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# Coupled tidal tomography and thermal constraints for probing Mars viscosity

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## Abstract

Computing the tidal deformations of Mars, we explored various spherical internal structures and different types of interface between the mantle and the liquid core. We demonstrate that the geodetic records associated with thermal constraints are very sensitive to the presence of a 2-layered interface on the top of the liquid core. This interface is composed by a liquid (Newtonian) and a viscoelastic (Andrade) layers with very different viscosity properties. Our results show that tidal deformation is a powerful tool to constrain the Martian interior, confirming densities and thicknesses consistent with the literature and proposing new viscosity estimates. The 2-layered interface strongly impacts the viscosity profiles, suggesting a stagnant lid regime consistent with the absence of plate tectonics on Mars. Finally, the existence of a Newtonian liquid layer excludes the presence of a solid inner core.

## Introduction

- Marsquakes detection by NASA's InSight seismometer provides valuable informations to improve our understanding of the deep interior of the planet. Many models of the Martian interior have emerged in recent years, particularly the models of Khan et al. (2023) and Samuel et al. (2023) proposing specific stratifications in the deep mantle.

- According to Khan et al. (2023), P and S-waves measurements obtained by InSight suggest a smaller and denser liquid core than previous estimations, composed of 27% of light elements and overlain by a fully molten of silicate layer.

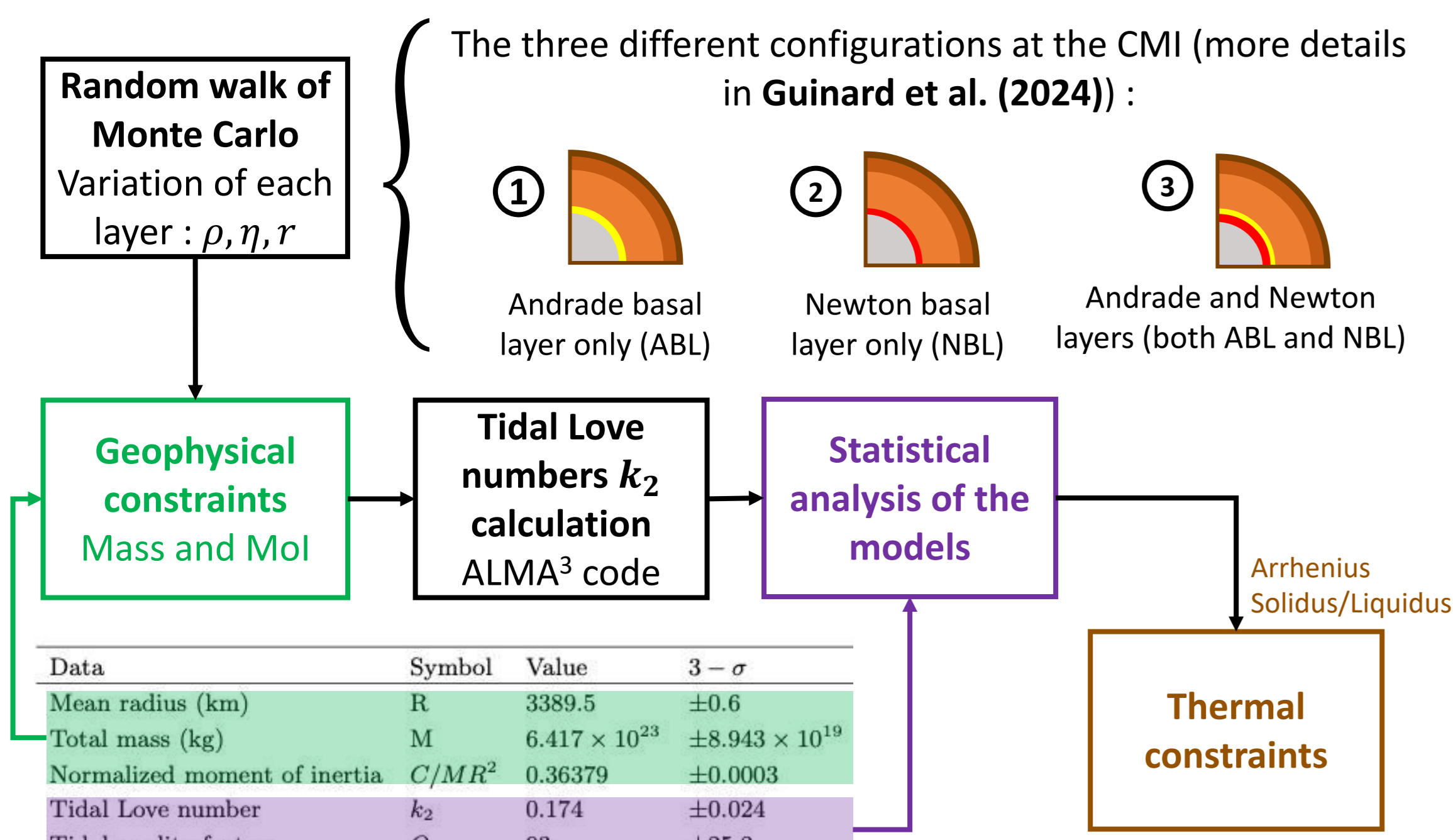
- Mars would have had a global magma ocean at the beginning of its formation, the crystallization and fractionation of which would have produced a heterogeneous mantle with, according to Samuel et al. (2023), a molten silicate layer topped by a partially molten layer enriched in iron and radiogenic elements.

- From Guinard et al. (2024), we propose to detect and constrain the interface between the mantle and the core independently of seismic and thermodynamic models, by modeling tidal deformations. Here, we first present the methodology and the models derived from tidal geophysical constraints. In a second step, we compute the temperature profiles corresponding to these models and analyze those that satisfy the thermal constraints.

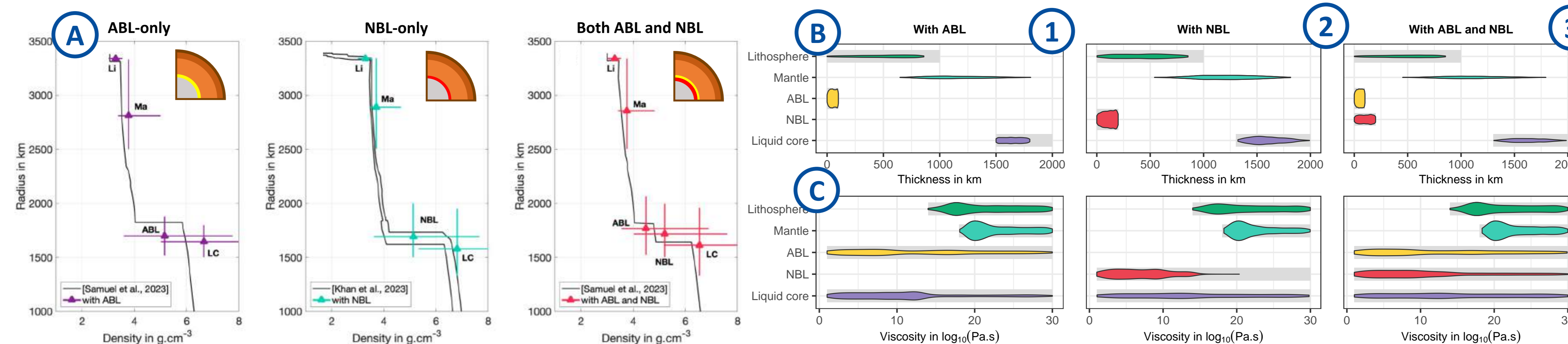
## Method

Tidal deformations have proven to be an effective tool for studying and constraining the internal structures of planetary bodies. This tool has notably been used to constrain the interior of Venus (Saliby et al., 2023), Mercury (Goossens et al., 2022) and more recently the lunar interior (Briaud et al., 2023) showing the existence of a solid inner core at its center. Here, we present the results obtained in Guinard et al. (2024), where we use the same method by modeling tidal deformations with the semi-analytical software ALMA<sup>3</sup> for a wide range of 1D Martian interiors. More details on the ALMA<sup>3</sup> modeling can be found in Melini et al. (2022). This study focuses on the periodic deformation induced by Phobos tides on Mars (5h55).

The idea is then to randomly explore different possible rheological profiles for **three different configurations at the core-mantle interface (CMI)** with ALMA<sup>3</sup> and to produce Love numbers  $k_2$ , quality factor  $Q$  for a wide range of tidal excitations. Comparisons to observed mass, moment of inertia, Love numbers  $k_2$  and  $Q$  are done and  $\chi^2$  selections are operated.



## Martian inner structure from tides

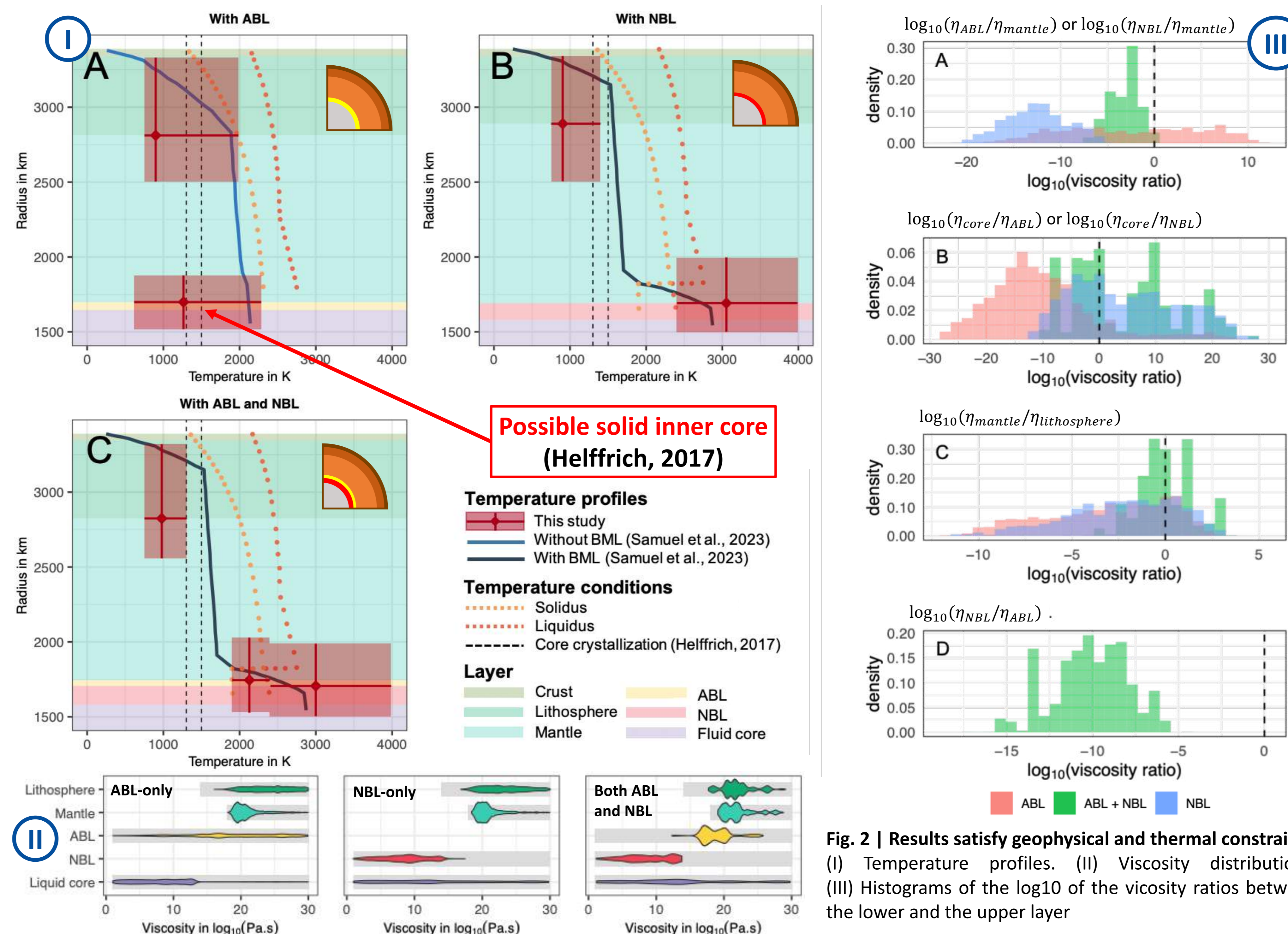


**Fig 1 | Results from ALMA<sup>3</sup>.** (A) Density profiles, (B) Thickness distributions and (C) Viscosity distributions. The gray background corresponds to the exploration interval of the input models.

**Fig. 1 shows some interesting results :**

- Radius and density profiles remain stable regardless the choice between the three configurations and are in good agreement with the literature (Khan et al. 2023; Samuel et al. 2023)
- Tides reduce the possible viscosity range of the NBL by a factor of 2
- The NBL viscosity is systematically lower than that of the mantle and the lithosphere (Fig. 1.C.2)
- 50% of the models show an ABL viscosity lower than that of the NBL
- The presence of NBL reduces the constraints on the viscosity of the LC compared to models without an NBL (Fig. 1.C.1. versus F1.C.2 and F1.C.3)

## Martian inner structure from tides



**Fig. 2 | Results satisfy geophysical and thermal constraints** (I) Temperature profiles. (II) Viscosity distributions. (III) Histograms of the log10 of the viscosity ratios between the lower and the upper layer

### Highlights from Fig. 2 :

- The presence of the NBL above the core imposes high temperatures at such depths and prevents the existence of solid inner core according to Helffrich (2017) (Fig. 2.I.A)
- $\log_{10}(\eta_{mantle}/\eta_{lithosphere})$  is centered around 0 for models with both ABL and NBL. These models are in favor of a stagnant lid regime supported by current absence of Earth-like plate tectonics on Mars (Fig.2.III)
- $\eta_{ABL} > \eta_{NBL}$  compatible with the solidus and liquidus thresholds (Fig. 2.III.D)
- For models with ABL-only,  $\eta_{ABL} > \eta_{core}$  what is expected but it's not systematic for models with a liquid layer overlain the liquid core. Such viscosity contrast can be explained by an increase of temperature at the NBL induced by the presence of heat producing element and by a small contribution of tidal friction (Khan et al., 2023) (Fig. 2.III.C)
- When assuming an Earth-like liquid core ( $\eta_{core} < 10^{10} Pa.s$ ), 75% of models with ABL-only, less than 50% for models with NBL-only and only 33% for models with both ABL and NBL remain consistent with geophysical and thermal constraints. The physical properties of each layer show no significant variation (see in Guinard et al. (2024))

## Conclusion

- Tidal deformation with visco-elastic rheologies, despite short excitation periods, is highly effective for constraining Mars internal structure  
 → New density and thickness estimates match with previous studies
- By adding thermal constraints, this approach gives also new tools to estimate layer viscosities
- A key result indicates that a liquid layer atop the liquid core prevents the presence of a solid inner core  
 → Supporting the scenario of Mars without a solid inner core
- The viscosity contrast between the lithosphere and the mantle helps to detect a two-layered interface above the liquid core  
 → Models with 2-layered interface suggest minimal viscosity contrast between the lithosphere and the mantle favoring a stagnant lid regime and explaining the absence of Earth-like tectonics on Mars
- Inversion of viscosities between the ABL and the NBL is possible  
 → Further investigation are required to determine if these inversions arise from differences in chemical composition or partial melt

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