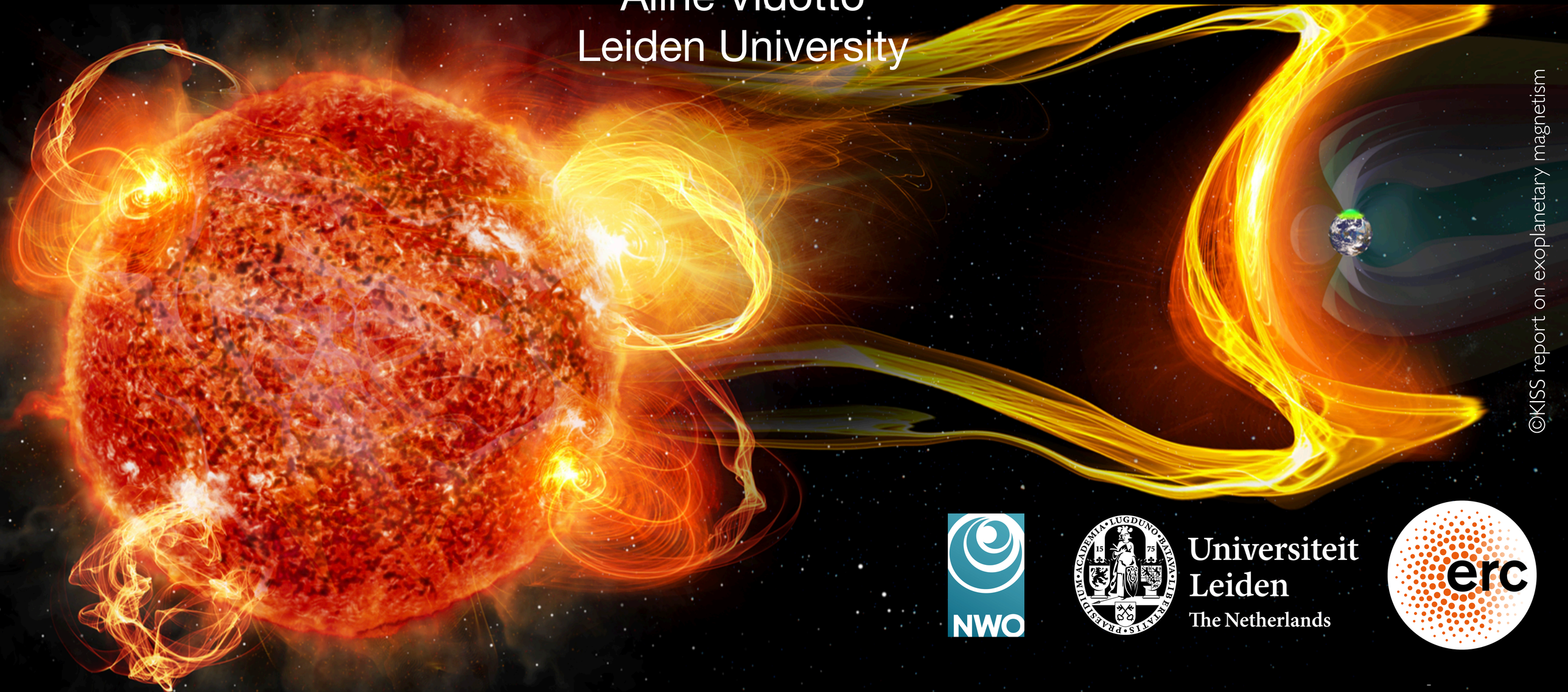
Advances in Our Understanding of Space Weather in Habitable Zone Systems

Aline Vidotto
Leiden University



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Exo-space weather/climate

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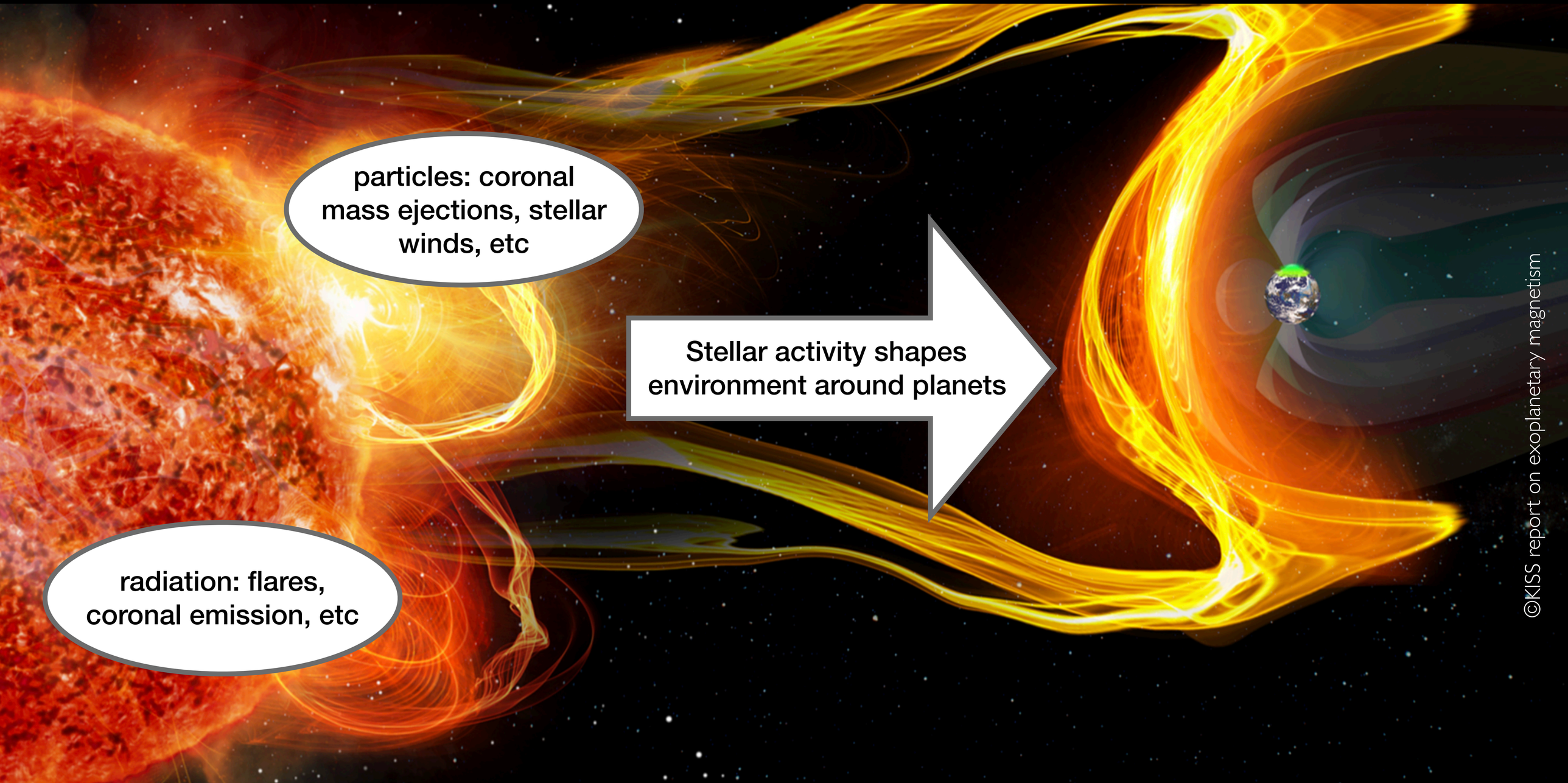
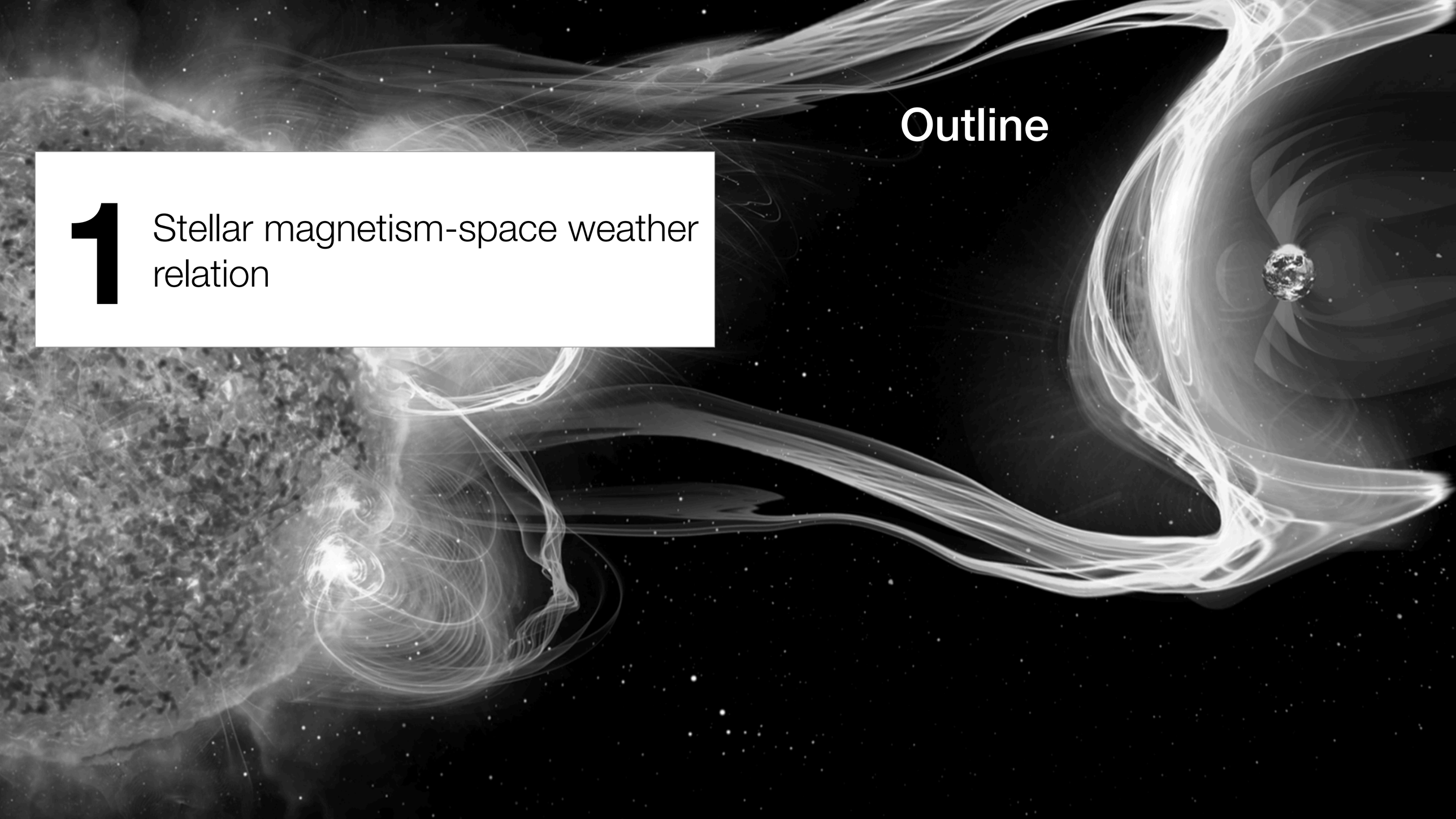


Outline

1 Stellar magnetism-space weather relation

2 Stellar outflows: effects on planetary magnetospheres

3 Open questions & future prospects with PLATO

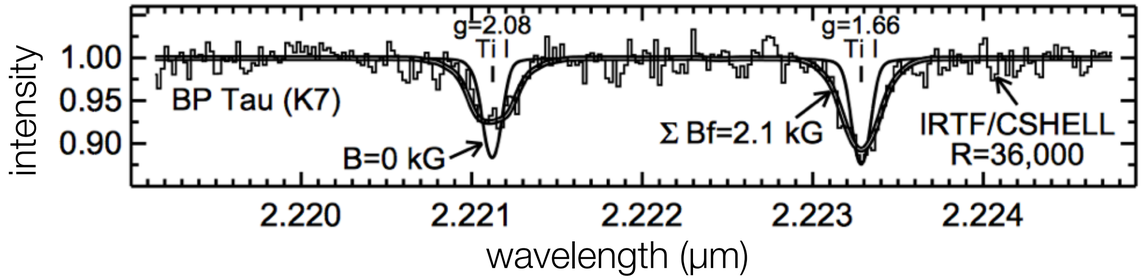


Outline

1 Stellar magnetism-space weather relation

Stellar magnetism is probed with different techniques

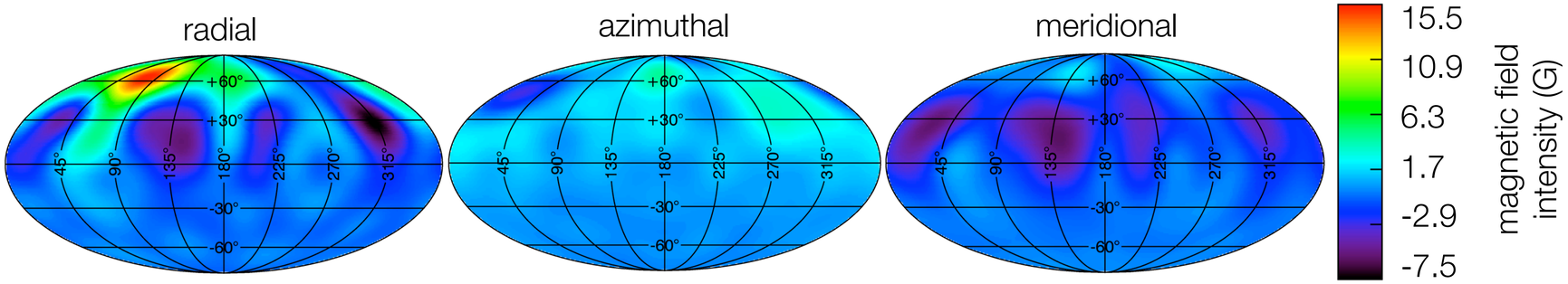
- **Zeeman broadening** (ZB): probes unsigned average surface magnetic field (integrated light)



Johns-Krull 2009

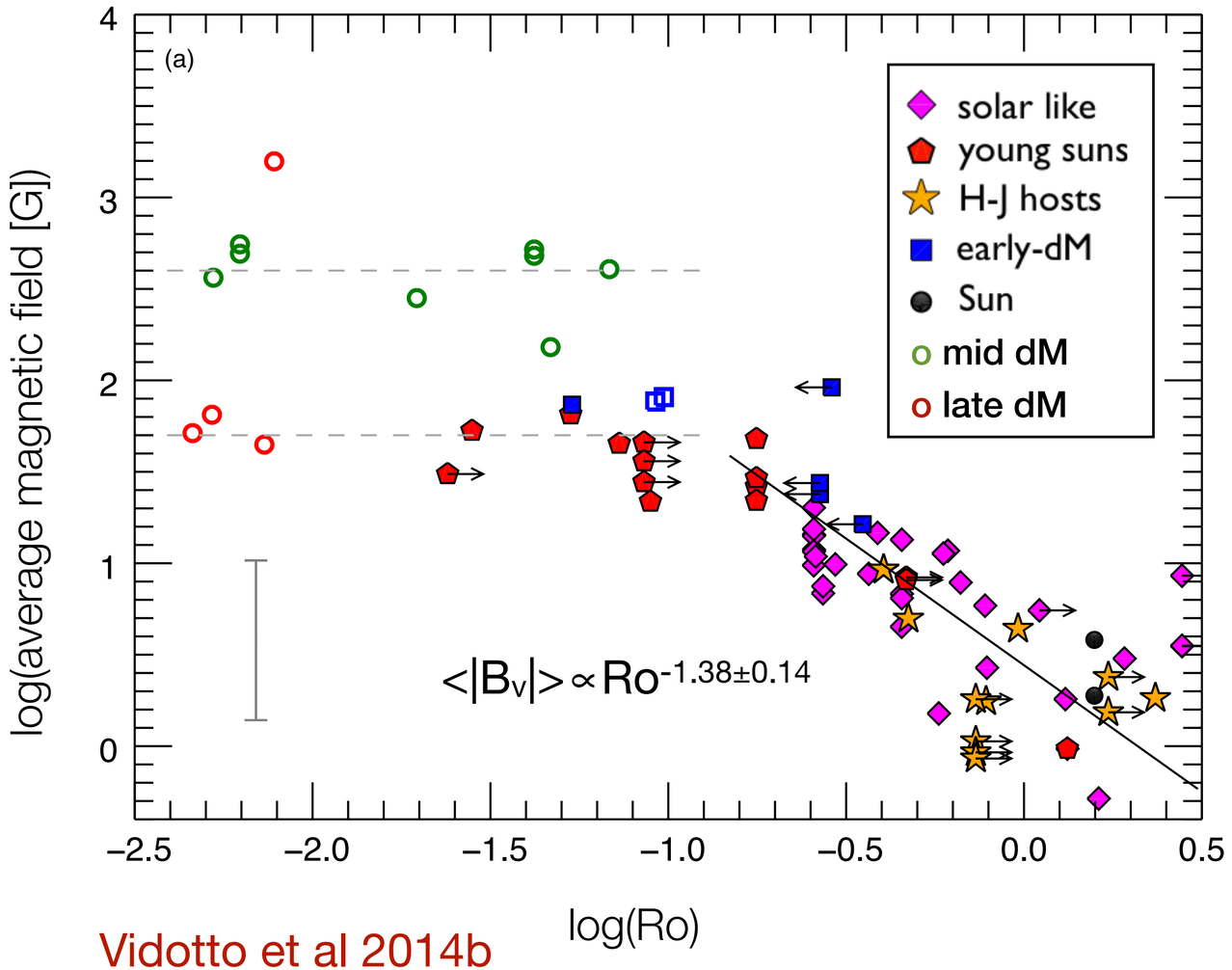
- **Zeeman-Doppler imaging** (ZDI): probes magnetic field topology & intensity (spectropolarimetric monitoring)

Fares et al 2009



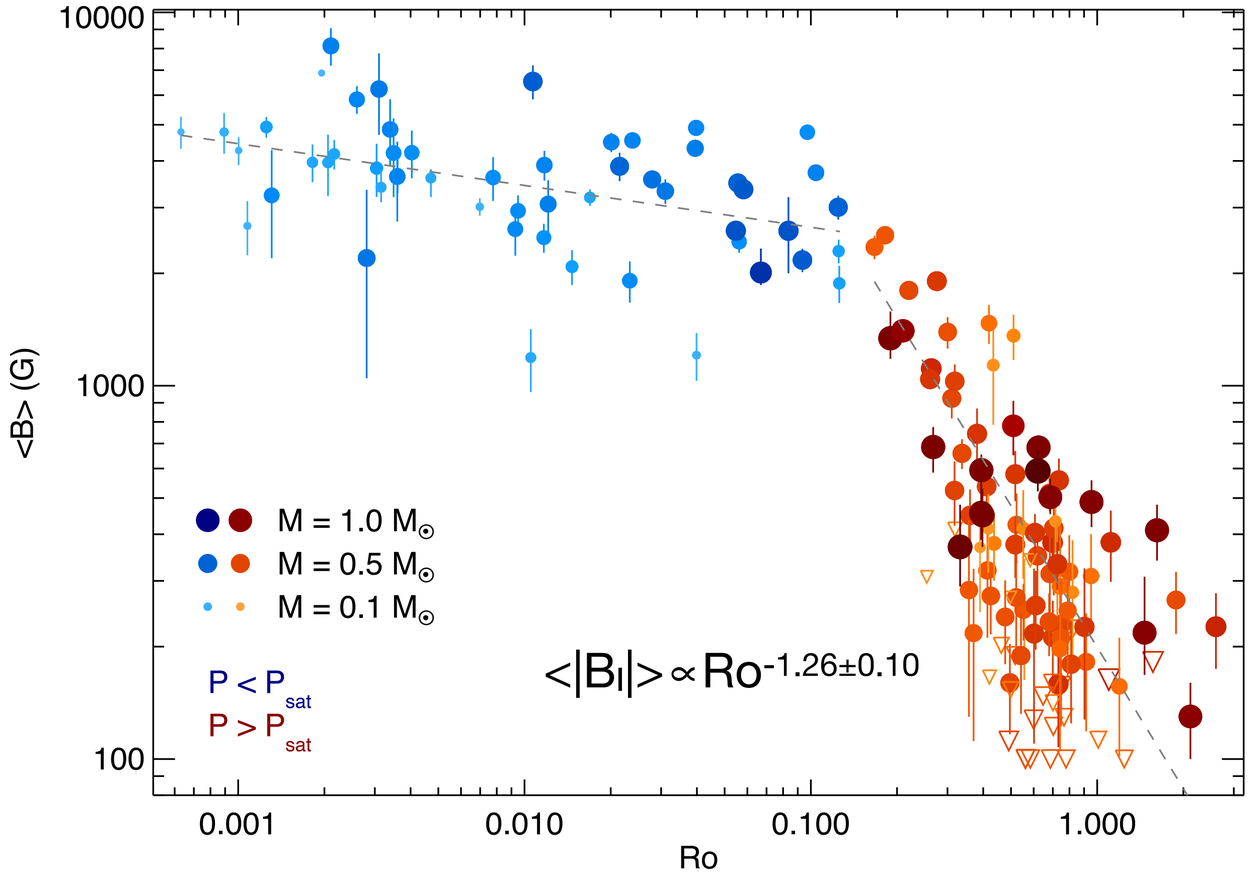
Small- and large-scale fields: (*seem* to have) similar trends with rotation

Zeeman-Doppler imaging (large scale)



Vidotto et al 2014b

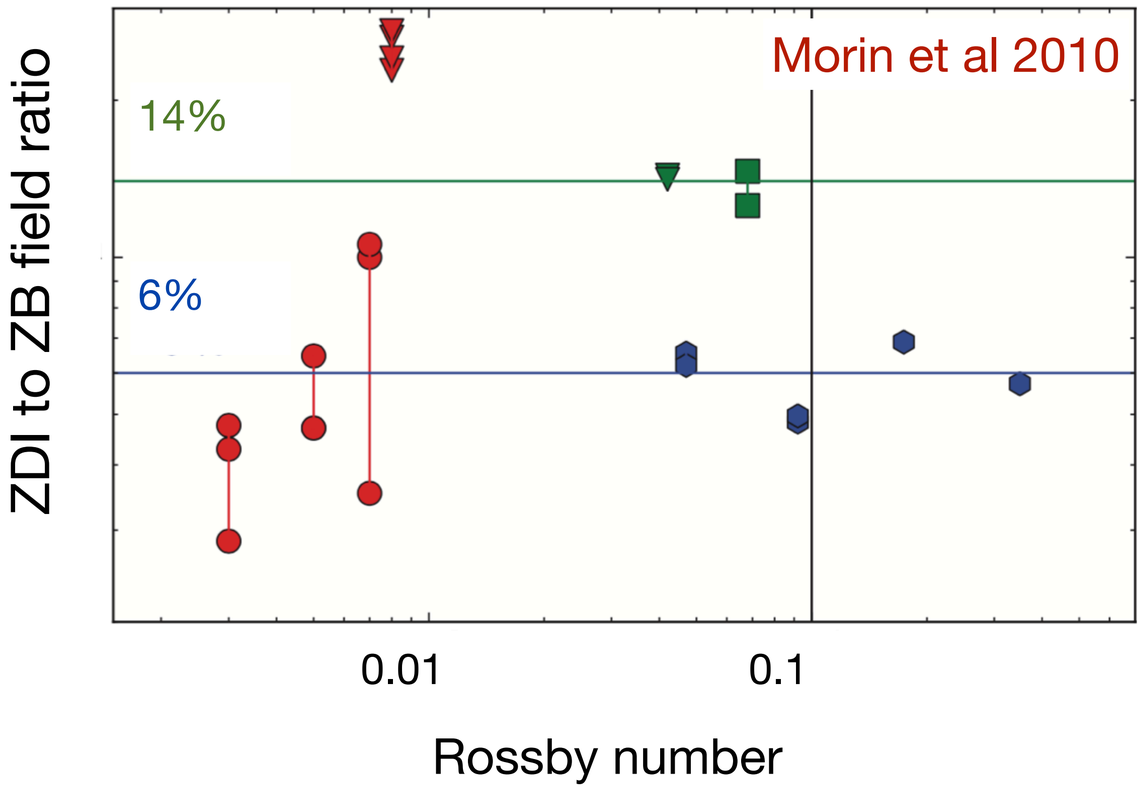
Zeeman broadening (small+large scale)



Reiners et al 2022

$Ro = P_{rot}/\tau_{conv}$

ZDI reproduces ~ 5 - 15% of the field observed by ZB



- Flux cancelation of unresolved regions (small scale) of opposite polarity field causes this discrepancy

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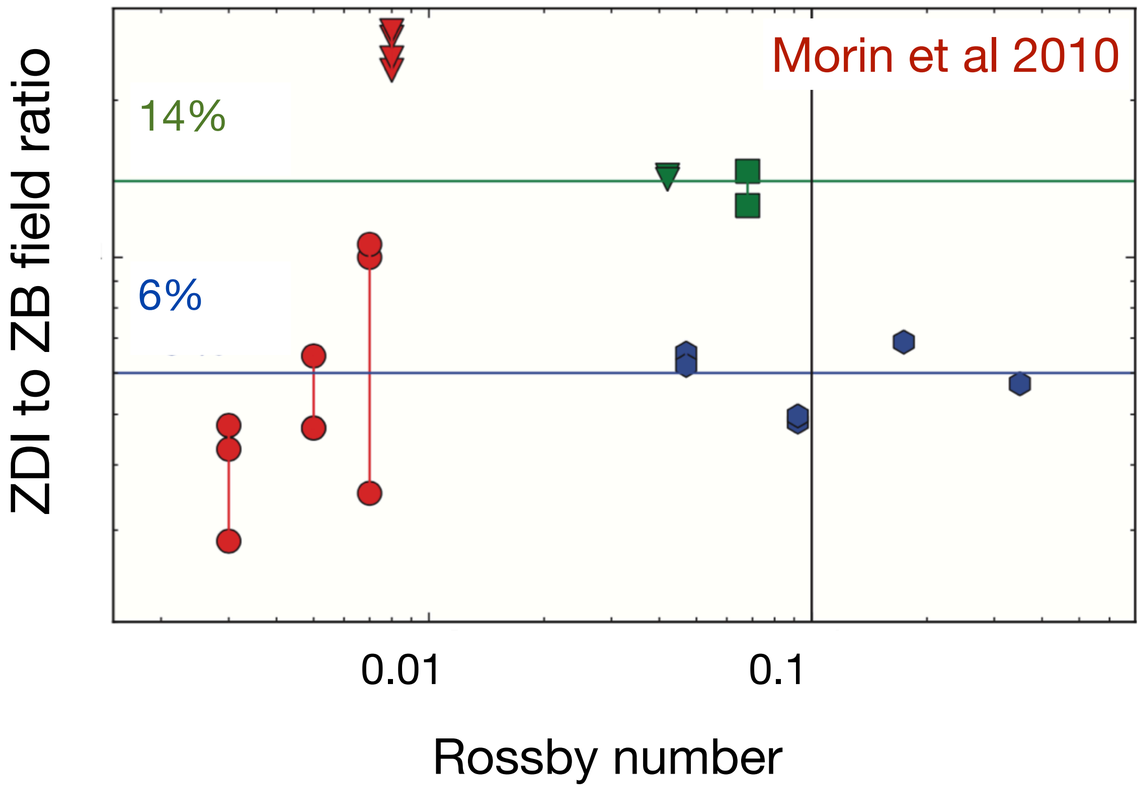

Two Complementary techniques

	Zeeman Broadening	Zeeman Doppler Imaging
Total field measured?	**Yes:** large and small scales	**No:** limited to large-scale fields
Topology studied? (ie, vector **B**)	**No:** average over entire surface only	**Yes:** surface distribution of B_r, B_ϕ, B_θ

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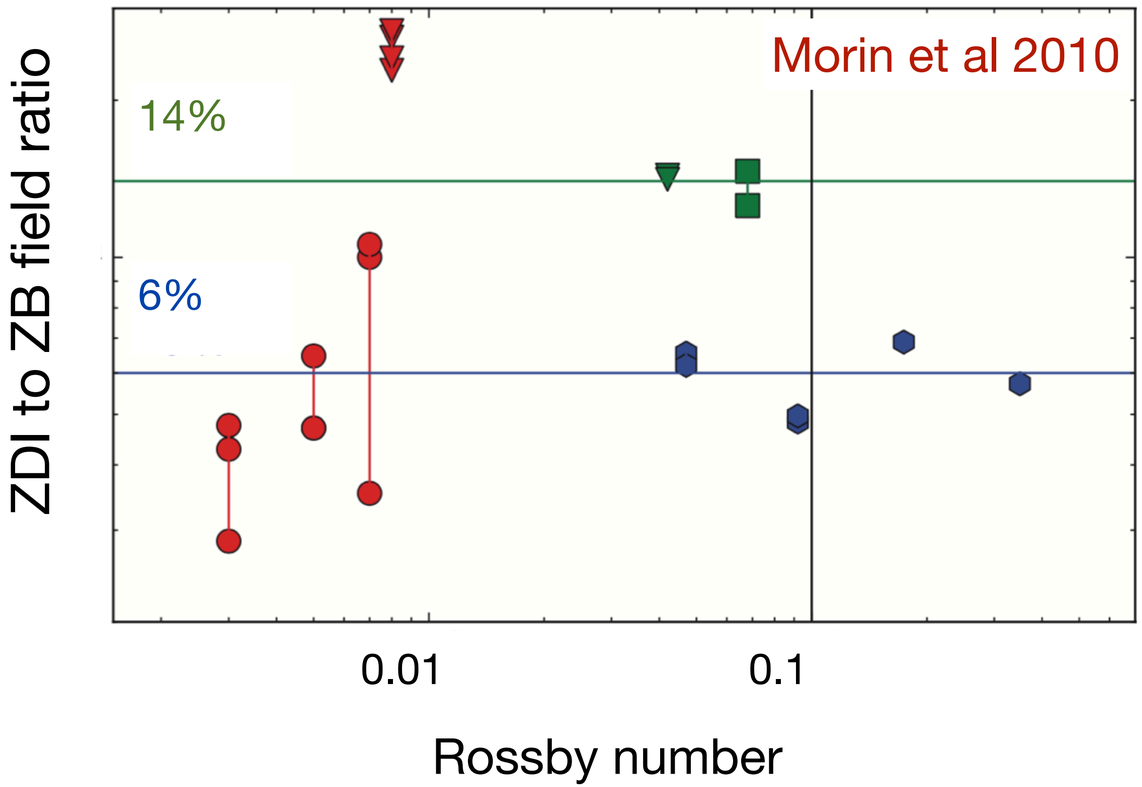

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Which "scale" is more relevant for the exoplanet community?

The diversity of star-planet interactions

Magnetic interaction

Tidal interaction

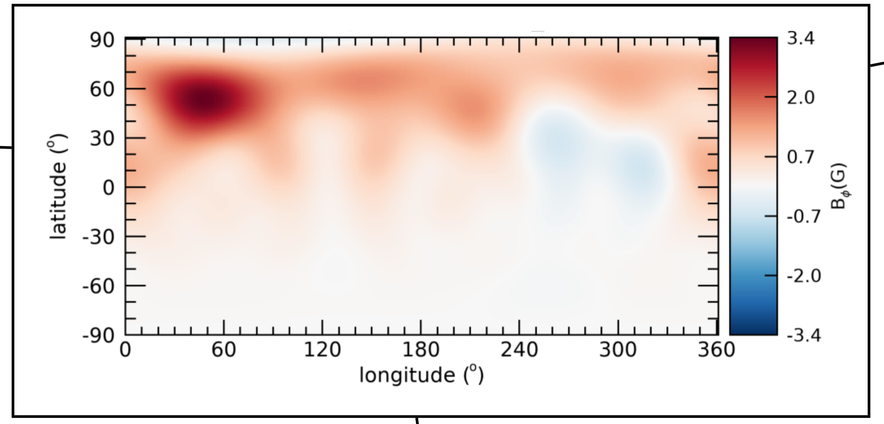
Stellar outflow (particle) interaction

Radiative interaction

see Vidotto (2025, ARAA)

Stellar magnetism at the heart of these interactions

Magnetic interaction



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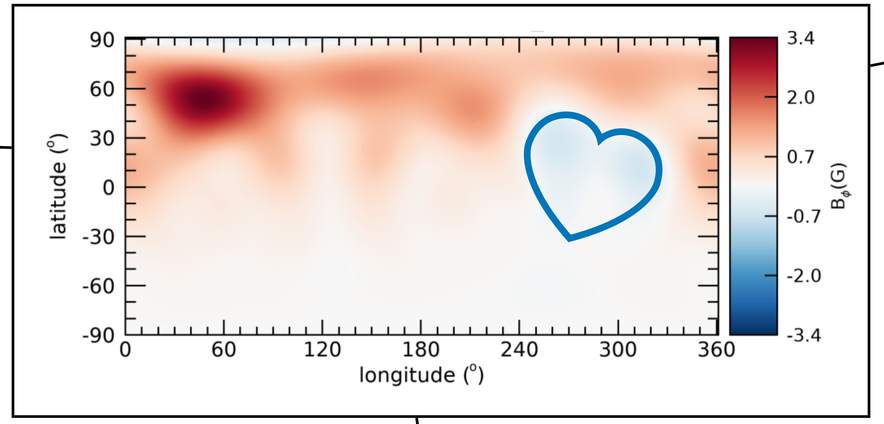

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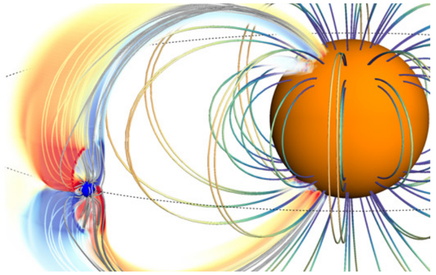
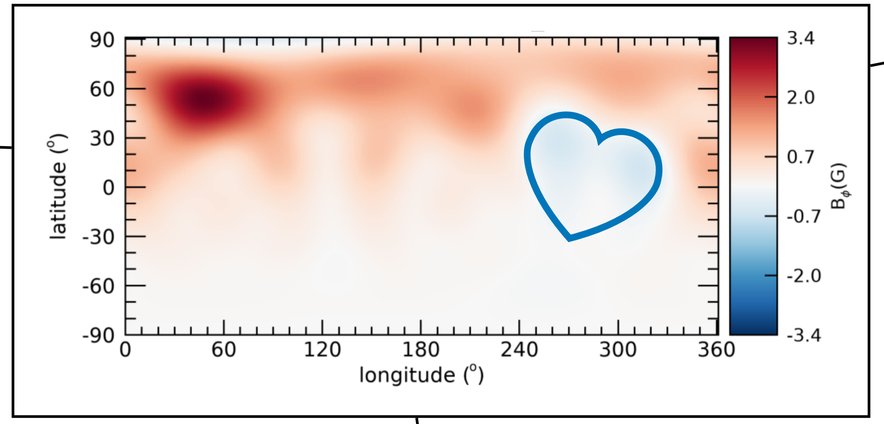
Magnetic interaction

Large-scale stellar magnetic field connects stars and planets

Strugarek et al 2015





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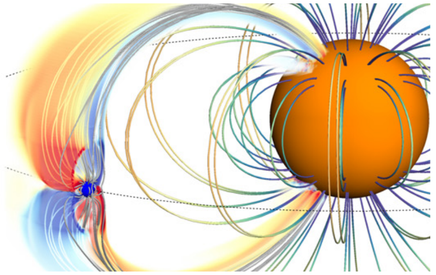

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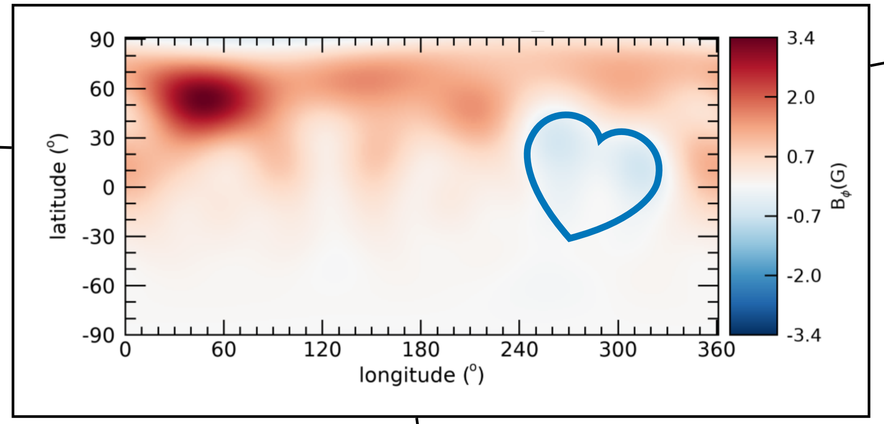
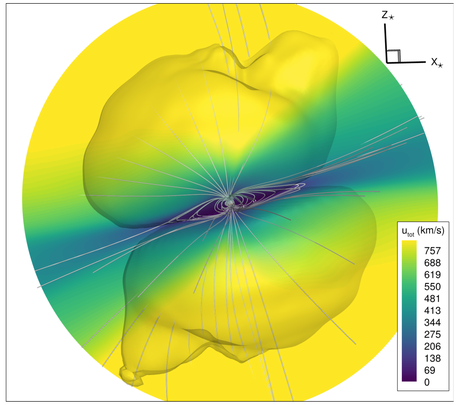


Radiative interaction

Stellar outflow (particle) interaction

Stellar winds flow through large-scale fields; position of Alfven surface



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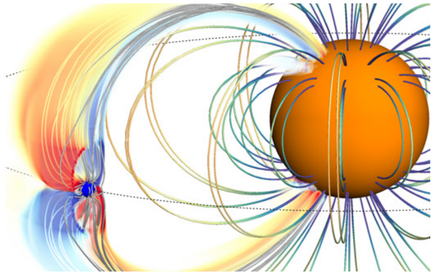

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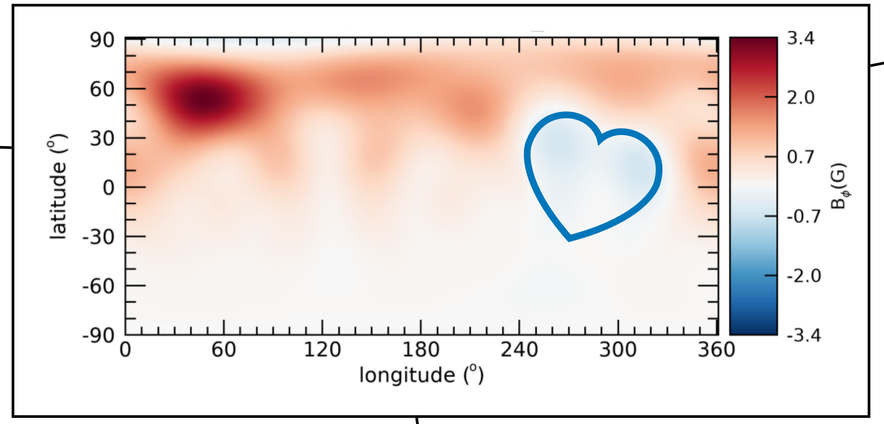

Radiative interaction

Small-scale magnetic field generates hot coronae, high-energy radiation

(If you are interested in planet detection, you probably don't like very much the small-scale fields)

Stellar outflow (particle) interaction

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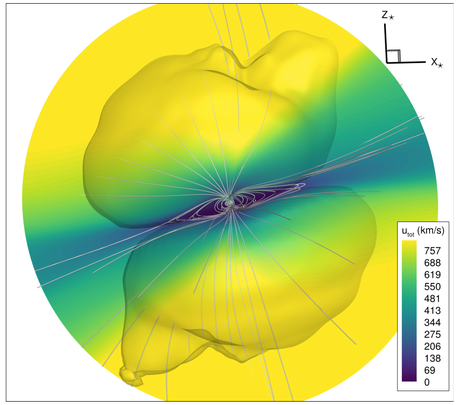
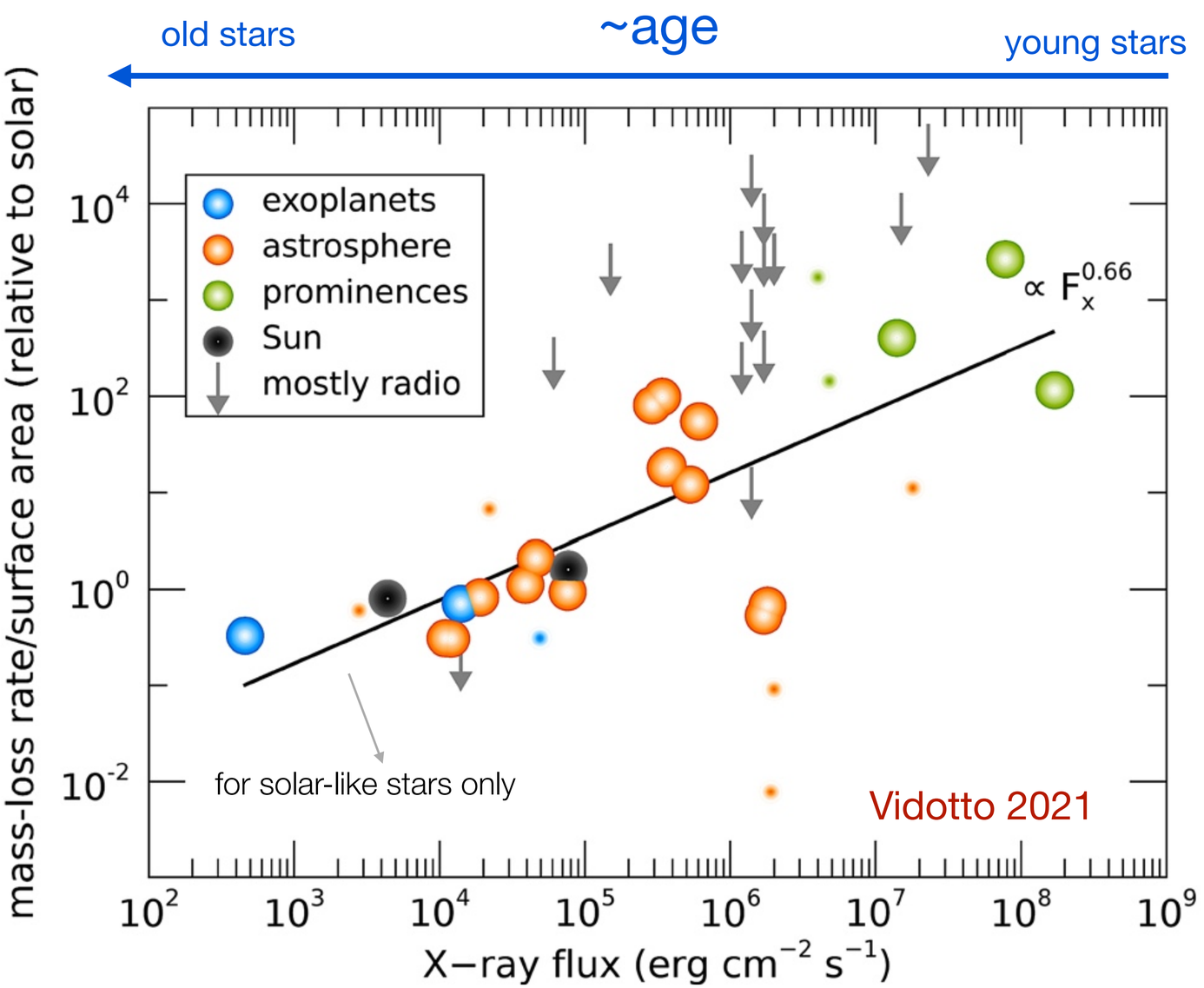


Vidotto et al 2023

Stellar wind-activity trends & evolution



(data from: Wood, Jardine, Fichtinger, Vidotto, Drake, Lim, Gaidos, Wargelin, OFionnagain)

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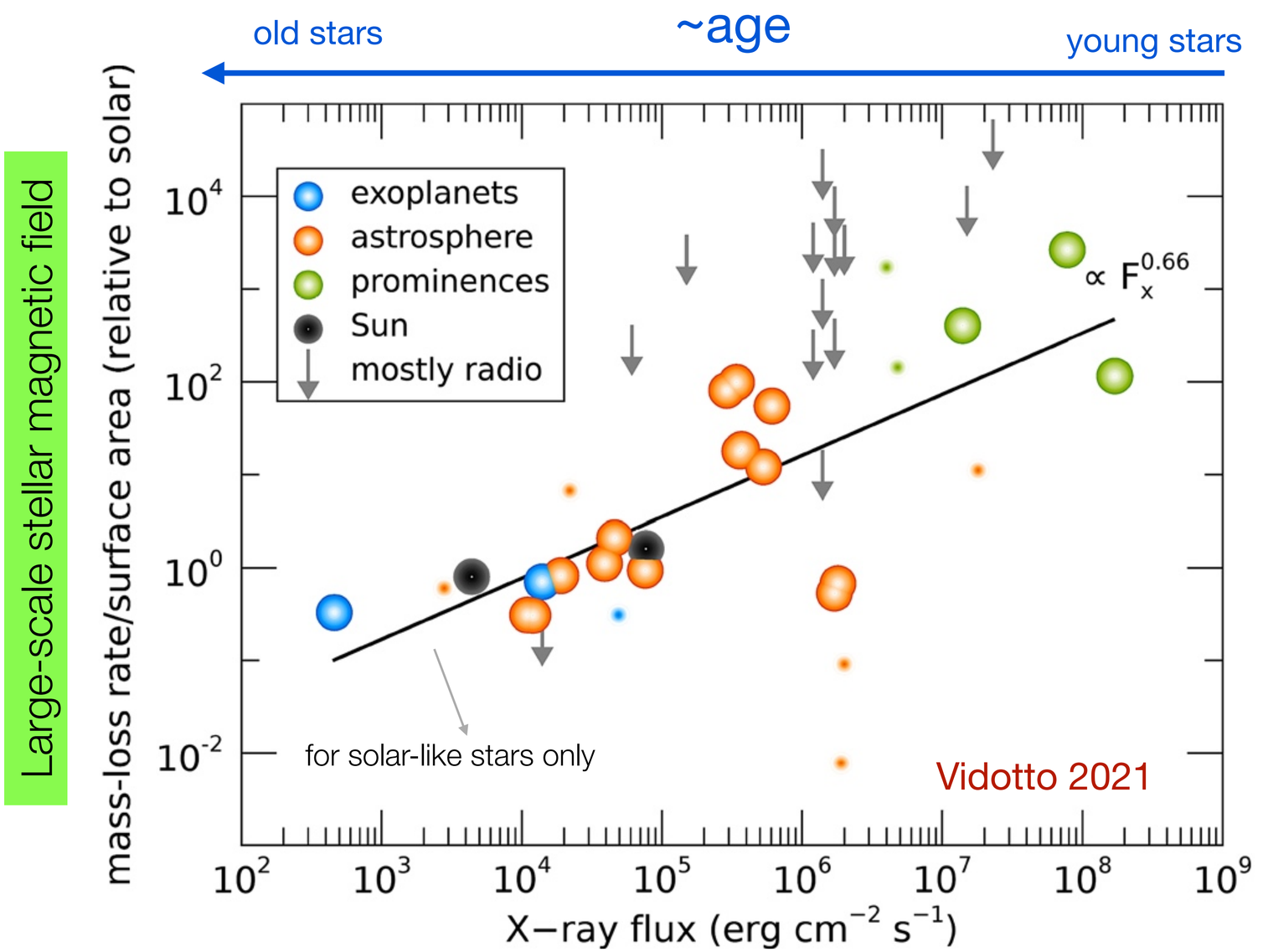

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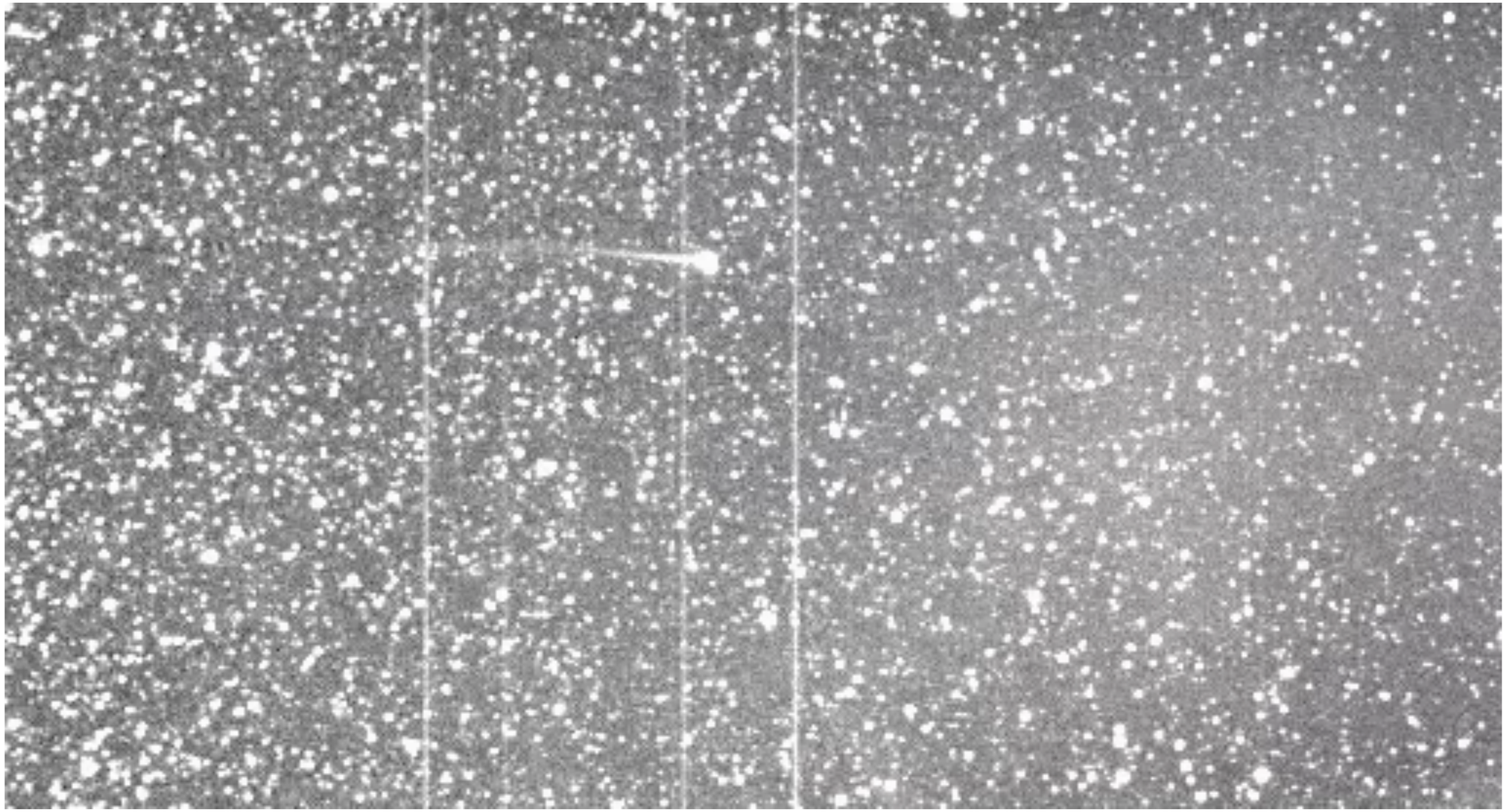
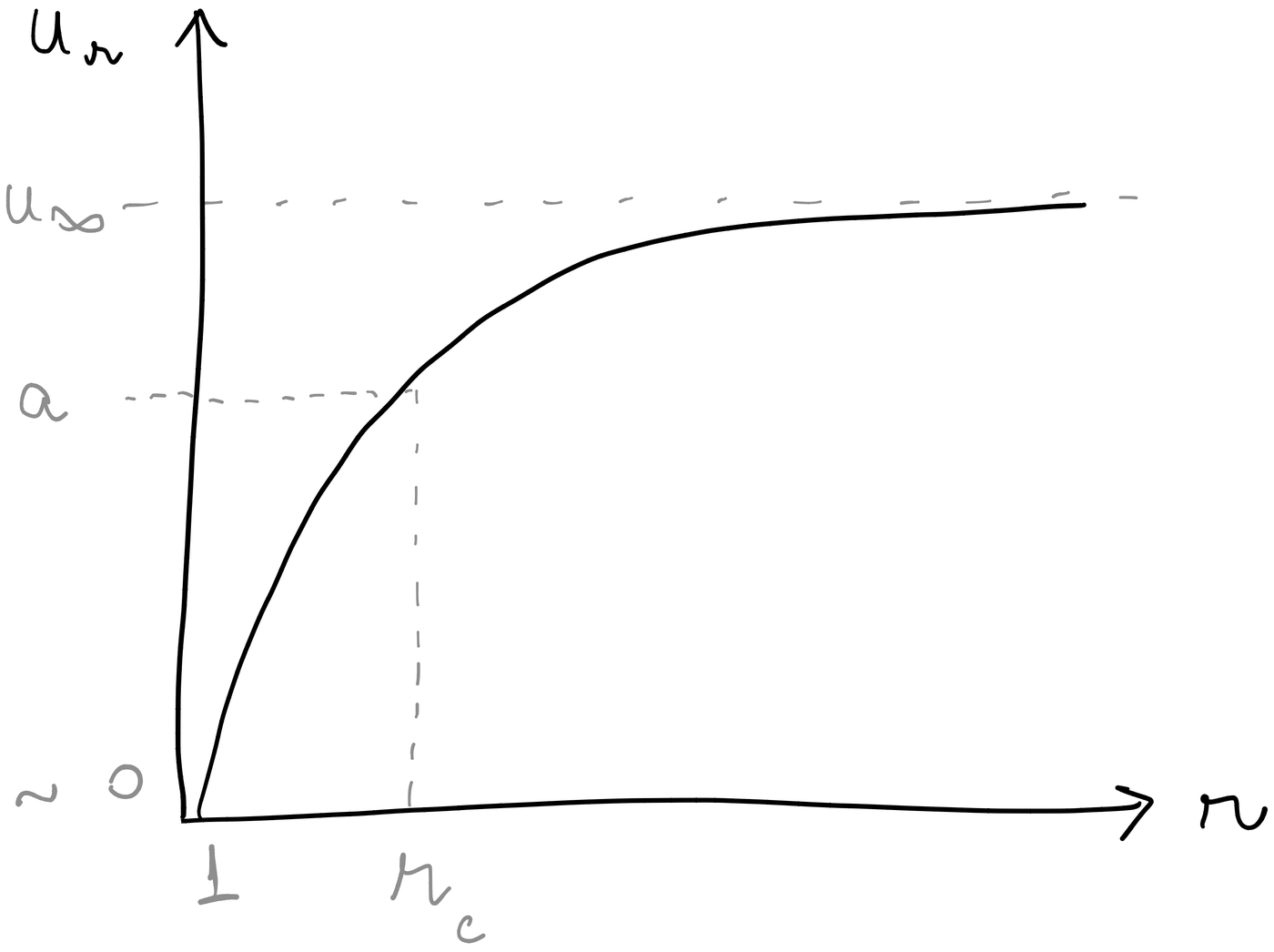


Comet Encke interacting with solar outflows (Vourlidas+07)

Some key features in winds of (solar-like, M-dwarf, etc) stars



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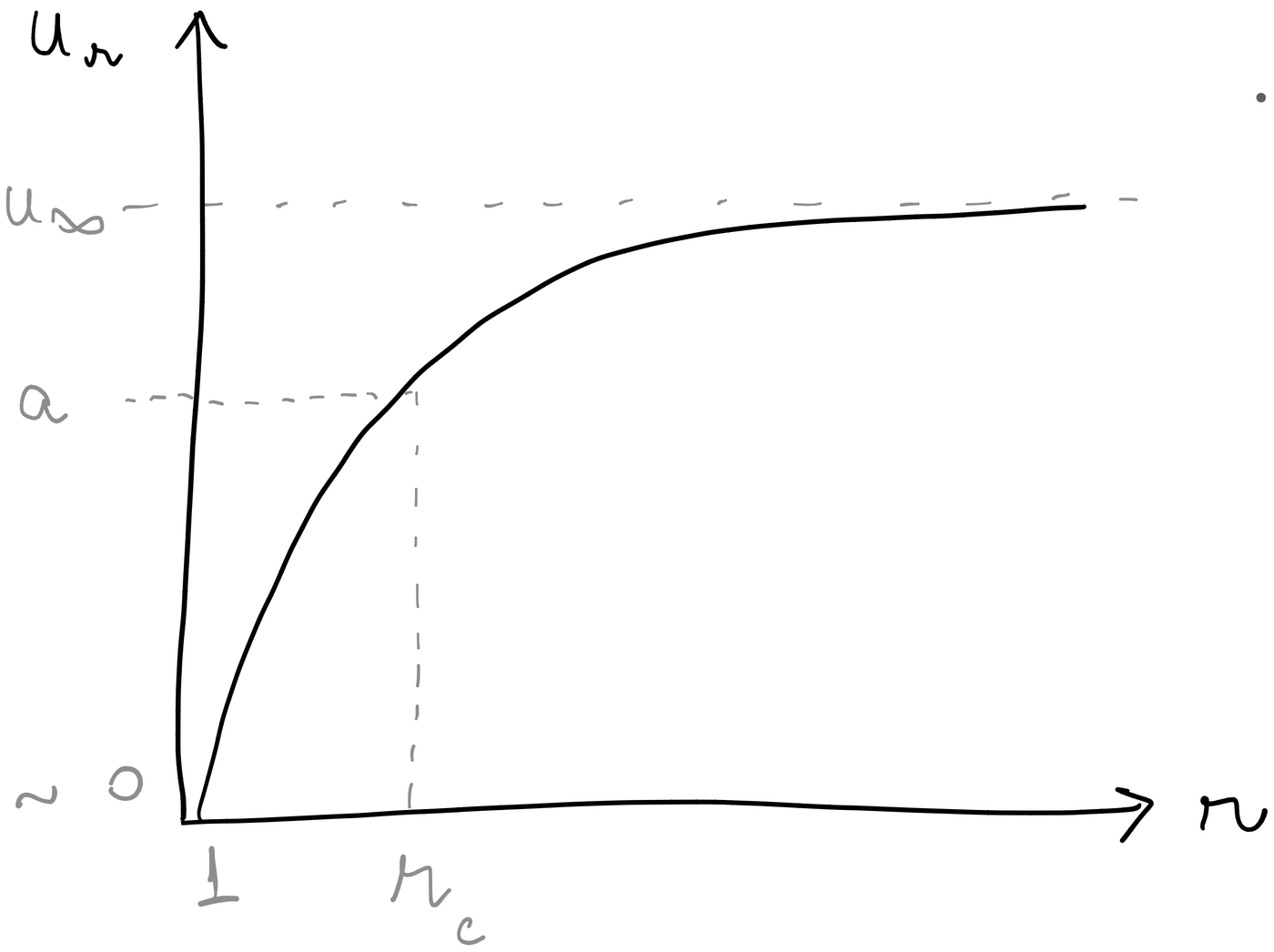

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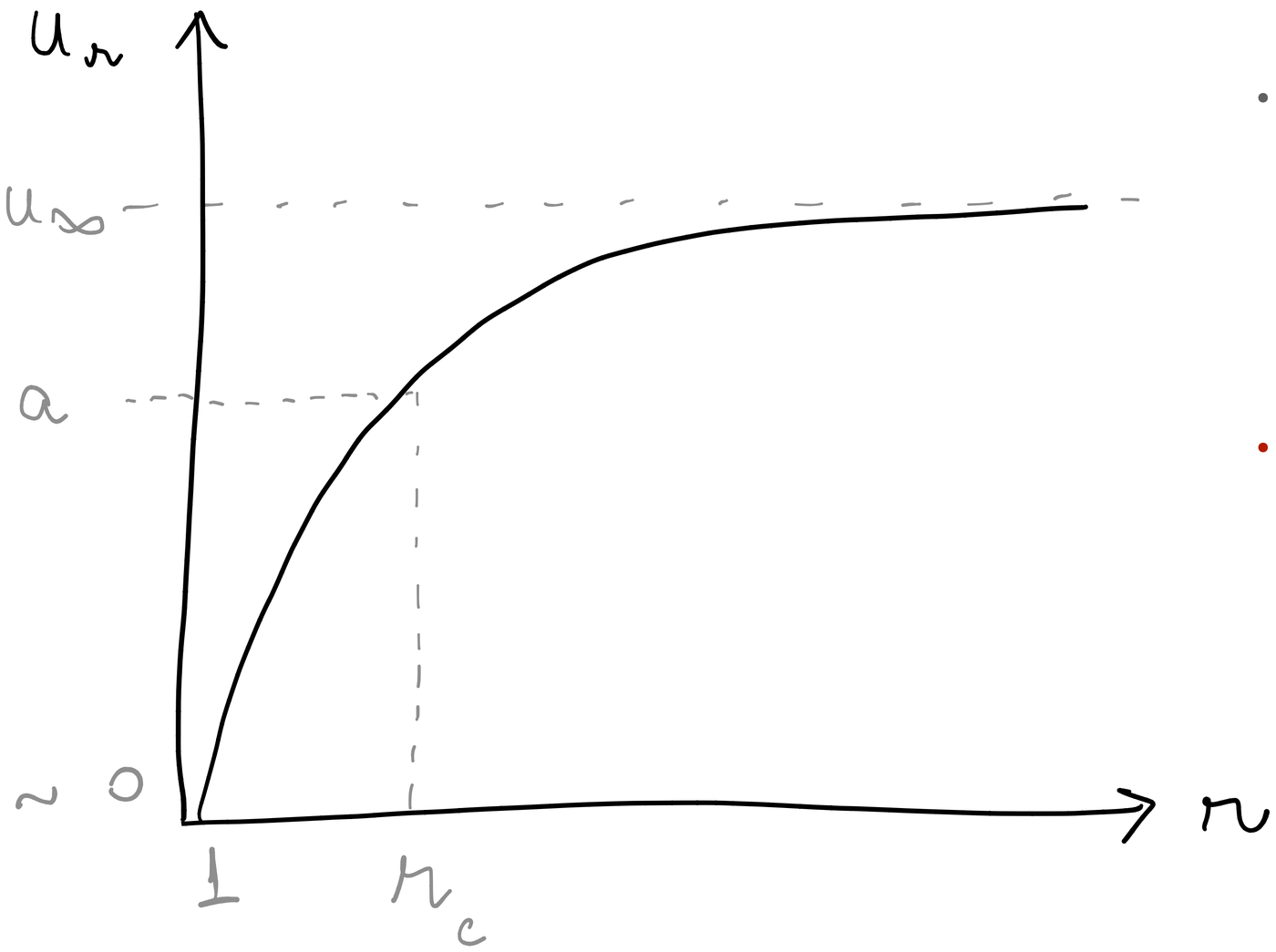

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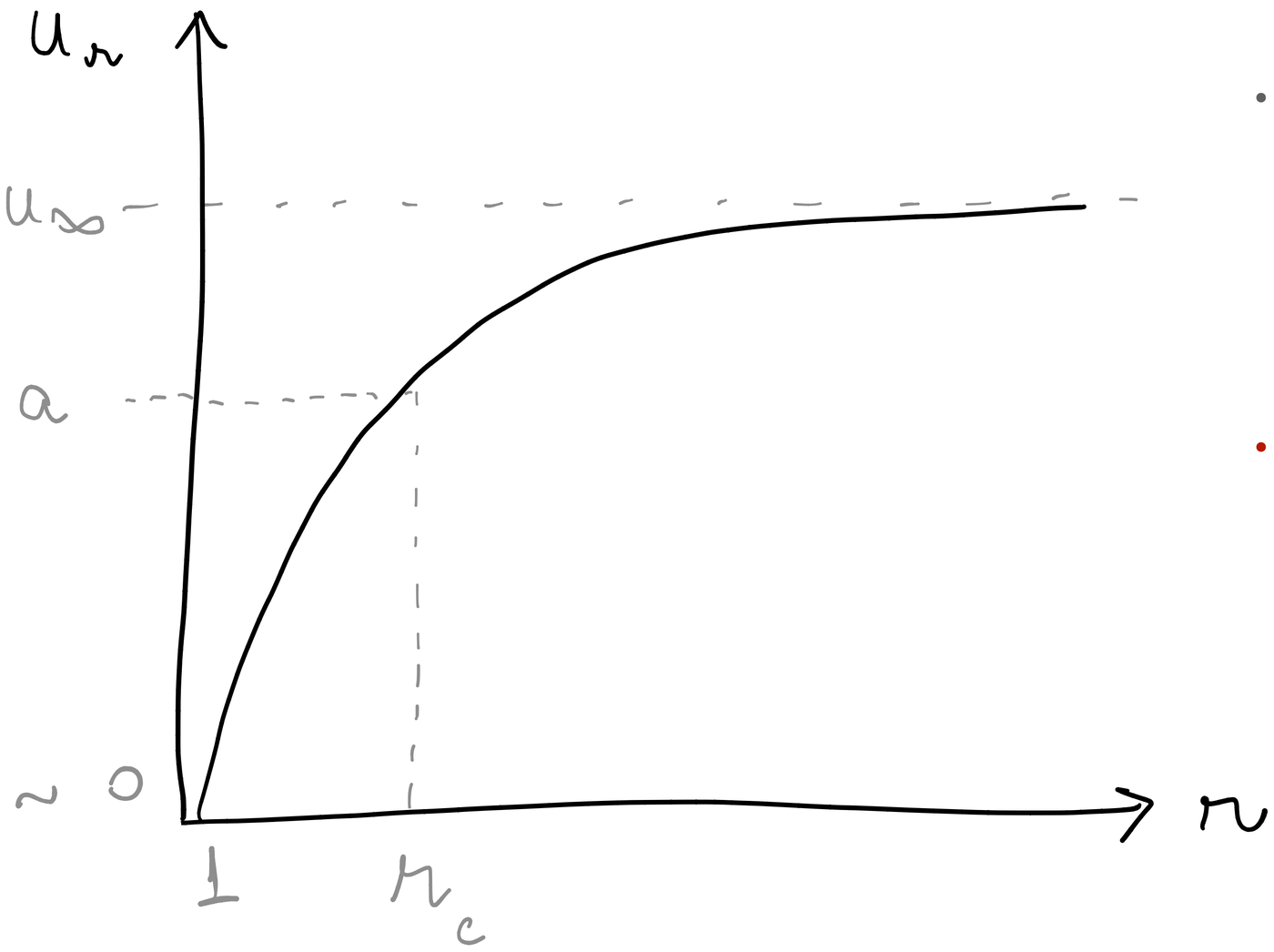

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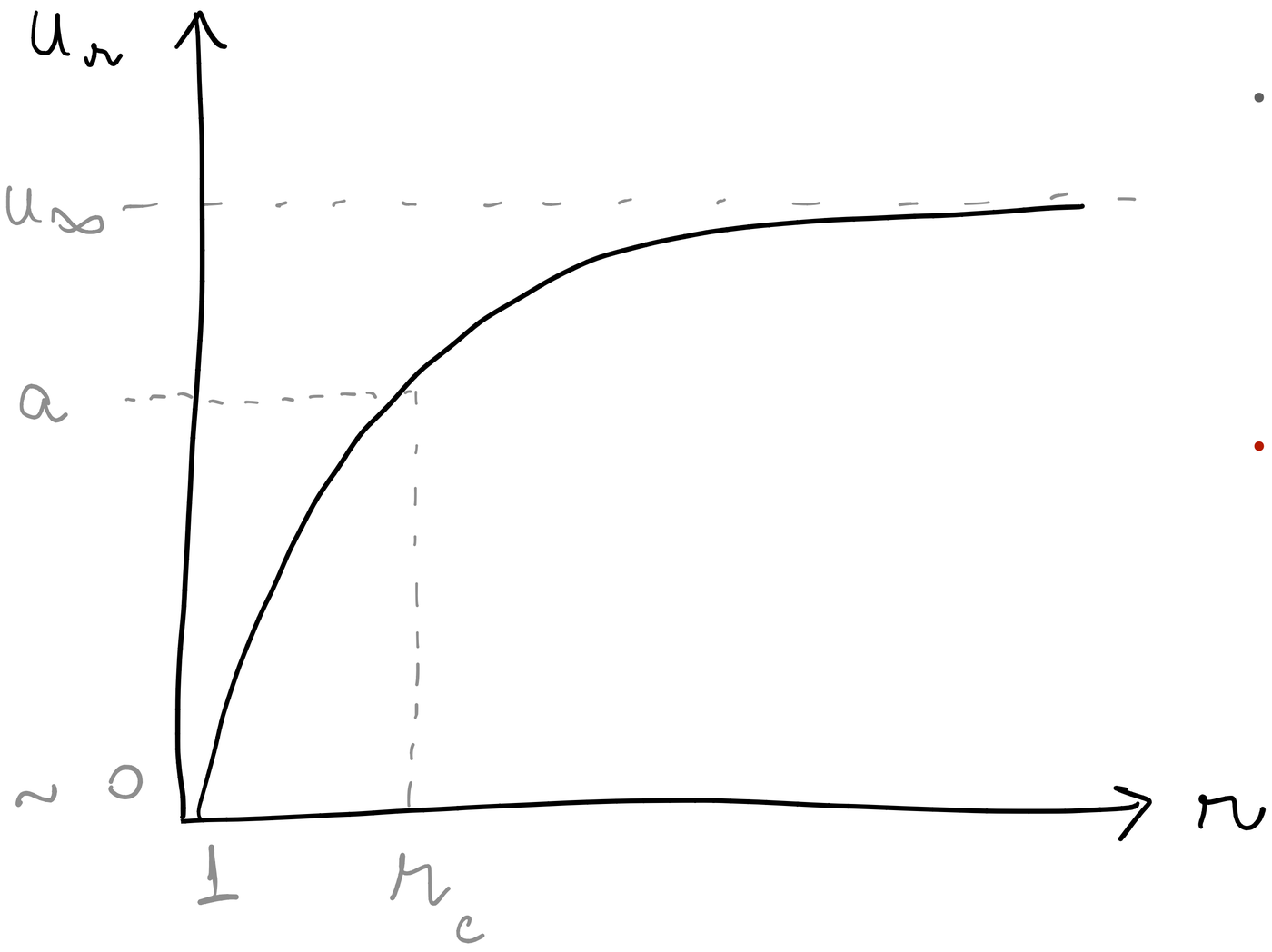

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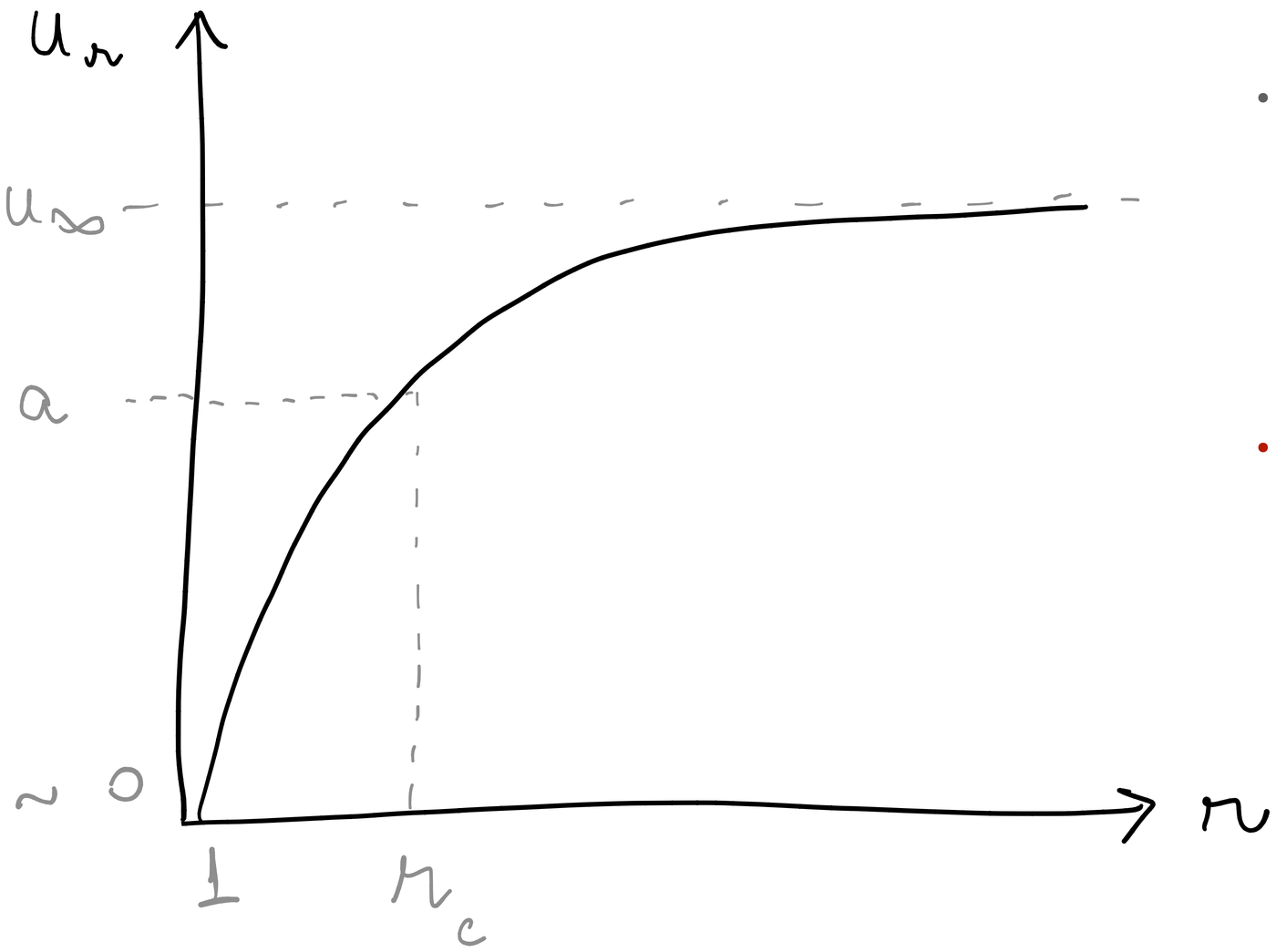

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- Key features:
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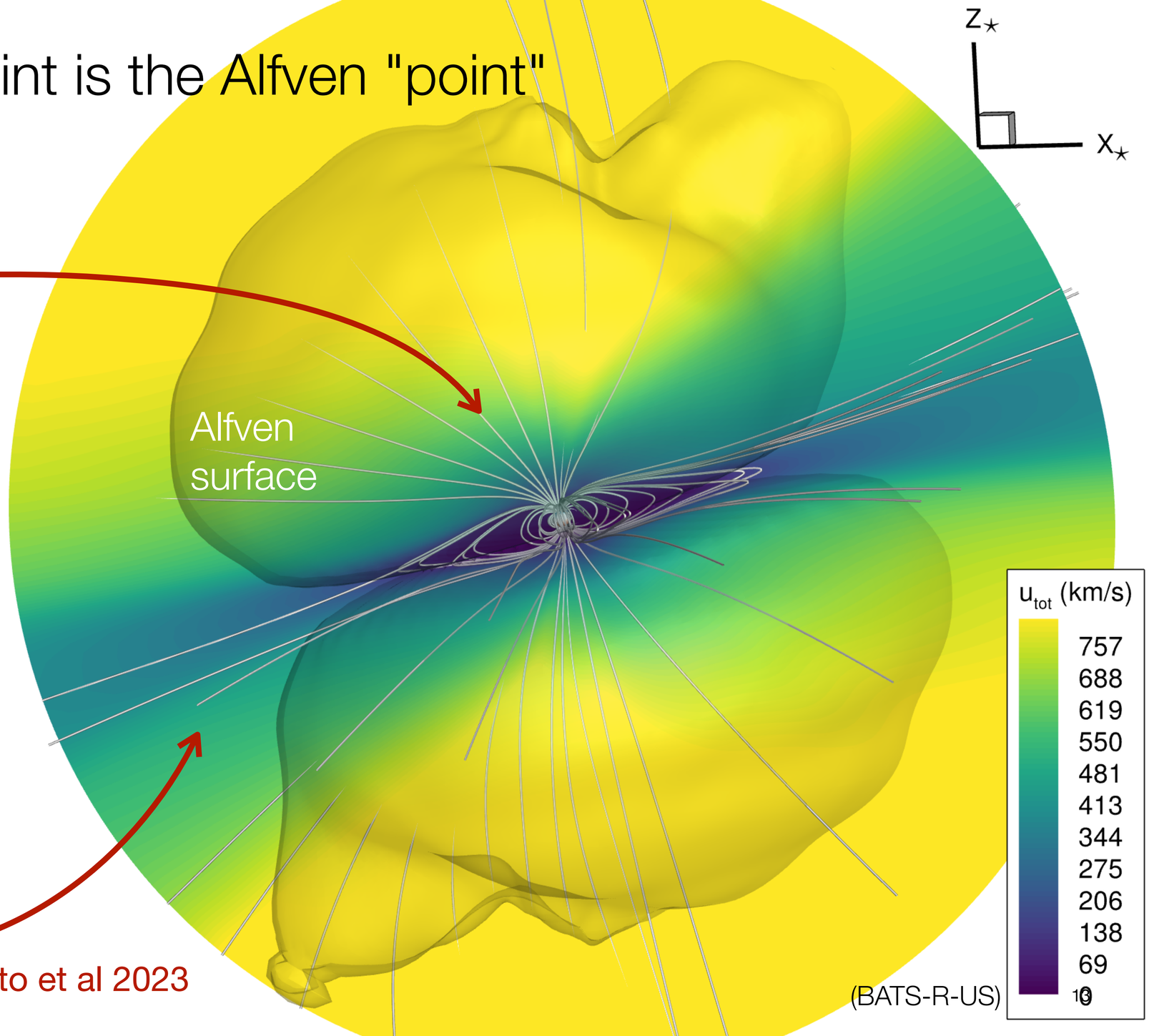
  - At large distances, the wind approaches the asymptotic wind speed: terminal speed (u_∞)
  - Wind crosses (multiple) critical points

One important critical point is the Alfven "point"

sub-Alfvénic: magnetically dominated

Kinetic energy < magnetic energy

super-Alfvénic: dominated by the wind inertia



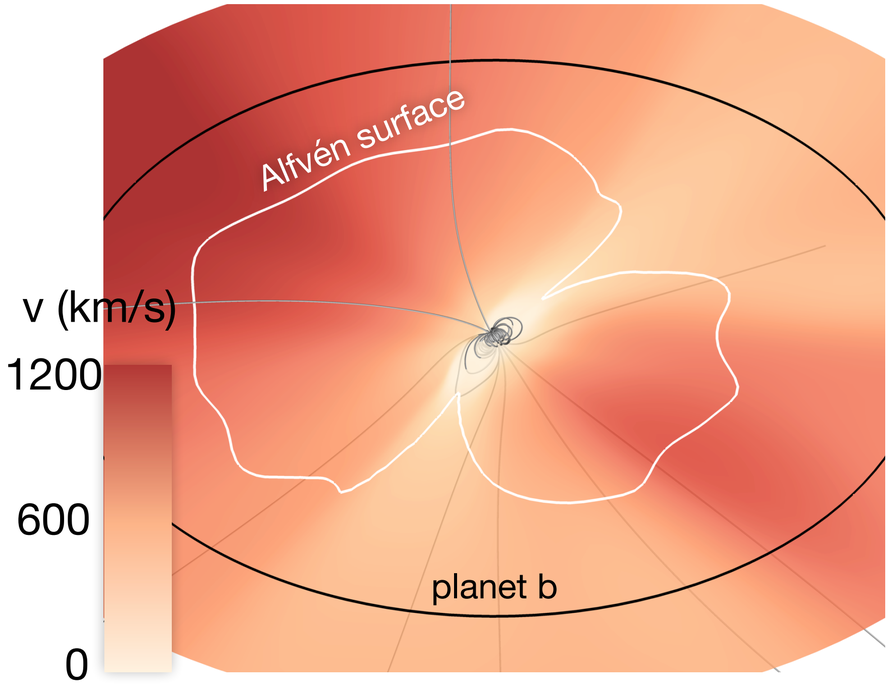
Vidotto et al 2023

Sub- & Super-Alfvenic star-planet interactions

Kavanagh, Vidotto et al 2021

Prox Cen

Mass-loss rate: 4x10^{-15} Msun/yr

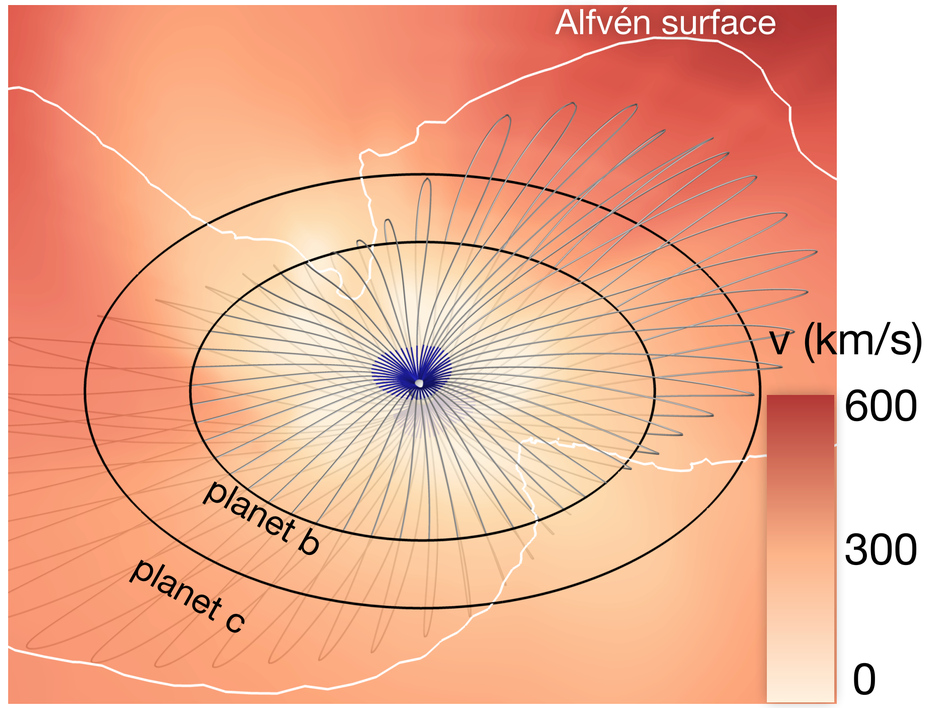


Key point

Compare planet orbit with Alfven surface

AU Mic

Mass-loss rate: 5x10^{-13} Msun/yr



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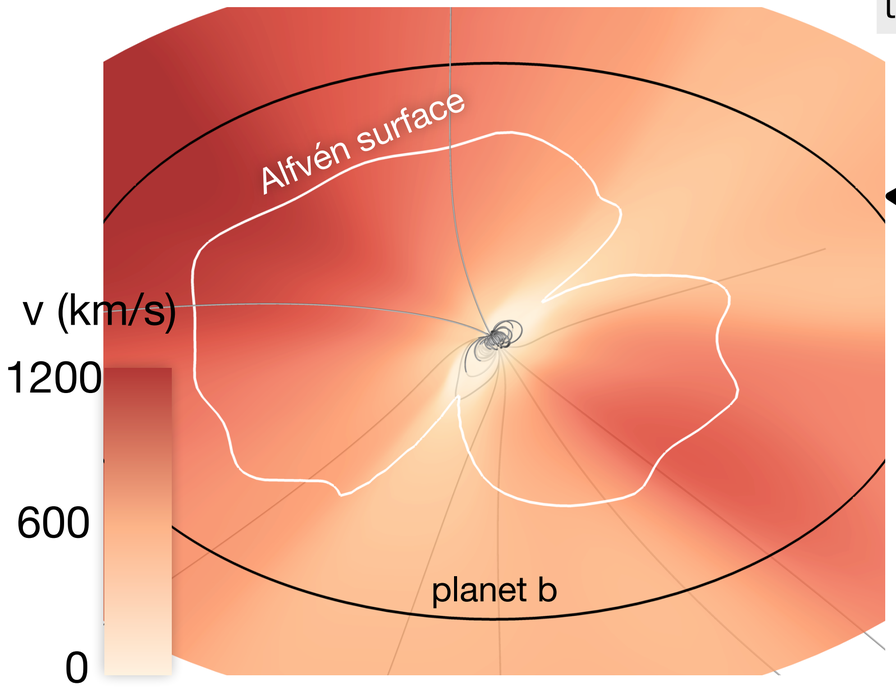

Planet beyond Alfven surface: star does not notice (or hear...) the planet!

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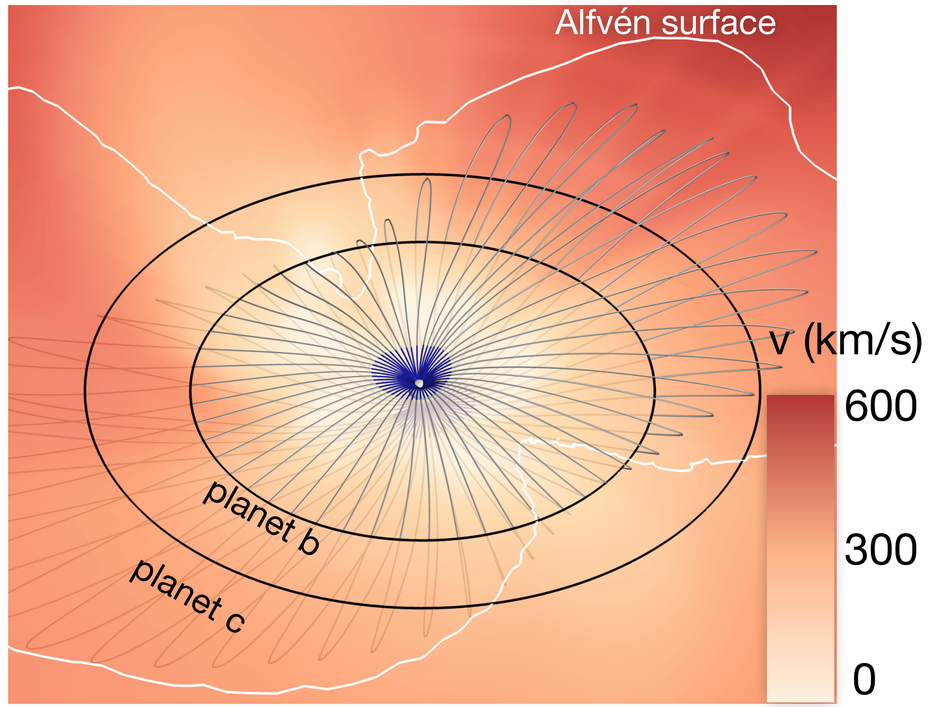

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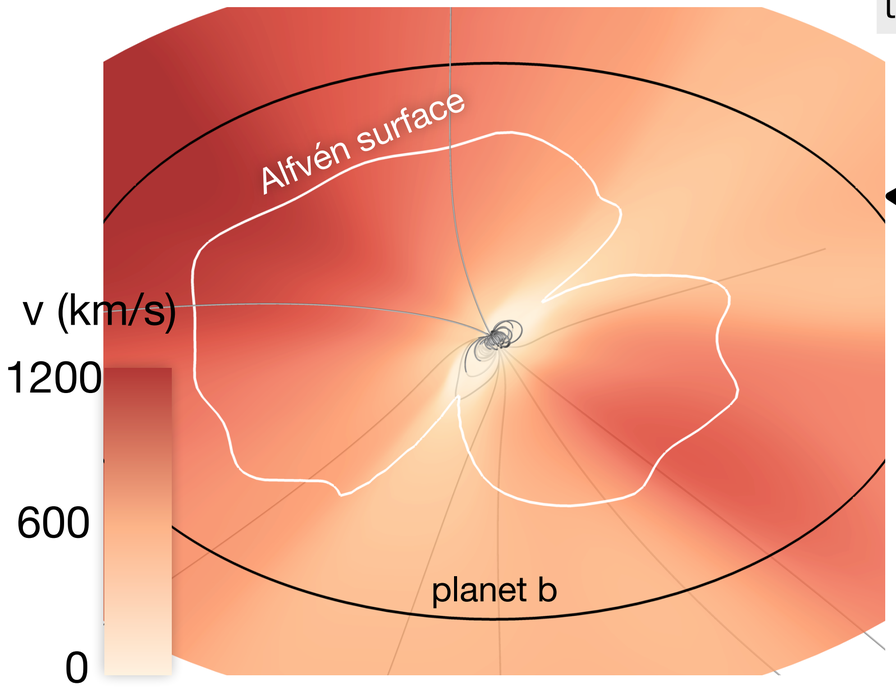

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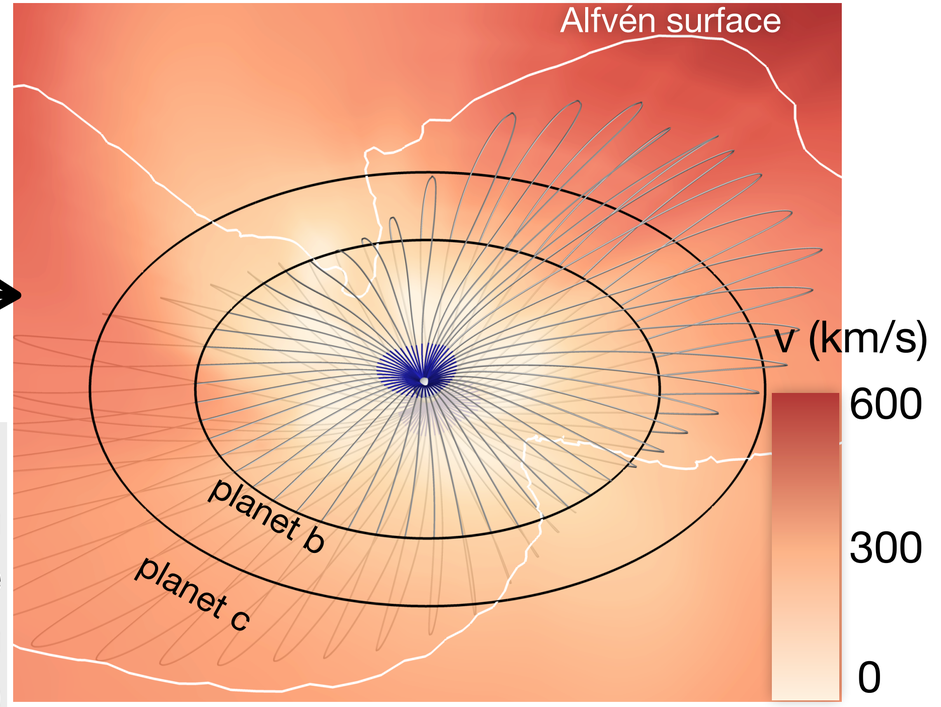
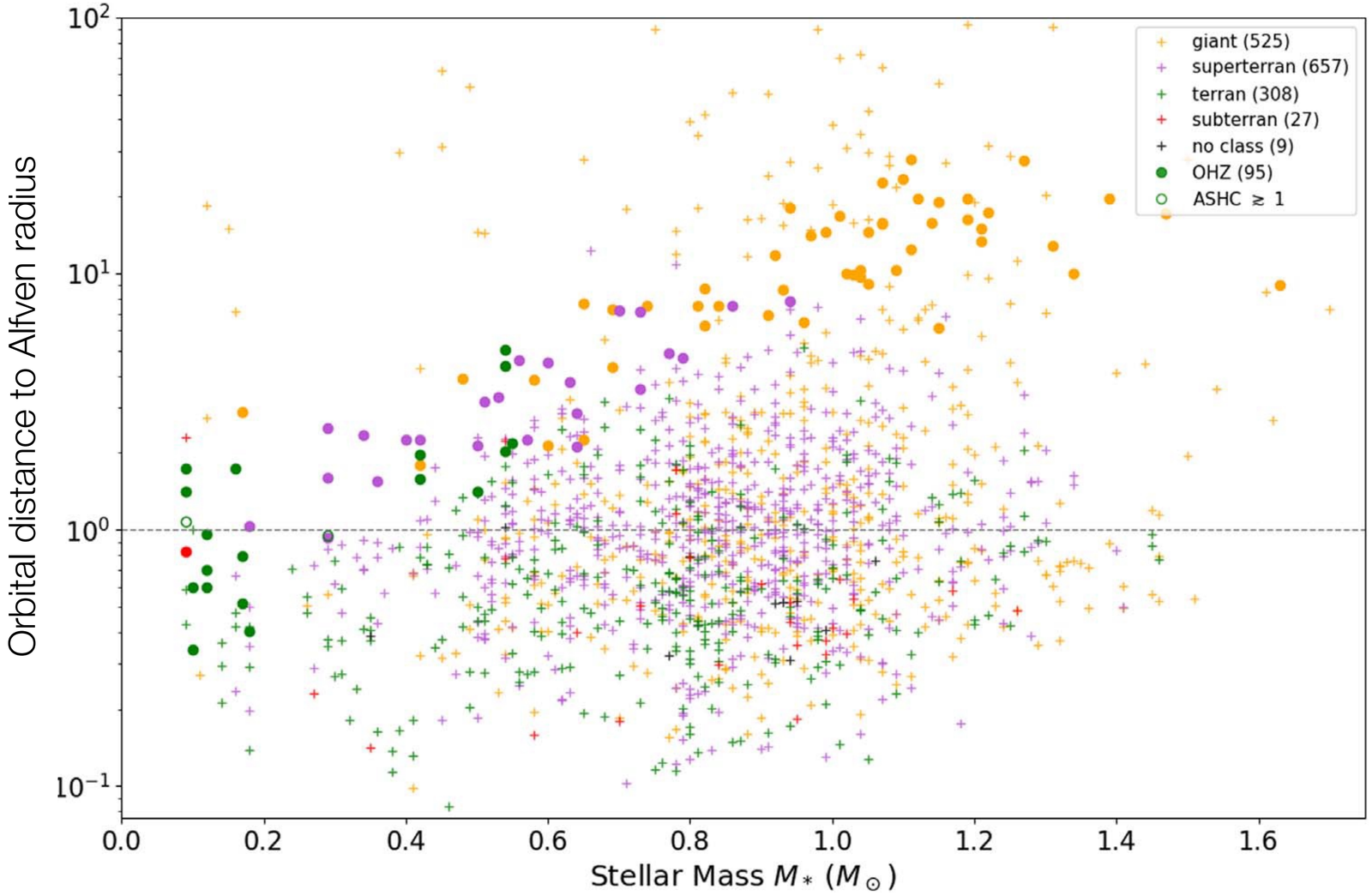


Planets within Alfven surface: magnetic connectivity between the planet and star can take place (e.g., information can travel towards host star)

Sub- & Super-Alfvenic SPIs in the context of exoplanet population

Atkinson et al 2024



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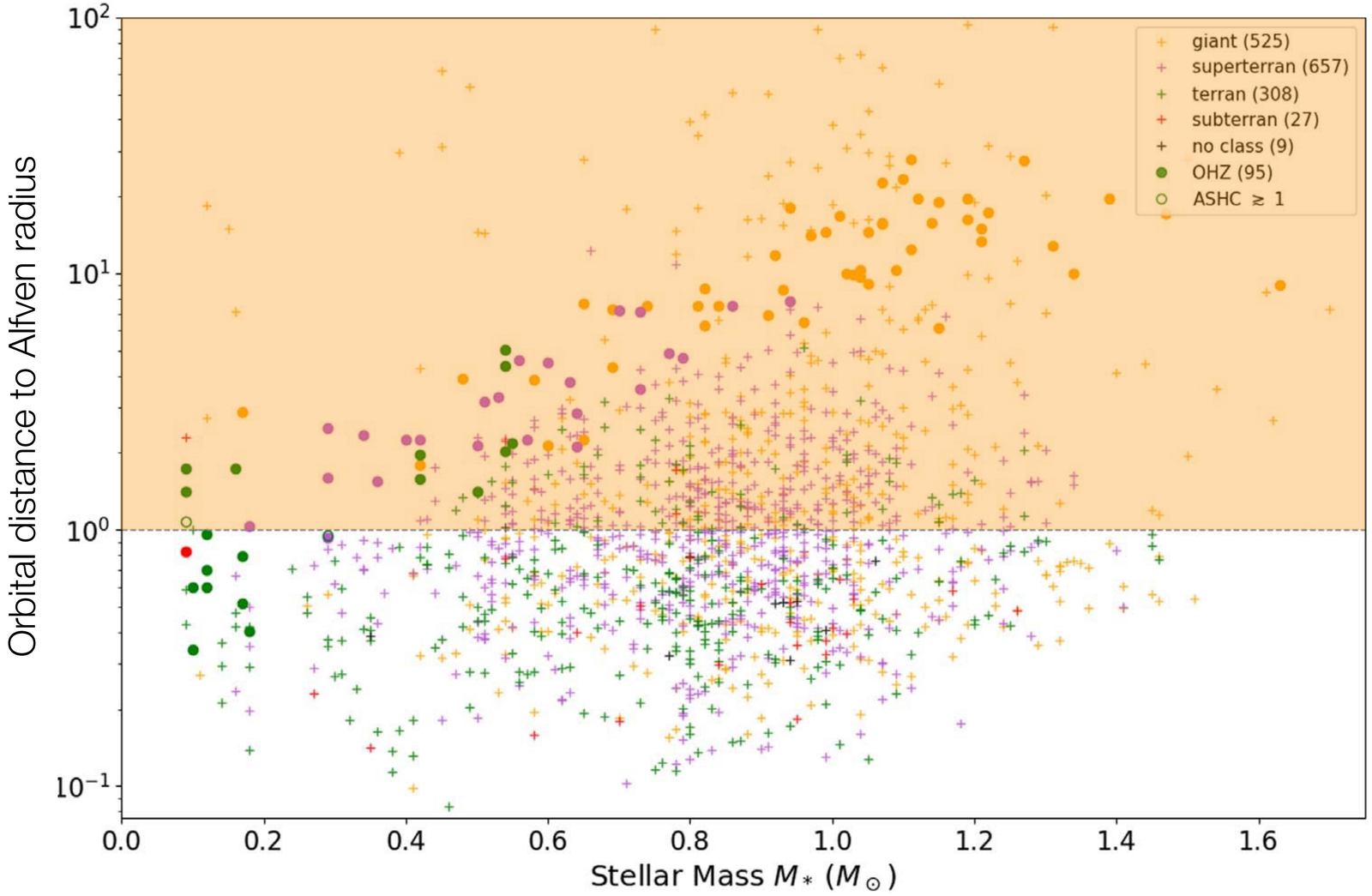

Super-Alfvenic orbits

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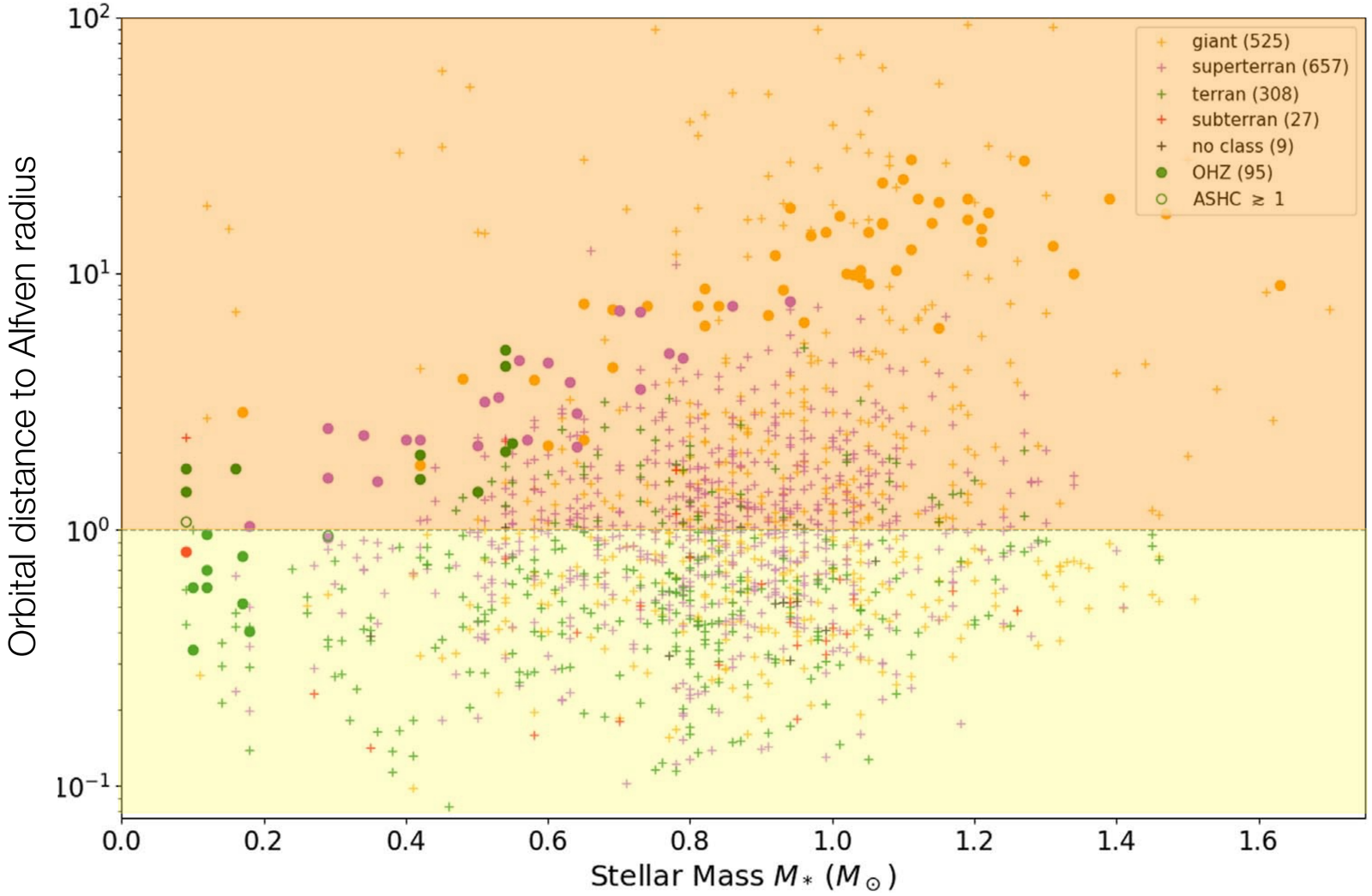

Super-Alfvenic orbits

Sub-Alfvenic orbits
(potentially catastrophic for atmospheric loss; paradise for magnetic SPI)

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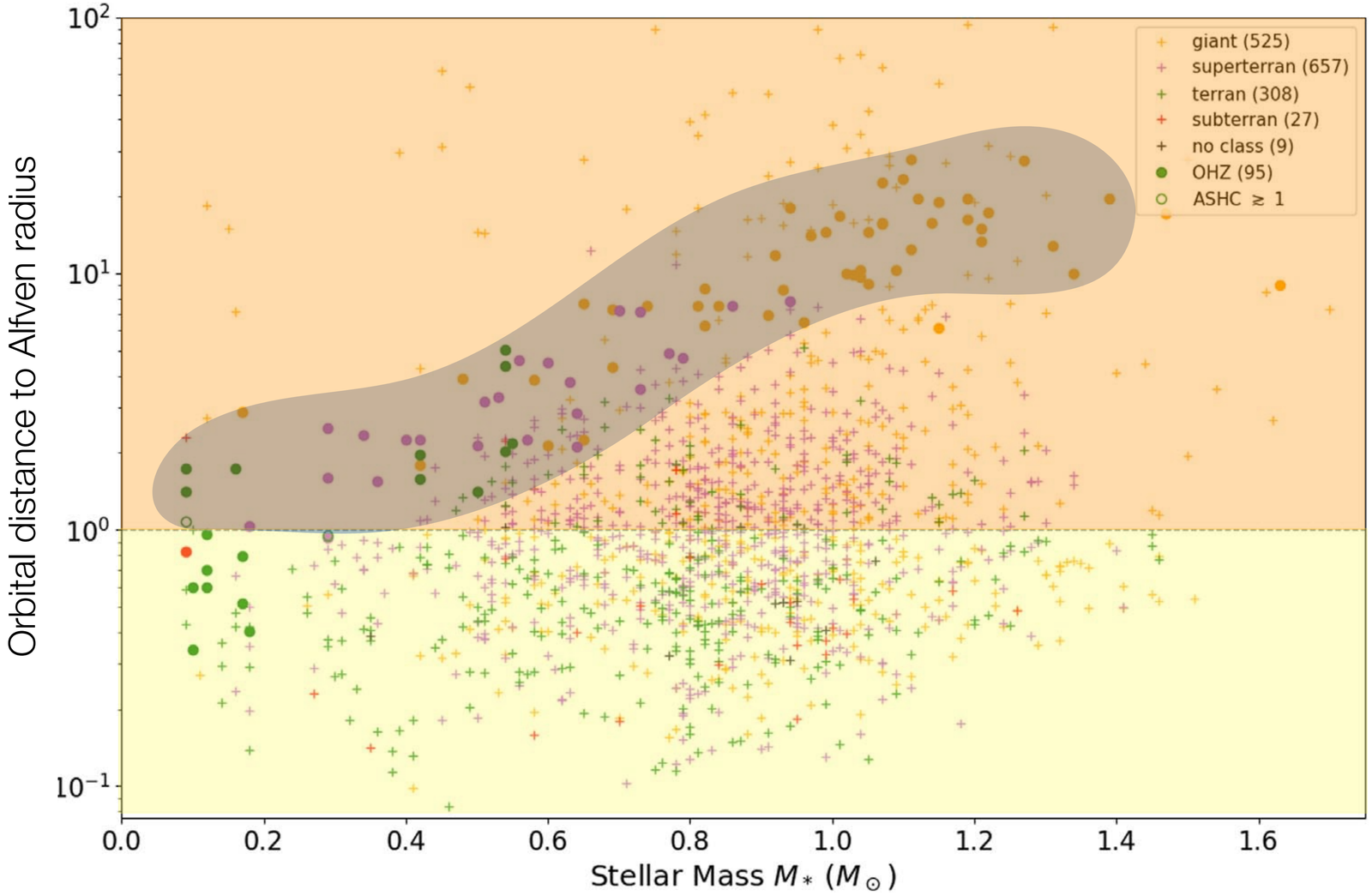

Super-Alfvenic orbits

Sub-Alfvenic orbits
(potentially catastrophic for atmospheric loss; paradise for magnetic SPI)

- planets inside habitable zone & outside Alfven surface, of which ~10 terrestrial planets. (PLATO will increase this number.)

Super-Alfvenic interactions: stellar wind-planet Interactions

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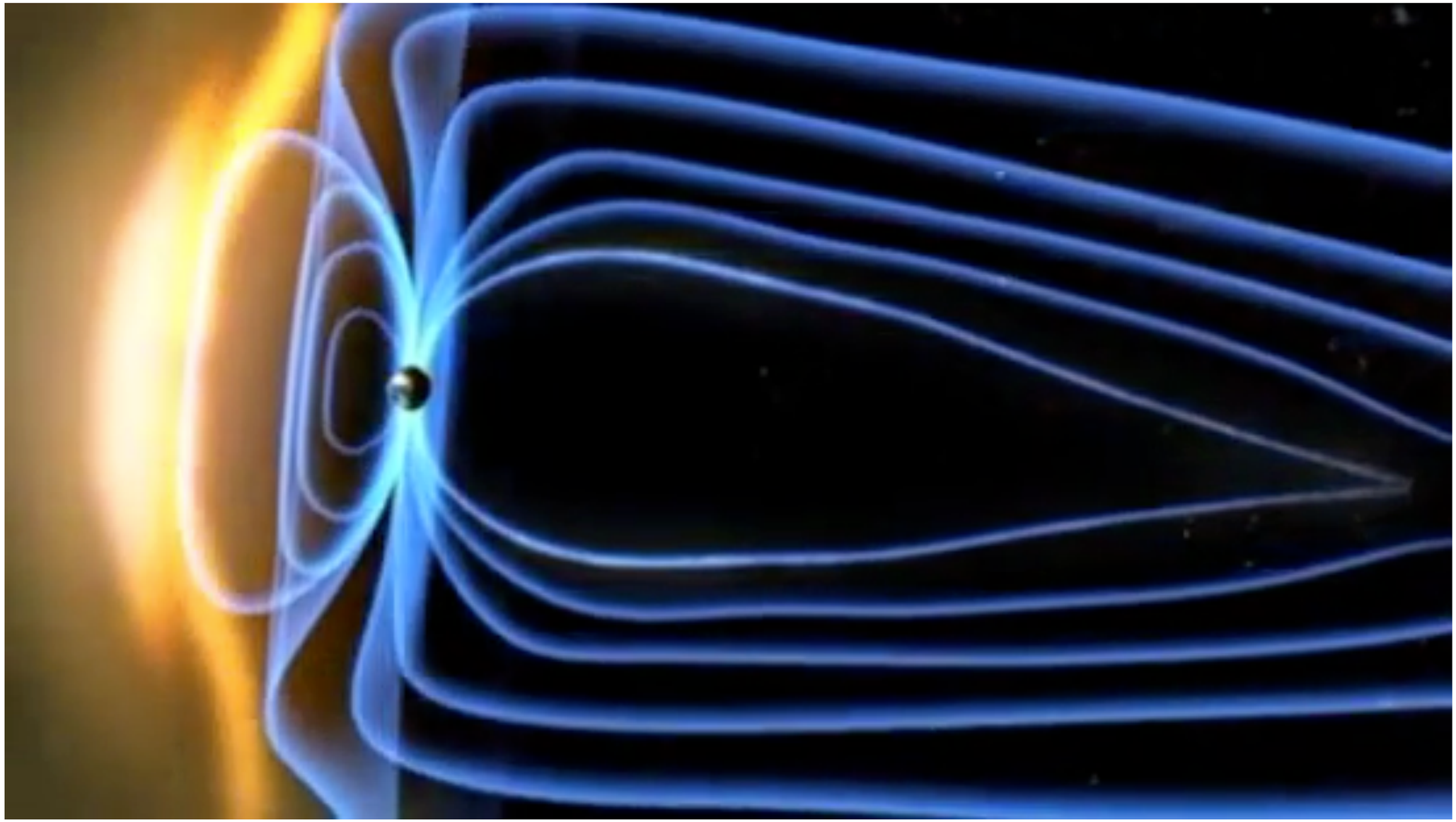

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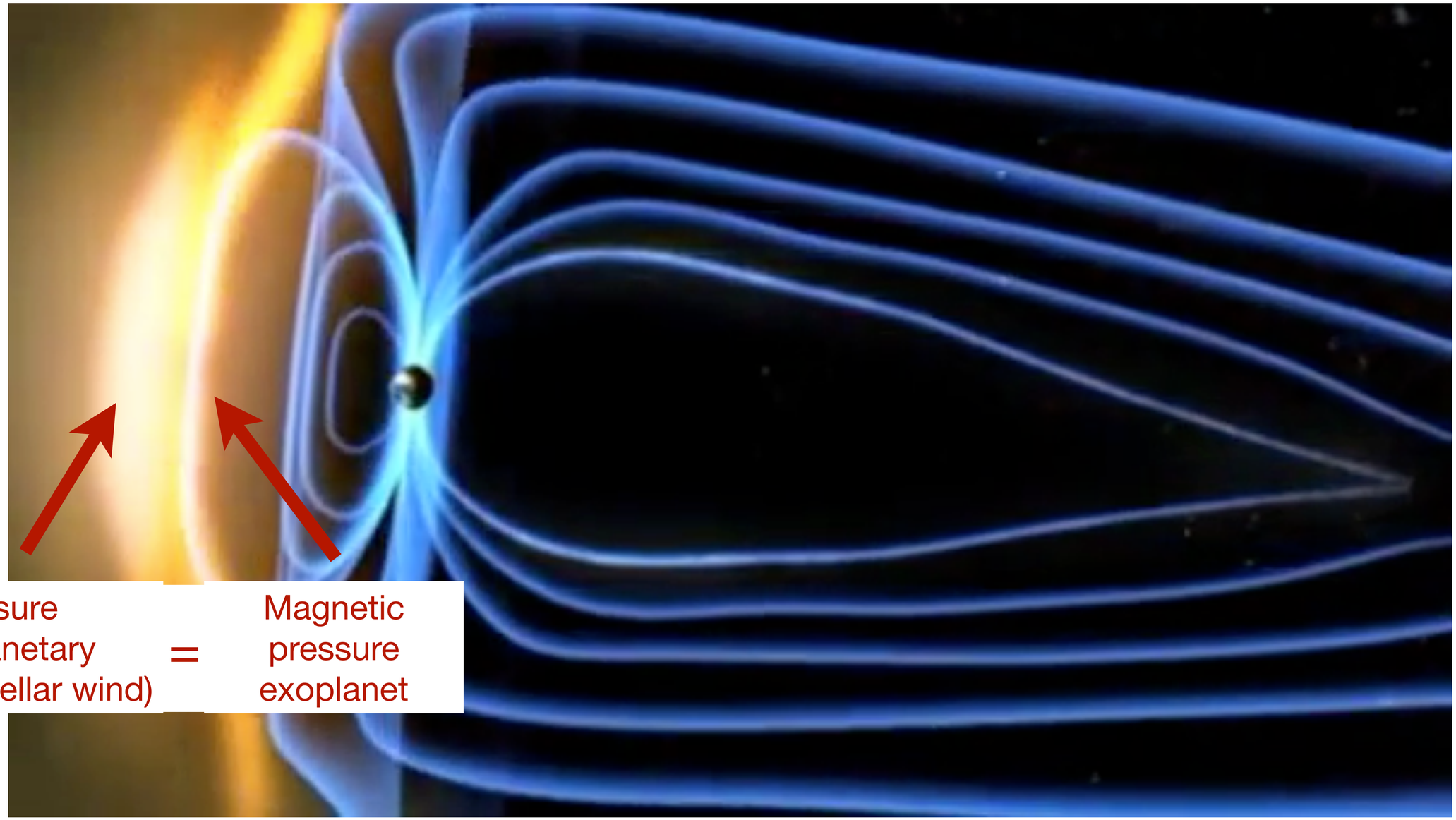

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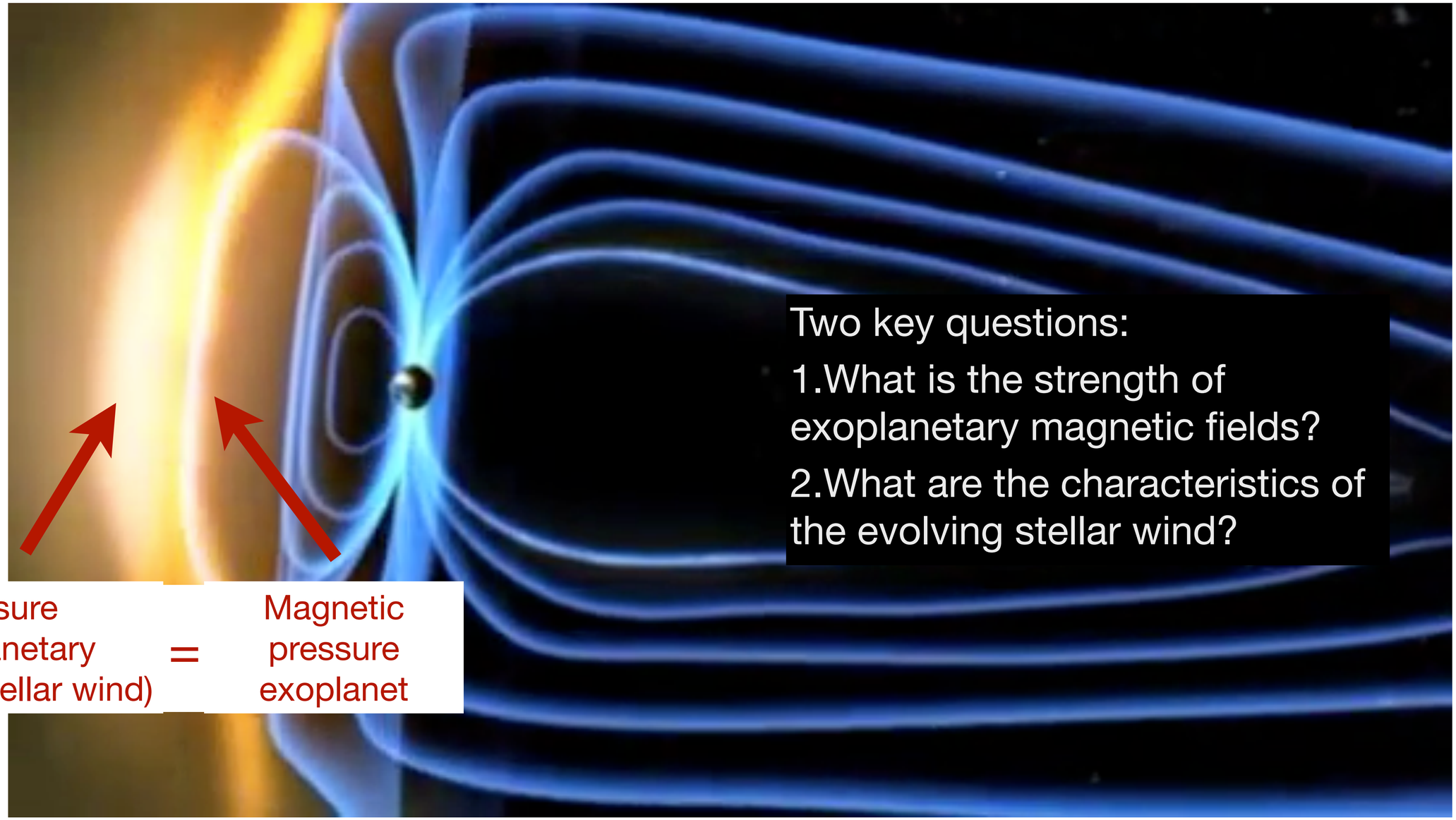


Two key questions:

1. What is the strength of exoplanetary magnetic fields?
2. What are the characteristics of the evolving stellar wind?

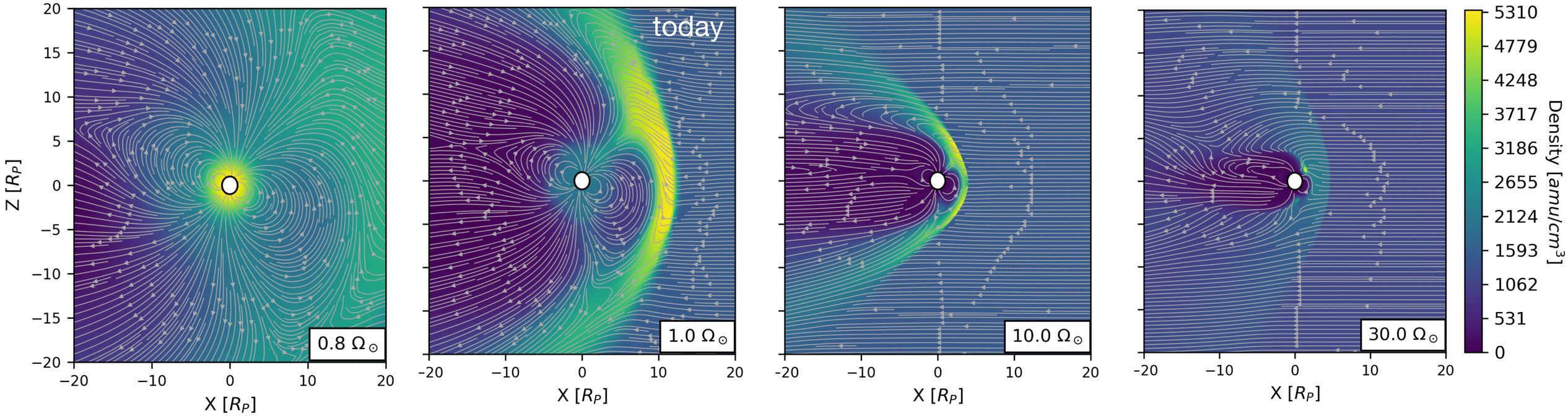
Pressure Interplanetary medium (stellar wind) = Magnetic pressure exoplanet

The evolution of Earth's magnetosphere during the solar main sequence

3D models of the interaction between the solar wind and Earth's magnetosphere

Long-term evolution of the solar wind: Vidotto 2021, LRSP

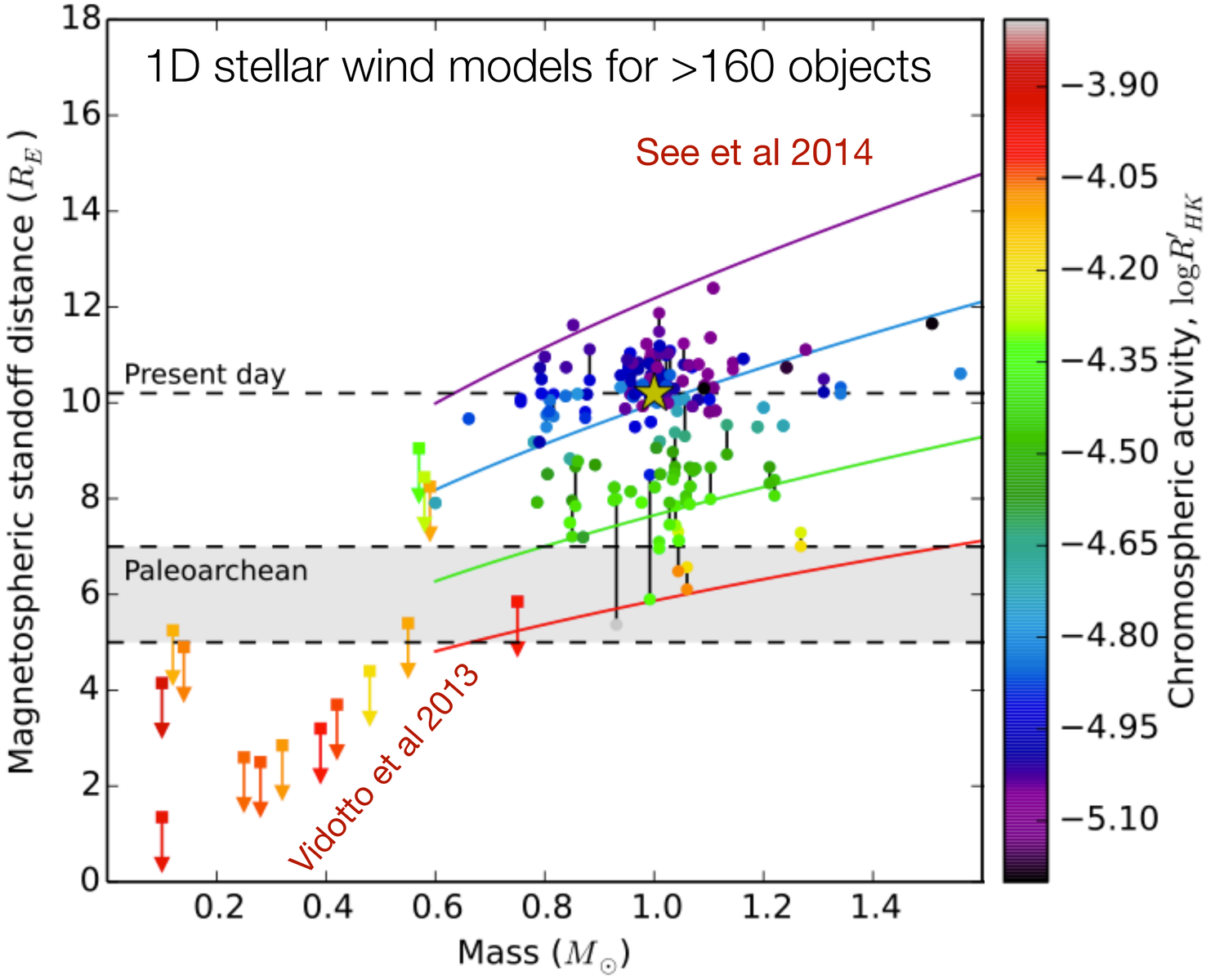
Increasing the strength of the solar wind as we look back in time



Smaller magnetospheres could provide direct access of atmospheres to stellar wind stripping.

Carolan, Vidotto et al 2019
(future: Veras & Vidotto)

Evolution of magnetosphere of an Earth-twin at the Habitable Zone



BCool collaboration

- As the system evolves, stellar activity decreases & planetary magnetospheres become bigger

- Note: M dwarf stars remain active for a long time...

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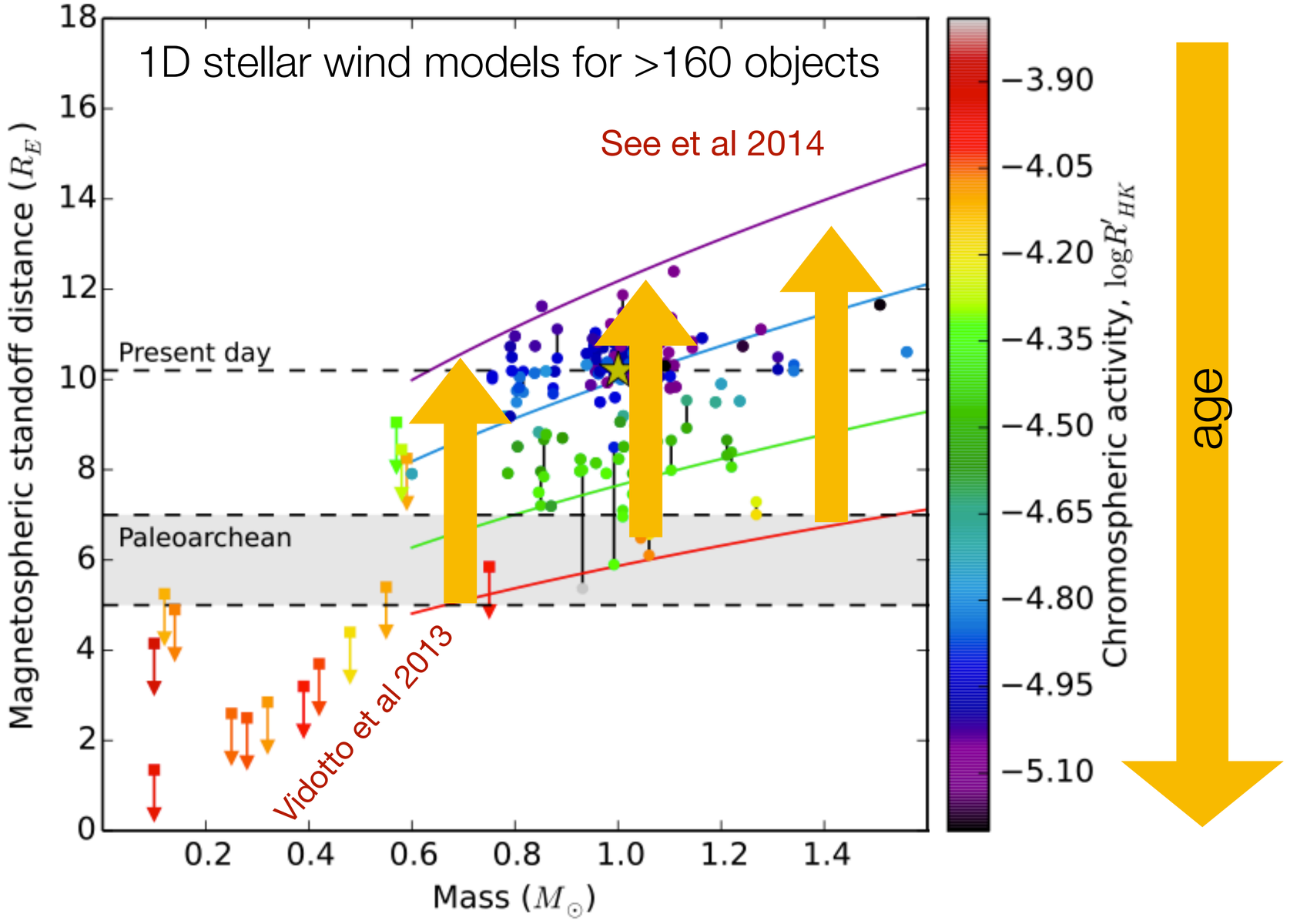

BCool collaboration

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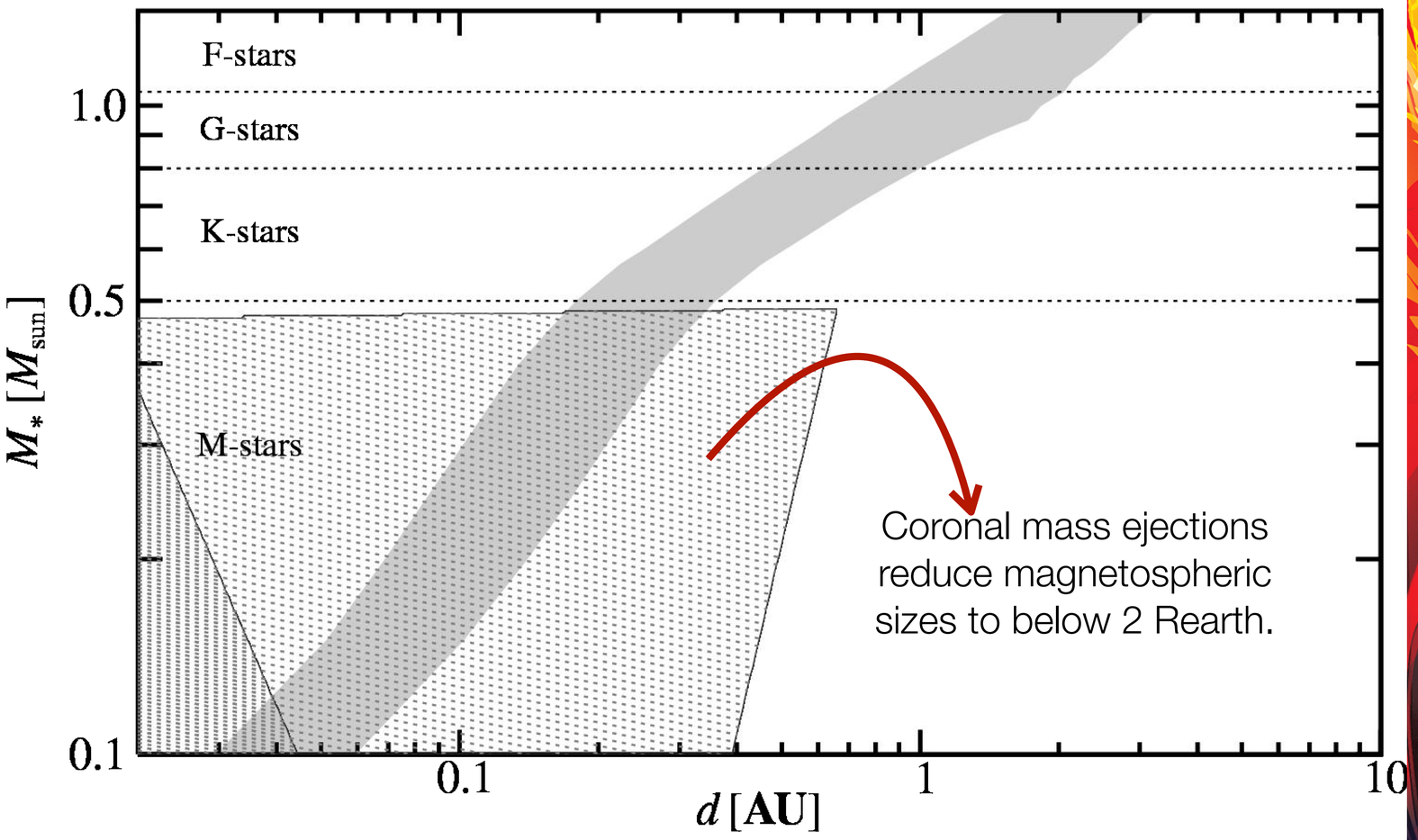
Coronal mass ejections: further reduce planetary magnetospheres

Khodachenko et al 2007



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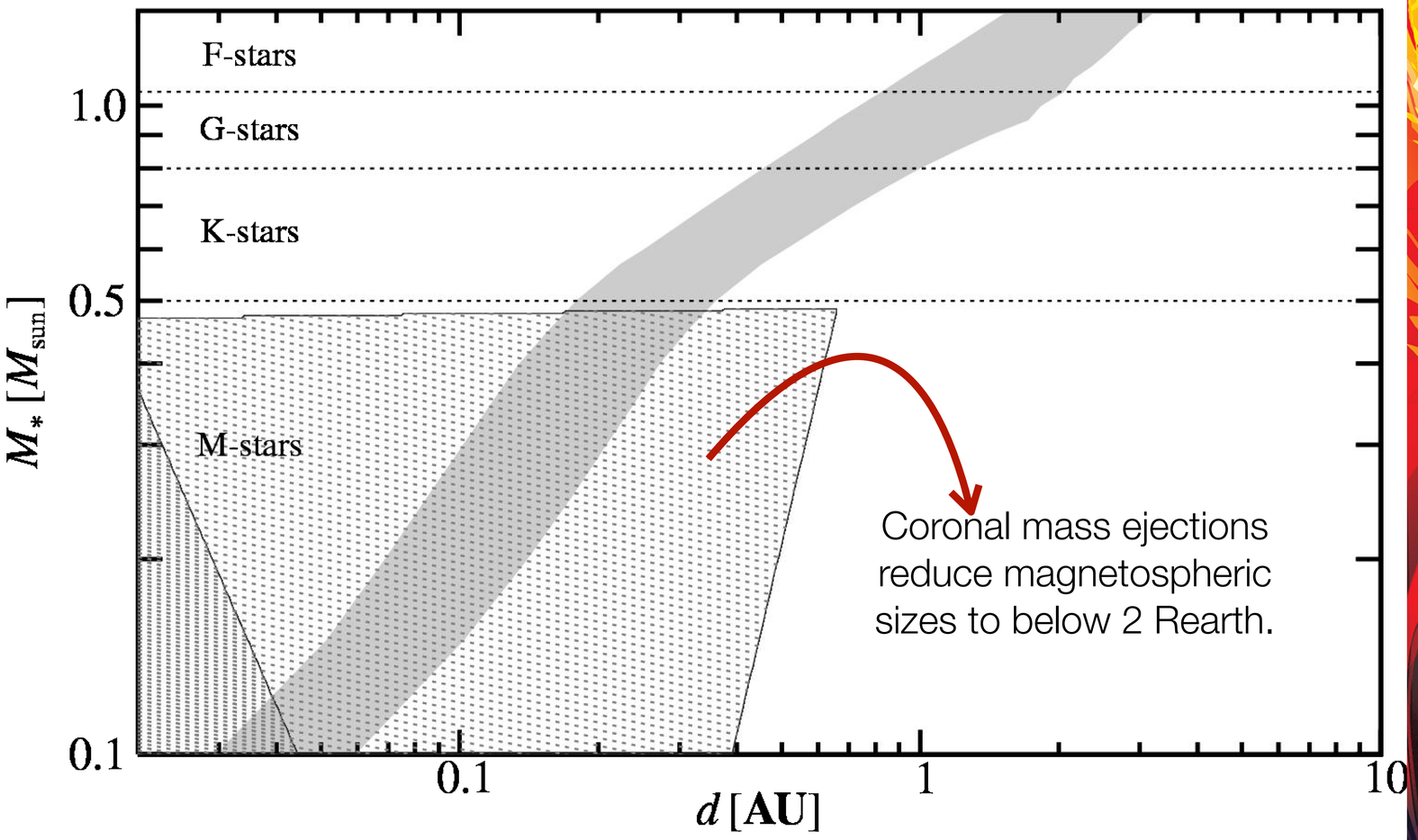
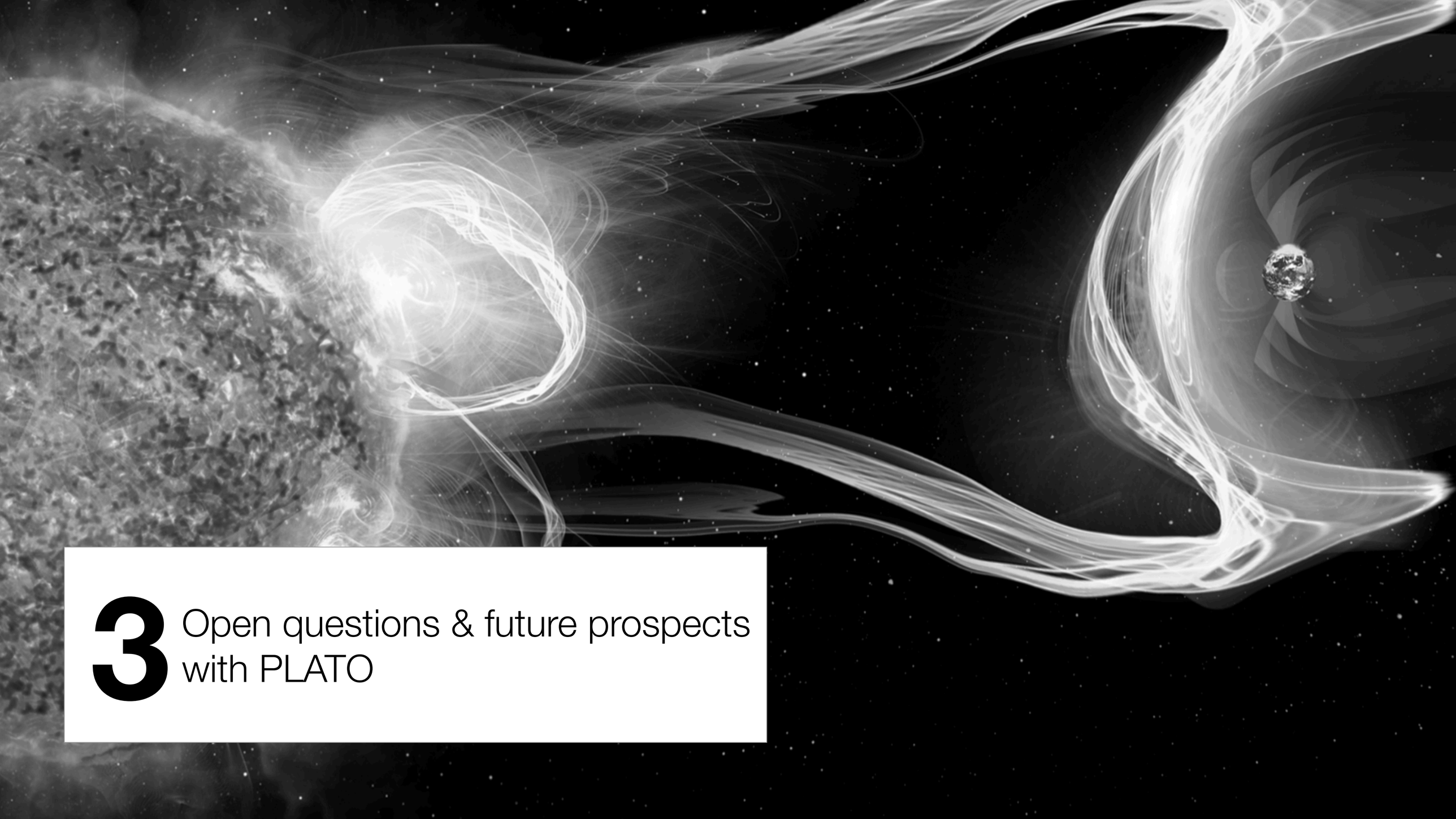
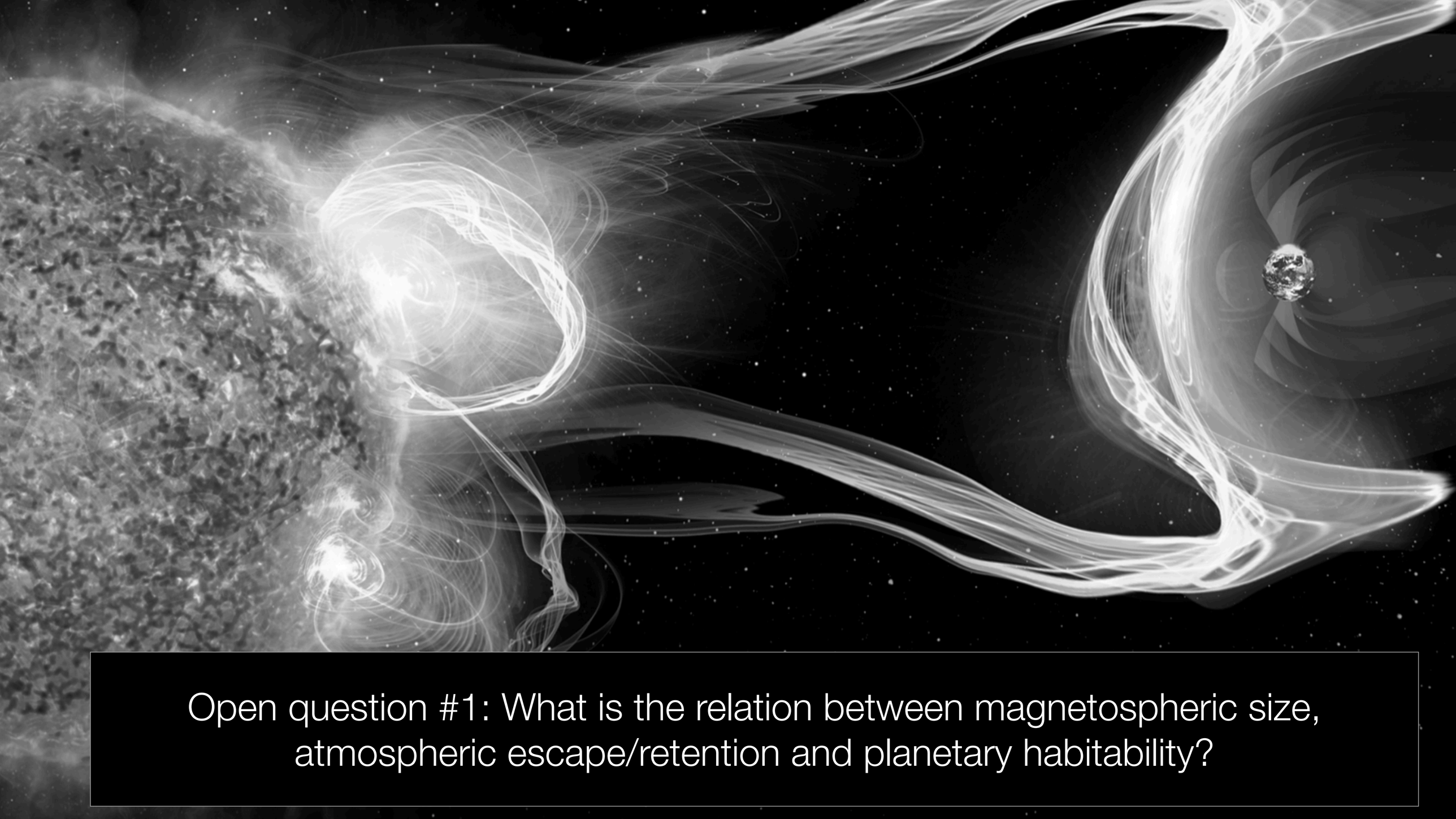


Do smaller magnetospheres expose atmospheres for solar wind erosion?



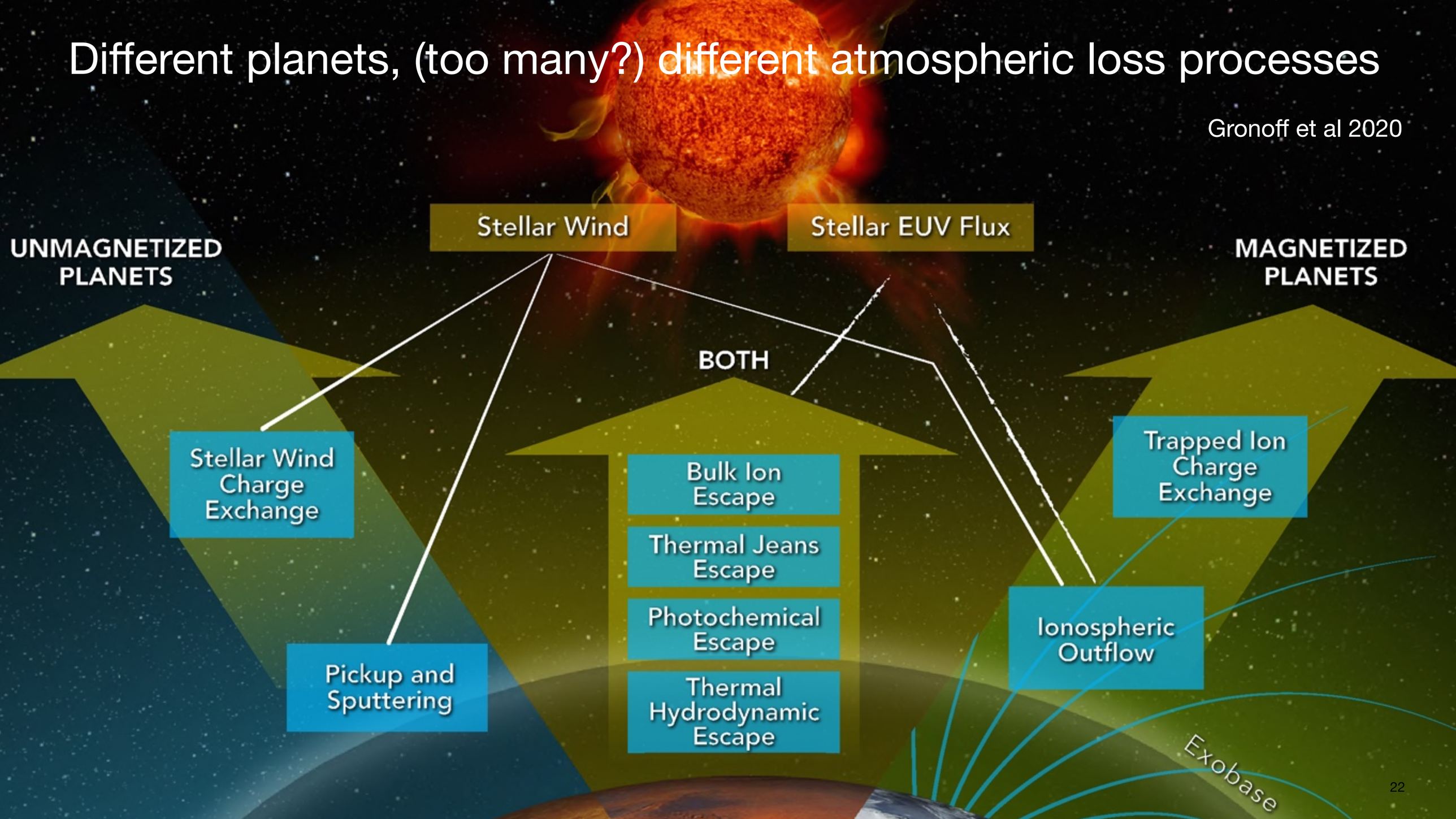
3 Open questions & future prospects with PLATO



Open question #1: What is the relation between magnetospheric size, atmospheric escape/retention and planetary habitability?

Different planets, (too many?) different atmospheric loss processes

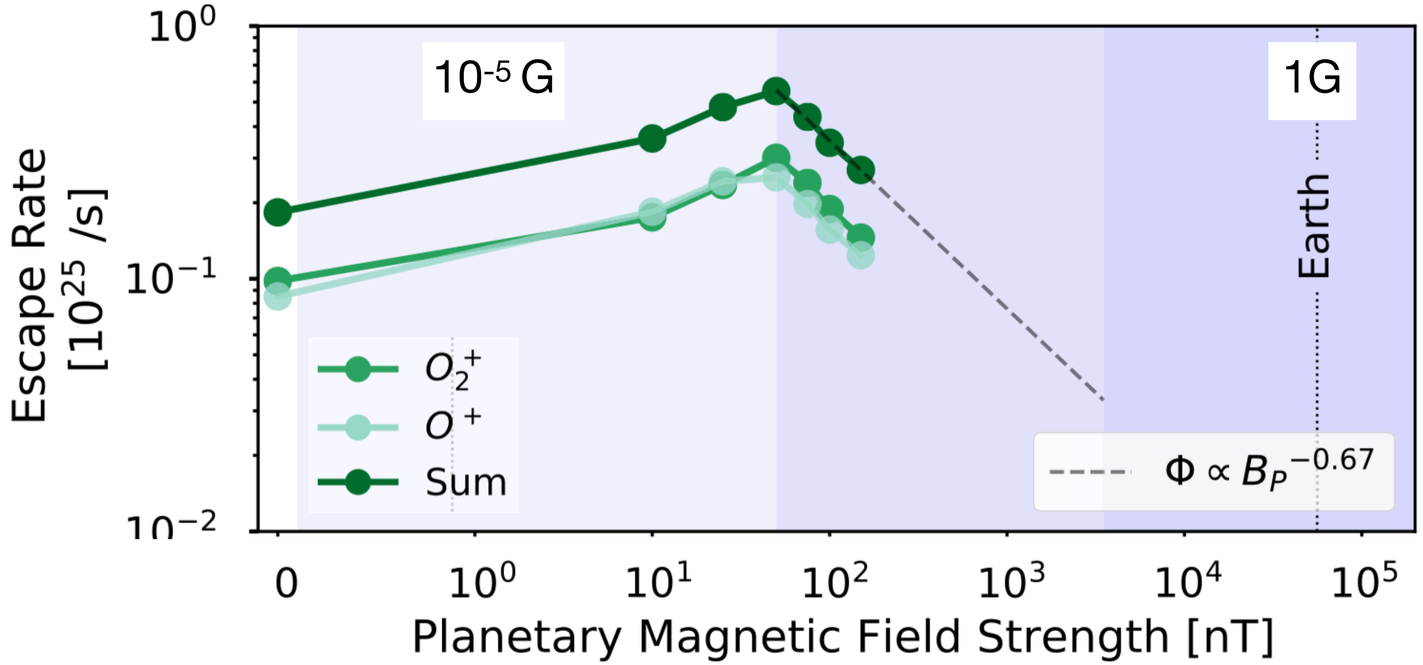
Gronoff et al 2020



Open question #2: Planetary magnetic fields: protection or increased atmospheric loss?

Escape could increase with planetary magnetic fields (oh...)

Egan et al 2019



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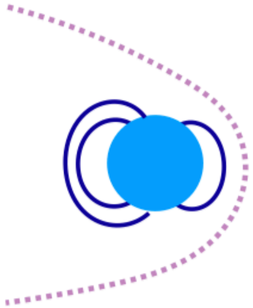

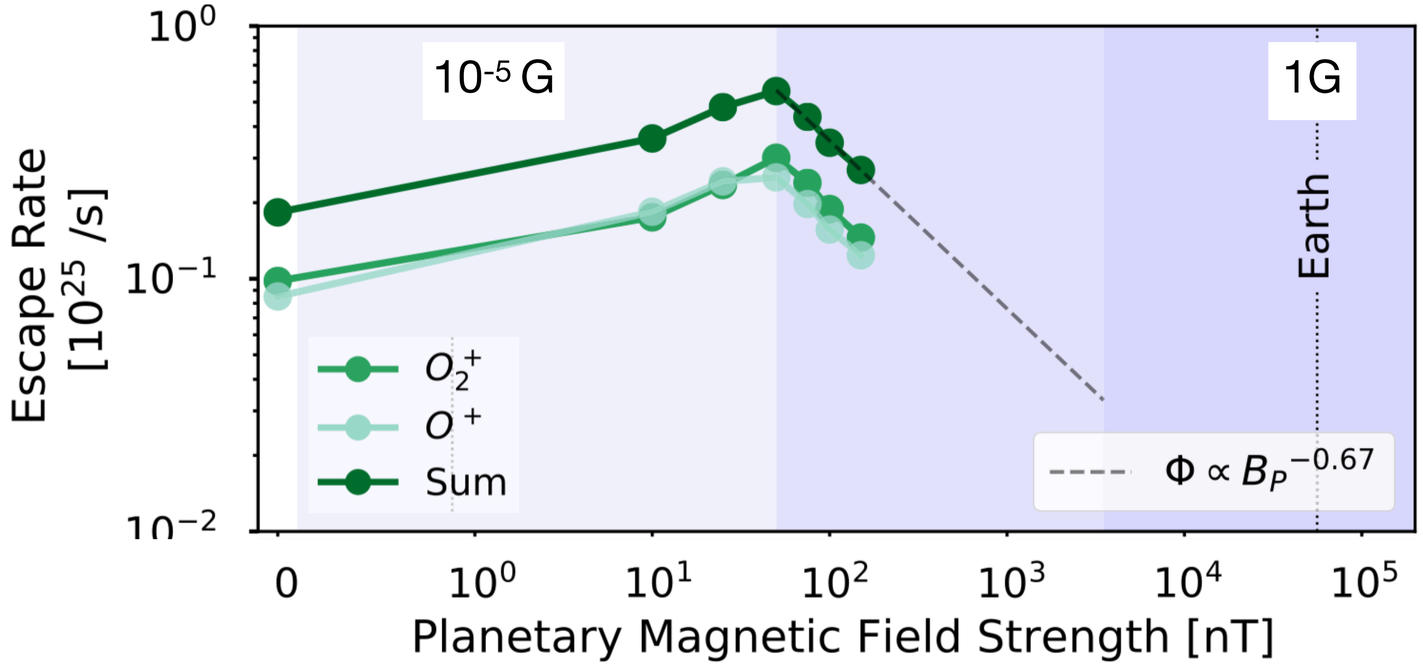

"induced" magnetospheres

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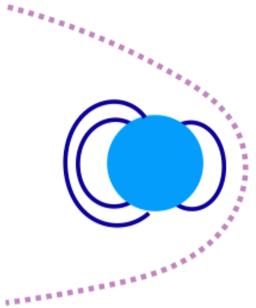
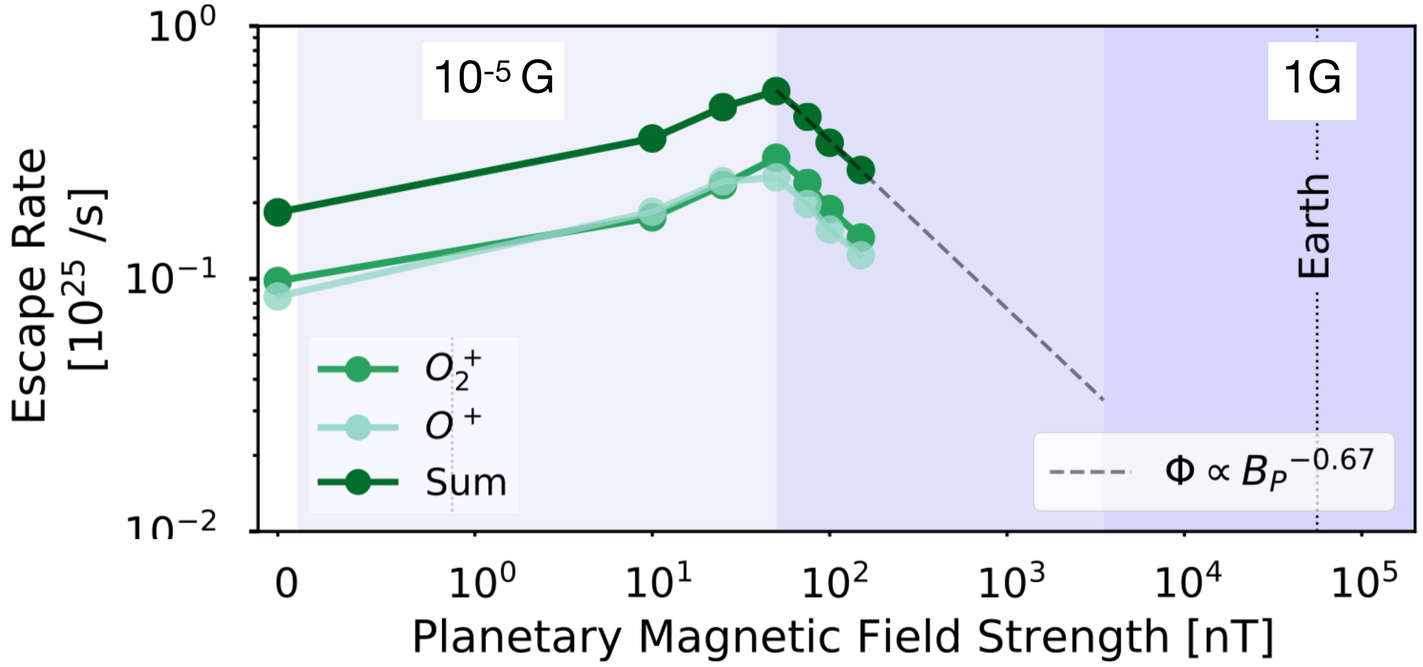
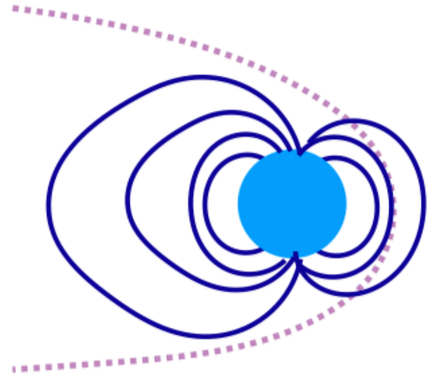
Weakly Magnetized





Magnetized

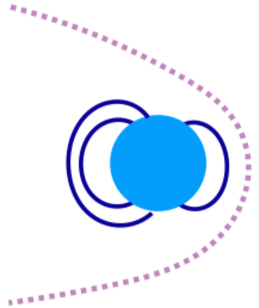


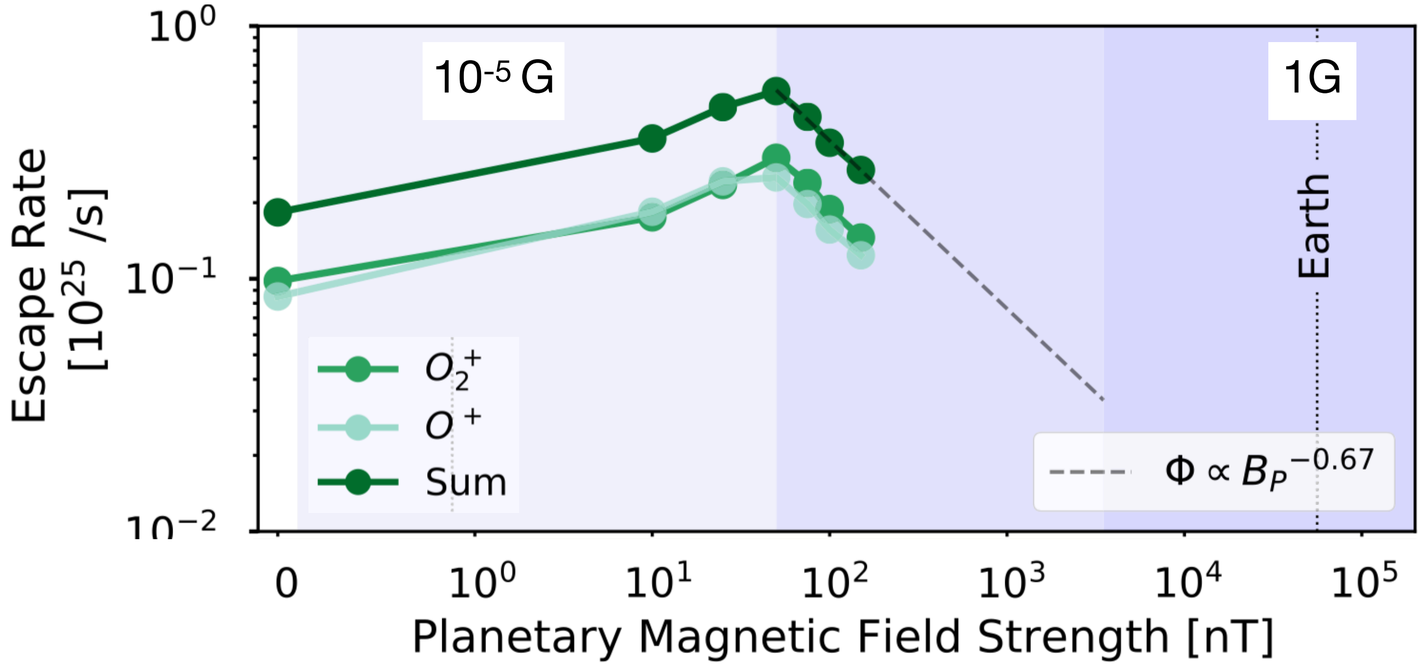
"induced" magnetospheres

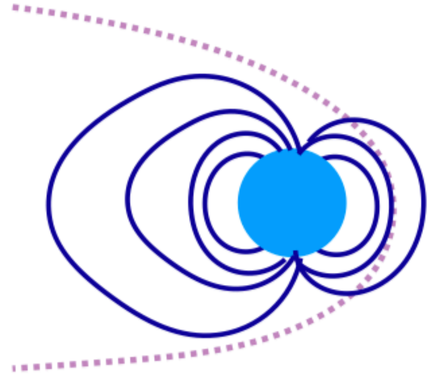
Intrinsic magnetospheres

Escape could increase with planetary magnetic fields (oh...)

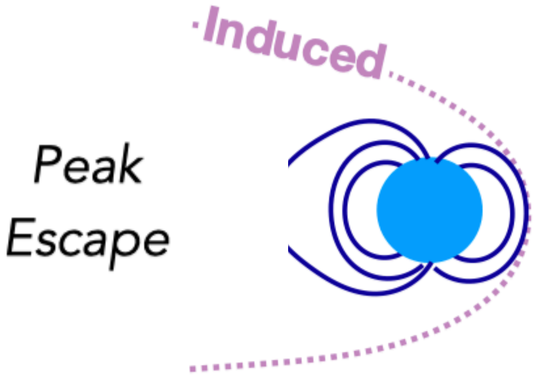
Egan et al 2019







"induced" magnetospheres



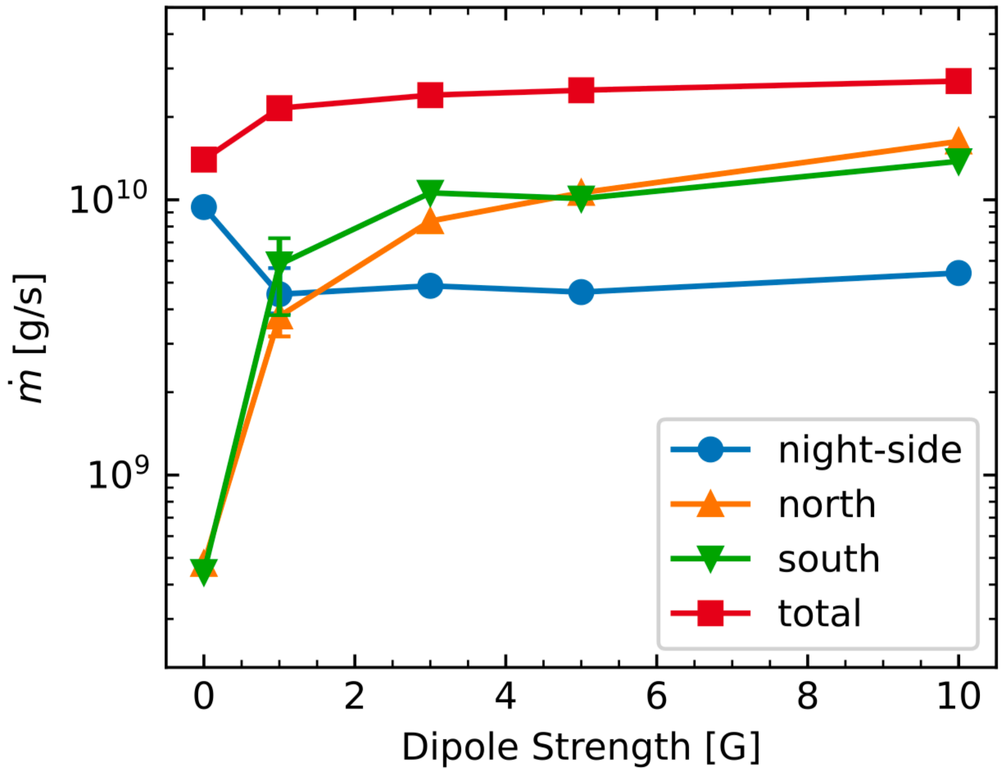
Intrinsic≈induced

Intrinsic magnetospheres

Magnetic field effects on atmospheric escape of hot Jupiters

Stellar wind is super-Alfvenic

Carolan, Vidotto et al 2021b



weak increase in escape rate with increase in B_{pl}…

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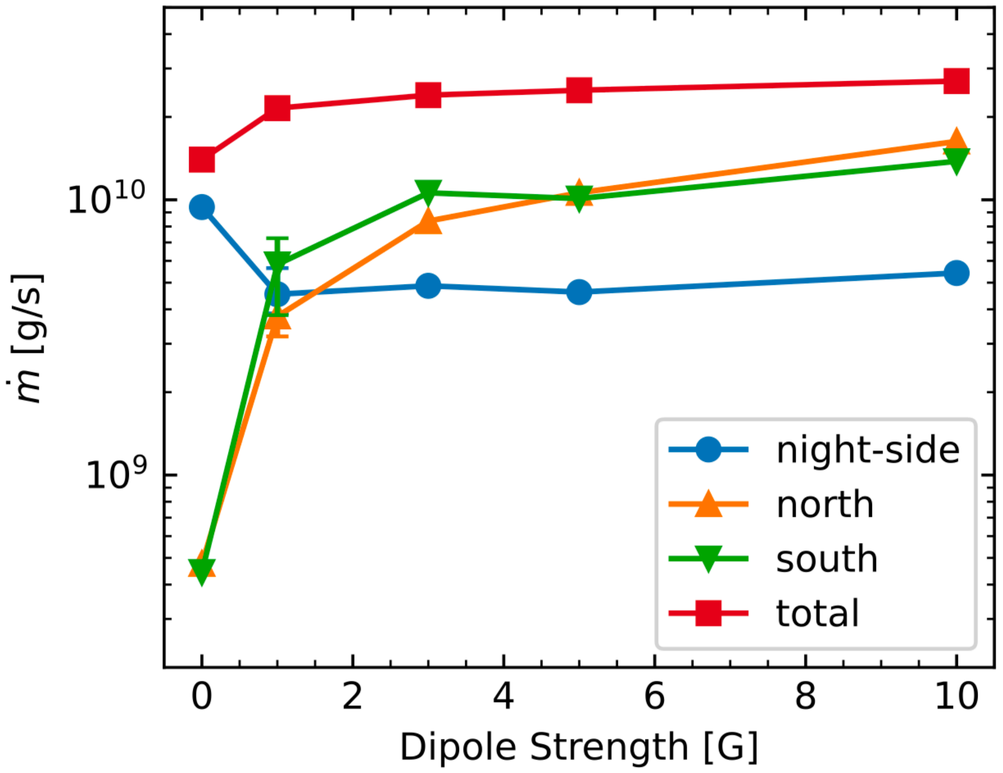

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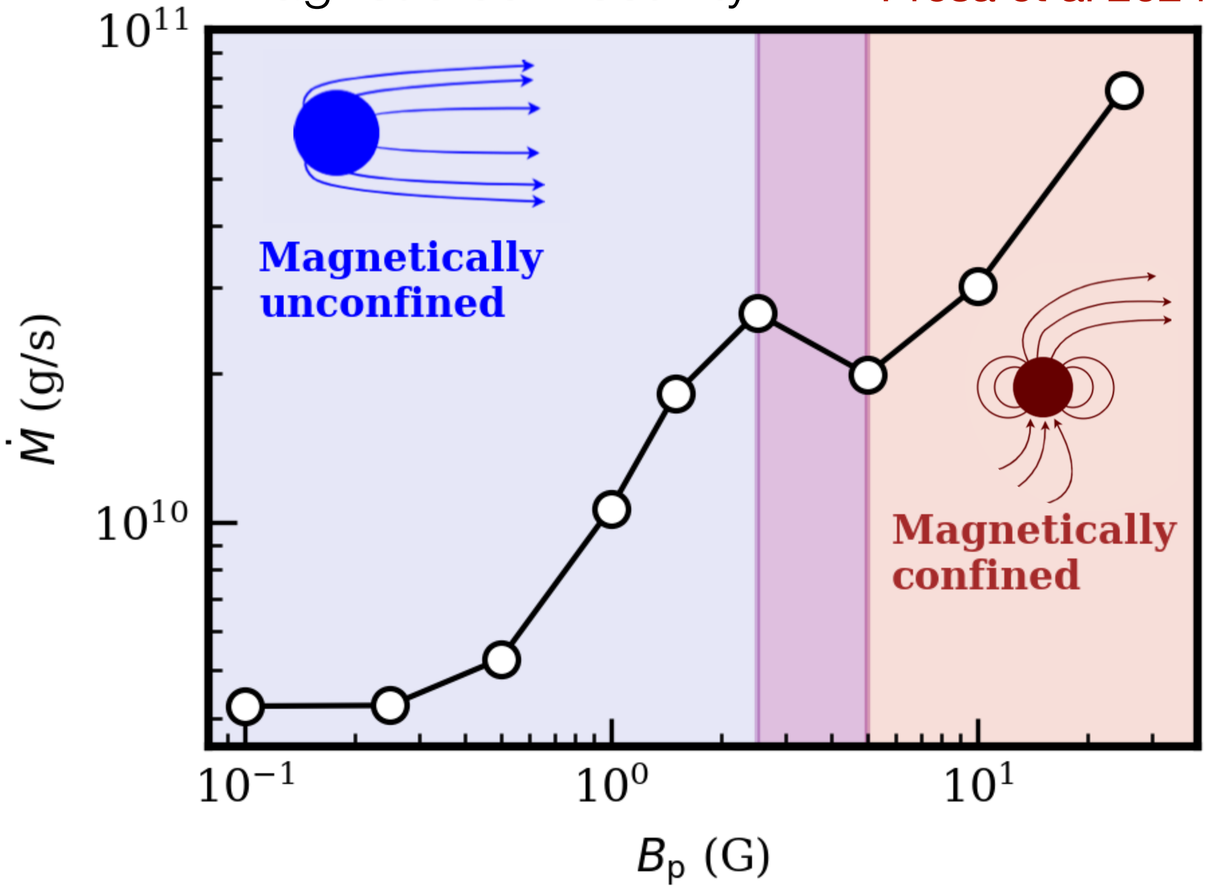
Magnetic connectivity

Presa et al 2024

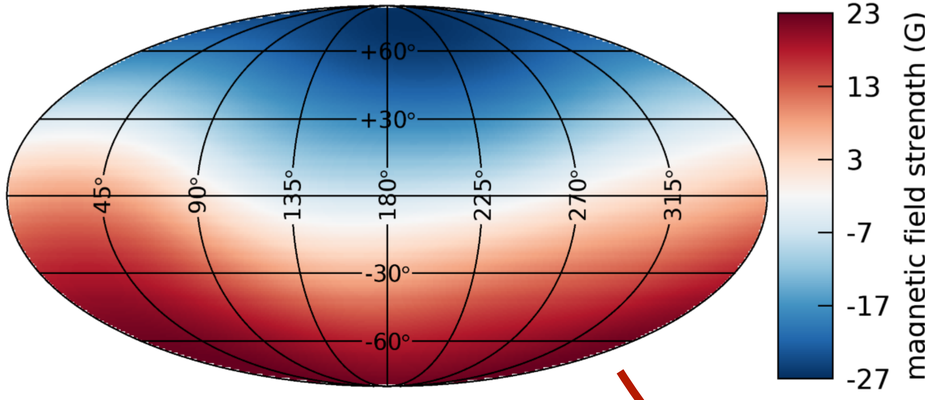


non-monotonic change in escape rate with increase in B_{pl}…

Open question #3: How do we move forward if we want to understand exo-space weather around PLATO stars?

Stellar wind models require surface magnetic fields

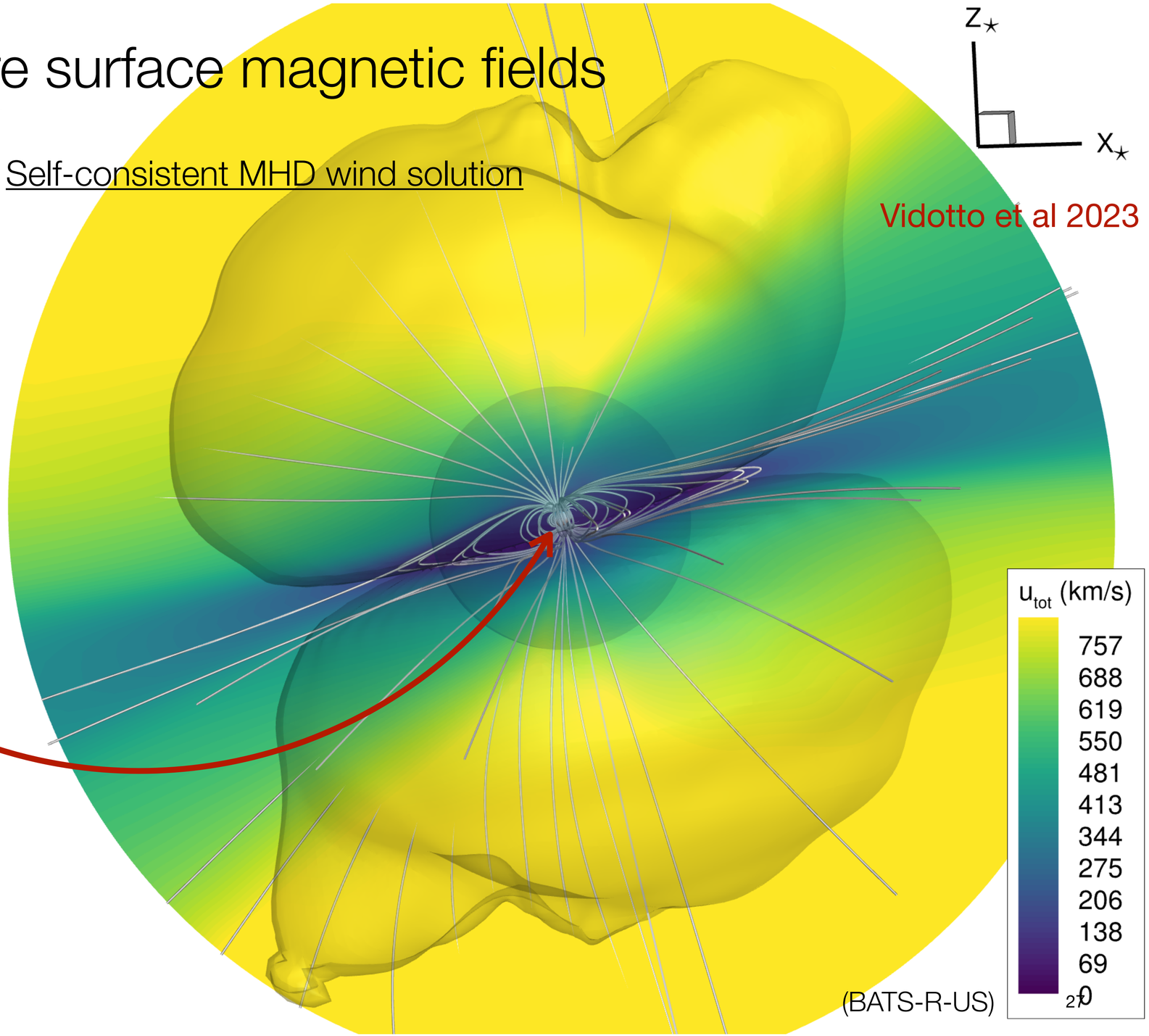
Stellar magnetic field from observations



Bellotti et al 2023

Self-consistent MHD wind solution

Vidotto et al 2023



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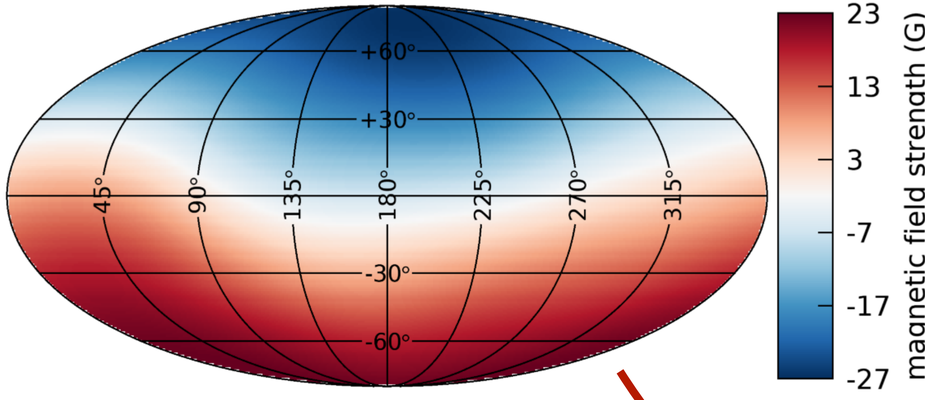

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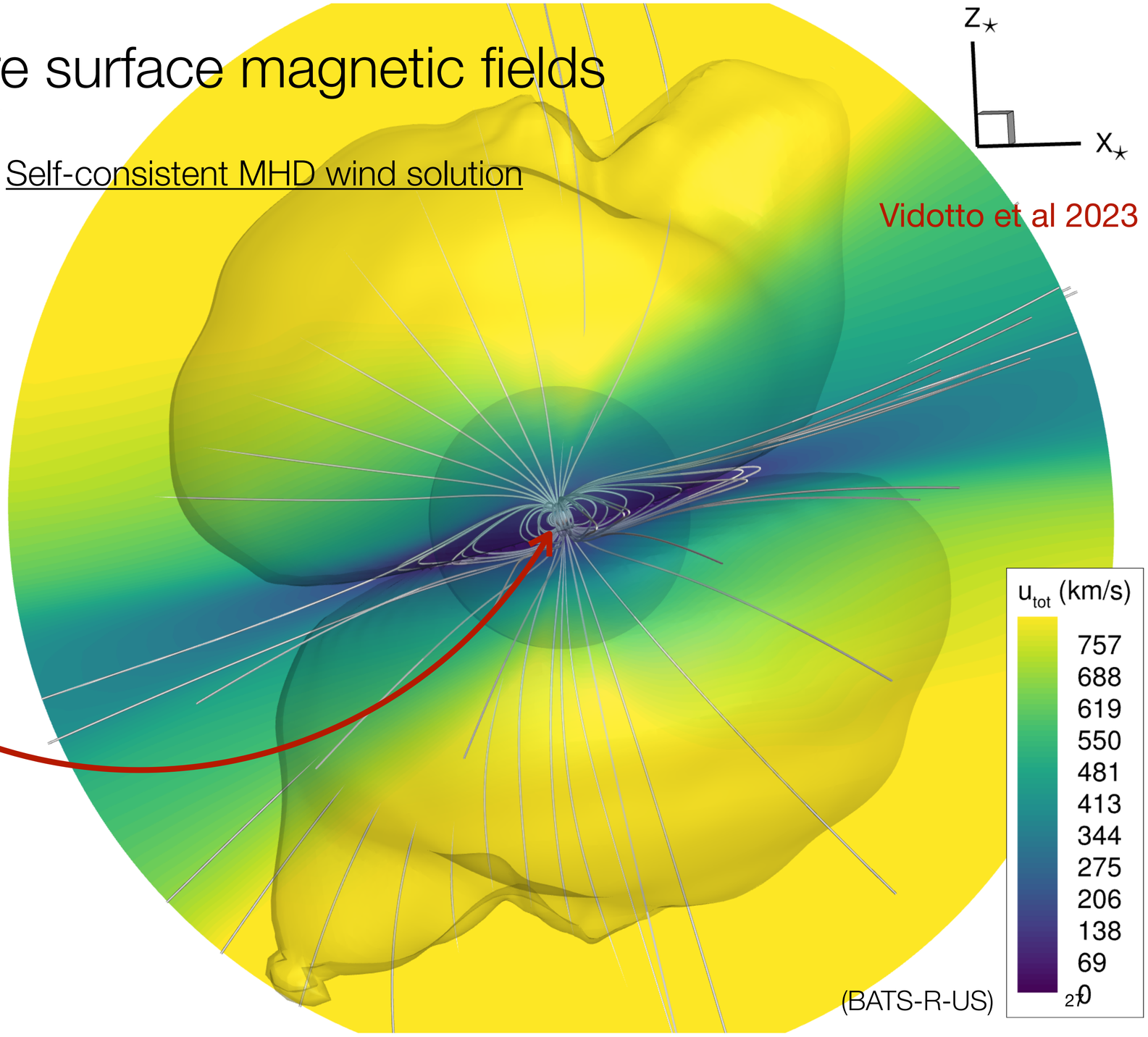

On-going spectropolarimetric campaigns of PLATO stars to reveal stellar magnetism:

- P. Petit: solar-like stars (Espadons)
- J. Alvarado: solar-like stars (HARPSPol)
- M. Diez: M dwarfs (Spirou)

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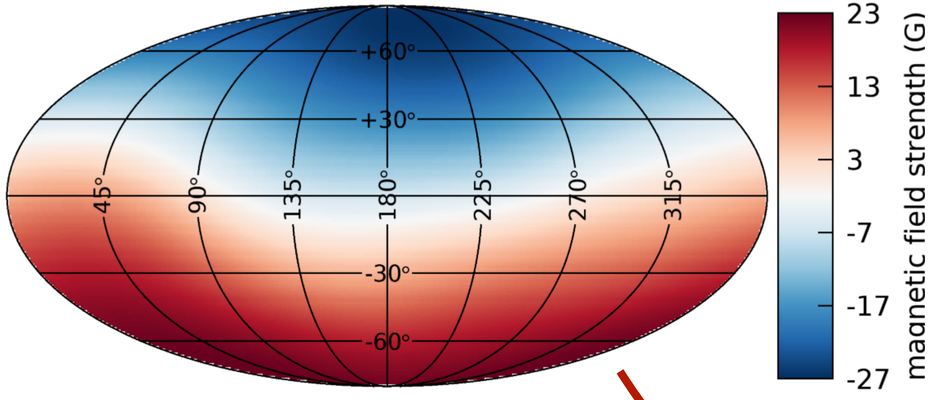

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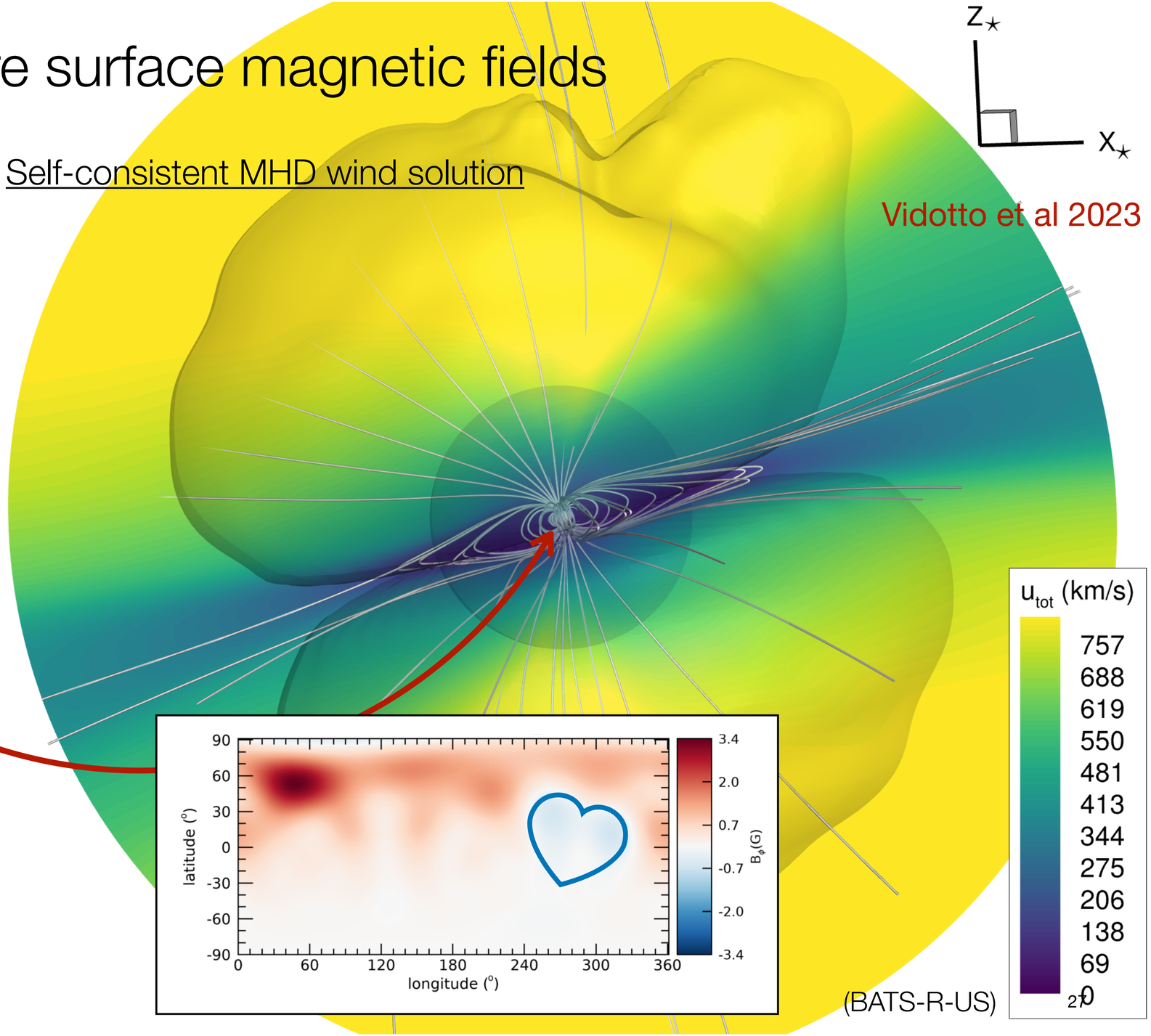

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Conclusions

Stellar magnetic activity is at the ❤️ of star-planet interactions mediated by: high-energy radiation, stellar winds, and magnetic connectivity

Long-term evolution of magnetospheres due to stellar wind evolution: older planets → larger magnetospheres

Long-period planets likely experience super-Alfvenic interactions. Affects sizes of planetary magnetospheres.

Open question:
How is magnetospheric sizes related to atmospheric retention and habitability?