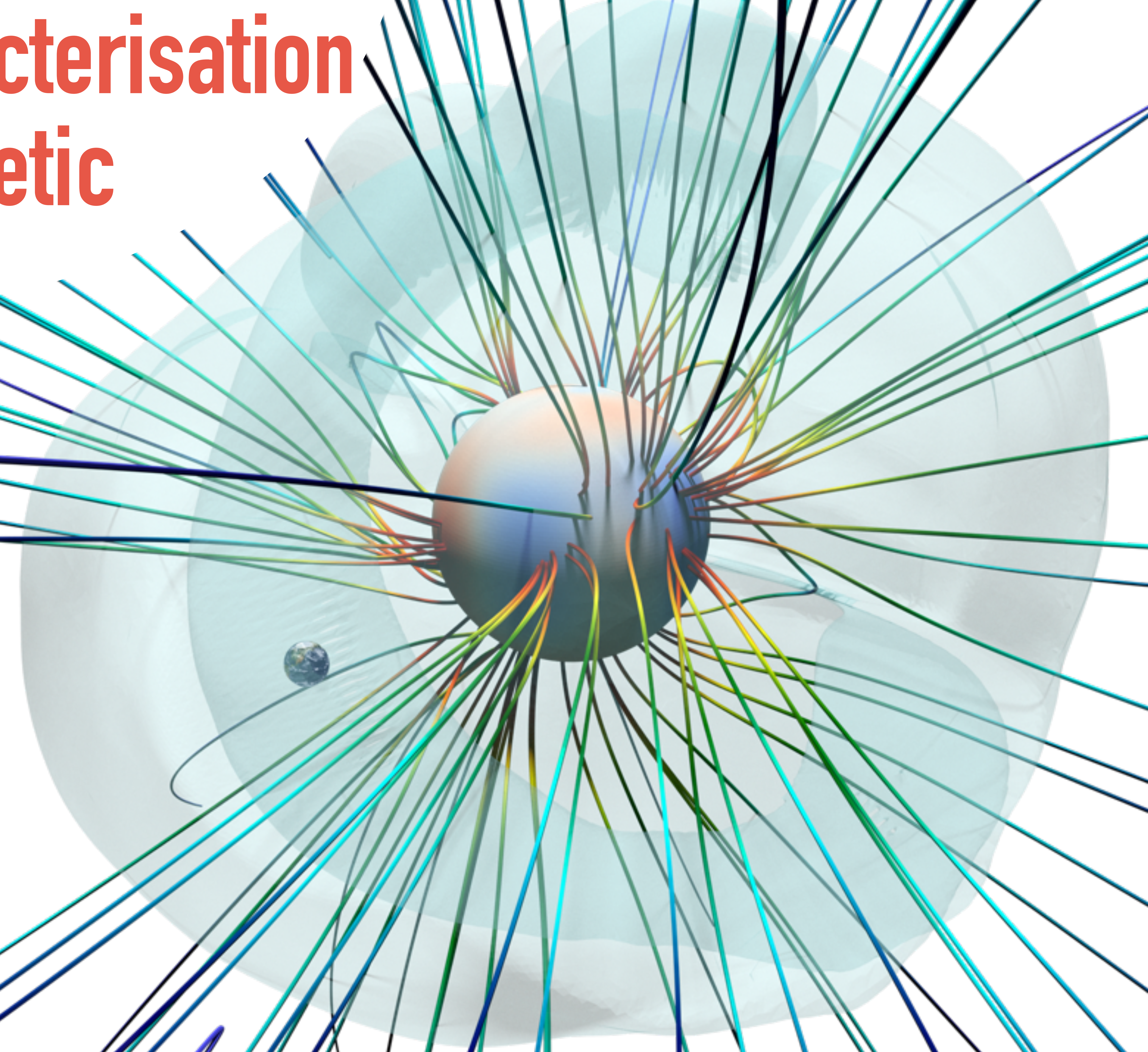
Detection and characterisation of star-planet magnetic interactions



Antoine Strugarek

AIM/CEA Paris-Saclay, France

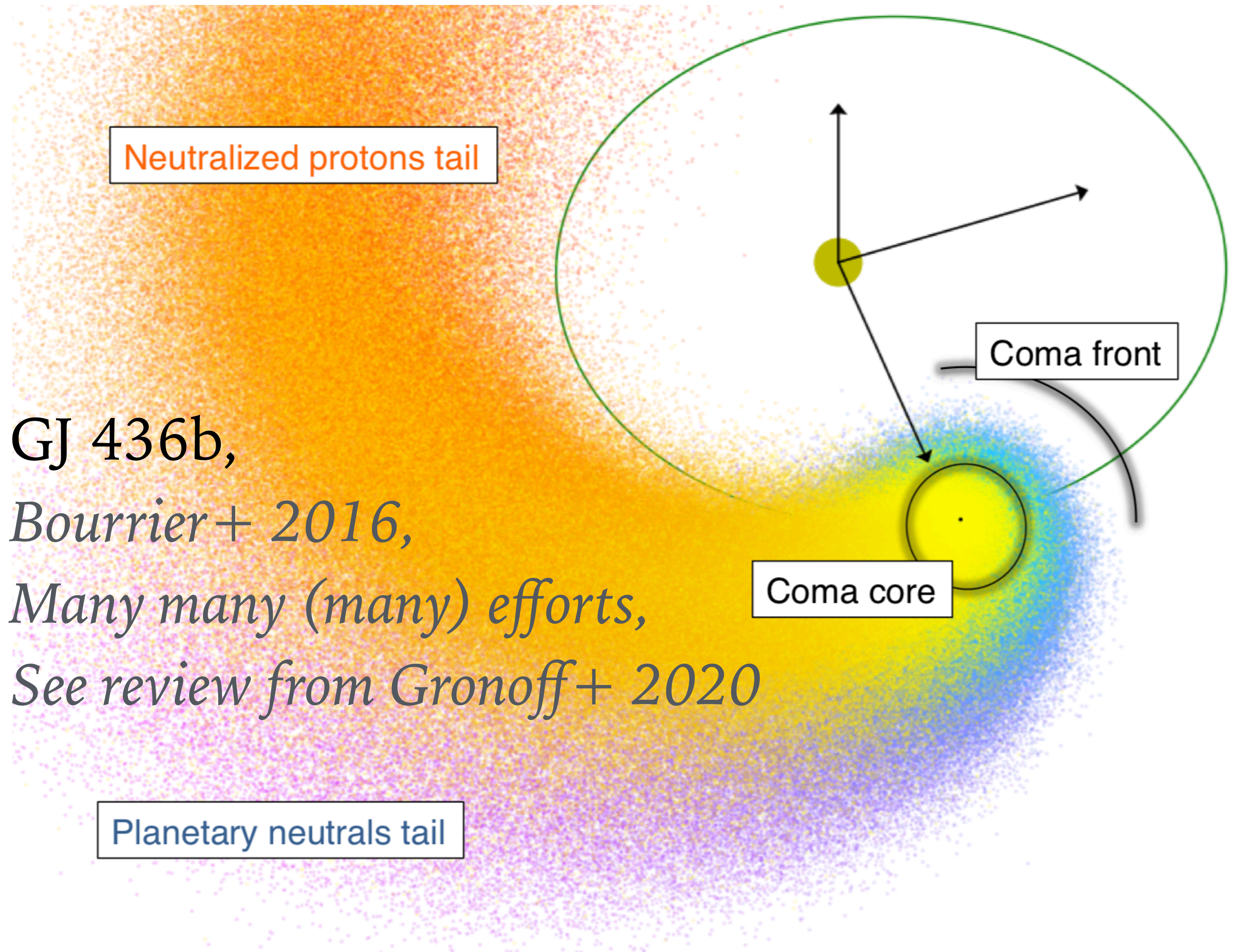
With R. Fares, V. Bourrier, A.S. Brun, C. Moutou, J.F. Donati, V. Réville and the MOVES collab., S. Mathis, R. Garcia, C. Gourvès, C. Charbonnel, S. Mathur

Star-planet interactions in compact systems

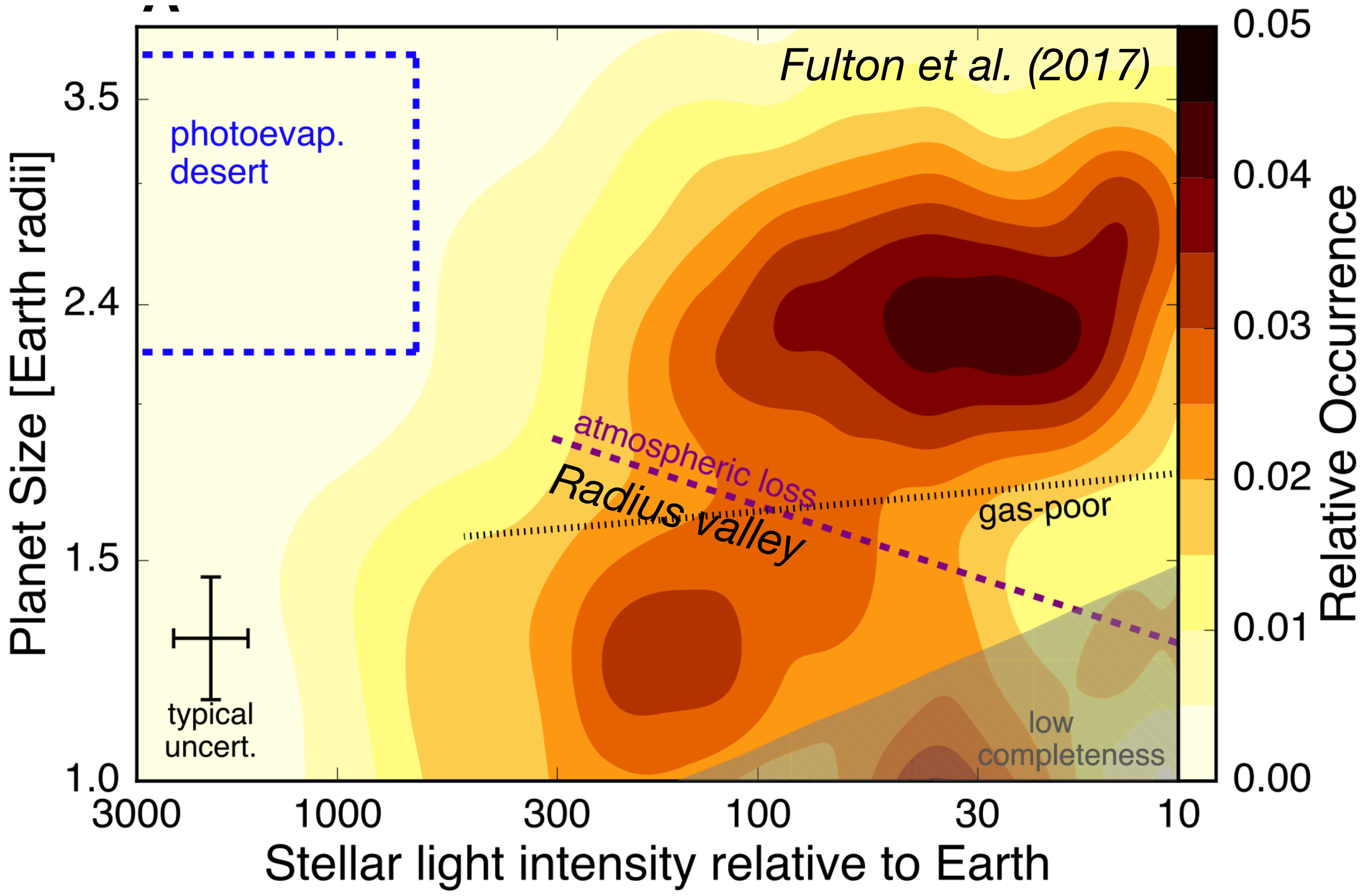
See seminal paper from Cuntz+ 2000 and review Strugarek, 2023

Star-planet interactions in compact systems

Strong irradiation



GJ 436b,
Bourrier+ 2016,
Many many (many) efforts,
See review from Gronoff+ 2020



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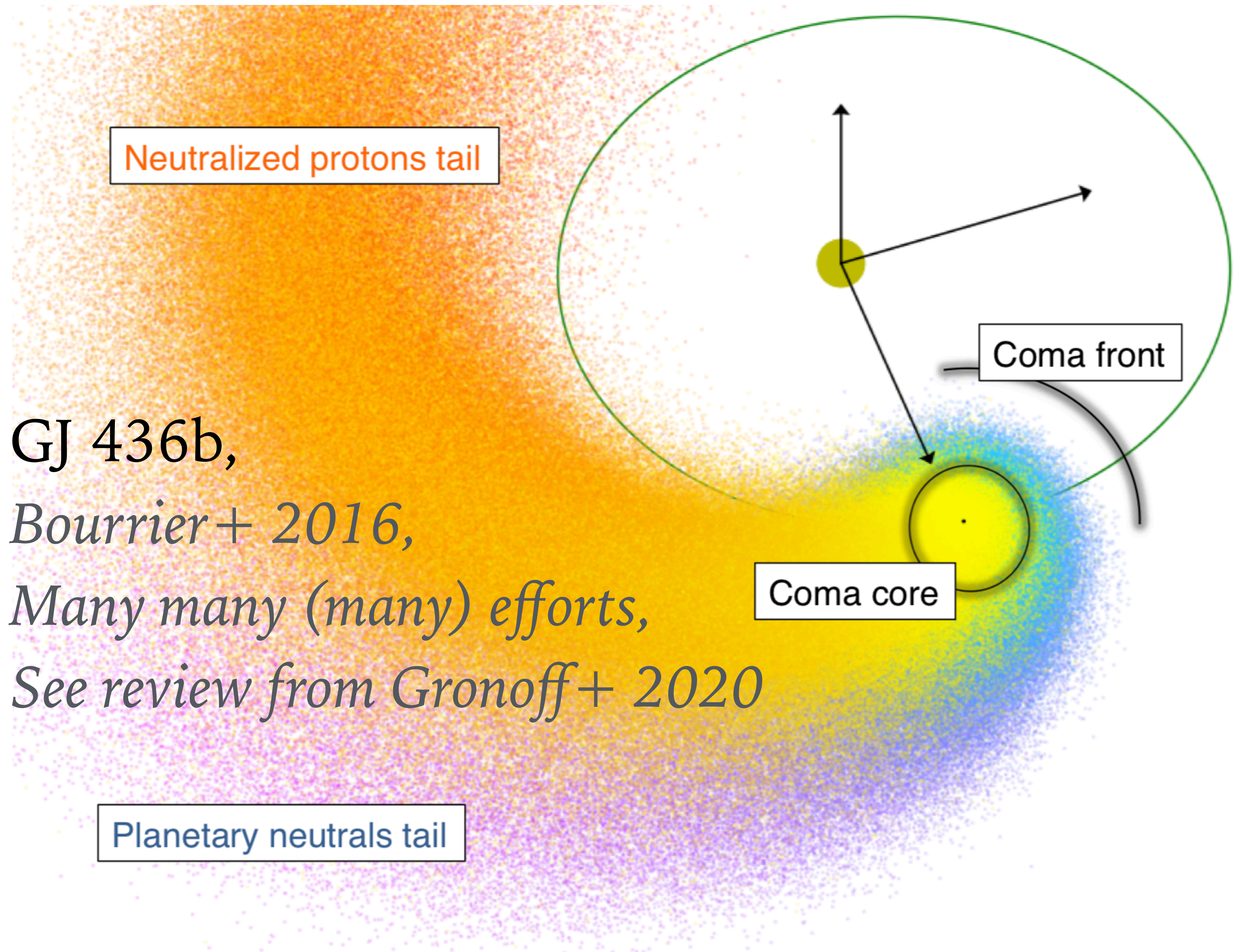

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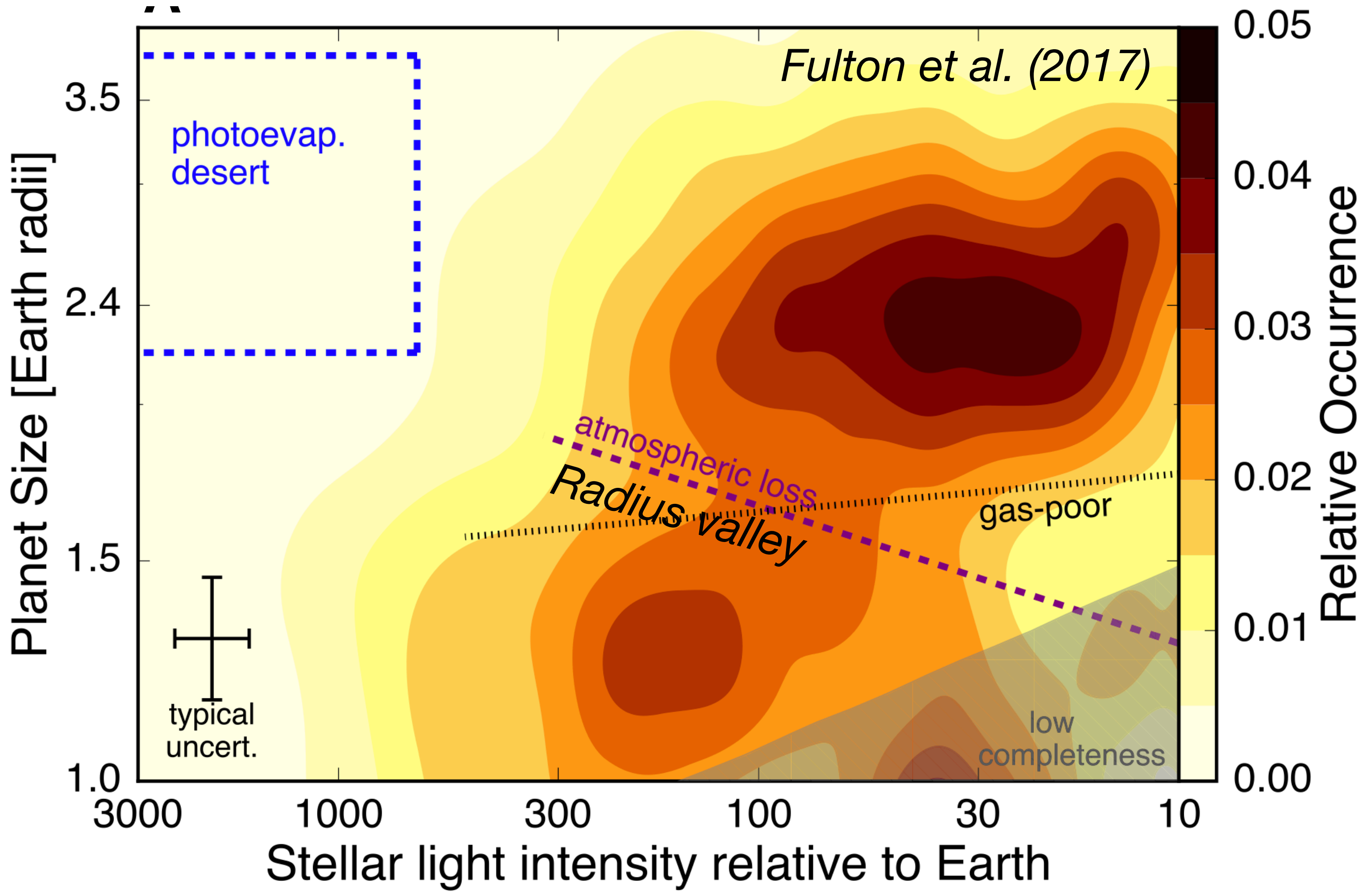
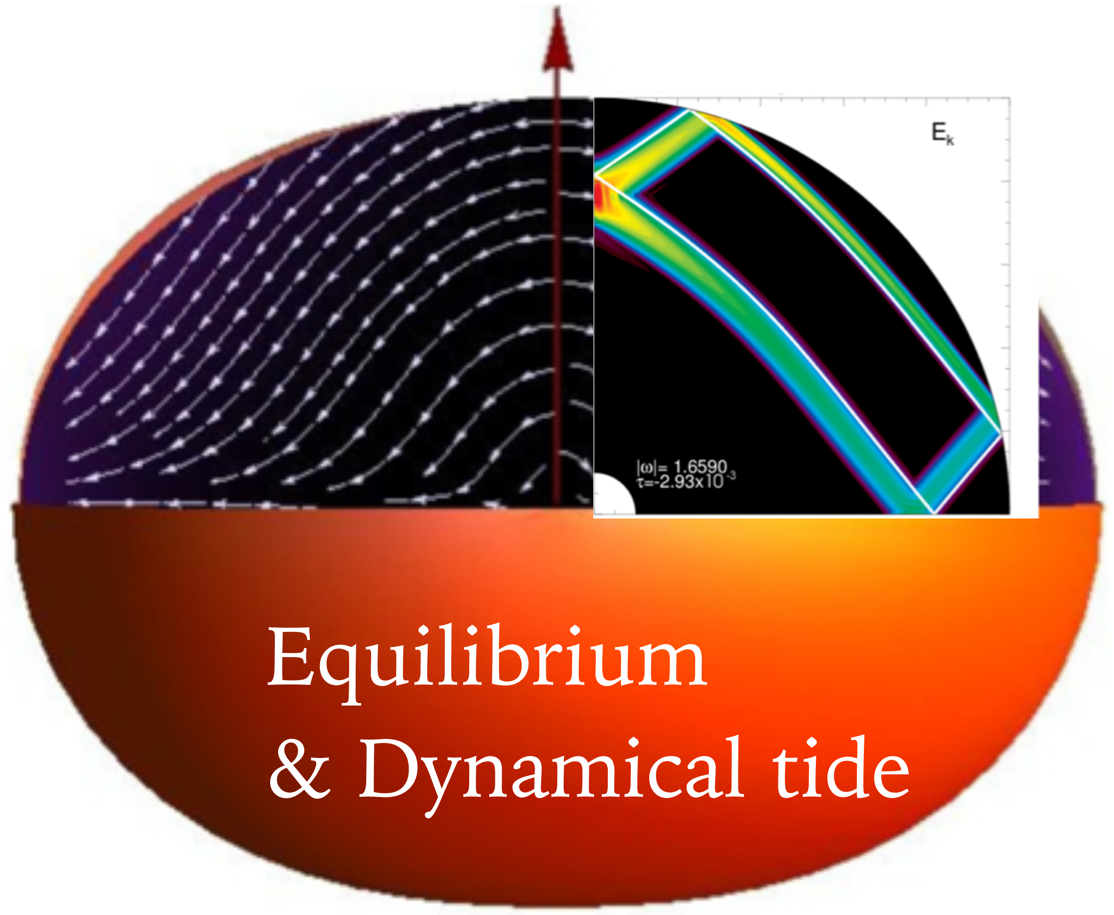
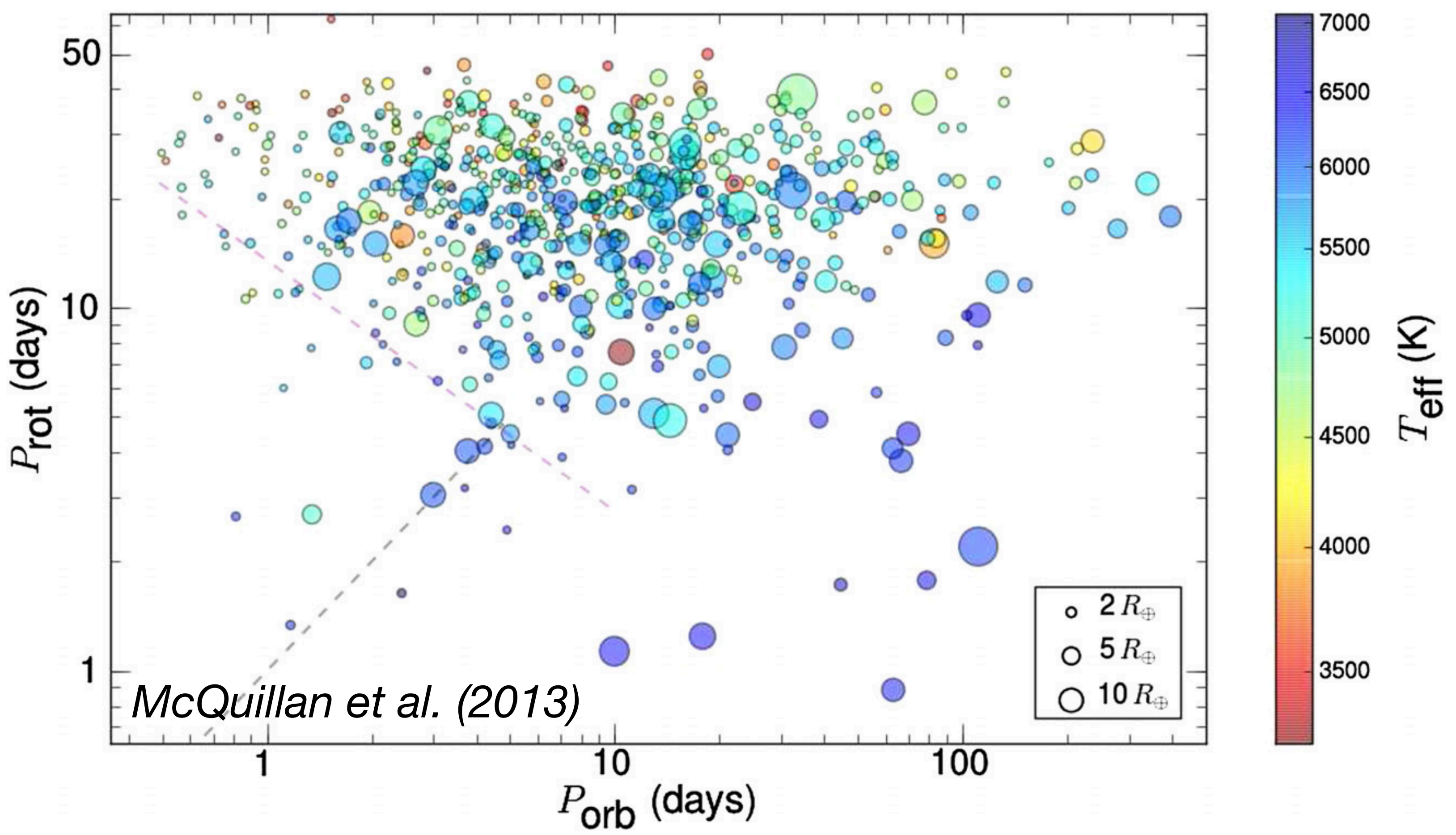


Strong tidal interactions



e.g.Zahn 1975; Ogilvie & Lin 2007;
Guenel+ 2016; Mathis 2015 Zahn 1966; Remus+ 2012



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Star-planet interactions in compact systems

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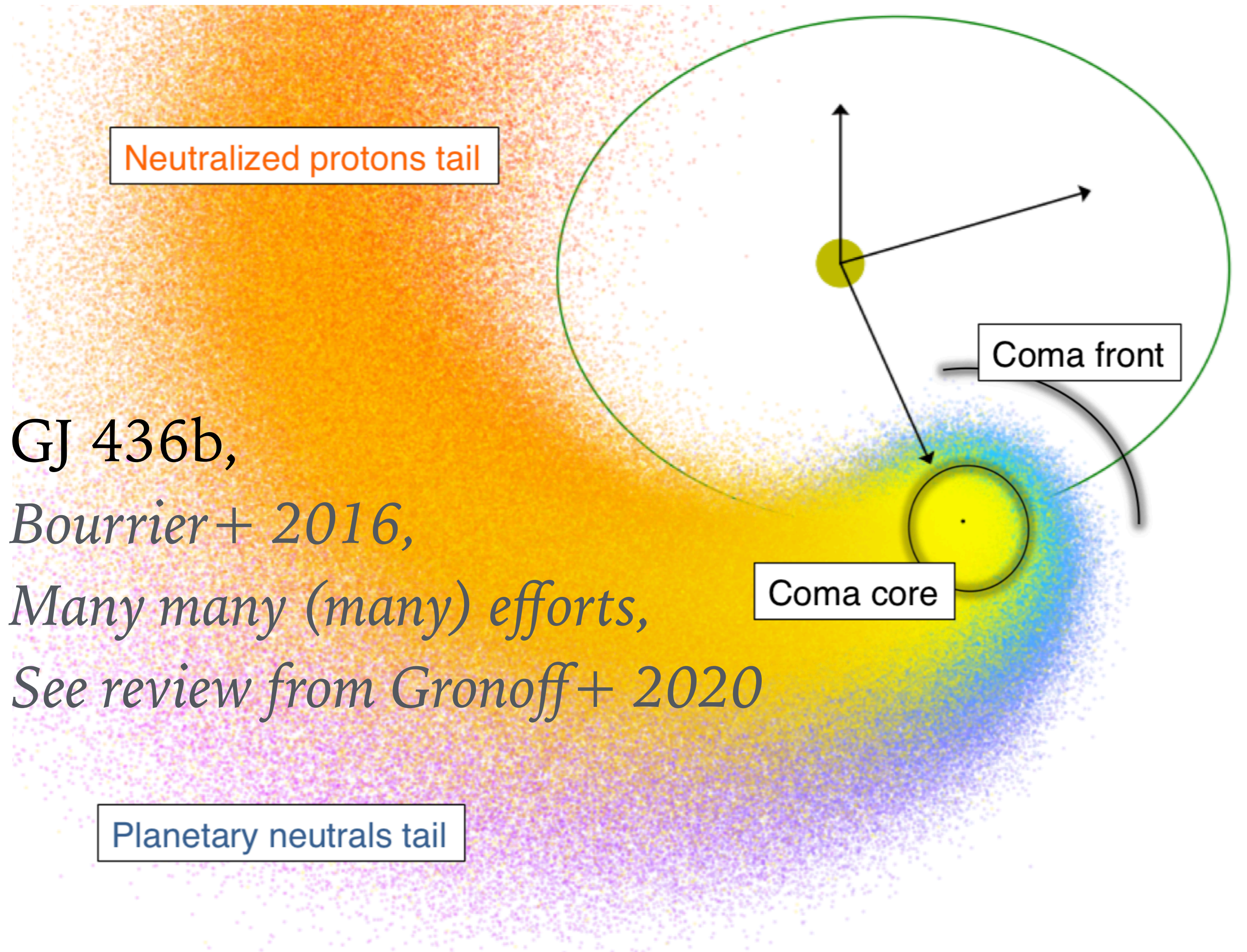

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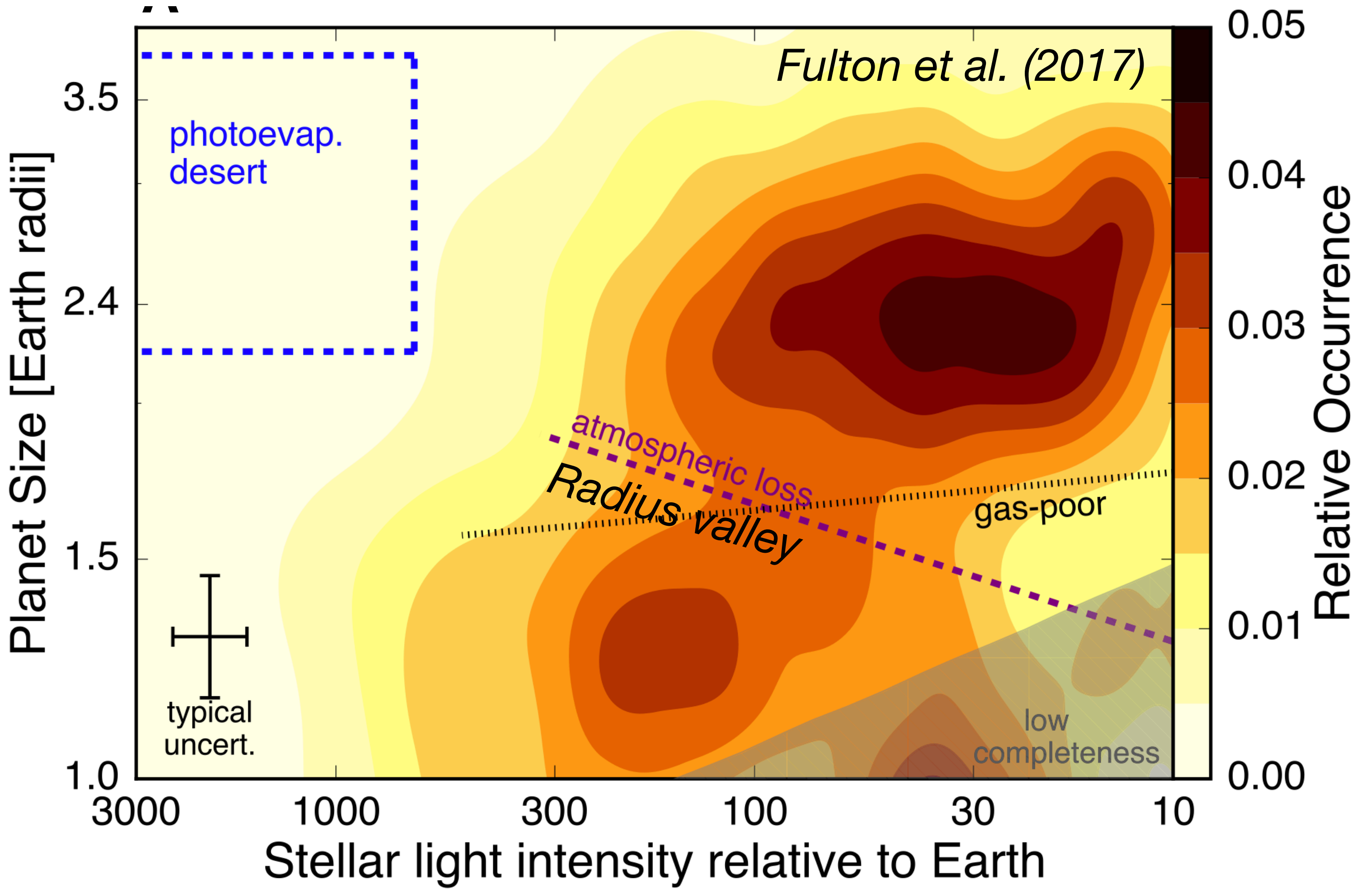
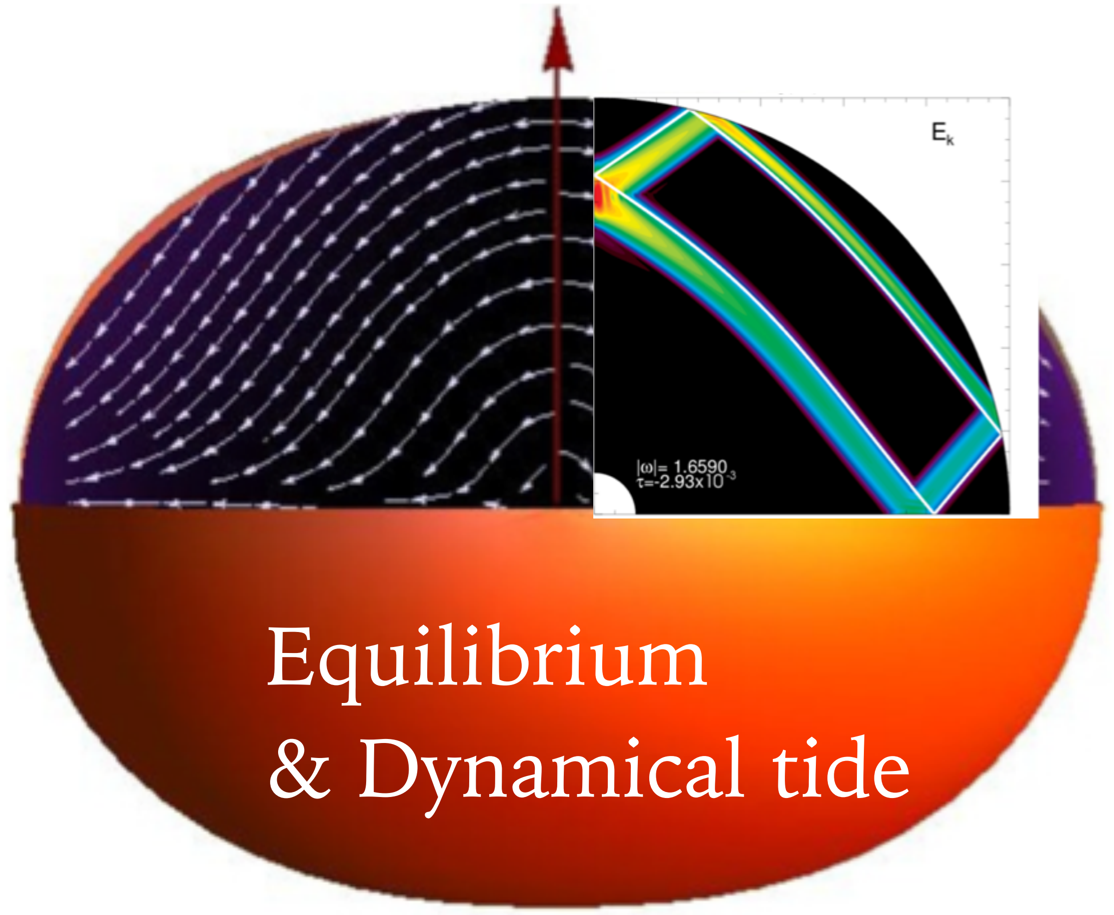


Strong tidal interactions



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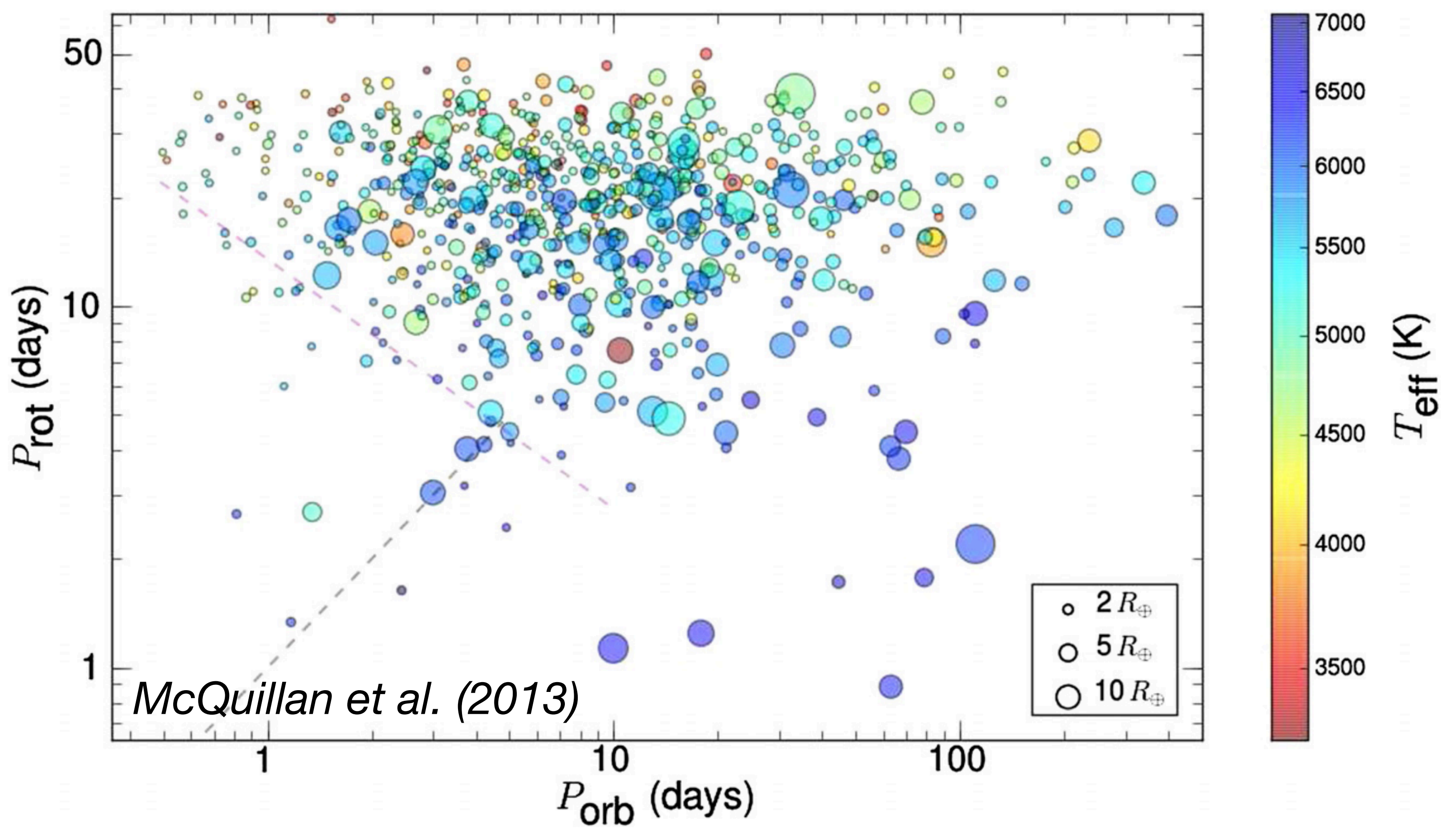
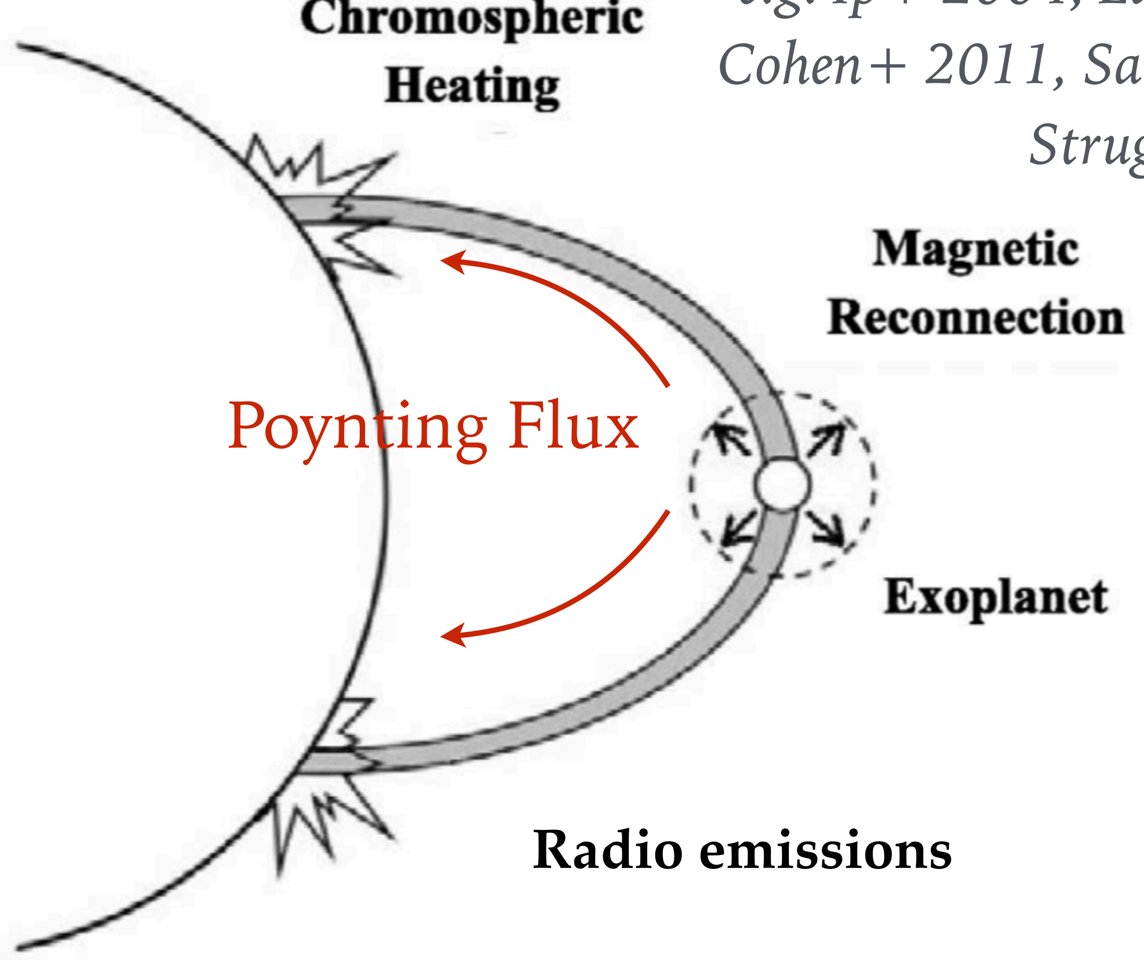
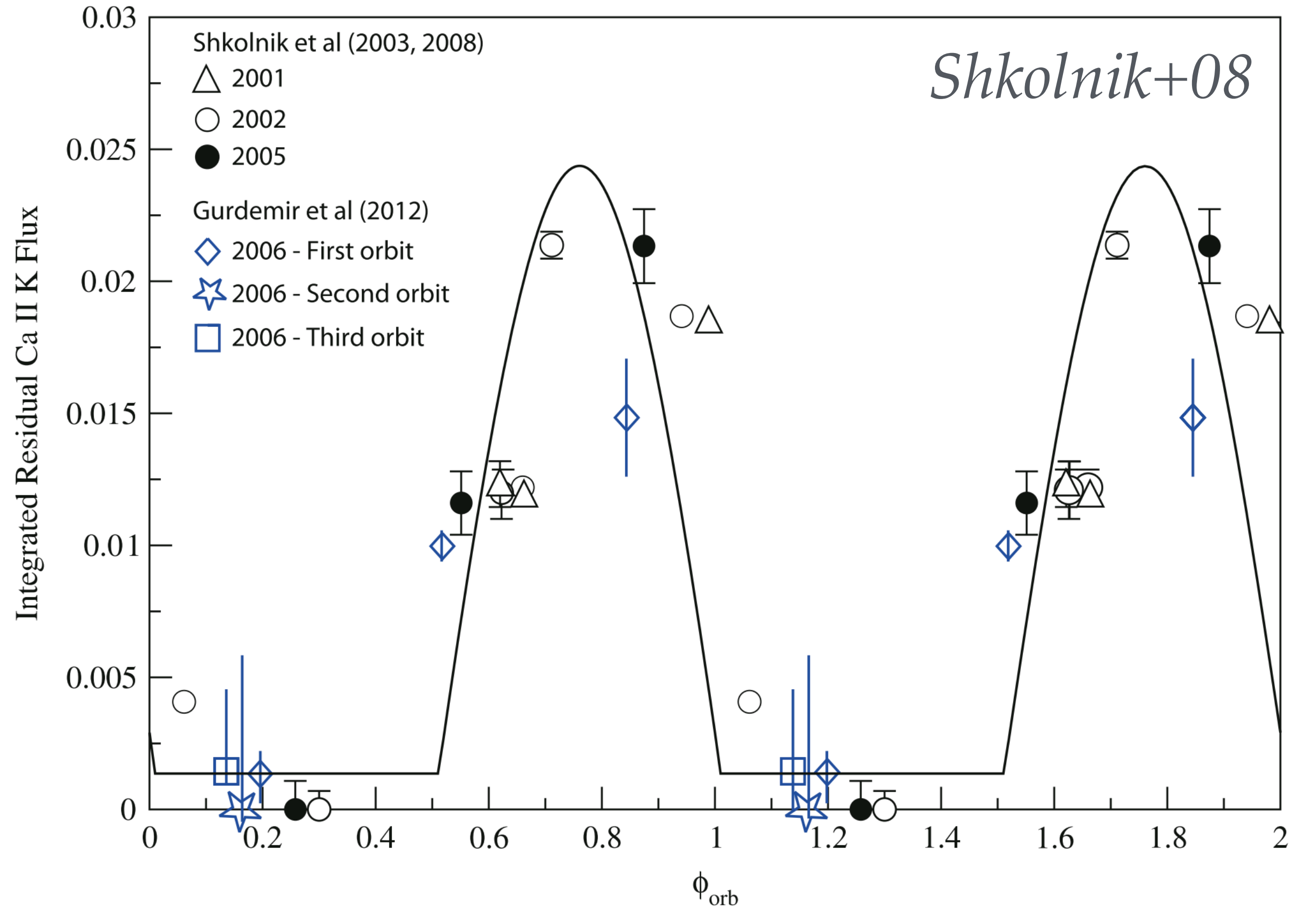


Strong magnetic interactions

e.g. Ip+ 2004, Lanza 2007,
Cohen+ 2011, Saur+ 2013,
Strugarek 2016



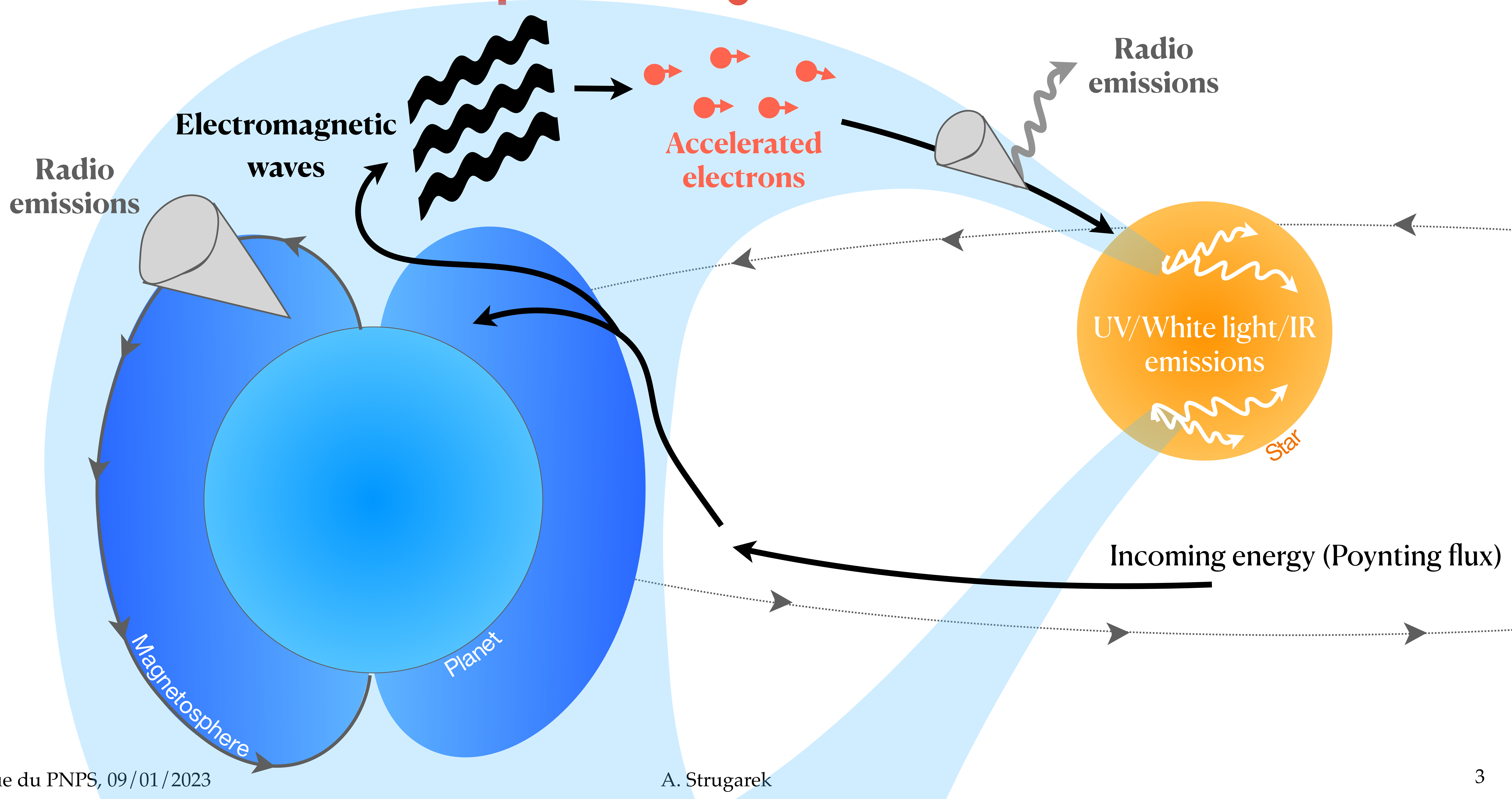
CaII K excess for HD 179949



See also Callingham+ 21, Vedantham+ 21, Turner+21

See seminal paper from Cuntz+ 2000 and review Strugarek, 2023

Schematic view of star planet magnetic interactions

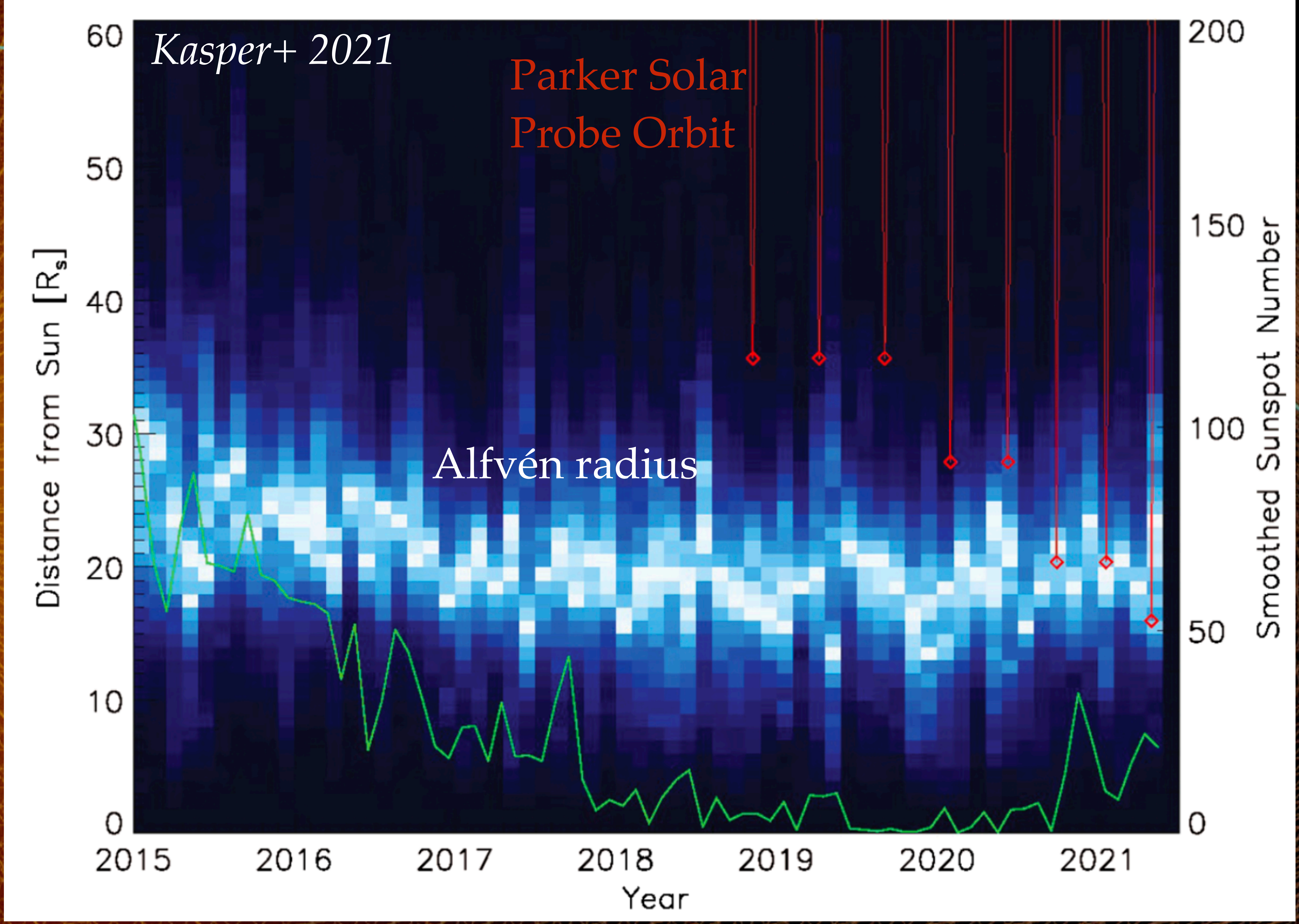


Close-in environment of cool-stars

Strong link with solar system research

Crossing of solar Alfvén surface by Parker Solar Probe. ©B. Smith

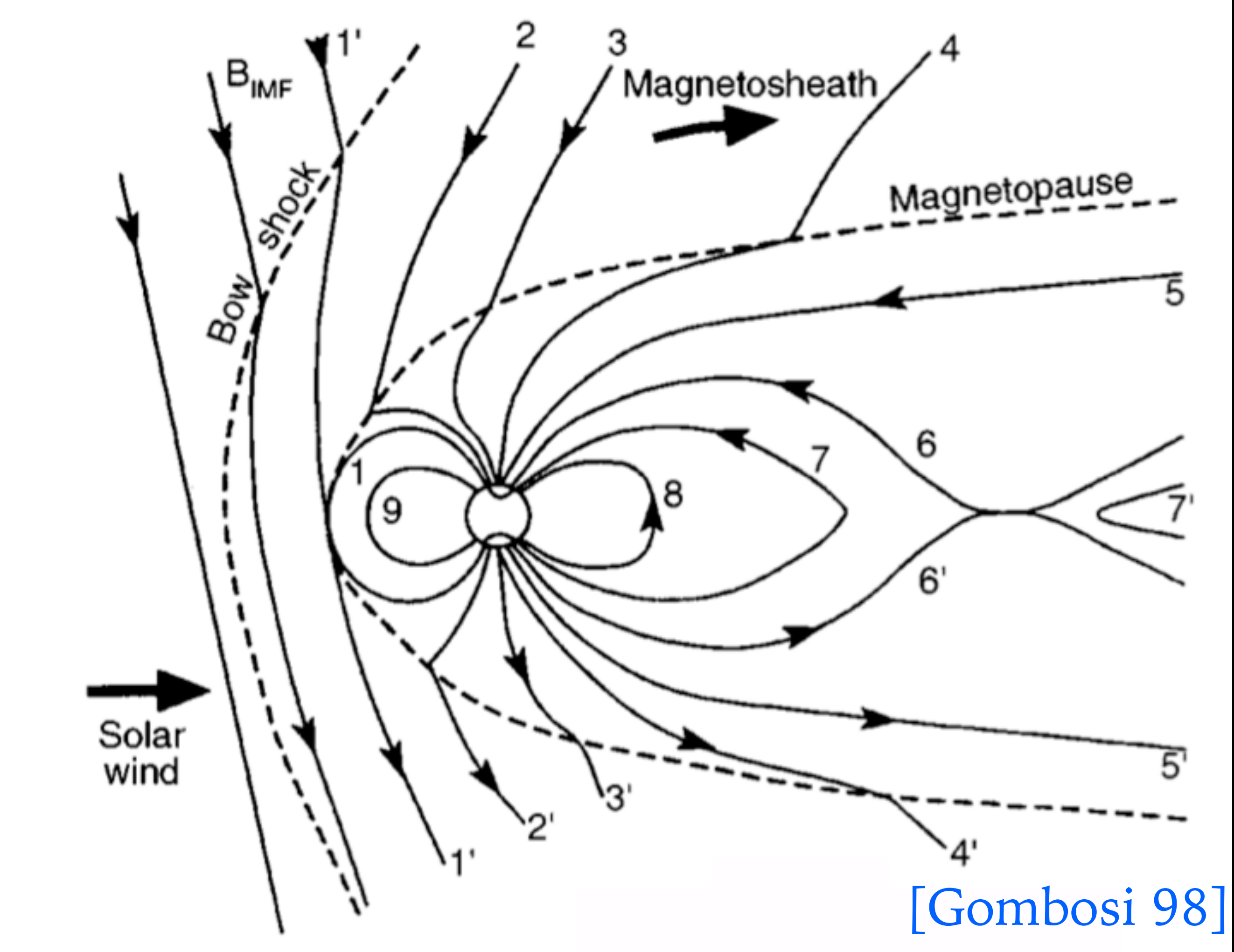
Close-in environment of cool-stars



Strong link with solar system research

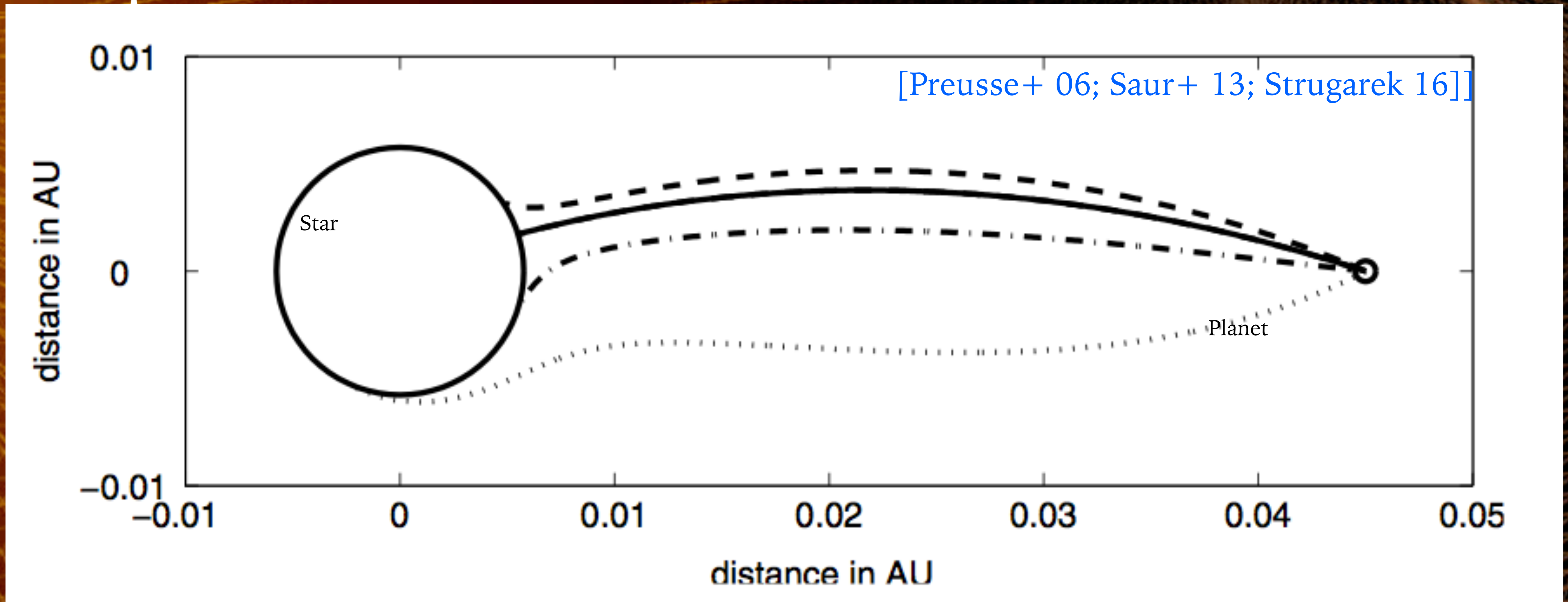
Crossing of solar Alfvén surface by Parker Solar Probe. ©B. Smith

Star–planet magnetic interactions regimes



Super-Alfvénic interaction:
shock formation

Sub-Alfvénic interaction:
star-planet connection



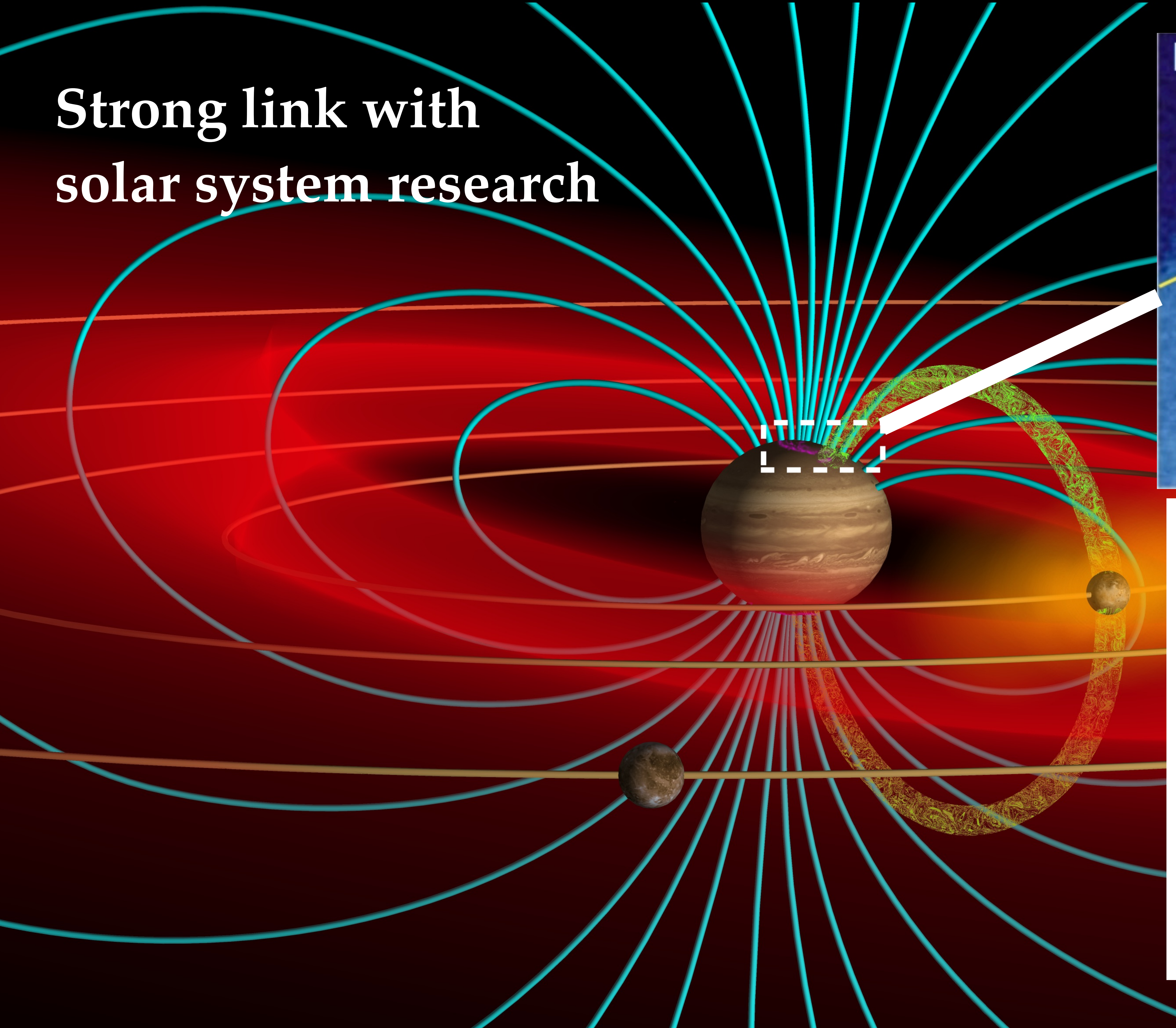
Strong link with solar system research

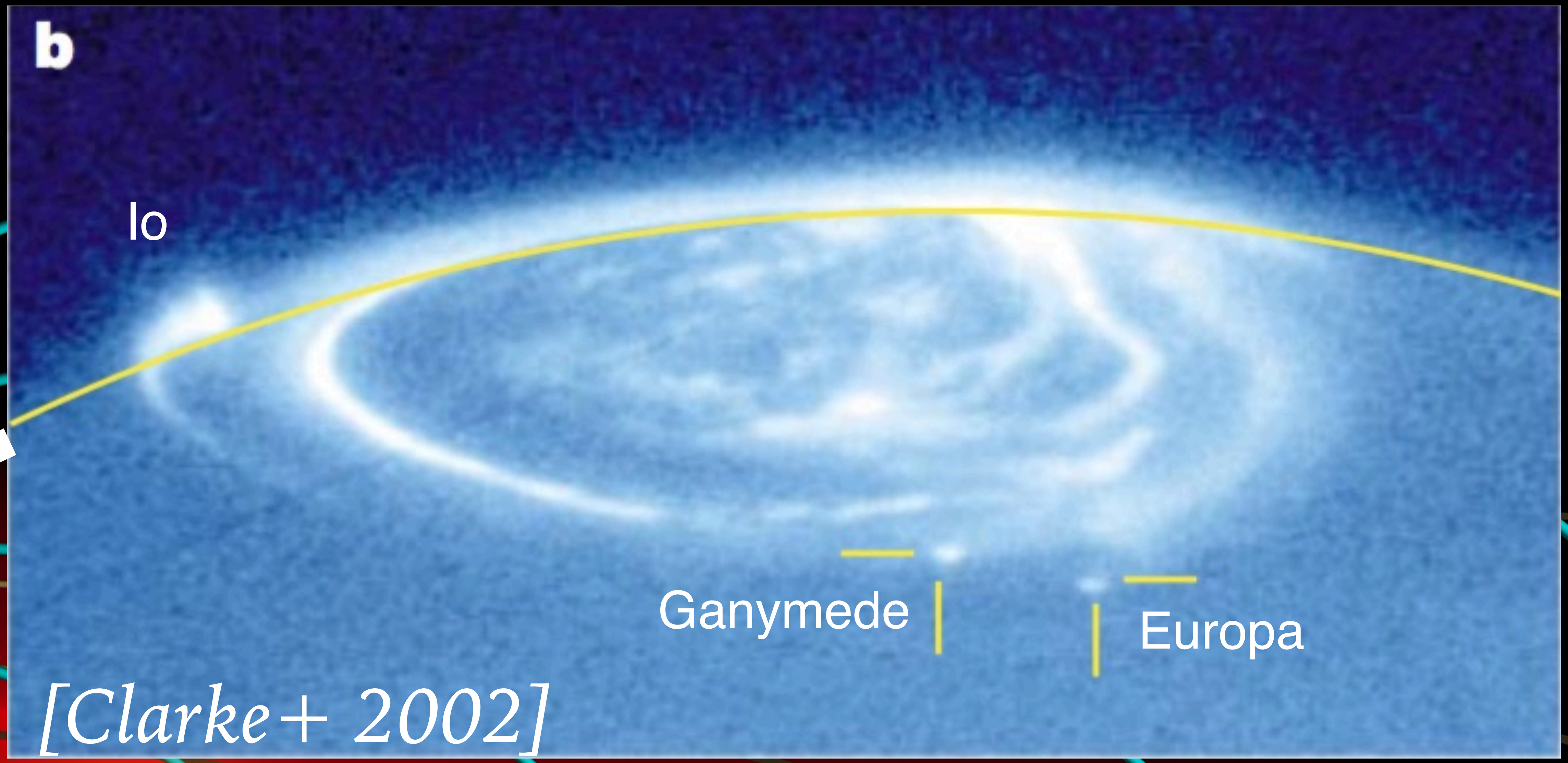
Crossing of solar Alfvén surface by Parker Solar Probe. ©B. Smith

Magnetic interactions in the Jupiter-Io system: Alfvén wings

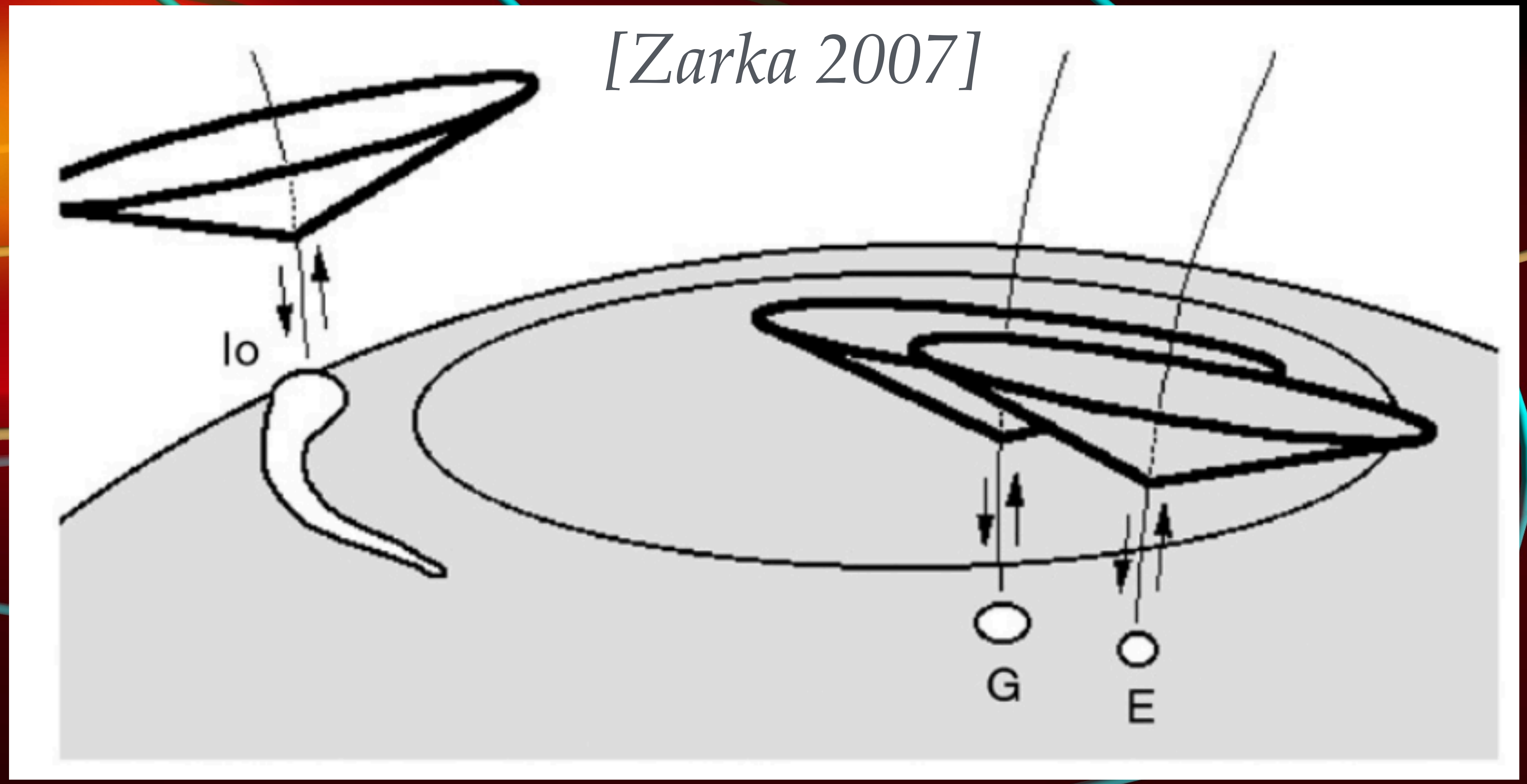
Magnetic interactions in the Jupiter-Io system: Alfvén wings

Strong link with solar system research





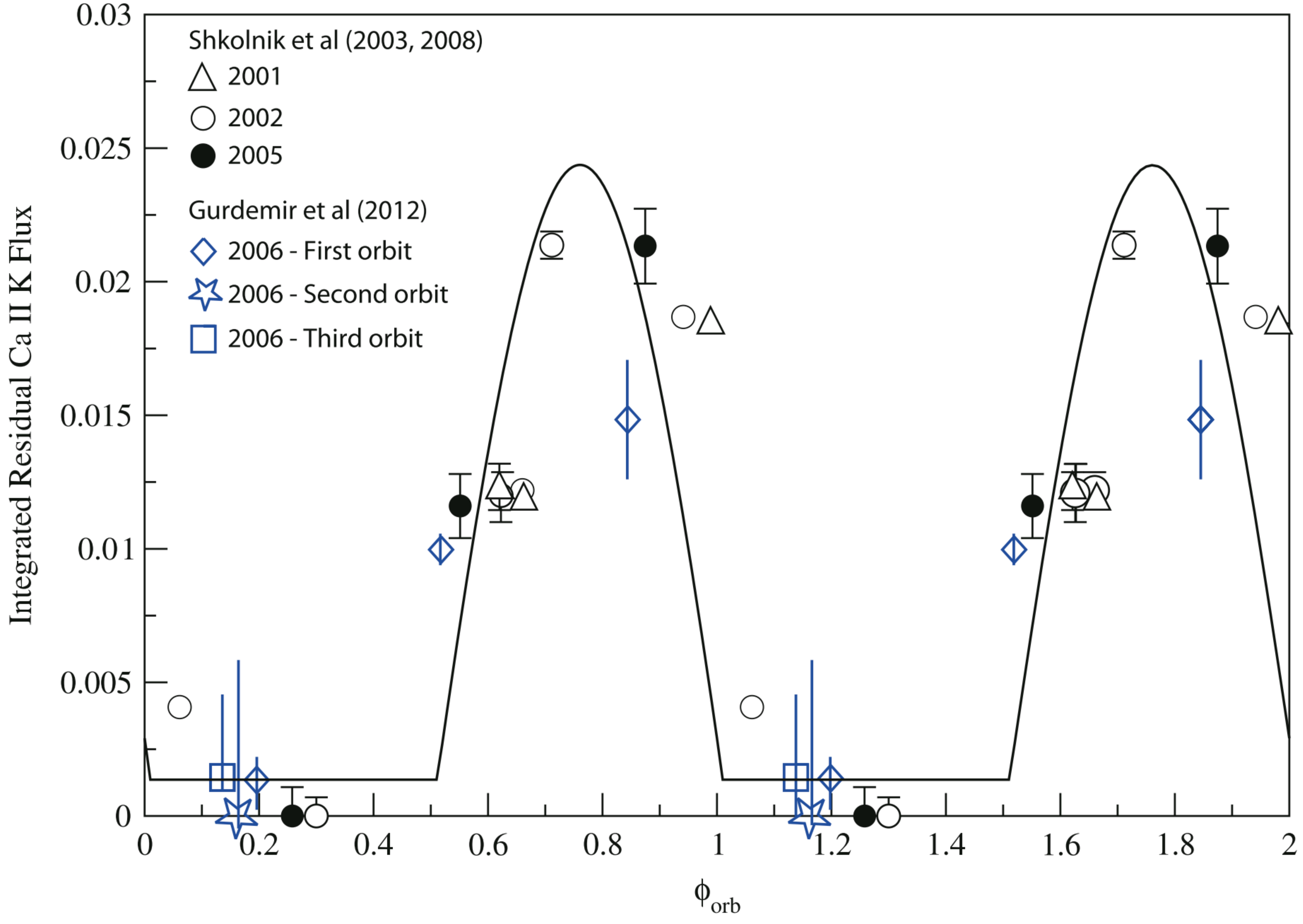
[Clarke+ 2002]



[Zarka 2007]

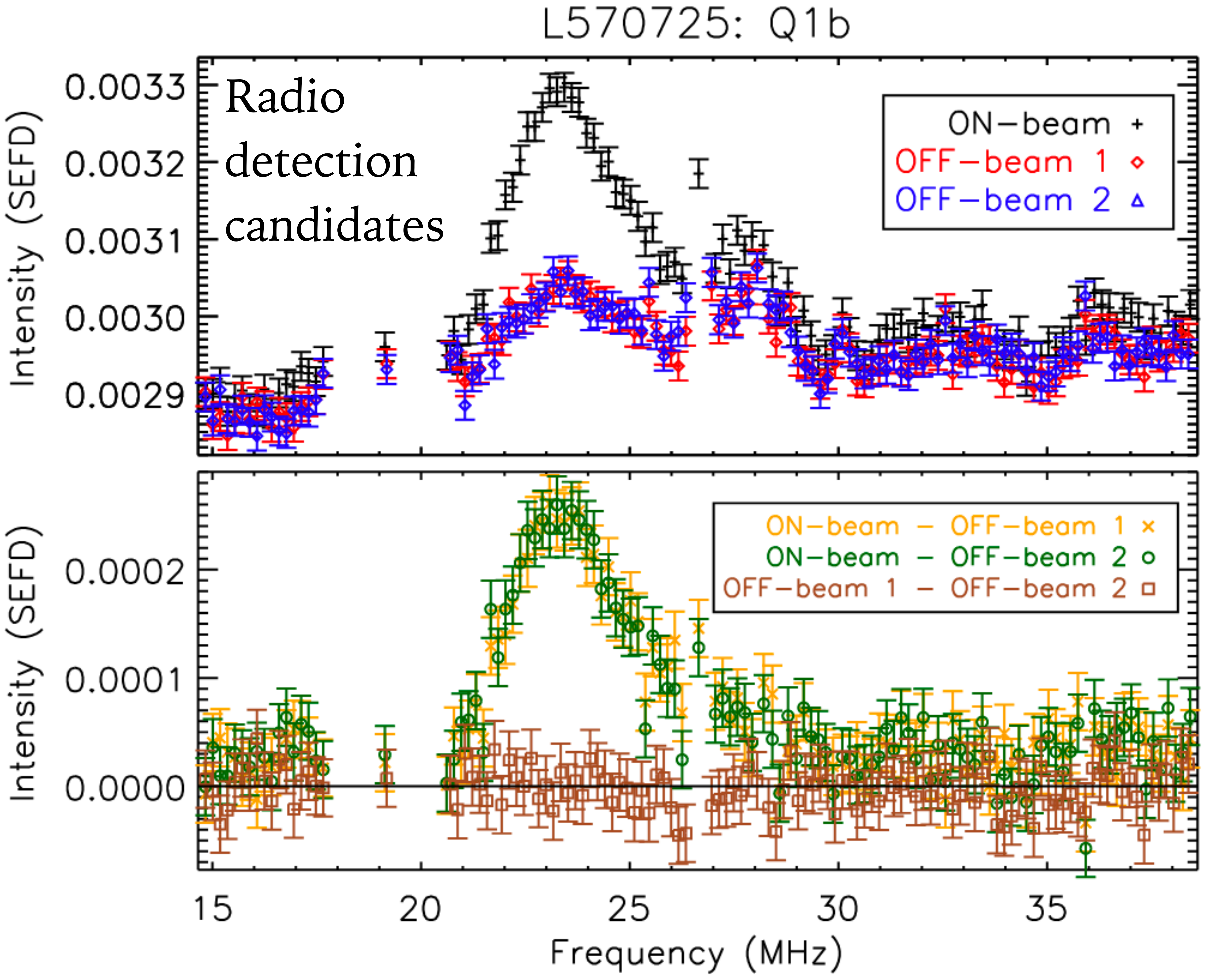
Detections of star-planet magnetic interactions?

CaII K excess for HD 179949



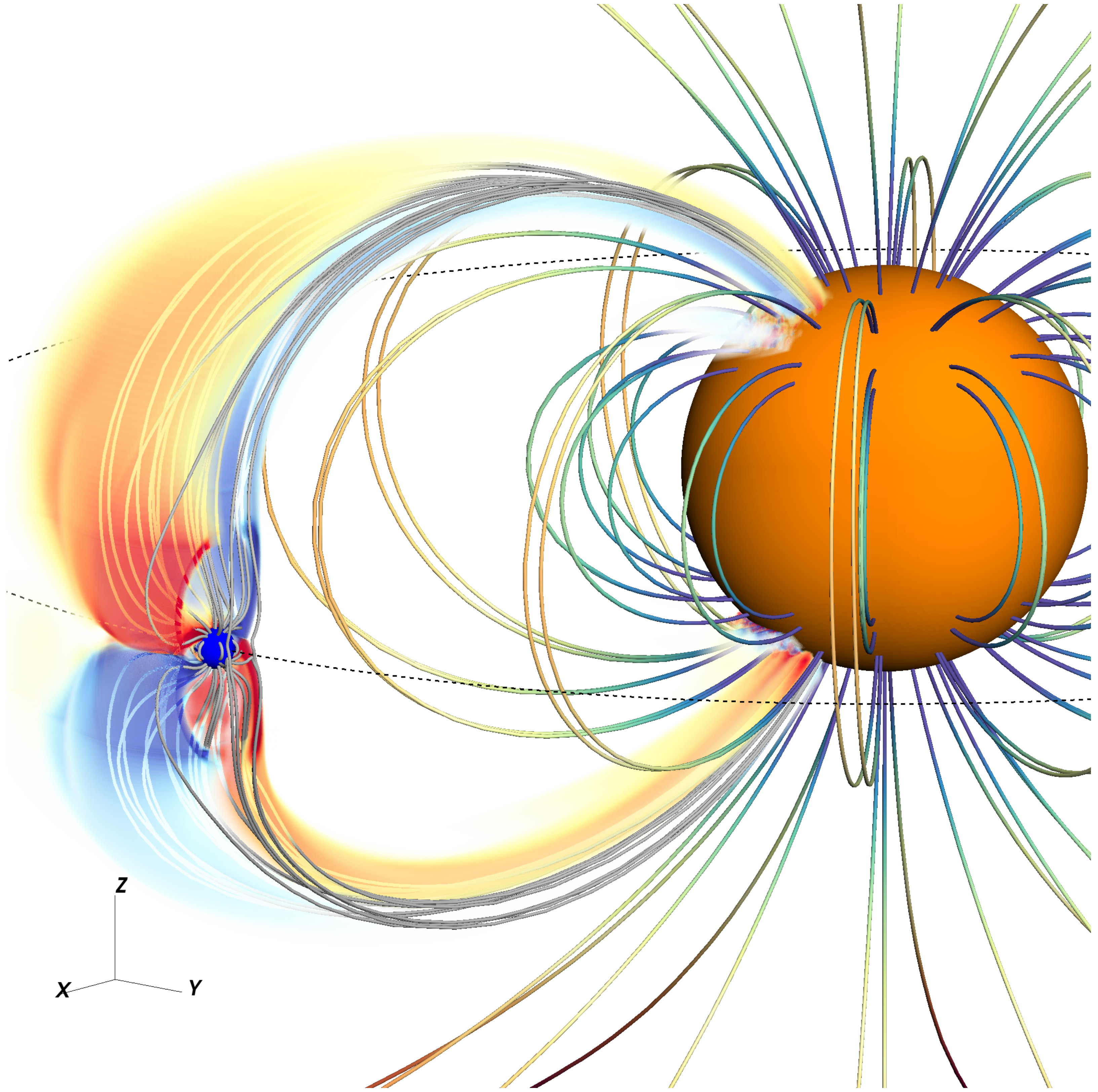
[Shkolnik & Llama 17, Shkolnik+ 03,08]
[see also Cauley+ 18,19]

[Turner, Zarka+21, & talk from yesterday!]



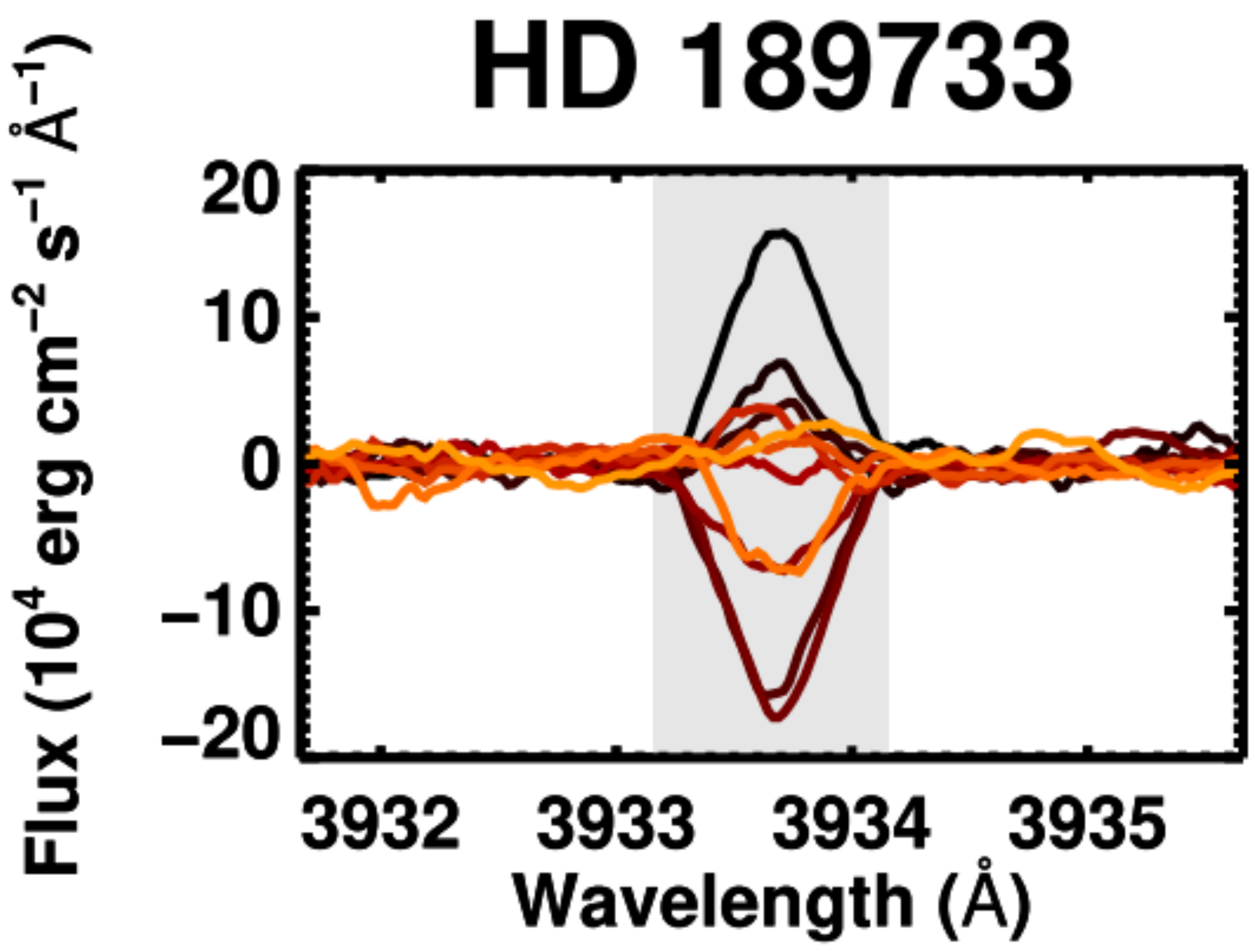
[see also Callingham+ 21, Vedantham+ 21]

Modelling star-planet magnetic interactions: The case of HD 189733

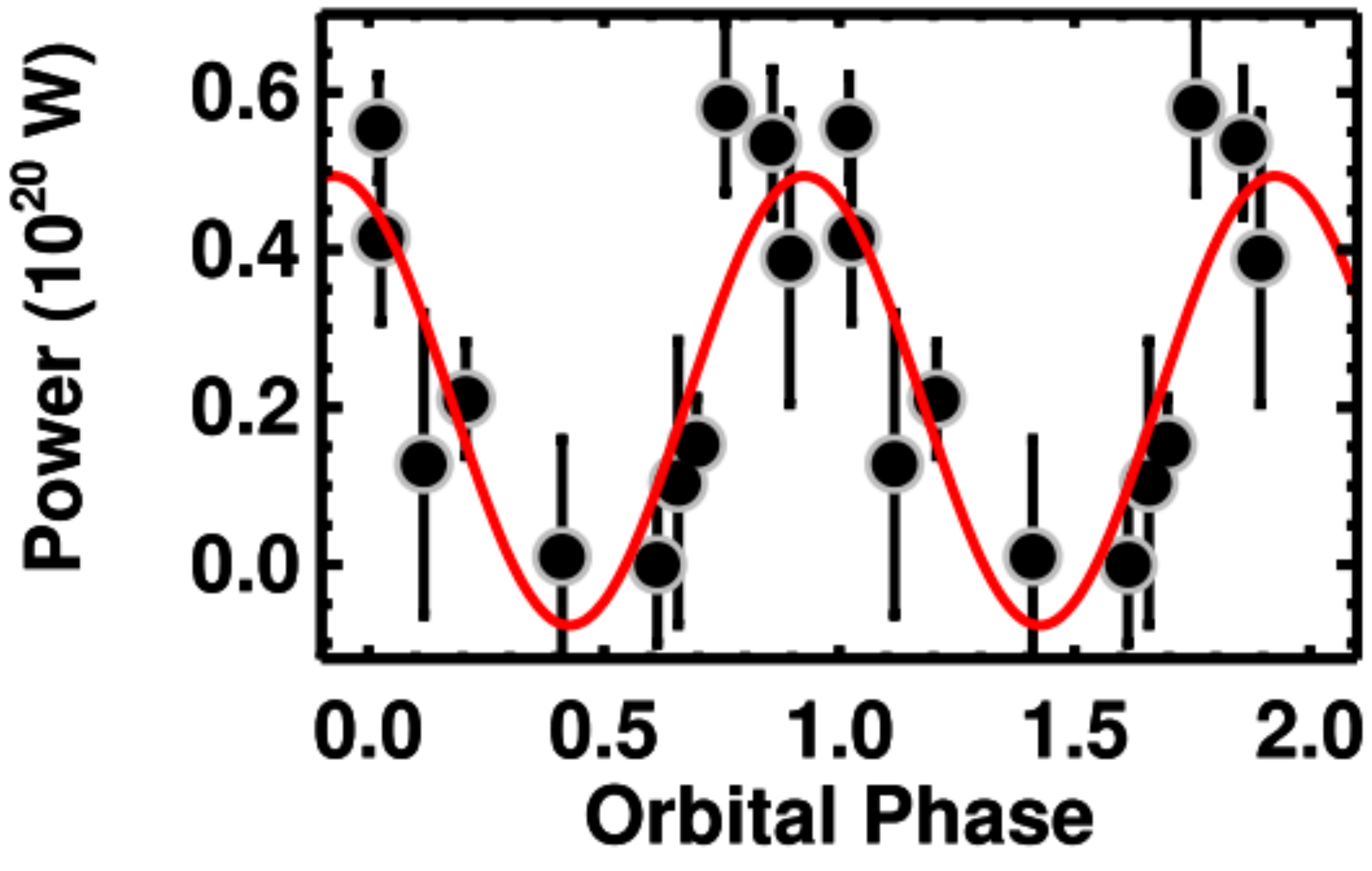


Strugarek+ 2015

Possible star-planet interaction in HD 189733



Cauley+2018, 2019



A signal in the Ca II H&K bands of the host star was observed to be correlated with the orbital phase of the hot exoplanet at **1 epoch out of 6 epochs studied** (Cauley+ 2018)

Applying star-planet interaction scaling law (stretch-and-break mechanism), Cauley+ 2019 deduced a field strength of about 80 G

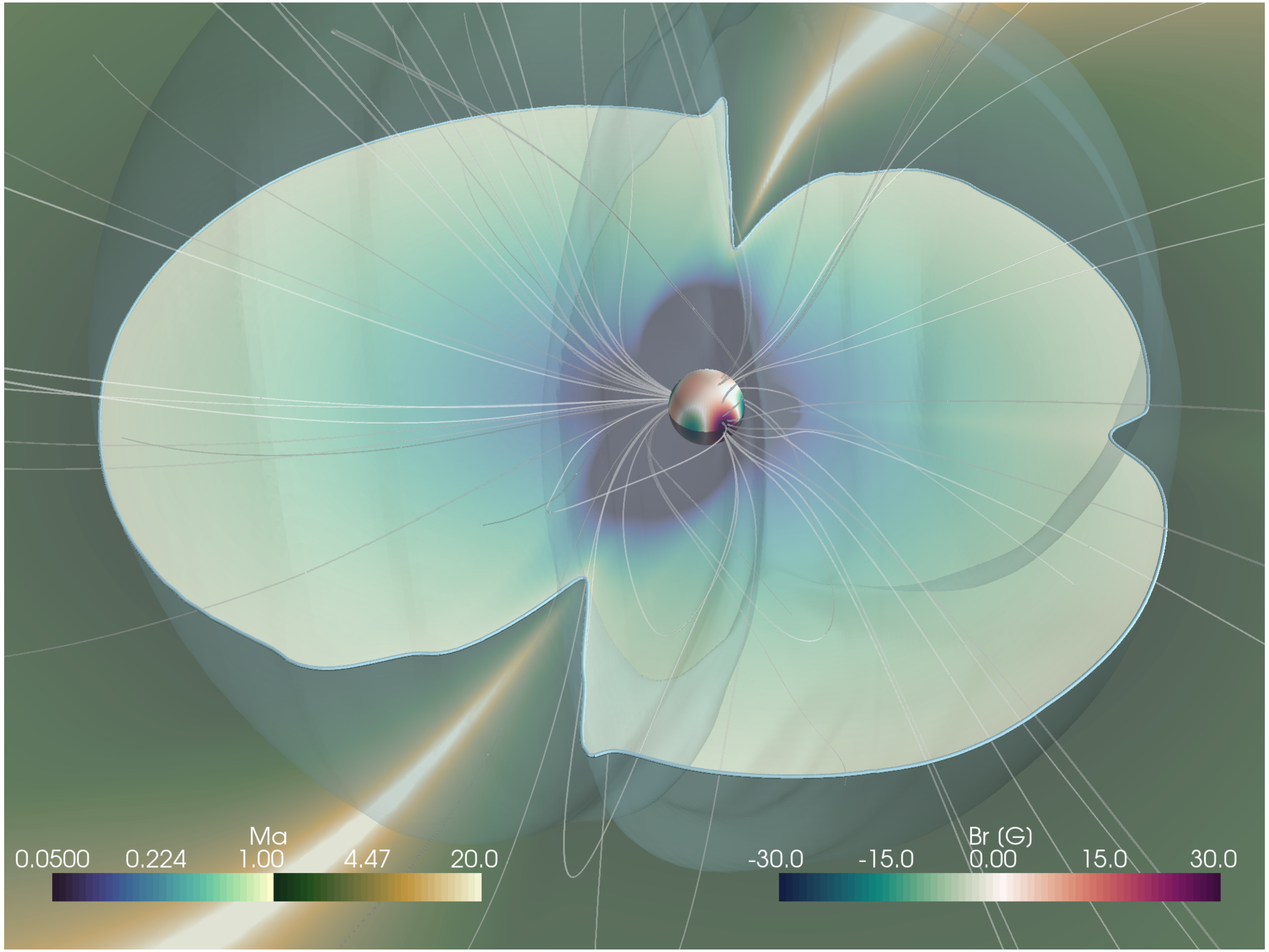
Can we test this?

HD 189733: the MOVES collaboration

Multiwavelength Observations of an eVaporating Exoplanet and its Star (MOVES), Bourrier & collaborators

MOVES I : ZDI maps of HD 18933 at five different epochs	*Fares+ 2017*
MOVES II: First wind model of HD 189733 and radios emissions	*Kavanagh+ 2019*
MOVES III: Variability of the X-ray and UV environment of HD 189733	*Bourrier+ 2020*
MOVES IV: Atmospheric composition of HD 189733b	*Barth+ 2021*
MOVES V: Magnetic star-planet interaction in HD 189733b	*Strugarek+ 2022*

Detailed modelling of HD 189733, August 2013



The hot Jupiter HD 189733b **could orbit within the Alfvén surface**

But the **connectivity is modulated** by the 'complex' **magnetic topology** of the star

Simulation data available on Galactica database

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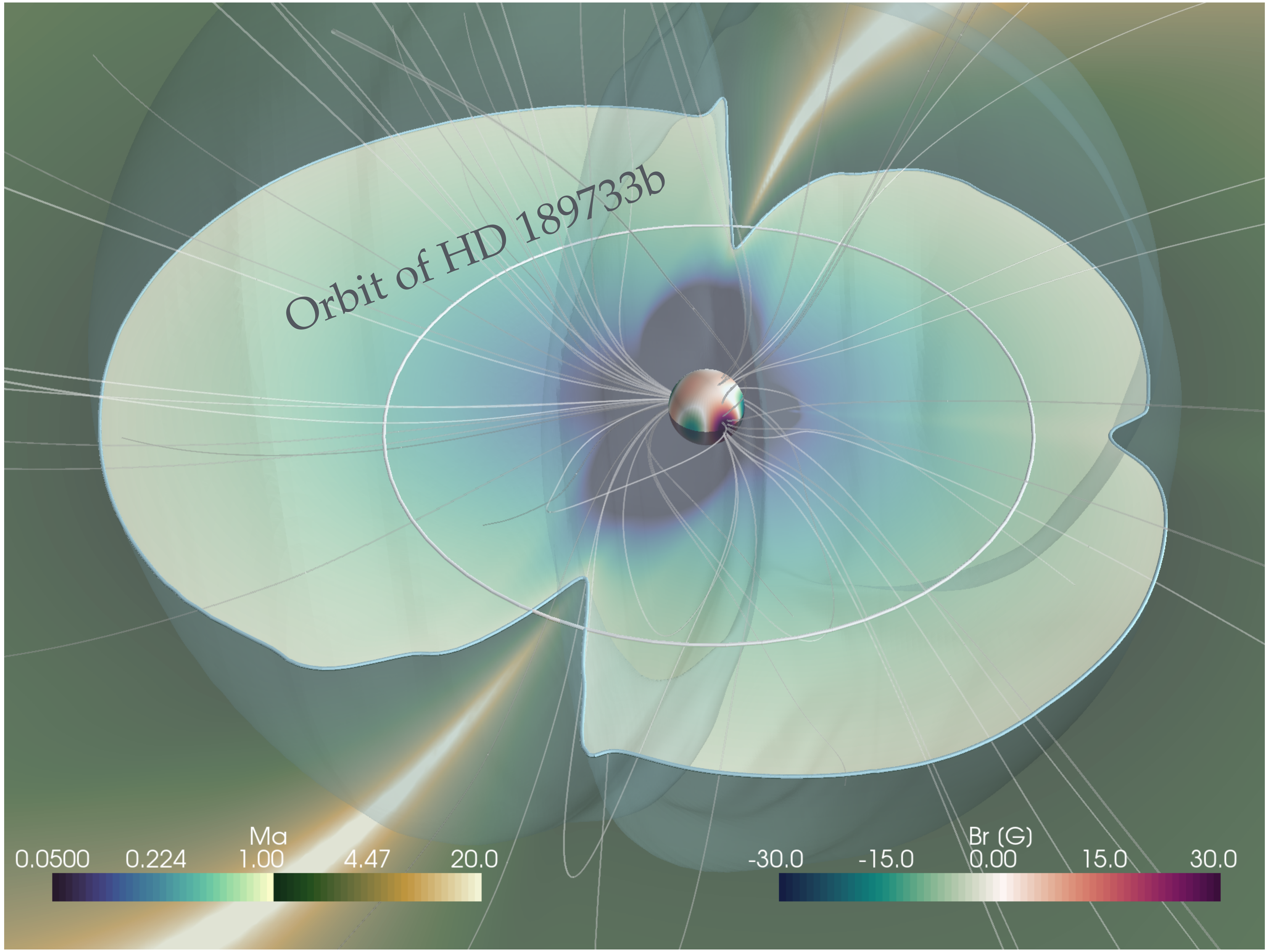

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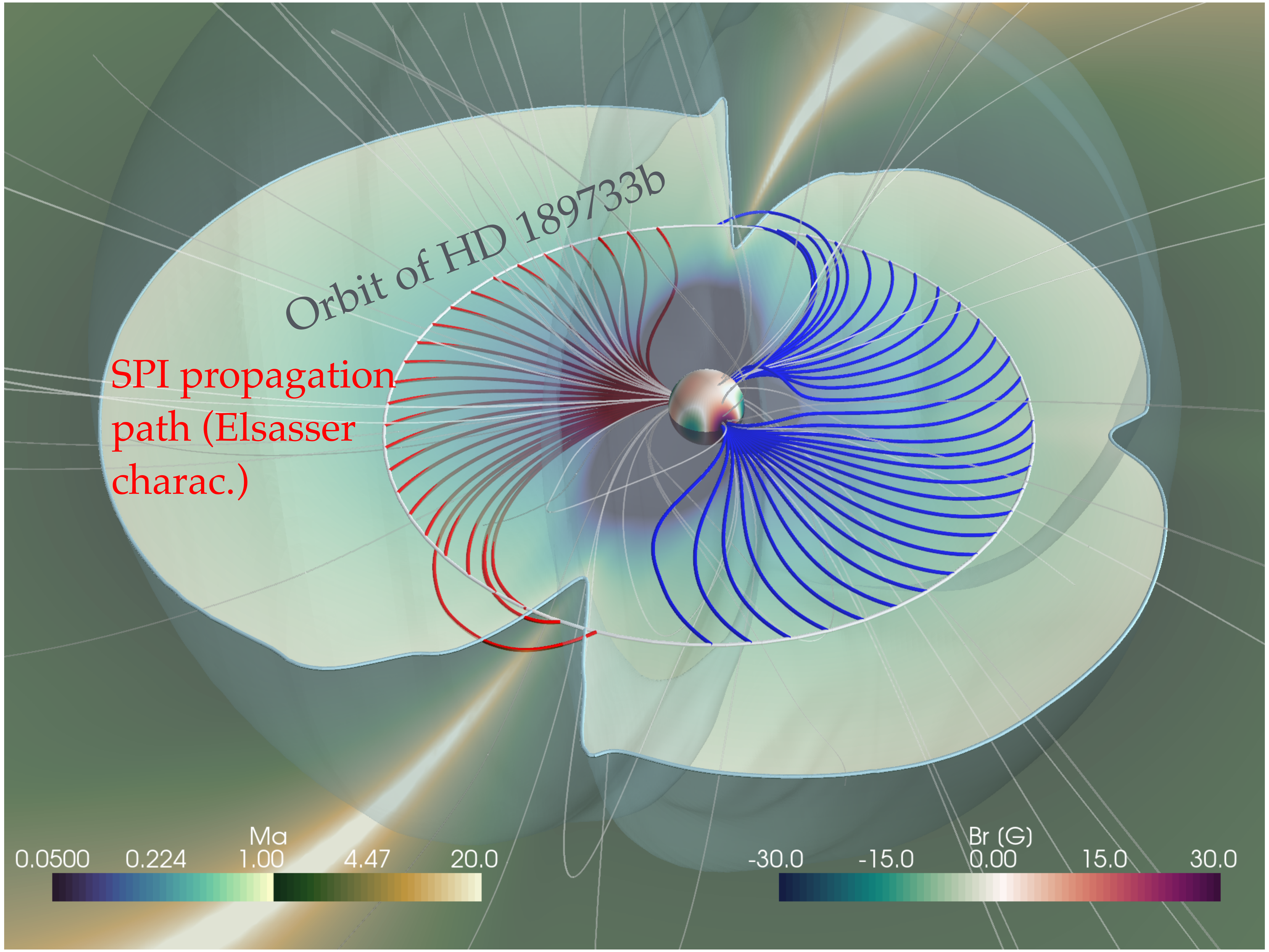

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Detailed modelling of HD 189733

Planetary signal statistically detectable only 1/6 of the time!

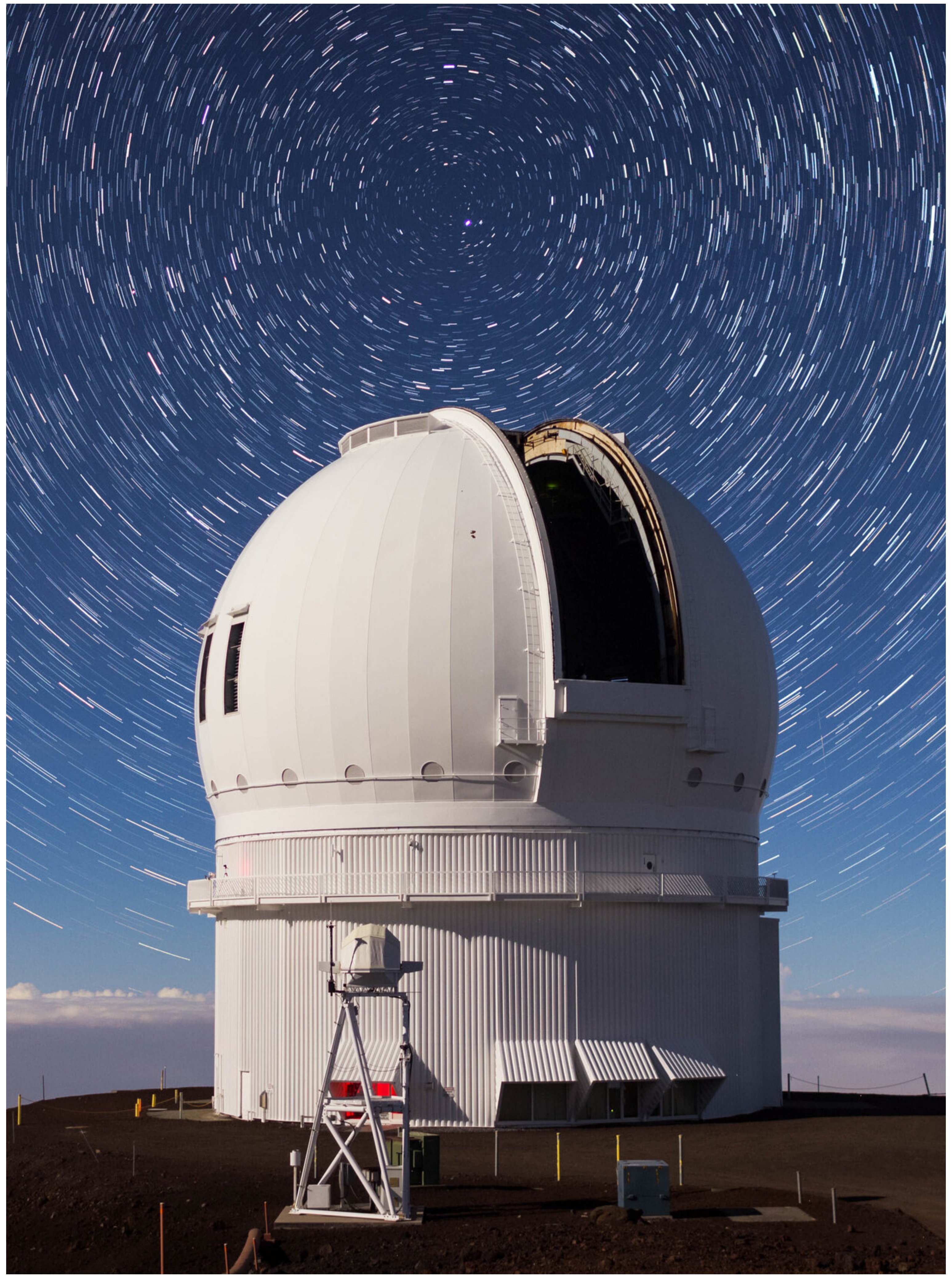
 [Strugarek+ 22]

Detailed modelling of HD 189733

Planetary signal statistically detectable only 1/6 of the time!

Denser observational campaigns are needed, and could lead to the confirmation of the star-planet magnetic interaction interpretation

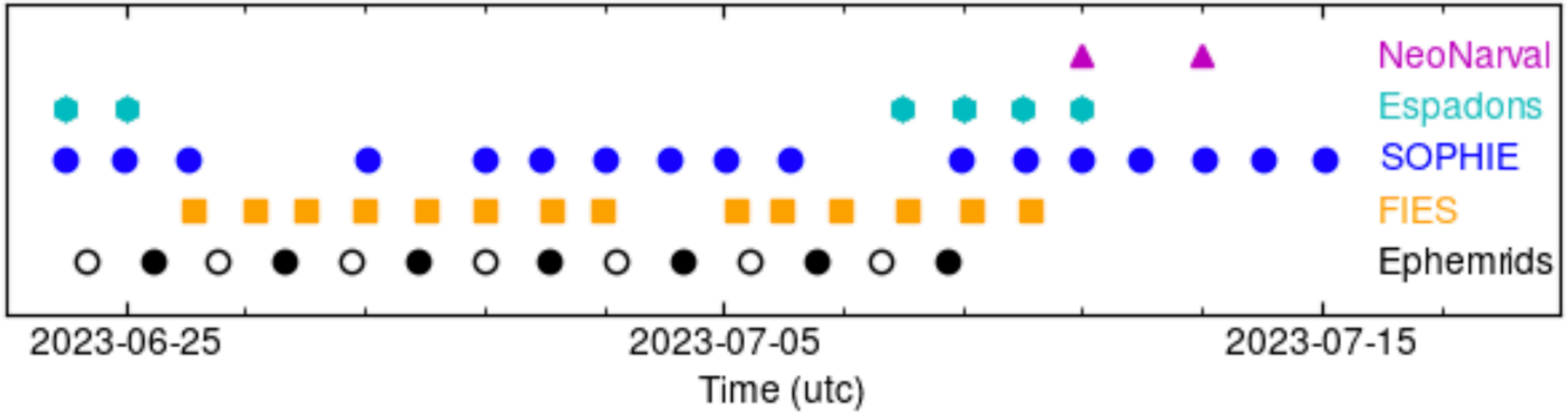
New observational campaign carried out in 2023A



Coordination of four ground-based telescopes
- CFHT/Espadons+SPIRou
- NOT/FIES
- TBL/NeoNarval
- OHP/SOPHIE

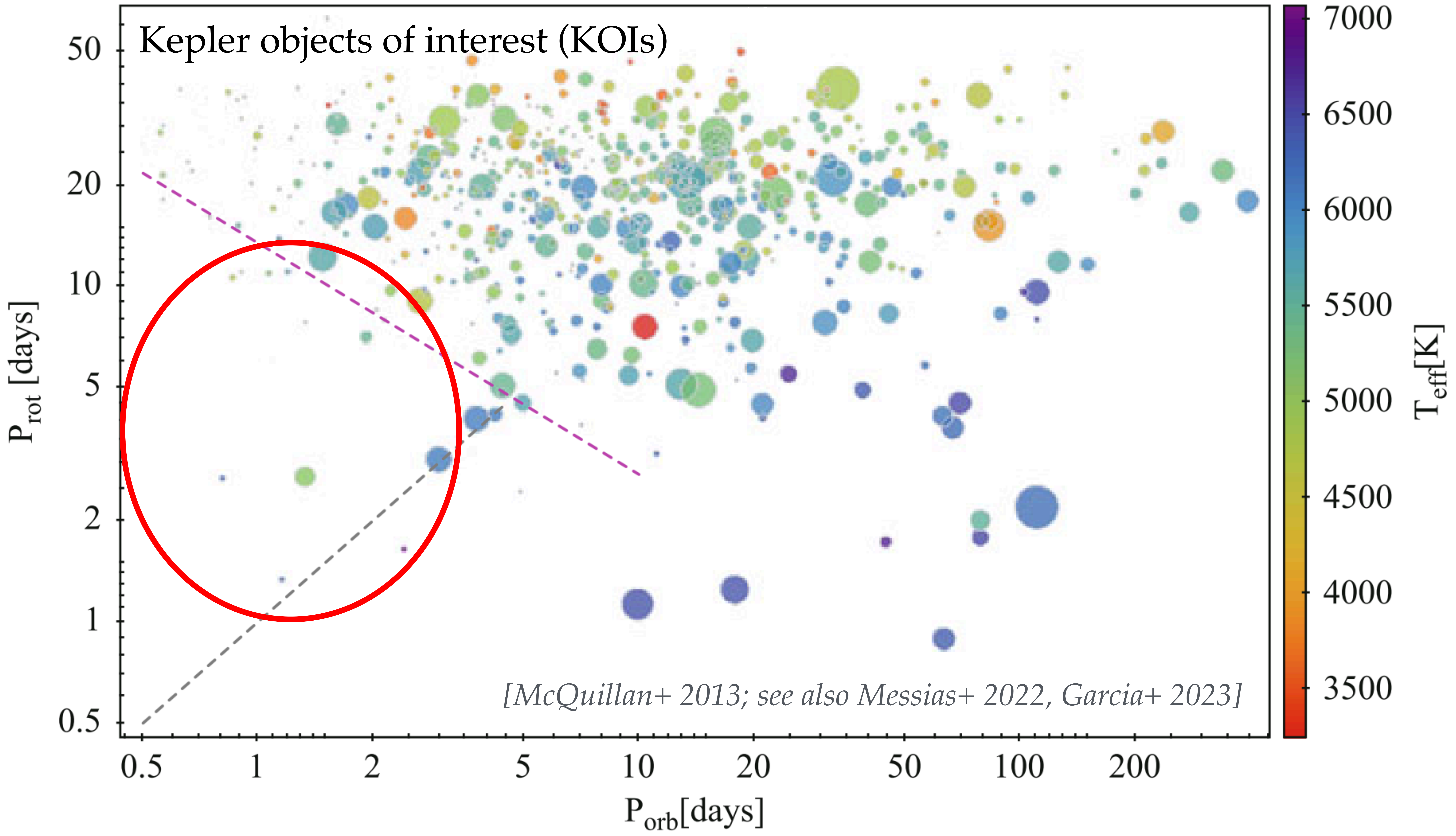
\+ coordinated radio campaign with NenuFAR at the same time

Stay tuned for new results on HD 189733…

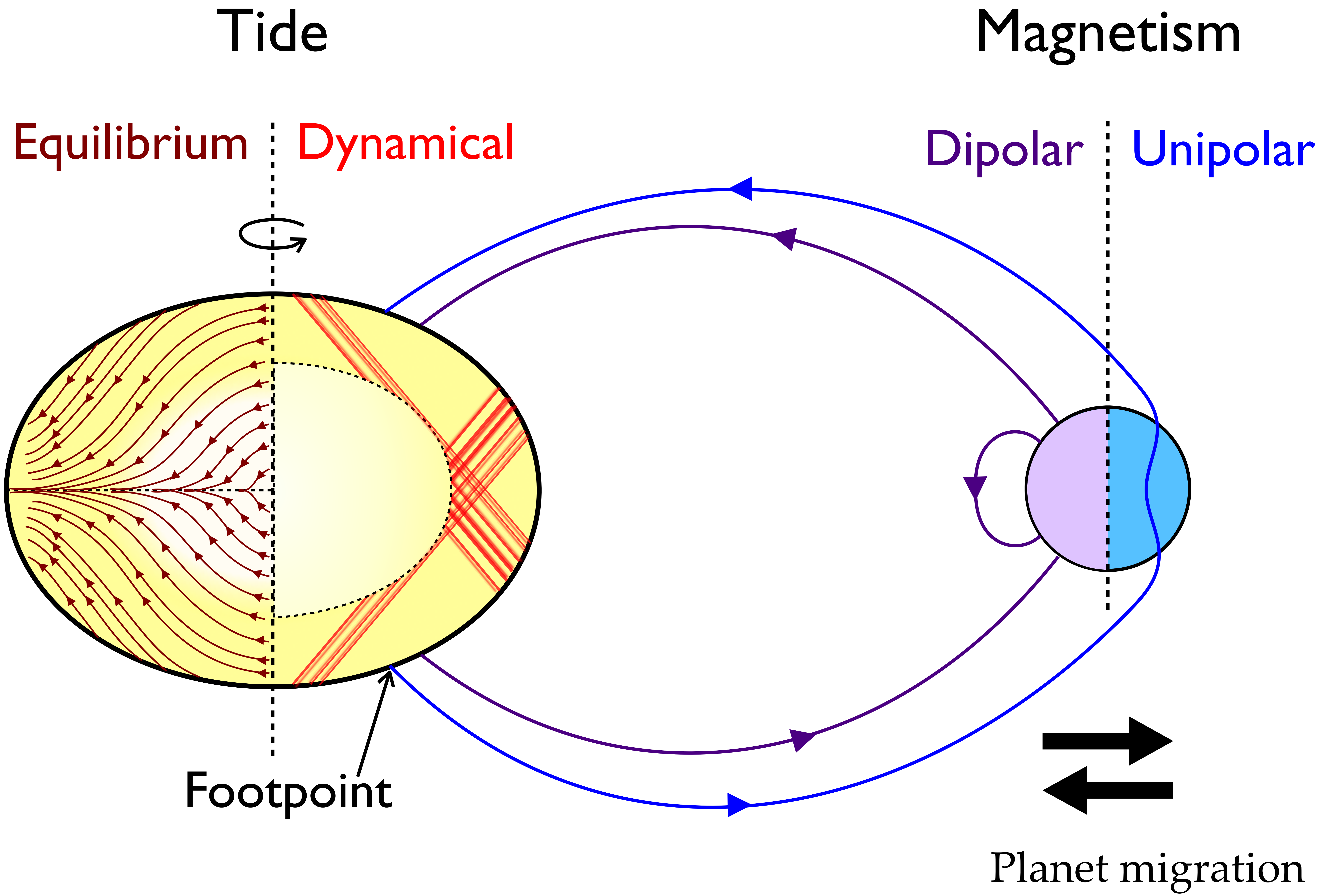


Long term, secular effect of star-planet interactions

A possible trace of secular star-planet interactions



Secular effects: magnetic vs tidal torques



[Strugarek+ 17]

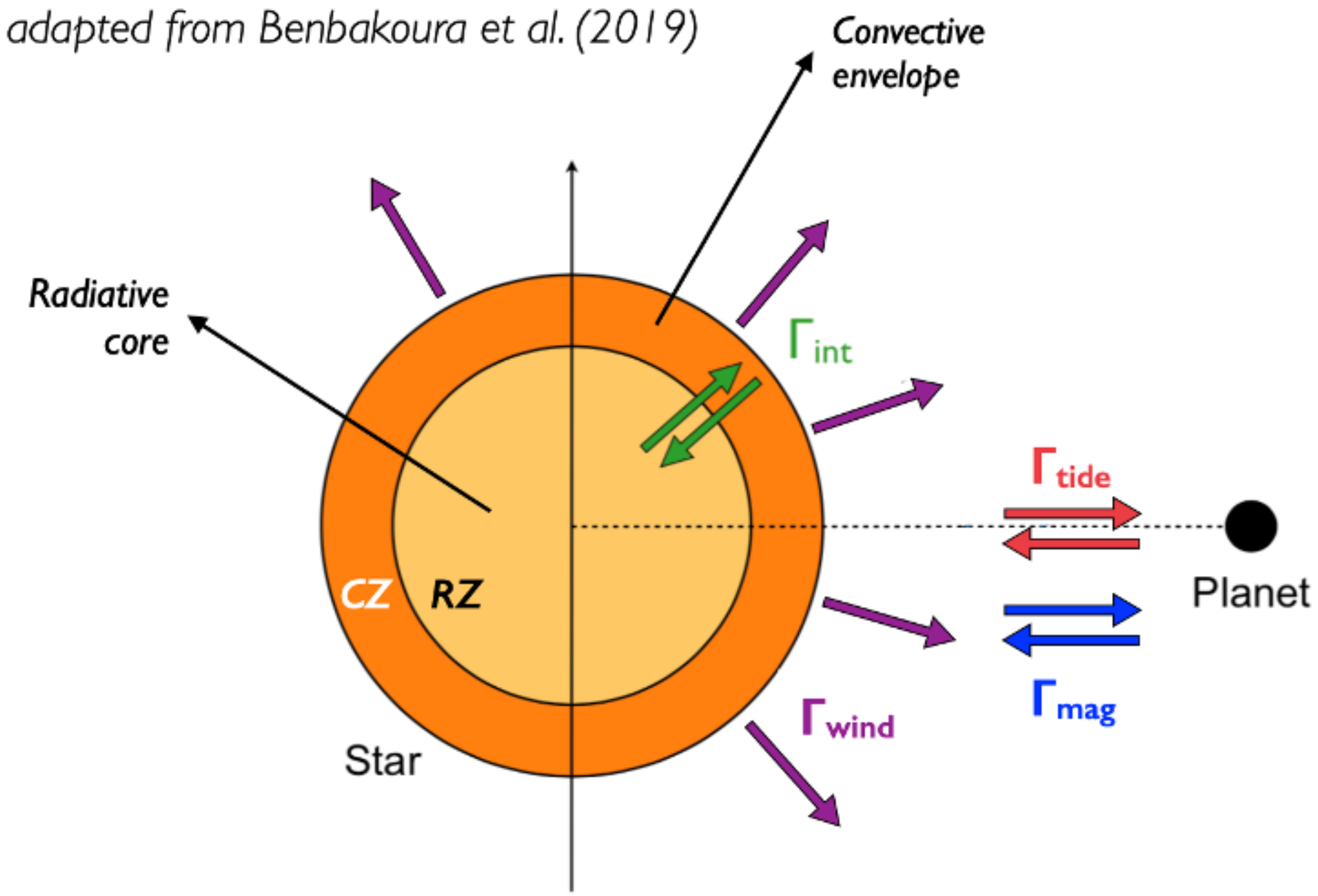
Modelling star-planet evolution: the ESPEM code

Benbakoura+ 2019
Ahuir+ 2021

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

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

adapted from Benbakoura et al. (2019)



Equilibrium tide

Dynamical tide
(inertial waves in the convective zone)

Two bodies, multiple interactions

Equations for the angular momentum evolution (uniform rotation both in RZ and in CZ):

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

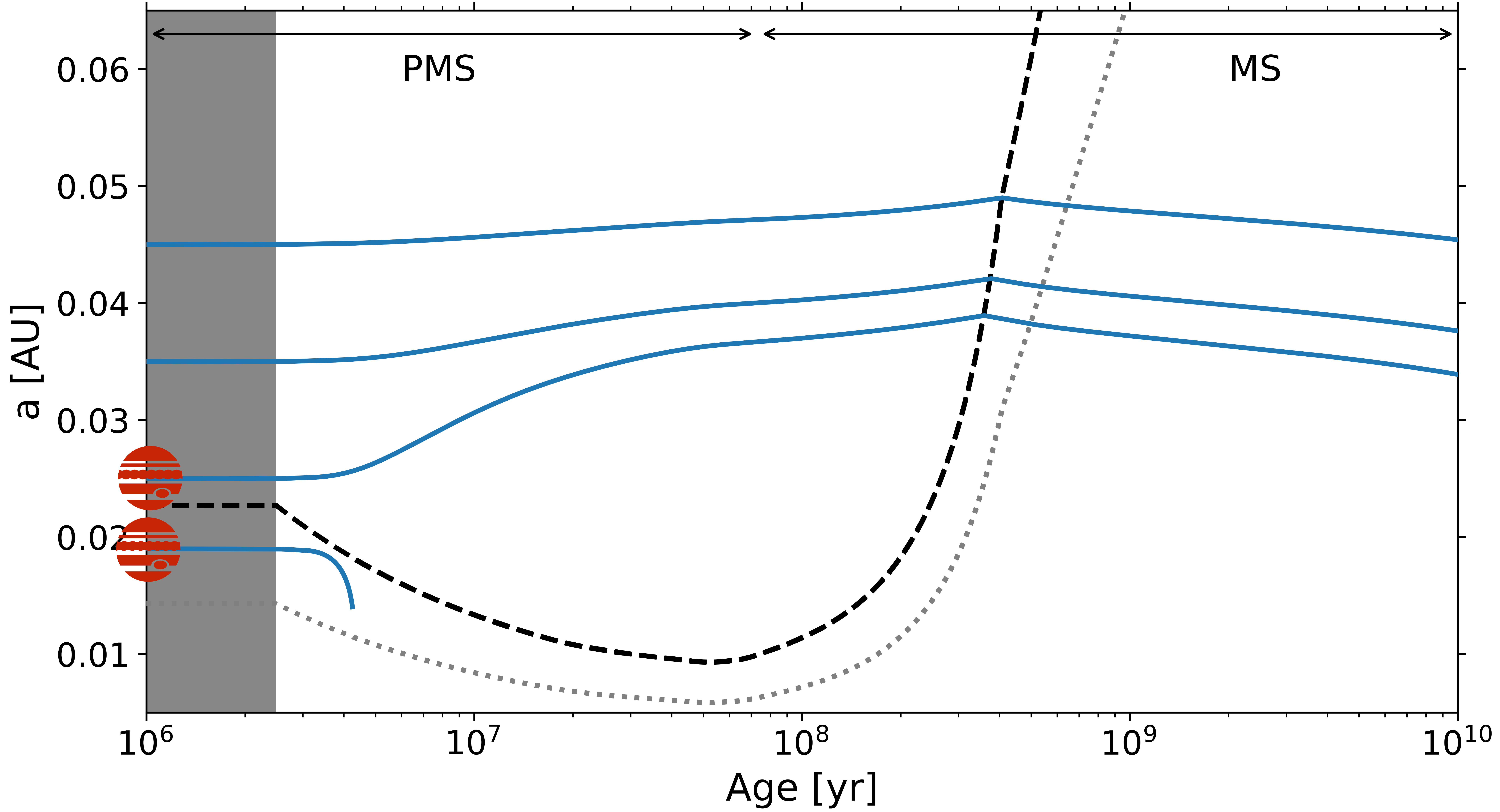
$$\frac{dL_c}{dt} = \Gamma_{int} + \Gamma_{tide} + \Gamma_{mag} - \Gamma_{wind}$$

$$\frac{dL_r}{dt} = -\Gamma_{int} + \Gamma_{tide}$$

Requires a 1D MHD wind

Close-in planets migration due to tidal and magnetic torques

ESPEM code



[Benbakoura+ 19; Ahuir+ 21]

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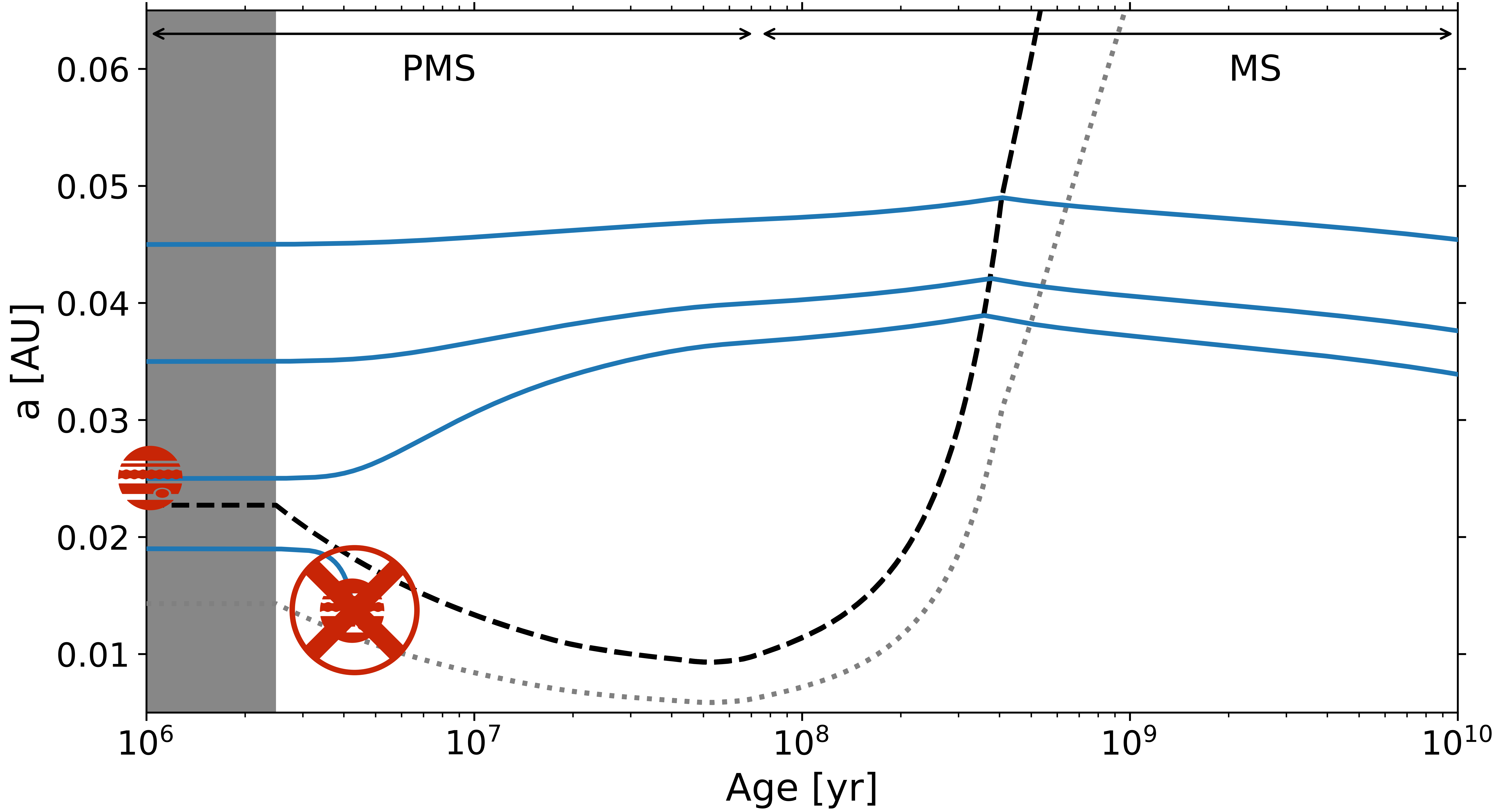

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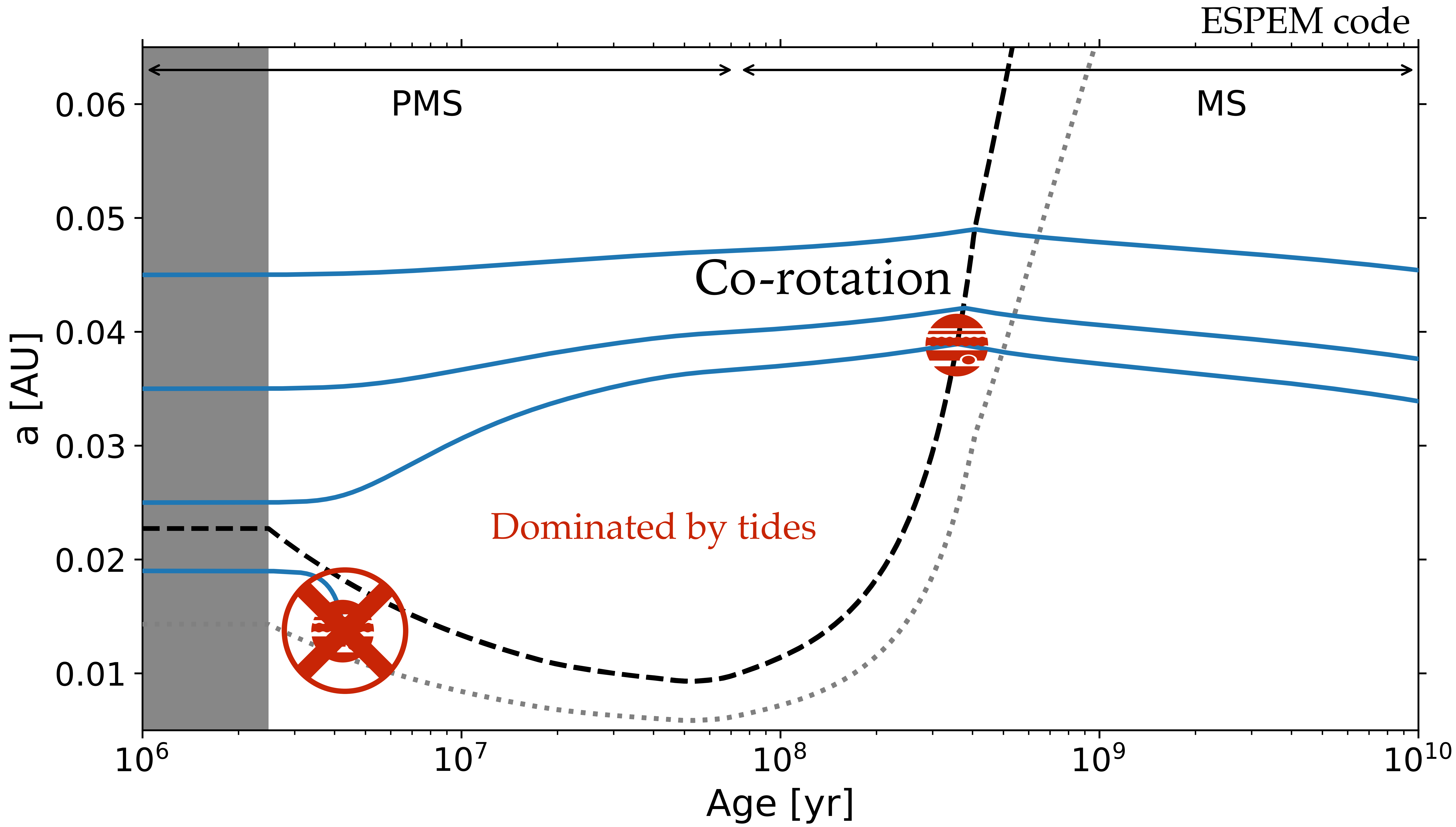

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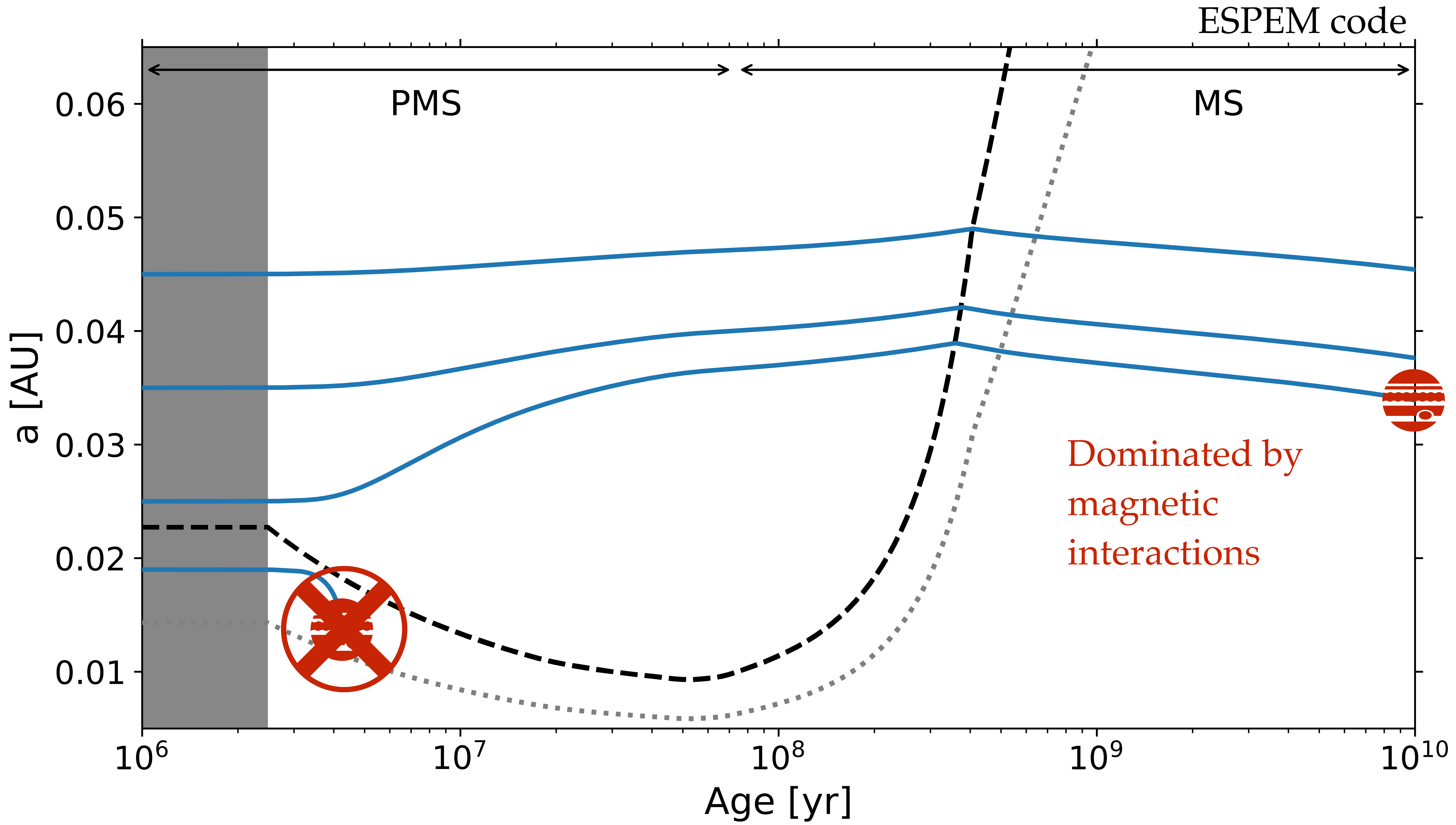
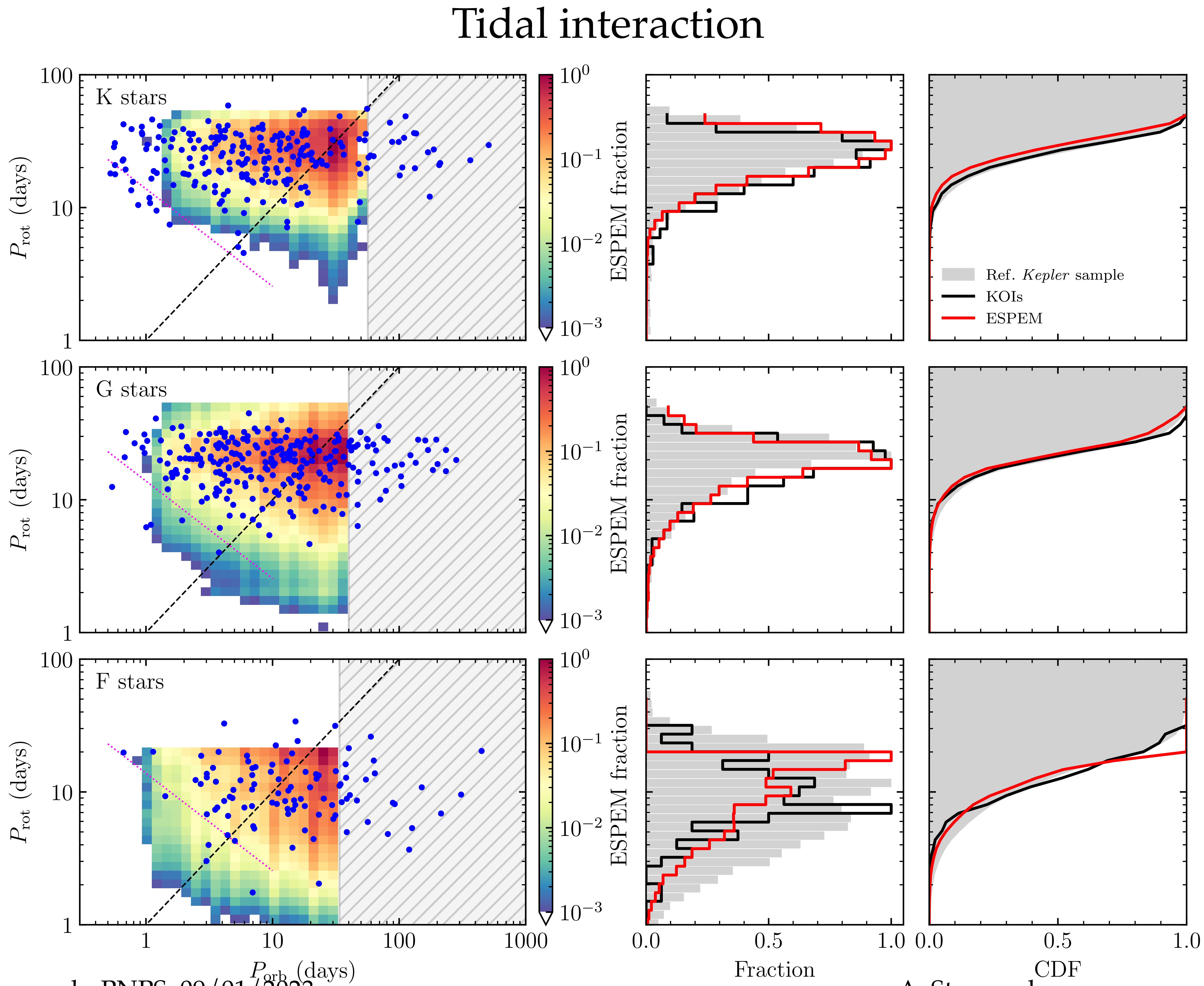


[Benbakoura+ 19; Ahuir+ 21]

Synthetic population vs Kepler-field population

[Garcia+ 2023]

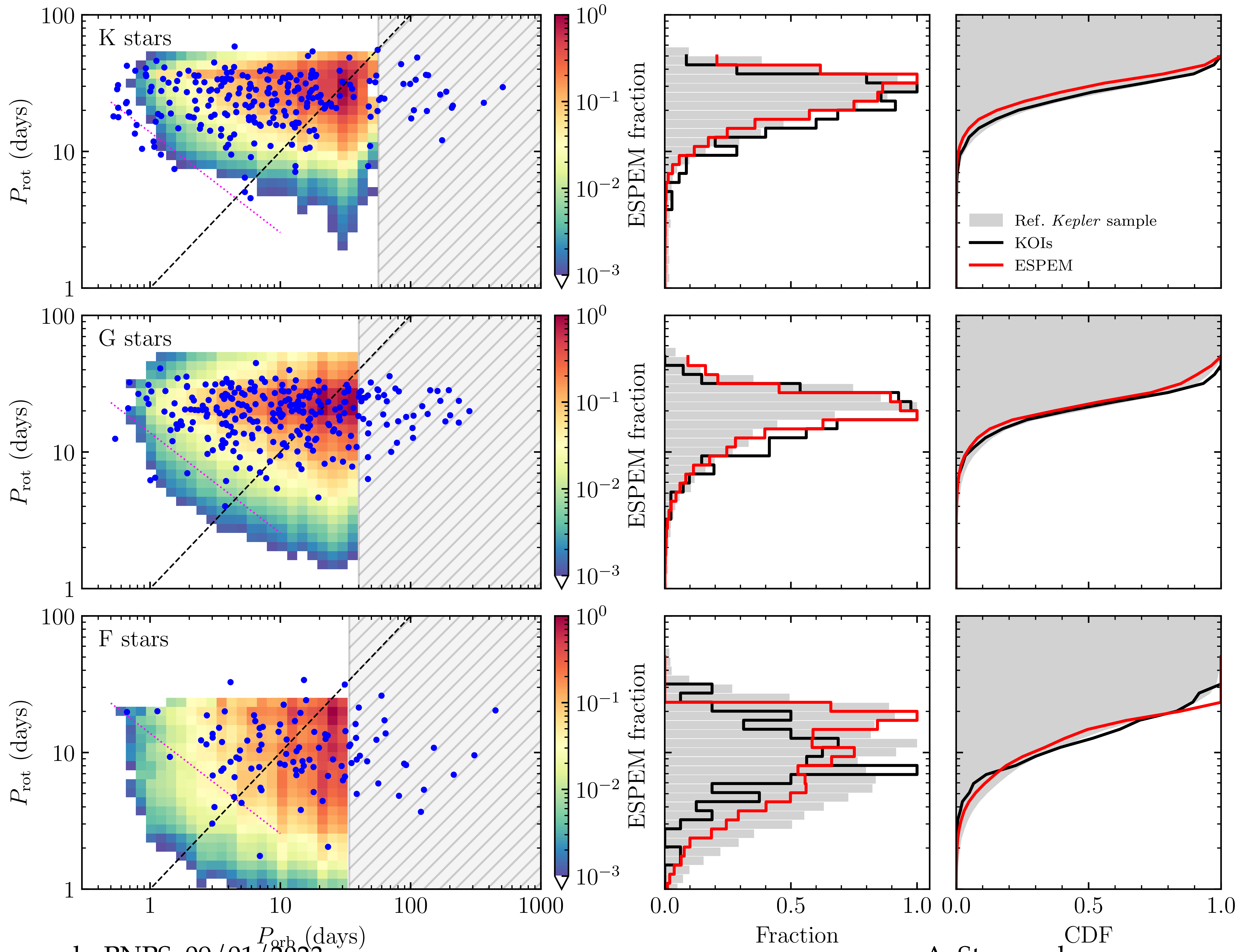


Initial conditions: no planets within the inner radius of the dead zone of protoplanetary disks

Synthetic population vs Kepler-field population

[Garcia+ 2023]

Tidal + 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**.

Synthetic population vs Kepler-field population

[Garcia+ 2023]

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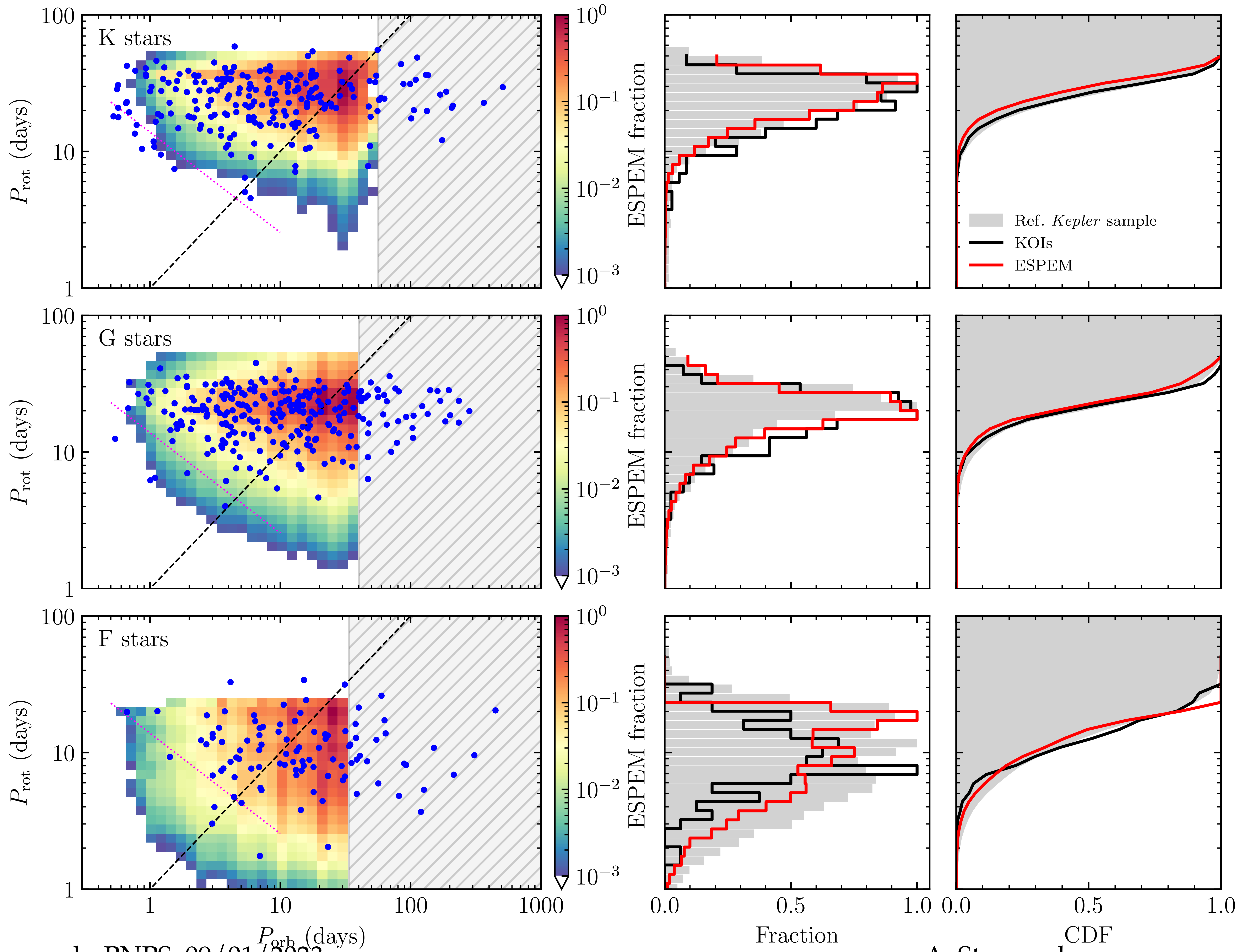

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ESPEM reproduces the dearth of exoplanets on short-period orbit around fast rotators, that appears from a **realistic distribution of planets** after the disk dissipation that **migrates due to tidal and magnetic torques**.

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

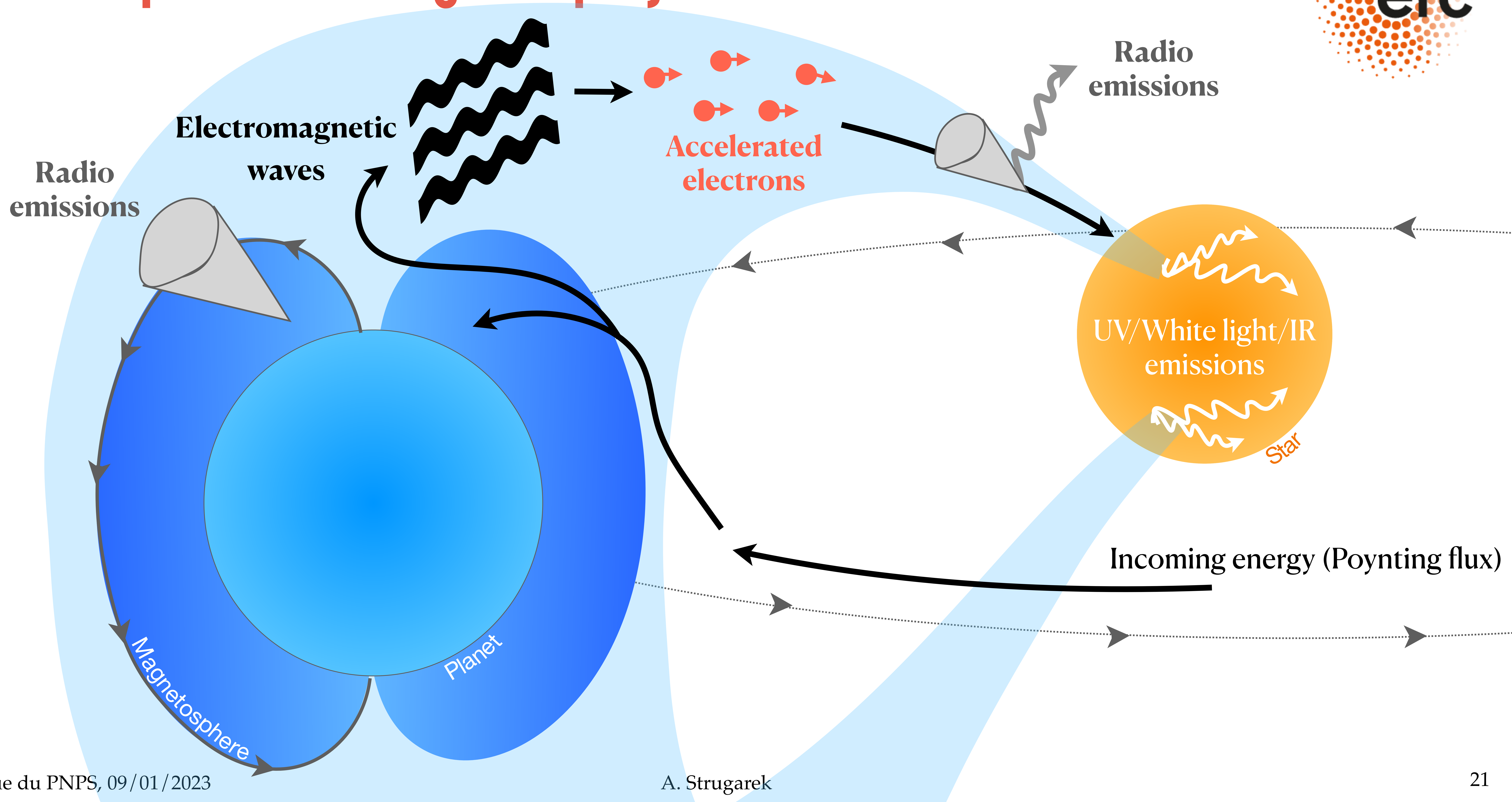
Conclusions & Perspectives

- Star-planet magnetic interactions can play an important role for planets **& stars,** including the evolution of stellar rotation (PLATO)
- Many attempts to detect star-planet interactions tracers over the past ~20 years. **Most detections remained tentative so far**, but **we start to have the tools** (instruments, theoretical models, HPC codes) to disentangle false detections from real detections.

- The magnetic interactions generally **strongly depend** on the **magnetic topology** of the **star** in the first place. Real need for **spectropolarimeters like e.g. future VISION** instrument.
- New constraints expected from **radio observatories** (LOFAR, NenuFAR, SKAO, see yesterday's talk from P. Zarka)

- To leverage existing and future observations, **we need to develop quantitative theories for the various tracers of star-planet magnetic interactions** (need support for **community codes**)…

Next step: the ExoMagnets project



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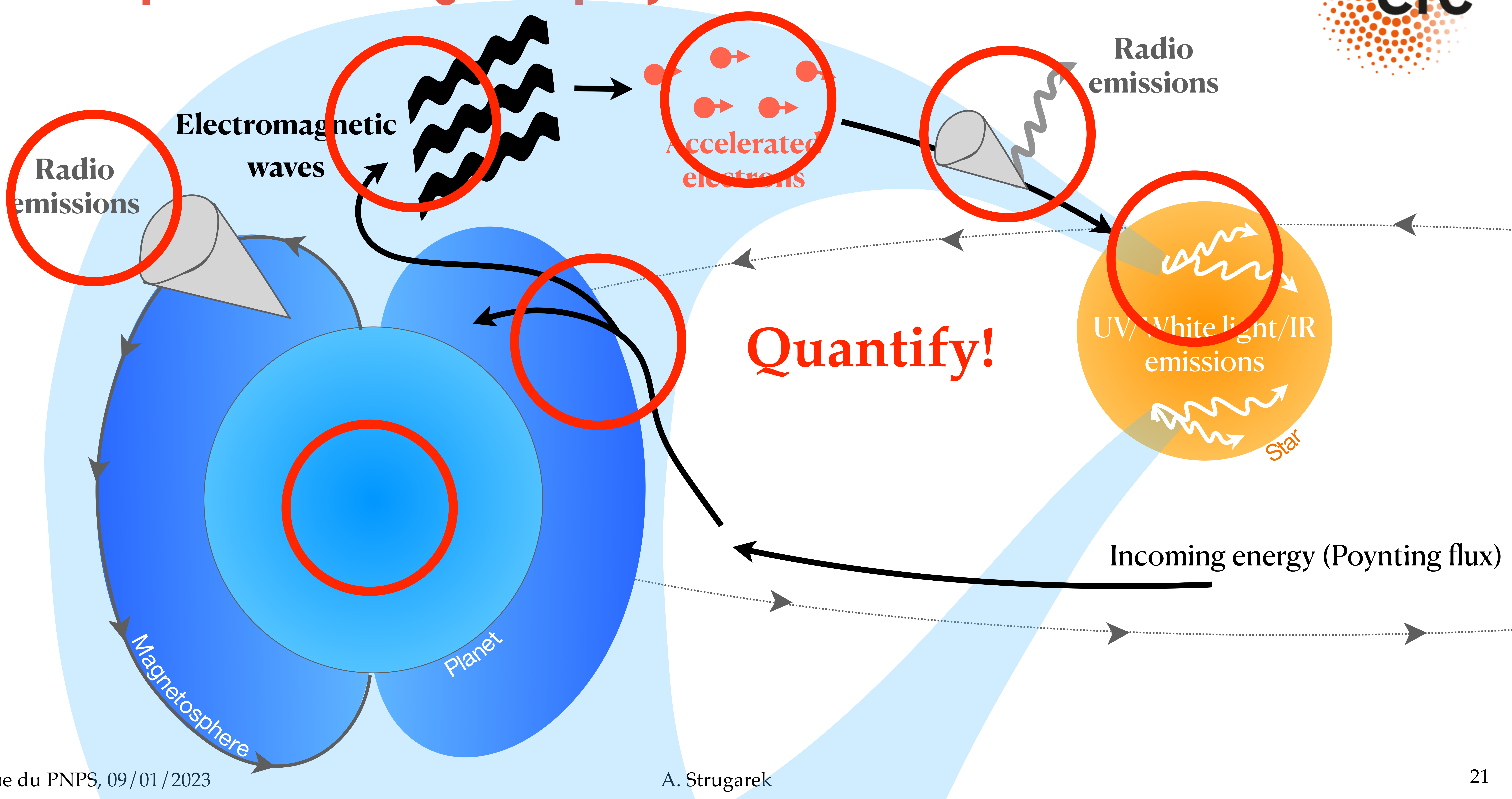
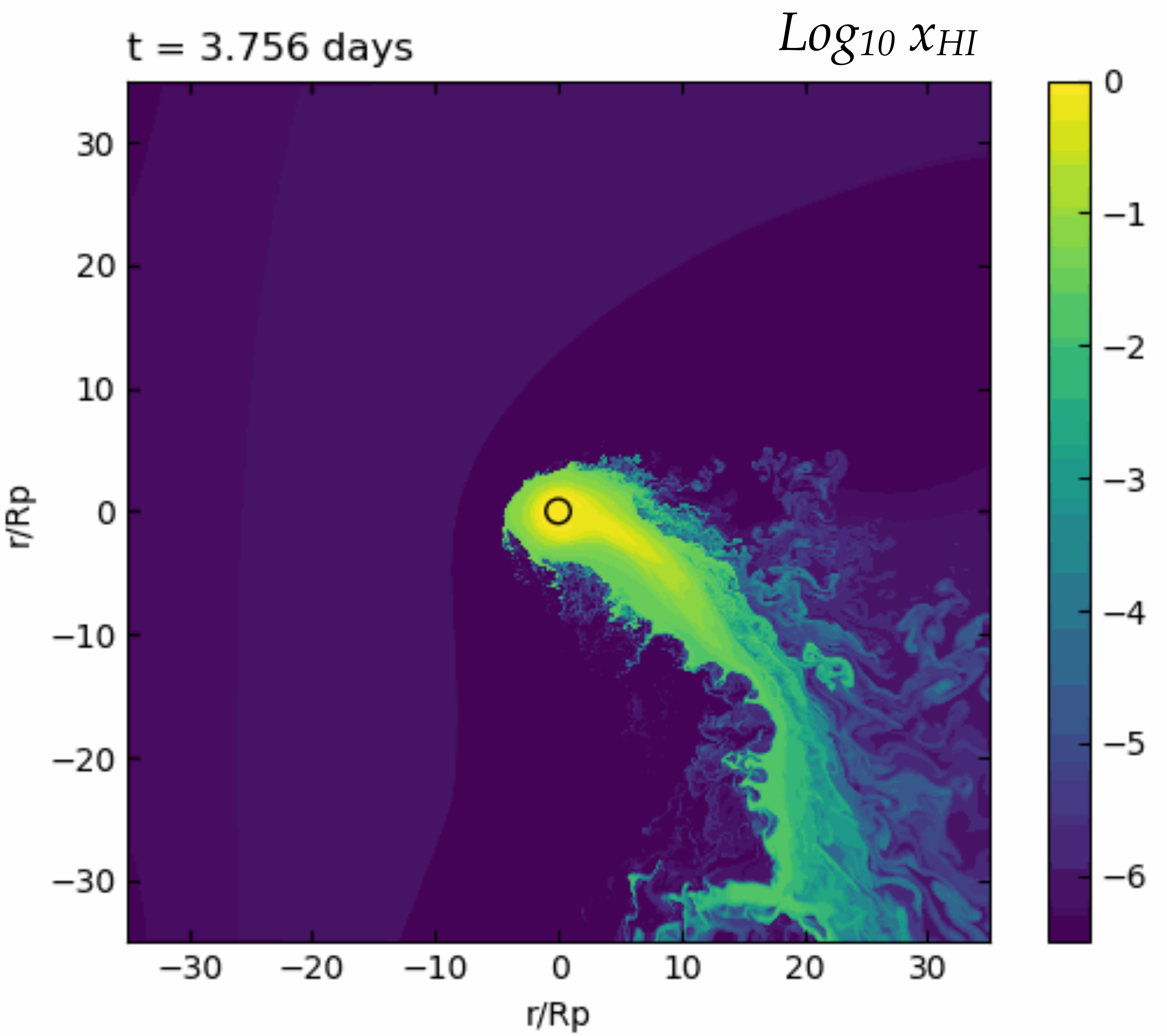
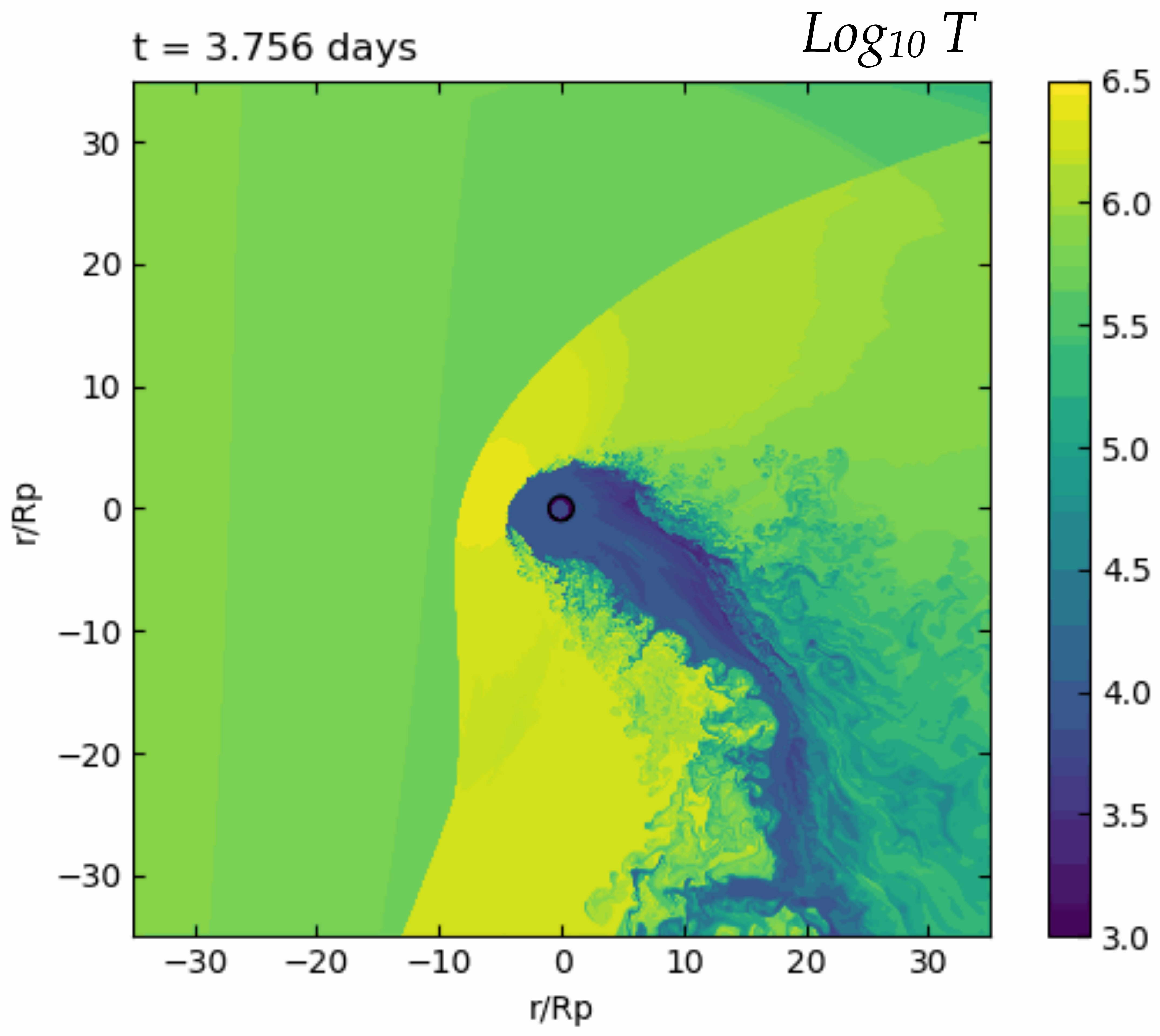


Antoine Strugarek

antoine.strugarek@cea.fr

Towards agnetic interactions and atmospheric escape

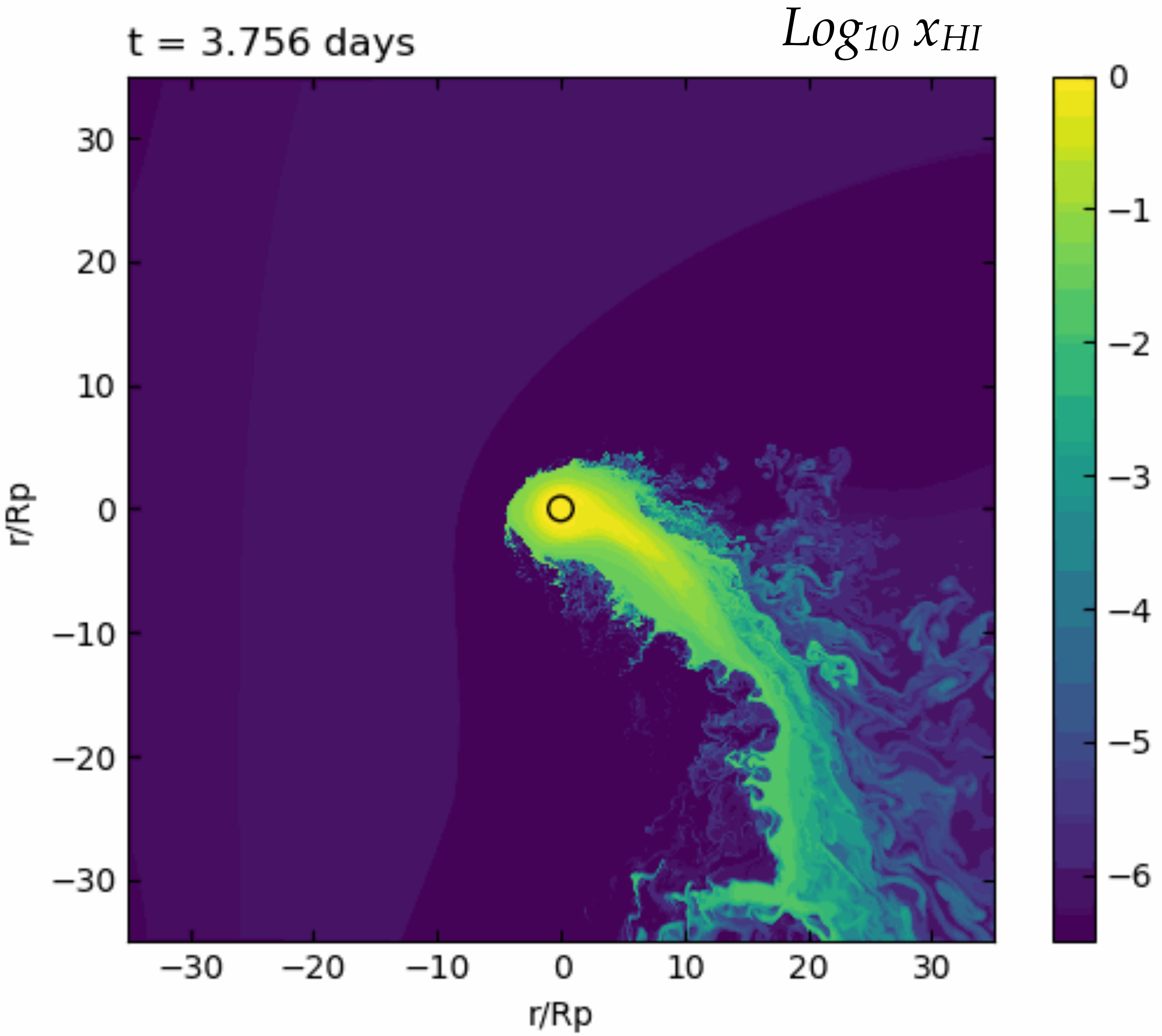


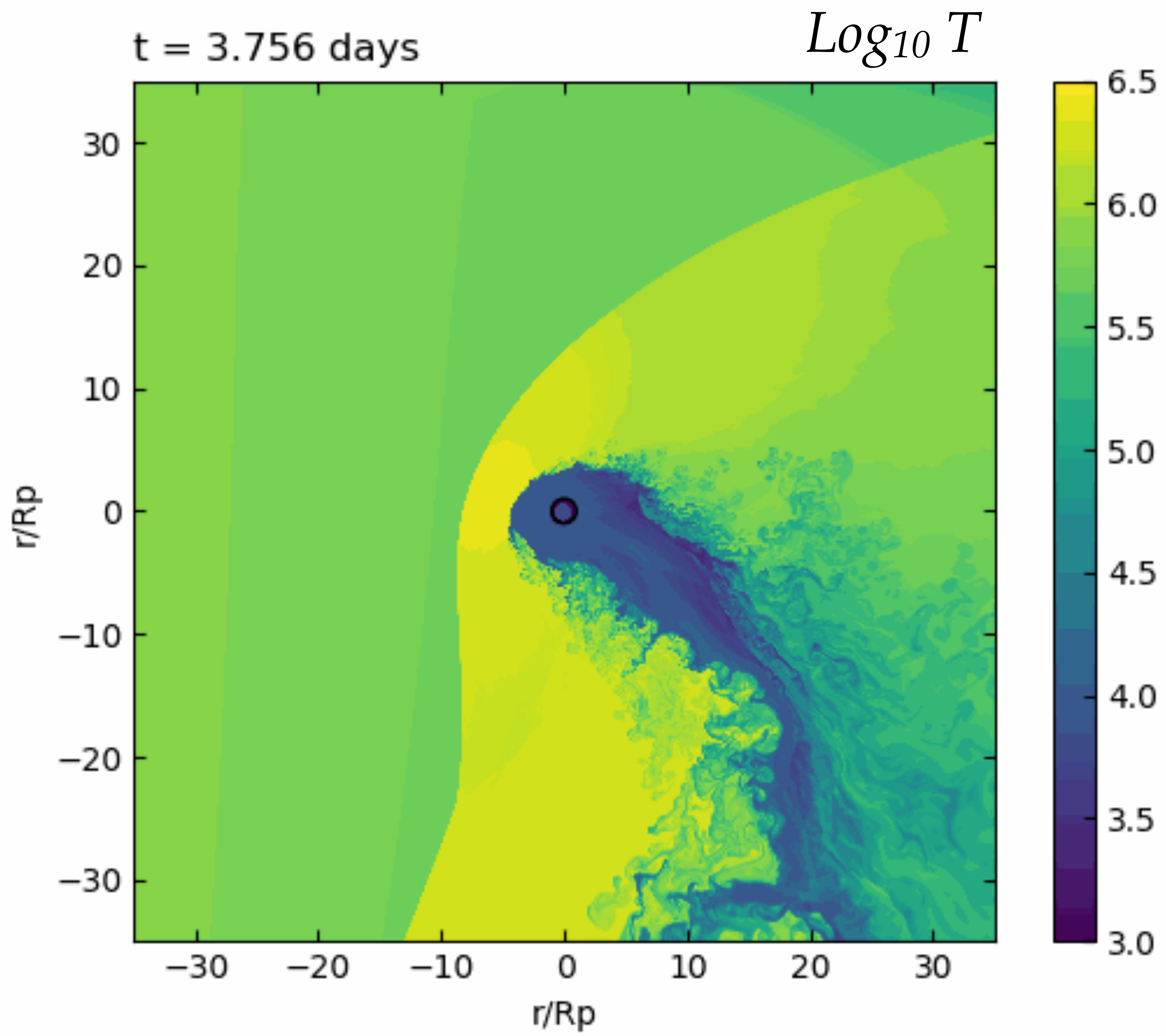


Gillet et al. (2023), Gillet et al. (2024)

See also Owen & Adams 2014, Khodachenko+ 2021, Hazra+ 2022

Towards agnetic interactions and atmospheric escape





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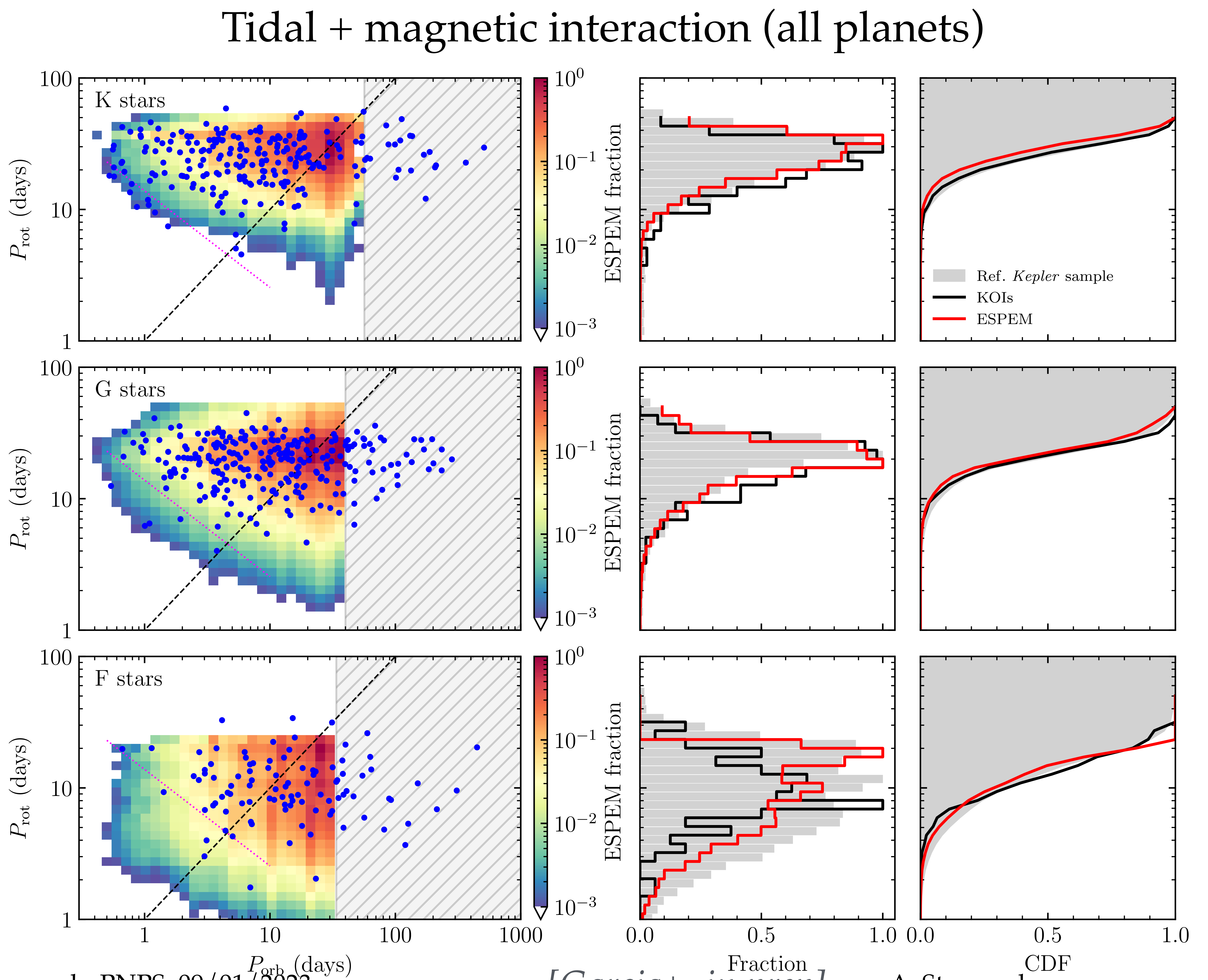
Synthetic population vs Kepler-field population

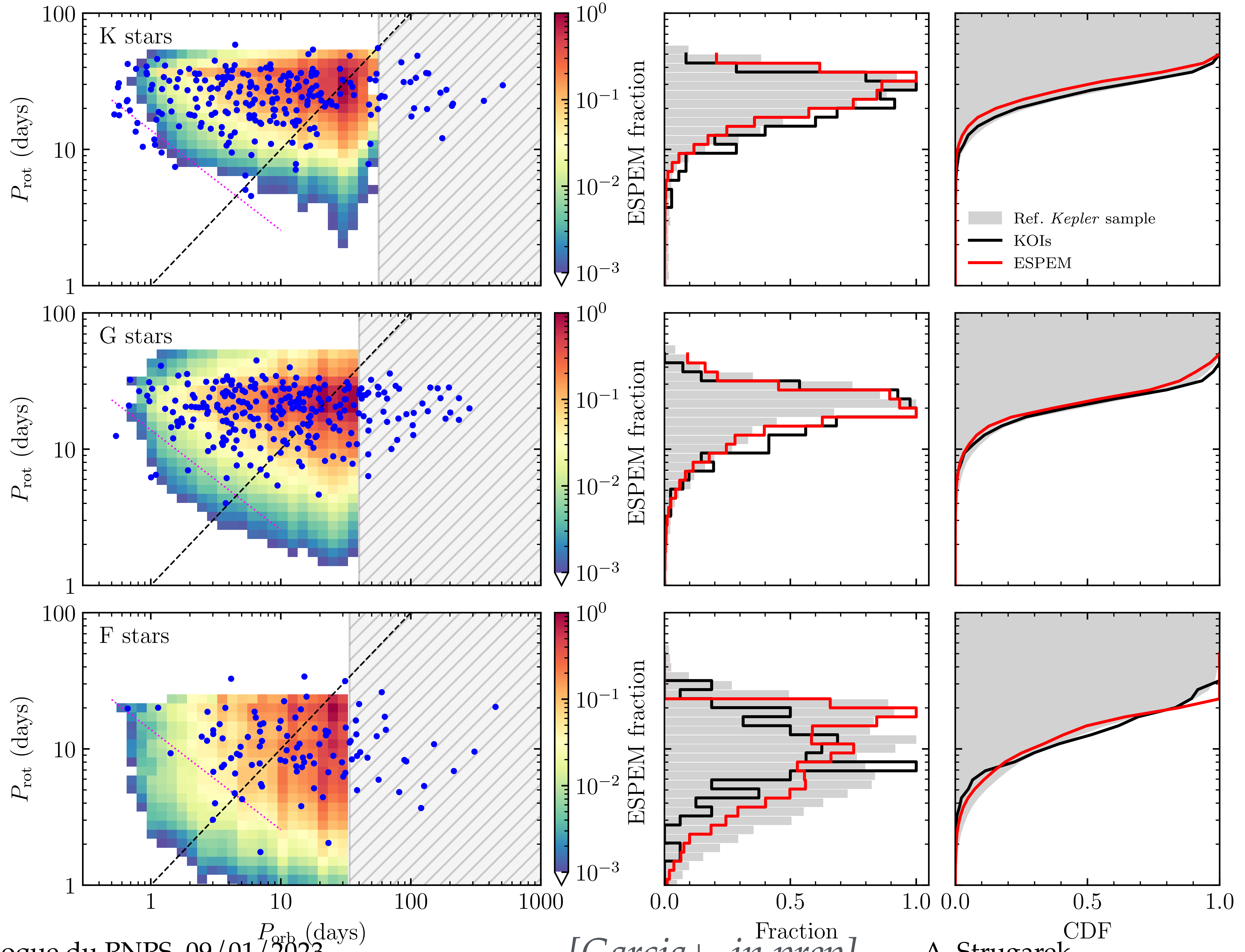


New initial conditions: no planets within the inner radius of the dead zone of protoplanetary disks

[Garcia+, in prep]

Synthetic population vs Kepler-field population

Tidal + magnetic interaction (planets beyond dead-zone)



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

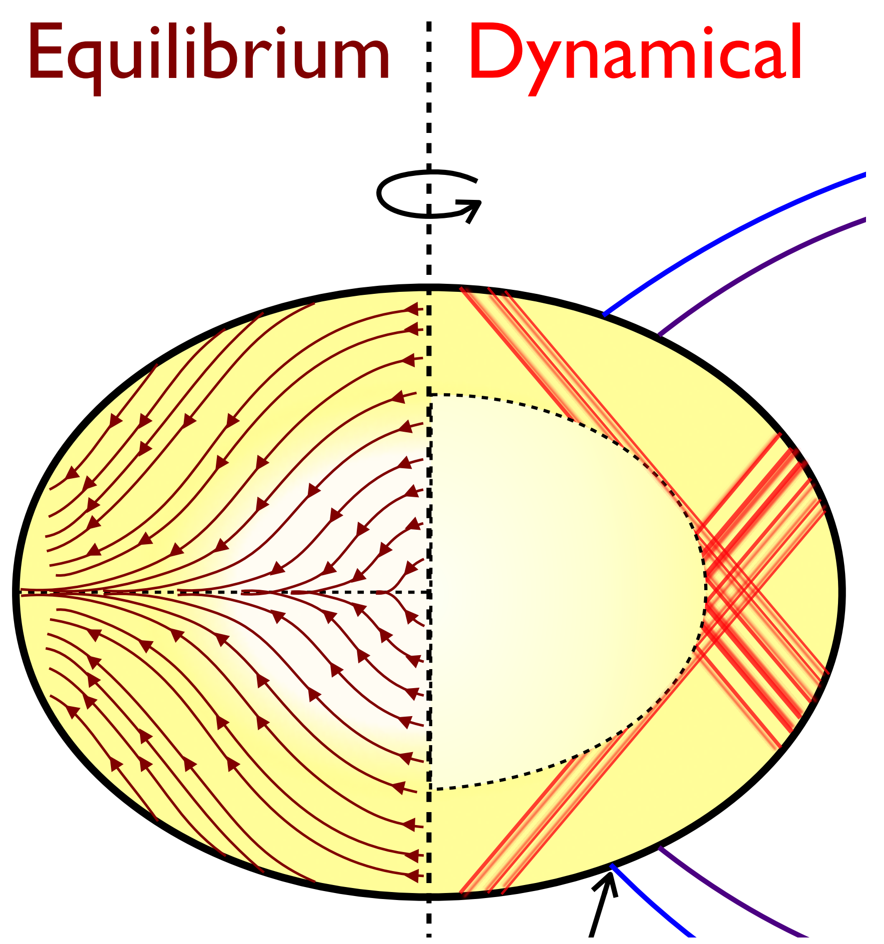
[Garcia+, in prep]

Torque from the equilibrium and dynamical tides

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

Orbital Frequency

Tide



[Rémus+ 2012; Ogilvie & Lin 2007; Mathis 2015,2016; Gallet+ 2017]

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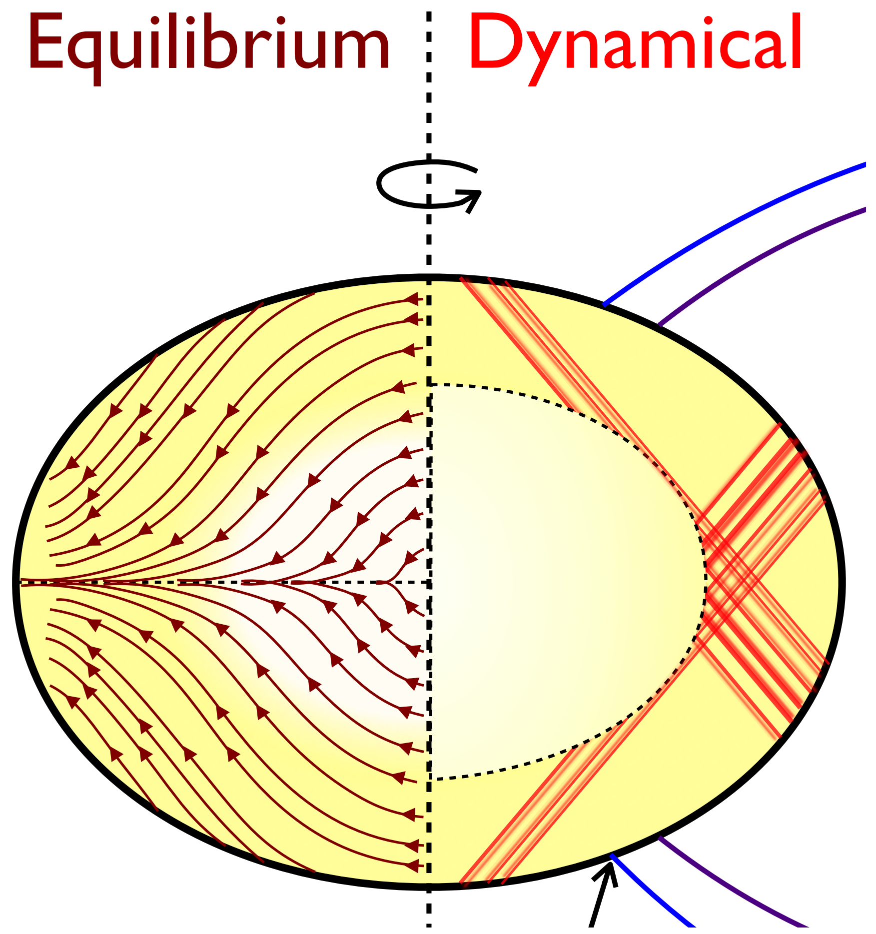
Orbital Frequency

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

Viscosity Density Aspect ratio

Tide



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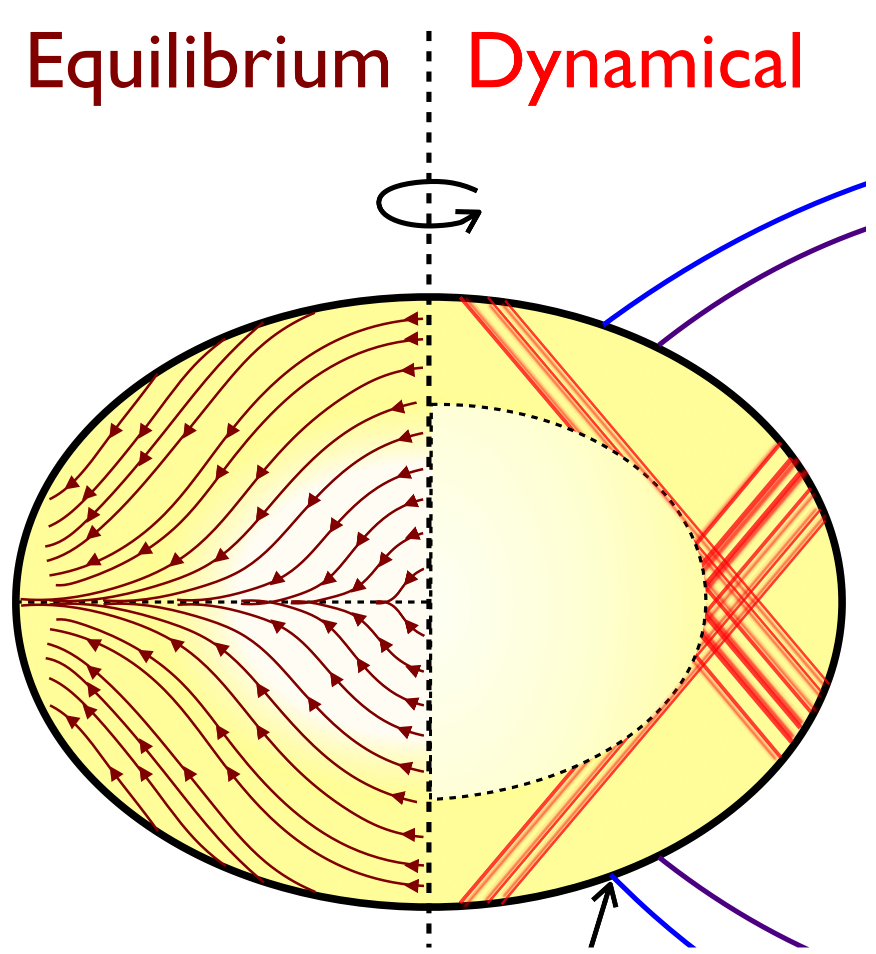
Orbital Frequency

Tide



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

Viscosity Density Aspect ratio

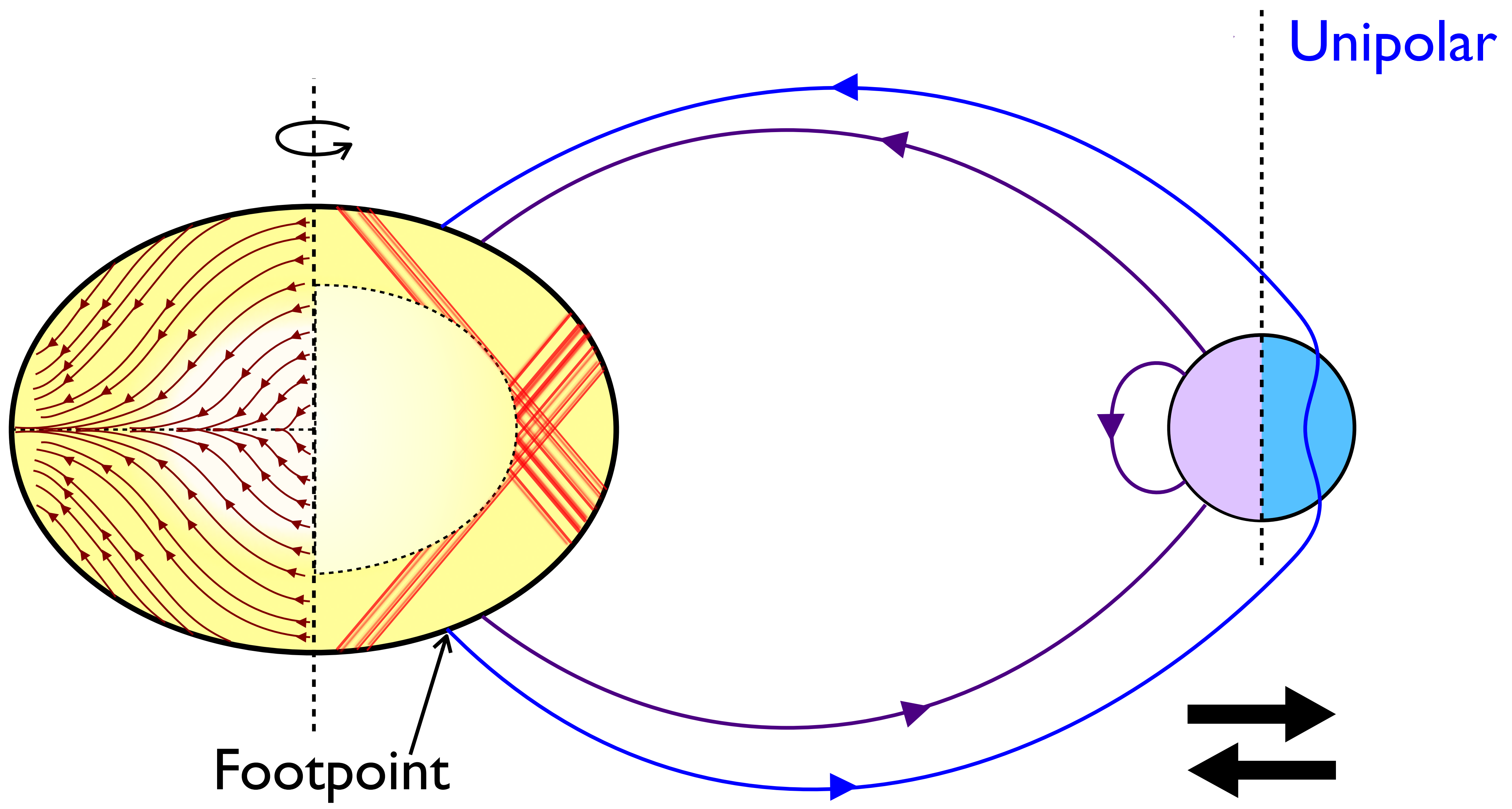
$$\frac{k_2}{Q_\star} = f\left(\alpha, \beta, \Omega_\star\right)$$

Aspect ratio Mass in the RZ

[Rémus+ 2012; Ogilvie & Lin 2007;
Mathis 2015,2016; Gallet+ 2017]

Magnetic torque: parametrization of the unipolar interaction

Magnetism



Plasma resistance at the footpoint

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

$n - \Omega_\star$

Stellar wind magnetic field

[Laine & Lin 2012]