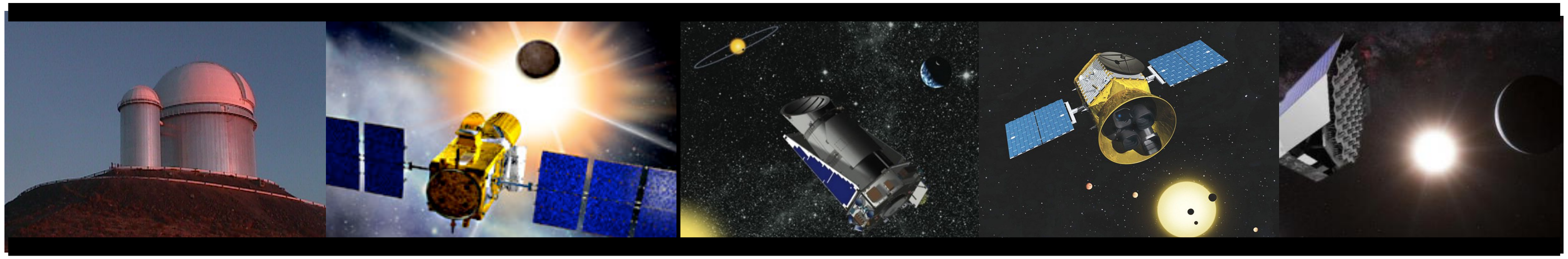
Tidal dissipation in stars and planetary fluid layers

S. Mathis, P. Auclair-Desrotour,
M. Guenel, F. Remus,
C. Le Poncin-Lafitte, V. Lainey, J.-P. Zahn

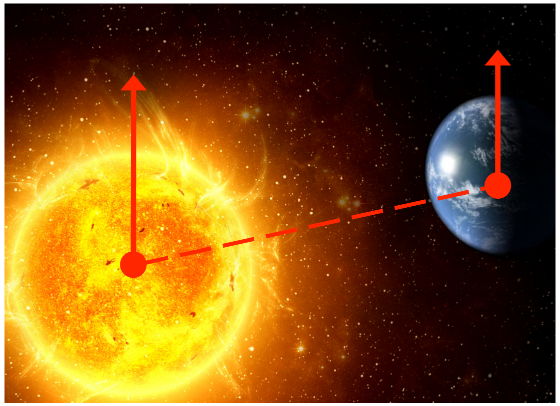
General context

A revolution in Astrophysics: the discovery of new planetary systems
and the characterisation of their host stars



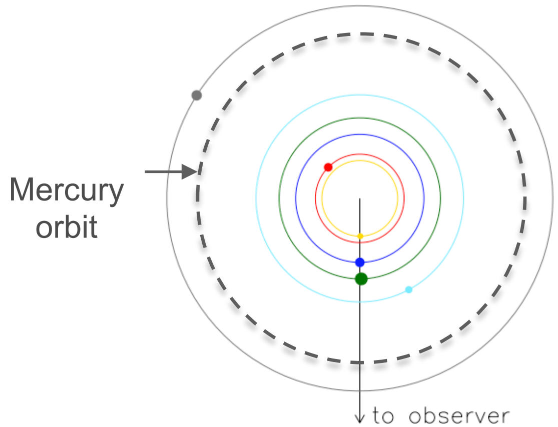
HARPS/ESO; SPIRou | CoRoT | *Kepler – K2* | *CHEOPS & TESS* | *PLATO*

Stellar and planetary rotation history



Albrecht et al. 2012; Gizon et al. 2013;
Talks V. Lainey & C. Damiani

Orbital architecture

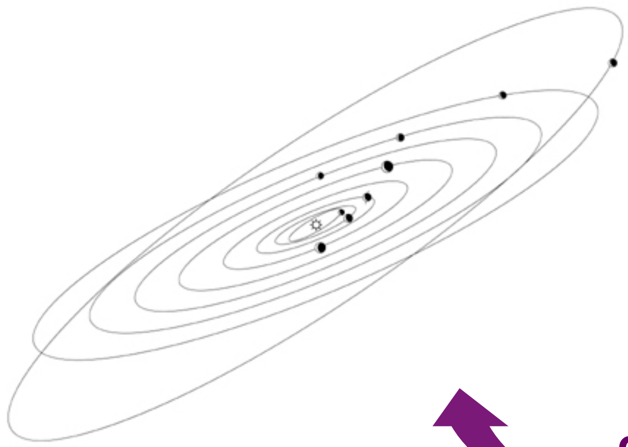


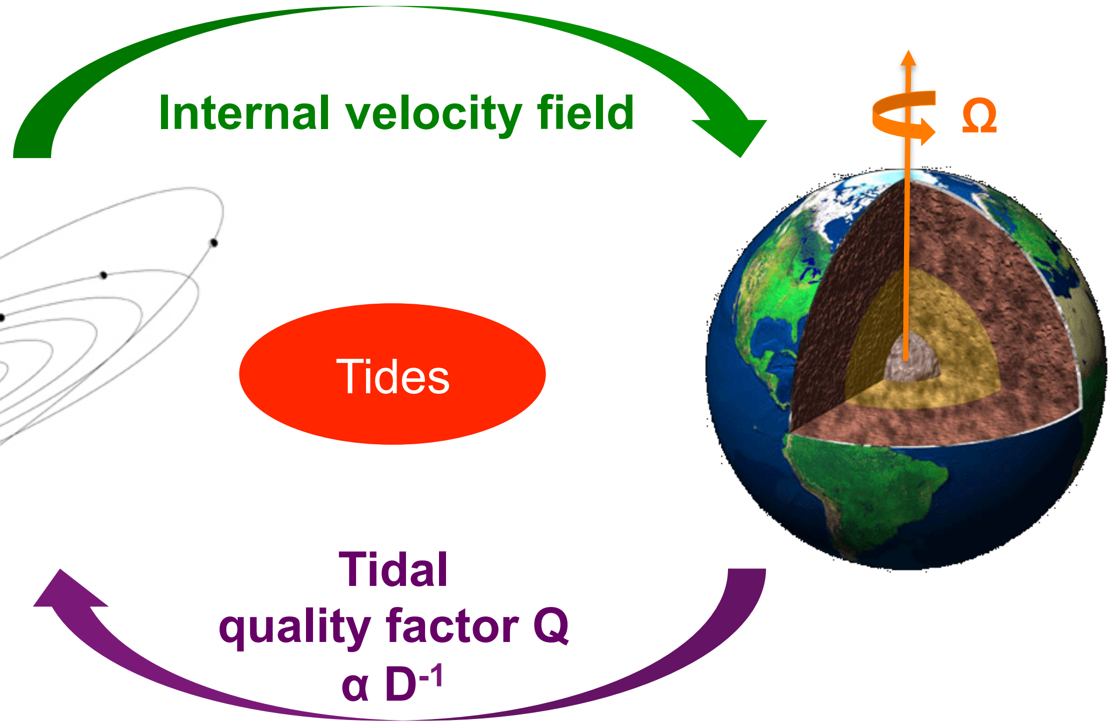
Kepler 11

Lissauer et al. 2011
Bolmont et al. 2014

→ Need to understand angular momentum exchanges within star-planet systems → TIDES

Tidal dissipation





$$\frac{da}{dt} = -\frac{3k_2 R_A^5 G n M_B}{M_A a^4} \boxed{Q^{-1}(\omega)} \mathrm{sgn}(\omega)$$

Energy dissipation
→ Dynamics of spins & orbits

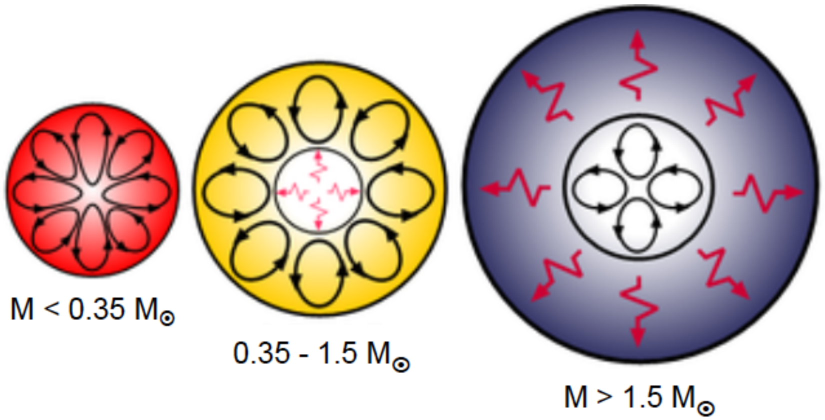
Spin/orbit | **Tidal dissipation** | **Internal structure**

State of the art

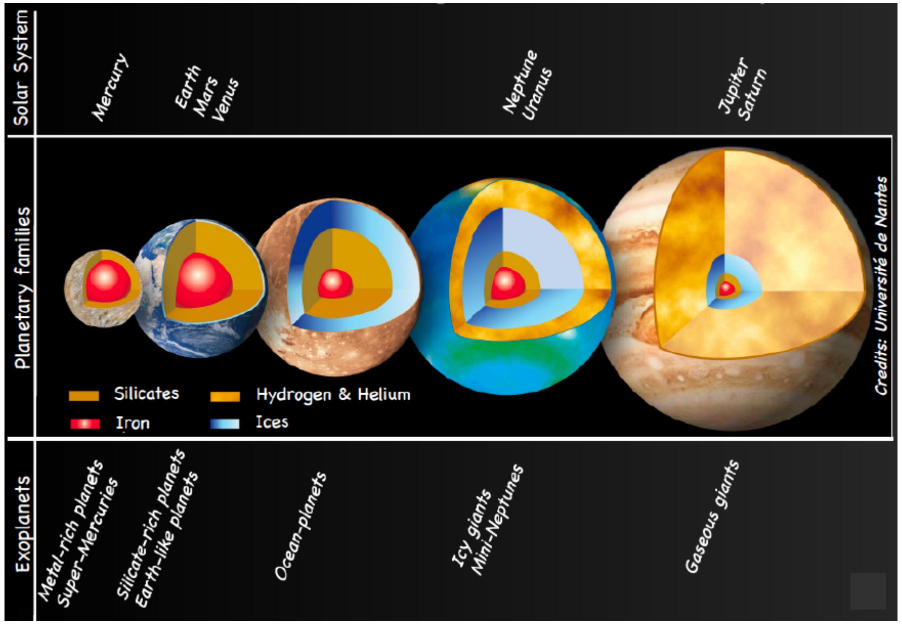
In studies of star-planet systems, bodies are treated as point-mass objects or solids with ad-hoc prescriptions for tides

However their complex internal structure, rotation, and magnetism impact tidal dissipation

Host star (M in $M_\odot$)

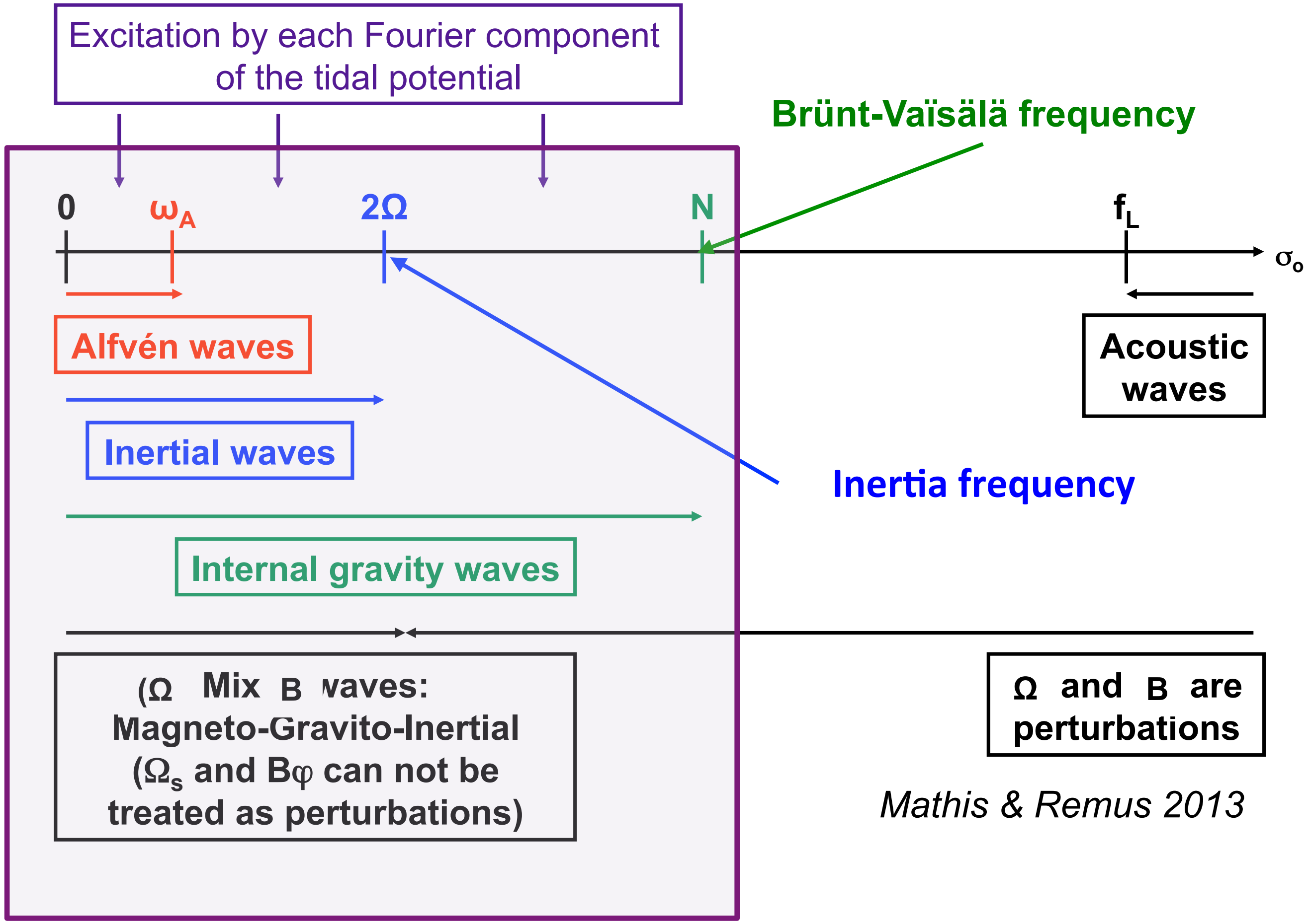


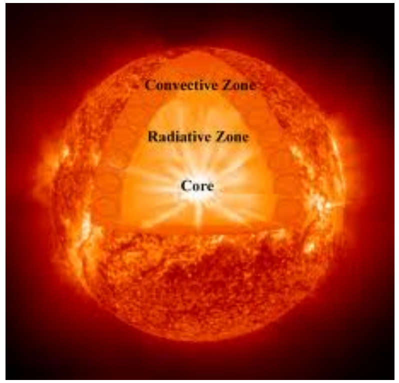
Planets

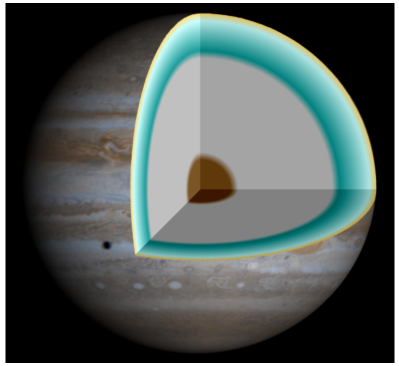


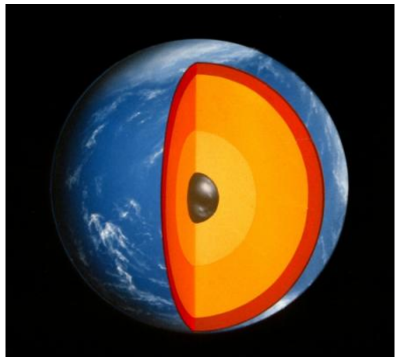
→ Need of an ab-initio physical modeling

Tidal waves in stars and fluid planetary layers





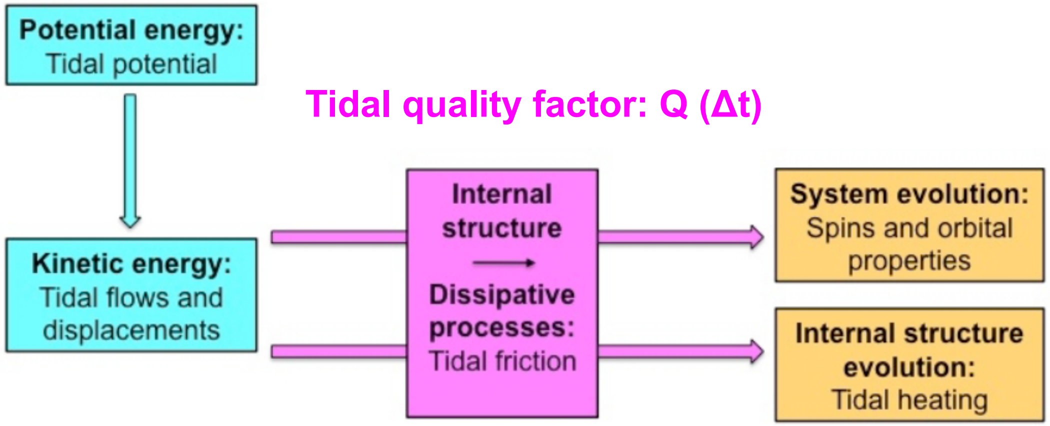




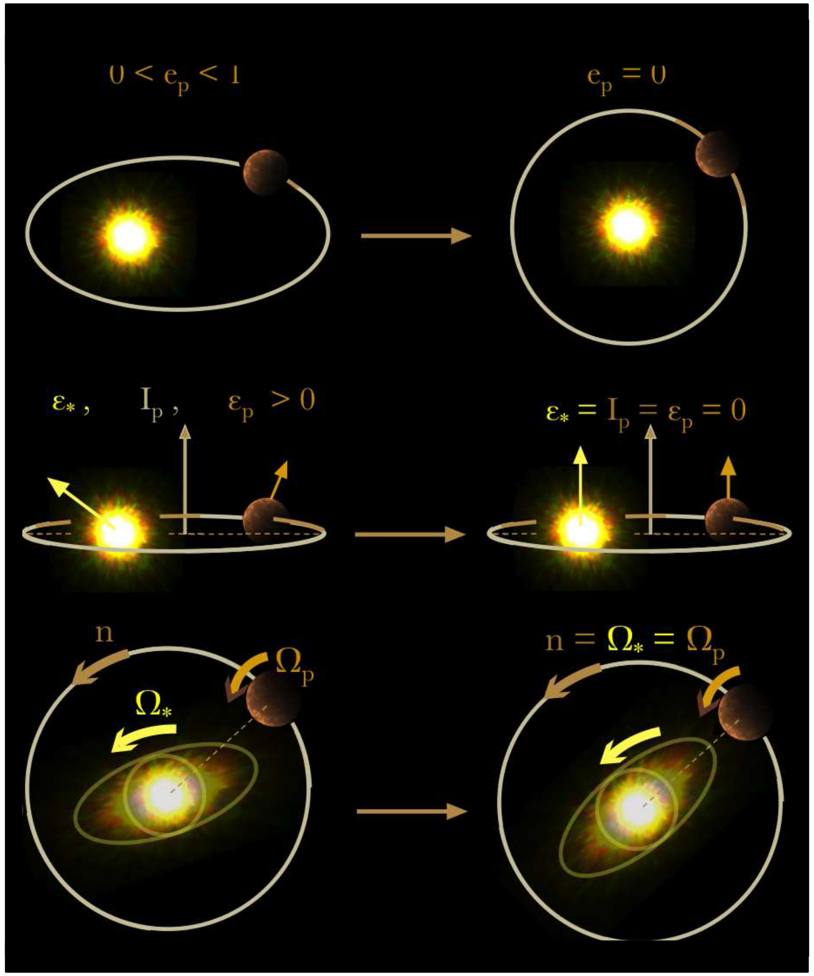
The "engine" of the dynamical evolution of binary systems: friction & energy dissipation

Dynamical evolution of a binary system:
<u>Morning talks</u>

Tidal quality factor: Q (Δt)



Mathis & Remus 2013

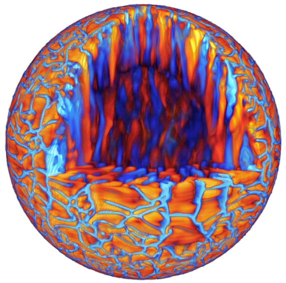


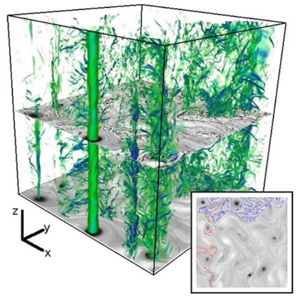
→ **Necessity to identify the dissipative processes that convert the kinetic energy into thermic one and to model their dependence on the structure and excitation frequency**

→ **Time-scales for circularization, synchronization, alignment, and migration → Age**

Dissipation mechanisms in stars and fluid planetary layers

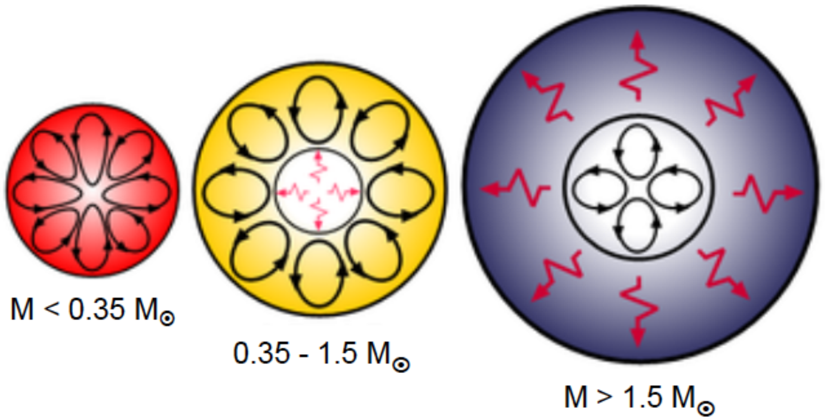
Convective regions:
turbulent friction
→ equilibrium tide
→ dynamical tide:
inertial waves

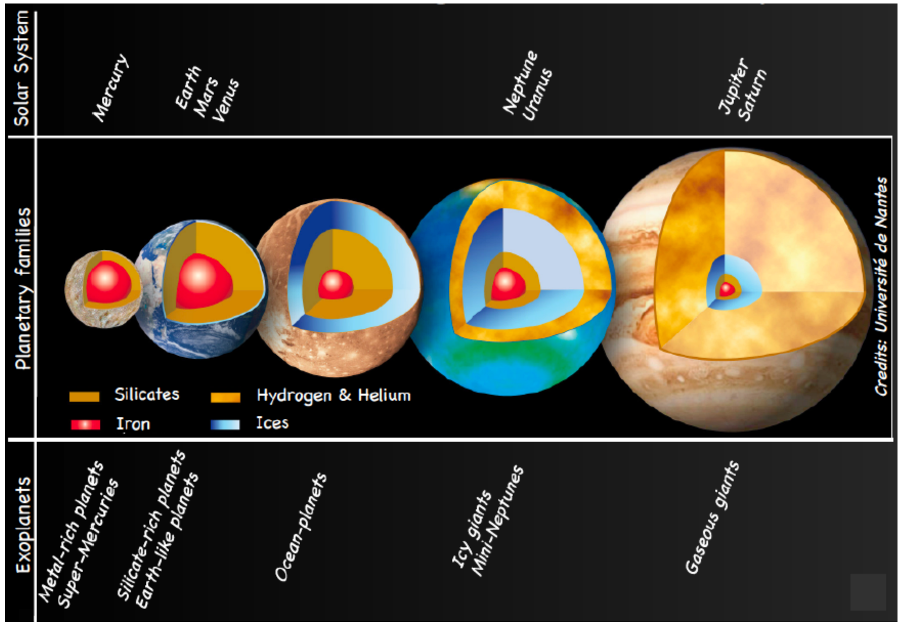




Brun et al. *Pouquet et al.*

Stably stratified regions:
radiative damping
→ dynamical tide:
gravito-inertial waves



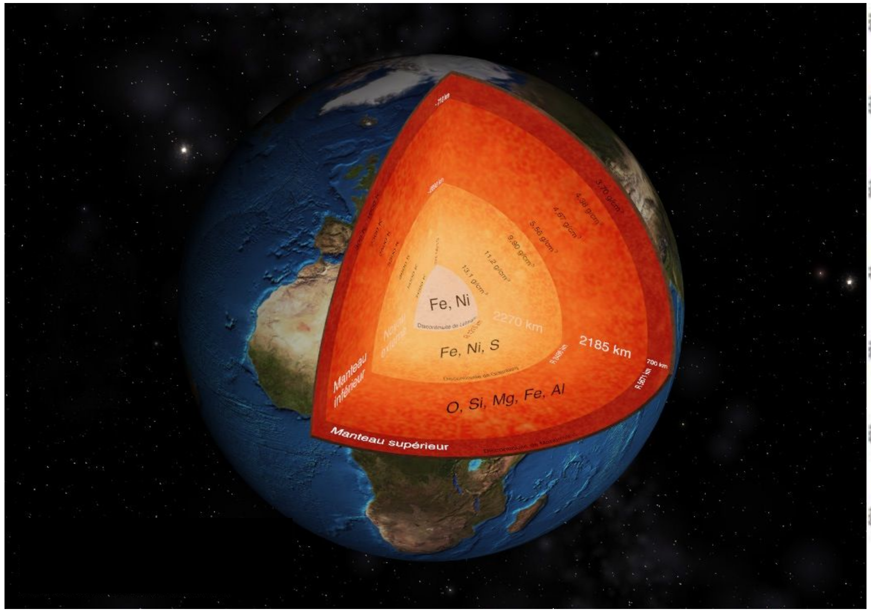


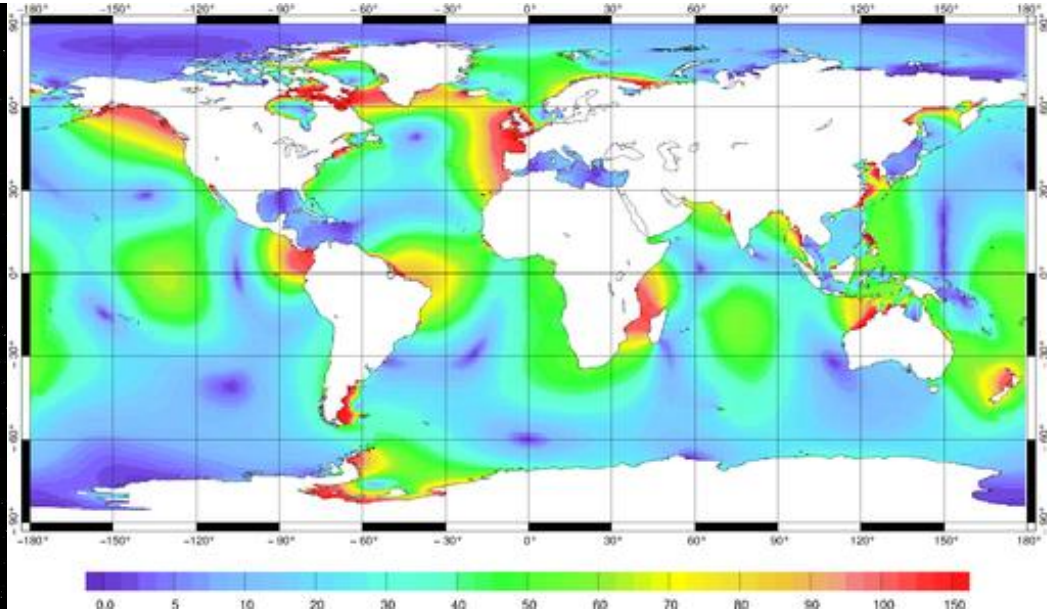
Elliptic instabilities: both in convective and radiative regions

→ **Challenge: coupling tides - turbulence** (*Lesur & Ogilvie 2012*)

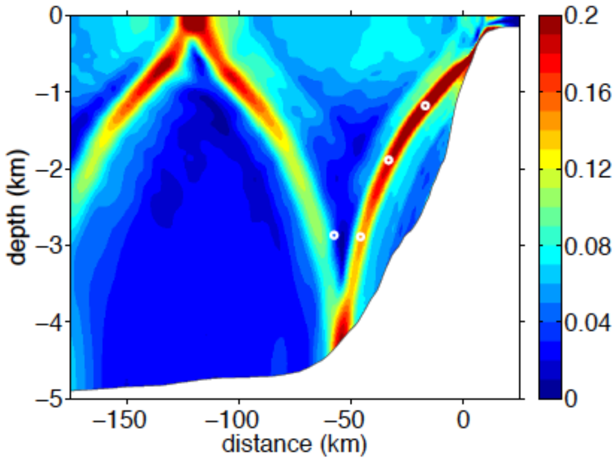
The case of the Earth

Satellites Jason 1 & 2 and Topex/Poséidon
Kantha 2014





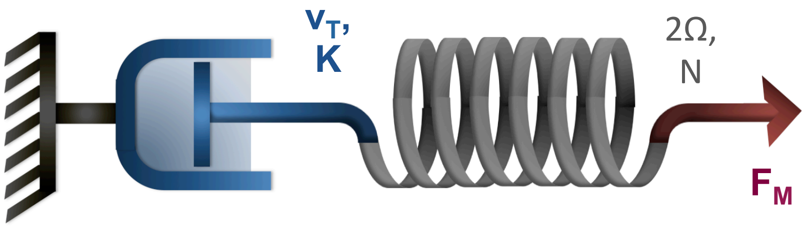
→ **Viscous friction on tidal gravito-inertial waves**

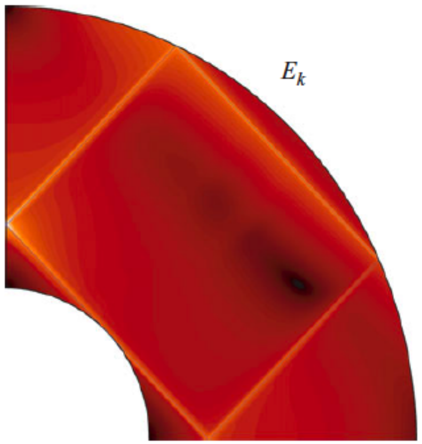


Gerkema, Lam & Maas 2004

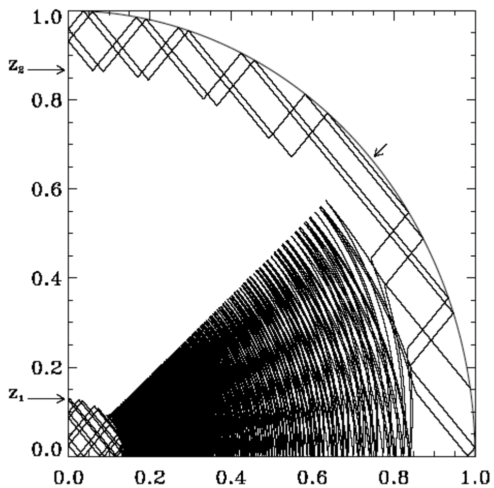
A resonant erratic tidal dissipation spectrum

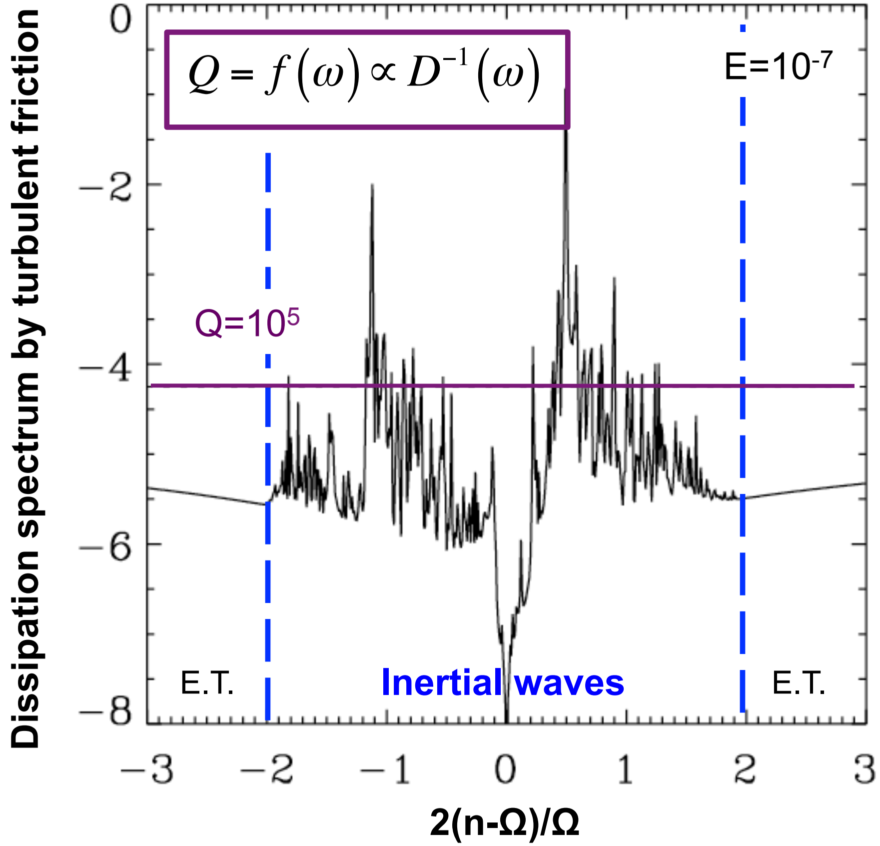
Forced (gravito-) inertial waves
→ resonant response





$Nr = 400\ L = 1200\ M = 0^{+}\ E = 2.0\times10^{-9}$
$\eta = 0.350\ \ \omega = 0.707\ CL = ff$





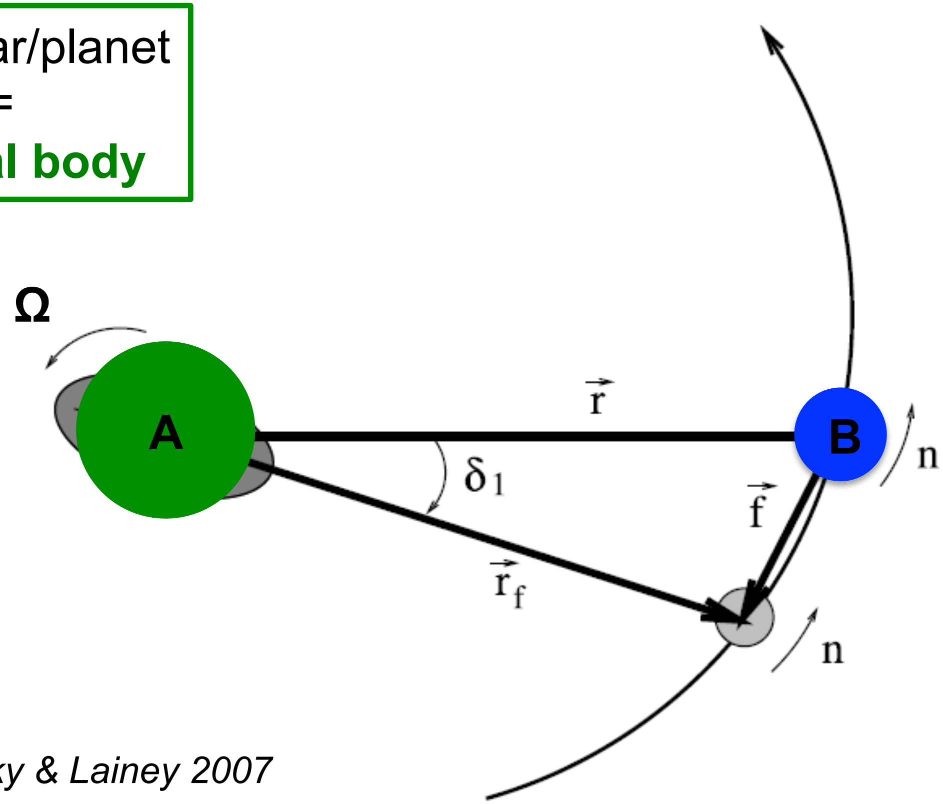
Ogilvie & Lin 2004: the case of Jupiter

Dintrans & Rieutord 2000
Ogilvie & Lin 2007
Rieutord & Valdetarro 2010
Baruteau & Rieutord 2013
Guenel et al. 2015

The impact of tidal dissipation on the spin dynamics and on systems orbital architecture

The coplanar two-bodies system:

Host star/planet
=
Central body



Punctual planet/satellite
=
Perturber

Tidal frequency: $\chi = 2(n - \Omega)$

Efroimsky & Lainey 2007

The impact of tidal dissipation: the case of rocky bodies

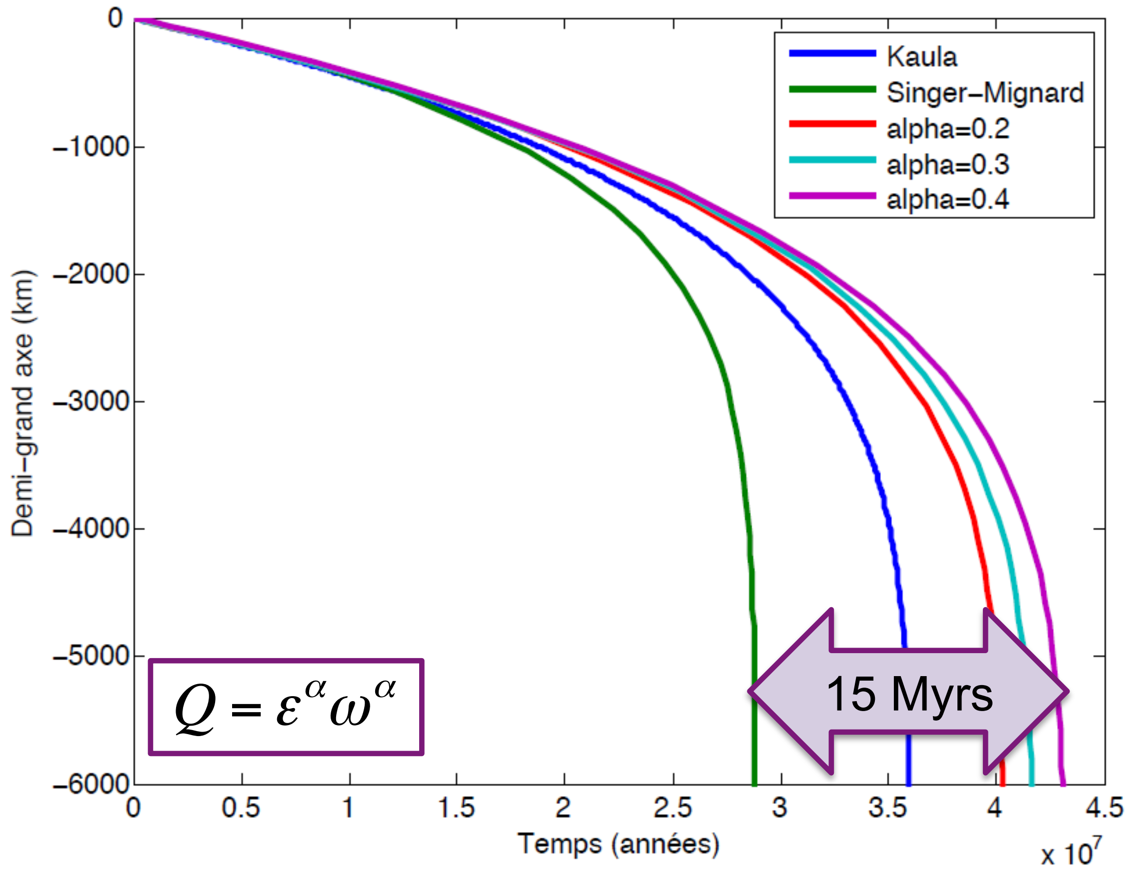
An example: the Mars-Phobos system

Regular evolution

Internal dissipation

Rheology: ε & α

Efroimsky & Lainey 2007

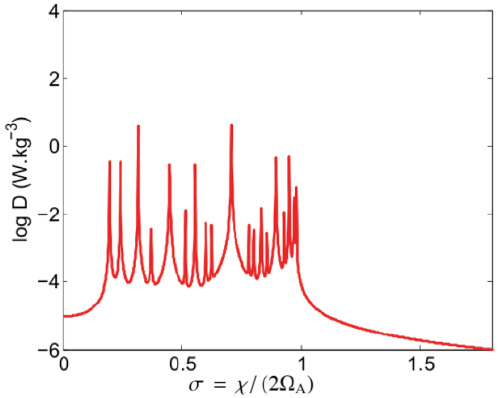


$$Q = \varepsilon^{\alpha}\omega^{\alpha}$$

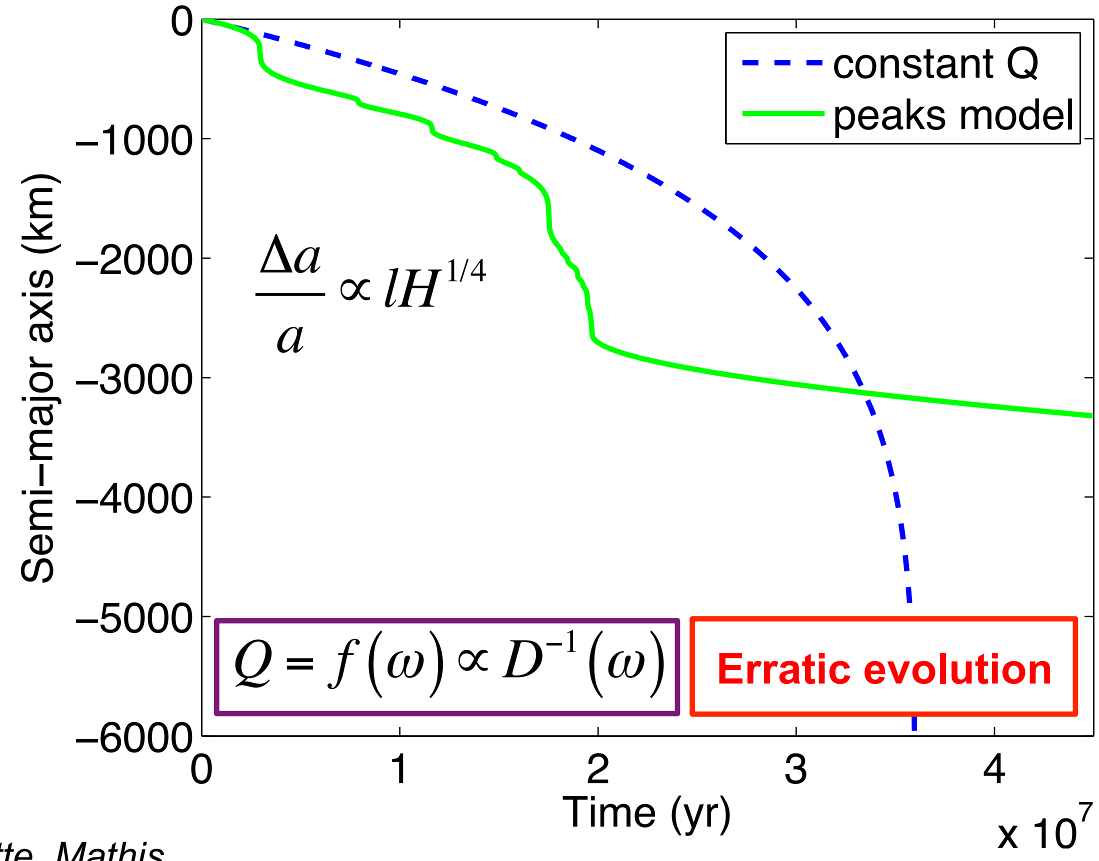
The impact of tidal dissipation: the case of fluid bodies

An example: a fully convective body of the mass of Mars-Phobos system

Internal dissipation



Fluid parameters



Auclair-Desrotour, Le Poncin-Lafitte, Mathis 2014a

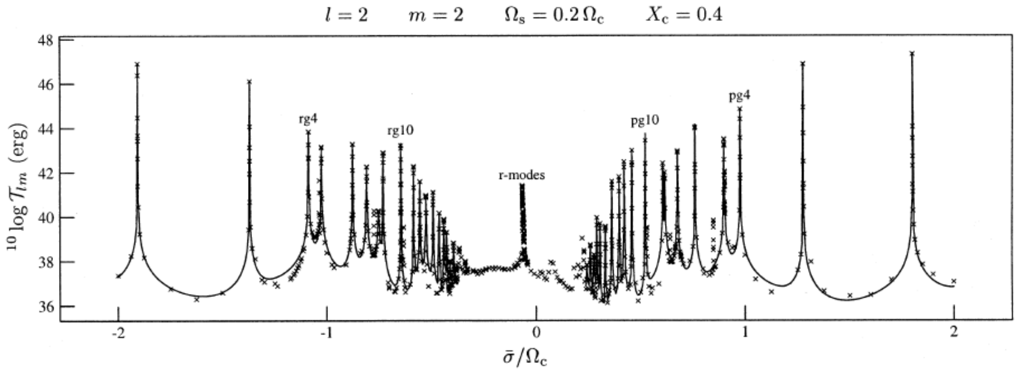
Back to the stars

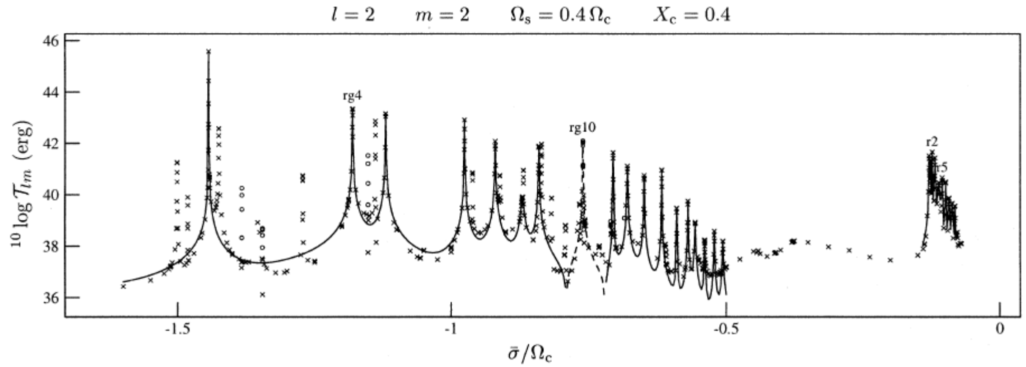
Dynamical tide

Zahn 1975

Witte & Savonije
1999a,b-2001-2002a,b

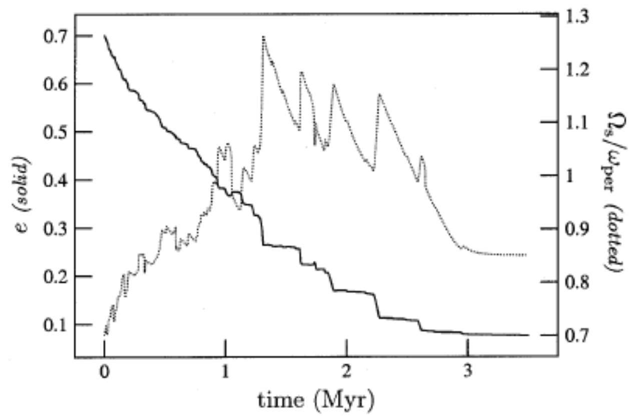
Tidal torques

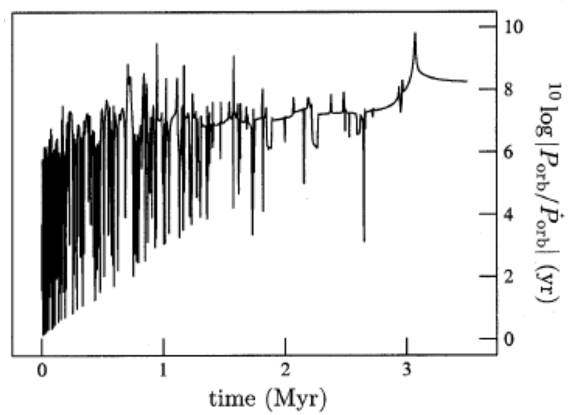




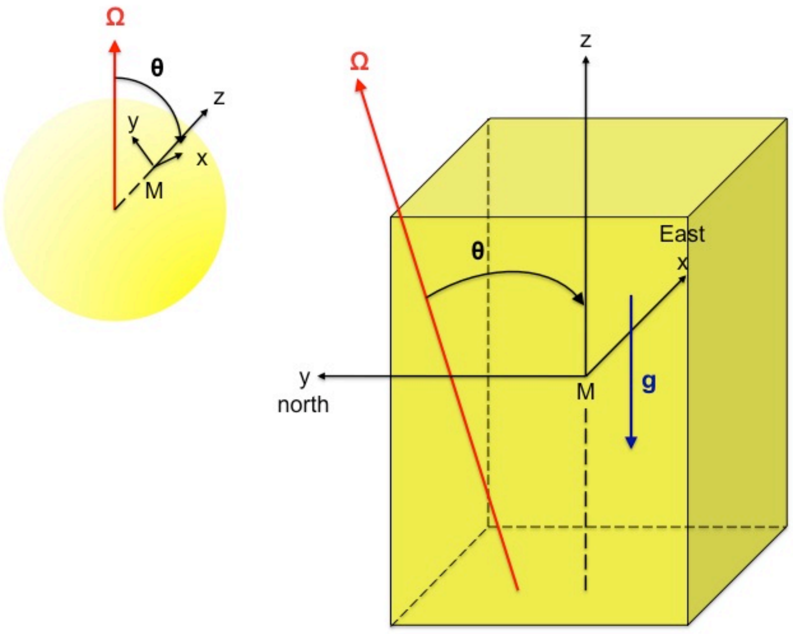
→ Complex orbital & spin evolution

Witte & Savonije 1999b





A reduced local model
to understand tidal dissipation in fluids



Ogilvie & Lin 2004

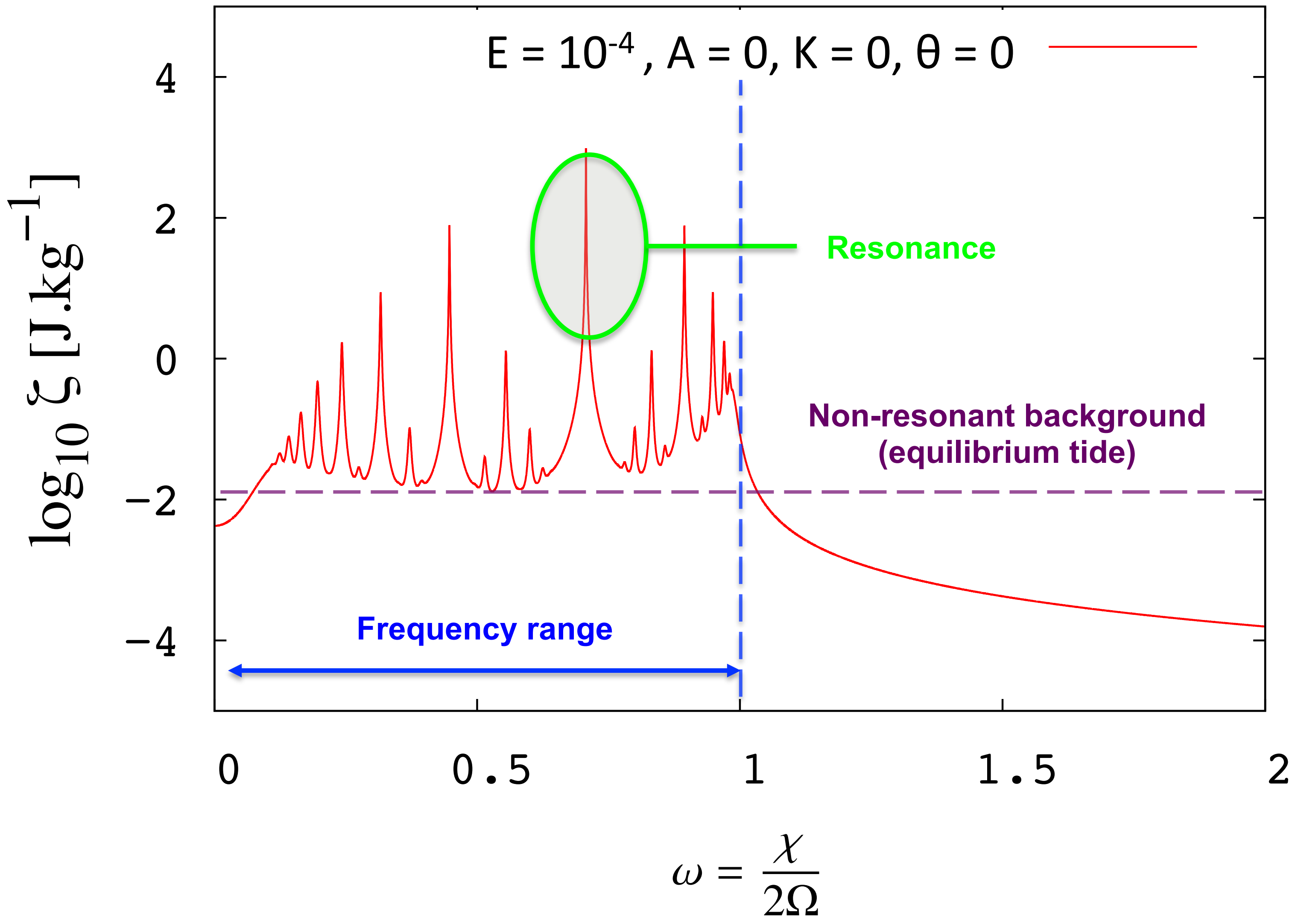
Auclair-Desrotour, Le Poncin-Lafitte, Mathis 2014b

- Cartesian geometry
- Rotating and inclined
- Possible stable stratification
- Viscous and thermal dissipation

Control parameters:

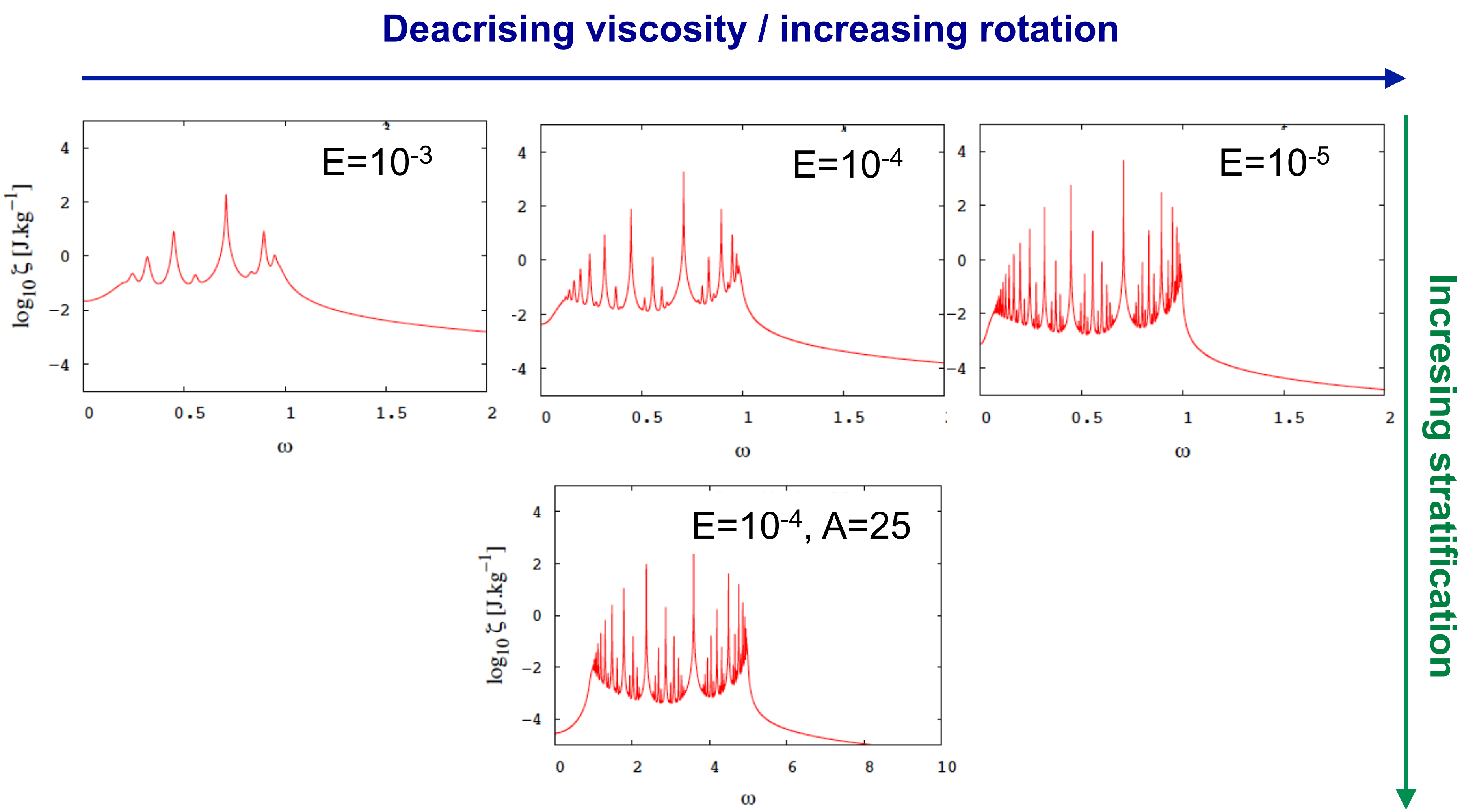
$A = \left(\frac{N}{2\Omega}\right)^2$	Stratification / Coriolis
$E = \frac{2\pi^2 \nu}{\Omega L^2}$	Viscous force / Coriolis
$K = \frac{2\pi^2 \kappa}{\Omega L^2}$	Thermal diffusivity / Coriolis

The complex erratic tidal dissipation spectrum



→ **Need to characterize spectra**

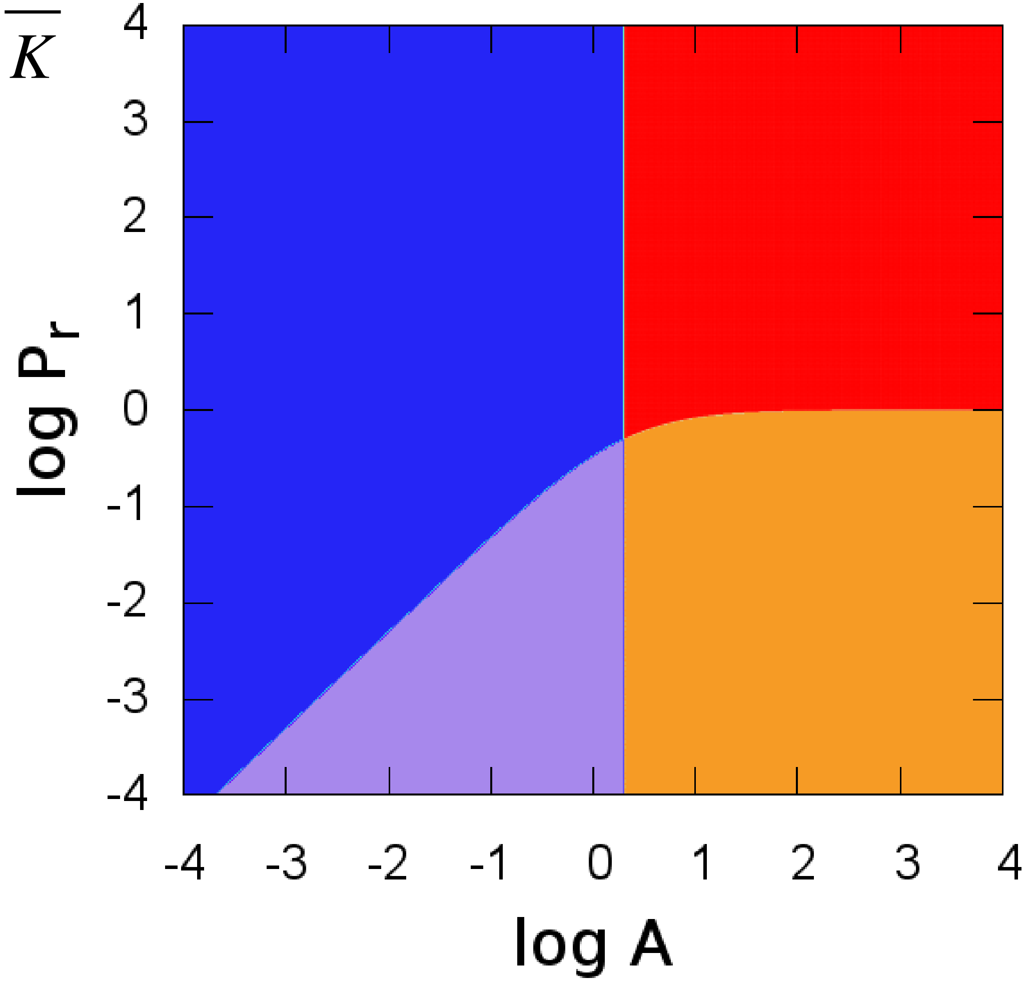
An evolving behaviour



The four main regimes

$$\mathrm{Pr} = \frac{E}{K}$$

Viscously driven dissipation



$$A_{mn}(\theta) = \frac{2n^2}{m^2}\cos^2\theta$$

$$Pr_{mn}(\theta, A) = \frac{A}{A + A_{mn}(\theta)}$$

Inertial waves
CZ

Gravito-inertial waves
Stable Zone

$$A = \left(\frac{N}{2\Omega}\right)^2$$

Thermal diffusion driven dissipation

Auclair-Desrotour, Le Poncin-Lafitte, Mathis 2014b

Asymptotic scaling laws

Domain	$A \ll A_{11}$		$A \gg A_{11}$	
$Pr \gg Pr_{11}$	$\omega_{mn} \sim \frac{n}{\sqrt{m^2+n^2}} \cos\theta$		$\omega_{mn} \sim \frac{m}{\sqrt{m^2+n^2}} \sqrt{A}$	
	$l_{mn} \sim E$	$k_c \sim E^{-1/4}$	$l_{mn} \sim E$	$k_c \sim A^{1/8} E^{-1/4}$
	$H_{mn} \sim F^2 E^{-1}$	$N_{kc} \sim E^{-1/2}$	$H_{mn} \sim F^2 E^{-1}$	$N_{kc} \sim A^{1/4} E^{-1/2}$
	$H_{bg} \sim F^2 E$	$\Xi \sim E^{-2}$	$H_{bg} \sim F^2 E A^{-1}$	$\Xi \sim A E^{-2}$
$Pr \ll Pr_{11}$	$\omega_{mn} \sim \frac{n}{\sqrt{m^2+n^2}} \cos\theta$		$\omega_{mn} \sim \frac{m}{\sqrt{m^2+n^2}} \sqrt{A}$	
	$l_{mn} \sim AK$	$k_c \sim A^{-1/4} K^{-1/4}$	$l_{mn} \sim K$	$k_c \sim A^{1/8} K^{-1/4}$
	$H_{mn} \sim F^2 A^{-2} E K^{-2}$	$N_{kc} \sim A^{-1/2} K^{-1/2}$	$H_{mn} \sim F^2 E K^{-2}$	$N_{kc} \sim A^{1/4} K^{-1/2}$
	$H_{bg} \sim F^2 E$	$\Xi \sim A^{-2} K^{-2}$	$H_{bg} \sim F^2 E A^{-1}$	$\Xi \sim A K^{-2}$

Auclair-Desrotour, Le Poncin-Lafitte, Mathis 2014b

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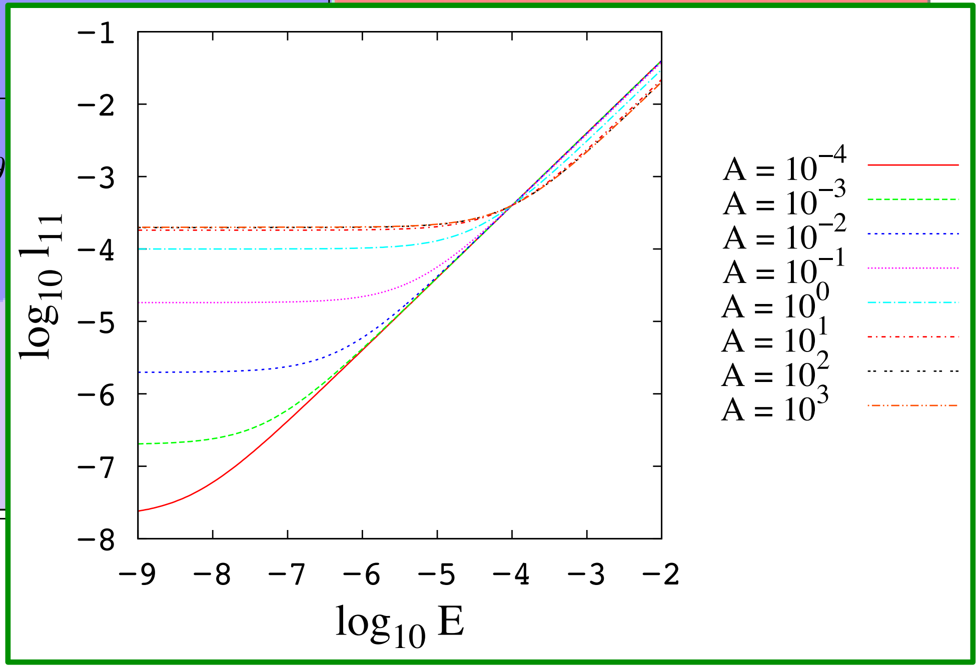
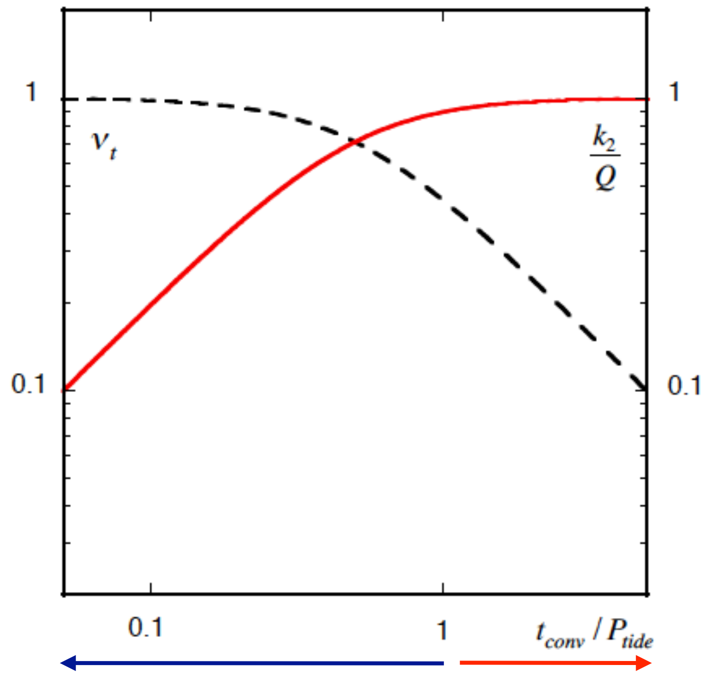
	$H_{bg} \sim F^2 E$			



Auclair-Desrotour, Le Poncin-Lafitte, Mathis 2014b

Turbulent friction in rotating convection zone

Viscous turbulent by non-rotating convection



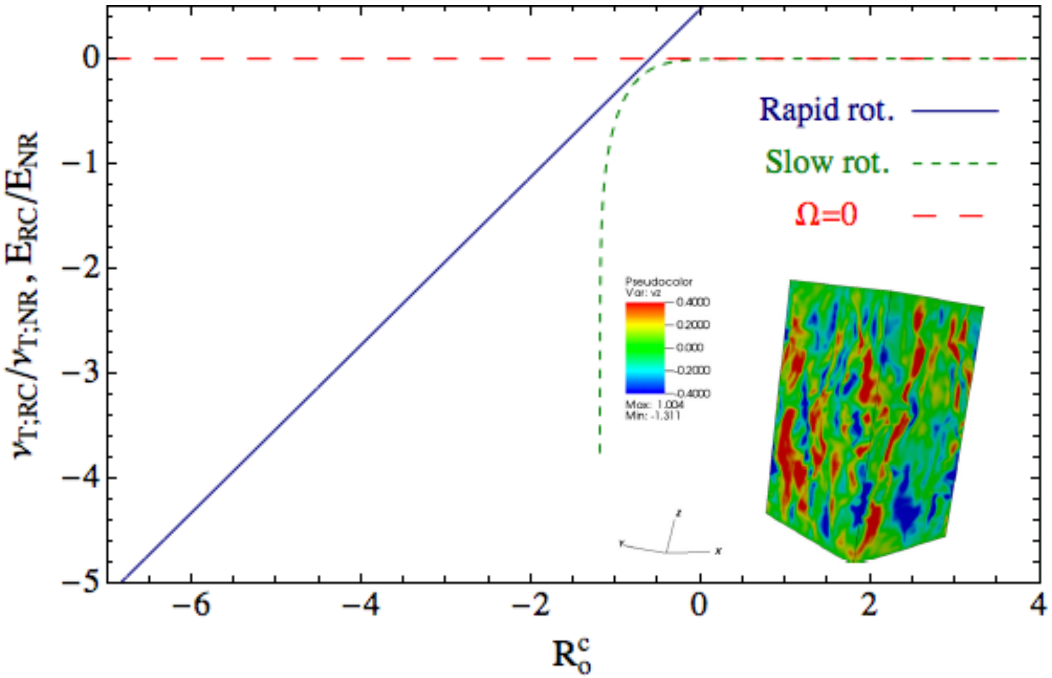
Slow tide
Q α ω[-1]

Fast tide
Q=cste

Zahn 1966

Remus, Mathis & Zahn 2012

Viscous turbulent by rotating convection

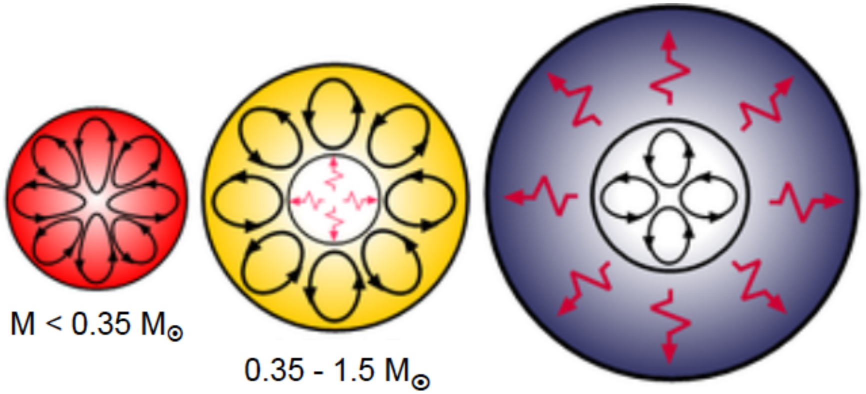


$$R_o^c = \left(\frac{V_c\,(\Omega = 0)}{L_c\,(\Omega = 0)\, 2\Omega |\cos\theta|} \right) \longrightarrow E = \frac{2\pi^2 \nu_T}{\Omega L^2}$$

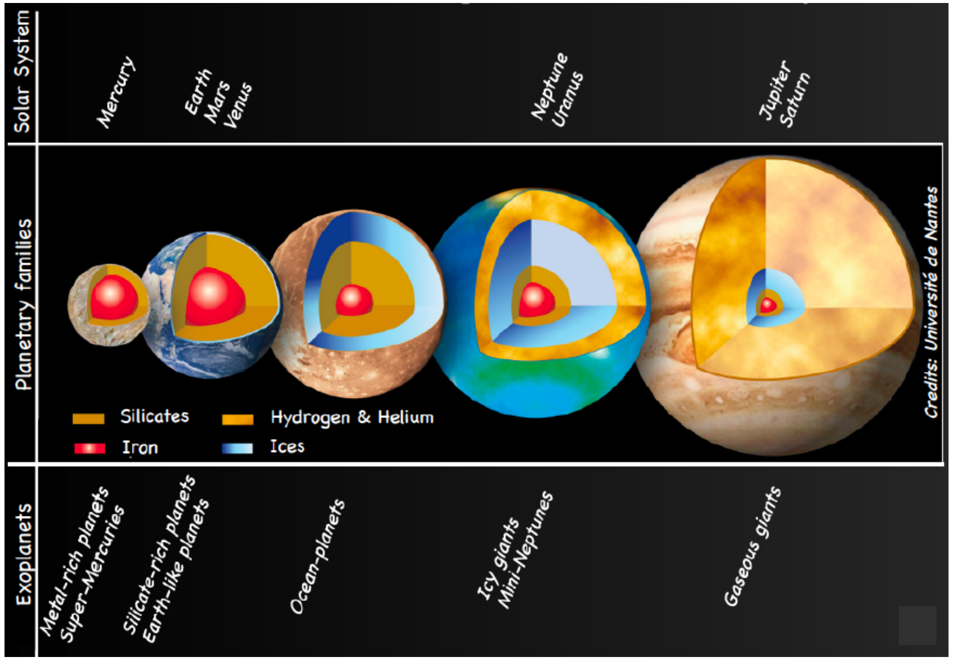
Mathis et al. 2014-15 (Barker 2014)

Towards global and multi-layer models

Host star (M in $M_\odot$)



Planets



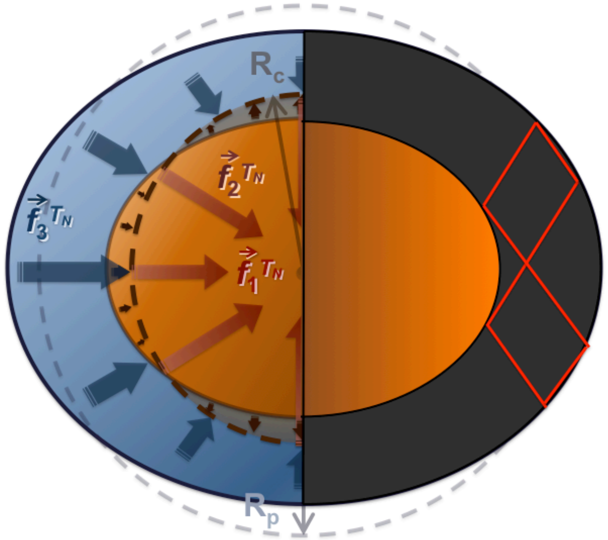
Their strong stratification
→ Need of a global ab-initio physical modeling

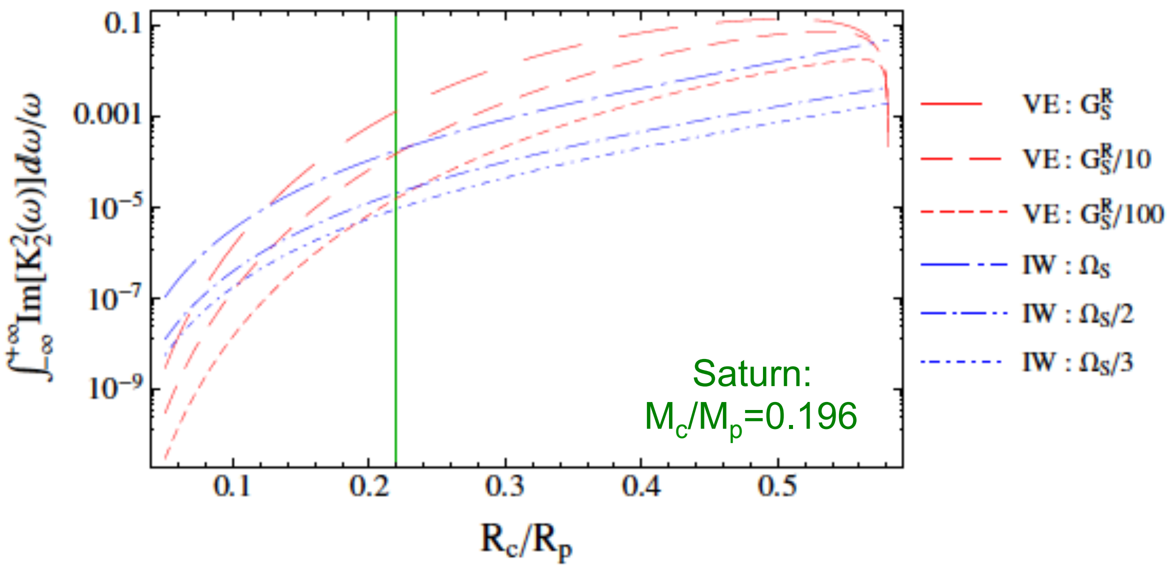
Frequency-averaged models

The example of a Saturn-like planet:

Remus, Mathis, Zahn & Lainey 2012, 2014

Ogilvie 2009, 2013





→ Integrated models needed for gaseous giant (and telluric) planets

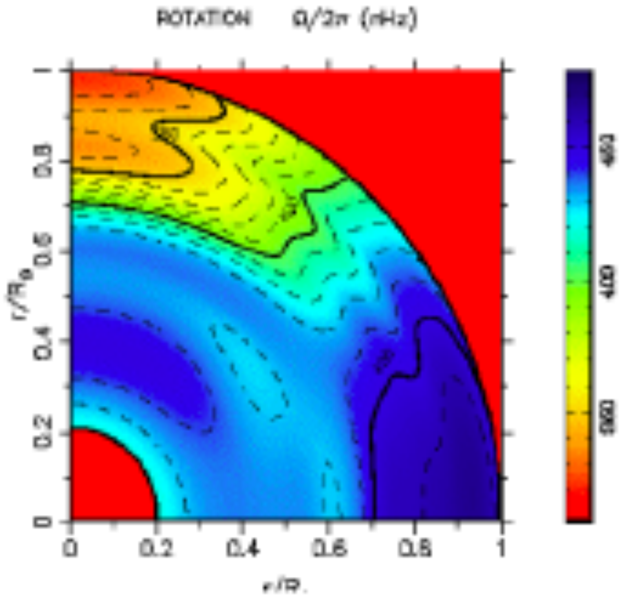
→ Possibility of frequency-averaged grids as a function of stellar and planetary properties

Guenel, Mathis & Remus 2014

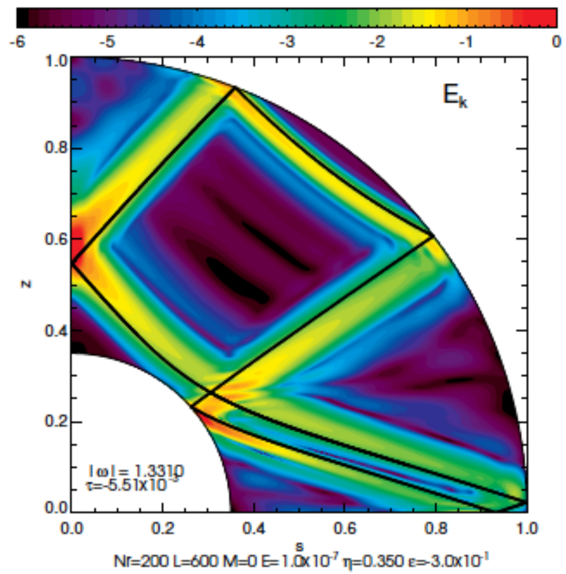
Global models

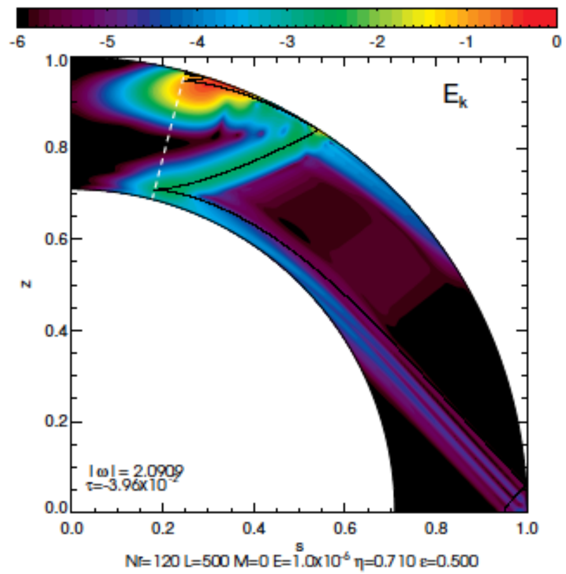
Tidal inertial waves in differentially rotating convective regions

Baruteau & Rieutord 2013; Guenel et al. 2015



Schou et al. 1998;
Garcia et al. 2007





Understanding stars with companions

Tides and stellar evolution

- Tides impact angular momentum exchanges within/between stars and planets

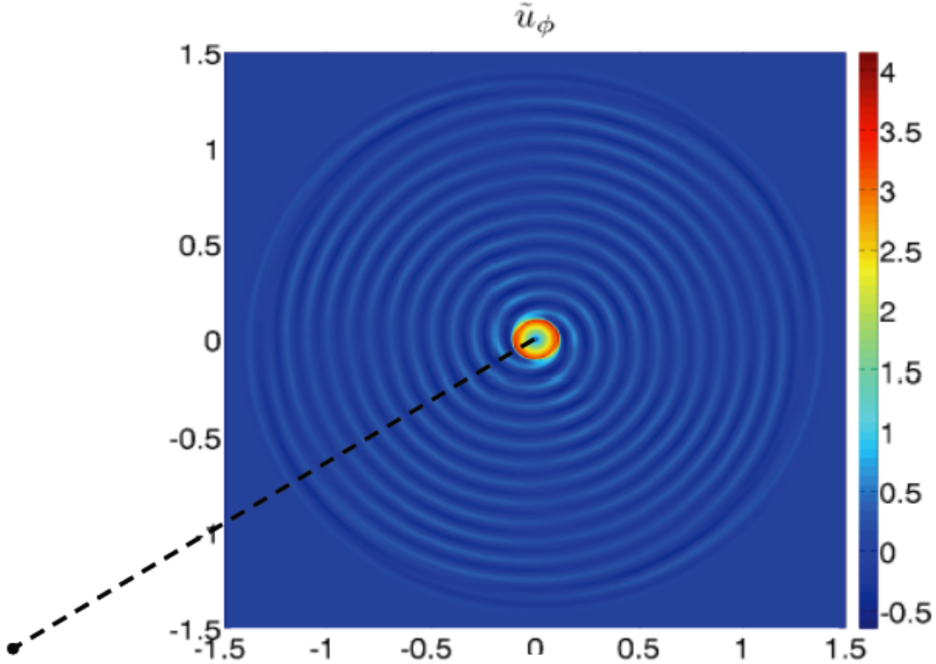
→ modification of the host star's evolution and internal differential rotation

Tides and magnetism

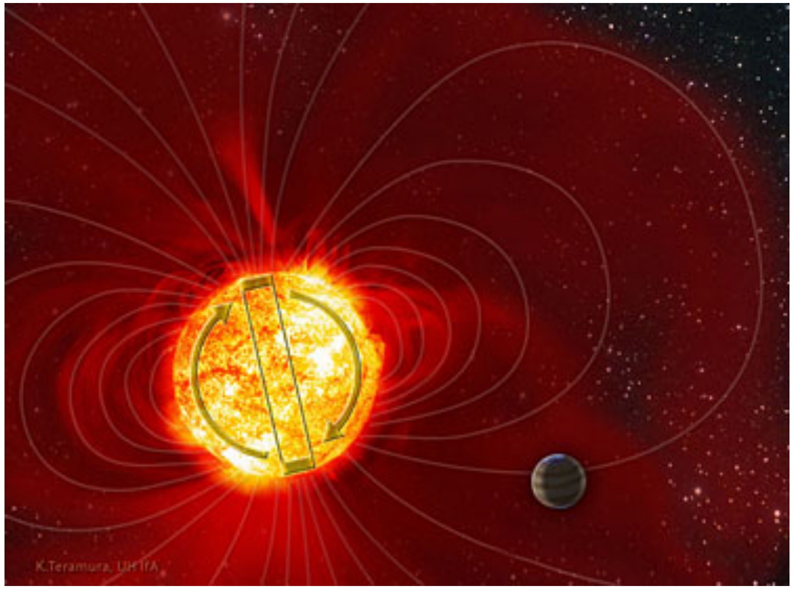
- Tides induce helical flows

→ able to modify magnetism in stars (BinaMIcS, Uvmag/Arago) and planets (magnetic fields also modify tidal flows)

- Tidal and MHD torques must be taken into account simultaneously to predict the correct evolution of a system



Barker & Ogilvie 2010



Donati et al. 2008; Strugarek et al 2014

Conclusions & perspectives

- Dependence of the spin/orbital dynamics on the resonant tidal fluid dissipation :

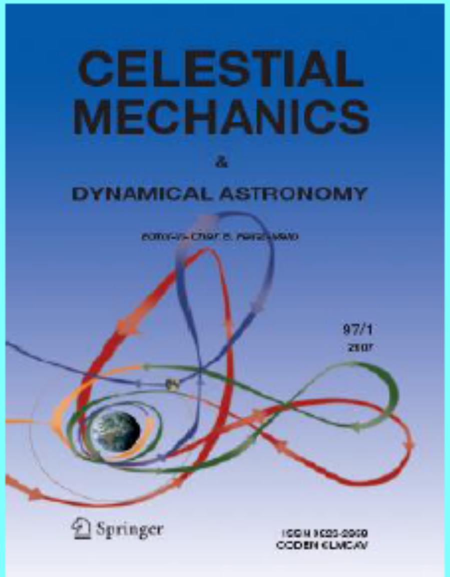
  → *width, height, non-resonant background level*
- Dependence of the characteristics of these resonances on the physical parameters of the fluid :

  → *rotation, stratification, viscosity, thermal diffusivity, etc.*
- Local model : general method and qualitative results

  → *Need of global models (Guenel, Baruteau, Mathis & Rieutord; Ogilvie et al.); need to characterize the case of stratified convection (Leconte & Chabrier)*
- Generalization to magnetic stars and planets :

  → *Alfvén waves; new asymptotic behaviors (Mathis, Auclair-Desrotour, Guenel, Le Poncin-Lafitte)*

Spin/orbit — **Tidal dissipation** — **Internal structure**



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SPECIAL ISSUE

TIDAL EVOLUTION

GENERAL INFORMATION

- **TOPICS**
  - Planetary systems
  - Close-in satellites
  - Exoplanets
  - Host stars rotation
  - Tidal evolution and habitability
  - Migration
  - Disipative mechanisms

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