Turbulent solar and stellar winds

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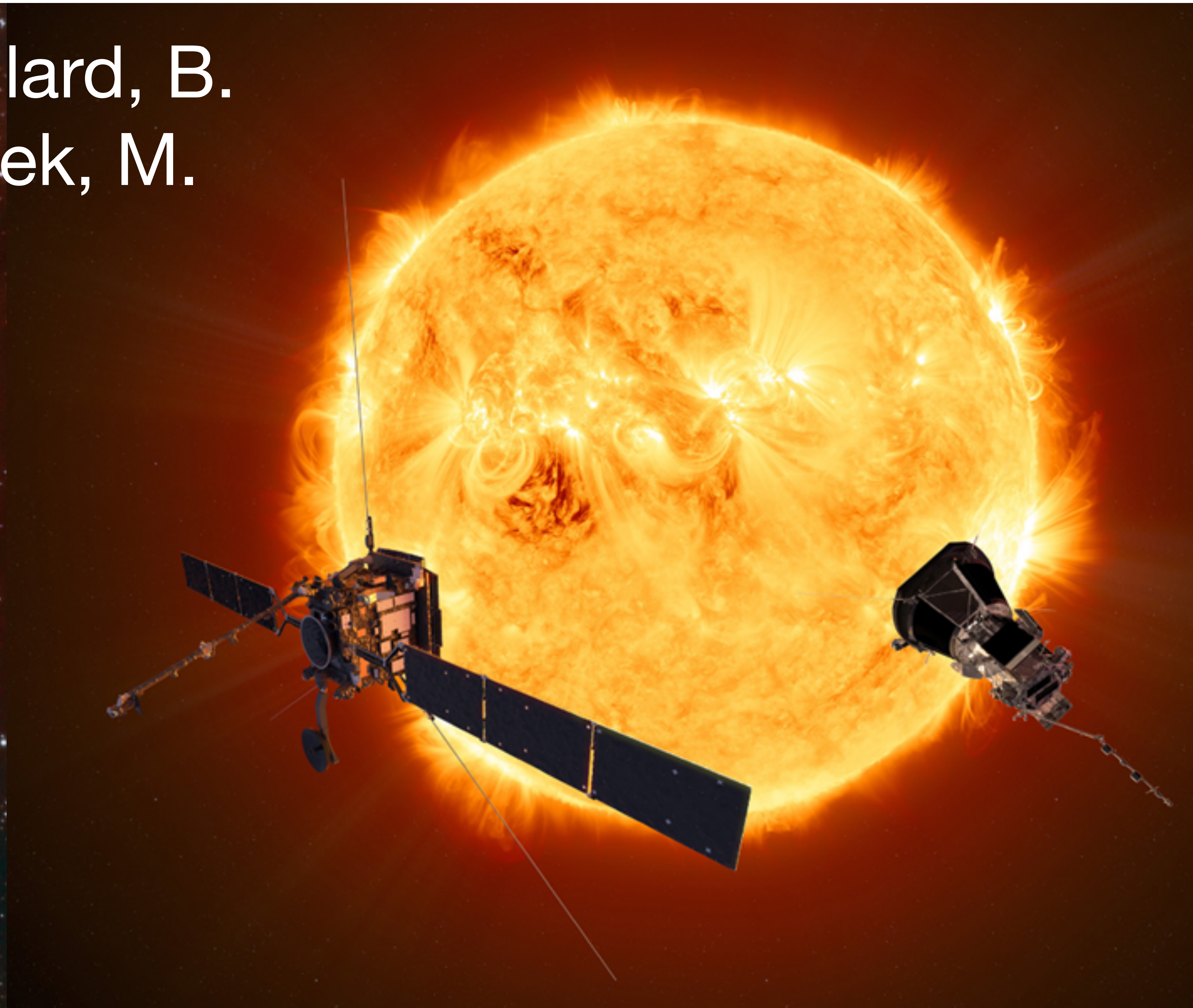


V. Réville, M. Velli, N. Fargette, A. Rouillard, B. Lavraud, S. Parenti, S. Brun, A. Strugarek, M. Shoda, PSP and SolO teams.

Journées SF2A, 9/6/2022

Atmospheres of solar-like stars

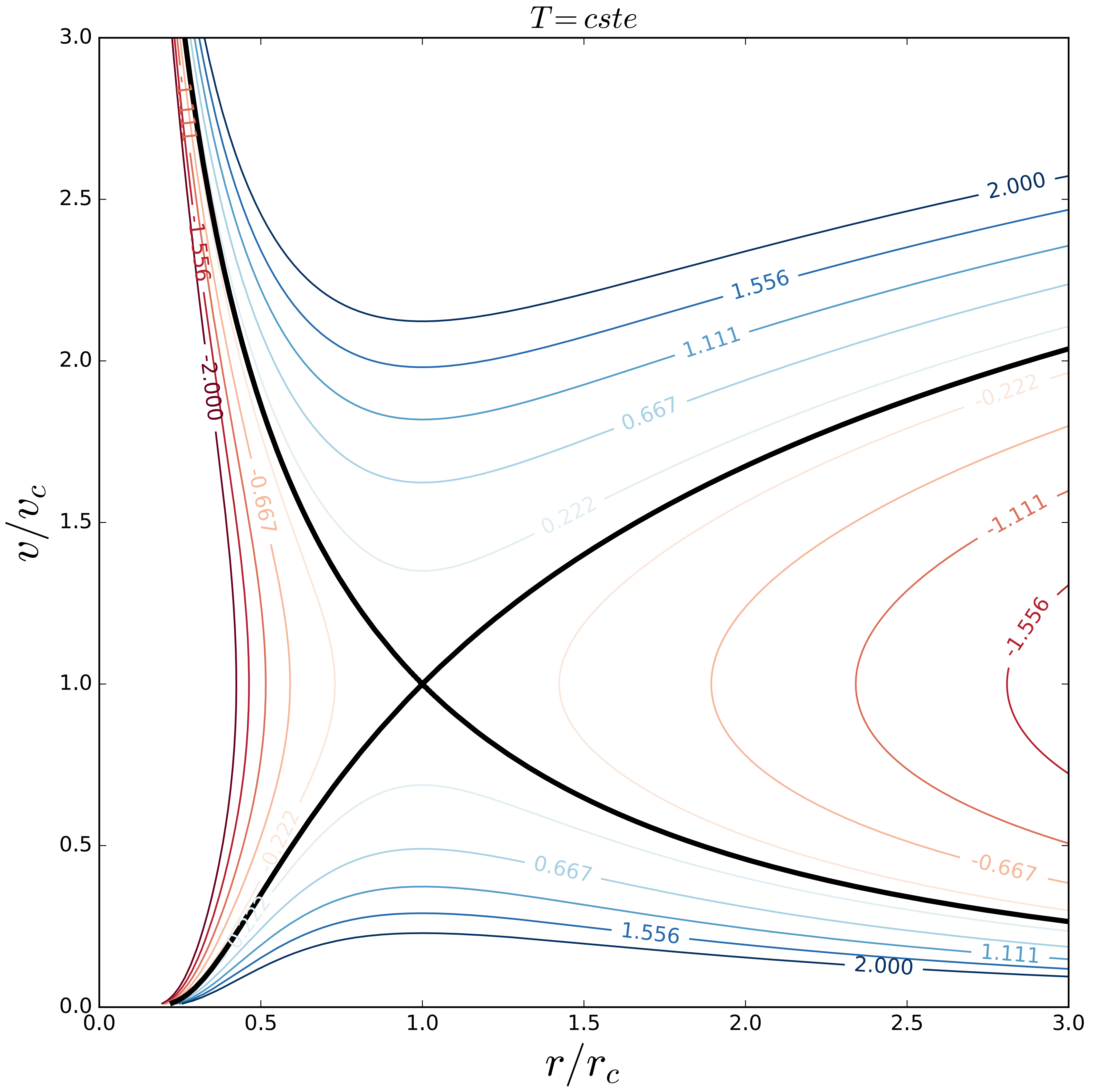
Wind = MK corona under gravity potential

- Hydrogen plasma of 1 MK
- Spherical geometry with a central object
- Very fast thermal conduction (electrons) ~isothermal

$$r_c = \frac{GM_\star}{2c_s^2}$$

[Parker 1958]

$$v_c = c_s = \sqrt{\frac{\partial p}{\partial \rho}}$$



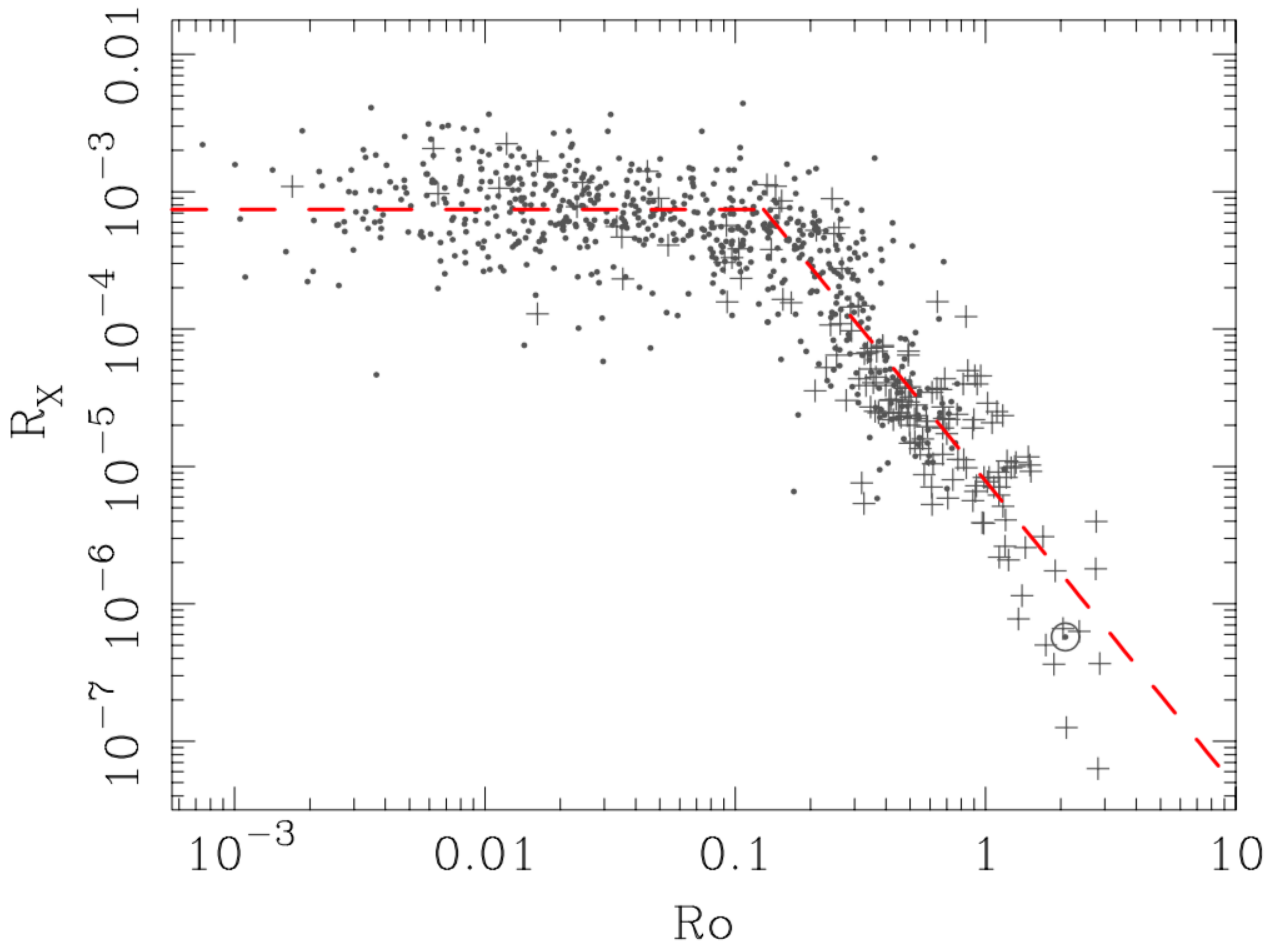
Stellar winds: observables

Transitioning to active/fast rotating stars

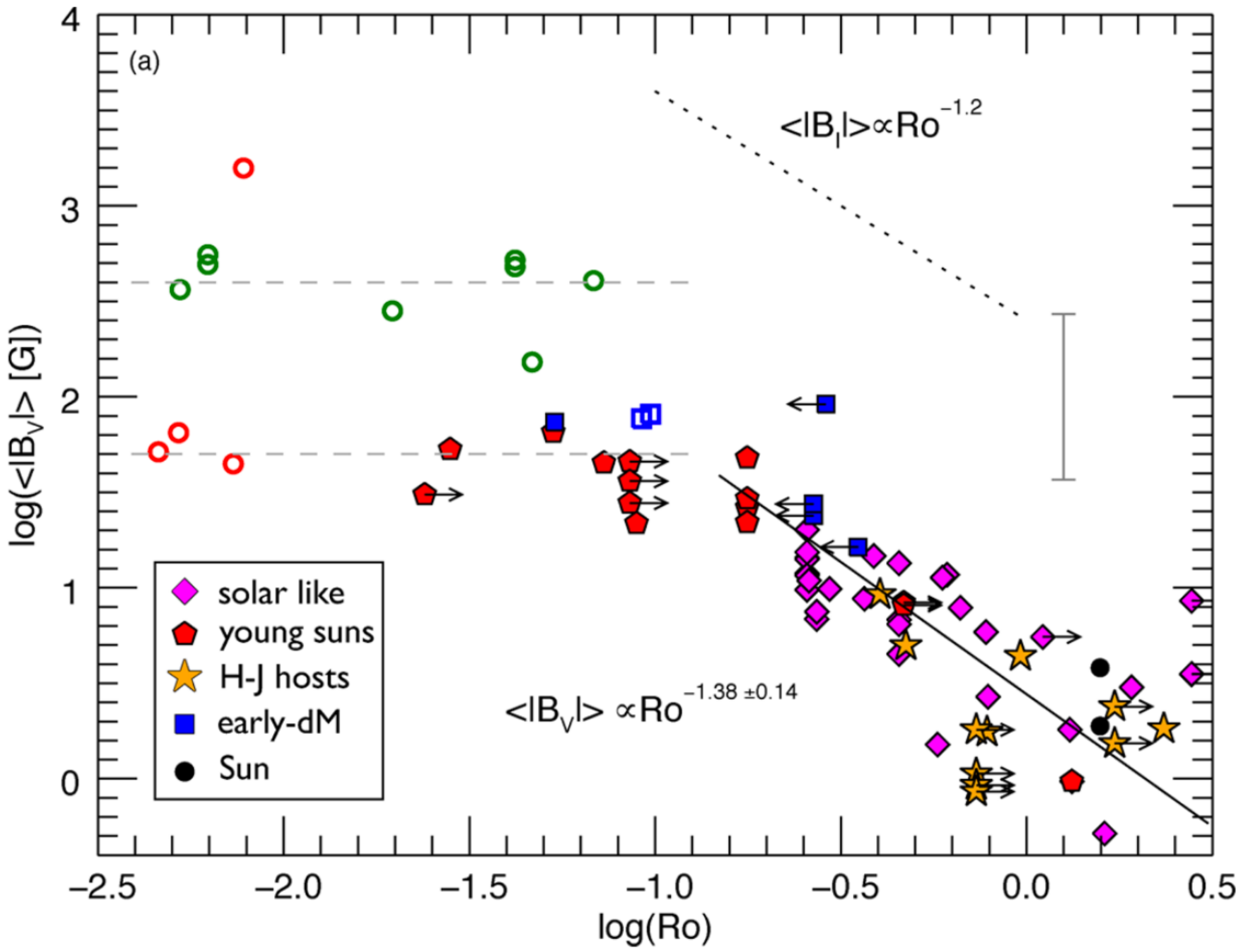
$$Ro = \frac{1}{\Omega_\star \tau_{cz}}$$

Rotation

X-ray



$\langle B \rangle$



[Benbakoura, Réville et al. 2021]

[Wright et al. 2011]

[Vidotto et al. 2014]

- Saturation phase for active stars in braking, X-ray and magnetic field

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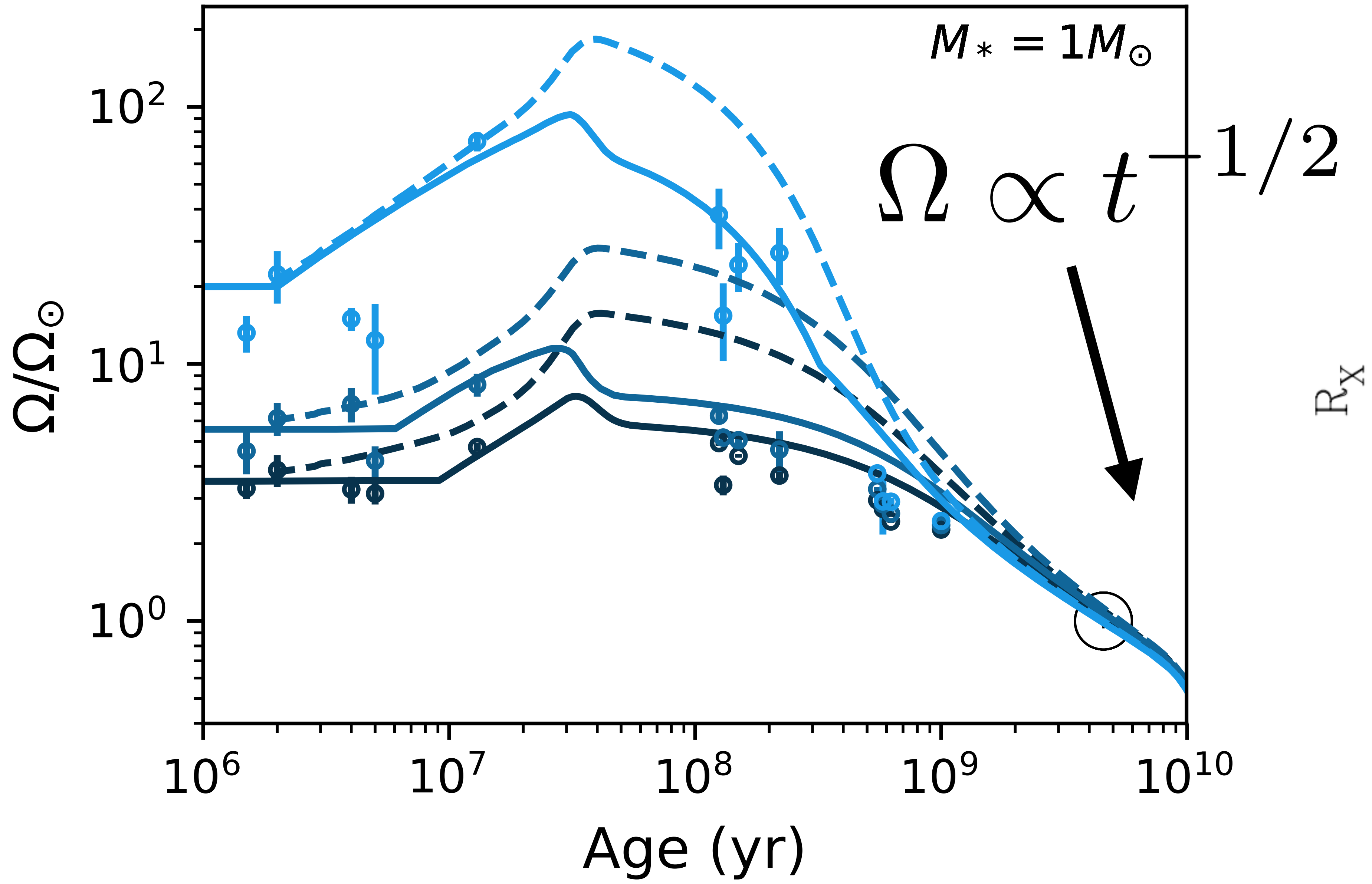

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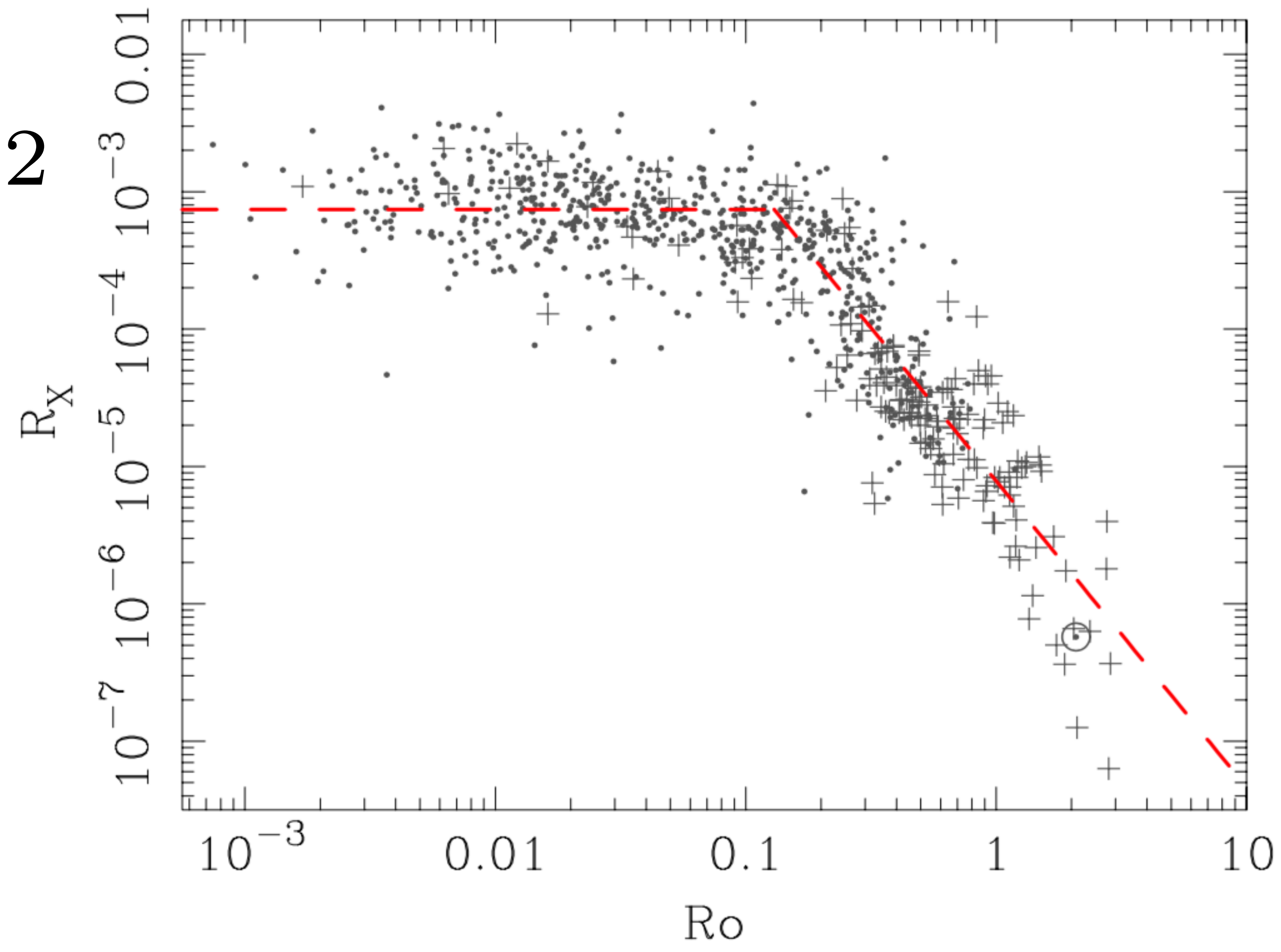
X-ray



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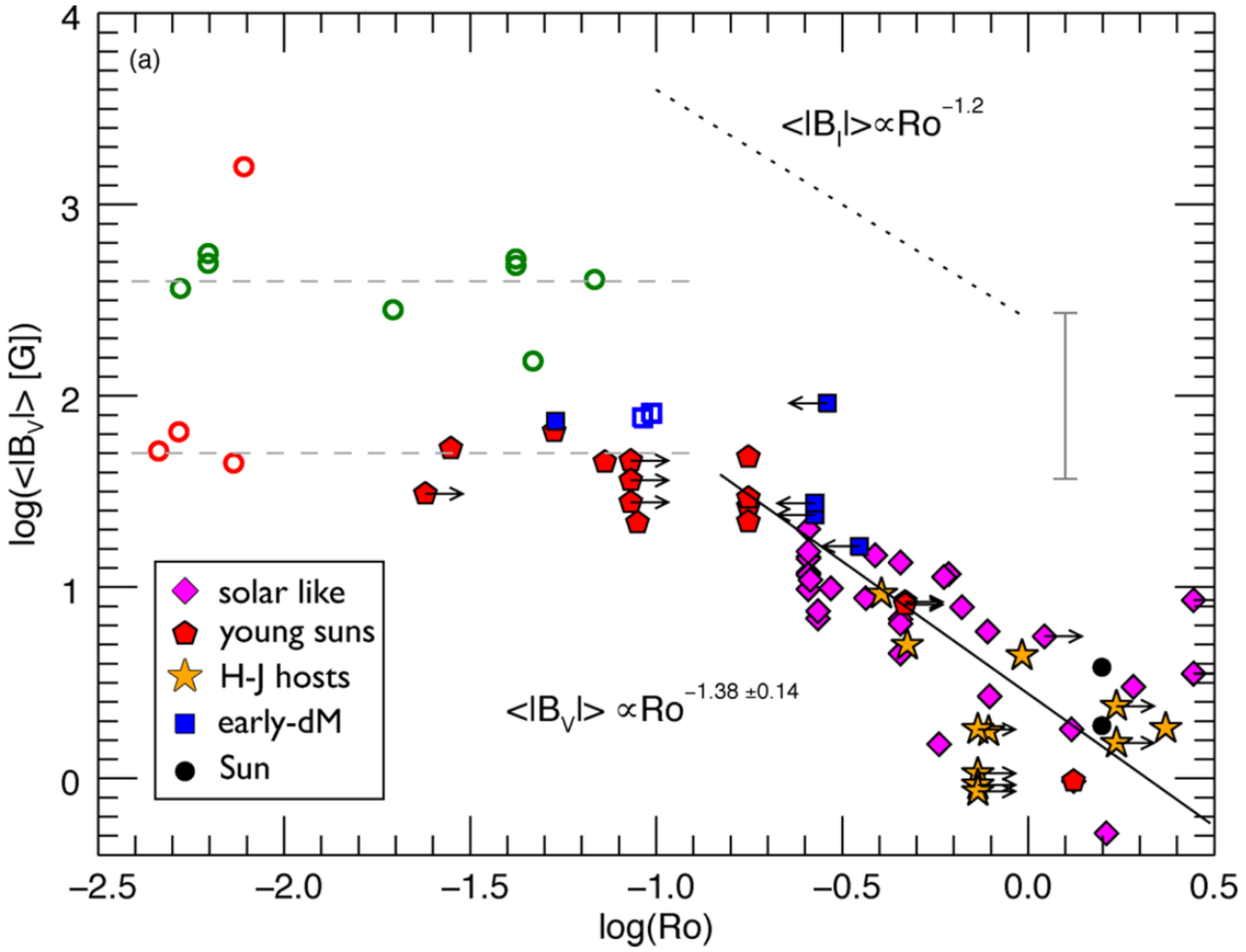


[Vidotto et al. 2014]

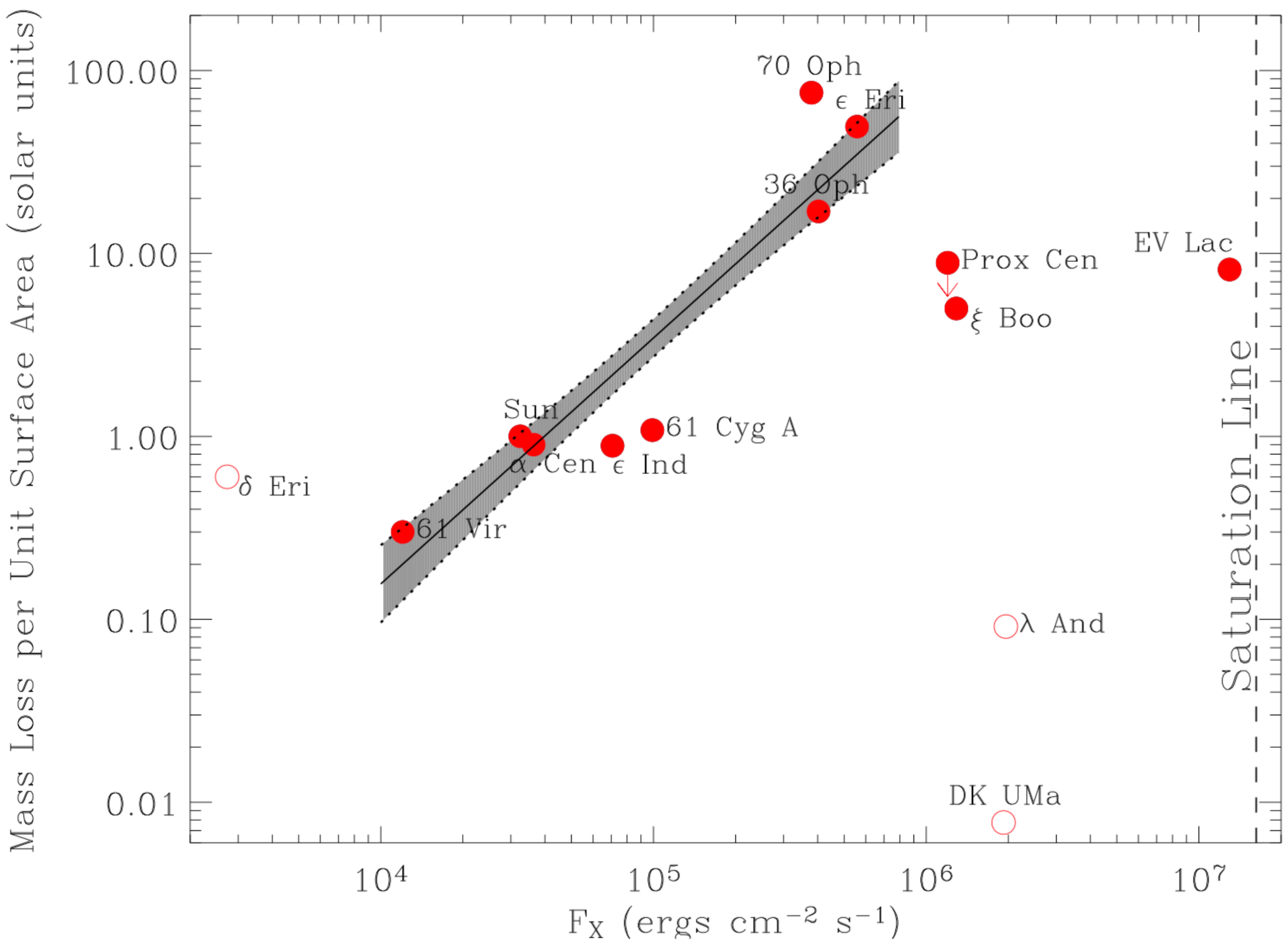
- Saturation phase for active stars in braking, X-ray and magnetic field

Stellar winds: observables

Mass loss saturation

- Very little (indirect) mass loss observations
- Correlation with Fx -> Rotation, Mag field
- Saturation (before X-ray sat.)
- Largely unexplained

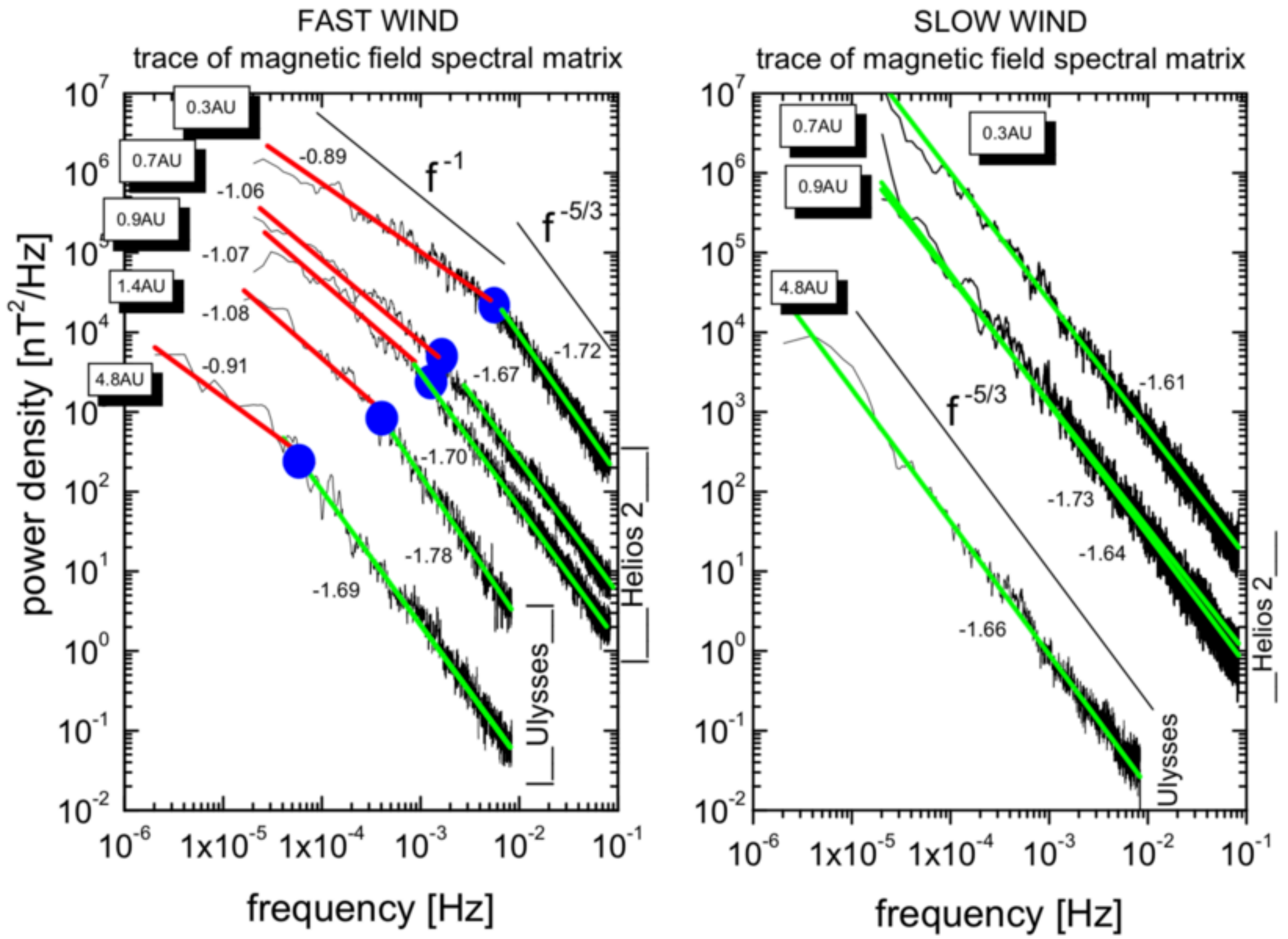
[Wood et al. 2005]



Turbulence as the main process of solar wind acceleration and coronal heating

Turbulence in the solar wind

Observations



- The solar wind is a large Reynolds (Lundquist) number system (> 10^{12}).
- Turbulence is the universal way to transfer energy from large scales to small, kinetic scales (heating).
- Observed in the solar wind with typical Kolmogorov spectra $f^{-5/3}$.

[Bruno & Carbone 2013]

Alfvén wave turbulence 3D MHD model

Equations

$$\partial_t \rho + \nabla \cdot [\rho \mathbf{v}] = 0,$$

$$\partial_t (\rho \mathbf{v}) + \nabla \cdot [\rho \mathbf{v}\mathbf{v} - \mathbf{B}\mathbf{B} + \mathbf{I}(p + \mathcal{E}/2)] = -\rho \nabla \Phi,$$

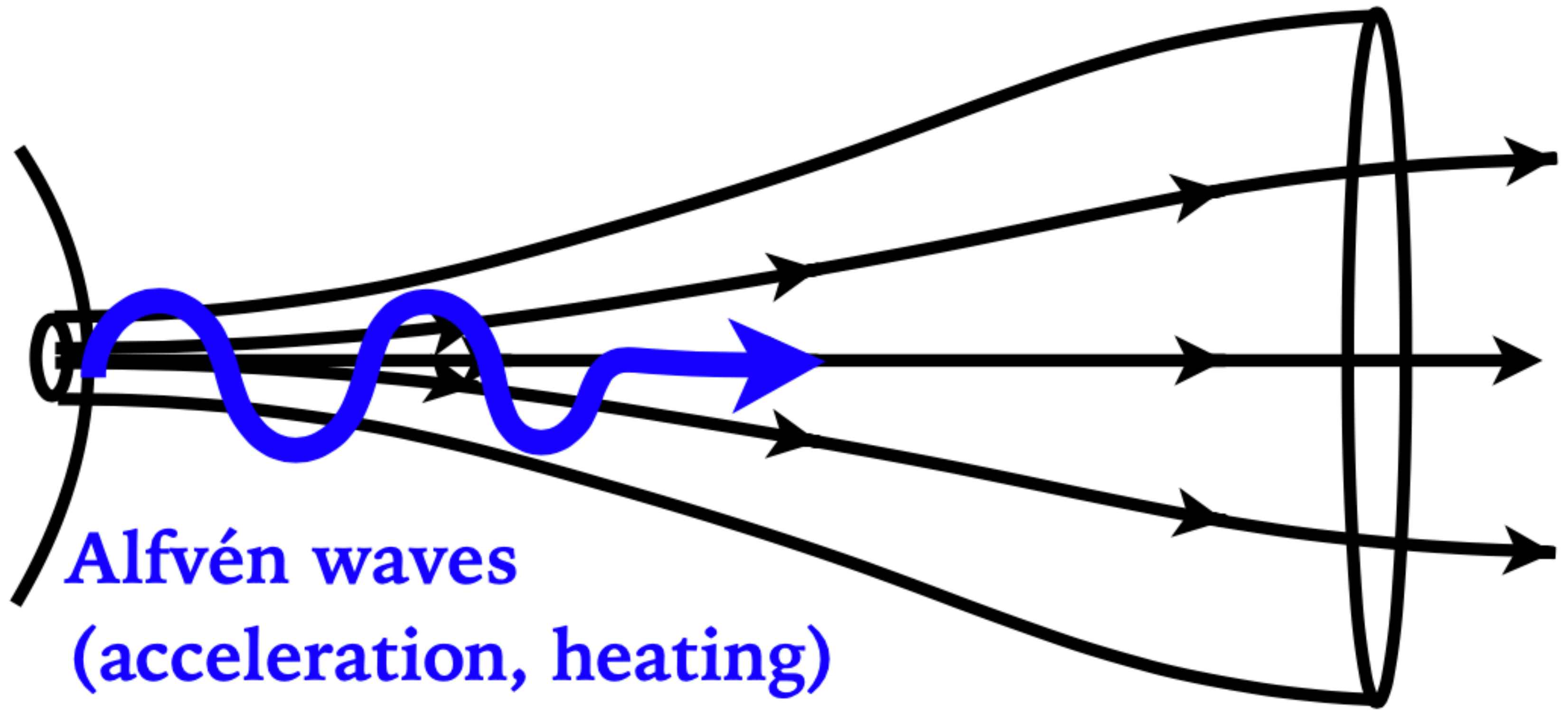
$$\partial_t (E + \mathcal{E} + \rho \Phi) + \nabla \cdot \left[(E + p + \mathcal{E}/2 + \rho\Phi)\mathbf{v} - \mathbf{B}(\mathbf{v} \cdot \mathbf{B}) + \mathbf{v}_g^+ \mathcal{E}^+ + \mathbf{v}_g^- \mathcal{E}^-\right] = Q,$$

Volume heating, Wave heating, Conduction, Radiation:

$$Q = Q_h + Q_w - Q_c - Q_r$$

$$\partial_t \mathbf{B} + \nabla \cdot [\mathbf{v}\mathbf{B} - \mathbf{B}\mathbf{v}] = \eta \nabla \times \mathbf{B},$$

$$\partial_t \mathcal{E}^{\pm} + \nabla \cdot \left[(\mathbf{v} \pm \mathbf{v_A})\mathcal{E}^{\pm}\right] = -\frac{\mathcal{E}^{\pm}}{2} \nabla \cdot \mathbf{v} - Q_w^{\pm},$$



- Core = PLUTO code (open source) [Mignone et al. 2007,2012]
- Physics of Alfvén wave propagation and dissipation [Réville et al. 2020]

$$\mathcal{E}^{\pm} = \rho \frac{|z^{\pm}|^2}{4}$$

$$Q_w^{\pm} = \rho \frac{|z^{\pm}|^2}{8\lambda_c} \left(\mathcal{R}|z^{\pm}| + |z^{\mp}|\right)$$

Reflection coeff. $\mathcal{R} = 0.1$

Parker Solar Probe

A quick presentation of the mission

- Launched August 2018
- 4 instruments suite (FIELDS, SWEAP, ISOIS, WISPR)
- First orbit was already the closest we'd been to the Sun
- Closest distance below 10 Sun, i.e., below the Alfvén surface
- Unravel the turbulence and heating mechanisms of the solar wind

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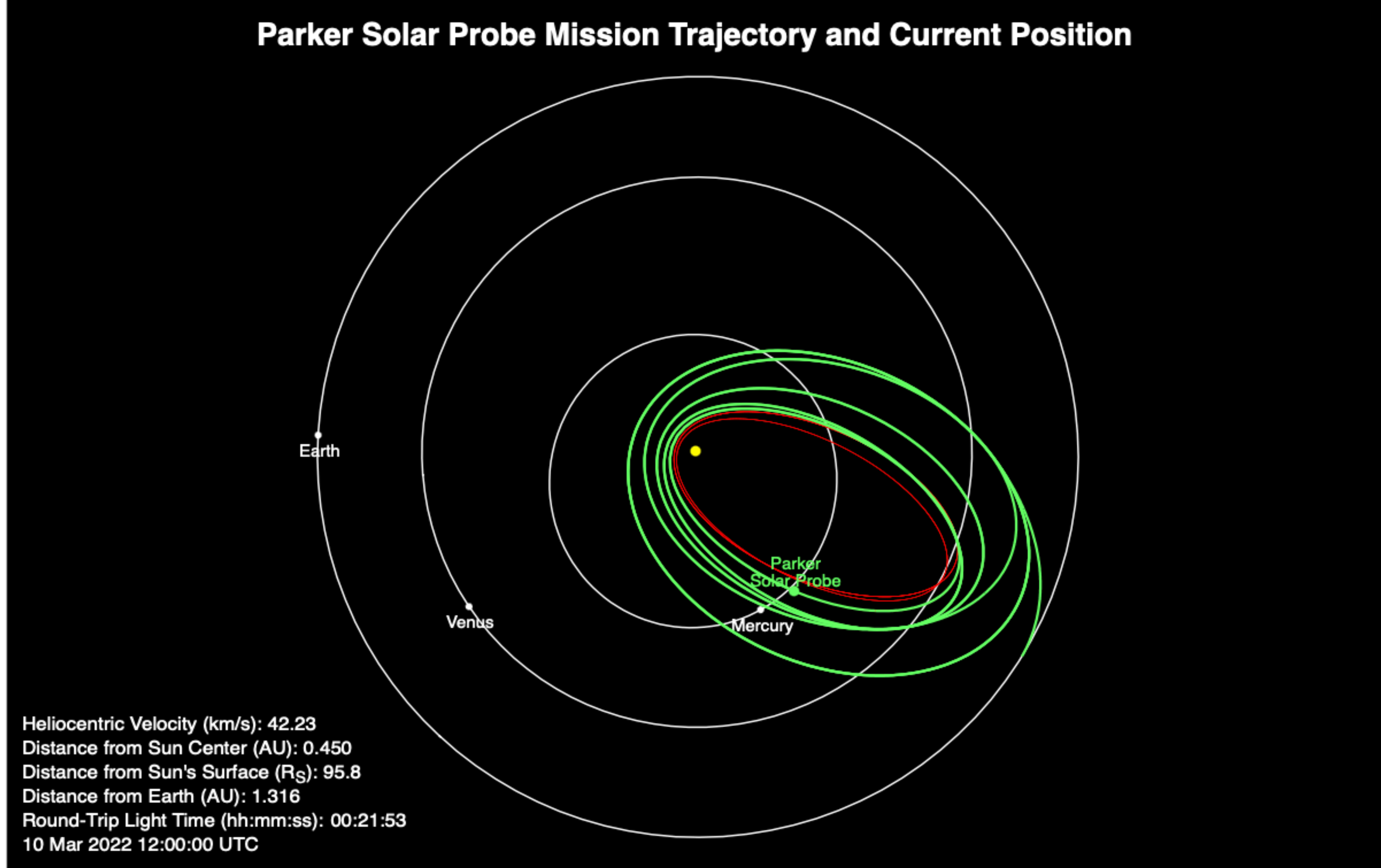
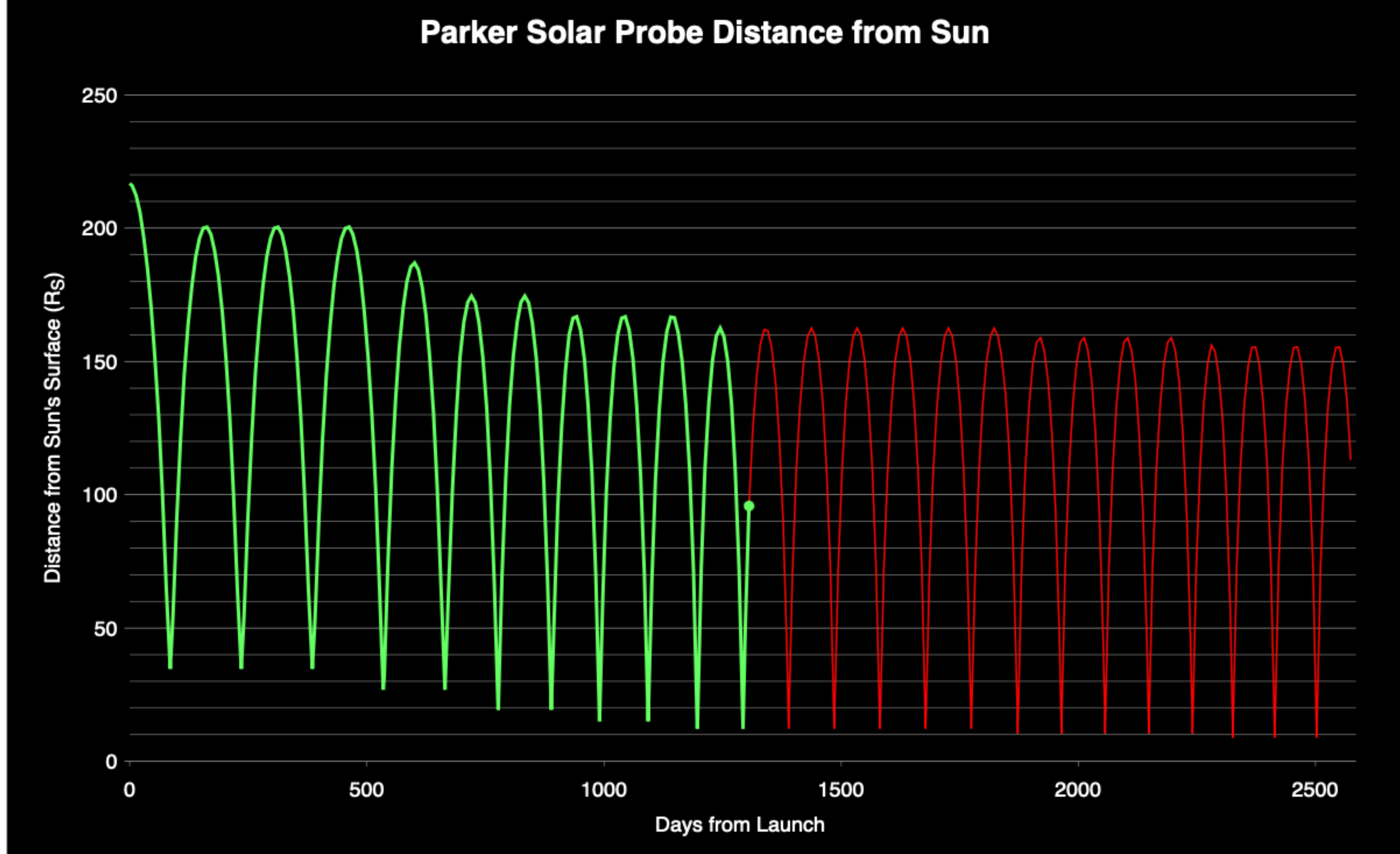


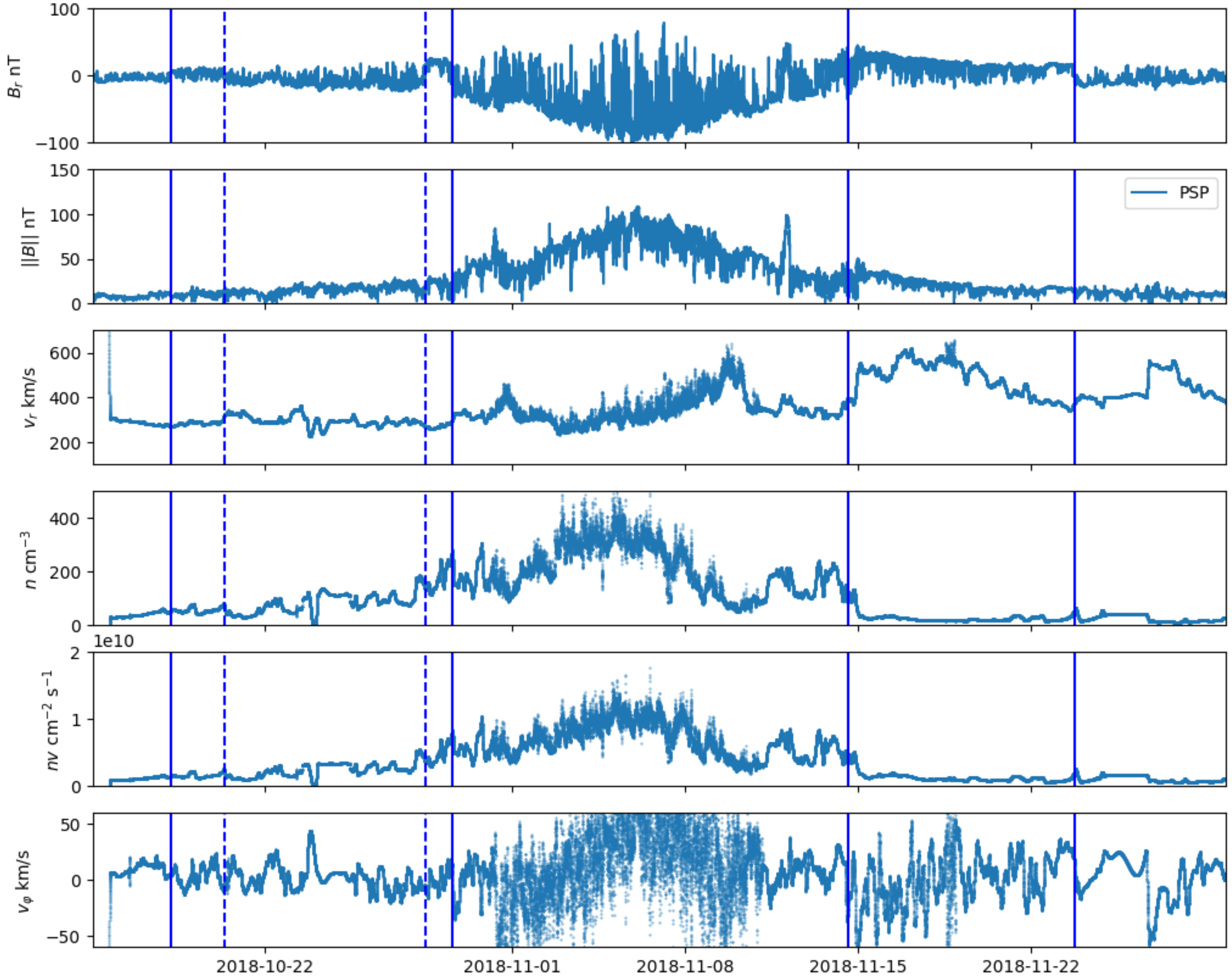


Alfvén wave turbulence 3D MHD model

Comparisons with PSP E1 data

[Réville et al. 2020]

- Particles (SWEAP) and magnetic field data (FIELDS)
- Single observational input : the magnetic field map (ADAPT) the day of perihelion.
- Average structures, change of polarity are very well reproduced.
- Fast evolving structure (switchbacks) are not meant to be reproduced.



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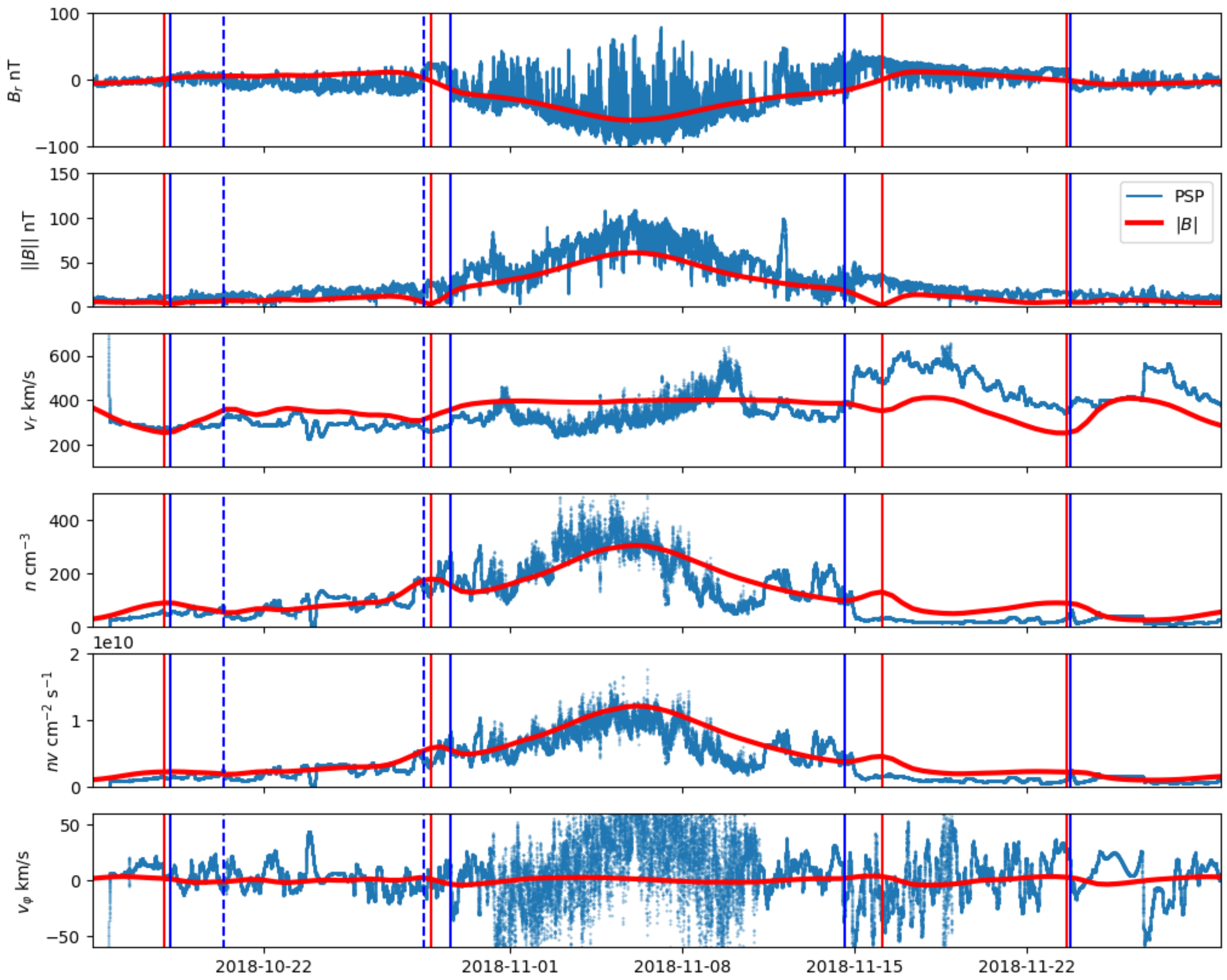
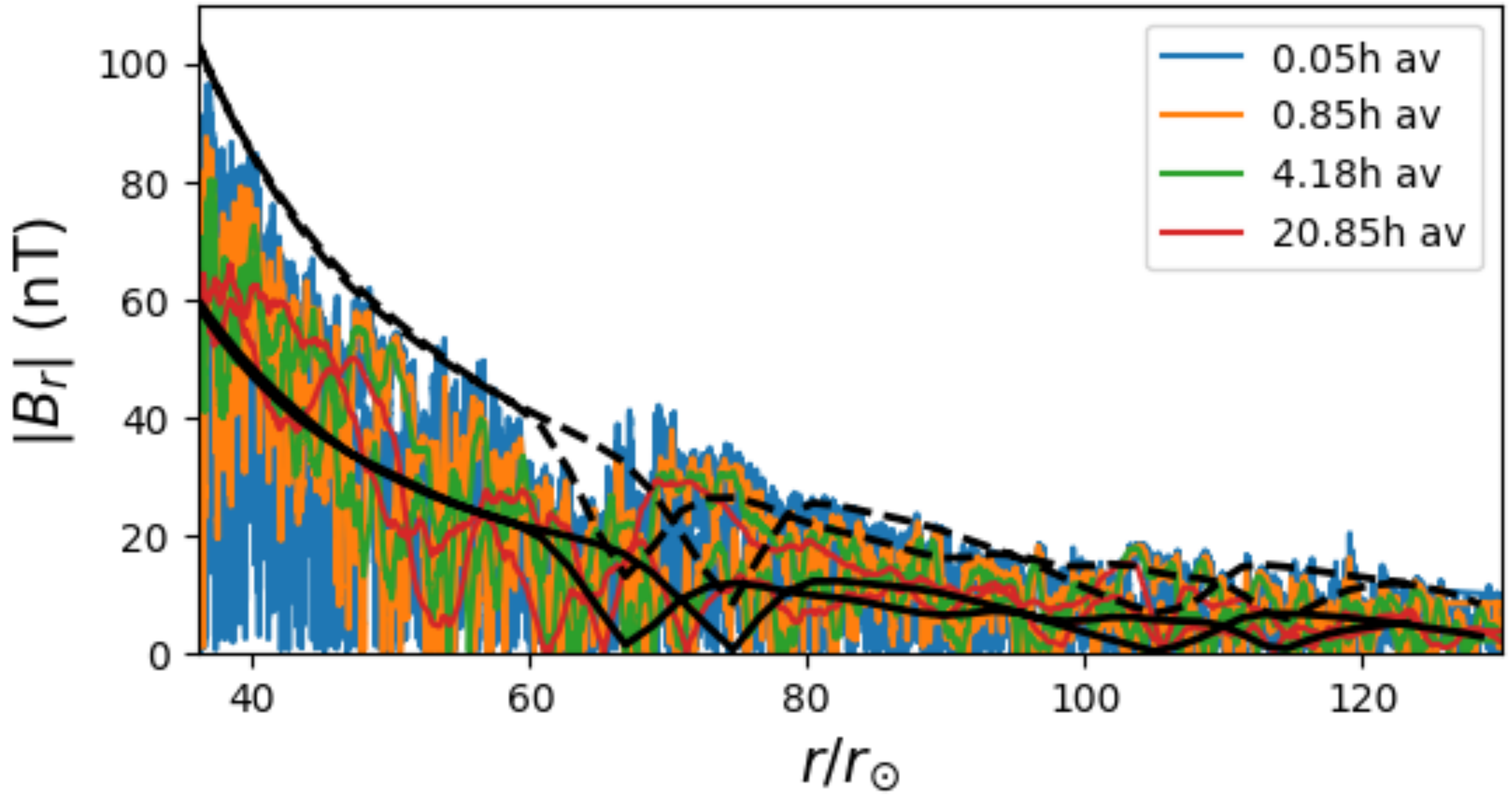


Alfvén wave turbulence 3D MHD model

Perturbations and switchbacks

- Averaging perturbations we fall back on the field amplitude of the model.
- The amplitude of the perturbations in the model is consistent with the observations.
- It proves that a AW turbulence models are very good at reproducing solar wind properties.
- Switchbacks are 3D non linear Alfvén waves, probably contributing to the turbulence.



$$\delta b^{\pm} = \sqrt{\mu_0 \mathcal{E}^{\pm}}$$

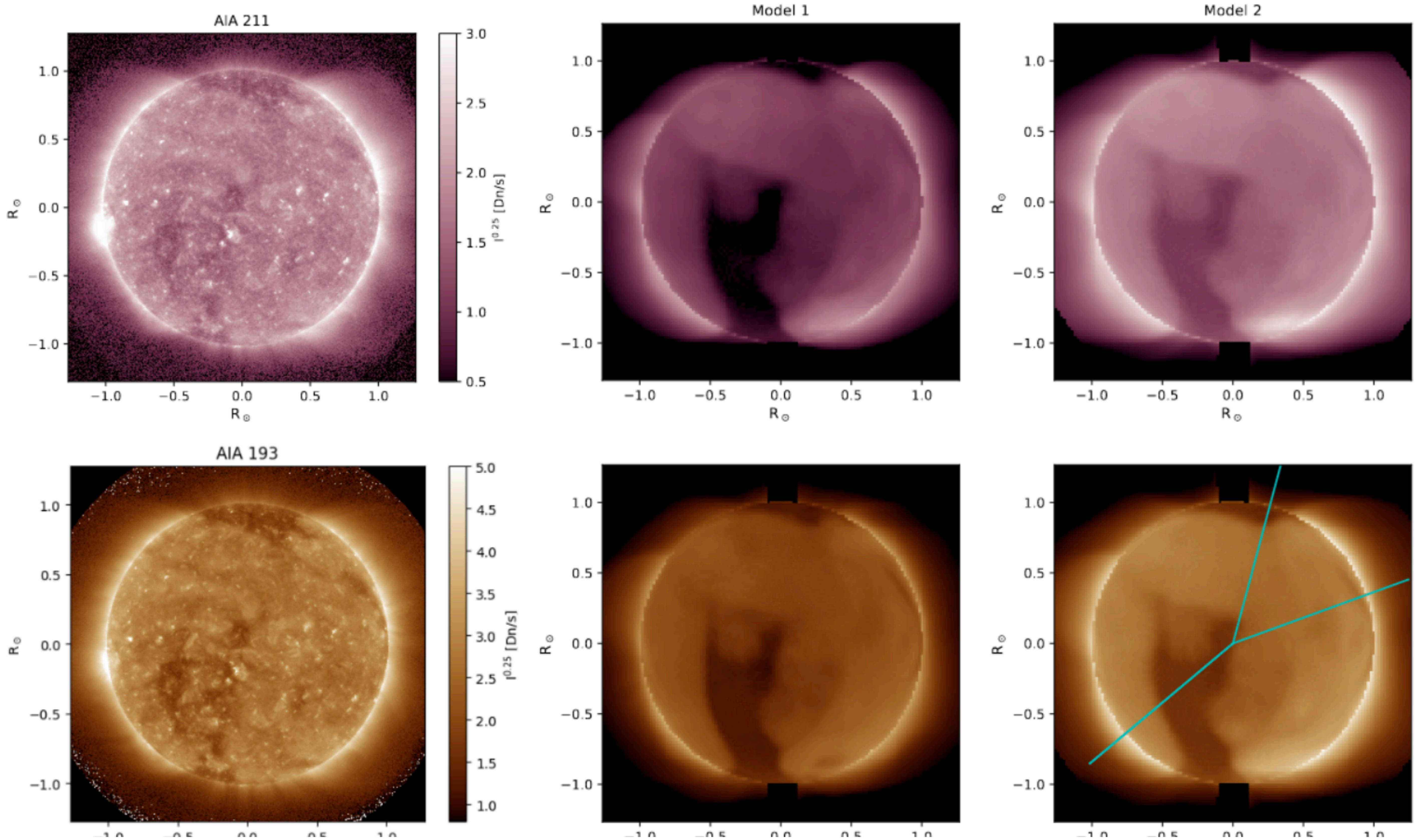
Alfvén wave turbulence 3D MHD model

Synthetic remote observations

[Parenti, Réville et al. 2022, ApJ]

- EUV instruments image the solar atmosphere using lines from strongly ionized ions (e.g. Fe)
- SDO/AIA probes temperatures ranging from 0.5 to 2-3 MK.
- We use the instrument response to compute the synthetic emissions from the model

$$I = \int_{LOS} n^2 \mathcal{R}(n,T) dl$$

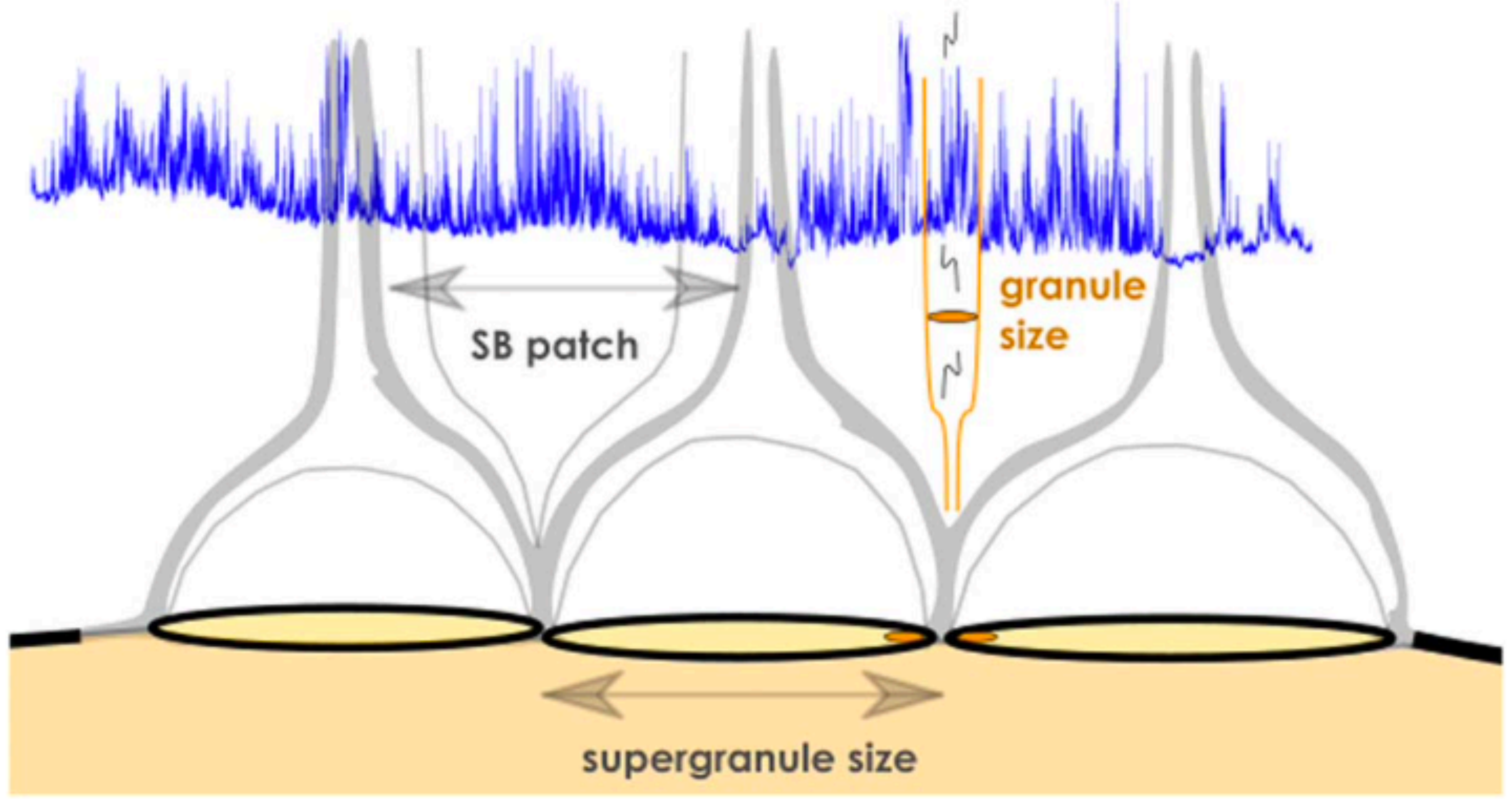


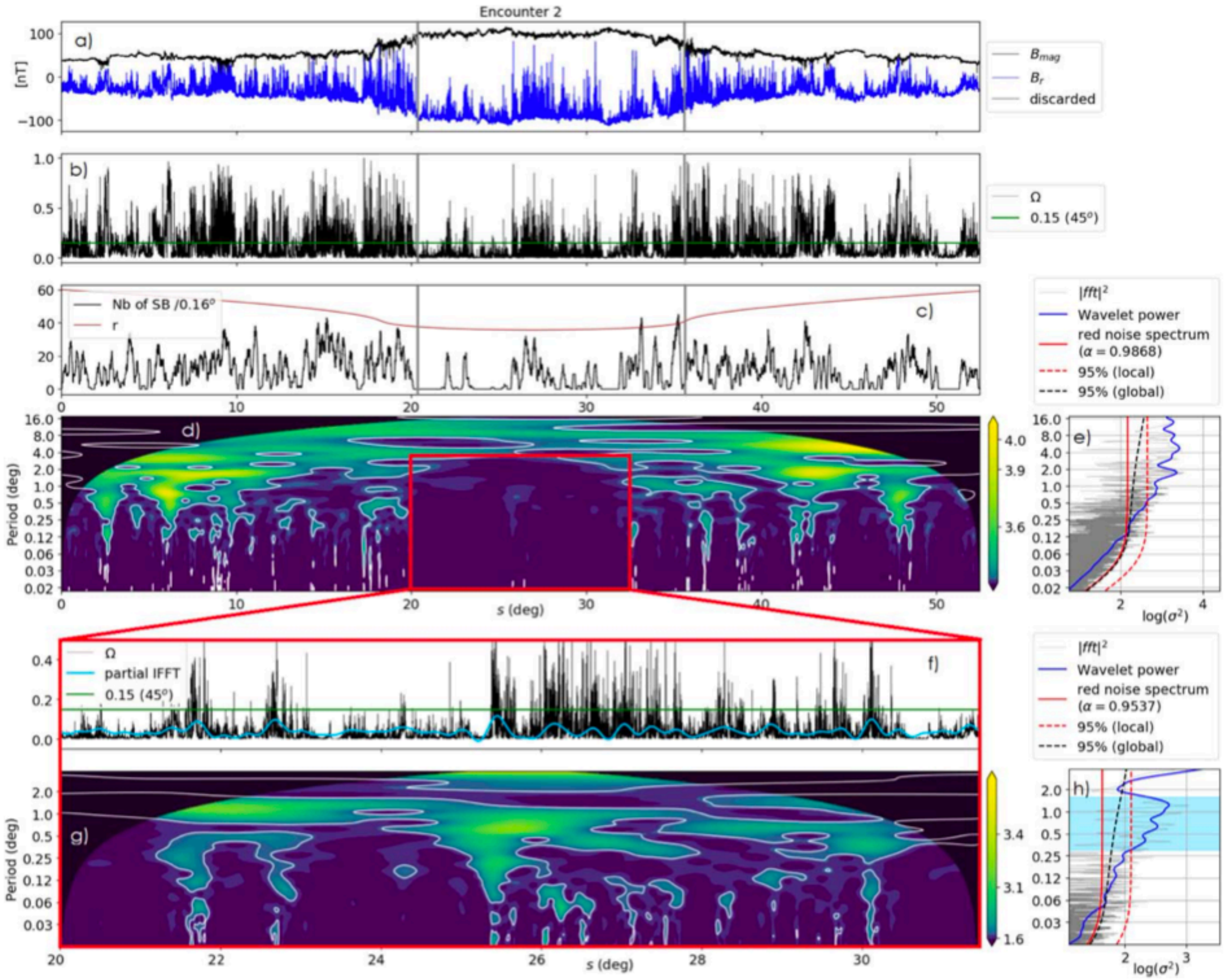
Switchbacks and surface structures

Link with the supergranulation

[Fargette et al., 2021]

- Wavelet analysis of SB shows that packets are related to granulation and super granulation scales





Alfvén wave driven stellar winds

$$\mathcal{P}_{\rm ram} = \rho v^2$$

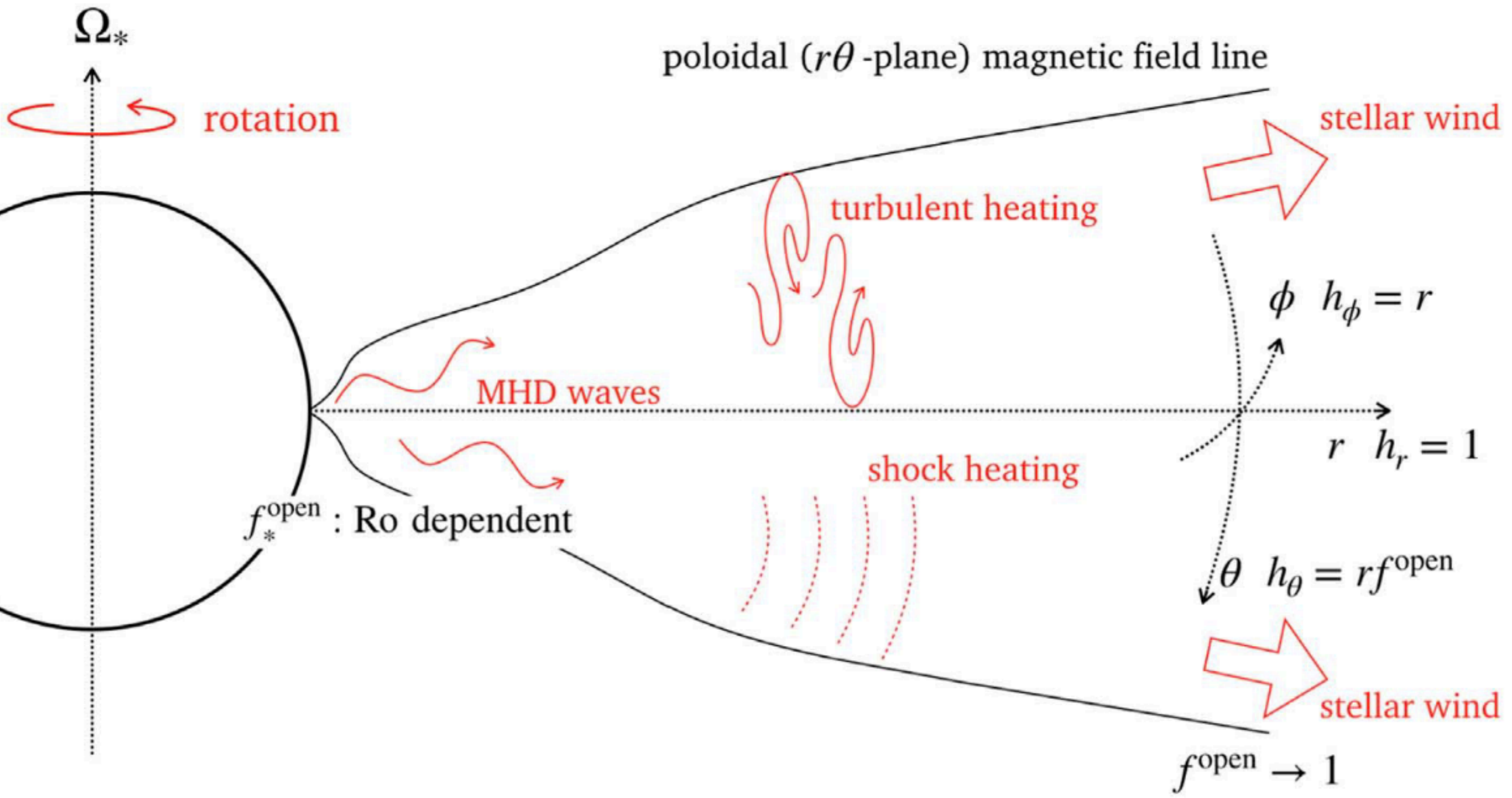
1D models of fast rotators

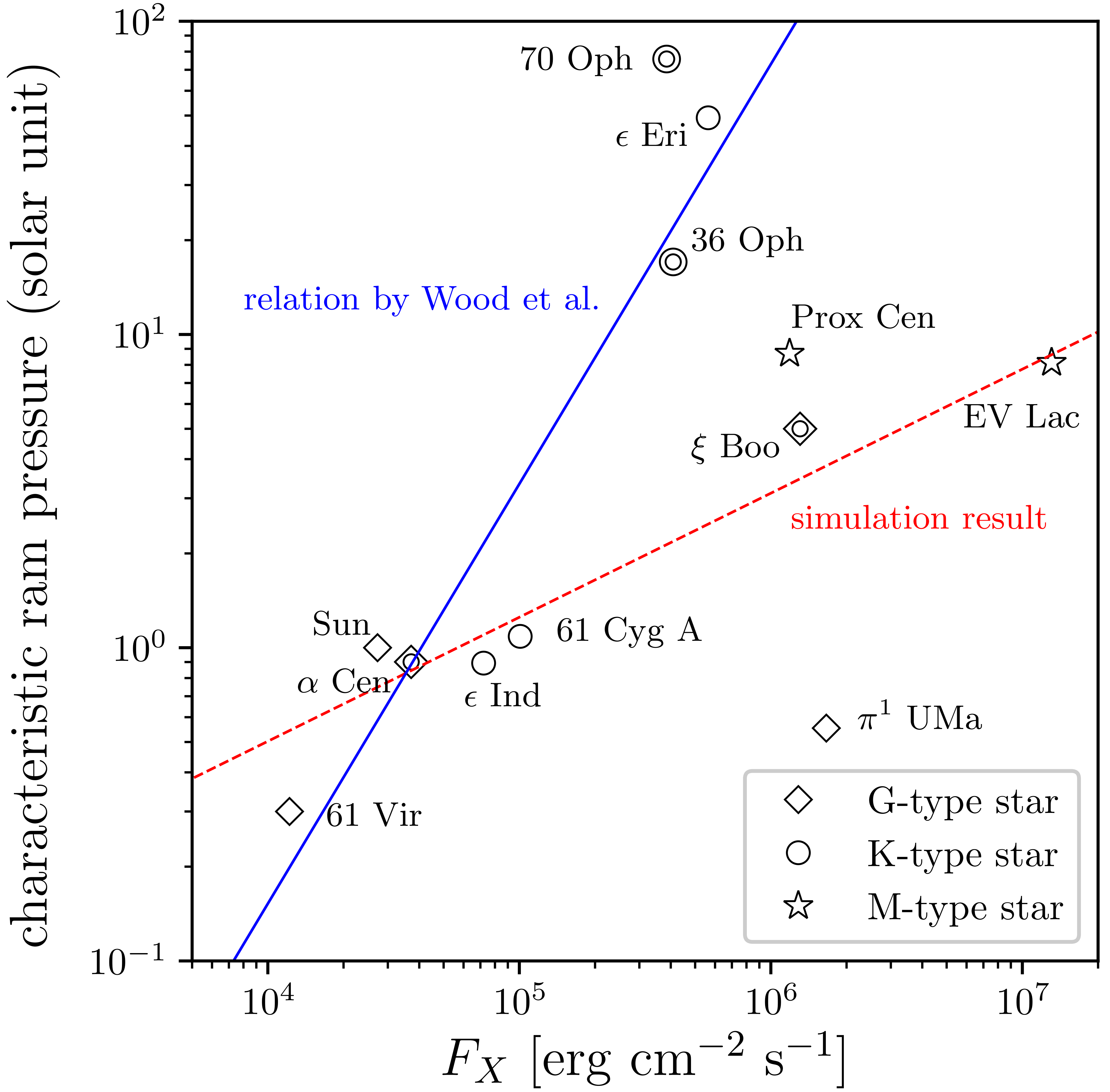
[Shoda, Suzuki, ..., Réville et al., 2020]

- An equipartition field at the photosphere and the same wave amplitude for all rotation.
- We use the relation :

$$\langle B \rangle \propto P_{\rm rot}^{-1.2}$$

- We change the 'expansion' of the flux tube





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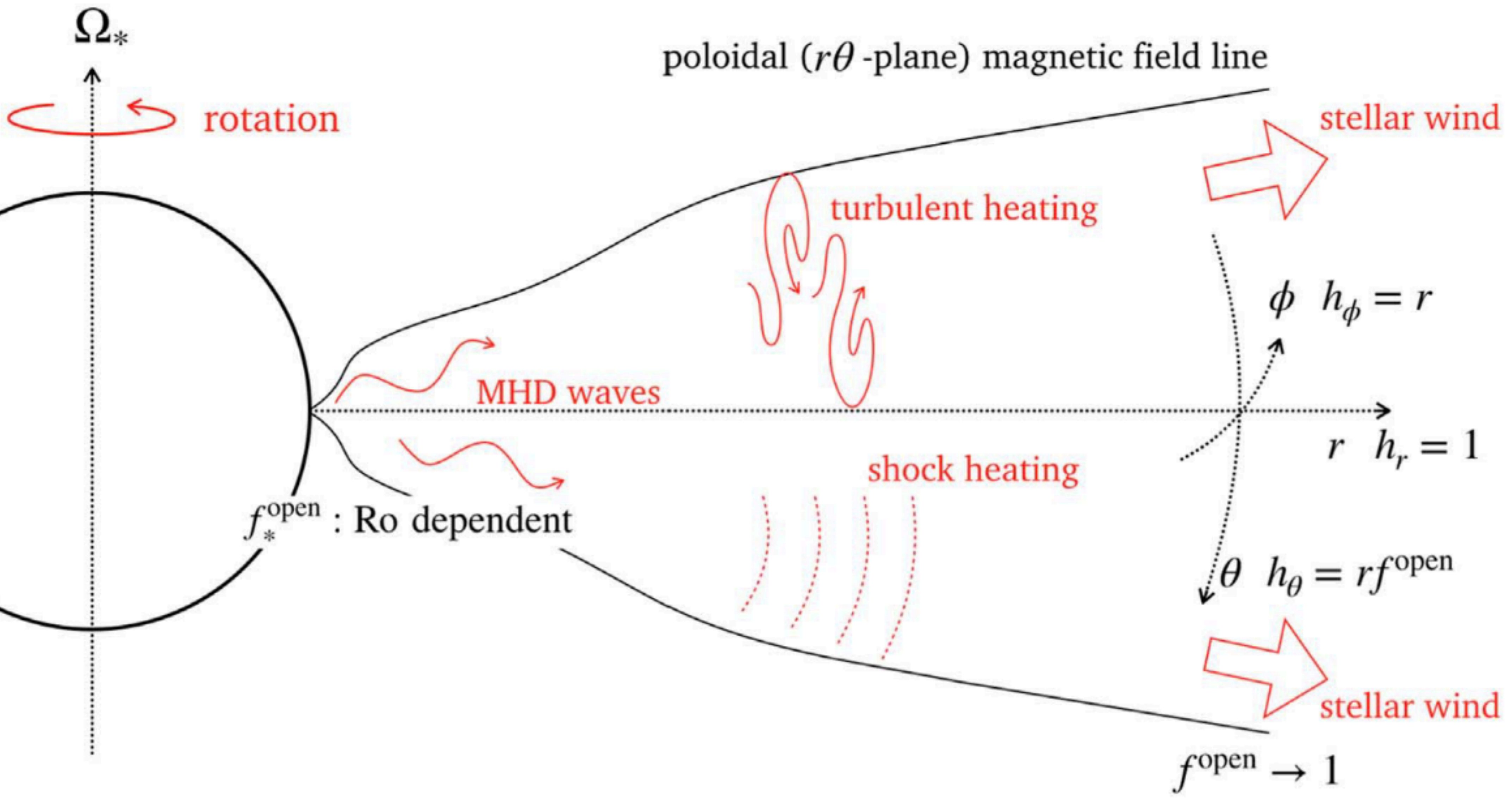
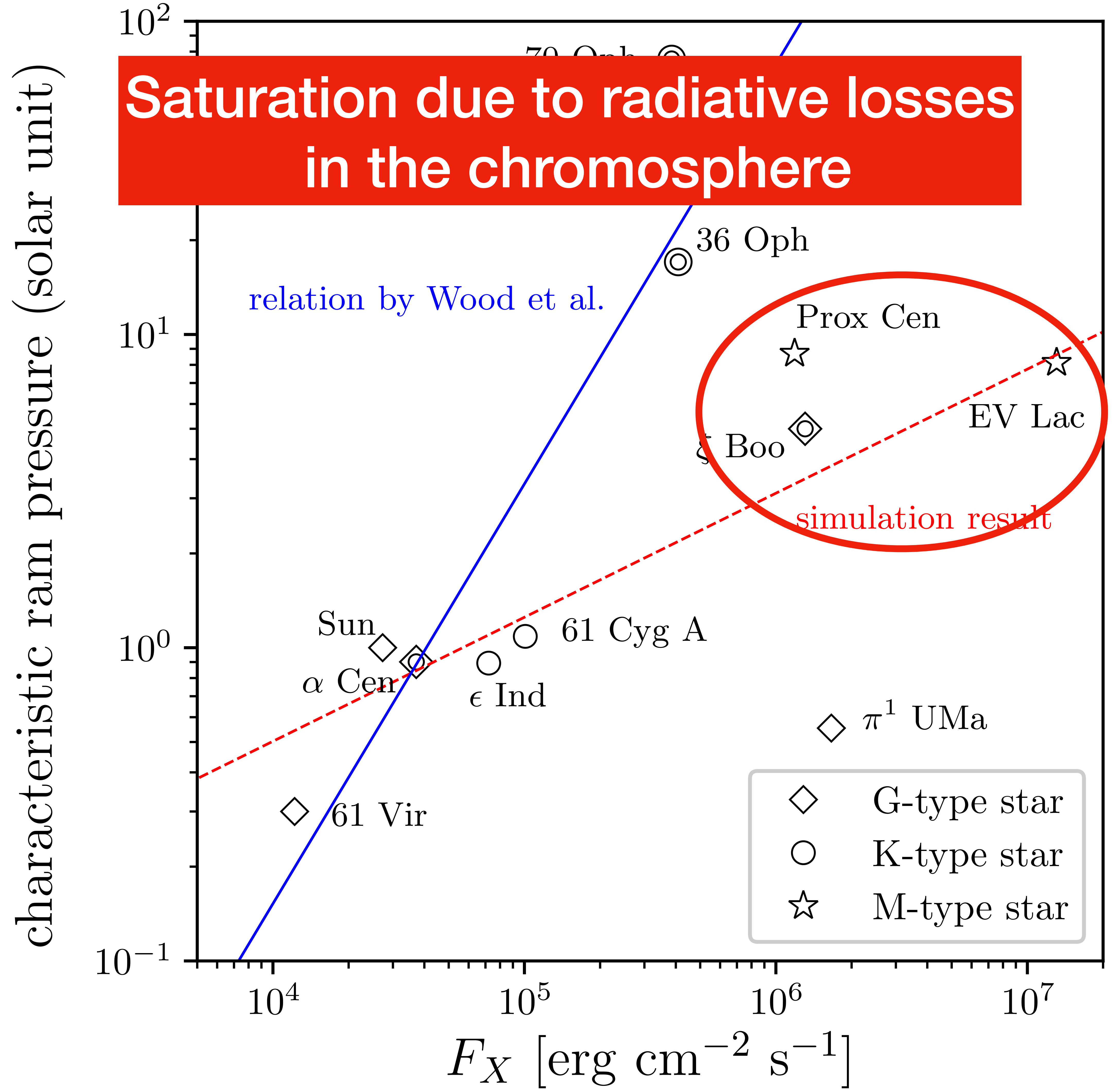




Alfvén wave driven stellar winds

Fully convective stars / M-dwarf

- TRAPPIST-1 System (M-dwarf+ 7 planets)

  $\langle B \rangle = 600\ G \qquad P_{\mathrm{rot}} = 3.3\ d$

- Garraffo et al. 2017 (AWSoM) $1\dot{M}_\odot$
- Dong et al. 2018 (AWSoM) $0.1\dot{M}_\odot$

Poynting Flux
w/ AW turbulence wind

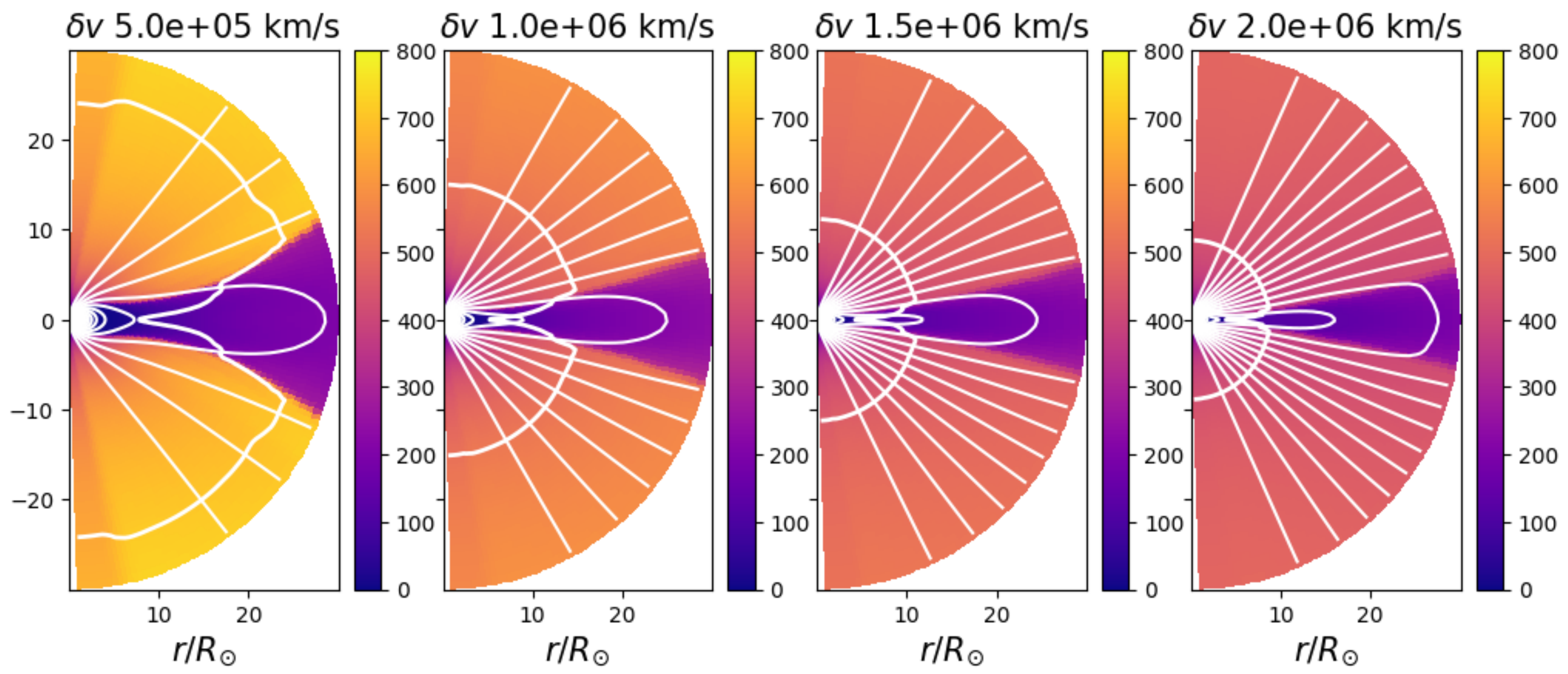
$$\dot{M} \propto F_p \propto \rho_\star v_{A,\star} \delta v^2$$

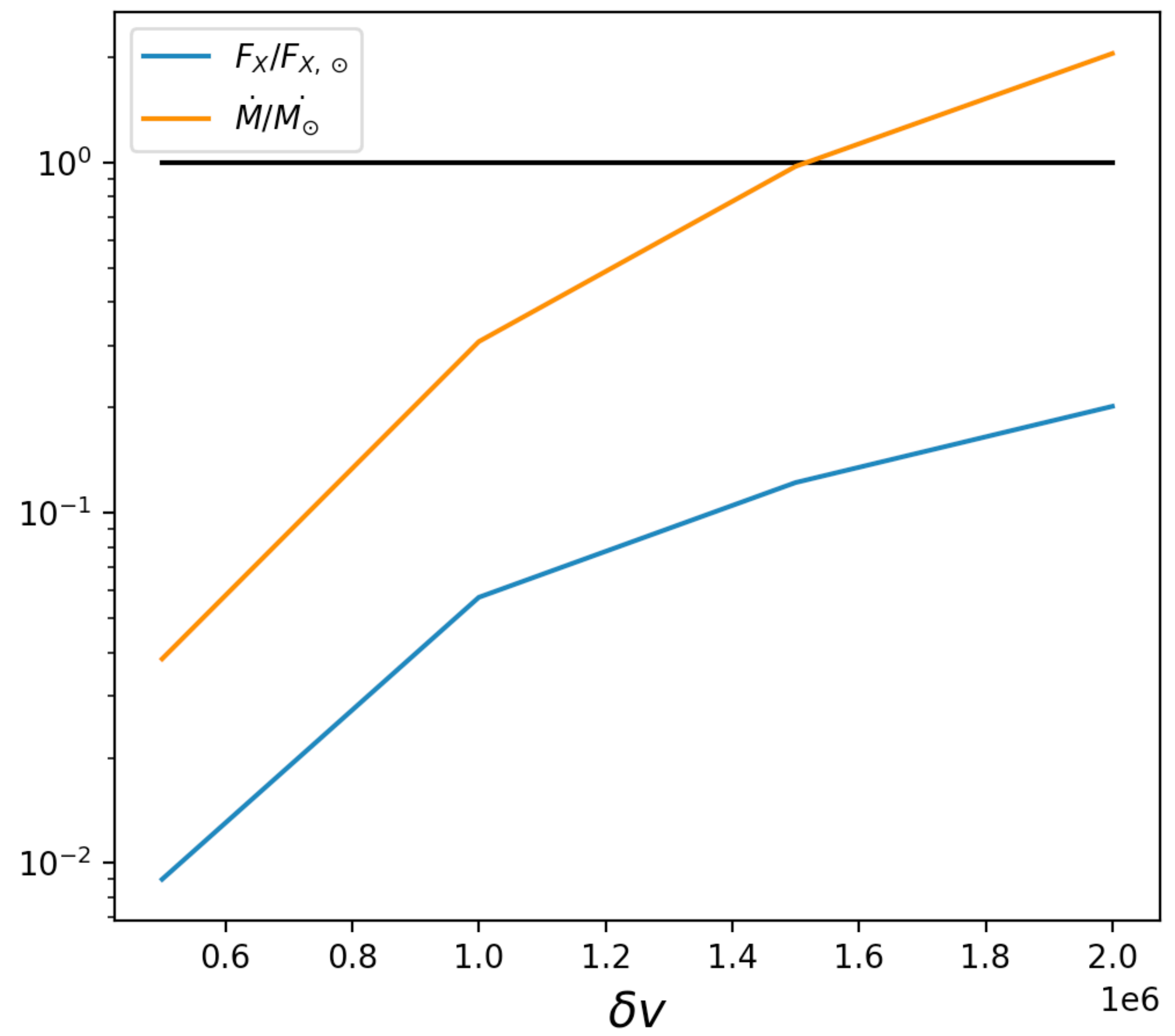
M-dwarfs stellar winds?

Estimating the mass loss using X-ray constraints

$$B_\star = 600G$$

[Réville et al., in prep]





- Using Chianti, we integrate the response of the coronal for 2.5D simulation of typical M-dwarf:

Still below observations -> more small scale structures ?

Summary

- *Stellar winds are ubiquitous.*
- *AW turbulence driven models are very efficient at reproducing the solar wind.*
- *Stellar observables, and in particular saturation phases remain mysterious and start to be investigated in the framework of AW turbulence.*
- *Results from the Parker Solar Probe mission show promising leads to bridge the gap! Solar Orbiter will ideally complete the picture.*

Thanks!