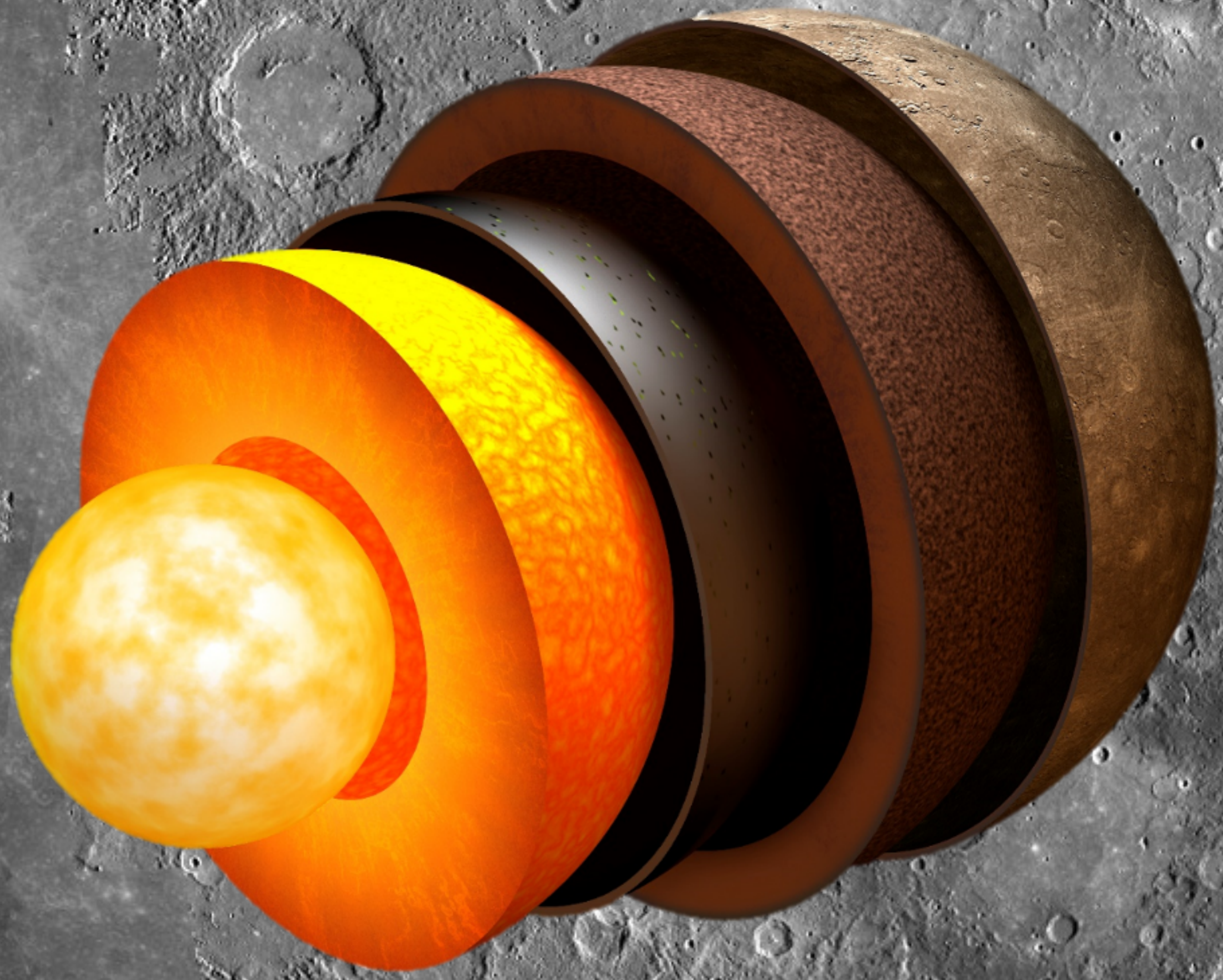
Geodesy constraints on the interior structure of Mercury



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Some of the main scientific questions related to the deep interior of Mercury BepiColombo aims to answer and relation to main mission objectives

- Scientific questions:
  - What is the size, density and physical state (liquid, solid) of the core?
  - What is the relative amount of volatiles in the core?
  - What is the present-day thermal state to the interior (reason for dynamo action)?
  - What is the structure and rheology of the mantle?
- Mission objectives:
  - Geodesy: gravity field, tidal Love numbers (h_2, k_2), forced longitudinal libration, obliquity
  - magnetic field
  - surface imaging and spectra

Current interior structure constraints

- Geodesy (mainly MESSENGER)
  - mean density, crust thickness+density (gravity field+topography)
  - libration amplitude and time series, obliquity, tidal Love numbers, mantle quality factor

  ⇒ iron-rich partially fluid core, core radius (~2000 km), inner-core??, mantle soft ??

- surface spectra+formation conditions ⇒ highly reducing formation conditions
  - mantle: FeO poor, enstatite rich (e.g. Boujibar+ 2025) ~12 wt%S (e.g. Malavergne+ 2014), graphite? (e.g. Lark+ 2023, Xu+ 2024)
  - core: Fe+Si+S+C+P?+.. (e.g. Namur+ 2016, Steenstra+ 2020)
- thermal state: radial contraction ≲7 km, effusive volcanism ≲3.5Ga, dynamo action ≳4Ga and today

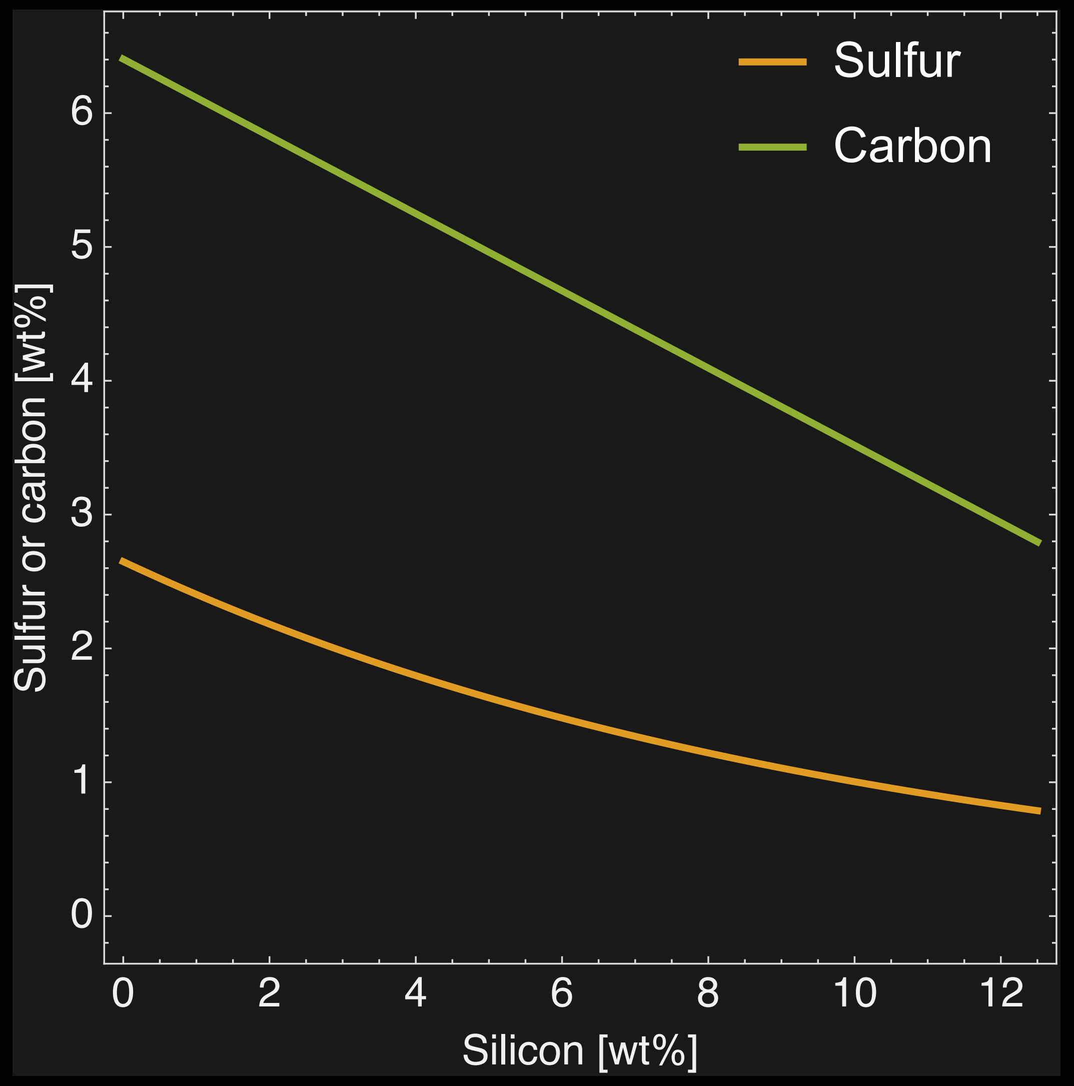
  ⇒ thermal evolution studies: can match timing of effusive volcanism, sub-adiabatic CMB heat flow, thick upper core boundary layer, large inner core, match timing of dynamo period (e.g. Davies+ 2024, Knibbe+ 2025)

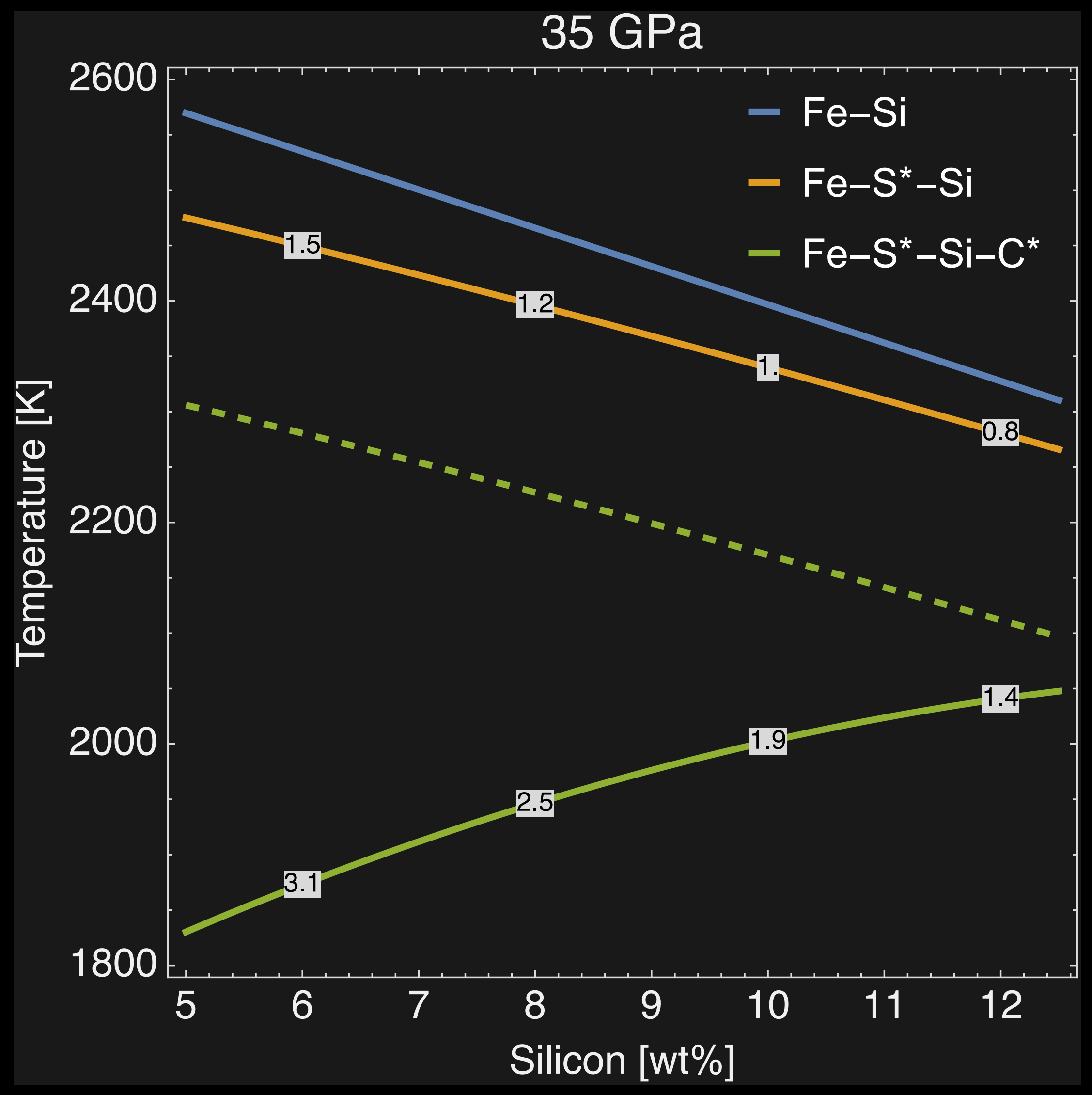
- dynamo generated magnetic field
  - weak, rotation axes aligned, northward equatorial offset (~480 km), suppressed high frequency and small scale features

  ⇒ dynamo models that reproduce those features (e.g. Takahashi+ 2019, Kolhey+ 2025) have a thick stable upper core thermal boundary layer (≳700km), inner core 400-1000 km

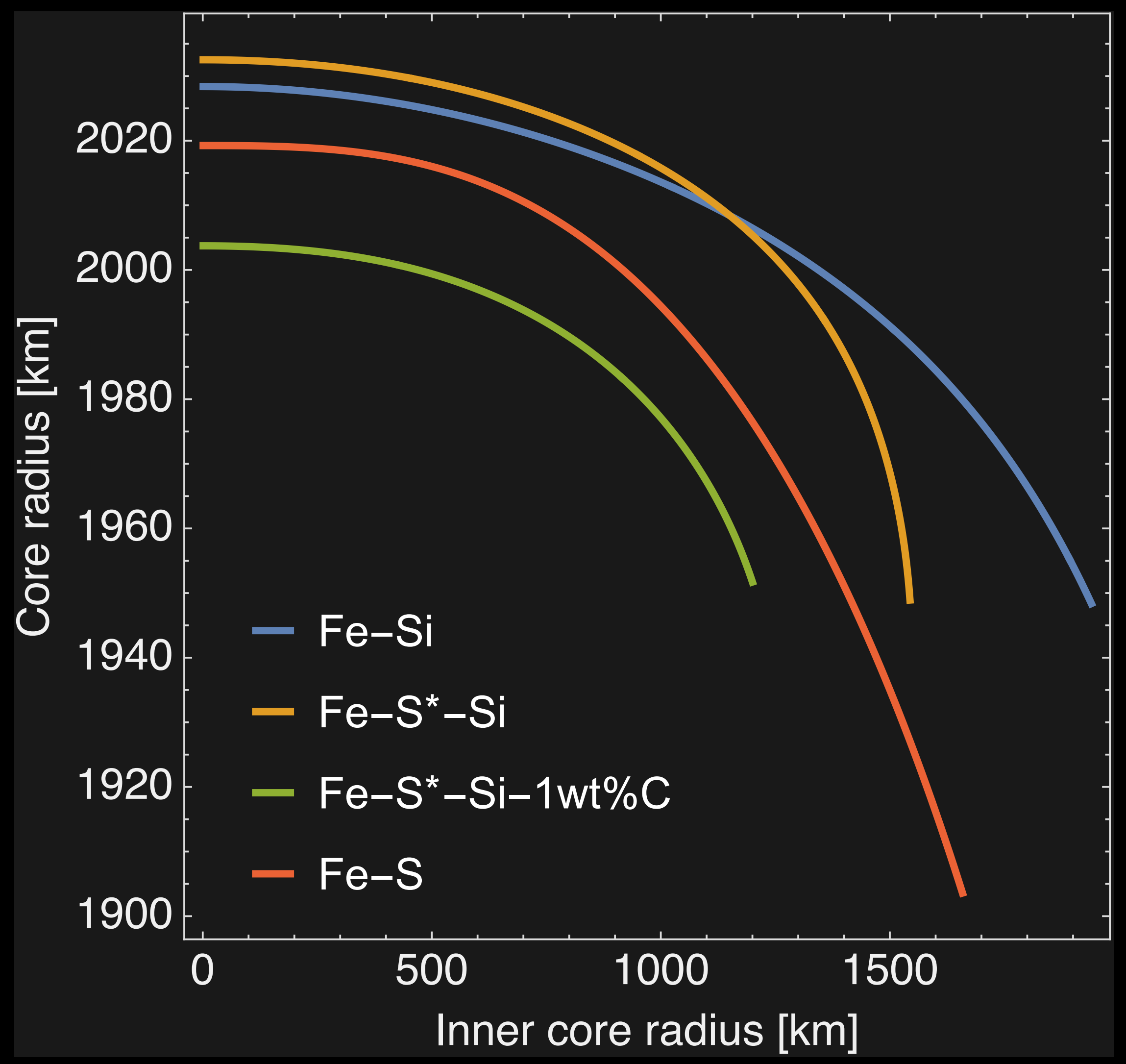
Effect of composition on core structure

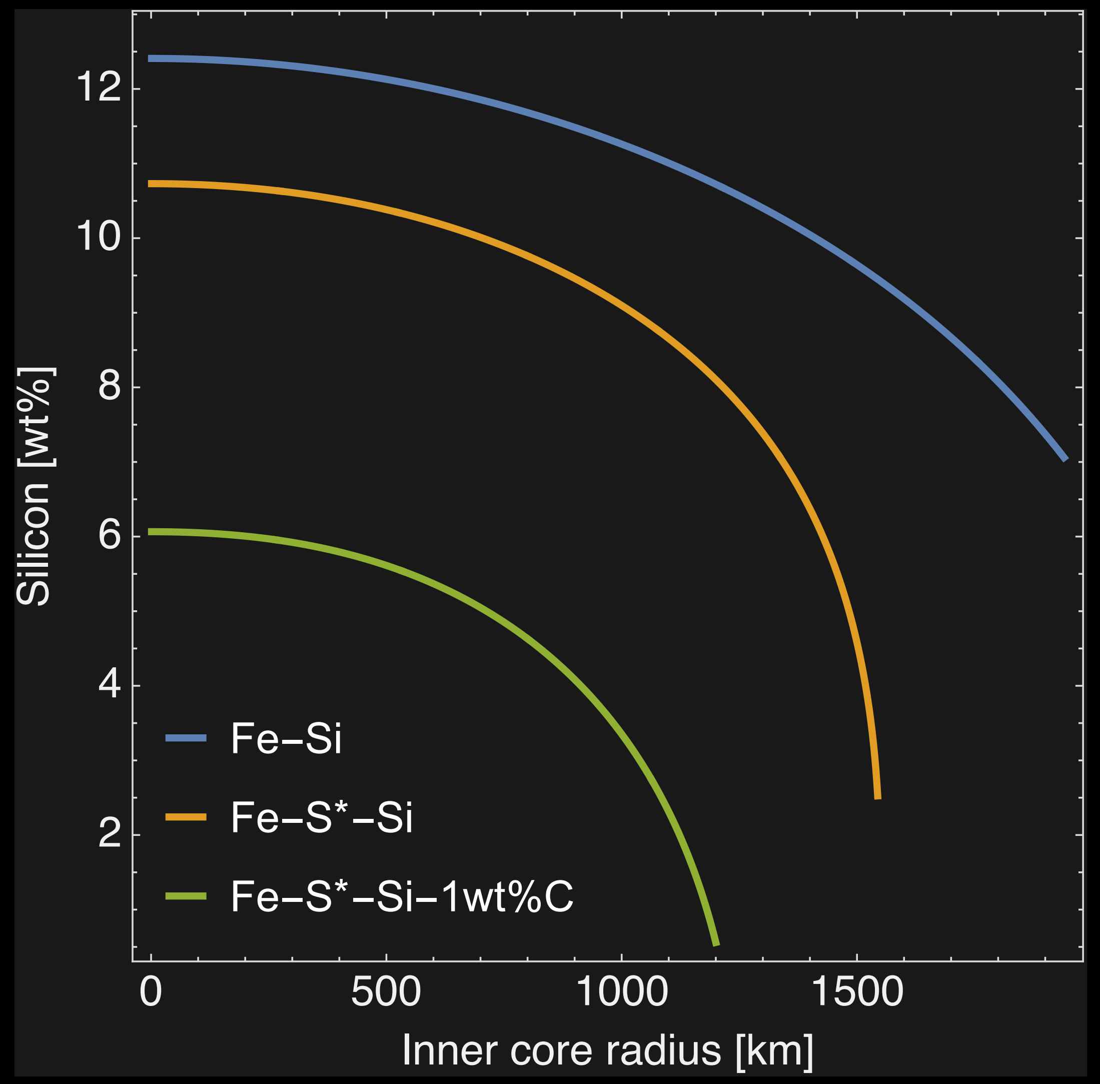
- the maximal amount of S and C decreases with increasing Si (e.g. Namur+ 2016, Boujibar+ 2019)
- unlike Si, S and even more C in the core have a strong effect on its liquidus





- r_{cmb} decreases with increasing r_{icb} (mass conservation) and rate depends on core composition
- r_{icb} decreases with amount of light elements (liquidus) also depends on eos and partitioning of light elements





Libration (Interlude)

- Gravitational torques acting on the ellipsoidal figure of Mercury give rise to longitudinal libration of its solid mantle

- Gravitational-pressure coupling between the mantle and inner core affect the libration of the mantle (Van Hoolst+ 2012, Dumberry+ 2013)
  ⇒ moment of inertia of the mantle deduced form libration is model dependent!

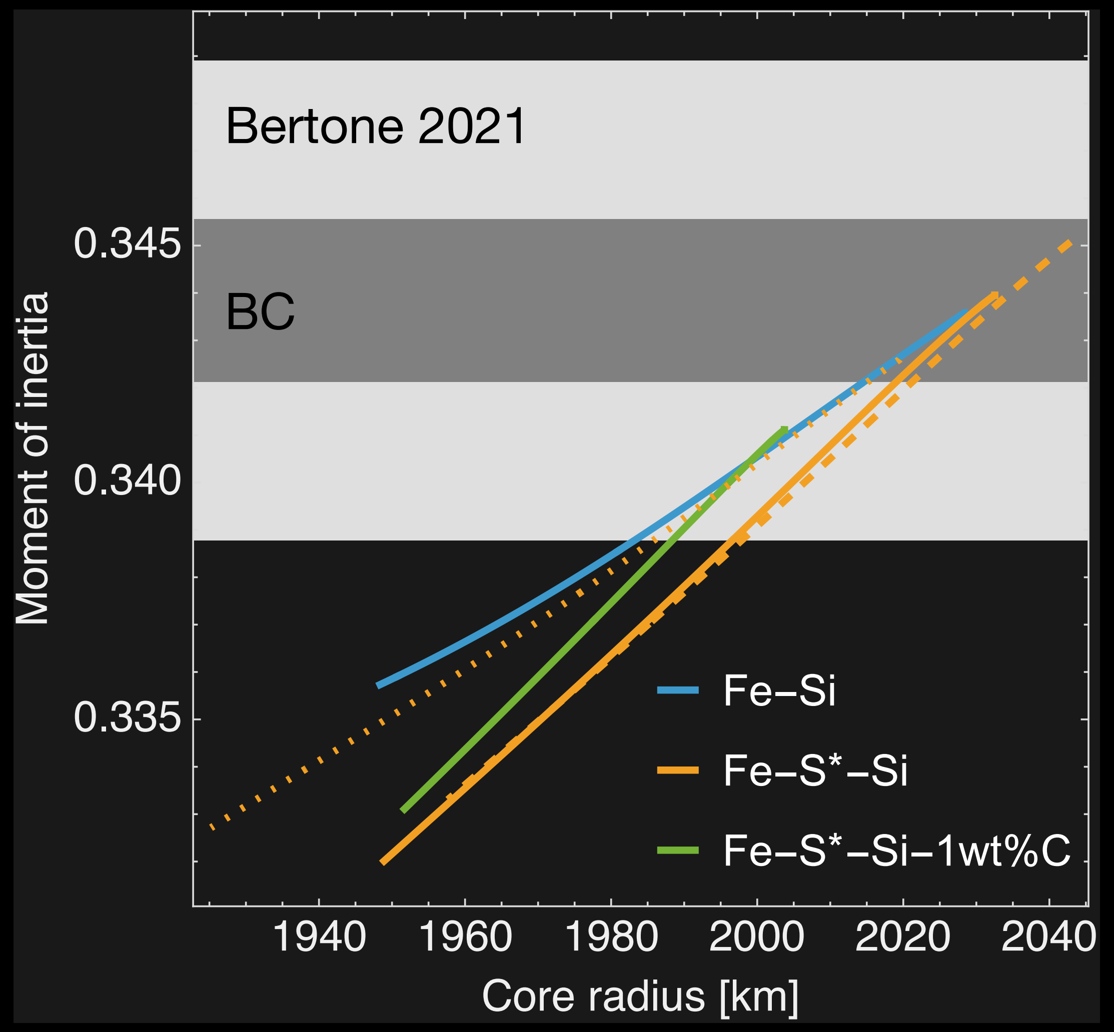
- The coupling strength between mantle and inner-core depends on the density structure within the core and the partitioning behaviour of light elements between the solid and liquid Fe (Van Hoolst+ 2012, Dumberry+ 2013, Rivoldini+ 2022)

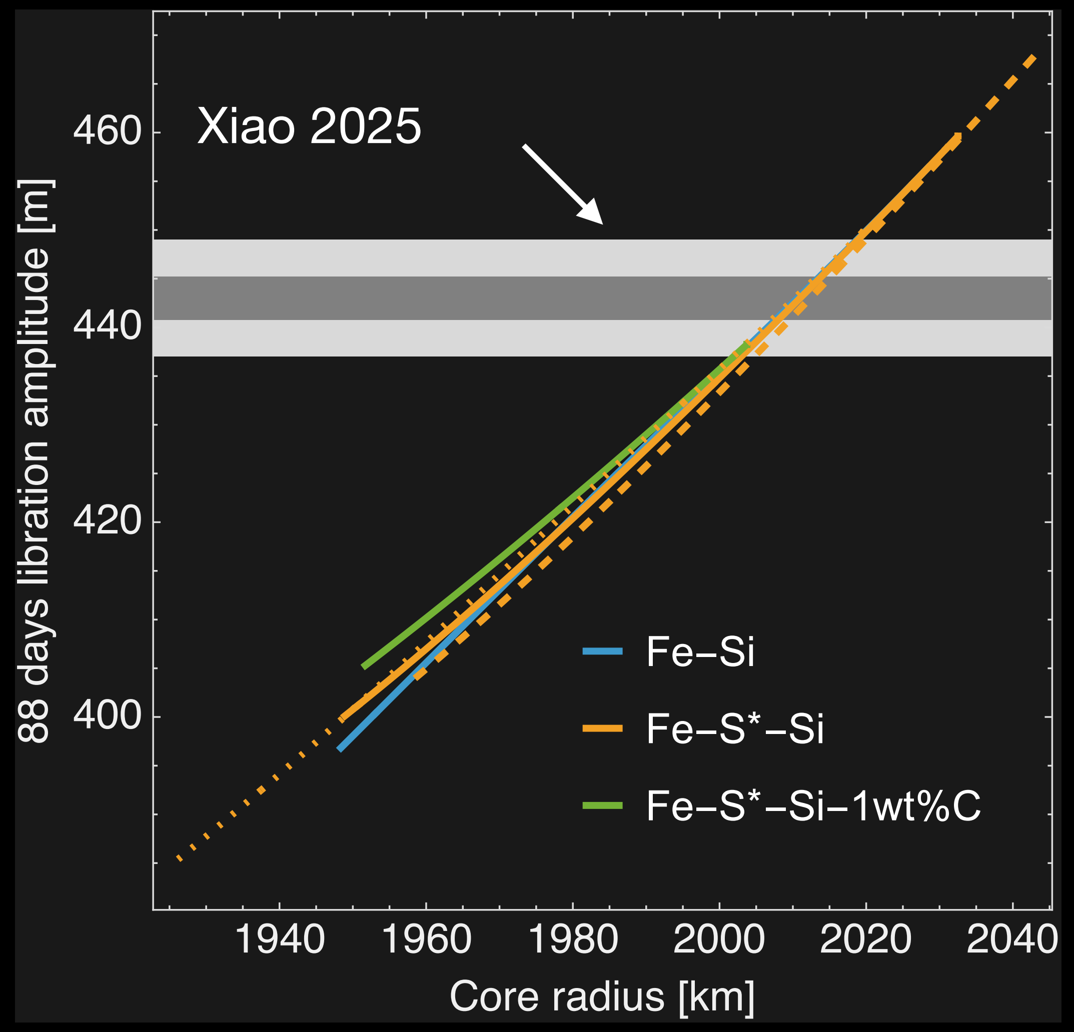
- Since Si, S, and C partition differently between solid and liquid Fe a substantial effect on the libration can be expected ($D_{\mathrm{S}}^{\mathrm{sol/liq}} \sim 0.$, $D_{\mathrm{Si}}^{\mathrm{sol/liq}} \sim 1.$, $D_{\mathrm{C}}^{\mathrm{sol/liq}} \sim 0.3$)

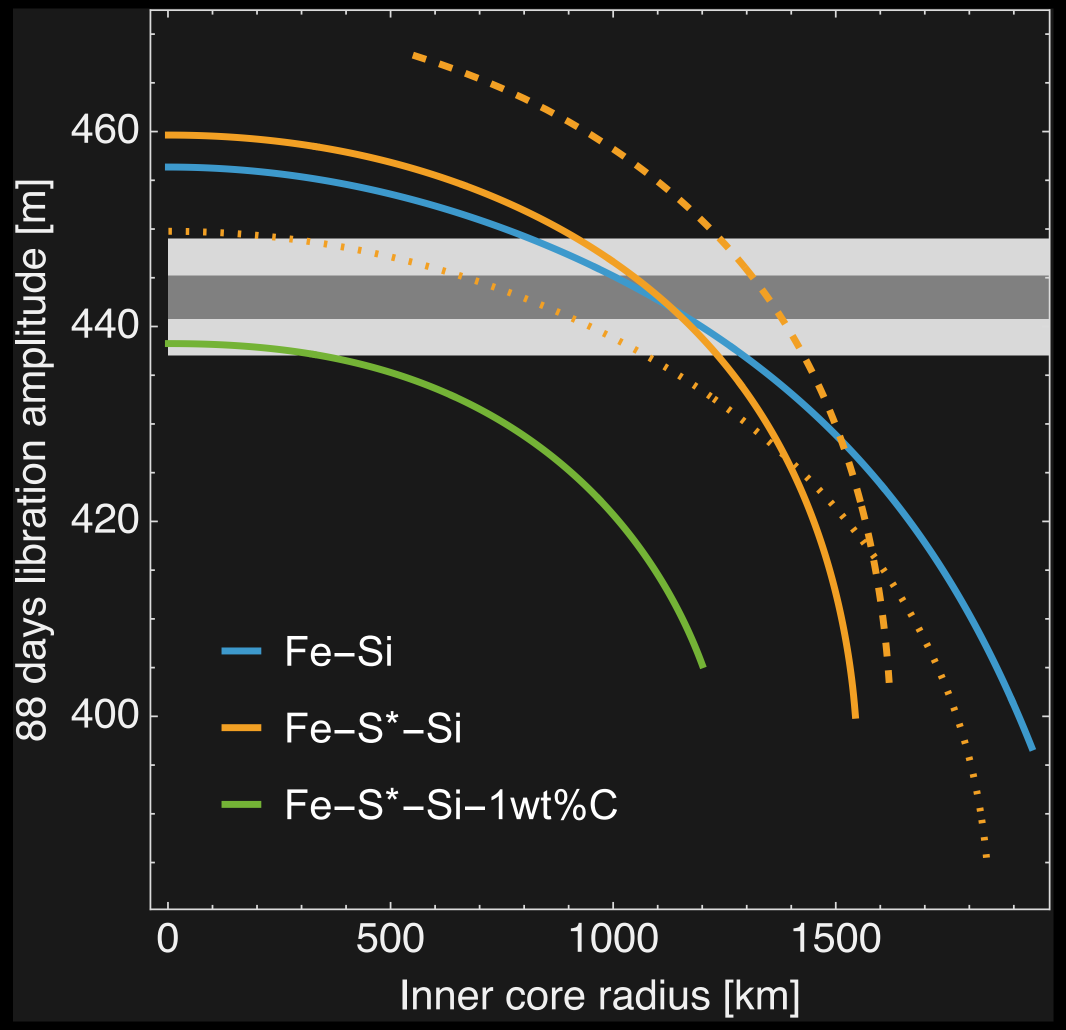
⇒ specific core composition affects the forced and free libration of Mercury

Effect of thermal state and composition on geodesy observations

- MOI decreases with increasing r_{icb} and depends on ic. light element partitioning
- libration amplitude increases with r_{cmb} (decreasing mantle moment of inertia)
- core composition and temperature have a small effect on libration amplitude
- with compositional and thermal prior knowledge libration amplitude can constrain r_{icb}



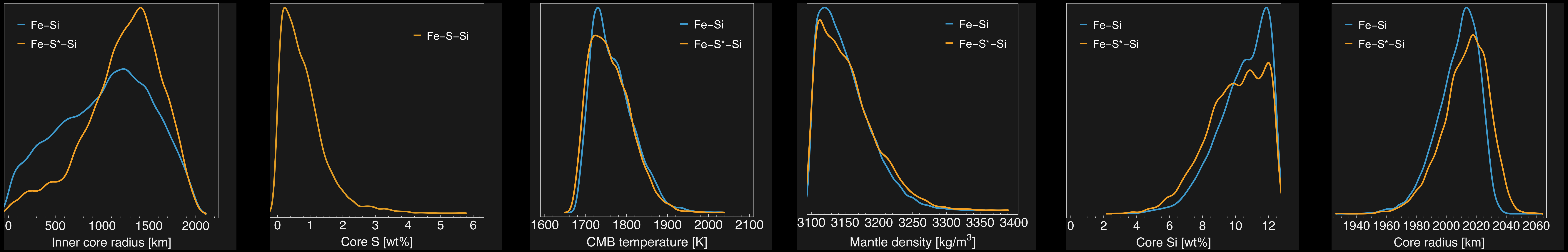




MCMC interior structure inference

Fe-Si versus Fe-(0<S_{max})S-Si core composition

- **model**: include effect of gravitational coupling between mantle and core, use Fe-S-Si core liquidus (relates inner and outer core radius through mass conservation, bcc-Fe-Si inner core (Edmund+ 2022), Fe-S-Si outer core (Dorogokupets+ 2017, Terasaki+ 2019), adiabatic core temperature
- **parameters**: r_{icb}, T_{cmb}, ρ_{mantle} (empirical relation between density and rigidity), ρ_{crust} + d_{crust}, core S fraction
- **prior** assumptions: $0 \leq S \leq S_{max}$(Si) (Boujibar+ 2019), $0 \leq Si \leq Si_{eutectic}$ (12.5 wt%, Edmund+ 2022) $T_{cmb} < T_{mantle,solidus}$ (Namur+ 2016)
- **data**: libration amplitude 455.±6 m (Xiao+ 2025), obliquity 2.031±0.03 arcmin (Bertone+ 2021), gravity field HgM009, k_2=0.53±0.03 (Konopliv+ 2020)

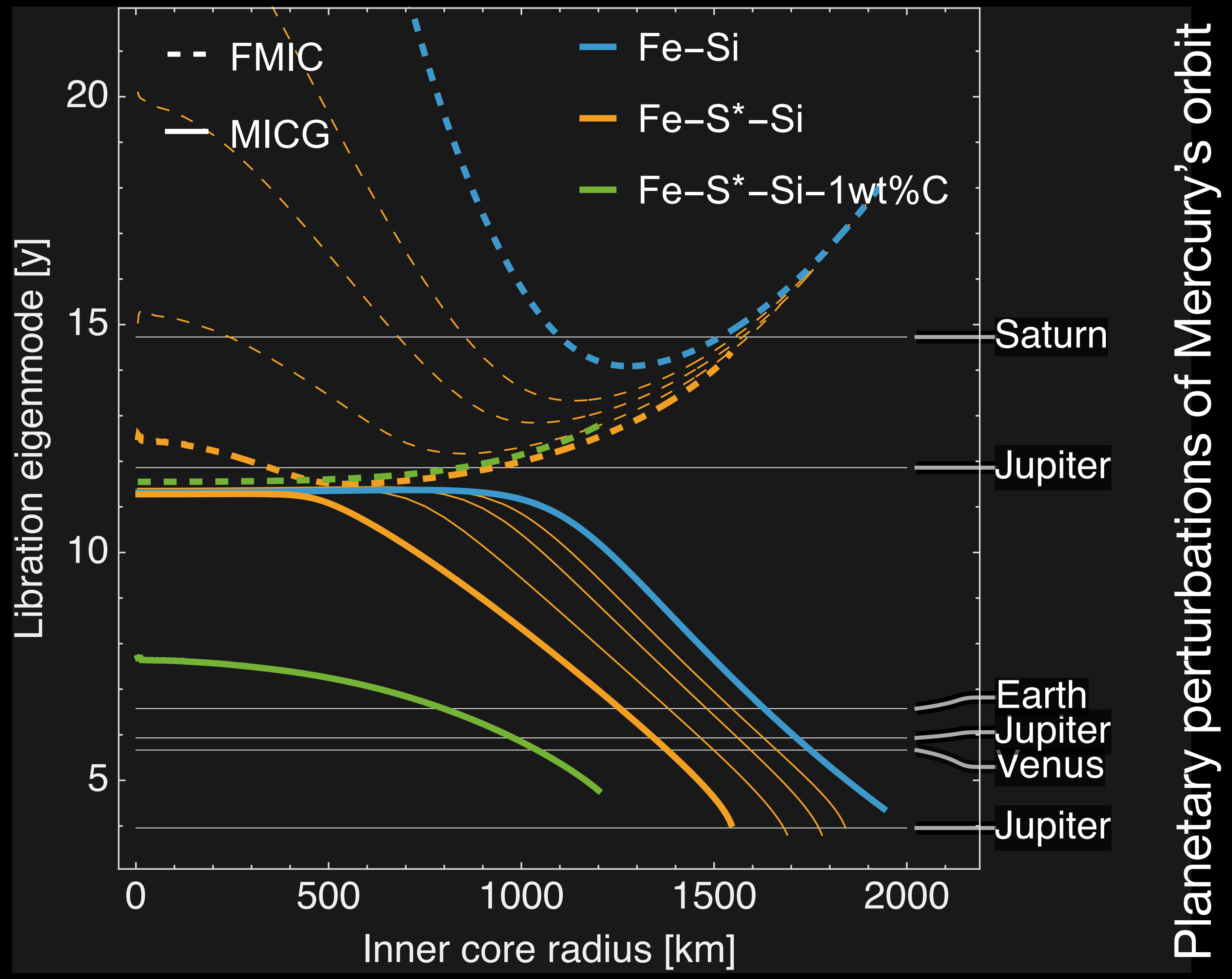


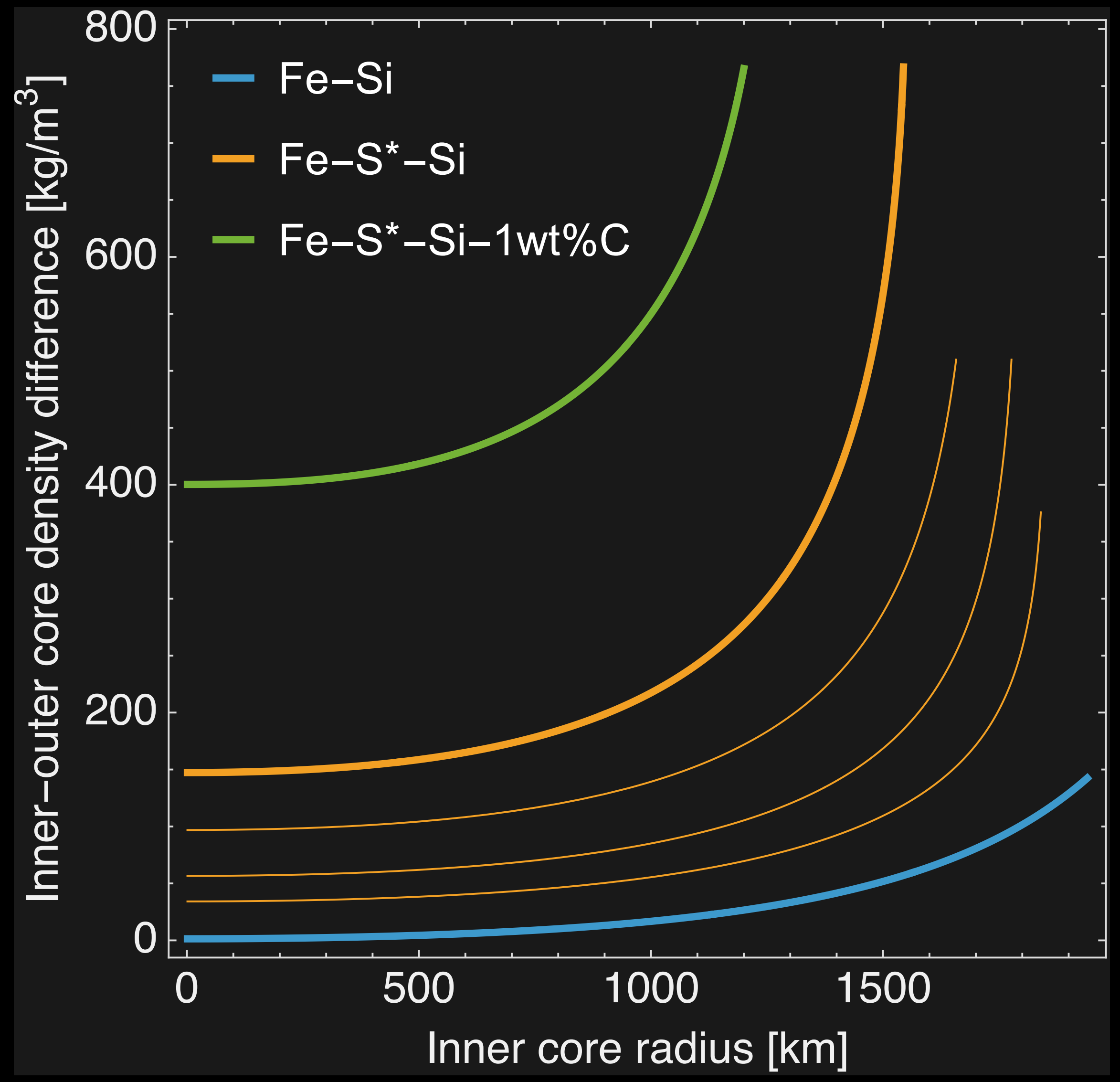
	r_{cmb} [km]	r_{icb} [km]	S [wt%]	Si [wt%]	T_{cmb} [K]	ρ_{mantle} [kg/m3]
Fe-Si	1994- 2024	486-1556	-	9-12	1717-1819	3113- 3188
Fe-S-Si	1997-2028	849-1621	0.1-0.8	8-12	1709-1812	3114-3195

- small effect of core composition (except r_{icb})
- r_{cmb} ~2010 km, large amount of Si, low T_{cmb}, low ρ_{mantle}, almost no constraint on ρ_{crust} + d_{crust}
- most likely predicted model libration amplitude ≲1std smaller than measurement
- weak constraint on r_{icb} (⇒ mostly determined by core thermodynamic properties)

Free libration modes

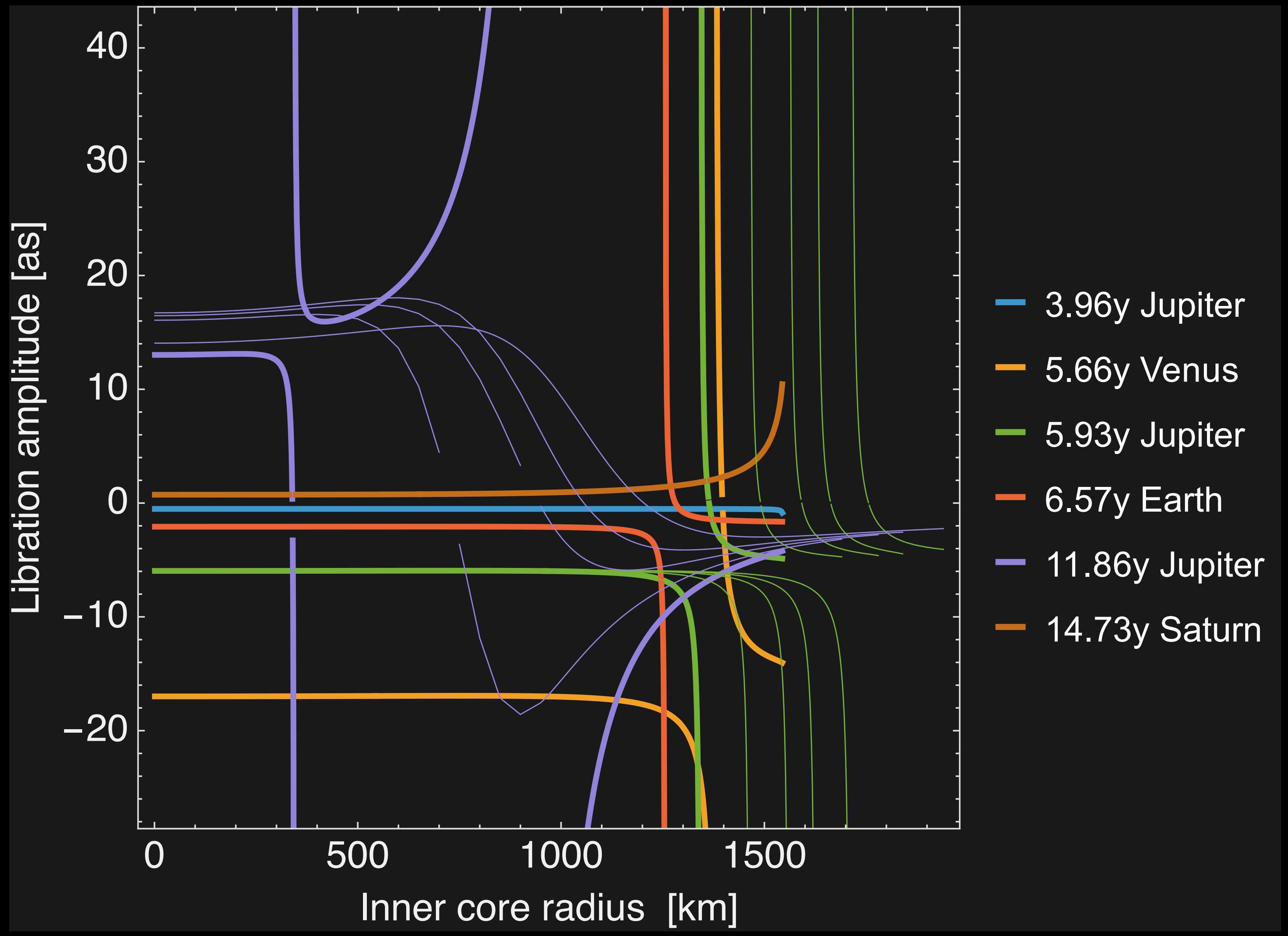
- oscillation of the combined figures of the mantle and inner core → Free Mantle–Inner Core mode (FMIC)
- mutual out-of-phase oscillation between mantle and inner core→ Mantle-Inner Core Gravitational mode (MICG)

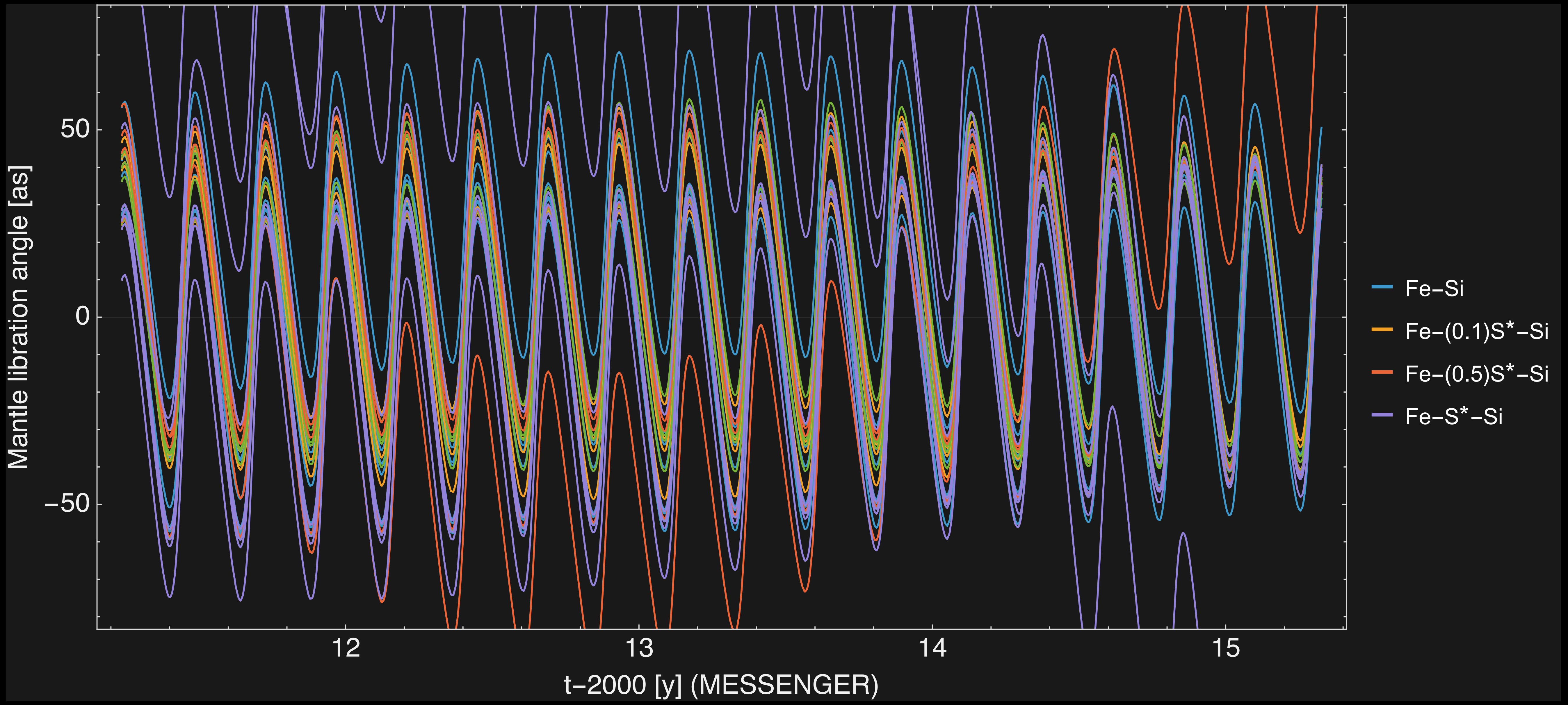




- FMIC has complex behaviour with r_{icb} and composition
- MICG decreases with r_{icb} radius and increasing $\Delta\rho_{icb}$
- core composition (density structure and light element partitioning) have a significant effect on libration normal modes
- several long period forced libration can be resonantly amplified for small or large r_{icb}

Predicted libration amplitude time series (Yseboodt+ 2013)
Fe-Si → Fe-S*-Si

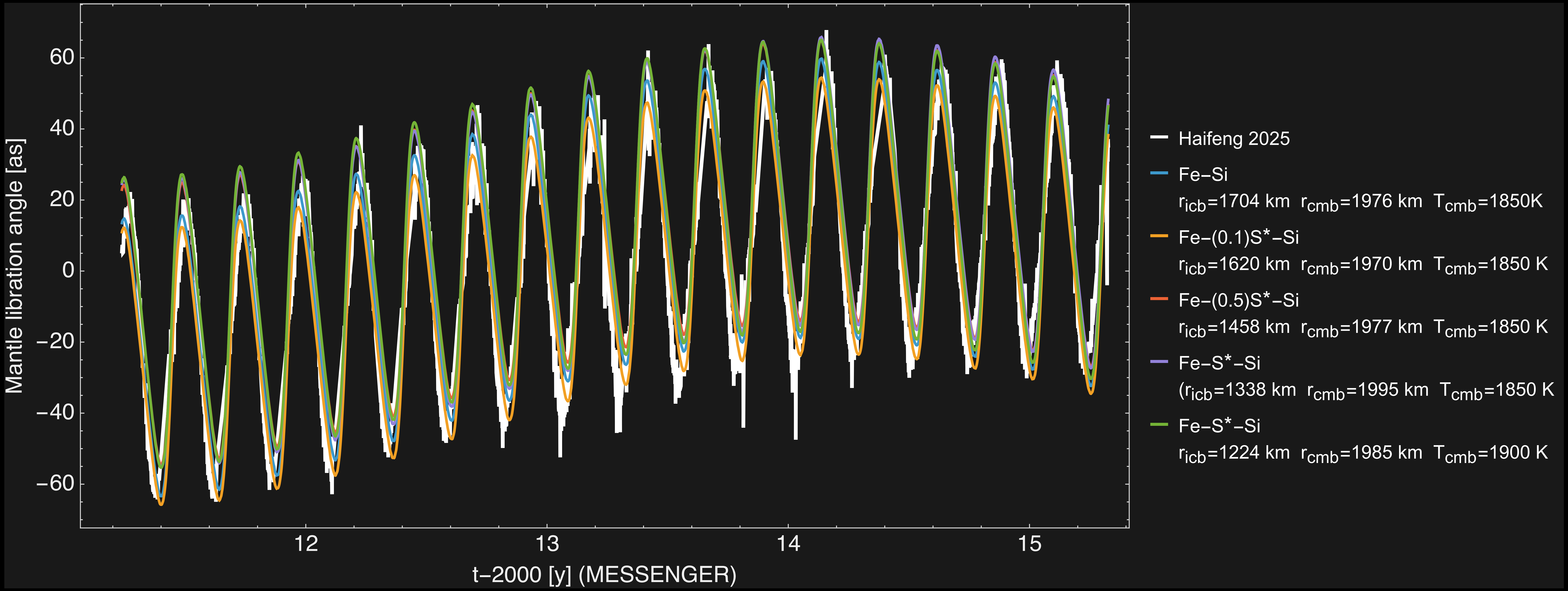




- width of resonances resulting form MICG are very narrow (⇒ for given T_{cmb} and core composition quite narrow r_{icb} range)
- libration can be resonantly amplified by planetary perturbations of Venus, Jupiter, and Earth if $r_{icb} \gtrsim 1000$ km
- resonance shift to smaller r_{icb} with increasing S in Fe-S*-Si
- core structure and composition have a strong effect on the libration time series

Predicted libration time series versus measured time series during MESSENGER period: Fe-Si→Fe-S*-Si

Deduced from self-registration of MESSENGER Laser Altimeter profiles (Xiao+ 2025)



- several very specific Fe-(0<S_{max})S-Si models can well reproduce the reconstructed time series (minimal misfit)
- retrieved r_{cmb}, r_{icb}, and T_{cmb} values are somewhat at odds with MCMC joint inversion (MOI, g_{88}, k_2) 1σ estimates
- high potential to further improve interior structure inference by combining libration time series with other geodesy data

MCMC	r_{cmb} [km]	r_{icb} [km]	T_{cmb} [K]
Fe-Si	1994- 2024	486-1556	1717-1819
Fe-S-Si	1997-2028	849-1621	1709-1812

Caveats (not extensive)

- phase diagram of Fe-Si not well known but crucial (location of 1st Fe-Si eutectic debated) ⇒ for Si fraction above the eutectic the solid Fe-Si compound is likely buoyant → no bottom-up inner core formation
- even less known are the effect of adding S and C to Fe-Si on thermodynamic properties (Fe-S-Si is miscible close to CMB conditions)
- equations of state of liquid Fe-S-Si-C not available
- effect of C on solid Fe-Si not known (no rigidity data for solid Fe-Si)
- effect of CaS+MgS on mantle rigidity unknown (softer?)
- effect of upper core thermal boundary neglected and effect of (composition,p,T) dependent partitioning of light elements into the core ⇒ requires modelling Mercury's thermal evolution (results even more dependent on material properties)

⇒ seek cooperation with material science experts

Conclusions

- the partitioning behaviour of S, Si, and C between solid and liquid Fe has a substantial effect on the core density structure and density contrast at the inner-outer core boundary

- core composition affects libration normal modes and long-term forced libration amplitudes

- combining libration time series with other geodesy data will help to reduce the parameter space of plausible interior structure governing parameters

- however, to obtain more precise information about the core will require to combine geodesy observation and geochemical constraints with constraints deduced from thermal evolution studies that account for the presence of a past and present-day dynamo