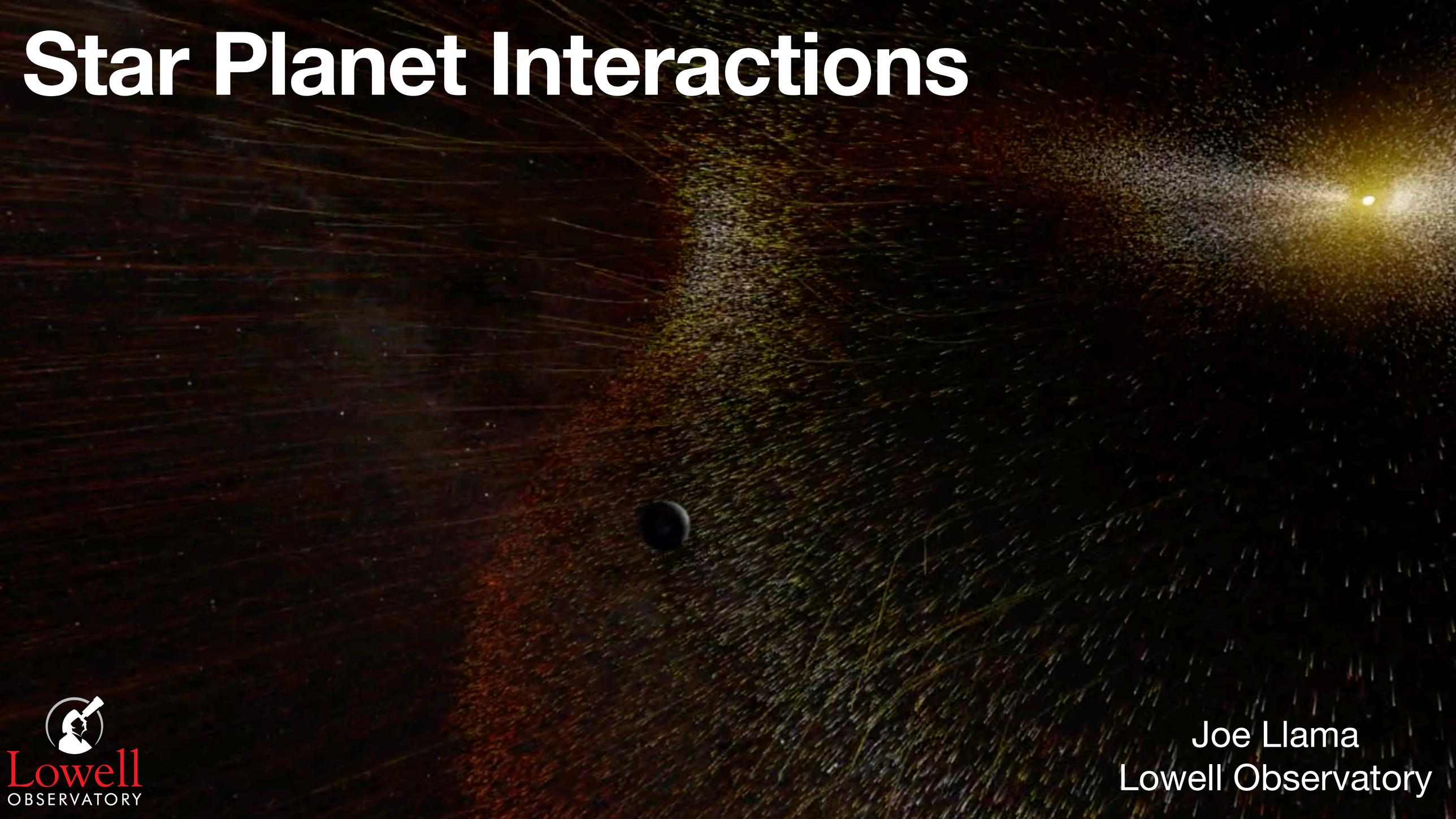
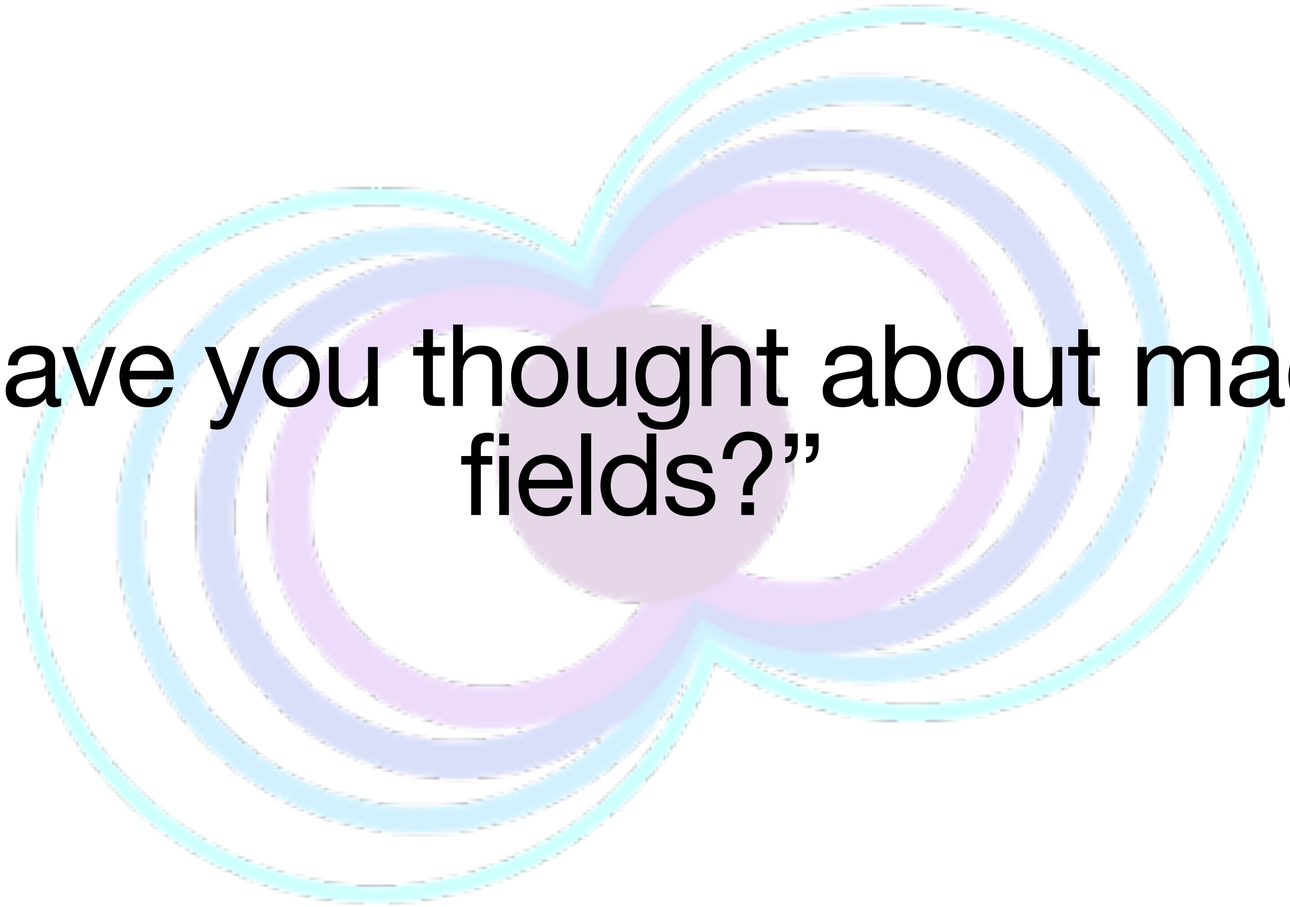
Star Planet Interactions



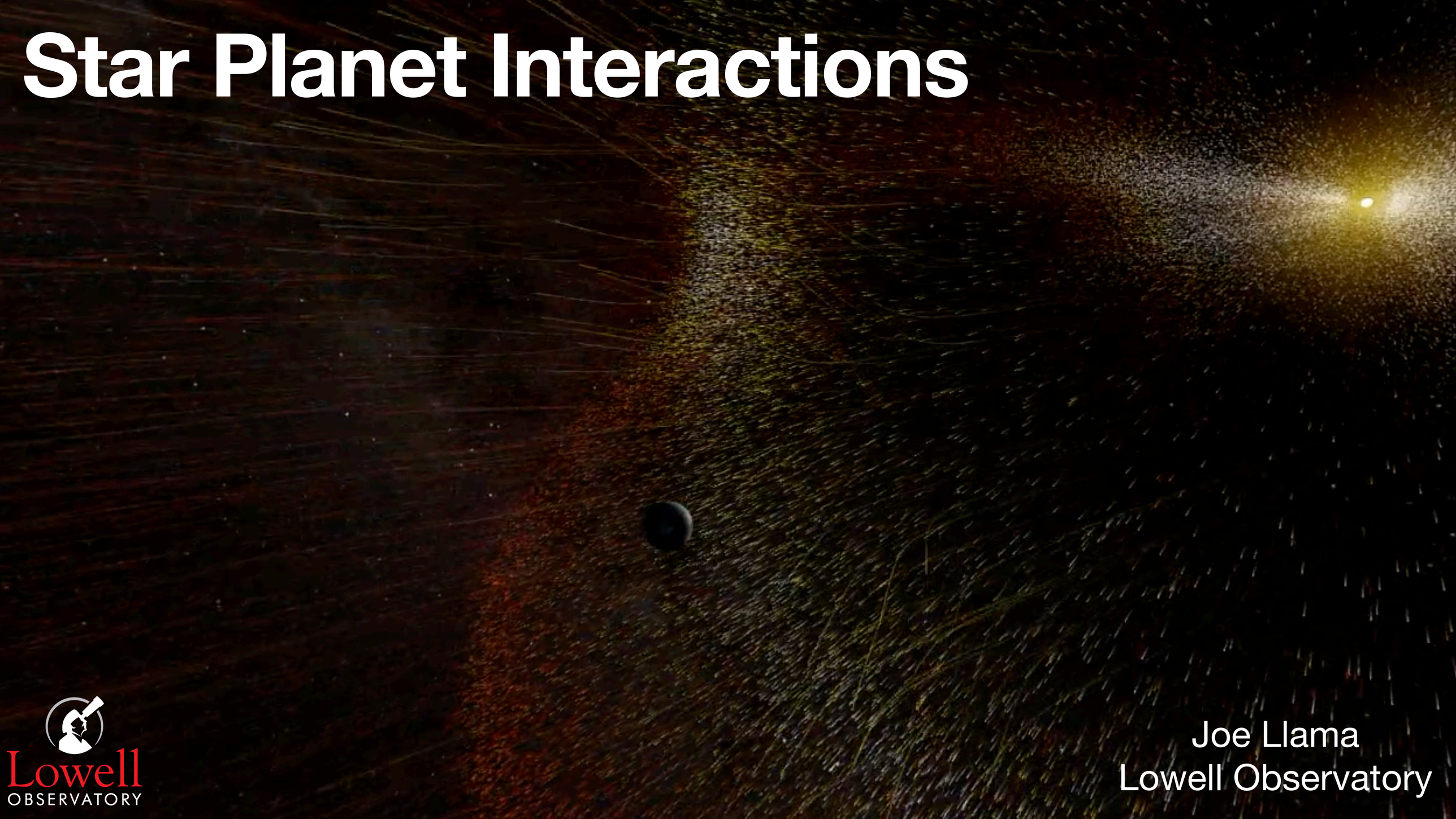
Joe Llama
Lowell Observatory



“So, have you thought about magnetic fields?”

Image credit: R. Dragushan

Star Planet Interactions



Joe Llama
Lowell Observatory

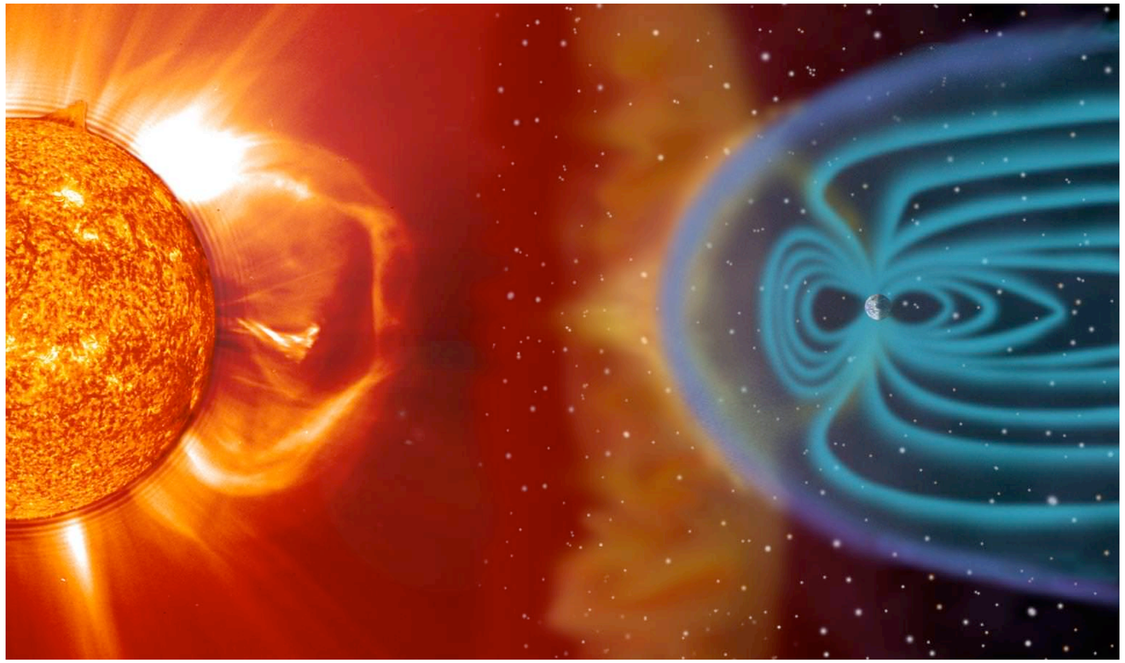
Lowell
OBSERVATORY

What are star-planet interactions?

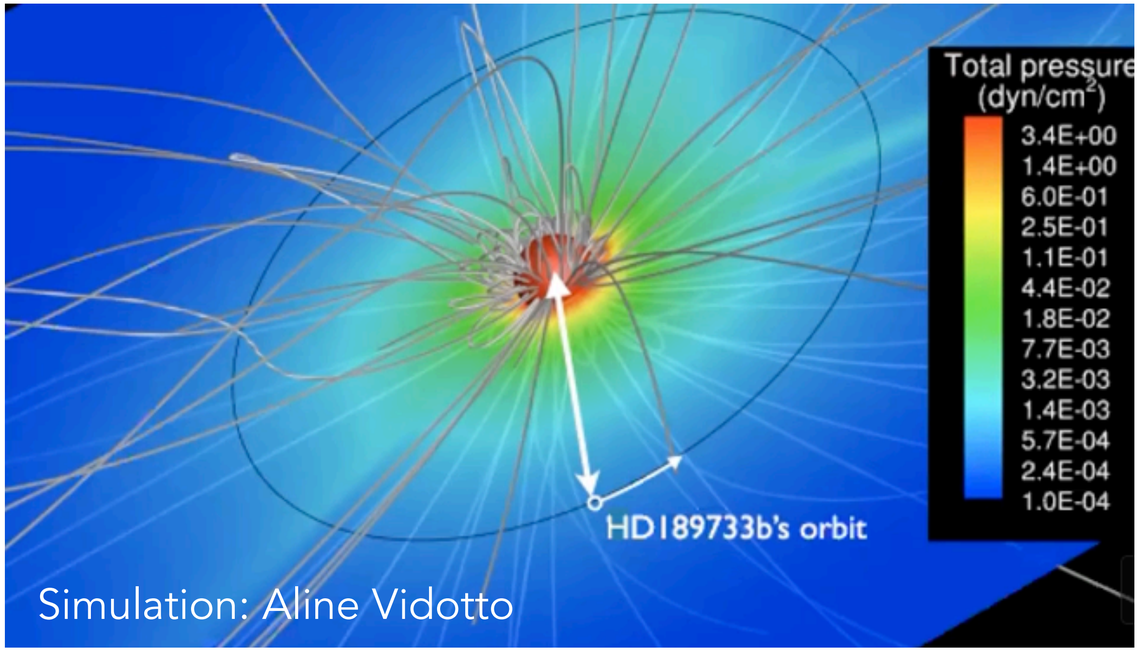
KISS Report on exoplanetary magnetism

How does space-weather impact a planet?

Earth
1 AU = 215 R_{sun}



Hot-Jupiter
0.05 AU = 6 R_{sun}



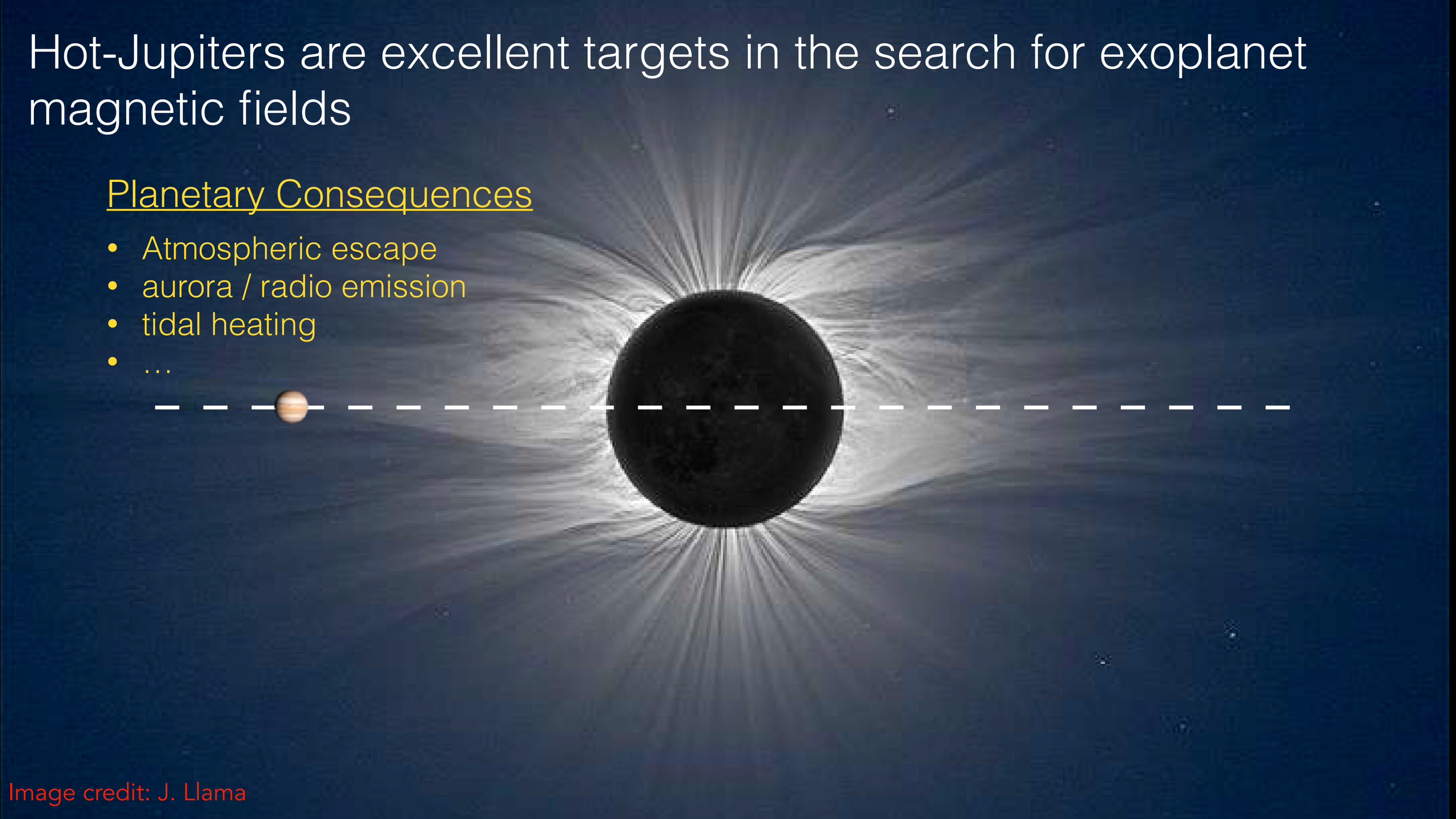
Close-in planets, in general, experience

- Higher density external environment
- Higher ambient magnetic field
- Higher radiative flux

Hot-Jupiters are excellent targets in the search for exoplanet magnetic fields

Image credit: J. Llama

Hot-Jupiters are excellent targets in the search for exoplanet magnetic fields

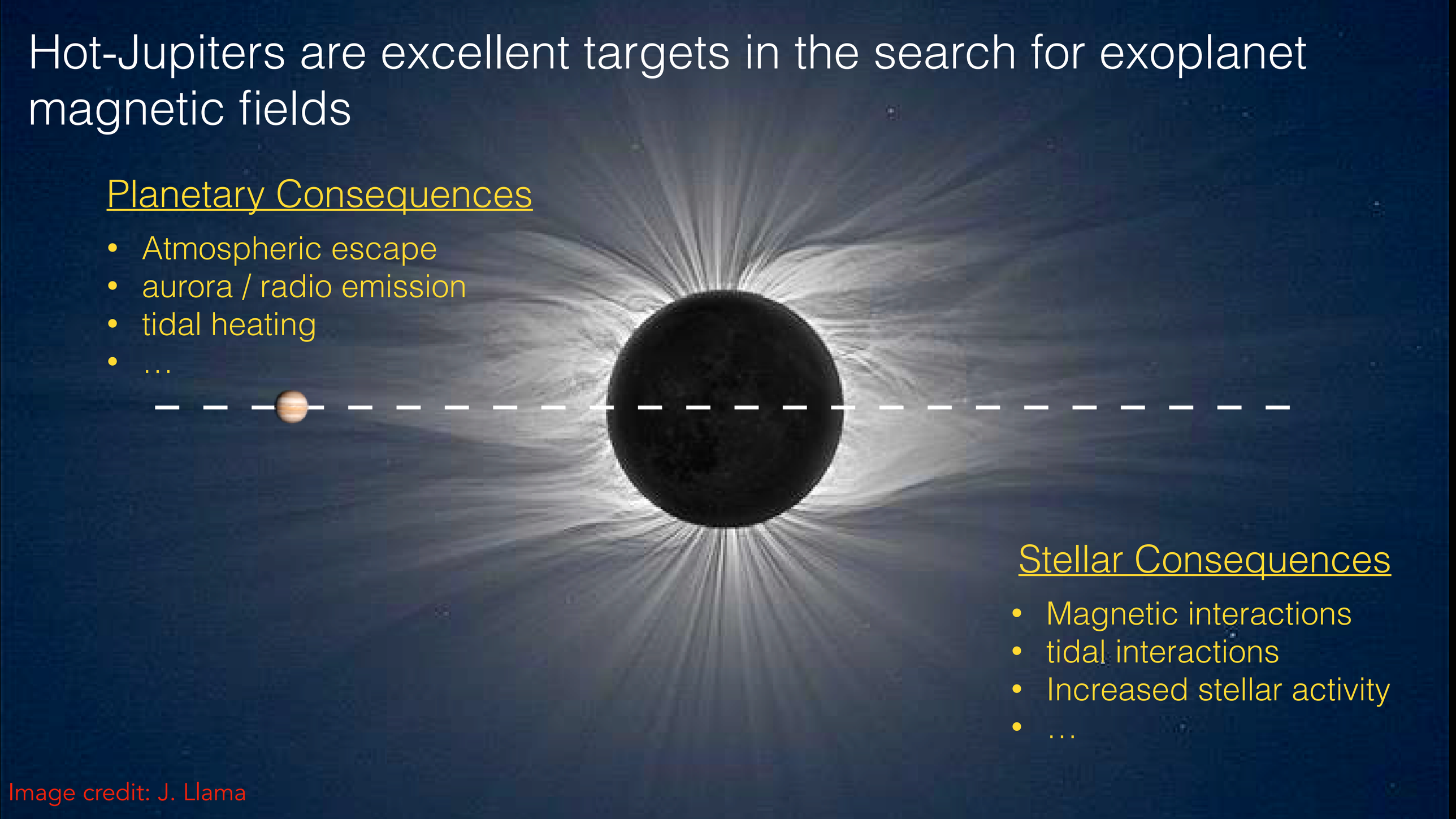


Planetary Consequences

- Atmospheric escape
- aurora / radio emission
- tidal heating
- …

Image credit: J. Llama

Hot-Jupiters are excellent targets in the search for exoplanet magnetic fields



Planetary Consequences

- Atmospheric escape
- aurora / radio emission
- tidal heating
- …

Stellar Consequences

- Magnetic interactions
- tidal interactions
- Increased stellar activity
- …

Image credit: J. Llama

How do we detect Star-Planet Interactions?

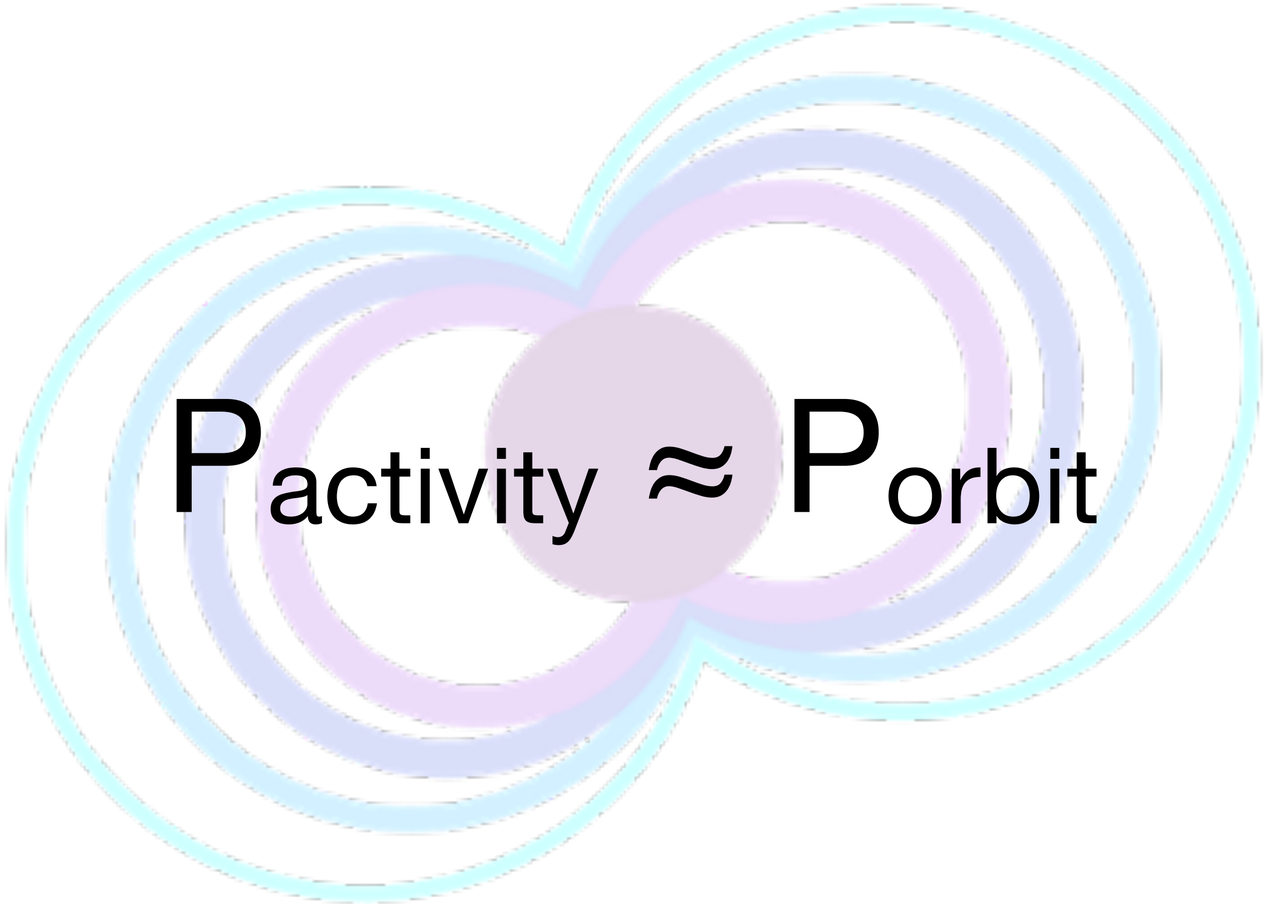
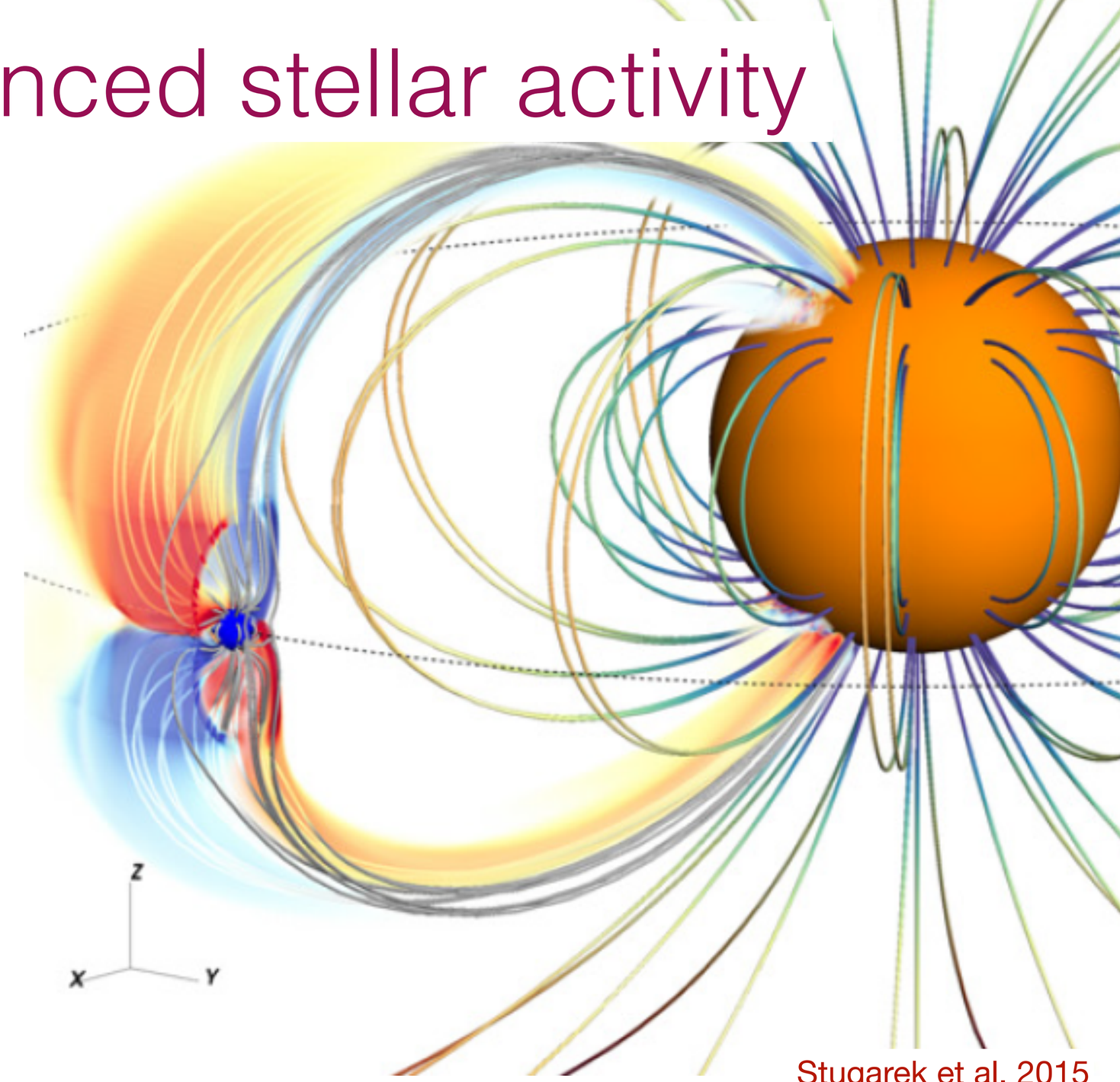


Image credit: R. Dragushan

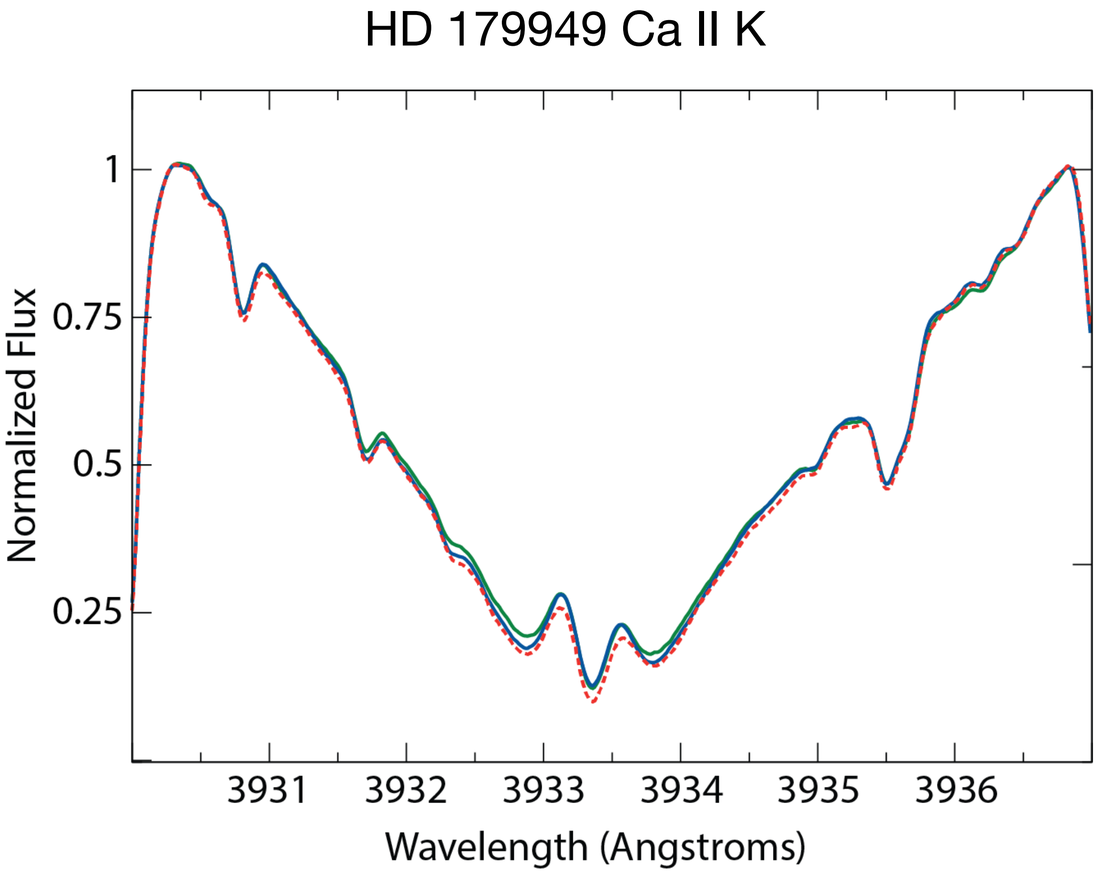
Searching for enhanced stellar activity

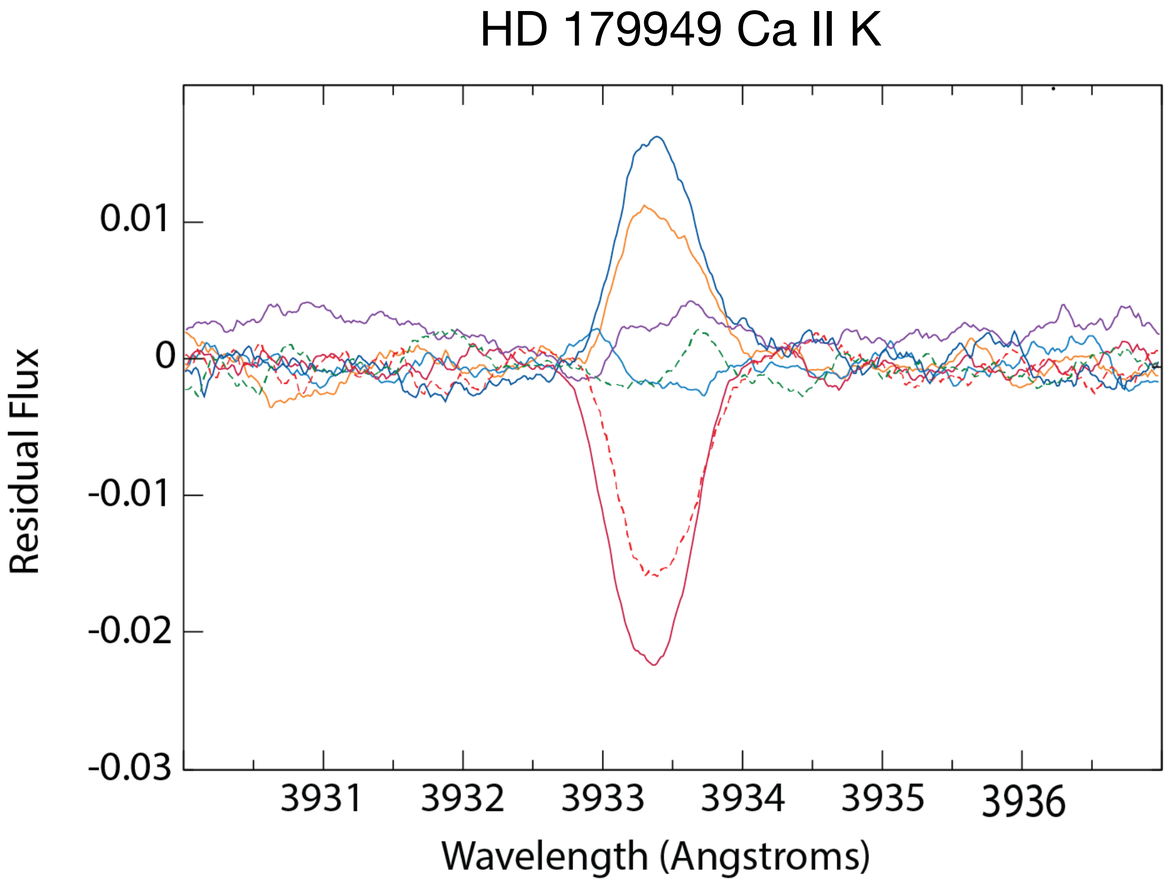
- Stellar magnetic field and planetary magnetic field lines can connect.
- Results in “hot spots” that can be detected as enhanced chromospheric activity.



Stugarek et al. 2015

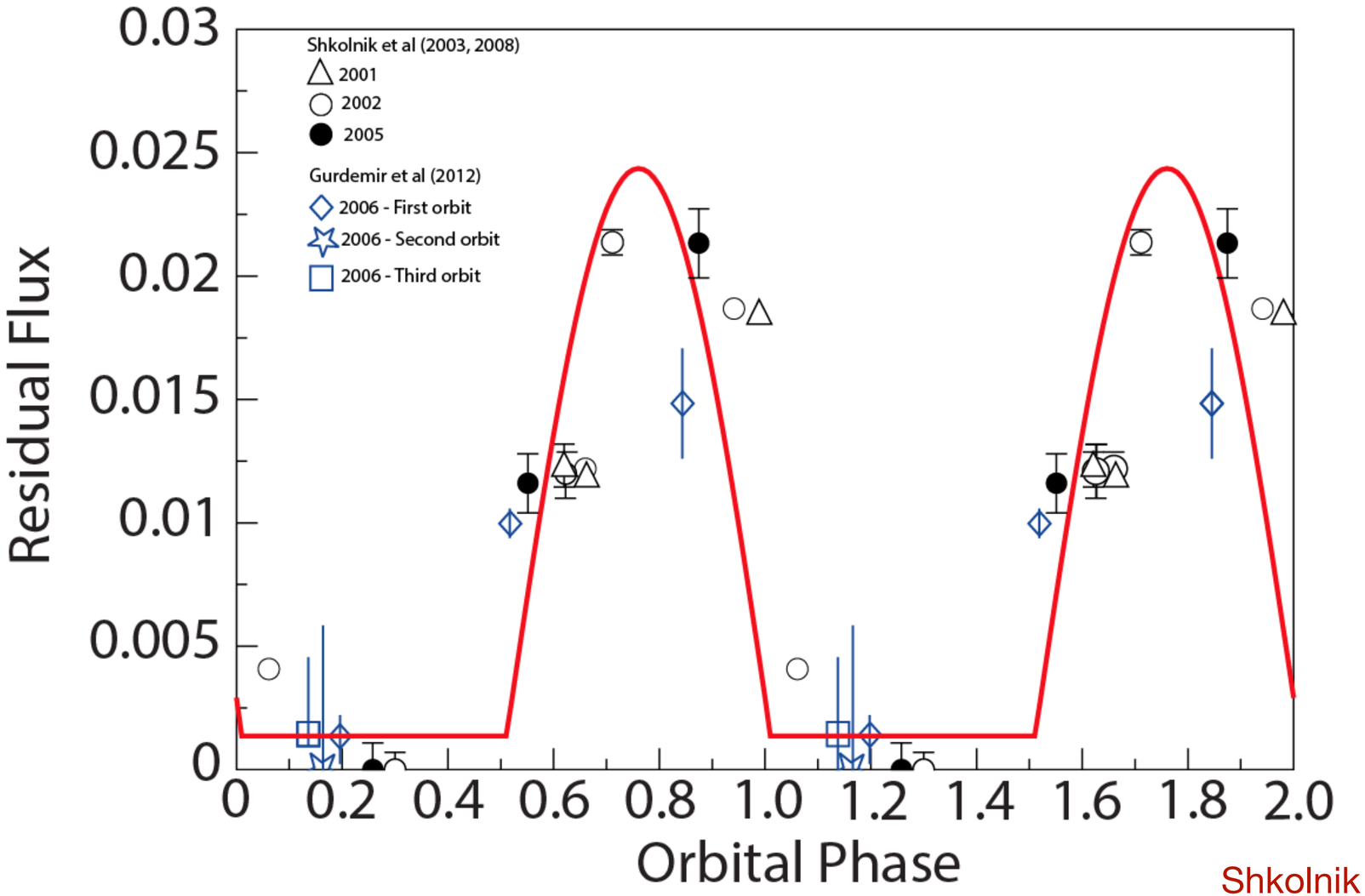
Searching for enhanced stellar activity





Shkolnik et al. 2003, 2005

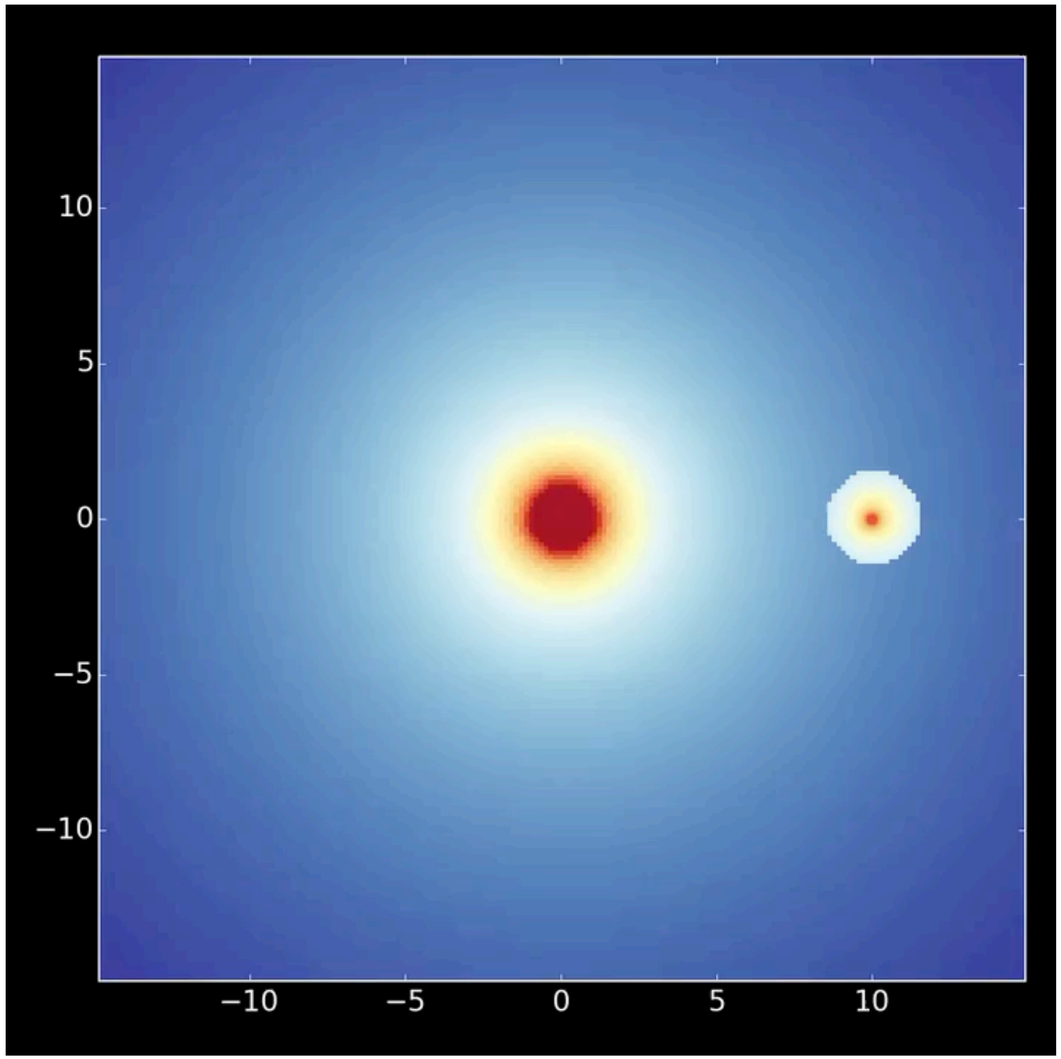
Searching for enhanced stellar activity



Shkolnik et al. 2003, 2005, 2008
Gurdemir et al. 2012

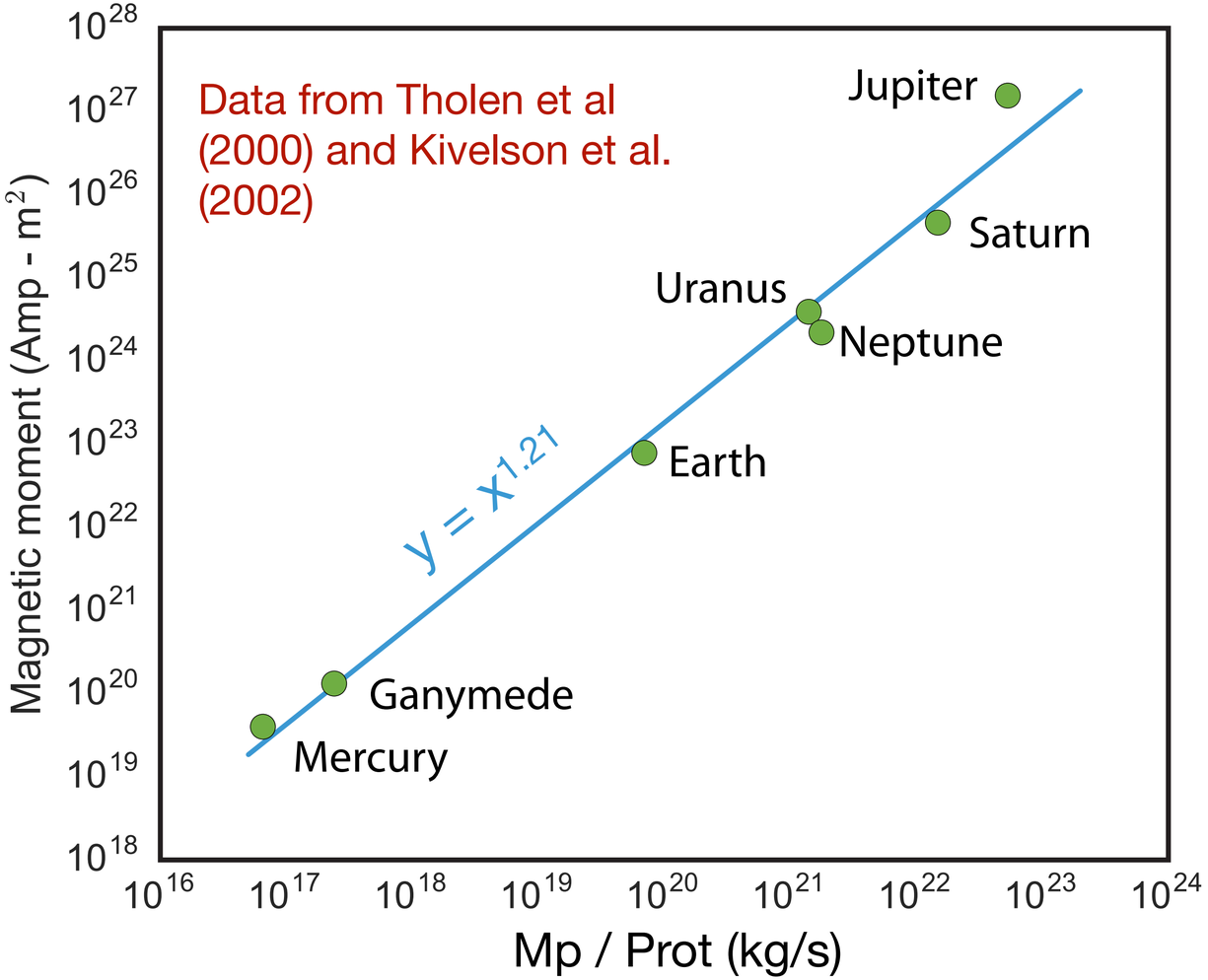
Searching for enhanced stellar activity

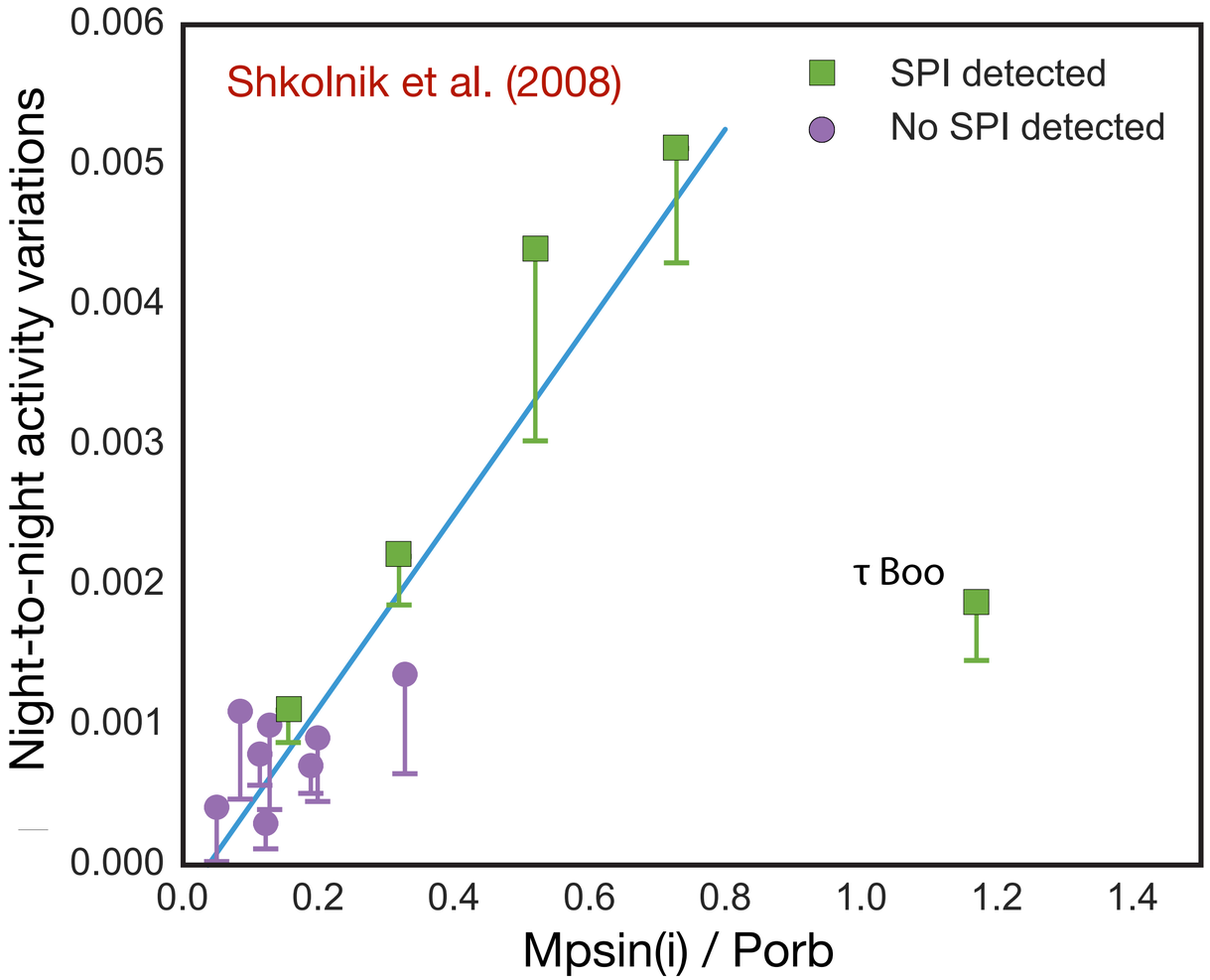
- MHD modeling predicts enhanced activity that phases with the orbital period of the planet.
- The “hot spot” on the stellar surface leads the orbit of the planet by ~30^{o}.



Matsakos et al. 2015

Detections of exoplanet B-fields



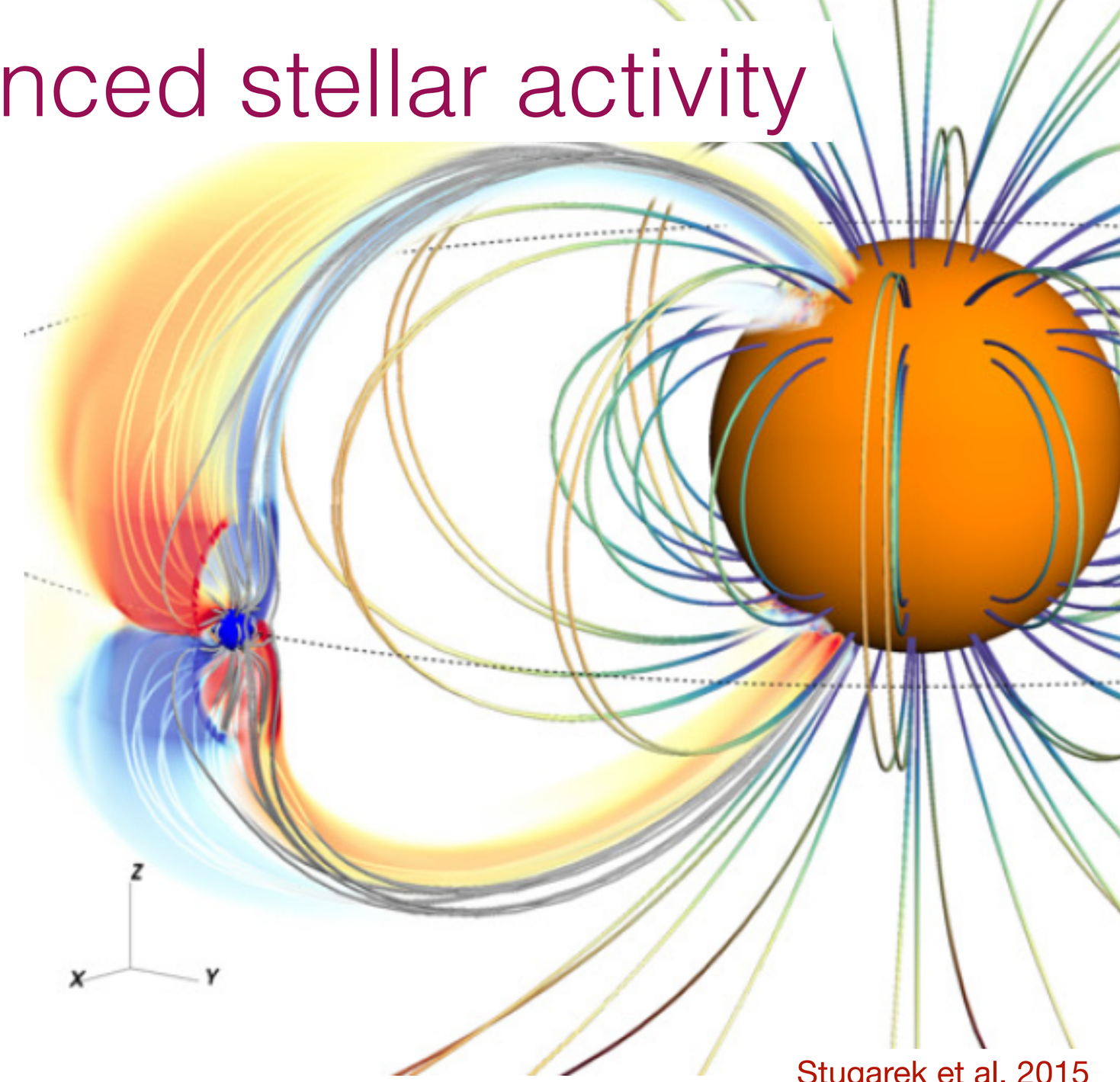


Searching for enhanced stellar activity

- Stellar magnetic field and planetary magnetic field lines can connect.
- Results in “hot spots” that can be detected as enhanced chromospheric activity.
- Measured SPI power can be used to estimate planetary field strength:

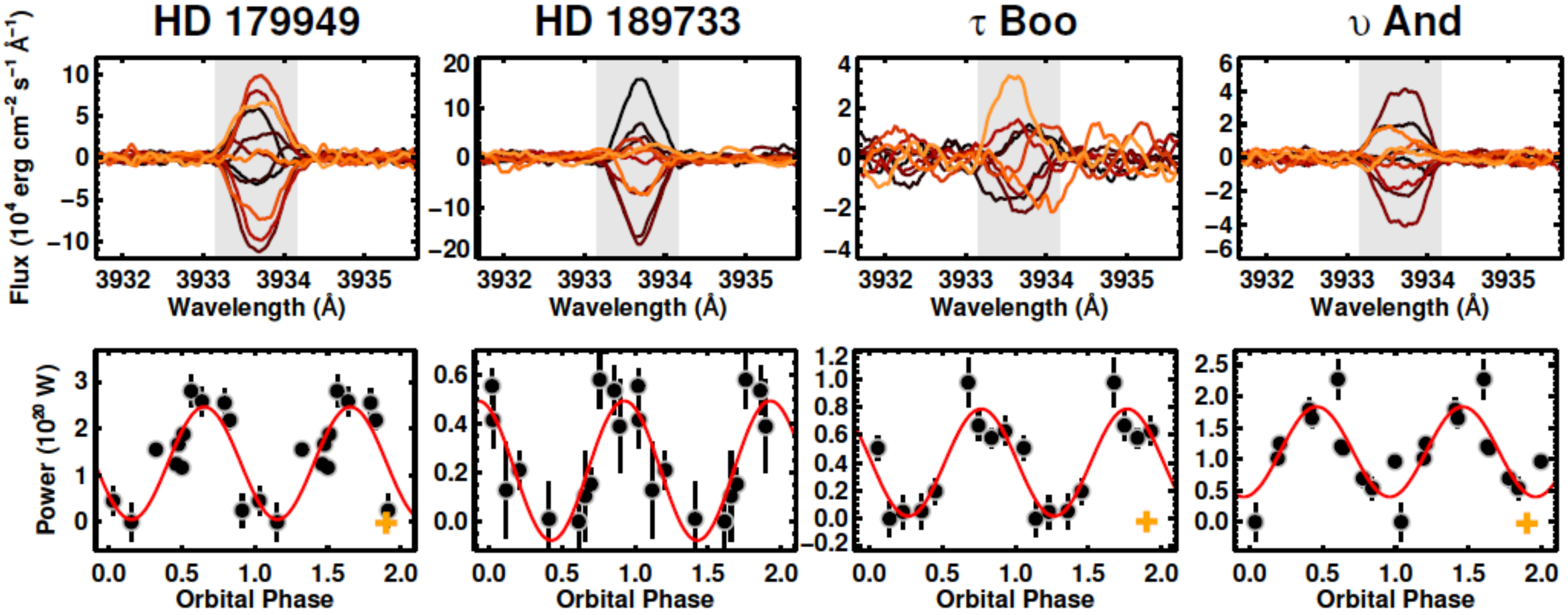
$$\text{SPI Power} \propto B_\star^{4/3} B_p^{2/3} v_{rel}$$

Lanza et al. (2009, 2012, 2013)



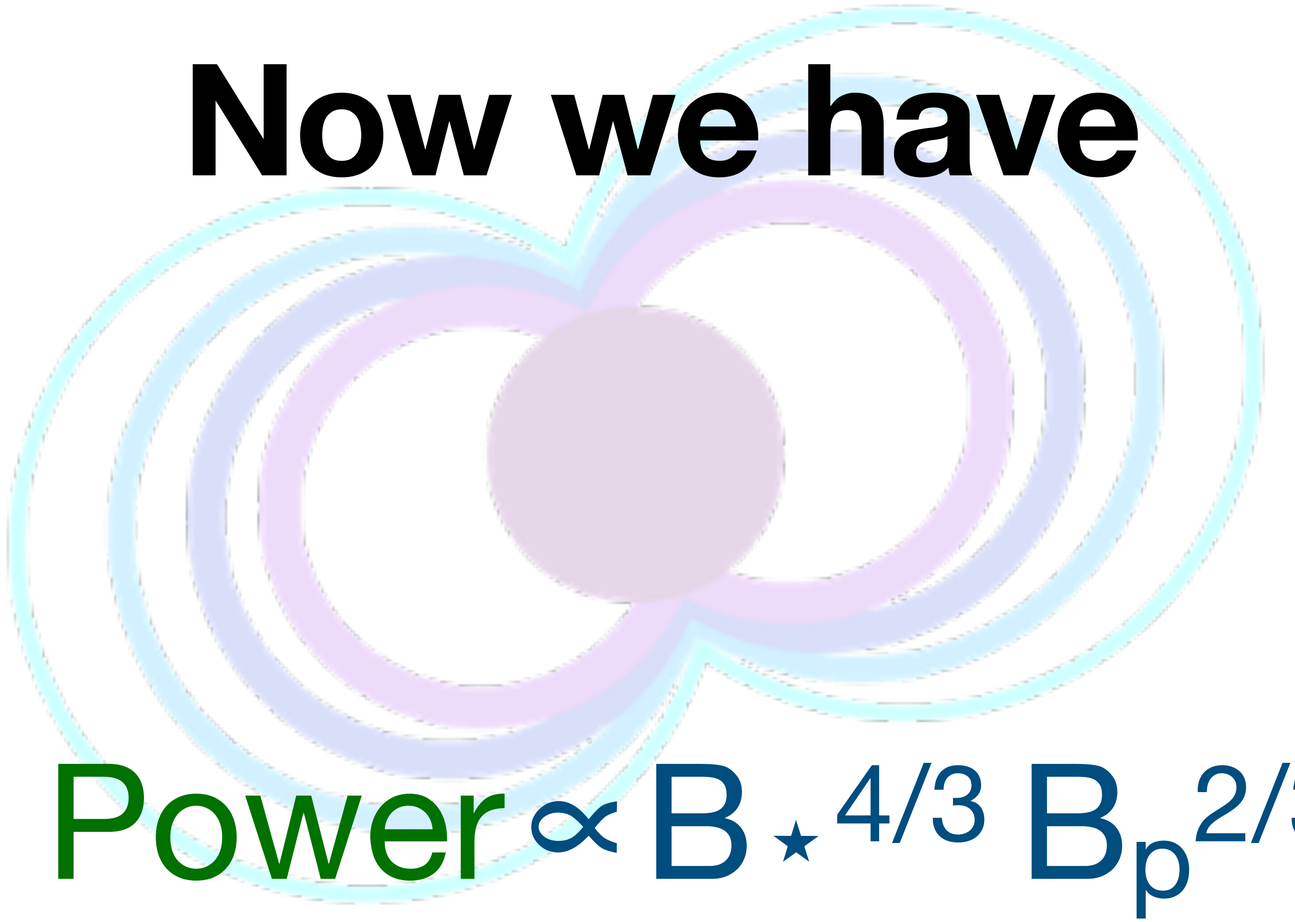
Stugarek et al. 2015

SPI sample with accurate flux calibration and stellar magnetic fields measured measurements.



Cauley et al. 2018, 2019

Now we have



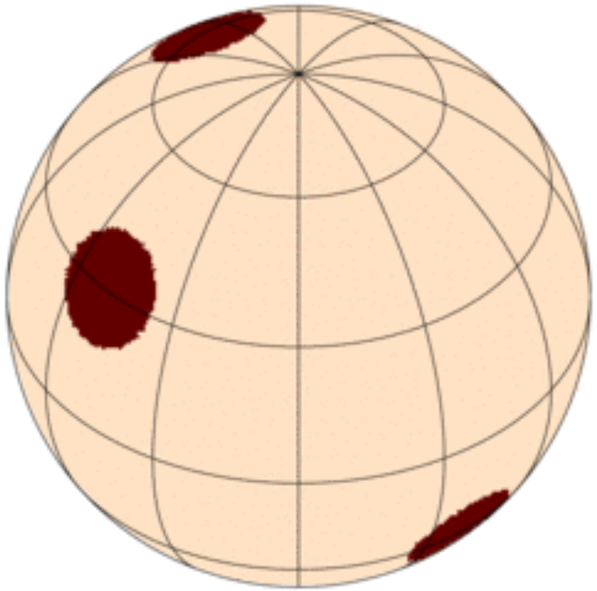
$$\text{SPI Power} \propto B_\star^{4/3} B_p^{2/3} v_{rel}$$

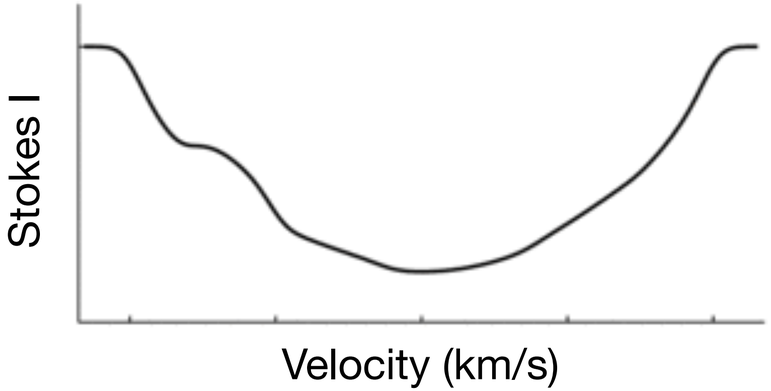
Image credit: R. Dragushan

Lanza et al. (2009, 2012, 2013)

How do we observe stellar magnetic fields?

Doppler Imaging recovers dark spots

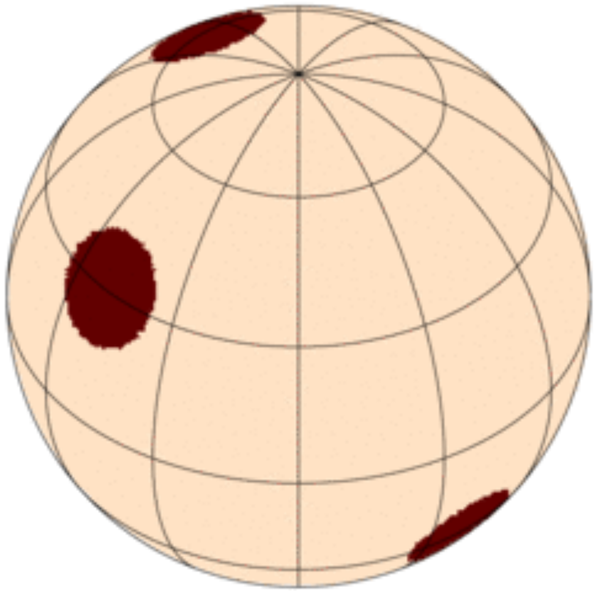


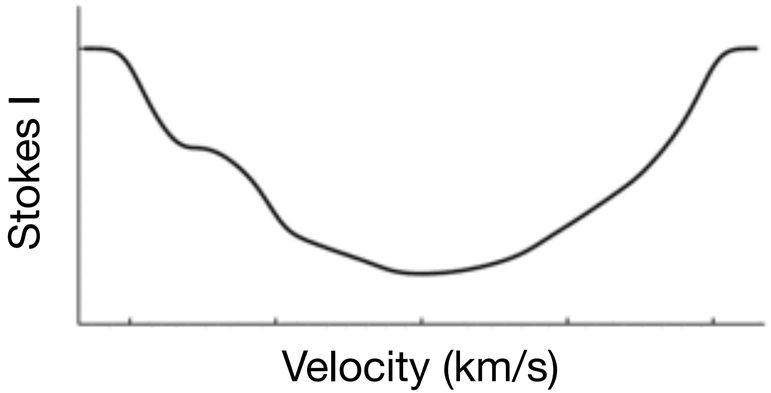


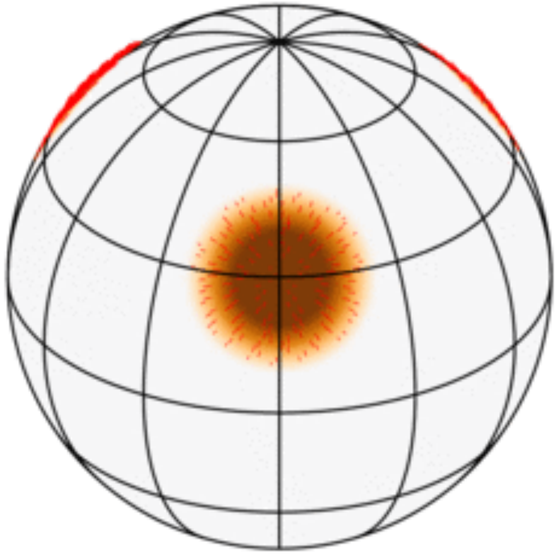
Simulation credit: Oleg Kochukhov

How do we observe stellar magnetic fields?

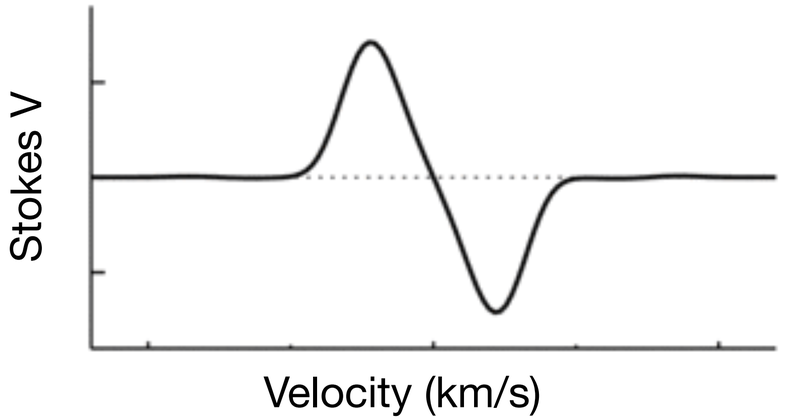
Doppler Imaging recovers dark spots





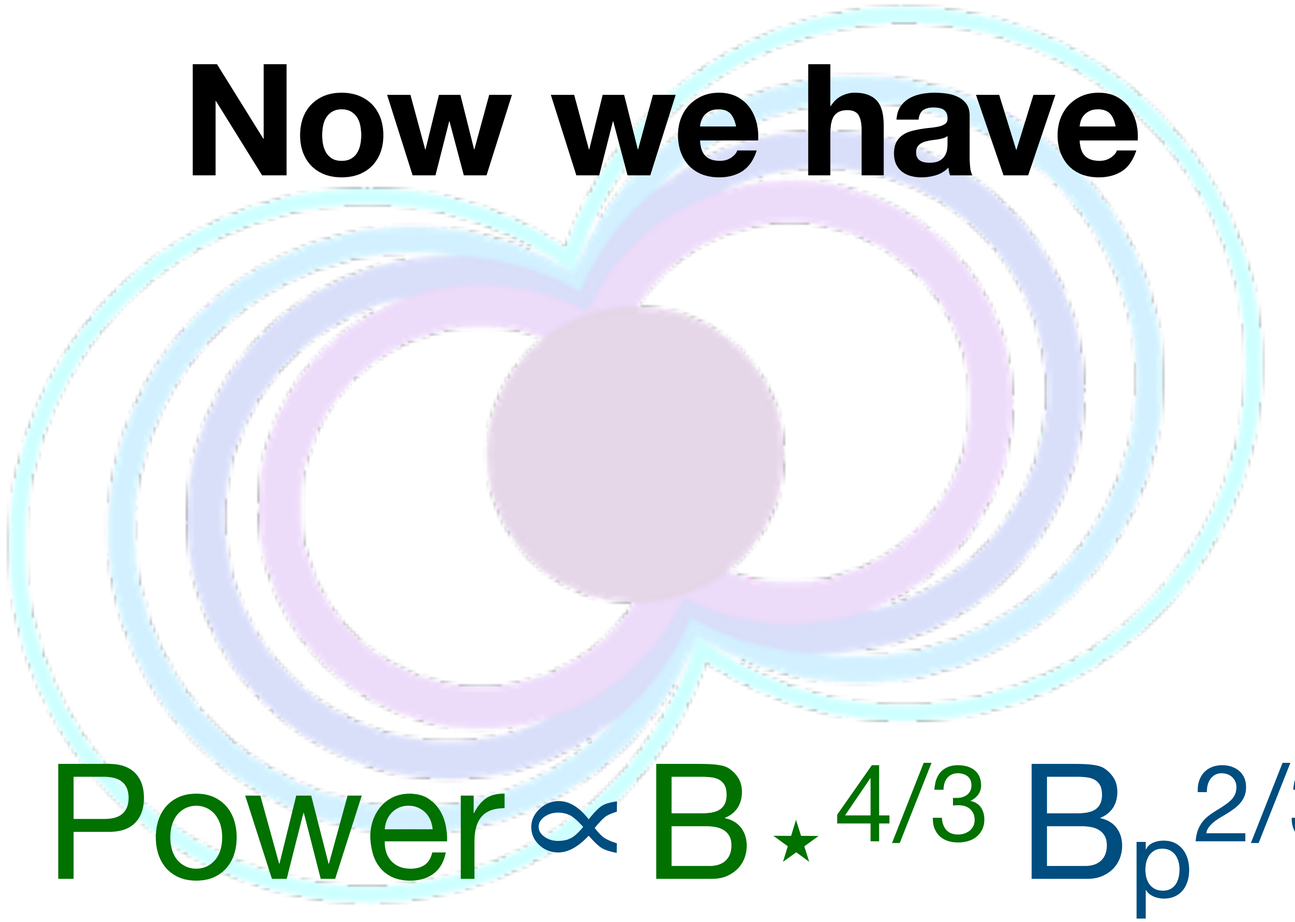


Zeeman Doppler Imaging uses circularly polarized light to recover magnetic field



Simulation credit: Oleg Kochukhov

Now we have



$$\text{SPI Power} \propto B_\star^{4/3} B_p^{2/3} v_{rel}$$

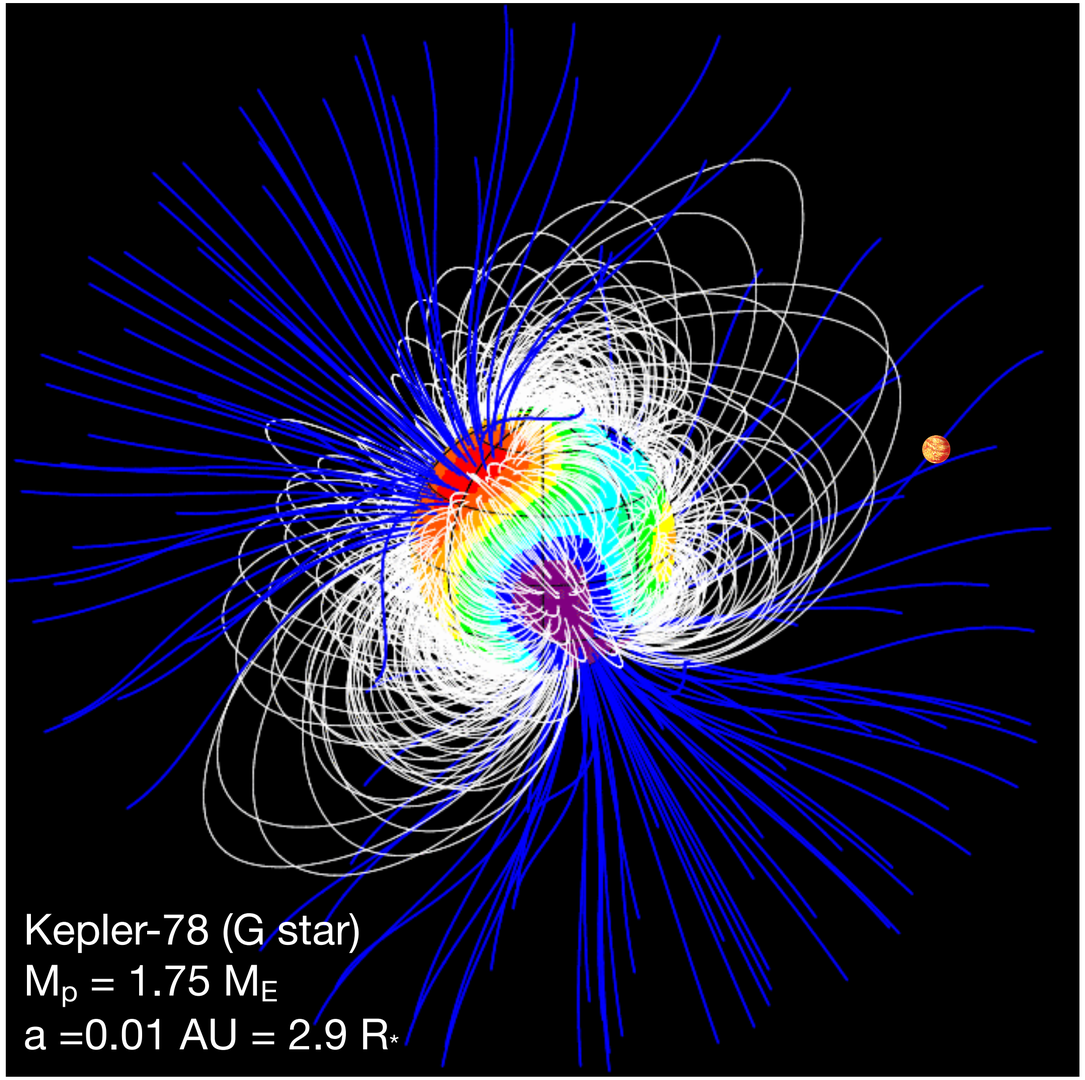
Image credit: R. Dragushan

Lanza et al. (2009, 2012, 2013)

Magnetic maps of exoplanet host stars

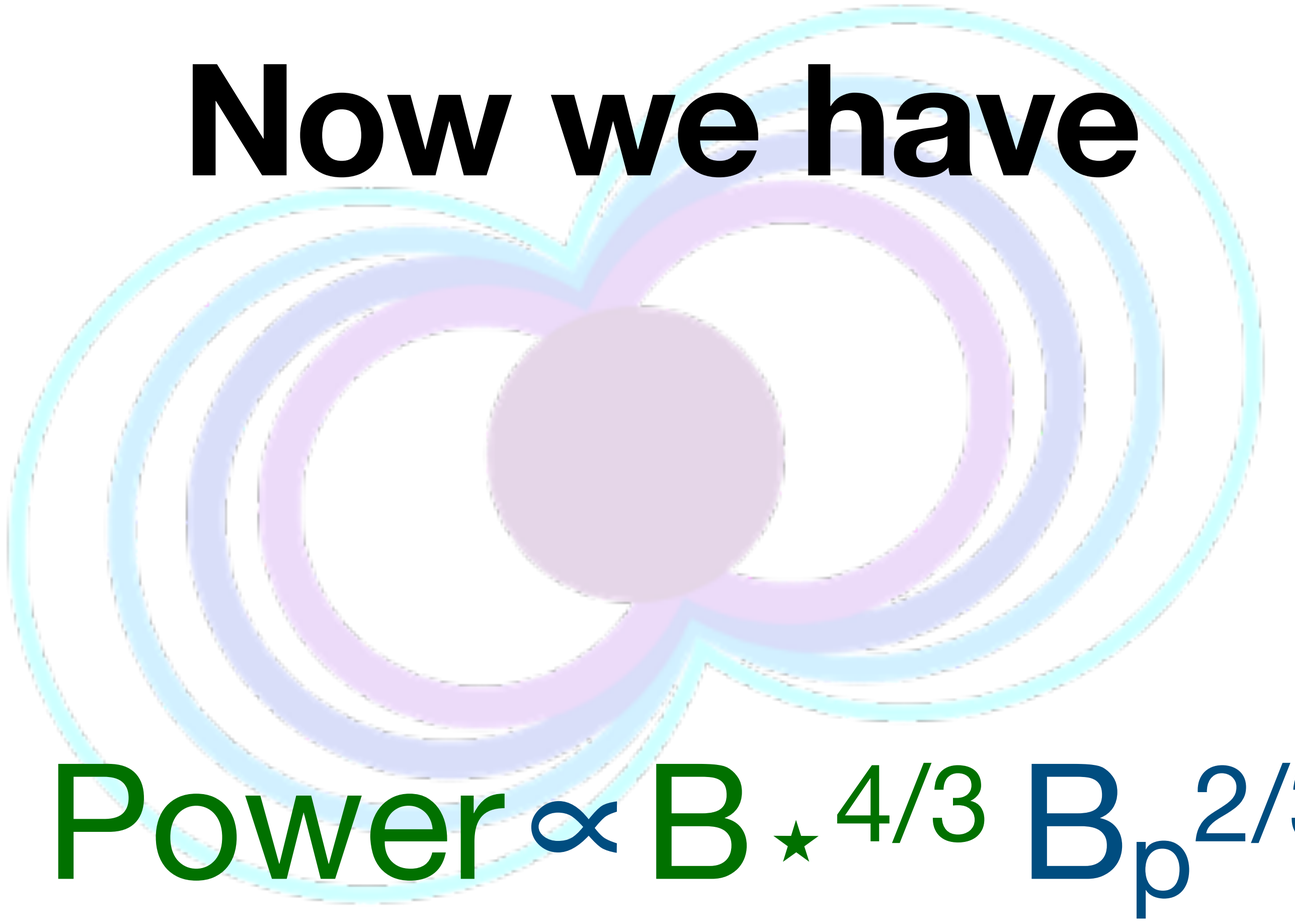
- Zeeman-Doppler Imaging maps can be used as input into MHD models to extrapolate the stellar wind (e.g., Jardine et al. 2006, Vidotto et al. 2015, Cohen et al. 2023)

- Allows us to study the space-weather conditions around an orbiting exoplanet.



Moutou et al. 2016
Fares et al. 2009, 2012, 2013

Now we have

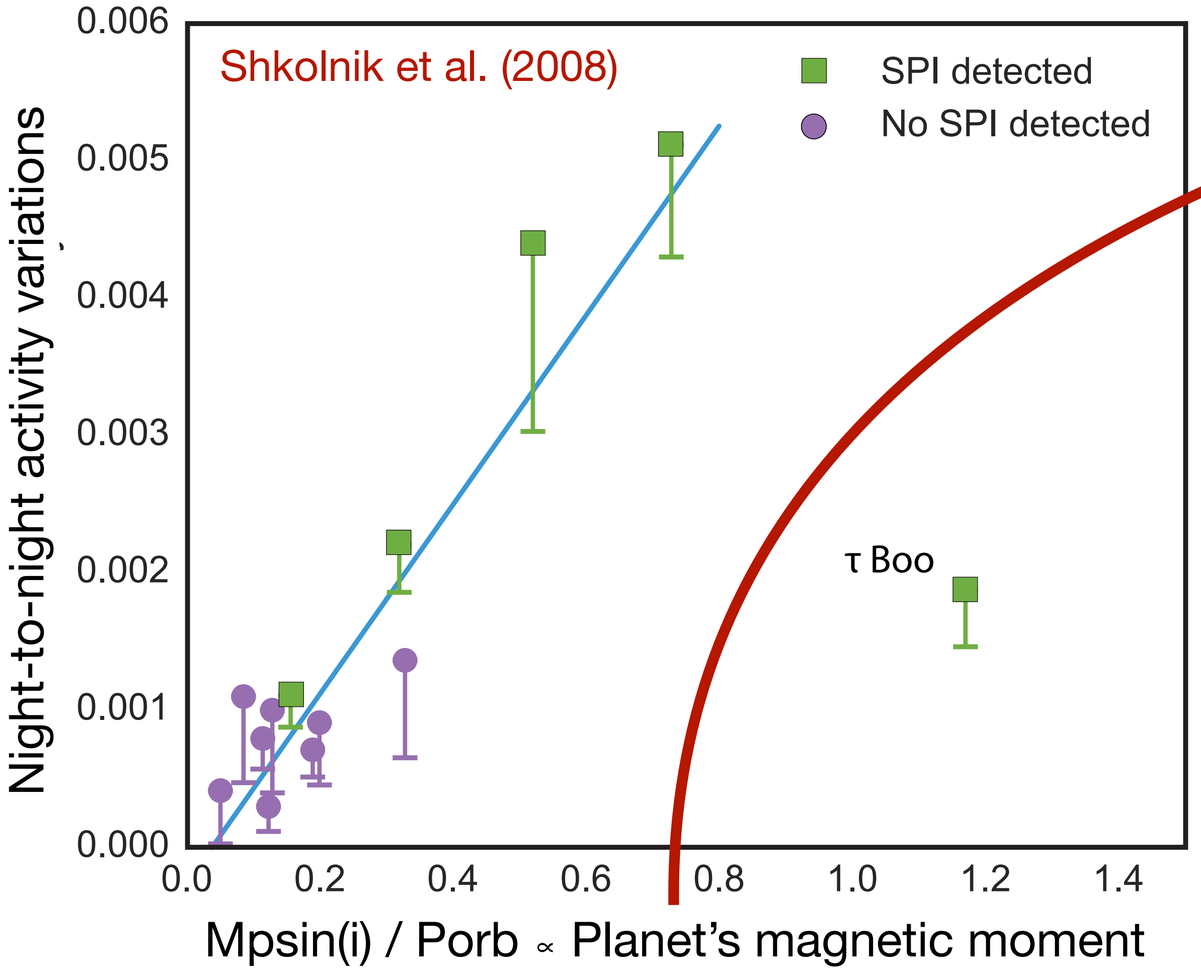


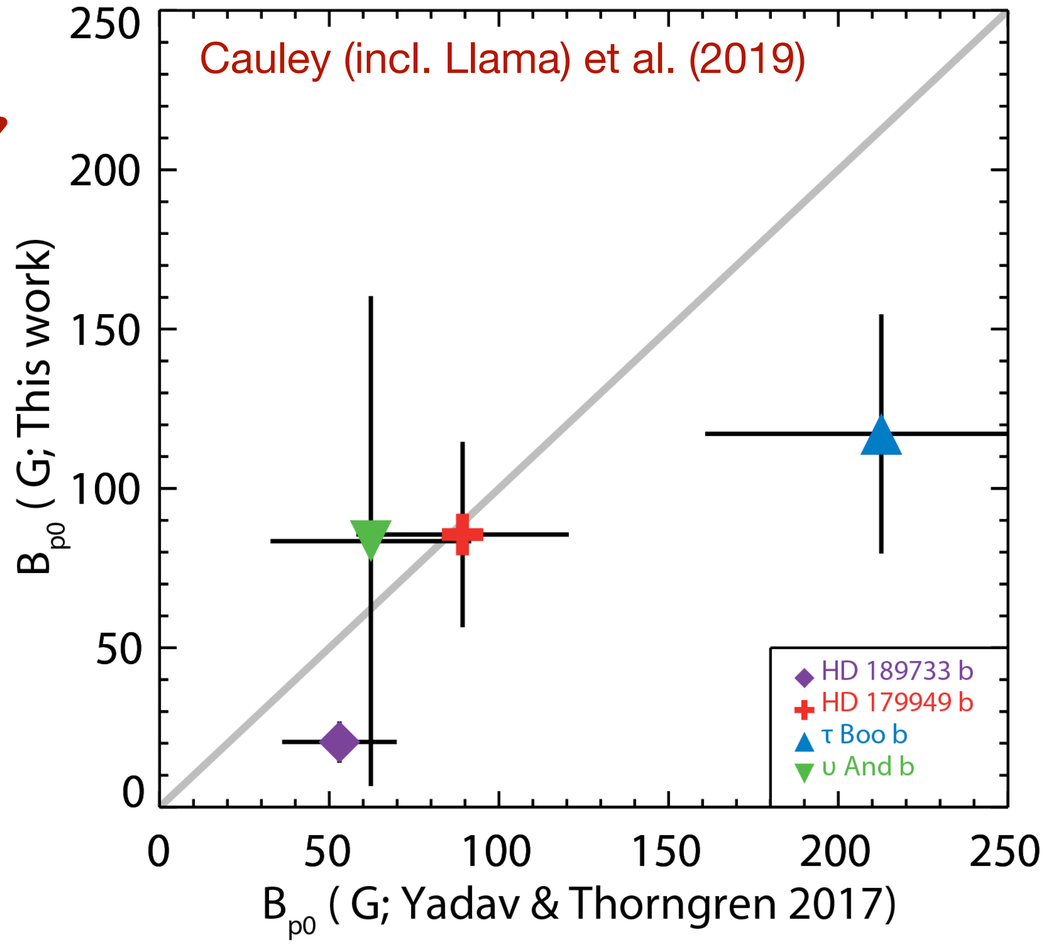
$$\text{SPI Power} \propto B_\star^{4/3} B_p^{2/3} v_{rel}$$

Image credit: R. Dragushan

Lanza et al. (2009, 2012, 2013)

Detections of exoplanet B-fields



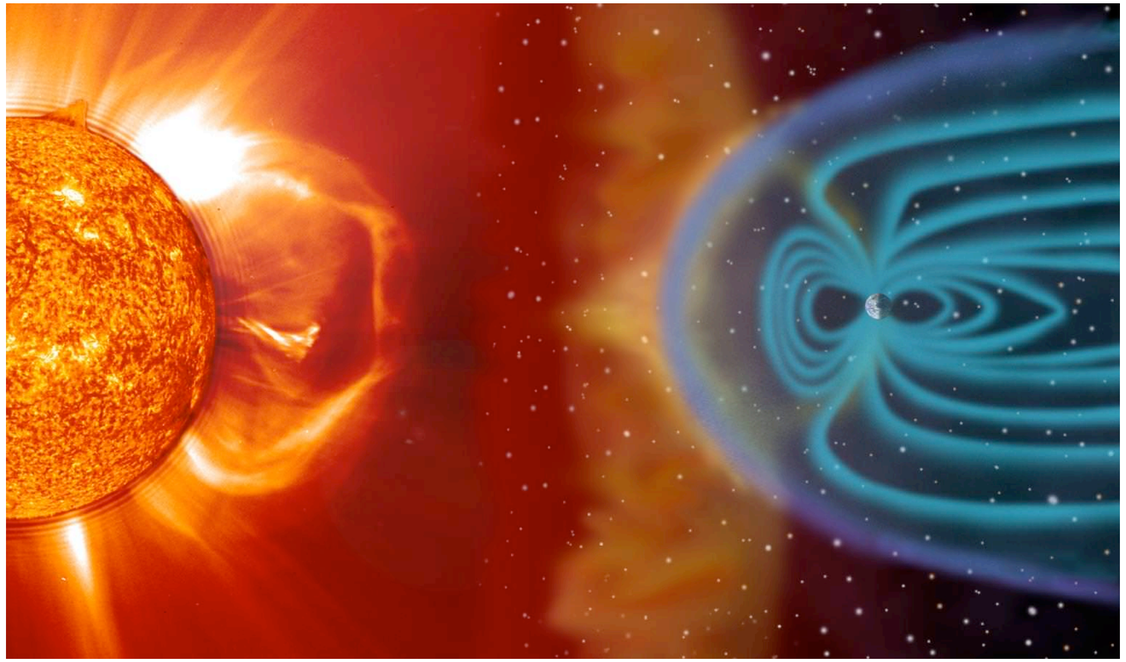


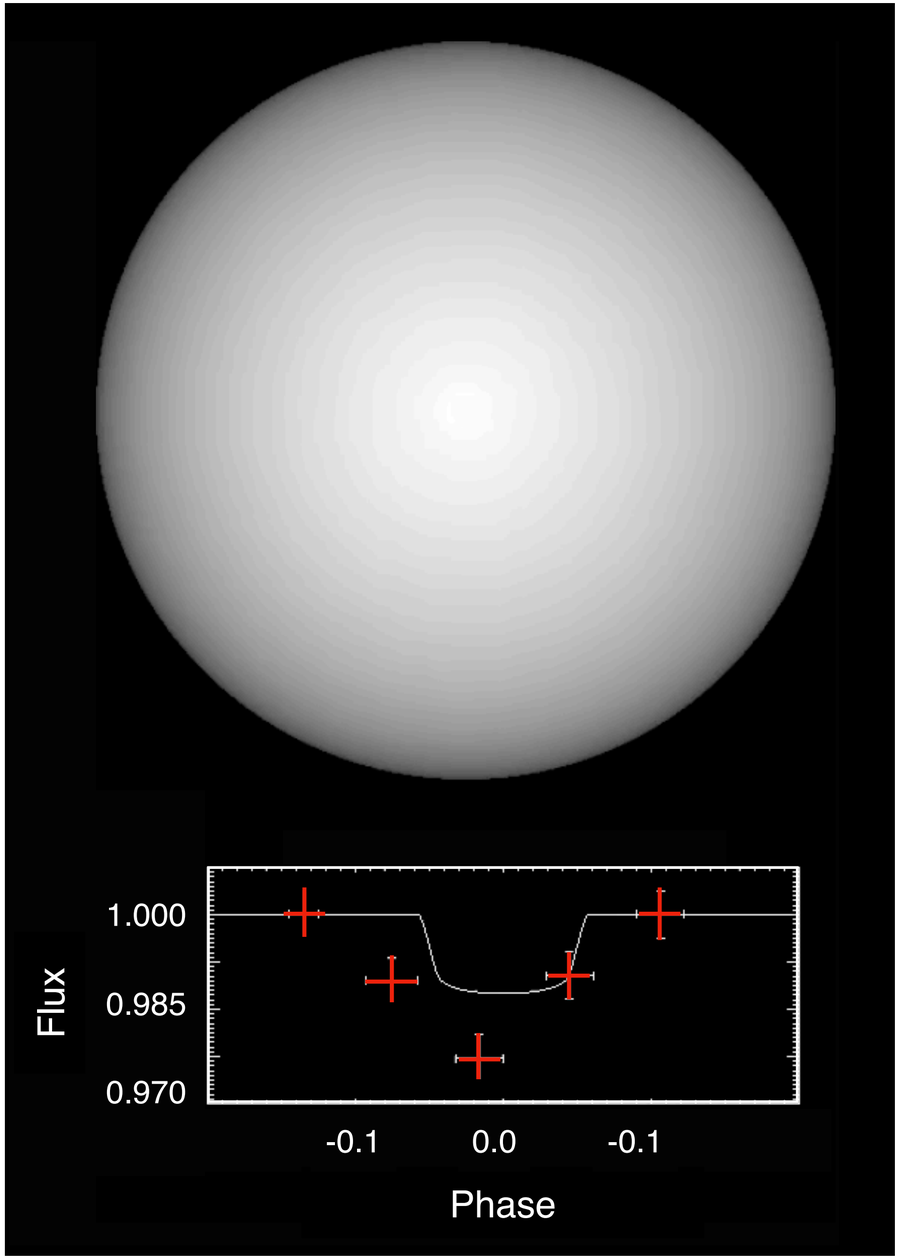
Typical magnetic field strengths of these hot-Jupiters: 20 - 120 G

Other star-planet interaction manifestations

Image credit: R. Dragushan

Searching for transit asymmetries

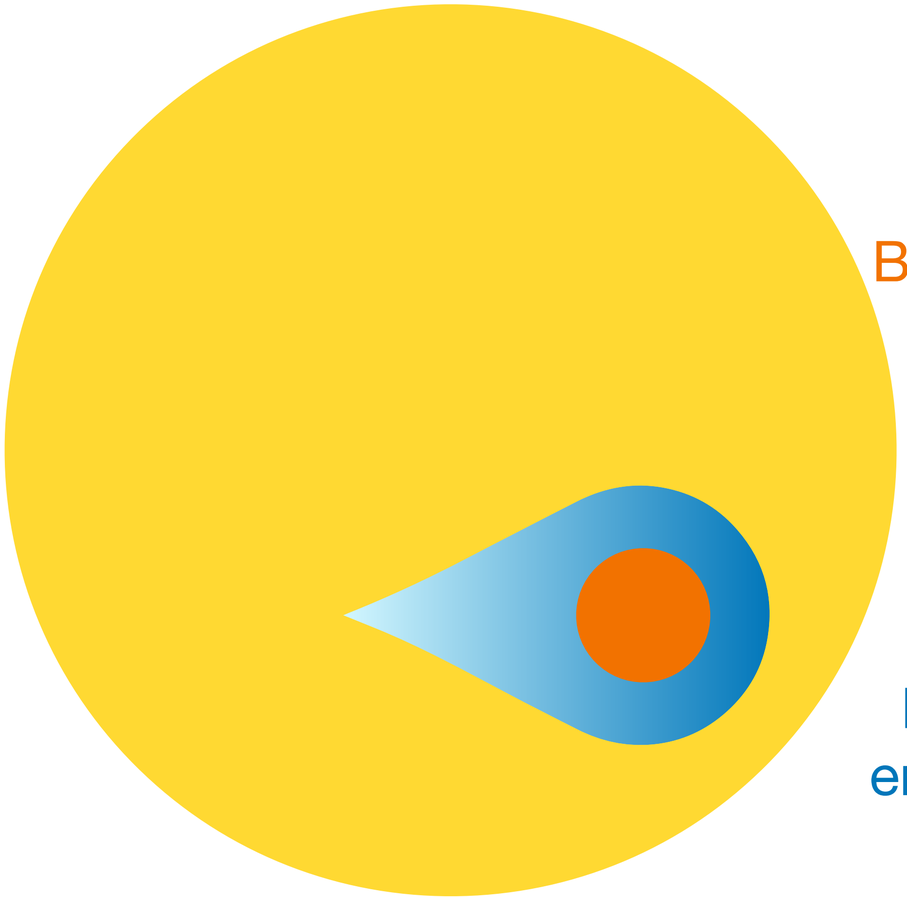




- Potential detections of a magnetic field induced bow-shock around:
  - WASP-12b (Near-UV) with Bp < 24G.
  - HD 189733 b (H-alpha) with Bp ~ 28G.

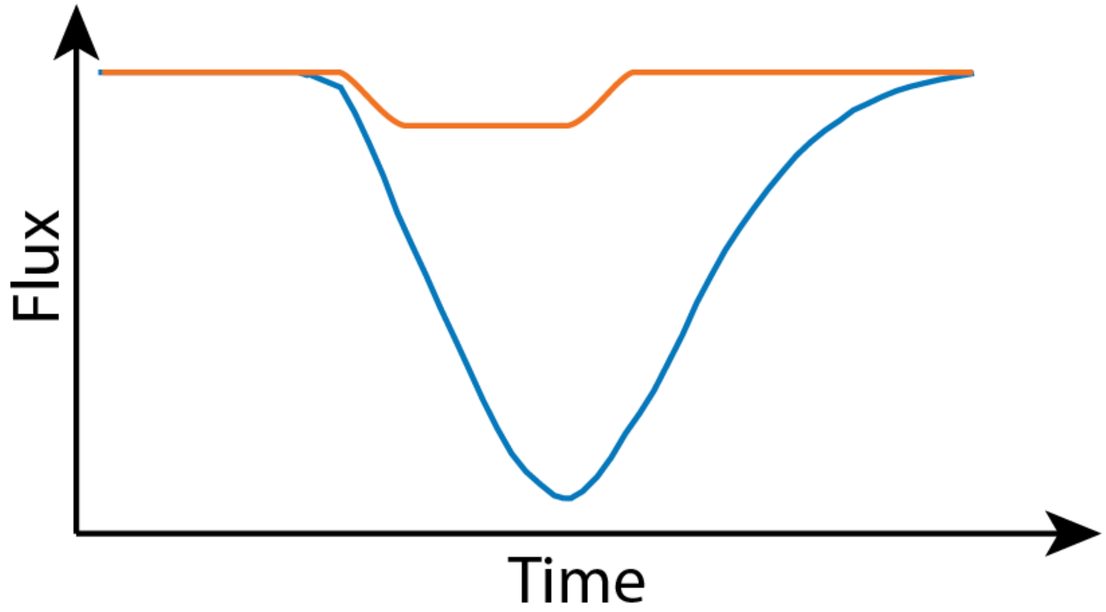
Fossati et al. 2010, Vidotto et al. 2011, Llama et al. 2011, Cauley et al. 2015

Space weather and planetary escape



Broadband optical transit

Deep high-energy transit (e.g., Ly-α)

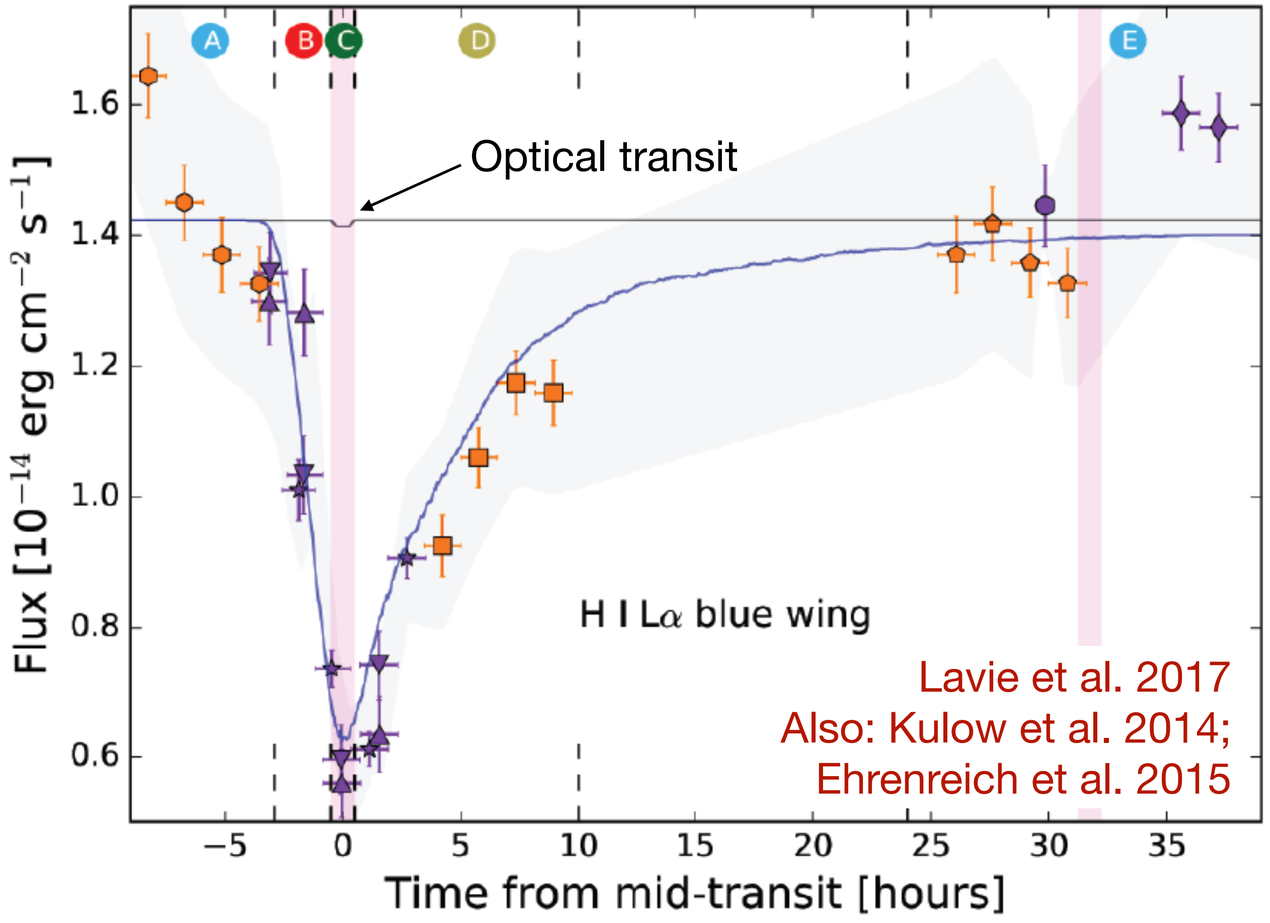


- Ratio in-and-out of transit as a function of wavelength to find % of absorption by the planetary atmosphere

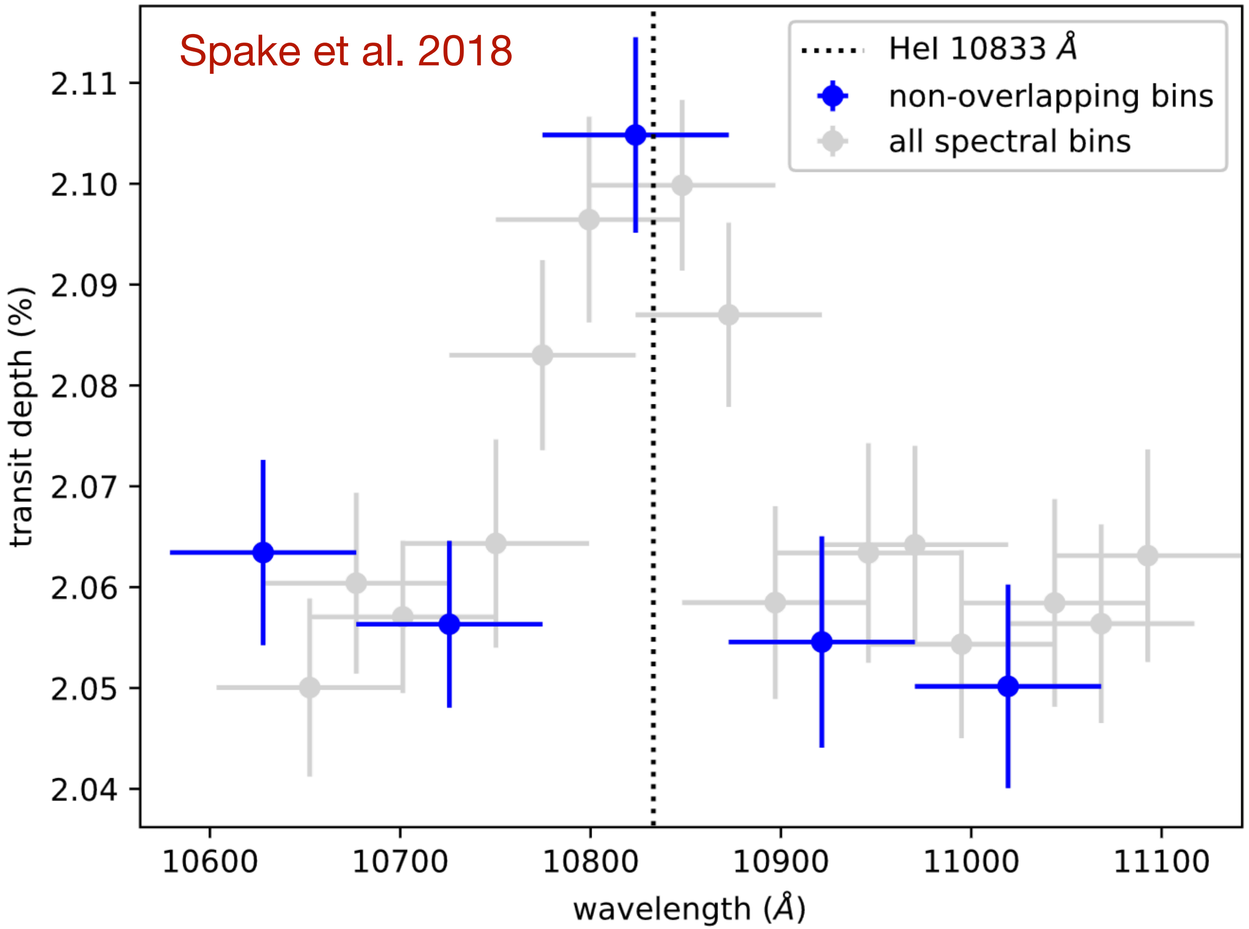
Slide credit: Aline Vidotto, Leiden

Space weather and planetary escape

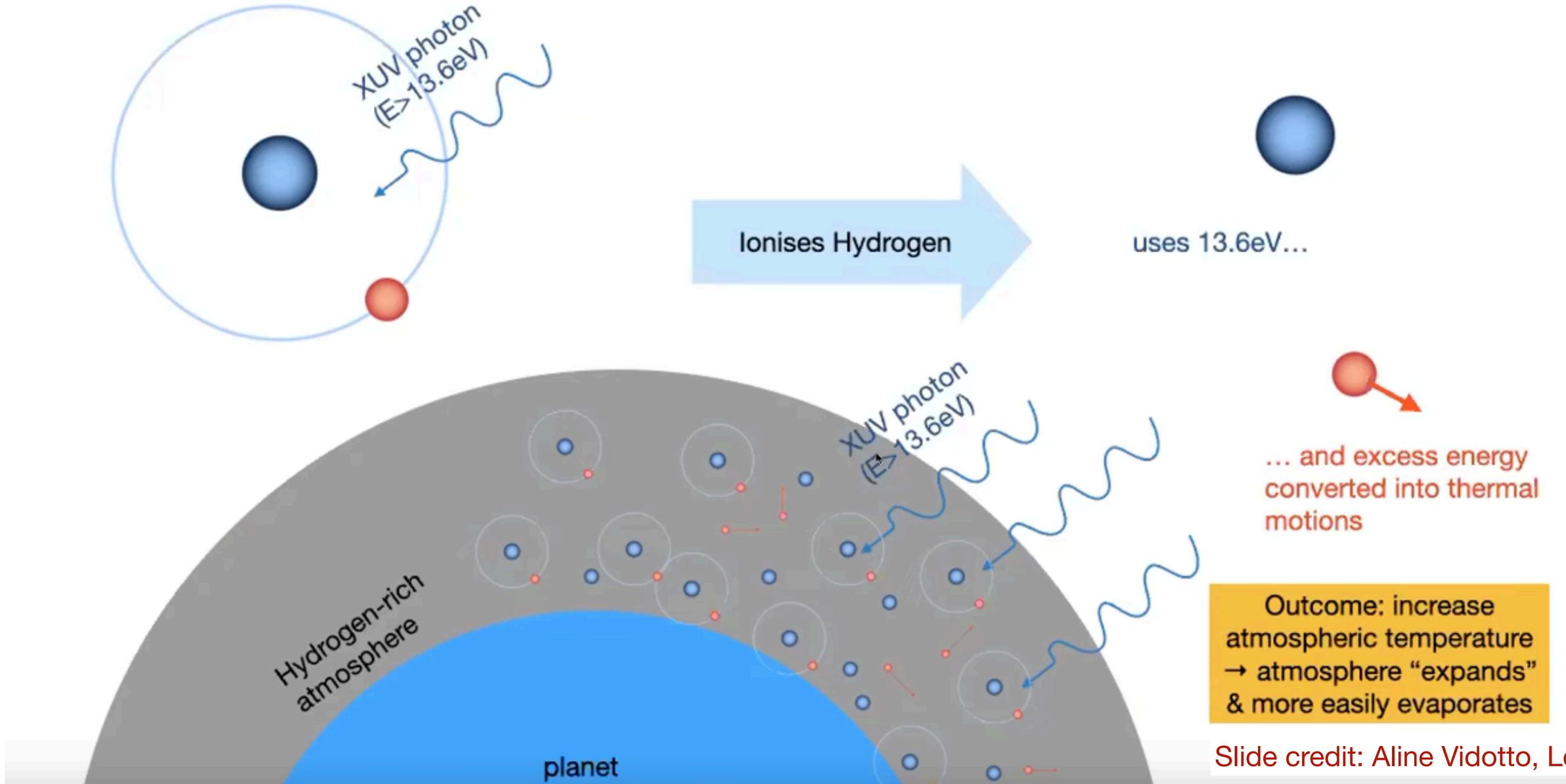
Lyman-alpha transit of GJ 436b



He-I transit of WASP-107b

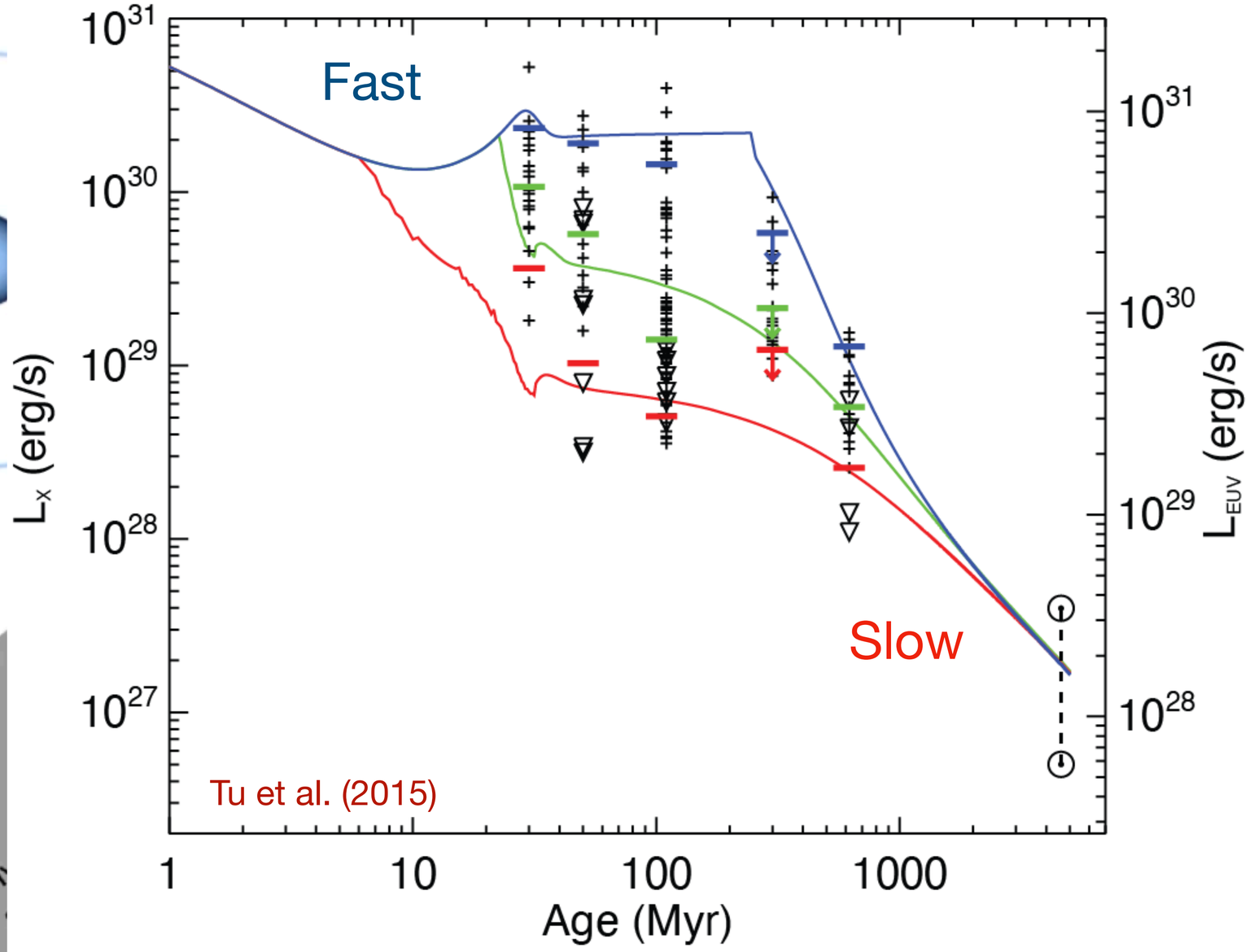


Space weather and planetary escape



Slide credit: Aline Vidotto, Leiden

Space weather and planetary escape



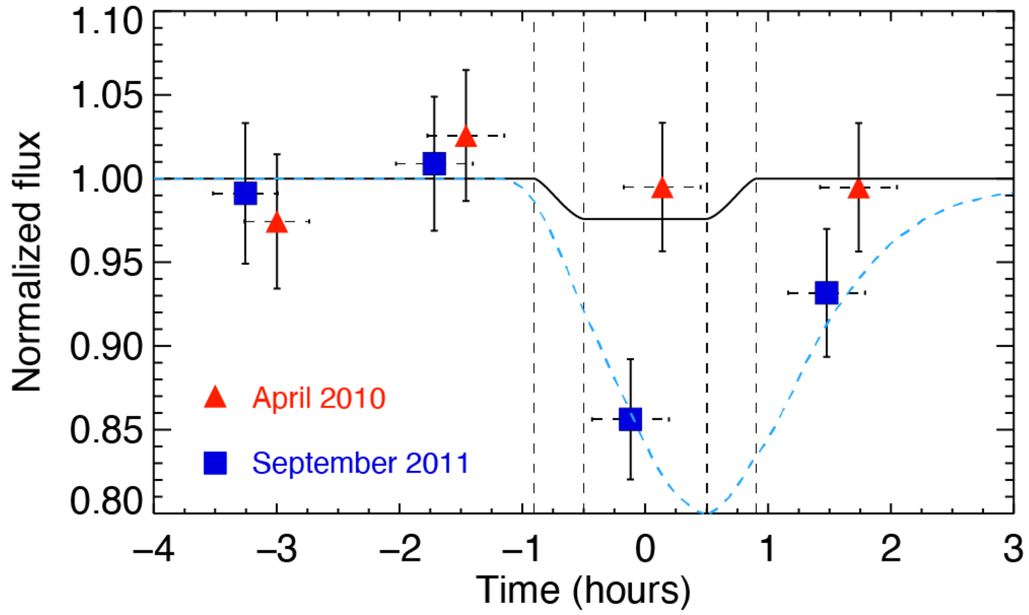
and excess energy
verted into thermal
tions

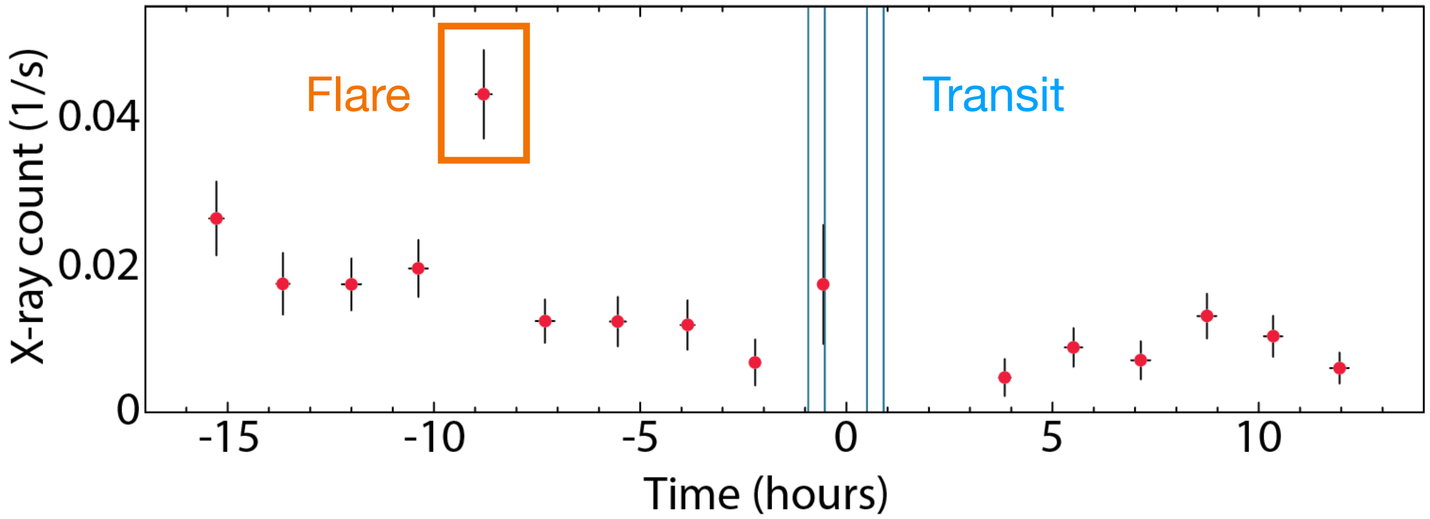
come: increase
pheric temperature
osphere "expands"
easily evaporates

planet

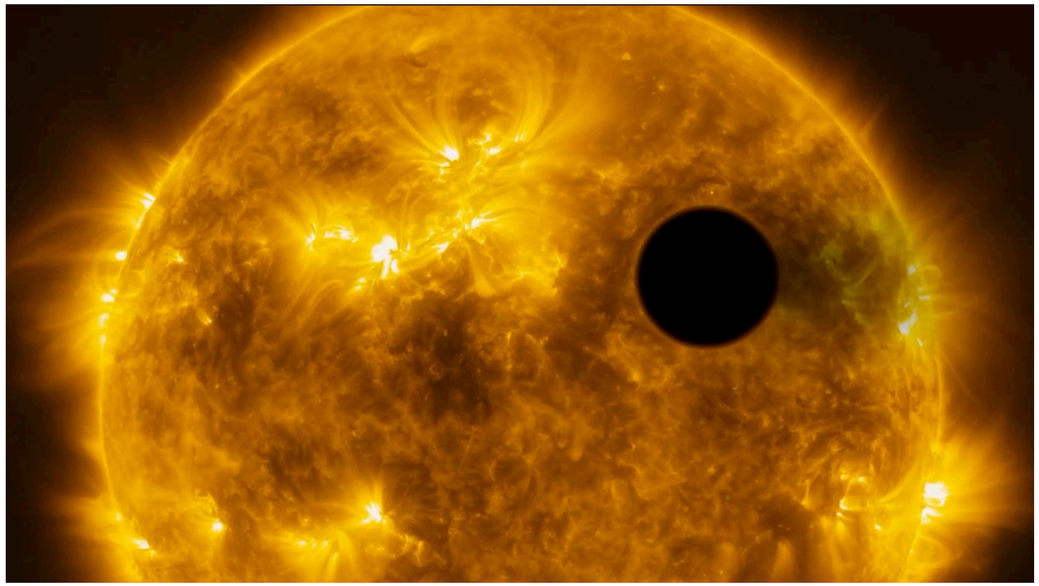
Slide credit: Aline Vidotto, Leiden

Space weather and planetary escape





Lecavalier et al. 2012
Bourrier et al. 2013



Credit: NASA/ESA, L. Calcada, SDO

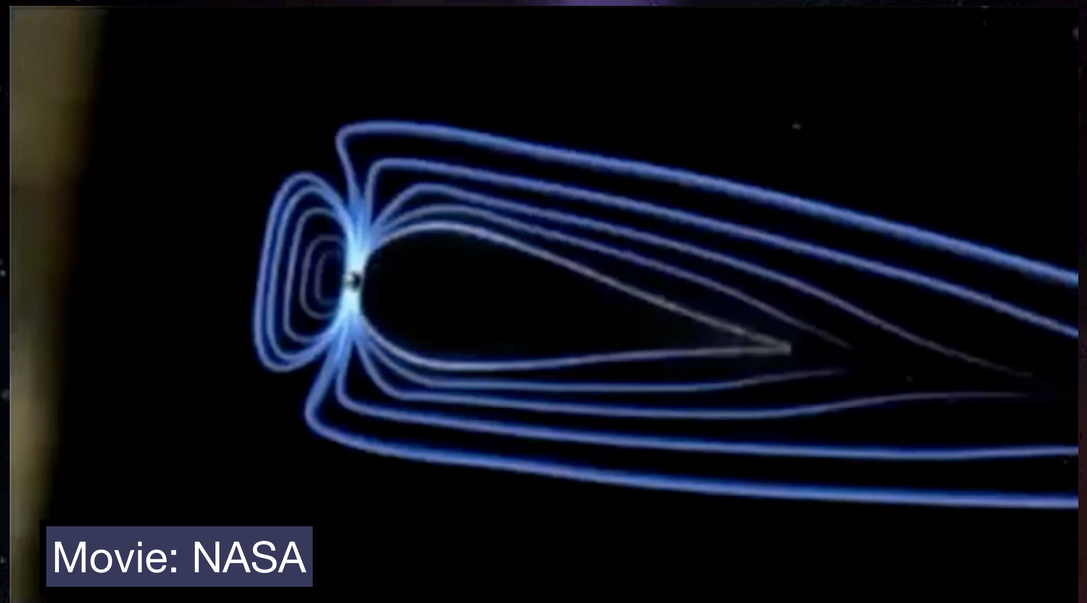
- <u>Possible Interpretation:</u>
  - Increase of stellar energy input into the planet's upper atmosphere caused increased escape?

The search for radio emission from exoplanets

Radio emission from the exoplanet's magnetic field is emitted at the local cyclotron frequency:

$$\nu_{MHz} = 2.8 \times B_{planet}$$

B_{planet} [1, 10] G -> Emission at [2.8, 28] MHz



Movie: NASA

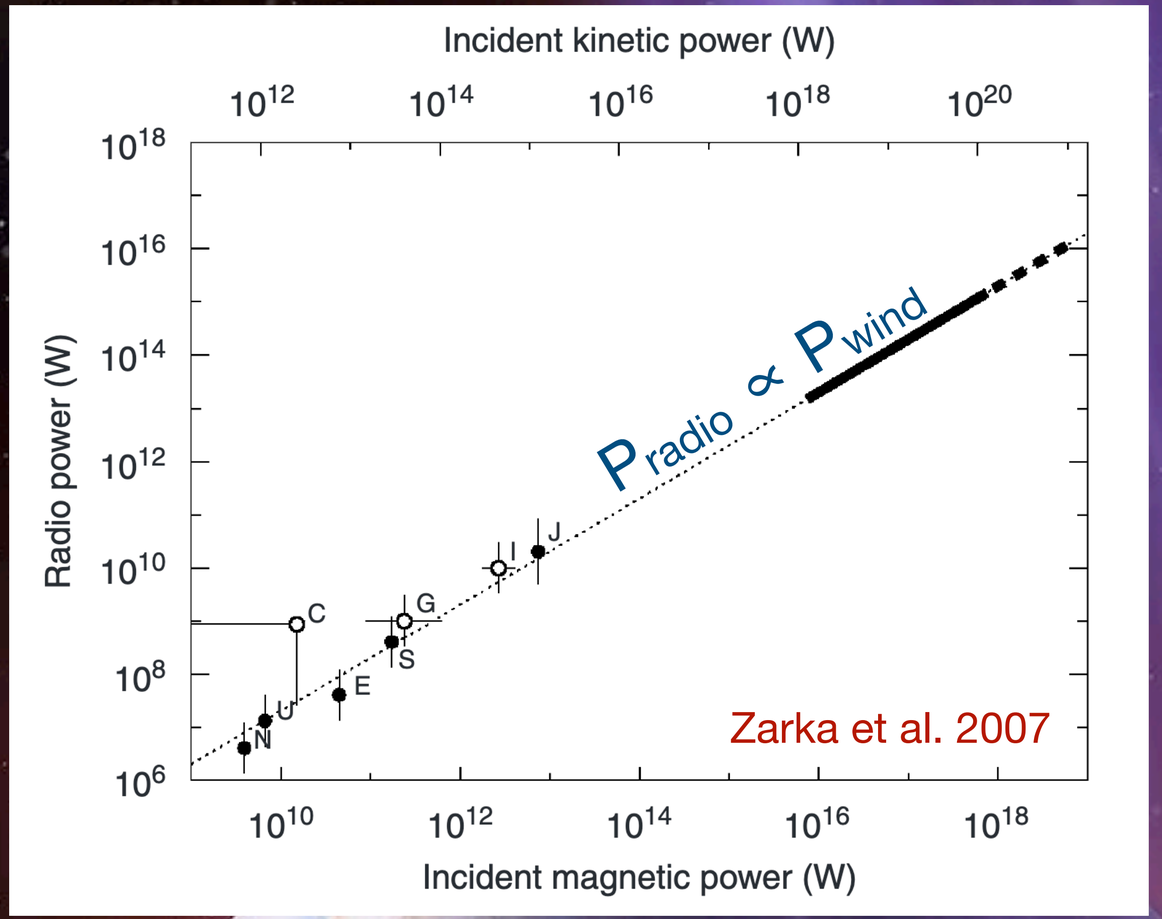
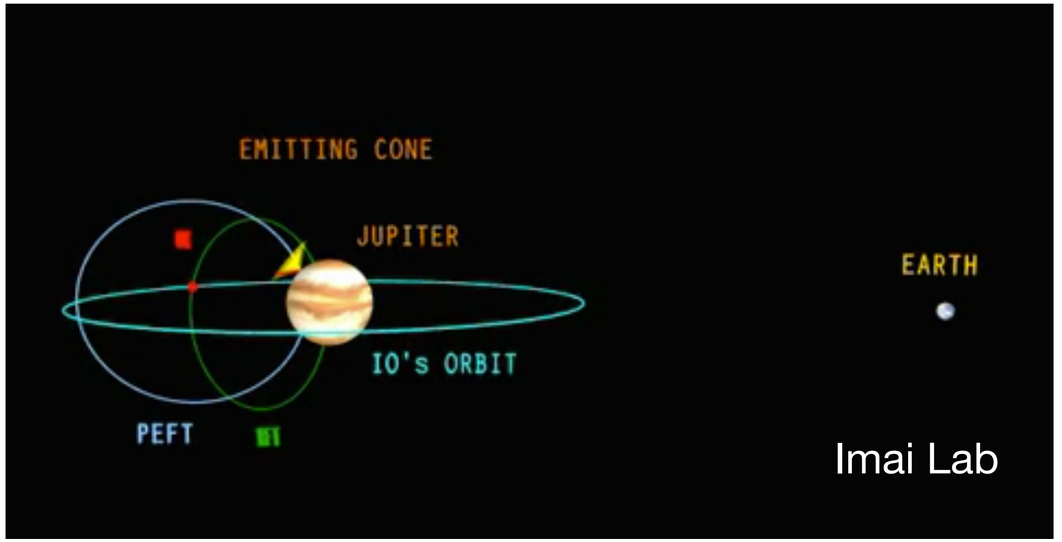


Image Credit: Danielle Futselaar, ASTRON

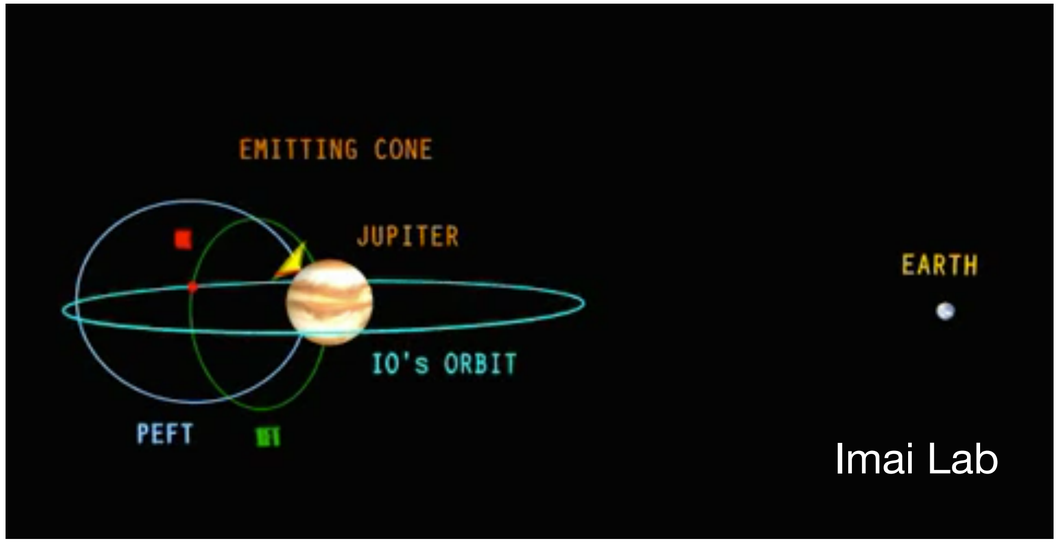
The search for radio emission from exoplanets

- Many unsuccessful searches:
  - Lack of sensitivity?
  - Low incident stellar wind power?
  - Lower planetary B-field?
  - Geometry of emission cone?

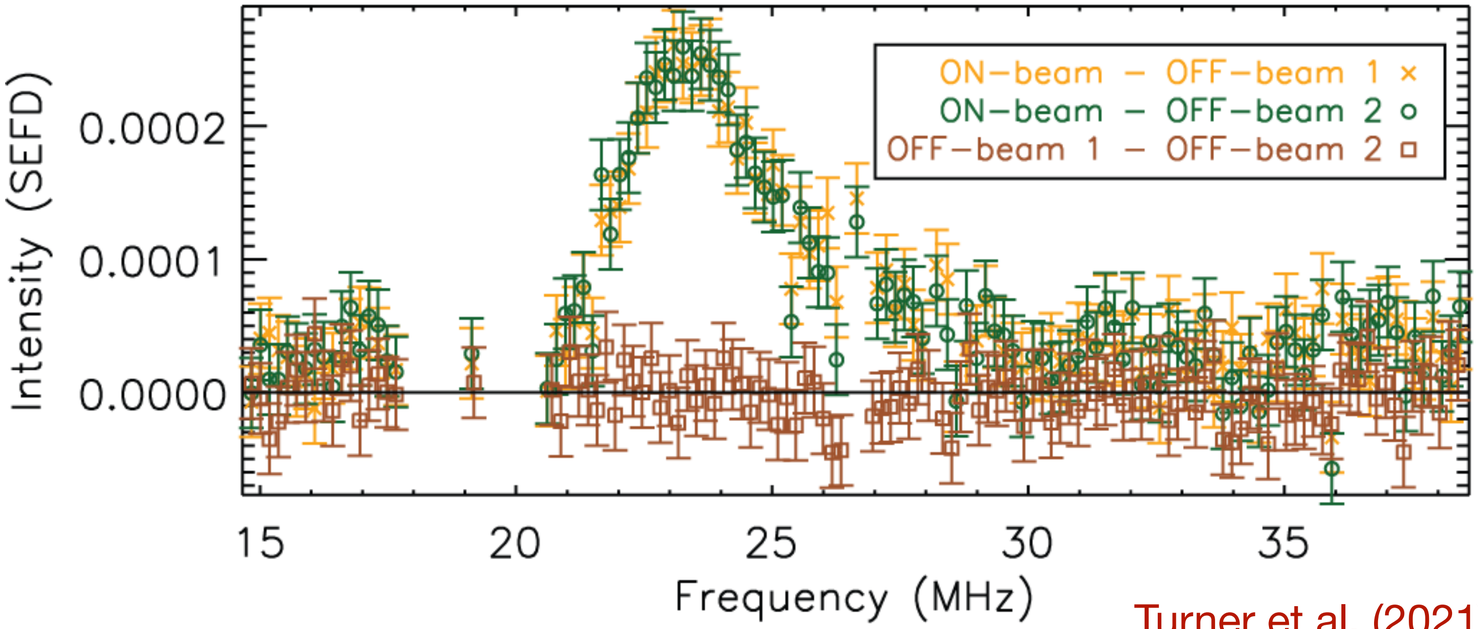


The search for radio emission from exoplanets

- Many unsuccessful searches:
  - Lack of sensitivity?
  - Low incident stellar wind power?
  - Lower planetary B-field?
  - Geometry of emission cone?

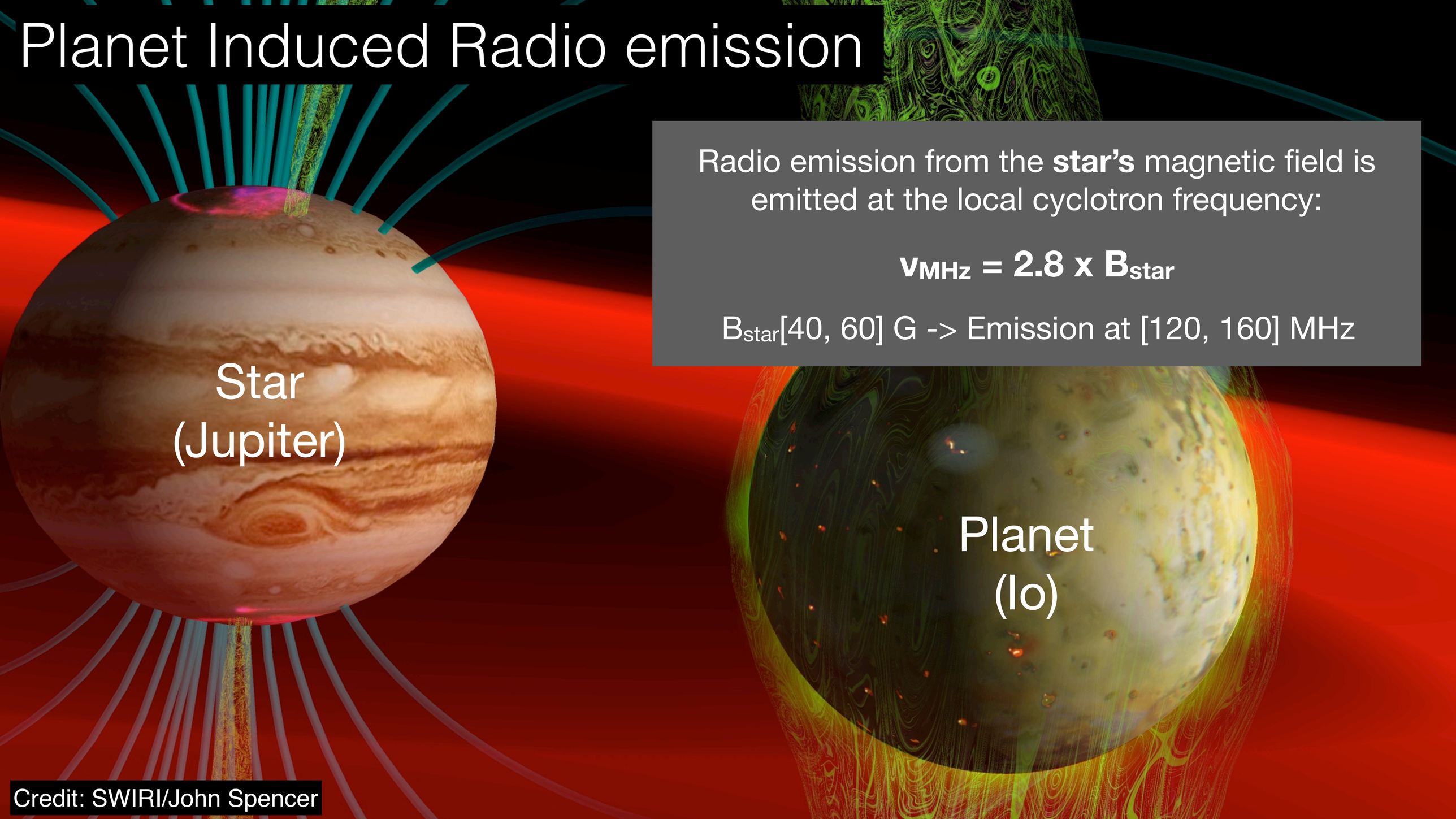


- However!
  - Turner et al. 2021 find bursty emission from Tau Boo at 15-30 MHz using LOFAR.
  - Possible planetary radio signature (5-11G)



Turner et al. (2021)

Planet Induced Radio emission



Radio emission from the **star's** magnetic field is emitted at the local cyclotron frequency:

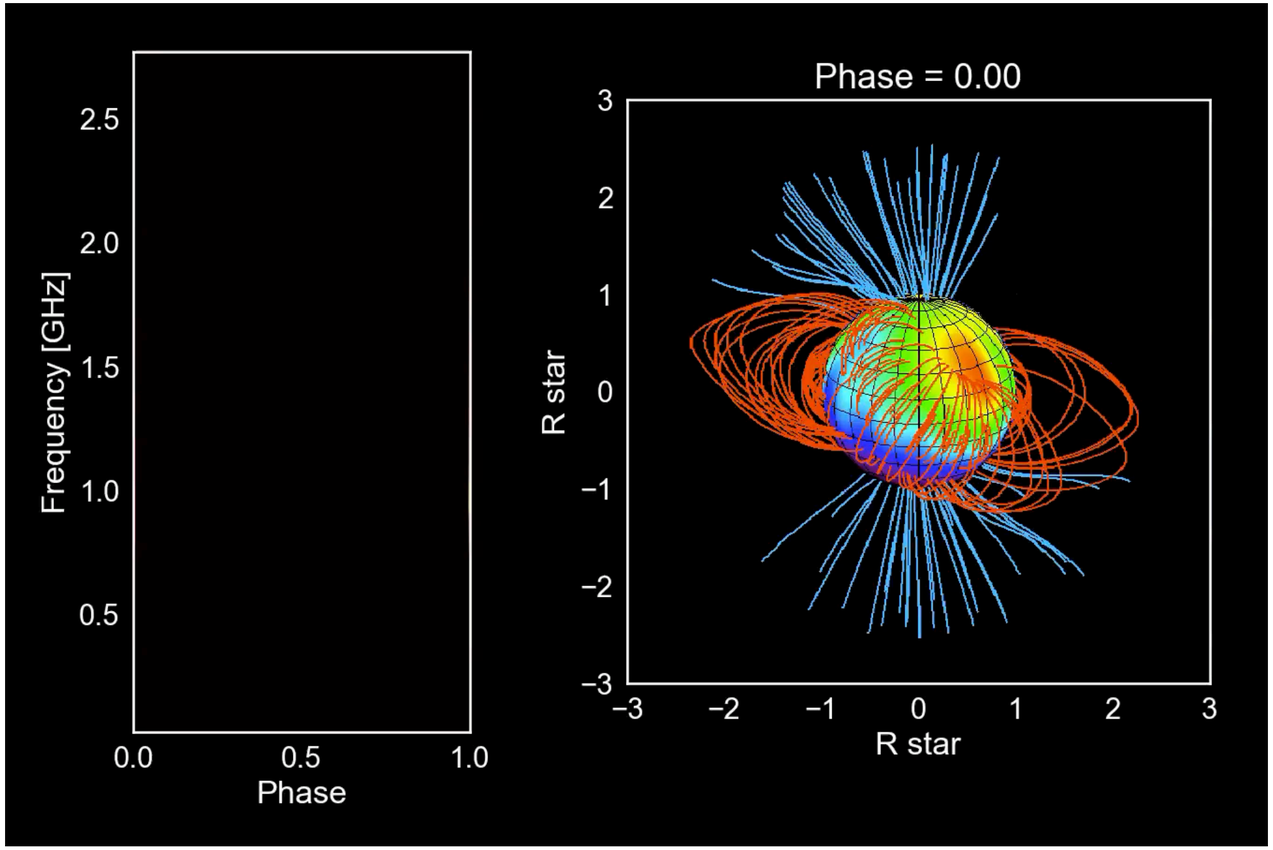
$$\nu_{MHz} = 2.8 \times B_{star}$$

B_{star}[40, 60] G -> Emission at [120, 160] MHz

Credit: SWIRI/John Spencer

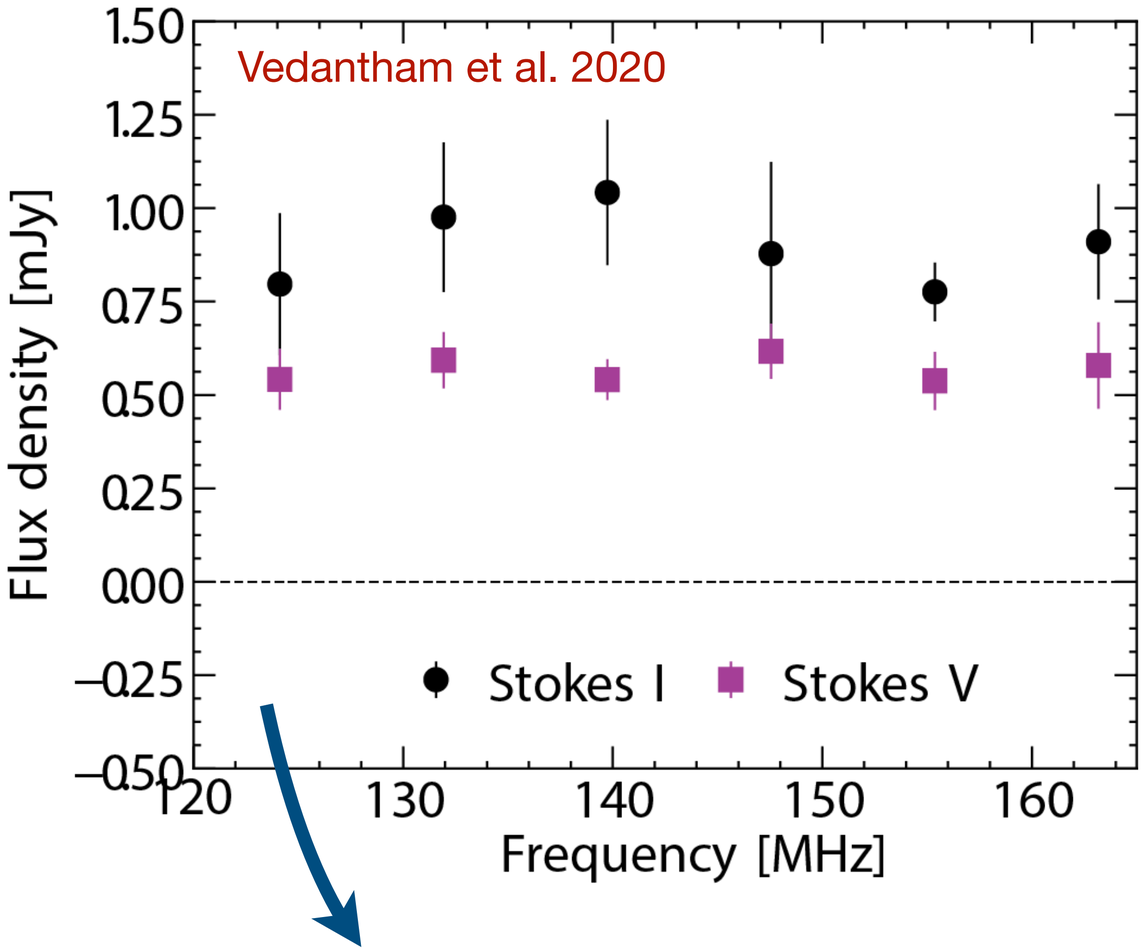
Simulating Planet-induced radio emission

ECM Emission from an active M-star



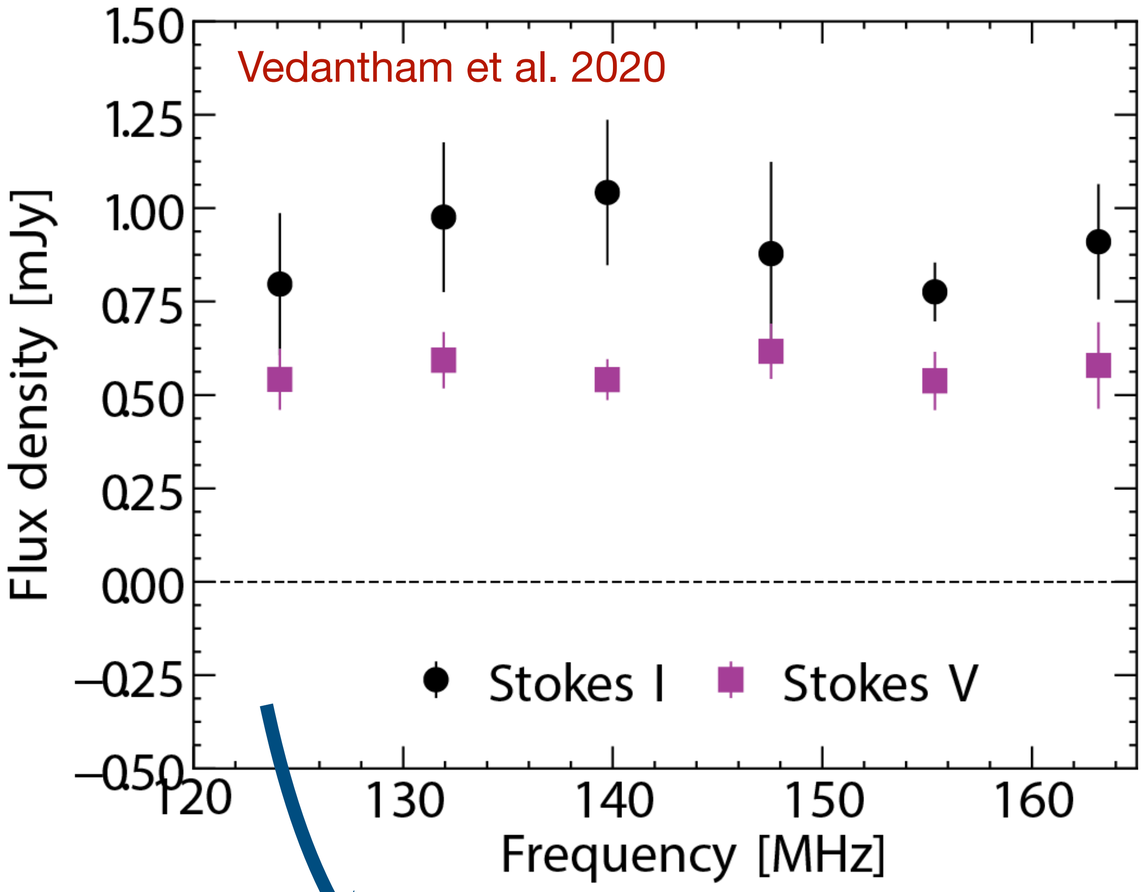
Llama et al. 2018

Planet-induced radio emission on GJ 1151



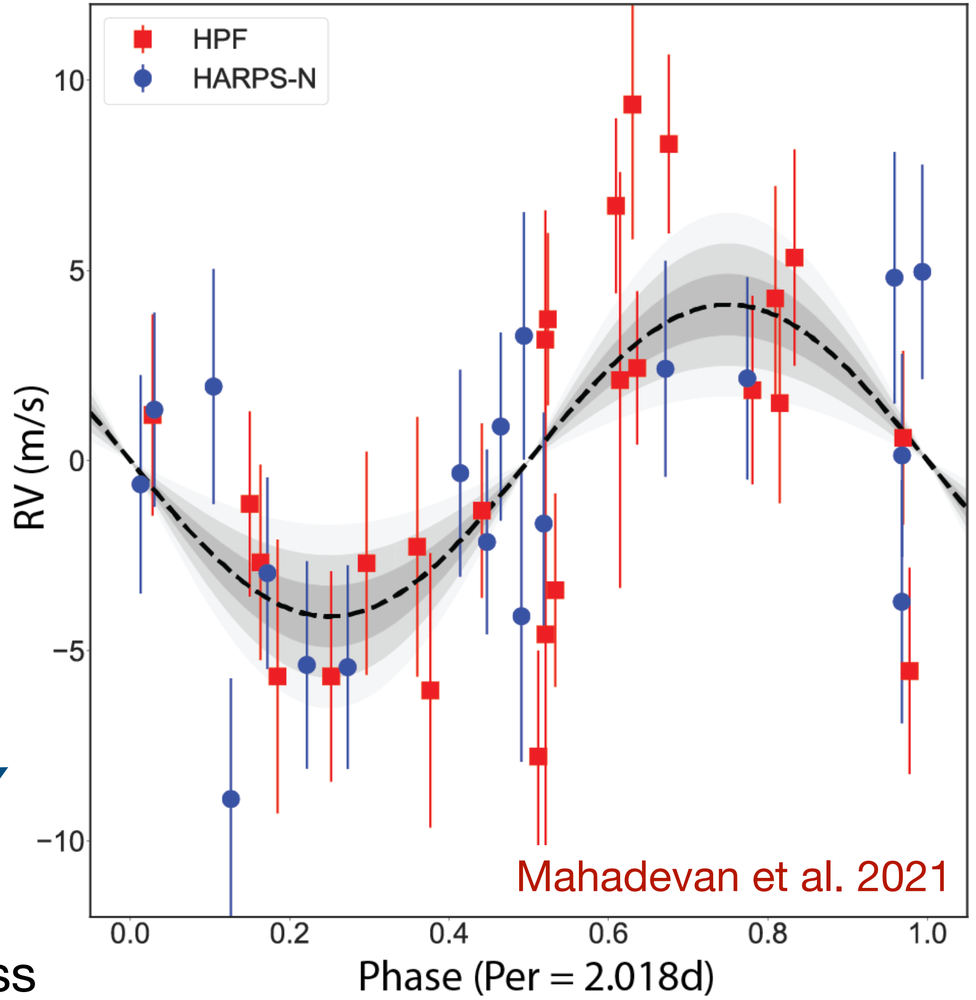
Consistent with ECM induced by a planet with P_{orb} = 1-5 days

Planet-induced radio emission on GJ 1151



Consistent with ECM induced by a planet with P_{orb} = 1-5 days

2.5 Earth mass planet found in RVs



Summary and Outlook

- Star-planet interactions are a powerful tool for learning about exoplanet magnetic fields and atmospheric evolution.
- Magnetic star-planet interactions occur on the orbital period of an exoplanet and are observed across the EM spectrum.
- SPI may be a method for detecting exoplanets using radio emission.
- Want to learn more?

Review on Magnetic Star-Planet Interactions - Shkolnik & Llama (2018)
Physics of star-planet magnetic interactions - Stugarek (2021)