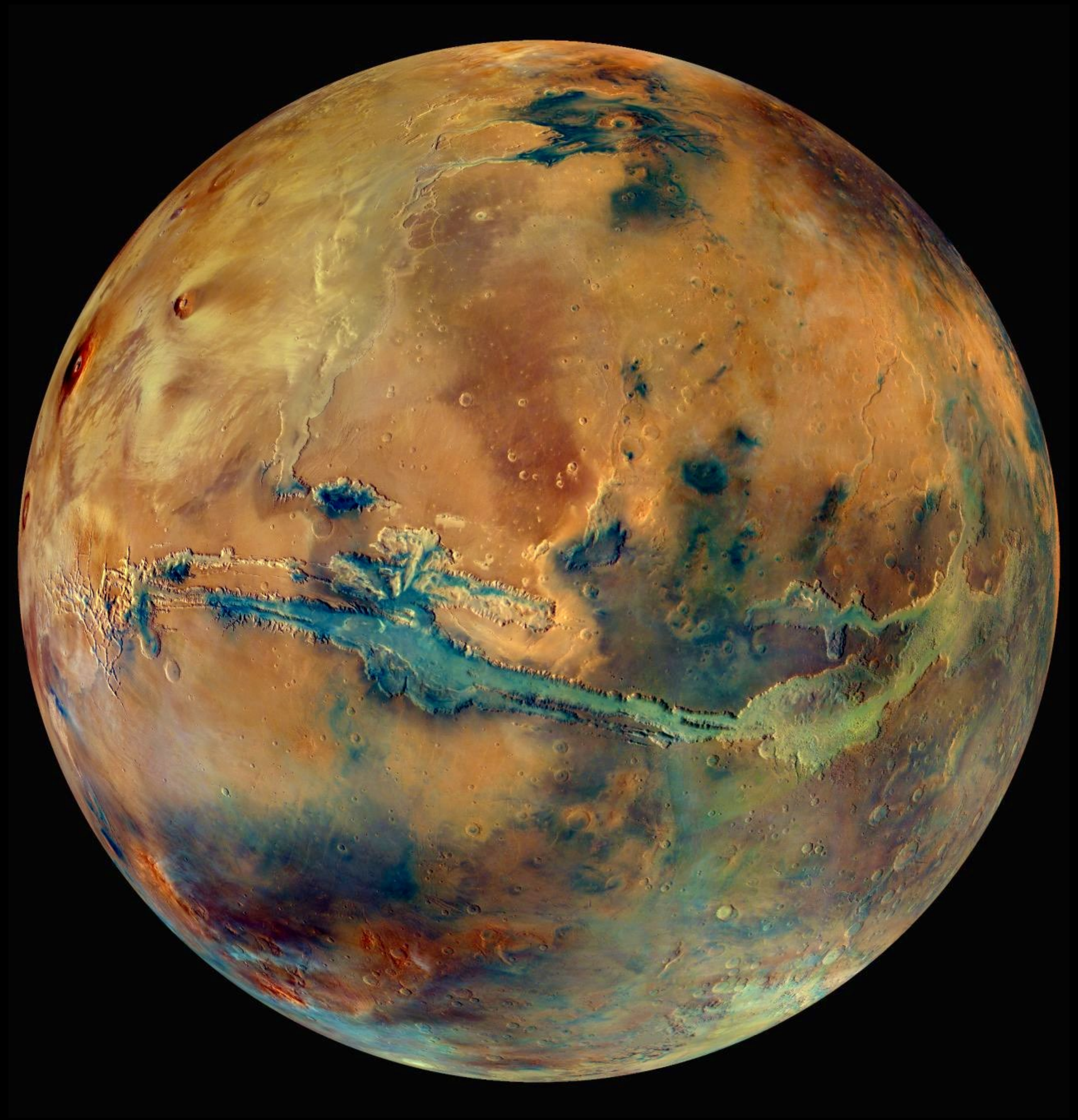
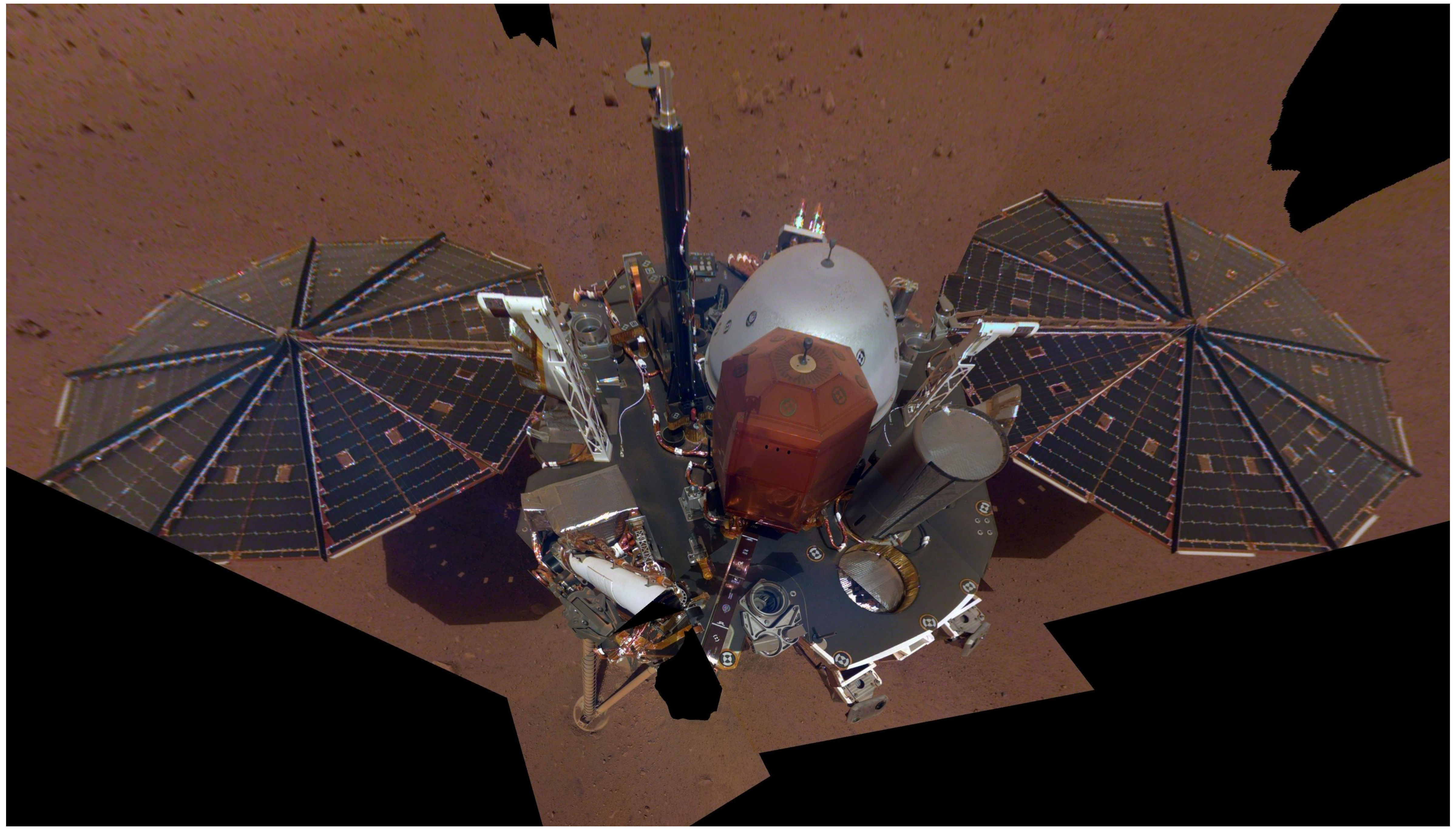
A deep dive into the interior structure of Mars



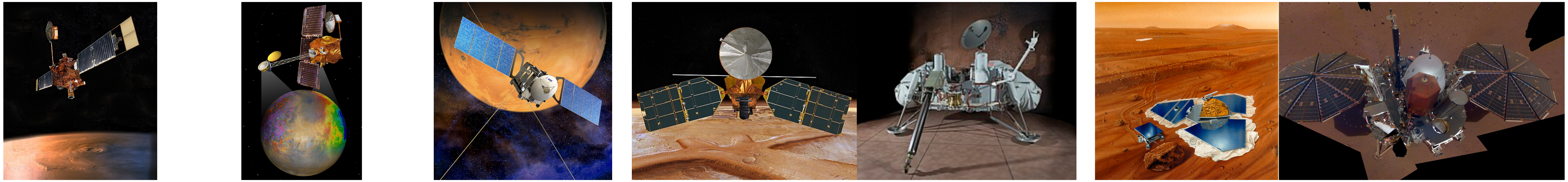
Attilio Rivoldini, Royal Observatory of Belgium, SEDI 2024 Great Barrington

InSight mission to Mars (2018-2022)



- first geophysical mission dedicated to the study of the interior structure, evolution, and formation of Mars
- 3 main instruments: seismometer **SEIS**, heat-flow measurement probe **HP3**, radio-science experiment **RISE**
- mission objectives related to deep structure:
  crust structure, mantle seismic velocity profiles, core state and radius, surface heat flow

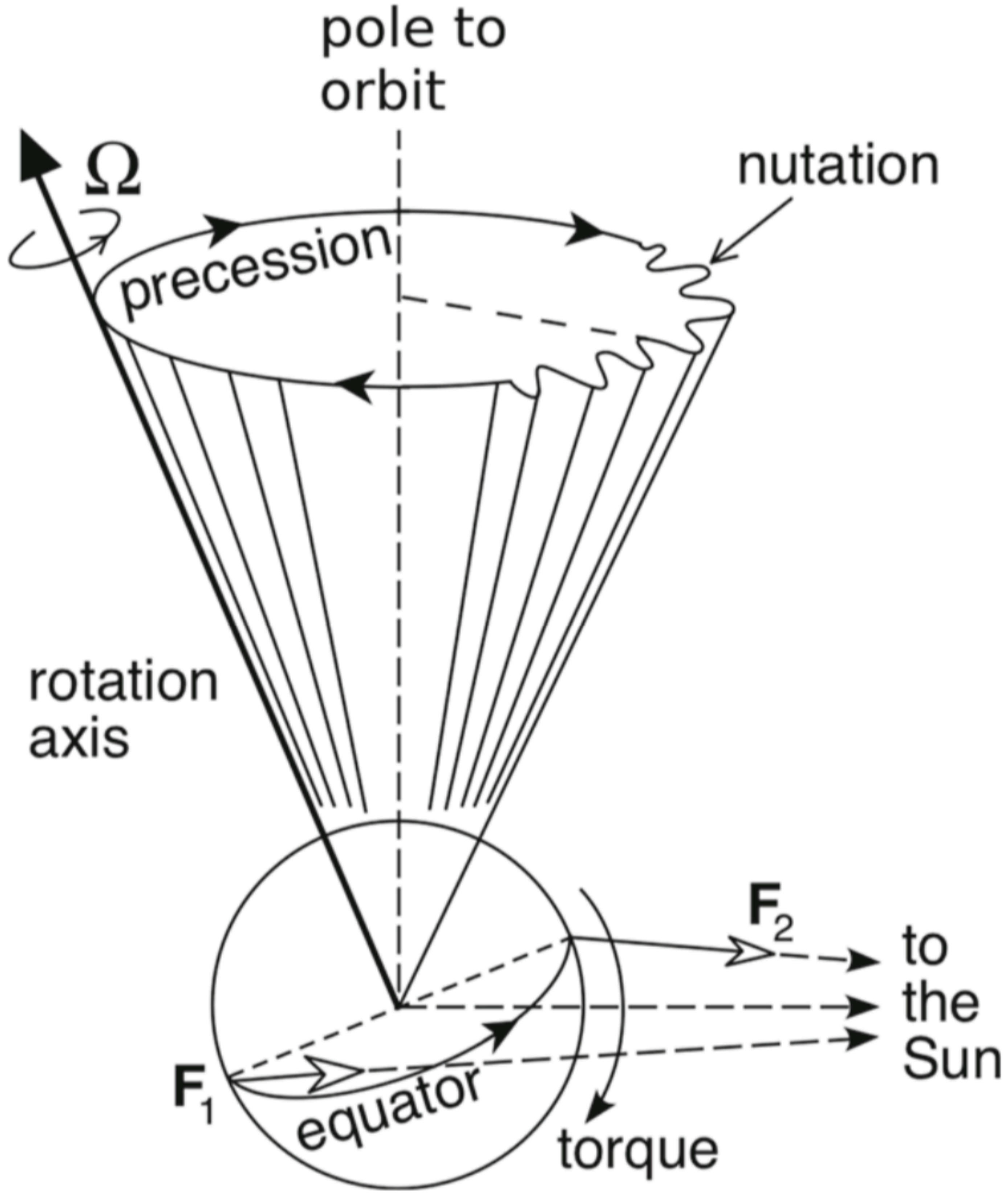
Geodesy observations: tracking orbiters and landers from Earth with DSN antennas



- orbiter tracking over more than 25 years (Mars Global Surveyor: 1996-2006, Mars Odyssey: 2001, Mars Express: 2003, Mars Reconnaissance Orbiter: 2006,..)
- lander tracking (Viking 1+2: 1976-1982, Mars Pathfinder: 1997, InSight: 2018-2022*)
- **static gravity field** up to degree 120 (Moon: 1200, Earth 5399)
- **time variable gravity field**: Love number k_2 at period 12 h
- **rotation**: precession, spin rate, Chandler Wobble, nutation
- **rotation normal modes**: **C**handler **W**obble (CW), **F**ree **C**ore **N**utation (FCN)

k_2, precession, nutation, wobble, and all that

- periodic tidal forcing by the Sun and other planets causes Mars’ shape to change periodically, the yielding is characterised by Love numbers (~measure of planet rigidity)
- the gravitational torque exerted on the flattened rotating Mars causes a precession of the rotation axis in space (~171 00 years)
- periodic torque variations due to the relative positions between the Sun and other planets and Mars lead to periodic motions of the rotation axis, the nutations (±1,±1/2,±1/3,±1/4.. year)
  ⇒ lander position changes by ~10 m on the surface
- the motion of the flattened Mars’ rotational axis relative to its crust is called polar motion (includes nutation), a component of that rotation is caused by the Chandler Wobble rotation normal mode (amplitude 10 cm, Earth 9 m)

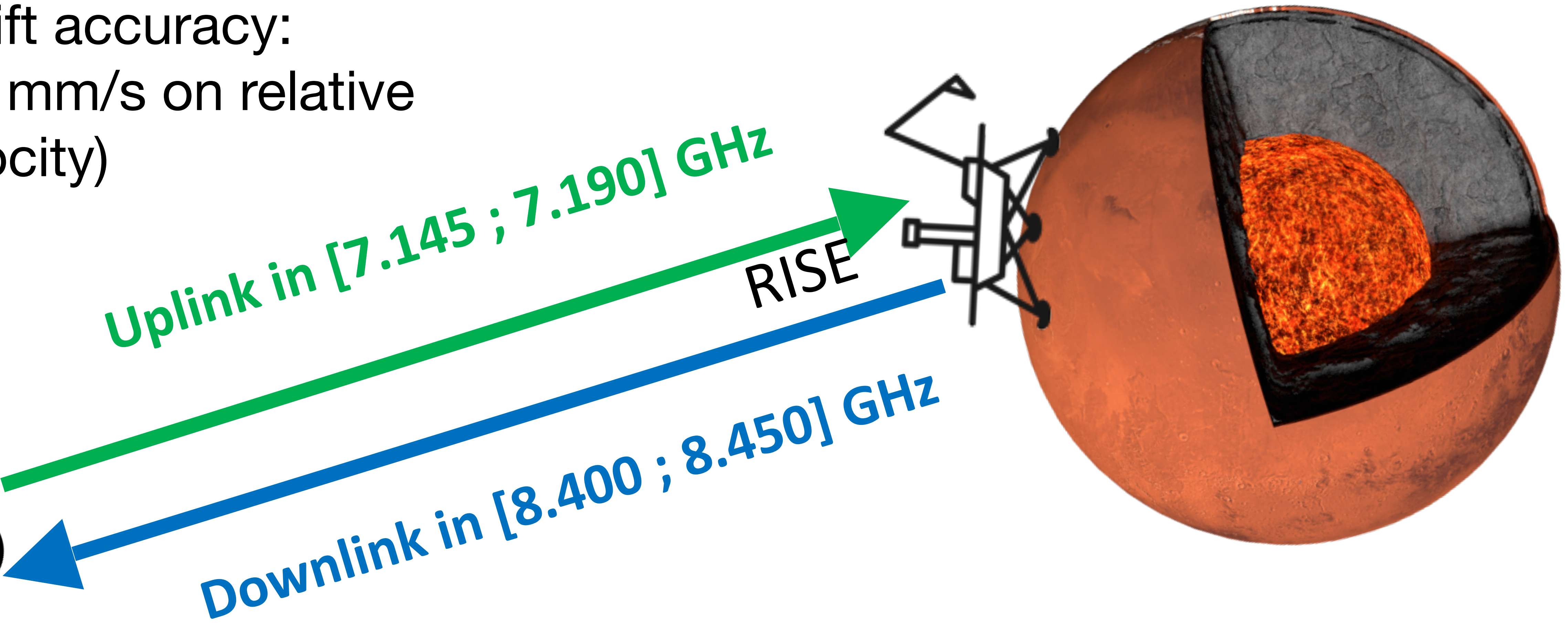


Example geodesy observations: RISE

Doppler shift accuracy:
~1.5mHz (0.027 mm/s on relative velocity)

Deep **S**pace **N**etwork tracking stations (USA, Australia, Spain)

DSN

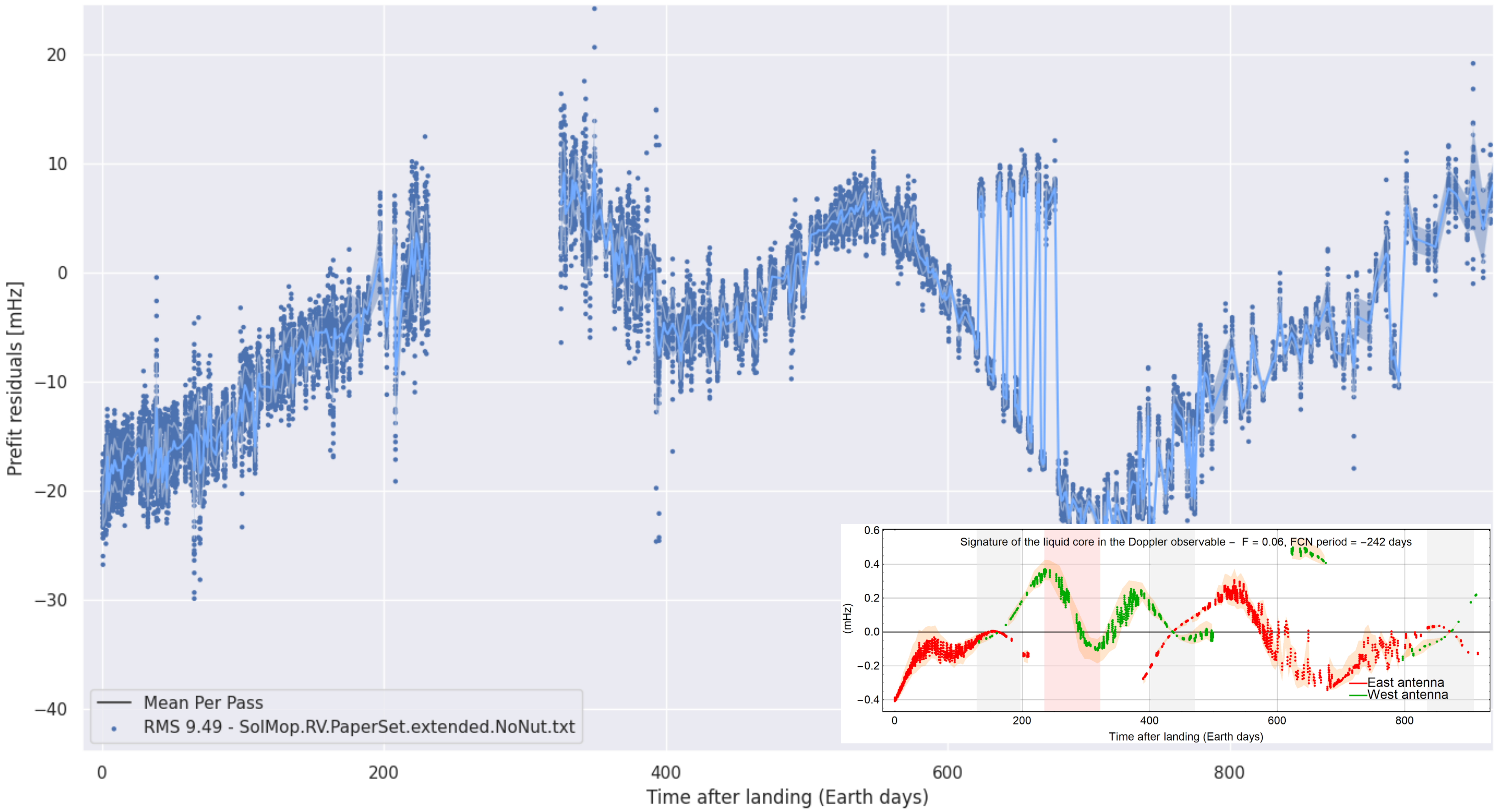


Uplink in [7.145 ; 7.190] GHz

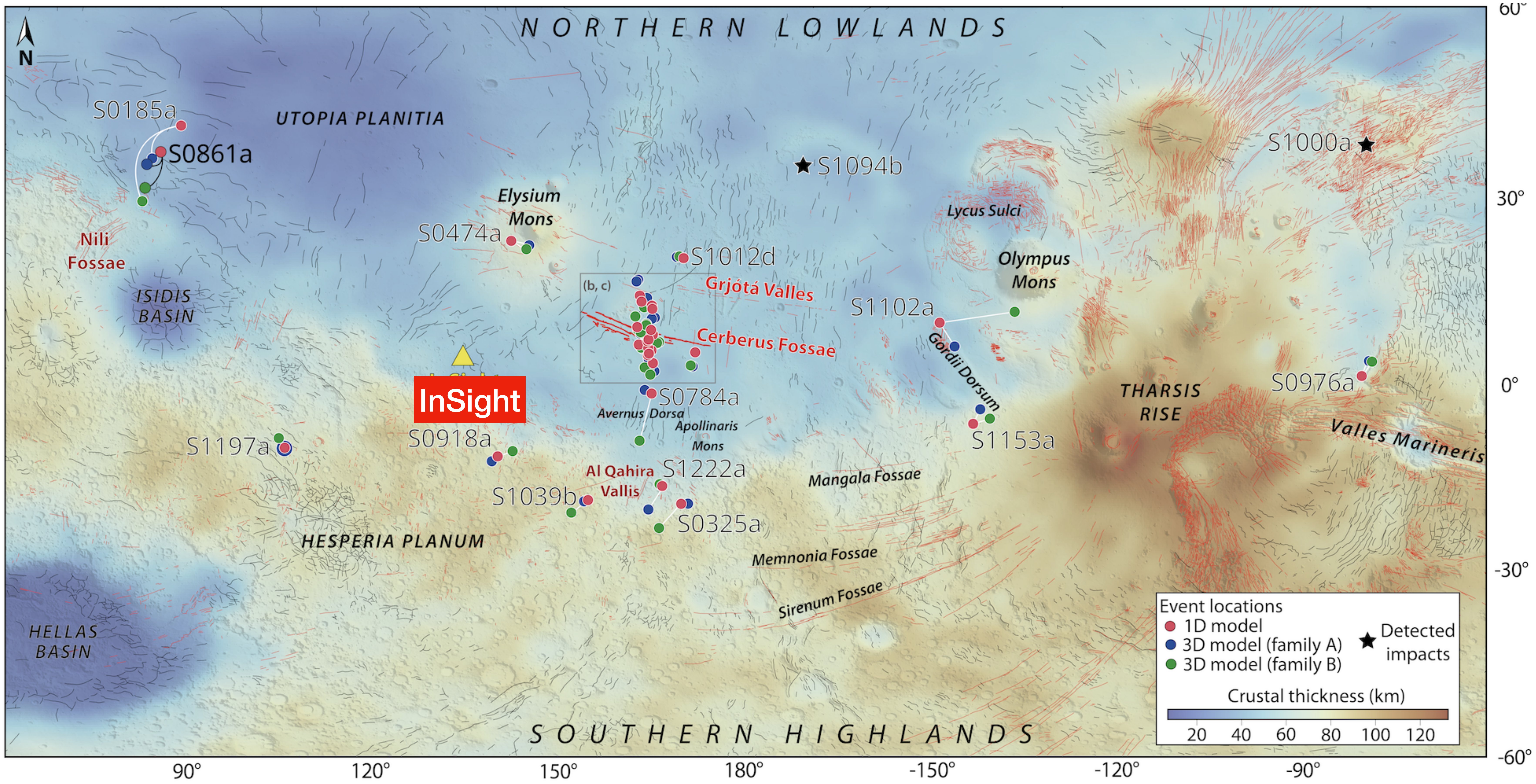
RISE

Downlink in [8.400 ; 8.450] GHz

Coherent transponder and 2 horn-antennas fixed on the Mars surface

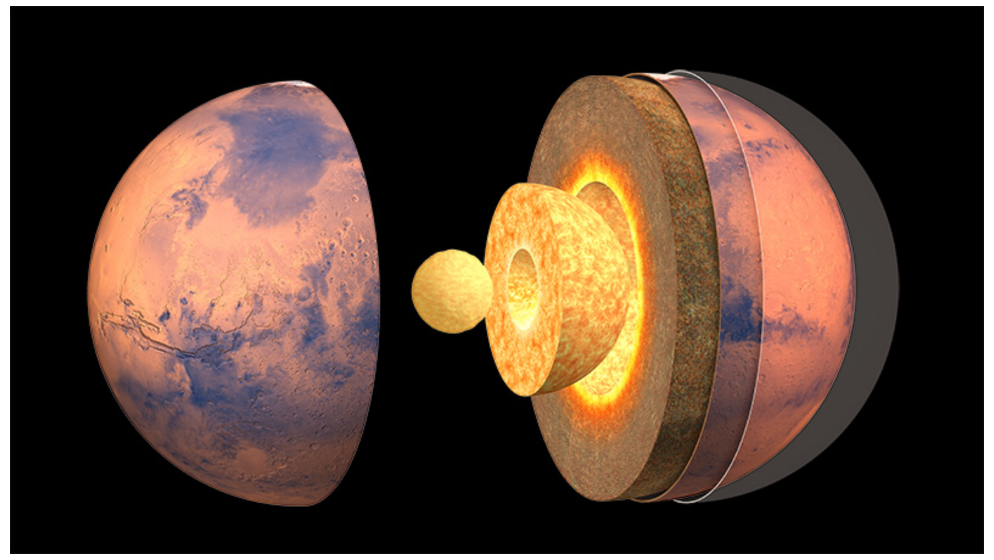


Location of events used to infer deep interior structure



- more than 1300 events recorded
- almost all on northern hemisphere
- only 2 far side events
  sol 1000a (impact), sol 0976a
- most events occur in Cerberus Fossae or close to InSight
  (tectonic active, e.g. Stähler 2022, Broquet 2022)
- largest quake S1222a (M4.2)
- identified phases in the 31 events used to infer interior structure:
  P, PP, PPP, S, SS, SSS (115)
  ScS (10), SKS (2), Pdiffx (>1?)

Important modelling assumption (not exhaustive)



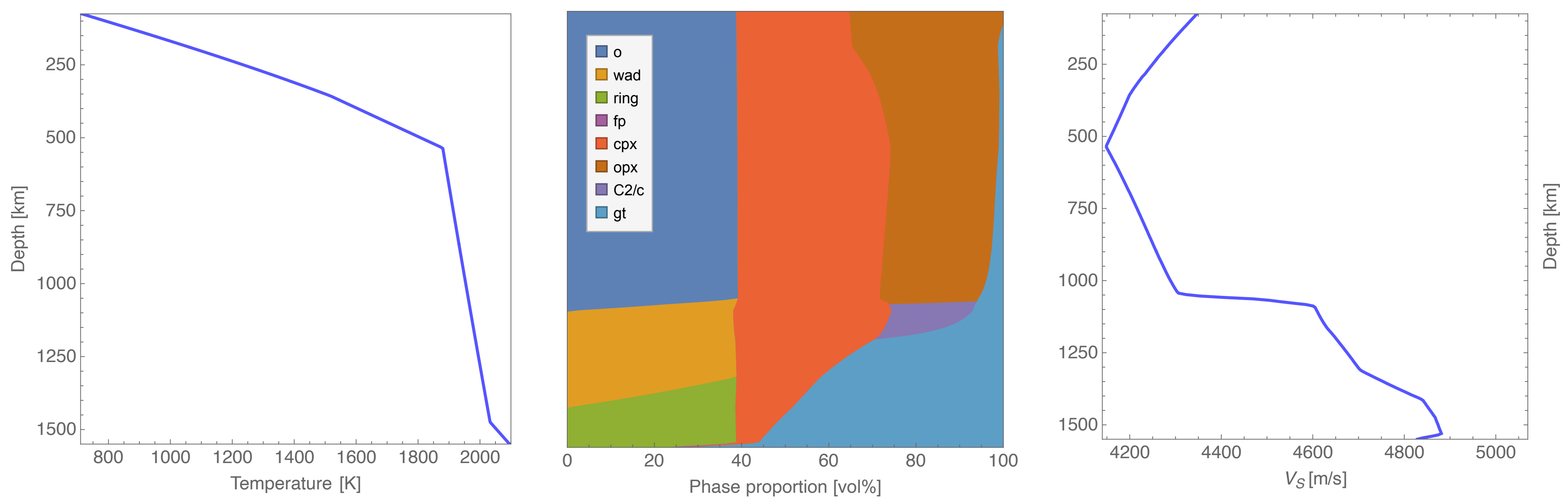
- geodesy data and small number of quakes as well as uneven sampling requires strong prior assumptions
  → Mars is layered and spherical isotropic (crust, mantle, (fluid lower mantle), fluid core)

- use mass, moment of inertia, and tidal Love number k_2 as data → need model of whole planet: density and seismic velocities

- consistent link between density and seismic velocities though assumed chemical mantle composition
  (from literature and based on formation, Martian meteorites, in situ samples, e.g. Wänke 1994, Taylor 2013, Yoshizaki 2020, Lodders & Fegley 1997; Sanloup 1999)

  → mantle rich in FeO (~14-18wt%) ⇒ affects depth of major phase transition, density, and elastic properties

  → mantle is chemical homogeneous and in thermodynamical equilibrium → use Gibbs energy minimisation to obtain elastic properties
  (Perple_X: Connolly 2005, Stixrude & Lithgow-Bertelloni 2011)



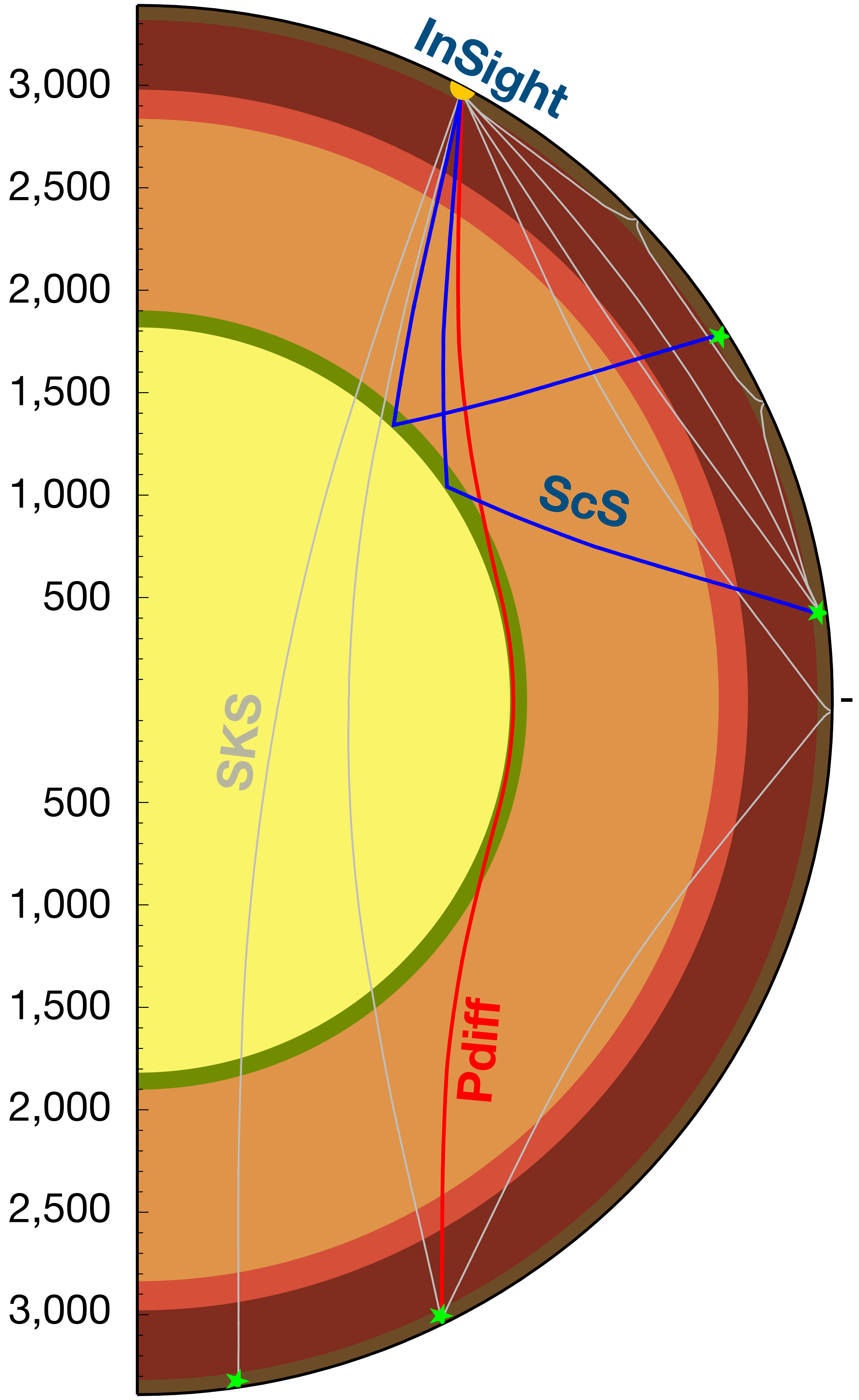
- temperature profile: shape parameterised, 1d thermal evolution calculation, end-members for 3d thermal evolution studies

- core is fluid and isentropic → use isentropic equation of state to model elastic properties (3 parameters) → does not require assumption about core composition

  → remaining degrees of freedom: mantle temperature profile, core radius, core eos parameters, crust velocity structure, event locations

Seismic detection and sampling of the martian core

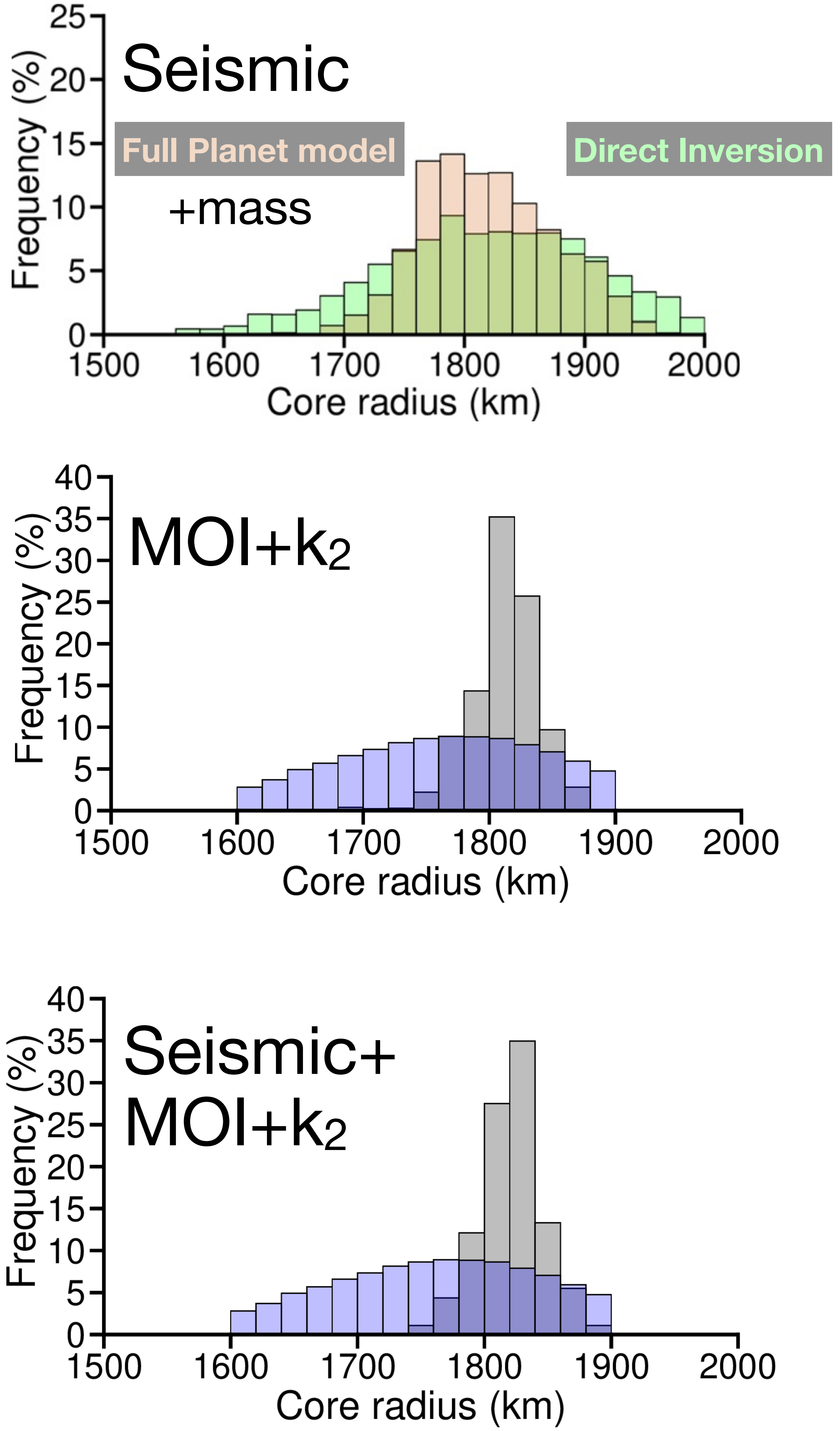
- from S waves reflected at the solid-fluid interface (ScS), S waves transformed to P waves traversing the core (SKS)
- + core mass, MOI, k_2, and (P, S, PP, SS, PPP, SSS) phases
- direct inversion without interior model and geodesy data: 1817± 87 km (e.g. Drilleau 2022)



Samuel 2023

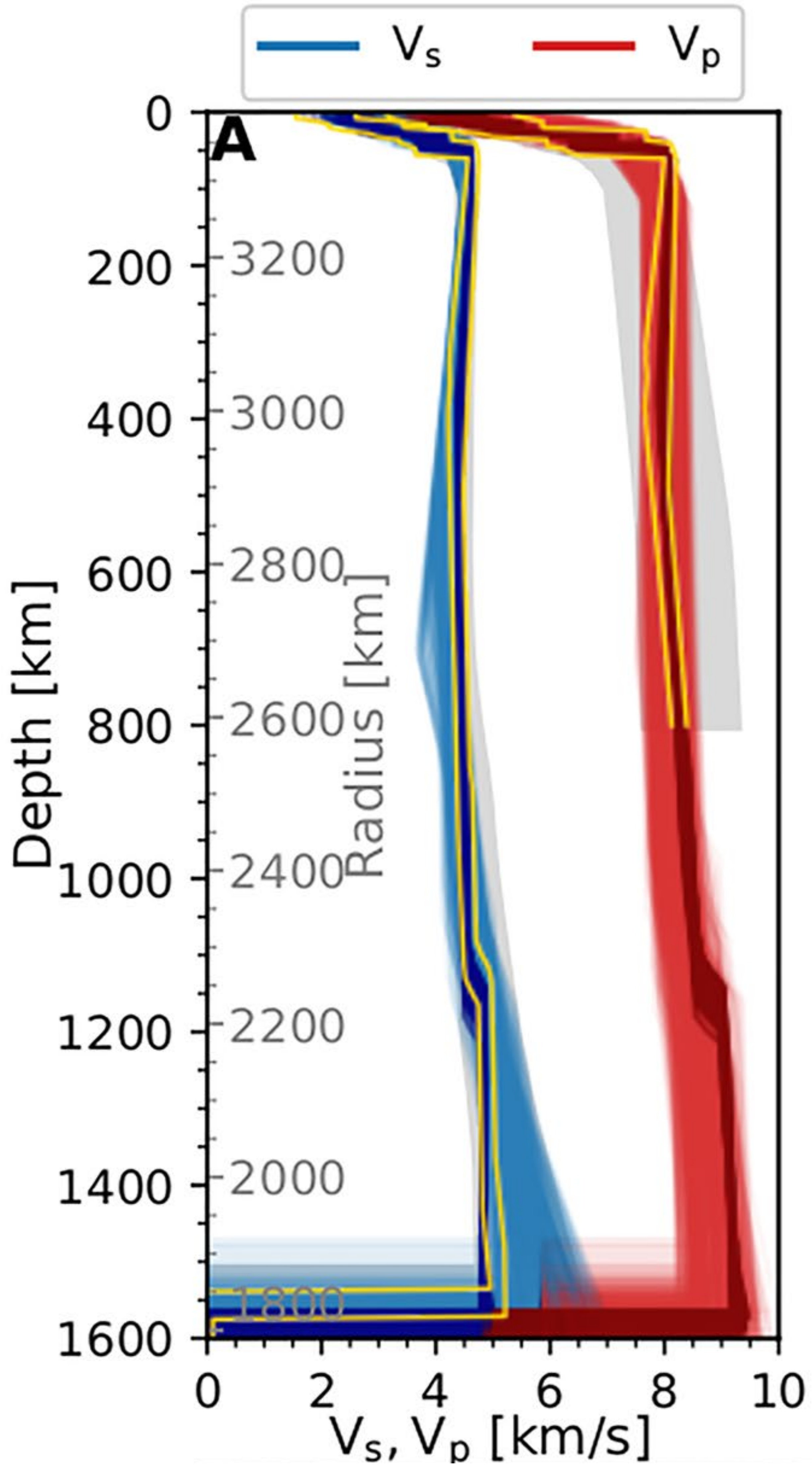
Effect of full planet model and geodesy data

(Drilleau 2022, 2024)



Direct inversion for velocity profiles

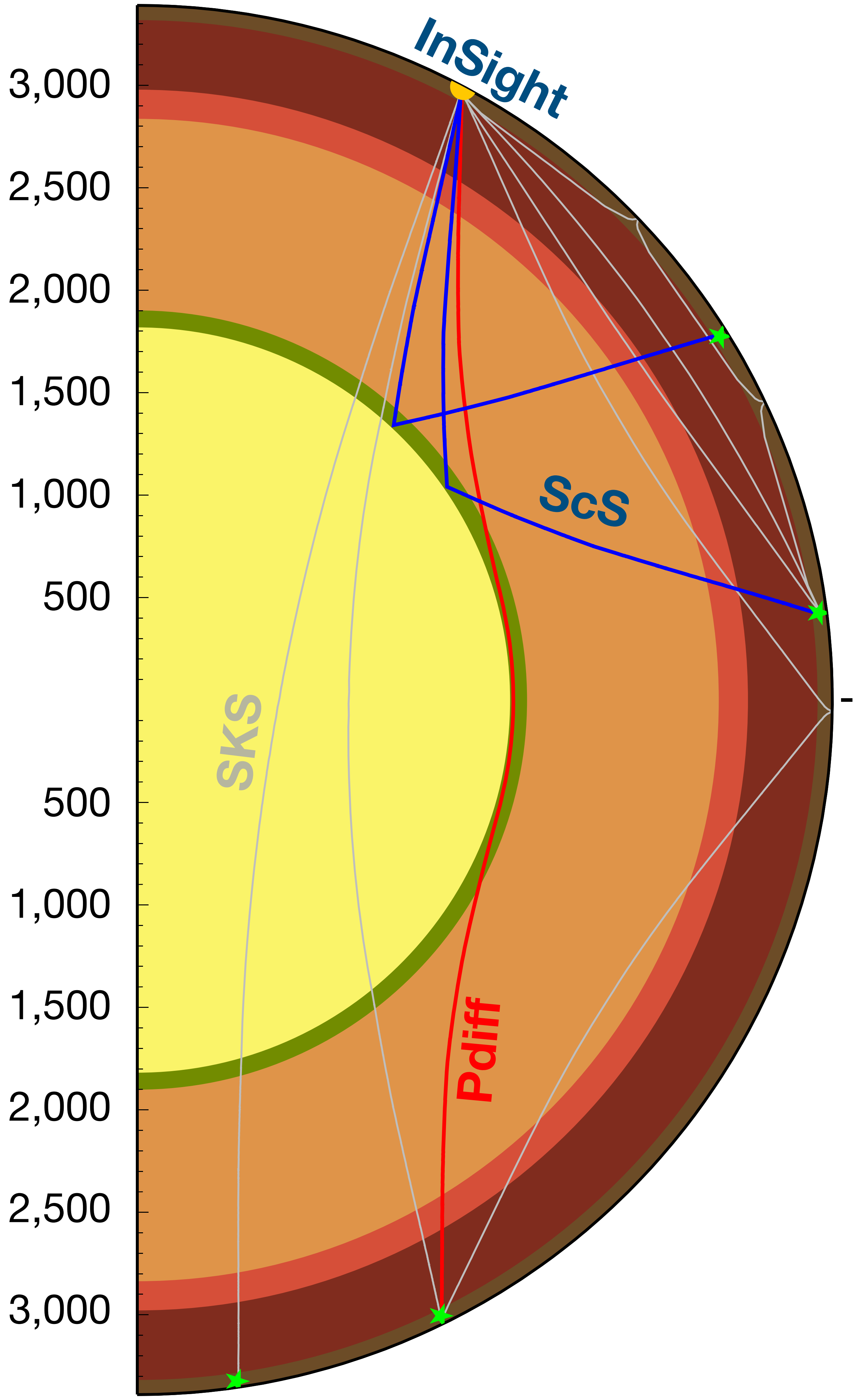
(Durán 2023)



Seismic detection and sampling of the martian core

- from S waves reflected at the solid-fluid interface (ScS, 10 events), S waves transformed to P waves traversing the core (SKS, 2 events)
- direct inversion using only seismic phases: 1817± 87 km
  (e.g. Drilleau 2022)
- + core mass, MOI, k_2, and (P, S, PP, SS, PPP, SSS) phases
  + no prior assumption about core composition
- core: radius 1839±25 km, density 5.97±0.11 g/cm^3
  (e.g.: Stähler 2021, Durán et al. 2022, Irving 2023, Drilleau 2024)

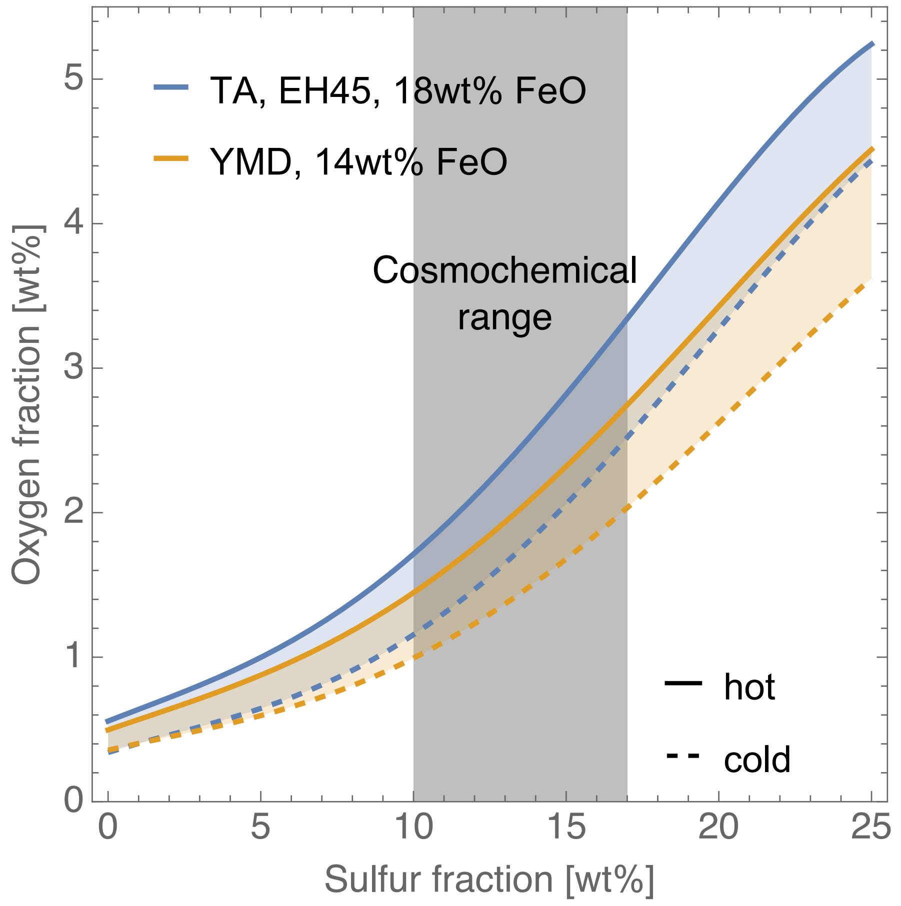
  → before InSight: 1794±65 km, 6.1±0.2 g/cm^3
  (e.g.: Rivoldini 2011)
- core velocity 4.9-5.0 km/h (Irving 2023) (l-Fe~4.9-5.6 km/h)
- no wave reflection detected in the core
  → core is liquid down to r=800 km (Irving 2023)



Samuel 2023

Interlude: Core composition

- candidate light elements that are siderophile or dissolve into Fe at formation: S, O, C, H (e.g. Steenstra 2018)
- Cosmo-chemical constraints: **S~10-17wt%** (e.g. Steenstra 2018)
- **O (≲3.5wt%)** fraction correlated to mantle FeO and core S (Gendre 2022)

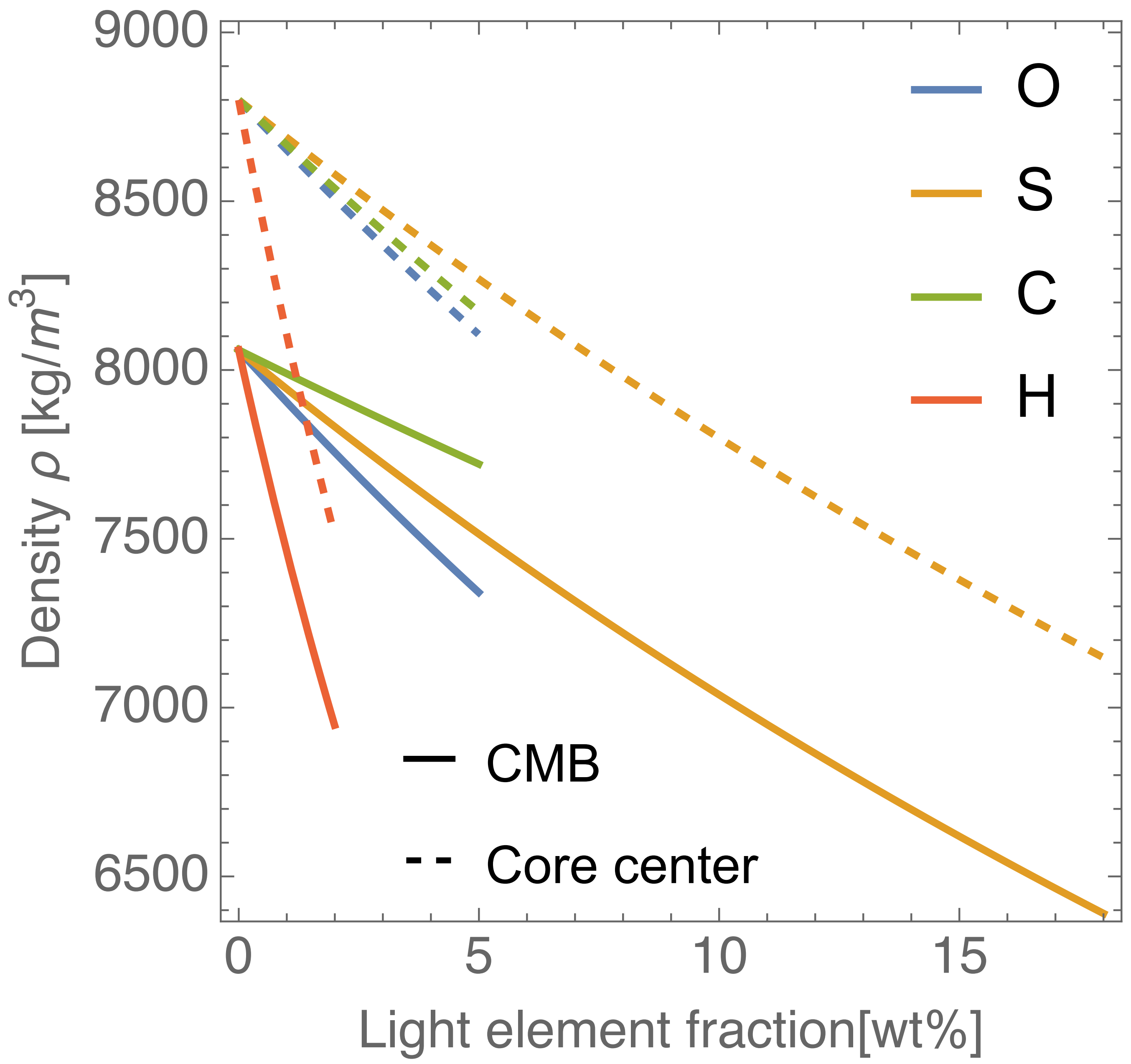


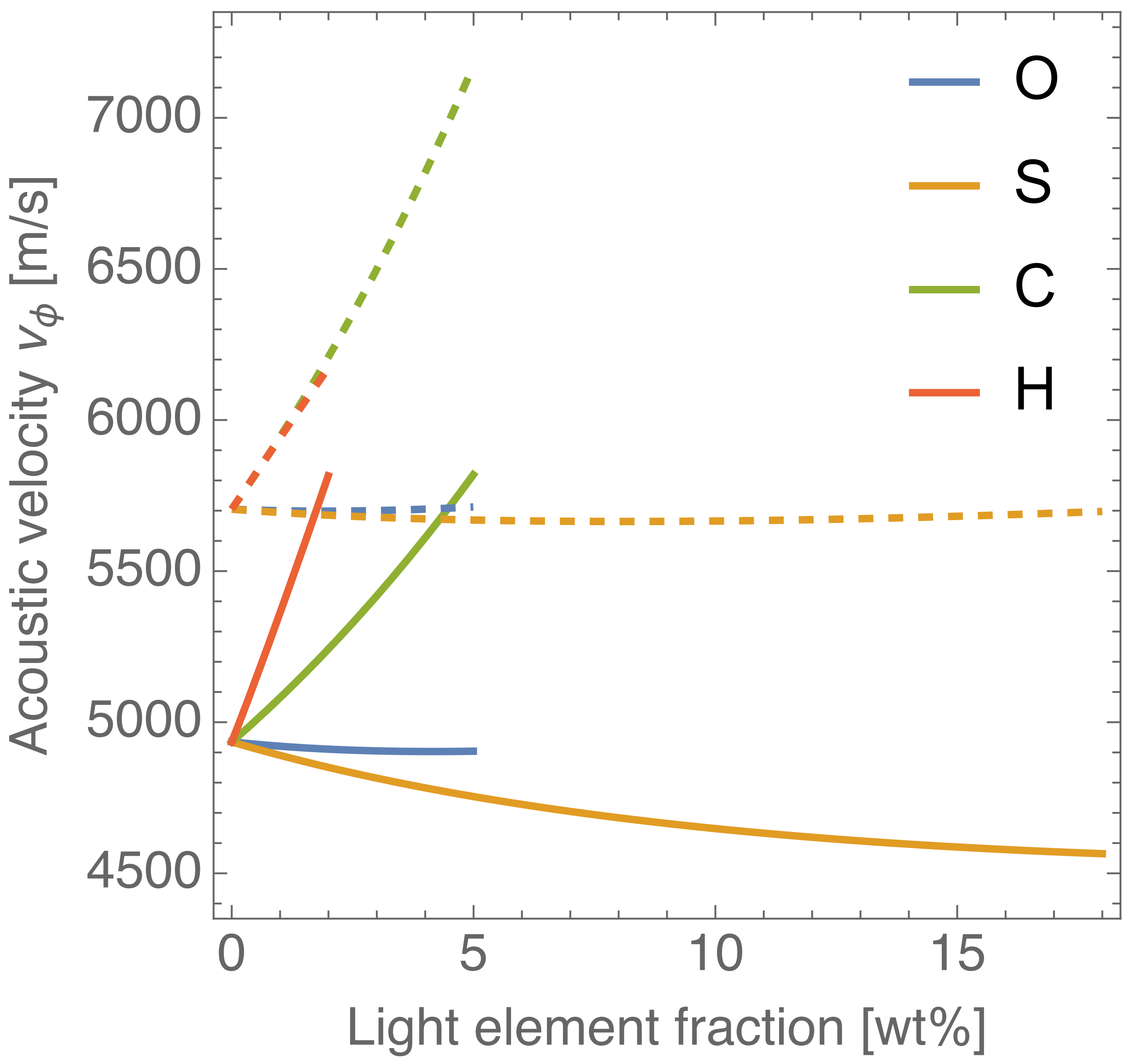
- maximal amount of **C (≲1.5wt%)** limited by its solubility in Fe-S (Dasgupta 2016)
- **H (<1wt%)** depends on initial amount of H_2O and solubility in Fe (Shibazaki 2009, Tagawa 2022)

Effect of light element on core density and velocity

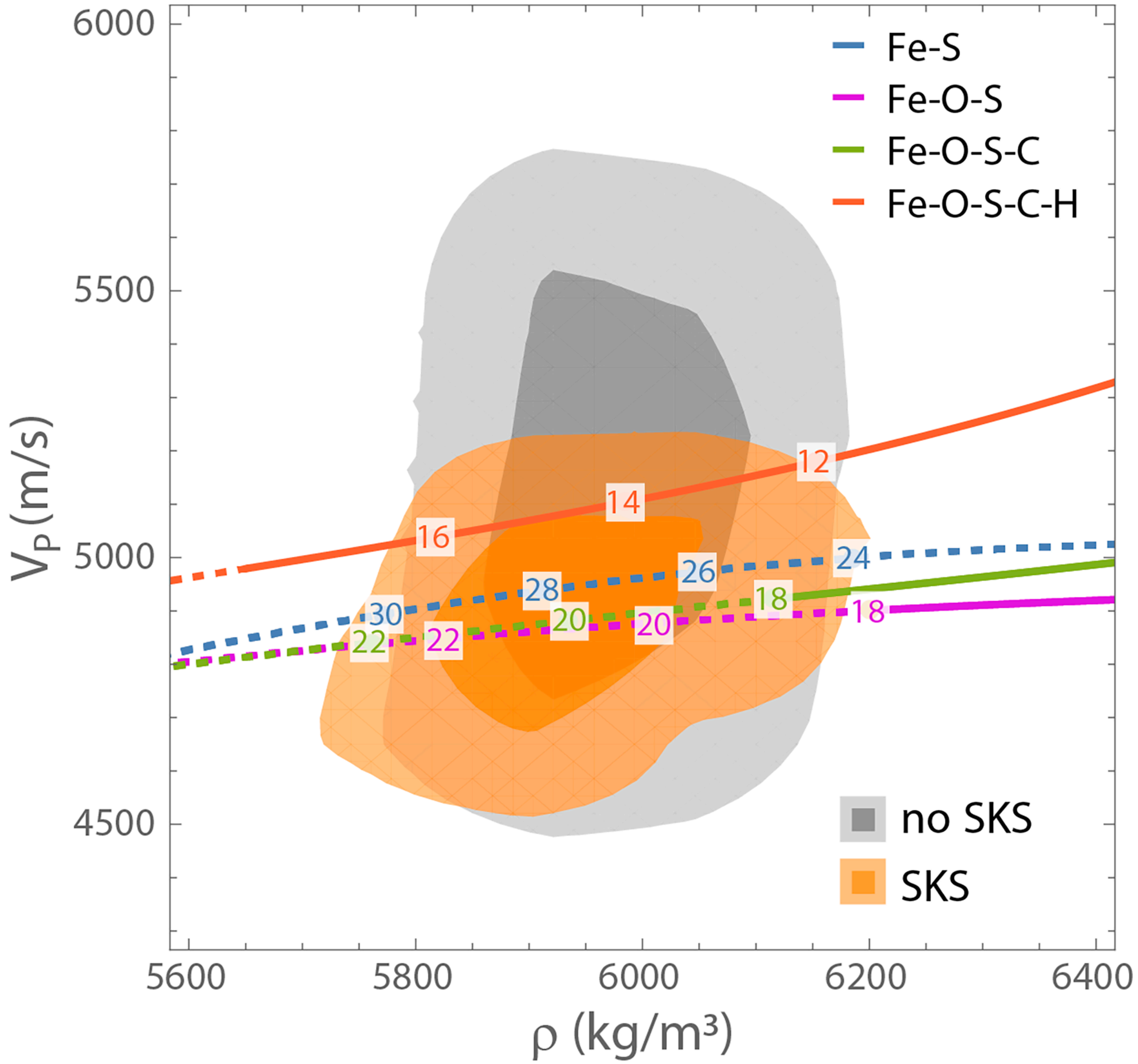
- based on equations of state deduced from **experimental data** at conditions relavant for the Martian core: **Fe**: Dorogokupets 2017, **Fe-S**: Nishida 2016, Shimoyama 2016, Kawaguchi 2017, Morard 2018, Terasaki 2020, Xu 2021, Nishida 2020, **FeO**: Morard 2022, **Fe-C:** Terasaki 2010, Shimoyama 2016, Morard 2017, **FeH:** Tagawa 2022

- liquid Fe-O-S-C-H equations of state neglects non-ideal mixing behaviour between Fe-O (non-ideal), Fe-S (non ideal), Fe-C, and Fe-H



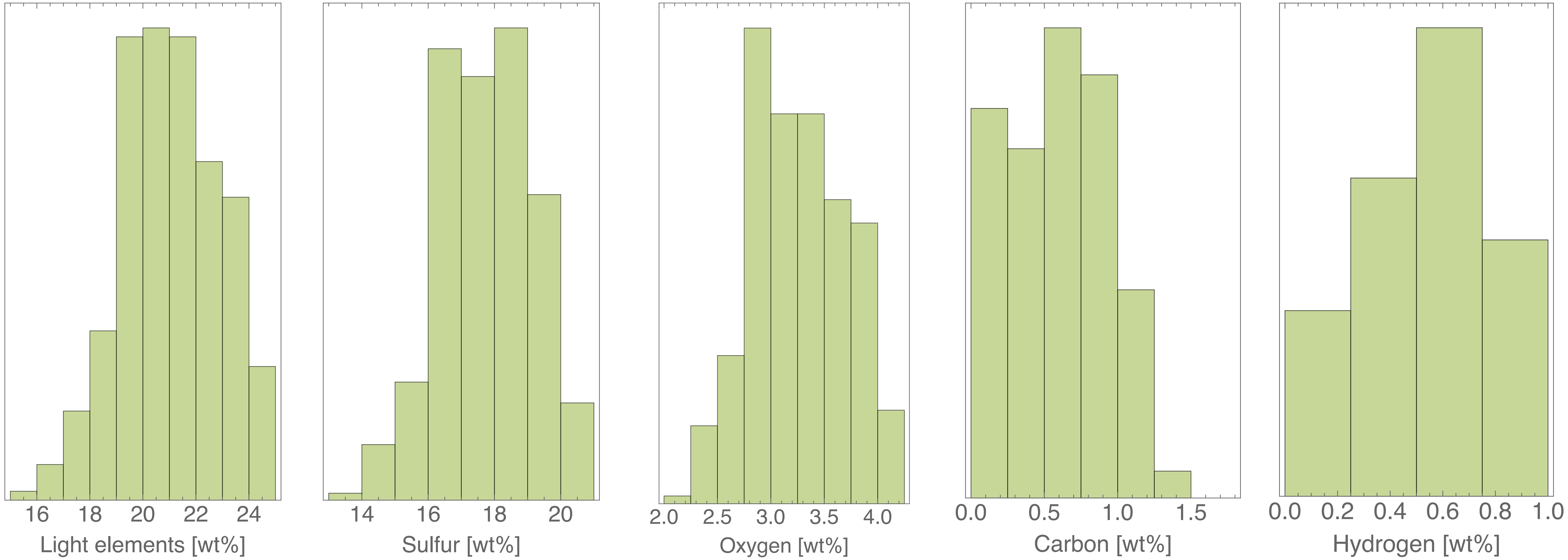


What about the composition of the core?



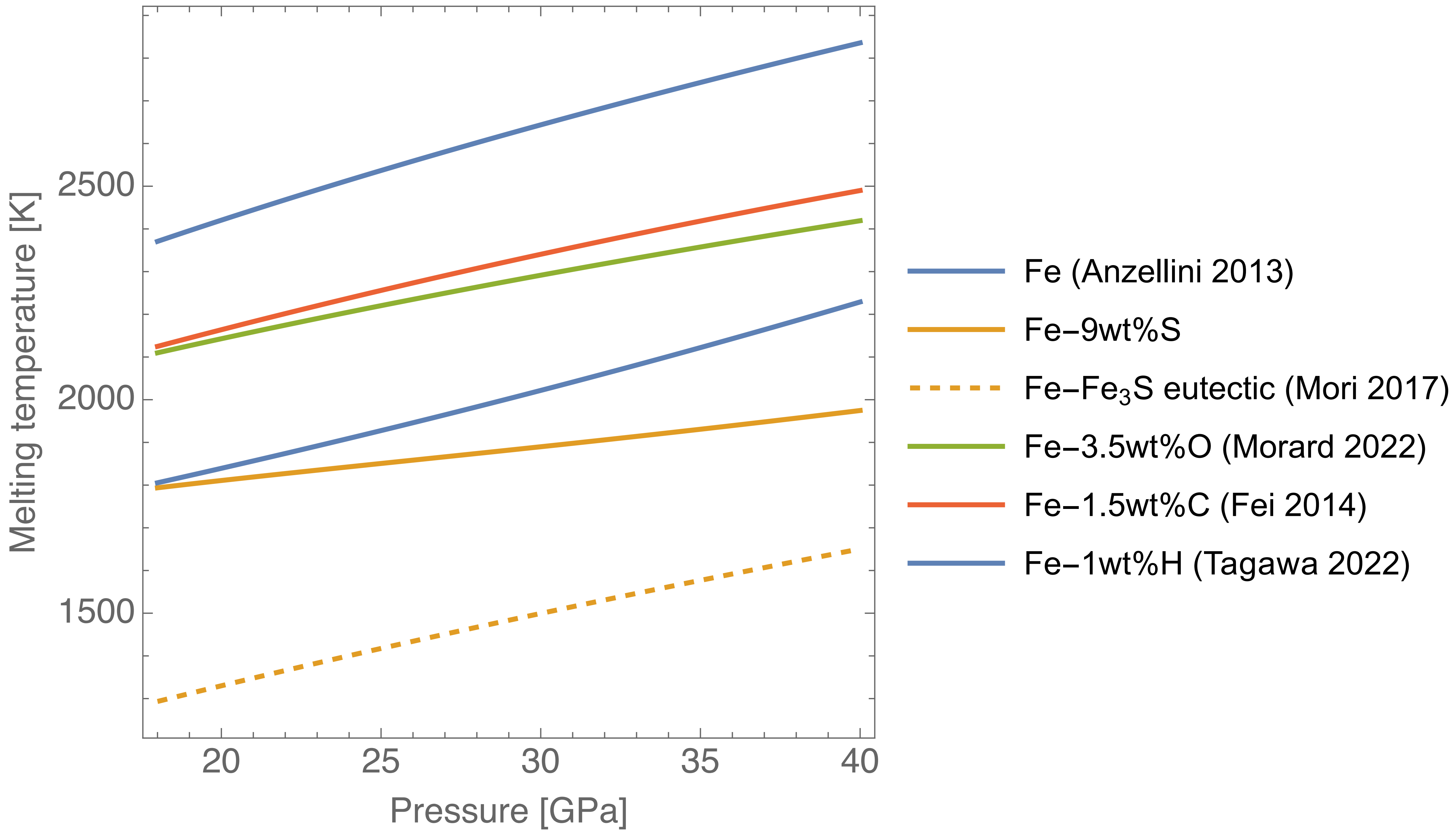
- using SKS data significantly reduces the range of possible velocities in the core
- Fe alloys with combinations of O,S,C, H agree with inferred density and acoustic velocity
- without H, the S > cosmo-chemical range
- a large domain in the inferred $(\rho \times v_p)$ space is inconsistent with the elastic properties of a liquid Fe-O-S-C-H alloy

Optimal core composition



- the core contains ~21wt% of light elements (Earth ≲10wt%)
- no unique solution for composition: many combinations of Fe, O-S, C, and H can explain the seismic observation
- but only if a small fraction of H is present does the fraction of S agree with cosmochemical constraints (S≲17wt%)
- mean composition: **Fe**-**3.5**wt%**O**-**16.5**wt%**S**-**0.7**wt%**C**-**0.5**wt%**H**
  (Fe-27wt%**S, Fe-4.5**wt%**O-21**wt%**S, Fe-4**wt%**O-20**wt%**S-1**wt%**C)**

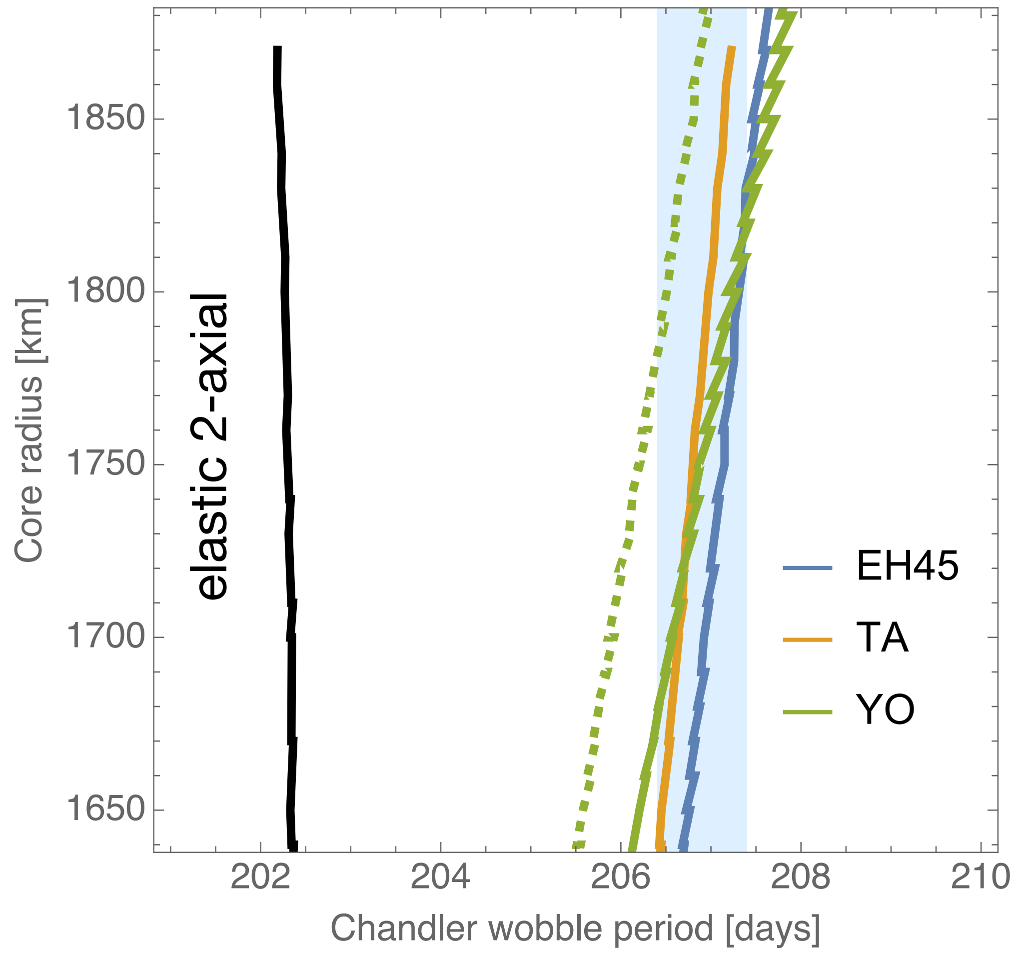
Core liquidus and inner core

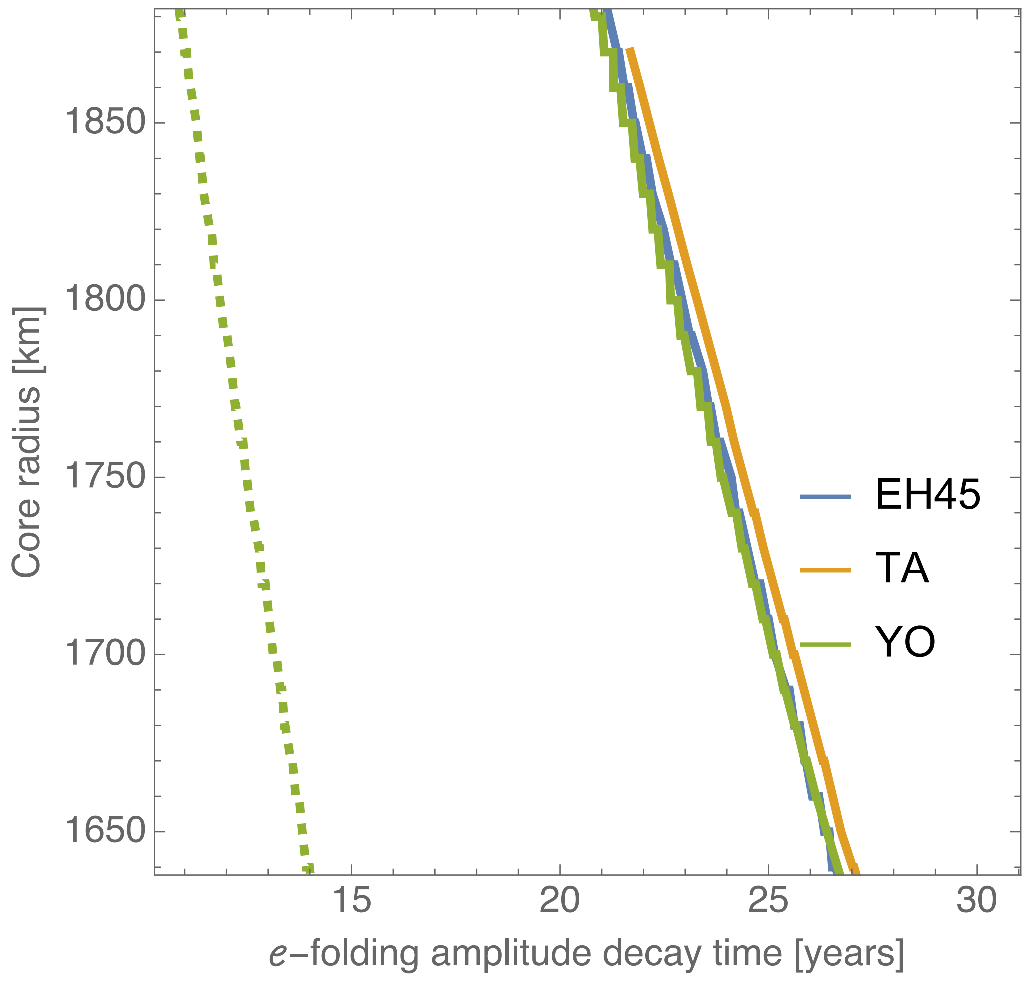


- at 40 GPa (below eutectic) 1wt% (O, S, C, H) decrease Fe_{liq} ~(140, 60, 190, 600) K
  → liquidus **Fe-3.5**wt%**O-16.5**wt%**S-0.7**wt%**C-0.5**wt%**H < 1500K**

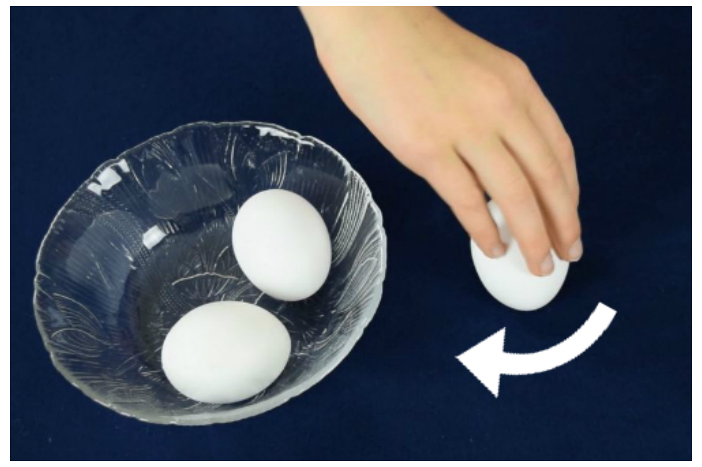
- inner core nucleation is highly unlikely: T_{cmb}~1700K-1900K
  (core cools by <200 K over 4.5 Ga. e.g. Greenwood 2021)

Chandler Wobble period and interior structure





- Period $\tau_{CW} = 209 \pm 0.5$ d from radio tracking orbiters over 20 years (Konopliv 2021) (hard boiled Mars 189.9 d)



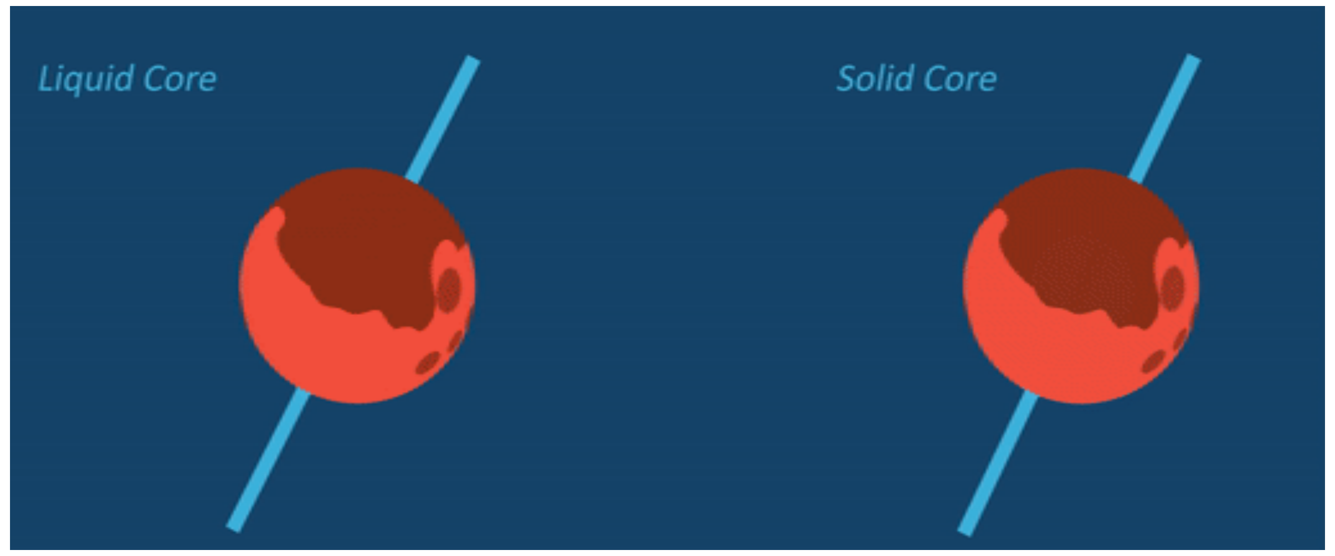
- τ_{CW} depends on the well known moments of inertia (A,B,C) and informs about the state of the core, its moment of inertia A_f, and planet rigidity κ

$$2\pi/\tau_{CW} = \frac{A}{A - A_f}\sqrt{(e-\kappa)^2 - \frac{1}{4}\left(\frac{B-A}{A}\right)^2}$$

- A_f and κ increase with core radius but τ_{CW} almost not
- but non-elastic effects are important (~3d)
- Mars significantly more damped at CW period than Earth (~28-299 years, e.g. Gross 2015)

Nutation and interior structure

(e.g. Dehant 2015)



- the relative rotation between core and mantle is characterised by FCN rotational normal mode
- forcing close to the FCN period can resonantly amplify nutations
- nutation can be characterised by the *amplification strength* F and FCN period
- both depend on the interior structure (moments of inertia A, A_f, dynamic shape e, e_f, compliances γ, β, coupling constant K_{cmb})

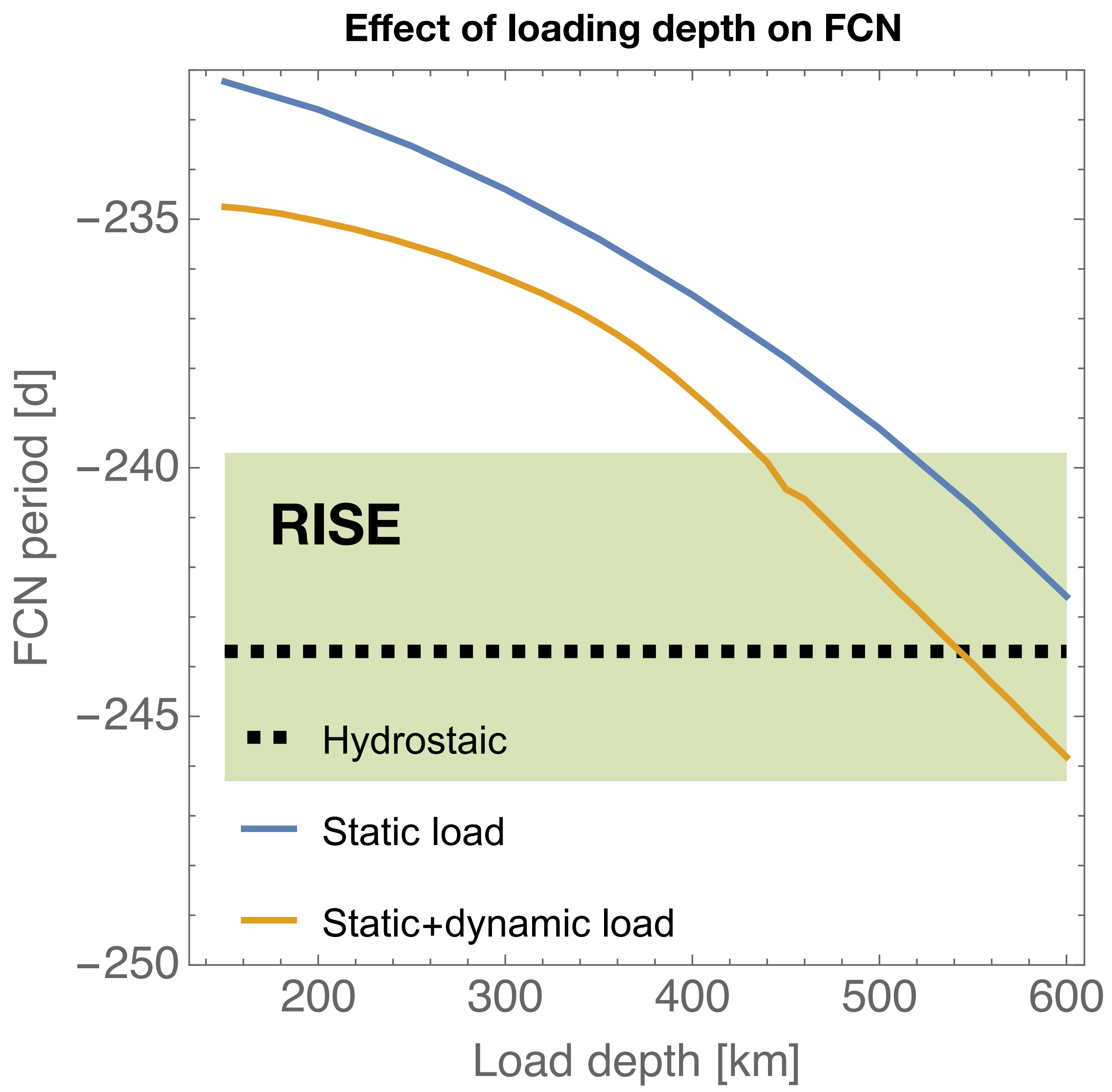
$$F = \frac{A_f}{A - A_f}\left(1 - \frac{\gamma}{e}\right) \text{ and } 2\pi/\tau_{FCN} = -\Omega \frac{A}{A - A_f}\left(e_f - \beta + K_{\text{cmb}}\right)$$

- > 600d of RISE data allow to obtain a robust estimate of F and τ_{FCN} (Le Maistre 2023)

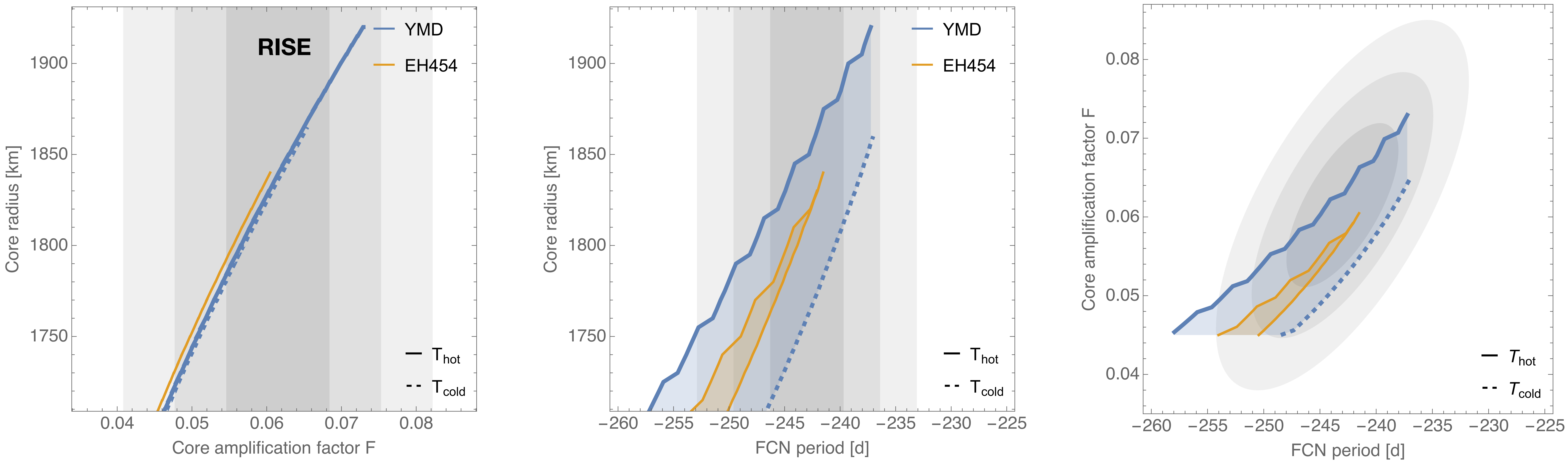
$F = 0.061 \pm 0.0064$ and $\tau_{\text{FCN}} = -242.25 \pm 2.7 \text{ days}$ (Earth -430 days)

Core shape (Le Maistre 2023)

- geometric and dynamic shape of Mars can be explained by its rotation and from external (surface topography) and internal mass anomalies (e.g. Zharkov 2009, Wieczorek 2019)
- loads are *frozen in* the rigid lithosphere (relief, horizontal temperature variations) or density anomalies induced by mantle convection
- internal loads can be specified to match geometric and dynamic shape of Mars, they also affect the shape of the core
- effect on core shape: rotation ~-5000 m, internal loading static ~-250 m (depth ~550km), dynamic ~-100m

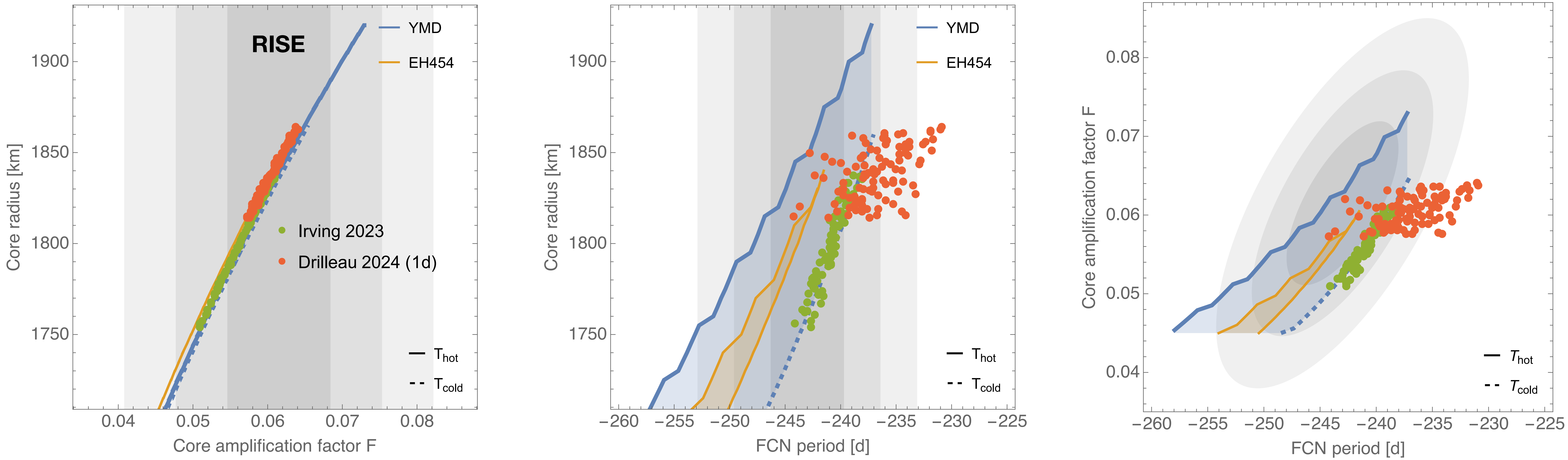


Nutation: interior structure (Le Maistre 2023)



- F (~core moment of inertia ~core radius) weakly dependent on mantle composition, temperature, and core shape
- but **not** the *FCN* period: crust density and thicknesses affect surface loading as well as mantle composition and temperature affect core shape
- inferred core radius range of 1825±55 km is in excellent agreement with tides and seismic observations (e.g. Stähler et al. 2021, Duràn et al 2022)

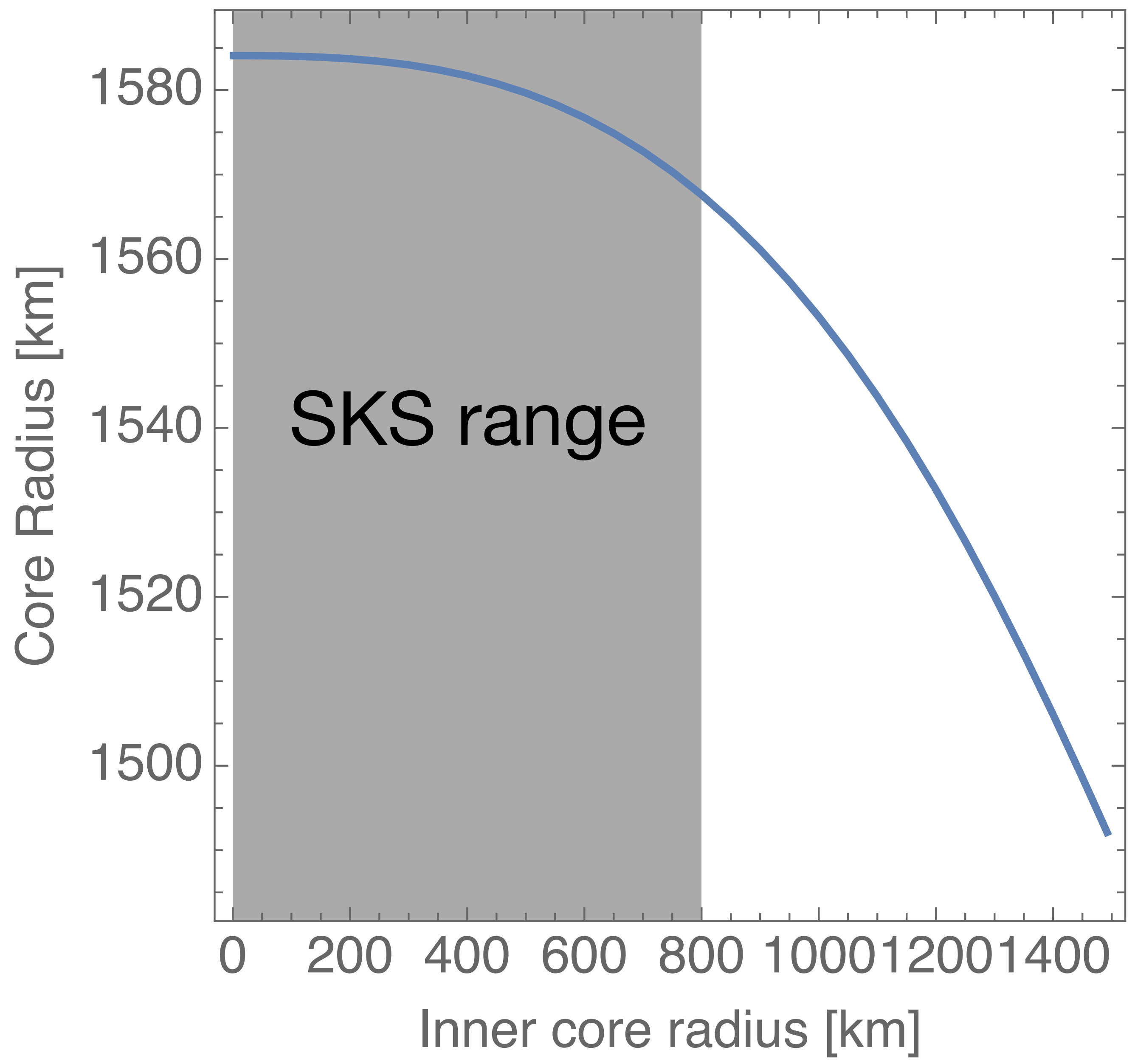
Predicted Nutation: Seismic models

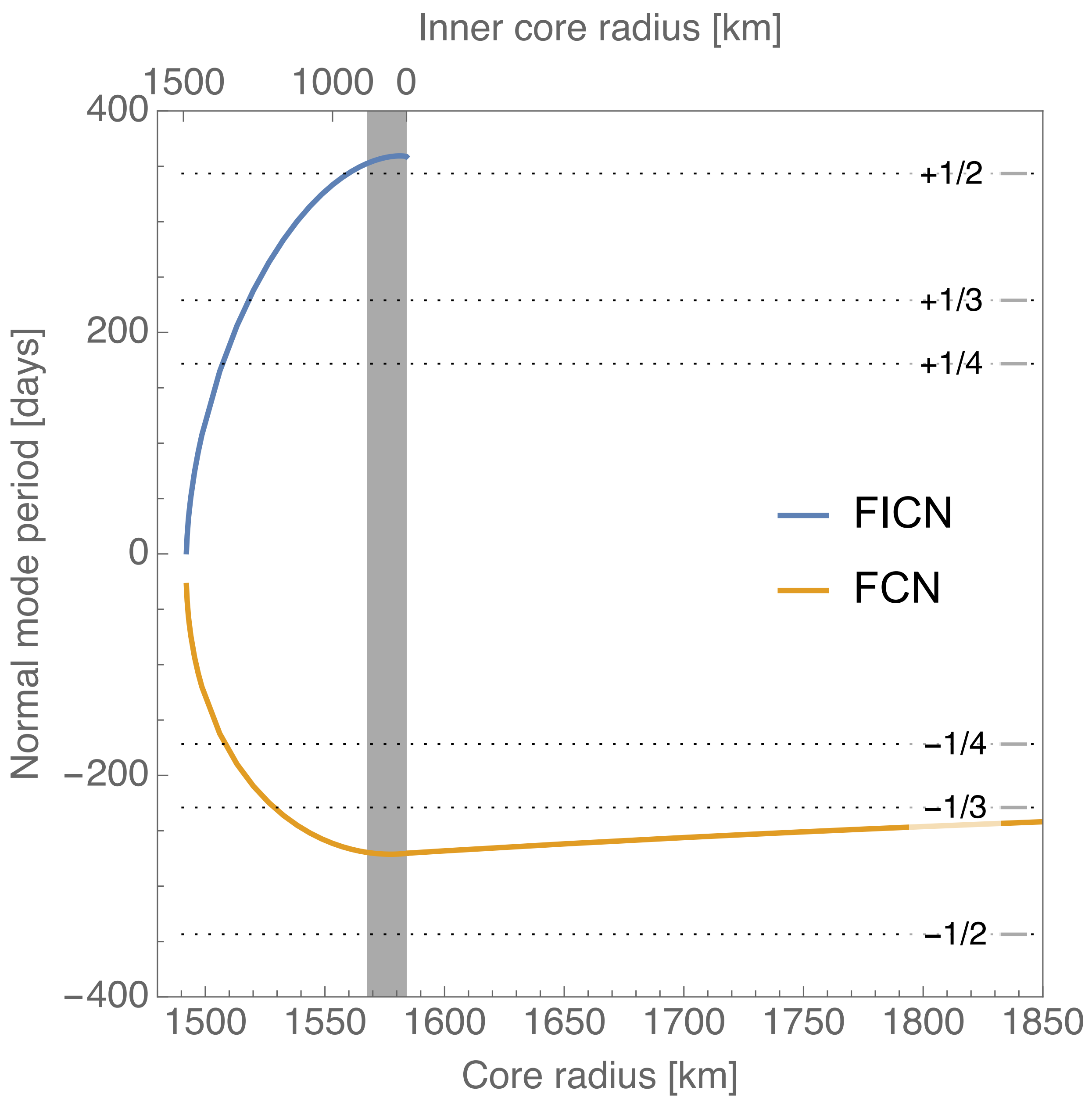


- seismic models agree with RISE observations if their lithosphere is thick (≳500 km)
- expected further refinement on core radius estimate and mantle thermal structure determination if RISE data are inverted together with seismic data (ongoing)

Inner core signature

- assume Fe-S-1wt%H core composition, H partitions equally between solid and liquid Fe, neglect effect of H on liquidus!!
- mass conservation requires that the core radius decreases with inner core radius
- the inner core gives rise to the FICN rotation normal mode (e.g. Dehant 2015)
- direct effect: forcing close to the FICN period can resonantly amplify nutations
- indirect effect: FCN can be significantly smaller than expected if no inner core is assumed for data interpretation (affects also nutation amplitudes)
- inner core signature was **not** detected in RISE data and FCN period is consistent with InSight core radius (no inner core or FICN period away from forcing periods)





Take home message

- coherent picture of interior structure of Mars emerges from joint interpretation of seismic and geodesy data

- inferred present-day mantle thermal state is in good agreement with end-member scenarios of 3d thermal evolution studies (e.g. Plesa 2022, Murphy 2024)

- mantle composition models from the literature are mostly compatible with the new data and initial hypothesis of chemical homogeneous mantle in thermodynamical equilibrium seems well founded

- the core is most likely fully liquid, the radius is ~1839±25 km, and it contains about ~21wt% of light elements (mean composition: **Fe**-3.5wt%**O**-16.5wt%**S**-0.7wt%**C**-0.5wt%**H**)

- the required amount of H in the core is too large to agree with initial water content estimation and most recent metal-silicate H partitioning studies (e.g. Tagawa 2022)
  → results about core composition will likely evolve with new experimental data

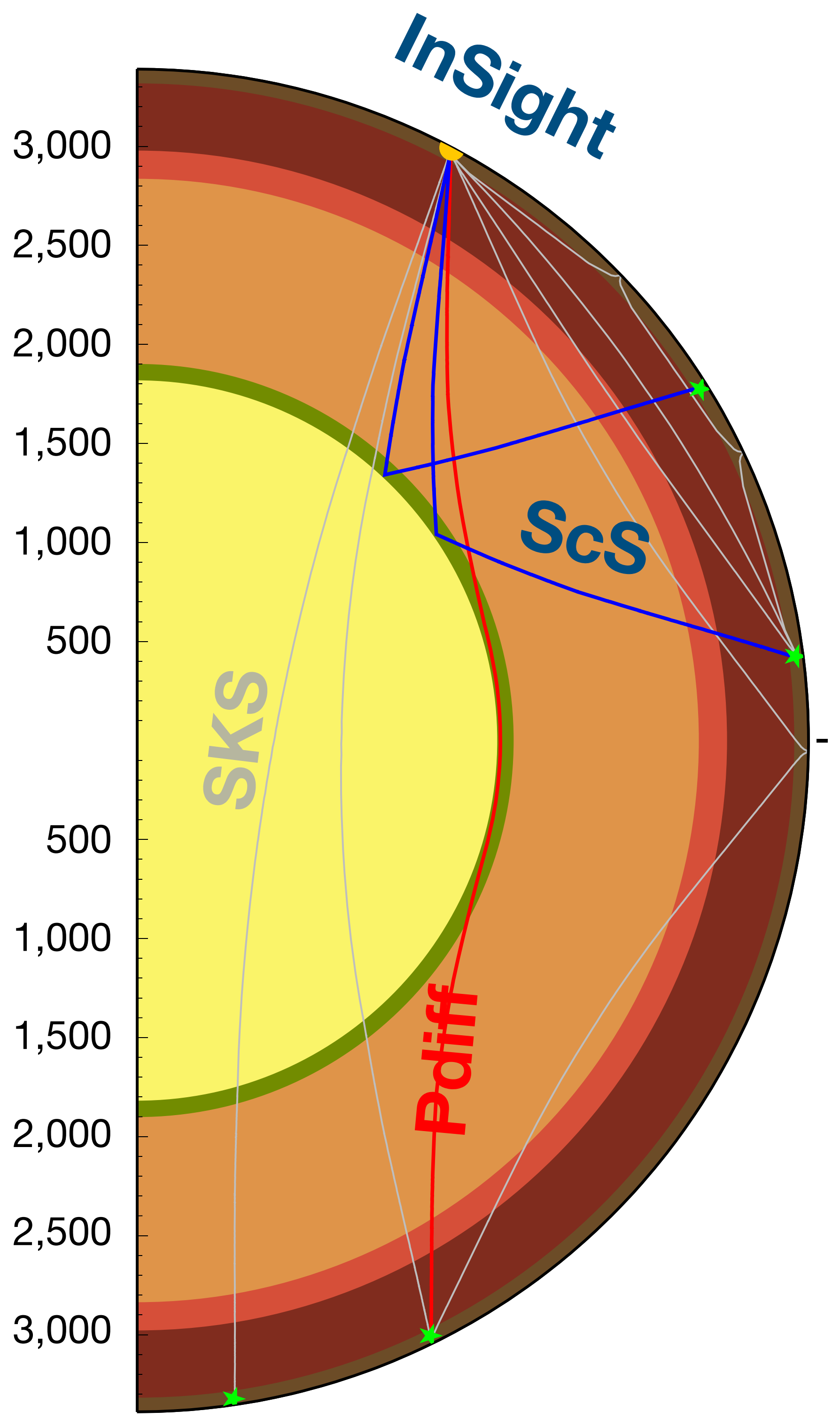
Did we get the interior structure of Mars all wrong?

1. Evidence for a liquid silicate layer atop the Martian core (**K**: Khan 2023)

2. Geophysical evidence for an enriched molten silicate layer above Mars's core (**S**: Samuel 2023)

Motivation for new paradigm

- predicted arrival time of core diffracted P wave too early compared to observation → lower mantle contains P-wave low velocity zone → basal layer is fluid
- layer is molten silicate layer:
  - **K:** based on eos of Huang 2023 → impossible to find an iron alloy that matches v_p below the CMB and lower core (**Irving 2023 shows that it is possible**) → upper fluid part cannot be a metallic alloy
  - **S**: layer result from mantle overturn



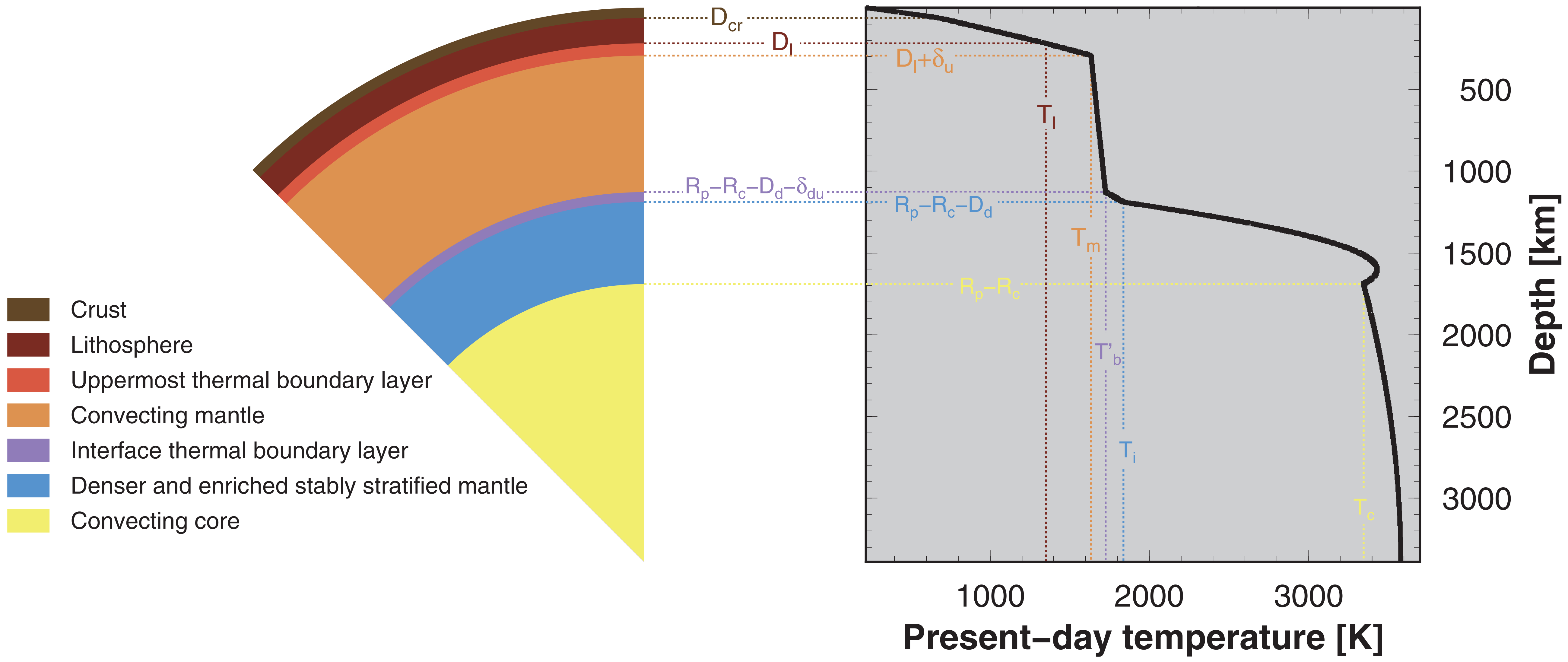
Samuel 2023

Dynamic orgin of basal magma layer (BML) (Samuel 2021)

- cooling of the initial magma ocean resulted in gravitational unstable situation that led to an overturn
  → most upper part is enriched in Fe and Heat Producing radioactive **E**lements

- resulting in a dense (Fe rich) molten (rich in HPE) layer at the base of the mantle that is stably stratified and remains liquid until today

- the hot BML heats up the core and preclude core cooling → no thermochemical dynamo



Did we get the interior structure of Mars all wrong?
A new paradigm.

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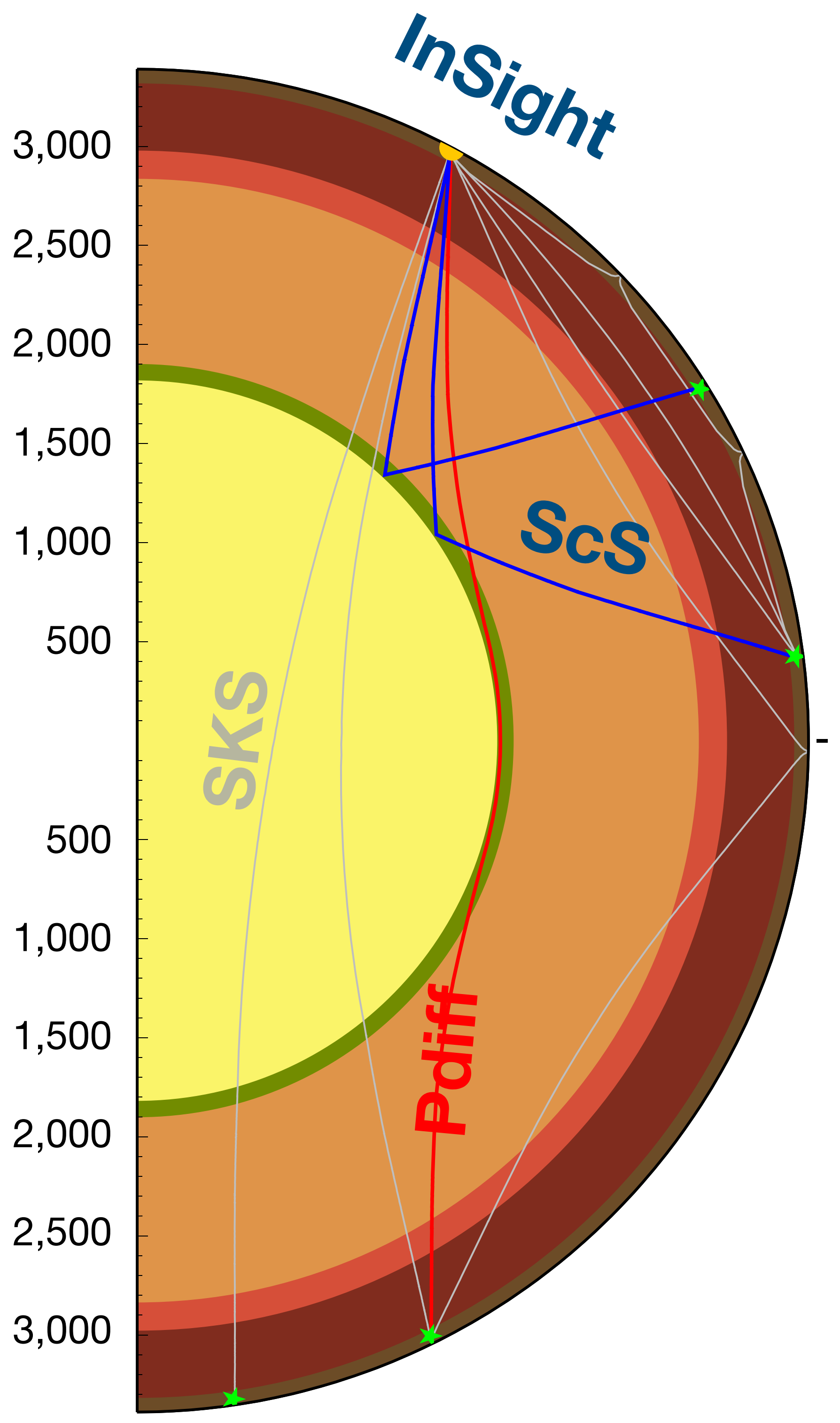
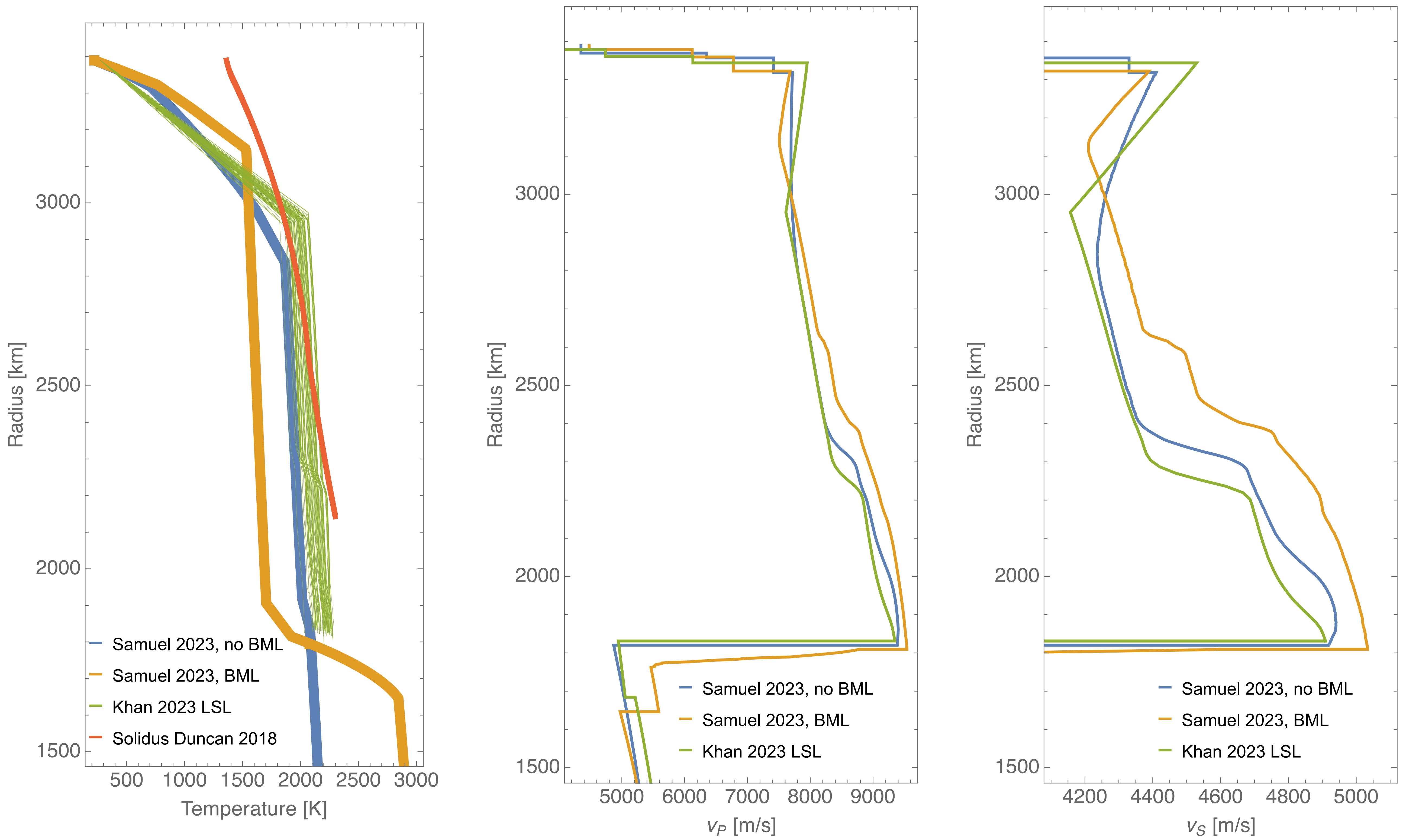
- a BML implies a smaller denser core → reduced amount of light elements required to match core density



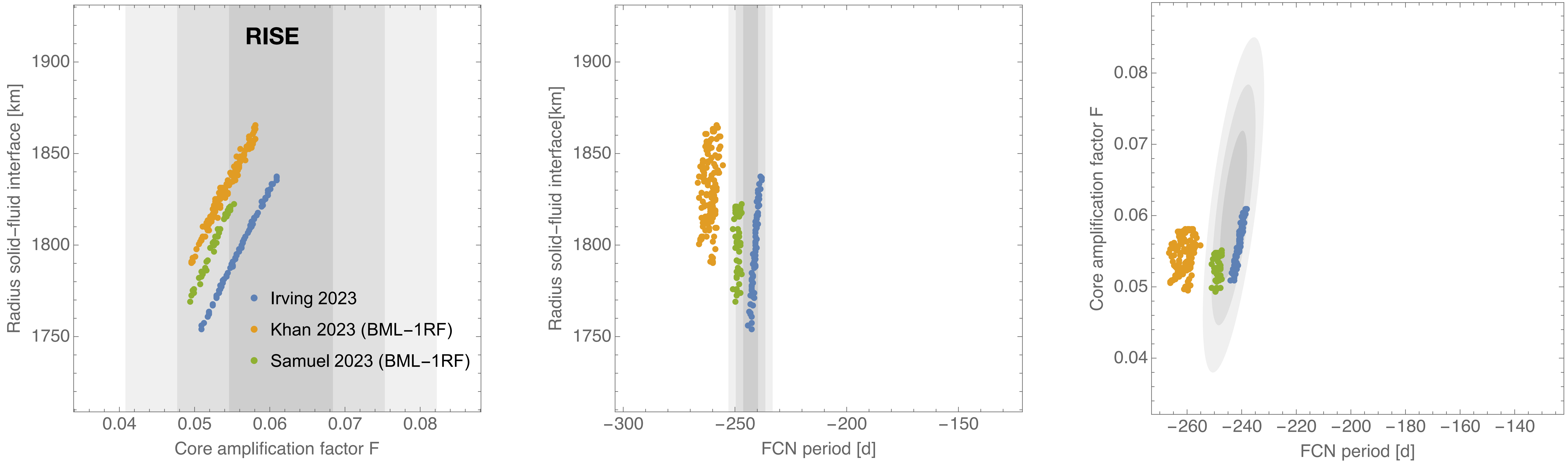
Samuel 2023

New thermal state and velocity profiles



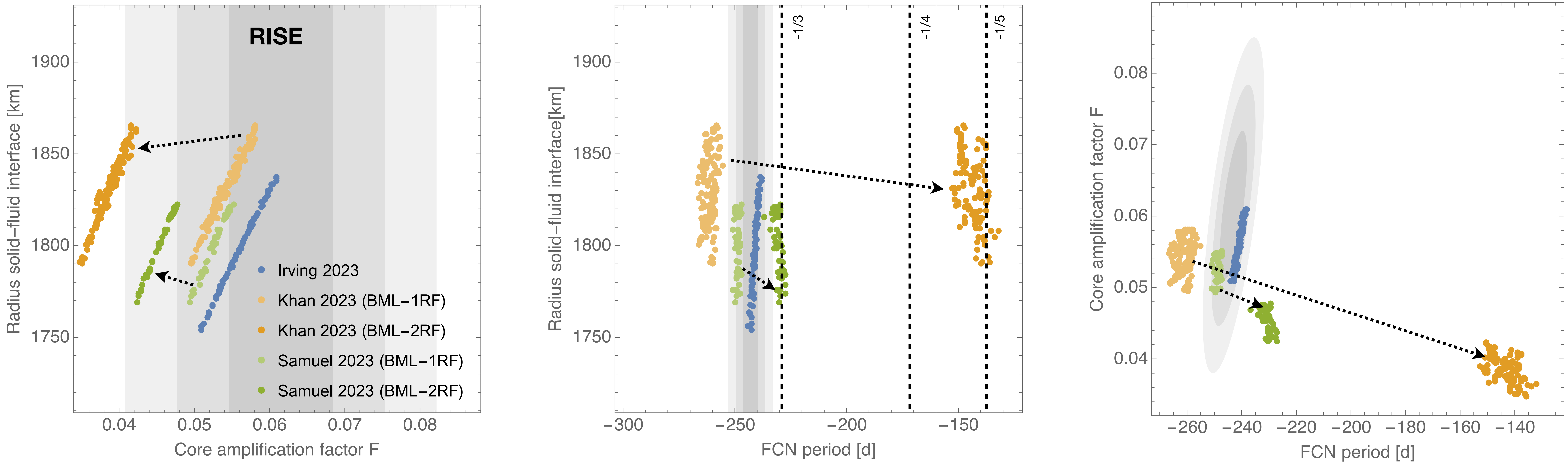
- both approaches lead to very different outcomes but agree with seismic observations and geodesy data (MOI,k_2)
- mantle either stiff (S) or soft (K), mantle temperature above solidus (K), no core cooling (S)
- the metal core is ~190 km smaller and denser and requires up to ~5 wt% less light elements (average composition: **Fe**-2.wt%**O**-13.wt%**S**-1.wt%**C**-0.25wt%**H**)

Predicted Nutation: BML models
Naive interpretation: Core and BML rotate as one fluid



- BSL models have a smaller effective core moment of inertia → F decreases
- models of Khan 2023 are softer (warm mantle) → core can deform more → lower period FCN lower

Predicted Nutation: BML models
Core and BML can have relative rotation (preliminary)



- a new rotational normal mode resulting from the relative rotation of the BML with respect to the core affects the period of the FCN (comparable to what occurs with a very large inner core)
- the FCN period of BML models is shifted to higher values and expected to lead to resonant amplification of the -1/3 annual or -1/5 annual nutation neither → -1/3 not observed and -1/5 not detectable
- neither set of BML models agree with RISE observations

New Mars structure and open questions

- the core is most likely fully liquid, the radius is 1630-1695 km (1814-1864 km), and it contains about ~17wt% (21wt%) of light elements
- the core is overlain by a molten silicate layer of ~190km
- a hot or a cold mantle temperature profile can explain the seismic data
- models with a BML do not agree with RISE observations (preliminary)
- BML models from Khan 2023 predict ongoing mantle melting (in contradiction with observations)
- BML models of Samuel 2023 preclude thermochemical dynamo action from the moment of BML emplacement on, but observations state the dynamo was still functional ~3.7 Ga ago, e.g. (Mittelholz 2020)
- can core chemical stratification due to immiscibility explain the observation?
  (immiscibility possible in Fe-O-S, e.g. Terasaki 2011 and Fe-O-S-H, Yokoo 2022)
- need for a comprehensive dynamic model that describes the emplacement of the BML and its presence to today