

Star-Planet Interactions

Habitable Zone and Drake Equation

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Environnement*

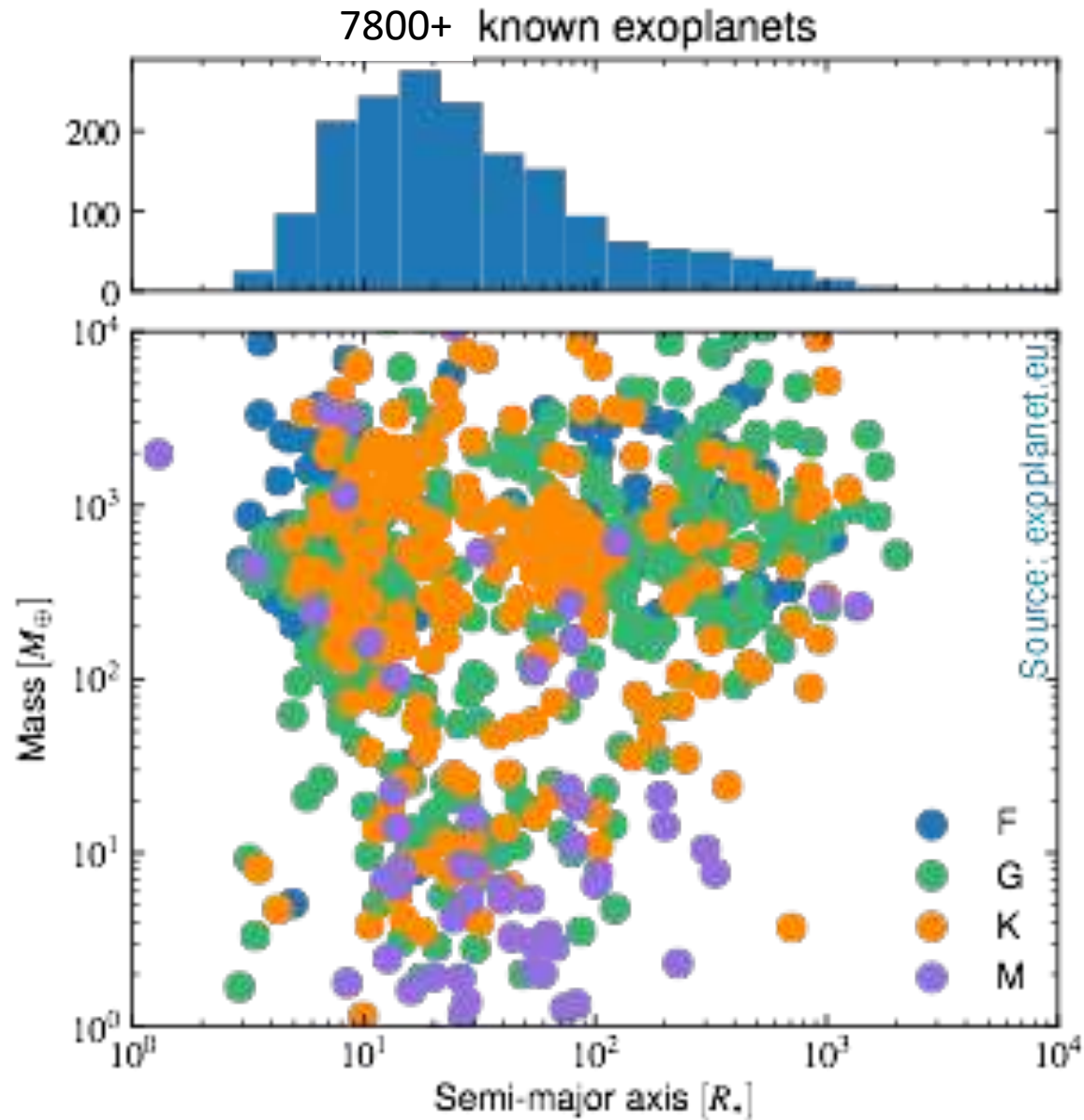
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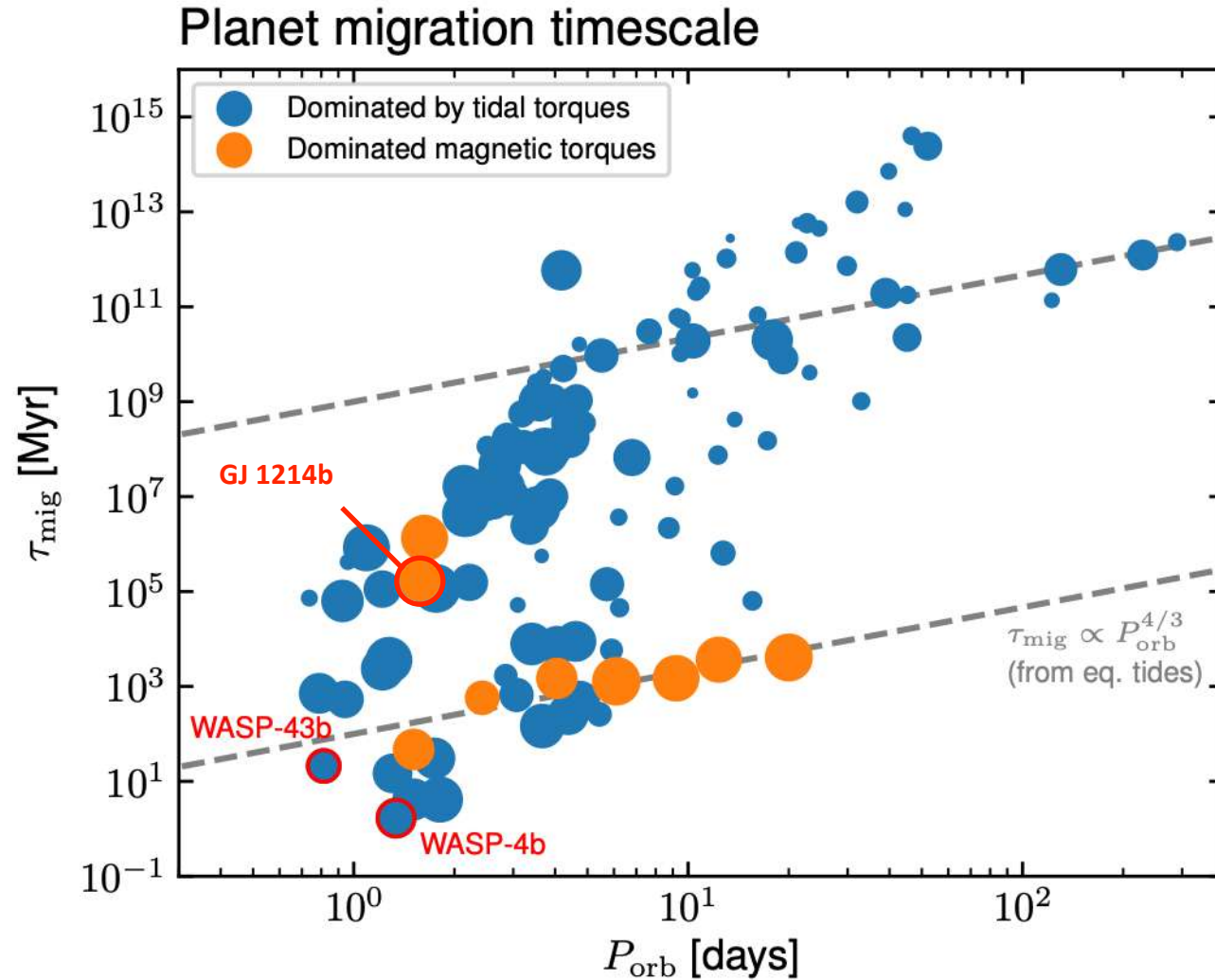
Exo - Planetary Systems

Many are very close exoplanets (because of obs bias)



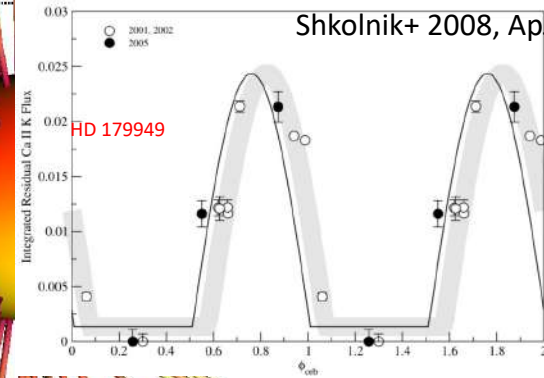
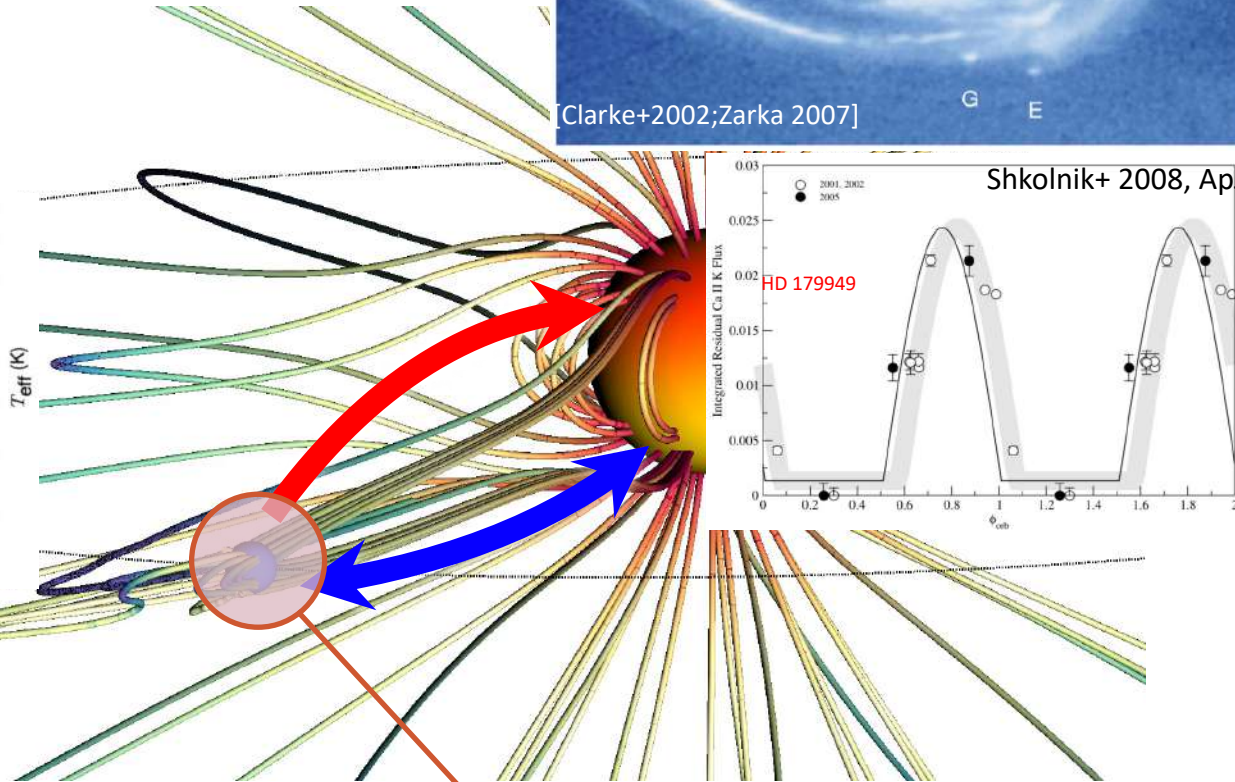
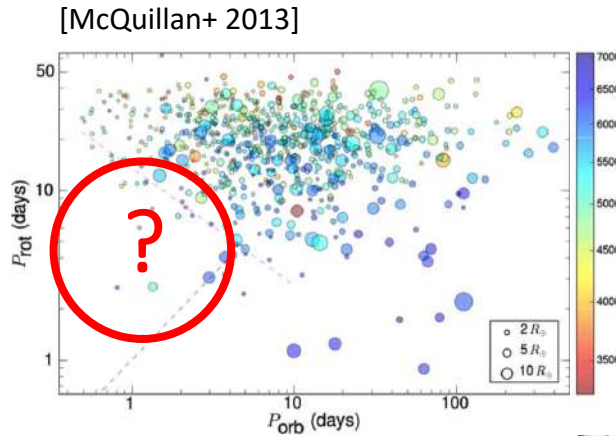
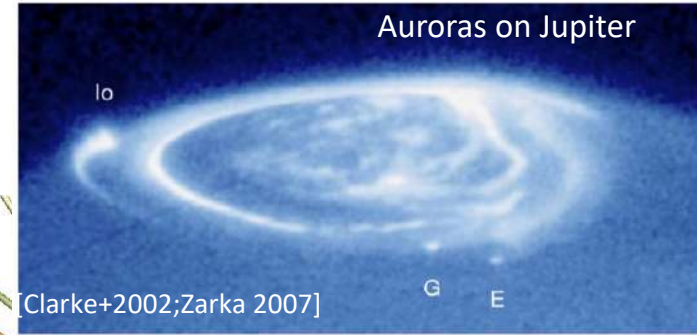
Modelling star-planet interactions

Comparing magnetic vs tidal migration timescales



Sub-Alfvénic interaction: important effects

Energy flux (Alfvénic perturbations)



Momentum exchange (planet migration, spin up/down of the star)

Localized emissions and planetary winds

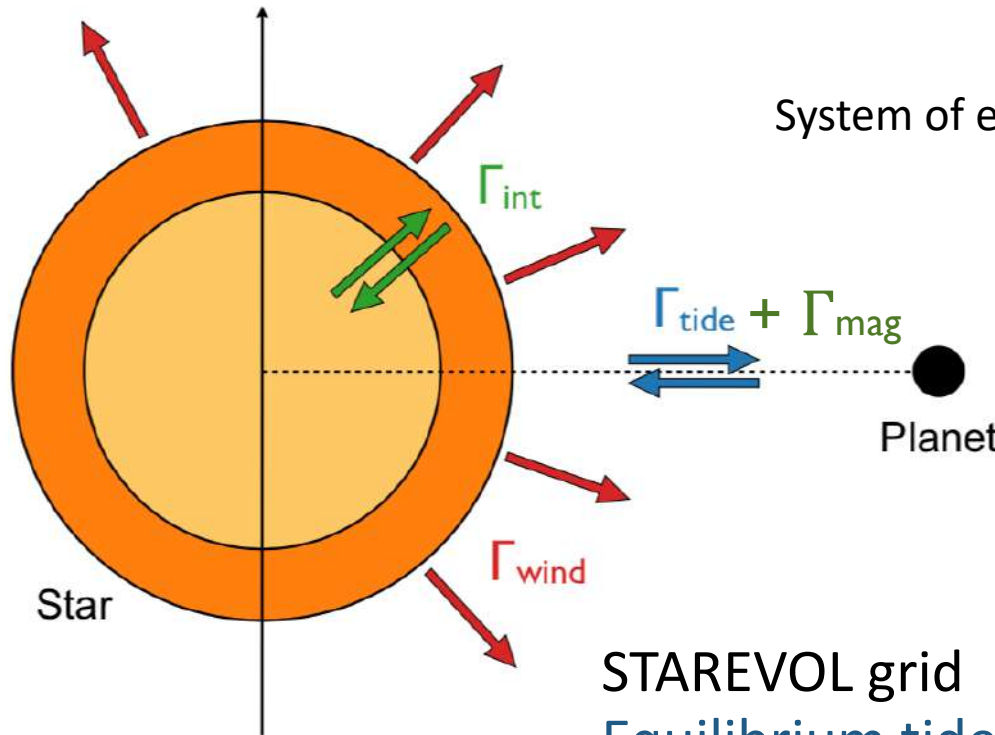
Modelling star-planet interactions with ESPEM

ESPEM : a 1D numerical model \longrightarrow Coplanar circular star-planet system

\searrow Secular evolution of the semi-major axis and the stellar rotation rate

Two bodies, multiple interactions

Benbakoura et al. (2019)



System of equations (angular momentum balance) :

$$\frac{dL_{\text{orb}}}{dt} = -\Gamma_{\text{tide}} - \Gamma_{\text{mag}}$$

$$\frac{dL_{\text{r}}}{dt} = -\Gamma_{\text{int}}$$

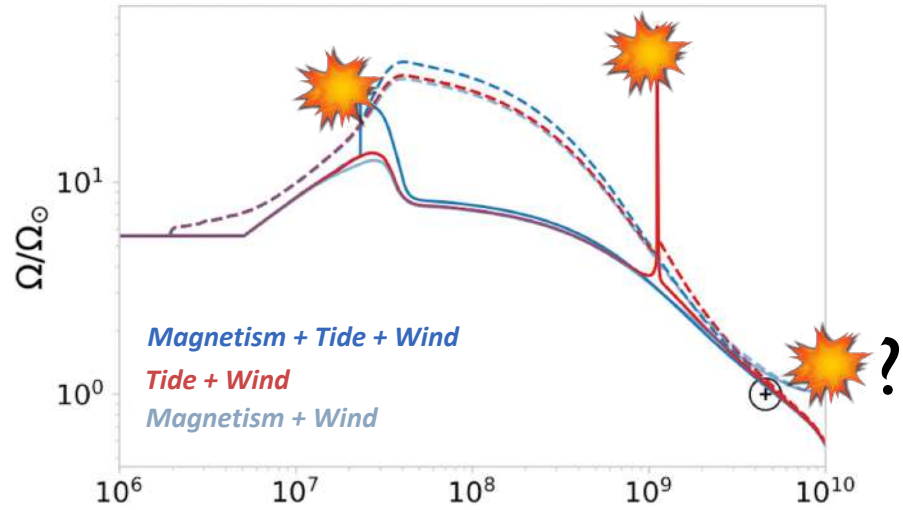
$$\frac{dL_{\text{c}}}{dt} = \Gamma_{\text{int}} + \Gamma_{\text{tide}} - \Gamma_{\text{wind}} + \Gamma_{\text{mag}}$$

STAREVOL grid

Equilibrium tide + Dynamical tide

Magnetic (wind-planet) torque

Modelling star-planet interactions with ESPEM



$$M^* = 1 M_{sun}$$

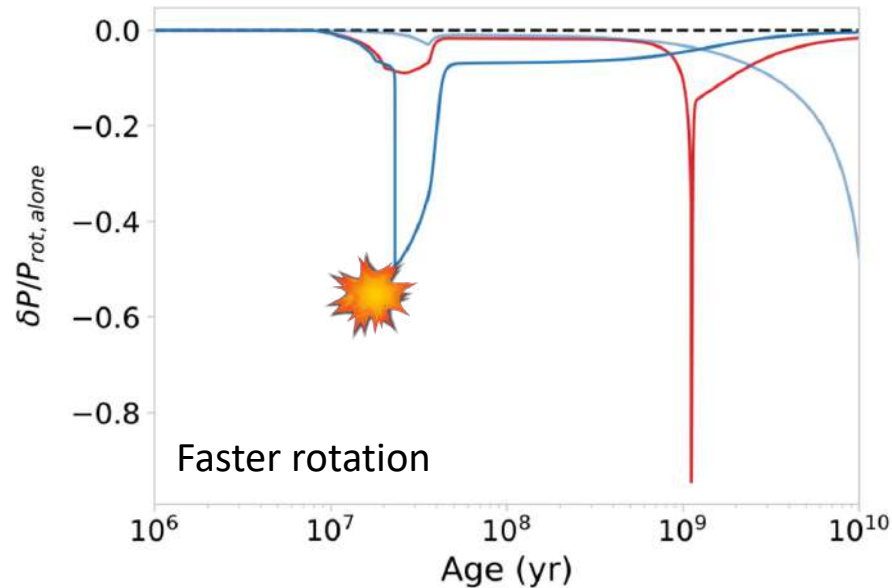
$$P_{rot, ini} = 5 d$$

$$m_p = 1 M_{Jup}$$

$$R_p = 1 R_{Jup}$$

$$a_{ini} = 0.03 UA$$

$$B_p = 10 G$$



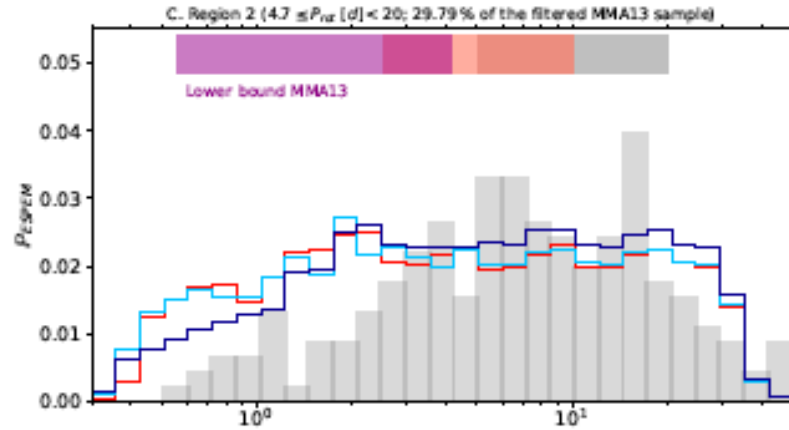
Planet destruction = spin-up of the star

Magnetic torques: earlier destruction

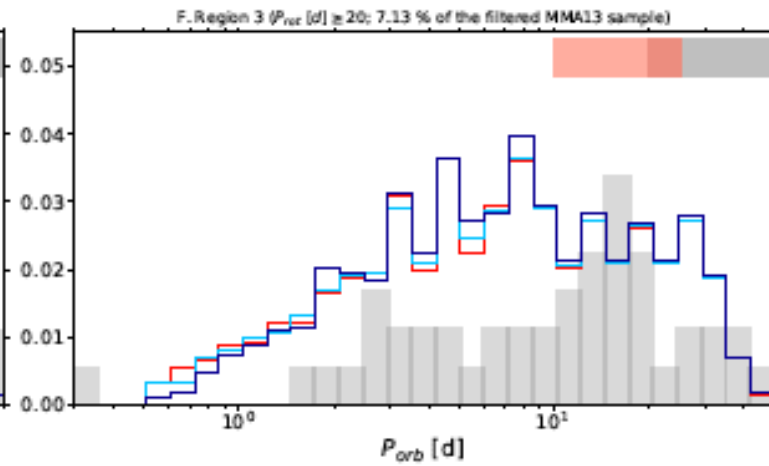
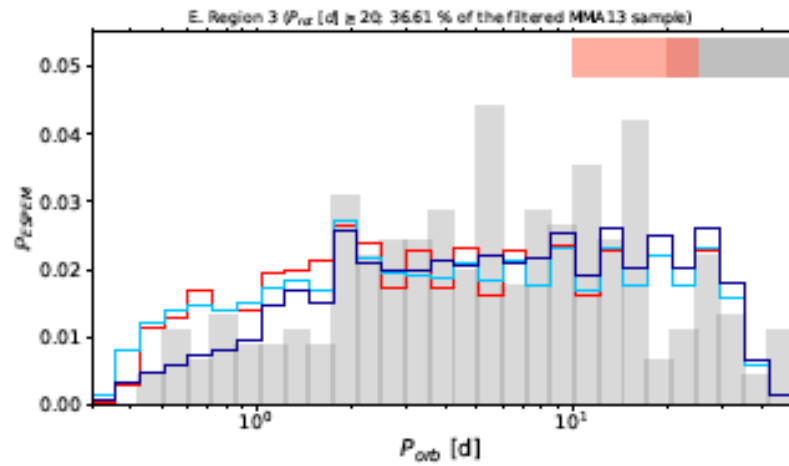
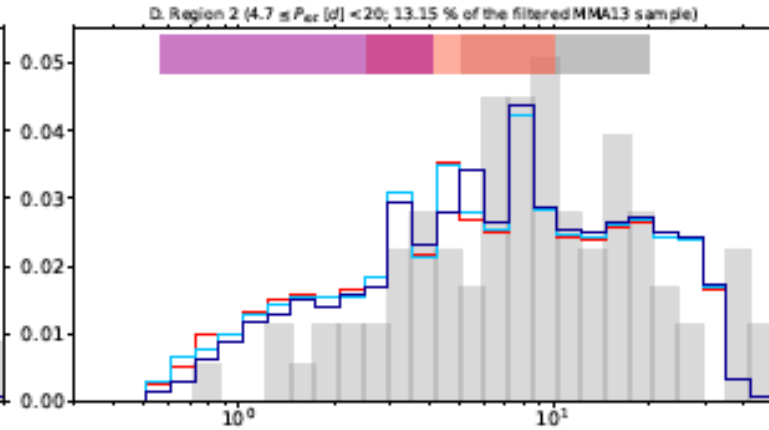
Magnetic torques: earlier stellar spin-up

$$\Delta P = P_{rot, with planet} - P_{rot, without planet}$$

Super-Earths ($M_p < 10 M_E$)



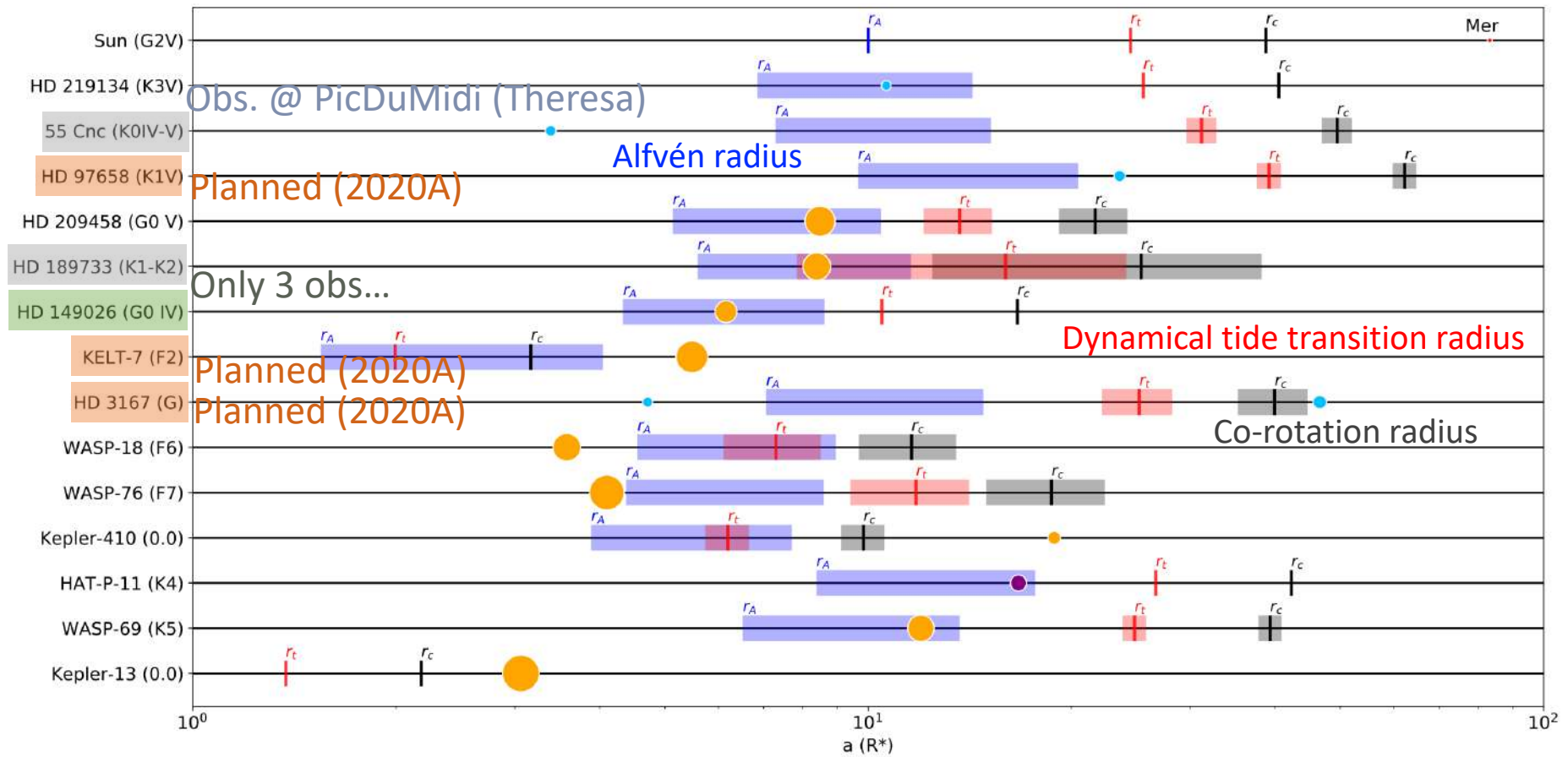
Giants planets ($M_p > 10 M_E$)



Tide only, Tide + 1 G, Tide + 10 G planetary field

Modelling star-planet interactions

Brightest targets for star-planet magnetic interactions



Compared to the planets in the solar system,
planets orbiting close to their stars

Interact with a **stronger** stellar wind **magnetic field**

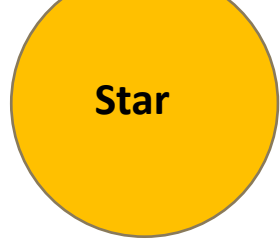
Develop stronger tidal interactions

Are exposed to stronger radiation from their host

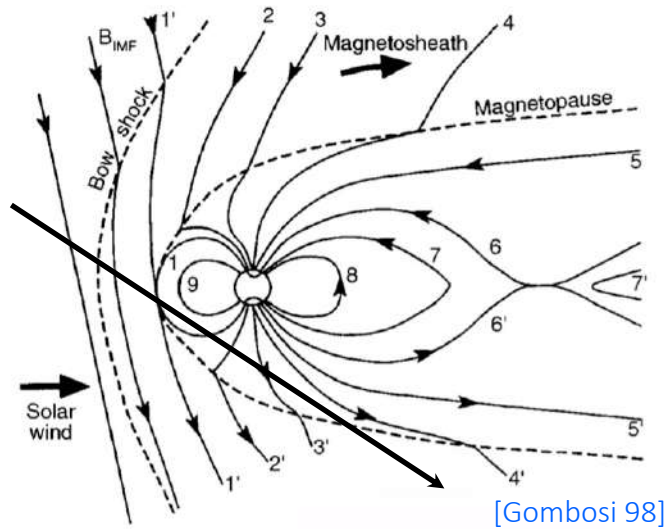
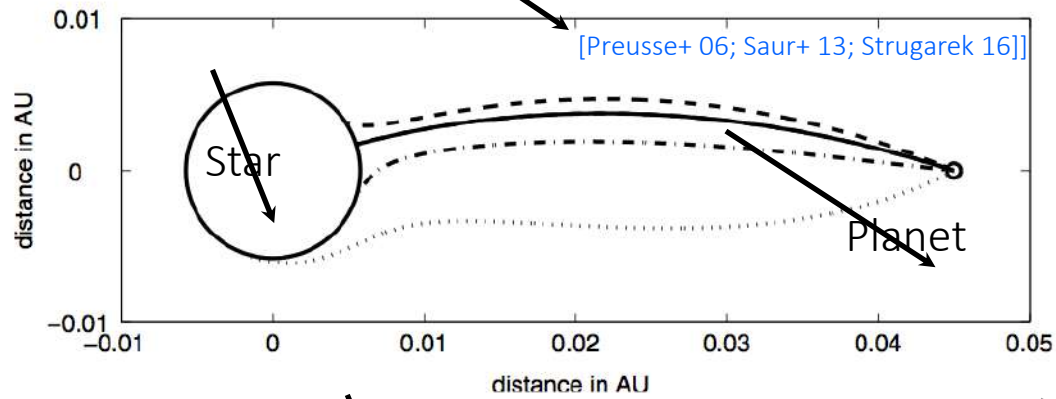
Orbit in a denser interplanetary medium

...

Star-planet magnetic interaction regimes



Sub-Alfvénic interaction:
star-planet **connection**



Super-Alfvénic interaction:
shock formation

Alfvén radius

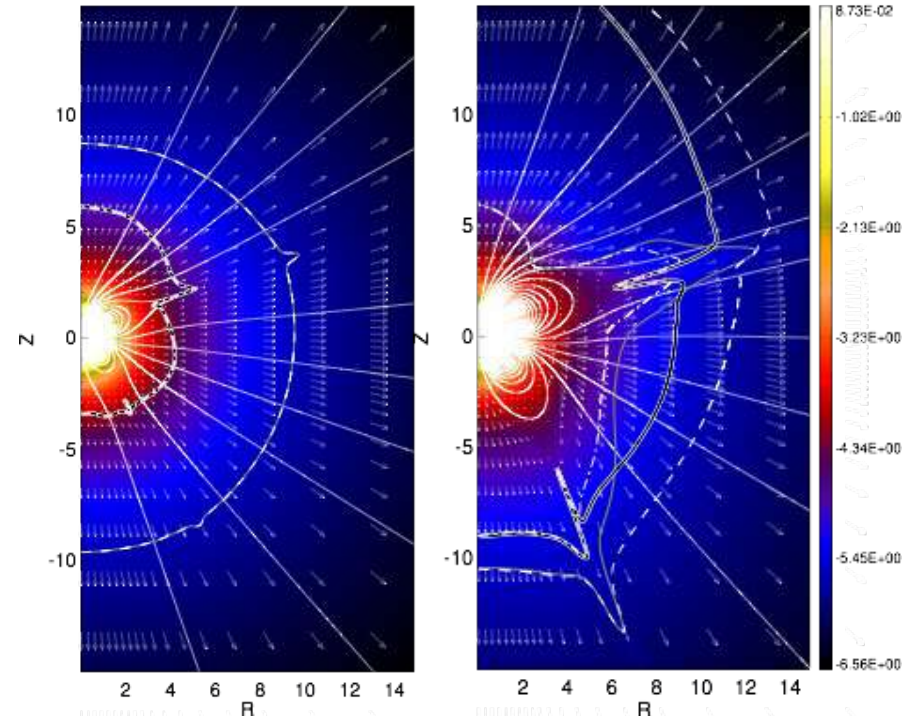
Surface magnetic field and Zeeman Doppler Imaging

Spectropolarimeters:

Narval 375nm à 1050nm @TBL
& Espadons (370nm à 1000 nm) @CFHT

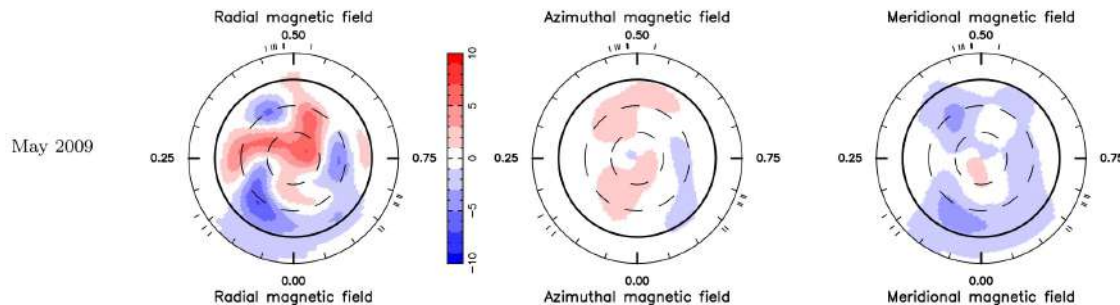
Zeeman Doppler Imaging consist in extracting Stokes parameters as a function of phase, on several wave-lengths to increase signal over noise ratio.

Works well on fast rotators.



The Sun at maximum of cycle 22

Young K-Star TYC-0486-4943-1

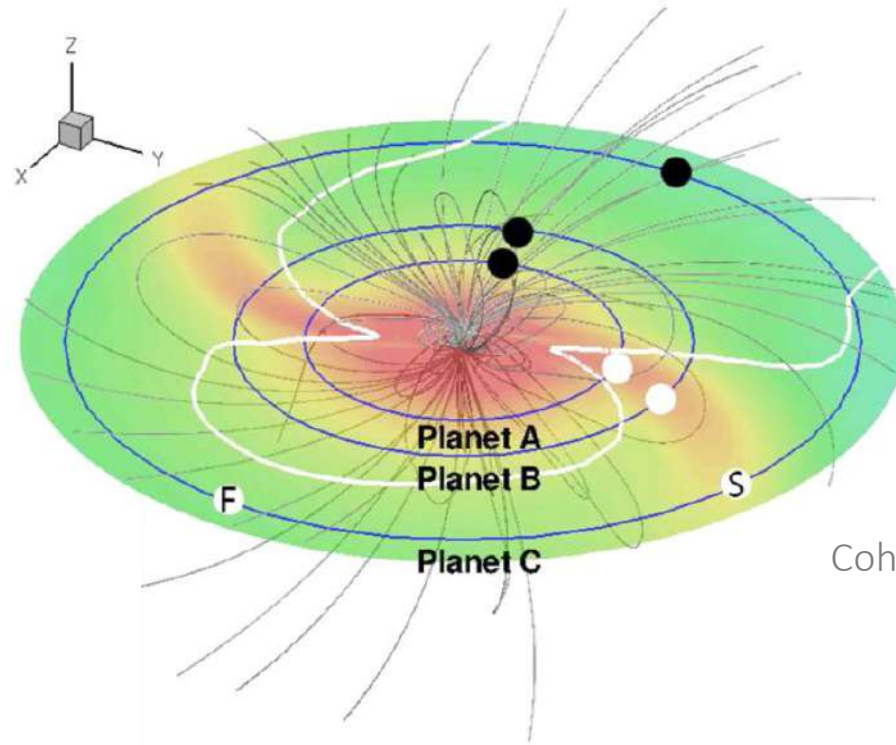


Regression methods ->

List of spherical harmonics decomposition coefficients.

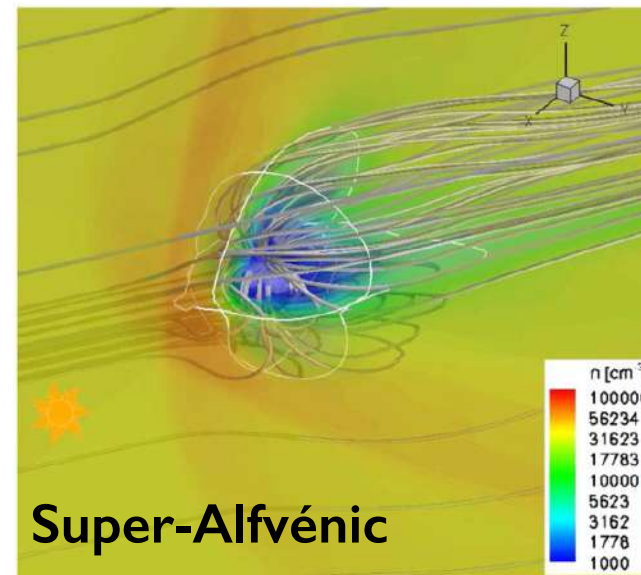
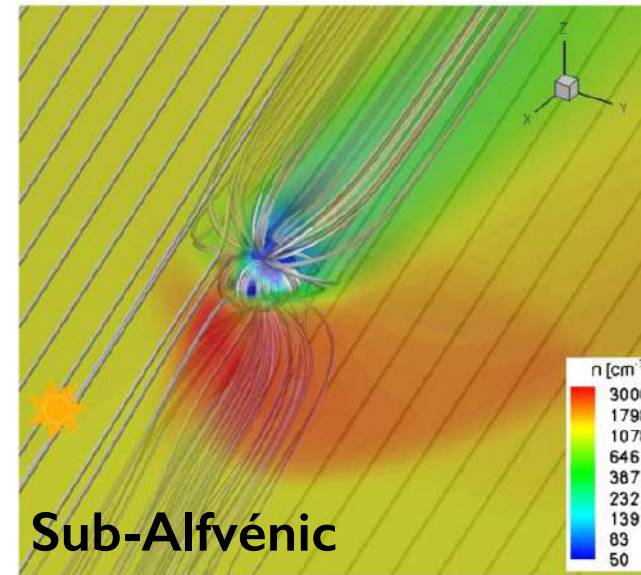
A typical case with multiple interaction regimes:

M-dwarf EV Lac



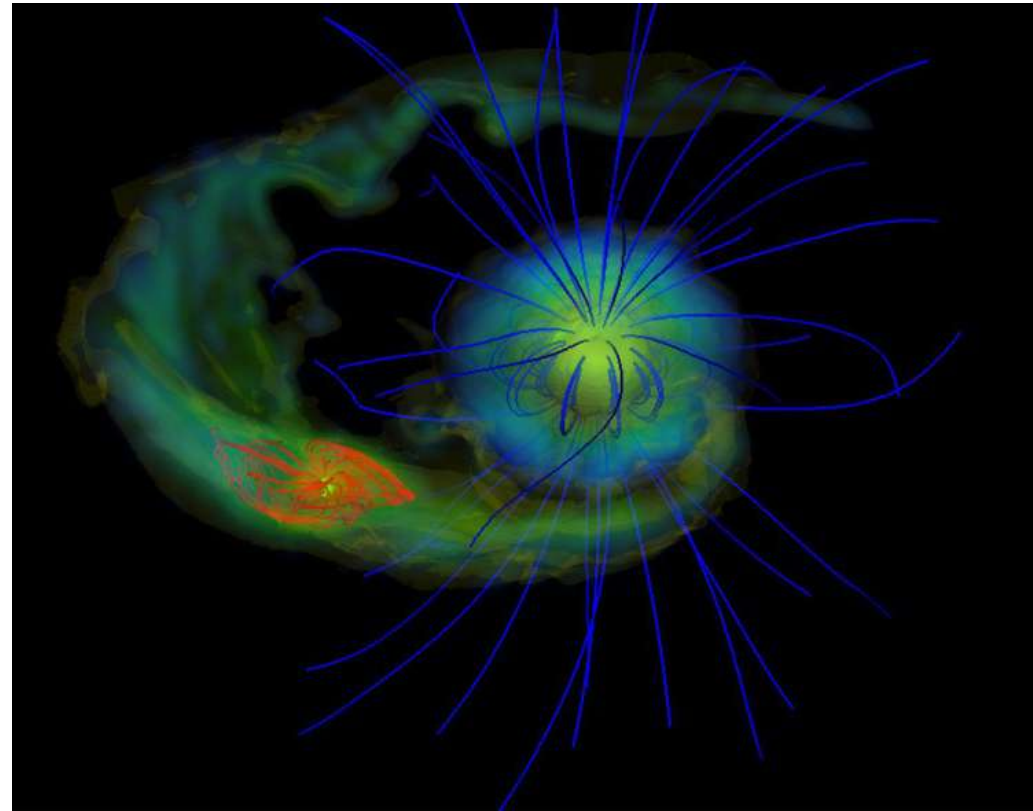
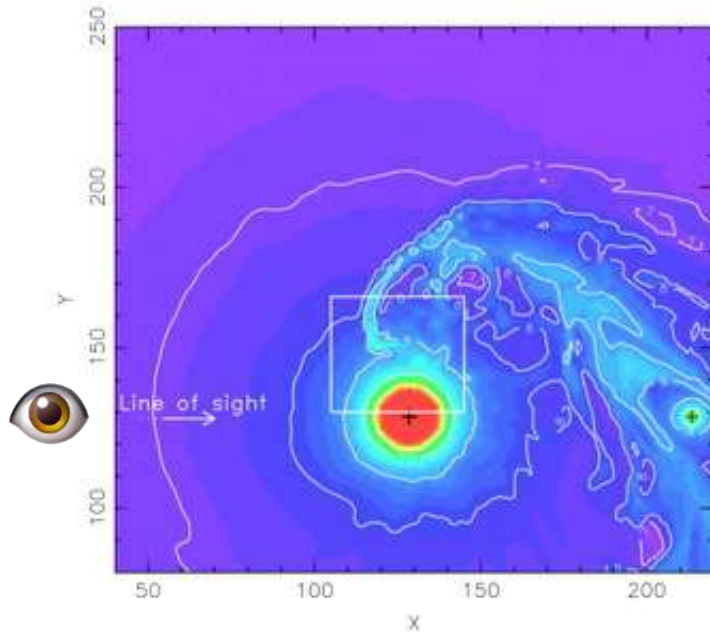
Cohen+ 2014

- Alfvén surface shape
- Relative orbital velocity
- Planetary magnetic field



Planetary 'winds' and material accretion on the host

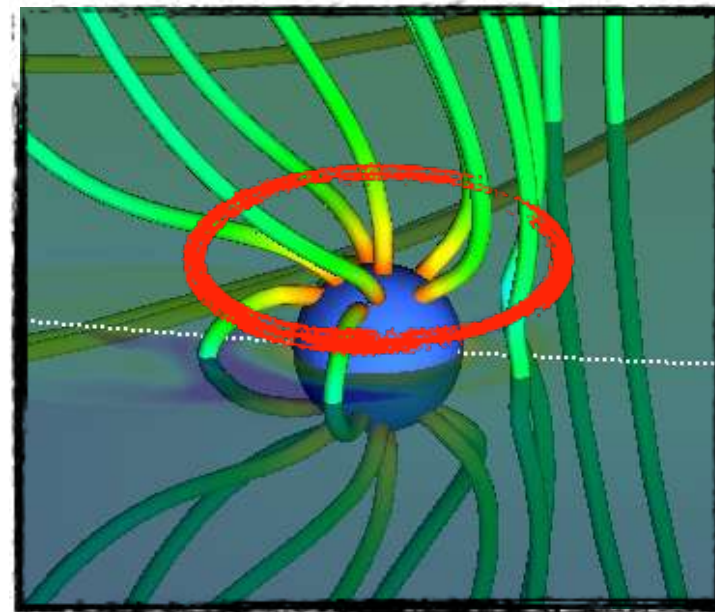
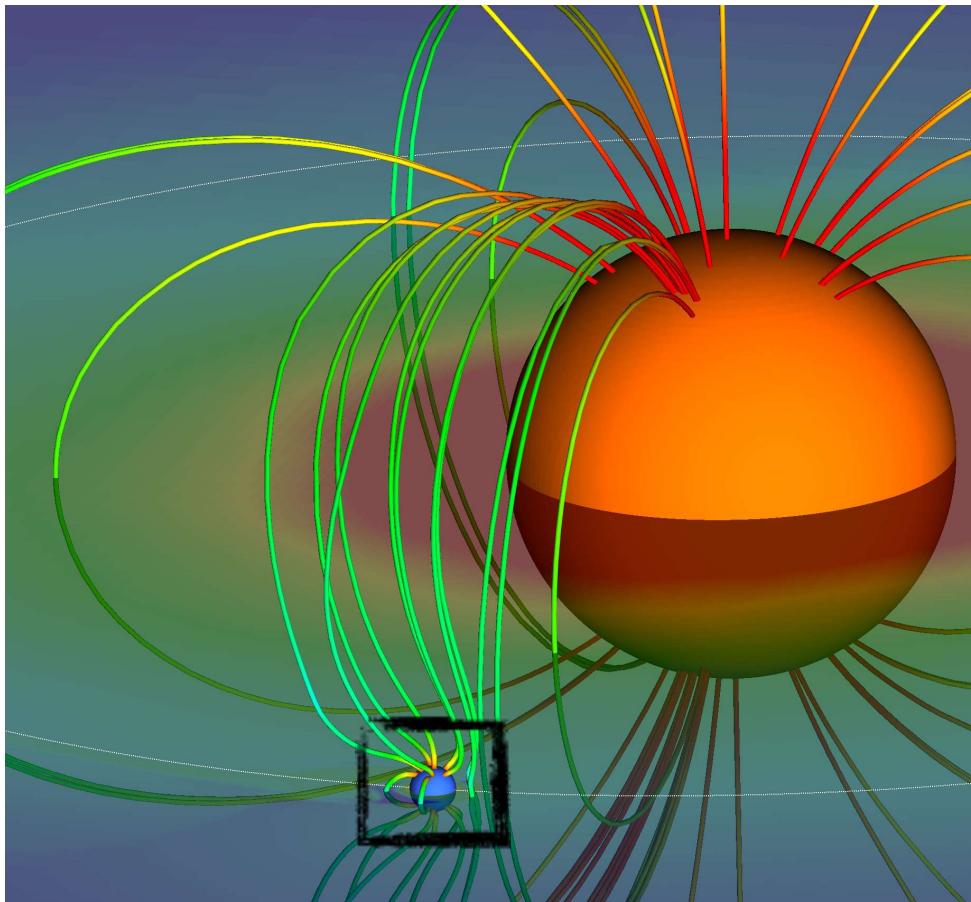
Different scenarios for the interaction, in some of them some planetary (atmospheric) material is able to fall onto the central star.



This mechanism promotes the monitoring of the central star **out of transit** due to the phase lag

- May a planet migrate due to magnetic interactions?
- What are the associated time-scales?

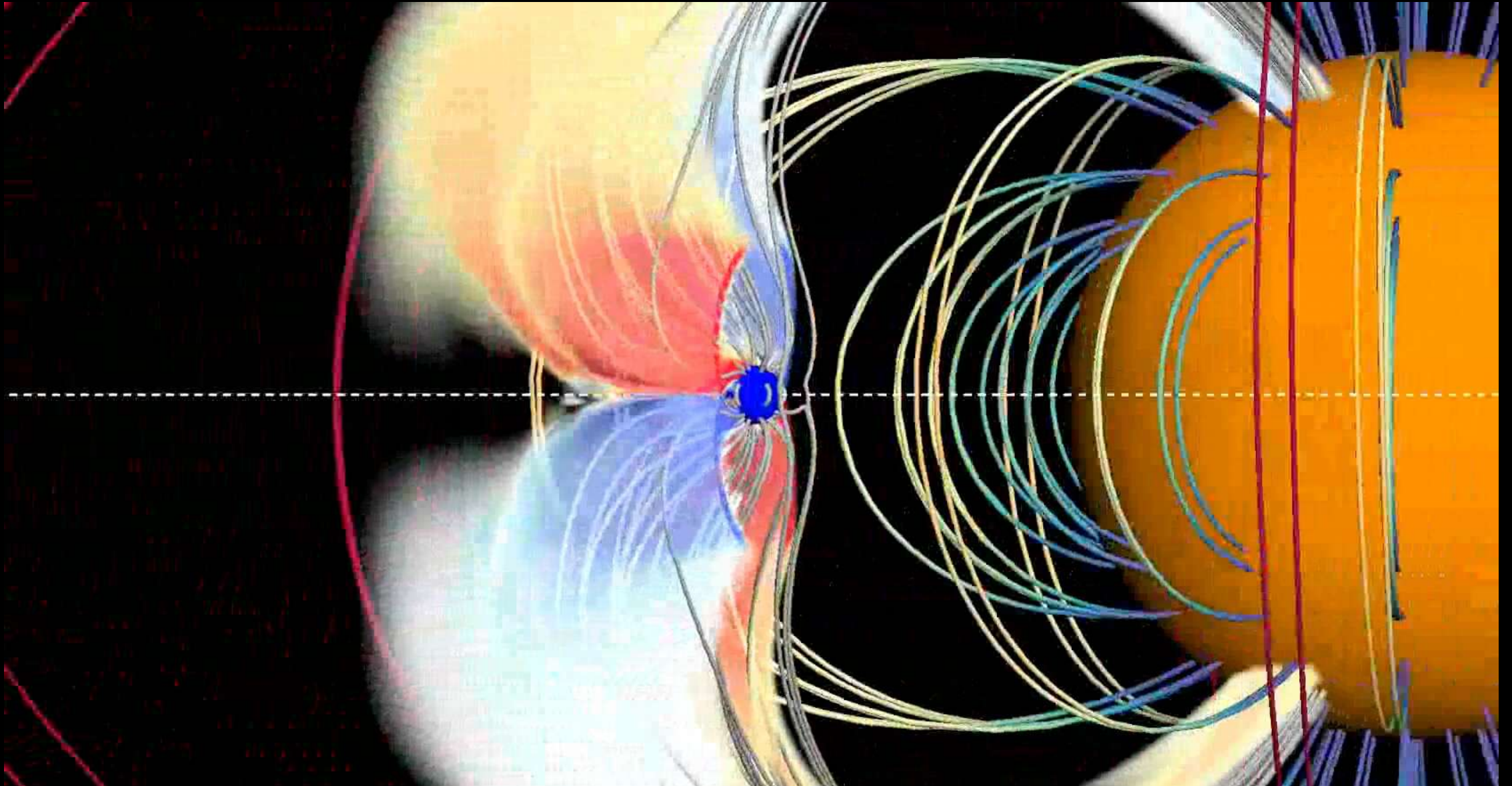
Origin of the planet migration: a 3D picture



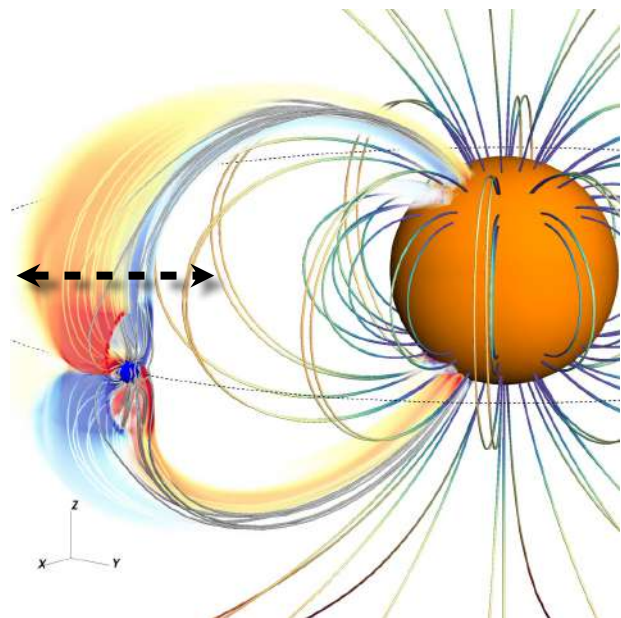
Integrate the flux of angular momentum on concentric spheres around the planet

The magnetic torque originates mainly from the connection of the planet's field to the ambient magnetic field

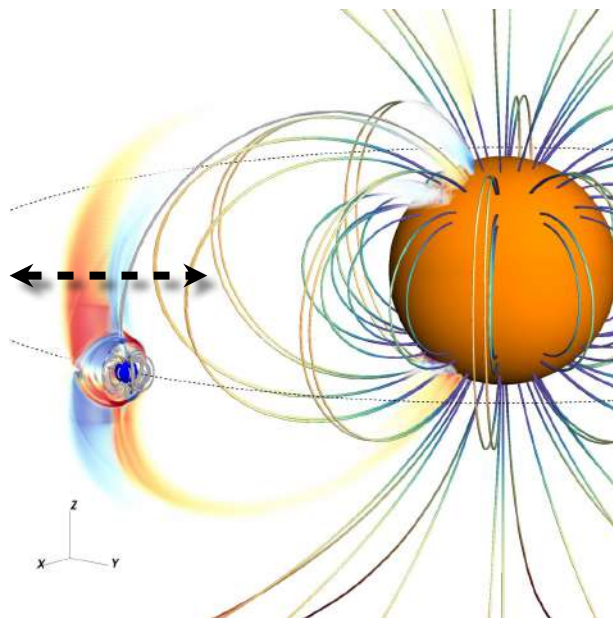
Star-Planet Interaction and Alfvén wings



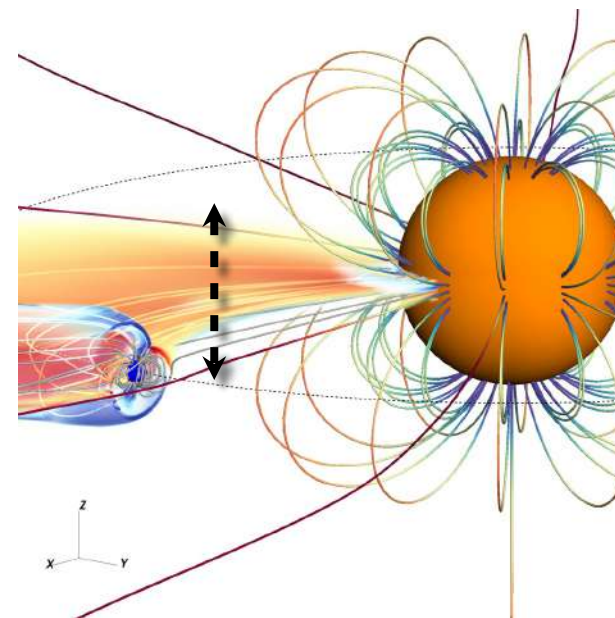
3D modelling of star-planet interactions



Two strong Alfvén wings



Two weak Alfvén wings

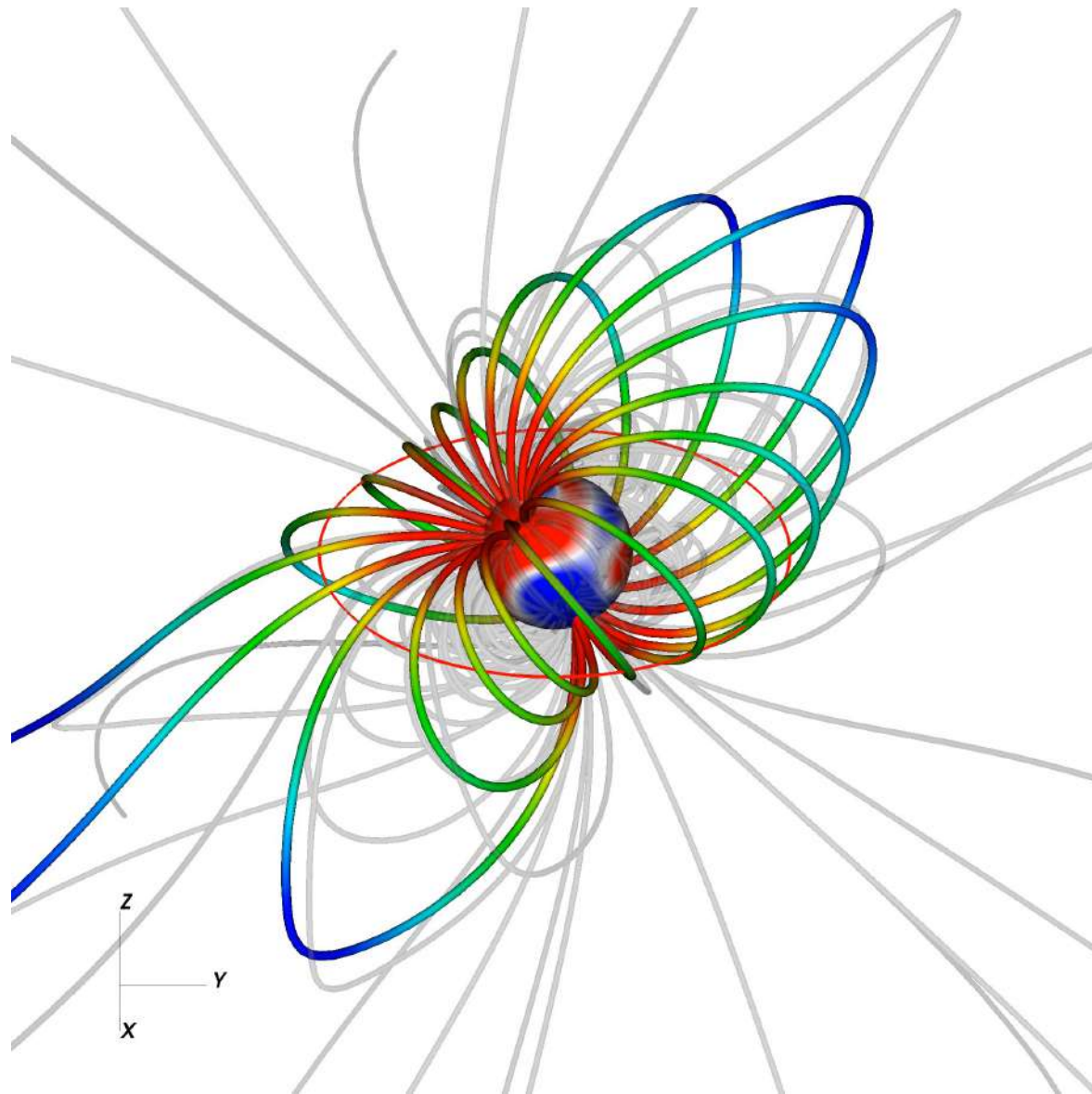


One strong Alfvén wing

Alfvén wings foot point localized at specific latitude and longitude

Alfvén wing foot point localized at the equator over a large longitudinal range

Application: Kepler 78 wind model using an observed ZDI map

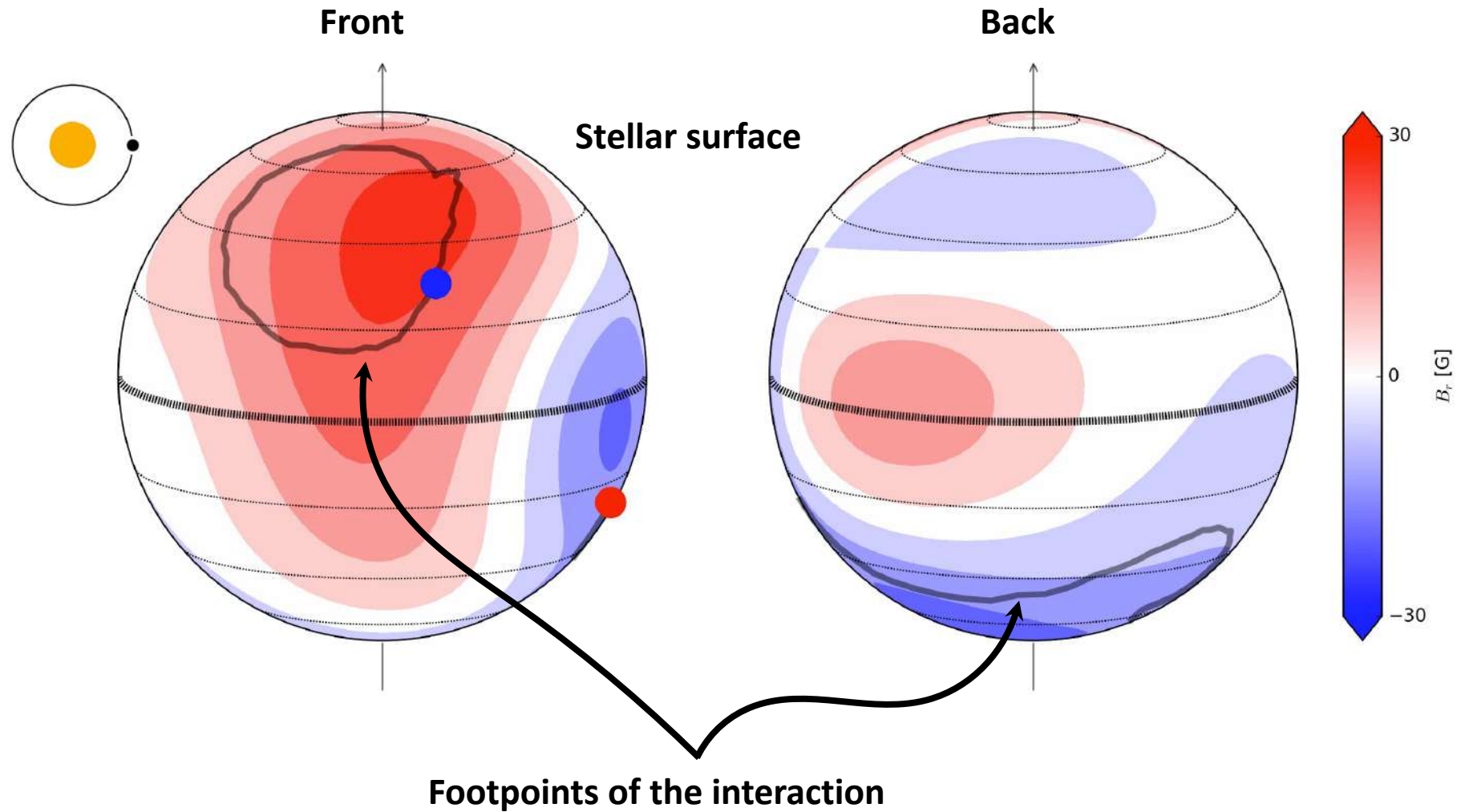


Stellar and Planet parameters

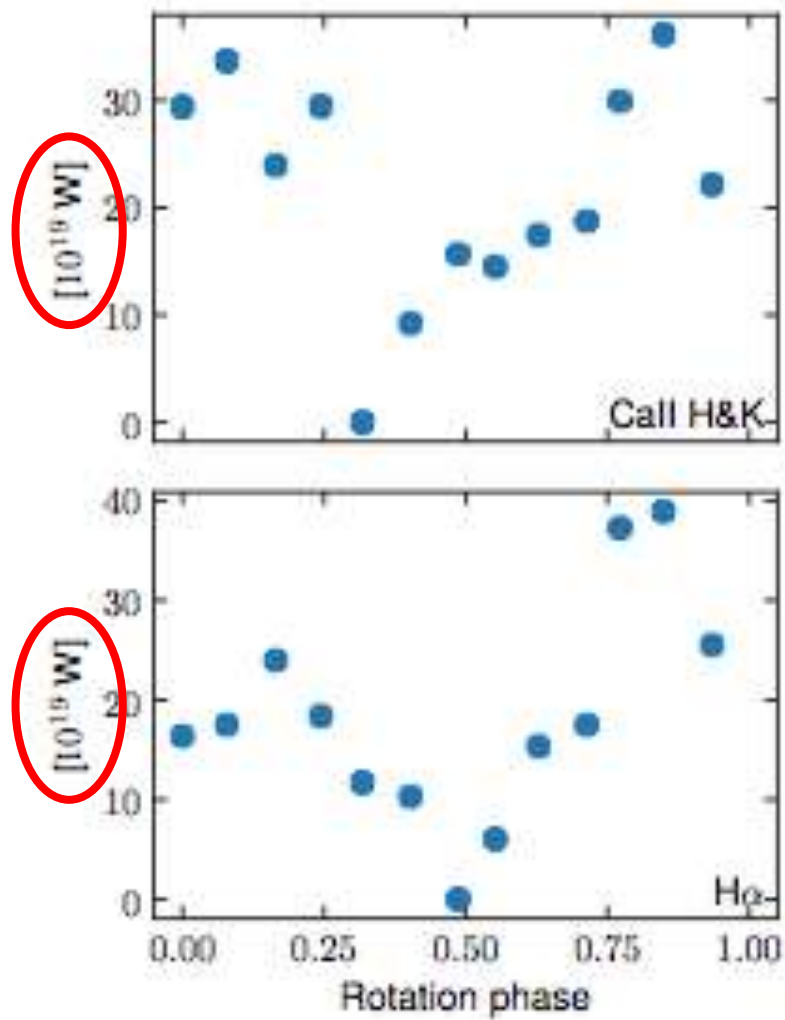
T_{eff} [K]	5089 ± 50
M_{\star} [M_{\odot}]	0.81 ± 0.08
R_{\star} [R_{\odot}]	$0.74 +0.1, -0.8$
P_{rot} [days]	12.5

R_p [R_{\oplus}]	$1.16 +0.19, -0.14$
M_p^1 [M_{\oplus}]	1.86 ± 0.25
R_{orb} [R_{\star}]	$3.0 +0.5, -1.0$

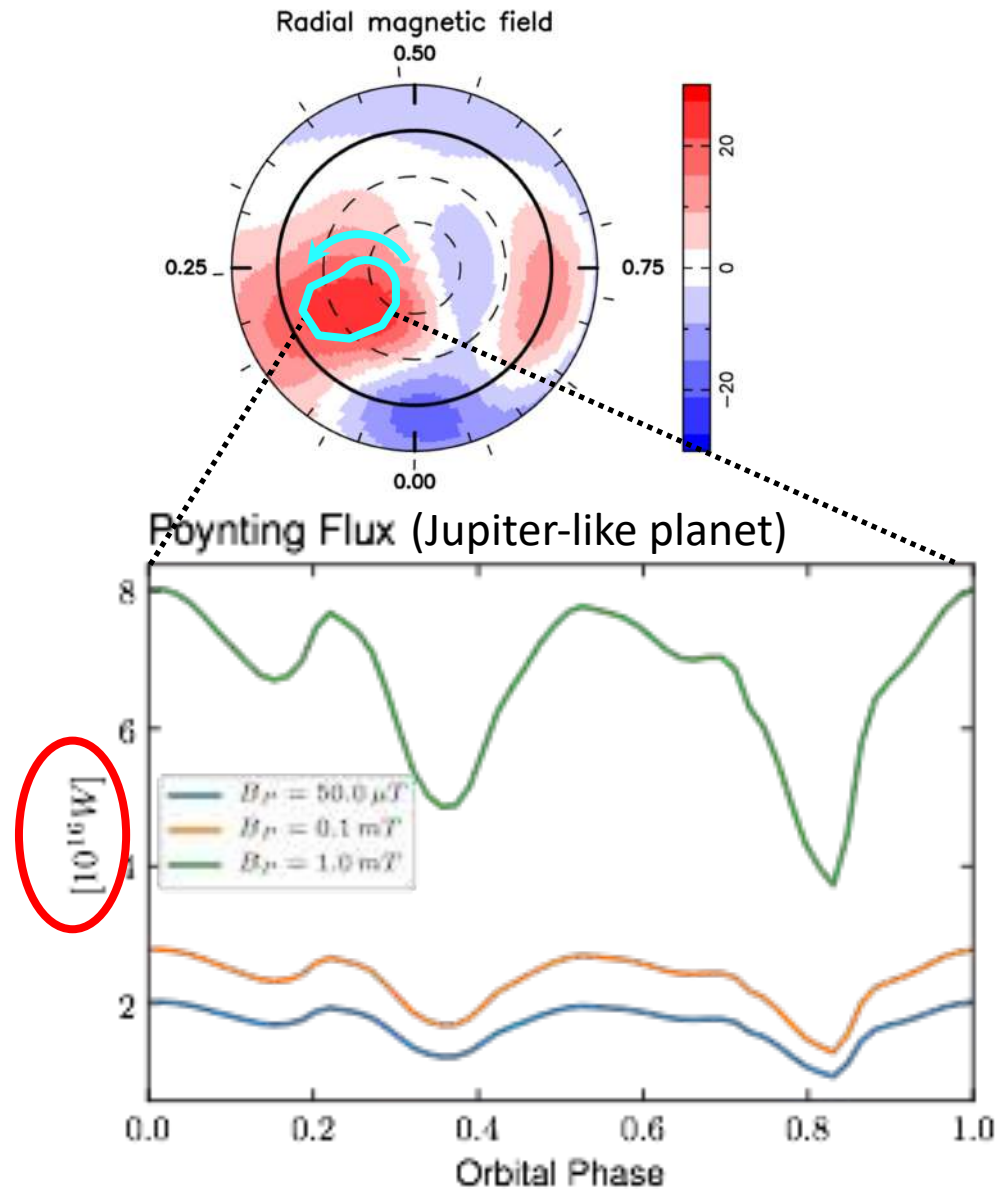
Footpoints of the interaction at the stellar surface



Anomalous emissions/absorption: is there enough power?

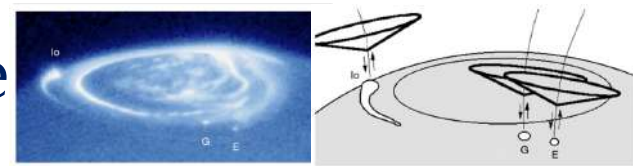


Moutou+ 2016

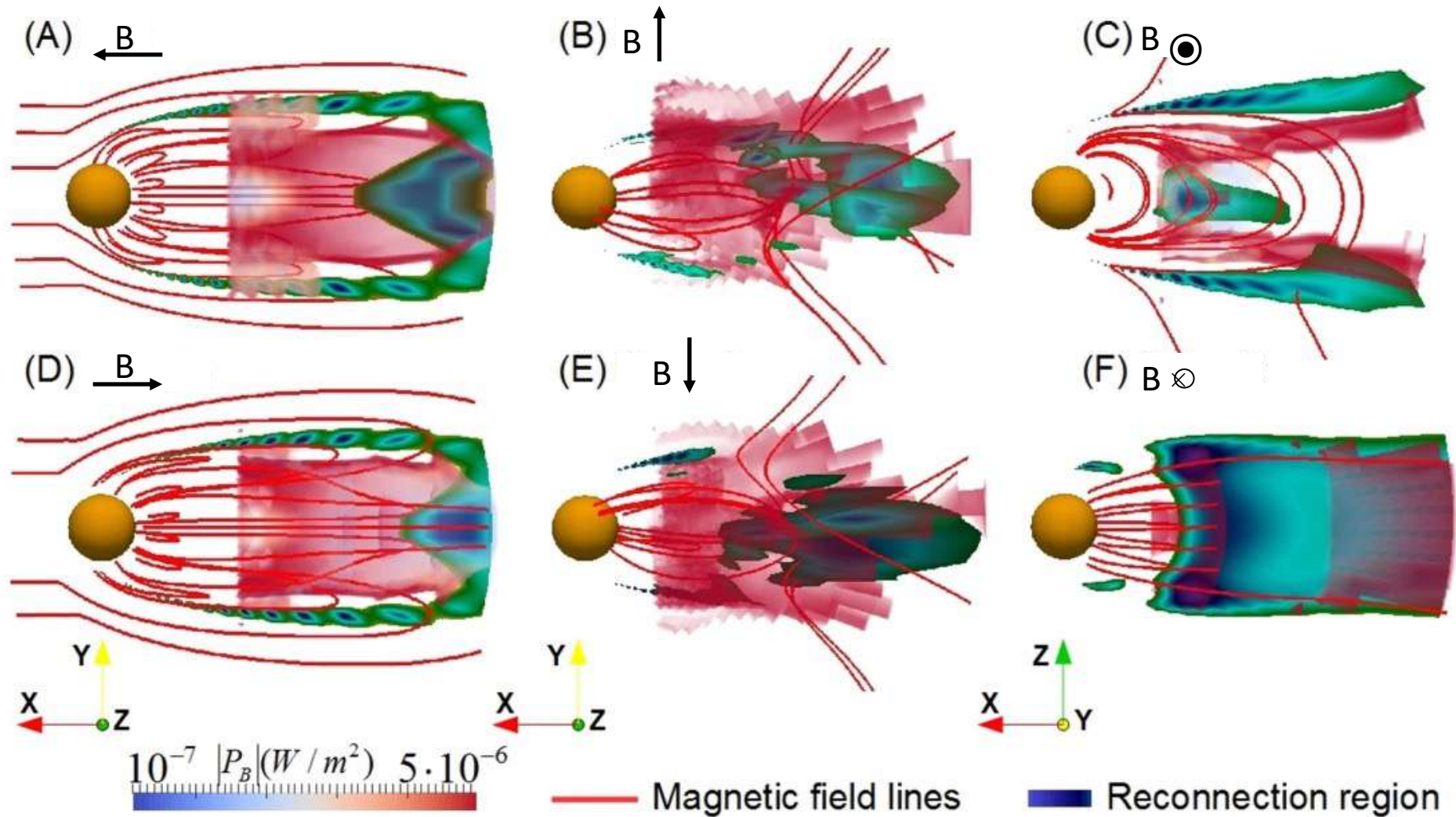


Strugarek, Brun, et al. 2019

Planetary emissions: the Hermean case

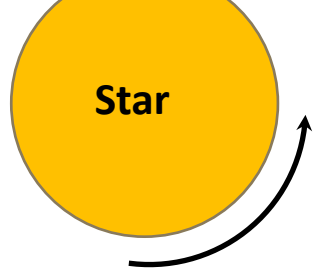


Cyclotron-Maser Instability

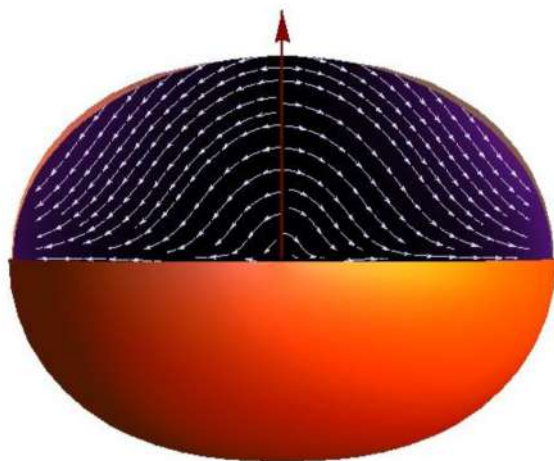


Possible **emission** (typically in radio) in the **planetary magnetospheres**

Star-planet tidal interaction regimes



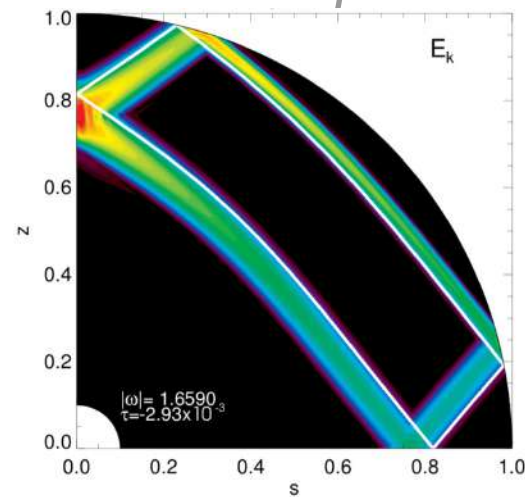
Equilibrium tide



[Zahn 1966; Remus+ 2012]



Dynamical Tide



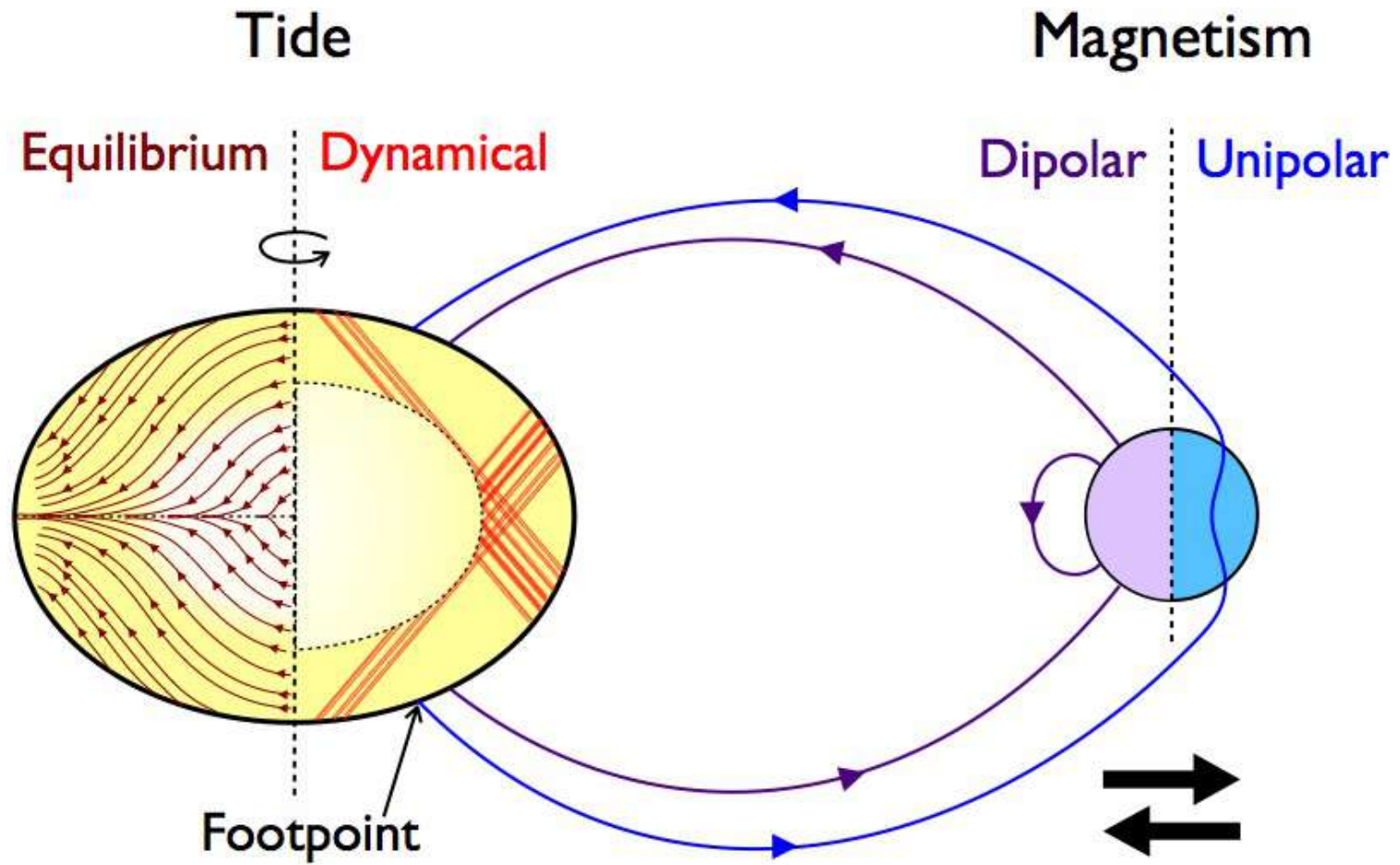
[Zahn 1975; Ogilvie & Lin 2007; Guenel+ 2016]



$P_{orb} = P_{rot}/2$

Co-rotation

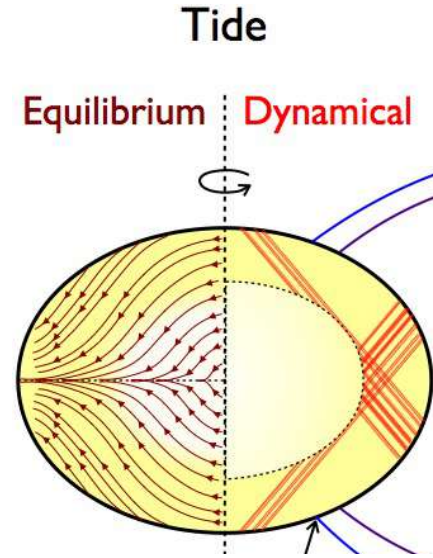
Magnetic vs tidal torques in close-in systems



Torque from the equilibrium and dynamical tides

$$|\Gamma_T| = 6J_p n \frac{M_p}{M_\star} \left(\frac{R_\star}{a}\right)^5 \frac{k_2}{Q_\star}$$

Orbital Frequency



$$\frac{k_2}{Q_\star} = f(n - \Omega_\star, \nu_t, \rho, \alpha)$$

Viscosity

Density

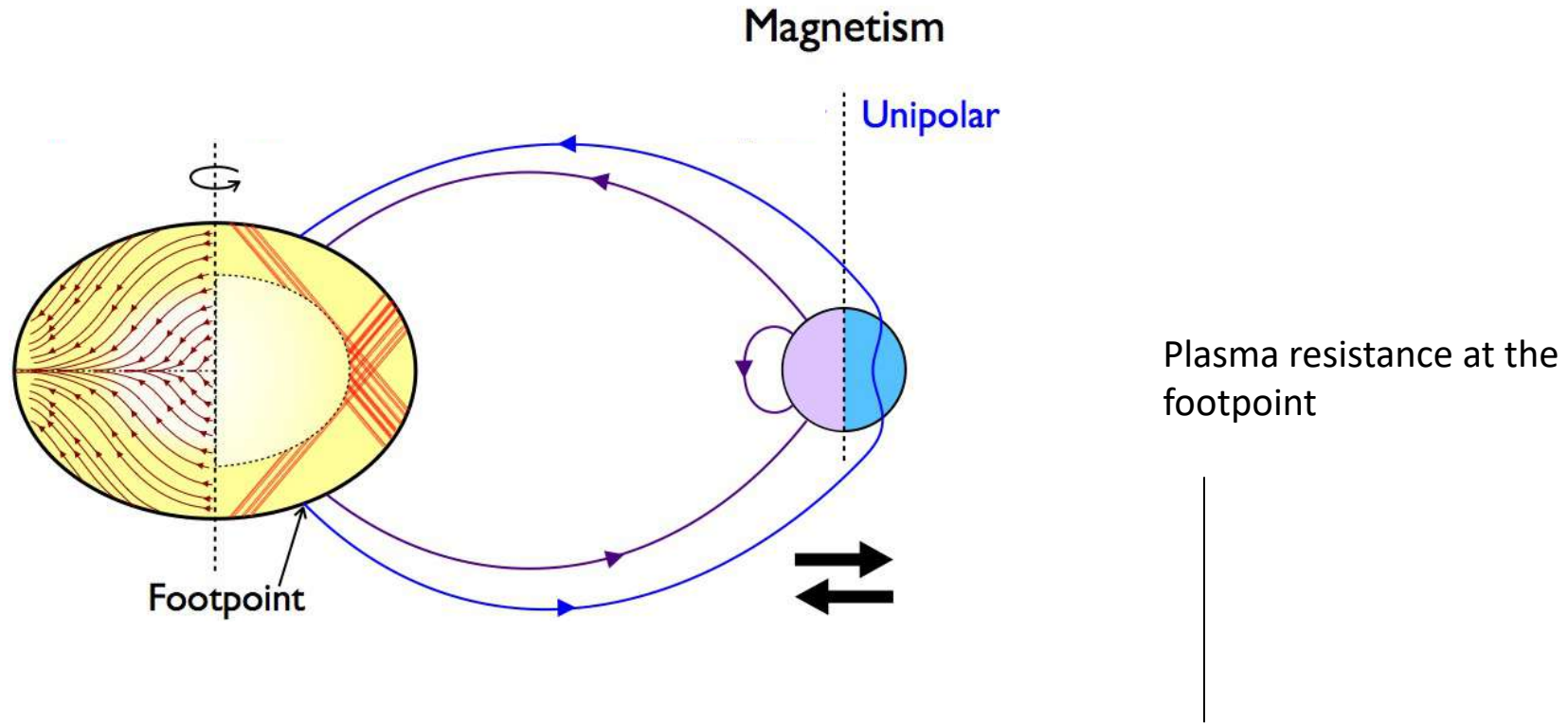
Aspect ratio

$$\frac{k_2}{Q_\star} = f(\alpha, \beta, \Omega_\star)$$

Aspect ratio

Mass in the RZ

Magnetic torque: parametrization of the unipolar interaction

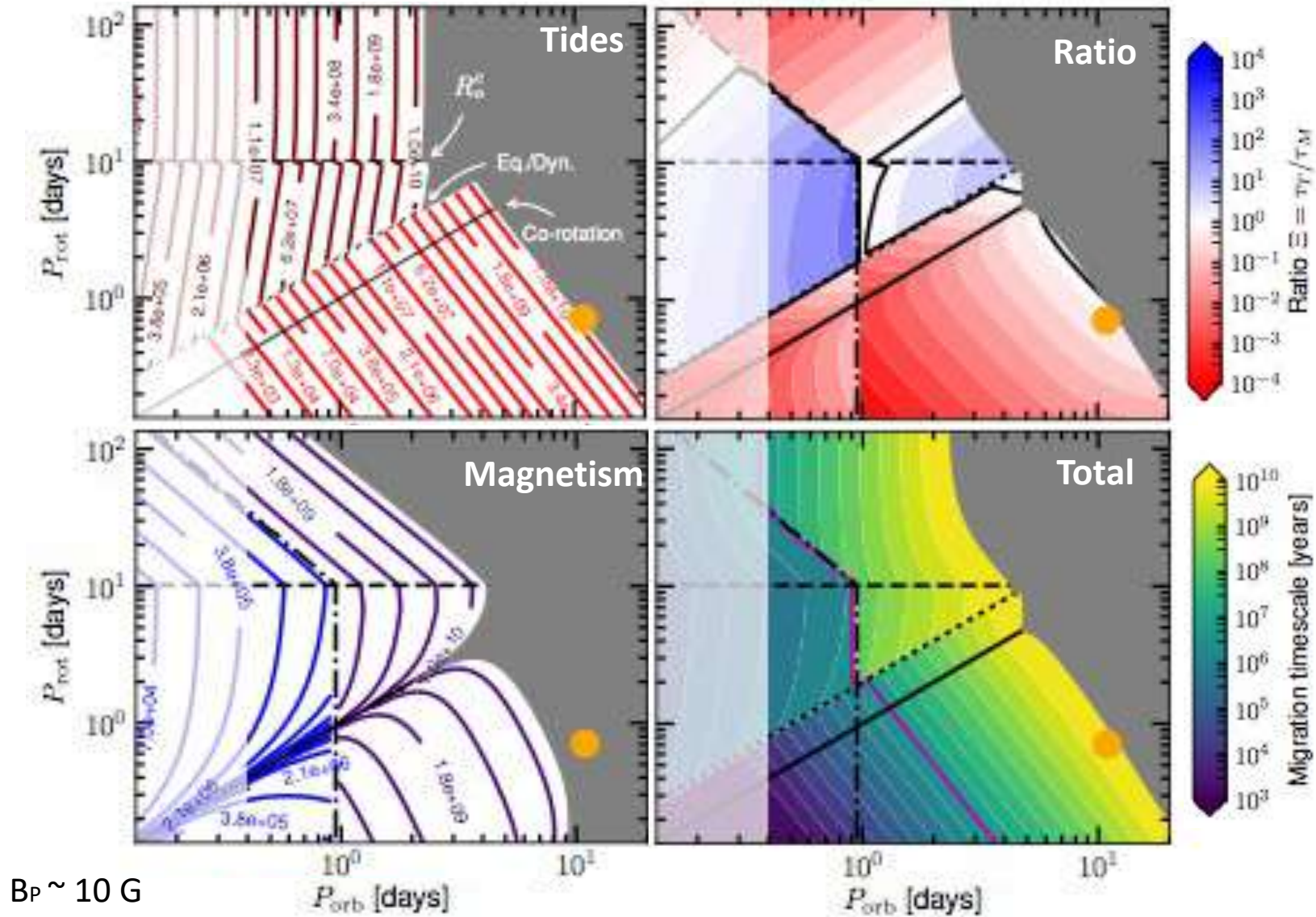


$$|\Gamma_M| = 8R_p^2 a^2 |\sigma| B_w \Sigma$$

$n - \Omega_*$

Stellar wind magnetic field

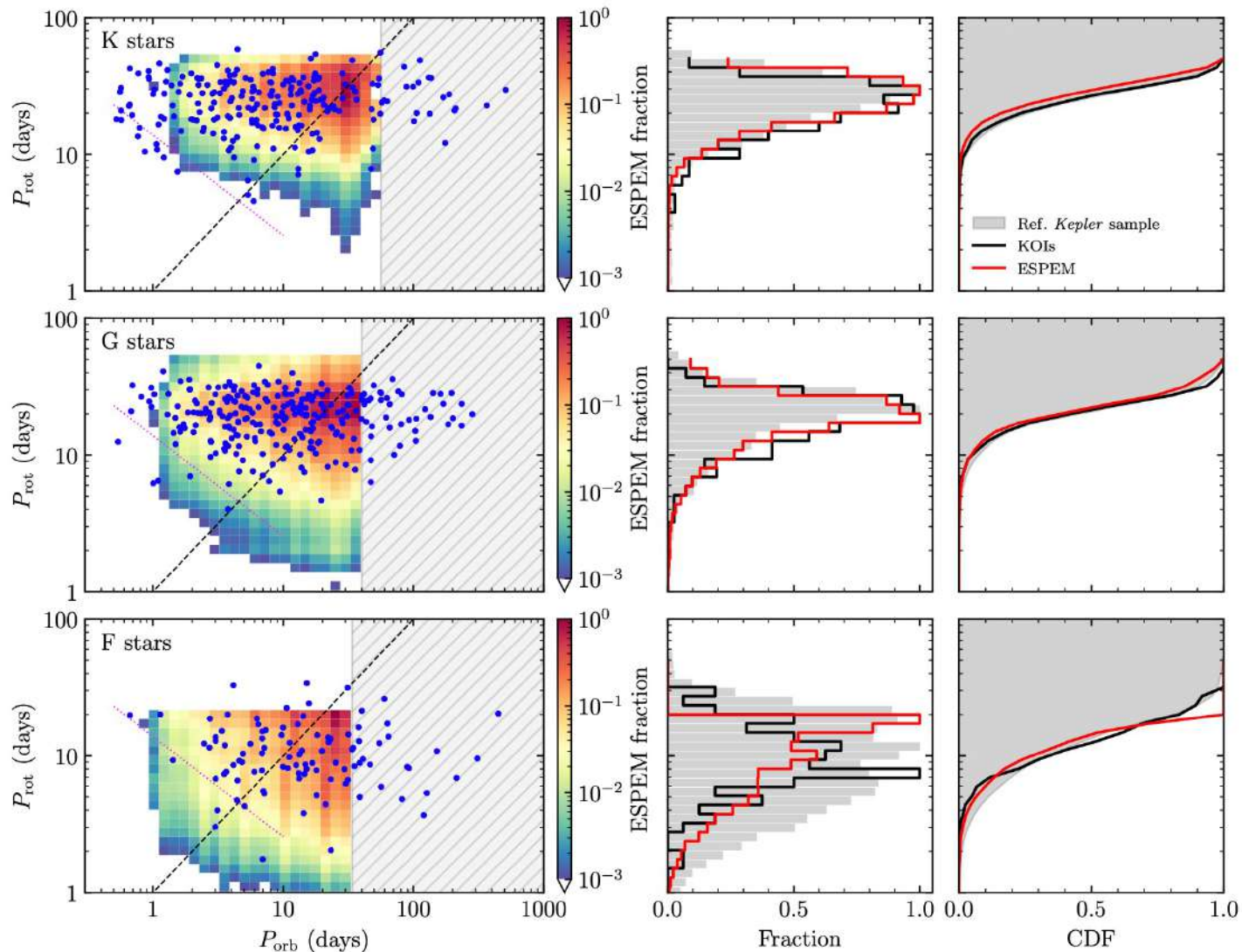
Application: T Tauri with hot Jupiter (like Tap 26 system)



Synthetic population vs Kepler-field population

[Garcia+ 2023]

Tidal w/wo magnetic interaction



Initial conditions: no planets within the inner radius of the dead zone of protoplanetary disks

ESPEM reproduces the dearth of exoplanets on short-period orbit around fast rotators, that appears from a **realistic distribution of planets** after the disk dissipation that **migrates due to tidal and magnetic torques.**

ESPEM predictions are coherent with Kepler observation, but we still produce too many slow rotators -> need to **slightly** revise the stellar wind breaking law for these stars

Conclusion

Close-in planets are expected to interact **magnetically** with their host in a large variety of ways

The knowledge of the **location** of the **stellar wind's Alfvén surface** is **mandatory** to estimate the effect of magnetic interactions

↳ **Rotation, magnetic field, mass loss rate and T** of the host star

The magnetic interactions **strongly** depend on the **topology** of the **stellar and planetary** magnetic field

A close-in planet can *a priori* **migrate** due to star-planet magnetic interactions

Magnetic and Tidal torques can jointly influence planet's orbit and conditions of habitability