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

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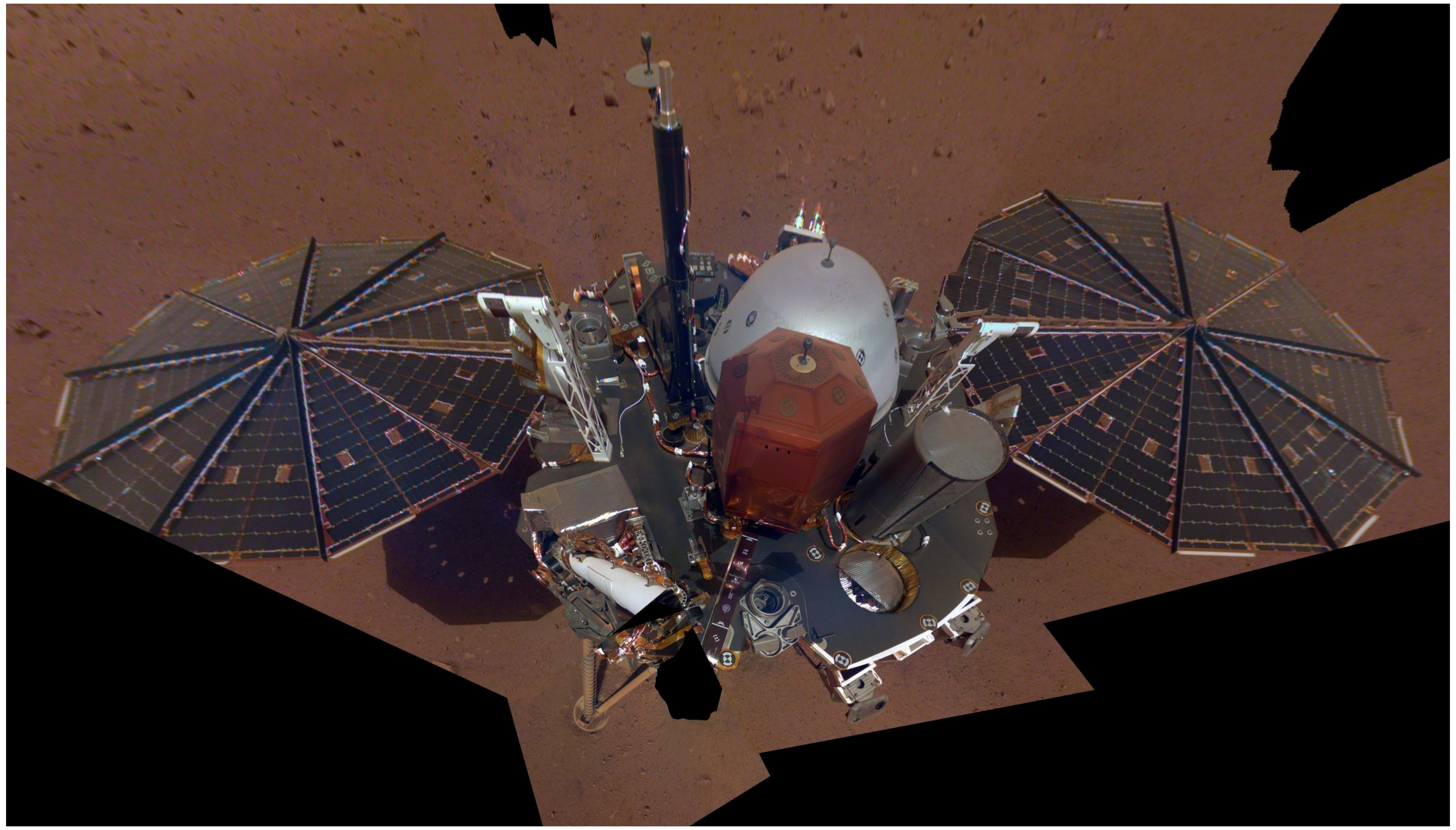
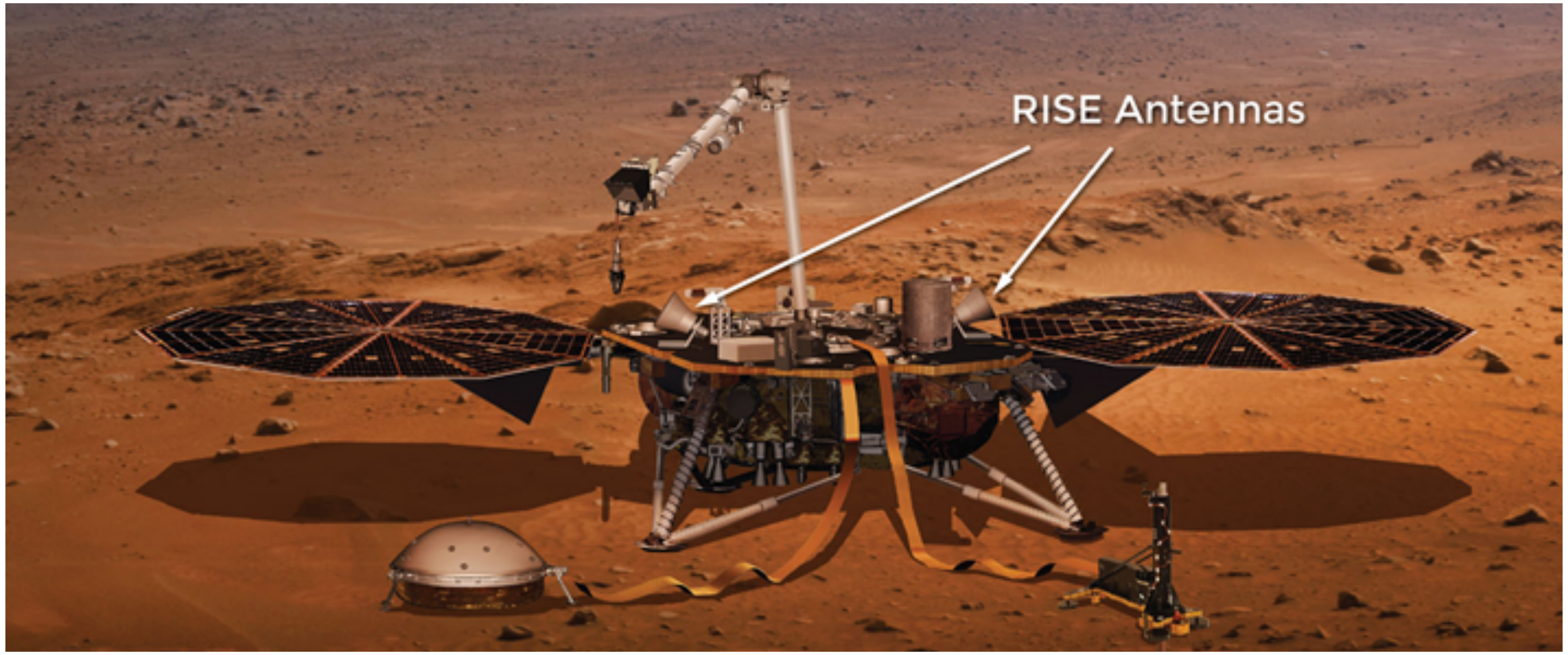
The Rotation and Interior Structure Experiment



- **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



- Mars: 2 medium gain antennas (east and west) and a X-band radio transponder placed on the InSight platform
- Earth: **D**eep **S**pace **N**etwork tracking stations (USA, Australia, Spain)
- mesure 2-way Doppler shifts at DSN stations of a radio signal sent from the DSN to the InSight lander and coherently retransmitted back to the DSN

Doppler shifts and lander positioning in space

- the measured Doppler shift is proportional to the rate of change of distance between the DSN station and the lander ρ (approx.:)

right ascension
declination
of Earth

$$\frac{\partial \rho}{\partial t} = \underbrace{\frac{\partial \rho_{EM}}{\partial t} + \frac{\partial \rho_{DSN}}{\partial t}}_{\text{distance Mars DSN}} - \frac{\partial}{\partial t}\left[R_z \sin \delta_E + R_s \cos \delta_E \cos(\phi + \lambda - \alpha_E)\right]$$

distance
RISE
Mars equator

distance
RISE
Mars spin axes

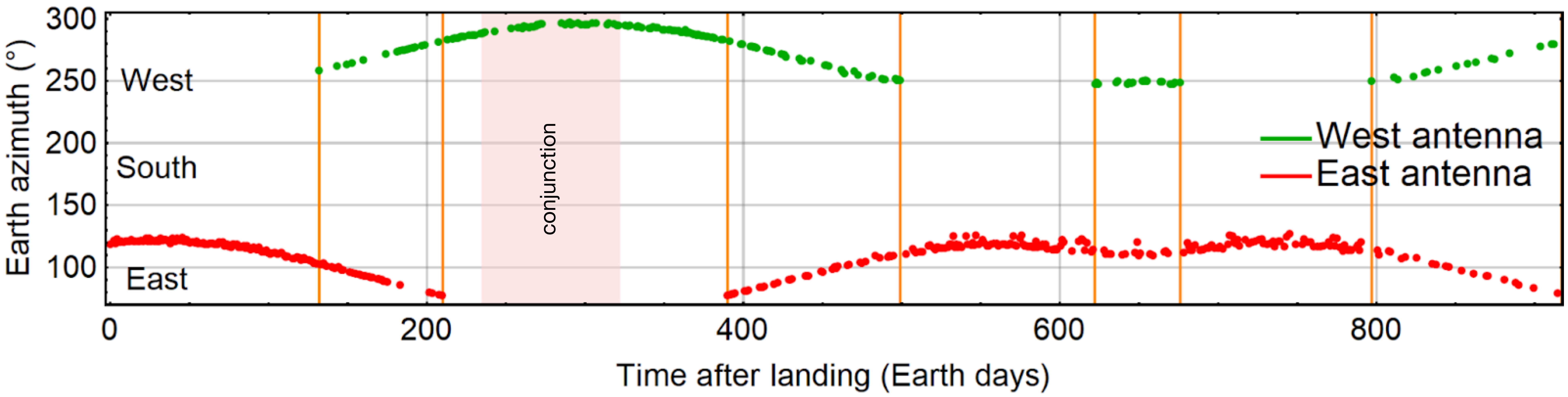
rotation angle
of Mars

RISE
longitude

- know: DSN-Mars distance

- infer: lander position, rotation angle, declination, right ascension
  ⇒ precession rate and nutation determined from declination and right ascension

Tracking

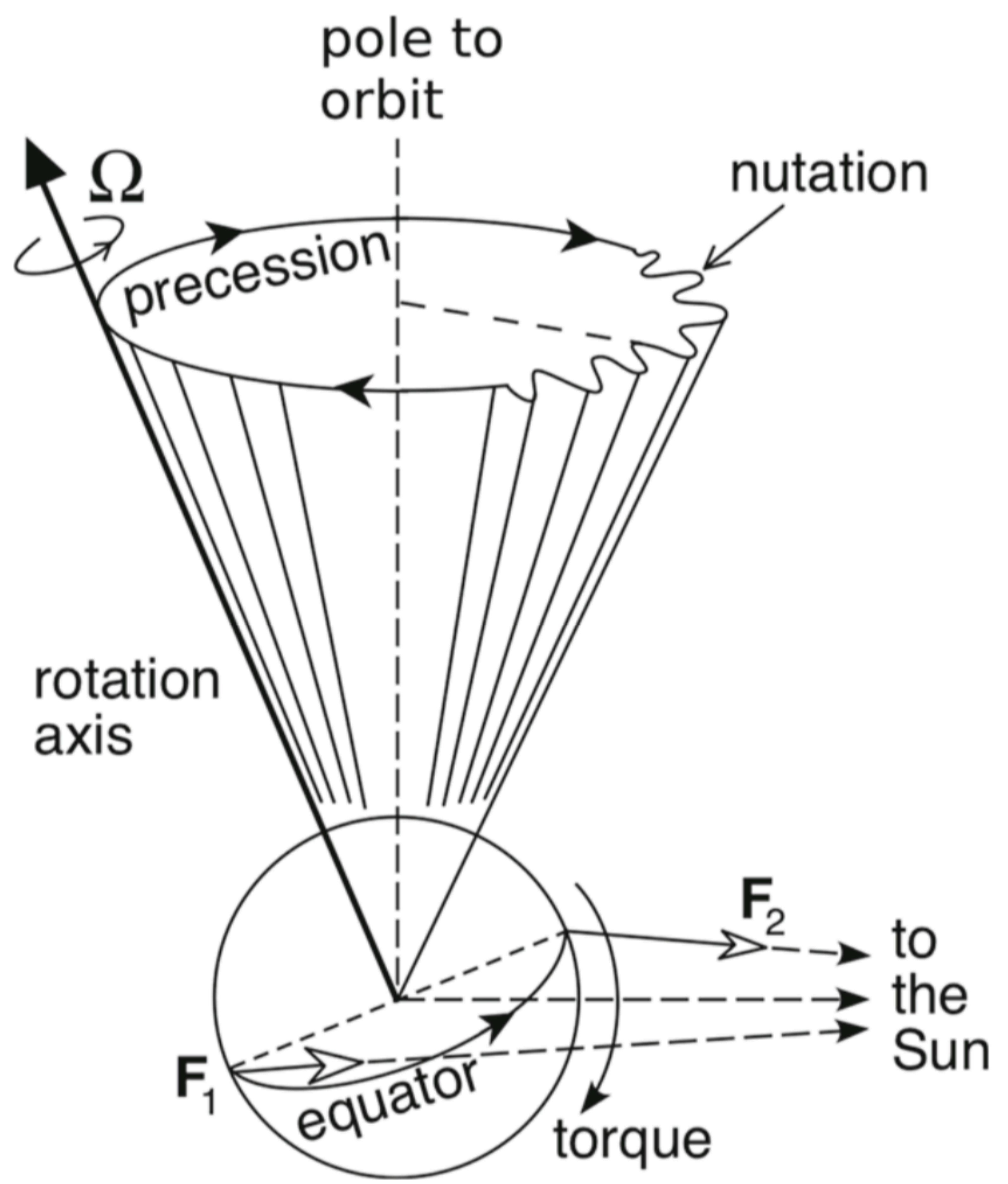


- Earth seen in the morning with the eastward antenna and with the westward in the the afternoon (elevation 10º to 50º)
- first Martian year days: 5-7 trackings each week (60min) later reduced to 1-3 (30min)
- collected 25 0000 Doppler data points over 915 days

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)
  ⇒ precession rate ~ to the polar moment of inertia

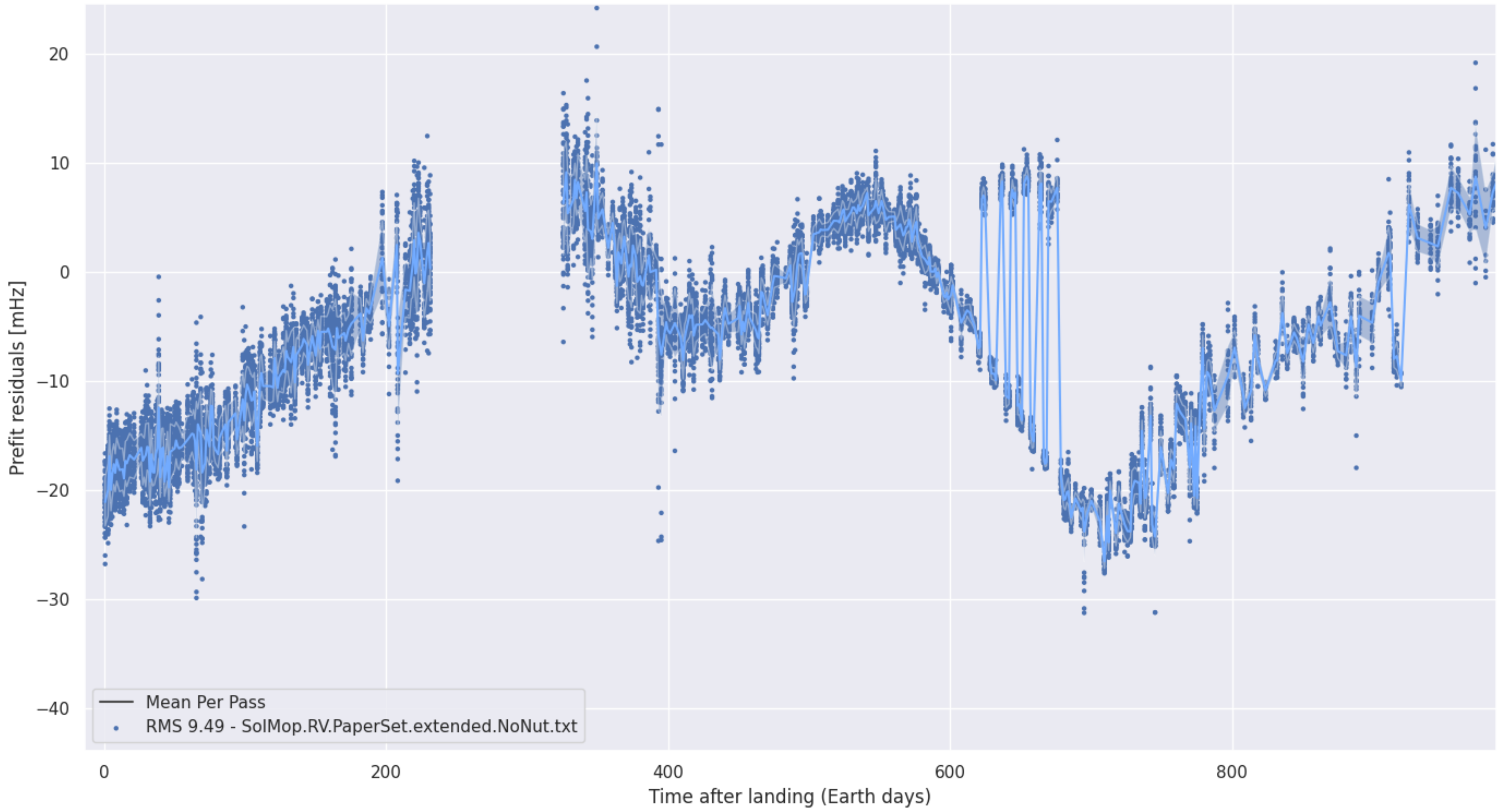
- torque variations due to the relative positions between the Sun and Mars lead to periodic motions of the rotation axis, the nutations (1/(1,2,3,4..) year)
  ⇒ lander position changes by about 10m on the surface



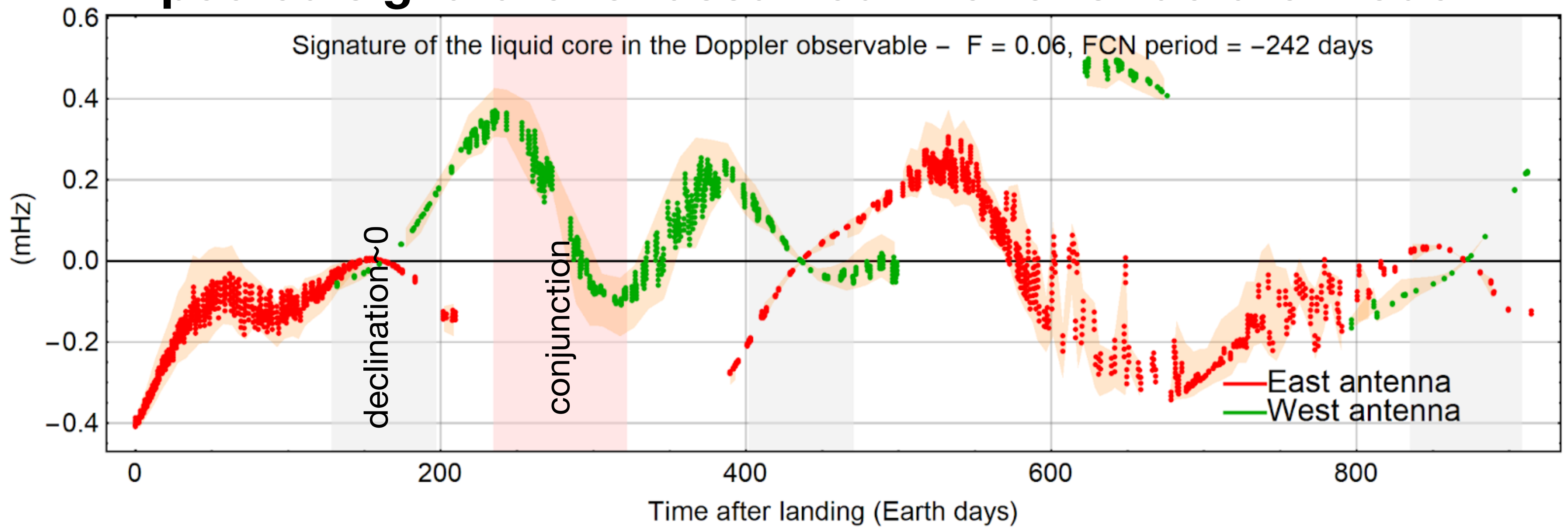
Nutation: interior structure

- 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
  ⇒ moments of inertia of the planet (A) and core (A_f), planet (e) and core dynamic shape (e_f), core compliances due to tidal forcing (γ) and rotation rate variation (β)

Liquid core signature and real data

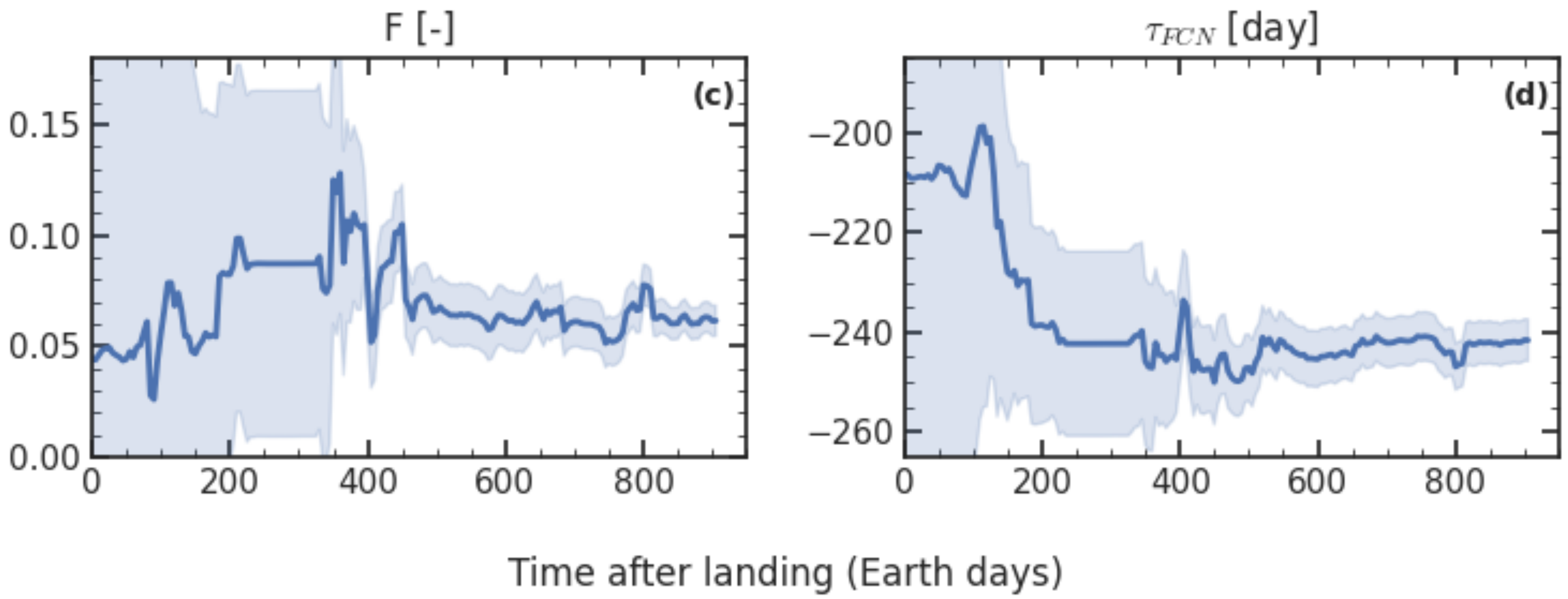


Expected signature for assumed interior structure model



- 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

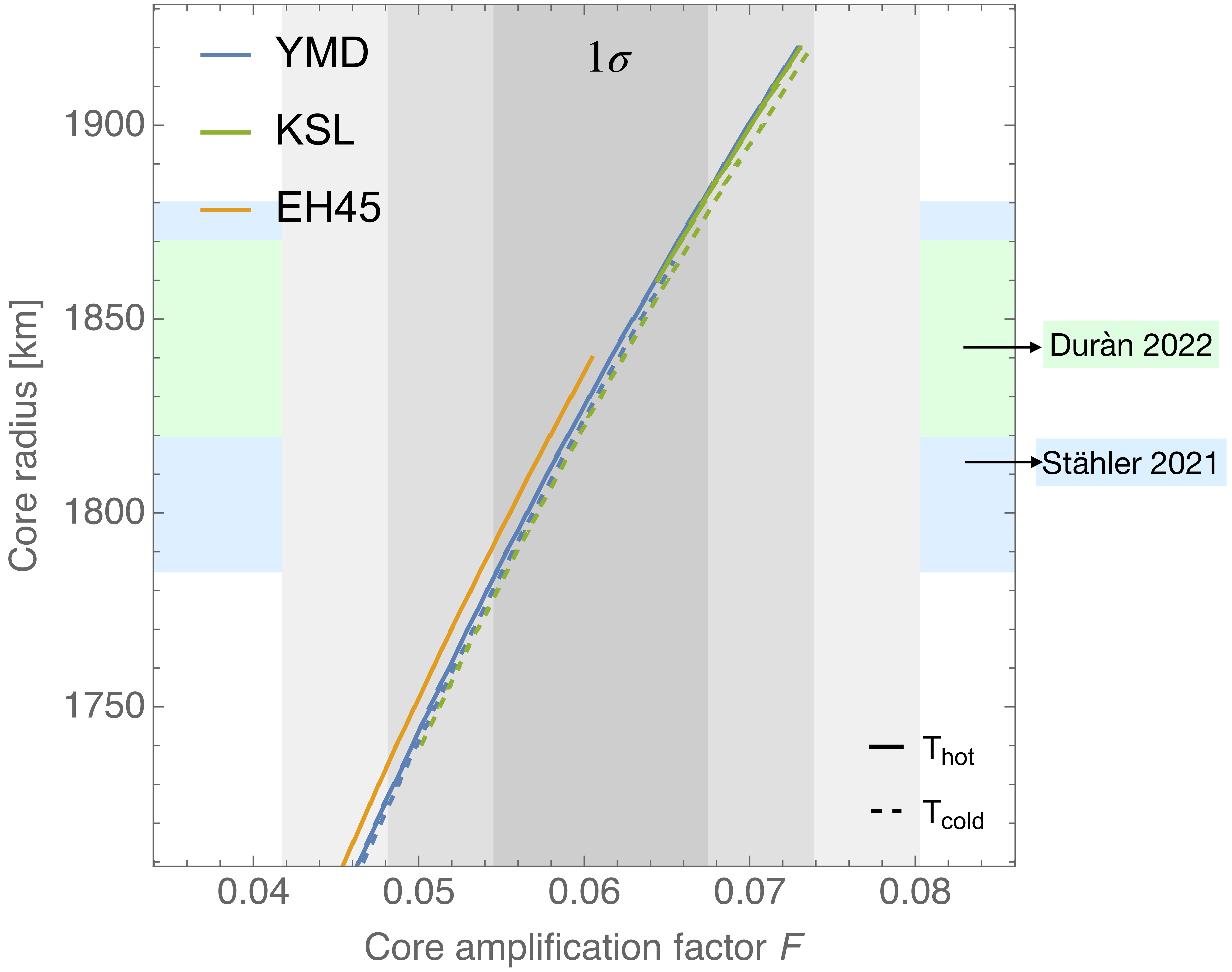


- >600 days of data are required to obtain robust estimates for the core amplification factor F and FCN period τ_{FCN}
- $F = 0.061 \pm 0.0064$ and $\tau_{\mathrm{FCN}} = -242.25 \pm 2.7$ days
- F in expected range but τ_{FCN} somewhat lower than expected

Interpretation: core radius

- assume 3 mantle compositions (E45 Sanloup 1999, YMD Yoshizaky 2020, KSL Khan 2022) mantle temperature end-members, average crust structure in agreement with seismic data (Knapmeyer-Endrun 2021)
- F (~A_f) is robust with respect to T and mantle 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)

$$\Rightarrow r_{\text{cmb}} = 1825 \pm 55 \text{ km}$$

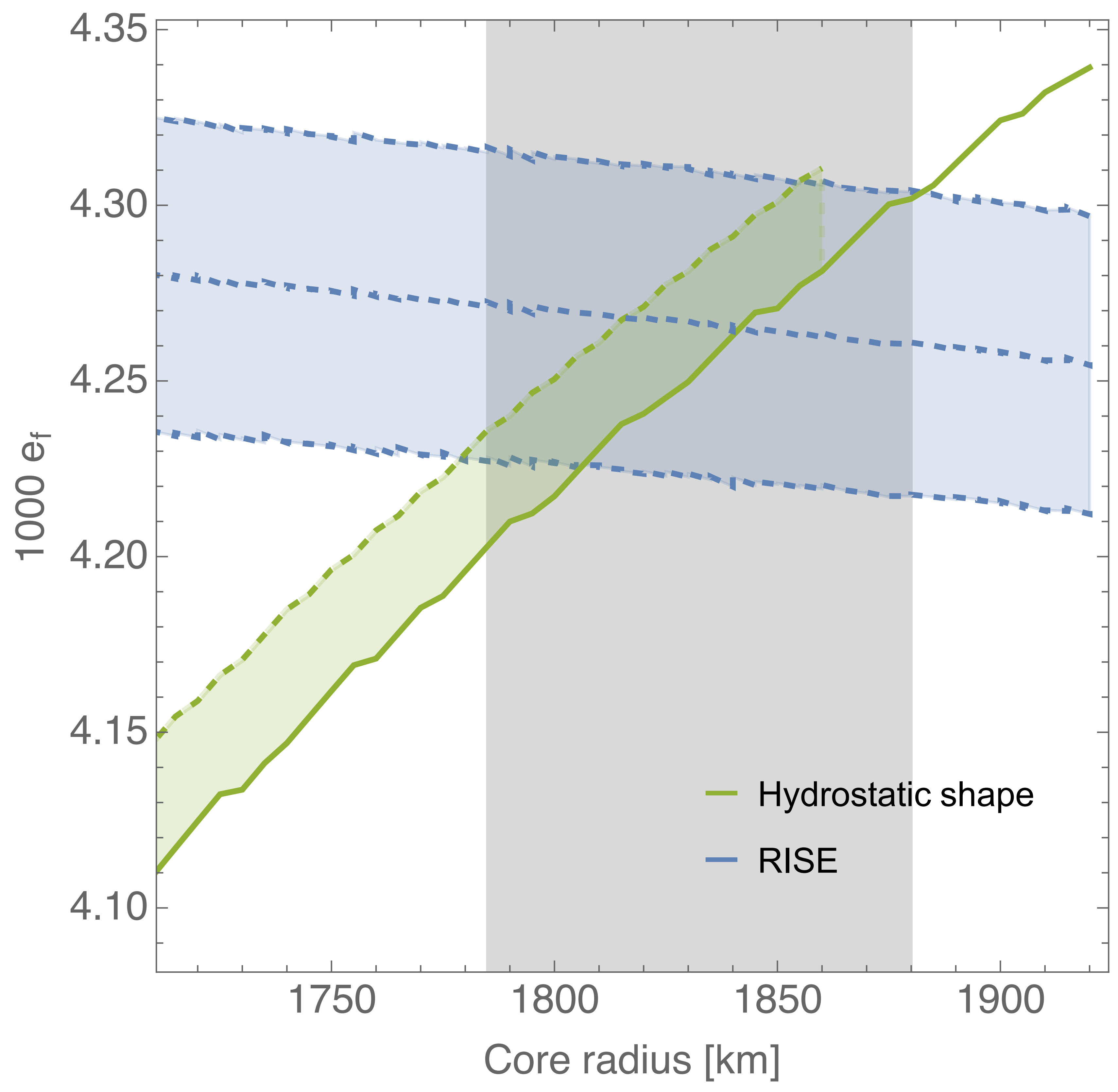


Interpretation: FCN period

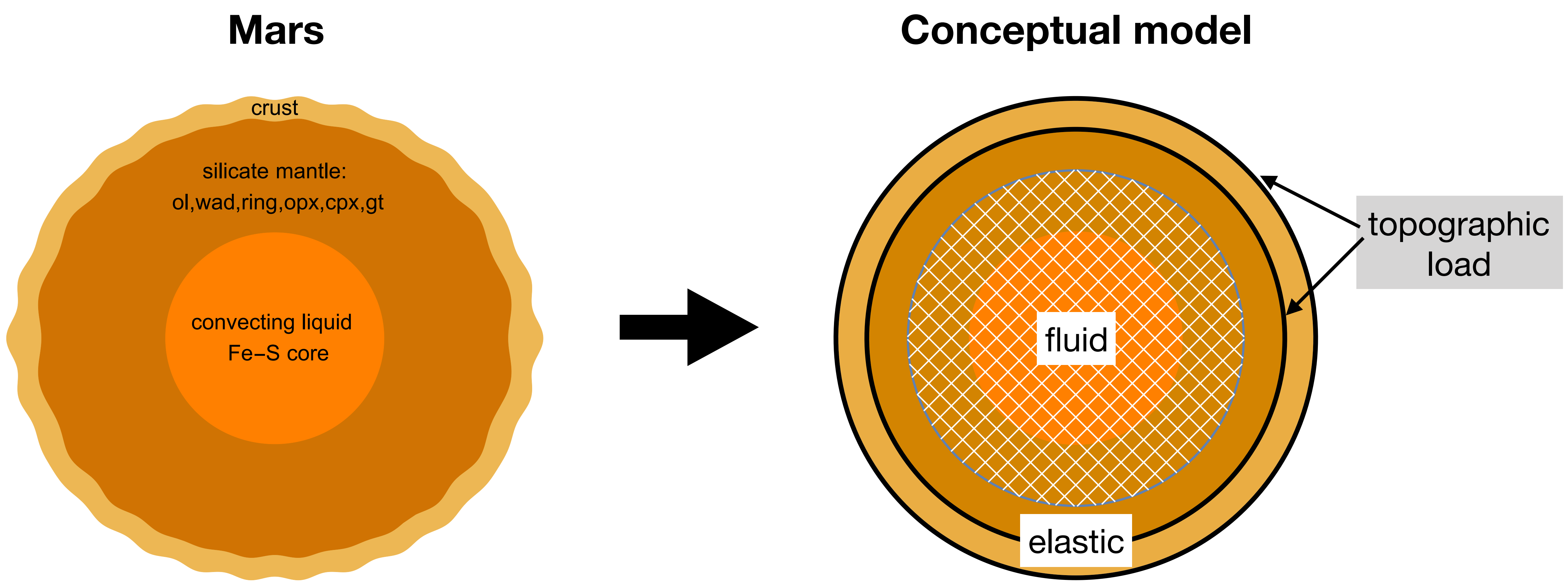
- FCN frequency proportional to dynamic core shape $e_f = \dfrac{C_f - A_f}{A_f}$ which is directly related to the density jump at the core mantle boundary

- RISE data implies an almost hydrostatic core shape

- **but** Mars' geometric and dynamic shape $\left(e = \dfrac{C - A}{A}\right)$ are **not hydrostatic**



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

Interpretation: FCN period

Models agree with the FCN period if:

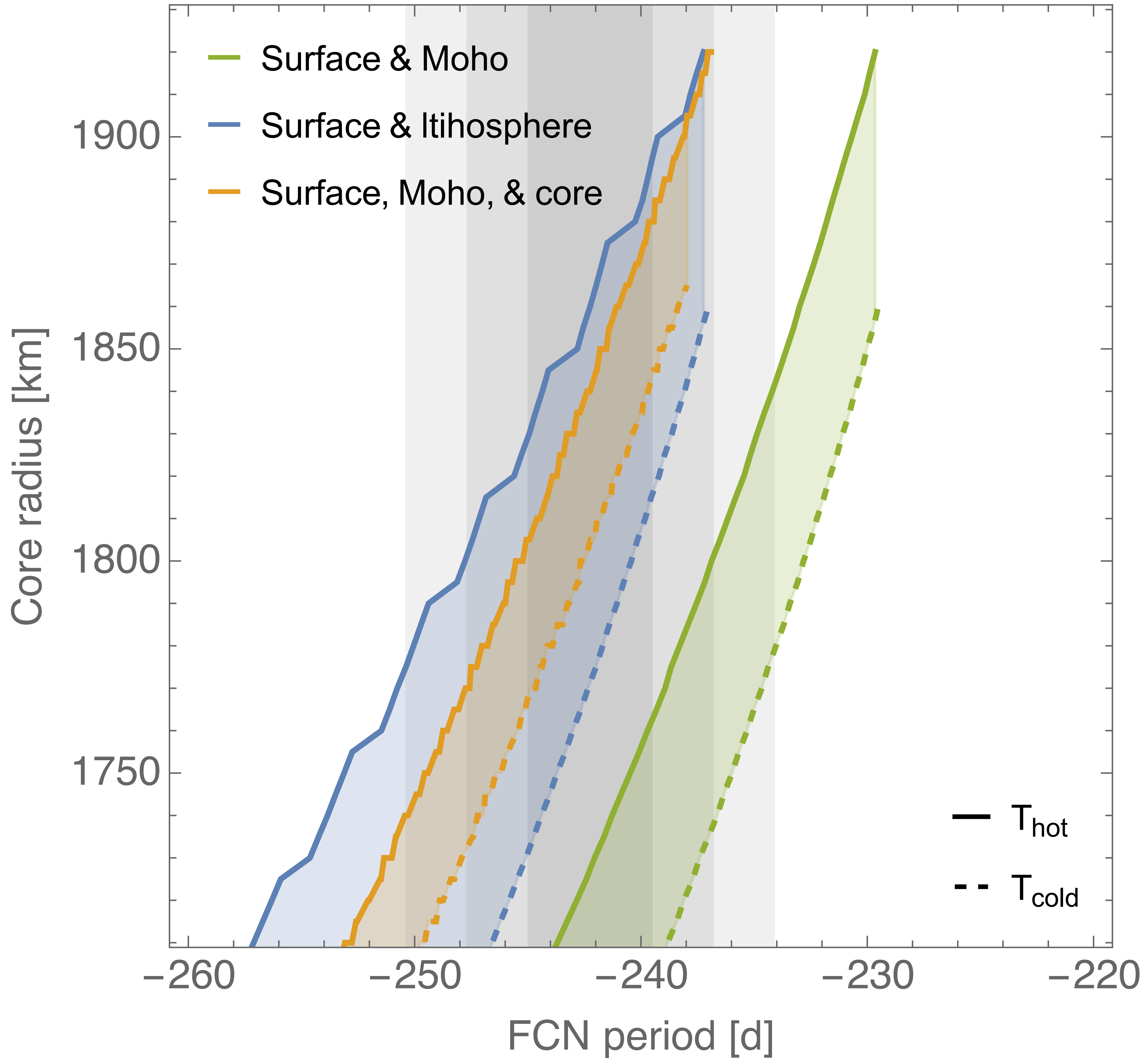
- a load is placed at the Moho, but the core radius of those models does not agree with F

  (an equivalent approach is used to deduce the average crust thickness of Mars in Knapmeyer-Endrun 2021)

- a load is placed at the bottom of the lithosphere, but the lithosphere is >550km

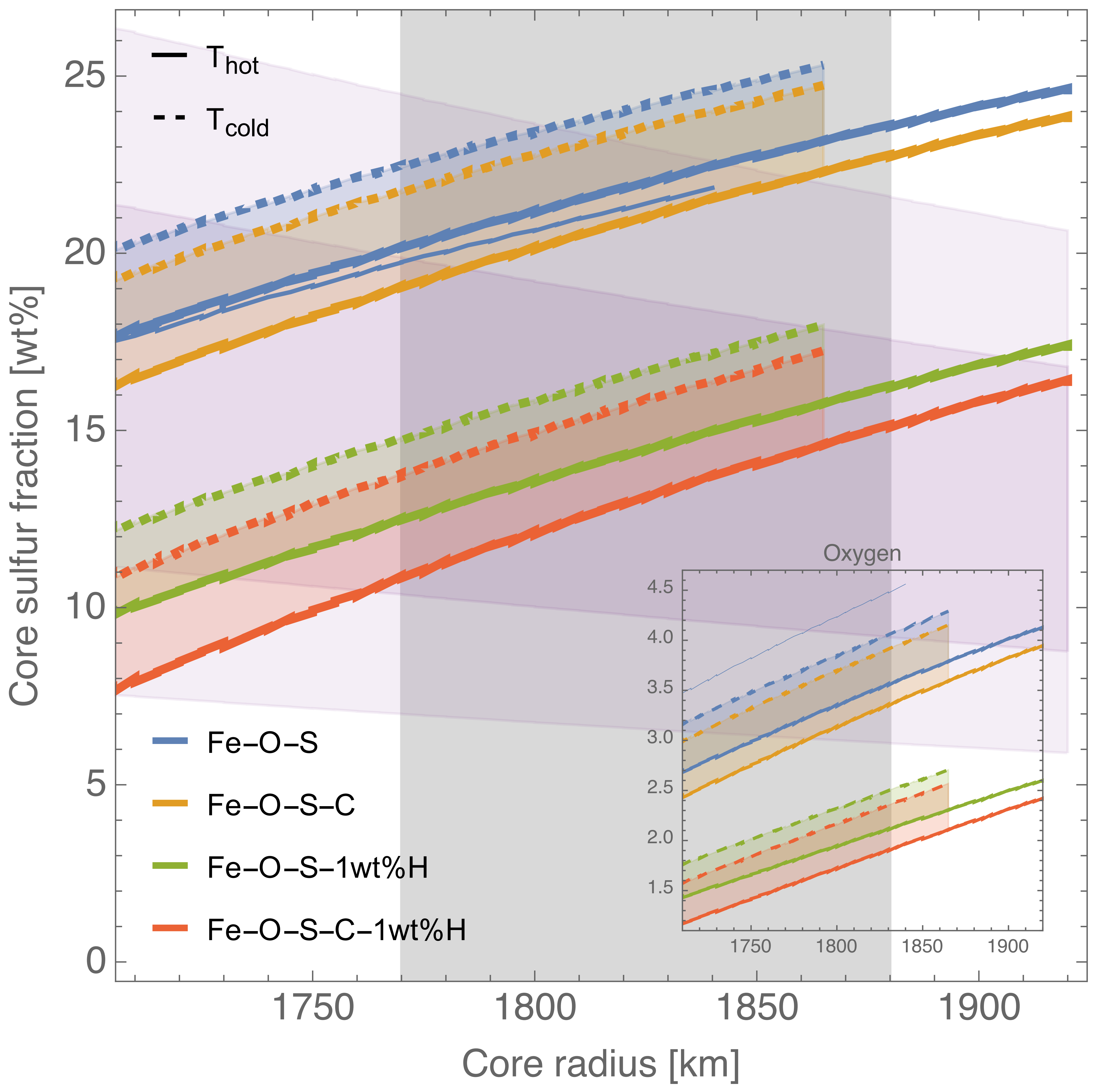
  $\Rightarrow$ requires that the crust is highly enriched in heat producing elements compared to the mantle

- a load placed at shallower depth and at the core-mantle boundary



Interpretation: core composition

- candidate light elements that are siderophile at core forming conditions: O, S, C, H
- amounts of light elements are not independent and dependent on the bulk chemistry
- use core formation model to relate O to S and mantle composition and set C to its saturation
    - O increases with S and mantle FeO
    - C decreases with increasing S (C≲2wt%)
- models without H are only possible if the core radius is at the lower end of our estimate
- RISE compatible models require >0.6wt% of H if S is in agreement with geochemical constraints



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 2.1±0.3wt% O, 14.5±1.5wt% S, and 1.5±0.3wt% 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
- one supplemental Earth year of RISE data will decrease the uncertainties on F and τ_{FCN} by 5%