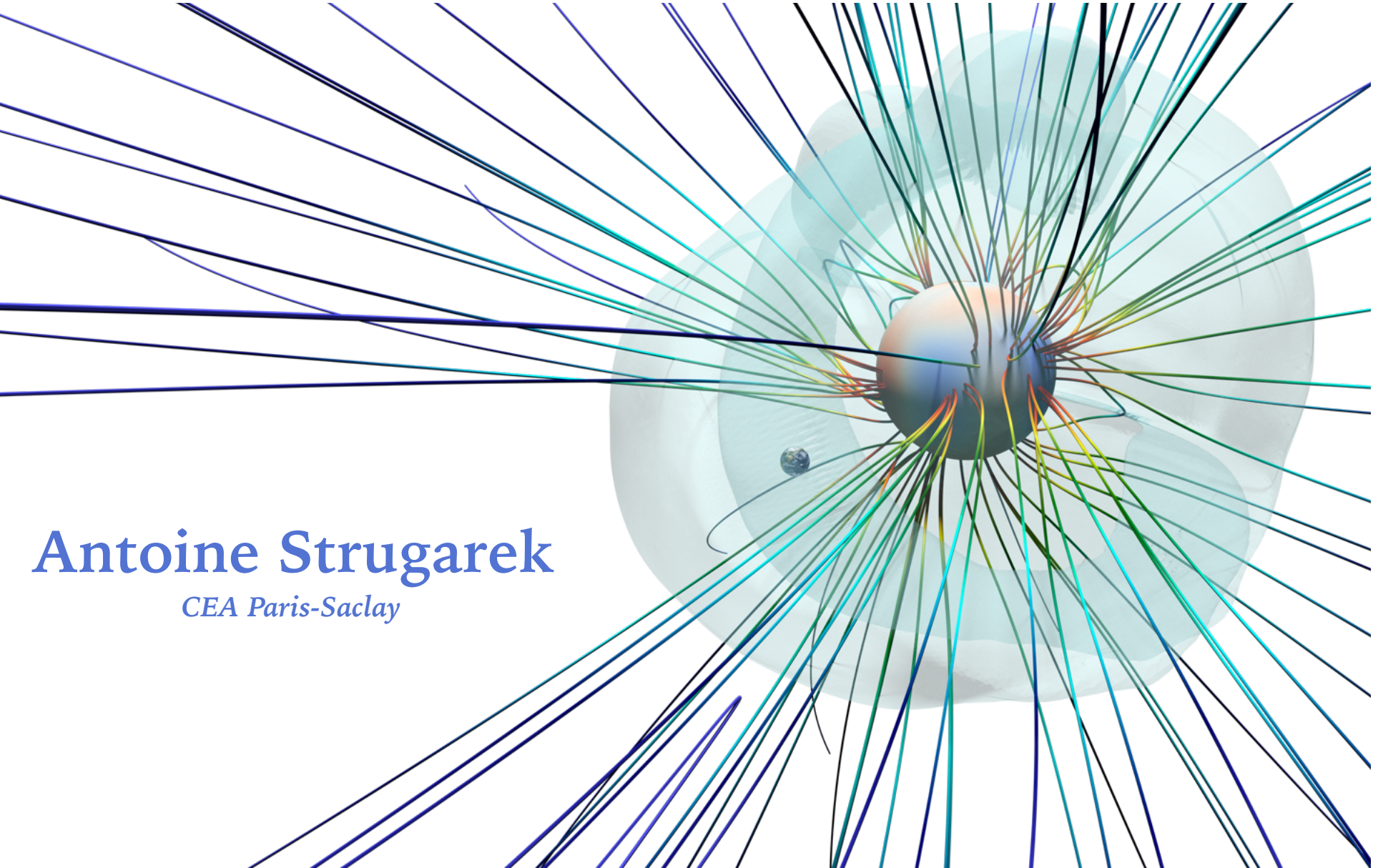
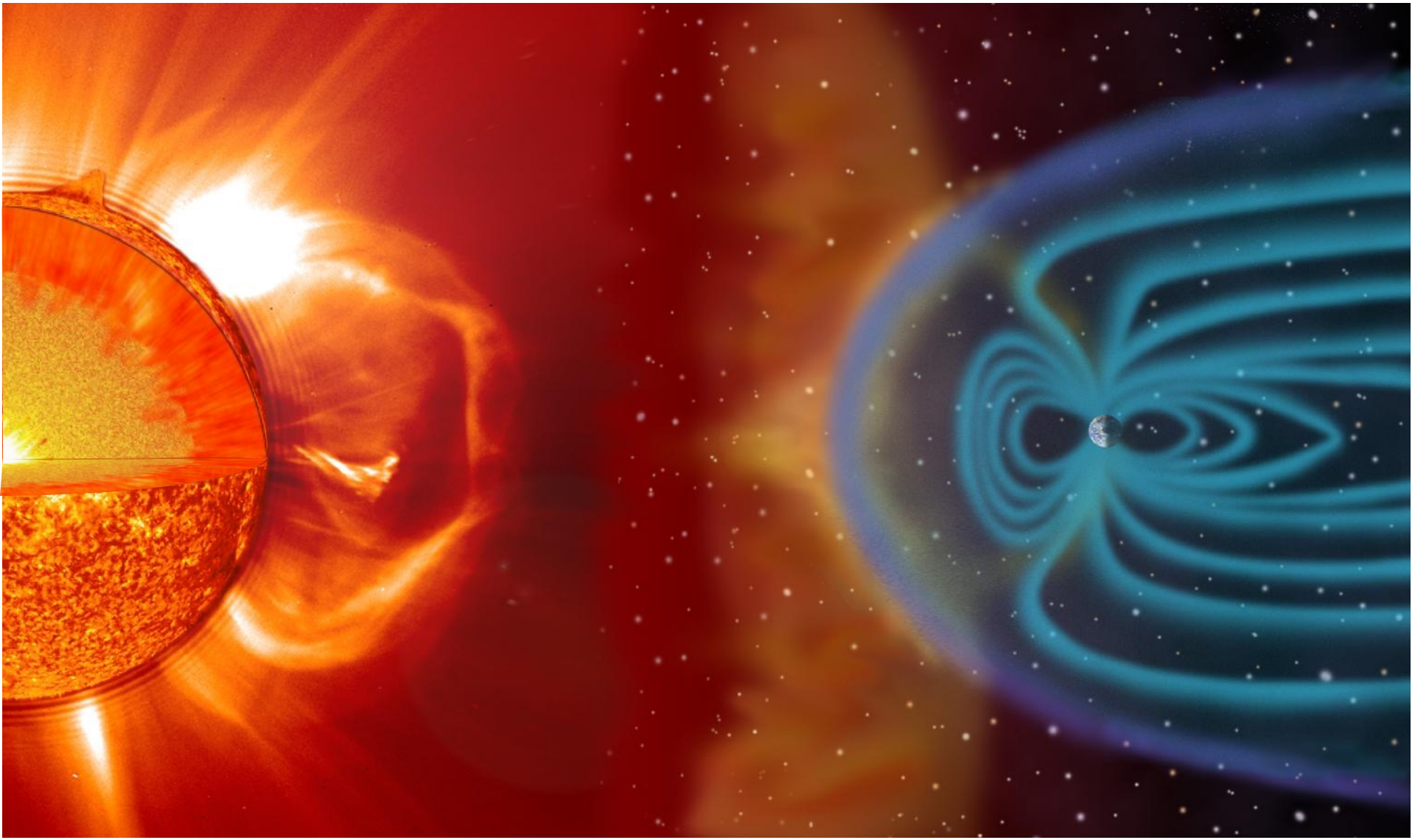
Star-planet magnetic interactions



Antoine Strugarek

CEA Paris-Saclay

What are star-planet magnetic interactions?



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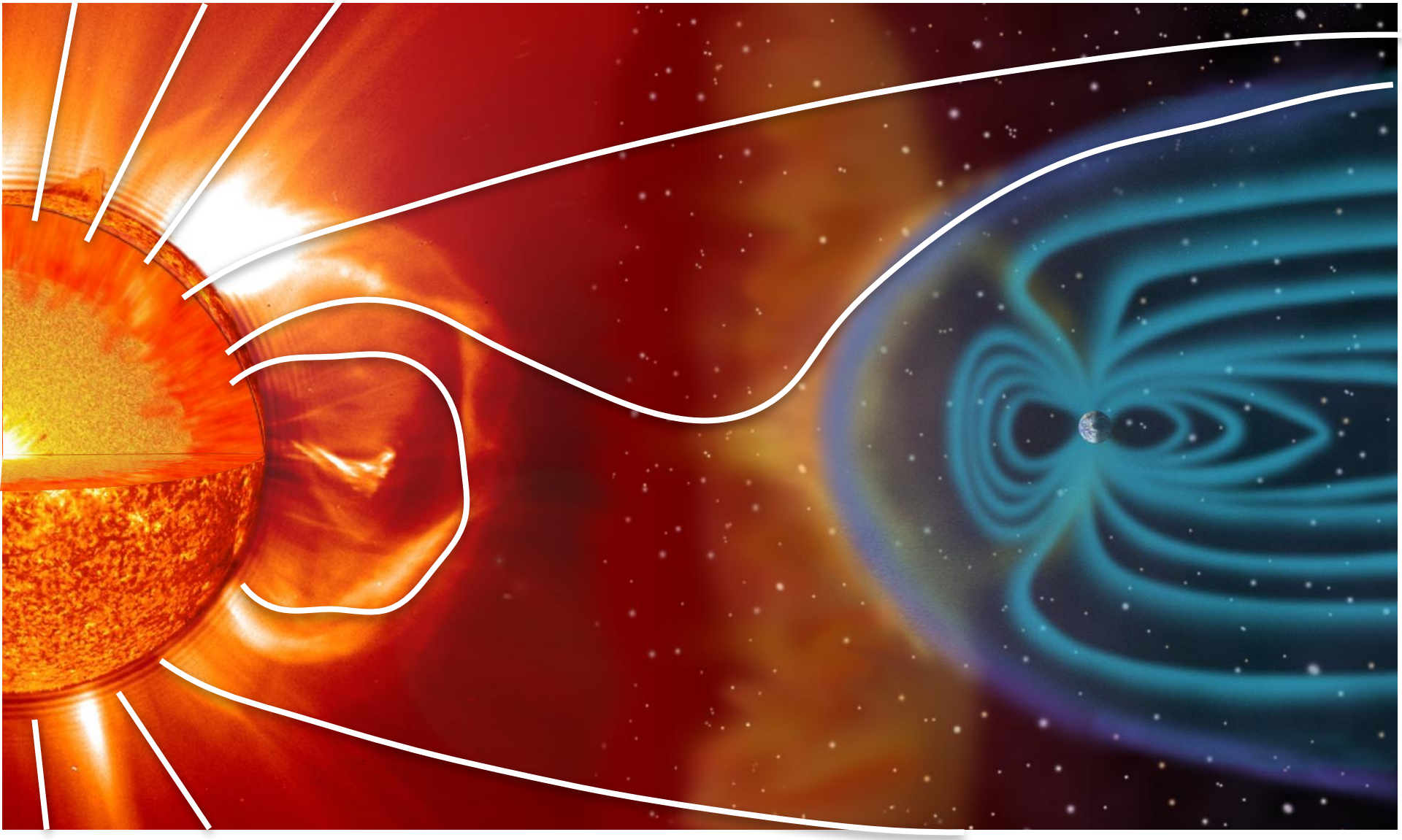

Outline

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   A. Stellar magnetism
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   C. Planetary magnetism

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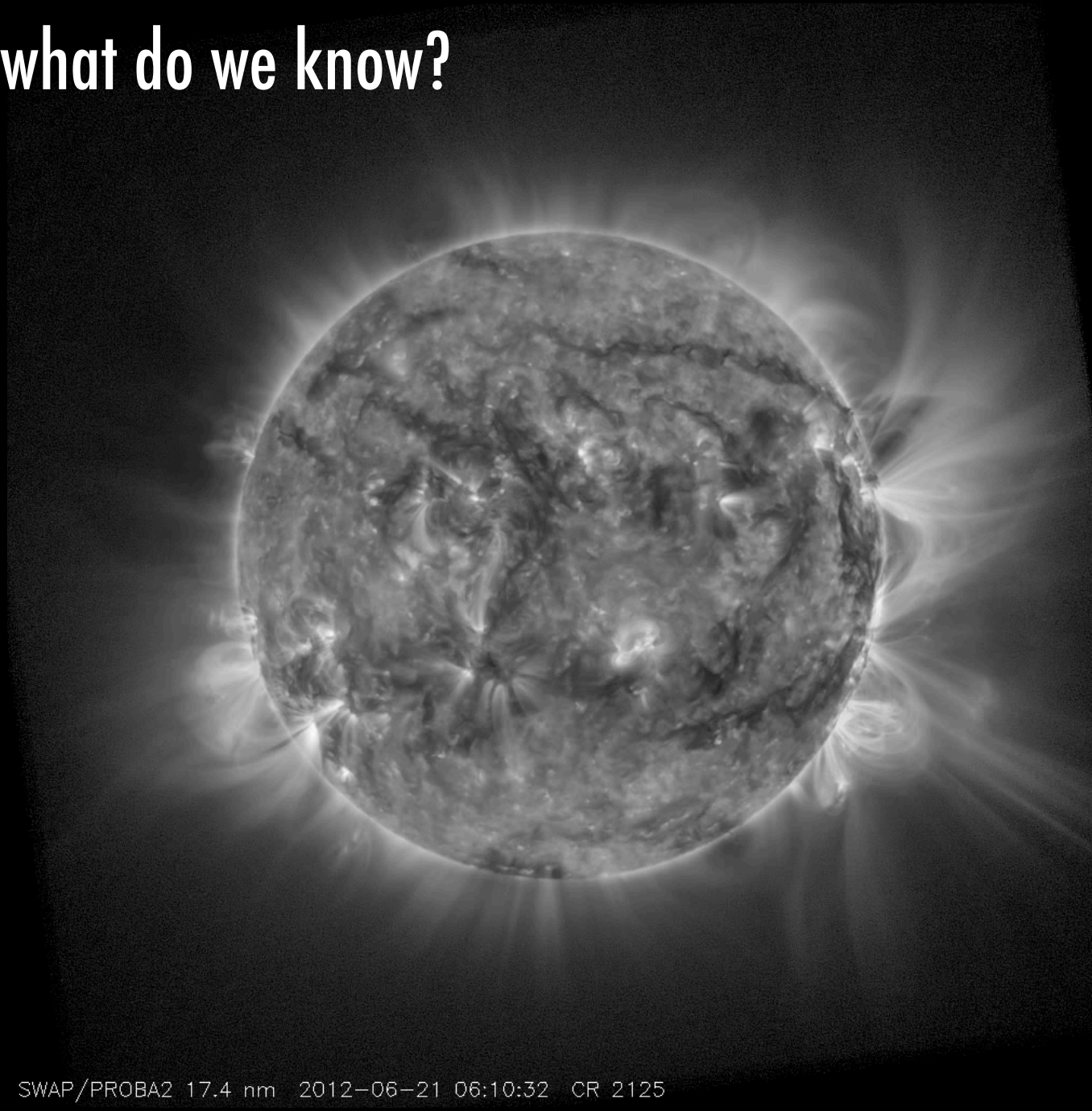
Solar Magnetism: what do we know?



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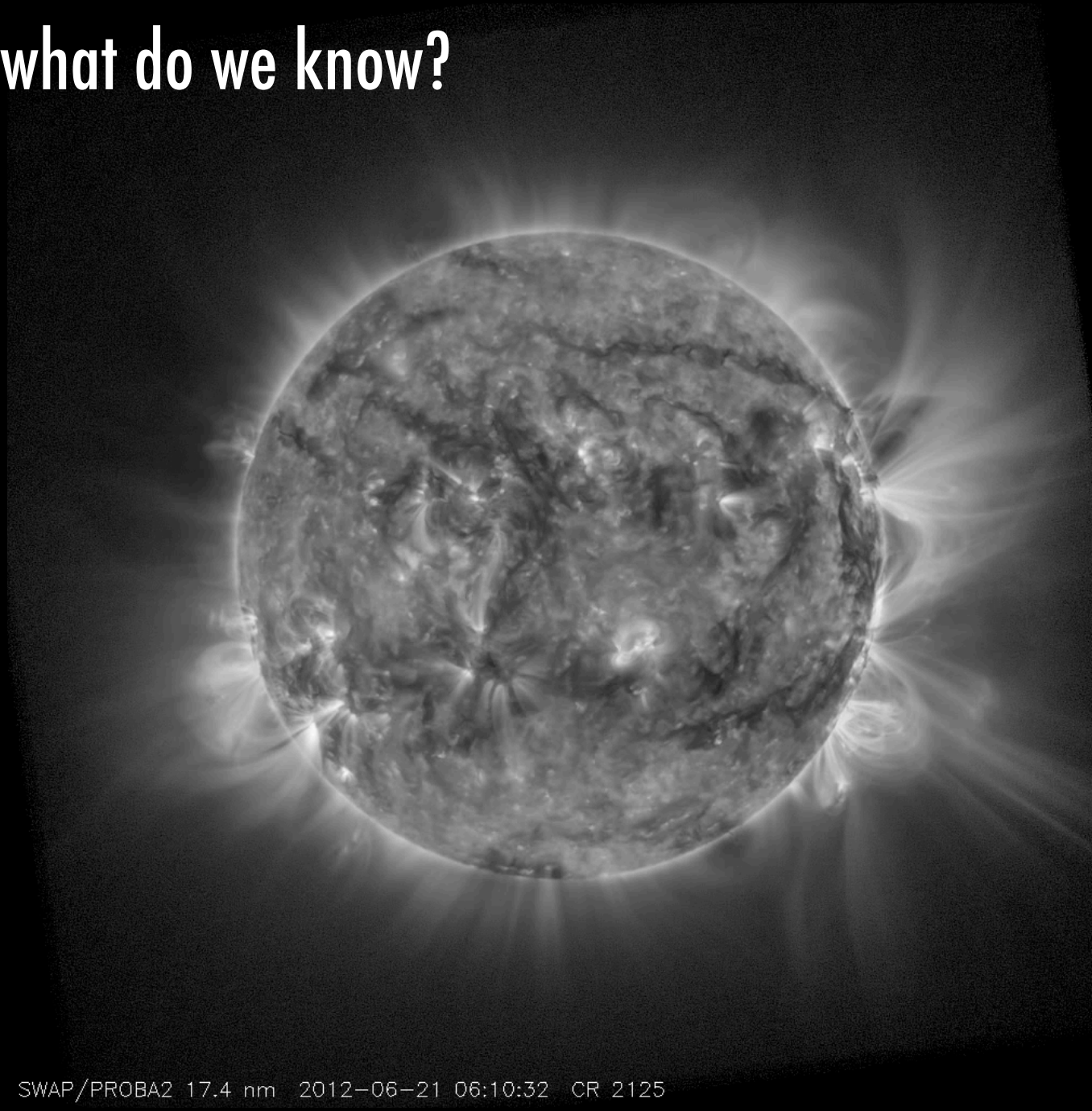

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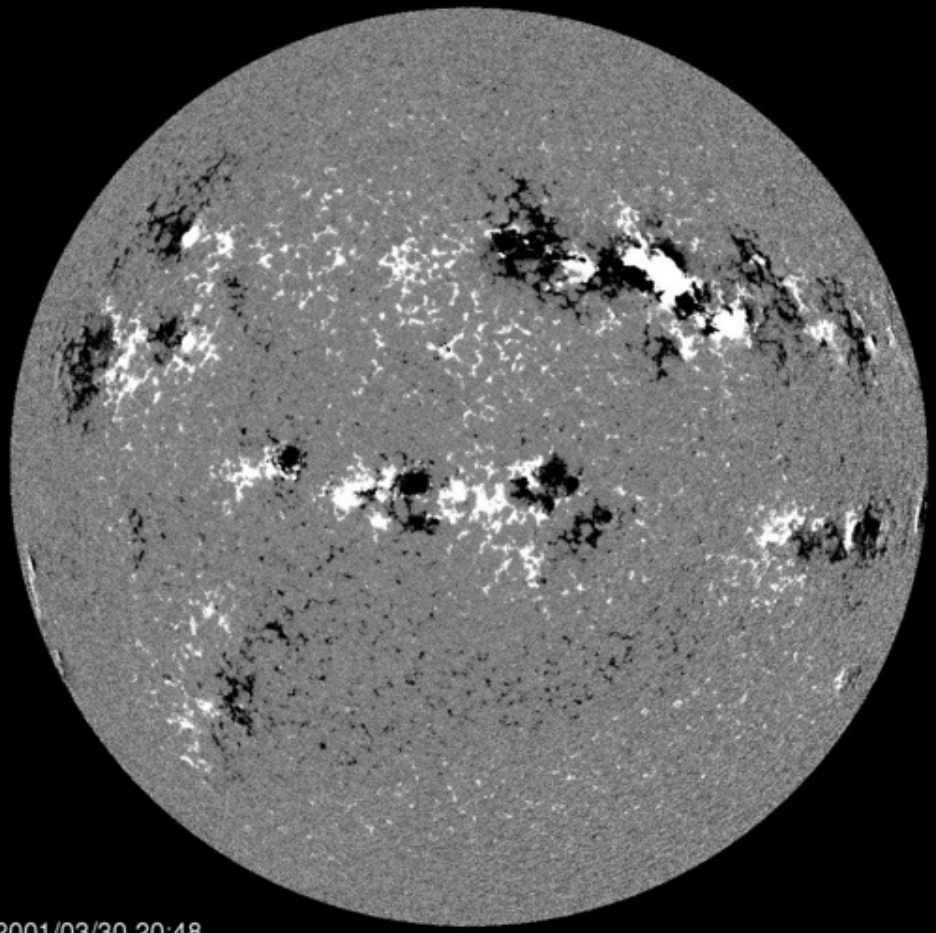
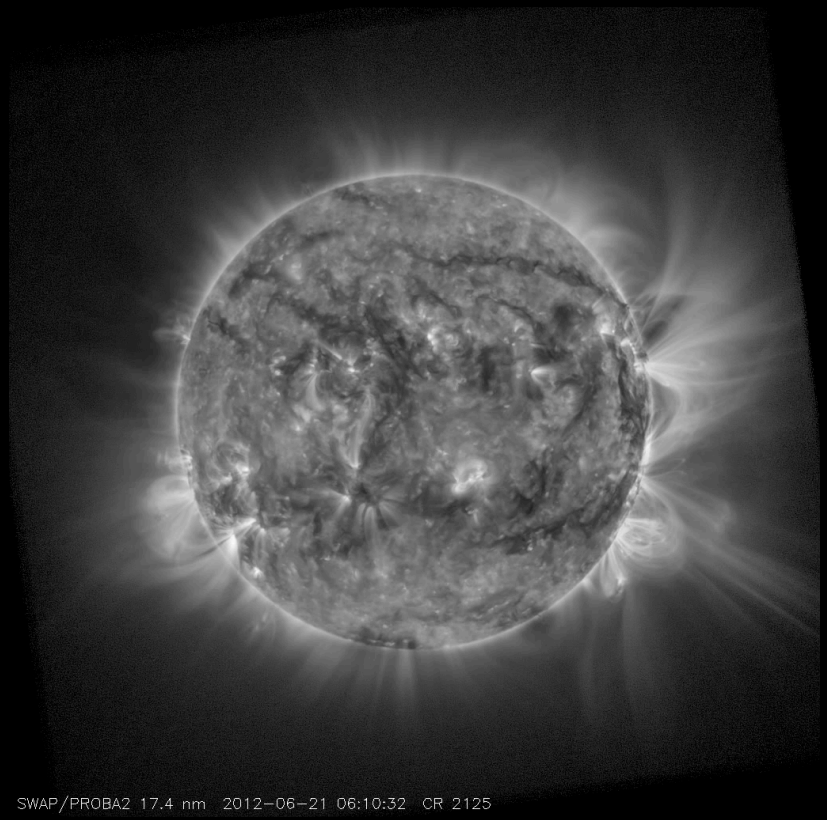
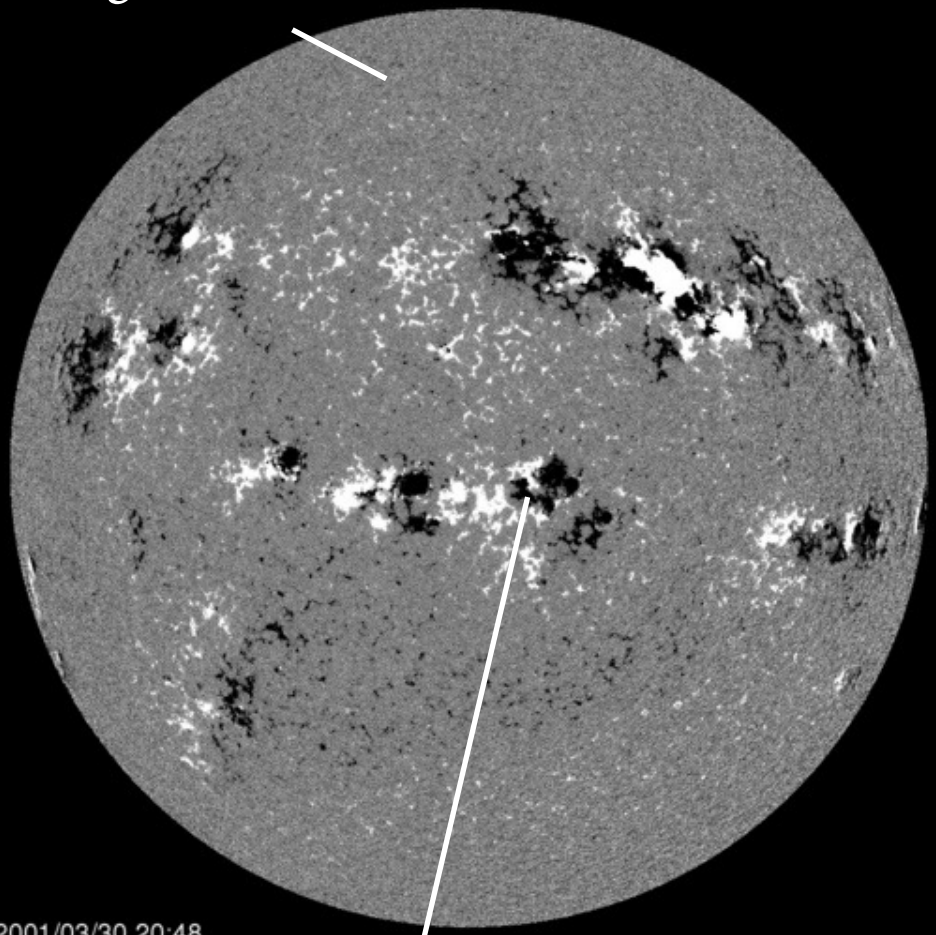


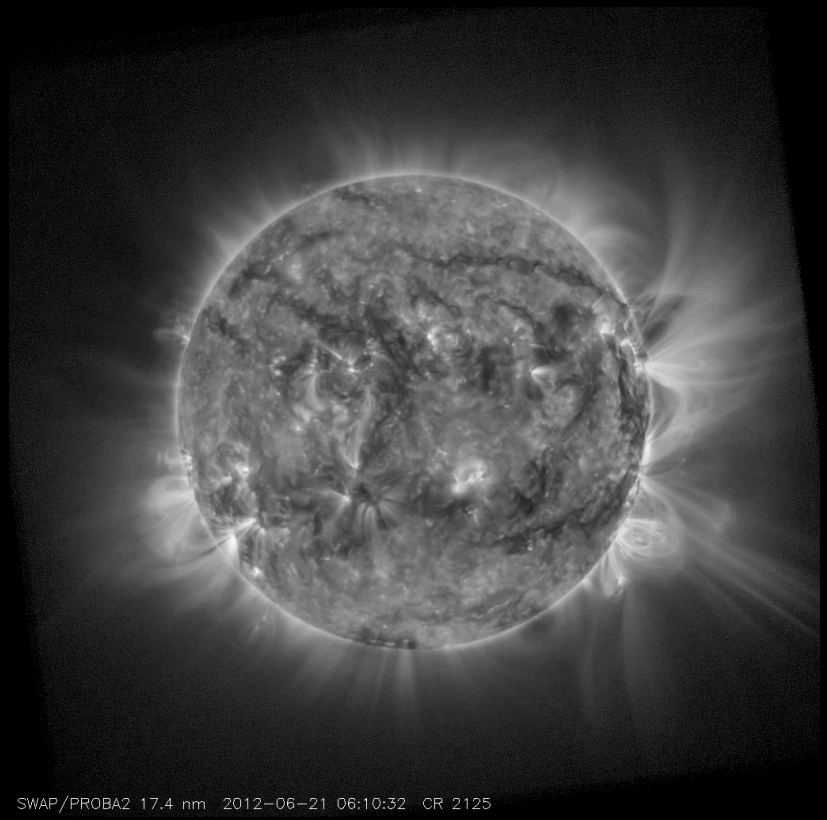


Solar Magnetism: what do we know?

Large scale field ~ 2-5 G



In active regions ~ 10^4 G



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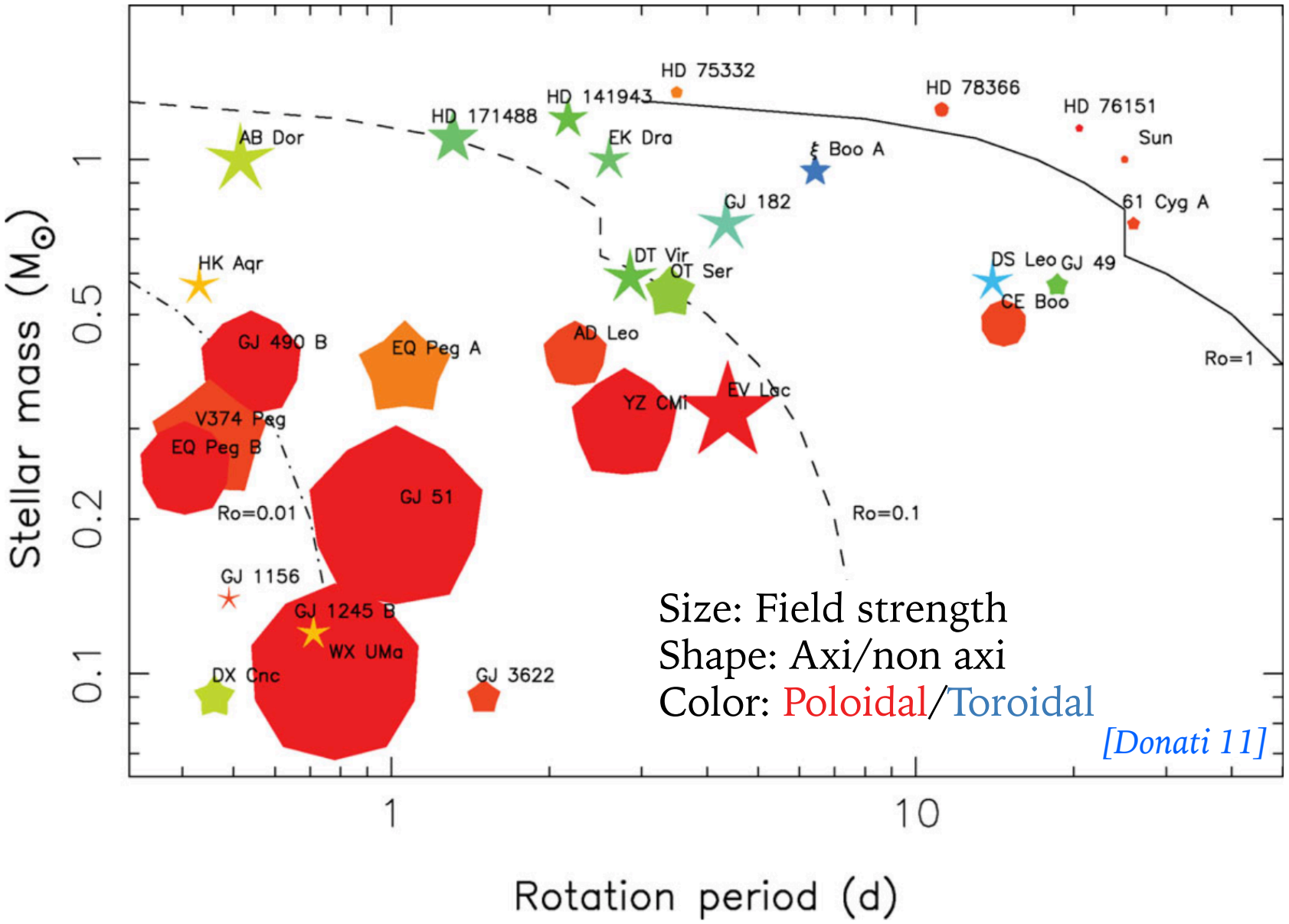
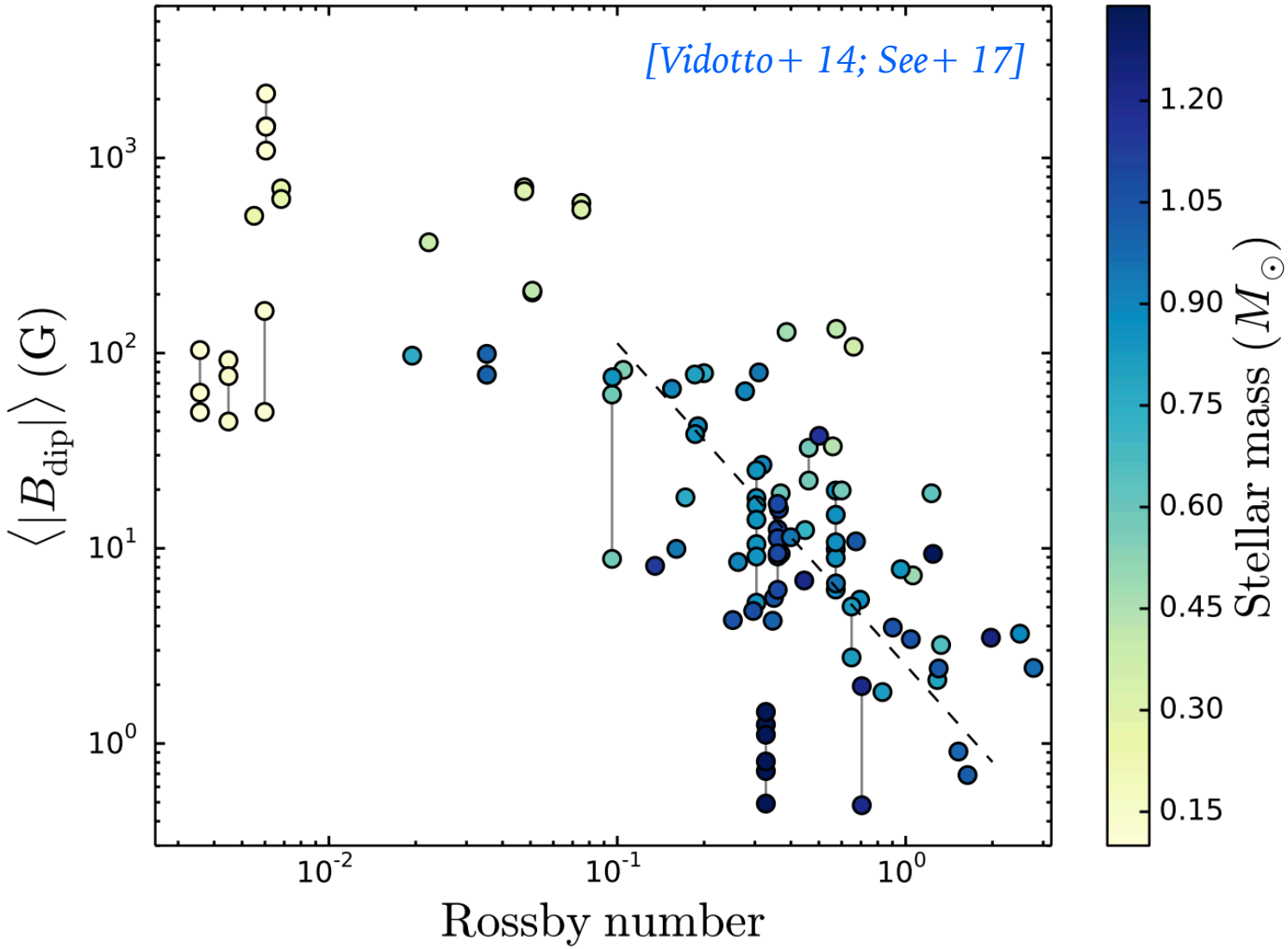


Stellar Magnetism: what do we know?

Caution: strong bias in stellar mass



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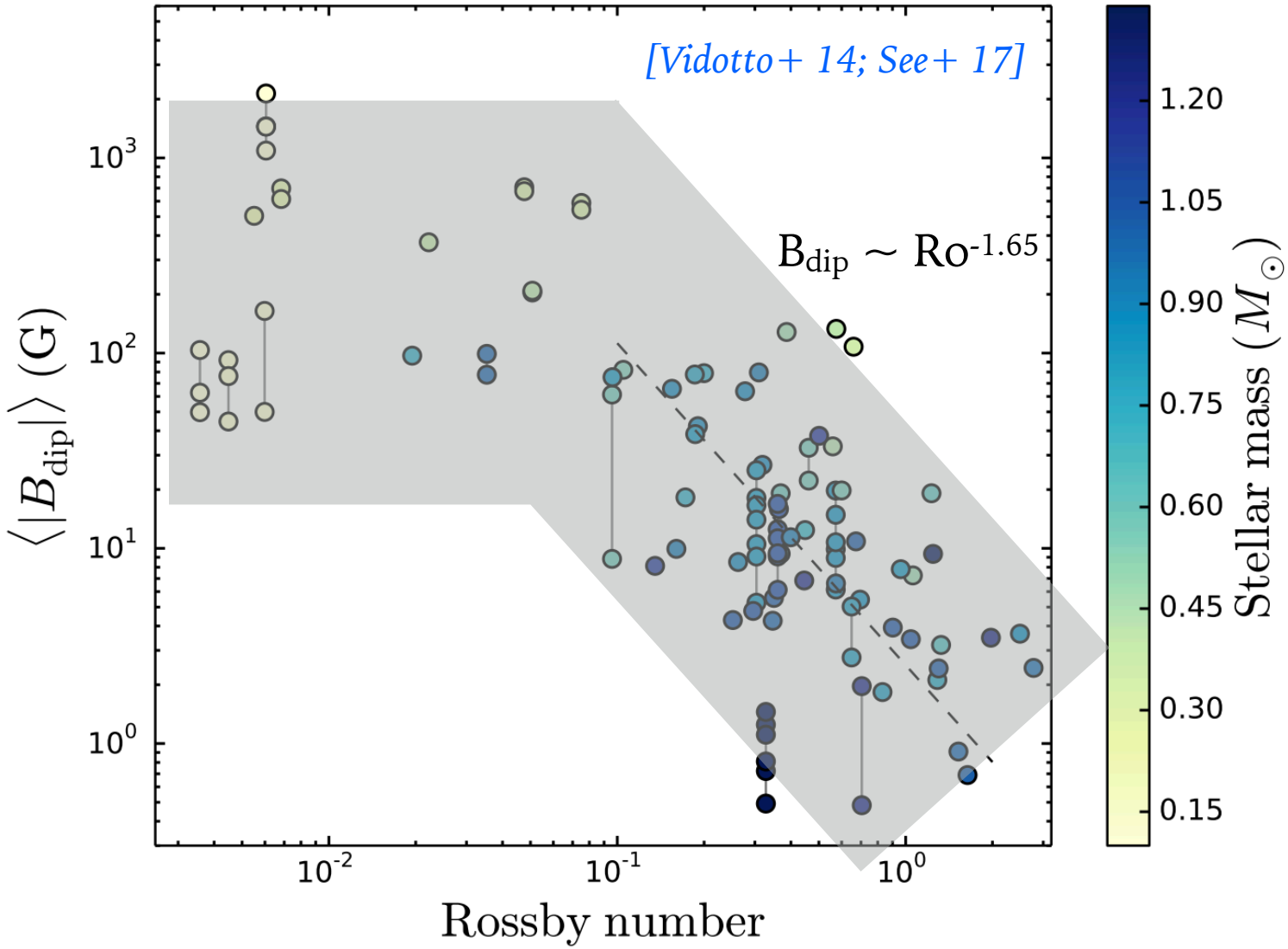

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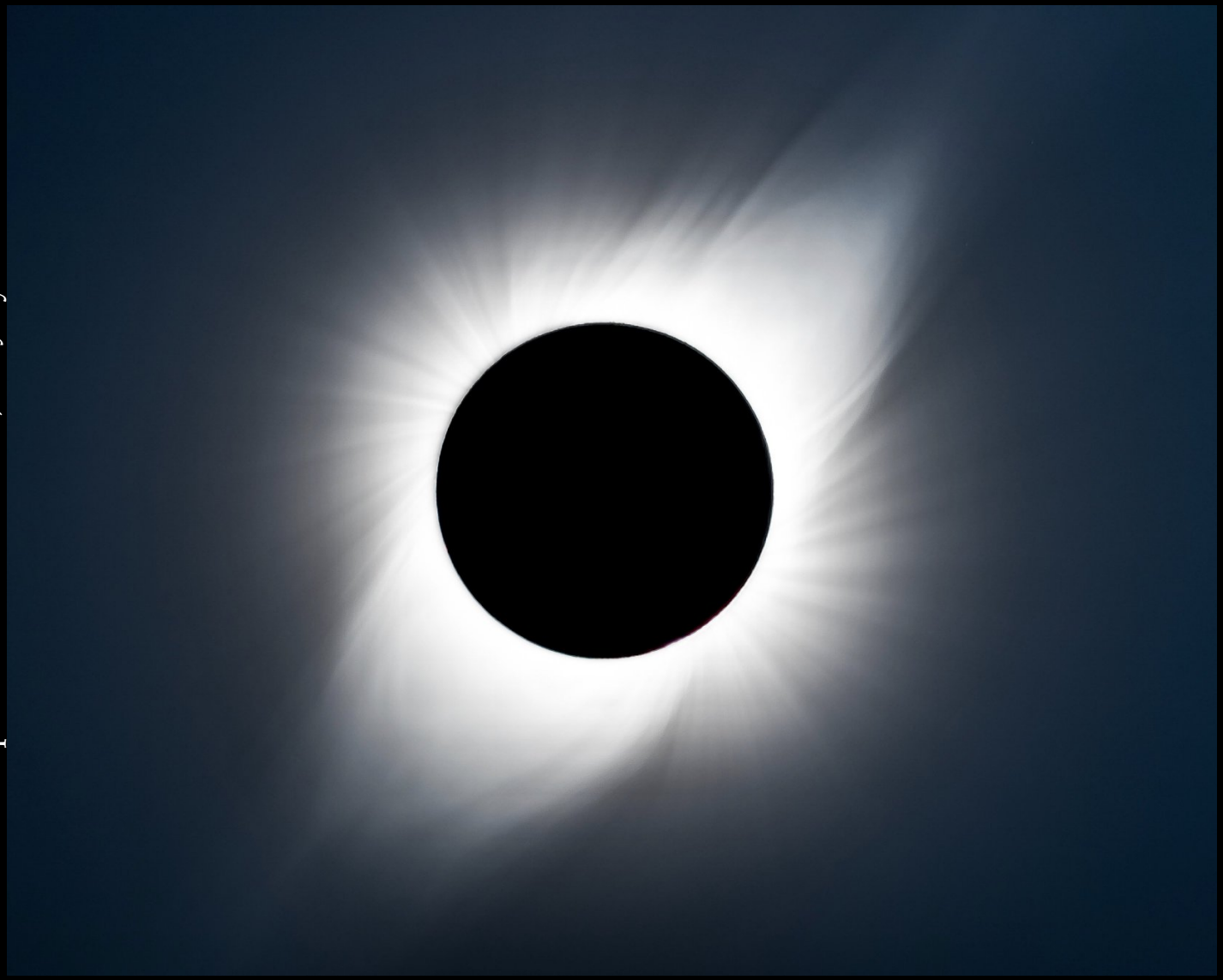
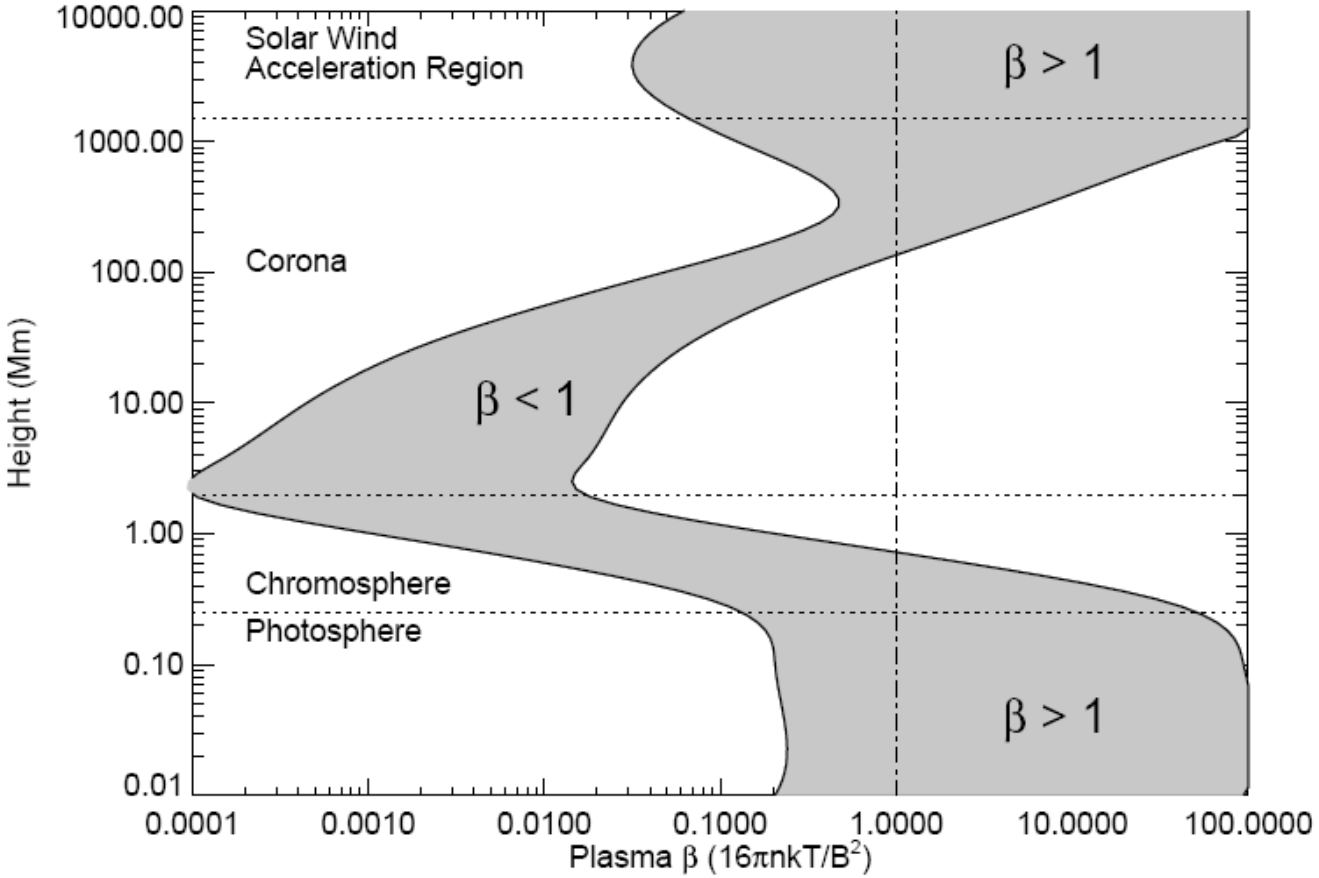
Stellar magnetism sculpts the stellar environment (I)



Total solar eclipse in Atacama desert, 2nd July 2019

Stellar magnetism sculpts the stellar environment (II)



$$\beta = \frac{8\pi n k_B T}{B^2}$$

Figure 1.22: Plasma β in the solar atmosphere for two assumed field strengths, 100 G and 2500 G. In the inner corona ($R \lesssim 0.2 R_\odot$), magnetic pressure generally dominates static gas pressure. As with all plots of physical quantities against height, a broad spatial and temporal average is implied (Gary, 2001).

The winds from cool stars

Let us assume a static (u=0) and isothermal (T∼1MK) solar corona. A back-of-the-enveloppe calculation gives a ratio between the solar surface pressure (∼ 100 mb) and pressure infinitely away from the Sun to be $P_{inf}/P_{surf} \sim 10^{-4}$. But estimates from interstellar pressure give $P_{inf}/P_{surf} \sim 10^{-14}$!!

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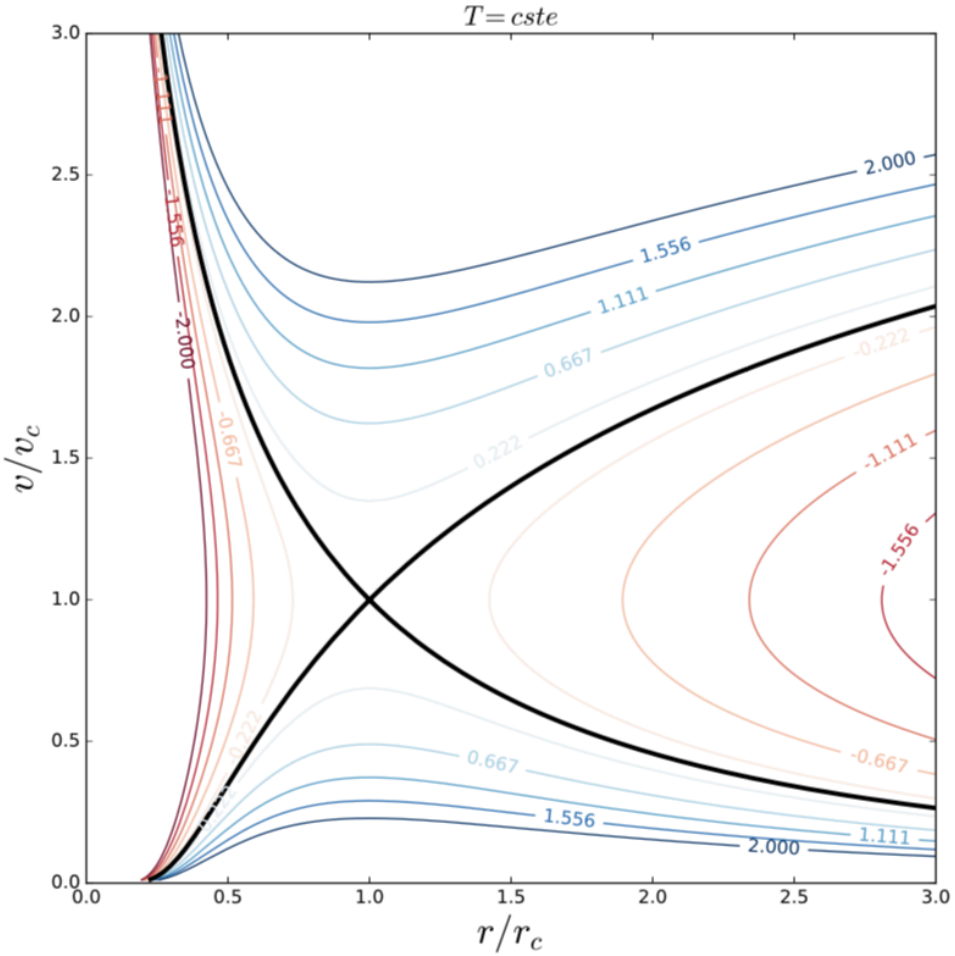

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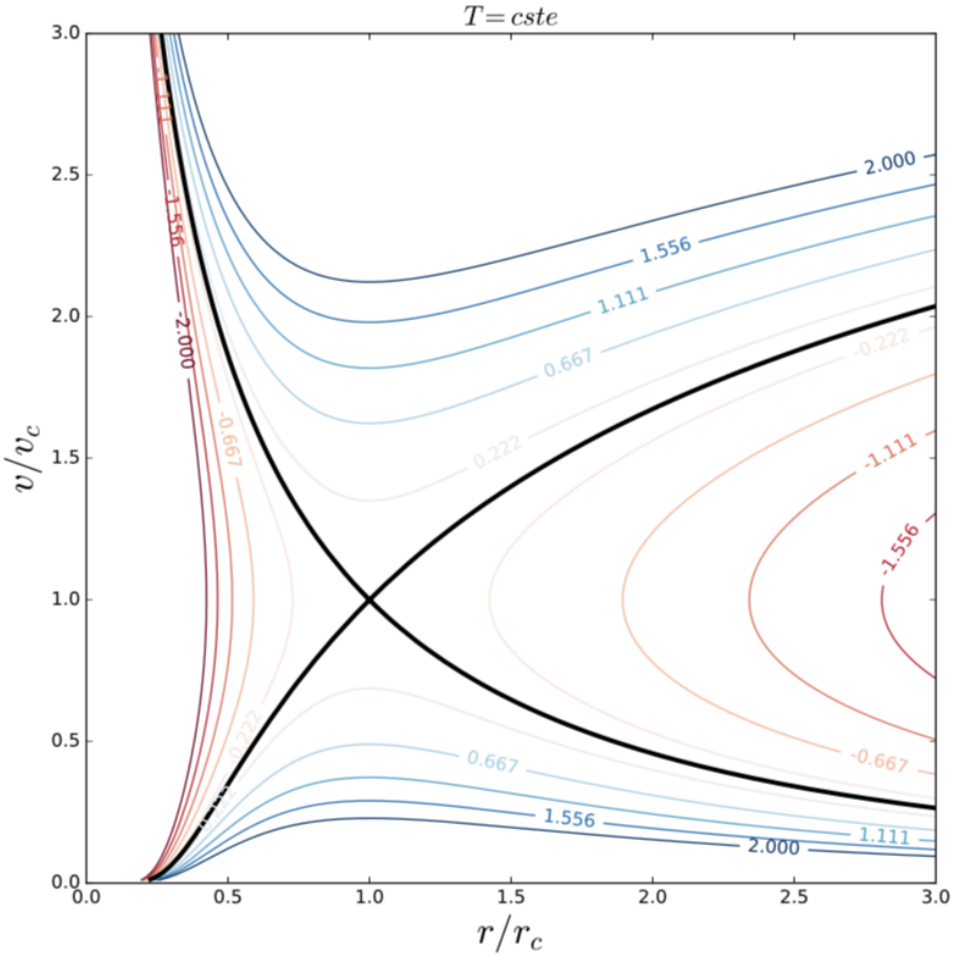

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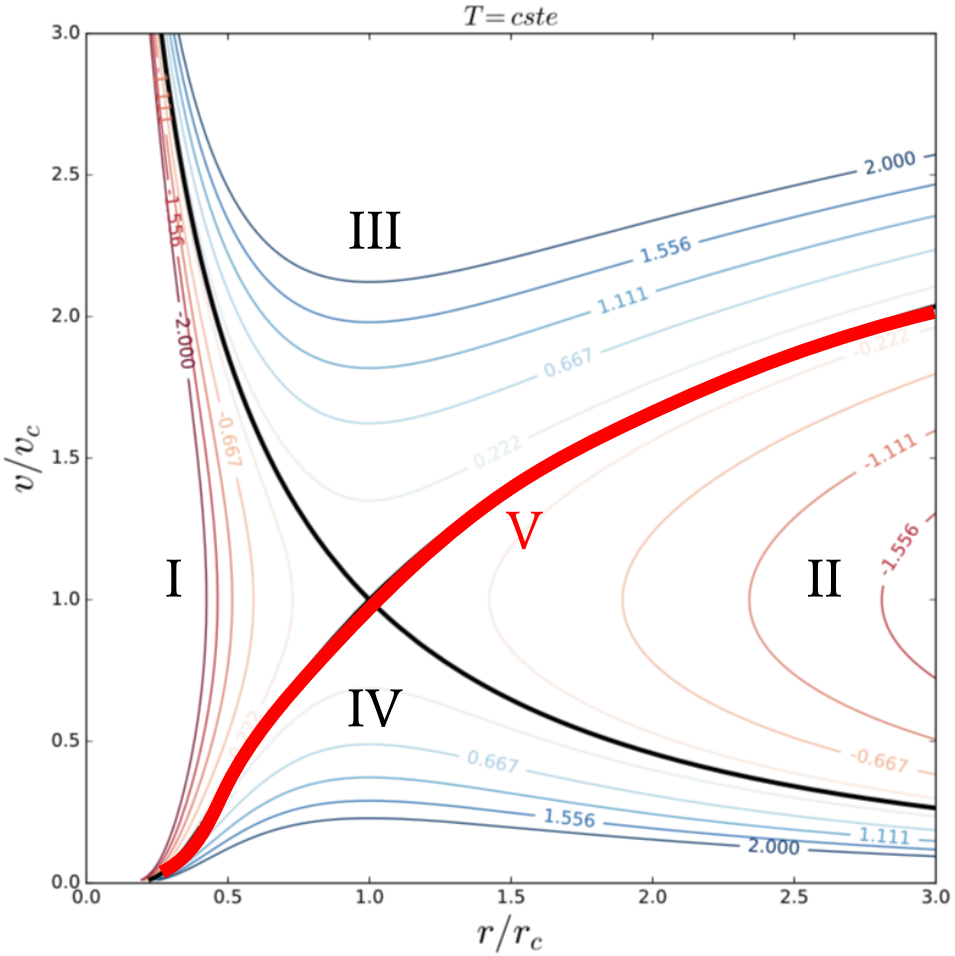

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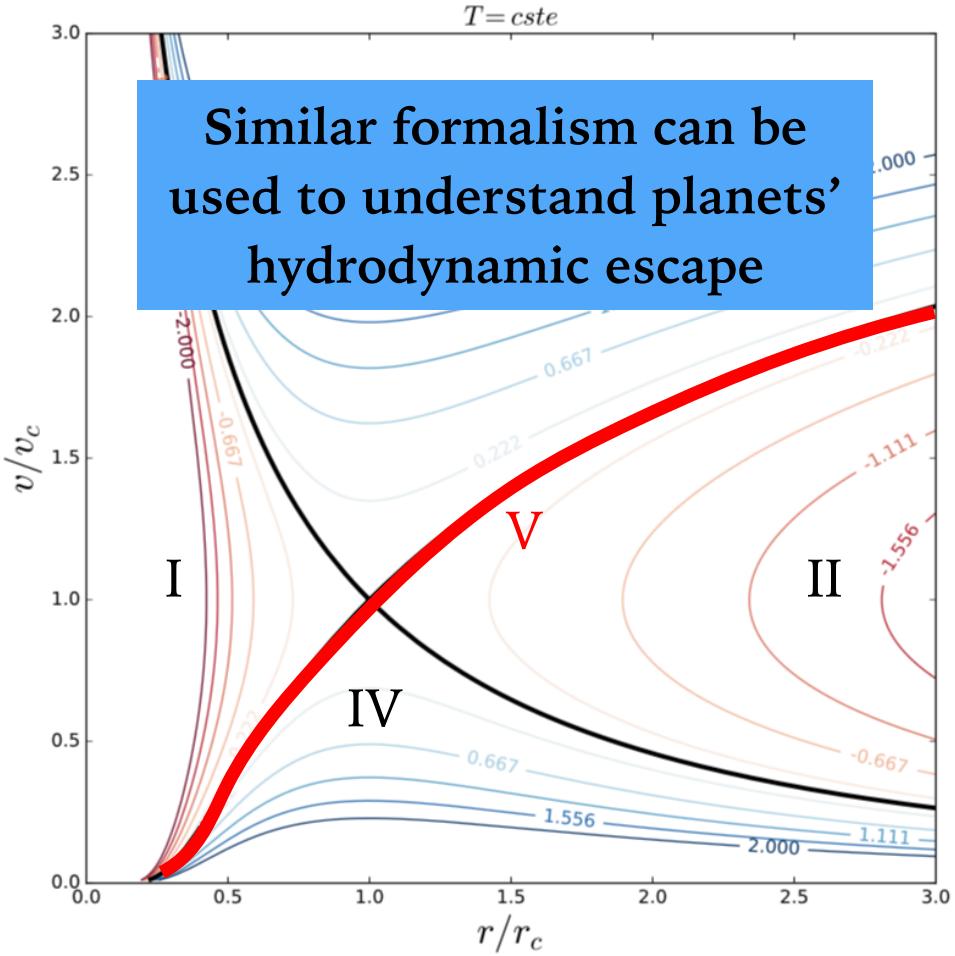
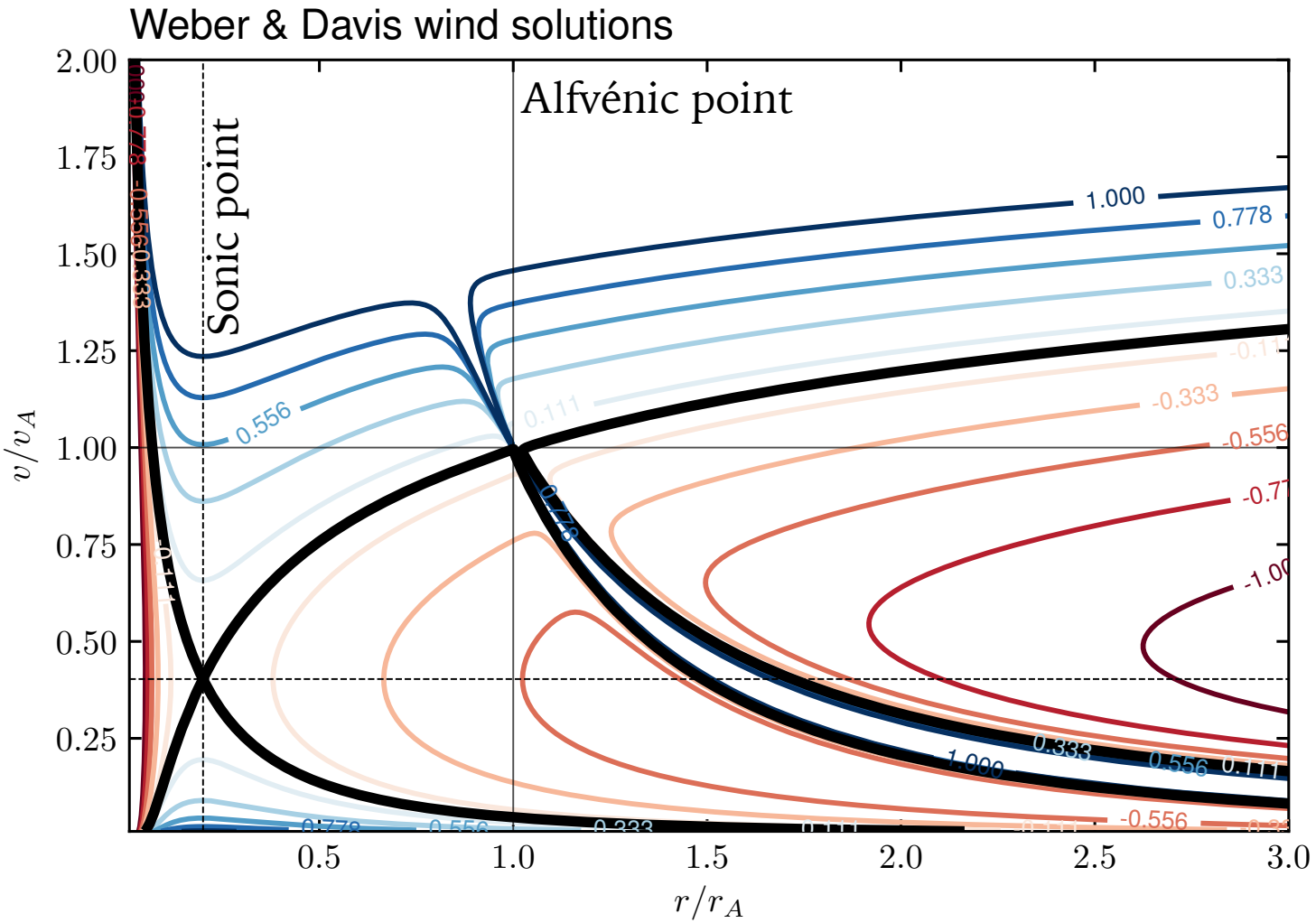


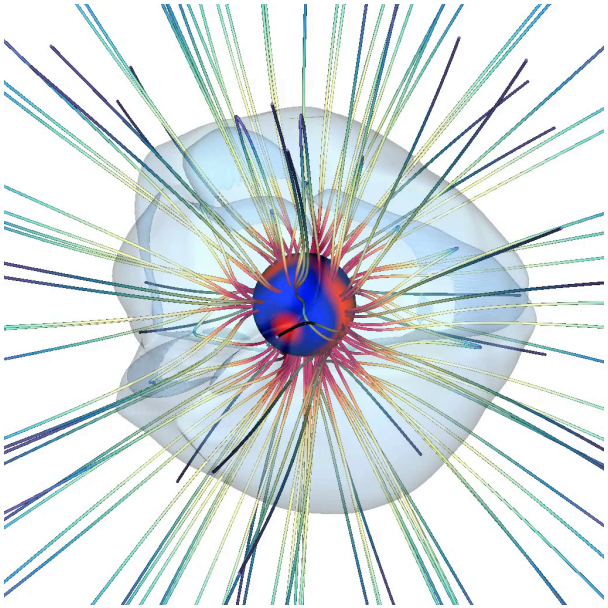
Magnetized stellar winds

But the wind develops in a magnetized medium. Hence, Weber & Davis (1967) expanded Parker's theory in the MHD case



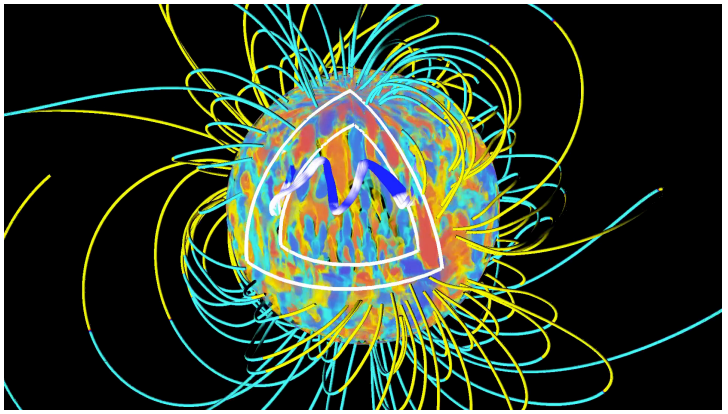
Stellar magnetism is directly related to stellar evolution

Rotation

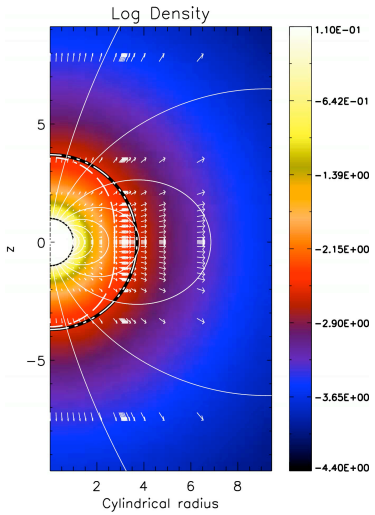


Dynamo

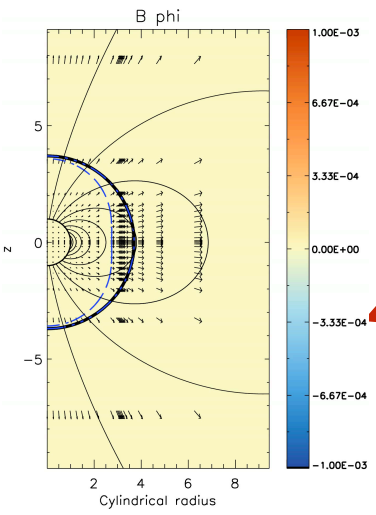
Magnetic field



Torques



Wind



Coronal heating

Stellar magnetism is directly related to stellar evolution

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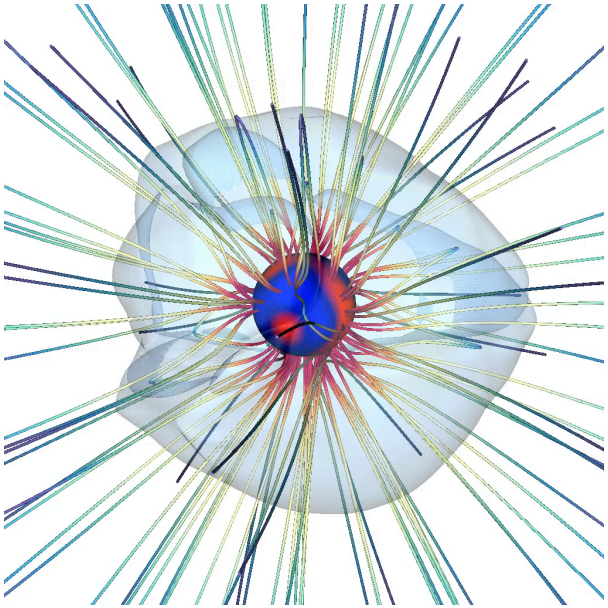
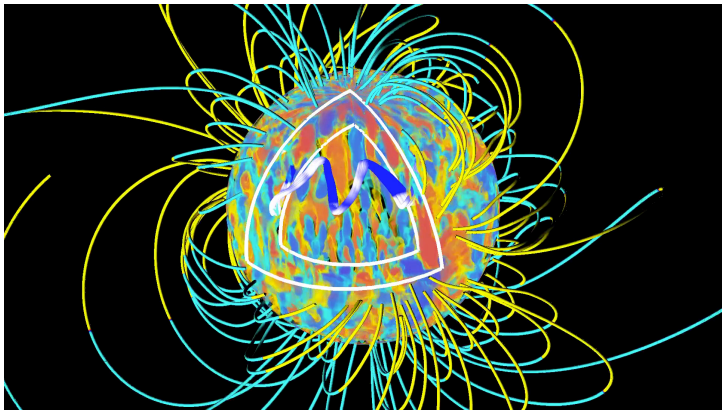
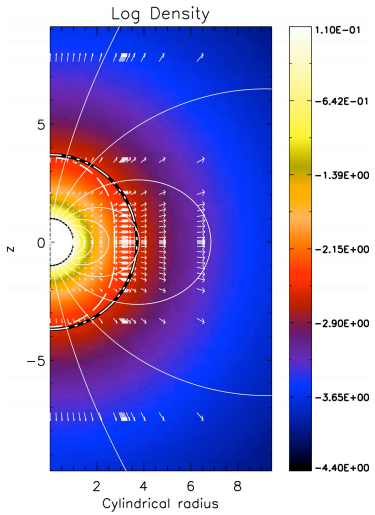


Dynamo

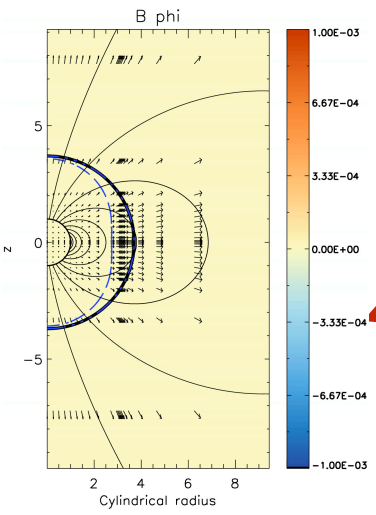
Magnetic field



Torques



Wind



Coronal heating

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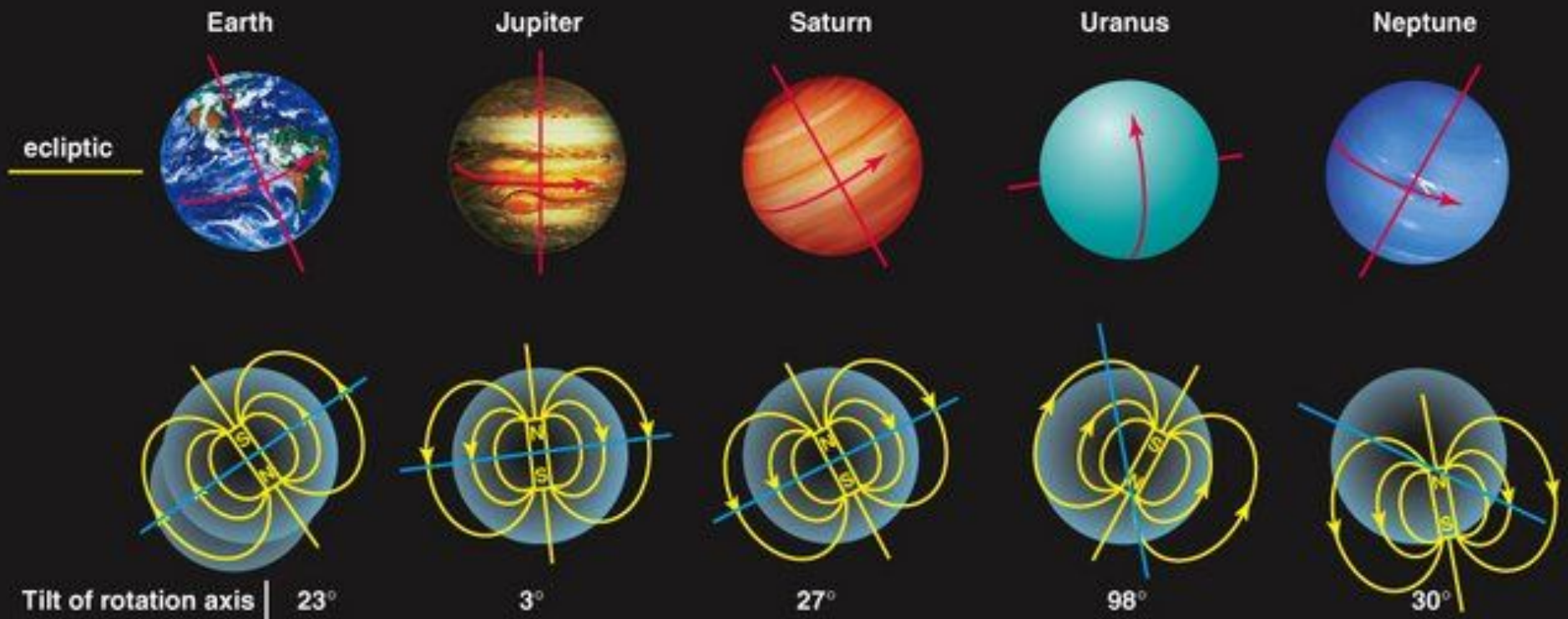
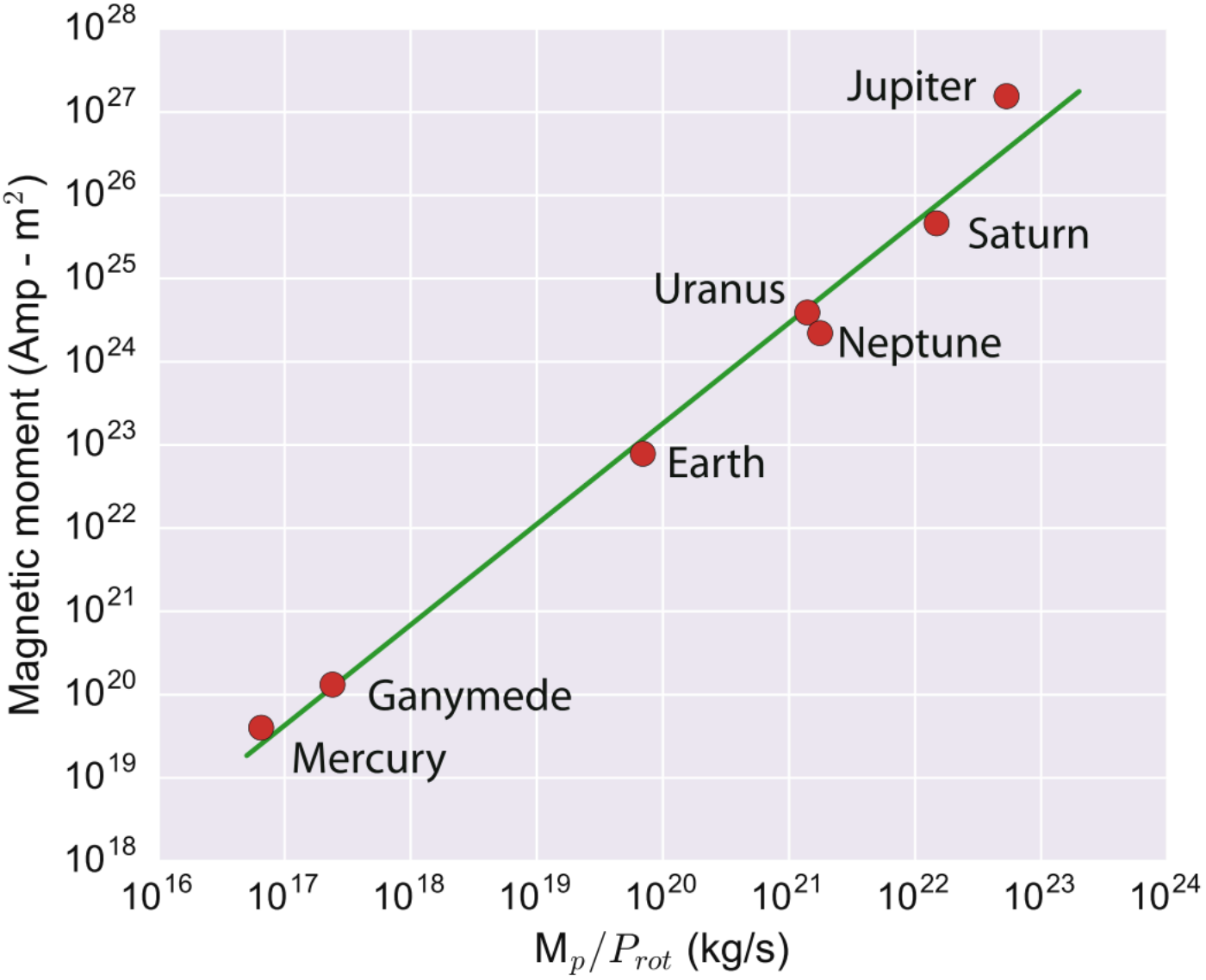
What do we know about planet magnetism?



	Earth	Jupiter	Saturn	Uranus	Neptune
Tilt of rotation axis	23°	3°	27°	98°	30°
Tilt of magnetic axis	12°	−10°	−0°	−59°	−47°
Offset of magnetic axis	8%	10%	5%	31%	55%
Field at equator	31,000 nT	428,000 nT	22,000 nT	23,000 nT	13,000 nT
Magnetosphere	10 R_{Earth}	65 $R_{Jupiter}$	20 R_{Saturn}	18 R_{Uranus}	25 $R_{Neptune}$
Planet size	1 R_{Earth}	11 R_{Earth}	9 R_{Earth}	4 R_{Earth}	4 R_{Earth}
Rotation period	1 day	9 hours	10 hours	18.6 hours	16 hours

What do we know about planet magnetism?



[Shkolnik & Llama 2018]

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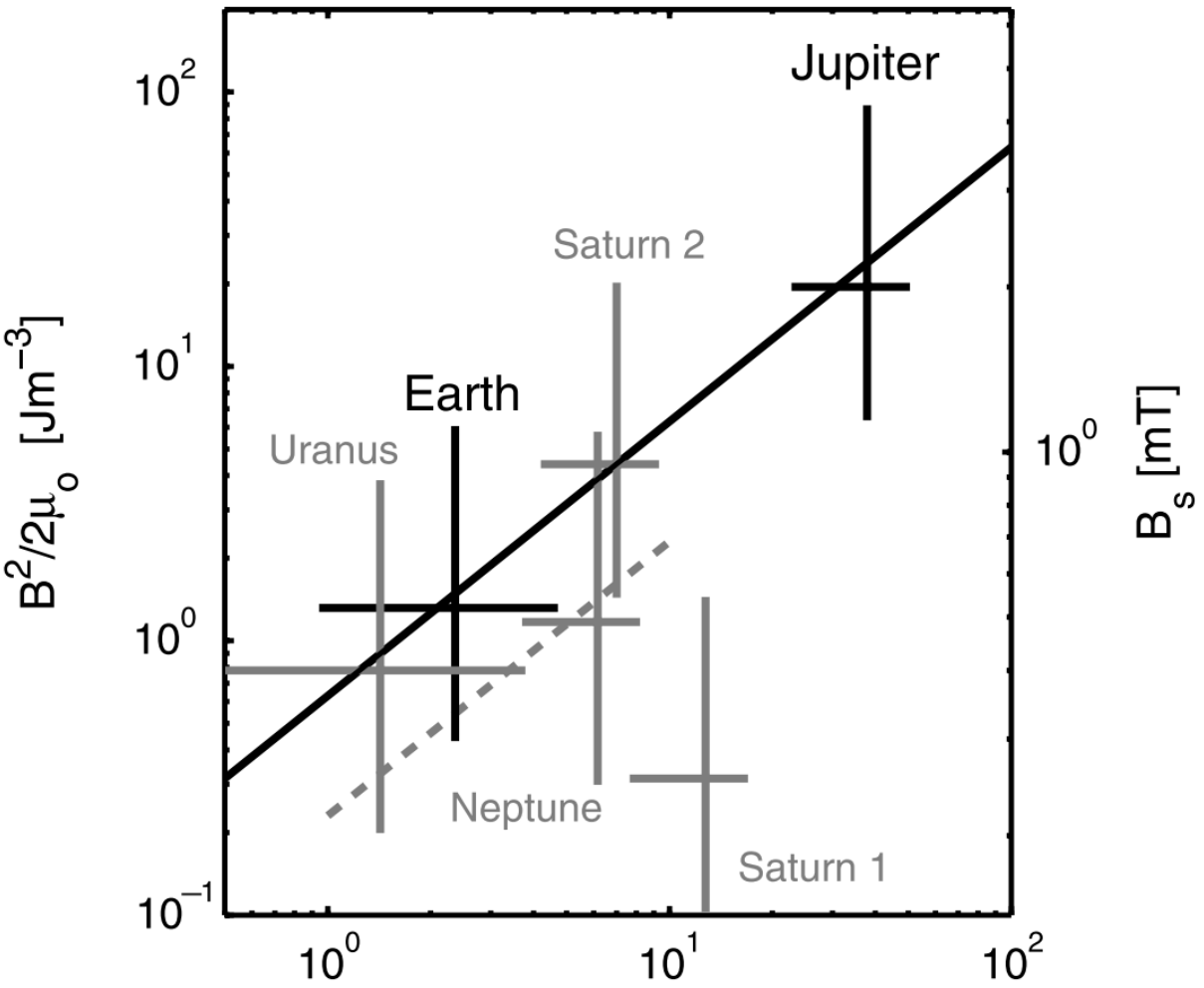

ohmic/total dissipation —— $f_{ohm}\ \rho^{1/3}\ (F\ q_o)^{2/3}$ [Jm^{-3}]

average density

geometric factor ~ 1

Bolometric flux

[Christensen 2010]

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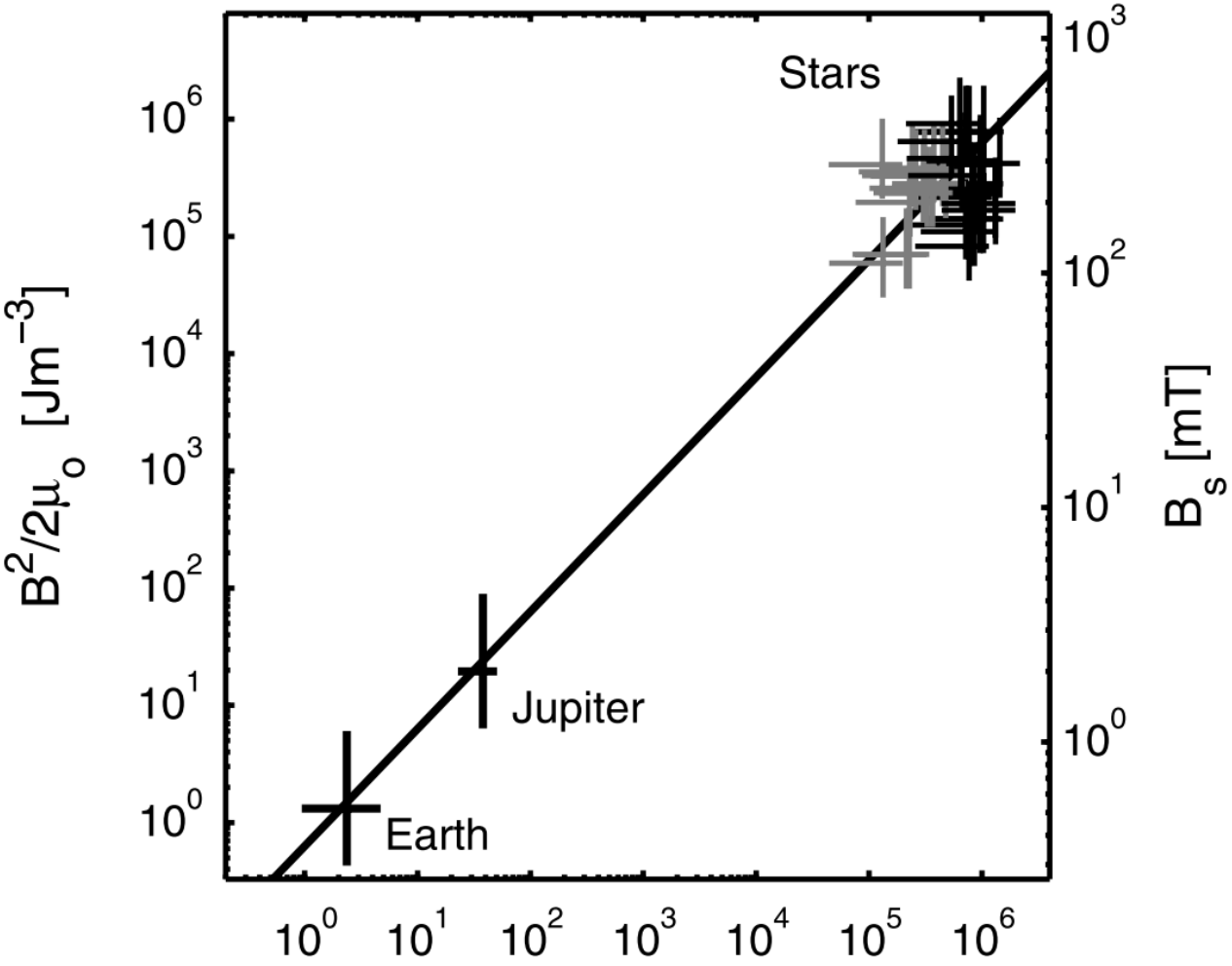

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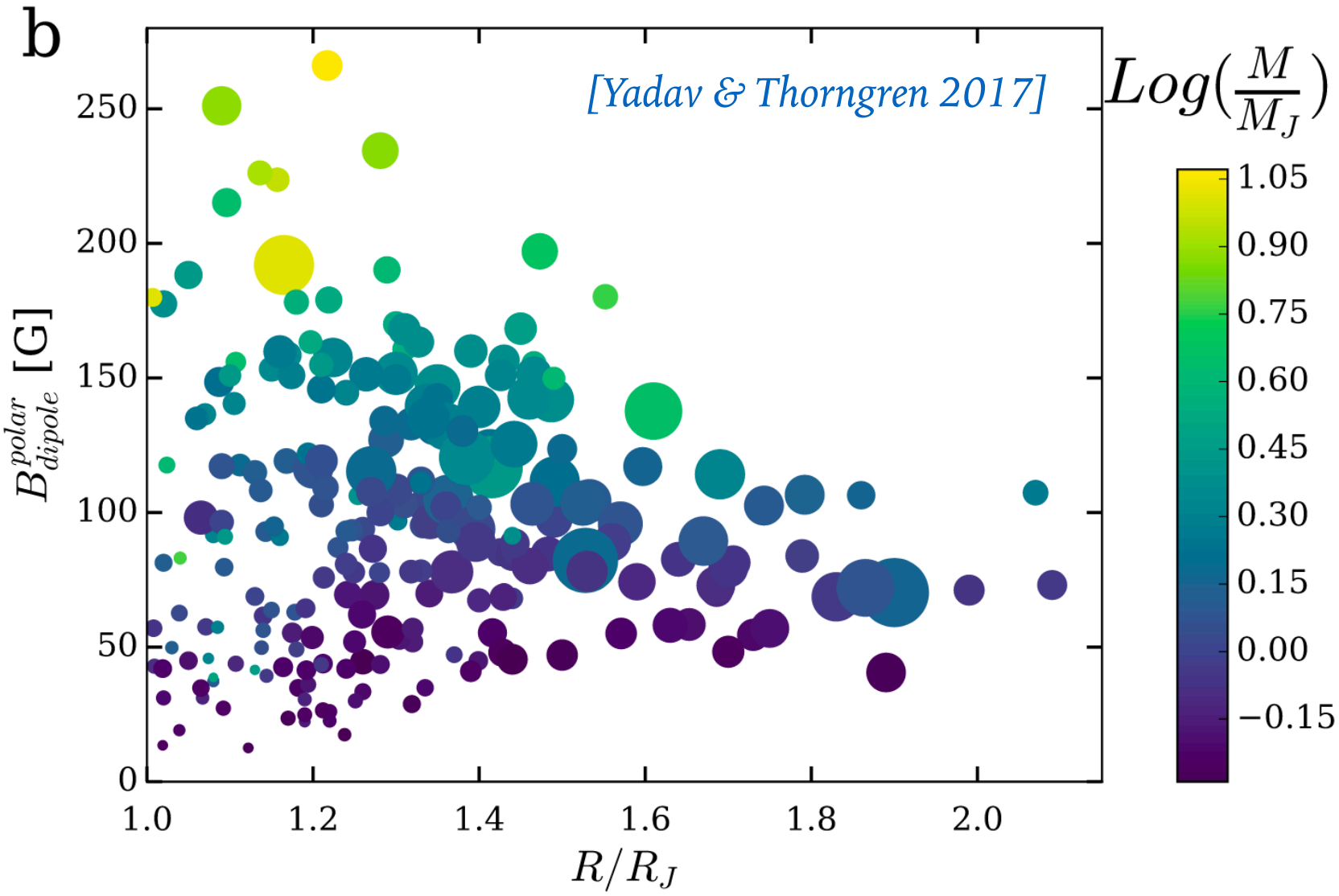
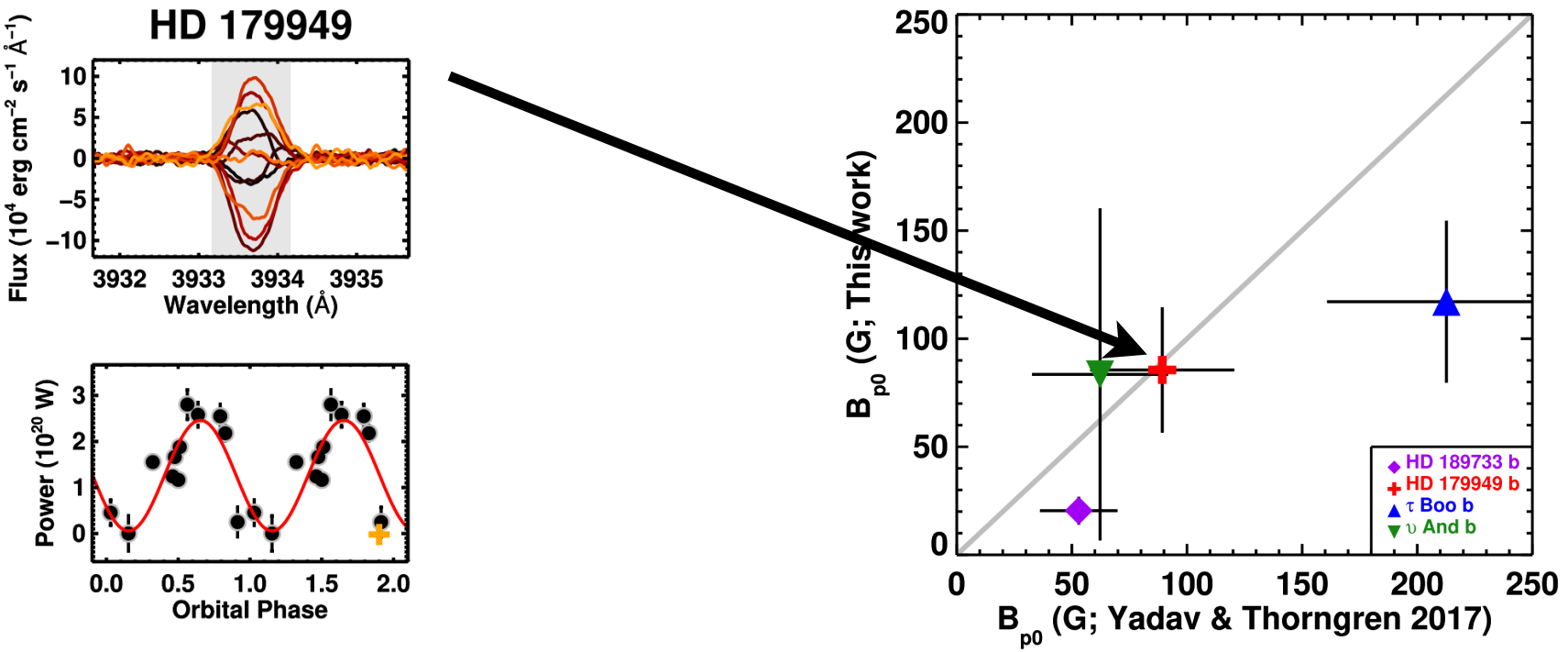
Planetary dynamos powered by the stellar incident radiation



See also Hori 2021

What do we know about exoplanets' magnetism?



A signal in the Ca II H&K bands of 4 host stars was observed to be correlated with the orbital phase of the hot exoplanet (generally once the rotational modulation of the star is removed)

[Cauley+ 2019]

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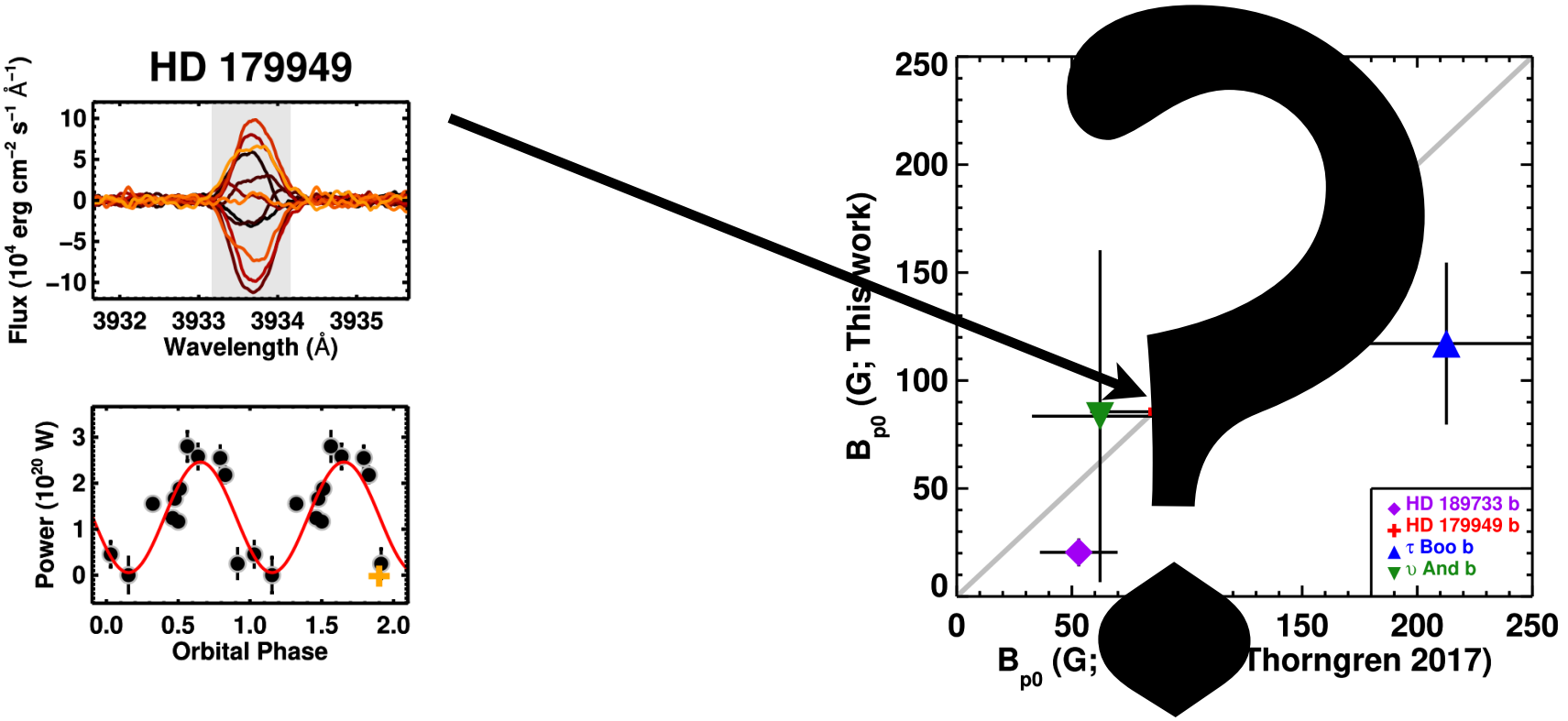

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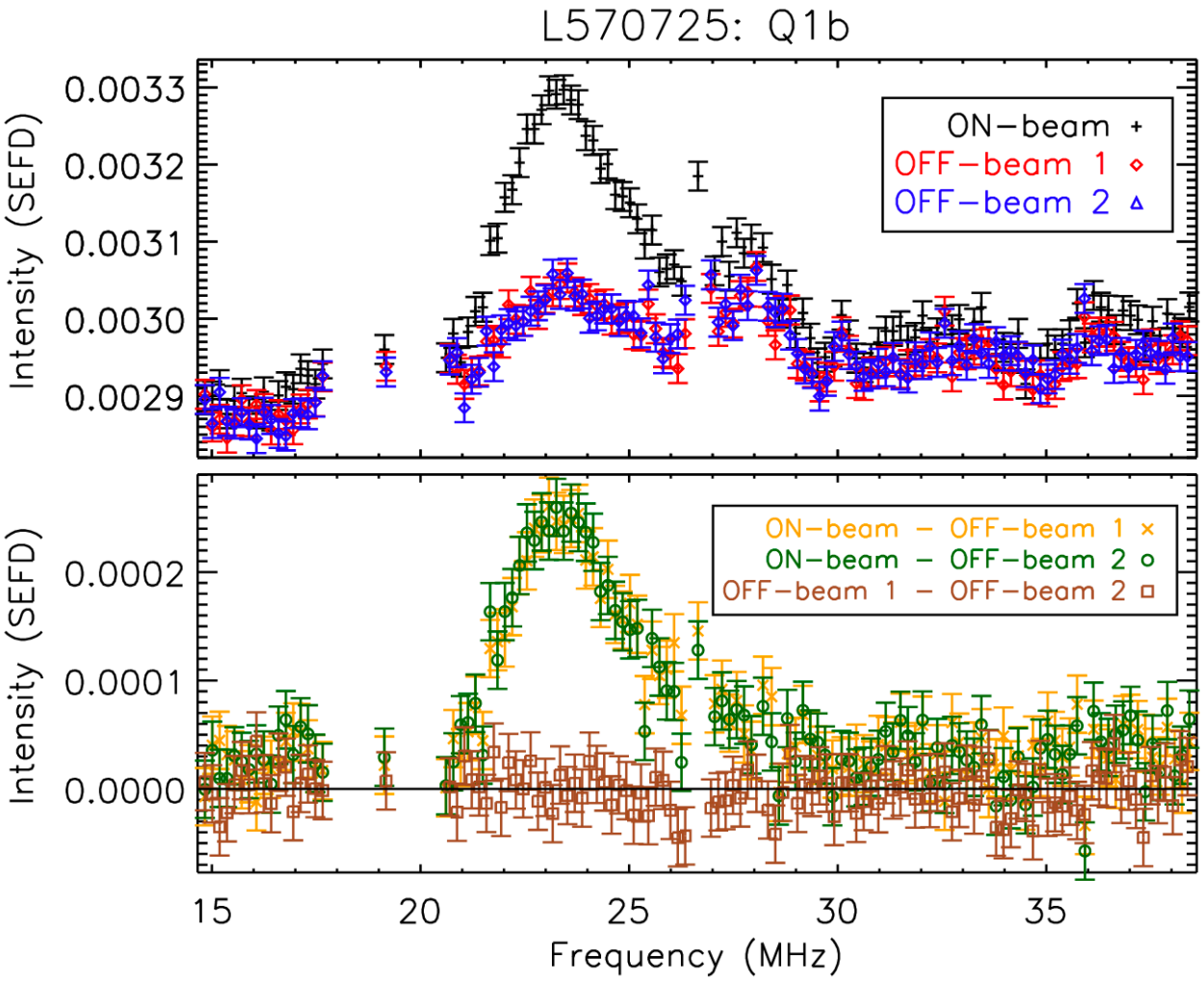
[Cauley+ 2019]

The promise of radio detections: the case of τBoo



[Turner+21]

First tentative detection!

$B_P \sim 5\text{-}10$ G

[See also Callingham+ 21, Vedantham+ 21]

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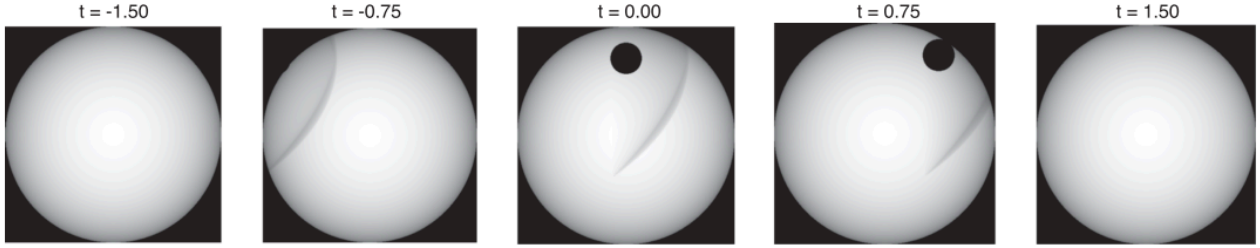
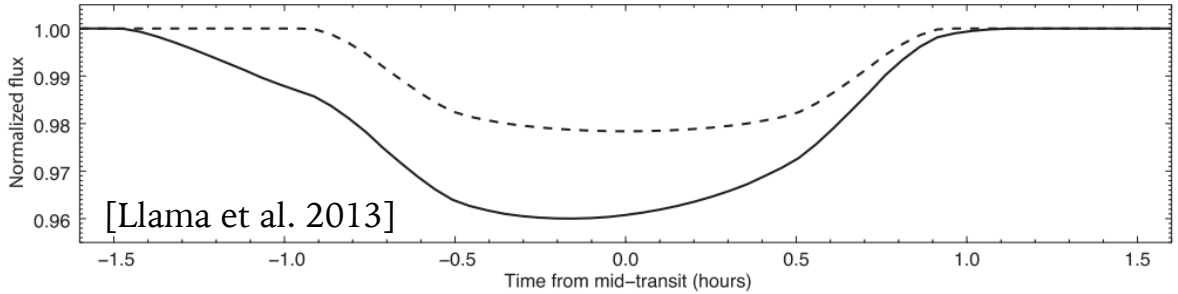
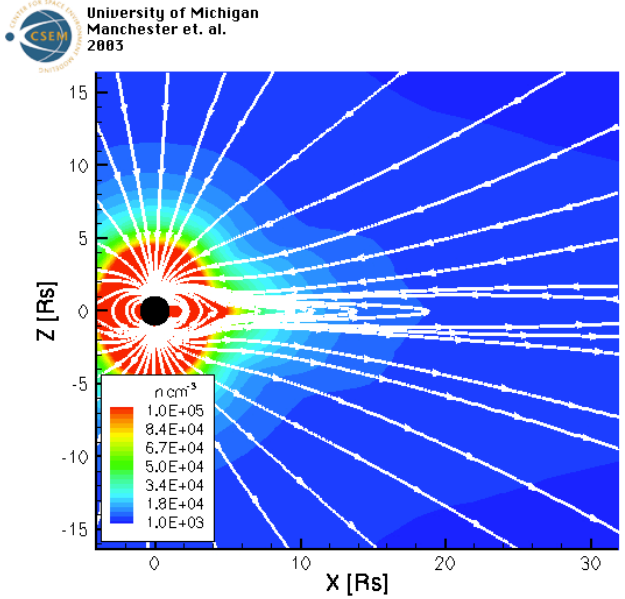
Star-planet (magnetic) interactions

Transients and short-timescale effects



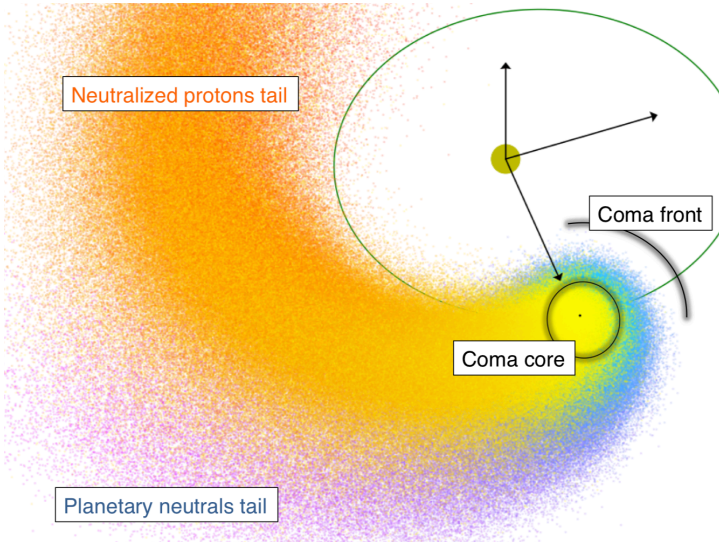


Pre-shock absorption



Transient interactions

Atmospheric escape



GJ 436b, Bourrier+ 2016

Star-planet (magnetic) interactions

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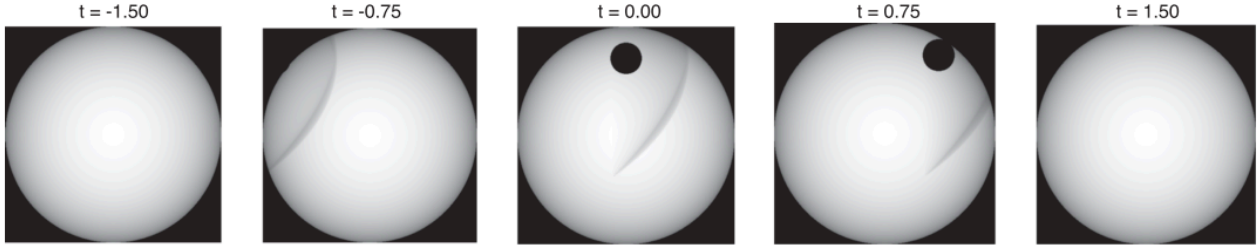

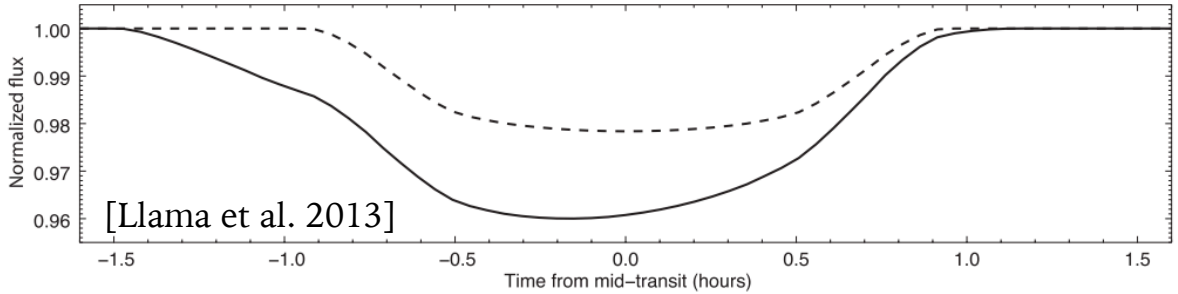

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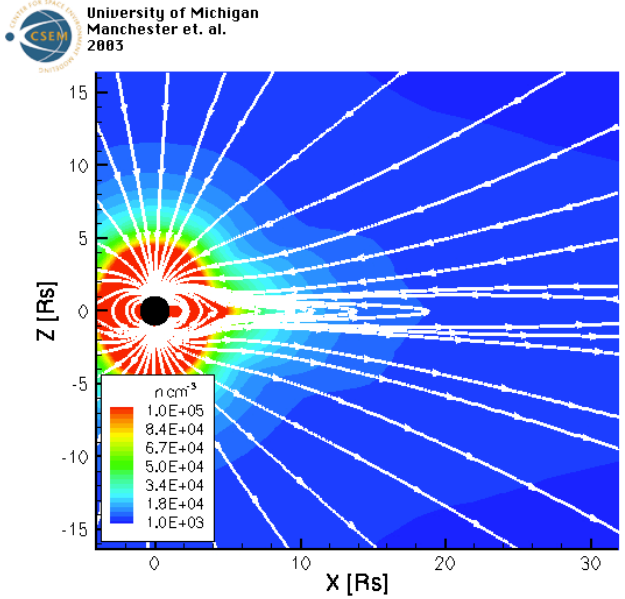

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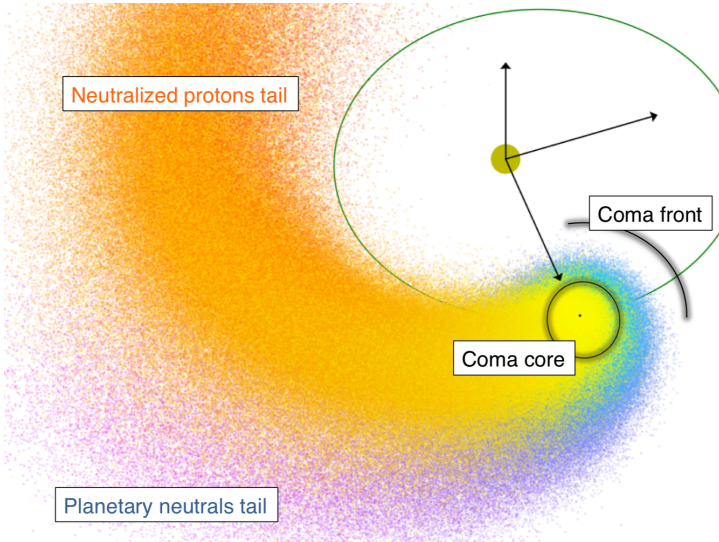

GJ 436b, Bourrier+ 2016

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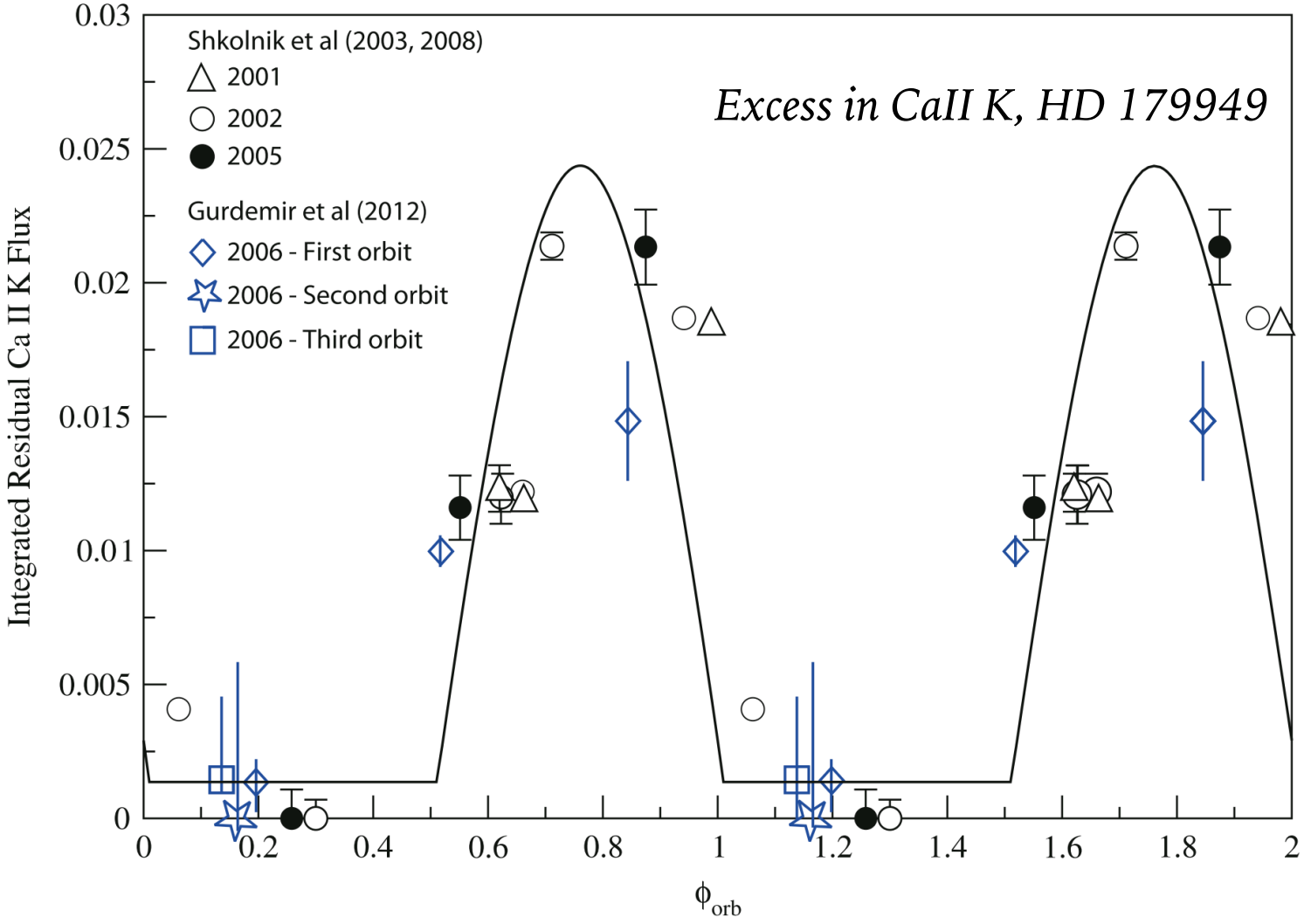
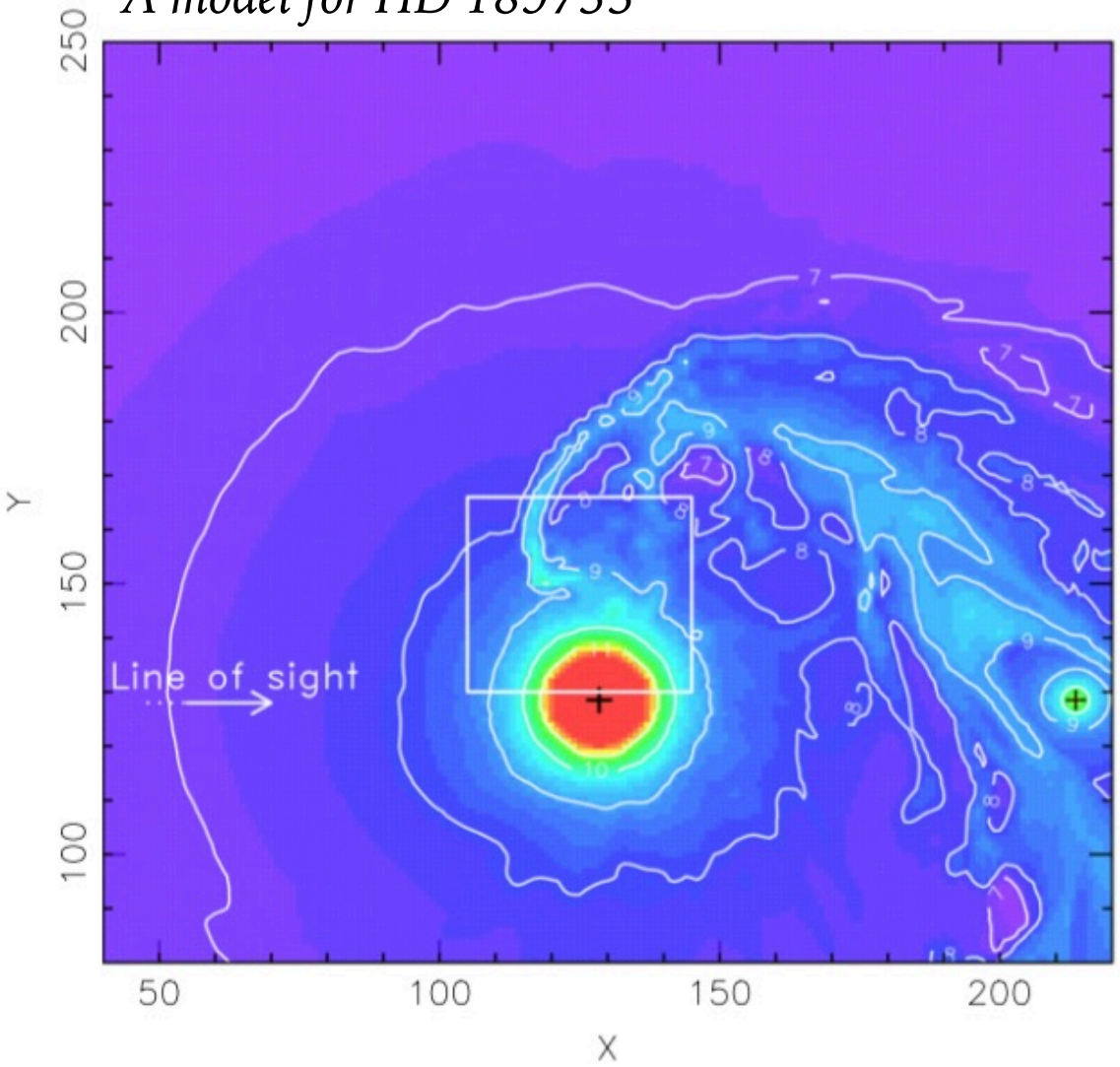


[Shkolnik & Llama 2017, Shkolnik+ 03, 08]

Star-planet (magnetic) interactions
Transients and short-timescale effects

A model for HD 189733



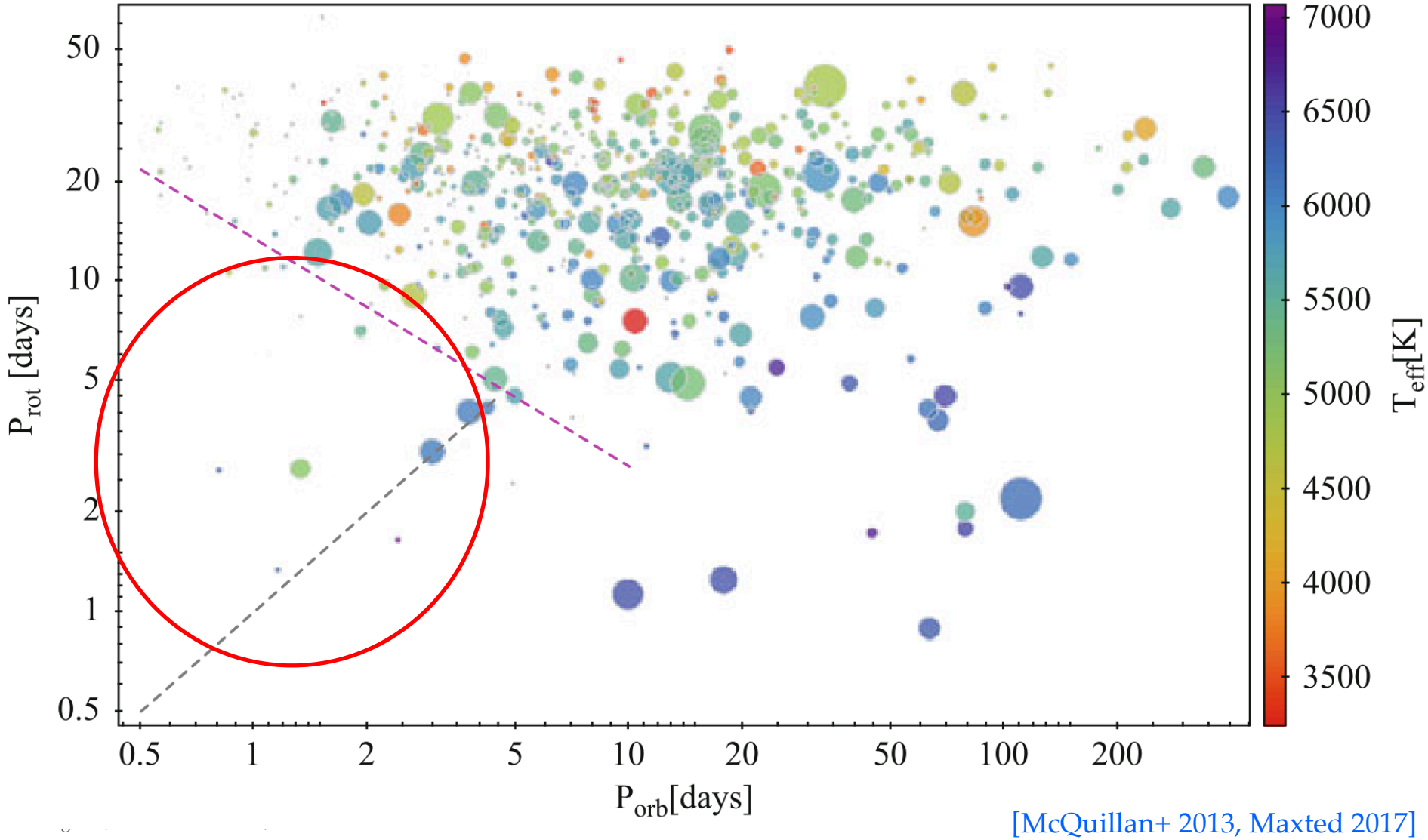
Back-reaction on the central star, potentially observable?

[Matsakos+ 15; Pillitteri+ 15]

Star-planet (magnetic) interactions

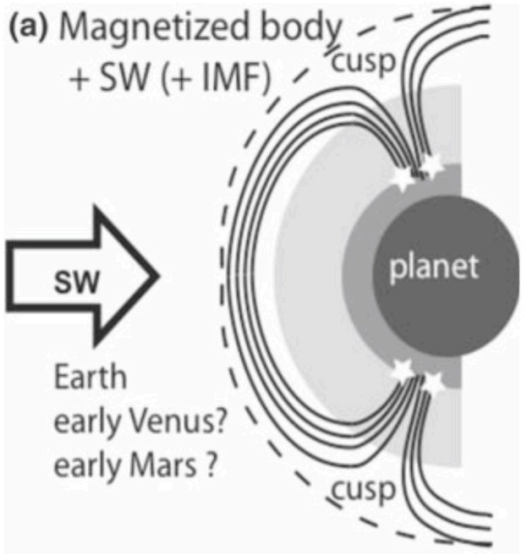
Secular effects

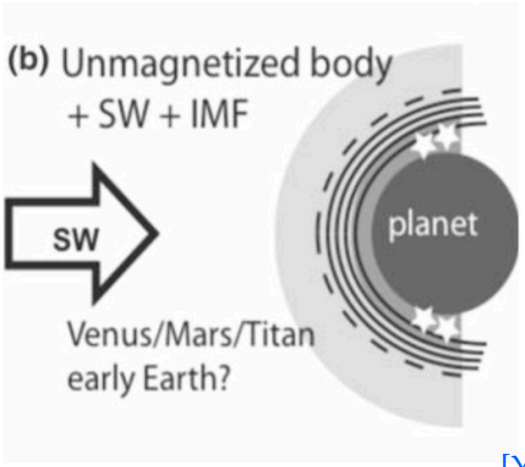
737 Kepler Objects of Interest (KOI)

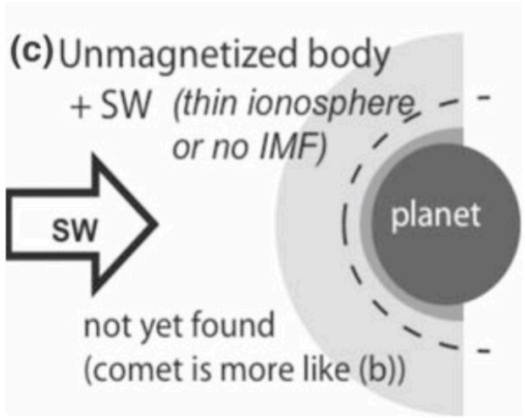


[McQuillan+ 2013, Maxted 2017]

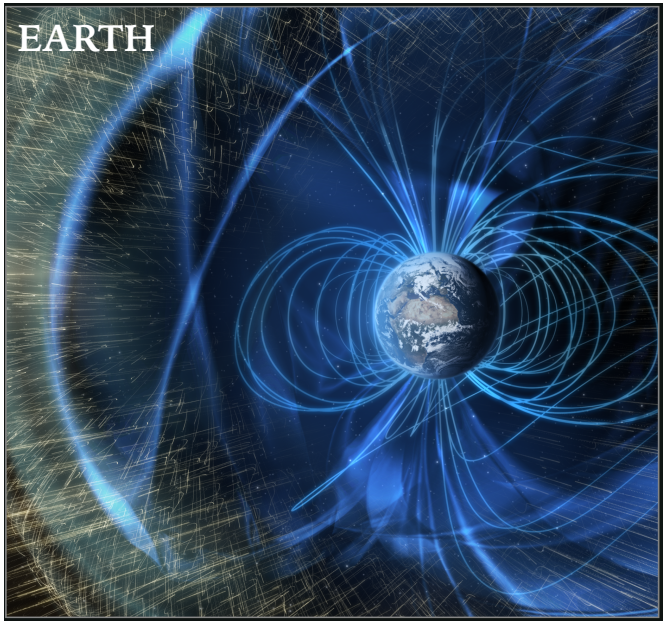
Star-planet (magnetic) interactions towards habitability?

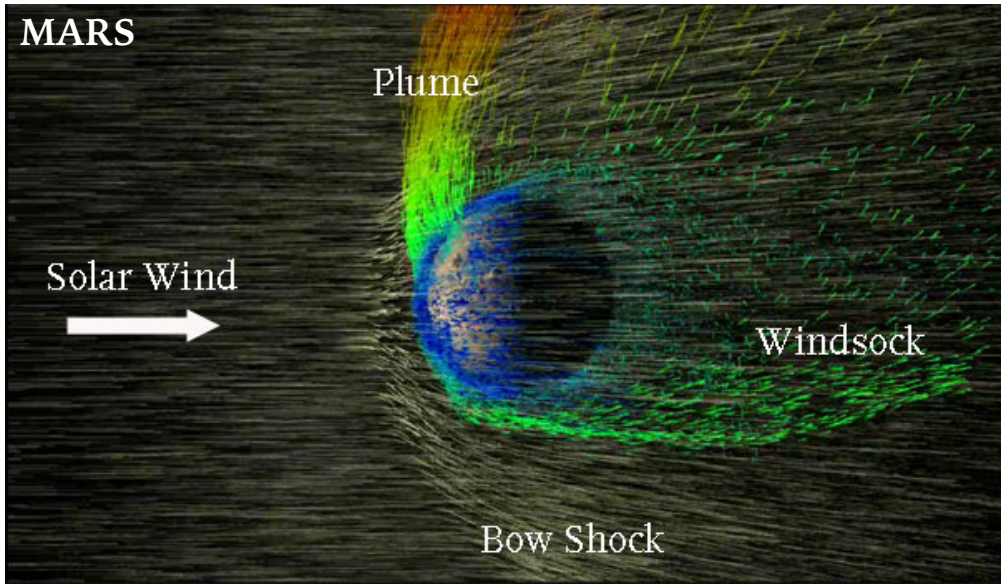




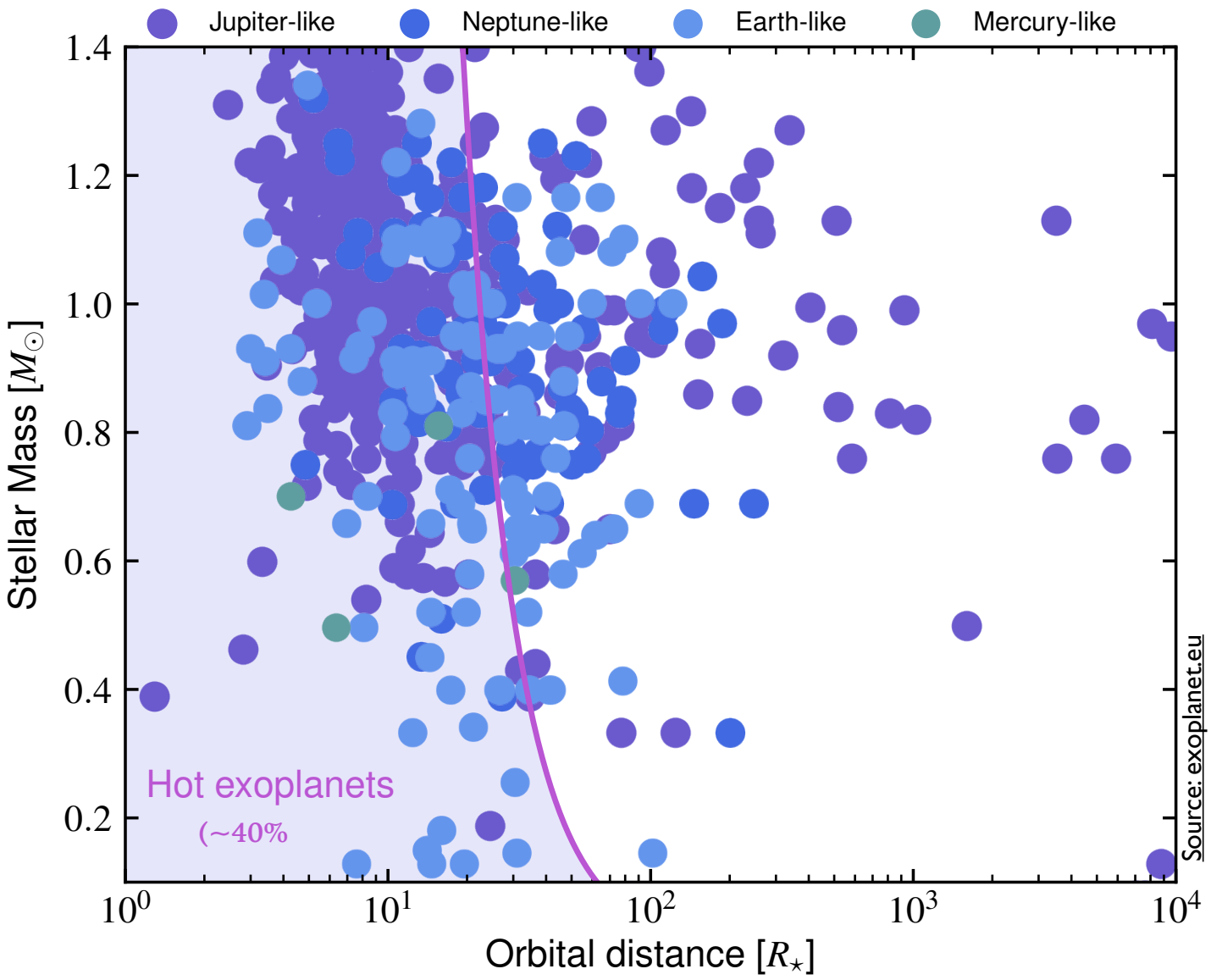


[Yamauchi and Wahlund 2007]

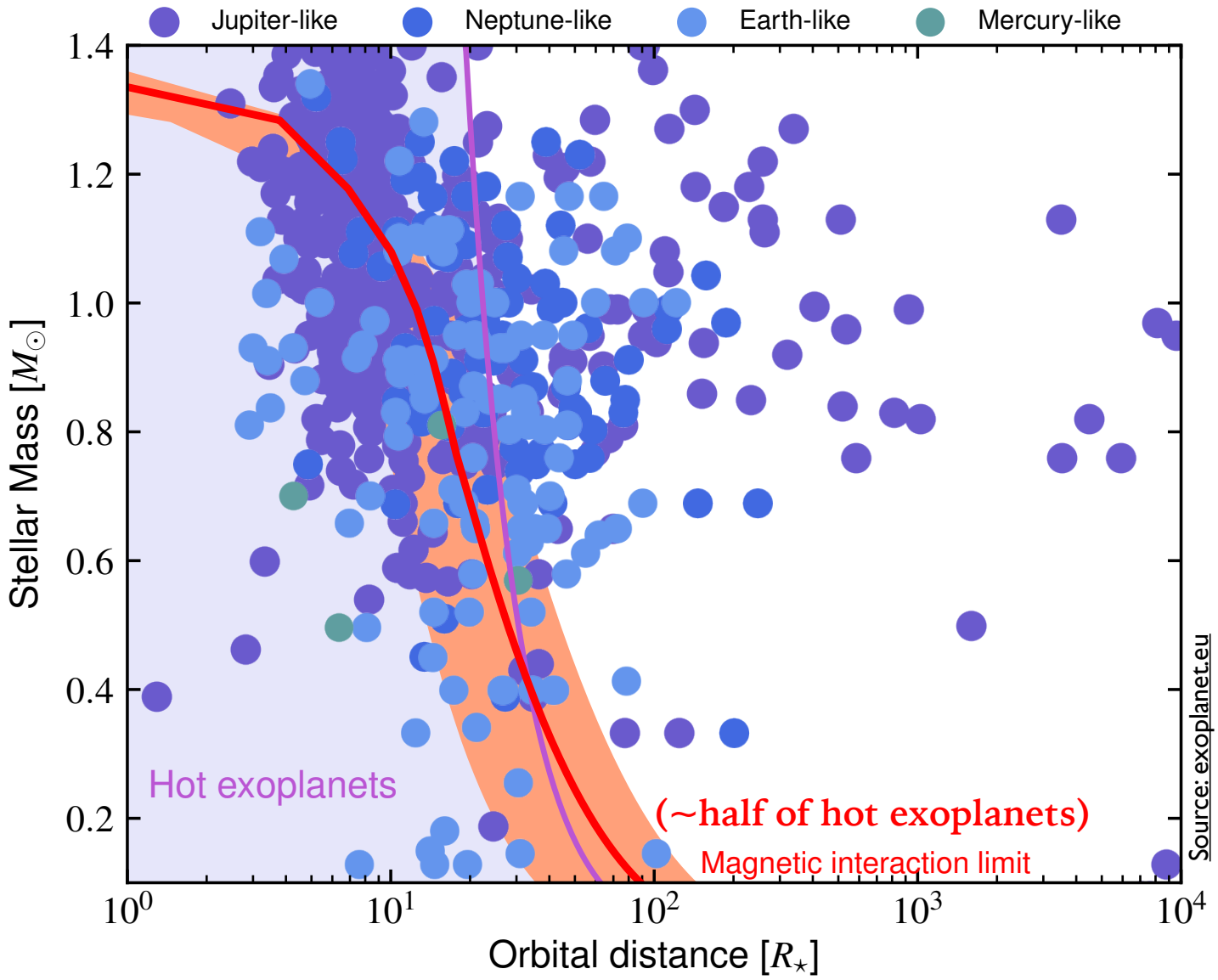




Magnetic connection in hot exosystems

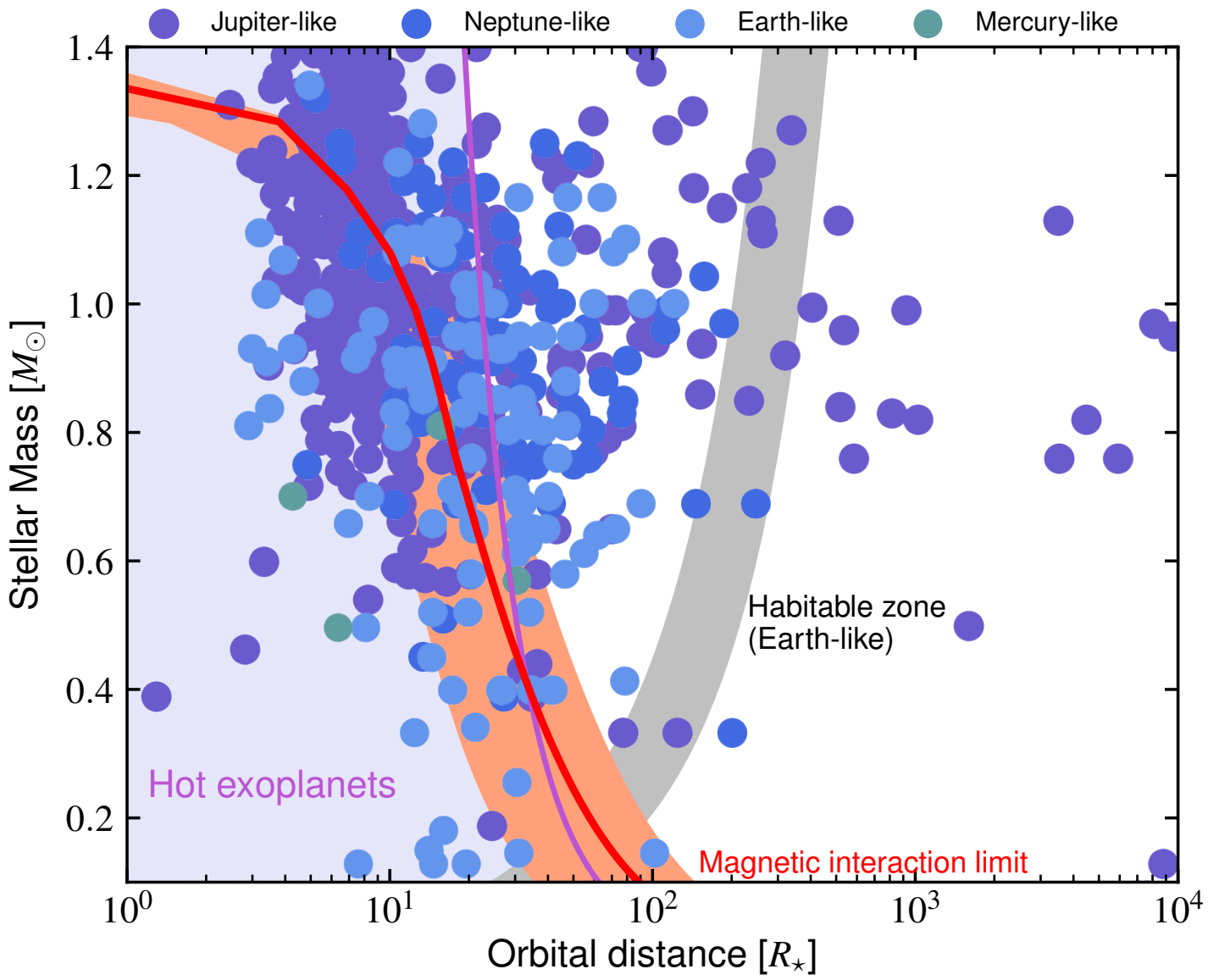


Magnetic connection in hot exosystems



starAML 1D code
Réville+ 2015

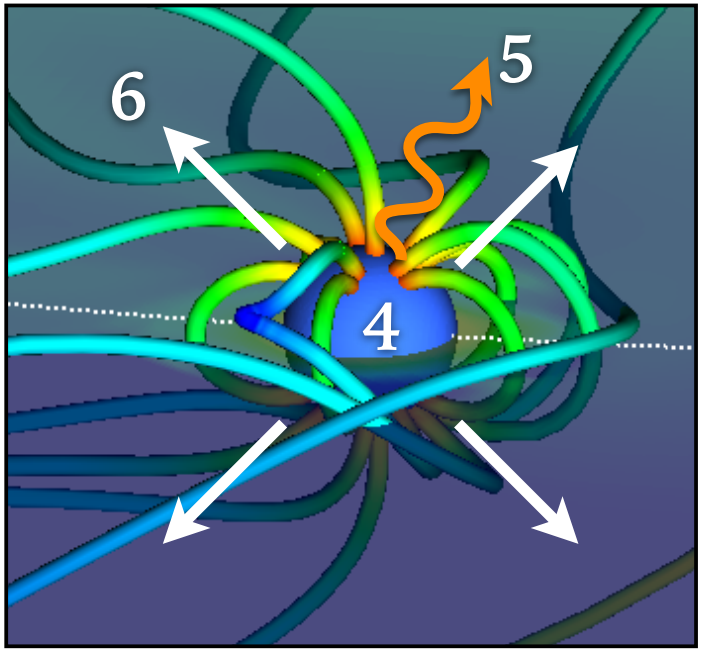
Magnetic connection in hot exosystems

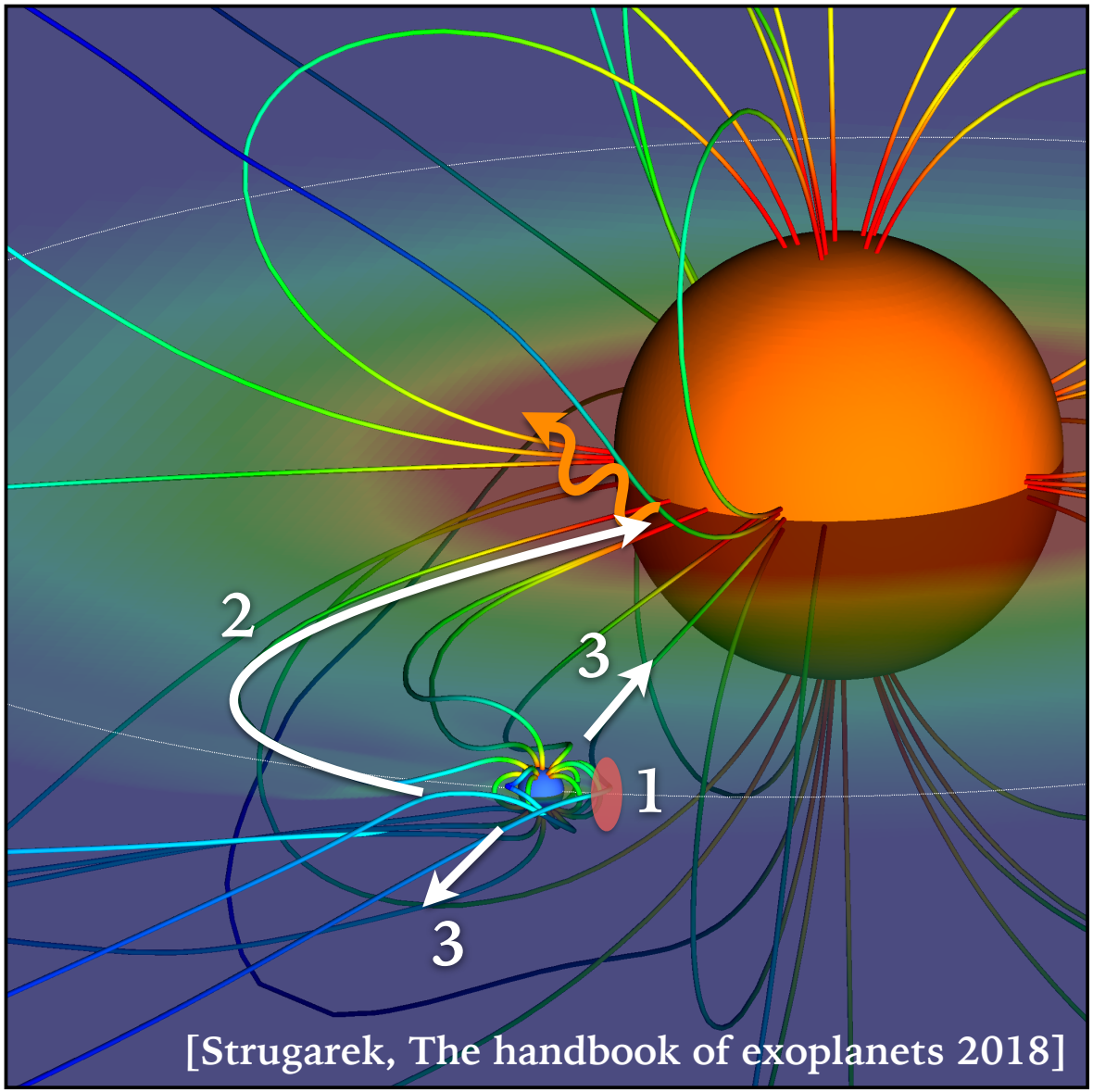


starAML 1D code
Réville+ 2015

Major effects of star-planet magnetic interactions

1. Shocks & geometry
2. Energy channeling
3. Planet migration
4. Planet heating
5. Planet emissions
6. Atmospheric escape





Major effects of star-planet magnetic interactions

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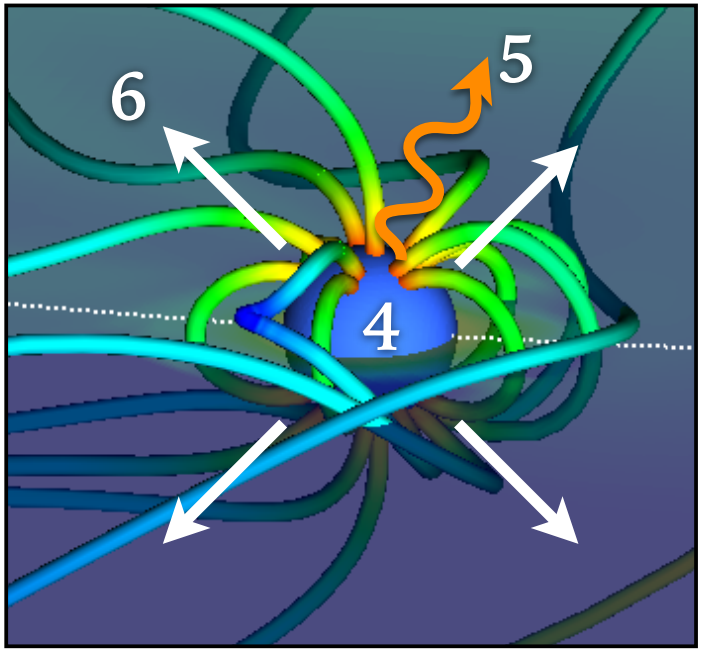
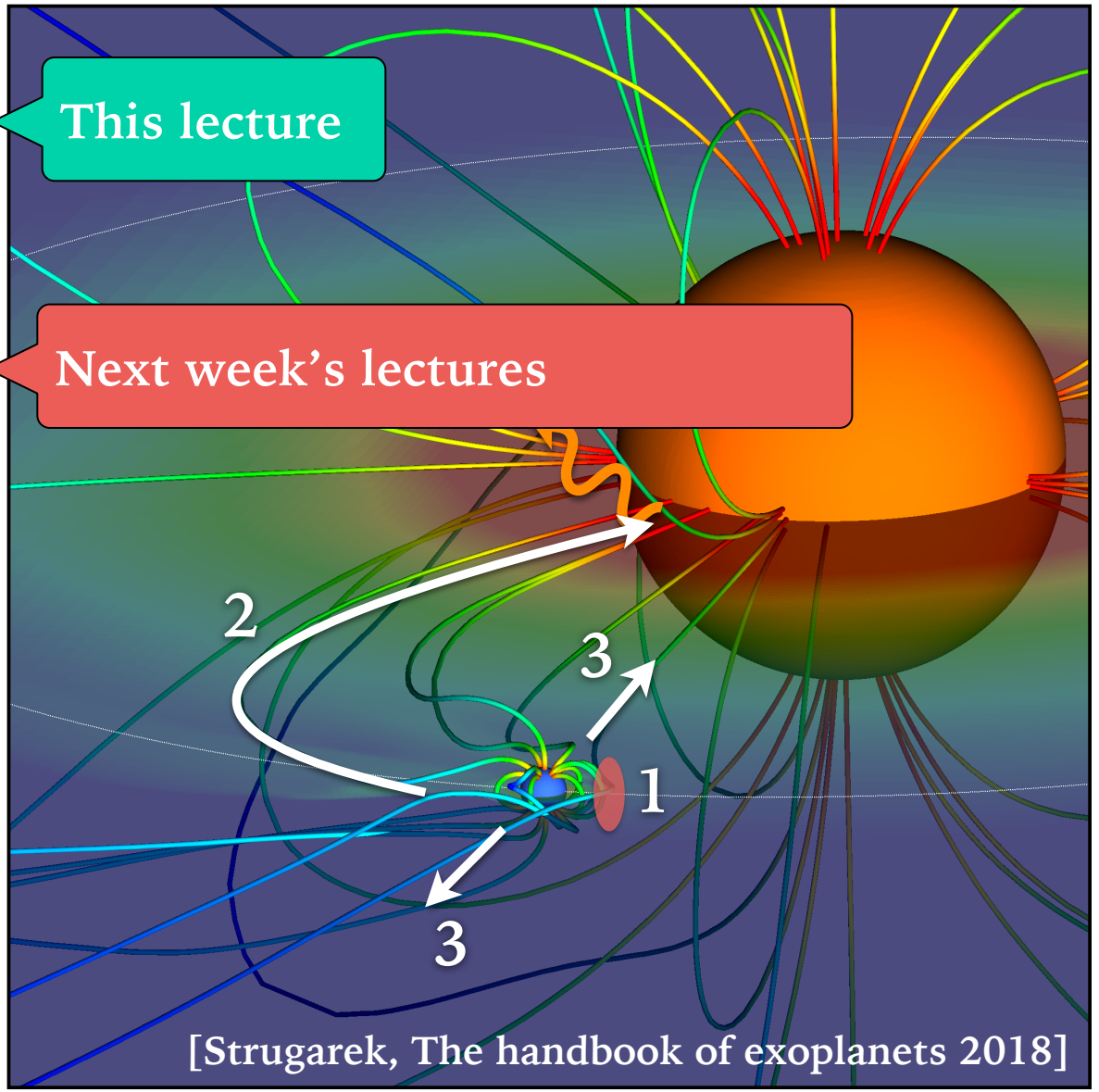
This lecture

Next week's lectures





Major effects of star-planet magnetic interactions

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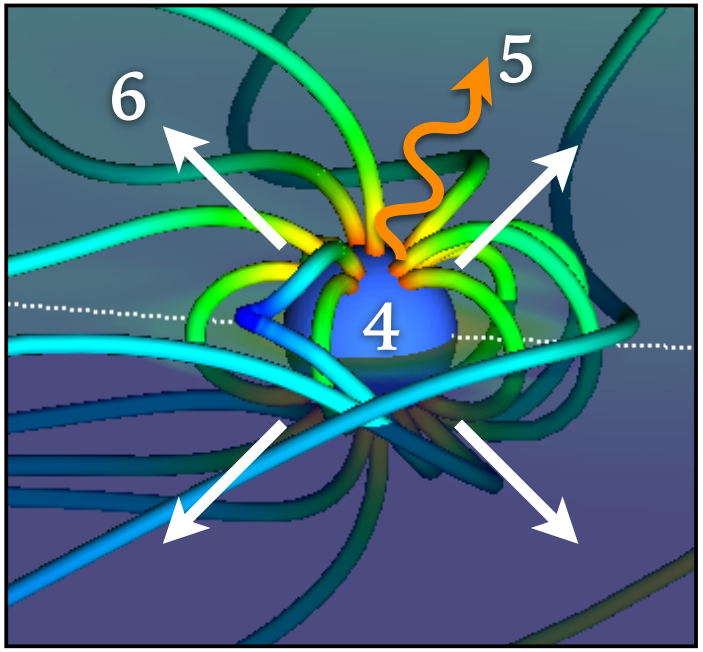
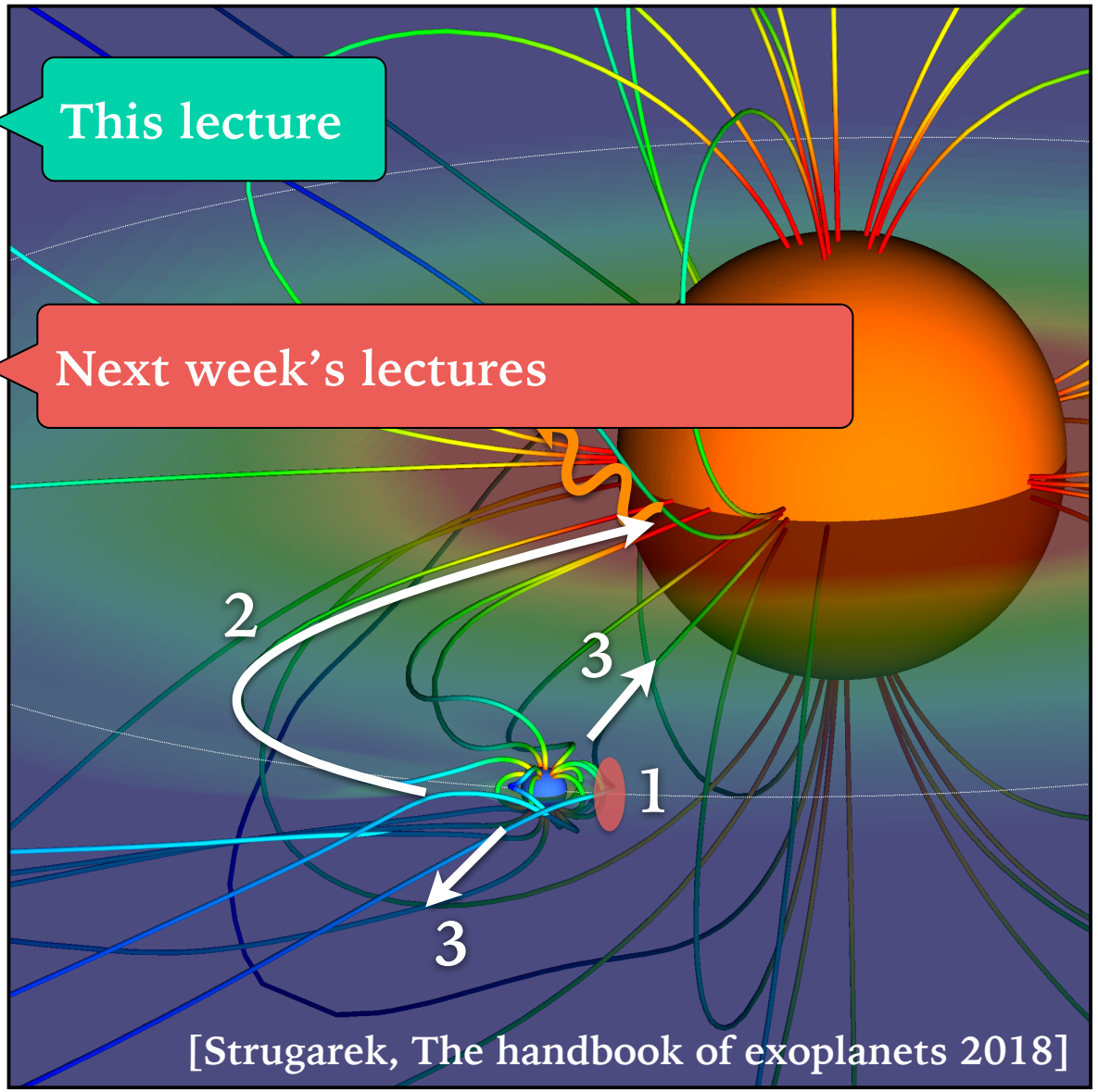
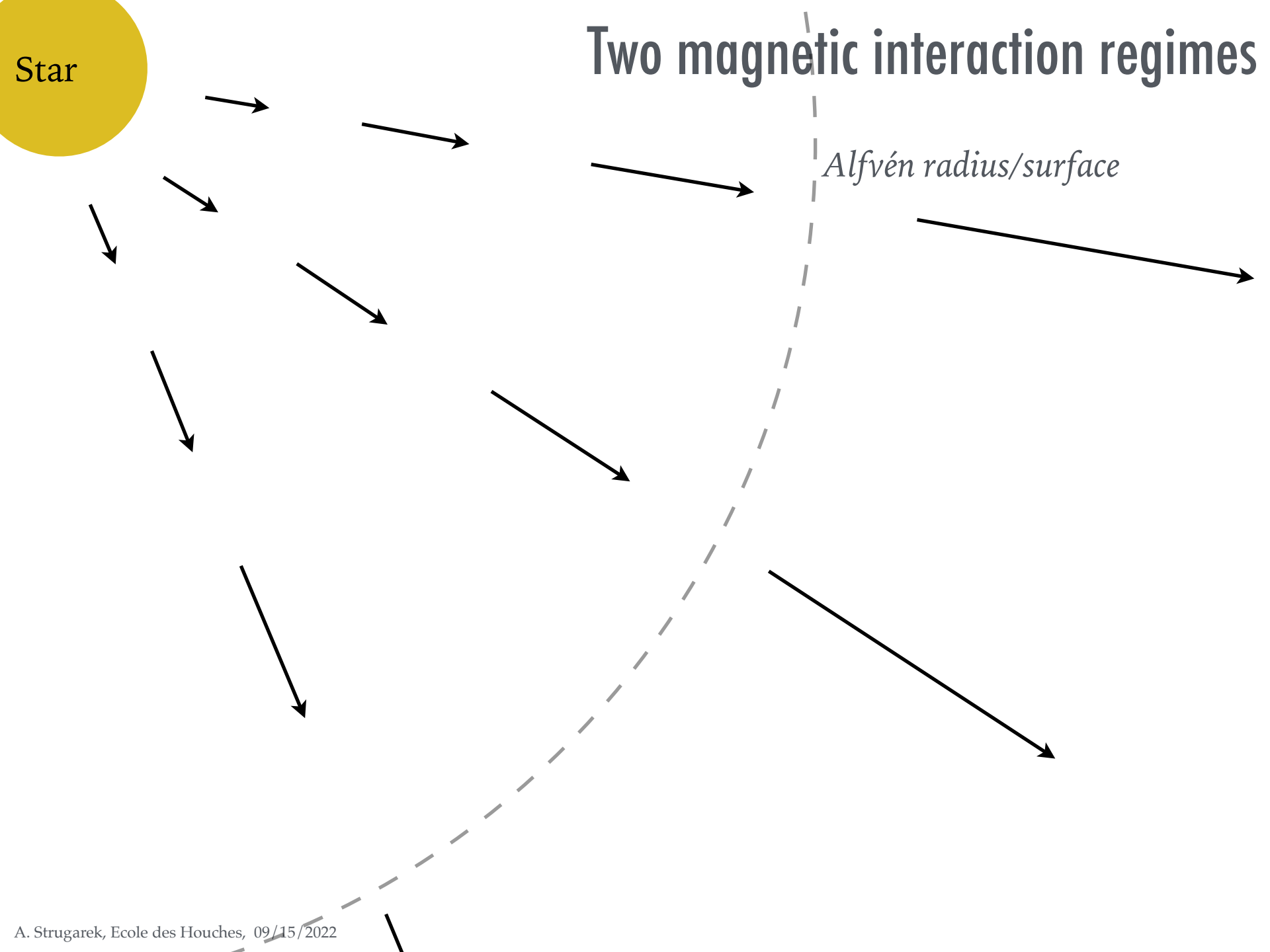




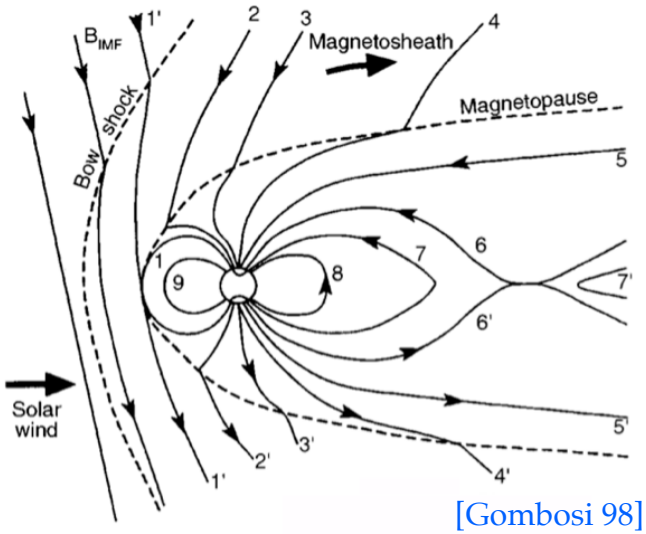
Two magnetic interaction regimes



Two magnetic interaction regimes

Star

Alfvén radius/surface



[Gombosi 98]

Super-alfvénic interaction

Shocks

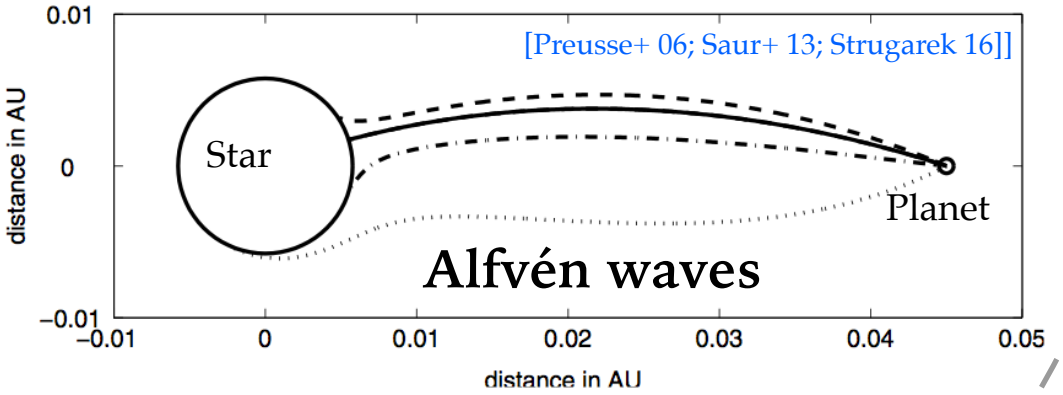
Two magnetic interaction regimes

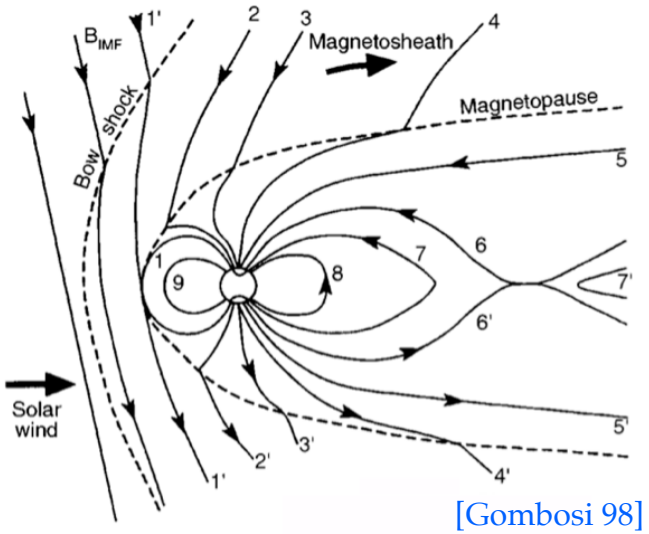
Star

Alfvén radius/surface

Sub-alfvénic interaction

Star-planet **connection**

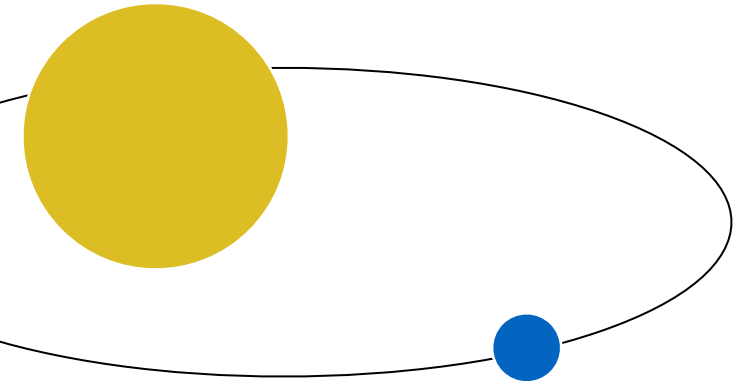




Super-alfvénic interaction

Shocks

What are the necessary criteria for shocks?



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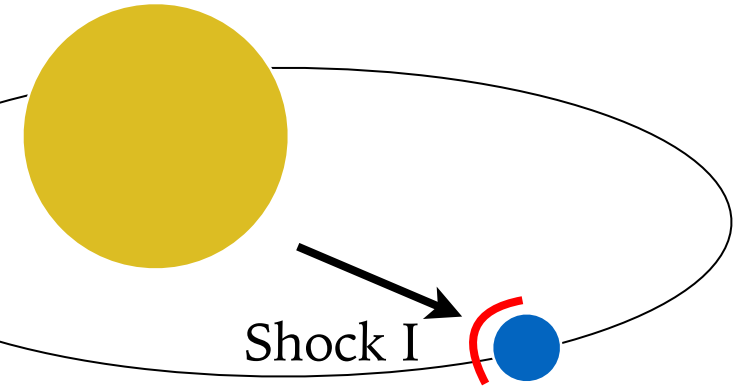
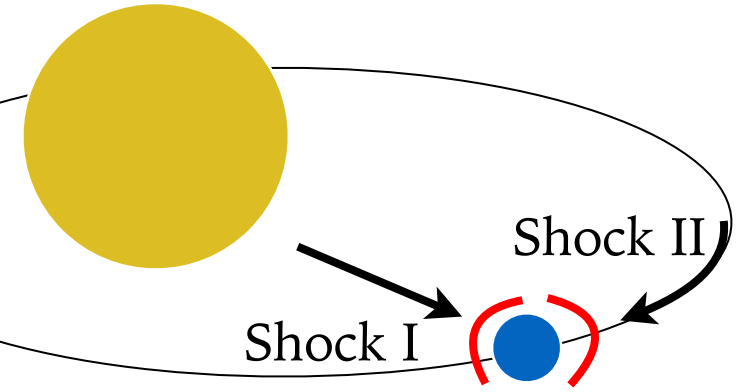


Shock I

Radial wind velocity $> v_A$

What are the necessary criteria for shocks?



Shock I

Radial wind velocity $> v_A$

Shock II

$|$*Keplerian motion - rotation* $| > v_A$

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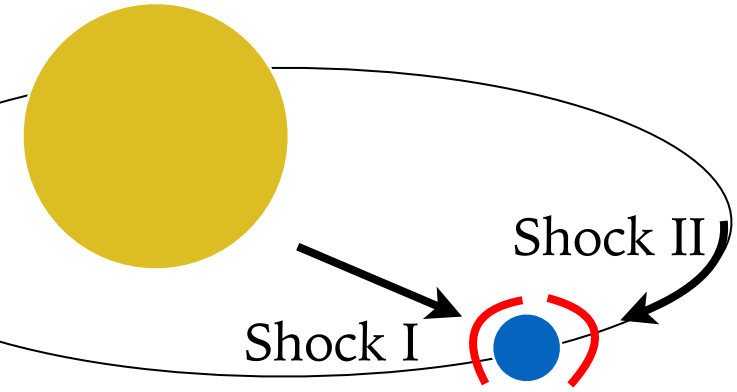

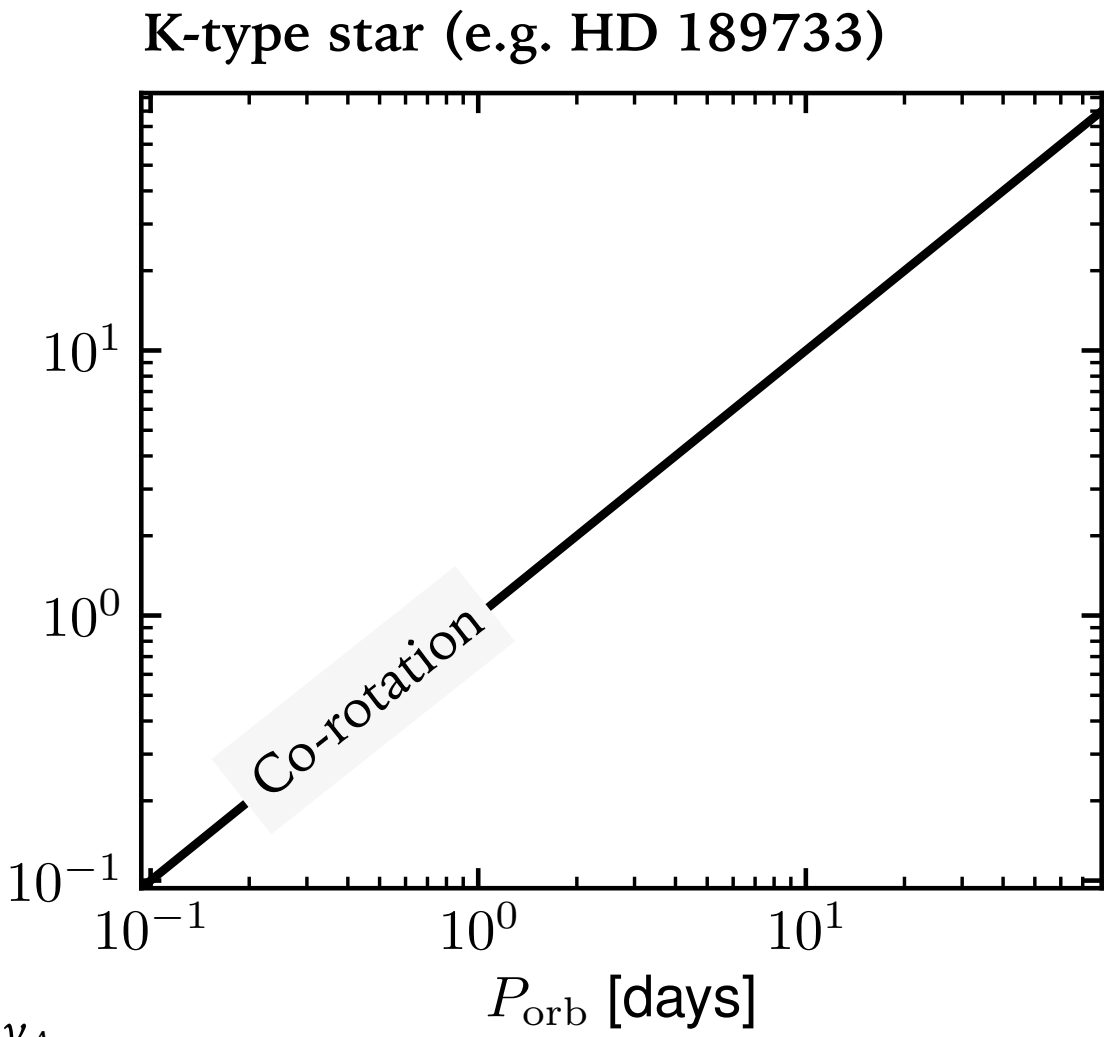

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(Weber-Davis wind model)

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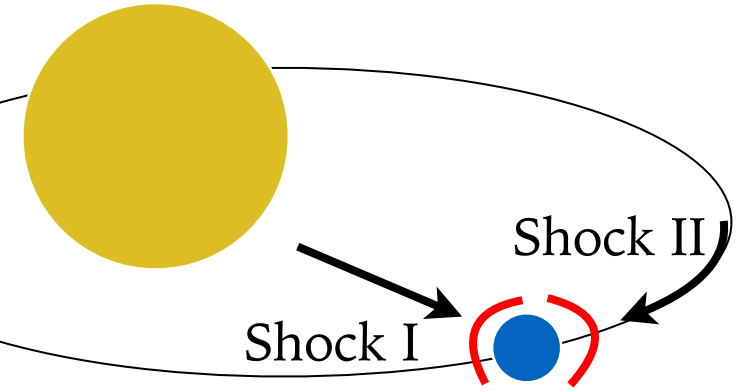

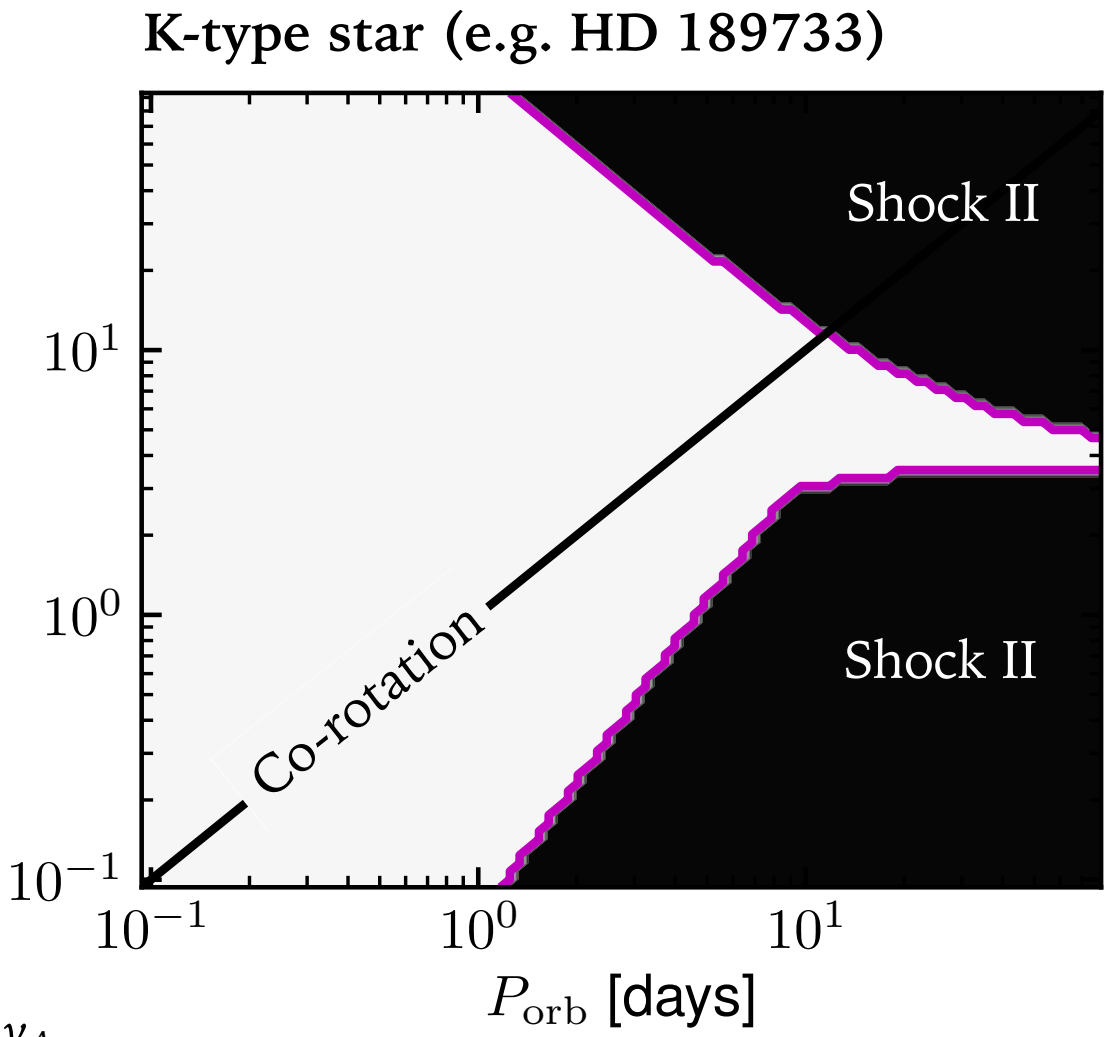

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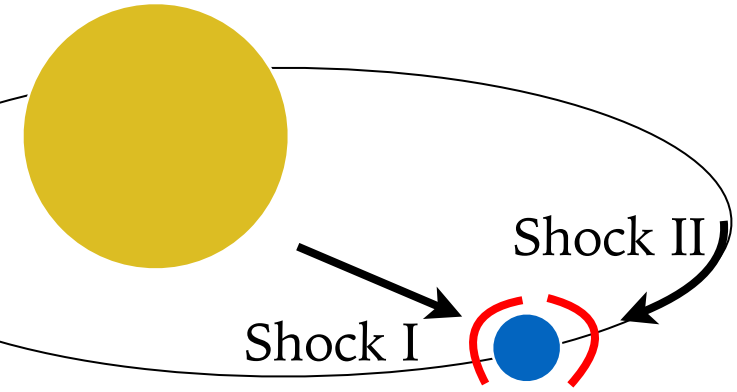
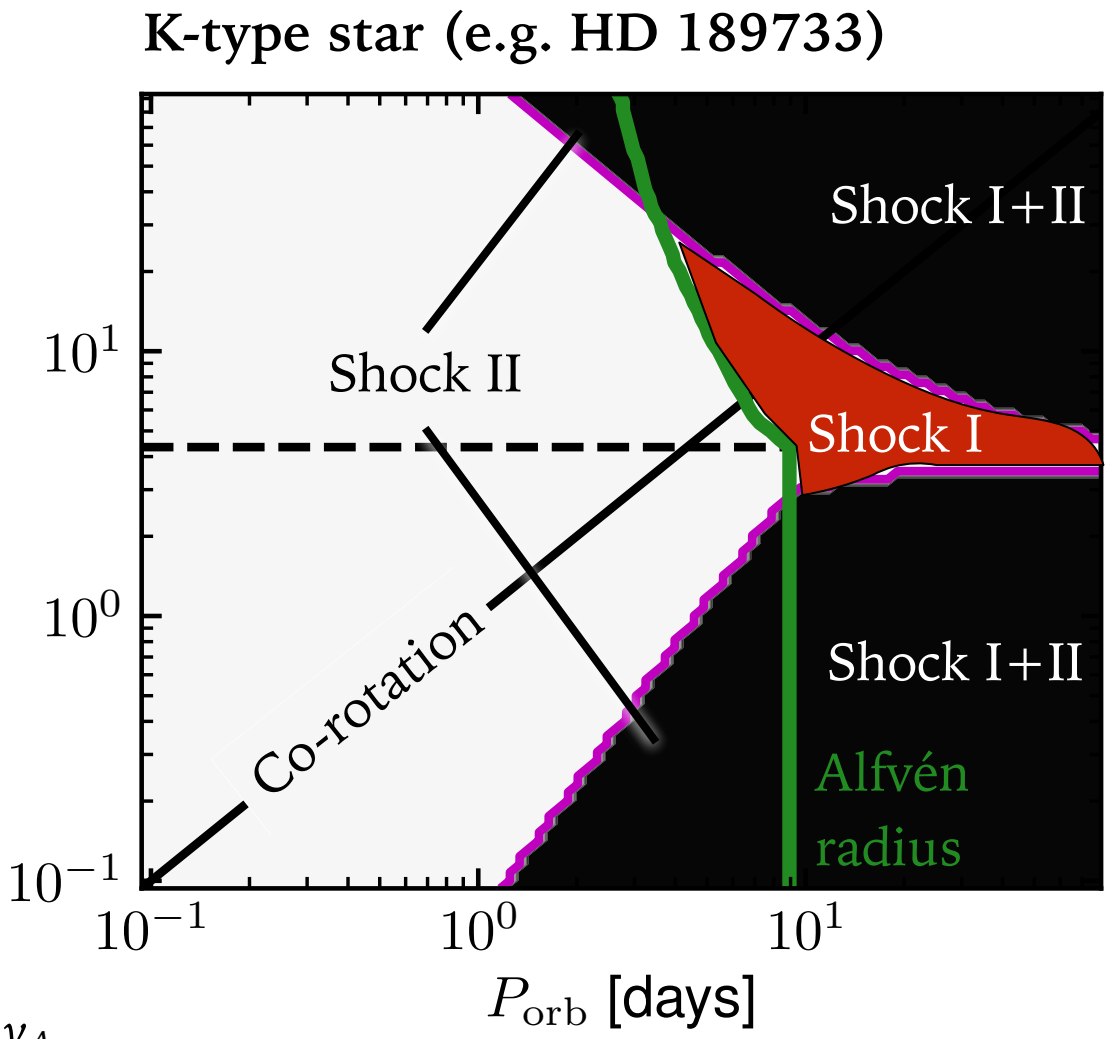




Shock I

Radial wind velocity $> v_A$

Shock II

$|$*Keplerian motion - rotation* $|> v_A$

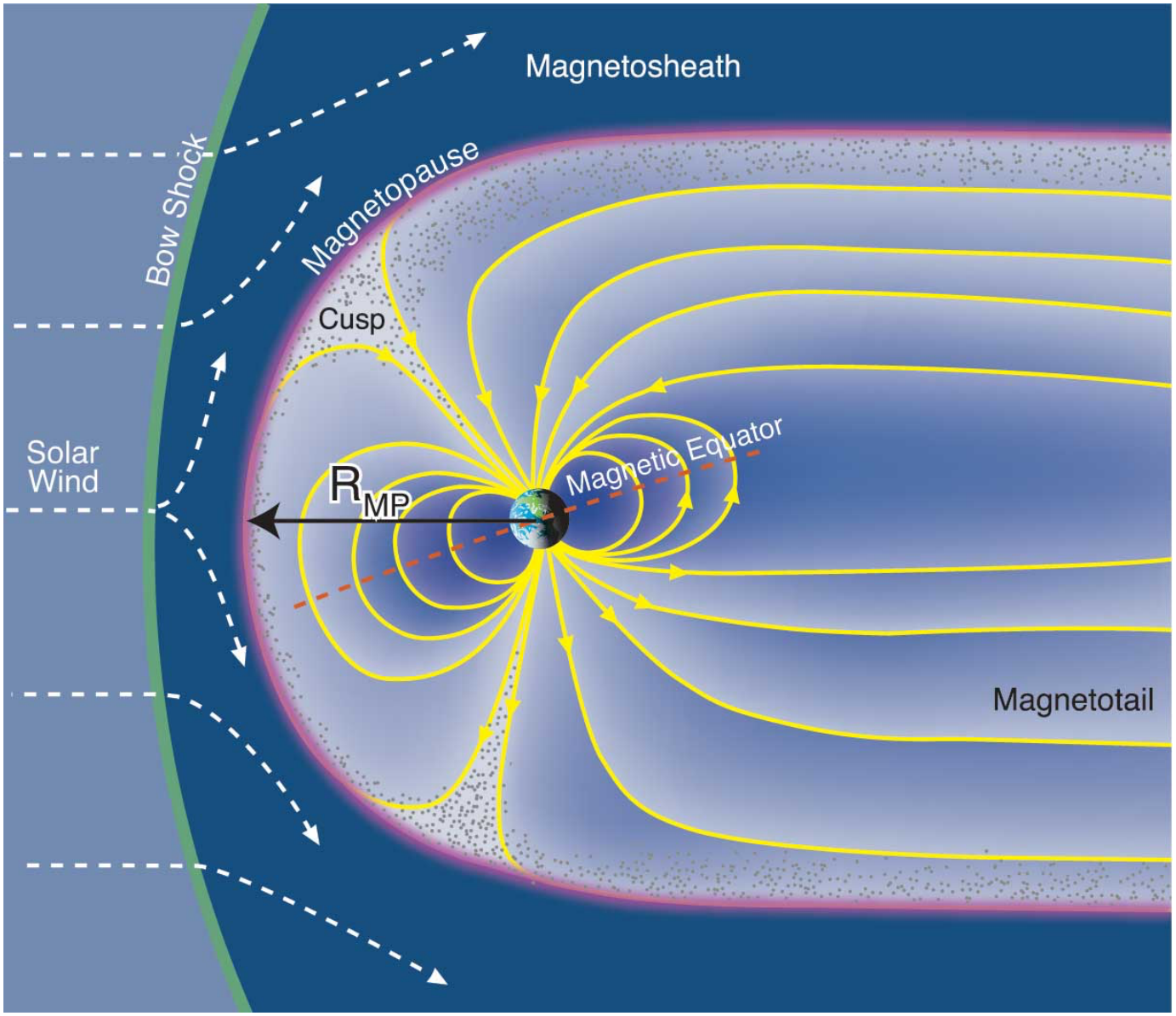
(Weber-Davis wind model)

Nomenclature of (magnetized) interactions

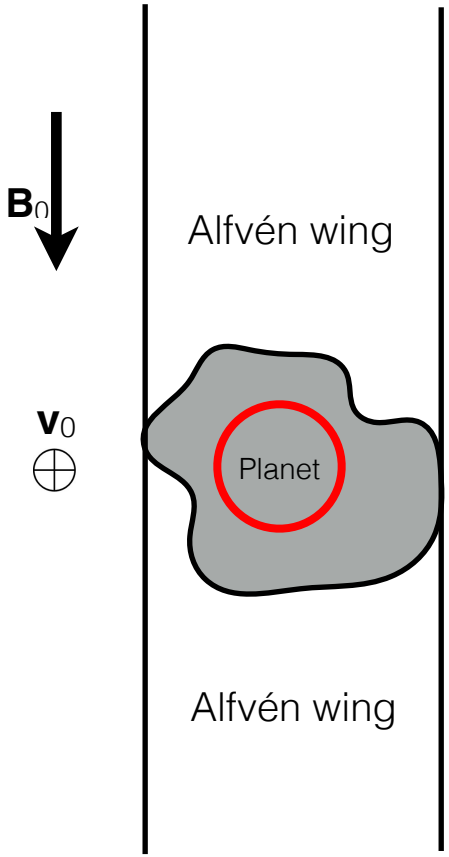
Flow / Obstacle	Weakly/non magnetized	Strongly magnetized
Weakly/non magnetized	*Venus, Mars*	**Unipolar** interaction ***(Io, hot exoplanets?)***
Strongly magnetized	*Earth, Jupiter*	**Dipolar** interaction ***(hot exoplanets?)***
	Super-Alfvénic	Sub-Alfvénic

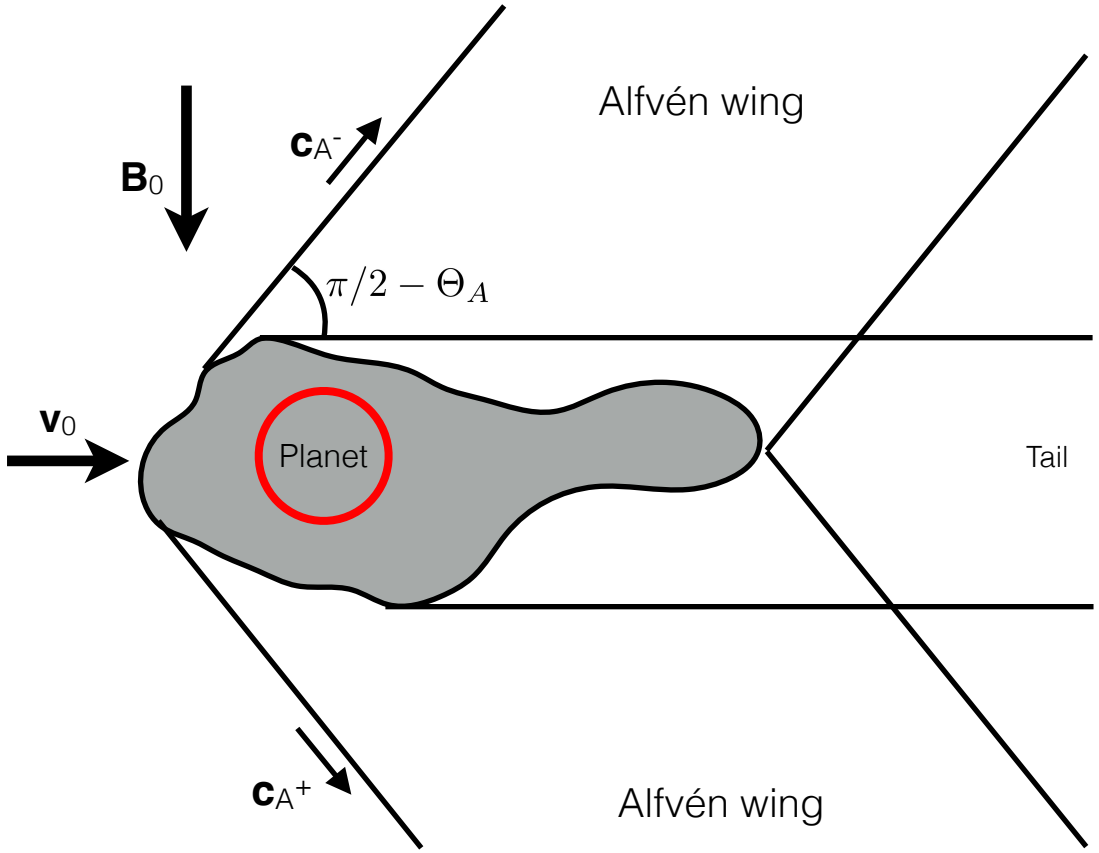
[Zarka 2007]

Super-alfvénic regime: the case of the Earth



The concept of Alfvén wings



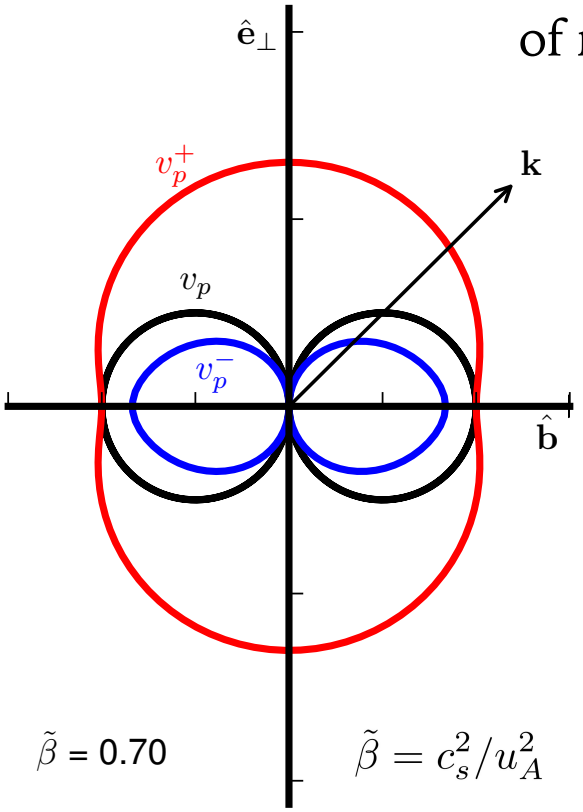


Alfvén wings are the **superposition** of Alfvén waves. In general, all types of magneto-sonic waves are triggered by the interaction between the obstacle and its environment.

[Neubauer 1980]

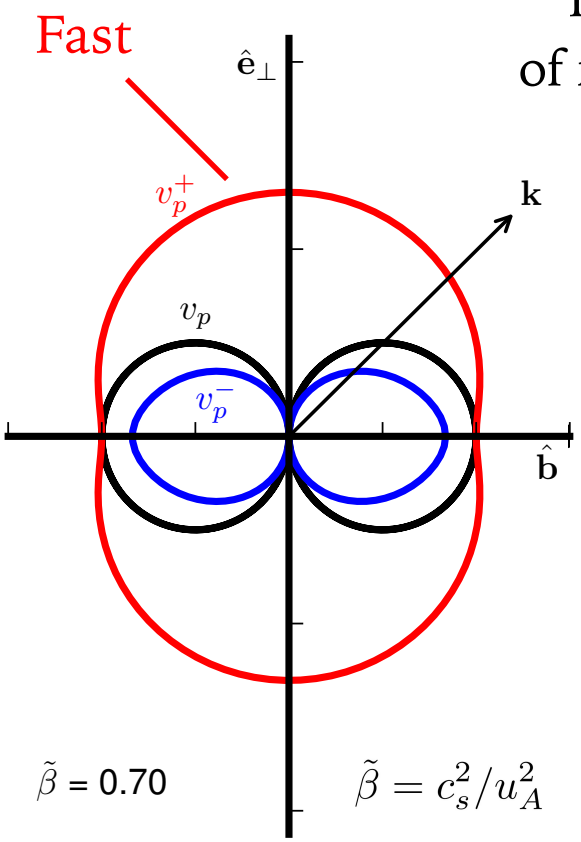
Side note on magneto-sonic waves (I)

Friedrichs diagram
of magnetosonic waves



Phase velocity of magnetosonic waves:
no preferred direction

Side note on magneto-sonic waves (I)



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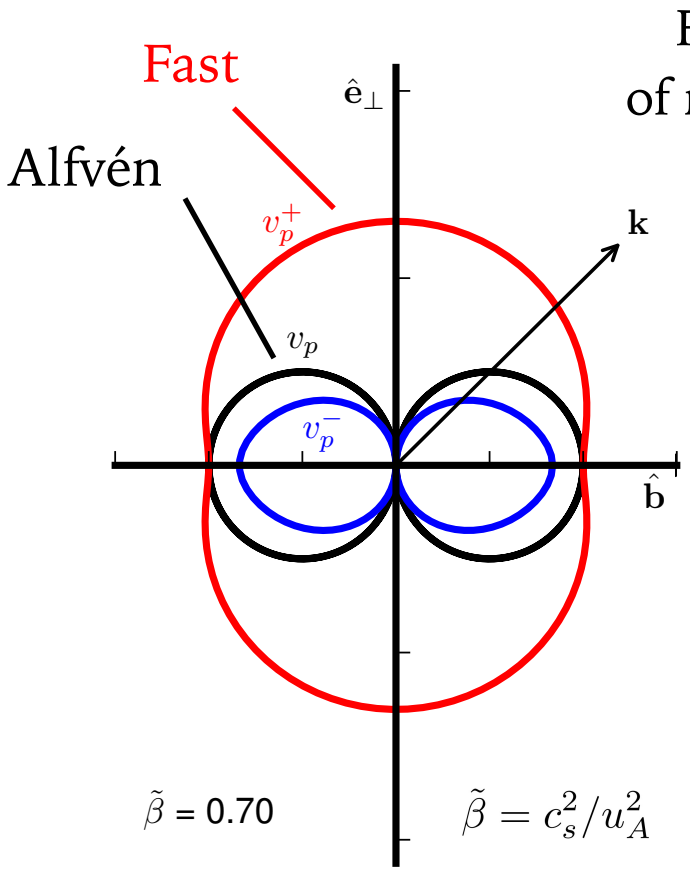

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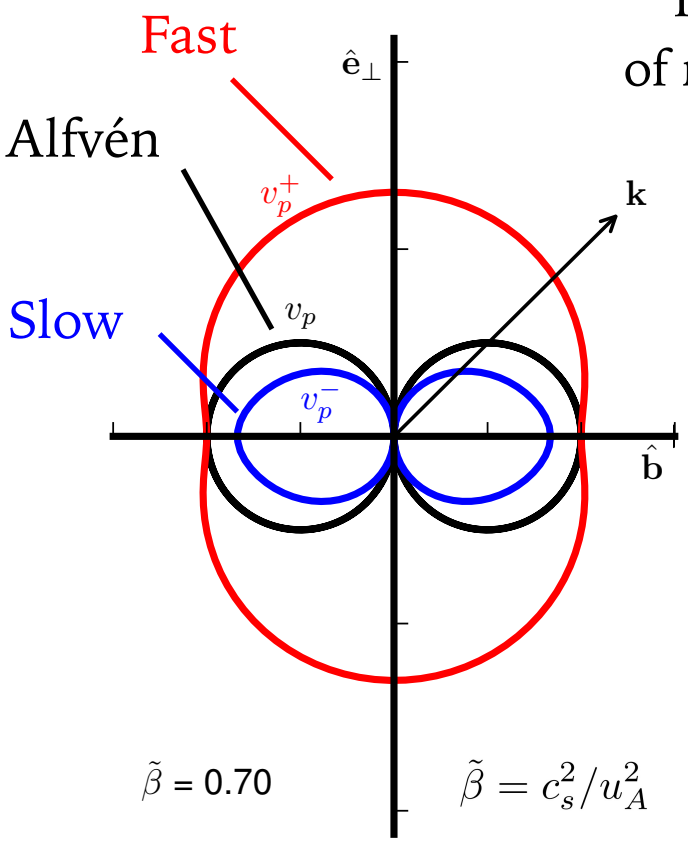

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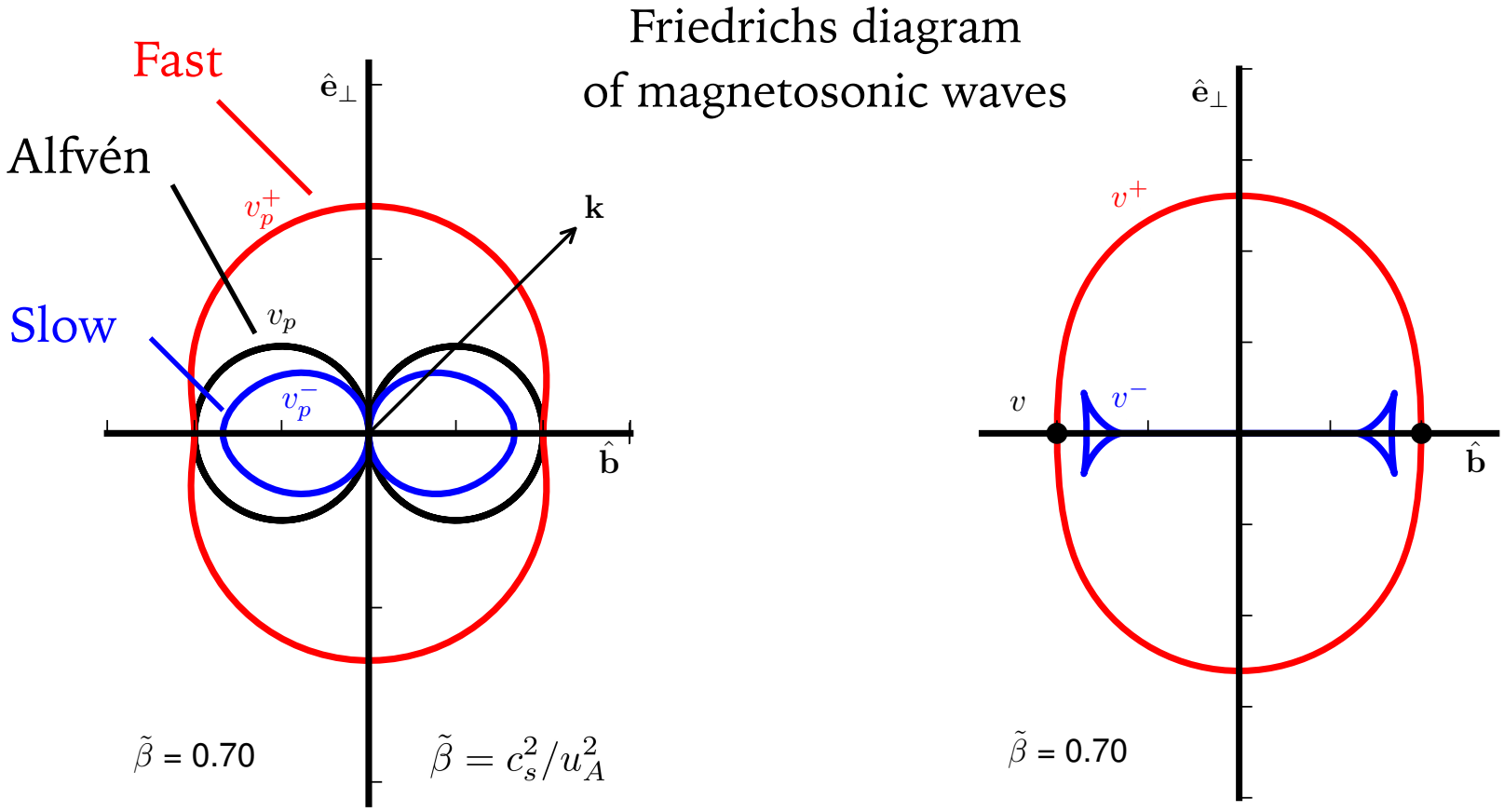
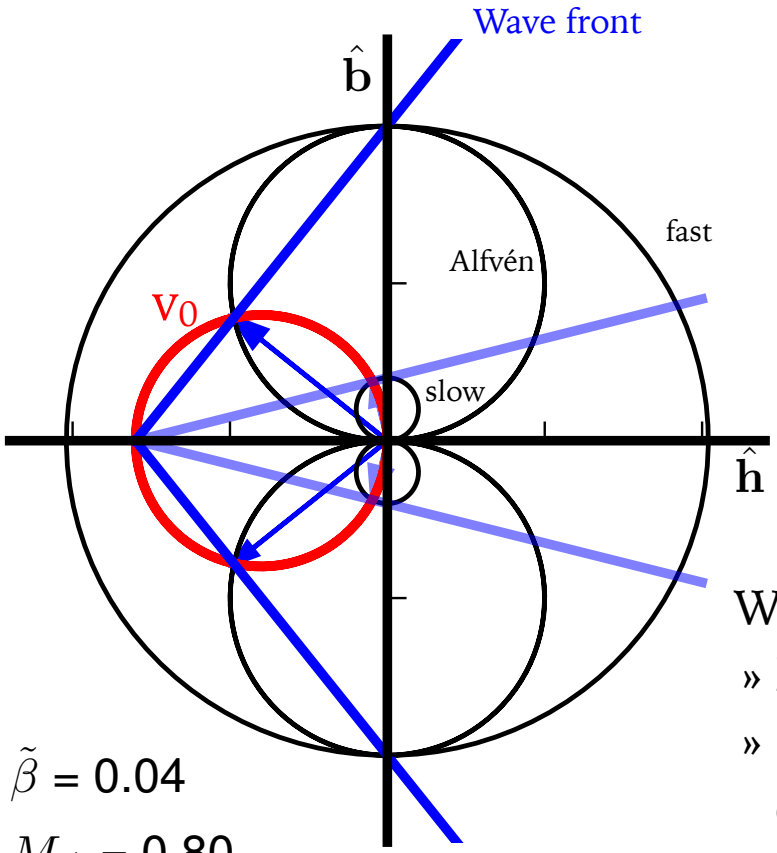


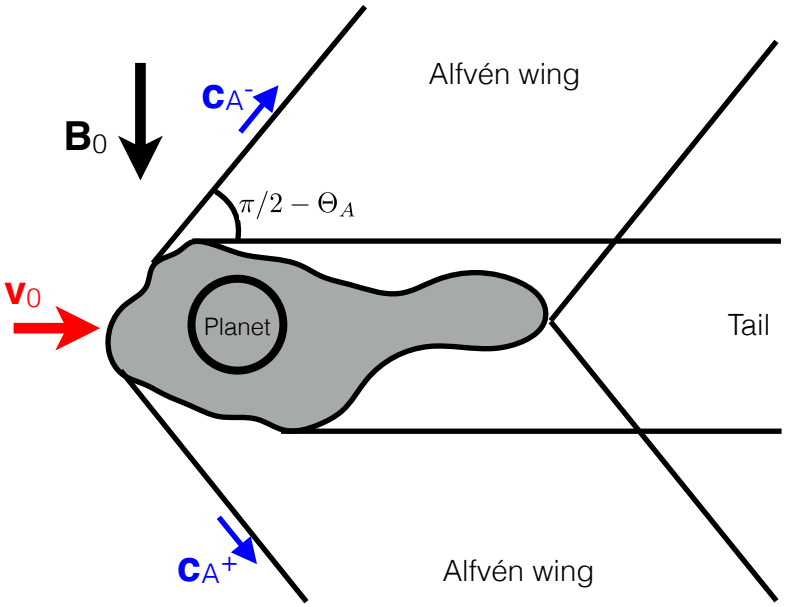
Phase velocity of magnetosonic waves: no preferred direction

Group velocity of magnetosonic waves: the pure Alfvén wave (black dots) is degenerate, energy is always transported along **b**

Side note on magneto-sonic waves (II)

Friedrichs diagram
in the frame where the obstacle is at rest





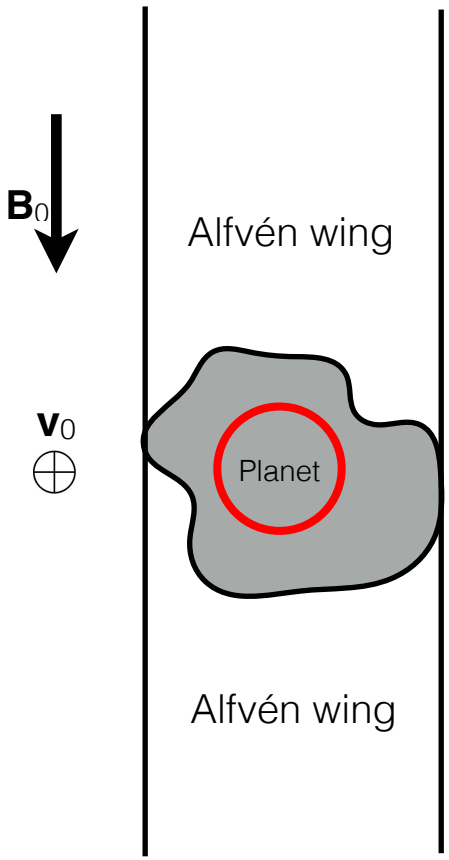
Which waves can actually propagate?

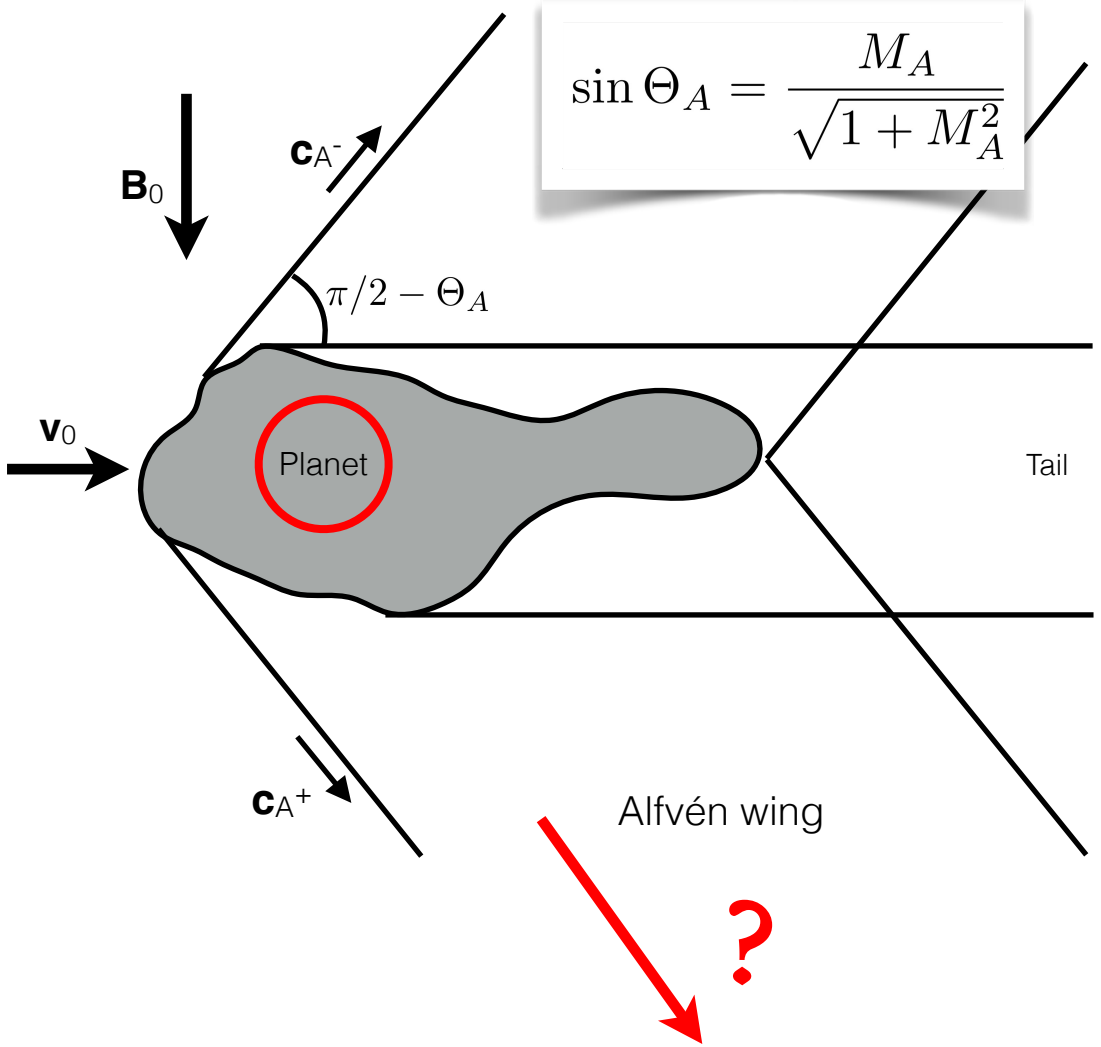
» **Fast magnetosonic**: no intersection ($M_A < 1$)

» **Slow magnetosonic**: the group velocity distribution dilutes the wave energy over a large volume far from the obstacle

» **Alfvén**: propagate along $\mathbf{c}_A^{\pm} = \mathbf{v}_0 \pm \mathbf{u}_A$

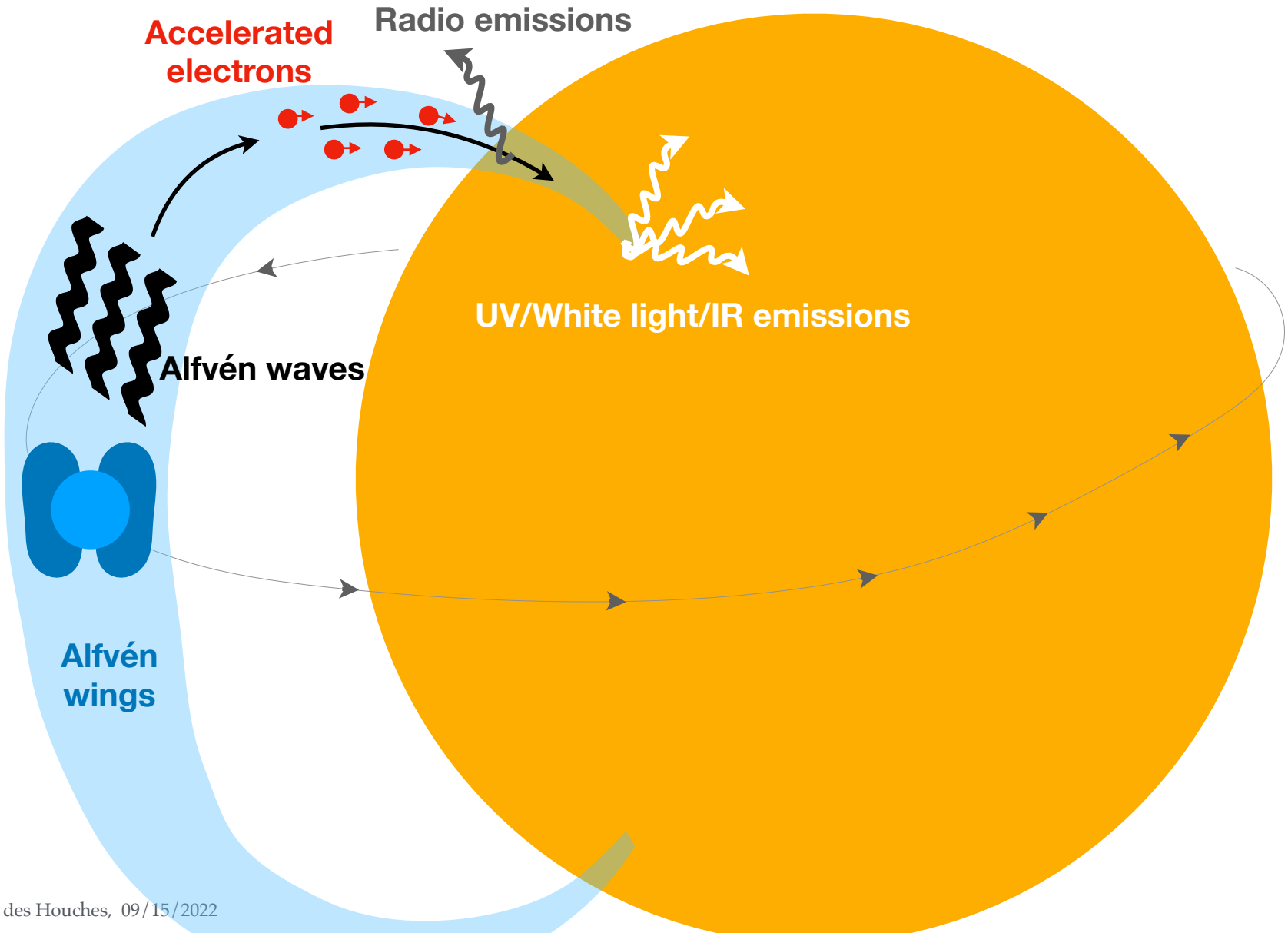
The concept of Alfvén wings



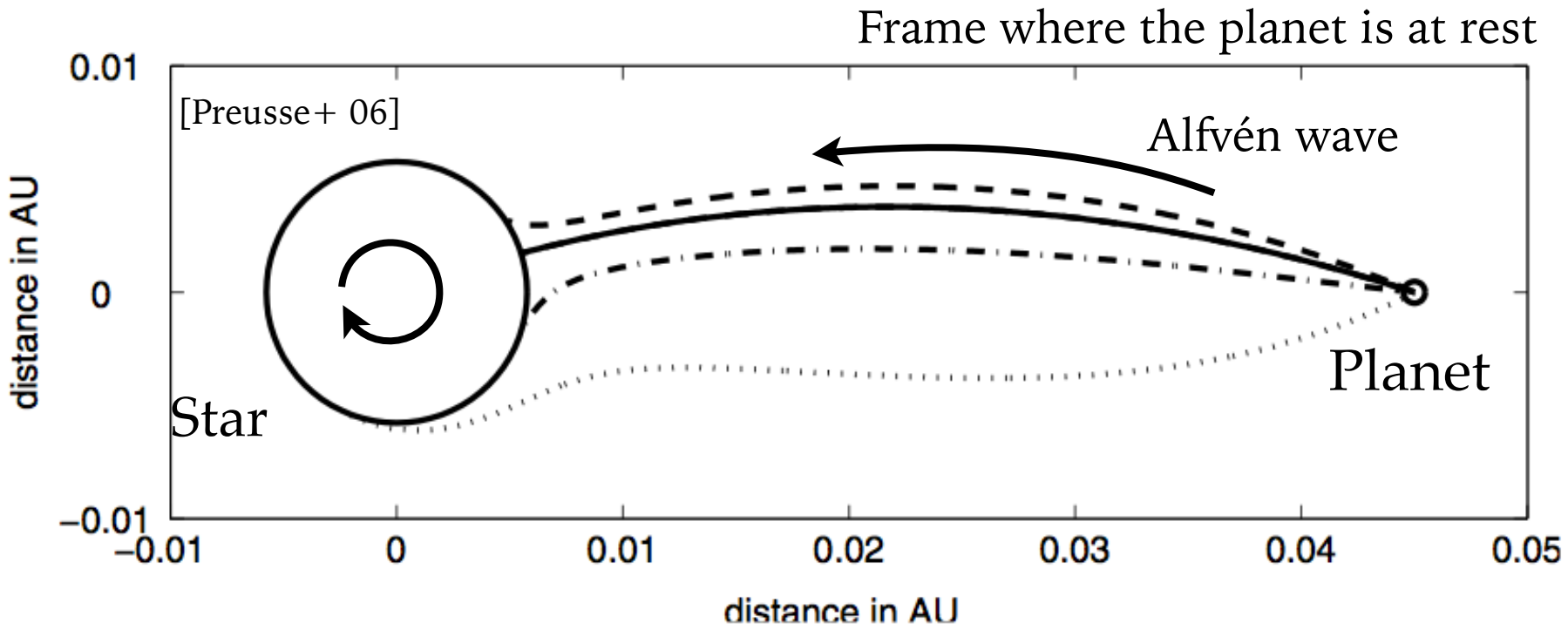


$$\sin\Theta_A = \frac{M_A}{\sqrt{1+M_A^2}}$$

The concept of Alfvén wings: a global picture



Sub-alfvénic regime: magnetic connectivity



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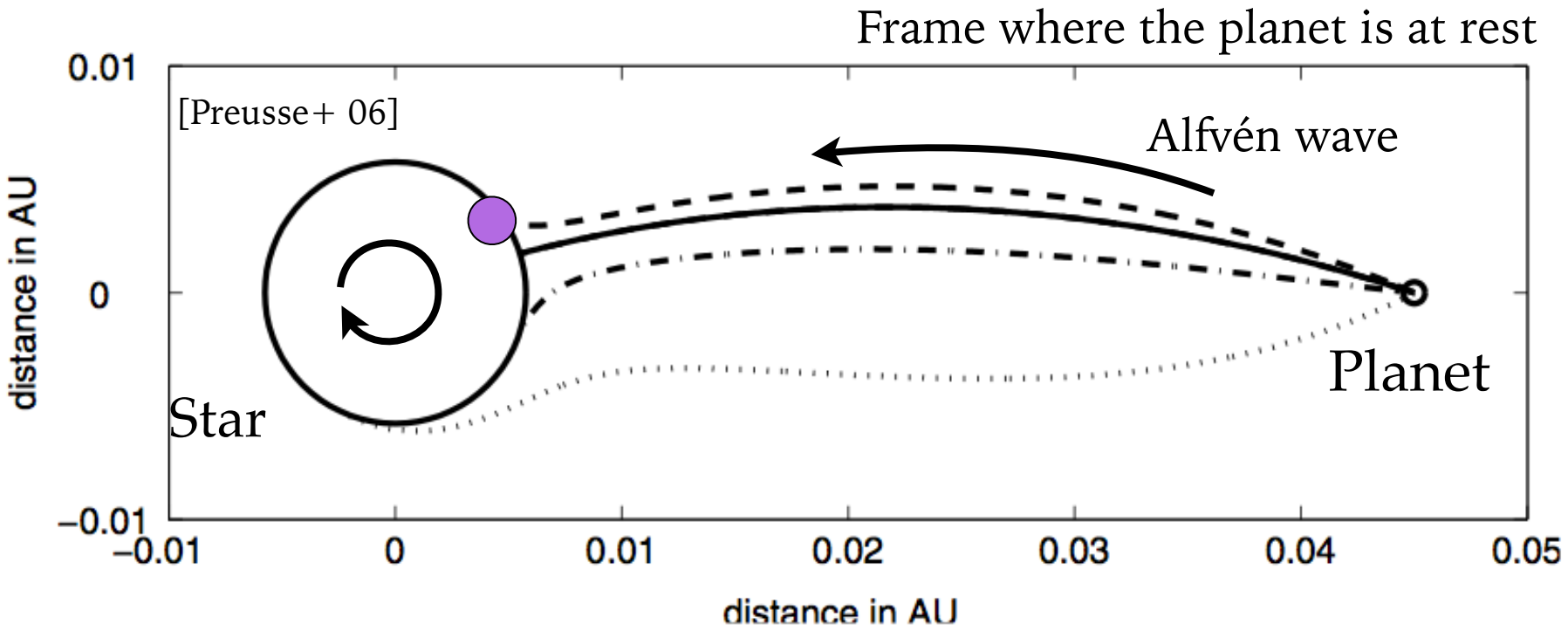
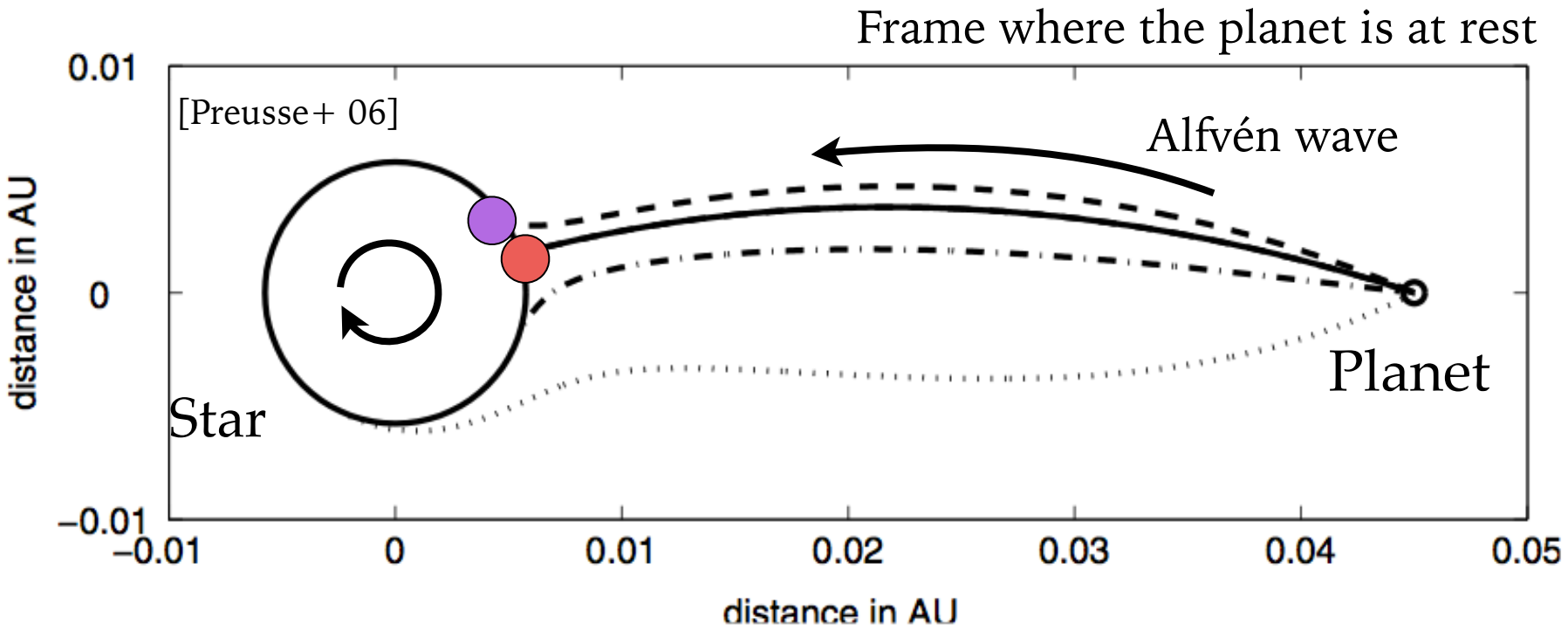


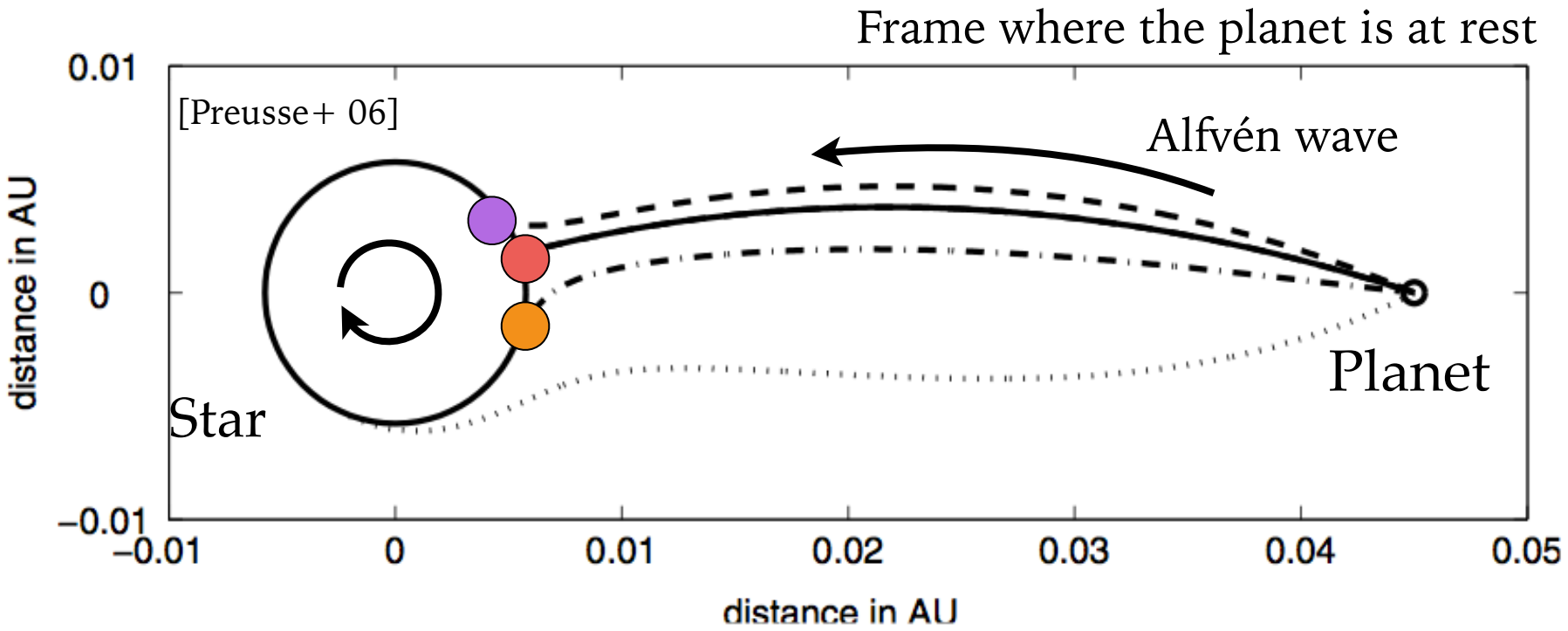
- P_{orb} = 12 days

Sub-alfvénic regime: magnetic connectivity



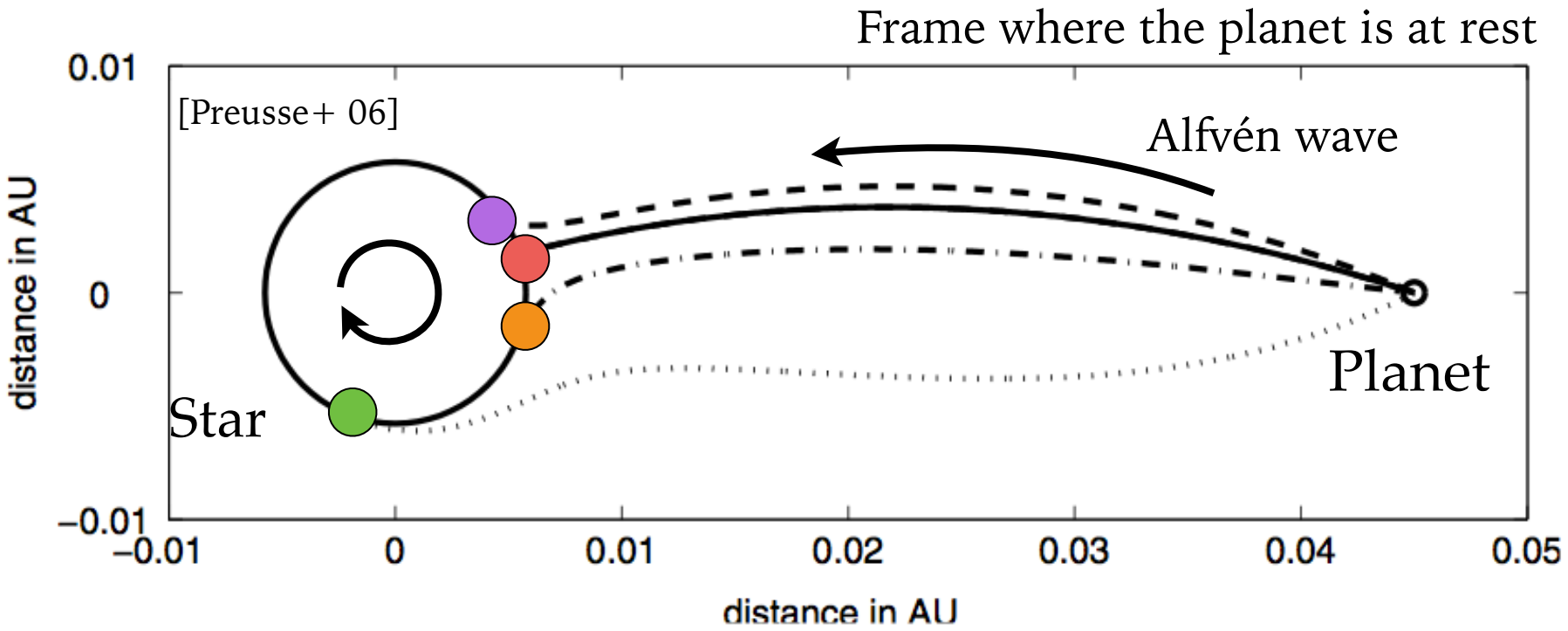
- P_{orb} = 12 days
- P_{orb} = 9 days

Sub-alfvénic regime: magnetic connectivity



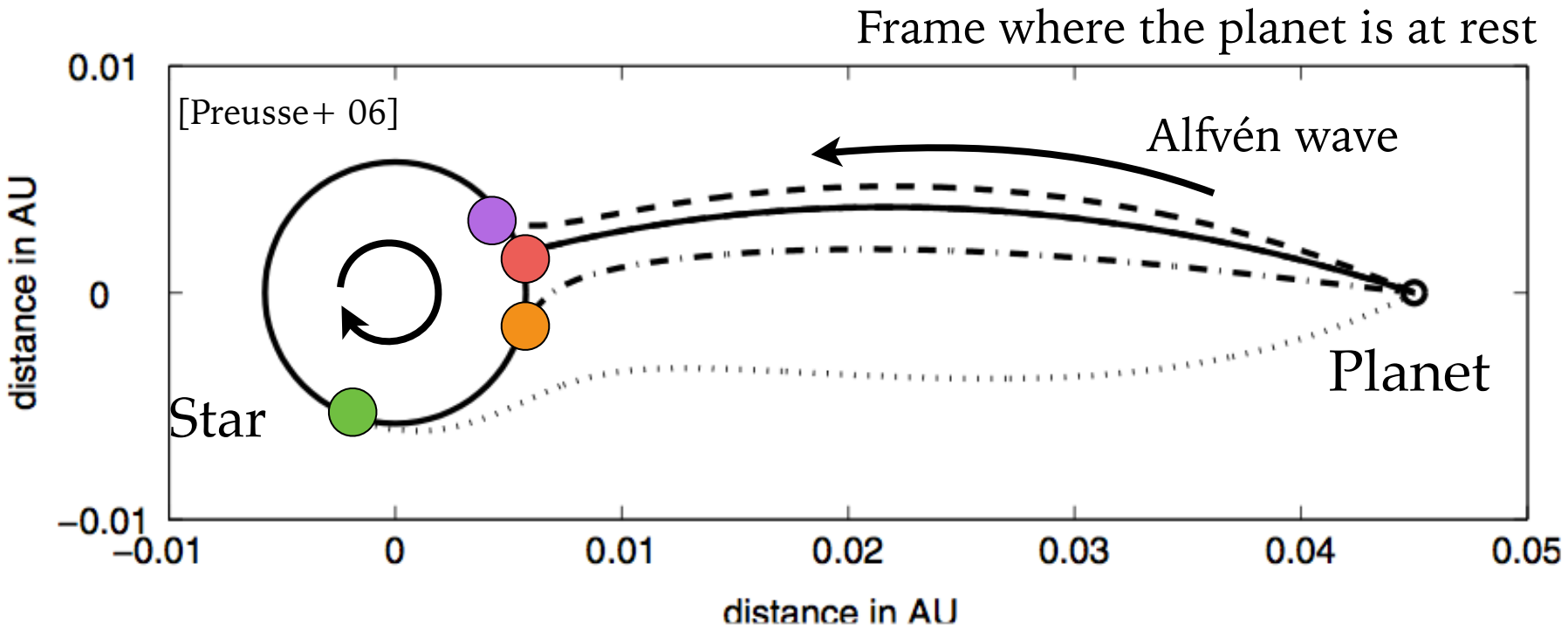
- P_{orb} = 12 days
- P_{orb} = 9 days
- P_{orb} = 6 days

Sub-alfvénic regime: magnetic connectivity



- P_{orb} = 12 days
- P_{orb} = 9 days
- P_{orb} = 6 days
- P_{orb} = 3 days

Sub-alfvénic regime: magnetic connectivity



- P_{orb} = 12 days
- P_{orb} = 9 days
- P_{orb} = 6 days
- P_{orb} = 3 days

» The impact point can be dephased ($\Delta\varphi$)

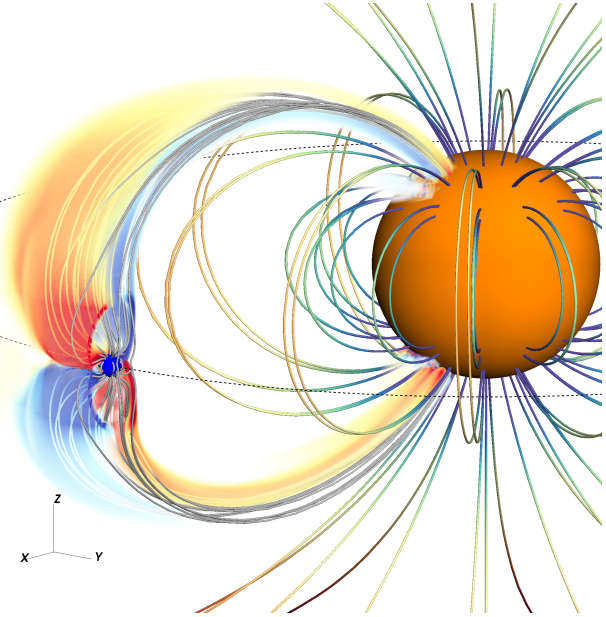
» $\Delta\varphi$ strongly depends on the **star**

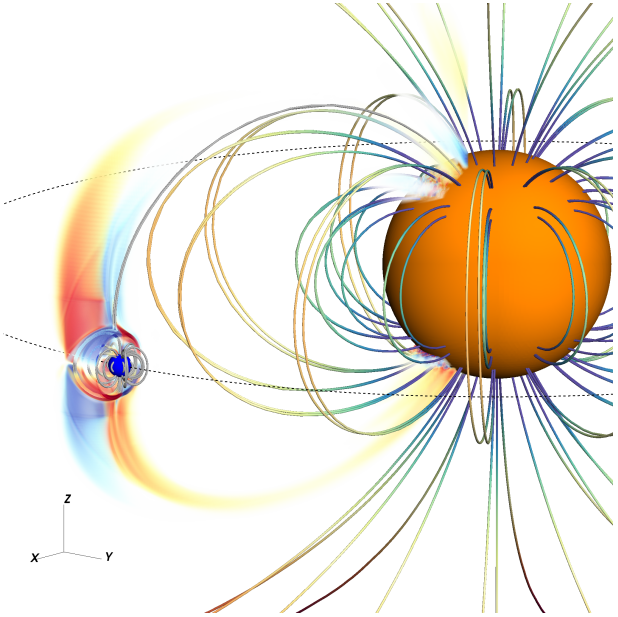
- » $B_\star$ (amplitude, topology)
- » T_{corona} & stellar wind
- » Rotation

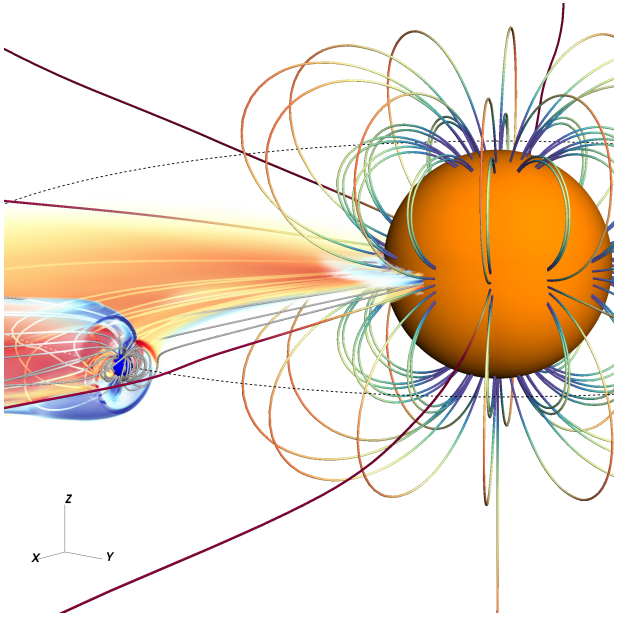
Towards complex magnetic topologies

Stellar dipole

Stellar quadrupole







Two strong wings

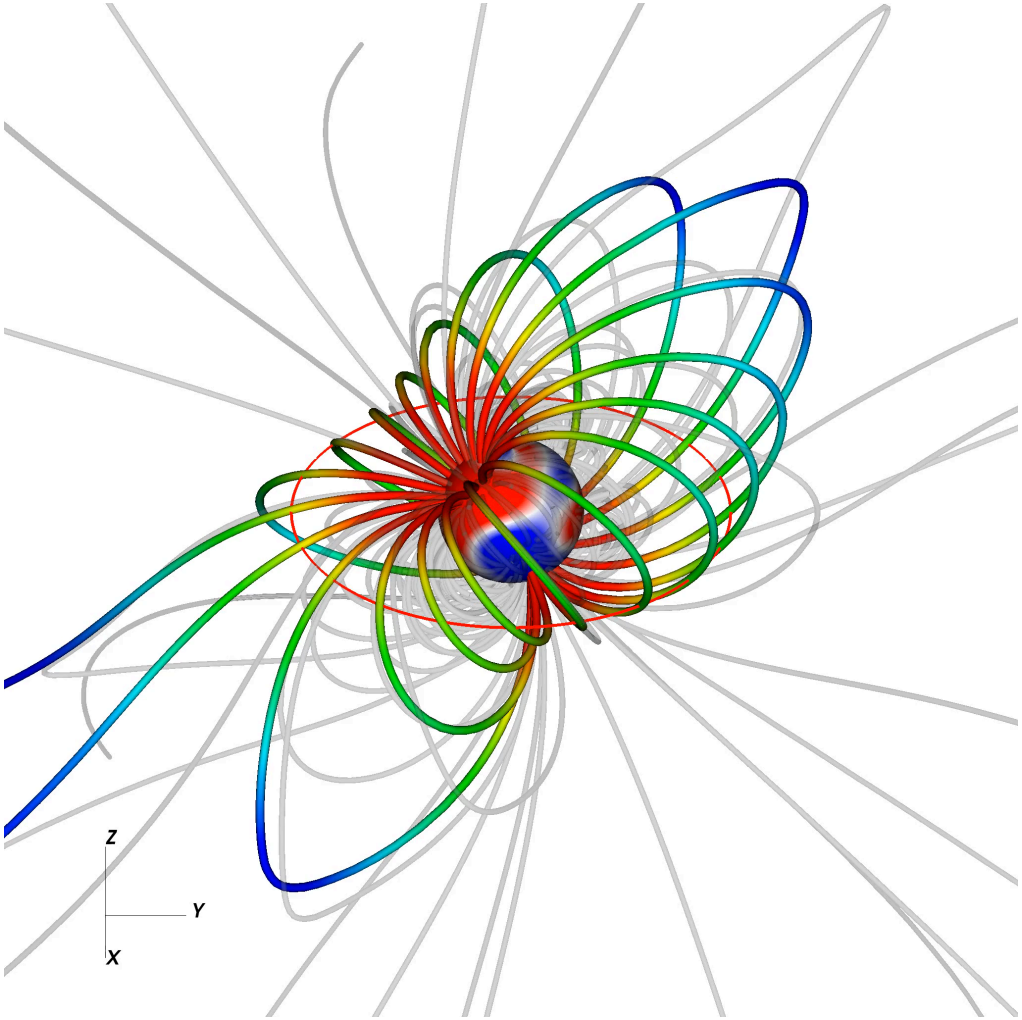
Two weak wings

One strong wing

The interaction footpoint is at a given (latitude, longitude) position

The interaction footpoint is a longitudinal band at the equator

Towards realistic complex magnetic topologies: Kepler-78



Kepler-78 system

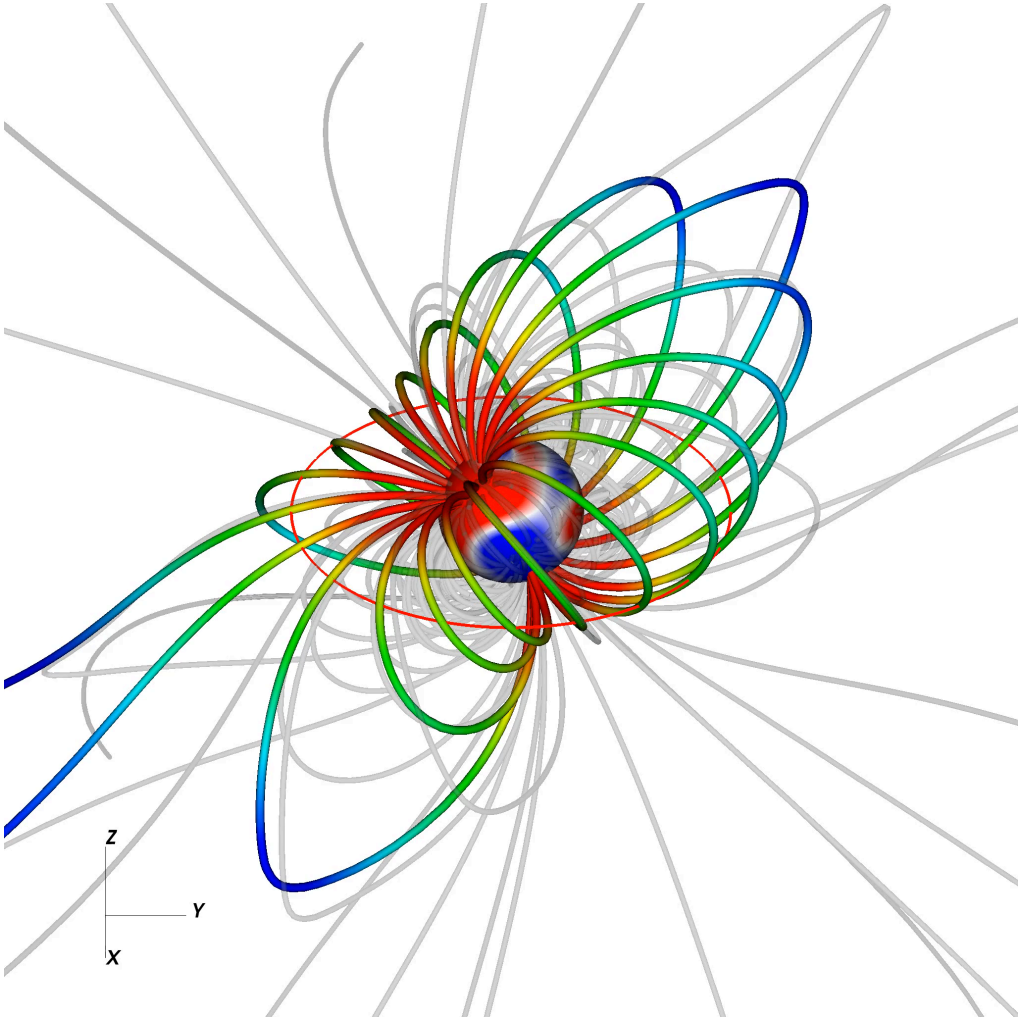
Stellar characteristics

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

Planet characteristics

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

Towards realistic complex magnetic topologies: Kepler-78



Kepler-78 system

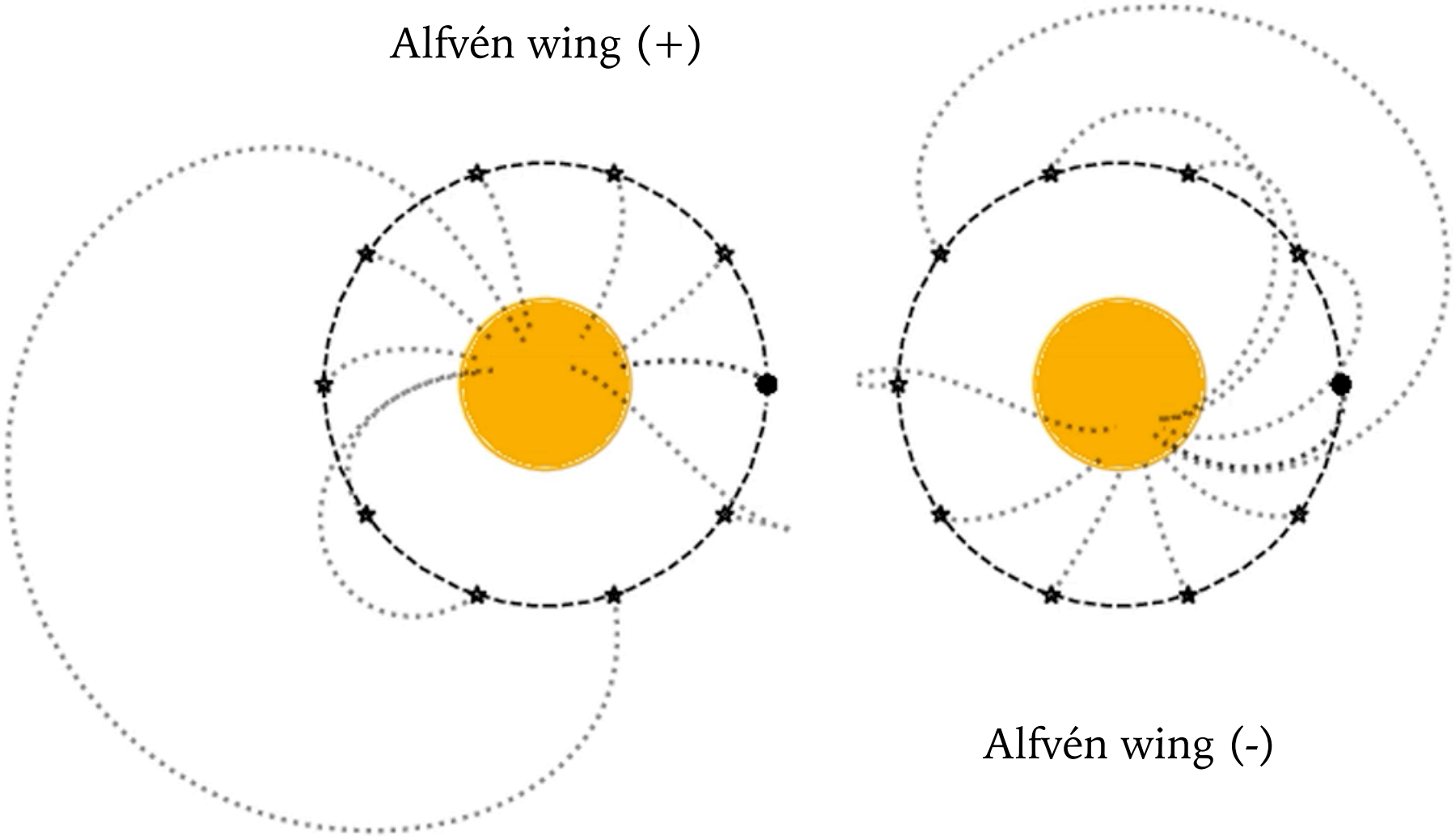
Stellar characteristics

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

Planet characteristics

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

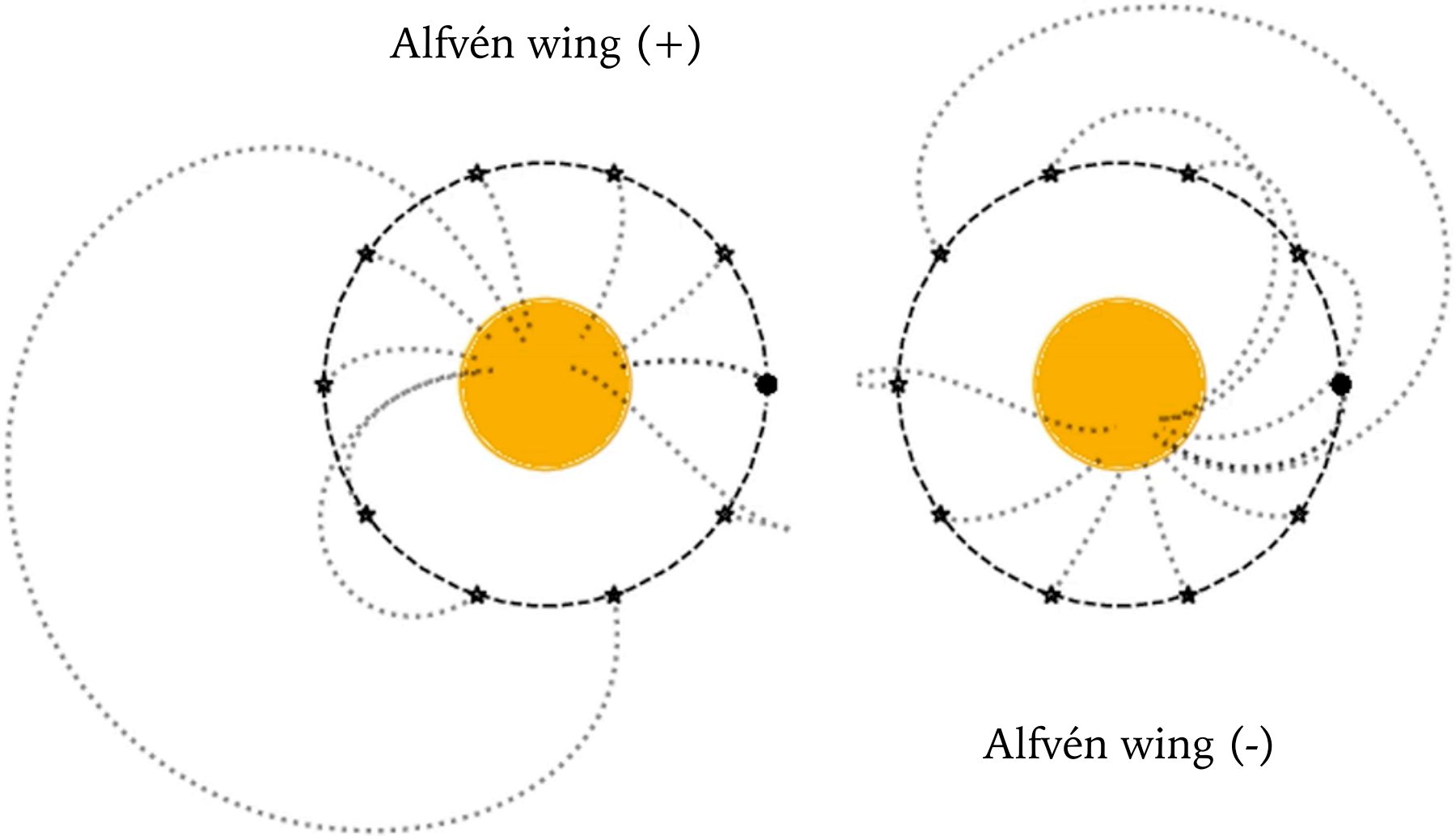
Towards realistic complex magnetic topologies: Kepler-78



View from top

[Strugarek+ 19]

Towards realistic complex magnetic topologies: Kepler-78



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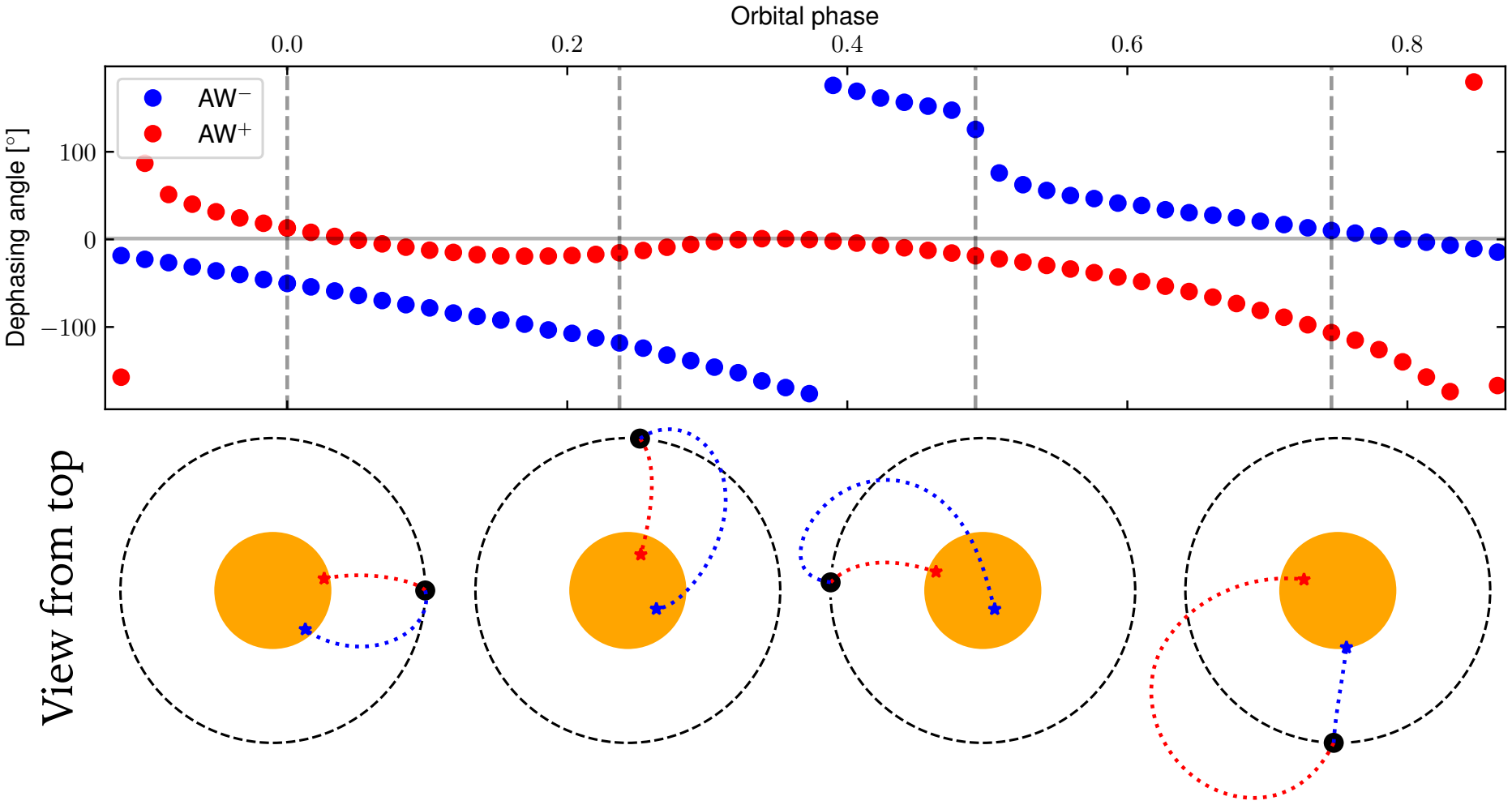
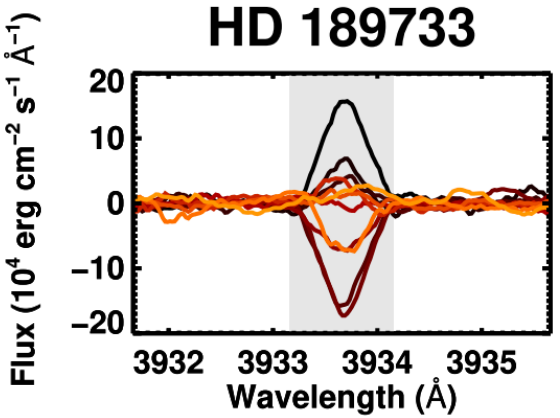
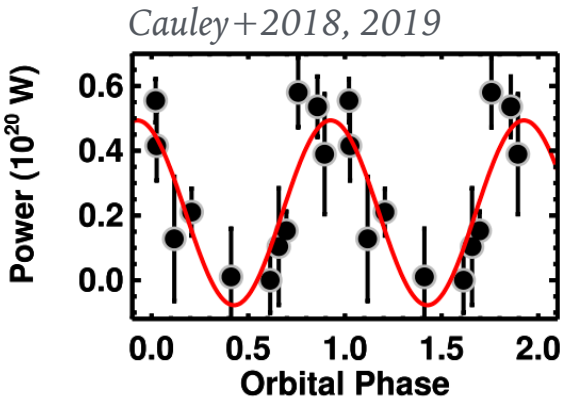


[Strugarek+ 19]

Possible star-planet interaction in HD 189733



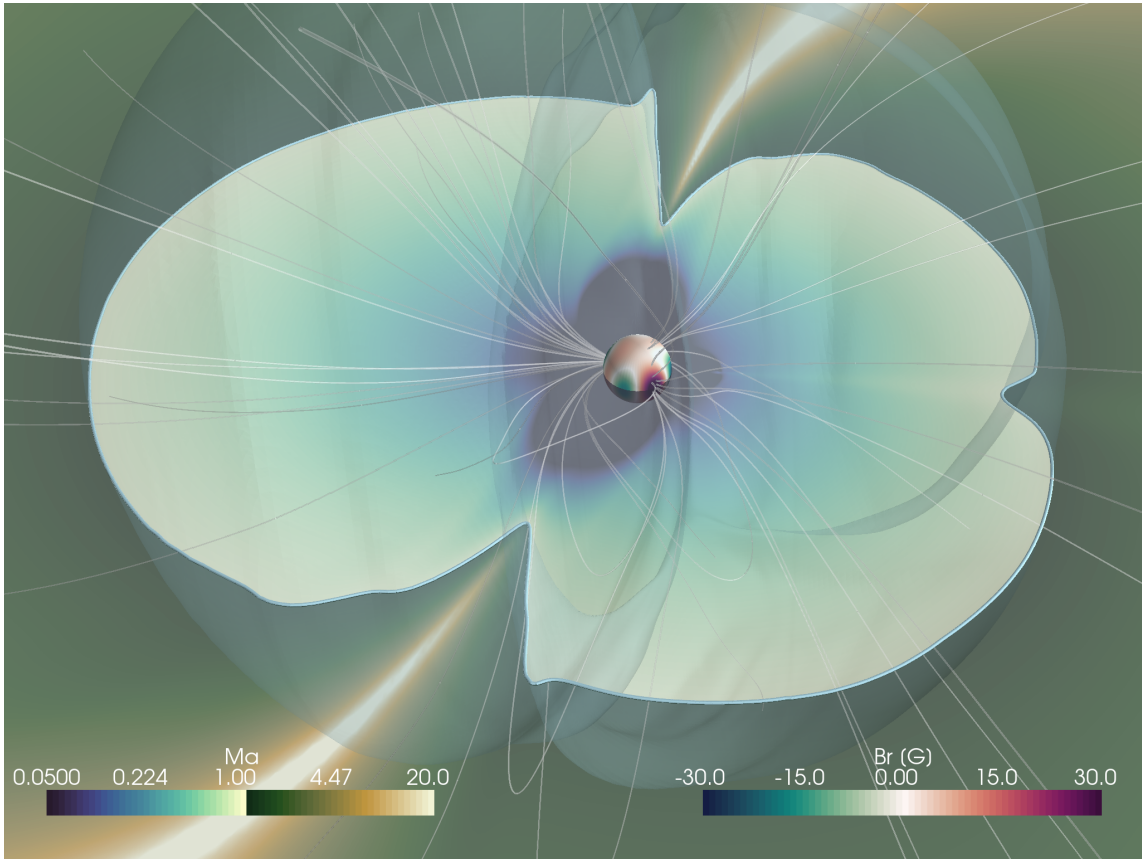
A signal in the Ca II H&K bands of the host star was observed to be correlated with the orbital phase of the hot exoplanet at **1 epoch out of 6 epochs studied** (Cauley+ 2018)



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

Can we test this?

Detailed modelling of HD 189733, August 2013



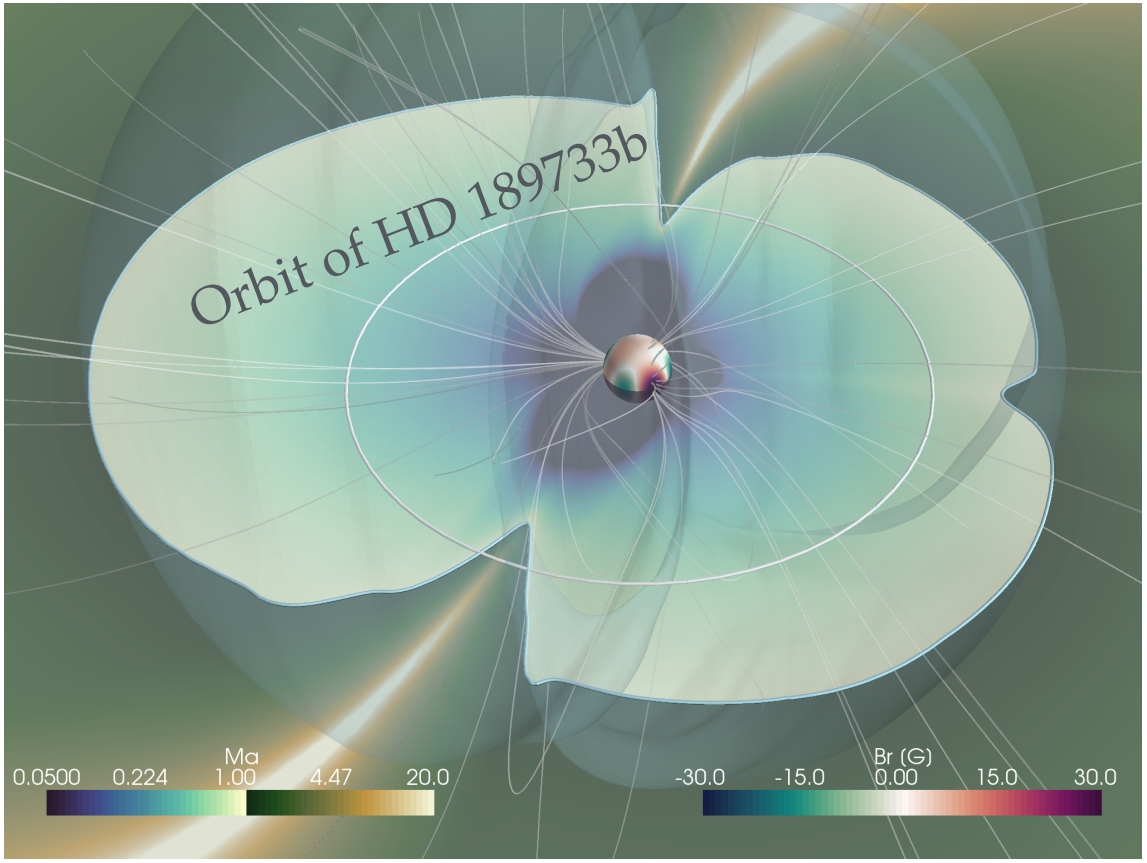
[Strugarek+ 22]

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

Detailed modelling of HD 189733, August 2013



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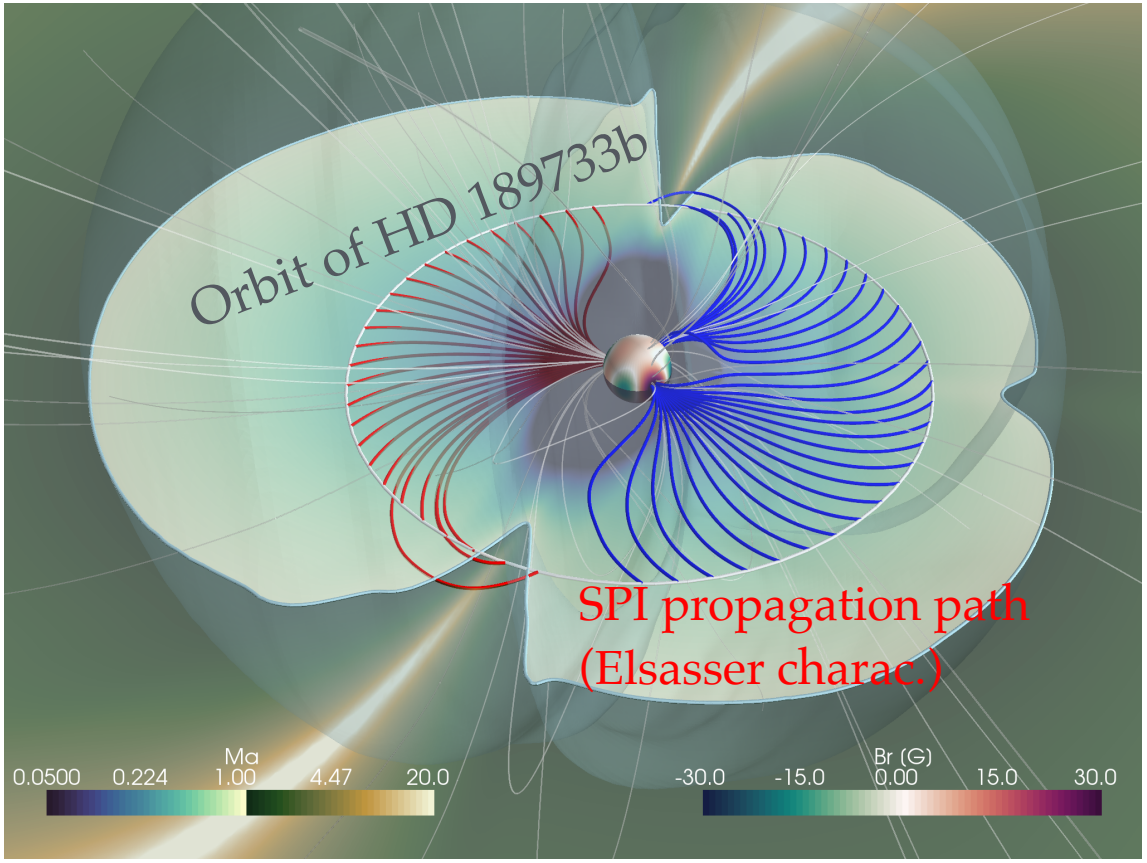

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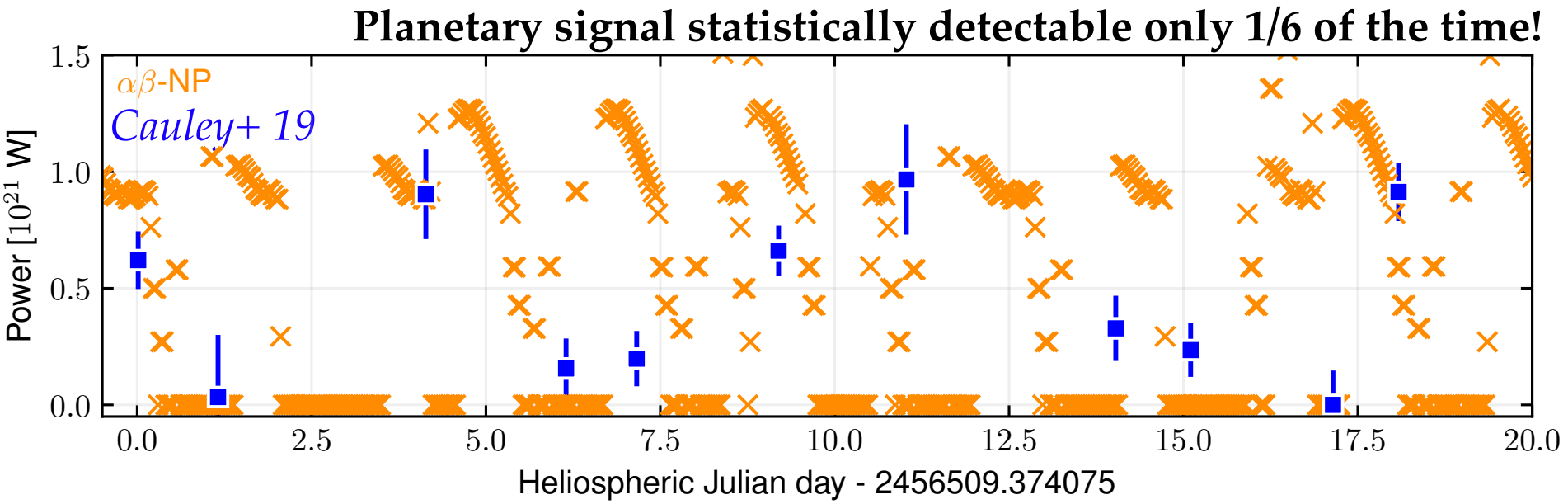

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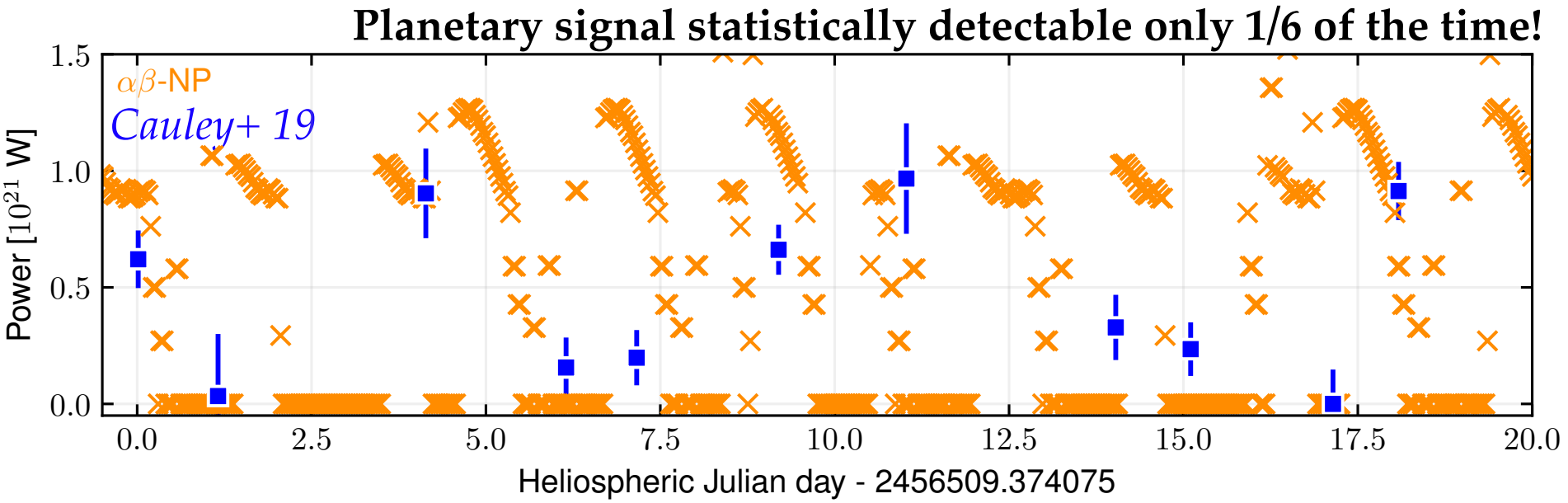
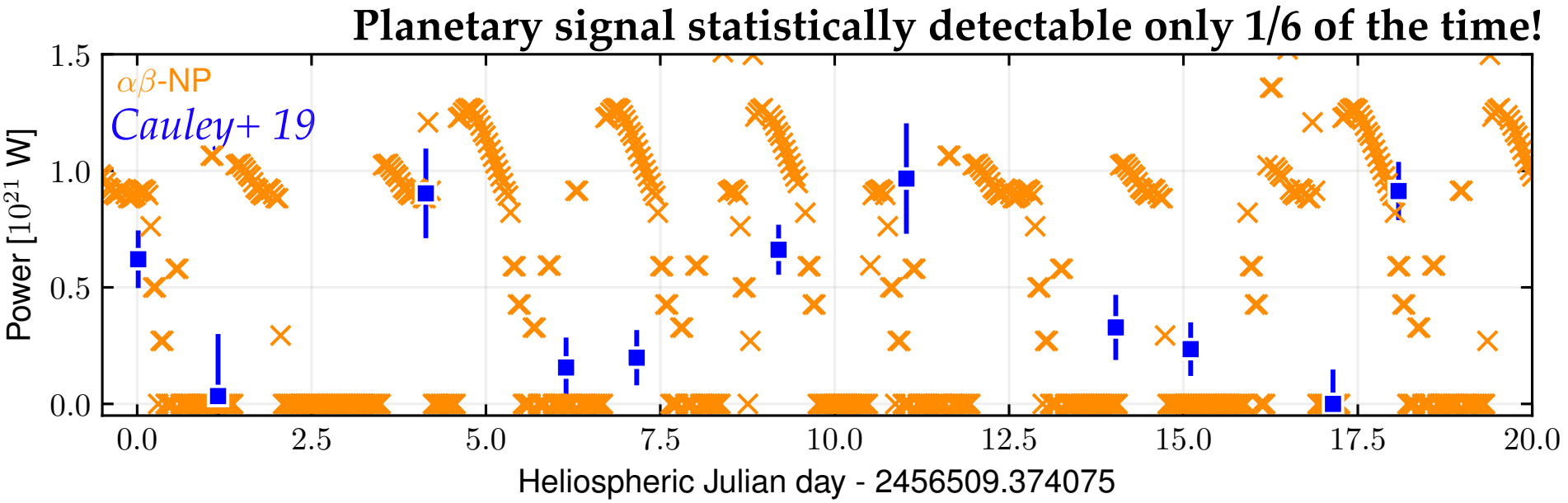


Only the stretch-and-break mechanism provides enough power to explain the level of stellar chromospheric emission

[Strugarek+ 22]

Detailed modelling of HD 189733



Only the stretch-and-break mechanism provides enough power to explain the level of stellar chromospheric emission

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

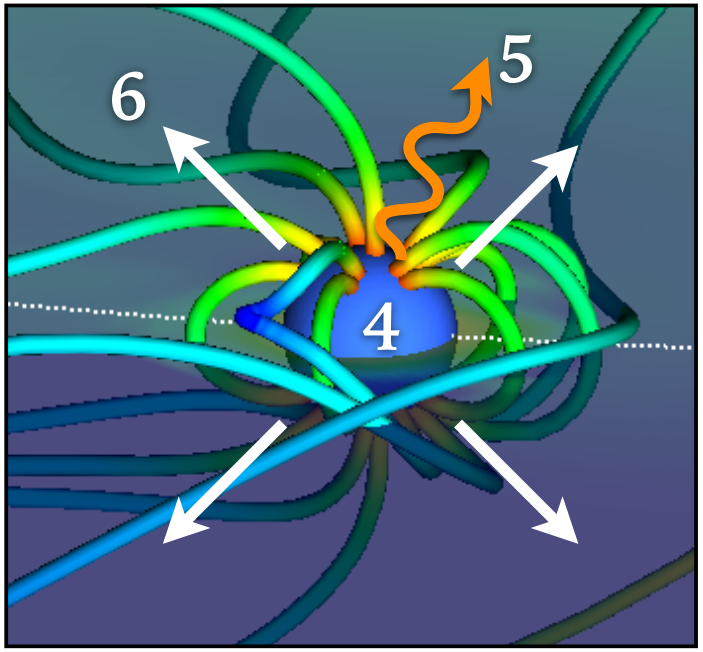
[Strugarek+ 22]

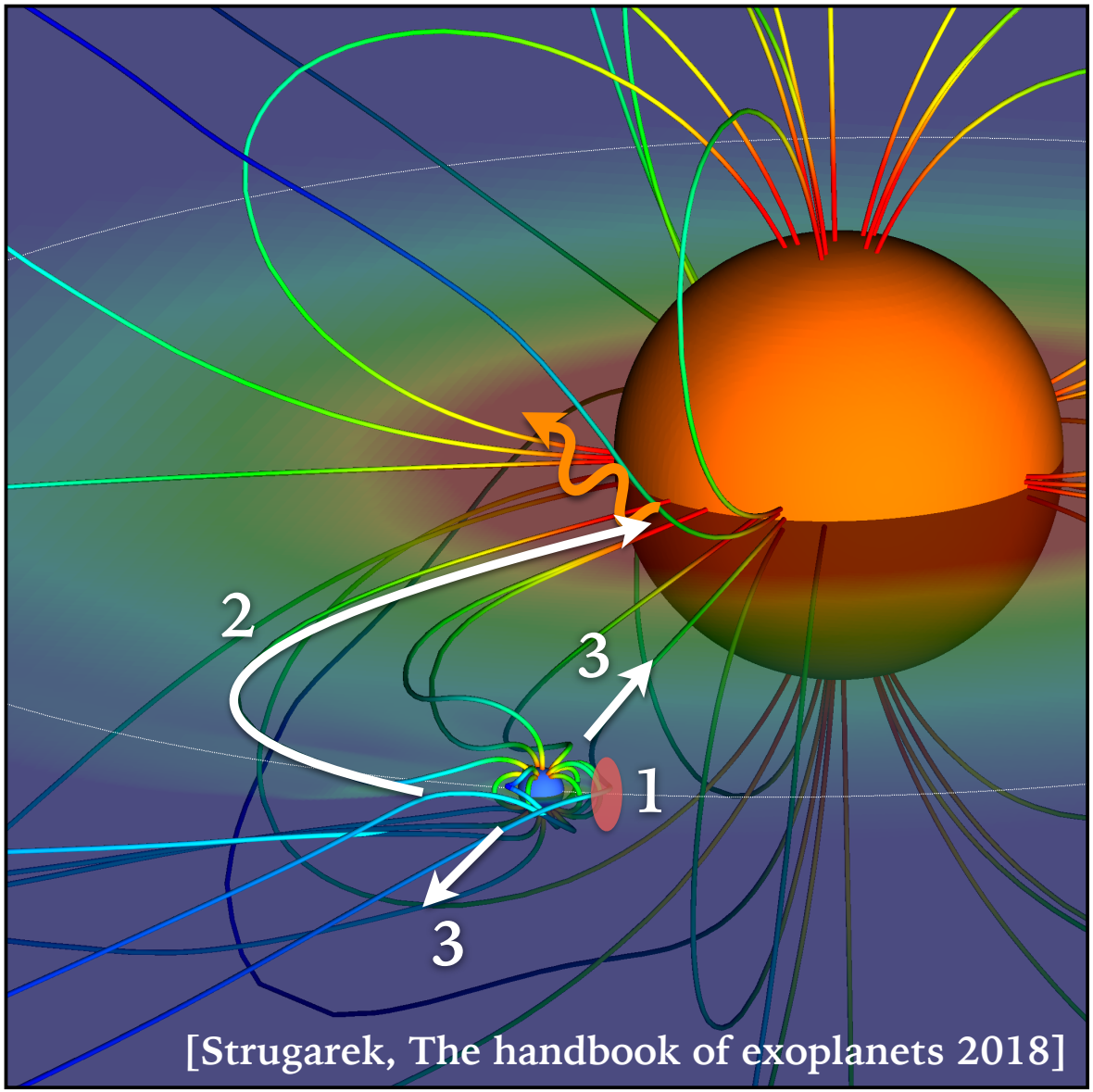
A few points to remember about star-planet magnetic interactions

- Any tracer can be **strongly dephased** from the orbital phase
- It is in general not necessarily directly correlated by the orbital motion : its temporal variability originates from the convolution between the
  - Orbital period (**observed**)
  - Alfvén wave travel time (**requires a wind/corona model**)
  - Stellar rotation period (**observed**)
- It is generally variable on **short timescales** (inhomogeneities along the orbital path) and **long timescales** (stellar magnetic cycle/variability)
- It is **systematically awaited** for planets close to their host

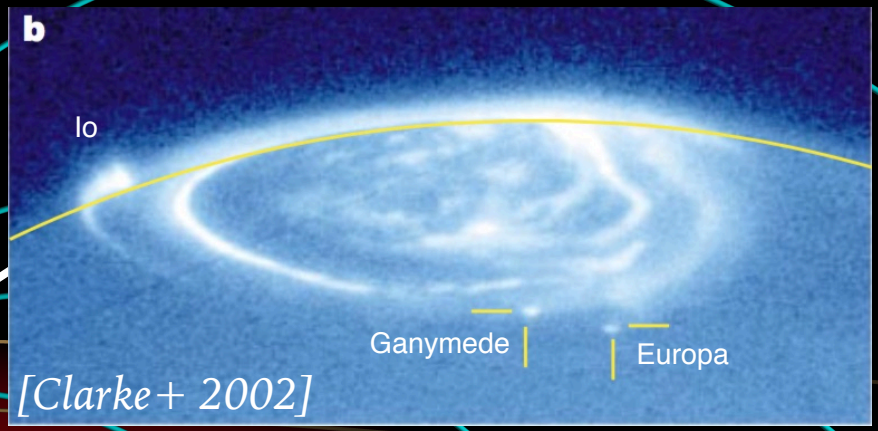
Major effects of star-planet magnetic interactions

1. Shocks & geometry
2. Energy channeling
3. Planet migration
4. Planet heating
5. Planet emissions
6. Atmospheric escape





Alfvén wings in the solar system : the Jovian case



Energetics of magnetic interaction

Kinetic energy flux

$$P_c = \left(\frac{1}{2}\rho v^2\right) v A_{\rm obst}$$

Poynting flux intercepted by obstacle

$$P_m = \frac{B_\perp^2}{2\mu_0} v A_{\rm obst}$$

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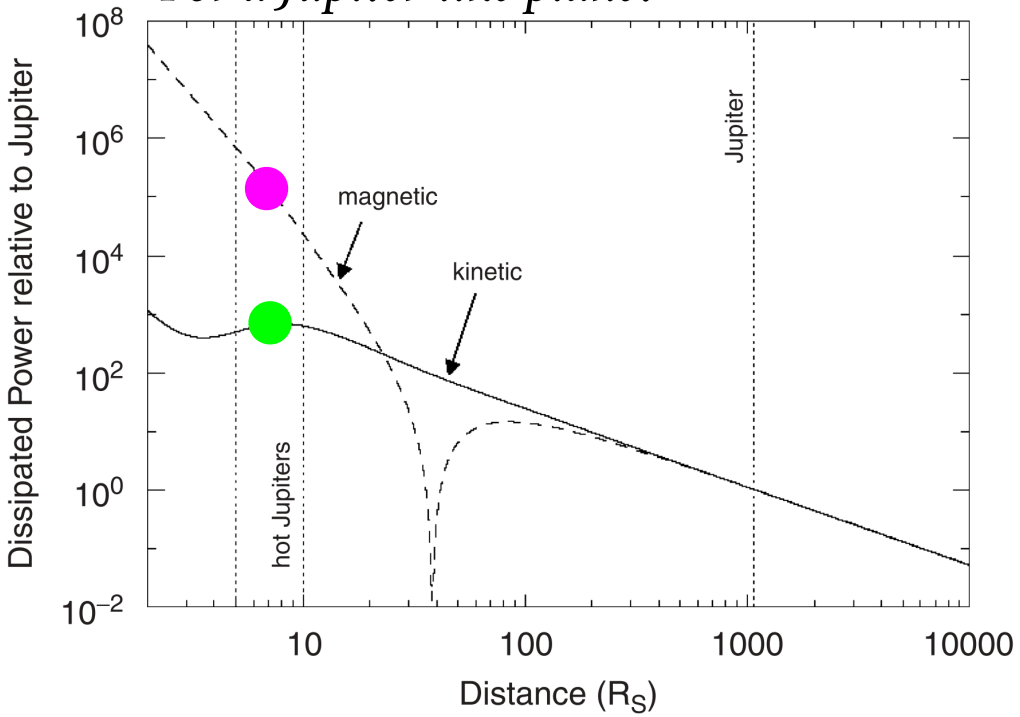
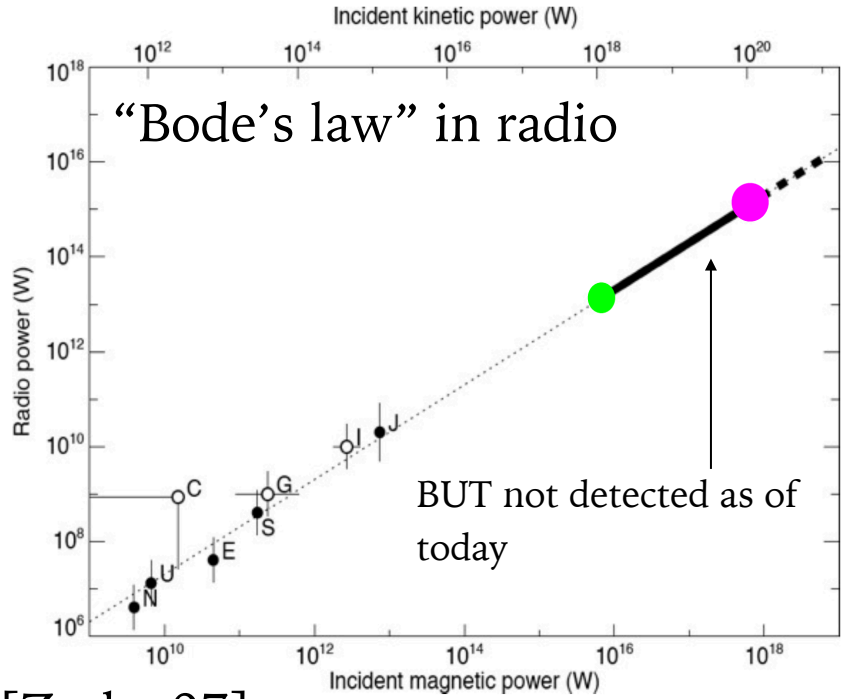
For a Jupiter-like planet

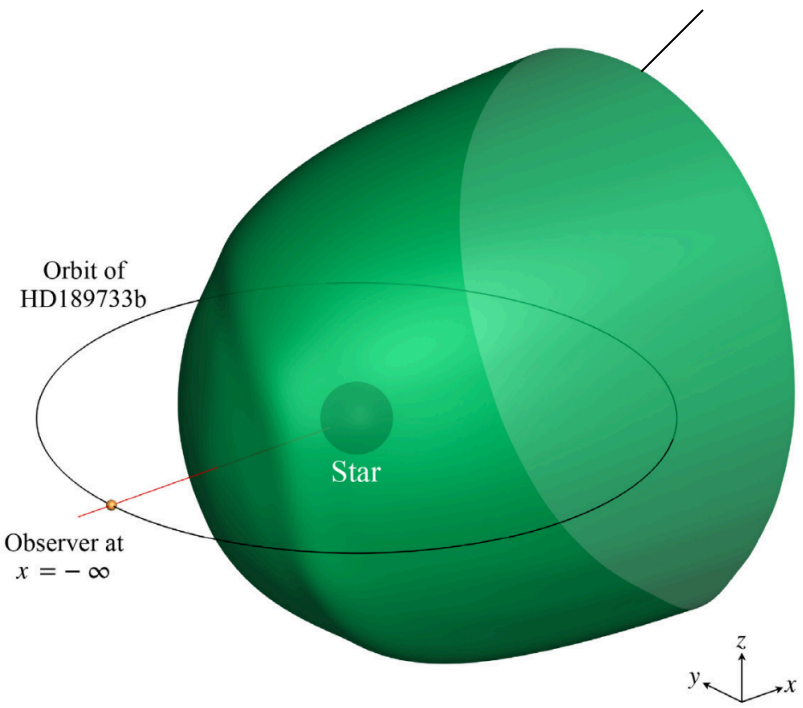




[Zarka 07]

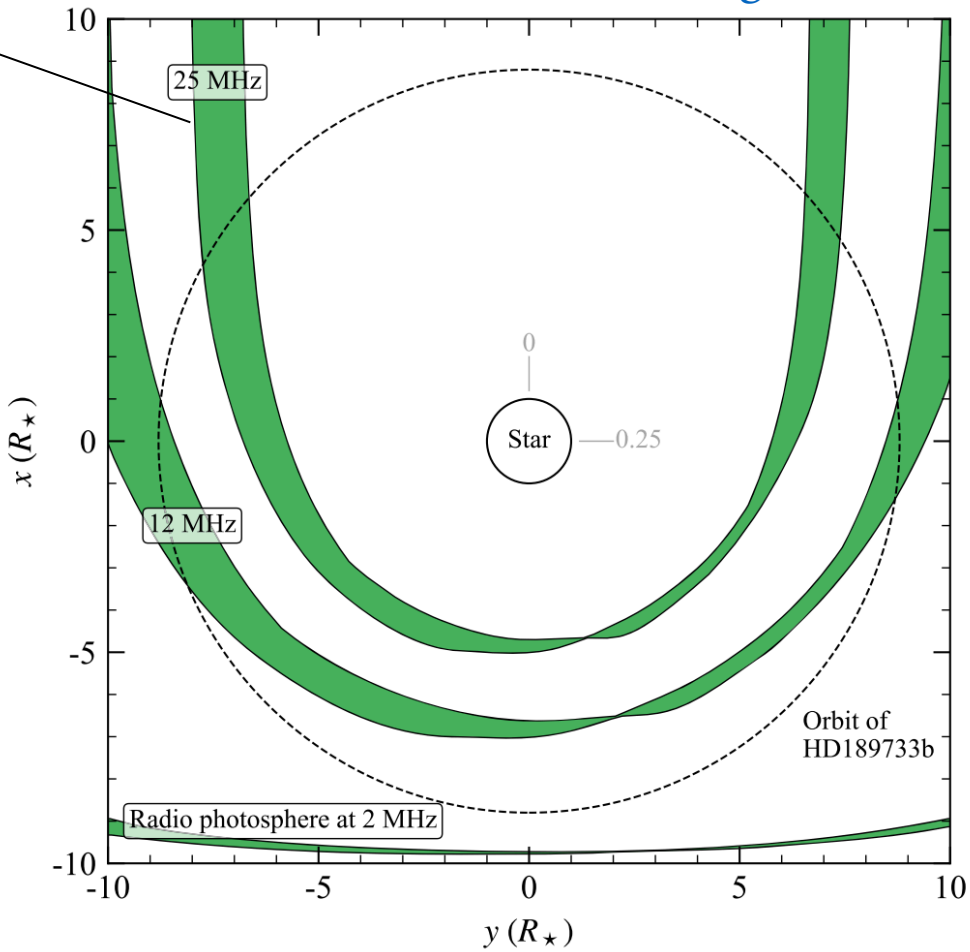
Why is it so hard to detect radio emissions from exoplanets?

Radio 'photosphere' @ 25 MHz



HD 189733

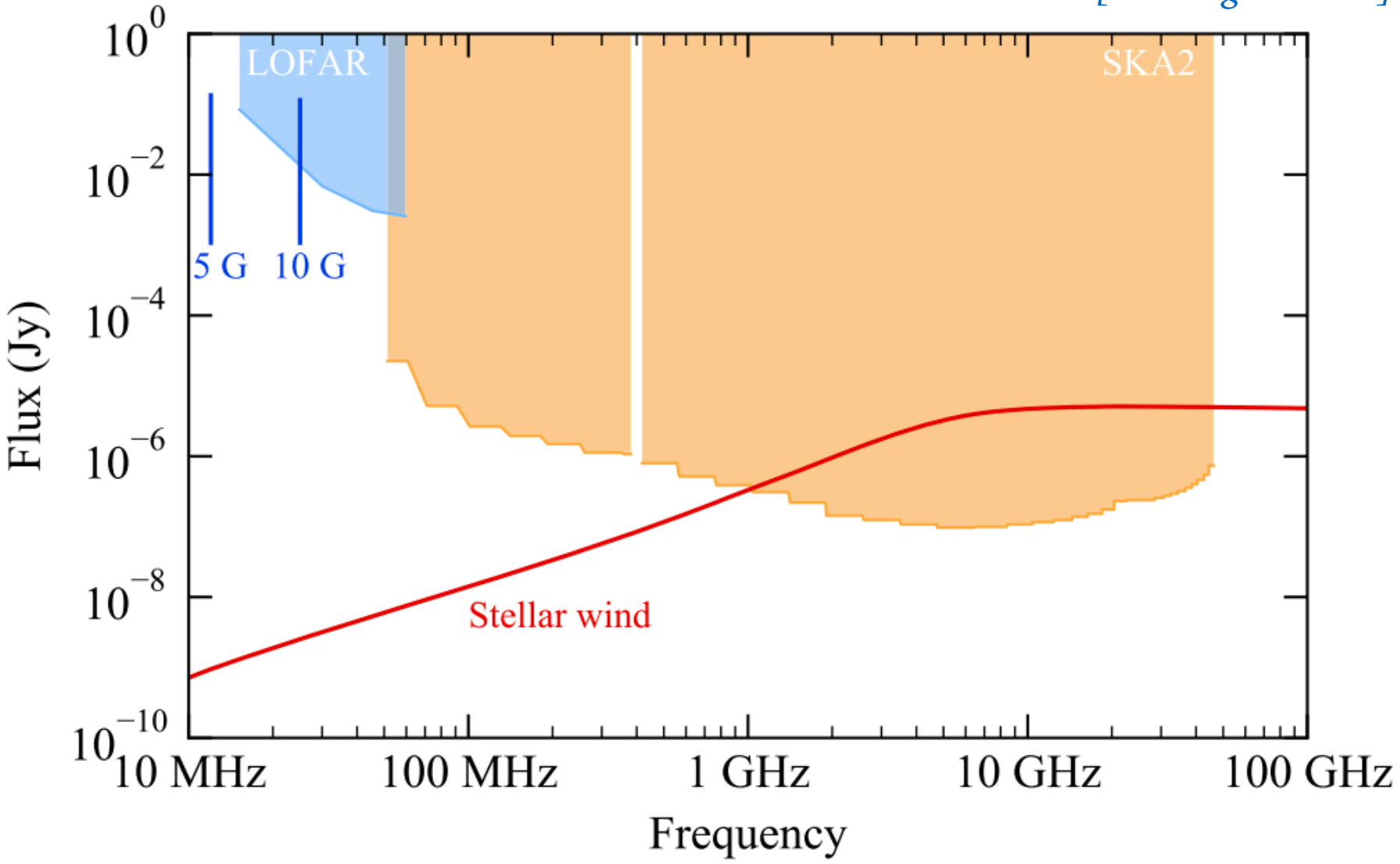
[Kavanagh+ 2019]



[see also Nichols & Milan 2016]

Why is it so hard to detect radio emissions from exoplanets?

[Kavanagh+ 2019]



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Poynting flux intercepted by obstacle

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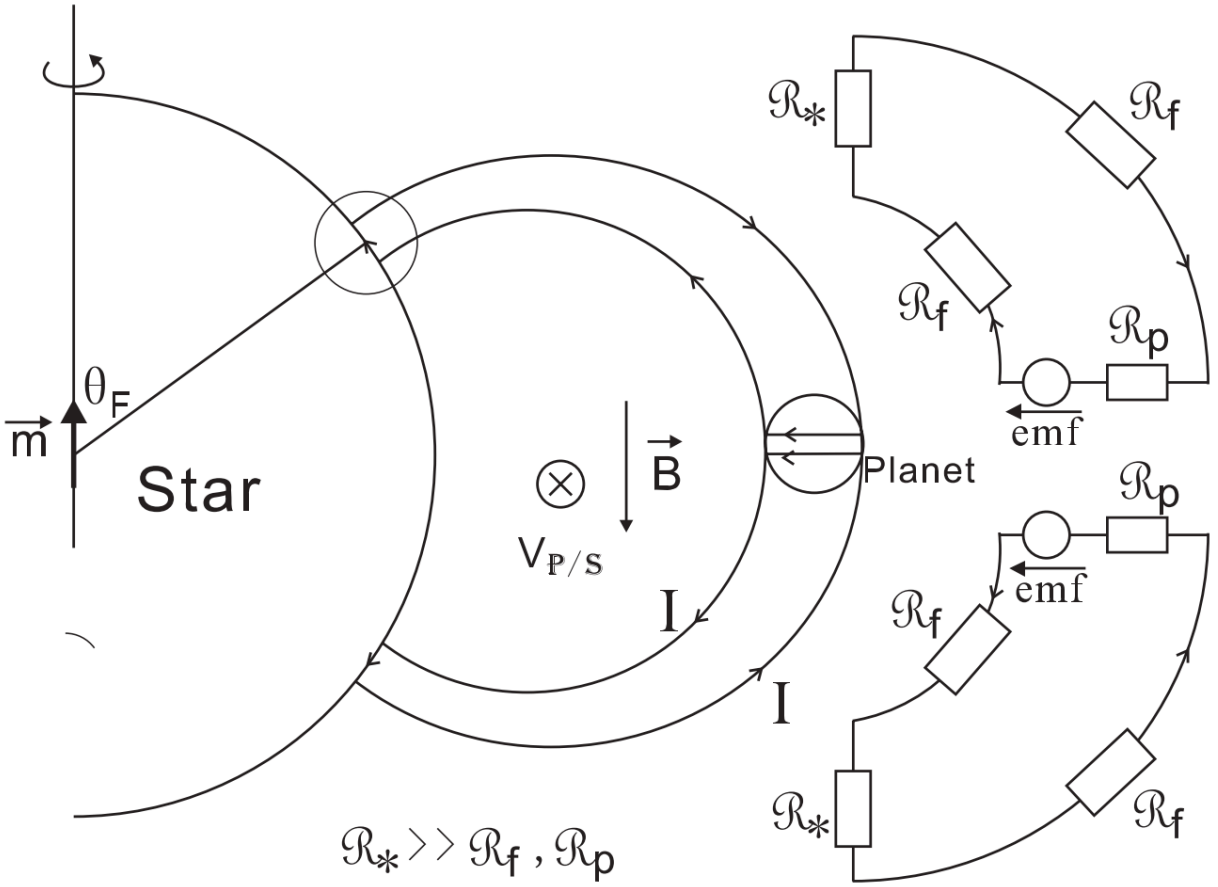
Several non-trivial questions need now to be answered:

- **What are the shape and size (A_{obst}) of the obstacle?**
- **Which fraction of the available power is channeled by the interaction ?**
- **How much energy is actually available in the end?**

Obstacle & energy conversion: the unipolar inductor case



Hypotheses:

» Negligible planet magnetic field

» Resistance **Σ** at the foot of the interaction is **larger** than in the planet (i.e. conductivity is the largest in the planet)

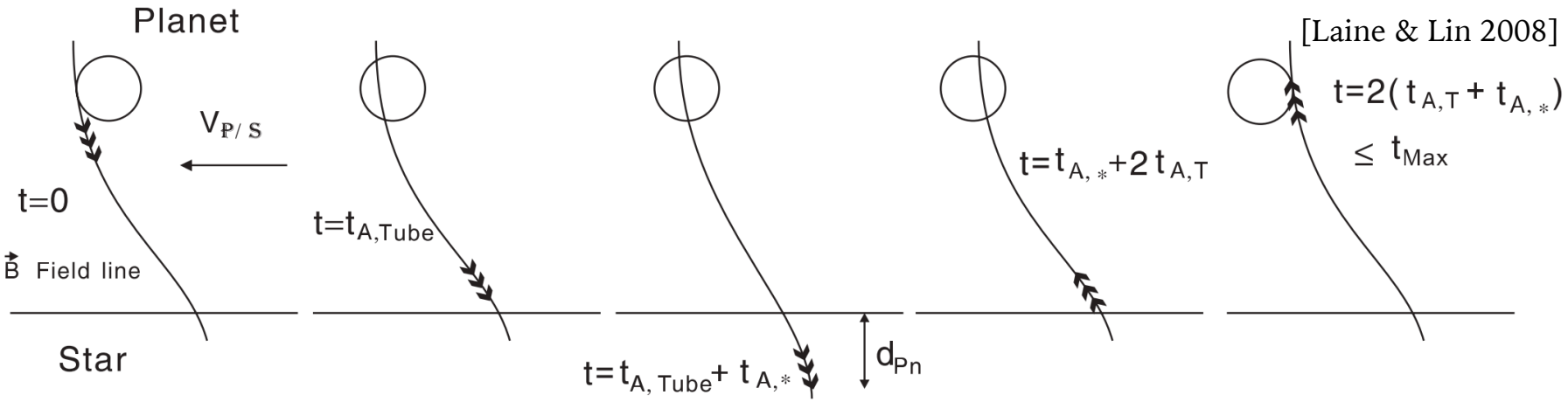
Note: one can derive the net torque applied to the planet's orbit

$$\mathcal{T}_\star = 8 R_P^2 R_{\rm orb}^2 \sigma B_w^2 \Sigma$$

[Laine & Lin 2008]

Obstacle & energy conversion: the unipolar inductor case

The unipolar inductor model is valid only if the current systems is closed between the star and the planet:



[Laine & Lin 2008]

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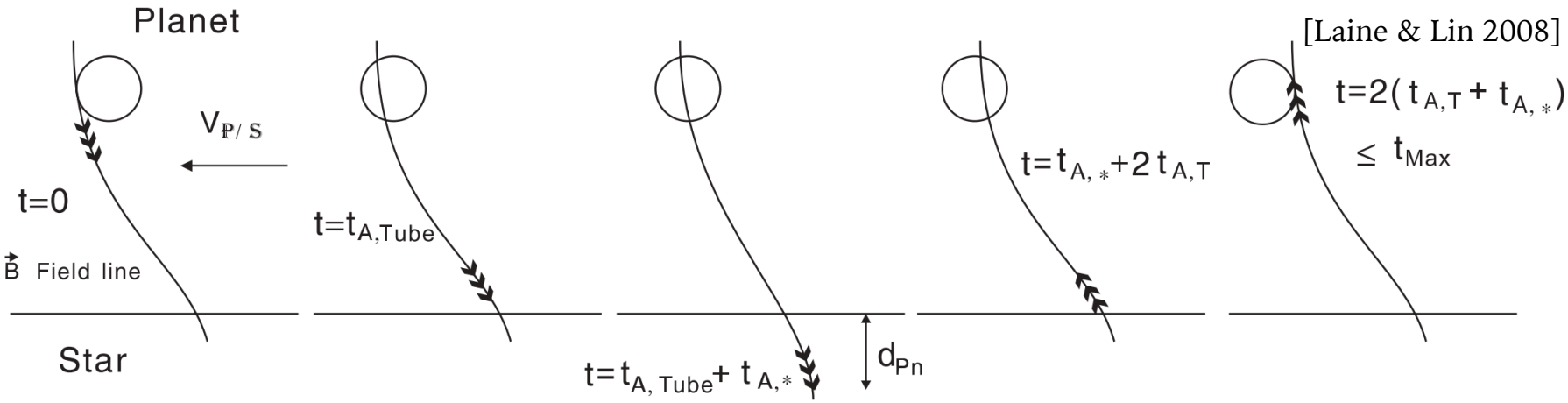

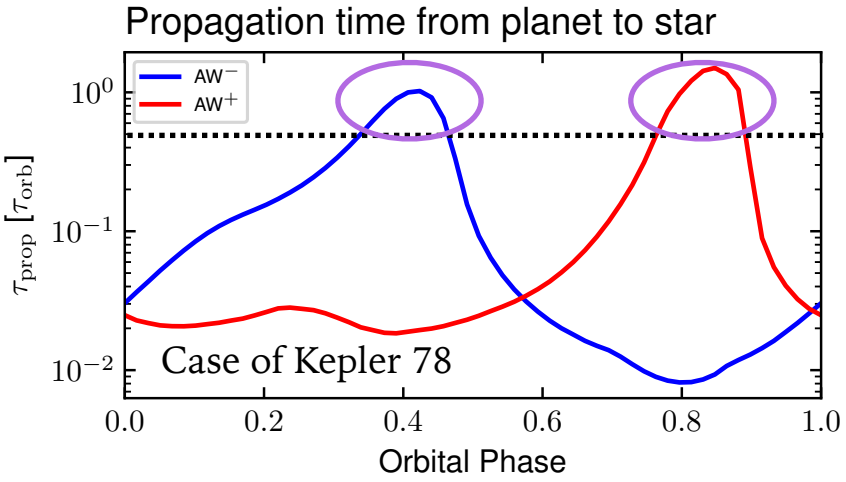

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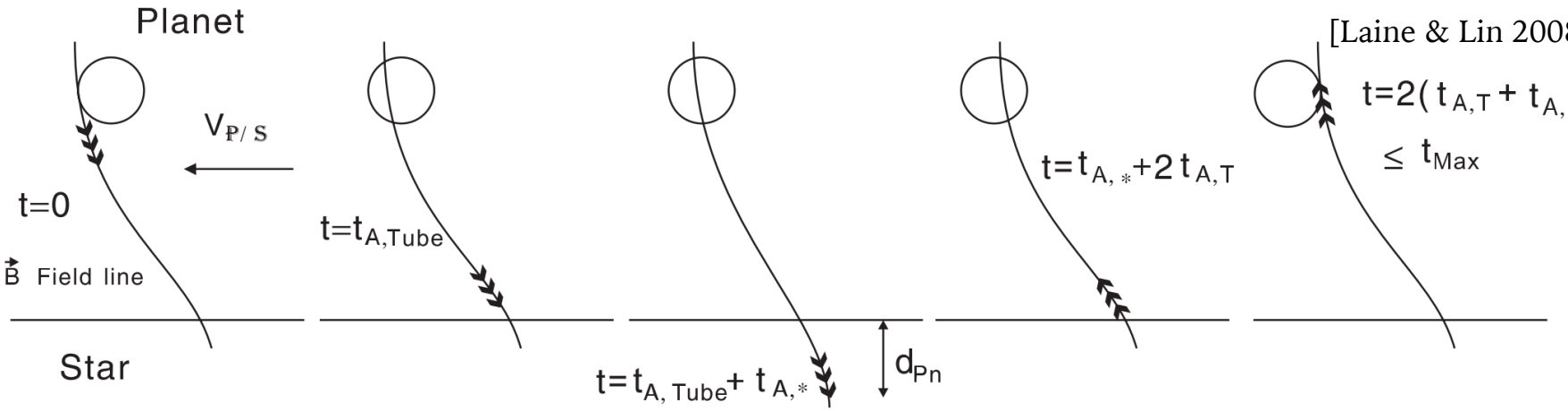
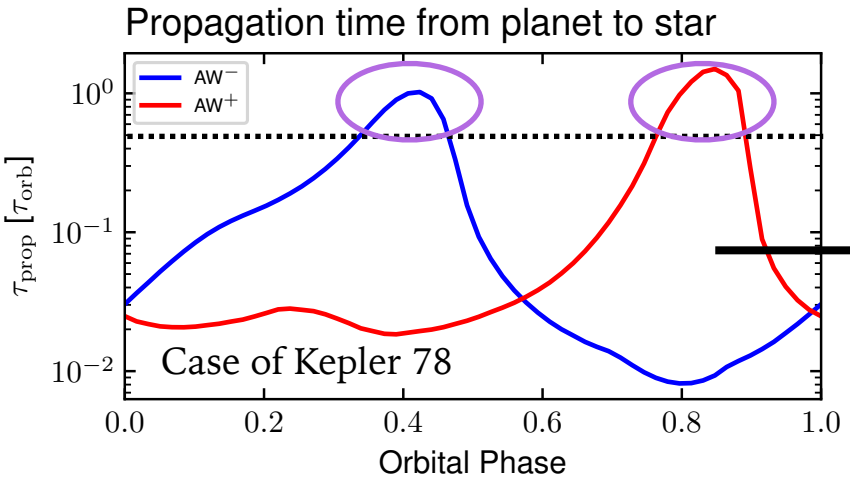
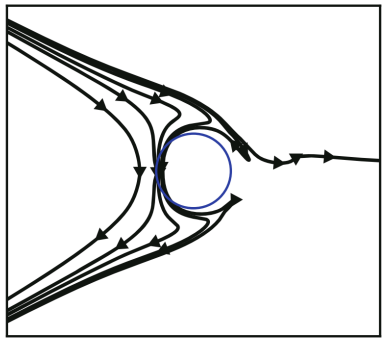
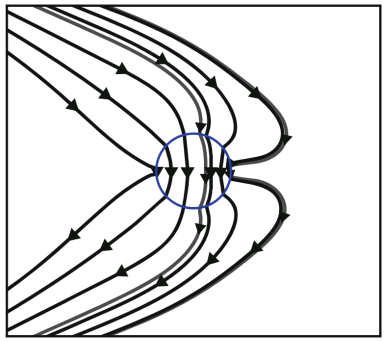




Two possible situations:



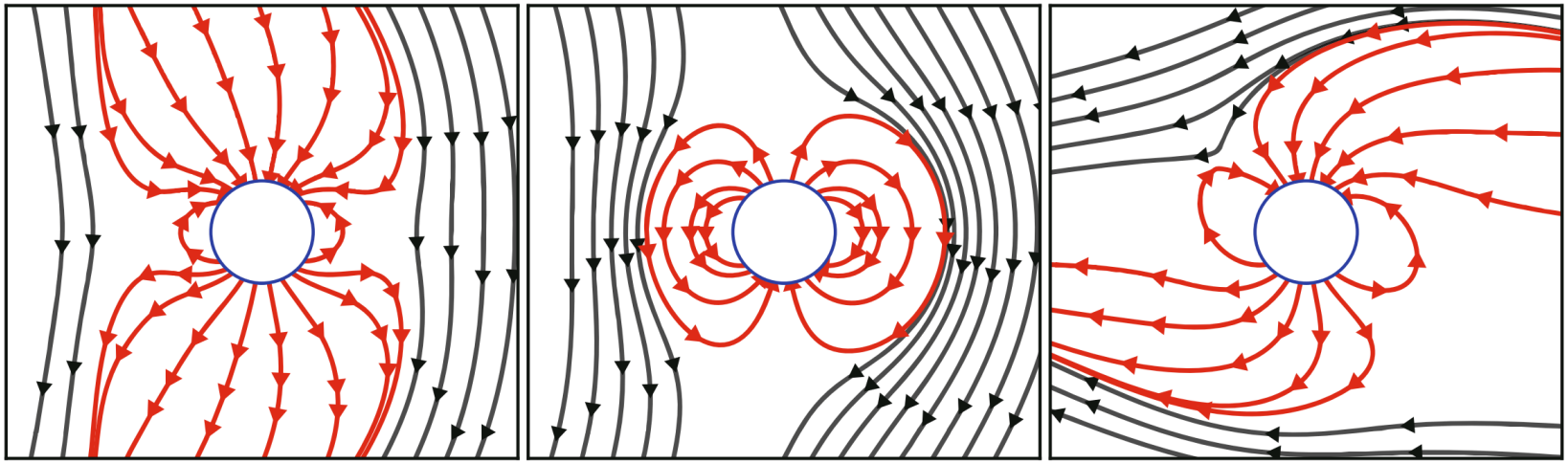
Magnetic 'screening'



Ohmic dissipation

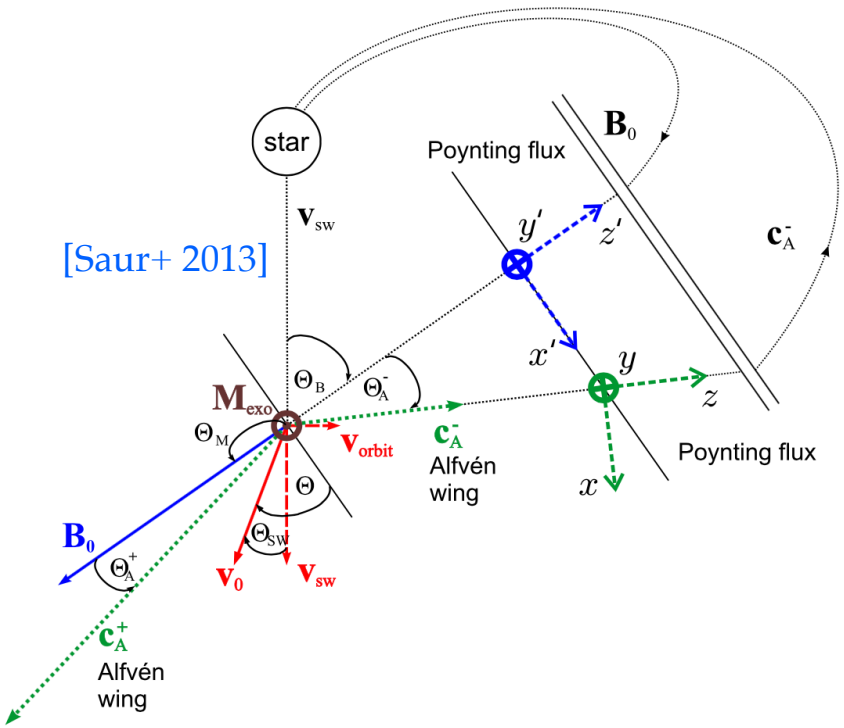
Obstacle & energy conversion: the dipolar case

What if the planetary field cannot be neglected?



Aligned Anti-aligned Perpendicular

Obstacle & energy conversion: the dipolar case



[Saur+ 2013]

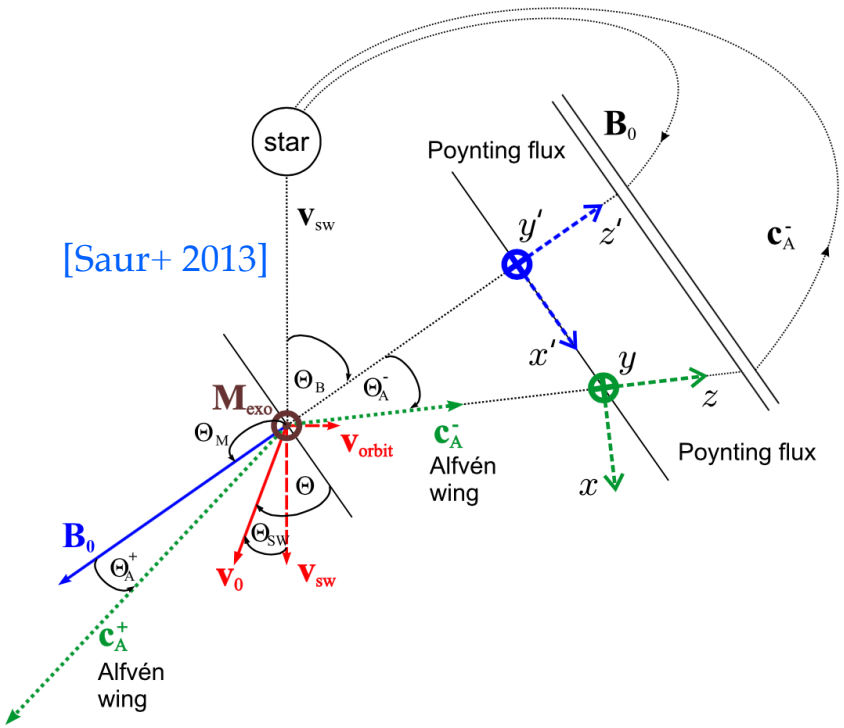
The power channeled by the interaction is $P = \left[M_A \left(\frac{\Sigma_P}{\Sigma_P + 2\Sigma_A} \right)^2 \right] S_w A_{\text{obst}}$

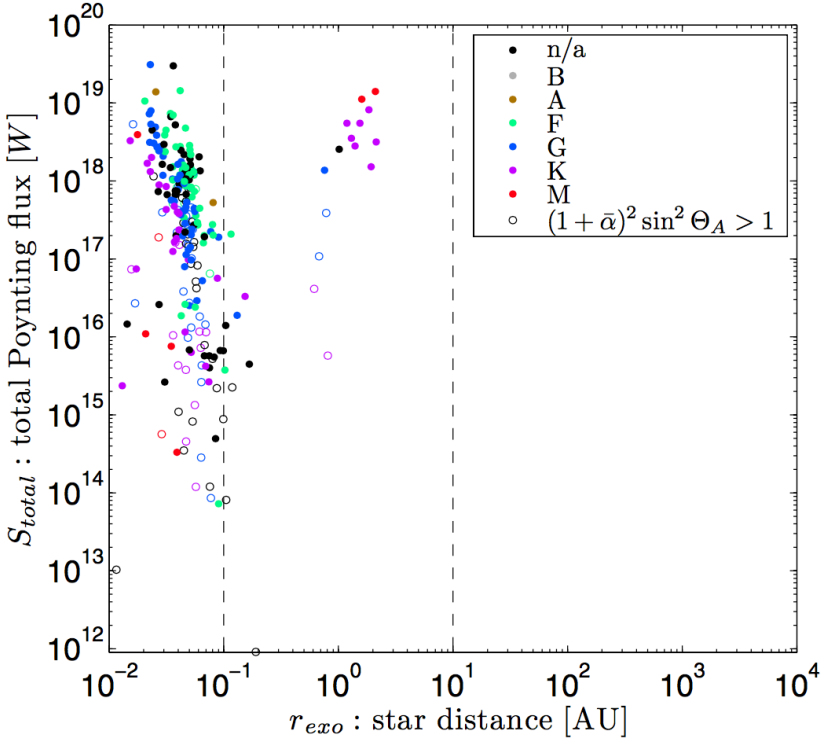
'Alfvén conductance'

$$\Sigma_A = \frac{1}{\mu_0 v_A \left(1 + M_A^2 - 2M_A \cos\Theta\right)^{1/2}}$$

Σ_P: *Pedersen conductance (integrated ionospheric conductivity* $\perp$ *to* E_{iono} *and* $\parallel$ *to* B_{iono}*)*

Obstacle & energy conversion: the dipolar case





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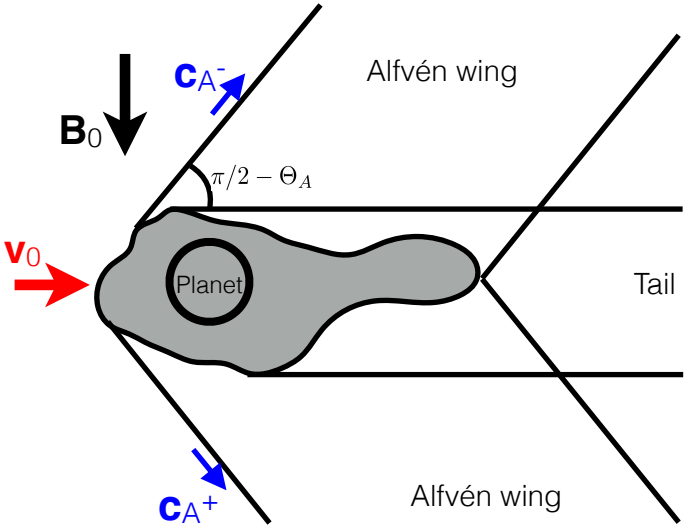
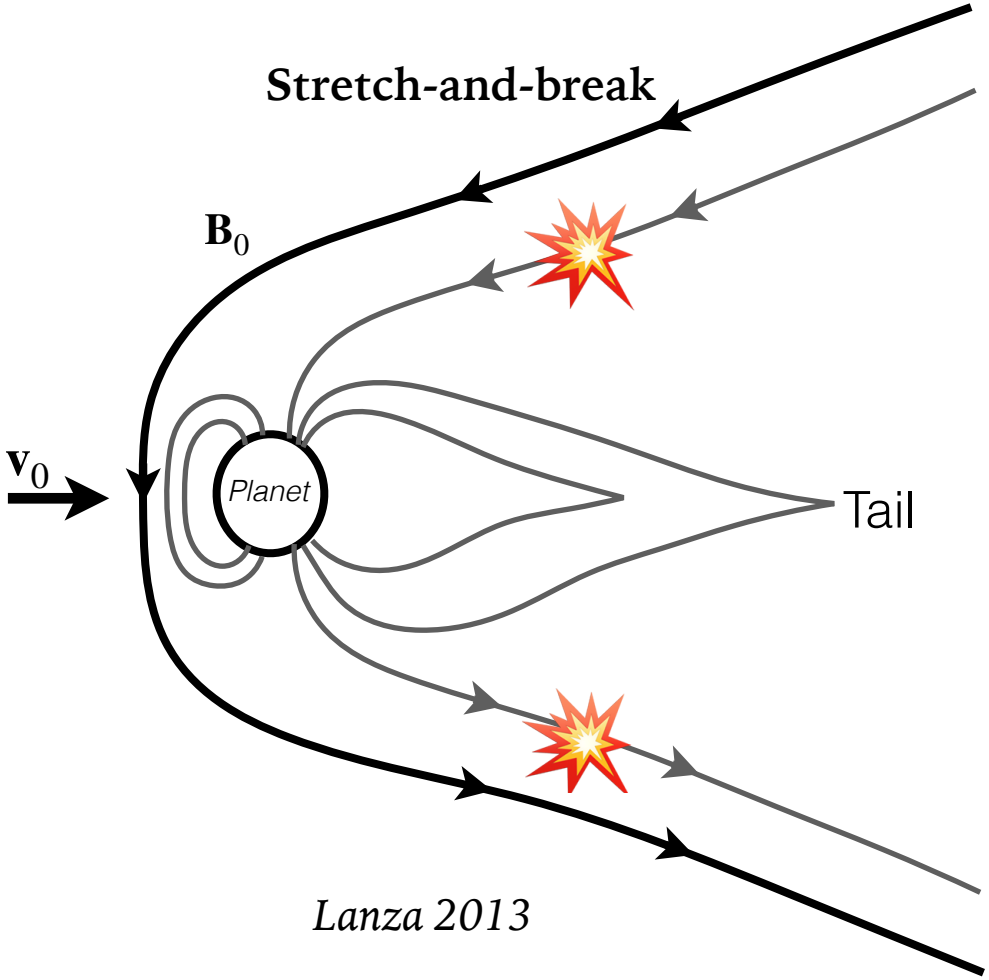
Alternative theory: the stretch-and-break mechanism

Alfvén wings



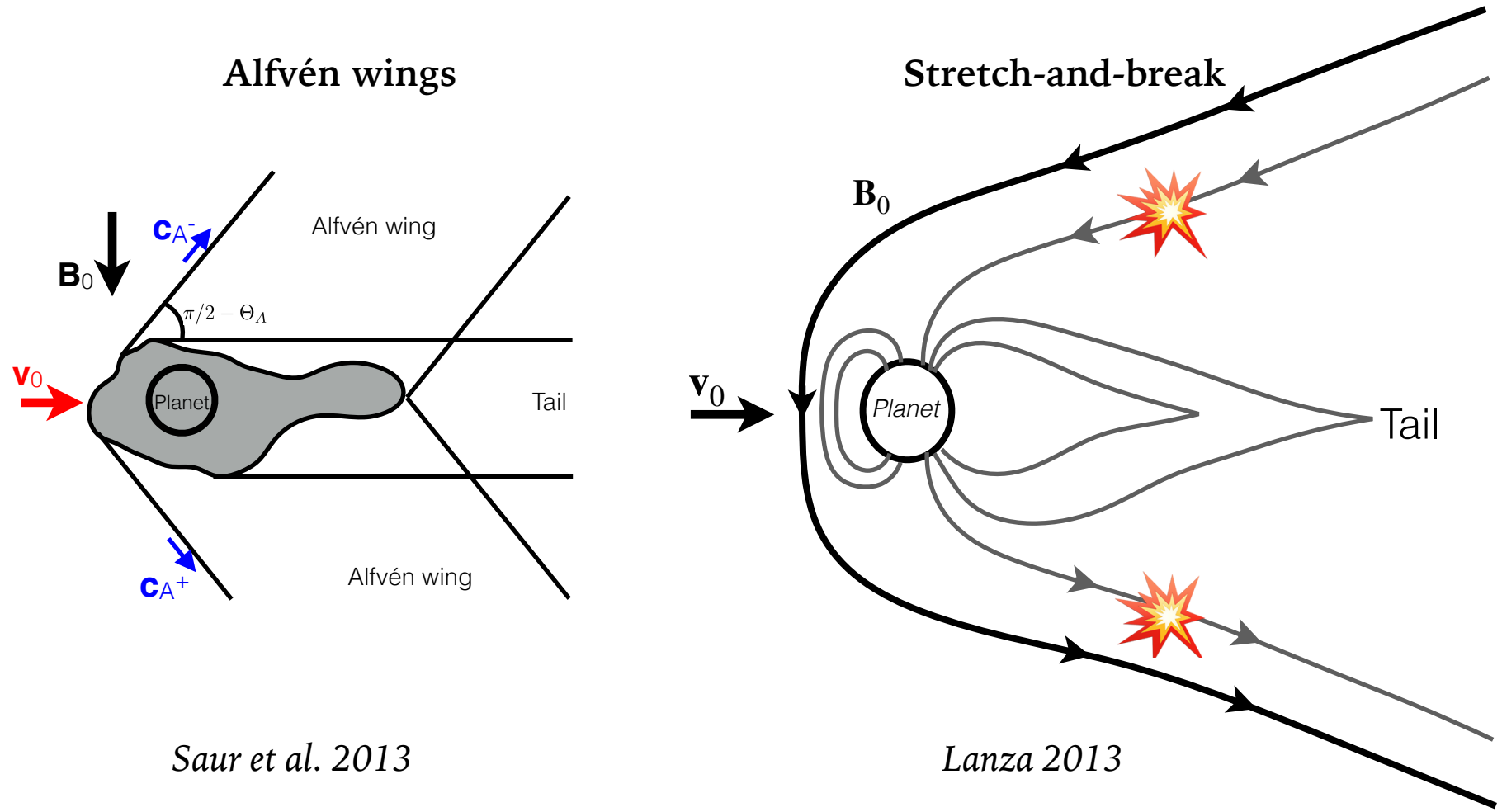
Saur et al. 2013

Stretch-and-break



Lanza 2013

Alternative theory: the stretch-and-break mechanism



Saur et al. 2013

Lanza 2013

$$\text{Poynting flux} \propto v_0 B_w^2 M_a \left(\frac{B_P}{B_w}\right)^{2/3} << \text{Poynting flux} \propto v_0 B_w^2 \left(\frac{B_P}{B_w}\right)^2 f_{\text{AP}}$$

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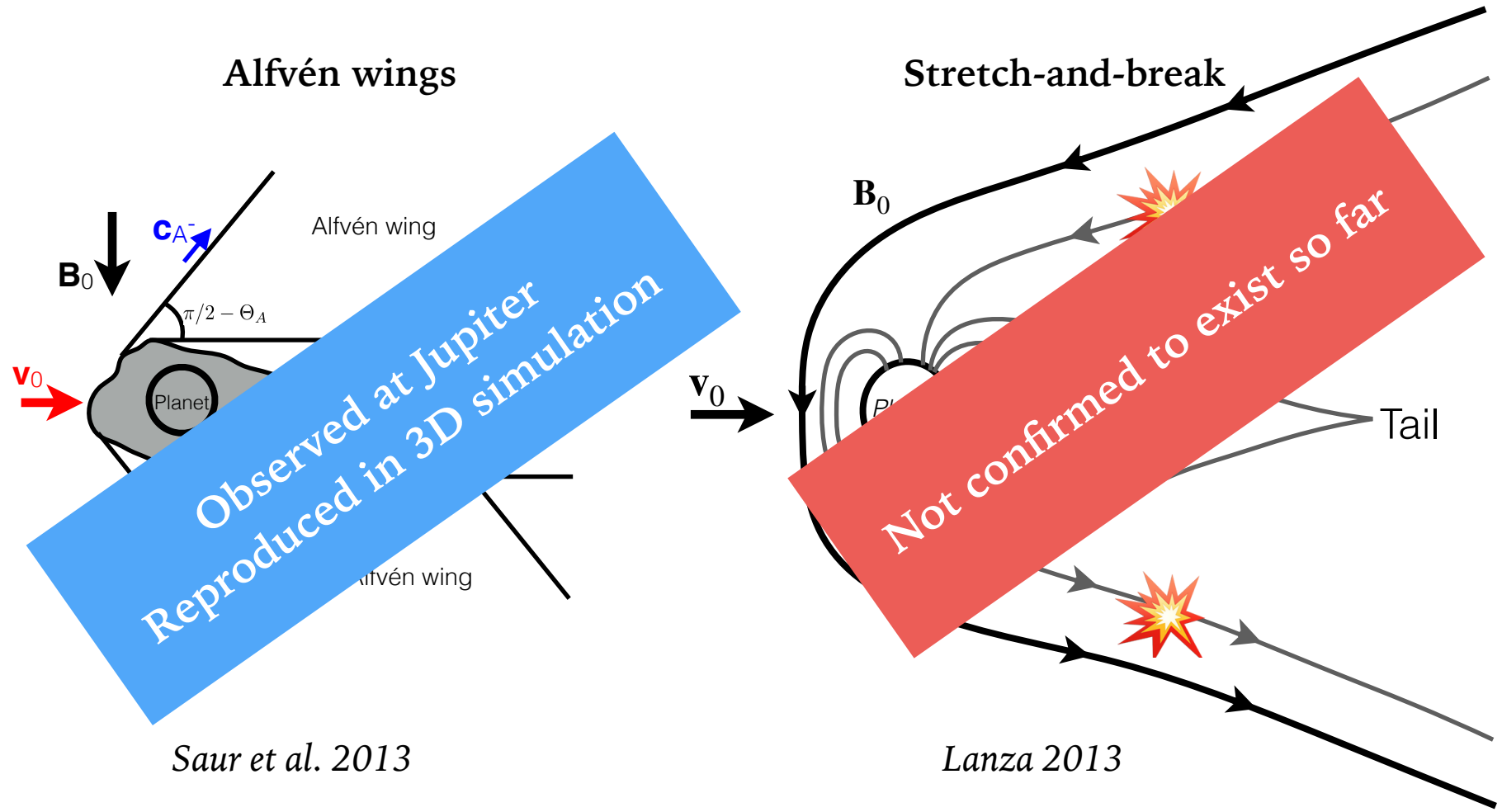
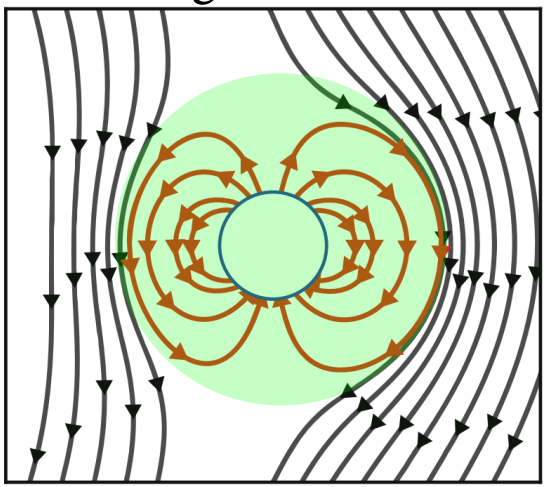


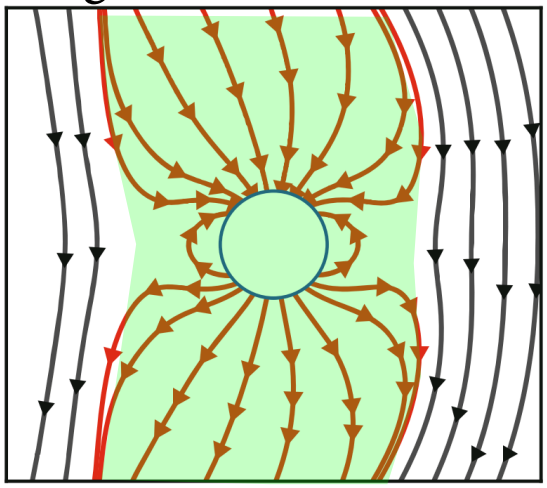
$$\text{Poynting flux} \propto v_0 B_w^2 M_a \left(\frac{B_P}{B_w}\right)^{2/3} \ll \text{Poynting flux} \propto v_0 B_w^2 \left(\frac{B_P}{B_w}\right)^{2} f_{\text{AP}}$$

The obstacle size strongly depends on the topology

Anti-aligned



Aligned

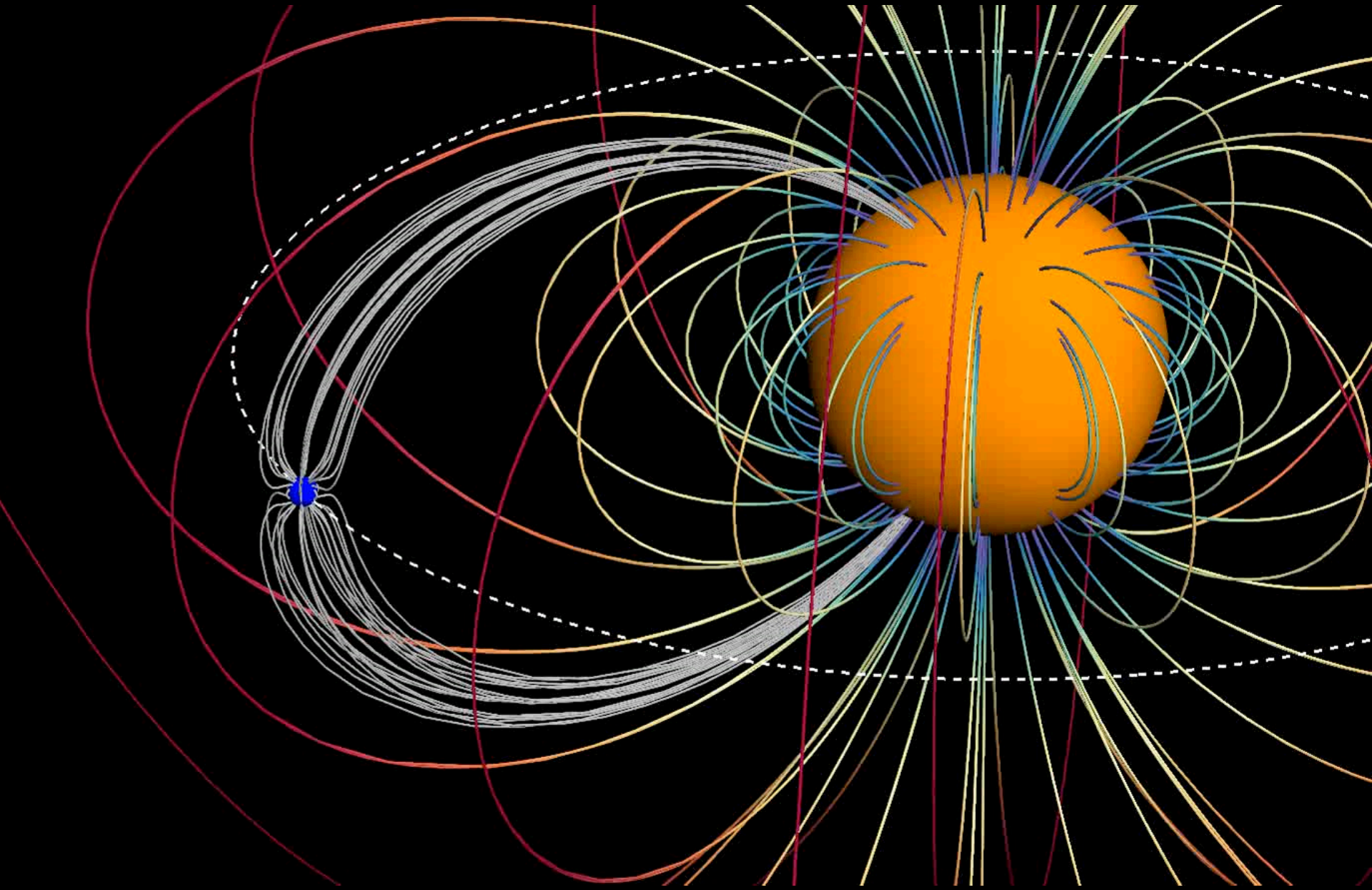


$$R_{\rm obst} = R_P \left(\frac{B_P^2}{8\pi\ P_t} \right)^{1/6}$$

The obstacle can be much bigger, so much more power is accessible to the interaction

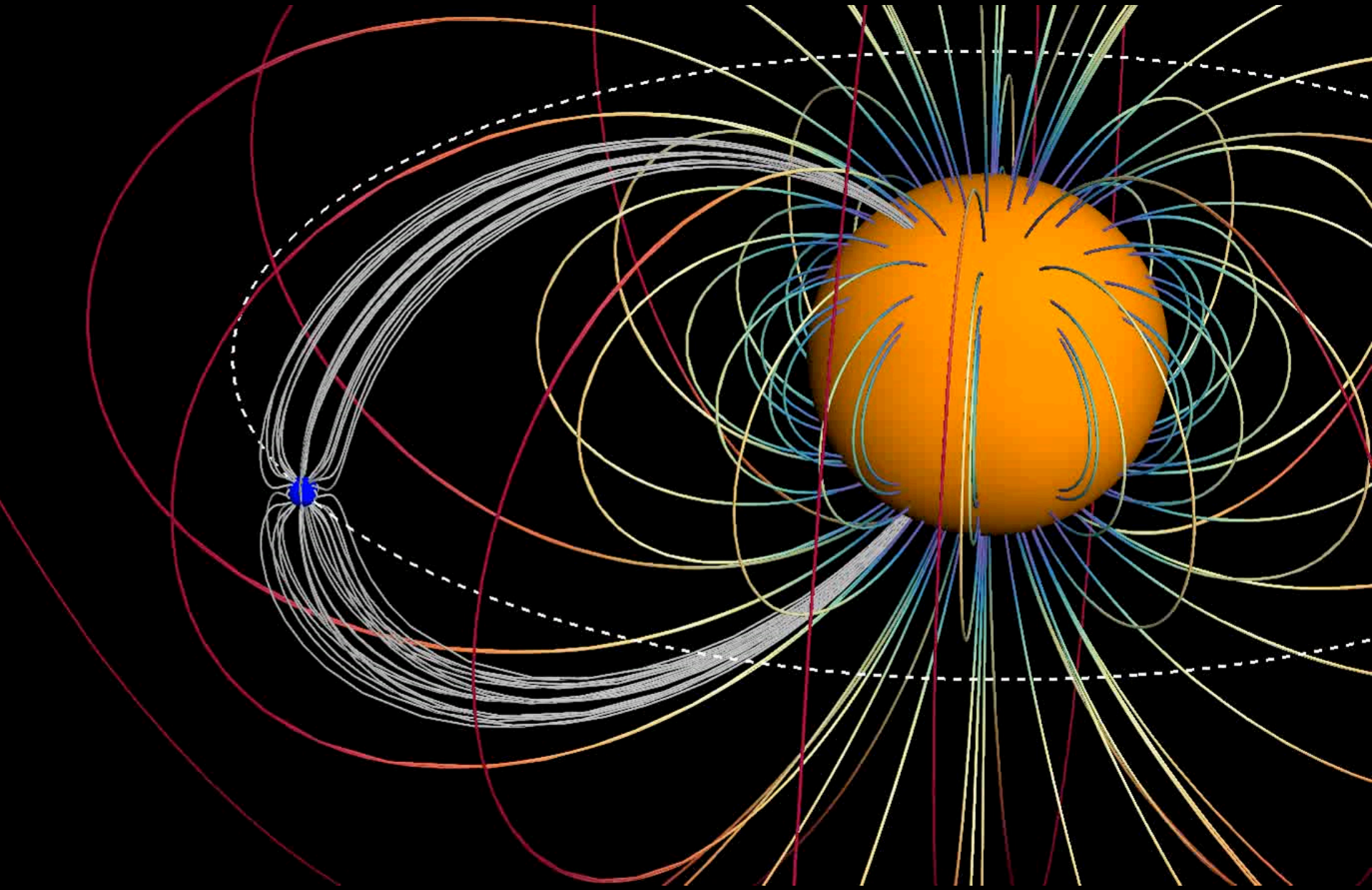
☛ possible to constrain this with numercial simulations

3D model of magnetic star-planet interactions



[Strugarek+, 15]

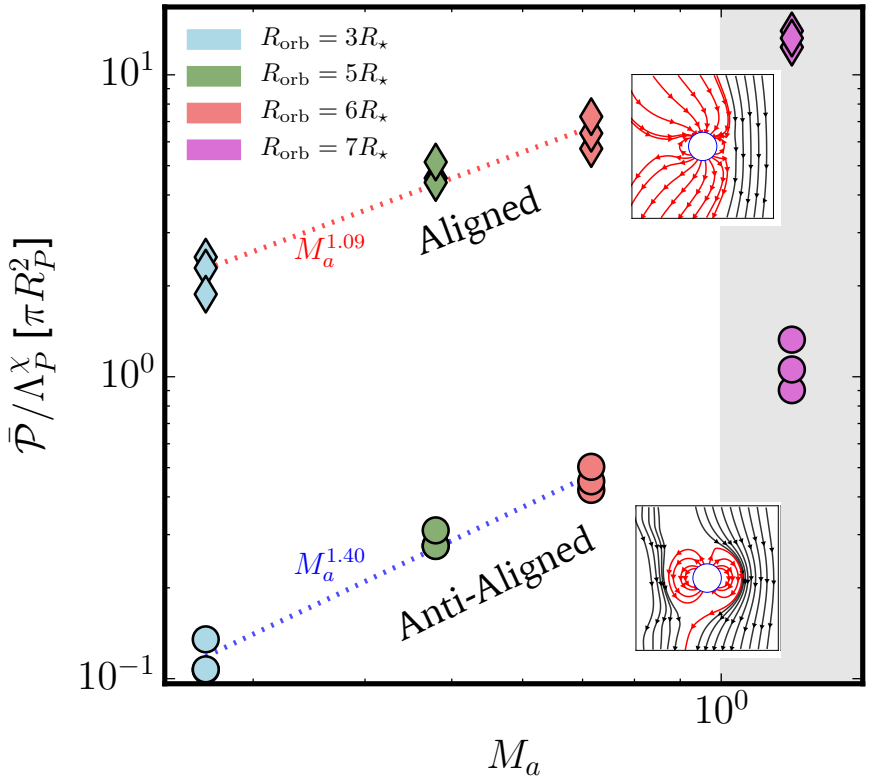
3D model of magnetic star-planet interactions



[Strugarek+, 15]

Poynting flux in Alfvén wings: parametrization

$$\mathcal{P} = A_1 \pi \left(c_d S_w M_a^{\xi} \bar{\eta}_a^{\nu_3} \right) \cdot \left(R_P^2 \bar{\eta}_P^{\nu_4} \right) \cdot \left(\Lambda_P^{\chi} \right)$$



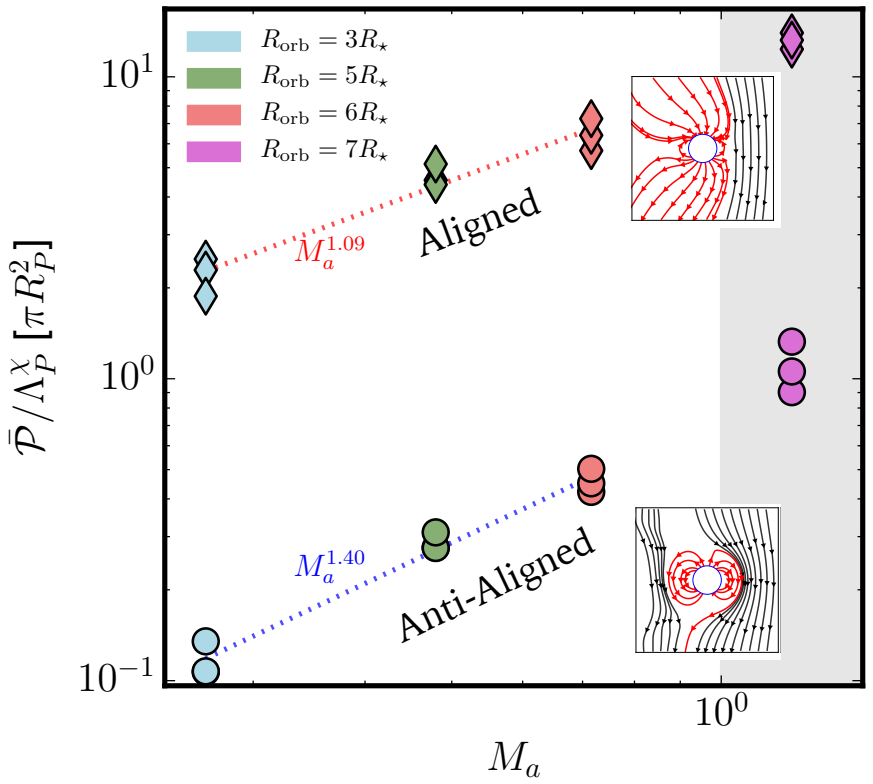
[Strugarek 2016]

Poynting flux in Alfvén wings: parametrization

Poynting flux *Reconnection eff.*

$$\mathcal{P} = A_1 \pi \underbrace{\left(c_d S_w M_a^{\xi} \bar{\eta}_a^{\nu_3}\right)}_{\text{drag coeff.} \quad \text{Alf. Mach}} \cdot \left(R_P^2 \bar{\eta}_P^{\nu_4}\right) \cdot \left(\Lambda_P^{\chi}\right)$$

Wind-dependent parameters
(magnetic field, density, velocity)



[Strugarek 2016]

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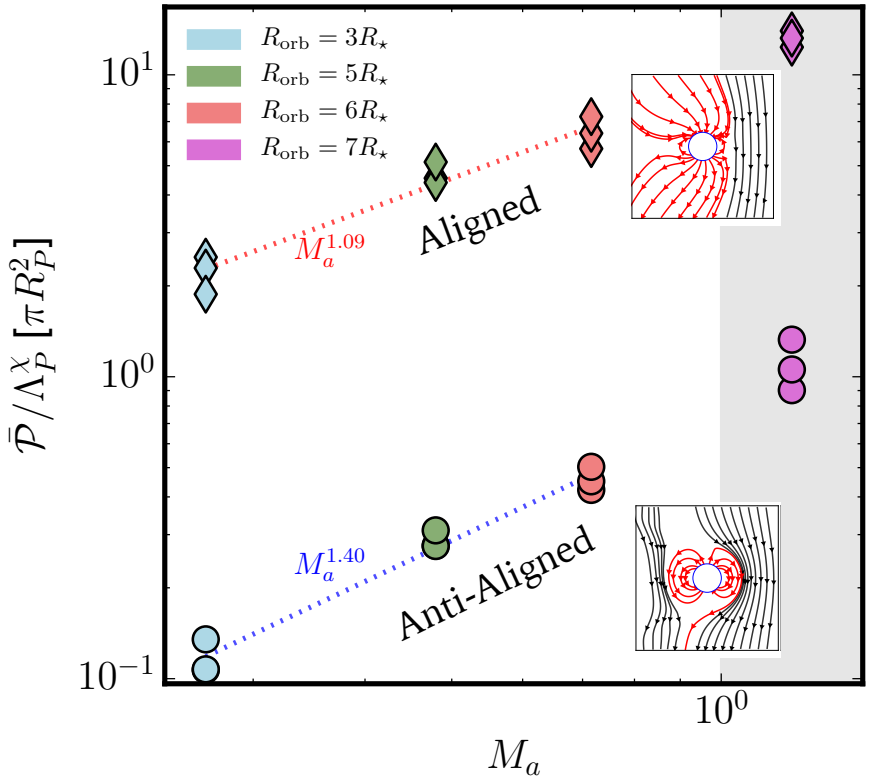
Wind-dependent parameters
(magnetic field, density, velocity)

Planet-dependent parameters
(radius, composition)



[Strugarek 2016]

Poynting flux in Alfvén wings: parametrization

Poynting flux *Reconnection eff.* *Pedersen diff.*

$$\mathcal{P} = A_1 \pi \underbrace{\left(c_d S_w M_a^{\xi} \bar{\eta}_a^{\nu_3}\right)}_{\text{drag coeff.}} \cdot \underbrace{\left(R_P^2 \bar{\eta}_P^{\nu_4}\right)}_{\text{Alf. Mach}} \cdot \left(\Lambda_P^{\chi}\right)$$

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Magnetosphere/wind pressure ratio
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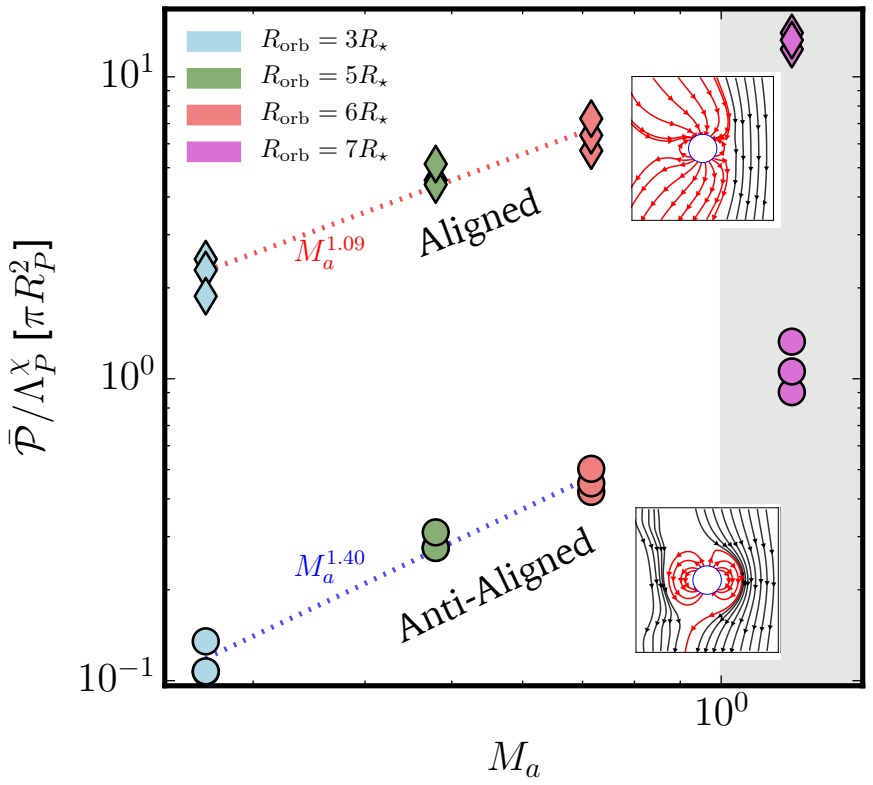

[Strugarek 2016]

Major effects of star-planet magnetic interactions

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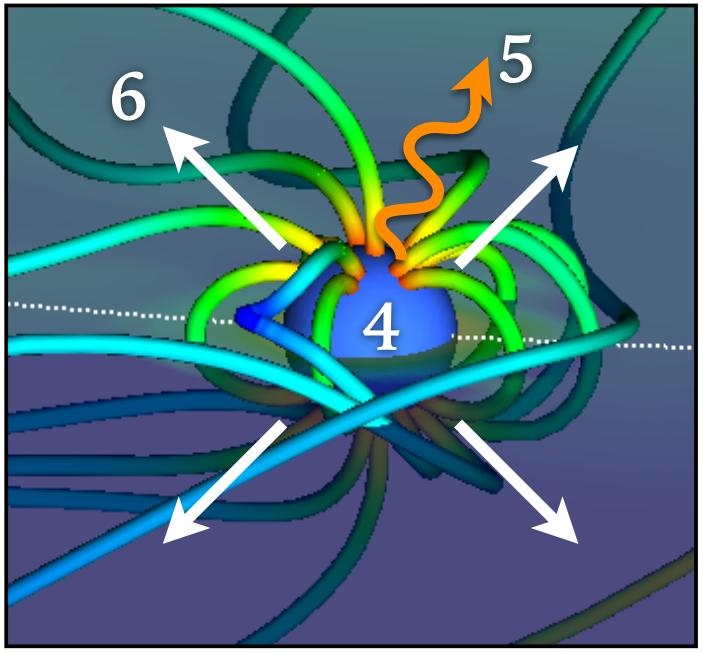

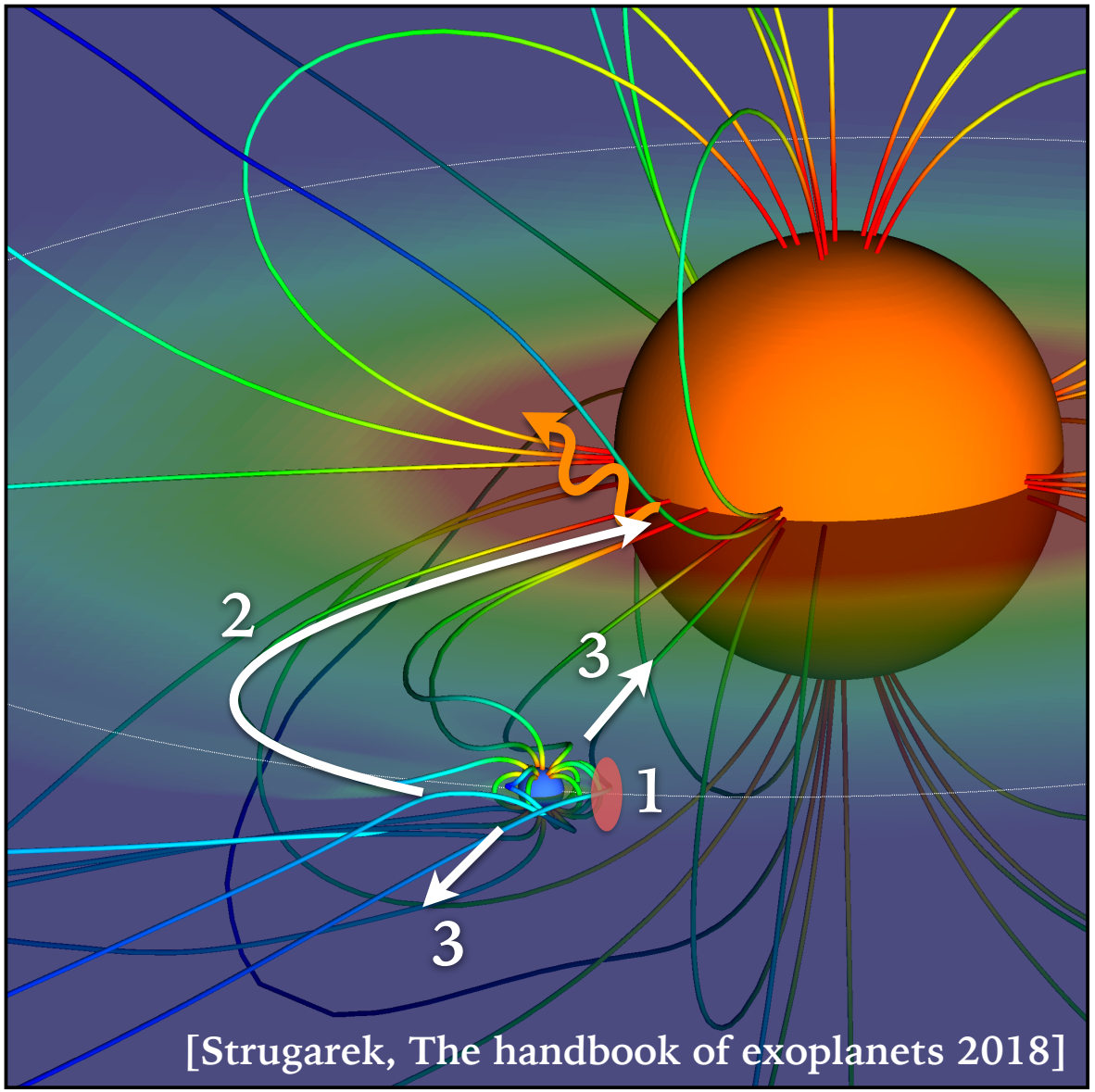

Planetary migration due to a net torque

The total angular momentum is conserved: a planet migration corresponds to an angular momentum exchange between the orbit of the planet and stellar rotation (in a two-body problem), i.e. $\dot{J}_\star = -\dot{J}_P$

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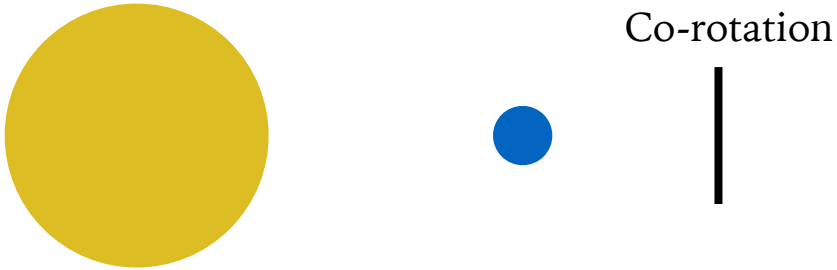

The system evolves towards synchronisation

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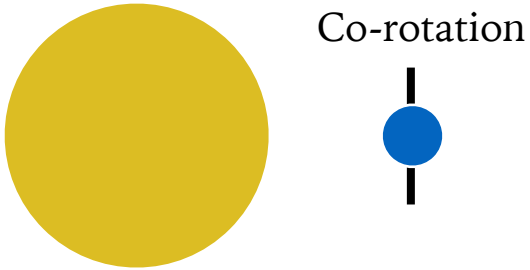

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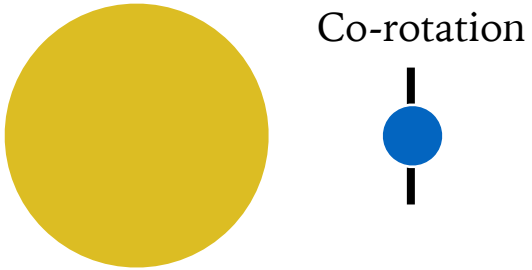

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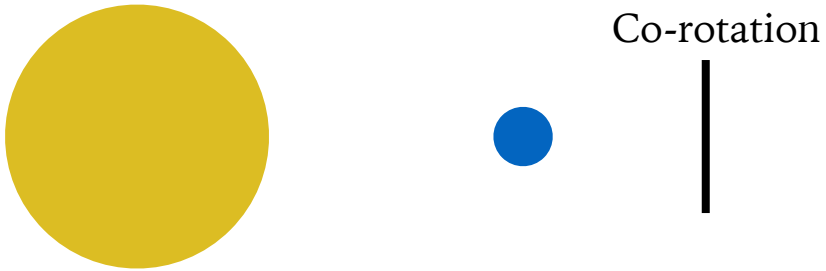

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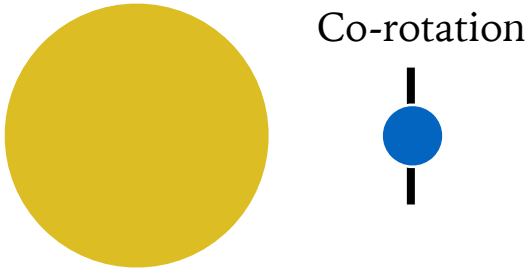

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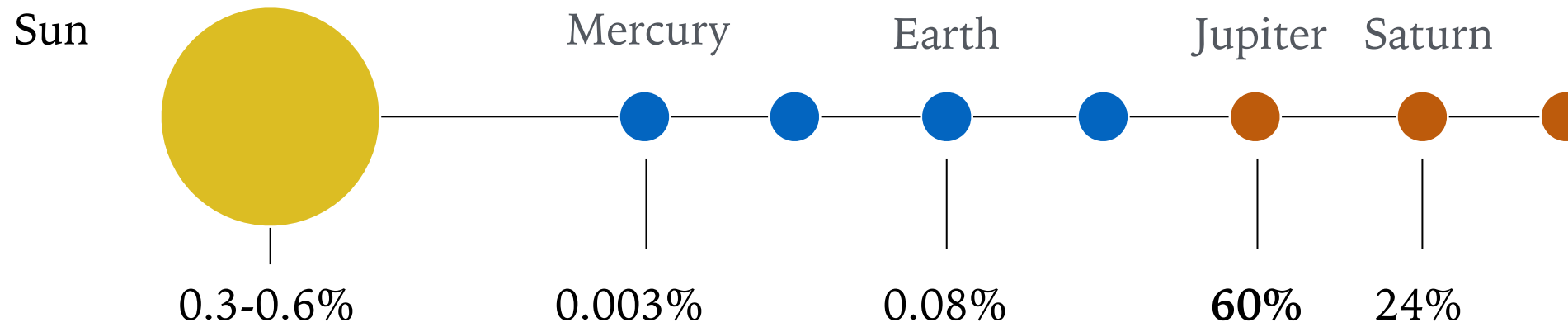
Angular momentum in orbital systems



$$J_\star \simeq \beta M_\star R_\star^2 \Omega_\star$$

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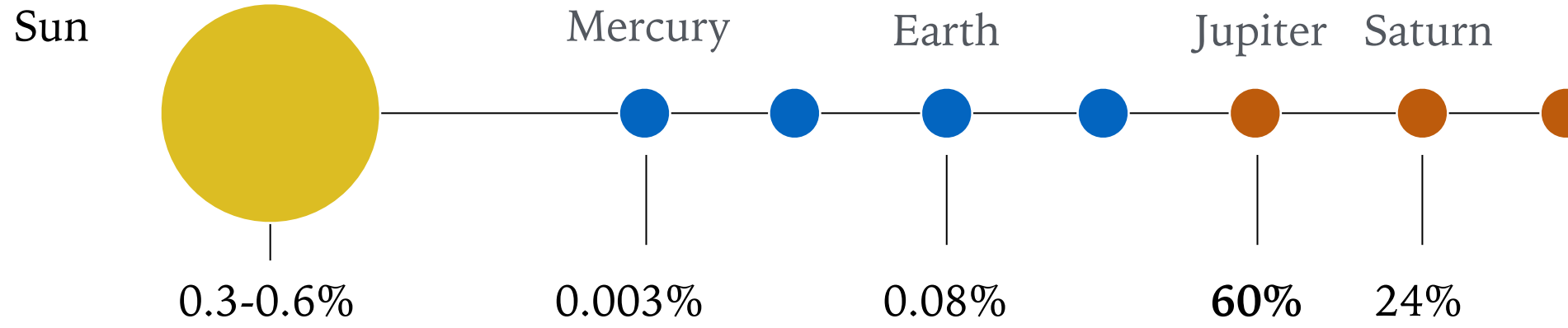
Angular momentum in orbital systems



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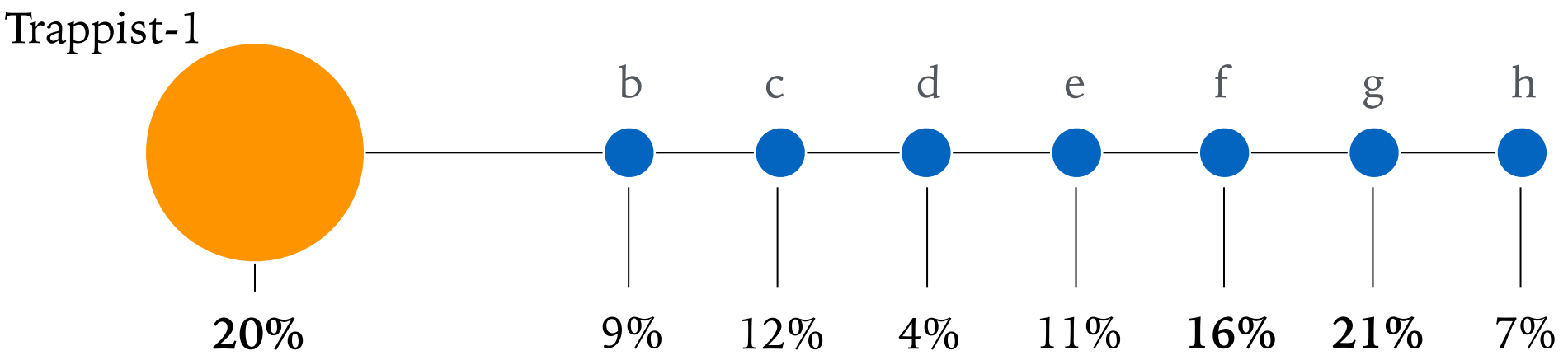
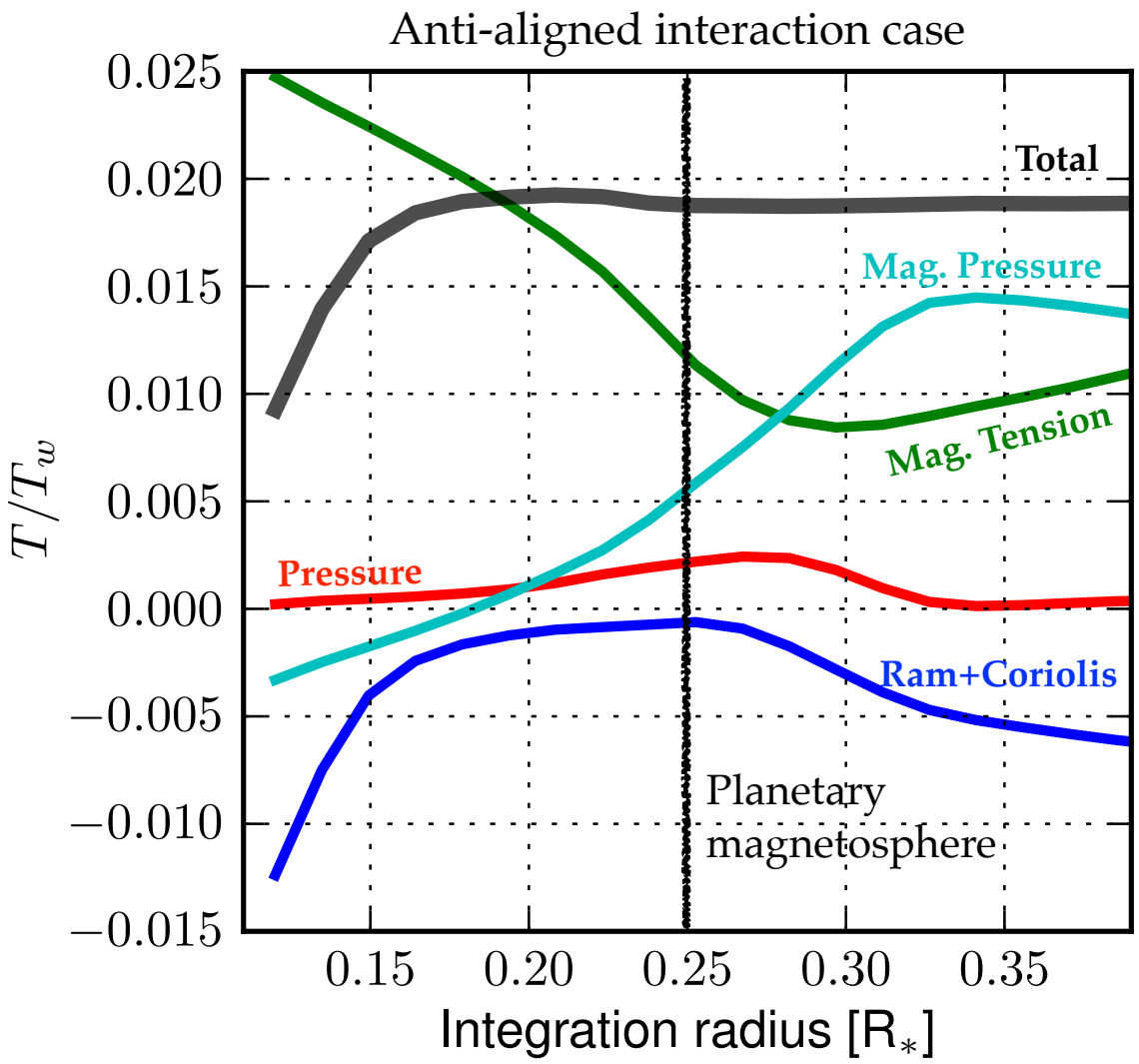
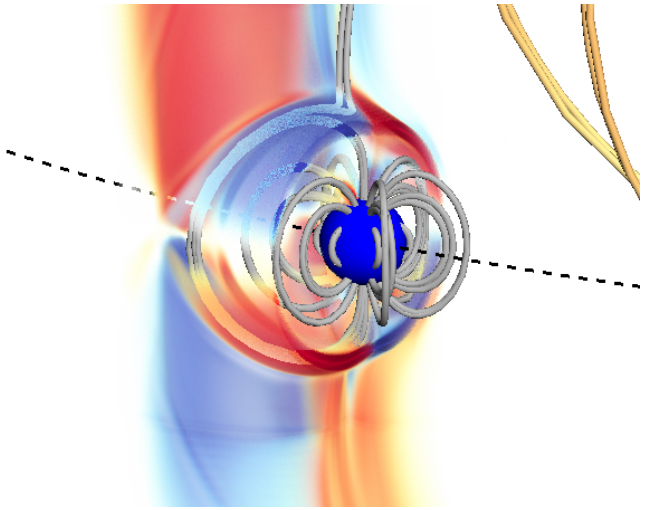


Can magnetic interaction lead to a net torque?

Magnetic torque applied to close-in planets



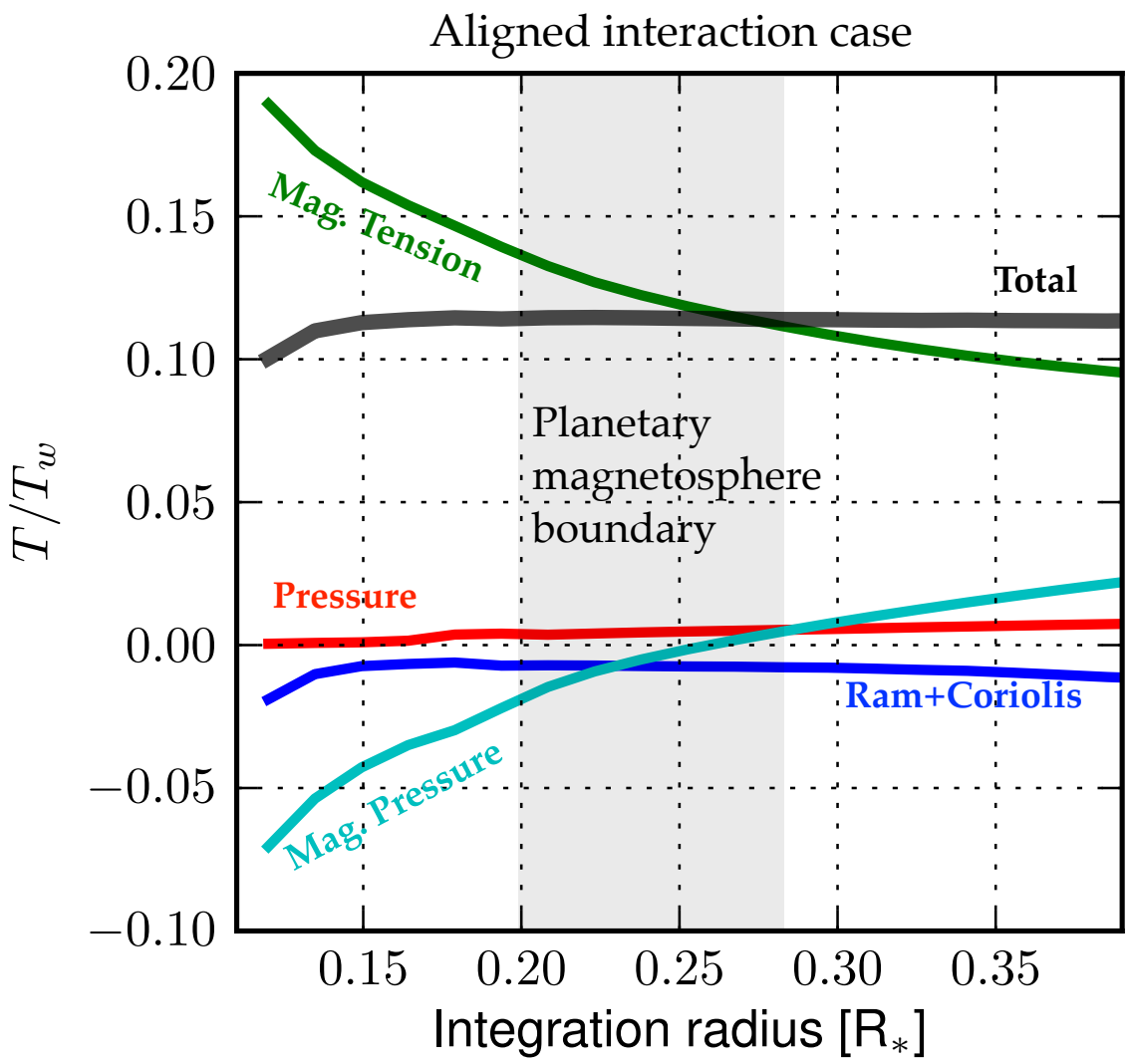
The two magnetic contributions dominate in the anti-aligned case



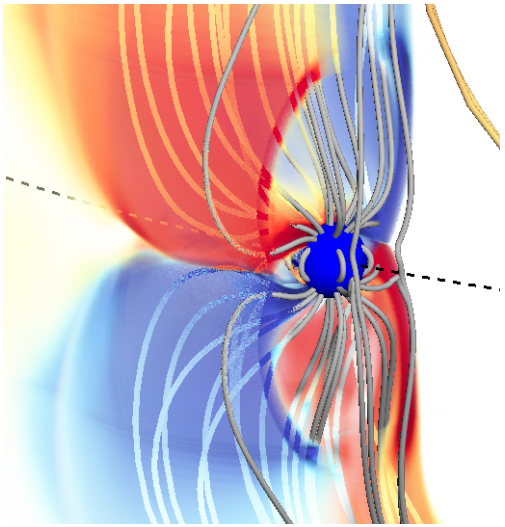
For a standard TTauri-Star ($\dot{M}$~10^5 $\dot{M}_{sun}$), τ_{mig} ~ **850 Myr**

[Strugarek+ 2015]

Magnetic torque applied to close-in planets



The magnetic tension (field lines connecting the planet to the star) is the main contributor to the planet migration



For a standard TTauri-Star ($\dot{M}$~10^5 $\dot{M}_{sun}$), τ_{mig} ~ **140 Myr**

[Strugarek+ 2015]

Magnetic torque: parametrization

$$\mathcal{T} = A_0 \pi \left(c_d P_t M_a^{\beta} \bar{\eta}_a^{\nu_1} \right) \cdot \left(R_P^2 R_o \bar{\eta}_P^{\nu_2} \right) \cdot \left(\Lambda_P^{\alpha} \right)$$

Wind-dependant parameters
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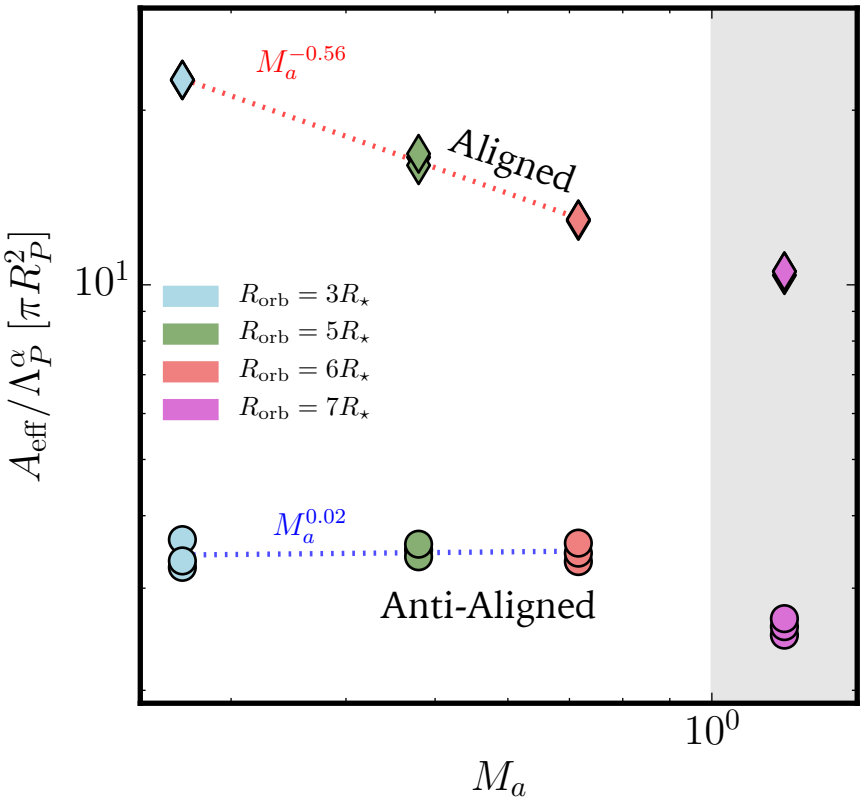
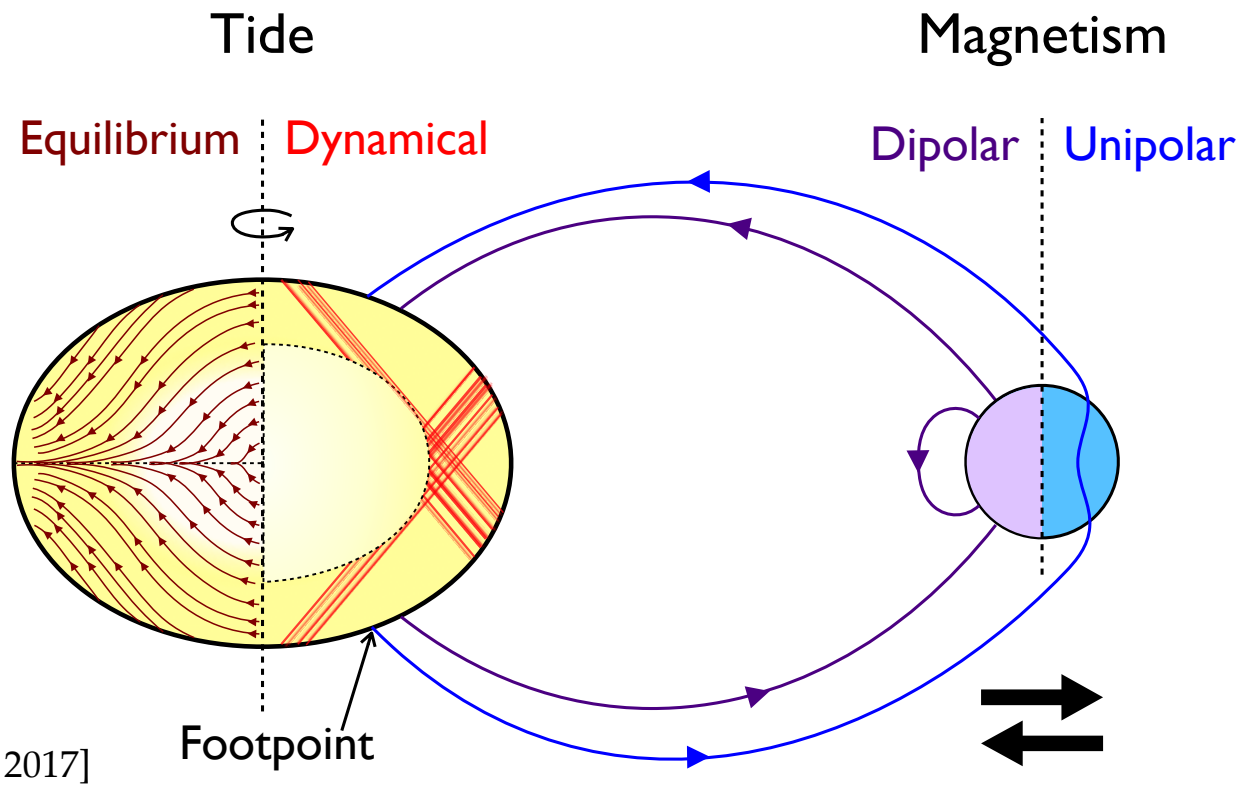


[Strugarek 2016]

Let's compare tidal and magnetic torques



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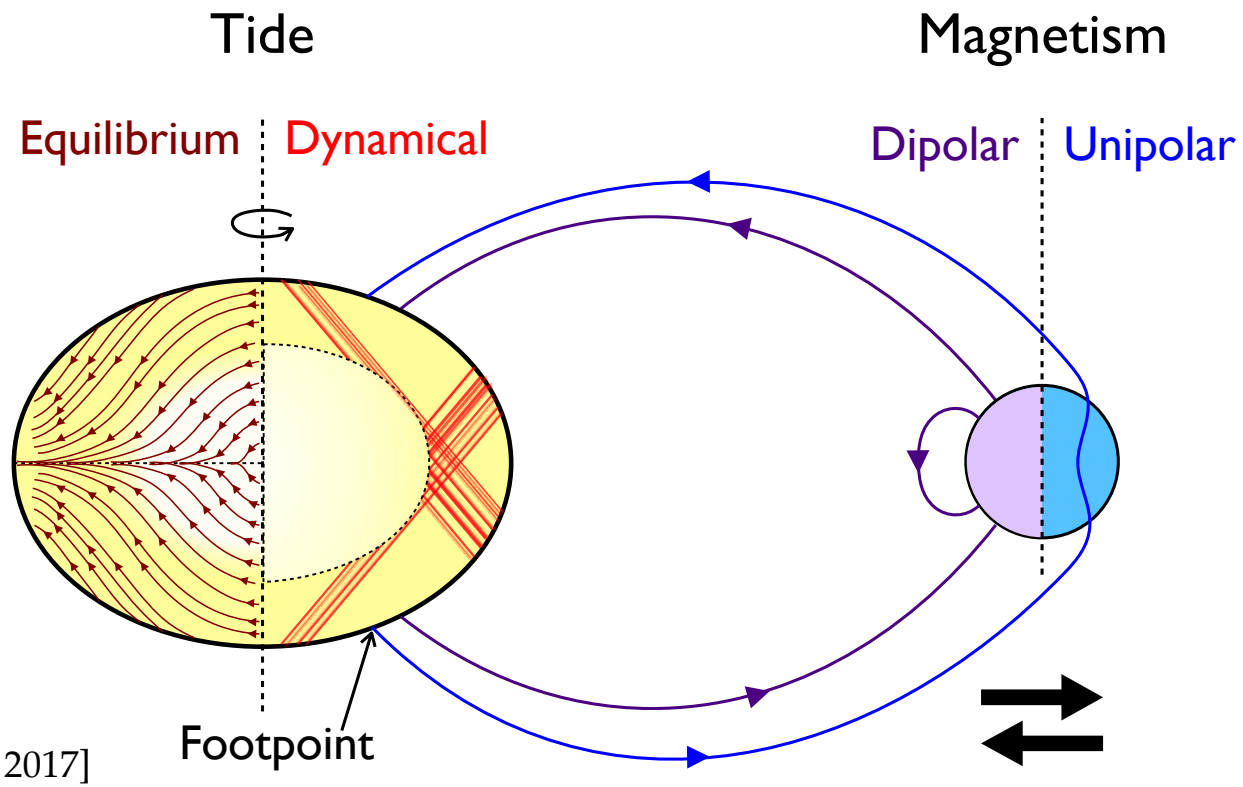

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Stellar evolution code (STAREVOL) from Gallet+ 2017

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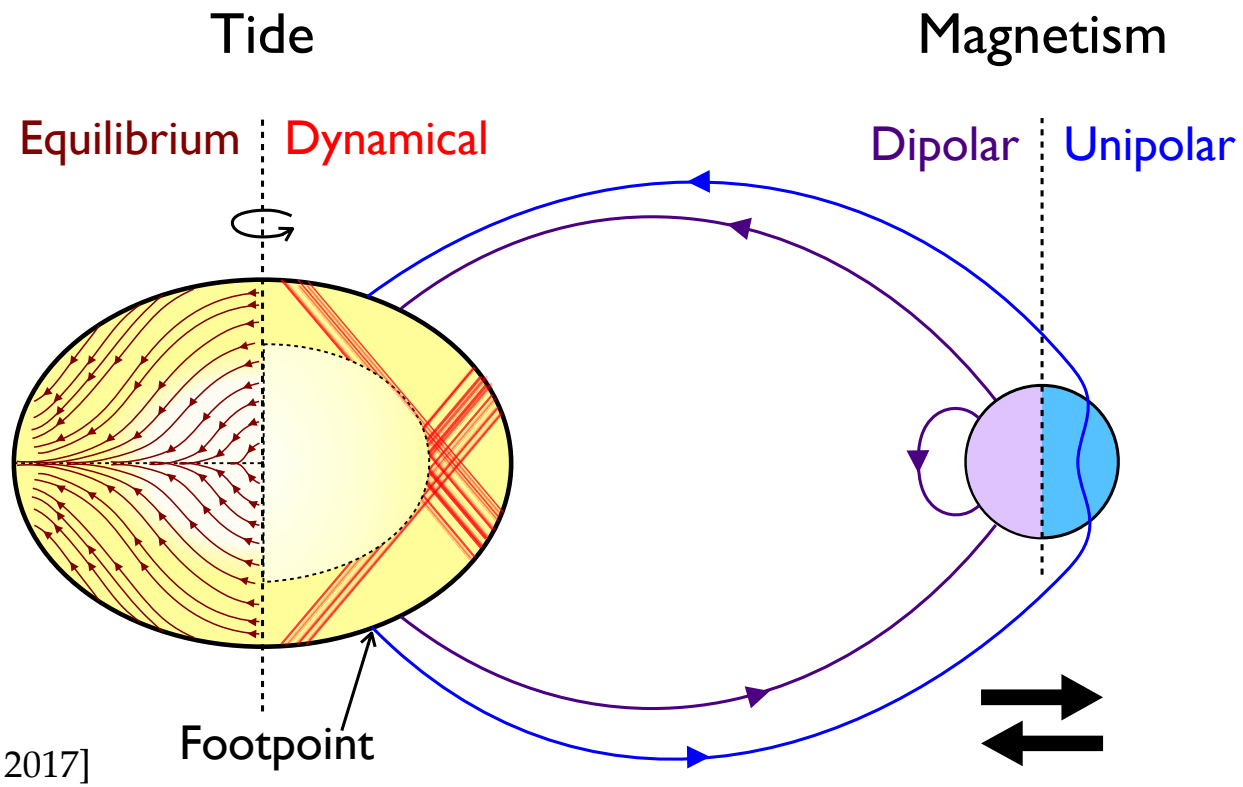

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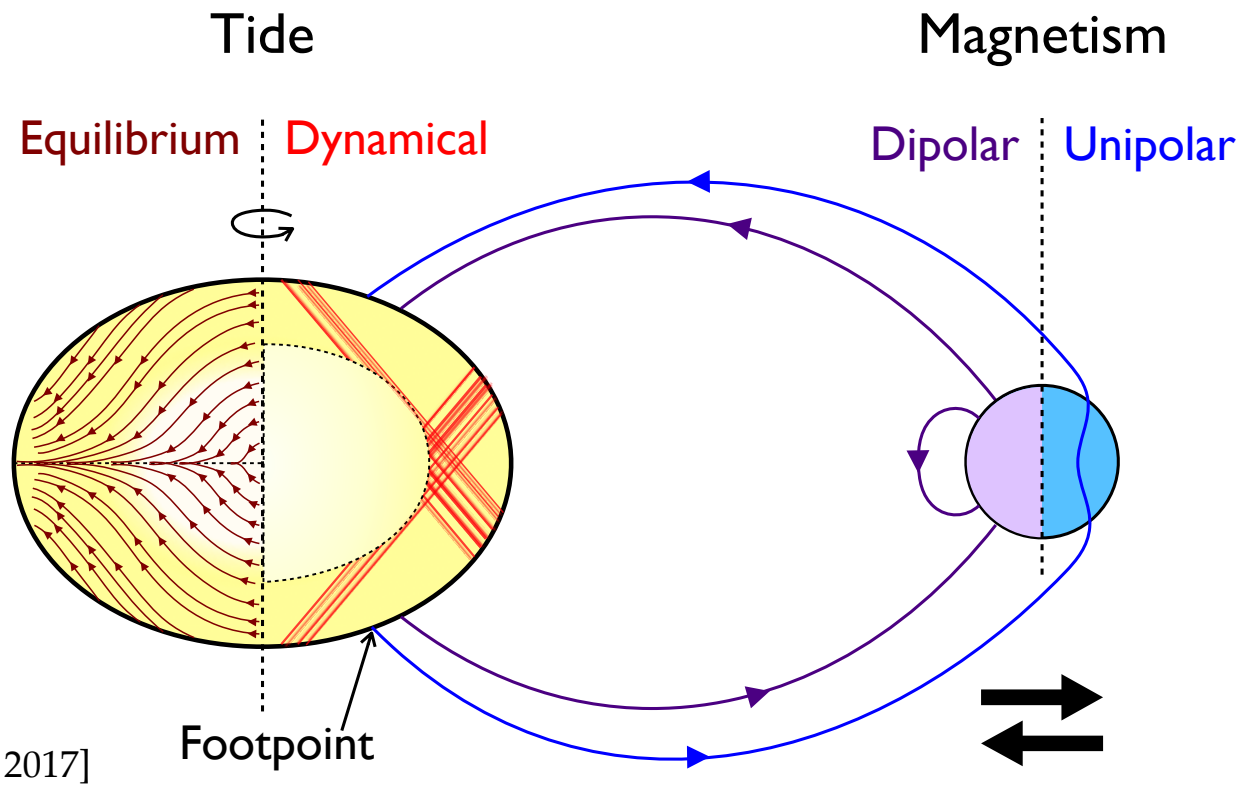

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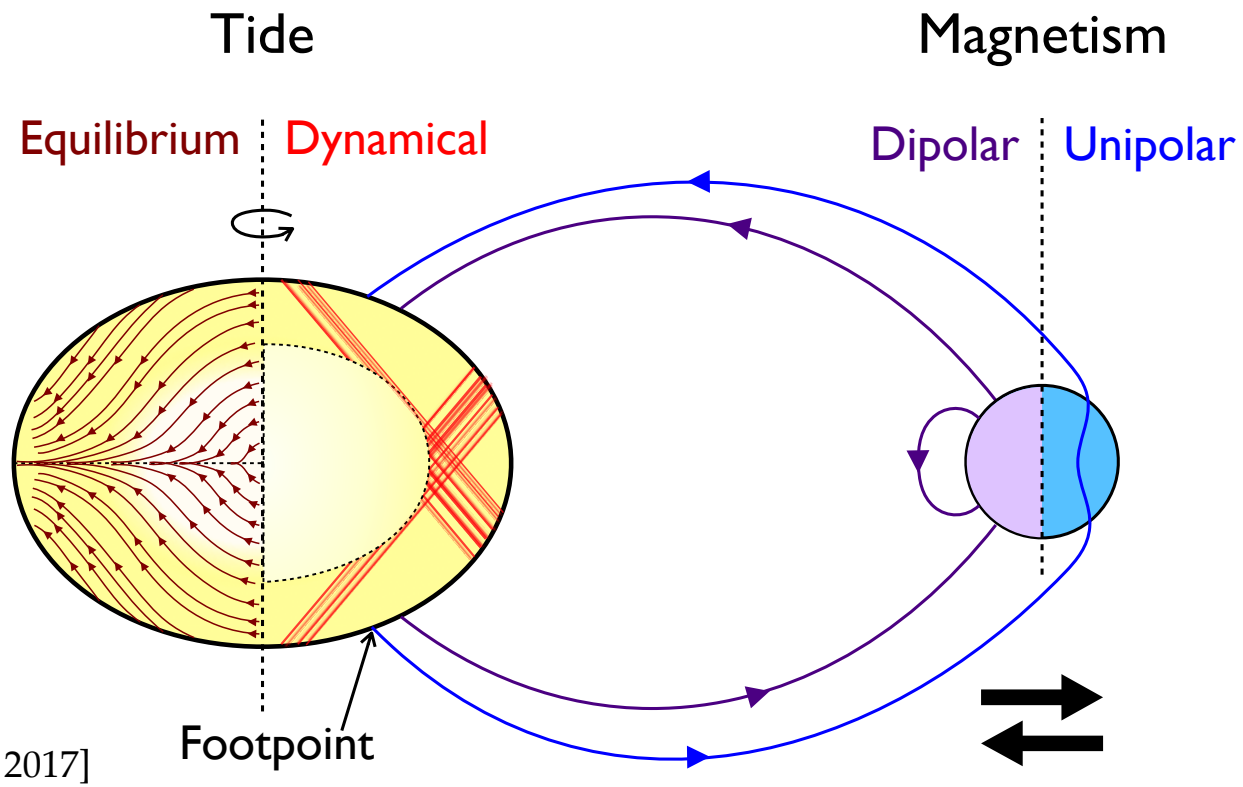

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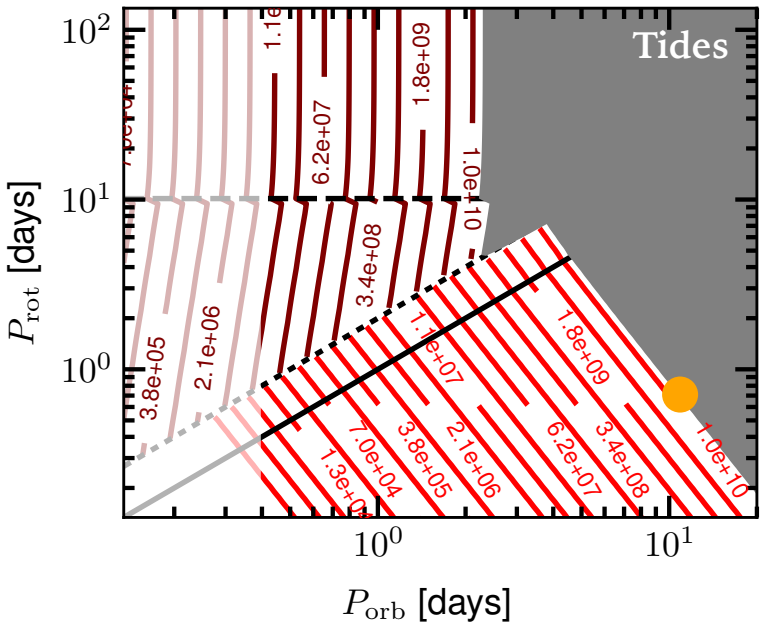
Magnetic torque formulation Strugarek 2016

Application: TTauri star & hot Jupiter (e.g. Tap 26)



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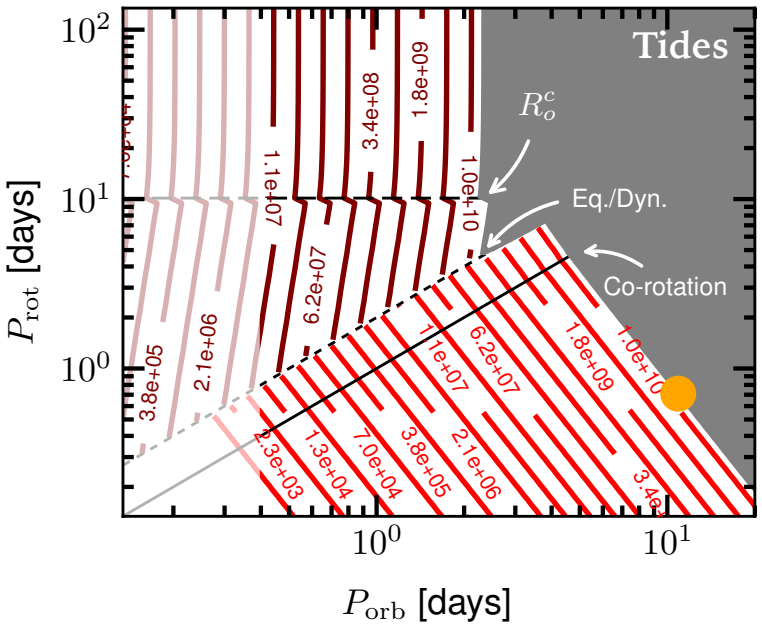

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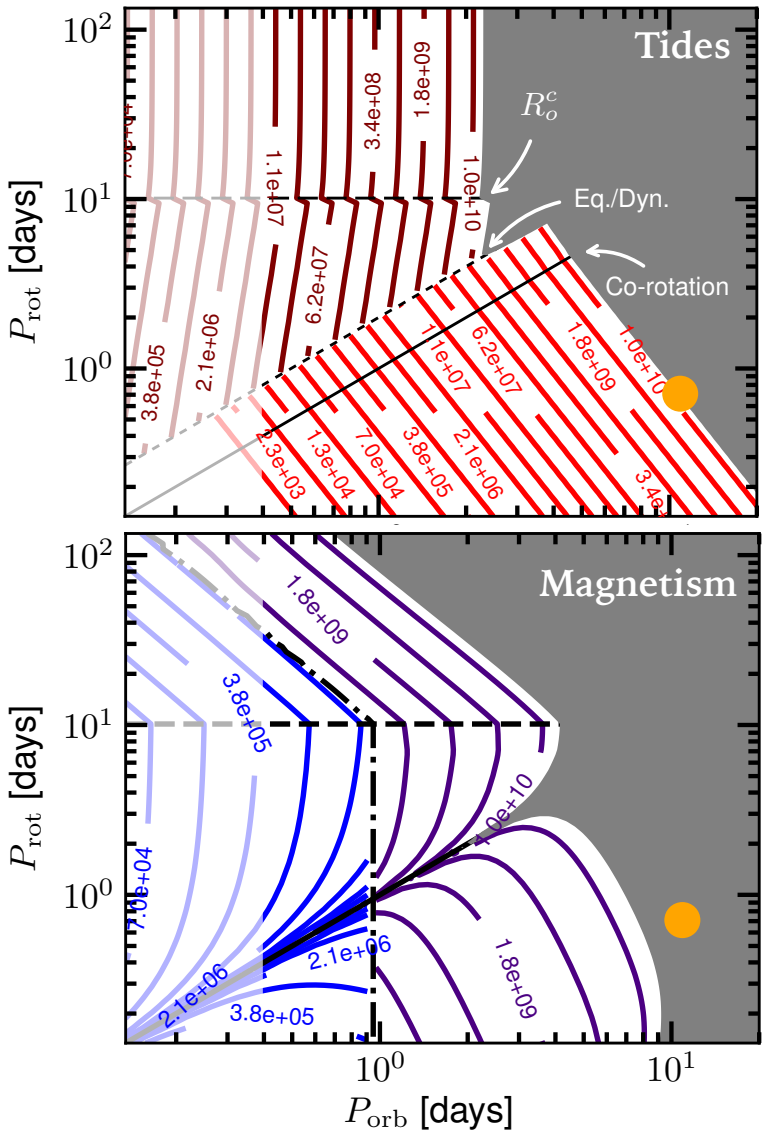

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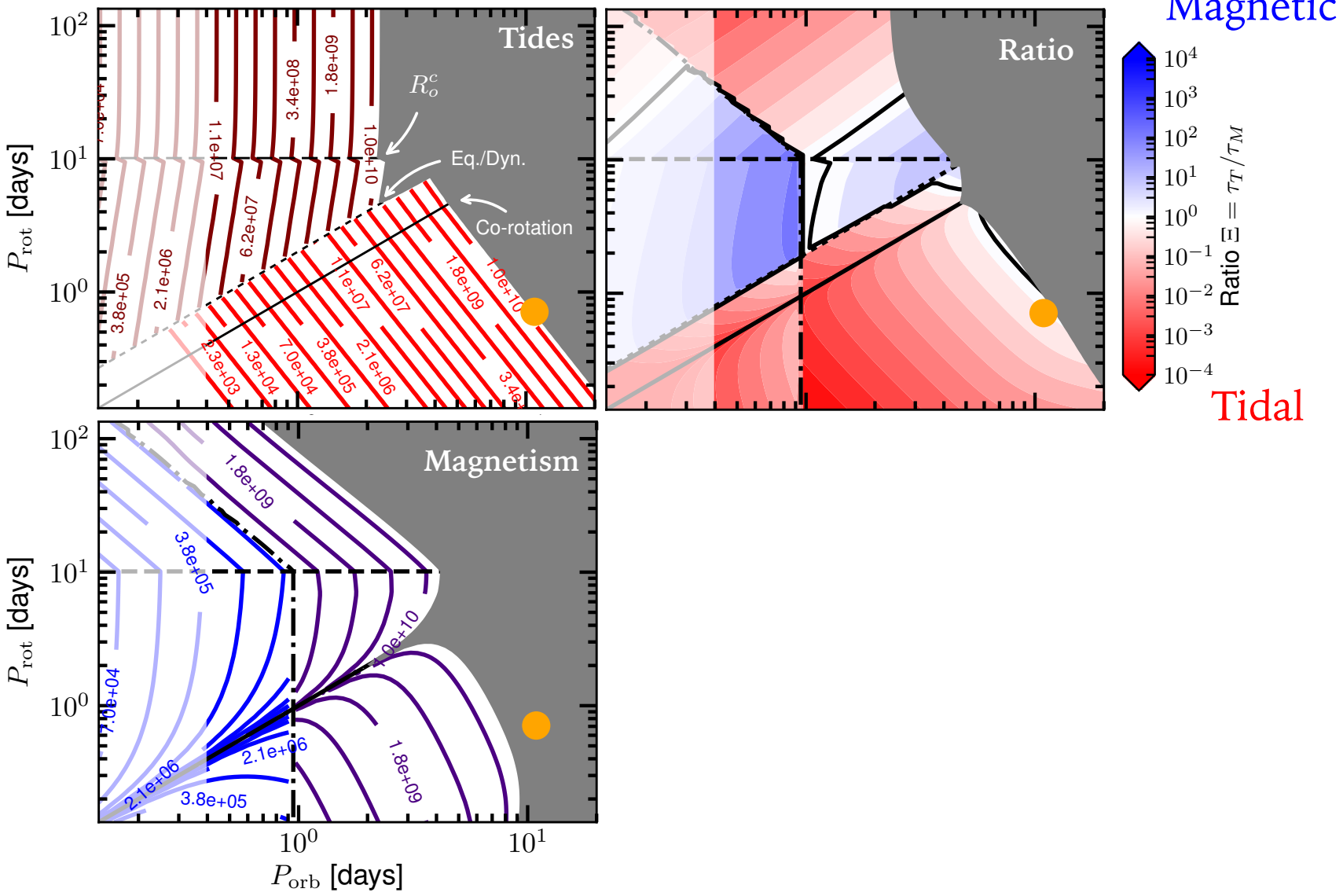

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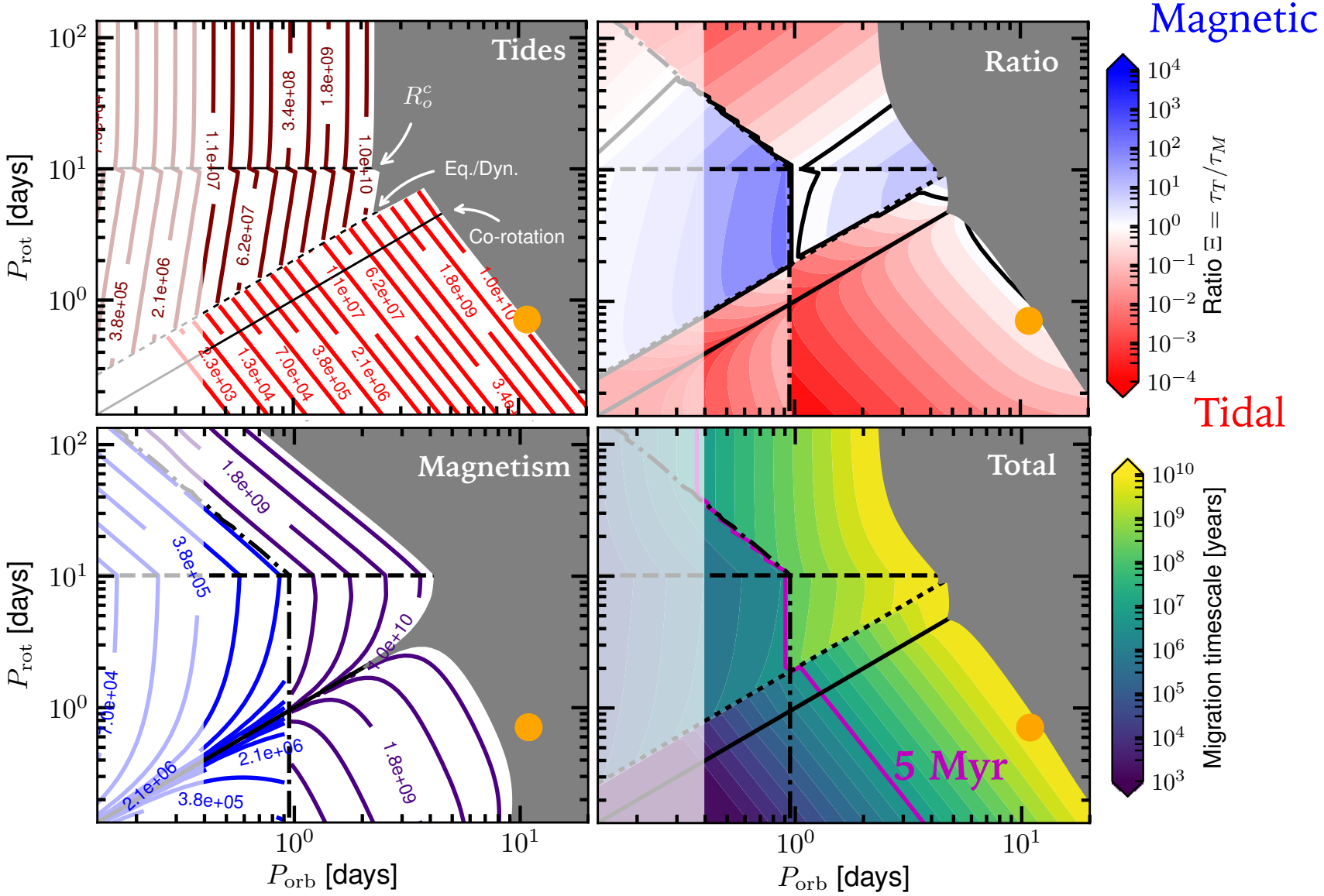
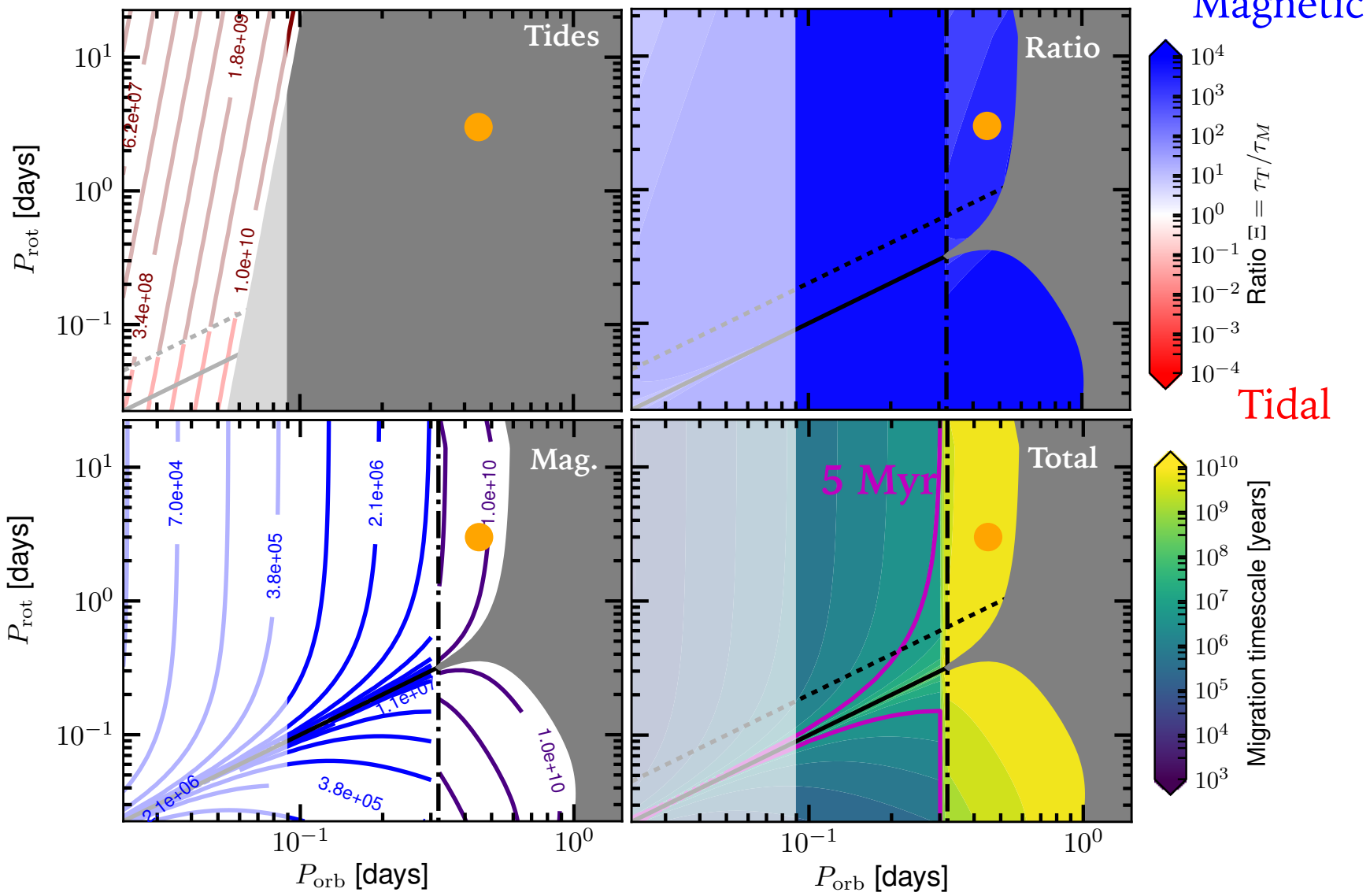


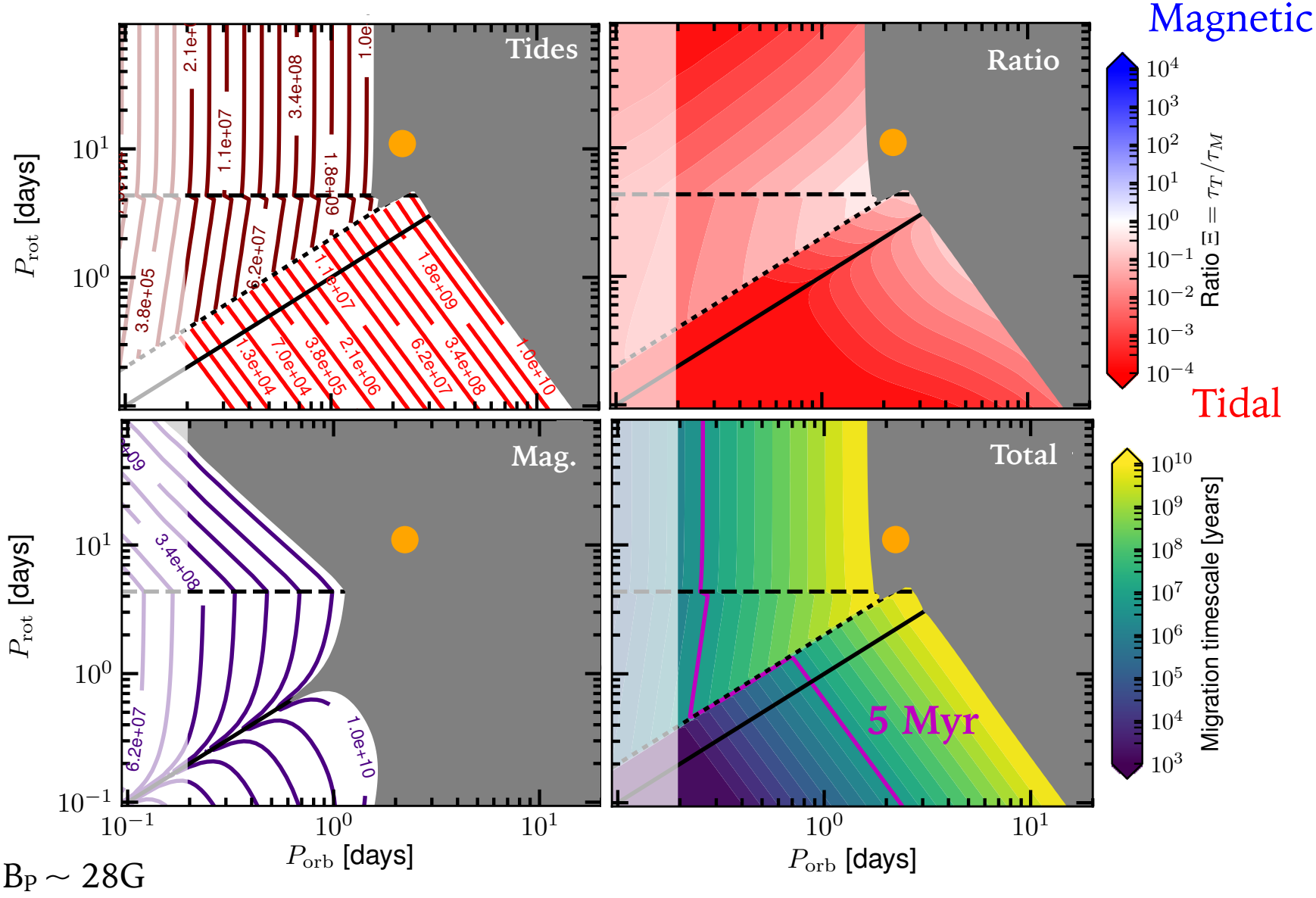
[Strugarek+, ApJL 2017]

Application: M dwarf & Earth-like planet (e.g. Kepler-42)



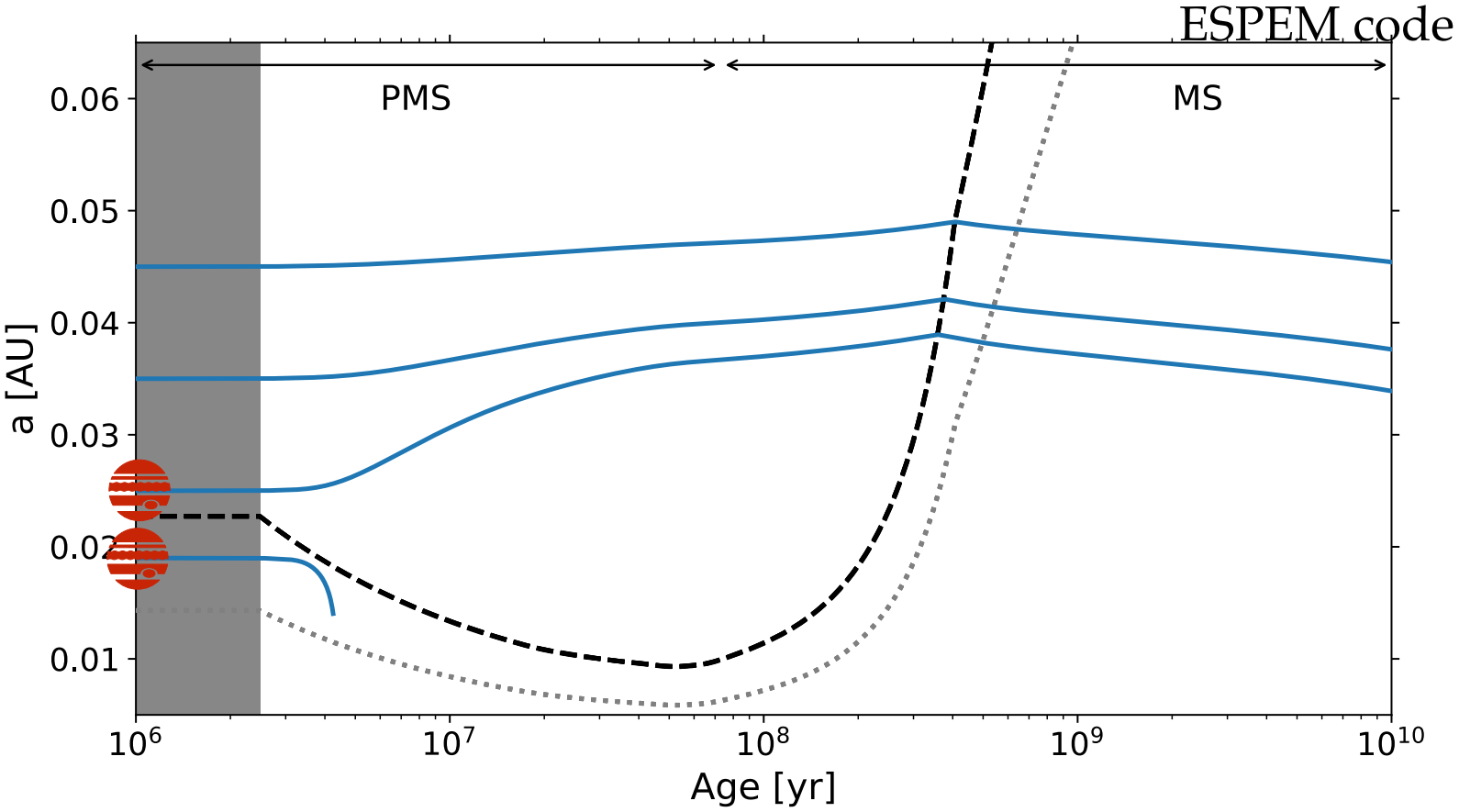
[Strugarek+, ApJL 2017]

Application: K star & hot Jupiter (e.g. HD 189733)



[Strugarek+, ApJL 2017]

Close-in planets migration due to tidal and



[Benbakoura+ 19; Ahuir+ 21]

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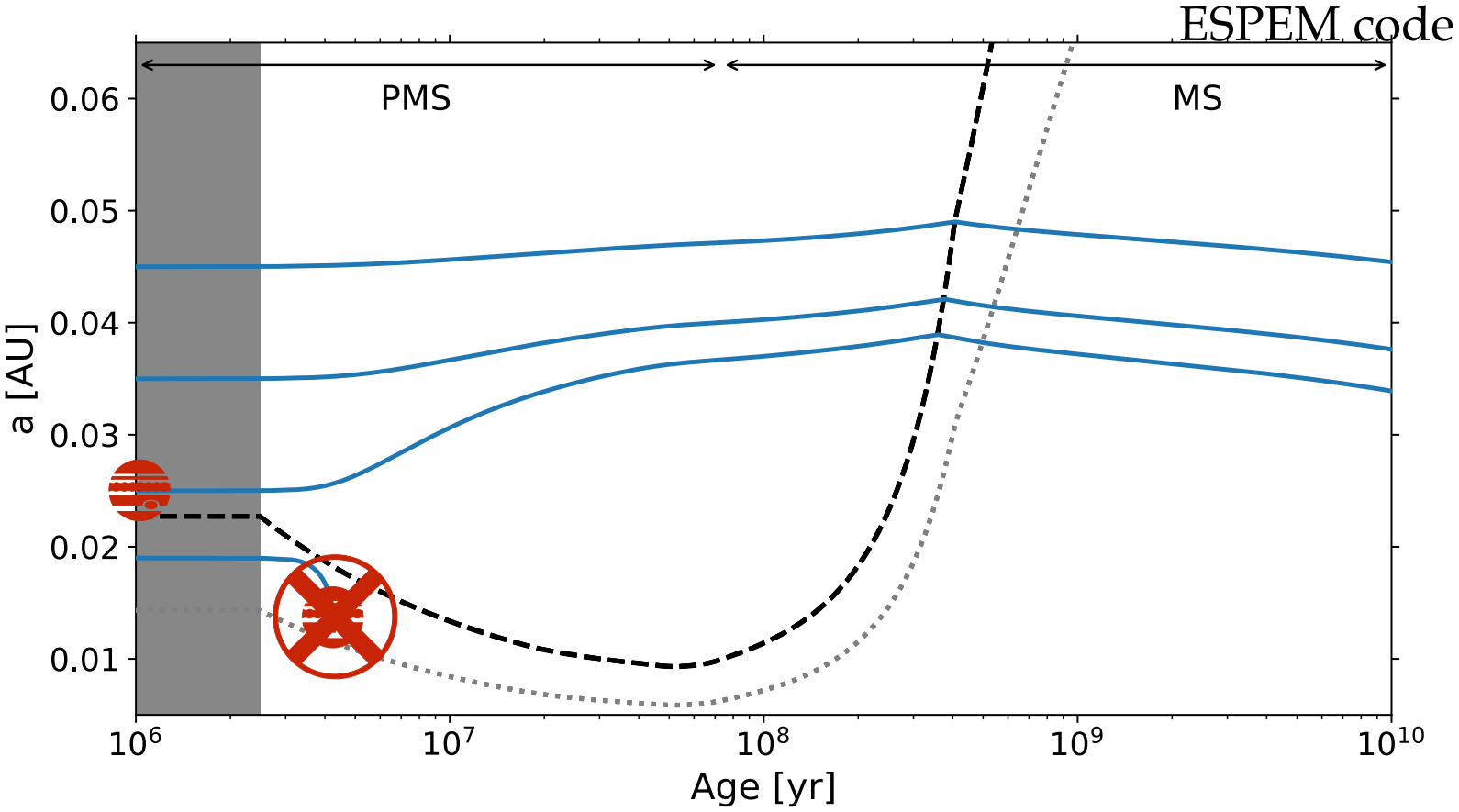

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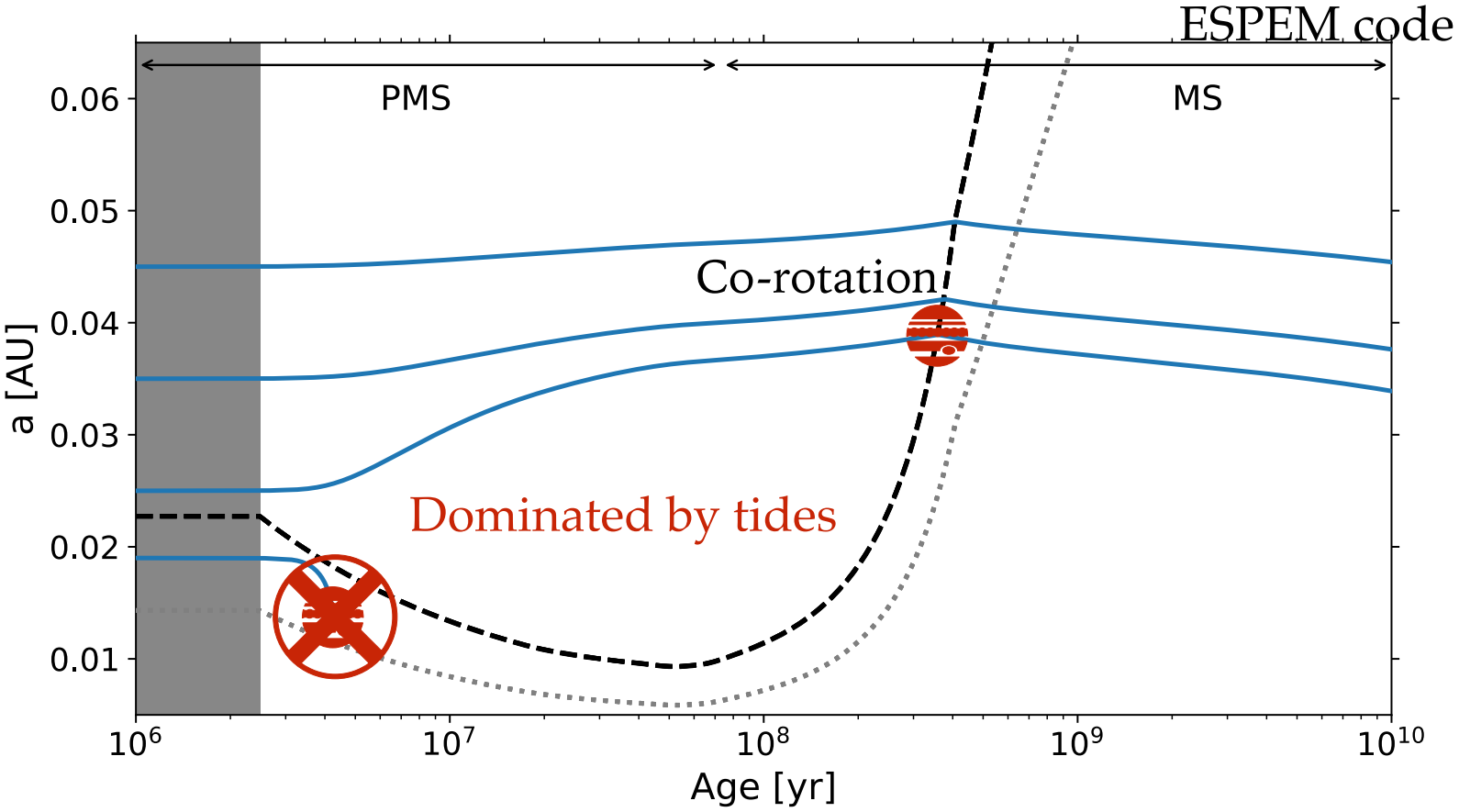

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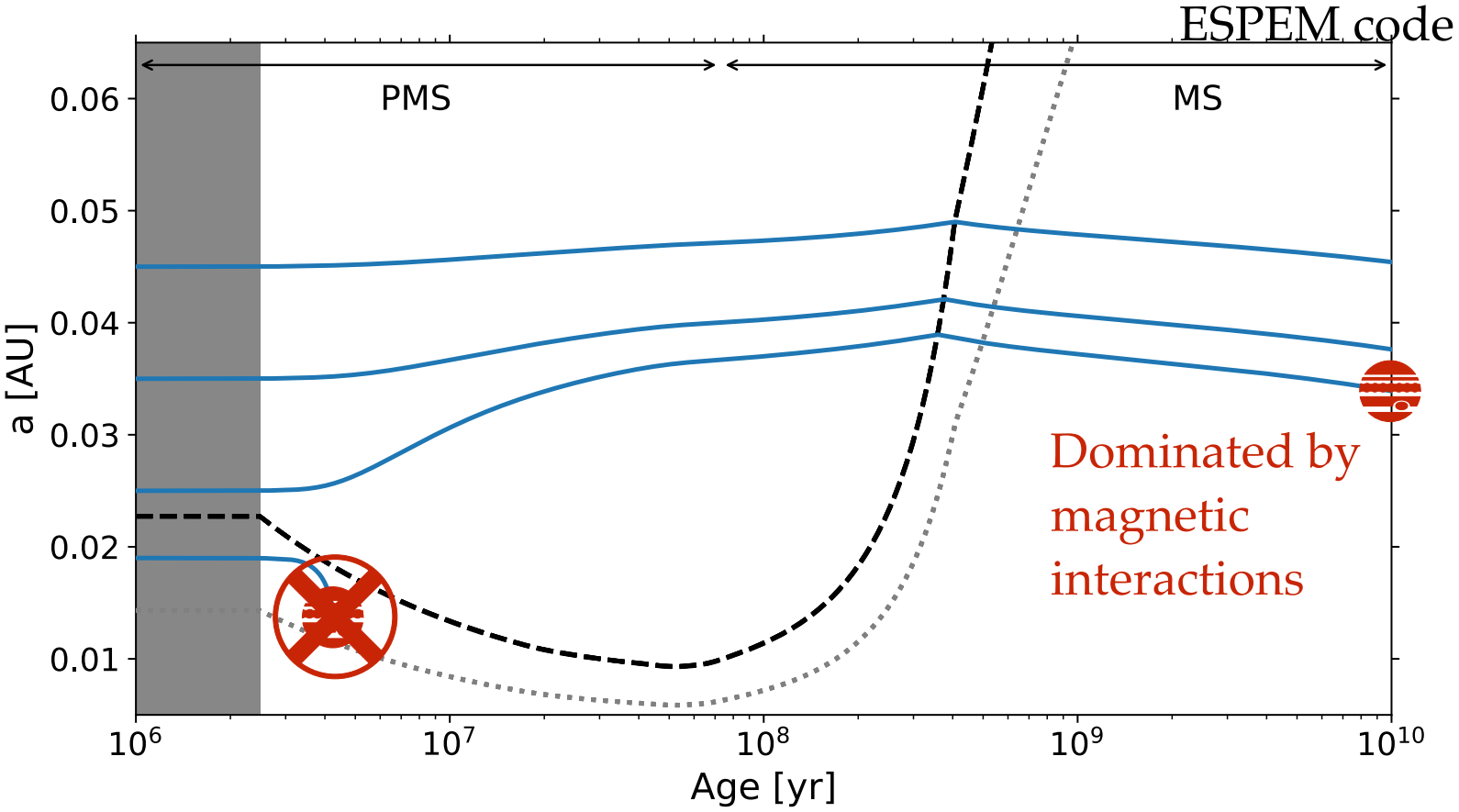

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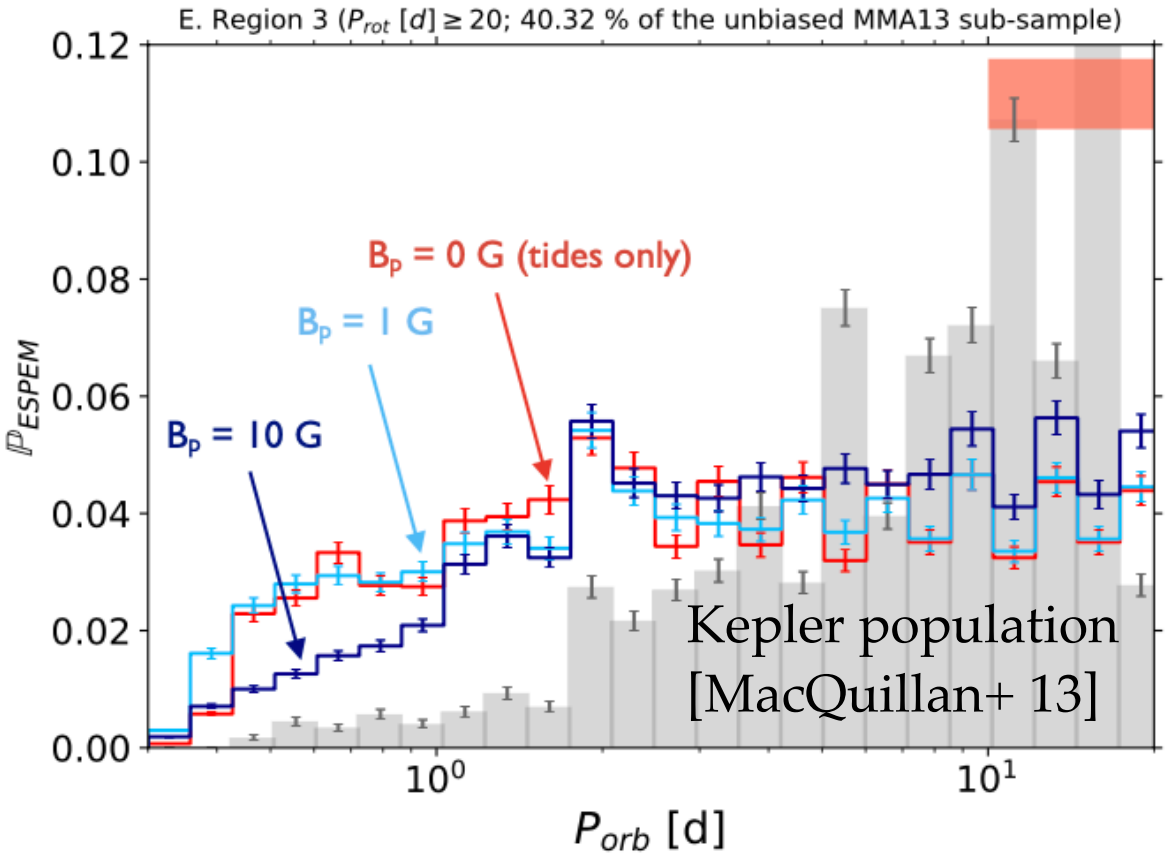
Synthetic population vs Kepler-field population



Magnetic effects shape the distribution of close-in super-Earths (Porb < 1d) around slow rotators (Prot > 5d)

But we still have an excess of hot planets in our synthetic sample:

- Initial conditions effects?
- Extreme planetary dynamo?
- Additional Star-Planet interactions?

[Ahuir+ 21]

Major effects of star-planet magnetic interactions

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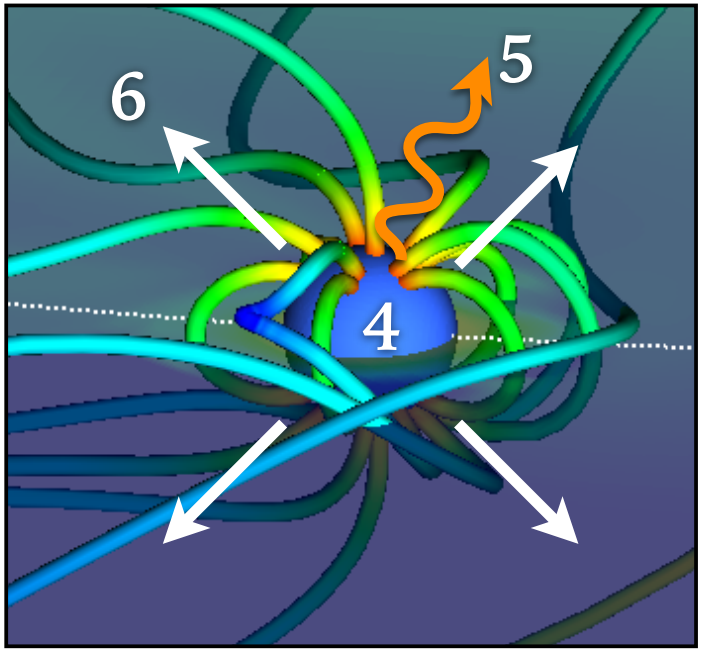
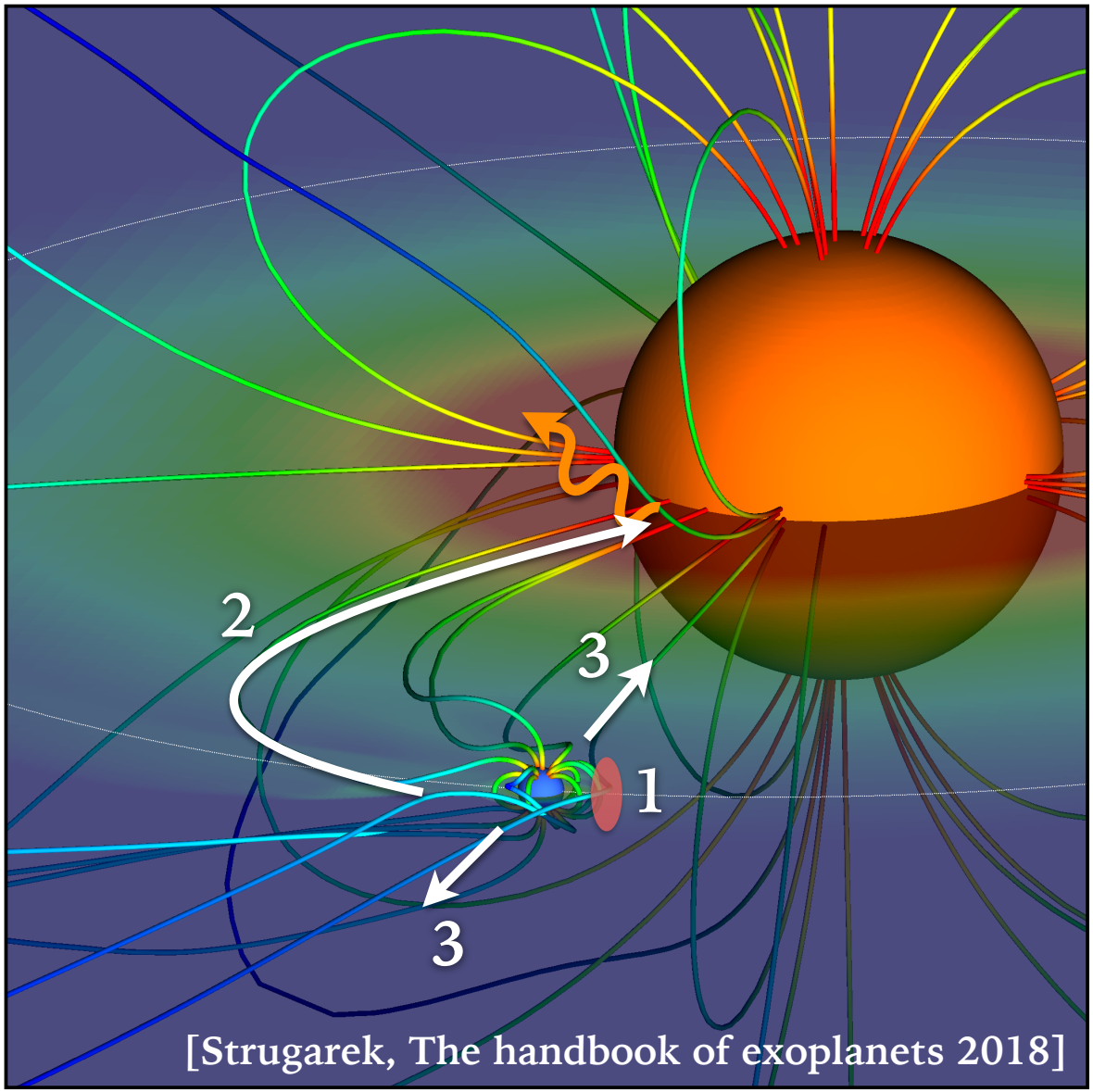
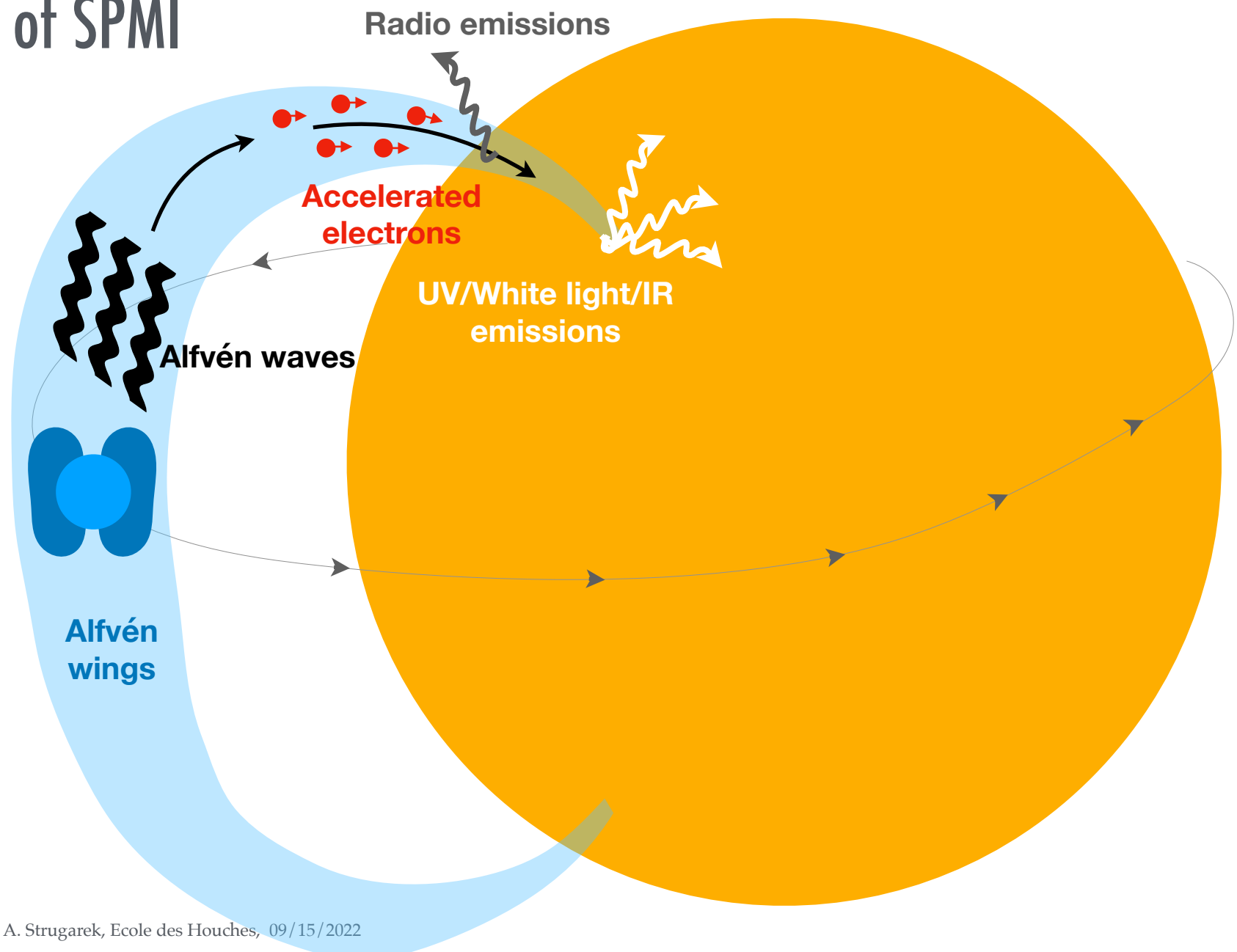




Perspectives: the missing aspects of SPMI



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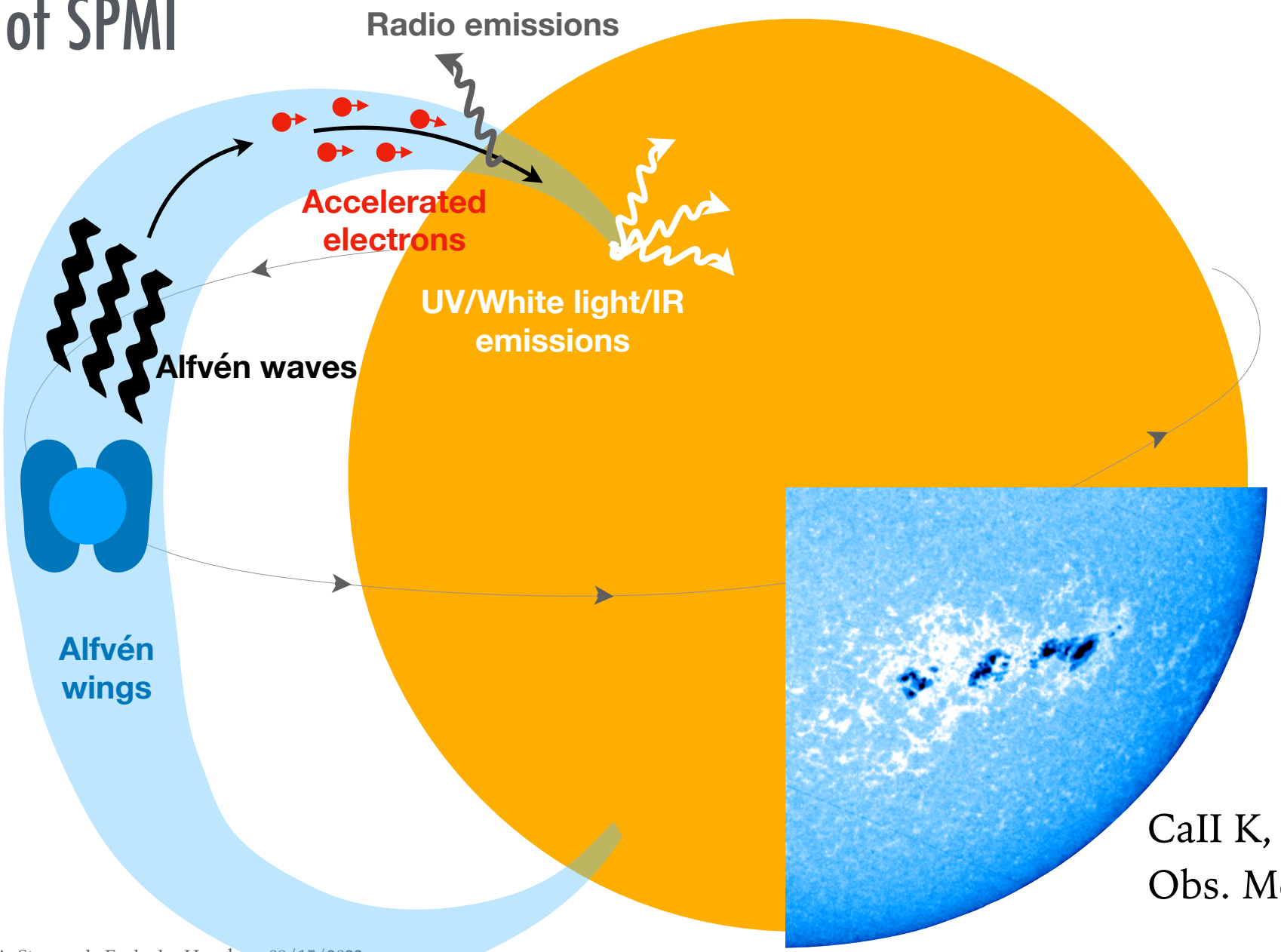

CaII K,
Obs. Meudon

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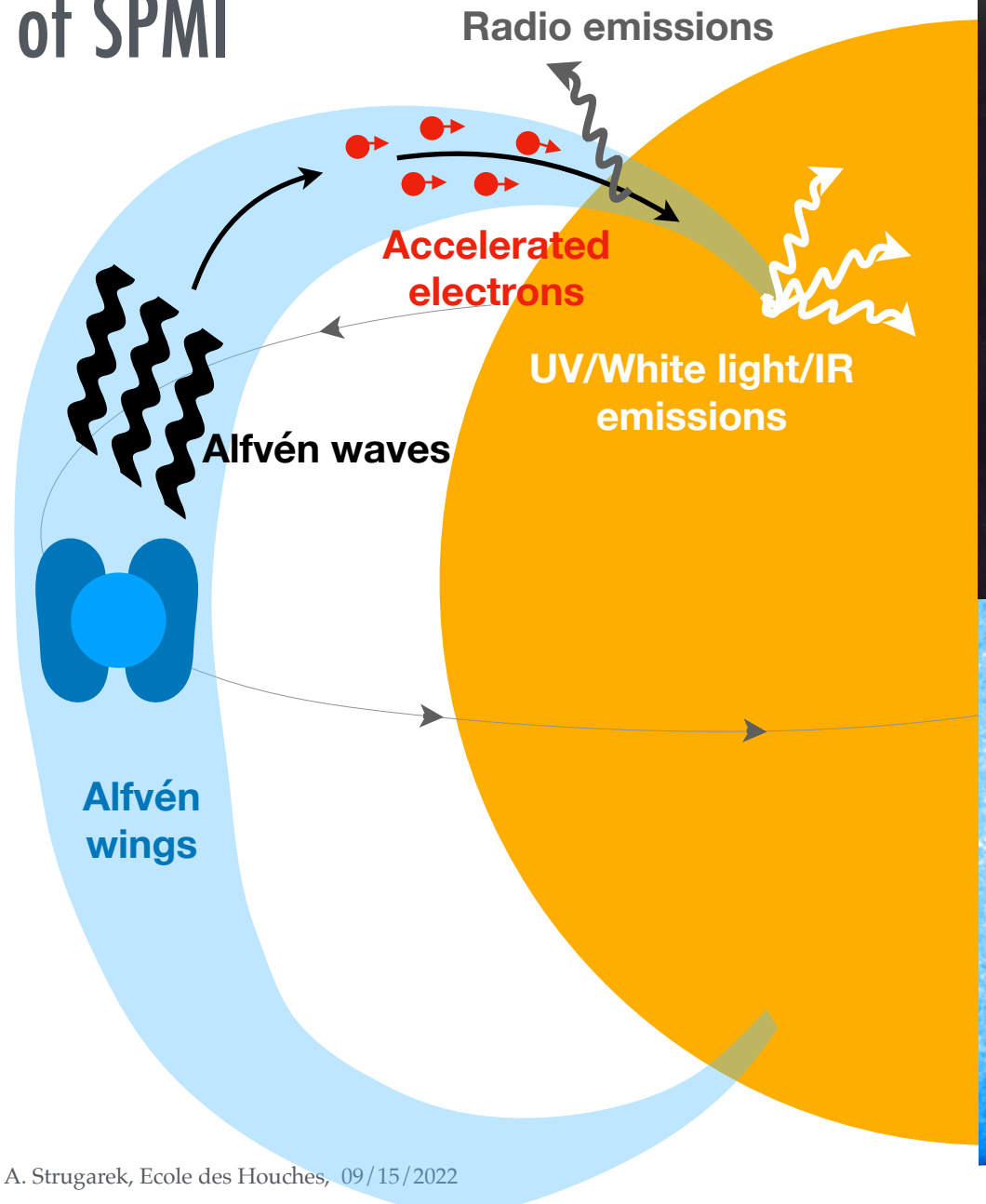
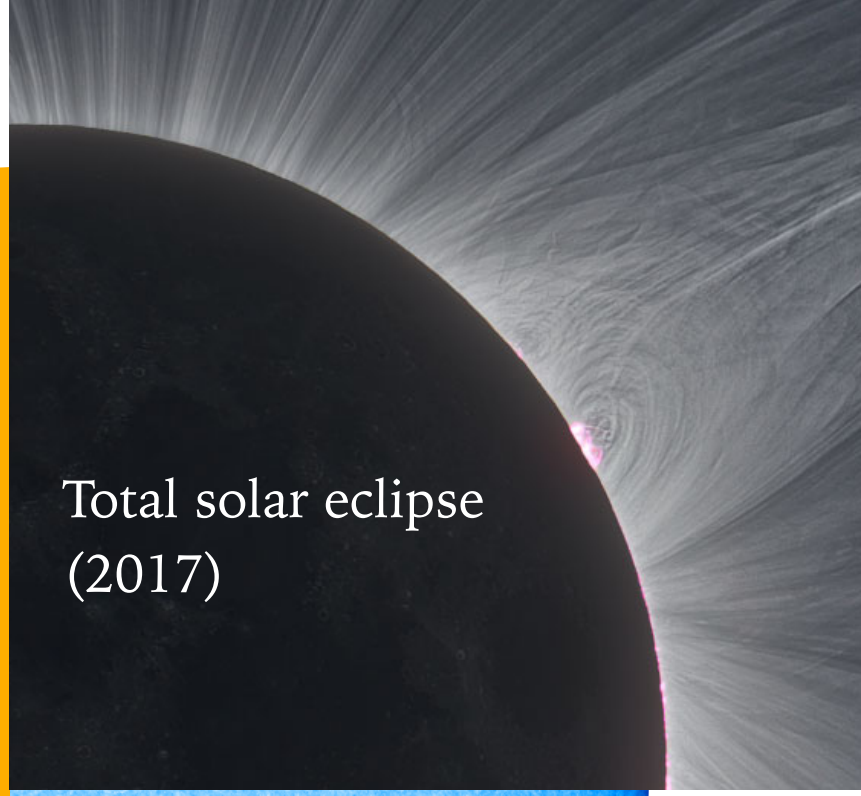
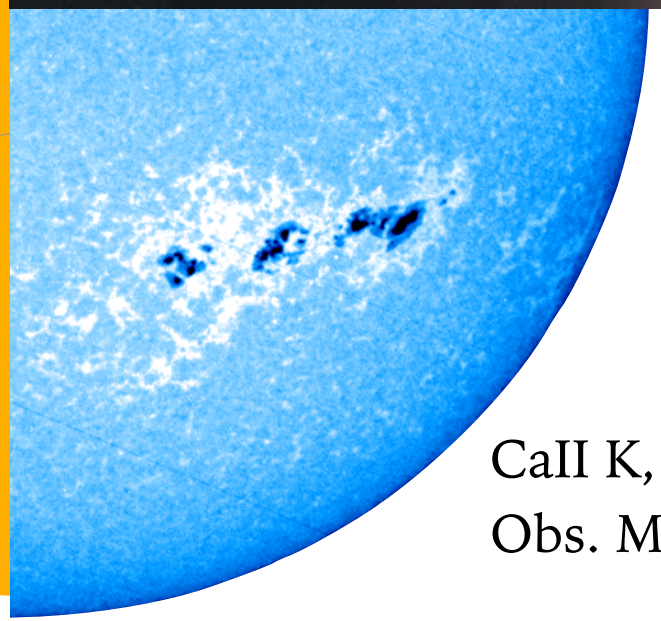




Total solar eclipse (2017)

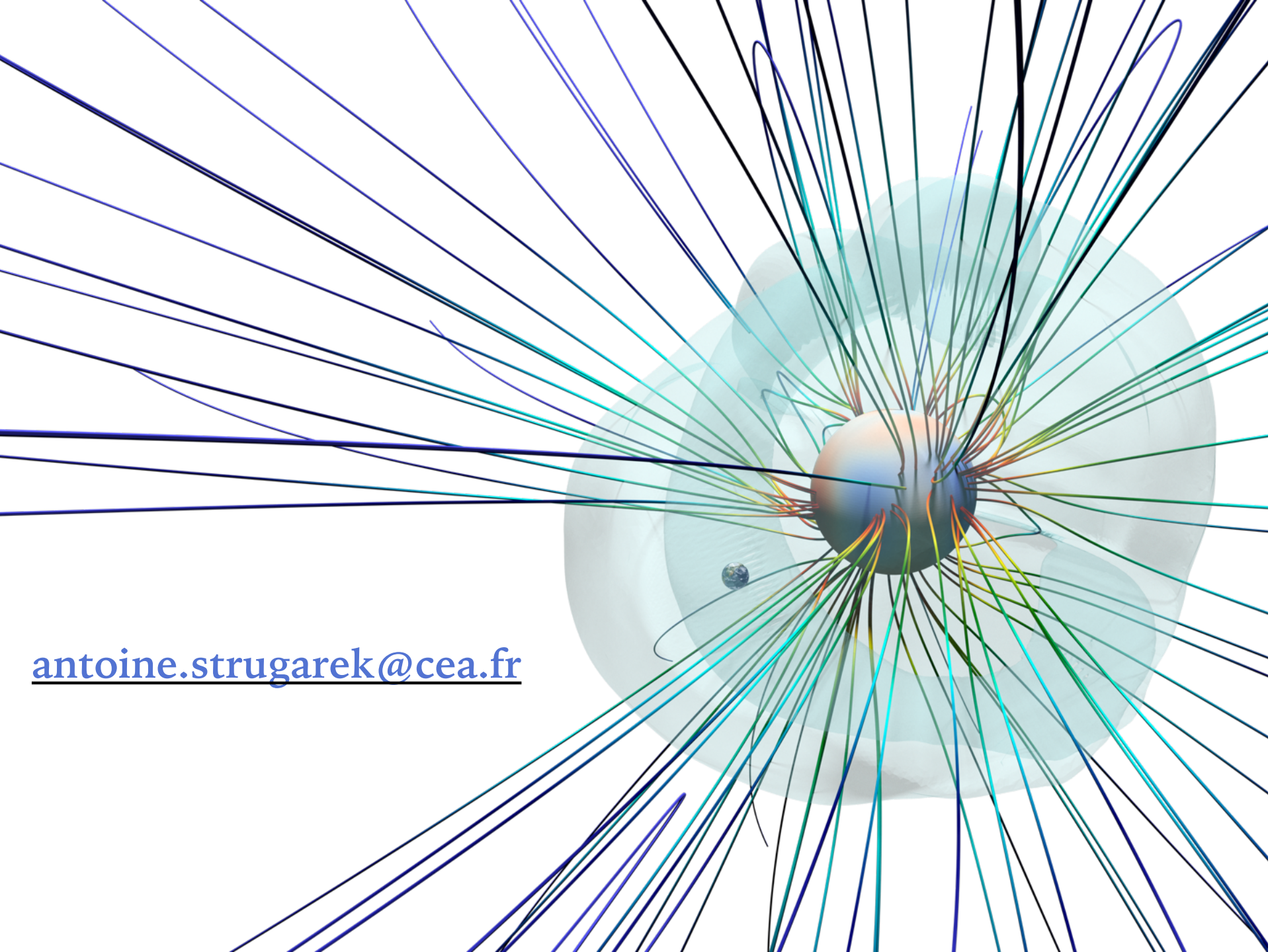


CaII K, Obs. Meudon

Third 'atelier ExoSystèmes' for the french community

SOC

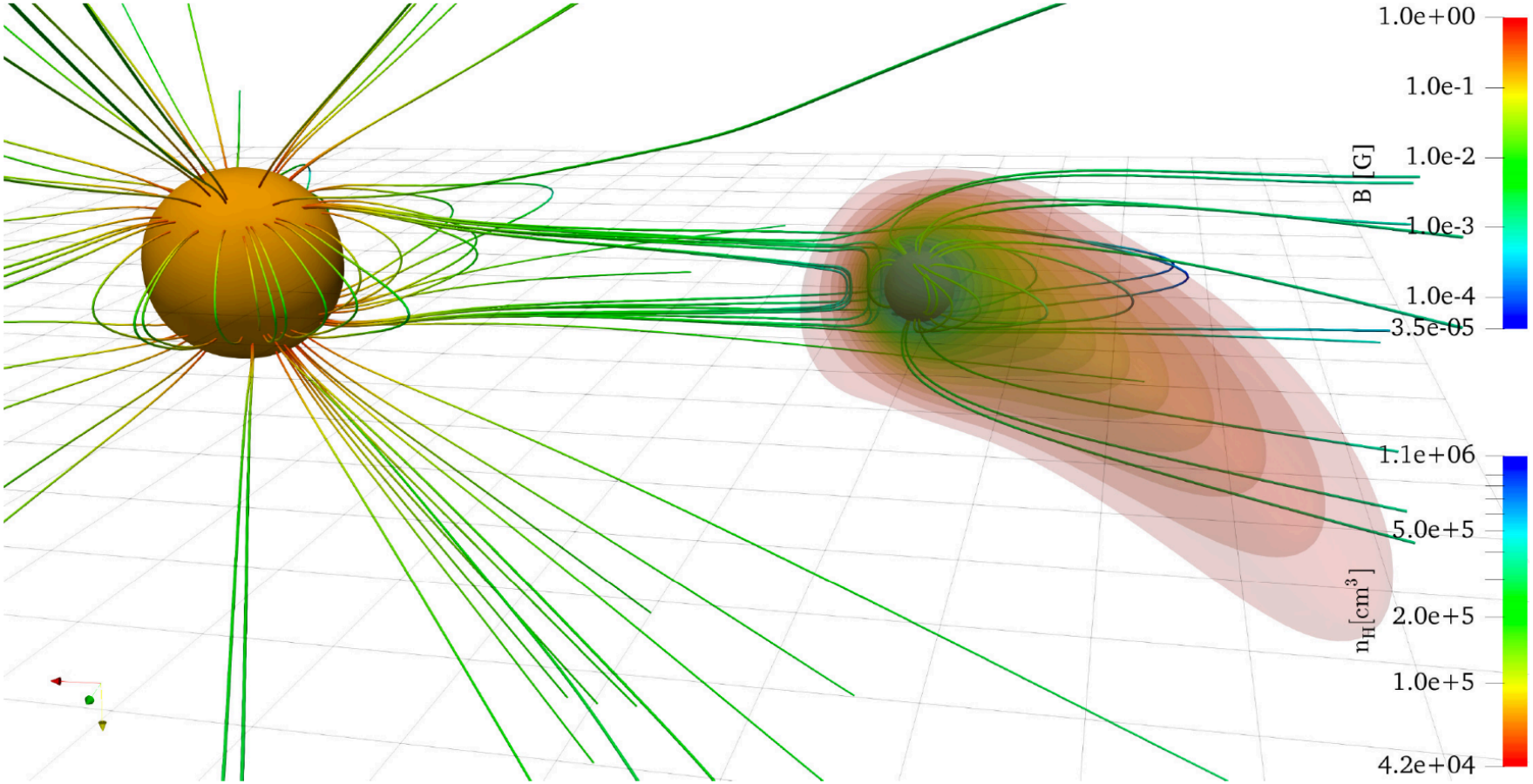
F. Cantaloube
M. Deleuil
Q. Kral
P.O. Lagage
J. Leconte
A. Santerne
A. Strugarek



antoine.strugarek@cea.fr

Lyman-alpha absorption in HD 209458b

Villarreal d'Angelo+ 18: MHD model including a neutral escaping atmosphere of H



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