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Alfvén wave as a power source of the solar wind: energy and momentum deposition and evolution of switchbacks

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Parker's isothermal model ($\gamma = 1$)

- Thermal pressure gradient powers the solar wind

$$P = nkT \propto n$$

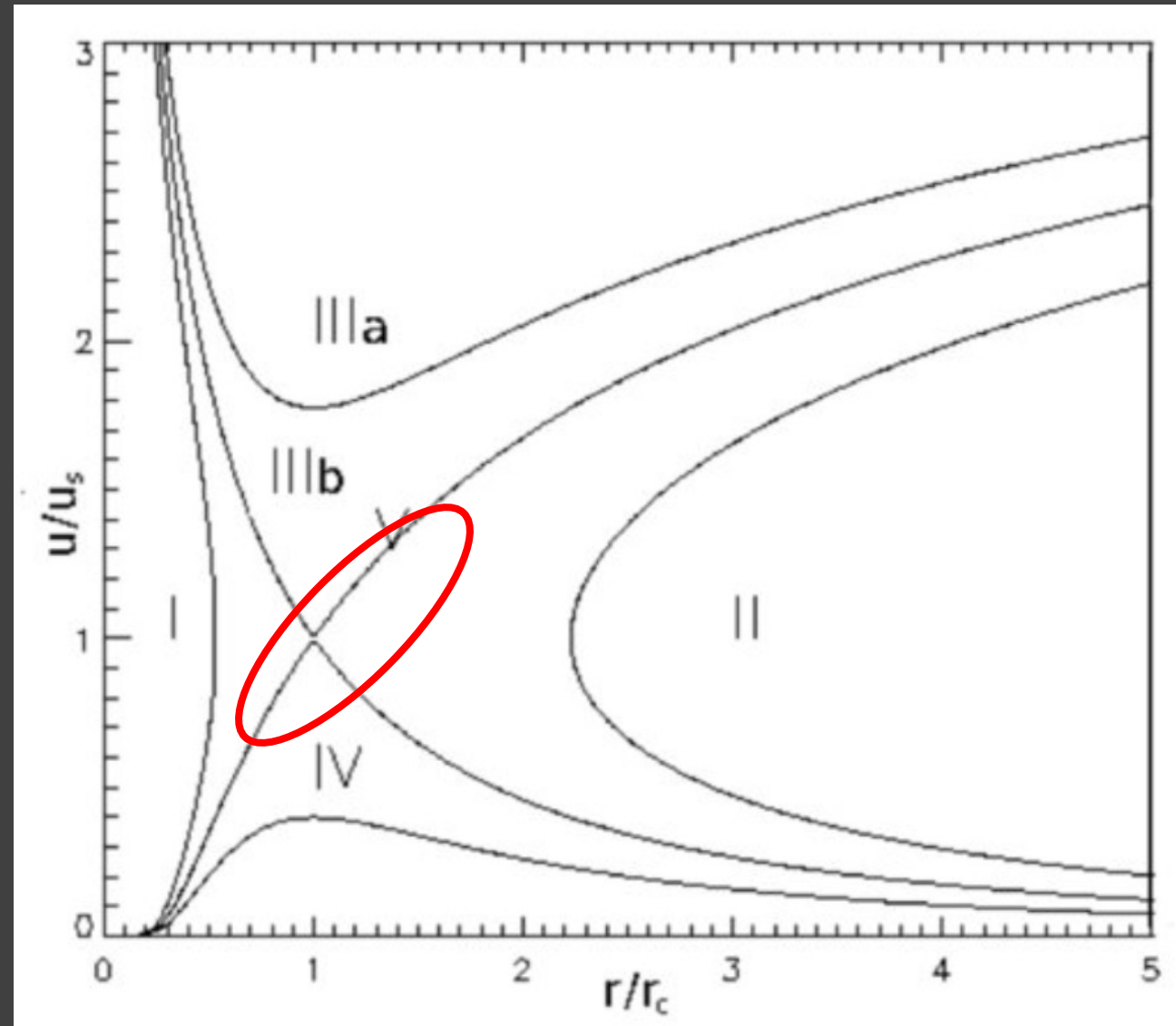
- Momentum equation

$$\left(V - \frac{C^2}{V} \right) \frac{dV}{dr} = \frac{2C^2}{r} - \frac{GM}{r^2}$$

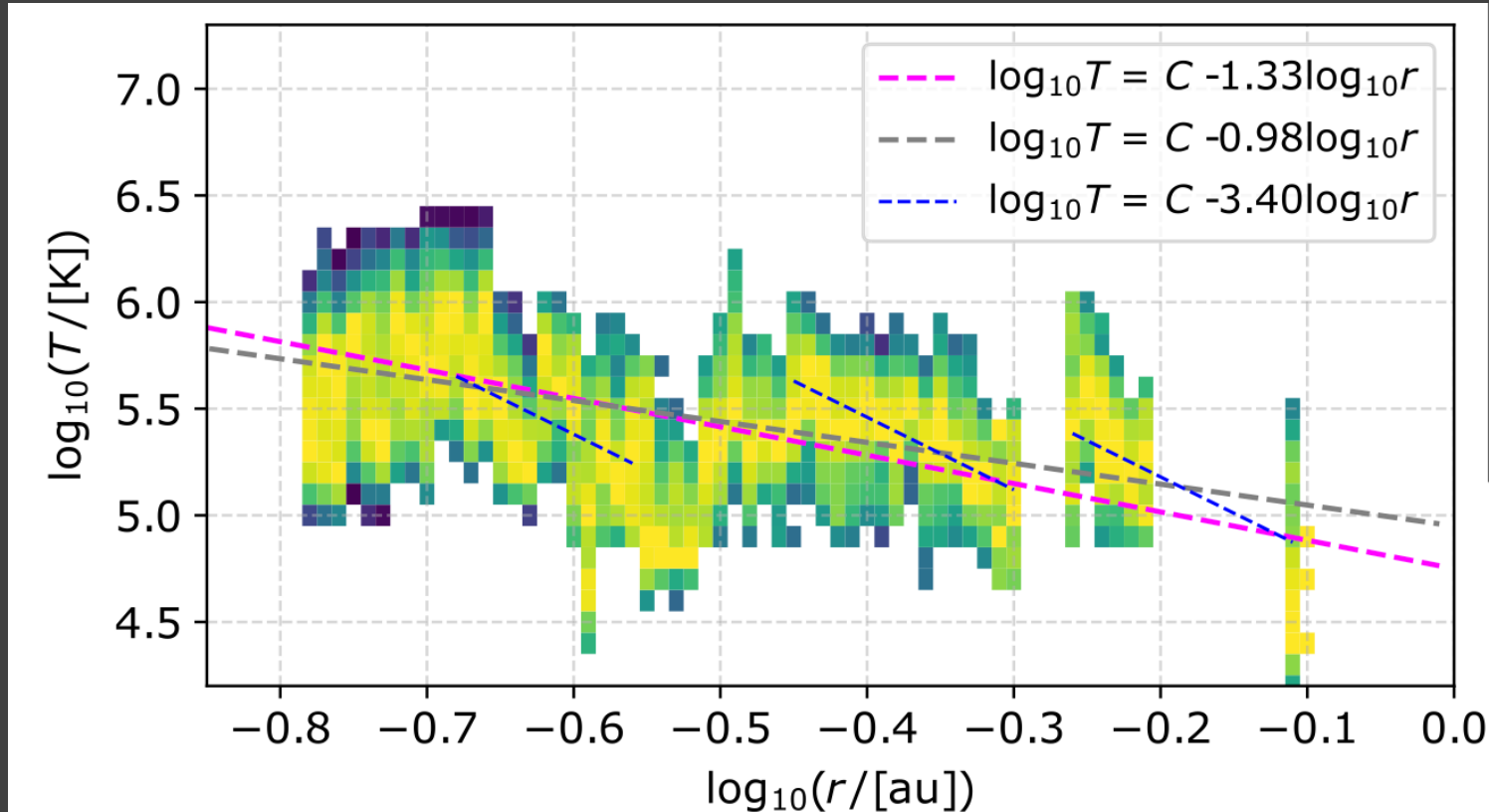
where $C^2 = kT/m_p$

- Critical point:

$$r_c = \frac{GM}{2C^2}$$
$$V = C$$



Solar wind is not isothermal



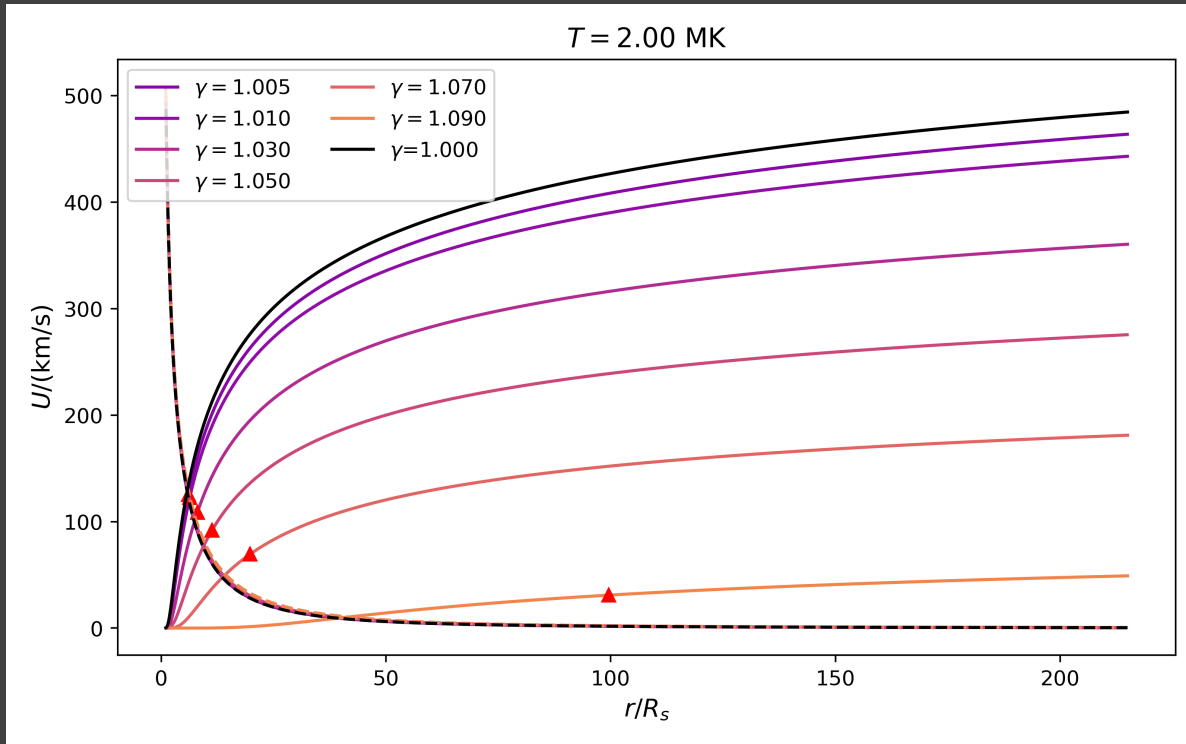
Nicolaou+2020

Proton temperature is not isothermal, but its radial decay rate is slower than adiabatic cooling.

$$T \propto r^{-2(\gamma-1)}$$

$$\text{Adiabatic: } T \propto r^{-4/3}$$

Polytropic solar wind ($\gamma > 1$)

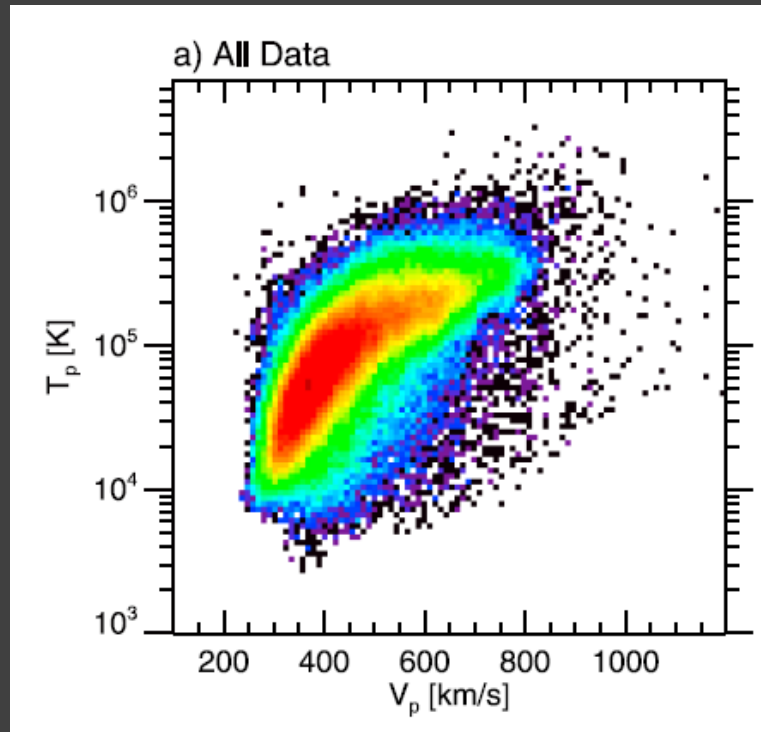


For $\gamma > 1$, the wind speed drops rapidly

Simple polytropic wind model cannot explain the observed solar wind speed

Power source is needed!

Strong $T_p - V_{sw}$ correlation

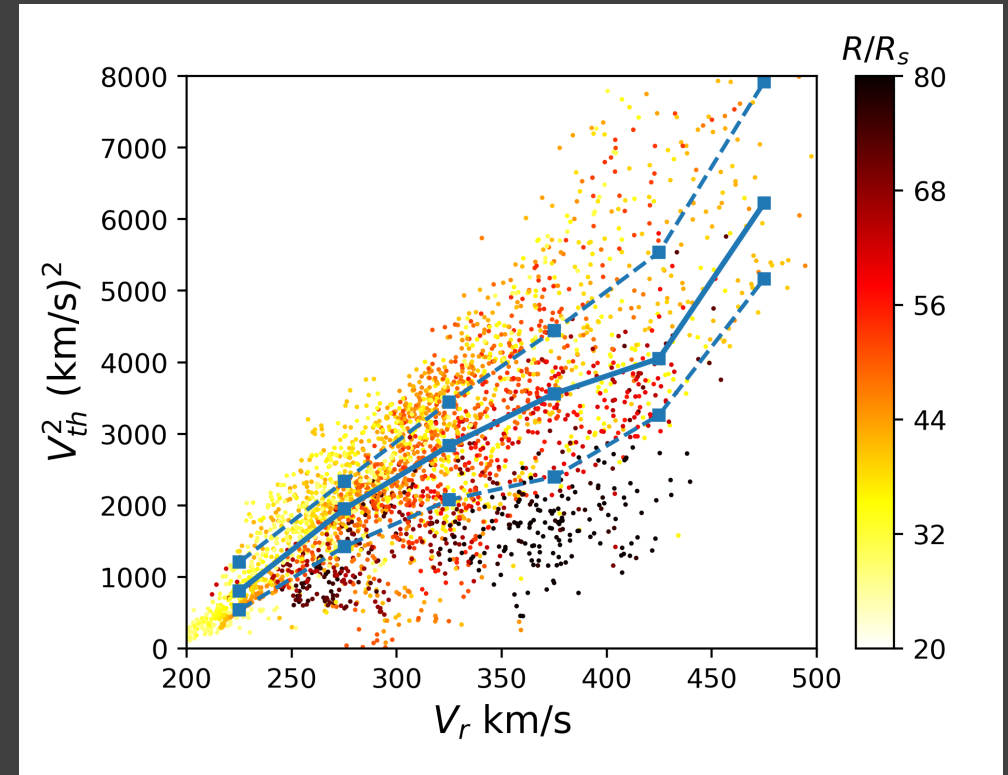


Elliott+2012

OMNI2 data to 2009

$T_i - V$ correlation is already established very close to the Sun

Power sources likely heat and accelerate the solar wind simultaneously

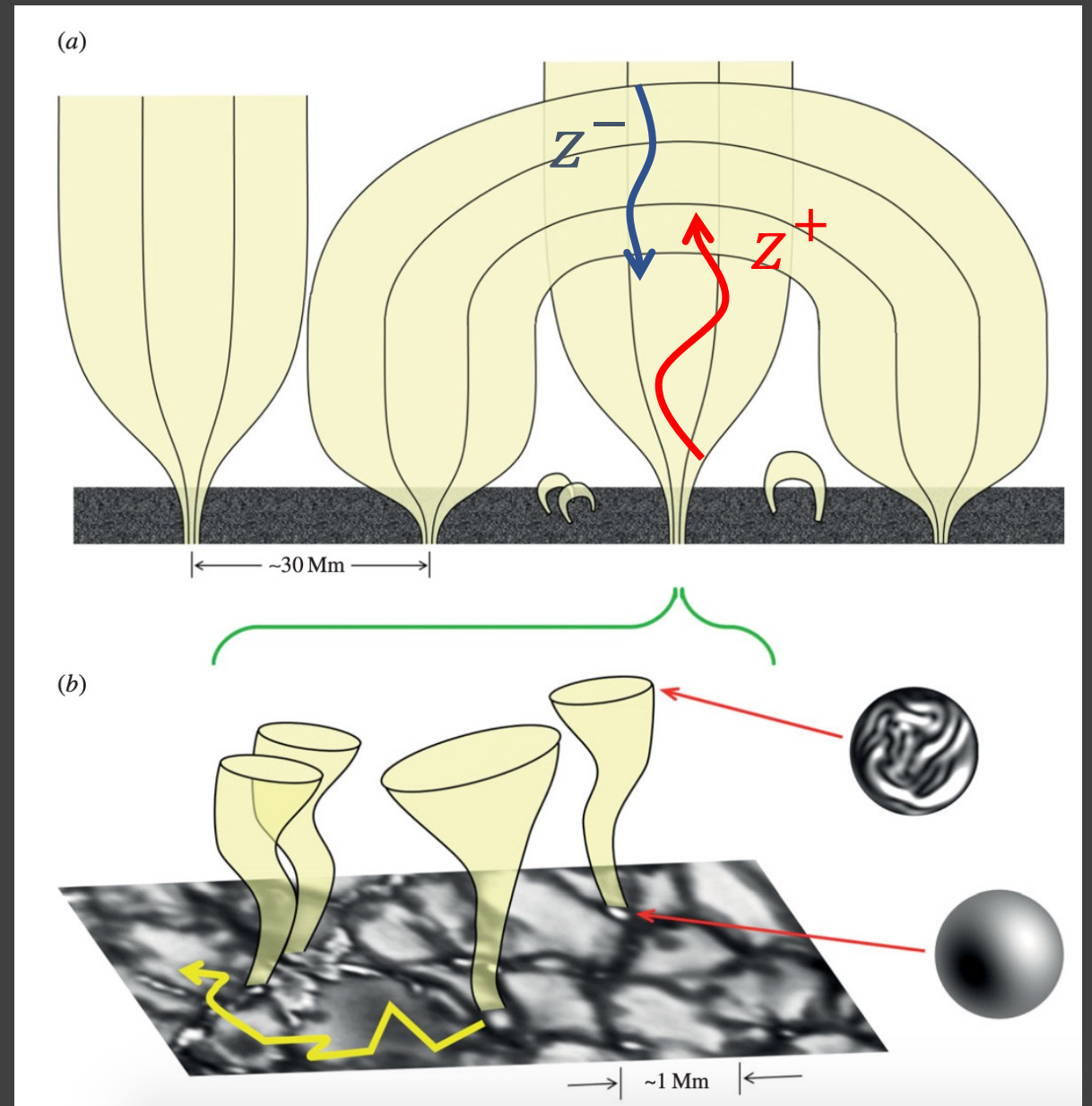


Shi+2021

PSP Encounter 1-5

Two popular models

- Impulsive process: Reconnection (a.k.a. nanoflares)
- Alfvén wave/turbulence



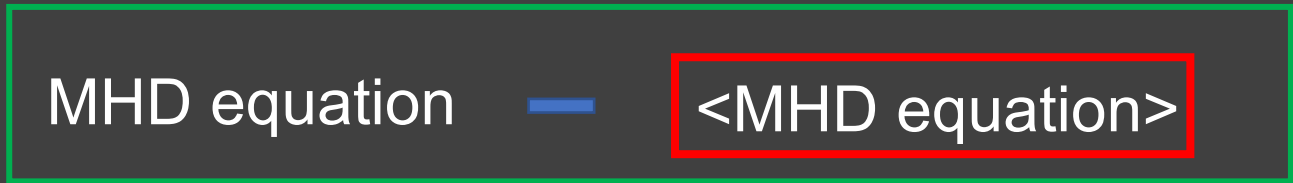
Alfvén waves

- (Quasi)-ubiquitous in the solar wind
- Can be of large amplitude $|\delta\mathbf{B}| \sim |\mathbf{B}|$: wave pressure
- Turbulence energy cascade can heat the plasma
- Reynolds-averaged MHD equation set
- Decompose fields:

$$F = F_0 + F_1$$

Slowly varying background waves

Not necessarily $|F_1| \ll |F_0|$



Subtract the average from original
Get equation for waves

Time-average
Get equation for background fields

Alfvén wave driven solar wind model

$$\frac{\partial \rho}{\partial t} = -\nabla \cdot (\rho \mathbf{V})$$

$$\frac{\partial \mathbf{V}}{\partial t} = -\mathbf{V} \cdot \nabla \mathbf{V} - \frac{1}{\rho} \nabla \left(P + \frac{1}{2} (\varepsilon^+ + \varepsilon^-) \right) - \frac{GM_s}{r^2} \hat{e}_r$$

wave pressure

$$\frac{\partial P}{\partial t} = -\mathbf{V} \cdot \nabla P - \gamma P (\nabla \cdot \mathbf{V}) + (\gamma - 1) (Q_w + Q_h)$$

Wave heating

Other heating/loss (close to the Sun)

$$\frac{\partial \varepsilon^+}{\partial t} = -(\mathbf{V} + \mathbf{V}_A) \cdot \nabla \varepsilon^+ - [\nabla \cdot (\mathbf{V} + \mathbf{V}_A)] \varepsilon^+ - \frac{1}{2} (\nabla \cdot \mathbf{V}) \varepsilon^+ + R_+ + D_+$$

$$\frac{\partial \varepsilon^-}{\partial t} = -(\mathbf{V} - \mathbf{V}_A) \cdot \nabla \varepsilon^- - [\nabla \cdot (\mathbf{V} - \mathbf{V}_A)] \varepsilon^- - \frac{1}{2} (\nabla \cdot \mathbf{V}) \varepsilon^- + R_- + D_-$$

Wave dissipation

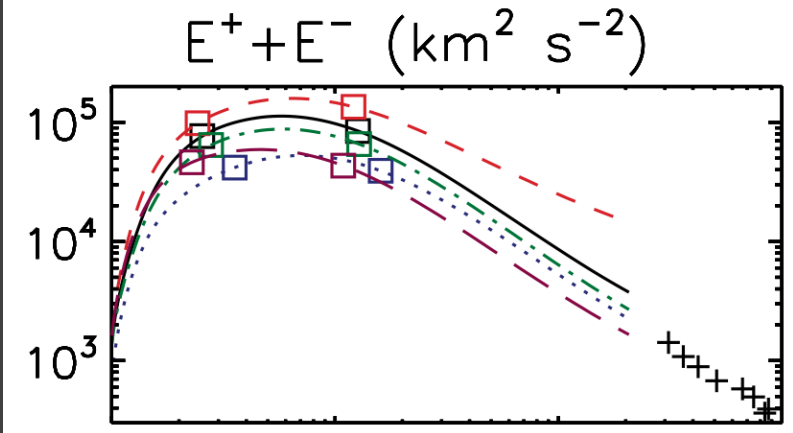
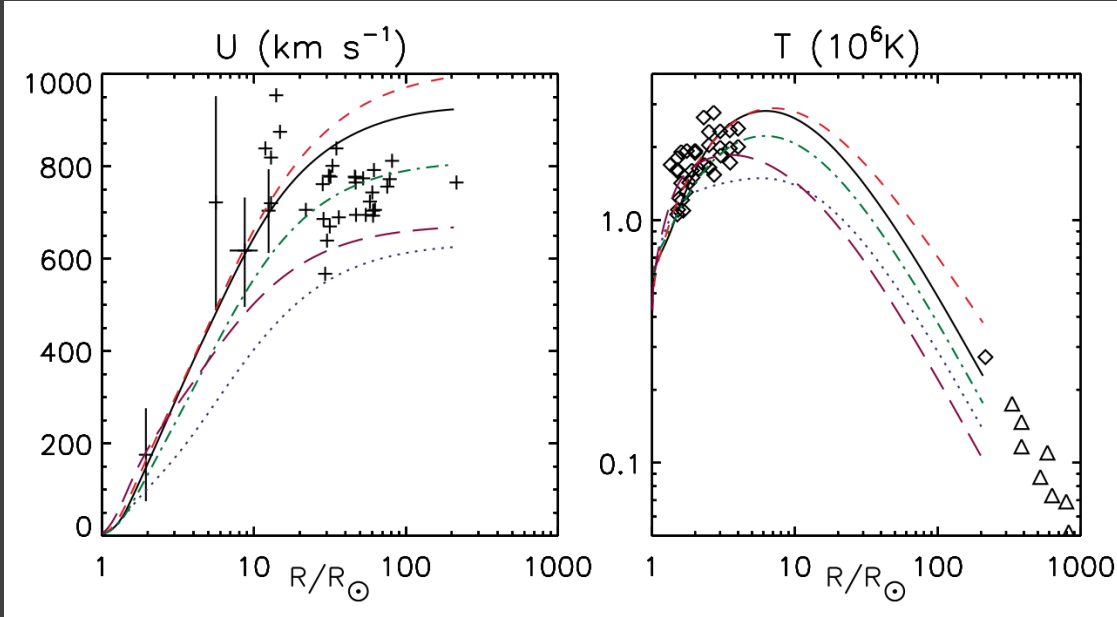
$$\varepsilon^\pm = \frac{1}{4} \rho (Z^\pm)^2$$

Compressibility of the fluctuations is neglected here, but may be important through parametric decay of Alfvén waves (Shoda+2019)

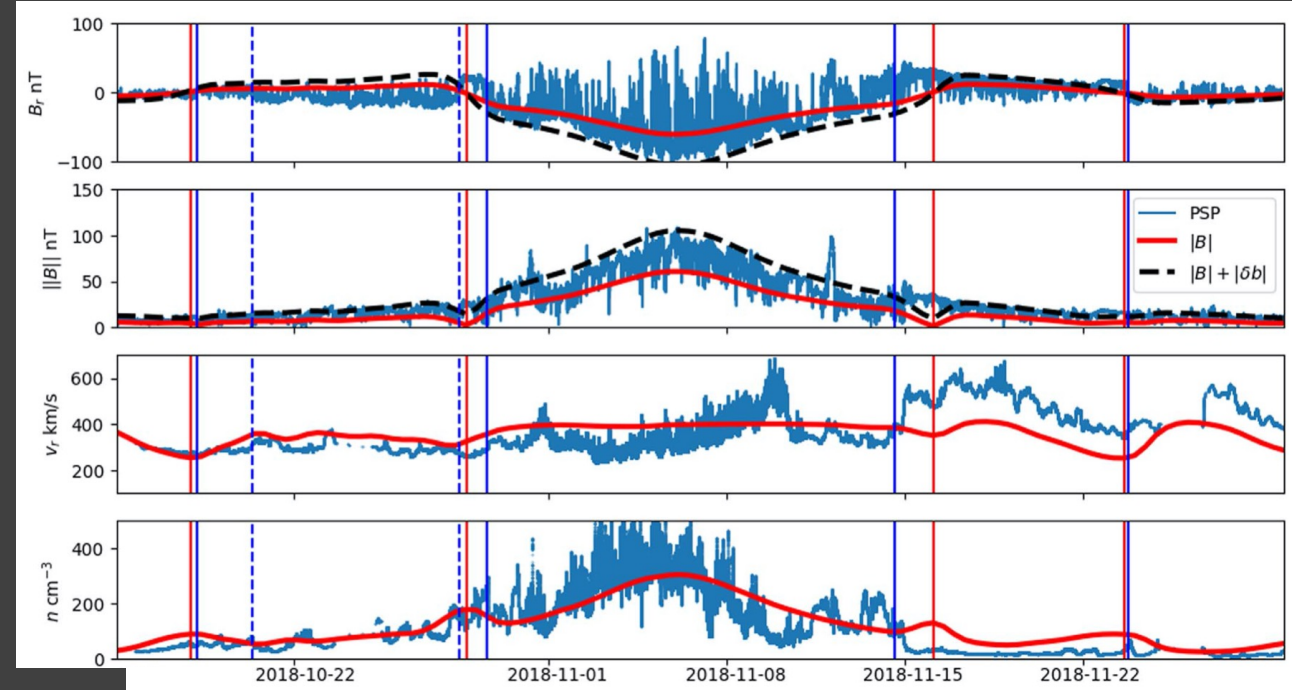
Wave reflection

Numerical results

Verdini+2010. 1D model



Réville+2020. 3D model

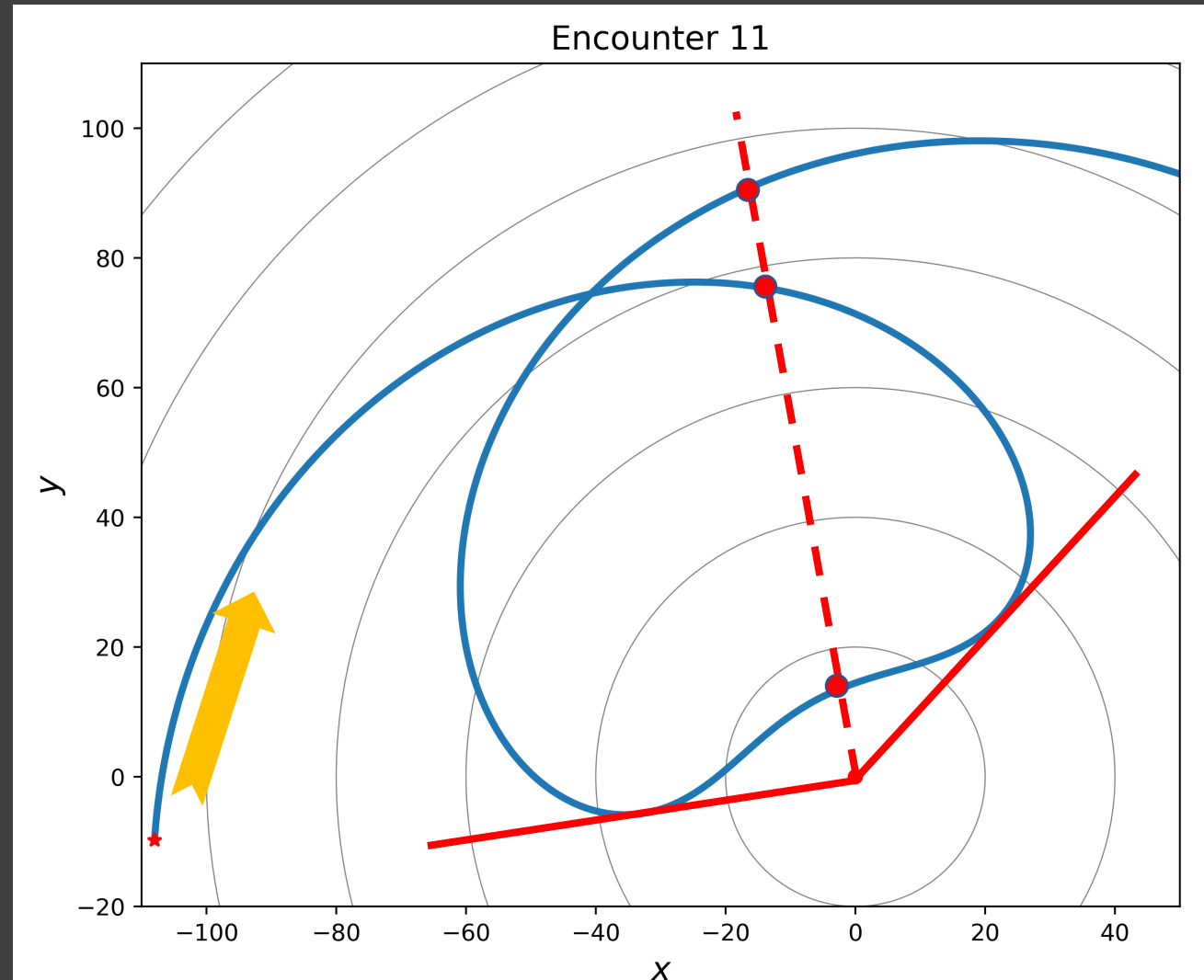


At low altitude, following processes can be important (sometimes necessary)

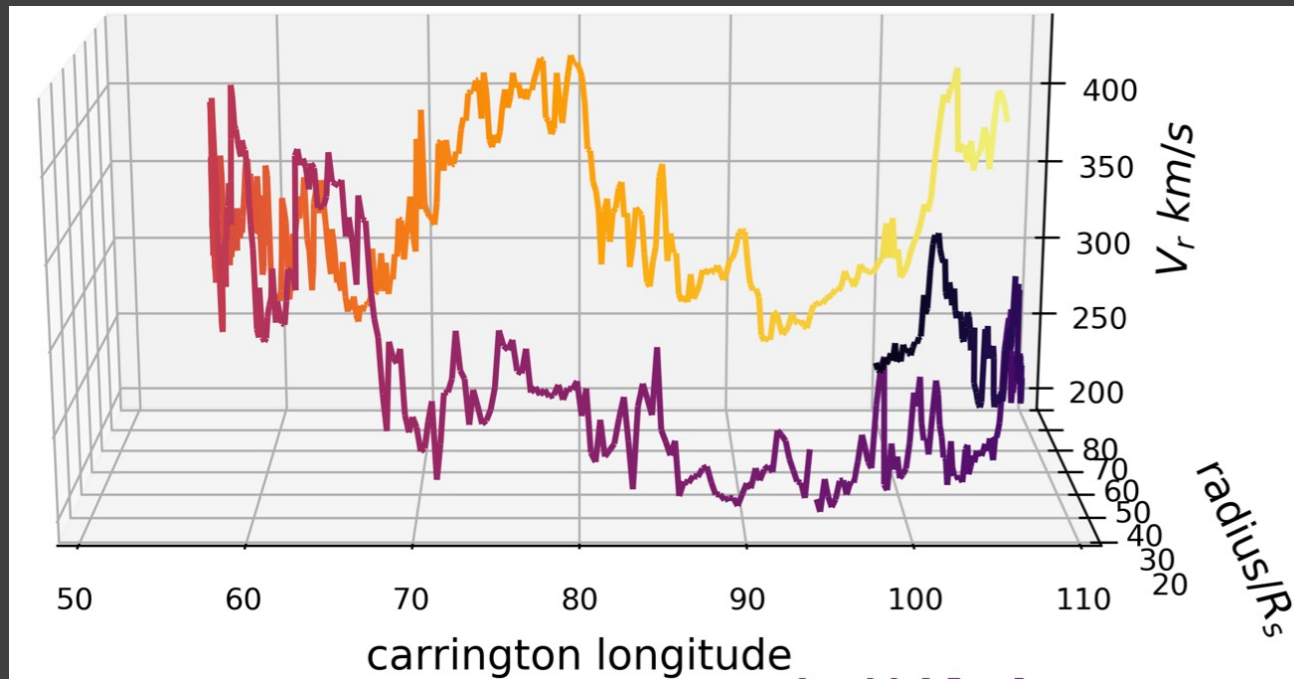
1. Thermal conduction
2. Local heating source (acoustic wave damping, reconnection, etc.)
3. Radiative cooling
4. Non-thermal population

In-situ evidence of accelerating solar wind

- Orbit of Parker Solar Probe is low, so its angular speed becomes faster than solar rotation near perihelion.
- In the corotating frame of the Sun, it travels back-and-forth in longitude.

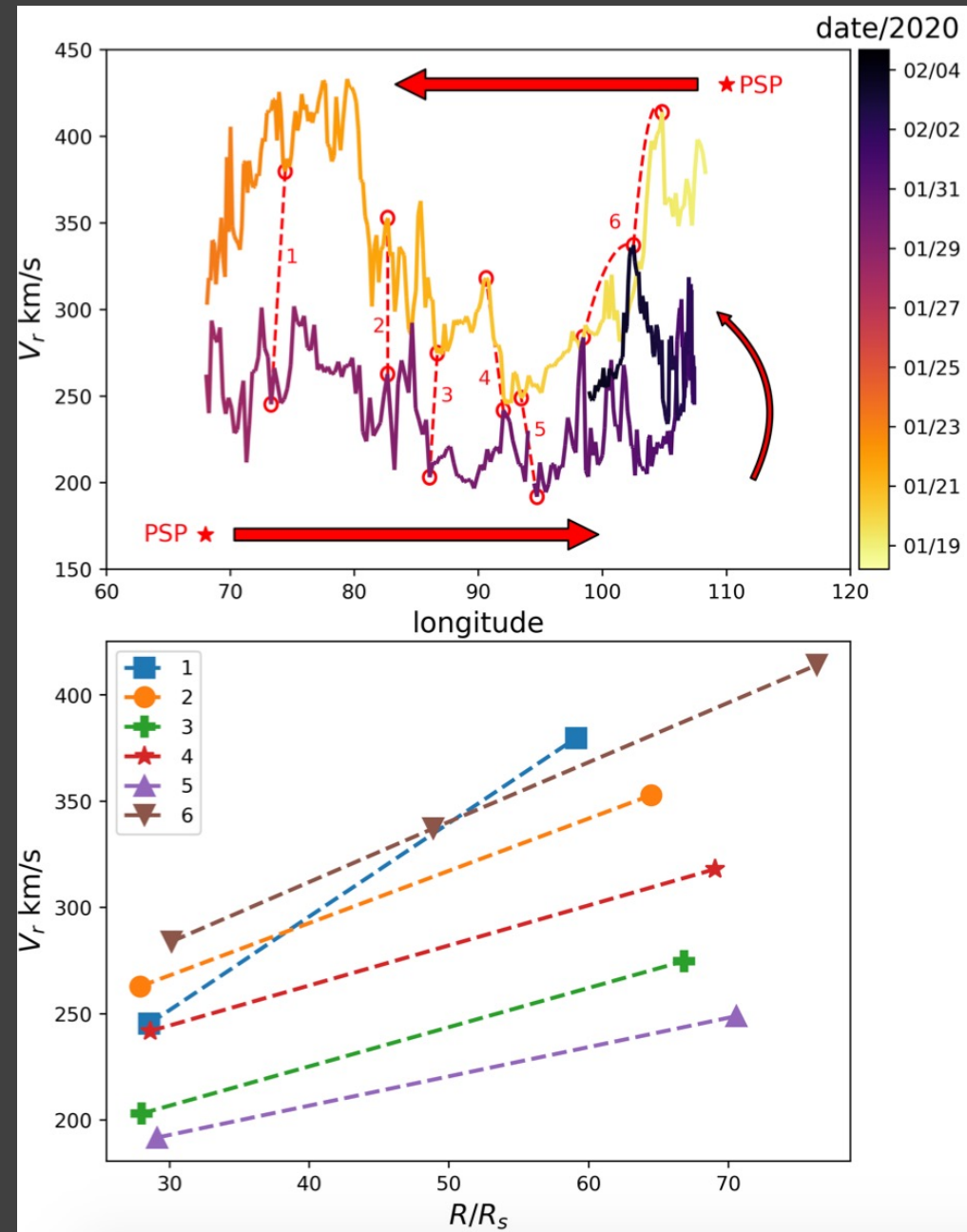


Encounter 04



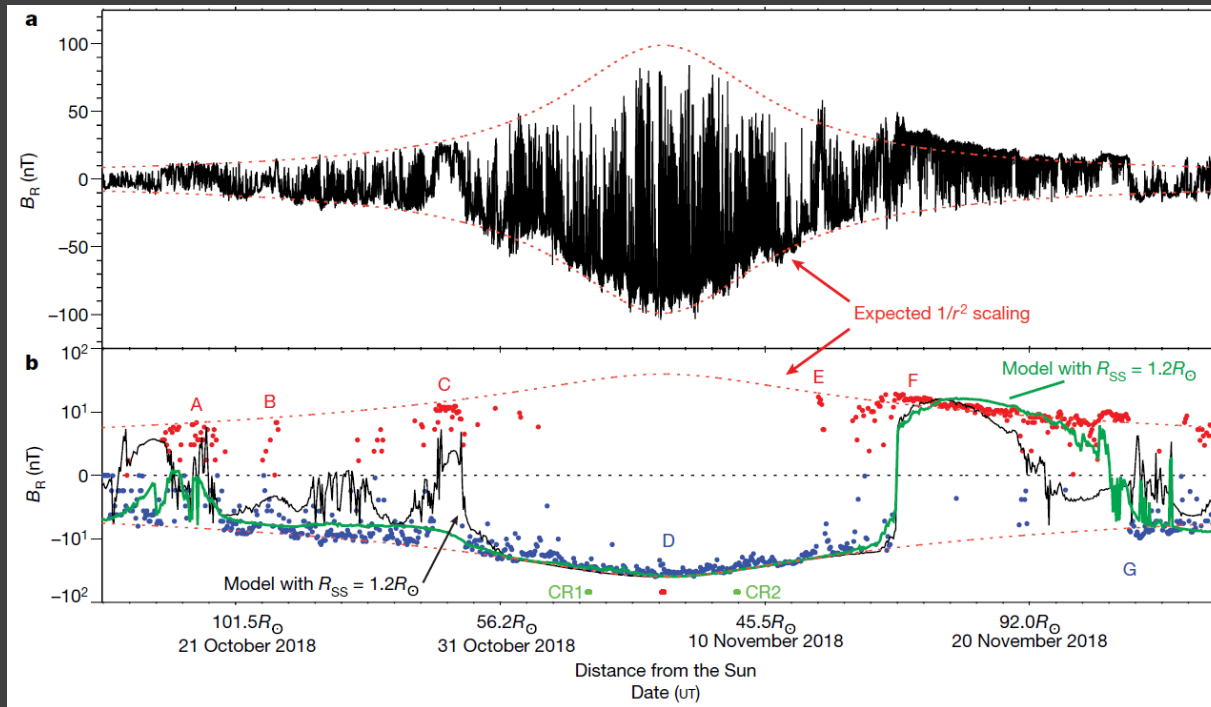
Evidence of accelerating solar wind

Shi+2021

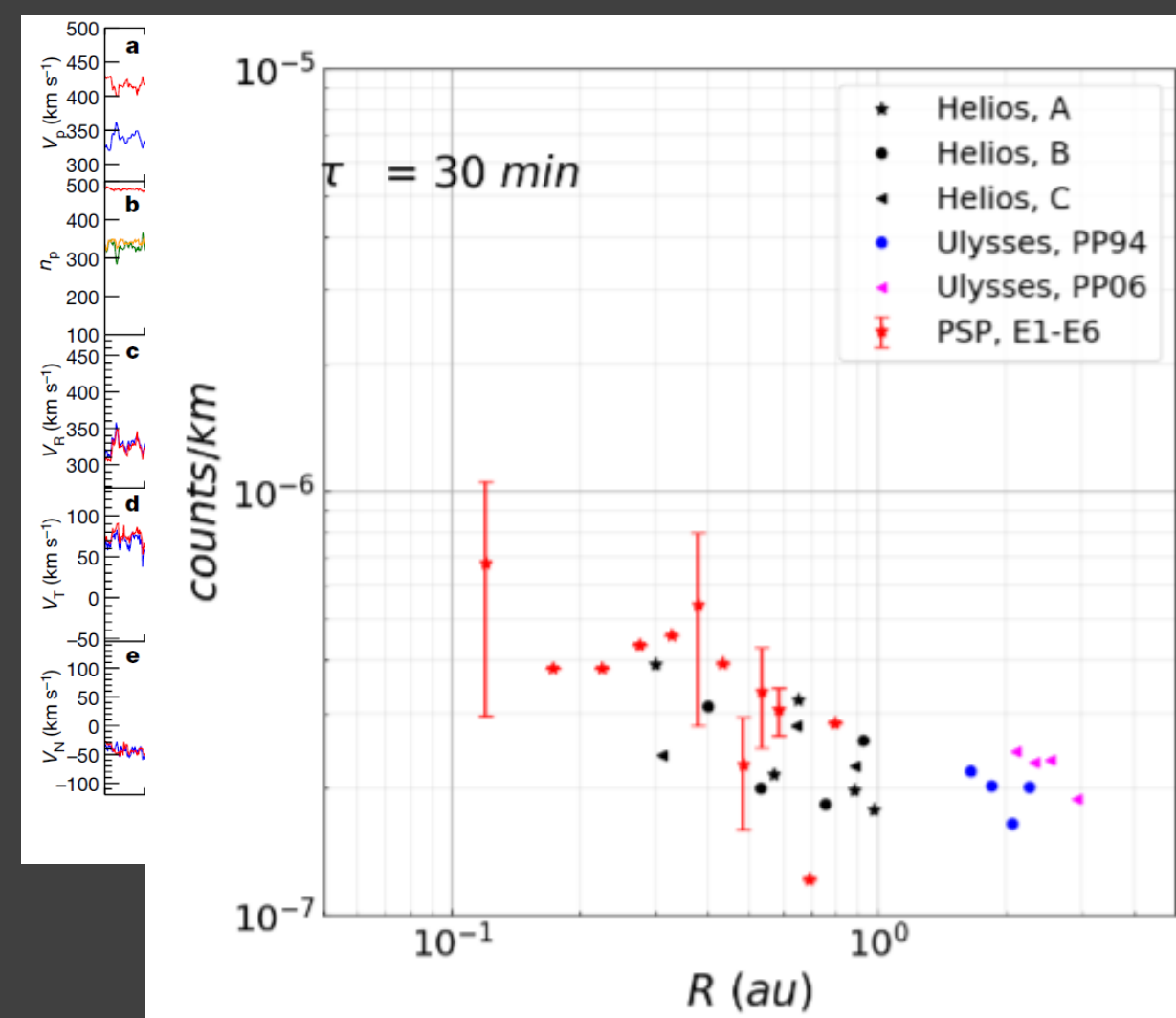


Magnetic switchbacks

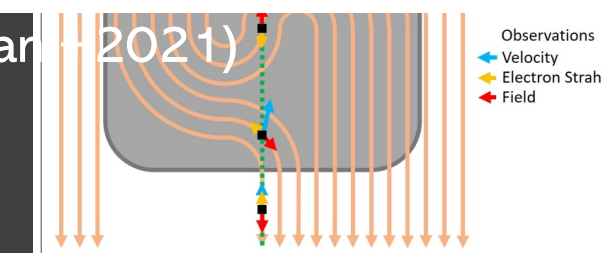
- Local polarity reversals of B_R



(Bale+, 2019)



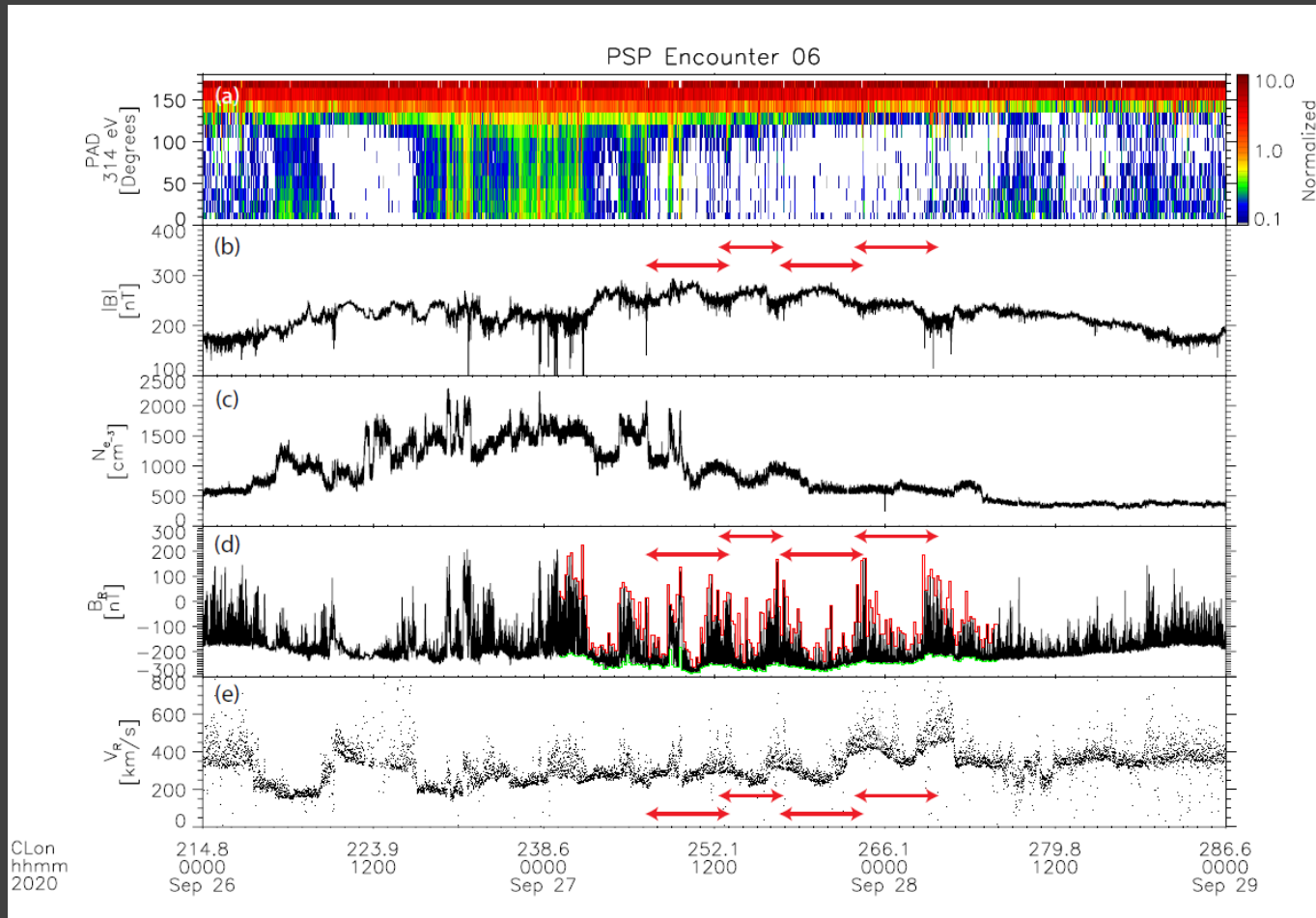
(Tenerani + 2021)



- Switchbacks are Alfvénic: outward radial jets

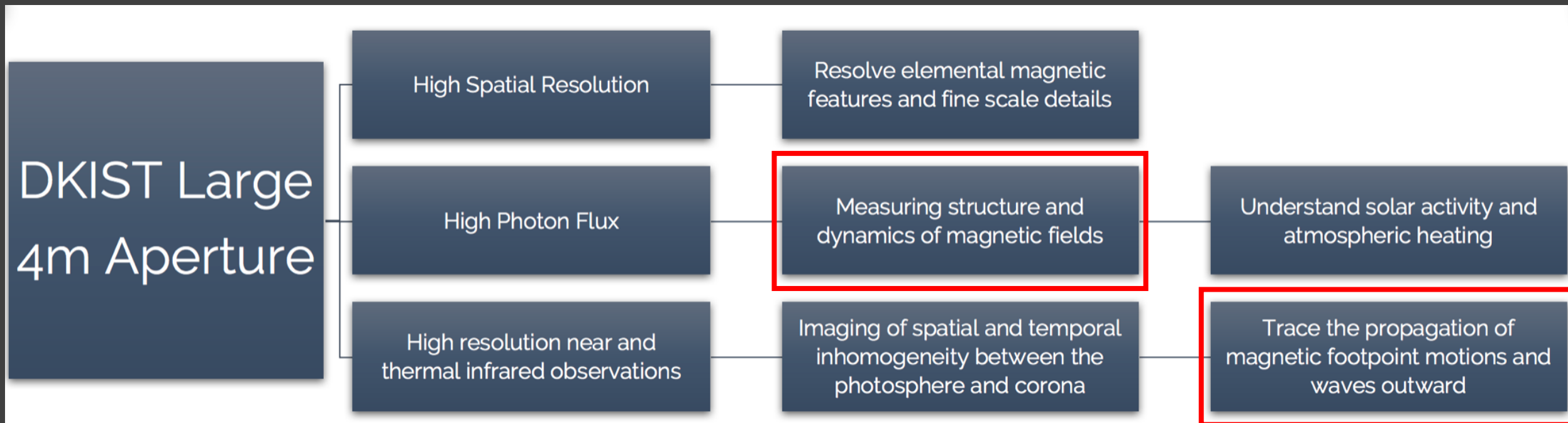
Patches of magnetic switchbacks

- Increase of proton temperature and radial speed



(Bale+, 2021)

DKIST: origins of waves and structures in the solar wind



Open questions/Future work

- Can we determine the acceleration zone (radial extent) of the solar wind using PSP data?
- Verify whether Alfvén waves provide enough power for the local solar wind acceleration
- In the solar corona, how does the energy provided by Alfvén waves compare with that by other mechanisms like reconnection?
- What is the difference between the acceleration of fast wind and that of slow wind?
- More questions...