NGC 2112 (LRGB) by Dan Crowson (BBC Sky at Night)

Placing Solar Activity and Rotation in the Context of Other Sun-like Stars

Adam J. Finley,

Victor See, Travis Metcalfe, et al.

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WholeSun Synergy Grant

European Research Council
Established by the European Commission

UK NAM– Durham – July 2025

NGC 2112 (LRGB) by Dan Crowson (BBC Sky at Night)

Outline

How and why does magnetic activity vary across low-mass stars?

Gyrochronology – the link between stellar rotation and activity.

Stellar spin-down – angular momentum-loss due to magnetised stellar winds.

Solar activity and spin-down as measured by modern heliophysics missions.

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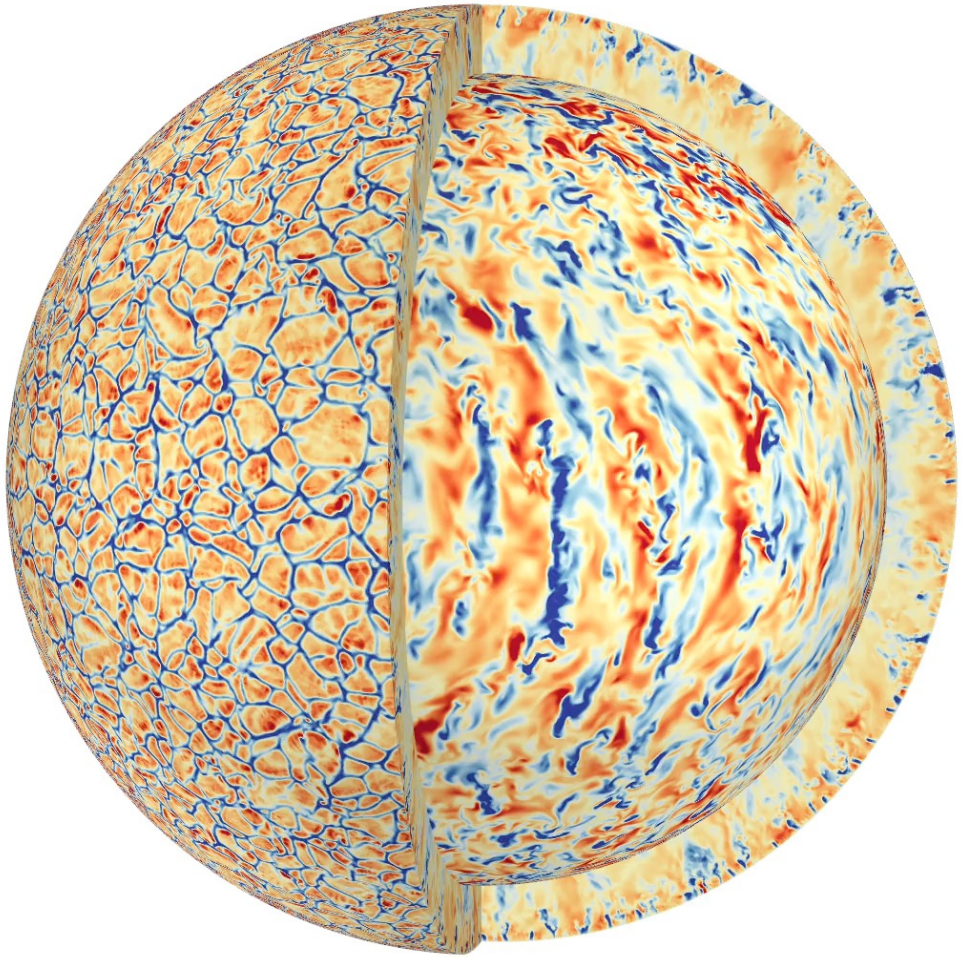
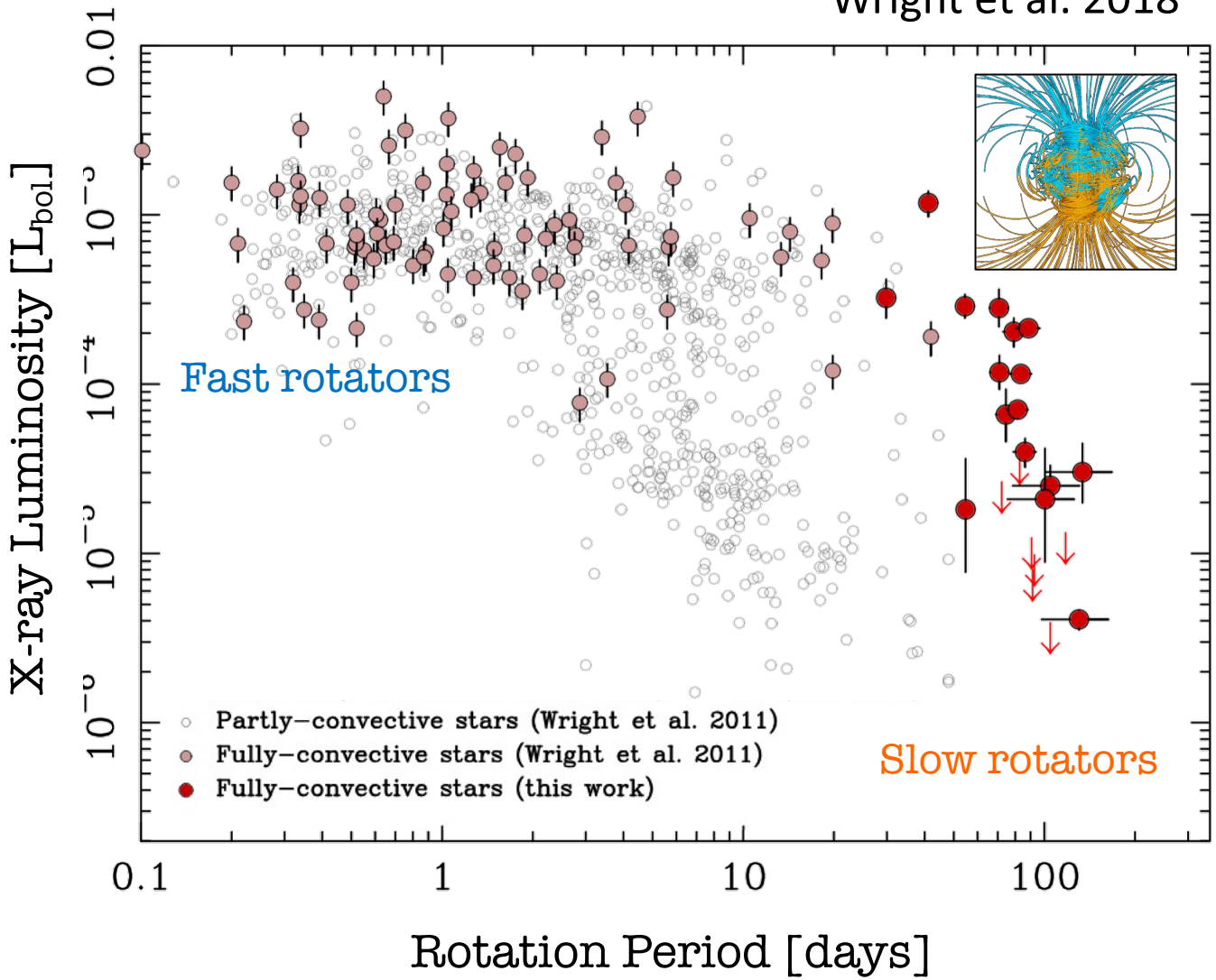
Activity-Rotation Relation



Noraz et al. 2025 (ASH Simulation)

Wright et al. 2018



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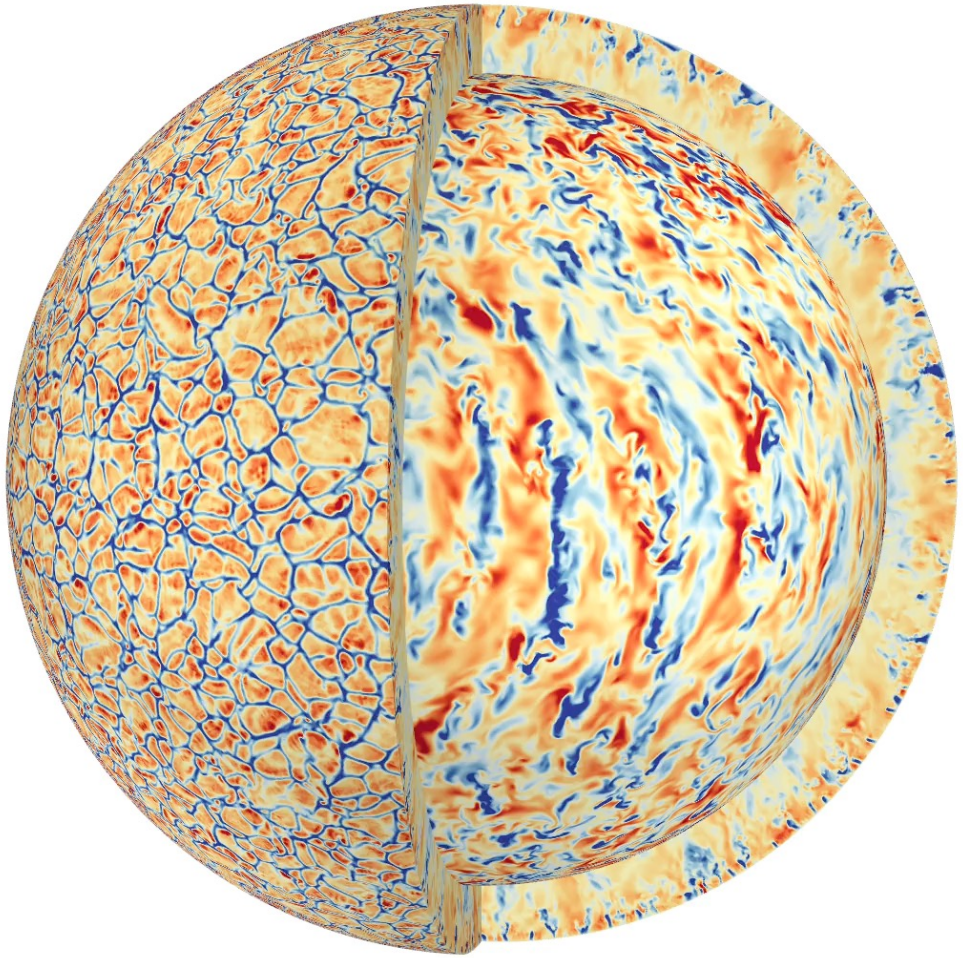

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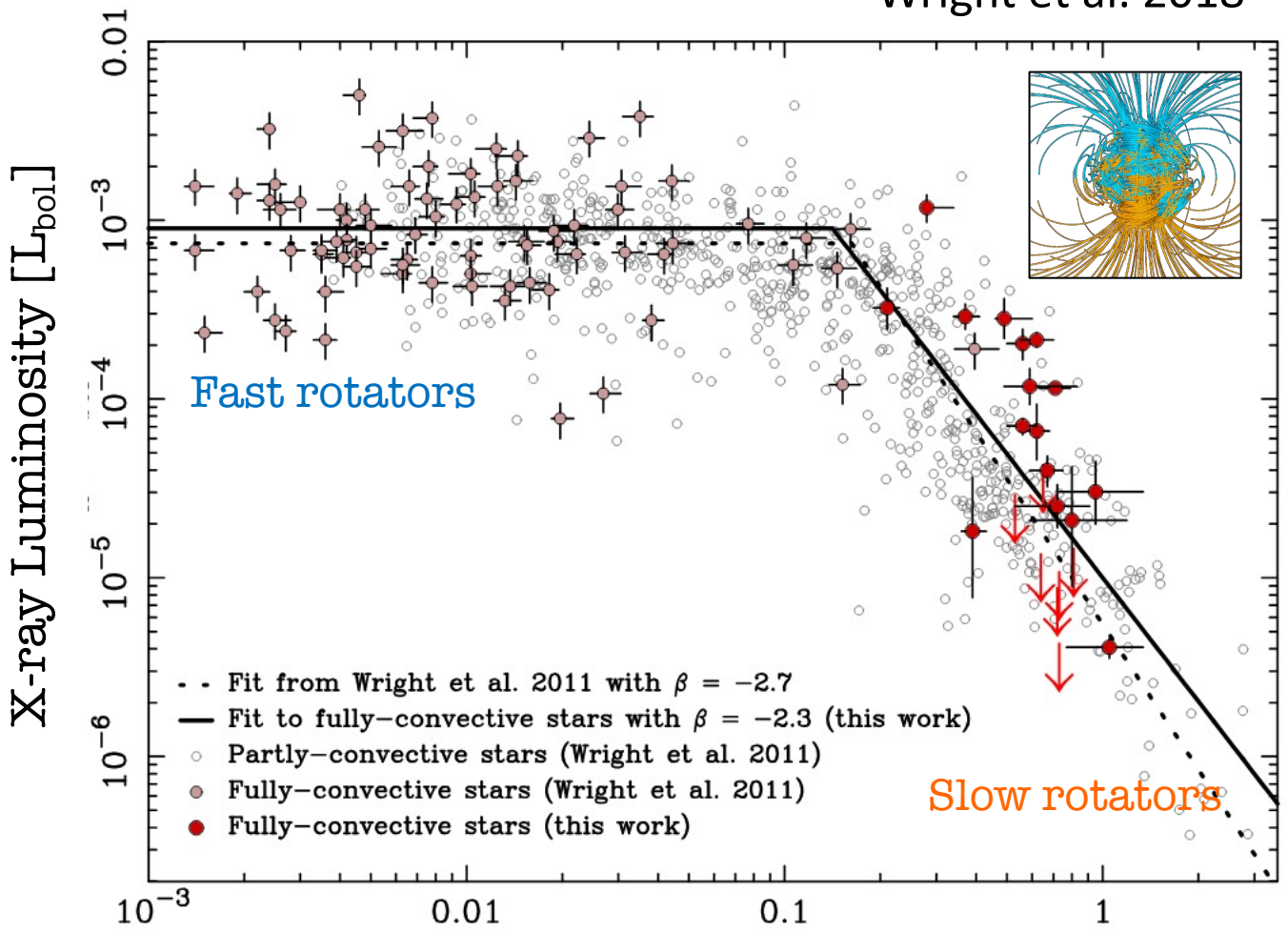

$$\text{Rossby Number} = \frac{\textbf{Rotation Period}}{\text{Convective Turnover Timescale}}$$

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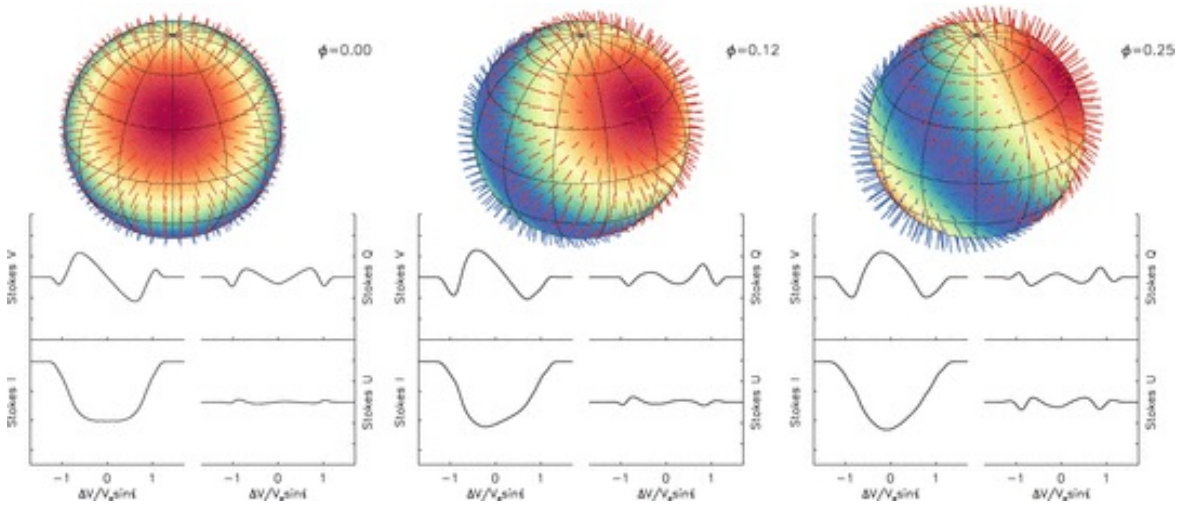
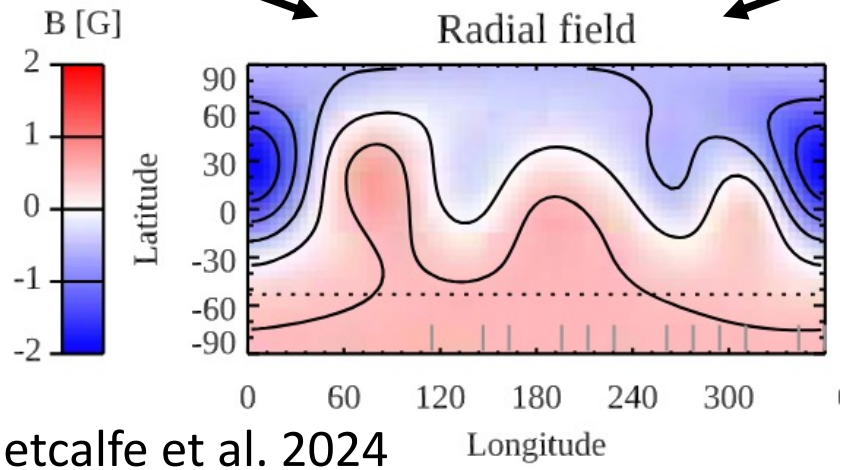
Zeeman-Doppler Imaging

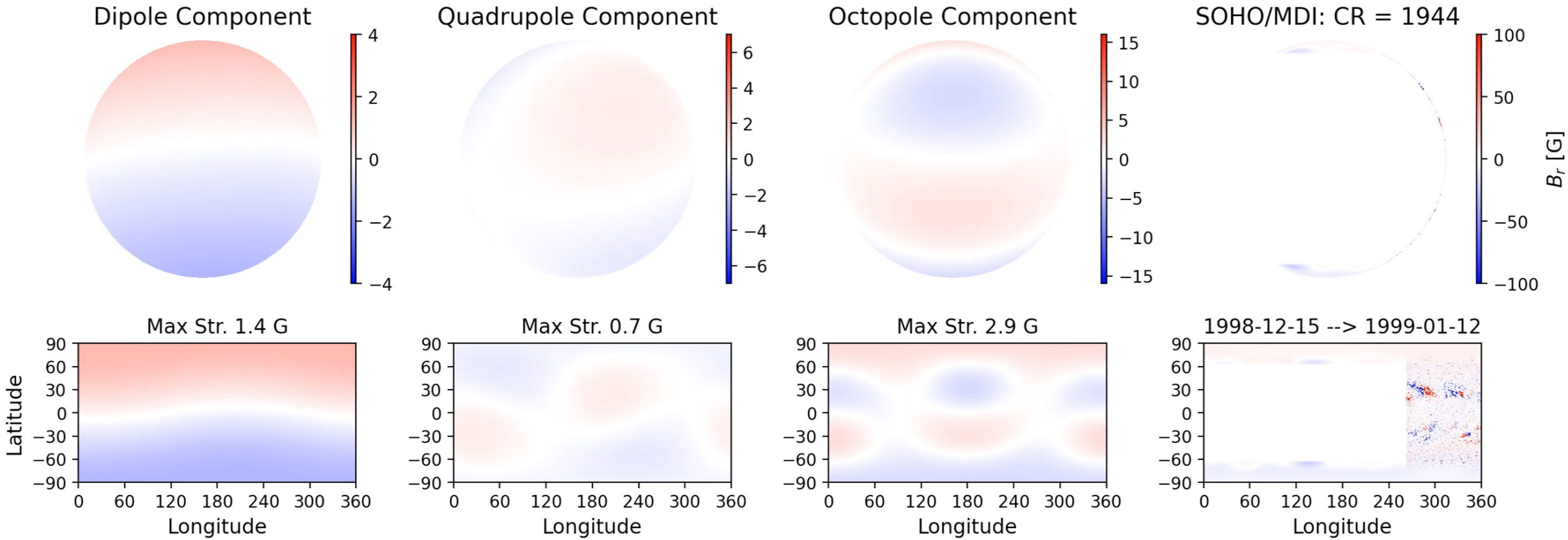
Kochukhov 2016





Metcalfe et al. 2024

Dipole, Quadrupole, Octupole, ……



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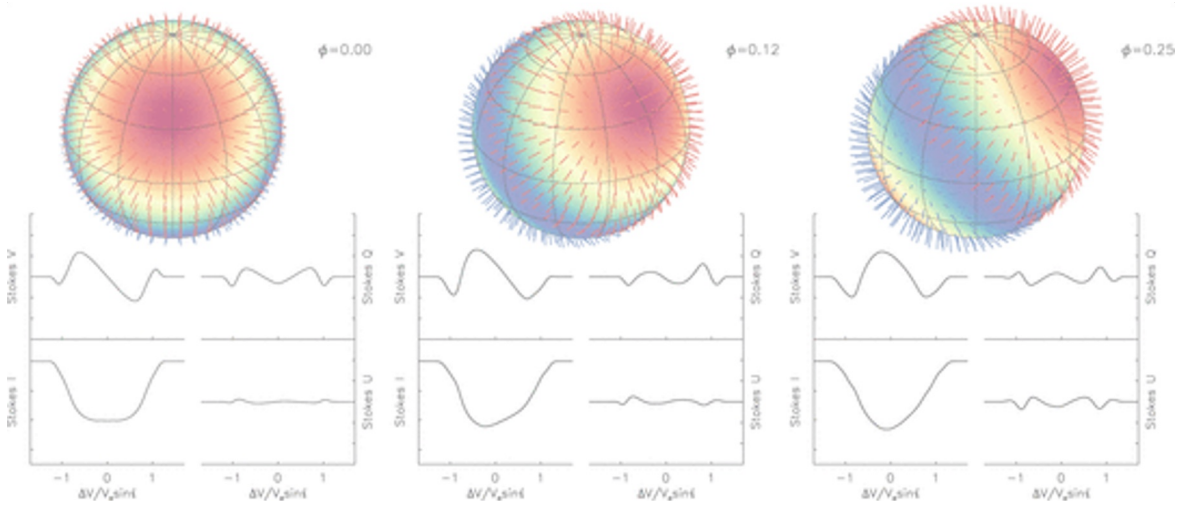
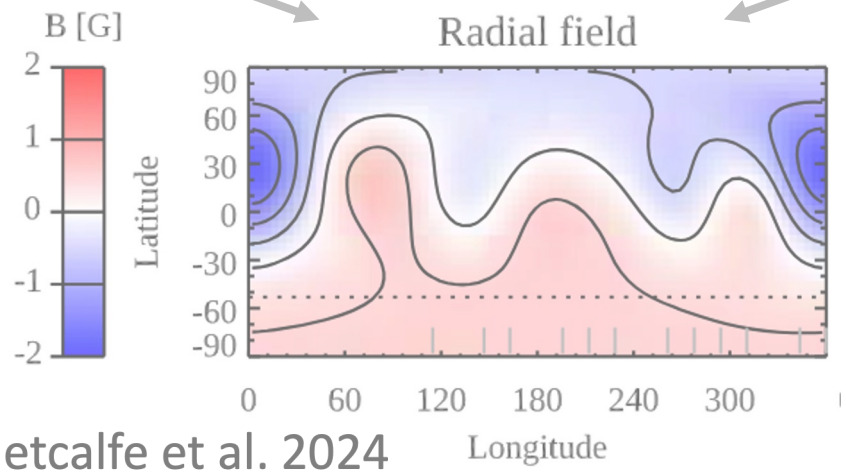
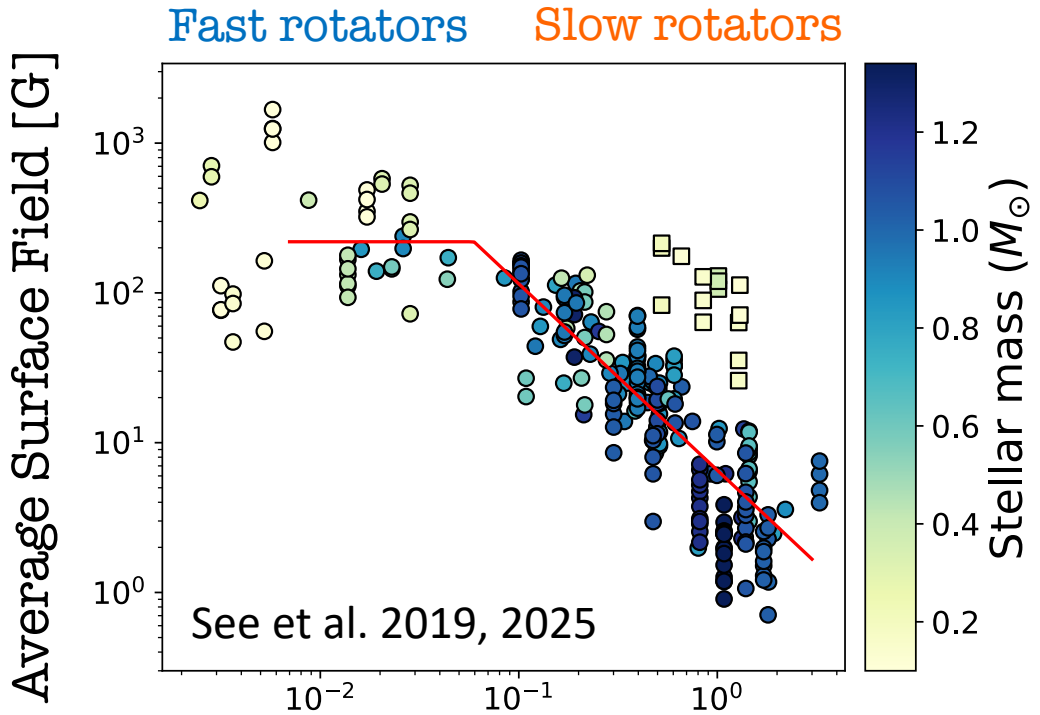
Kochukhov 2016





Metcalfe et al. 2024



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Dipole, Quadrupole, Octupole, ……

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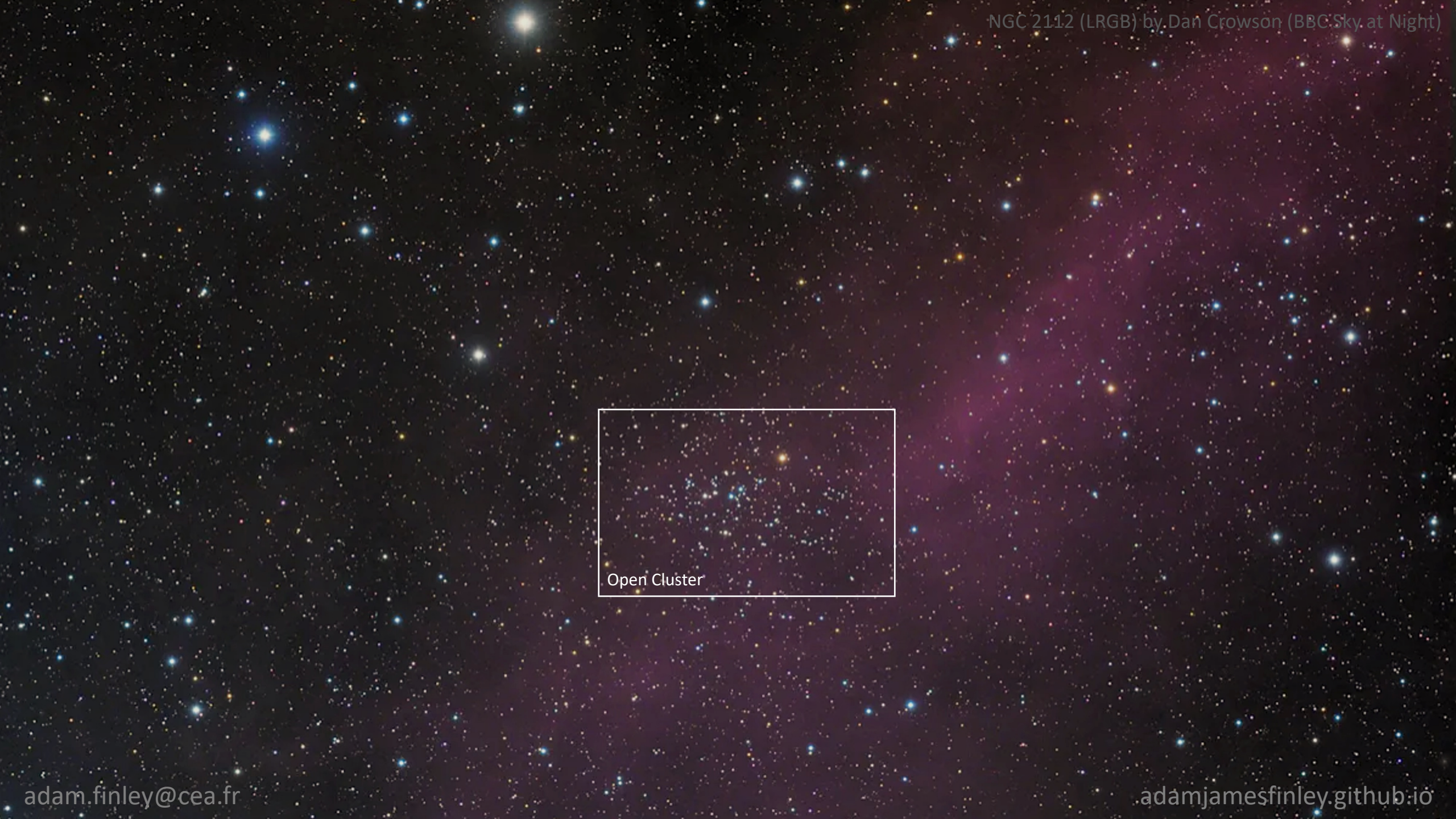

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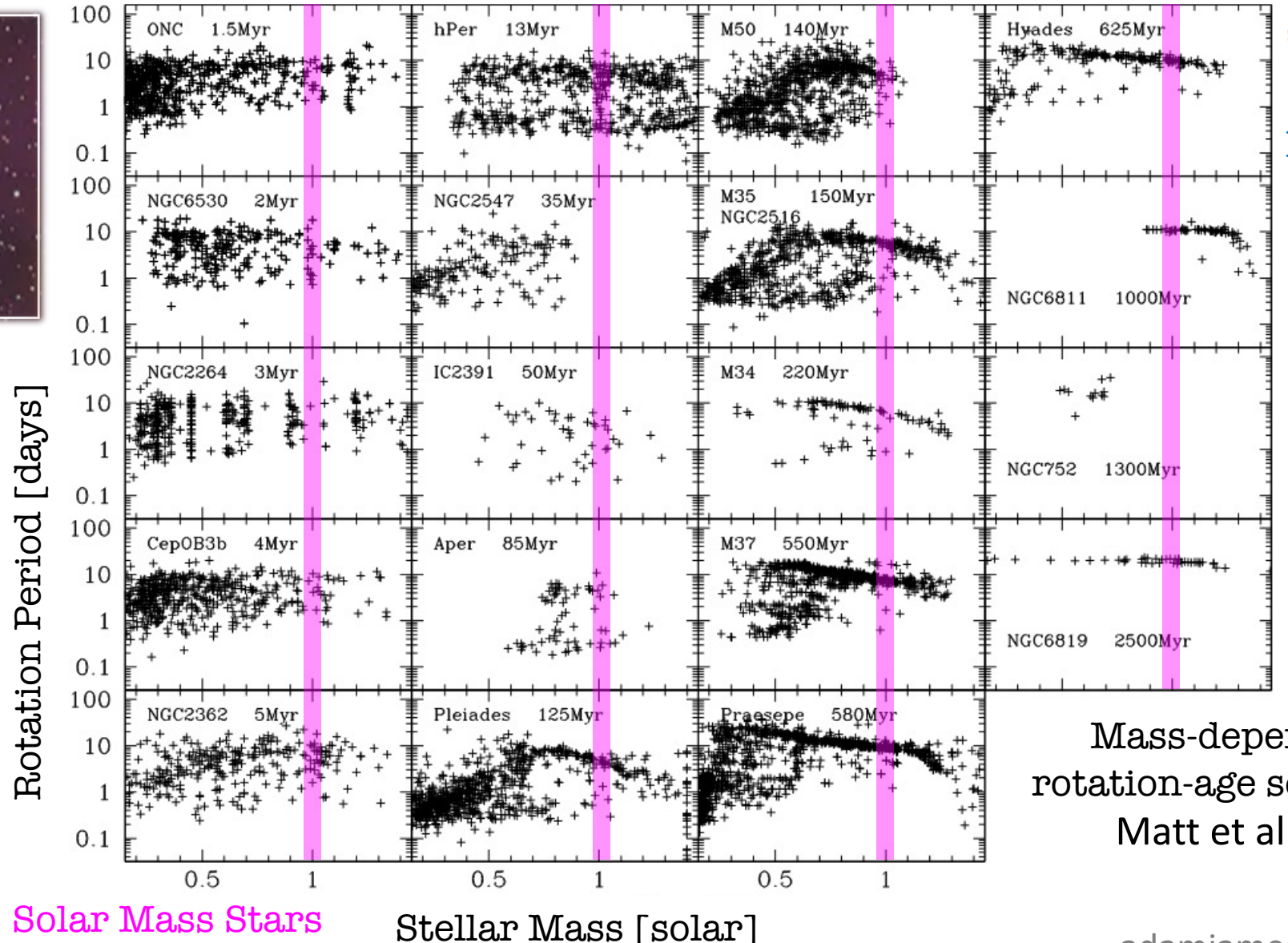
Stellar Rotation Evolution

Louis Amard, Private Comm

Initial Distribution
(formation?)



Slow rotators

Fast rotators

Solar Mass Stars

Mass-dependent rotation-age sequence!
Matt et al. 2015

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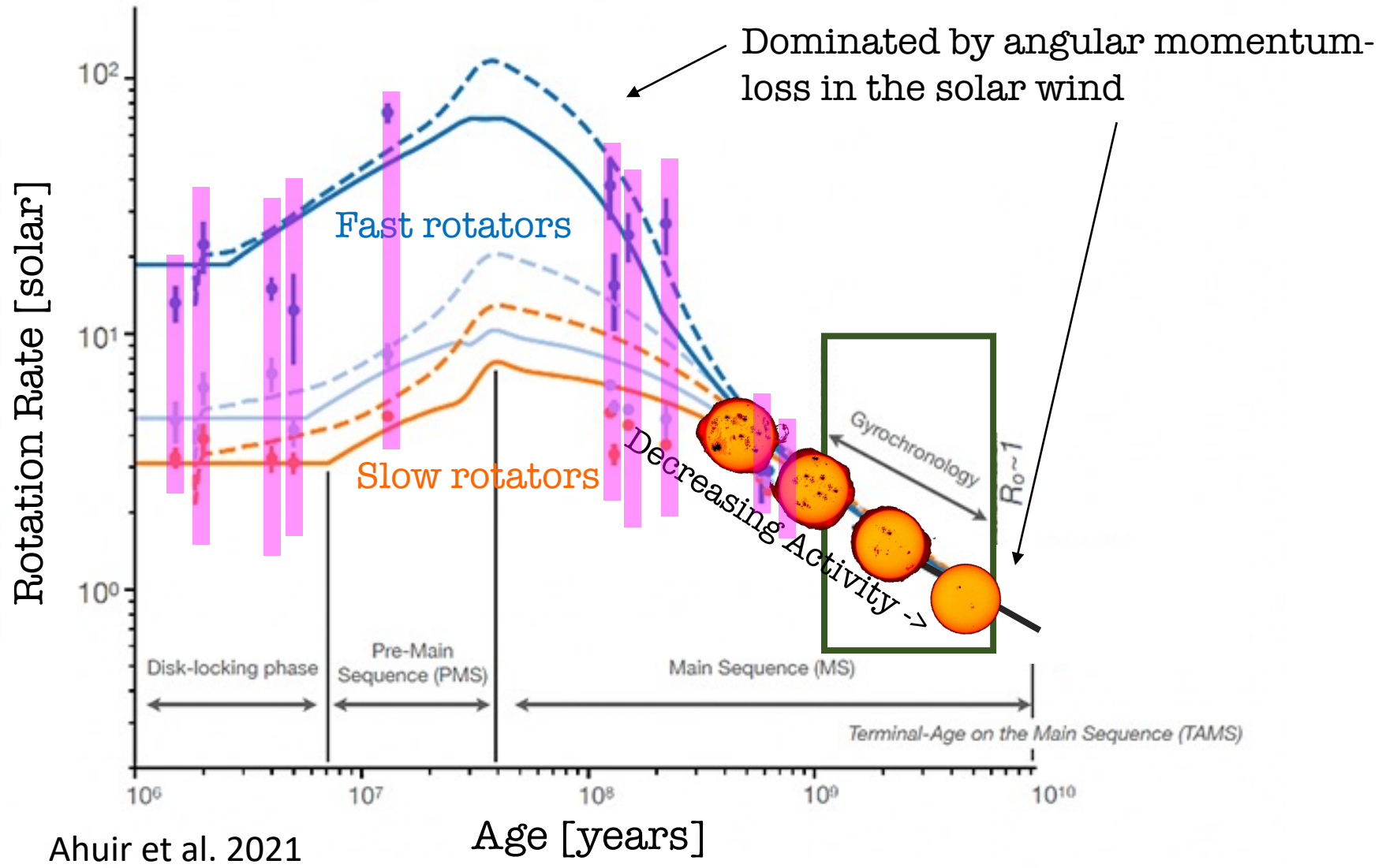
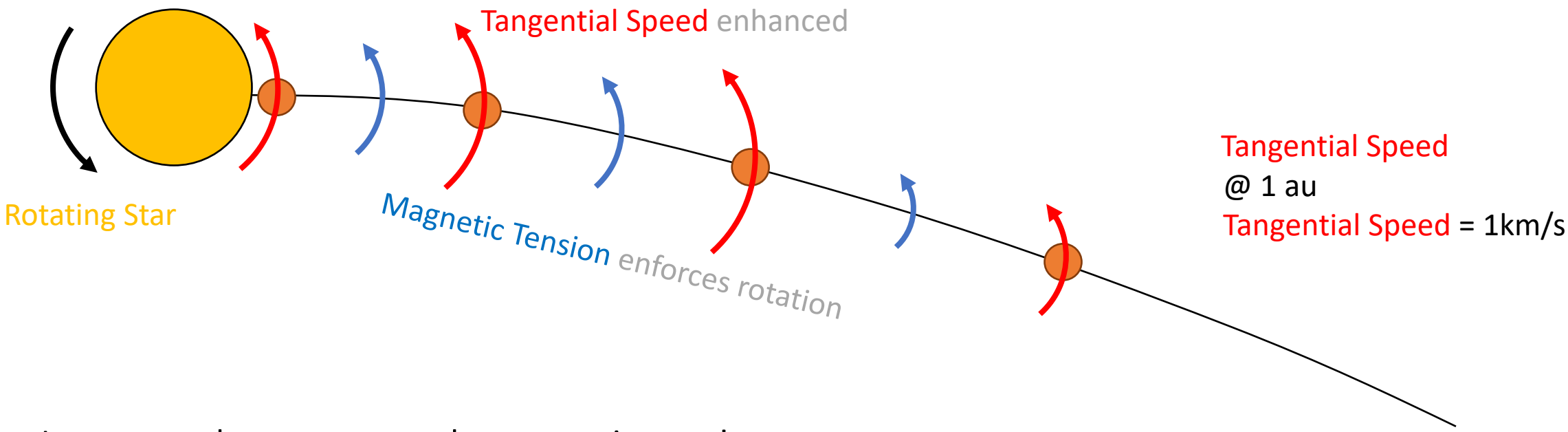
Stellar Spin-down (one solar mass)



Ahuir et al. 2021

Stellar Wind Angular Momentum-loss

As viewed from above
in the rotating frame



Larger angular momentum-loss per unit mass!
-Plasma angular momentum
-Magnetic stresses

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More details in **Finley et al. (2017, 2018)**

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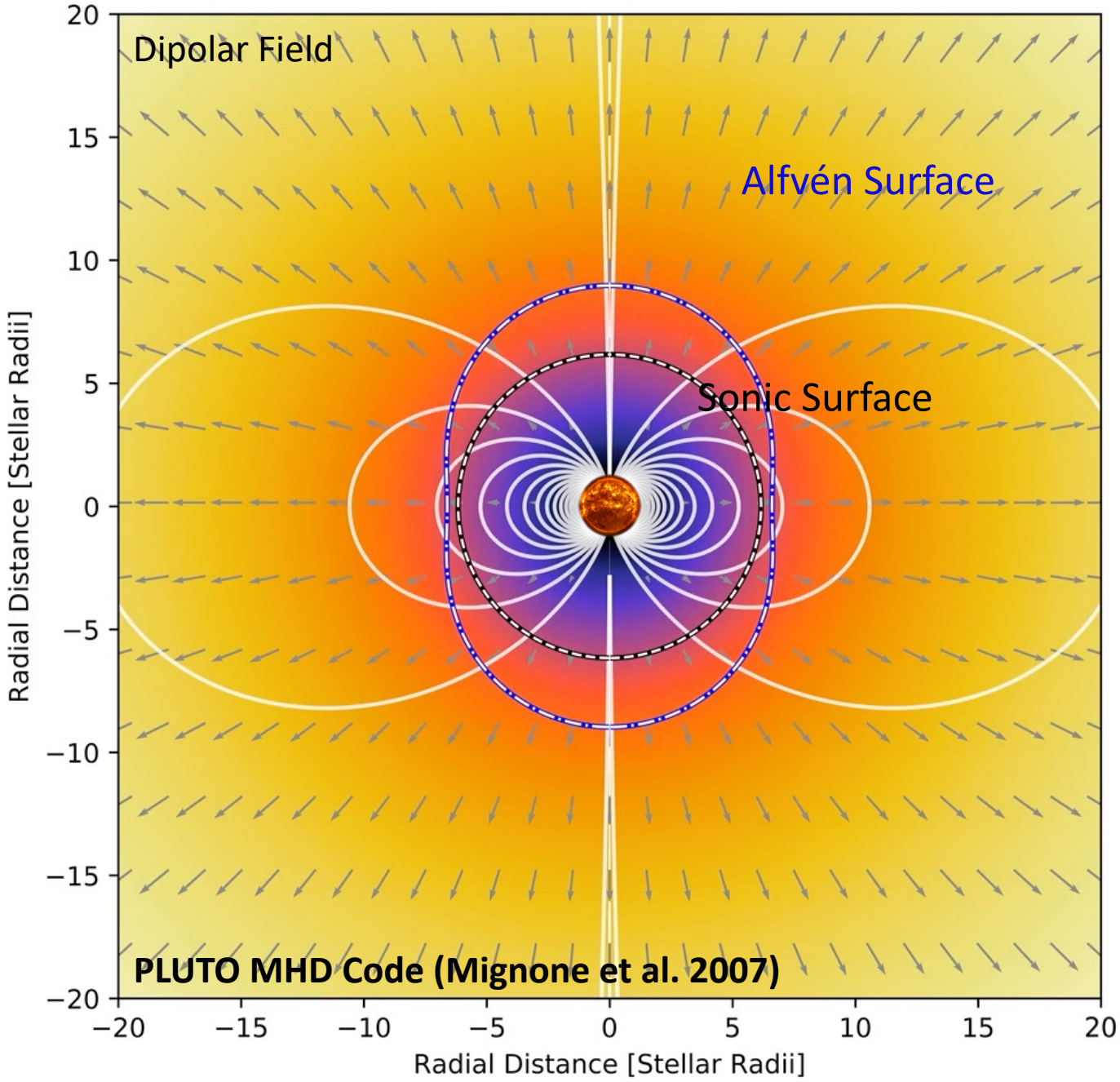

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MHD Stellar Wind Simulations

Angular Momentum-loss Rate (Torque):

$$\tau = \dot{M}\Omega_* R_*^2 \left(\frac{\langle R_A \rangle}{R_*} \right)^2$$

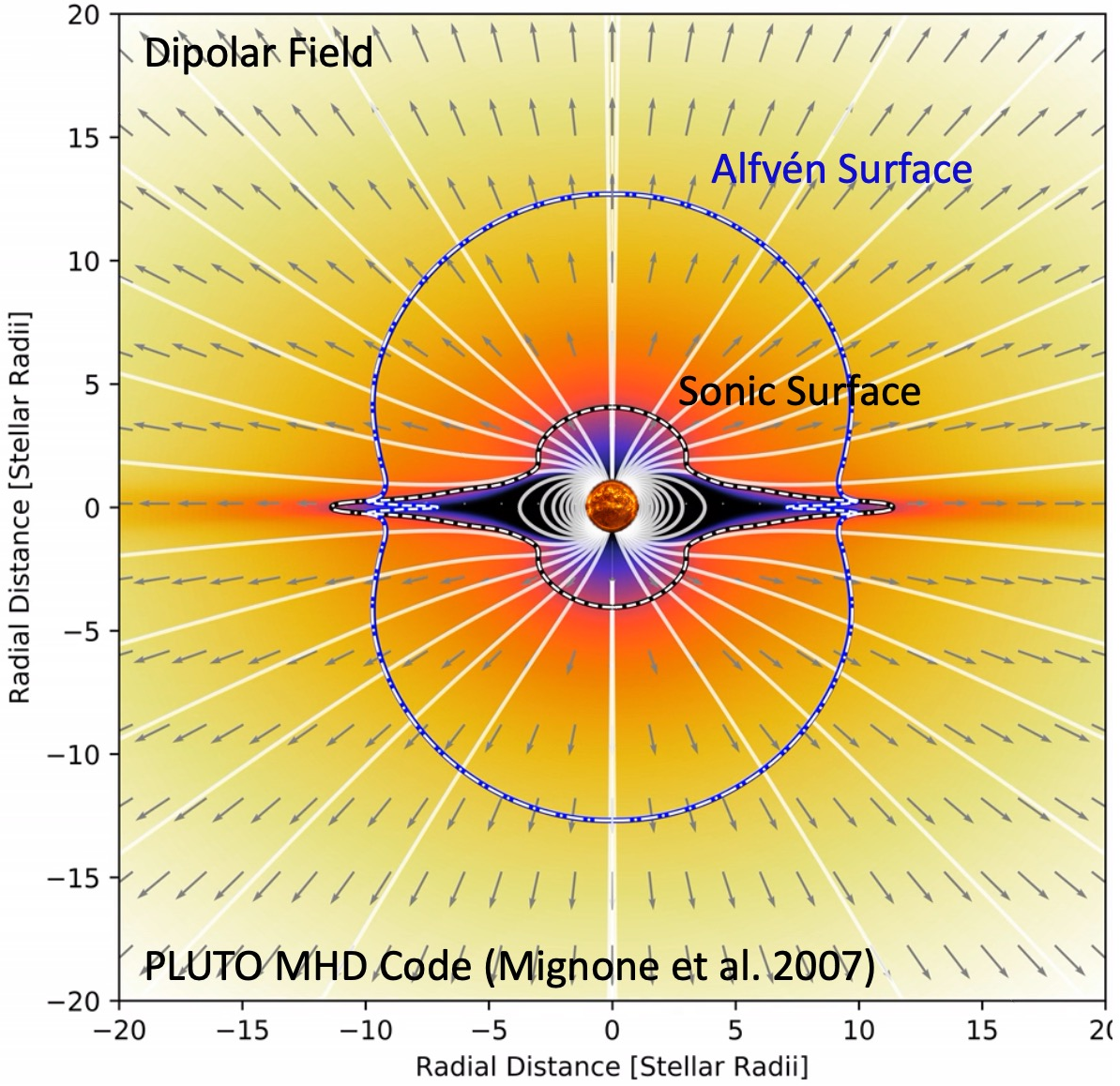
Mass-loss Rate

Rotation Rate

Alfvén Radius

-Heating of the Corona
-Braiding, reconnection...
-Alfvén Wave Heating
-Small-scale magnetic fields

-Heating of the Wind
-Alfvén Wave Acceleration
-Open flux, density, speed...
-Large-scale magnetic field



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More details in **Finley et al. (2017, 2018)**

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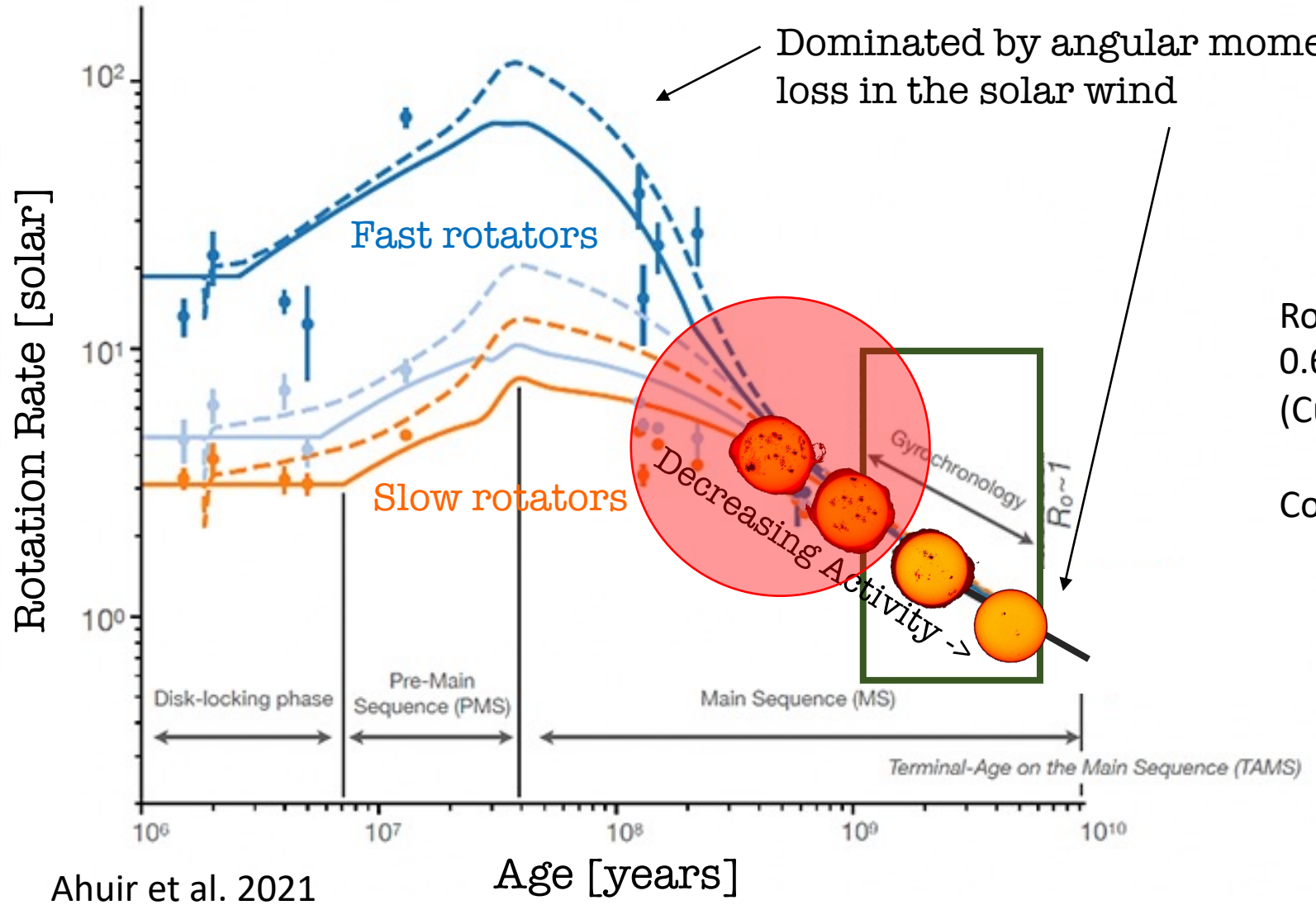
Puzzle 1: Stalling of Spin-down Around 1Gyr

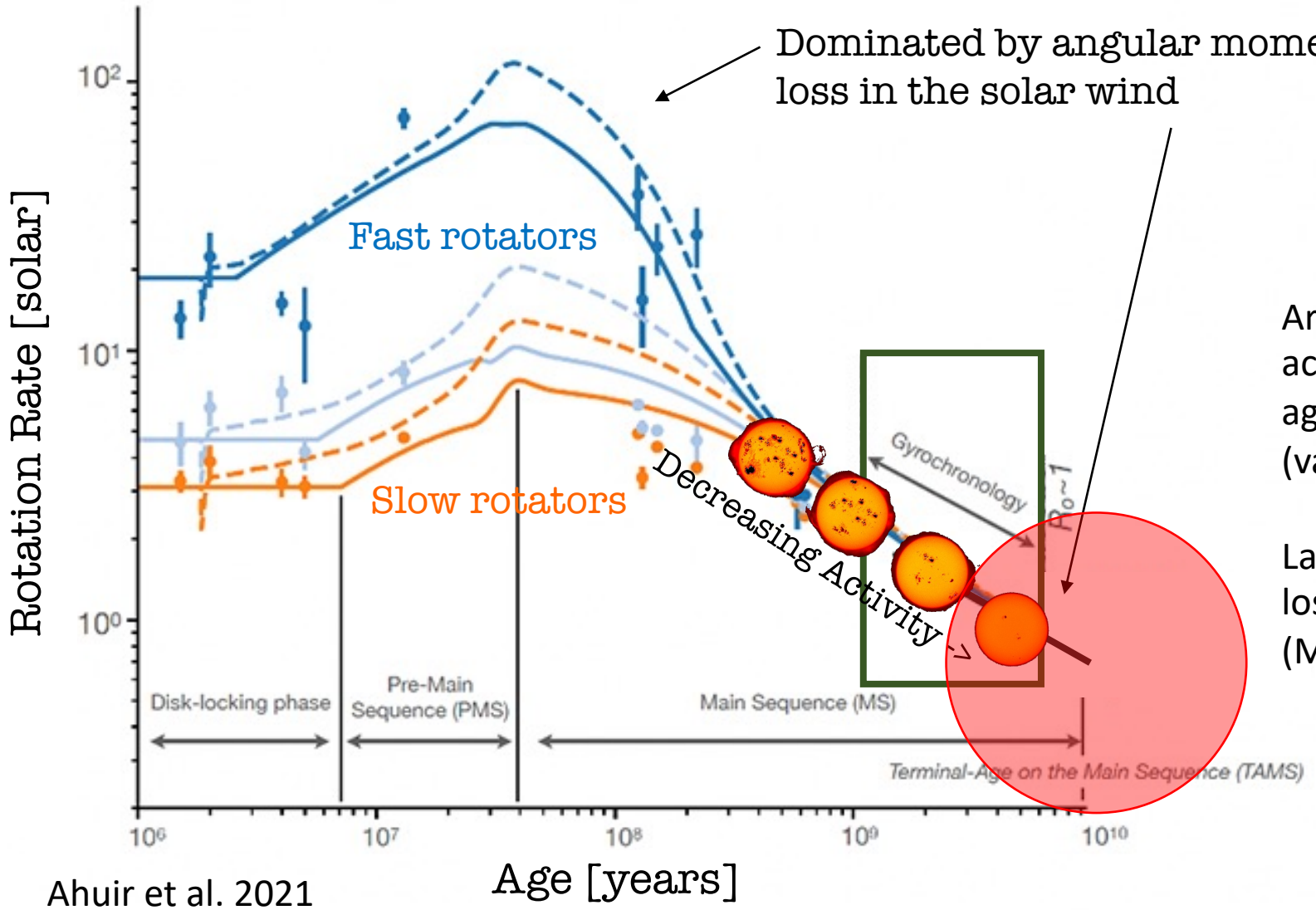


Ahuir et al. 2021

Rotation evolution stalls around 0.6-1Gyr into the main sequence. (Curtis et al. 2019)

Core-envelope coupling?

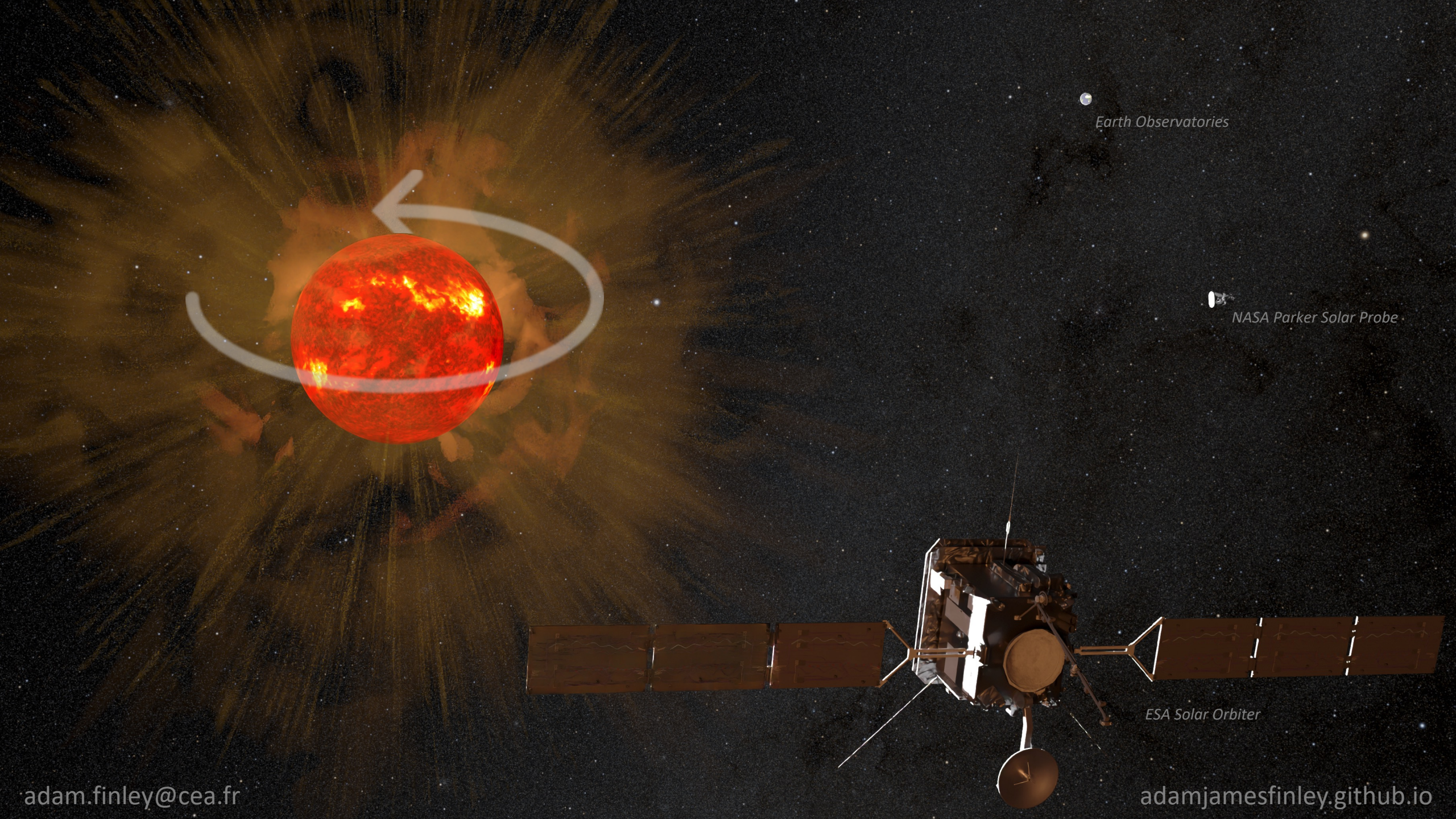
Puzzle 2: Weakened Spin-down at Late-ages



Ahuir et al. 2021

Around the Sun's age, magnetic activity continues to decrease with age but rotation remains constant… (van Saders et al. 2016)

Large-scale magnetic field, mass-loss rate, Alfvén surface? (Metcalfe et al. 2022, 2023, …)



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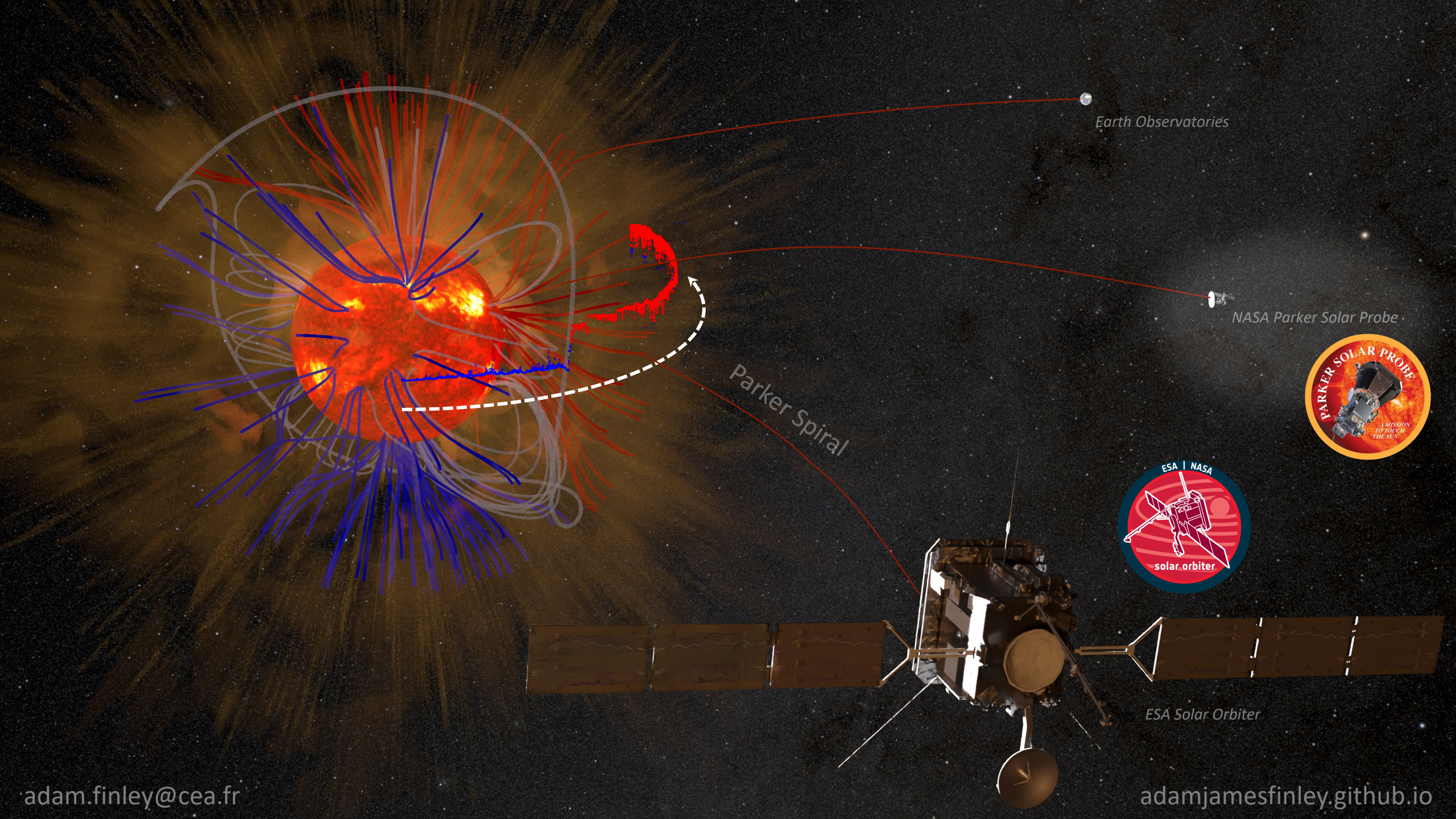

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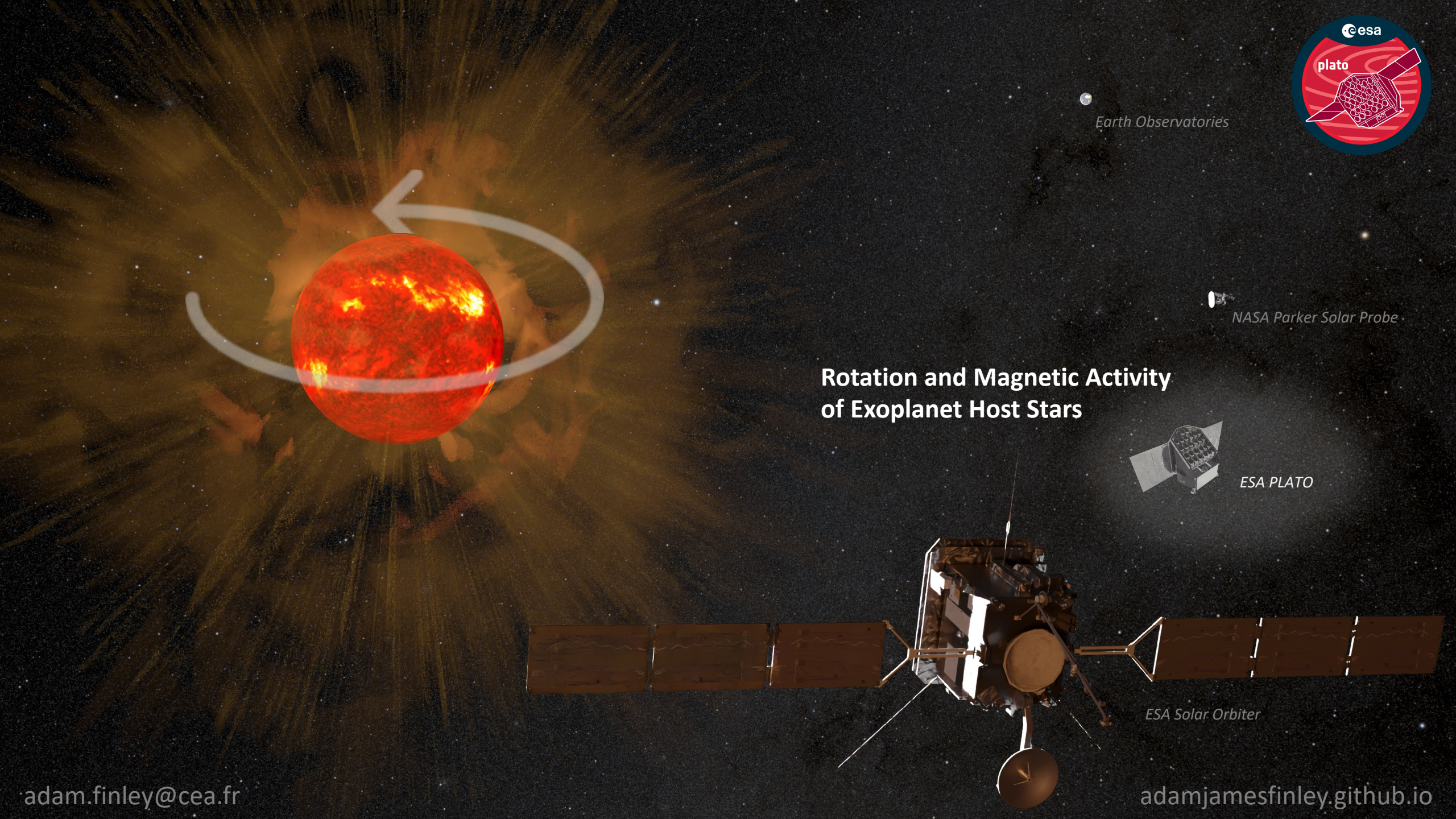

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Differential Rotation

Ireland et al. (2022)

Finley & Brun (2023a, 2023b)

Angular Momentum Transport and Stellar Spin-down

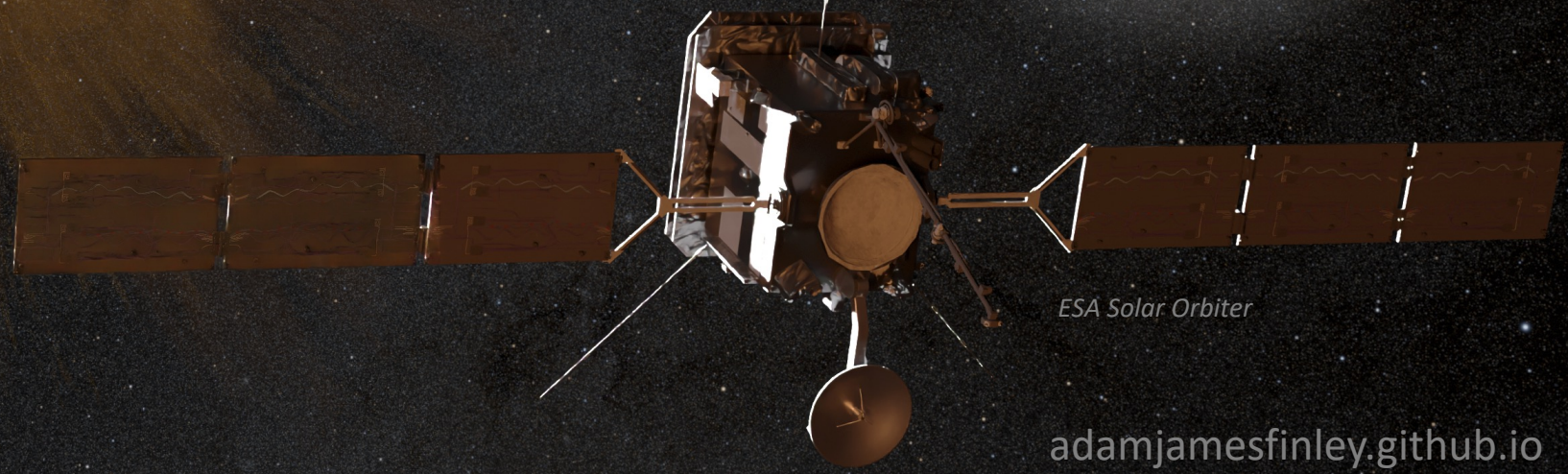
Finley et al. (2017, 2018, 2019)

See et al. (2019, 2020)

Metcalfe et al. (2022, 2023a, 2023b, 2024)

Enforces Rotation into the Solar Corona and Wind

Finley et al. (2019, 2020)



Earth Observatories

NASA Parker Solar Probe

ESA PLATO

ESA Solar Orbiter

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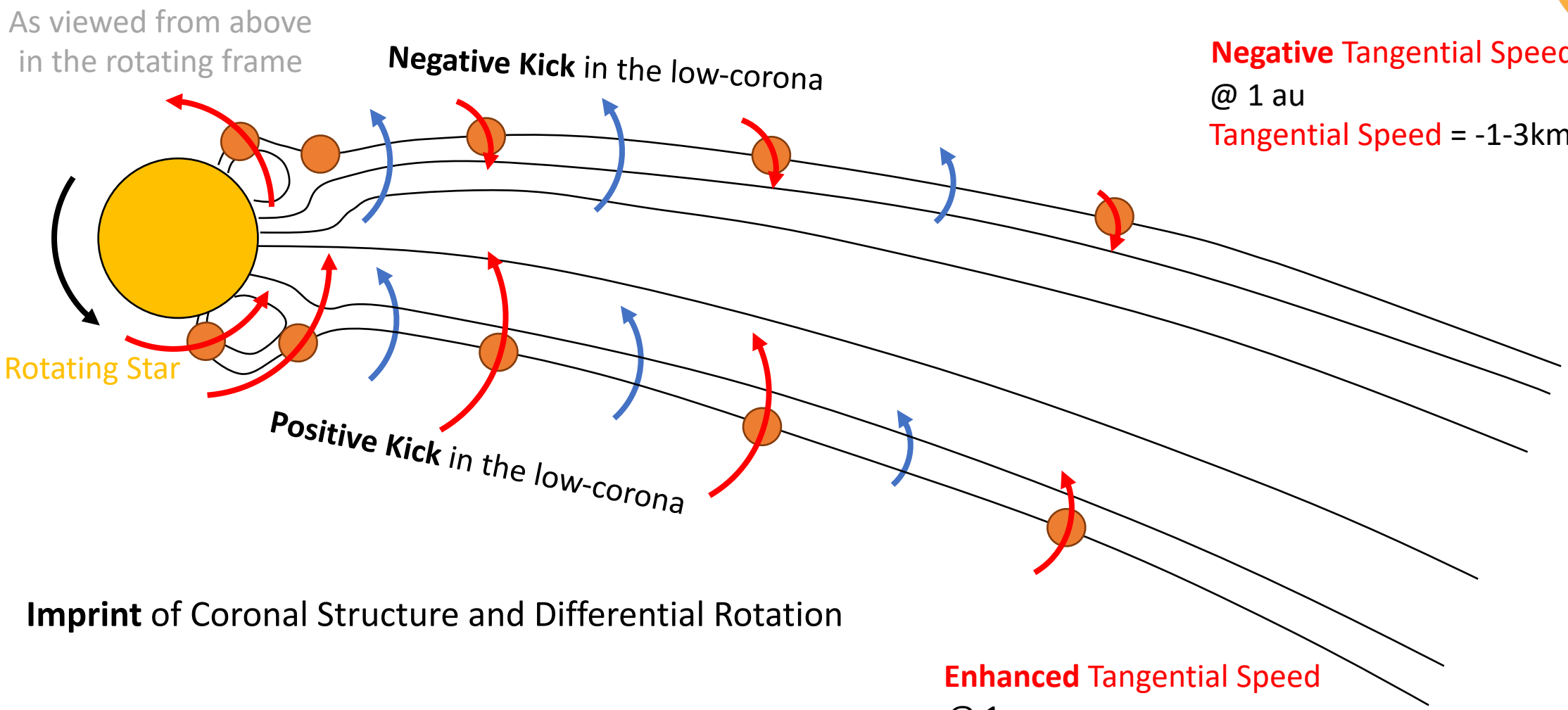
Complexity in the Solar Wind Observations



Negative Tangential Speed
@ 1 au
Tangential Speed = -1-3km/s

Imprint of Coronal Structure and Differential Rotation

Enhanced Tangential Speed
@ 1 au
Tangential Speed = 3-5km/s

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More details in **Finley et al. (2019, 2020)**

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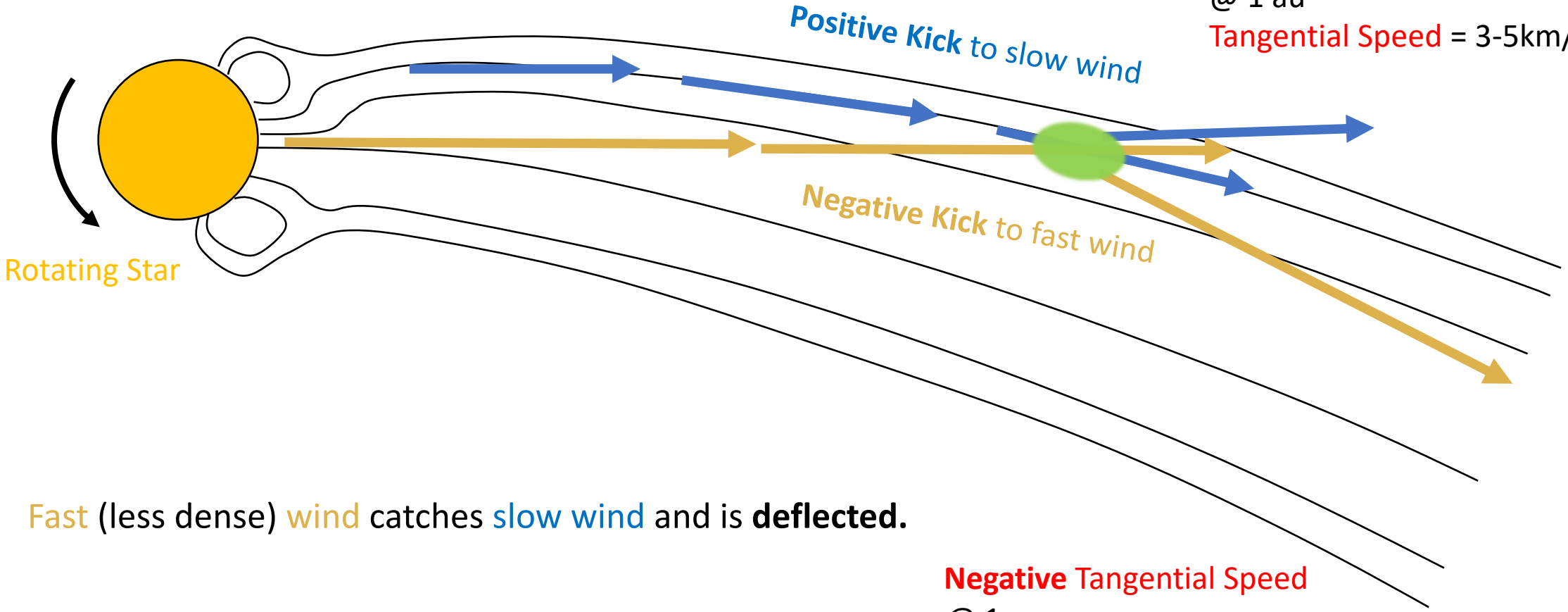
Solar Angular Momentum Redistribution

As viewed from above
in the rotating frame

Enhanced Tangential Speed
@ 1 au
Tangential Speed = 3-5km/s



Fast (less dense) wind catches slow wind and is **deflected.**

Negative Tangential Speed
@ 1 au
Tangential Speed = -5-10km/s

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More details in **Finley et al. (2019, 2020)**

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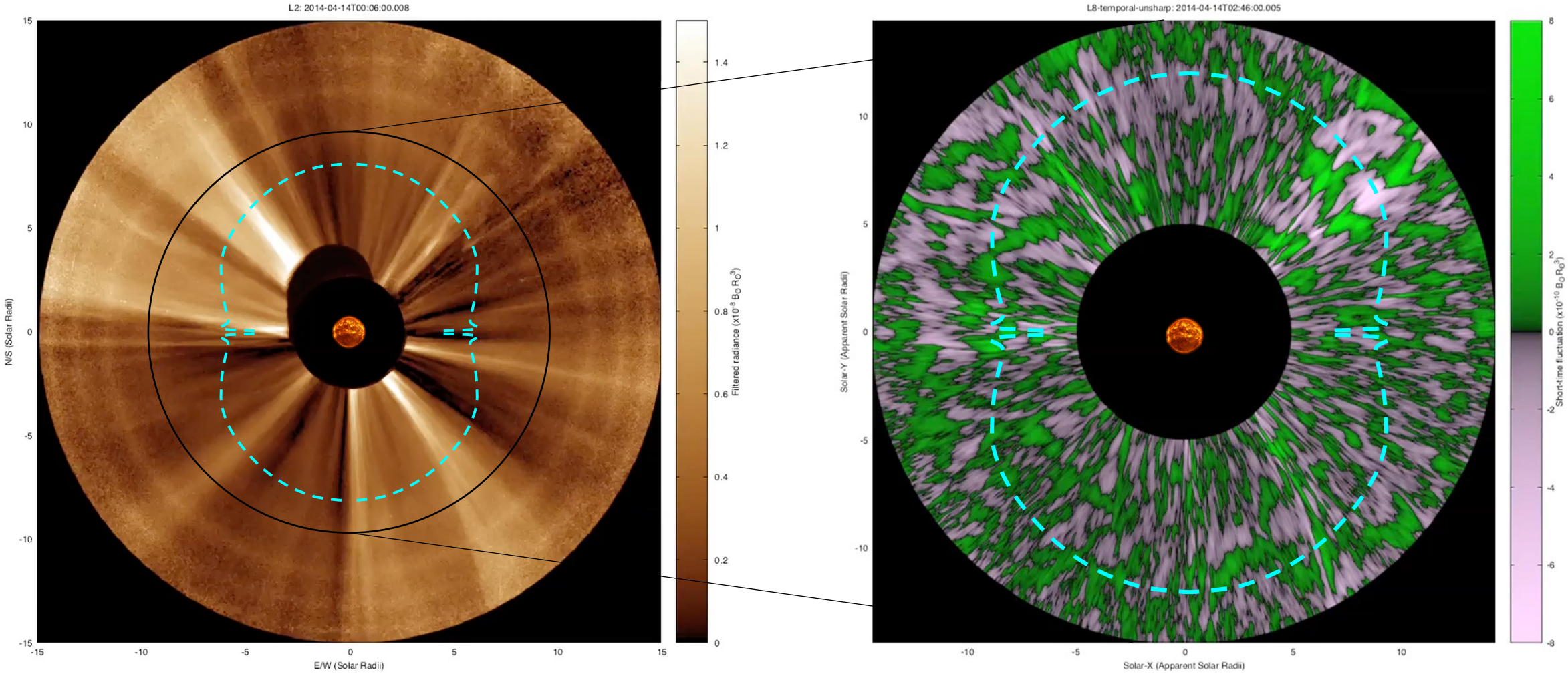
Where is the Sun's Alfvén Surface?



DeForest et al. 2014 *(plus the recently launched PUNCH mission)*

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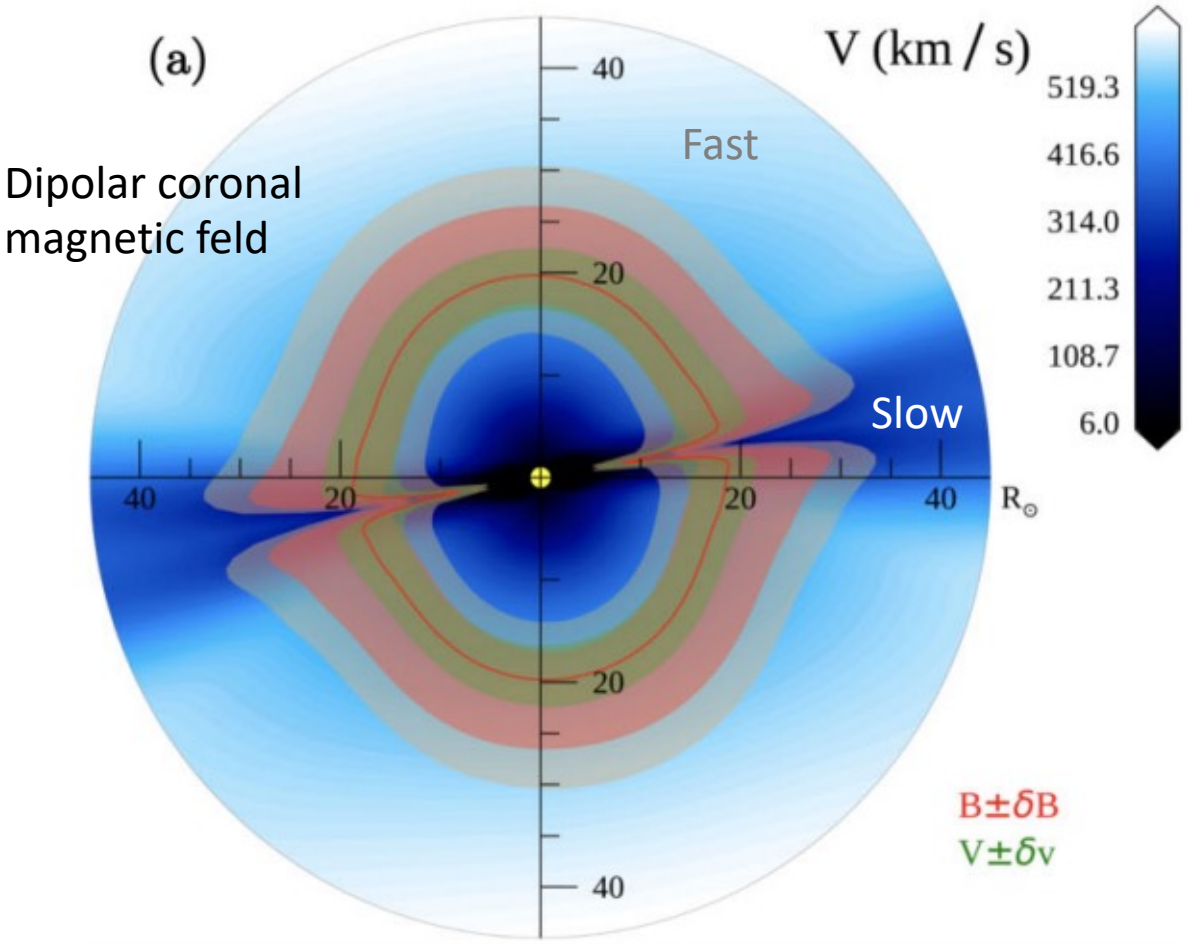
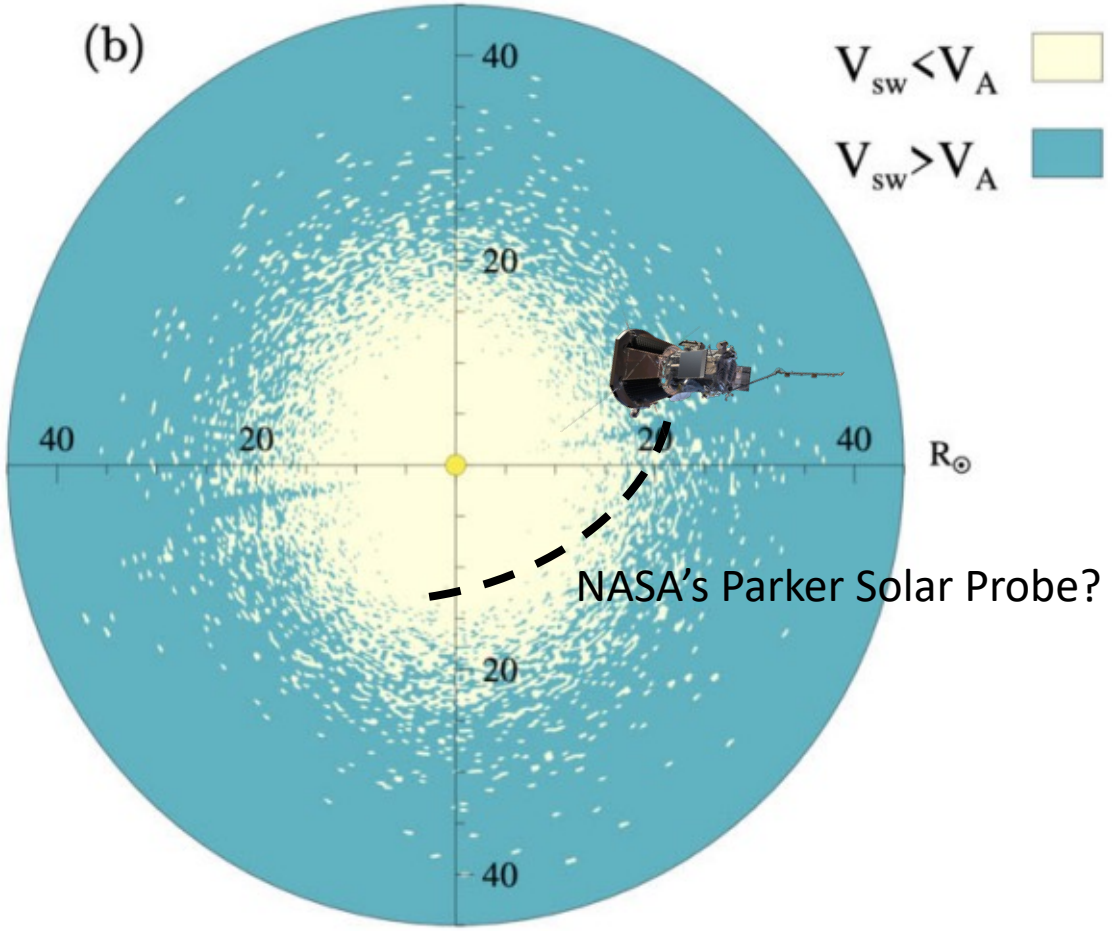
Where is the Sun's Alfvén Surface?



Dipolar coronal magnetic feld



Chhiber et al. 2022

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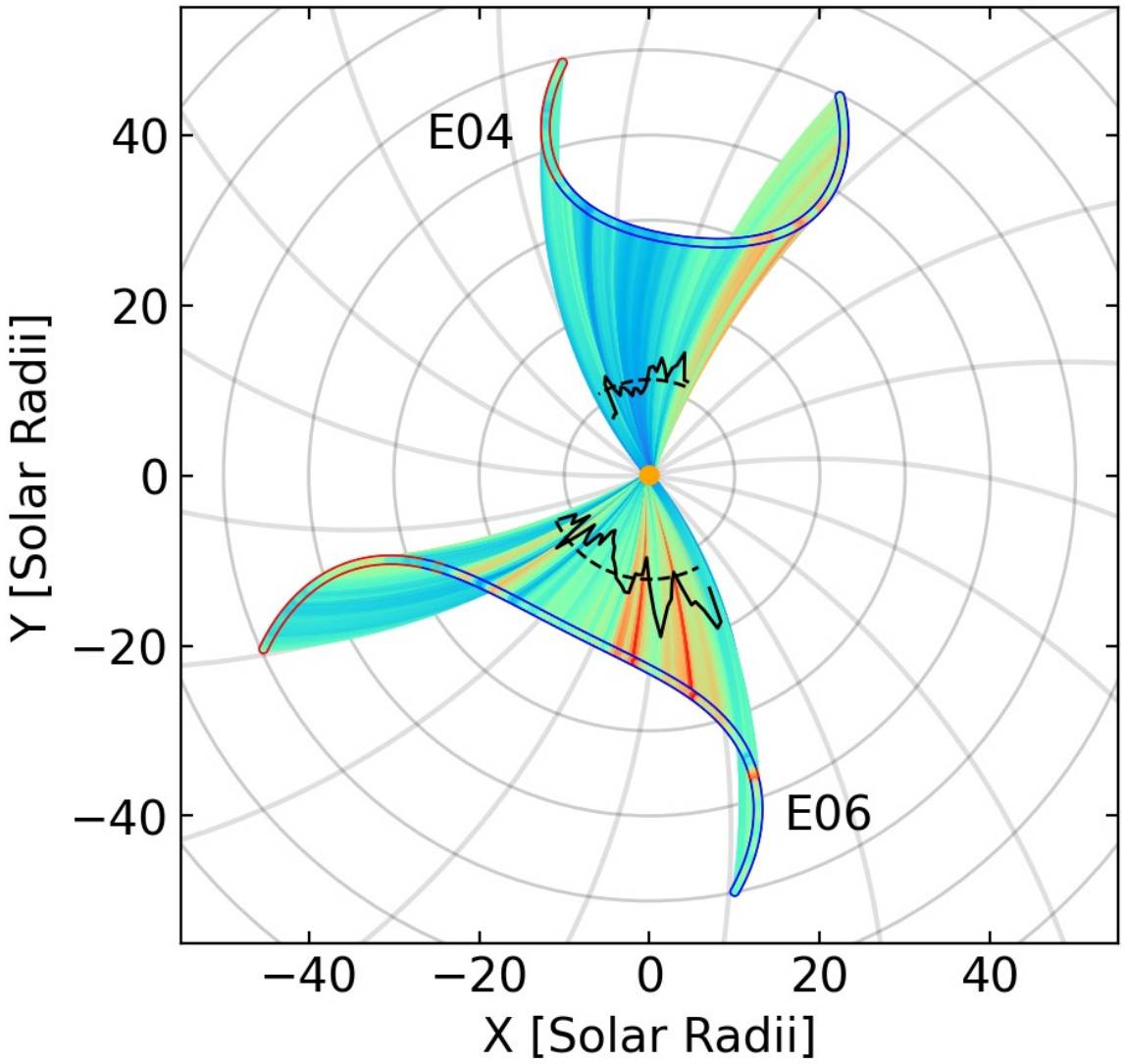
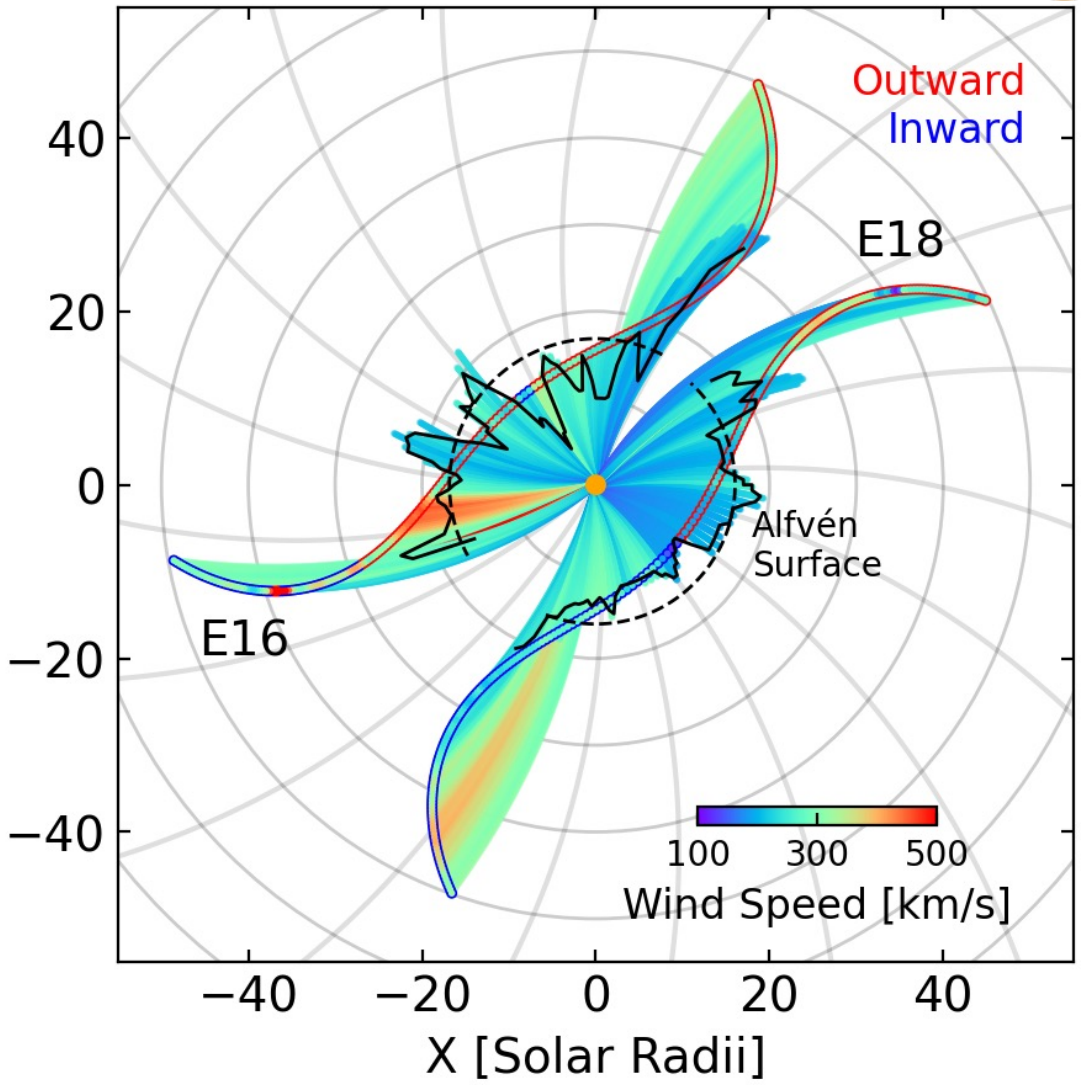
NASA's Parker Solar Probe





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Finley et al. (in preperation)

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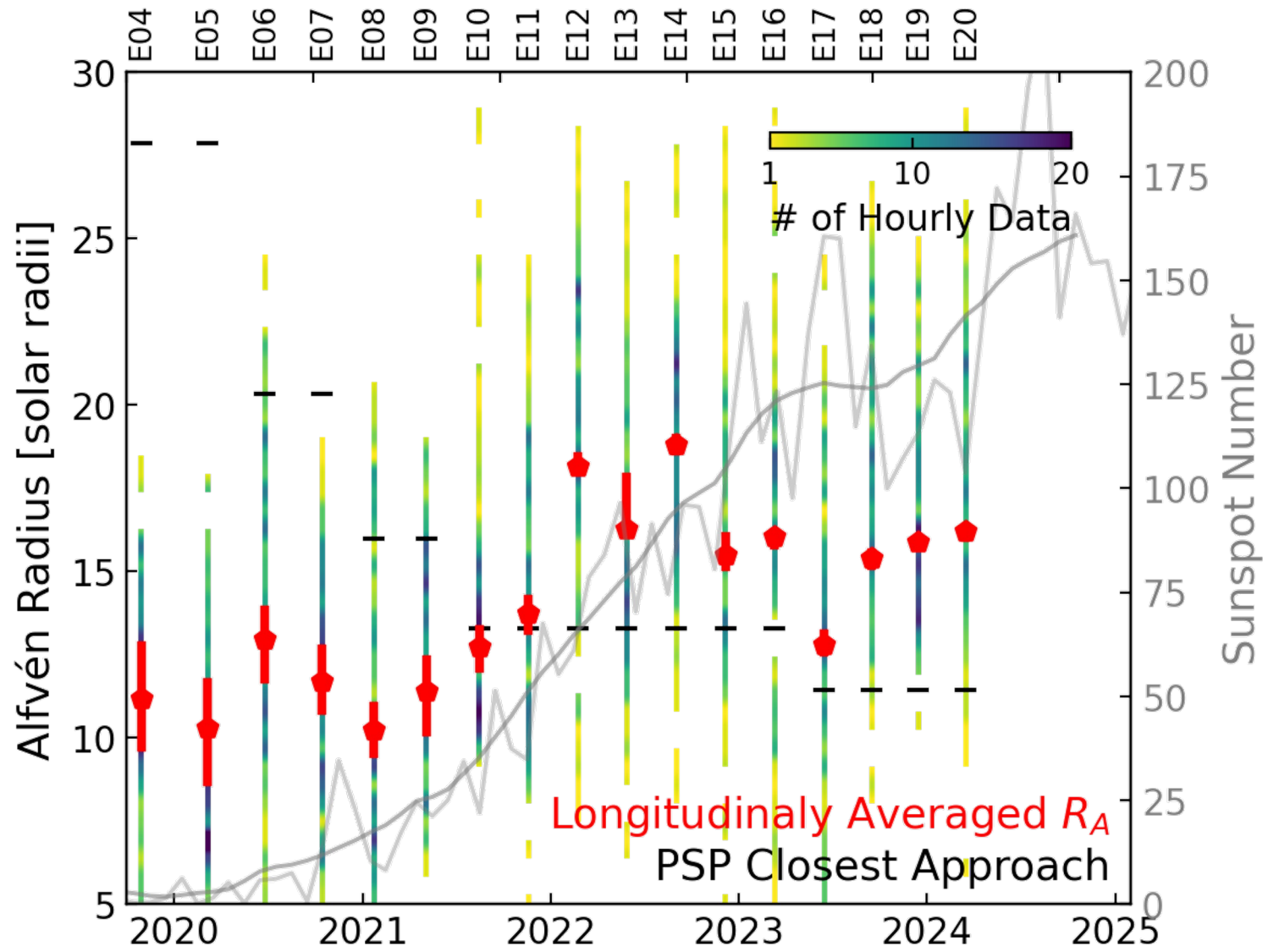
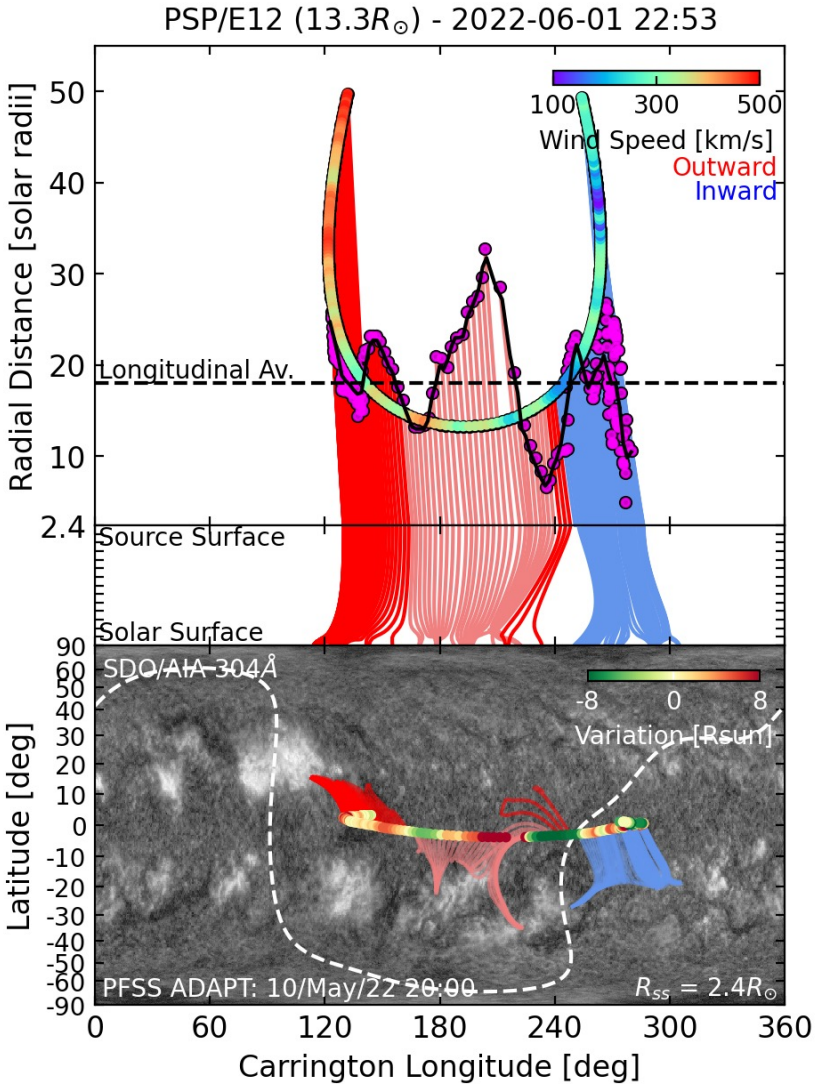
Solar Cycle Variation



Link to Corona:



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Finley et al. (in preperation)

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NGC 2112 (LRGB) by Dan Crowson (BBC Sky at Night)

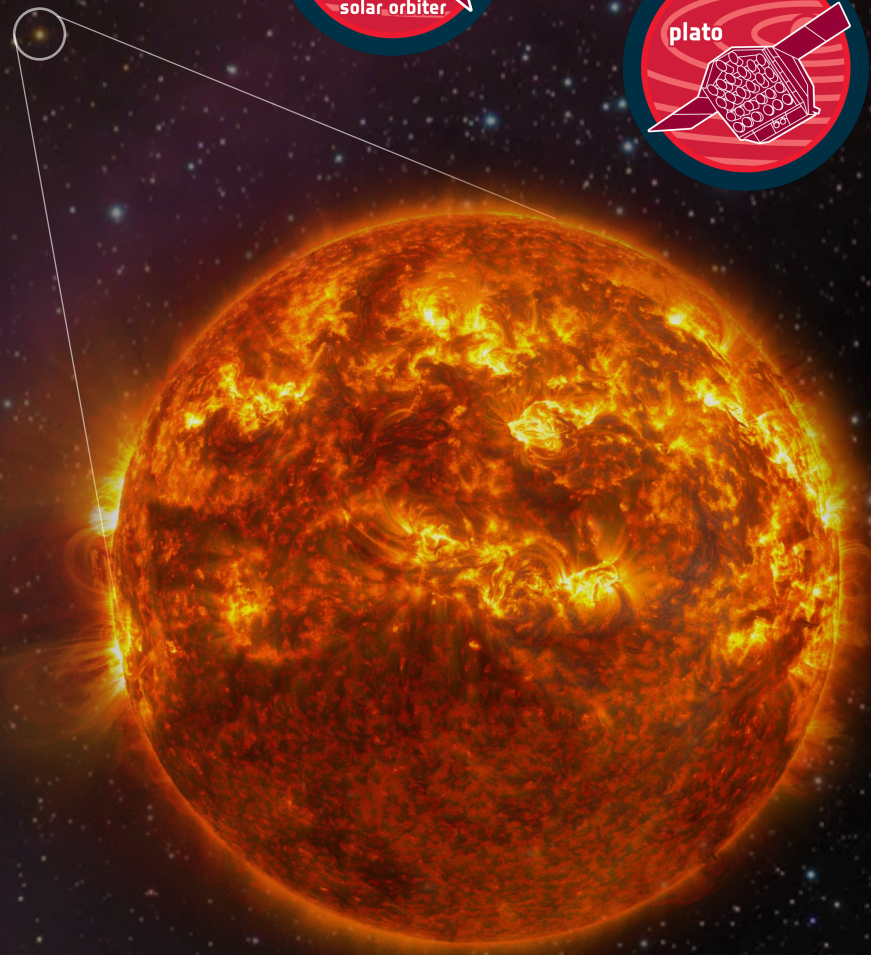
Conclusions

Magnetic **activity**, **rotation** and stellar **age** are linked due to the loss of angular momentum in **stellar winds**.

This relationship shapes the **coronae** and astrospheres of stars, which directly impact the secular evolution of **exoplanetary atmospheres**.

Gyrochronology is useful for determining stellar ages, however its accuratcy is **limited** by at least two physical phenomena:

1. The **stalling** of spin-down around **1 billion years**.
2. The **weakening** of spin-down around the **Sun's age**.



Take Home Message: Currently in a golden age of solar and heliospheric physics. Developing a **better physical understanding** of the solar corona and wind, including direct measurements of the **Alfvén surface** and angular momentum transport. **Application** to other Sun-like stars with **the PLATO mission**.

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