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The tidal response of super-Earths and large icy worlds

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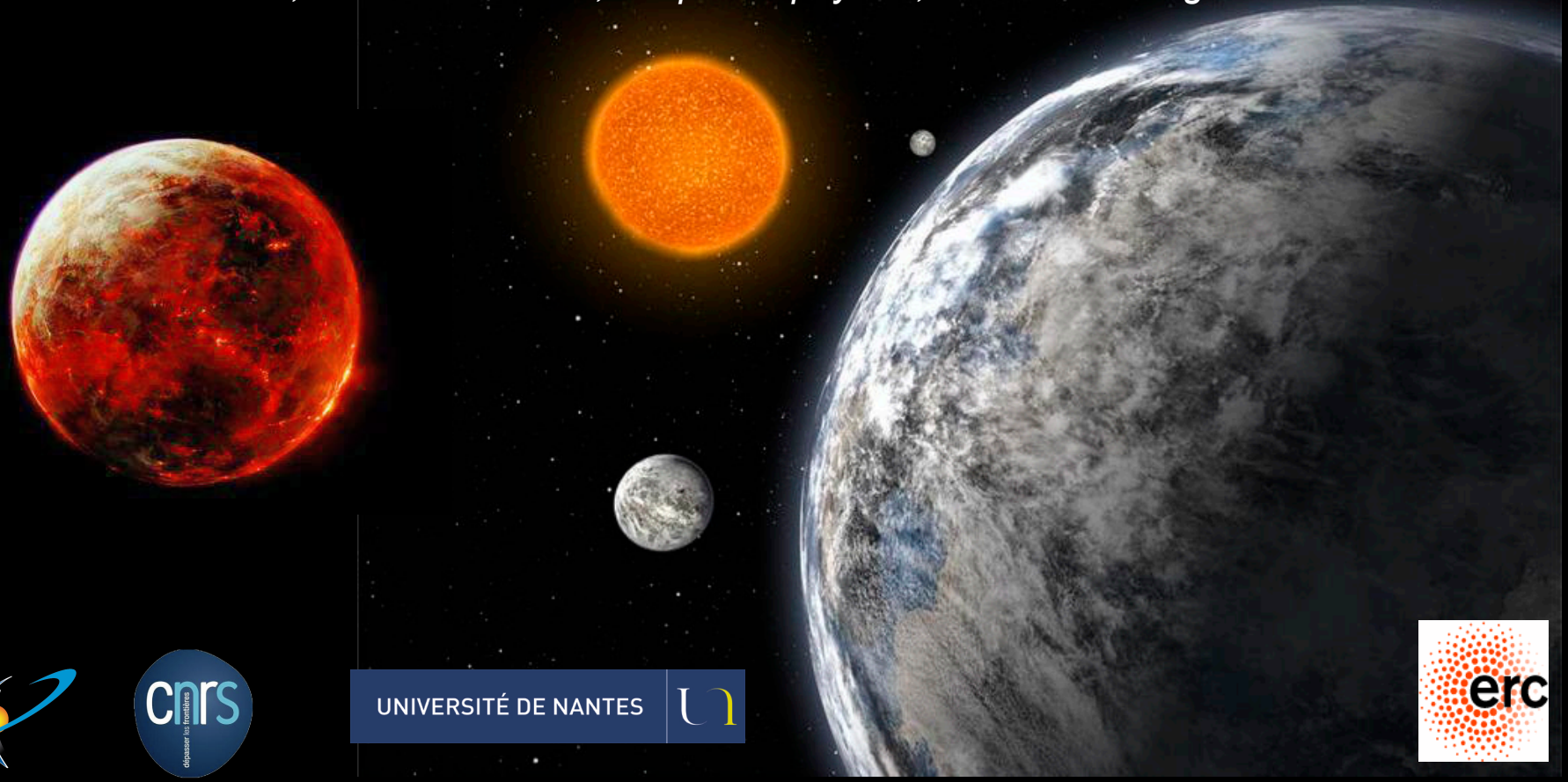
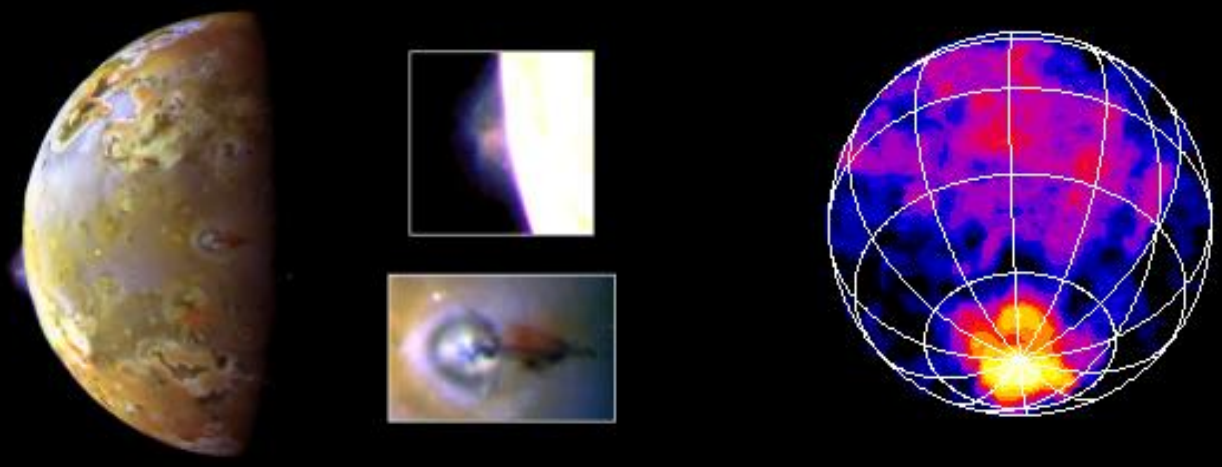


Introduction

Tidal dissipation: a potentially large source of energy in planetary interiors

Evidence for tidal dissipation in the Solar System:

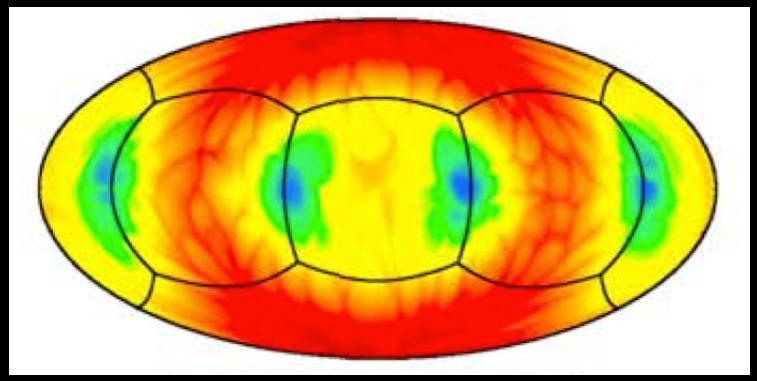


Surface heat flow on Io and Enceladus > 10-100 x radiogenic heat flow

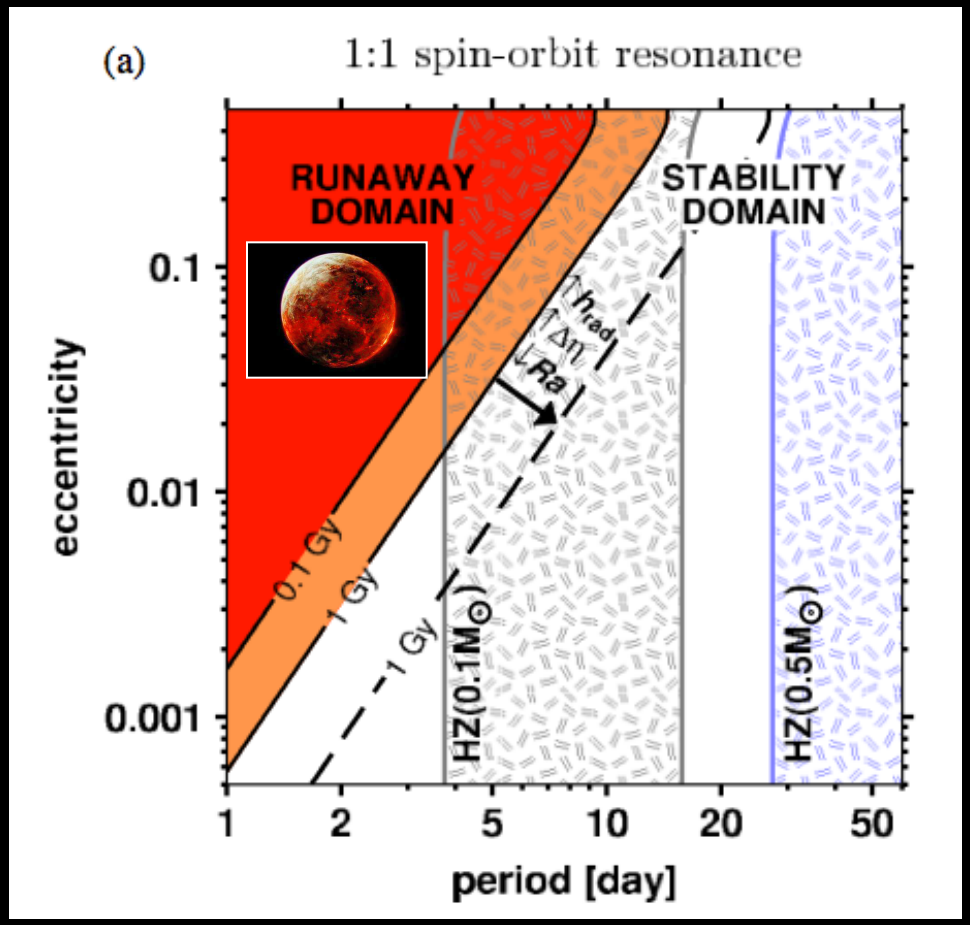
Large tidal heating expected in tidally-locked exoplanets on eccentric orbits as well as during their despinning stage.

- **Effect of tidal heating on thermal and orbital evolution ?**
- **In which conditions thermal runaways can occur ?**

Introduction



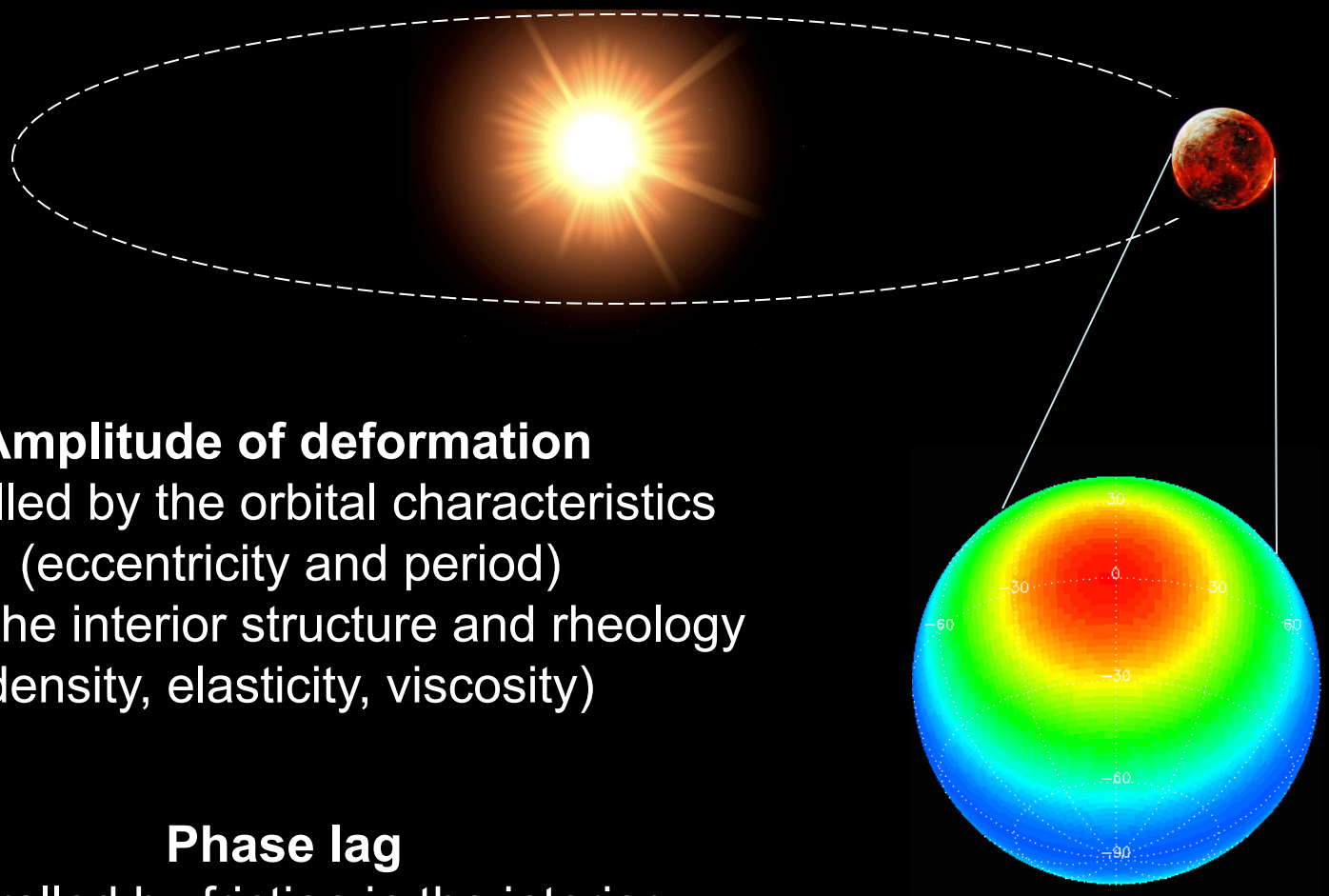
Prediction of Io-like thermal runaways for Earth-like planets from 3D models of coupled tidal dissipation and thermal convection (*Behounkova et al. 2010*)



Behounkova et al. ApJ (2011)

- **In which conditions thermal runaways can occur for a wide range of planet size and composition ?**
- **Impact on planet habitability ?**

Principle of tidal deformation



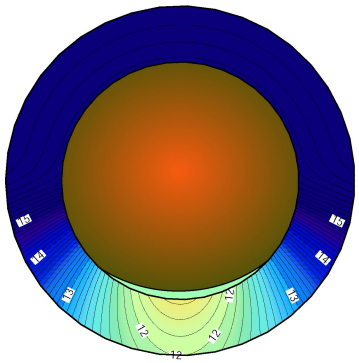
Amplitude of deformation
controlled by the orbital characteristics
(eccentricity and period)
and by the interior structure and rheology
(density, elasticity, viscosity)

Phase lag
controlled by friction in the interior,
surface and atmosphere

Computation of body tides

2 – In the time domain, by directly integrating the equation of motions in 3D and assuming an incompressible viscoelastic media.

3D interior model



$$\nabla \cdot (-p\mathbf{I} + \mathbf{D}) + \mathbf{f} = 0$$

$$\nabla \cdot \mathbf{u} = 0$$

$$\frac{\partial \mathbf{D}}{\partial t} - \frac{\partial}{\partial t}\left[\mu\left(\nabla \mathbf{u} + \nabla^{\tau}\mathbf{u}\right)\right] = -\frac{\mu}{\eta}\mathbf{D}$$

Tobie, Cadek et Sotin (2008)

Local dissipation rate averagerd over one cycle.

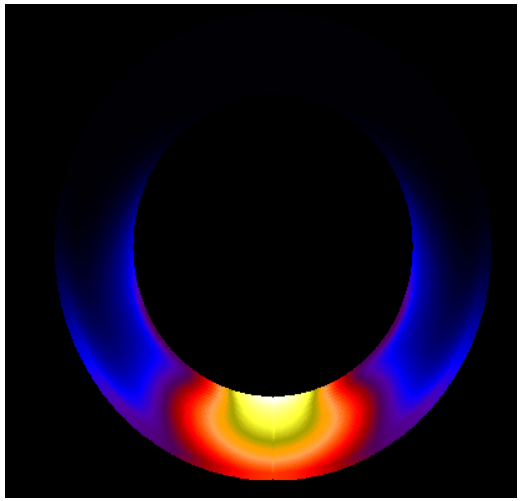
$$h = T^{-1}\int_{t_1}^{t_1+T} \frac{\mathbf{D}:\mathbf{D}}{2\eta}\,\mathrm{d}t,$$

Tidal potential

$$\mathbf{f} = -\rho(\nabla\Phi + \nabla V)$$

$$\Phi = r^2\omega^2 e\left\{-\frac{3}{2}P_2^0(\cos\theta)\cos\omega t\right.$$

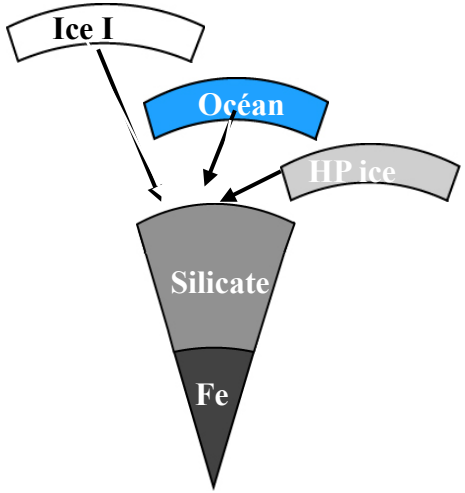
$$\left.+\frac{1}{4}P_2^2(\cos\theta)[3\cos\omega t\cos 2\phi + 4\sin\omega t\sin 2\phi]\right\}$$



Computation of body tides

In the frequency domain, using an effective complex shear modulus and by resolving the "equivalent elastic compressible problem" for layered interior models.

Layered structure



Poisson's equation

Equations of motions

Displacement

Stress

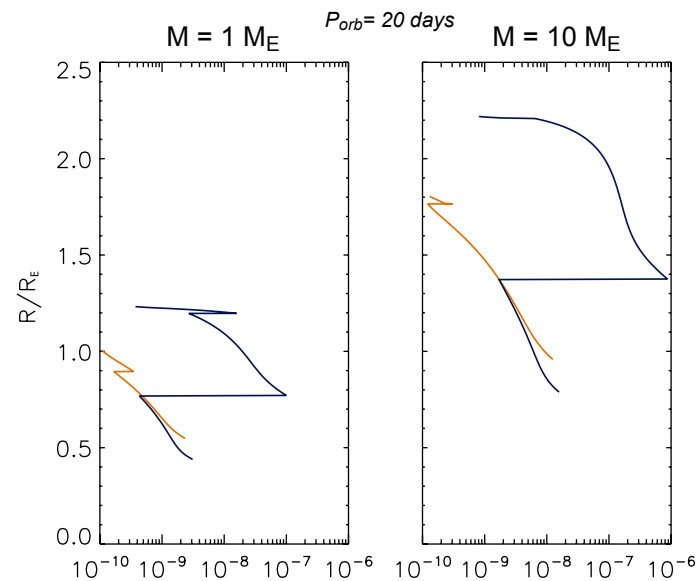
Deformation

Global dissipation:
k_2/Q

Radial distribution of shear dissipaton

$$\dot{H}(r) = -\frac{21}{10}\frac{\omega^5 R_s^4 e^2}{r^2} H_\mu \times Im(\mu^c)$$

Tobie et al. Icarus (2005)



Tidal potential

$$\Phi = r^2\omega^2 e\left\{-\frac{3}{2}P_2^0(\cos\theta)\cos\omega t + \frac{1}{4}P_2^2(\cos\theta)[3\cos\omega t\cos 2\phi + 4\sin\omega t\sin 2\phi]\right\}$$

The Earth as a reference

Density profile computed following Sotin et al. (2007)

Mie-Grüneisen-Debye- EOS

Liquid Iron core
Lower silicate mantle
Ice VII layers

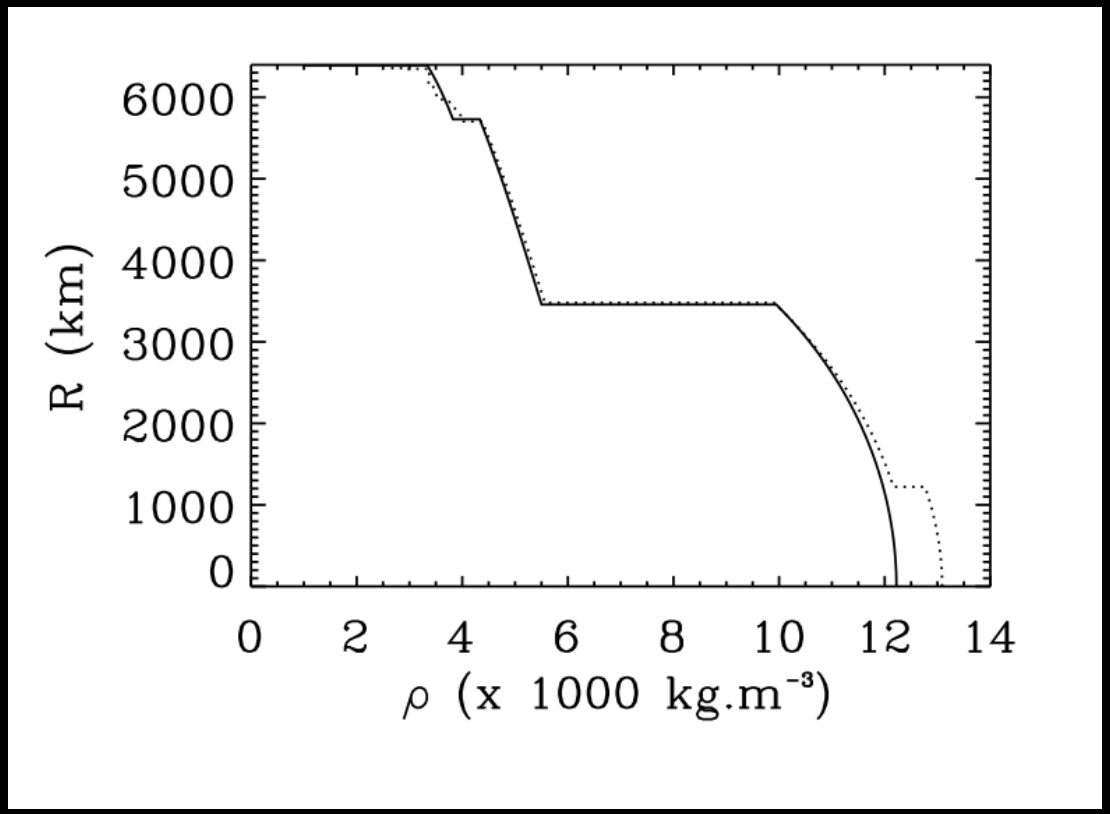
Birch-Murnaghan EOS

Upper mantle
Low-pressure water layers

Approximation

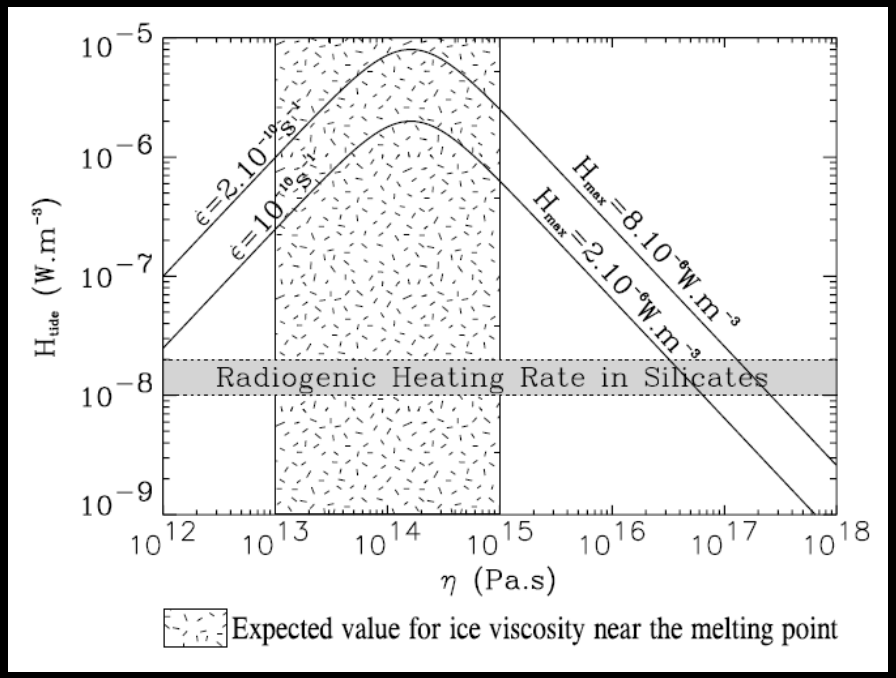
- No Solid inner core
- No phase transition in the upper mantle and in ice layers

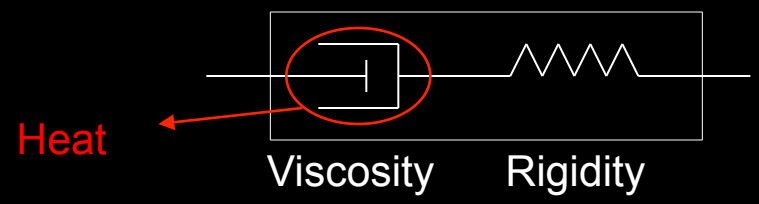
Comparison with the PREM (Preliminary Reference Earth Model)



Interior structure and rheology

The Maxwell rheological model





Dissipation ~ work of tidal forces
= stress x strain rate

A first order approximation, relatively correct for forcing time close to the Maxwell time (~η/μ).

$$\tilde{\sigma}_{ij}(\omega) = \mu^c(\omega)\tilde{\epsilon}_{ij}(\omega)$$

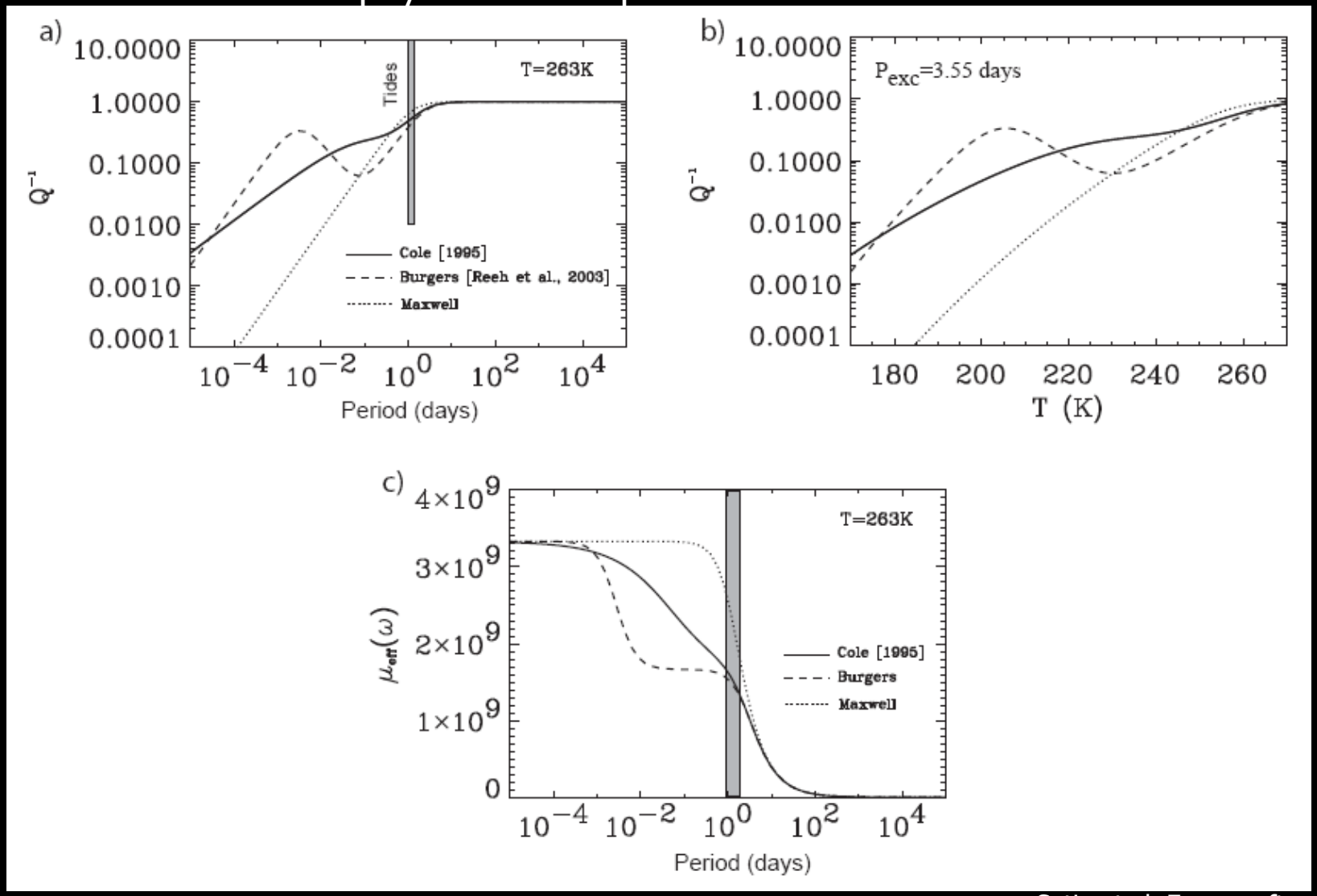
$$Re(\mu^c) = \frac{\mu\eta^2\omega^2}{\mu^2+\eta^2\omega^2}$$

$$Im(\mu^c) = \frac{\mu^2\eta\omega}{\mu^2+\eta^2\omega^2}$$

Interior structure and rheology

Dissipation in the ices

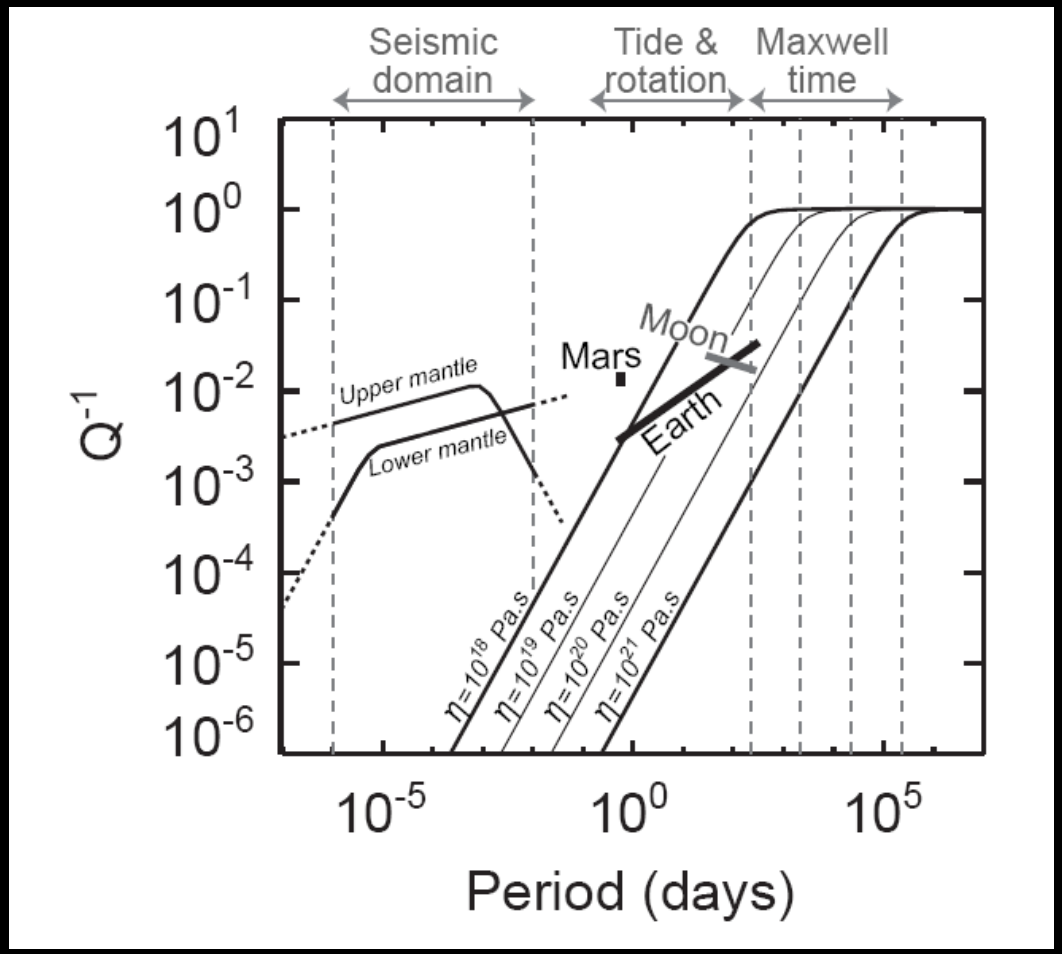
Geophysical and experimental constraints



Sotin et al. Europa after *Galileo*

Interior structure and rheology

Dissipation in the Earth's mantle



Sotin et al. (2009), Europa after *Galileo*

Except for forcing period close to the Maxwell time, Maxwell viscoelastic rheology usually underestimates the dissipation rate.

Maxwell rheology fails also to explain the frequency dependence observed for the Earth's mantle.

Andrade rheology appears more appropriate:

$$J(\chi) = \frac{1}{\mu} - \frac{i}{\eta\chi} + \beta(i\chi)^{-\alpha}\Gamma(1+\alpha)$$

Castillo-Rogez t al. (2011)

Interior structure and rheology

Rheological model: Andrade

Elastic properties

Bulk modulus K_s determined from density profile

Shear modulus μ:

μ/K_s=0.631-0.899 x P/K_s

μ/K_s=0.6-0.9 x P/K_s *(ice)*

Viscosity :

Assumed constant in each layer

Lower mantle: 10^{22}-10^{23} Pa.s

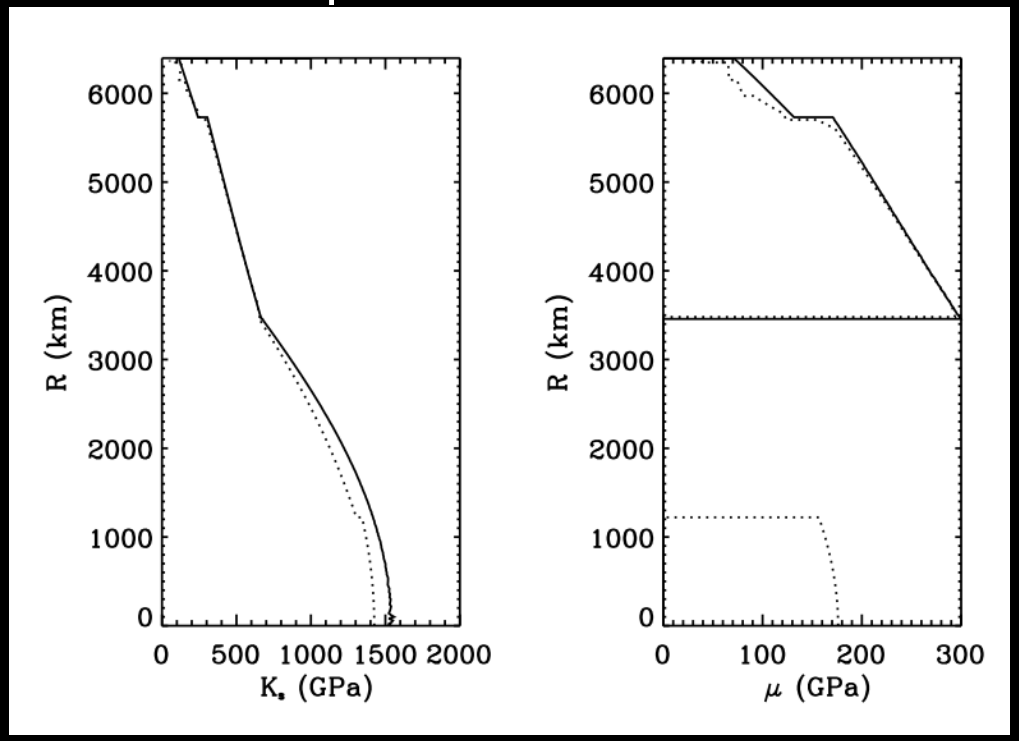
Upper mantle: 10^{20}-10^{21} Pa.s

HP ice: 10^{15}-^{17} Pa.s

η_{LM}=5.10^{22} Pa.s,
η_{UM}=10^{20} Pa.s

The Earth as a reference

Comparison with the PREM

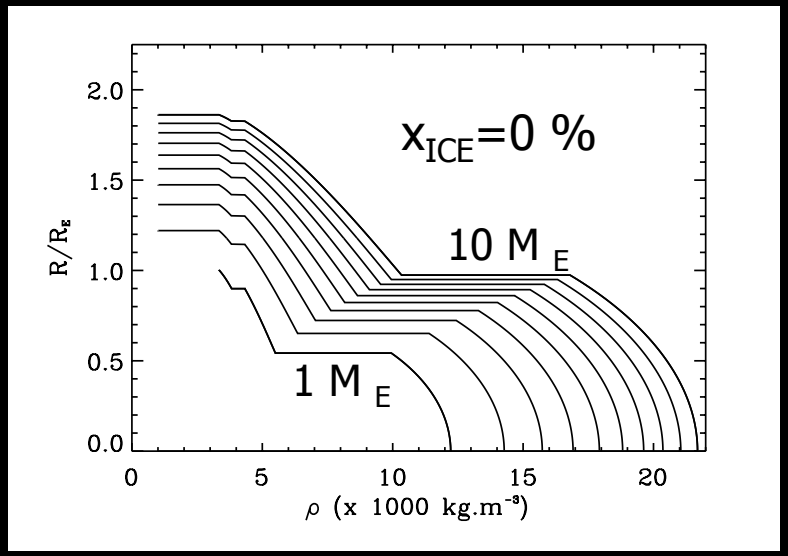


	k_2	Q
Observed (Ray et al. 2001)	0.302	280
Computed from PREM	0.303	303
Computed from synth. Prof.	0.294	292

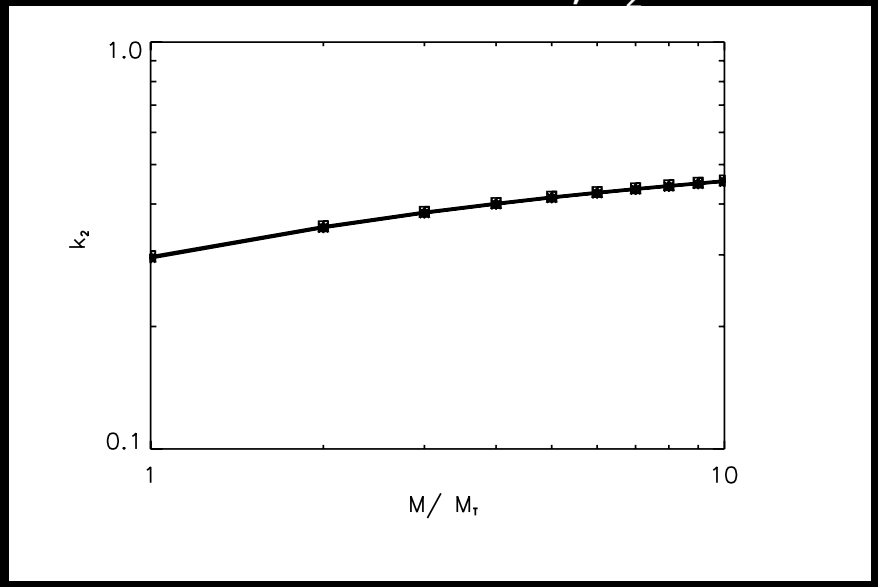
Earth-like exoplanets from 1 to 10 Earth's mass

Tidal period::
0.5, 10, 20, 30, 40 days

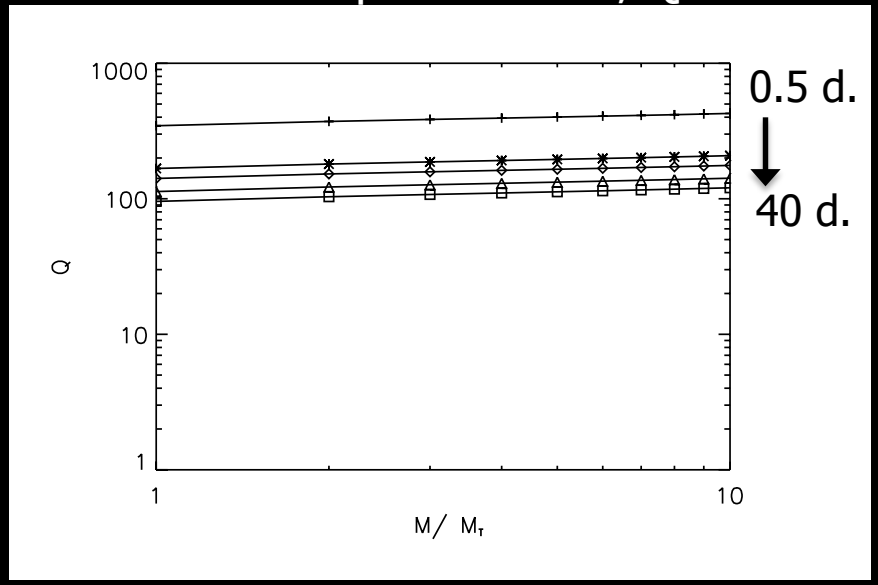
Density profile



Tidal Love number, k_2



Tidal dissipation factor, Q



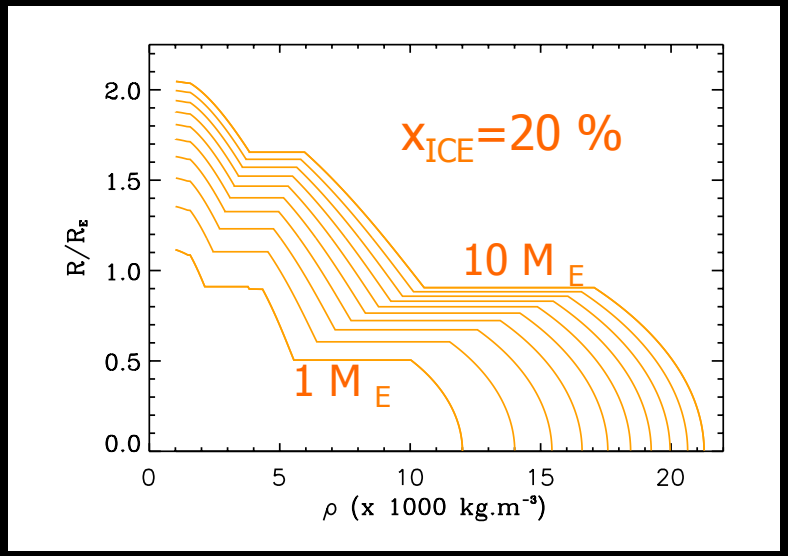
k_2 depends on mass.

Q depends mainly on tidal period, very slighly on mass.

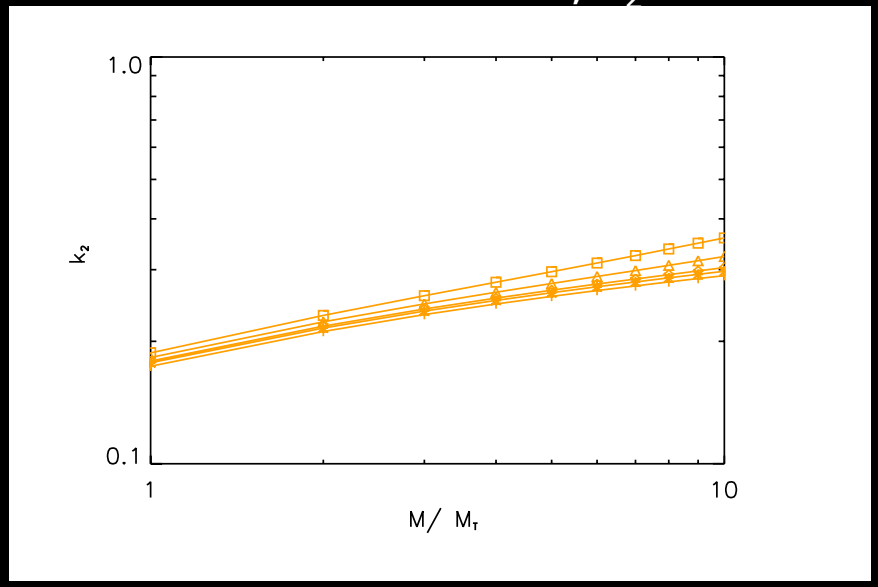
Exoplanets with 20% water ice from 1 to 10 Earth's mass

Tidal period::
0.5, 10, 20, 30, 40 days

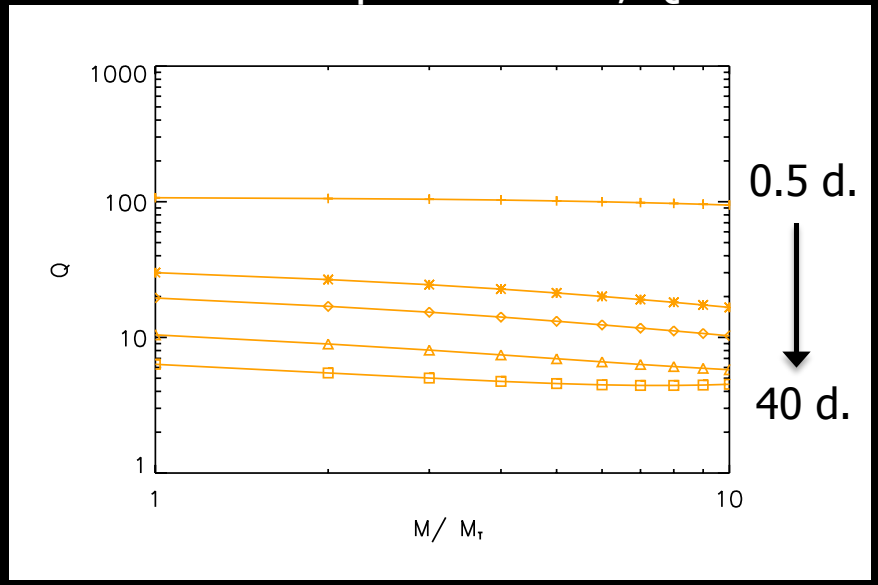
Density profile



Tidal Love number, k_2



Tidal dissipation factor, Q



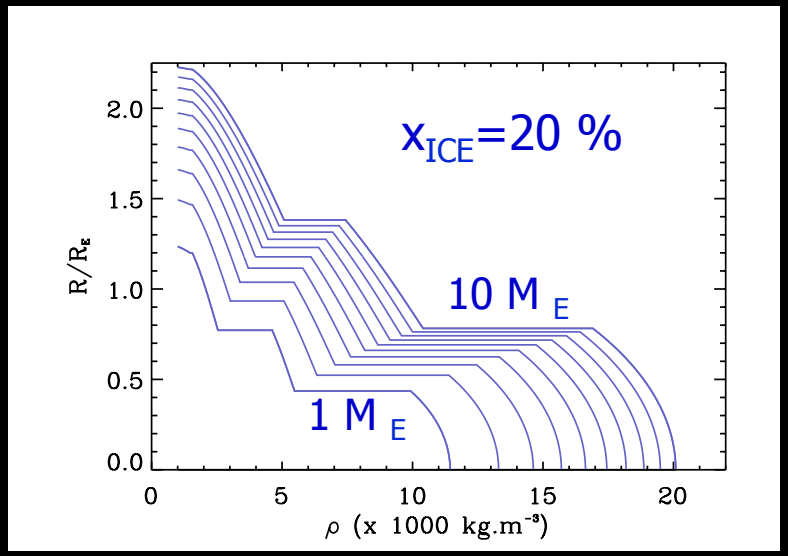
k_2 depends mainly on mass, slightly on tidal periods

Q depends mainly on tidal period, and slightly on tidal periods.

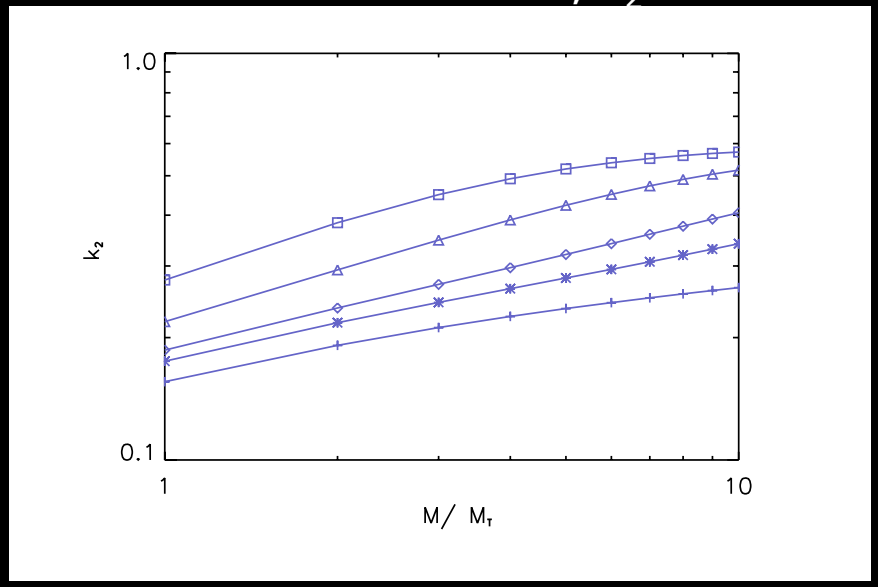
Exoplanets with 50% water ice from 1 to 10 Earth's mass

Tidal period::
0.5, 10, 20, 30, 40 days

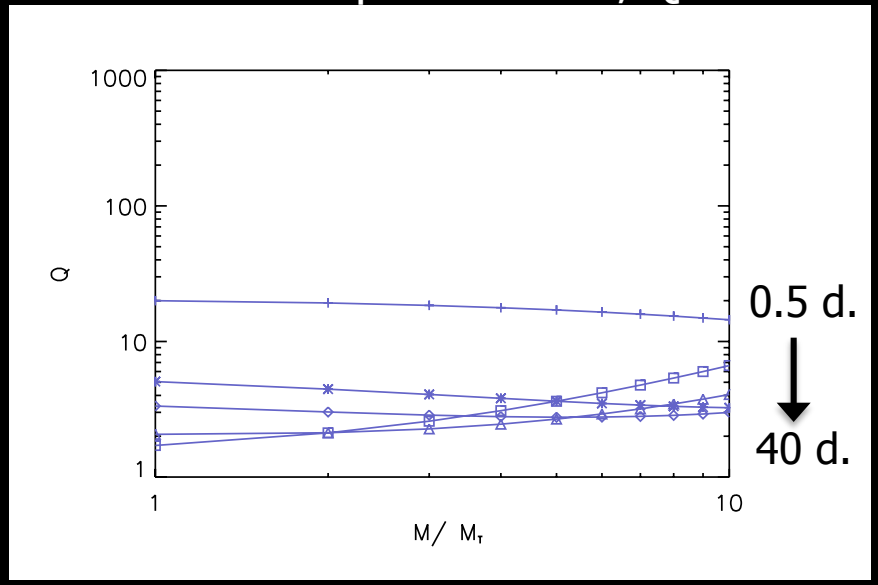
Density profile



Tidal Love number, k_2



Tidal dissipation factor, Q

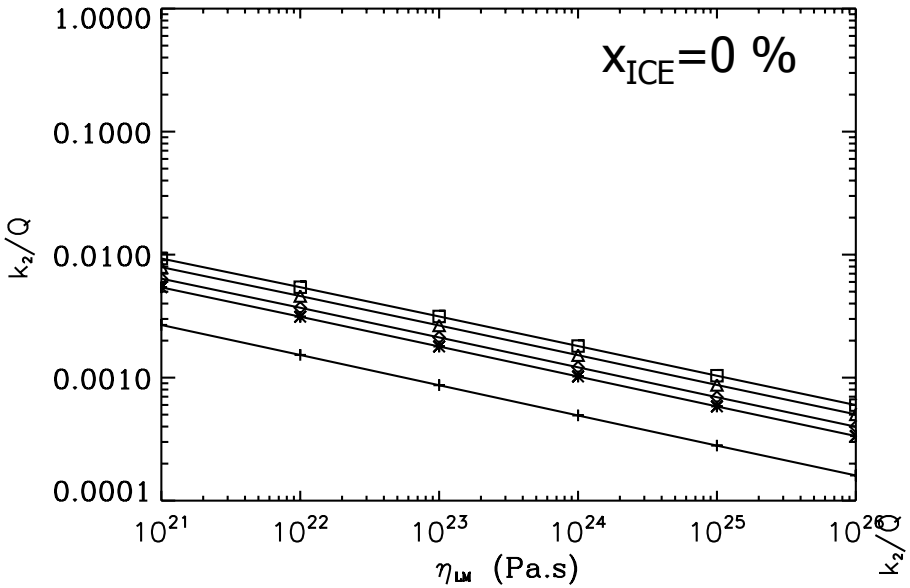


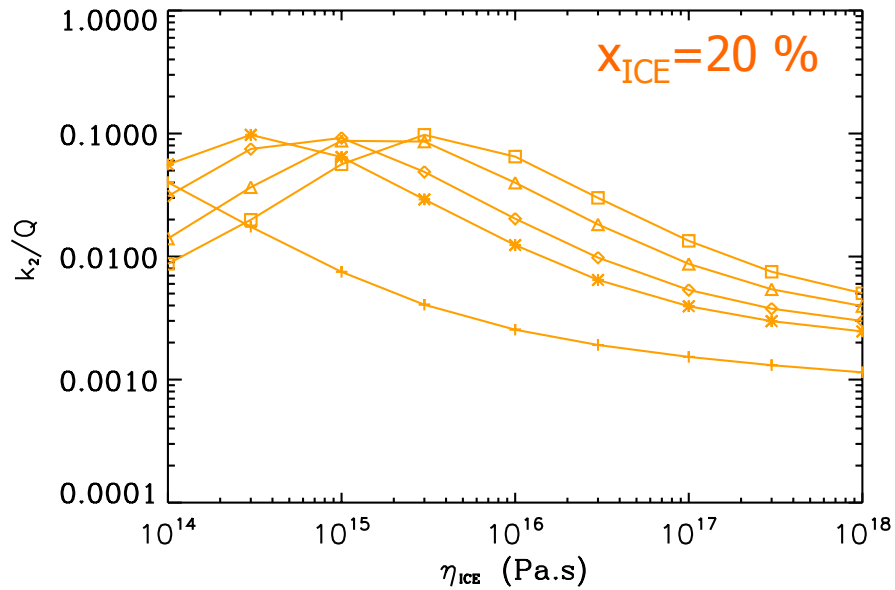
k_2 depends both on mass and tidal period.

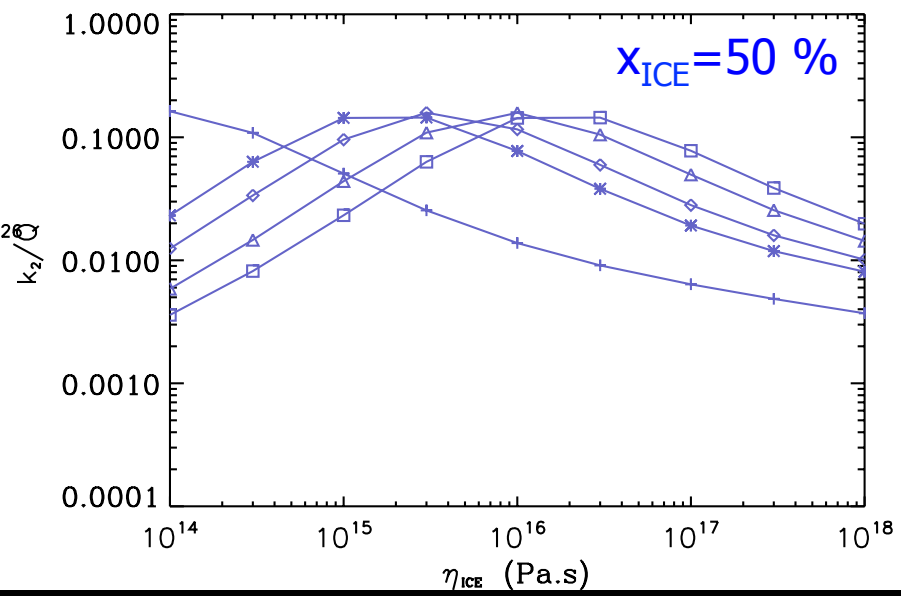
Q depends mainly on tidal period, and significantly on mass for P > 10 days.

Synthetic results on k_2/Q for 5-M_E planets

Tidal period::
0.5, 10, 20, 30, 40 days



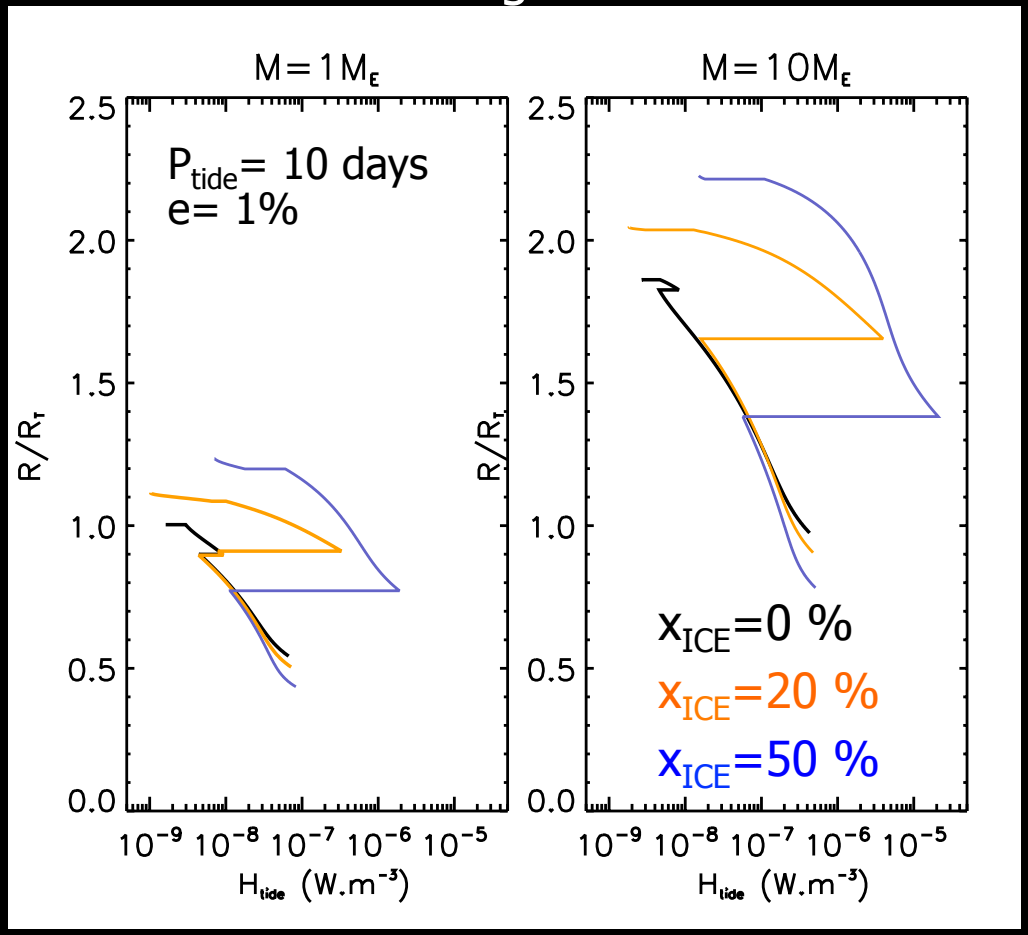




- Ice-rich exoplanets is about 20-30 times more dissipative than Earth-like planets

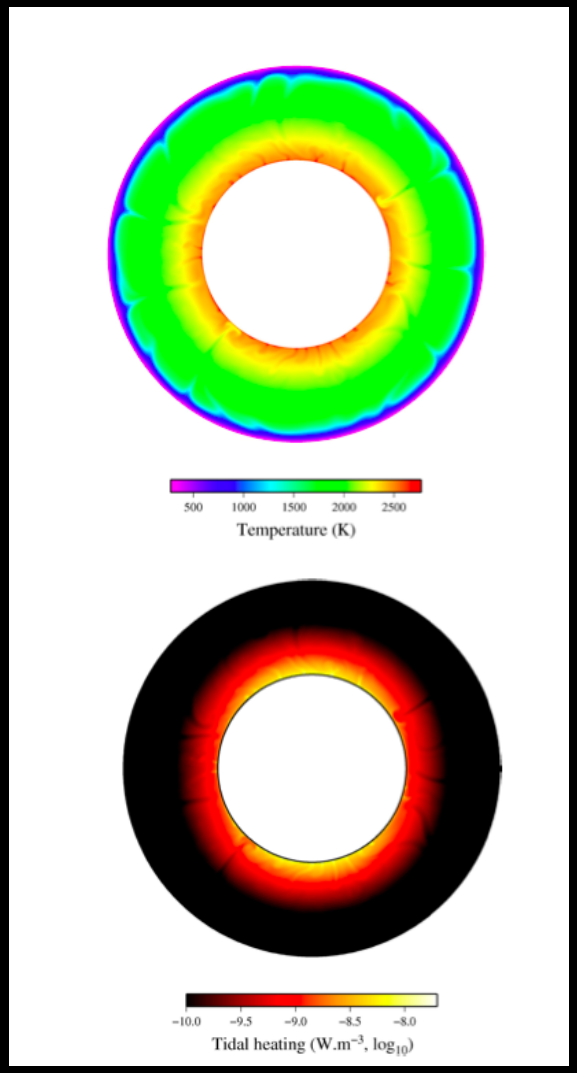
Implications for thermal evolution

Tidal heating distribution



Tidal heating comparable to radiogenic heating in the silicate mantle.
Much larger in the ice mantle: ~100-300 TW
(>> Earth's radiogenic power = 20-25 TW)

Coupling with thermal convection: *CHEOPS-2D*



Besserer et al. in prep.

CONCLUSION

- ✓ The amplitude of gravitational response (k_2) is mainly determined by the planet mass for Earth-like planets, and becomes more sensitive to orbital periods with increasing ice ratio.
- ✓ For similar orbital periods and masses, the total dissipated power in ice-rich planets can be more than one order of magnitude above that in silicate-dominated planets.
- ✓ Moreover, for ice-rich planets, an optimal dissipation rate is obtained for viscosity values comprised between about 10^{15} and 10^{16} Pa.s (typical values at the ice melting point) for orbital periods between 10 and 50 days, respectively.

Future works:

- Deriving a scaling law for the tidal response as a function of M and x_{ice}
- Including the effect of partial melting and surface liquids (water or magma ocean).
- Determining the condition under which thermal runaways may occur.

Thank you for your attention !