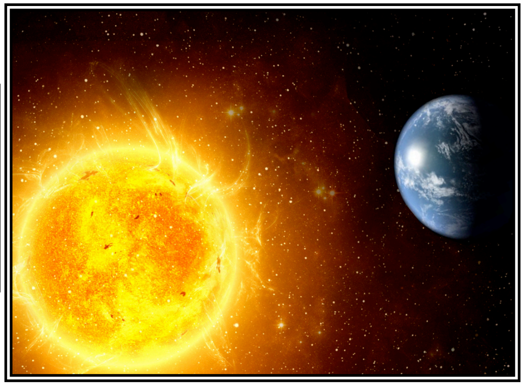
The role of star-planet interactions and binarity in stellar evolution



S. Mathis

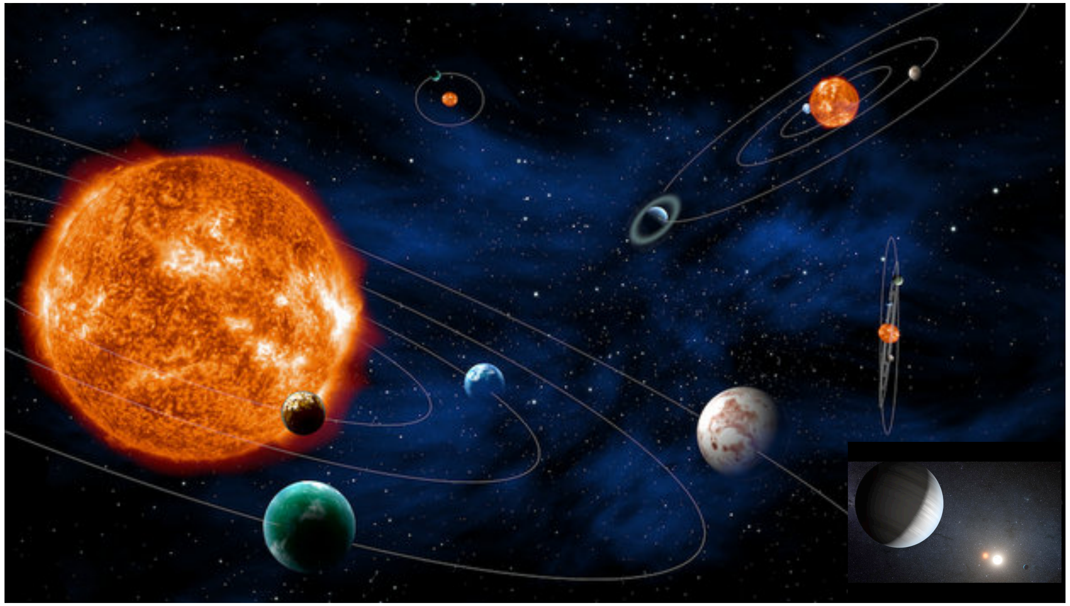
CEA/DSM/IRFU/SAp; Laboratoire AIM Paris-Saclay, CEA/DSM - CNRS - Université Paris Diderot

Laboratory Dynamics of Stars and their Environment

PNPS prospective meeting, 24 – 27 February 2014, Besançon

Binarities in stellar systems

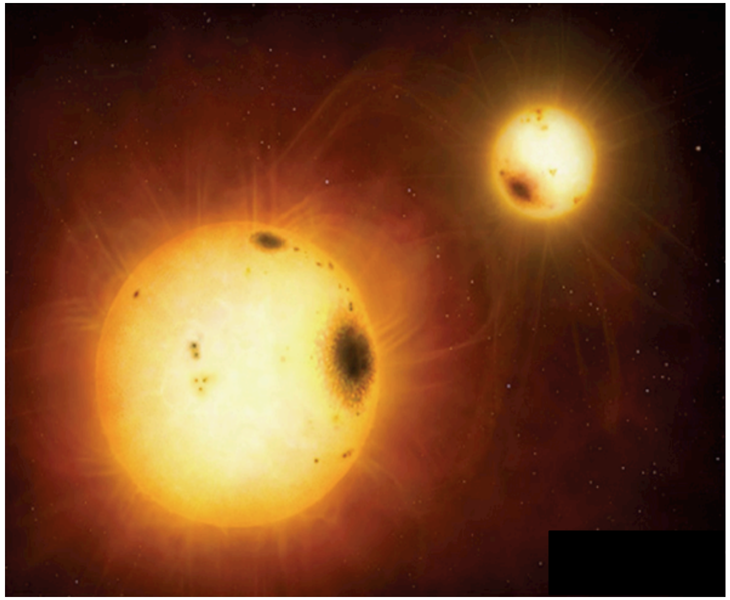
Star-planet systems



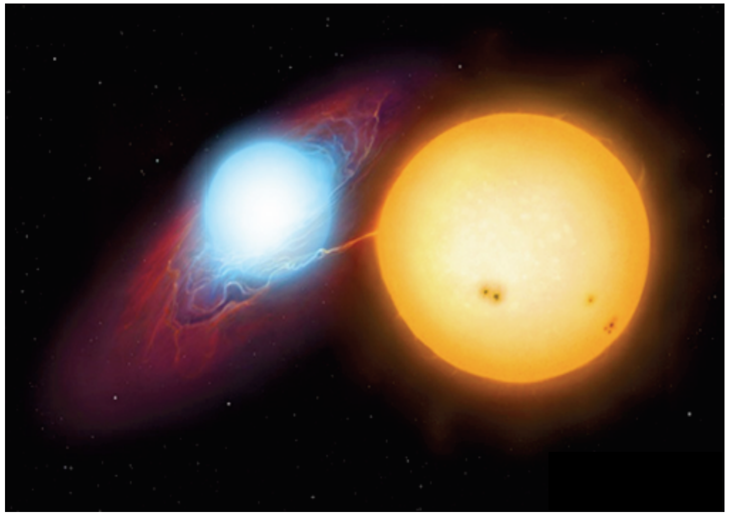
PLATO, SPIRou (*J.-F. Donati*)

Laboratory to study interactions and their impact on the evolution of stellar systems

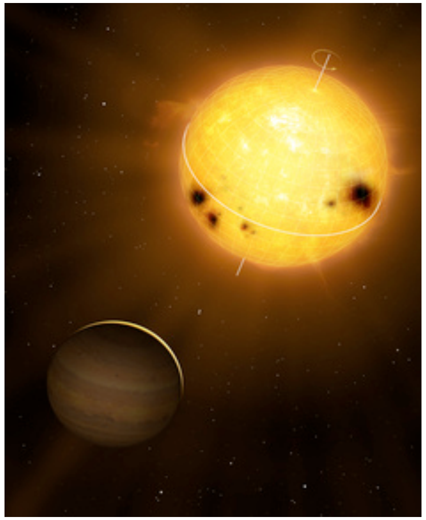
Binary stars



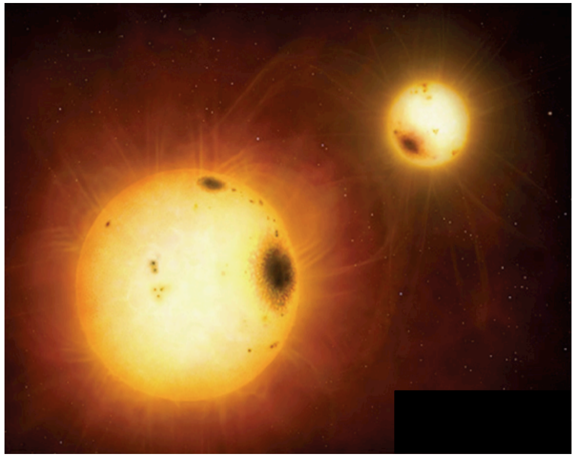
Star-compact object systems



Interactions and related torques

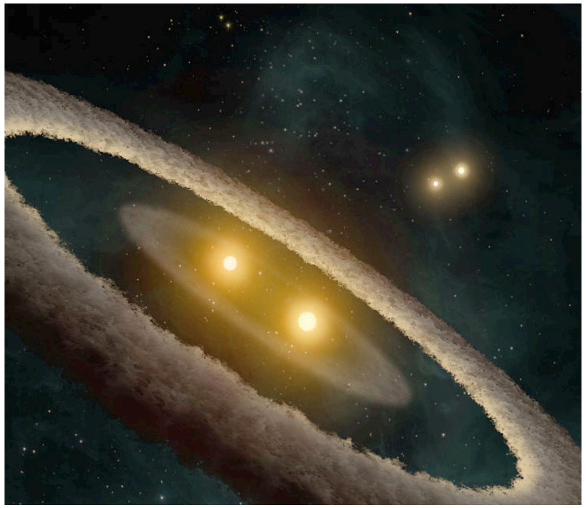


Tides (& irradiation)

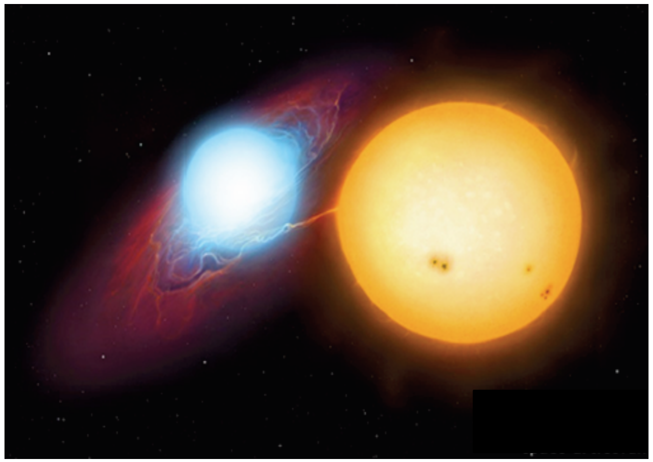


Magnetospheric interactions
& winds

Circumstellar disk



Mass transfer



→ Need to undestand each of these interactions, their couplings and their impact

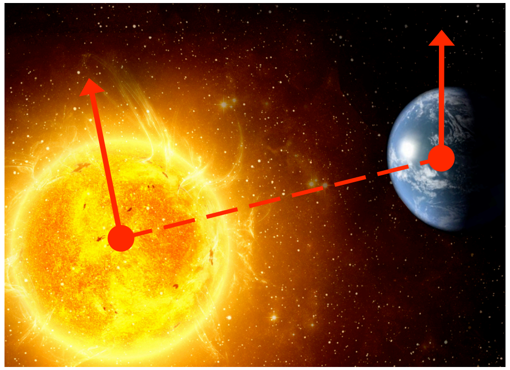
Rotational & orbital evolution of stellar systems

In studies of star-planet and multiple stars systems, bodies are often treated as point-mass objects or solids with ad-hoc prescriptions for angular momentum exchanges and torques

However the stellar internal structure impacts rotation, magnetic field and tides

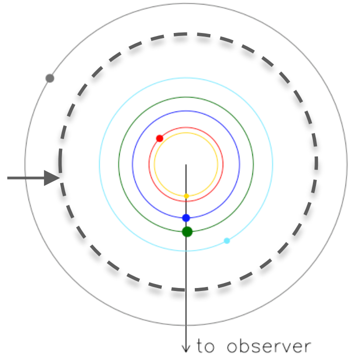
→ Need of an ab-initio physical modeling

Star-planets:



Huber et al. 2013; Chaplin et al. 2013; Gizon et al. 2013

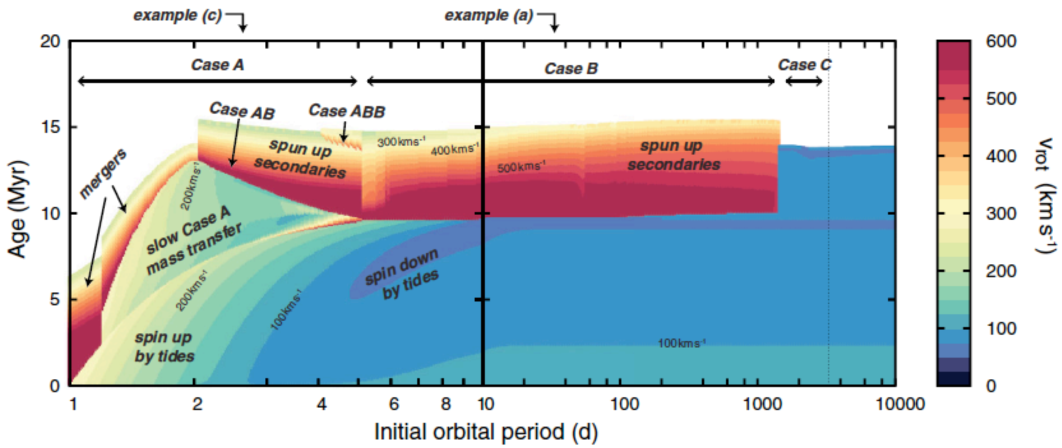
Mercury orbit



Kepler 11

Lissauer et al. 2011

Binary stars:



De Mink et al. 2013 (Siess et al. 2013; Song et al. 2013)

A first "engine" for the dynamical evolution of binary systems: the tidal energy dissipation

Tidal evolution of a binary system (e.g. *Zahn 1977*)**:**

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

- circularised orbits
- components synchronised with the orbital motion
- aligned spins

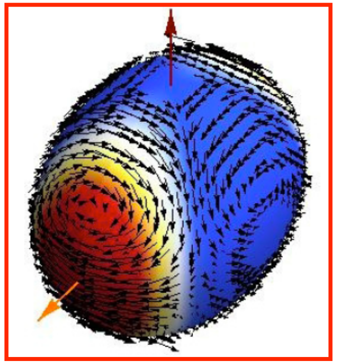
or spiraling (*Hut 1980, 1981; Levrard et al. 2009*)

→ **Necessity to identify the dissipative processes that convert the kinetic energy of tidal flows into thermic one (→ time-scales for circularisation, synchronisation ($\Omega \rightarrow B$) and alignment or of tidal migration)**

The tidal fluid velocity fields in stars

- **Equilibrium tide:** large-scale circulation induced by the hydrostatic adjustement to the tidal potential perturbation

- **Dynamical tide:** waves excited by the tidal potential (and their elliptical instabilities)



Remus, Mathis & Zahn 2012 & Zahn 1966

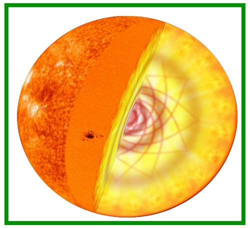
Excitation by each Fourier component of the potential

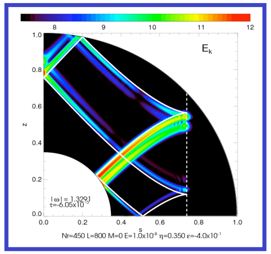
2Ω N f_L **Acoustic waves**

σ_0

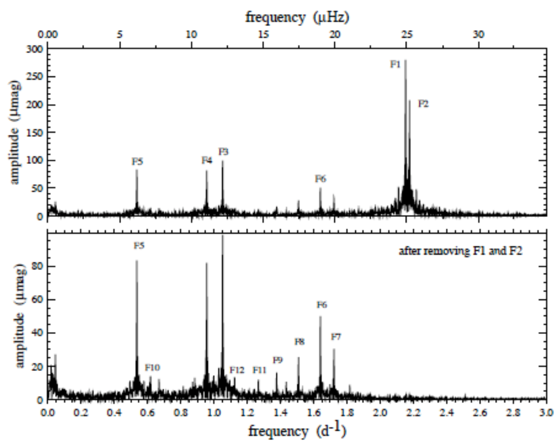
Gravito (-inertial) waves (R.Z.)

Inertial waves (C.Z.)





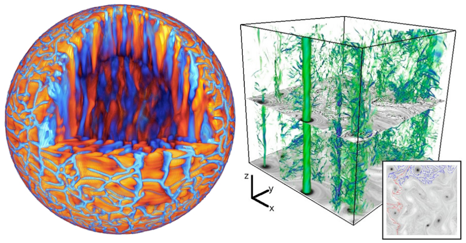
KOI-54: Welsh et al. 2011



Mathis & Remus 2013 (Zahn 1975; Rieutord & Valdetarro 2010; Mathis & de Brye 2012; Baruteau & Rieutord 2013; Jouve & Ogilvie 2013; etc.)

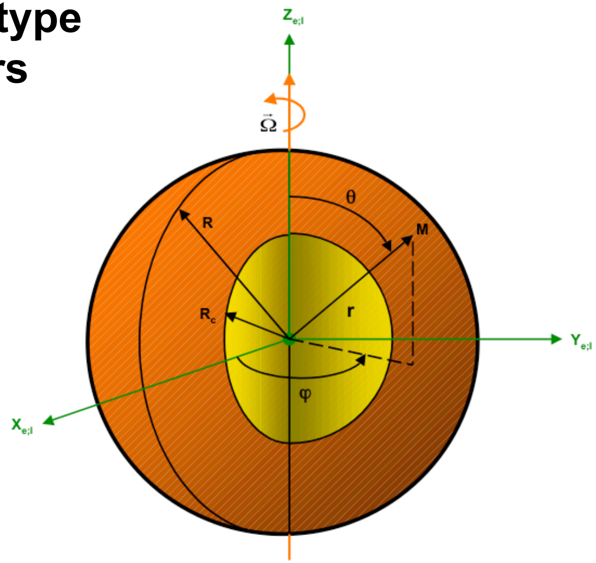
Dissipative processes

C. E.: turbulent friction
- equilibrium tide
- dynamical tide: inertial waves

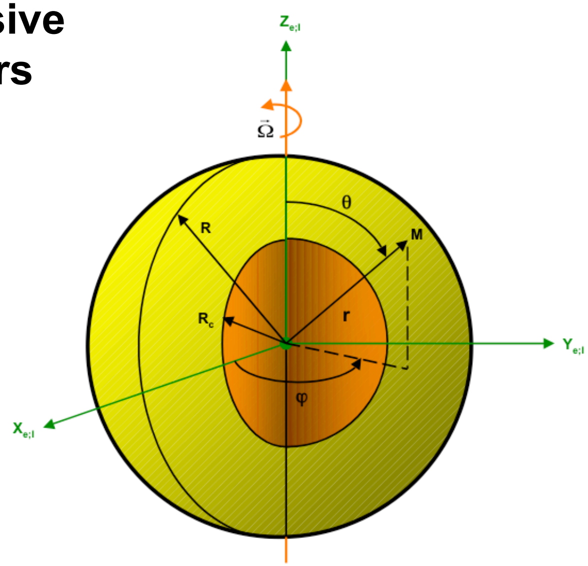


R. E.: radiative damping
dynamical tide: gravito-inertial waves

Solar-type stars



Massive stars



R. C.: radiative damping
dynamical tide: gravito-inertial waves

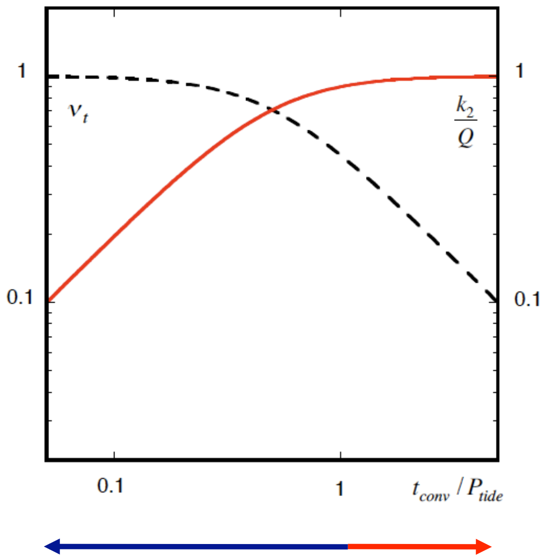
C. C.: turbulent friction
dynamical tide: inertial waves

Elliptic instabilities: both in convective and radiative regions

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

Impact on global rotation & orbit

Equilibrium tide

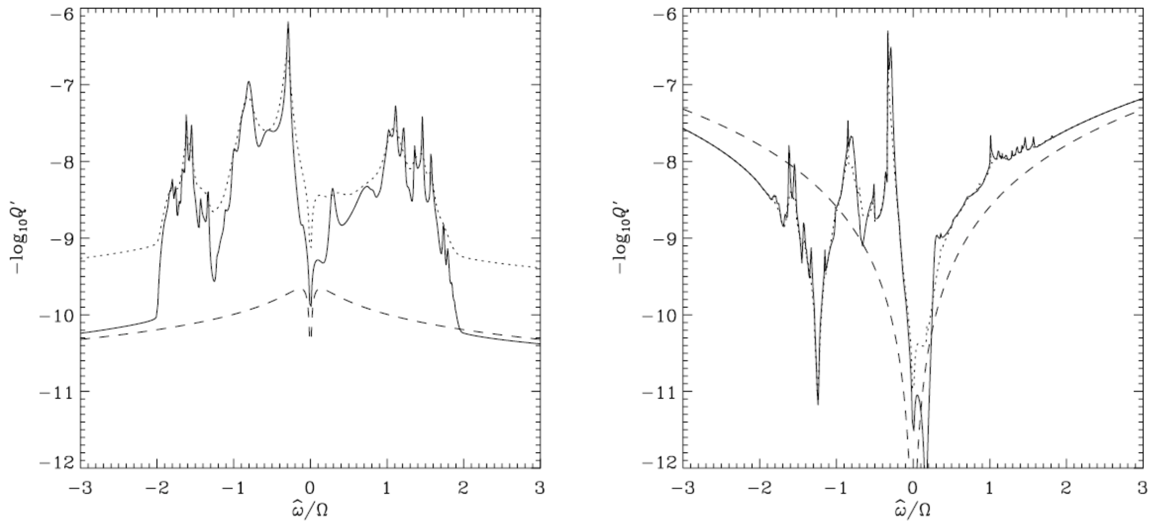


Slow tide *Fast tide*

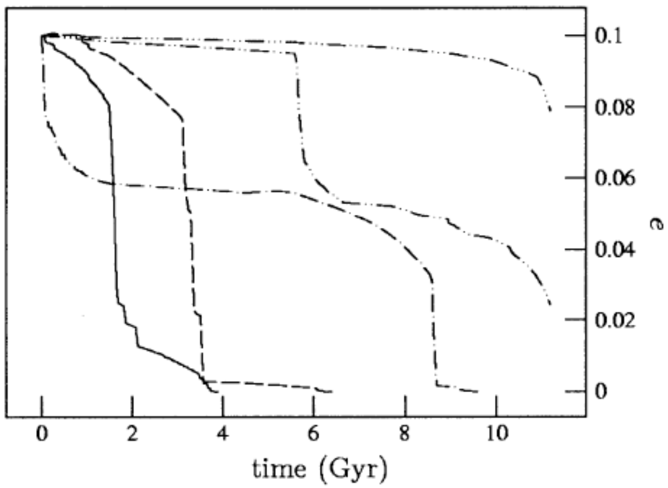
Remus, Mathis, Zahn 2012

Dynamical tide

Tidal torque



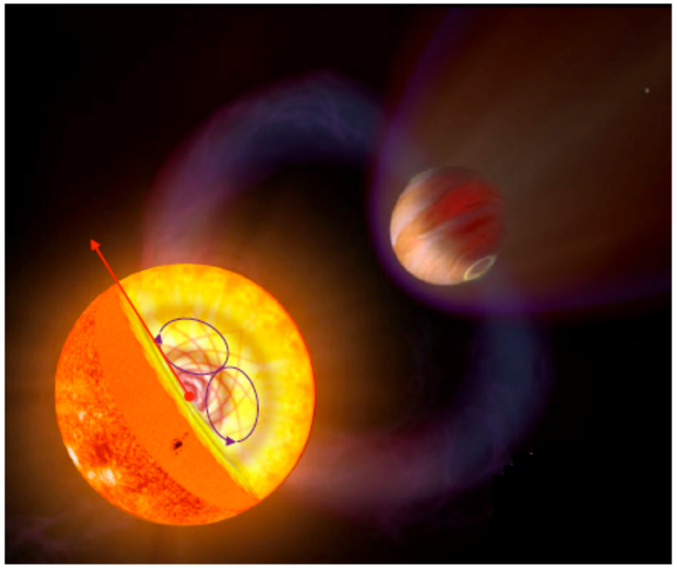
Ogilvie & Lin 2007; Rieutord & Valdettaro 2010



→ Complex orbital & spin evolution

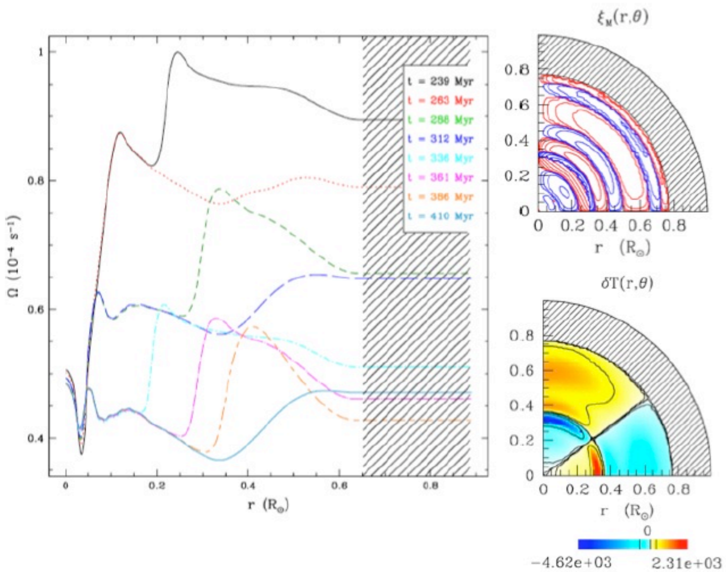
Witte & Savonije 1999-2002;
Auclair-Desrotour, Le Poncin-Lafitte & Mathis 2014

Angular momentum transport in stars with a companion

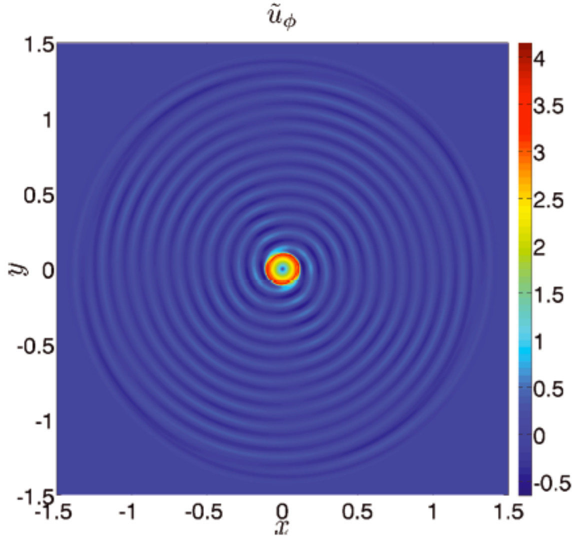


Transport mechanisms

- 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

Stellar magnetism and binarities

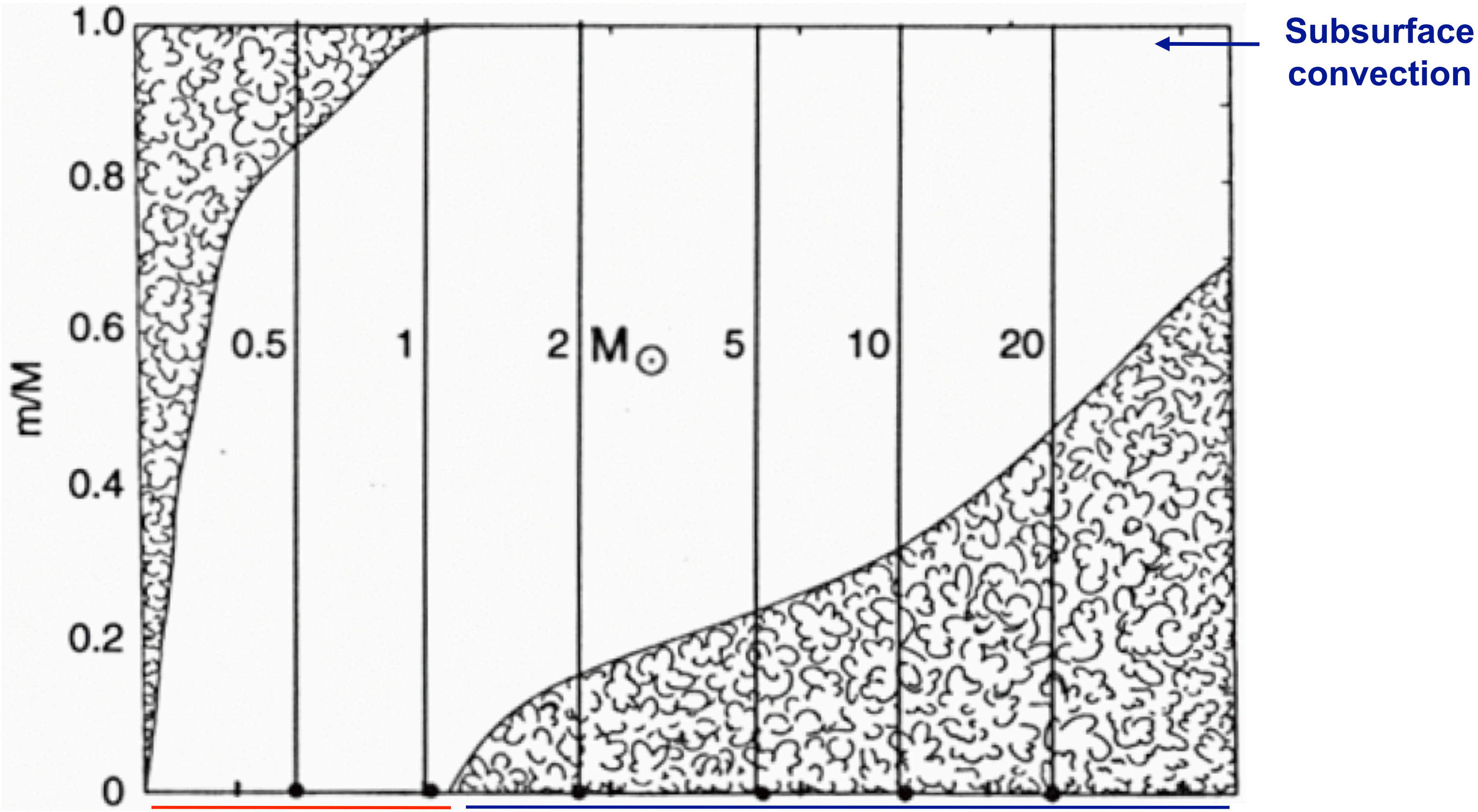
- What is the impact of magnetic fields during stellar formation, and vice-versa?
- How do tidally-induced internal flows impact fossil and dynamo fields?
- How do magnetospheric Star-Star Interactions modify stellar activity?
- What is the magnetic impact on angular momentum exchanges and mass transfers?

LPs TBL (C. Neiner) & CFHT (E. Alecian)

BinaMIcS

Binarity and Magnetic Interactions in various classes of Stars

Magnetic fields: convection vs. radiation



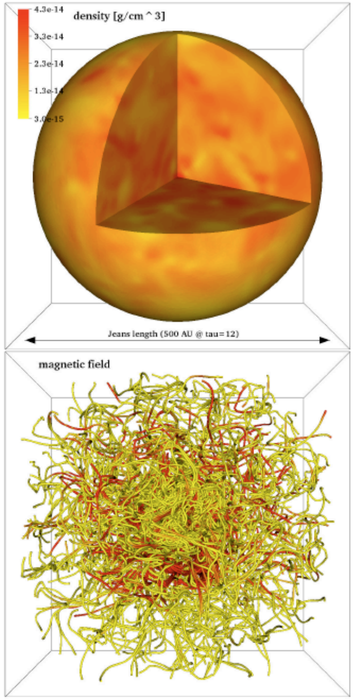
Cool stars:
C.E.: Dynamo field
(correlations with M, age, Ω)
R.C.: Fossil field

Hot stars:
C.C.: Dynamo field
R.E.: Fossil field
(not correlated)

Kippenhahn & Weigert 1997

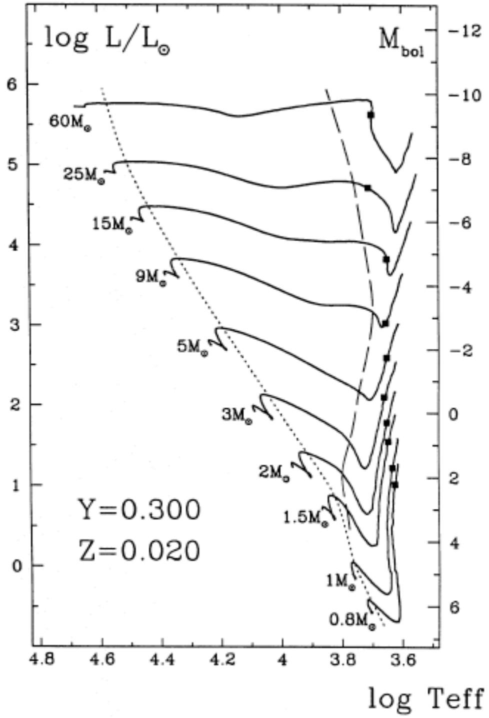
Magnetic field and stellar formation: the case of fossil fields

Interstellar medium



Federrath et al. 2011

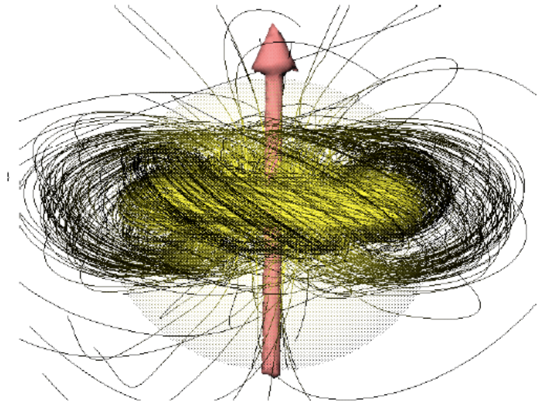
PMS

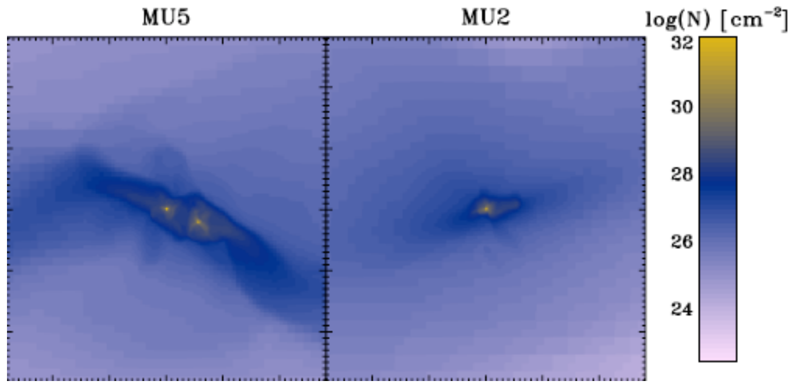


Bernasconi & Maeder 1996

Stable zone relaxation

Braithwaite & Nordlund 2006;
Duez & Mathis 2010



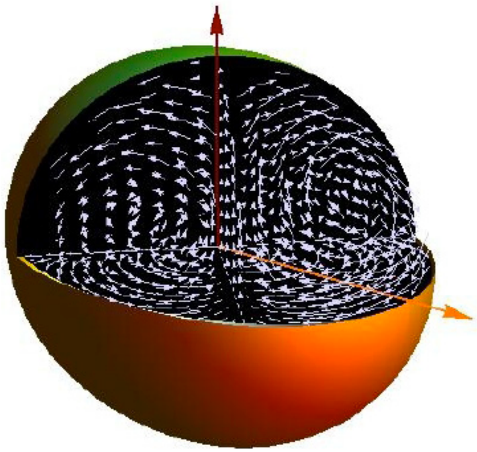


Impact of magnetic field on stellar formation (fragmentation; *Commerçon, Hennebelle & Henning 2011*)

→ Magnetic dichotomy in hot stars?

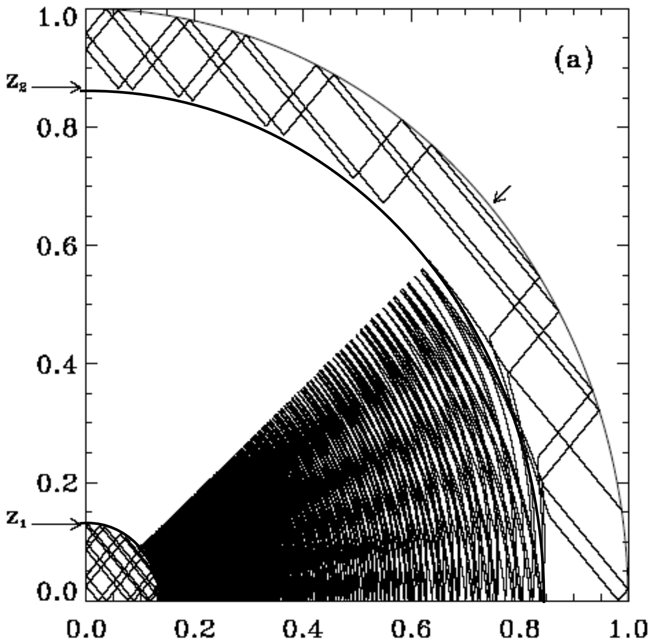
Impact of tidal velocity fields on internal dynamics and magnetism

Equilibrium tide



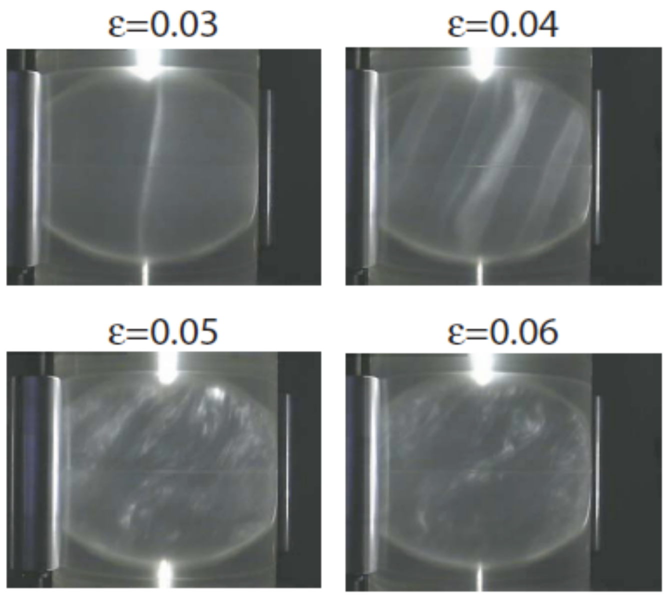
Remus, Mathis, Zahn 2012

Dynamical tide



Dintrans & Rieutord 2000

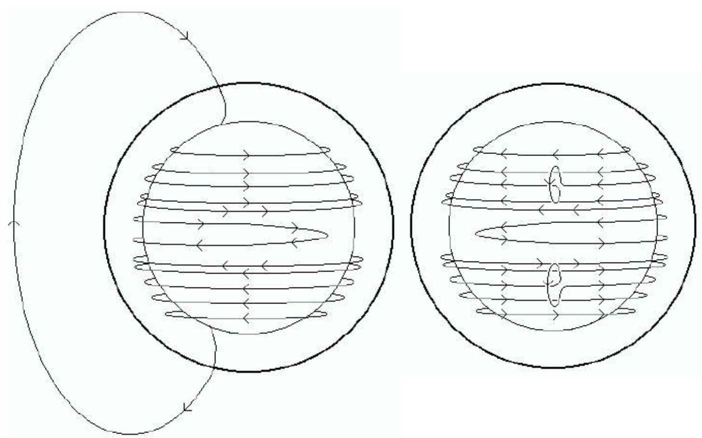
Elliptical instabilities



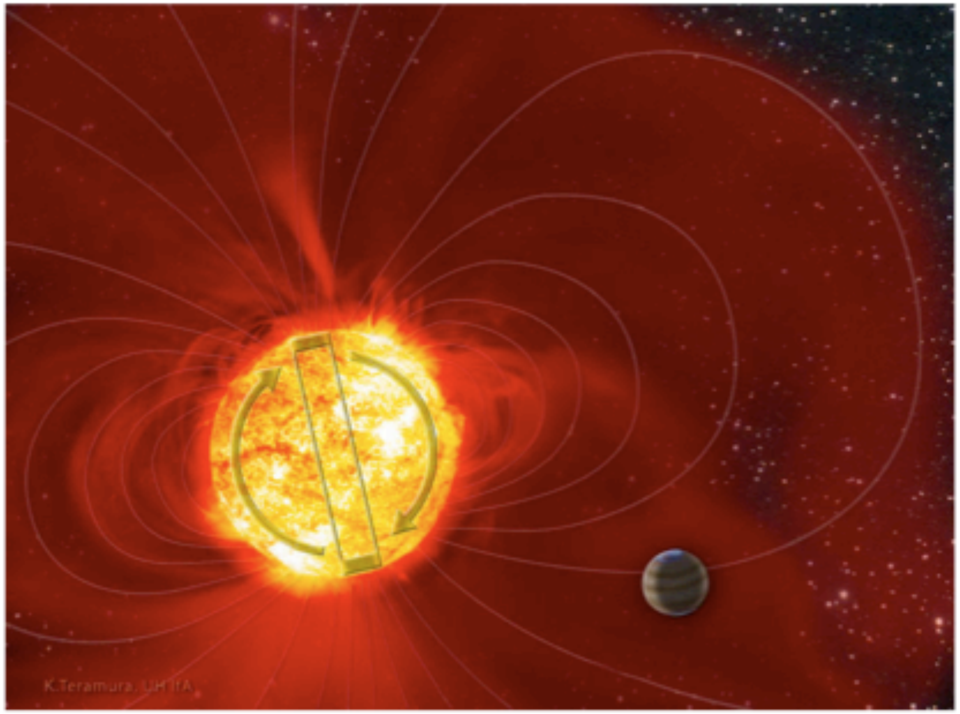
Lebars et al. 2010
Cebron et al. 2010

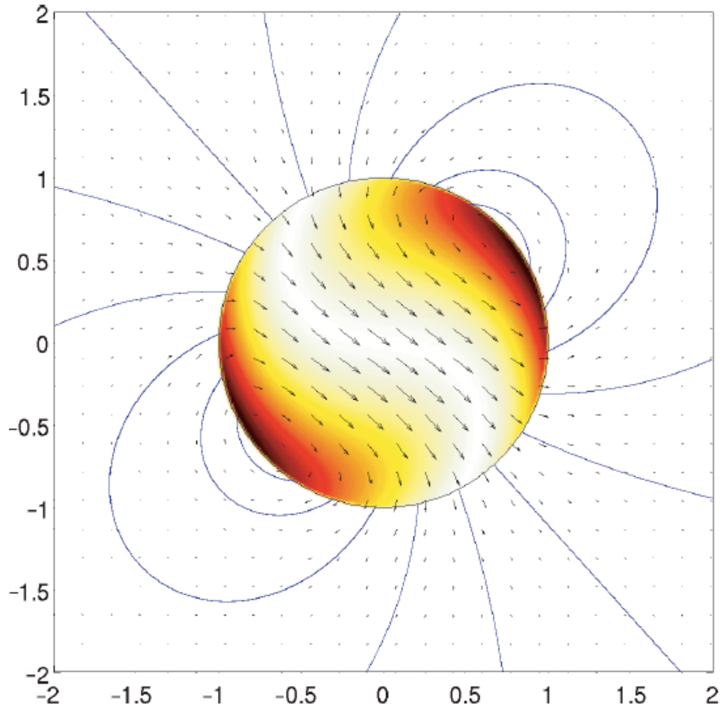
Transport angular momentum → modify ΔΩ and Ω – effect

Helical flows → α - effect



Modification of stellar magnetism



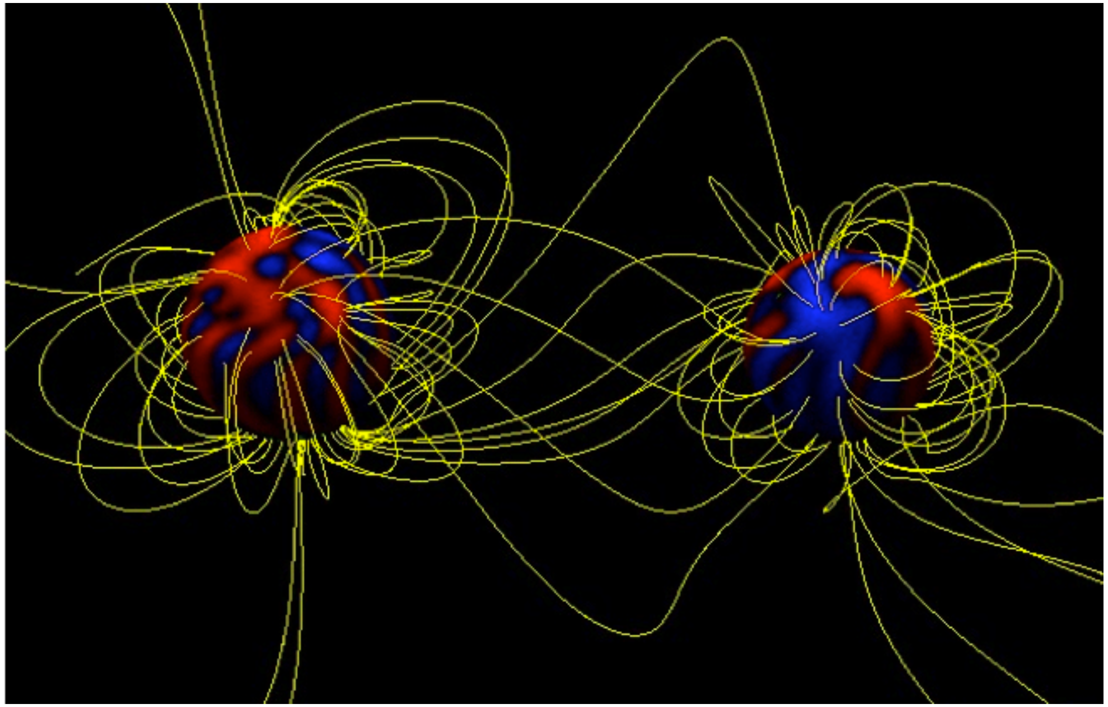


Donati et al. 2008 *Lacaze et al. 2006*

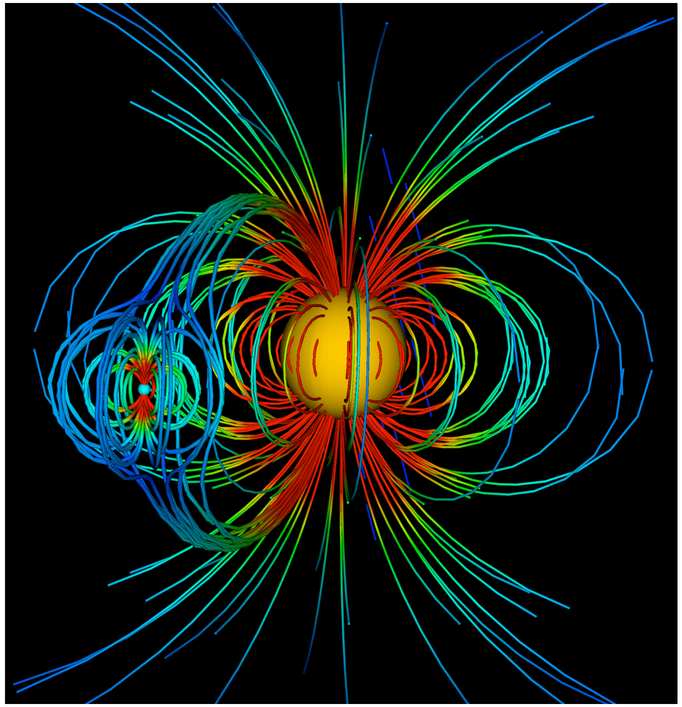
Interactions between tides and magnetic fields

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

Magnetospheric interactions



Dunstone & Holzwarth, et al. 2008



Cohen et al. 2009;
Strugarek, Brun, Matt 2012

MHD connexions between components

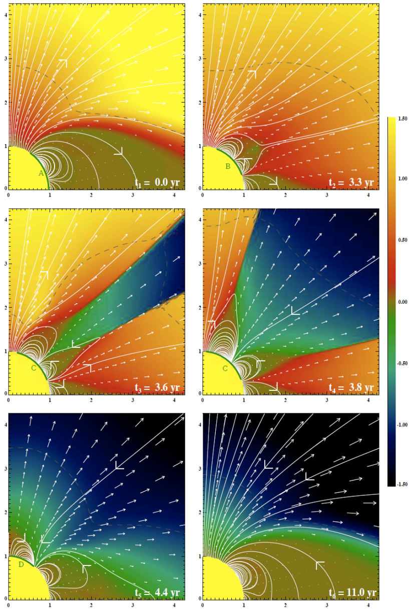
- Applied torques (added to tides and winds)
- Helicity exchanges → modification of the magnetic activity *(Lanza 2012)*

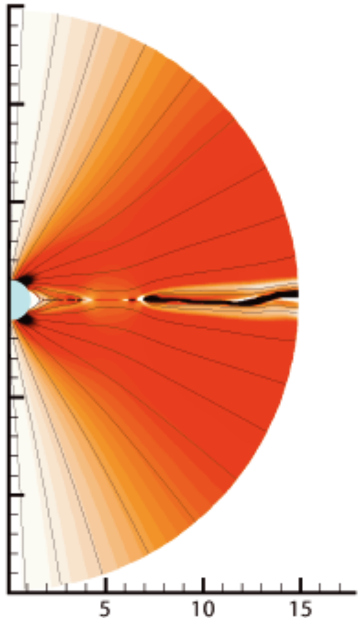
Interaction with MHD stellar environment: winds & accretion disks

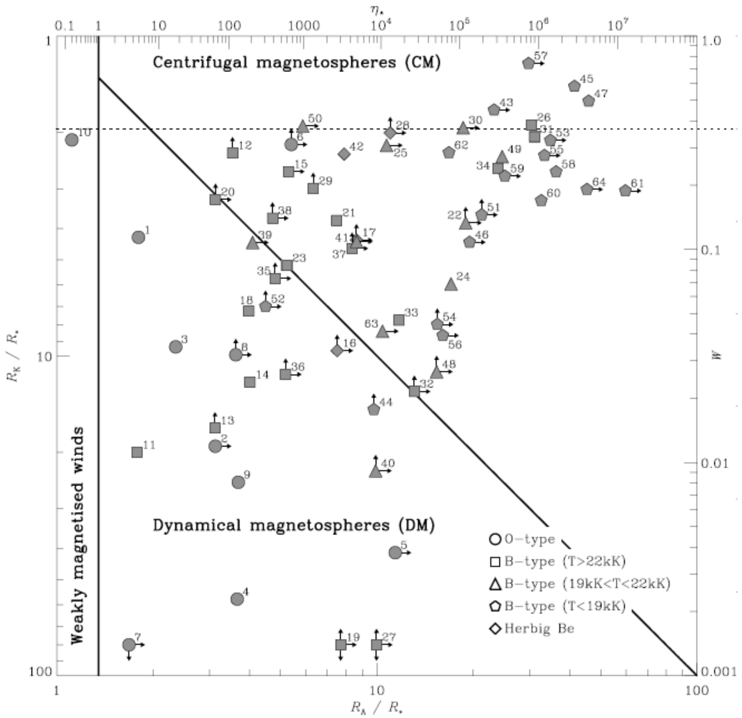
Winds: pressure-driven, line-driven (and colliding winds)

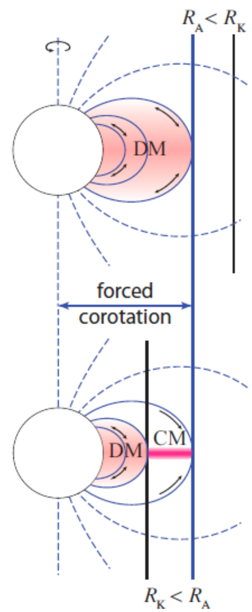
Pinto et al. 2011
Matt et al. 2012

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



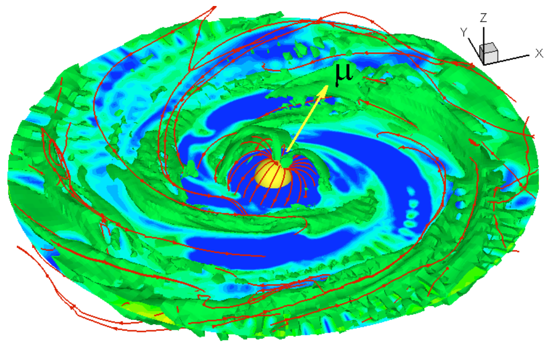






Accretion disks (J. Bouvier)

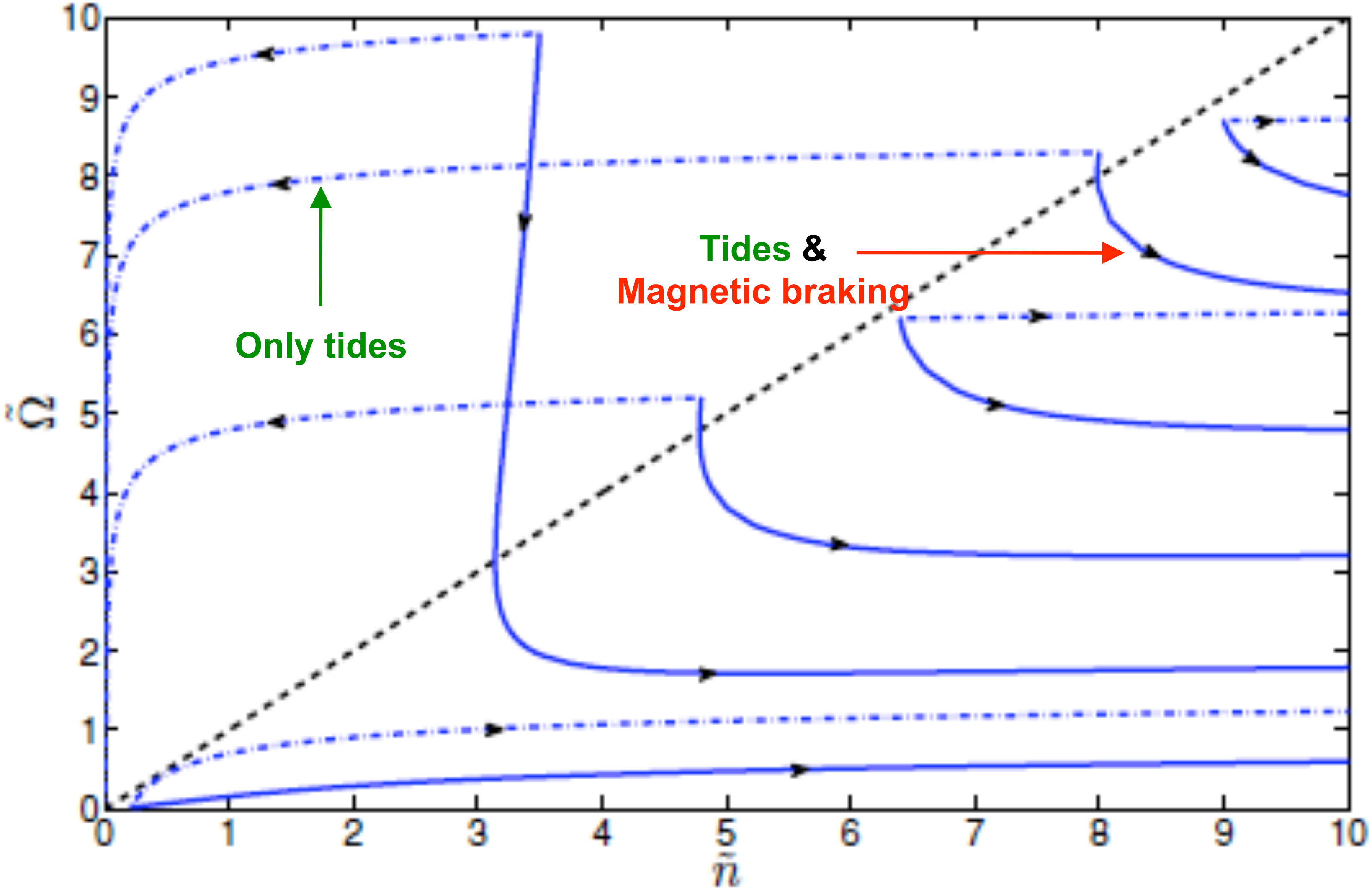
Matt & Pudritz 2005, Romanova et al. 2010



MaPP, MaTYSSE

Whole system evolution

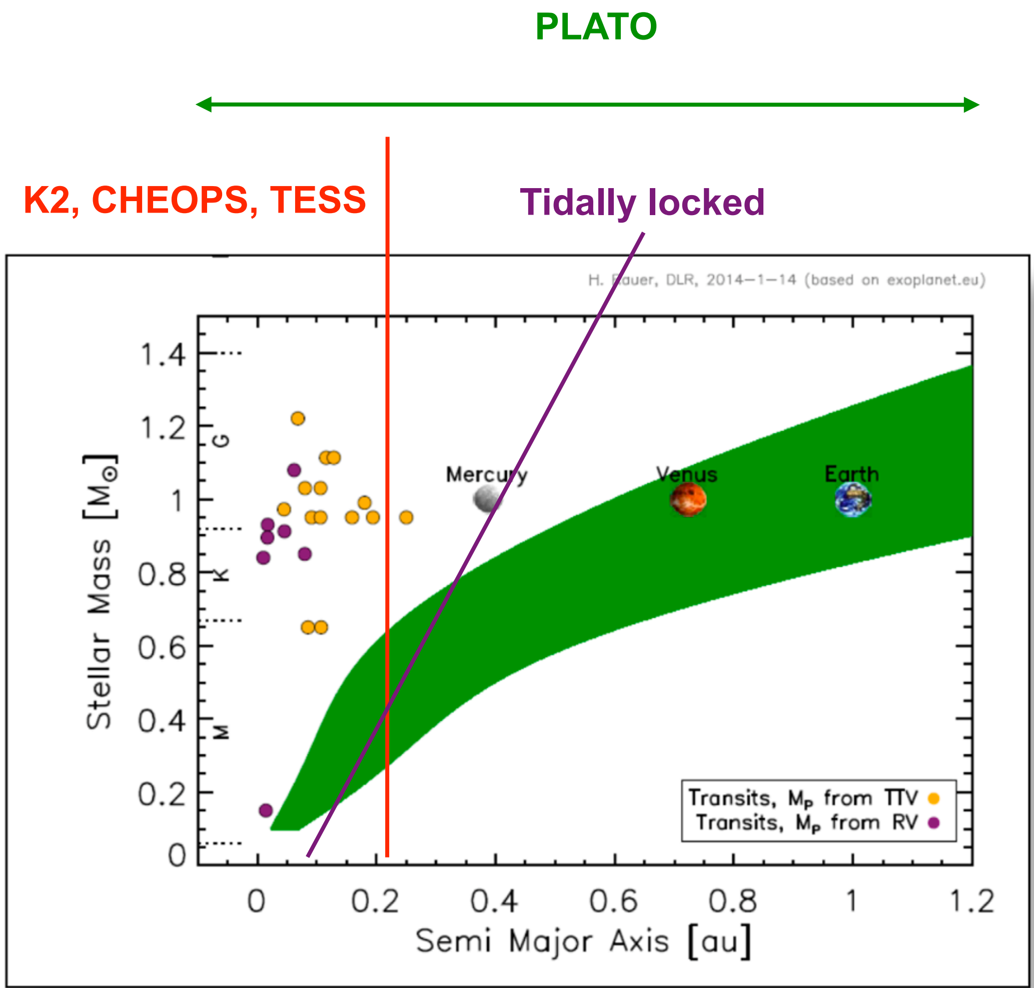
Barker & Ogilvie 2009



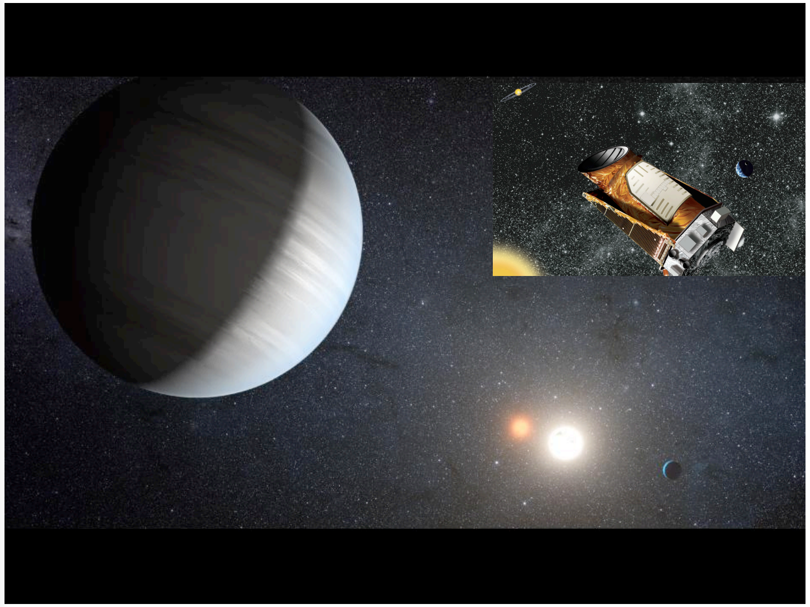
Need to
- treat simultaneously gravific and MHD interactions
- determine their relative orders of magnitudes

The study of habitability

Stars are the **core** of planetary systems



Rauer et al. 2013



Orosz et al. 2012 (Kepler 47)

Towards a complete picture

Dynamical evolution of stars interacting with companions

- How do tidal dissipation and torque vary as a function of stellar mass and evolutionary stage?
- What is the relative importance of the different applied torques along their evolution?
- For a given evolutionary stage, which physical processes dominate the transport?
- How do this rotational evolution and binarity impact stellar chemical properties (mixing) and magnetism?

Dynamical evolution of multiple systems

- What are the respective impact of tides and magnetic interactions on multiple 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 the evolution of stars and their environment: transverse to PNPS/PNP(/PNST/GRAM)