The parametric decay instability of Alfven waves and the applications in the solar wind

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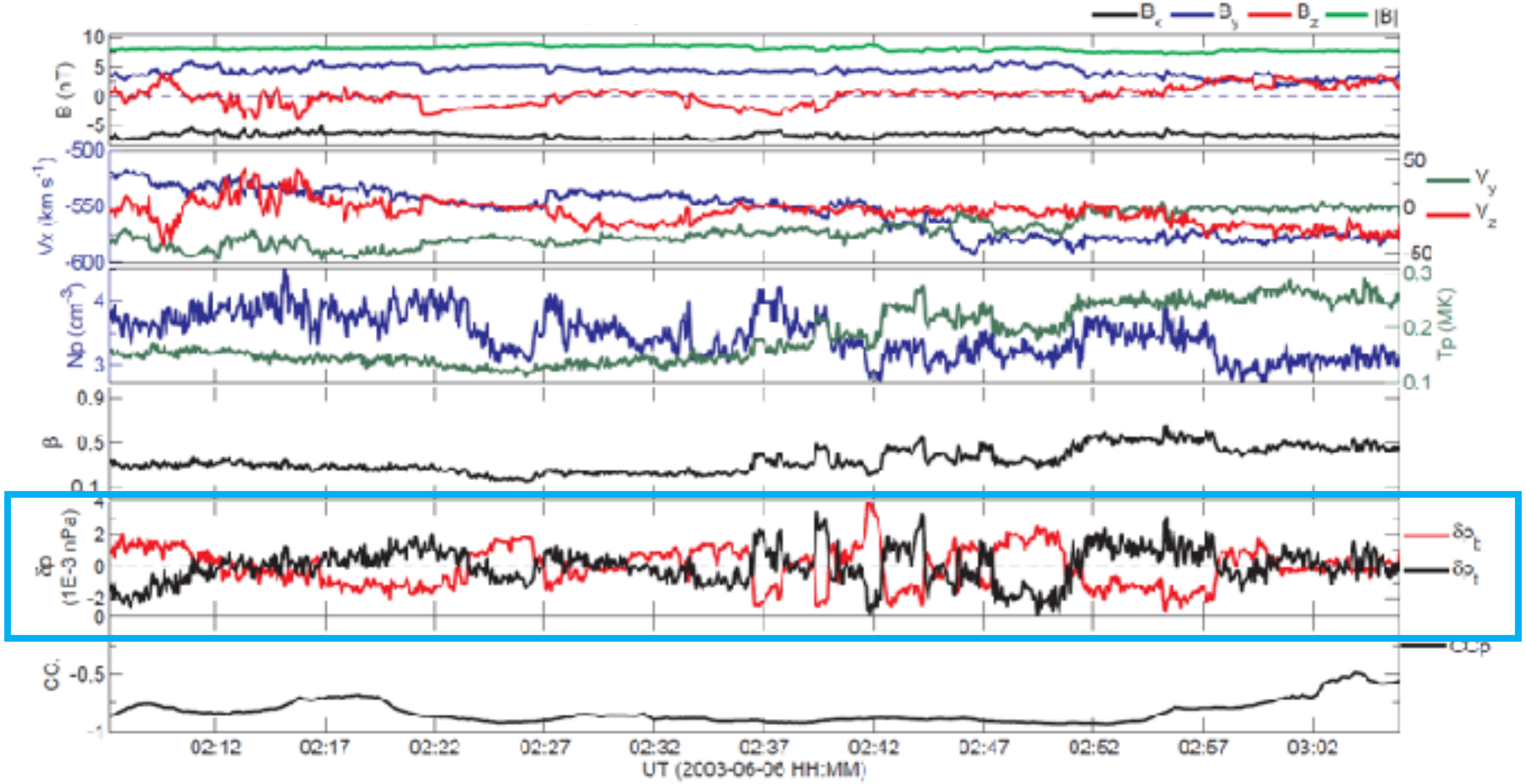
Motivation

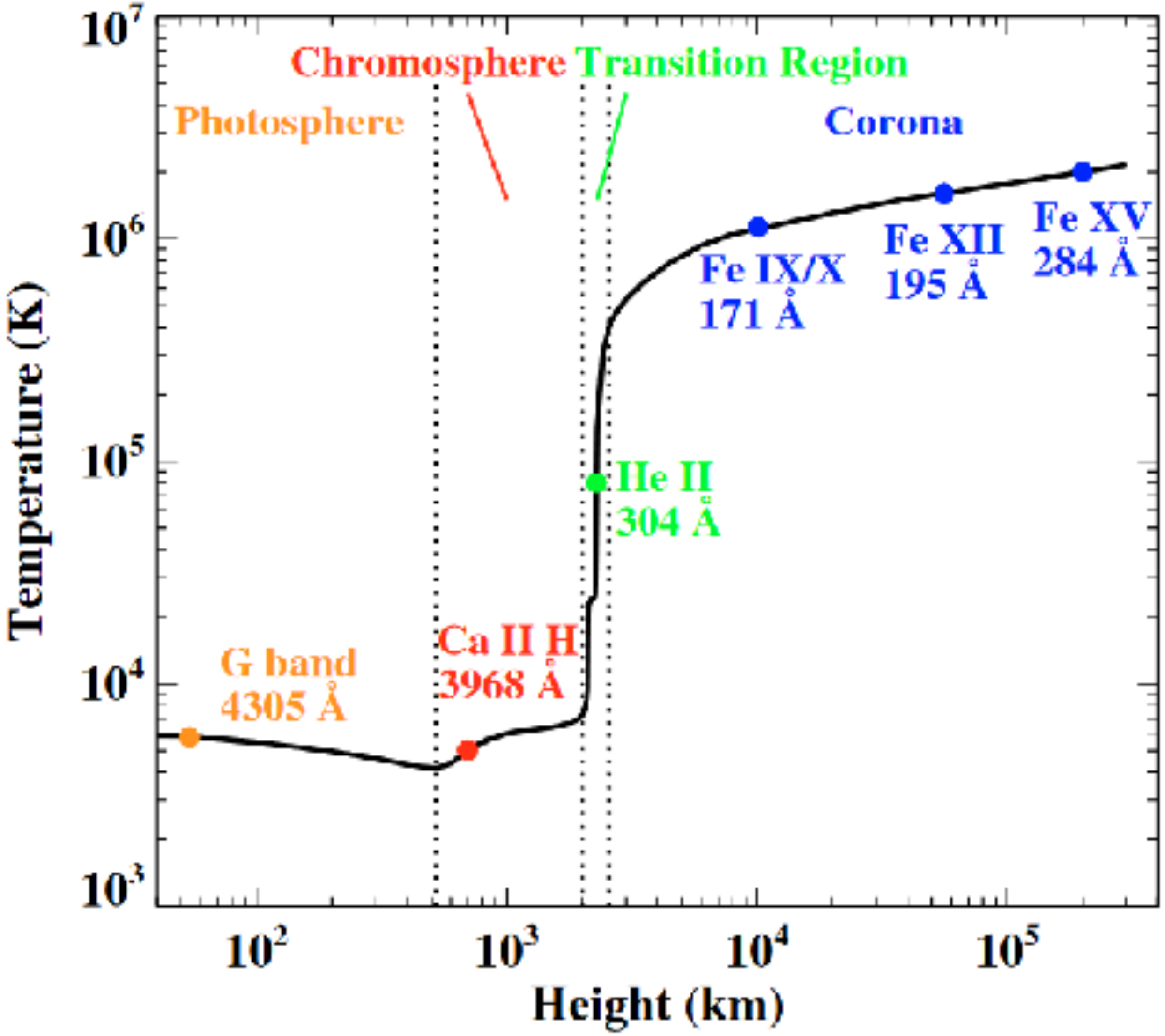
- Local generation of slow waves at 1 AU solar wind



Anti correlated thermal pressure and magnetic pressure

Shi et al. ApJ, 815, 122, 2015

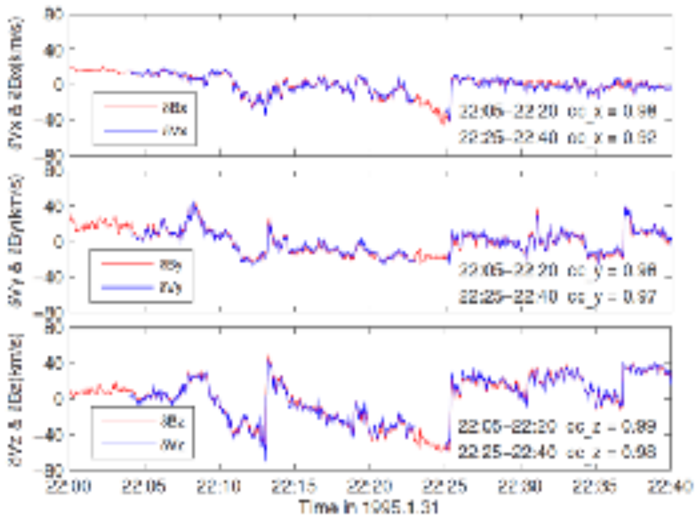
- Coronal heating and solar wind acceleration



Yang et al. A&A 501, 745, 2009

Alfven wave (AW)

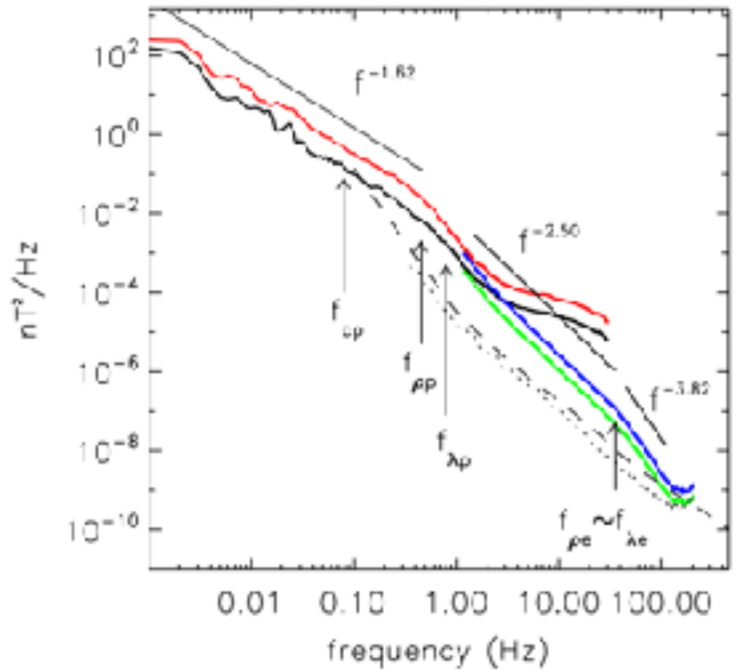
- Ubiquitous in the solar wind (Belcher and Davis JGR,1971)
- Sufficient power for coronal heating and solar wind acceleration (De Pontieu et al. Science, 2007; McIntosh et al. Nature, 2011)



Wang et al. ApJ, 746, 147, 2012

AW dissipation

- Alfvenic turbulence cascade
- Phase mixing (Heyvaerts & Priest A&A,1983)
- Parametric decay instability

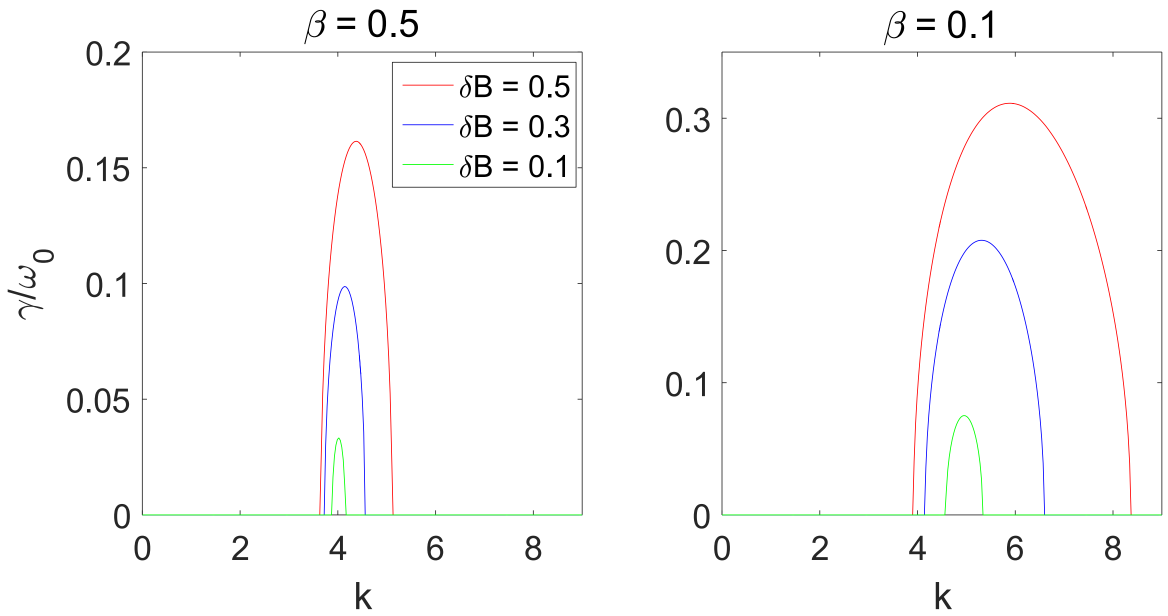


Sahraoui et al. PRL, 102, 231102, 2009

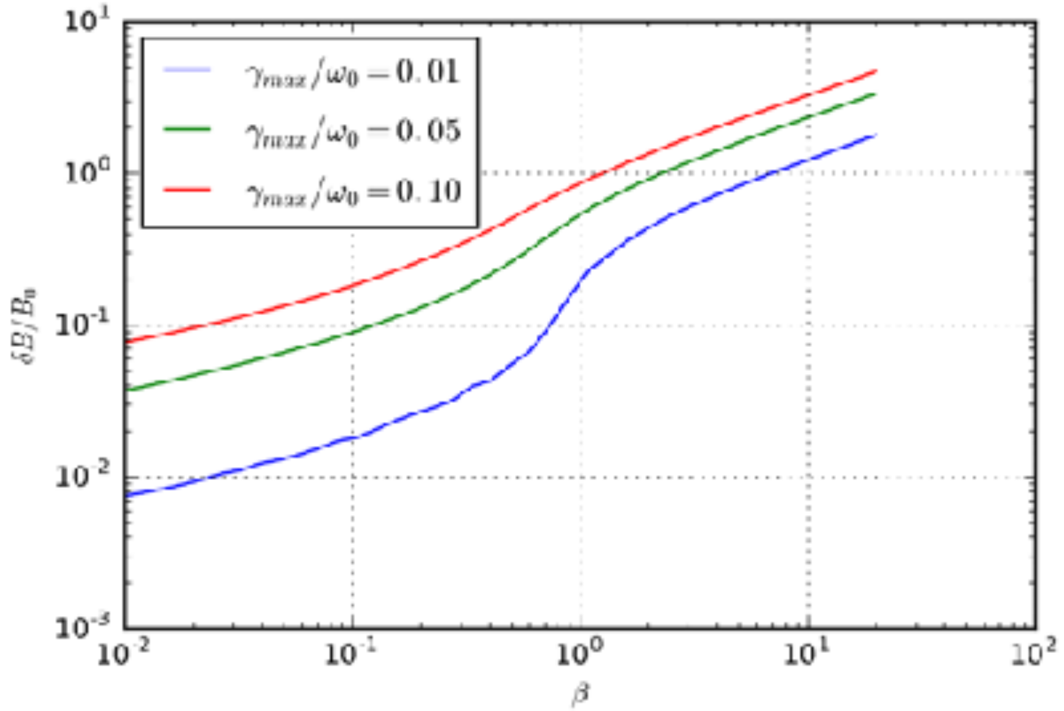
Parametric decay instability (PDI)

- Nonlinear 3 wave interaction
  - AW → Backward AW + Slow wave
- For a circularly polarized Alfven wave, the growth rate of PDI (Derby, ApJ, 1978) :

$$(\omega + k + 2)(\omega + k - 2)(\omega - k)(\omega^2 - \beta k^2)$$
$$= \eta^2 k^2 (\omega^3 + k\omega^2 - 3\omega + k)$$



maximum growth rate

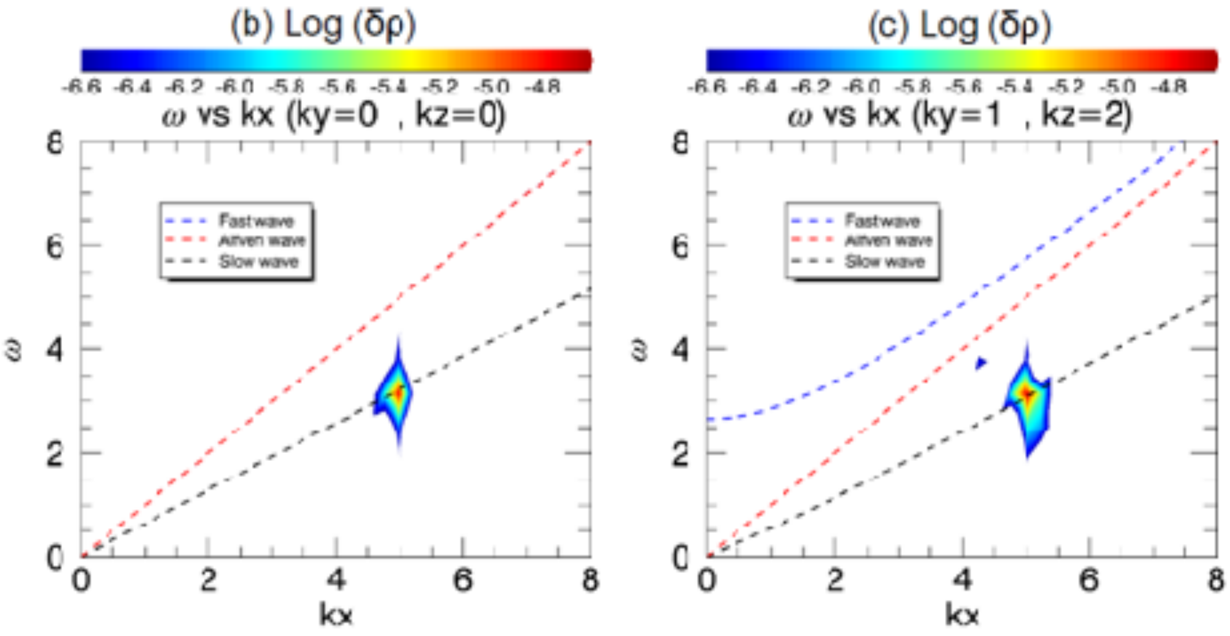


(Fu et al. ApJ, 855, 139, 2018)

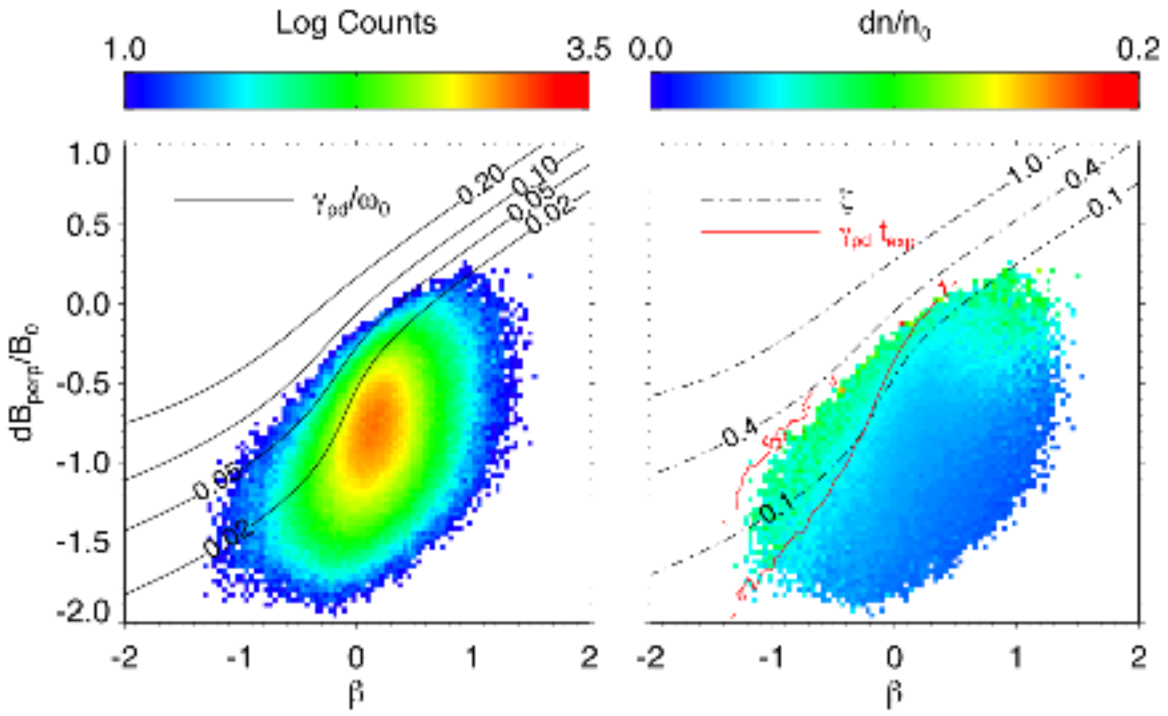
PDI at 1 AU solar wind

- PDI of Alfven wave can occur in turbulent plasma (e.g., the solar wind)
- Slow waves are generated during PDI.

- Possible evidence of PDI from 1 AU in-situ observations

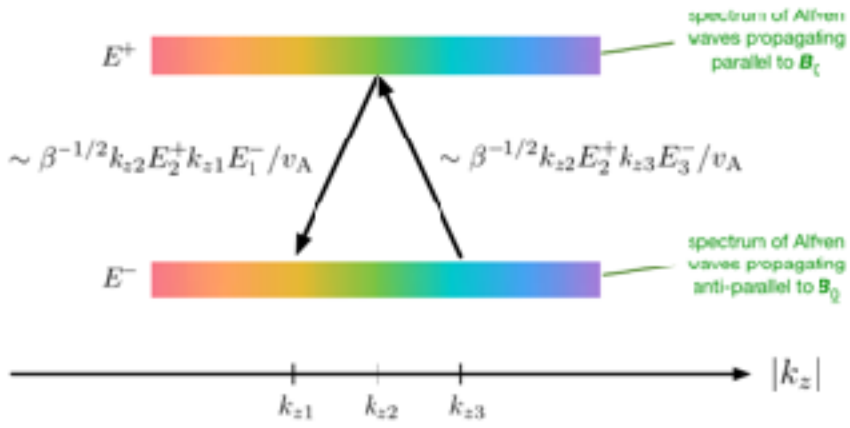


(Shi et al. ApJ, 842, 63, 2017)



(Bowen et al. ApJL, 854, L33, 2018)

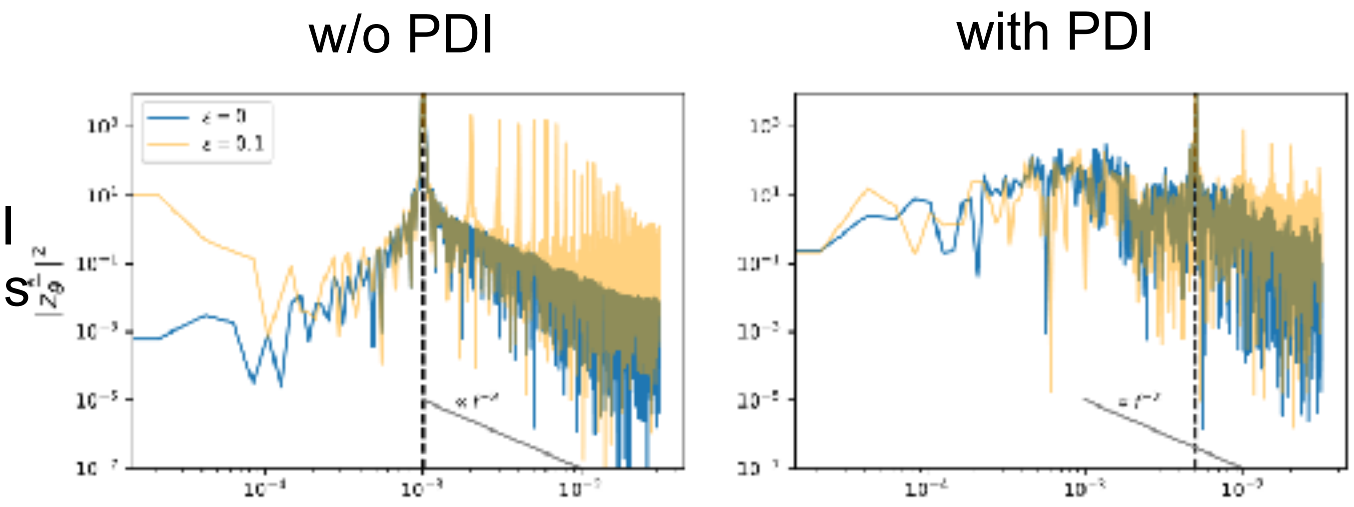
PDI caused inverse cascade



(Chandran, J. Plasma Phys., 2018)

- Chandran (2018) studied the PDI using wave kinetic equations and found that PDI can modify the power spectrum of AWs and cause the inverse cascade.

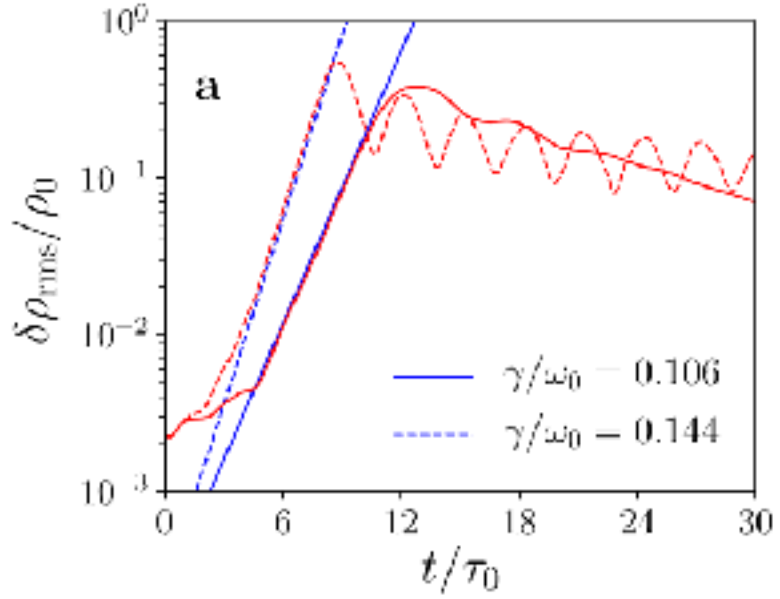
- The inverse cascade caused by PDI is shown using 1-D MHD simulations (Victor et al., 2018)

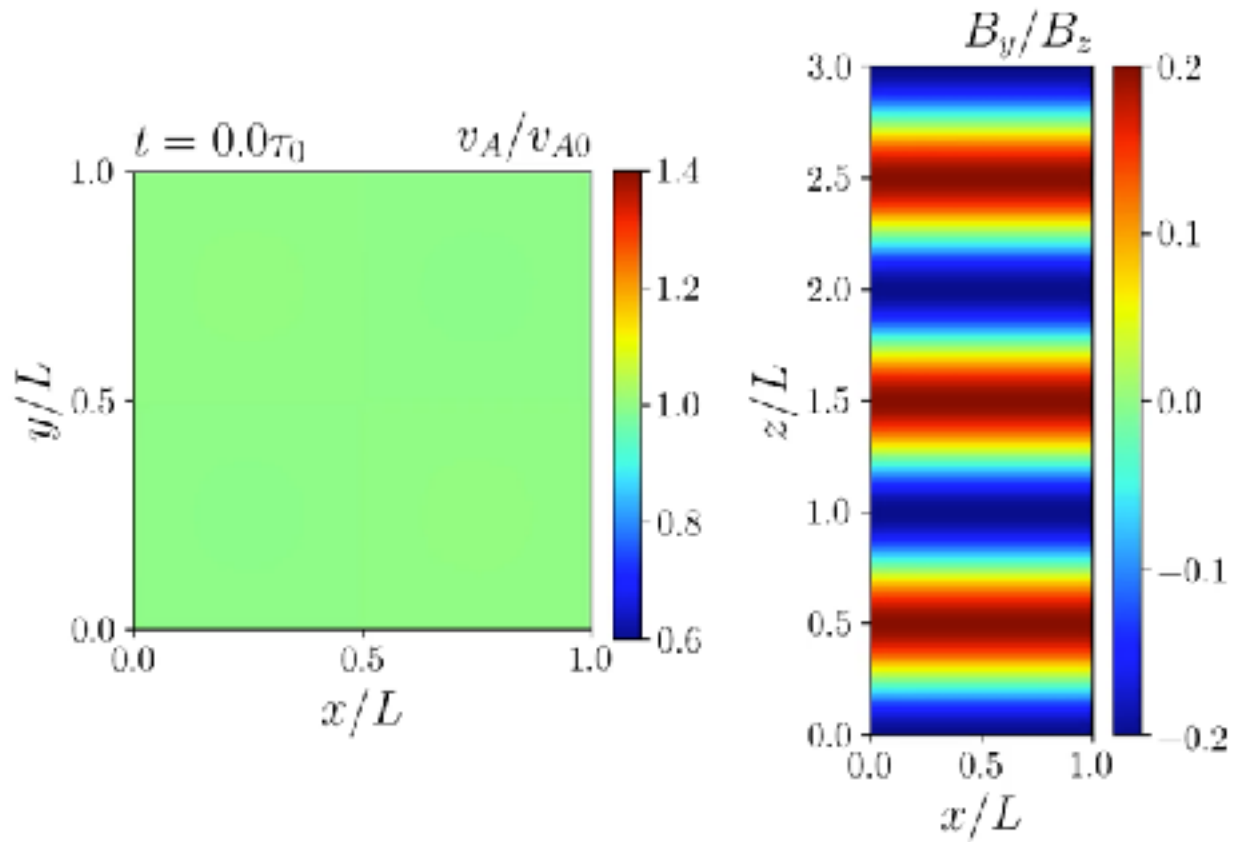


(Victor et al. arXiv:1806.05762, 2018)

PDI caused turbulence

- PDI can cause both phase mixing and turbulence at the saturation stage.





(Shoda & Yokoyama ApJL, 859, L17, 2018)

PDI in decaying turbulence

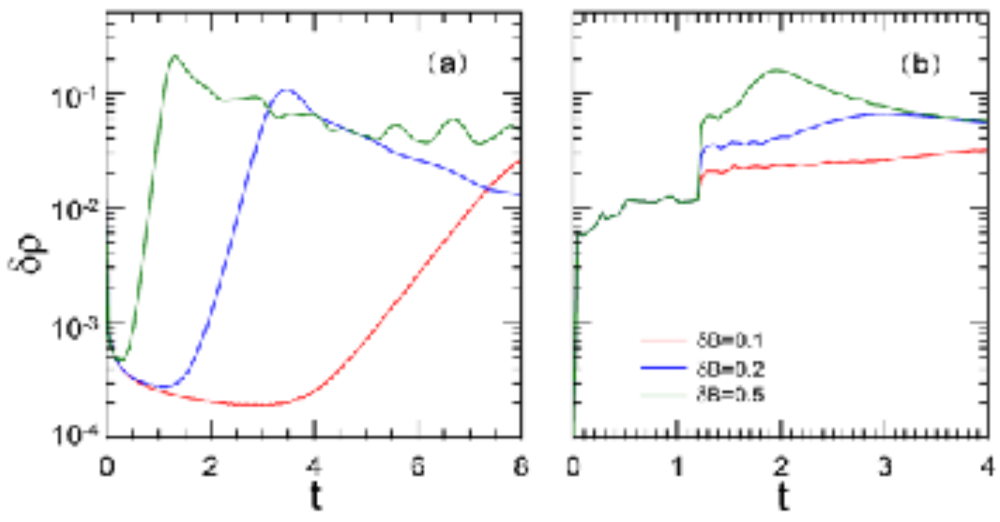
- Decaying turbulence background

$$\delta \boldsymbol{B}_{\rm turb} = \sum_{j,k} \delta B_{\rm turb} \cos(jk_x x + lk_z z + \phi_{j,l})\hat{\boldsymbol{y}} + \sum_{m,n} \delta B_{\rm turb} \cos(mk_x x + nk_y y + \phi_{m,n})\hat{\boldsymbol{z}}$$

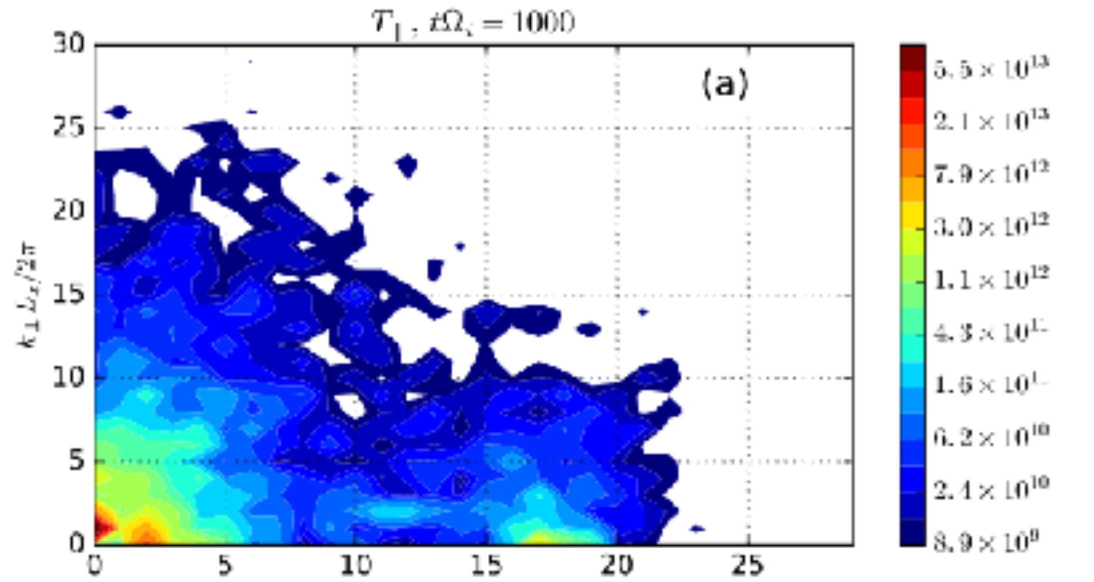
$$\delta \boldsymbol{v}_{\rm turb} = -\sum_{j,k} sgn(j)\delta v_{\rm turb} \cos(jk_x x + lk_z z + \phi_{j,l})\hat{\boldsymbol{y}} - \sum_{m,n} sgn(m)\delta v_{\rm turb} \cos(mk_x x + nk_y y + \phi_{m,n})\hat{\boldsymbol{z}}$$

- AW injection

Non Turb | Turb



MHD simulations by Shi et al. ApJ, 842, 63, 2017



Hybrid simulations by Fu et al. ApJ, 855, 139, 2018

PDI in driven turbulence | Preliminary results

- Driven turbulence

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{v}) = 0$$

$$\frac{\partial \boldsymbol{v}}{\partial t} + \boldsymbol{v} \cdot \nabla \boldsymbol{v} + \frac{1}{\rho} \boldsymbol{B} \times (\nabla \times \boldsymbol{B}) + \frac{1}{\rho} \nabla p = \boldsymbol{f}_v$$

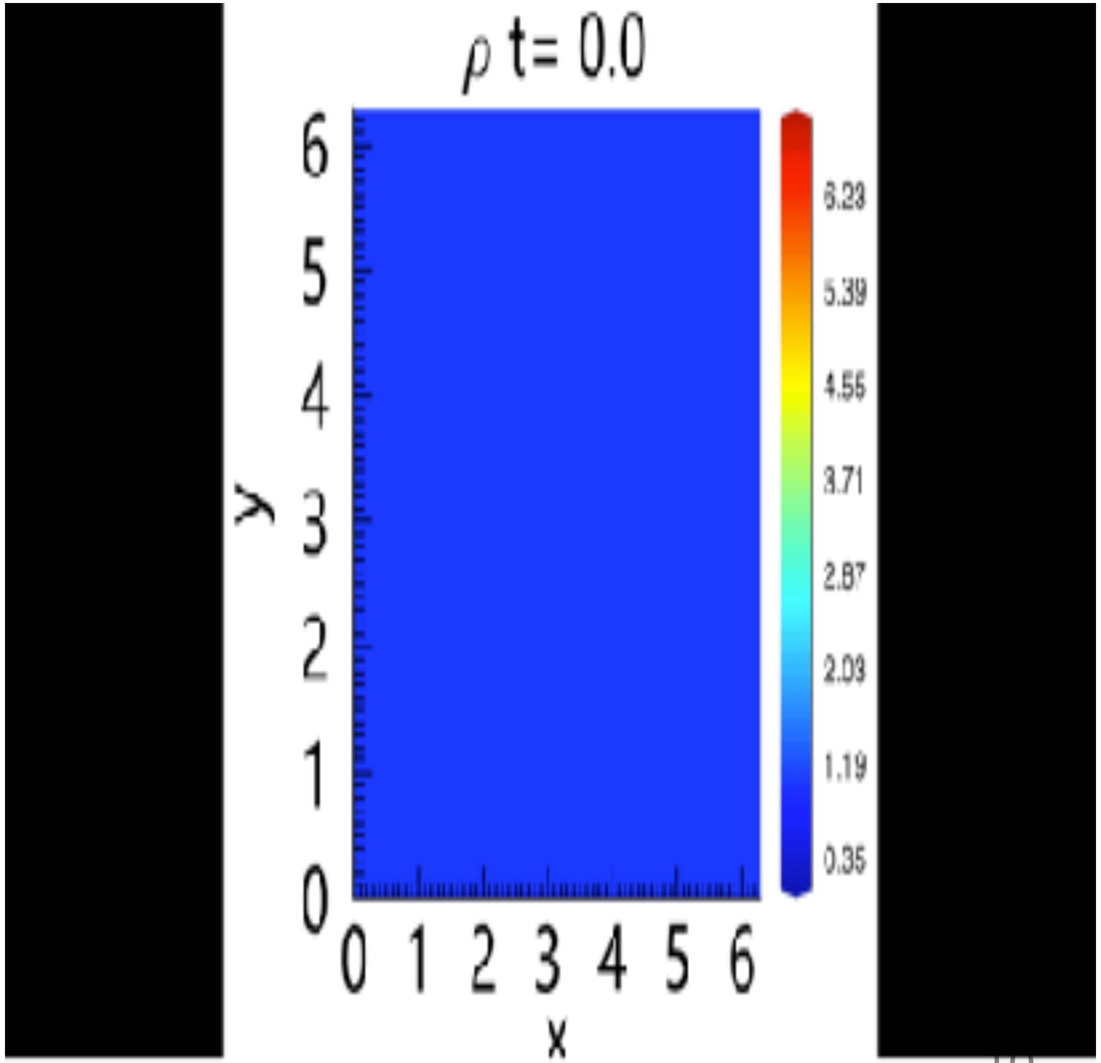
$$\frac{\partial \boldsymbol{B}}{\partial t} - \nabla \times (\boldsymbol{v} \times \boldsymbol{B}) = \boldsymbol{f}_b$$

$$p = \rho c_s^2$$

- AW injection at t = 30

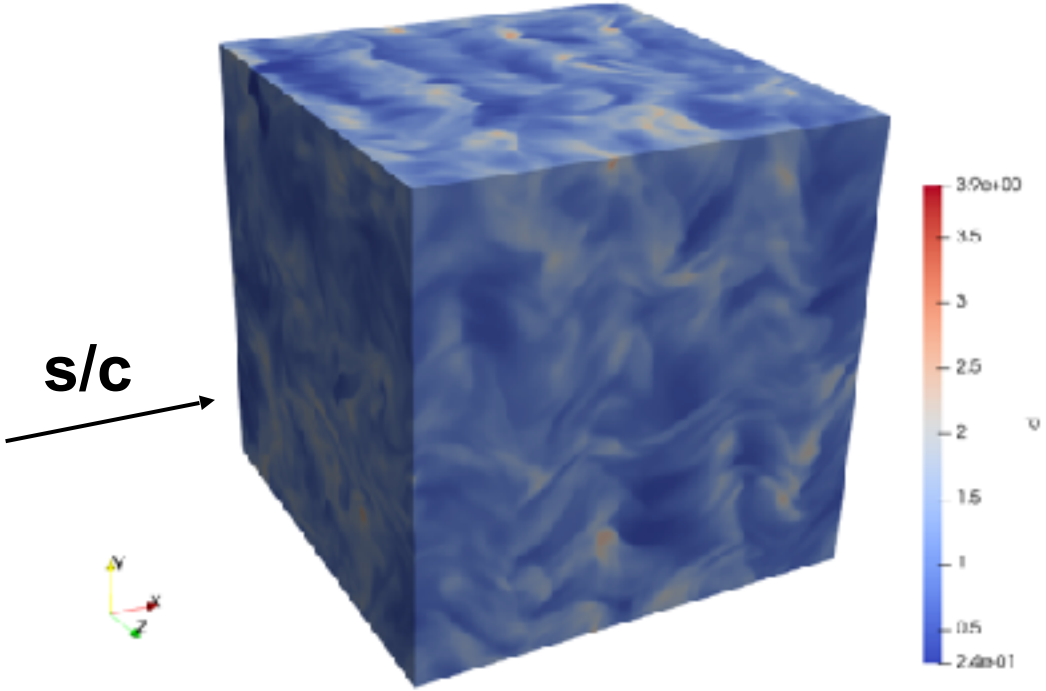
$$\delta B_{cir} = \delta B \cos(3x) \hat{y} + \delta B \sin(3x) \hat{z}$$

$$\delta v_{cir} = -\delta B_{cir}$$

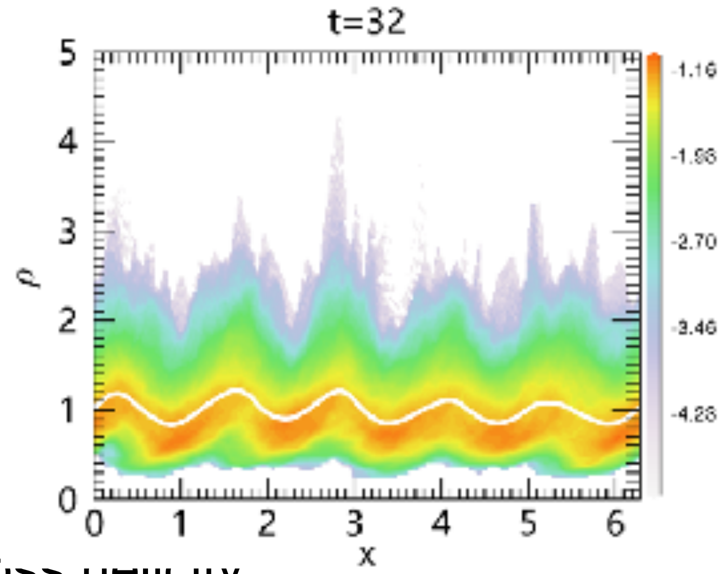


Signatures of PDI | Preliminary results

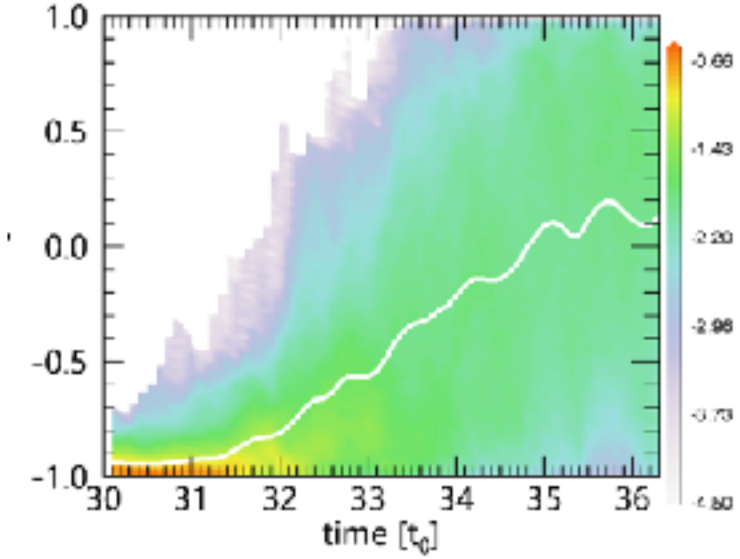
- Take line cuts along B_0



- Density



- Cross helicity

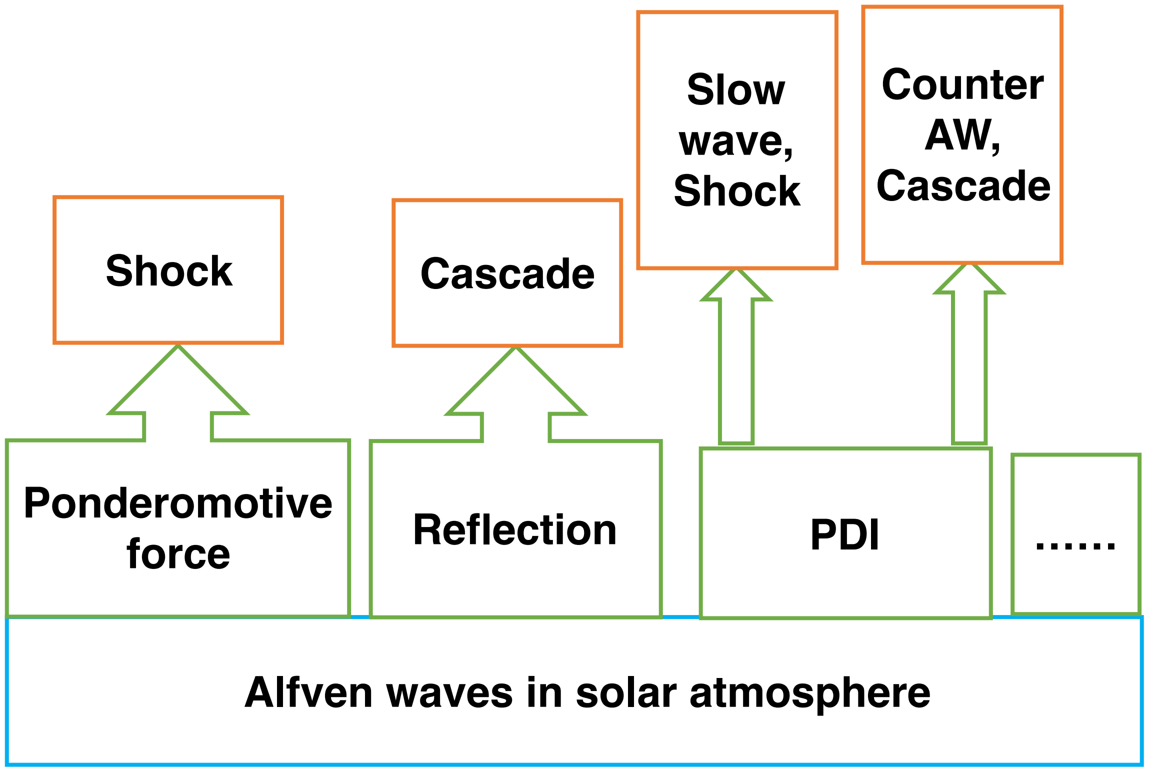


$$\sigma_C = \frac{E^+ - E^-}{E^+ + E^-}$$

Summary and Prospect

- PDI can occur in many plasma environments.
- Single Alfven wave can generate slow waves and cause turbulence.
- PDI can cause inverse cascade and influence the power spectrum.

- Currently, simulation studies are ahead of observations.
- In the low beta region, where *Parker Solar Probe* is to explore, PDI effect is more pronounced, and possibly can influence to the Alfven wave behaviors.



Thanks for your attention!

Three turbulence levels

Figure:
Grids averaged rms density fluctuations.

By changing the drive force, we select three different turbulence levels, both for beta = 0.5 and beta = 0.1.

A circularly polarized Alfven wave is injected at t = 30.

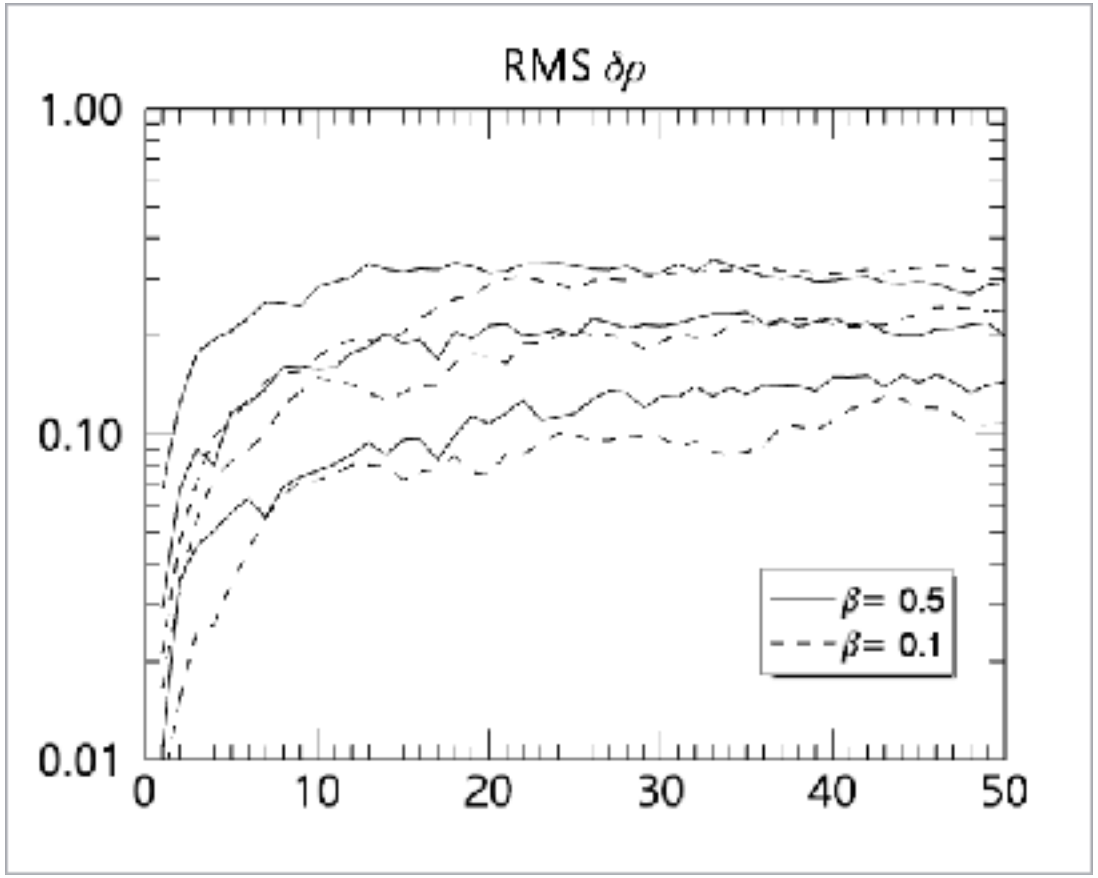


Figure:
PDI modes versus turbulence level (columns) and plasma beta (rows)

Difference from previous results in decaying turbulence using PLUTO

- No initial jump when Alfven wave is injected.
- The saturation level does not change much.

Beta = 0.5

Beta = 0.1

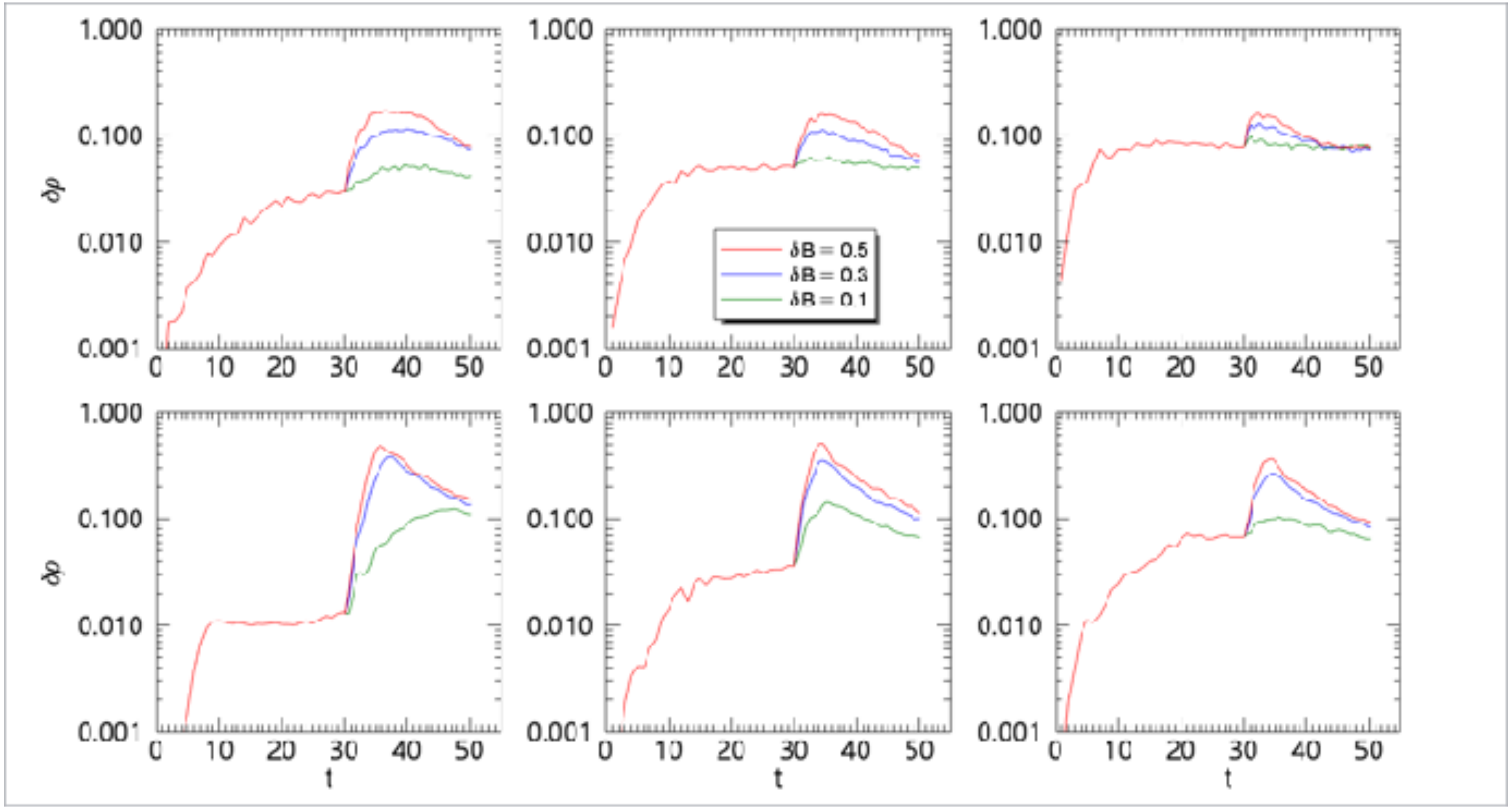


Figure:
PDI mode (left) and cross helicity (right)

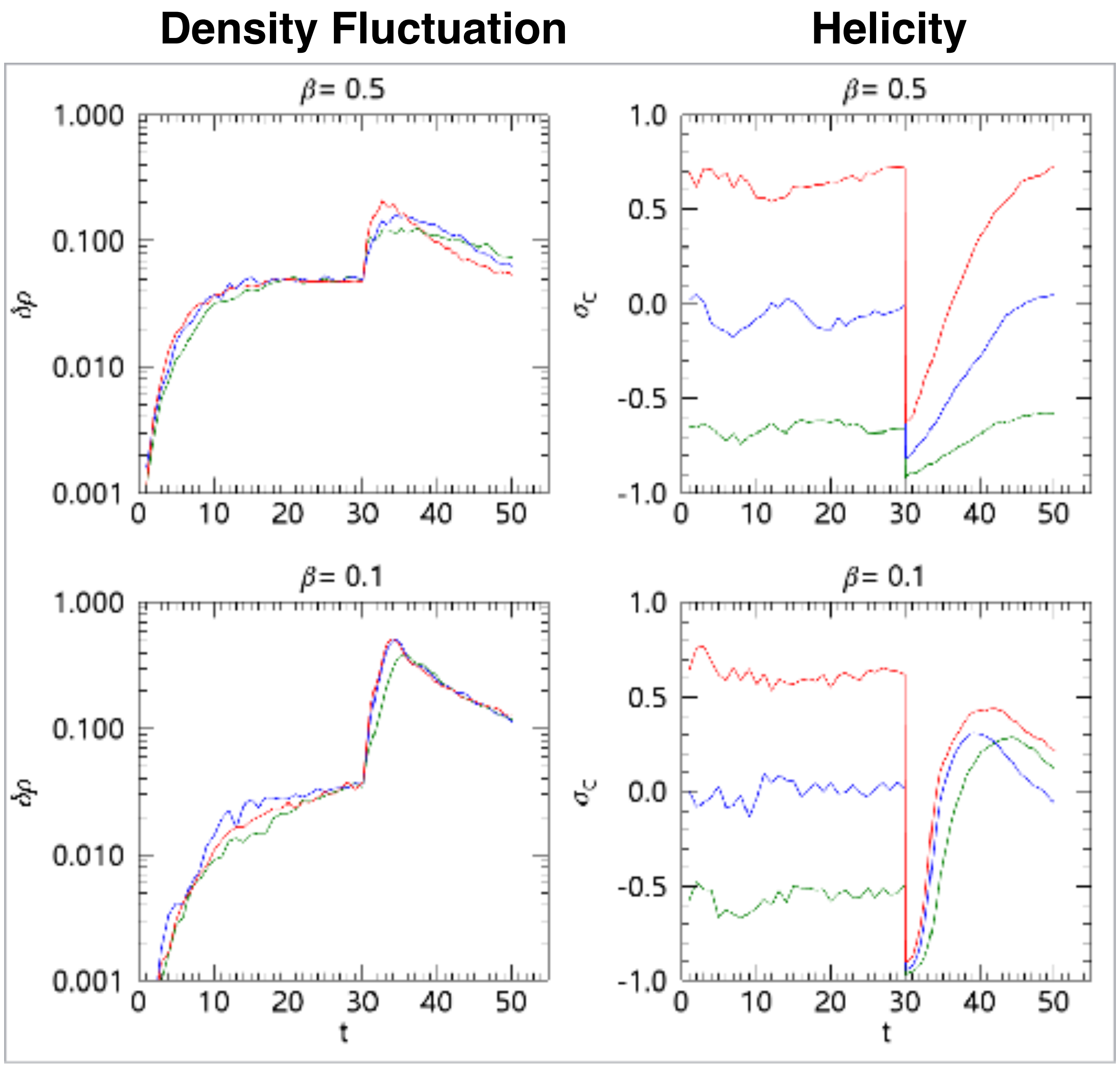
Cross helicity: $$\sigma_C = \frac{E^+ - E^-}{E^+ + E^-}$$

$$E^\pm = \frac{1}{2}|z^\pm|^2, z^\pm = \delta v \pm \delta b$$

The injected Alfven wave put additional E- into the domain (propagating along B0).

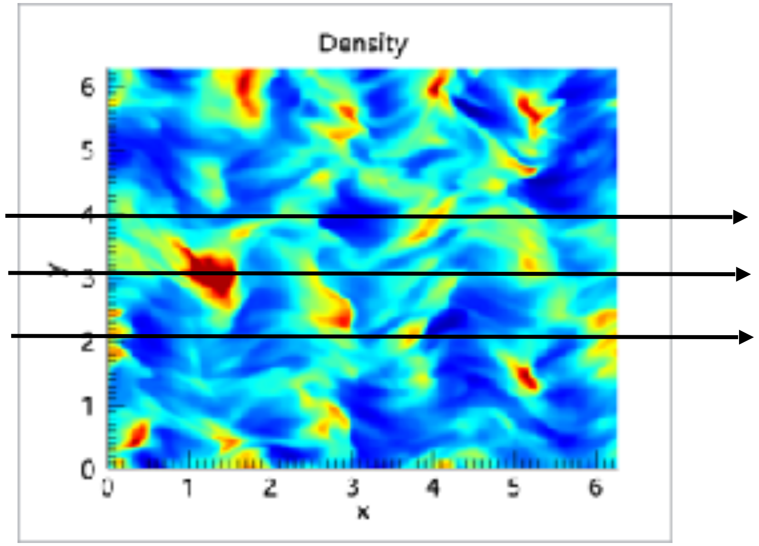
Cross helicity is changing gradually as PDI grows.

The influence of cross helicity to PDI?

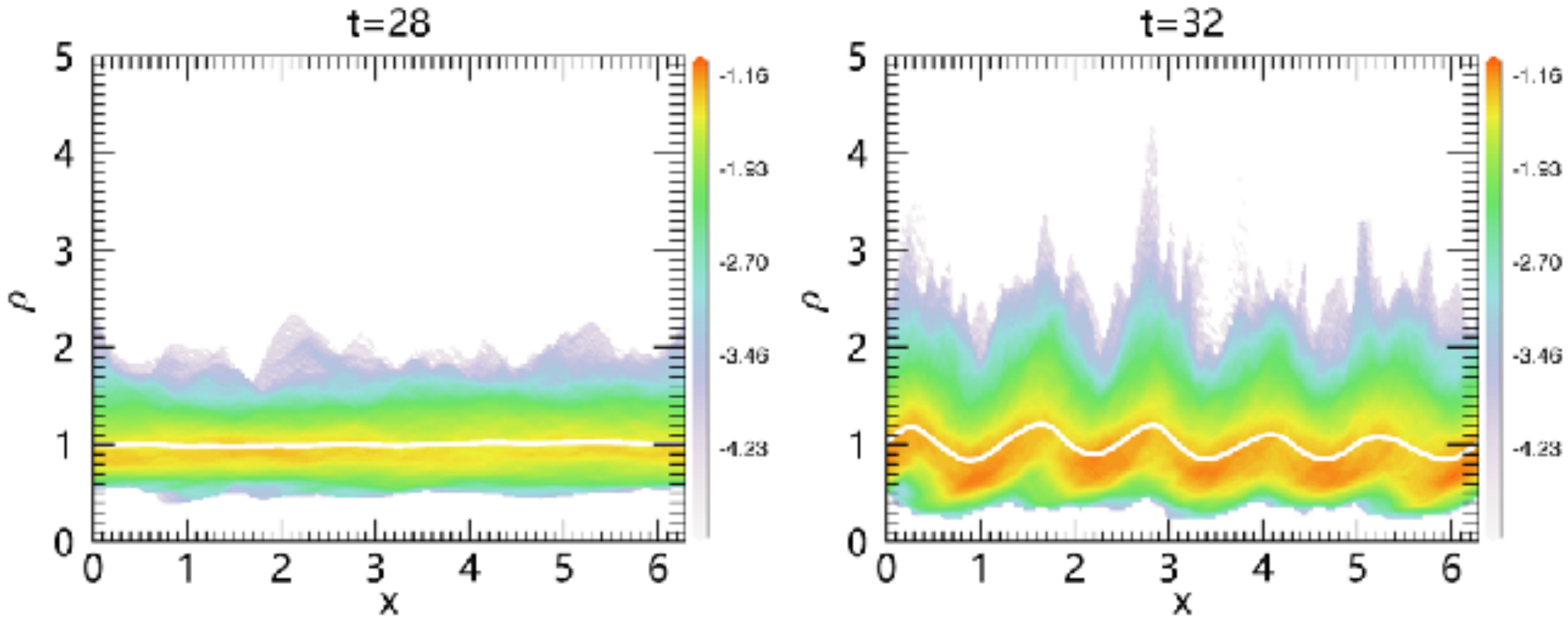


Observational signatures of PDI

- At 1 AU, solar wind speed (~500 km/s) is much larger than Alfven speed (~50 km/s). So we get line cuts along x axis from one time frame.
- Figure is for beta = 0.5.



Average density (white line) and density distribution (color contour)



Observational signatures of PDI

- At 0.1 AU, where PSP can reach, solar wind speed and Alfven speed are similar (~ 300 km/s). So when spacecraft crosses the solar wind, the variation of solar wind need to be considered.

- Figure is for beta = 0.1 and take v_sw = v_A