Role of Longitudinal Waves in Alfvén-wave-driven Solar/Stellar Wind

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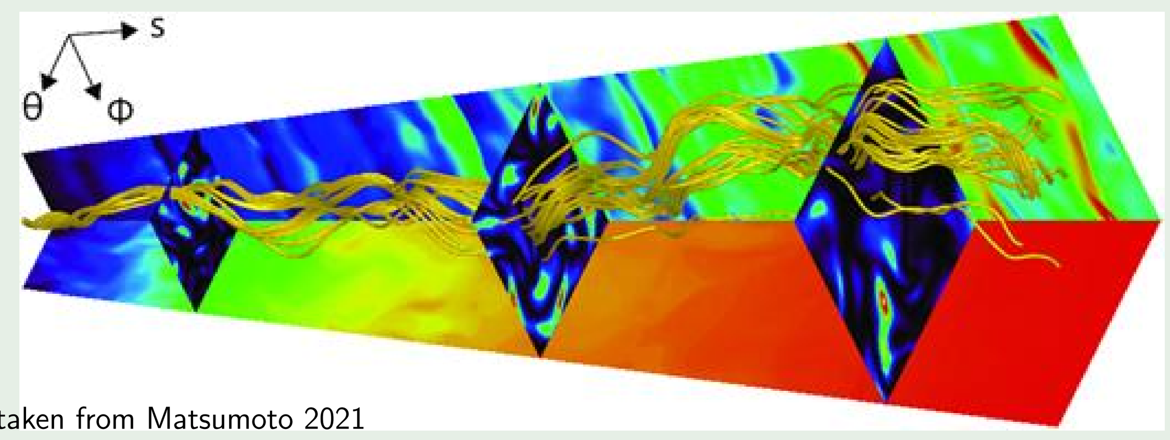
We revisit the role of longitudinal waves in driving the solar wind. We study how the p-mode-like vertical oscillation on the photosphere affects the properties of solar winds in the framework of Alfvén-wave-driven winds. We perform a series of one-dimensional magnetohydrodynamical numerical simulations from the photosphere to beyond several tens of solar radii. We find that the mass-loss rate drastically increases with the longitudinal-wave amplitude at the photosphere by up to a factor of ∼4, in contrast to the classical understanding that acoustic waves hardly affect the energetics of the solar wind. The addition of the longitudinal fluctuation induces longitudinal-to-transverse wave mode conversion in the chromosphere, which results in enhanced Alfvénic Poynting flux in the corona. Consequently, coronal heating is promoted to give higher coronal density by chromospheric evaporation, leading to the increased mass-loss rate. This study clearly shows the importance of longitudinal oscillation in the photosphere and mode conversion in the chromosphere in determining the basic properties of the wind from solar-like stars.

Reference: Shimizu, Shoda, & Suzuki, ApJ, 931, 37 (2022)

Alfvén wave-driven winds

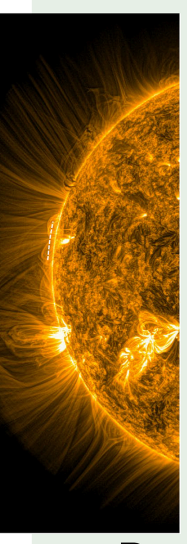
Convection ⇒ Alfvén(ic) waves ⇒ Corona & Wind



taken from Matsumoto 2021

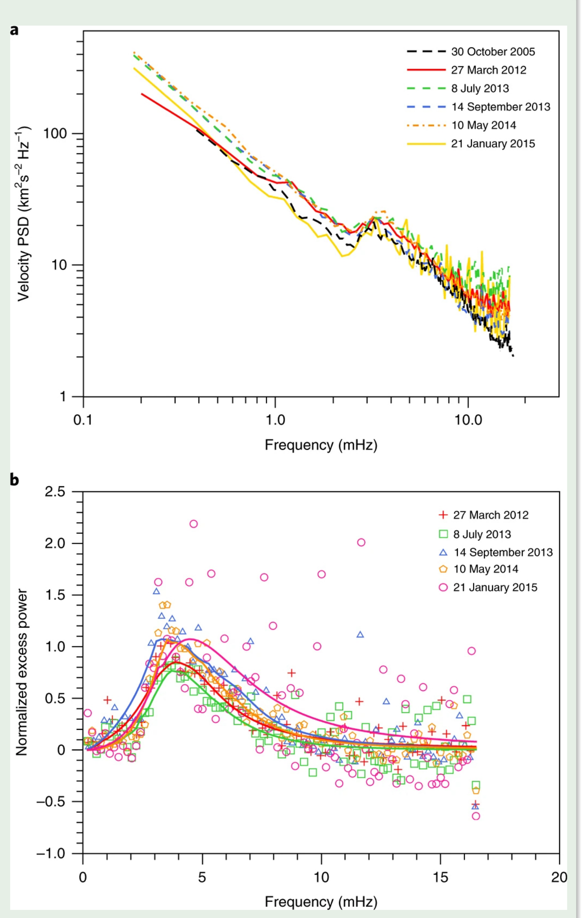
- Alfvénic turbulence Matthaeus+ 1999; Oughton+ 2003; Cranmer+ 2007; Verdini & Velli 2007; Chandran & Hollweg 2009; Verdini+ 2010; van der Holst+ 2013; Lionello+ 2014; van Ballegooijen & Asgari-Targhi 2016; Zank+ 2018; Adhikari+ 2019; 2020 Review by van Doorsselaere+ 2020...
- Parametric decay ⇒ compressible waves Goldstein 1978; Terasawa+ 1990; Suzuki & Inutsuka 2005; 2006; Tenerani & Velli 2017; Shoda+ 2018

p-modes to Alfvénic waves ?



Alfvénic $\delta v_\perp$ at solar limb

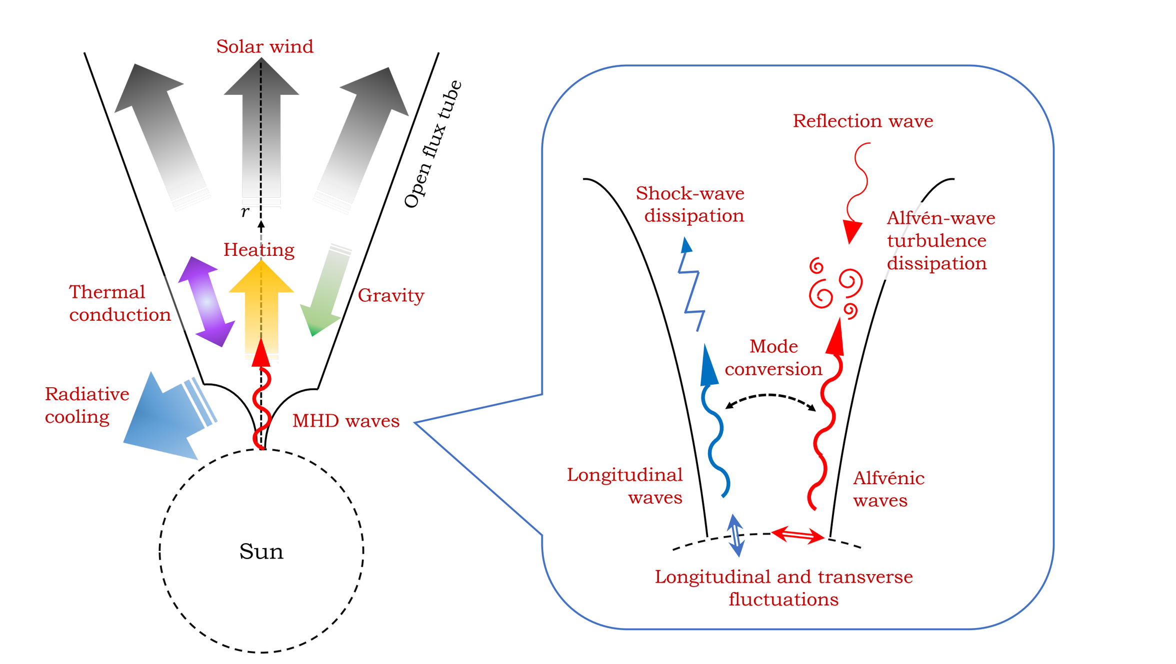
(SDO/AIA 171.1nm)



taken from Morton+ (2019)

- Peak at 4 mHz
- p-modes ⇒ $\delta v_\perp$?

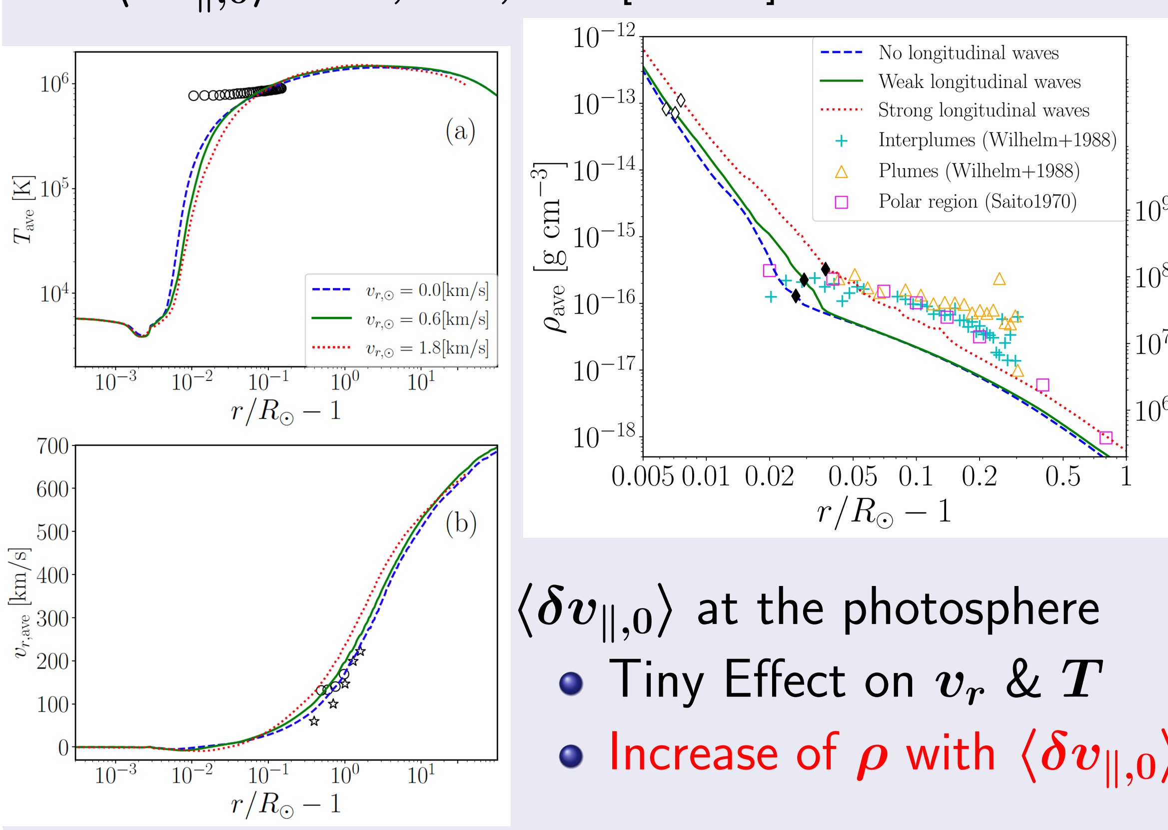
Simulation Setup



- MHD + radiation cooling + thermal conduction in 1.5D flux tubes
- Simulation region: Photosphere to $\approx 100 R_\odot$
- $B_{r,\odot} = 1.3$ kG; $B_r = 1.3$ G $(r/R_\odot)^{-2}$ in Corona – Wind
- Dissipation of Alfvén waves:
  - Parametric decay (through compressible waves)
  - Alfvénic turbulent cascade
    Shoda,+2018 after Dobrowolny+ 1980; Hossain+ 1995; Matthaeus+ 1999
  - $\frac{\partial z^\pm_\perp}{\partial t} \approx -(\vec{z}^\mp \cdot \vec{\nabla})\vec{z}^\pm \approx -\frac{c_d}{2\lambda_\perp}|z^\mp|z^\pm$; $\lambda_\perp$:correlation length
  - Elsässer variables: $z^\pm_\perp = v_\perp \mp B_\perp/\sqrt{4\pi\rho}$

$\delta v_\parallel$ in Alfvén wave-driven winds

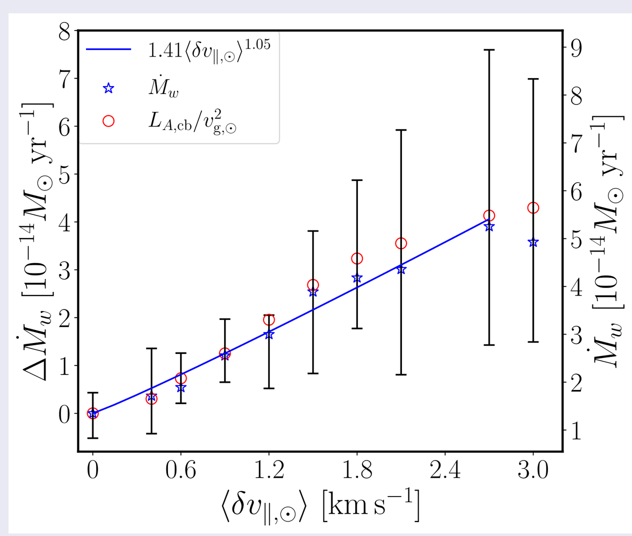
- $\langle \delta v_{\perp,0} \rangle = 0.6$ [km s^{-1}] ⇒ Alfvénic waves
- $\langle \delta v_{\parallel,0} \rangle = 0, 0.6, 1.8$ [km s^{-1}]



$\langle \delta v_{\parallel,0} \rangle$ at the photosphere

- Tiny Effect on v_r & T
- Increase of ρ with $\langle \delta v_{\parallel,0} \rangle$

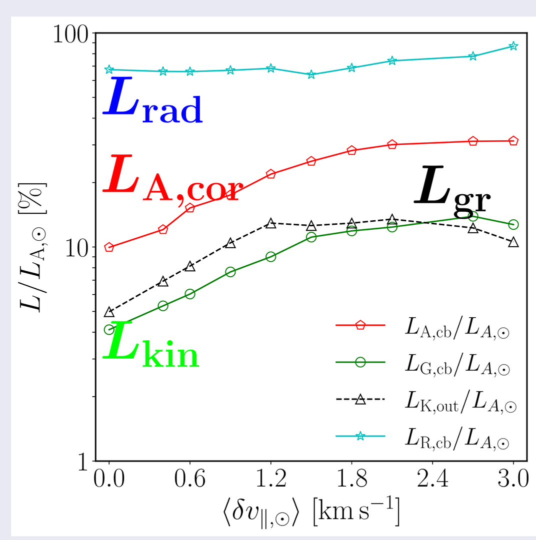
Mass-loss rate



$\dot{M}_w$ $(= 4\pi\rho v_r r^2)$ increases $\gtrsim 3$ times!

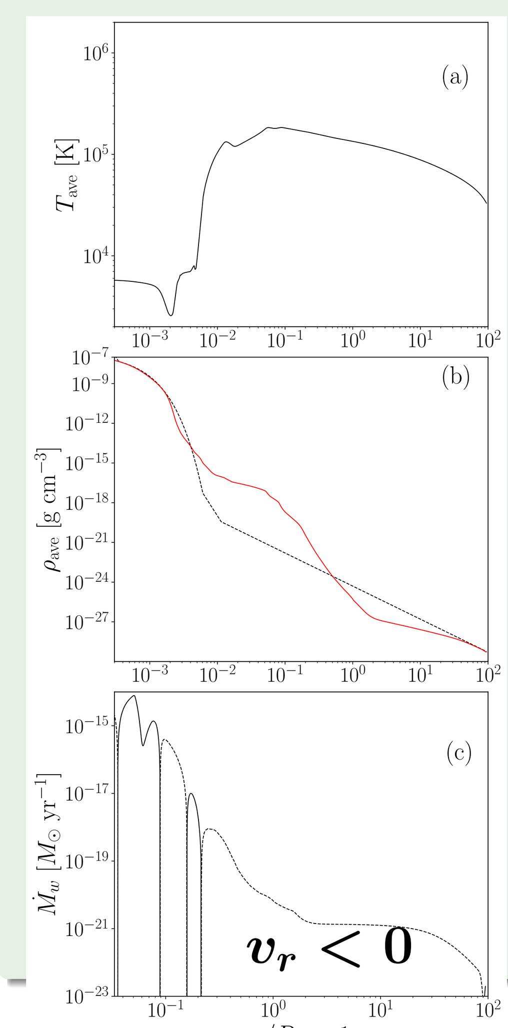
Energetics

Energy/$L_{A,0}$



$L_{A,cor} \approx \dot{M}\frac{v^2}{2} + \dot{M}\frac{GM_\star}{r} \approx \dot{M} v_{esc}^2$ Cranmer & Saar 2011

Wind driven only by $\delta v_\parallel$?



v fluctuations at the photosphere

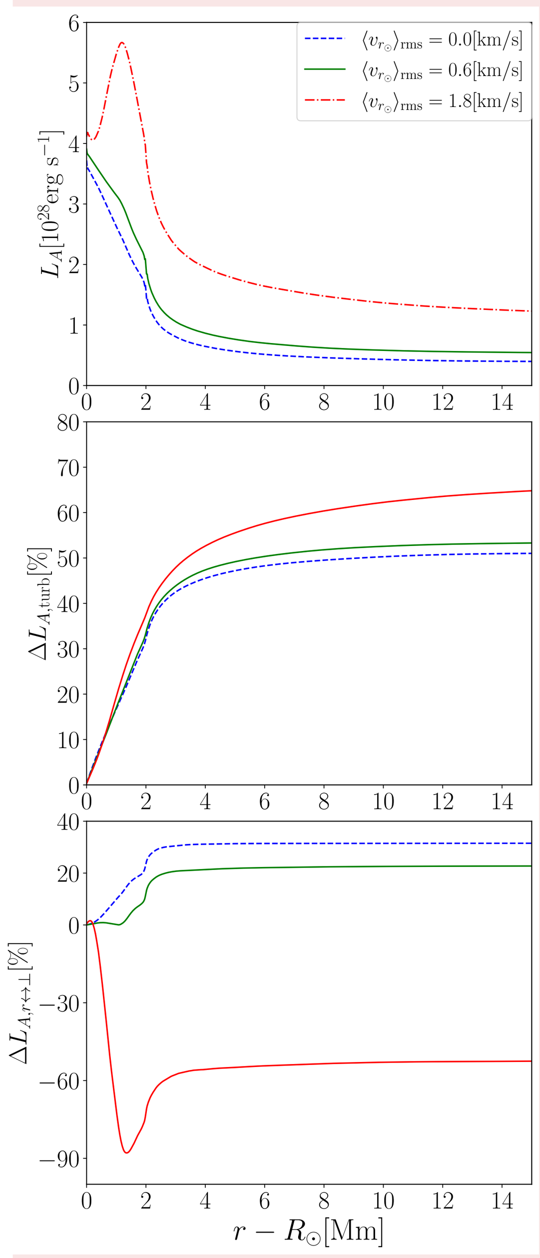
- $\langle \delta v_{\parallel,0} \rangle = 0.6$ [km s^{-1}] ⇒ Acoustic waves
- $\langle \delta v_{\perp,0} \rangle = 0$ [km s^{-1}] ⇒ No Alfvénic waves

The upper atmosphere does NOT stream out only by $\langle \delta v_{\parallel,0} \rangle$ but falls down.

- Acoustic waves ↛ Corona & Wind

Stein & Schwartz 1972; Jacques 1977

Mode conversion in Chromosphere



- Small $\langle \delta v_{\parallel,0} \rangle$: ⊥ ⇒ ∥
- Large $\langle \delta v_{\parallel,0} \rangle$: ∥ ⇒ ⊥
  "Inverse" mode conversion at $\beta \approx 1$ in the chromosphere

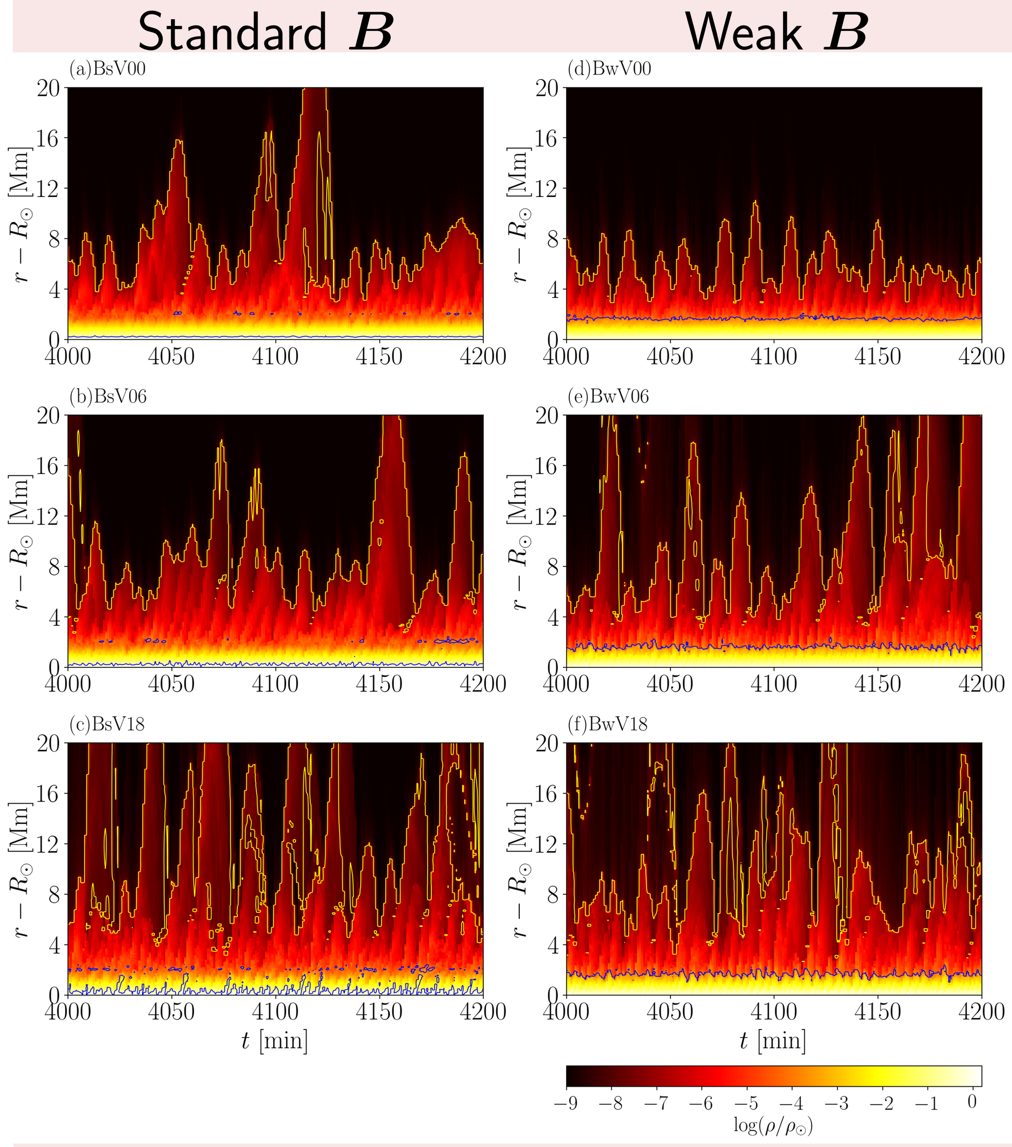
Schunker & Cally 2006; Cally & Goossens 2008

Note: $\vec{k}(\parallel \vec{r}) \nparallel \vec{B}(= B_0\hat{r} + \vec{B}_\perp)$ even in 1.5D (Finite attacking angle between $\vec{k}$ & $\vec{B}$)

- $L_A = A\left[\left(\frac{1}{2}\rho v_\perp^2 + \frac{B_\perp^2}{8\pi}\right) v_r - \frac{B_r}{4\pi}\vec{v}_\perp \cdot \vec{B}_\perp\right]$
- Turbulent loss: $\Delta L_{A,turb} = \int_{r_{ph}}^{r} dr A c_d \rho \frac{|z^+_\perp| z^{-2}_\perp + |z^-_\perp| z^{+2}_\perp}{4\lambda_\perp}$
- Mode conversion: $\Delta L_{A,\perp\to\parallel} = \int_{r_{ph}}^{r} dr A v_r \left[-\frac{\partial}{\partial r}\left(\frac{B_\perp^2}{8\pi}\right) + \left(\rho v_\perp^2 - \frac{B_\perp^2}{4\pi}\right)\frac{d\sqrt{A}}{dr}\right]$

Spicules

Standard B | Weak B



$\langle \delta v_{\parallel,0} \rangle$ 0km/s

0.6km/s

1.8km/s

Summary

"Classical" understanding

- $\langle \delta v_{\perp,0} \rangle$ ⟶ Alfvénic waves ⟶ Corona & Wind
- $\langle \delta v_{\parallel,0} \rangle$ ⟶ Acoustic waves ↛ Corona & Wind

But 1.5D MHD simulations show

- $\langle \delta v_{\parallel,0} \rangle$ ⟶ (∥⇒⊥ conversion) ⟶ Corona & Wind