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Magnetically Driven Turbulence in the Inner Regions of Protoplanetary Disks

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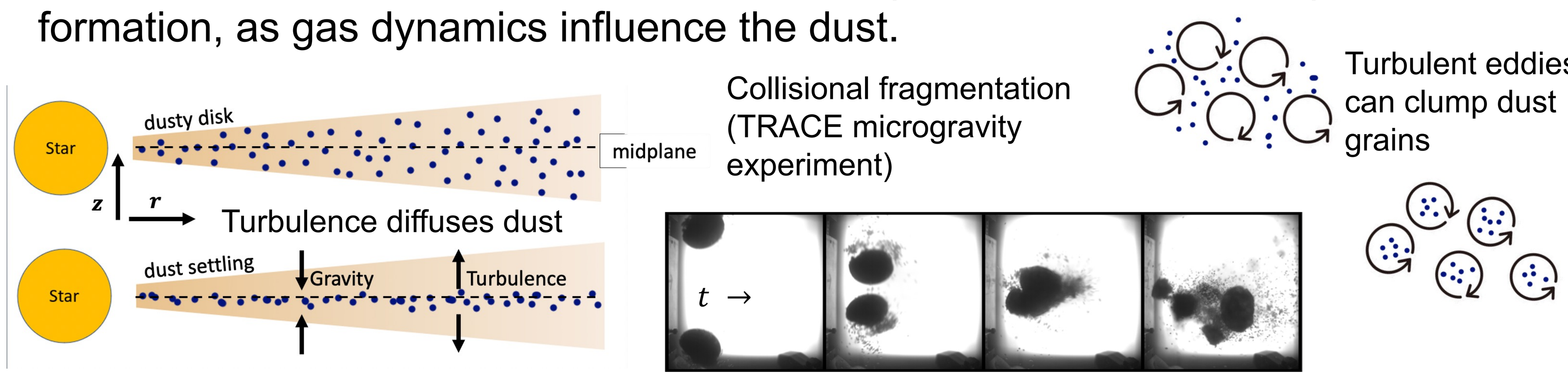
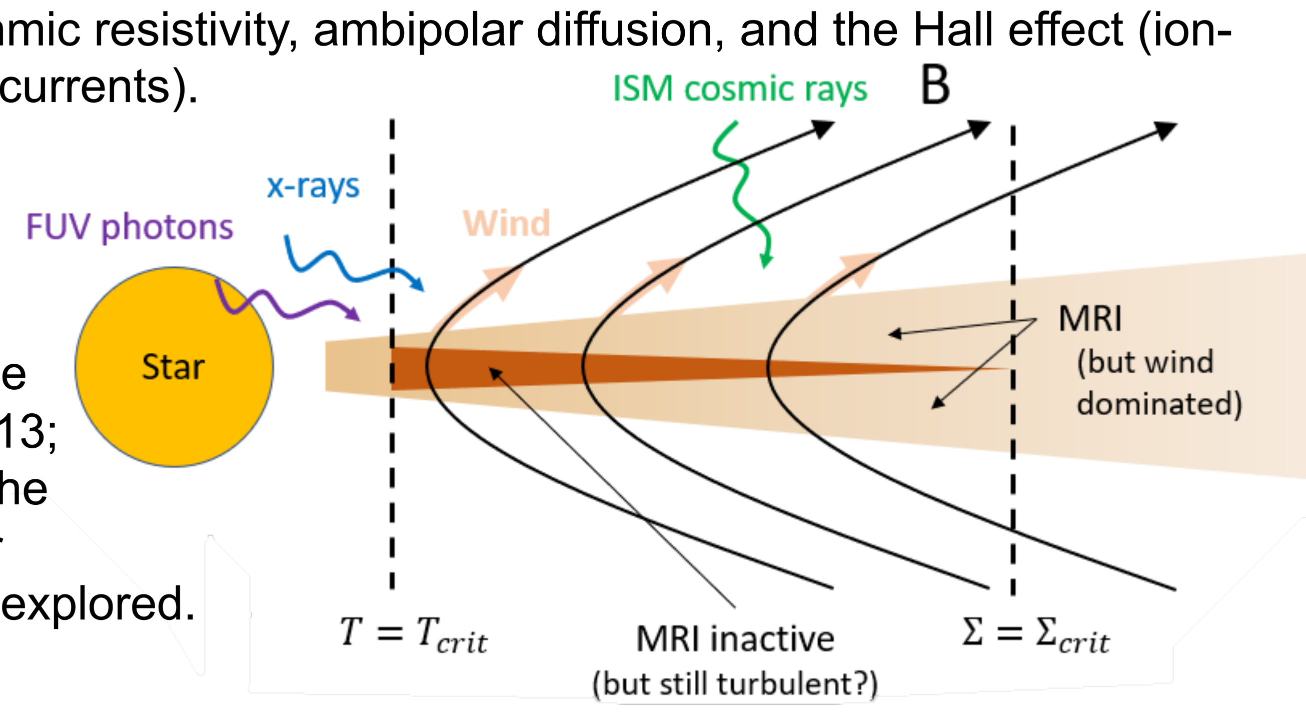
Background & Motivation

How dust grain grow from sub-micron scales to $\sim 10^4$ km or larger planets remains not well understood. Turbulence is important at all scales of planet formation, as gas dynamics influence the dust.



The nature of turbulence in protoplanetary disks is still debated. Protoplanetary disks are cold and weakly ionized, and much of the disk is dominated by low-ionization physics: Ohmic resistivity, ambipolar diffusion, and the Hall effect (ion-electron drift induced currents).

Ohmic and ambipolar diffusion generally weaken MRI-driven turbulence (Gammie 1996; Fleming & Stone 2003; Simon et al. 2013; Cui & Bai 2021), but the Hall effect in the inner 1~30 AU is largely unexplored.



When the Hall effect is strong, the orientation of the magnetic field plays an important role (Balbus & Terquem 2001; Kunz 2008; Simon et al. 2015). The Hall-Shear Instability (HSI) occurs when the Hall effect conservatively rotates azimuthal magnetic field into radial magnetic field, which is then sheared by Keplerian rotation when the field and disk rotation are aligned (see **Numerical Details**)

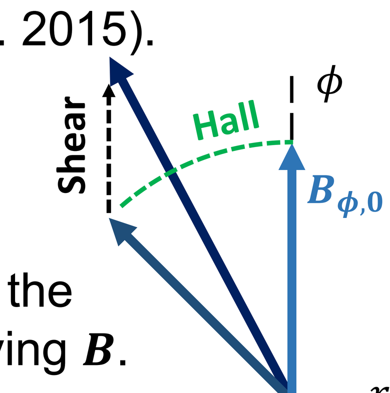
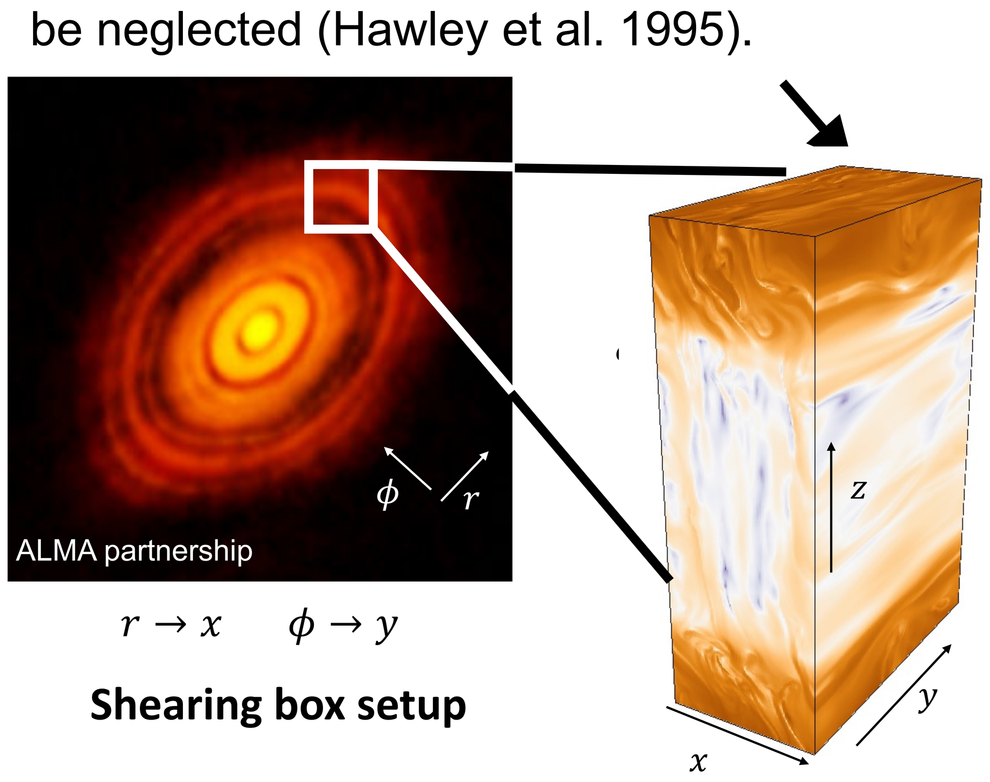


Diagram of the HSI amplifying $\boldsymbol{B}$.

1) **What is the strength of non-laminar, non-Keplerian motions (if present) in the 1-30 AU region of protoplanetary disks?**
2) **Do any such gas motions resemble turbulence, or a coherent flow?**
3) **What are the origins of these gas motions?**

Numerical Details

We carry out **3D** magnetohydrodynamic (**MHD**) **shearing box** simulations using the **Athena** code (Stone et al. 2008; Stone & Gardiner 2010) The shearing box is a local, co-rotating disk patch that is small enough that the effects of curvature can be neglected (Hawley et al. 1995).

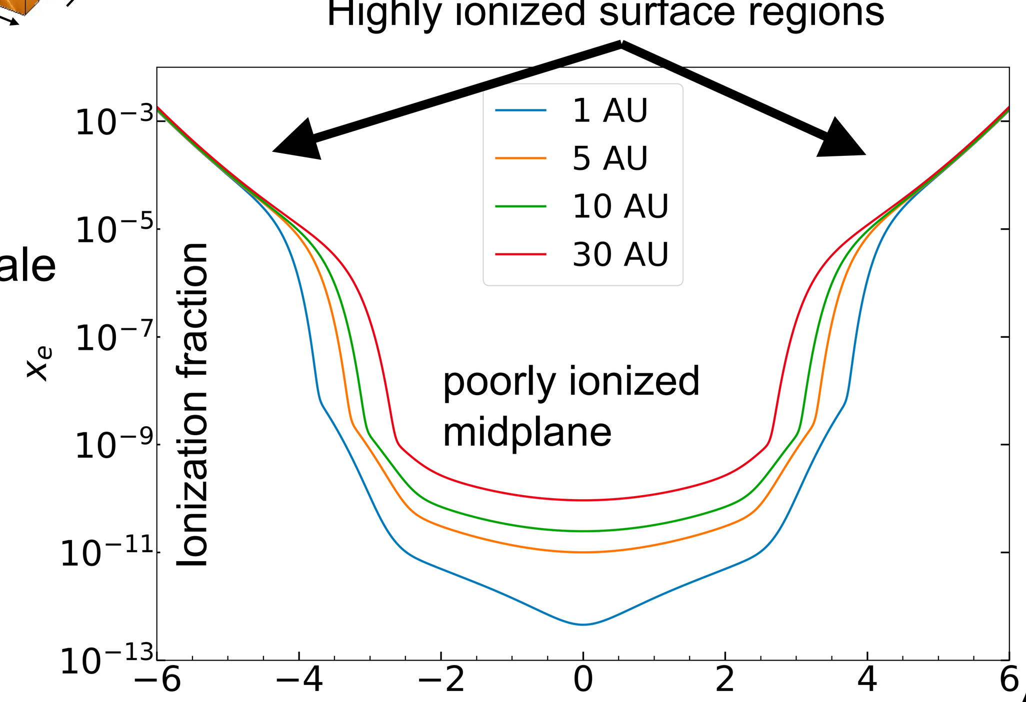


Shearing box setup

We include ionization from
- radioactive decay
- cosmic rays
- stellar x-rays
- far-ultraviolet photons

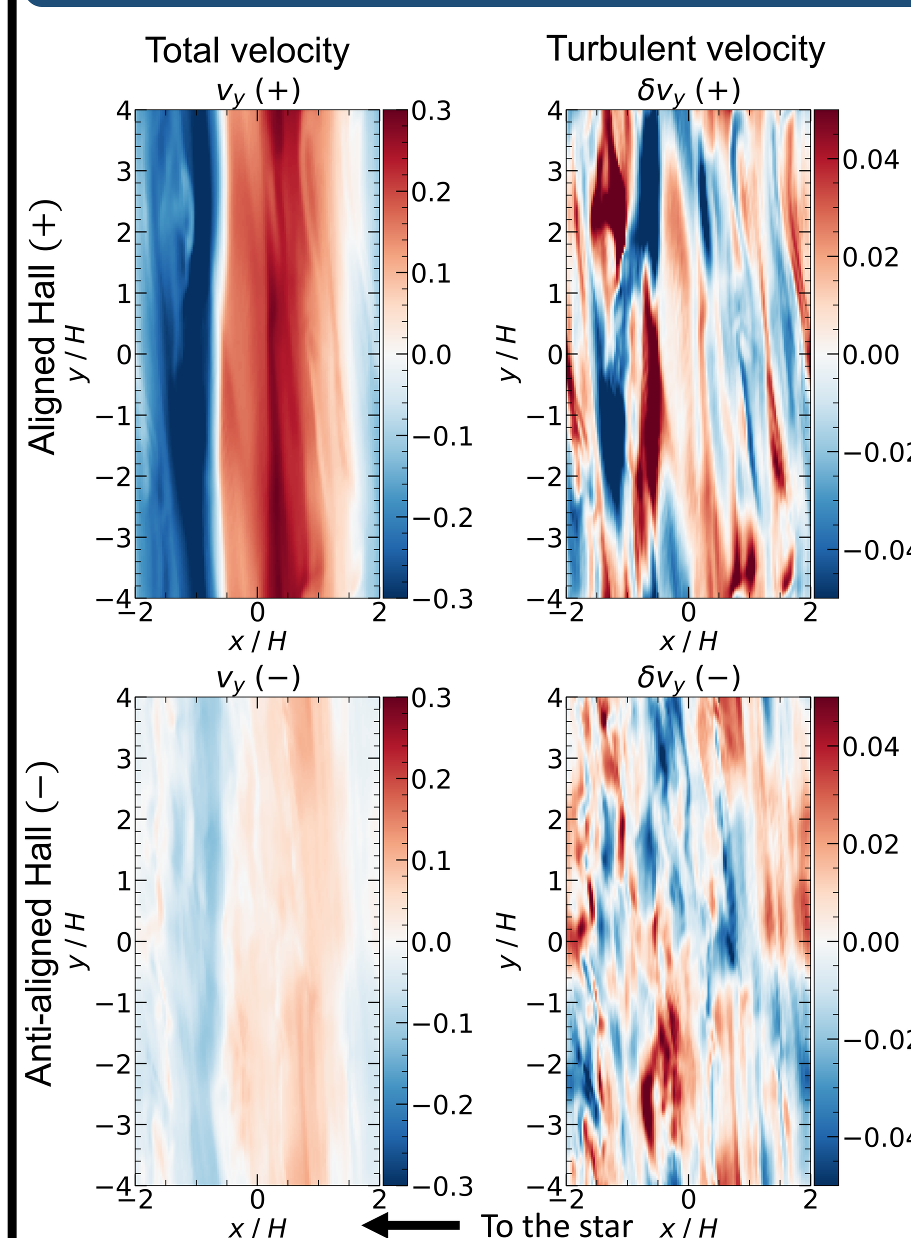
Photons are attenuated as they pass through the disk, which results in **highly ionized surface** layers surrounding a **poorly ionized midplane**, with a sharp transition between the two layers.

Turbulence is **not driven** and is quantified (see **Key Results**) by subtracting the influence of large-scale background flows from the velocity field (Rea et al. 2024). The Magnetic field $\boldsymbol{B_0} = \pm B_0\,\hat{\boldsymbol{z}}$ and is either aligned $(+)$ or anti-aligned $(-)$ with the disk rotation vector $\boldsymbol{\Omega}$. Initial plasma $\beta_0 = 10^4$.

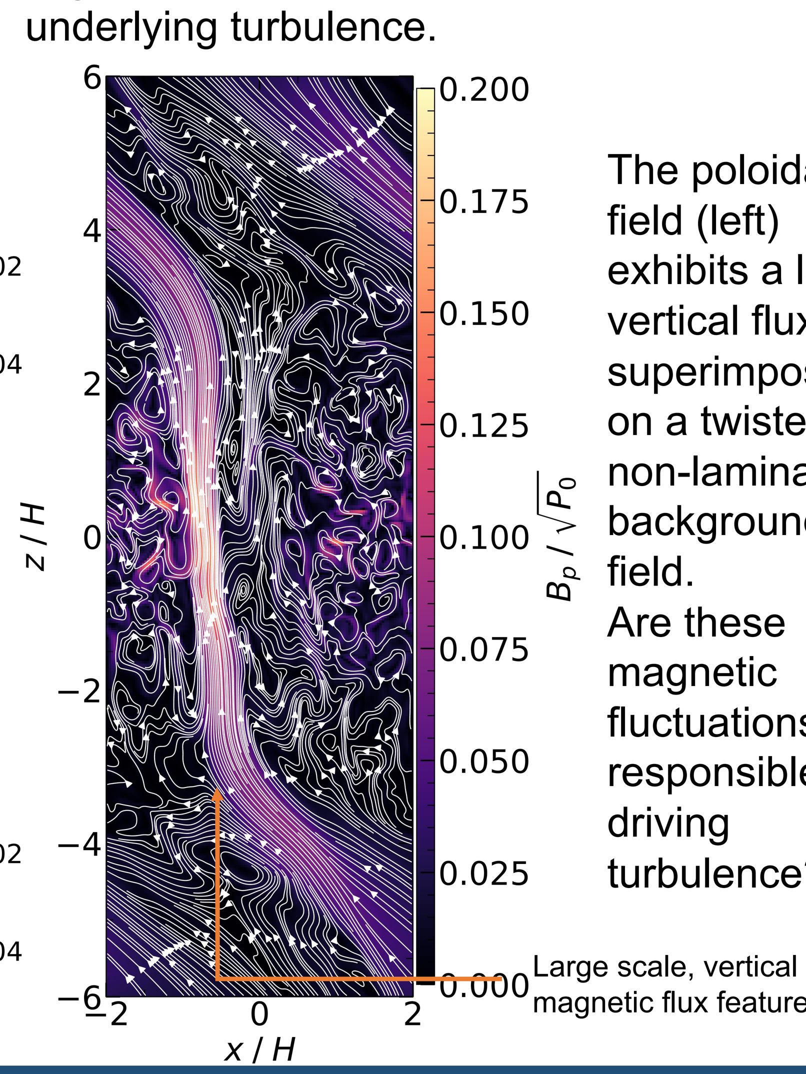


Key Results

Result: Gas motions and magnetic field at the midplane appear turbulent.



The Hall effect (HSI) appears to drive strong laminar flows when the magnetic field in the aligned field orientation but does not change the underlying turbulence.

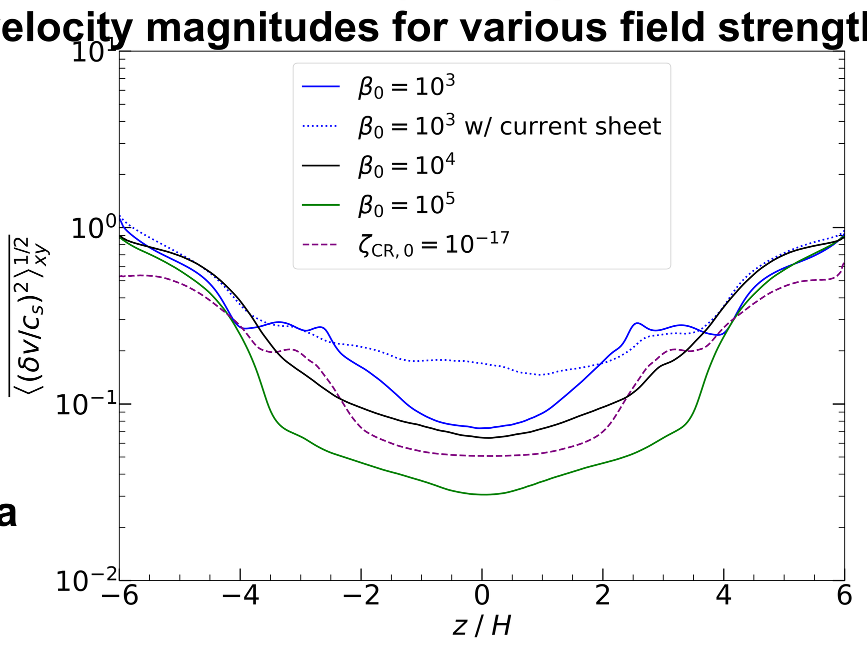


The poloidal field (left) exhibits a large, vertical flux tube superimposed on a twisted, non-laminar background field. Are these magnetic fluctuations responsible for driving turbulence?

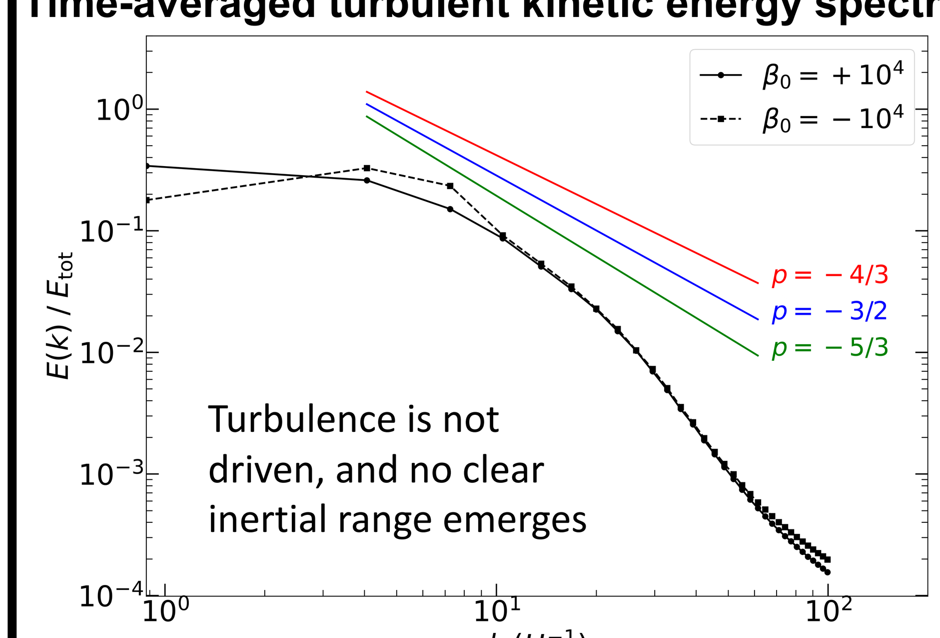
Result: Gas velocity fluctuations are $\sim c_s$ in the highly ionized layers of the disk, and $\gtrsim 0.05\ c_s$ near the disk midplane.

The gas turbulence for the aligned $(+)$ field approaches the sound speed c_s at the disk surface and $\sim 0.1\ c_s$ at the disk mid-plane. Stronger magnetic fields result in stronger turbulent velocities. The anti-aligned field $(-)$ results in nearly identical turbulence, but the turbulence is occasionally enhanced by thin sheets of current near the mid-plane.

Time- and horizontally-averaged turbulent velocity magnitudes for various field strength



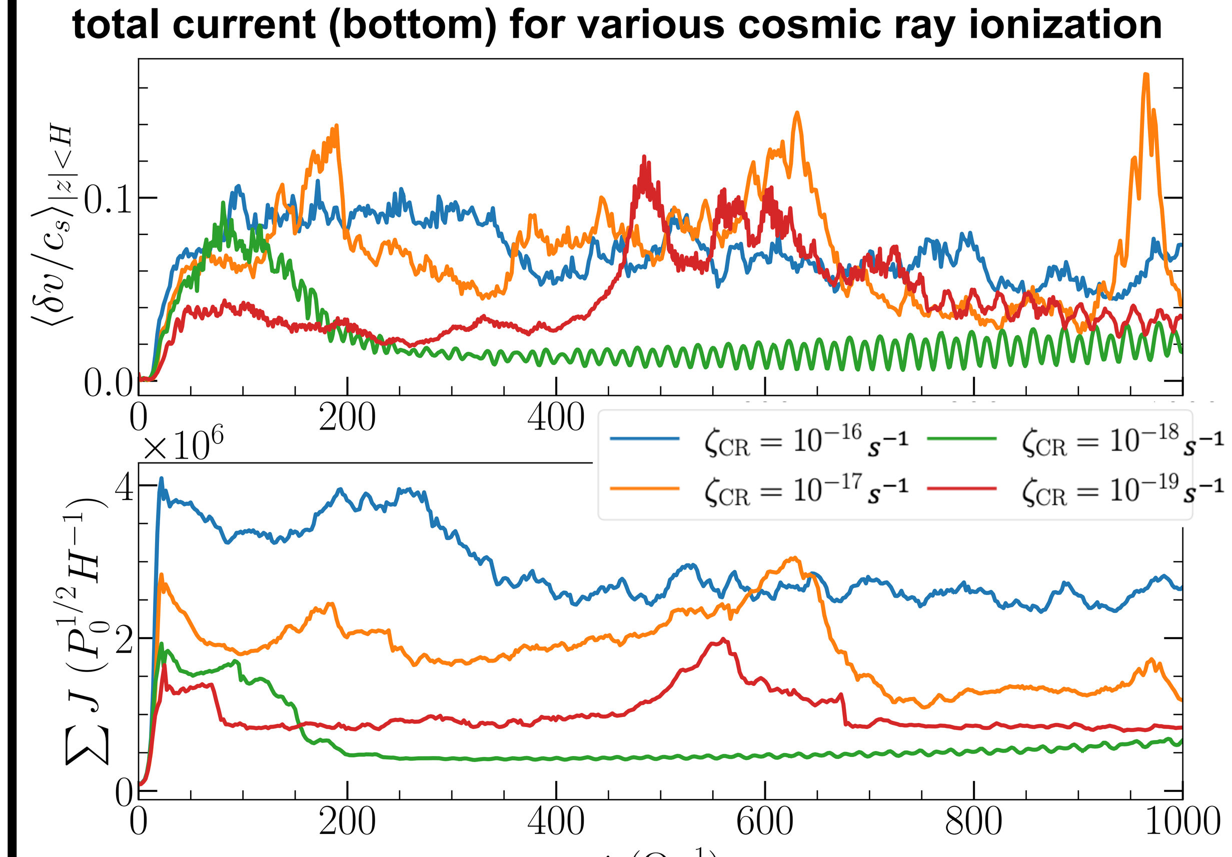
Time-averaged turbulent kinetic energy spectra



The turbulent kinetic energy power spectrum does not exhibit a clear inertial range scaling, due to a combination of strong magnetic and numerical dissipation (Sengupta & Umurhan 2023; Rea et al. 2024).

Result: Strong turbulent velocities are loosely correlated with strong currents, which accelerate gas parcels via the Lorentz force.

Mid-plane RMS-averaged turbulent velocities (top) and total current (bottom) for various cosmic ray ionization



The amount of disk ionization is highly uncertain (e.g. Fujii & Kimura 2022). When the cosmic ray ionization rate is low, $\zeta_{CR} = 10^{-18}\ s^{-1}$ (green), the velocities are characterized by non-turbulent, hydrodynamic disk modes (Lubow & Pringle 1993). However, even lower ionization (red) can again result in turbulence when strong currents are present

SUMMARY

- **Hall effect drives strong zonal flows, but not turbulent fluctuations**
- **Turbulence is instead driven by current sheets**
- **Currents generate turbulence even in low ionization**

GitHub link: digital poster + movies!