Spin state and deep interior structure of Mars from InSight radio tracking

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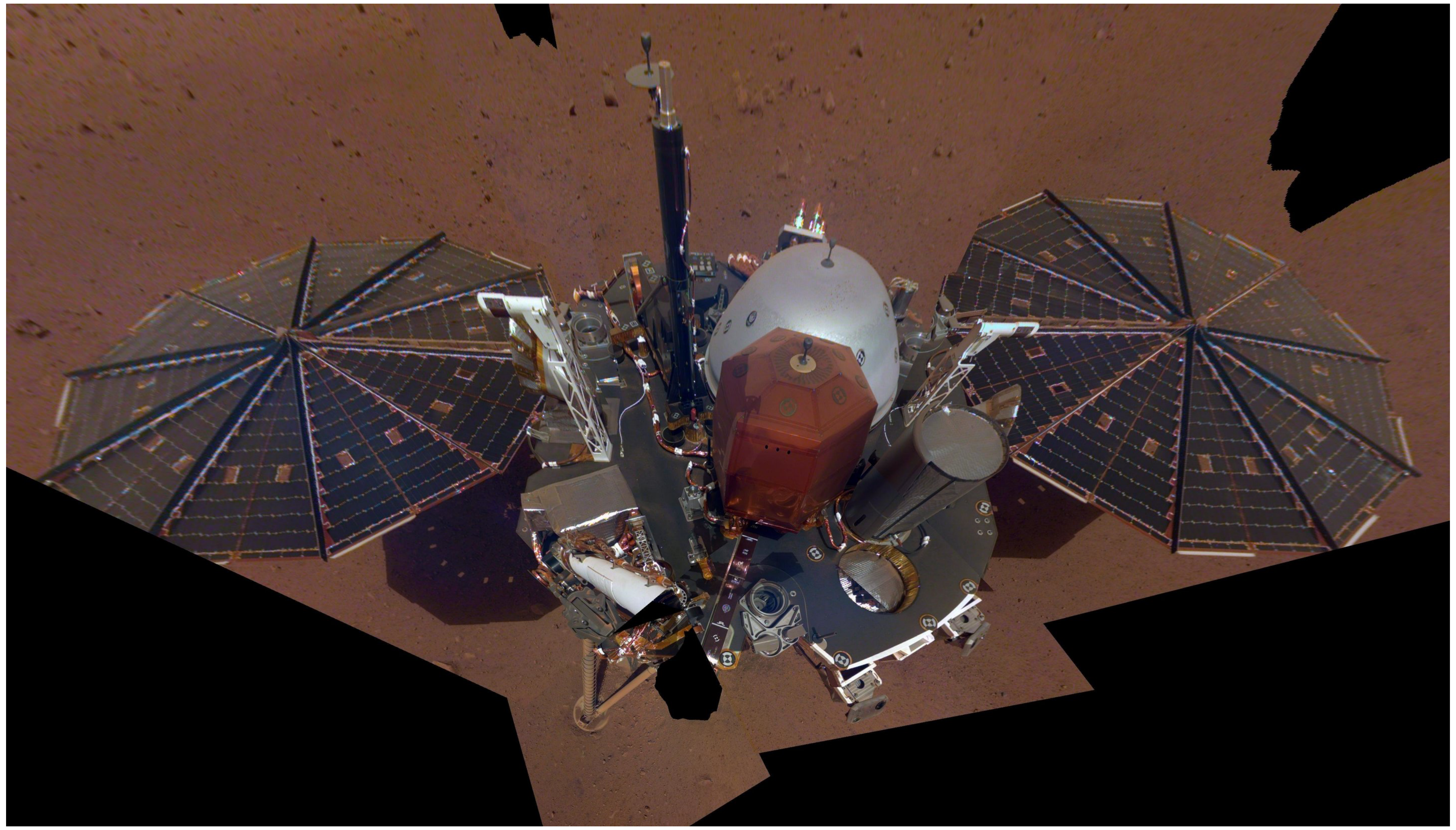
The Rotation and Interior Structure Experiment



- **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

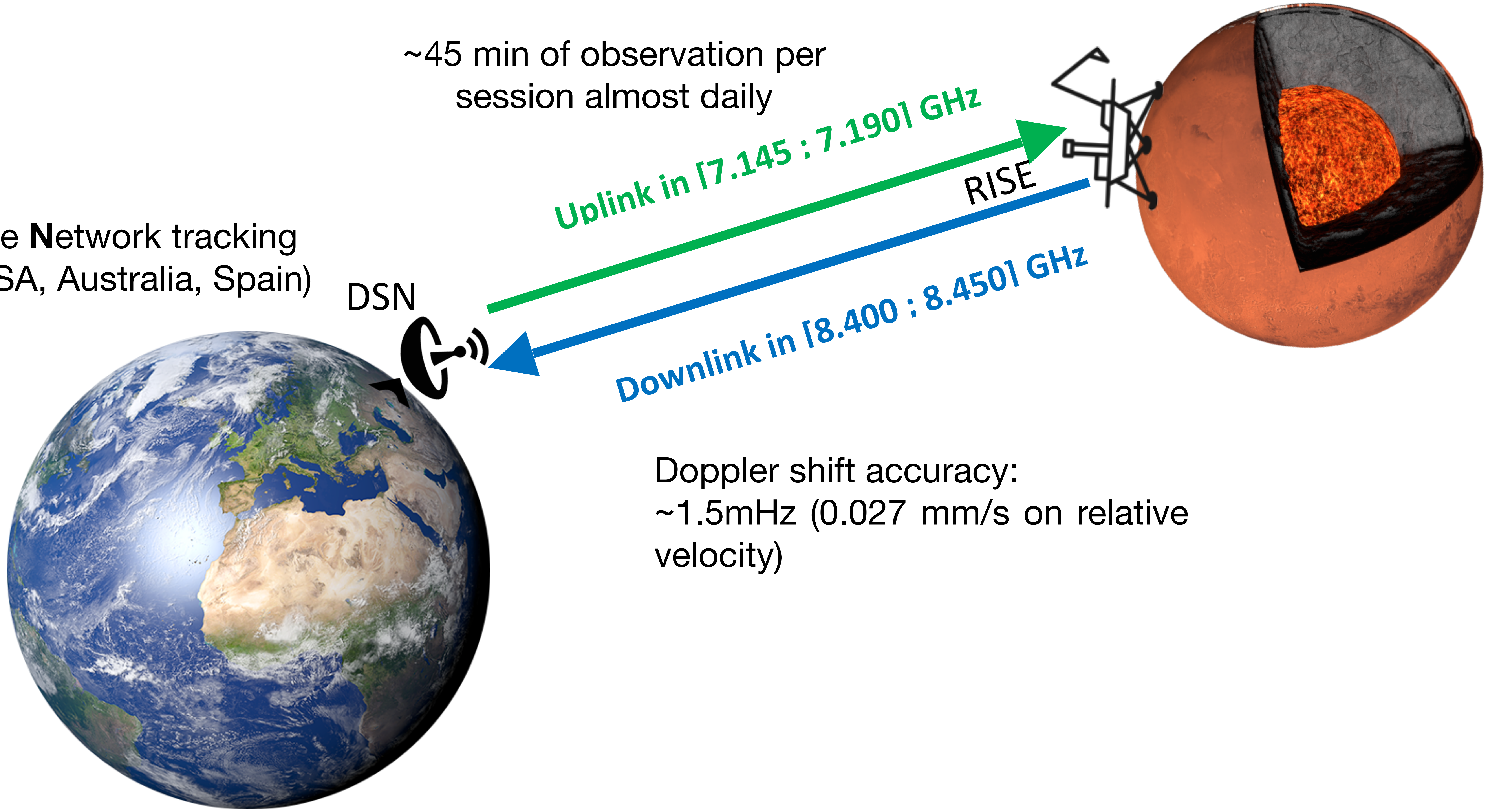
RISE setup

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

~45 min of observation per session almost daily

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

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



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

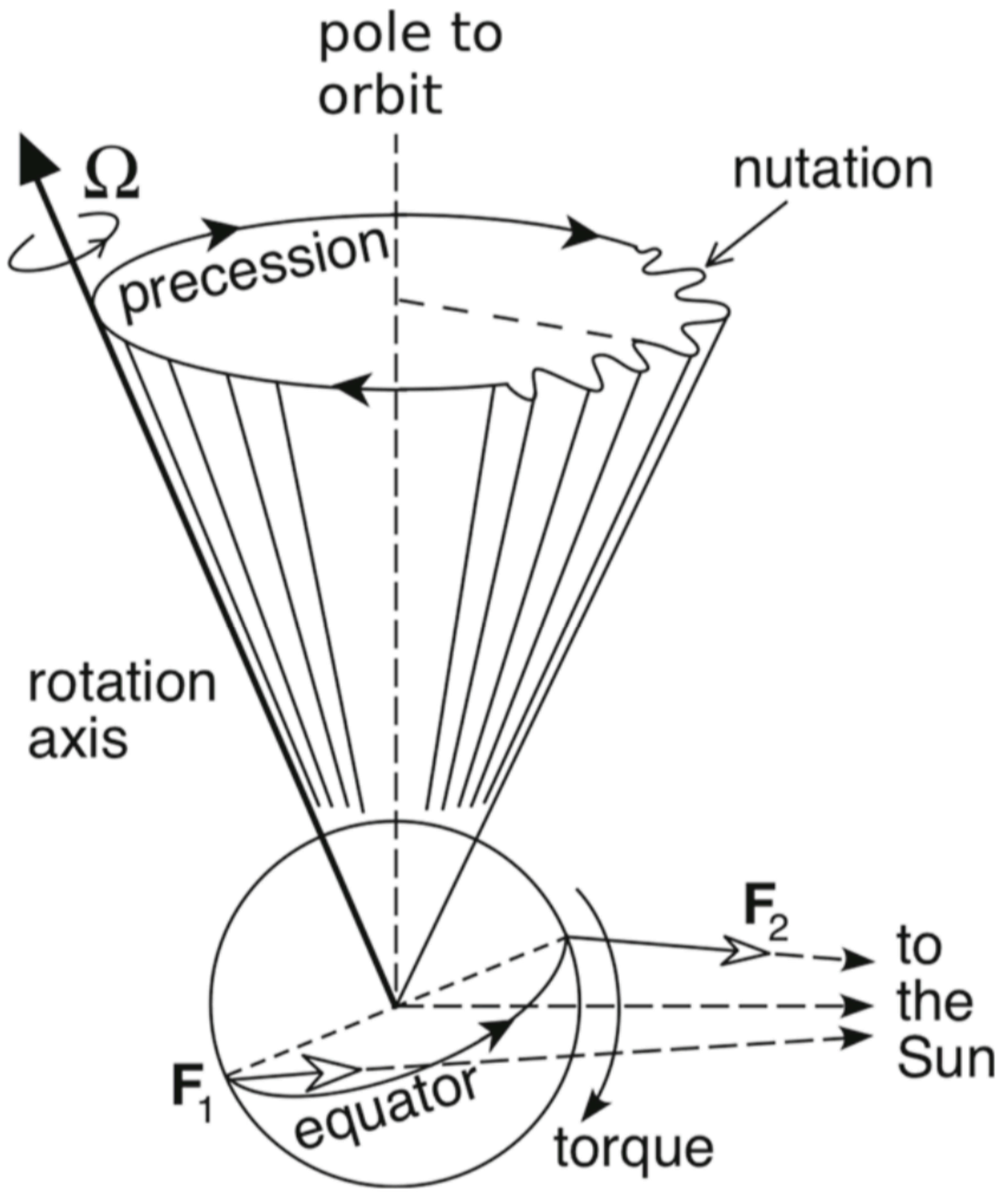
- **measure**: lander position, rotation rate, rotation in space
- **determine**: precession rate and nutation

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

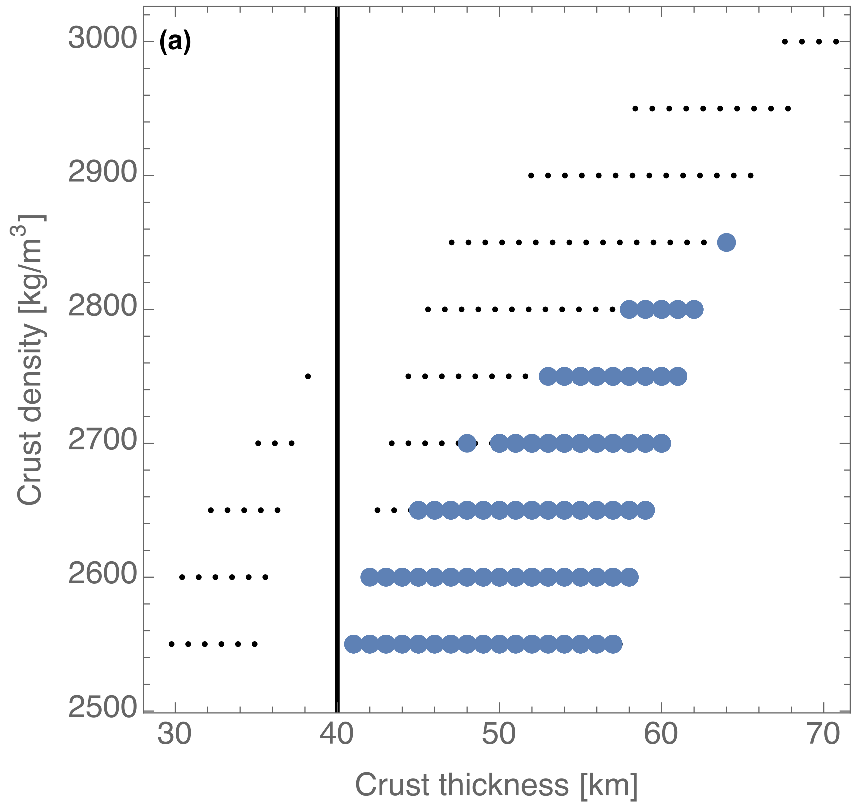


Precession: interior structure

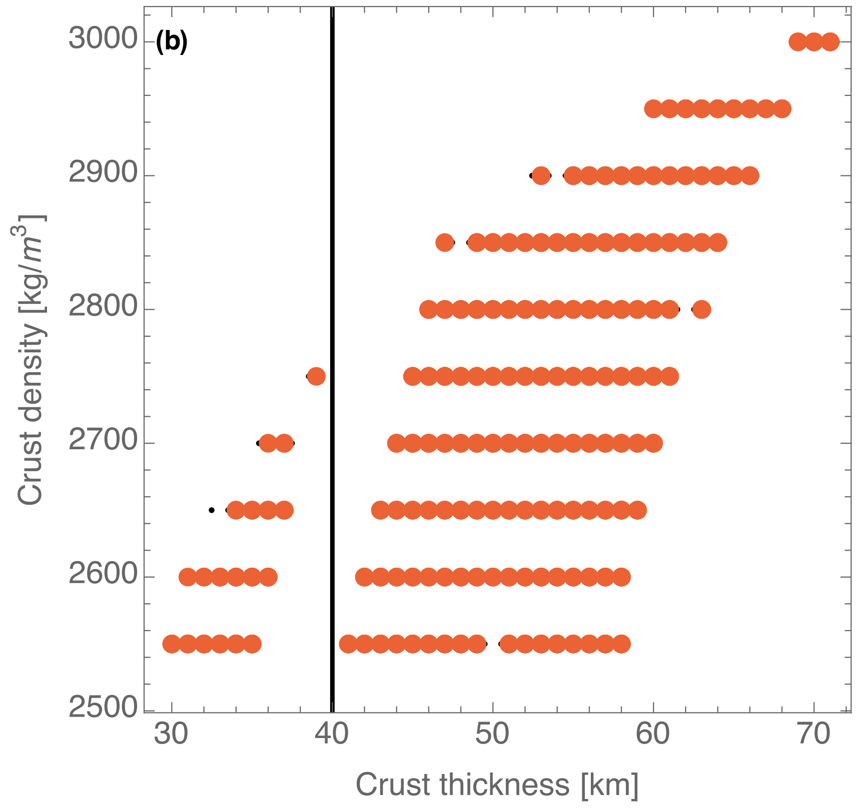
- precession rate together with degree 2 gravity field provides **polar moment of inertia**
- leads to constraints on the mass distribution within Mars
- allows to further constrain crustal models deduced from seismic data, surface gravity, and topography (BSM models of Wänke&Dreibus 1994 and Taylor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

Mars mantle composition YMD

Cold mantle

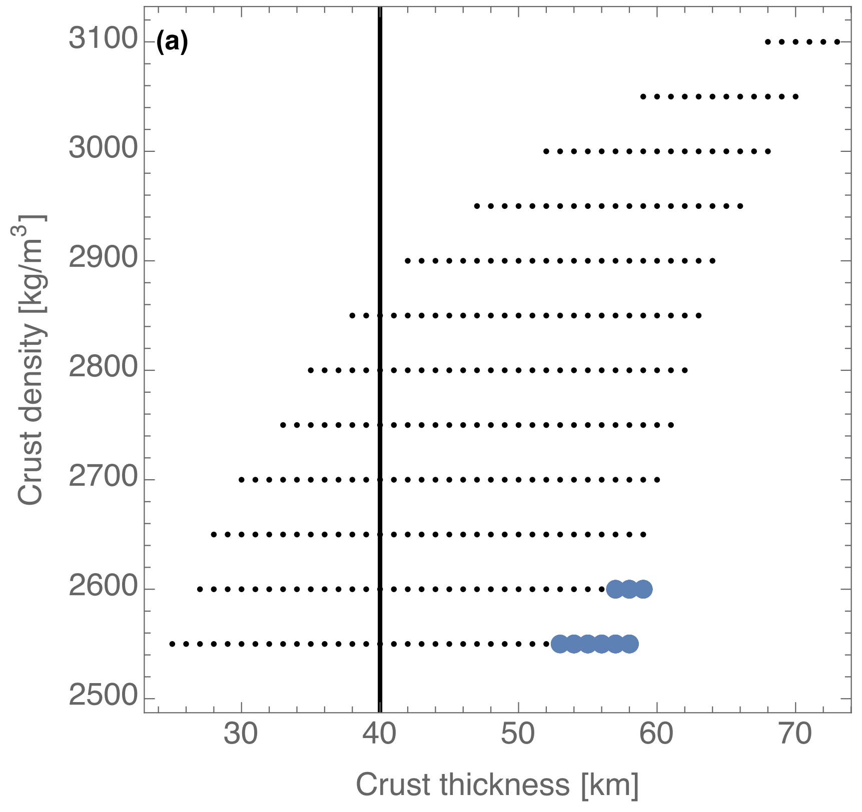


Hot mantle

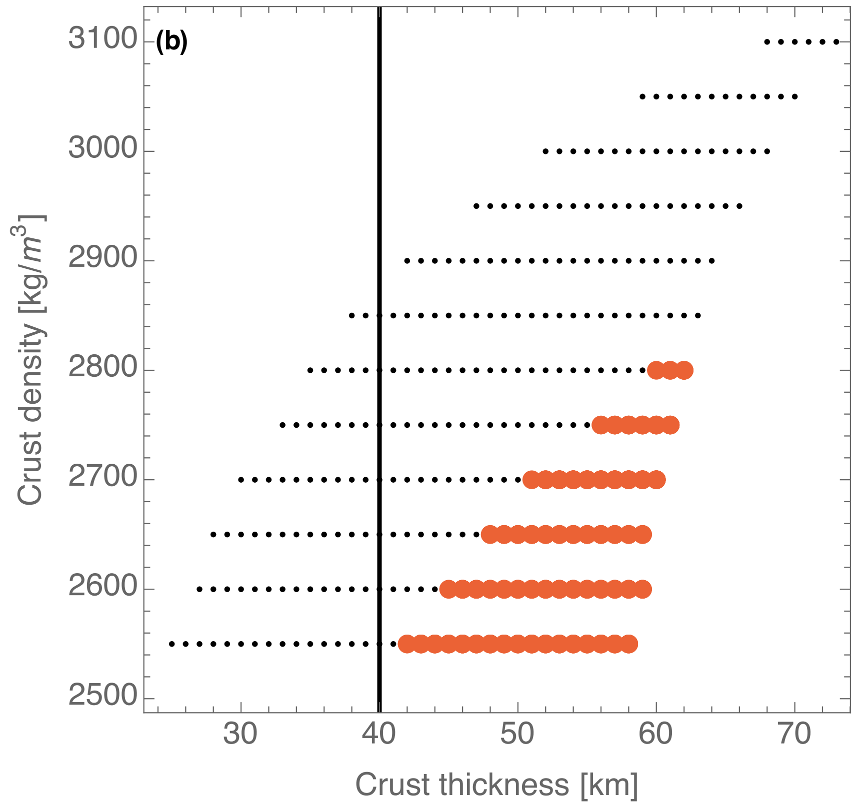


Mars mantle composition EH45

Cold mantle

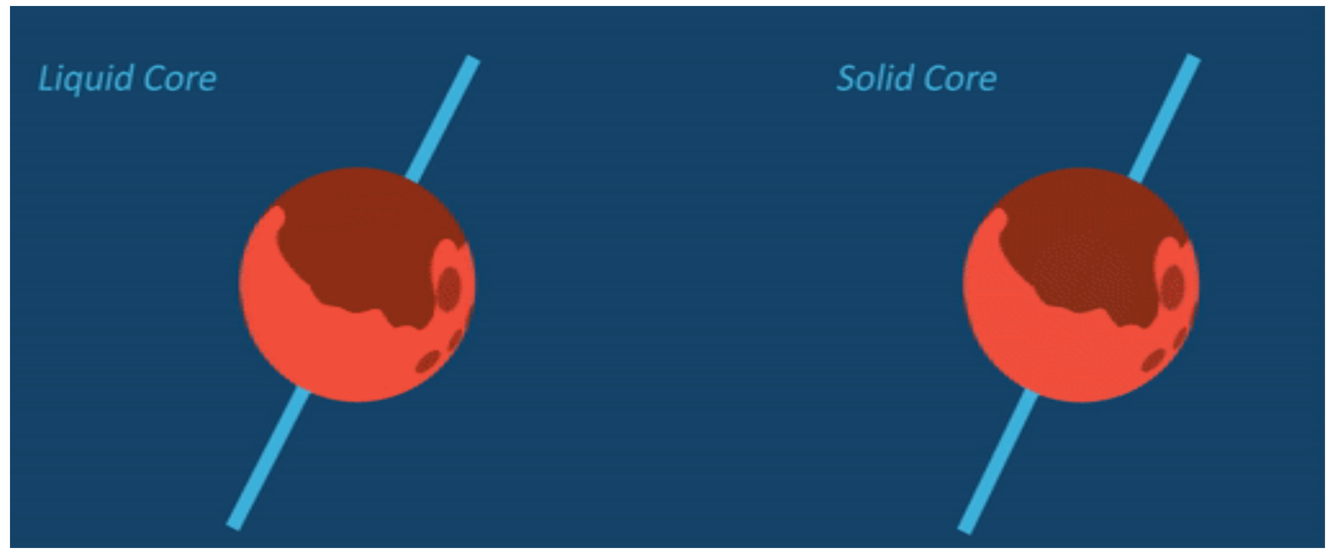


Hot mantle



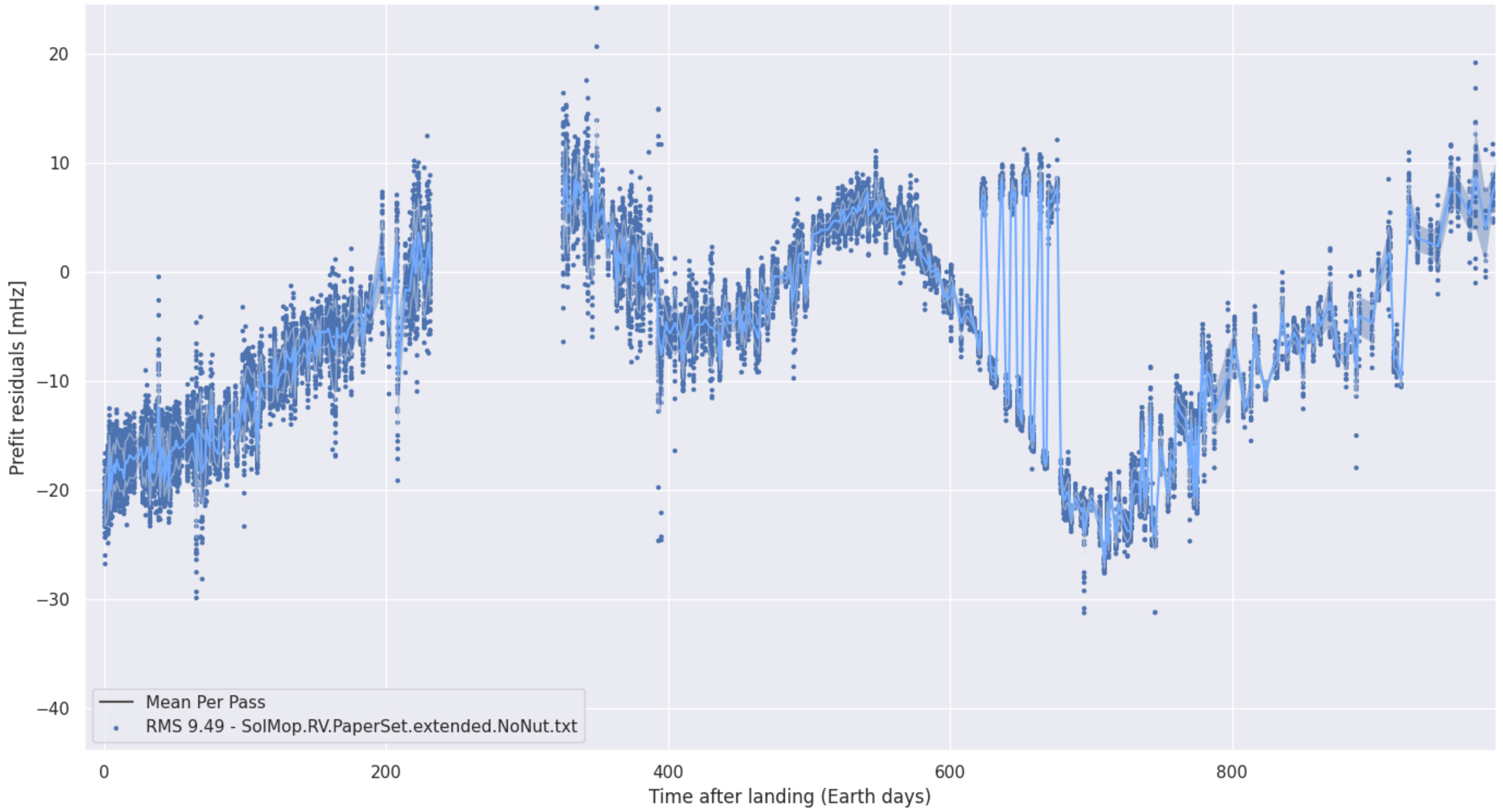
Nutation: interior structure

- 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

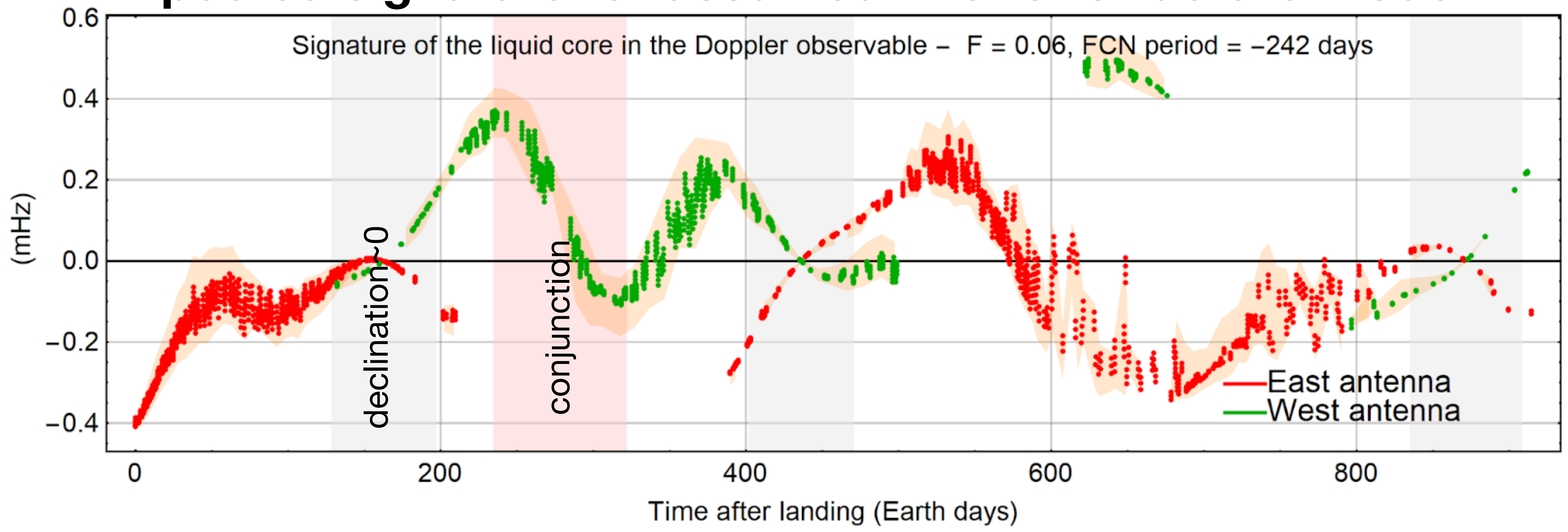


- if the FCN frequency ω_{FCN} is close to forcing frequency ω the nutation amplitude can be resonantly amplified
- the amplification strength $F = \frac{A_f}{A - A_f}\left(1 - \frac{\gamma}{e}\right)$ and $\omega_{FCN} = -\Omega \frac{A}{A - A_f}(e_f - \beta)$ are related to the interior structure of the planet
  ⇒ 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

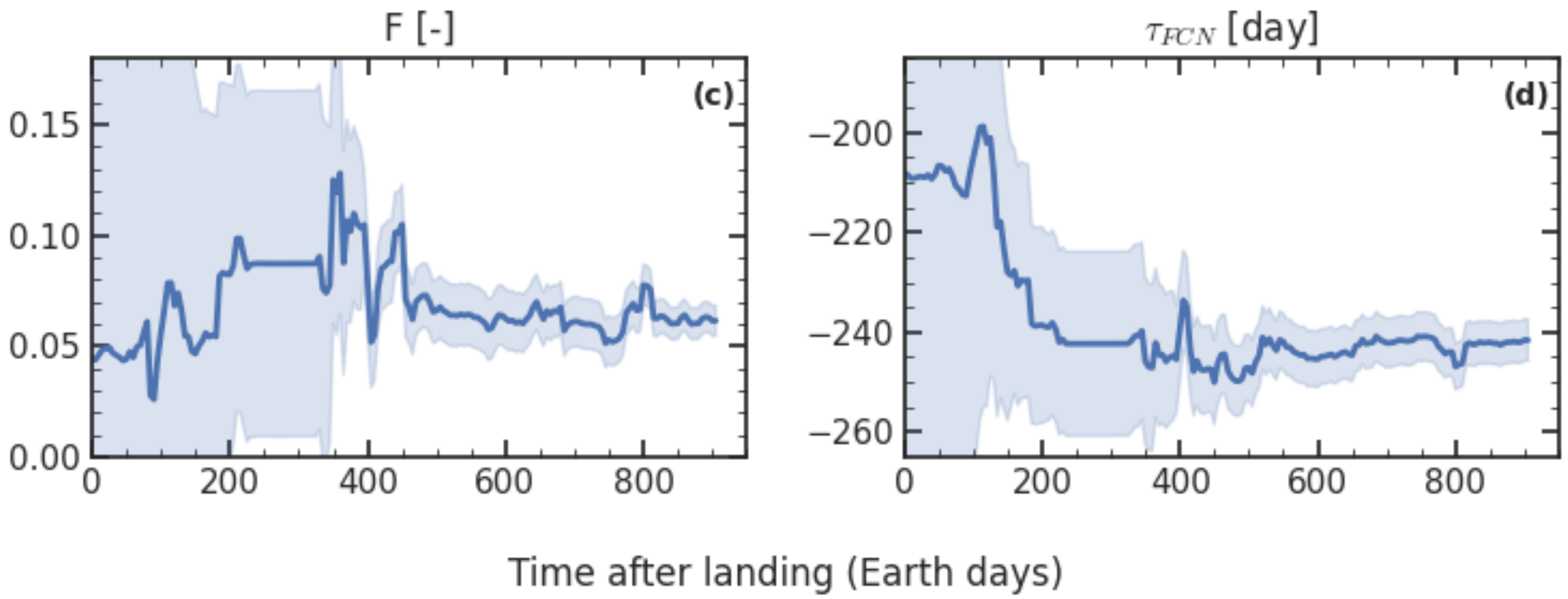


Expected signature for assumed interior structure model



- 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

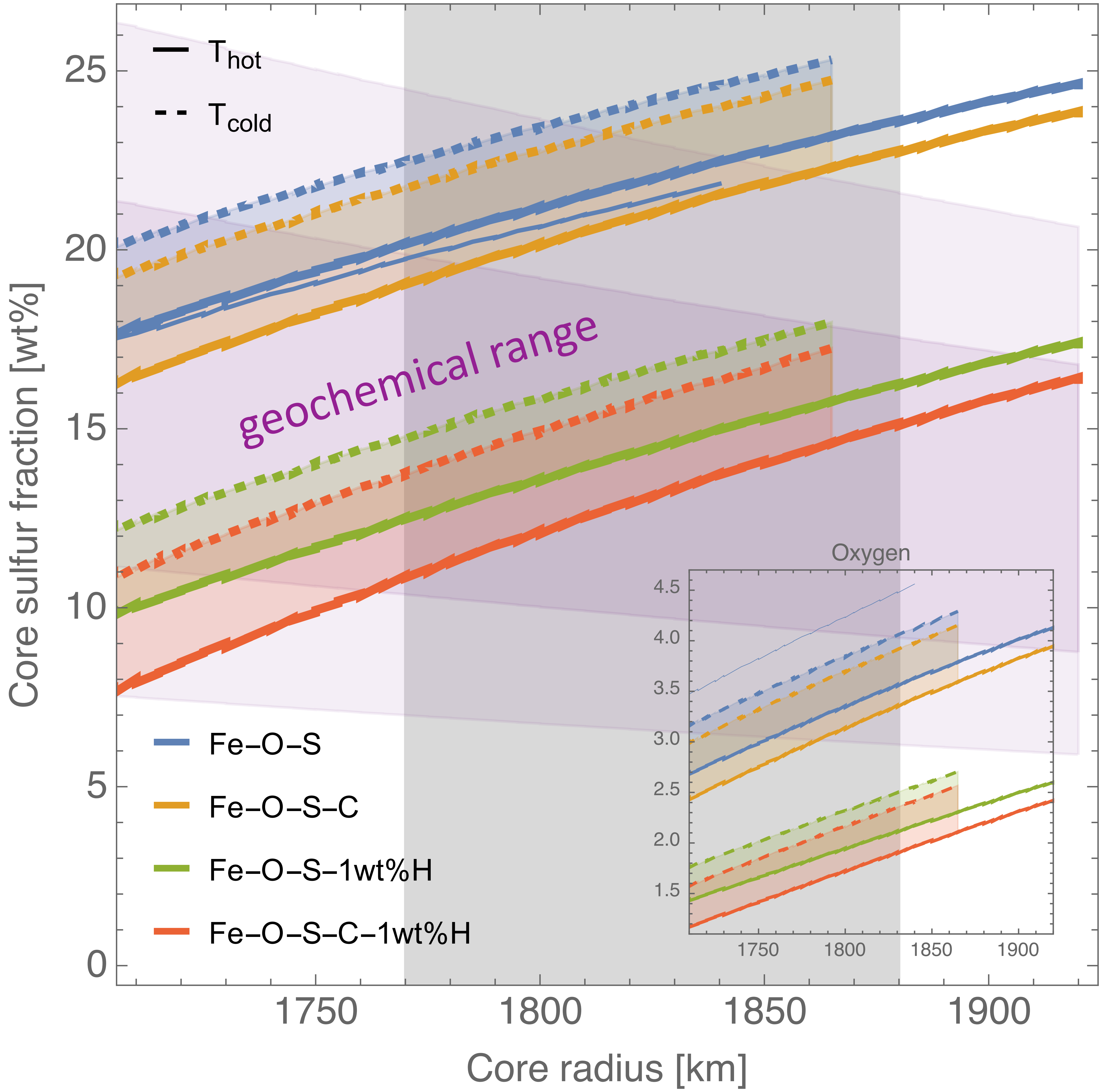
Core radius and composition

- inferred core range in excellent agreement with tidal measurements (e.g. Rivoldini et al. 2011) and seismic data (Stähler et al. 2021, Duràn et al 2022)
  $\Rightarrow r_{\mathrm{cmb}} = 1825 \pm 55\ \mathrm{km}$

- candidate light elements that are siderophile at core forming conditions: S, O, C, H

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

- RISE data and geochemical constraints require a core with 2.5±0.5wt% O, 14.5±1.5wt% S, and 1.5±0.5wt% C if 1wt% H is assumed in the core (Dorogokupets 2017; Nishida 2016,2020; Morard 2017, 2018; Xu 2021; Komabayashi 2014, Shimoyama 2016, Terasaki 2010, Kawaguchi 2017, Thomson 2018, Gendre 2022)



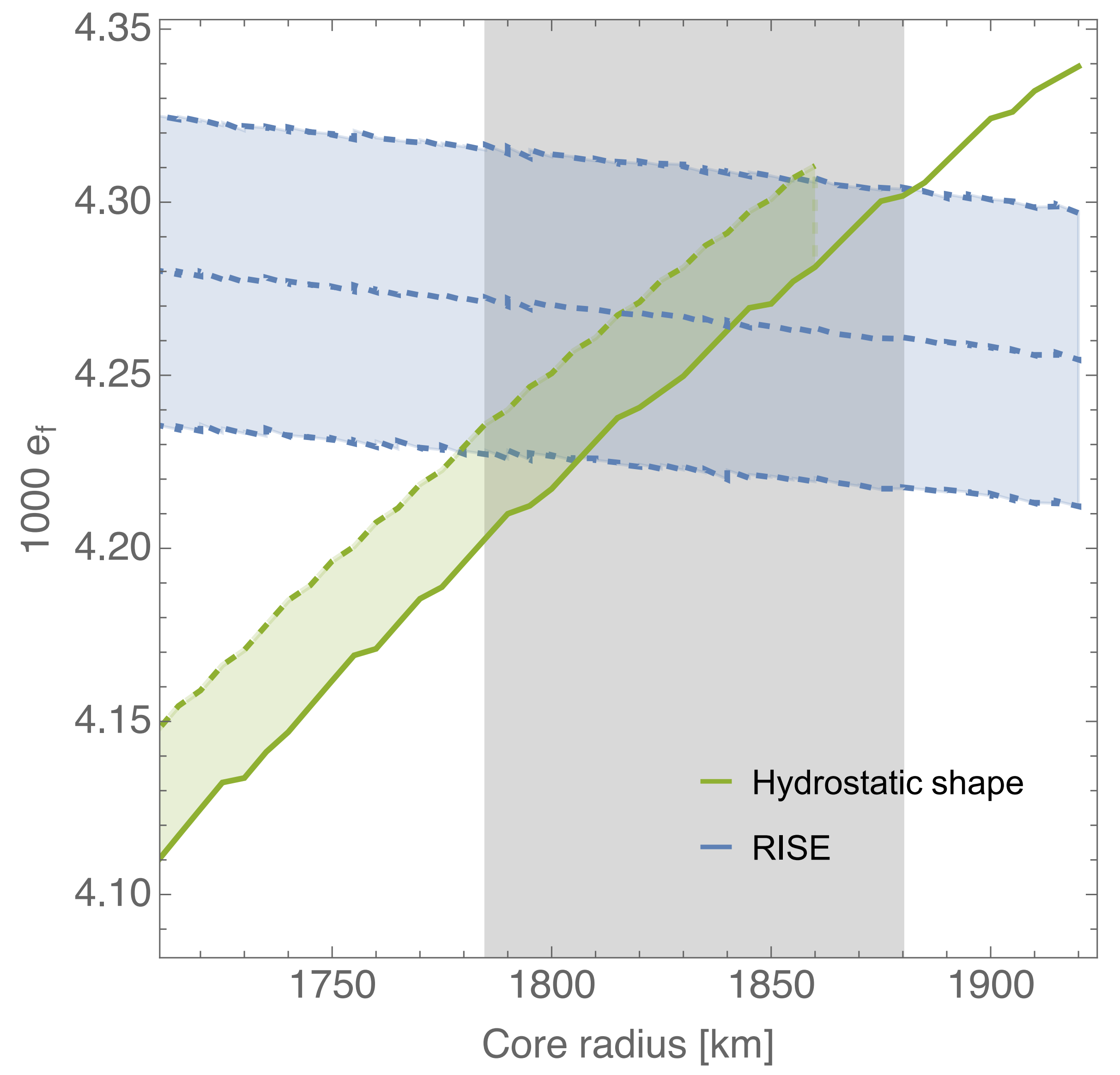
Interpretation: FCN period

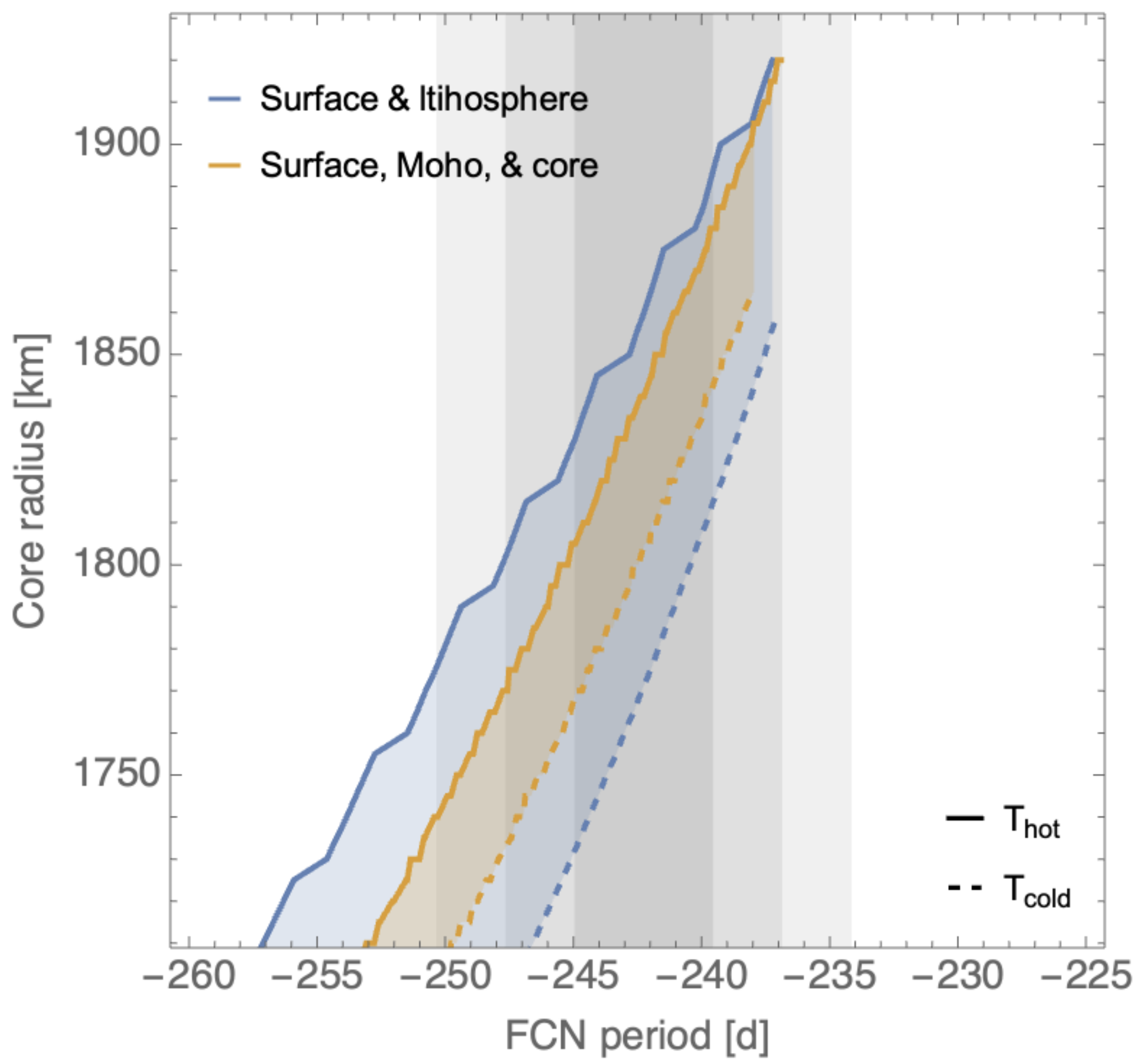
- FCN frequency proportional to core shape which is directly related to the density jump at the core mantle boundary (⇒ constraints density jump at the core-mantle boundary)

- 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

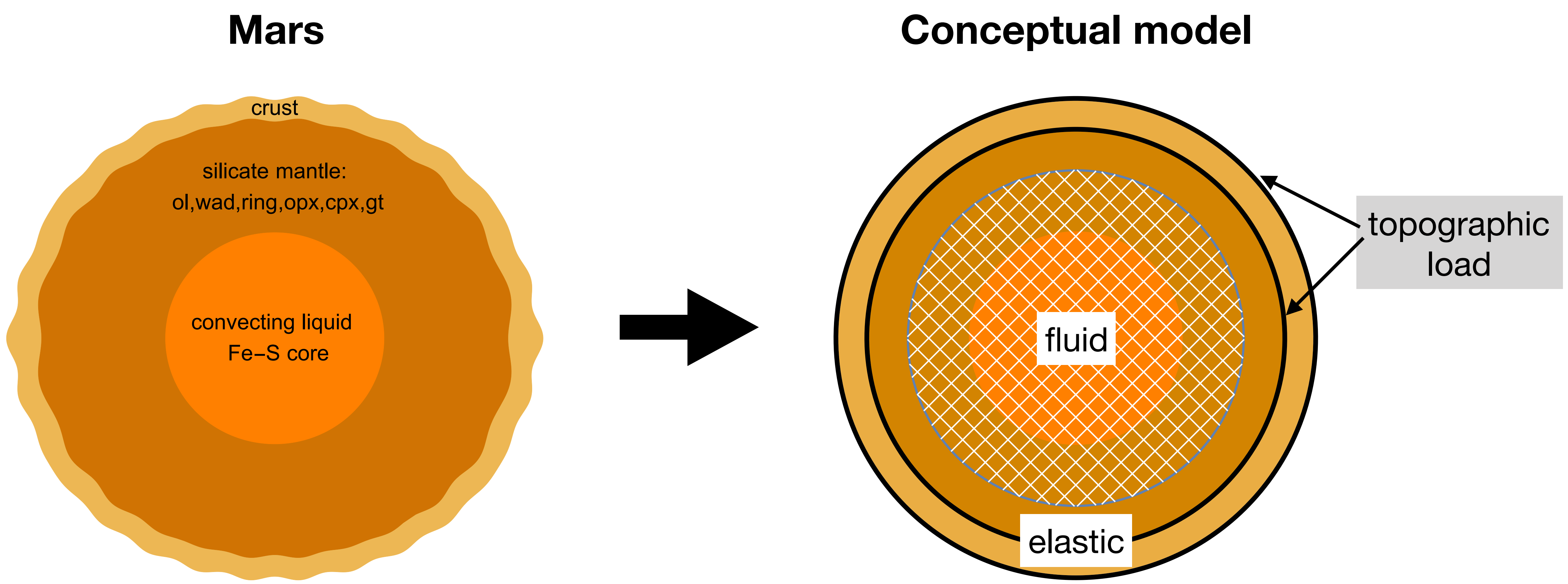




Conclusions

- 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 is in excellent agreement with estimates obtained from tides and seismic data
- RISE data and geochemical constraints require a core with 2.5±0.5wt% O, 14.5±1.5wt% S, and 1.5±0.5wt% C if 1wt% H is assumed in the core
- the measured FCN period requires an almost hydrostatic core shape, such a core shape can be explained by deep seated mass anomalies within the mantle that originate form thermal or chemical anomalies

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