Effect of Mercury's interior structure on its long-period libration

A. Rivoldini[1] (Attilio.Rivoldini@oma.be), T. Van Hoolst[1,2], H. Xiao[3], A. Trinh[1], M. Yseboodt[1], R.-M. Baland[1], J. Rekier[1], S. A. Triana[1], N. Tosi[4], and A. Briaud[4]
1: Royal Observatory of Belgium, 2: KU Leuven, Belgium, 3: IAA-CSIC, Granada, Spain, 4: DLR, Berlin, Germany, 5: TU Berlin, Germany

BELA-MORE meeting Bruxelles 2025

Scope

- Mercury experiences long-period forced librations as a result of periodic gravitational perturbations from other planetary bodies (Venus, Earth, Jupiter, Saturn, ..) on its orbit
- Forced librations can be resonantly amplified when planetary perturbations are close to one of the two free libration normal modes
- Free libration normal modes and librational response dependent on interior structure and coupling between solid shell, outer core, and inner core
- 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 iron

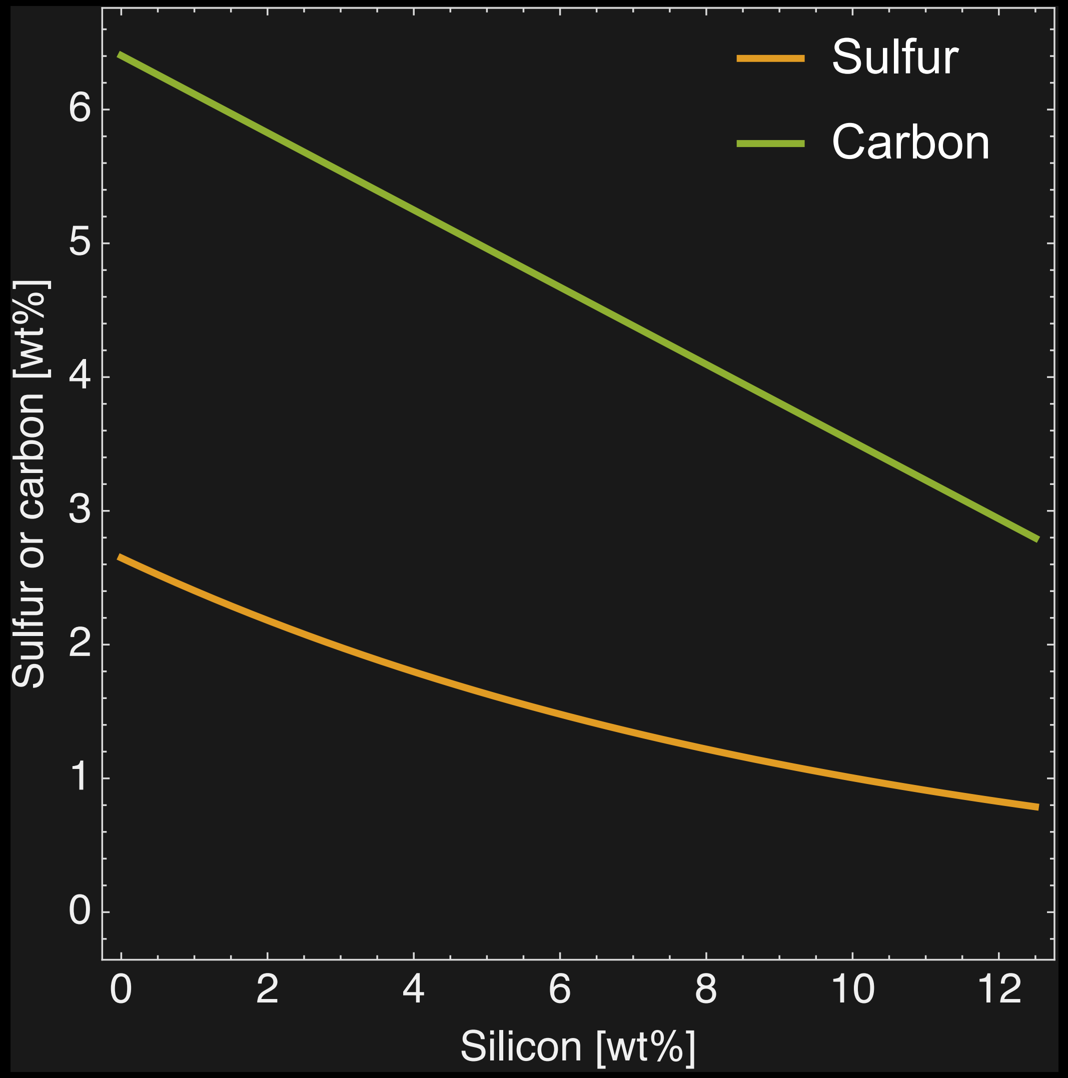
⇒ specific core composition and structure affect long period forced and free libration of Mercury

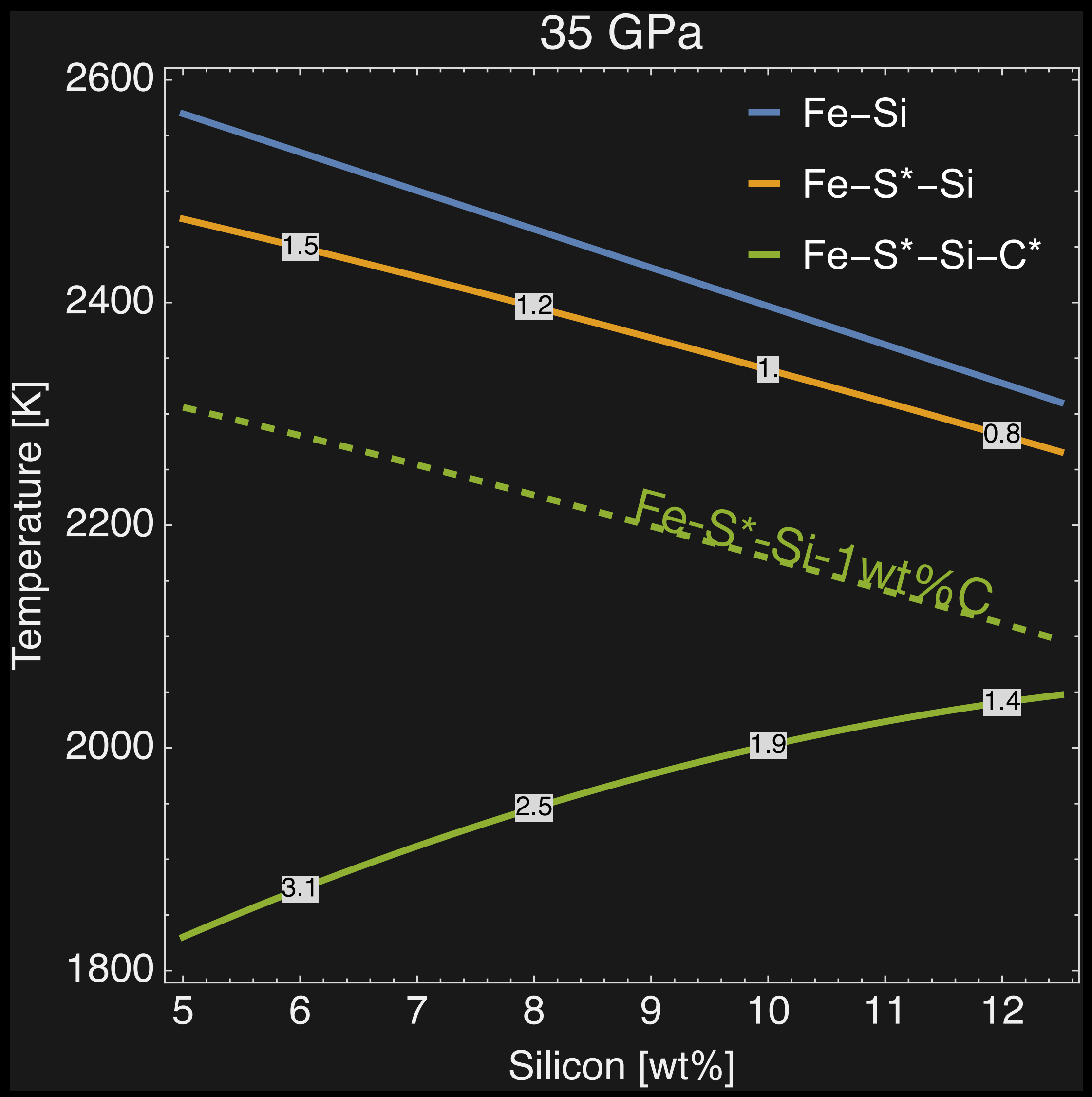
Effect of composition on core structure

- Candidate core light elements:
  Si, S,C,..
  (e.g. Namur+ 2016, Steenstra+ 2020)

- the maximal amount of S and C decreases with increasing Si (e.g. Namur+ 2016, Boujibar+ 2019)

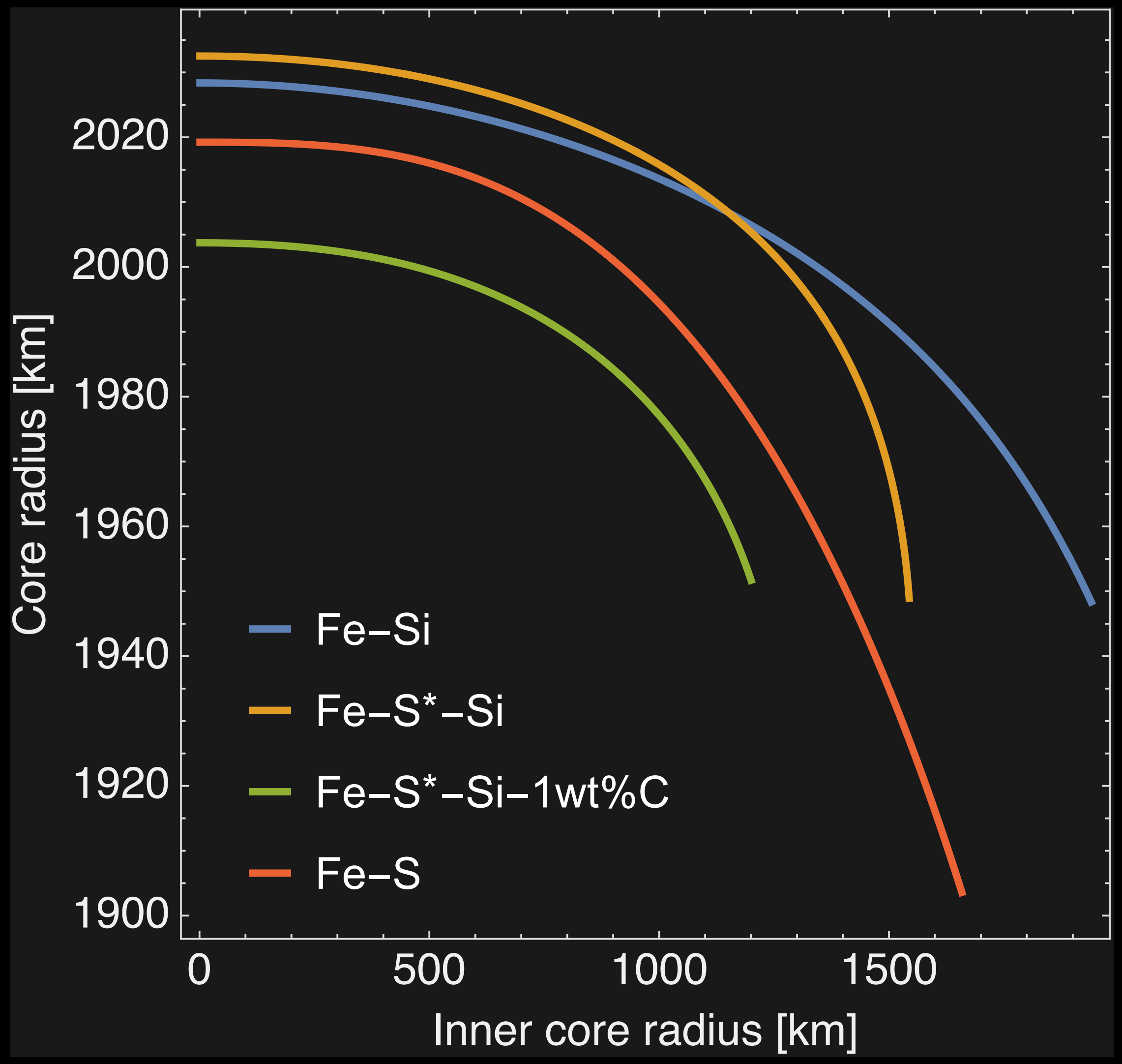
- unlike Si, S and even more C in the core have a strong effect on its liquidus

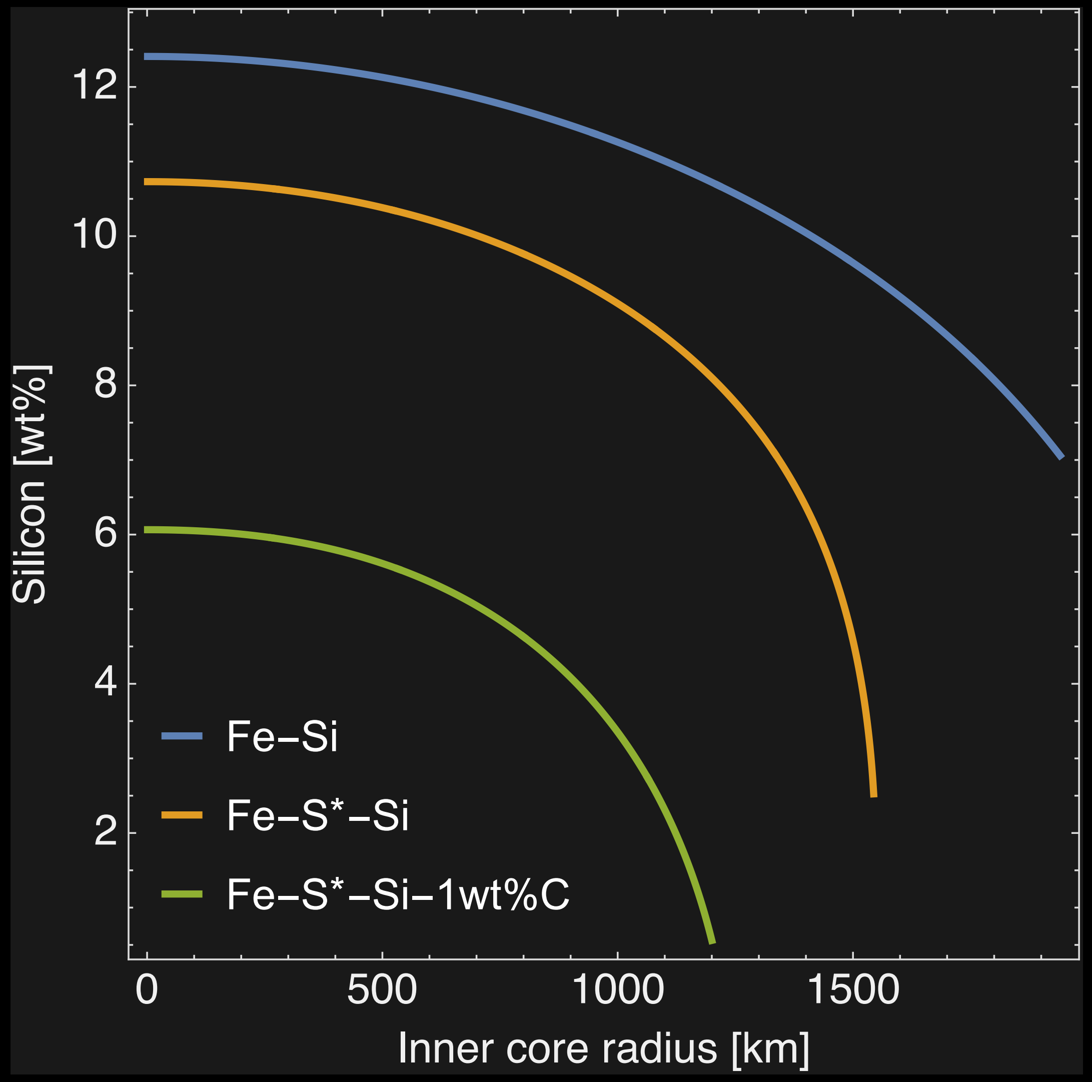




- r_{cmb} decreases with increasing r_{icb} (mass conservation) and rate depends on core composition

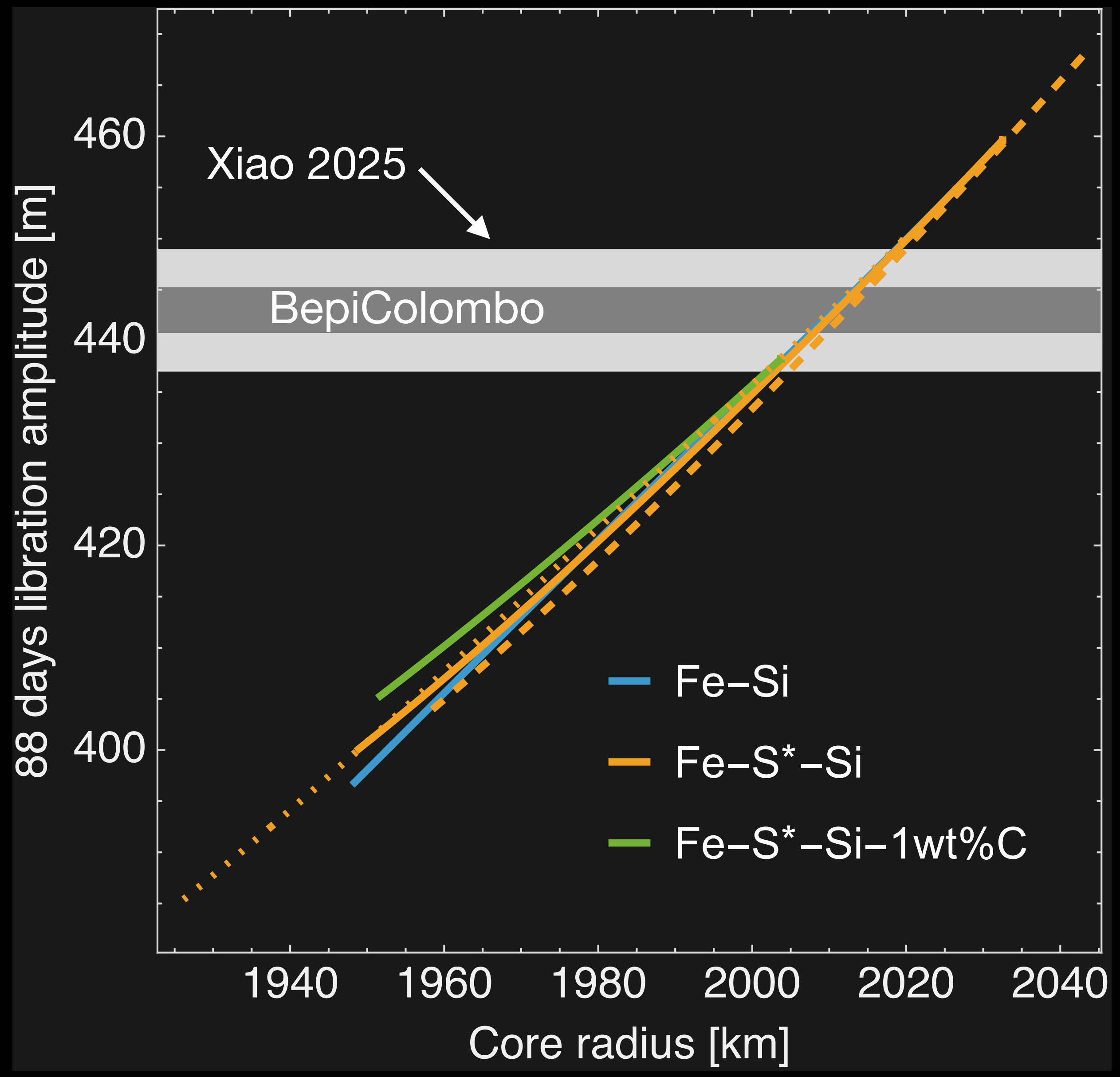
- r_{icb} decreases with amount of light elements (liquidus) also depends on equation of state and partitioning of light elements:
  $D_{S}^{sol/liq} \sim 0., D_{Si}^{sol/liq} \sim 1.\,, D_{C}^{sol/liq} \sim 0.3$

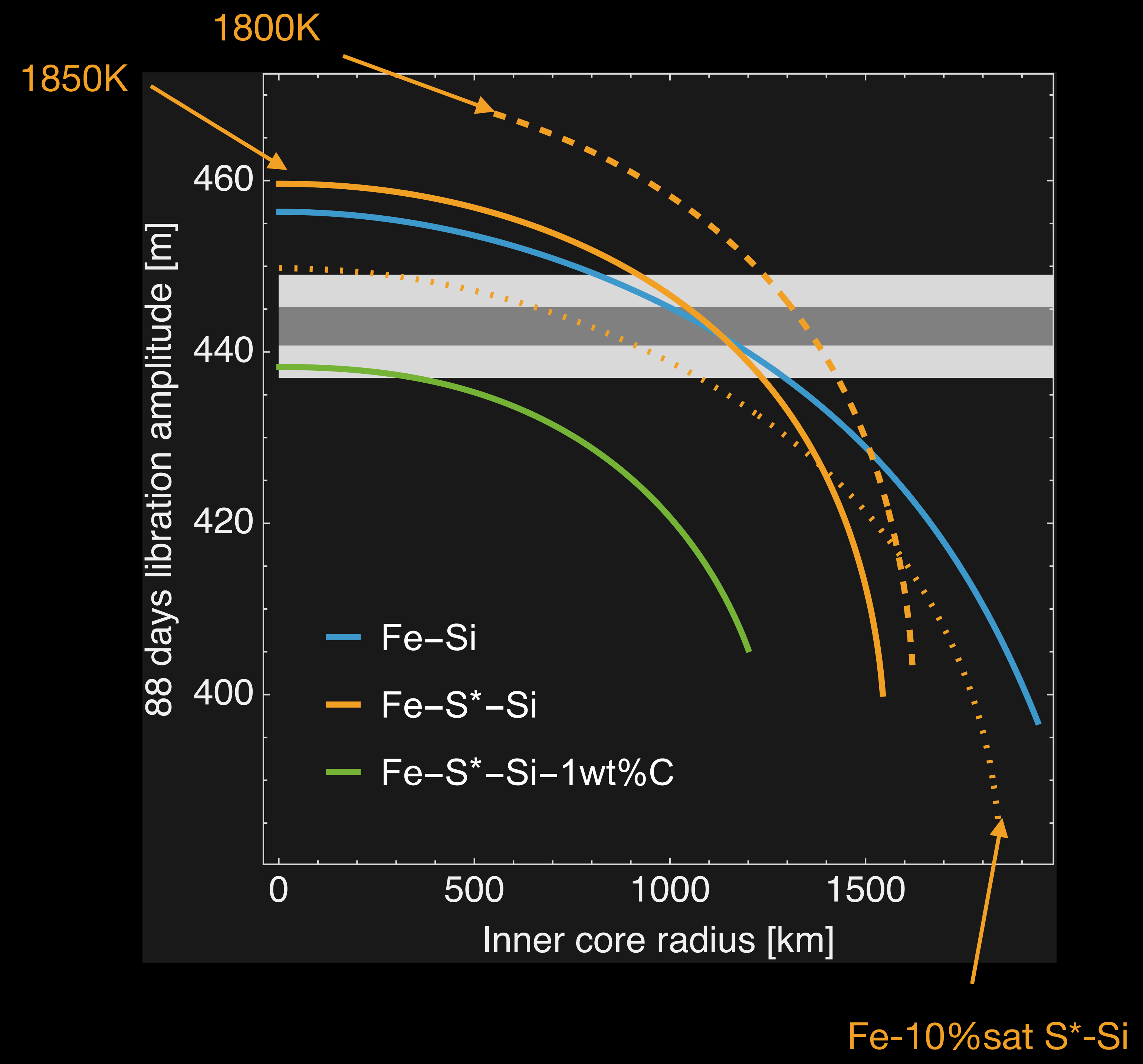


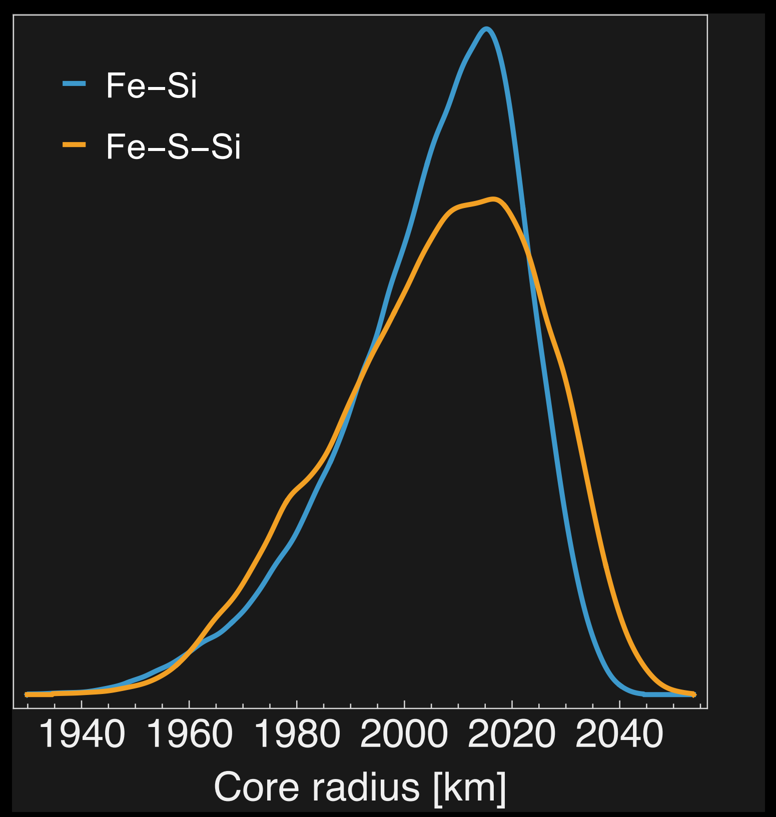


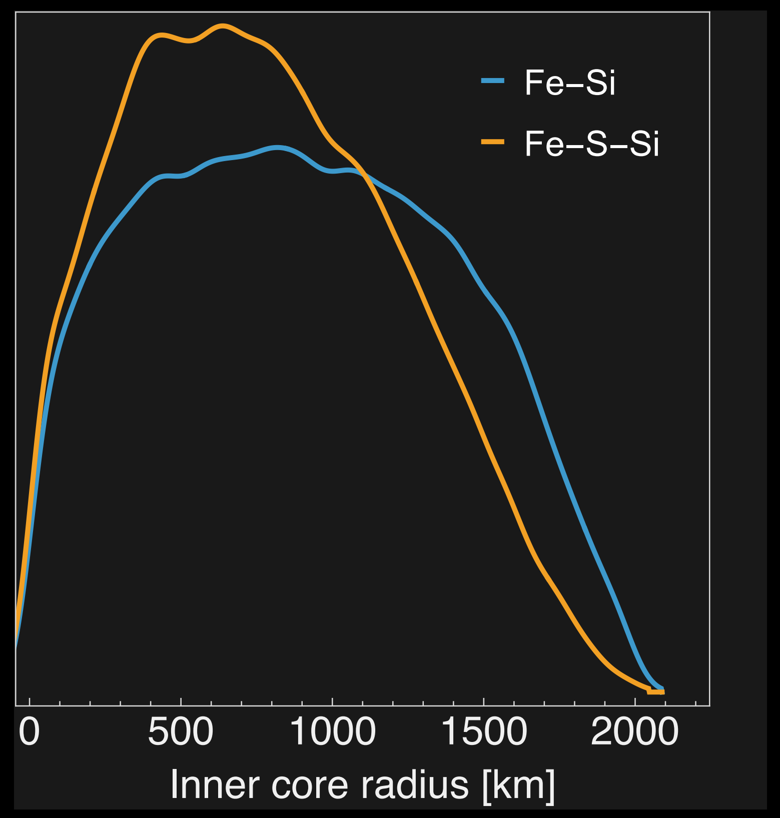
Effect of thermal state and composition on 88 d libration

- libration amplitude increases with core radius (decreasing mantle moment of inertia)
- specific core composition and temperature have a small effect on libration amplitude
  ⇒ robust proxy for core radius
- without detailed compositional and thermal prior knowledge weak constraint on inner core radius
- **Structure inference** (MCMC) using 88d lib., MOI, k_2:
  $1\sigma : \Delta(r_{cmb}) \sim 18$ km $\quad \Delta(r_{icb}) > 450$ km



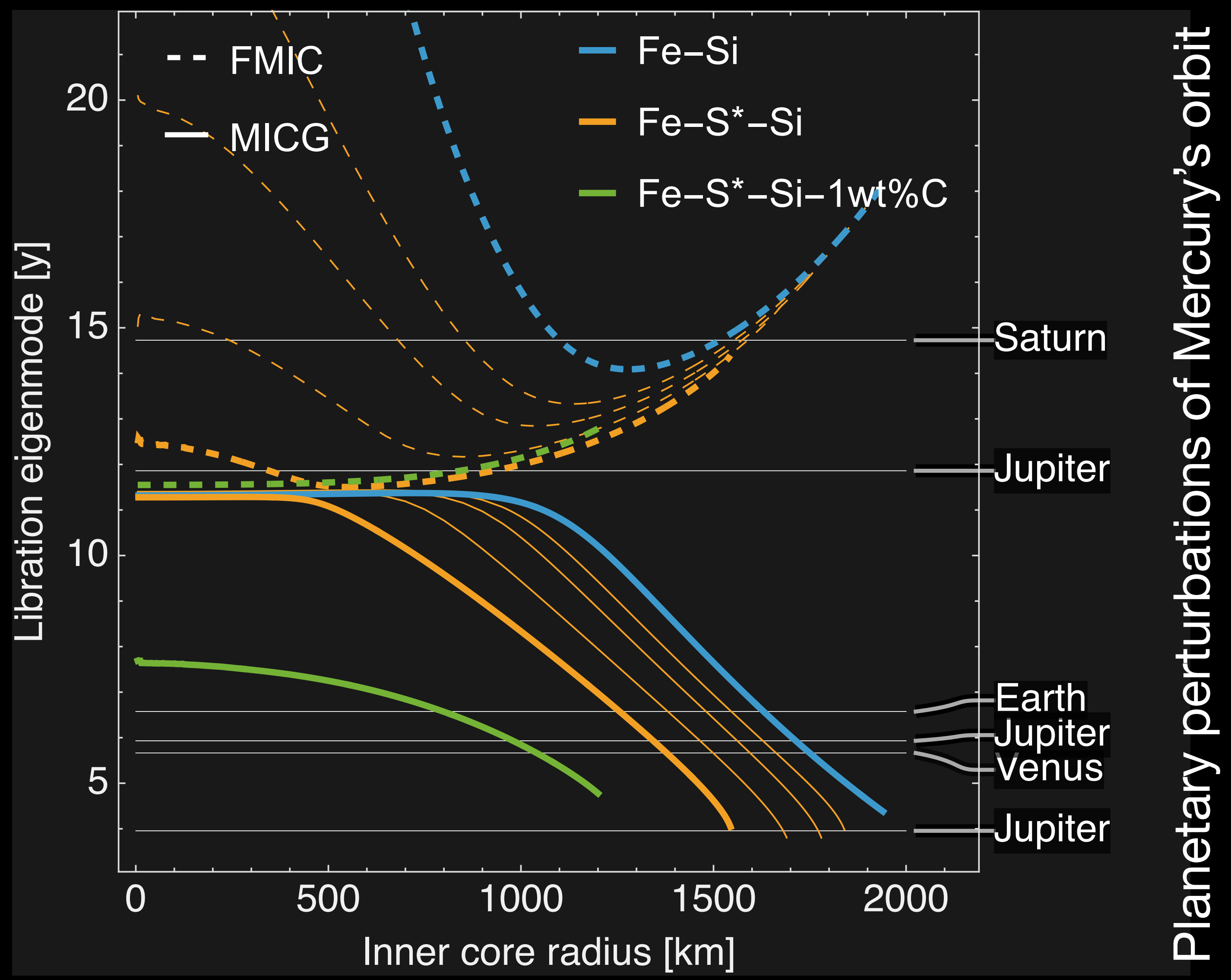


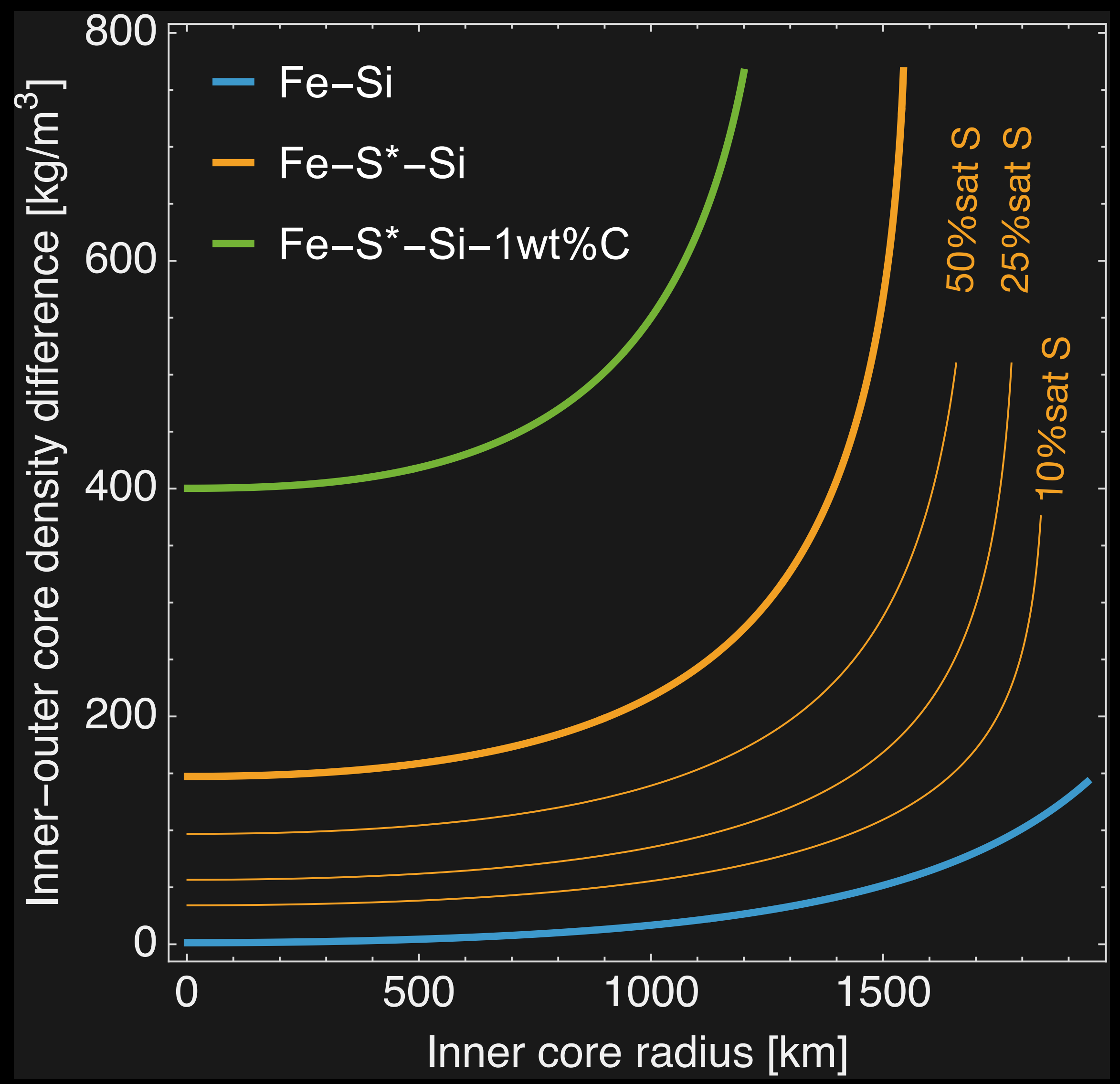




Effect of compositions on free libration modes

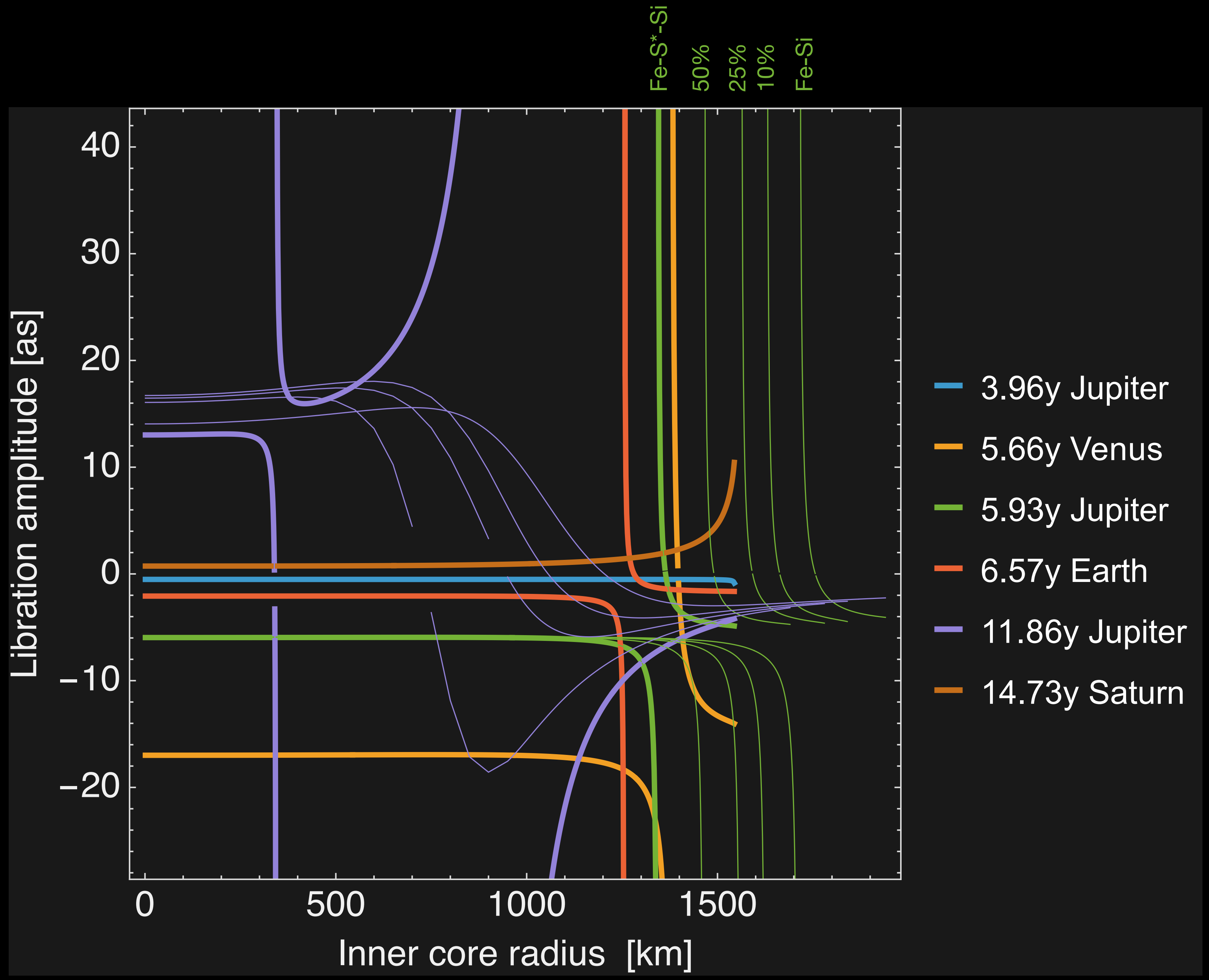
- oscillation of the combined figures of the mantle and inner core → Free Mantle–Inner Core mode (FMIC)
- mutual out-of-phase oscillation between mantle and inner core→ Mantle-Inner Core Gravitational mode (MICG)

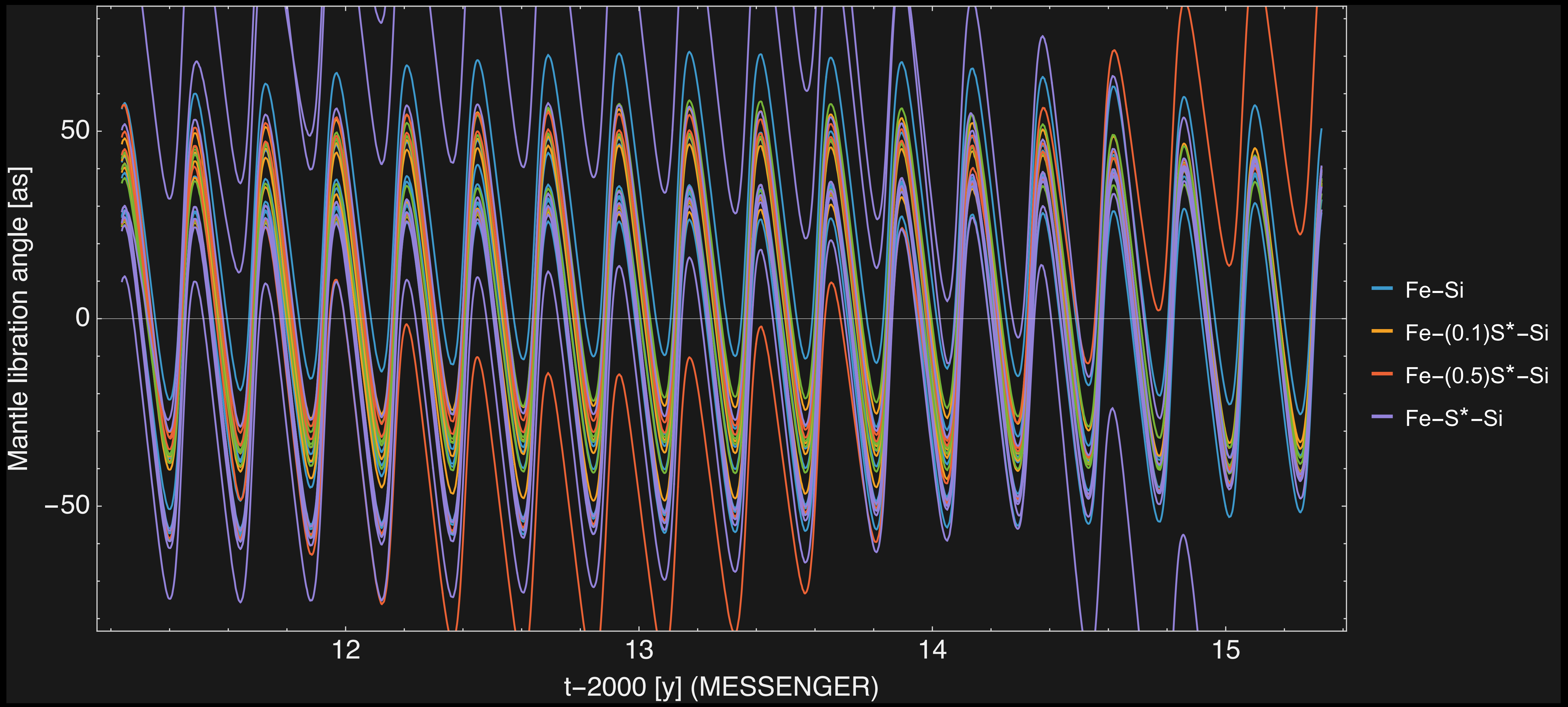




- FMIC has complex behaviour with r_{icb} and composition
- MICG decreases with r_{icb} radius and increasing $\Delta\rho_{icb}$
- core composition (density structure and light element partitioning) have a significant effect on libration normal modes
- several long period forced libration can be resonantly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

Predicted libration amplitude time series (Yseboodt+ 2013)
Fe-100% sat S-Si → Fe-Si

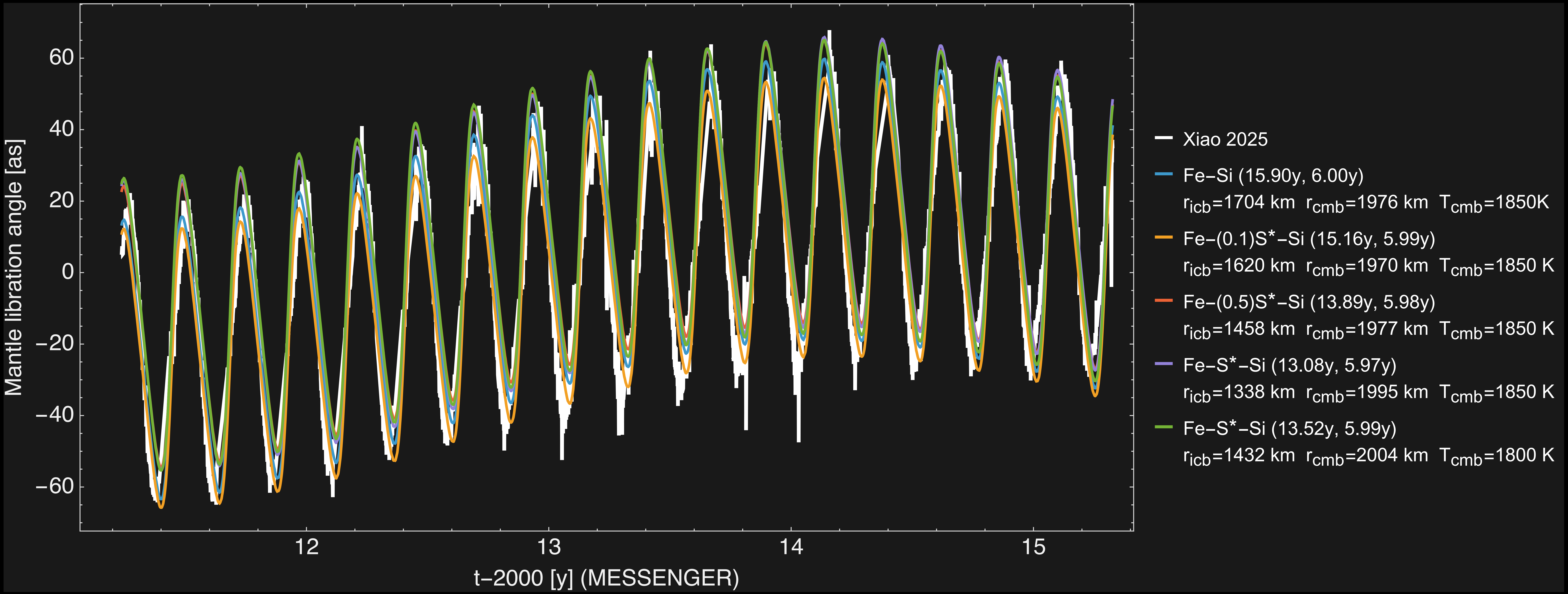




- width of resonances resulting from MICG are very narrow (⇒ for given T_{cmb} and core composition quite narrow r_{icb} range)
- libration can be resonantly amplified by planetary perturbations of Venus, Jupiter, and Earth if $r_{icb} \gtrsim 1000$ km
- resonance shift to smaller r_{icb} with increasing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

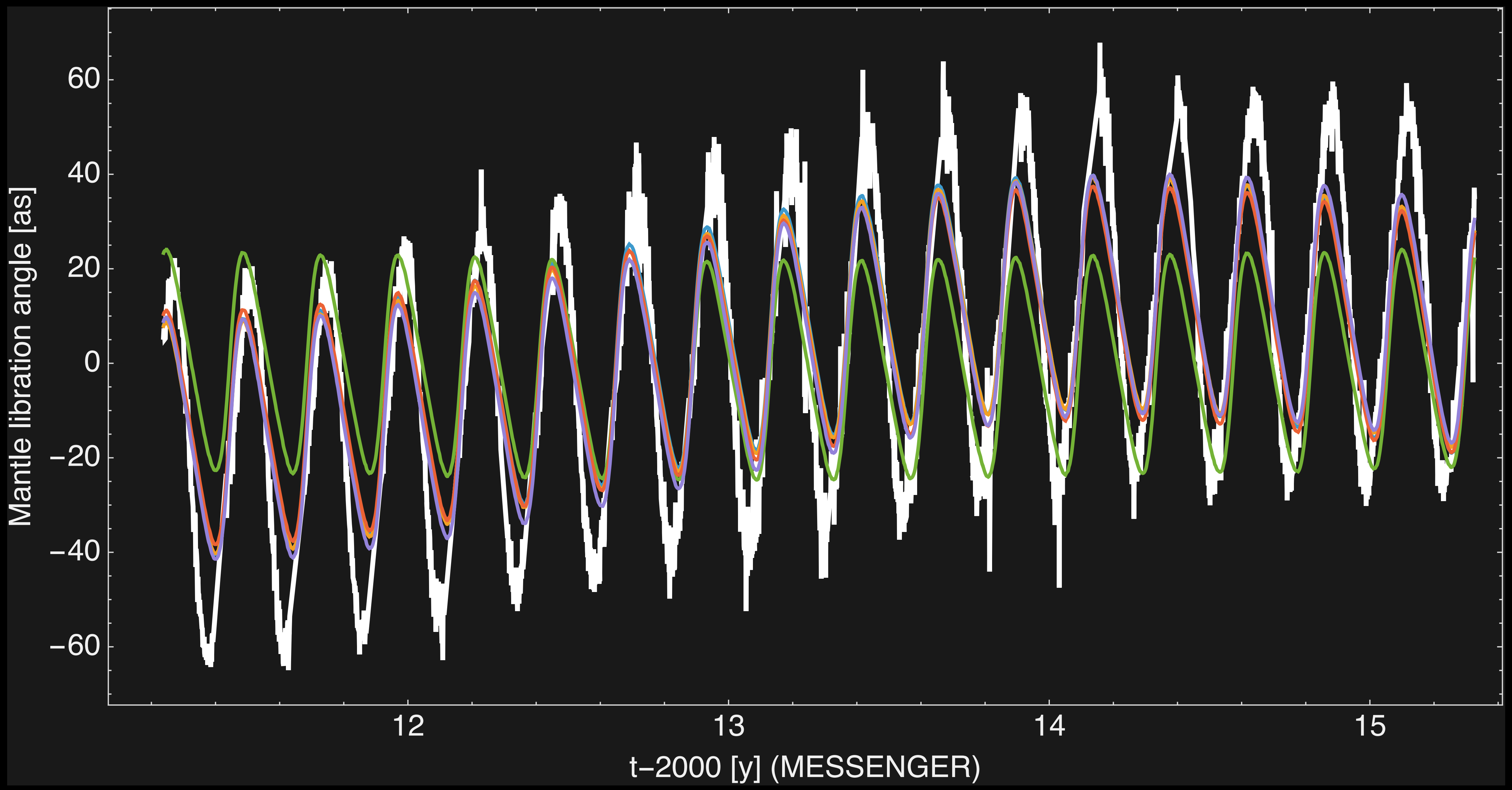
Deduced from self-registration of MESSENGER Laser Altimeter profiles (Xiao+ 2025)



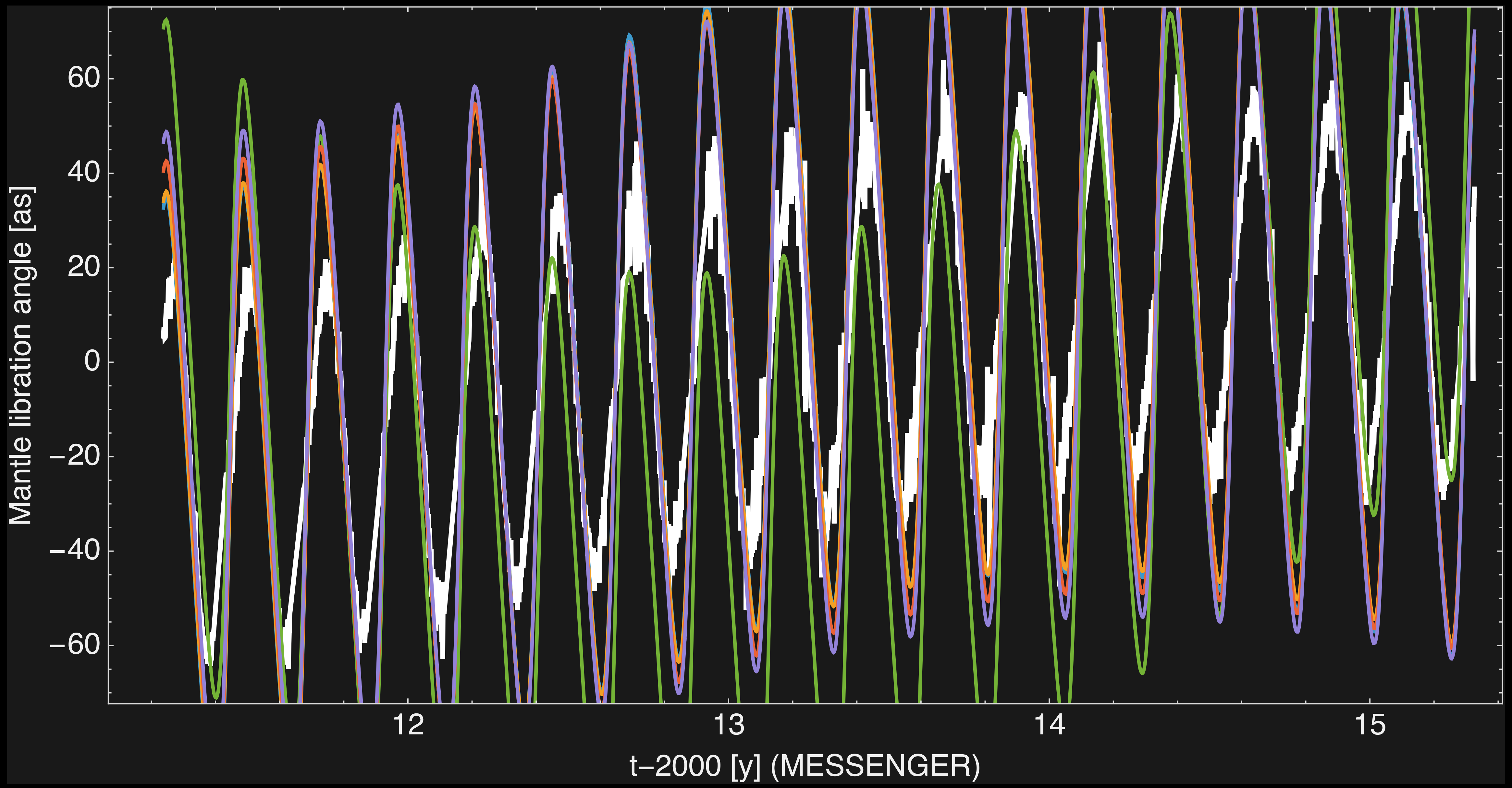
- several very specific Fe-(0<S_{max}) S-Si models (1300 km<r_{icb}<1710 km) can well reproduce the libration time series (minimal misfit)
- those structure models have an out-of-phase free libration period (MICG) close to the Jupiter (5.93 y) orbit perturbations

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
- interior structure models with a large inner core (>1300 km) and a liberation eigenperiod close to the Jupiter orbit perturbation (5.93 y) agree best with the liberation time series
- inner core radii >1300 km supported by thermal evolution studies that model Mercury's past and present-day dynamo (Rivoldini+ 2025 WG1)



Mantle libration angle [as]
60
40
20
0
−20
−40
−60
12
13
14
15
t−2000 [y] (MESSENGER)



Mantle libration angle [as]
60
40
20
0
−20
−40
−60
12
13
14
15
t−2000 [y] (MESSENGER)