A view into the deep interior of Mars from nutation measured by InSight RISE

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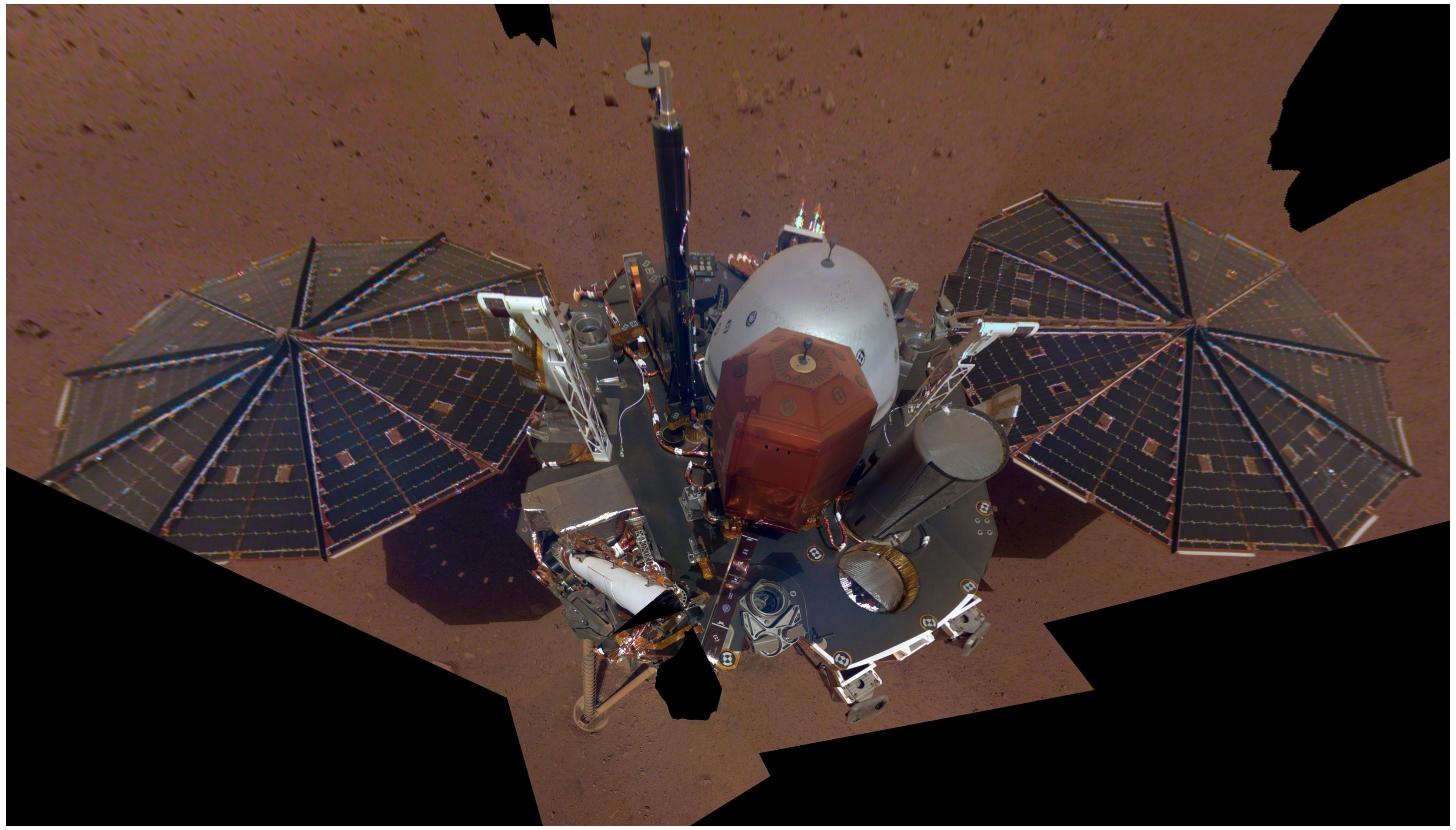
The Rotation and Interior Structure Experiment



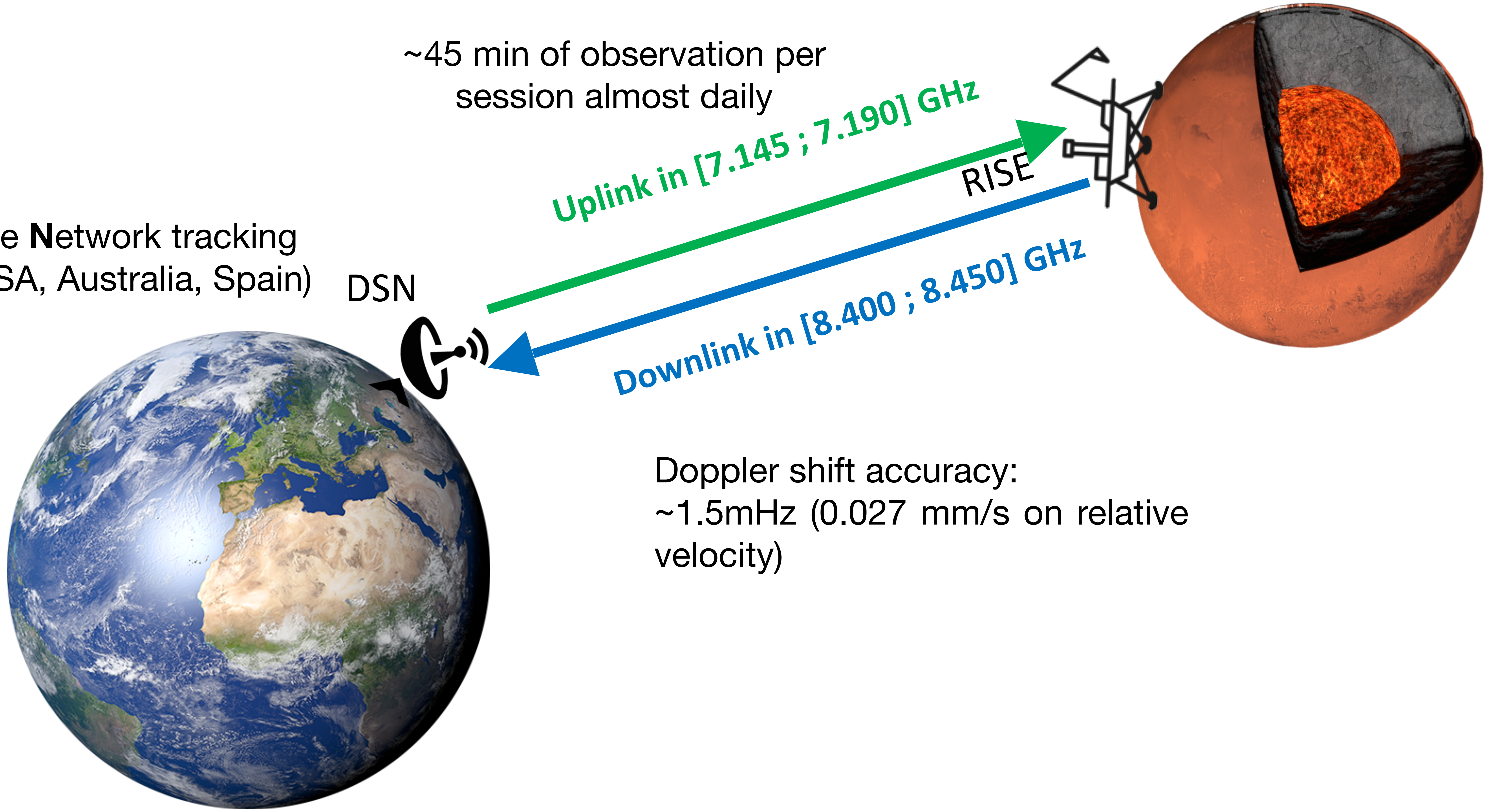
- **RISE** is together with **SEIS** and **HP3** one of the main instruments of the InSight mission
- **RISE**: determine the rotation of Mars
    - precession
    - measure the nutation of the spin axes to detect and quantify the effect of the liquid core
    - measure the rotation rate of Mars on a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

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



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

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

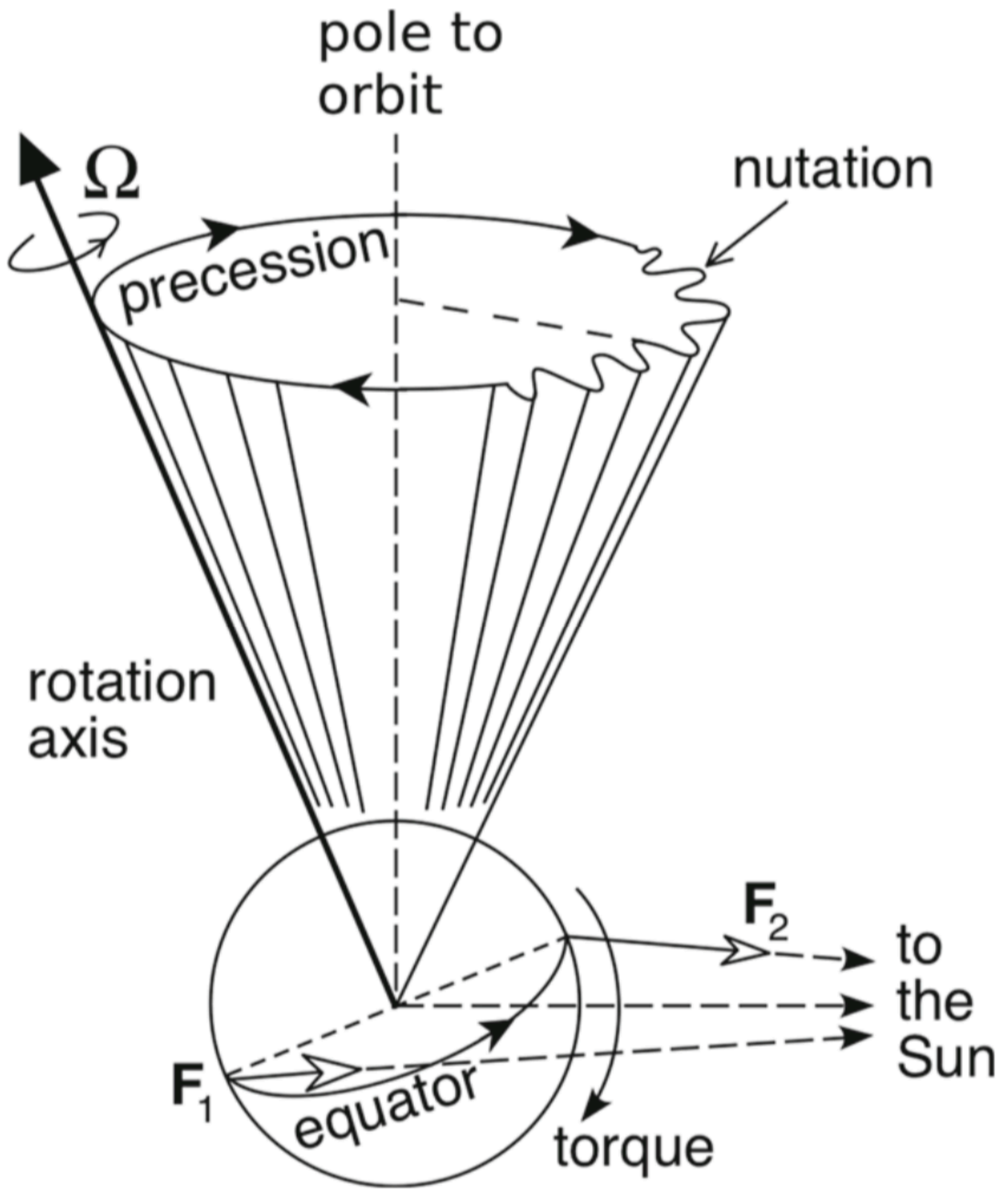
- **measure**: lander position, rotation rate, rotation in space
- **determine**: precession rate and nutation

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

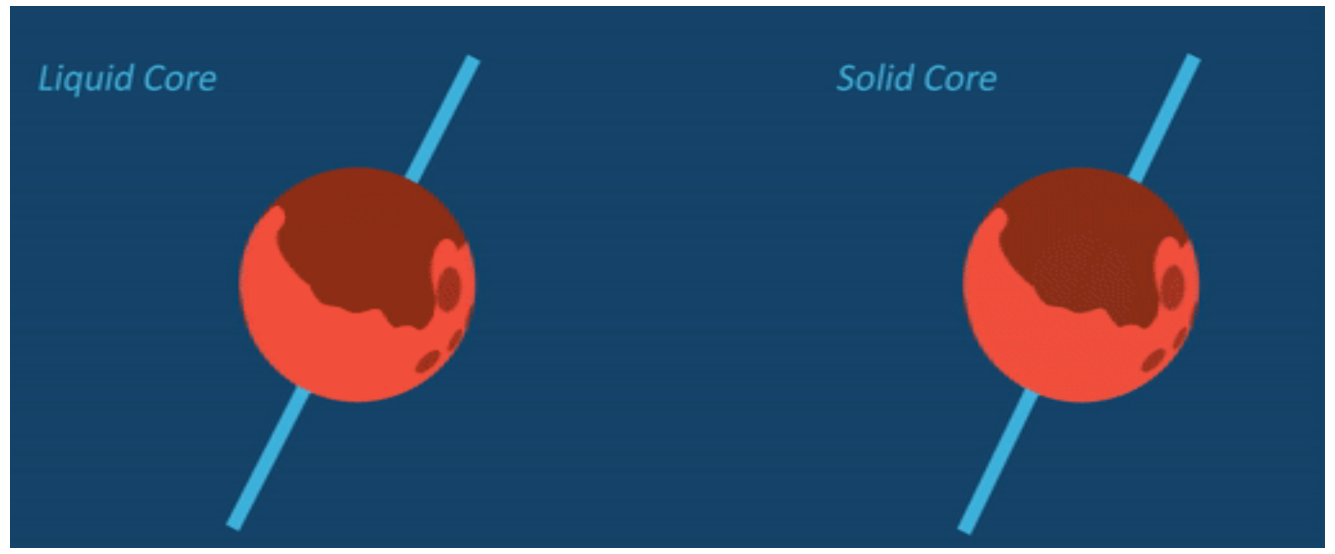


Nutation: interior structure

- 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

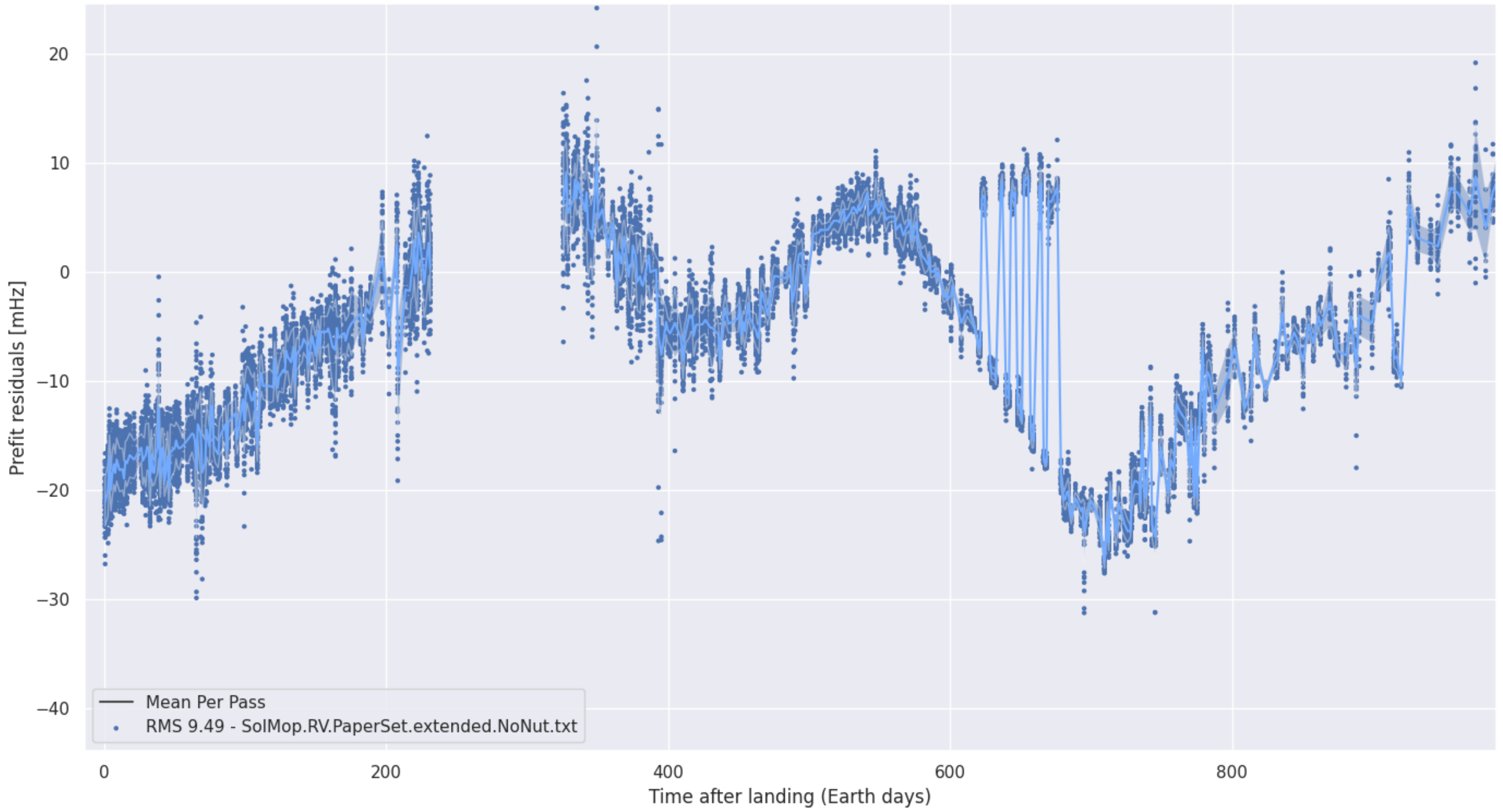
- the relative rotation between the fluid core and solid mantle is characterised by a rotational normal mode, the **F**ree **C**ore **N**utation



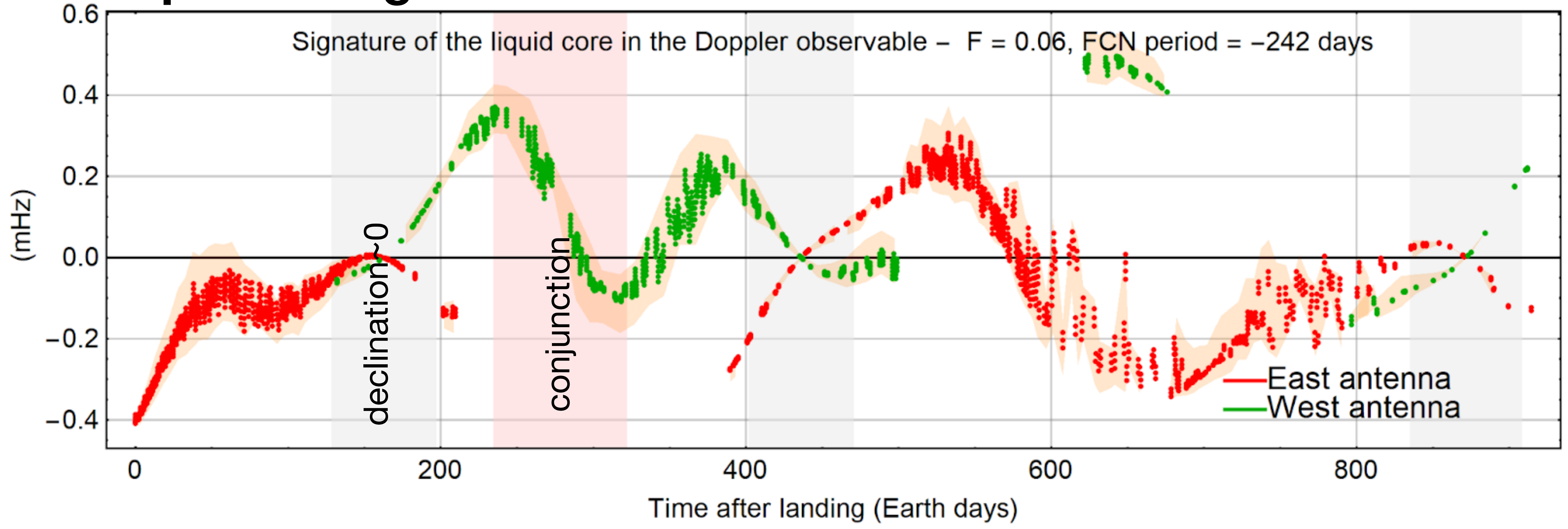
- if the FCN frequency ω_{FCN} is close to forcing frequency ω the nutation amplitude can be resonantly amplified

- 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

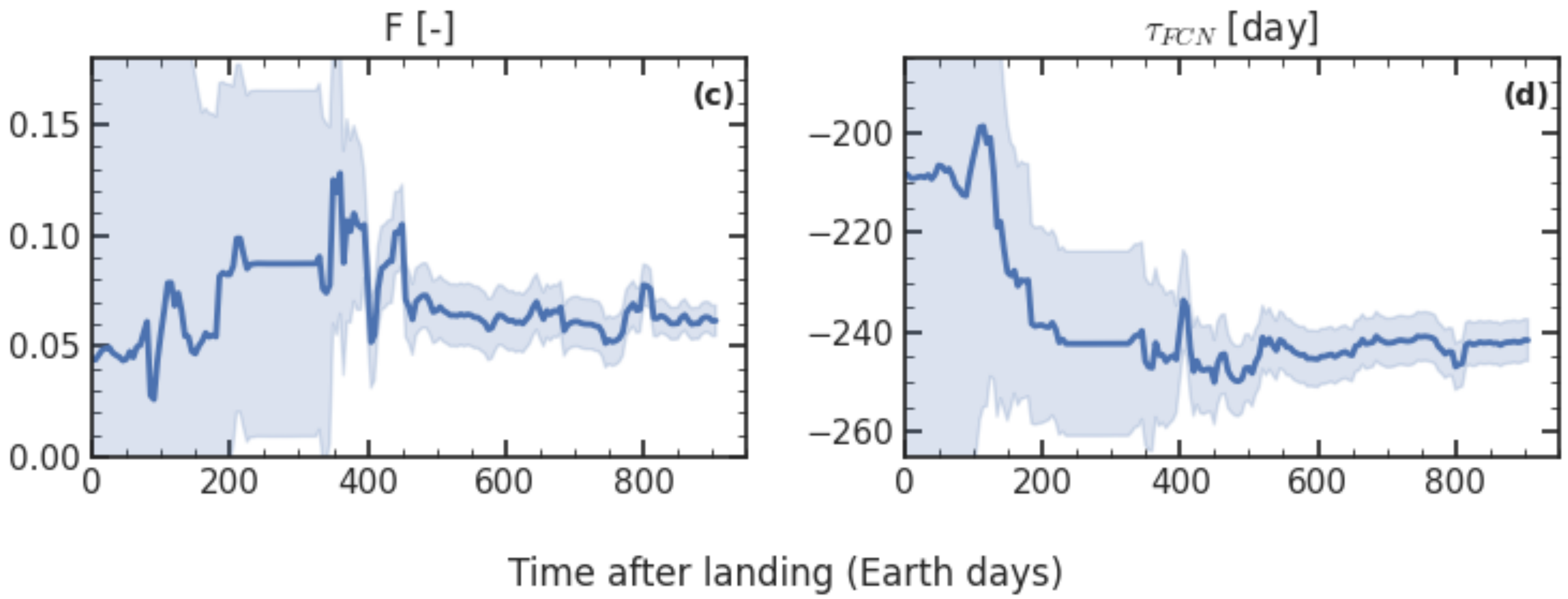


Expected signature for assumed interior structure model



- 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

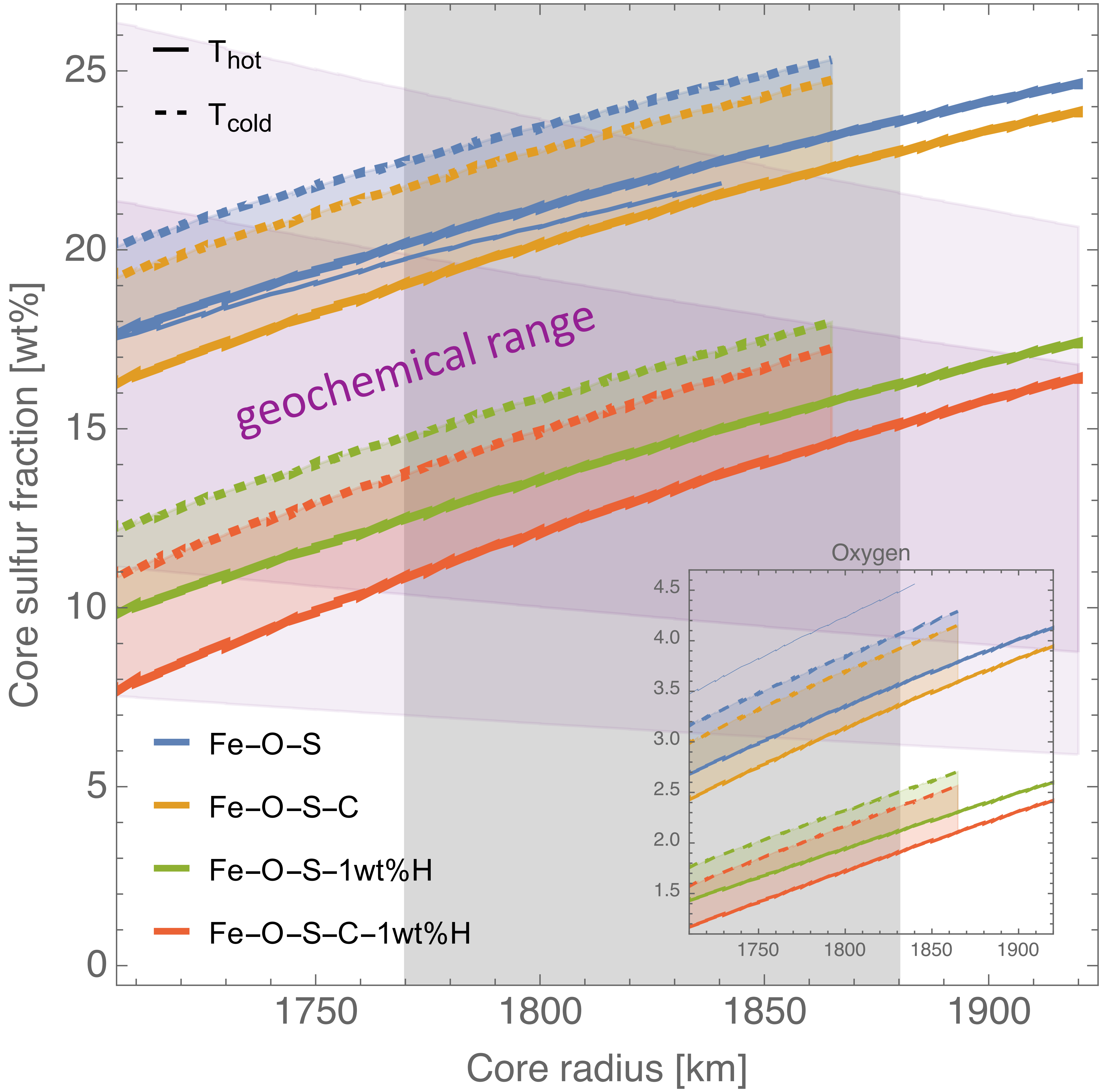
RISE results



- >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)
  $\Rightarrow r_{\text{cmb}} = 1825 \pm 55$ 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)



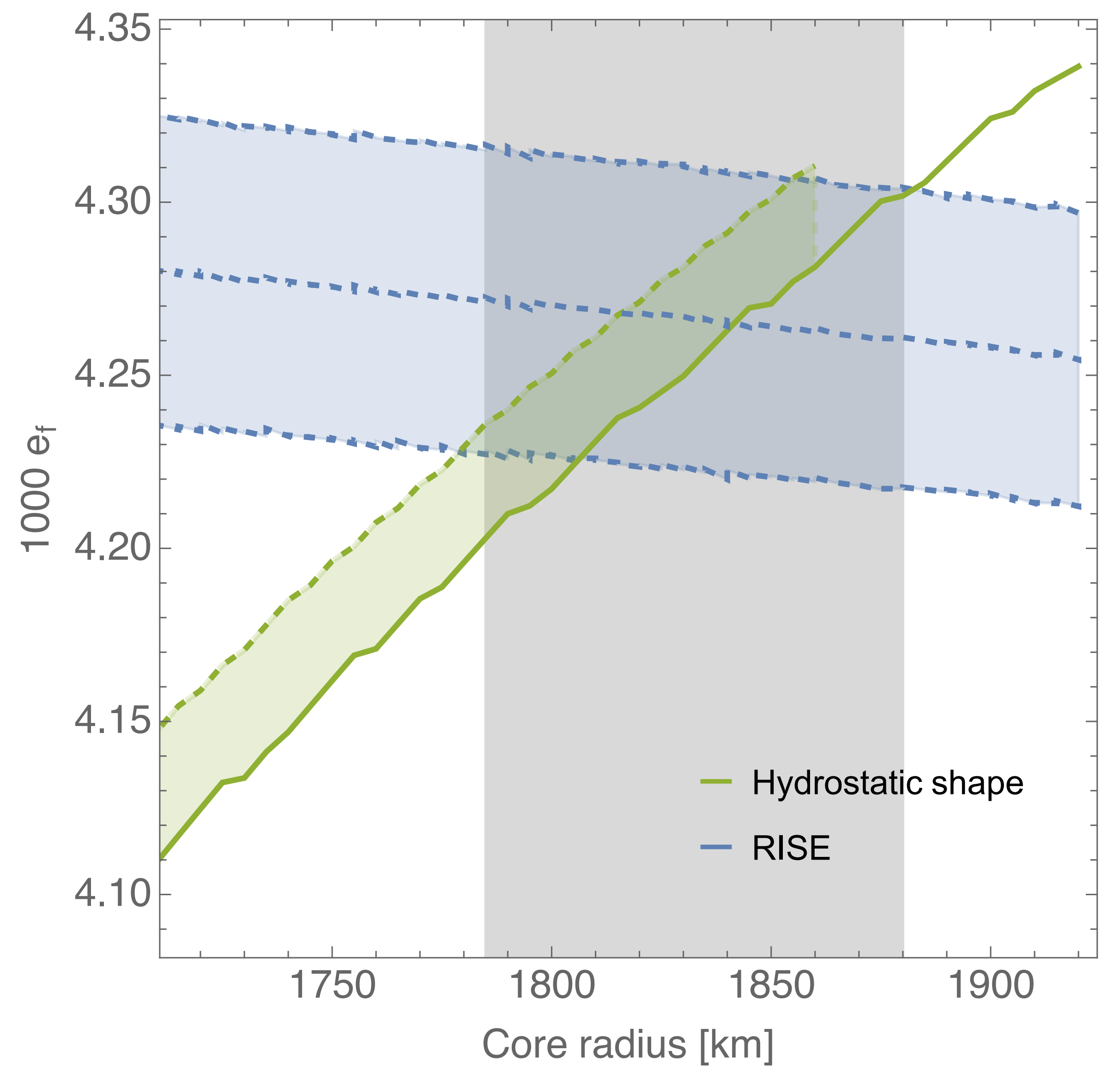
Interpretation: FCN period

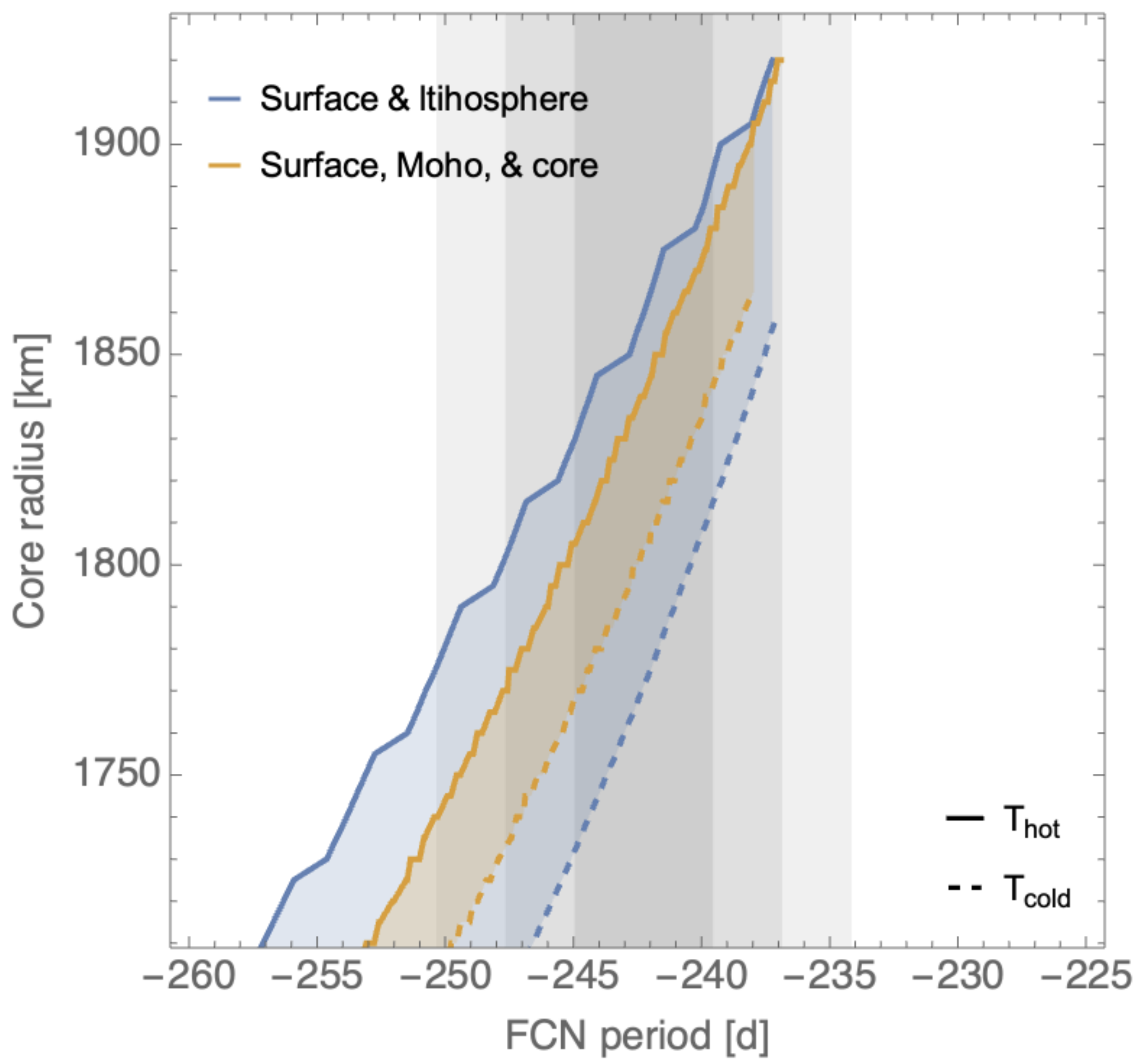
- FCN frequency proportional to core shape which is directly related to the density jump at the core mantle boundary
  (⇒ constraints density jump at the core-mantle boundary)

- RISE data implies an almost hydrostatic core shape, b**ut** 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 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