Evolution of stars in multiple systems (WP121500):
First steps to improve stellar models

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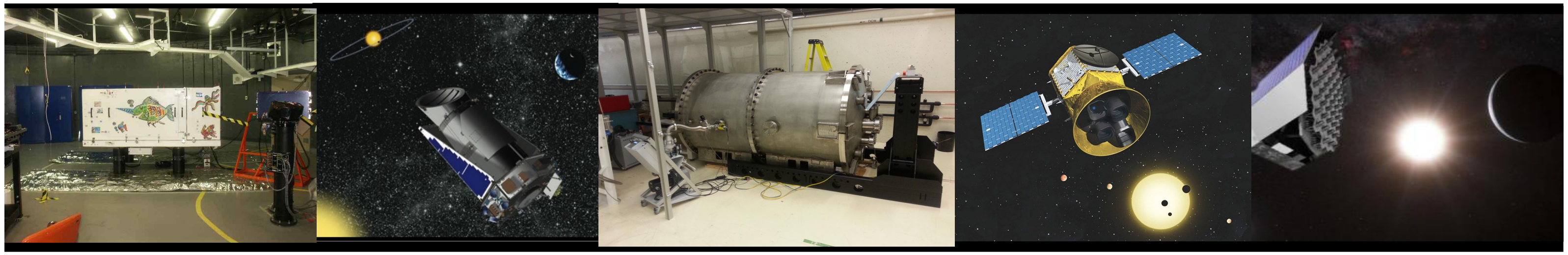
C. Charbonnel, L. Amard, A. Palacios, A.-S. Brun, V. Reville, A. Strugarek, N. Lanza et al.

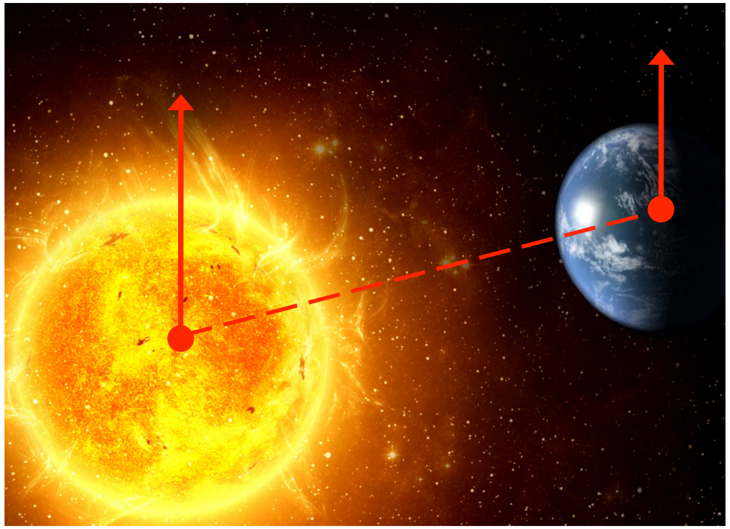
The general context

A revolution in astrophysics: discovery of **new planetary systems** & characterisation of **the dynamics of their host (multiple) stars** (asteroseismology and spectropolarimetry)



ESPaDOnS@CFHT LPs | *Kepler – K2* | *SPIRou* | *CHEOPS & TESS* | ***PLATO***

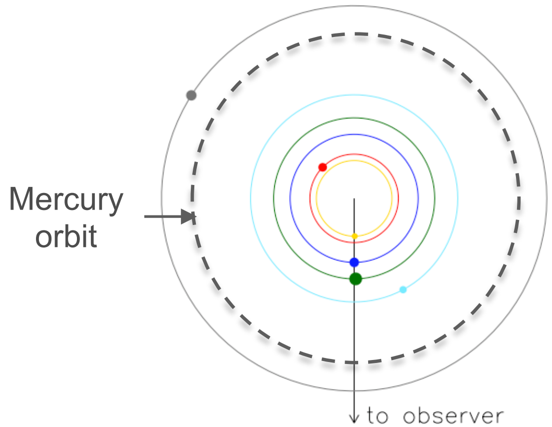
Stellar rotation & magnetism – planetary dynamics



Albrecht et al. 2012; Gizon et al. 2013

Orbital architecture

Kepler 11



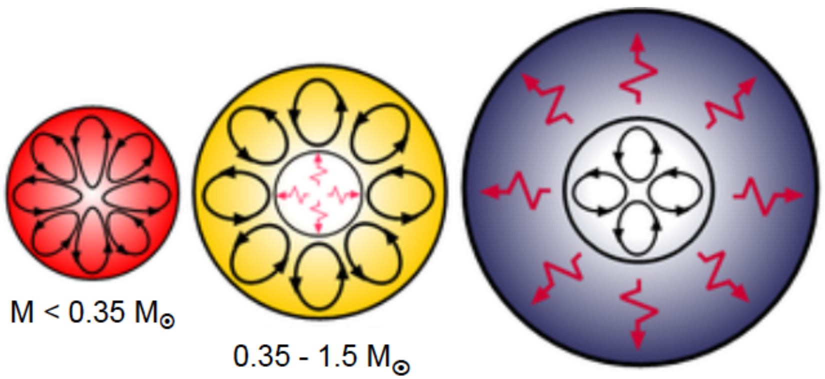
Lissauer et al. 2011
Bolmont et al. 2014

State of the art

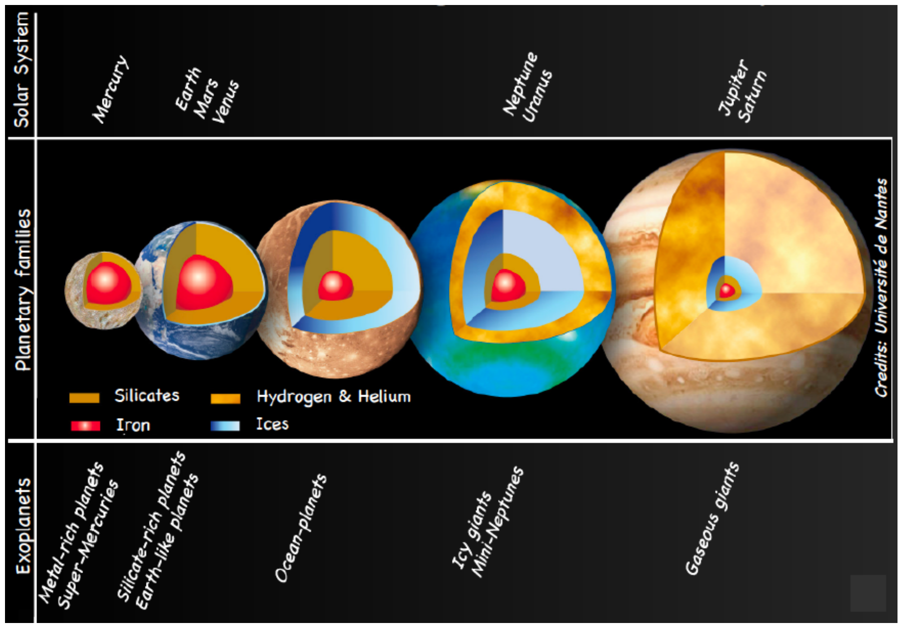
In studies of star-star or star-planet systems, bodies are treated as point-mass objects or solids with ad-hoc models for tides, stellar winds and electromagnetic interactions

However their complex internal structure, evolution, rotation, and magnetism impact tidal (and magnetic) Star-Planet Interactions

Host star (M in $M_\odot$) – WP 121500



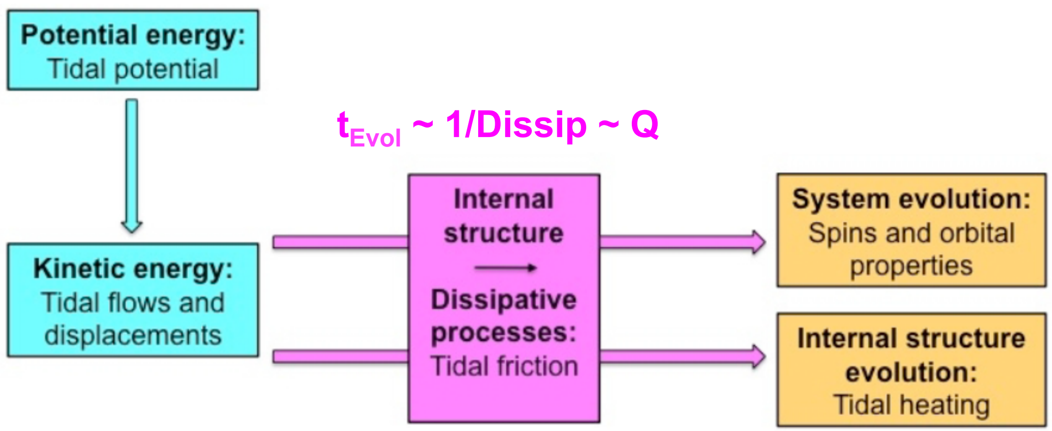
Planets – WP 115300

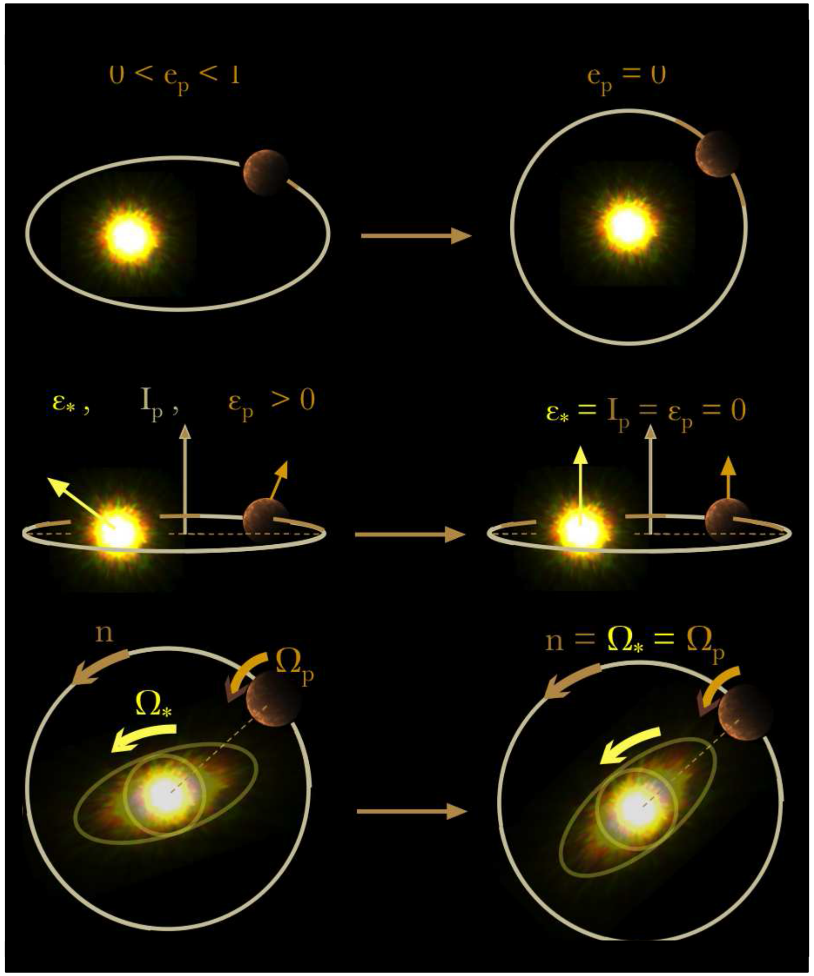


→ Need of an ab-initio physical modeling to accompany the study of discovered systems

The “engine” of the tidal evolution of binary systems: friction & energy dissipation

Dynamical evolution of a binary system





Mathis & Remus 2013

→ Necessity to identify/***implement*** the dissipative processes and to evaluate their strength along the evolution of systems and of their components

→ Time-scales for circularization, synchronization, alignment, and migration (→ Age); modification of rotational evolution; seismic signatures

Tidal velocities/displacements

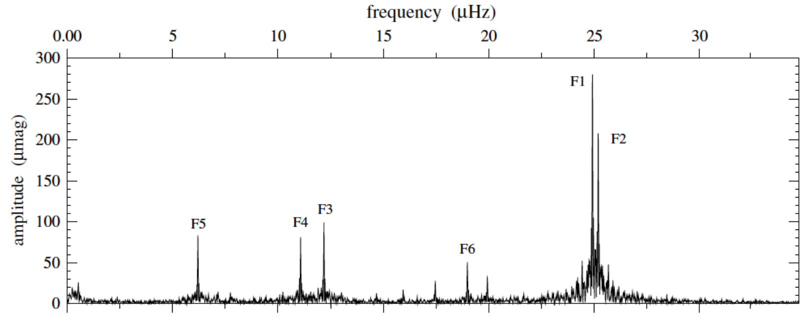
In stars (and fluid planetary layers):

- Large-scale circulation resulting from the hydrostatic adjustment to the tidal perturbation: **Equilibrium Tide**

- Waves excited by the tidal potential: **Dynamical Tide**

Excitation by each Fourier component of the forcing

KOI-54: Welsh et al. 2011



2Ω N f_L σ_0

Inertial waves (C.Z.)

Gravito-inertial waves (Stab. strat.)

Acoustic waves

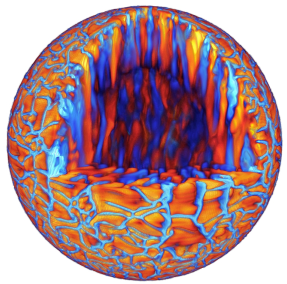
Mathis & Remus 2013

Dissipative mechanisms:

- **Convective regions:** turbulence

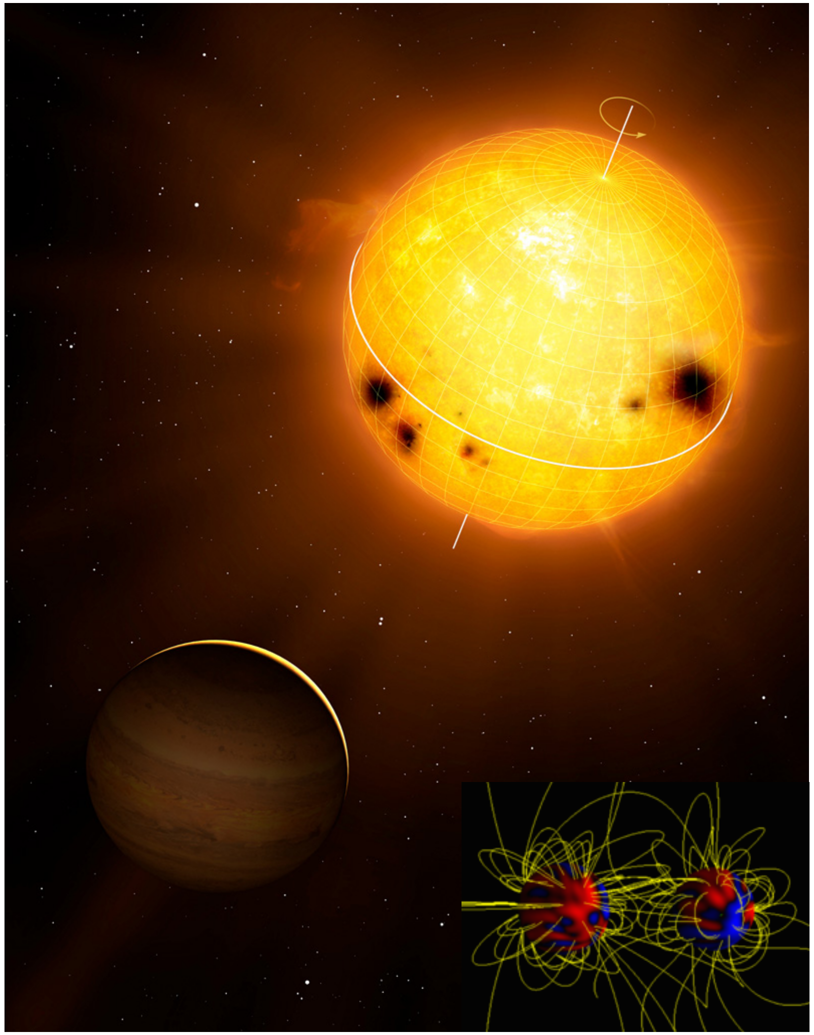
- **Stably stratified regions**: heat diffusion

Brun et al.

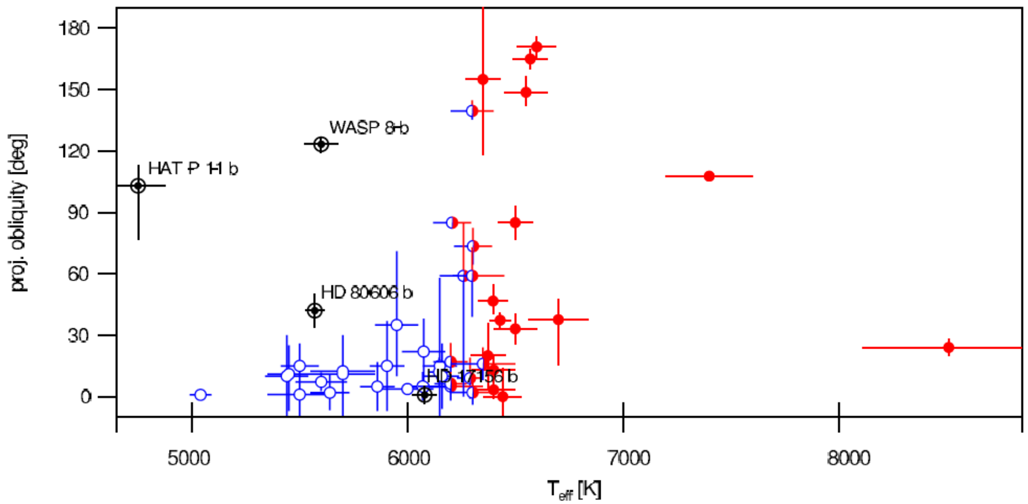


The signature of tidal interactions in exoplanetary systems & multiple stars

The case of hot-Jupiter systems (and binary solar-type stars)



Gizon et al. 2013; Davies et al. 2015; Gregory



Albrecht et al. 2012

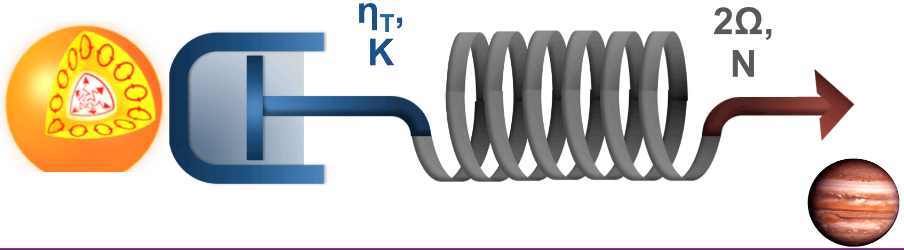
→ Tidal dissipation in a star varies over **several orders of magnitude** as a function of:

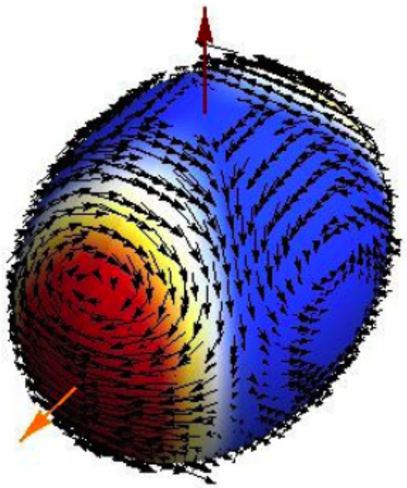
- The mass
- The age
- The dynamics (rotation)

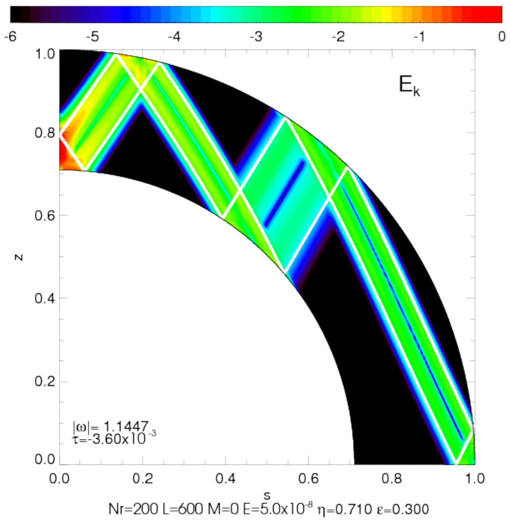
→ **need for ab-initio modeling**

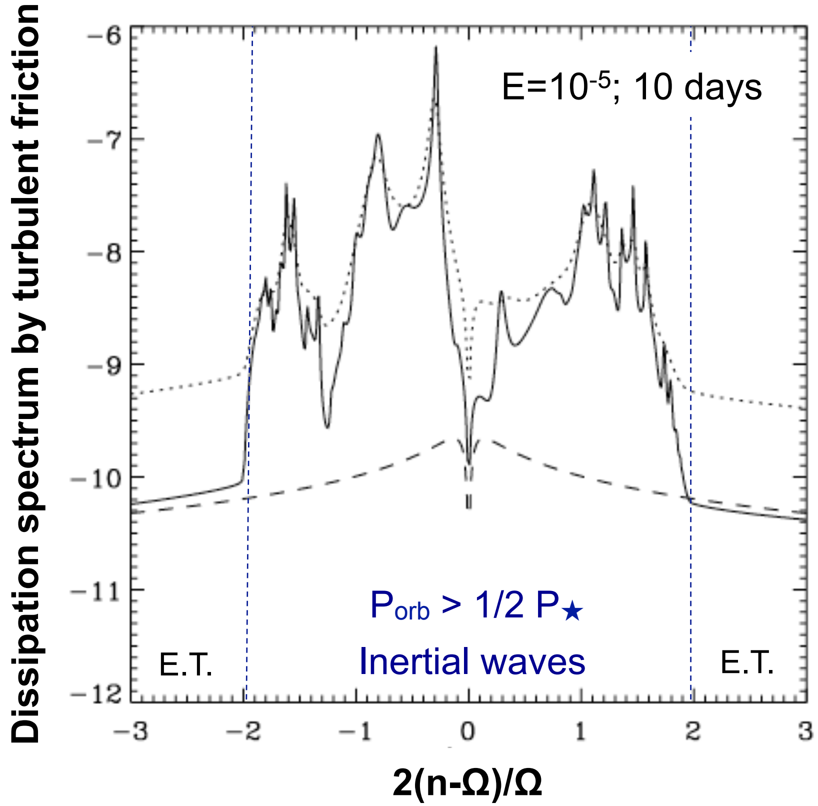
First step: Tides in low-mass star convection zones

Fluid dynamical tide: forced (gravito-) inertial waves → resonant response







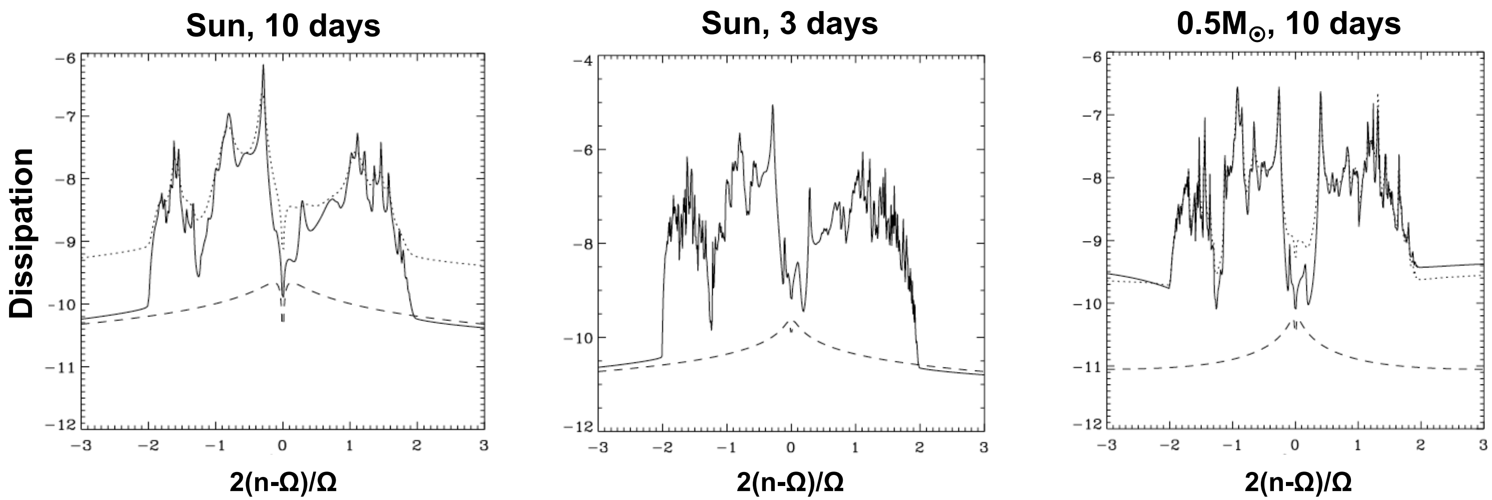


Ogilvie & Lin 2004, 2007
Rieutord & Valdetarro 2010
Baruteau & Rieutord 2013
Guenel et al. 2016

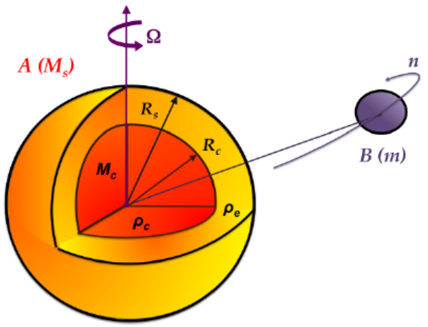
Dissipation variations with stellar parameters

As a function of stellar mass, age and rotation

Ogilvie & Lin 2007



To get an <u>order of magnitude</u> of tidal dissipation <u>along the evolution of stars</u>
→ a frequency-averaged dissipation



Dissip = $$\int_{-\infty}^{+\infty} \mathrm{Im}\left[k_2^2(\omega)\right]\frac{d\omega}{\omega} = \left\langle \mathrm{Im}\left[k_2^2(\omega)\right]\right\rangle_\omega = \frac{100\pi}{63}\epsilon^2\left(\frac{\alpha^5}{1-\alpha^5}\right)(1-\gamma)^2$$

$$\times(1-\alpha)^4\left(1+2\alpha+3\alpha^2+\frac{3}{2}\alpha^3\right)^2\left[1+\left(\frac{1-\gamma}{\gamma}\right)\alpha^3\right]\left[1+\frac{3}{2}\gamma+\frac{5}{2\gamma}\left(1+\frac{1}{2}\gamma-\frac{3}{2}\gamma^2\right)\alpha^3-\frac{9}{4}(1-\gamma)\alpha^5\right]^{-2}$$

with
$$\begin{cases} \alpha = \dfrac{R_c}{R_s}, \quad \beta = \dfrac{M_c}{M_s} \quad \text{and} \quad \gamma = \dfrac{\rho_e}{\rho_c} = \dfrac{\alpha^3(1-\beta)}{\beta(1-\alpha^3)} < 1. \\ \epsilon^2 \equiv \left(\Omega/\sqrt{\mathcal{G}M_s/R_s^3}\right)^2 = (\Omega/\Omega_c)^2 \ll 1 \end{cases}$$

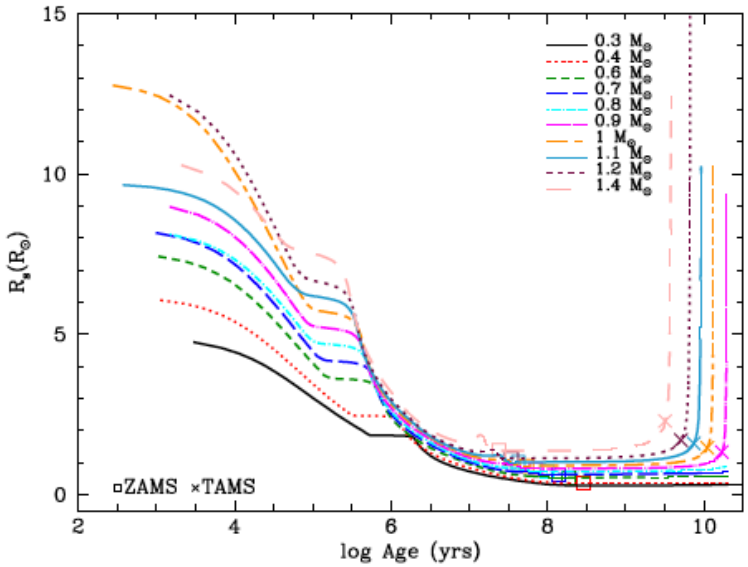
structure

rotation

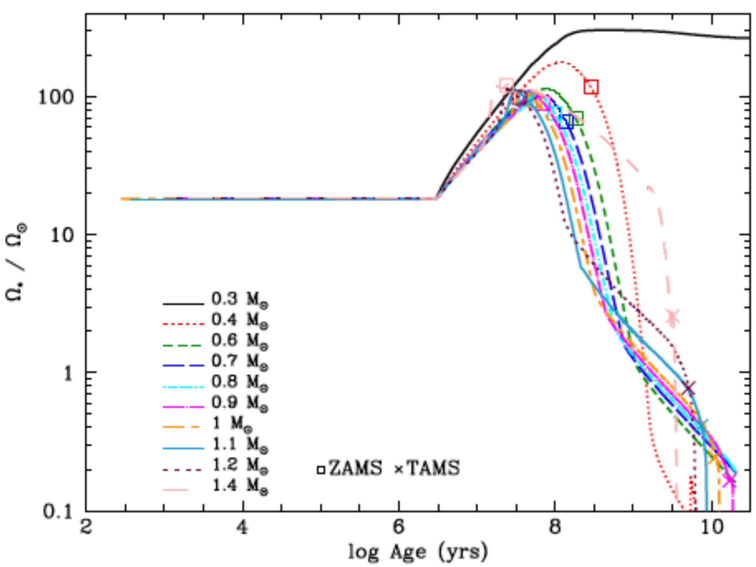
Ogilvie 2013; Mathis 2015

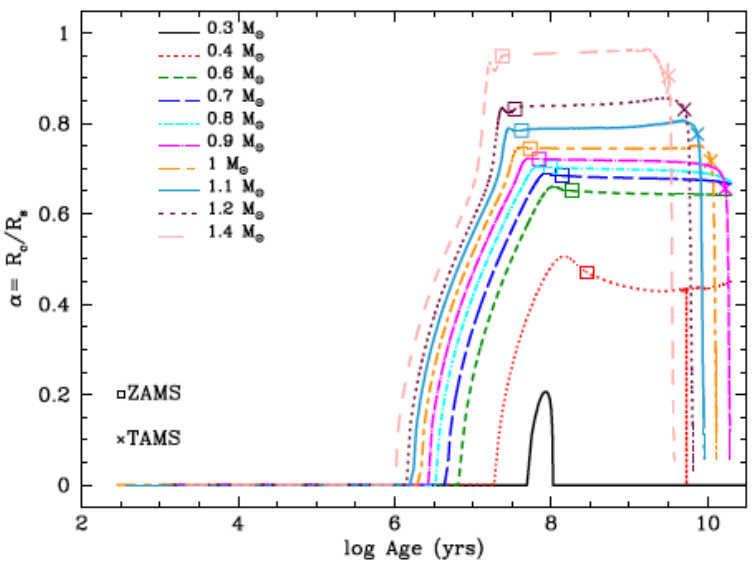
The evolution of key structural and dynamical parameters

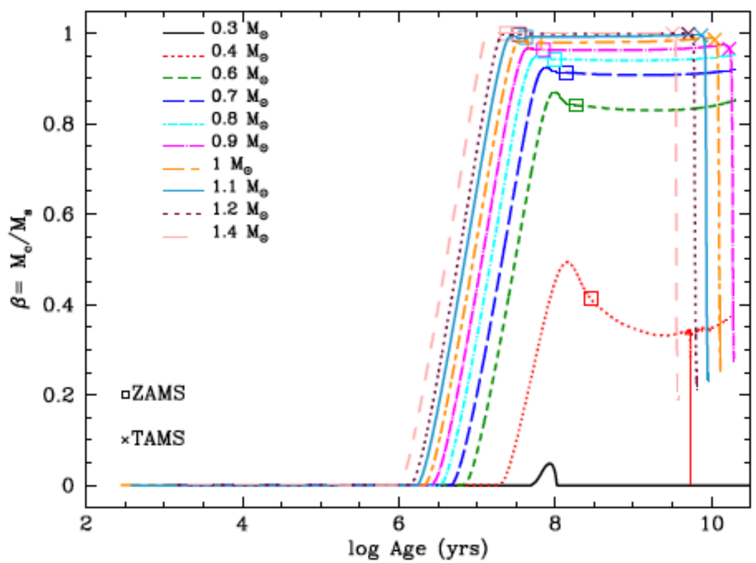
Total radius



Global rotation



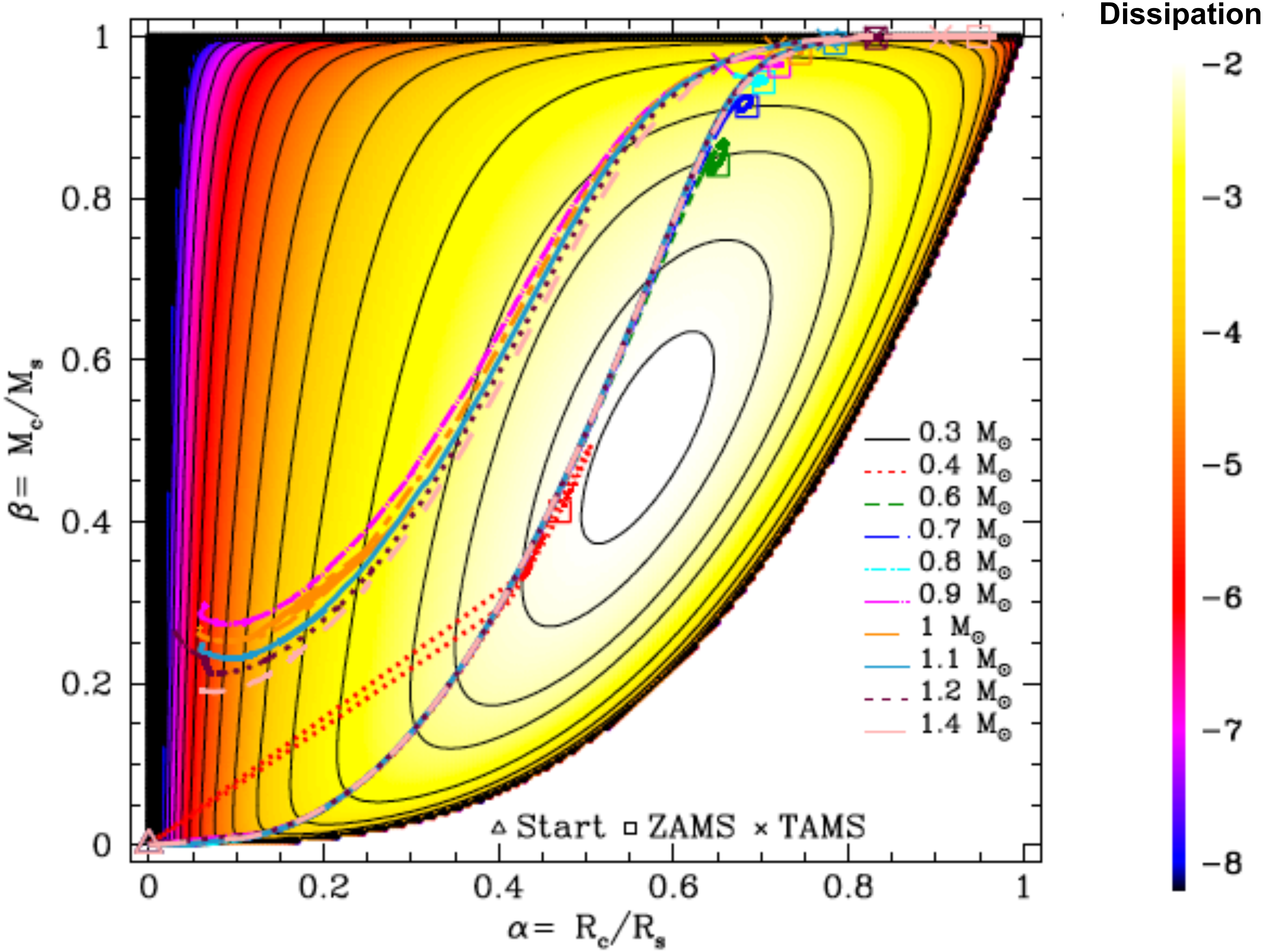




Mathis 2015; Gallet, Mathis, Charbonnel & Amard 2016

Aspect ratios: radius & mass

The tidal H-R diagram



Mathis 2015; Gallet, Mathis, Charbonnel & Amard 2016

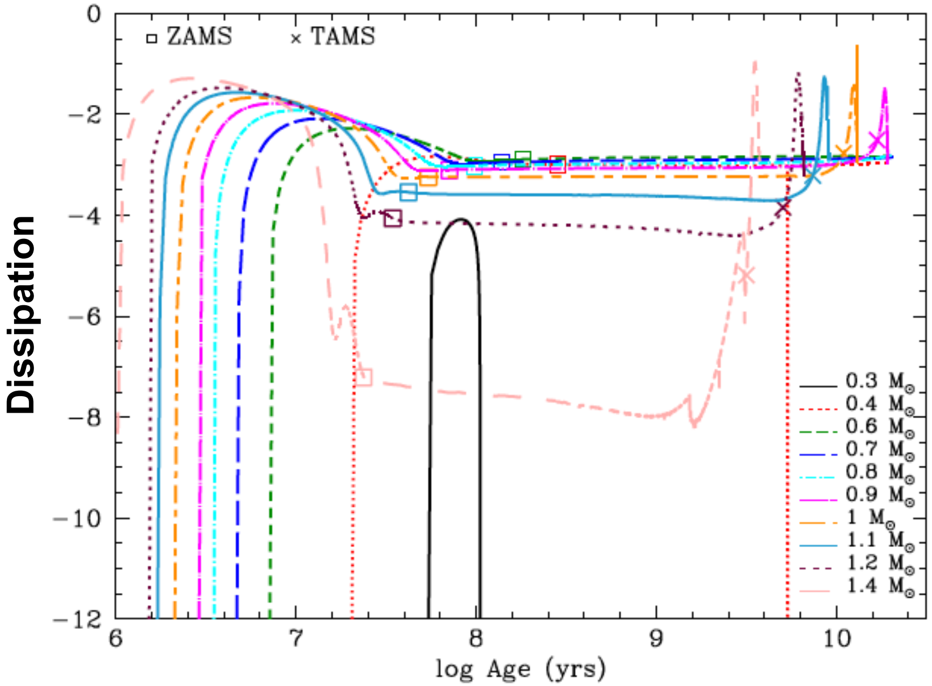
Grids of tidal dissipation
for star-planet and multiple star systems

In low-mass and solar-type stars, it varies over several orders of magnitude:

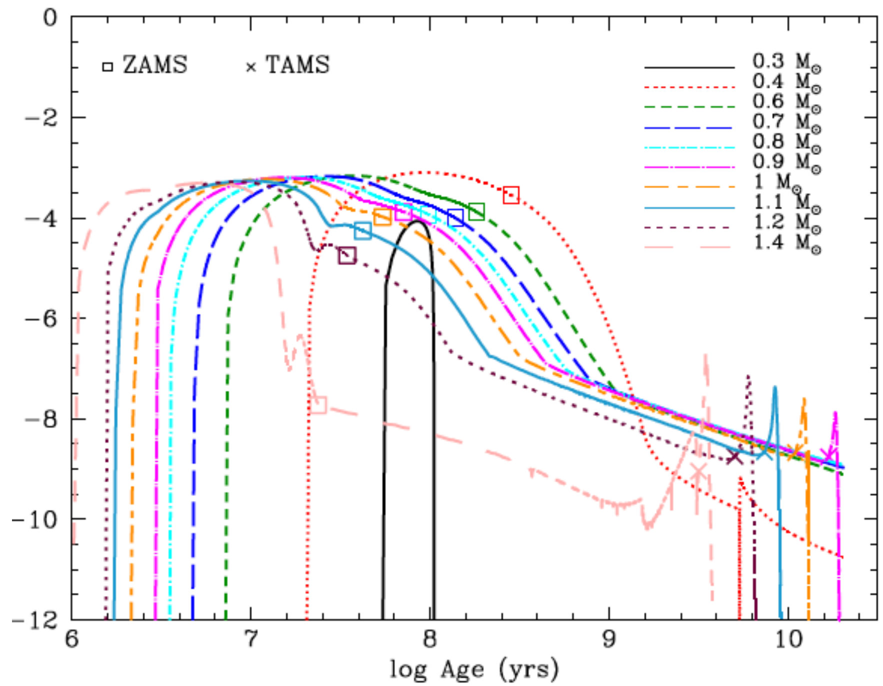
→ Stronger Dynamical Tide along the Pre-Main-Sequence and Sub-Giant phases

→ Its amplitude on the MS diminishes with mass (and the thickness of the CE)

→ Necessity to **couple structural and rotational evolutions**



Structural evolution

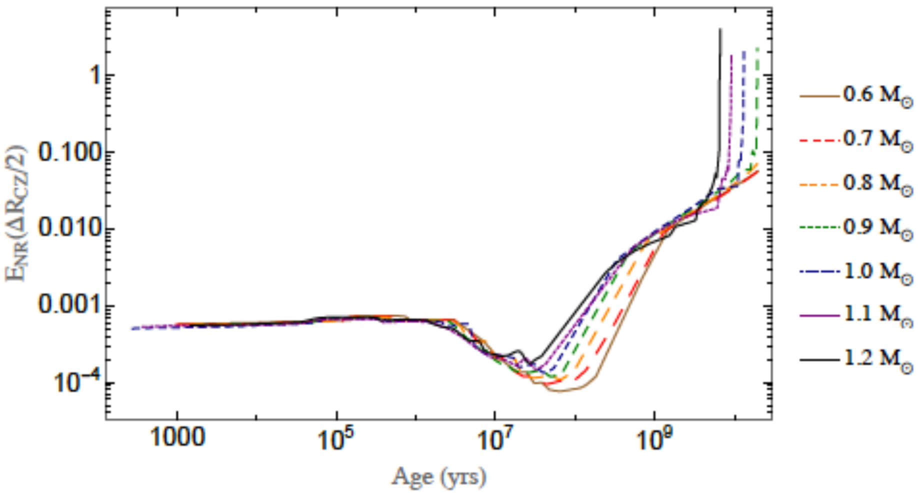


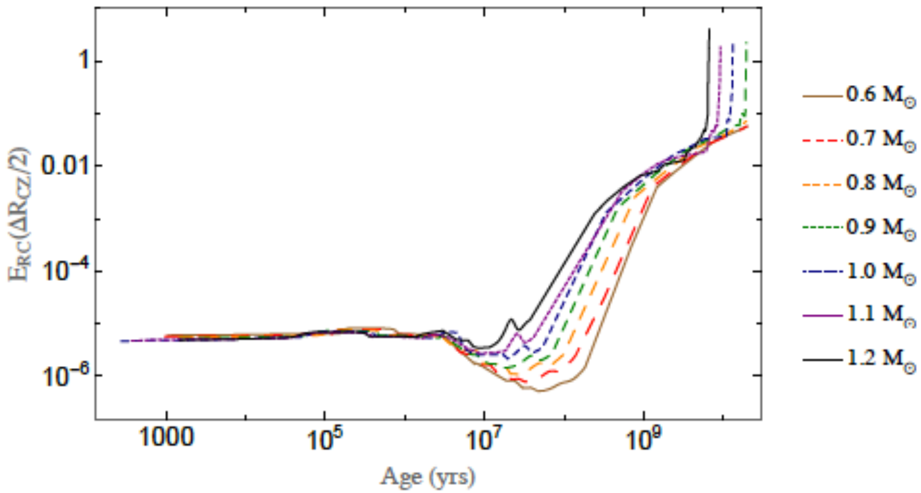
Structural & rotational evolutions

Mathis 2015; Gallet, Mathis, Charbonnel & Amard 2016

Grids of friction parameters

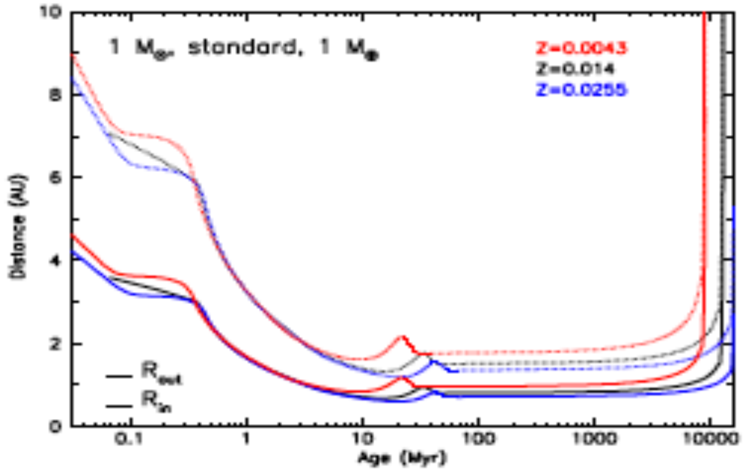
Mathis, Auclair-Desrotour, Guenel, Gallet, Le Poncin-Lafitte 2016

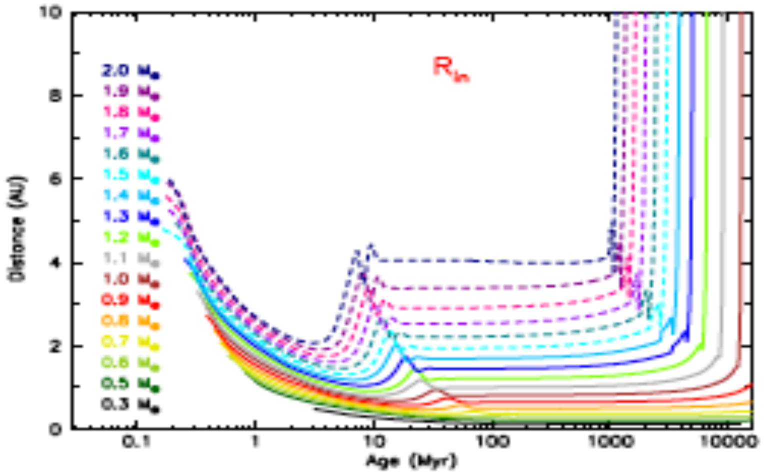




Grids of habitability parameters

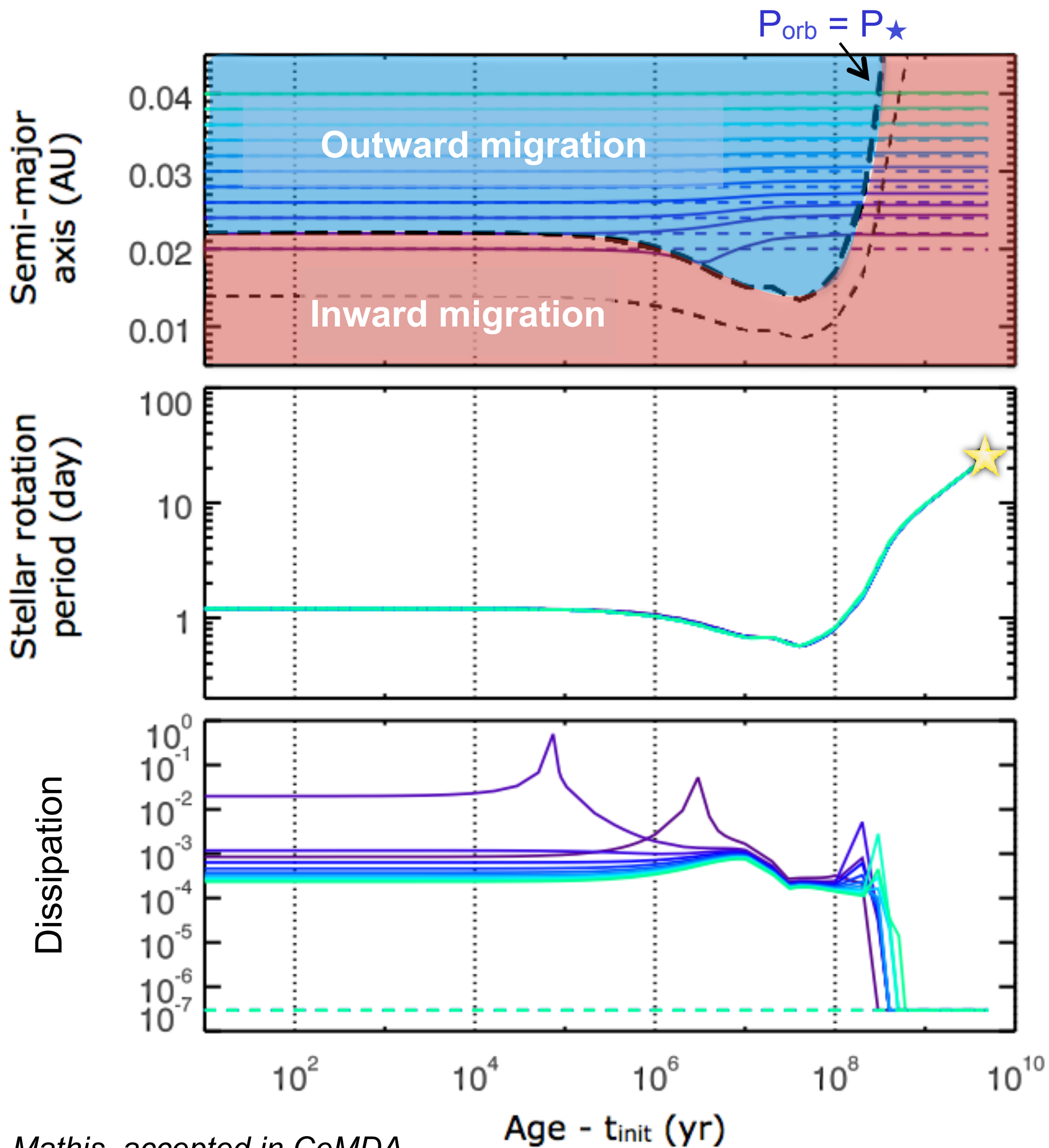
Gallet, Charbonnel, Amard, Brun, Palacios, Mathis 2016





Codes couplings: Star-planet systems dynamical evol. I

- Low-mass star-planet systems - circular & coplanar
- Ab-initio frequency-averaged dissipation of stellar tides in the convective envelope



Standard model

Model Bolmont & Mathis

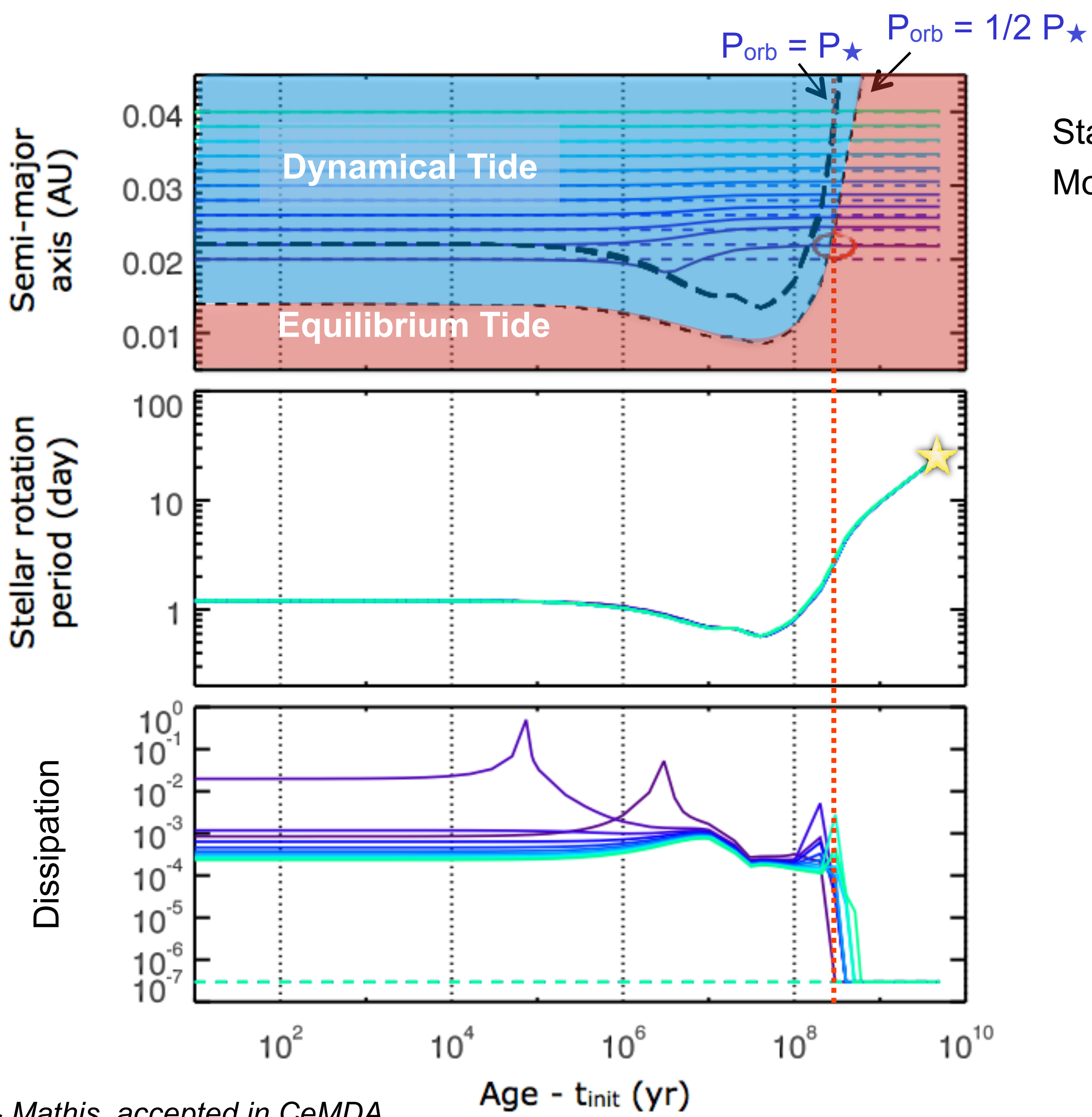
$M_p = 1\ M_\oplus$

$M_\star = 1\ M_\odot$

$P_{\star,i} = 1.2$ day

Bolmont & Mathis, accepted in CeMDA

Star-planet systems dynamical evolution (II)



Standard model

Model Bolmont & Mathis

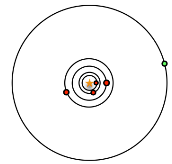
$M_p = 1\ M_\oplus$

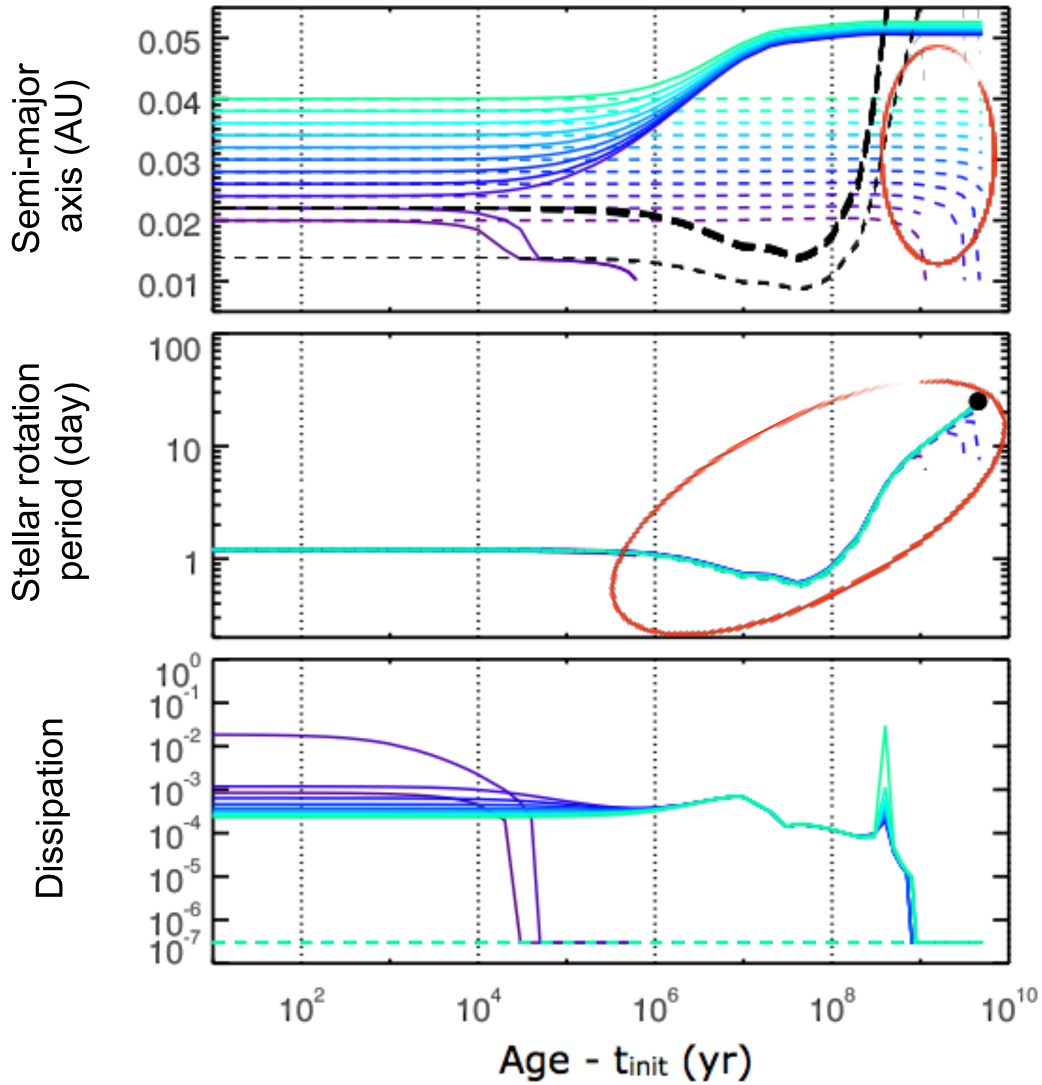
$M_\star = 1\ M_\odot$

$P_{\star,i} = 1.2$ day

Bolmont & Mathis, accepted in CeMDA

Star-planet systems dynamical evolution (III)





Standard model

Model Bolmont & Mathis

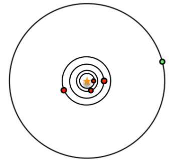
$M_p = 1\ M_{jup}$

$M_\star = 1\ M_\odot$

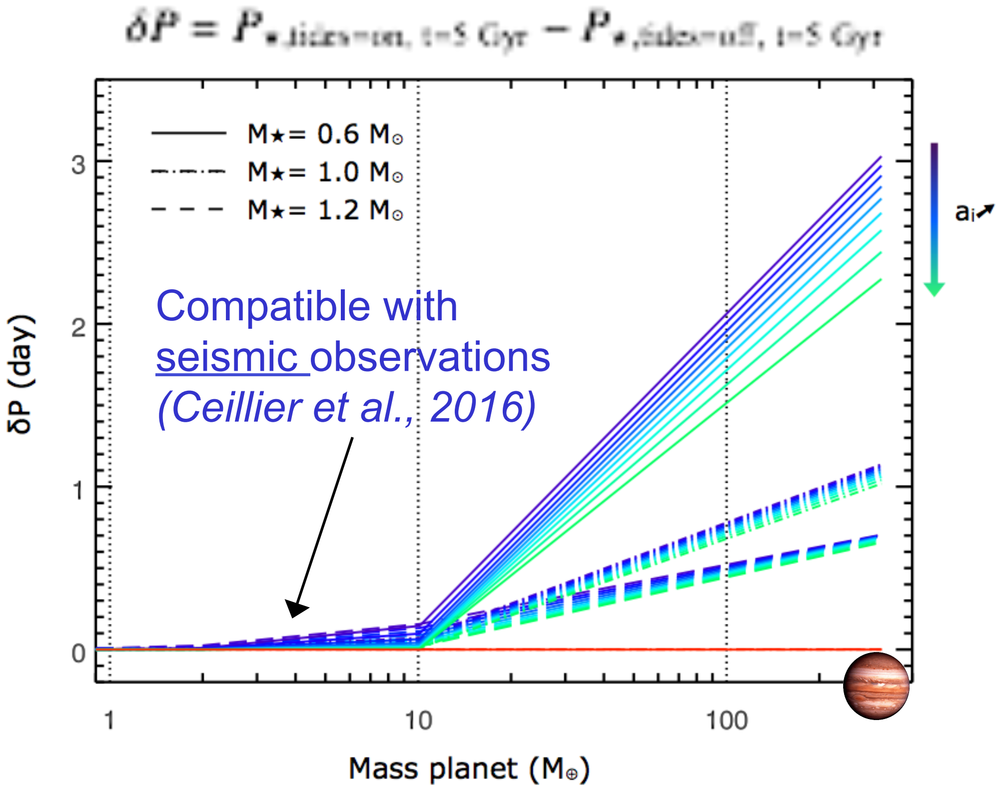
$P_{\star,i} = 1.2$ day

Bolmont & Mathis, accepted in CeMDA

Impact on stellar rotation (I)



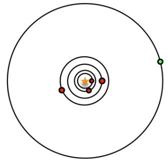
$P_{\star,i}$ = 1.2 day



All planets here migrate
outwards
→ the star spins down

Bolmont & Mathis, accepted in CeMDA

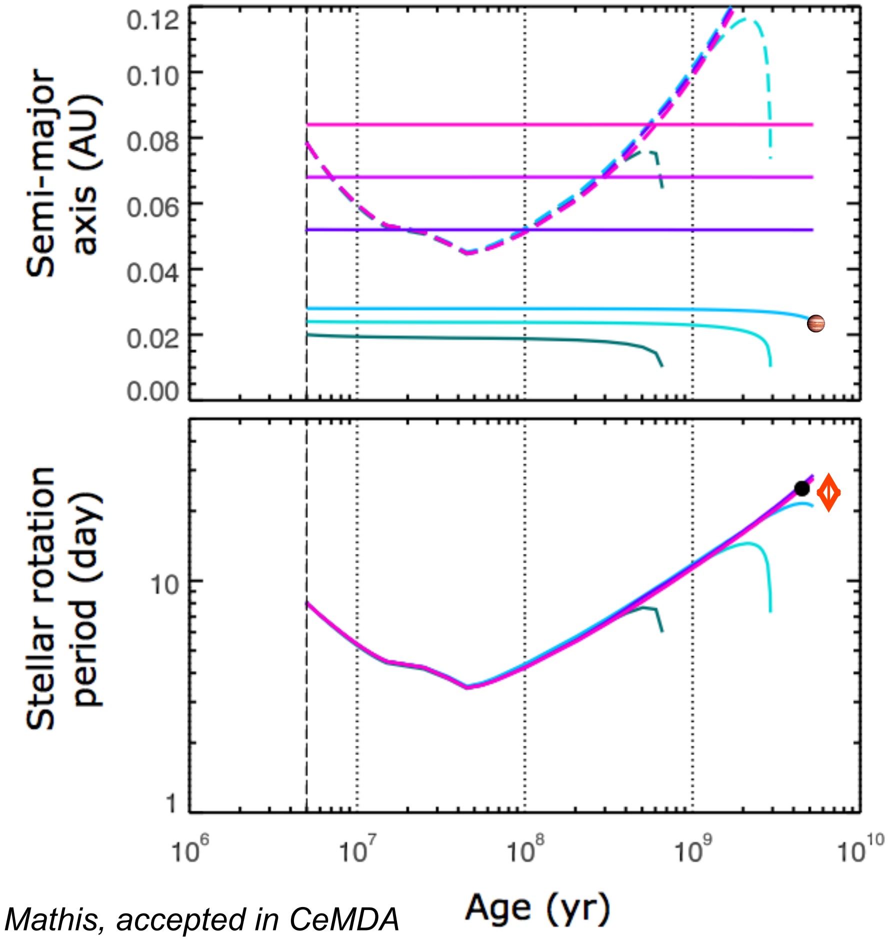
Impact on stellar rotation (II)



$M_\star = 1\ M_\odot$

$P_{\star,i} = 8.0$ day

$M_p = 1\ M_{jup}$



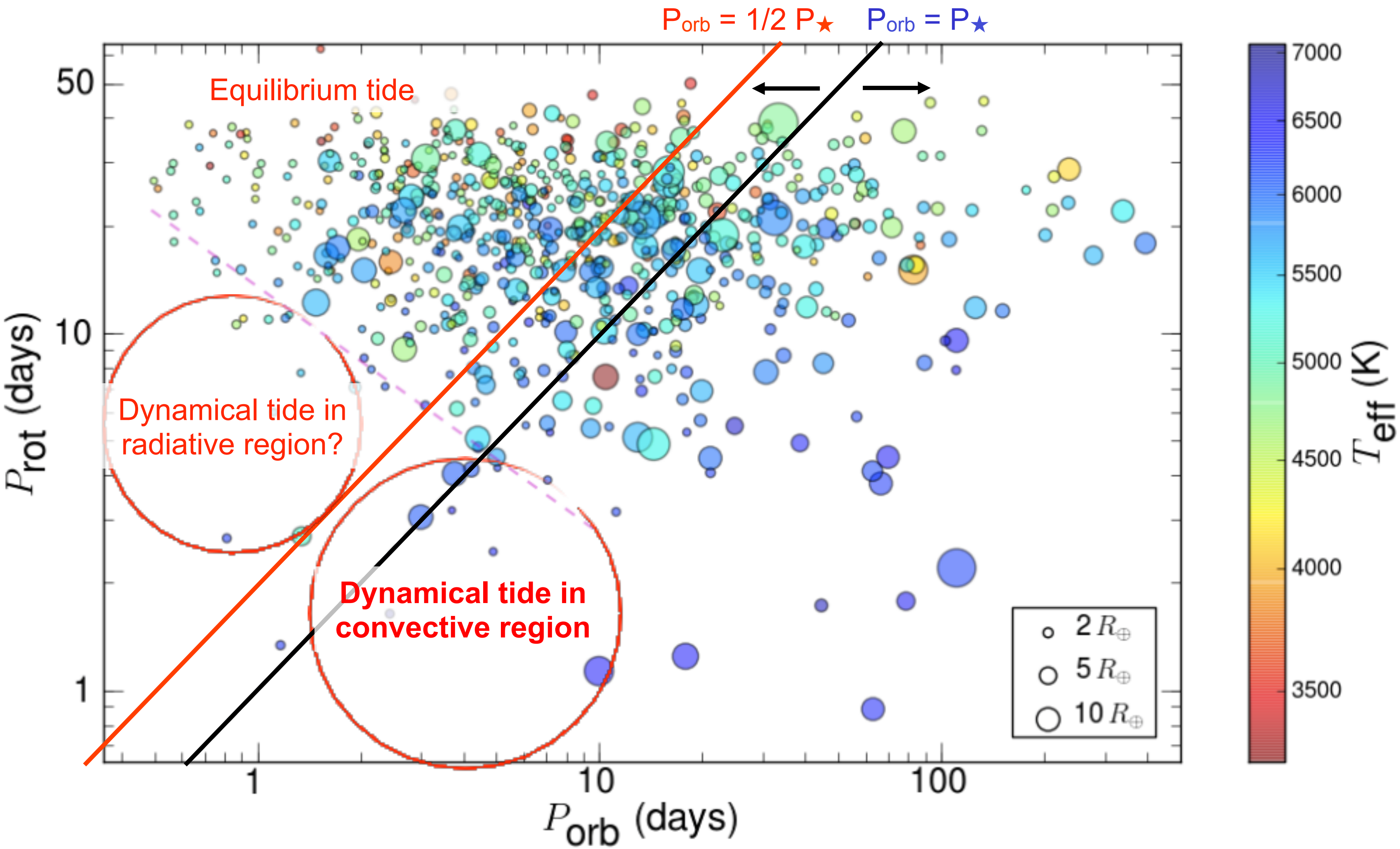
Planets migrate inwards
→ the star spins up

➡ Rotation excess: star initially slow rotator

➡ Rotation deficiency: star initially fast rotator

Bolmont & Mathis, accepted in CeMDA

Understanding hot-Jupiters systems



McQuillan et al. 2013

Conclusions and perspectives

Take into account:

→ Tidal dissipation frequency-dependence
→ Tidal dissipation in stellar radiation zones (and in planets)
→ Associated transport processes *(e.g. Lanza & Mathis 2016)*

→ Best ab-initio models as possible of MHD stellar winds & SPI

Deliver:

→ Web page with grids of "multiplicity/interactions parameters" (CEA/Geneva)

→ New generation of rotating models

→ Corresponding seismic diaganosis

Conclusions and perspectives

Summary:

- Tidal dissipation in stellar convective zones varies over several orders of magnitude as a function of stellar mass, age and rotation
- The Dynamical Tide causes a much faster evolution than the Equilibrium Tide

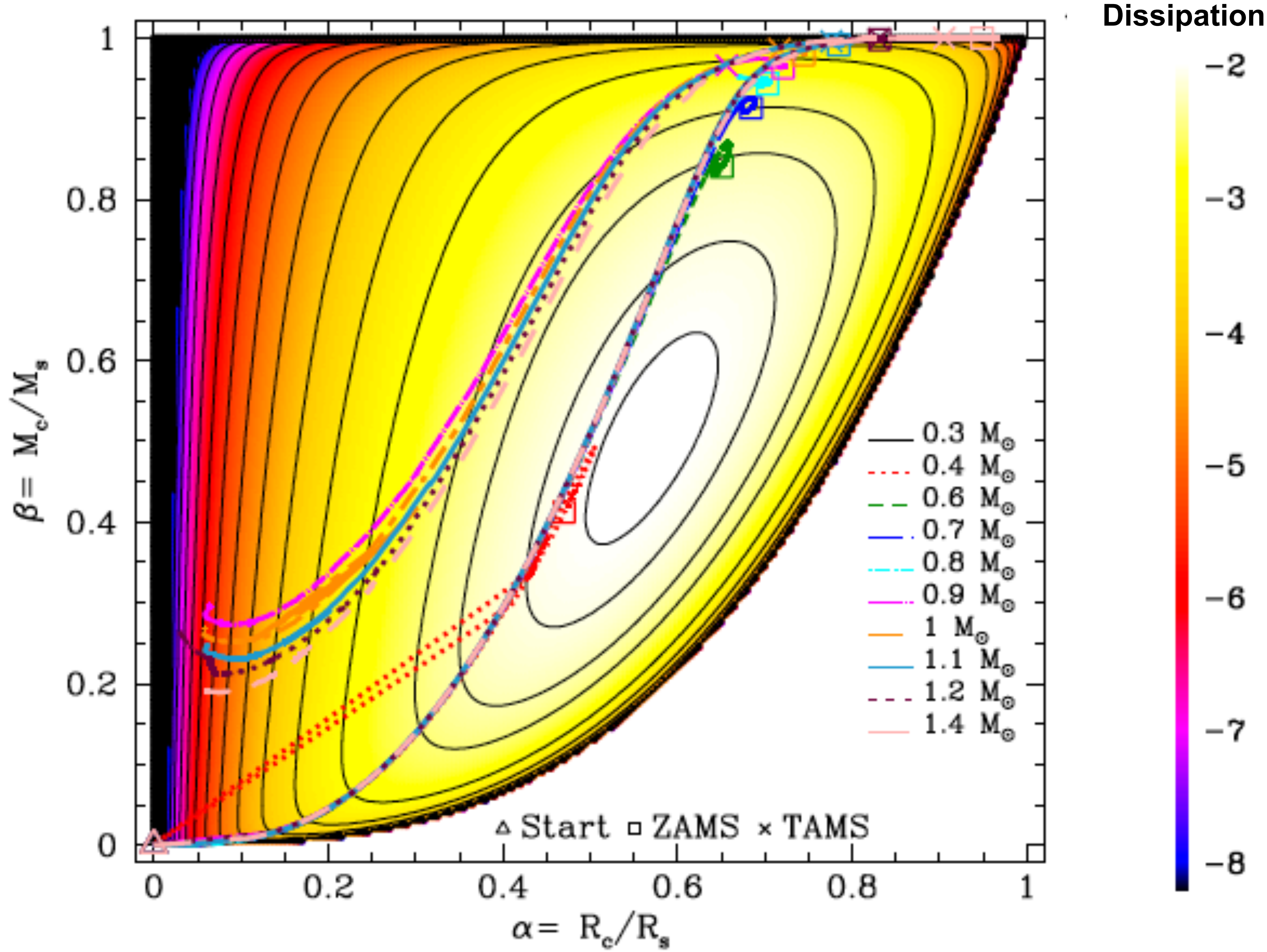
  → Needs to be taken into account in tidal studies
  → Implications on the understanding of planets distribution
- The Dynamical Tide is strong enough so that the star's early rotation history has a strong influence on close-in planets
- For $M_p > 10\ M_\oplus$, the dynamical tide induced migration is strong enough to influence the star's rotation

Perspectives:

Treat:
→ Multiple systems
→ Eccentric orbits and inclined systems

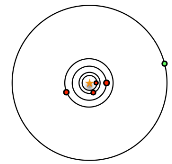
Take into account:
→ Tidal dissipation frequency-dependence
→ Tidal dissipation in stellar radiation zones and in planets
→ Best ab-initio models as possible of MHD stellar winds & SPI

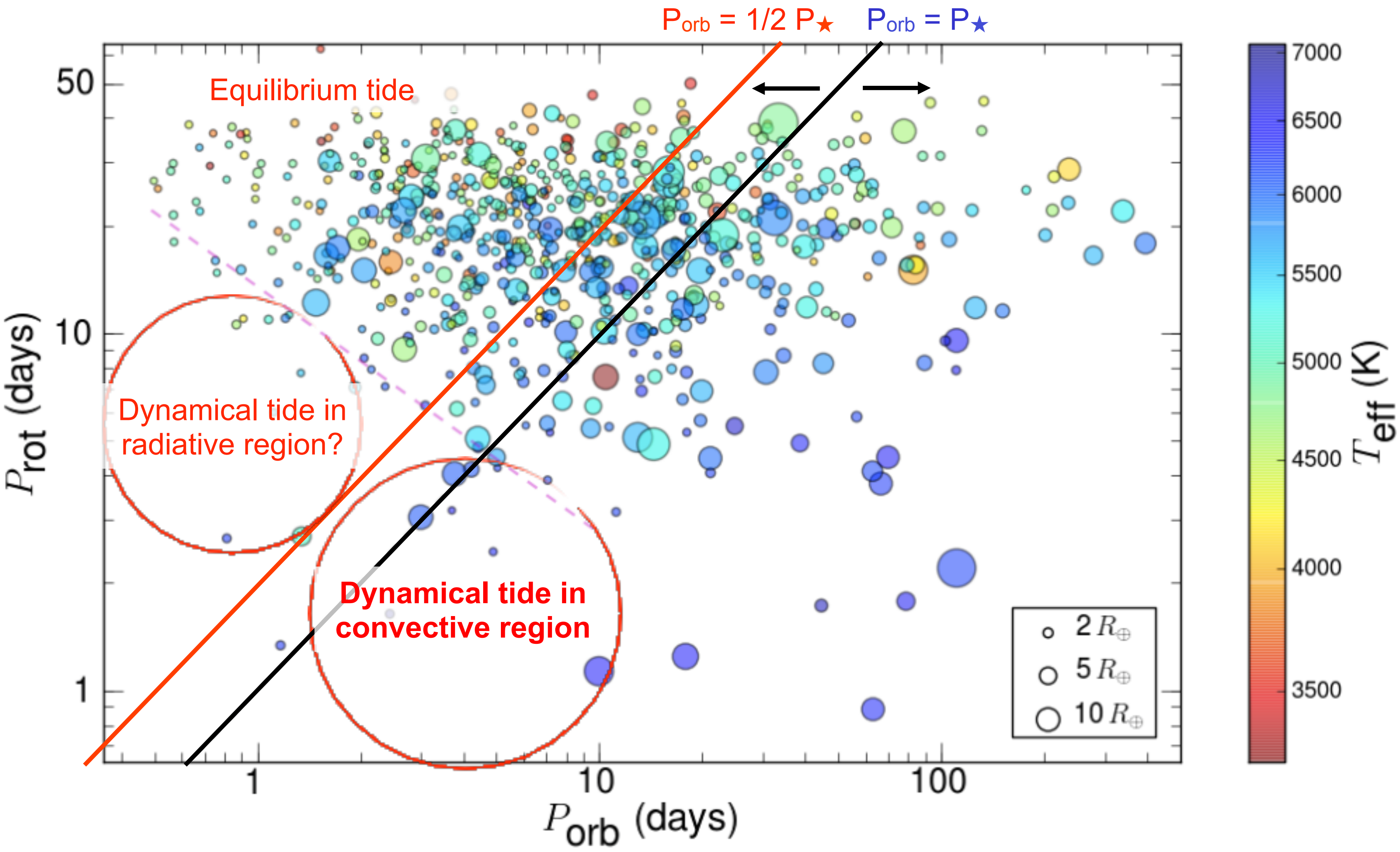
The tidal H-R diagram



Mathis 2015; Gallet, Mathis, Charbonnel & Amard 2016

Understanding hot-Jupiters systems

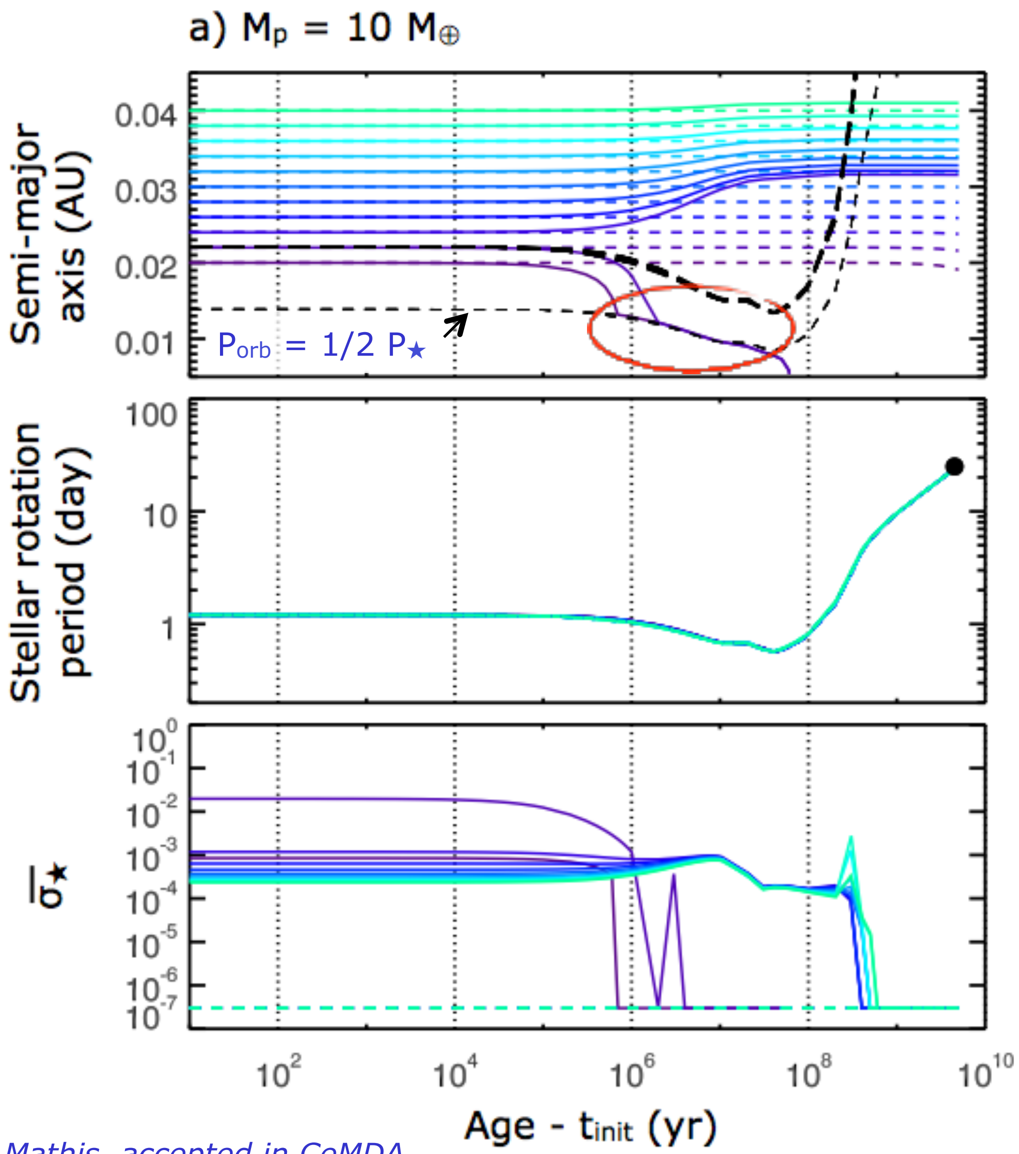




McQuillan et al. 2013


CFHT instruments key players
to guide future theoretical investigations

Improving the standard model



Standard model

Model Bolmont & Mathis

$M_p = 10\ M_\oplus$

$M_\star = 1\ M_\odot$

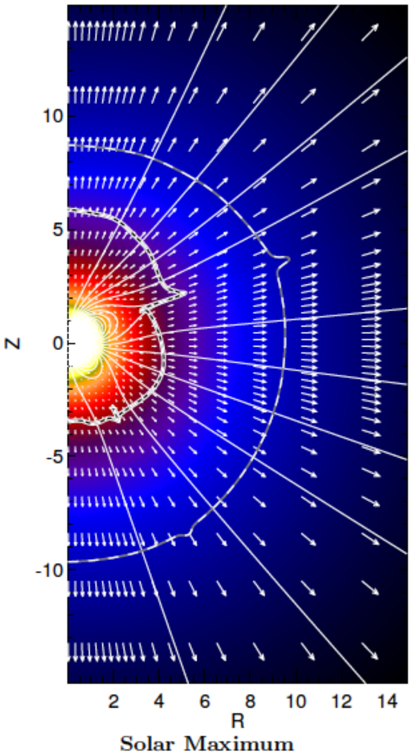
$P_{\star,i} = 1.2$ day

Bolmont & Mathis, accepted in CeMDA

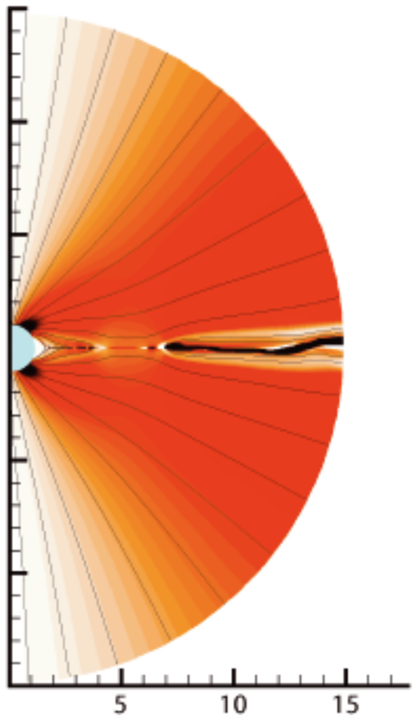
Interactions with magnetic stellar environments: winds, accretion disks

Winds: pressure-driven, line-driven

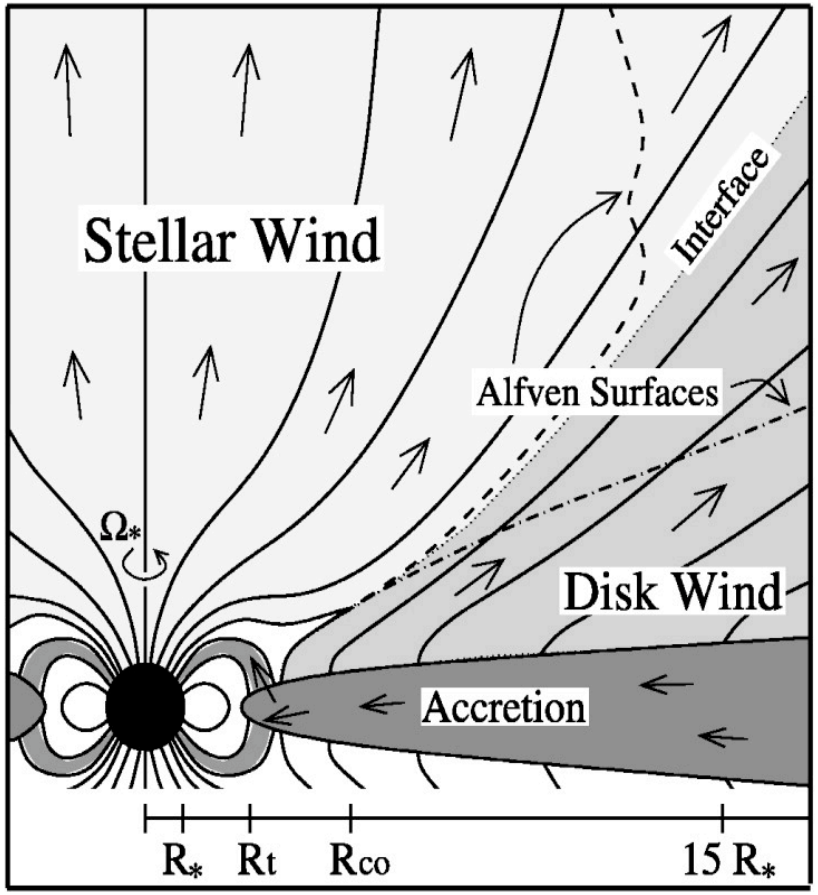
Reville et al. 2015



Ud-Doula et al. 2008



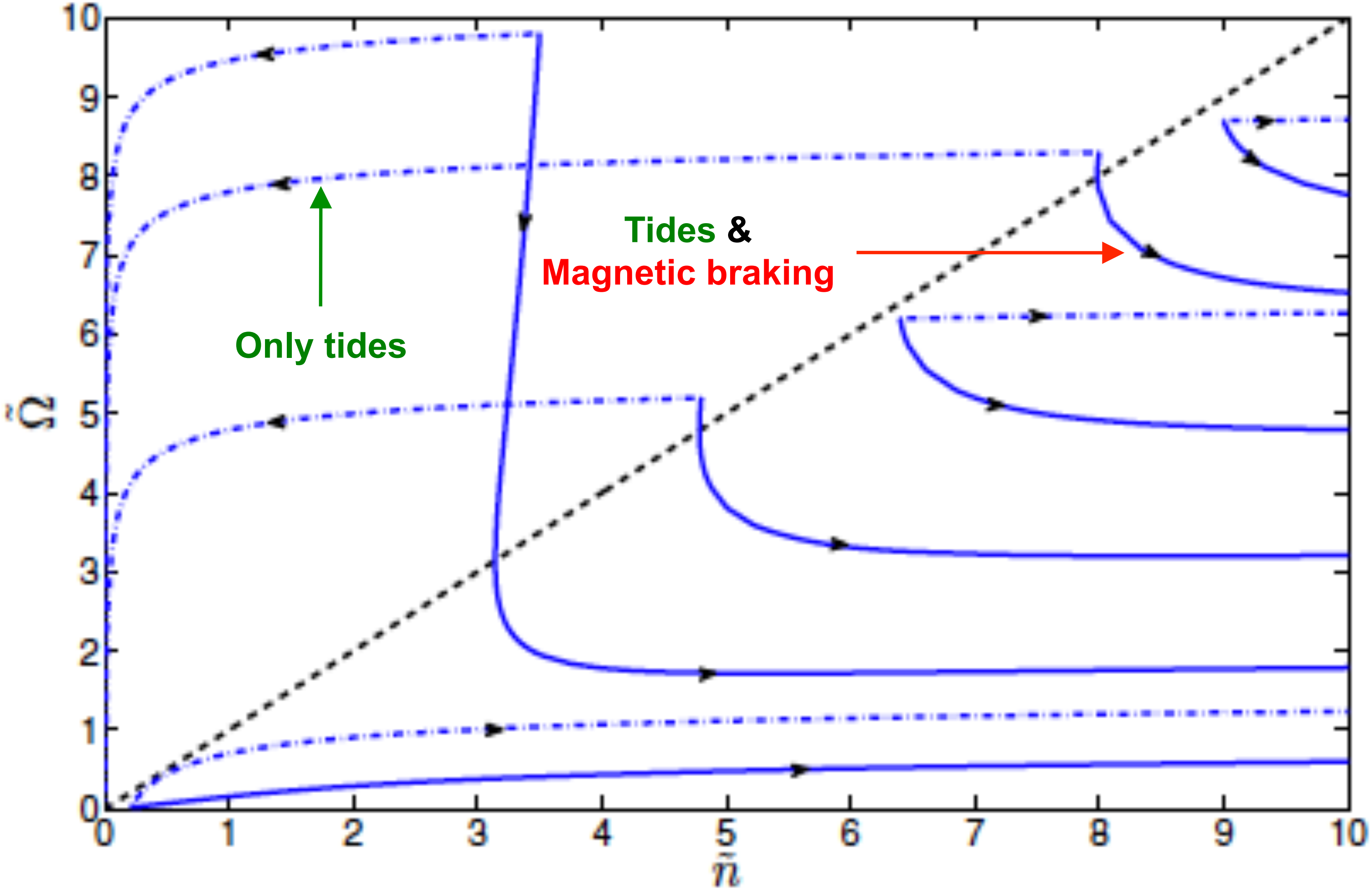
Accretion disks



Matt & Pudritz 2005

Whole system evolution

Barker & Ogilvie 2009
Damiani & Lanza 2015



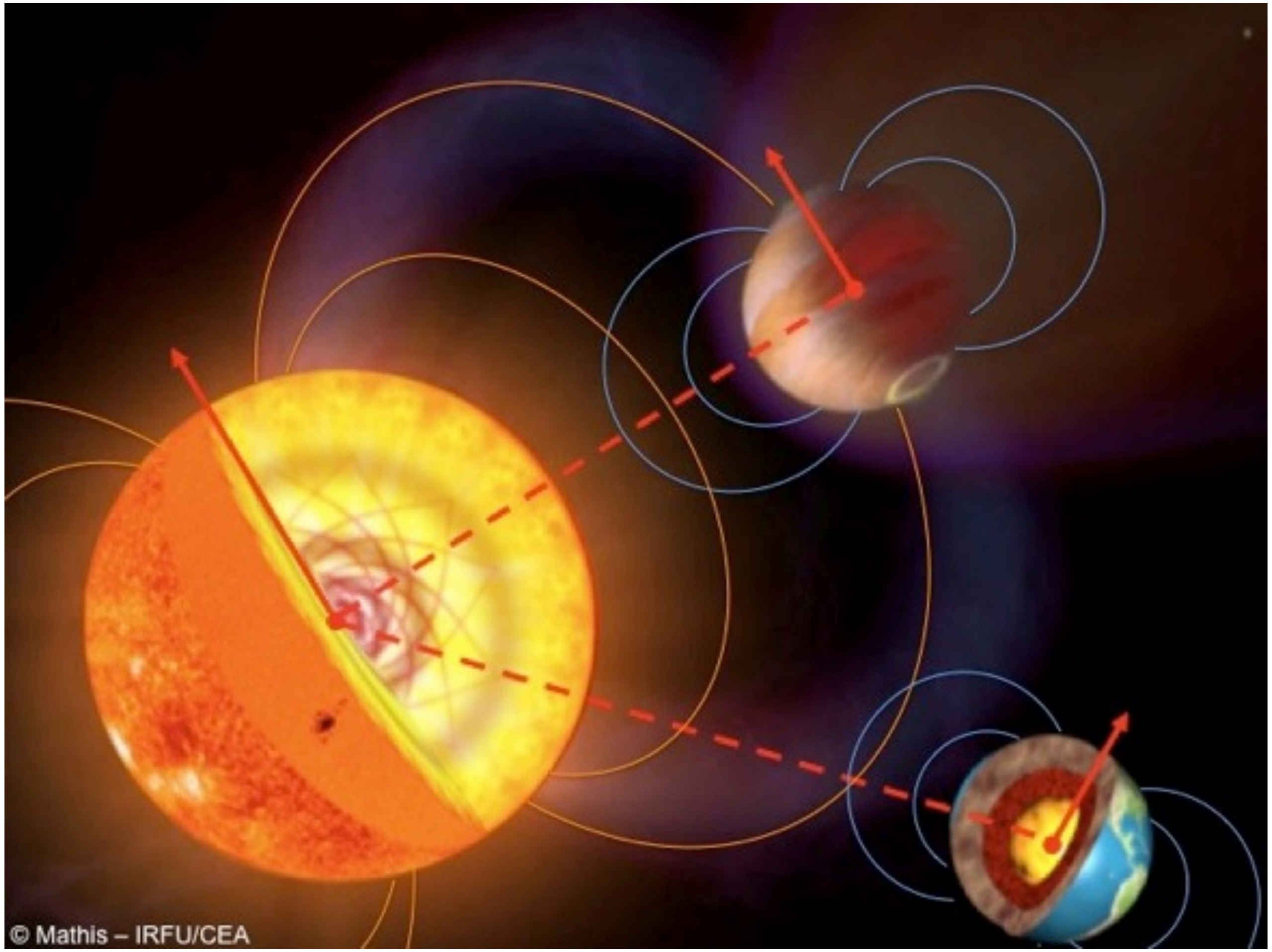
Need to
- treat simultaneously gravific and MHD interactions
- determine their relative orders of magnitudes

Improving the standard model

Assumptions:

- We consider here one planet orbiting one star.
- We consider here circular orbits and coplanar systems.
- We adopt a frequency-averaged approach to treat tides *(Ogilvie 2013, Mathis 2015a, b)*.
- We only consider here the effect of the stellar tide.
- We only consider here the inertial waves in convective regions *(Ogilvie & Lin, 2007)*.

Systems in interaction



Gravitation: tides

Electromagnetic interactions

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

Dynamical evolution of a binary system:

- Initial state:

- elliptic keplerian orbits of the two components

- non-synchronized rotations with the orbital motion

- non-aligned orbital and components' spins

- Final state: minimum energy state

- circularized orbits

$$\boxed{\frac{1}{t_{\rm circ}} = \frac{21}{2}\frac{k_2}{t_f}q\,(1+q)\left(\frac{R}{a}\right)^8} \qquad q = \frac{M_2}{M_1}$$

- components synchronized with the orbital motion

$$\boxed{\frac{1}{t_{\rm sync}} = 6\frac{k_2}{t_f}q^2\frac{M_1R^2}{I}\left(\frac{R}{a}\right)^6}$$

- aligned spins

or spiraling (*Hut 1980, 1981; Levrard et al. 2009*)

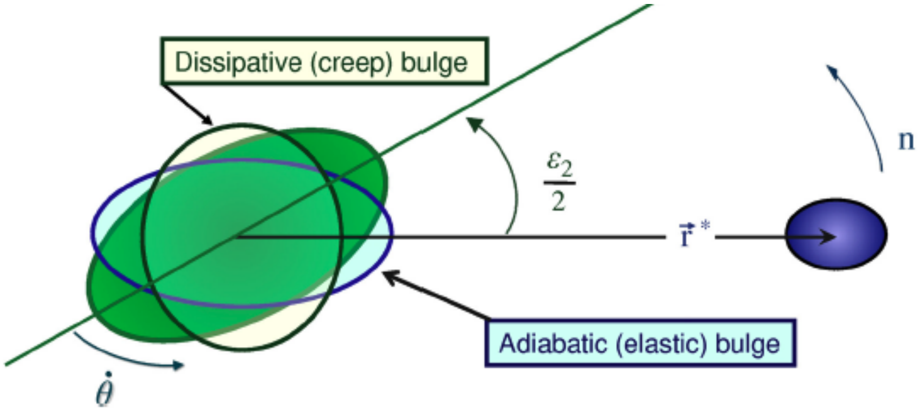
$\longrightarrow$ **Necessity to identify the dissipative processes that convert the kinetic energy into thermic one ($\longrightarrow$ time-scales for circularization, synchronization, and alignment or spiraling)**

Modelling the friction

$$\boxed{\tilde{k}_2 = |\tilde{k}_2|\, e^{-i\epsilon}}$$

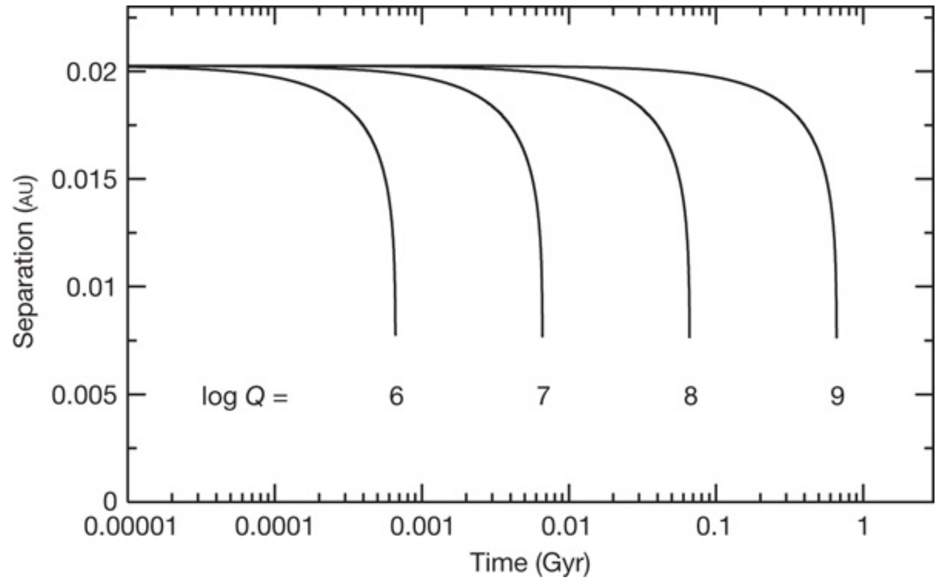
tidal elastic deformation: $\mathcal{R}e\left(\tilde{k}_2\right) = k_2^{ad} = |\tilde{k}_2| \cos\epsilon$

tidal dissipation: $\mathcal{I}m\left(\tilde{k}_2\right) = \dfrac{|\tilde{k}_2|}{Q} = |\tilde{k}_2| \sin\epsilon$



Efroimsky 2012

WASP-18b: $10M_J$, $1.106R_J$, $1.24M_\odot$



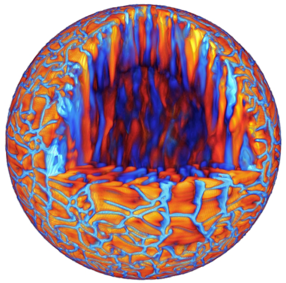
Hellier et al. 2009

→ Need to link the tidal quality factor Q to bodies' internal stucture and dynamics and to describe its behaviour as a function of the tidal frequency Ln-mΩ

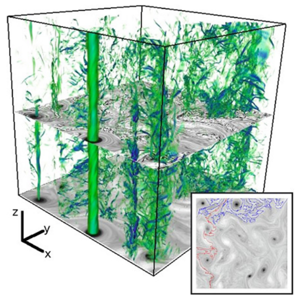
Mathis & Le Poncin-Lafitte 2009

Dissipation mechanisms in stars and fluid planetary layers

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

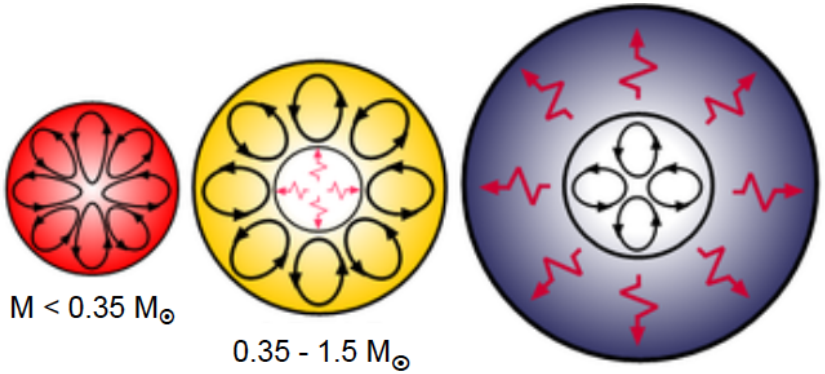


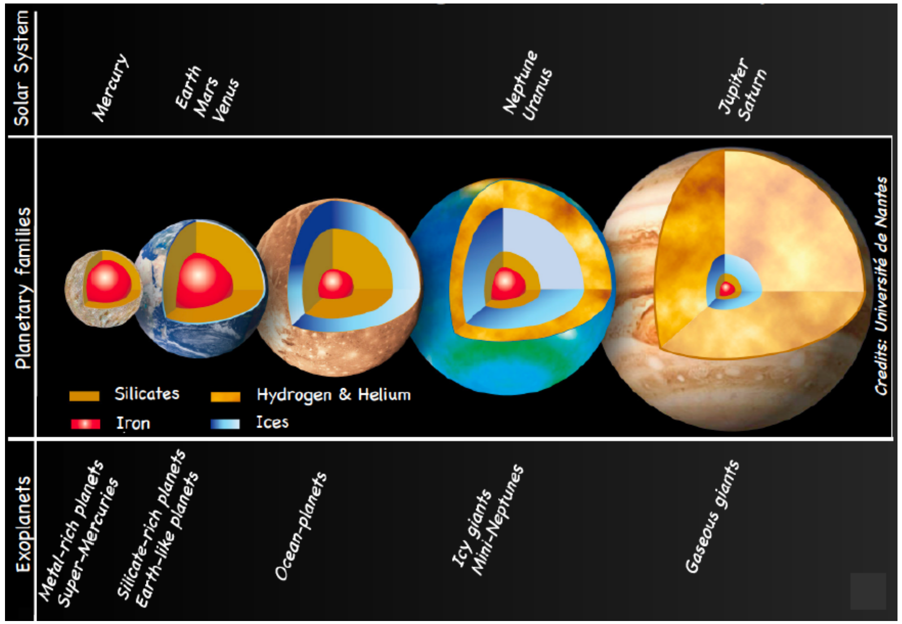
Brun et al.



Pouquet et al.

Stably stratified regions:
heat diffusion
→ dynamical tide:
gravito-inertial waves





Elliptic instabilities: both in convective and radiative regions

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

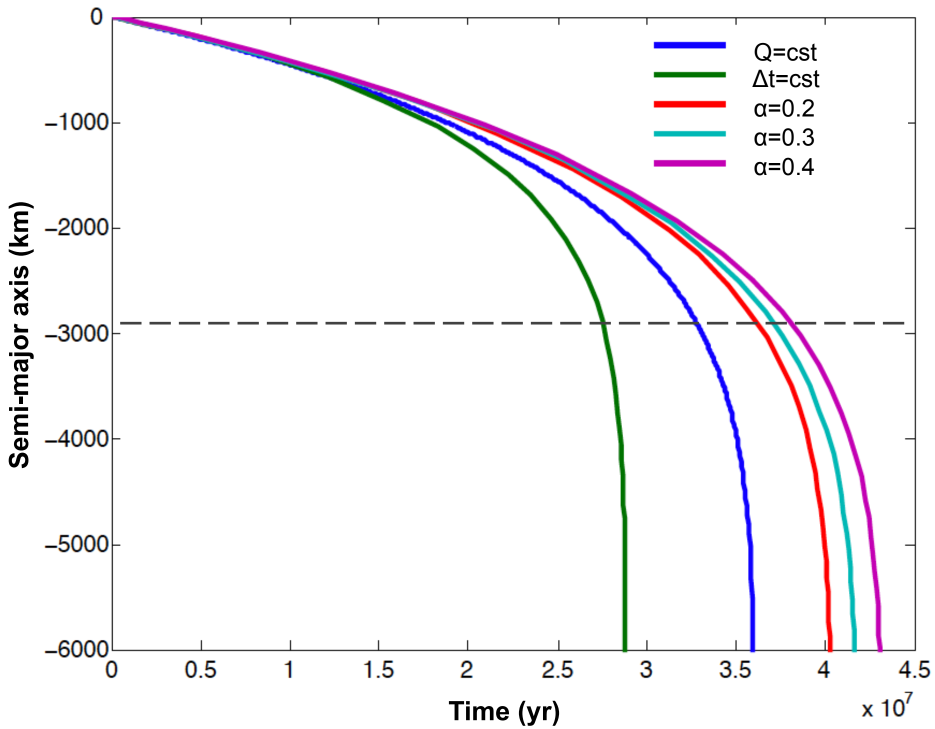
Impact of the rheology/friction on tidal dissipation and the evolution of planetary systems

The case of rocky bodies

Efroimsky & Lainey 2007 → Mars-Phobos system

$Q = K\omega^{\alpha}$ (Q_0=79)

→ Smooth evolution



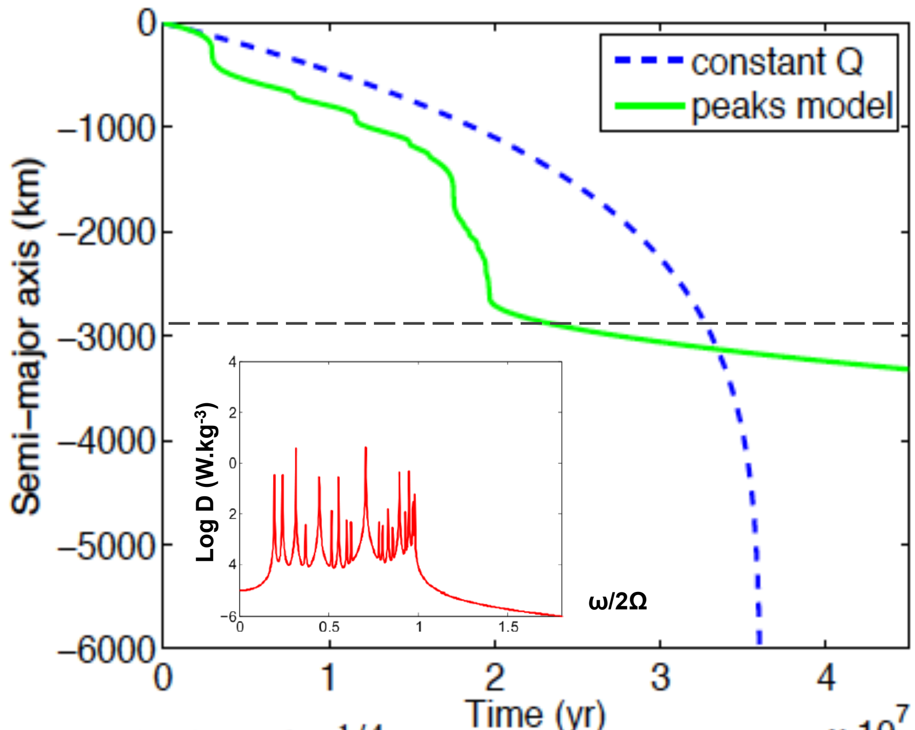
→ **Internal structure is a key actor**

The case of fluid bodies

Mathis & Le Poncin-Lafitte 2009
Auclair-Desrotour, Le Poncin-Lafitte & Mathis 2014

Resonant tidal dissipation

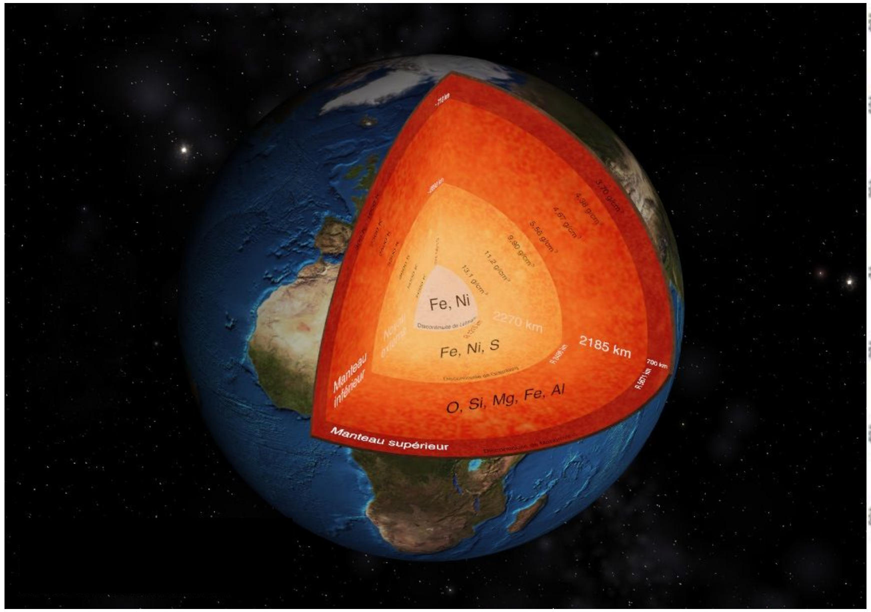
→ Erratic evolution: resonance locking

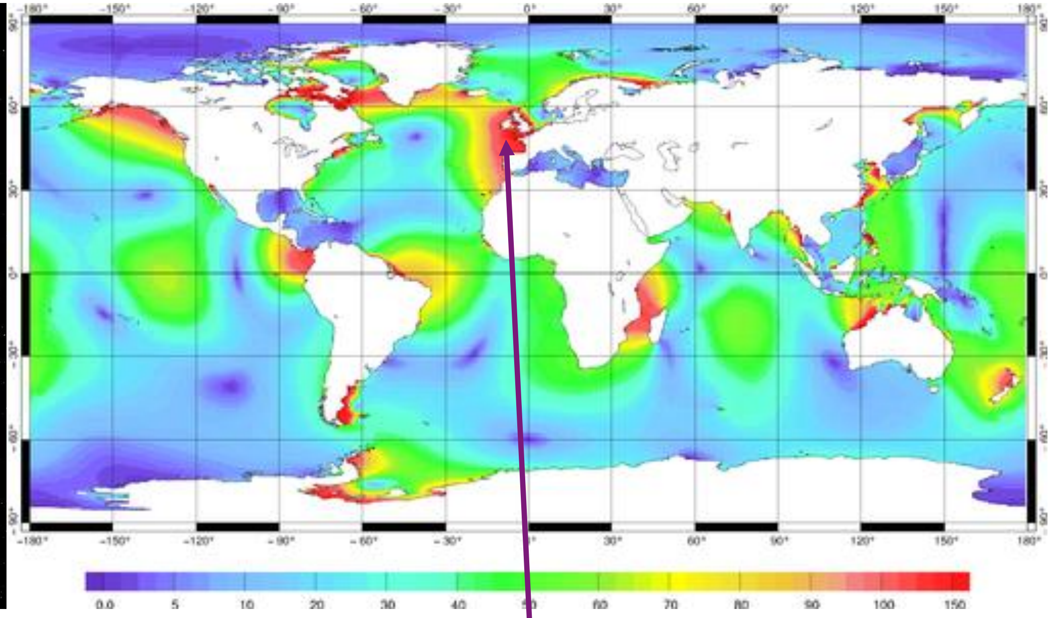


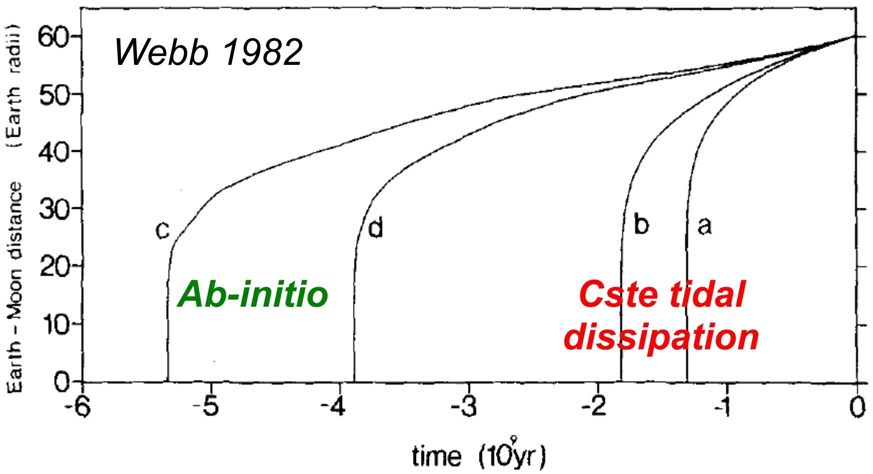
→ $\Delta a/a \propto l\, H^{1/4}$

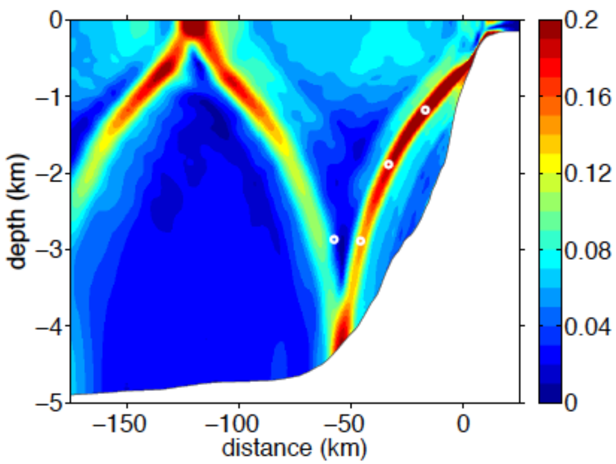
The case of the Earth

Satellites Jason 1 & 2 and Topex/Poséidon
Kantha 2014







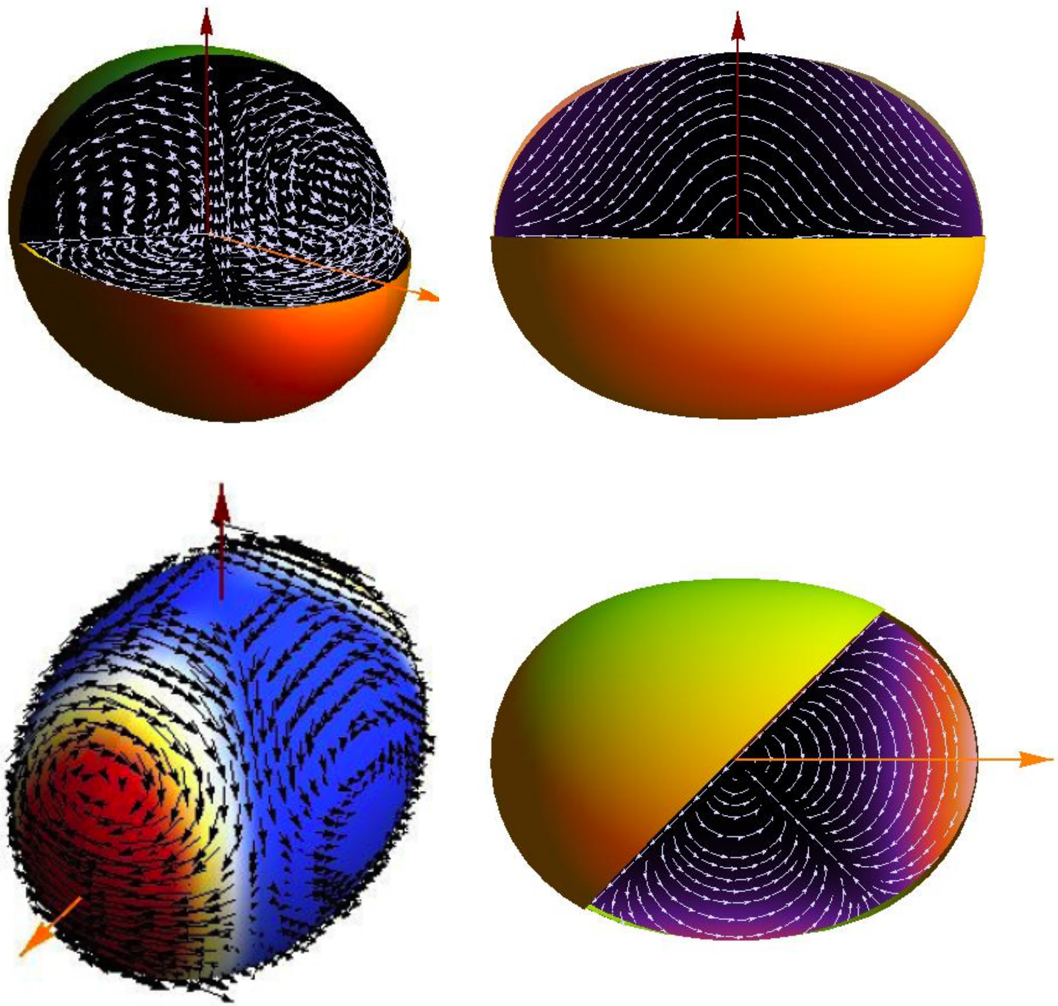


→ **Need to have a stratified view of tidal dissipation in celestial bodies**

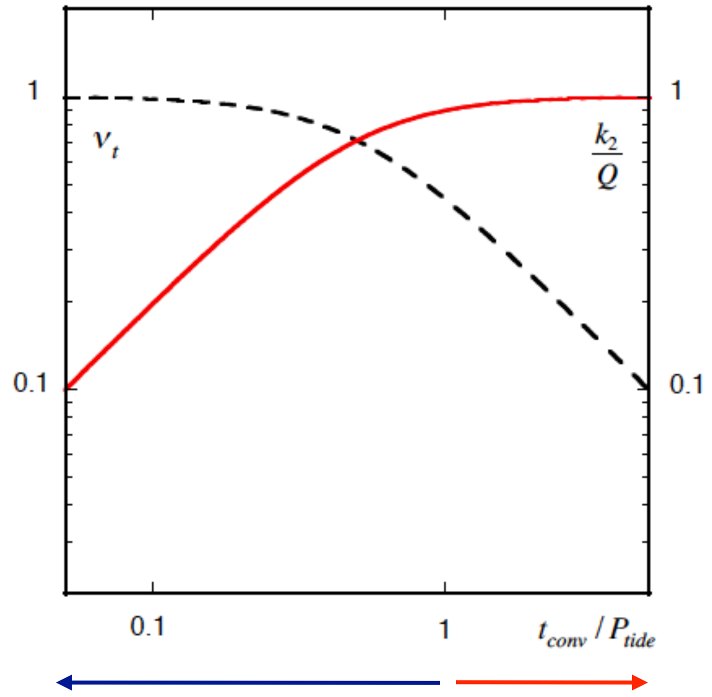
Gerkema, Lam & Maas 2004

The fluid equilibrium tide in stars and fluid planets

Velocity field



Viscous turbulent dissipation in convection zones



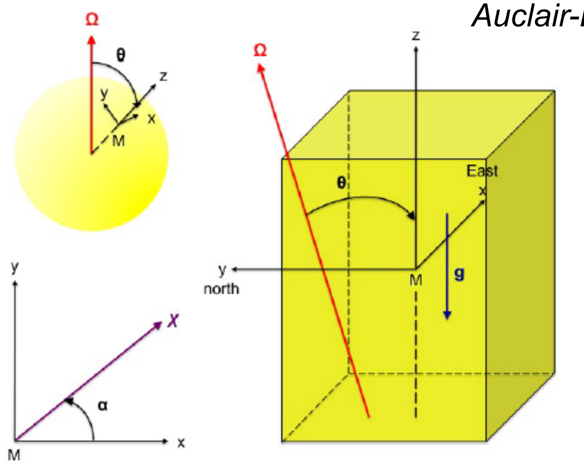
Slow tide
Q α ω[-1]

Fast tide
Q=cste

Zahn 1966-89;
Remus, Mathis & Zahn 2012;
Mathis et al. 2015-16

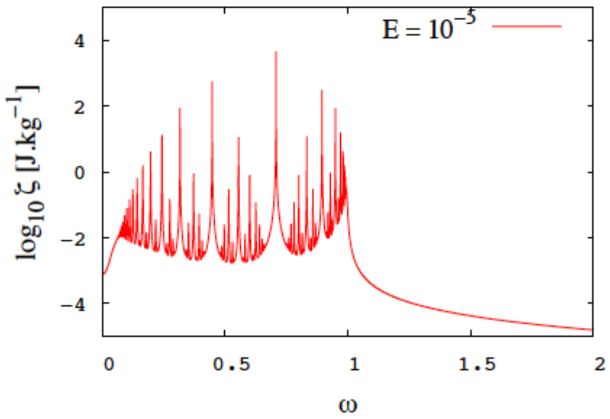
Simplified local models to understand fluid dissipation

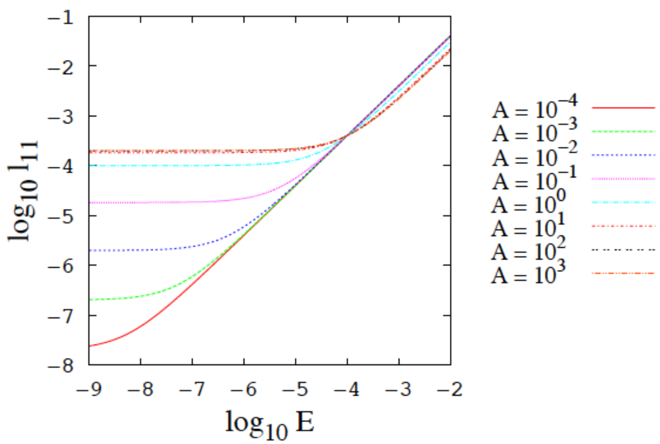
Auclair-Desrotour, Mathis & Le Poncin-Lafitte 2014
Mathis et al. 2015

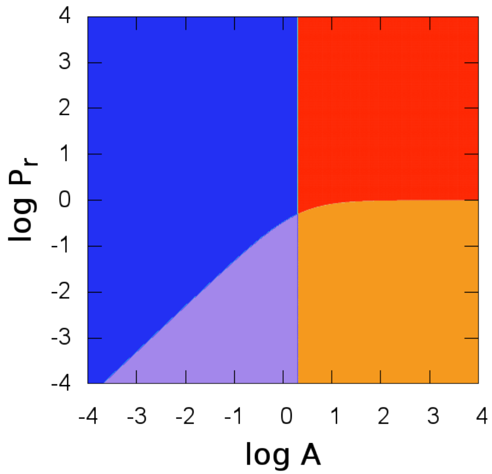


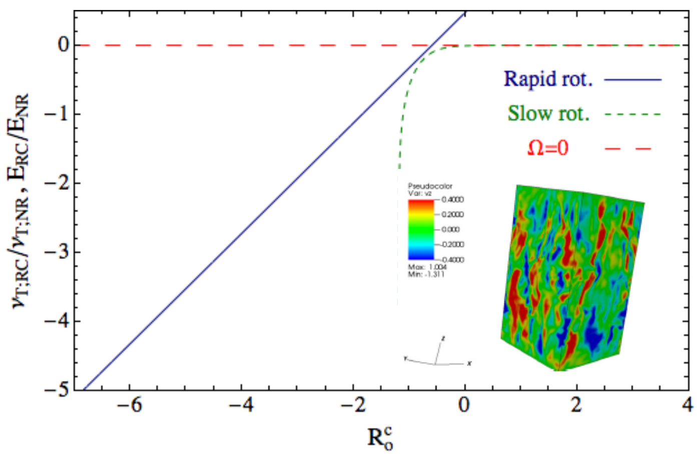
$$E = \frac{\pi^2 \nu}{2\Omega L^2} \qquad A = \left(\frac{N}{2\Omega}\right)^2$$

$$K = \frac{\pi^2 \kappa}{2\Omega L^2} \qquad P_r = \frac{\nu}{\kappa} = \frac{E}{K}$$





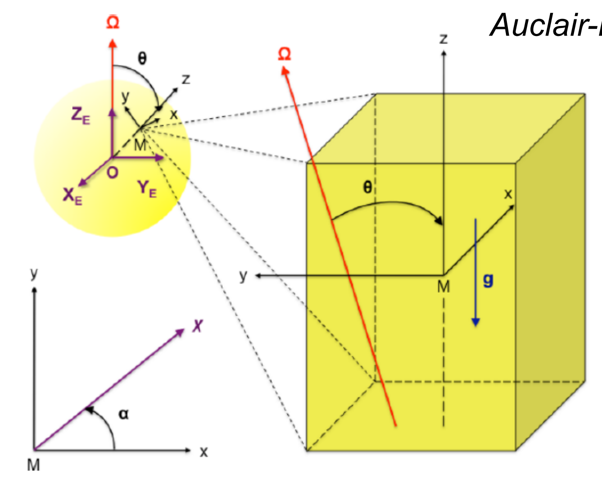




→ **Dynamical properties of fluid layers strongly impact tidal dissipation**

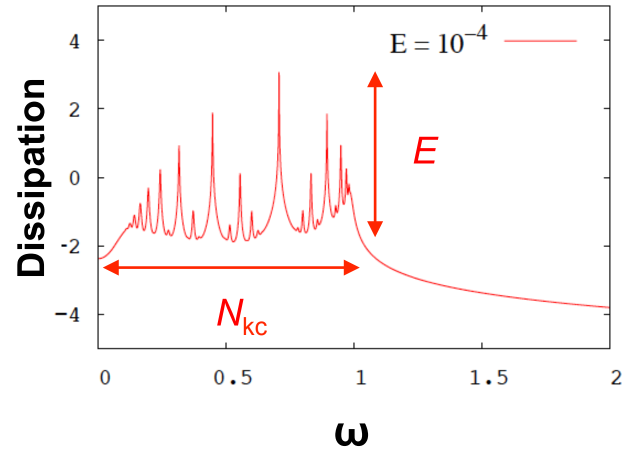
Simplified local models to understand fluid dissipation

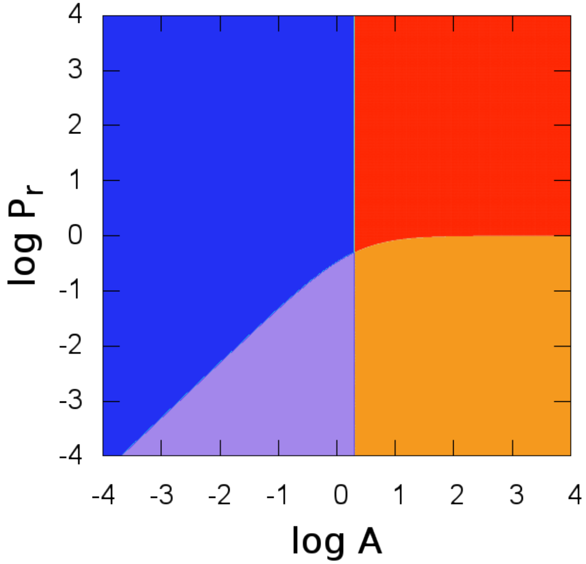
Auclair-Desrotour, Mathis & Le Poncin-Lafitte 2015



$$E = \frac{\pi^2 \nu}{2\Omega L^2} \qquad A = \left(\frac{N}{2\Omega}\right)^2$$

$$K = \frac{\pi^2 \kappa}{2\Omega L^2} \qquad P_r = \frac{\nu}{\kappa} = \frac{E}{K}$$





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

→ Dynamical properties of fluid layers strongly impact tidal dissipation

The new landscape for tidal dissipation in gaseous giant planet systems

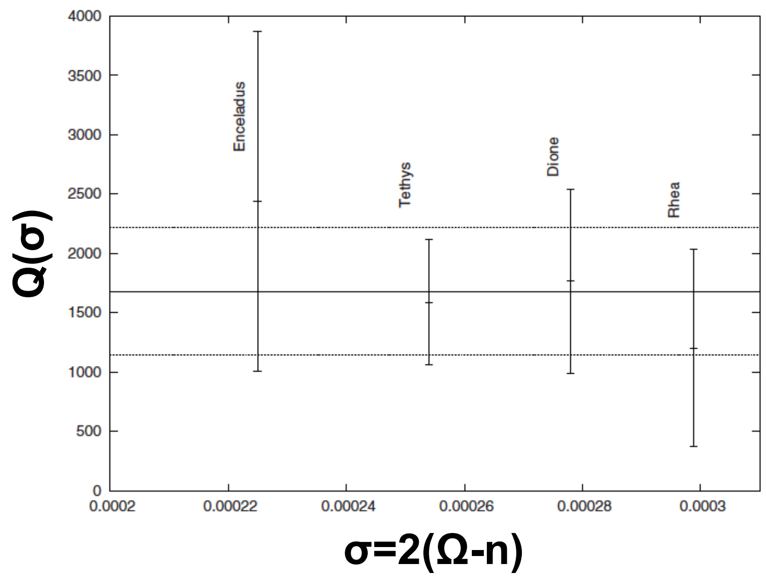
A strong tidal dissipation

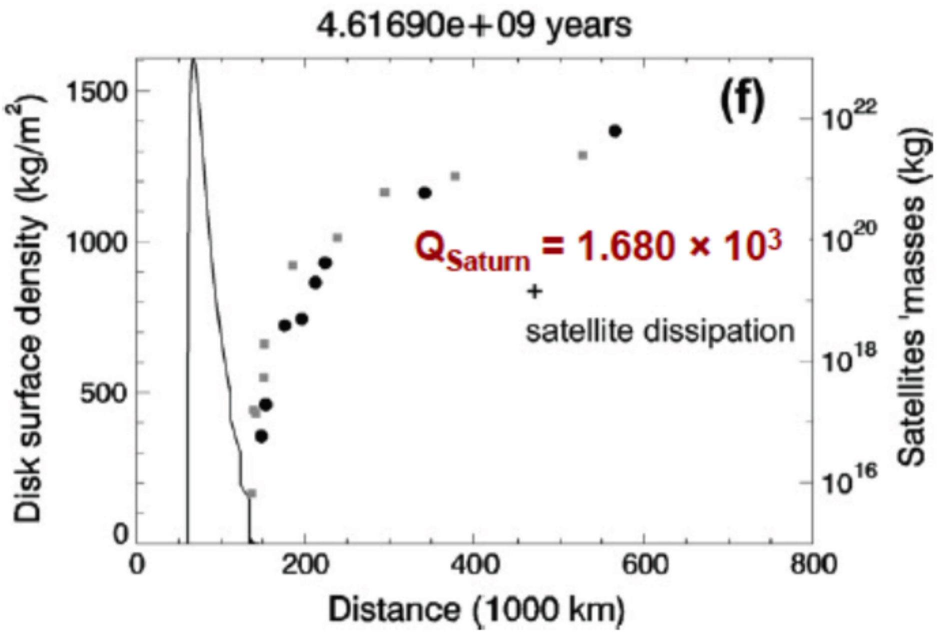
Lainey et al. 2009, 2012, 2015

A new scenario of formation for the moons

Charnoz et al. 2010, 2011; Crida & Charnoz 2012

Saturn





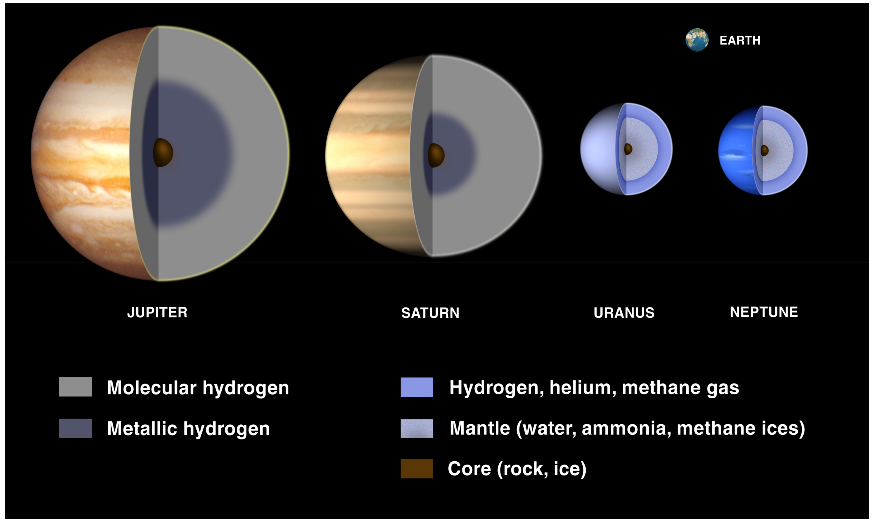
→ allows to explain the thermal state of Enceladus

→ Internal structure is a key actor

Tides in the dense core of giant planets

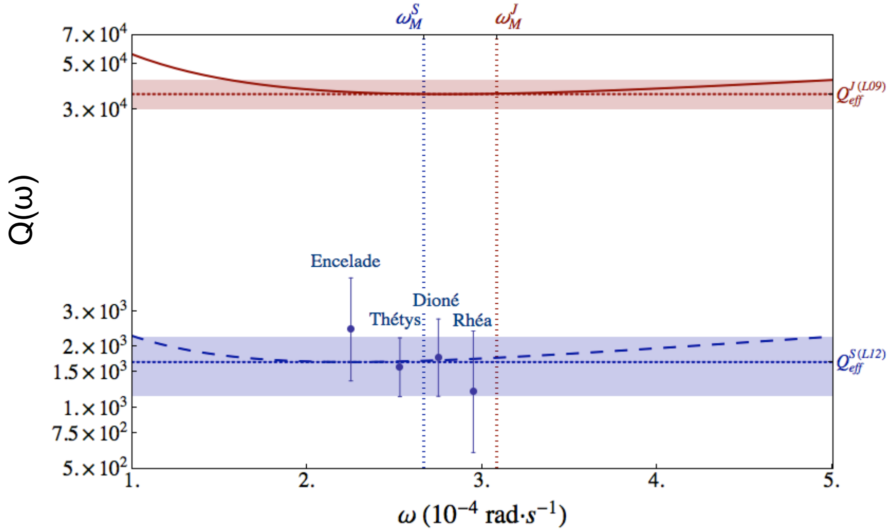
Internal structure

e.g. Guillot 1995



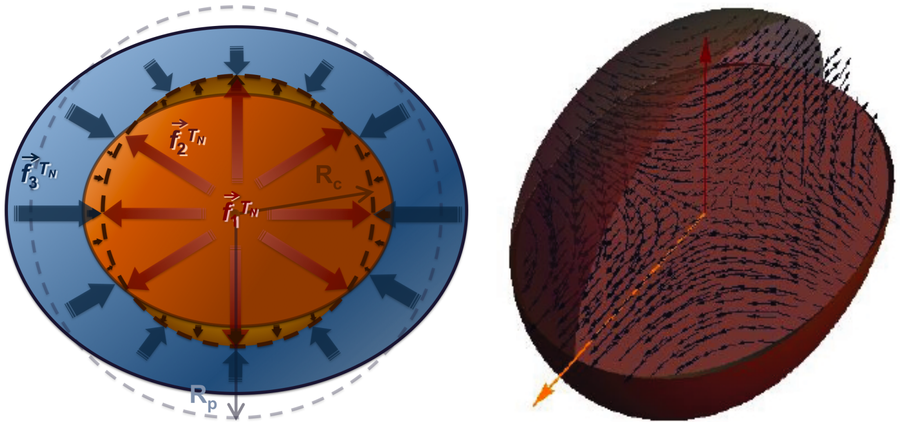
Application to gaseous giants

Remus, Mathis, Zahn & Lainey 2012; Storch & Lai 2014-15



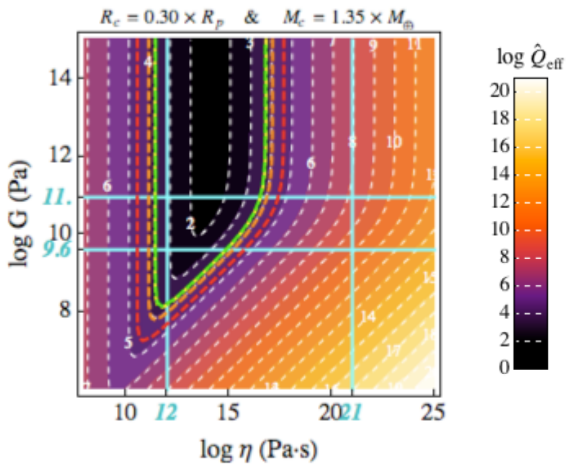
The inelastic rocky/icy core

Remus, Mathis, Zahn & Lainey 2012-15

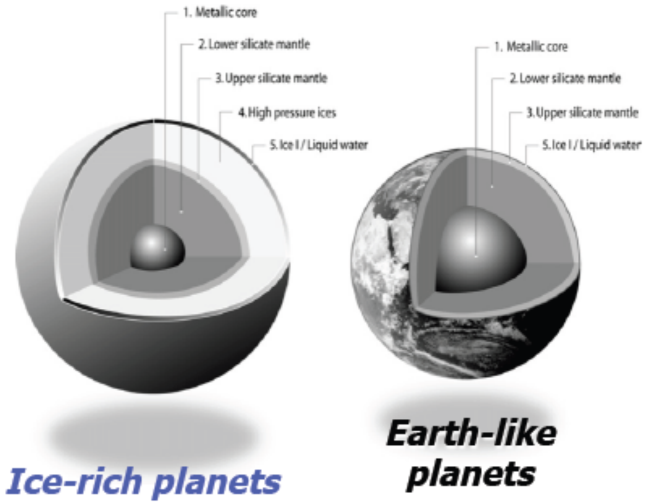


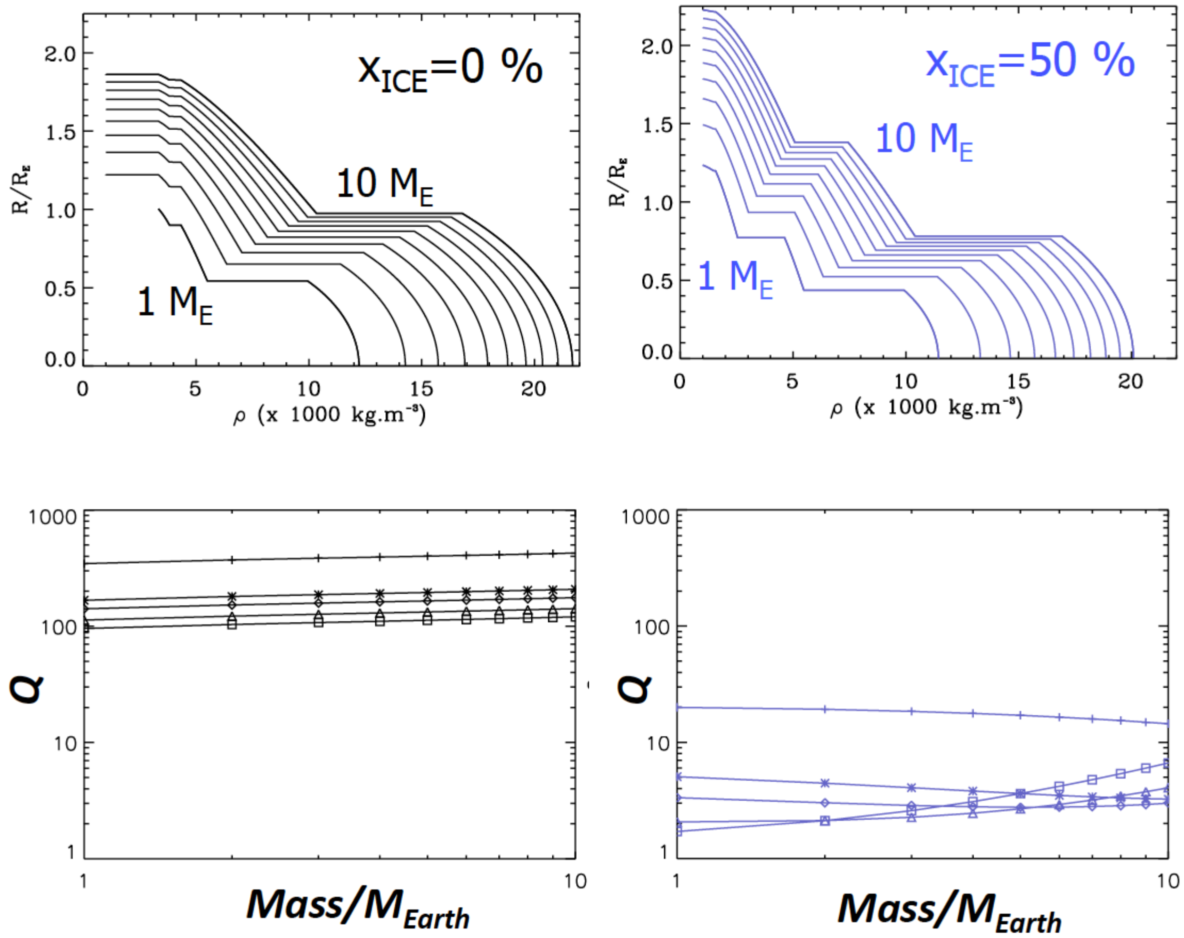
Application to icy giants

Remus, Mathis, Zahn, Lainey & Charnoz 2015



Tides in the solid part of super-Earth and large icy worlds





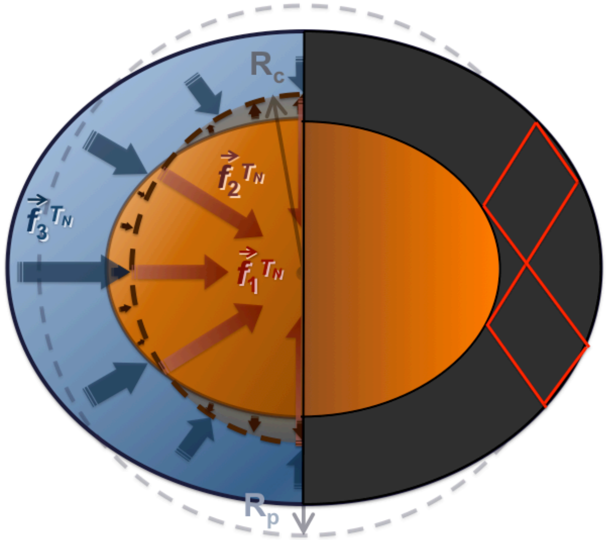
Tobie et al., in prep.

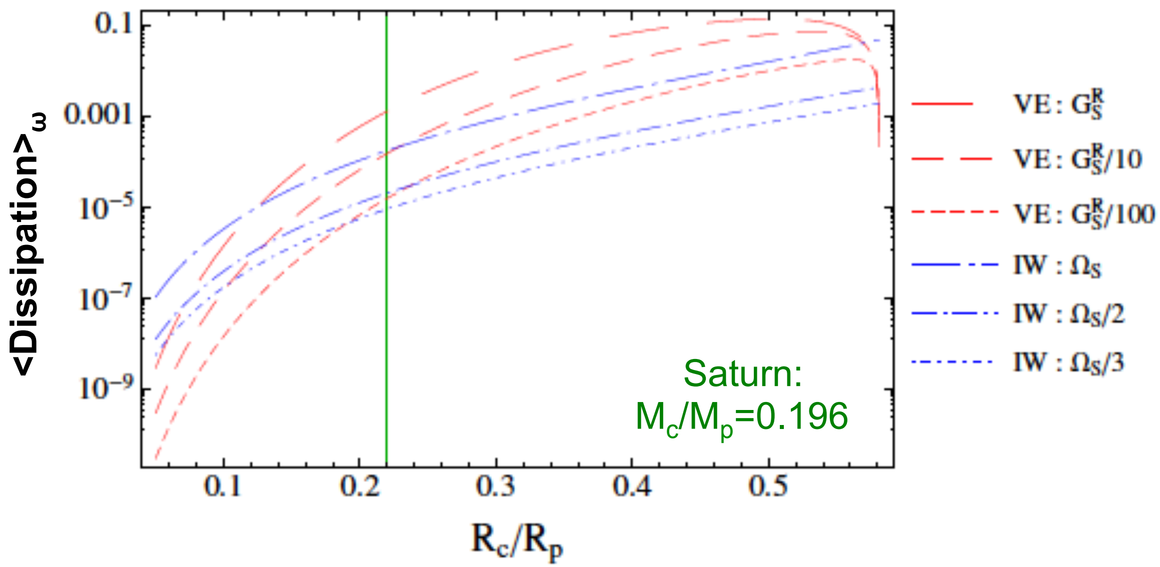
→ **Need for advanced EOS and rheological models**

Towards integrated models for multi-layer planets

Remus, Mathis, Zahn & Lainey 2012

Ogilvie 2009, 2013

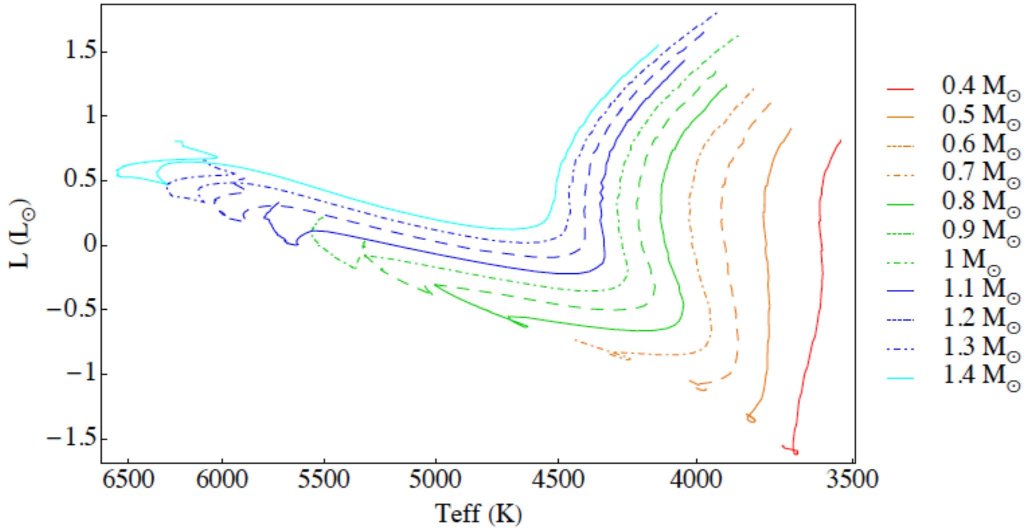




→ Integrated models needed for gaseous giant (and telluric) planets

Guenel, Mathis & Remus 2014

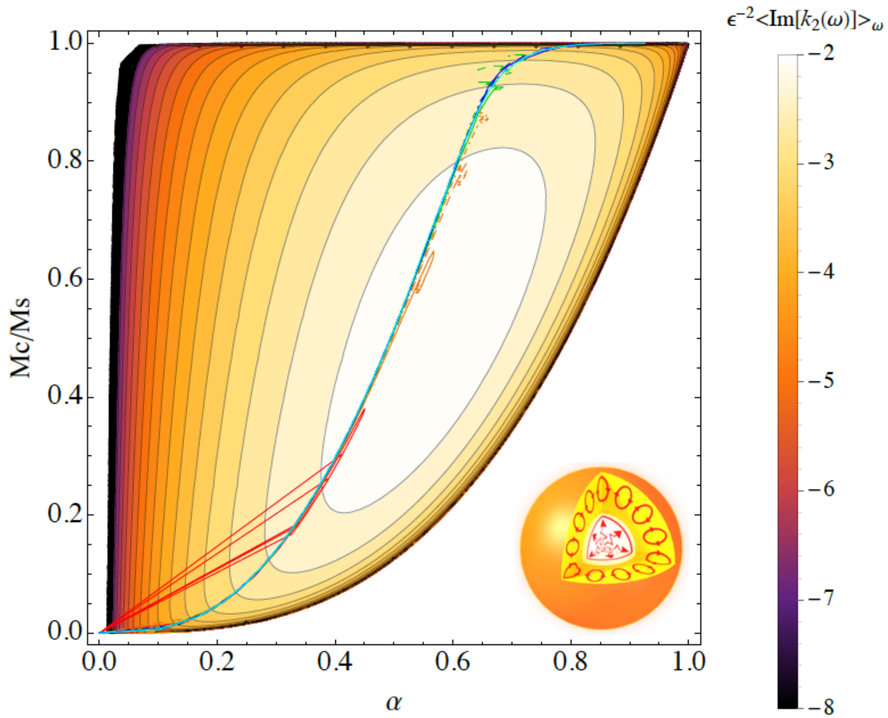
Tidal dissipation along the evolution of host stars

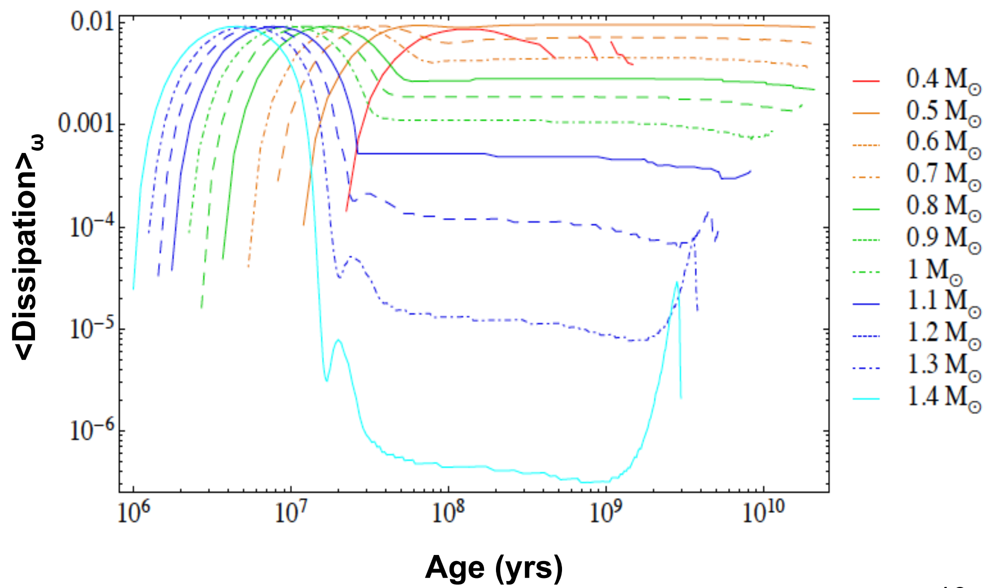


In low-mass and solar-type stars, it varies over several orders of magnitude:

→ Strong dynamical tide along the PMS

→ Its amplitude on the MS decreases with mass (and the thickness of the CE)





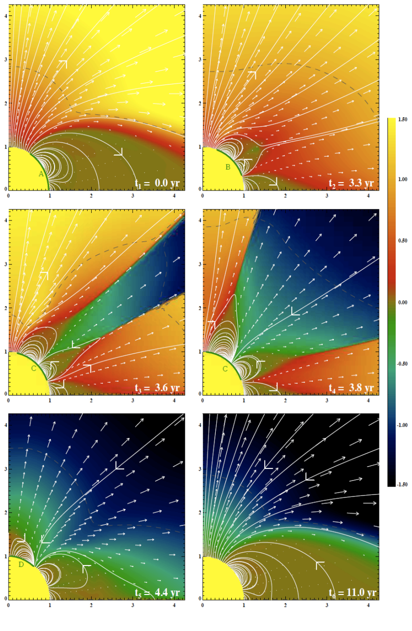
Mathis 2015 & Mathis et al. 2015

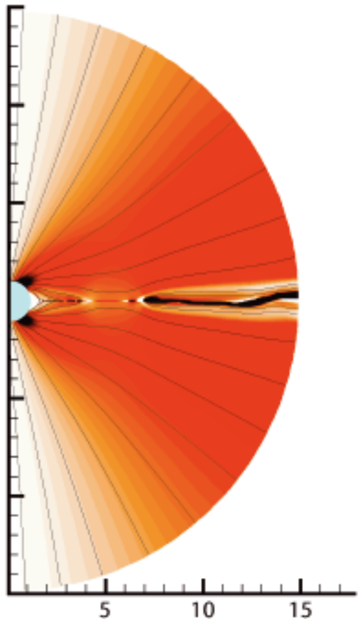
Interaction with MHD stellar environment: winds & accretion disks

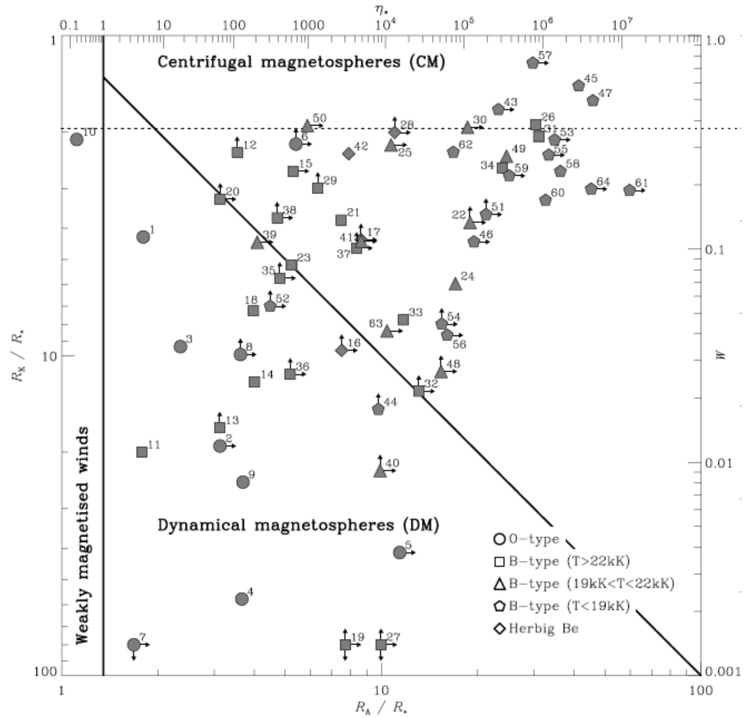
Winds: (pressure-driven), line-driven (and colliding winds)

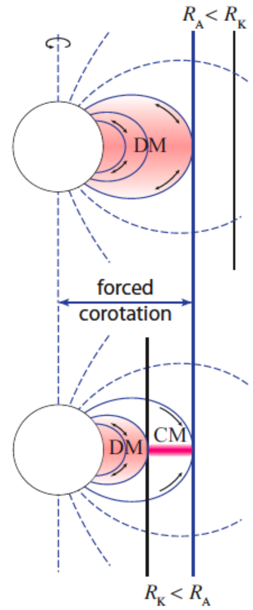
Pinto et al. 2011
Matt et al. 2012
Reville et al. 2014

Ud-Doula et al. 2008, Petit et al. 2013 MiMeS



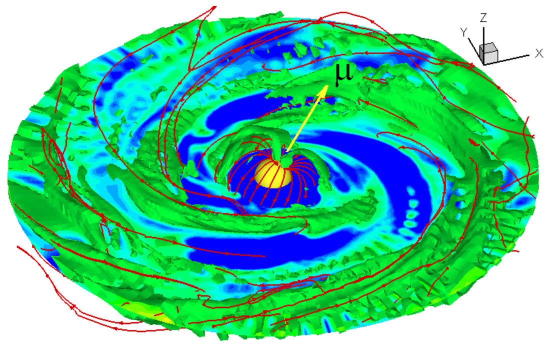






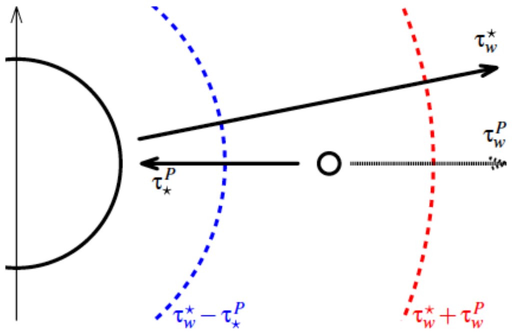
Accretion disks

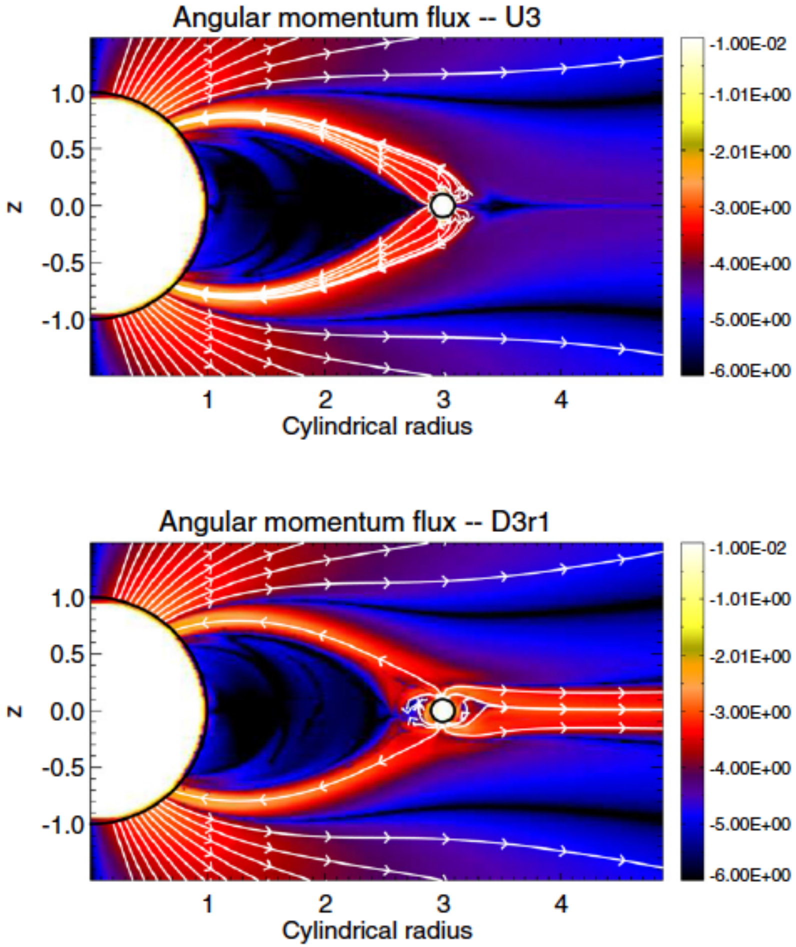
Matt & Pudritz 2005, Romanova et al. 2010

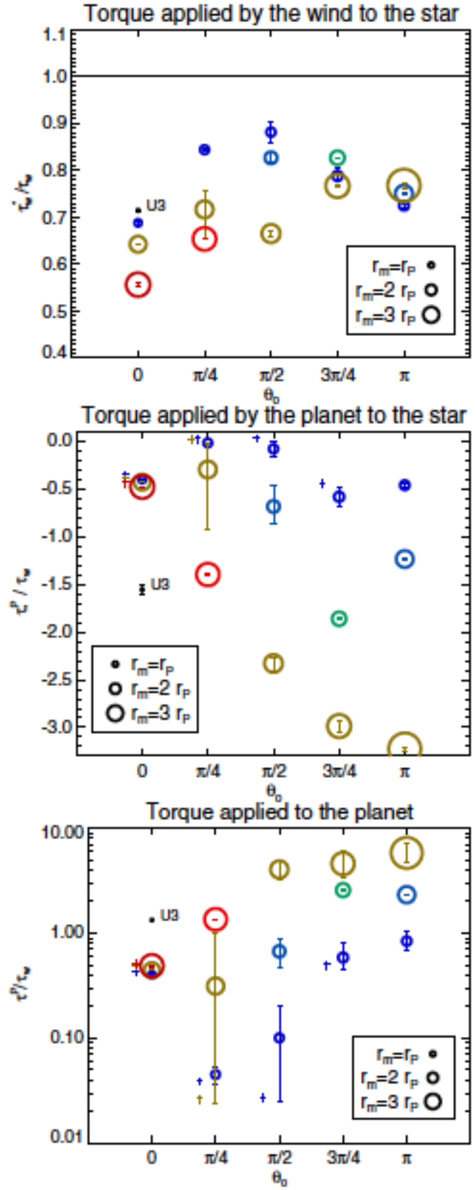


MaPP, MaTYSSE

Magnetic Star-Planet Interactions





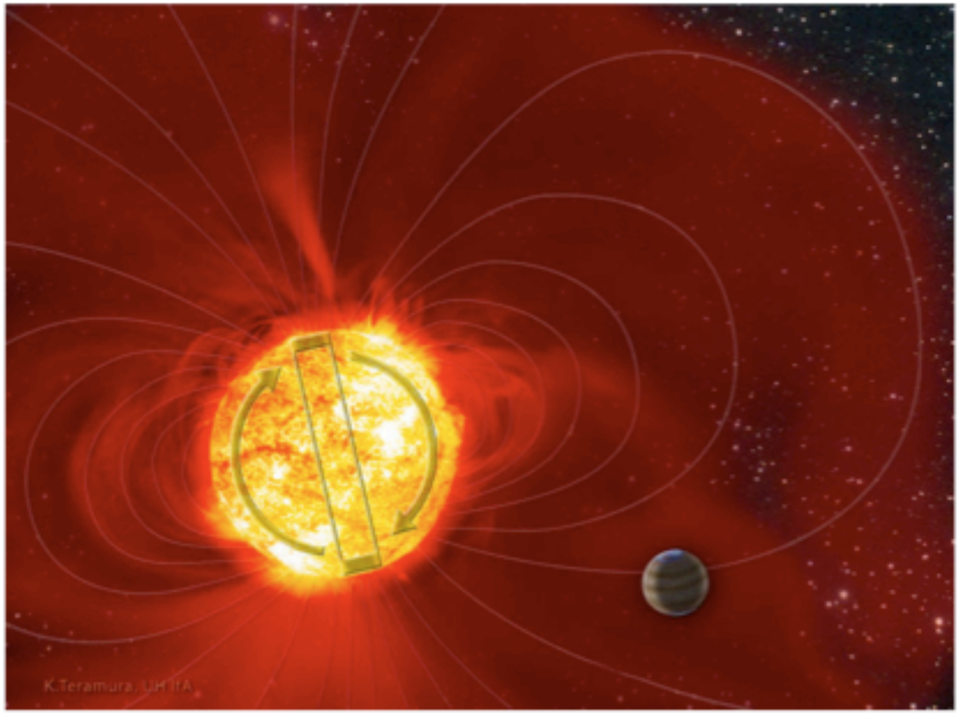


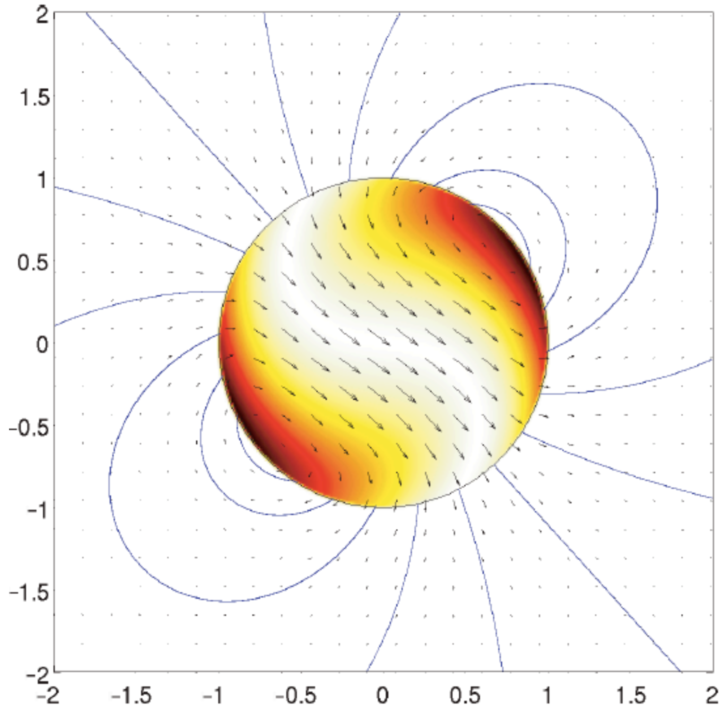
Strugarek et al. 2014 (see also Vidotto et al. 2013-14; See et al. 2014)

MHD connexions between components

- Applied torques (added to tides and winds)
- Helicity exchanges → modification of the magnetic activity *(Lanza 2012)*

Modification of stellar magnetism?





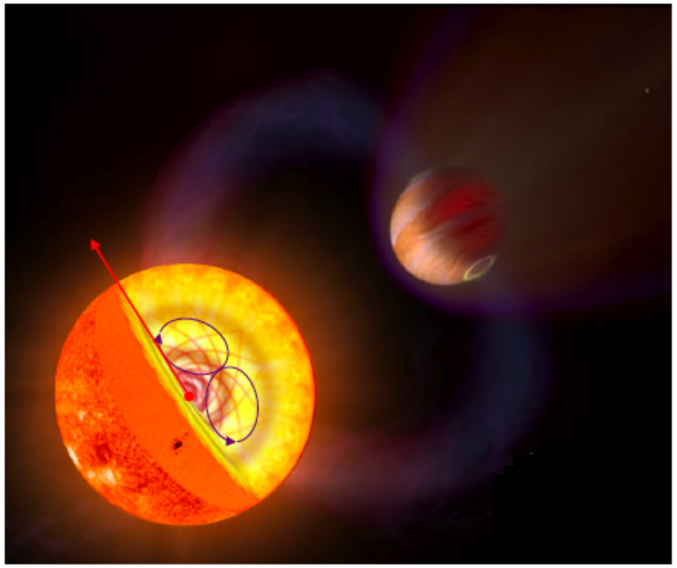
Donati et al. 2008

Lacaze et al. 2006
Cébron & Hollerbach 2014

Interactions between tides and magnetic fields

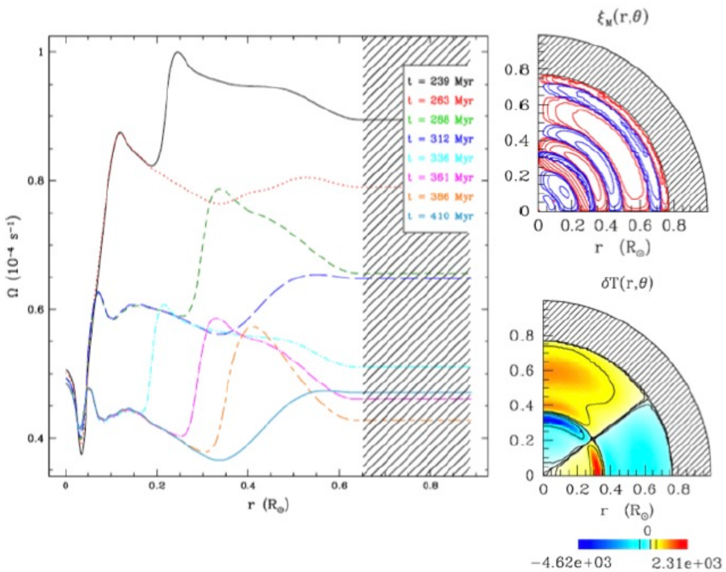
- Tides (& precession, libration) → modification of dynamo mechanisms and of the topology and stability of fields?
- Comparison external mechanical forcings v.s. internal convective driving and instabilities (mass ratio threshold?) → SPI (SSI)
- Magnetic fields → modification of tidal flows and related torques?

Angular momentum transport in stars with a companion

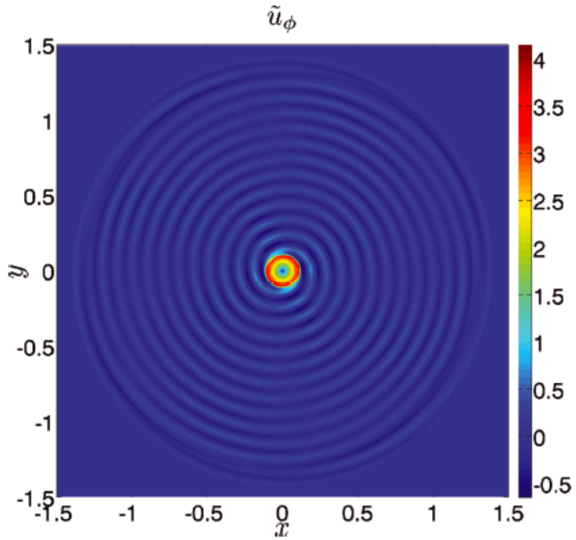


Transport mechanisms

- Meridional circulation: *stresses; **applied torques***
- Turbulence
- Fossil field
- Gravito-inertial waves: *convection* & ***tides***
- Thermohaline: ***accretion***
(*Theado & Vauclair 2012*)



Talon & Charbonnel 2005; Mathis et al. 2013



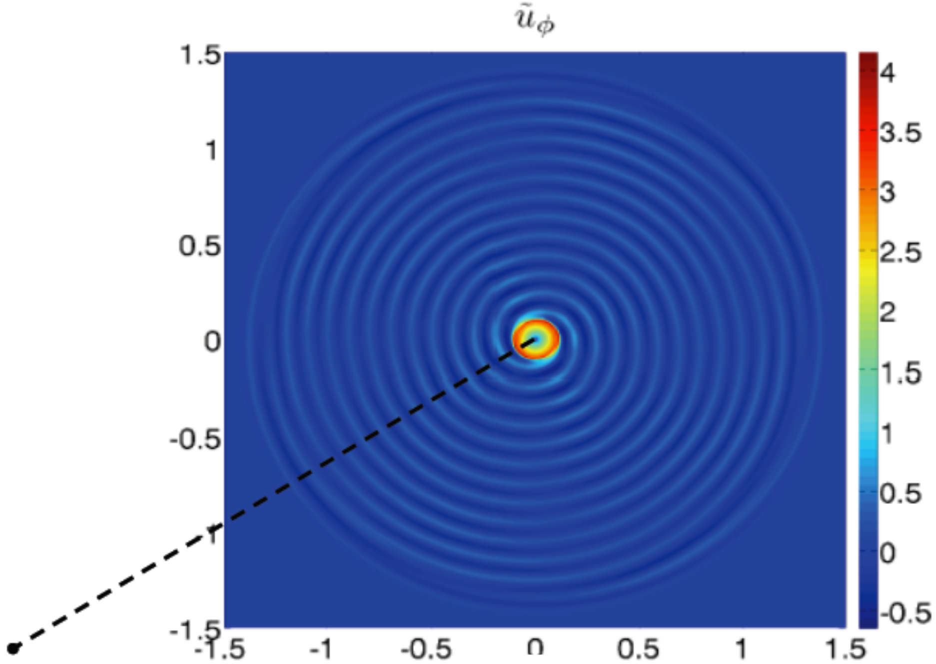
Barker & Ogilvie 2010

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



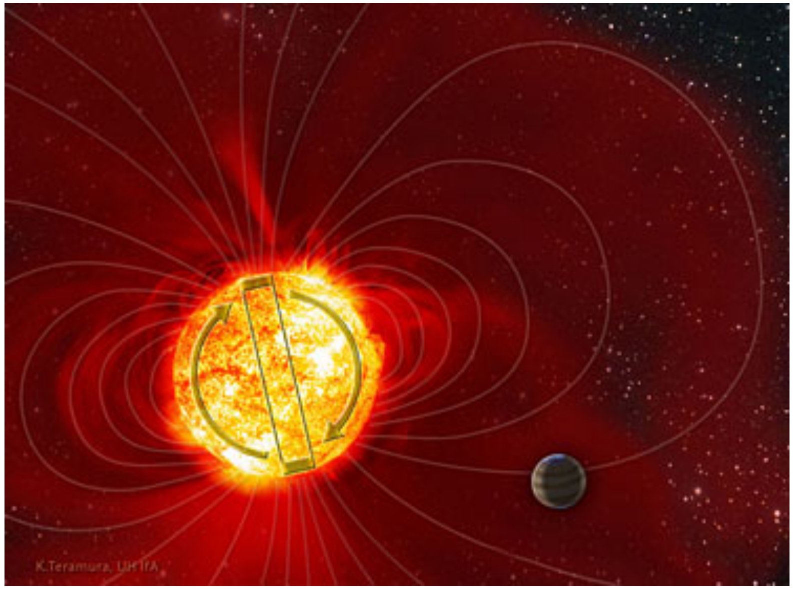
Barker & Ogilvie 2010

Tides and magnetism

- Tides induce helical flows

→ able to modify magnetism in stars (BinaMIcS, UVmag) 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



Donati et al. 2008; Strugarek et al 2014

Towards a complete picture

Rotational dynamics of planets in interaction with stars

- How does tidal dissipation (Q factor) depend and impact planetary structure and evolution?

- How does rotation and obliquity evolve through the combined action of tidal (and MHD) torques?
Outputs for climatology, magnetism, habitability

Dynamical evolution of low-mass stars interacting with planets

- How does tidal dissipation (Q factor) vary as a function of stellar mass and evolutionary stage?

- What is the relative importance of the different torques applied on their envelope along their evolution?

- How does the evolution of stars hosting planets differ from those of single stars?

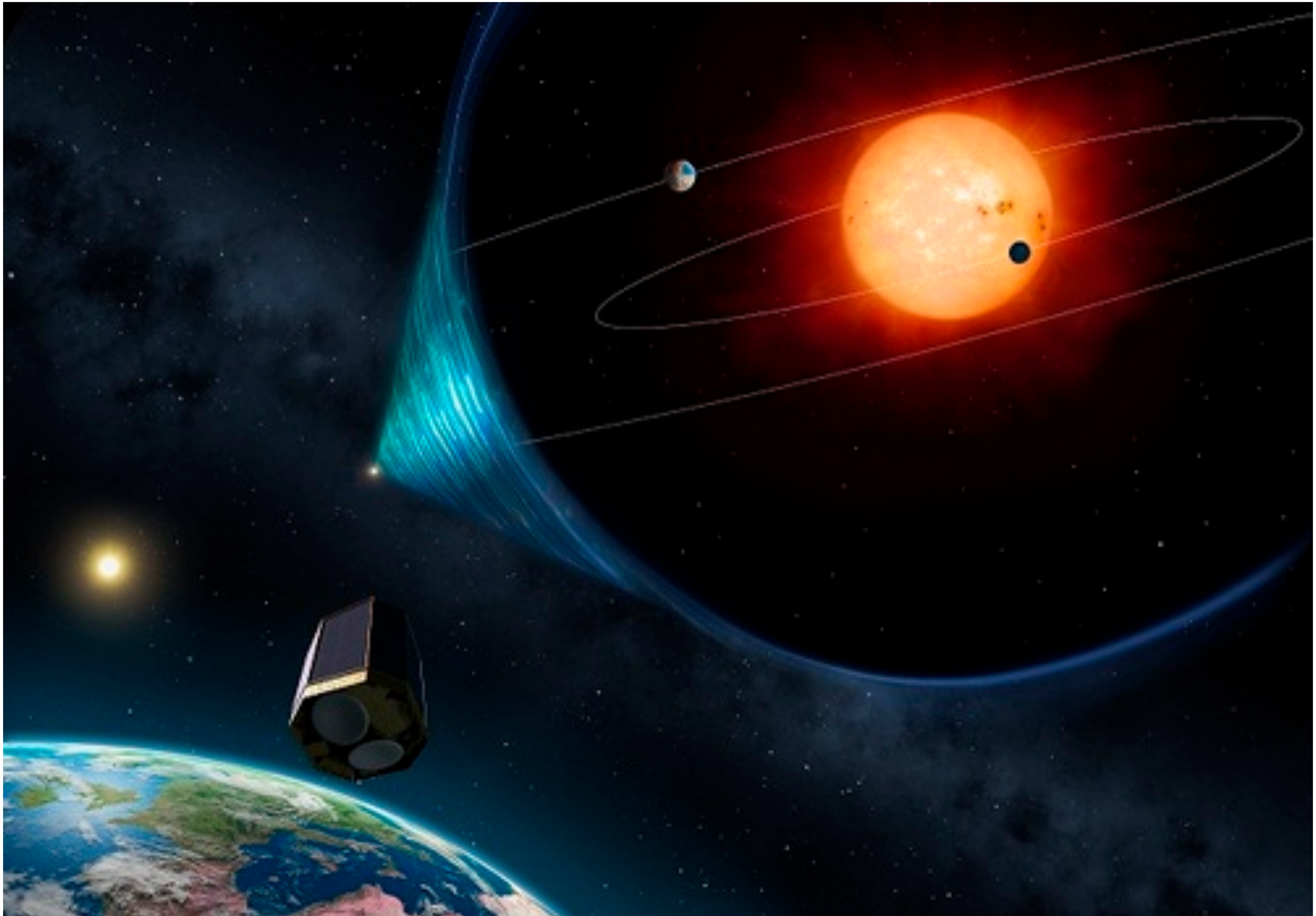
Dynamical evolution of star-planet systems

- What are the respective impact of tides and magnetic interactions on star-planet system evolution?

- In multi-body systems, how do tidal and MHD interactions couple with resonances?

- How do the orbital architecture and the habitable zone change along the host star's evolution?

Dynamical vision of star-planet systems



PLATO / PSI WP / stephane.mathis@cea.fr