.g Hauck 2006, Knibbe 2018 and 2021)
- reducing formation conditions imply that Si is the main light element in the core together with a smaller fraction of S or C (e.g. Namur 2016, Steenstra 2020)
    - unlike S, Si and C partition into the solid inner core

      ⇒ power available to drive the dynamo decreases with increasing Si and C

MESSENGER



Dynamo simulation



Takahashi 2019

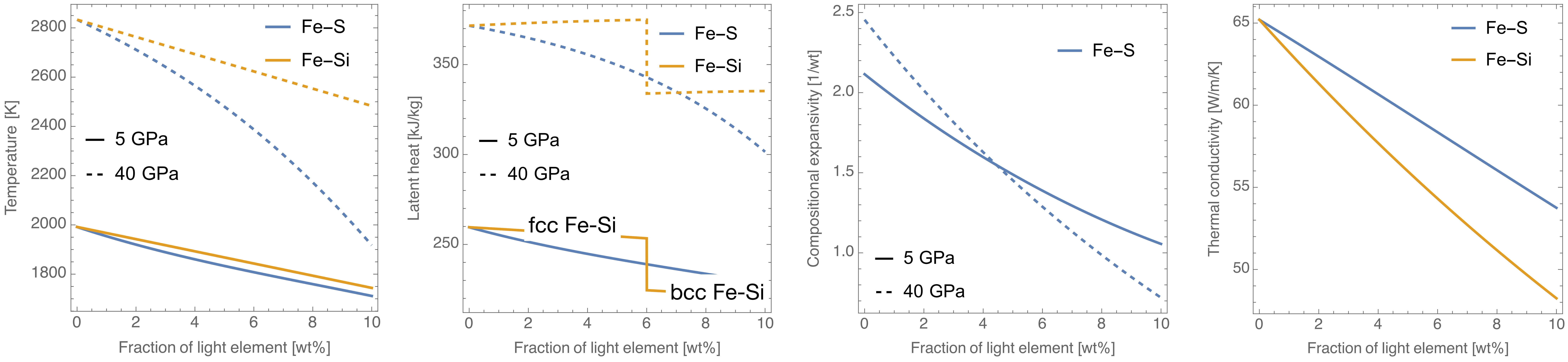
- the long-lived dynamo and the presence of a stable layer place important constraints on the interior structure and evolution of the core and planet
- and in particular on the inner core radius and core composition

This study

- Investigate the necessary conditions for a long-lived and present-day dynamo
- 1-D mantle model (Thiriet 2019) coupled to core thermal evolution model (Greenwood 2021) that takes into account the formation of a stably stratified layer in the core and evolving core material properties
  - scaling law parameters in mantle model are calibrated to agree with 2-D dynamic evolution models (core-mantle boundary and surface heat flow, mantle temperature profile, cessation of convection)
- interior structure models agree with geodesy data and use the most recent core material properties

Core thermodynamic and transport properties of Fe-S-Si alloy

- Thermodynamic propertied of liquid Fe-S-Si and solid fcc or bcc Fe-Si based on experimental results of Terasaki et al. 2019 and Edmund et al. 2022
- New core liquidus parameterisation based on existing Fe-S and new Fe-Si melting data (Edmund et al. 2022)
- Assume equipartition of Si between liquid and solid Fe and no partitioning of S in solid Fe
- Thermal conductivity calculated from electrical conductivity (Wagle et al 2019) using Wiedemann-Franz relation with Sommerfeld value for the Lorenz number

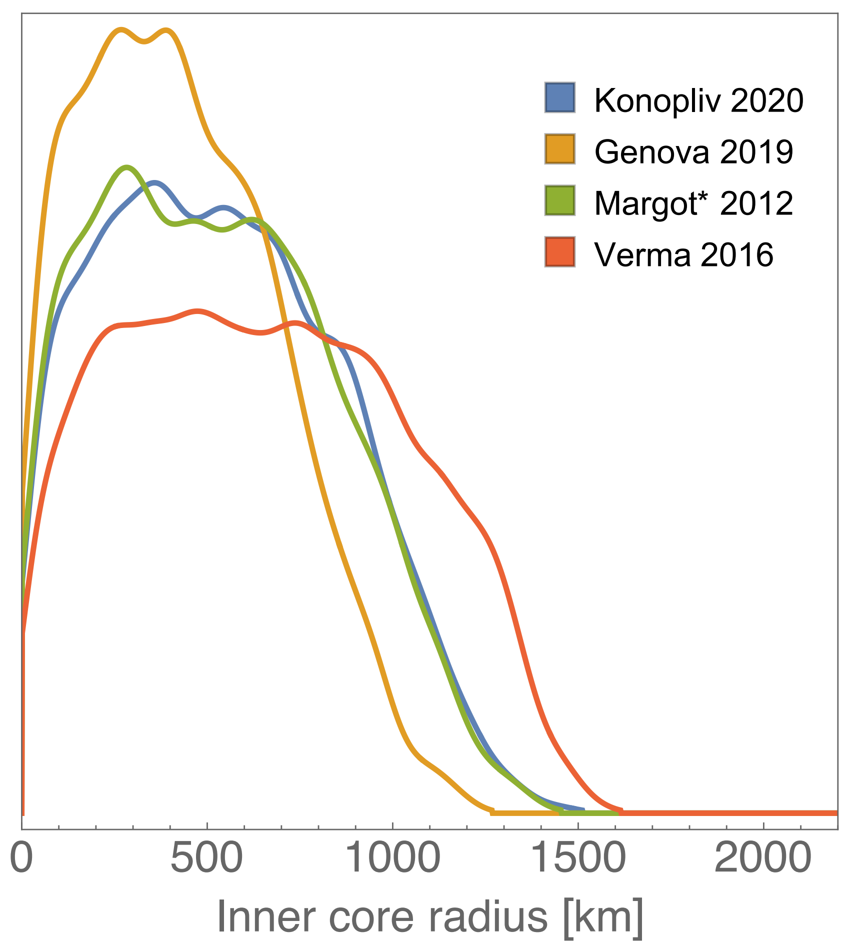


Prior constraints on the core

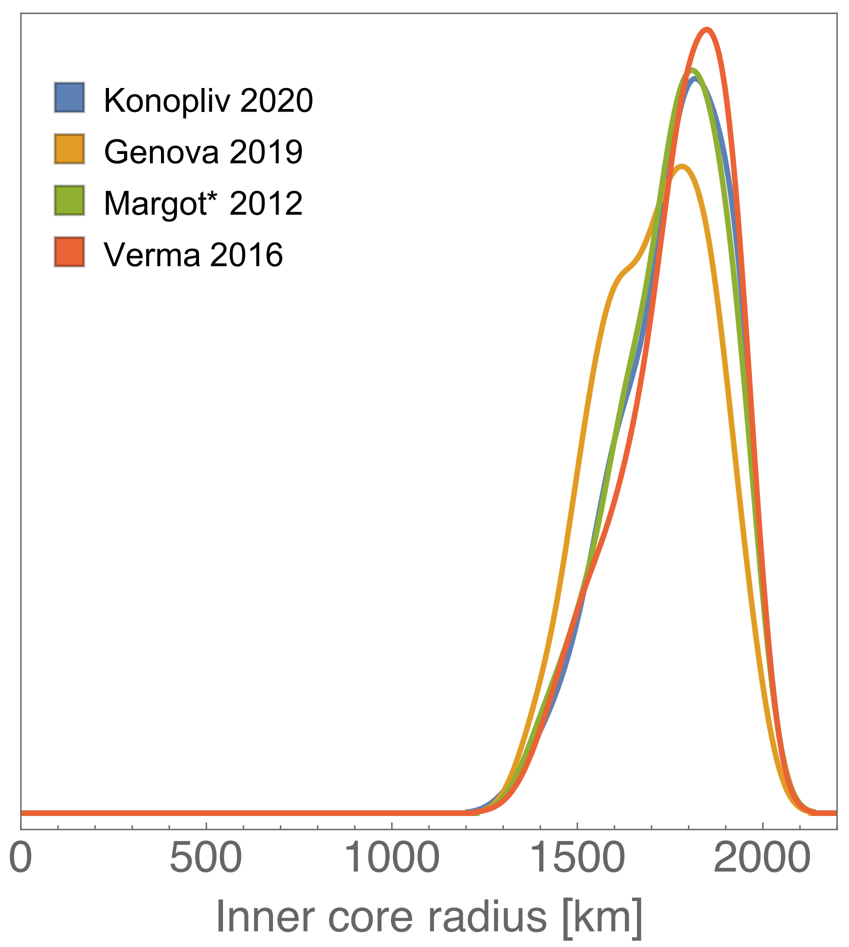
- core radius: 2000±50km
  (moment of inertia, libration amplitude, k_2)
  (e.g. Rivoldini 2019, Knibbe 2020, Steinbrügge 2020)

- inner core radius:
  Fe-S: 0-1500km and Fe-Si: 1300-2010km

Fe-S



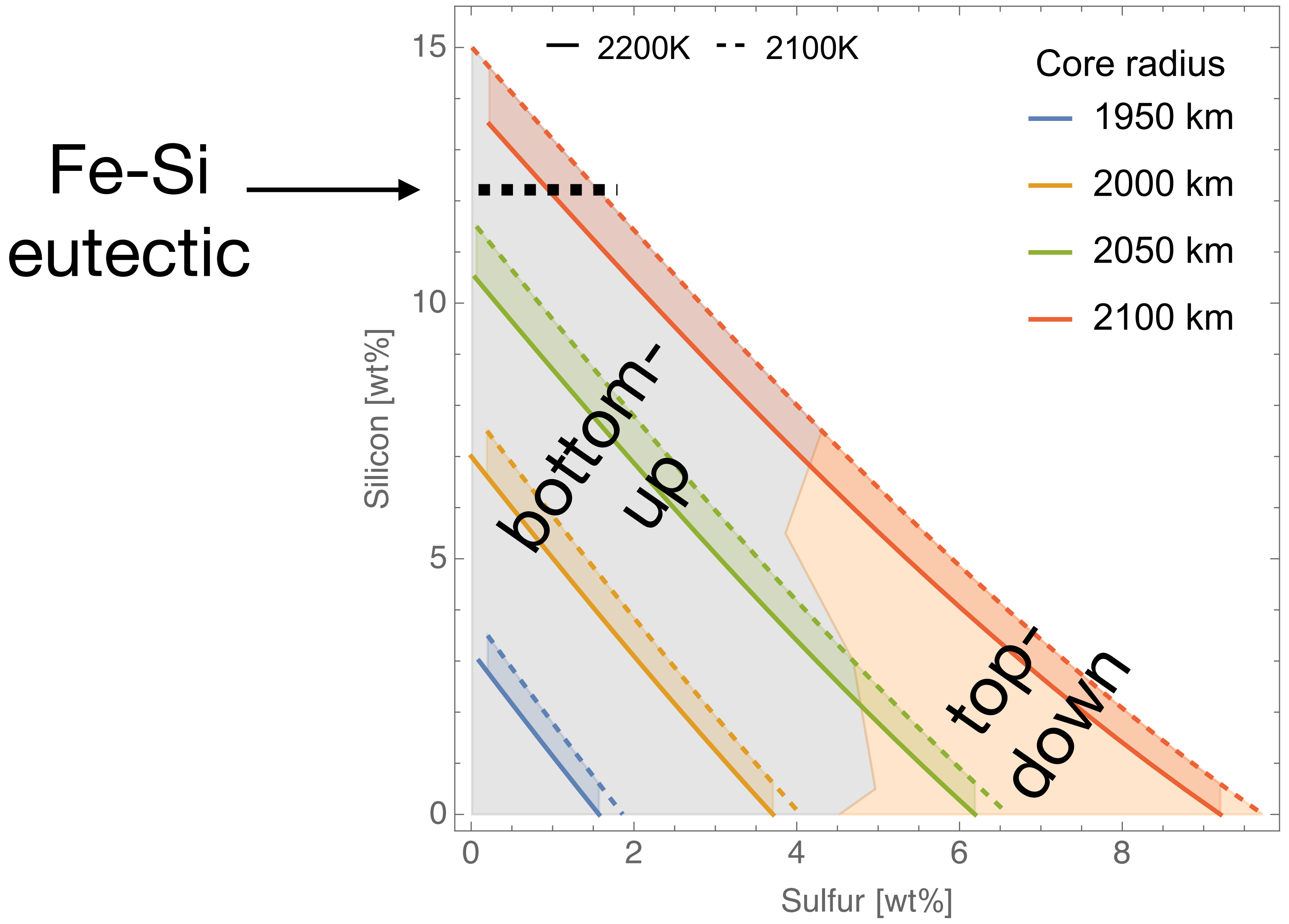
Fe-Si



Models without an inner core agree with geodesy data but are difficult to reconcile with the past and present core generated magnetic field

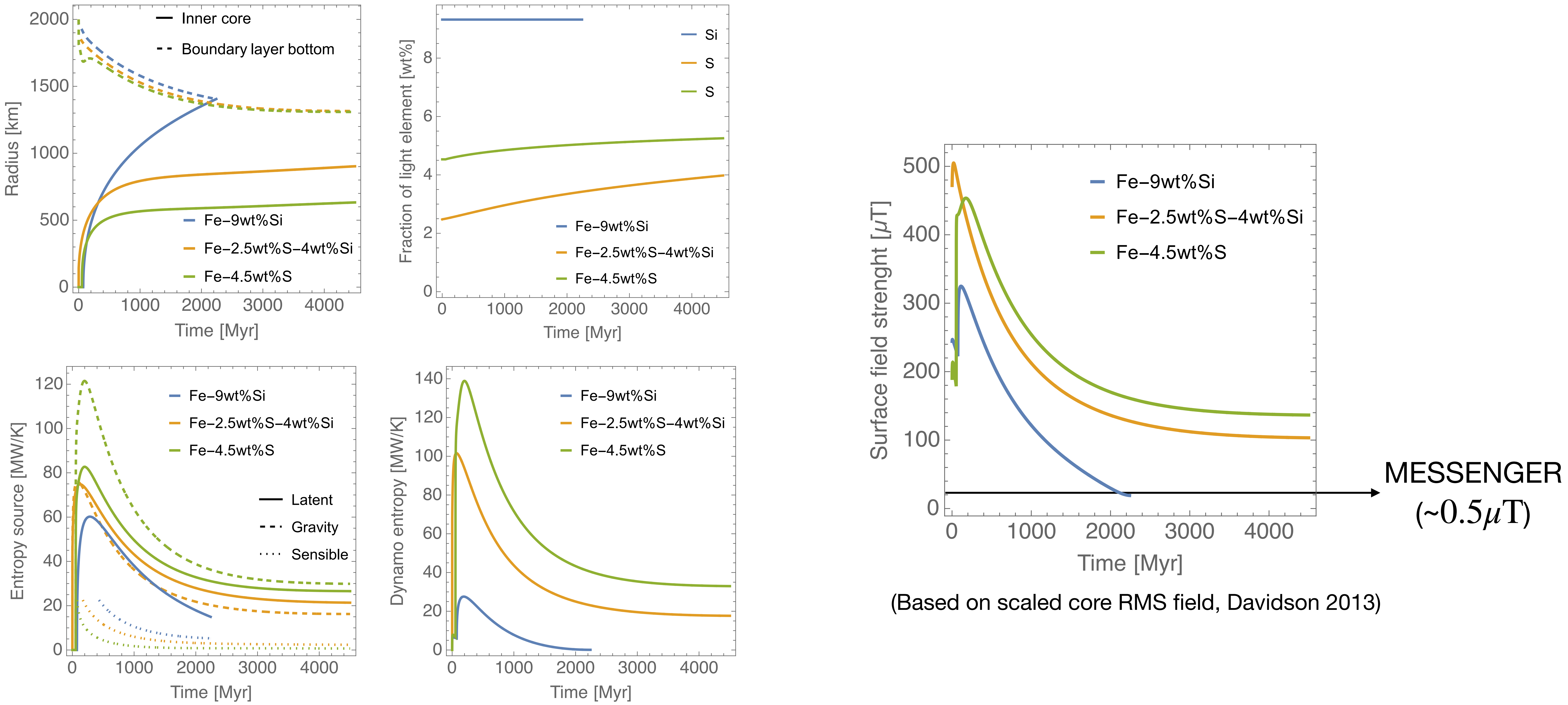
⇒ require bottom up inner core formation

Light element fraction after formation



Thermal evolution of the core alone

r_{cmb} = 2000 km, exponentially decreasing CMB heat flow to 10mW/m²

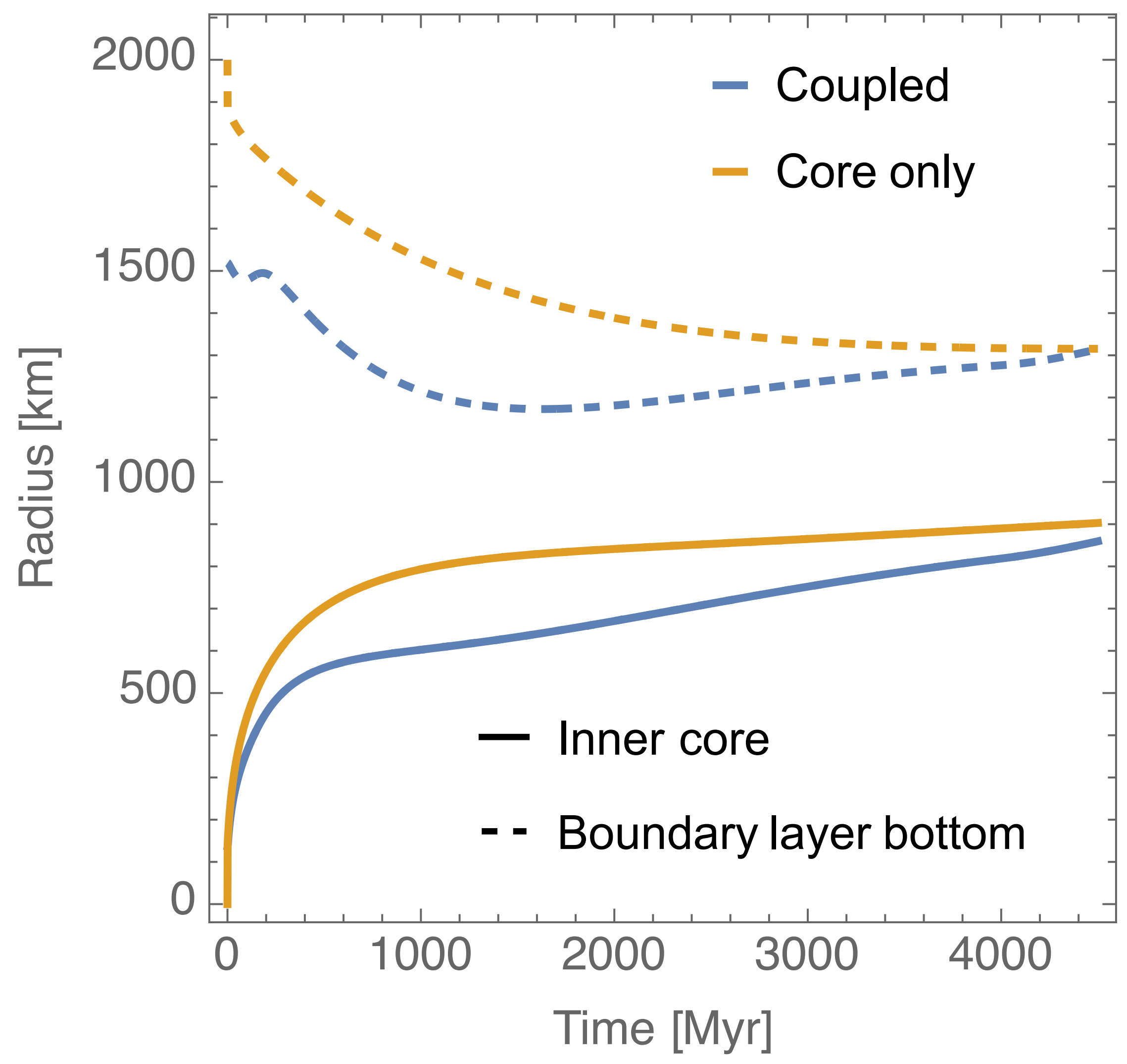


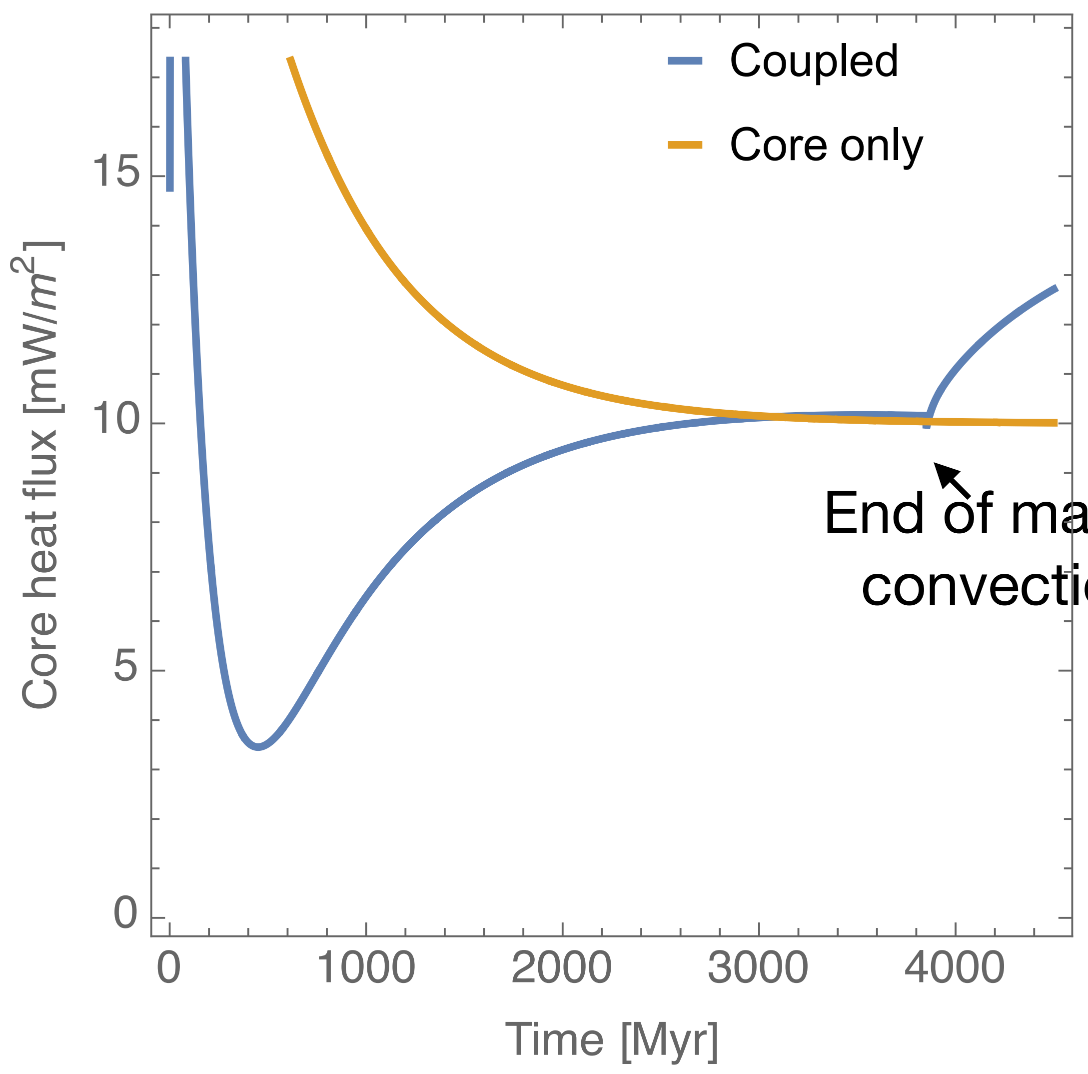
(Based on scaled core RMS field, Davidson 2013)

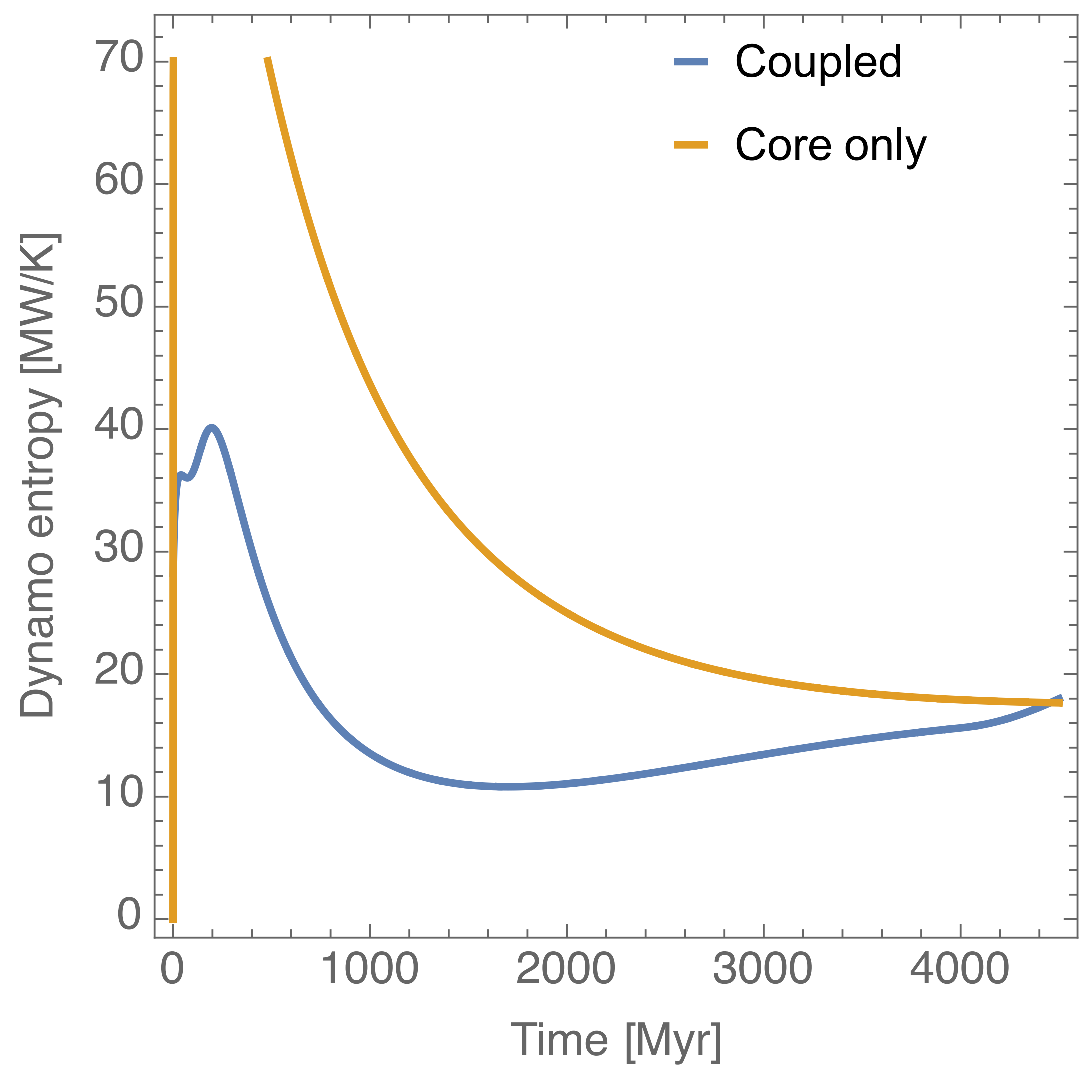
- Comparable boundary layer thickness because of comparable convective power
- Present day dynamo unlikely for models without S in the core

Thermal evolution of Mercury

r_{cmb} = 2000 km with Fe-2.5wt%S-4wt%Si







- Cessation of mantle convection increases CMB heat flow and promotes dynamo generation

- Ignoring the occurrence of stratification in the core leads to early cessation of convection in the mantle

Summary

- a stable layer in the core delays cessation of mantle convection and allows for a past and present-day dynamo
- present day dynamo is highly unlikely for Fe-Si models
- models with a small fraction of S have a present-day inner core of ~1000km, a ~600km thermal boundary layer, and generate sufficient ohmic dissipation to drive a past and present-day dynamo
- our results show that the cessation of mantle convection decreases the thickness of the thermally stratified layer and increases ohmic dissipation