Mars interior structure and spin state from InSight’s RISE radio-science experiment

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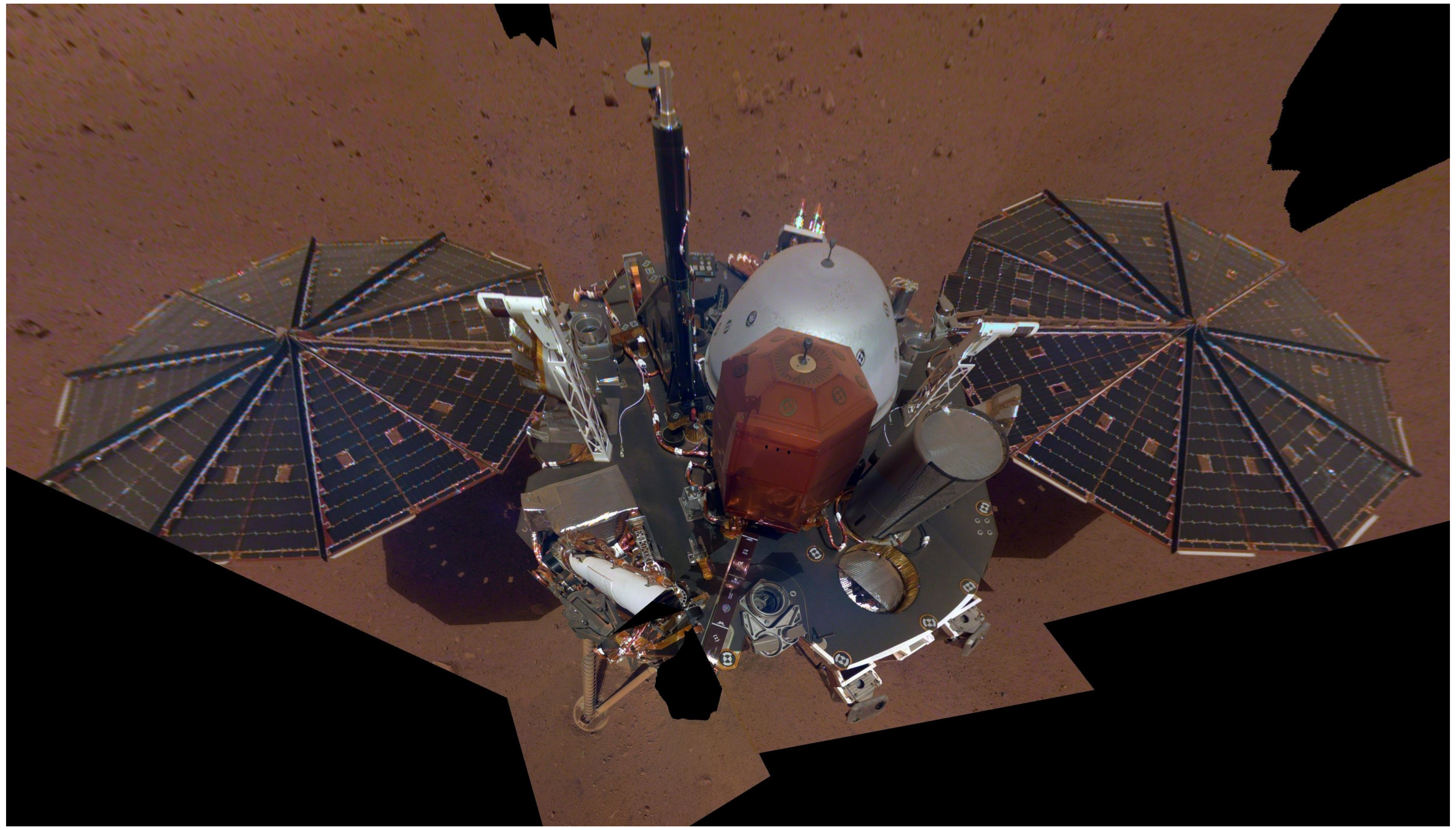
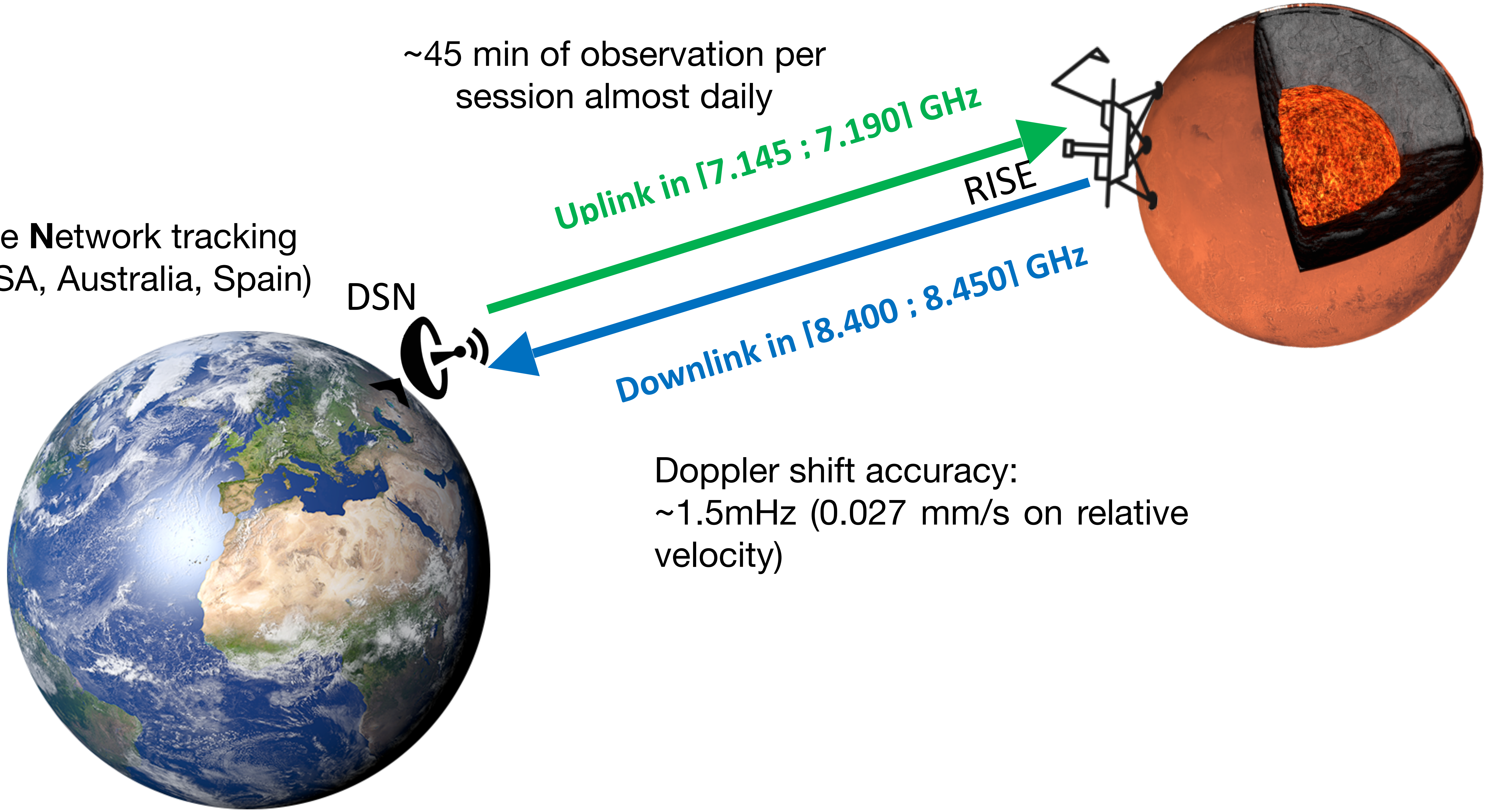
The Rotation and Interior Structure Experiment



- **RISE** is together with **SEIS** and **HP3** one of the main instruments of the InSight mission
- **RISE**: determine the rotation of Mars
  - precession
  - measure the nutation of the spin axes to detect and quantify the effect of the liquid core
  - measure the rotation rate of Mars on a seasonal timescales to constrain the atmospheric angular momentum budget

RISE setup

⇒uses radio-links to reconstruct the motion of the lander in space



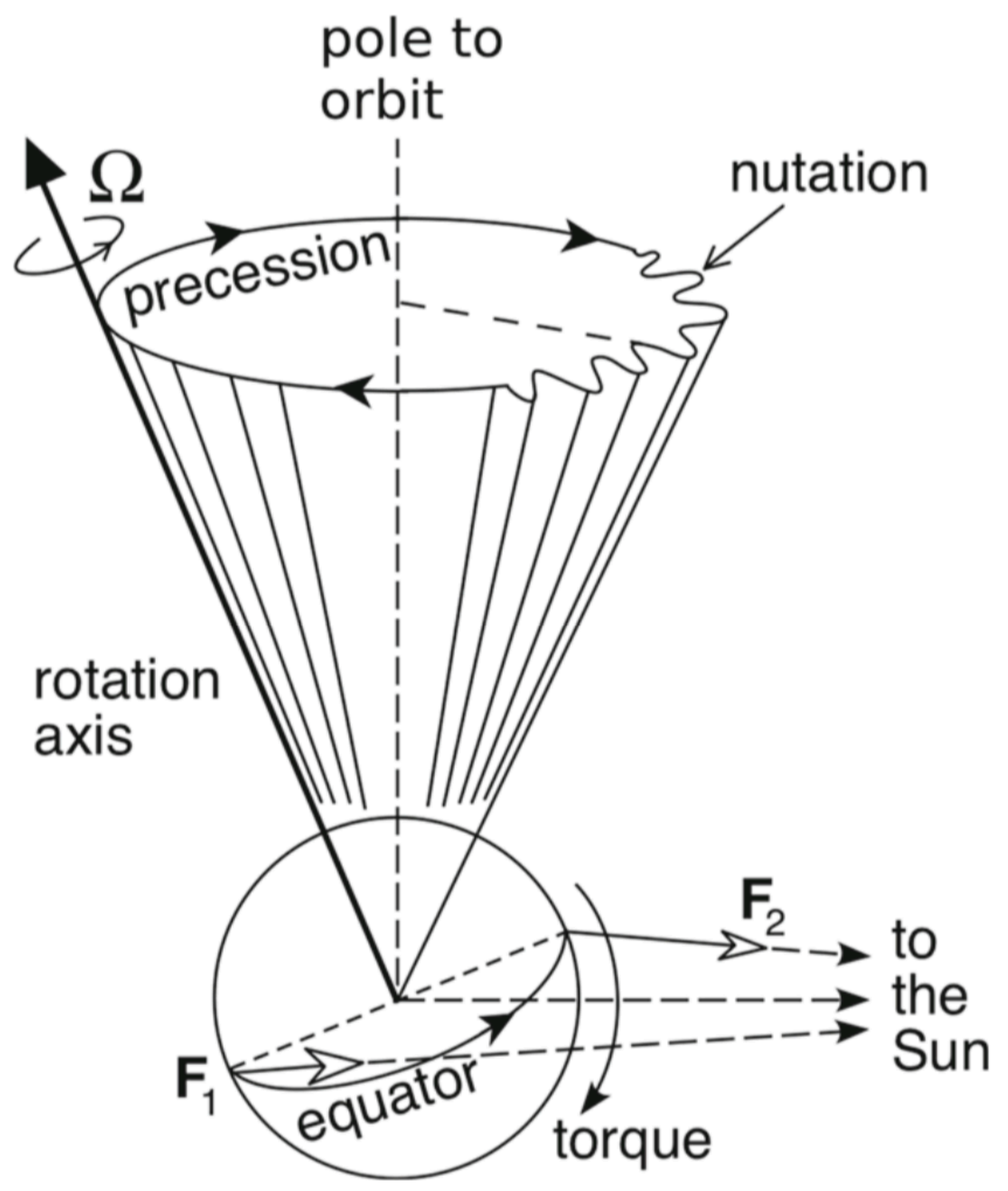
- **measure**: lander position, rotation rate, rotation in space
- **determine**: precession rate and nutation

Precession and nutation

- the gravitational torque exerted by the Sun on the flattened rotating Mars causes a precession of the rotation axis in space (~171000 years)

- torque variations due to the relative positions between the Sun and Mars lead to periodic motions of the rotation axis, the nutations (1/(1,2,3,4..) year)
  ⇒ lander position changes by about 10 m

  on the surface

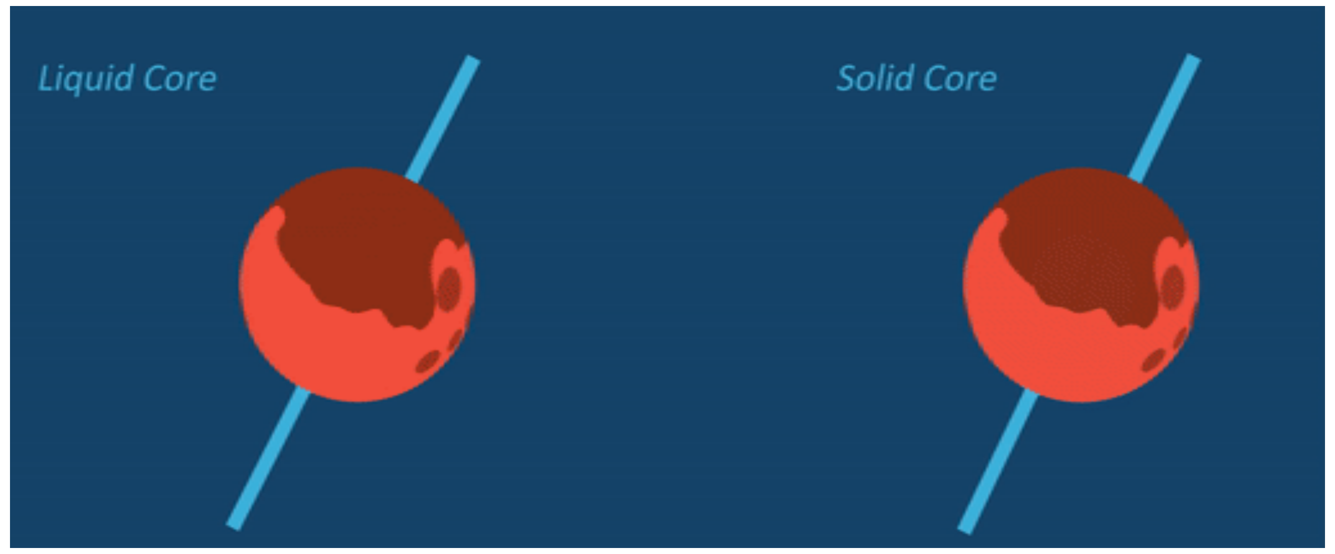


Nutation: interior structure

- if a planet were rigid then nutation amplitudes can be predicted very precisely from its moment of inertia and from the tidal potential (well known forcing periods)

- nutation amplitudes depend on the interior structure of Mars and in particular on the liquid core

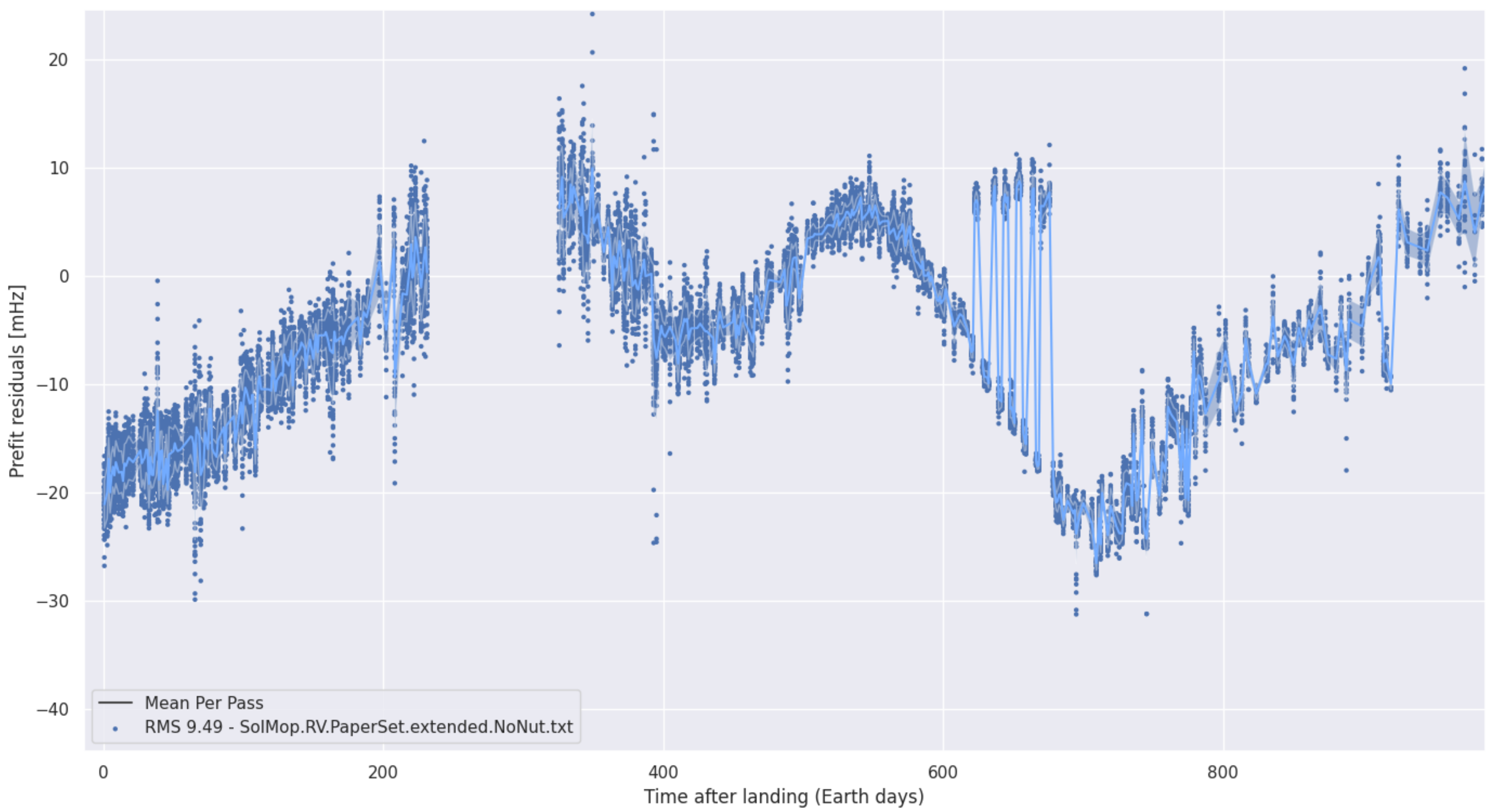
- the relative rotation between the fluid core and solid mantle is characterised by a rotational normal mode, the **F**ree **C**ore **N**utation

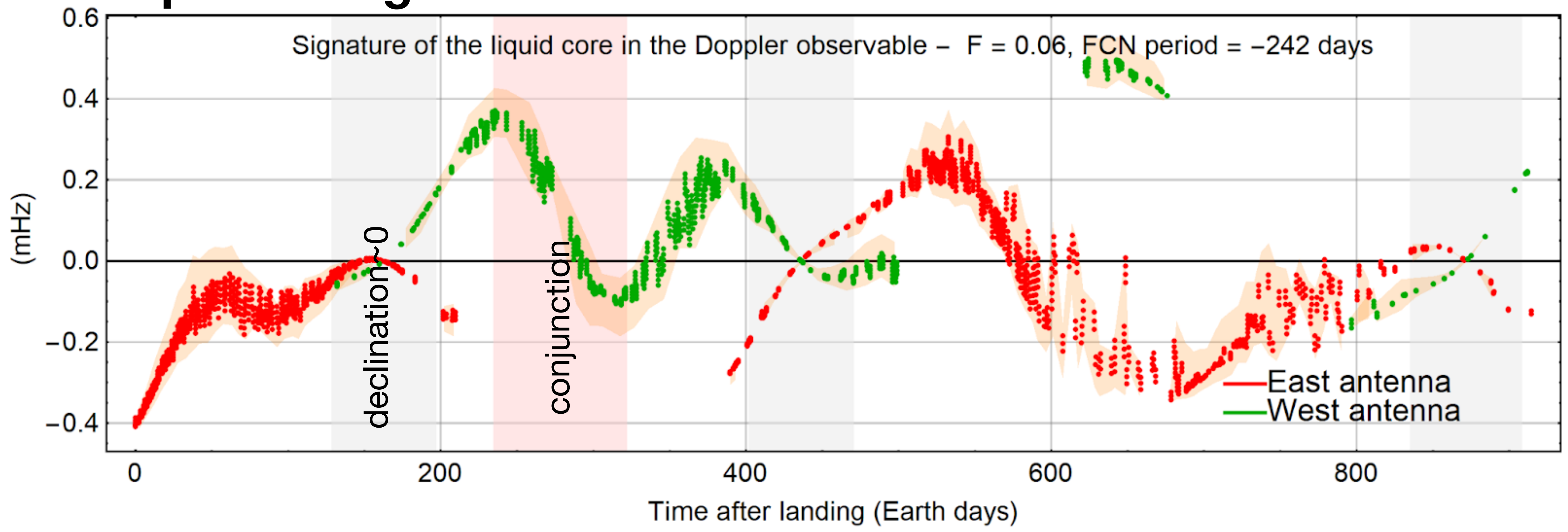


- if the FCN frequency ω_{FCN} is close to forcing frequency ω the nutation amplitude can be resonantly amplified

- the amplification strength $F = \dfrac{A_f}{A - A_f}\left(1 - \dfrac{\gamma}{e}\right)$ and $\omega_{FCN} = -\Omega\dfrac{A}{A - A_f}(e_f - \beta)$ are related to the interior structure of the planet
  $\Rightarrow$ moments of inertia of the planet (A) and core (A_f), planet (e) and core shape (e_f), core compliances due to tidal forcing (γ) and rotation rate variation (β)

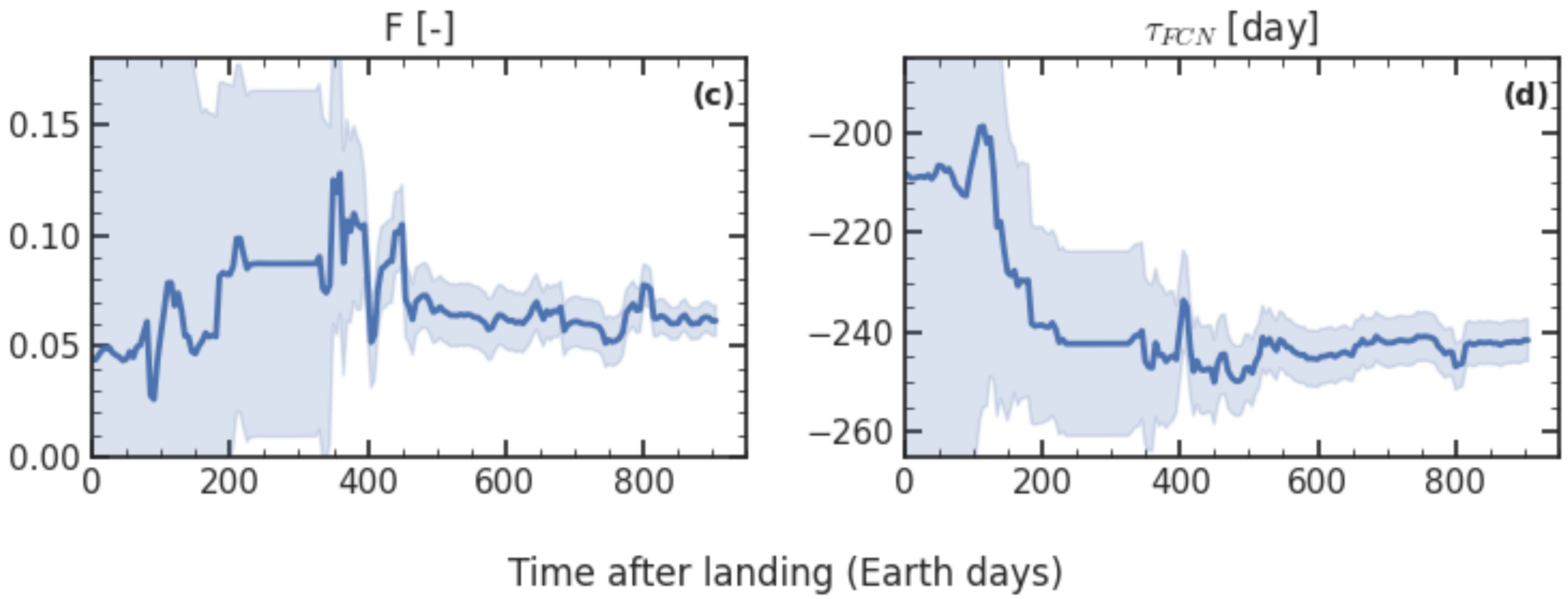
Liquid core signature and real data





- the measured doppler shift is about 20-30 mHz
- the signature of the liquid core is 2 orders of magnitude smaller
- since its periods are well known and because of data accumulation it can be determined

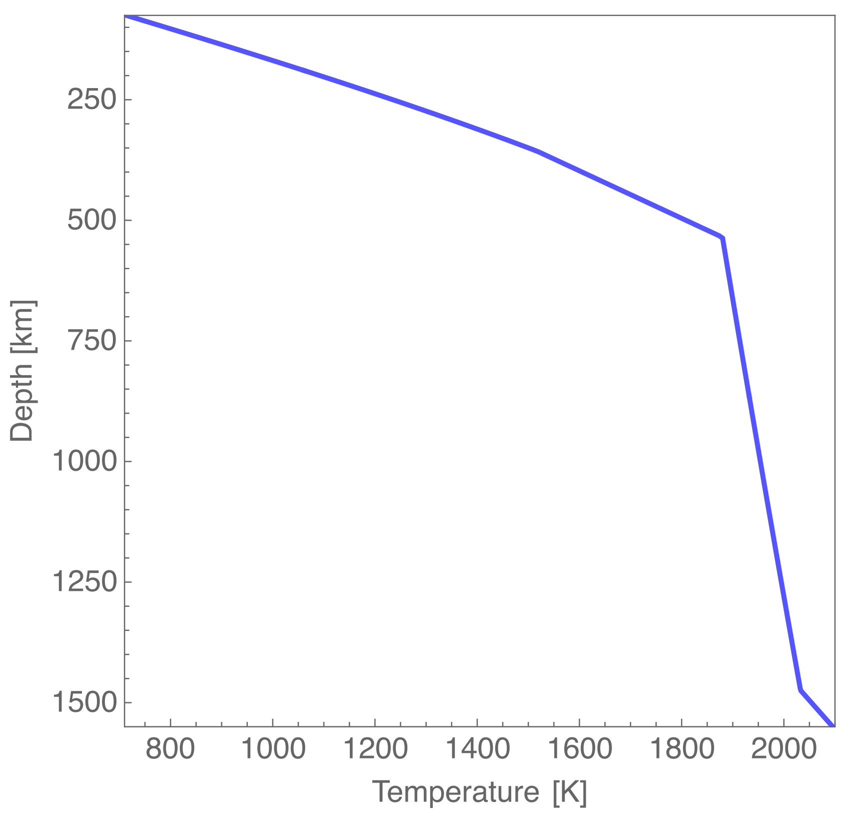
RISE results

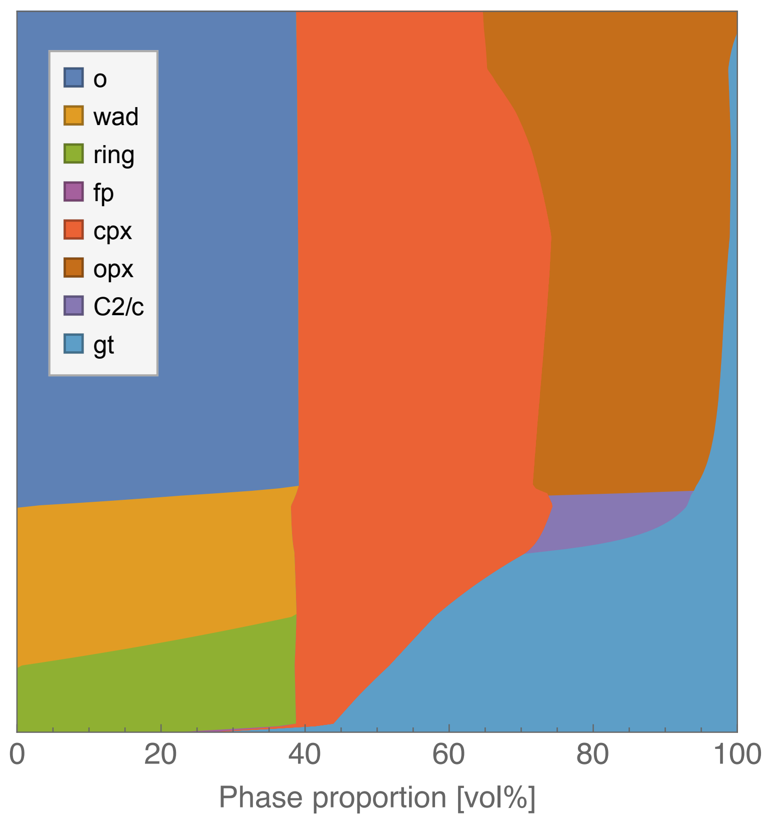


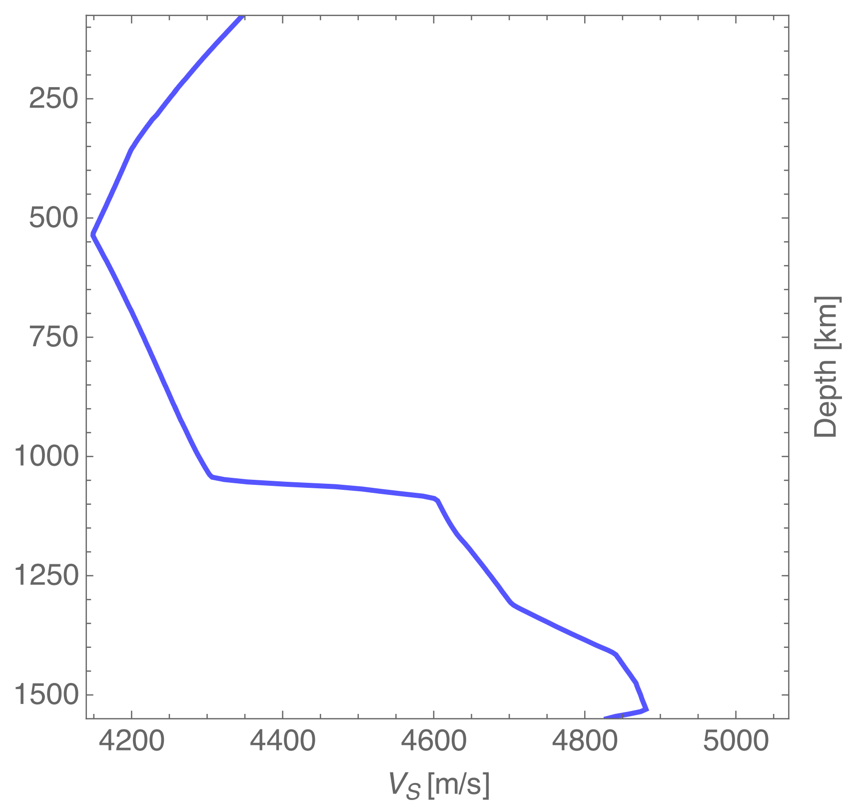
- >600 days of data are required to obtain robust estimates for the core amplification factor F and FCN period τ_{FCN}
- $F = 0.061 \pm 0.0064$ and $\tau_{\mathrm{FCN}} = -242.25 \pm 2.7$ days
- F in expected range but τ_{FCN} somewhat lower than expected

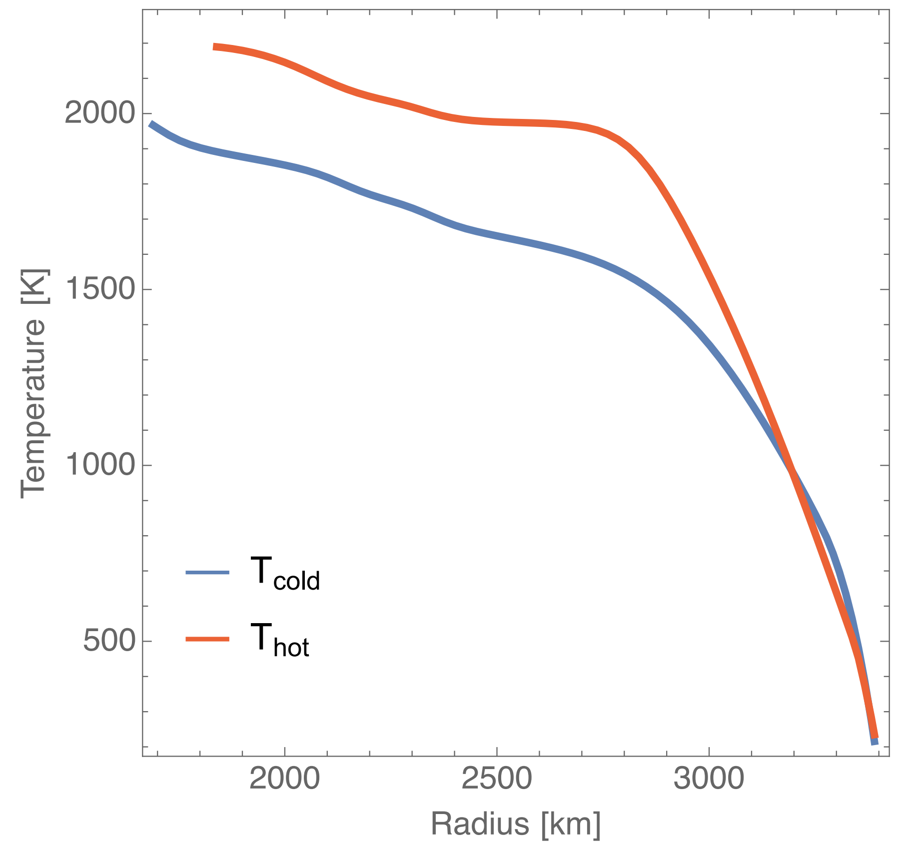
Prior modelling assumption

- layered spherical isotropic structure (crust, mantle, core)
- bulk mantle chemical composition deduced from Martian meteorites and assumptions about its formation matching either refractory elements (i.e. Wänke & Dreibus 1994, Taylor 2013, Yoshizaki & McDonough, 2020 (**YMD**)) or oxygen isotope systematics (i.e. Lodders & Fegley, 1997; Sanloup et al., 1999 (**EH45**))
    - mantle rich in FeO (~18wt%) except YMD model (~14wt%) ⇒ affects depth of major phase transition, density, and elastic properties
    - mantle is chemical homogeneous and in thermodynamical equilibrium ⇒ use Gibbs energy minimisation (Perple_X (Connoly 2005) + Stixrude & Lithgow-Bertelloni 2011) to compute all thermoelastic properties in the mantle from bulk composition and thermal state ⇒ density, bulk moduli, and shear moduli are related by bulk composition and remaining degree of freedom: **thermal state**
    - assume a hot and cold mantle temperature end-member deduced from 3D spherical geometry thermal evolution studies (Plesa et al . 2018)

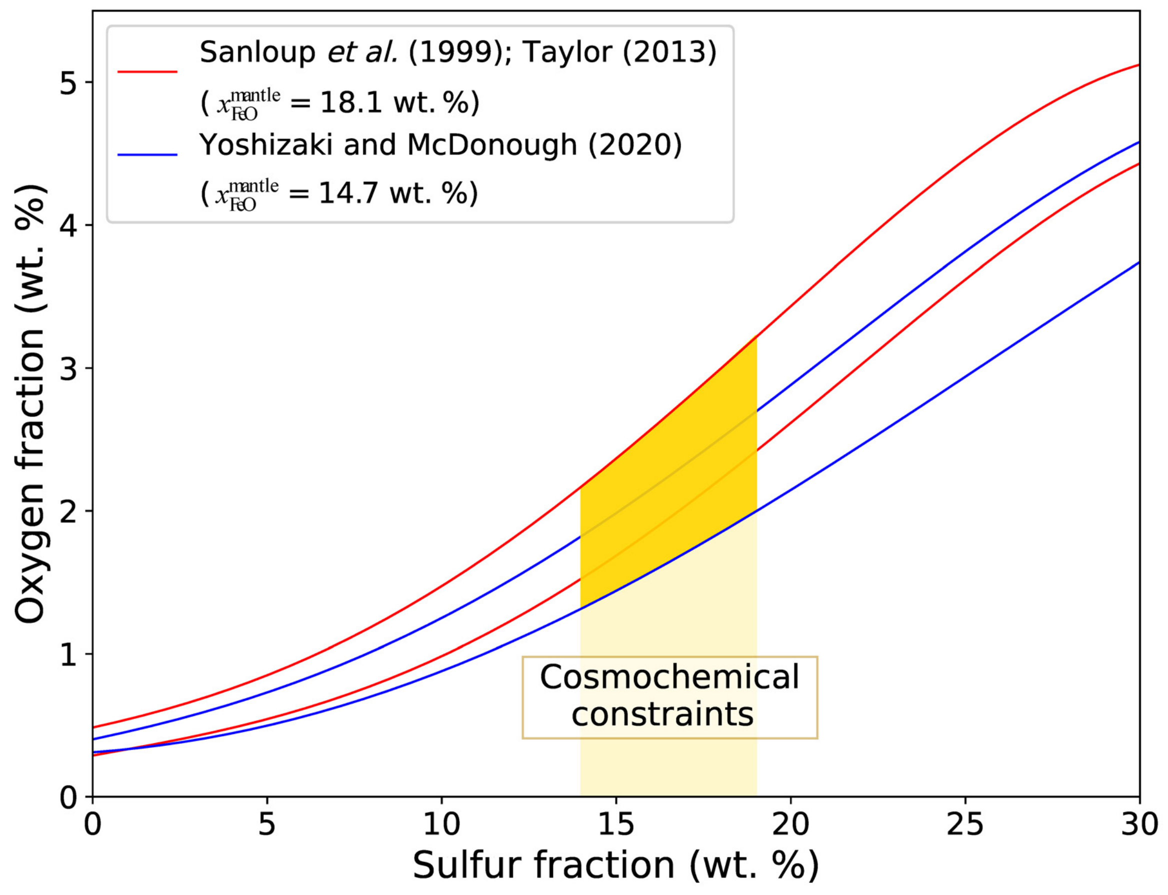


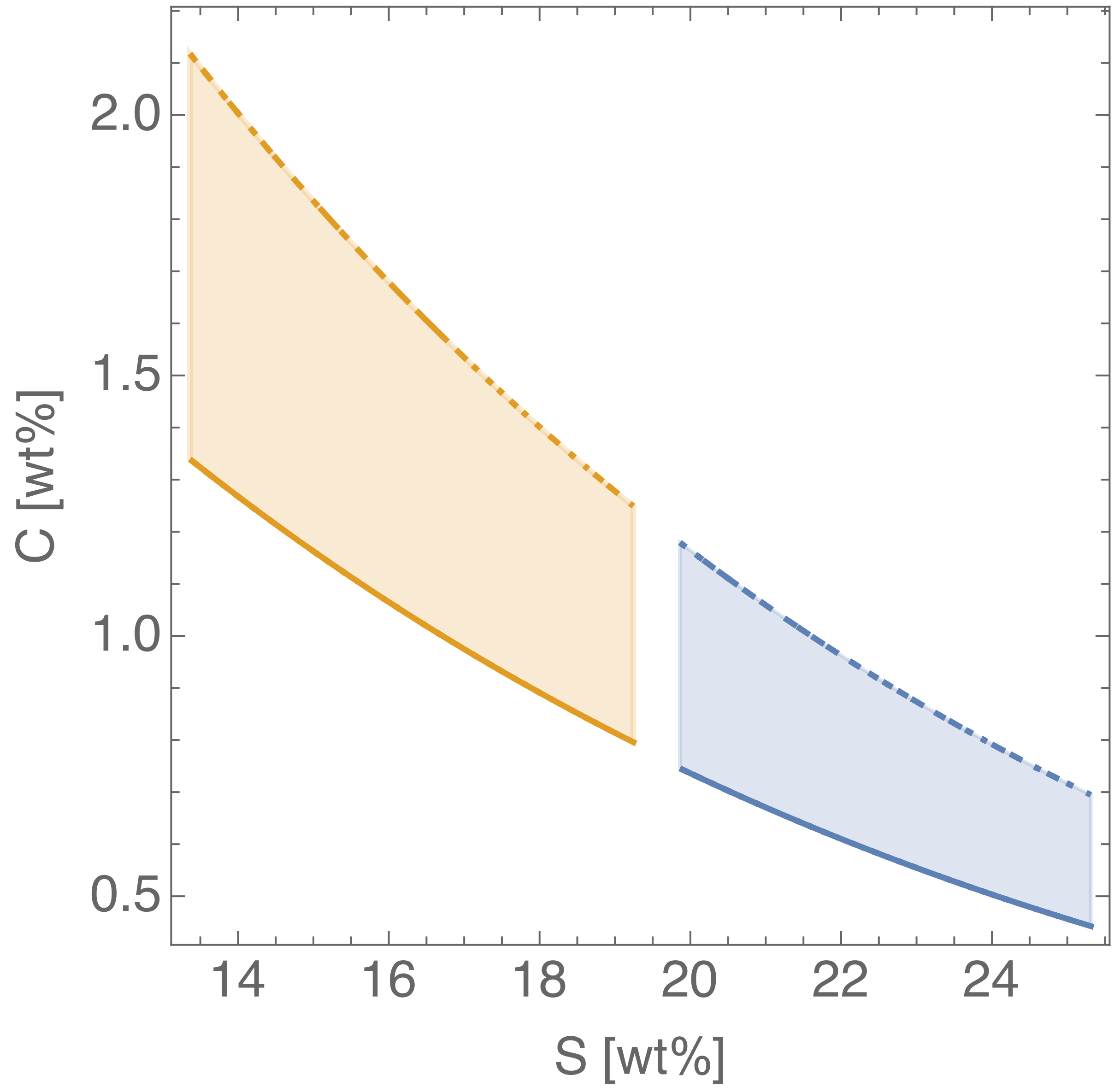




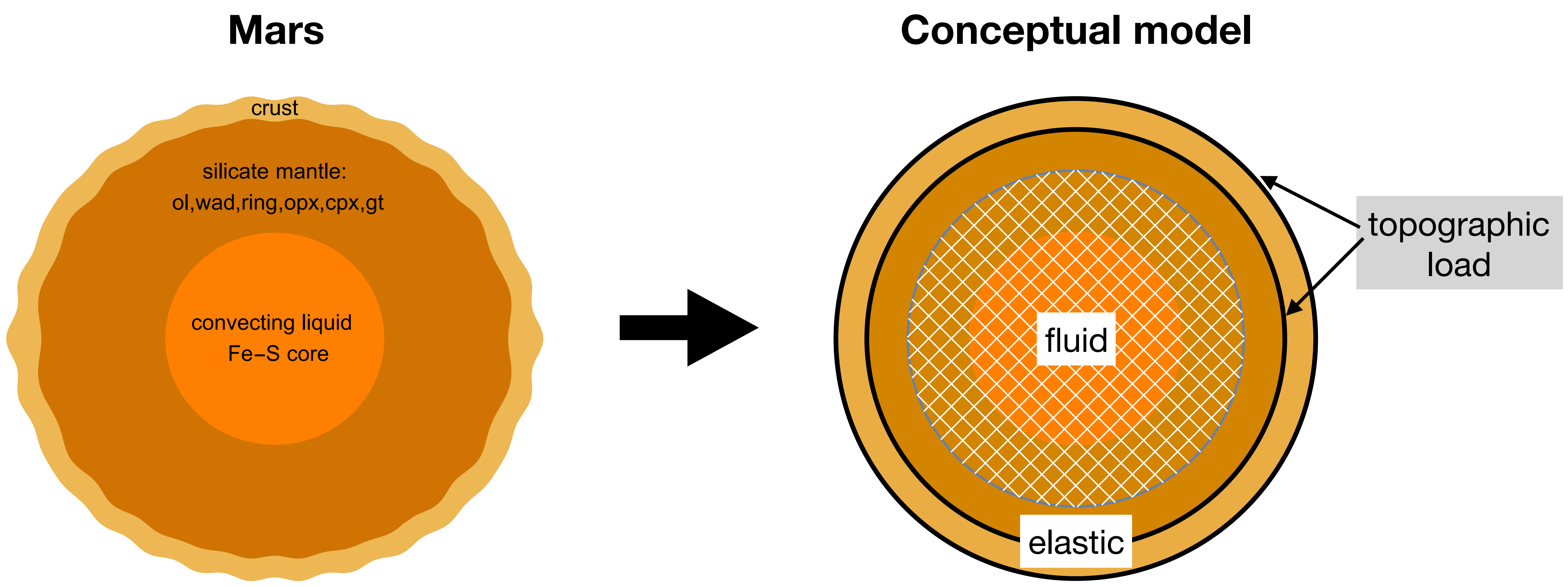


- core is fluid, homogeneous, and isentropic
  - candidate light elements that are siderophile or dissolve into Fe at formation and affect thermoelastic properties of the core: S, O, C, H (e.g. Steenstra 2018)
  - bulk composition models and formation allow for **S≲17wt%** (e.g. Steenstra 2018)
  - **O** (≲**4wt%)** fraction dependents on mantle FeO and bulk S (Gendre & Badro 2022)
  - maximal amount of **C** (≲**1.5wt%)** limited by S (Dasgupta 2016)
  - **H** (<**1wt%)** depends on initial mantle H_2O and extremely scarce experimental data (Tagawa 2022)





Shape model



- geometric and dynamic shape (deg 2) of Mars results from rotation, mass anomaly induced by the surface topography, and internal mass anomalies placed deep within the planet (Moho, bottom of the lithosphere, core-mantle boundary) (see also Zharkov 2009, Wieczorek 2019)
- internal loads are specified to match geometric and dynamic shape of Mars
- effect of rotational flattening on core shape ~5000 m (also dependent on density jump at the CMB)
- effect of internal loads on core shape ~100m

Interior structure before InSight

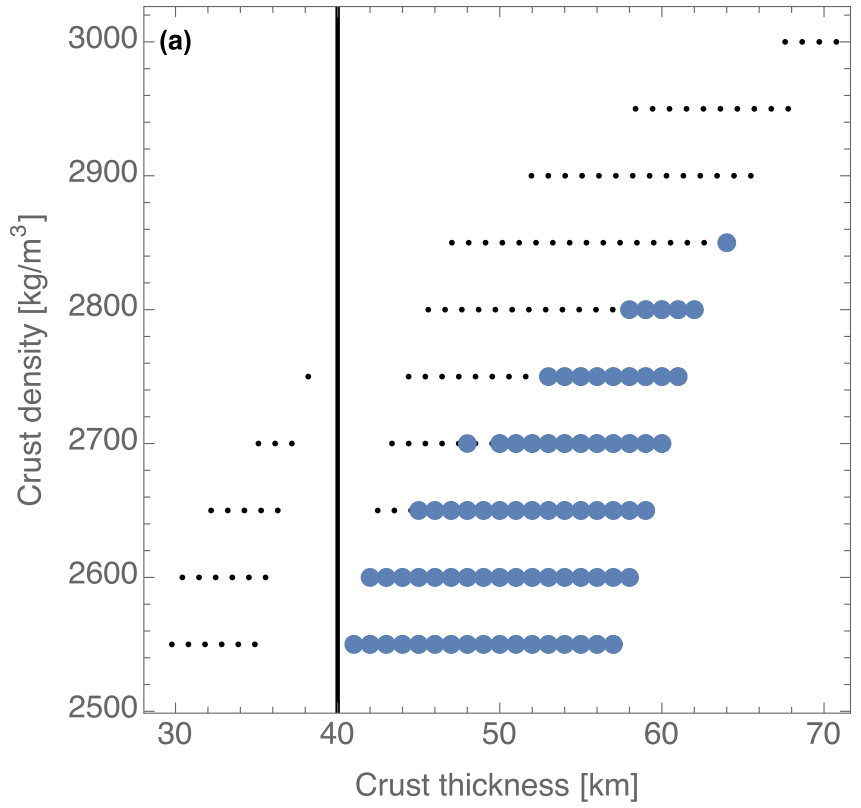
- constraints mostly from geodesy data (gravity field, precession rate, tides)
- structure models based on mantle compositions deduced from bulk composition models agree with observations (but often disagree on core composition)
- measured tides can only be explained with a liquid core (Yoder 2003)
- cessation of core generated dynamo about 3.7 Ga ago (Mittelholz 2020) → inner core unlikely?
- core radius 1790±65km (e.g. Rivoldini 2011, Khan 2019)
- inferred core density can be explained with a liquid Fe-16.5wt%S alloy
  → about the eutectic concentration any plausible present-day thermal state implies that inner core is fully molten
- new experimental data about elastic properties (density and acoustic velocity) of liquid Fe-S show that more than 25wt%S is required to match the density of the core (Nishida 2016, Shimoyama 2016, Kawaguchi 2017, Morard 2018, Terasaki 2020, Xu 2021, Nishida 2020)
  → if S were the sole light element would lead to up-floating solid FeS

Precession: interior structure

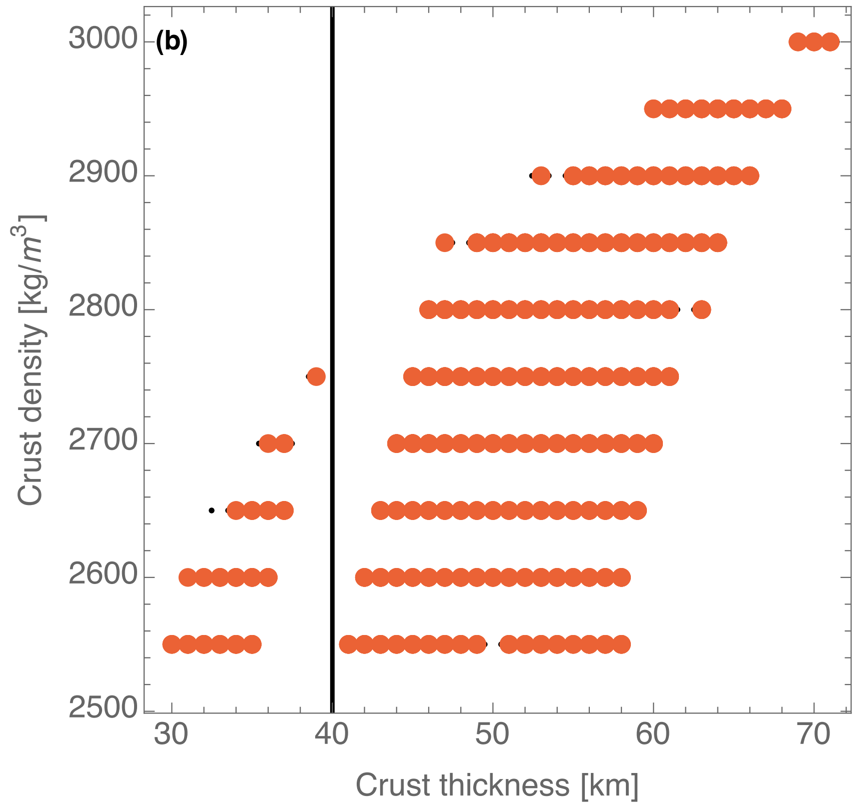
- precession rate together with degree 2 gravity field provides **polar moment of inertia**
- leads to constraints on the mass distribution within Mars and in particular on the crust
- allows to further constrain crustal models deduced from seismic data, surface gravity, and topography → Wänke & Dreibus 1994 and Taylor 2013 BSM models incompatible with the data!

Mars mantle composition YMD

Cold mantle

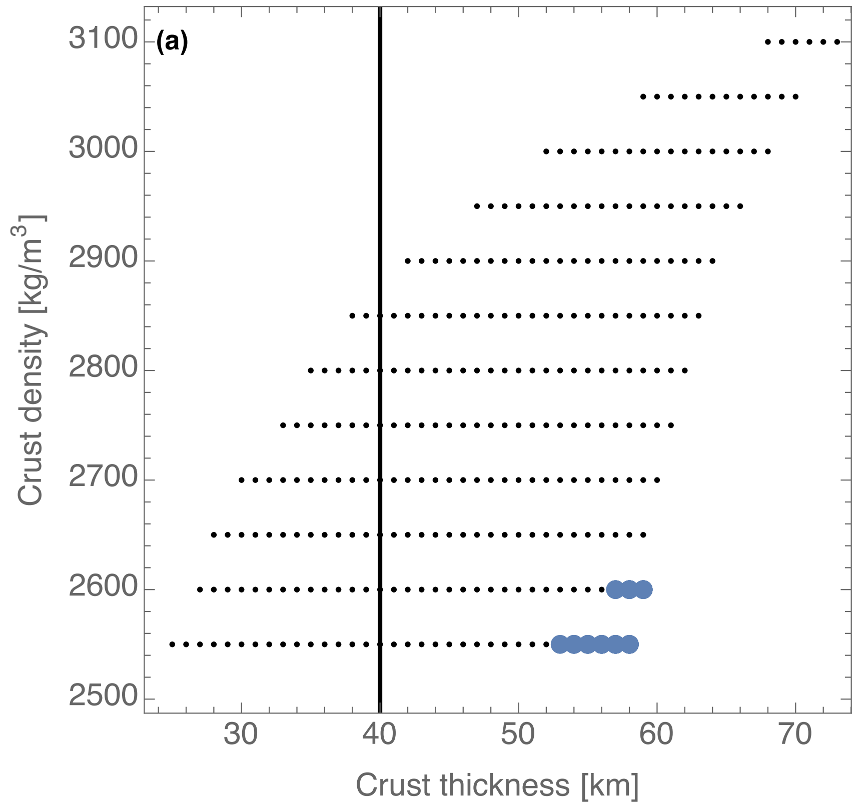


Hot mantle

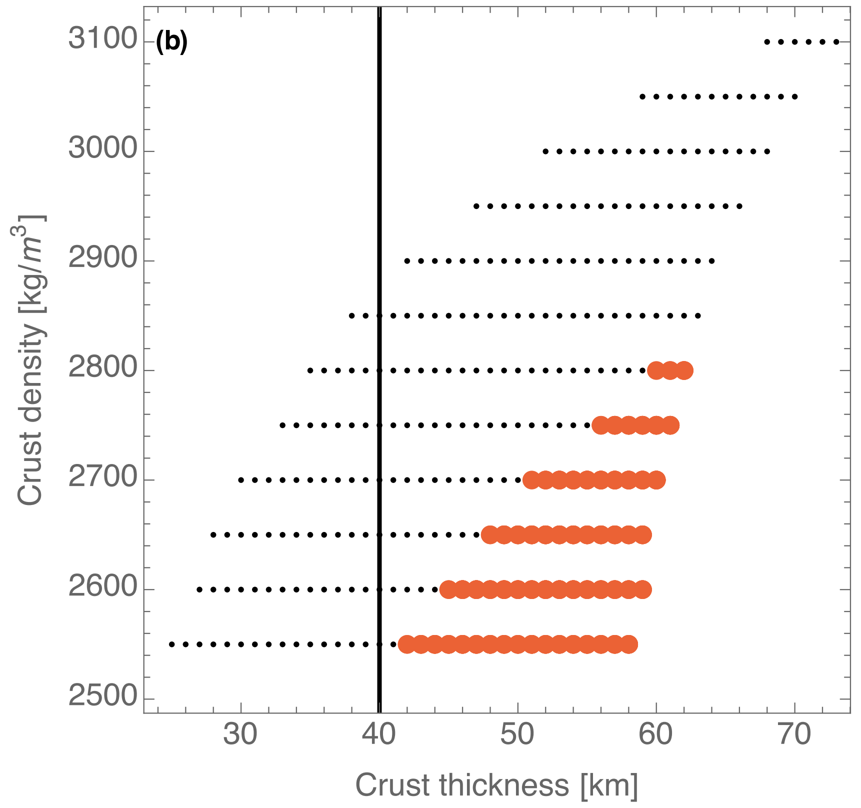


Mars mantle composition EH45

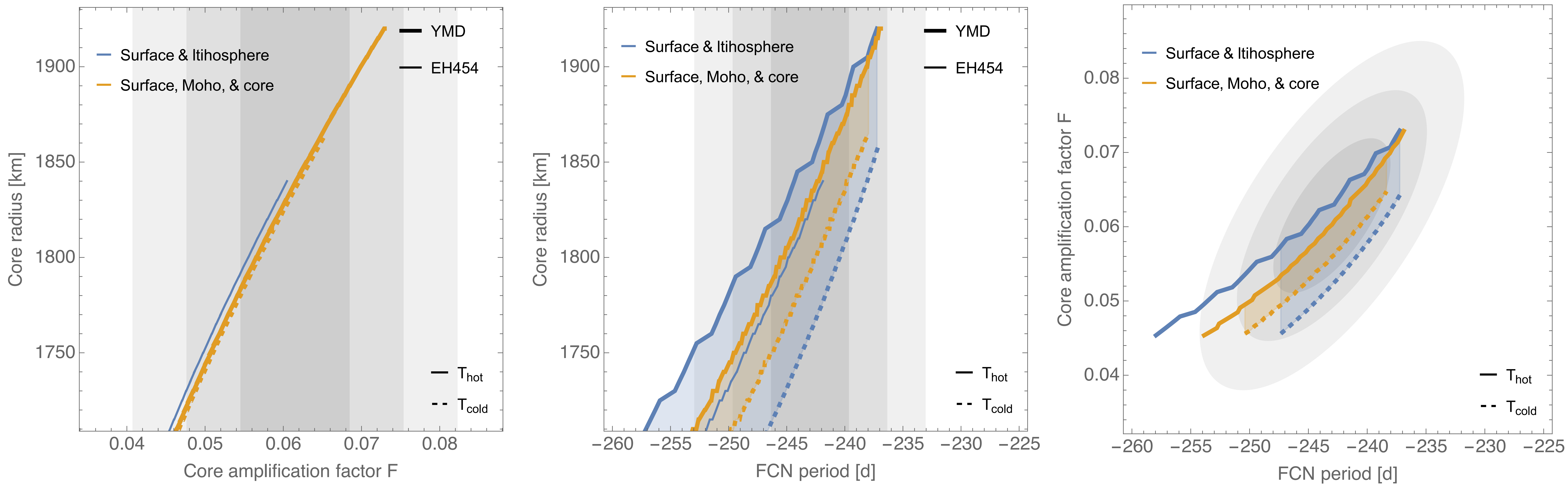
Cold mantle



Hot mantle



Nutation: interior structure



- *F* (~core moment of inertia~ core radius) weakly dependent on mantle composition and temperature as well as nearly independent on core shape

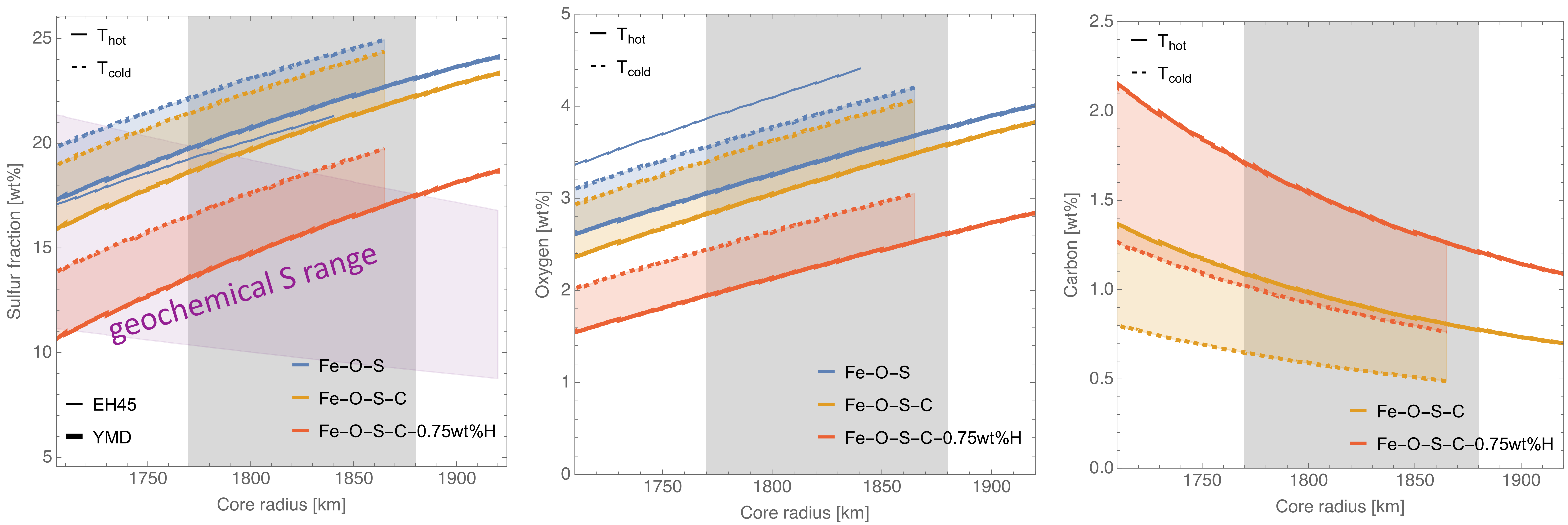
- but **not** the *FCN* period: precession compatible crust density and thicknesses affect internal loading and density profile affect hydrostatic core shape

- inferred core radius range of 1825±55 km is in excellent agreement with tides and seismic observations (Stähler et al. 2021, Duràn et al 2022)

Nutation: Core composition

- models without H are unlikely if S in agreement with geochemical constraints

- RISE data and geochemical constraints require a core with 17±2.5wt% S, 2.5±0.5wt% O, and 1.0±0.5wt% C if 0.75wt% H is assumed in the core in good agreement with arrival times of core traversing seismic waves (Irving 2023)
  (eos used for core composition deduction: Dorogokupets 2017; Nishida 2016,2020; Morard 2017, 2018; Xu 2021; Komabayashi 2014, Shimoyama 2016, Terasaki 2010, Kawaguchi 2017, Tagawa 2022)



What about the inner-core?

- if there is an inner core it can have a relative rotation with respect to the fluid core giving rise to a another rotational normal mode the Free Inner Core Nutation (FICN) that can like the FCN lead to a resonant amplification of the nutation

- the signature of the inner core has not been detected in RISE data
  → either the FICN period differs significantly from tidal forcing periods or the inner is rather small and its effect on nutation is below current precision

- core traversing seismic waves (SKS) are not reflected inside the liquid core and sample the core down to a radius of about 800km (Irving 2023) → the inner-core is smaller than 800km

- an S concentration close to the Fe-S eutectic together with the naïve assumption that the remaining light elements further reduce the melting temperature of Fe requires an implausible low core temperature (<1300K) to initiate solidification in the core → the core is fully molten

- very early cessation of the core generated dynamo (~3.7 Ga ago) in favour of a purely thermally driven dynamo

Conclusions

- the measured nutation and the detection of the FCN normal mode confirm the liquid state of the core
- RISE data constrain the moment of inertia of the core, the density jump at the core mantle boundary, and the shape of the core
- the core radius of 1825±55 km is in excellent agreement with estimates obtained from tides and seismic data
- RISE data and geochemical constraints require a core with 17±2.5wt% S, 2.5±0.5wt% O, and 1.0±0.5wt% C if 0.75wt% H is assumed
- a small fraction of H is required to obtain an acceptable fraction of S
- the FCN period can be explained if the core has an almost hydrostatic shape, such a core shape can result from deep seated mass anomalies within the mantle that originate form thermal or chemical anomalies

Caveats and motivation for future work

- thermal evolution and thermal state of the core cannot are difficult to assess since transport properties of liquid Fe-O-S-C-H alloys are unknown
- eos of liquid Fe-H at Mars core conditions is really not well known (almost not)
- current eos of the core based on ideal mixing assumption of Fe-S, Fe-O, Fe-C, and Fe-H but it is well known that the individual light elements do not mix ideally with Fe→ bias inferred core composition
- non-deal mixing will lead to immiscibility fields in the composition space → the core could be chemically stratified (e.g. Fe-O-S (Tsuno 2007), Fe-S-H (Yokoo 2022)
- joint effect of O,S,C, and H on melting temperature of Fe unknown → is the liquidus really that low?
- thermodynamic database of mantle minerals calibrated on samples close to earth mantle composition
- suggested presence of present-day molten layer in the bottom of the mantle (Samuel 2021) → is the metallic core is smaller and denser?
- LVZ and soft lower mantle due to the interaction of liquid Fe-S with olivine aggregates (Kono 2023) → can this explain the LVZ like layer in the lower evidenced in seismic data? (Durán 2022)

Interpretation: FCN period

- FCN frequency proportional to core shape which is directly related to the density jump at the core mantle boundary
(⇒ constraints density jump at the core-mantle boundary)

- RISE data implies an almost hydrostatic core shape, **but** the shape of Mars is **not hydrostatic**
    - requires mass anomaly at the bottom of a thick lithosphere (>550km)
    - or two loads at shallow depth and at the core-mantle boundary