Interior structure after MESSENGER
Next steps and best practice

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Interior structure constraints

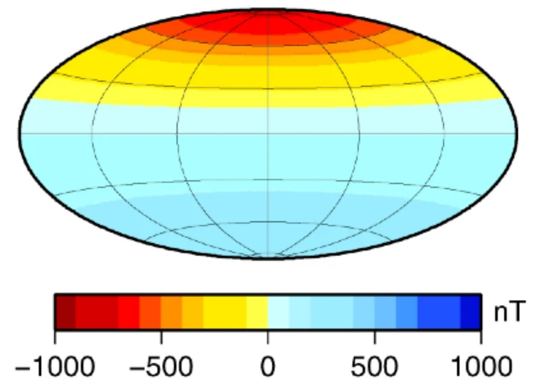
- Geodesy (rotation and gravity field):
  - mass and radius: mean density
  - crust density and thickness (more details next WG1 meeting)
  - Annual libration amplitude (Stark 2015: 38.9” ±1.3”, Bertone 2021: 39.03” ±1.1”): 38.9” ±1.30”
  - Polar moment of inertia (Stark 2015: 0.346 ± 0.011, Bertone 2021: 0.343 ± 0.006): 0.346 ± 0.011
    From gravity field 🙁: Verma 2016: 0.318 ± 0.028, Genova 2019: 0.333 ± 0.005
  - Love numbers:
    k_2: (Genova 2019: 0.569 ± 0.025, Konopliv 2020: 0.53 ± 0.03): 0.55 ± 0.05
    h_2: Bertone 2021: 1.55 ± 0.65

=> core state (liquid outer core), density structure (large core), mantle rigidity (soft), core radius (~2000km)
=> not enough data to construct precise interior structure models
(i.e. layering and depth dependent density/elastic structure)
=> requires to make assumptions about composition to select most suitable equations of state (thermodynamic and transport)

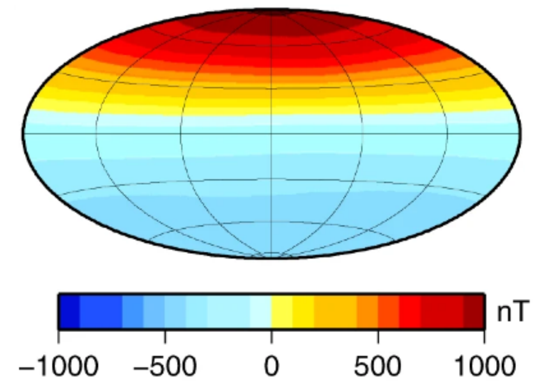
Interior structure: indirect constraints

- formation conditions highly reducing (e.g. Peplowski 2011)
    - mantle: FeO poor (almost none) rich in S (~12wt%)+ C (graphite crust)
    - core: candidate light elements in decreasing order of occurence: Si, S, C, P?,.. (e.g. Steenstra 2020)
- thermal state of planet: radial contraction, timing of crust emplacement, major volcanic activity
- magnetic field (core structure and thermal state)
    - dynamo: long lived (~3.9 Gyr), surprisingly weak dipole field, axisymmetric, equatorially asymmetric.. (e.g. Johnson 2015)
    - dynamo models require a thick upper core stable 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 and dynamo only sustainable with ongoing inner core nucleation requires unequal partitioning of light elements between solid and liquid core (e.g Hauck 2006, Knibbe 2018, 2021, 202x, Davies 2024)

MESSENGER



Dynamo simulation



BepiColombo

- significant improvement on precision of geodesy data
- updated information about magnetic field strength and geometry
- improve knowledge about bulk composition from surface spectra
- …

➡ tighter constraint on core radius, crust, and mantle structure (rheology, thermal state, ..) are expected

➡ direct constrain on core structure (inner core radius, thermal/chemical stratification, ..)
only if inner core signature is detectable (=> requires large inner core, precise determination of liberations (annual and longer), your new clever idea, ..)

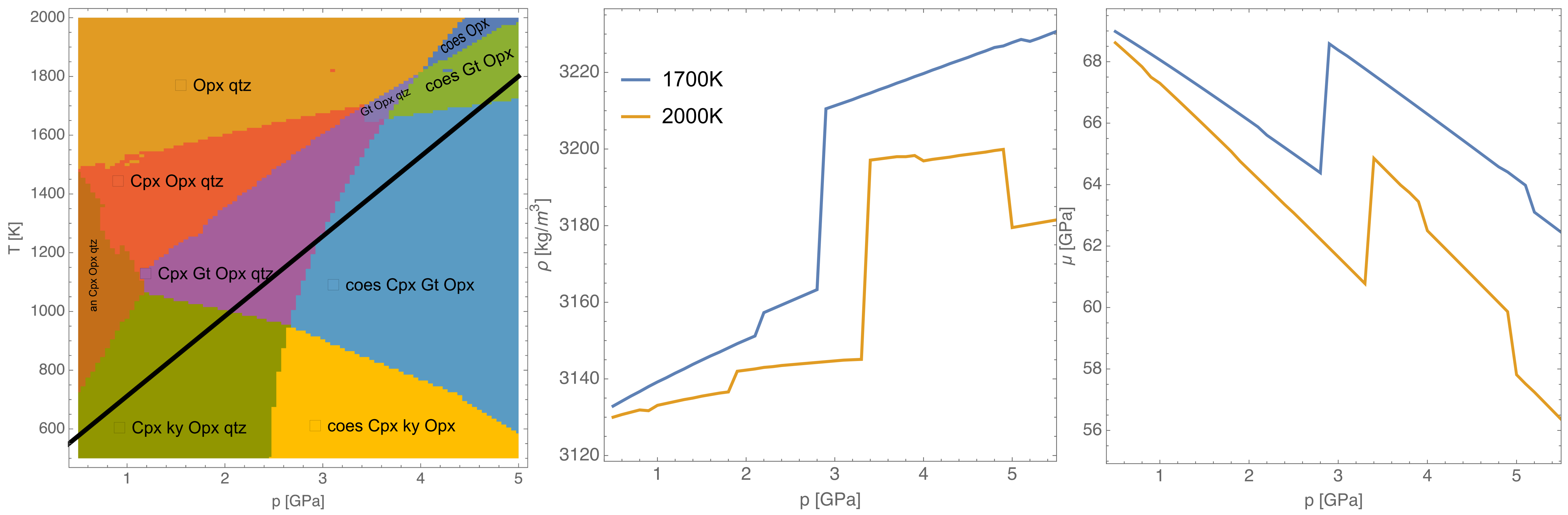
➡ structure inference requires precise modelling of whole planet using the most recent material properties (thermodynamic and transport)

➡ information about the core structure will mostly follow from the set of models that best agree with observations and prior assumptions (mainly core composition)

➡ inferred core structure information leans heavily on material properties and will be biased by our current lack of knowledge

Mantle composition
=> link density with elastic properties

- unlike Mars no meteorites or in situ samples only surface spectra
  - best analog: enstatite chondrite (predicts too much Si)
  - literature model: enstatite EC: (Wasson and Kalleymen, 1988)
    use Gibbs energy minimisation (PerpleX, Connoly 2005) to compute phase diagram and elastic properties from thermodynamic database (Stixrude 2024)

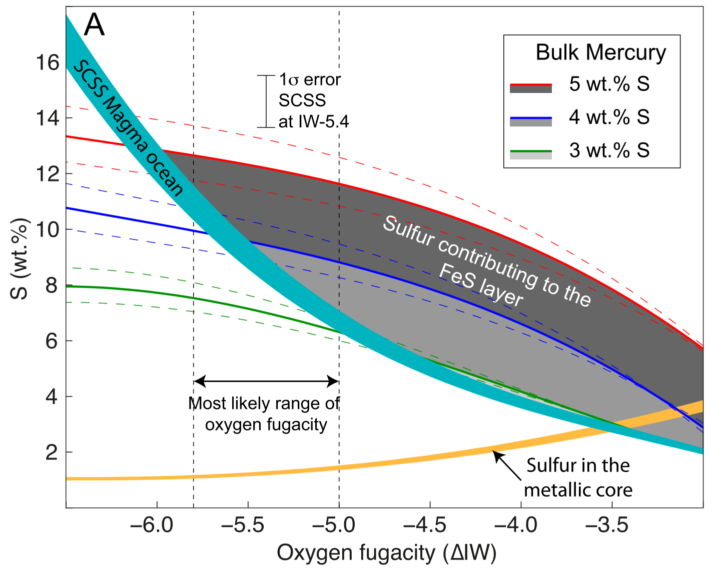


- opx(~70wt%) + cpx (~7%)+ gt(~11%)+quartz (over p range small variation in density and rigidity)
- caveat: requires experimental verification (end-members without Fe) not clear whether still in agreement with most recent studies and effect of mantle S on thermodynamic equilibrium not well known
- alternative: mechanical mixture of opx+cpx+fo (use equations of state from Stixrude 2024)

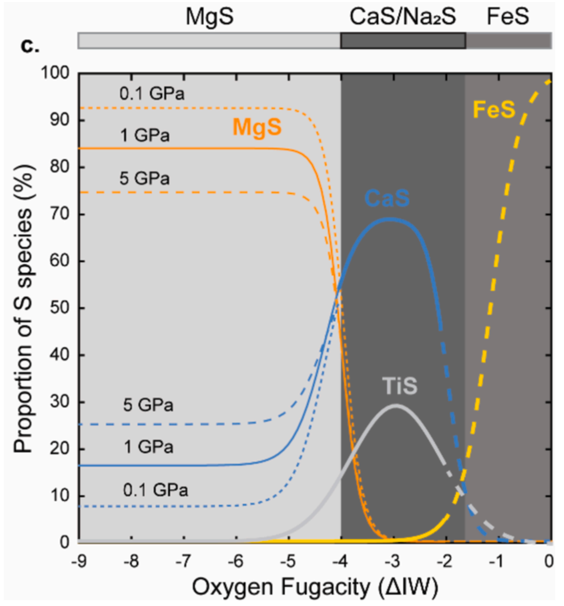
Mantle composition => effect of sulfur

- Mercury's mantle contains ~12wt% of S (e.g. Malavergne 2014) as FeS+CaS+MgS. Sulphide speciation depends on (p,T, fo2) (Anzures 2025)

Namur 2016

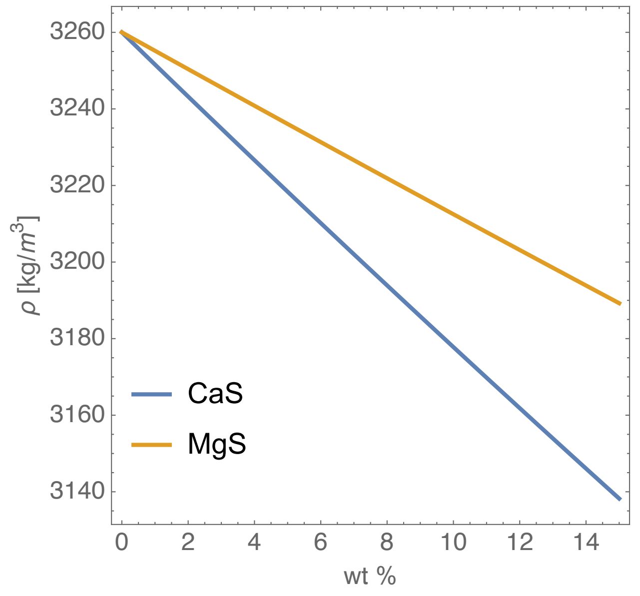


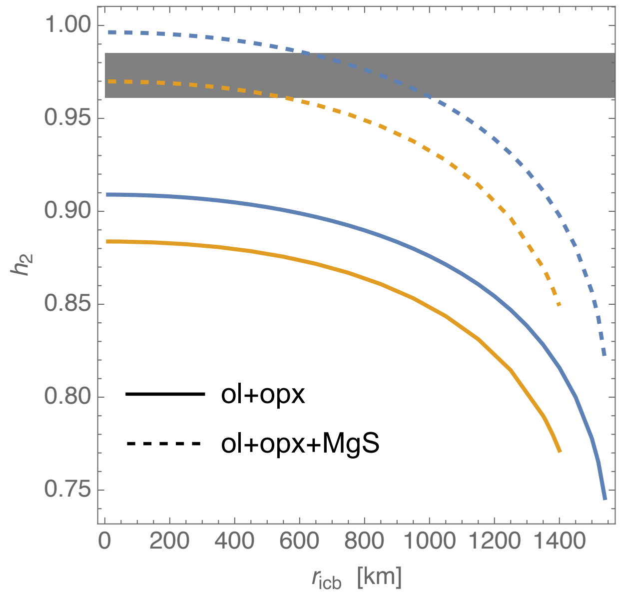
Anzures 2025

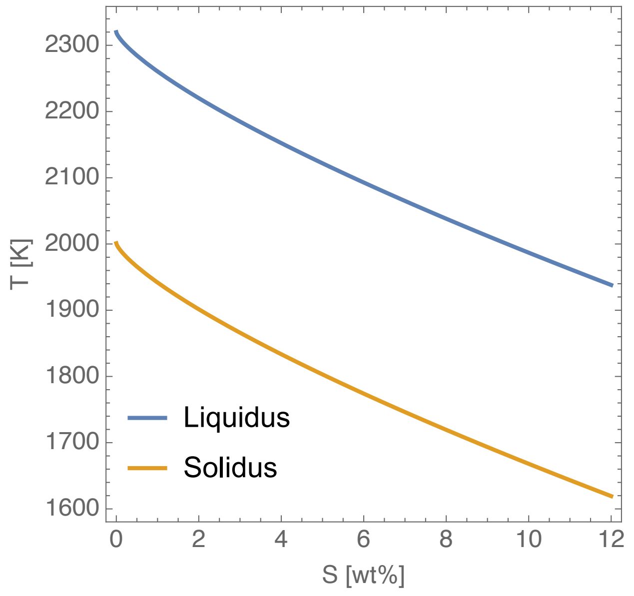


=> the most likely S compounds are MgS and CaS

- MgS and CaS are significantly less dense than silicate mantle phases (2590kg/m³ and 2840 kg/m³) and both make the mantle softer. Sulfur has a strong effect on the solidus and liquidus temperature of the mantle (Xu 2024).





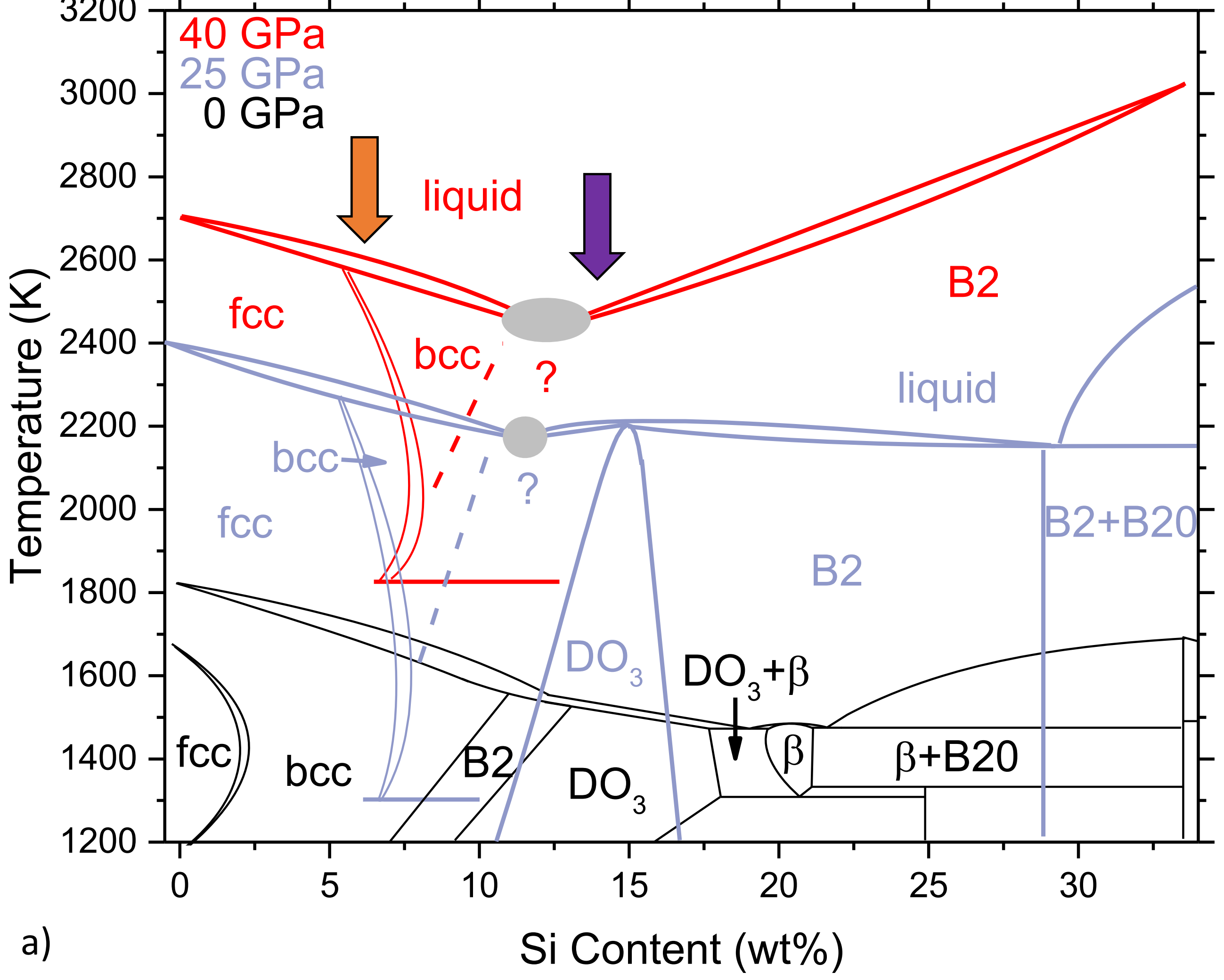


=> elastic Love numbers can be significantly larger
=> significant effect on Mercury's thermal state via timing of crust emplacement and core dynamics

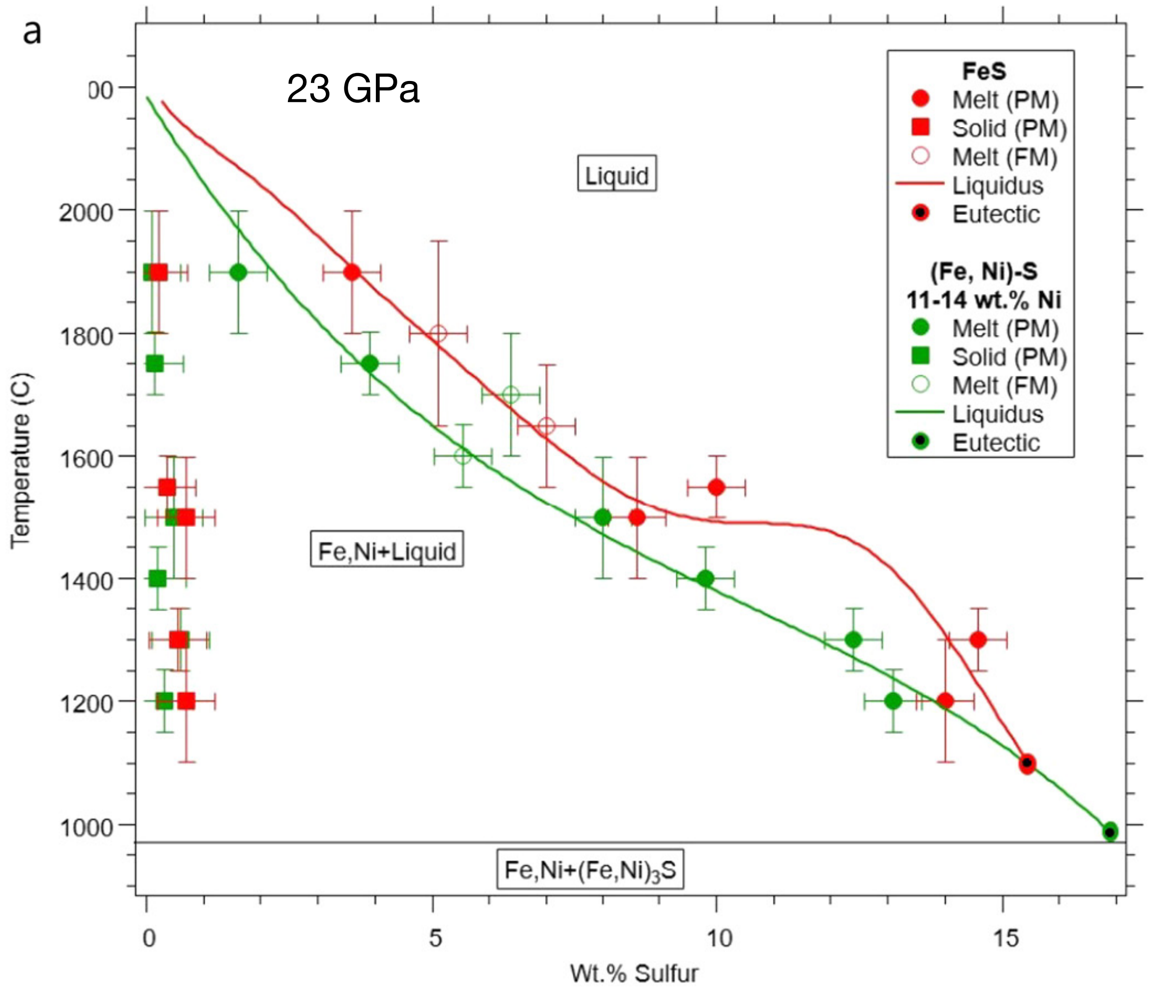
- Caveats:
  - equations of state of MgS and CaS not so well known (rigidity computed from bulk modulus assuming a Poisson ratio)
  - distribution of CaS/MgS in the mantle is not known: layering or homogeneous

Core composition: binary phase diagrams

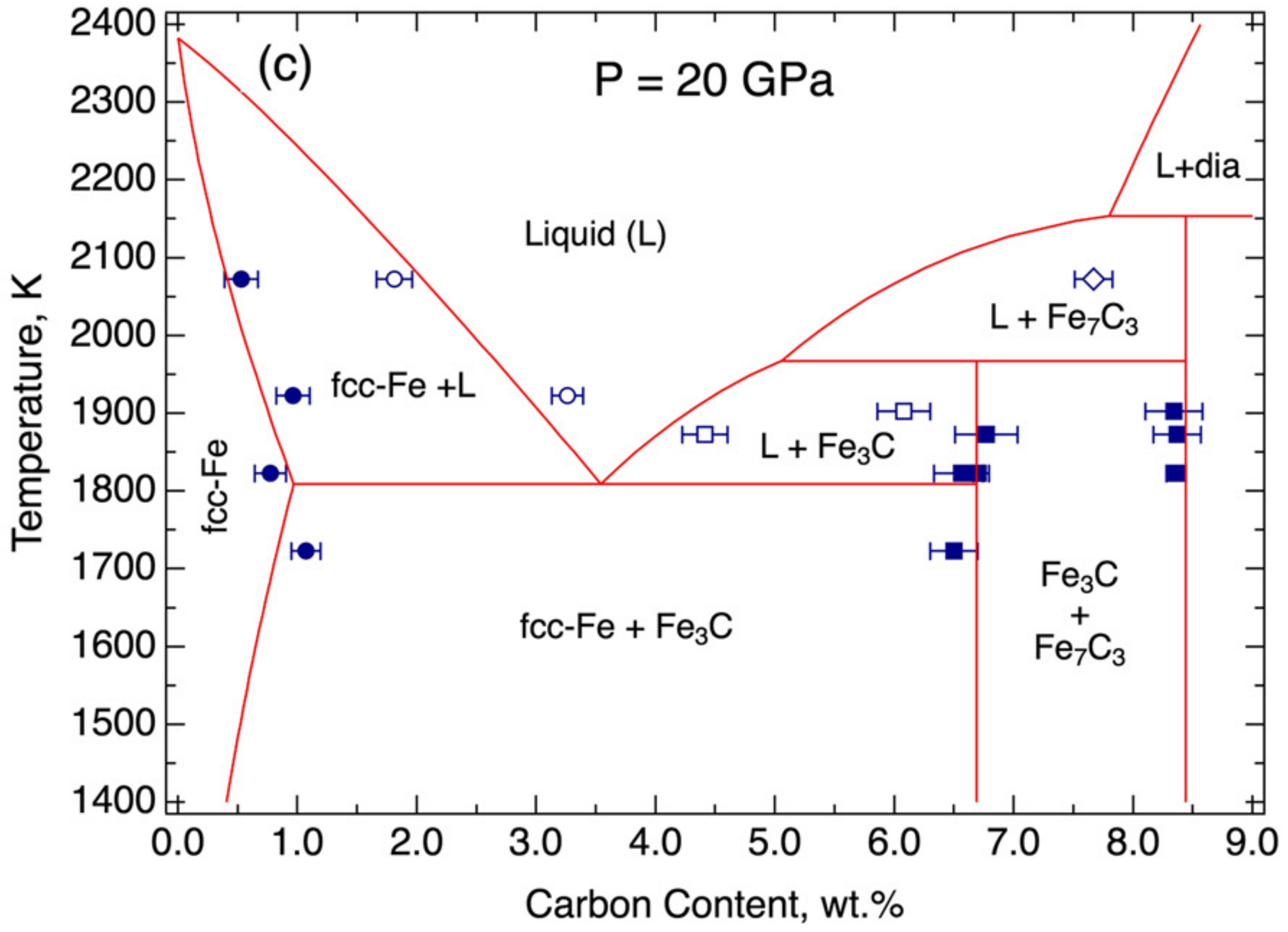
Edmund 2022



Pease 2022



Fei 2014



- least well known
- eutectic: 23wt% (1bar) -12.5wt% (40GPa)
- 25GPa: 12.5wt%(eutectic) Si -> ΔT~200K
- $D_{\mathrm{Si}}^{\mathrm{sol/liq}} \sim 1.$
- liquidus phases: fcc Fe-Si, bcc Fe-Si,B2 Fe-Si, l Fe-Si
- equations of state:
  Terasaki 2019, Edmund 2022, Yokoo 2023
  approximate rigidly of fcc/bcc Fe-Si from its bulk modulus and Poisson ratio of fcc/bcc Fe

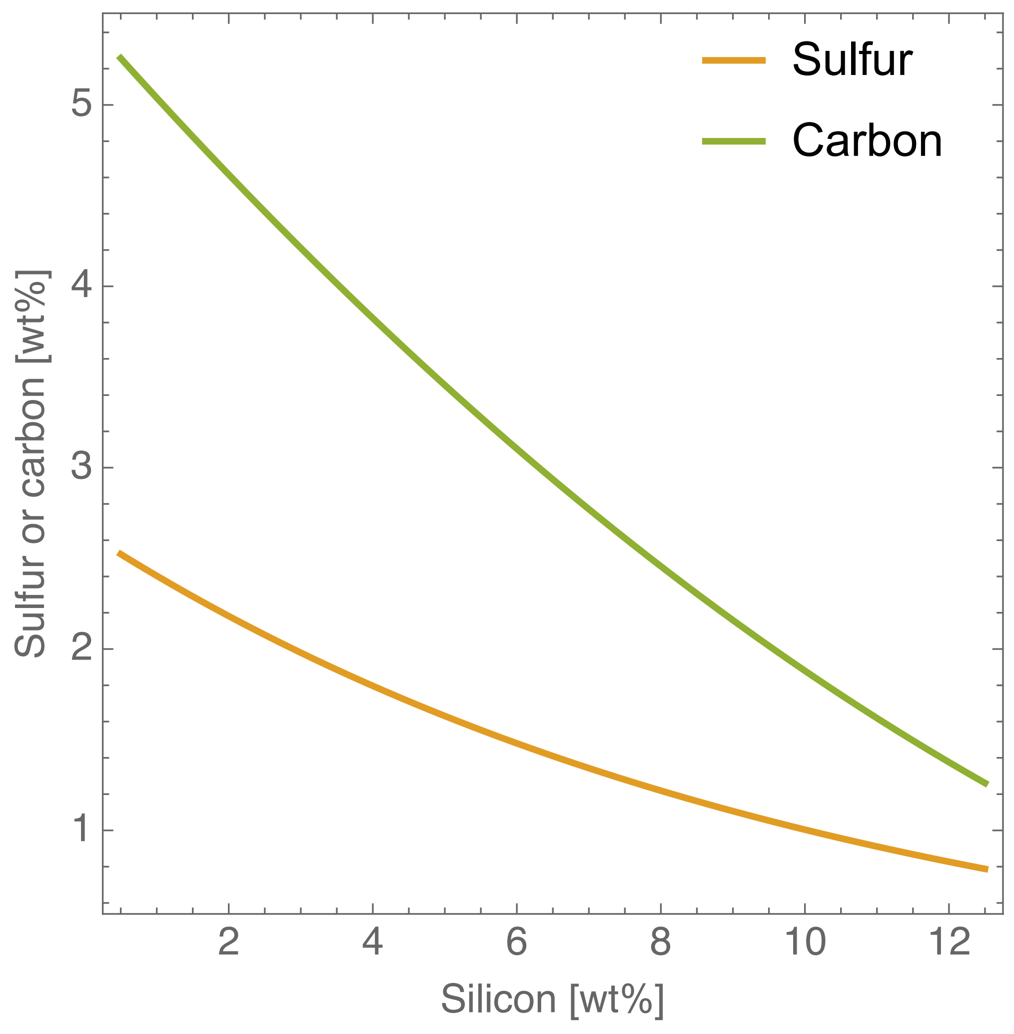
- extensive data
- eutectic: 25.wt% (5GPa) -12.wt% (40GPa)
- 23 GPa: 15.wt%(eutectic) S -> ΔT~850K
- $D_{\mathrm{S}}^{\mathrm{sol/liq}} \sim 0.$
- liquidus phases: fcc Fe, l-Fe-S
- equations of state:
  Le Maistre 2023,Terasaki 2019, Dorogokupets 2017

- thermodynamic model (not in very good agreement with elastic properties of Fe-C)
- eutectic: 4wt% (5 GPa) -2.8wt% (40GPa)
- 20 GPa: 3.5wt%(eutectic)-> ΔT~600K
- $D_{\mathrm{C}}^{\mathrm{sol/liq}} \sim 0.3$
- liquidus phases:
  fcc Fe-C, l-Fe-C
- equations of state:
  McGuire 2021, Le Maistre 2023

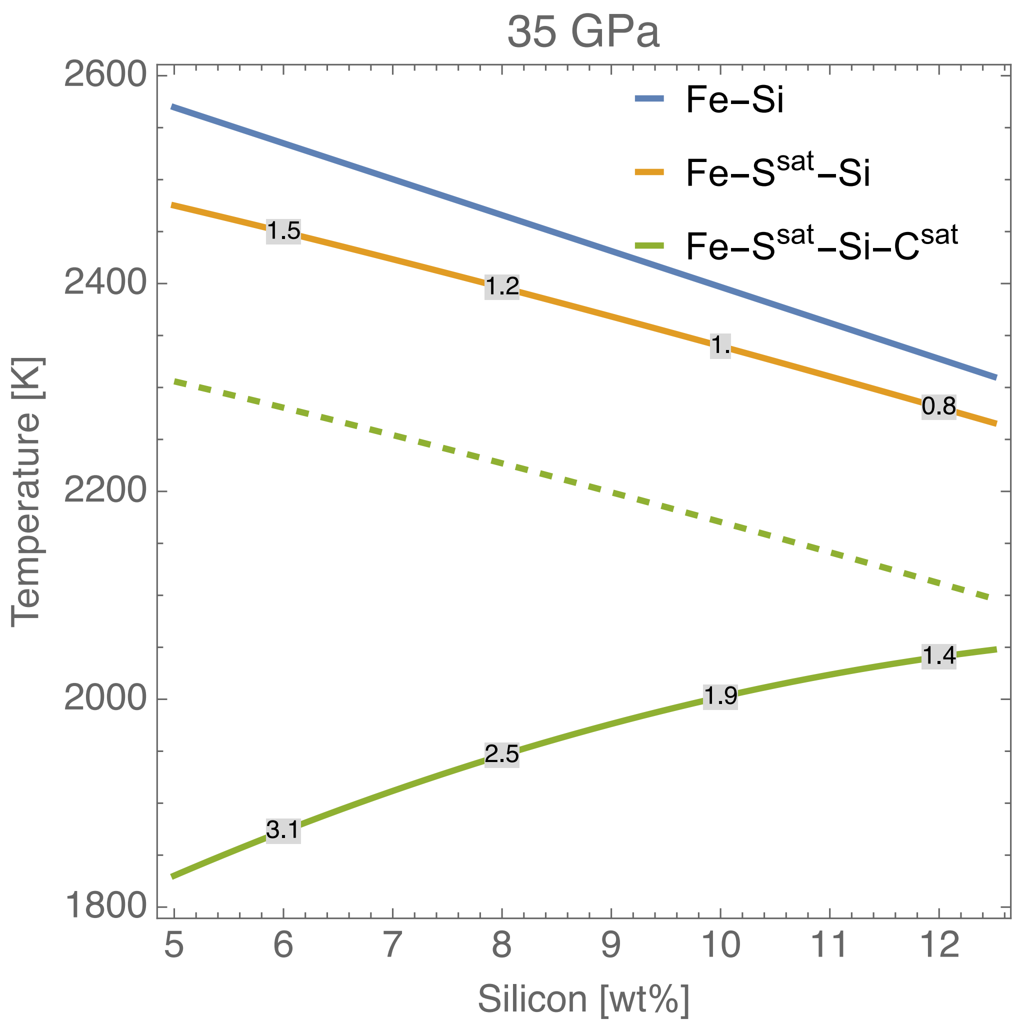
Core composition: Fe-S-Si-C

- why bother?
    - liquid Fe-Si core requires present-day T_{cmb} close or above mantle solidus
    - cannot explain the present-day magnetic field (Rivoldini 2022)
- a few wt% of S or C are enough to reduce core temperature below mantle solidus and allow for a present day dynamo
- Si, S, and C partition differently between solid and liquid Fe => affects inner core density structure (can affect libration, could be detected?)
- the maximal amount of sulphur and carbon in the core decreases with increasing amount of silicon (e.g. Namur 2016, Boujibar 2019) => reduction of degrees of freedom
- Mercury's core is carbon saturated (e.g. Lark 2023, Xu 2024)
  => Mercury's core contains a solid graphite or diamond upper layer (~1-2 km) (Xu 2024)
  => if C is saturated in Fe-S-Si inner core nucleation requires T_{cmb}<1600K (assuming T is adiabatic) ⇾ present day T_{cmb} ~150K lower!!
  => Mercury not C saturated, or can we build a model consistent with observations? (geodesy, dynamo, crust emplacement timing, ..)

S(Si)-C(Si)

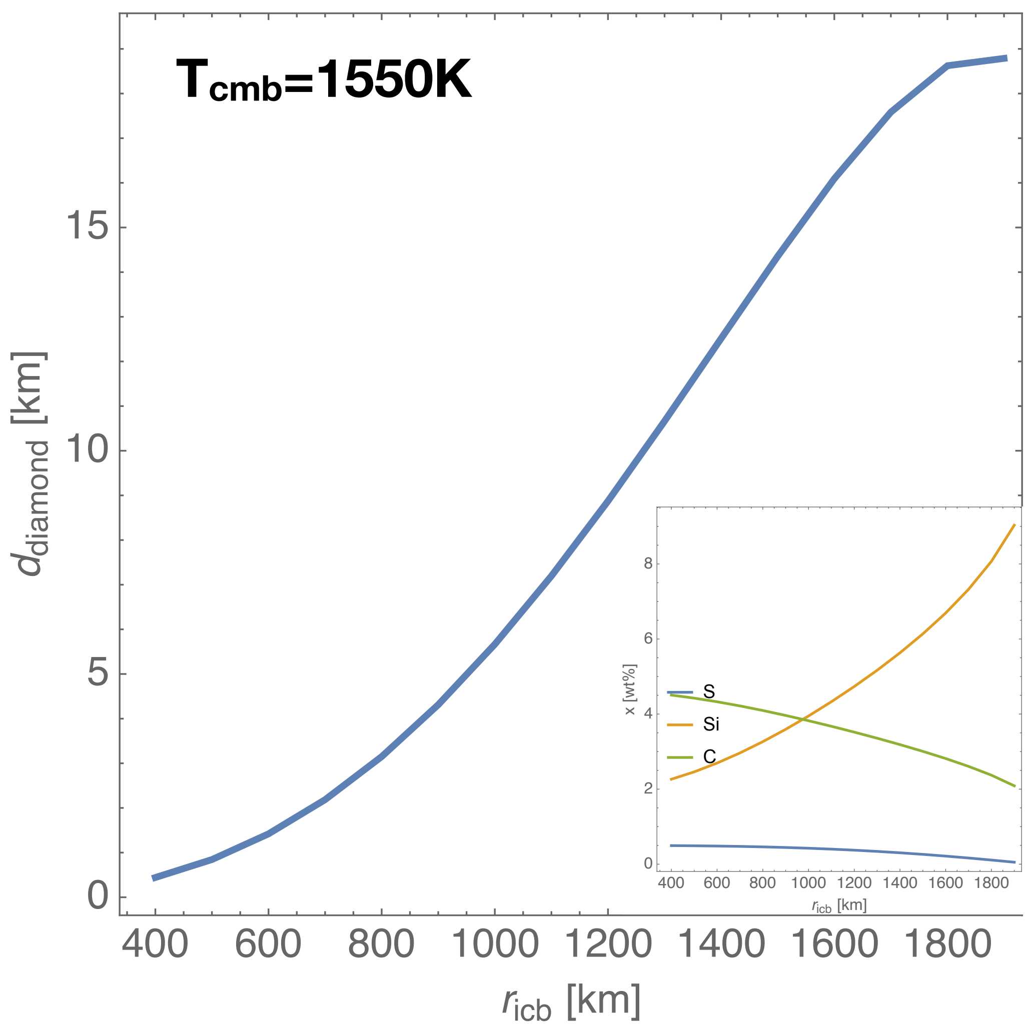


Inner core nucleation temperature



(isentropic ΔT_{core} ~ 500K)

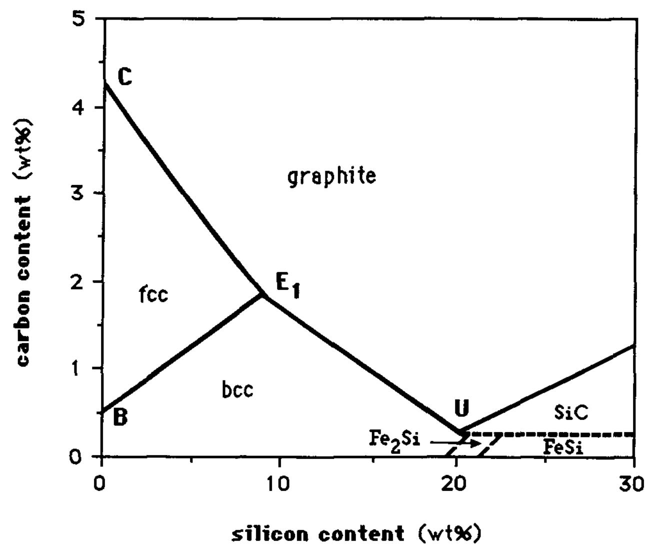
Diamond layer thickness



Core composition: further complexities

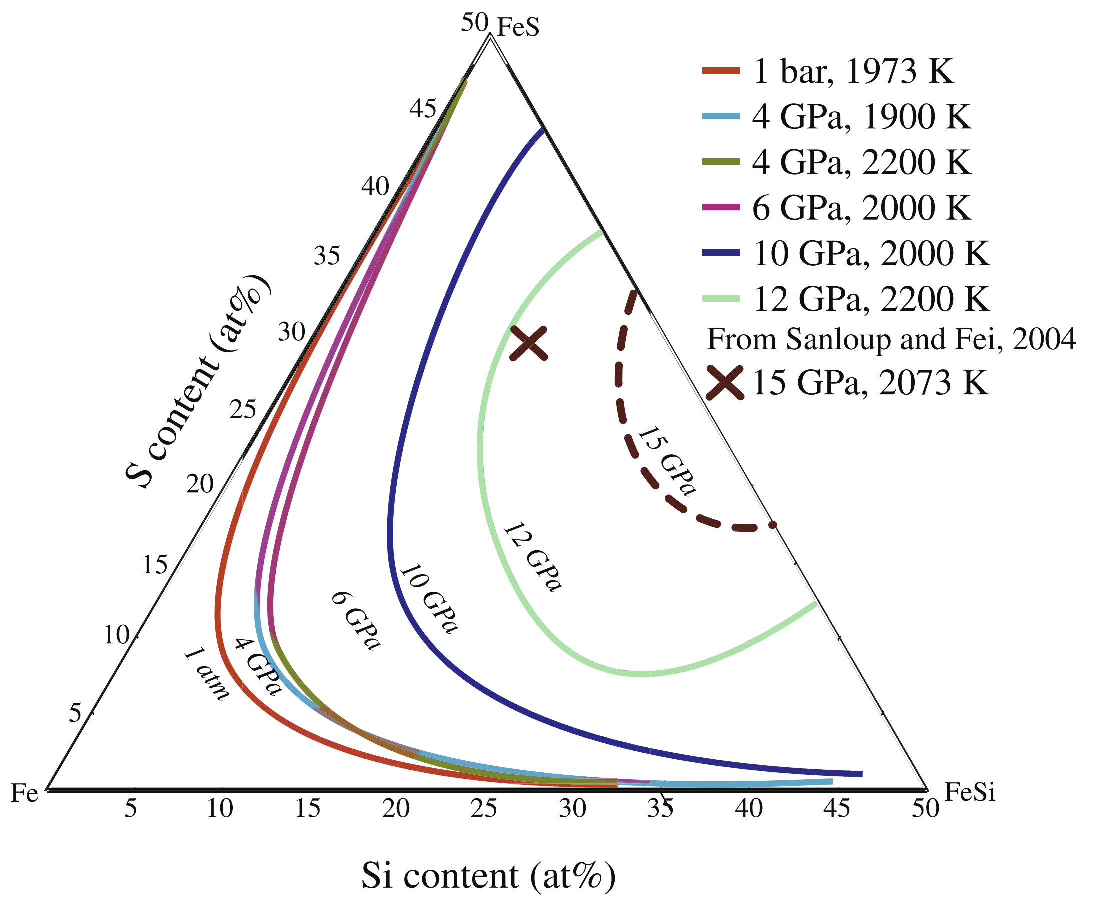
- combined effect of Si,S,C on melting T of Fe not well known
  => since amount of S and C ~O(1) wt% assume ideal mixing behaviour of S and C in l-Fe-Si:
  $T_m(S,Si,C)=T_{mFeSi}(p,Si)-(1-x_S)\ \Delta T_{Fe\text{-}S}(p)-(1-x_C)\ \Delta T_{Fe\text{-}C}(p)$

- effect of C on structure of solid Fe-Si unknown, 1 bar fcc or bcc Fe-Si-C



  => eos of bcc and fcc Fe-Si-C unavailable: approximate by solid ideal solution with bcc/fcc Fe-Si and Fe_3C

- Fe-S-Si liquids are miscible in a reduced composition field

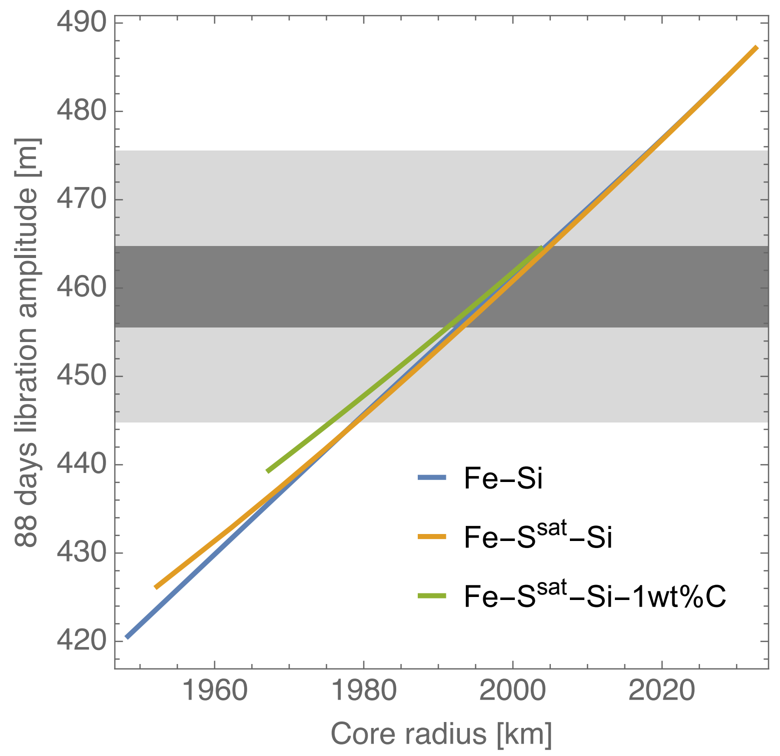


  => depending on initial bulk composition an almost liquid FeS layer can form below the CMB (effect of adding C unknown (except at 1bar))

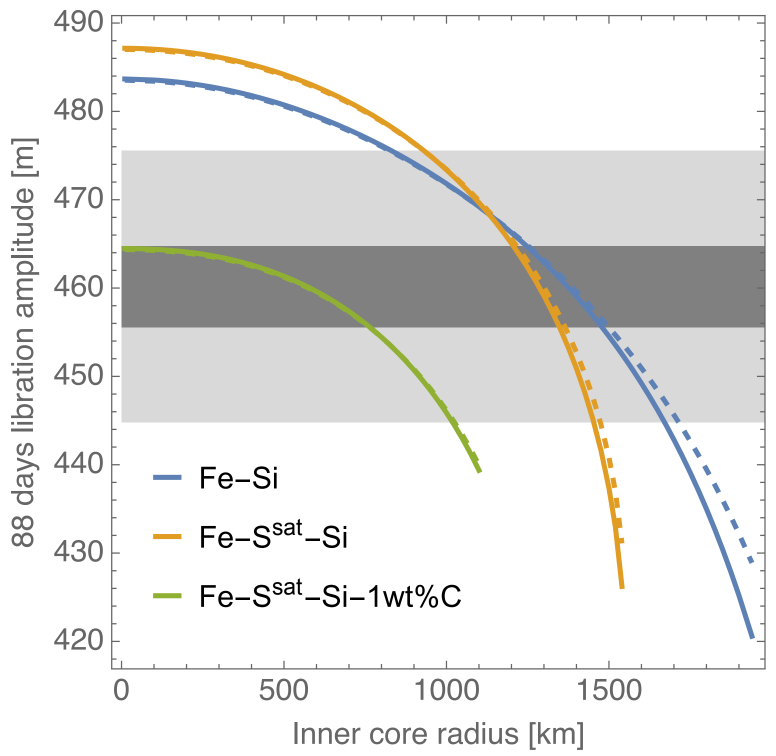
Untangling the core

- Libration (annual and long period)

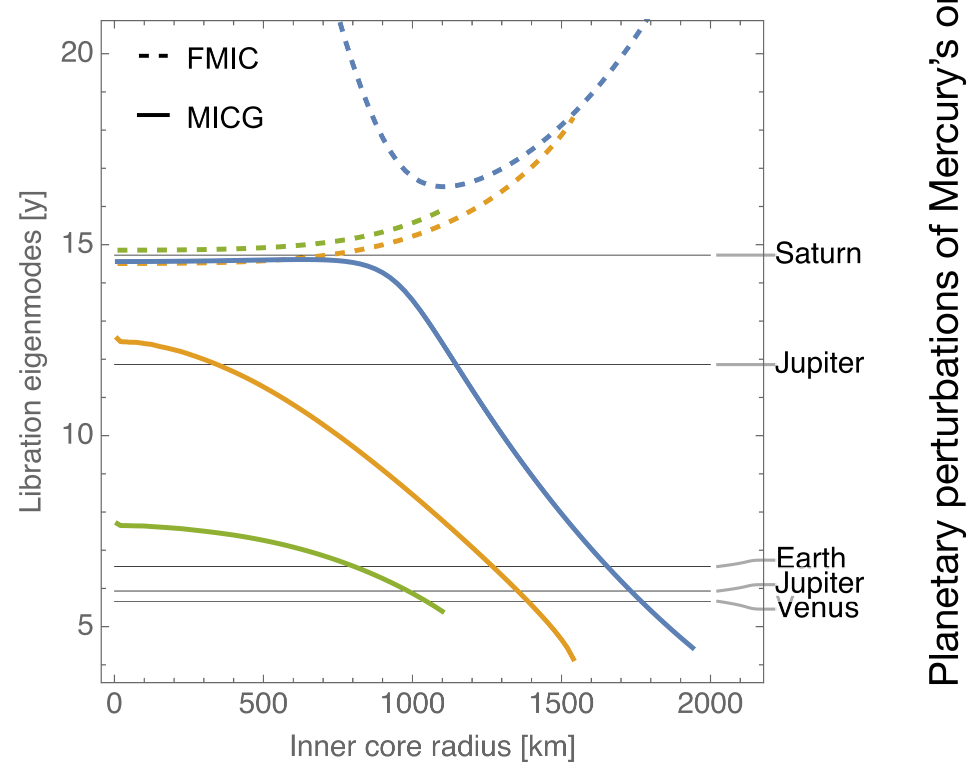
88d



88d



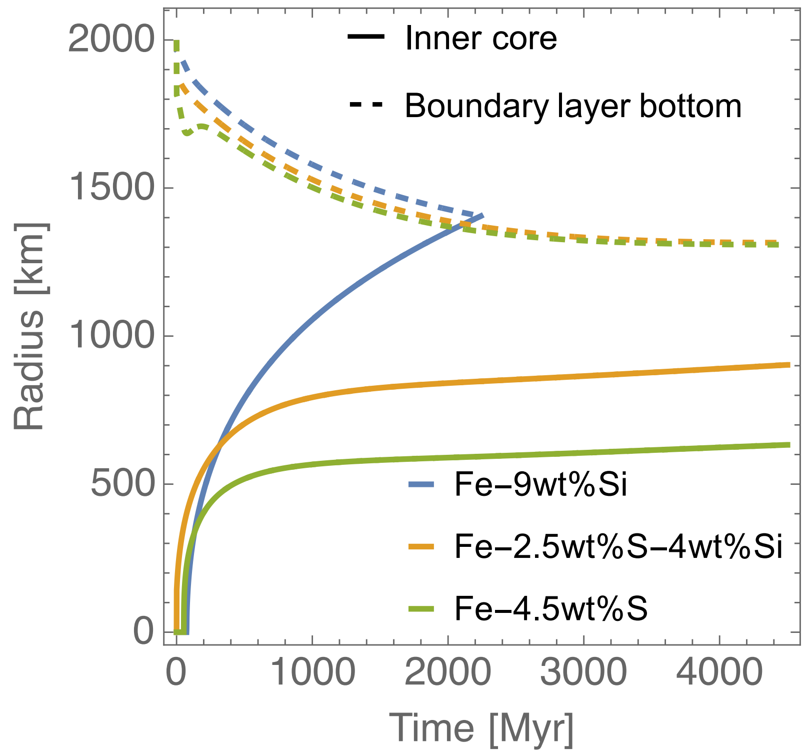
Long period

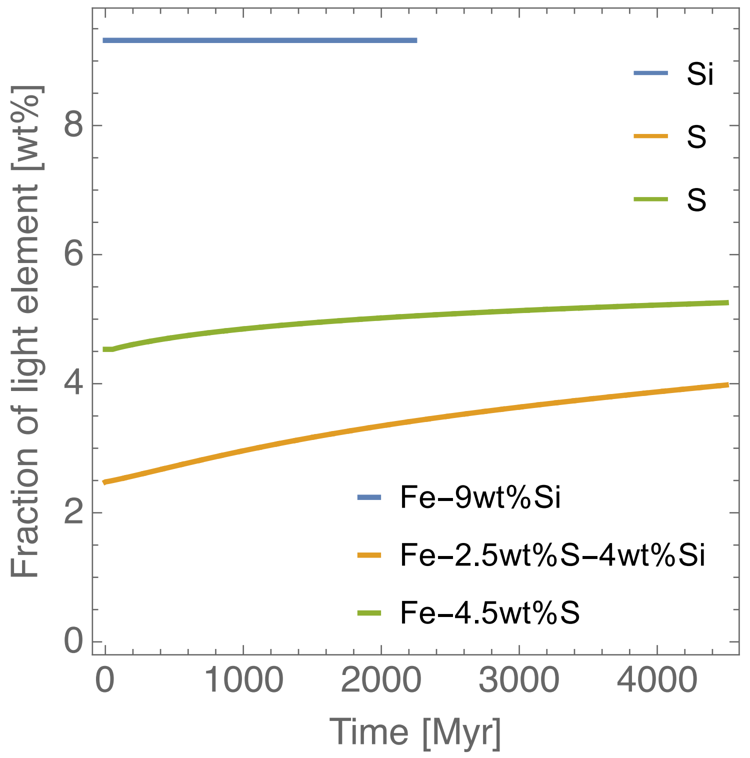


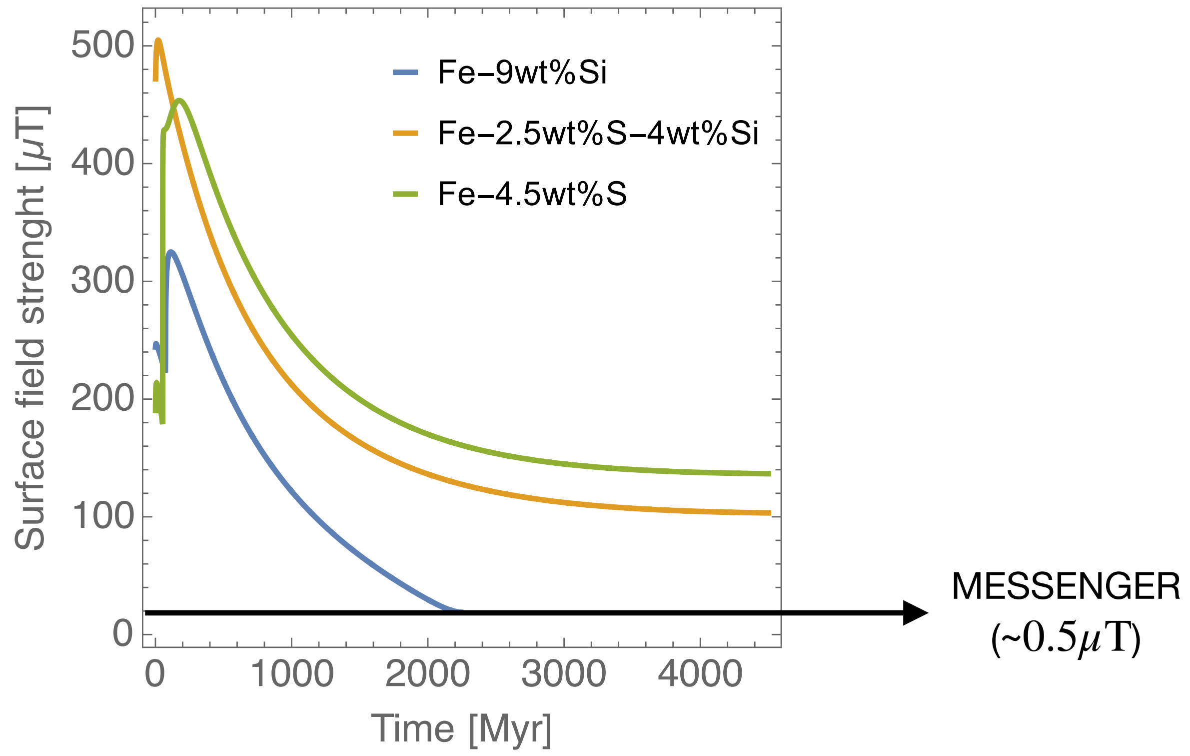
=> 88d libration: precise core radius determination, indirect determination of core structure if composition is known, informs directly about inner core radius if it is large

=> long period eigenmodes are directly affected by core composition

- Whole planet thermal evolution that also models the core's capacity to generate a magnetic field





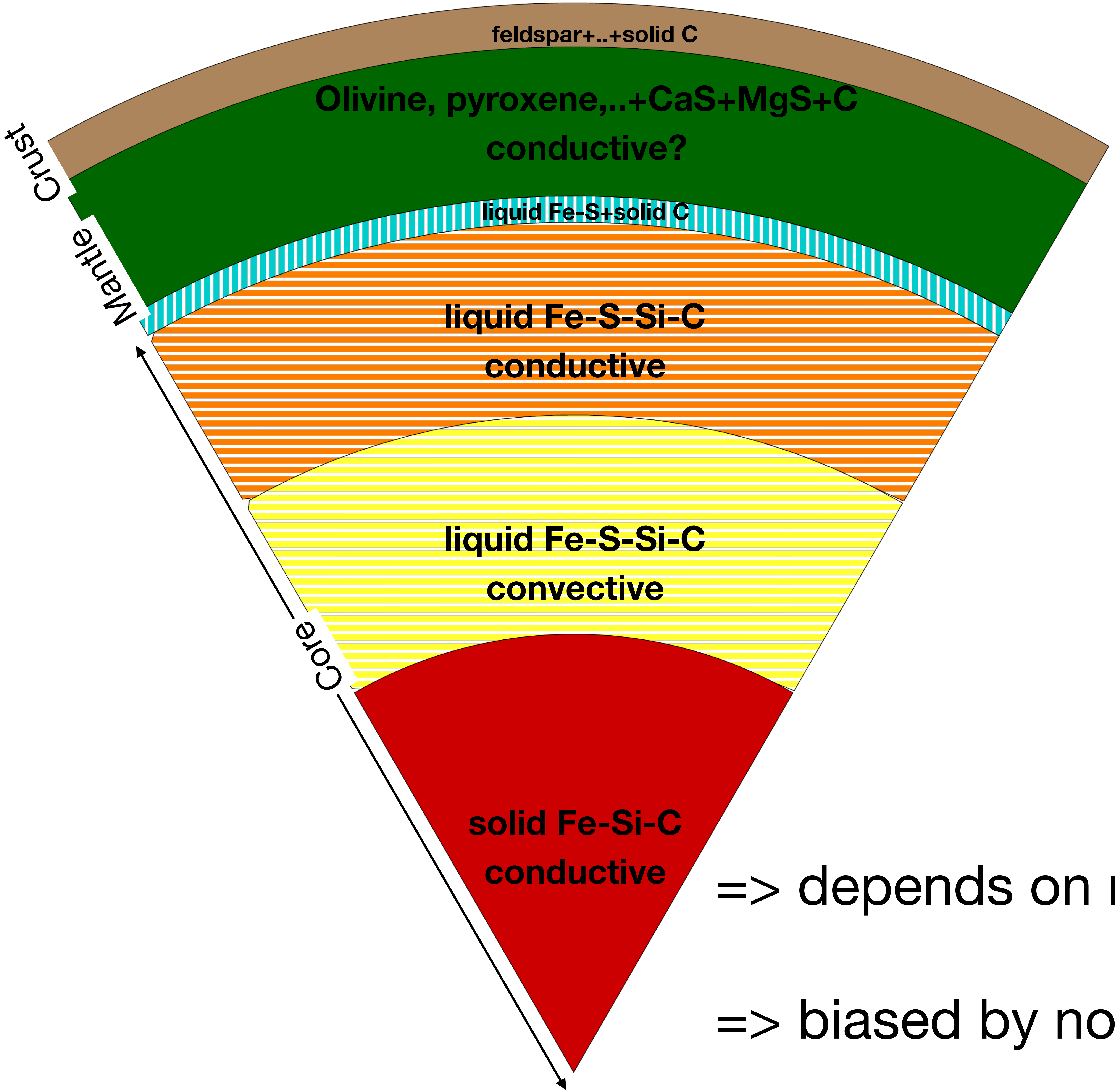


=> informs about the core structure (inner core radius, thermal boundary layer thickness)

=> Fe-Si models with present day dynamos require a small fraction of S or C

=> combine interior structure modelling with whole planet thermal evolution

Expected end-result



- internal layering
- thermal state
- core structure

=> depends on results obtained from BC

=> biased by not well-known material properties

Not mentioned

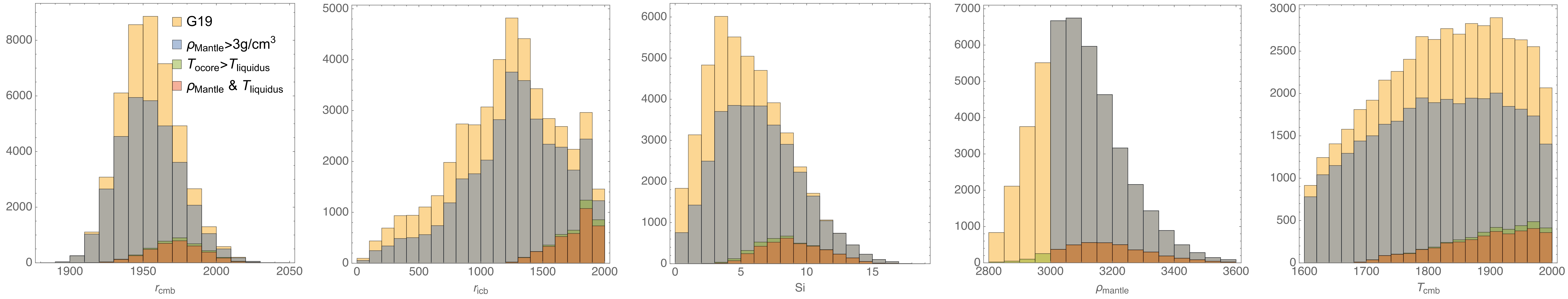
- modelling of core thermal boundary layer (use results from thermal evolution calculation). requires knowledge of thermal conductivity of Fe-S-S-C alloy

- composition and pressure dependent partitioning of light elements between solid and liquid Fe (can that be done without a cooling scheme) => does it affect libration in a measurable way

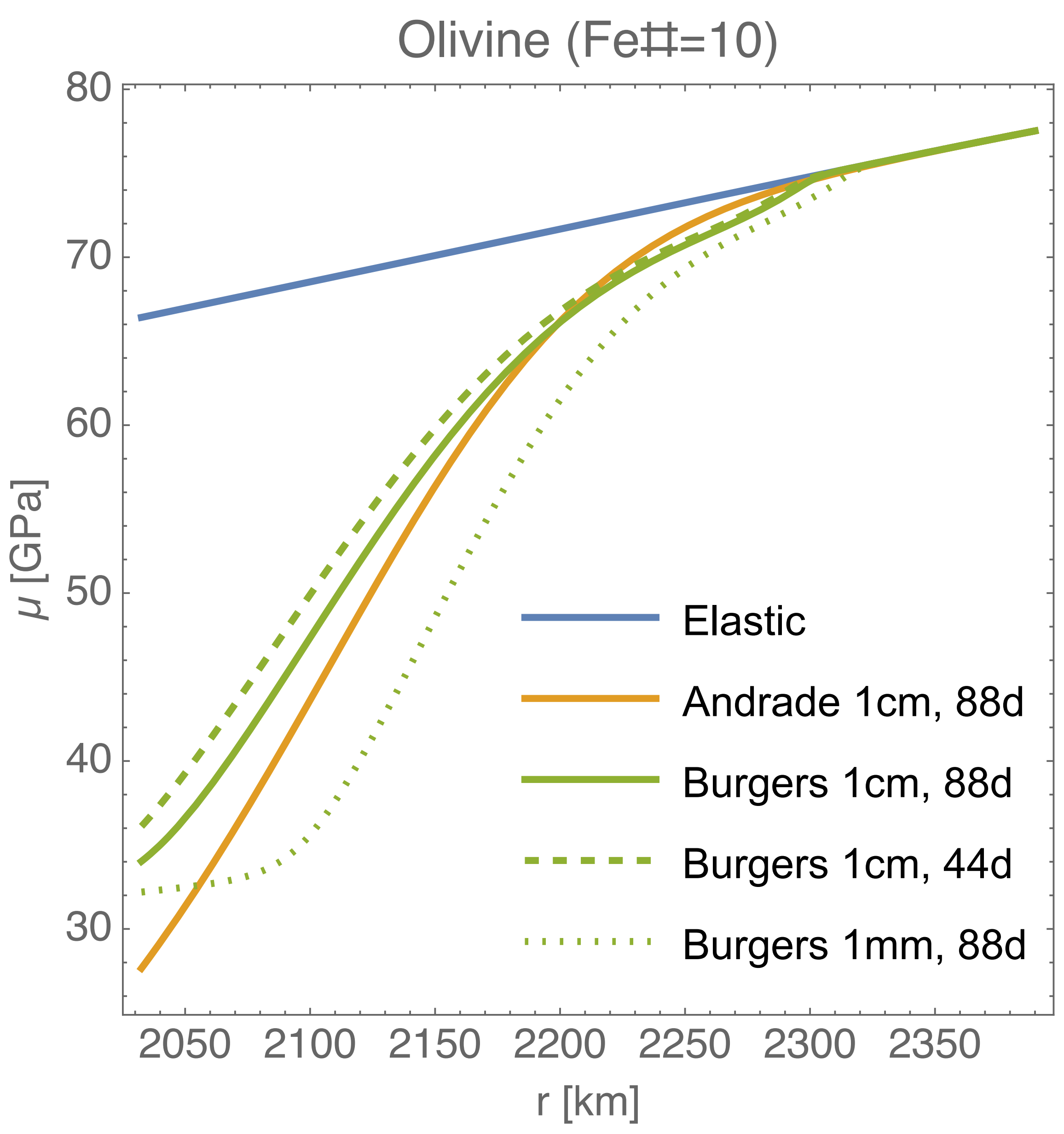
- melting entropy of Fe-Si-C (well known at 1bar) required for thermal evolution

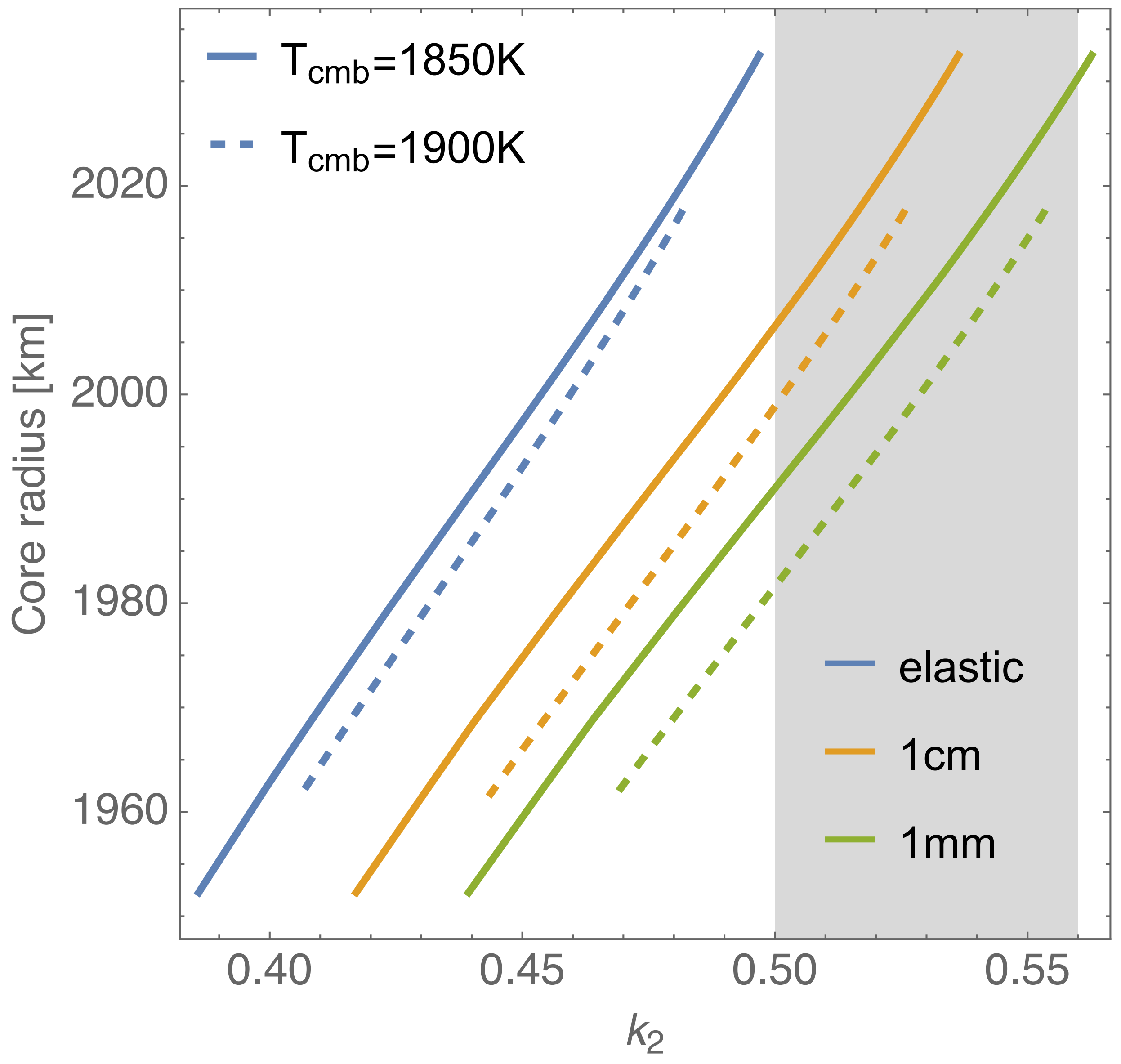
The Goossens 2022 way

- neglect core liquidus
- assume unphysical prior ranges
- make an uninformed choice for the equations of state
- neglect mantle solidus



Love numbers and rheology





- Love numbers inform on the core radius of a planet (Mars Δk2<4% -> core radius 50km)
- unlike Mars (tidal forcing 12h) the tidal response of Mercury (tidal forcing 88d) is significantly affected by its anelasticic rheology ~ strong effect on real part of h2 and k2
- core radius can only be constrained by Love numbers if mantle rheology is well known
- precise determination of Love number (~0.5%) will constrain rheology of the Mantle (not straightforward to relate this constraint to rheology effective at mantle convection time scale)

- lab. data for olivine (Fe#=10) (Jackson 2014)
  and ol-px mixtures (Fe#=10,1bar, Qu 2021)
- effect of Fe on Ol and pox not well known ~ viscosity increases with decreasing Fe (Zhao 2009)