Effect of the core structure on the nutation of Mars

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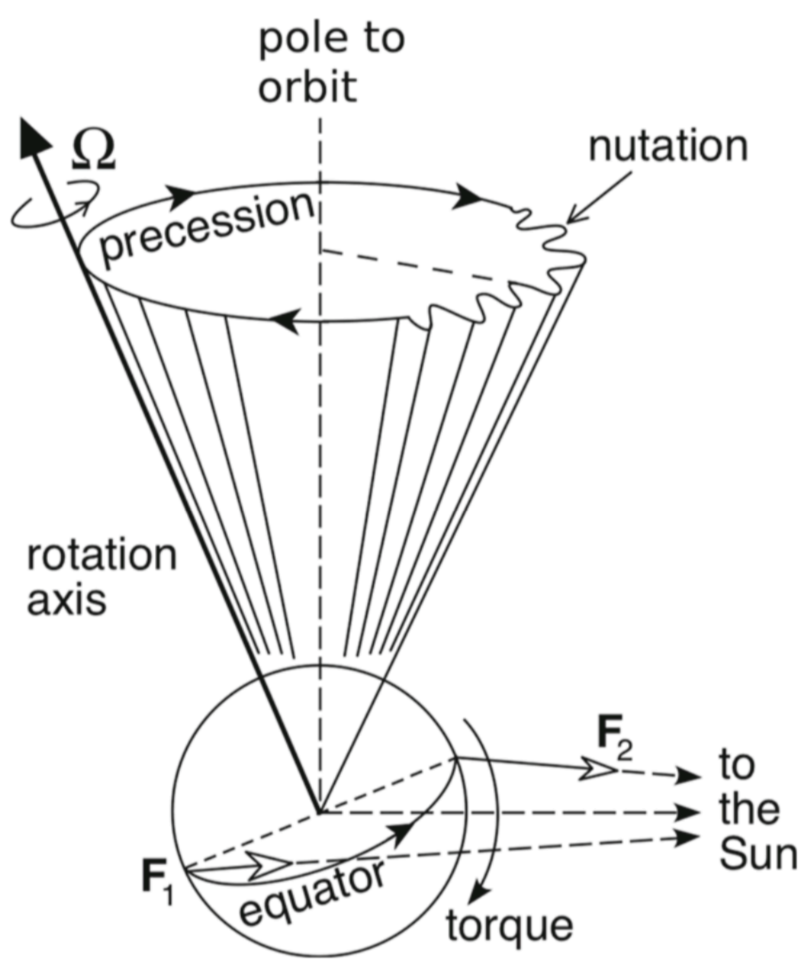
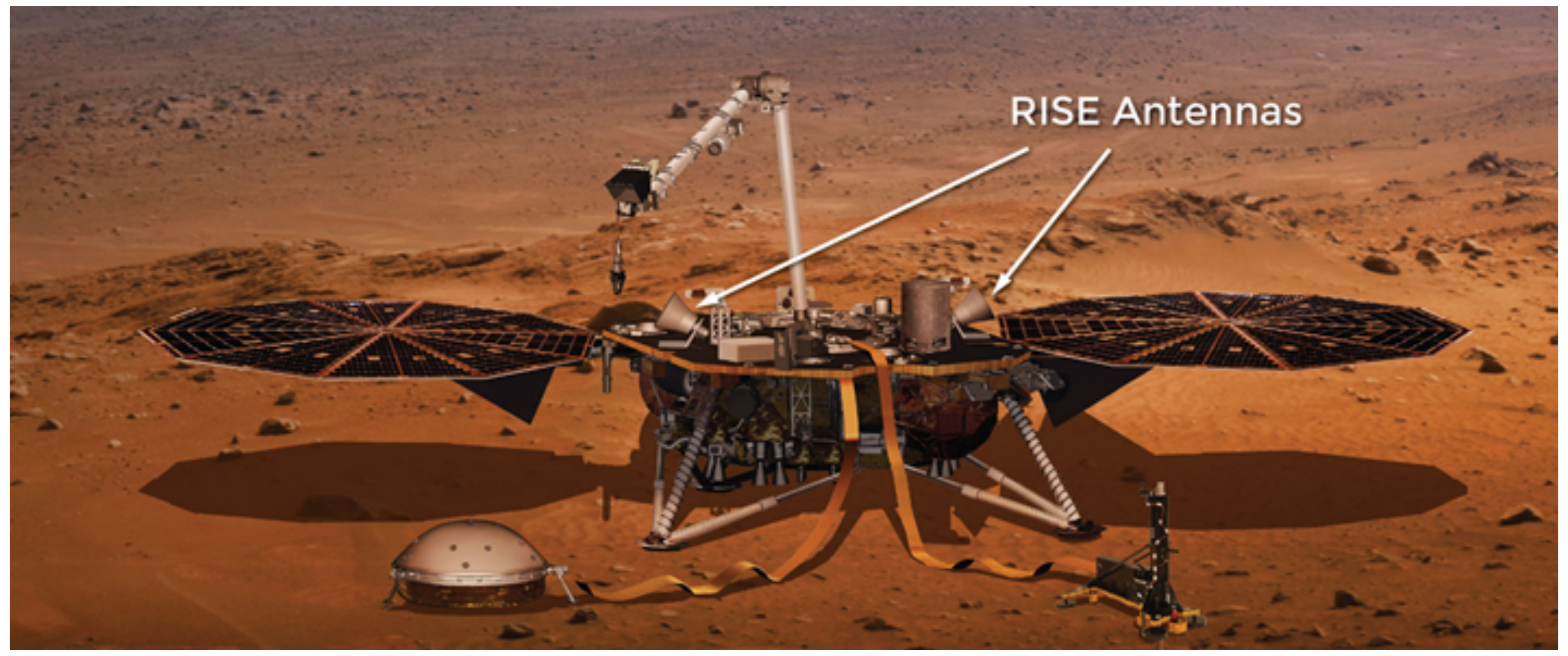
Scope

- the large core radius inferred from geodesy data (mass, moment of inertia, tides) requires a relatively low density for the core (≲6400kg/m^3)(e.g. Rivoldini 2011)
- recent thermoelastic data about liquid Fe-S alloys (Nishida 2016, Morard 2018, Terasaki 2019, Nishida 2020, Xu 2021)- S is the major light element inside the core of Mars - imply that the amount of S can be larger than 25wt% (Terasaki 2019)
- significantly more than any predictions from formation and geochemical model (≲22wt%, e.g. Taylor 2013, Steenstra 2018, Brennan 2020)
- other candidate light elements than can alloy with Fe-S at Mars core conditions (p,T, fO_2) are Oxygen, Carbon, and Hydrogen
- are those light elements detectable by measuring the nutation of Mars with RISE on InSight?

Nutation

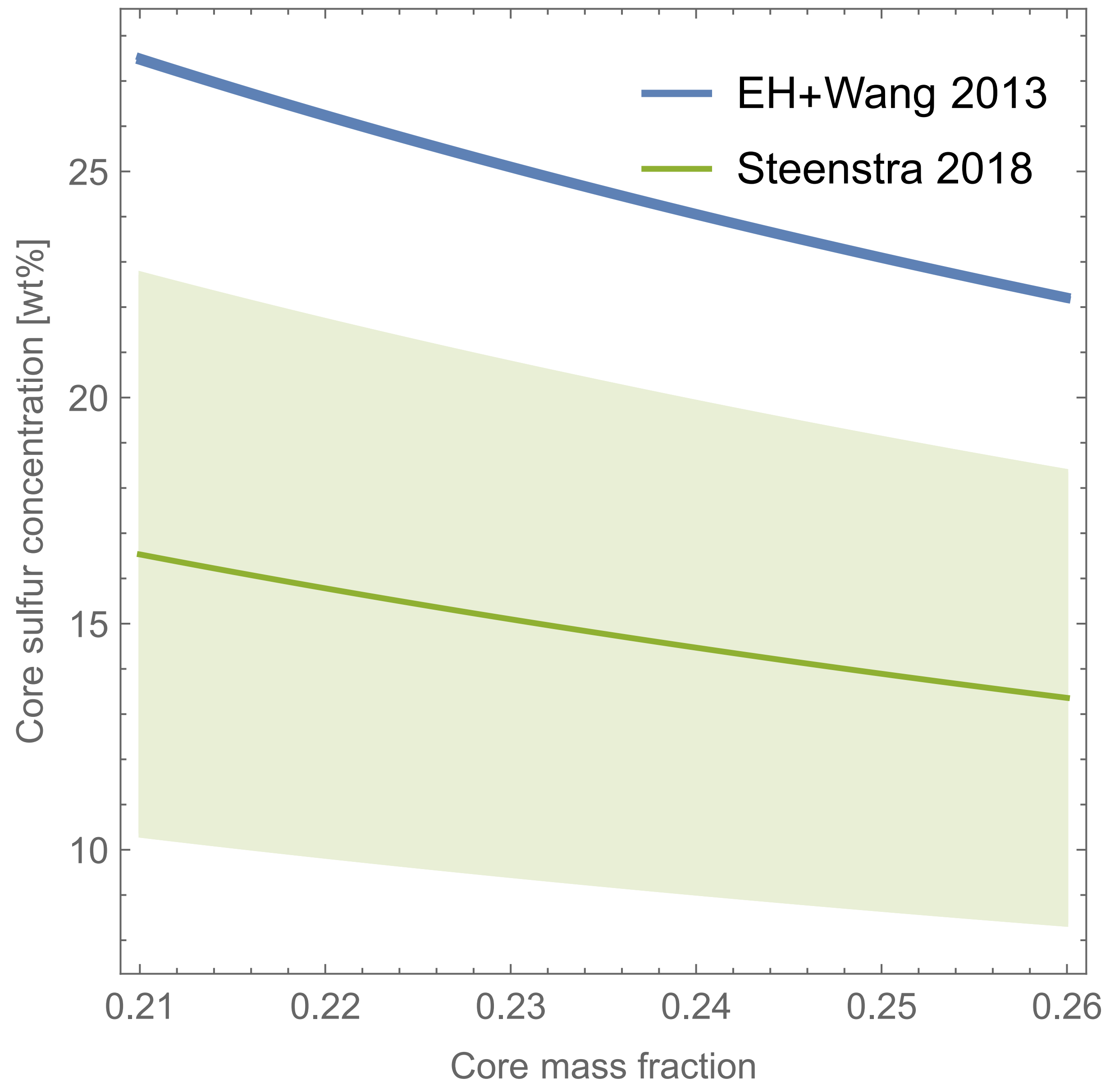




- variations in the torque due to the relative positions between Mars and the Sun lead periodic time variations of the rotation axis, the nutations
- nutations can be resonantly amplified due to a rotational normal mode (FCN) that exists because of the liquid core
- nutation amplitudes and the FCN depend on the moment of inertia of the core and its ability to deform
- the RISE experiment aims to determine the FCN period and the amplitudes of the nutations by measuring the Doppler shift on a two-way radio link between the Earth and Mars

Candidate light elements: Sulfur

- siderophile at Mars (p,T,fO_2) conditions
- abundant in thought building blocks
- mantle abundance 240-480 ppm (Wang 2013)
- if Mars were made of EH chondrites S~25wt%
- geochemical models 13-17wt% (e.g. Steenstra 2018)

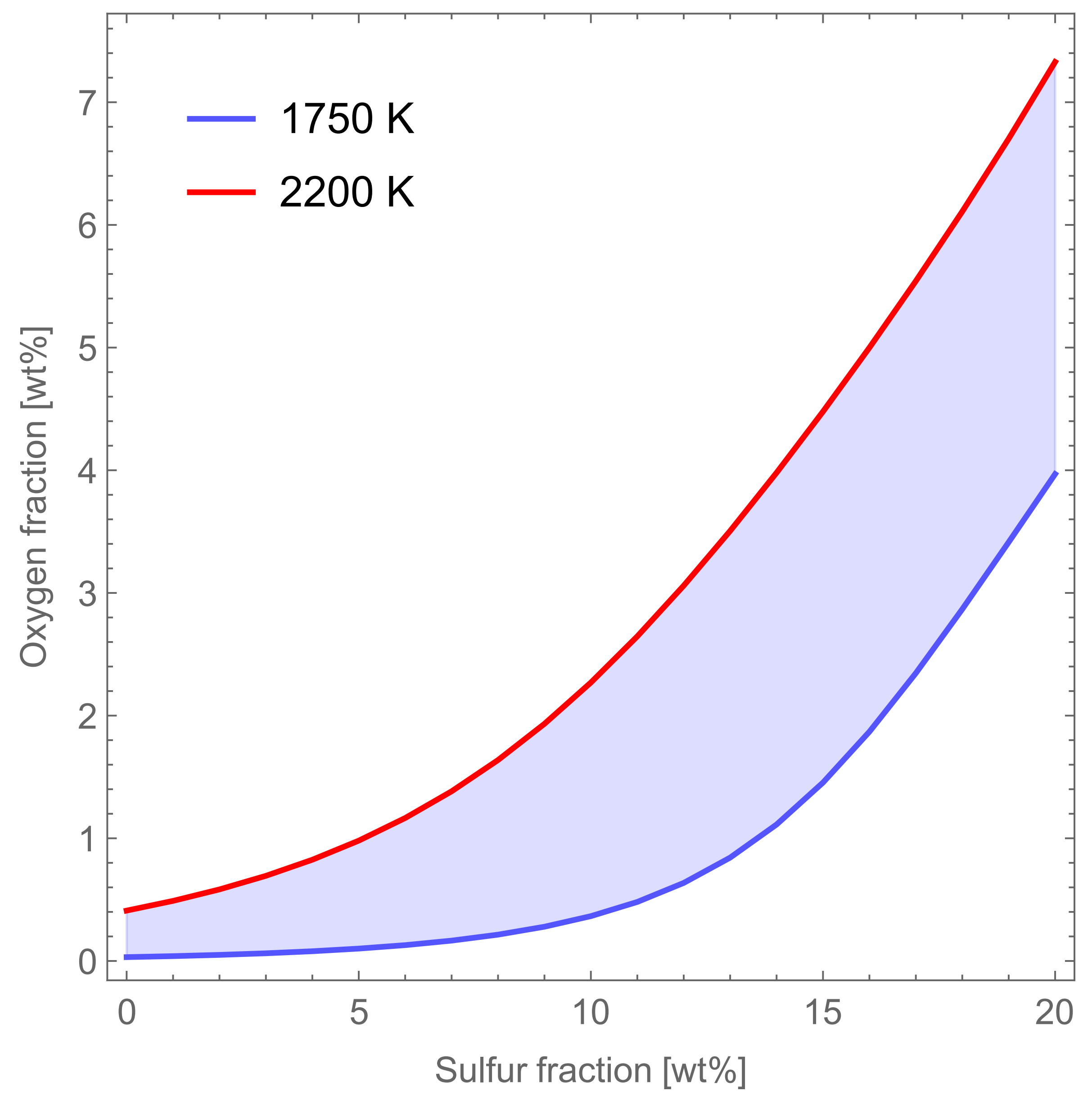


Candidate light elements: Oxygen

- small amounts of O (<1wt%) can dissolve in Fe at Mars (p,T,fO_2) conditions

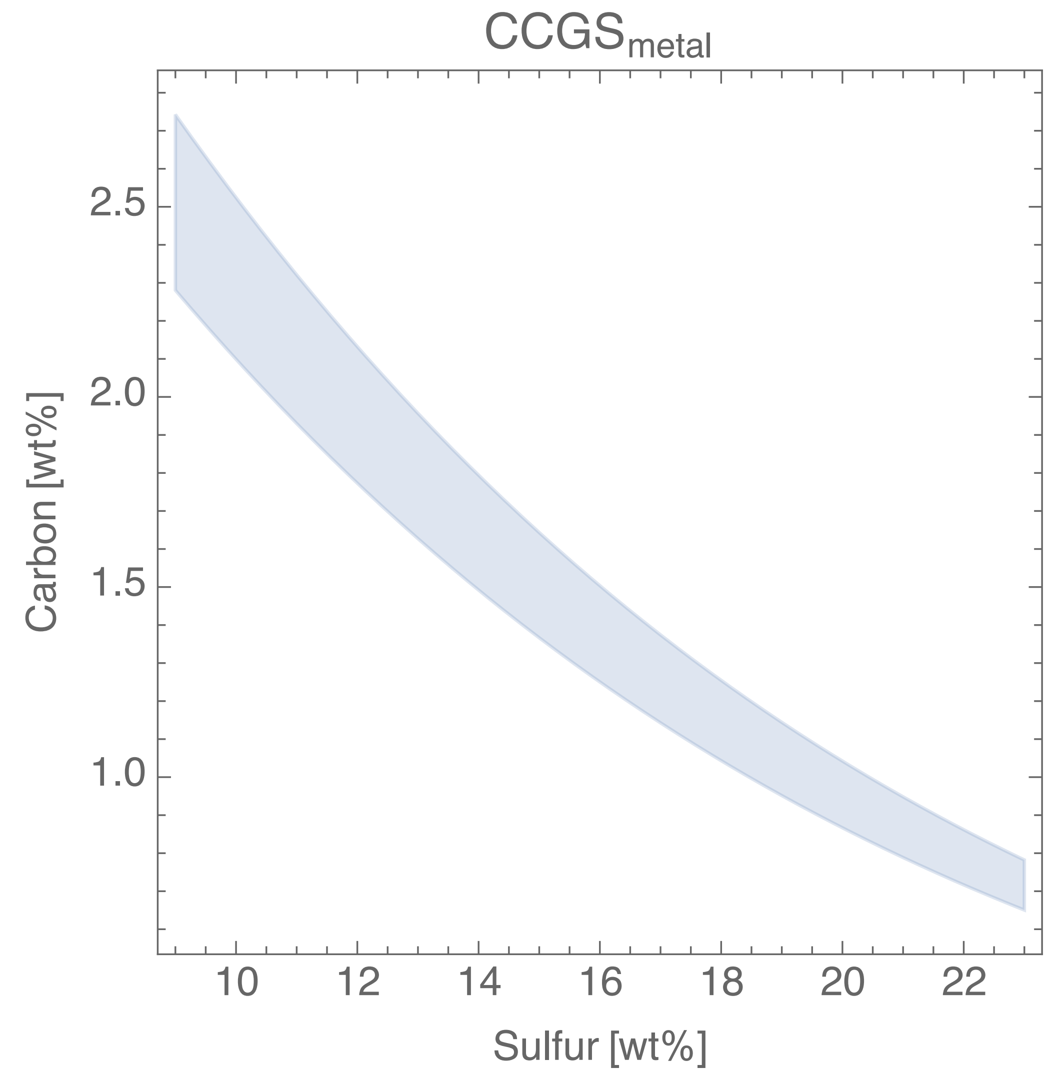
- but O increases with increasing S (e.g Tsuno 2011)
  O~3-5wt% if S~15-20wt%

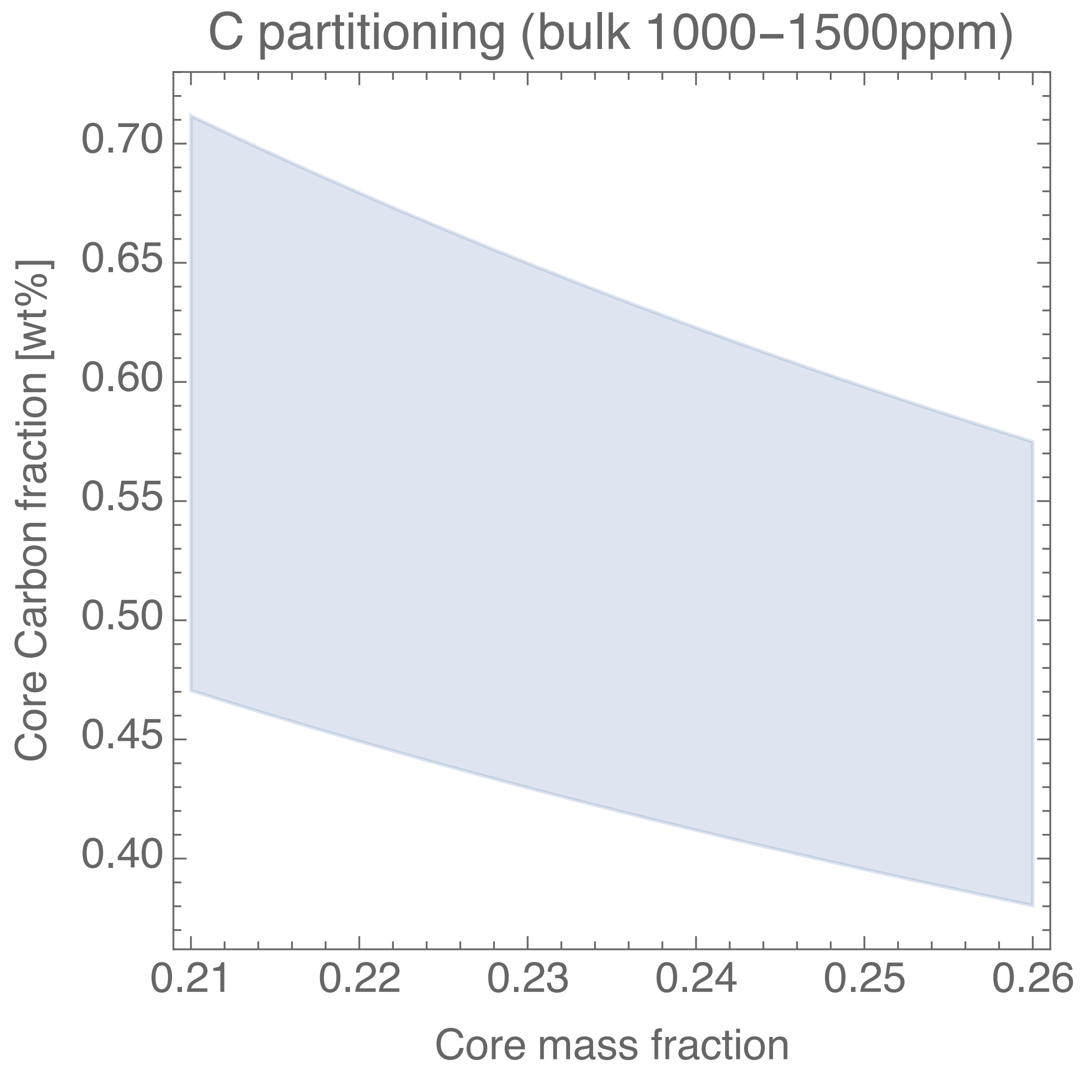
- implied complexities:
  - amount of dissolved O decreases with T
  => ex-solution of FeO?
  - Fe-O-S has immiscibility field (relevant if S≲13wt% close to CMB, e.g Tsuno 2011)
  => liquid layering in the upper core



Candidate light elements: Carbon & Hydrogen

- maximal dissolved amount of C in Fe-S decreases with increasing S and decreasing temperature (e.g Tsuno 2018)
- <1wt% C for Fe-S core but
  ~1 wt% Carbon can dissolve in liquid Fe-5wt%O-S
- graphite saturation unlikely but not impossible
- ~1wt% of C together with Fe-O-S likely not enough to bring S concentration in line with geochemical/formation models
- add ~1wt% (?) Hydrogen (e.g Zharhov 1999, Shibazaki 2009)
  => strong effect on density of Fe
  => requires water saturated magma ocean
  => or water dissolved in Wad and Ring (wherefrom ? no plate tectonics)
  => difficult to assess the effect of H precisely because of lack of eos for liquid Fe-H





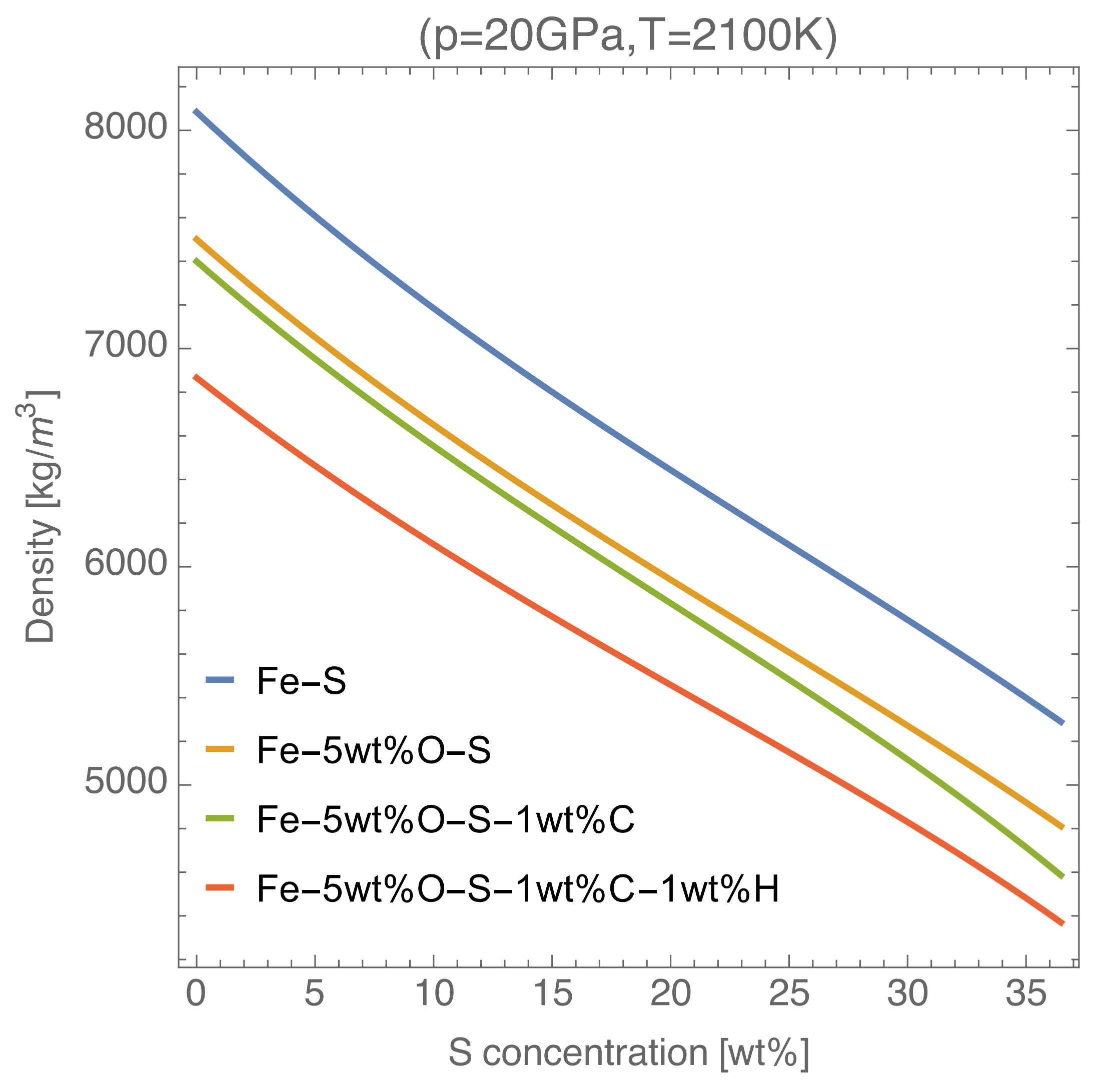
Effect of light elements on density and acoustic velocity

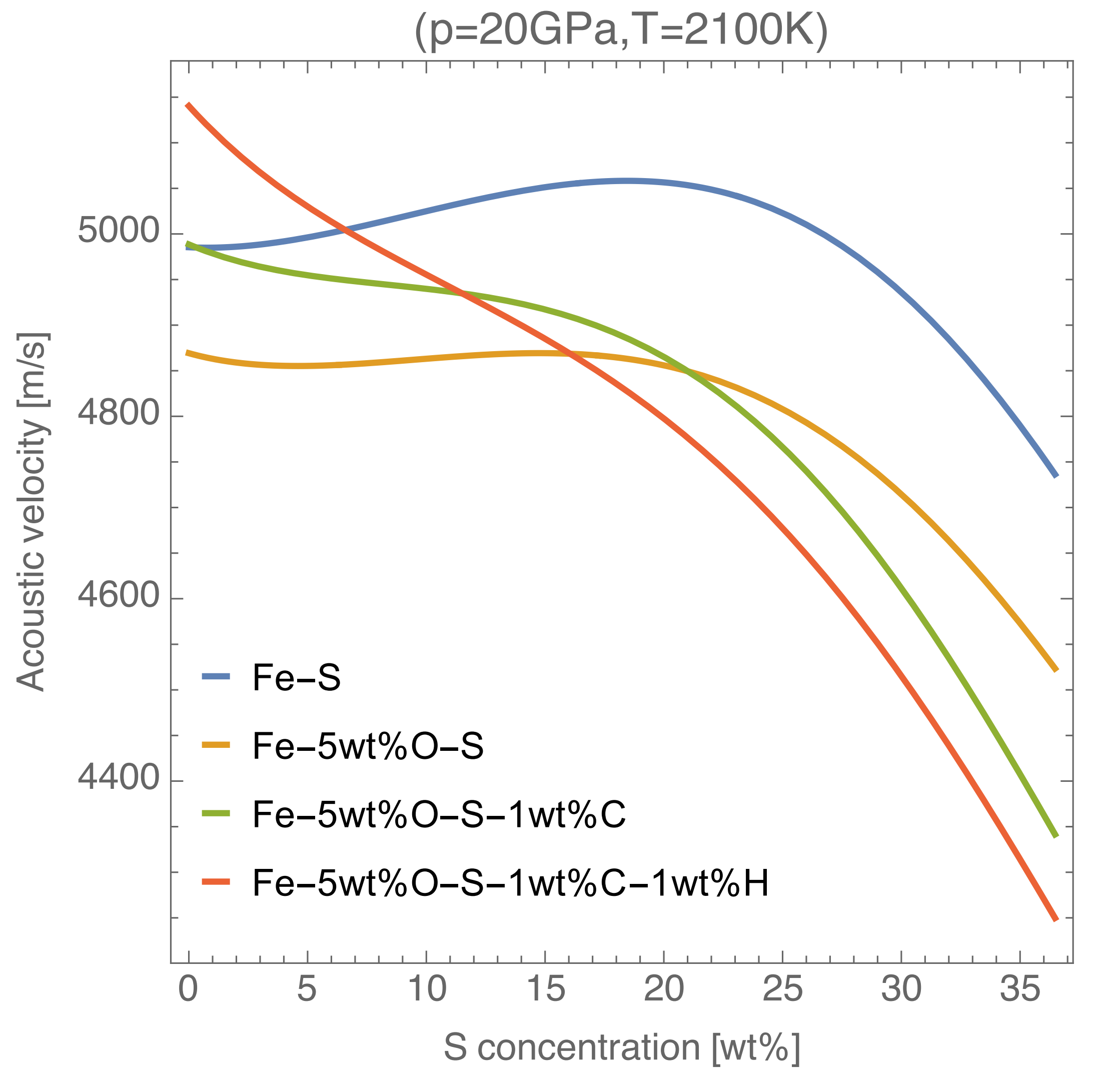
- model for liquid Fe-O-S-C-H based on eos' of Nishida 2020, Xu 2021, Morard 202x, Morard 2017, Shimoyama 2016, Badding 2013),

- non ideal mixing of Fe and S required to mach measured density and sound velocity

- 1wt%C has a small effect on Fe-S density but 1wt%H has a larger effect than 5wt%O

- non ideality induces complexity in sound velocity

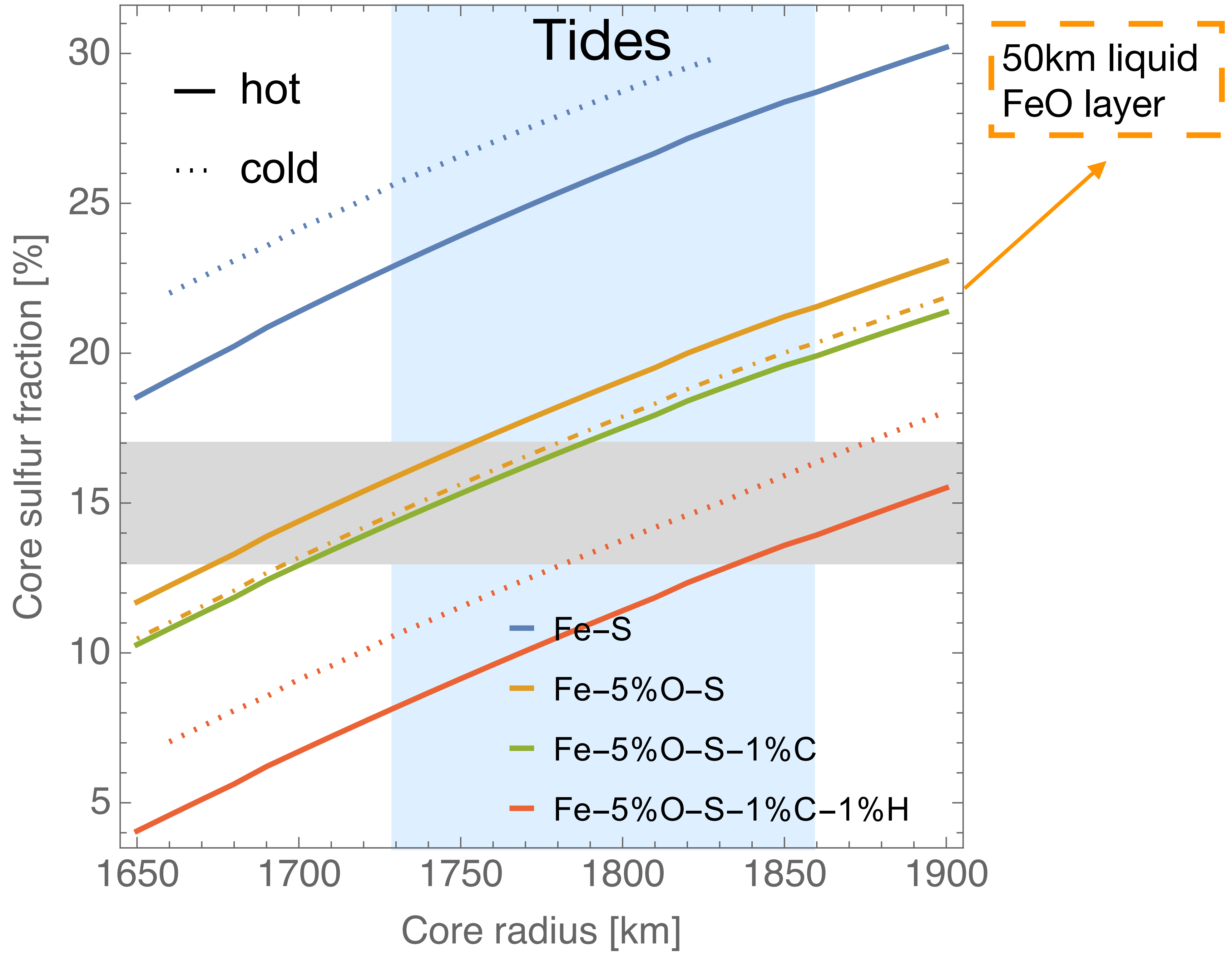




Effect of light elements on core structure

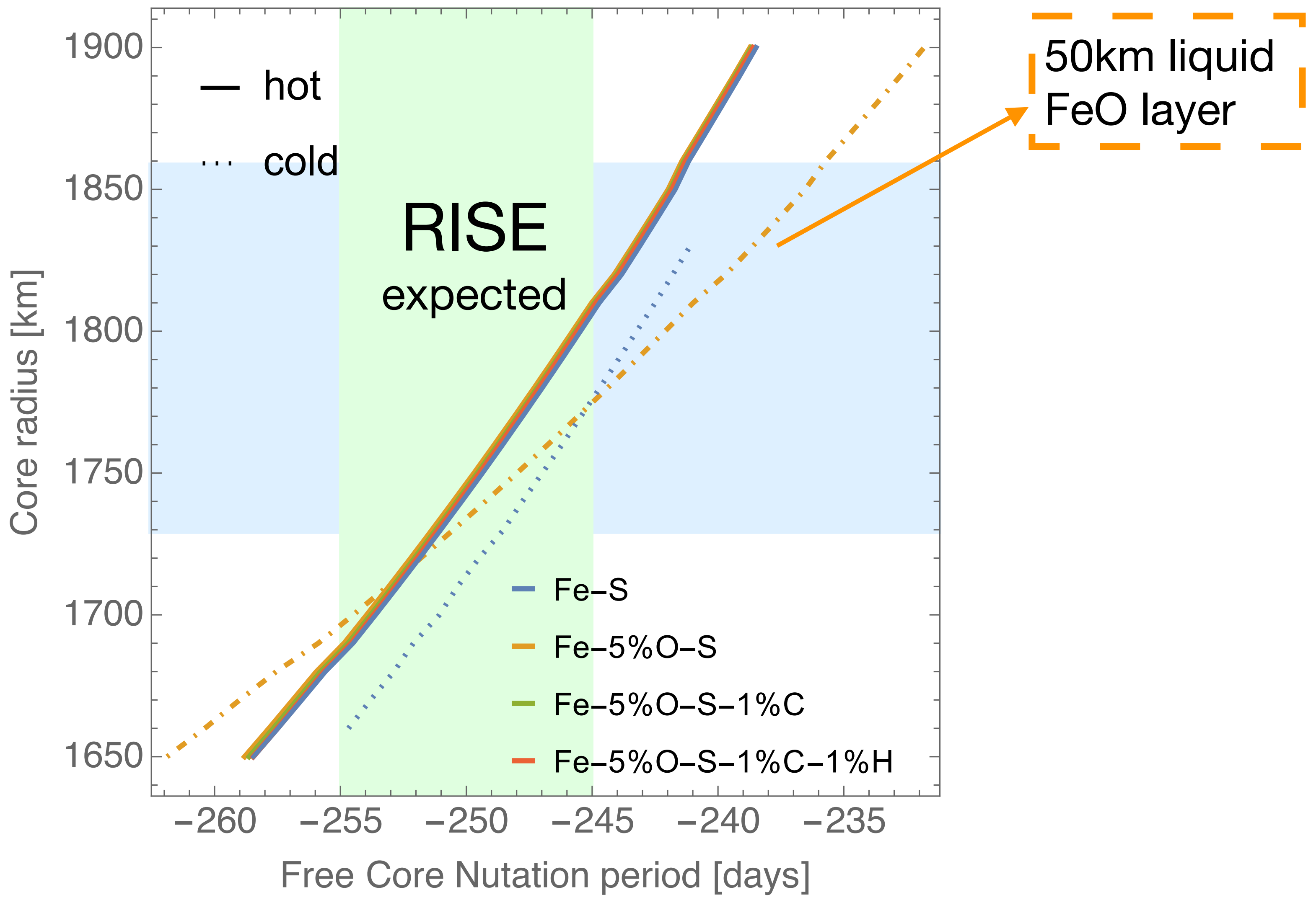
- to match the density and bring the S concentration in line with geochemical/formation model if the core is large requires ~ the maximal “allowed” amount of O, C, and H

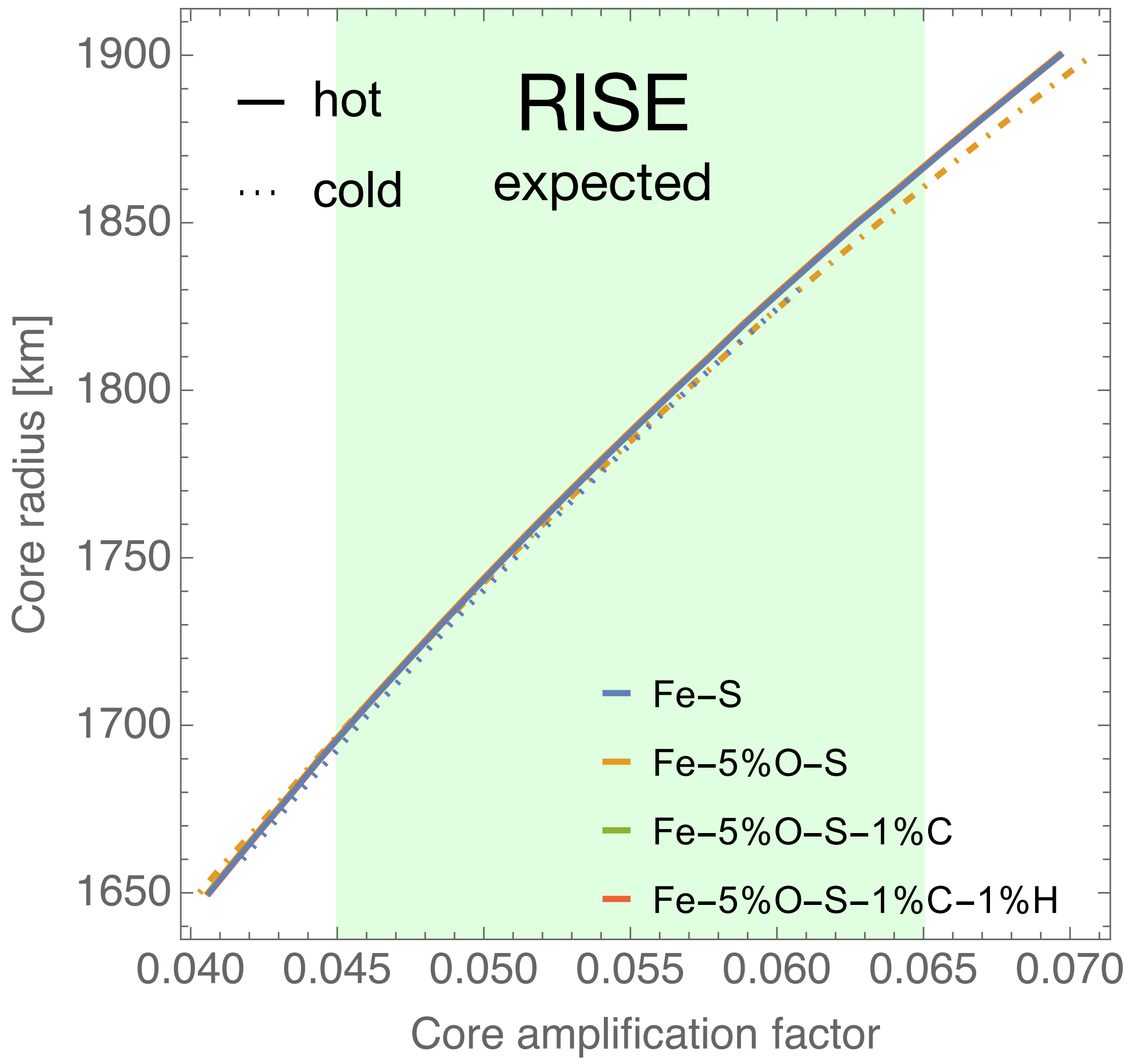
- only models with the smallest core require beside Fe-5wt%O-S (C,H)<1wt%



Effect on nutation

- nutations do not provide a direct constraint on core composition if the core is a homogeneous liquid (as do tides)
- deductions about core composition requires prior knowledge
- liquid layering in the upper core is potentially detectable (requires higher precision than RISE)





Conclusions

- the core radius of Mars inferred from tides implies that the core has a relatively low density (≲6400kg/m^3) implying a large amount of light elements
- recent thermoelastic data shows that if S is the only light element the required amount (>25wt%) is not in agreement with geochemical/formation models (~17wt%)
- maximal “plausible” amounts of O (~5wt%), C (1wt%), and H (~1wt%) are required to match the density of the models with the largest cores if S≲17wt%
- nutations are sensitive to average core density and require prior knowledge about light elements to constrain its composition
- supplemental data about thermoelastic properties of Fe-**O**-S-**C**-**H** is required to decrease modeling uncertainty
- ~> if actual core is smaller and/or mantle is less dense (smaller amount of FeO, higher temperature) the amount of light elements could be reduced