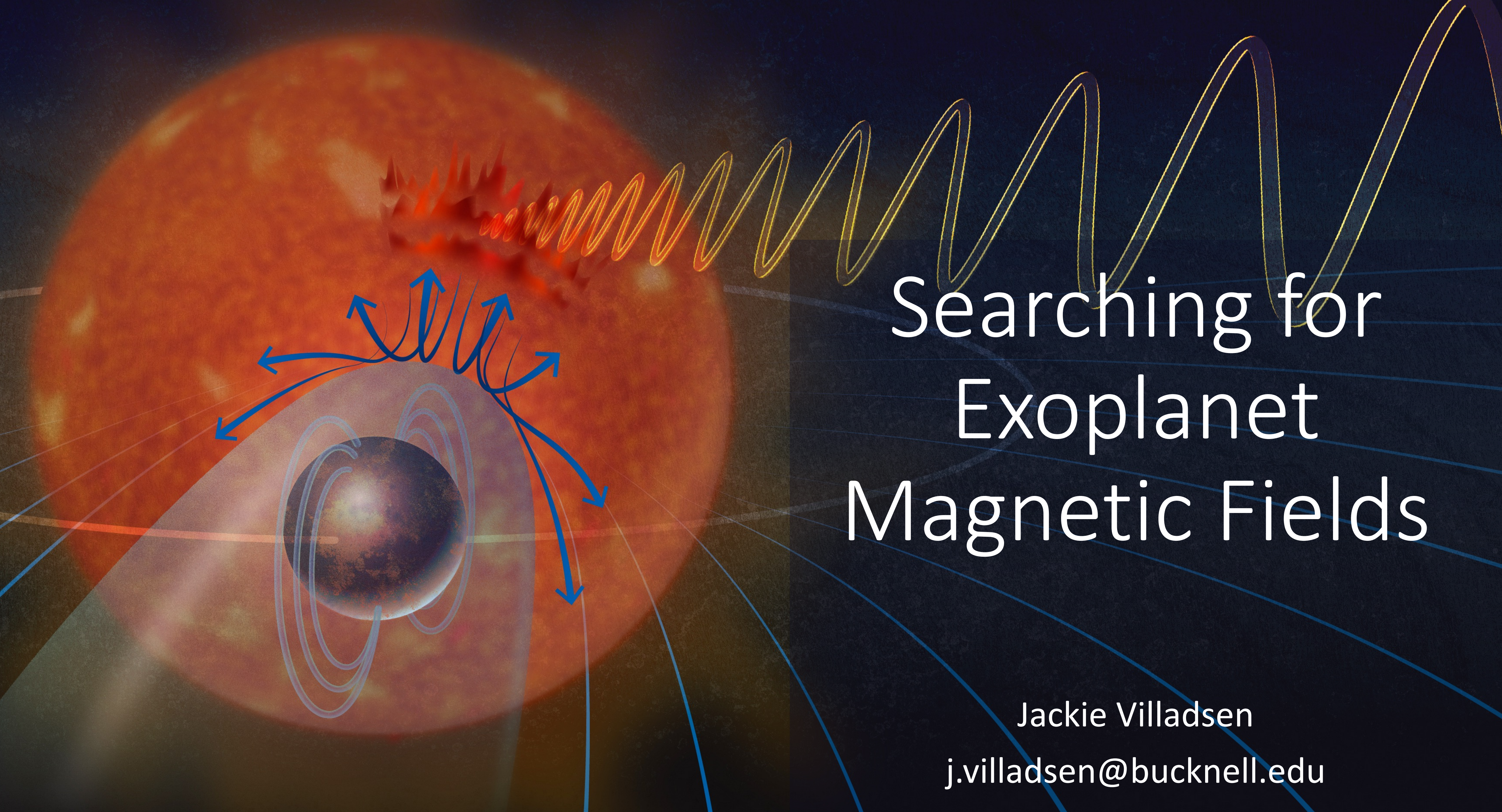

Image credit: Alice Kitterman/National Science Foundation

Searching for Exoplanet Magnetic Fields

Jackie Villadsen

j.villadsen@bucknell.edu

Outline

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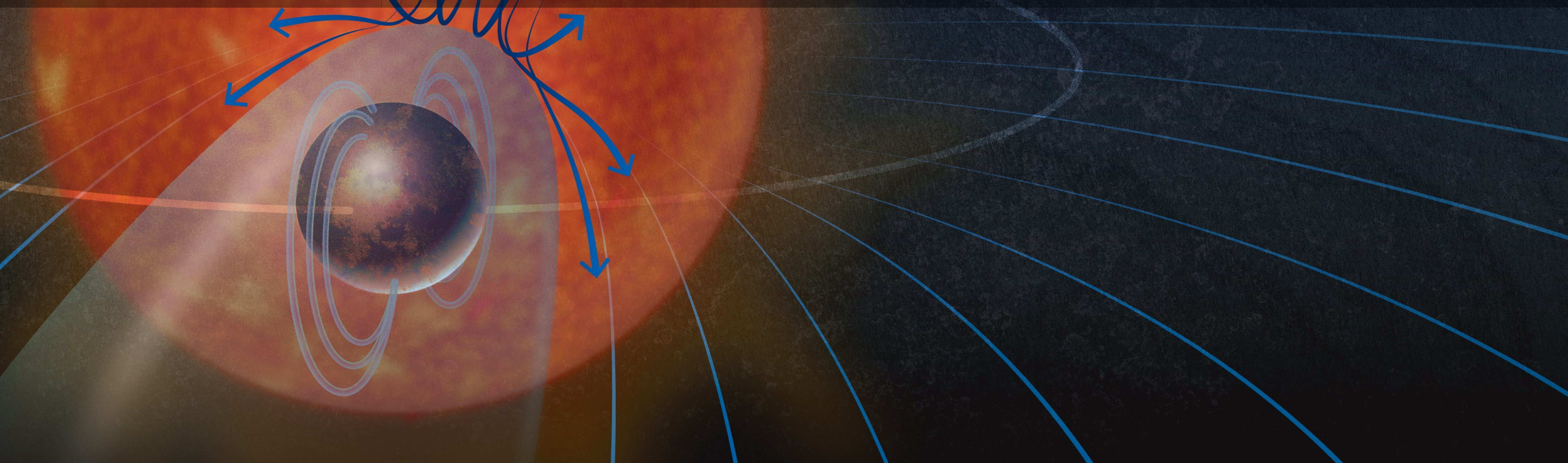
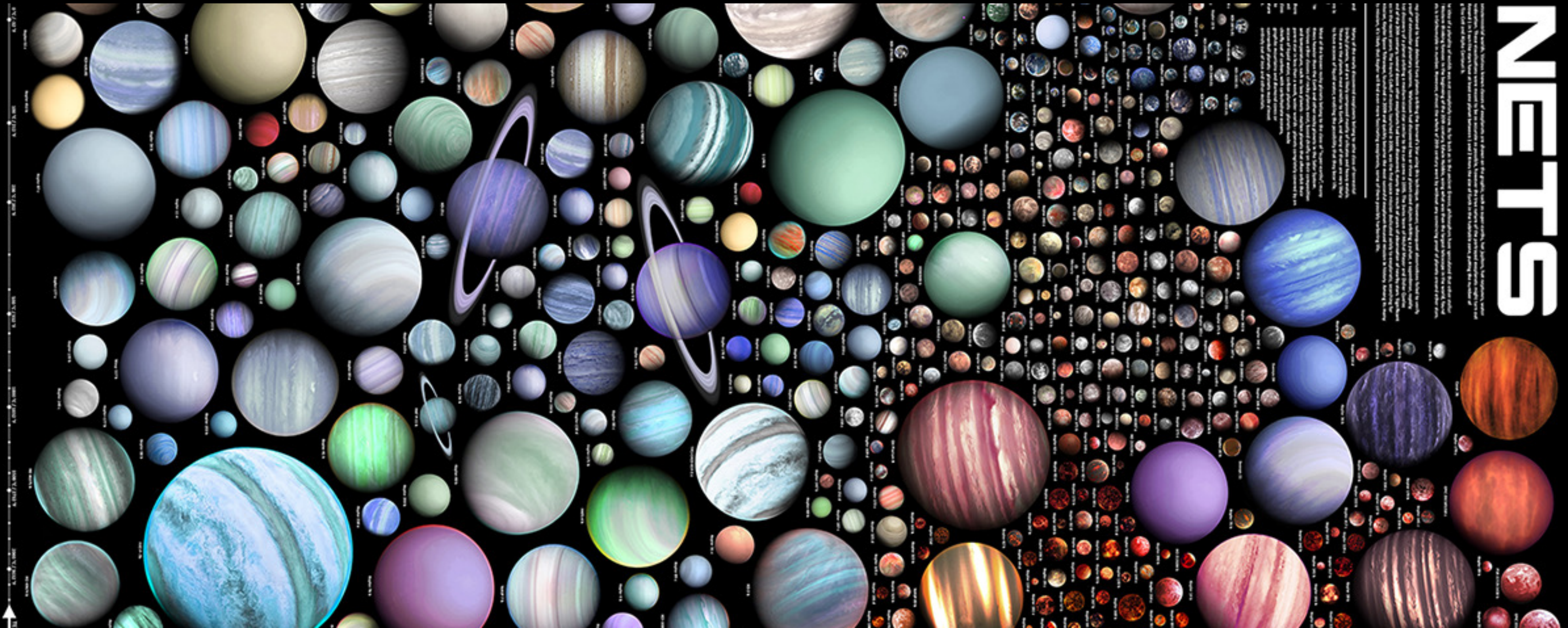


Image credit: Alice Kitterman/National Science Foundation

Could there be life on other planets?

Since 1995, astronomers have discovered over 5,000 planets outside our solar system

Image: Martin Vargic



Could there be life on other planets?

"The Alka-Seltzer principle":

Liquid water (oceans) was essential for the complex chemistry that led to life on Earth

Mysterymanblue/Wikipedia

Could there be life on other planets?

Astronomers consider a planet *habitable* if it has the right conditions for liquid water.

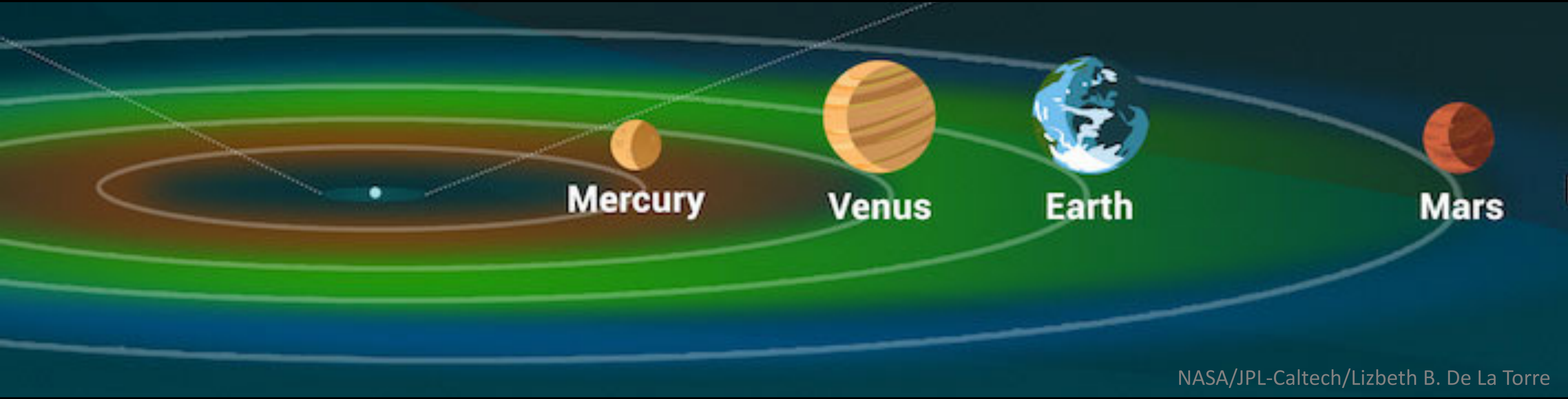
So far, we measure:

- Distance from the star → temperature
- Planet radius & mass → Earth-like, made of rock

Erik Petigura/UC Berkeley, Howard/UH-Manoa, Marcy

Could there be life on other planets?

Problem: Based only on size & distance from star, there are multiple "habitable" planets in our solar system!



Could there be life on other planets?

Venus and Mars are <u>not</u> actually habitable. Why not?

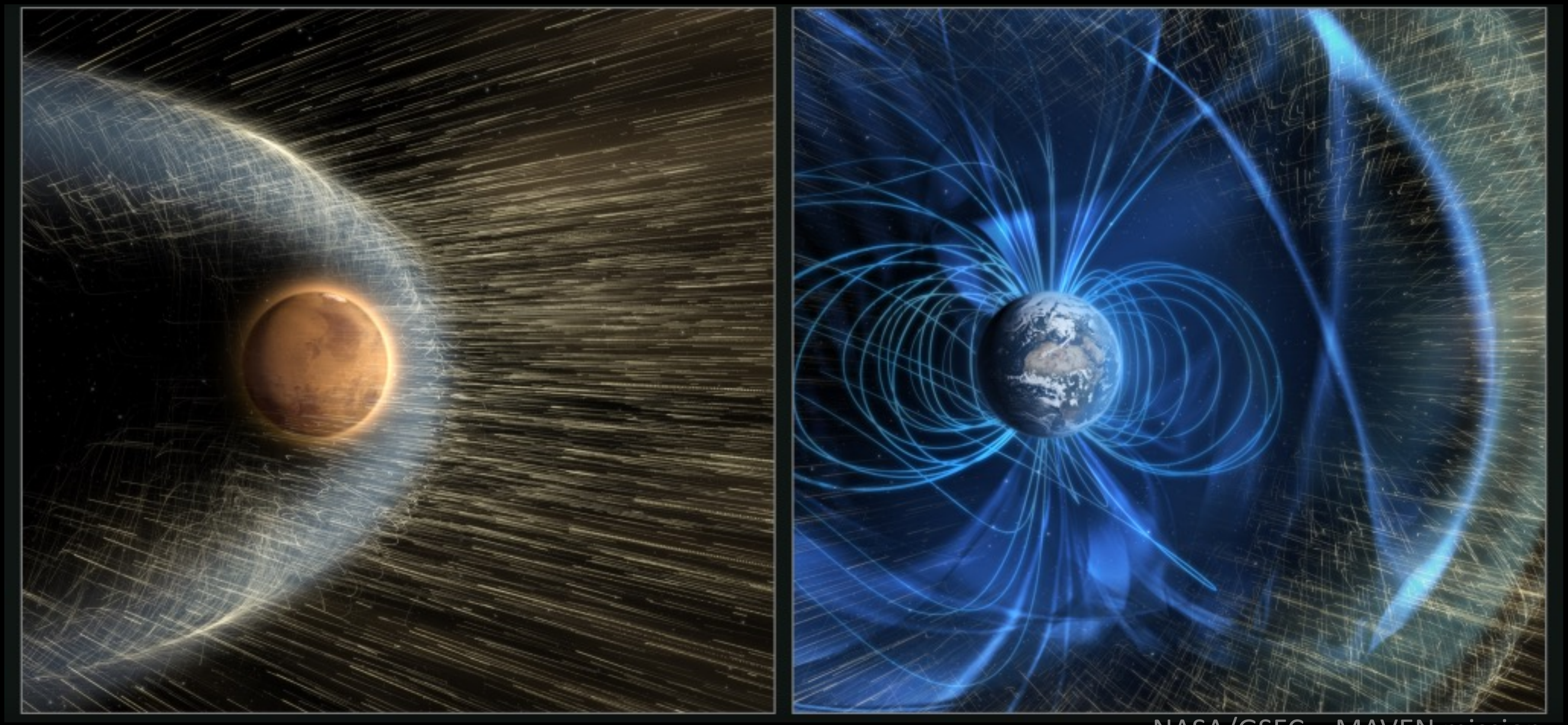
Too hot
No water (even vapor)

Too cold
No liquid water

NASA/JPL-Caltech/ESA

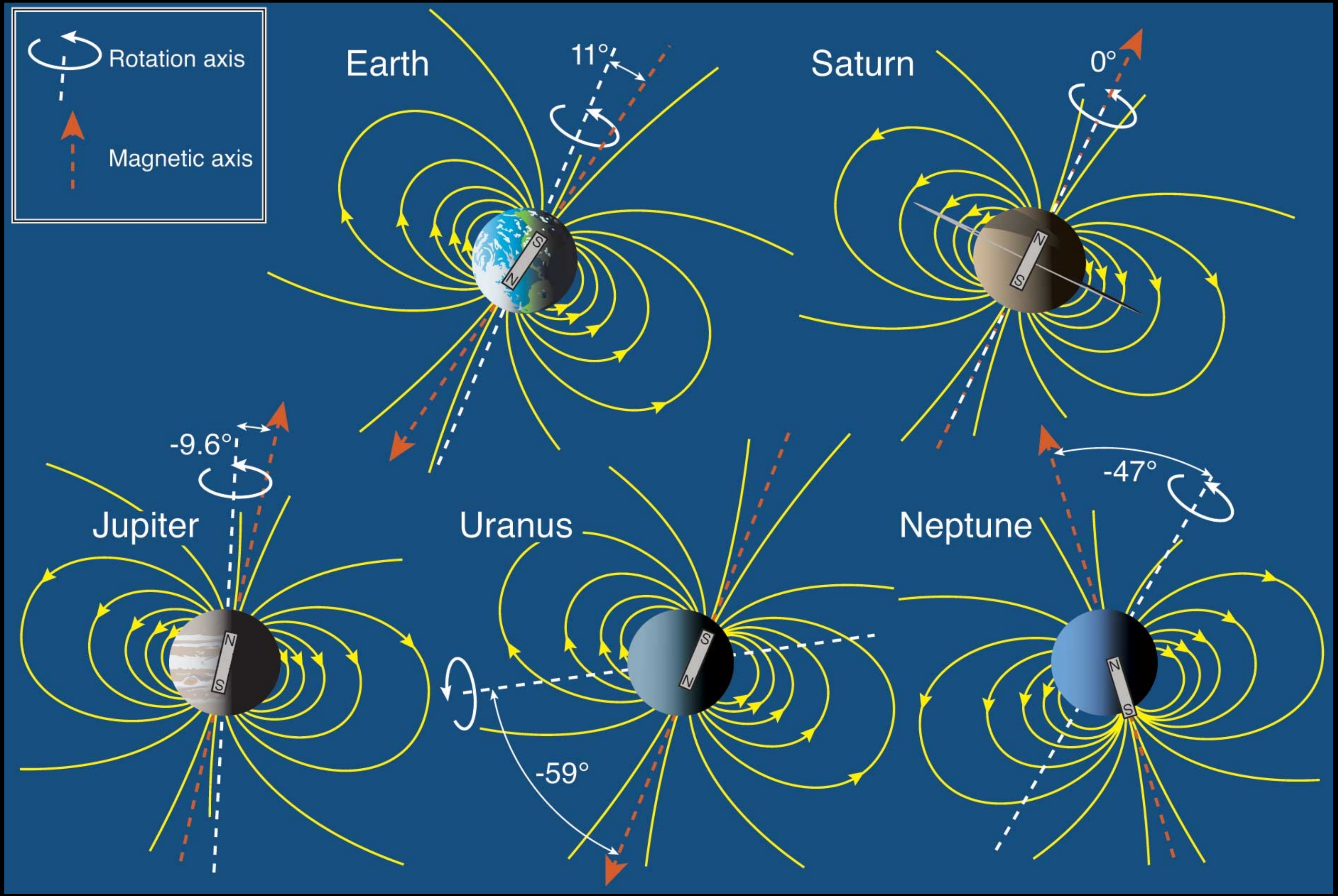
Could there be life on other planets?

Magnetic fields are an “invisible” force field that shields planets.



NASA/GSFC – MAVEN mission

Could there be life on other planets?



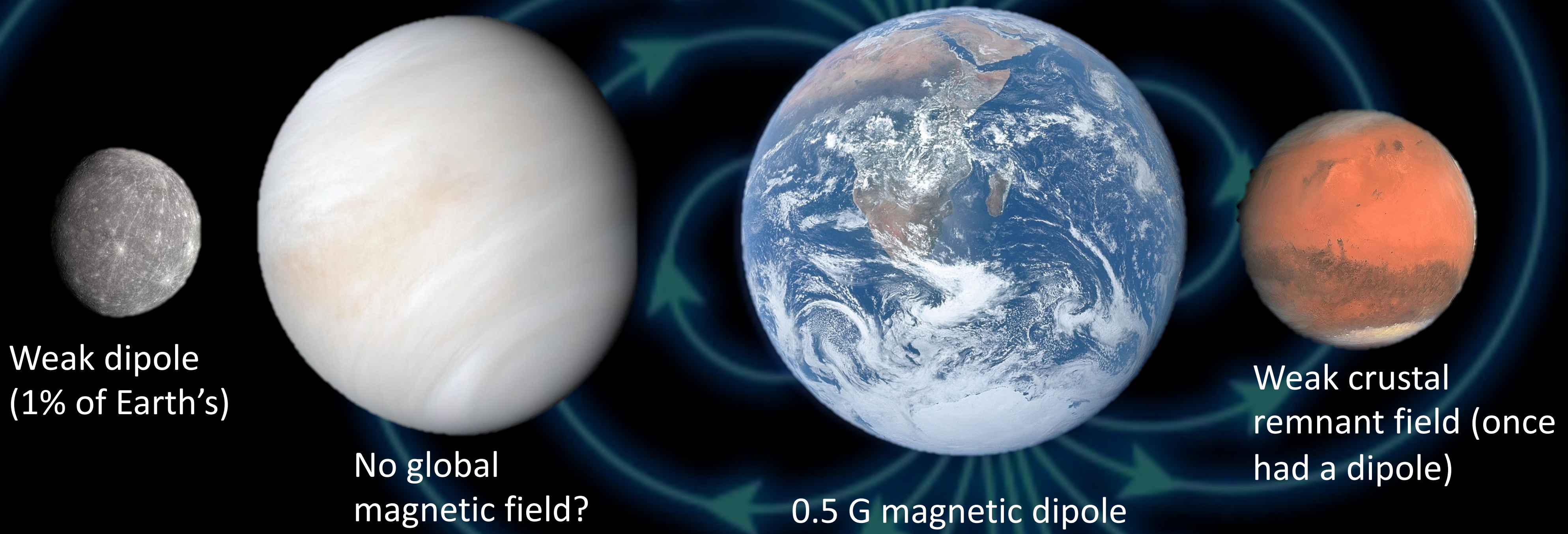
Fran Bagenal & Steve Bartlett

In our solar system, Earth is the only *terrestrial planet* with a strong global magnetic field

Could there be life on other planets?

My research question: What fraction of terrestrial (rocky, Earth-like) exoplanets have a strong magnetic field like Earth? (“Is Earth special?”)

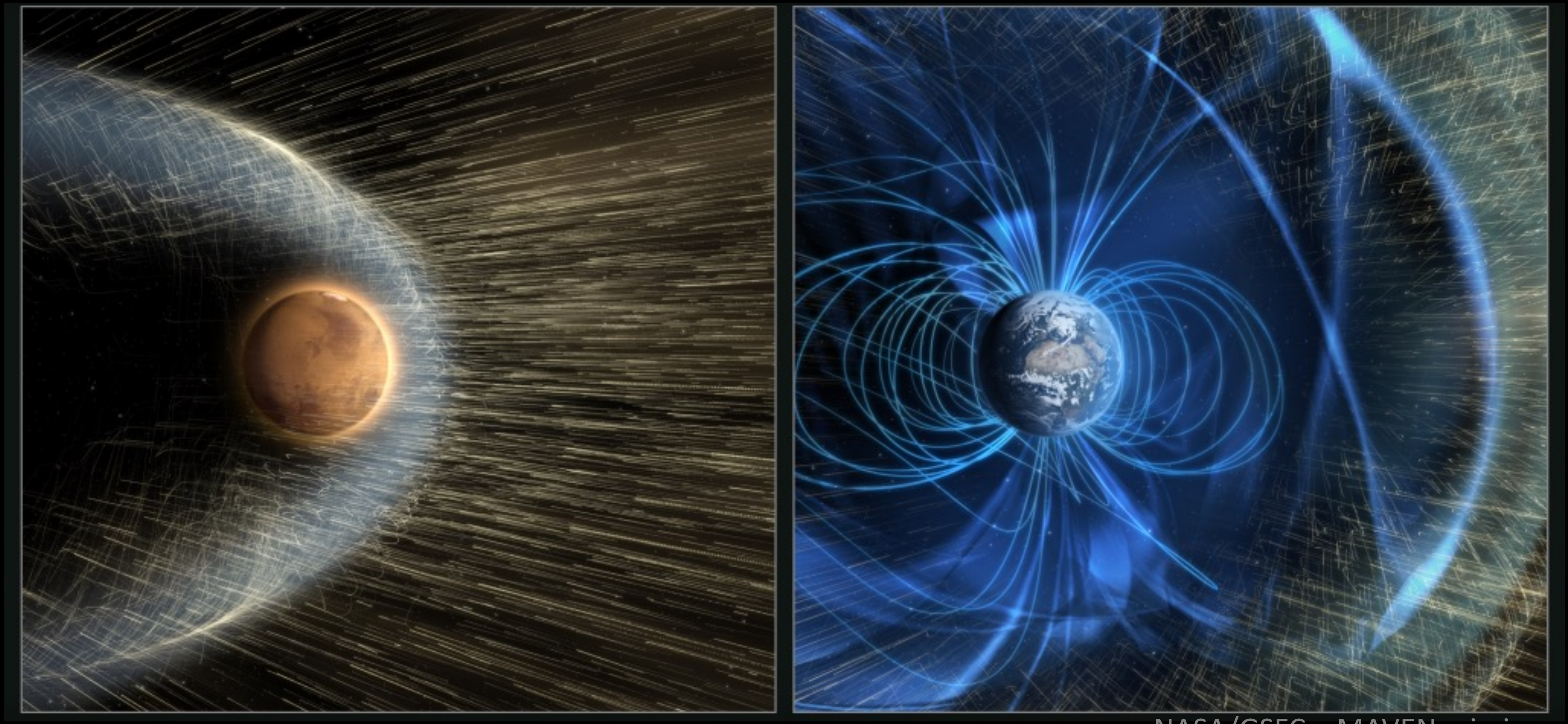
In our solar system: 1/4



Aaron1a12/Wikipedia (NASA images), The COMET Program (UCAR)

What do we want to know about exoplanet magnetic fields?

1) Do they *actually* protect? Get data points outside our solar system!



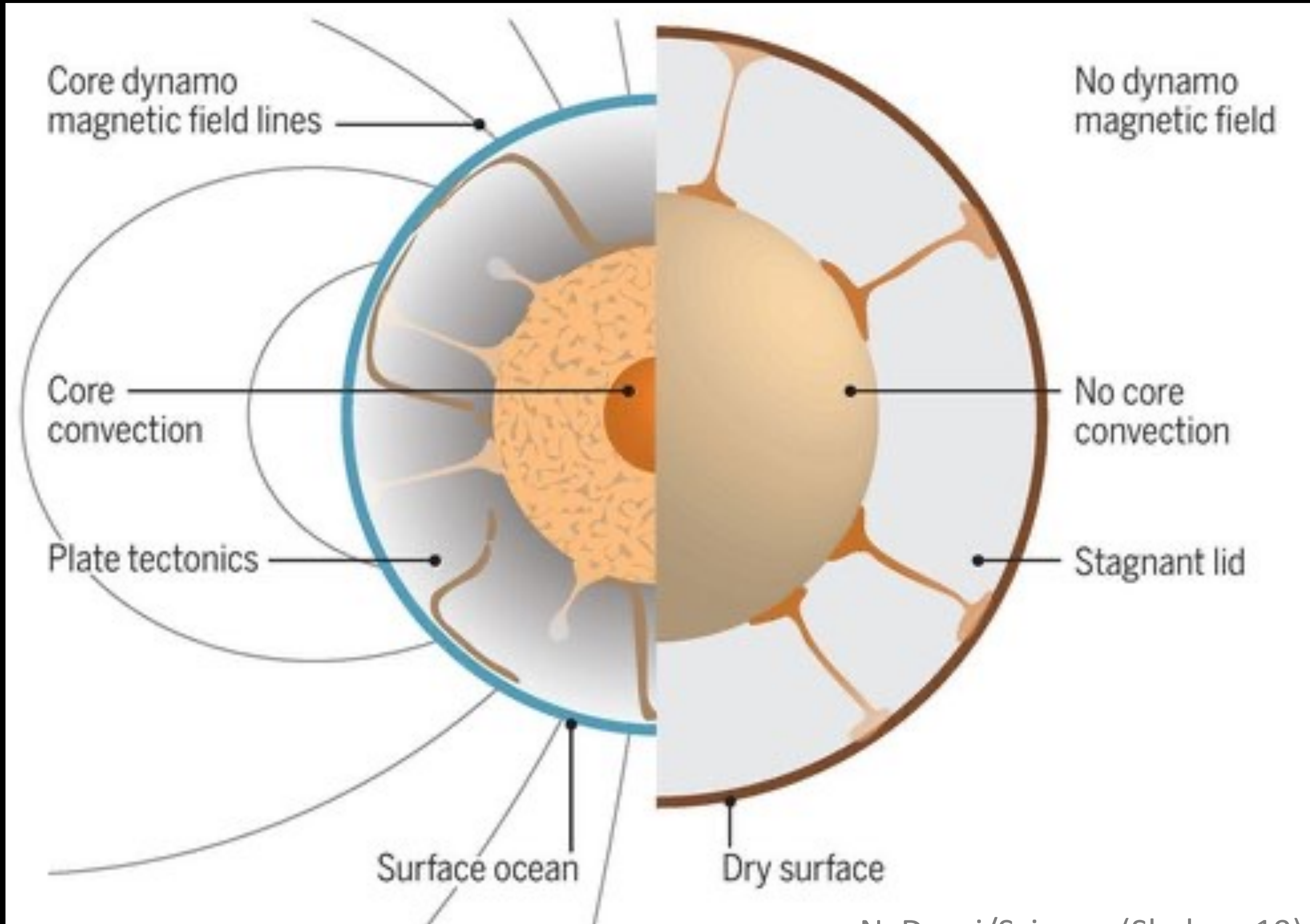
NASA/GSFC – MAVEN mission

Good: Deflect solar wind

Bad: Increased interaction cross-section

What do we want to know about exoplanet magnetic fields?

2) What is the hidden structure inside of exoplanets?



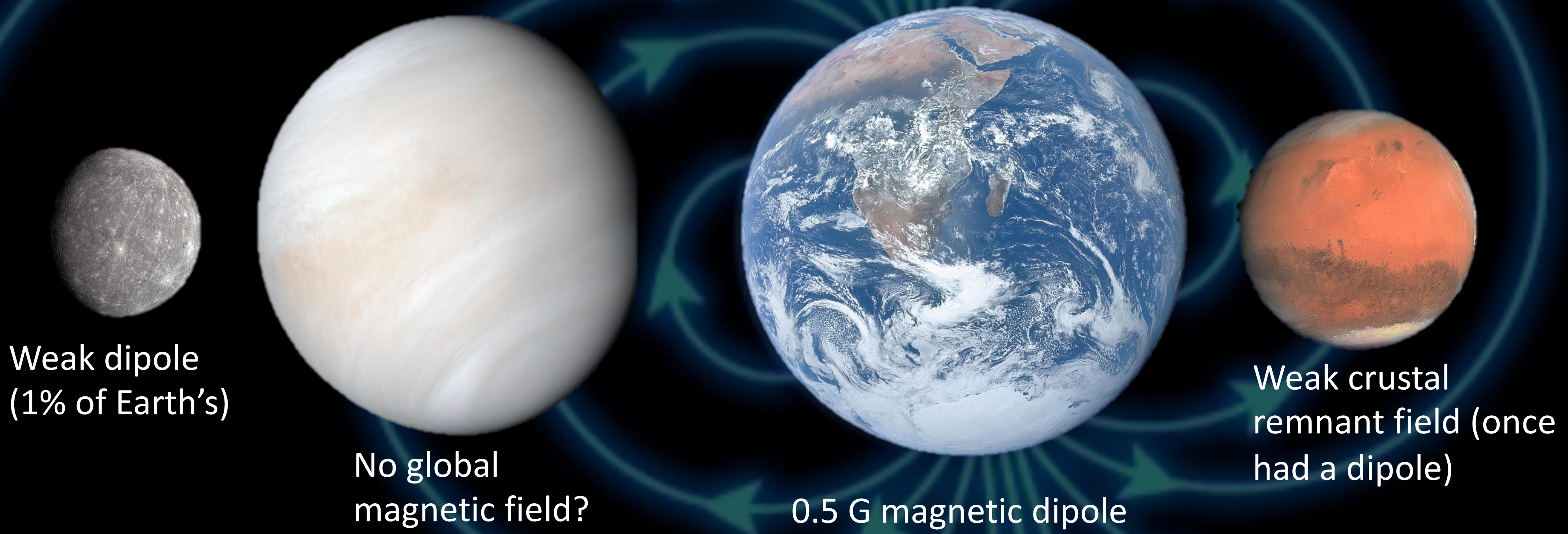
N. Desai/Science (Shahar+19)

Plate tectonics + heat source → convection (boiling) → magnetic field

What do we want to know about exoplanet magnetic fields?

3) Is there a mass cutoff for making a strong magnetic field?

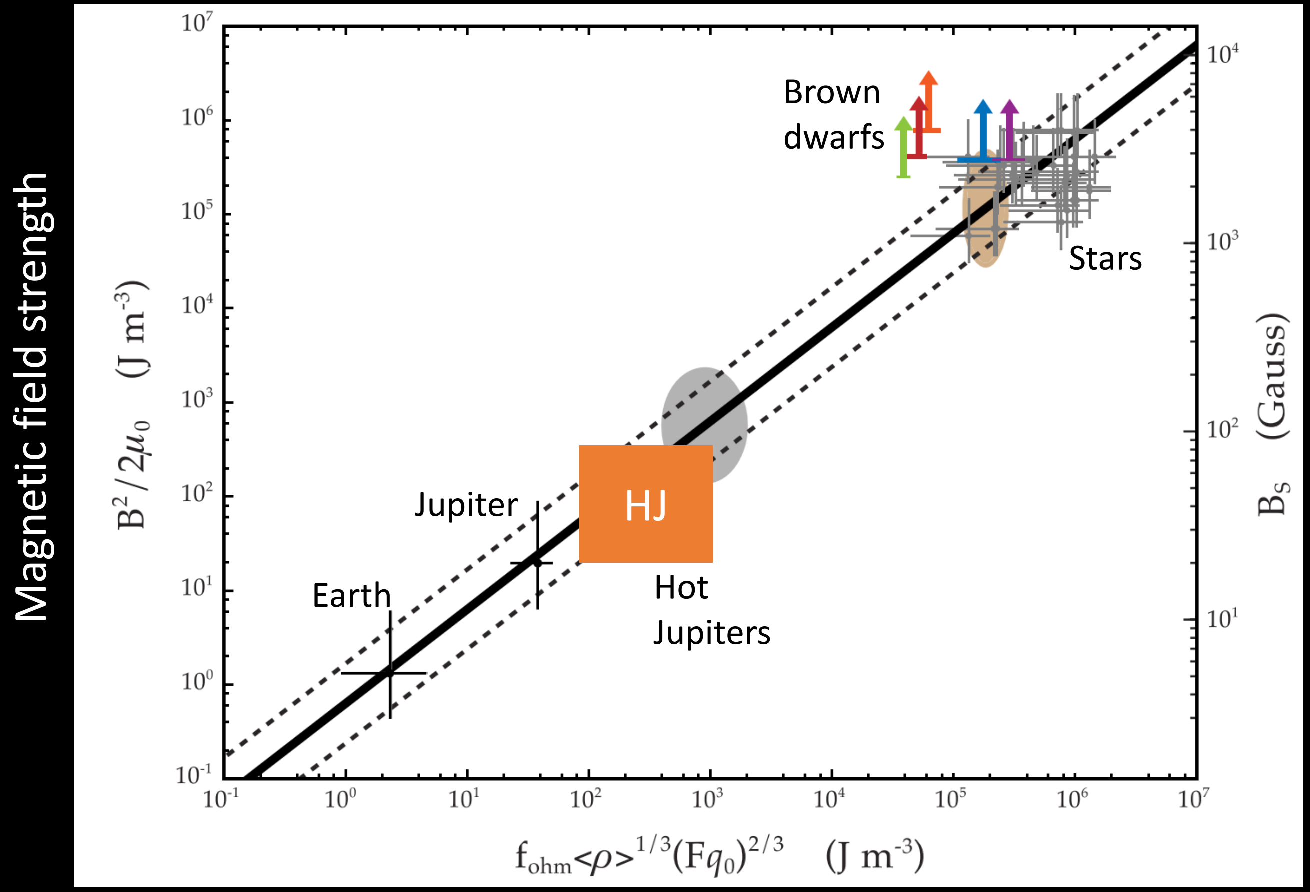
Earth is the highest mass terrestrial planet in our solar system
→More radioactive material to heat core
→Longer time to cool & solidify inside → convection



Aaron1a12/Wikipedia (NASA images), The COMET Program (UCAR)

What do we want to know about exoplanet magnetic fields?

4) Does magnetic field strength depends on rate of heat leaving planet’s core?



Rate of heat leaving core

Kao et al. 2018, with references to Christensen 2009 & Cauley et al. 2019

There are *a few* measurements of magnetic fields of “hot Jupiters” (gas giant planets close to their star)

There are *no* measurements of magnetic fields of Earth-like exoplanets

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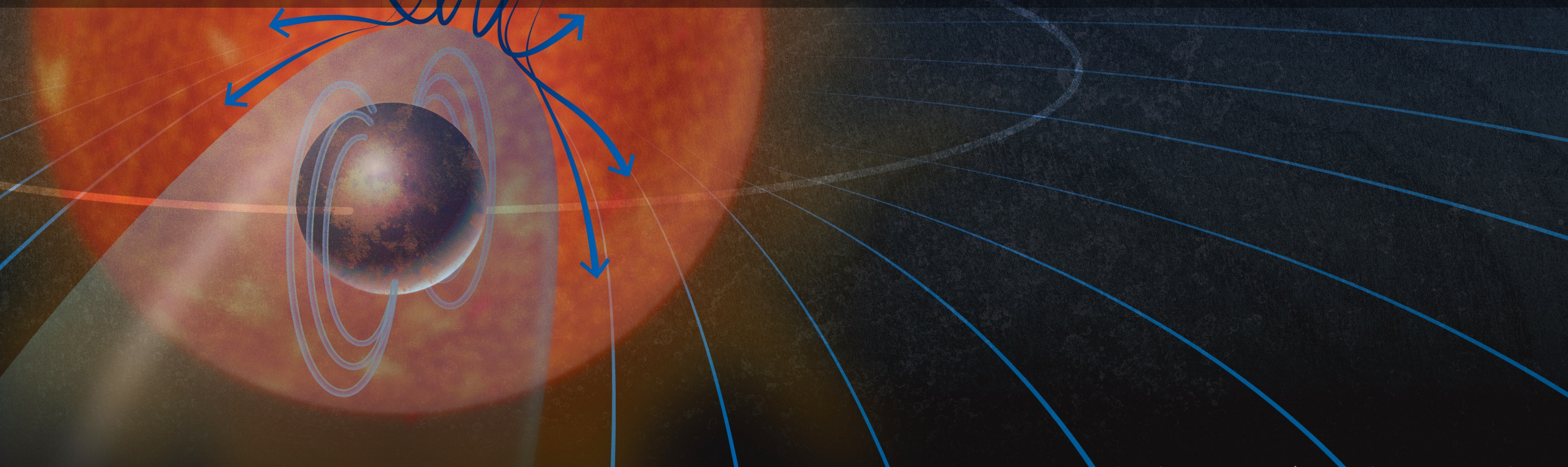
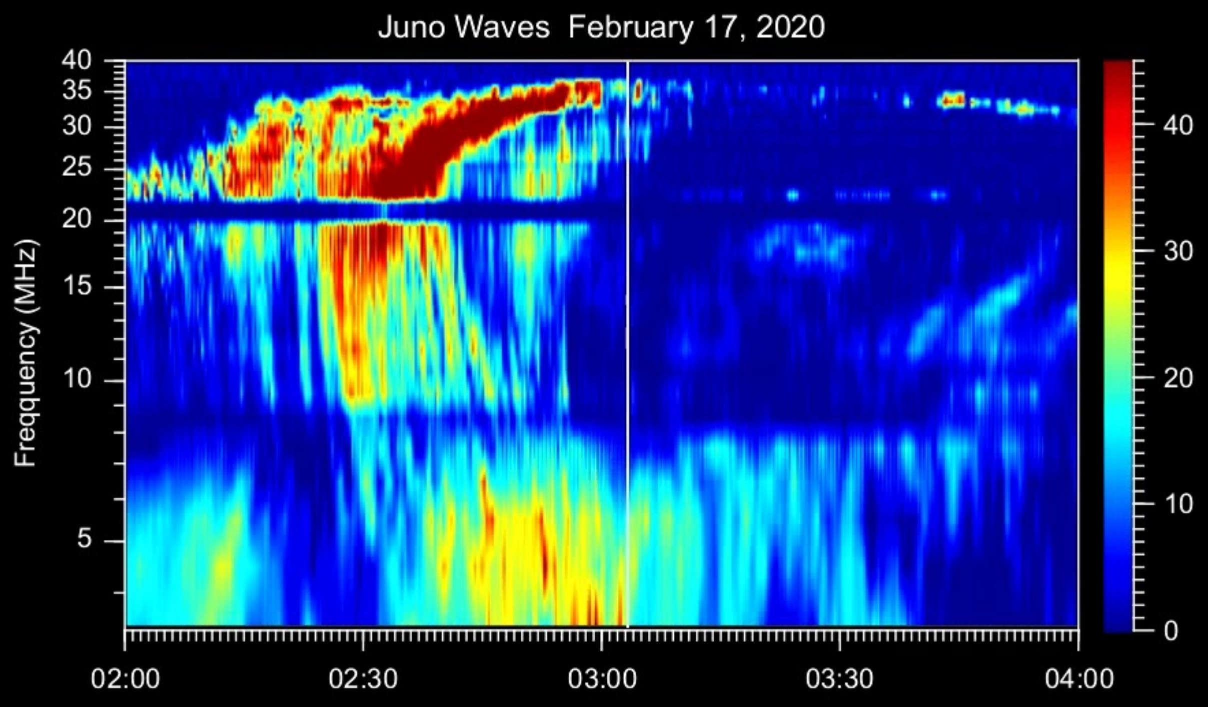


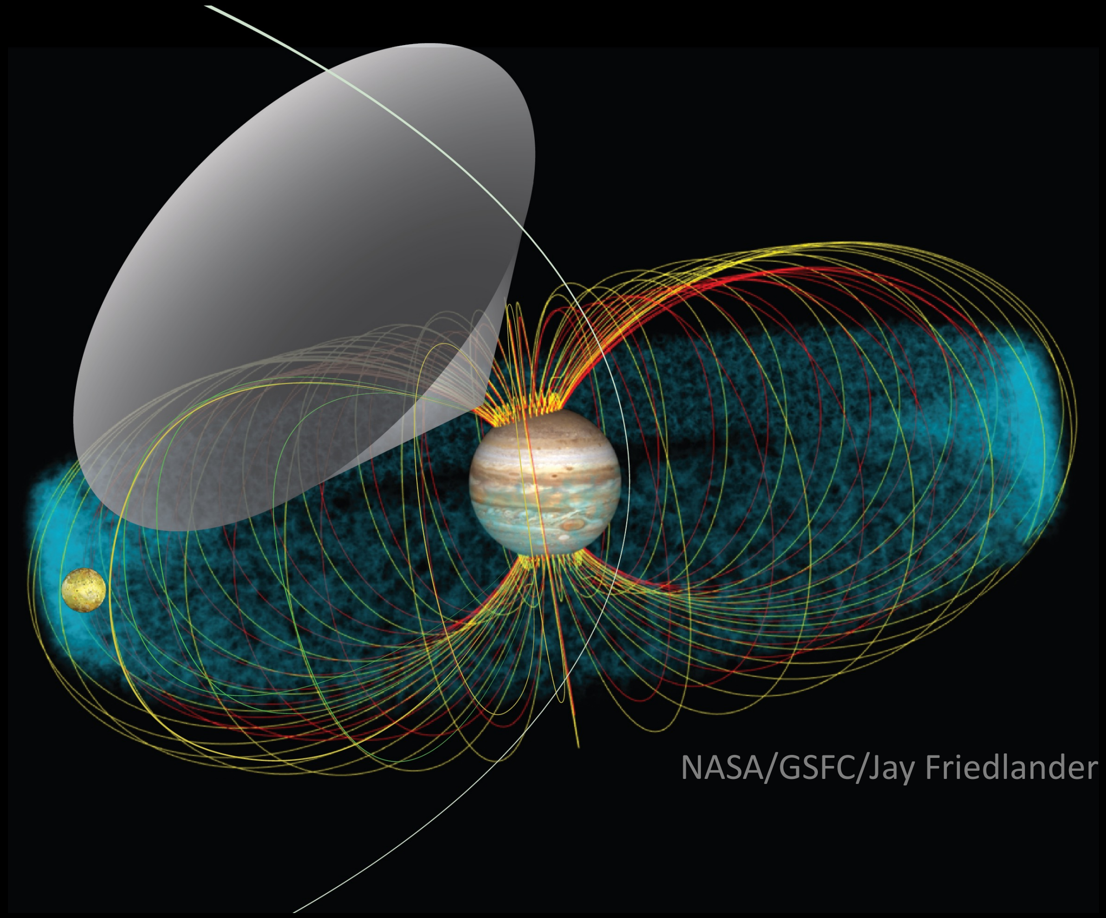
Image credit: Alice Kitterman/National Science Foundation

How can we measure exoplanet magnetic fields?

Jupiter (the 3rd-discovered source of radio waves from space) is the key



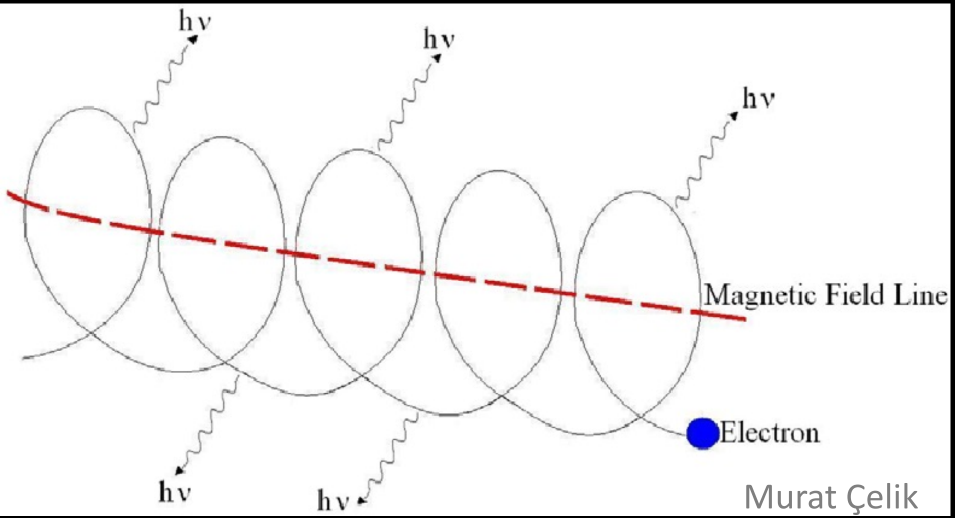
University of Iowa/SwRI/NASA



NASA/GSFC/Jay Friedlander

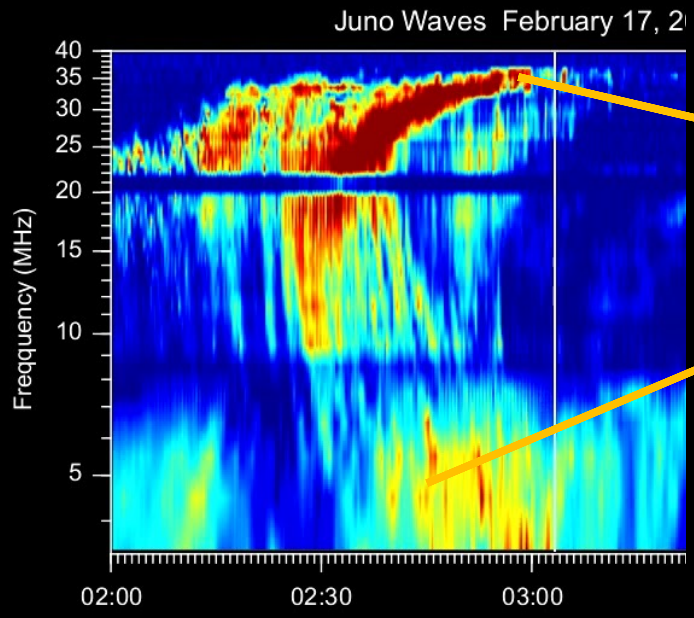
How can we measure exoplanet magnetic fields?

Jupiter makes radio waves by *cyclotron*. The frequency of the waves tells us the magnetic field strength of Jupiter.

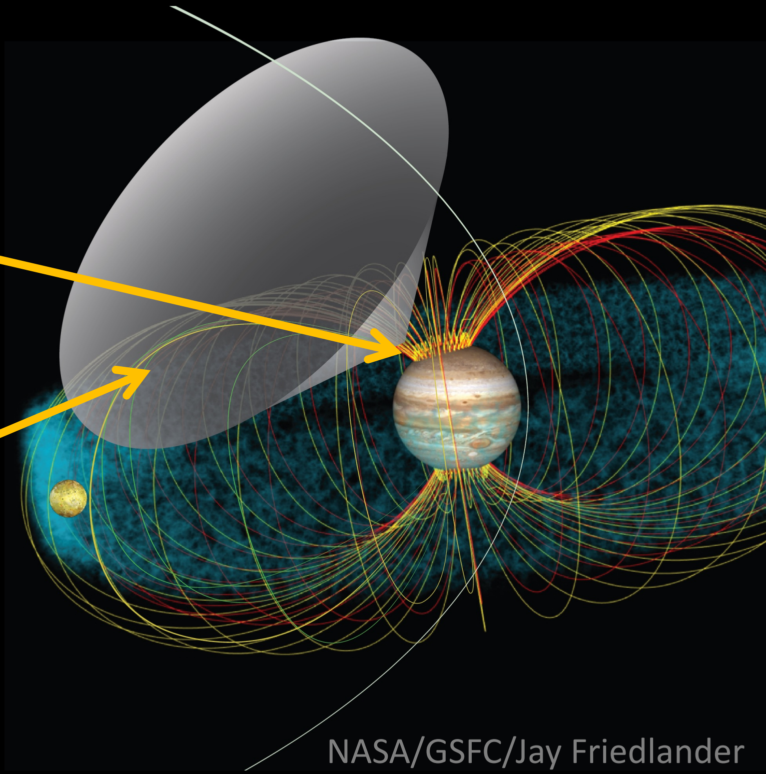


Murat Çelik

$$f = \frac{\omega}{2\pi} = \frac{qB}{2\pi m}$$



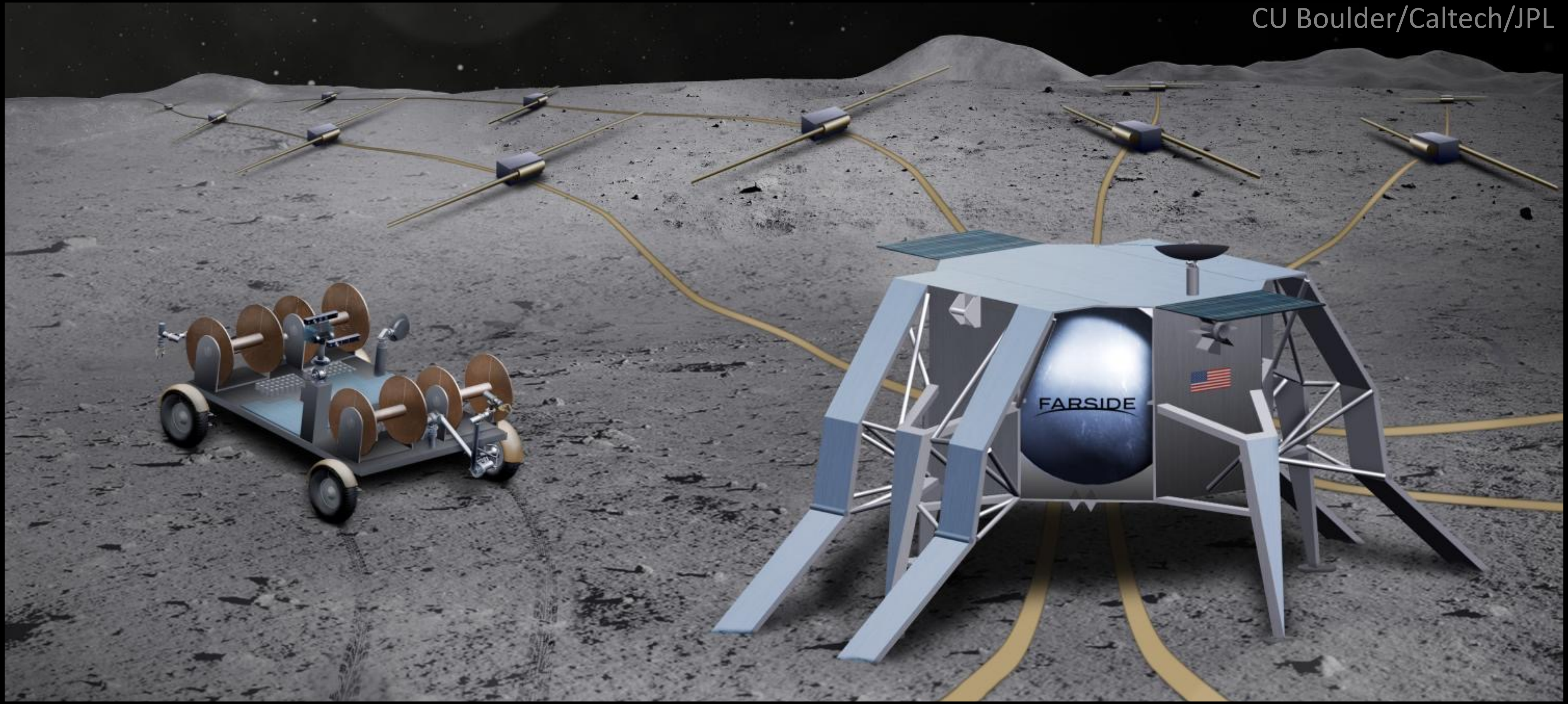
University of Iowa/SwRI/NASA



NASA/GSFC/Jay Friedlander

How can we measure exoplanet magnetic fields?

If we could see radio waves *directly* from exoplanets, we would know their magnetic field strength for sure



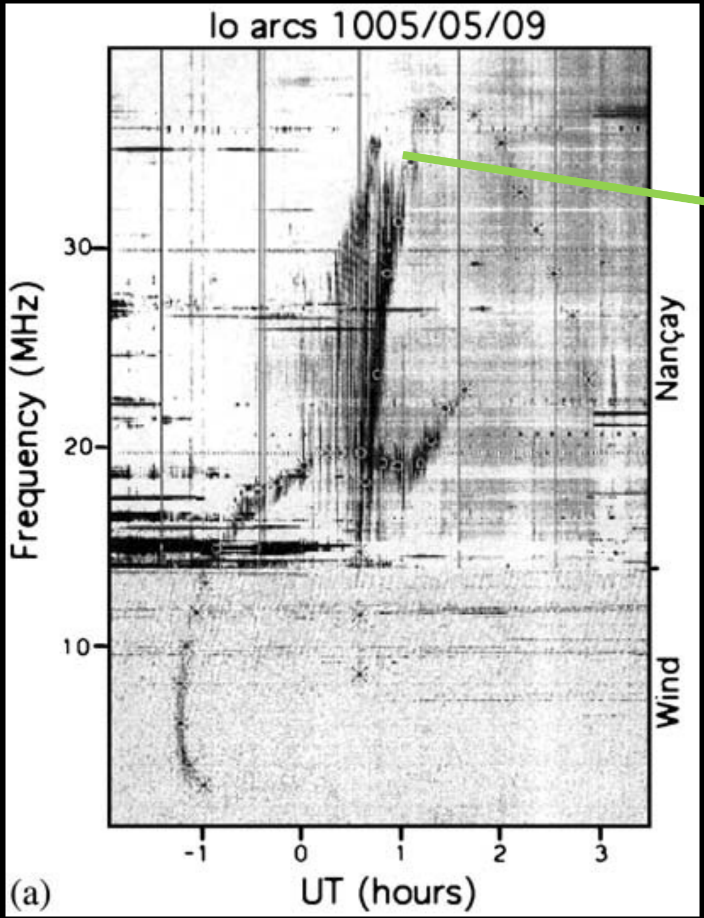
CU Boulder/Caltech/JPL

For an Earth-like field, cyclotron radio waves would be at 1 MHz – can only be seen from space! Lunar far-side observatory in 20-40 years??

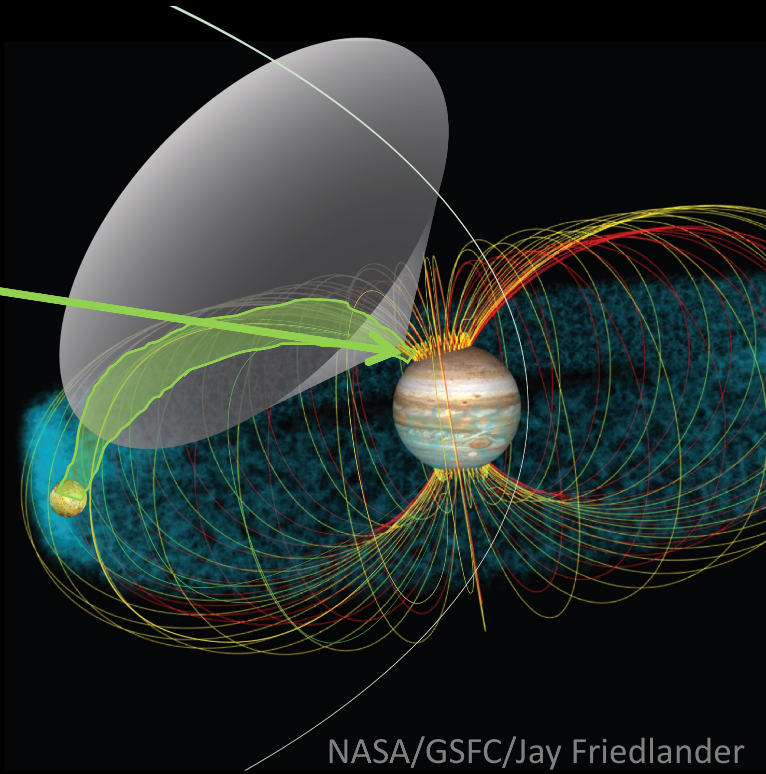
How can we measure exoplanet magnetic fields?

Some of Jupiter's radio waves are caused by its moon Io, pointing to an *indirect* way to estimate magnetic fields.

As Io plows through Jupiter's magnetic field, it pushes aside the magnetic field and gas, creating a disturbance that transfers energy back to Jupiter.



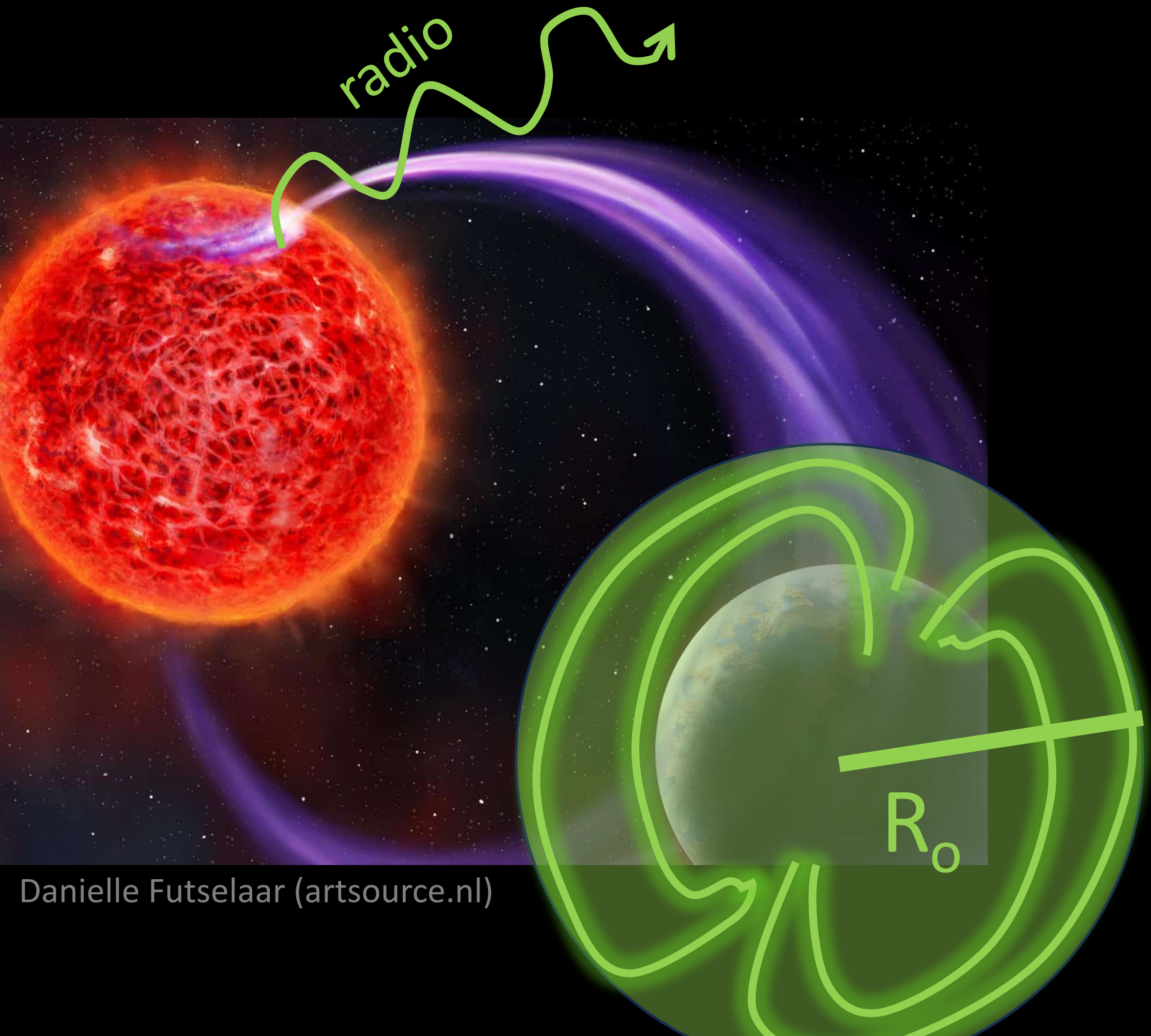
Zarka 2004



NASA/GSFC/Jay Friedlander

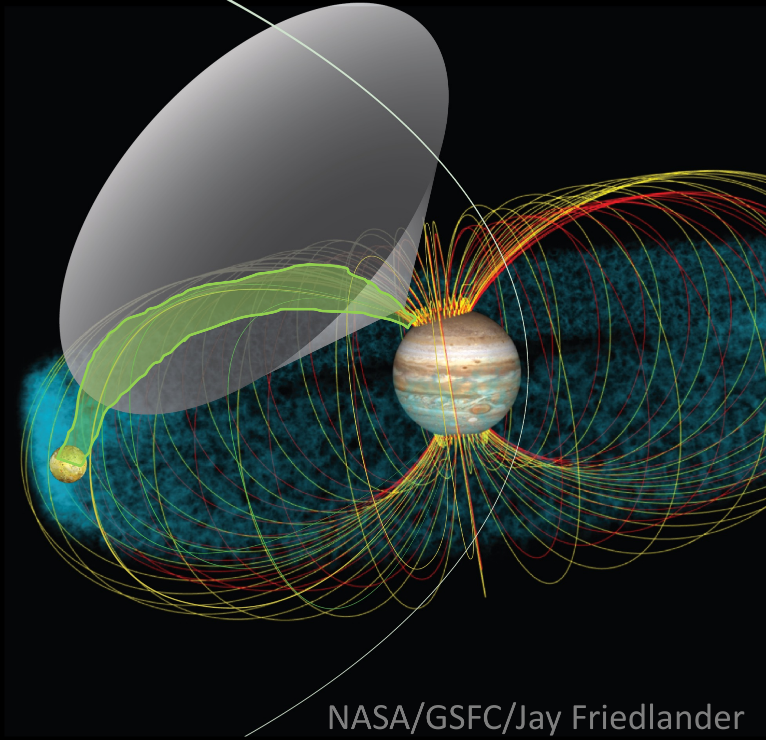
How can we measure exoplanet magnetic fields?

Interaction cross-section (size of deflection region) → amount of energy transferred back to Jupiter/star → brightness of radio waves



Danielle Futselaar (artsource.nl)

Stronger magnetic fields make a larger "bubble" → use brightness of radio waves to measure magnetic field



NASA/GSFC/Jay Friedlander

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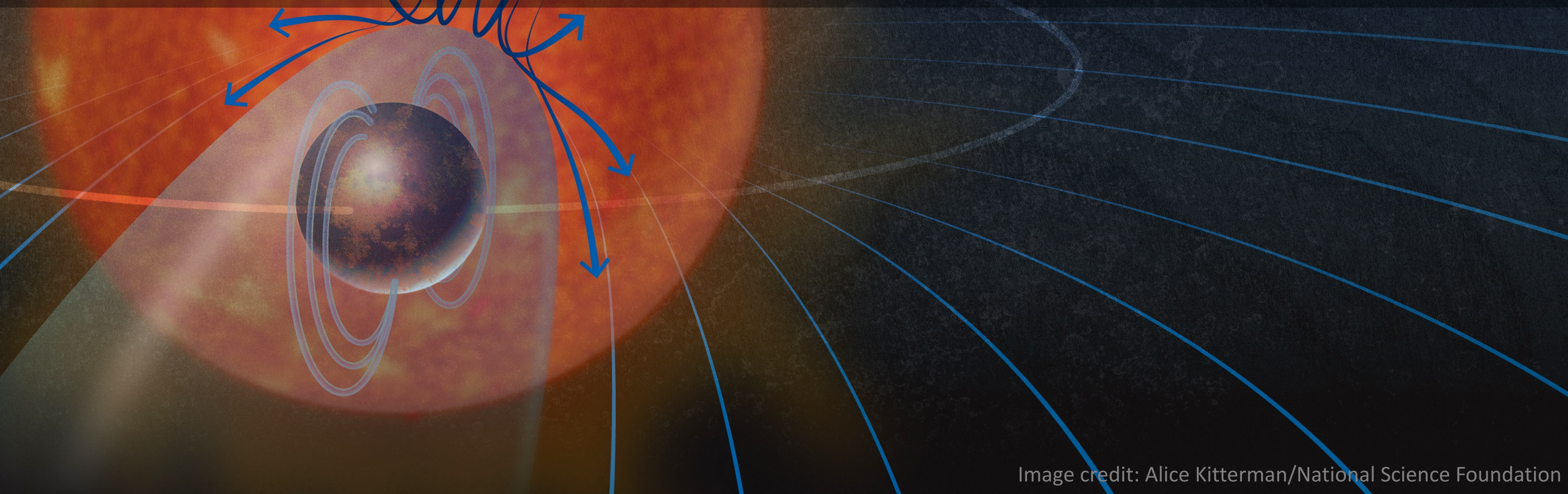
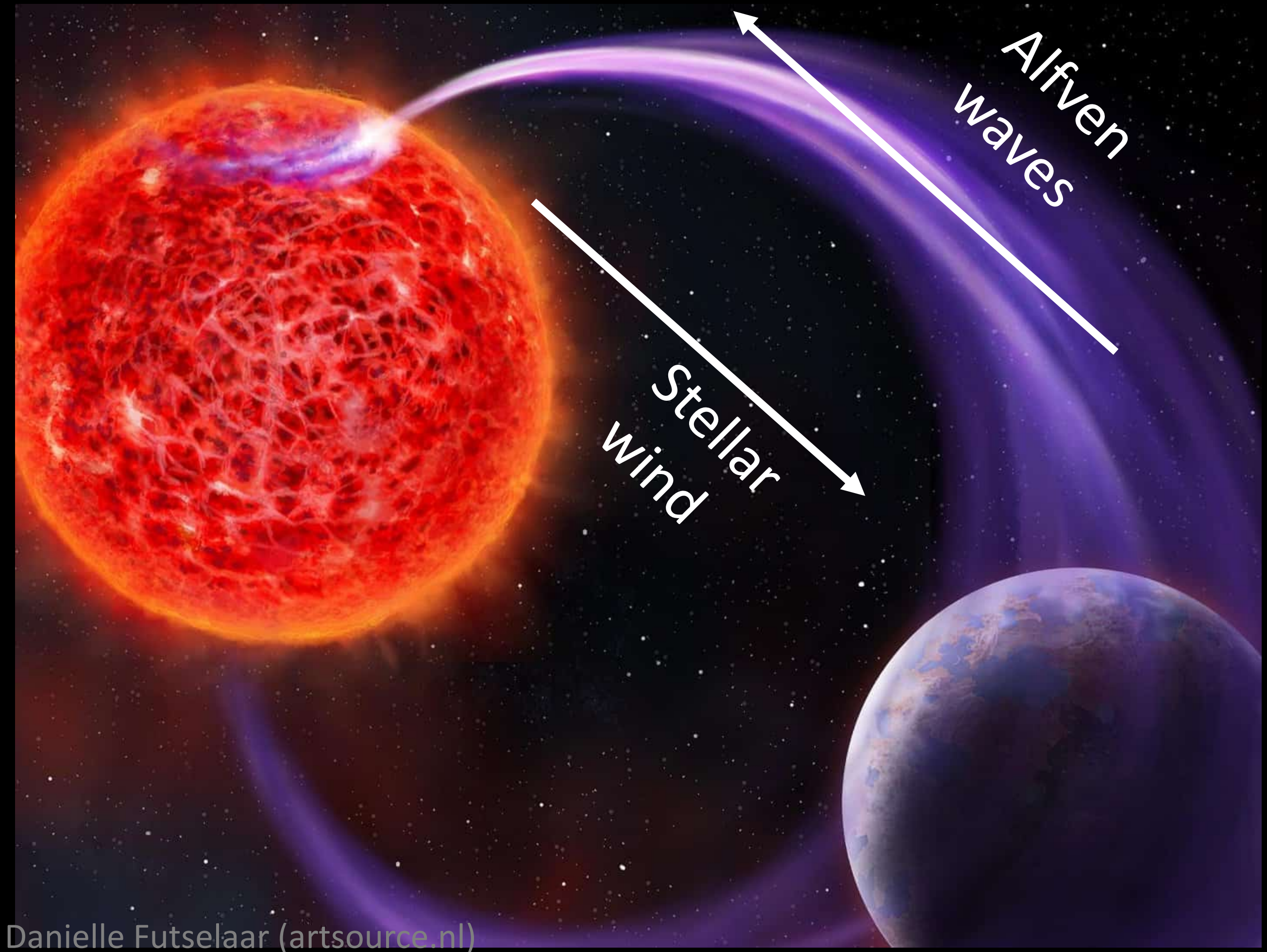


Image credit: Alice Kitterman/National Science Foundation

Only close-in planets can cause the star to emit radio waves



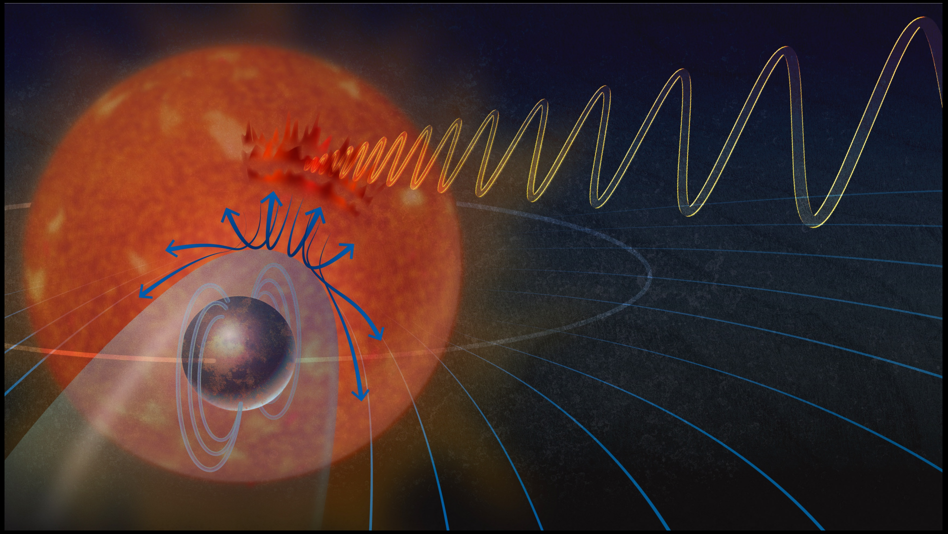
Close to star:

$v_{wind} < v_{Alfven}$ → Alfven waves can swim upstream to reach the star

Far from star:

$v_{wind} > v_{Alfven}$ --> Alfven waves can't swim upstream → no energy transport to star

Our project: radio observations of stars with close-in terrestrial planets



6 terrestrial planets, all have orbits < 2 days (planet is 7 – 20 R_* away from star)

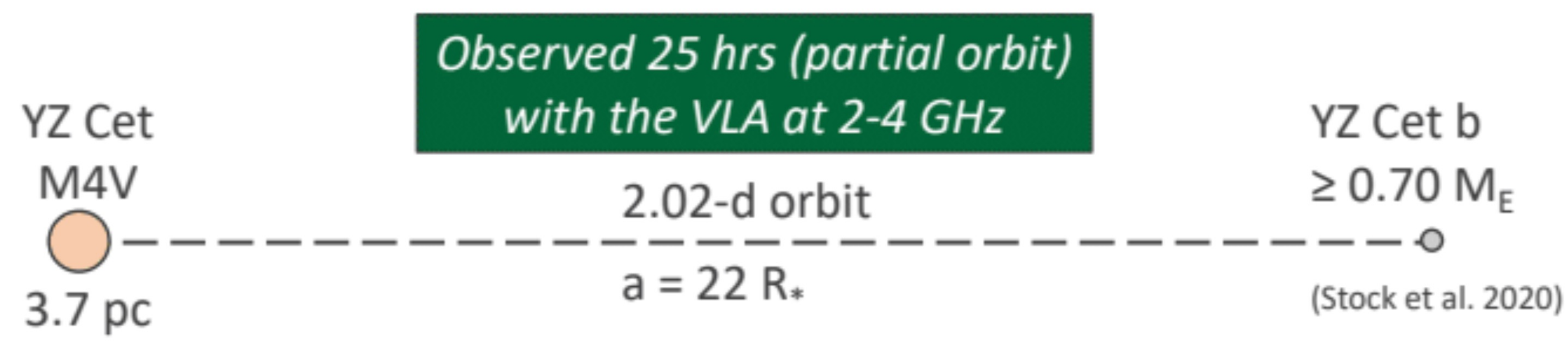
1-4 GHz radio, VLA and ATCA telescopes

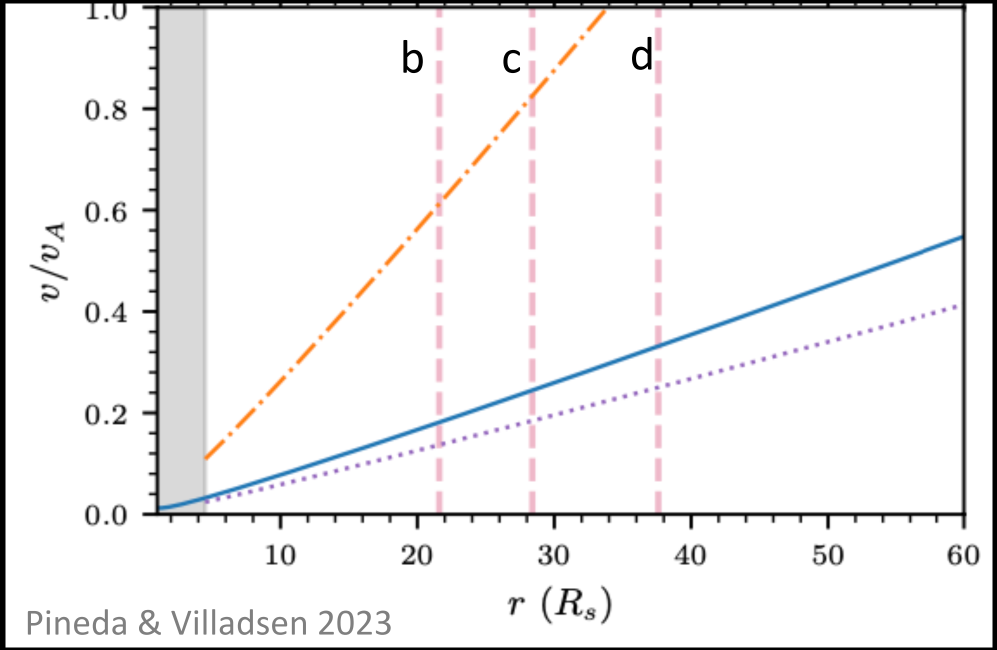
1 candidate detection: YZ Ceti (this talk)
    Follow-up observations coming!
2 non-detections (forthcoming)
3 observed, pending data analysis

<u>Co-PI</u>: Sebastian Pineda (LASP/CU Boulder)

<u>Team</u>: (students)
Arjun Anand (Bucknell University)
Juan Guerrero (Vassar College)
Carter Russell (St. Mary's College of Maryland)
Vanessa Moss (CSIRO/University of Sydney)
Andrew Zic (Macquarie University/CSIRO)
Jake Turner (Cornell)
Elizabeth Cappellazzo (Macquarie University)
Louisa Canepa (University of New South Wales)

YZ Ceti: an M dwarf hosting 3 terrestrial planets





For a range of stellar models (diagonal lines), planet b is always predicted to be sub-Alfvenic (v/v_A <1) → able to send energy back to the star

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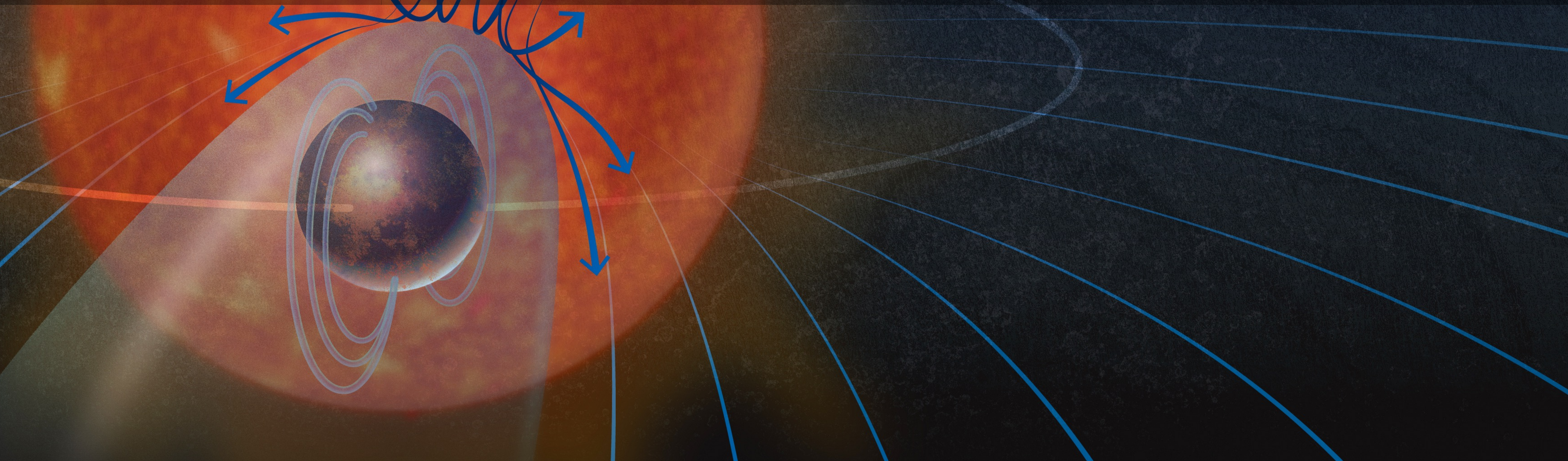
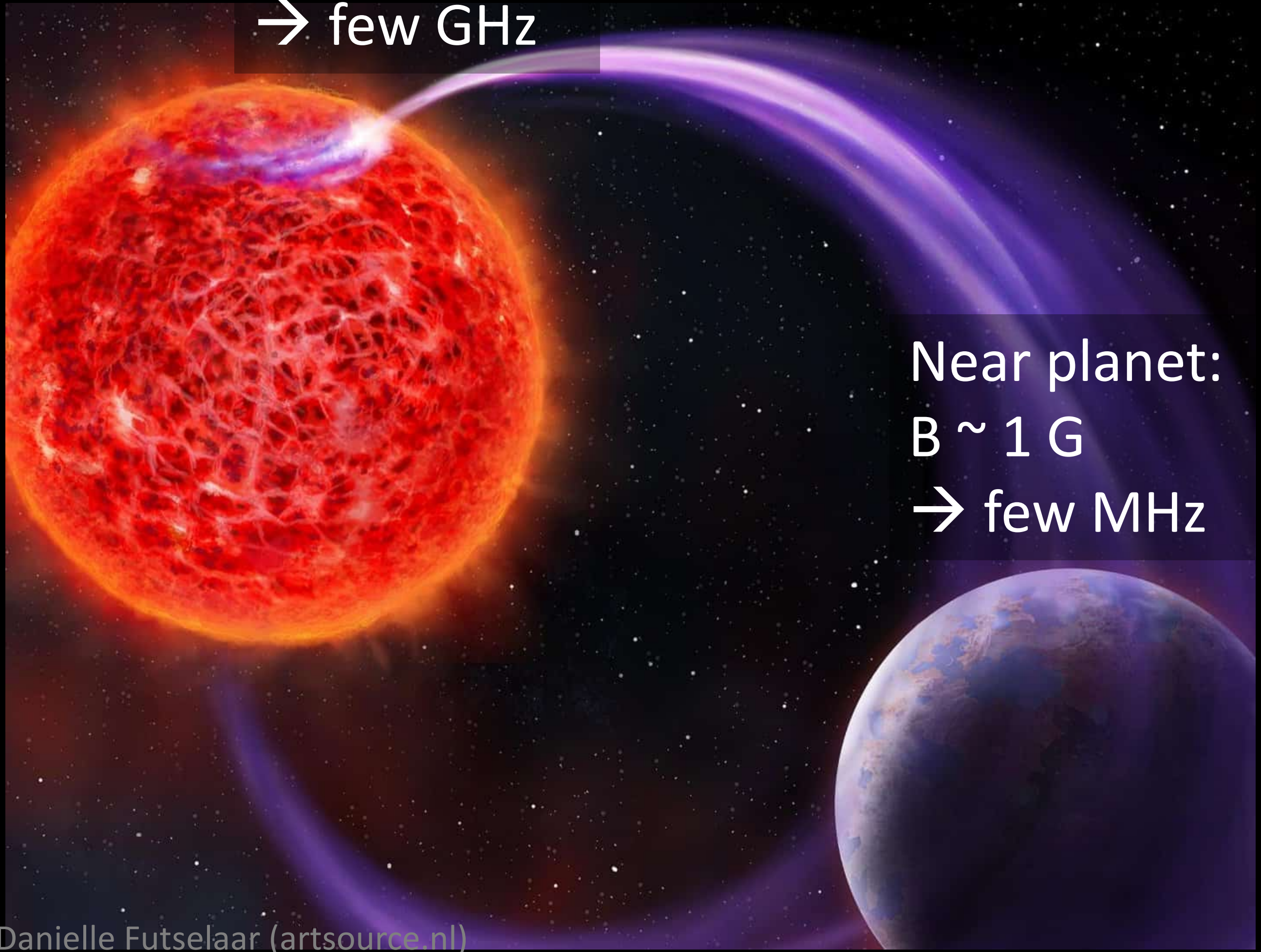


Image credit: Alice Kitterman/National Science Foundation

Radio waves at 1-4 GHz can detect stellar cyclotron

Near star:
B ~ 1000 G
→ few GHz



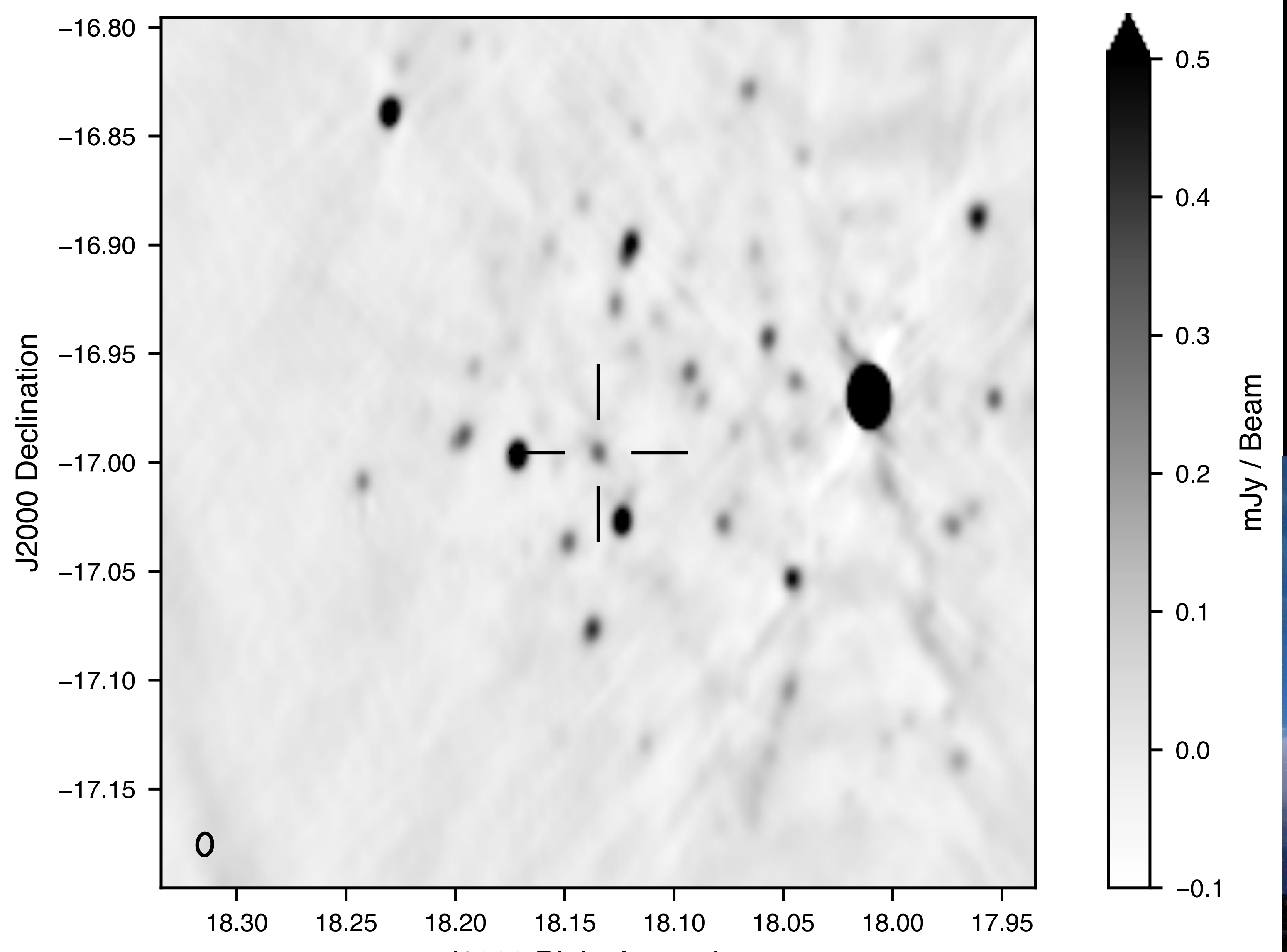
Near planet:
B ~ 1 G
→ few MHz

Danielle Futselaar (artsource.nl)

Very Large Array (VLA) in New Mexico

Australia Telescope Compact Array (ATCA)

Imaging YZ Ceti



Pineda & Villadsen 2023

How do we create images with radio telescopes?

Fourier transforms!

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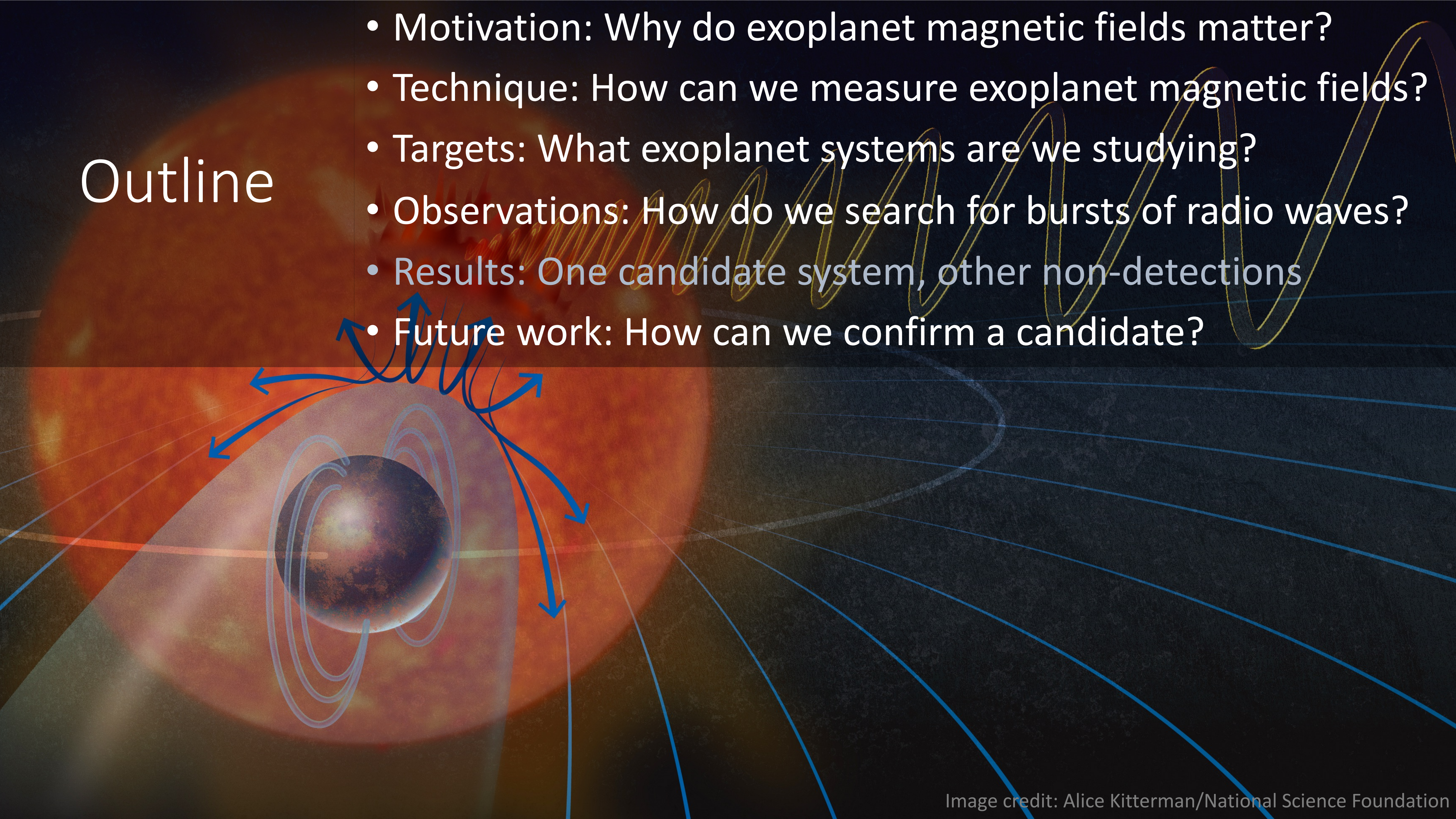
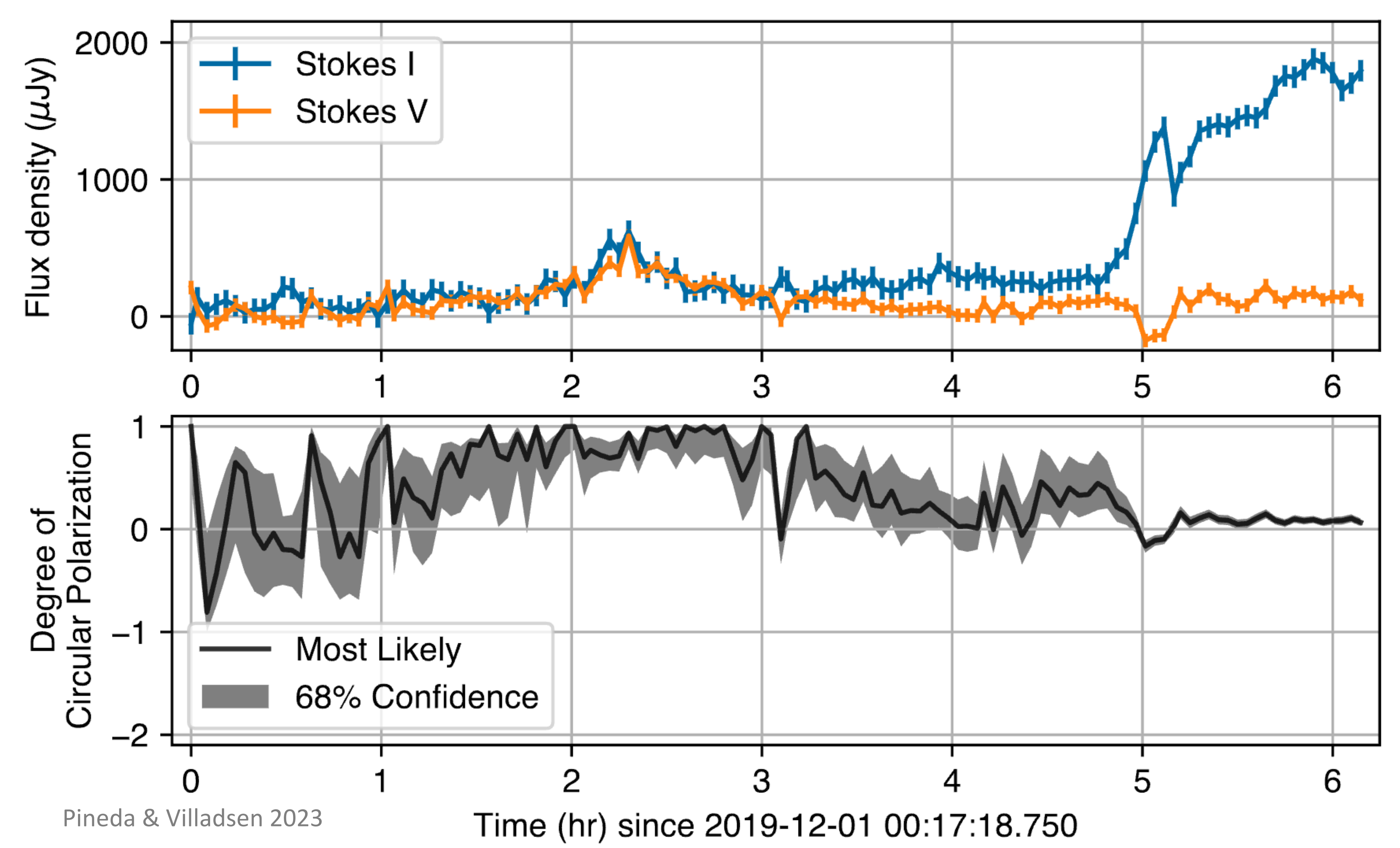


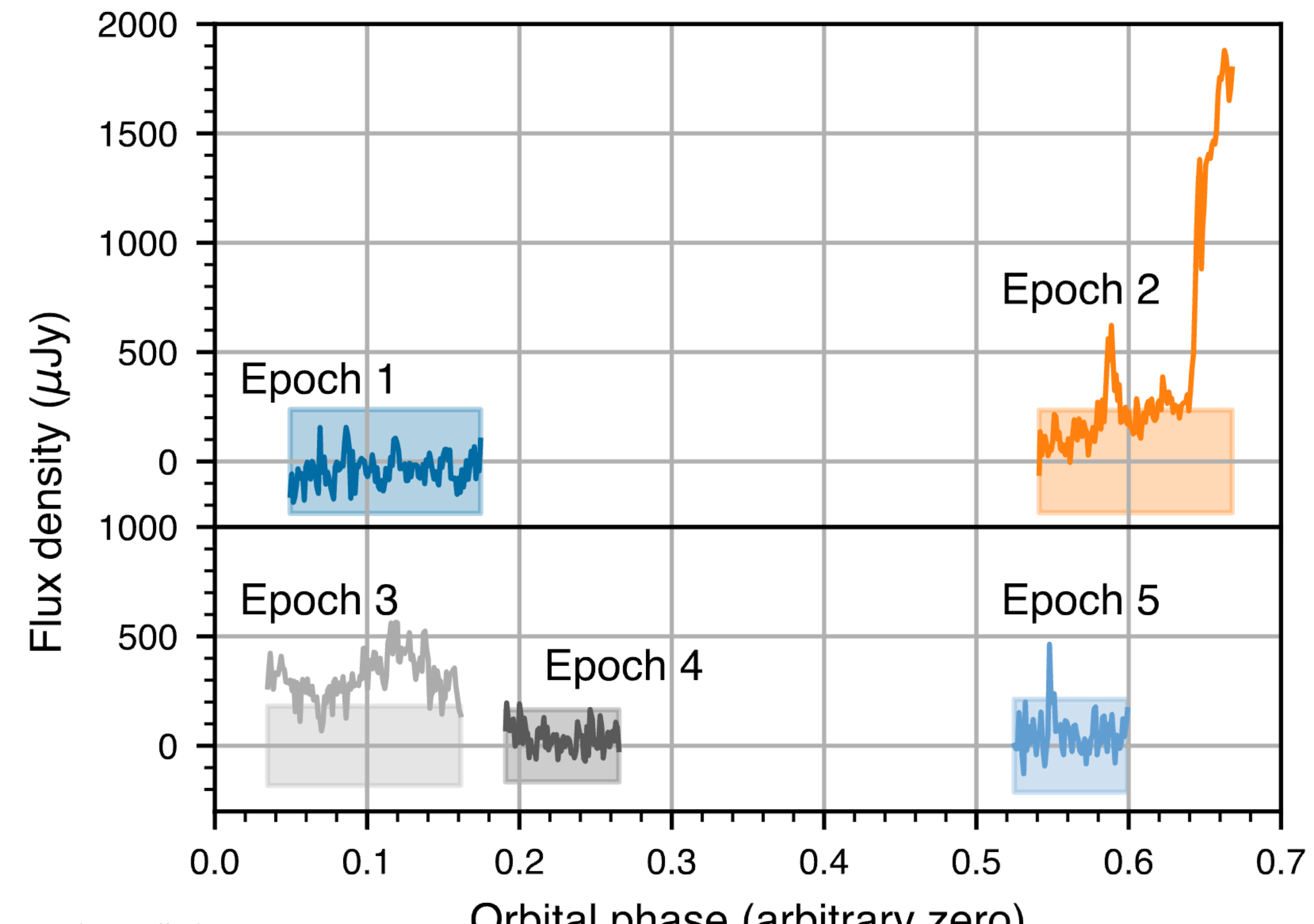
Image credit: Alice Kitterman/National Science Foundation

YZ Ceti: Candidate SPI bursts show strong circular polarization, pointing to cyclotron



Pineda & Villadsen 2023

In follow-up, a polarized burst occurred at a similar orbital phase (not identical!)



Pineda & Villadsen 2023

3 initial epochs: only bursts in epoch 2

Follow-up epochs: 4 & 5

Based on Jupiter-Io, burst timing/morphology can vary slightly depending on stellar rotation. This makes it trickier to confirm orbital periodicity, since it's not always identical timing!

How can we infer an exoplanet's magnetic field from *stellar* radio bursts?

$$S \propto R_o^2 \, B_{sw} \, \Delta u^2 \, \sin^2\theta \sqrt{\rho_{sw}}$$

Saur et al. (2013)

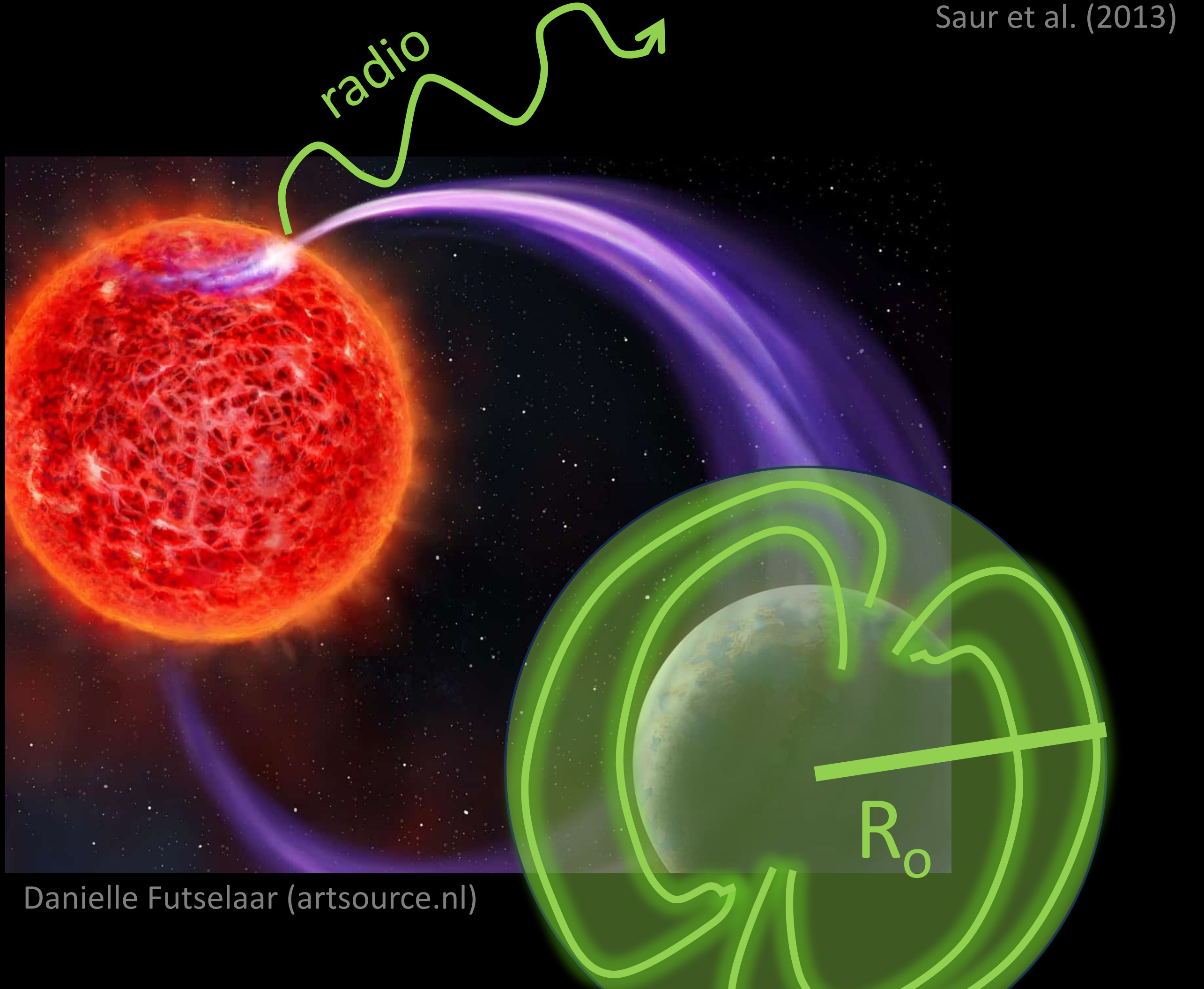
Brightness of radio waves:
0.6 mJy (6 x 10^{-24} erg/cm^2/s/Hz)

→

Obstacle radius
(from interaction cross-section):
Few x times planet radius

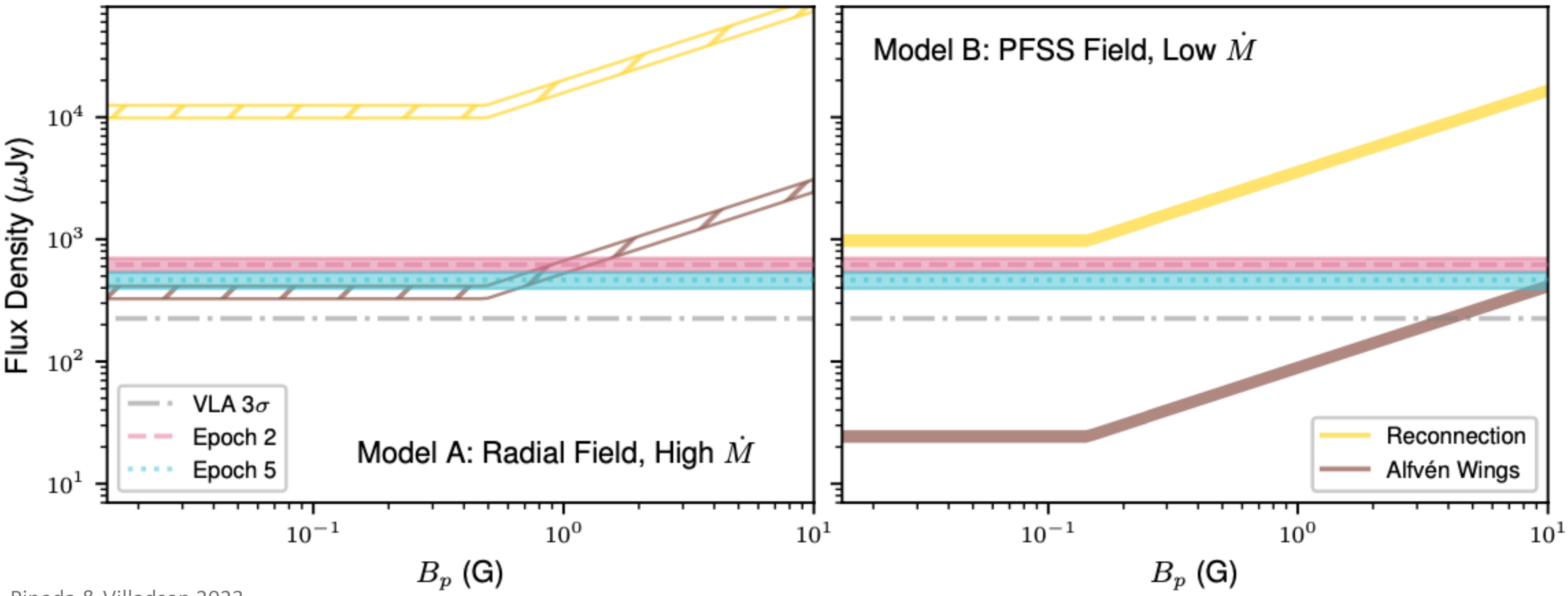
→

Magnetic field strength:
1-10 G   (Earth is 0.5 G)



Danielle Futselaar (artsource.nl)

If the radio waves are caused by the planet, what does that tell us about the planet's magnetic field?



Pineda & Villadsen 2023

To explain the observed flux densities, the planet field should be of order ~1-10 G. Many assumptions involved → need stellar magnetic measurements to improve assumptions!

To improve estimate, need stellar magnetic map & stellar gas density measurement

Radio measurement

Exoplanet magnetic field

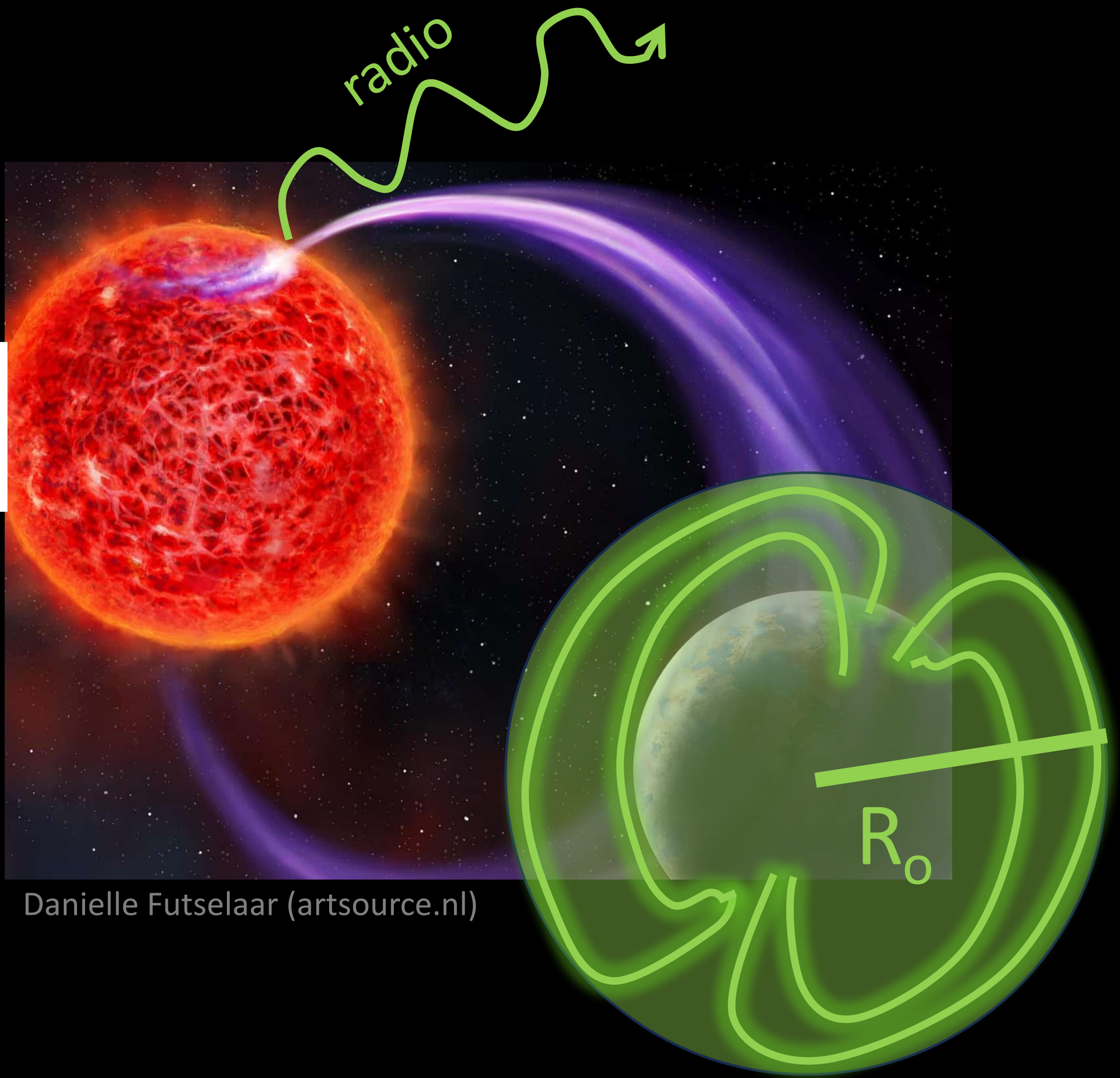
Orbital speed

$$S \propto R_o^2 \, B_{sw} \, \Delta u^2 \, \sin^2\theta \sqrt{\rho_{sw}}$$

Saur et al. (2013)

Stellar magnetic field at planet location (unknown)

Stellar wind density (unknown)



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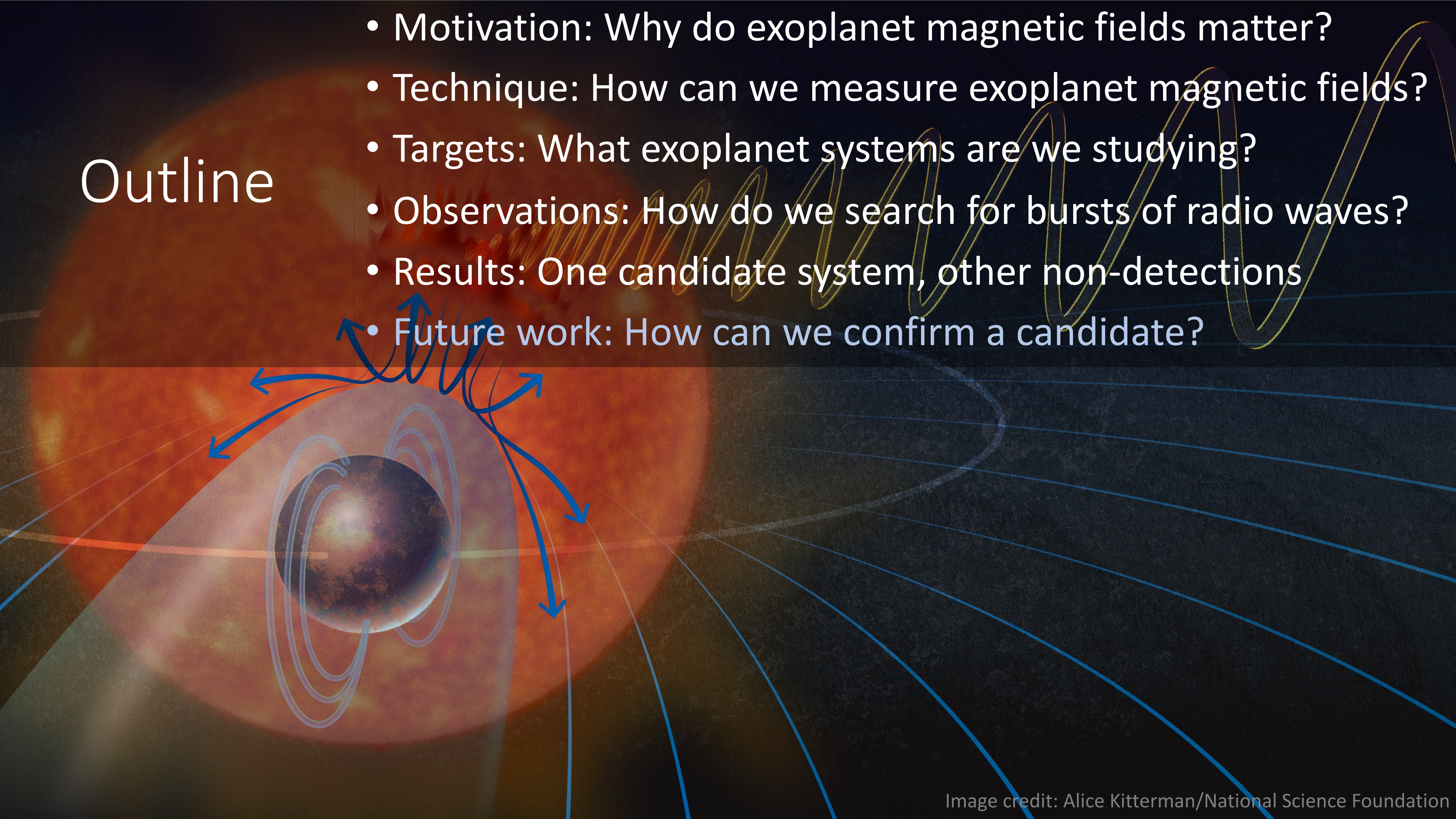
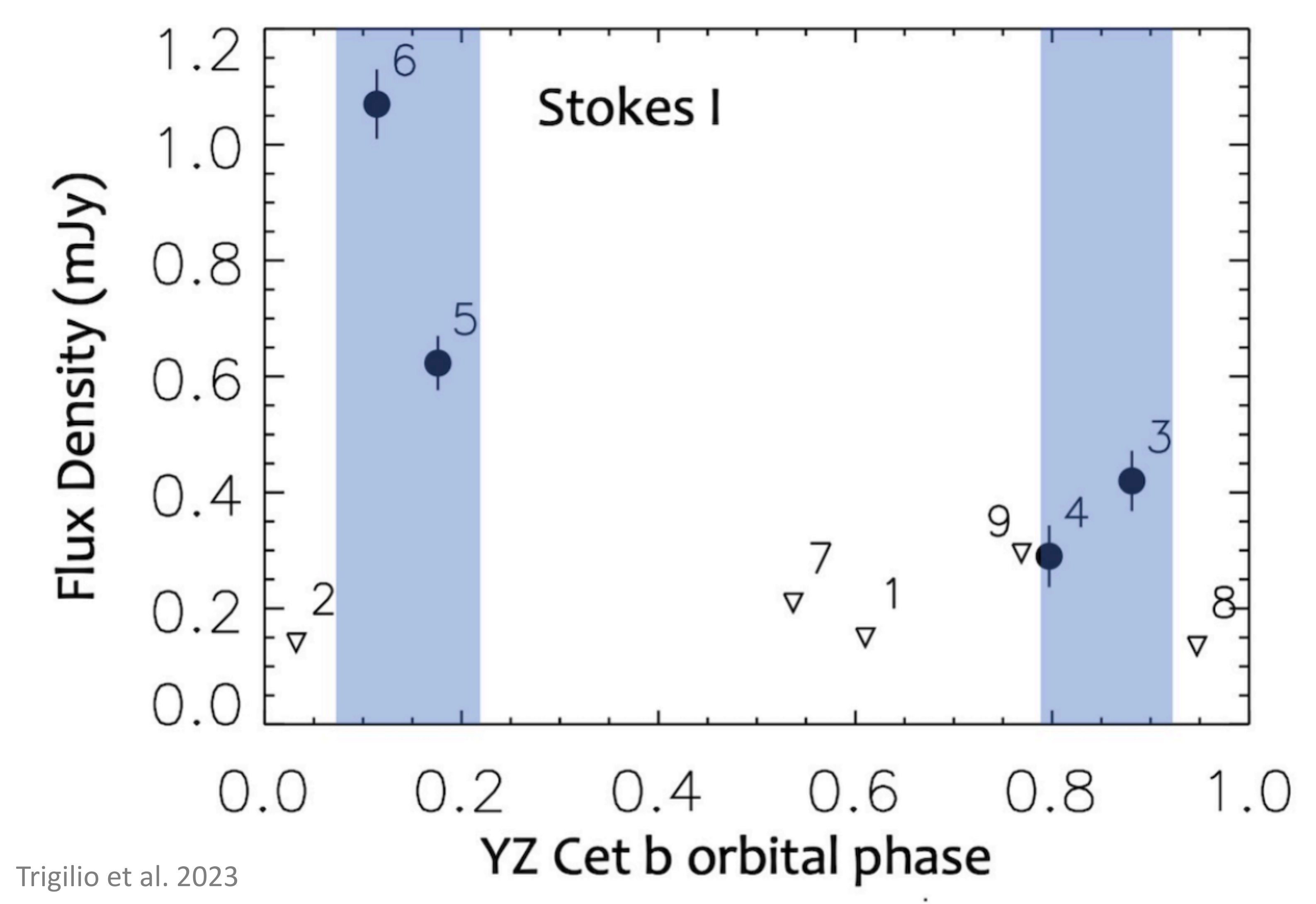


Image credit: Alice Kitterman/National Science Foundation

Observations by another team detected polarized radio bursts in 2 additional epochs



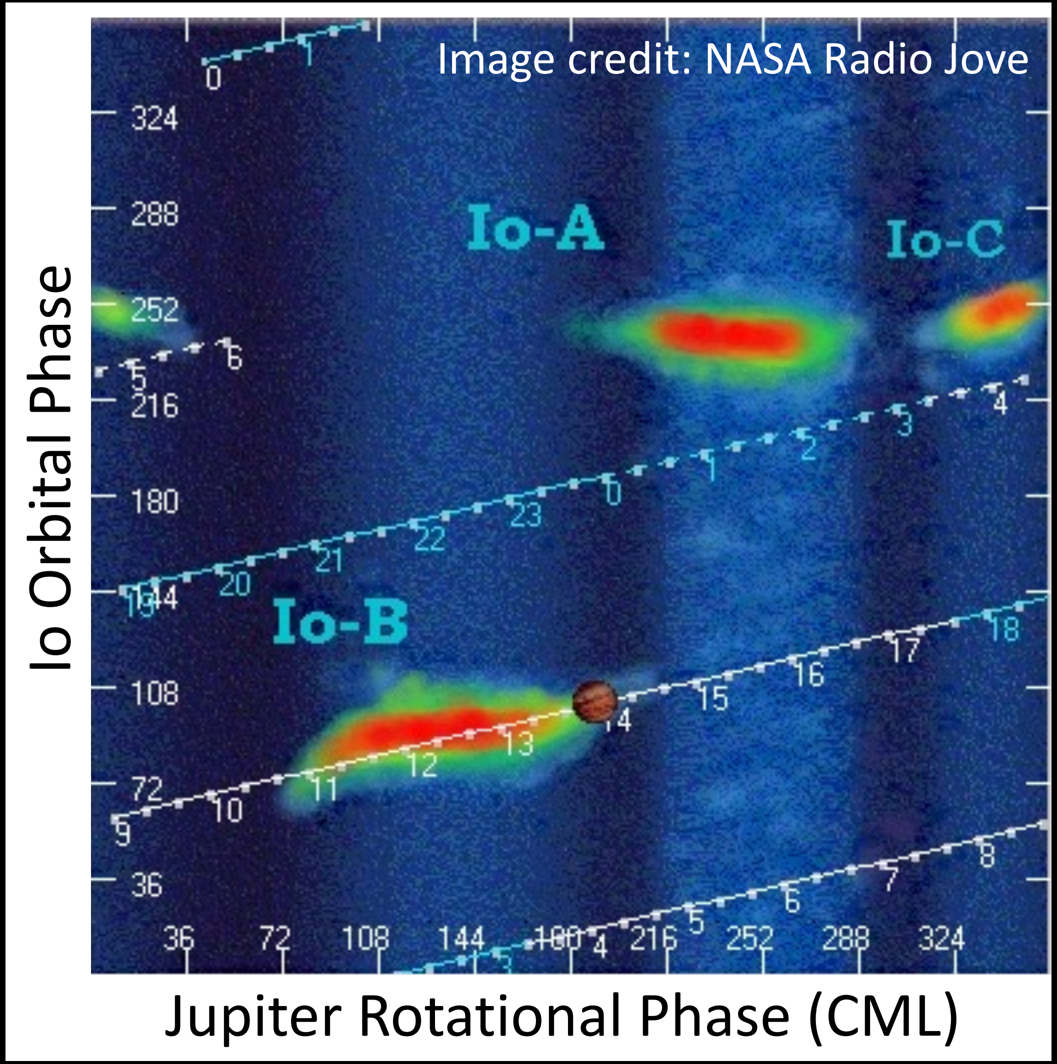
Trigilio et al. 2023

Epochs 5 & 6 have strong circular polarization → cyclotron emission process

Trigilio et al. find 4-sigma significance in enhanced rate of radio bursts at this orbital phase range when combining with our data

Explain: why don't I feel 4-sigma confident?

How can we test for orbital periodicity?



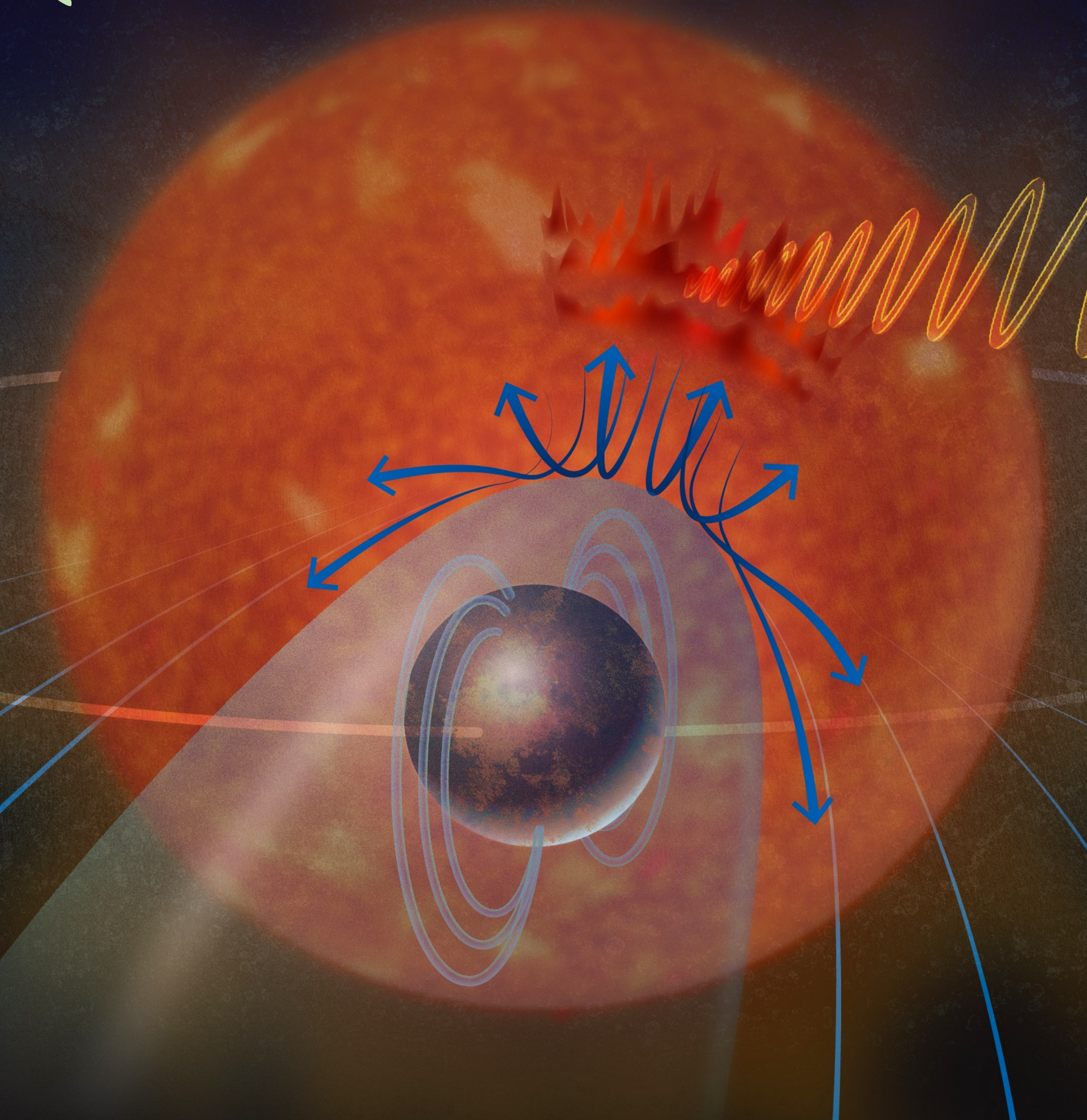
Based on Jupiter-Io: Look for enhanced *probability* of radio bursts at certain orbital phases.

Plan for upcoming observations:

- Determine burst rate at orbital phase range where bursts have occurred so far
- Compare to average burst rate overall

Questions?

Image credit: Alice Kitterman/National Science Foundation



What we have discovered:

- 2 radio bursts on a star
- The bursts occur near similar orbital phases of a close-in planet

What we want to know:

- Is the planet causing the bursts? Do they recur consistently near these orbital phases?
- Measure stellar magnetic properties → better estimates of planet magnetic field strength