Tidal dissipation in stars and the orbital evolution of close-in systems

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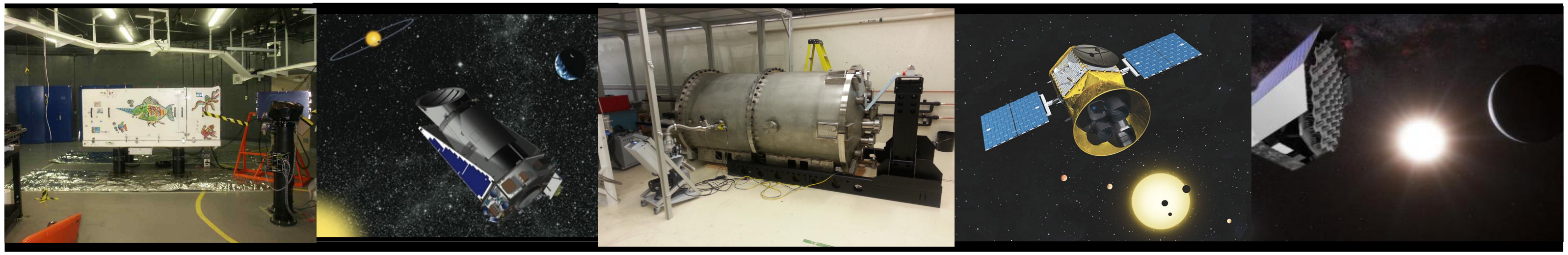
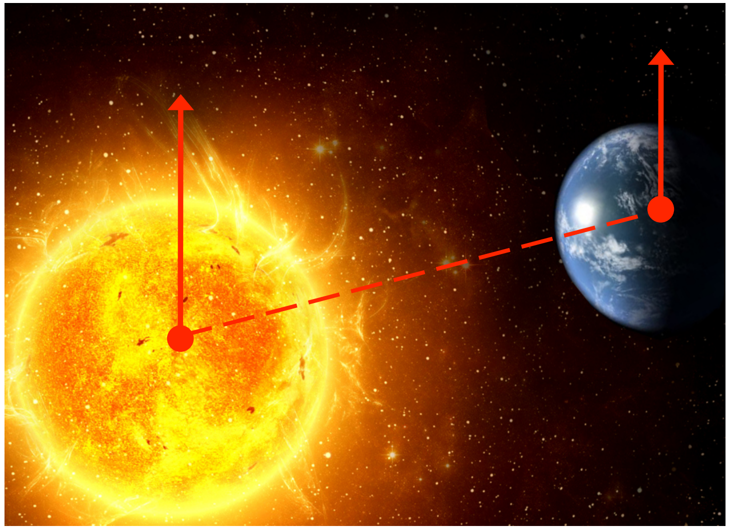
The general context

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*

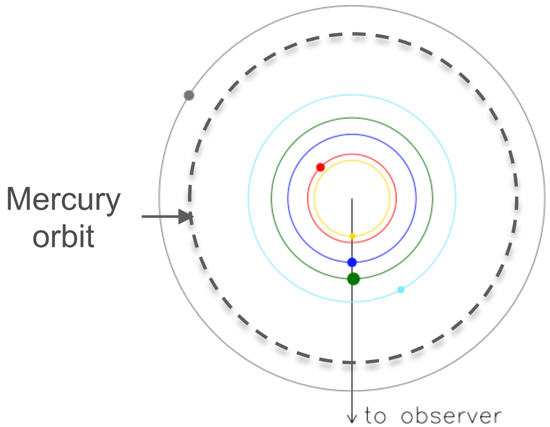
Stellar rotation & magnetism – planetary dynamics



Albrecht et al. 2012; Gizon et al. 2013

Orbital architecture

Kepler 11



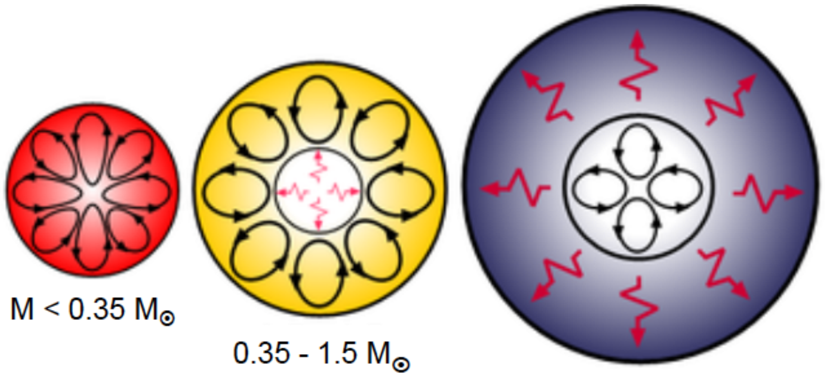
Lissauer et al. 2011
Bolmont et al. 2014

State of the art

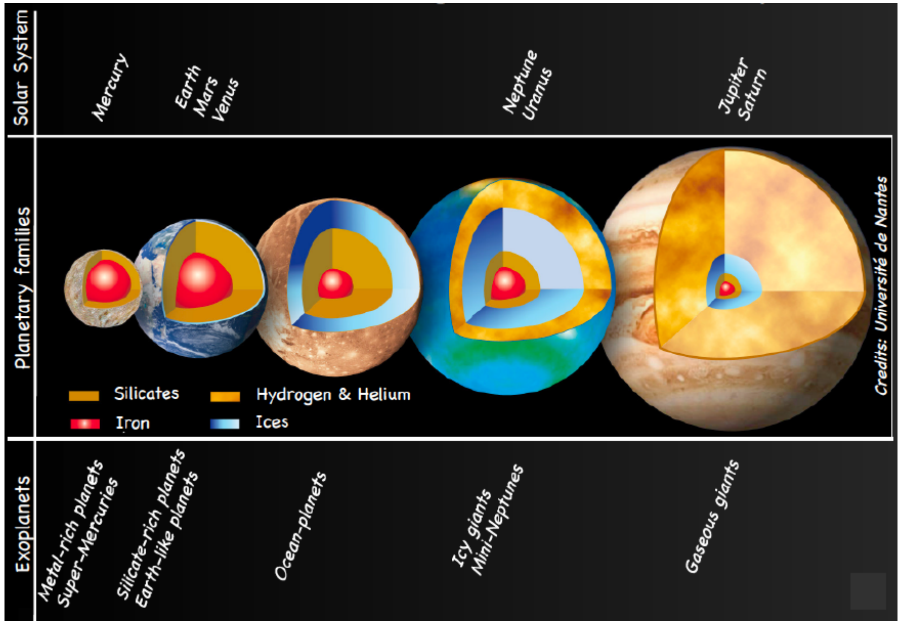
In studies of star-star or star-planet systems, bodies are treated as point-mass objects or solids with ad-hoc models for tides, stellar winds and electromagnetic interactions

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

Host star (M in $M_\odot$)



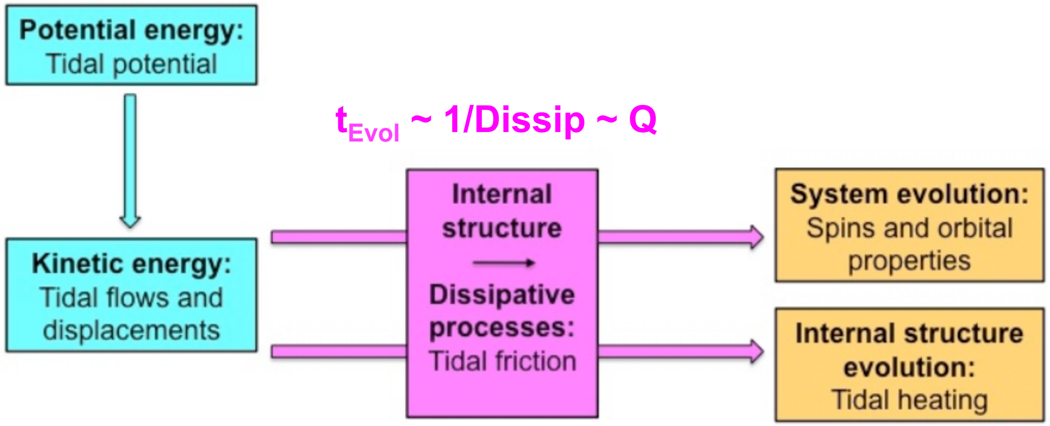
Planets

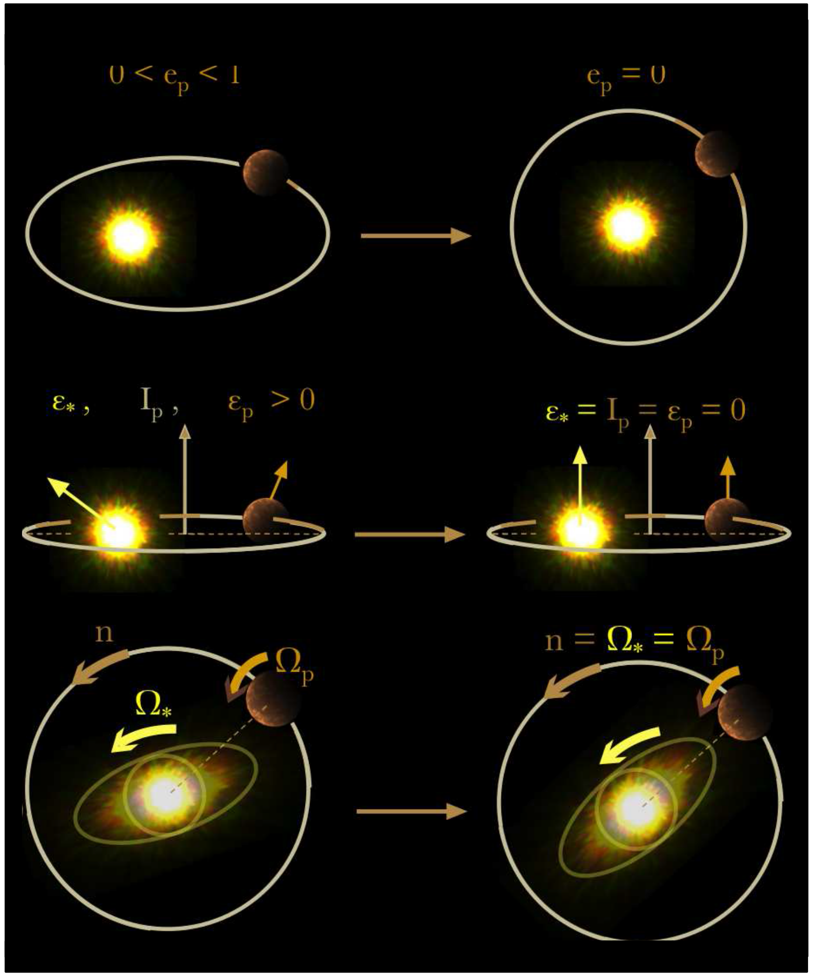


→ Need of an ab-initio physical modeling to accompany the study of discovered systems

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

Dynamical evolution of a binary system





Mathis & Remus 2013

→ **Necessity to identify 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)**

Tidal velocities/displacements

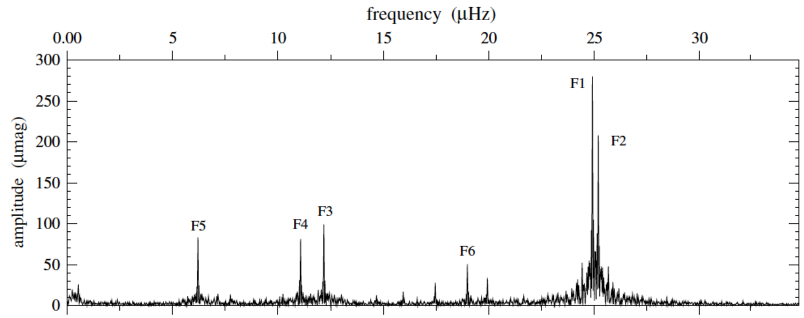
In stars and fluid planetary layers:

- 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.)

Acoustic waves

Gravito-inertial waves (Stab. strat.)

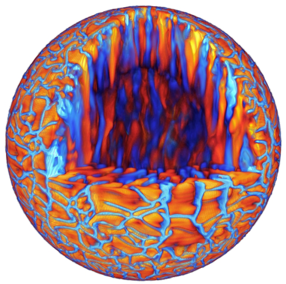
Mathis & Remus 2013

Dissipative mechanisms:

- **Convective regions:** turbulence

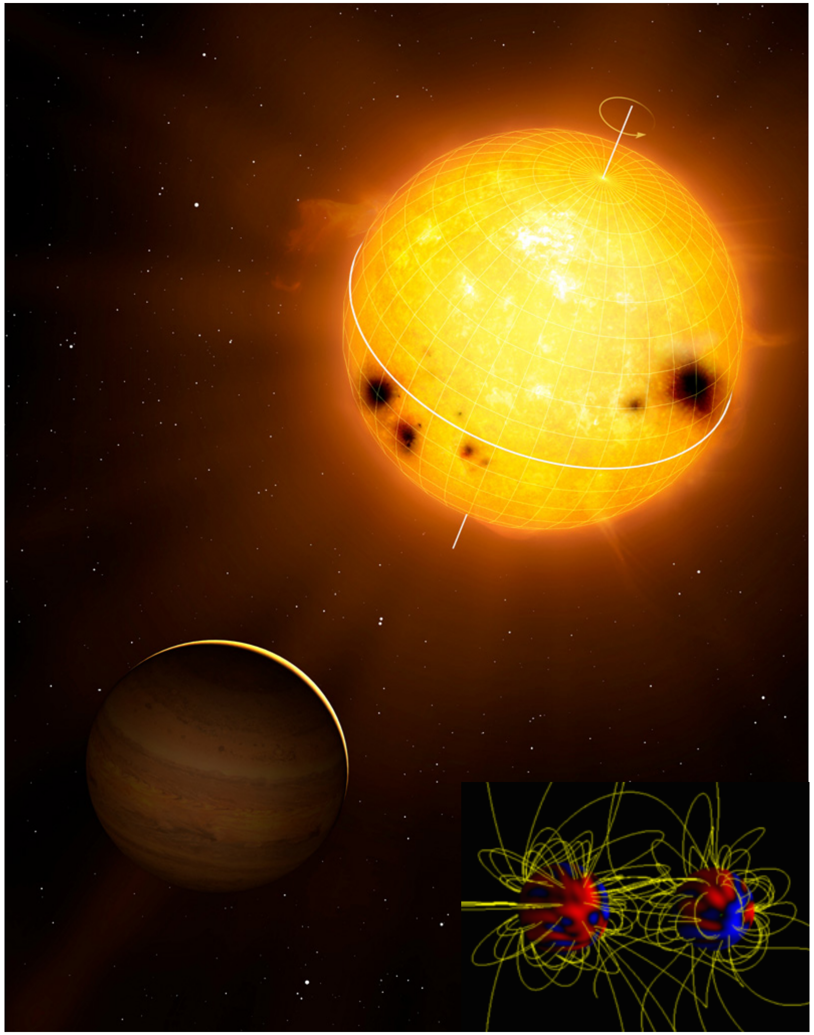
- **Stably stratified regions**: heat diffusion

Brun et al.

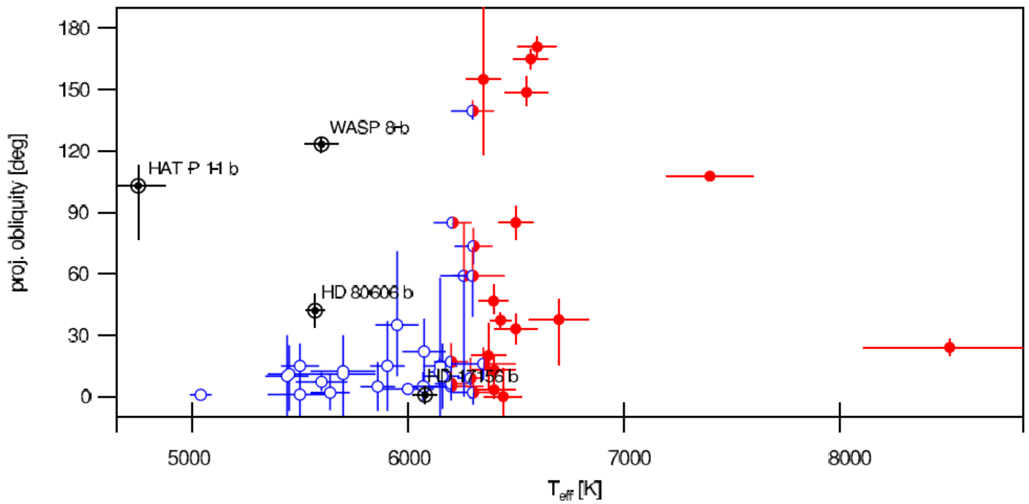


The signature of tidal interactions in exoplanetary systems & multiple stars

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



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



Albrecht et al. 2012

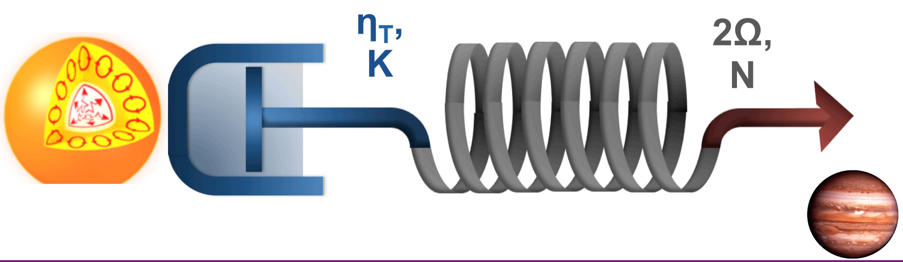
→ Tidal dissipation in a star varies over **several orders of magnitude** as a function of:

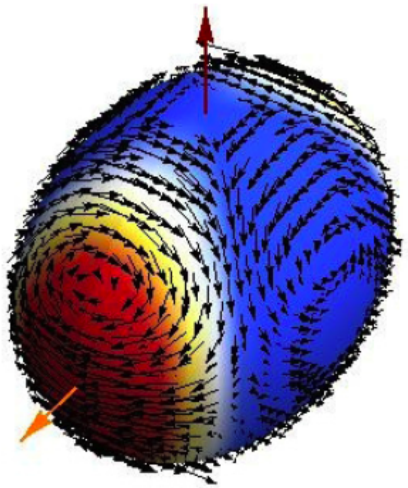
- The mass
- The age
- The dynamics (rotation)

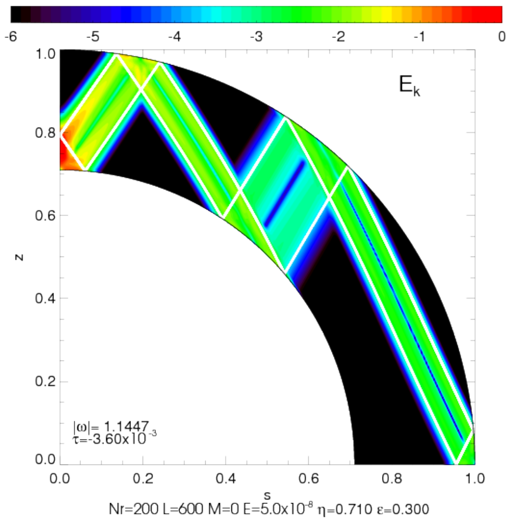
→ **need for ab-initio modeling**

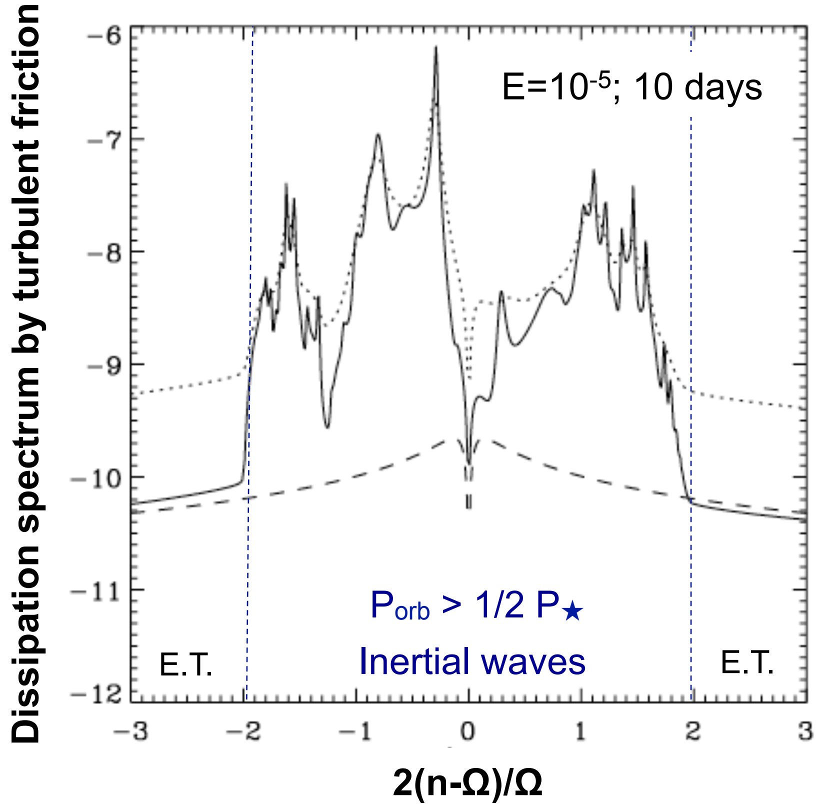
Tidal dissipation in low-mass star convective envelopes

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





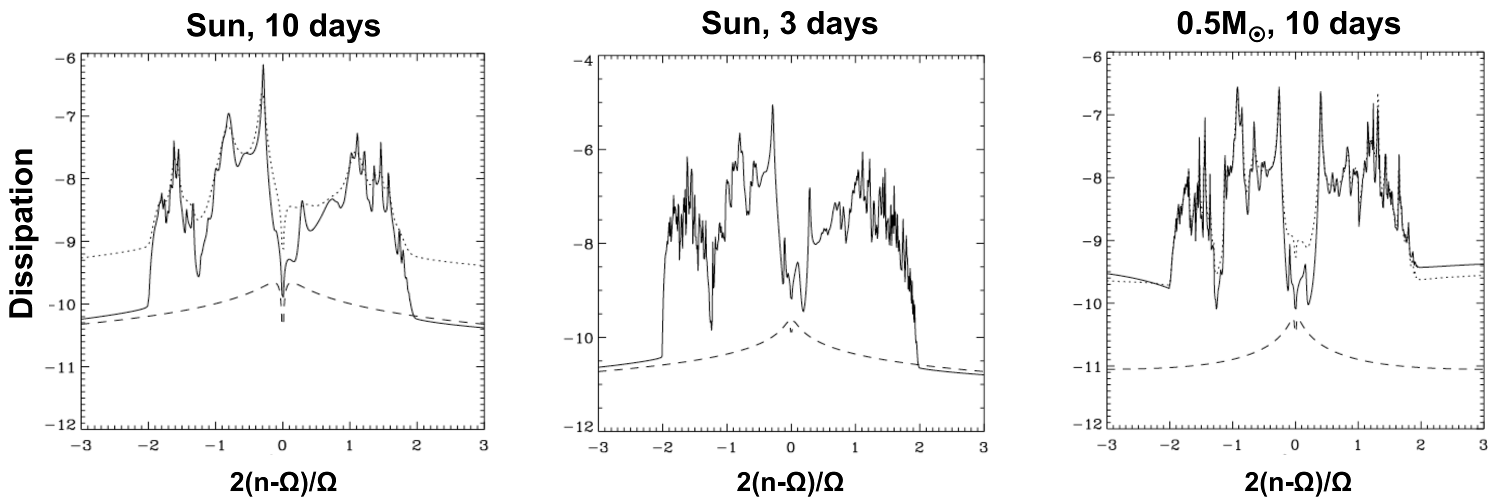




Ogilvie & Lin 2004, 2007
Rieutord & Valdetarro 2010
Baruteau & Rieutord 2013
Guenel et al. 2016

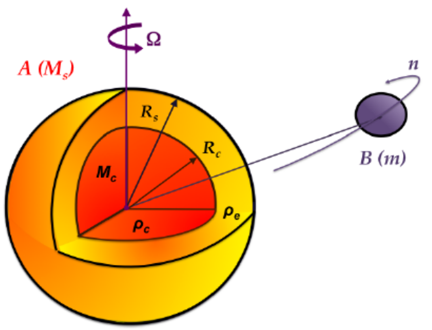
Dissipation variations with stellar parameters

As a function of stellar mass, age and rotation



Ogilvie & Lin 2007

To get an order of magnitude of tidal dissipation along the evolution of stars
→ 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

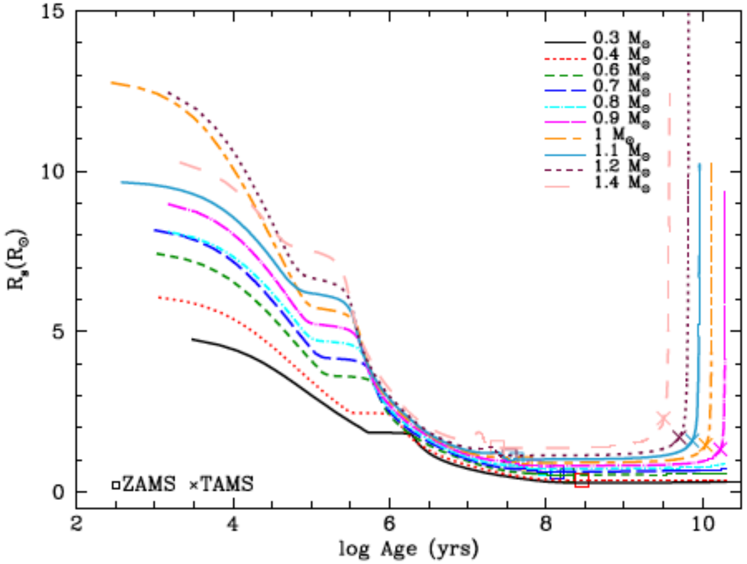
$$\alpha = \frac{R_c}{R_s},\quad \beta = \frac{M_c}{M_s} \quad \text{and} \quad \gamma = \frac{\rho_e}{\rho_c} = \frac{\alpha^3(1-\beta)}{\beta(1-\alpha^3)} < 1.$$ structure

$$\epsilon^2 \equiv \left(\Omega/\sqrt{\mathcal{G}M_s/R_s^3}\right)^2 = (\Omega/\Omega_c)^2 \ll 1$$ rotation

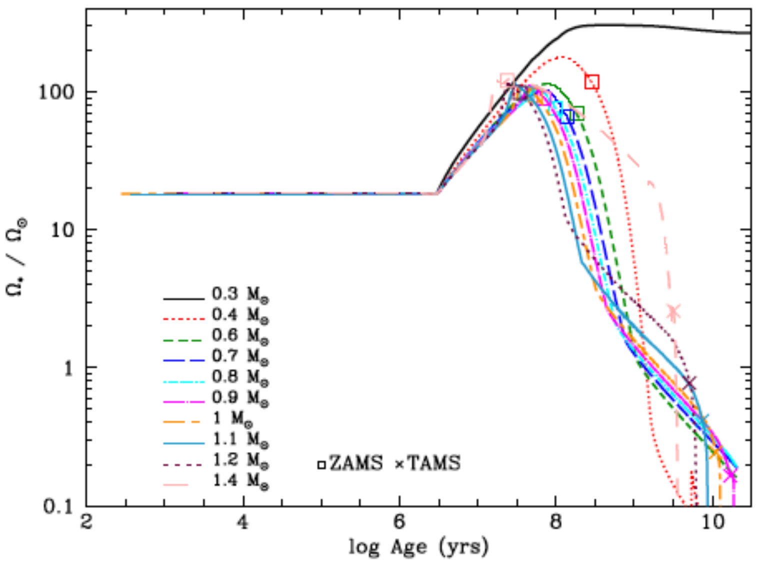
Ogilvie 2013; Mathis 2015

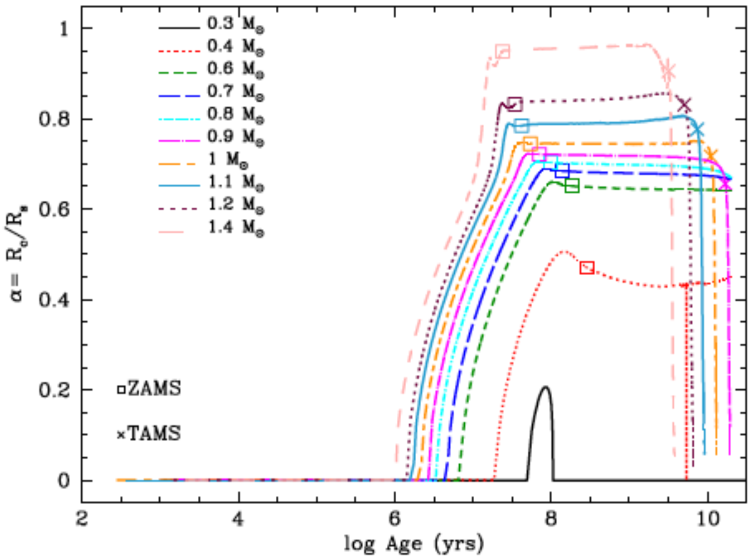
The evolution of key structural and dynamical parameters

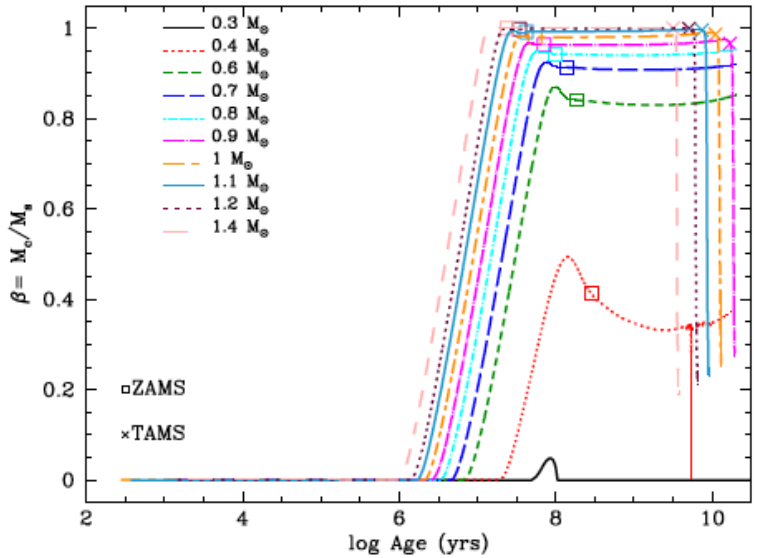
Total radius



Global rotation



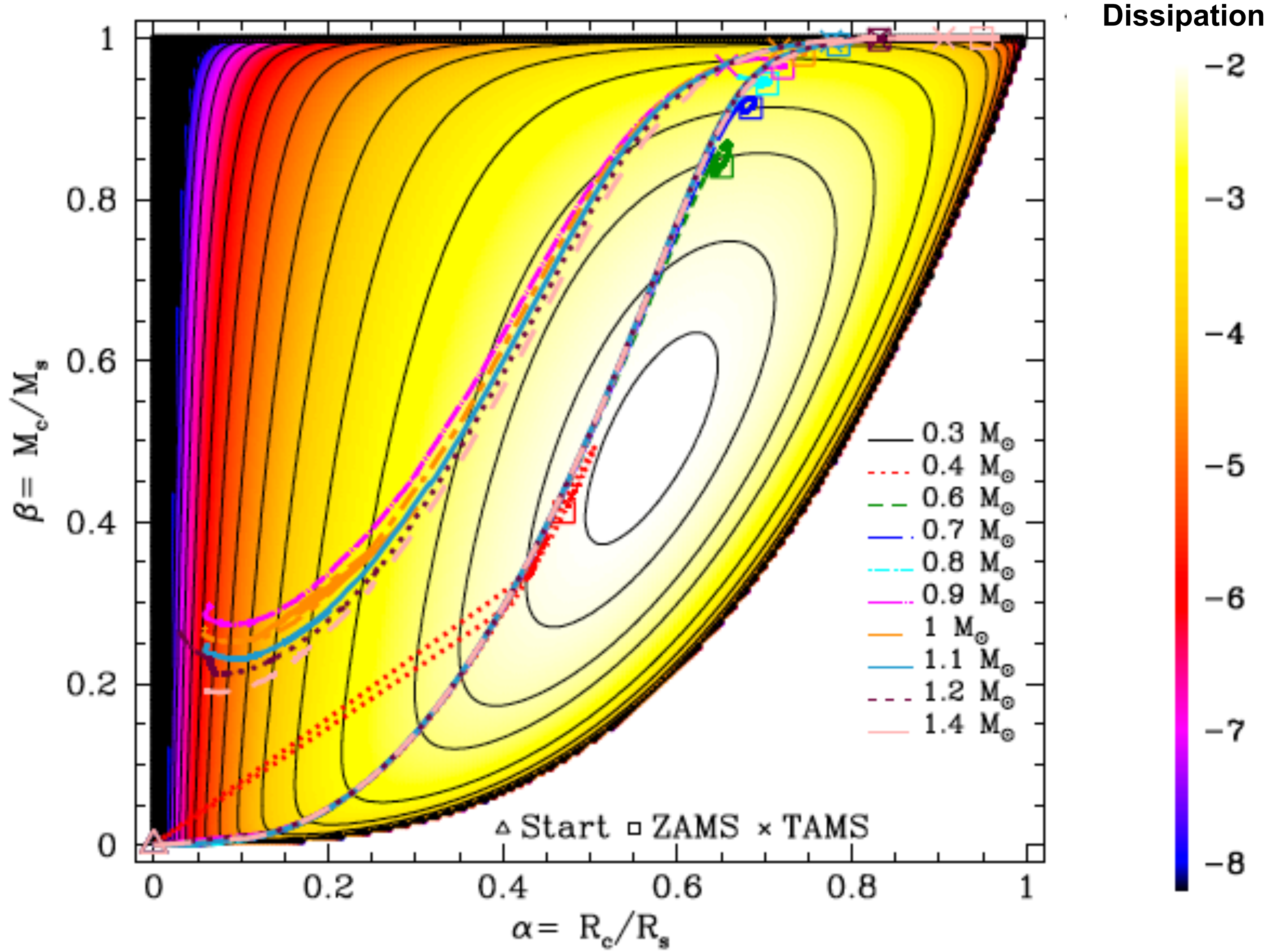




Mathis 2015; Gallet, Bolmont, Mathis, Charbonnel & Amard 2016

Aspect ratios: radius & mass

The tidal H-R diagram



Mathis 2015; Gallet, Bolmont, Mathis, Charbonnel & Amard 2016

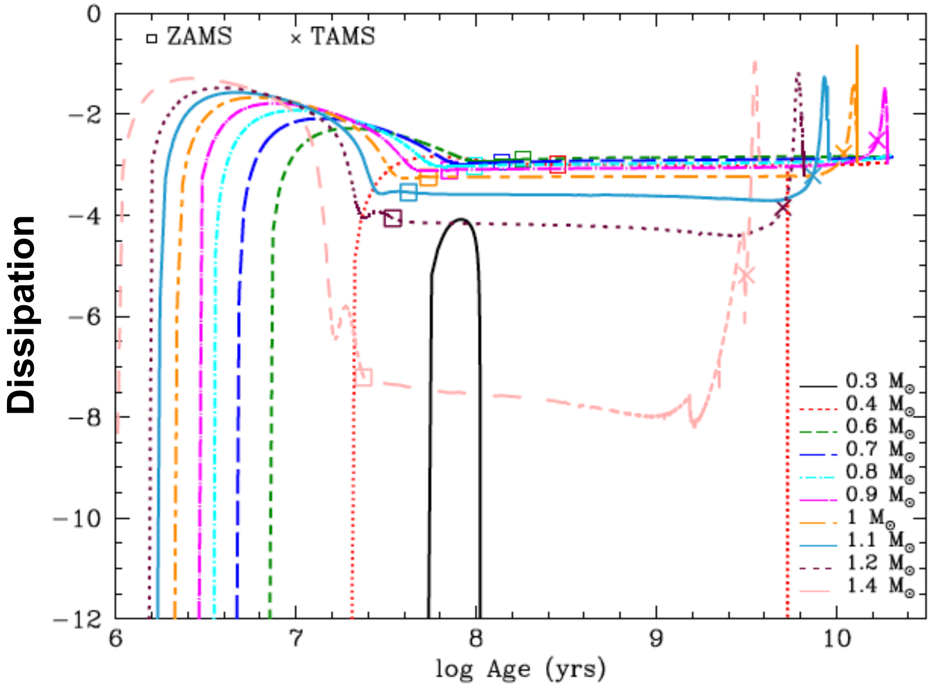
Grids of tidal dissipation for star-planet and multiple star systems

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

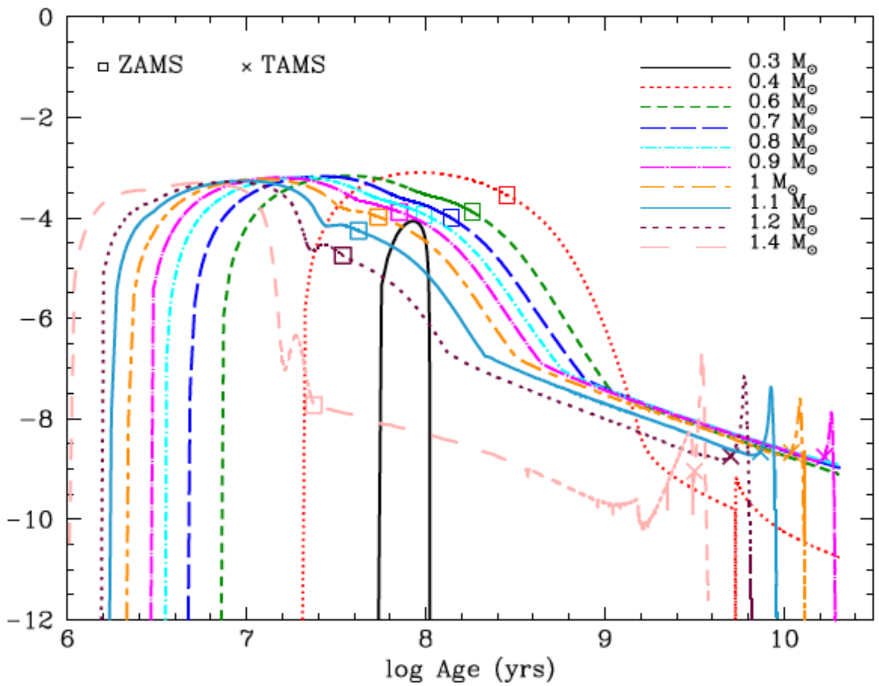
→ Stronger Dynamical Tide along the Pre-Main-Sequence and Sub-Giant phases

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

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



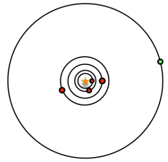
Structural evolution



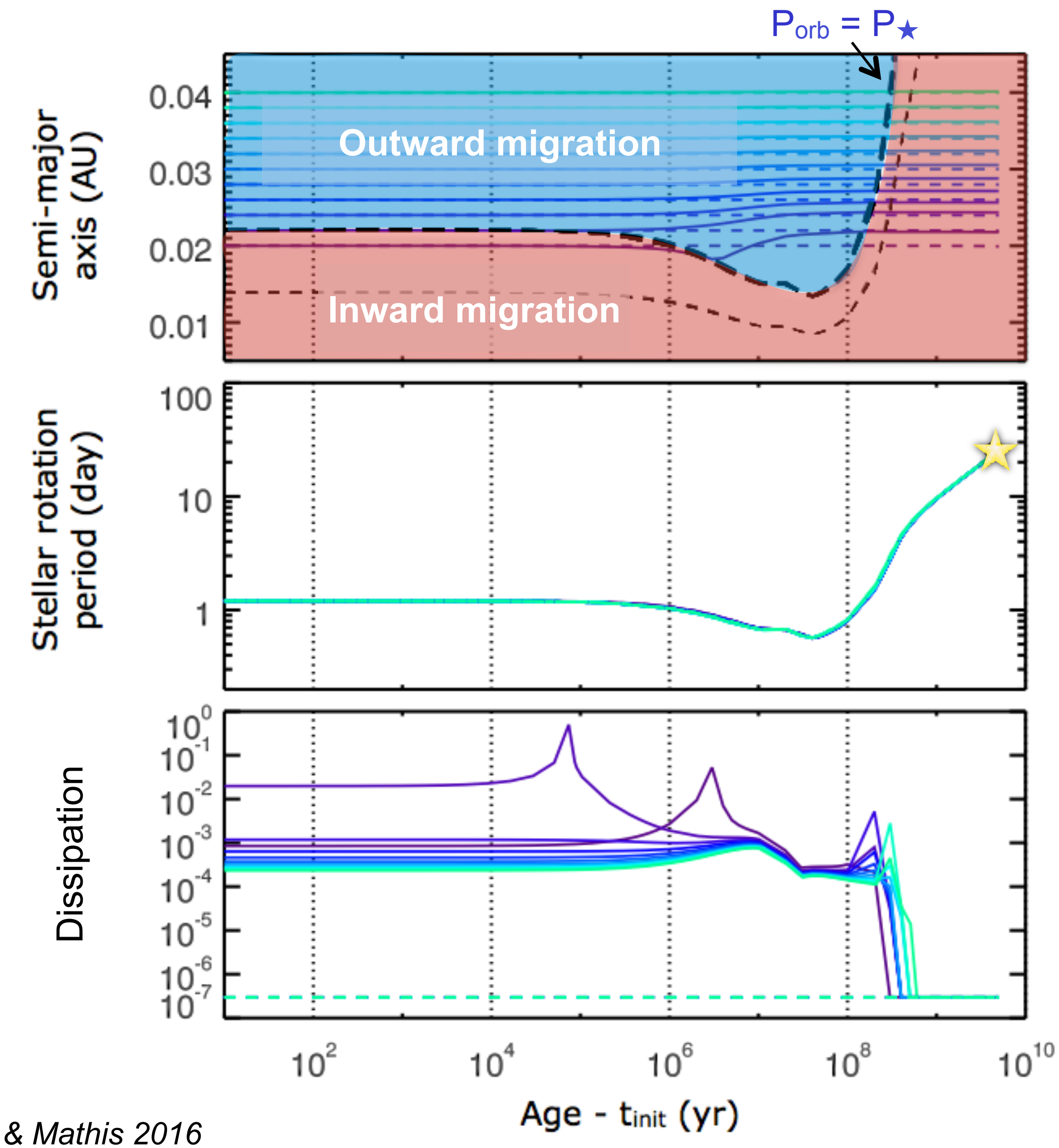
Structural & rotational evolutions

Mathis 2015; Gallet, Bolmont, Mathis, Charbonnel & Amard 2016

Star-planet systems dynamical evolution (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

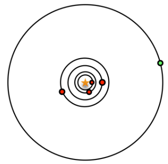
$M_p = 1\ M_\oplus$

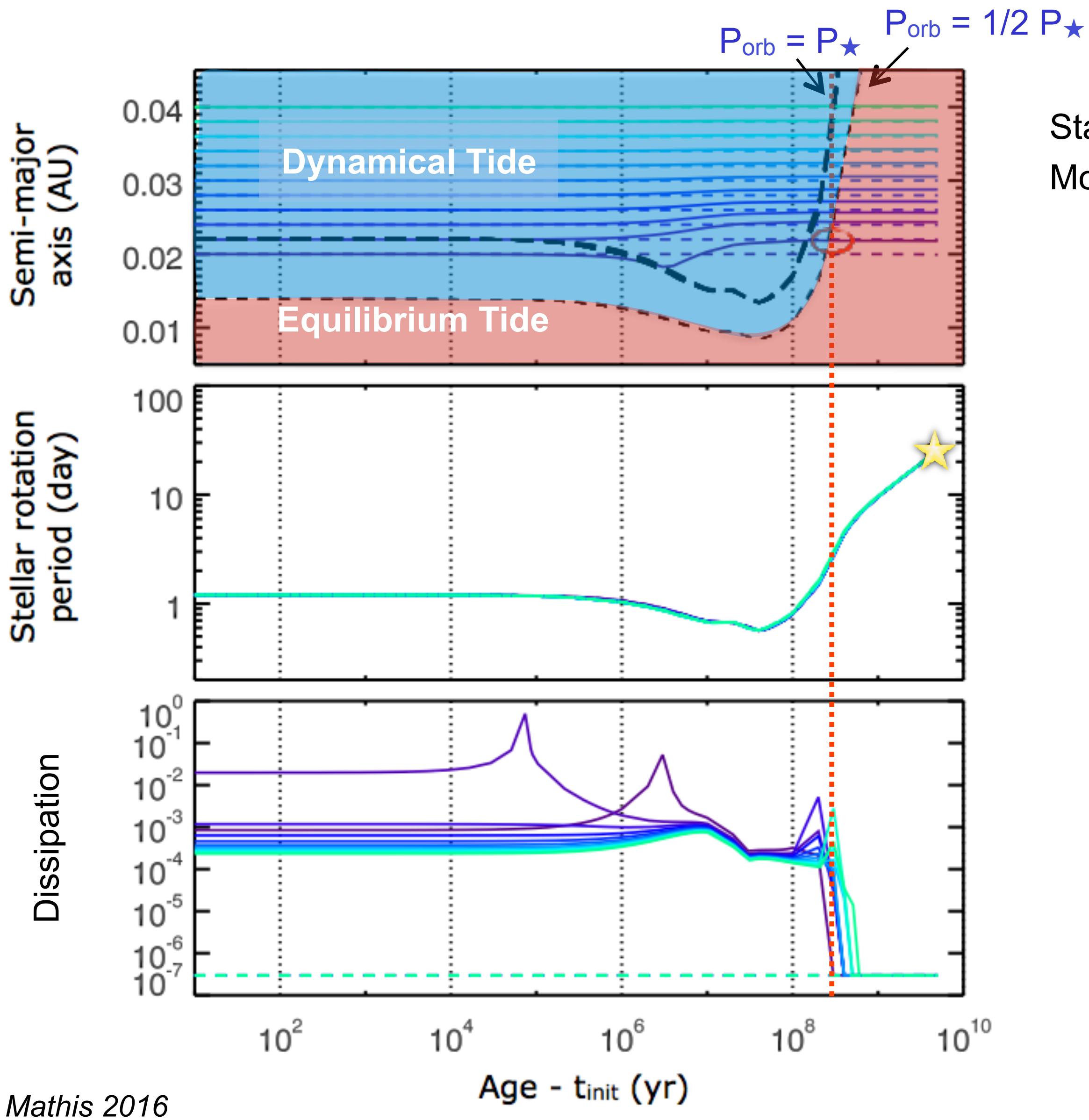
$M_\star = 1\ M_\odot$

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

Bolmont & Mathis 2016

Star-planet systems dynamical evolution (II)





Standard model

Model Bolmont & Mathis

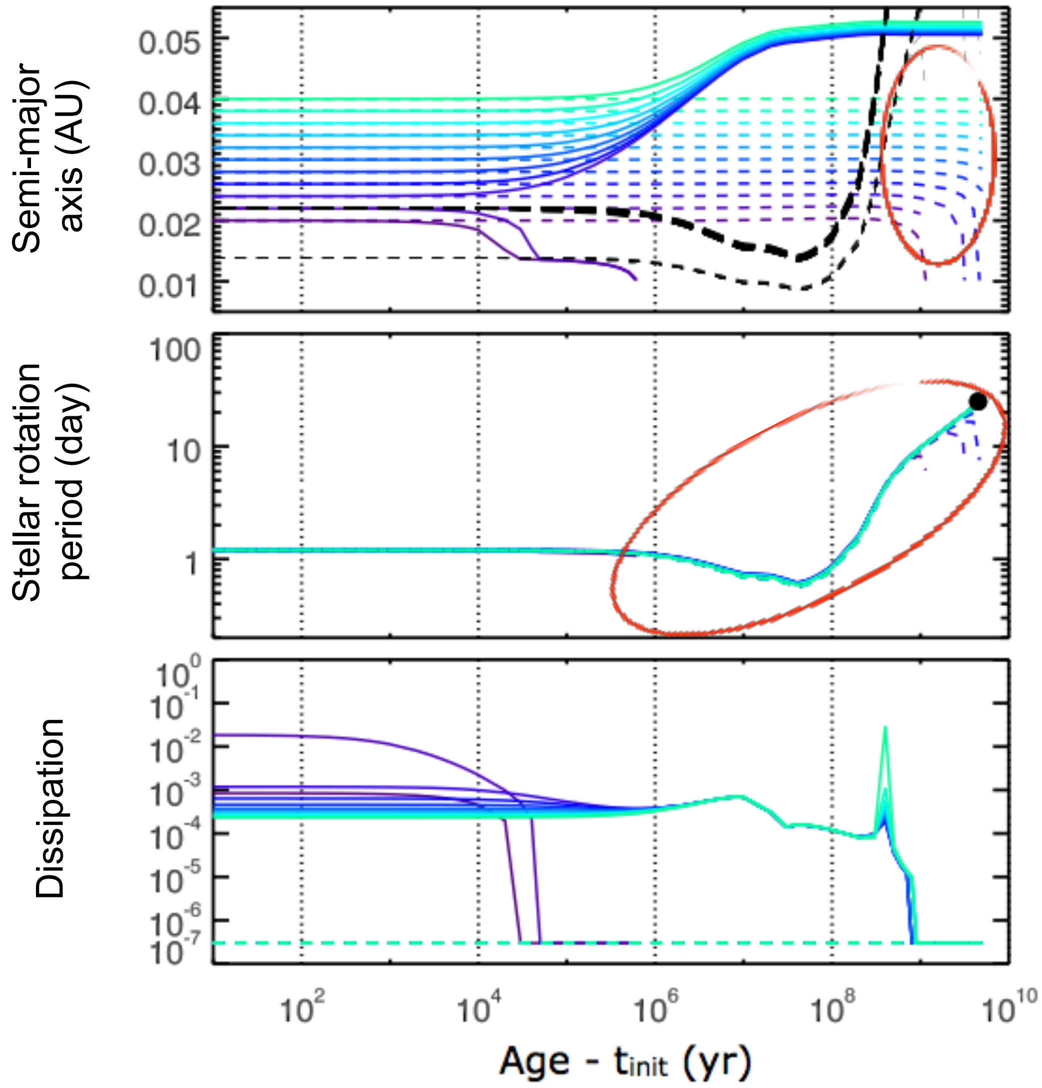
$M_p = 1\ M_\oplus$

$M_\star = 1\ M_\odot$

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

Bolmont & Mathis 2016

Star-planet systems dynamical evolution (III)



Standard model

Model Bolmont & Mathis

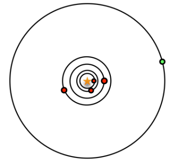
$M_p = 1\ M_{jup}$

$M_\star = 1\ M_\odot$

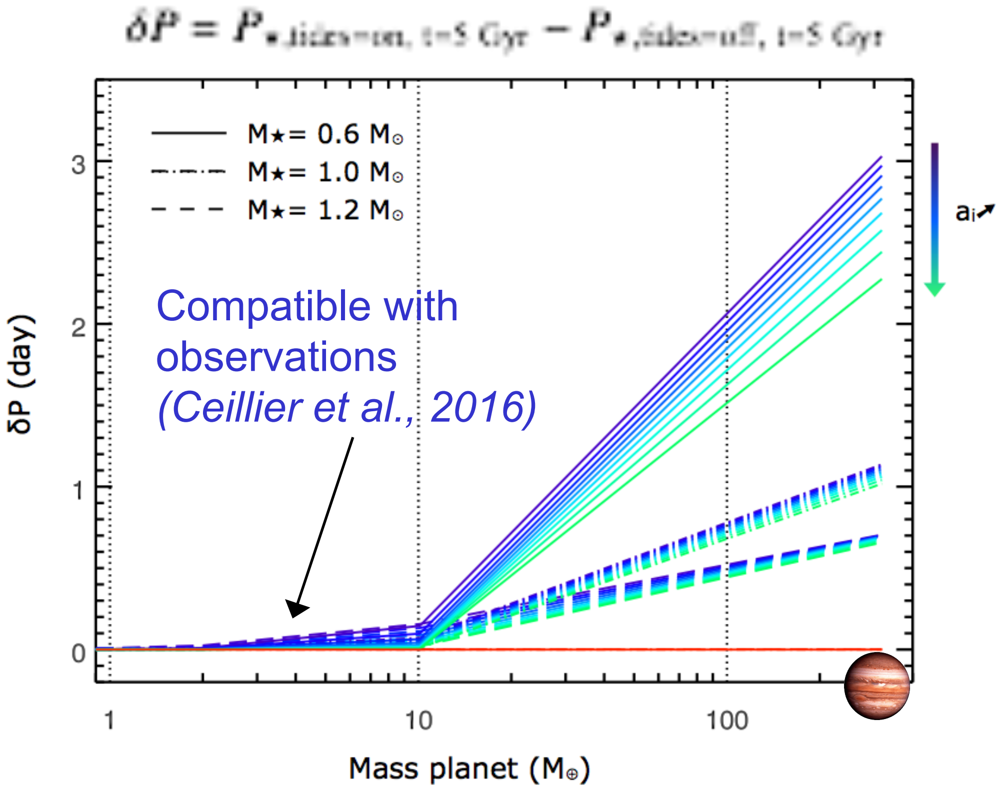
$P_{\star,i} = 1.2$ day

Bolmont & Mathis 2016

Impact on stellar rotation (I)



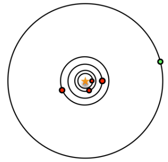
$P_{\star,i}$ = 1.2 day



All planets here migrate outwards → the star spins down

Bolmont & Mathis 2016

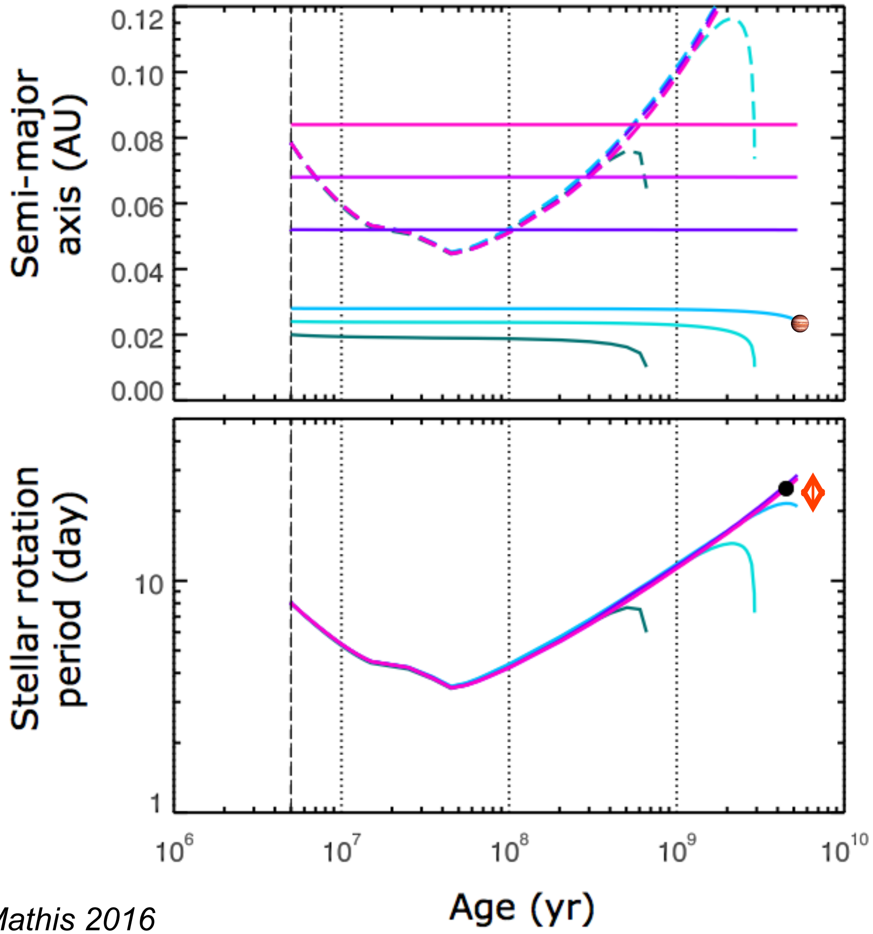
Impact on stellar rotation (II)



$M_\star = 1\ M_\odot$

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

$M_p = 1\ M_{jup}$



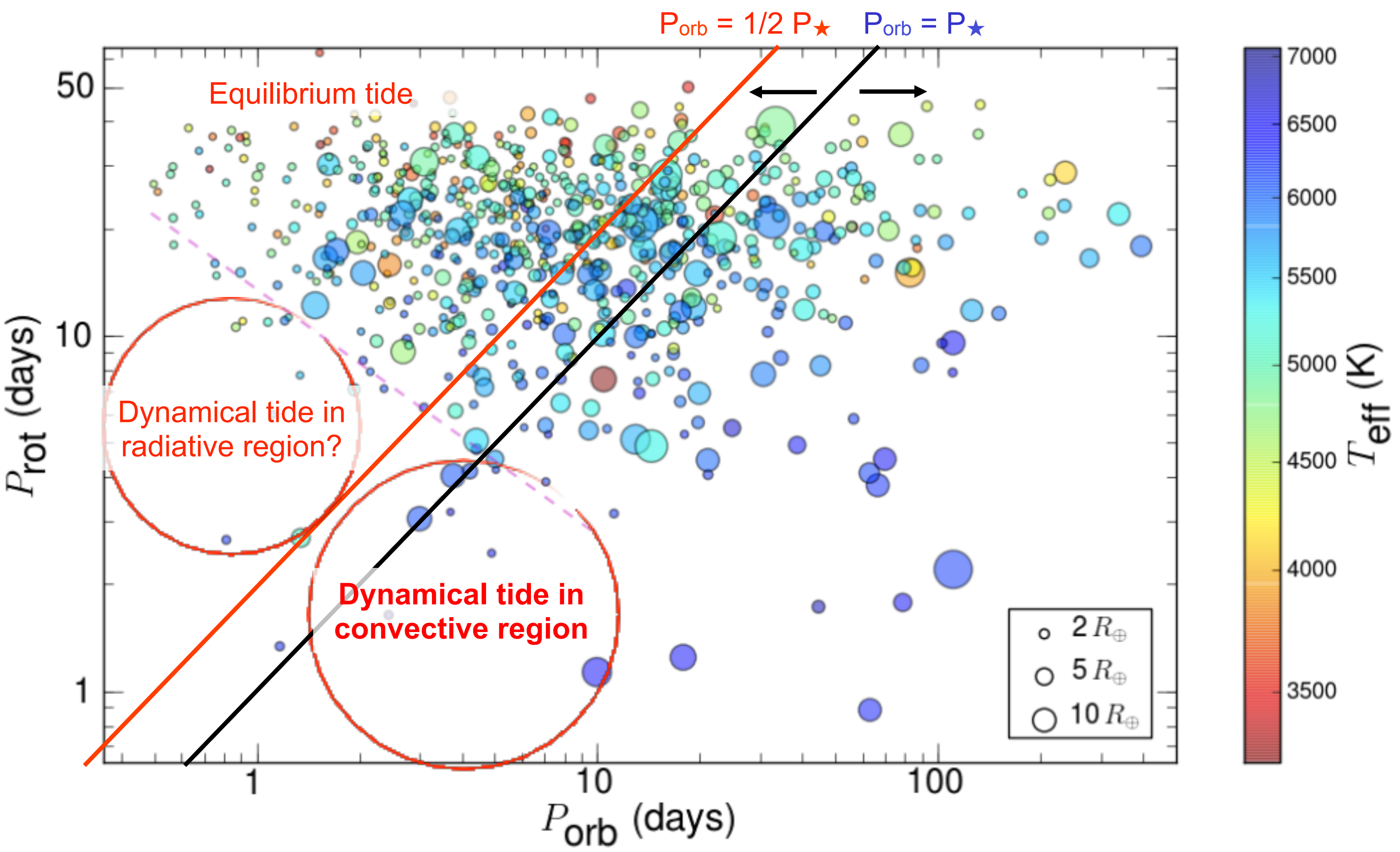
Planets migrate inwards
→ the star spins up

➡ Rotation excess: star initially slow rotator

➡ Rotation deficiency: star initially fast rotator

Bolmont & Mathis 2016

Understanding hot-Jupiters systems



McQuillan et al. 2013

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