

A predictive framework for realistic star-planet radio emission in compact systems

Presenter: Judy chebly

Collaborators:

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Corentin Louis & Philippe Zarka – LIRA, Observatoire de Paris, Université PSL, Sorbonne Université

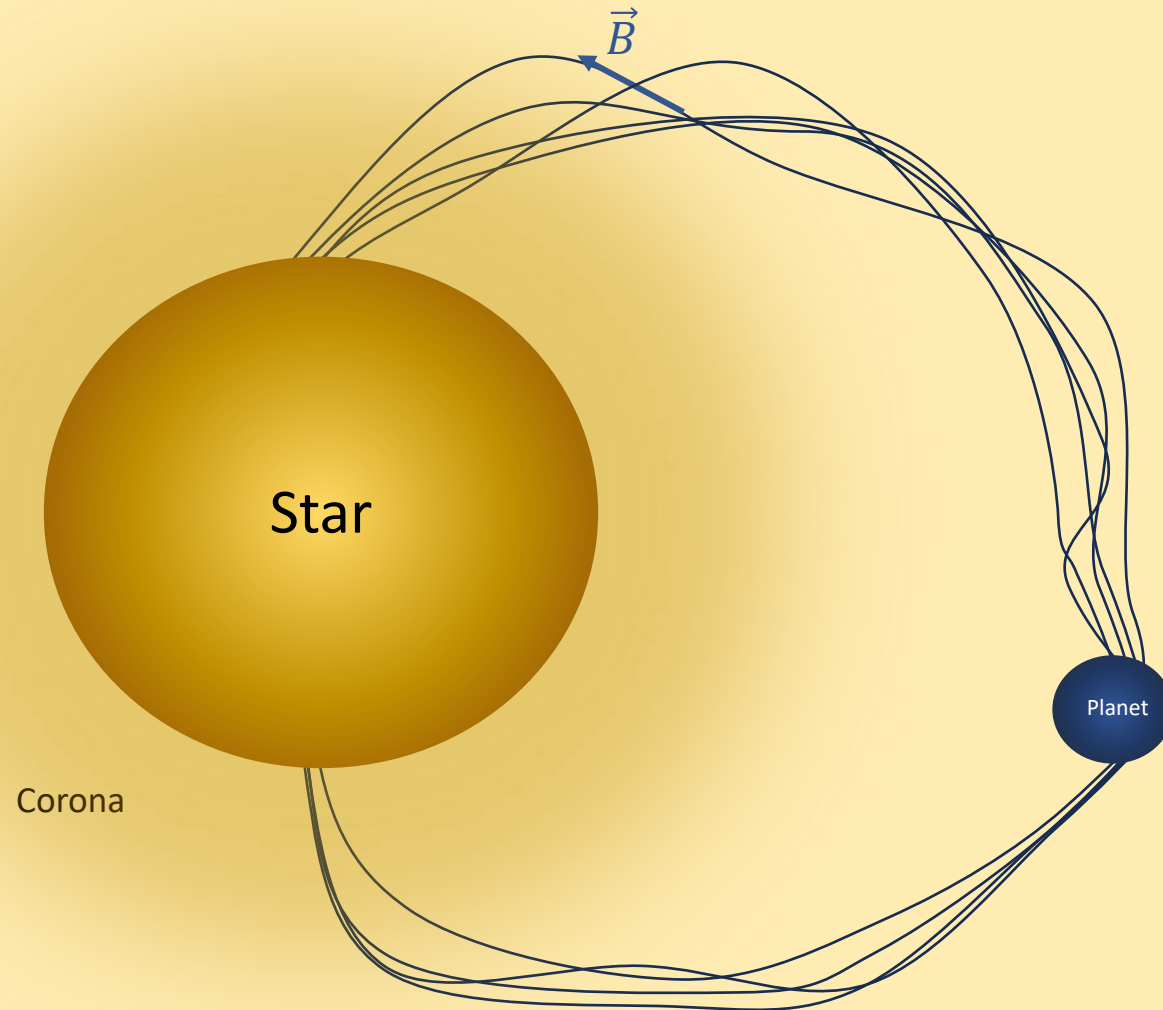
Julián David Alvarado Gómez– Leibniz institute for Astrophysics, Potsdam Germany



Credit: NASA, ESA, and A. Schaller

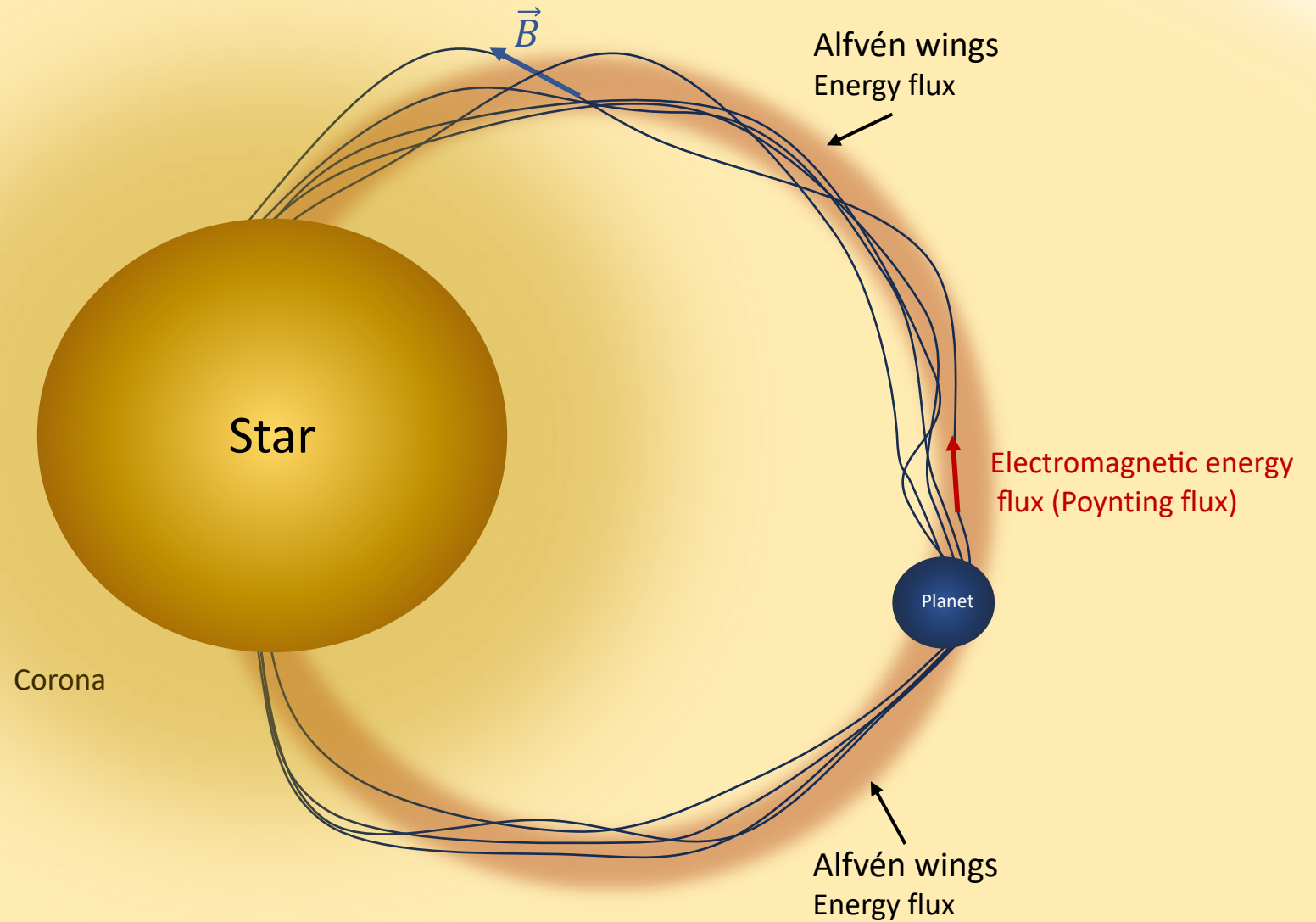
Star-planet interaction (SPI) induced radio emission

Planet in sub-Alfvénic regime
Conducting plasma permeated by the stellar magnetic field.

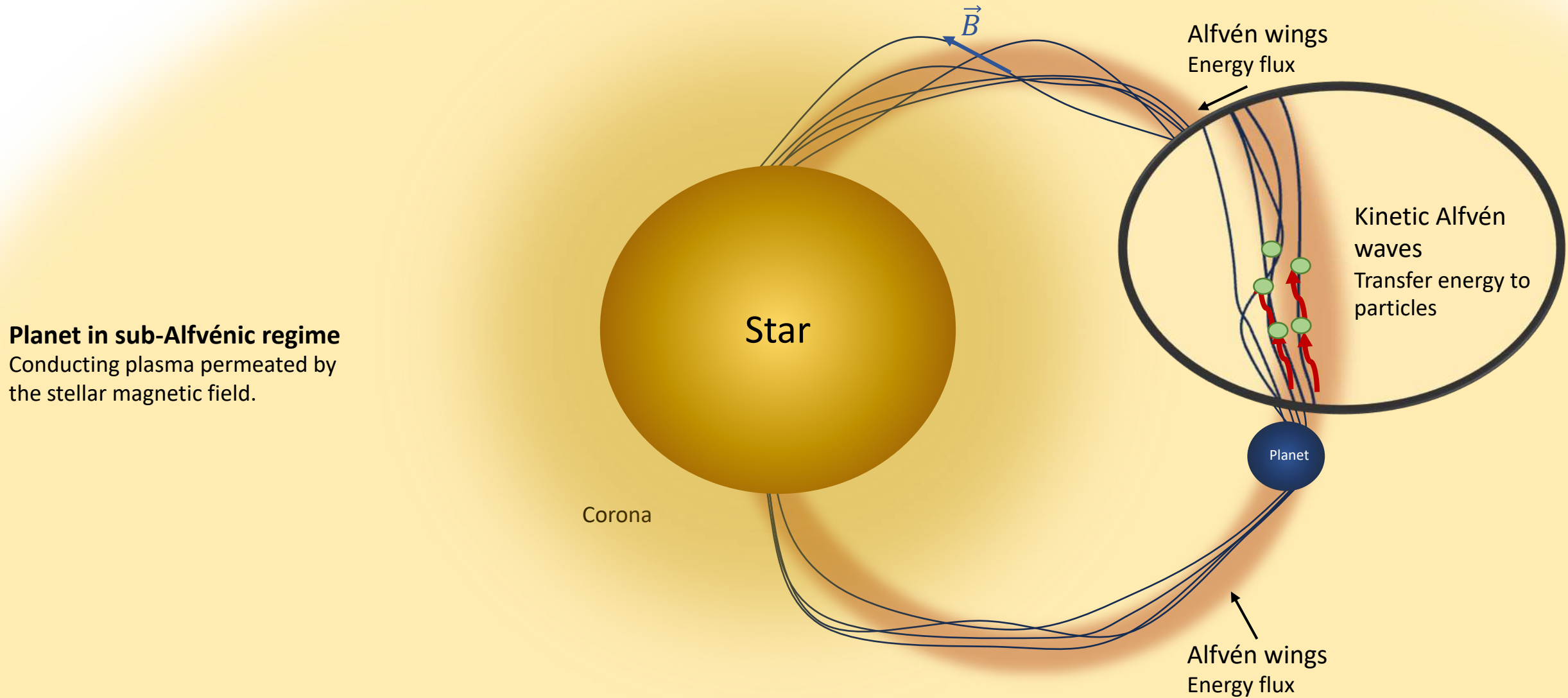


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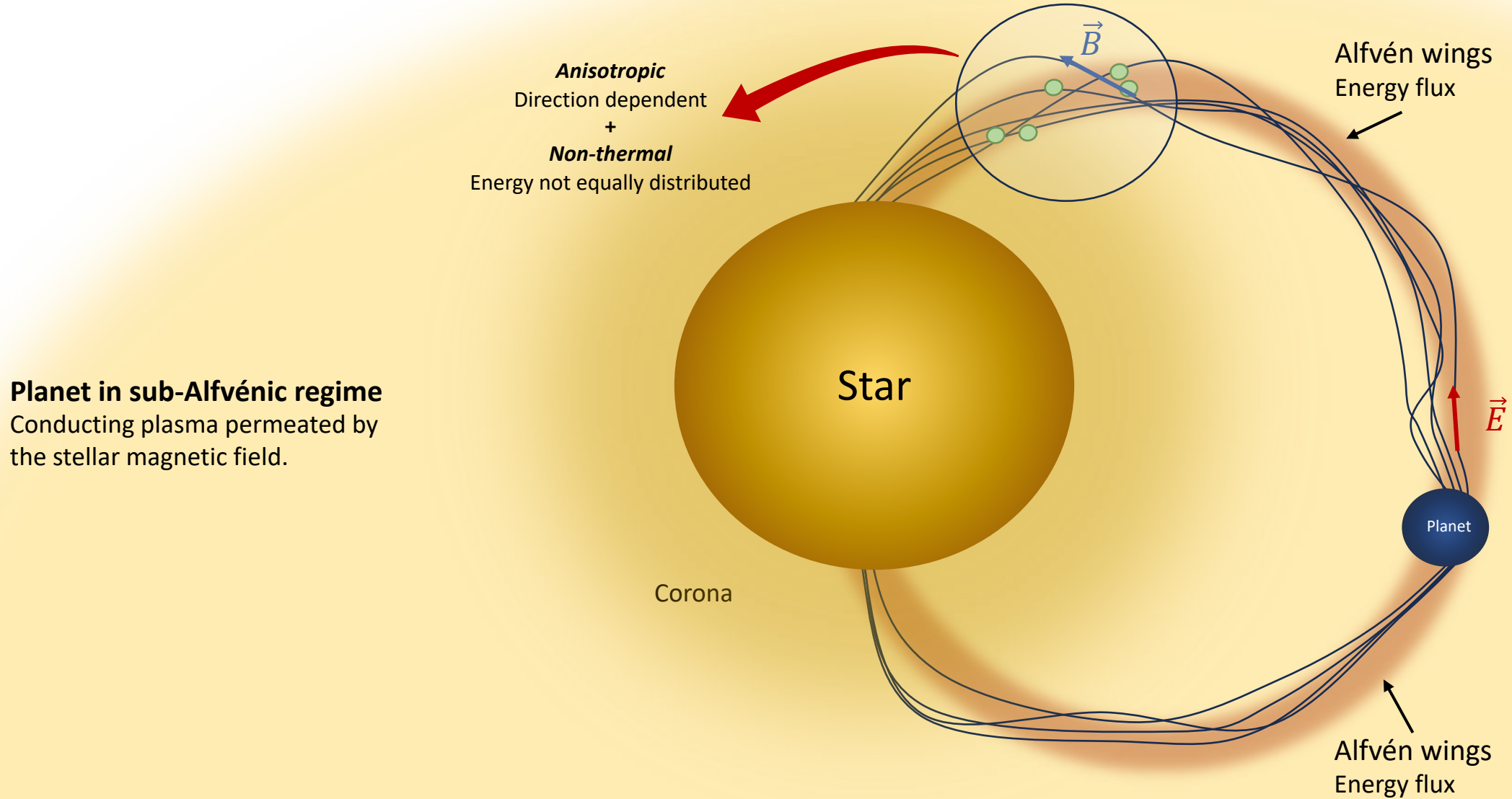
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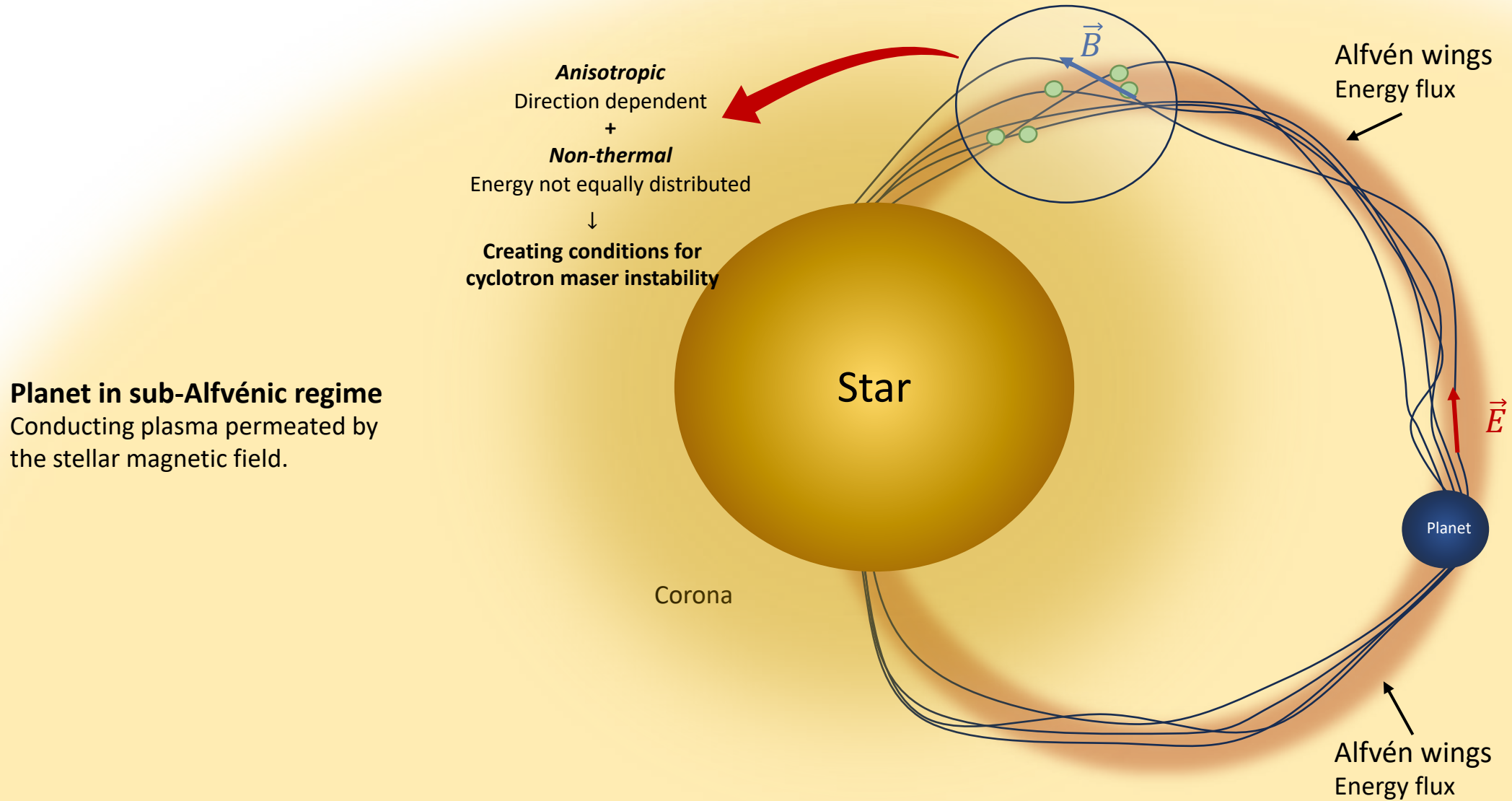
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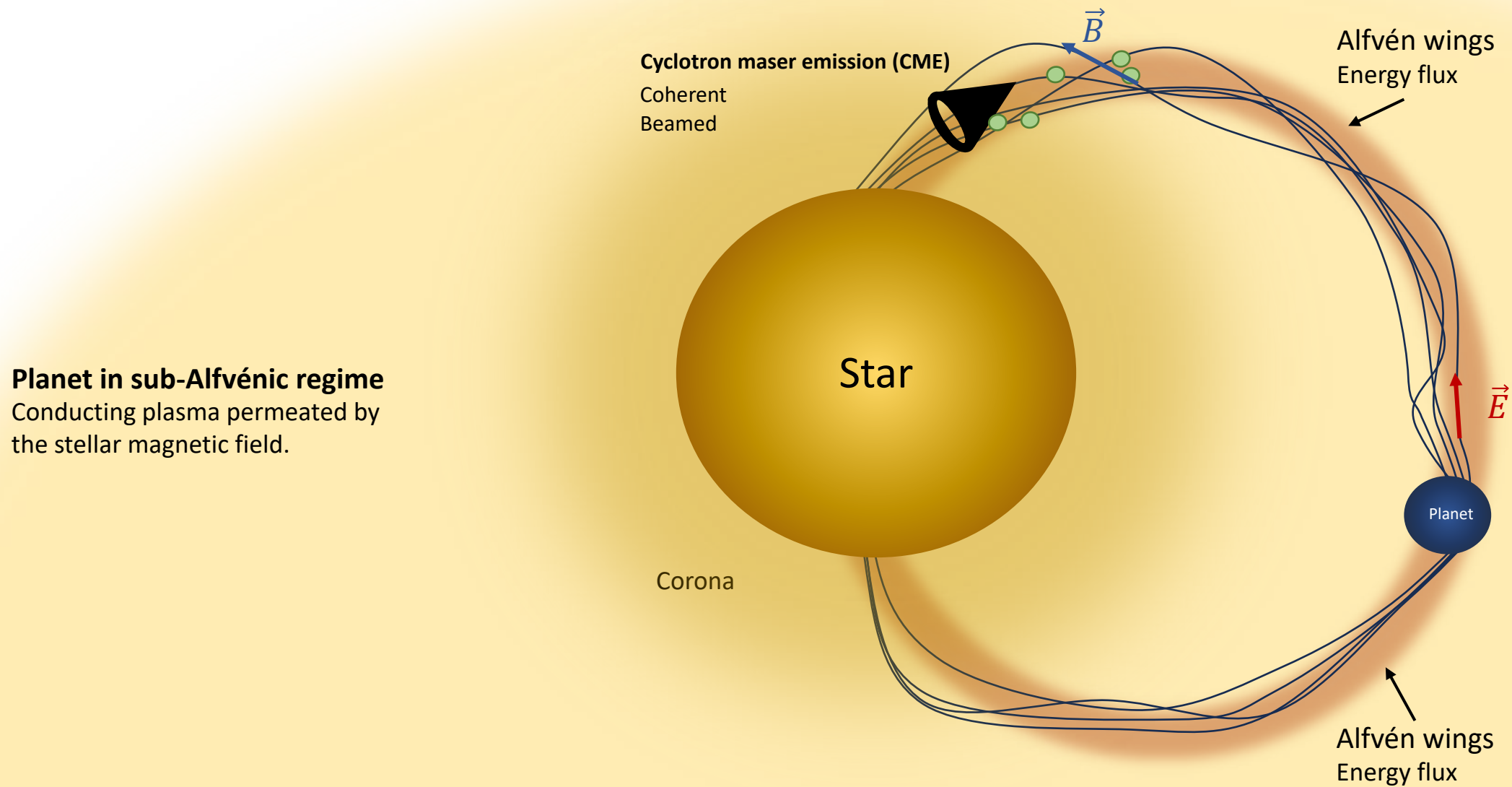
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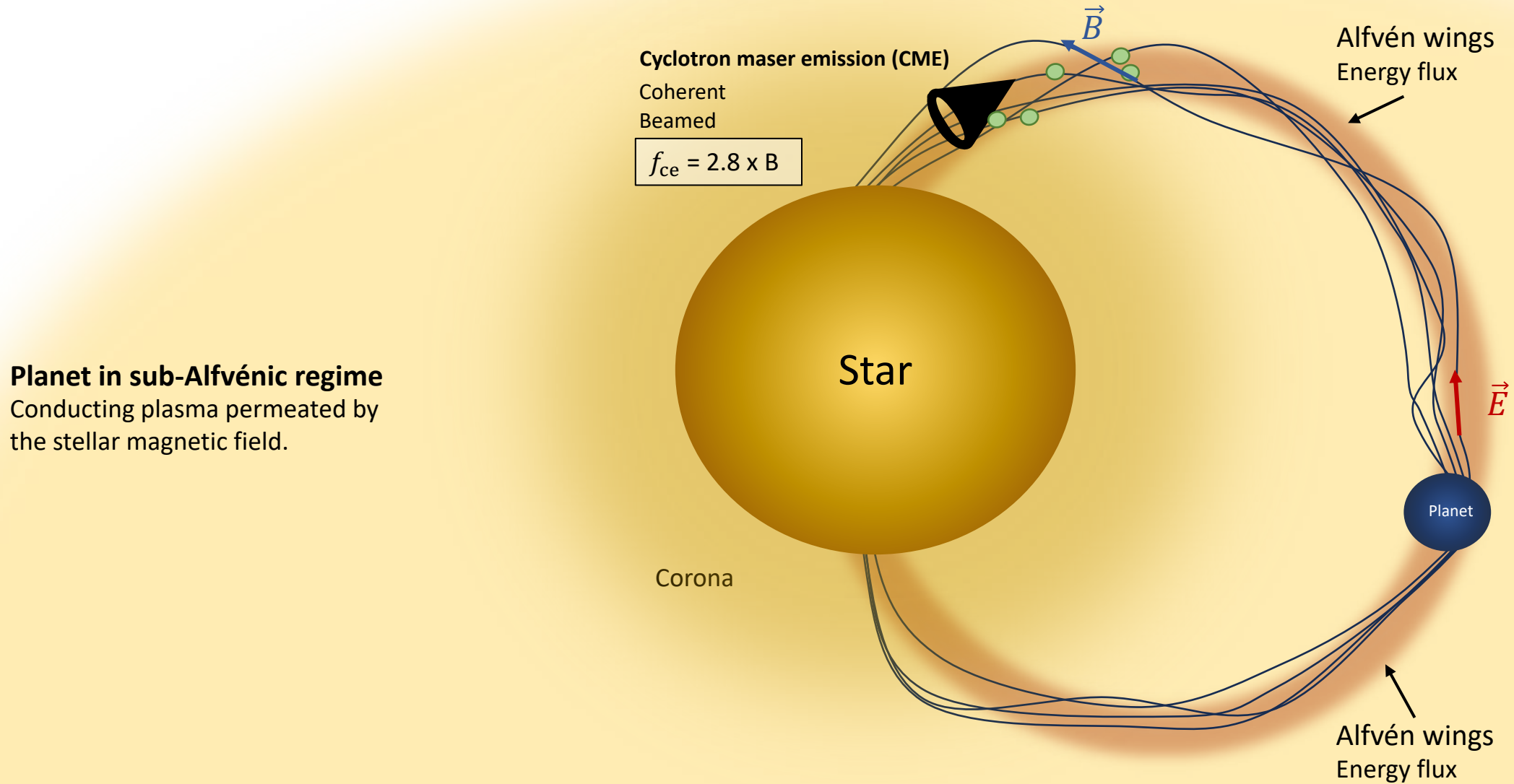
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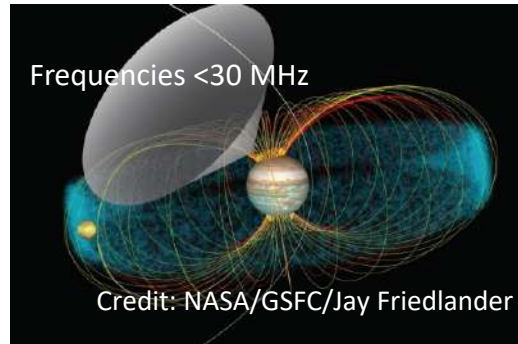
Star-planet interaction (SPI) induced radio emission

Observation from the
Solar system

Observation from Exosystems

Detection

Jupiter-Io interaction

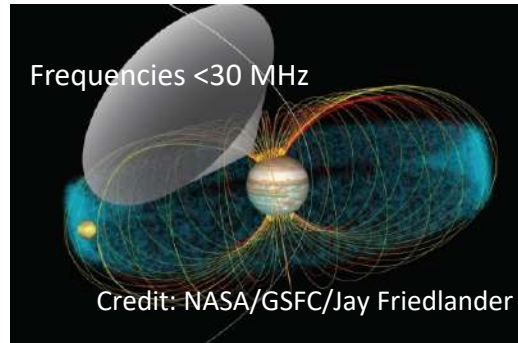


Star-planet interaction (SPI) induced radio emission

Observation from the
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Observation from Exosystems

Lack of detection / lack of clear
detection

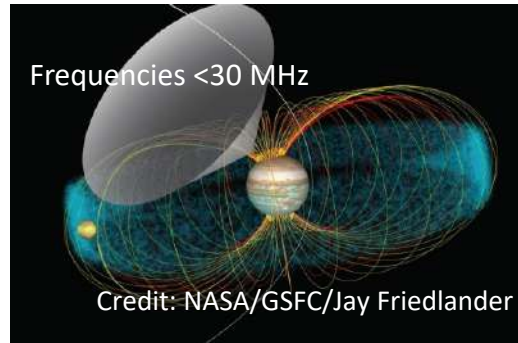
Plasma environment that
controls generation, escape, and
observable frequency **cannot be
directly observed.**

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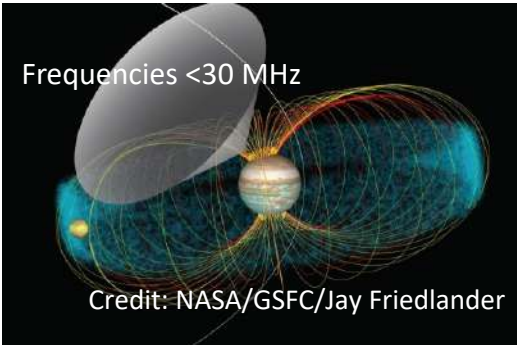
Making current searches largely
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Star-planet interaction (SPI) induced radio emission

Observation from the Solar system

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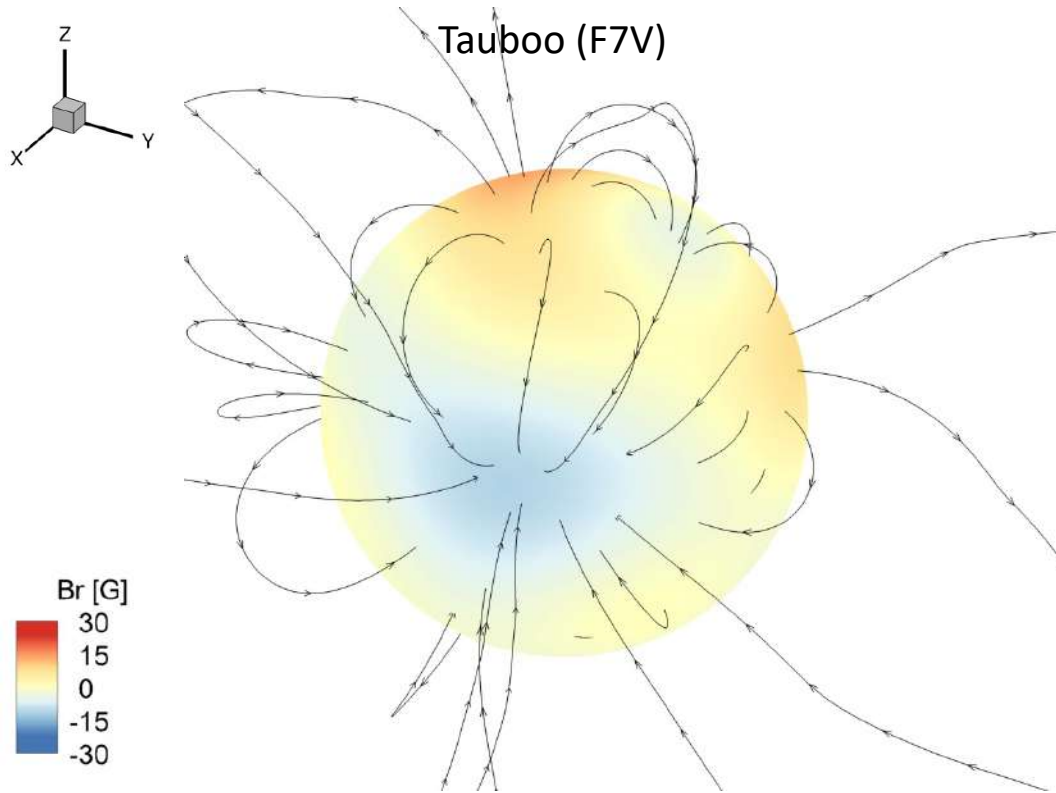
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Plasma environment that controls generation, escape, and observable frequency **cannot be directly observed.**

Data driven 3D MHD wind simulation

Making current searches largely unconstrained.

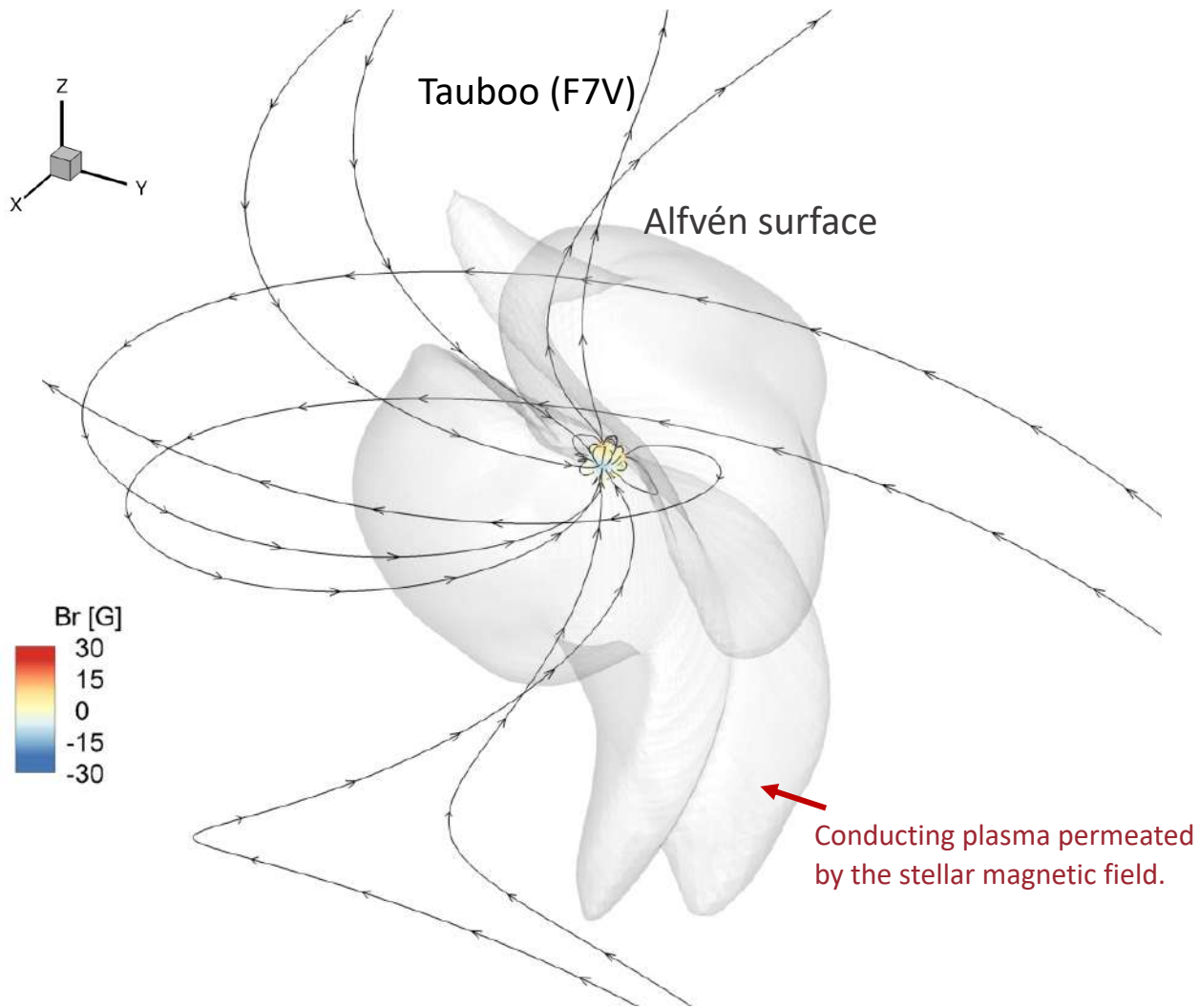
Simulation pipeline (Part 1: Plasma environment)



Radial magnetic field strength and distribution reconstructed from **Zeeman-Doppler Imaging (ZDI)** maps. These maps provide all the components of the surface magnetic vector field.

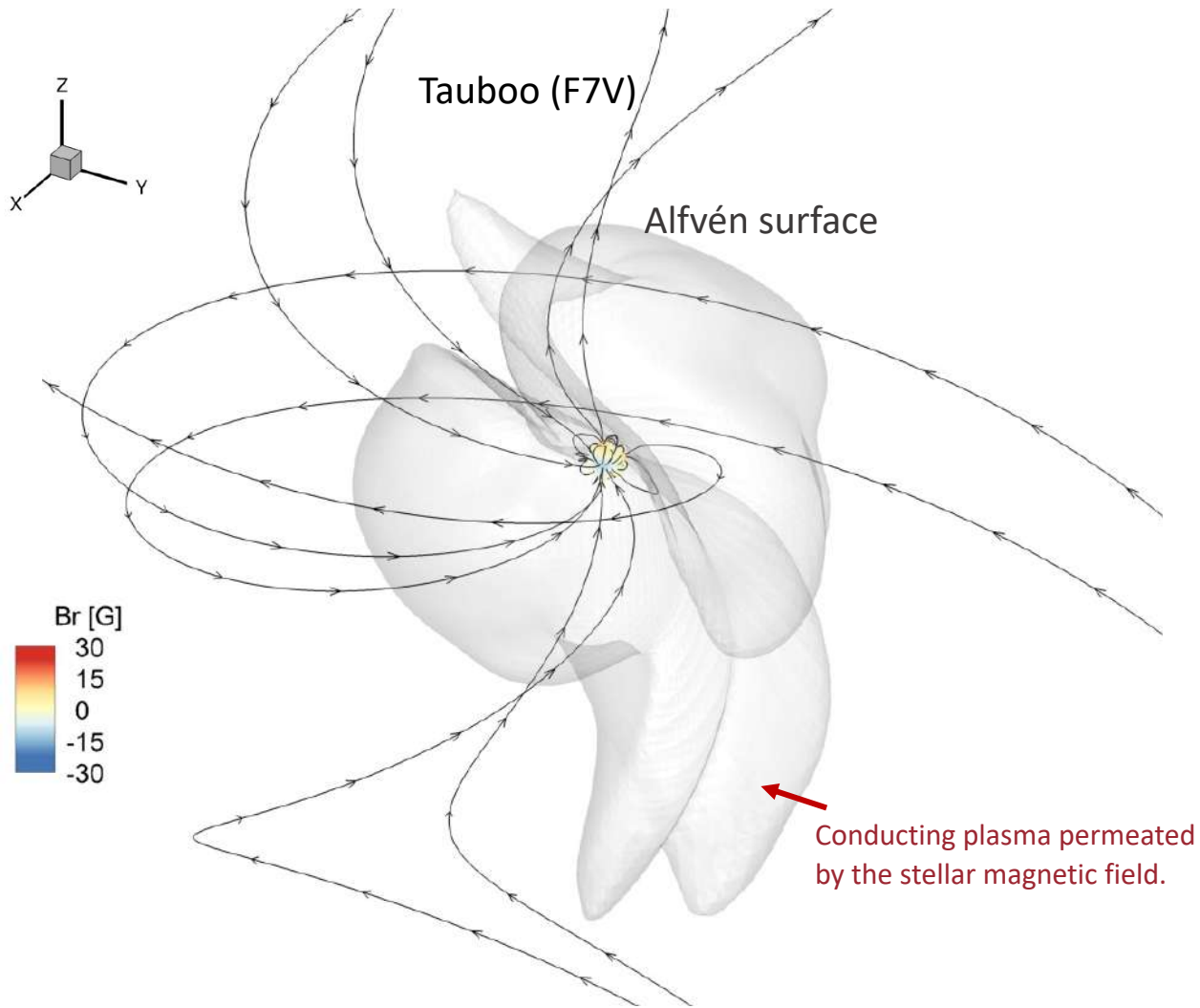
Tomographic technique that allows the reconstruction of the large-scale magnetic field strength and polarity at the star's surface.

Simulation pipeline (Part 1: Plasma environment)



State-of-the-art **3D MHD Alfvén Wave Solar Model (AWSOM-R)**
Extensively validated and updated using remote and in-situ solar data (e.g., Oran + 2017; Sachdeva + 2019; Van der Holst + 2019; Jivani + 2022).

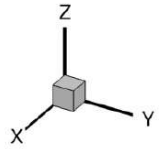
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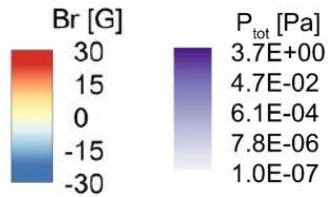
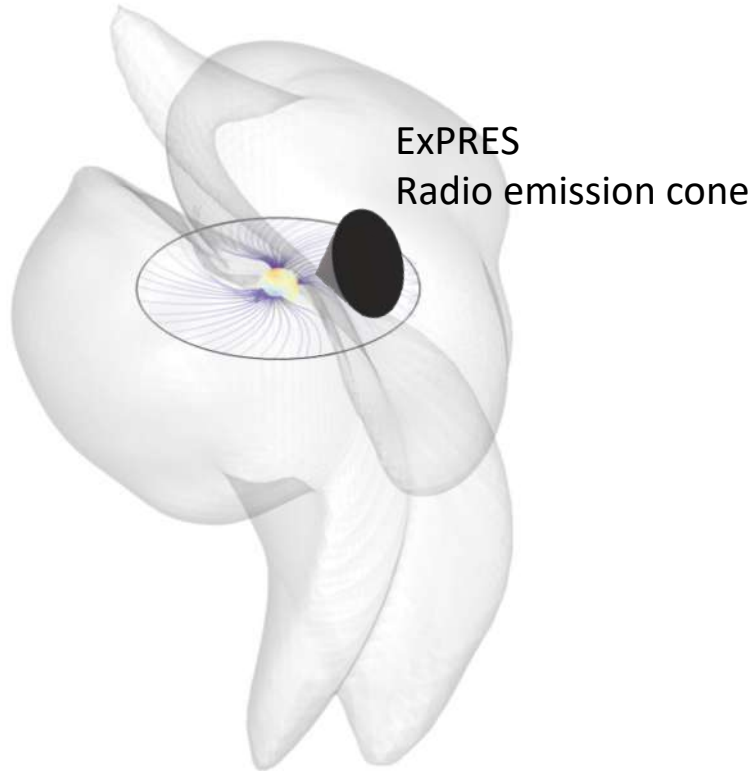
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3D MHD stellar wind models can reconstruct the plasma environment, however they do not give any information on SPI induced radio emission.

Simulation pipeline (Part 2: radio emission)

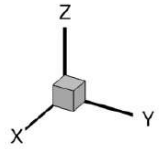


Tauboo (F7V)

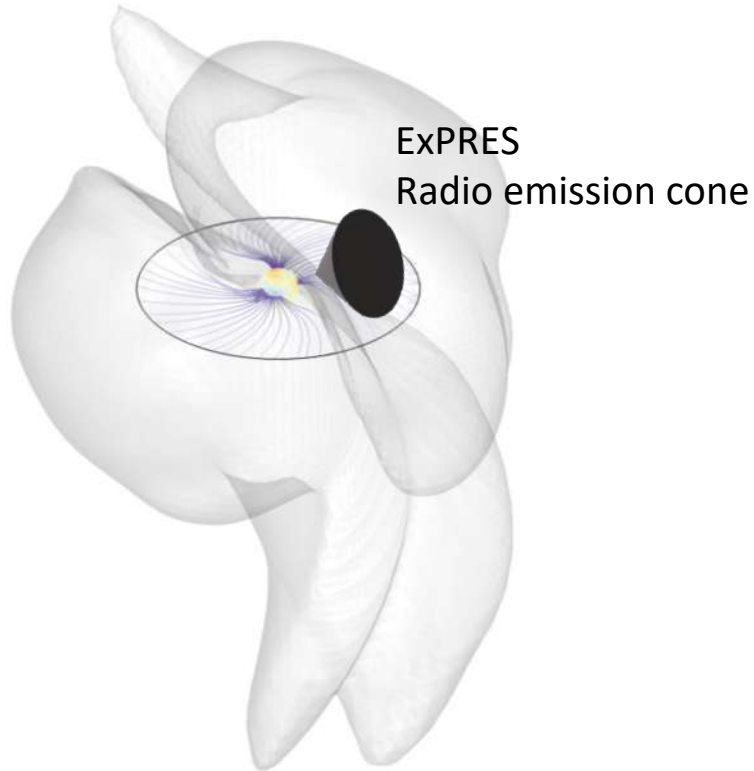


The Exoplanetary and Planetary Radio Emissions Simulator (**ExPRES**) was originally developed to model Jupiter-Io radio emissions generated by the cyclotron maser instability (**CMI**, Hess + 2008; Louis + 2017a).

Simulation pipeline (Part 2: radio emission)



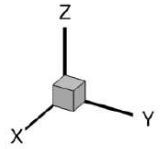
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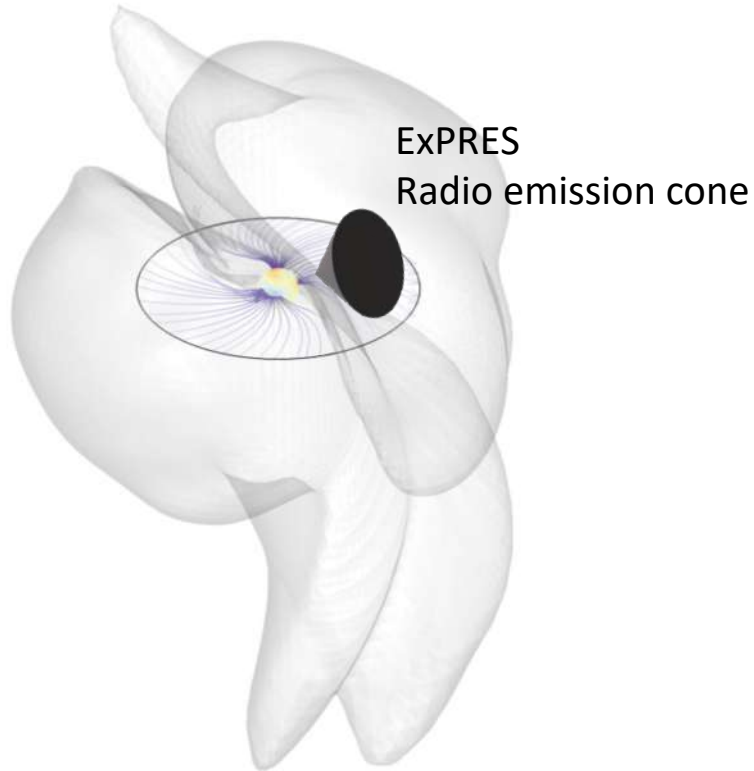
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The code assumes a hollow cone for the radio emission. The beam opening is controlled by the electron distribution and energy.

Simulation pipeline (Part 2: radio emission)



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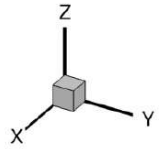


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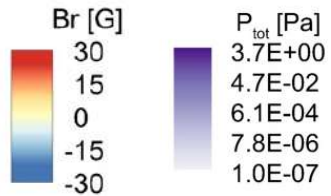
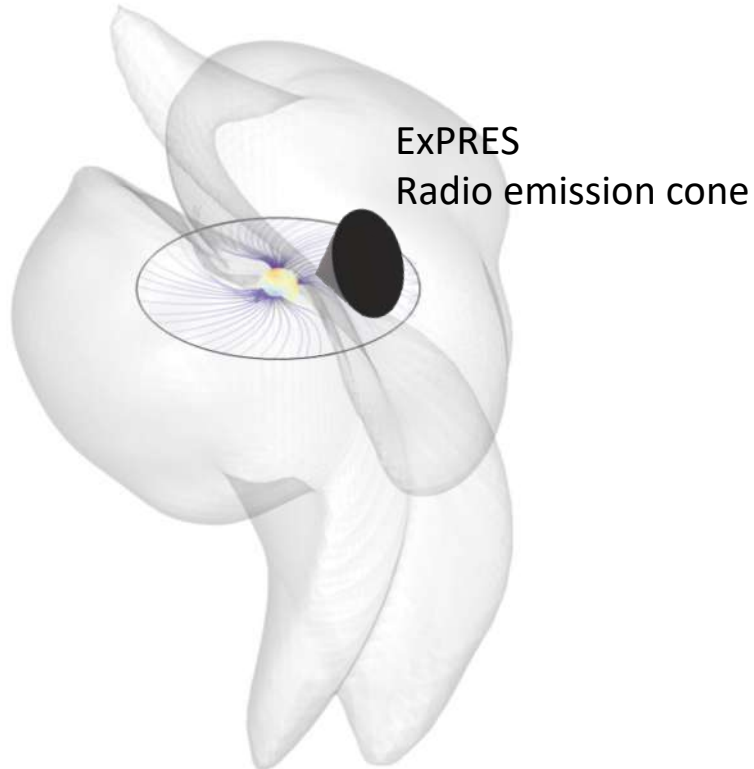
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Simulation pipeline (Part 2: radio emission)



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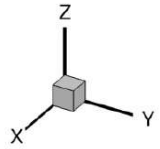
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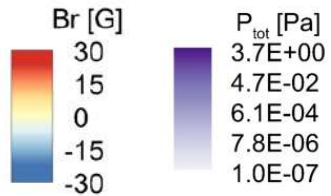
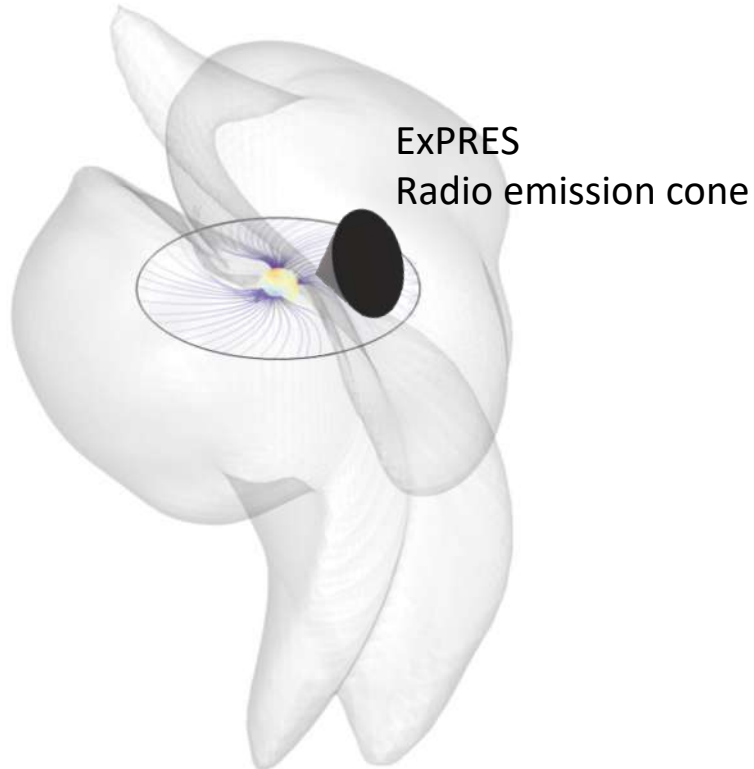
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The code includes the full **star–planet–observer geometry**.

Simulation pipeline (Part 2: radio emission)



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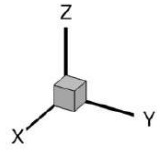
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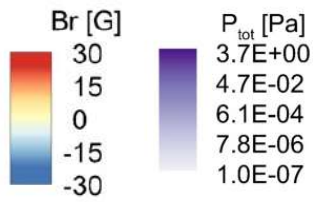
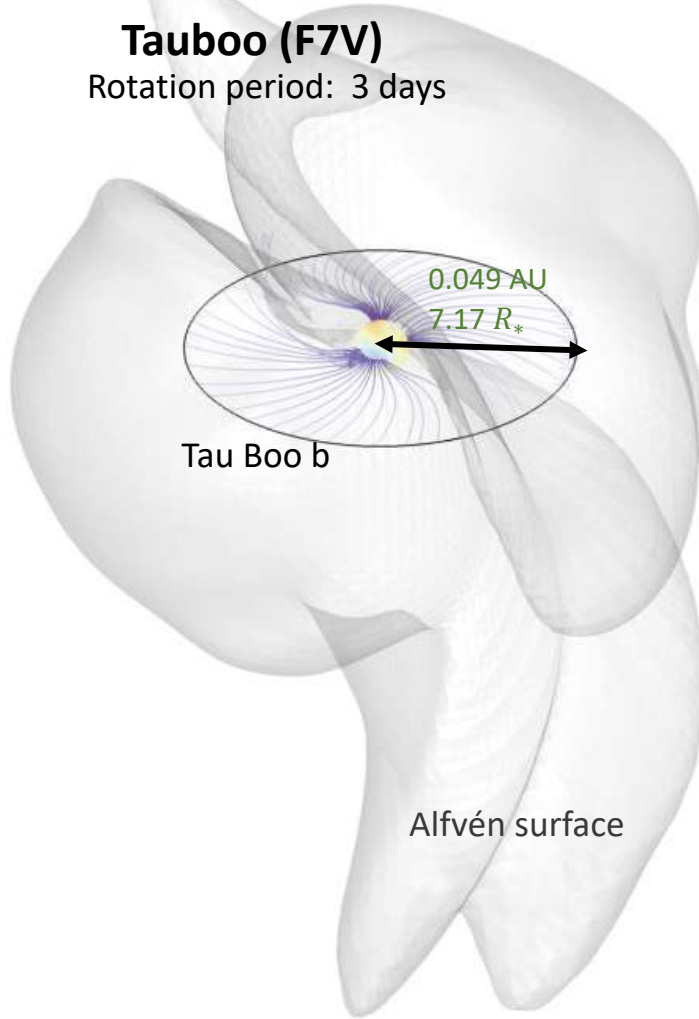
The code includes the full **star–planet–observer geometry**.

The code will simulate the motion of the planet and the star and evaluates whether radio emission is visible to a given observer.

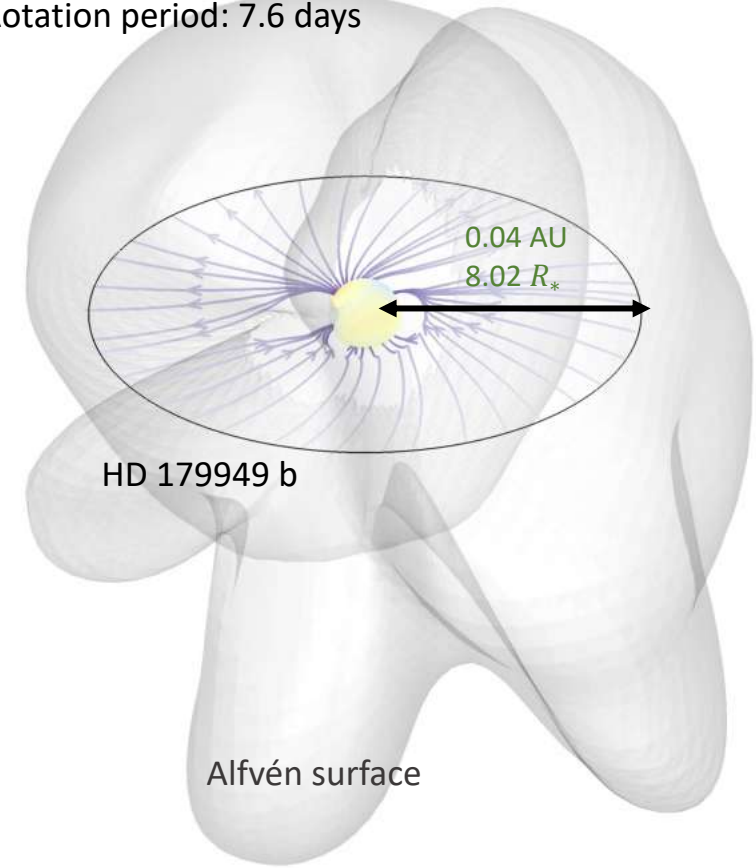
Exoplanet system



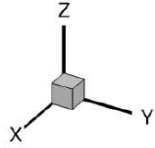
Tau Boo (F7V)
Rotation period: 3 days



HD 179949 (F8V)
Rotation period: 7.6 days

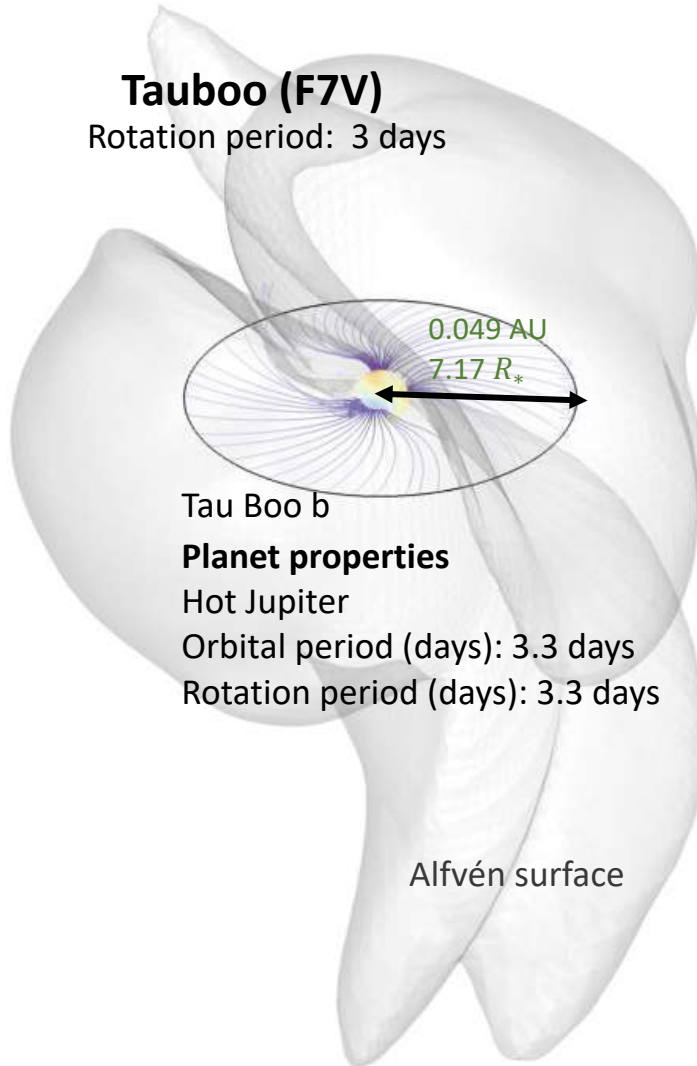


Exoplanet system



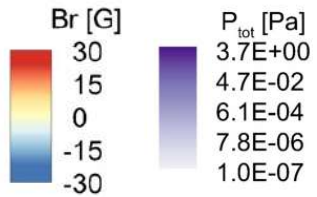
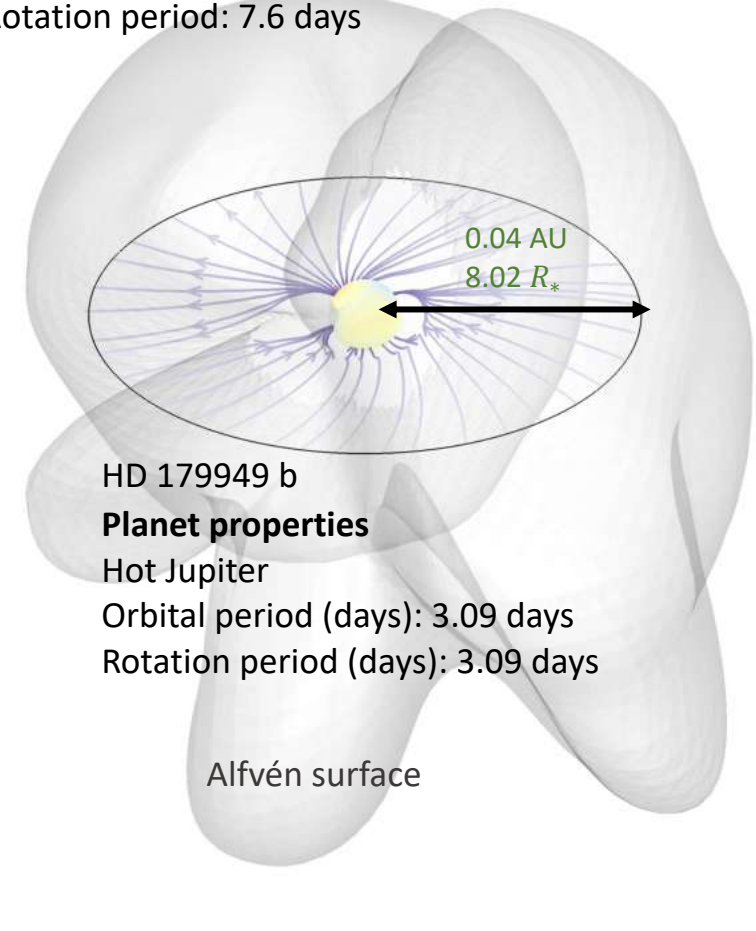
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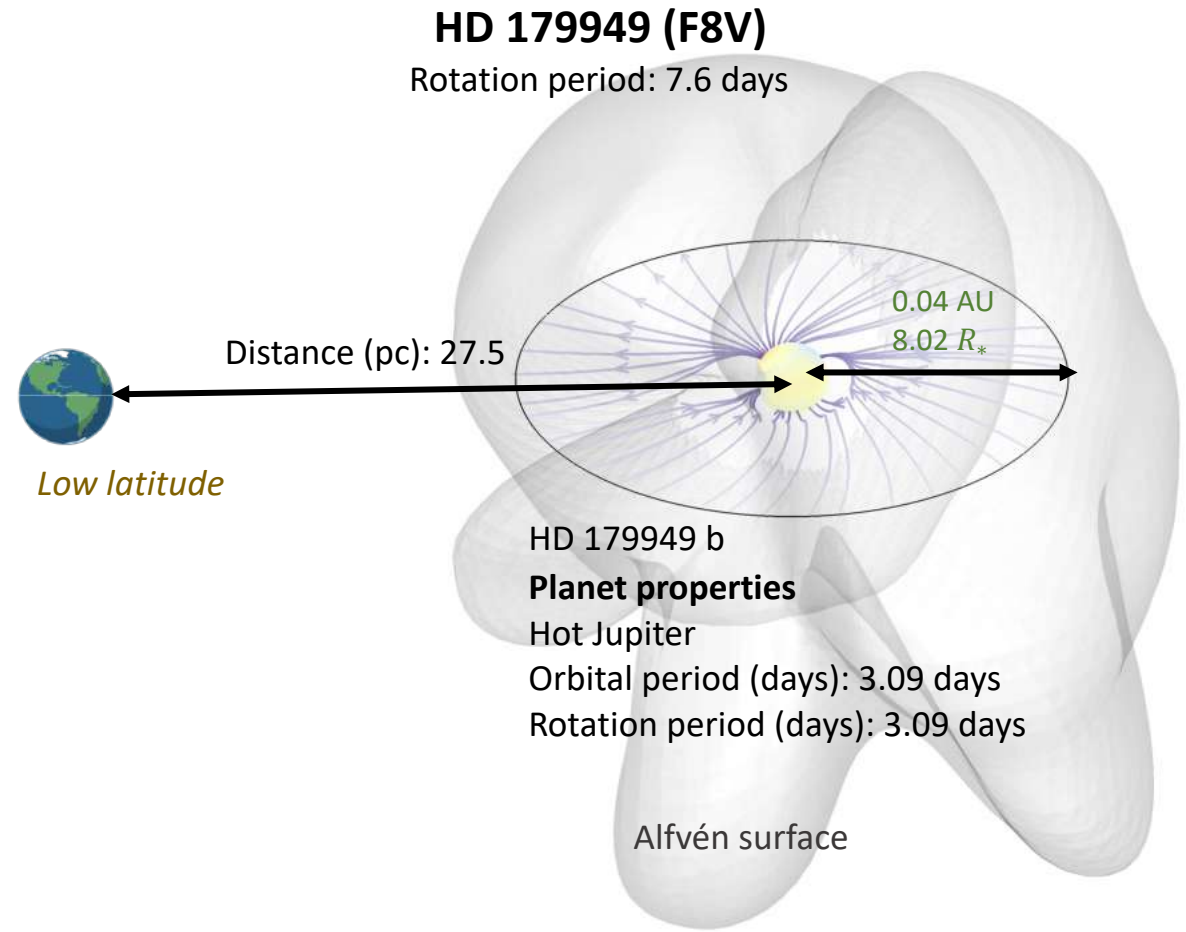
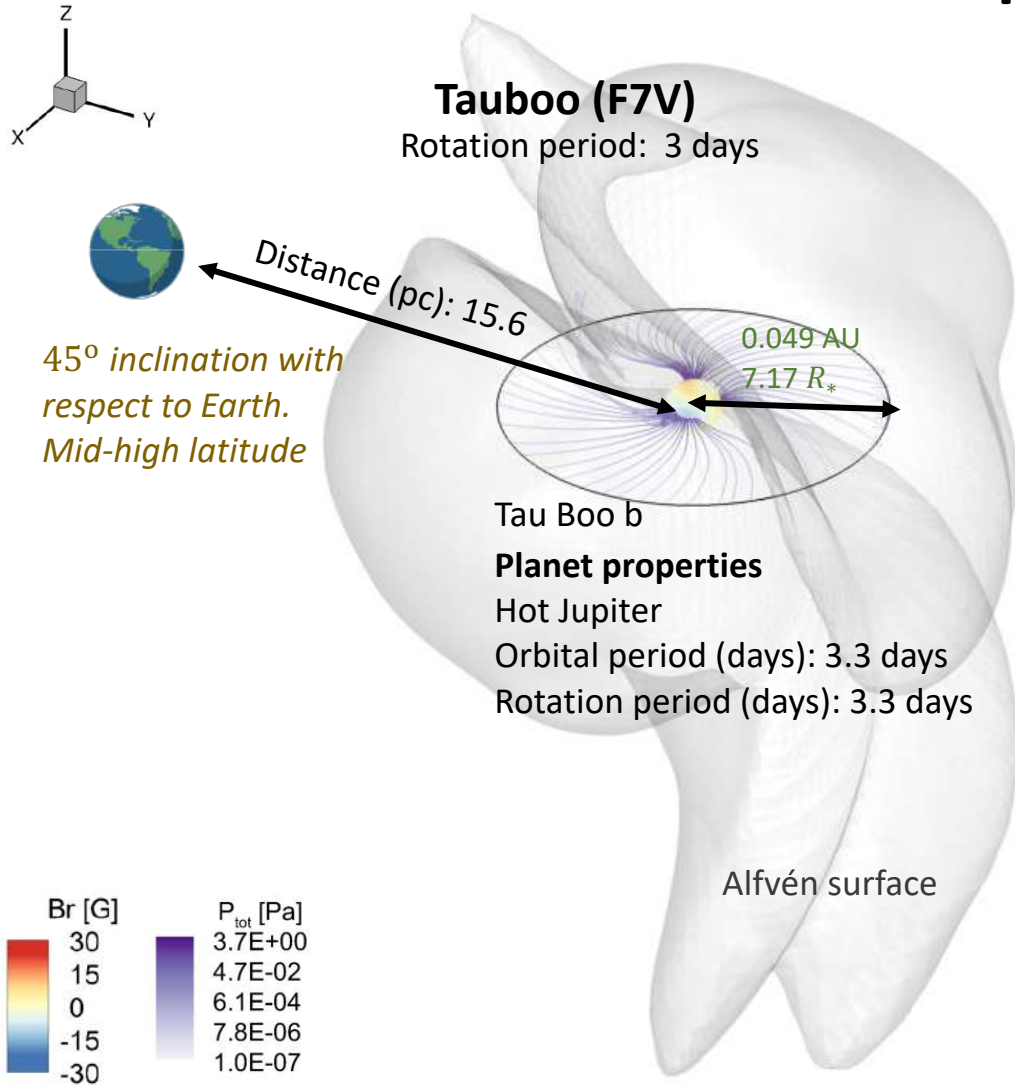


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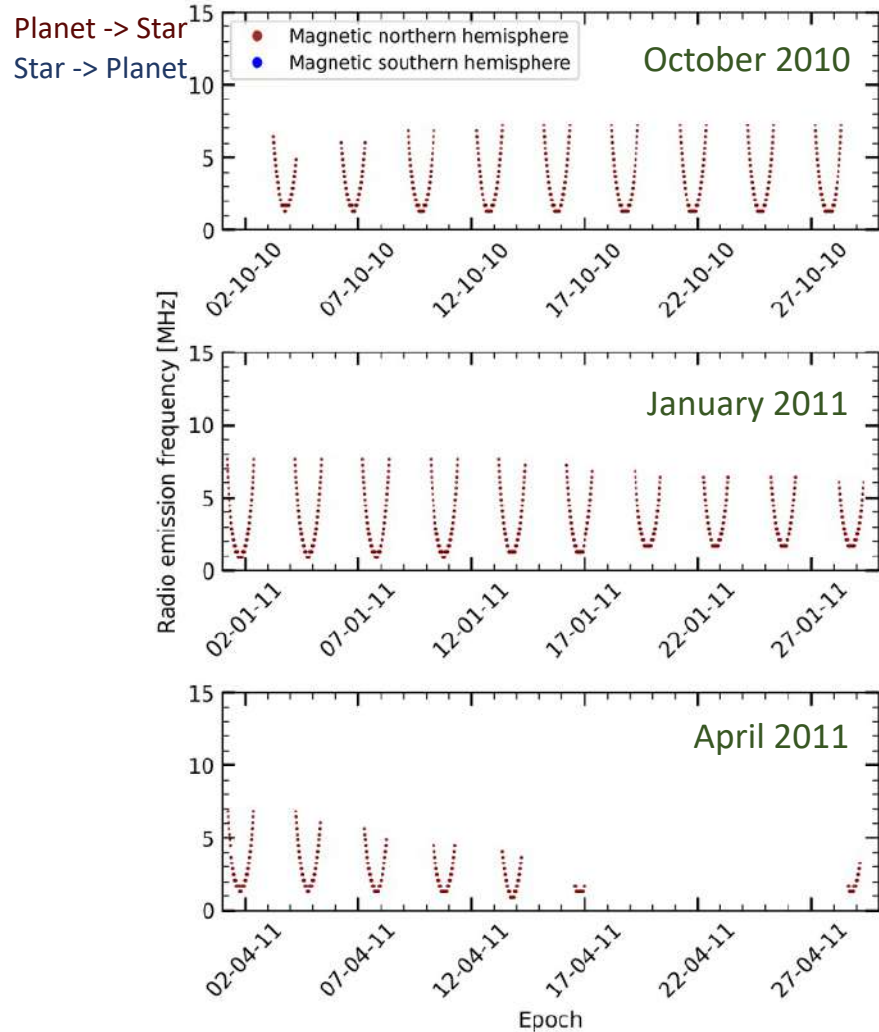


Exoplanet system



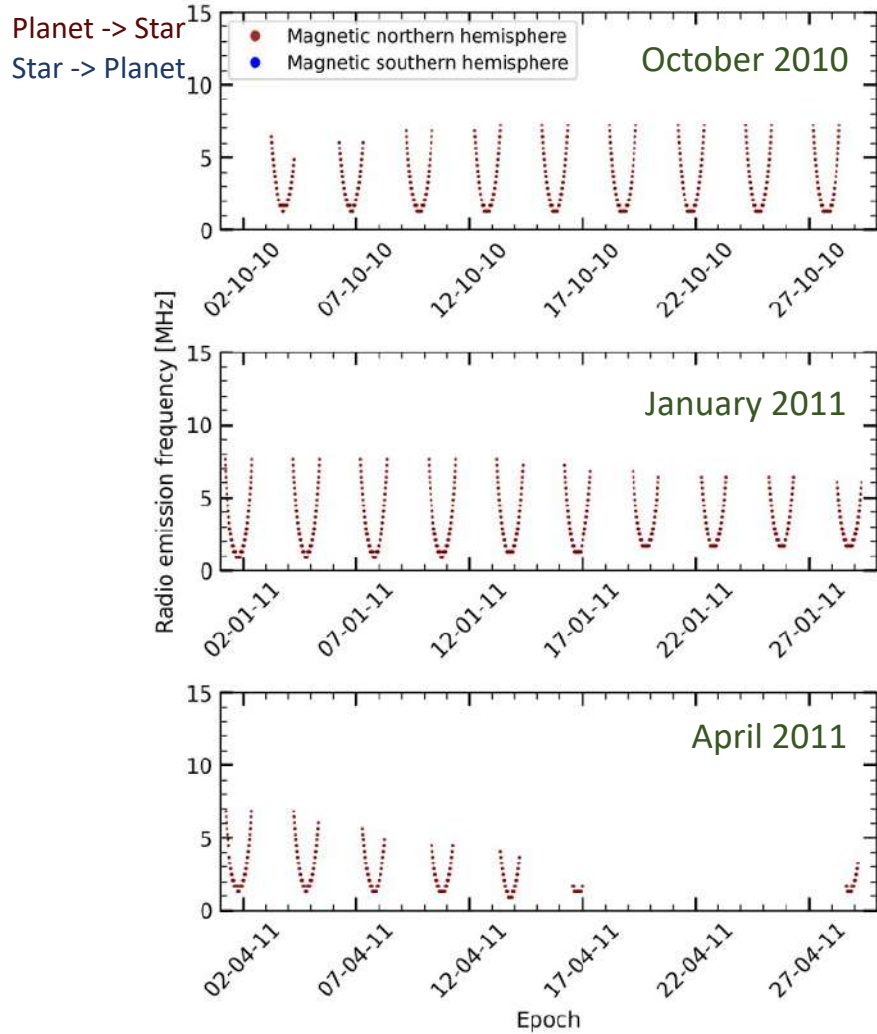
Radio emission frequency

Taiboo

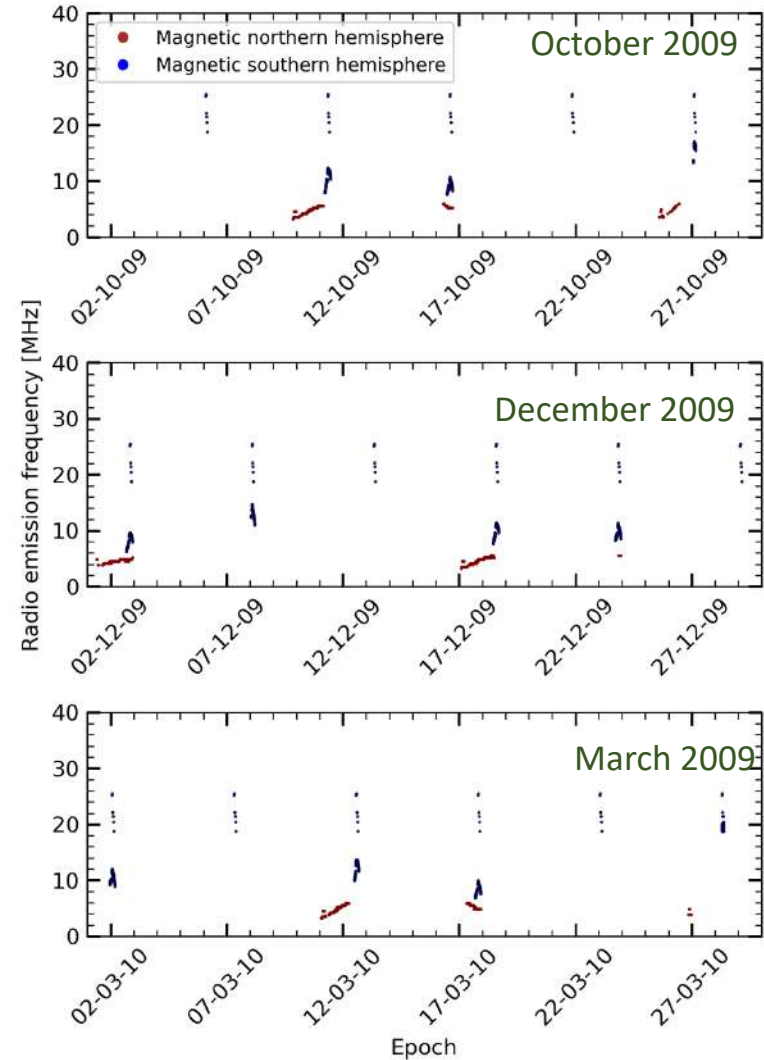


Radio emission frequency

Taiboo

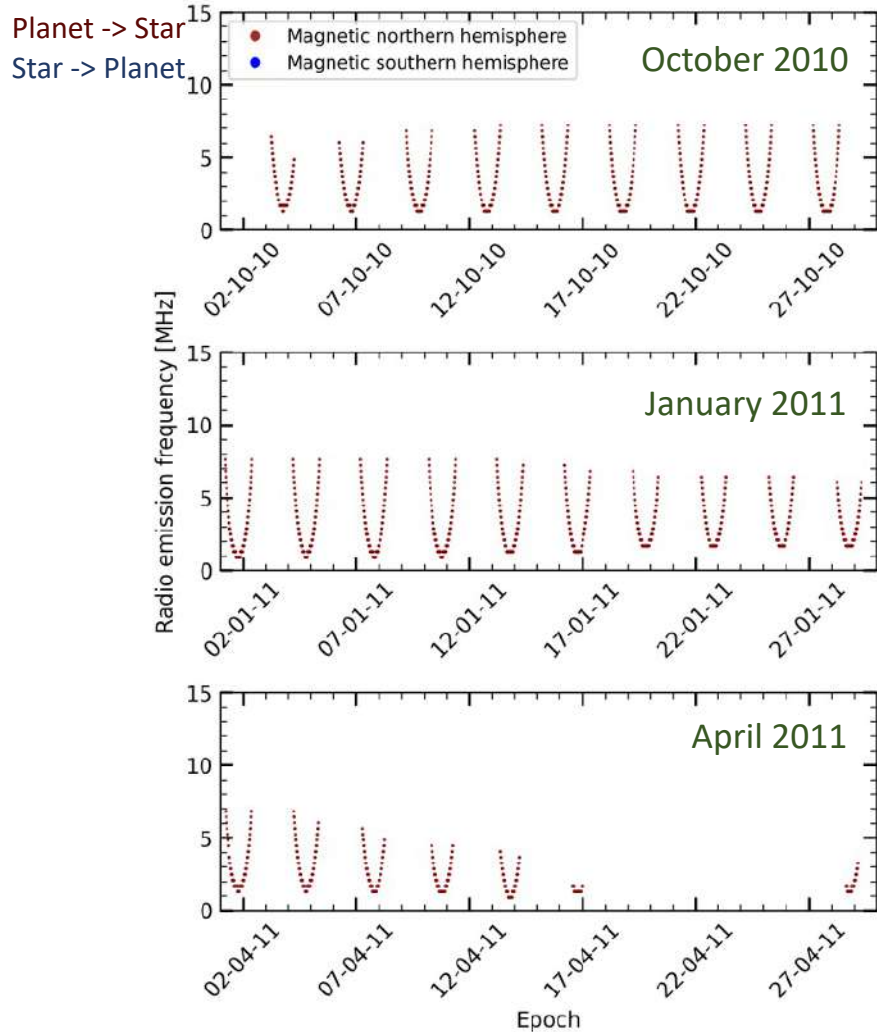


HD 179949

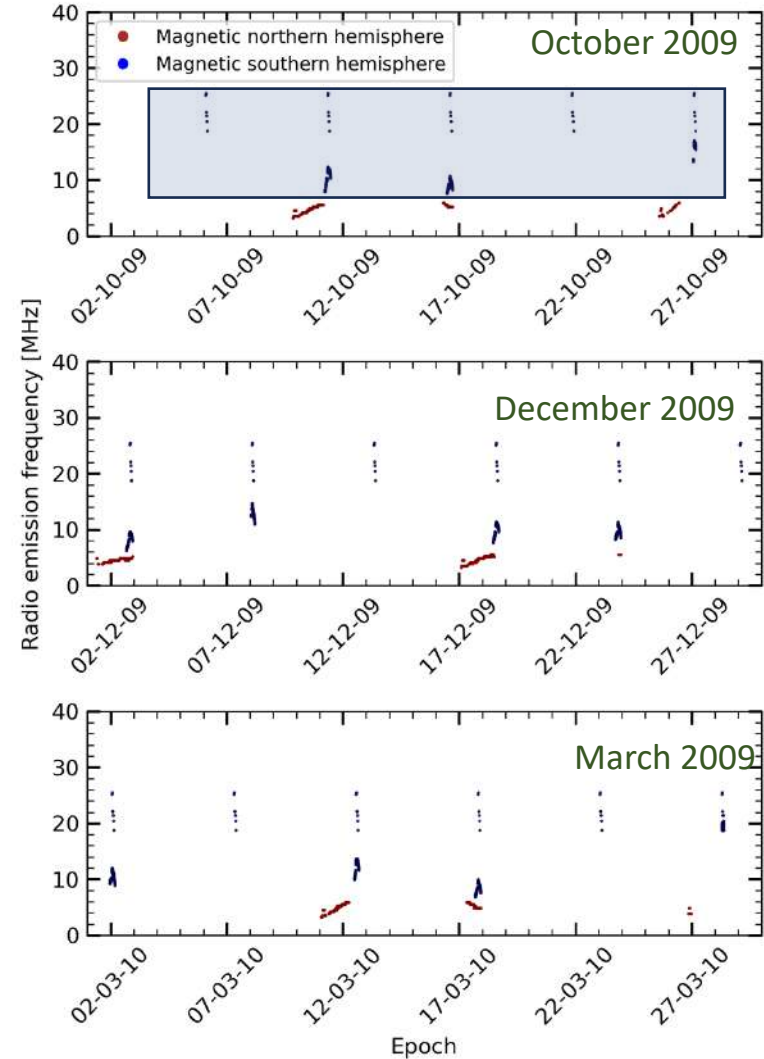


Radio emission frequency

Taobao

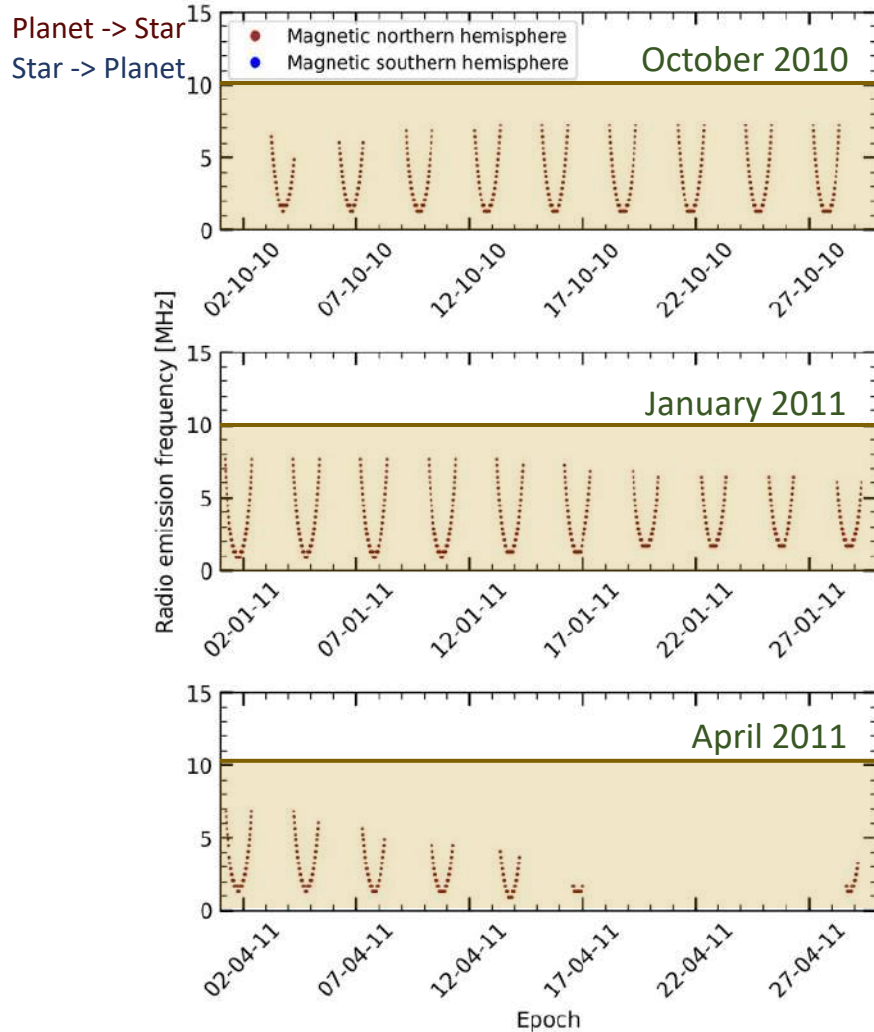


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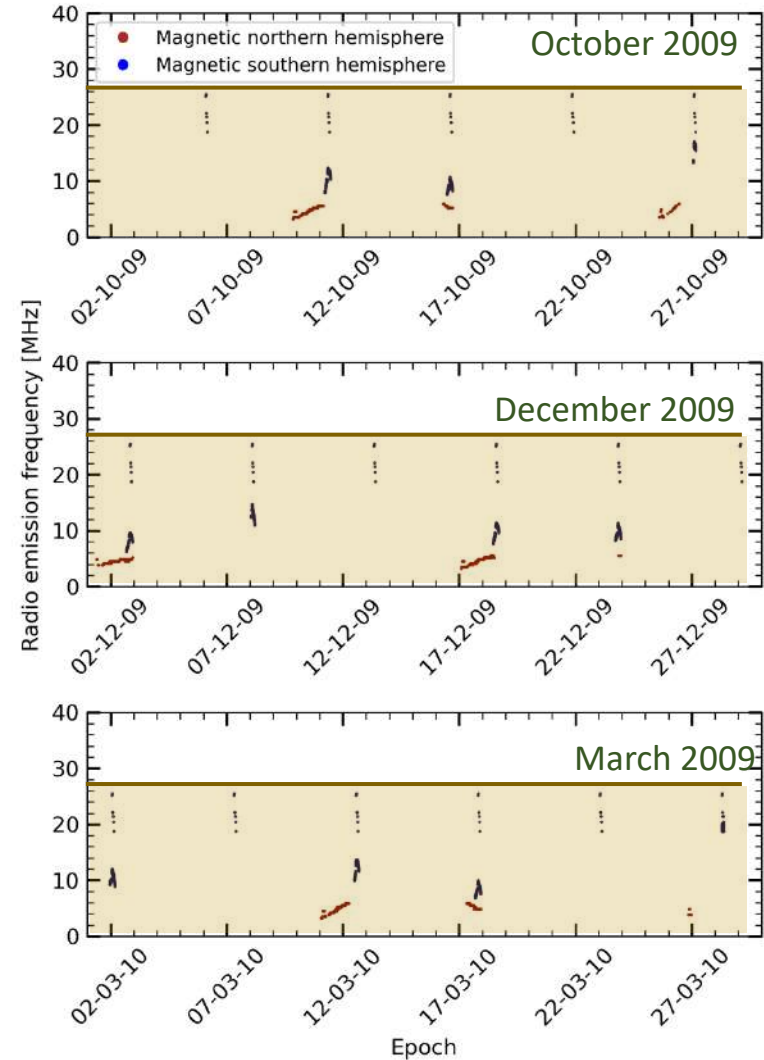


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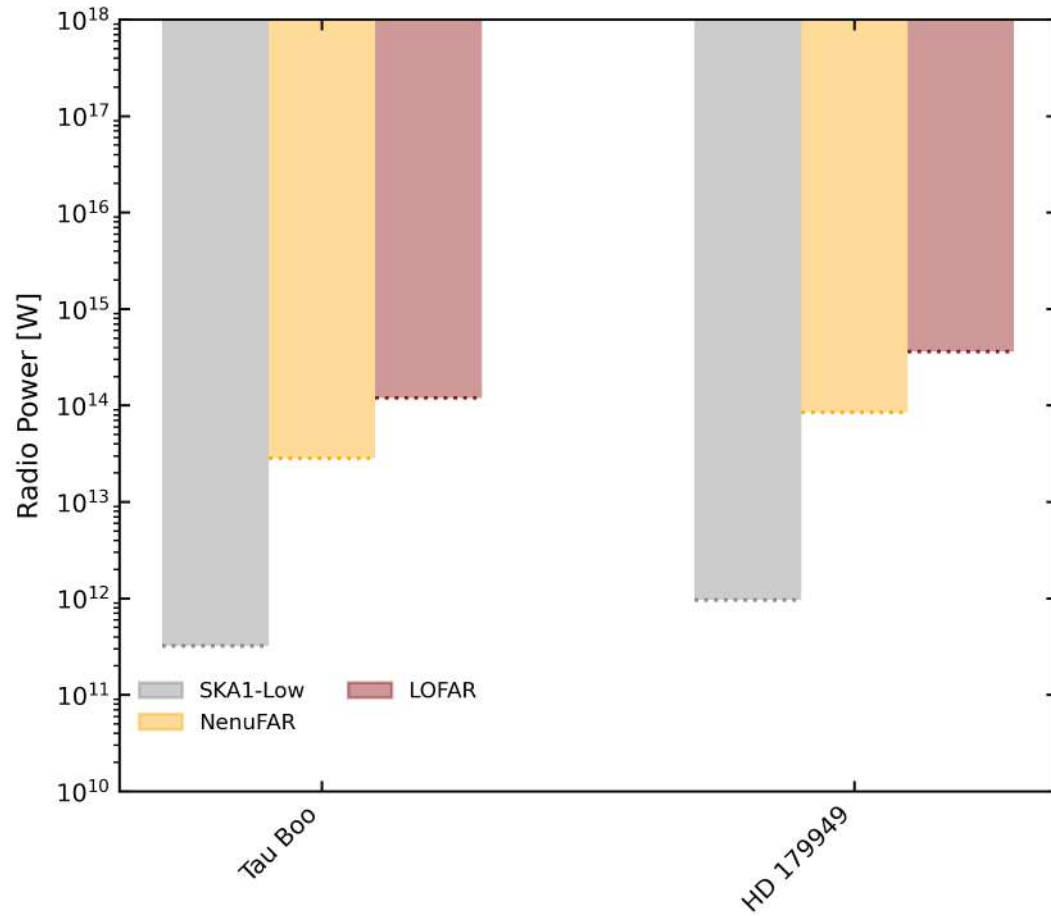
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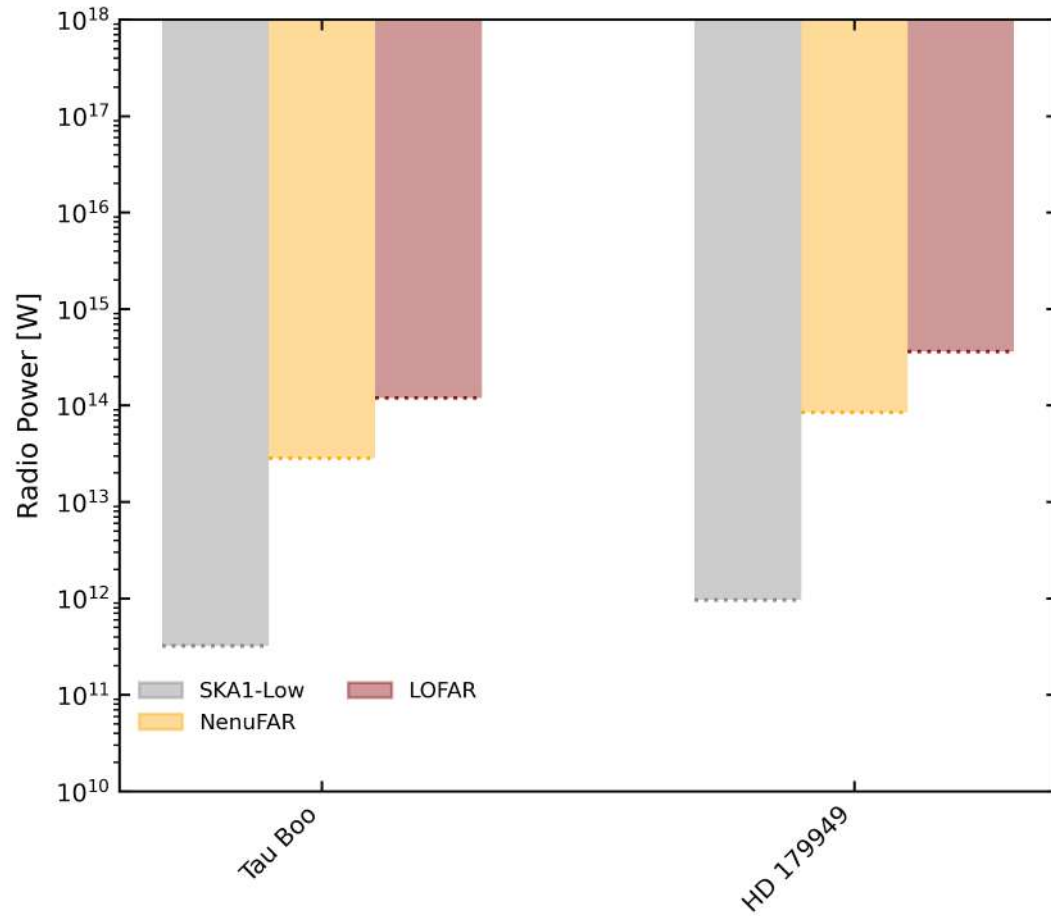
HD 179949



Radio power and telescope sensitivity




Radio power and telescope sensitivity

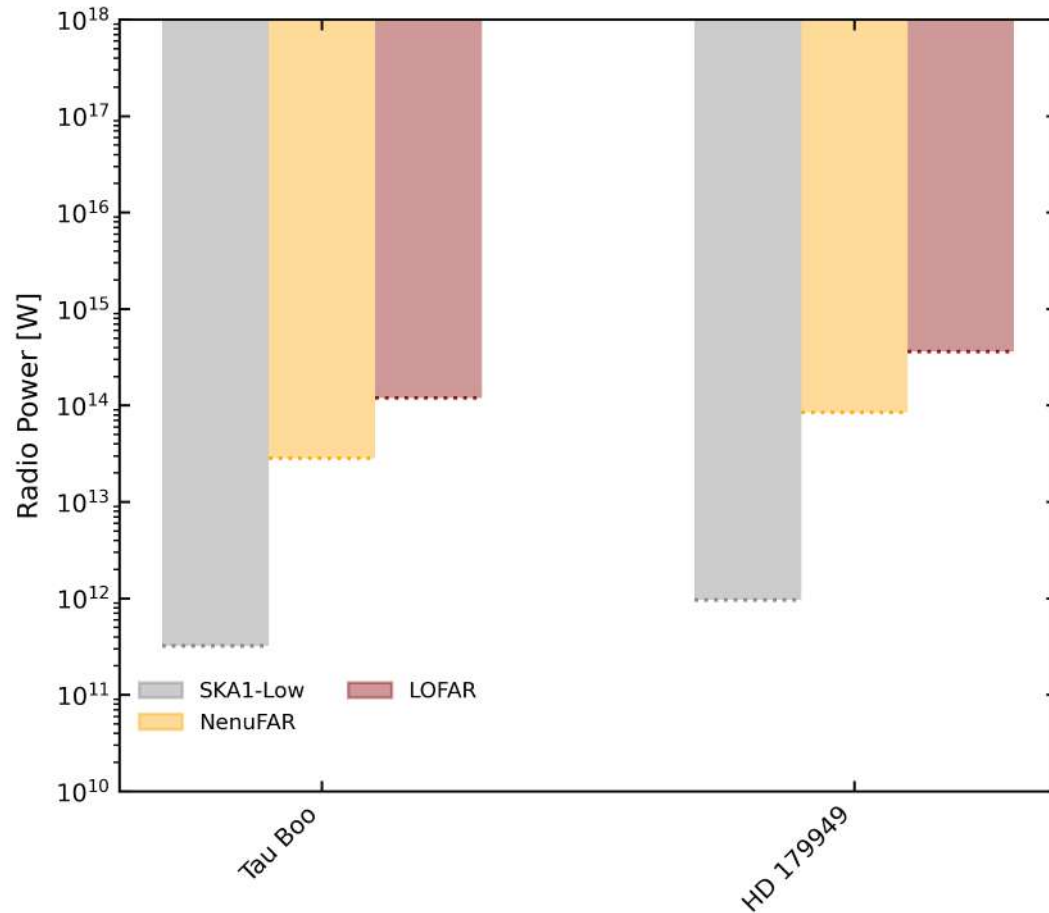


How much *magnetic* power will be transformed into *radio* power from a specific system?

Magnetic energy


$$P_{\text{radio}} = \epsilon P_{\text{mag}}^{\alpha}$$

Radio power and telescope sensitivity



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Magnetic energy

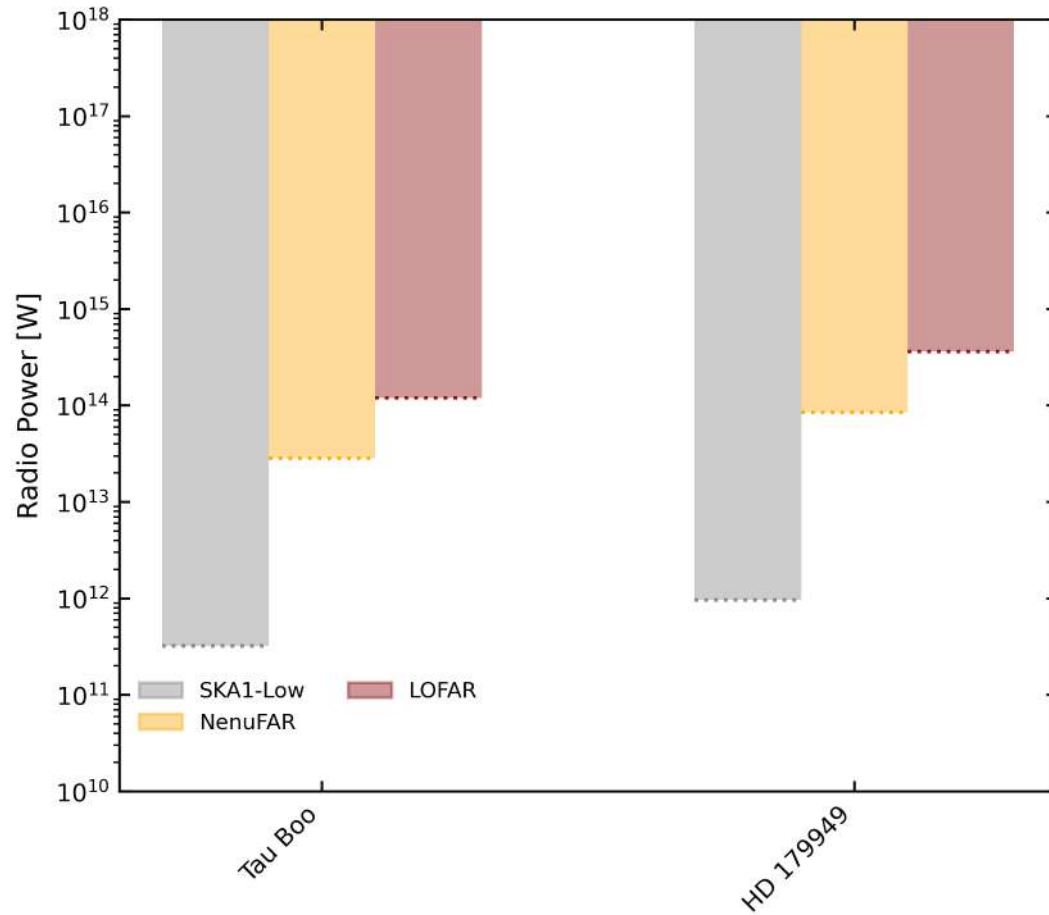
Efficiency factor representing the fraction of magnetic energy converted into radio emission.

Power-law index.

Radio Magnetic Scaling Law (RMSL) adapted from Zarka + 2018 for the Satellite-Planet scaling law.

$$\alpha = 1 \text{ and } \epsilon \approx 2 \times 10^{-3}$$

Radio power and telescope sensitivity

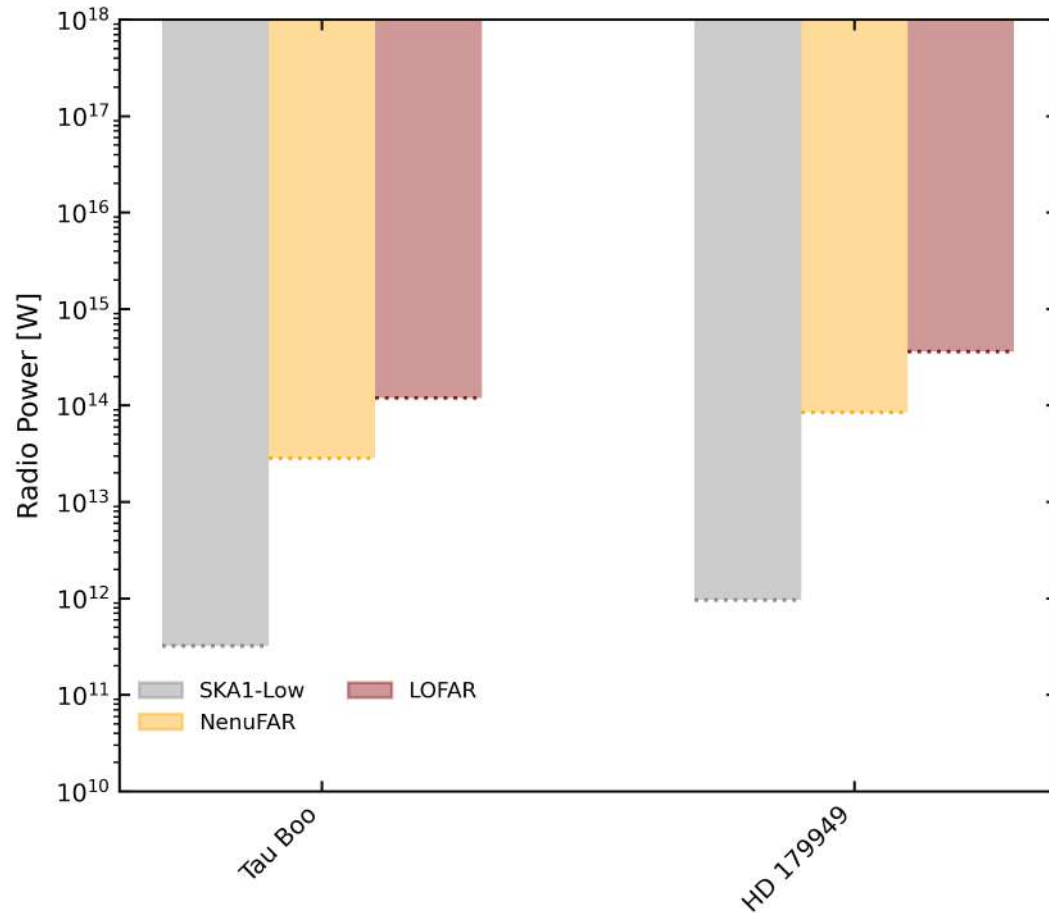


Magnetic field strength (from wind simulation)

$$P_{\text{mag}}(\text{W}) = \frac{B_{\perp}^2}{\mu_0} V_{\text{rel}} \pi R_M^2$$

Vacuum permeability $\mu_0 = 4\pi \times 10^{-7} \text{ H/m}$
 Relative velocity (from wind simulation)
 Magnetospheric standoff distance

Radio power and telescope sensitivity



Magnetic field strength (from wind simulation)

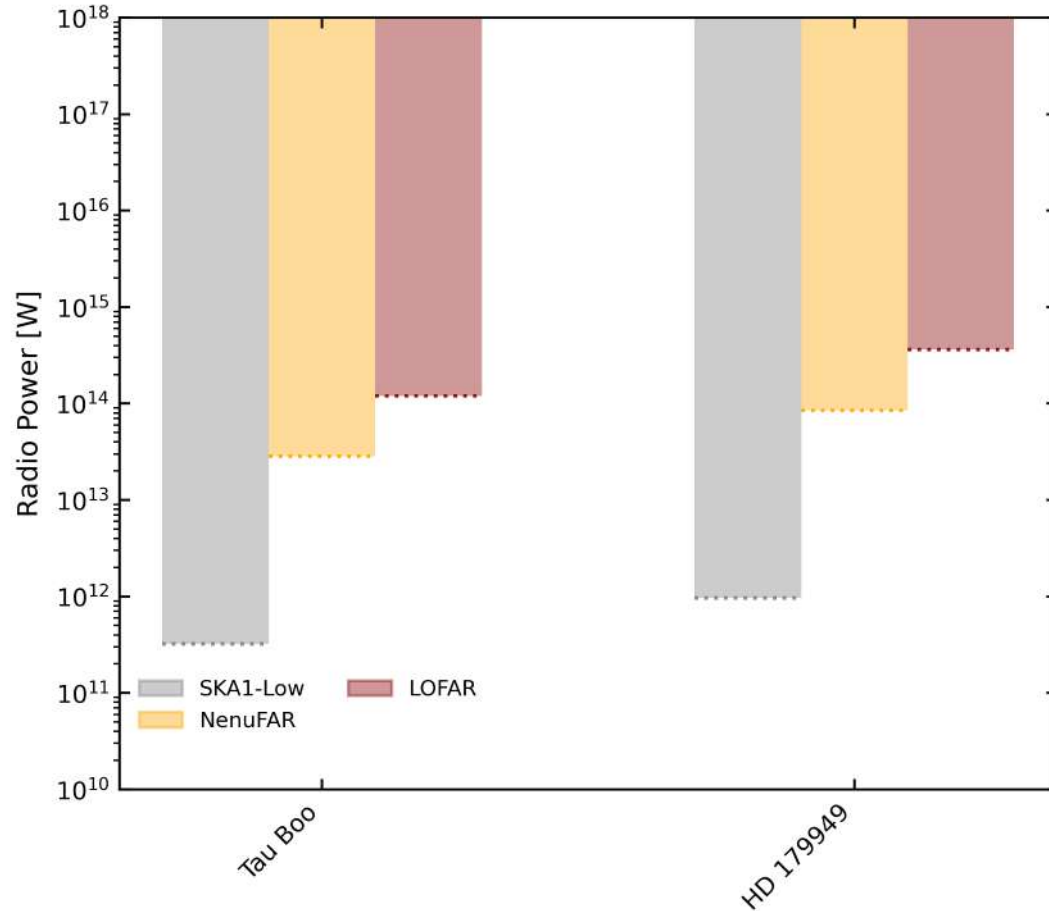
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 Relative velocity (from wind simulation)
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$$R_M = R_p \left(\frac{B_p^2}{2\mu_0 P_{\text{tot}}} \right)^{1/6}$$

Planetary radius
 Total pressure (from wind simulation)

Radio power and telescope sensitivity



Magnetic field strength (from wind simulation)

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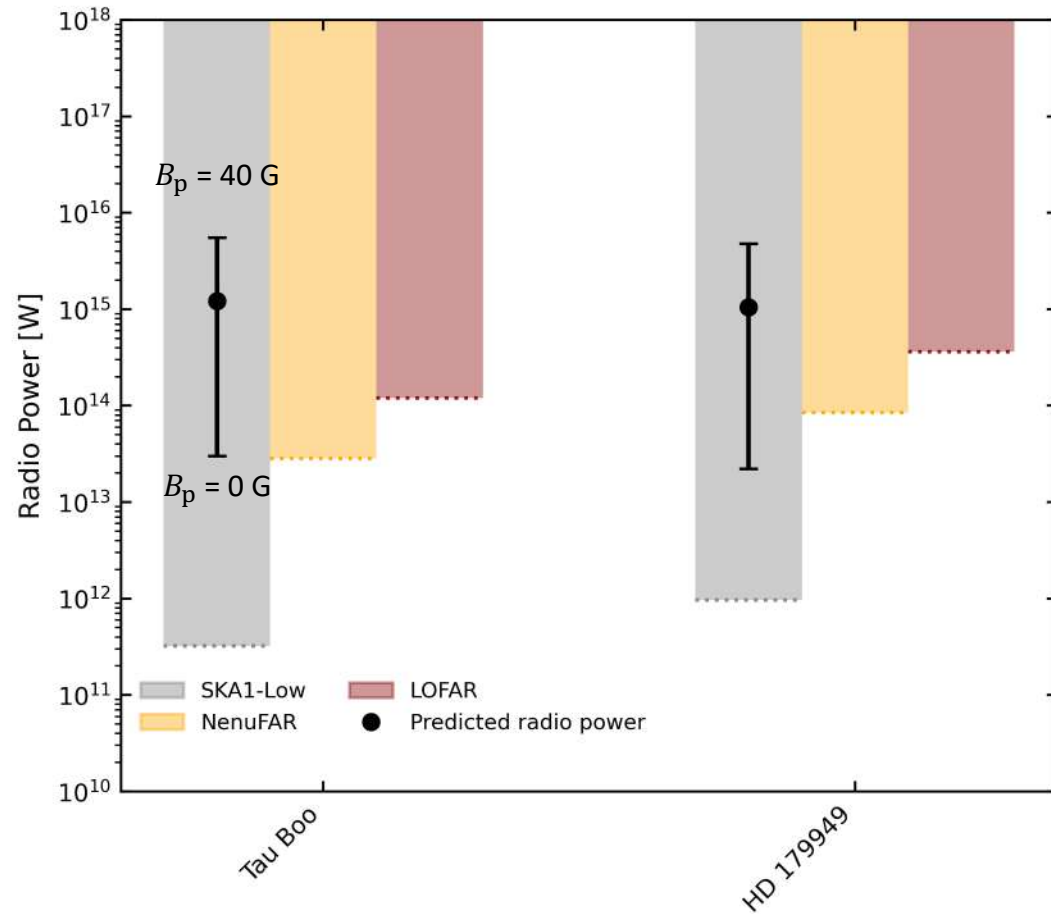
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Planetary radius R_p
 Total pressure (from wind simulation) P_{tot}

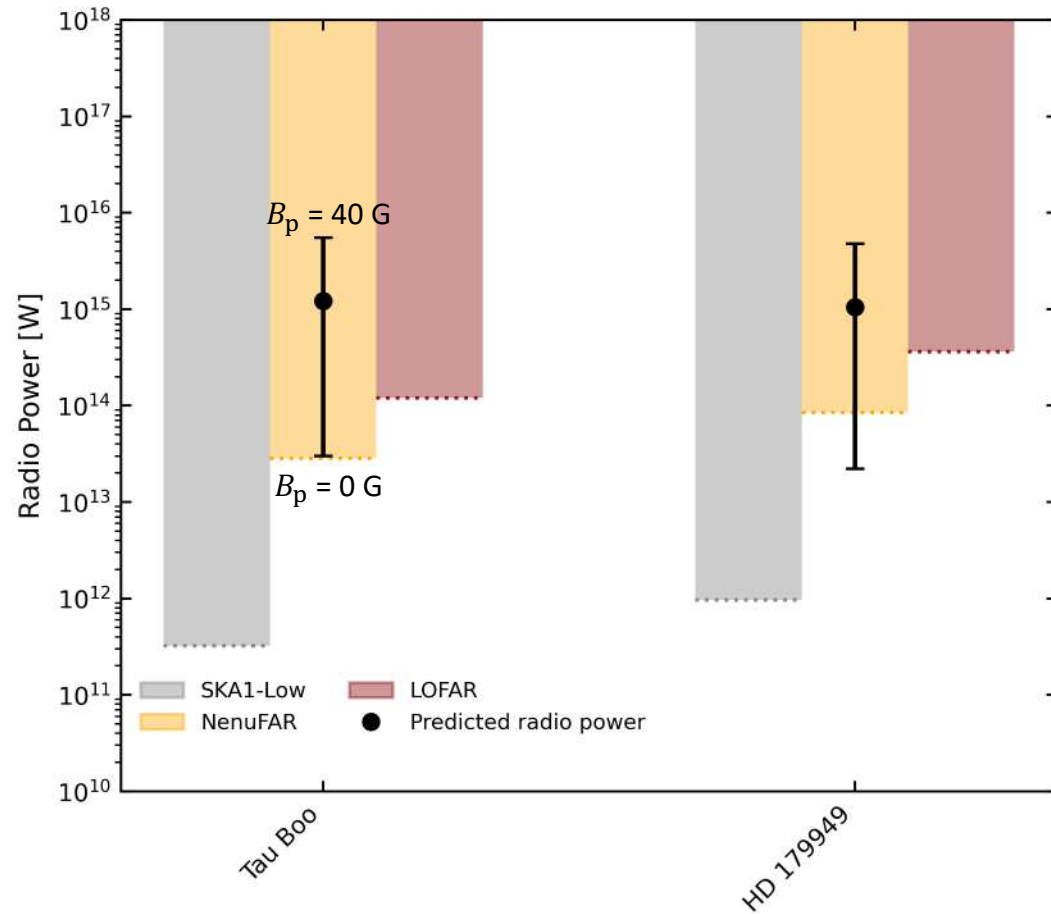
Lower limit $B_p = 0$
 No magnetosphere
 Upper limit $B_p = 40$ Gauss consistent with dynamo models for hot Jupiters under strong stellar irradiation.
 Large magnetosphere

Radio power and telescope sensitivity



SKA1-Low allow even weakly magnetized planets (down to $B_p \sim 0.4 \text{ G}$ for Tau Boo b and HD 179949 b) to be detected.

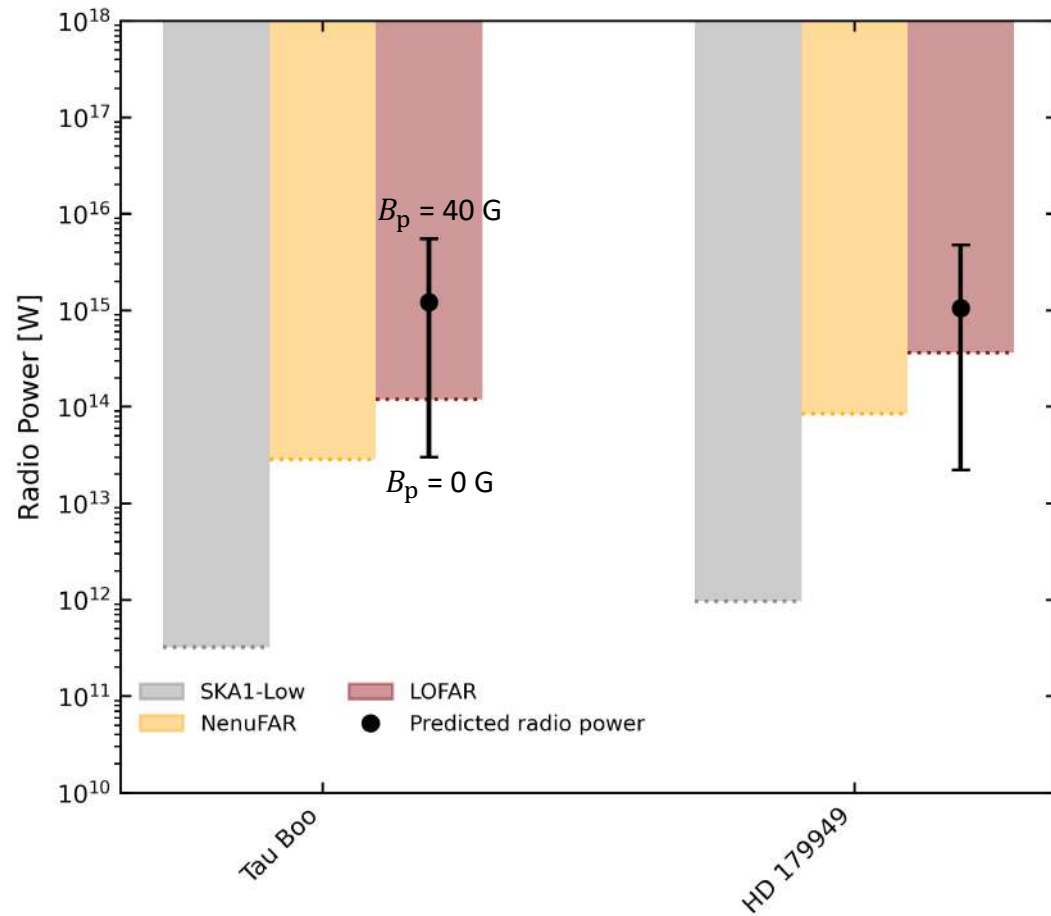
Radio power and telescope sensitivity



NenuFAR same case as SKA1-Low for *Tau Boo* but less sensitive to very weak B_p

For *HD 179949* not sensitive to $B_p < 0.2$ G

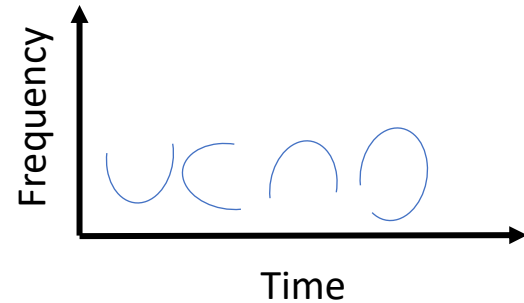
Radio power and telescope sensitivity



LOFAR can detect radio emission only if TauBoo b has a $B_p \gtrsim 2$ G and HD 179949 b has a $B_p \gtrsim 3$ G weaker fields produce signals too faint.

Assessment for SPI-induced radio detection

Radio emission frequency



For Tauboo, given the ZDI maps used detecting SPI radio emission from Earth is unlikely.

For HD 179949, the radio frequency > 10 MHz

Radio power and telescope sensitivity



Tauboo and HD 179949 radio power falls in telescope sensitivity of **SKA1-low**.

Conclusion

Combining ExPRES simulations with ZDI-driven 3D MHD stellar wind models provides a practical framework to assess SPI-induced radio emission. **It is applicable to any star-planet system with available ZDI maps and wind models.**

This approach coupled with the Radio Magnetic Scaling Law (RMSL) helps estimate possible radio power and schedule observations based on telescope sensitivity. It also help predict conditions that enhance detectability and guides targeted radio observations.

This framework provides a pathway to constrain exoplanetary magnetic fields, key for assessing atmospheric retention and potential habitability.

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Qr code for the paper

A screenshot of a research paper page from the PADC website. The page features a header with logos for Observatoire de Paris, PSL, CNRS, PADC, CDFP, Sorbonne Université, CNES, Université de Paris, and LESIA. The main content area displays the title "Predicting realistic radio emission from compact star-planet systems. Online Supplementary Material" by Corentin Louis, dated Thursday 4 September 2025. The abstract states: "This collection contains figures and movies showing the results of star-planet interaction simulations using the ExPRES code for three different exoplanetary systems: Tau Bootis, HD 189733, and HD 179949. This collection supplements Appendix B and C of Chebly et al. (2025a) 'Predicting realistic radio emission from compact star-planet systems', submitted to Astronomy & Astrophysics". It includes a DOI link (10.25935/4pks-d207), publisher (PADC), license (CC-BY 4.0), and a citation. A "Link to data repository" section provides links for data products for Tau Bootis, HD 189733, and HD 179949. A footer note explains that data directories are organized by Poynting flux values and electron energy.

Follow up project

Predict & prioritize: Guiding target selection and observation planning.

Diagnose & interpret: Provides criteria to distinguish SPI-related radio signals from other stellar or planetary radio emissions, helping interpret detections and assess their physical origin.

Telescope sensitivity

Distance from earth to the source

$$P_{\text{radio, telescope}} (W) \propto d^2 S_{\text{min}}$$

Minimum detectable flux density

A diagram illustrating the relationship between telescope power, distance, and minimum detectable flux density. The central equation is $P_{\text{radio, telescope}} (W) \propto d^2 S_{\text{min}}$. A red arrow points from the text "Distance from earth to the source" above to the variable d in the equation. Another red arrow points from the text "Minimum detectable flux density" below to the variable S_{min} in the equation.