

Constraining the interior structure and thermal state of Venus

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Venus is similar to the Earth:
mass, radius, distance from the Sun

Why did the fates of the planetary twins diverge?

Venus is dissimilar to the Earth:
lower uncompressed density
lack of plate tectonics
no (or very weak) magnetic field
“infernal” surface conditions
slow, retrograde rotation

Context and outline

This is the third Venus-related seminar of the winter semester!

6. 11.	Julia Maia (DLR Berlin) The interior structure of Venus as seen by gravity and topography data
28. 11.	Diogo Lourenco (ETH Zurich) Influence of possible bulk compositions and tectonic regimes on the long-term evolution of Venus

Today:

- > inverse modelling of the (1d) interior structure, constrained by geodetic data and assisted by a parameterised thermal evolution code
- > tentative prediction/illustration of the improvements that might be obtained with the upcoming missions

Global constraints on Venus interior

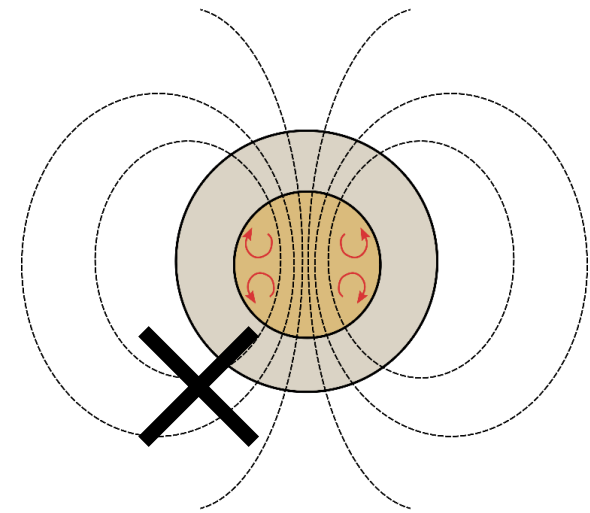
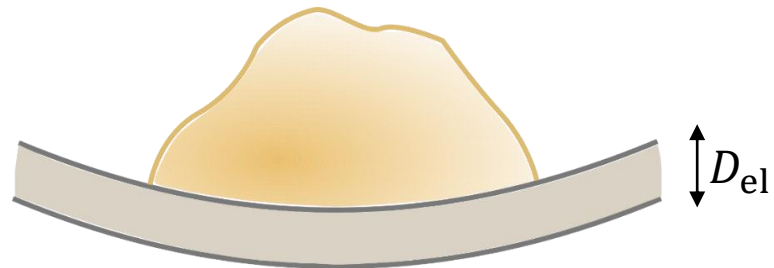
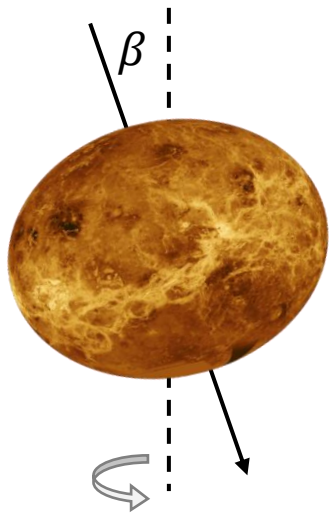
(used in this study)

Interior structure + rheology

- > Mass and radius
- > Moment of inertia factor (MoIF)
- > Tidal deformation (Love number k_2)

Thermal state and history

- > Elastic thickness of the lithosphere
- > Average crustal thickness
- > Non-detectability of an intrinsic magnetic field at present



Moment of inertia factor

Measure of mass concentration: $\text{MoIF} = \frac{C}{MR^2}$, where $C = \int_V \rho r_{\perp}^2 dV$

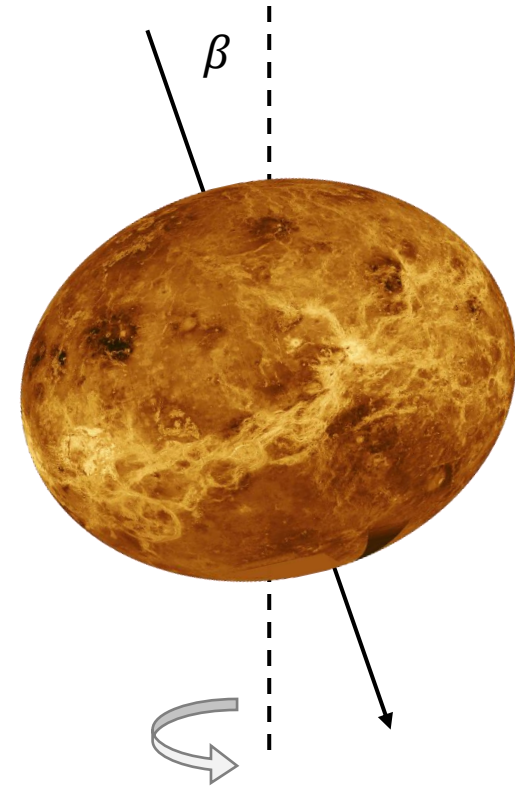
$\text{MoIF} = 0.4$ homogeneous (constant-density) sphere

$\text{MoIF} < 0.4$ density increasing with depth

For Venus, the polar MoIF is inferred from obliquity and precession of the spin axis
(both can be measured from the Earth)

$$\text{MoIF} = 0.337 \pm 0.024$$

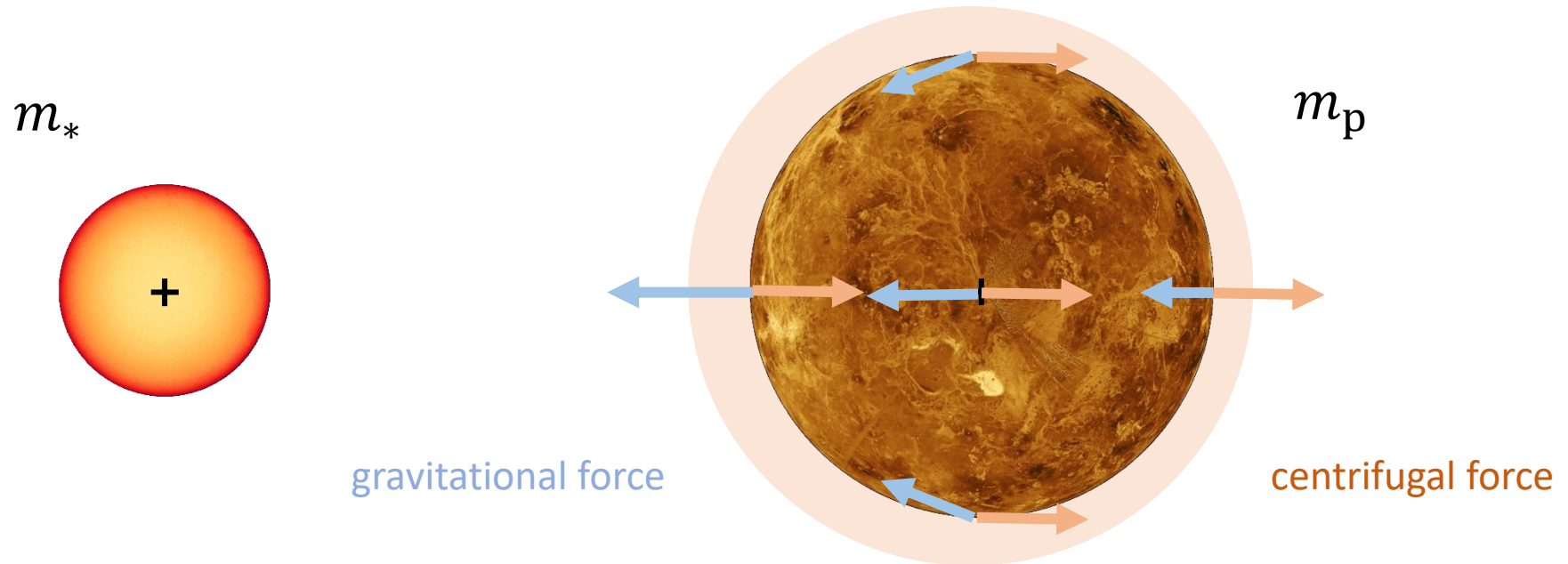
Margot et al. (2021)



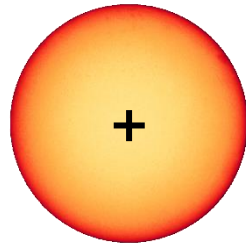
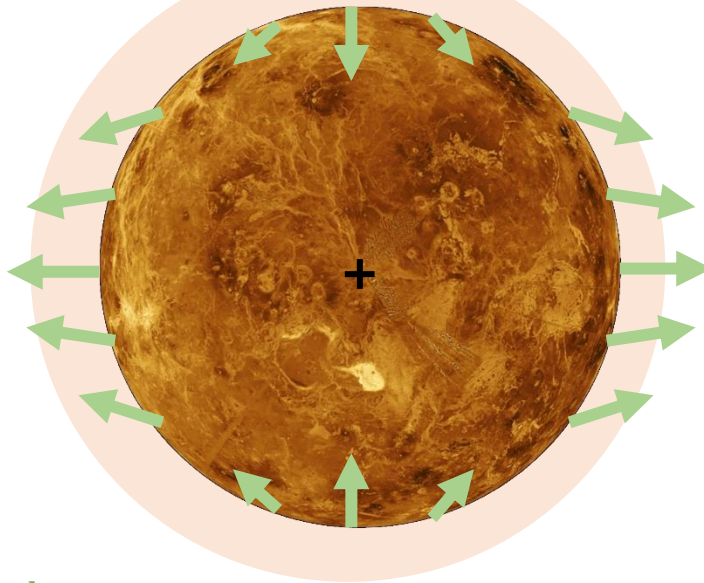
$$\frac{d\psi}{dt} = \frac{3}{2} \left(\frac{n^2}{\dot{\theta}} \right) J_2 \left(\frac{MR^2}{C} \right) \cos \beta$$

Period of precession: ~29,000 years

Tidal deformation



Tidal deformation

 m_*  m_p 

tidal force

$$F_t = \nabla \mathcal{U}_t = \nabla \sum_{l=0}^{+\infty} \mathcal{U}_{t,l}$$

Tidal deformation

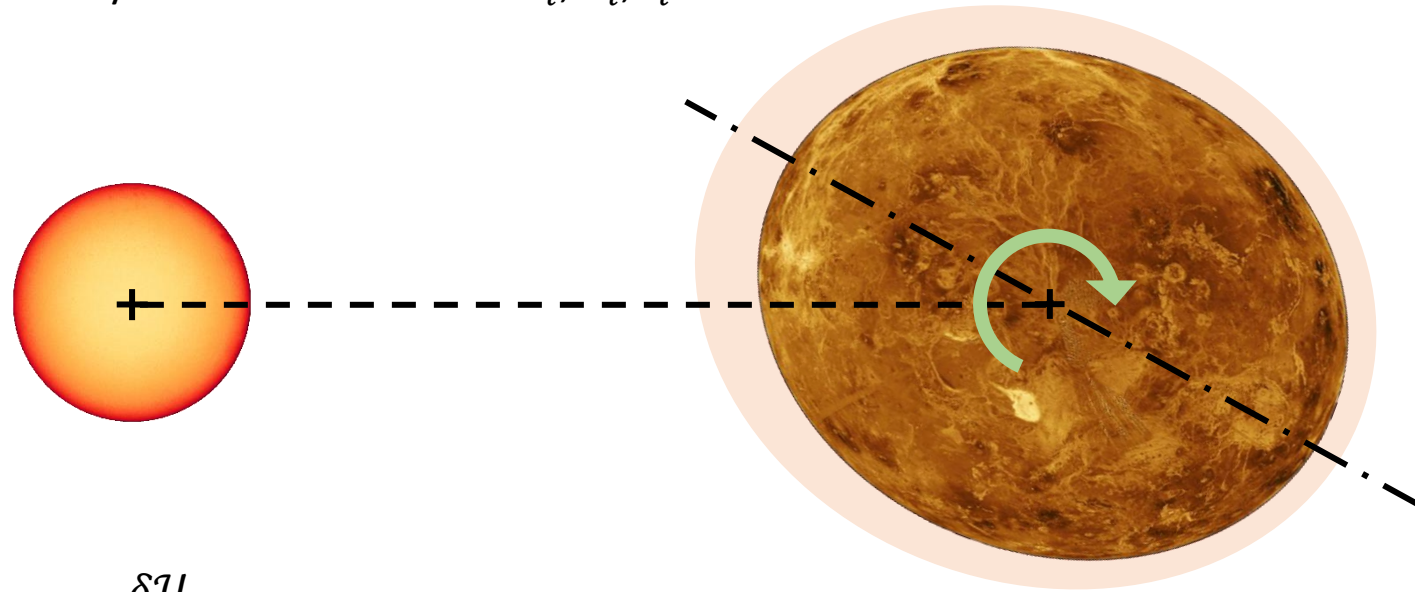
tidal potential

$$u_t = \sum_{l=0}^{+\infty} u_{t,l}$$

additional potential due to surface deflections

$$\delta u = \sum_{l=0}^{+\infty} \delta u_l$$

Planet's reaction represented by Shida-Love numbers k_l, h_l, l_l



Potential Love number $k_2 = \frac{\delta u_2}{u_{t,2}}$

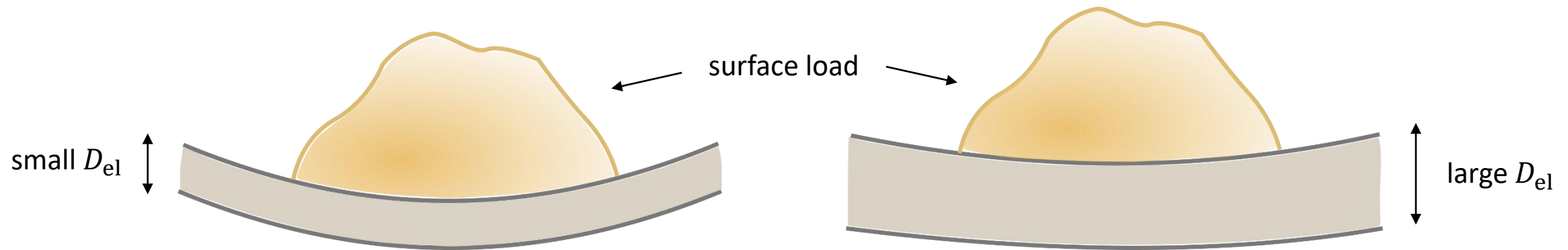
Potential phase lag $\sin |\varepsilon_2| = \frac{1}{Q_2}$ ← tidal quality factor

$$k_2 = 0.295 \pm 0.033$$

Konopliv and Yoder (1996)

Elastic thickness

How flexible is the lithosphere under surface loads? (elastic compensation)



Elastic thickness $\sim$ **temperature gradient at shallow depths**
at the time of the load's emplacement

calculated as in *Grott & Breuer (2010)*

On Venus typically small: mean value below **20-30 km**

(e.g., *Maia & Wieczorek, 2022; O'Rourke & Smrekar, 2018*)

Crustal thickness

James et al. (2013), Figure 10

Crust = compositionally distinct layer

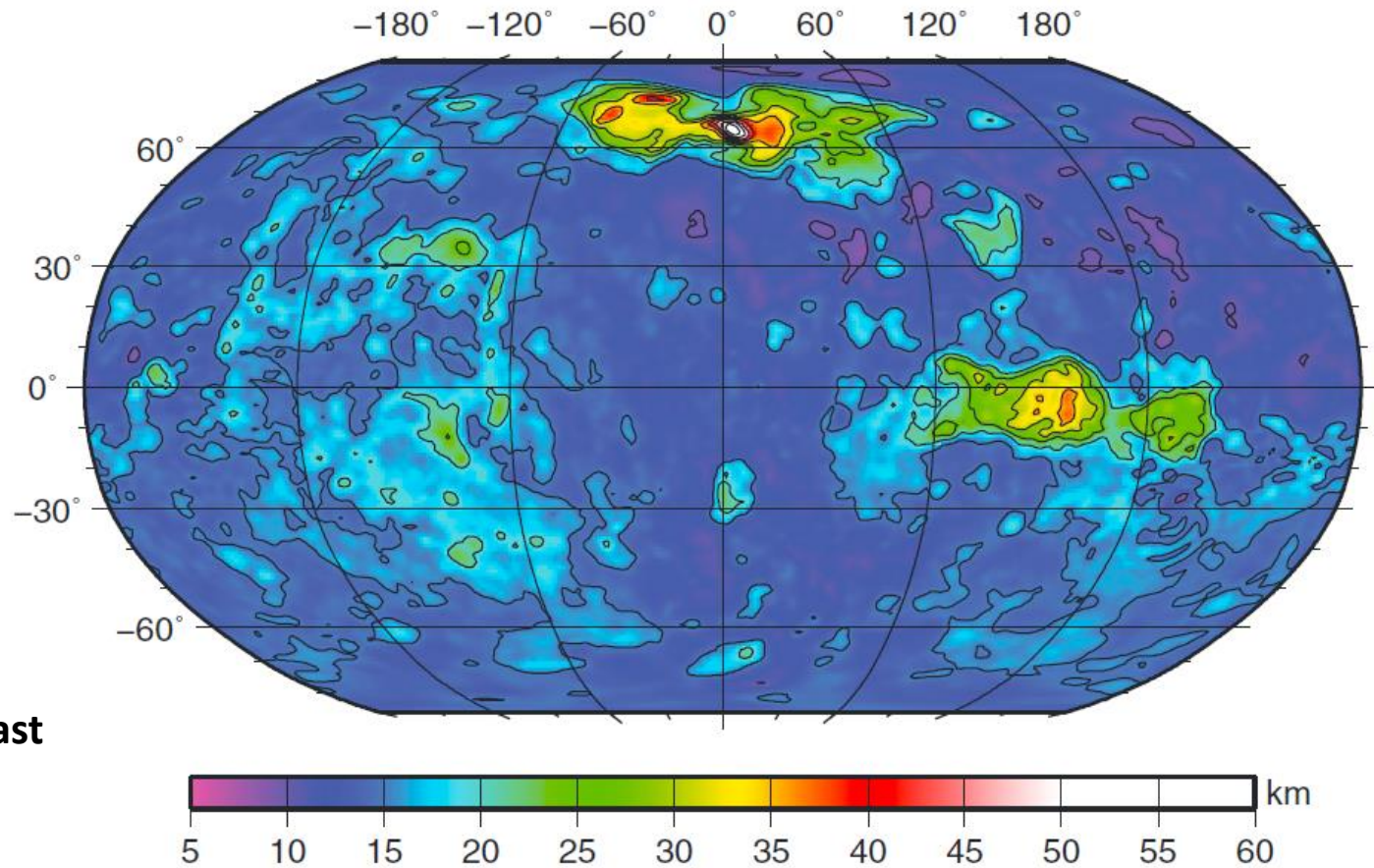
Maximum possible crustal thickness: **80 km**

– limited by the transition to eclogite

Minimum crustal thickness: **8 km**

Volume of crust

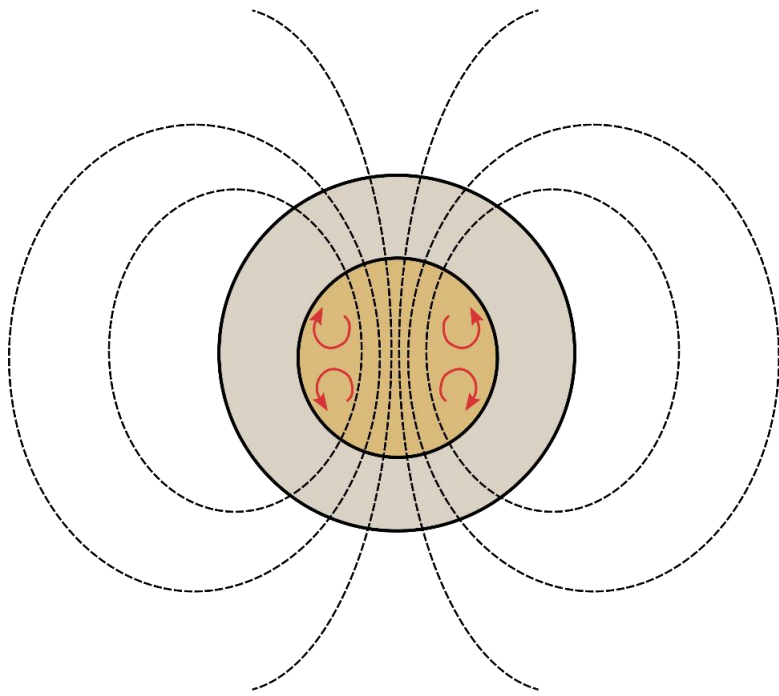
~ amount of mantle melting in the past



Magnetic field generation

Intrinsic magnetic field $\sim$ convection in the (liquid) core

Fully conductive liquid core + assumption on adiabatic temperature profile (*Nimmo and Stevenson, 2000; Nimmo, 2002*):



$$q_{\text{CMB}} = q_{\text{adiab}} = \frac{k_c \alpha_c g_c T_c}{c_{p,c}}$$

There is no detectable intrinsic magnetic field on Venus

We will require that $q_{\text{CMB}} \leq q_{\text{adiab}}$

Global constraints on Venus interior

(used in this study)

Interior structure + rheology

- > Surface gravity $g = 8.8700 \pm 0.0029 \text{ m s}^{-2}$
- > Moment of inertia factor (MoIF) $\text{MoIF} = 0.337 \pm 0.024$
- > Tidal deformation (Love number k_2) $k_2 = 0.295 \pm 0.033$

Thermal state and history

- > Average elastic thickness $T_e < 20 \text{ km}$
- > Average crustal thickness $8 \text{ km} < D_{\text{cr}} < 80 \text{ km}$
- > CMB heat flux $q_{\text{cmb}} < q_{\text{adiab}}$

Assumption: the mantle of Venus is and has always been convecting in the stagnant-lid regime

Additional information: bulk composition

Basaltic Volcanism Study Project (1981): compilation of mineralogical models based on planet formation, etc.

Table 4.3.2b Model compositions (major and heat-producing elements) of Venus.

	V1	V2	V3	V4	V5
<i>Mantle + Crust</i>					
SiO ₂	52.9	53.9	49.8	40.4	45.9
TiO ₂	0.20	0.20	0.21	0.24	0.3
Al ₂ O ₃	3.8	3.9	4.1	3.4	3.9
Cr ₂ O ₃	-	-	0.87	0.3	0.3
MgO	37.6	38.3	35.5	33.3	38.0
FeO	0.24	2.1	5.4	18.7	8.1
MnO	-	-	0.09	0.2	0.1
CaO	3.6	3.6	3.3	3.4	3.2
Na ₂ O	1.6	1.5	0.28	0.15	0.1
H ₂ O	0	0	0.22	-	-
K(ppm)	1442	1318	221	185	129
U(ppm)	0.021	0.021	0.022	0.019	0.021
Th(ppm)	0.073	0.075	0.079	0.066	0.075
<i>Core</i>					
Fe	94.4	84.7	88.6 [†]	78.7	86.2
Ni	5.6	5.2	5.5	6.6	4.8
S	0	10	5.1	4.9	1.0
O	-	-	-	9.8	8.0
<i>Relative Masses</i>					
Mantle + crust	69.8	69.1	68.0	76.4	71.8
Core	30.2	30.9	32.0	23.6	28.2

[†] Also 0.26% Co, 0.58% P.

V1: Equilibrium Condensation. V2: Equilibrium Condensation modified by use of feeding zones of Weidenschilling. V3: Chondrite Model (Morgan and Anders, 1980). V4: Model of Ringwood, discussed in section 4.3.2. V5: Iron-deficient model: same as model E5 for the Earth, with core/(mantle + crust) mass ratio satisfying lower mean density (section 4.5.4).

End-members:

V1 (iron-poor) – “Venus formed in a hotter environment than Earth, closer to the Sun, too hot for FeO to form”

V4 (iron-rich) – “Venus formed in a colder environment than Earth, smaller mass -> less accretion heat, FeO in greater amount”

Earth-like composition:

Cytherean mantle slightly depleted in iron, constant MgO+FeO, otherwise mimicking the Earth (Trønnes *et al.*, 2019; Mittlefehldt *et al.*, 2008)

FeO: 6.30 wt%, MgO: 39.6 wt%

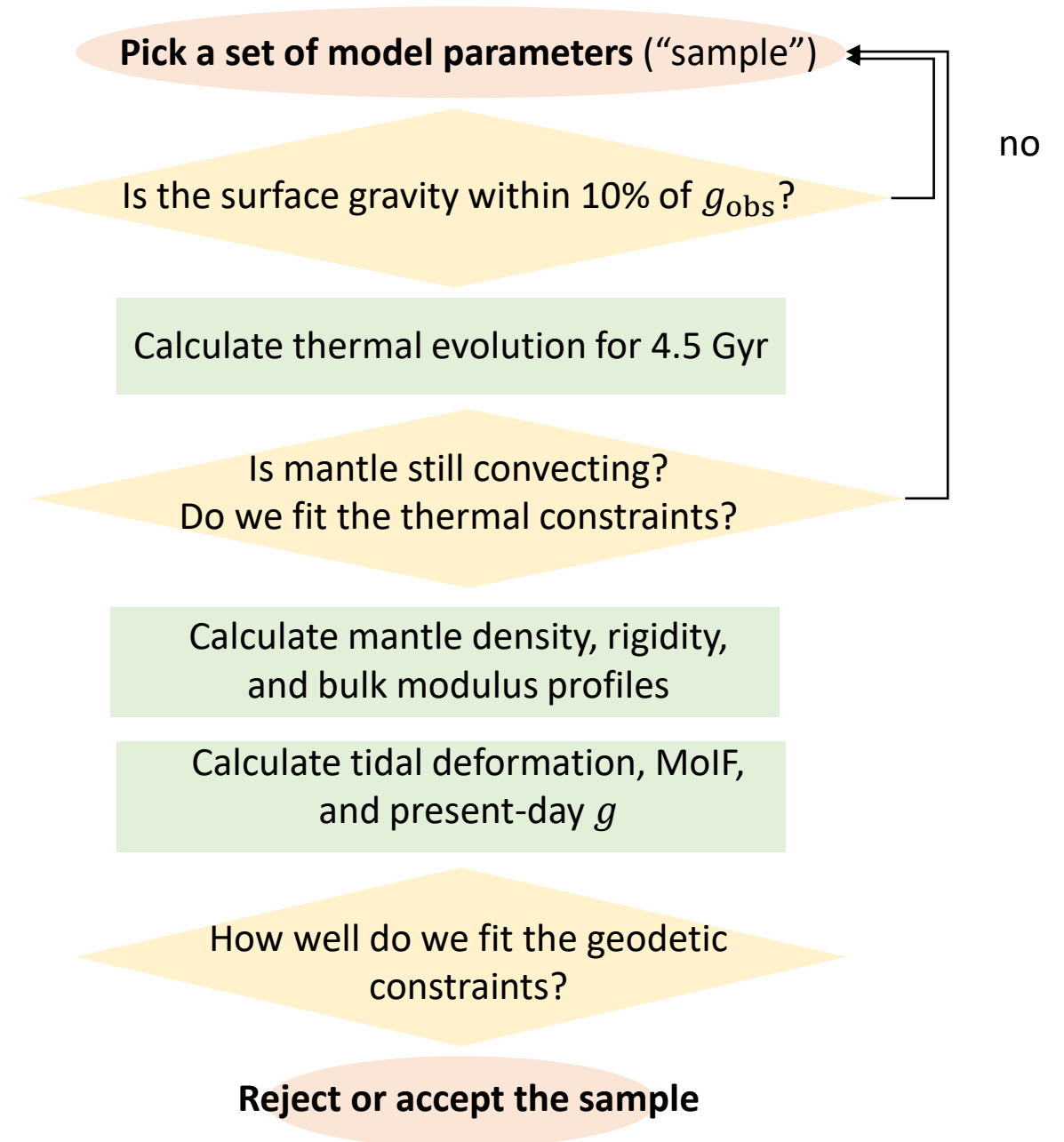
The model

Built around a thermal evolution model

Forward problem solved in the following way:

Next slides:

- > thermal evolution
- > interior structure
- > tidal deformation



The model: thermal evolution

Calculate thermal evolution for 4.5 Gyr

Python model of Philipp Baumeister, based on *Morschhauser et al. (2011)*, *Tosi et al. (2017)*, and other works

1-d parameterised full-mantle convection in the stagnant-lid regime, tested against 3-d codes

Input: outer radii of the main layers, densities, initial T profile, thermodynamic and material parameters

Output: evolution of T , q , D_{cr} , outgassing and many other quantities

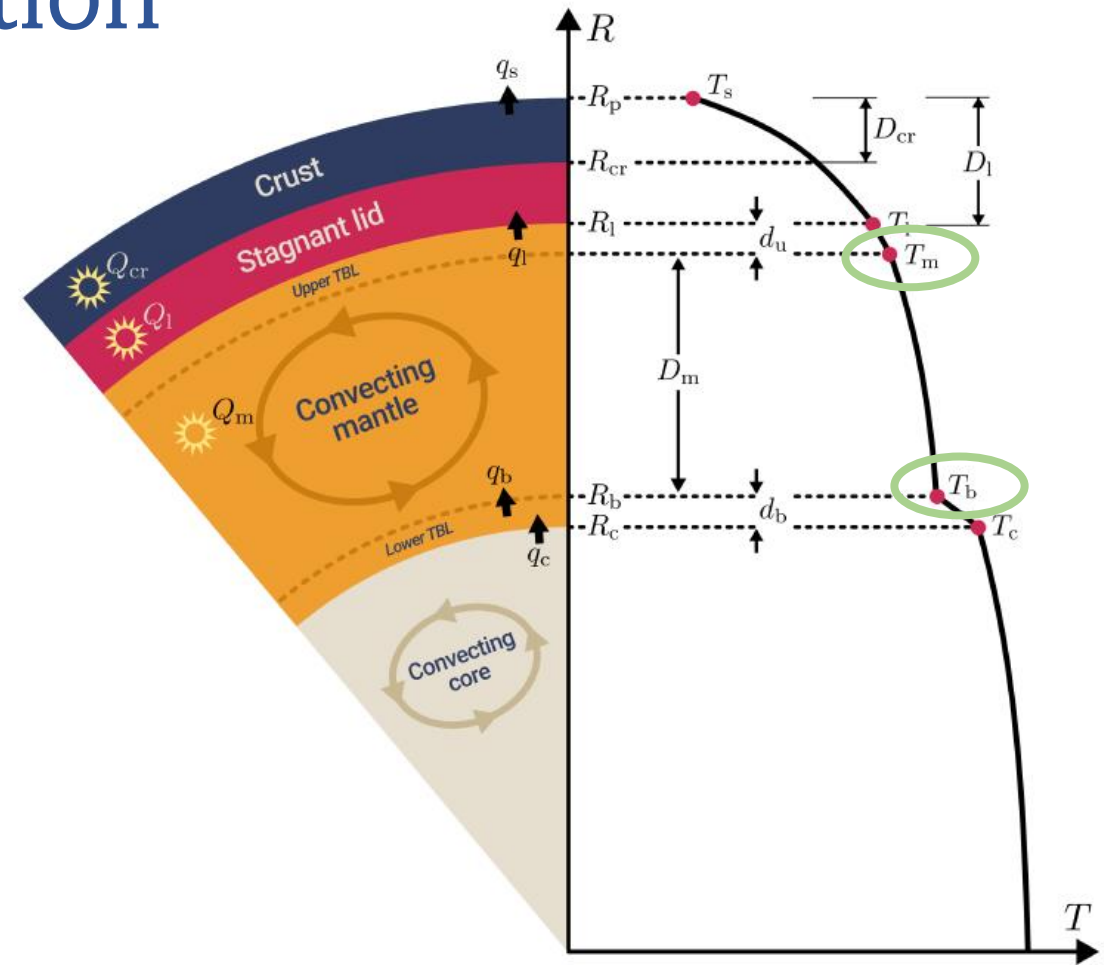


Fig. A.1. Schematic of the interior structure used in the thermal evolution model, alongside a diagram of the temperature profile (see the text for the explanation of the various symbols).

The model: interior structure

Calculate mantle density, rigidity,
and bulk modulus profiles

Precalculated P-T tables for each of the three compositional models
(V1, V4, Earth-like)

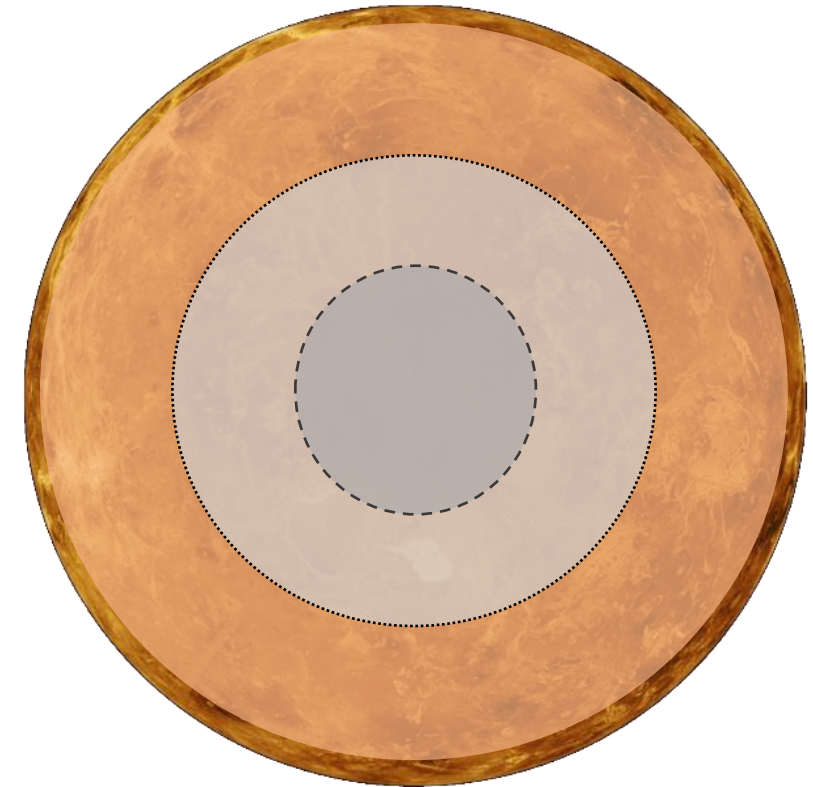
Software `Perple_X` (*Connolly, 2009*) – Gibbs free energy minimisation

Mantle structure calculated iteratively

Input: core size and density, temperature profile, composition

Output: profiles of P , ρ , μ , k + viscosity

Core is currently treated in a simplified way – single density for both
liquid and solid part (will be updated)



The model: tidal deformation

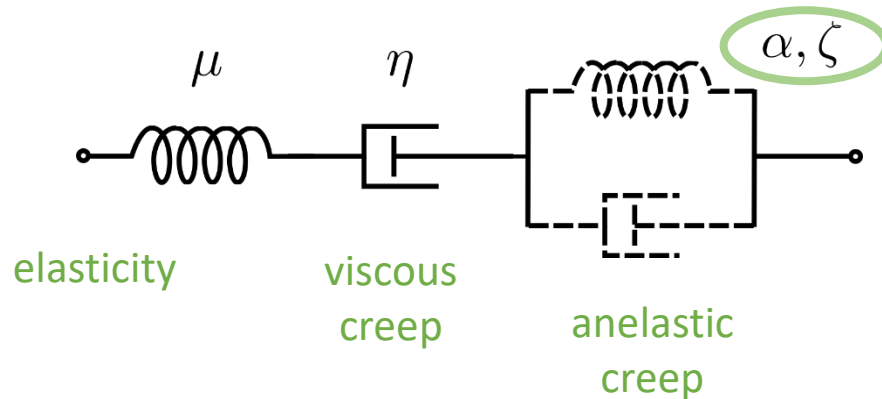
Calculate tidal deformation, MoIF,
and present-day g

Deformation of a layered, compressible, viscoelastic sphere

Model based on the normal mode theory

(Alterman et al., 1959; Takeuchi and Saito, 1972)

Viscoelasticity: Andrade rheological model



Dumoulin et al. (2017):

viscoelasticity increases planet's deformability, compared to an elastic model (*e.g.*, Yoder, 1995)

→ a fully solid core of Venus cannot be ruled out

Cascioli et al. (2023):

compressibility is important especially for deformation under surface loading, up to 23% difference in Love numbers w.r.t. incompressible models

Input: profiles of ρ, μ, k + viscosity, Andrade parameters

Output: Love numbers, tidal quality factor Q

MoIF and g calculated from the density structure

The model: prior parameter ranges

$\log \eta_{\text{ref}}$ [log Pa s]	18 – 23
E^* [kJ/mol]	150 – 550
V^* [cm ³ /mol]	0 – 10
enrichment factor	5 – 30
$D_{\text{cr},0}$ [km]	0 – 50
$\Delta T_{\text{cmb},0}$ [K]	0 – 700
$T_{\text{m},0}$ [K]	1600 – 1900
R_{c} [km]	2500 – 4500
ρ_{c} [kg/m ³]	6000 – 20,000
α	0.1 – 0.4
$\log \zeta$	(−2) – (2)
$\log \eta_{\text{ic}}$ [log Pa s]	11 – 22
$c_{\text{S},0}$ [wt.%]	4 – 16

Monte Carlo Markov Chain

Python library “emcee” (*Foreman-Mackey et al., 2013; based on Goodman and Weare, 2010*)

- ensemble of “walkers” exploring the parameter space

Convergence measured by autocorrelation time

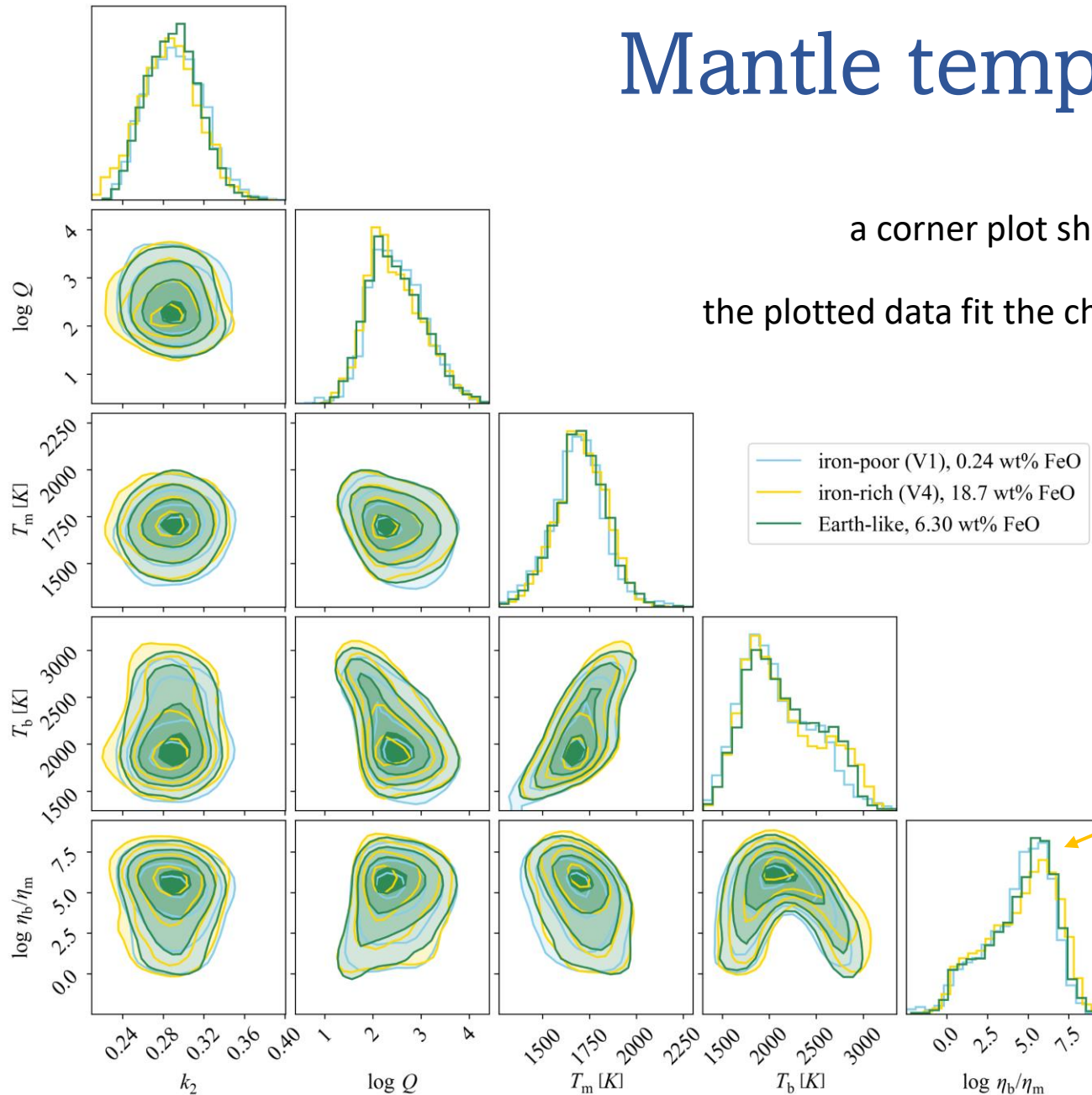
- first 2000 steps of each walker are discarded to minimise the effect of the chosen initialisation

Results: approximation of the probability density function over the parameter space

In addition to the explored quantities, we also output **average viscosity, inner core size, temperatures, and additional tidal parameters**

Mantle temperature

a corner plot show 1d and 2d posterior marginal probability distributions
the plotted data fit the chosen set of observables but are not necessarily “correct”



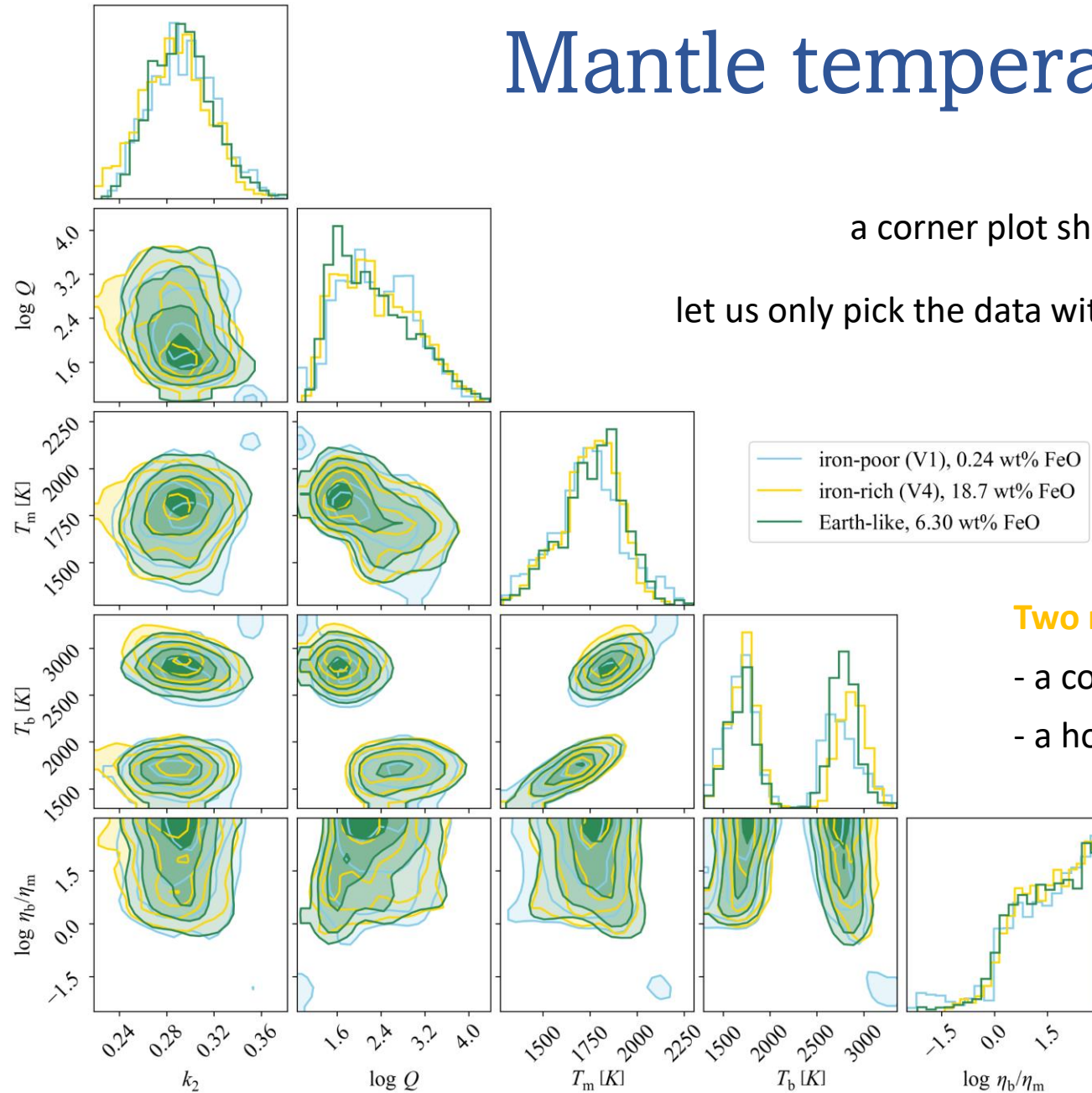
“in 3d models, such an increase results in decoupled lower mantle; no longer adiabatic” (- Ina Plesa)

Most of the models
show a large viscosity increase
with depth

“such an increase would produce negative correlation at low degrees of the gravity/topography spectra; we do not see that” (- Julia Maia)

Also: Pauer et al. (2006) – increase by the factor of 40
Steinberger et al. (2010) – relative increase by <400

Mantle temperature, postprocessed (1)



a corner plot show 1d and 2d posterior marginal probability distributions

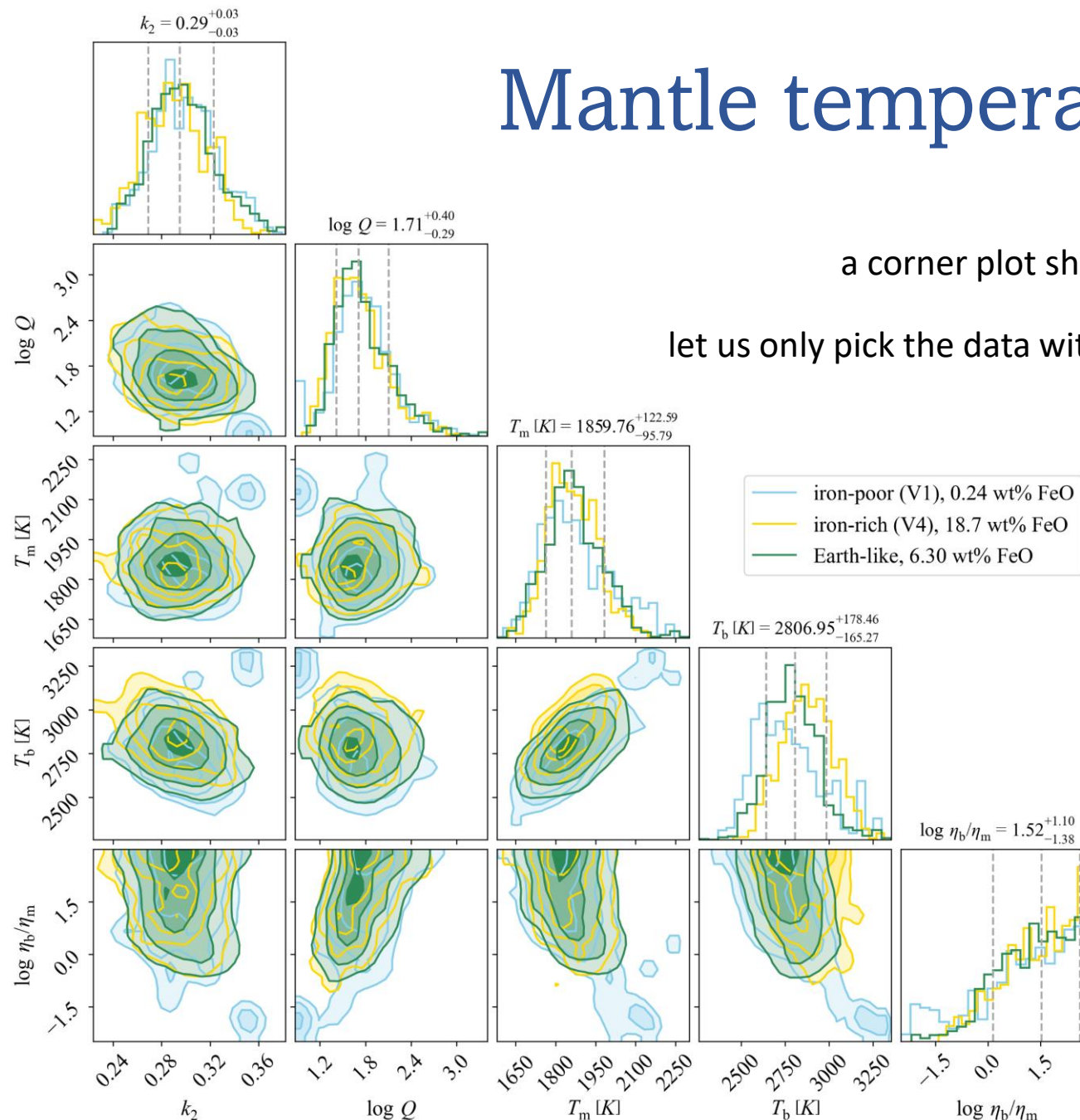
let us only pick the data with **maximum viscosity increase by 3 orders of magnitude**

Two modes:

- a cold, perhaps geologically dead Venus with Mars-like T_b
- a hot, more Earth-like Venus, consistent with previous works

temperature strongly linked to tidal dissipation, Q^{-1}

Mantle temperature, postprocessed (2)



a corner plot show 1d and 2d posterior marginal probability distributions

let us only pick the data with **maximum viscosity increase by 3 orders of magnitude** and “Earth-like” temperature profile

Predicted tidal quality factor: $Q = 51^{+76}_{-25}$

solid Earth: $Q \approx 280$

Mars: $78 < Q < 105$

Moon: $Q \approx 40$

Earlier studies evaluating Venus’s rotation:

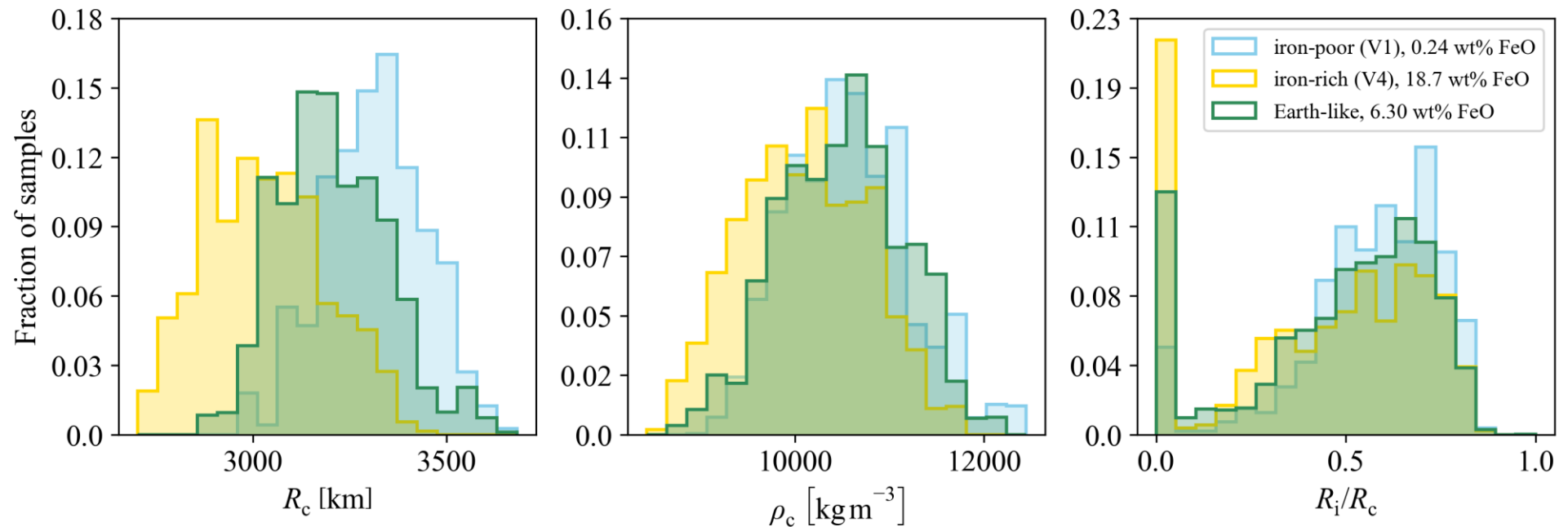
Dobrovolskis and Ingersoll (1980): $Q \approx 28$

Shen and Zhang (1990): $Q \approx 36$

Correia and Laskar (2003): $Q > 45$, not much more

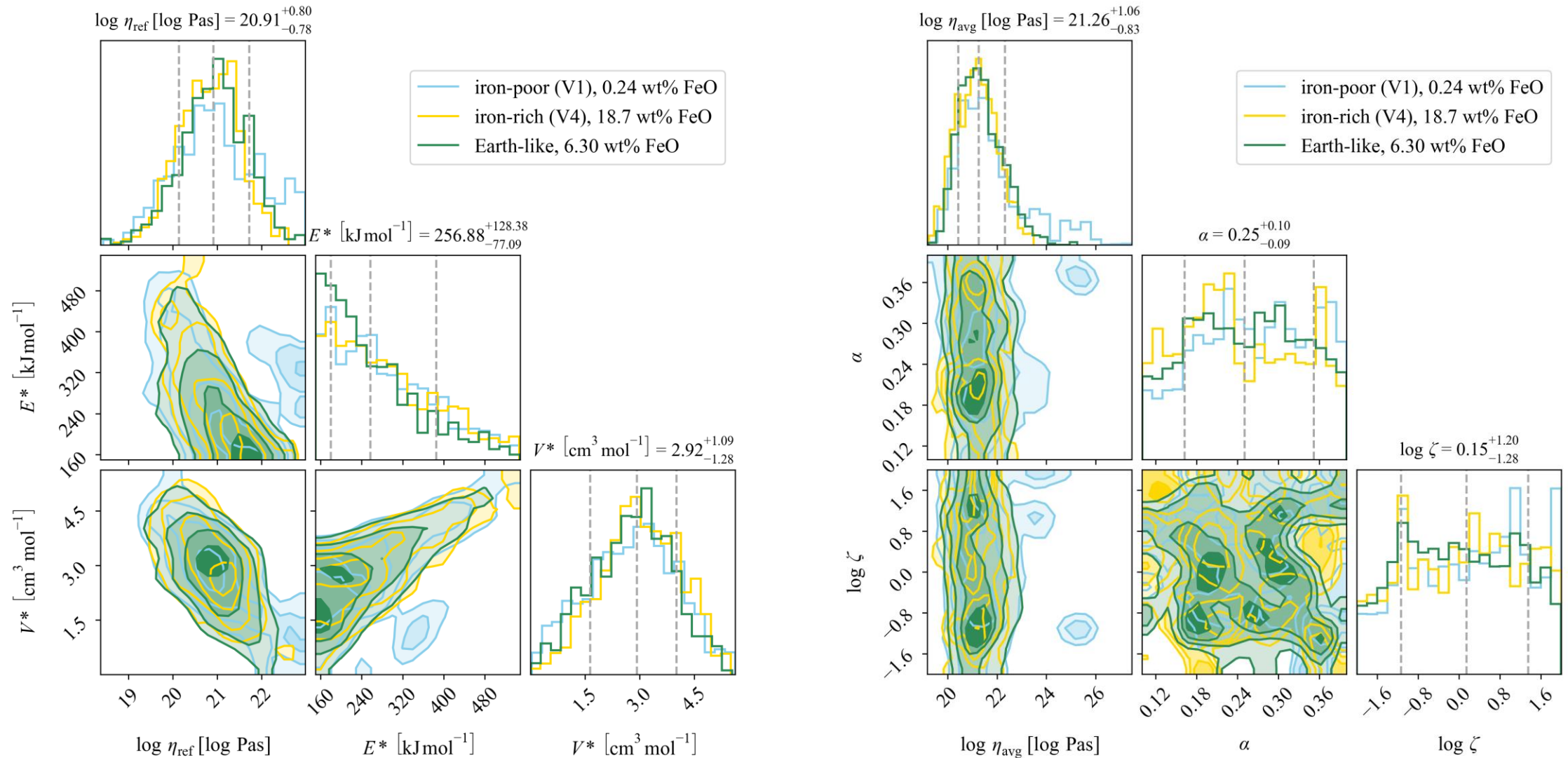
Core size and core density

(Only the postprocessed data are shown)



Core size and core state are **composition-dependent**; most samples have inner core (especially the “V1” cases)

Rheological parameters and viscosity profile



The model: prior parameter ranges

$\log \eta_{\text{ref}}$ [log Pa s]	18 – 23	
E^* [kJ/mol]	150 – 550	← Preferentially on the lower edge of the interval
V^* [cm ³ /mol]	0 – 10	
enrichment factor	5 – 30	← Unconstrained
$D_{\text{cr},0}$ [km]	0 – 50	←
$\Delta T_{\text{cmb},0}$ [K]	0 – 700	← Preferentially on the lower edge of the interval
$T_{\text{m},0}$ [K]	1600 – 1900	←
R_{c} [km]	2500 – 4500	
ρ_{c} [kg/m ³]	6000 – 20,000	
α	0.1 – 0.4	← Unconstrained
$\log \zeta$	(–2) – (2)	←
$\log \eta_{\text{ic}}$ [log Pa s]	11 – 22	← Unconstrained
$c_{\text{S},0}$ [wt.%]	4 – 16	←

Foreseen observables in 2030's

Petricca et al. (2022)

Thermal tides: atmospheric pressure follows the insolation cycle and periodically loads the surface (period = 1 Cytherean day)

Changes in gravitational potential caused by the imposed surface load characterised by **potential load Love numbers: k'_l**

Love numbers k'_2 to k'_5 might be measurable
Tidal **deformational Love number h_2** too

Additionally, the first direct estimation of **tidal dissipation (Q^{-1})** in Venus is expected (or hoped for)

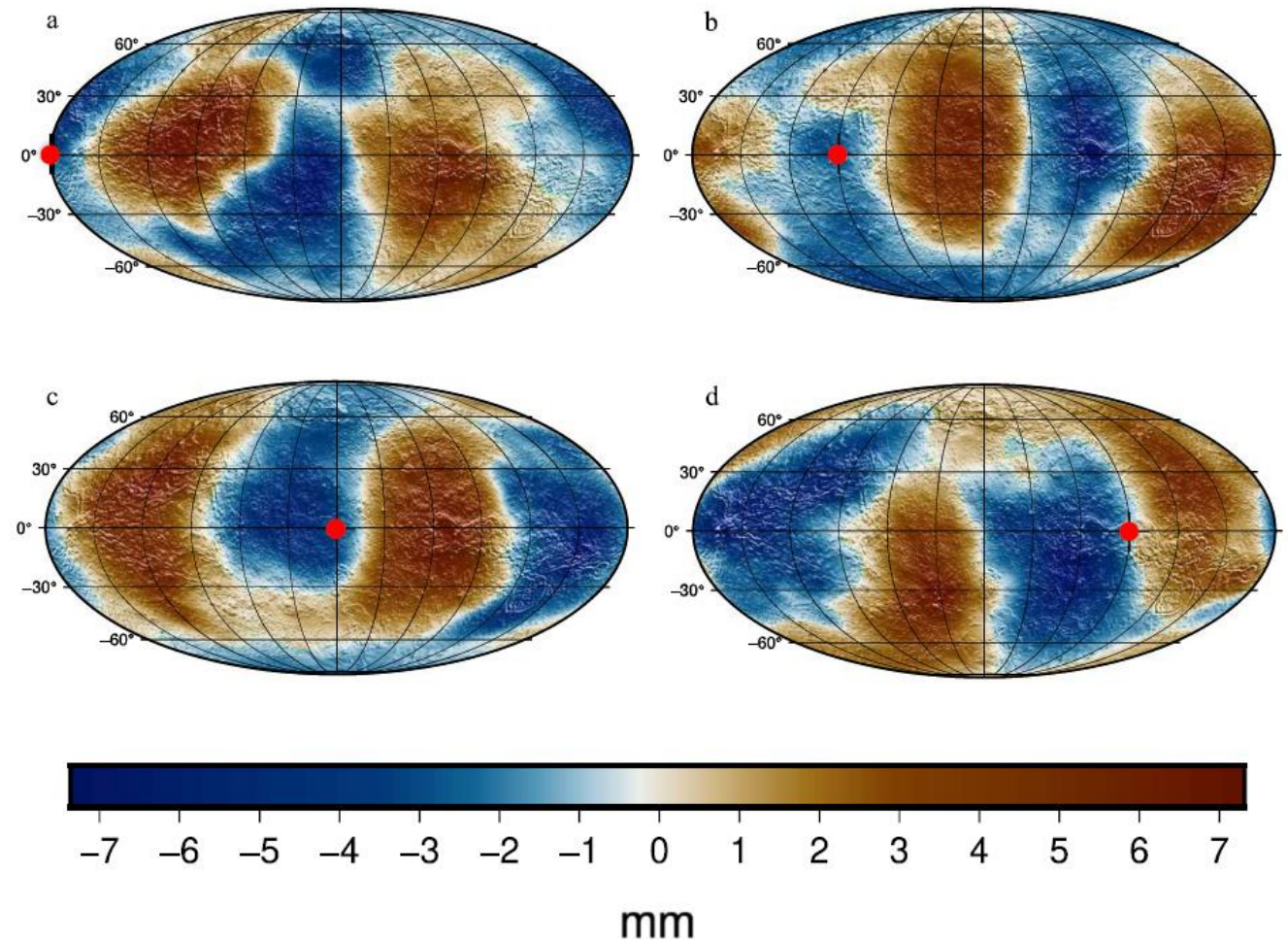


Figure 2. Temporal variations of the Venus geoid induced by the atmosphere over shaded topographic relief at four different times. The maps are centered at 180° longitude. The subsolar point (red dot) is located at longitude (a) 0°, (b) 90°, (c) 180°, and (d) 270°. The visible sectorial pattern is produced by the thermal tides and rotates in phase with the subsolar point.

Tidal Love numbers and load Love numbers

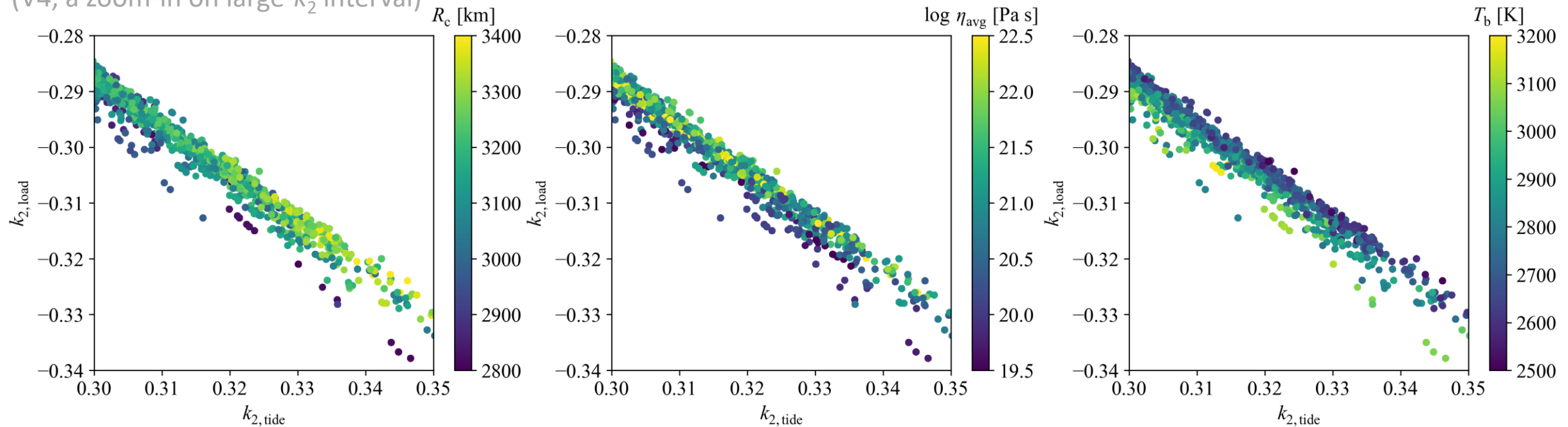
Love numbers parameterise the global deformation of a loaded planet

They depend on the interior structure, rheology, and frequency

Tidal loading has a **semi-diurnal frequency**, atmospheric loading a **diurnal frequency**

→ more frequencies, more information (*see also Petricca et al., 2022; Cascioli et al., 2023*)

(V4, a zoom-in on large- k_2 interval)

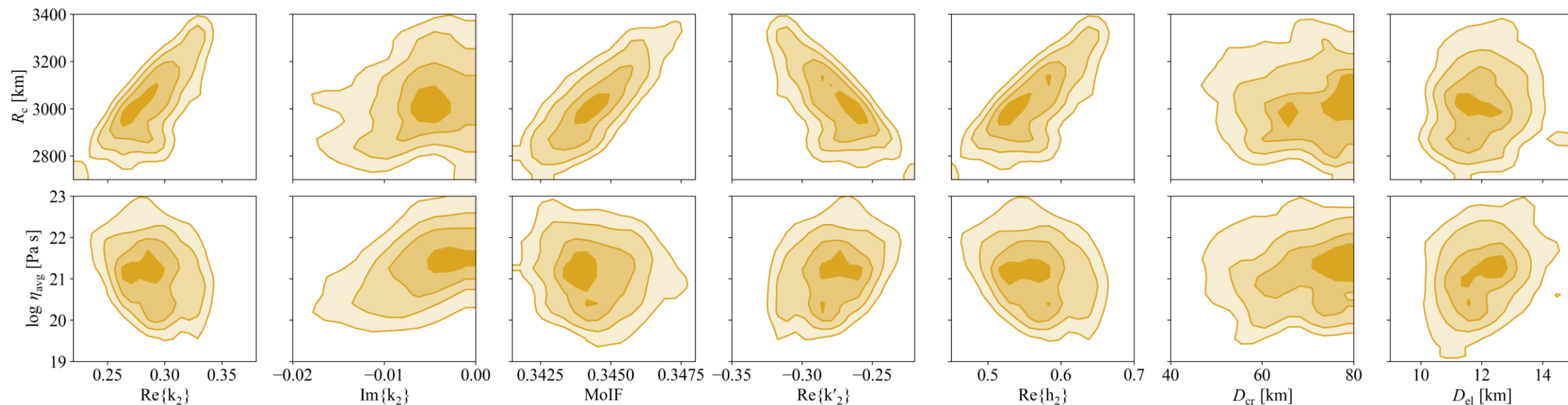


Observables vs. our samples (V4)

Real parts of Love numbers (+MoIF) inform us about the core size

Imaginary part of Love number informs us about the viscosity structure

Additionally, it is sensitive to the Andrade parameters α and ζ

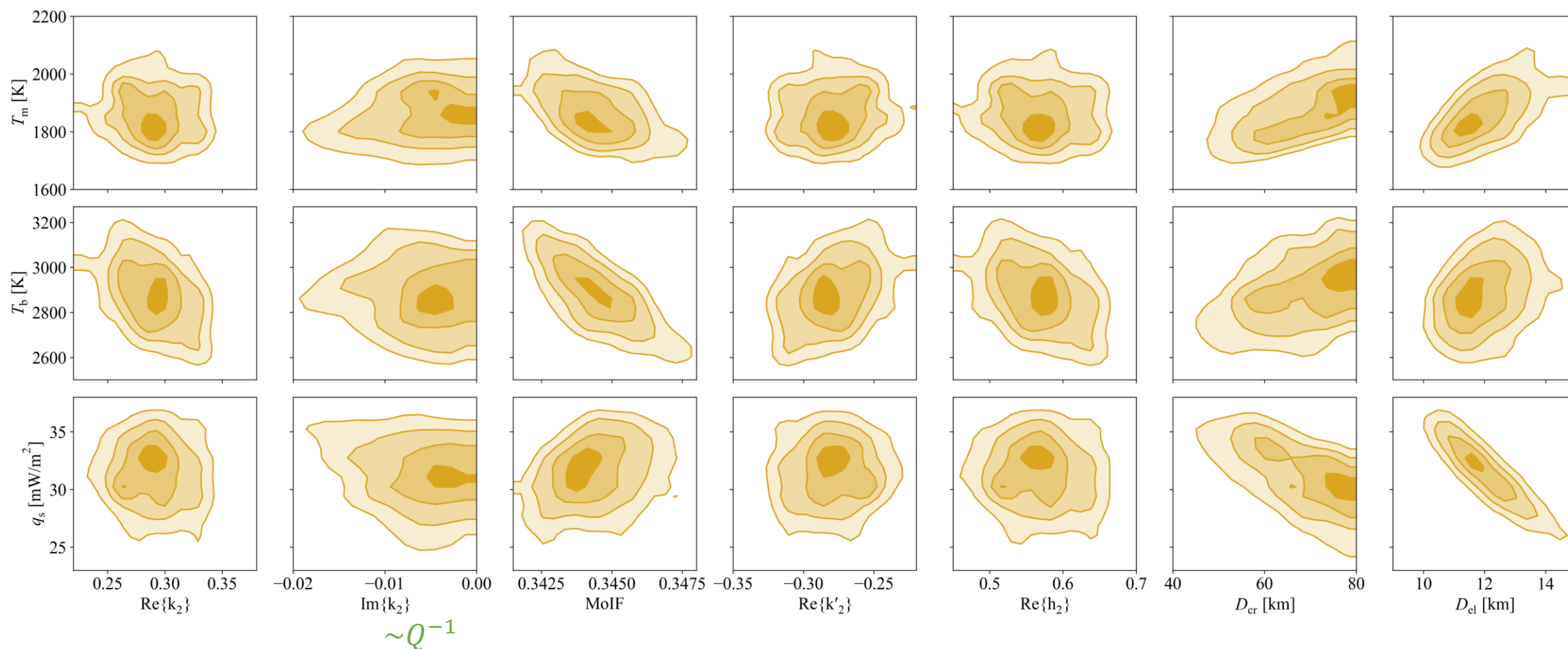


$\sim Q^{-1}$

D_{cr} typically large, D_{el} small in our models
(well below the imposed upper limit of 20 km)

Observables vs. our samples (V4)

Elastic thickness (and crustal thickness) sensitive to surface heat flux; MoIF also probes the lower-mantle temperature



Foreseen observables in 2030's: uncertainties

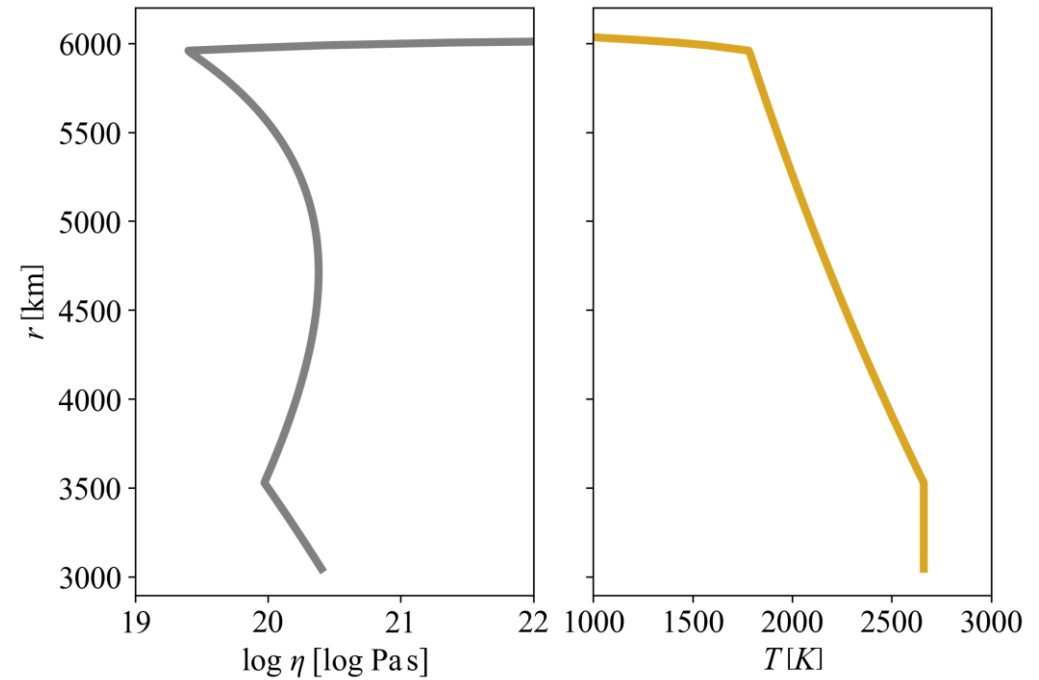
Present-day standard deviations of the k_2 and MoIF measurements are of the order 10^{-2}

	VERITAS (Cascioli et al., 2023)	EnVision (Rosenblatt et al., 2021)
$Re\ k_2$	1.2×10^{-4}	1×10^{-3}
$Im\ k_2$	1.2×10^{-4}	1×10^{-3}
MoIF	5×10^{-4}	5×10^{-3}
k'_2	5×10^{-3}	?
k'_3	4×10^{-2}	?
k'_4	1.3×10^{-2}	?
k'_5	4×10^{-2}	?
h_2	5×10^{-2}	?

How will these data improve our understanding of Venus's interior structure?

Venus (V4) in a parallel world

η_{ref} [Pa s]	2×10^{20}
E^* [kJ/mol]	286
V^* [cm ³ /mol]	2.23
enrichment factor	27
$D_{\text{cr},0}$ [km]	46
$\Delta T_{\text{cmb},0}$ [K]	3
$T_{\text{m},0}$ [K]	1645
R_c [km]	3045
ρ_c [kg/m ³]	9885
α	0.32
$\log \zeta$	99
η_{ic} [Pa s]	6×10^{17}
$c_{\text{S},0}$ [wt.%]	12



How well can we constrain the interior structure of this synthetic model, using the VERITAS-like uncertainties?

Venus in a parallel world: core size

(preliminary results after 1 week, about 200,000 samples, no filtering)

Present-day data, V4:

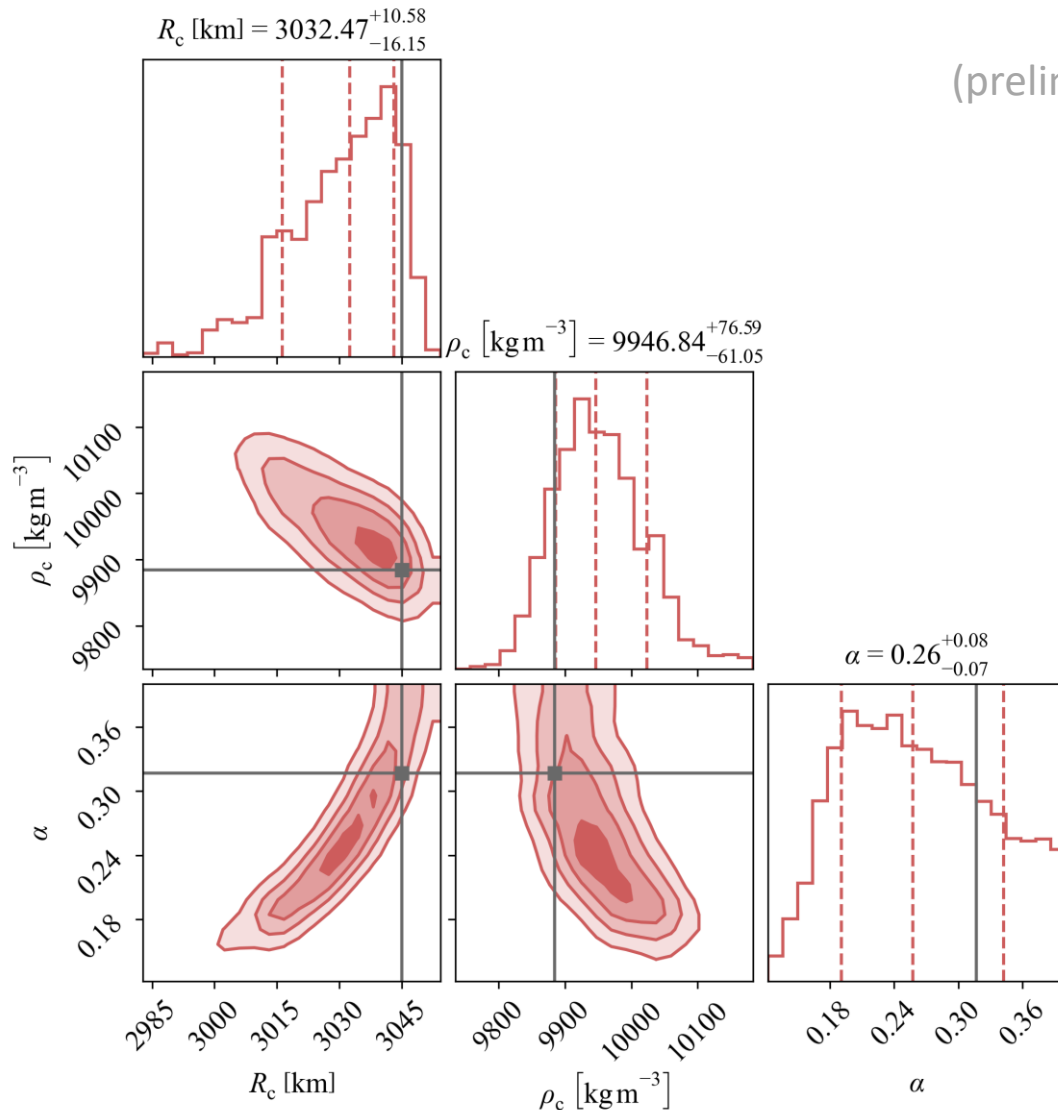
$$R_c = 3014_{-151}^{+165} \text{ km}$$

$$\rho_c = 10,153_{-722}^{+673} \text{ kg/m}^3$$

Estimates of Andrade parameters α , ζ improved only negligibly.

However, **the combination of core size/density and α** might be relatively well constrained.

Predictions for the inner core size did not improve
(ground truth among many possible solutions).



Venus in a parallel world: temperature and viscosity

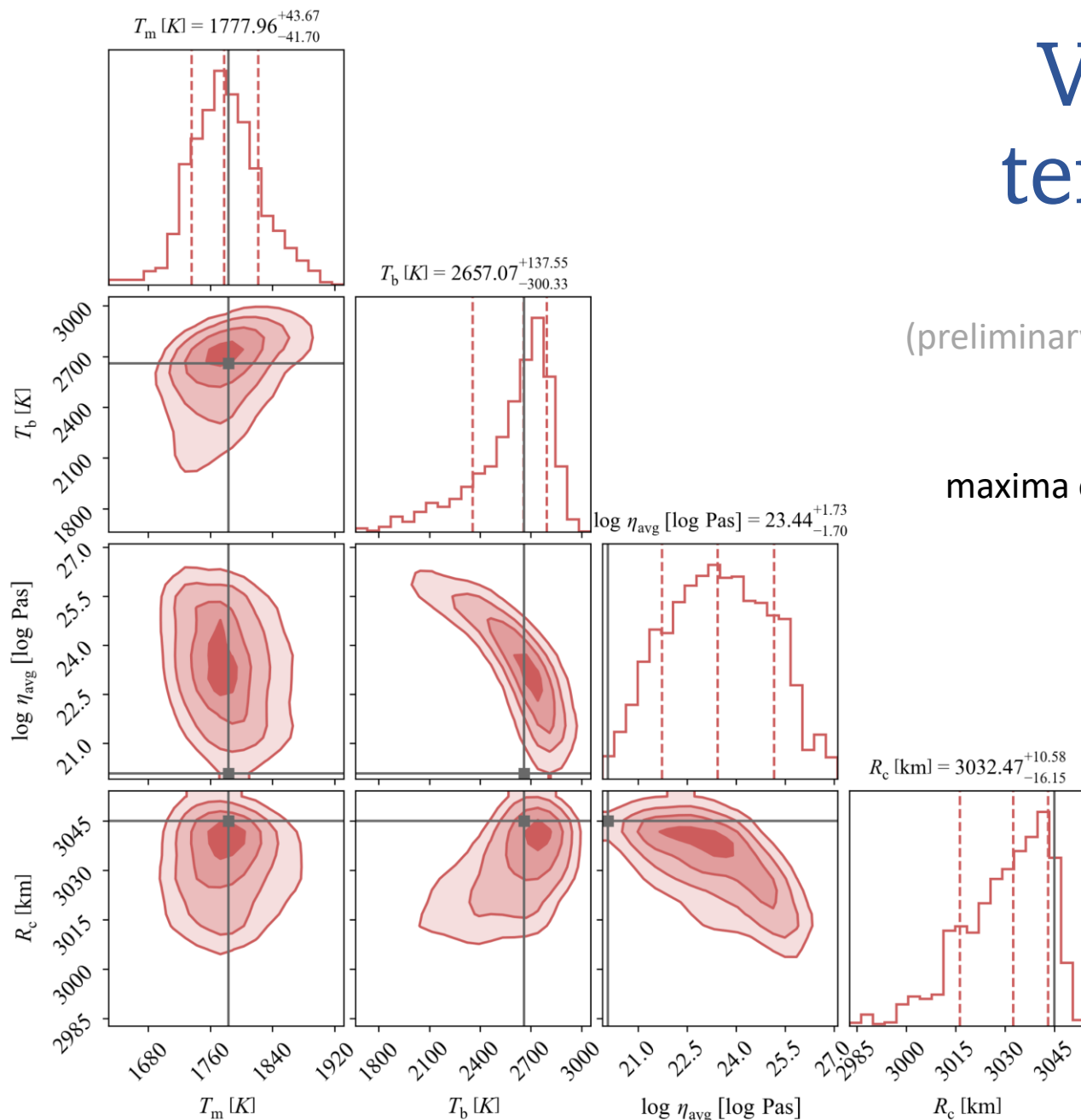
(preliminary results after 1 week, about 200,000 samples, no filtering)

maxima of the posterior distributions close to the true temperature profile

average viscosity not fitted well (not even after filtering)

reference viscosity fitted well but precision only slightly improved

almost no improvement for V^* and E^*



Conclusions

With present-day moment of inertia factor (MoIF) and k_2 , the interior structure of Venus cannot be well constrained

Core size: $R_c = 3171^{+174}_{-184} \text{ km}$

- depends on the assumed mantle composition: smaller for iron-rich mantle, bigger for iron-poor mantle
- will be improved by future measurements of MoIF, optimistic uncertainty of +/- 15 km

Average mantle viscosity: $\log \eta_{\text{avg}} = 21.26^{+1.06}_{-0.83} \log(\text{Pa s})$

Predicted tidal quality factor: $Q = 51^{+76}_{-25}$

consistent with measurements for other terrestrial planets

Future plans: combination with gravity/topography data (for viscosity profile)
improved model of the inner core growth



Thank you!