Solar and stellar winds origins and their impacts on planetary systems

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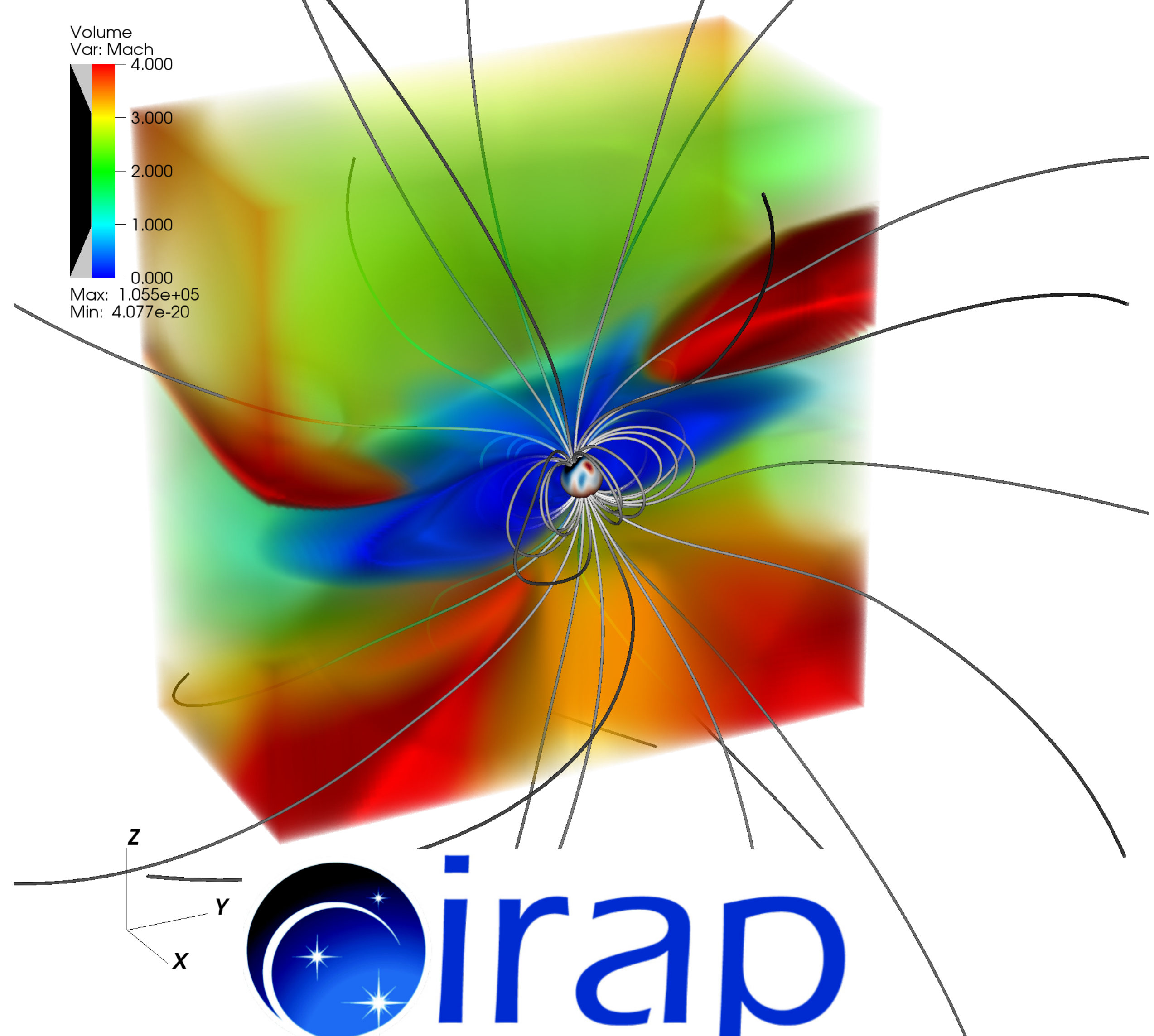

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PARKER SOLAR PROBE
A MISSION TO TOUCH THE SUN

What is the solar wind?

A hydrodynamical consequence of a hot corona

- Very recent SECCHI/HI-1 movie
- Comet ATLAS in the top panel
- Tail has been measured by Solar Orbiter (SWA/PAS)

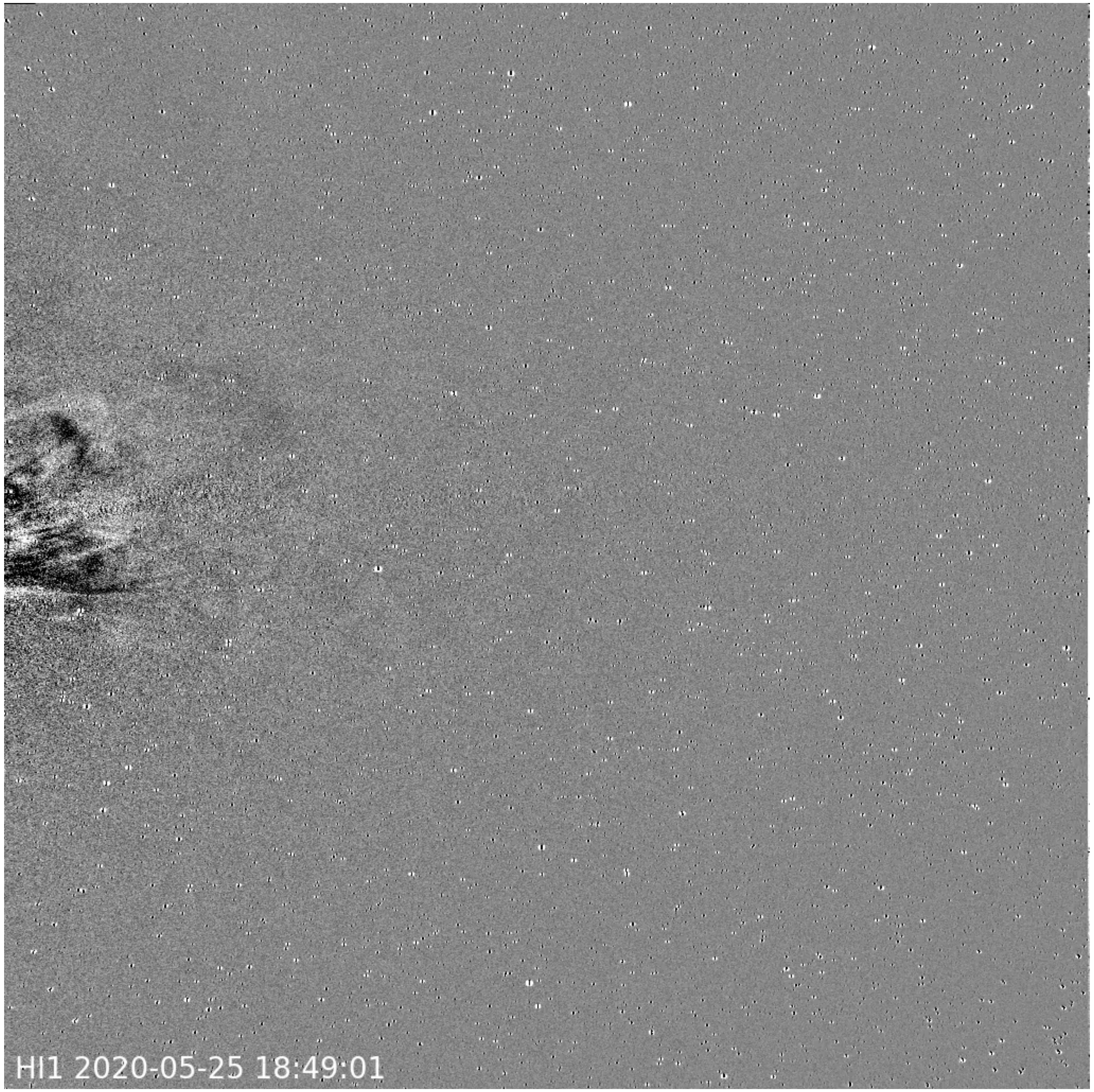
- First suspicion of a supersonic outflow looking at the secondary comet tails. [Biermann 1952]

- Description of the transonic solution first in accreting HD system

  [Bondi 1952, Mc Crea 1956]

- Then for supersonic winds (still HD)

  [Parker 1958]



What is the solar wind?

A hydrodynamical consequence of a hot corona

THE STUDY OF INTERPLANETARY IONIZED GAS, HIGH-ENERGY ELECTRONS AND CORPUSCULAR RADIATION OF THE SUN, EMPLOYING THREE-ELECTRODE CHARGED PARTICLE TRAPS ON THE SECOND SOVIET SPACE ROCKET*

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Translated by R. MATTHEWS from *skusstvennye Sputniki Zemli*, 6, 101, (1961).

In selecting the instrument characteristics the following models of interplanetary gaseous medium were taken as the most probable (in accordance with the available literature data[(1–4)]).

A. There is a stationary gaseous medium consisting mainly of ionized hydrogen with a concentration $n_i = 5 \times 10^2$–10^3 cm^{-3}, with an electron temperature in the order of 10^4 ° K, near to the ion temperature.

B. There are only sporadic corpuscular streams consisting of protons and electrons with velocities $(1–3) \times 10^8$ cm/s and with concentrations $n_i = 1$–10 cm^{-3} rising sometimes to $n_i \approx 10^3$ cm^{-3}.

[Gringauz et al. 1961]

- The interplanetary medium and the solar wind offers an extraordinary laboratory for studying stellar winds.
- The solar wind shapes the Sun-Earth interactions !

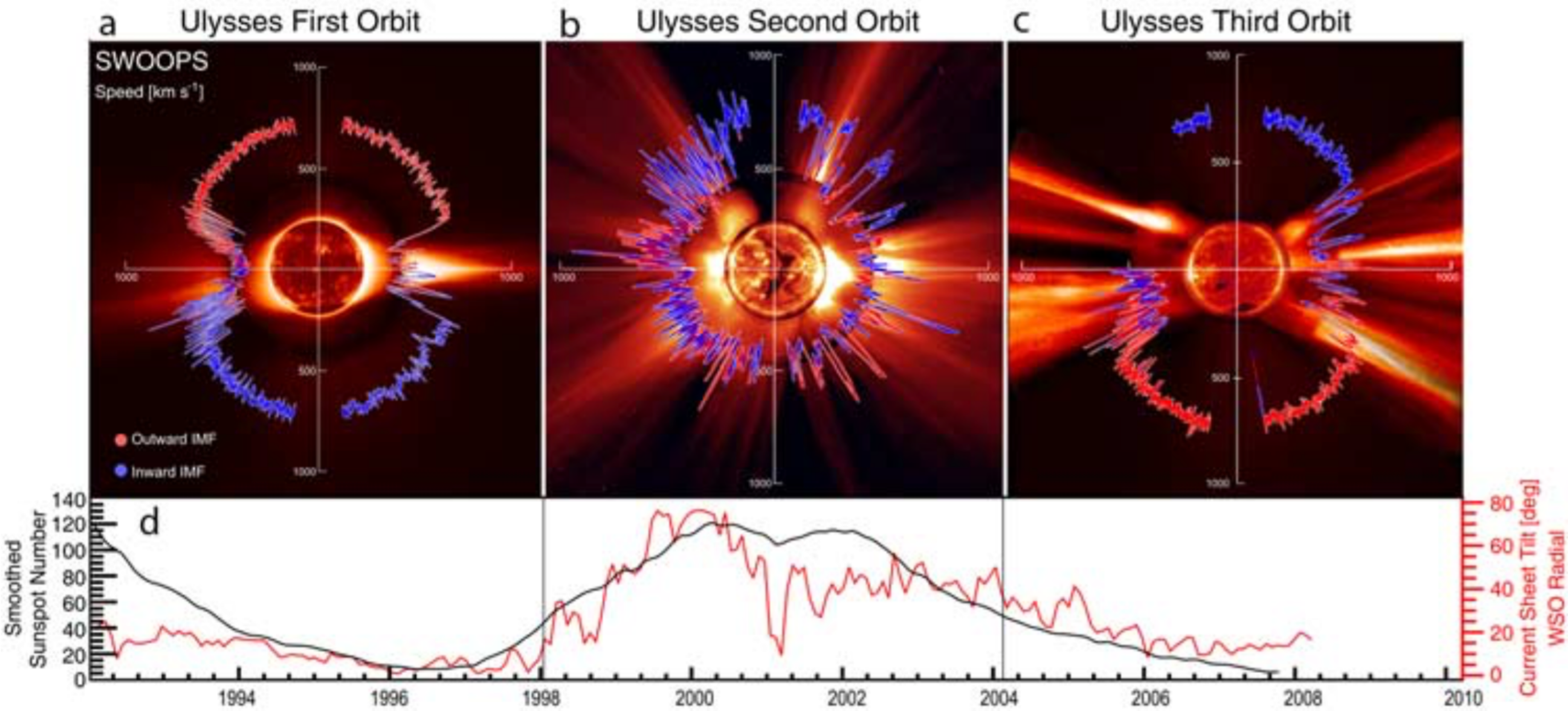
The Mission of Mariner II: Preliminary Observations

If we assume that the values of v_o, n, and T given above are approximately correct, and if we further assume an average value for the interplanetary magnetic field of $B = 5$ gamma $= 5 \times 10^{-5}$ gauss, we can compute the following important parameters for spectrum *a*, which appears to be fairly representative of quiet, non-storm conditions during the period of observation: Plasma flux $= nv_o = 1.2 \times 10^8$ cm^{-2} sec^{-1}; plasma energy density $= n(\frac{1}{2} mv_o^2 + \frac{1}{2}kT \approx \frac{1}{2}\ \ nmv_o^2 = 4.4 \times 10^{-9}$ erg cm^{-3}; magnetic field energy density $= B^2/8\pi = 1.0 \times 10^{-10}$ erg cm^{-3}; Alfvén velocity $= v_A = B/\ (4\ \pi\ mn)^{\frac{1}{2}} = 69$ km sec^{-1}; $v_o/v_A = 6.7$.

[Neugebauer & Snyder 1962]

What is the solar wind?

Yet strongly influenced by the solar magnetic field

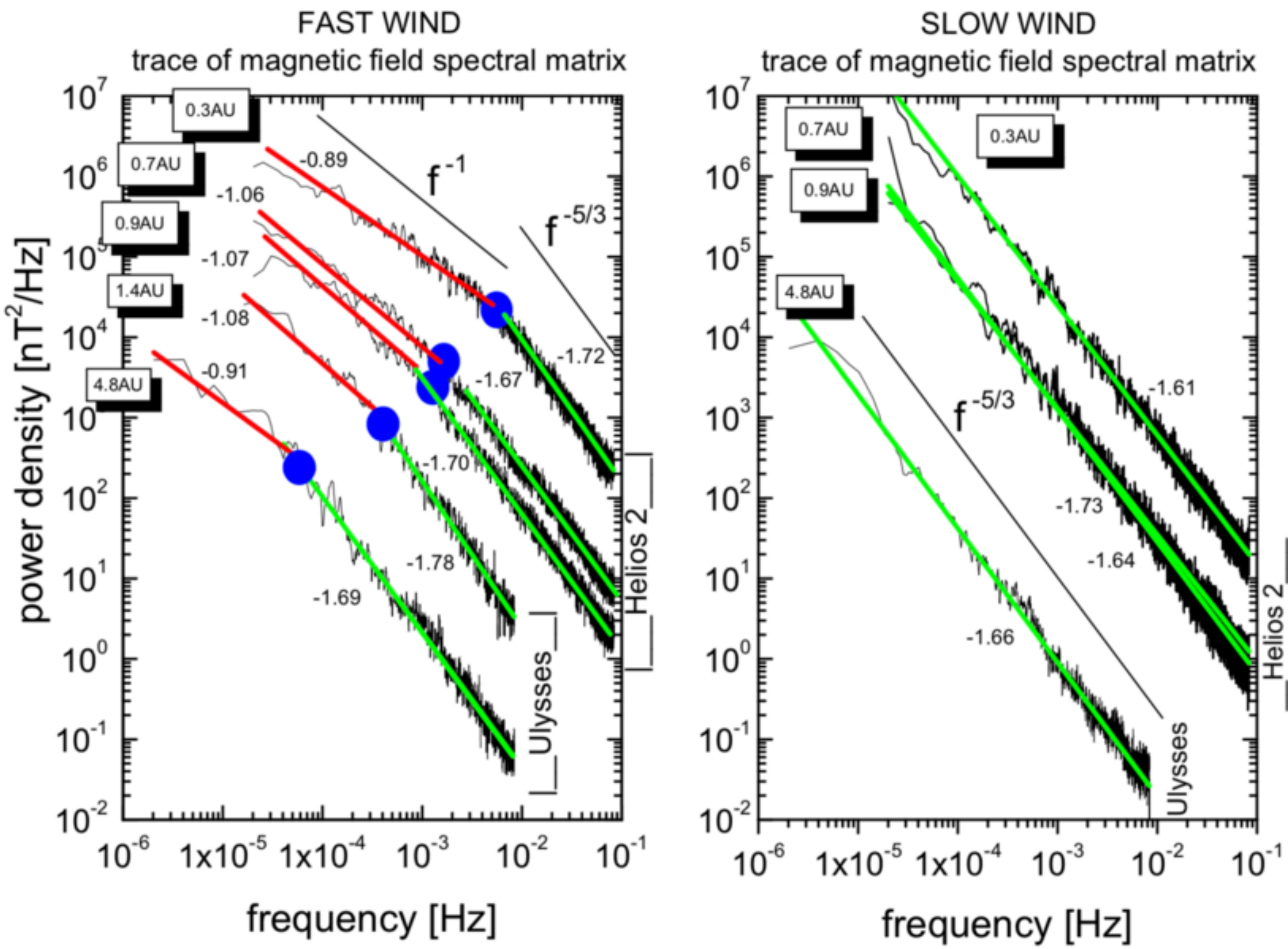


- Fast wind cannot be explained by the Parker Model!

[McComas et al. 2003, 2008]

What is the solar wind?

A turbulent medium



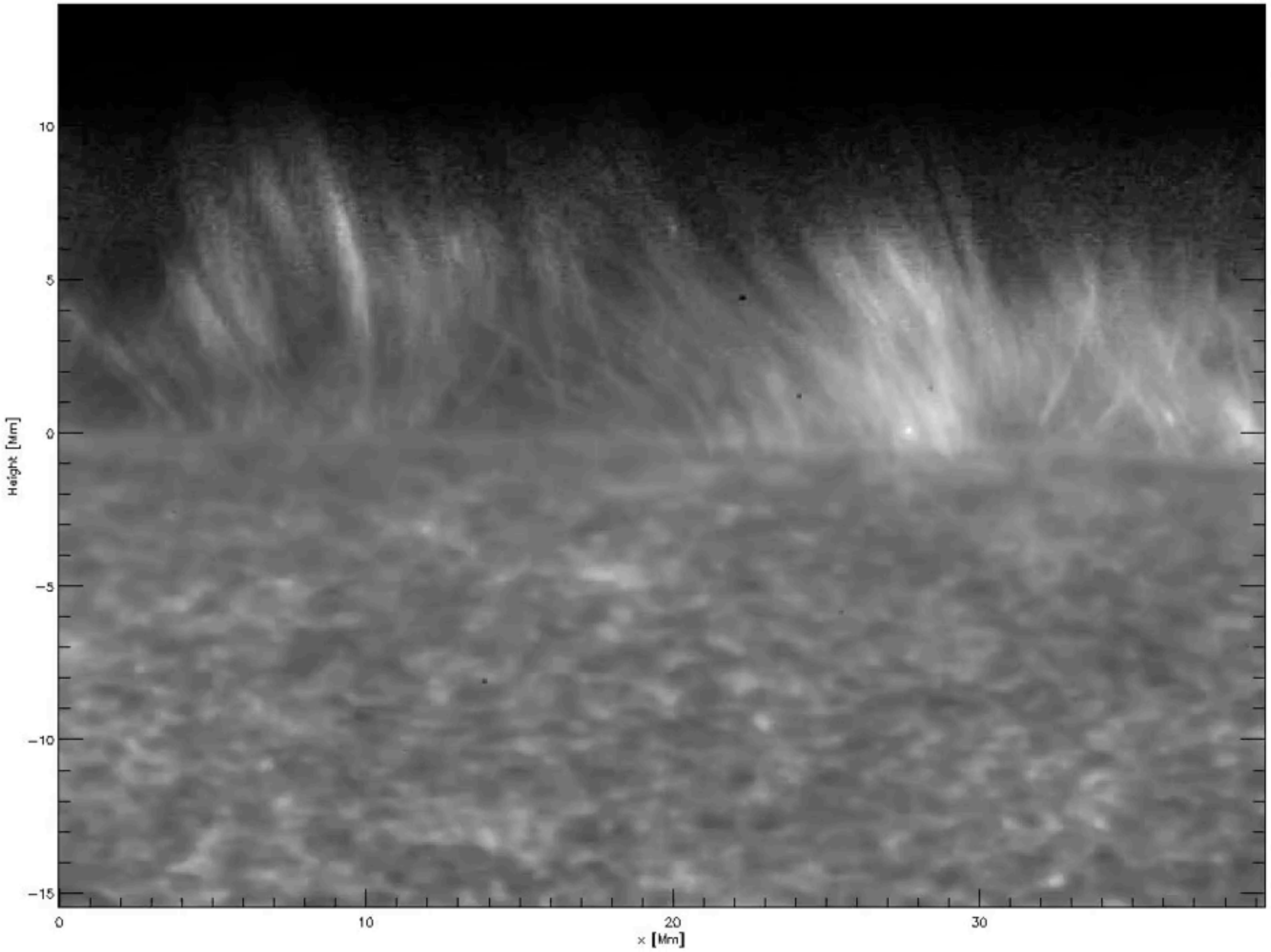
[Bruno & Carbone 2013]

- 1/f spectrum at low frequencies in the fast wind
- Kolmogorov spectrum in the in frequencies
- Steeper slope beyond the ion-cyclotron frequency (dissipation range)

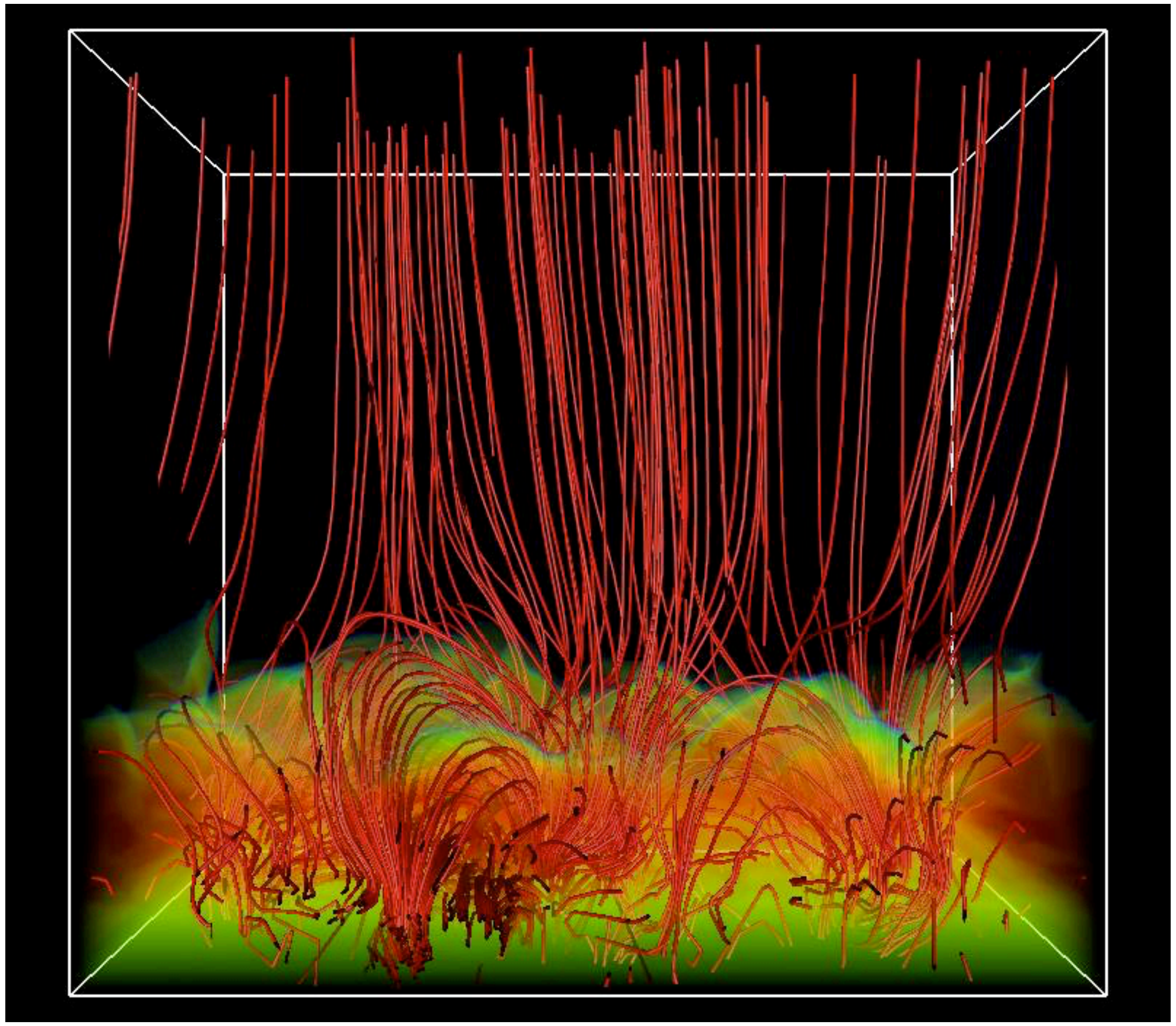
What is the origin of the perturbations?

Convective motions?

[De Pontieu et al., 2007, 2012]



Observations (Hinode)



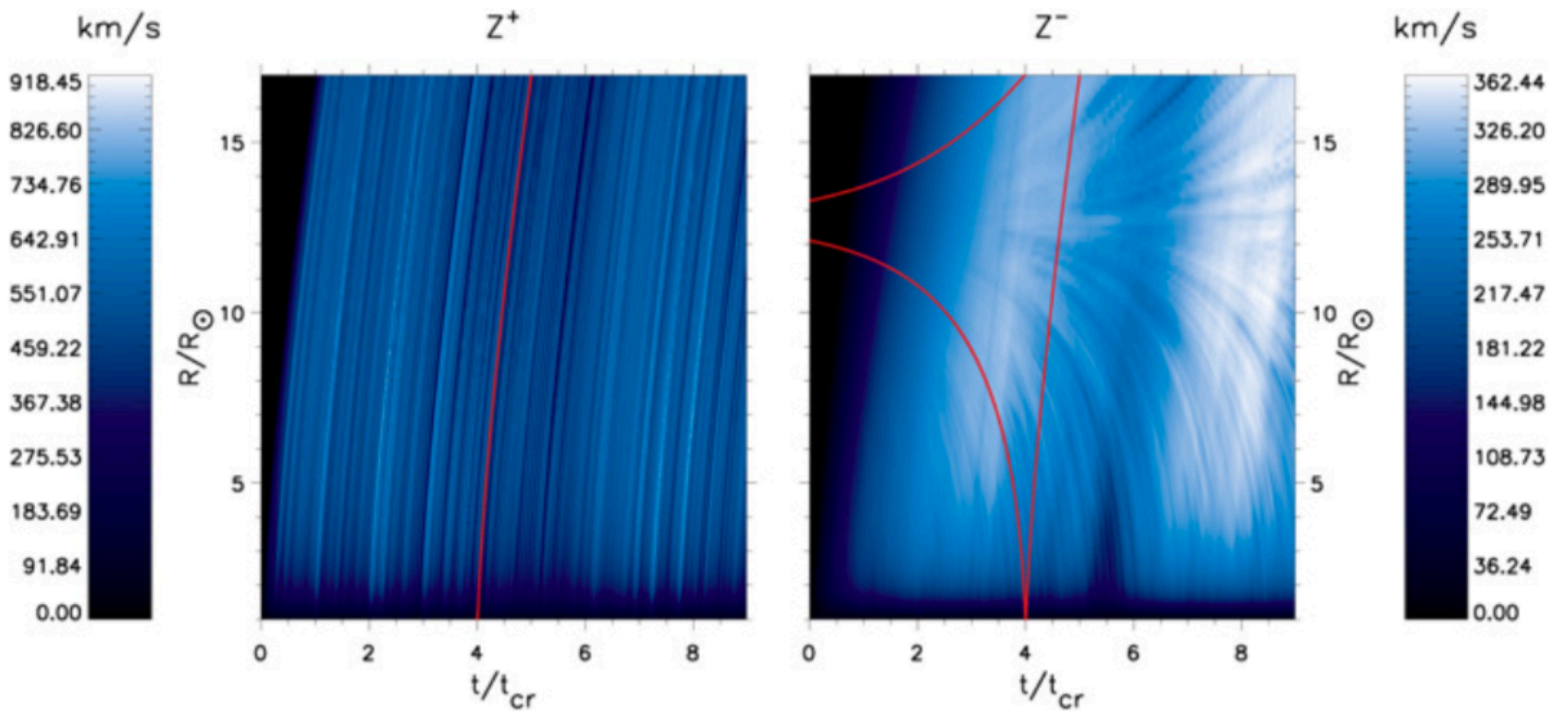
Simulations (BIFROST)

Photospheric motions launch Alfvén waves

- Transverse motions visible in the chromosphere: $\delta v_\perp \sim 20 \text{ km/s} \quad P \sim \text{min}$

Turbulence and dissipation?

Canonical theory: incompressible reflection



[Verdini & Velli 201]
[Perez & Chandran 2013]
[Shoda 2018]

$$z^{\pm} = \delta v \pm \delta b / \sqrt{\mu_0 \rho}$$

Incompressible Alfvén wave turbulence theory:

- Forward Alfvén waves reflect on large scale gradients and counter-propagating waves interact non linearly
- Leads to a forward cascade
- Several processes can lead to dissipation at small scales : wave-particle interactions, phase mixing, shocks, reconnection…

Fluid models of the corona and wind

Building a relevant MHD model

MHD equations:

$$\frac{\partial}{\partial t}\rho + \nabla \cdot \rho \mathbf{v} = 0,$$

$$\frac{\partial}{\partial t}\rho \mathbf{v} + \nabla \cdot (\rho \mathbf{v}\mathbf{v} - \mathbf{B}\mathbf{B} + \mathbf{I}p) = -\rho \nabla \Phi,$$

$$\frac{\partial}{\partial t}(E + \rho\Phi) + \nabla \cdot ((E + p + \rho\Phi)\mathbf{v} - \mathbf{B}(\mathbf{v}\cdot\mathbf{B})) = Q,$$

$$\frac{\partial}{\partial t}\mathbf{B} + \nabla \cdot (\mathbf{v}\mathbf{B} - \mathbf{B}\mathbf{v}) = 0,$$

[Sokolov+ 2013, van der Holst+ 2010, 2014, Lionello+ 2009, Riley+ 2017, Réville+ 2020]

+ *Energy sources:*

$$Q = Q_h - Q_c - Q_r$$

Thermal conduction:

$$Q_c = \nabla \cdot \left[\alpha \kappa T^{5/2} \nabla T + (1-\alpha)\frac{3}{2} p v\right]$$

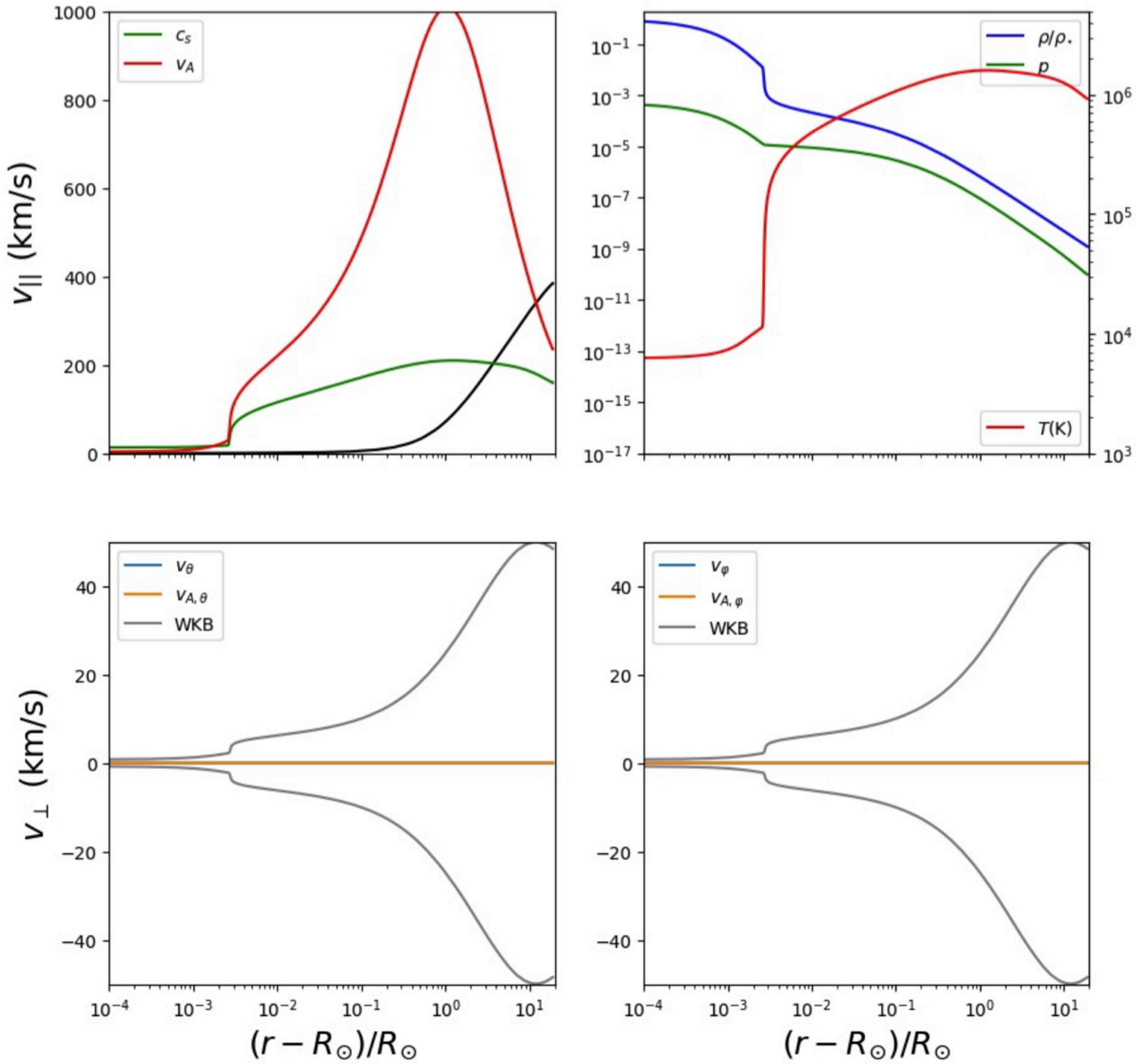
Spitzer (collisional) *Electron heat flux (collisionless)*

Optically thin cooling:

$$Q_r = n^2 \Lambda(T)$$

How do waves propagate in the solar wind?

Flux tube models



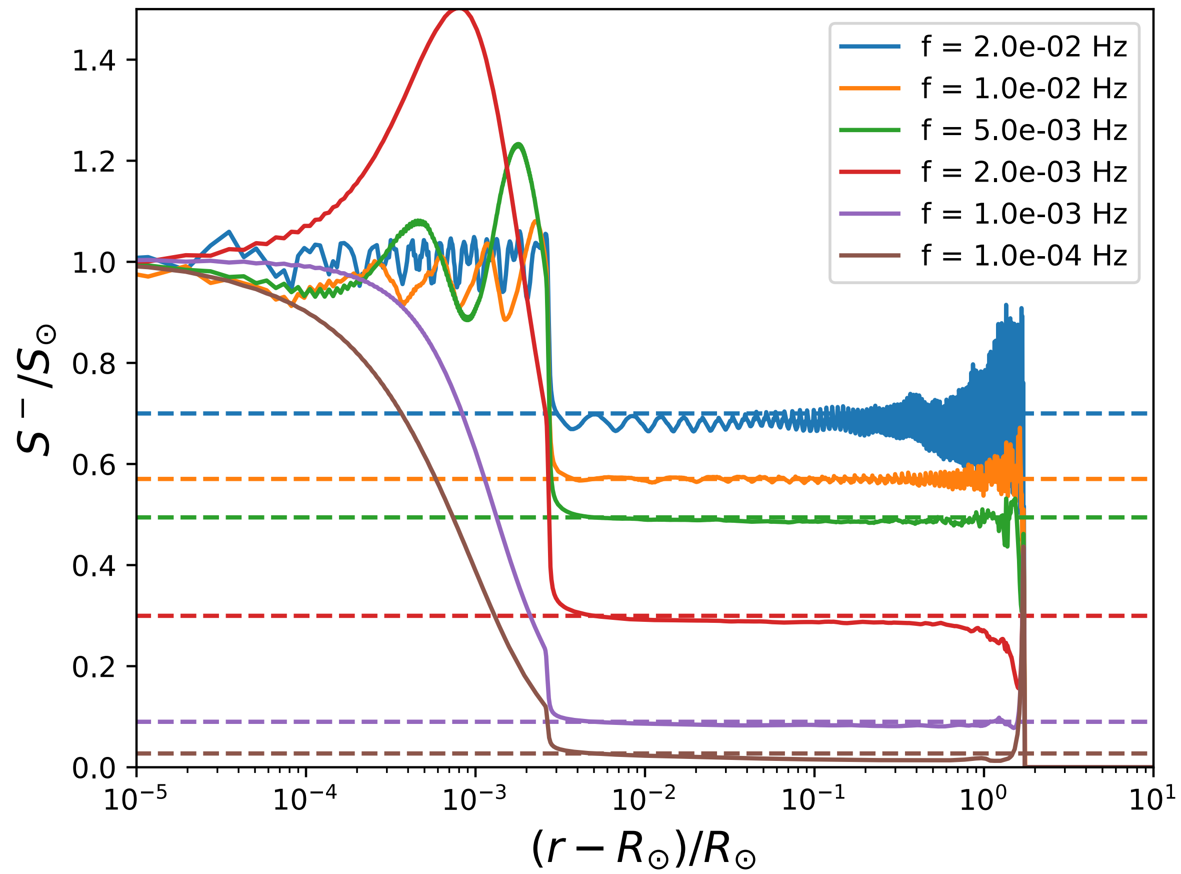
[Réville, Tenerani, Velli 2018]

- Waves at the chromosphere BC
- Monochromatic input : 100-500s
- ~15000 cells

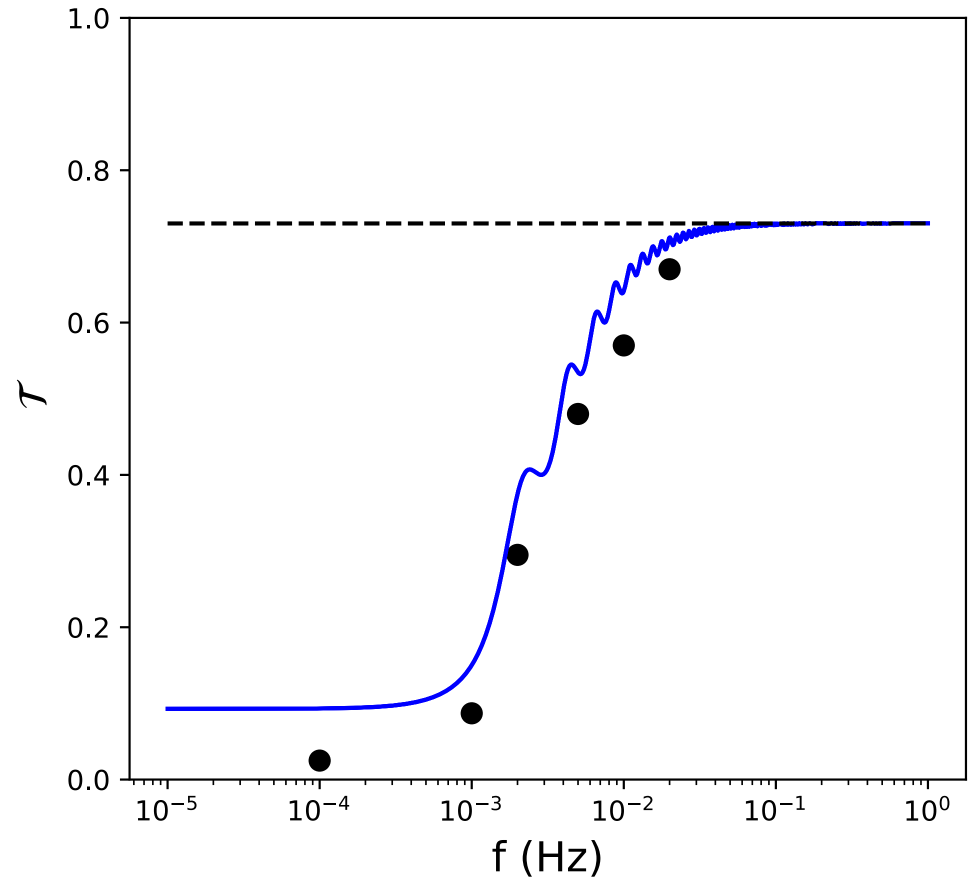
- Follows WKB theory at first
- Becomes unstable and creates compressive waves

How do waves propagate in the solar wind?

Crossing the transition region



[Réville, Tenerani, Velli 2018]



- Transmission coefficient based on the wave action

$$S^{\pm} = \frac{(V \mp V_A)}{V_A} \rho r^2 \frac{|z^{\pm}|^2}{8}$$

[Bretherton & Garret 1968, Jacques 1977]

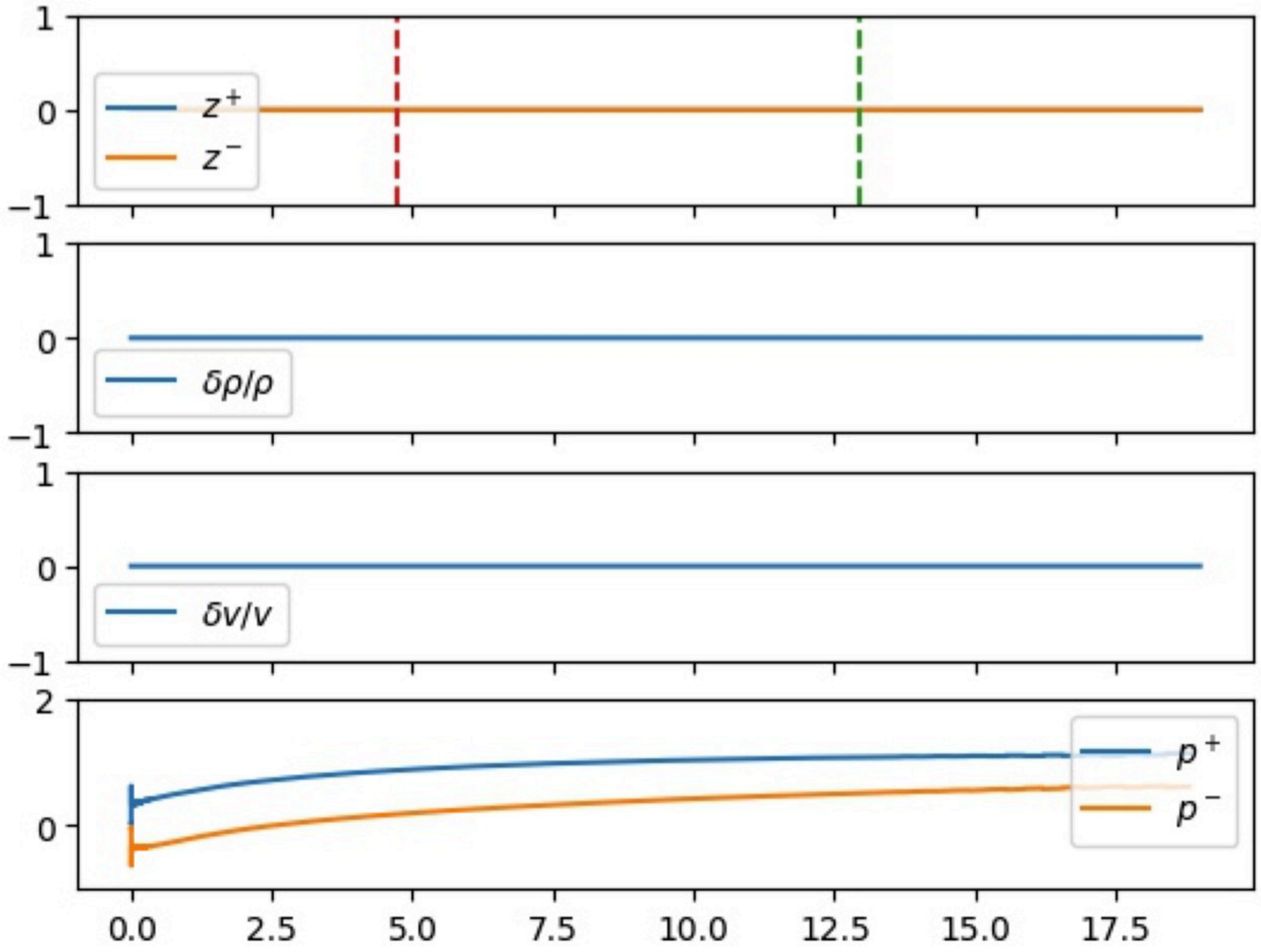
- Blue curve: analytical model of Leroy (1981)

$$\mathcal{T} = S^-_{\infty}/S^-_{\odot}$$

How do waves propagate in the solar wind?

The parametric decay instability

- *A three wave, compressible process*

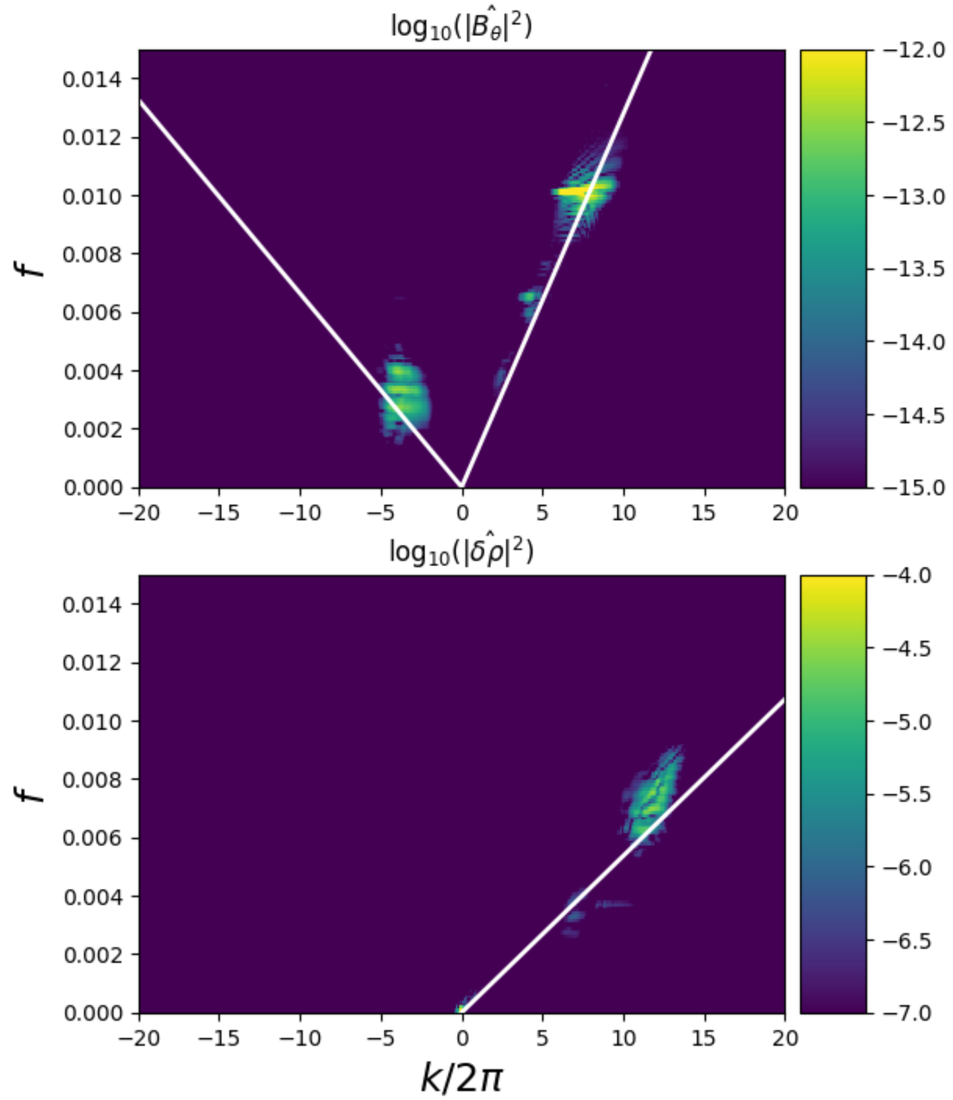


How do waves dissipate in the solar wind?

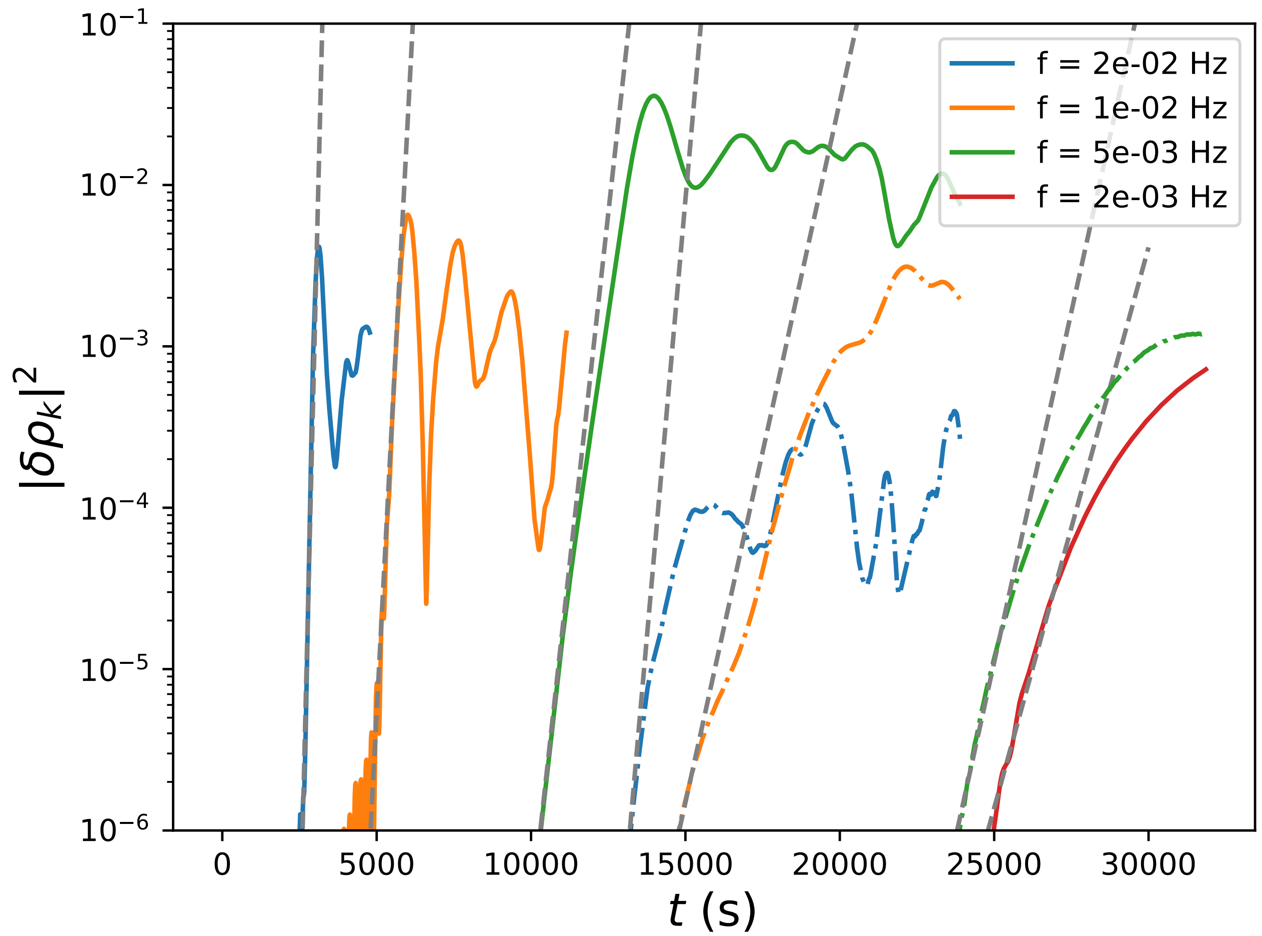
The parametric decay instability

- *Resonance conditions*

$$f_{A,\mathrm{out}} = f_S + f_{A,\mathrm{in}}$$
$$\mathbf{k}_{A,\mathrm{out}} = \mathbf{k}_S + \mathbf{k}_{A,\mathrm{in}}$$



[Réville, Tenerani, Velli 2018]

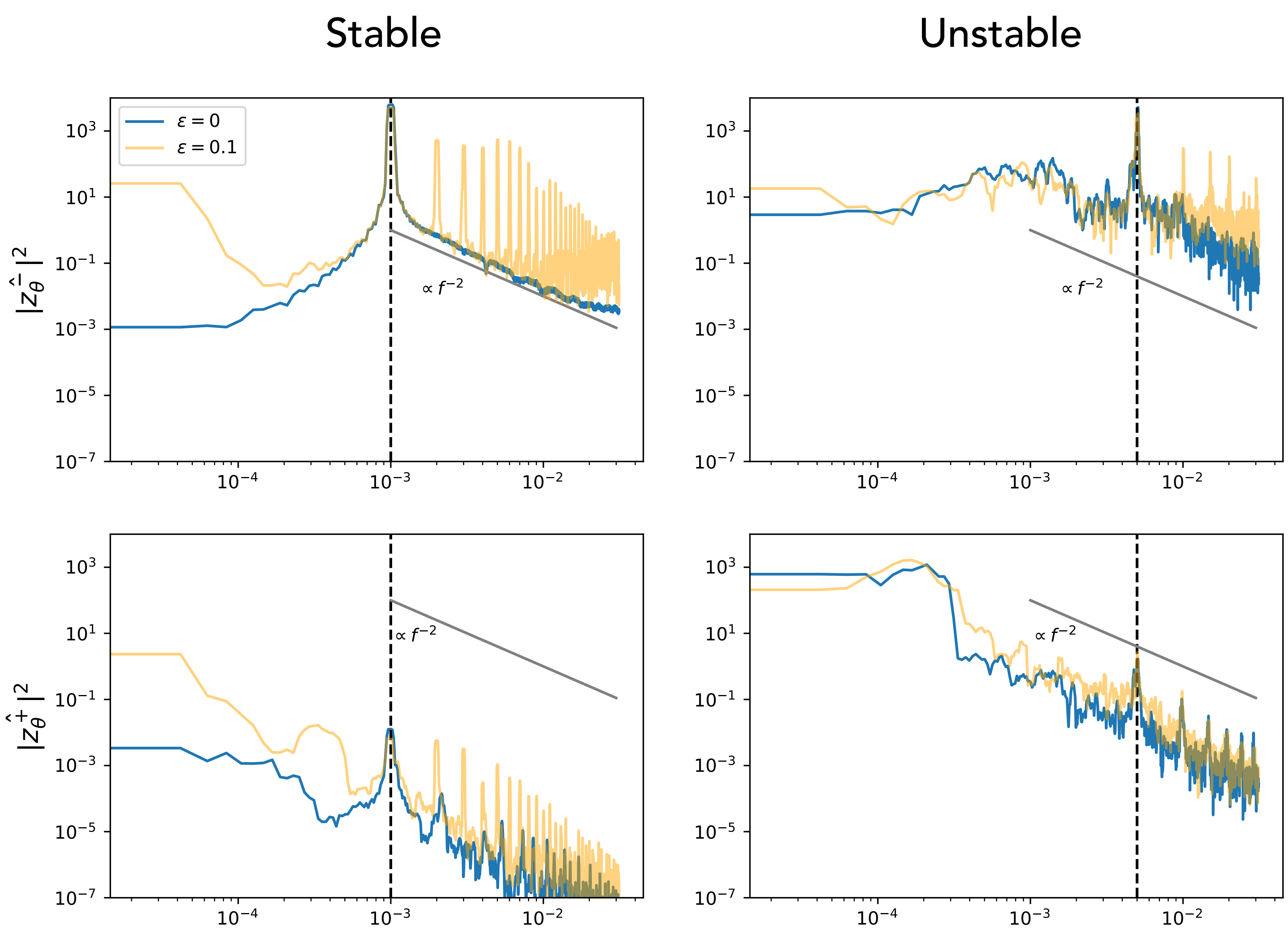


- *Growth rate comparison with linear theory* [Derby 1978, Goldstein 1978]

How do waves dissipate in the solar wind?

The parametric decay instability

[Réville, Tenerani, Velli 2018]



- *When unstable, a fully developed spectrum is rapidly created at 10 Rs.*
- *Parametric decay is responsible for an inverse cascade, and hourly fluctuations appear.*

Turbulence in global models?

How to implement WT in global models?

Working on transport equations

- Reflections, Instabilities (linear phase)

$$\frac{\partial \mathcal{E}^{\pm}}{\partial t} + \underbrace{\nabla \cdot \left[(\mathbf{U} \pm \mathbf{V_A})\mathcal{E}^{\pm}\right] + \frac{\mathcal{E}^{\pm}}{2}\nabla \cdot \mathbf{U}}_{\text{WKB}} + \underbrace{\mathcal{R}^{\pm}(\mathbf{z}^{+}, \mathbf{z}^{-})}_{\text{linear coupling}} = \underbrace{\mathcal{N}^{\pm}(\mathbf{z}^{+}, \mathbf{z}^{-})}_{\text{nonlinear terms}}$$

- Wave pressure -> Fast wind
- Dissipation -> Heating

Wave energy, (anti)-parallel (-)+

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

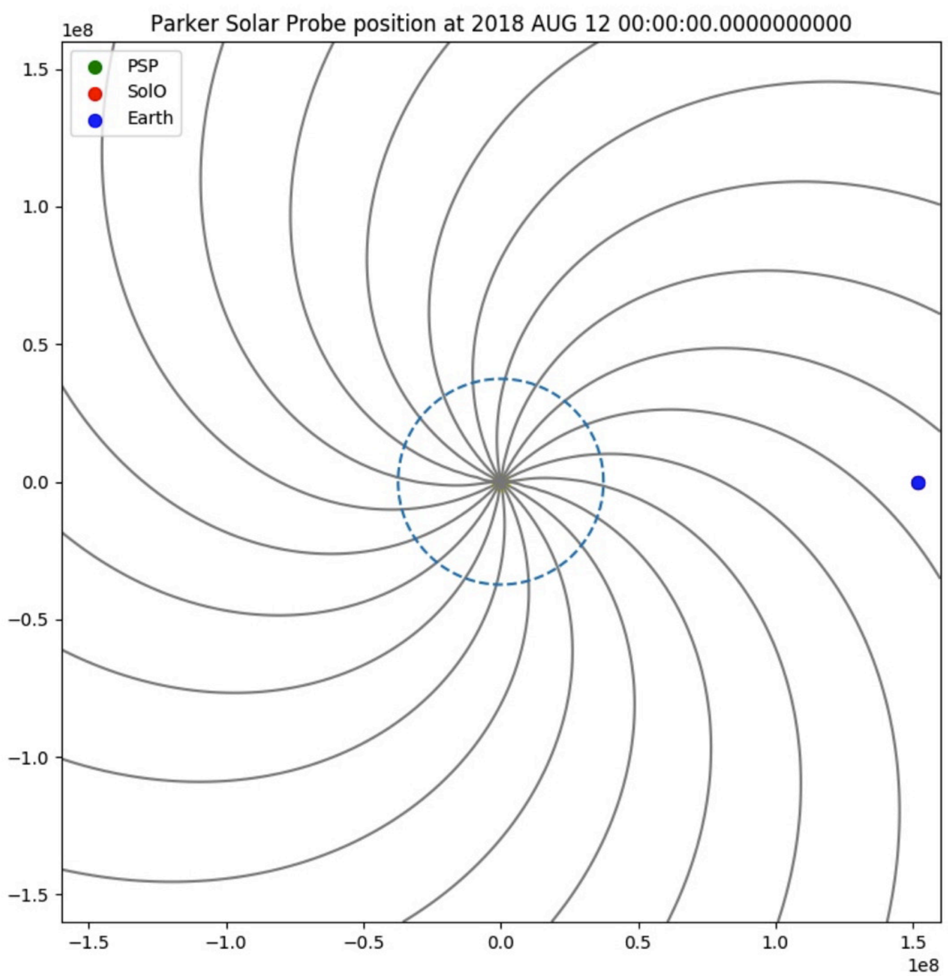
Phenomenological heating (Kolmogorov)

$$\mathcal{N}^{\pm} = -Q^{\pm} \propto -\frac{\rho |z^{\pm}|^{2} |z^{\mp}|}{\lambda}$$

Building models for new solar missions

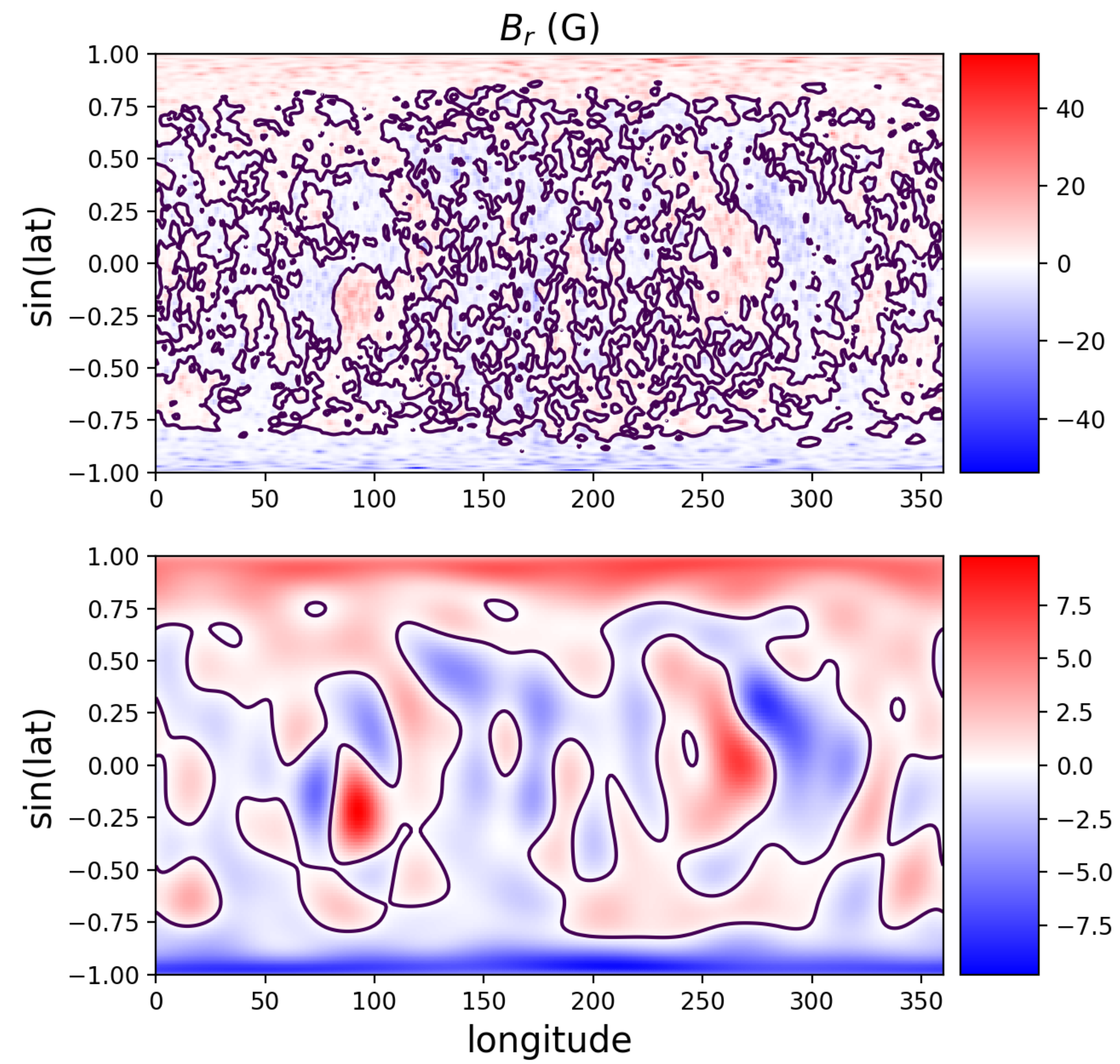
The first perihelion of Parker Solar Probe

PSP: FIELDS, SWEAP, ISOIS, WISPR



Magnetogram at BC:

ADAPT (Br) Nov 6th 2018



Building models for new solar missions

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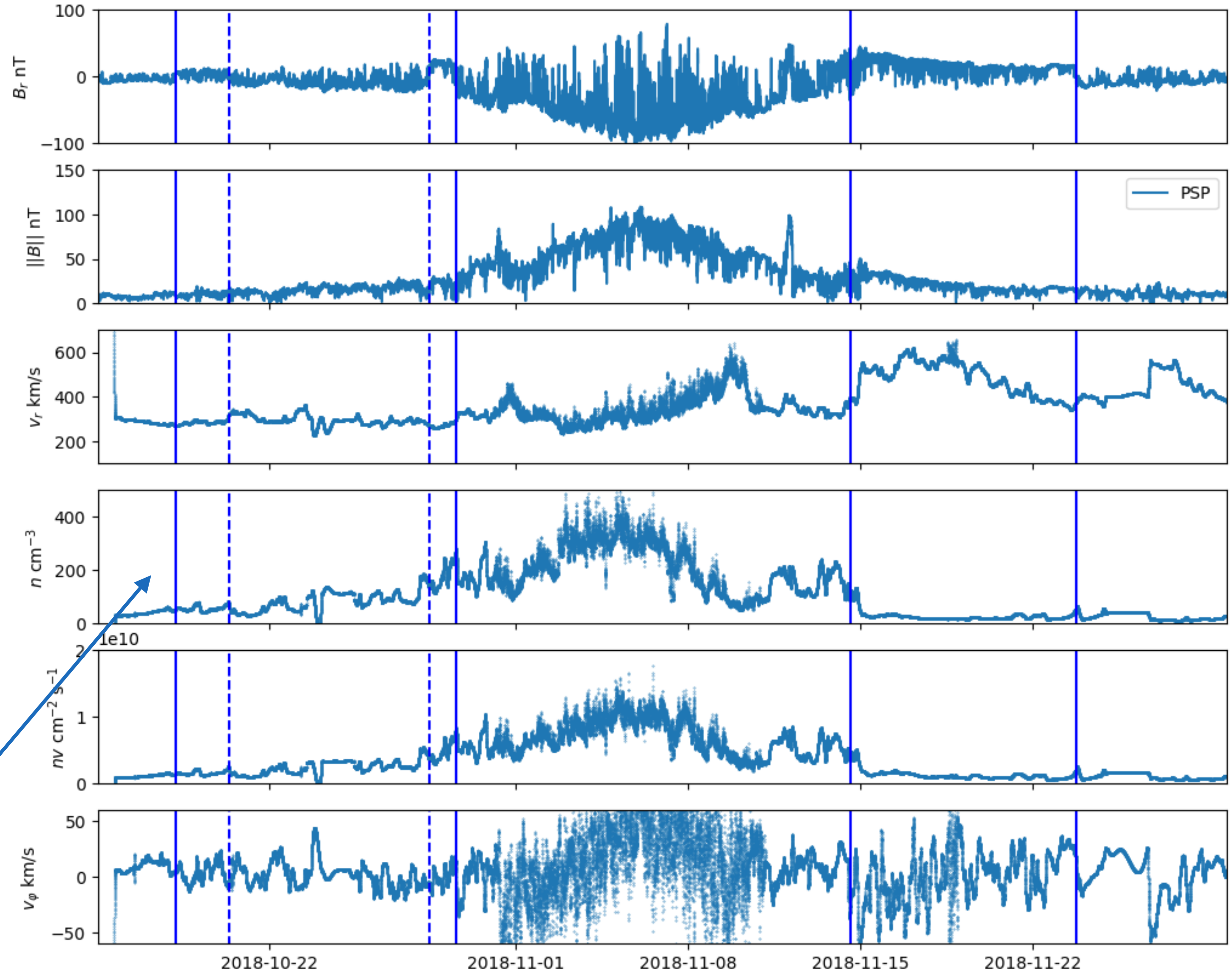
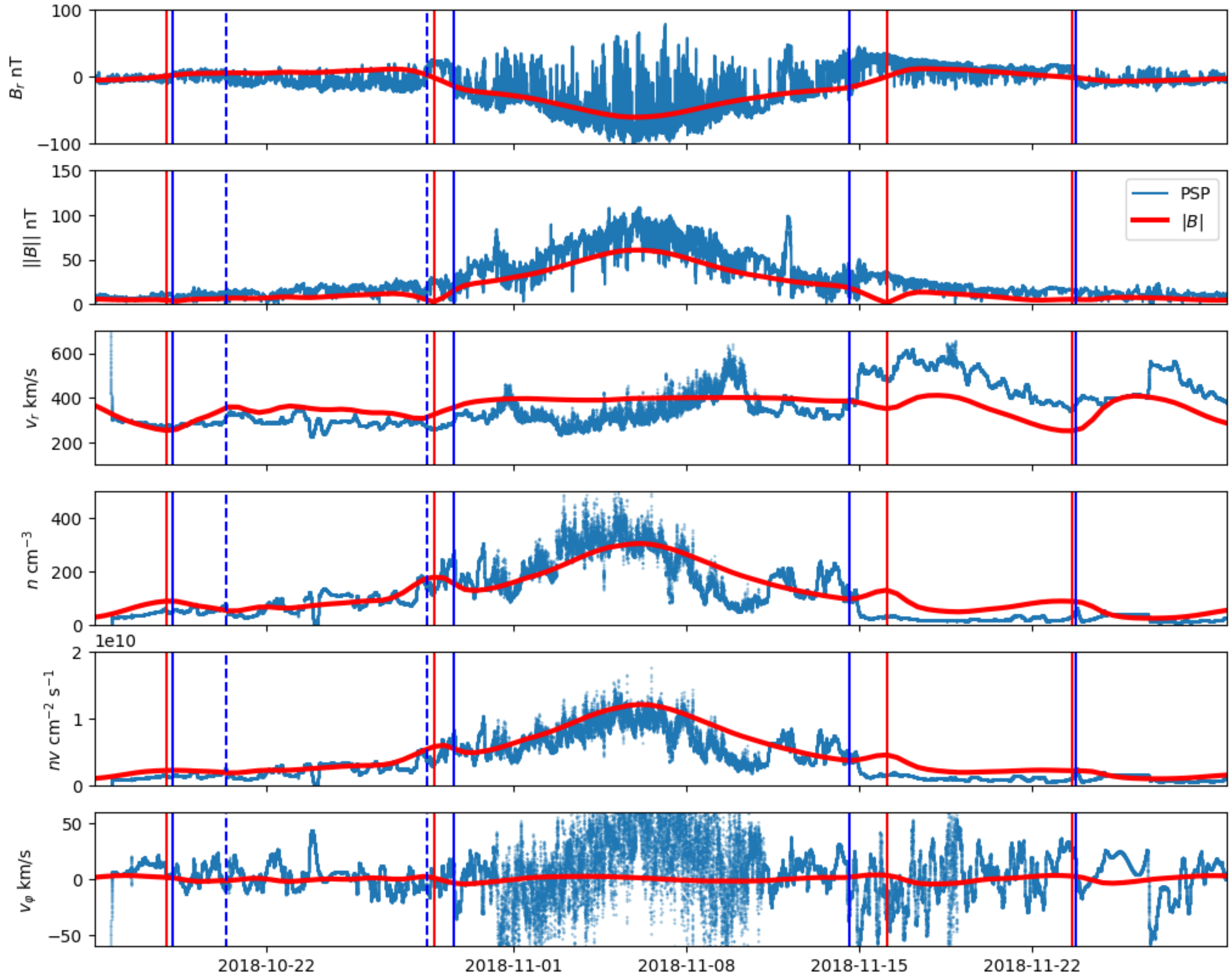


- HCS crossings

[Szabo et al. 2020]

Building models for new solar missions

The first perihelion of Parker Solar Probe



[Réville et al. 2020]

Building models for new solar missions

The first perihelion of Parker Solar Probe

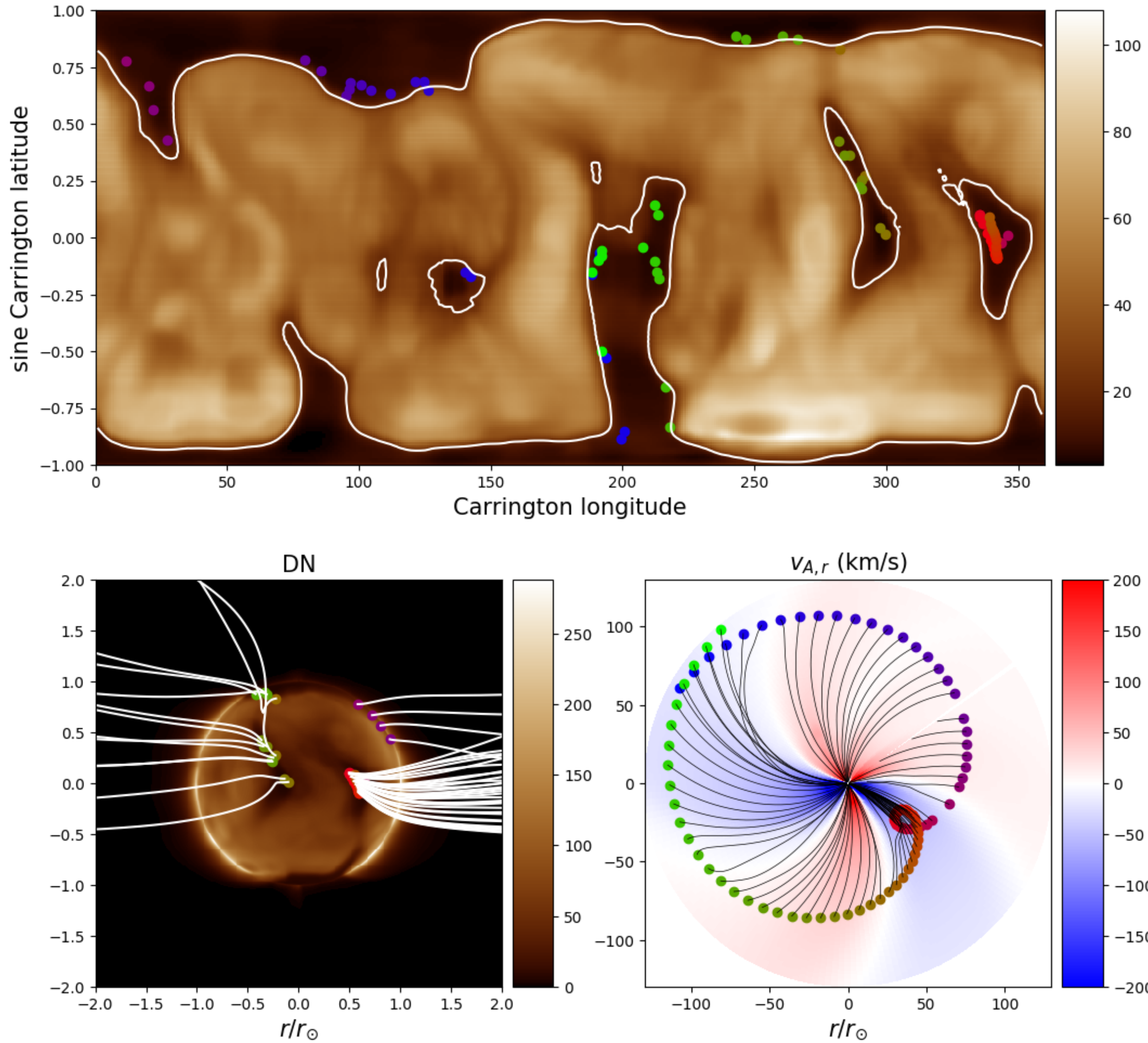
- Combining field line tracing and EUV forward modeling:

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

- Closed regions appear brighter
- Coronal holes darker
- Consistency for the closest approach between various models

[Badman et al. 2020, ApJS]

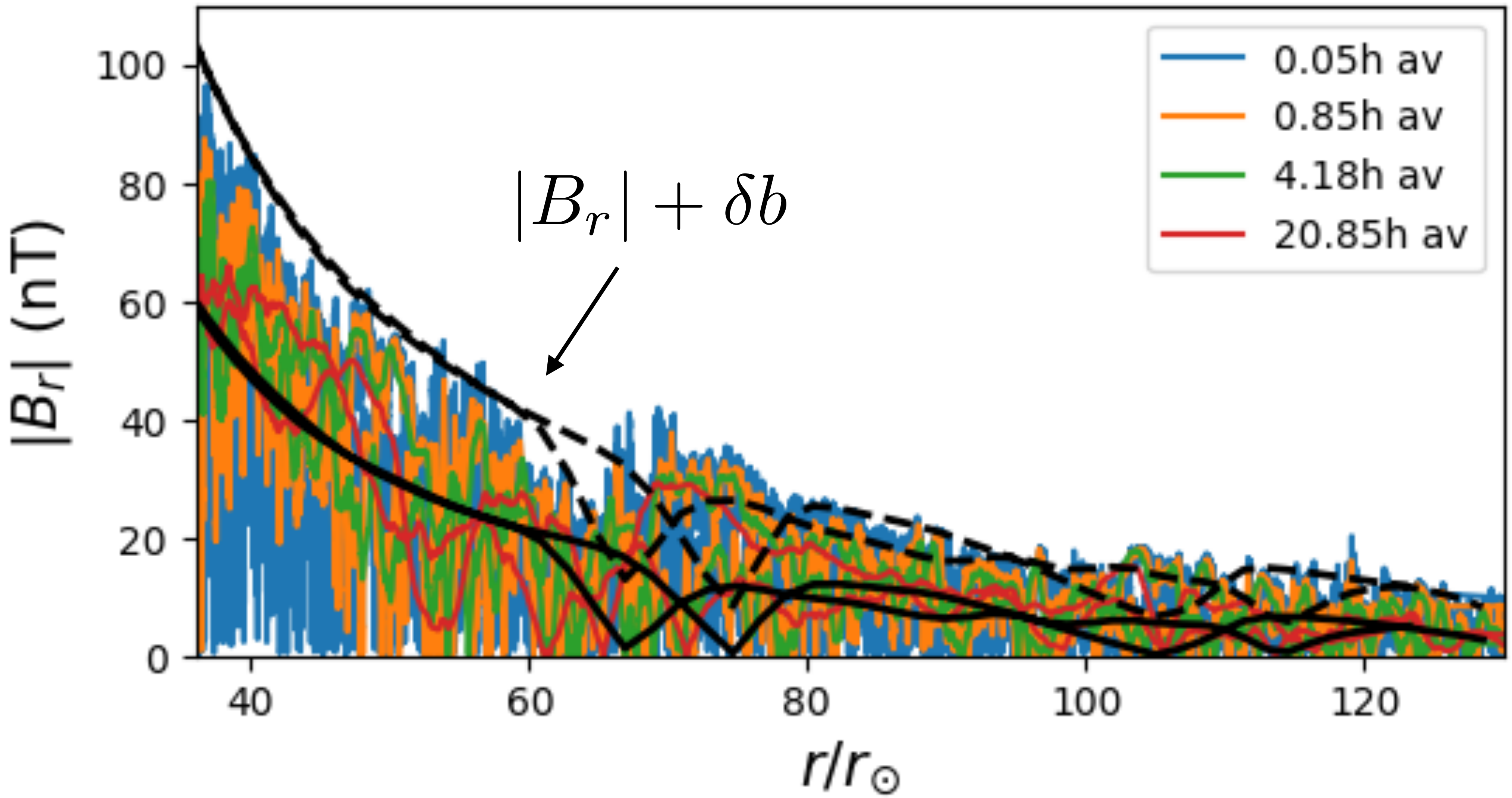
- This model will be very useful to compute sources of Solar Orbiter as well !



[Réville et al. 2020, ApJS]

Turbulence contribution

Signs of highly non linear, non transverse Alfvén waves



- Is the enveloppe of the radial field the steady component?
- Time averaging gives a very good agreement between the data and the simulation

- Turbulence level agrees with the observed perturbations

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

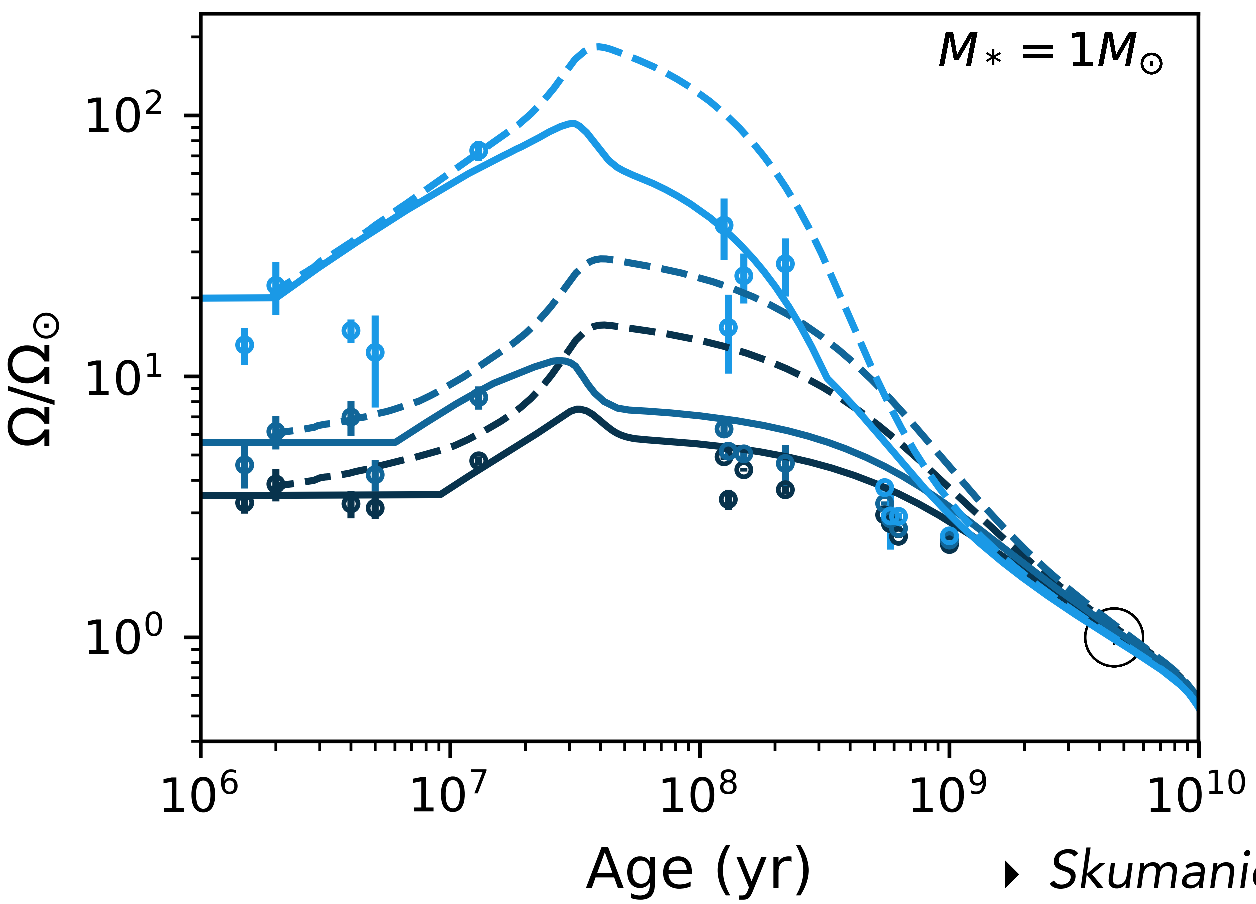
What about other stars? And planets?

Coronae & stellar winds

Ubiquitous stellar winds: loss of angular momentum?

[Réville et al. 2016]

[Benbakoura, Réville et al. 2019]

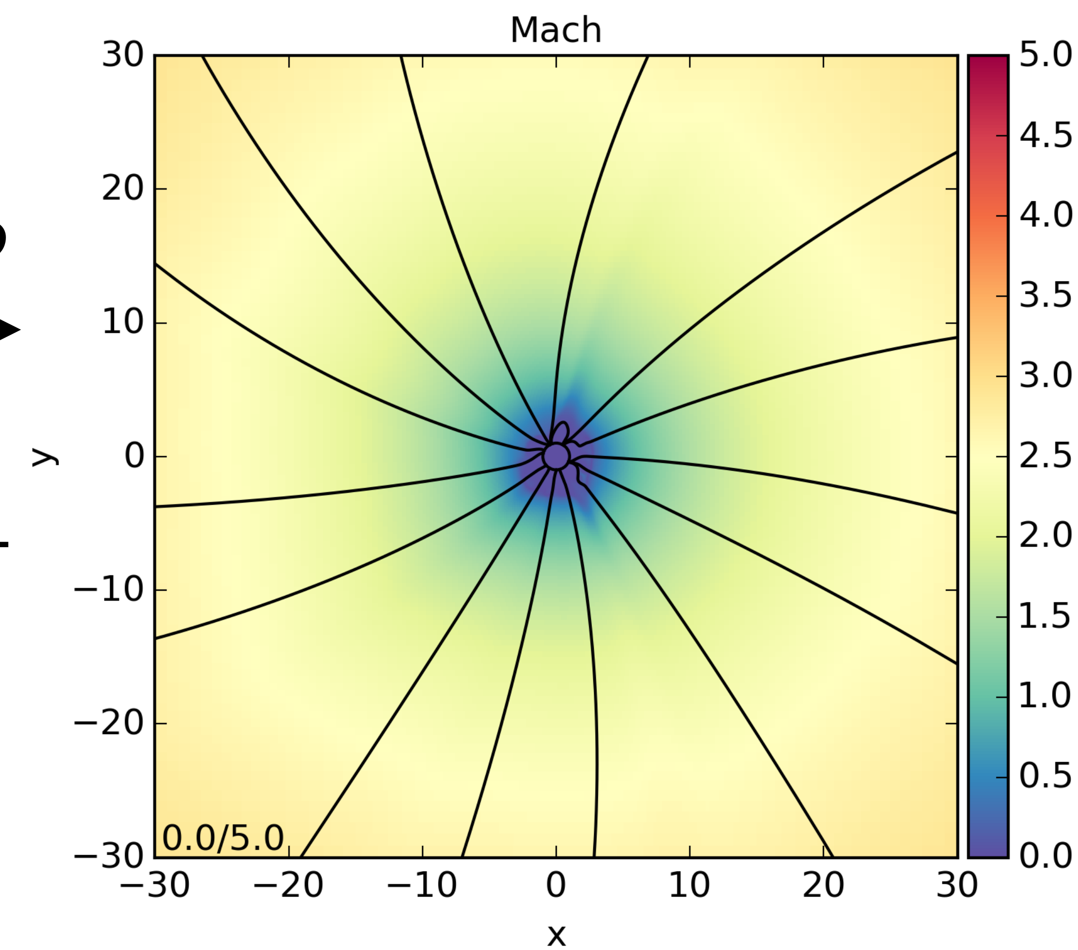


dynamo

wind

Young star

Sun



- *Skumanich's law*

$$\Omega_\star \propto t^{-1/2}$$

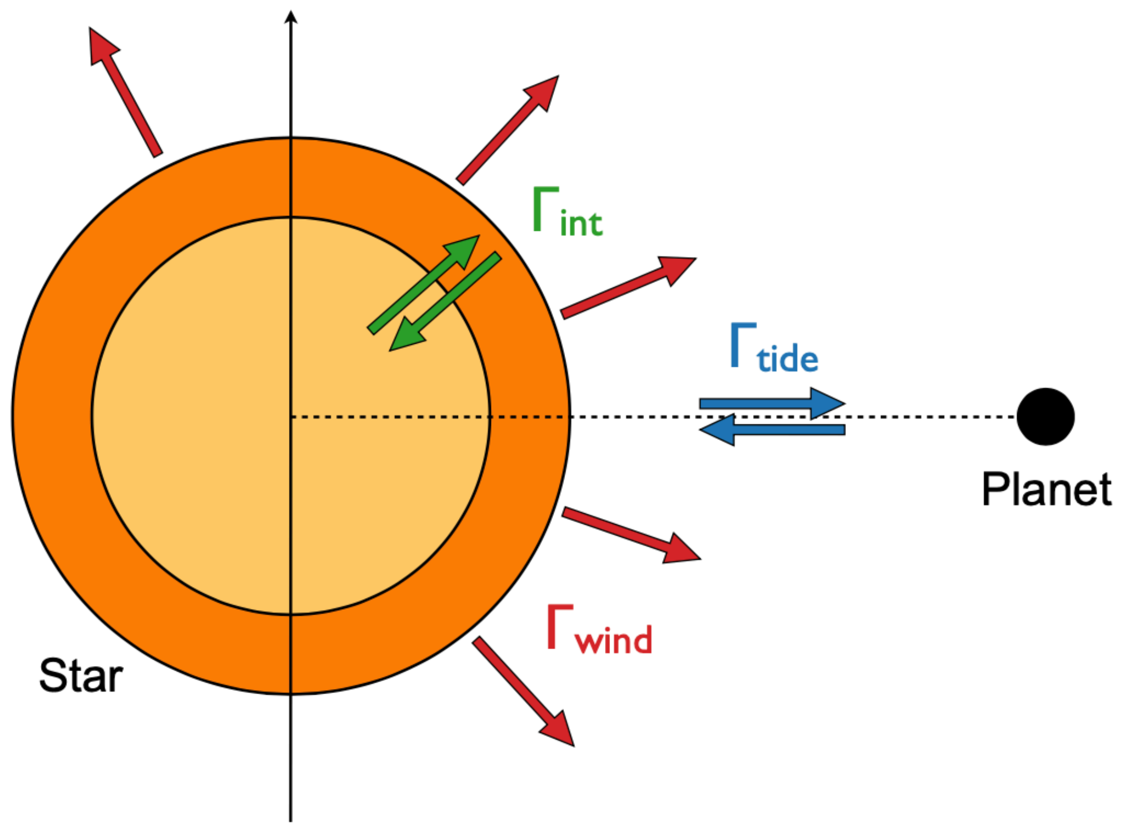
- *Complex magnetic fields*
- *Varying on timescales for min to Gy*

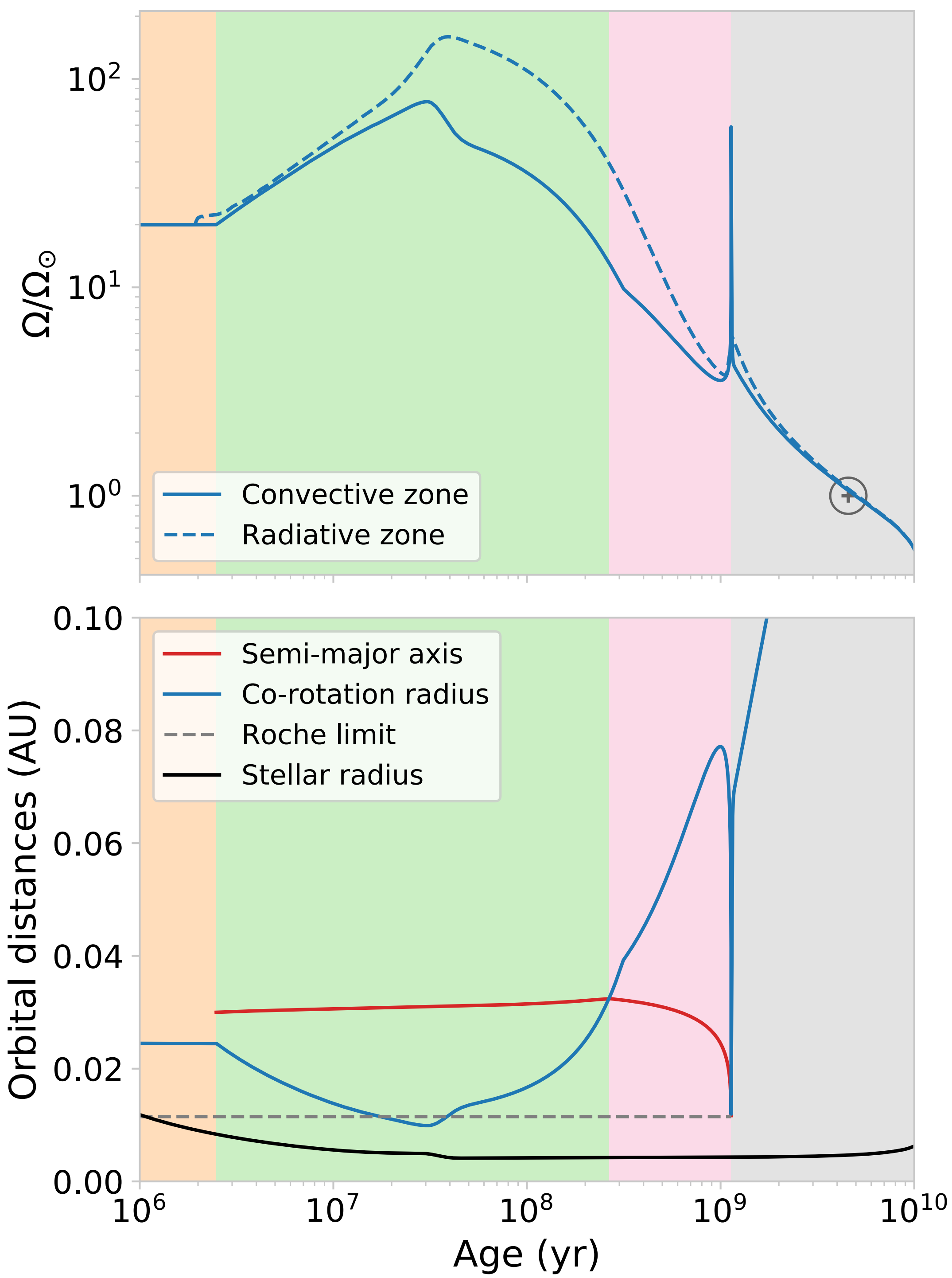
$$\dot{J} = \dot{M}\Omega_\star R_A^2$$

Mass loss *Rotation rate* *Alfvén radius*

Solving the evolution of a coupled star-planet system!

Mass loss and rotation





[Benbakoura, Réville et al. 2019]

- Model with three coupled non-linear equation for the angular momentum of the core, the enveloppe, and the planet.
- Wind and tidal torque are coupled to a stellar evolution model.

How do stellar winds evolve with age?

3D simulations without Alfvén wave turbulence

- Using coronal base parameters:

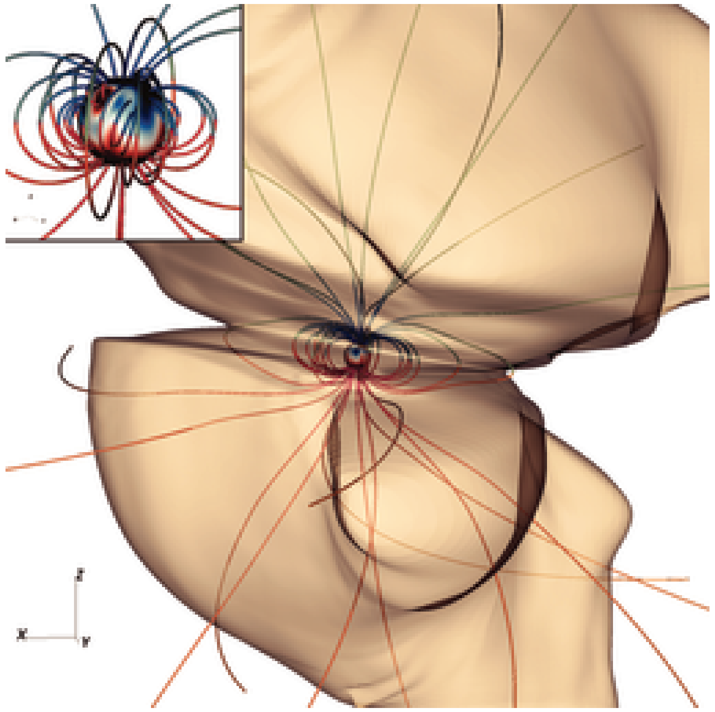
$$T_\star = T_\odot \left(\frac{\Omega_\star}{\Omega_\odot} \right)^{0.1} \qquad n_\star = n_\odot \left(\frac{\Omega_\star}{\Omega_\odot} \right)^{0.6}$$

[Ivanova & Taam 2003, Holzwarth & Jardine 2007]

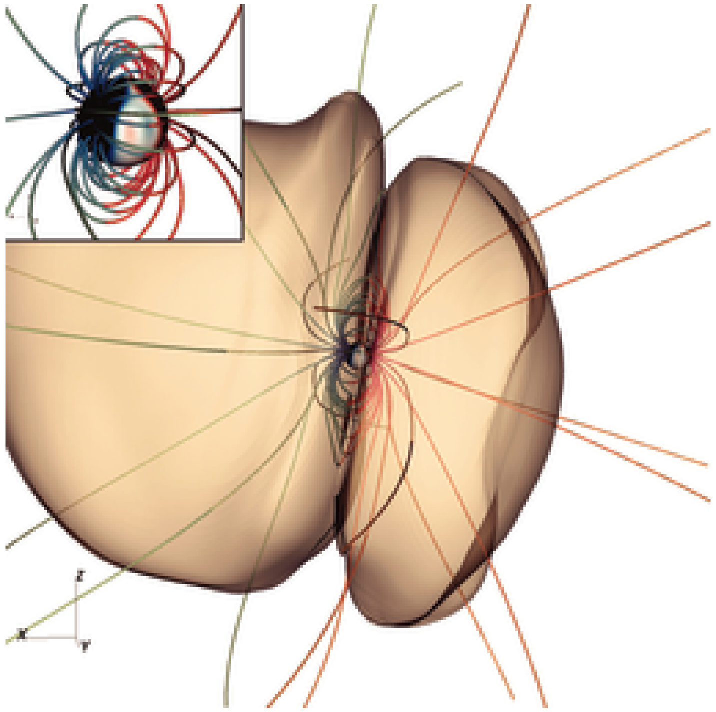
- And observed magnetograms (ESPADONS and NARVAL)

[Réville et al. 2016]

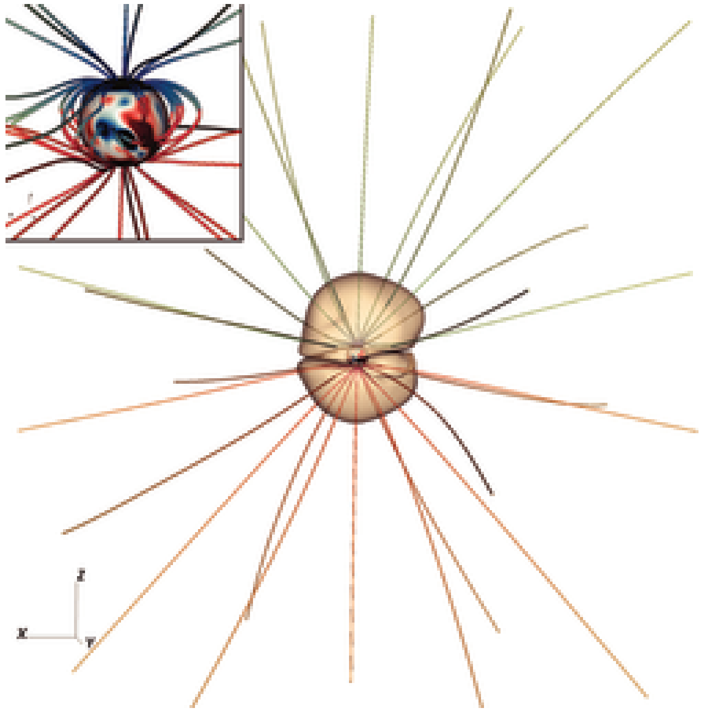
HII 296 *125 My*



DX Leo *257 My*



the Sun *4570 My*



How do stellar winds evolve with age?

3D simulations without Alfvén wave turbulence

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$$T_\star = T_\odot \left(\frac{\Omega_\star}{\Omega_\odot}\right)^{0.1} \qquad n_\star = n_\odot \left(\frac{\Omega_\star}{\Omega_\odot}\right)^{0.6}$$

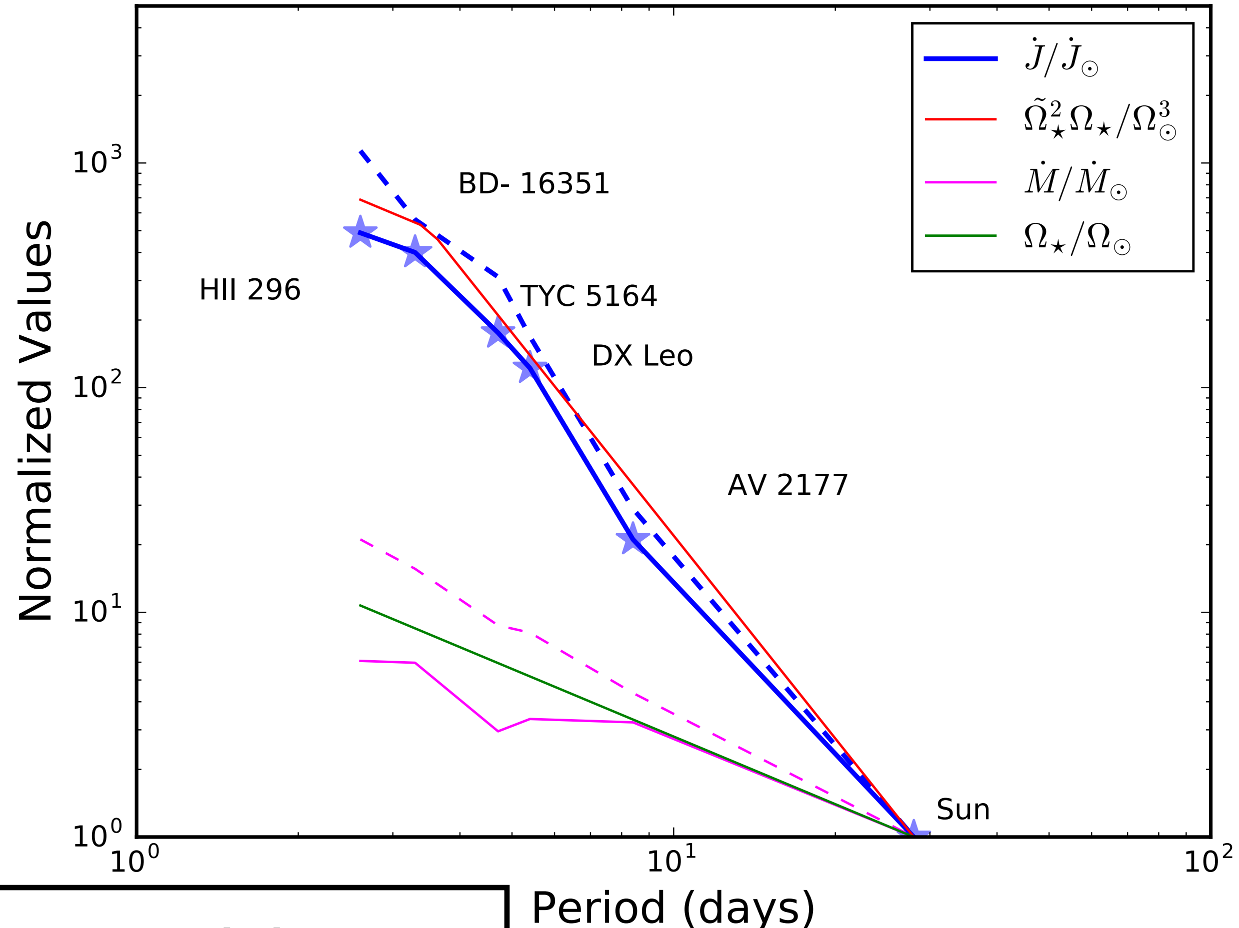
[Réville et al. 2016]

[Ivanova & Taam 2003, Holzwarth & Jardine 2007]

- We find the Skumanich's law

$$\dot{J} = \dot{M}\Omega_\star R_A^2 \propto \Omega_\star^3$$

- With some hints of a saturation for the fastest rotating star



But the scalings themselves are ad hoc!

A few results on Alfvén wave driven stellar winds!

Mass loss and rotation

- Using the observed relation :

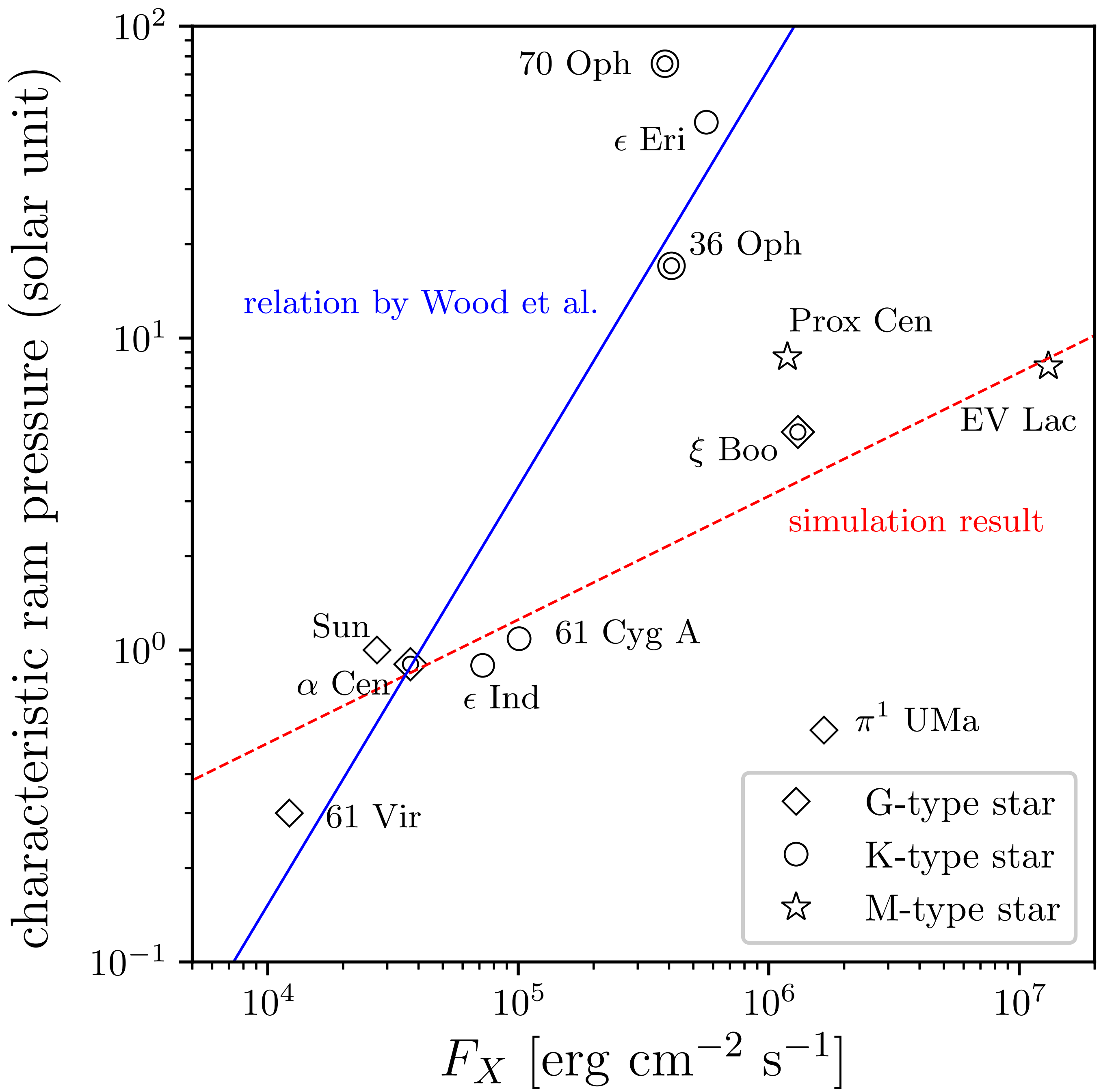
$$\langle B \rangle \propto P_{\rm rot}^{-1.2}$$

- An equipartition field at the sub granulation level, and the same wave amplitude for all rotation, we get stellar wind solutions consistent with observations.

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

[Wood et al. 2004, 2005]

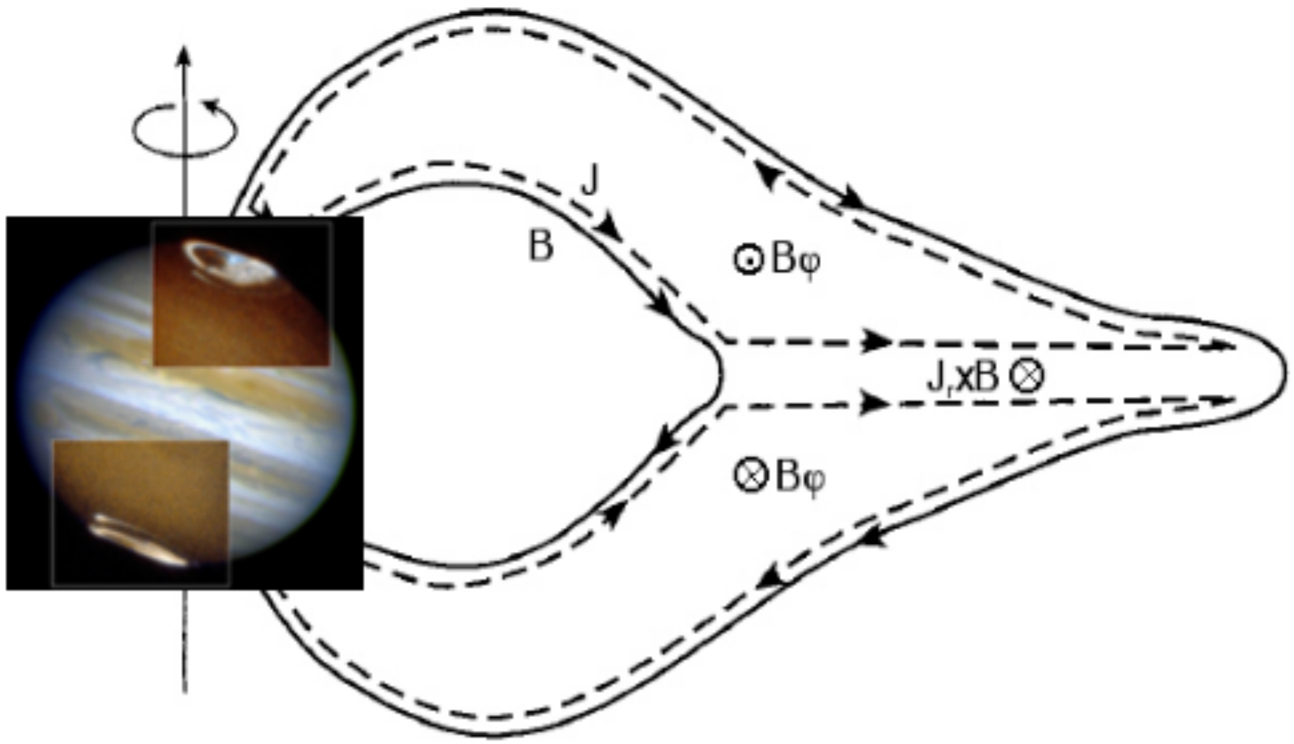
[Shoda, Suzuki, ..., Réville et al., 2020]



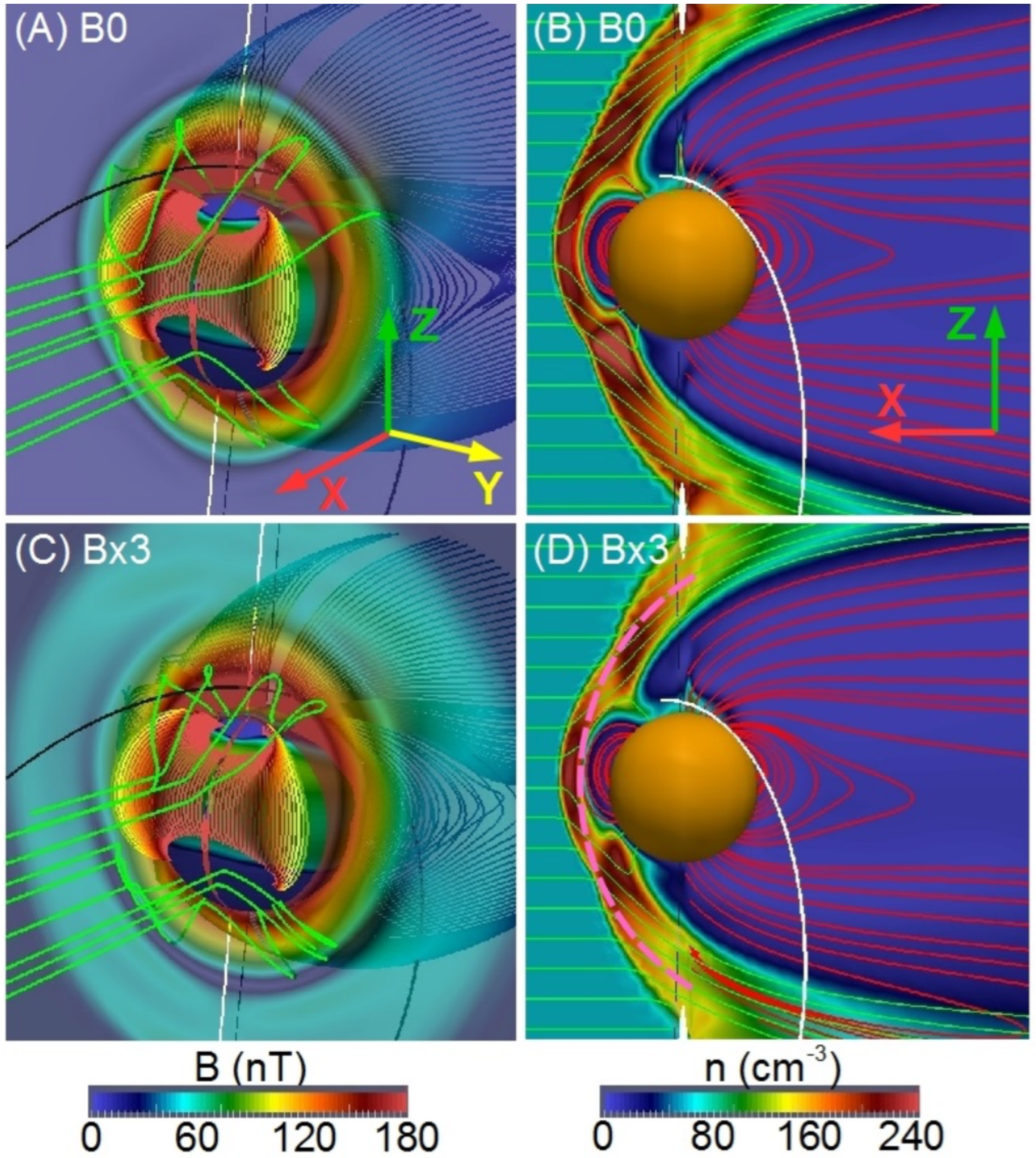
Wind-Magnetosphere interactions

Mass loss and rotation

- High energy electrons (~keV) create coherent, polarized cyclotron emissions.
- Solar wind / giant planet magnetosphere (reconnection).
- Magnetosphere / satellite coupling (Io, Ganymède).

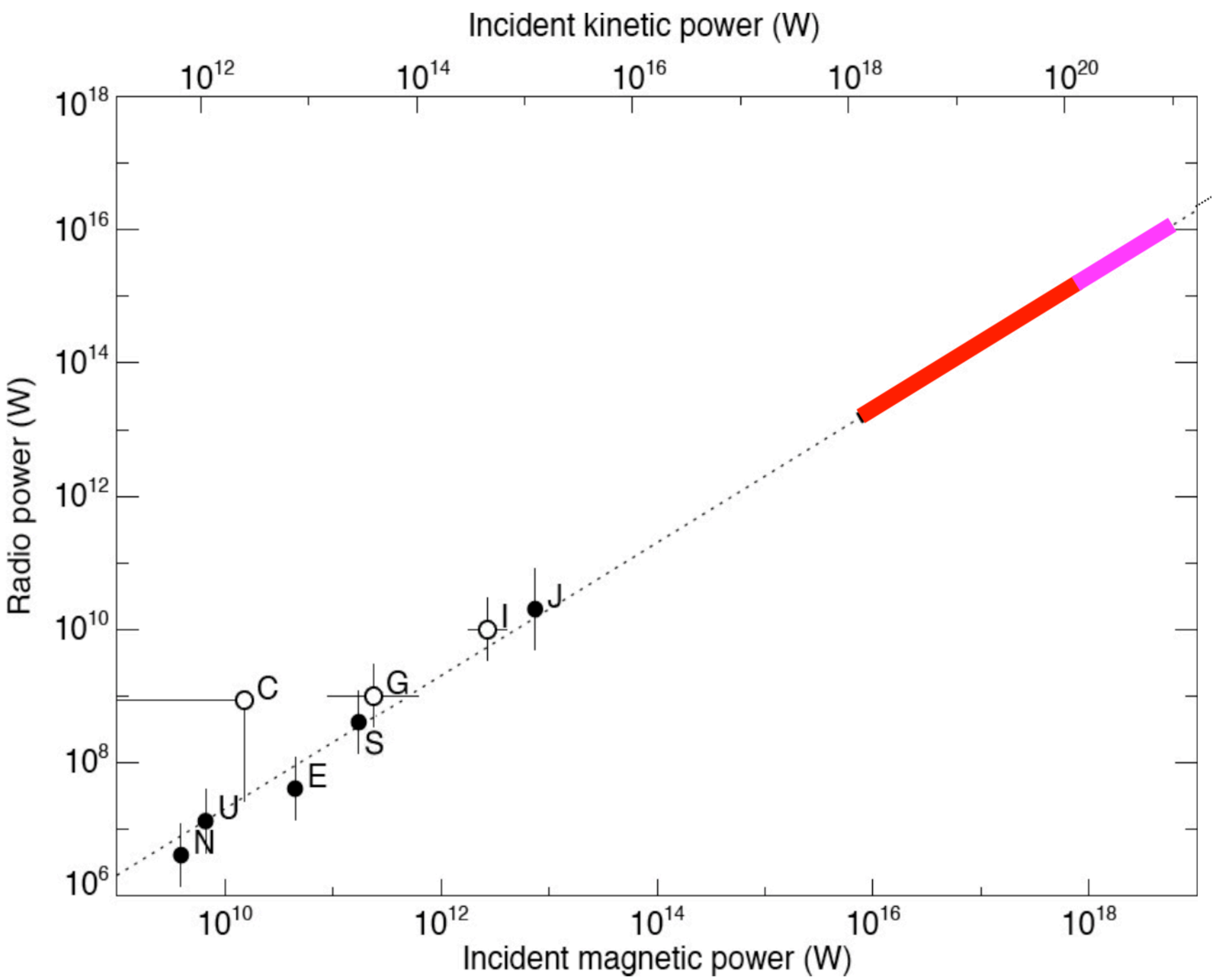


[Varela, Réville et al. 2016,18]



Wind-Magnetosphere interactions

Mass loss and rotation



- Cyclotron maser radio emission follow a scaling law throughout the solar system.
- Hot Jupiters close to their hosts stars can create detectable emissions.
- Very dependent on the stellar wind properties and magnetism.
- A first exoplanet case could have been detected by LOFAR, around a M-dwarf.
  [Vedantham et al. 2020]
- Potentially visible in chromospheric emissions.

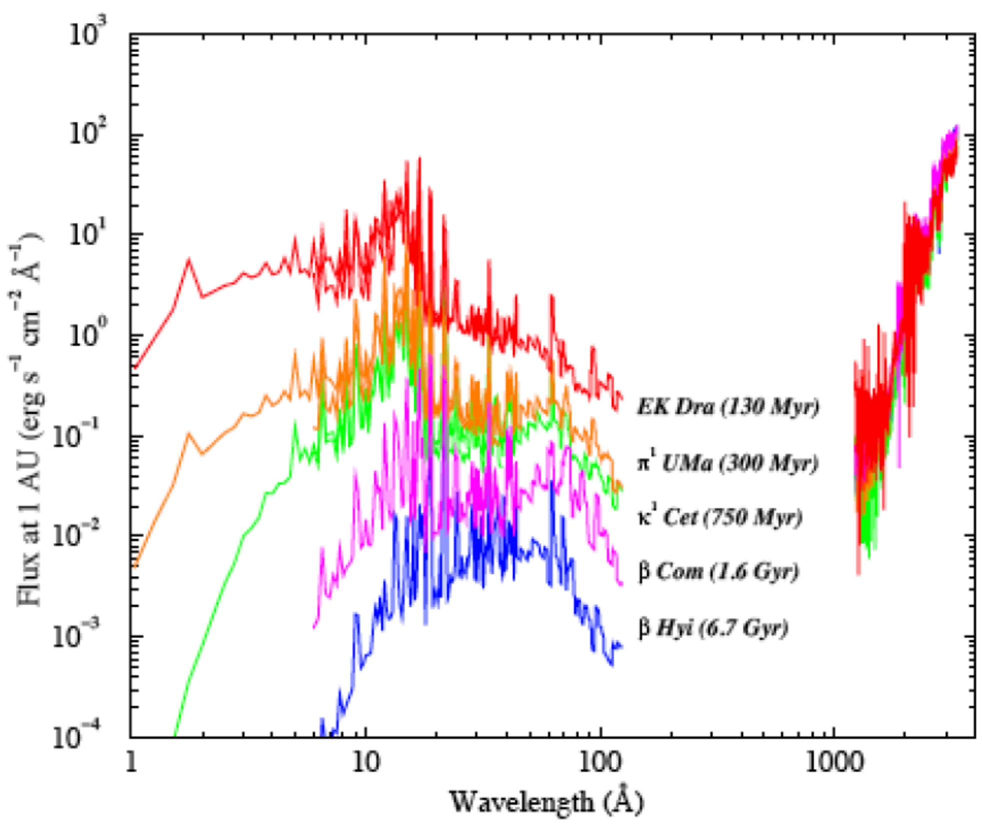
[Moutou et al. 2016, Strugarek et al. 2019]

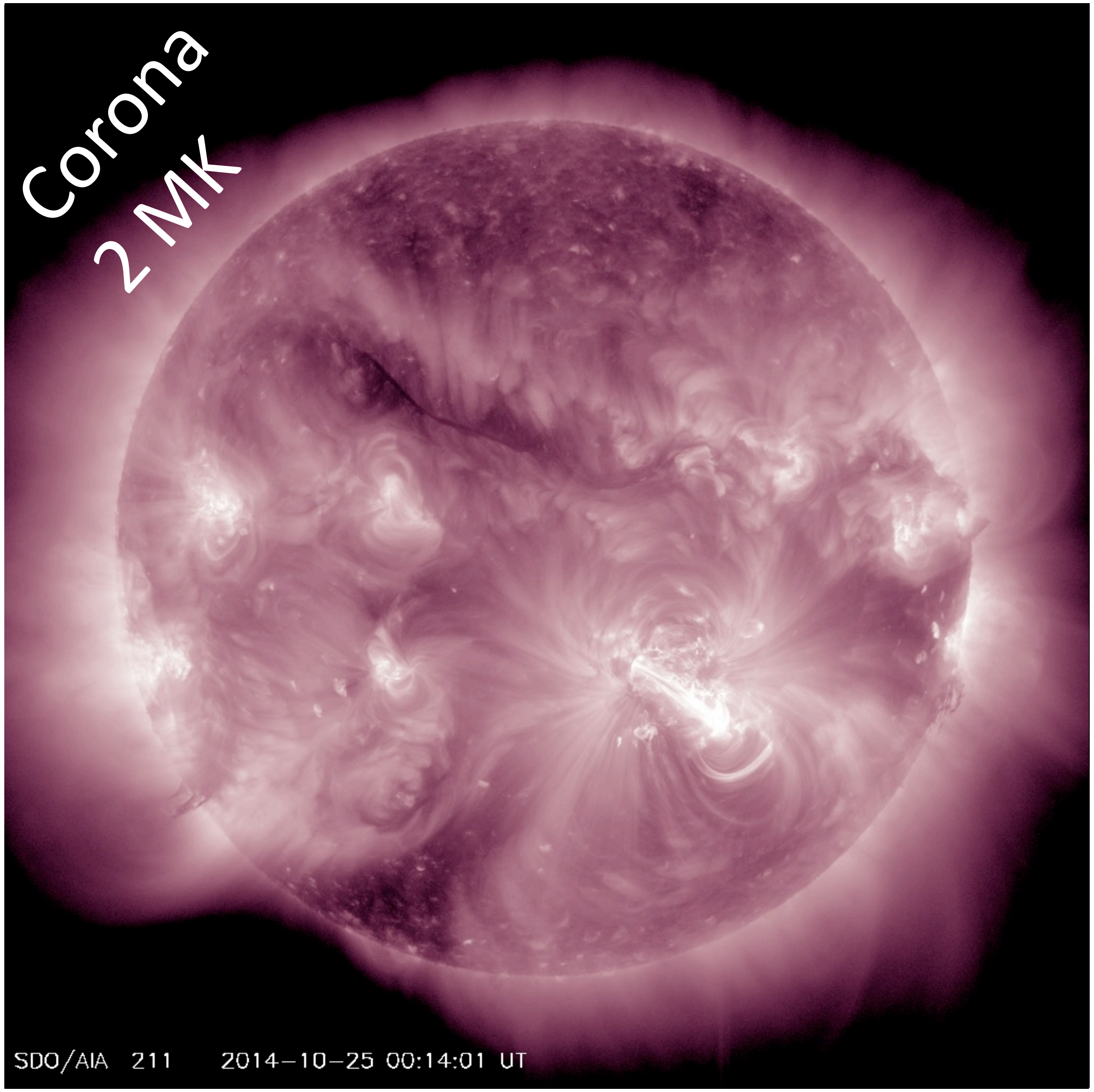
$$\mathcal{P}_{\rm radio} = \alpha \mathcal{P}_{\rm ram} = \alpha \rho v^2 (v \pi r_{\rm eq}^2) \ = \beta \mathcal{P}_{\rm mag} = \beta B^2/(2\mu_0)(v\pi r_{\rm eq}^2)$$

Coronal emissions and habitability

Mass loss and rotation

- Stellar X and UV emissions come mostly from the corona.
- Energetic radiations are responsible for pickup processes and erosion of planetary atmospheres.
- We have little constraints on other stars than the Sun as the UV light is absorbed by the ISM.





Summary & Perspectives

- Alfvén wave turbulence are likely a fundamental part of coronal heating and solar wind acceleration.
- Our 3D Alfvén waves driven model is able to reproduce both in-situ and remote observations
- Extremely useful in the PSP and Solar Orbiter era!
- AWT models also starts to explain stellar winds observables from first principles.
- Many more systems to characterize with SPIRou (ZDI+RV)

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PARKER SOLAR PROBE A MISSION TO TOUCH THE SUN

What is the solar wind?

A hydrodynamical consequence of a hot corona

- Hydrodynamic equations :

$$\frac{\partial}{\partial r}(\rho u r^2) = 0$$

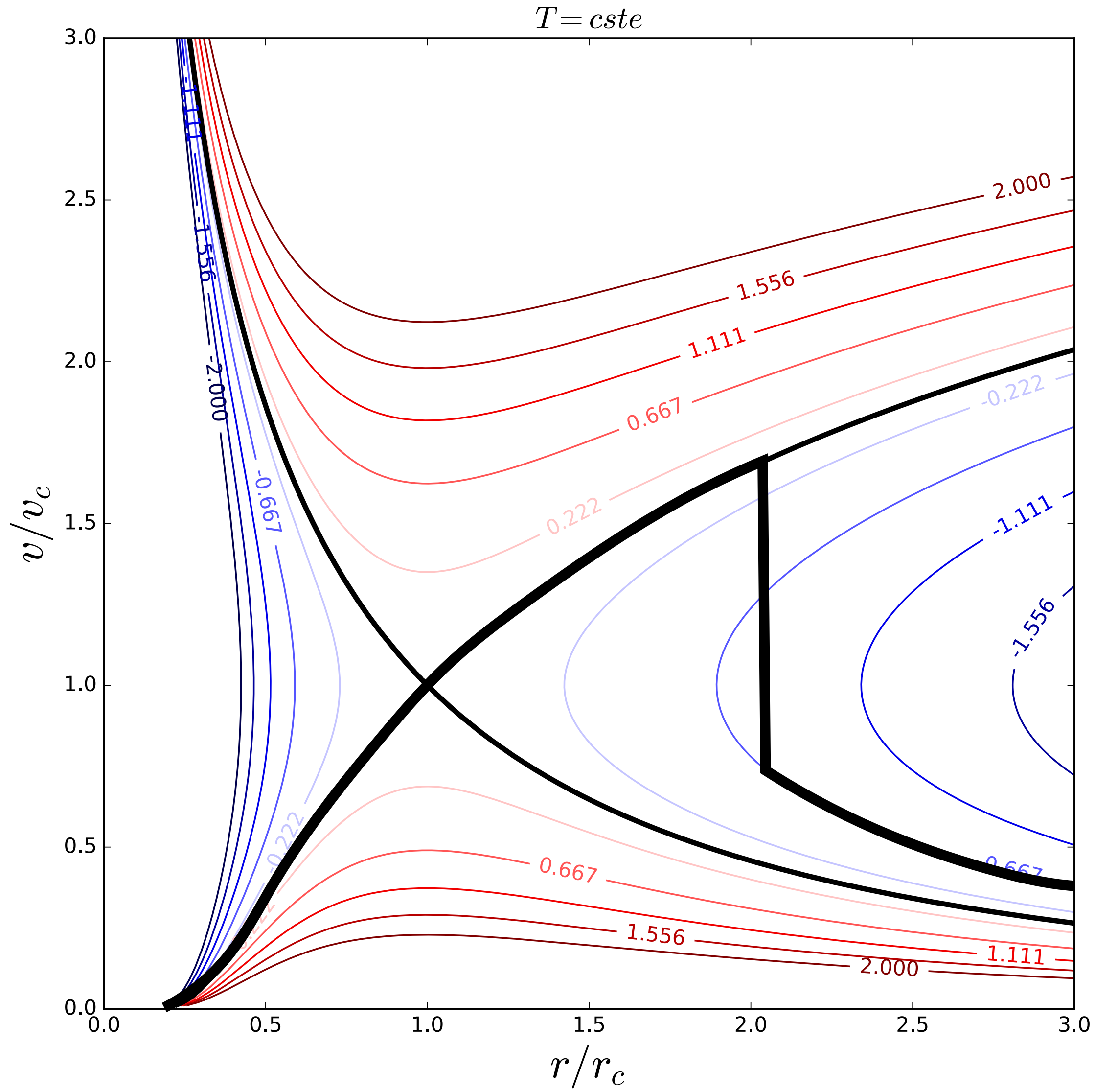
$$u\frac{\partial u}{\partial r} = -\frac{1}{\rho}\frac{\partial p}{\partial r} - \frac{GM_\odot}{r^2}$$

- Equation of state : isothermal

$$p = c_s^2 \rho$$

$$T \approx 10^6 \text{ K}$$

- Dynamical atmosphere

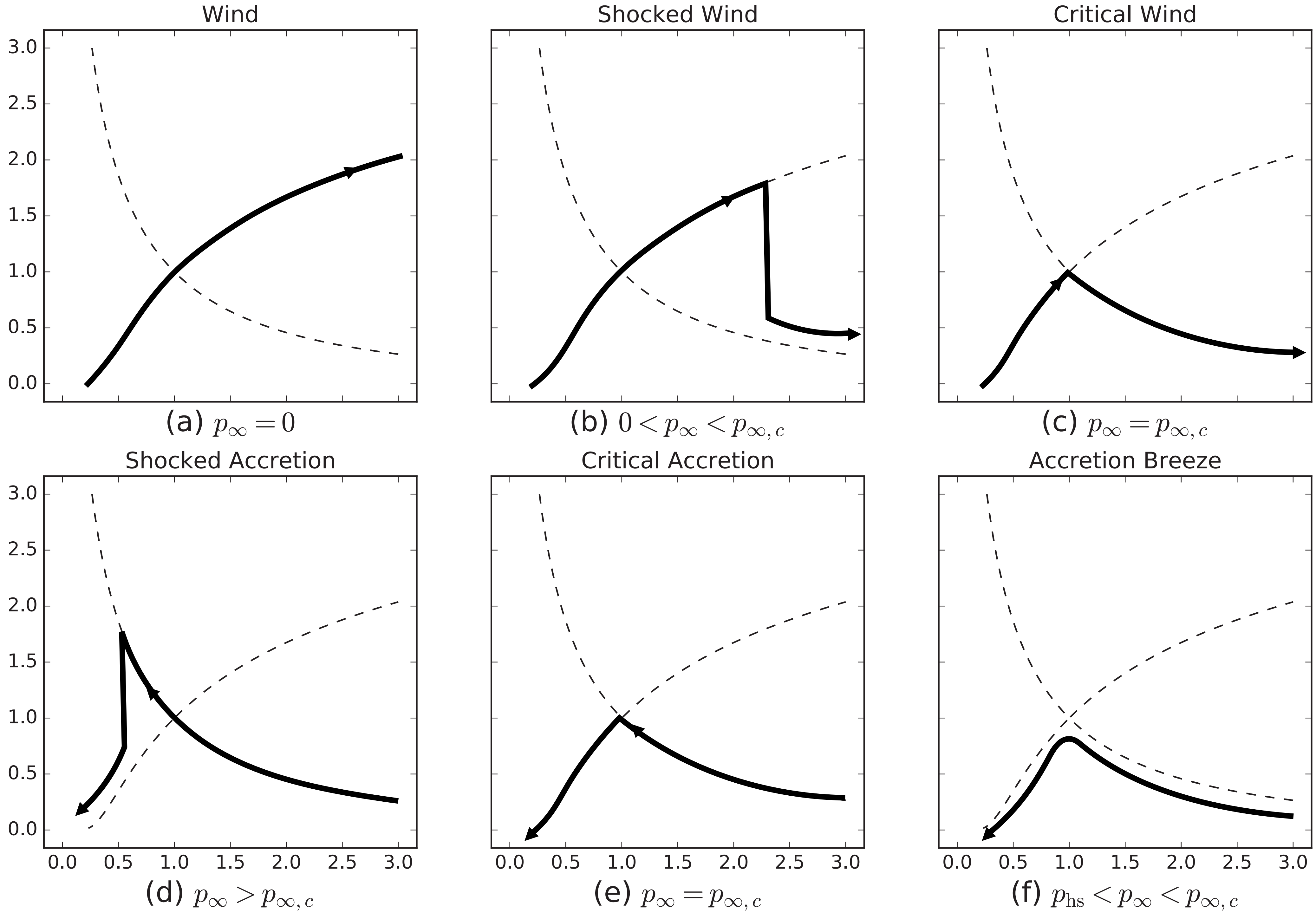


[Parker 1958]

Coronae & stellar winds

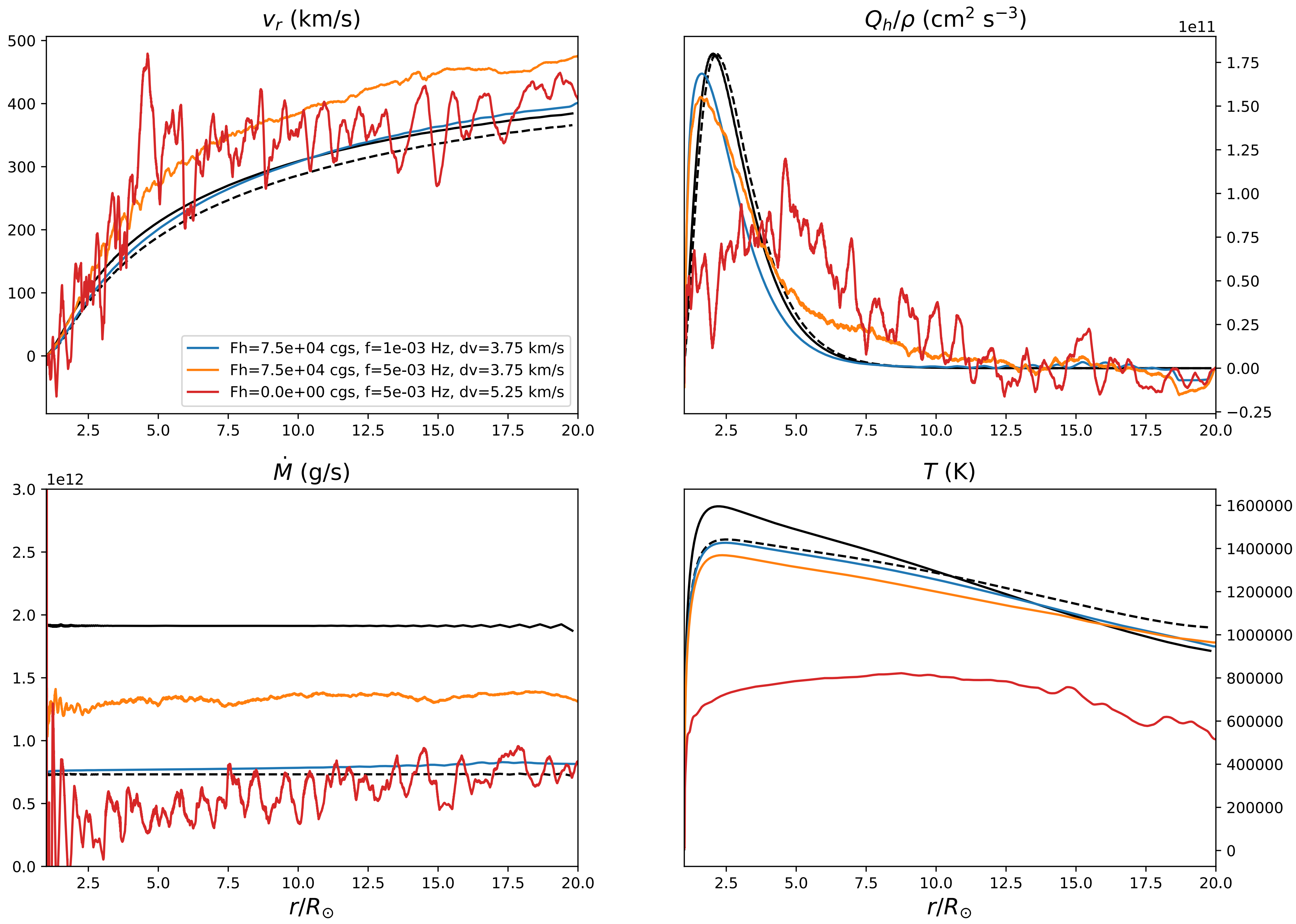
A wind/accretion hysteresis cycle

[Velli 1994, Priest 2014]



Wave heating in flux tube models

Shock heating

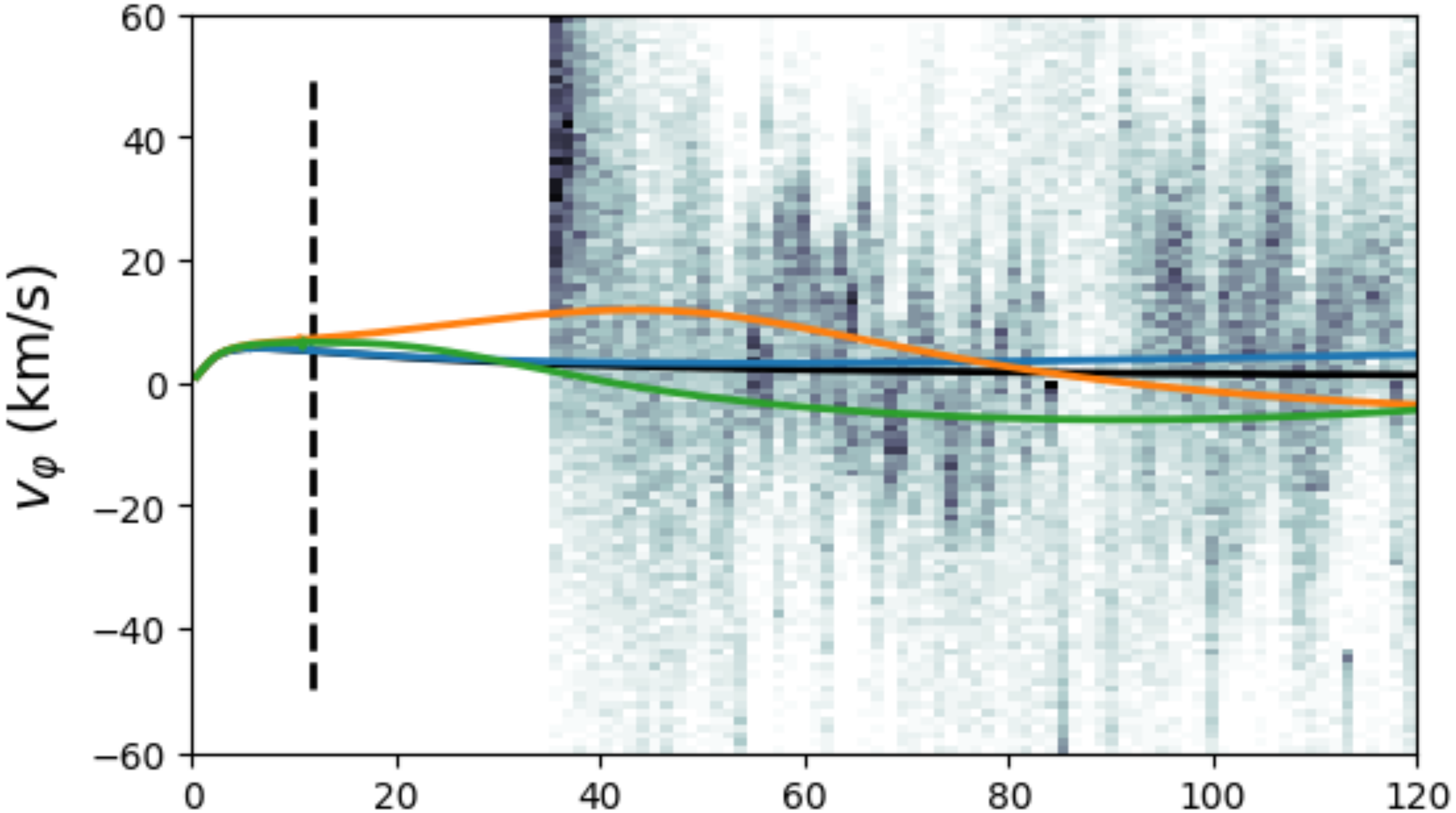


[Réville et al. 2019, SF2A]

The angular momentum paradox

A simple analytical enhancement of the WD model

[Réville et al. 2020a, PSP special issue]

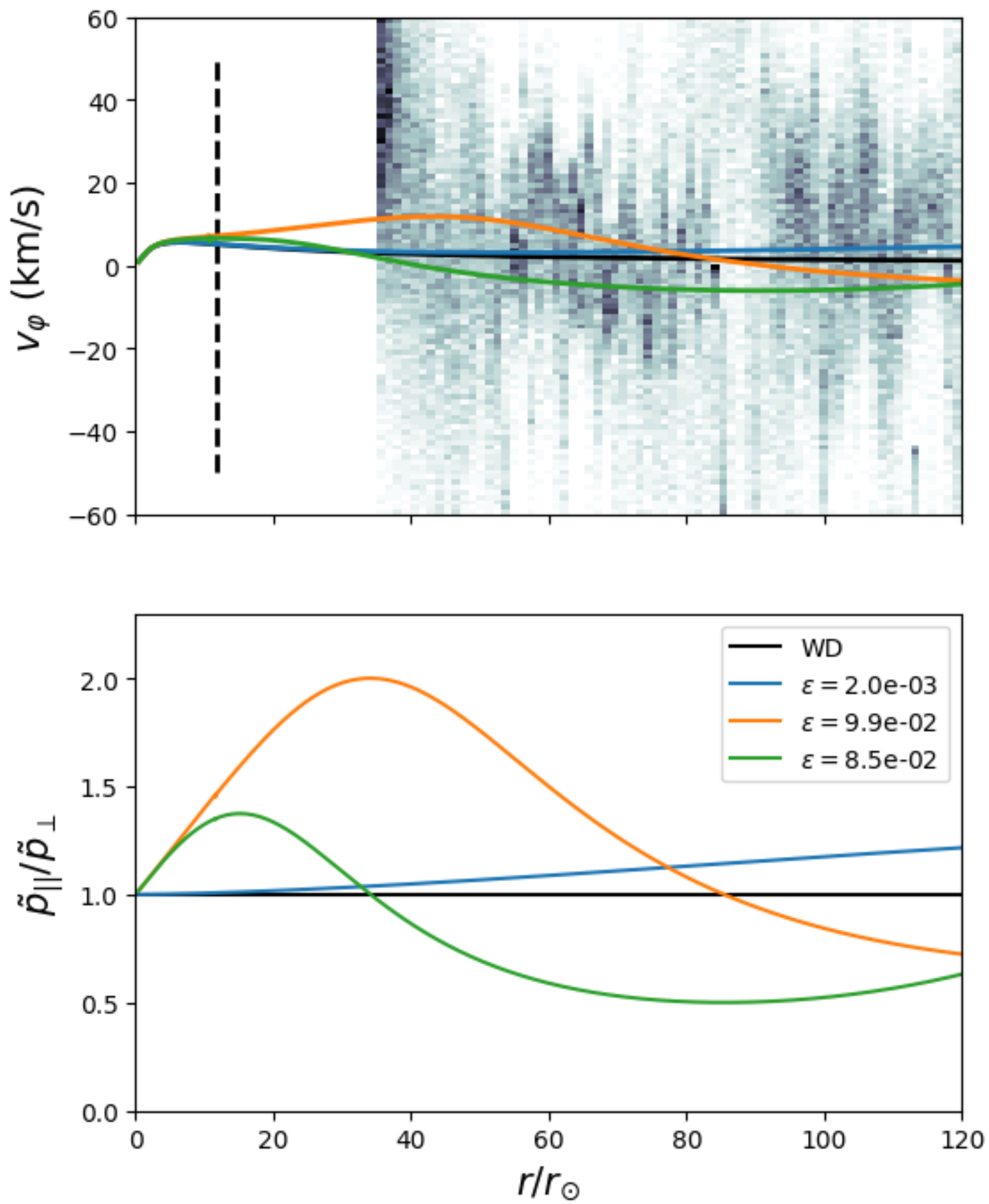


MHD models work for all large scale quantities…
…except for the angular momentum

Color lines introduce temperature anisotropies…
Must we go beyond MHD ?

Anisotropies effects on tangential velocities

A simple analytical enhancement of the WD model



- We look at the effect of the anistropies.
- Getting closer to the observations but not quite there yet…
- Switchbacks could enhance the effect of anisotropies.

[Hollweg 1973, Reville et al. 2020]

$$\Omega_\odot r_A^2 = r v_\varphi - r \frac{B_r B_\varphi}{4\pi\rho v_r}\left(1 - \boxed{\frac{4\pi}{||B||^2}(\tilde{p}_{||} - \tilde{p}_\perp)}\right)$$

[Weber & Davis 1967,1970]

- Conserved quantity