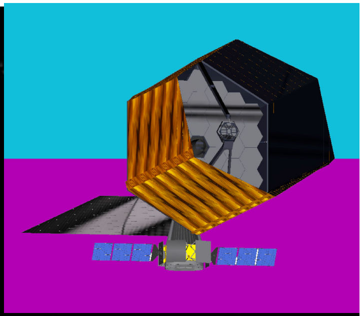


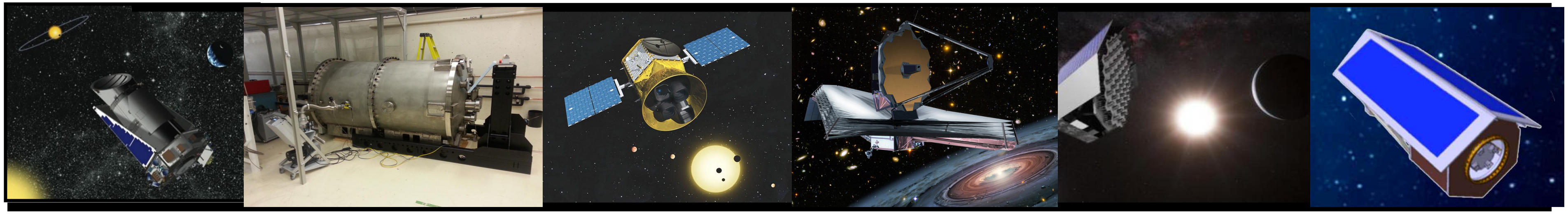
The dynamics of star-planet systems

Stéphane Mathis

CEA Saclay – Astrophysics division
Laboratory Dynamics of Stars and their Environment

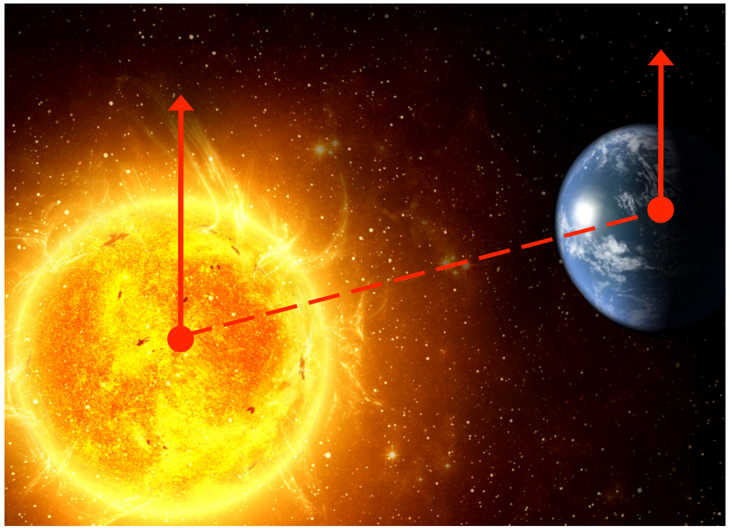
The general context

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



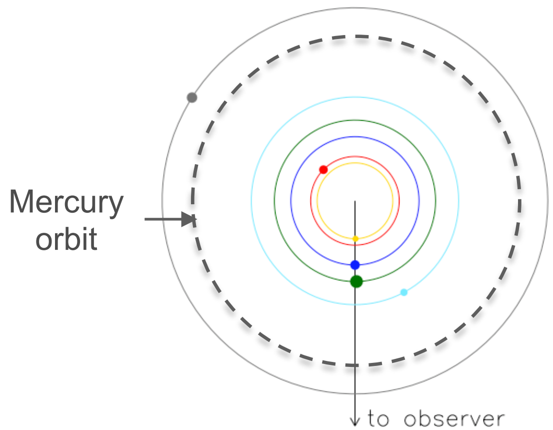
Kepler – K2 | *SPIRou* | *CHEOPS & TESS* | *JWST* | *PLATO* | *ARIEL/ARAGO*

Stellar rotation & magnetism/activity
– planetary dynamics/atmospheres



Albrecht et al. 2012; Gizon,…, Mathis,…, et al. 2013

Orbital architecture
→ Interacting systems



Kepler 11

Lissauer et al. 2011
Bolmont et al. 2014

LUVOIR and star-planet systems

Search for, characterize, and survey potentially habitable worlds.

a) Directly detect reflected starlight of Earth-sized planets in the habitable zones of other stars, with a statistically meaningful number of detections, in order to:

b) Analyze the frequency with which these worlds have certain atmospheric and surface properties, and specifically:

c) Constrain the frequency of habitability and biological indicators on Earth-sized planets in the habitable zones of other stars.

Place the Solar System in the context of a diverse set of exoplanetary systems.

a) Directly detect reflected starlight from a wide range of exoplanets, and transit spectra from a wide range of exoplanets, in order to:

b) Understand the atmospheric structure and composition of these exoplanets, and

c) Search for signs of habitability and biological activity in non-Earth-like planets.

d) Image faint debris disks and exozodiacal light, in order to constrain their structure and composition and lend insights on planet formation processes.

e) Characterize the architectures of exoplanet systems as a function of stellar type over time.

Study and characterize protoplanetary disks. LUVOIR would also enable the study and characterization of protoplanetary disks, and so address the science goals listed in 3 a-d above.

Gaudi et al. 2015

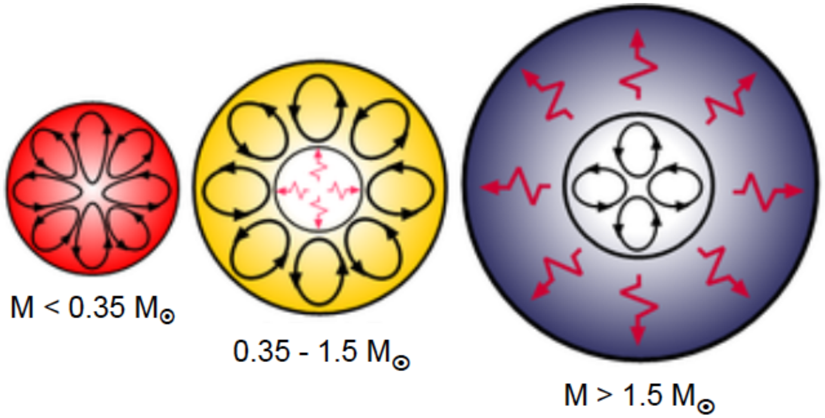
State of the art in star-planet system studies

In studies of star-planet systems, we need:

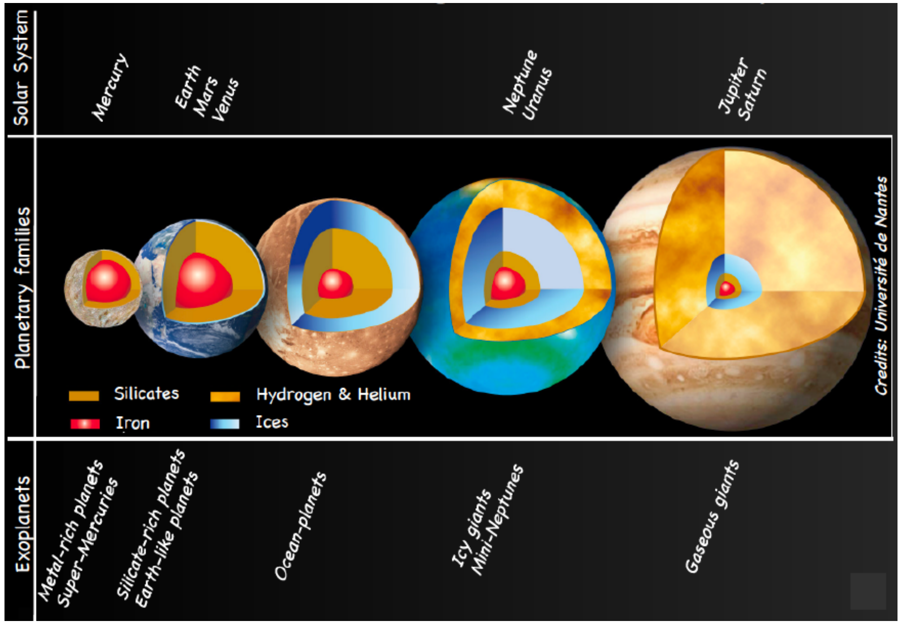
- to strongly improve our understanding of the **dynamical evolution of the host-star**
- to go beyond ad-hoc description of **Star-Planet Interactions**

Complex internal structure, evolution, rotation and magnetism should be considered

Host star (M in $M_\odot$)



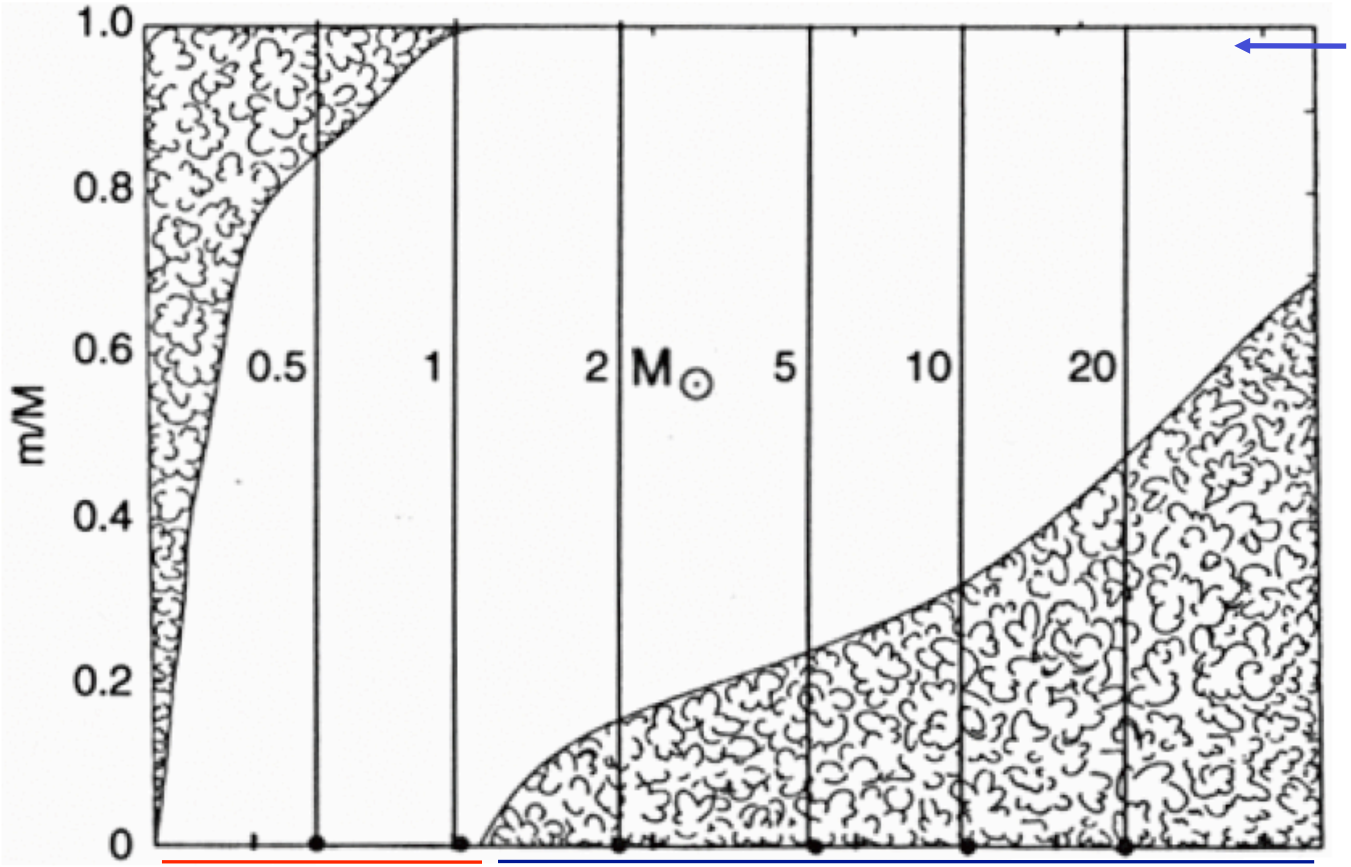
Planets



→ Ab-initio physical modeling to accompany the study of discovered systems

THE HOST STAR

Magnetic fields: convection vs. radiation



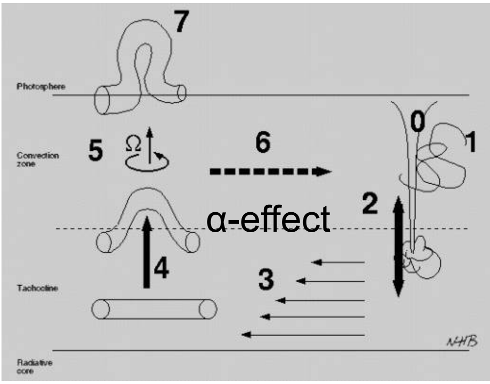
Cool stars:
C.E.: Dynamo field
(correlations with M, age, Ω)
R.C.: Fossil field
Pressure-driven winds

Hot stars:
C.C.: Dynamo field
R.E.: Fossil field
(not correlated)
Radiation-driven winds

Kippenhahn & Weigert 1997

Convection, Rotation, Turbulence & Dynamo action

Theoretical solar/stellar magnetic cycles



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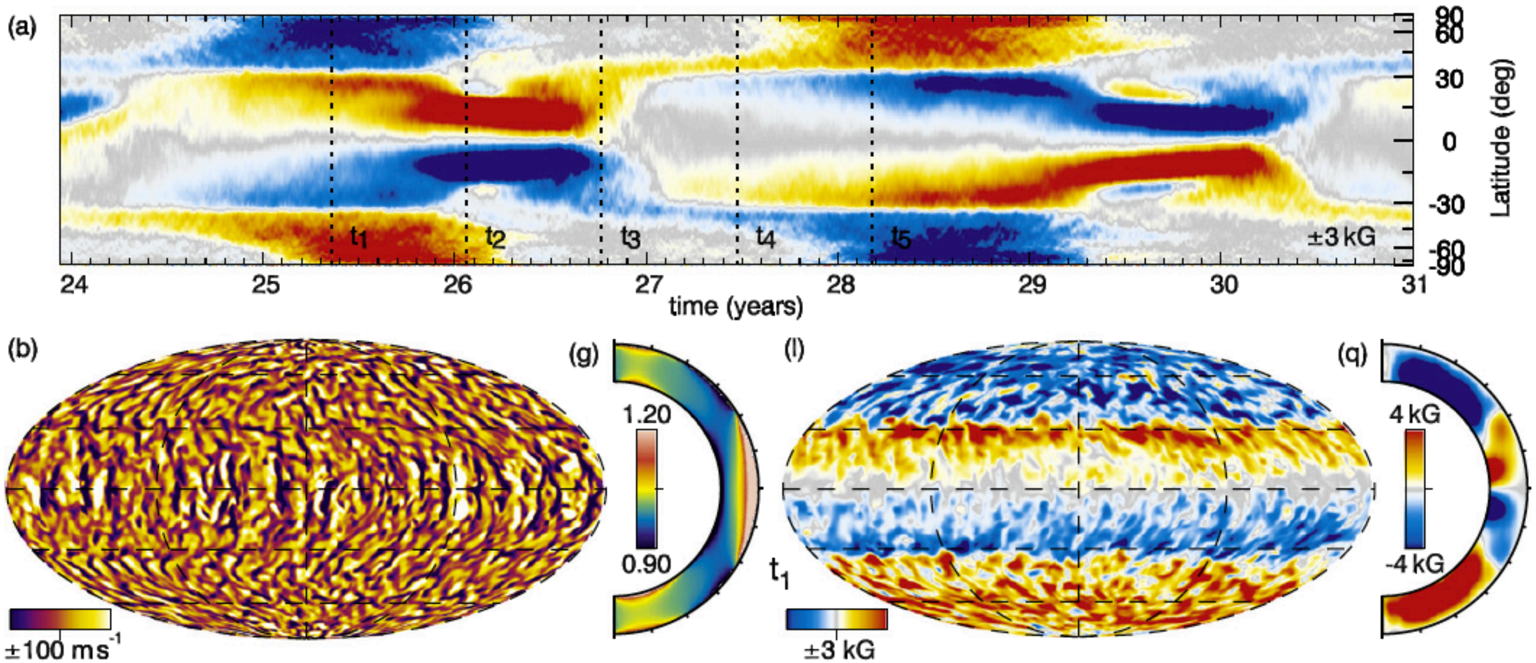
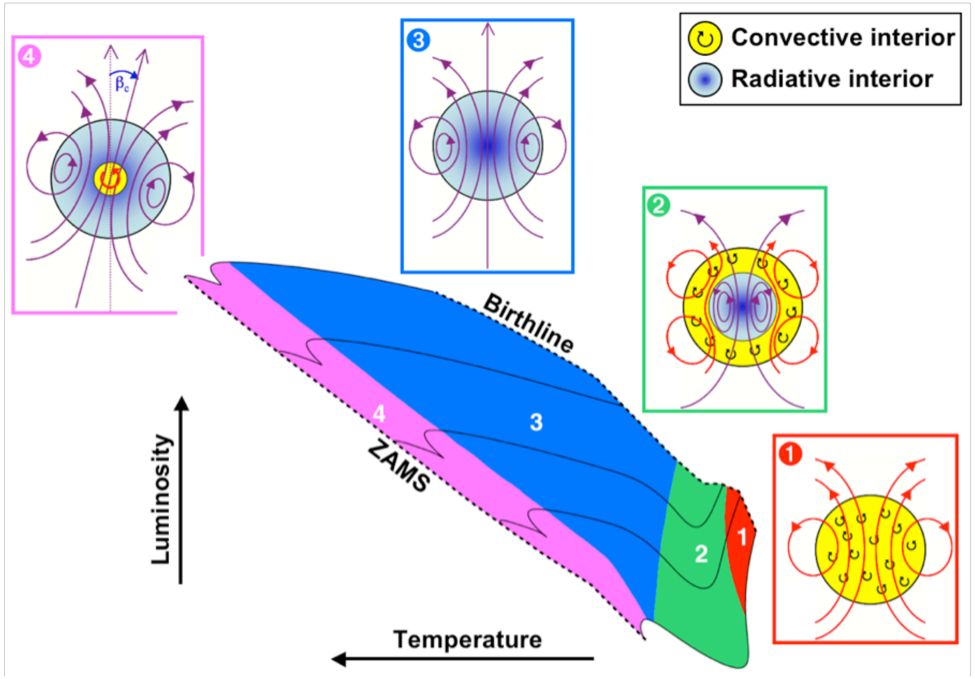
3D high resolution nonlinear simulations

e.g. Brun, Miesch, Toomre 2004; Augustson et al. 2015



Synergies spectropolarimetry – asteroseismology (Ground/ARAGO - PLATO)

Fossil magnetism (stellar radiation zones)

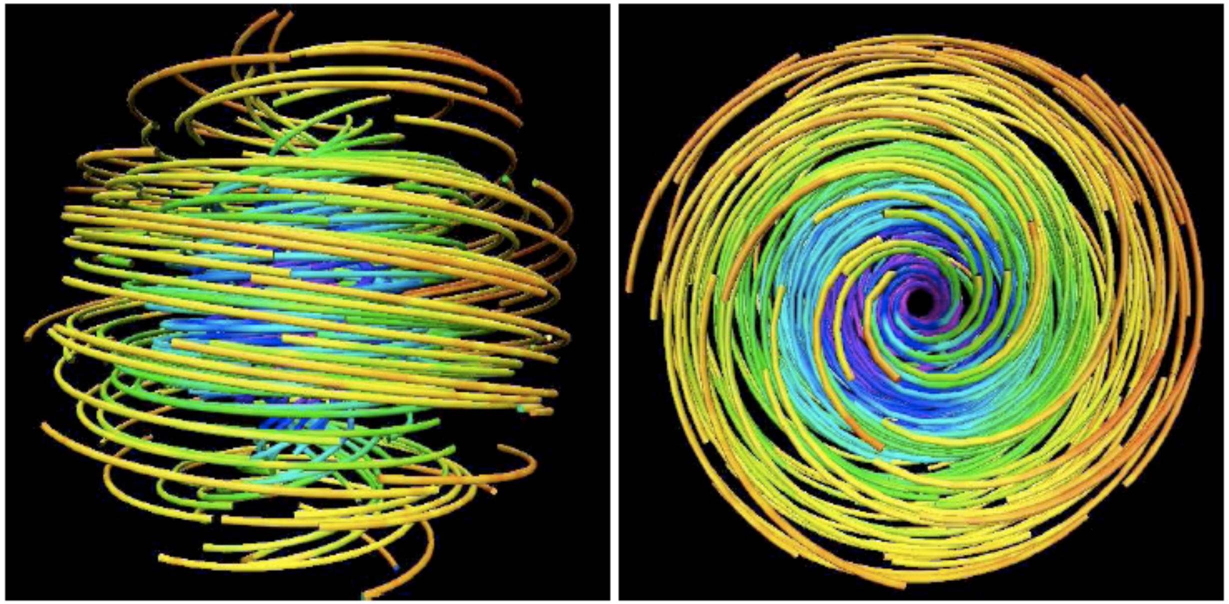


Fossil fields along stellar evolution

Alecian et al. 2013

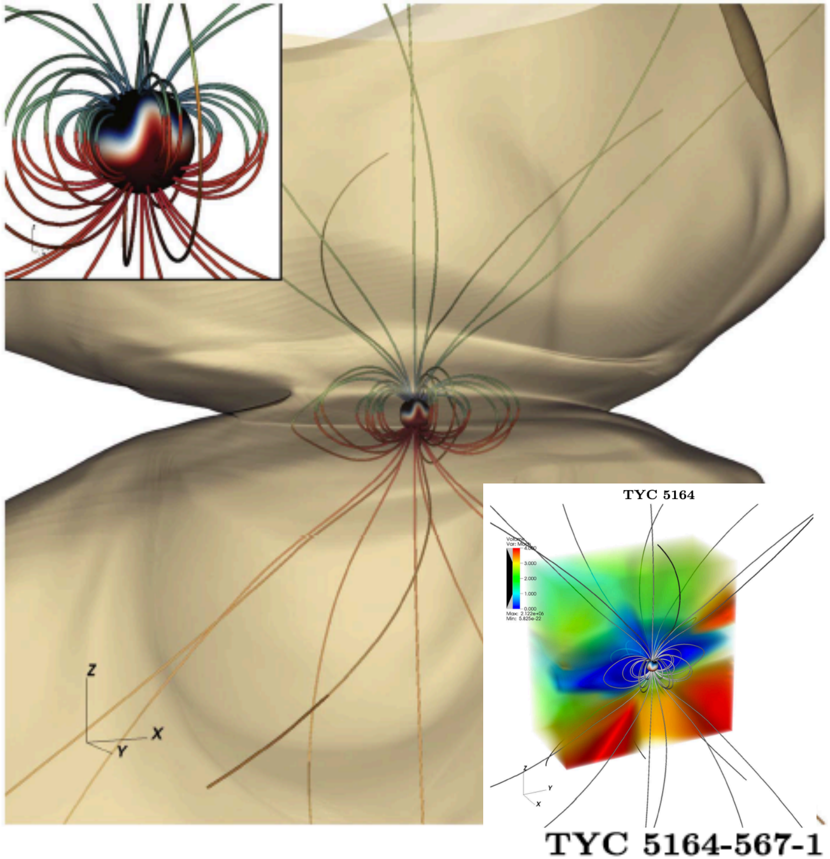
Fossil fields complex topology

Braithwaite & Spruit 2004;
Braithwaite 2008;
Duez & Mathis 2010;
Duez, Braithwaite & Mathis 2010



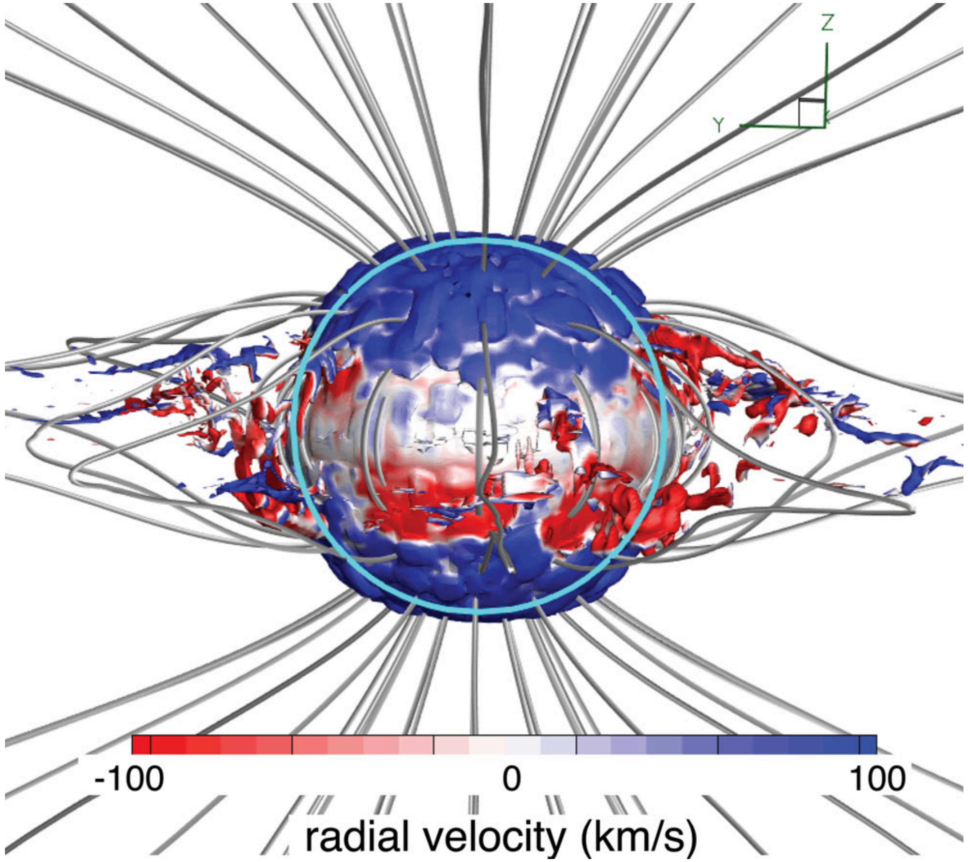
Stellar winds and magnetospheres

Late-type stars



Réville et al. 2016

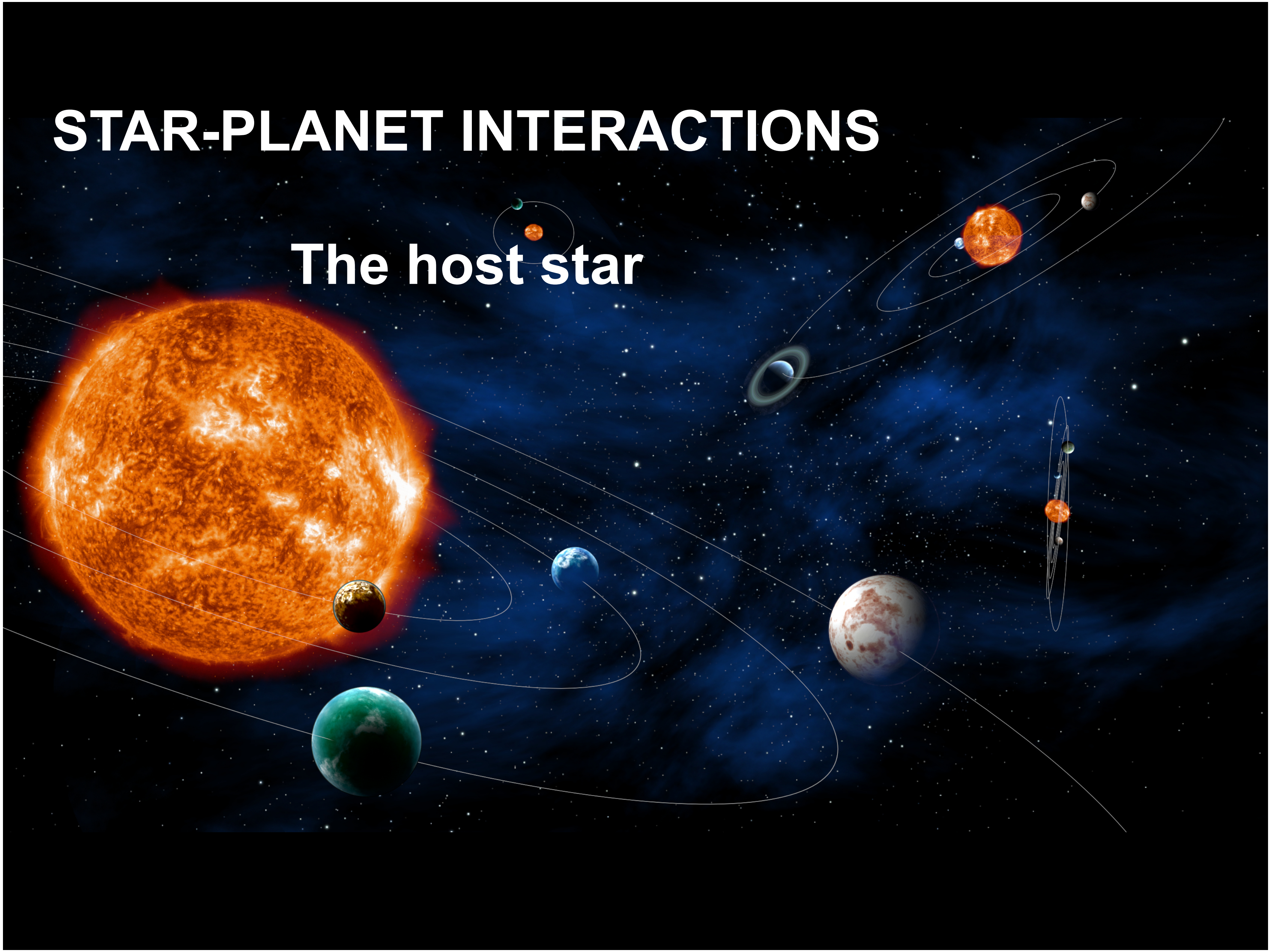
Early-type stars



Ud-Doula et al. 2013

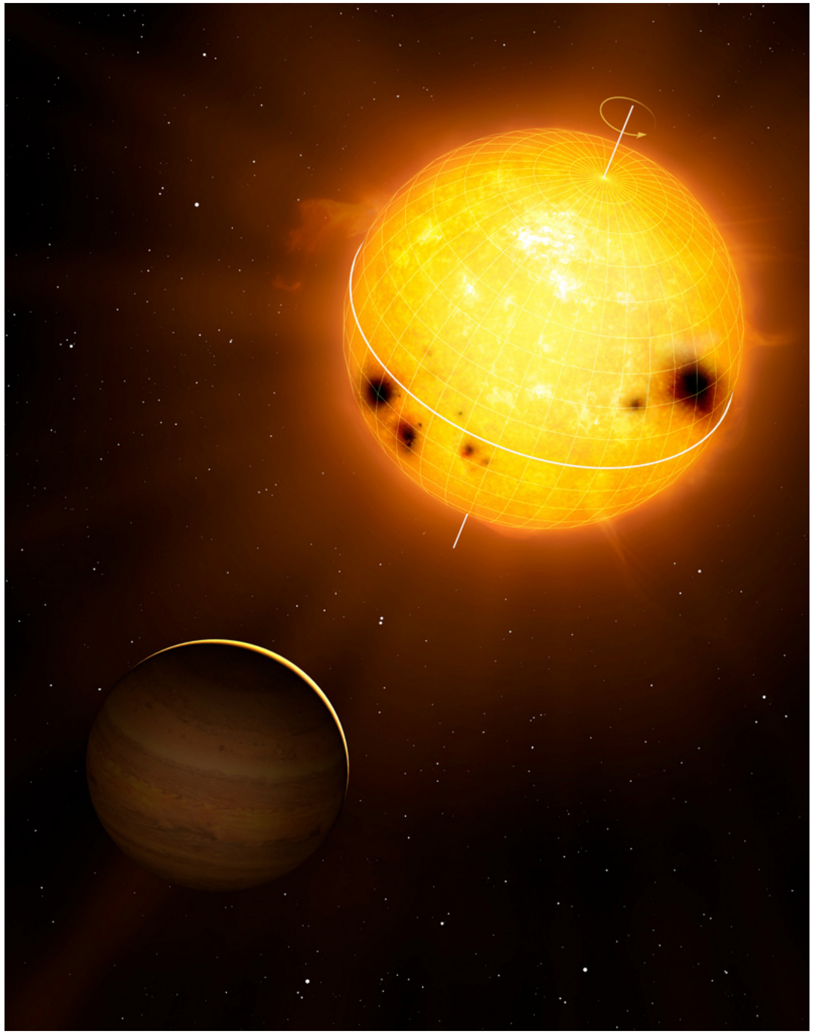
→ Strongly impact rotational (& chemical + magnetic) evolution of stars and Star-Planets Interactions

→ Need for UV diagnosis

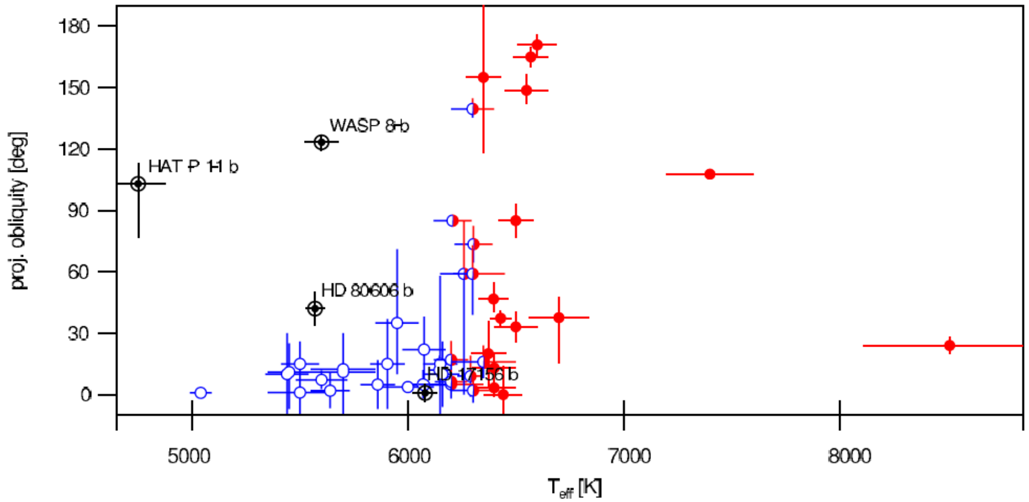

STAR-PLANET INTERACTIONS
The host star

Tidal interactions in exoplanetary systems

The case of hot-Jupiter systems



Gizon et al. 2013; Davies et al. 2015



Albrecht et al. 2012

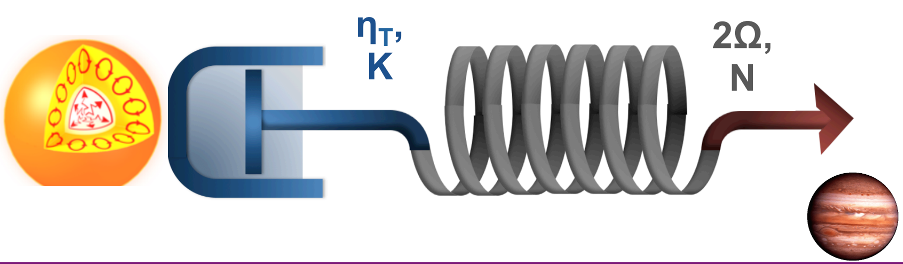
→ Tidal dissipation (the “engine” of secular evolution) in a star varies over **several orders of magnitude** as a function of:

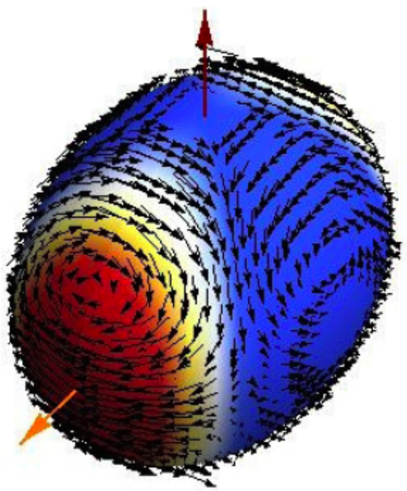
- The mass
- The age
- The dynamics (rotation)

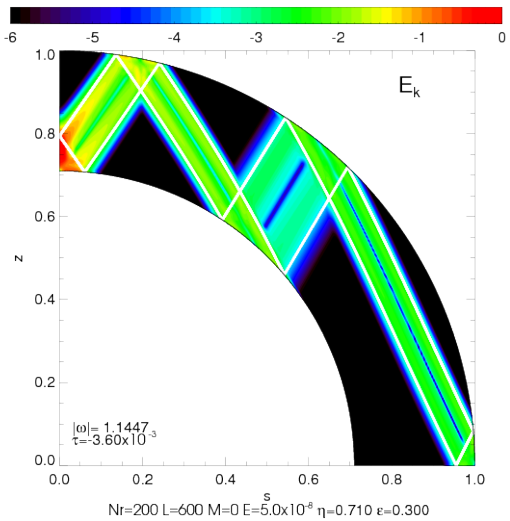
→ need for ab-initio modeling

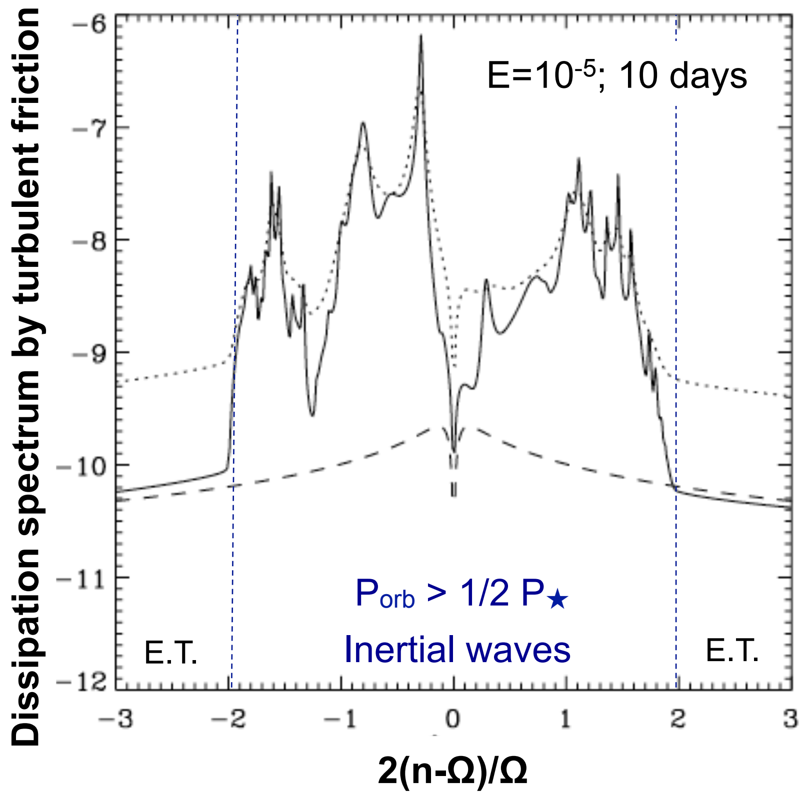
Tidal dissipation in low-mass star convective envelopes

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









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

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

Ogilvie 2013, Mathis 2015

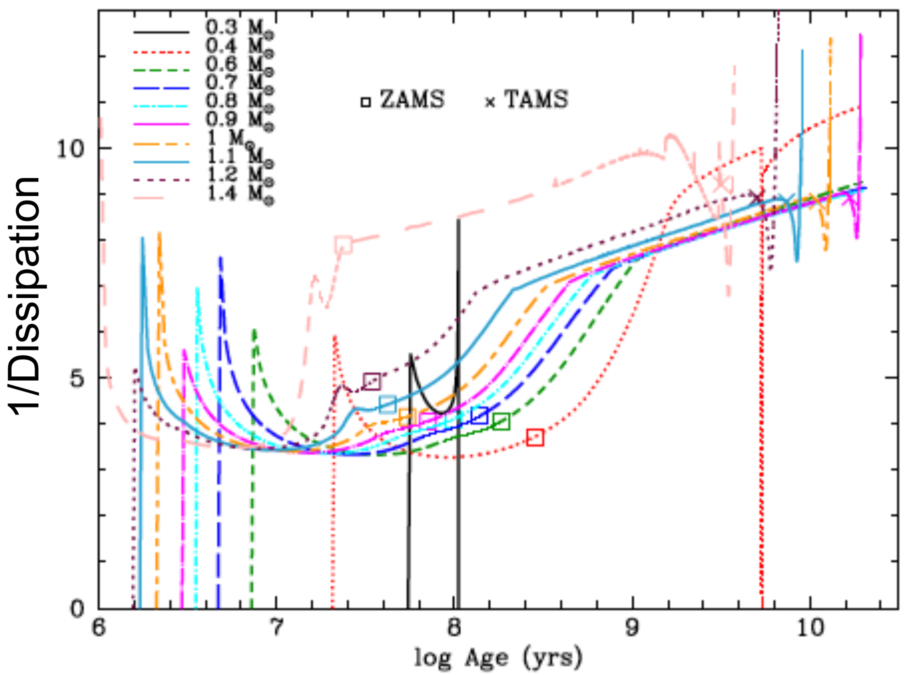
Grids of tidal dissipation for star-planet systems

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**

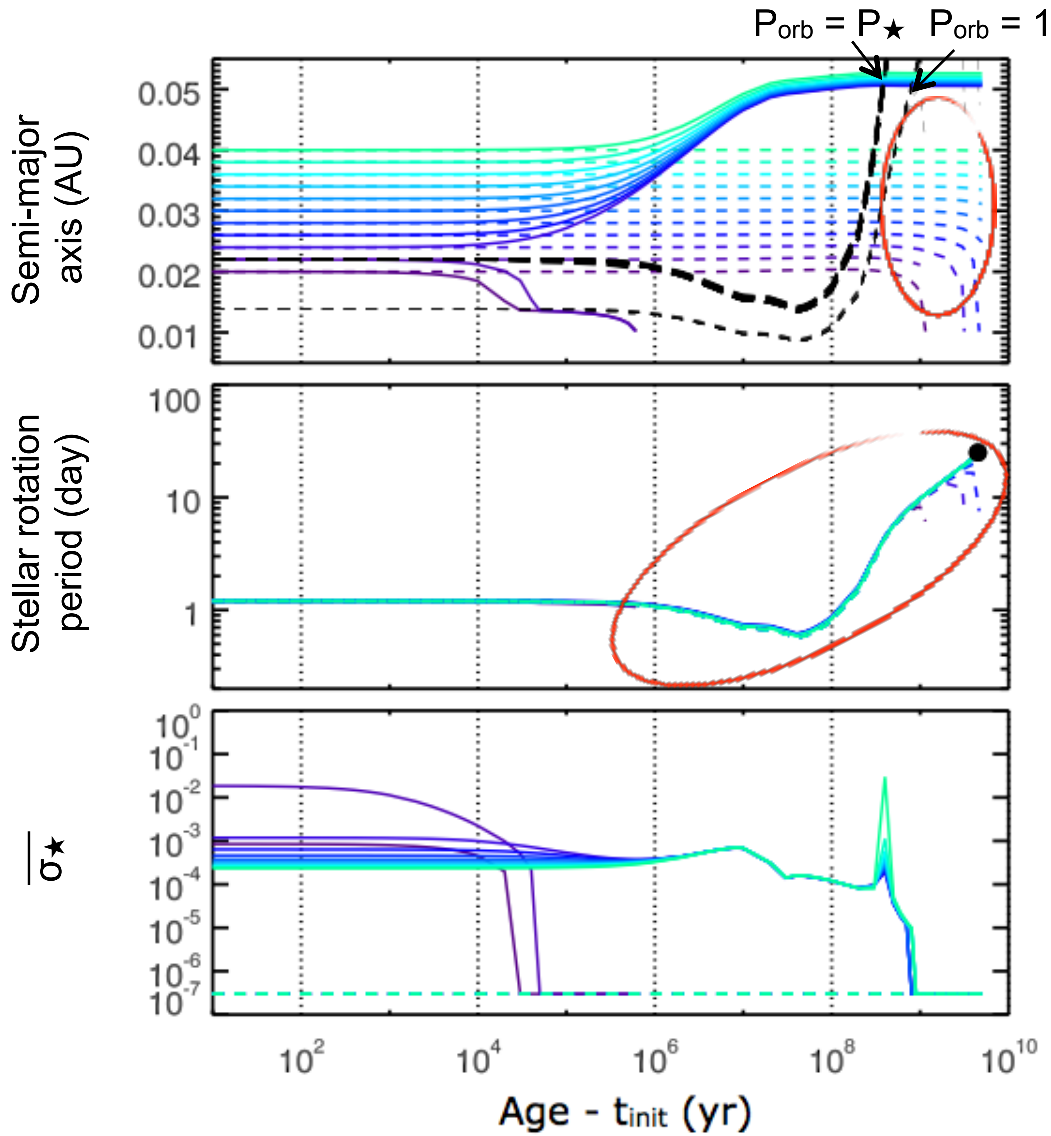


Structural & rotational evolution

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

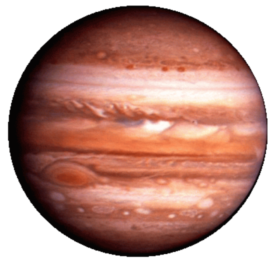
Star-planet systems dynamical evolution

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



Standard model - - -
Model Bolmont & Mathis ——

$M_p = 1\ M_{jup}$



$M_\star = 1\ M_\odot$

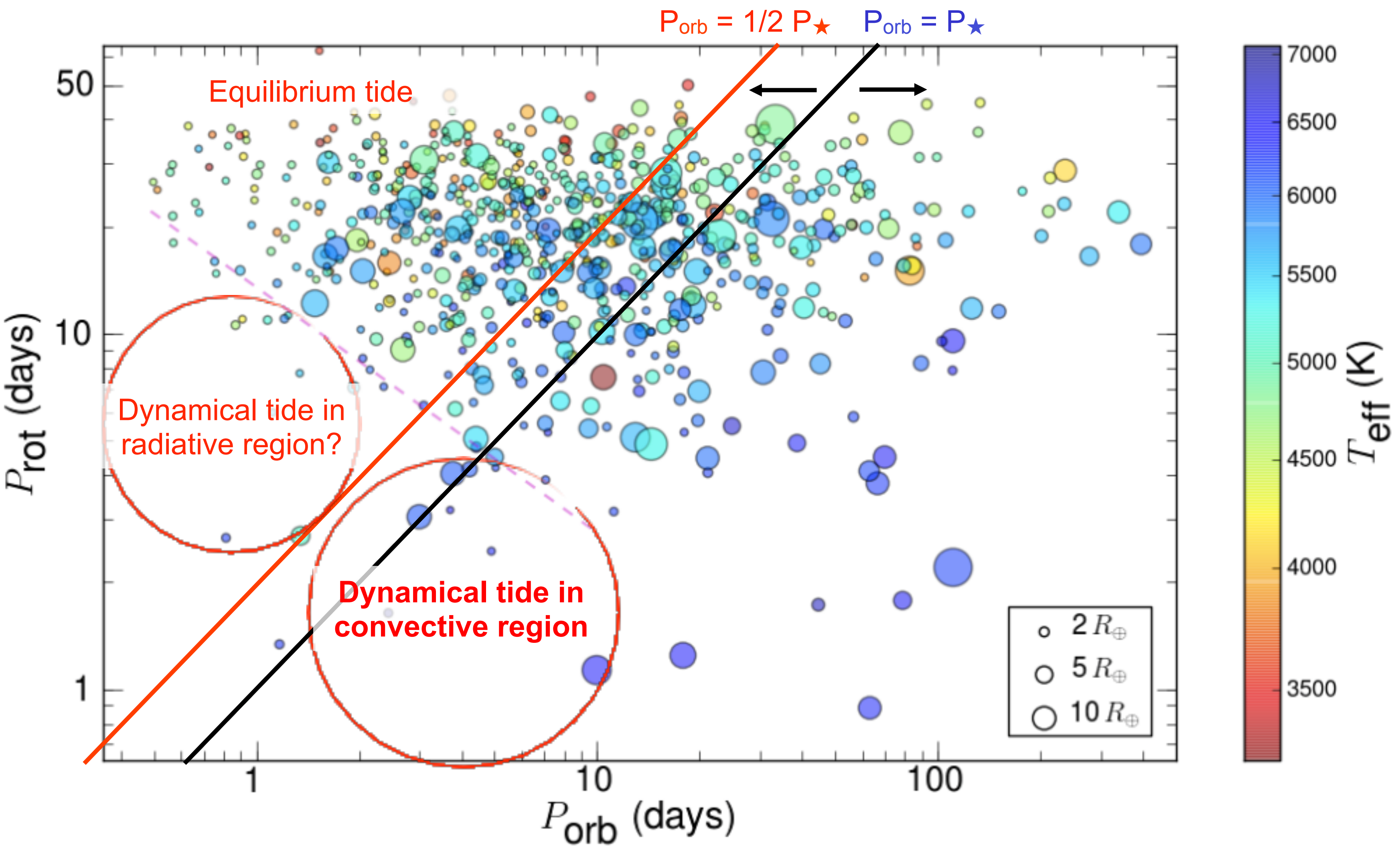
$P_{\star,i} = 1.2$ day

➡ Rotation deficiency: star initially fast rotator

➡ Rotation excess: star initially slow rotator

Bolmont & Mathis 2016

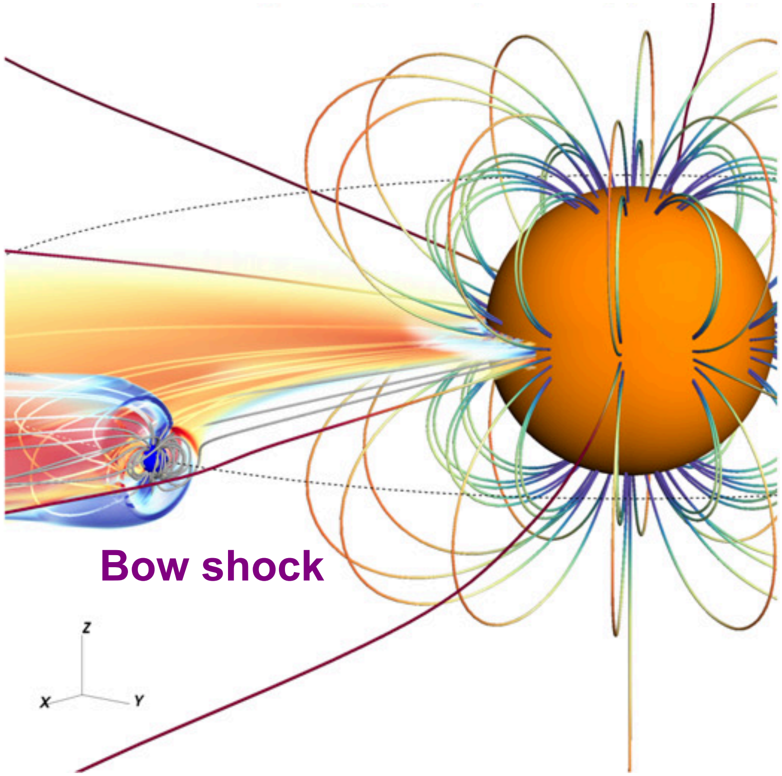
Understanding hot-Jupiters systems



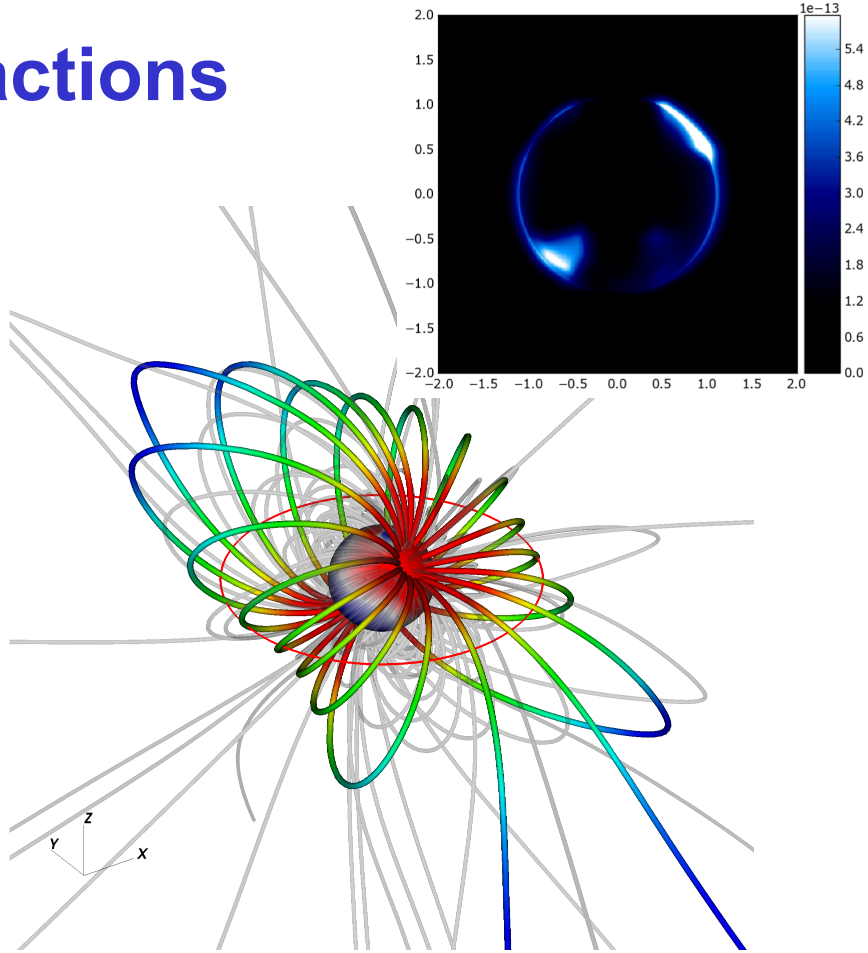
Direct imaging by LUVOIR

McQuillan et al. 2013

Magnetic star-planet interactions

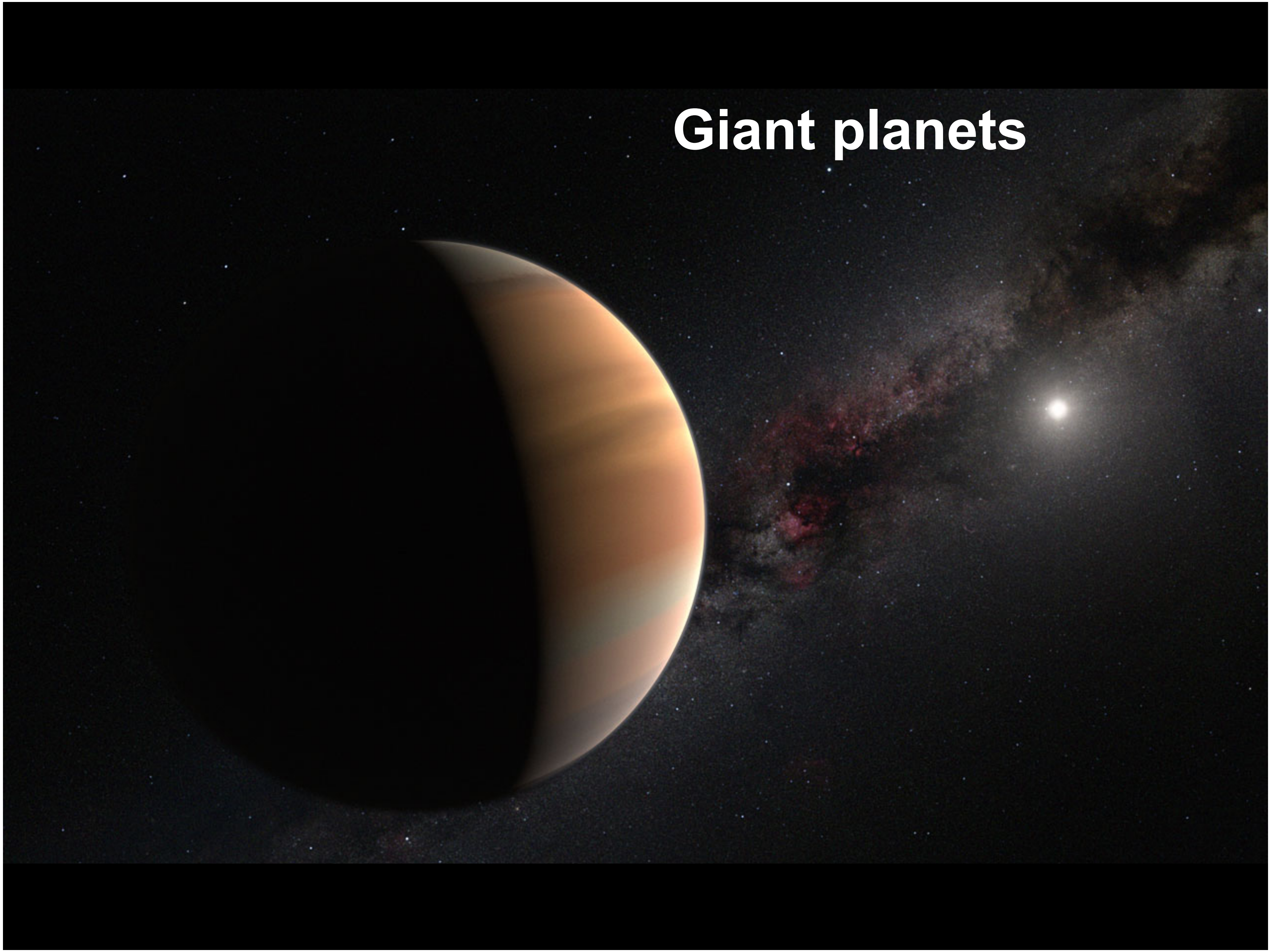


Strugarek et al. 2014-15; Strugarek 2016



MHD model of *Kepler* 78

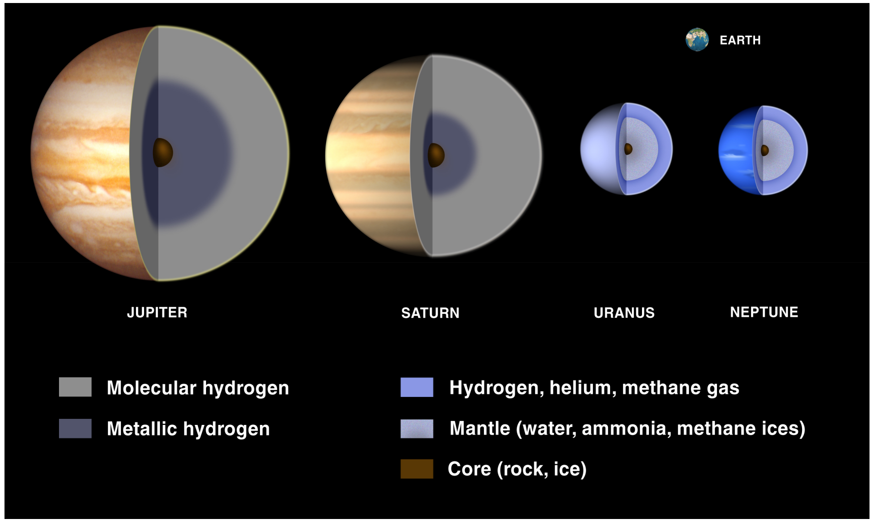
- Ab-initio modelling of MHD star-planet interactions with observed complex magnetic topologies and prediction of observational diagnosis (e.g. UV emission map)
- Potential strong impact on the evolution of the orbital architecture and planetary habitability (star – planetary atmosphere/magnetosphere interactions)


Giant planets

Tides in the dense core of giant planets

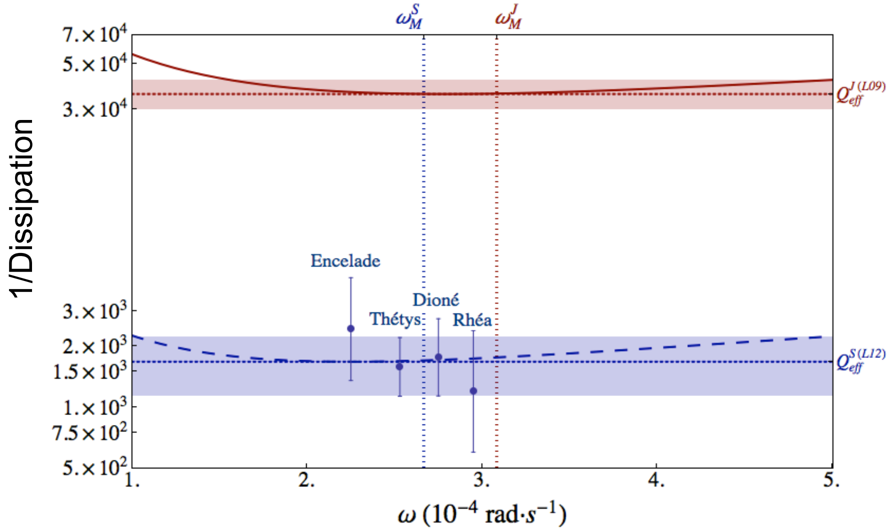
Internal structure

e.g. Guillot 1995



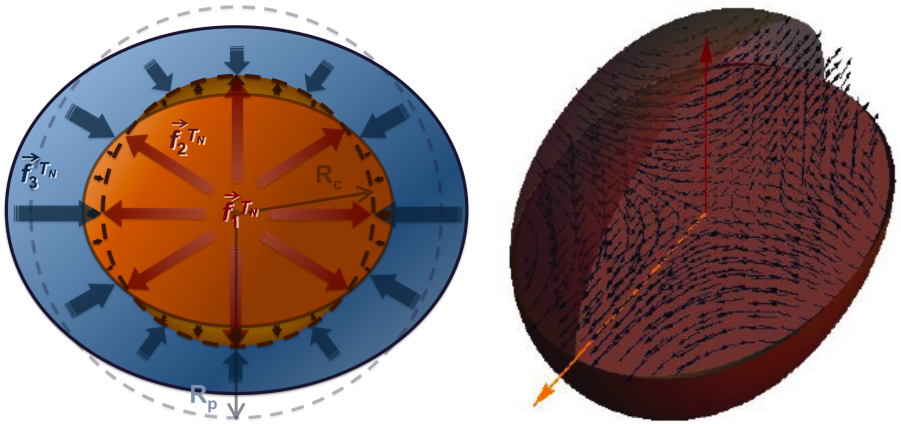
Application to gaseous giants

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



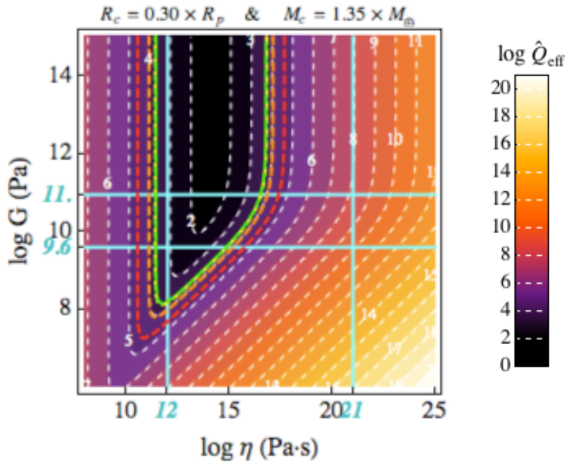
The inelastic rocky/icy core

Remus, Mathis, Zahn & Lainey 2012-15



Application to icy giants

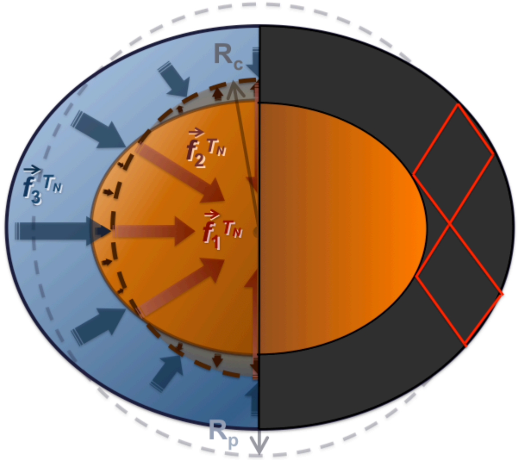
Remus, Mathis, Zahn, Lainey & Charnoz 2017



Towards integrated models for multi-layer planets

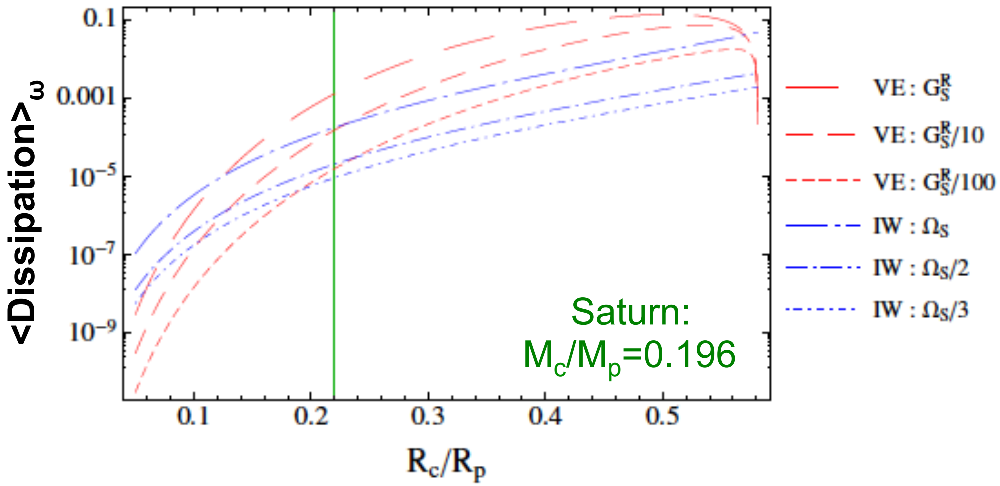
Remus, Mathis, Zahn & Lainey 2012

Ogilvie 2009, 2013



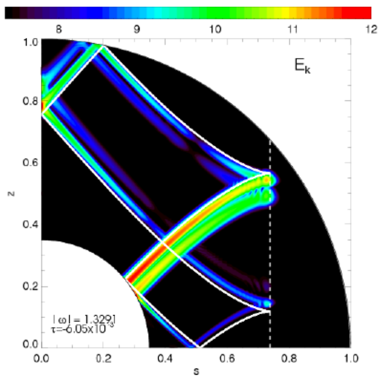
→ Integrated models needed for gaseous giant (and telluric) planets

Guenel, Mathis & Remus 2014



New physical ingredients in the atmosphere LUVOIR

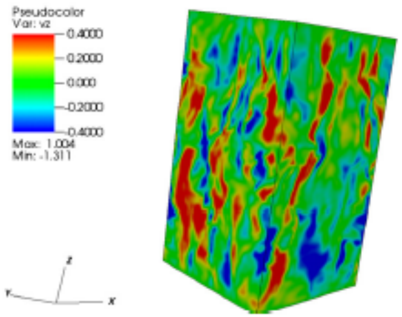
Zonal flows (driven by convection/tides)



Baruteau & Rieutord 2013

Guenel et al. 2016

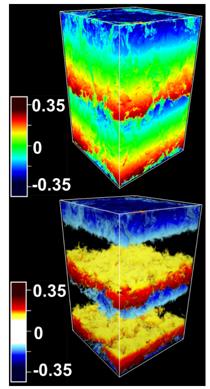
Convective turbulence

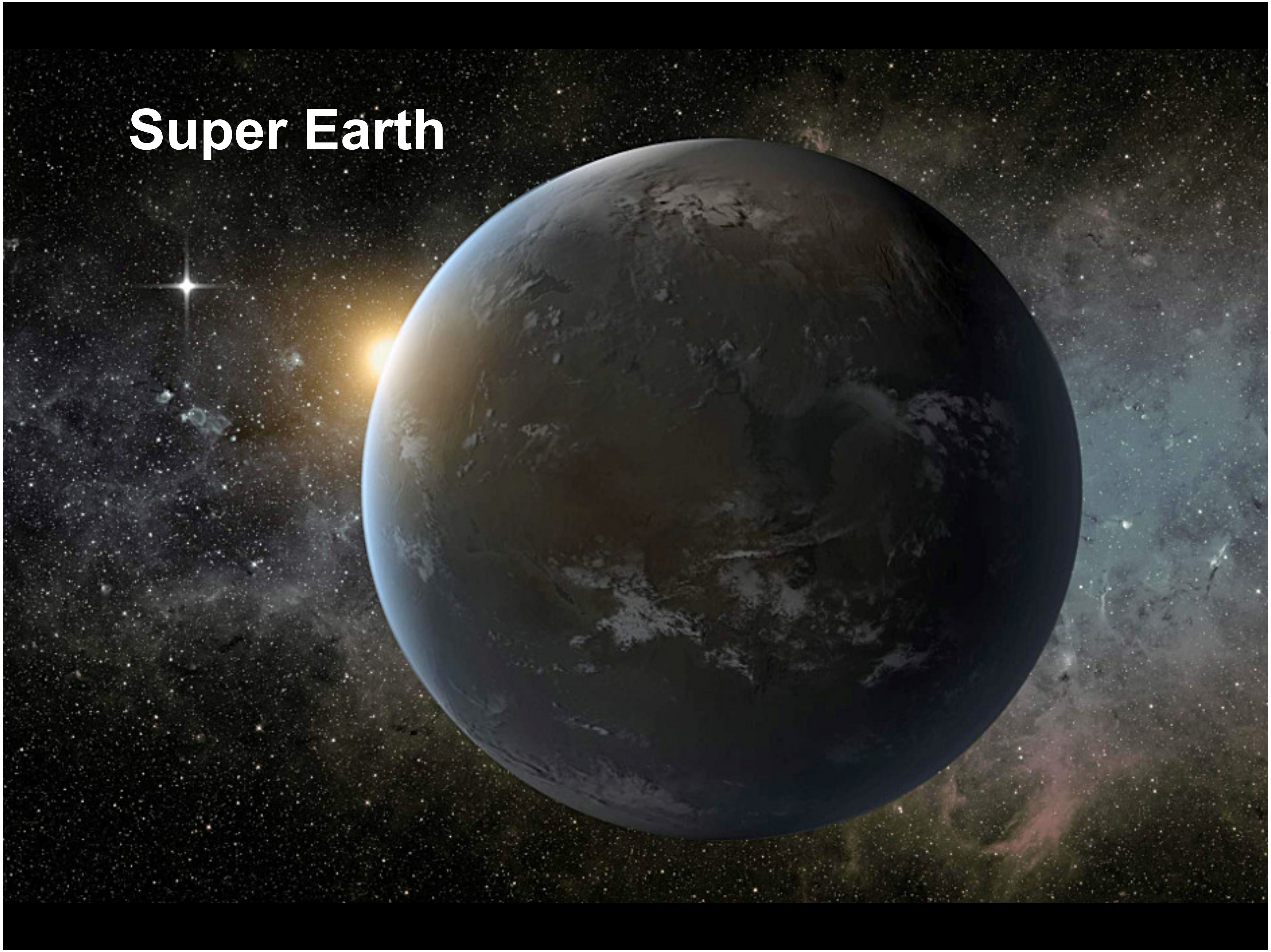


Double diffusive instabilities

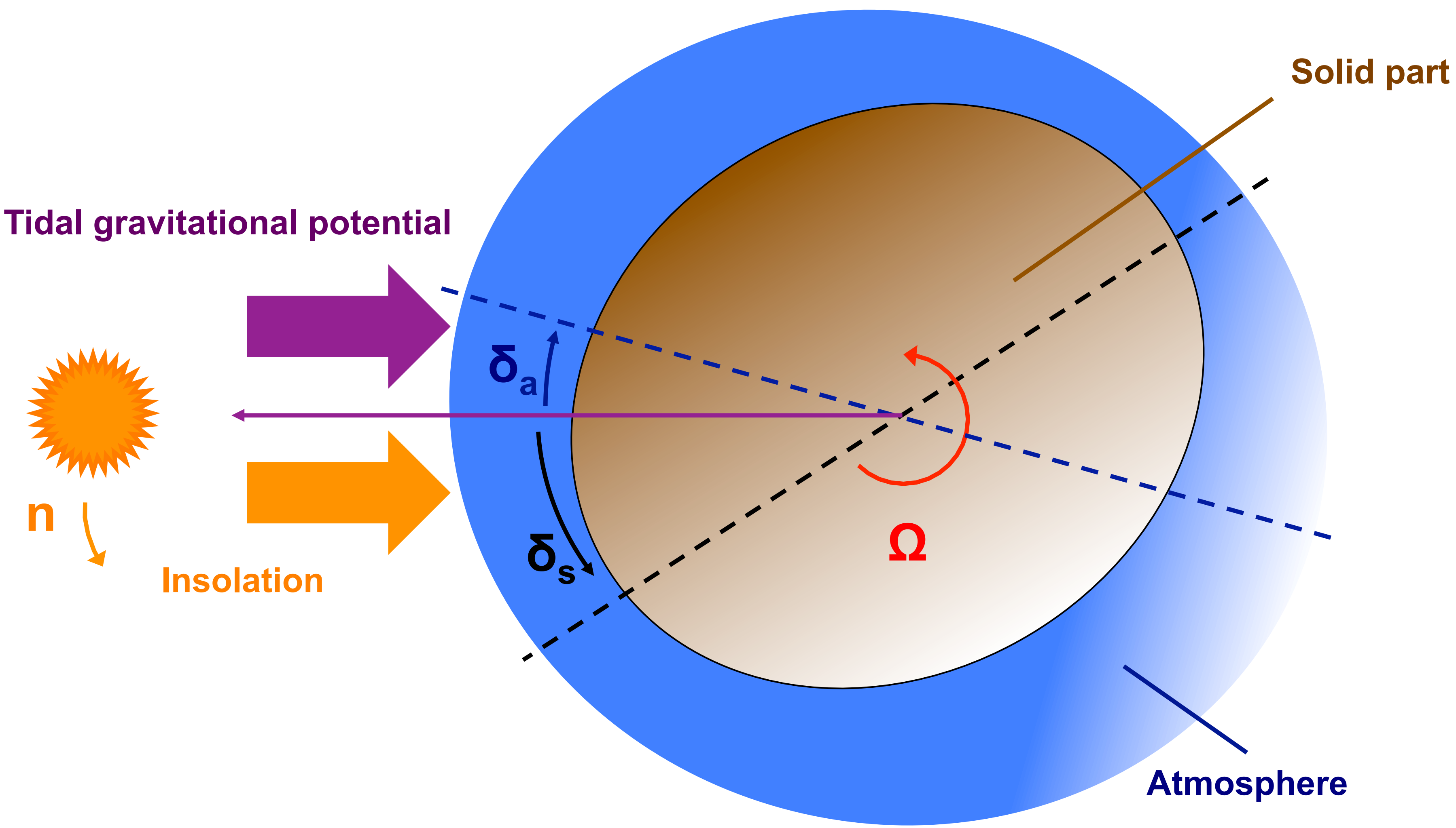
Mathis et al. 2016 (Barker et al. 2014)

André et al. 2017 (Stellmach et al. 2011)




Super Earth

Tides in telluric planets

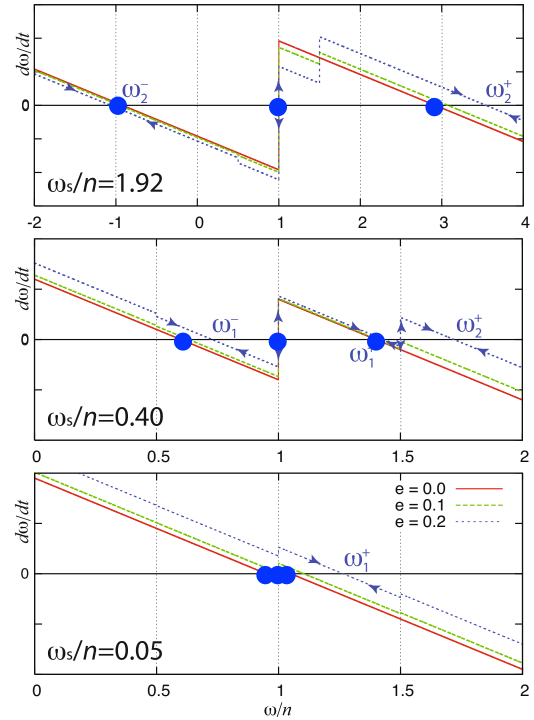


From Venus to super Earth in the HZ of low-mass stars: rotation equilibria

SOLID PART + **ATMOSPHERE**

↓ **Solid torque** ↓ **if alone, synchronized**

↓ **Atmospheric torque** ↓ **Surface pressure oscillations** ↓ **non-synchronized**

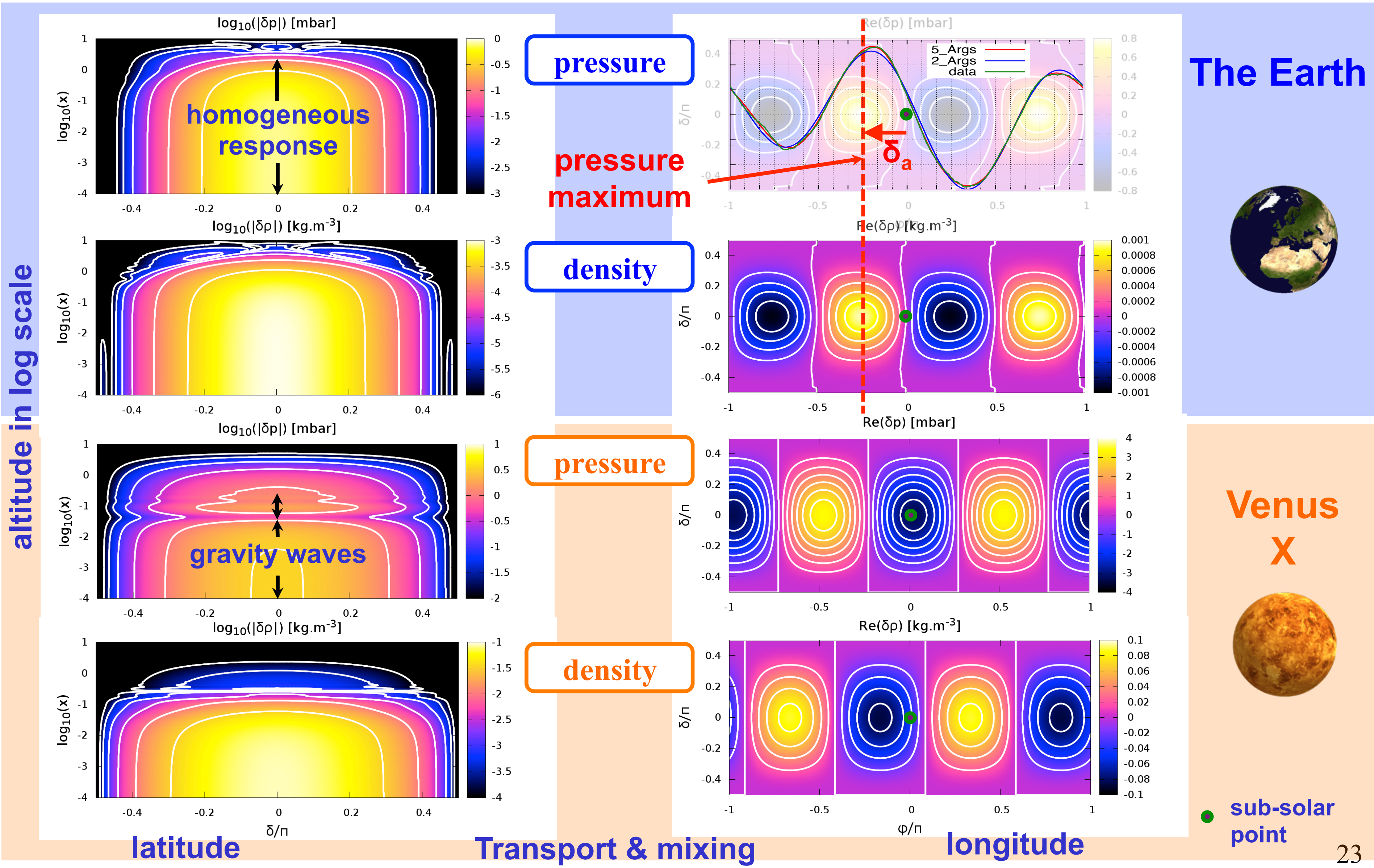


Correia, Levrard, Laskar (2008)

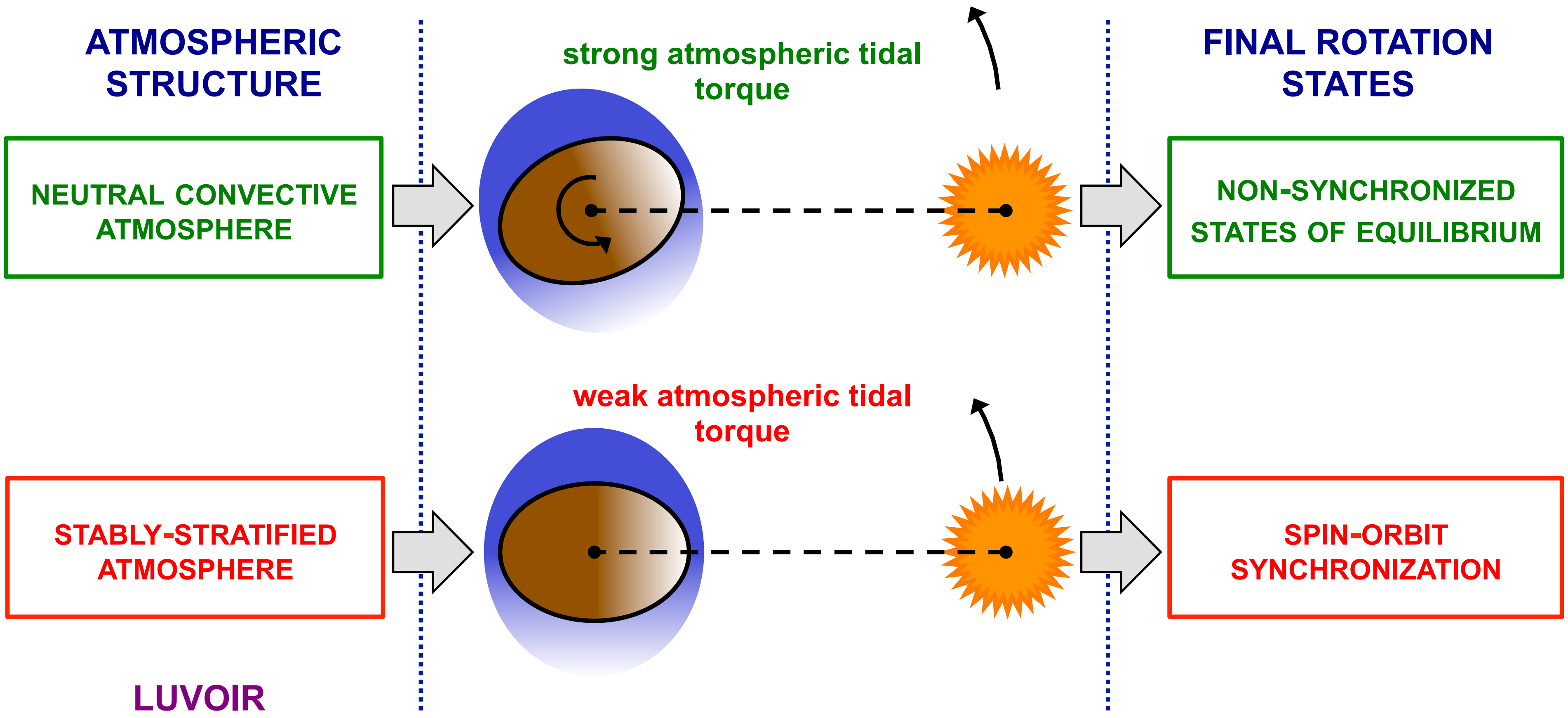
[see also Gold & Soter (1969), Correia, Laskar, Néron de Surgy (2001), Correia & Laskar (2003), Leconte et al. (2015)]

New global models for atmospheric tides

The case of an isothermal stably stratified atmosphere



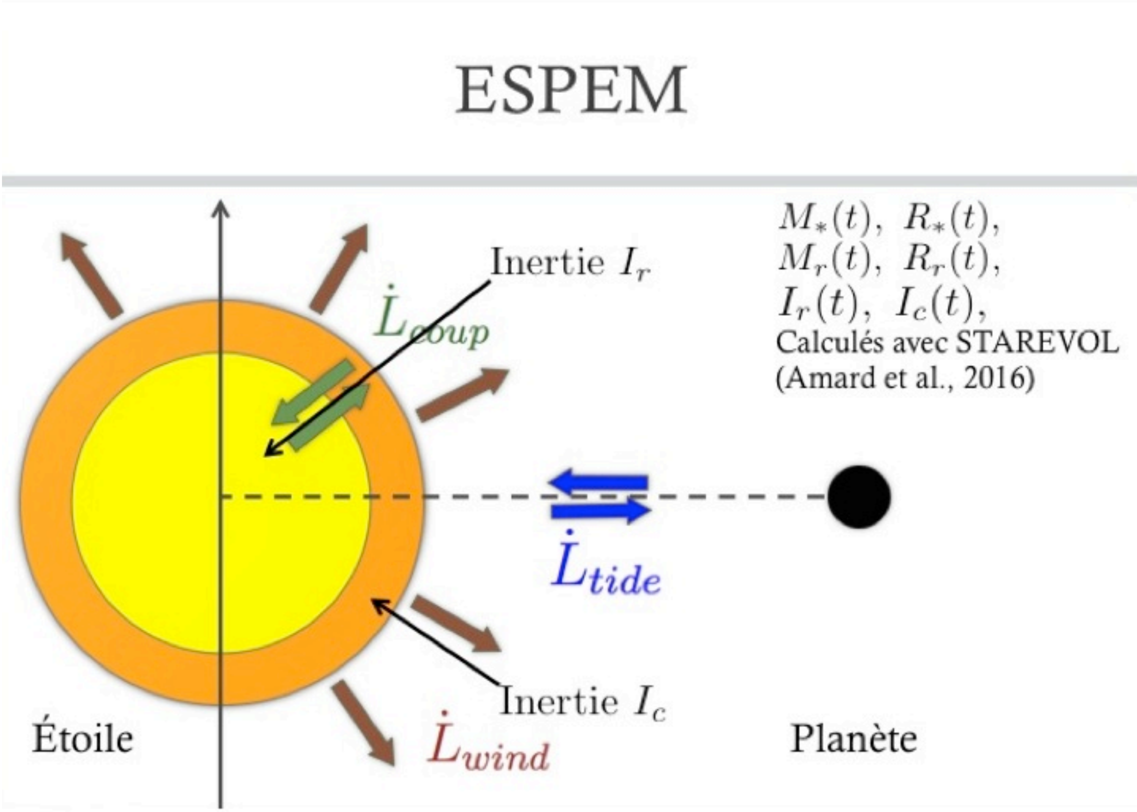
Prediction



Auclair-Desrotour, Laskar, Mathis (2016a)

Consequences on planetary habitability?

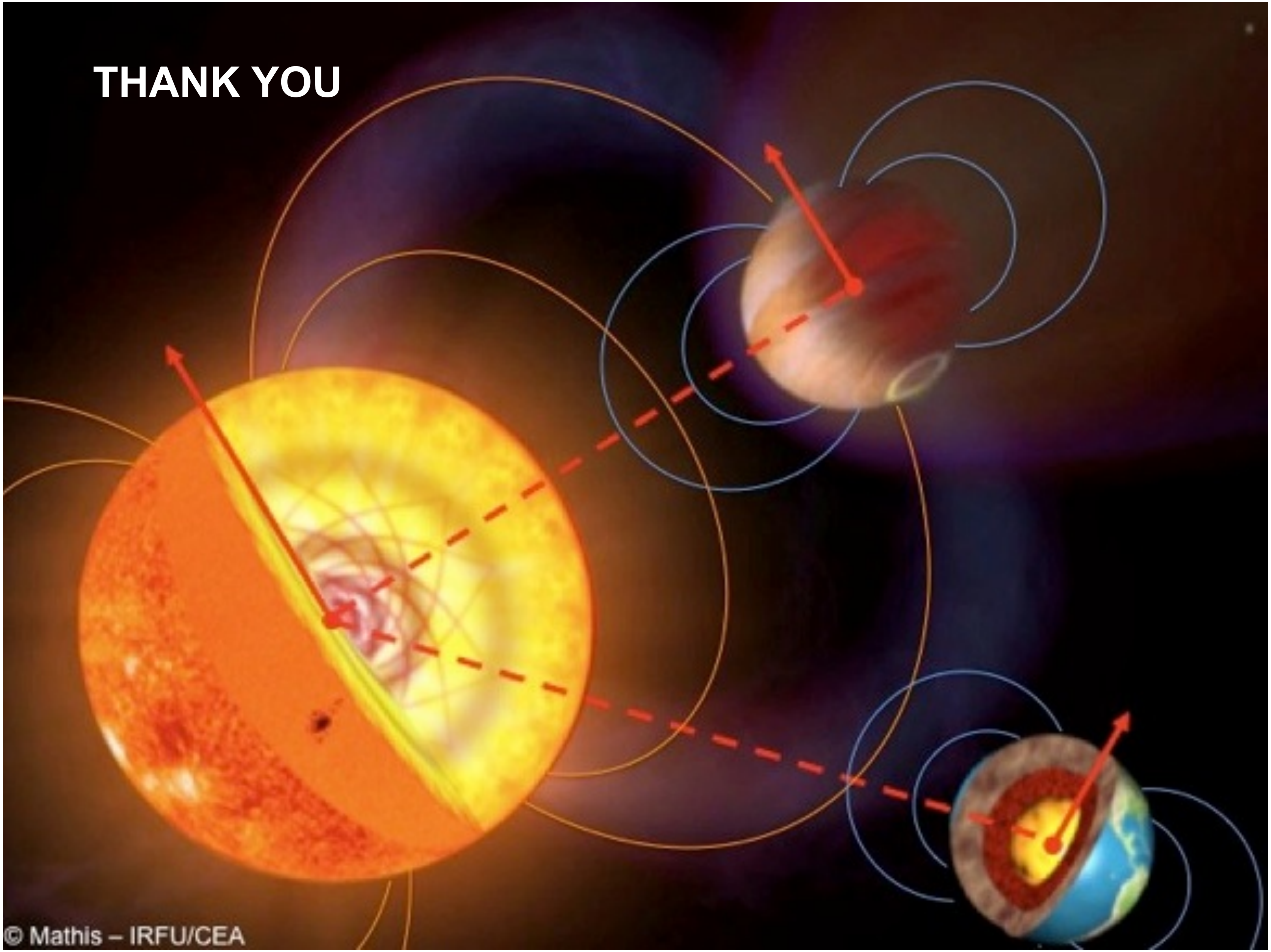
The future big picture



Benbakoura et al. 2017

Dynamical code taking into account simultaneously
ab-initio models of tidal and magnetic star-planet interactions

→ Simulation of the orbital architecture of planetary systems
along the evolution of the host star


THANK YOU
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