Mercury’s Long-Term Interior Evolution

Part II: more than core 🙃, magnetic field evolution

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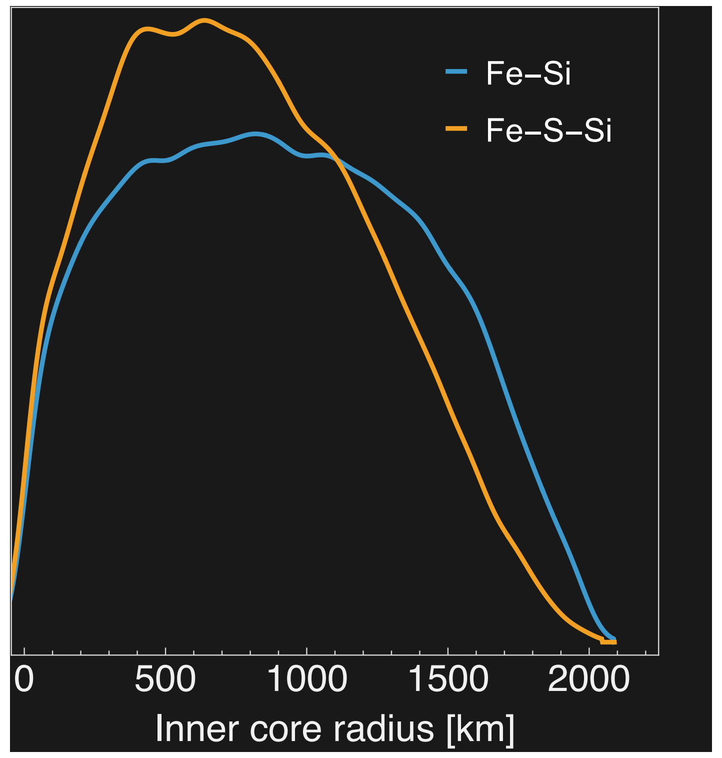
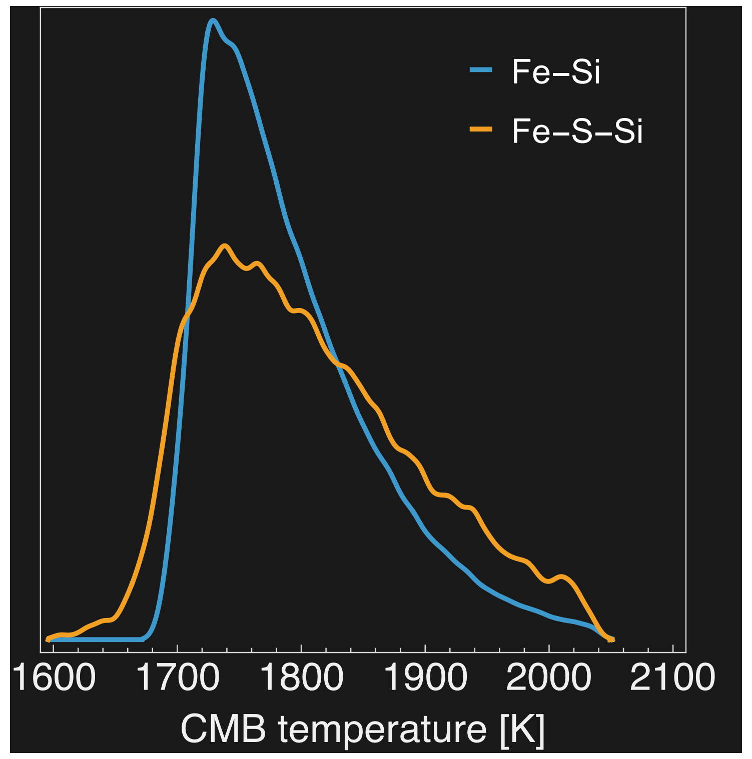
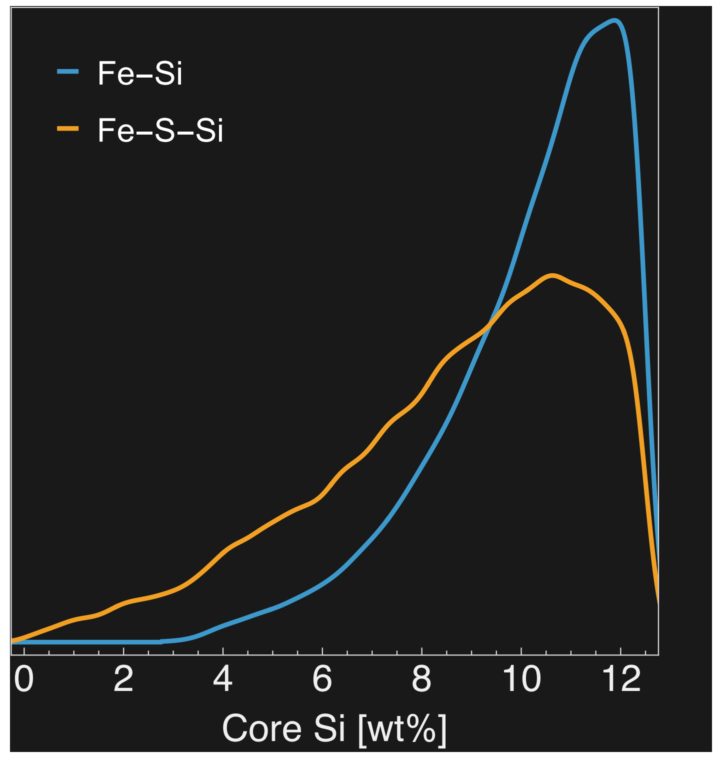
Motivation

- understand Mercury's present-day thermal state, evolution, dynamo field generation (use 1d parameterised evolution model → Nicolas talk from 28.05.25)

- use insights from thermal evolution and *desiderata* of successful numeric dynamo simulations to refine present-day interior structure inferences about the structure of the core







- data: libration amplitude, MOI, k_2

- can we devise plausible thermal evolution settings that agree with those findings?

Mercury dynamo features and numerical simulations

- dipole aligned with rotation axes, shifted by ~480 km northward
- weak dipole ~200 nT (Earth 29405 nT) and large quadrupole/dipole
- small scale and high frequency components of magnetic field are strongly attenuated ⇒ filtered out by thick upper core stable layer (skin effect)

(from Kolhey 2025)

Model setup					Magnetic field properties			
Convective driving	Inner core size	Stable layer? (Thickness)	Therm. Boundary condition at CMB	Imposed external magnetic field?	Weak magnetic field?	Axisymmetric field?	Persistent offset dipole field?	Reference
Single-diffusive/bottom driving	$a = 0.35$–0.60	Yes ($d_s = 0.56 - 0.7$)	Homogeneous (isothermal)	No	Yes	Yes	No	Christensen (2006), Christensen and Wicht (2008)
Double-diffusive/bottom driving	$a = 0.35$	Yes ($d_s = 0.36$–0.44)	Homogeneous (fixed heat flux)	No	No	No	No	Manglik et al. (2010)
Single-diffusive/bottom driving	$a = 0.34$	Yes (double snow layer)	Homogeneous (fixed heat flux)	No	Yes	Yes	No	Vilim et al. (2010)
Single-diffusive/bottom driving	$a = 0.35$	No	Homogeneous (isothermal)	Yes	Yes	Yes	No	Glassmeier et al. (2007), Heyner, Wicht, et al. (2011)
Single-diffusive/volumetric driving	$a = 0.2$	No	SH degree-2 heat flux pattern	No	No	Yes	Yes	Cao et al. (2014)
Single-diffusive/bottom driving	$a = 0.05$–0.50	Yes ($d_s = 0.31$–0.54)	SH degree-1 heat flux pattern	No	Yes	Yes	Yes	Tian et al. (2015)
Double-diffusive/therm. volumetric driving/ comp. bottom driving	$a = 0.2$	Yes ($d_s = 0.625$)	Homogeneous (fixed heat flux)	No	Yes	Yes	Yes	Takahashi et al. (2019), this study
Single-diffusive/bottom driving	$a = 0.2$	Yes ($d_s = 0.625$)	Homogeneous (fixed heat flux)	No	Yes	Yes	Yes	This study Kolhey

- thick upper core stable layer >~700 km and inner core ~400-1000 km
- degree 1 CMB heat flow pattern (reason ?)
- homogeneous CMB heat flow pattern, single diffusive bottom driving (latent heat, inner core cooling, no or very weak (?) gravitational power from light element release)
- homogeneous CMB heat flow pattern, double diffusive volumetric driving (without latent heat, no inner core cooling, possible??)

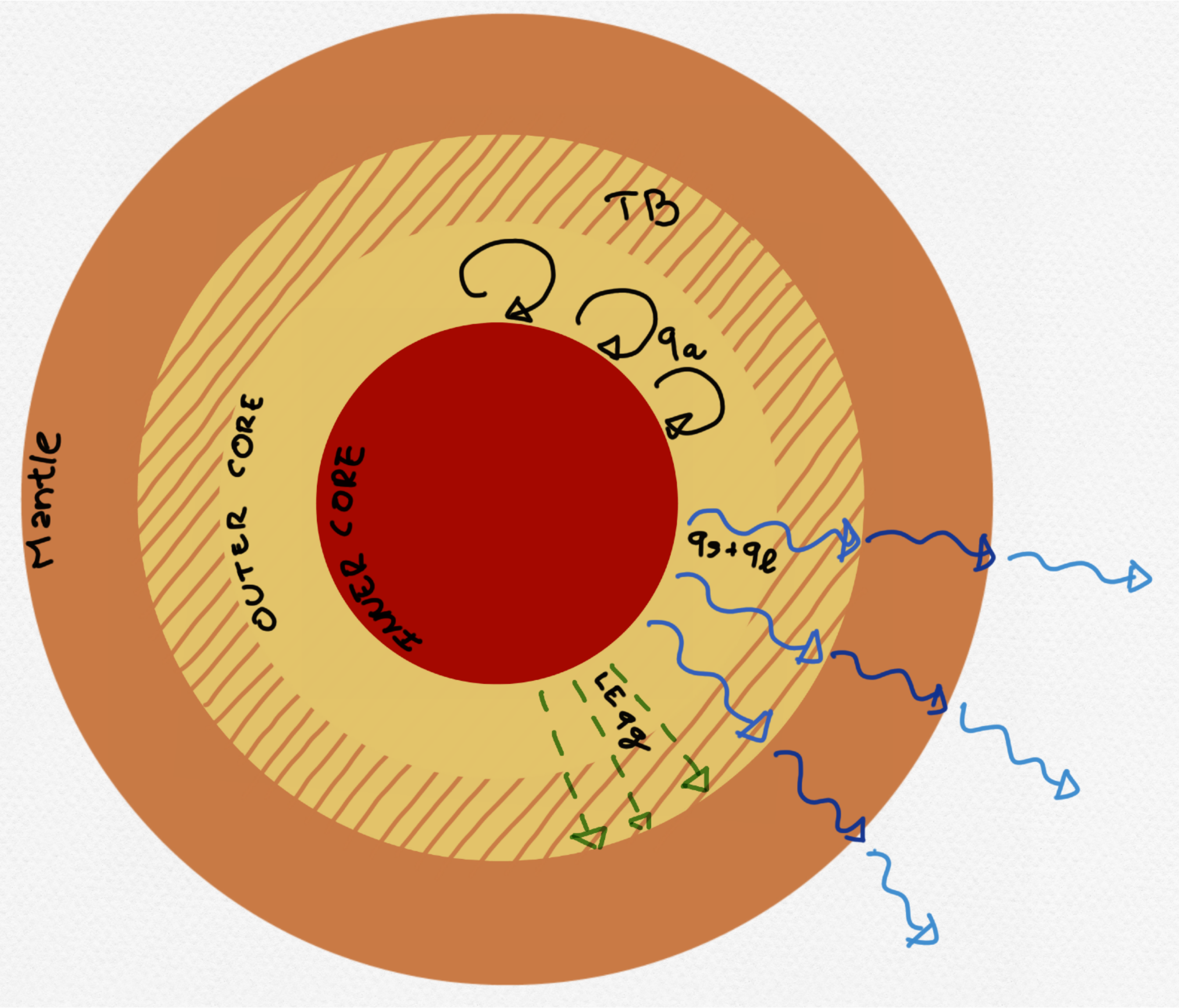
1D parameterised thermal evolution models with *dynamo action*

- based on heat balance consideration to model thermal evolution of core and mantle
- uses entropy balance to assess dynamo action in the core (allows to characterise ohmic dissipation within the core that is directly related to dynamo power) (e.g. Davies 2024) ⇒ difficult to relate to magnetic field strength at surface

  Dynamo power drivers:

  - core cooling (~mantle) ⇒ thermal conductivity, mantle viscosity, HPE, mantle melting, …
  - inner core freezing (latent heat at icb) ⇒ liquidus, light element identity (Si, S, C,..)
  - partitioning of light elements between solid and liquid core (gravitational energy, volumetric) light element identity:
    S (d~0, high) > C (d~0.3) > Si (d~1, low)

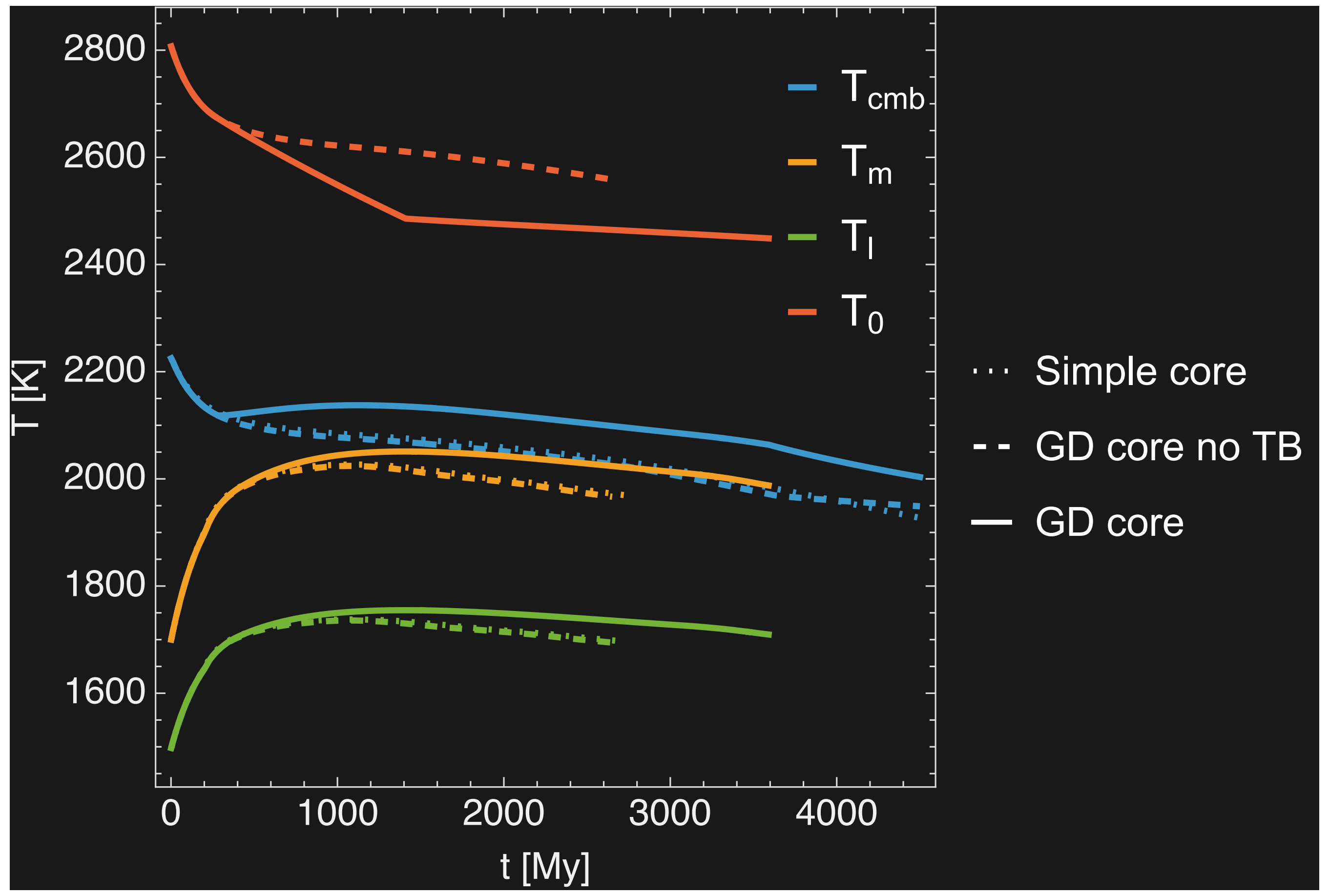
- employs thermodynamic and transport properties of the core and mantle
- persistent feature of parameterised thermal evolution models:
  cmb heat flow is sub-adiabatic in the core ⇒ modelling must account for sub-adiabatic cmb heat flow

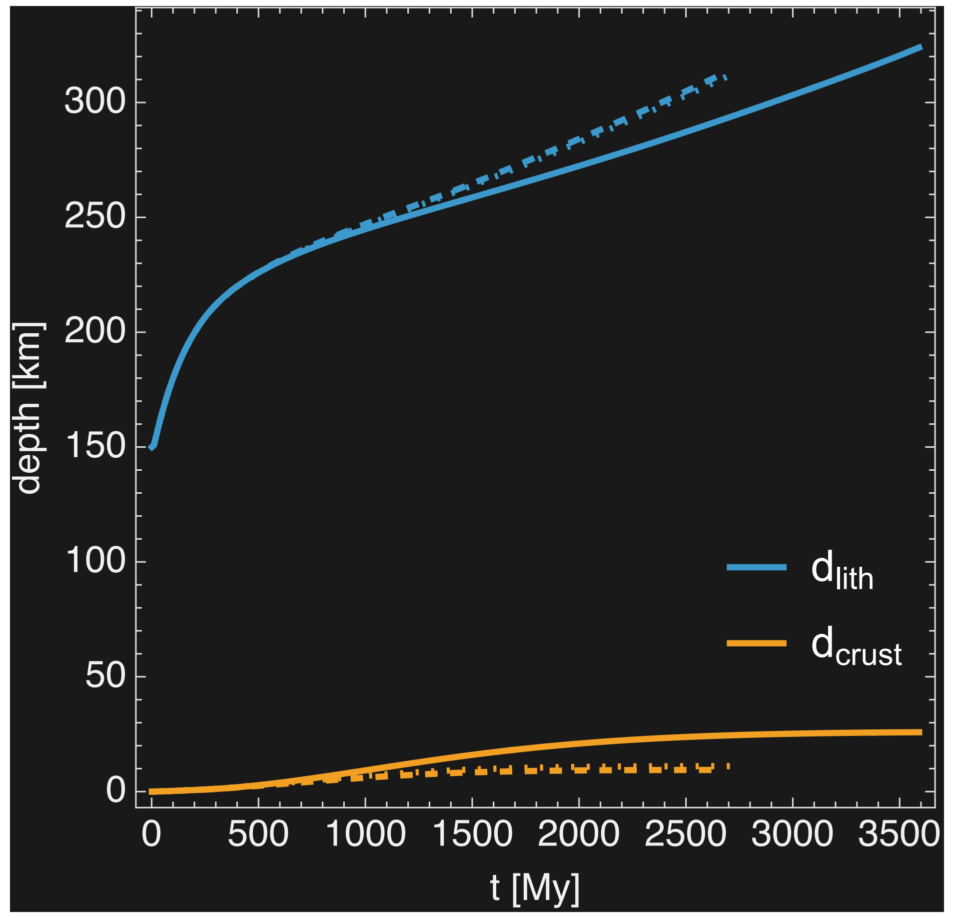


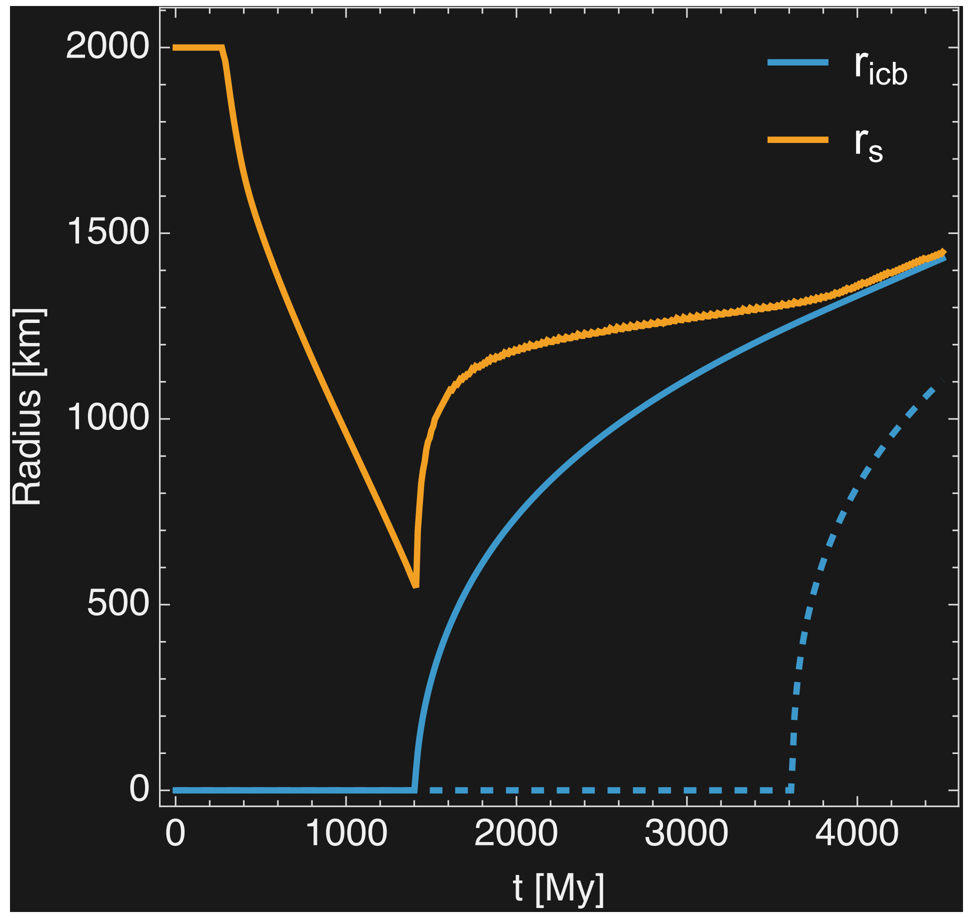
Effect of core on global thermal state

3 **cases** (all using Tempura 1d mantle code, Baumeister+2023)

- neglect detailed core structure (no inner core growing, only secular cooling)
- GD (Greenwood+Davies 2021) no TB: inner core cooling, latent heat release, secular cooling (assume outer core is adiabatic irrespective of CMB heat flow) https://github.com/sam-greenwood/thermal_history + coupled to interior structure model and uses structure dependent material properties (core+mantle)
- GD: like above but stable thermal layer forms if the heat flow at CMB is sub-adiabatic







- simple core and core model without TB lead to very similar thermal evolution (mantle stops convecting: 2.7 Gy, 2.6 Gy)
- with TB
  - thick thermal boundary layer
  - core and mantle cool slower, mantle convection runs longer (3.6 Gy)
  - centre core temperature drops faster inner core nucleation occurs much earlier (~2 Gy)

Neglecting occurrence of thermal boundary layer ⇒ strong bias on planet thermal evolution

Recent relevant studies

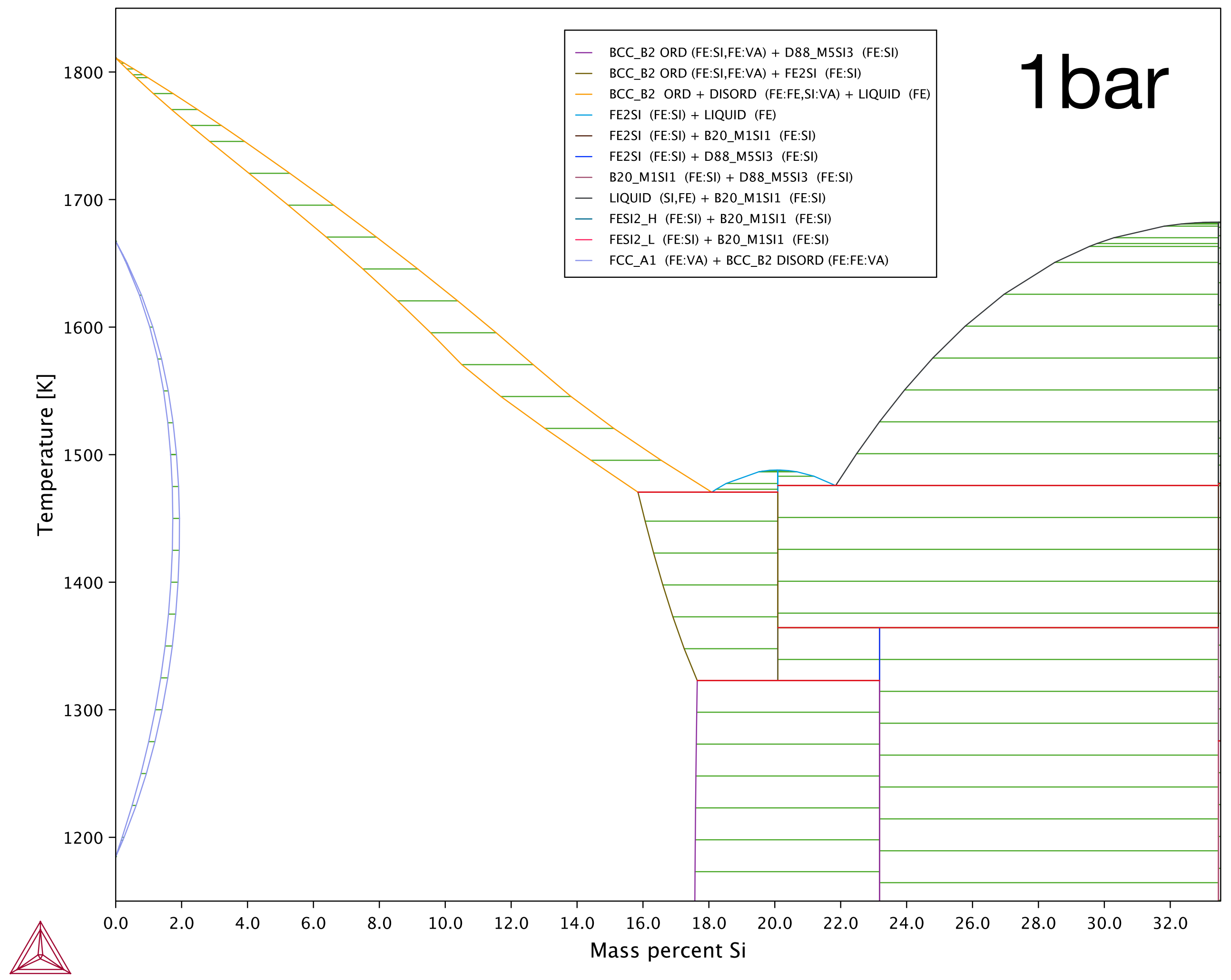
- Kolhey 2025: **Dynamo Models With a Mercury-Like Magnetic Offset Dipole** (present-day dynamic dynamo simulation)
  ⇒ successful models (present-day dynamo, magnetic field features, ..) r_{icb}~400 km, d_s~750 km, driven by latent heat released at the icb (negligible gravitational power?)

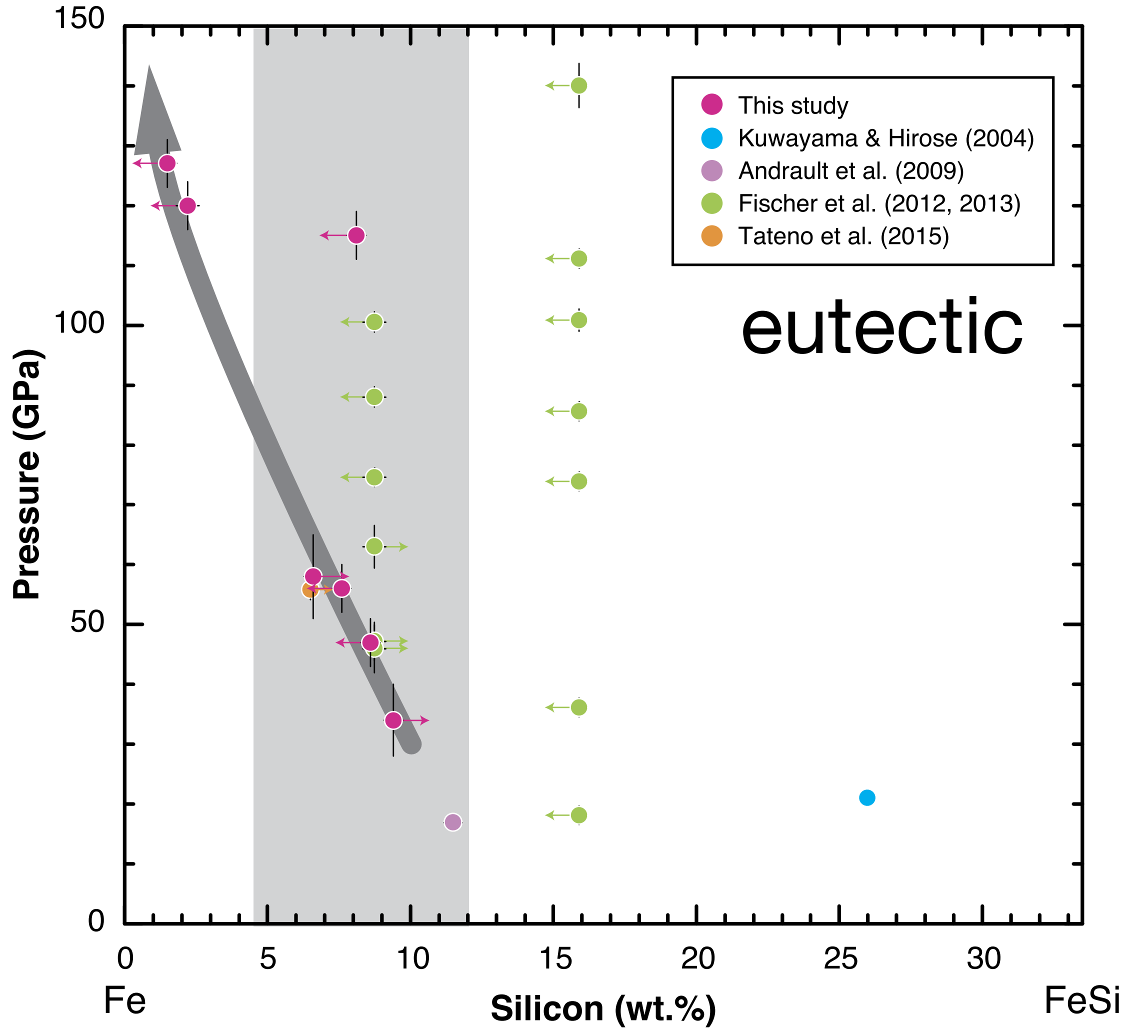
- Davies 2024: **Thermal and magnetic evolution of Mercury with a layered Fe-Si(-S) core** (thermal evolution+entropy balance)
  ⇒ successful models (dynamo lifetime, crust volume, contraction) require Si>15wt%! (d=1), r_{icb}~1200 km, d_s~600 km

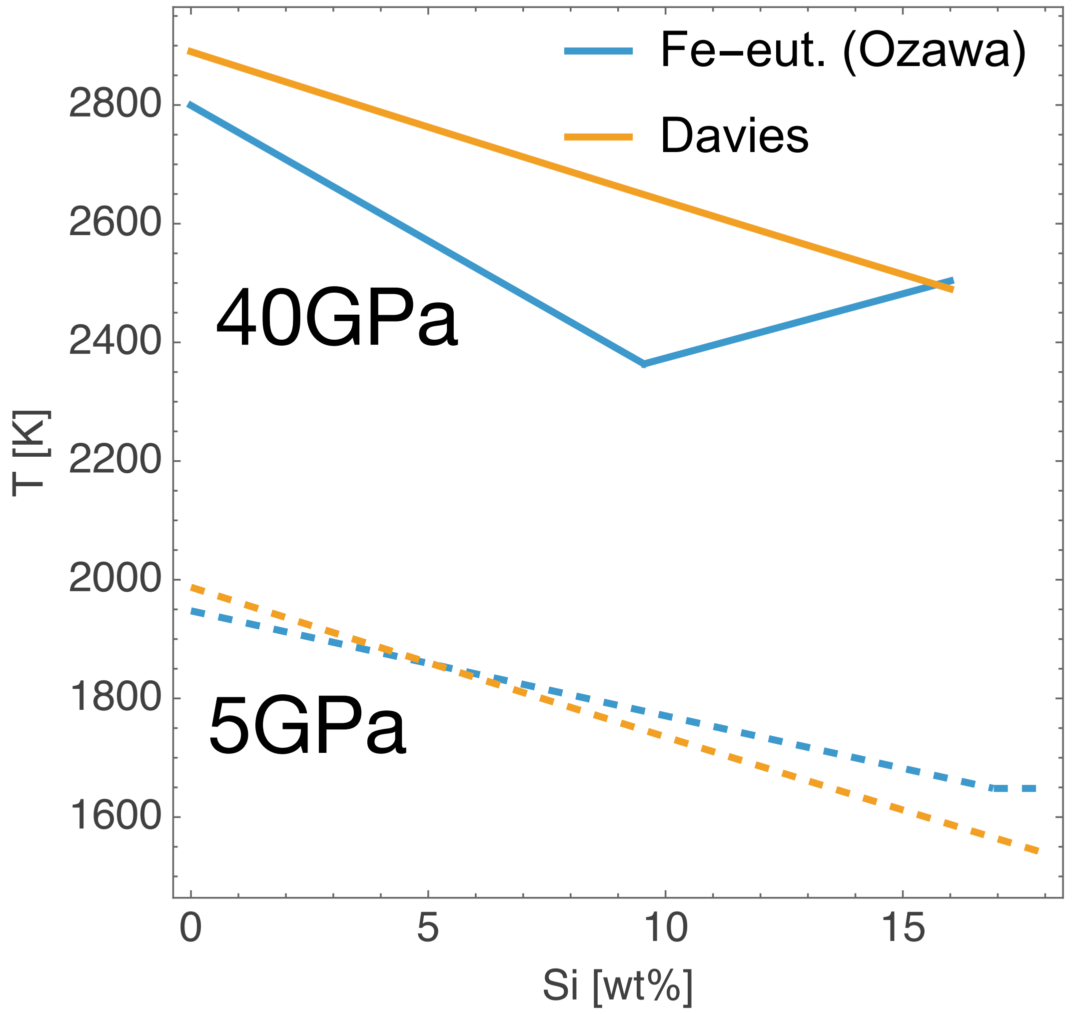
- Knibbe 2025: **On the thermal evolution and magnetic field generation of planet Mercury** (thermal evolution+entropy balance)
  ⇒ successful models (dynamo lifetime, ..) require other light elements (S, C) together with Si (d<1) (Si effect on liquidus too small), r_{icb}~900-1300 km, d_s~600 km,..

Reason for successful Fe-Si dynamo models in Davies 2024

- assumes latent heat that is ~1.7 times larger than informed estimates based on Fe-Si thermodynamic properties
- different thermal conductivity parameterisation (somewhat at odds with several experimental results)
- Si ≳15wt% (r_{cmb}=2036 km)
- liquidus parameterisation of Fe-Si (much higher in core centre, ignores occurrence of eutectic (<12wt% at 40 GPa), i.e. melting temperature decreases with increasing Si)





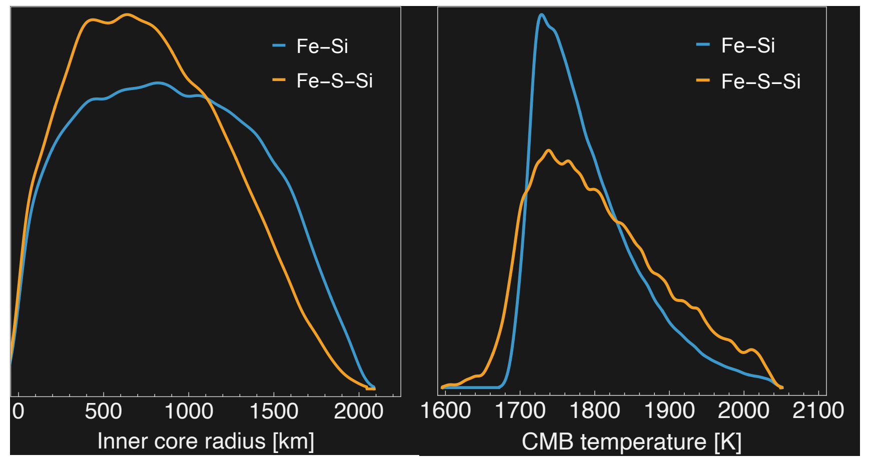


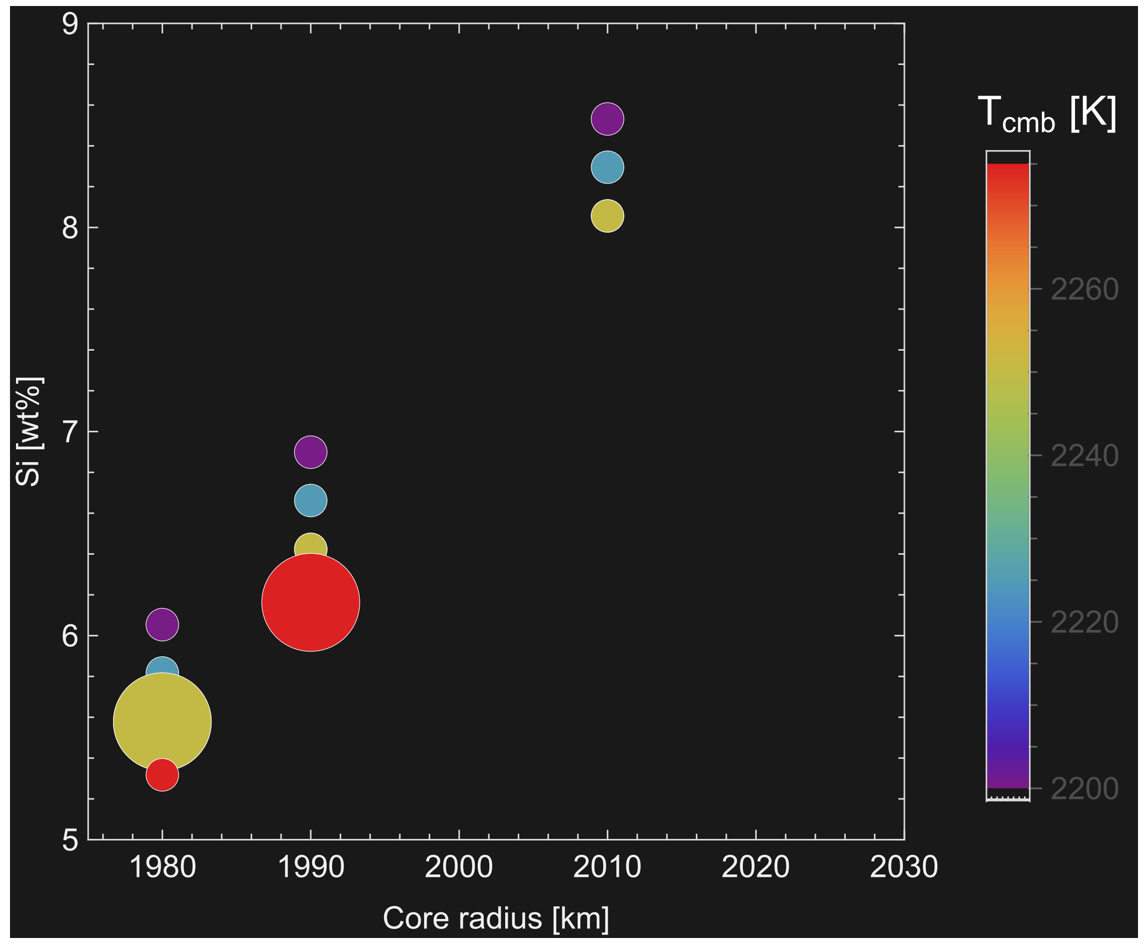
- Si>eutectic liquidus increases with Si and liquidus phase Fe-Si compound not bcc $Fe_{(1-x)}Si_x$
- solid liquid phase possibly less dense than liquid ⇒ up-floating Fe-Si compound ??

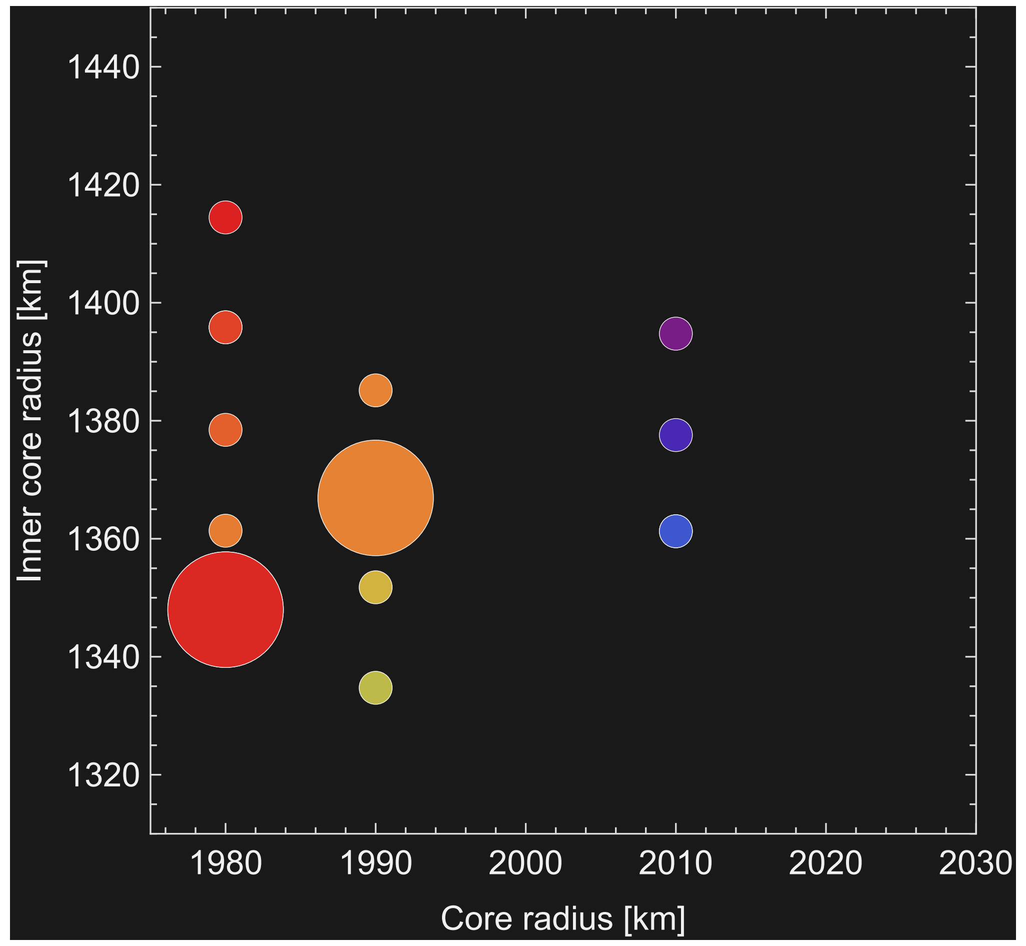
Parameter exploration study: Fe-Si

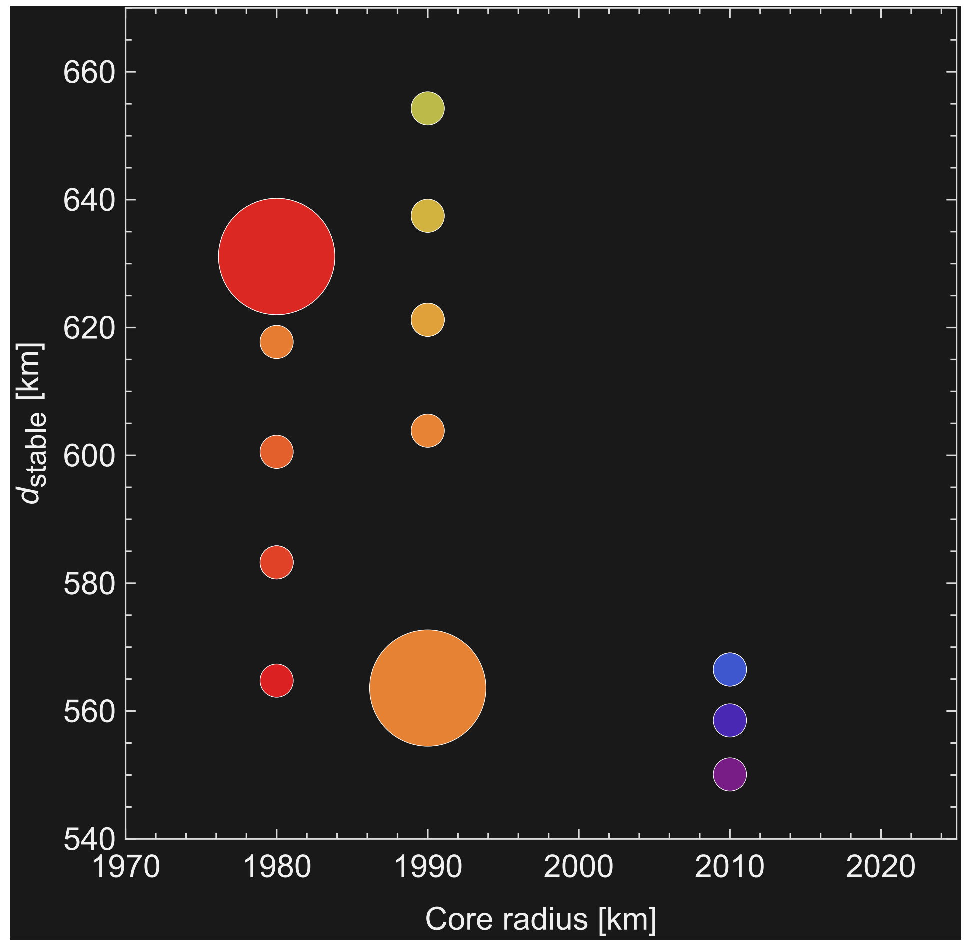
r_{cmb}=[1980,2030] km, T_{cmb}=[1900,2275] K, log(η/1Pa s)=[19.5,23]

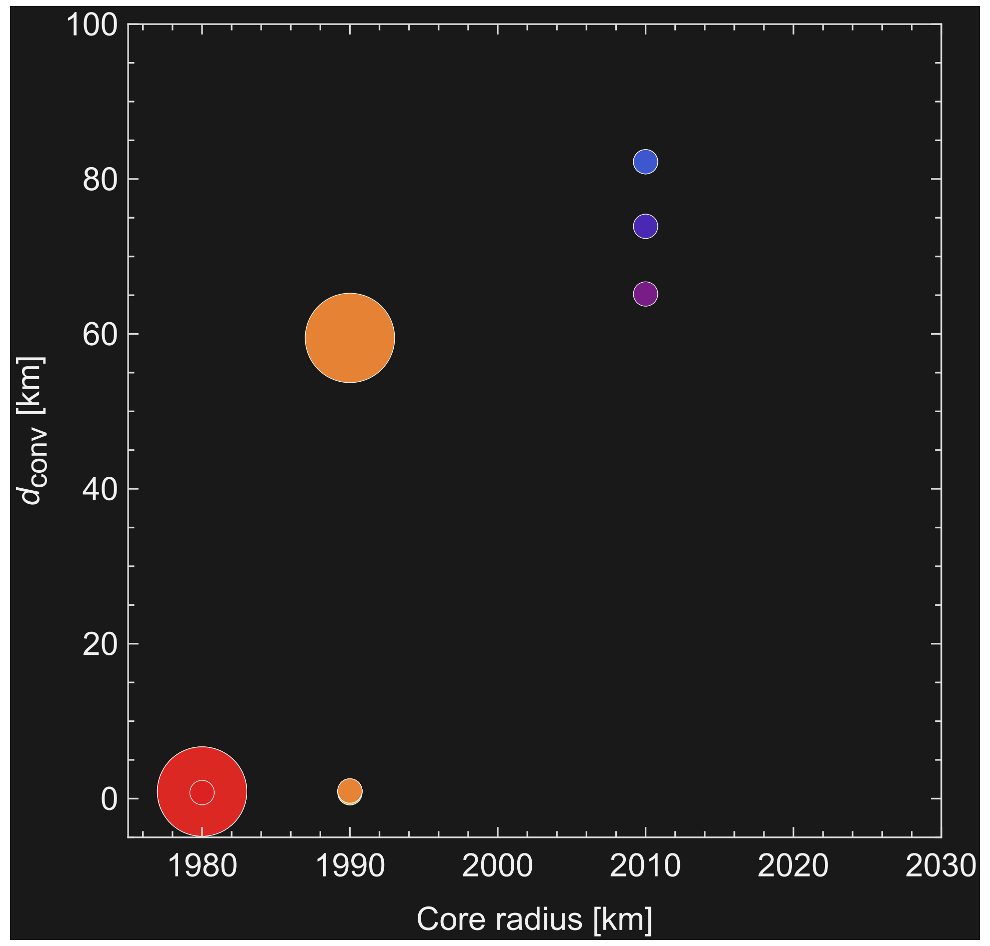
- runs on core cooling and latent heat agrees with Fe-Si phase diagram (Si≲eutectic), thermodynamic properties of mantle and core are (p,T), composition, and parameter dependent
- successful models (past and present-day dynamo, entropy>1MW/K) have
    - core radius: 1980-2010 km ; $T_{cmb,t=0}$: 2200-2275 K; ref. viscosity: $10^{22.5}$ -10^{23} Pa s
    - crust thickness: 18-50km, lithosphere thickness 310-345km
    - Si:5-9wt%, inner core radius: 1335-1430 km, thermal boundary thickness: 550-655km, convective layer thickness: 1-85 km, core cooling: 135-260 K
- inner core larger than “dynamo” model range: 400-1000 km (Kolhey 2025)
- entropy available to drive the dynamo ≲3 MW/K early dynamo ≲1 MW/K ⇒ likely challenging to explain early dynamo
- not yet explored: mantle HPE, solidus/liquidus parameterisation, mantle composition, other light elements in the core











Summary

- thermal evolution results that agree with the occurrence of a past and present dynamo can significantly reduce the set of geodesy compatible Mercury models (inner core radius, mantle thermal state, core composition, …)

- other light elements together with Si are vey likely required to explain past and present-day dynamo action

- result lean heavily on thermodynamic and transport properties (core alloy melting entropy, …)