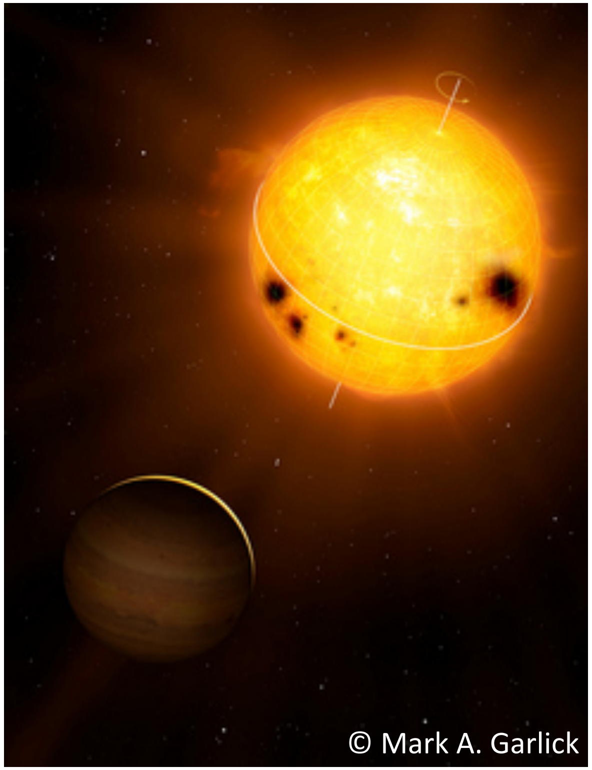
DDays – July 1st & 2nd, 2015

- Mathieu Guenel (IRFU/SAp, LDEE)
- Curriculum : ENSTA ParisTech (engineering « grande école ») + Master M2S (Modélisation et Simulation)
- Advisor : Stéphane Mathis
- Why am I here ? General taste for astrophysics + analytical and numerical modelling of complex physical processes

DDays – July 1st & 2nd, 2015

- Integrated study of the dynamics of stars and their planetary systems

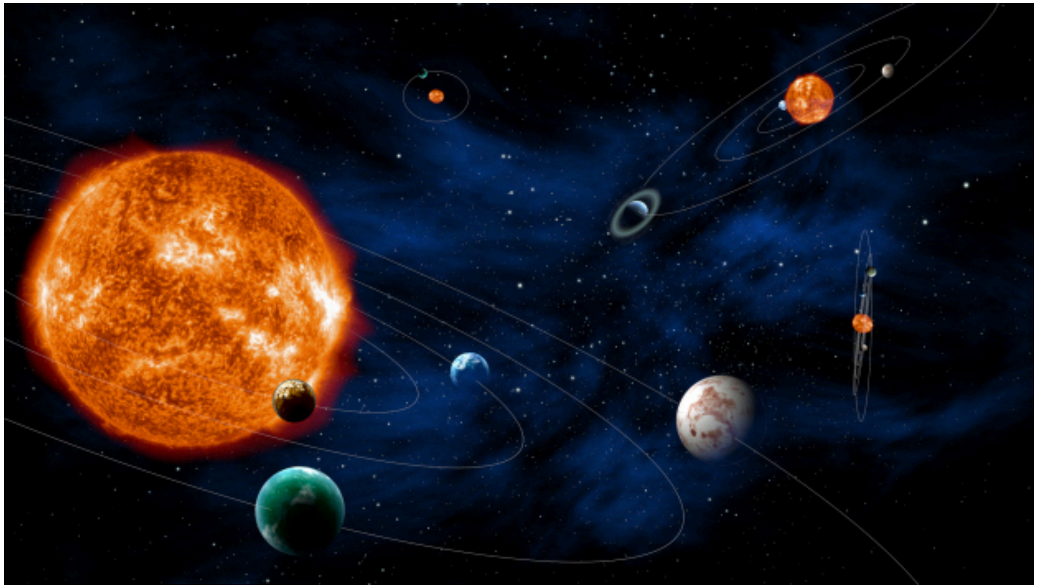
- Tides, energy exchanges/dissipation
- Internal structure, hydrodynamics
- Star-planet systems, dynamical evolution
- Observational constraints
  - Kepler, SPIRou, PLATO, TESS



Outline

- Introduction
  - Astrophysical motivations
  - How do tides work ?
- Master thesis : tidal dissipation in gaseous giant planets
  - Role of the internal structure
- Tidal inertial waves in differentially-rotating convective envelopes of low-mass stars
  - What are inertial waves ?
  - New families of free oscillation modes
  - Perspectives and ongoing work

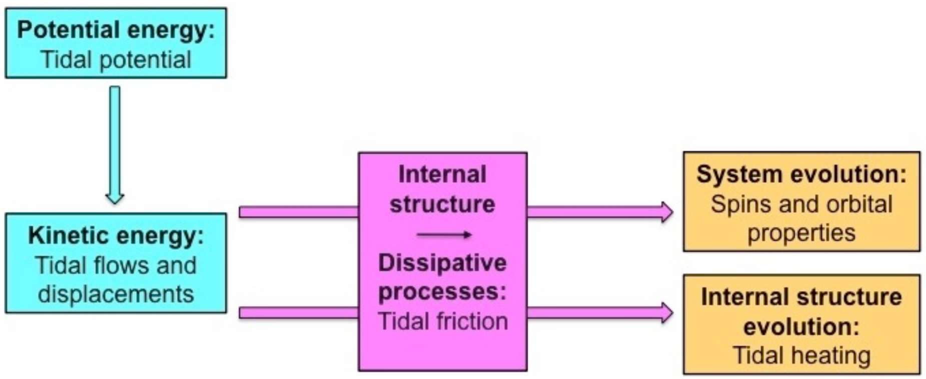
Dynamics of star-planet systems



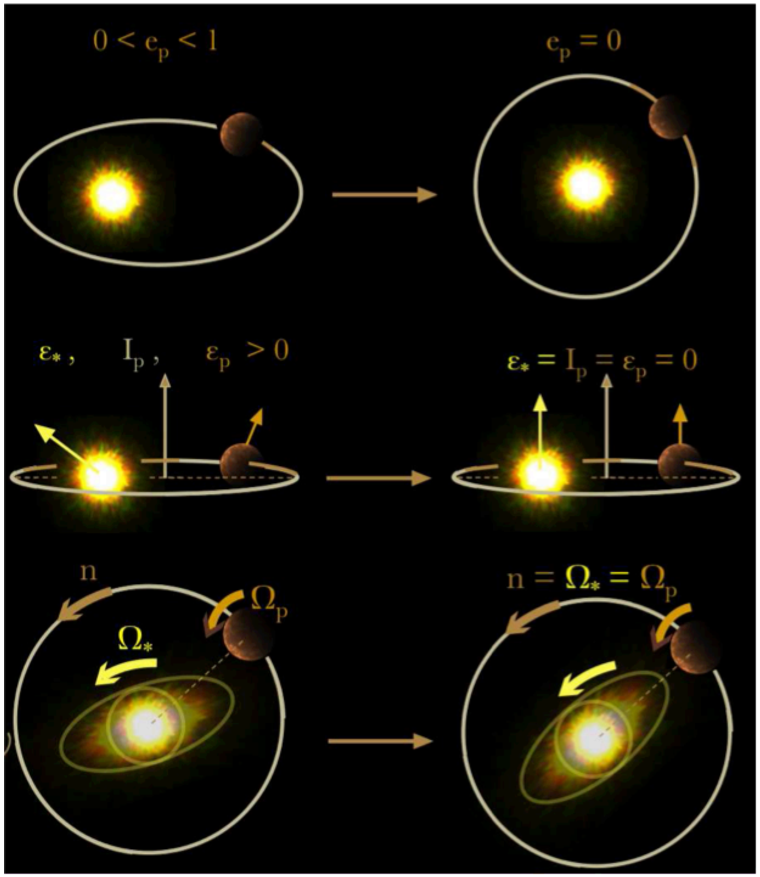
- A large diversity of planetary systems around many different kinds of host stars
- We want to understand their dynamical evolution as a whole, taking into account
  - Internal structure and dynamical properties of celestial bodies
  - Angular momentum and energy exchanges

→ Among the possible interactions, we focus on tidal interactions
→ For MHD interactions, cf. Victor Réville's talk this morning

Tidal evolution



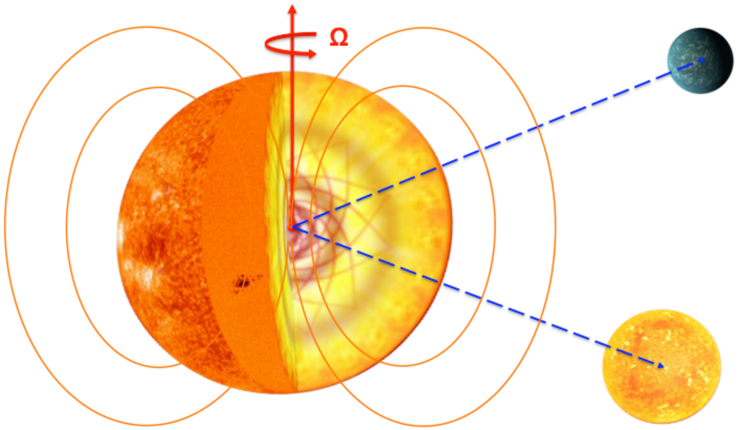
Mathis & Remus (2013)



F. Remus (2013)

Physical modelling of tidal torques

- State of the art : stars are treated with simplified structure models (two layers, purely 1D) with ad-hoc prescriptions for tidal effects : angular momentum exchanges / energy dissipation
- However, the complex internal structure and dynamics of stars impacts these mechanisms



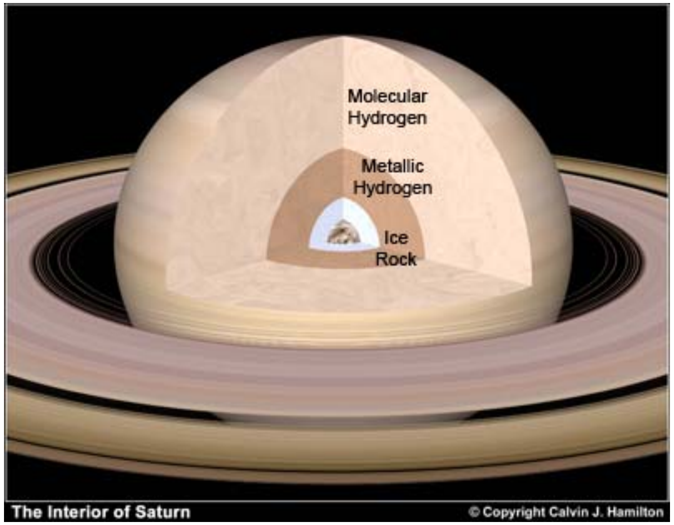
→ Need of an ab-initio physical modeling of the dynamics

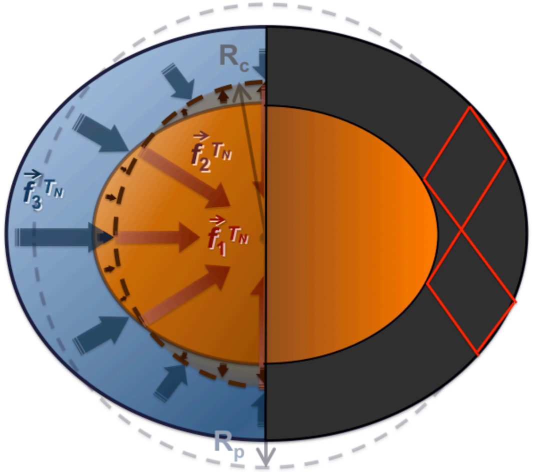
Master thesis : tidal dissipation in gaseous giant planets (1)

- Dynamics and evolution of systems with gaseous giant planets (Solar and exoplanetary systems)

- New astrometric measurements
  - Lainey et al. 2009 (Jupiter)
  - Lainey et al. 2012, 2015 (Saturn)
  - → Unexpectedly strong tidal dissipation (see F. Remus PhD)

- 2 candidates
  - Dissipation in the anelastic core
  - Viscous dissipation of inertial waves (Coriolis) in the deep envelope
  - → Which one is the most important ?

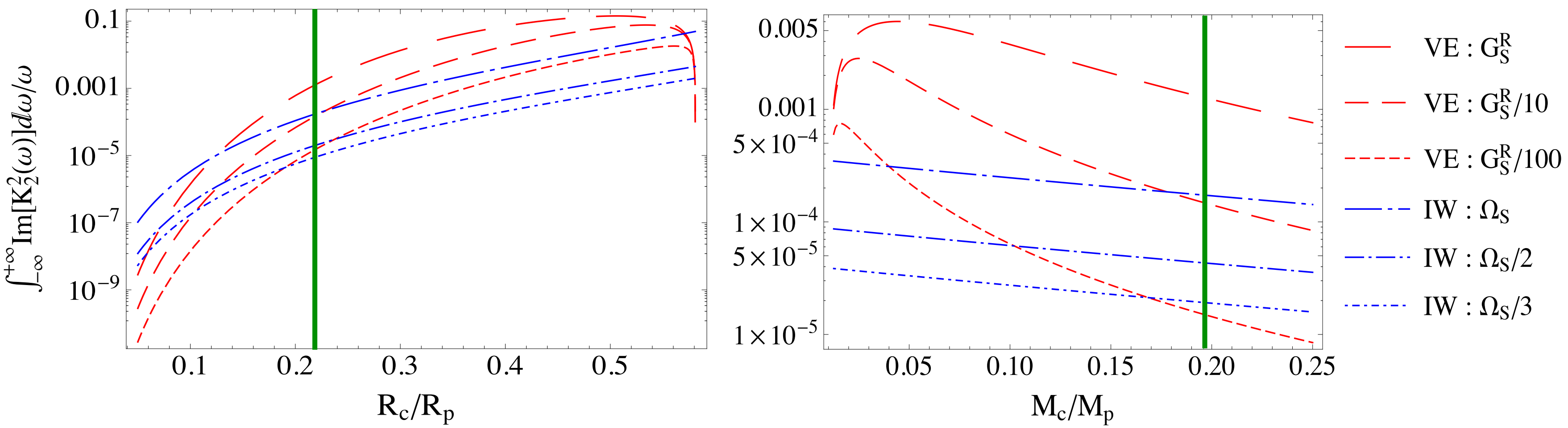




Guenel et al. (2014)

Master thesis : tidal dissipation in gaseous giant planets (2)

- Comparison of the two dissipation mechanisms in a Saturn-like planet :



- They differ by at most one order of magnitude
  → Both mechanisms have to be taken into account

- Similar results for Jupiter-like and extrasolar gaseous giant planets
  → Guenel et al. 2014, A&A, 566, L9

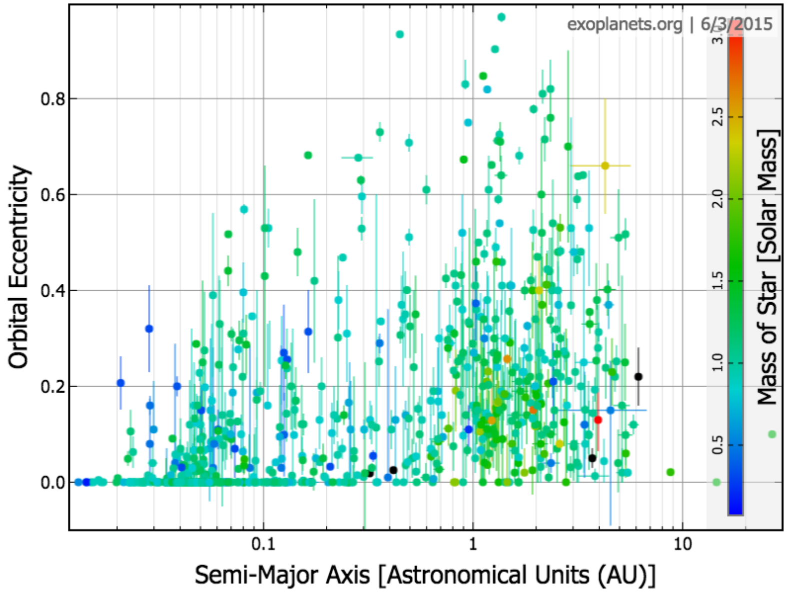
What about tidal dissipation in the host star ?

Dynamical evolution of stars hosting planetary systems

- Tidal star-planet interactions :
  - Impact the architecture of the system : migration, circularization, alignment (Davies et al. 2015, Pont 2009)
  - Modify stellar rotational dynamics :

  tidal torques → synchronization

- Tidal dissipation in host stars
  - Strongly impacts the dynamics of short-period systems
  - Varies over several orders of magnitude (stellar mass, age, rotation) : often roughly parametrized



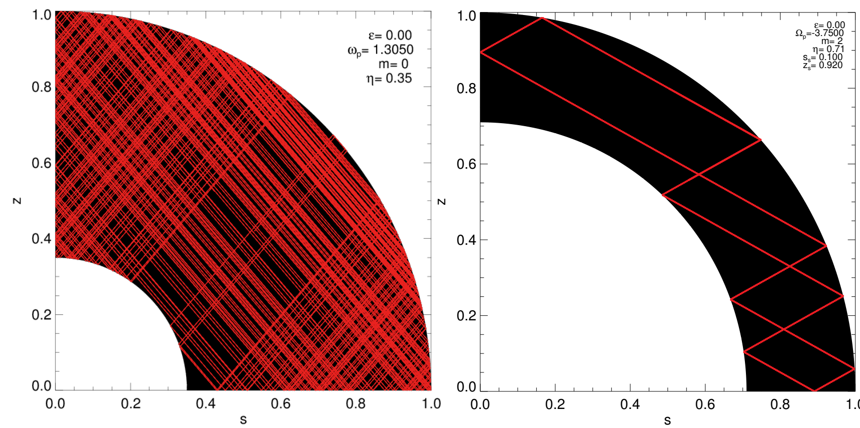
Observational constraints : transits and radial velocities
CoRoT, Kepler, HARPS, CHEOPS, TESS, SPIRou, PLATO

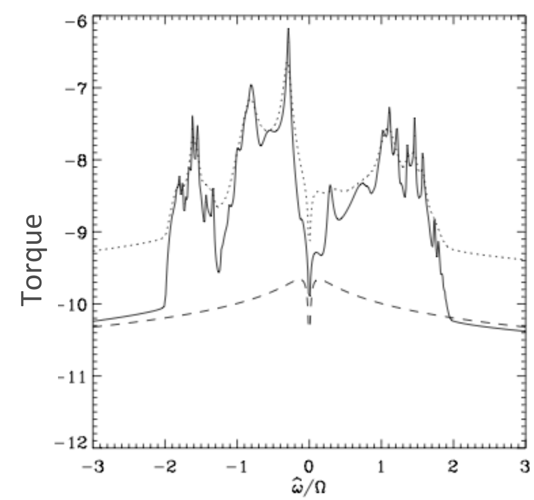
→ Need for a realistic *ab initio* modelling of tidal dissipation in stellar convective zones

Key mechanism : inertial waves in convective zones

- Solid-body rotation : $\frac{\partial \vec{u}}{\partial t} + 2\vec{\Omega} \times \vec{u} = -\nabla P_{eff}$
  - Balance between the Coriolis acceleration, pressure gradient and gravity
  - Transverse waves :
    - Doppler-shifted frequency is in [-2Ω, 2Ω],
    - propagate in the whole convective region along straight rays
  - For given parameters, the kinetic energy of the mode could concentrate and be efficiently dissipated around sheared structures which follow attractor cycles

→ Resonant dissipation varying over orders of magnitude for low viscosities

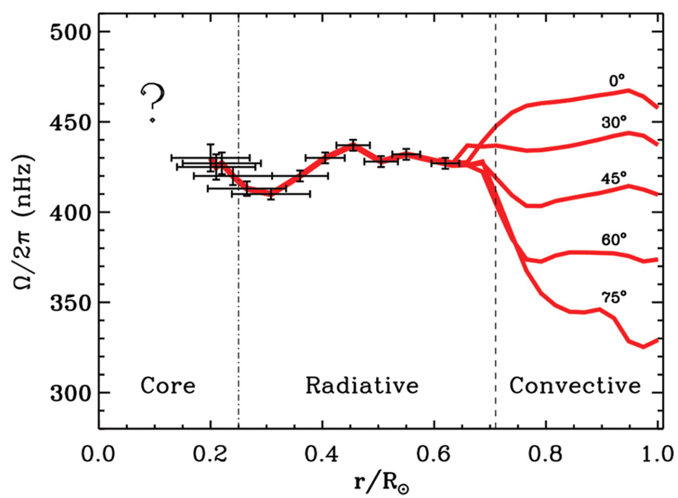




Ogilvie & Lin 2007

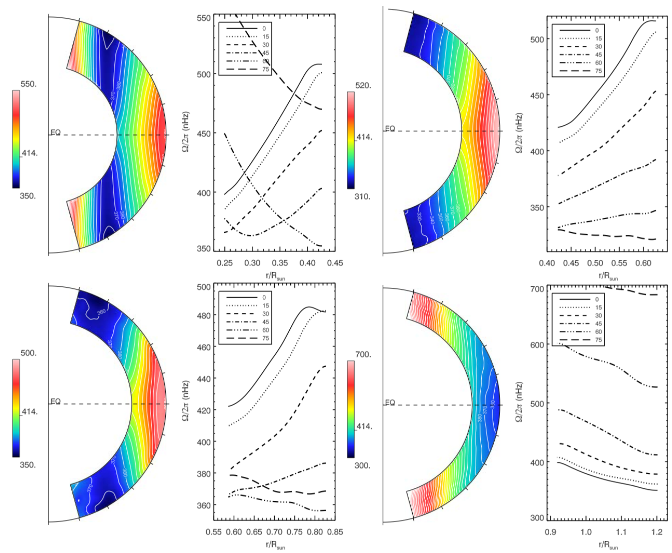
Differential rotation of low-mass stars

- Helioseismic observations



Garcia et al. 2007

- Simulations



Matt et al. 2011; Gastine et al. 2014

- Differential rotation strongly modifies inertial waves : *e.g.* Baruteau & Rieutord (2013) for cylindrical and shellular rotation profiles

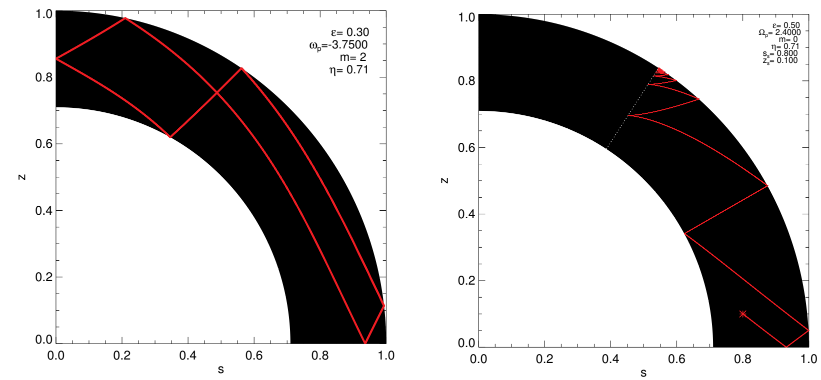
→ In stars, inertial waves in conical differential rotation have to be studied
→ Methodology : understanding the complex behavior of free modes before studying the tidal forced regime

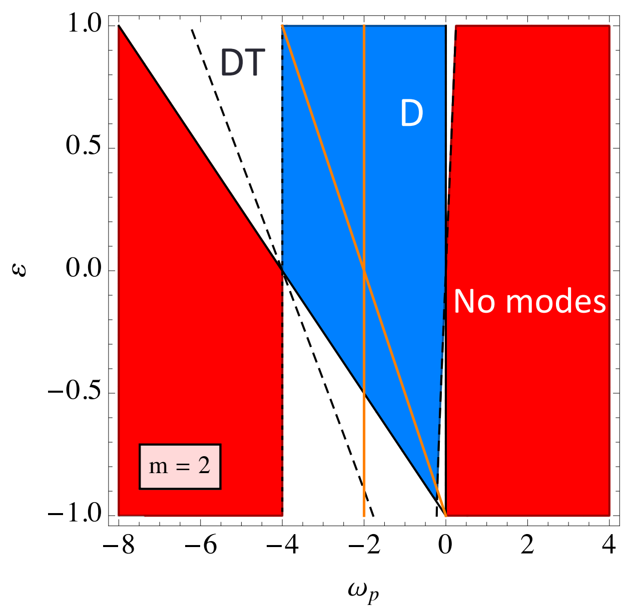
Free inertial waves in conically differentially rotating convective zones : inviscid analysis

- Conical rotation profile :

$$\Omega(\theta) = \Omega_{\text{ref}} \left(1 + \varepsilon \sin^2 \theta\right)$$

- Analytics shows that new features appear :
  - Paths of characteristics are curved and depend on azimuthal wavenumber m
  - They may still converge towards attractor cycles or focus towards a wedge (Dintrans & Rieutord 1999)
  - Turning surfaces : boundary between hyperbolic and elliptic domains (trapping)
  - Corotation layers (m≠0) : the Doppler shifted wave frequency vanishes



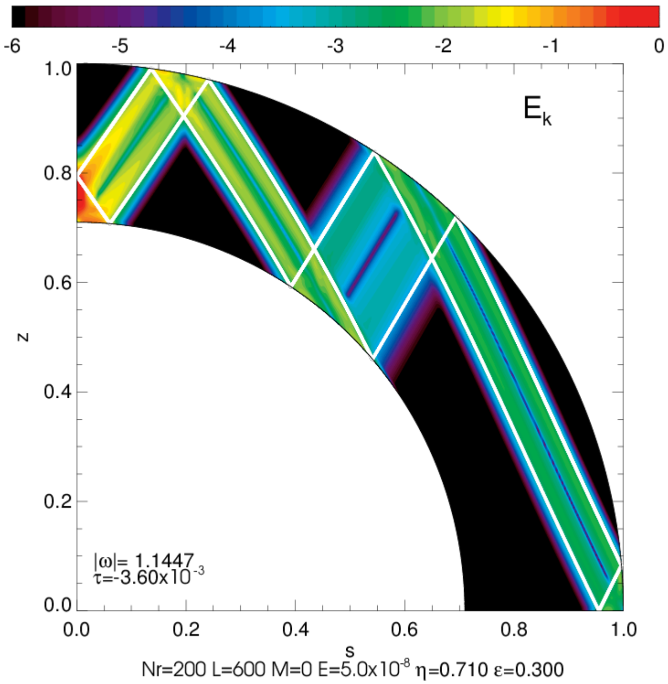


Viscous dissipation induced by waves (important for tides) → need to treat the viscous problem

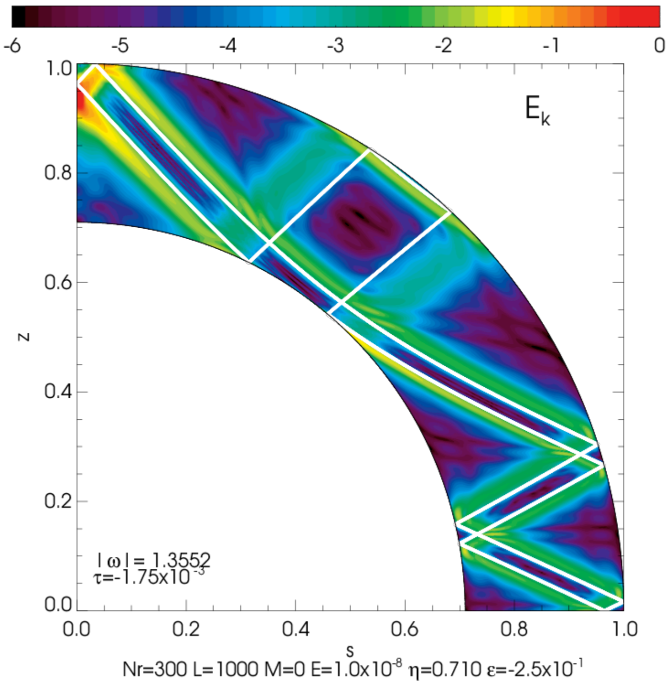
D modes

- Method : numerical simulations using the LSB linear solver after analytical projection of the equations on vectorial spherical harmonics (Rieutord 1987, Baruteau & Rieutord 2013)

- Curved propagation in the whole shell
- Overall properties similar to the solid-body rotation case



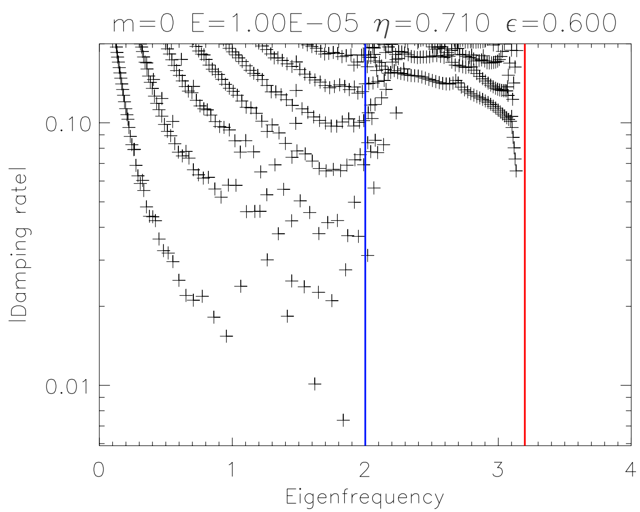
Solar case

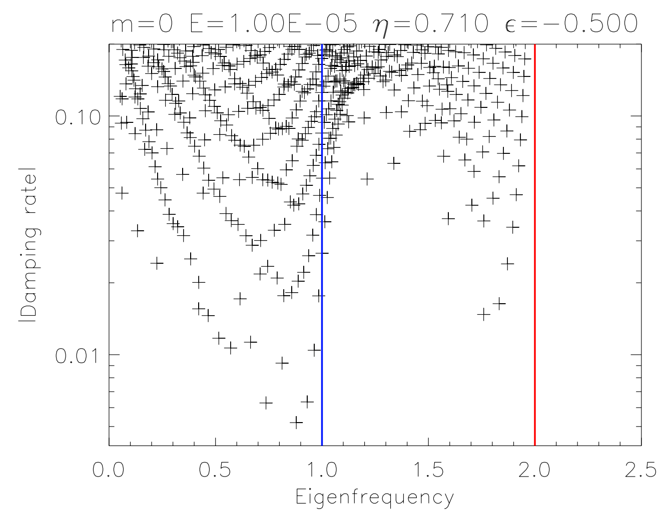


Anti-solar case

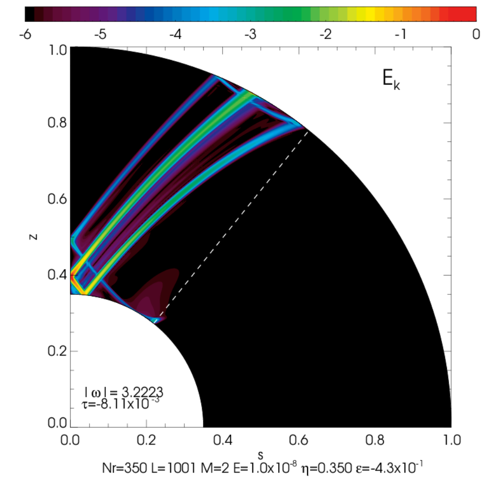
Existence and behavior of DT modes ?

Population diagrams : resonant DT modes seem to be less common than D modes for all m



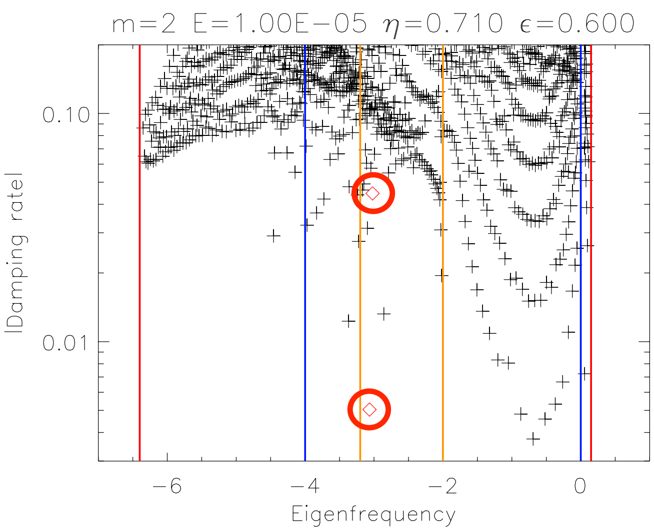


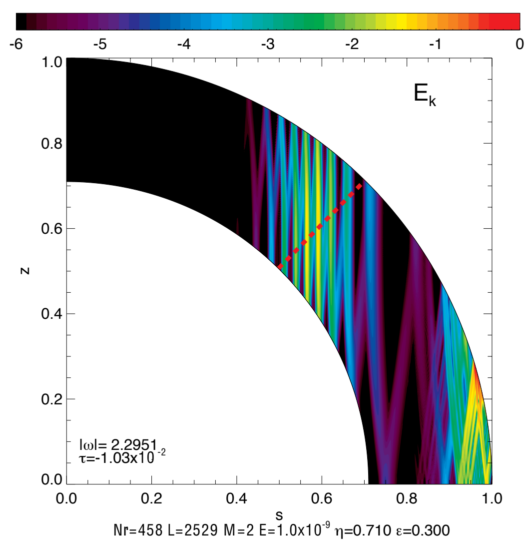
- Strongly differ from the solid-body rotation case : latitudinal trapping
- For m=0, DT modes preferably appear with anti-solar rotation ($\epsilon < 0$)
- The situation is more complex for m ≠ 0



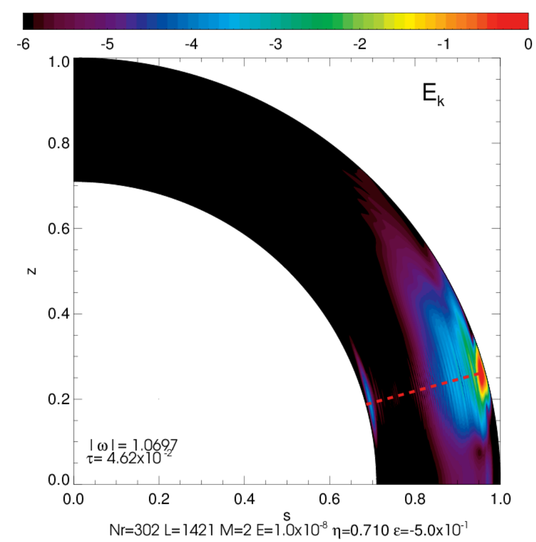
Non-axisymmetric modes & corotation resonances

- When m ≠ 0, the Doppler-shifted frequency may vanish inside the domain → corotation resonance





Stable



Unstable

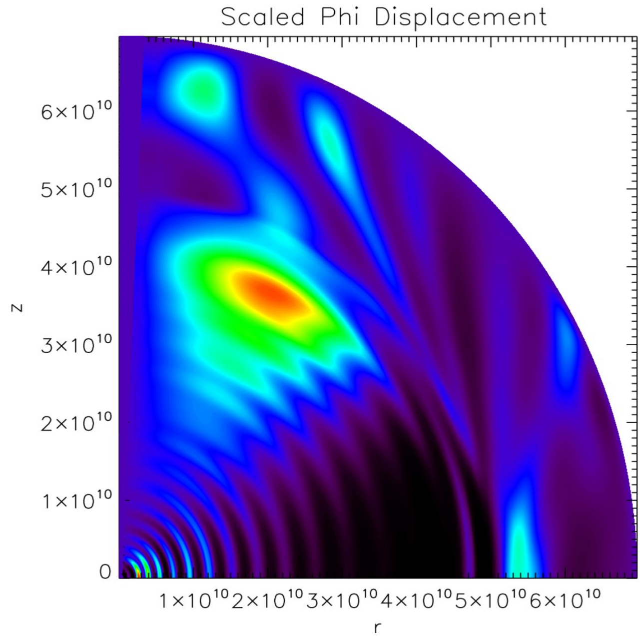
- Complex behavior : valve effect / instabilities that require a dedicated study (local model for corotation layers)

→ Guenel et al. 2015 (A&A, to be subm.)

Perspectives and ongoing work

- Forced regime : computation of tidal inertial waves dissipation spectra as a function of stellar mass, age and differential rotation and excitation frequency

- Modelling of the low-frequency oscillations of an entire low-mass star, including the stably-stratified radiative core.



Chernov et al. 2013

THANK YOU FOR YOUR ATTENTION !