Turbulence in Protoplanetary Disks

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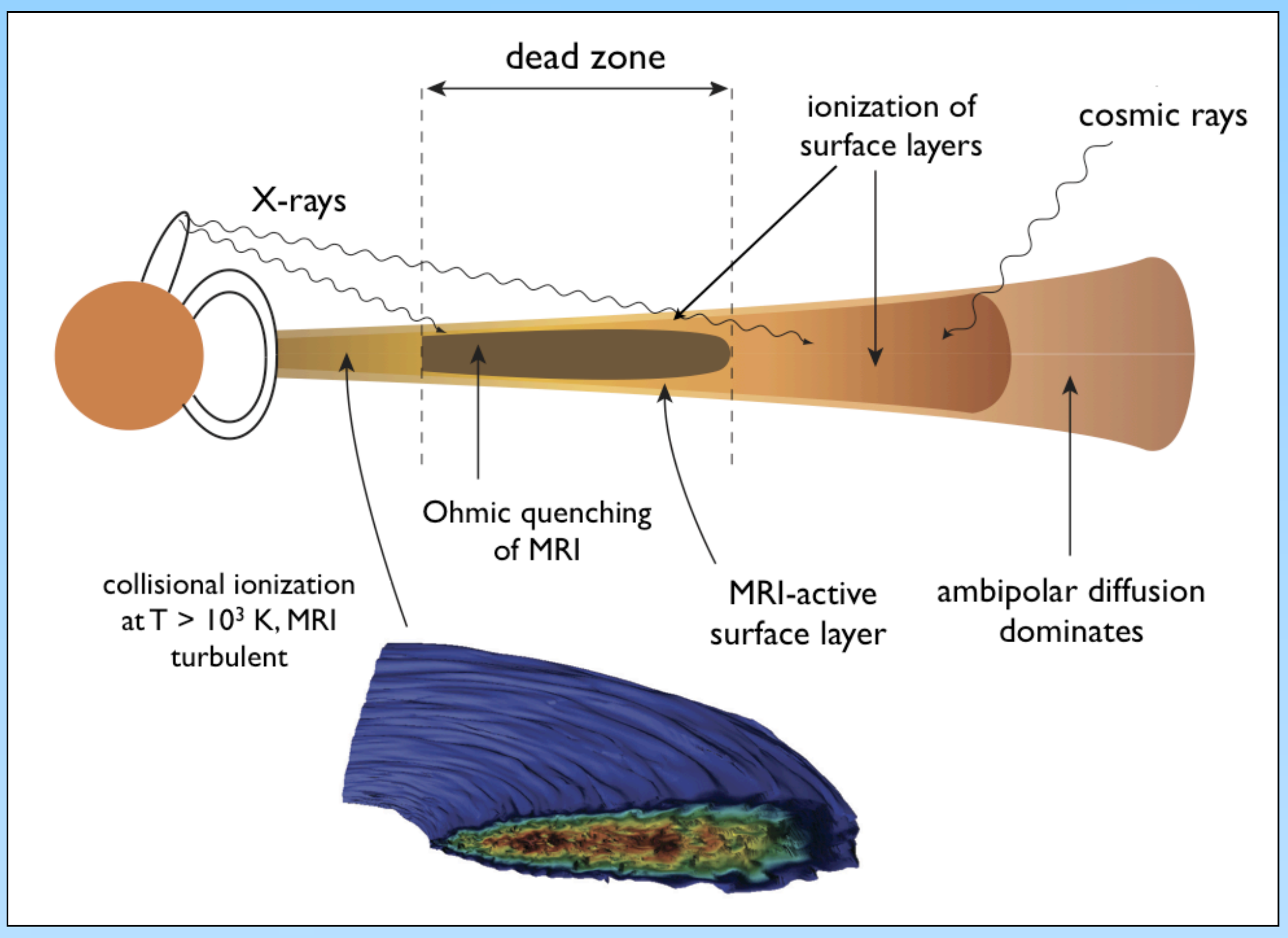
Abstract

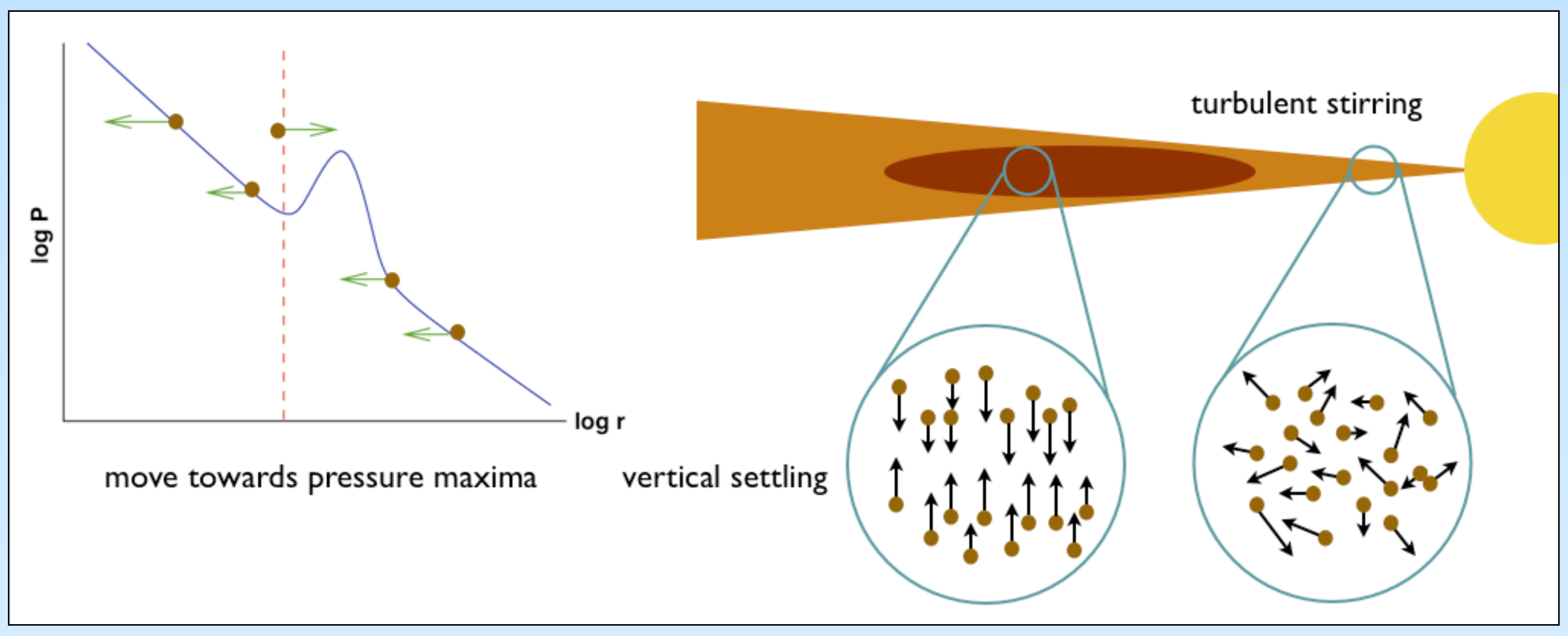
We study the nature of magnetohydrodynamic (MHD) turbulence in protoplanetary disks driven by the magnetorotational instability (MRI) in order to understand the conditions under which planets first begin to form. In particular, we present a series of high resolution gas dynamics simulations that are focused on several radial regions in a model protoplanetary disk. Close to the star where the gas is fully ionized, strong features called "zonal flows" appear in the gas pressure; these features could potentially trap small dust particles for long periods of time, playing a significant role in early planet formation processes. At large disk radii where the gas density is lower, ambipolar diffusion dominates and creates regions where the MRI is less efficient at generating turbulence. However, zonal flows may persist in these “ambipolar damping zones” as well, making them potential sites for planet formation in the outer disk. Finally, we show that at these large distances, the geometry and strength of the magnetic field play an important role in setting the level of turbulence throughout the disk’s vertical extent and thus the accretion rate onto the central protostar.

Motivation



The structure and evolution of gas and dust in protoplanetary disks play an integral role in the formation of stars and planets. Turbulent angular momentum transport (Shakura & Syunyaev 1973) allows disk gas to accrete onto the central protostar, and determines the global density distribution within which planets will form. Turbulence also influences the earliest stages of planet formation by inhibiting or enhancing dust coagulation and settling towards the disk mid-plane (e.g., Dubrulle et al. 1995; Ormel & Cuzzi 2007; Youdin & Lithwick 2007; Birnstiel et al. 2011).

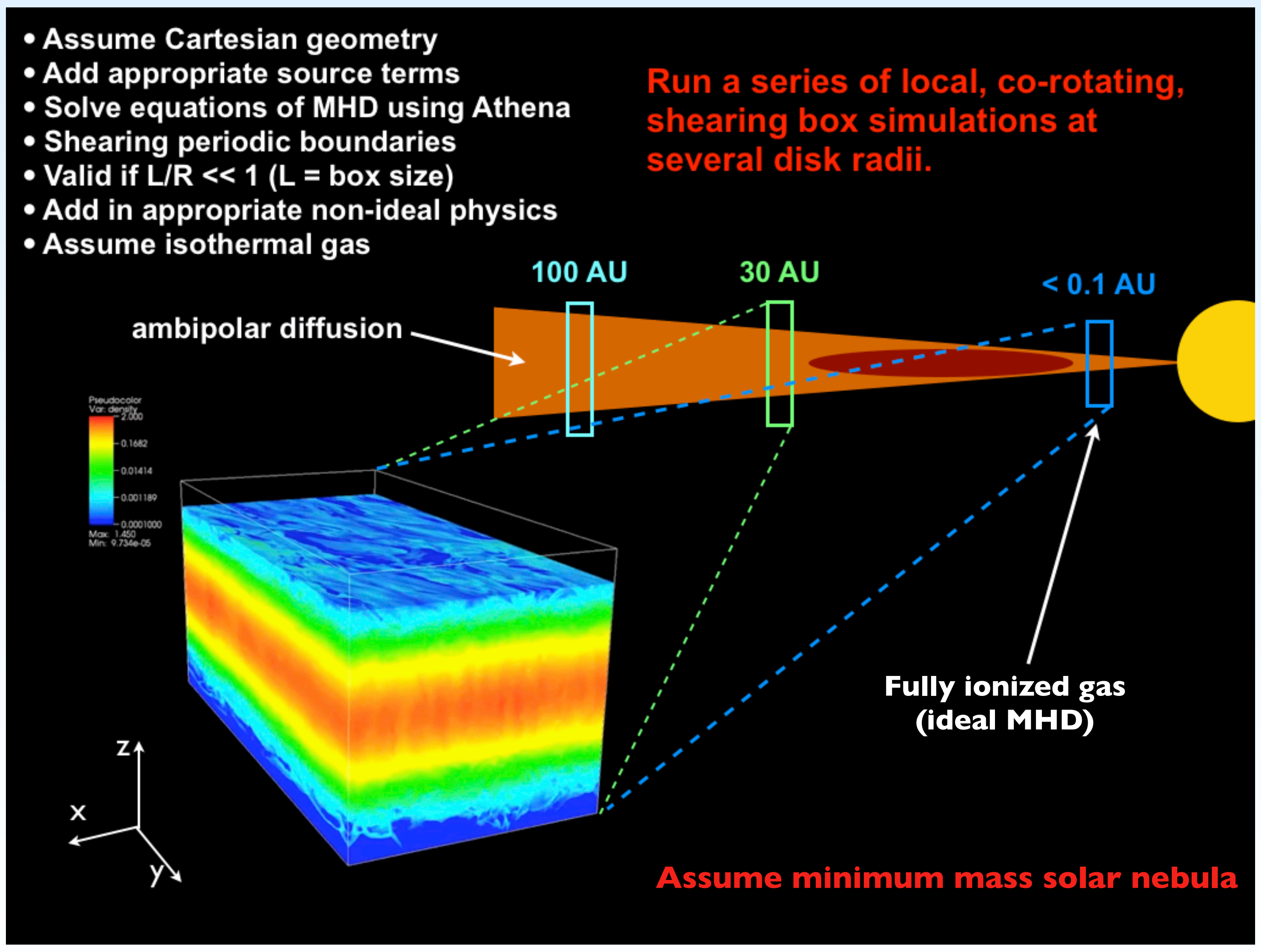
The most likely source for generating this turbulence is the magnetorotational instability (MRI; Balbus & Hawley 1998); magnetized, orbiting gas is extremely unstable, ultimately resulting in MHD turbulent stresses and outward angular momentum transport. However, as a result of the low ionization levels present in cold protoplanetary disks, magnetic fields are not always well-coupled to the gas, resulting in non-ideal MHD, diffusive like processes that either damp or altogether quench the MRI.



The dynamics of dust particles are influenced by this turbulence and will thus depend on the strength of these diffusive processes, which in turn depends on disk location.

Our main goal is to characterize the strength and structure of MRI-driven turbulence at different locations in a model protoplanetary disk. This is an important step towards understanding how these disks accrete and how planets begin to form.

Method

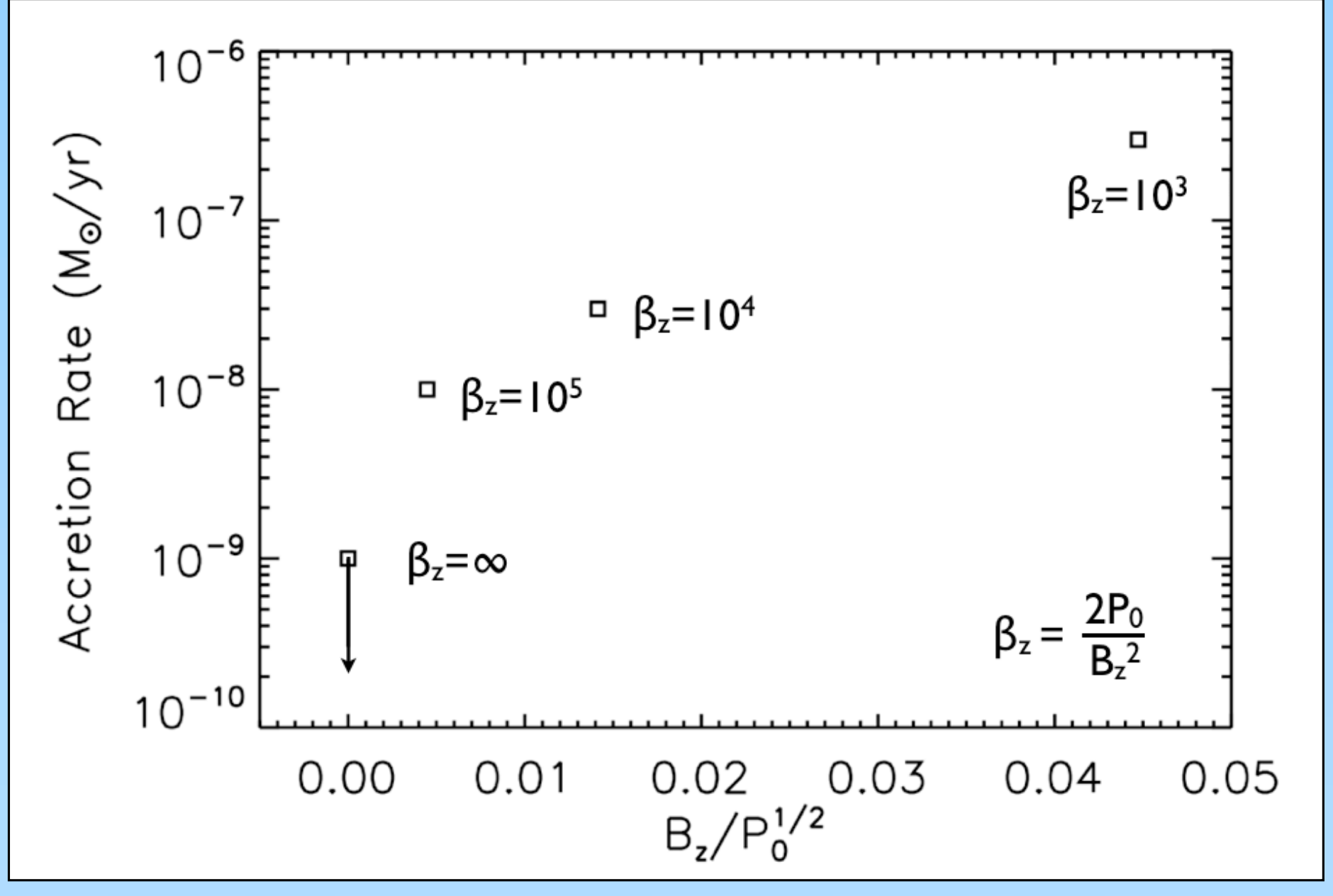


- **Assume Cartesian geometry**
- **Add appropriate source terms**
- **Solve equations of MHD using Athena**
- **Shearing periodic boundaries**
- **Valid if L/R << 1 (L = box size)**
- **Add in appropriate non-ideal physics**
- **Assume isothermal gas**

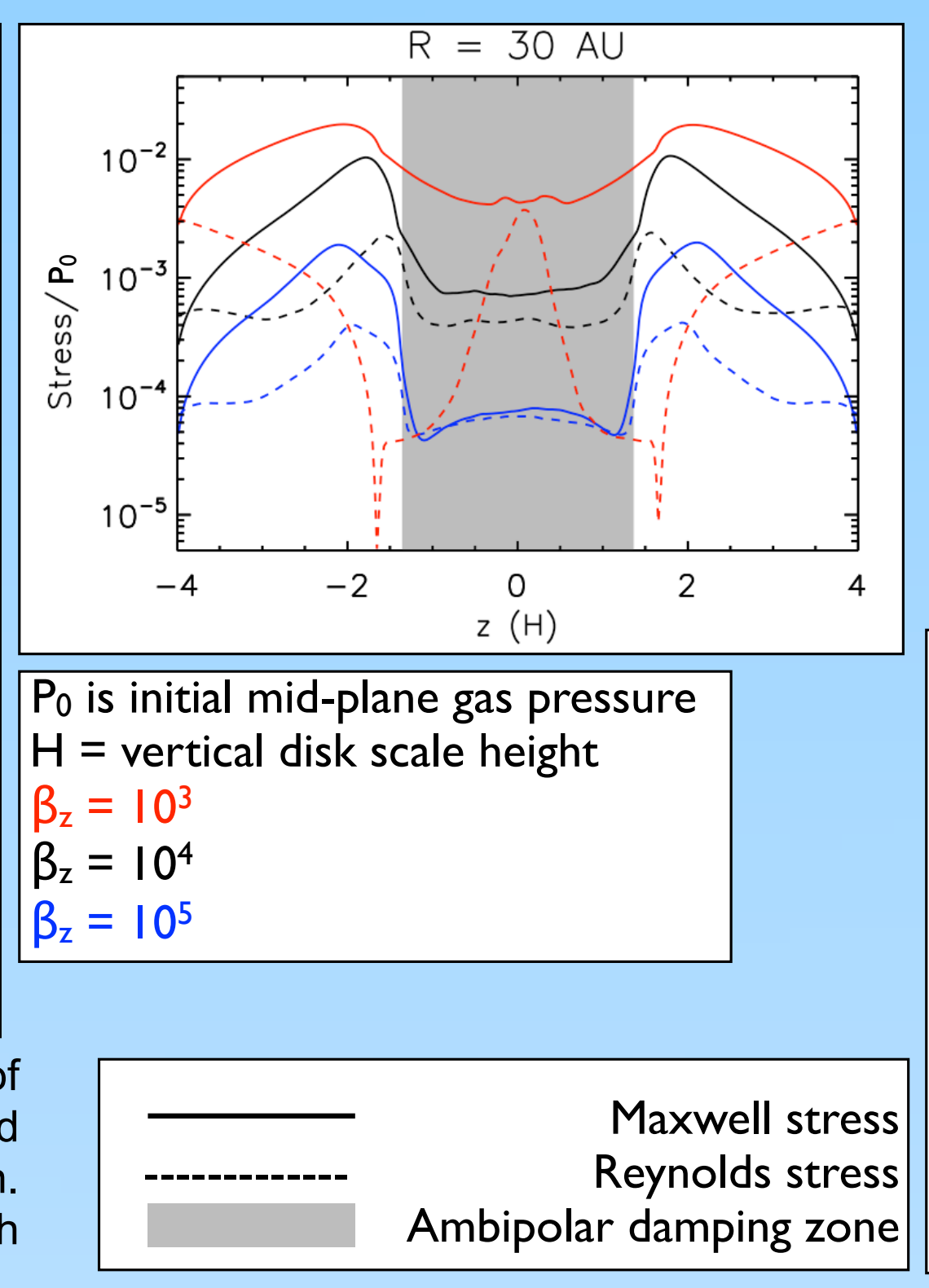
Run a series of local, co-rotating, shearing box simulations at several disk radii.

Assume minimum mass solar nebula

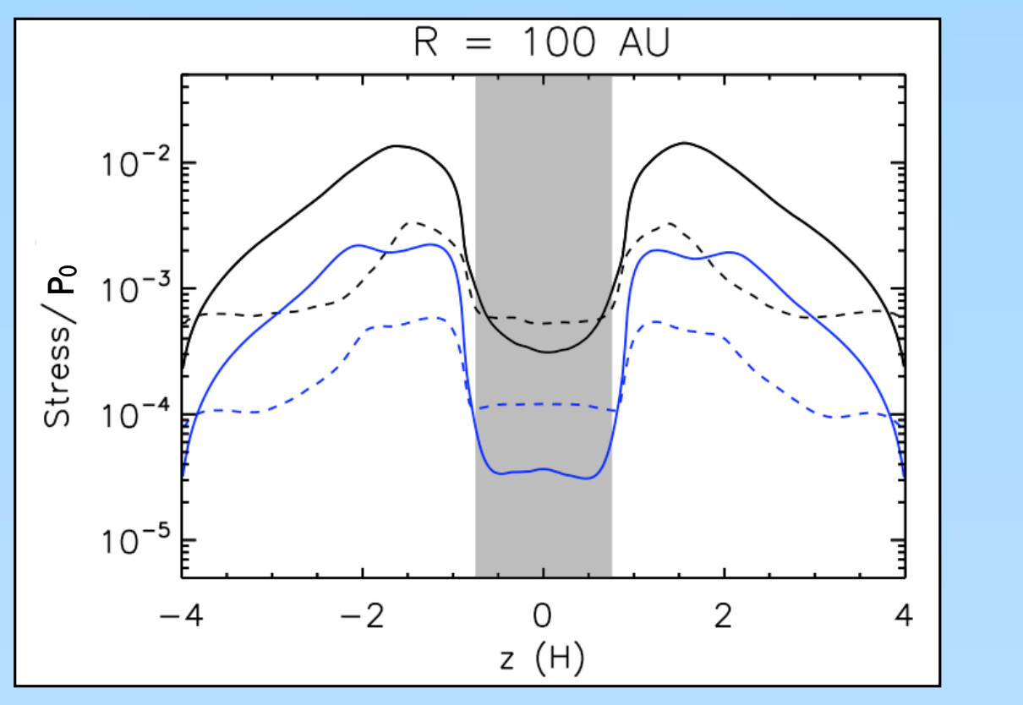
Results

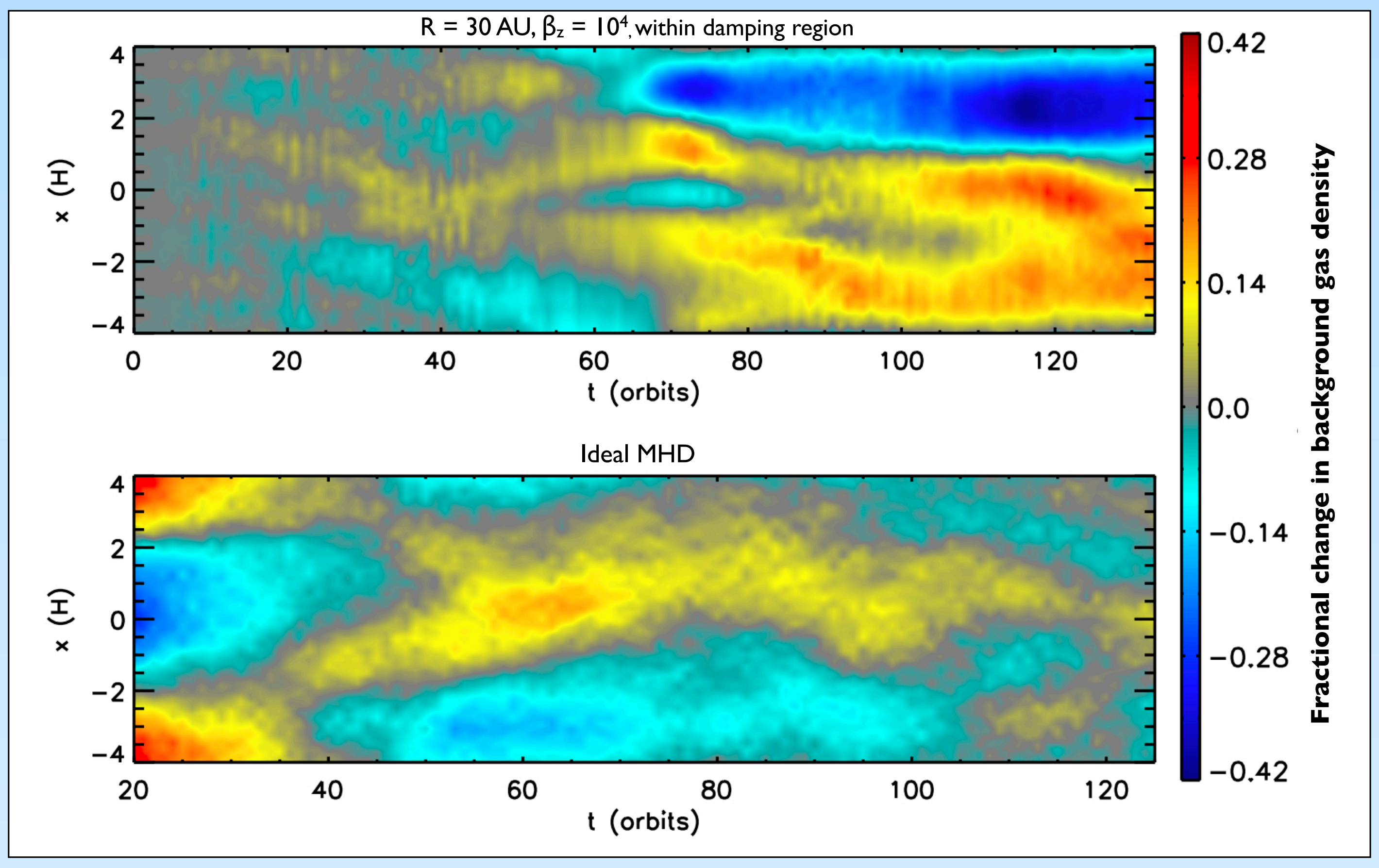


For *zero* net vertical magnetic field threading the disk, we find an upper limit of 10^{-9} $M_\odot$/yr for the accretion rate. In the presence of a net vertical field, we find a strong dependence of the accretion rate on the background field strength. Field strengths of $\beta_z = 10^4$-10^5 return accretion rates that best agree with observations (e.g., Hartmann et al. 1998).



Our simulations show a vertical stress profile that peaks on both sides of the ambipolar damping zone (gray region), while the entire amplitude of the stress increases with increasing background magnetic field strength. In the strongest field case (red curve on the left), the flow actually becomes quasi-laminar, and accretion is controlled largely by a wind stress.





MRI turbulence leads to the generation of large-scale, long-lived, axisymmetric density/pressure perturbations. The amplitude of these perturbations within the ambipolar damping zone (at R = 30 AU and $\beta_z = 10^4$) is roughly equal to that in the fully ideal MHD case. This suggests that the damping zones in the outer regions of protoplanetary disks could serve as areas of strong dust particle trapping, thus enhancing the growth of these particles into larger bodies. Without a net vertical field, these zonal flows are very weak.

Conclusions

- **The outer regions of protoplanetary disks are dominated by ambipolar diffusion. Nonetheless, in the presence of a *net vertical field* threading the disk, accretion is enhanced to significant levels, even near the low-ionization disk mid-plane (i.e., the ambipolar damping zone).**
- **There is a very strong dependence of turbulent fluctuations on the background vertical magnetic field in the outer regions of protoplanetary disks. Larger field strengths lead to larger accretion rates onto the star as well as higher turbulence levels in the ambipolar damping zone.**
- **Long-lived, axisymmetric “zonal flows” appear where the MRI is sufficiently active. The amplitude of these flows in the damping zone may be comparable to their amplitude in the ideal MHD limit.**

Next: Include particle dynamics and study influence of turbulence, vertical settling, and zonal flows on planetesimal formation.

Watch a movie of MRI turbulence in a shearing box.

http://jila.colorado.edu/~jasi1566/Large_Shearing_Box.html

Acknowledgments

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Questions?
See this guy! →

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