Mars Interior:
Part 1: Structure and Activity
Part 2: Geodesy and Rotation

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With the help of **Doris Breuer** (**blue** background with lines), **Sandra Schumacher** (**blue** background with lines&curves) and **Frank Sohl** (partially those with **black** background)

Content of my talk
Mars Interior: Part 1: Structure and Activity

1. Global constraints and structure
2. Interior structure and composition
3. Magnetism Mechanisms for magnetic field generation in the core
   - Thermal convection
   - Compositional convection
4. Thermal evolution; heat sources; heat transport mechanism; convection

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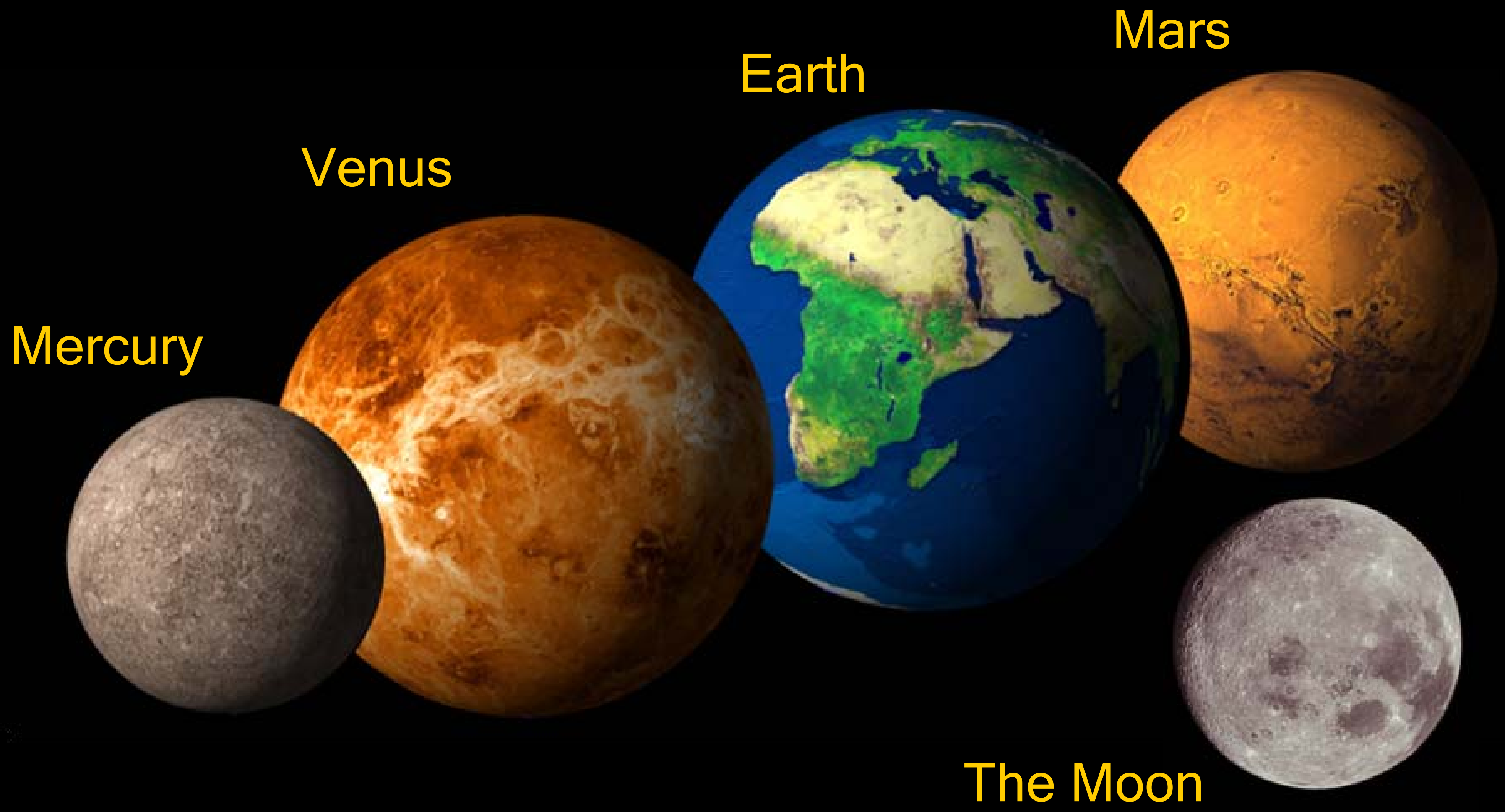
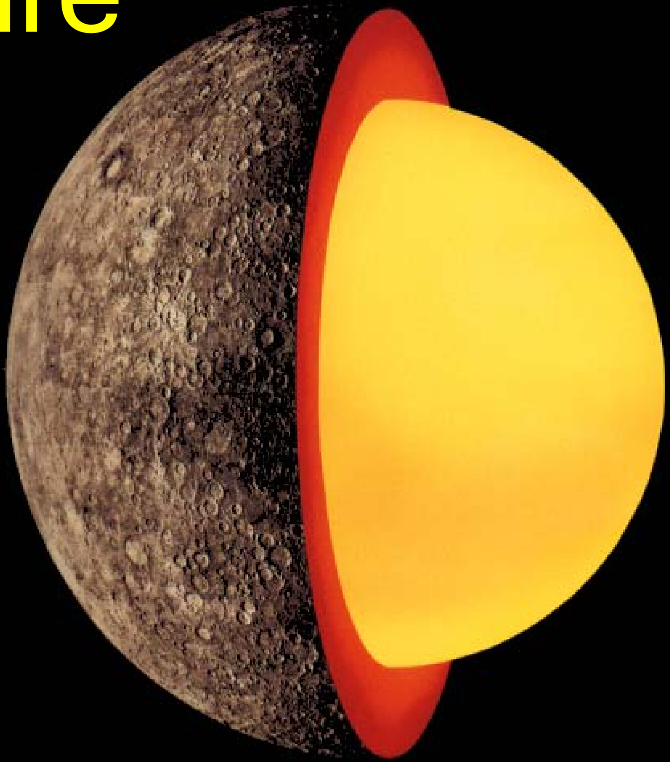
Next-door neighbours



Planetary Data

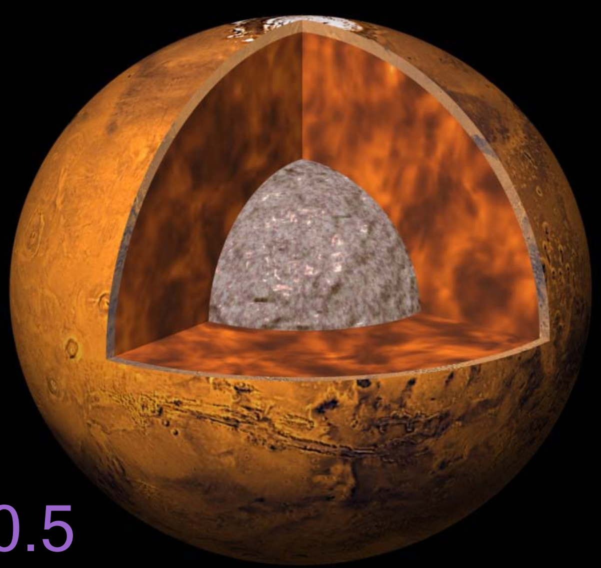
	Mercury	*Venus*	*Earth*	*Mars*	*Moon*
Radius	0.38	0.95	1.0	0.54	0.27
Mass	0.055	0.815	1.0	0.107	0.012
Density [kg/m³]	5430.	5250.	5515.	3940.	3340.
uncompressed Density [kg/m³]	5300.	4000.	4100.	3800.	3400.
Moment of Inertia factor	0.34?	?	0.3355	0.3650	0.3934
Core Radius/ Planet Radius	0.8	0.55	0.546	0.5	<0.25
Dipole Moment [10^{13} T m³]	0.316	-	790.	<0.08	$<4\text{x}10^{-9}$

Core & interior structure

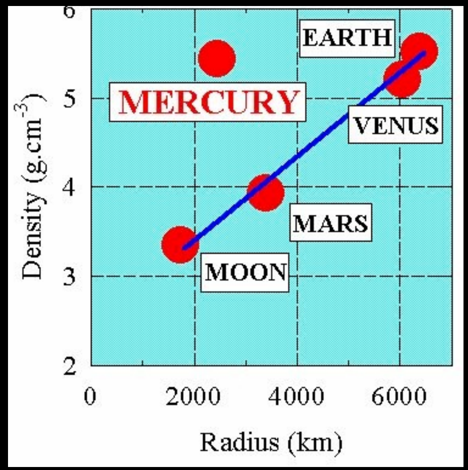


Mercury
R_c/R_p= 0.8

Moon
R_c/R_p= 0.25



Mars
R_c/R_p= 0.5



Mars: astronomical parameters

	Earth	Mars
solar distance	1.0 AU	1.5 AU
day	1.1:1	24.63 h
year	1.9:1	686.9 d
inclination	23.45º	25.19º

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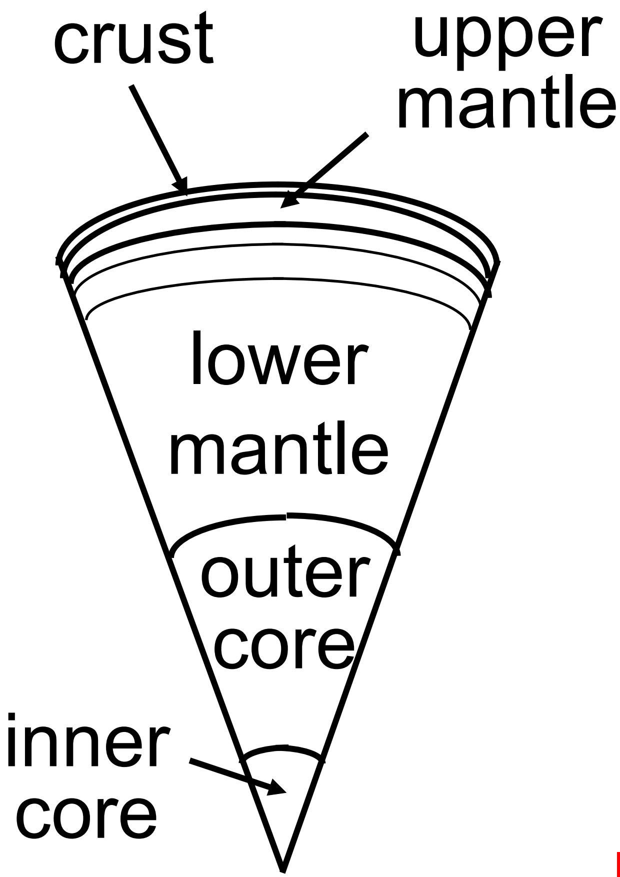
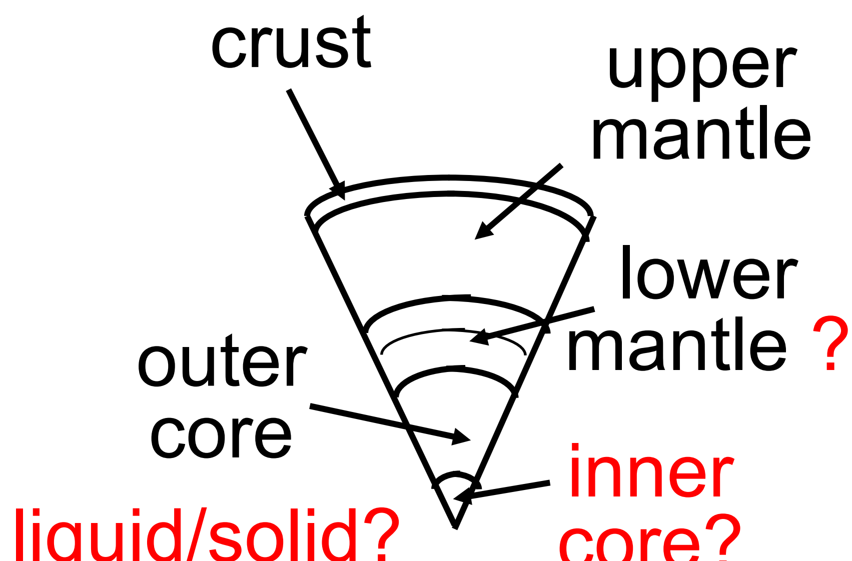
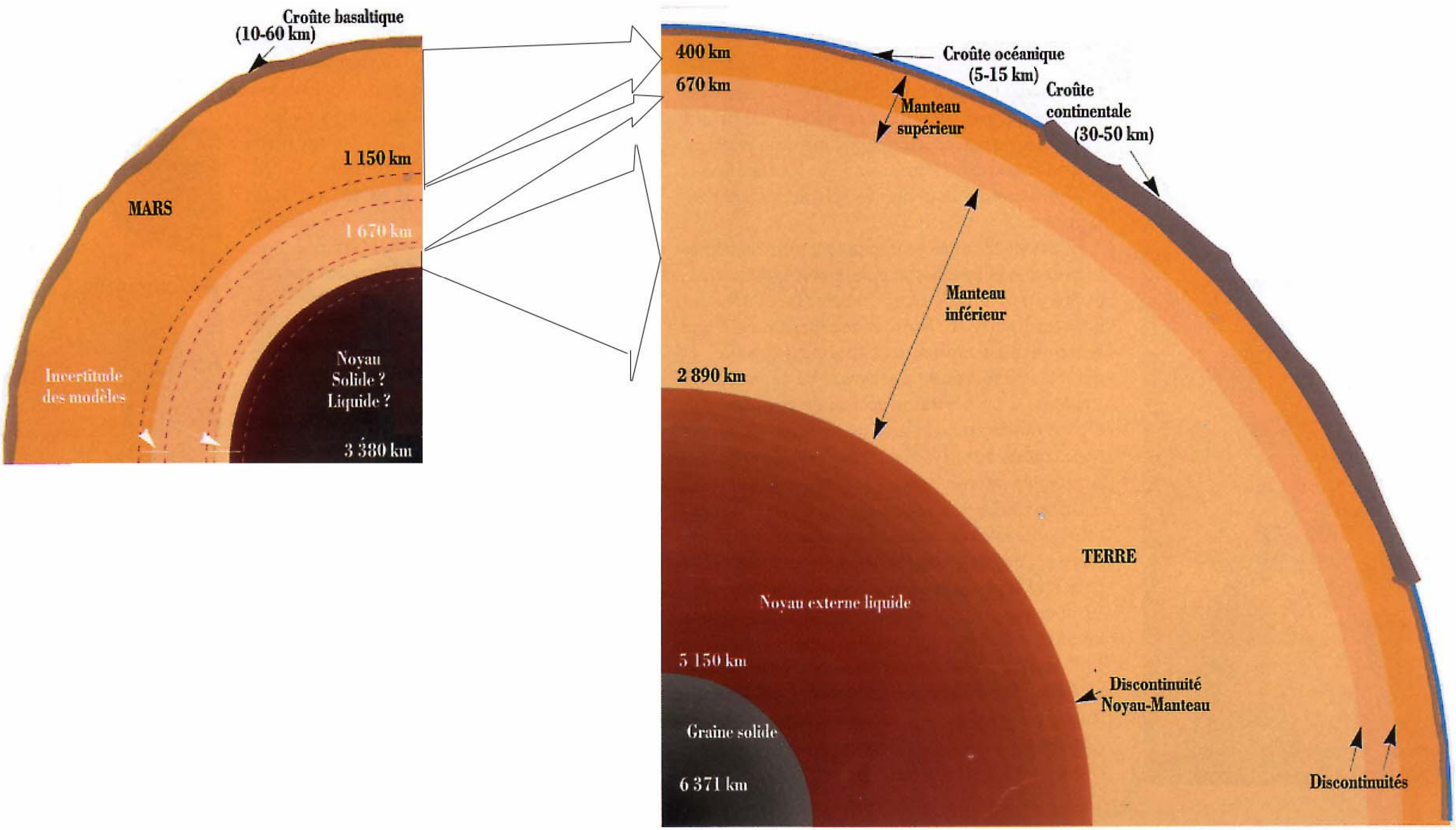
Comparison Earth/Mars



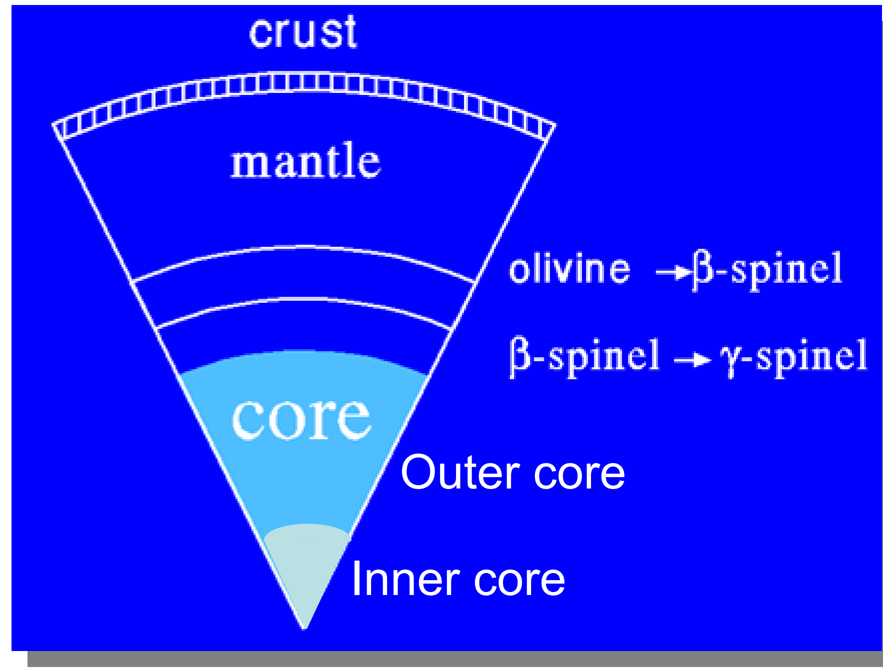



Croûte basaltique
(10-60 km)
MARS
1 150 km
1 670 km
Incertitude
des modèles
Noyau
Solide ?
Liquide ?
3 380 km
400 km
670 km
Croûte océanique
(5-15 km)
Croûte
continentale
(30-50 km)
Manteau
supérieur
Manteau
inférieur
2 890 km
TERRE
Noyau externe liquide
5 150 km
Discontinuité
Noyau-Manteau
Graine solide
6 371 km
Discontinuités

From the web

Interior Structure of terrestrial planets

- Interior Structure models aim at determining
  - the bulk chemistry of the planet (rheology)
  - the masses of major chemical reservoirs
  - the depths of chemical discontinuities and phase transition boundaries
  - the variation with depth of thermo-dynamic state variables pressure, temperature, and density (ρ, P, T)



  - the physical state of the reservoirs core mantle and possible inner core

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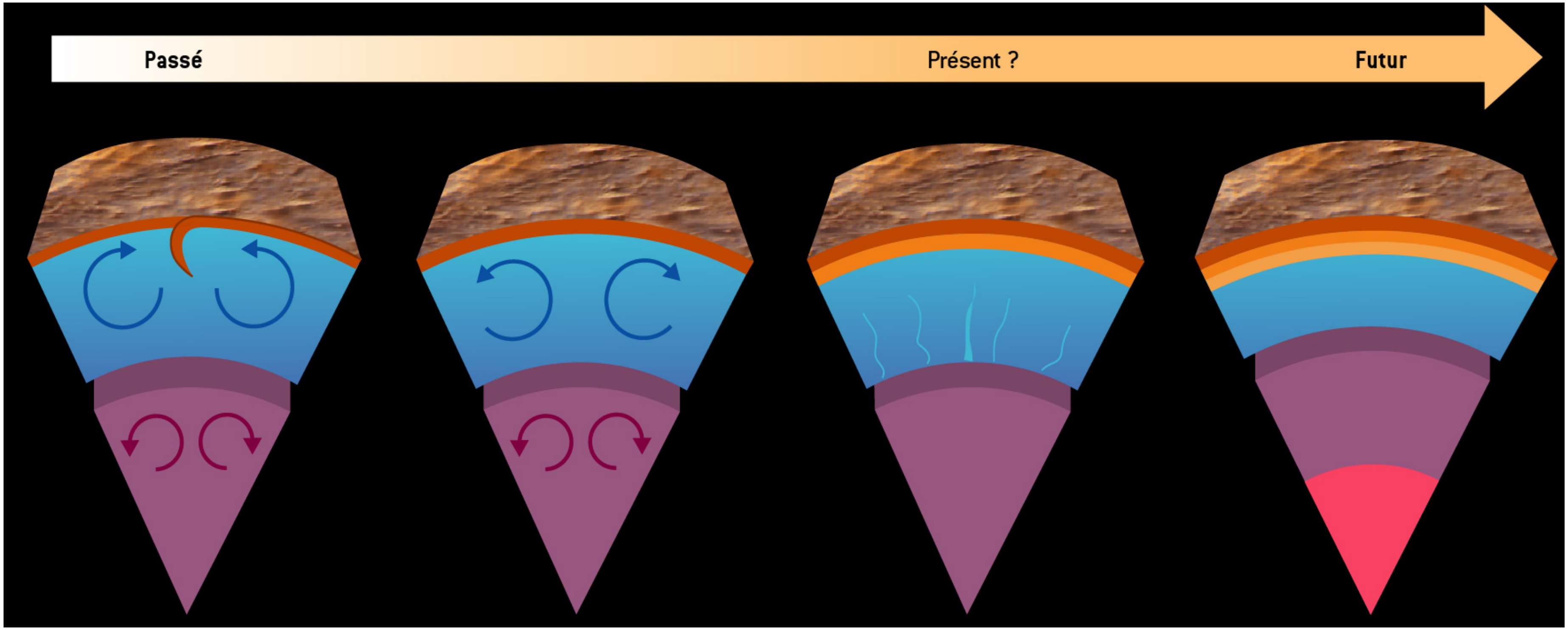
Many open questions!



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Top-level science goals for Interior

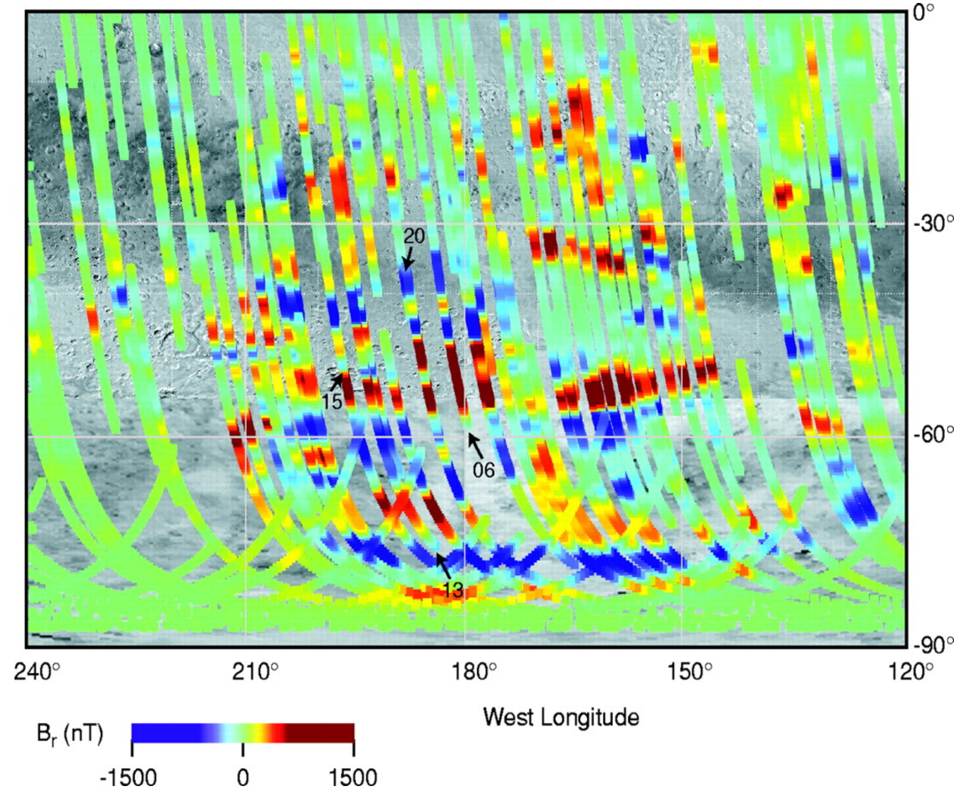
- Determine the radius of the Martian core to within (±50 km)
- Confirm the state of the core: solid, liquid and determine, if the core is liquid, whether there is or not an inner core
- Determine crustal thickness
- Determine mantle seismic velocities
- Determine the locations of major phase transition in the mantle (gives insight to the mineralogy)

Why that?

- ⇨To obtain the core and mantle density and composition
- ⇨Understanding planetary formation
- ⇨Understand planetary evolution
- ⇨Decide on the existence of an inner core
- ⇨Decide on the existence of giant mantle plumes
- ⇨Understanding the likely existence of an early active dynamo and an early magnetic field

What do we know about interior structure?

Constraints
- **Magnetic anomalies** (either present day magnetic field or remanent magnetic field)
- Mass
- Moment of inertia factor
- Gravity field
- Tides
- Surface rock chemistry/ mineralogy
- Topography
- Crustal thickness
- Cosmochemical
- Laboratory data
- Plate tectonics
- Volcanism



- Future:
  - Rotation!
  - Seismology!
  - Heat flow !
  - Conductivity!

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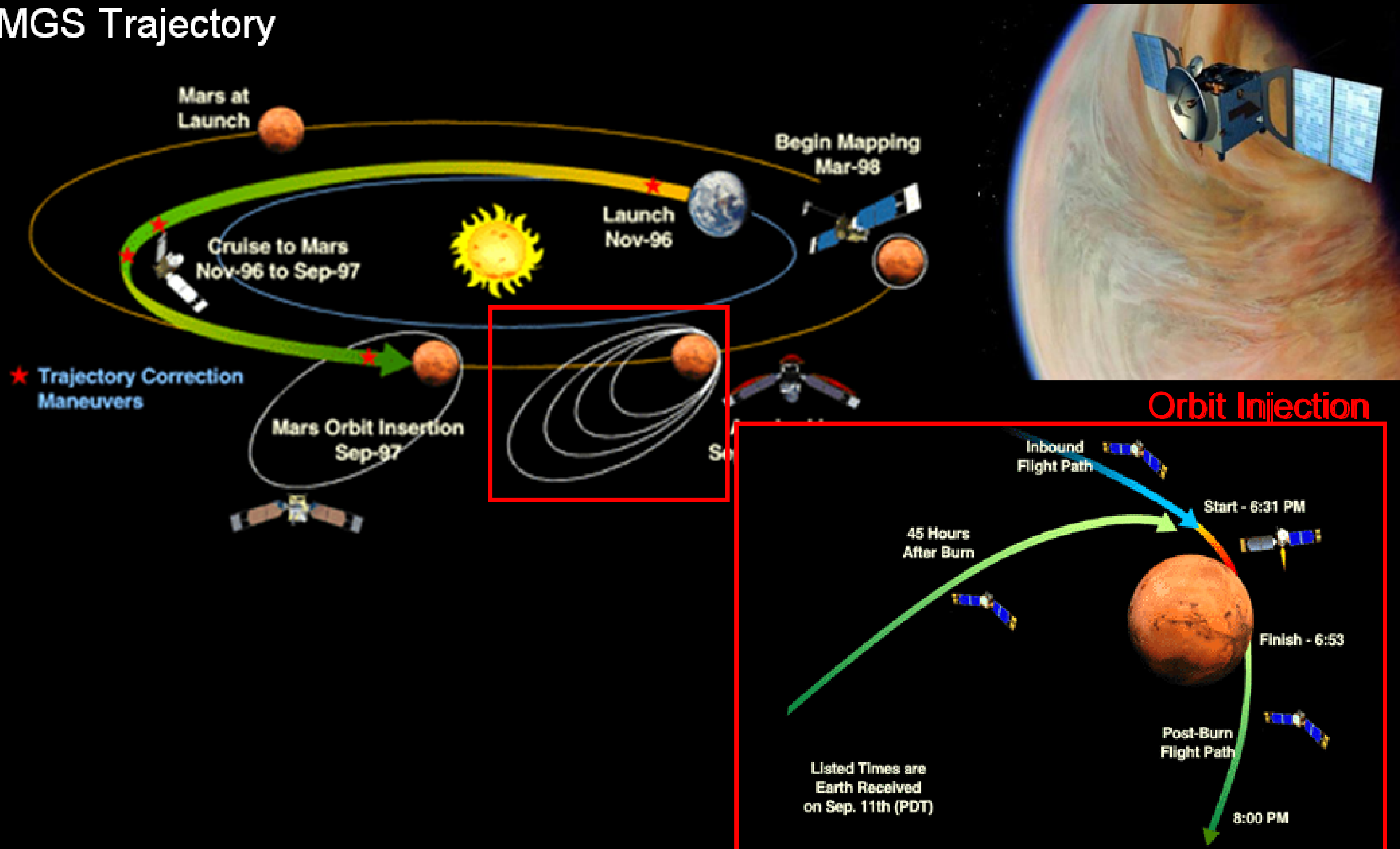
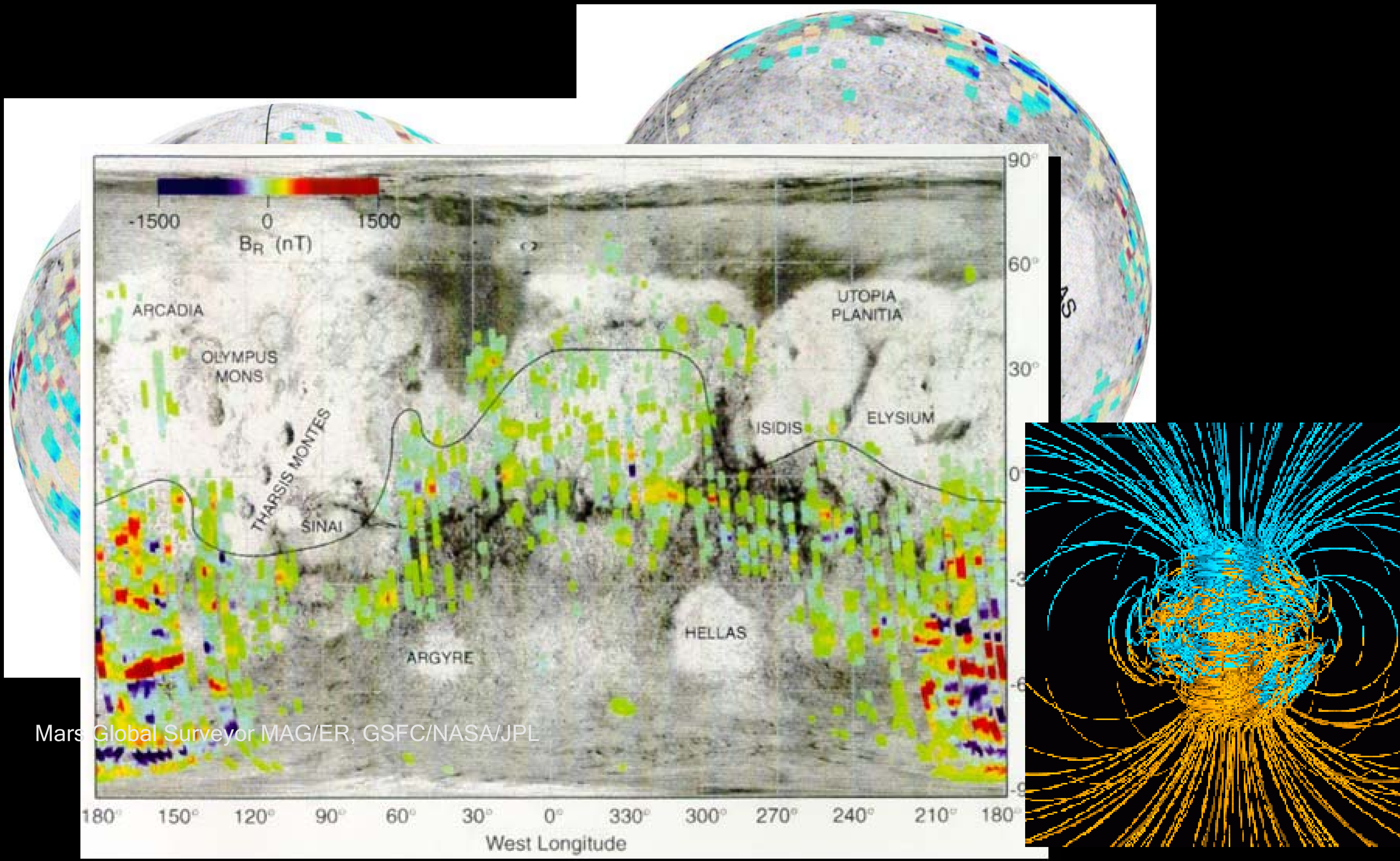
MGS Trajectory



Remnant crust magnetization



Mars Global Surveyor MAG/ER, GSFC/NASA/JPL

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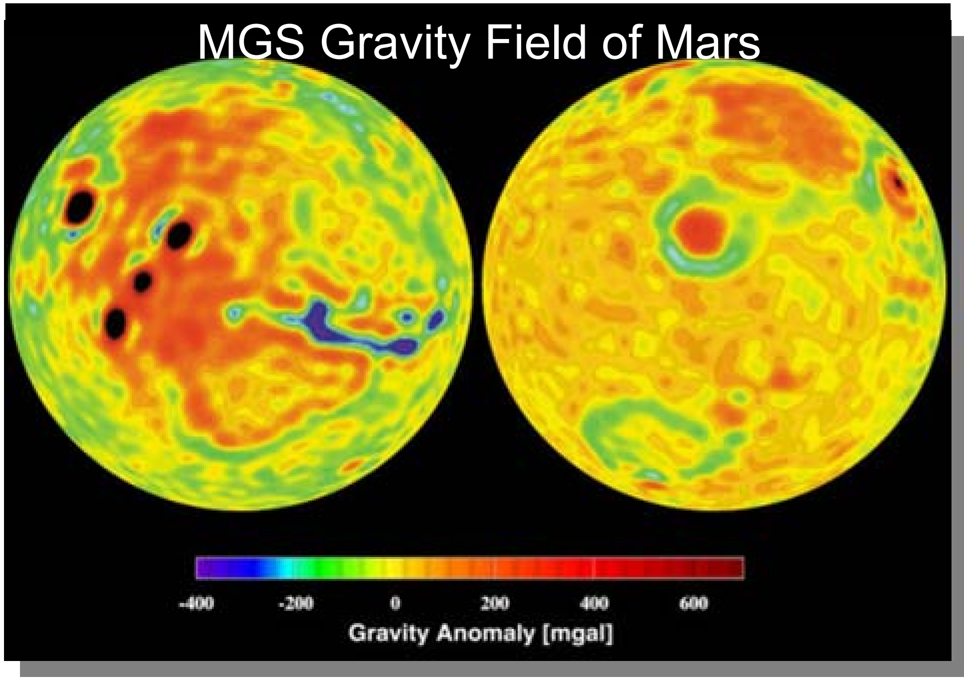

- Future:
  - Rotation! **GEODESY**
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Mean density constraint

- Mean (uncompressed) density is related to the bulk chemical composition of a planetary body.

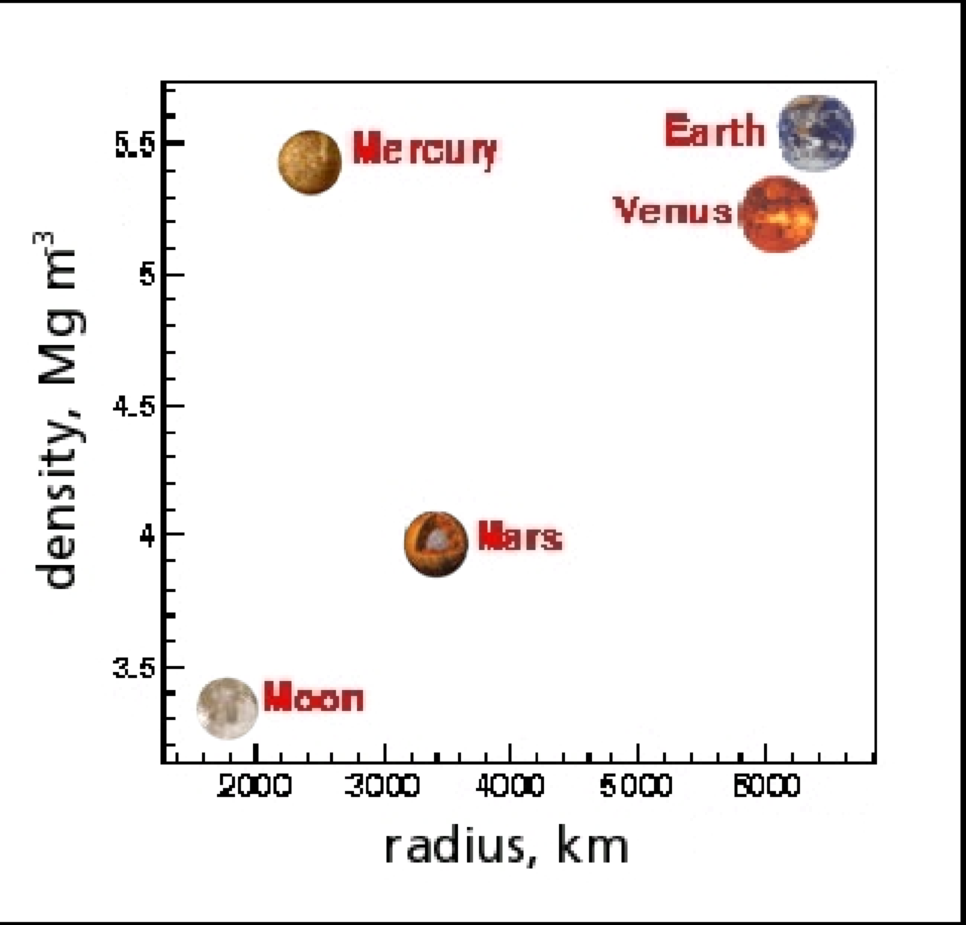
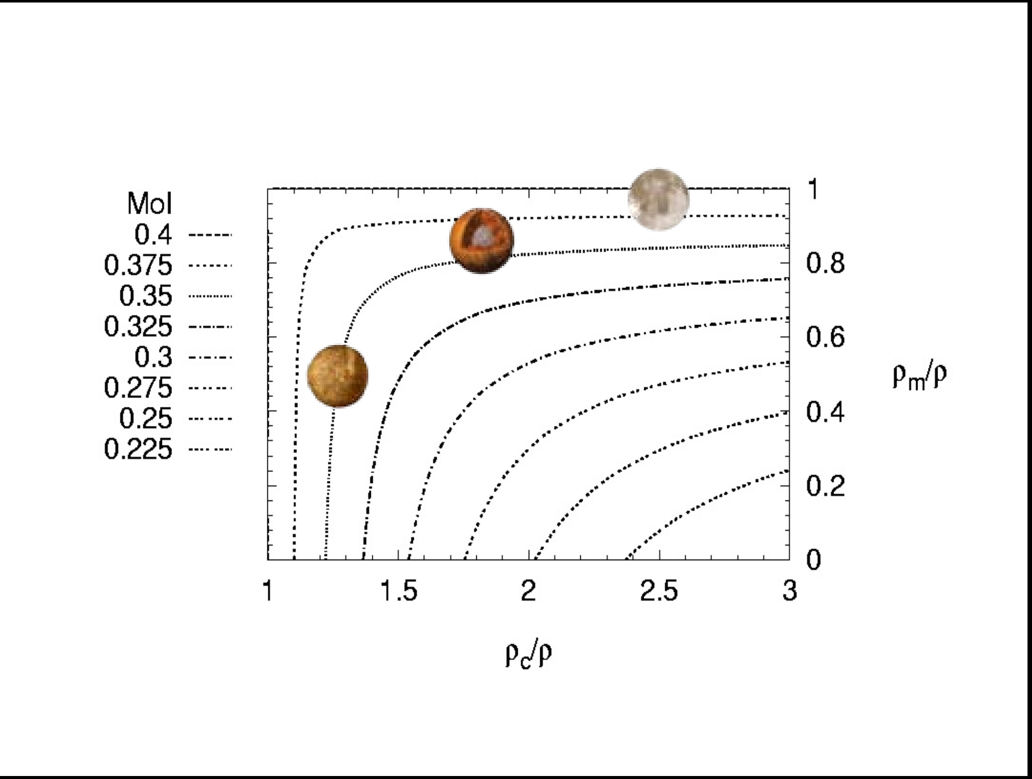


Illustration credit: R. Schulz, ESA.

Moment-of-Inertia factor (MoI) constraint

- MoI factor constrains
  - mantle density if similar to bulk density ($\rho_m/\rho \sim 1$ e.g., The Moon).
  - core density if similar to bulk density ($\rho_c/\rho \sim 1$ e.g., Mercury).



- The mean mantle density of Mars is relatively well determined by the planet's MoI factor.

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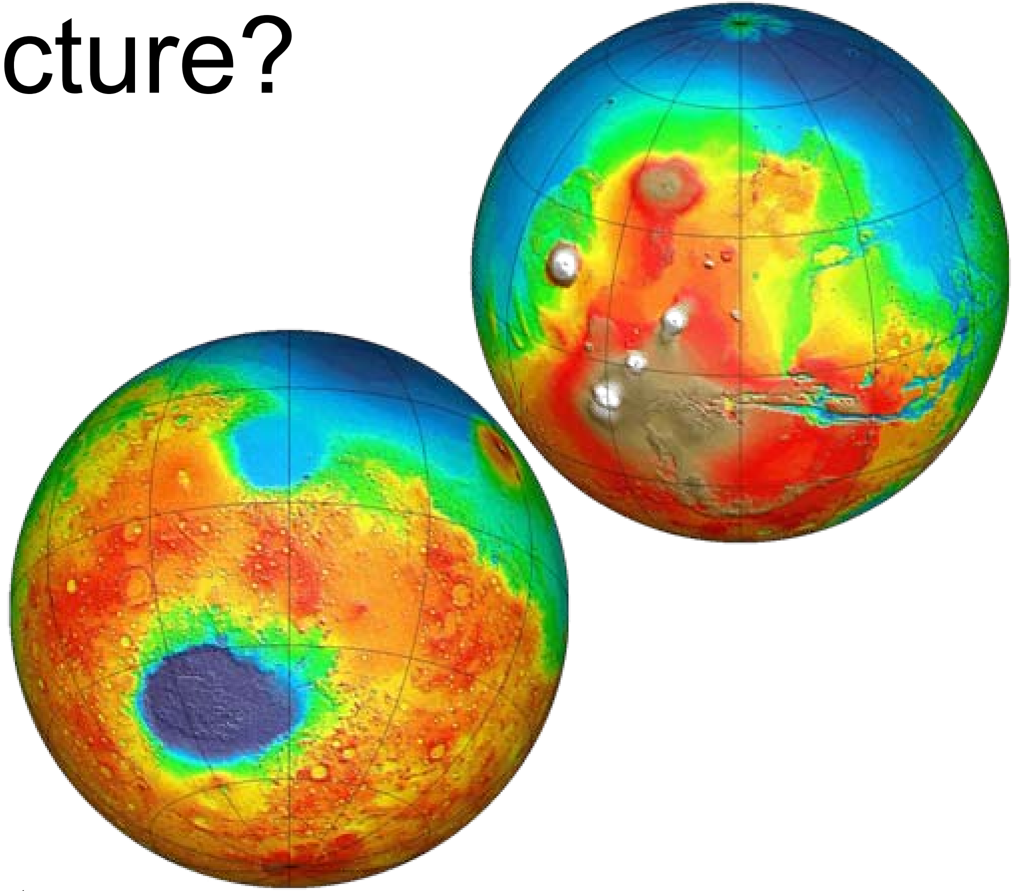

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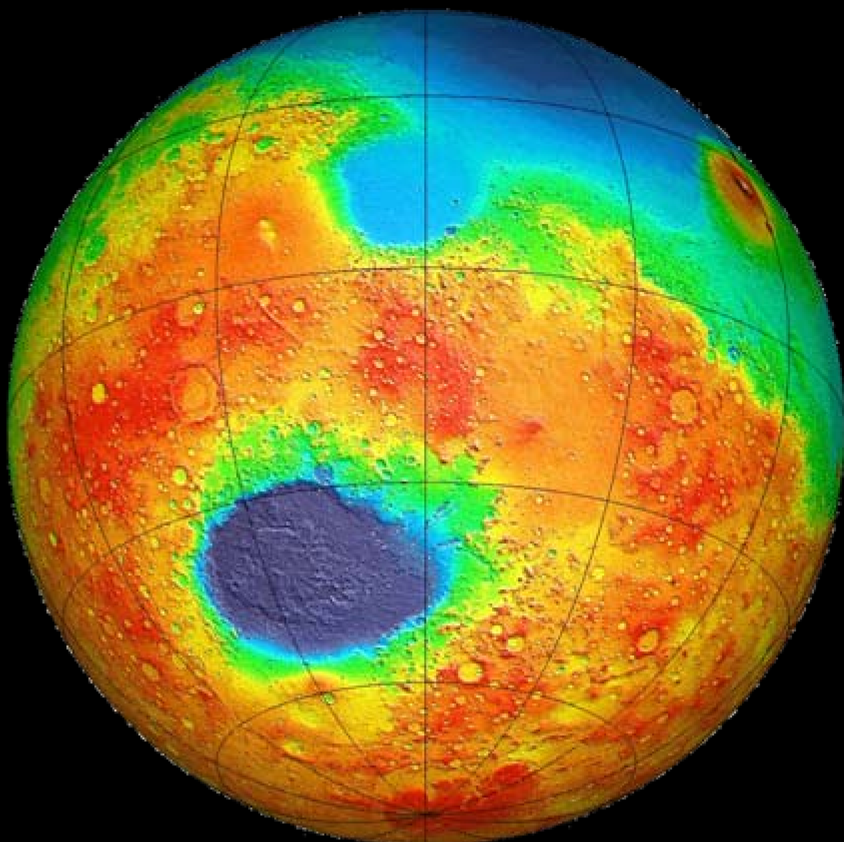
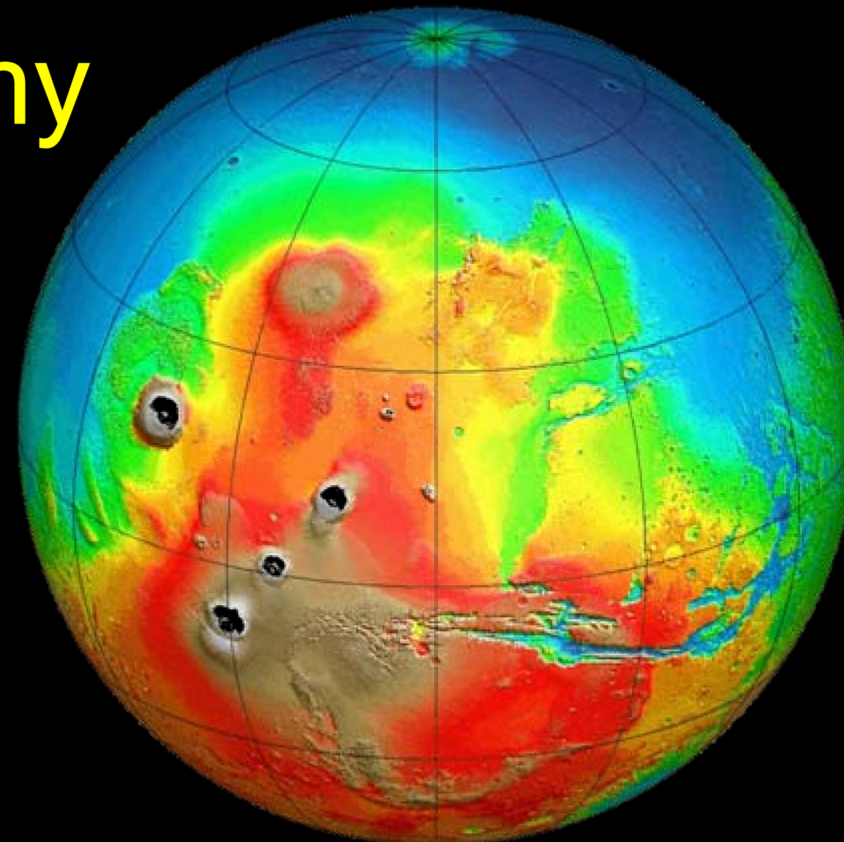
MOLA Topography



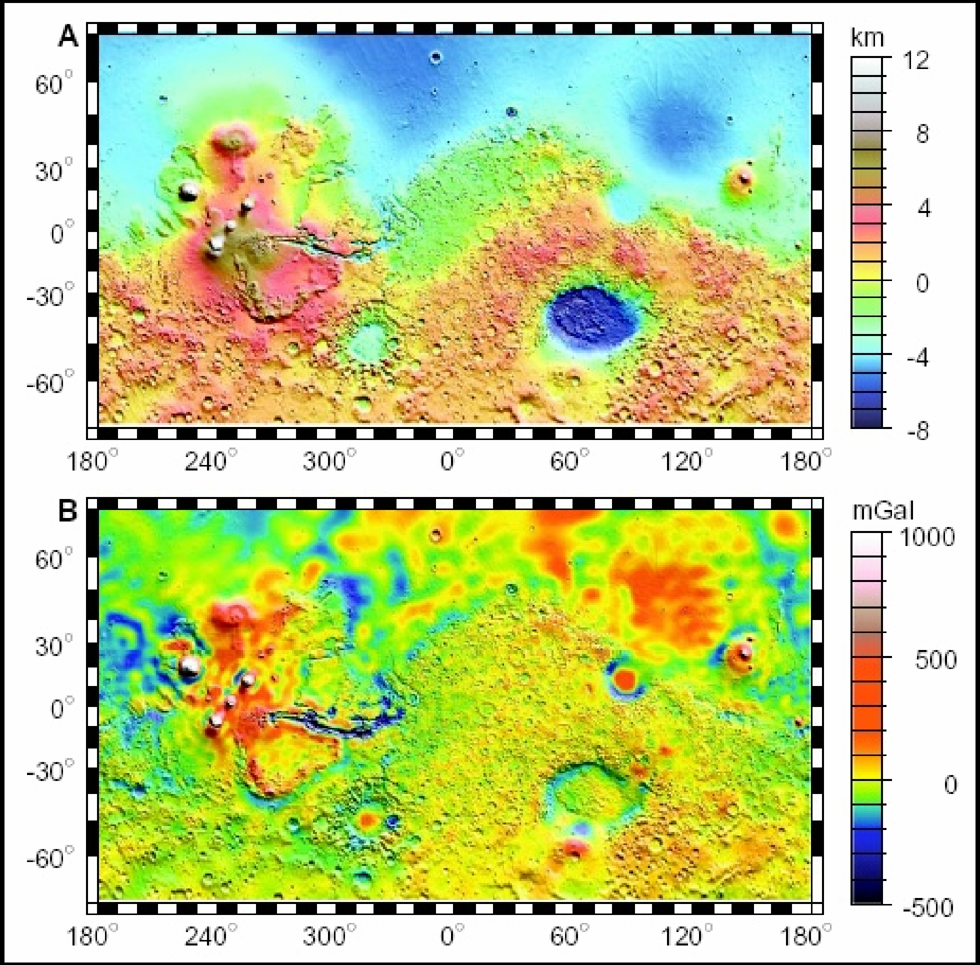


Mars Global Surveyor MOLA-Map, GSFC/NASA/JPL

- The topographic heights at the Martian surface range from plus 25km to minus 8km.
  - Earth: plus 9km to minus 11km.

Gravity and Topography

- Topography measured by MGS laser altimeter (600 million shots).
- Vertical accuracy ~1 m!
- Gravity data obtained from radio tracking; Doppler shift related to internal mass distribution (undulations of topography and crust-mantle boundary).



Zuber et al., Science, 2000.

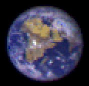
Crust thickness

- Present estimates of mean thickness are entirely based on indirect geophysical evidence, e.g. local relation between gravity and topography
  - Variable thickness

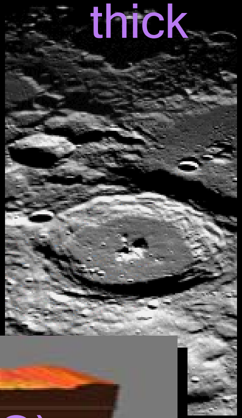
→ minimum underneath Hellas

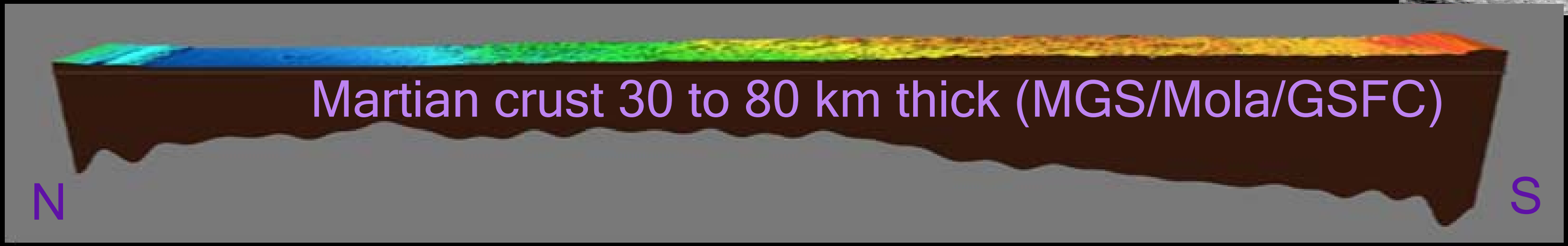
→ maximum underneath Tharsis

→ 30 km beneath northern lowlands 80 km beneath southern highlands



Lunar crust 60 to 110 km thick





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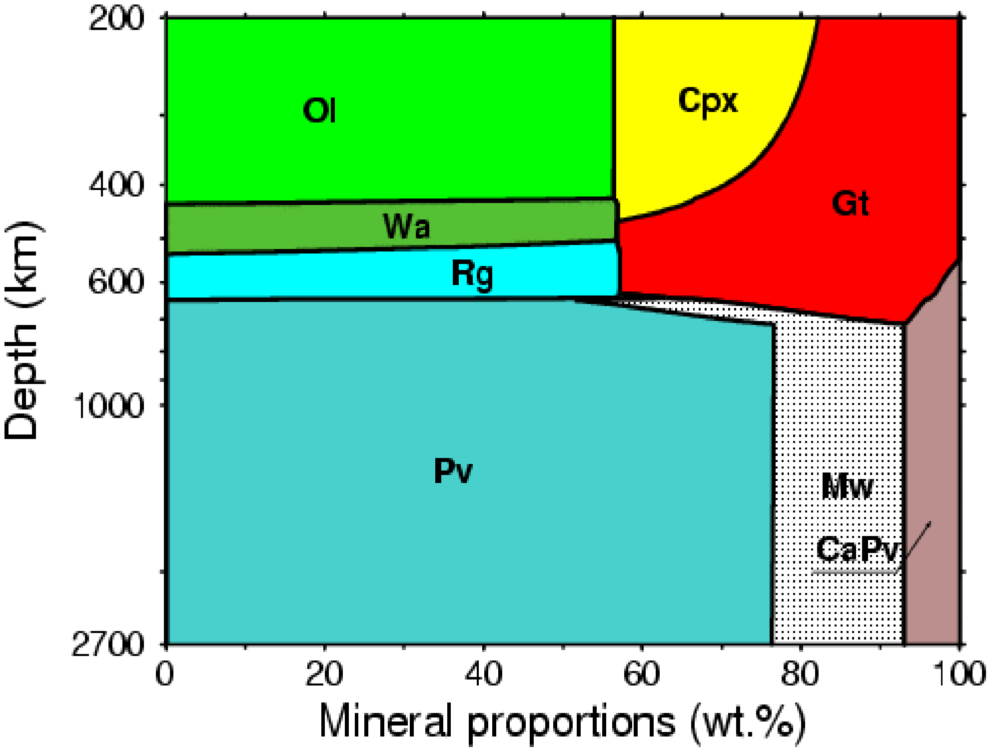
Pyrolite phase diagram
For Mars mantle



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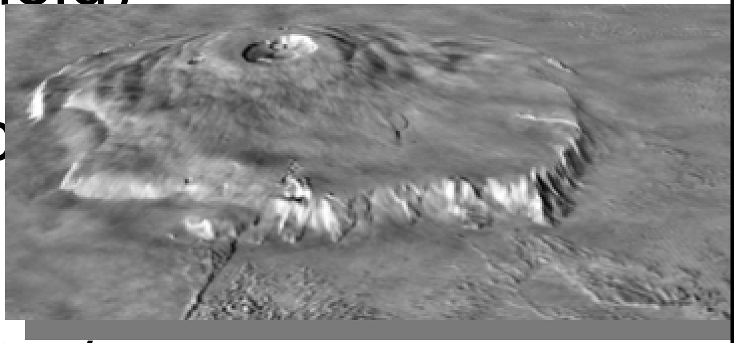

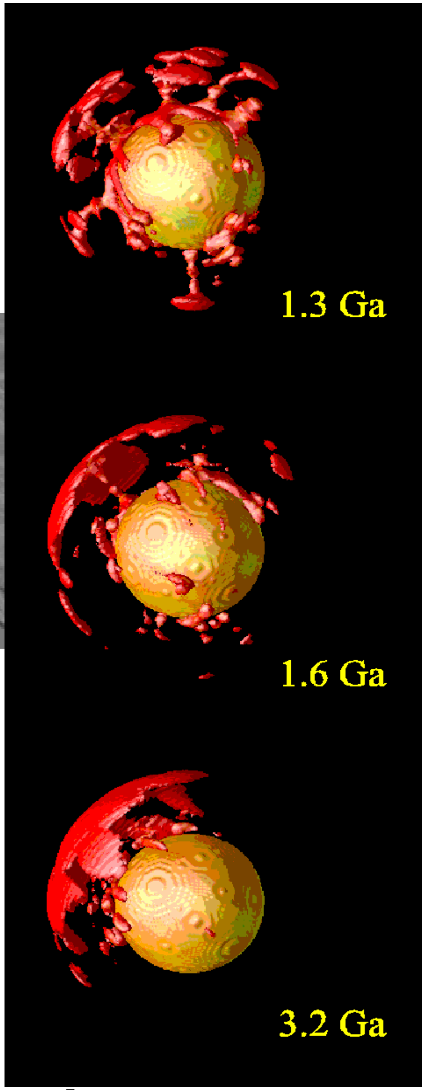

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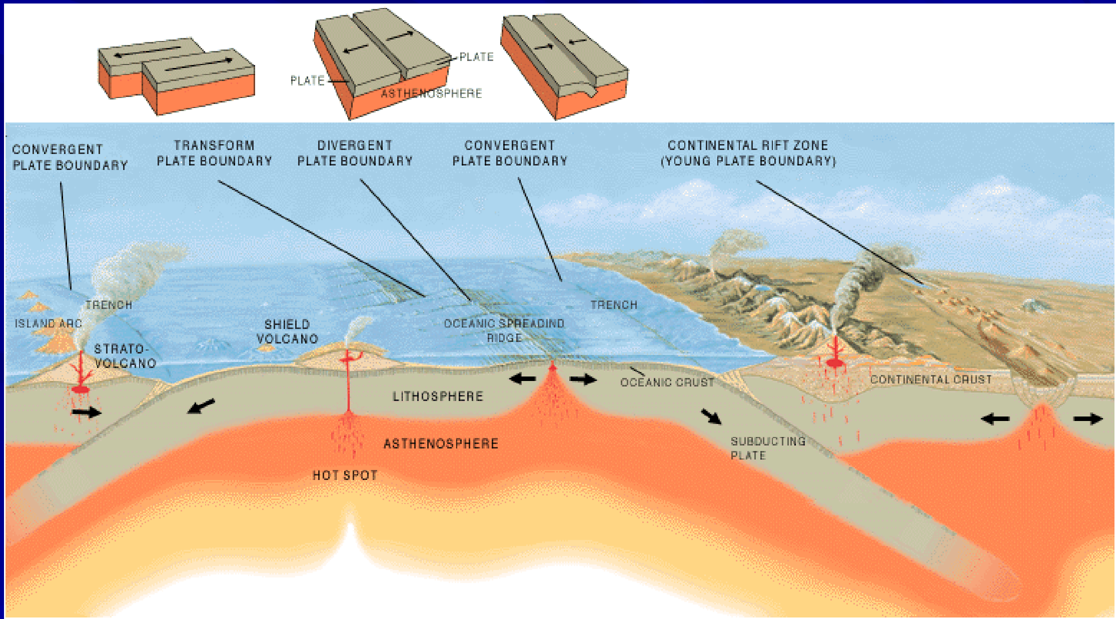
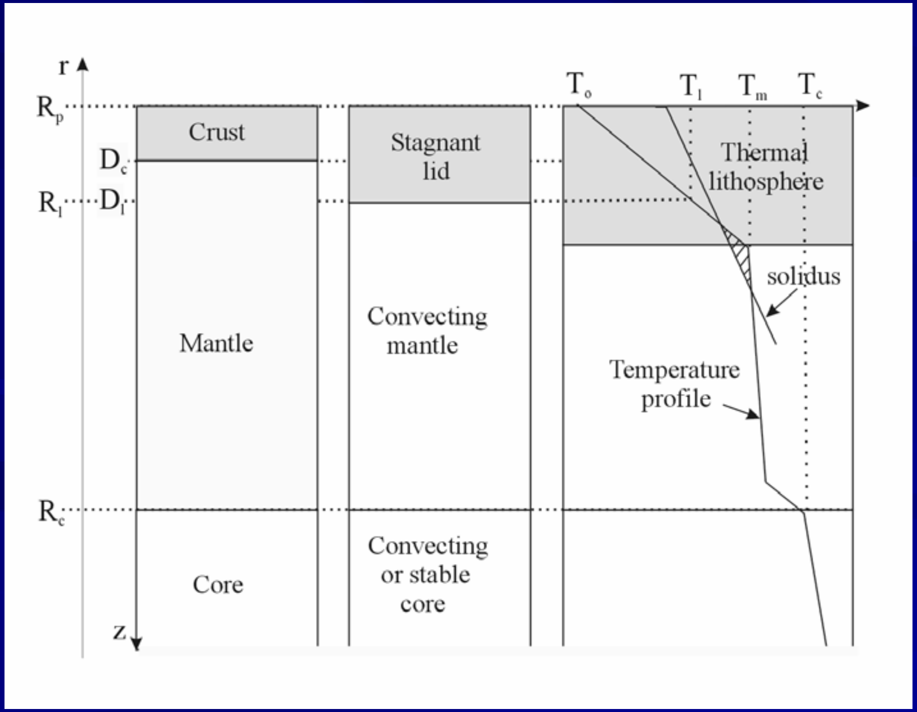
Earth: Crust Formation in Plate Tectonic Regime

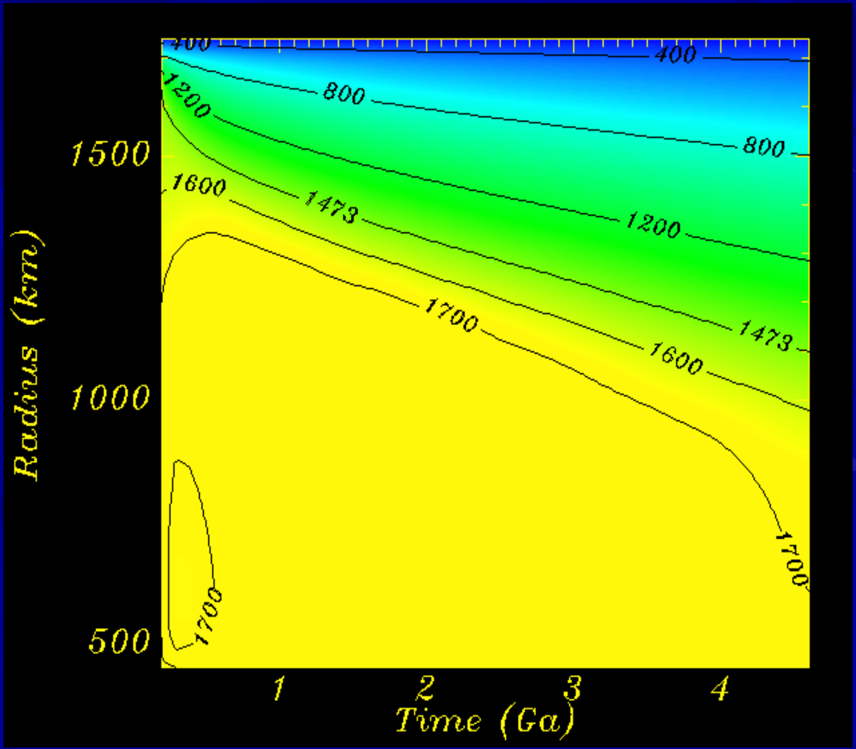
- Efficient crust formation at the divergent plate boundaries (pressure relased melting close to the surface) ~ 17 km^3/yr
- Two-stage crust formation
- Possible strong plume volcanism in early evolution



Crust Formation in a One-Plate Planet

- Melt production underneath the stagnant lid





CCL: Interior structure: The data set

Model constraints

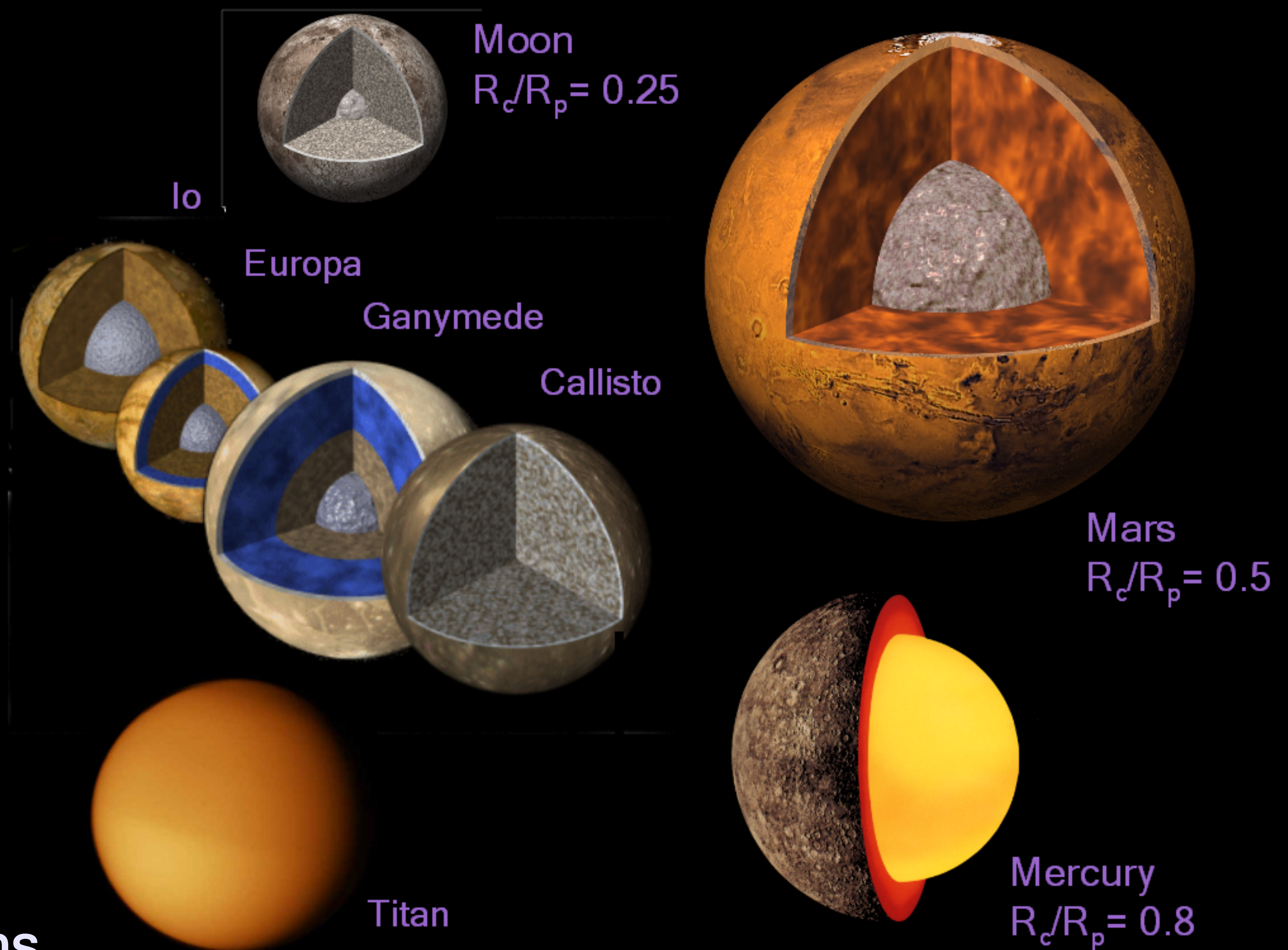
- surface radius
- mean density
- moment of inertia
- gravitational field
- surface chemistry
- cosmochemistry
- laboratory data

Future constraints

- geodesy
- seismology
- heat flow
- conductivity

Model assumptions

- hydrostatic conditions



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Two-layer structural models (1)

- 2 constraints: mean density ρ and MoI factor I/MR^2.

$$\rho = \rho_m + (\rho_c - \rho_m)\left(\frac{r_c}{R}\right)^3$$

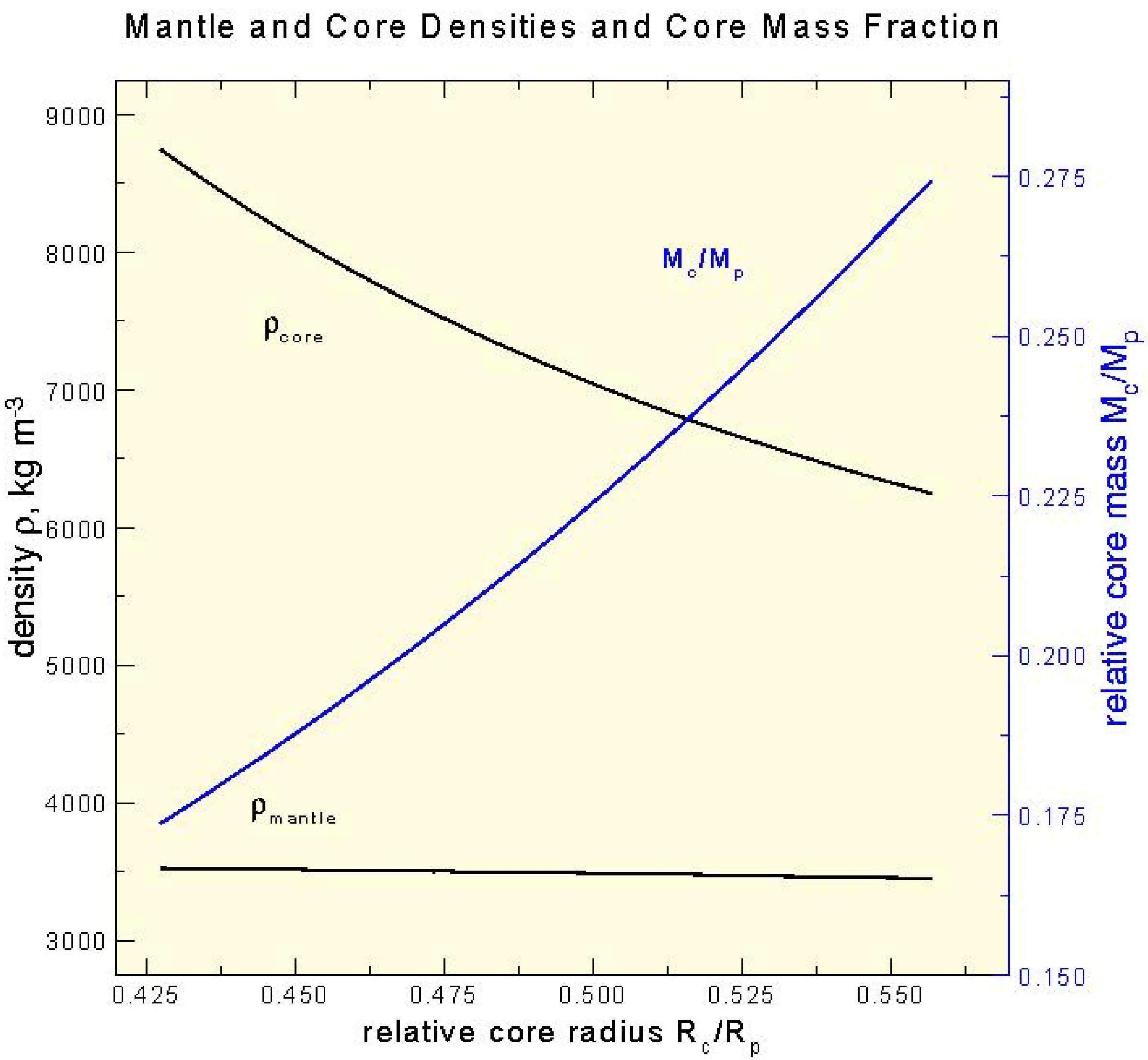
$$\rho\left(\frac{I}{MR^2}\right) = \frac{2}{5}\left[\rho_c\left(\frac{r_c}{R}\right)^5 + \rho_m\left\{1-\left(\frac{r_c}{R}\right)^5\right\}\right]$$

- 3 unknowns: core radius r_c, mantle density ρ_m, core density ρ_c.

Simple two layer structure

2 knows:
M mass
I moment of inertia

3 unknows:
R_c core radius
ρ_m mantle density
ρ_c core density



Three-layer structural models

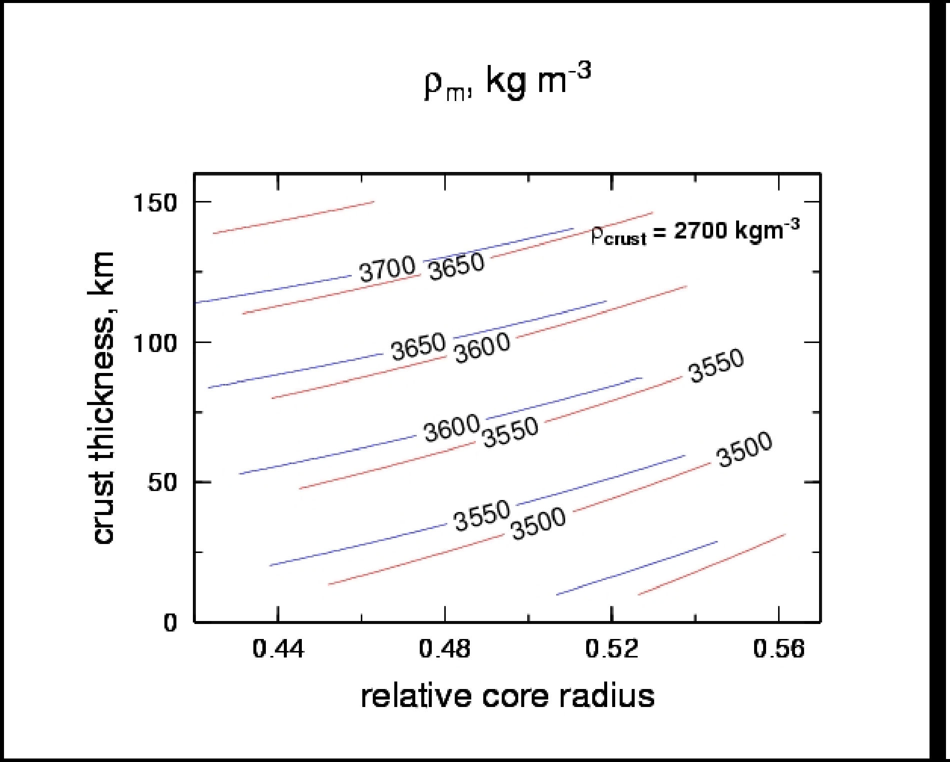
- 2 constraints: mean density ρ and MoI factor I/MR^2.

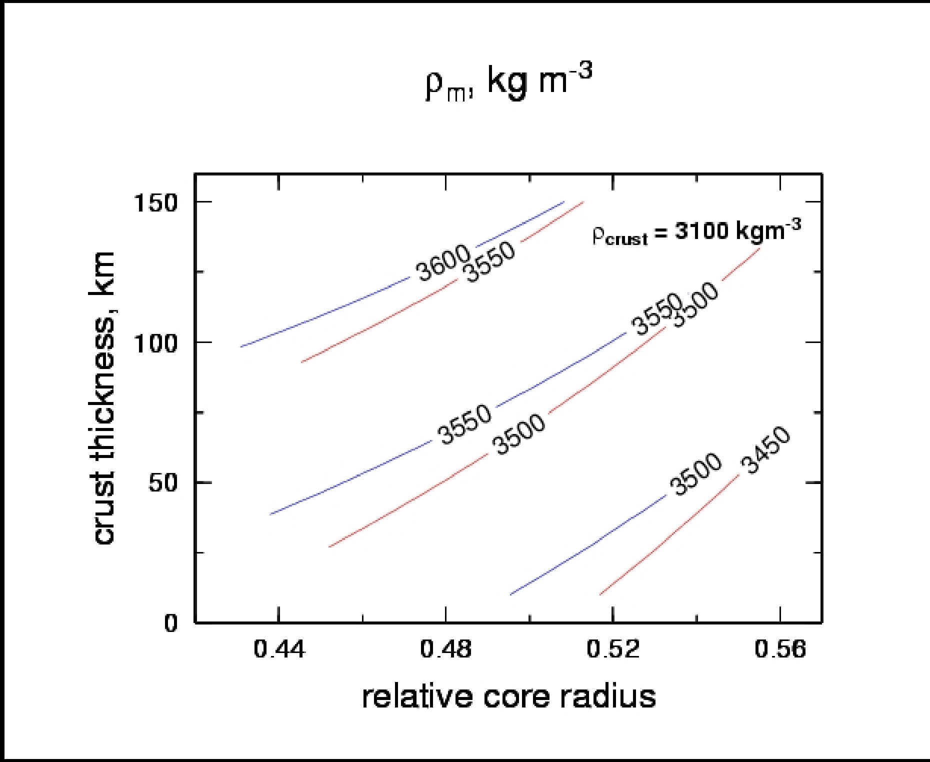
$$\rho = \rho_s + (\rho_c - \rho_m)\left(\frac{r_c}{R}\right)^3 + (\rho_m - \rho_s)\left(\frac{r_m}{R}\right)^3$$

$$\rho\left(\frac{I}{MR^2}\right) = \frac{2}{5}\left[\rho_s + (\rho_c - \rho_m)\left(\frac{r_c}{R}\right)^5 + (\rho_m - \rho_s)\left(\frac{r_m}{R}\right)^5\right]$$

- 5 unknowns: core radius r_c, crust-mantle radius r_m, crust density ρ_s, mantle density ρ_m, core density ρ_c.

Mantle density

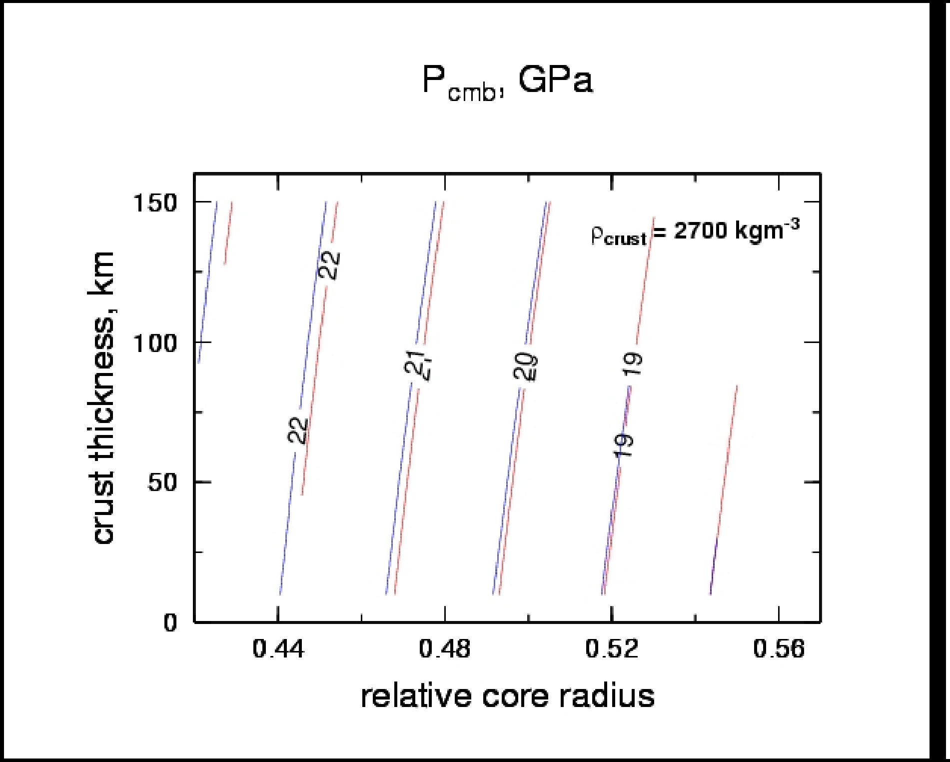


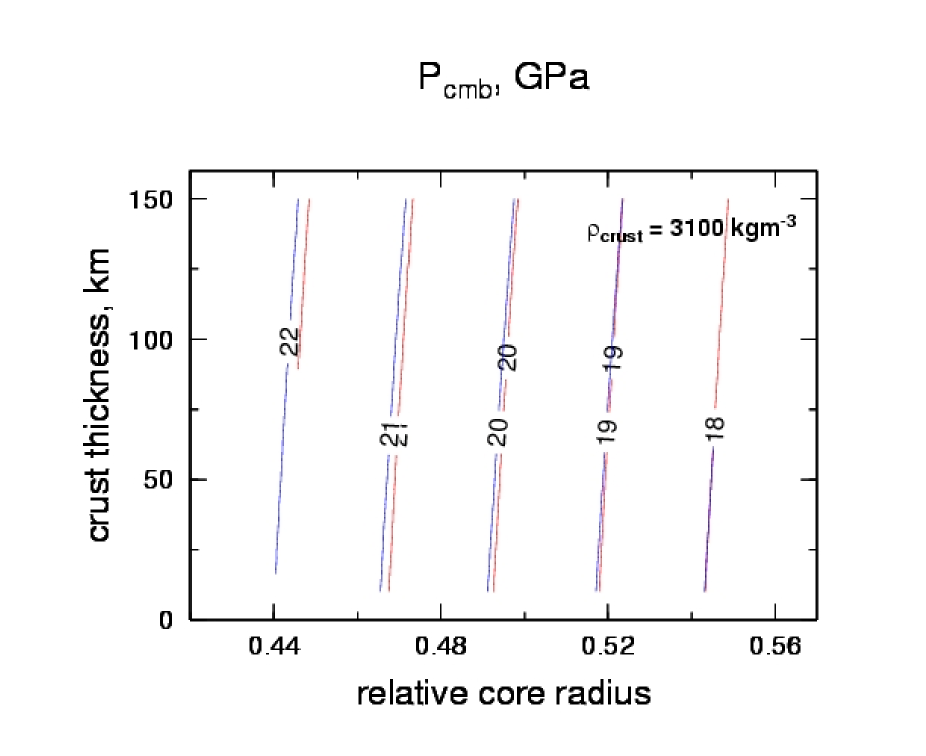


- Crust thickness increase is more pronounced for denser crusts if mantle density is kept.

Comparison of new and old MoI

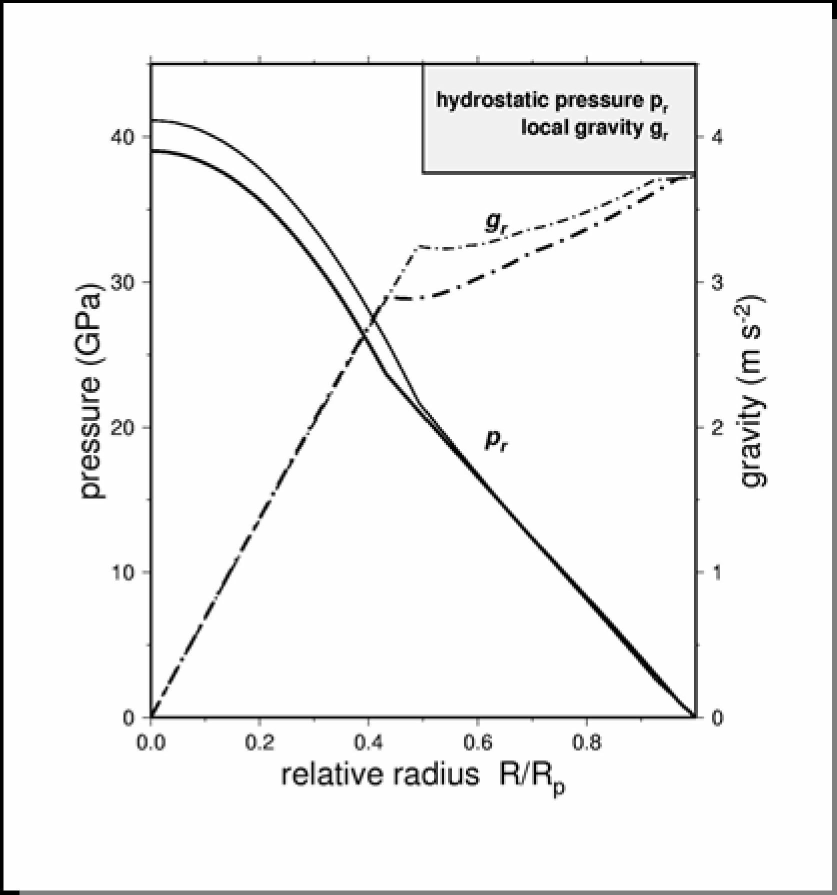
Core-mantle boundary pressure

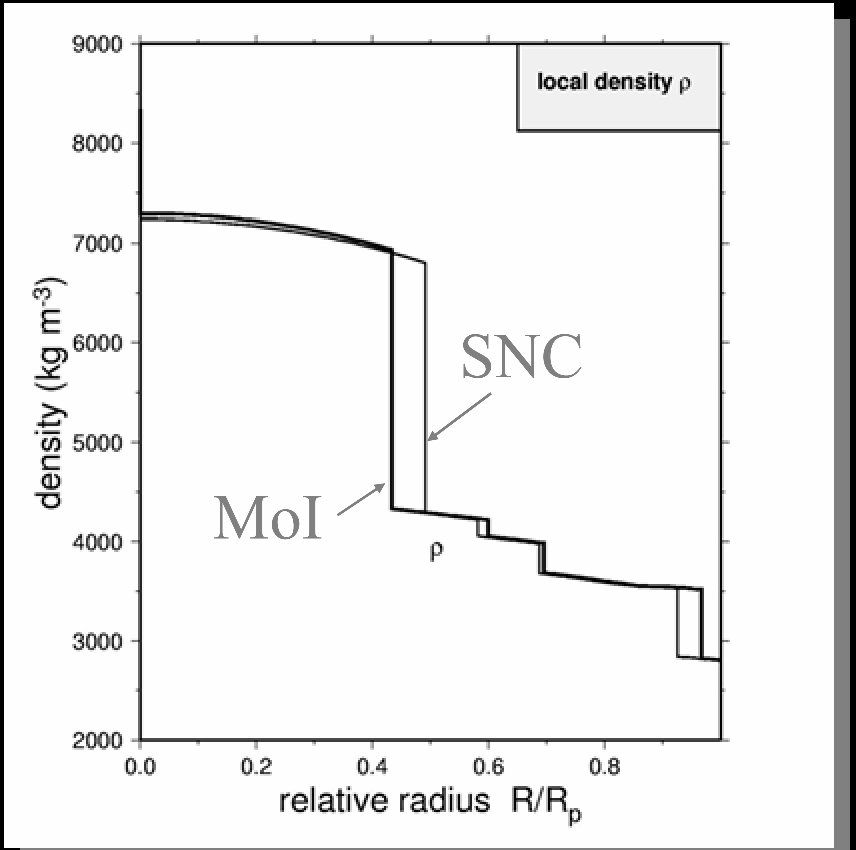


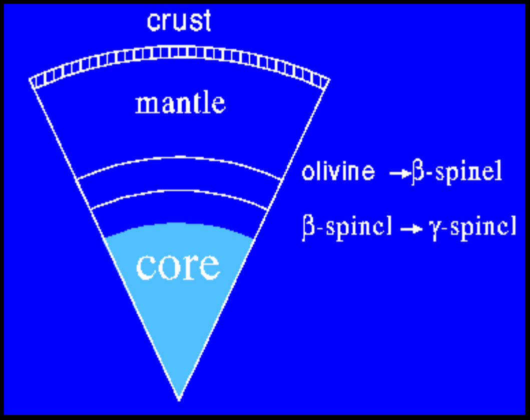


- Pressure at the core-mantle boundary is mainly determined by core size and is less dependent on crust thickness.
- Perovskite phase transition possibly between 22 and 24 GPa, so does not exist for large core (a planet with a P_{cmb}=20GPa might have no pv)

Mantle phase transitions

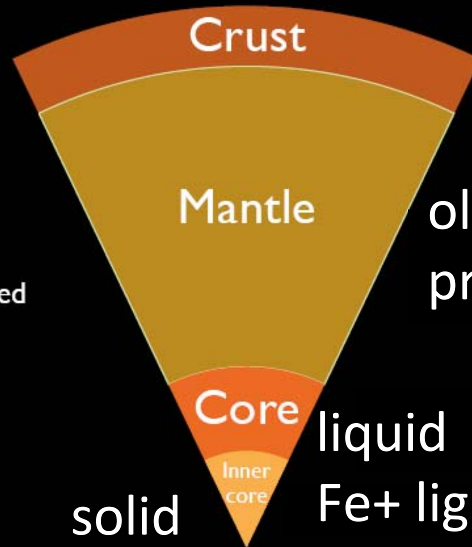






Sohl and Spohn, JGR, 1997.

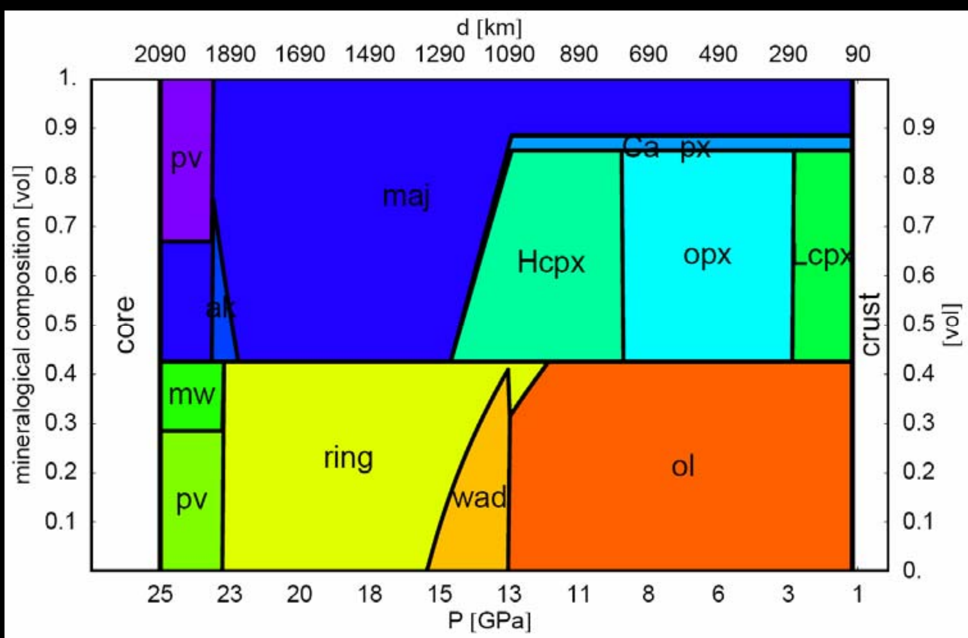
Spherical, non rotating
hydrostatic, differentiated

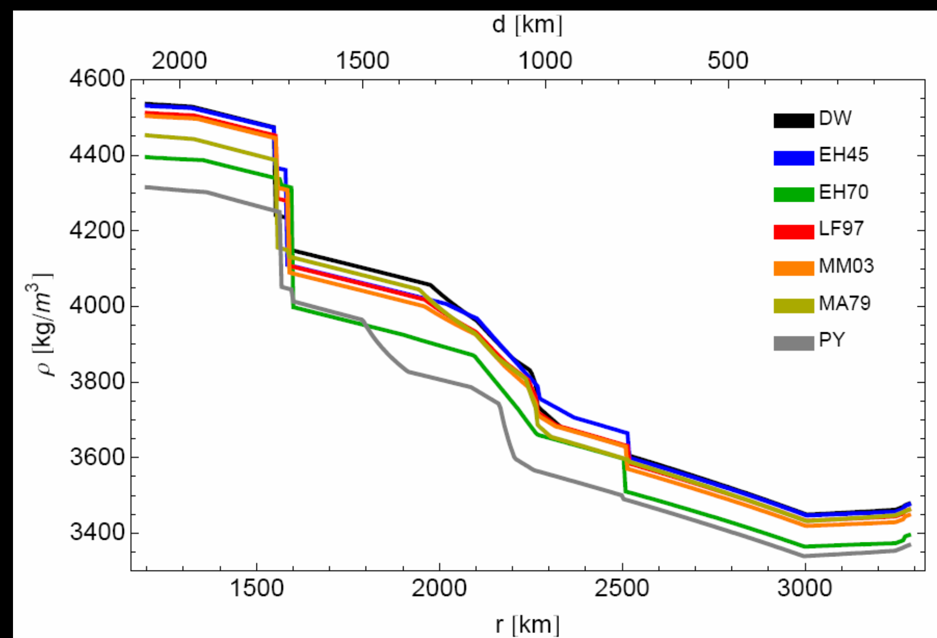


ol, px, gt, high
pressure phases

liquid
Fe+ light
elements (S)

solid
Fe





New geophysical observations

- Re-analysis of MGS tracking and MPF & VL ranging resulted in $C/MR^2 = 0.3650 \pm 0.0012$ (Yoder *et al.*, 2003).

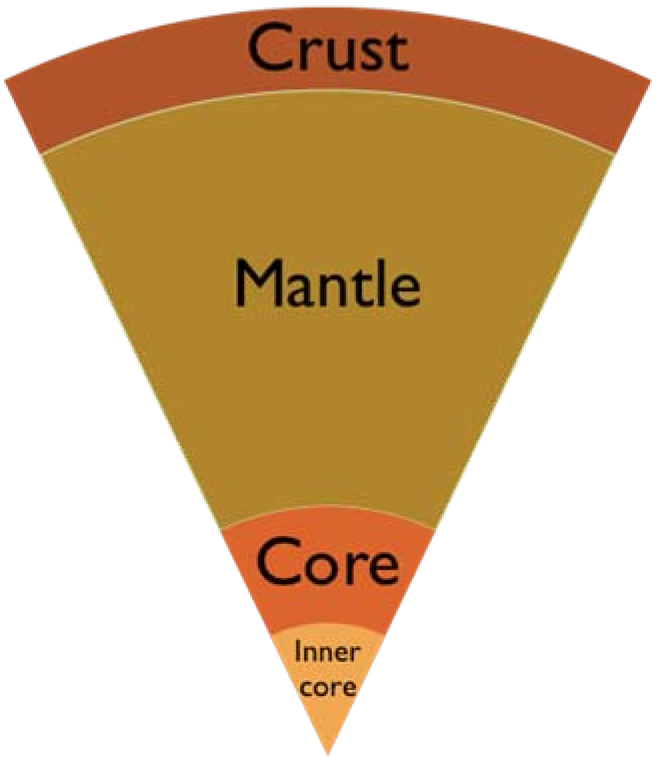
  → significantly lower than most often used value $C/MR^2 = 0.3662 \pm 0.0017$ (Folkner *et al.*, 1997).

  → implies stronger central mass concentration

- Tidal potential Love number $k_2 = 0.15 \pm 0.01$ (Yoder *et al.*, 2003), $k_2 = 0.15 \pm 0.01$ (Konopliv *et al.*, 2006), and $k_2 = 0.16 \pm 0.01$ (Konopliv *et al.*, 2010) suggests hot interior with liquid (outer) large core.

- Tidal potential Love number $k_2 = 0.12 \pm 0.01$ (Marty *et al.*, 2009) suggests smaller liquid core.

Interior structure model of Mars as recently derived at ROB (Rivoldini et al. 2010)



- spherical symmetric, hydrostatic and elastic
- homogeneous crust
- depth dependent thermoelastic properties in mantle and core
- convecting liquid Fe-S core
- solid γ-Fe inner core (melting data dependent)

Model parameters

- core size (allowing for solid pure Fe cores to liquid Fe-x wt%S cores with sulfur concentration x bounded by planet mass)

- several bulk mantle mineralogy models (input from SNC - Shergottites-Nakhlites-Chassigny- meteorites, SNC chemical composition representing early mantle, different from the CI chondritic composition)
(Dreibus and Wänke 1984, Lodders & Fegley 1997, Sanloup et al 1999, Mohapatra et al. 2003)

- 2 mantle temperature end-members (hot and cold) (resulting from convection simulations compatible with an early geodynamo)
(Verhoeven et al. 2005)

Interior structure relevant data

- size and mass

r_a=3389km, m_a=6.4185 10^{23} kg

- average moment of inertia

MOI=0.3655±0.00086 (Konopliv et al. 2005)

- crust density and thickness

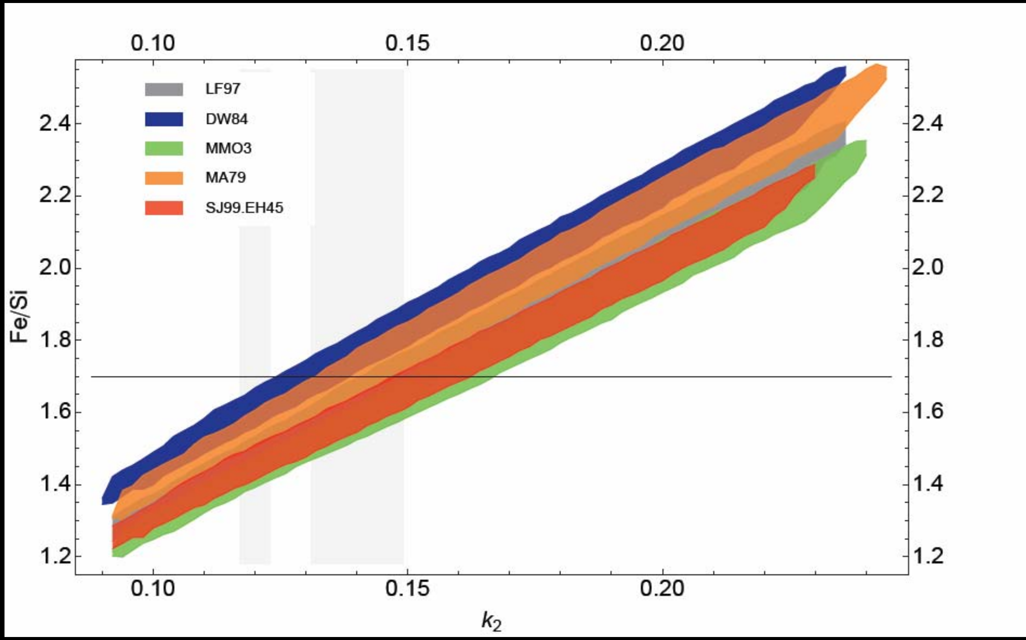
ρ=2900±200kg/m^3, d=50±12km (Wieczorek et al. 2004)

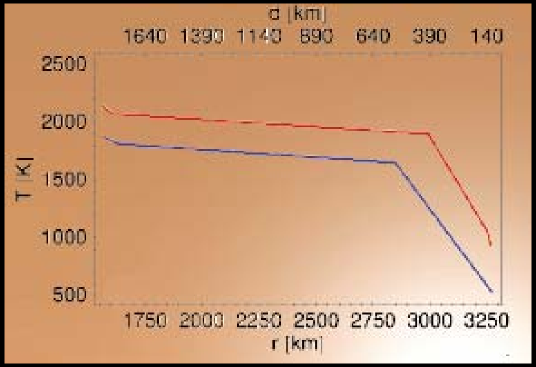
- phase diagrams of mantle minerals and core constituents

- high pressure and temperature thermoelastic data

Trade-off between Fe/Si and k_2

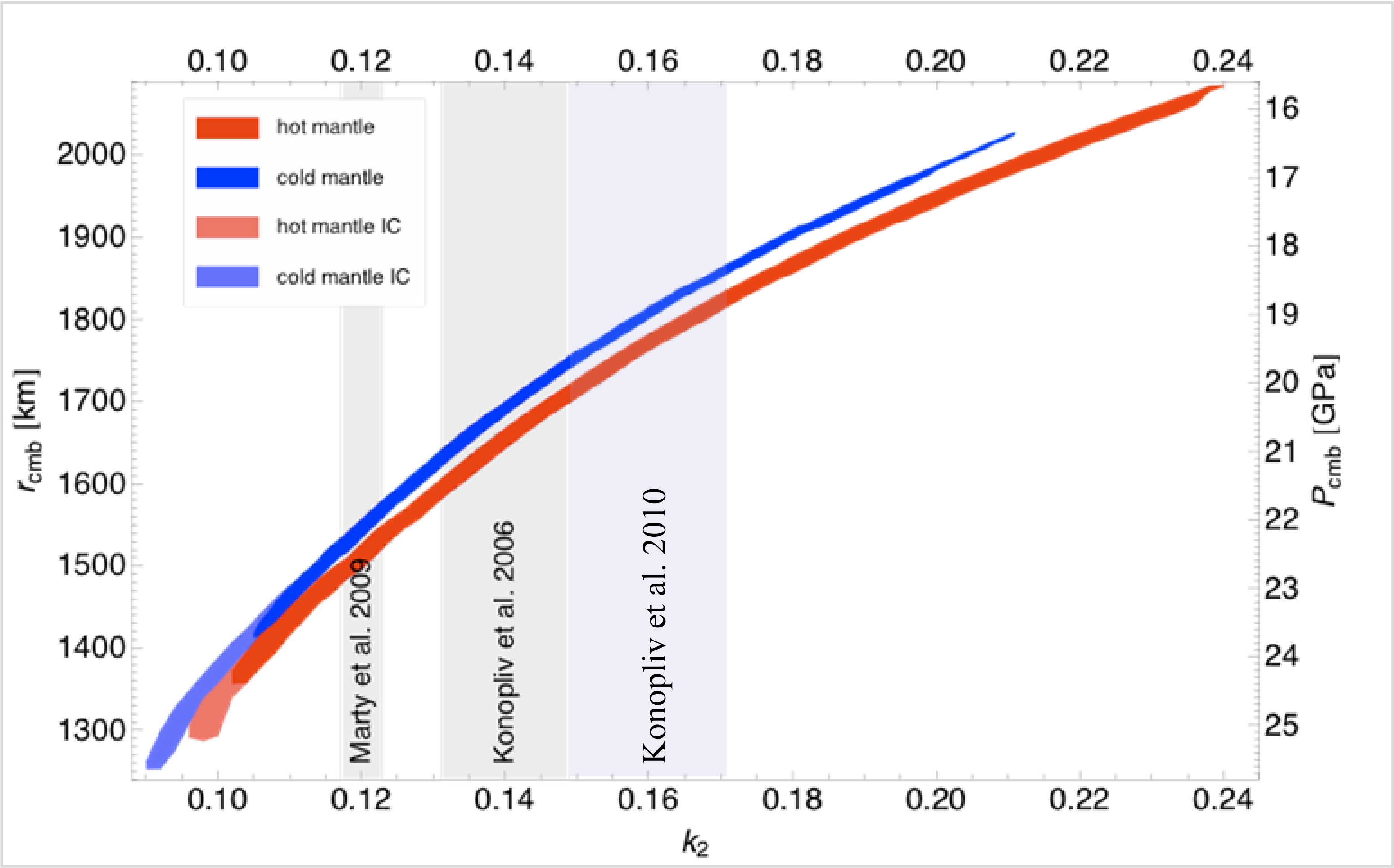
- Dreibus & Wänke compositional model.
- Hot and cold mantle temperature model (Breuer and Spohn, 2003).



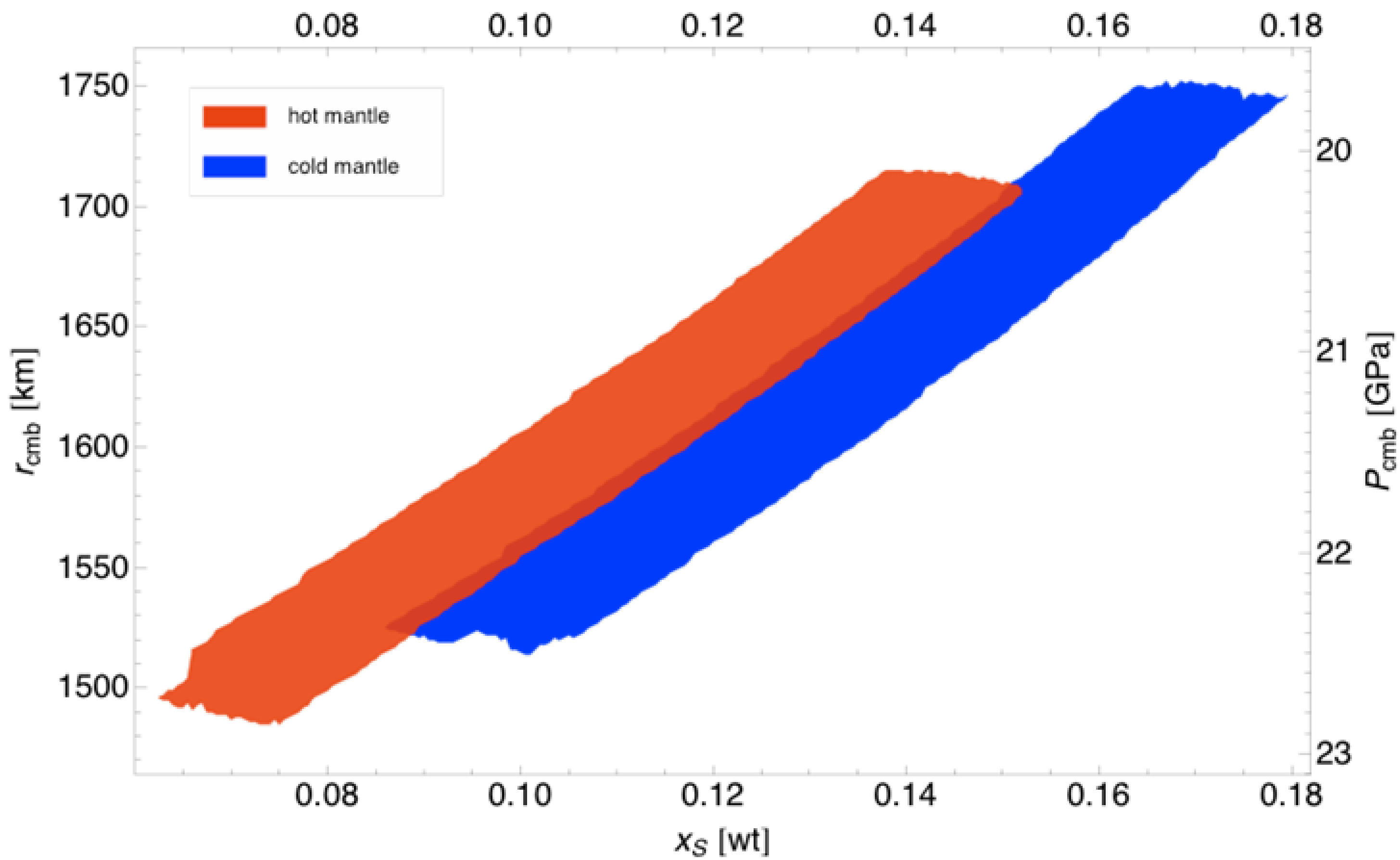


from A. Rivoldini from ROB

k_2 as a function of core size



Core size-core sulfur concentration (compatible with MoI and k_2 ranges)



Main results

- MOI and k_2 compatible models have fully molten cores

- core size: 1640±150km [1490km,1790km]

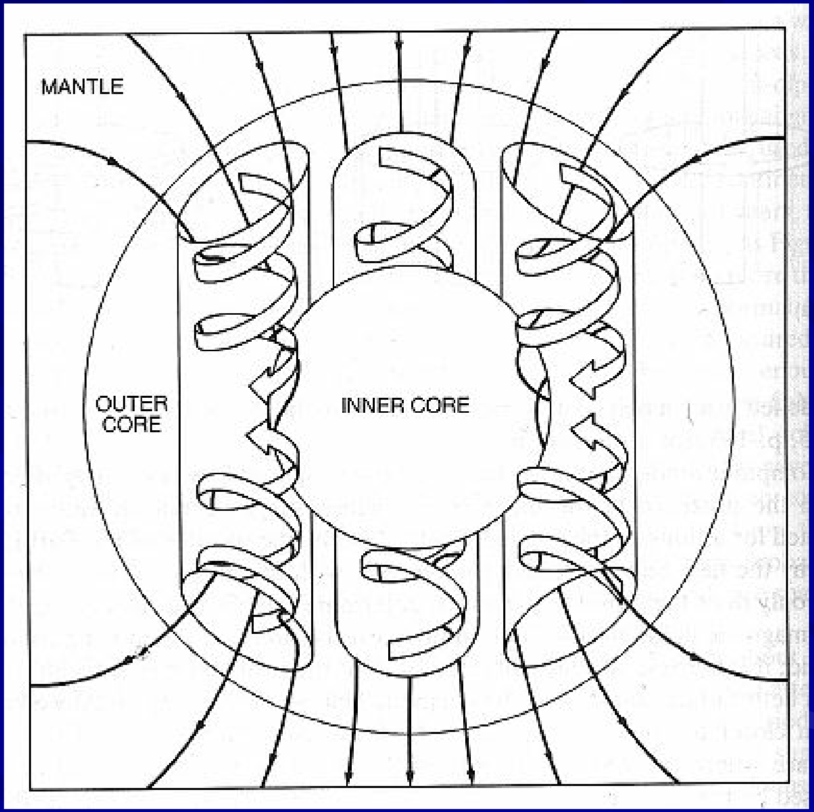
- core sulfur concentration: 13±6wt% [7wt%,19wt%]

Content of my talk
Mars Interior: Part 1: Structure and Activity part

1. Global constraints and structure
2. Interior structure and composition
3. Magnetism Mechanisms for magnetic field generation in the core
   - Thermal convection
   - Compositional convection
4. Thermal evolution; heat sources; heat transport mechanism; convection

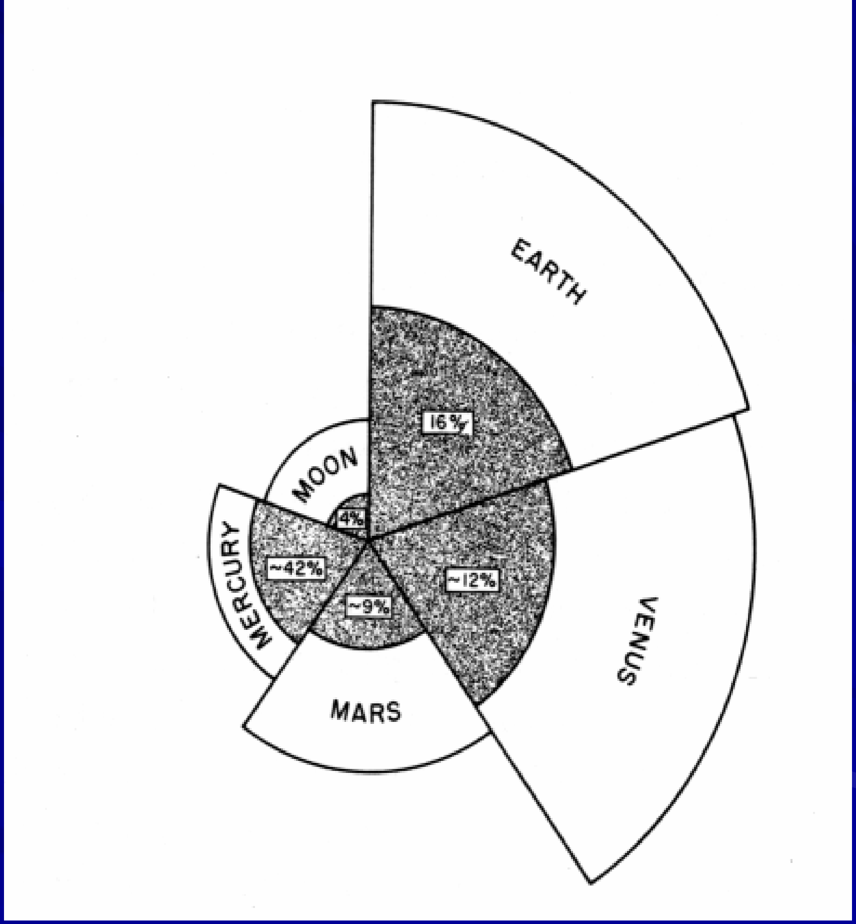
Magnetic Field Generation
Necessary conditions for existence

- A conducting fluid
- Motion in that fluid
- Cowling´s Theorem requires some helicity in the fluid motion



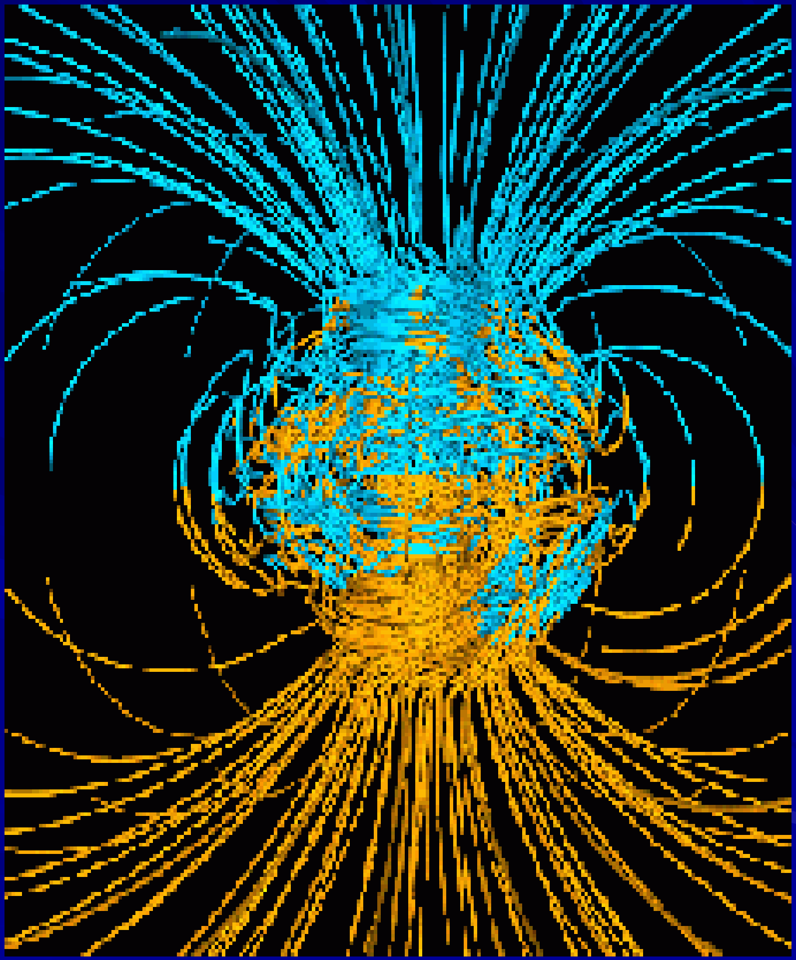
Cores

- The magnetic fields of terrestrial planets and satellites are produced in their cores
- There is no doubt that the planets and most of the major satellites have iron-rich cores



Dynamos

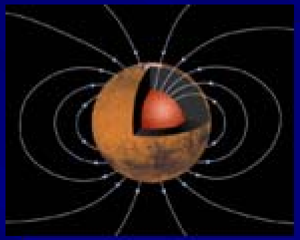
- Hydromagnetic dynamos
  - Thermal dynamos
  - Chemical dynamos

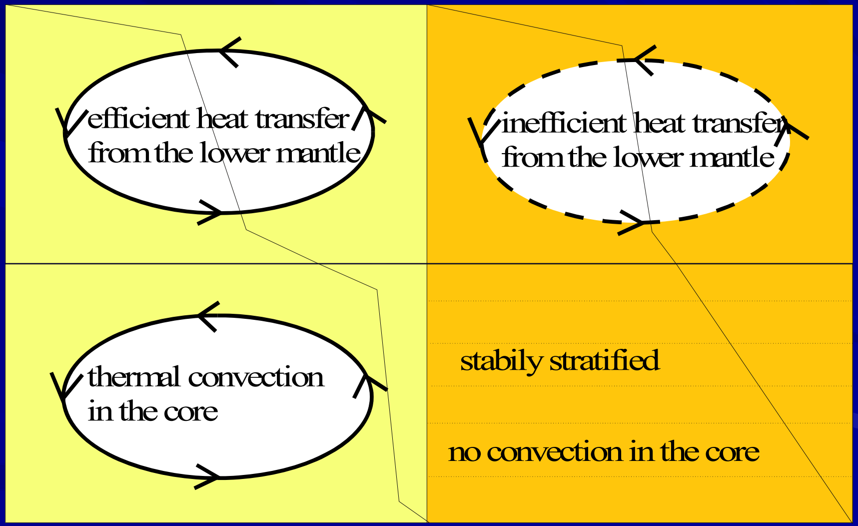


G. Glatzmeier's Dynamo model for Earth

Thermal Dynamo

- Fluid motion in the liquid iron core due to thermal buoyancy
(=> cooling from above)
- ‘Critical‘ heat flow out of the core





‘Critical‘ Heat Flow

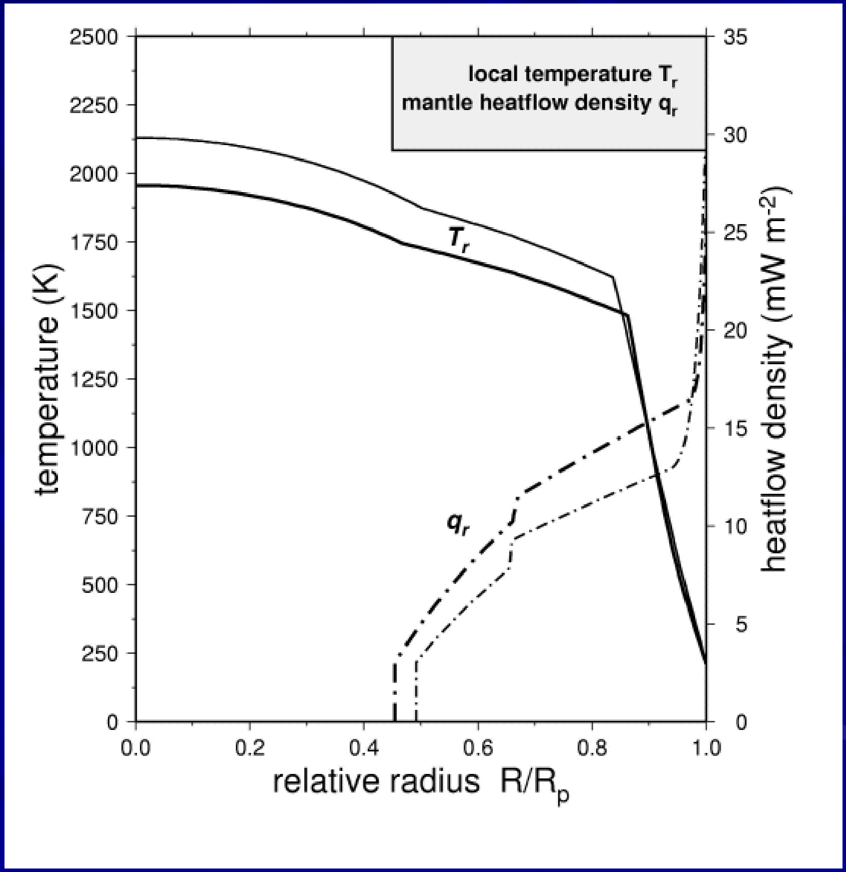
- Mars, Mercury 5 - 20 mW/m^2
- Earth, Venus 15 – 40 mW/m^2
- Galilean Satellites, Moon < 7 mW/m^2

Large uncertainities due to poorly known parameters

Vigour of Core Convection

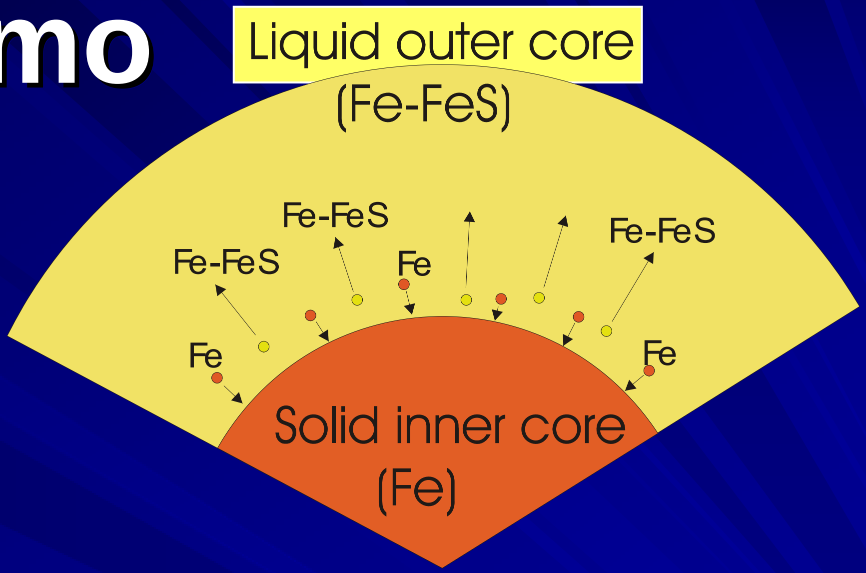
- A sufficiently large ΔT between the core and the mantle is required in order to drive thermal convection in the core

- If ΔT is too small than the core will be cooling by conduction

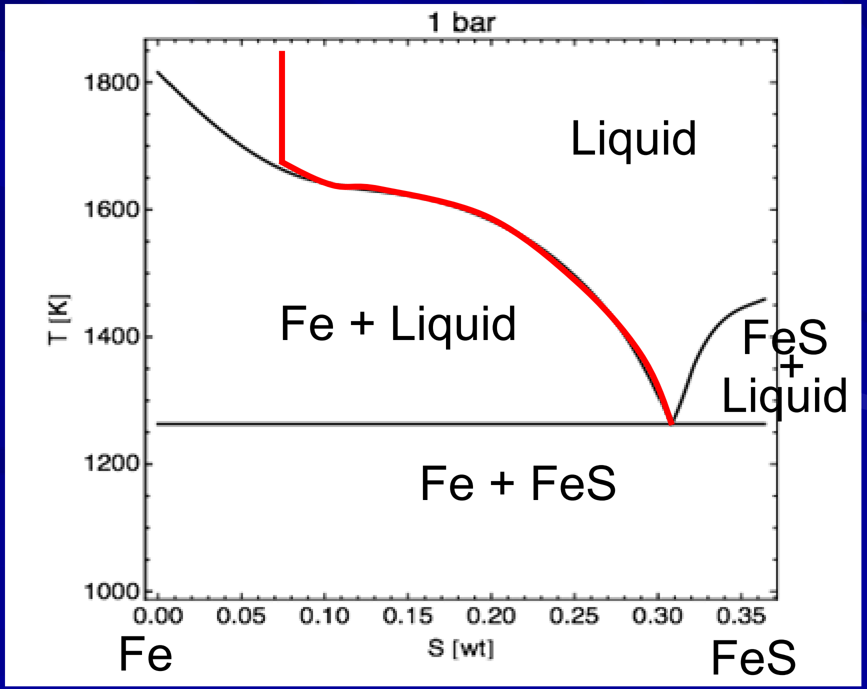


Sohl and Spohn, 97

Chemical Dynamo



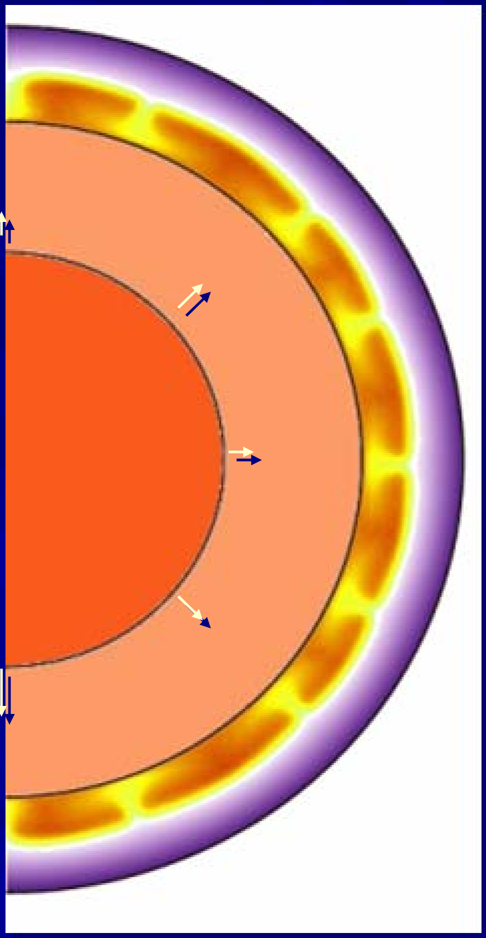
- Existence of light alloying elements in the core like S, O, Si
- Core temperature between solidus and liquidus



Phase diagram taken at 1 bar:
Courtesy A. Rivoldini

Chemical Dynamo

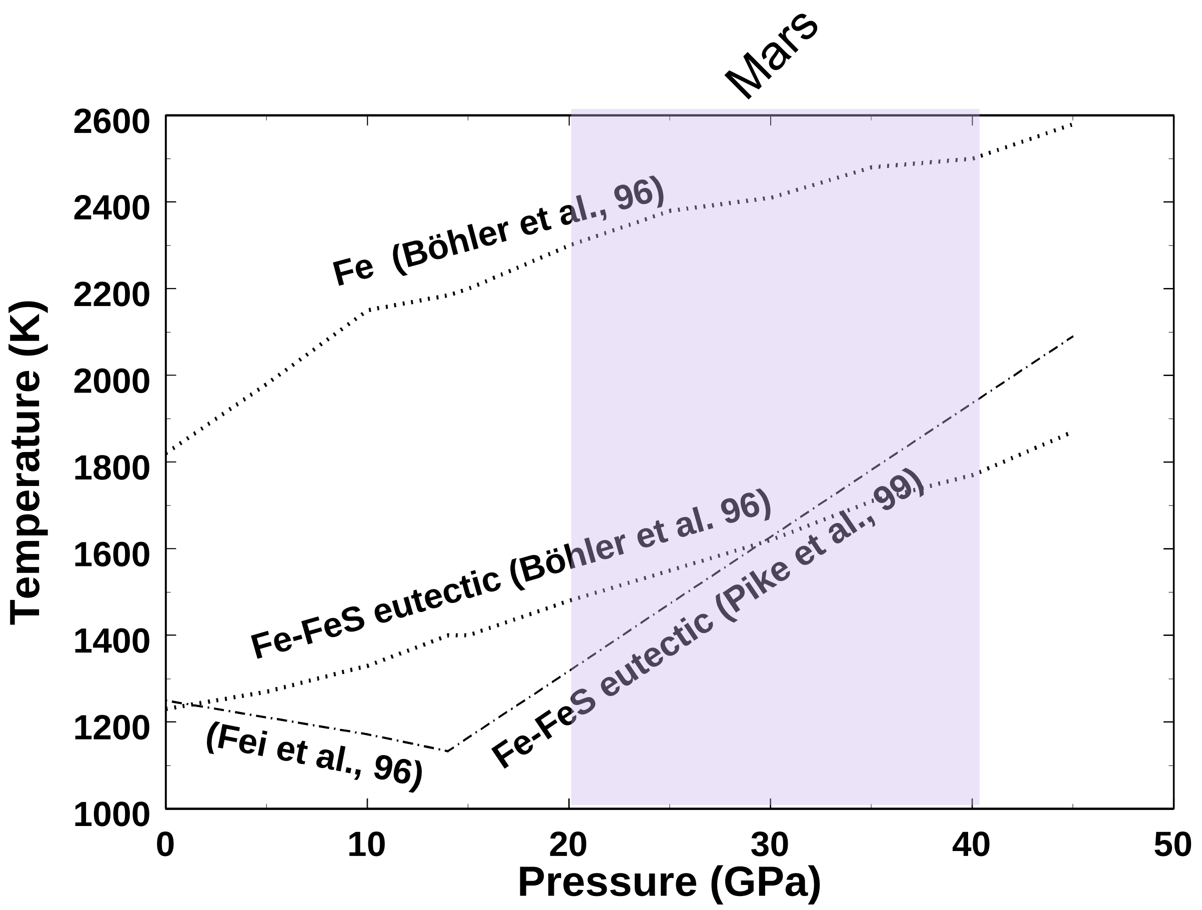
- Compositional bouyancy released by inner core growth
- Difficult to stop operating

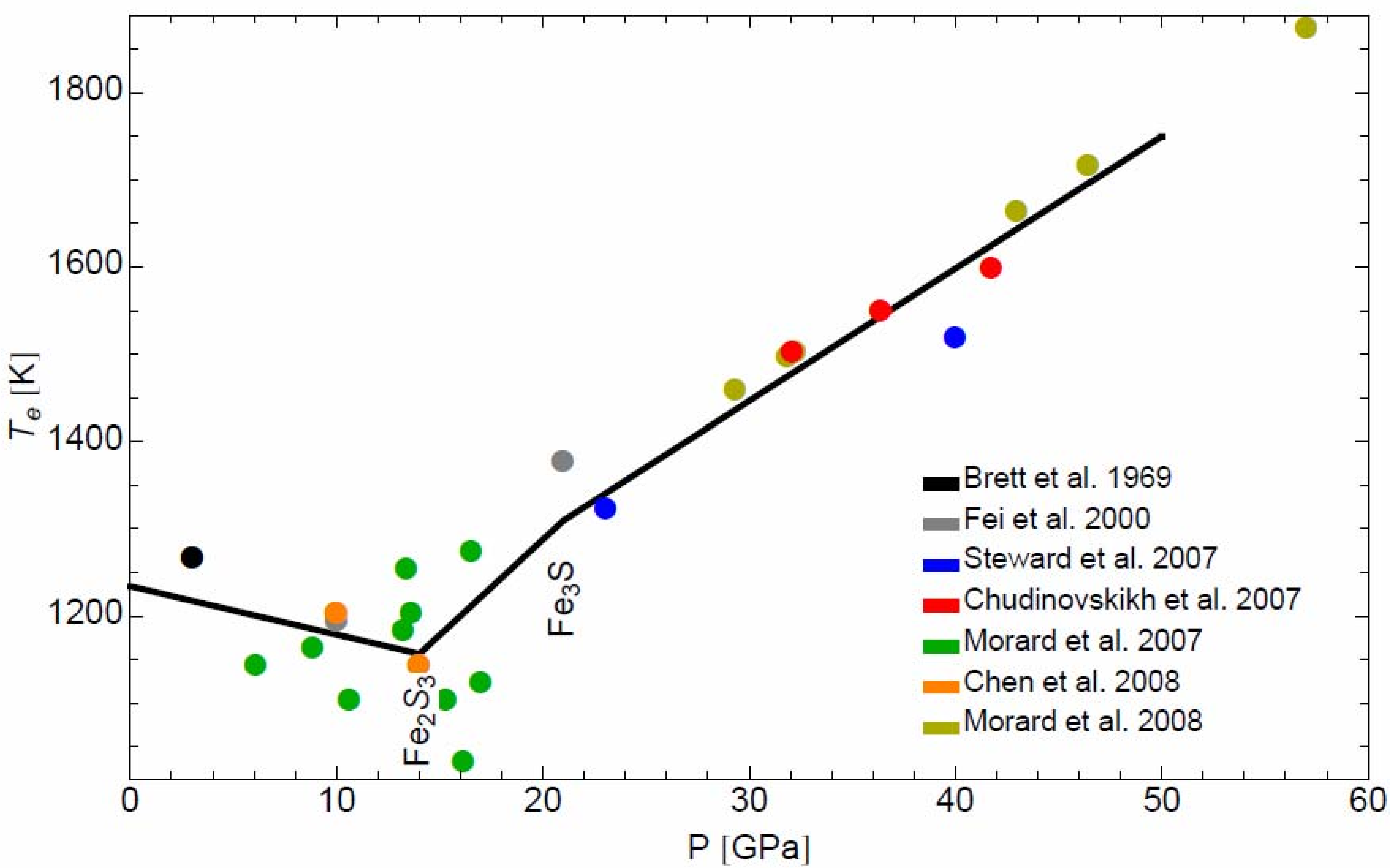


Mercury Model by Conzelmann and Spohn

Melting Temperature as Function of Pressure

Eutectic temperature as a function of pressure and melting temperature of Fe; for Mars, eutectic temperature increases as a function of pressure; eutectic sulfur fraction increases as a function of pressure (next slide).



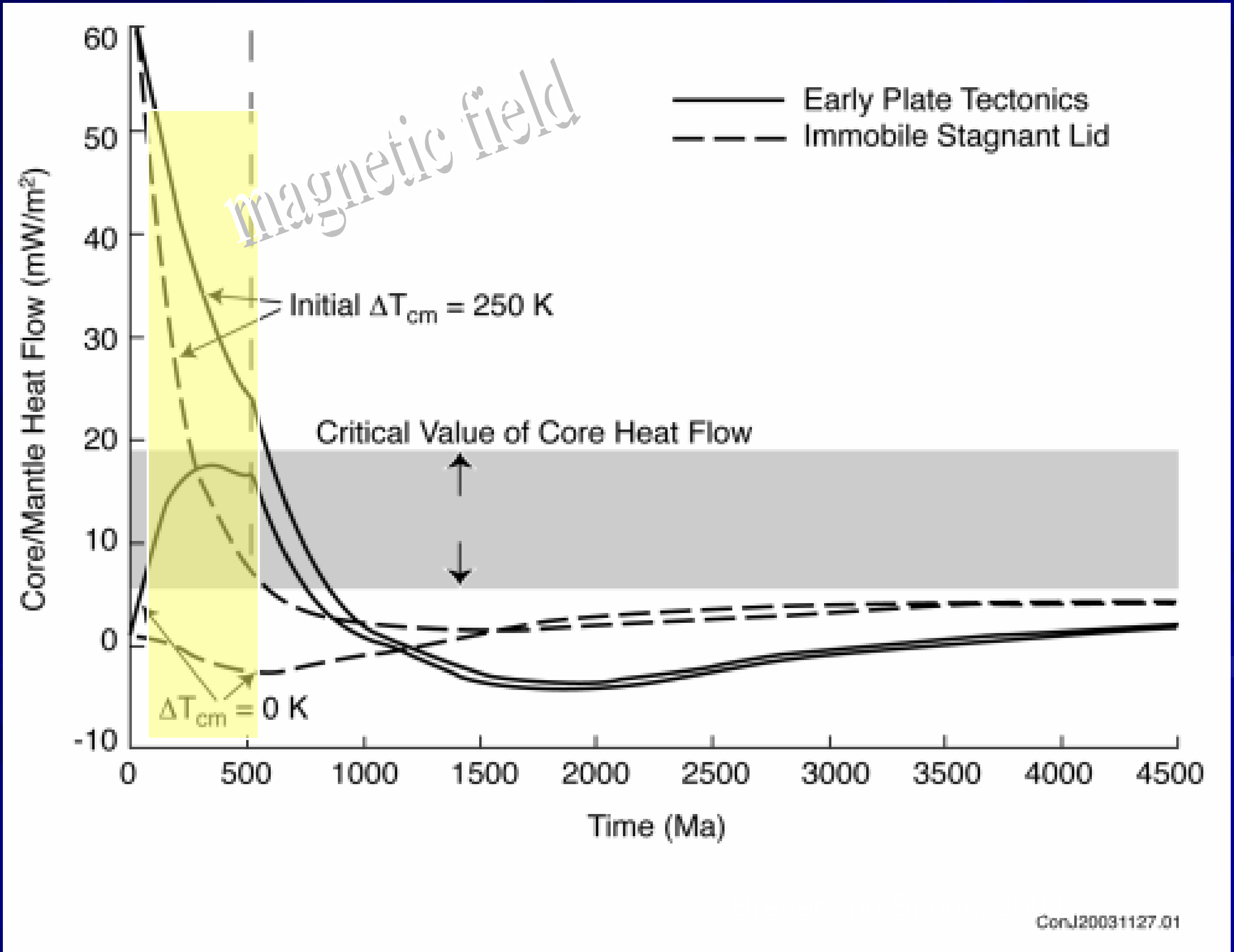


1800
1600
1400
1200
T_e [K]
0
10
20
30
40
50
60
P [GPa]
Fe_2S_3
Fe_3S
Brett et al. 1969
Fei et al. 2000
Steward et al. 2007
Chudinovskikh et al. 2007
Morard et al. 2007
Chen et al. 2008
Morard et al. 2008

Some First Conclusions

- Thermal convection (fluid core without inner core growth): Inefficient for long-term dynamo generation; a large ΔT is needed
- Compositional convection (inner core growth): Efficient for dynamo generation; difficult to stop
- The mantle determines (provides most important constraints) whether a terrestrial planet has core convection and whether it can have a dynamo

- Early Martian (thermal) dynamo possible with a superheated core



Conclusions about Mars' magnetic field

- Early plate tectonics consistent with early strong magnetic field
- Crustal evolution with early plate tectonics inconsistent with observations
- Stagnant lid convection consistent with crustal evolution and early magnetic field (thermal dynamo) if the core is superheated by more than 100 K.

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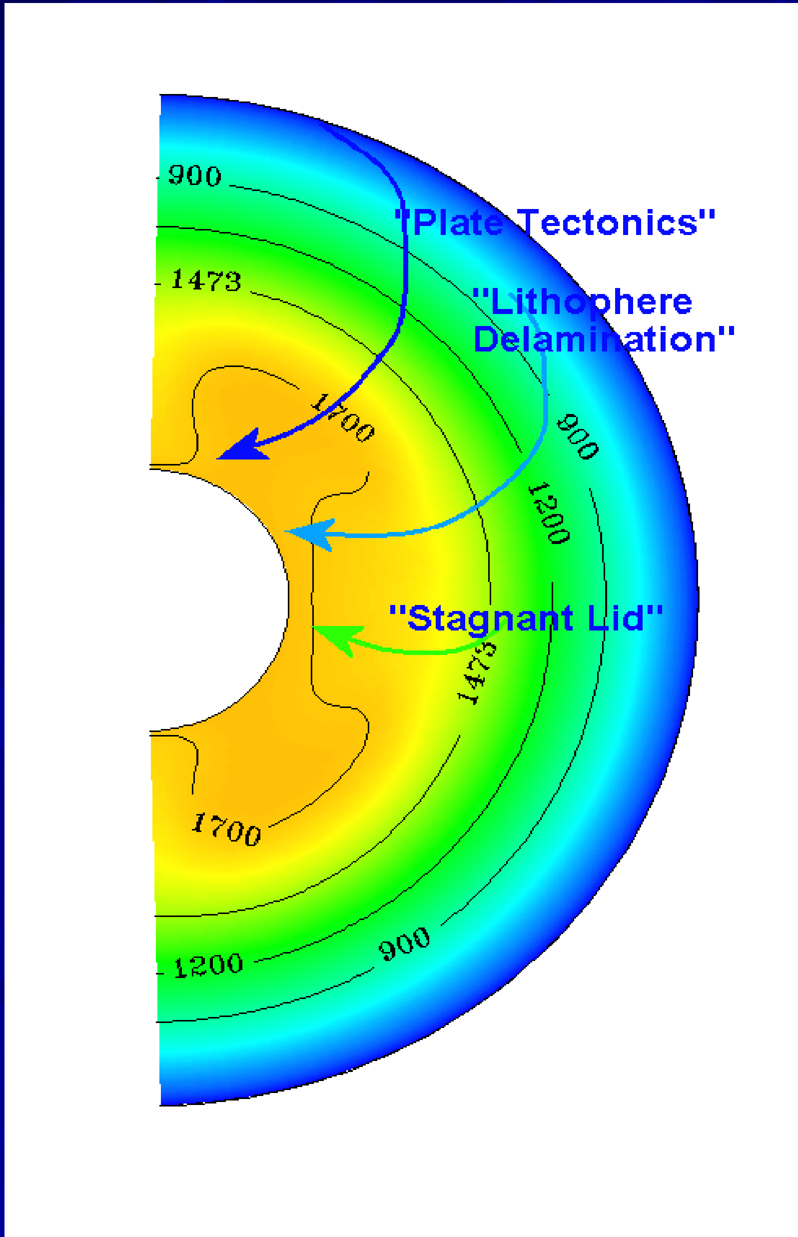
4. Thermal evolution;
   - heat sources;
   - heat transport mechanism;
   - convection

Heat Sources

- Primary energy
  - Accretion
  - Gravitational energy due to core formation
- Decay of radioactive elements
  - Uranium
  - Thorium
  - Potassium

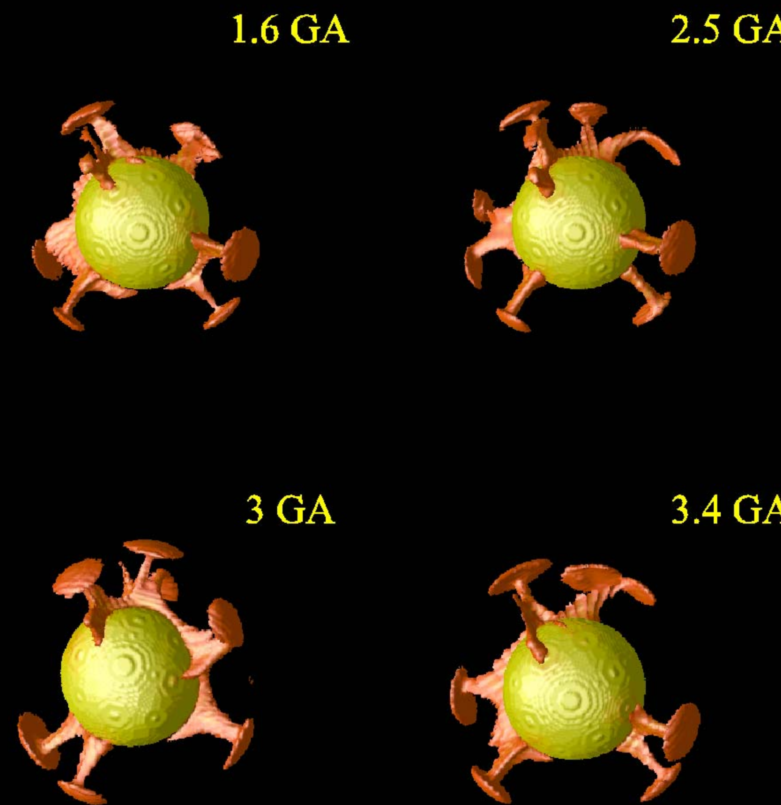
Heat Transport Mechanisms

- Plate tectonics
  (Earth, early Mars?, early Venus?)
- Stagnant lid convection
  (Mercury, Venus?, Mars, Moon
- Lithosphere delamination
  (Venus?)



Magma transport (volcanism)

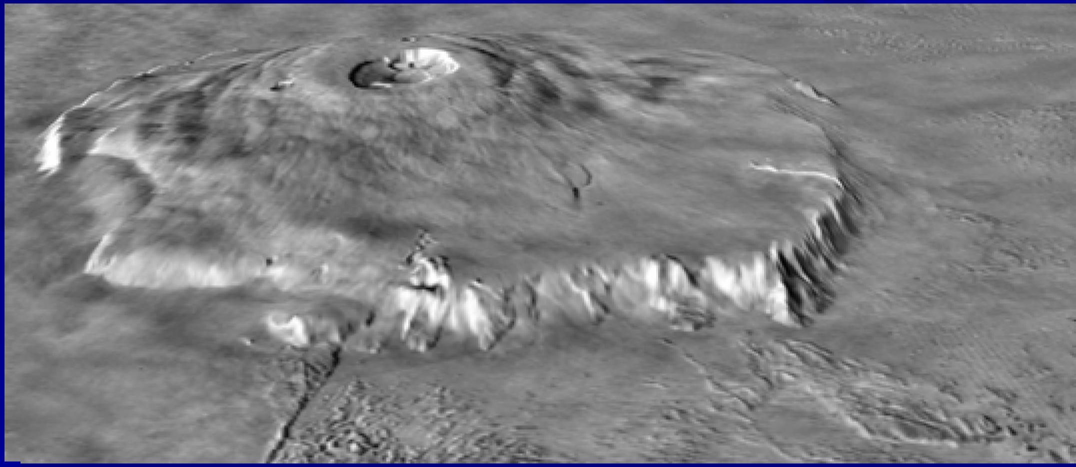
Martian mantle convection without phase transitions



ROB

Plume Volcanism on Mars?

- Early global volcanic activity reduces during the evolution in mainly one or two regions: Tharsis & Elysium

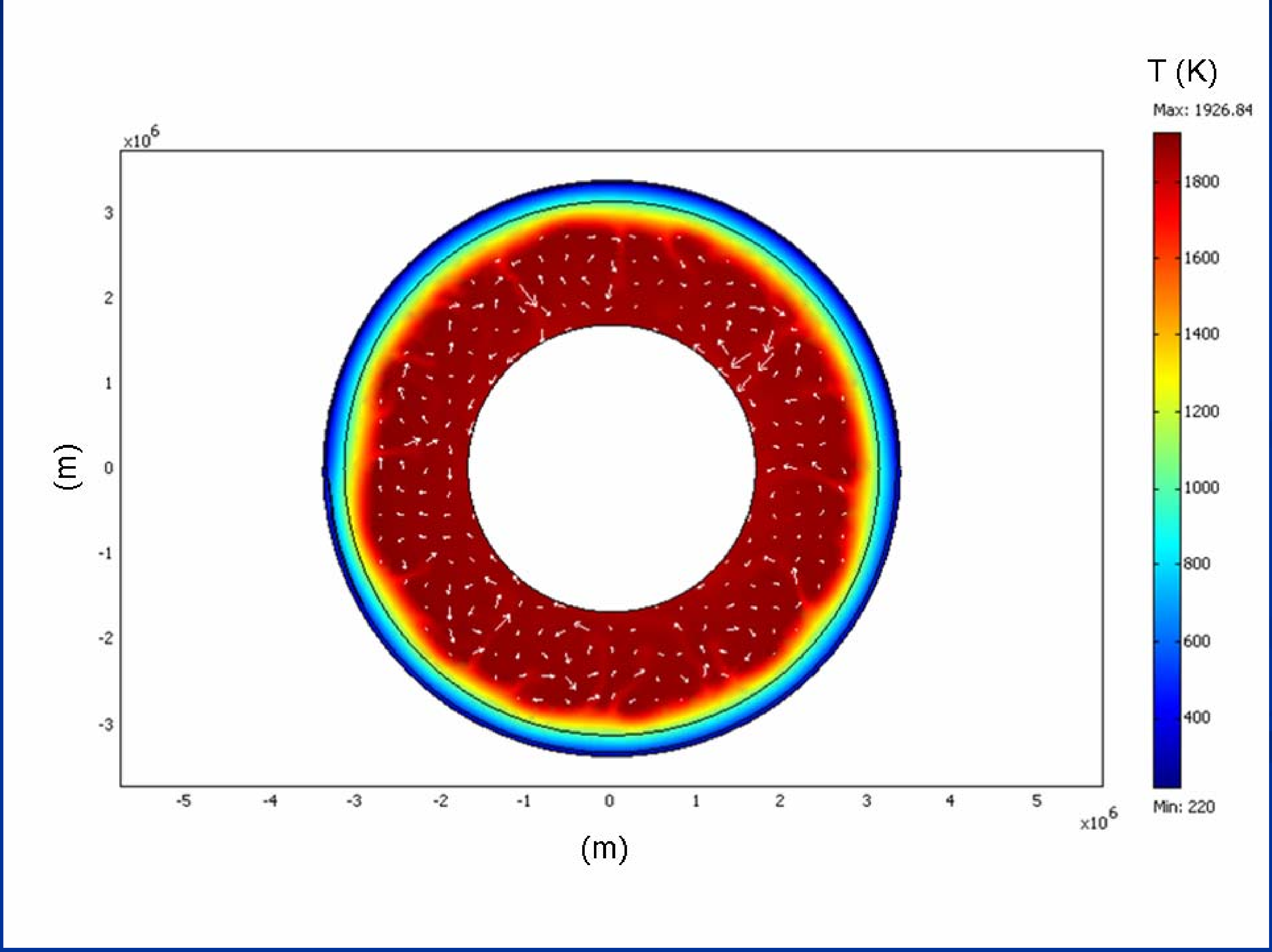


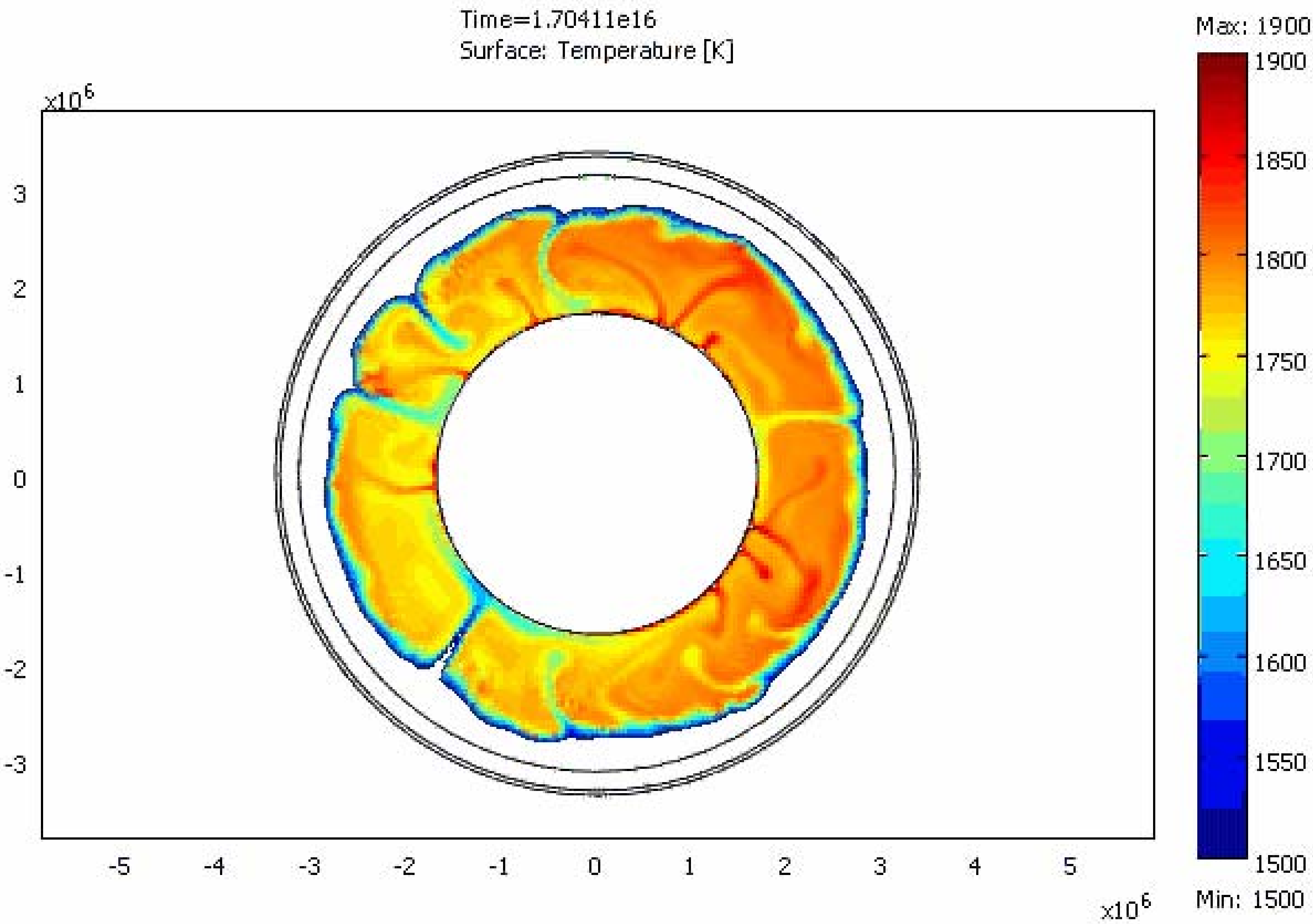
Conditions required to sustain plumes

- Perovskite layer
  - With a perovskite layer close at the core-mantle boundary it might be possible to generate a large plume early in the evolution but this will be very weak if existant after about 1Ga.
- Heated core
- Chemical layering

Model from Sandra Schumacher (ESA)

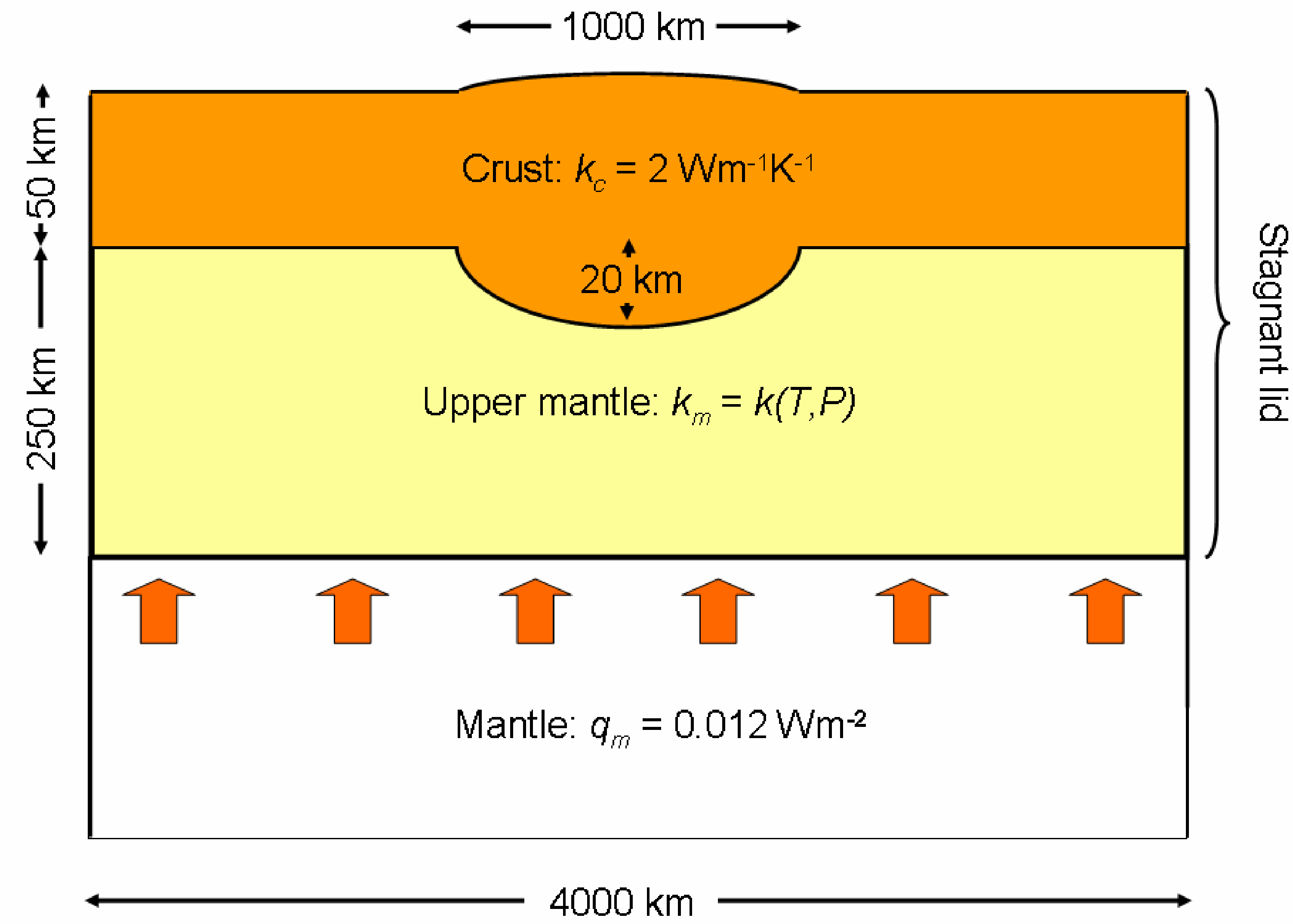
Temperature distribution




Time=1.70411e16
Surface: Temperature [K]
Max: 1900
1900
1850
1800
1750
1700
1650
1600
1550
1500
Min: 1500
x10^6
3
2
1
0
-1
-2
-3
-5
-4
-3
-2
-1
0
1
2
3
4
5
x10^6

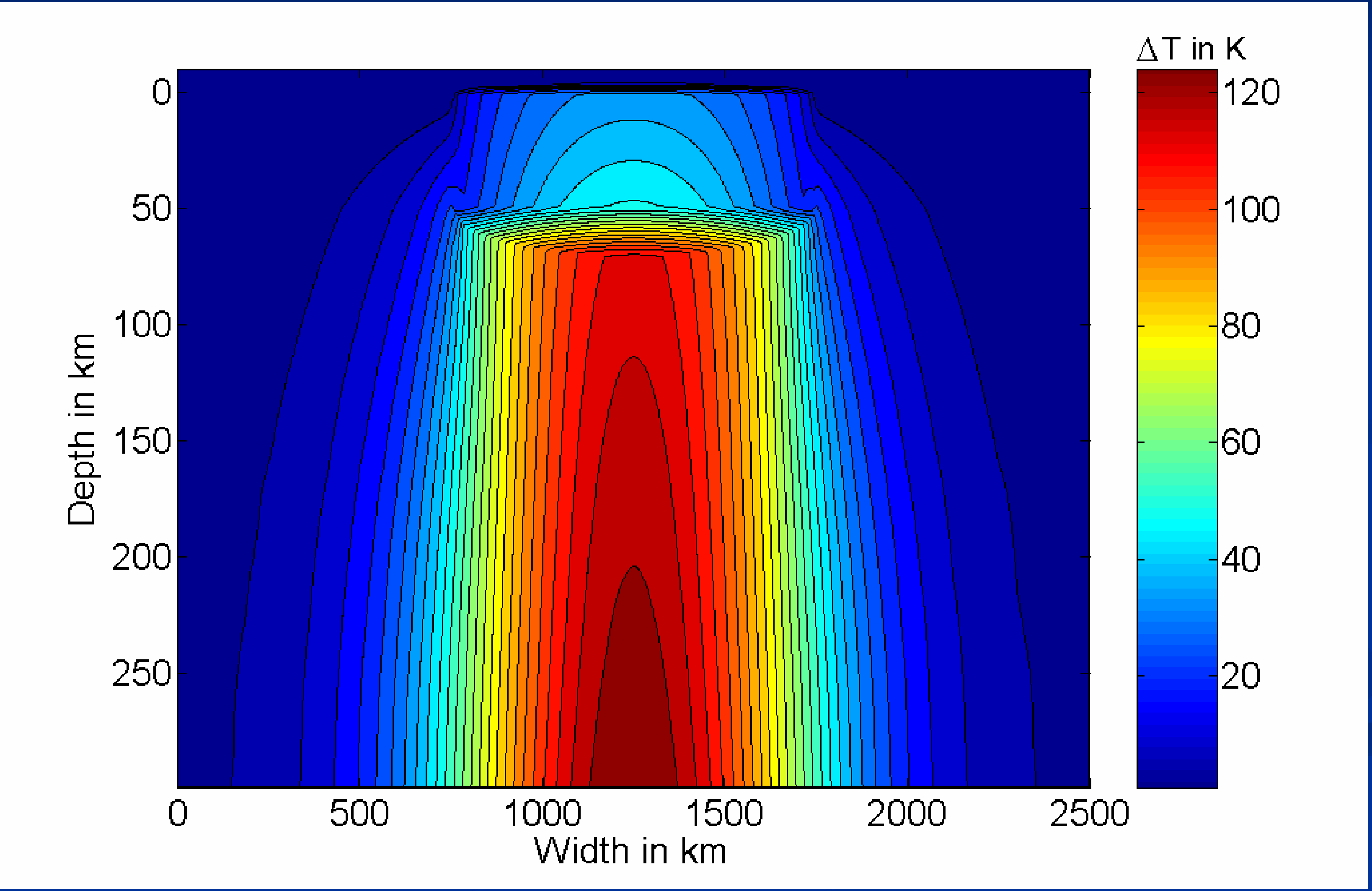
Model from Sandra Schumacher (ESA)

Model



Model from Sandra Schumacher (ESA)

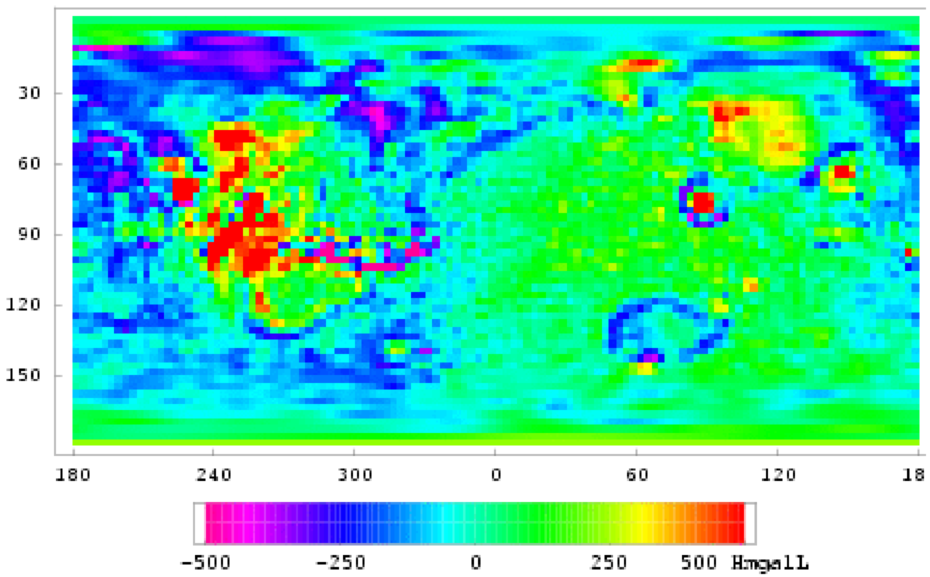
Temperature increase

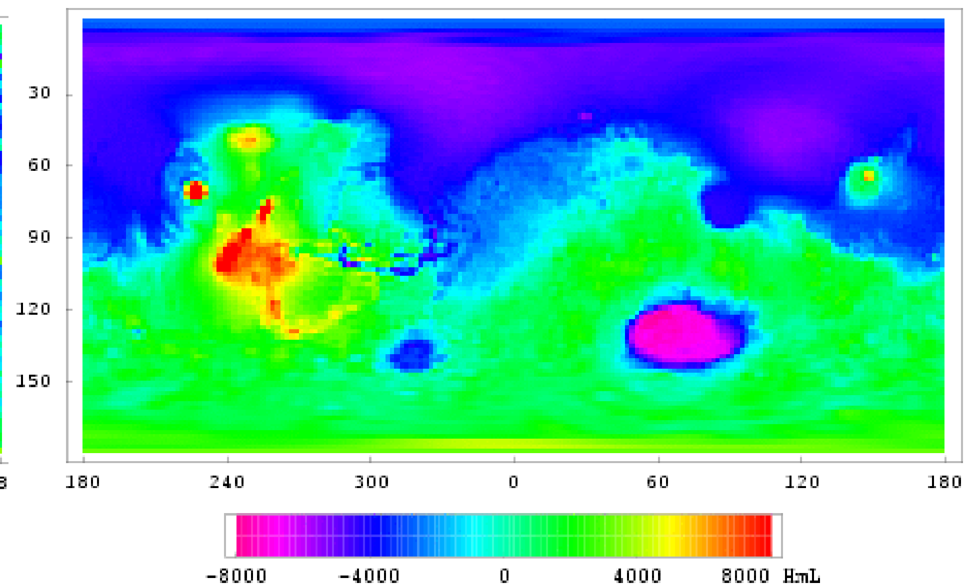


Mars Express 2003

Comparison between

gravity and topography

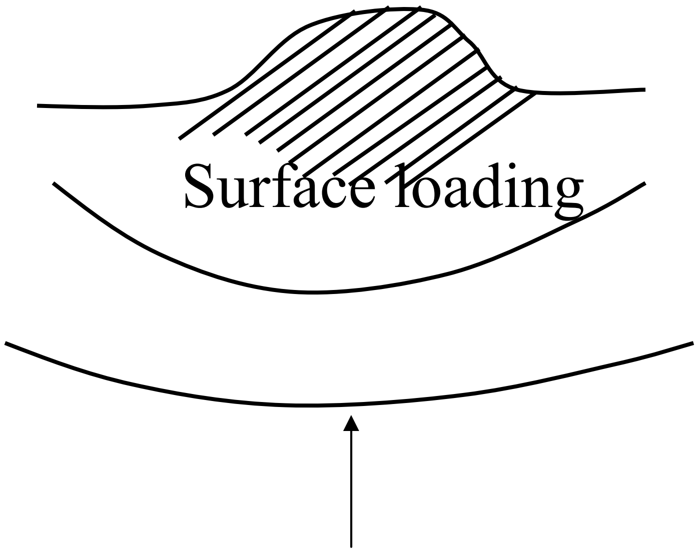




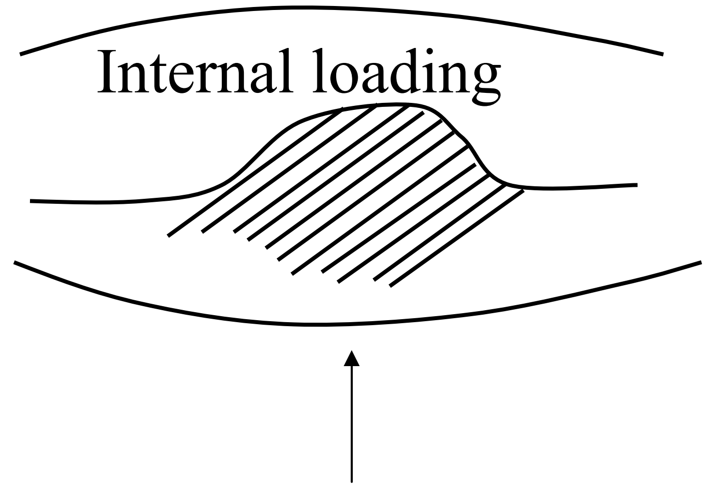
Sometimes very strong correlation, sometime no correlation at all, sometimes no topography signal when gravity signal, and sometimes no gravity signal when topography signal

ROB

Different types of loading

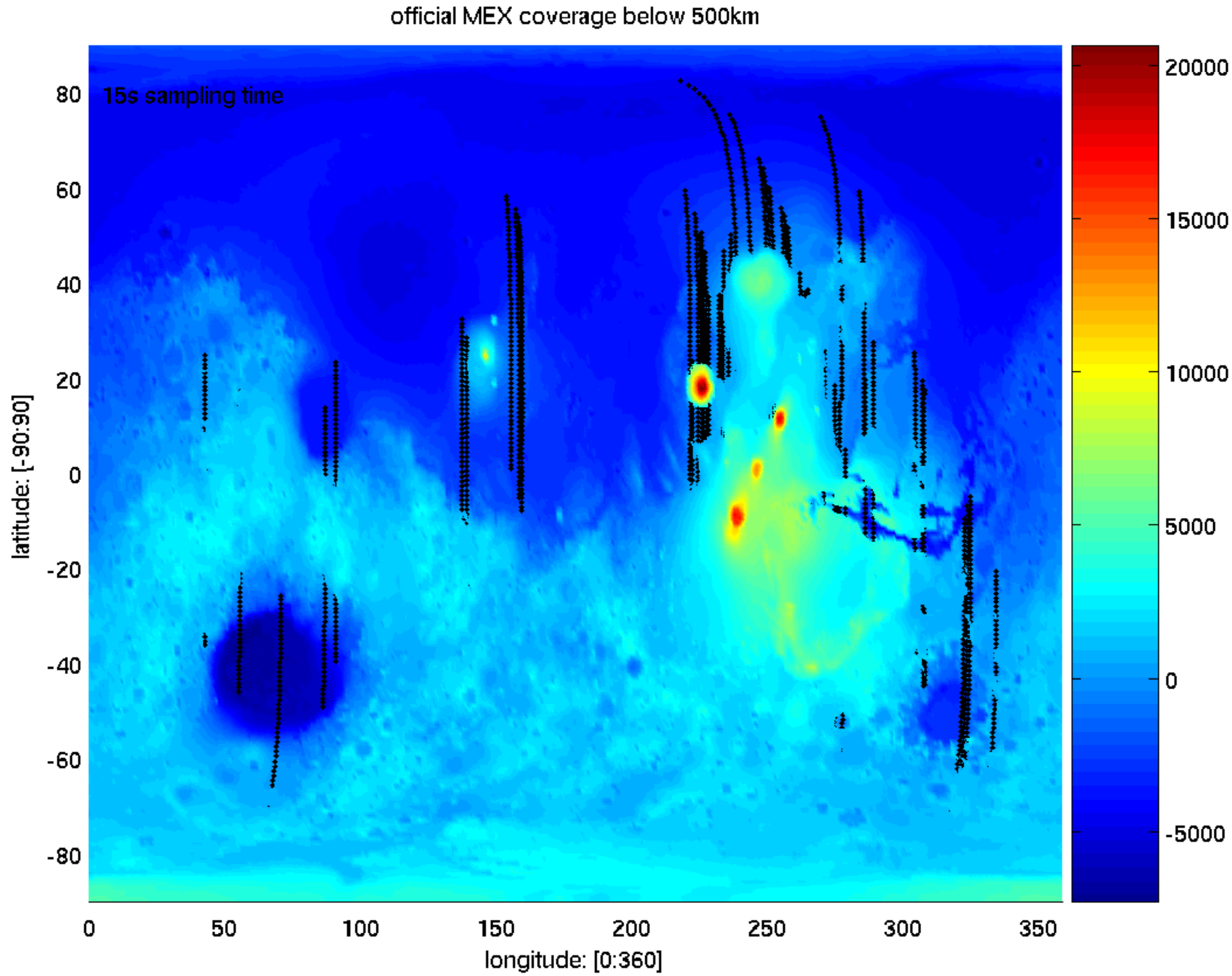


Good model if
gravity and topography
correlate well



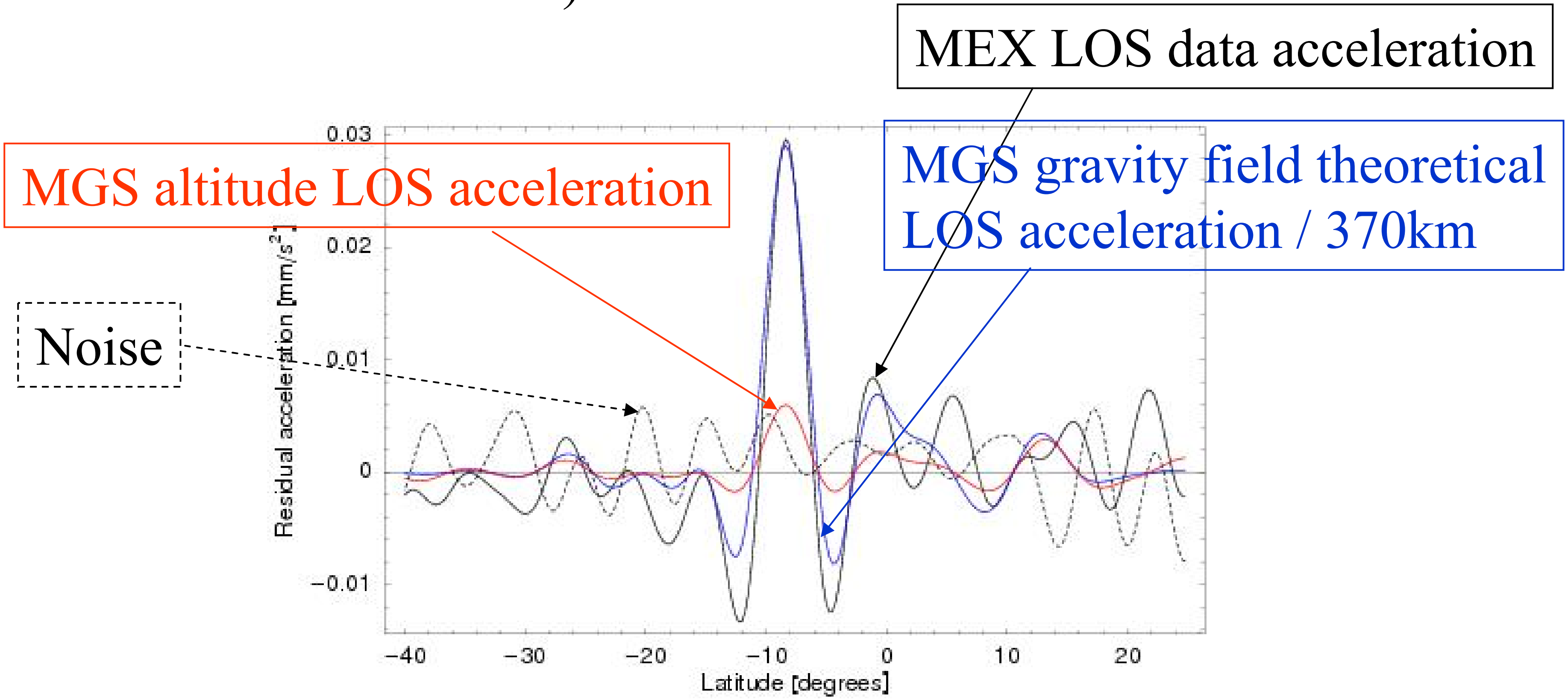
Necessary if
high gravity signal
but small topography

Gravity passes above targets



Sensitivity

- Pericenter: in the range 272-306 km
- Signal 4 times stronger than at altitude of 370 km
- Noise on velocity: 0.2 mm/s (0.0015-0.003 mm/s^2 on filtrated acceleration)

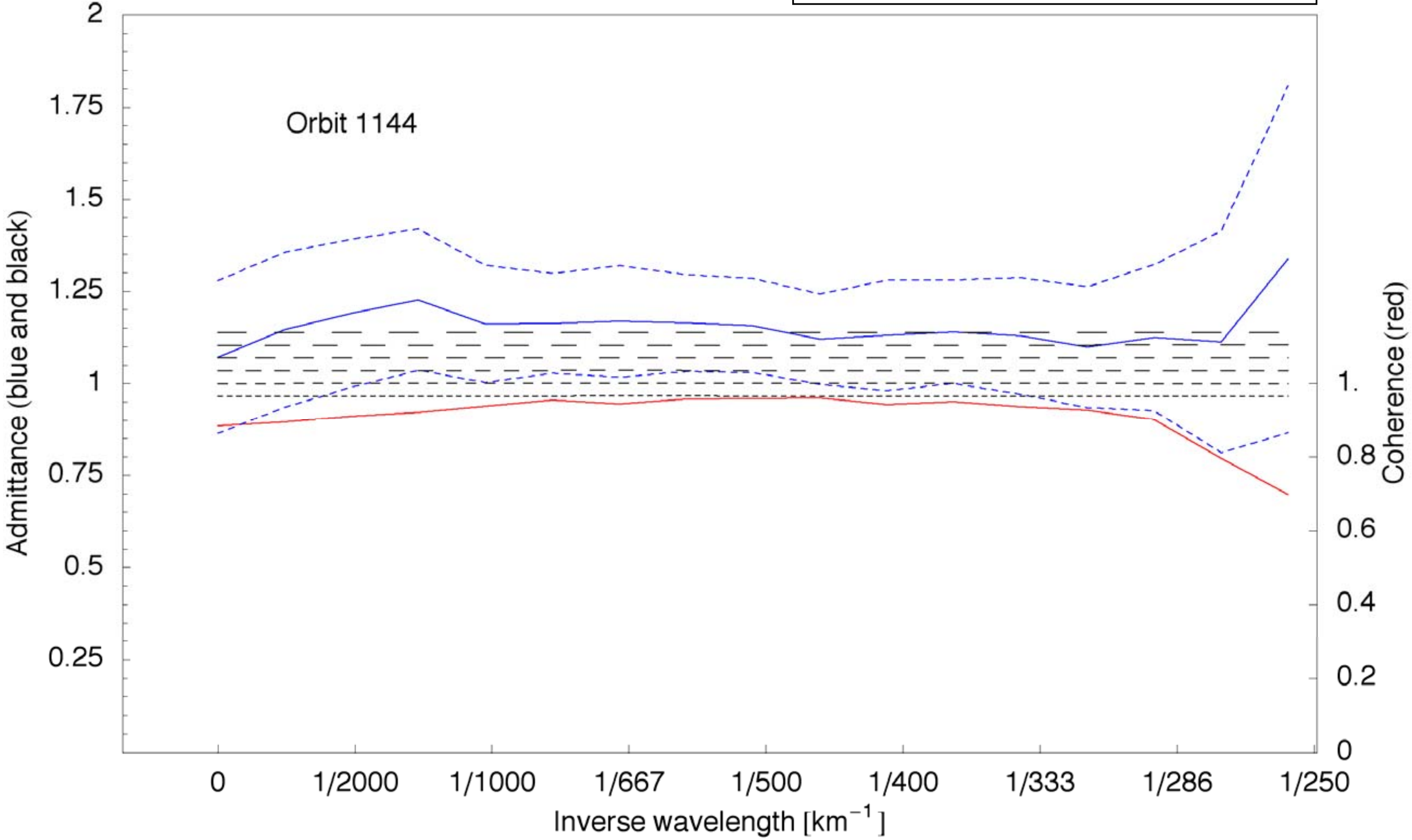


Method

- Acceleration = filtered derivative of raw Doppler residual (filtering at 70-80 sec)
- Resampling in space to get equal spacing at surface (no wavelengths under 300 km)
- Predicted acceleration along LOS from global field MGS85F2 and from topography compensated by lithospheric deflection
- Spectral analysis in 1-D of observations and predictions: power spectrum, coherences, and admittances

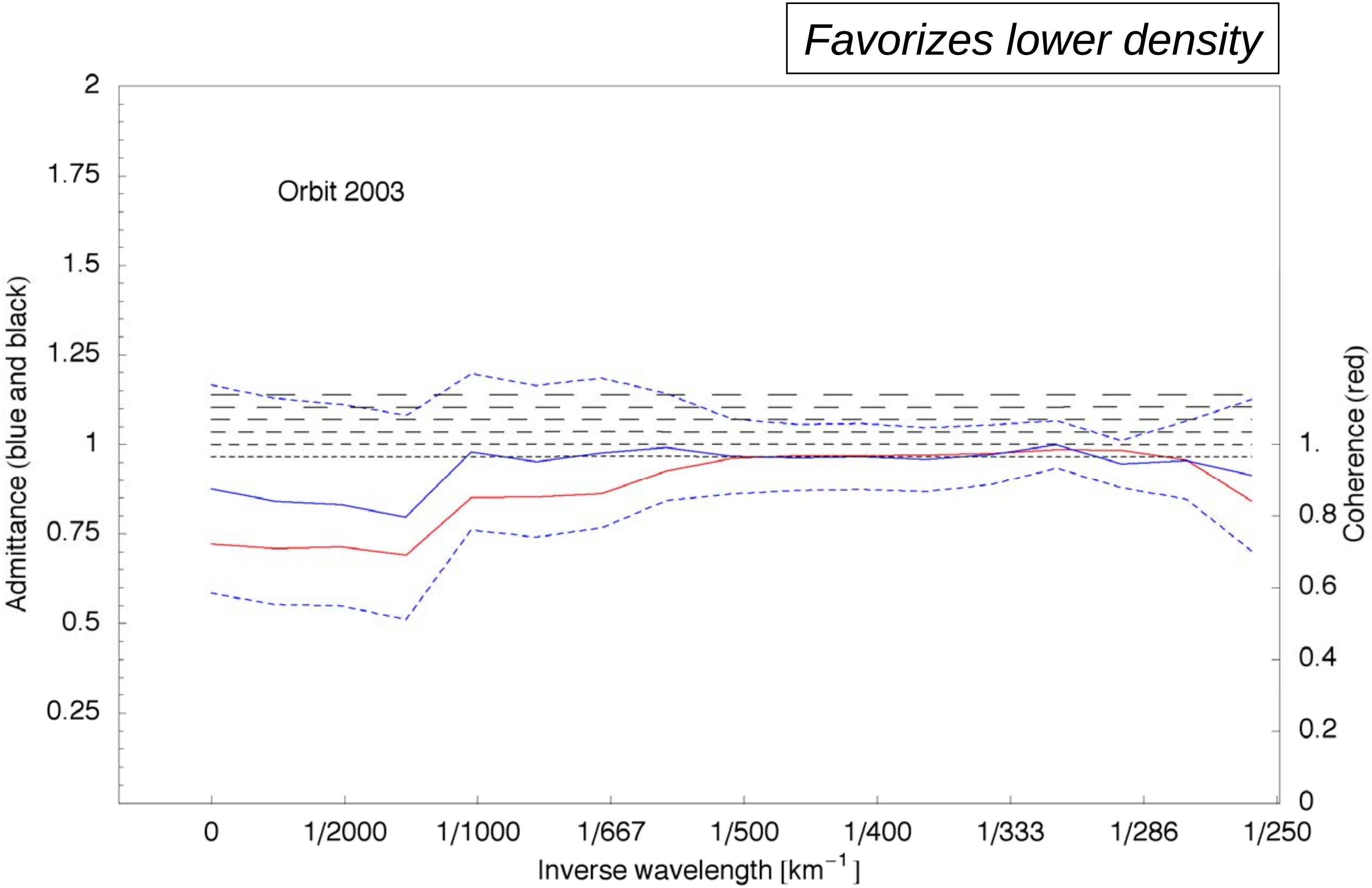
Profile 1144: spectral analysis

Favorizes higher density



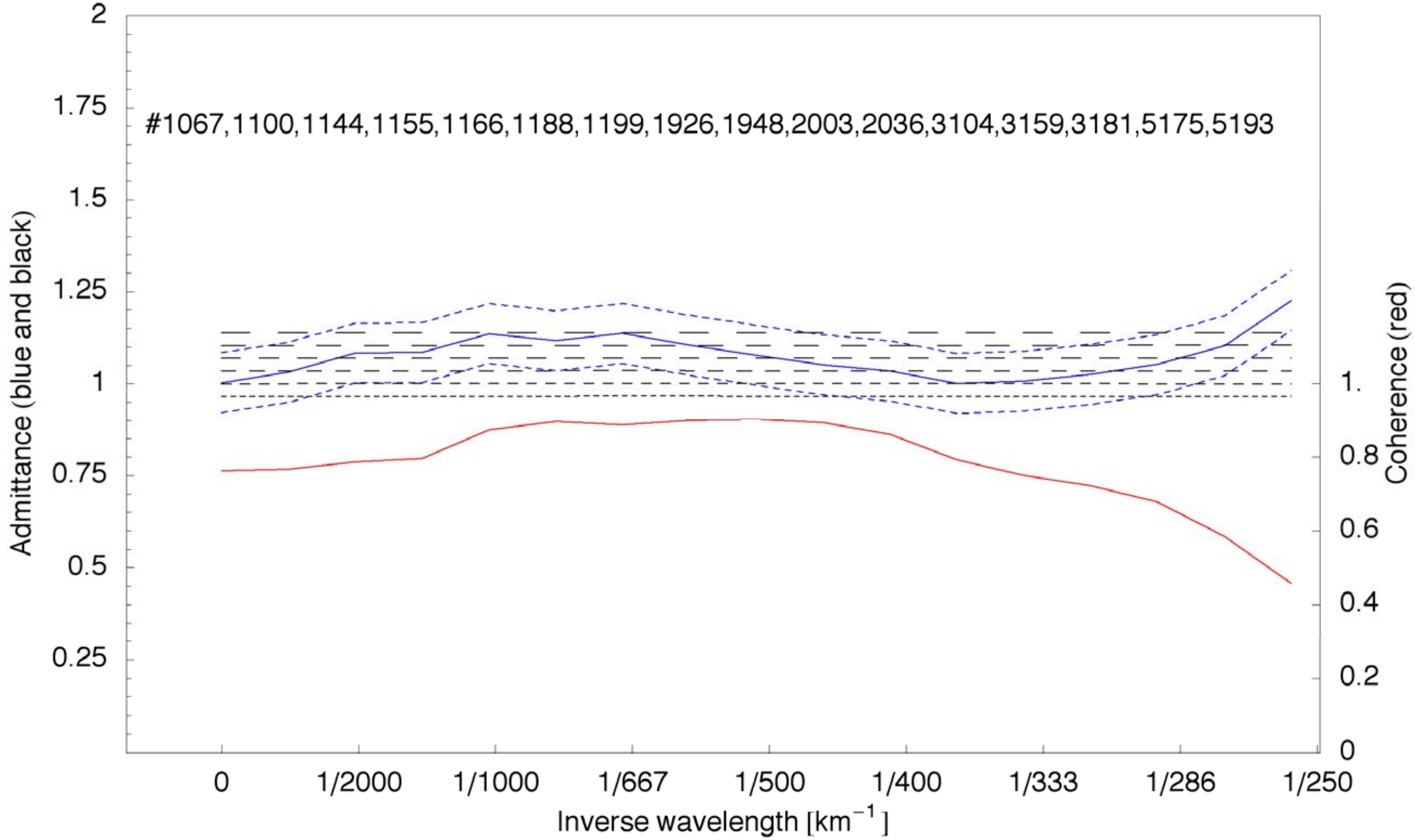
Models in dashed lines: density varies from 2800 (bottom) to 3300 kg/m3 (top)

Profile 2003: spectral analysis



Models in dashed lines: density varies from 2800 (bottom) to 3300 kg/m3 (top)

Profiles above Olympus: spectral analysis



Models in dashed lines: density varies from 2800 (bottom) to 3300 kg/m3 (top)

Mars Interior:
Part 2: Geodesy and Rotation

Veronique Dehant

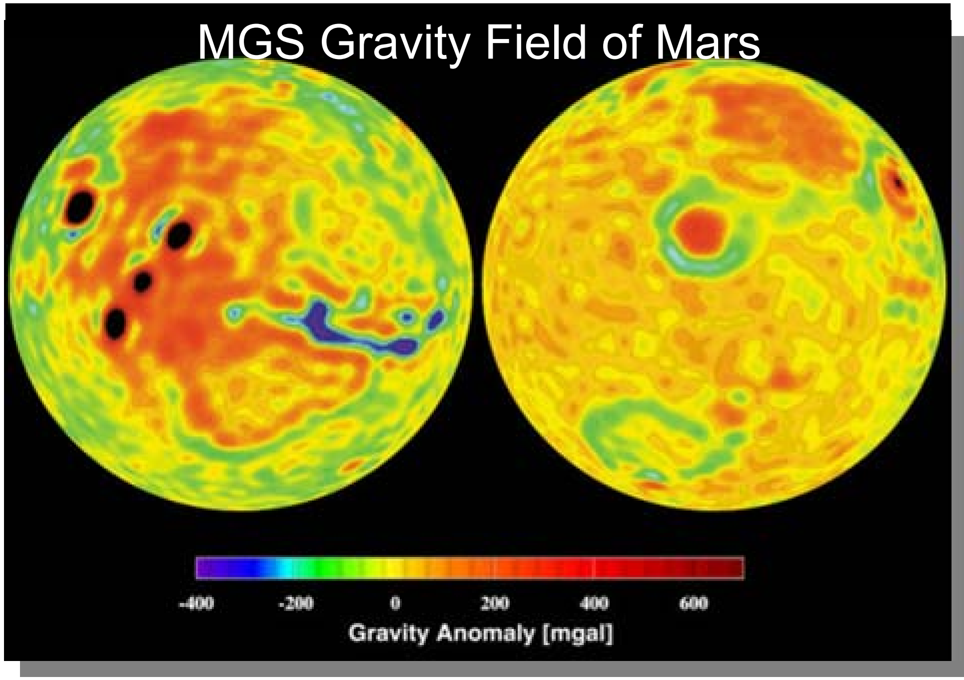
With the help of Pascal Rosenblatt, Attilio Rivoldini and ROB team

Royal Observatory of Belgium (ROB)

What do we know about interior structure?

Constraints

- Magnetic anomalies
- Mass
- Moment of inertia factor
- Gravity field
- Tides
- Surface rock chemistry/ mineralogy
- Cosmochemical
- Laboratory data
- Plate tectonics
- Volcanism

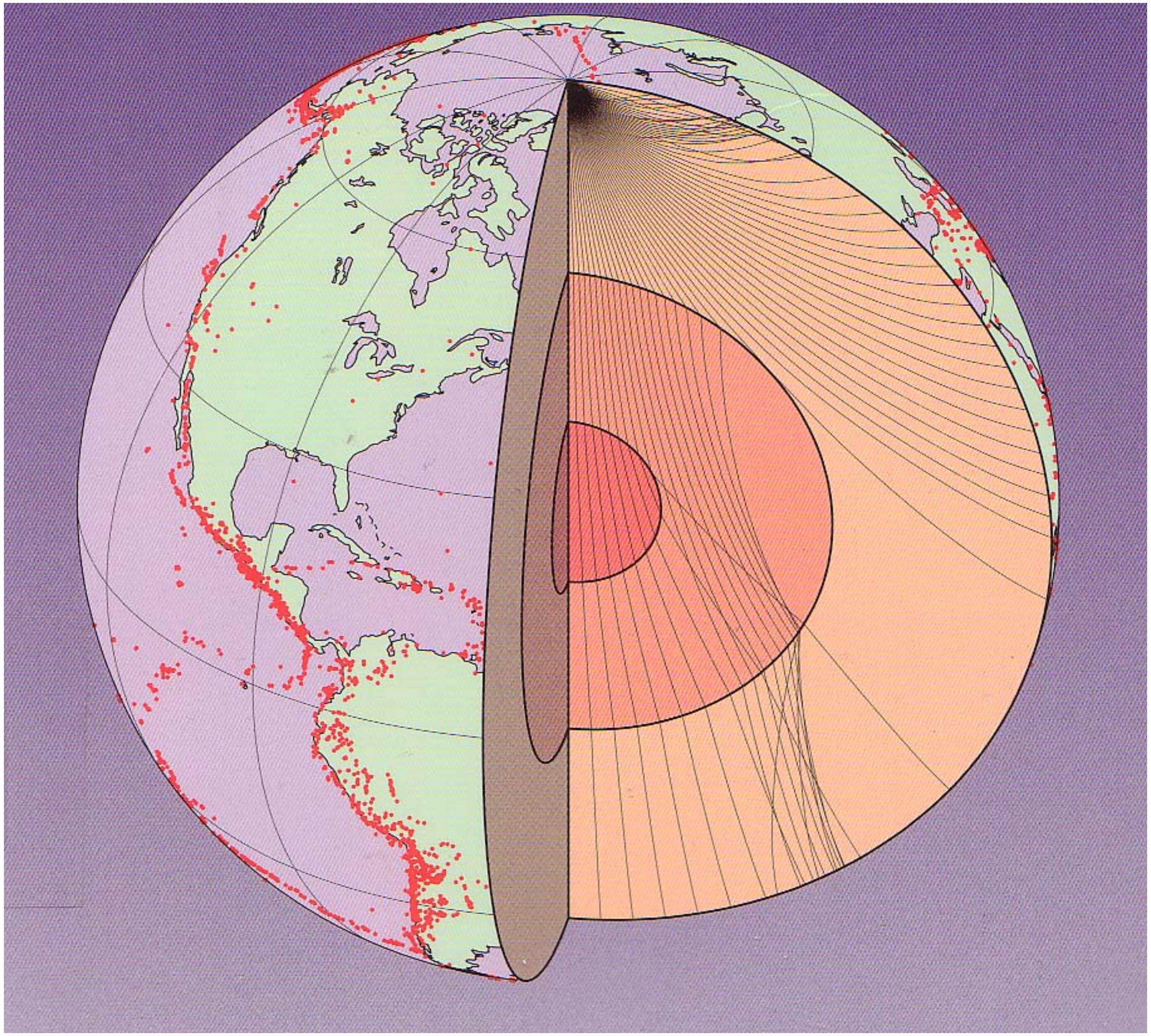


- **Future:**
  - **Rotation! Geodesy!**
  - **Seismology!**
  - **Heat flow!**
  - **Conductivity!**

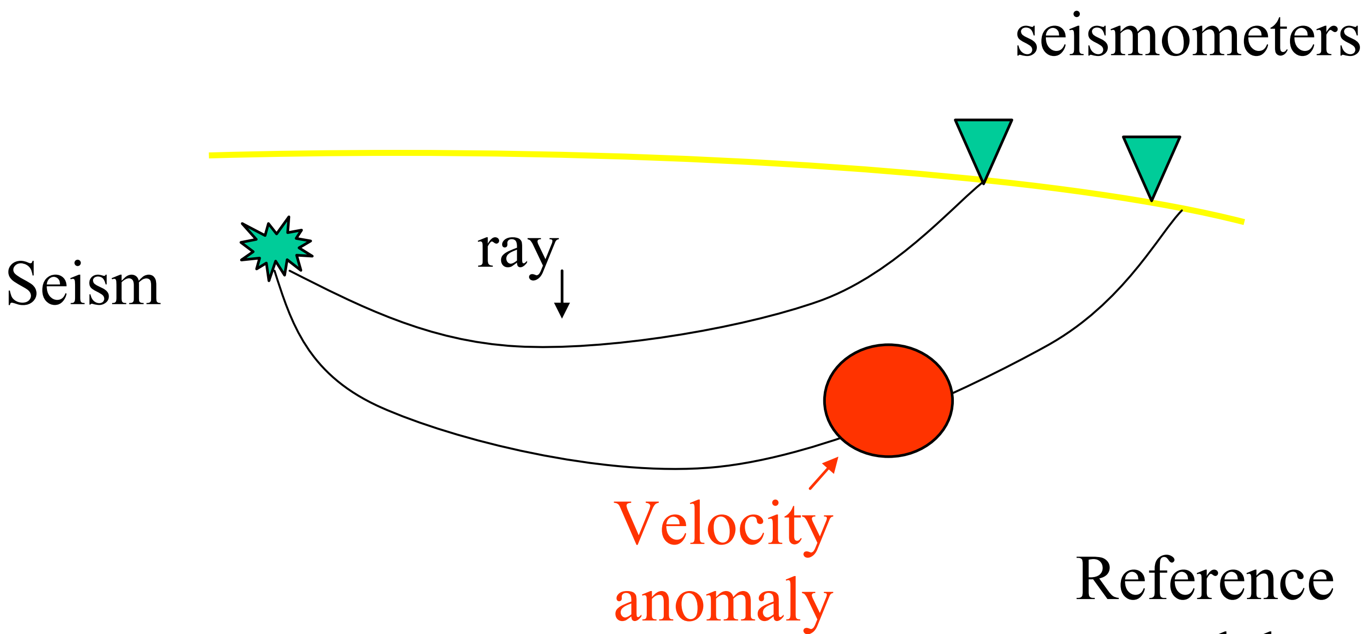
ROB

Interne structure of Mars

- Solid mantle
- Liquid core
- Inner core (!?)



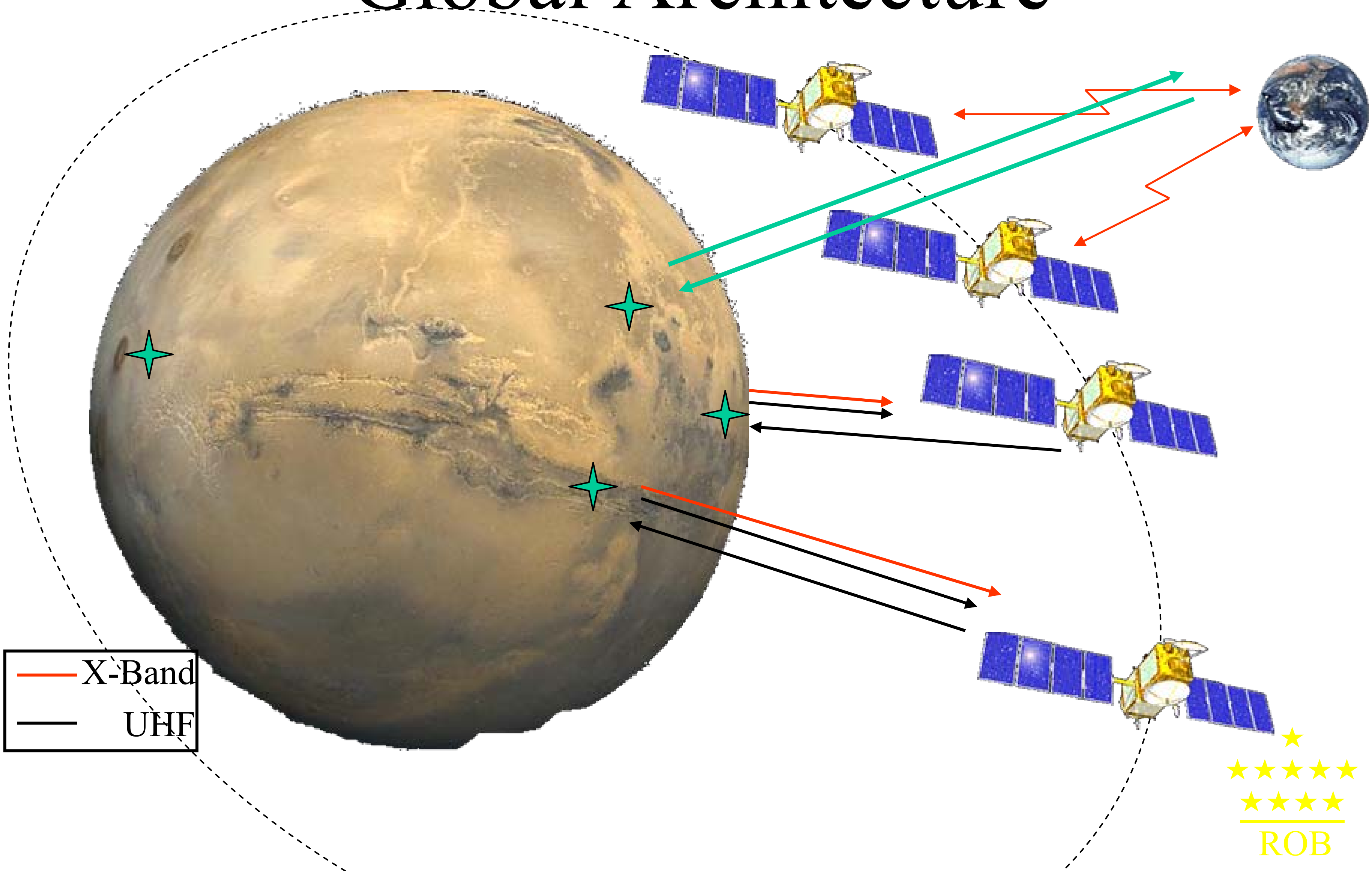
Tomography

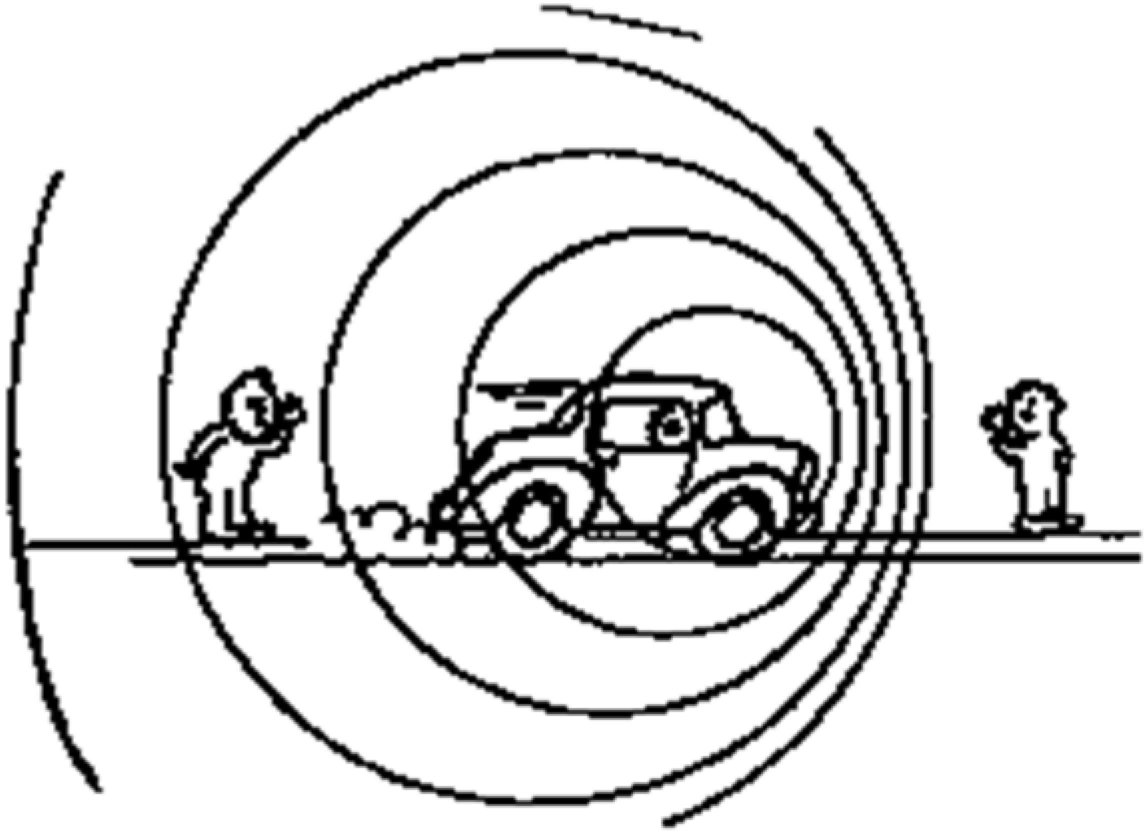


Reference model $+$ anomaly

Propagation time $=$ T $+ \delta T$

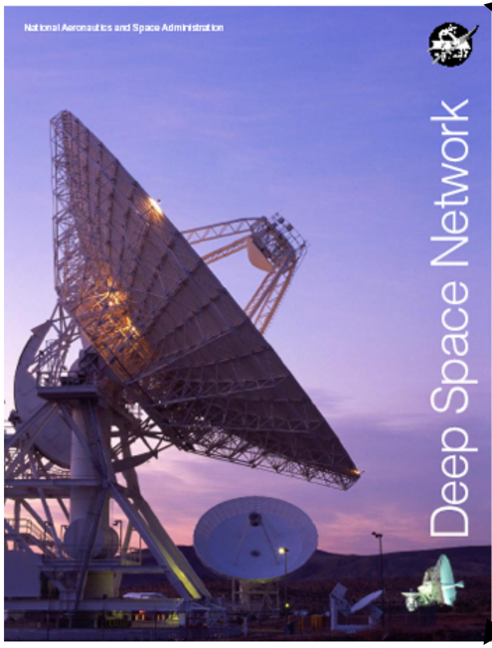
Global Architecture

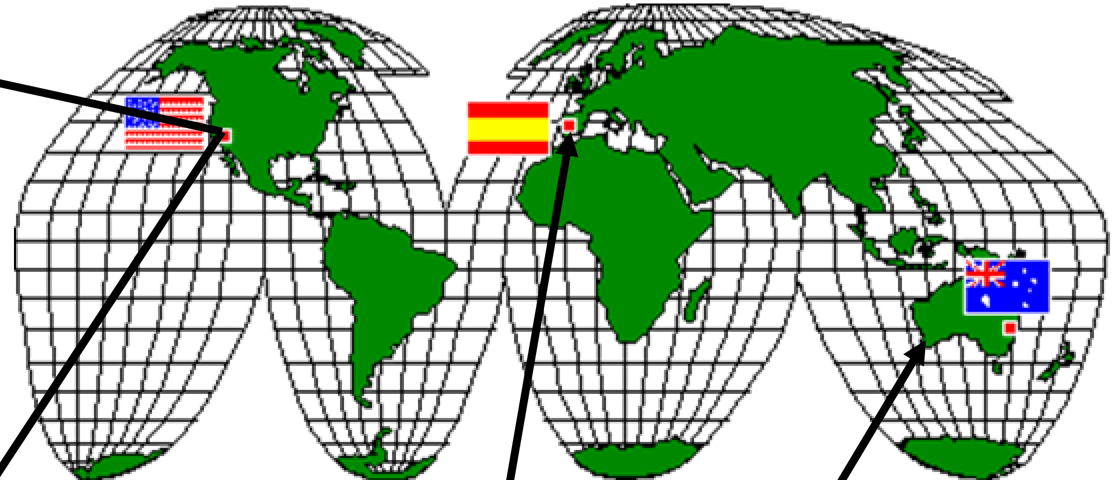




NASA’s DSN and ESA’s ESTRACK networks of tracking stations

- To track any spacecraft or Lander in the solar system

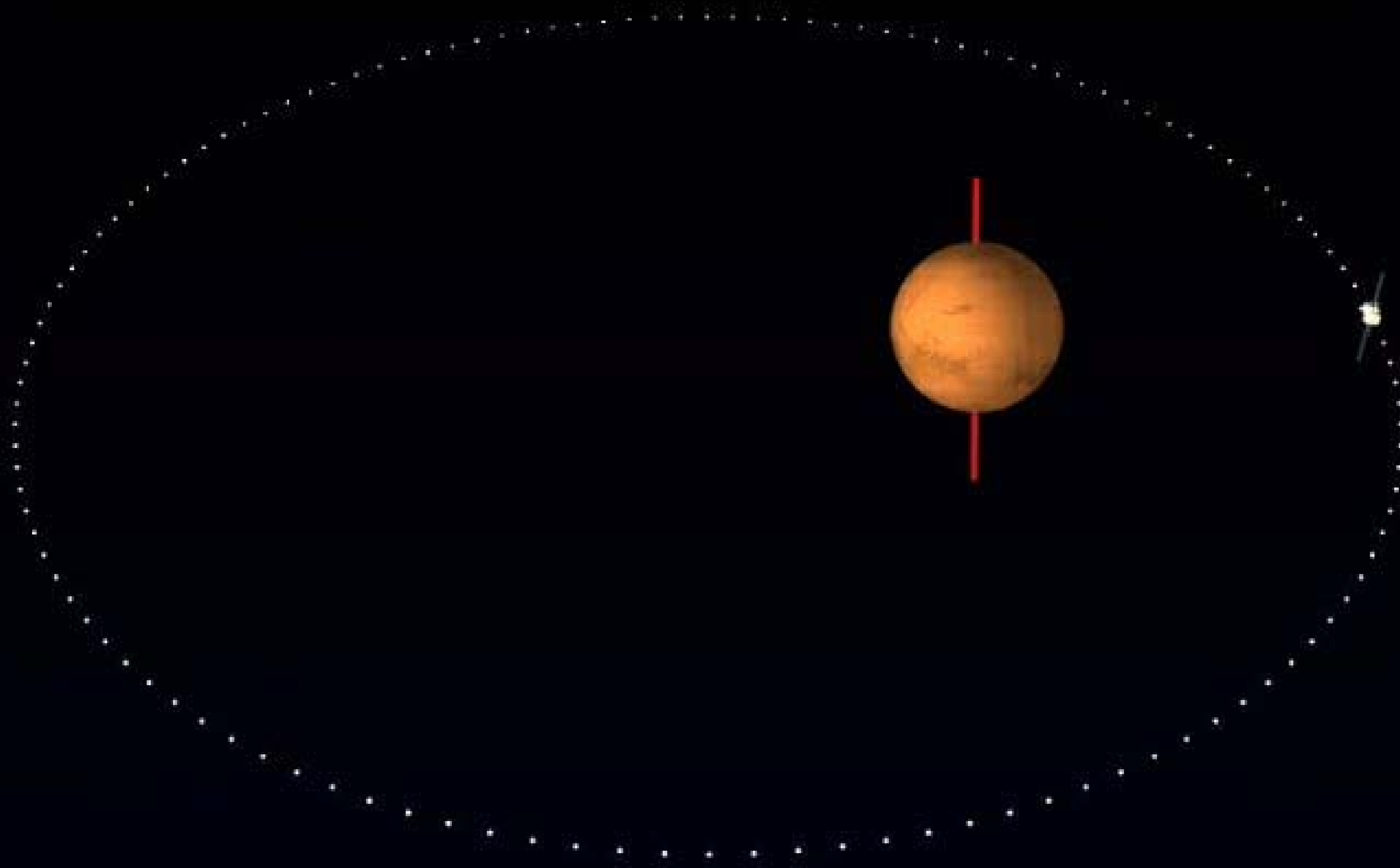




ESA’s 34 m. antenna at New Norcia
& Cebreros (Mars Express, Venus Express)

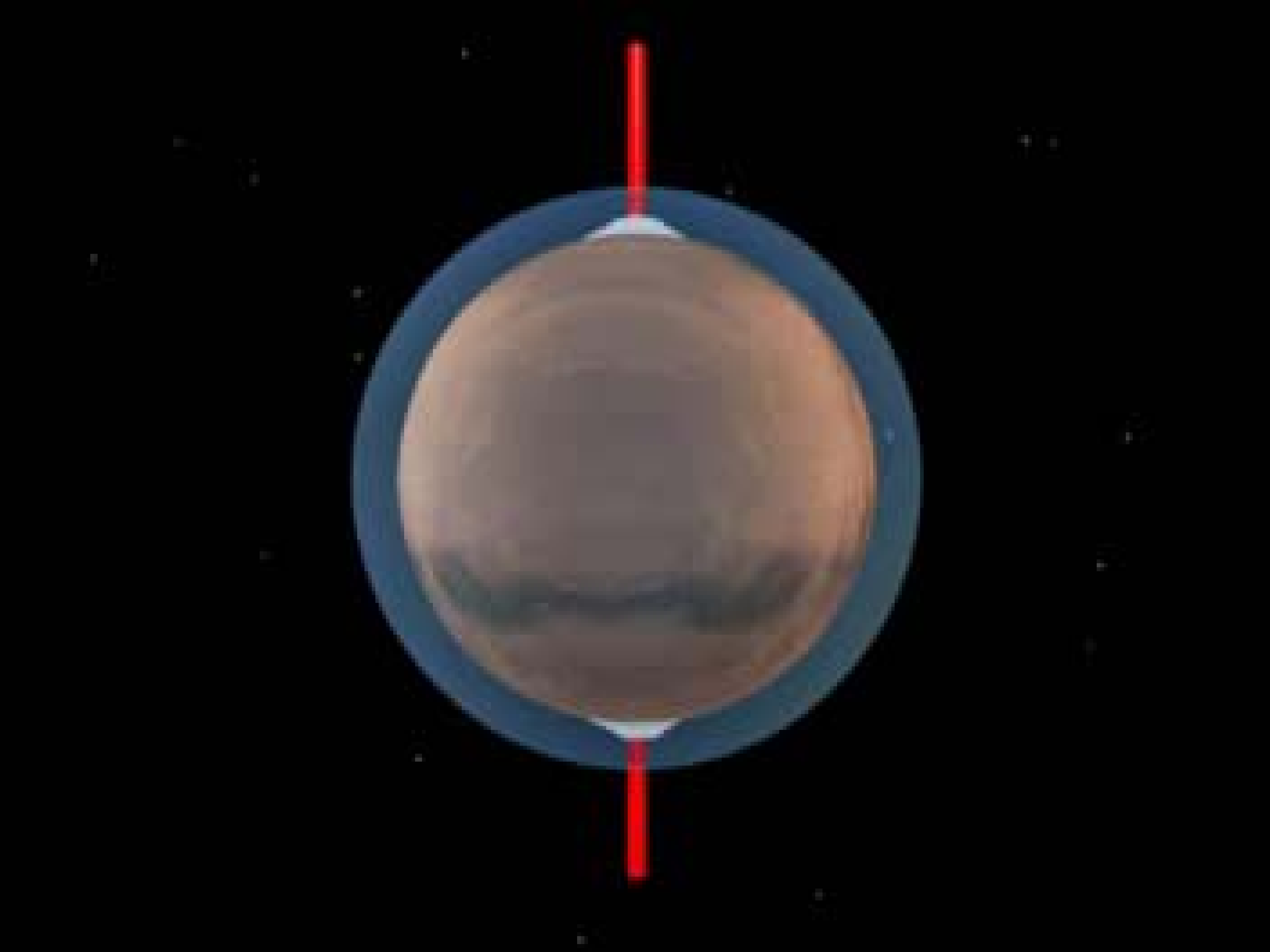
Diameter of 25 to 70 meters.
Precision:
0.02-0.05 mm/s (1-3 mHz)
< ~1 m. But bias of ~3-4 m.
Dating: Maser clocks

- Radio-link for data & telemetry
- Doppler & range radio-tracking mainly at frequencies of 8.4 Ghz (X band) (sometimes dual-frequency X/S bands to correct ionospheric and interplanetary plasma perturbations)



Orbit determination

- model of “macro-model” of the s/c i.e. 6 faces and 2 solar panels + reflectivity and absorptivity values for each face;
- orientation of the faces of the satellite from predicted quaternions;
- model of Mars’ surface albedo + Infra-Red flux ➔ radiation fluxes F_R
- model of Mars’ atmospheric density ➔ pressure drag F_D
- shift in position between the center of mass of MEX and the center of phase of the HGA
- event files will be used to evaluate the epoch of desaturation maneuvers
- Gravity field and its time variation, i.e. the first zonal coefficients of the gravity field (J2, J3, J4 and J5)
- Love number k2: later
- Ephemerides
- Phobos and Deimos mass/origin



Tides and interior structure

Tides can be used for the determination of core properties

- Core radius between 1400 km and 1800 km
- Core liquid?
- Tides depend on interior structure: e.g. larger tidal displacement for fluid core
- Driving force precisely known

Orders of magnitude

- Tidal potential $U_T \propto GM_{\odot} r^2/d^3$: 7% of Earth
- Relative to $U=-GM/r$, $g=GM/r^2$
  - $U_T/U \approx 1\ 10^{-8}$ $\longleftrightarrow$ Earth: $2.5\ 10^{-8}$

1. $\xi \propto U_T/g \approx 3$ cm
2. $g_T/g \approx 2U_T/U \approx 2U_T/U \approx 2\ 10^{-8}$

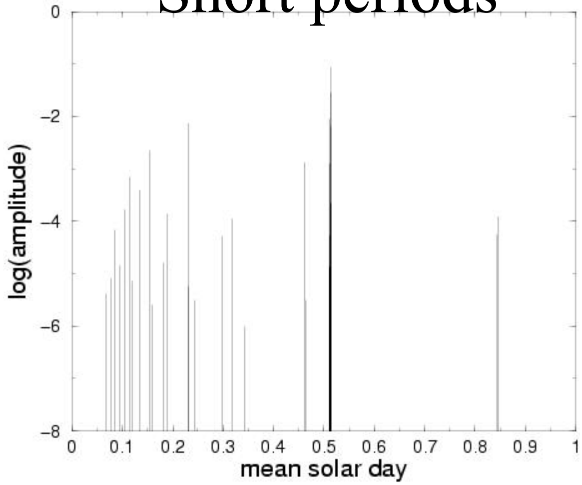
   $\longrightarrow$ $g_T \approx \mu$gal
3. $U_T/U \approx 1\ 10^{-8}$

Tidal potential

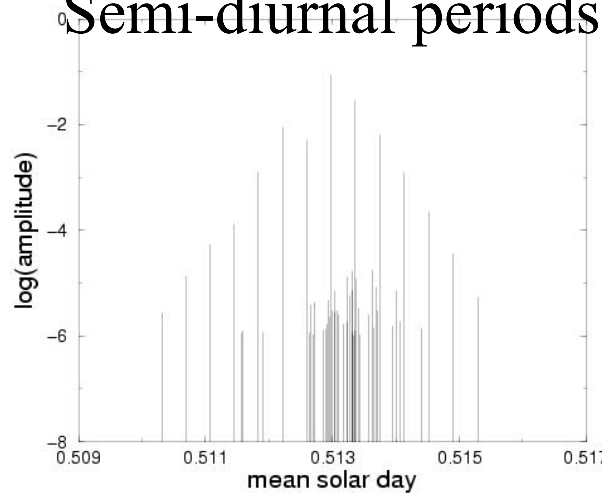
- Direct effect of Sun, Phobos, Deimos
- Indirect effect of other solar system bodies (ephemerides)
- Phobos/Sun: 8%, Deimos/Sun: 0.08%
- Up to degree 4
- Truncation at 10^{-6} m^2/s^2 (0.1 ngal): 203 tidal waves

Mars body tides

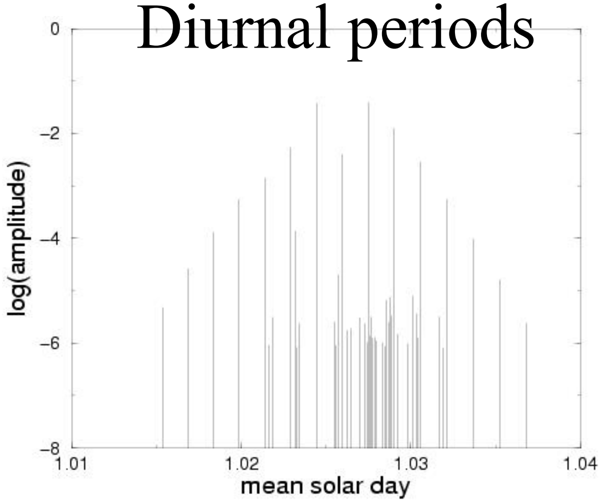
Short periods



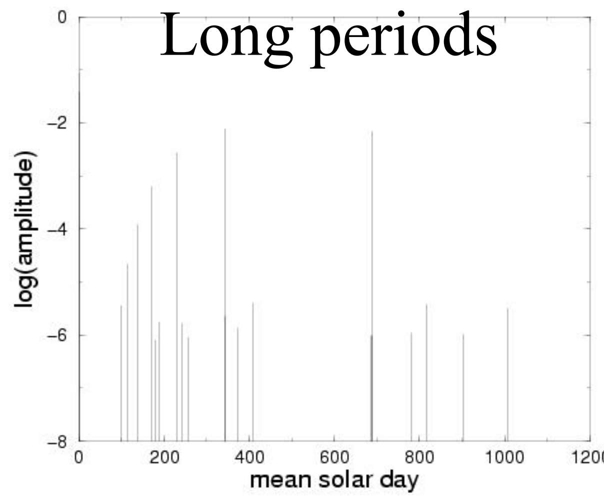
Semi-diurnal periods



Diurnal periods



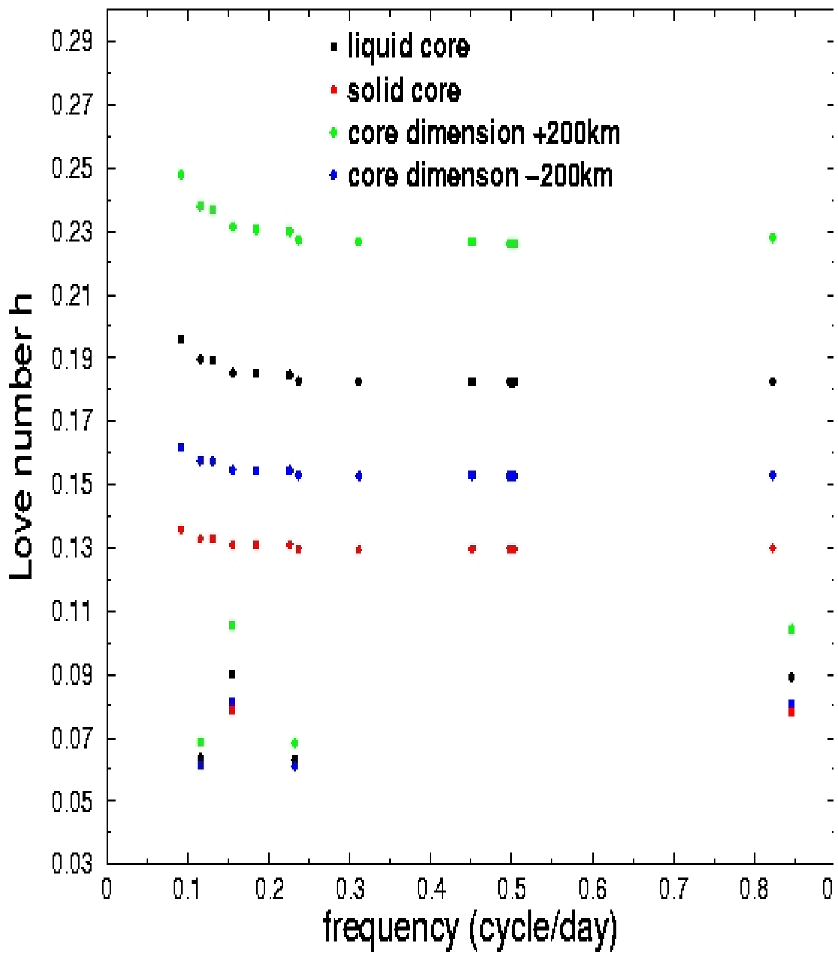
Long periods

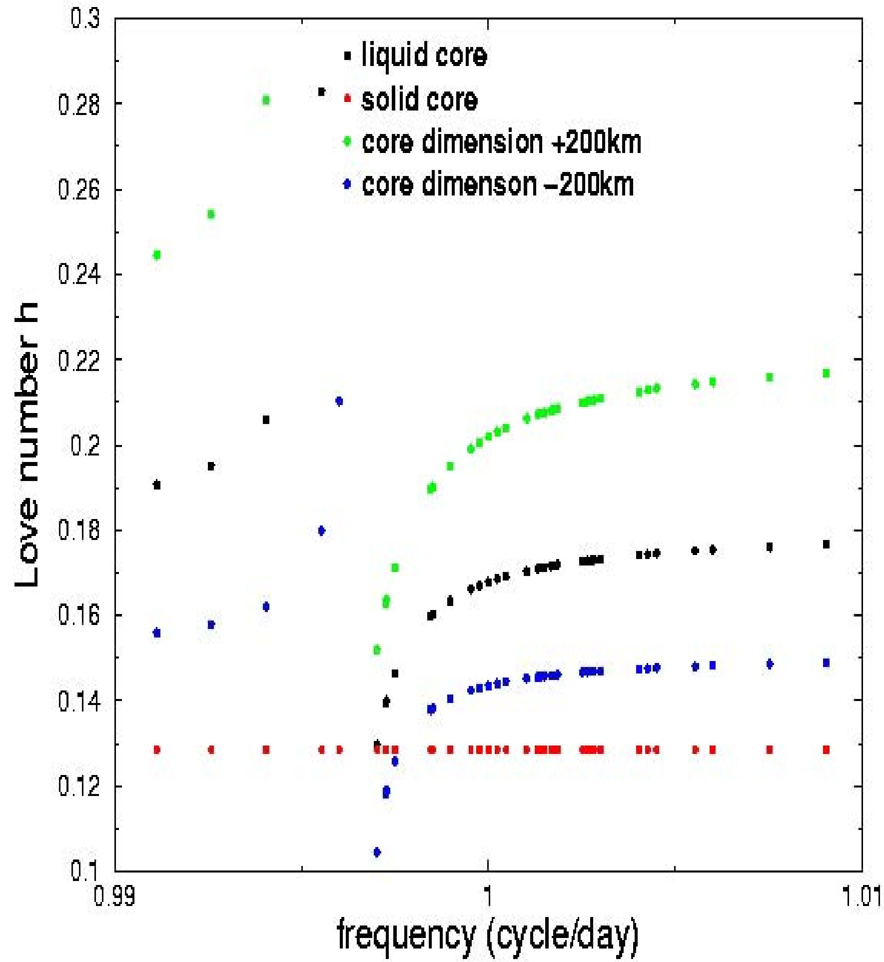


Love numbers

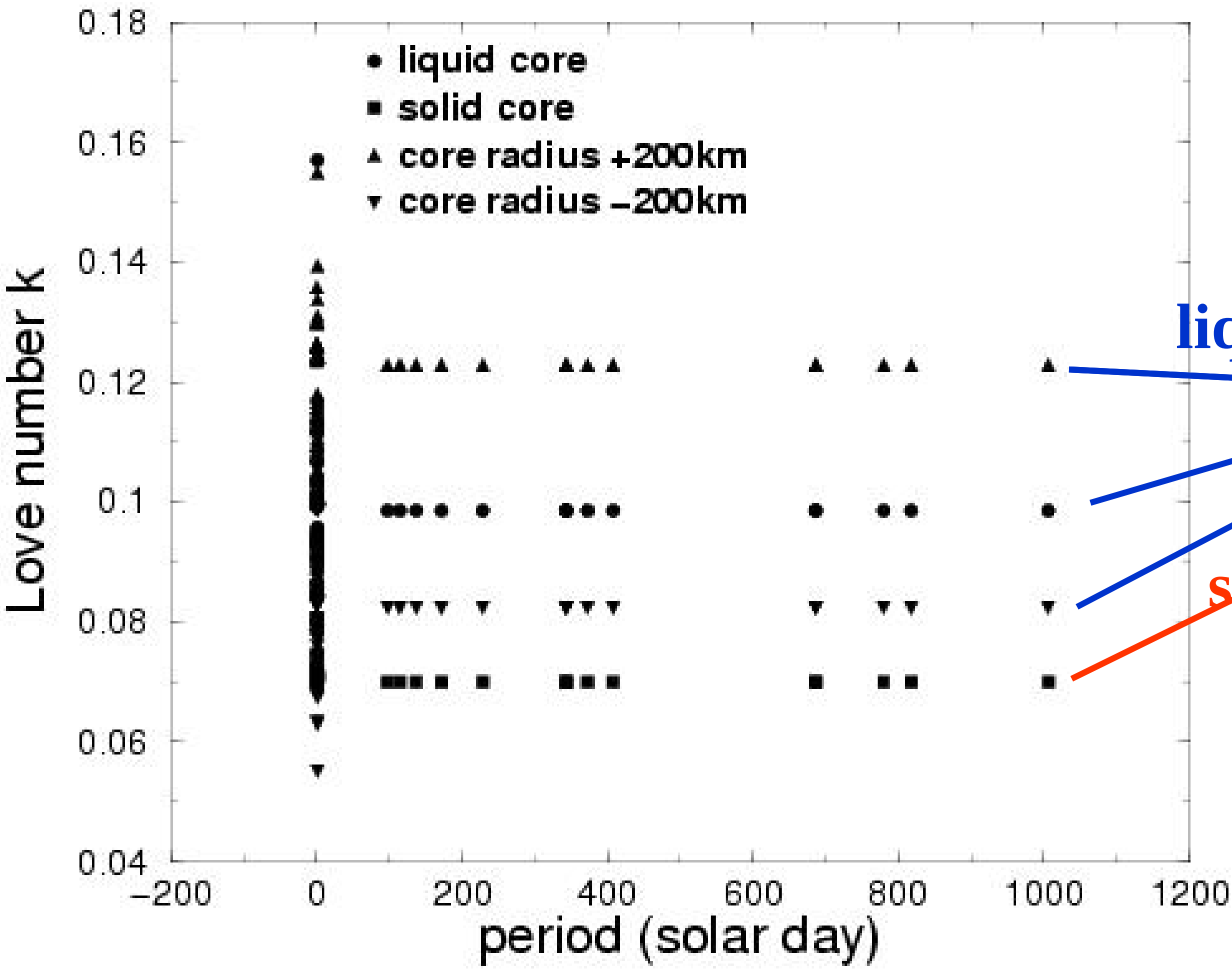
- Reaction of Mars to unit forcing
- Latitude and frequency dependence included
- *h*, *l* for tidal station displacements
- *k* for external potential perturbation
- Gravimetric factor δ for surface gravity variations
- Degree 2 Love number are very sensitive to the core: changes of 35% for different models

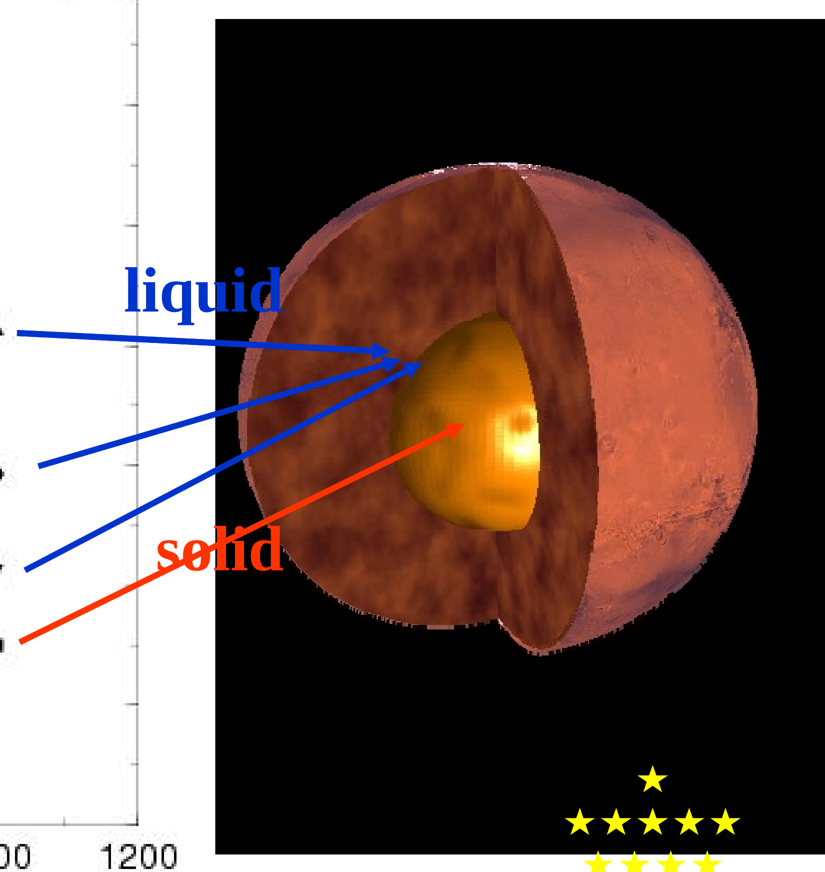
Love numbers

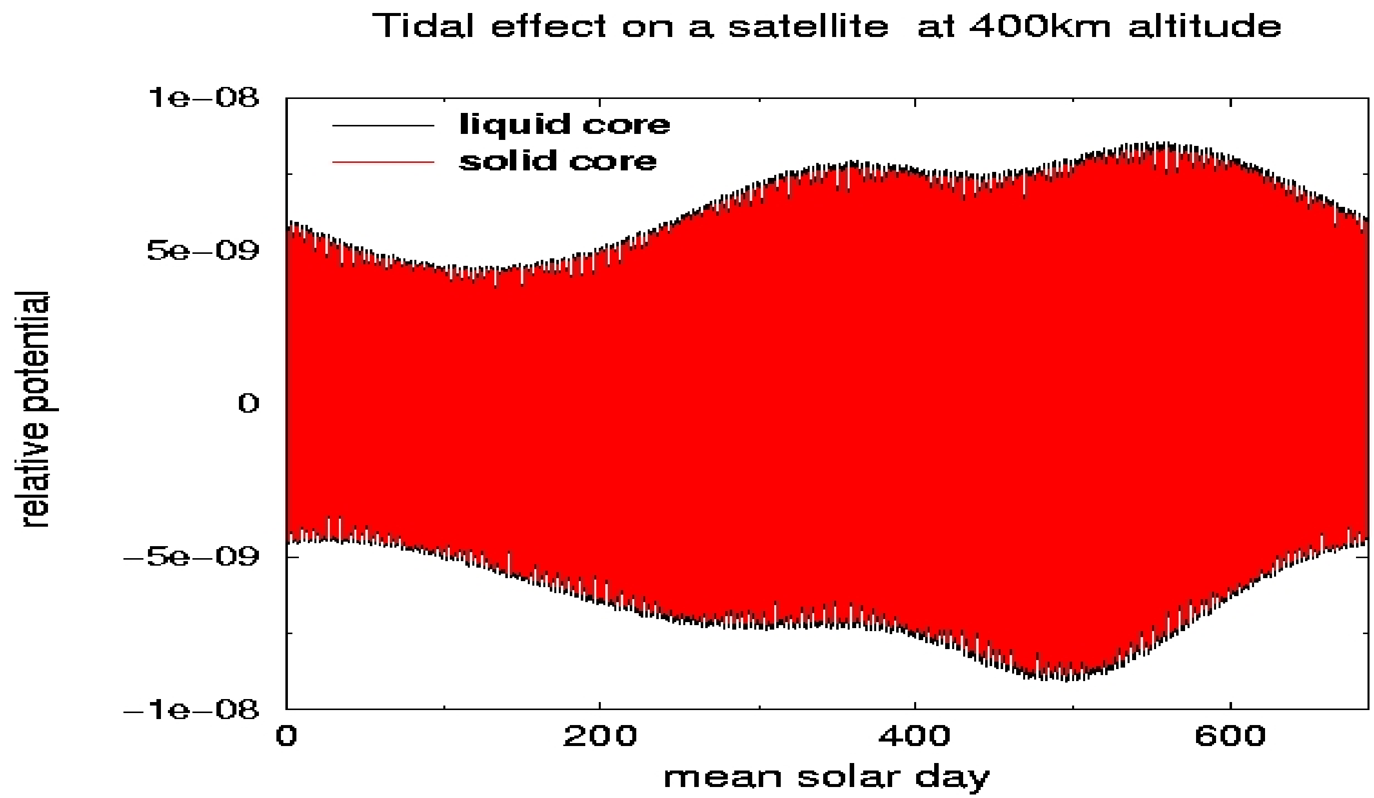




k Love numbers for solid/liquid core and different core sizes

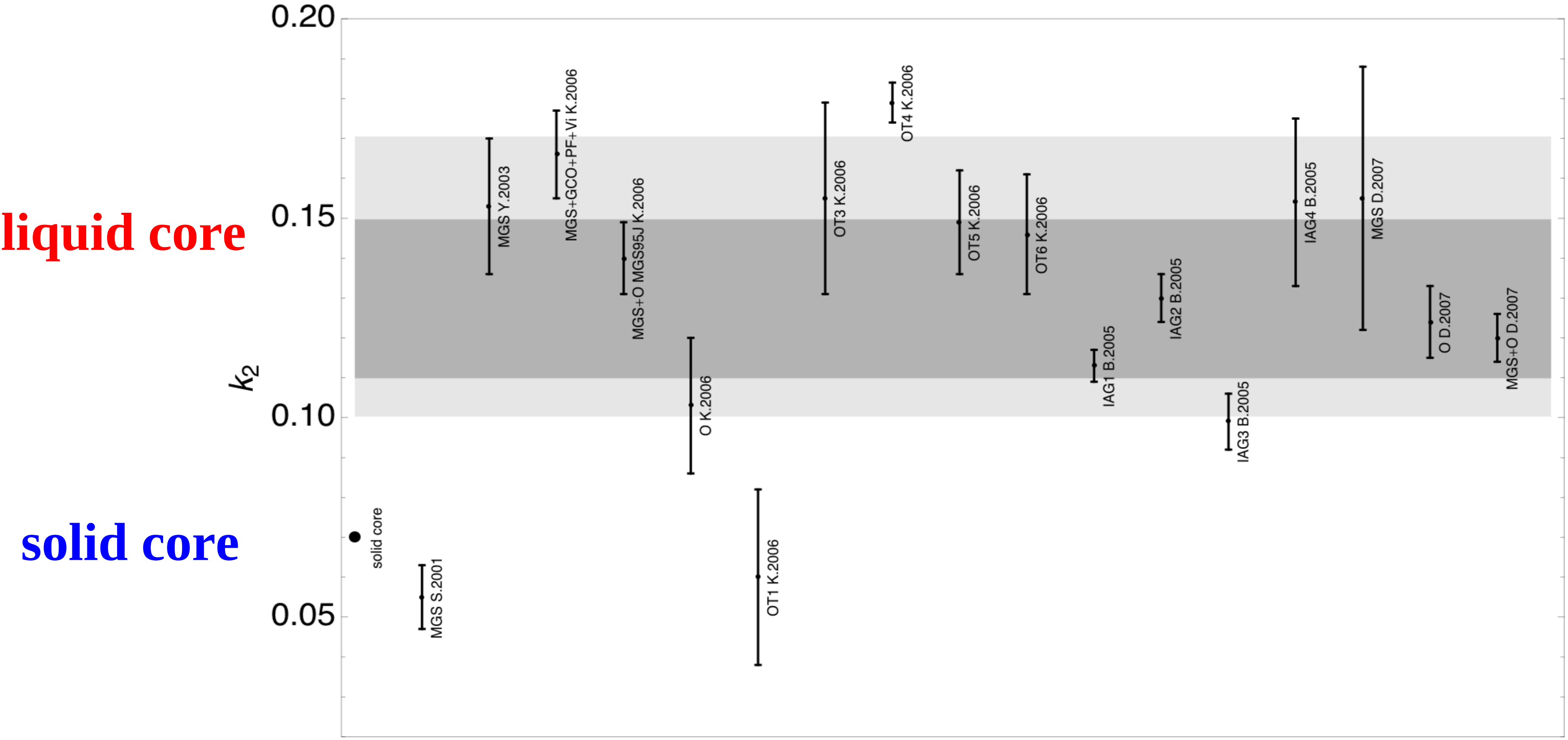


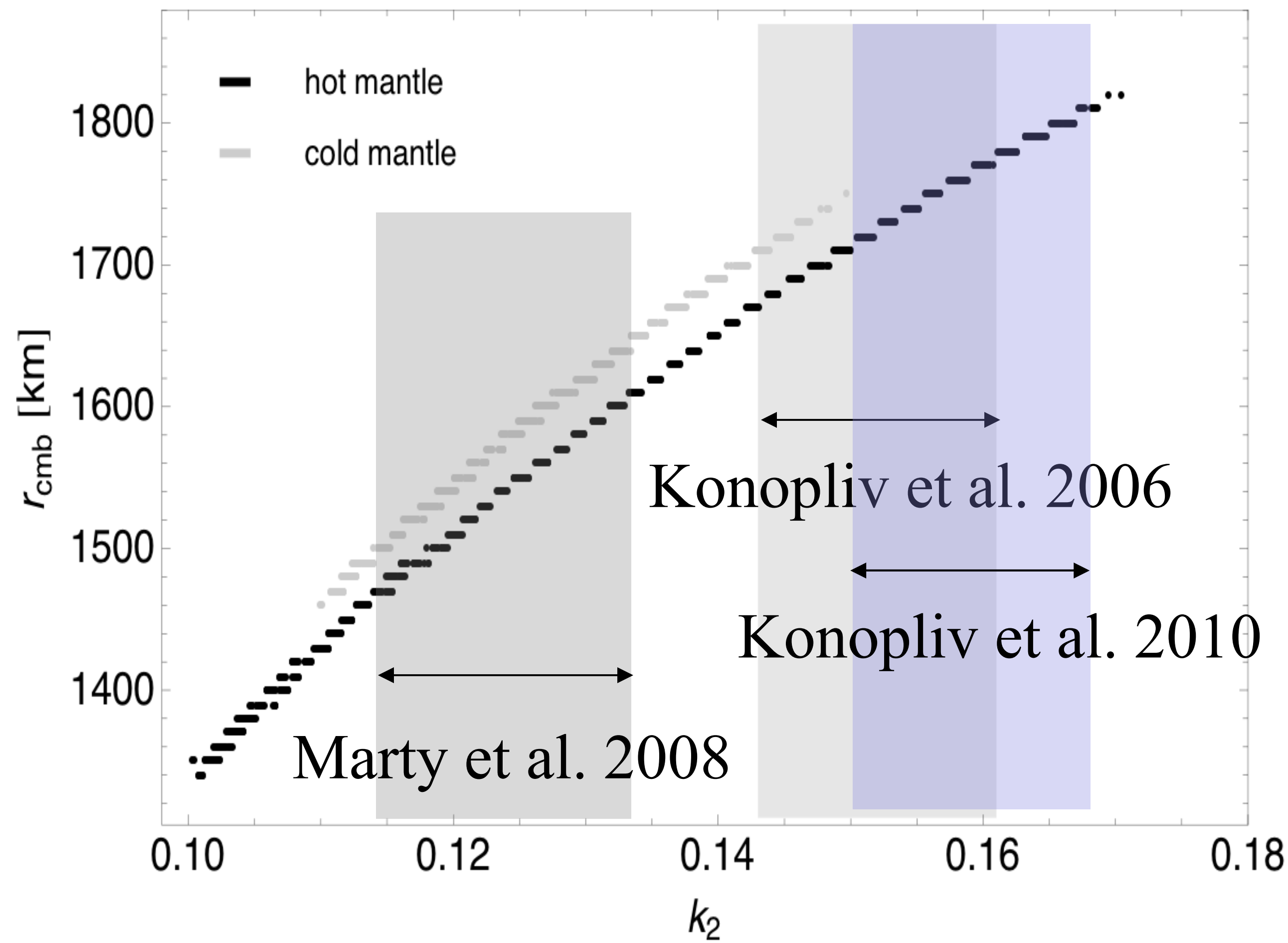




- Relative differences between models $\Delta U_T \approx 10^{-10}$ ($\Delta r < 1$mm)
- Recent JPL and GSFC gravity maps of Mars give uncertainties in estimated C_{lm} and S_{lm} coefficients of 10^{-10}.
- Total signal same order of magnitude as ice cap loading

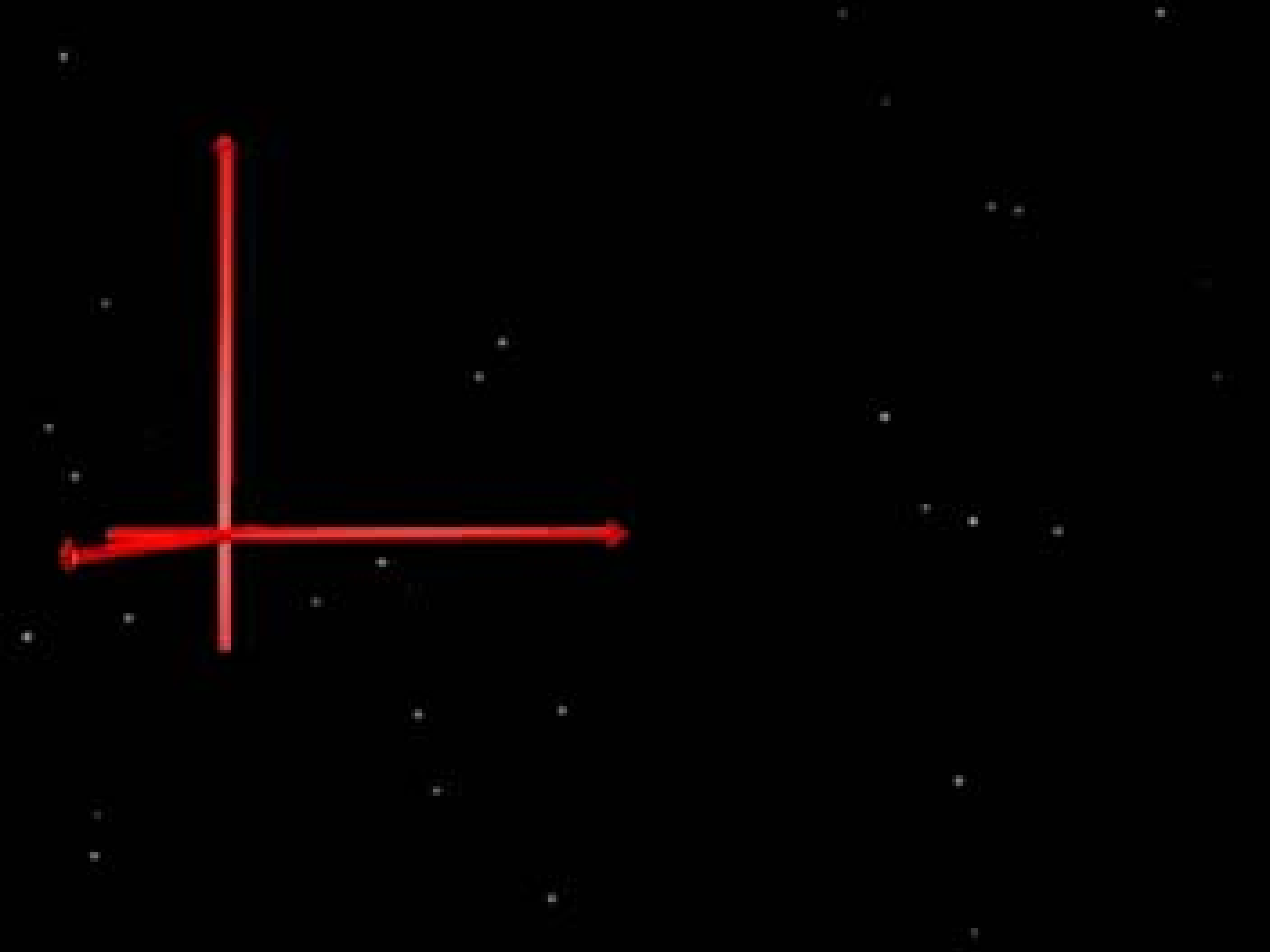
Values of the k2 tidal Love number found in the literature



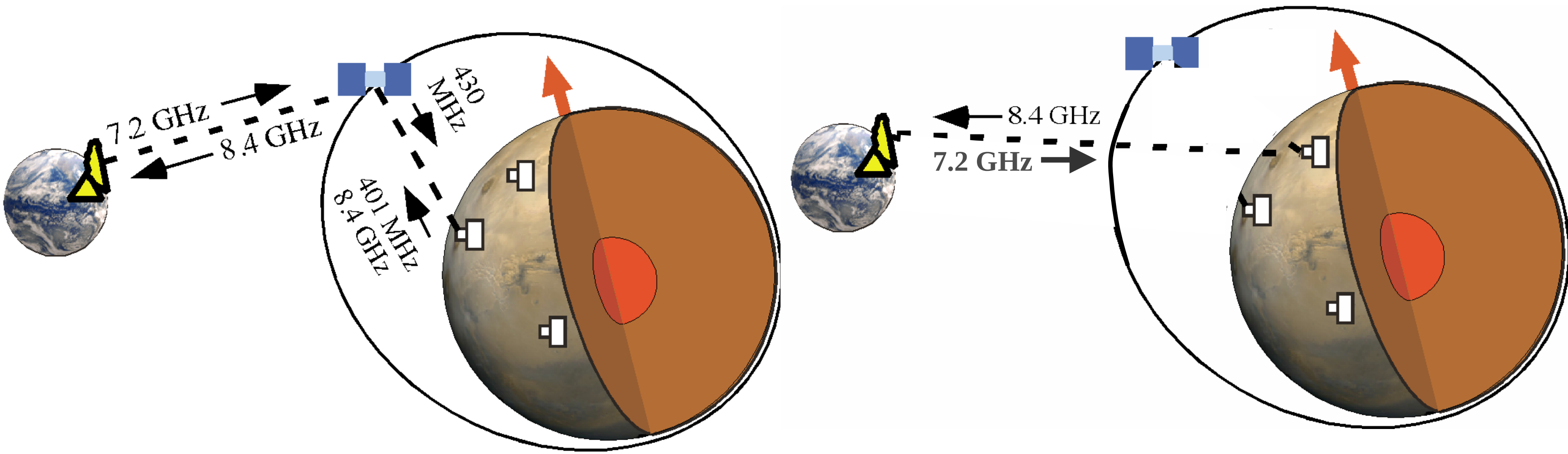


hot mantle
cold mantle
1800
1700
1600
1500
1400
r_{cmb} [km]
0.10
0.12
0.14
0.16
0.18
k_2
Konopliv et al. 2006
Konopliv et al. 2010
Marty et al. 2008

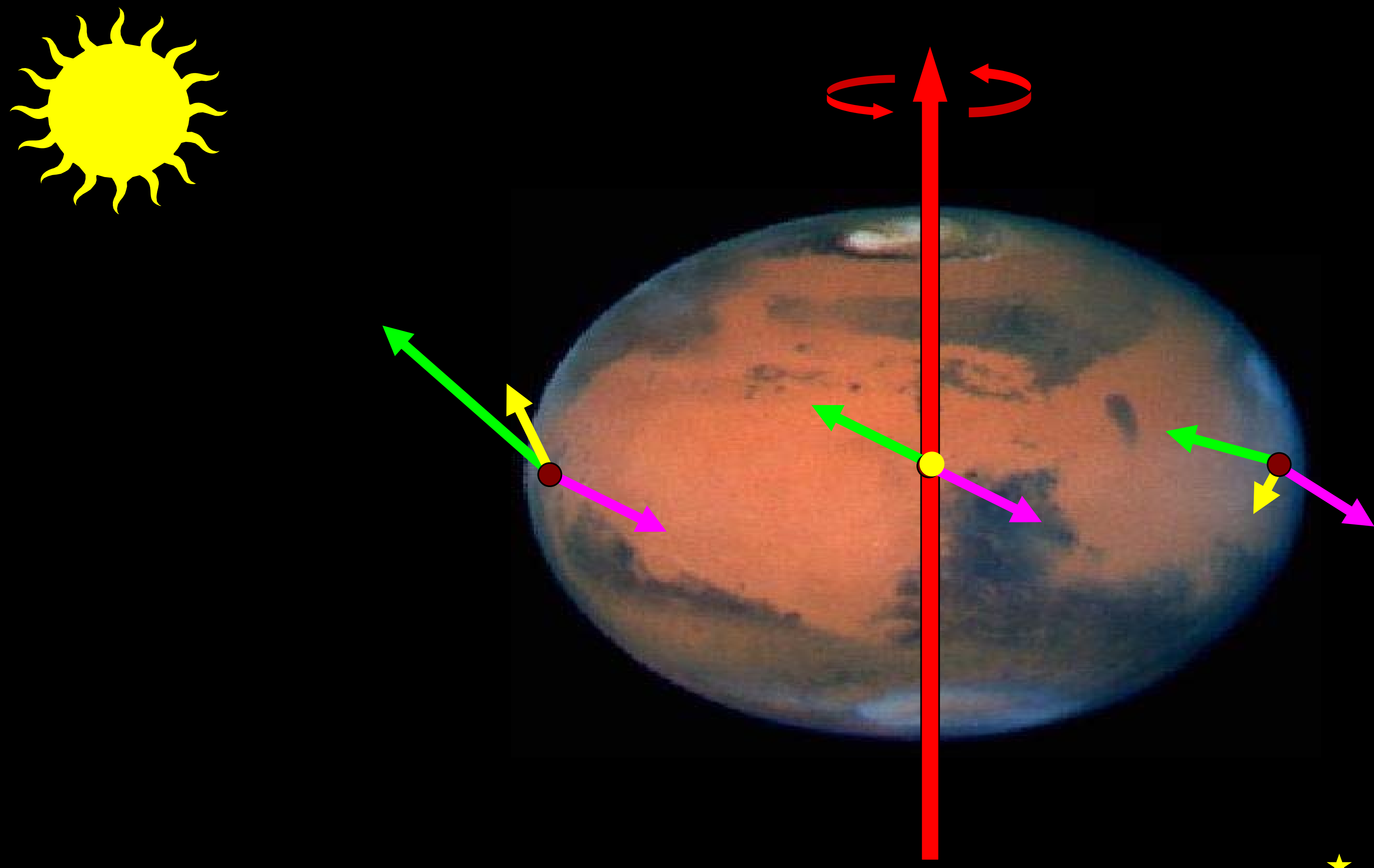
liquid core

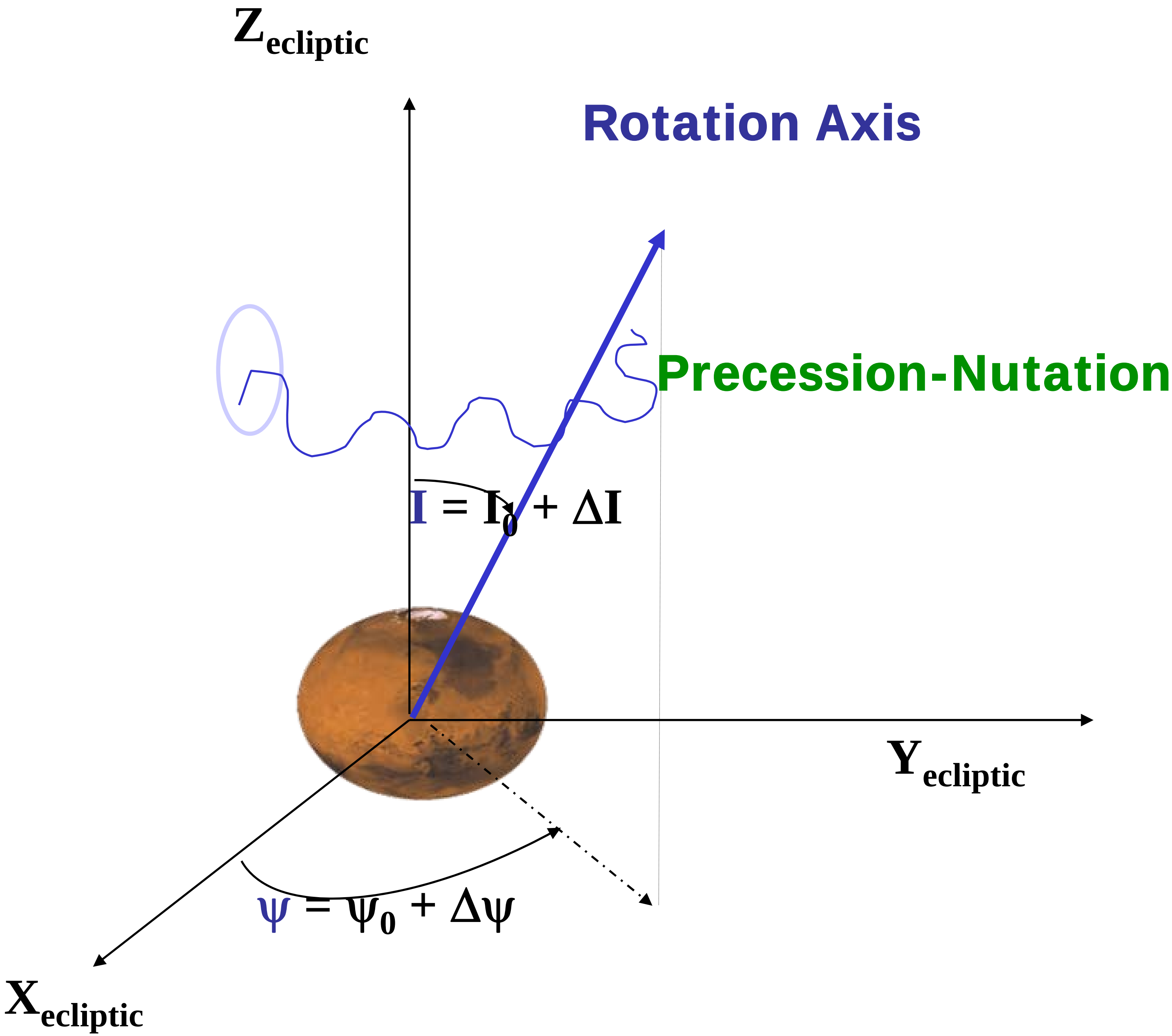


Also possible: a direct link with the Earth! MER Spirit!

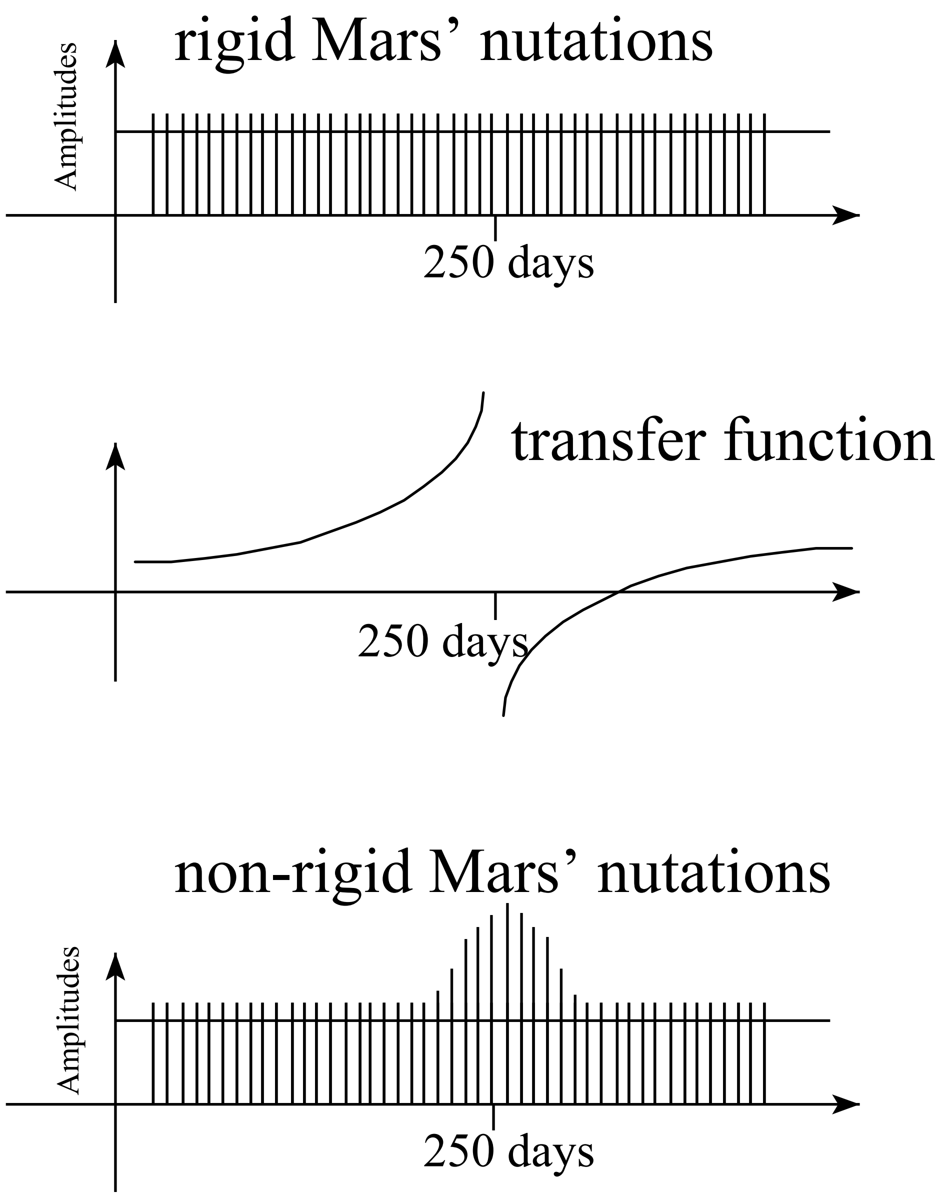


Precession and nutation of Mars





$Z_{ecliptic}$
Rotation Axis
Precession-Nutation
$I = I_0 + \Delta I$
$Y_{ecliptic}$
$\psi = \psi_0 + \Delta\psi$
$X_{ecliptic}$



IMPORTANT FOR:

- retrograde ter-annual nutation
- retrograde semi-annual nutation
- retrograde 1/4 year nutation
- prograde semi-annual nutation

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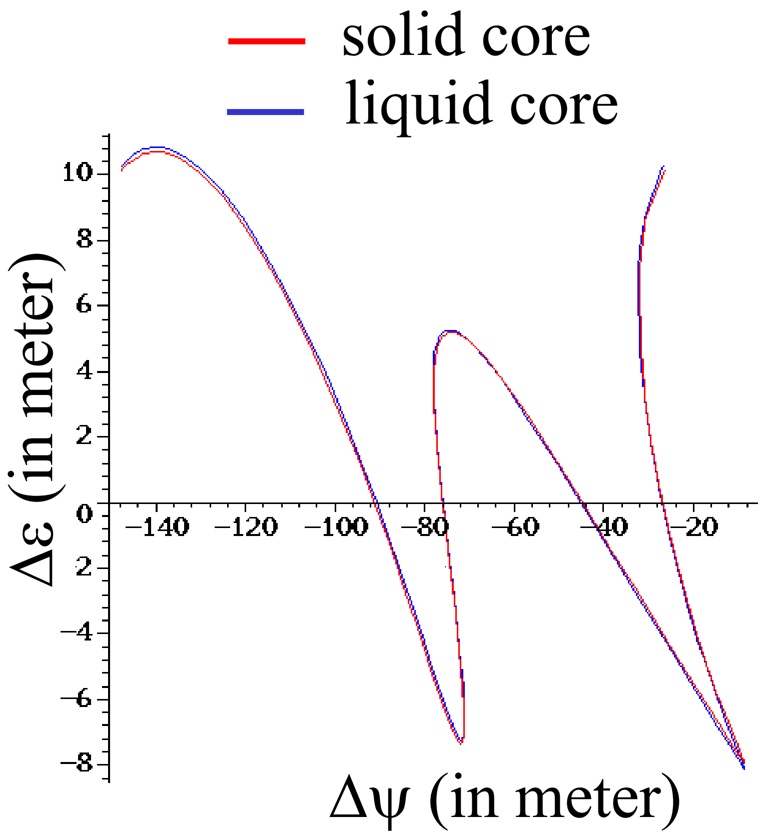
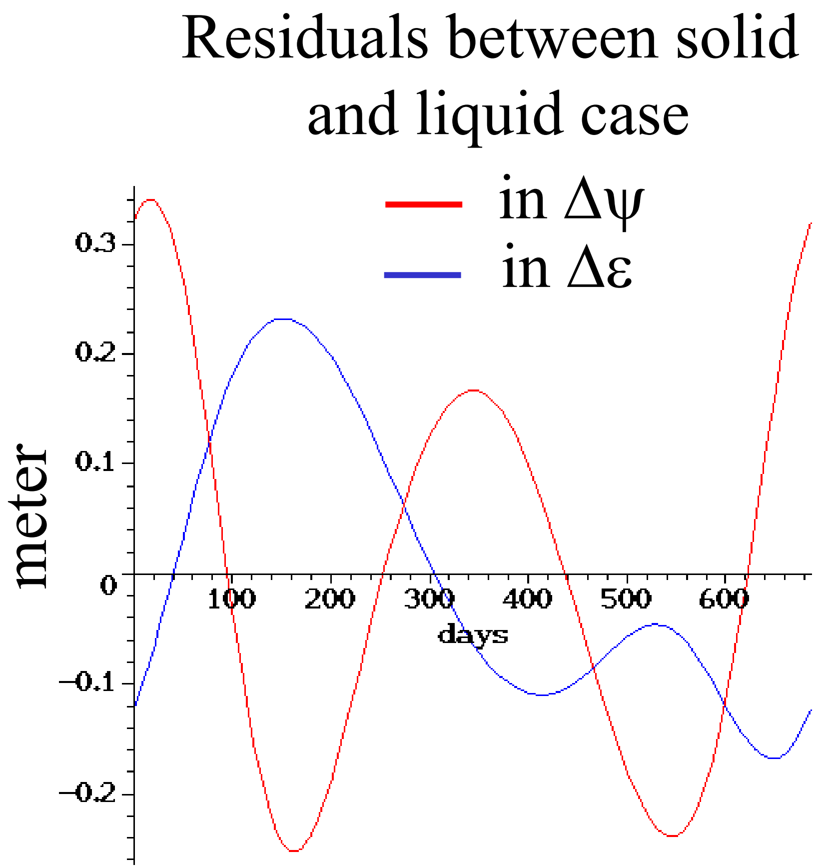
Nutation Amplitudes





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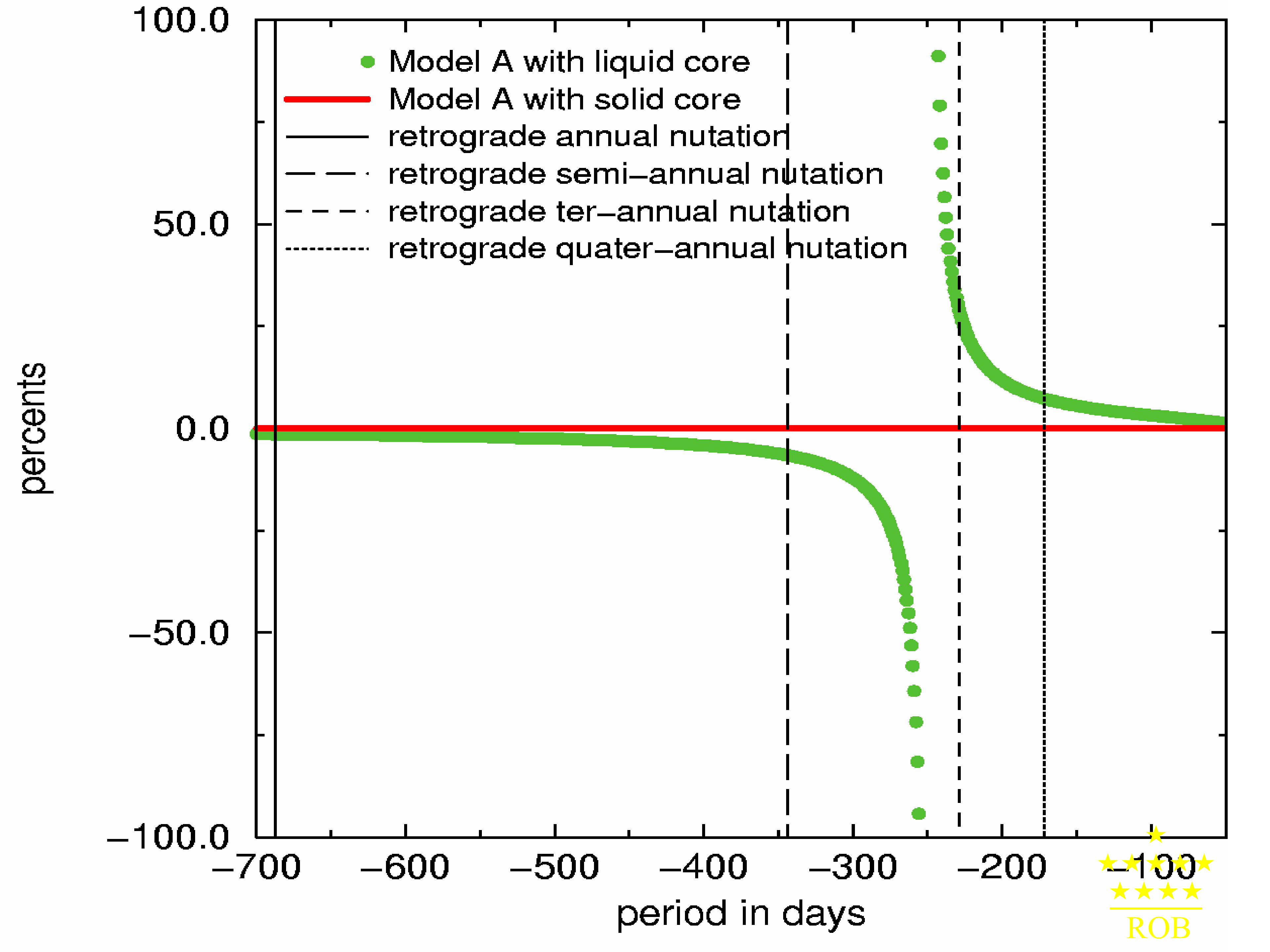
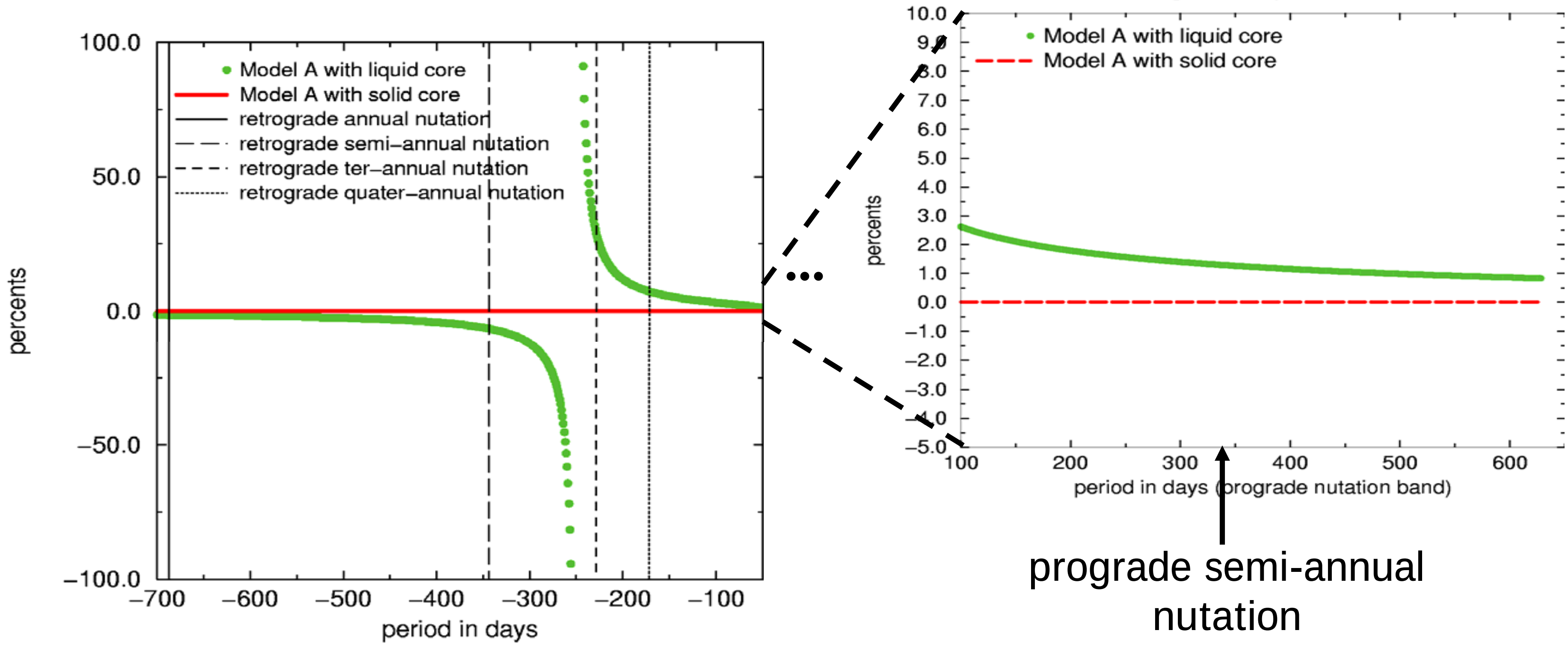
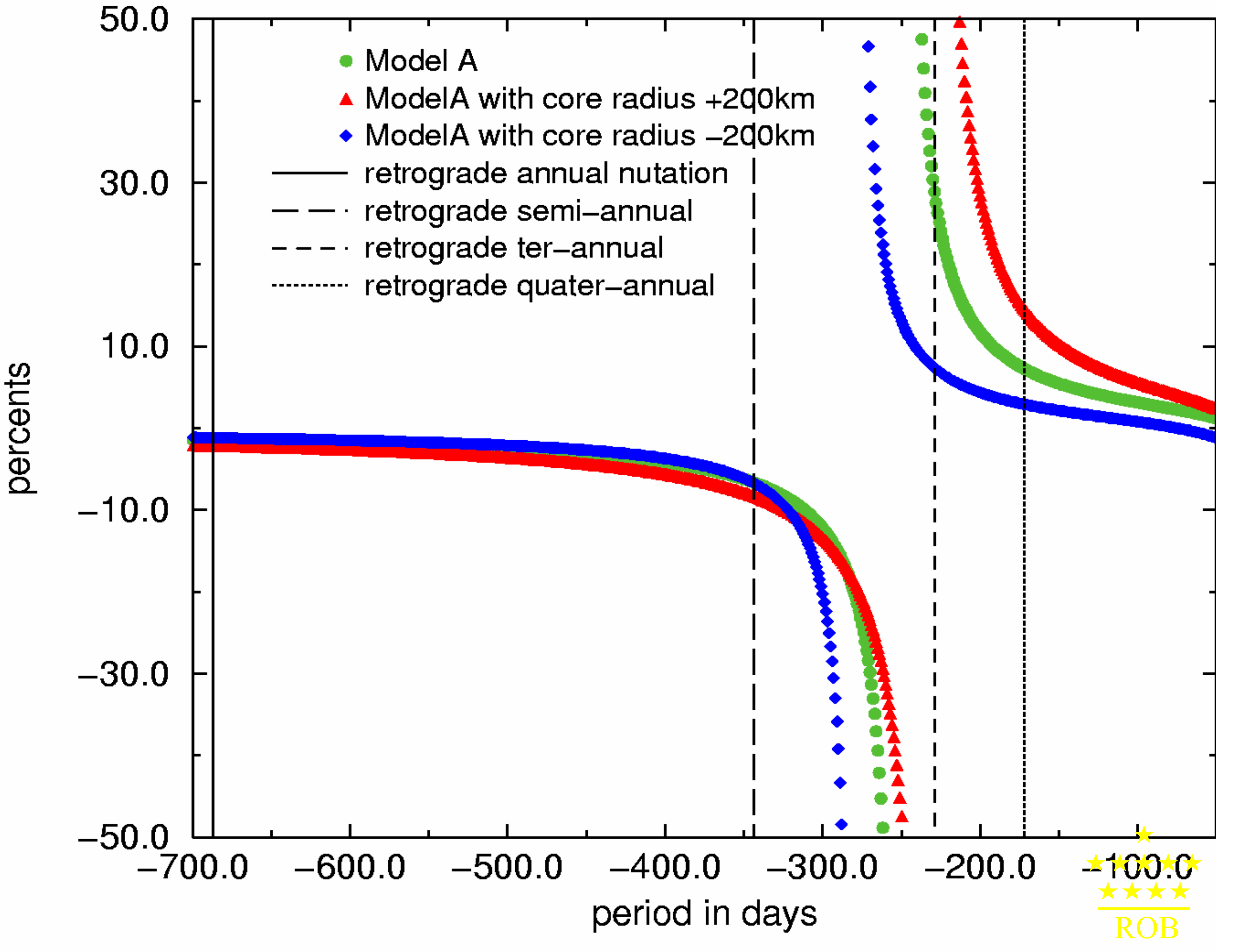


Model A with liquid core
Model A with solid core
retrograde annual nutation
retrograde semi–annual nutation
retrograde ter–annual nutation
retrograde quater–annual nutation
100.0
50.0
0.0
−50.0
−100.0
percents
−700
−600
−500
−400
−300
−200
−100
period in days
ROB



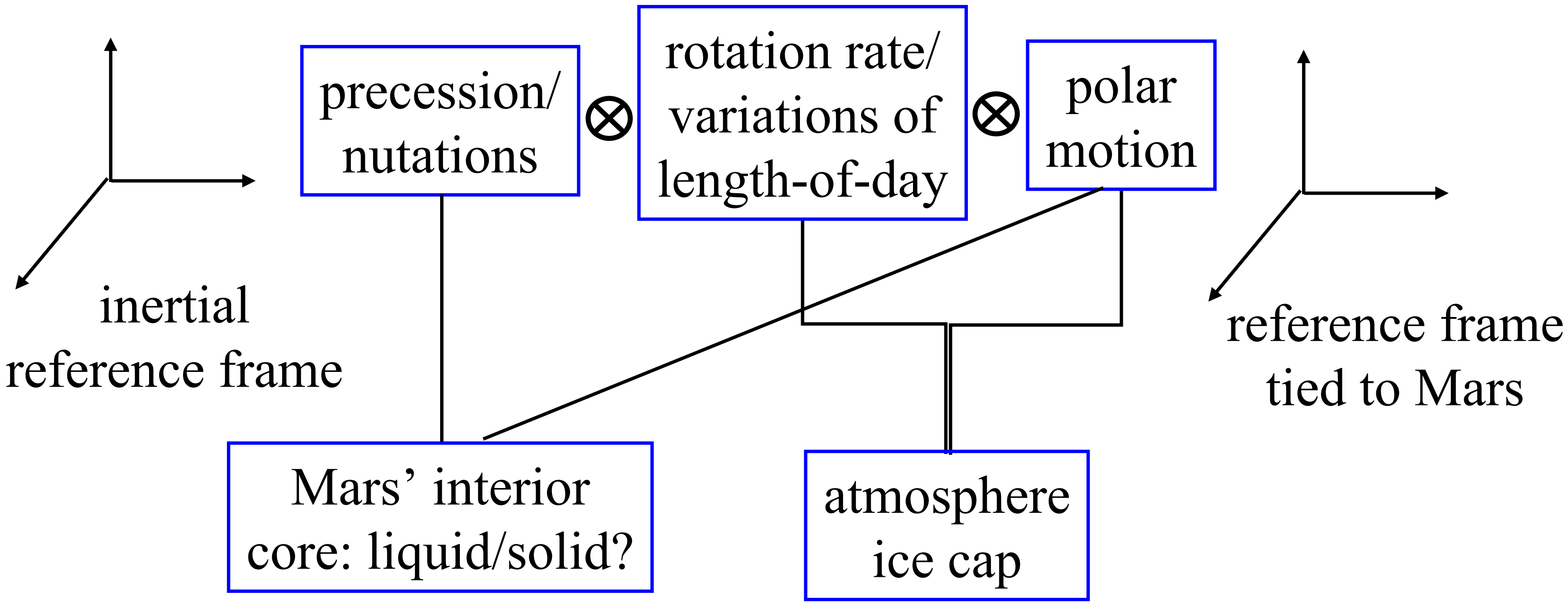
prograde semi-annual nutation

ROB



Model A
ModelA with core radius +200km
ModelA with core radius –200km
retrograde annual nutation
retrograde semi–annual
retrograde ter–annual
retrograde quater–annual
percents
period in days
50.0
30.0
10.0
–10.0
–30.0
–50.0
–700.0
–600.0
–500.0
–400.0
–300.0
–200.0
–100.0
ROB

Strategy for Geodesy



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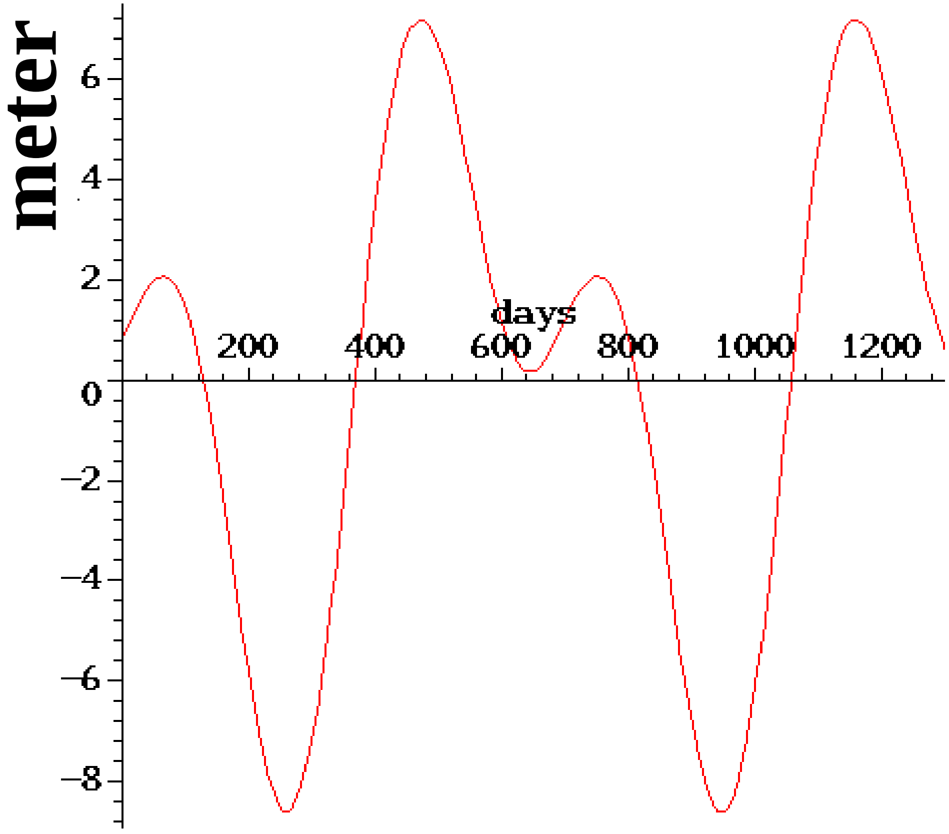
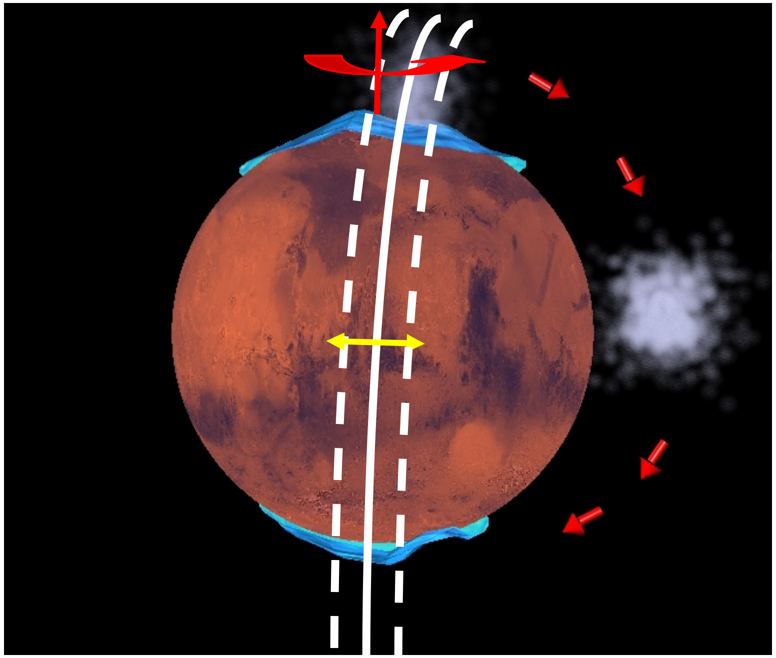
NEtlander Ionosphere and Geodesy Experiment

Length-Of-Day (LOD) Variations





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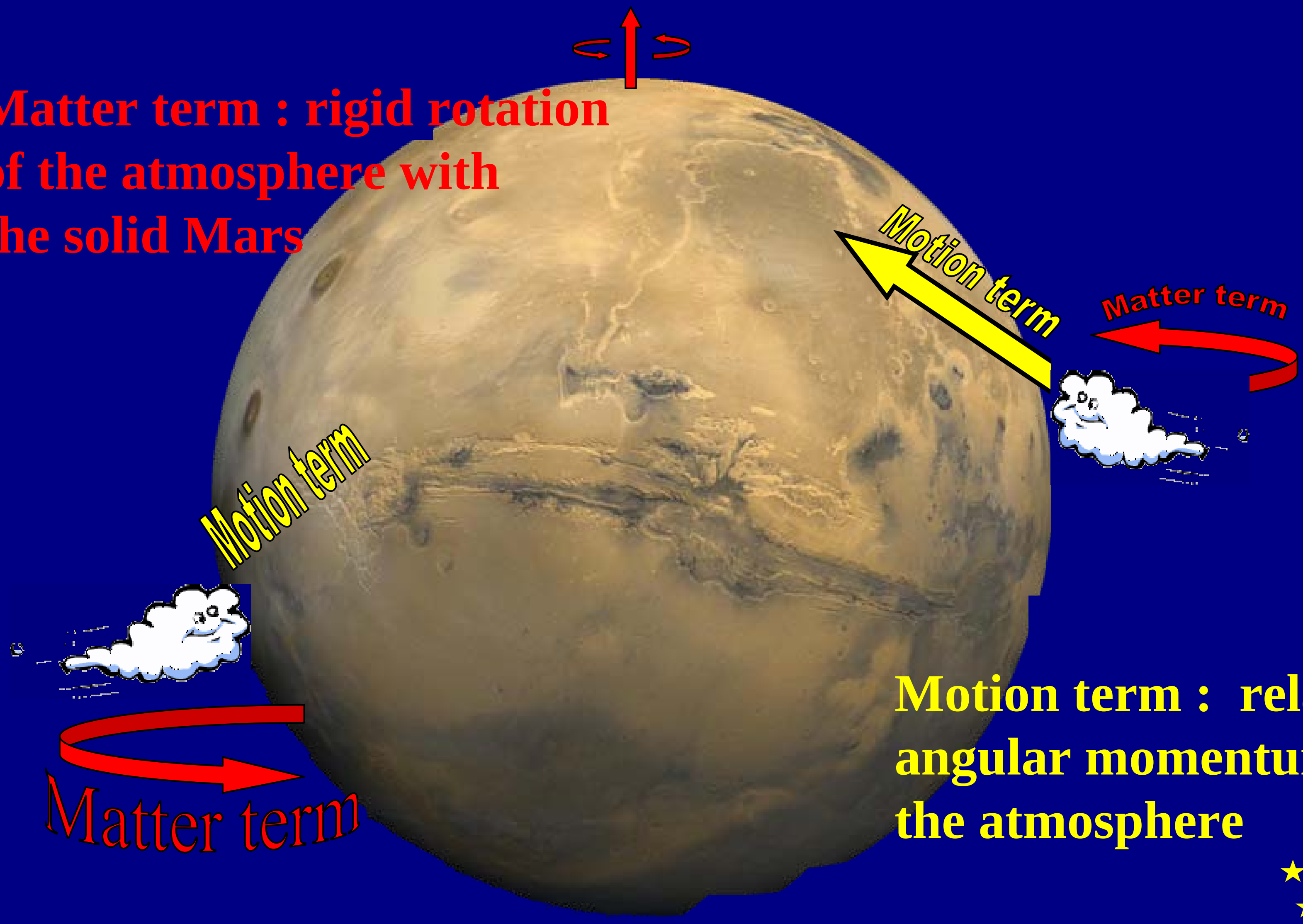
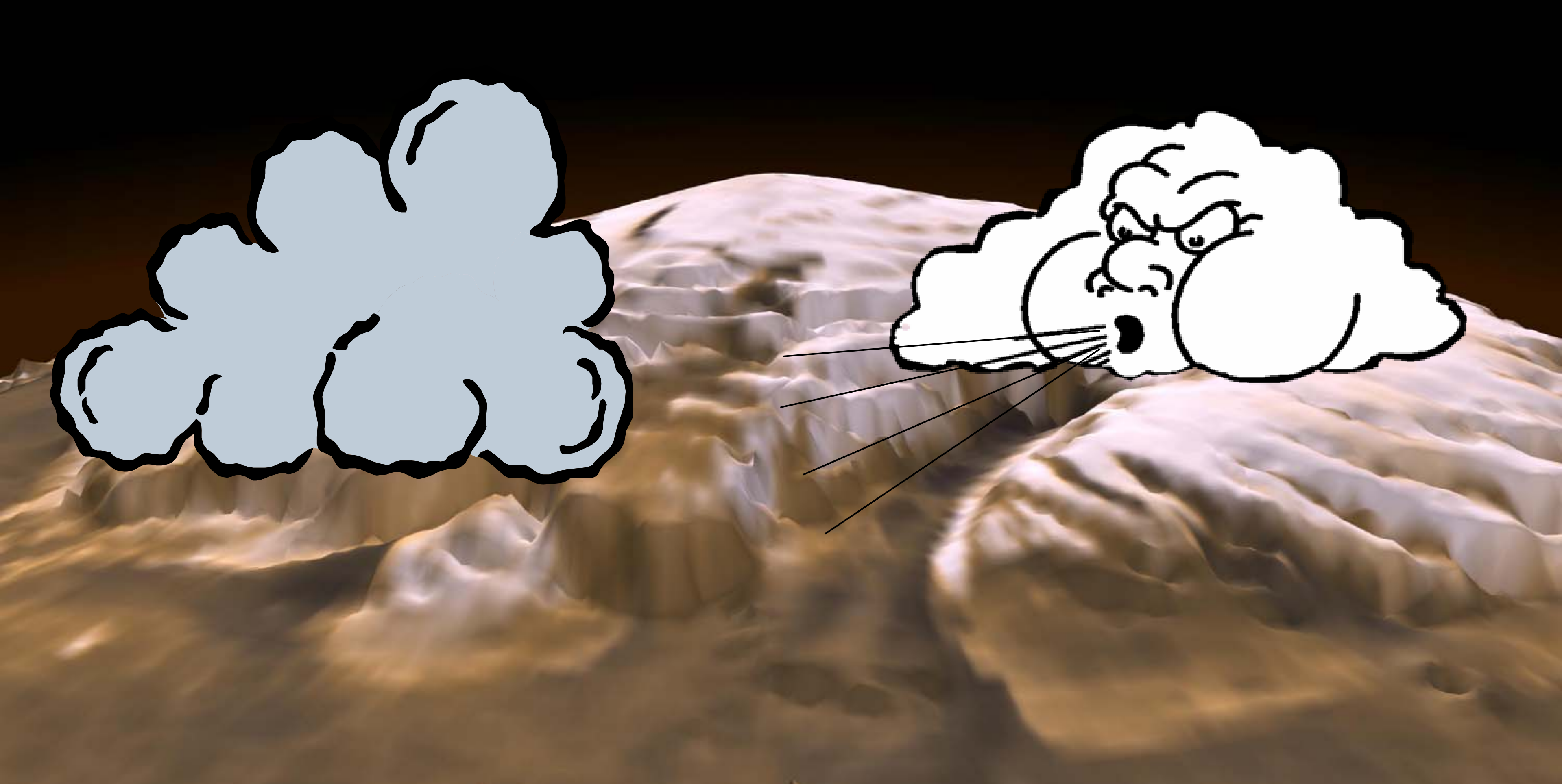
Computation of the Atmospheric angular momentum

Matter term : rigid rotation of the atmosphere with the solid Mars



Motion term : relative angular momentum of the atmosphere

ROB



Wind and matter term in angular momentum of the atmosphere

=> change in Mars’ rotation & polar motion

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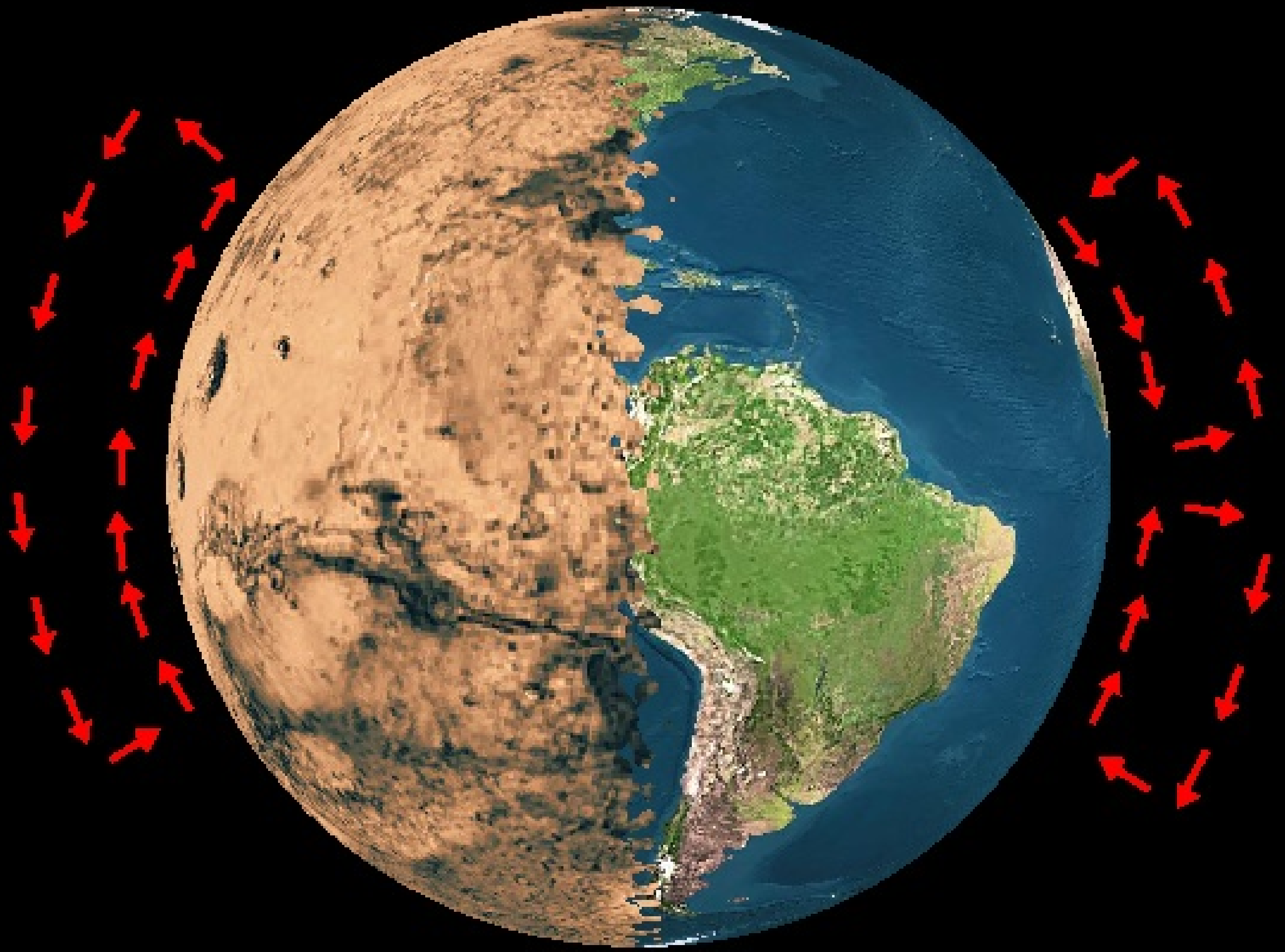
General circulation



Torque between Mars and its fluid layer

Pressure torque

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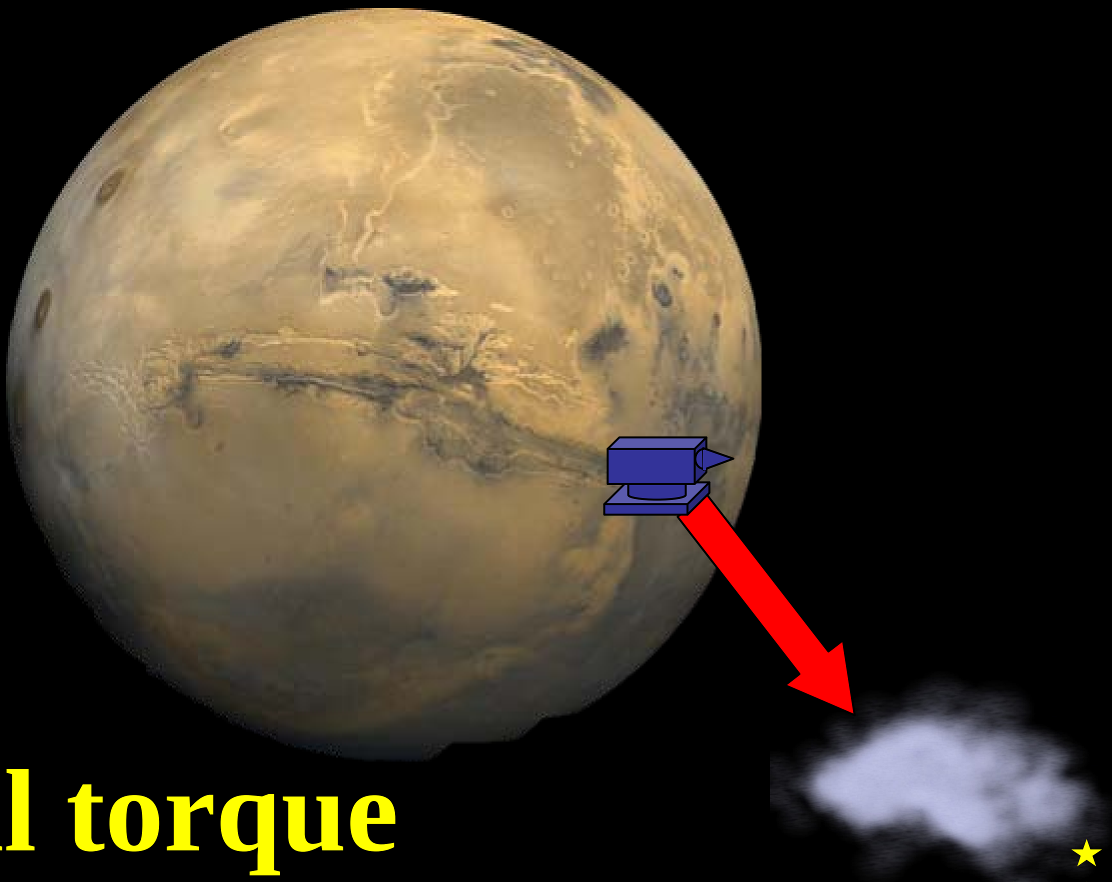
Torque between Mars and its fluid layer



Gravitational torque

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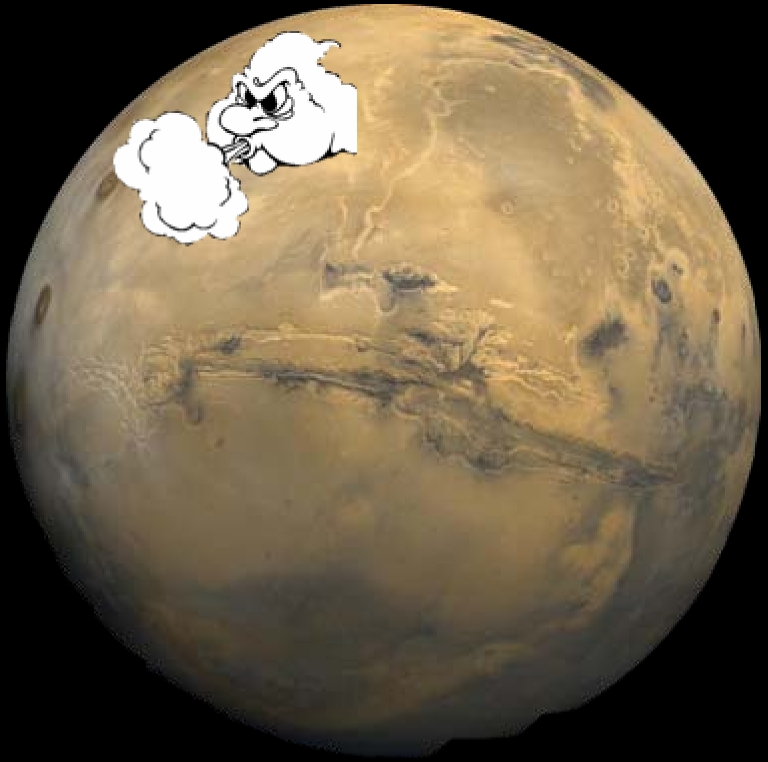
Torque between Mars and its fluid layer



Friction torque

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Length-Of-Day (LOD) Variations

	ice cap & atmosphere
annual signal on equator	7.6 m
semi-annual signal on equator	4.9 m

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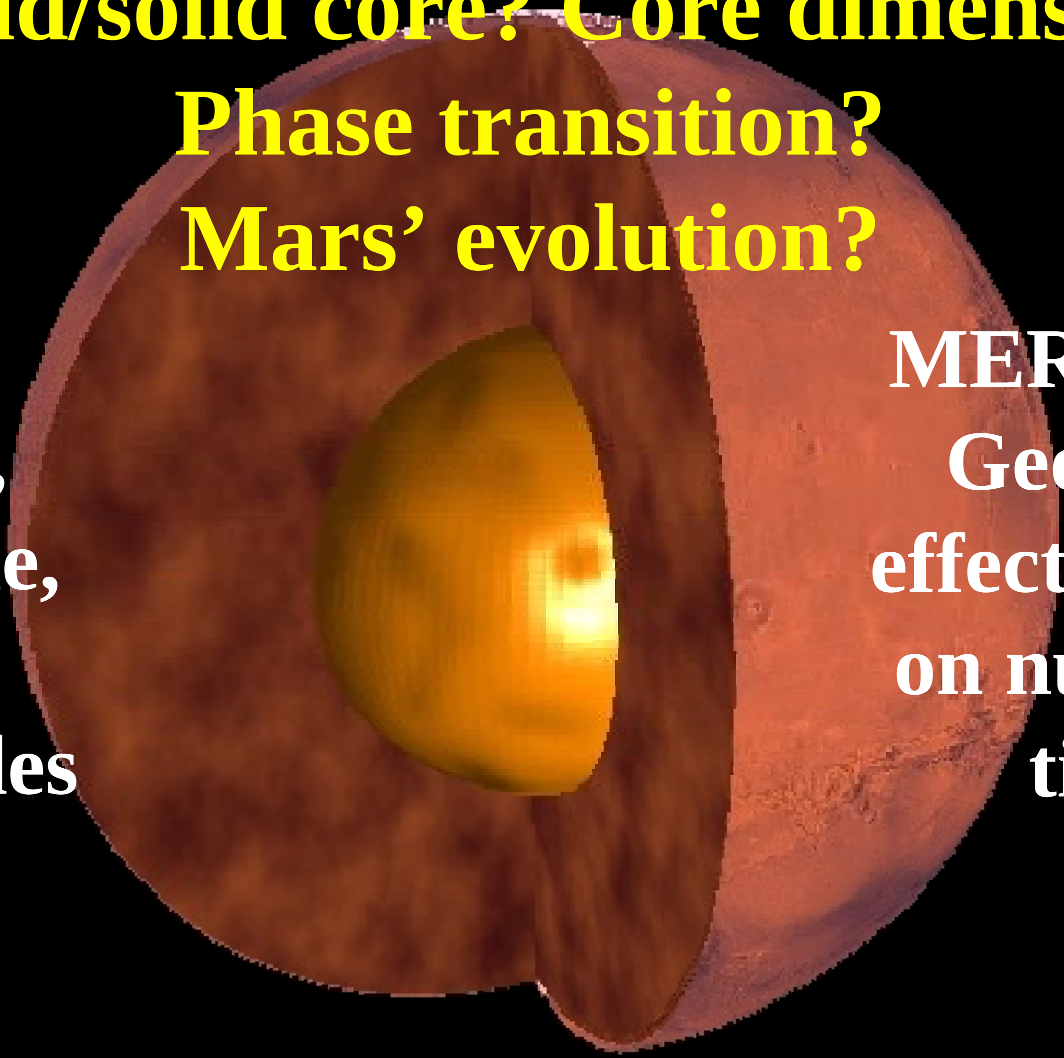
liquid/solid core? Core dimension?
Phase transition?
Mars' evolution?



SEIS:
PKP, PcP,
shadow zone,
tides,
normal modes

MER/LaRa/
Geodesy:
effect of FCN
on nutation,
tides

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The movies used in the presentation are on:
http://www.astro.oma.be/D1/DIDAC/index.php

Acknowledgements

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BELGIAN SCIENCE POLICY

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