Instabilities in Accretion Disks

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Review topics.

- What we (think we) know.
- Current efforts.
- Future work.

Numerical methods for MHD are crucial for this work.

Today, many different AMR MHD codes are available.

- AMRVAC (Toth 1996; Nool & Keppens 2002)
- BATSRUS (Powell et al. 1999)
- RIEMANN (Balsara 2000)
- FLASH (Fryxell et al. 2002)
- Nirvana (Zeigler 2005)
- RAMSES (Fromang et al. 2006)
- PLUTO (Mignone et al. 2007)
- AstroBEAR (Cunningham et al. 2008)

We use Athena, which implements slightly different algorithms from all of these. These differences can be important.

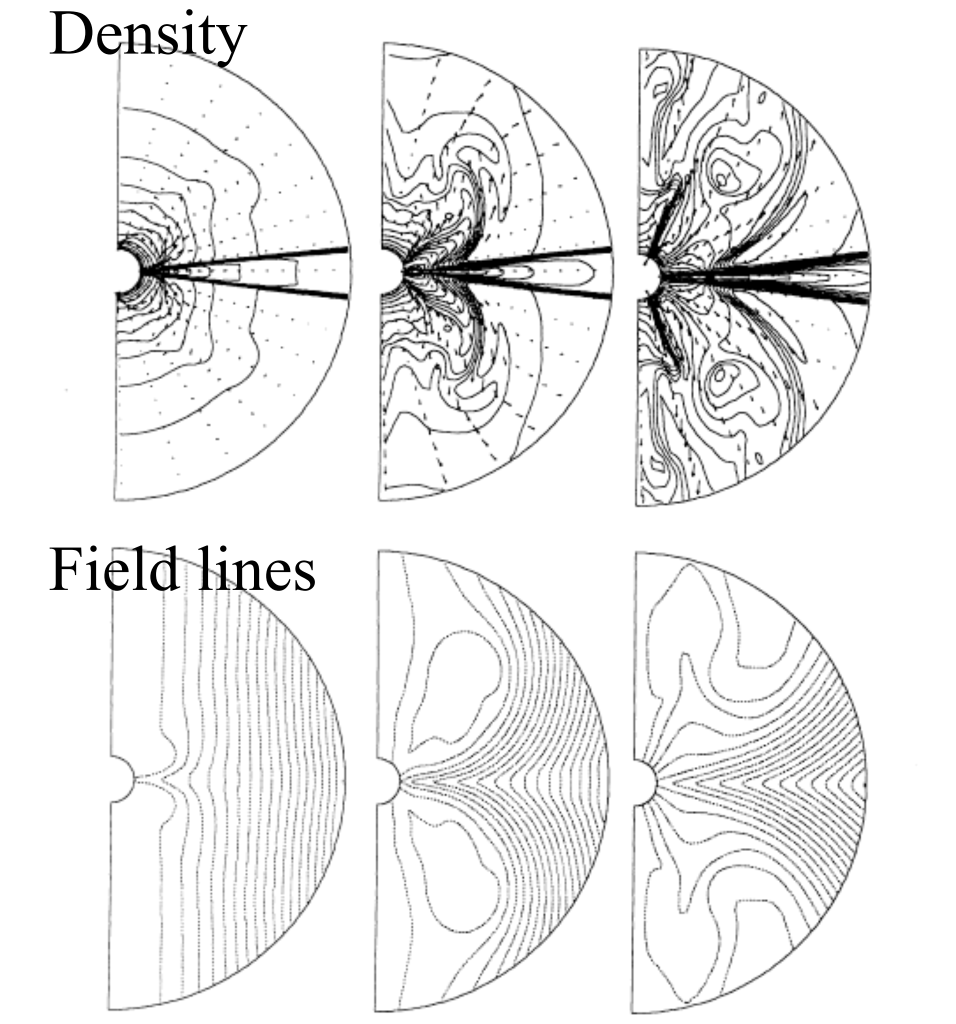
Diversity of methods is good.

Early time-dependent MHD simulations of disks showed they are very dynamic.

Example:

Evolution of Keplerian and sub-Keplerian disks in 2D

e.g. Uchida & Shibata 1986
Stone & Norman 1994



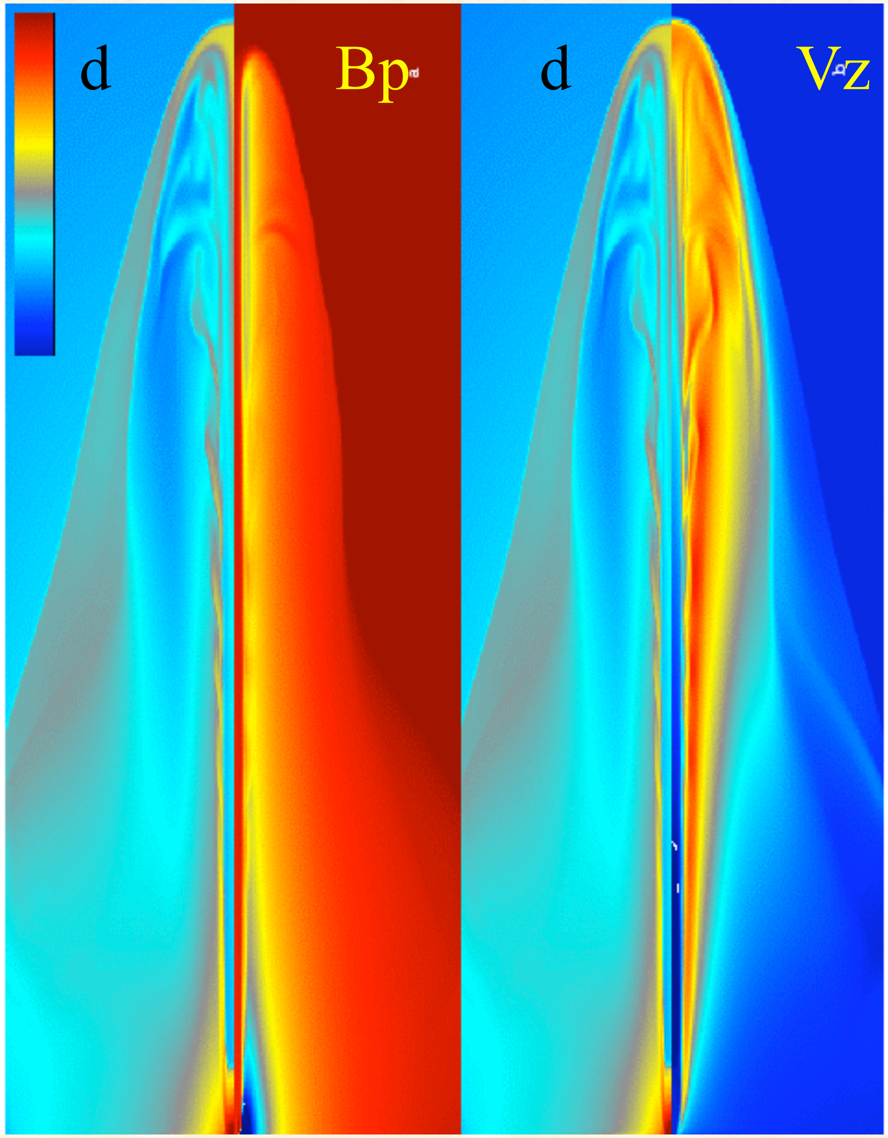
Disk collapses on an orbital time.

Strong outflow, but not a steady jet.

Evolution of Keplerian disks driven by MRI; not understood at the time.

Later studies focused on the jet; modeled the disk as a boundary condition.

e.g. Ustyugova et al, Ouyed & Pudritz, Krasnopolsky et al.



Internal dynamics of disk and feedback not included…

Disk is rotating plate at base of flow

Ouyed, Pudritz, & Stone 1999

Today it seems clear that to understand formation of jets from disks (and disk-star interaction) in detail…

…we need to understand the internal dynamics of the disk.

What would we like to know?

- Angular momentum transport: importance of turbulence versus winds?
- Does turbulence drive a dynamo?
- At what rate is vertical field advected inward?
- What role does corona play in disk dynamics?

All of this requires:

- Understanding nonlinear saturation of various instabilities in disks.
- Accurate and reliable numerical methods for studying MHD turbulence.
- Proper treatment of lots of physics: MHD, radiation transport, ionization/recombination, dust.

Which instabilities?

All the most important instabilities seem to be MHD:

1. *Magneto-rotational instability (MRI).* Seems to be important everywhere.
2. *Parker instability.* Produces vertical flux of magnetic energy.
3. *Magneto-viscous instability (MVI).* Important in hot, diffuse plasmas (AGN disks, coronae)
4. *Magneto-thermal instability (MTI).* Important in diffuse, thermally stratified plasmas
5. *Photon bubble instability.* May be important in radiation dominated disk atmospheres.
6. *Rayleigh-Taylor instability*. May be important in star-disk interaction region.

But hydrodynamic instabilities may contribute.

1. *Non-linear shear instability*

   Has long been proposed as hydrodynamic mechanism for shear turbulence.

   Recently work: either not present, or irrelevant (Ji et al 2006)

2. *Baroclinic instability* (Klahr & Bodenheimer, Li & Lovelace)

   Driven by radial entropy gradients in disk.

3. *Gravitational instabilities*

   Clearly will be important if $M_{disk} > 0.1 M_{star}$

4. *Kelvin-Helmholtz instability.* Operates in shear layer between dust and gas (Cuzzi; Youdin & Shu).

   Could be important for dust settling planet formation

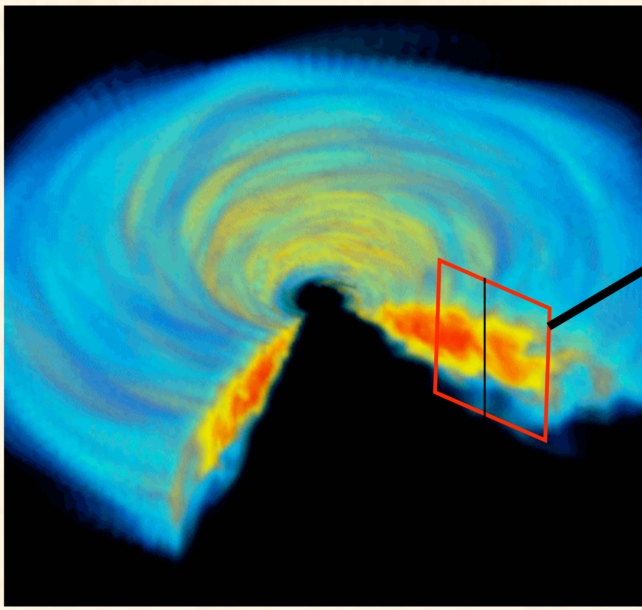
5. *Dust streaming instability* (Youdin & Goodman)

   Could be more important than KH in dust layer (Johansen & Youdin).

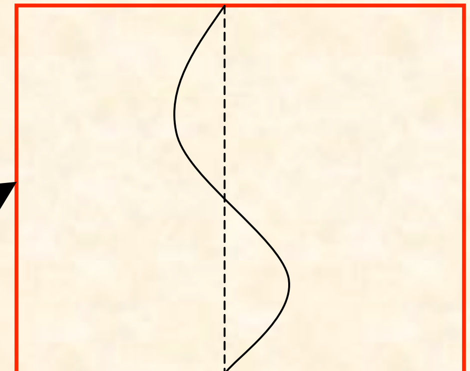
The MRI in accretion disks.

Weakly magnetized Keplerian rotation profiles are subject to local, linear instability.

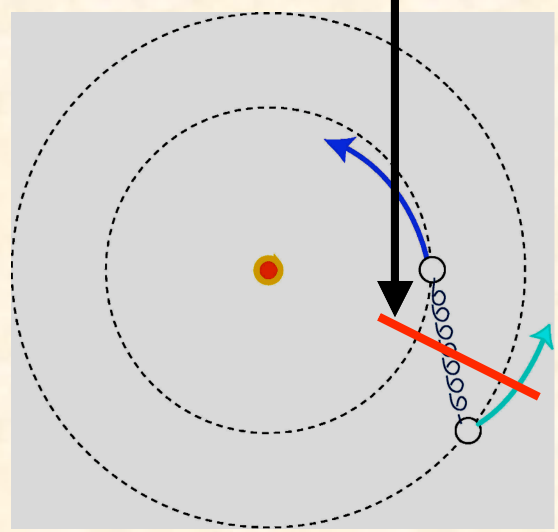
Mechanism:



Radial perturbations to vertical B



Side view
(r-z plane)



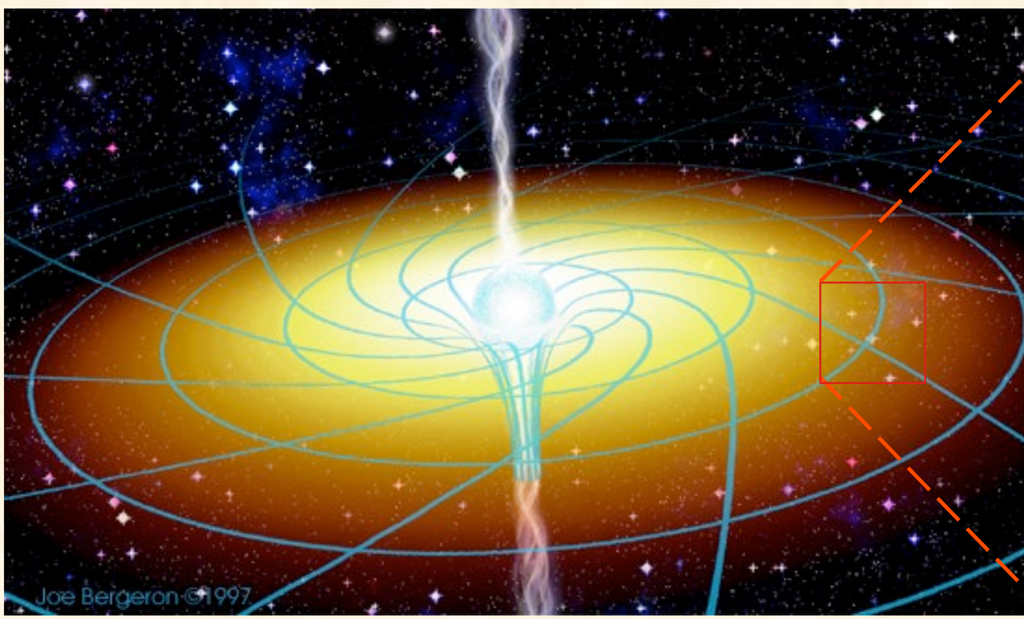
Top view
(r-ϕ plane)

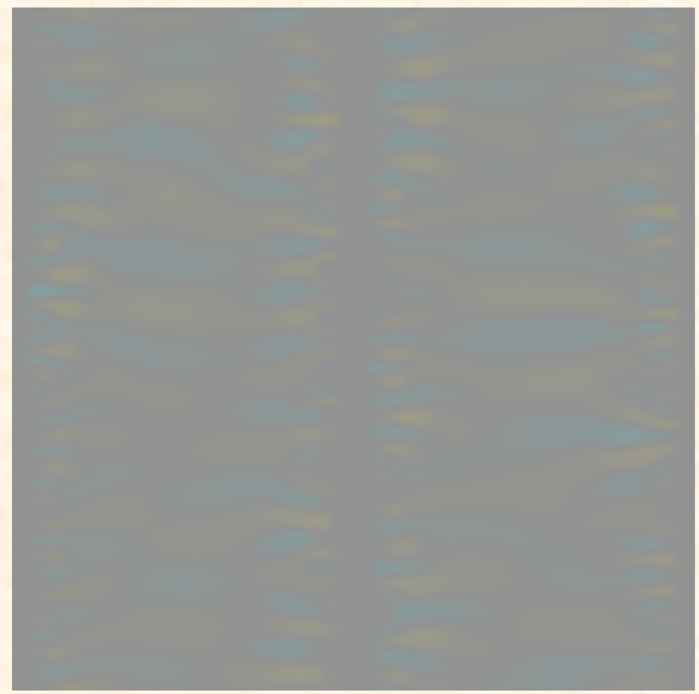
Instability when

$$(\mathbf{k} \cdot \mathbf{V_A}) \leq \sqrt{3}\Omega$$

MRI is *local, linear instability* with very large growth rate.
Use numerical MHD in shearing-box to study saturation.

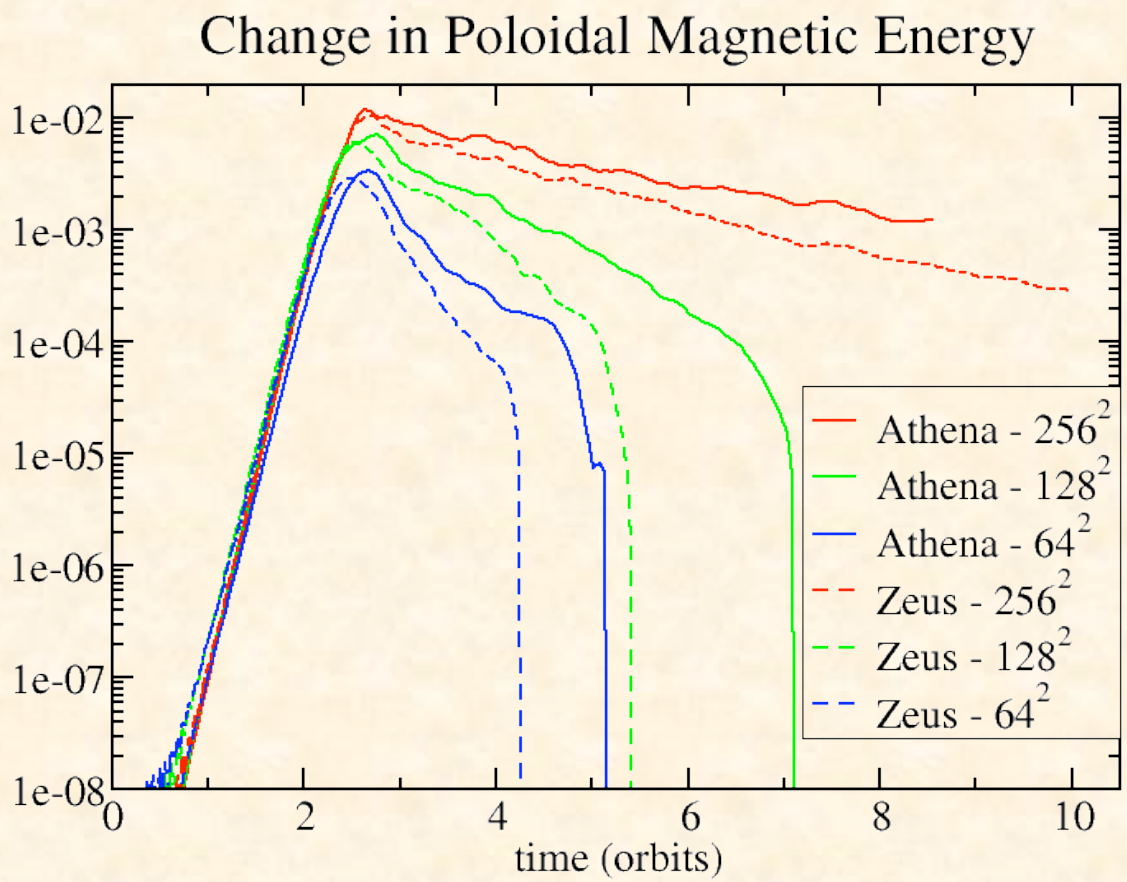
Start from a vertical field with zero net flux: $B_z = B_0 \sin(2\pi x)$
Sustained turbulence not possible in 2D… (anti-dynamo theorem)





Animation of angular velocity fluctuations: $\delta V_\phi = V_\phi - V_{Kep}$

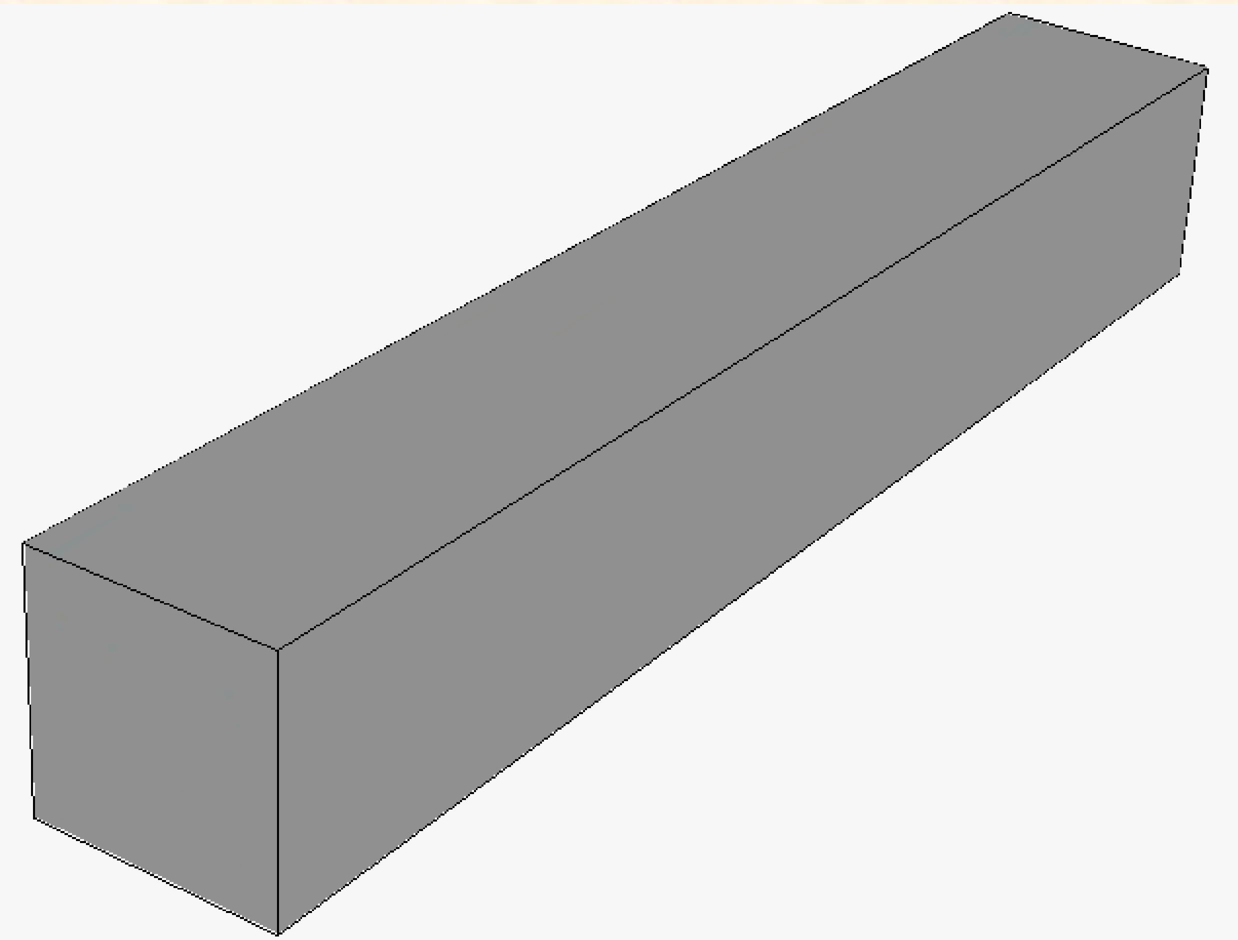
Decay of Magnetic Energy in 2D MRI with no-net-flux is a good code test.



Numerical dissipation is ~1.5 times smaller with Athena compared to ZEUS.

3D MRI

Animation of angular velocity fluctuations: $\delta V_\phi = V_\phi - V_{Kep}$
Initial Field Geometry is Uniform B_y

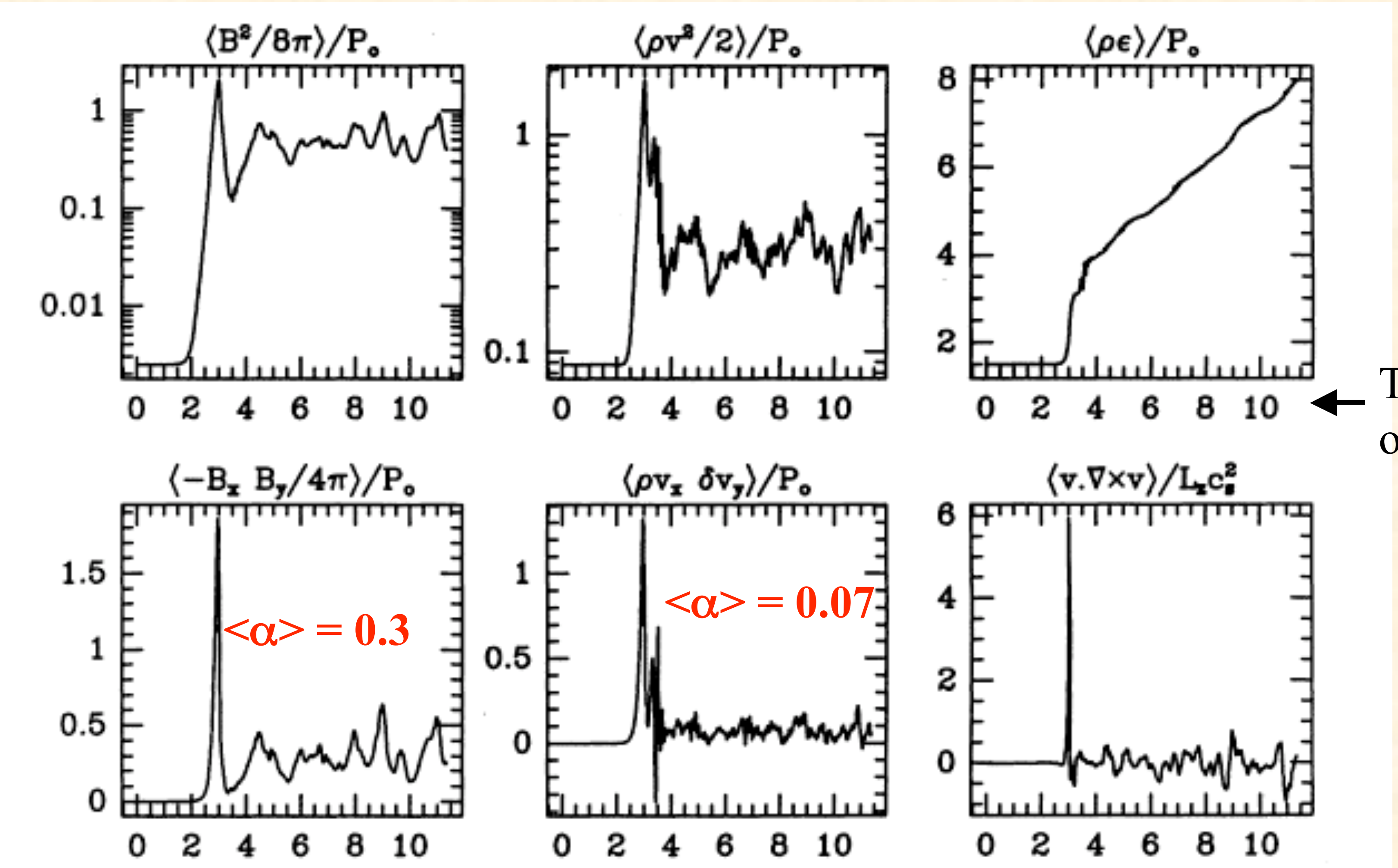


128 x 256 x 128 Grid
β_{min}= 100, orbits 4-20

In 3D, sustained turbulence

Significant angular momentum transport is associated with MHD turbulence driven by the MRI

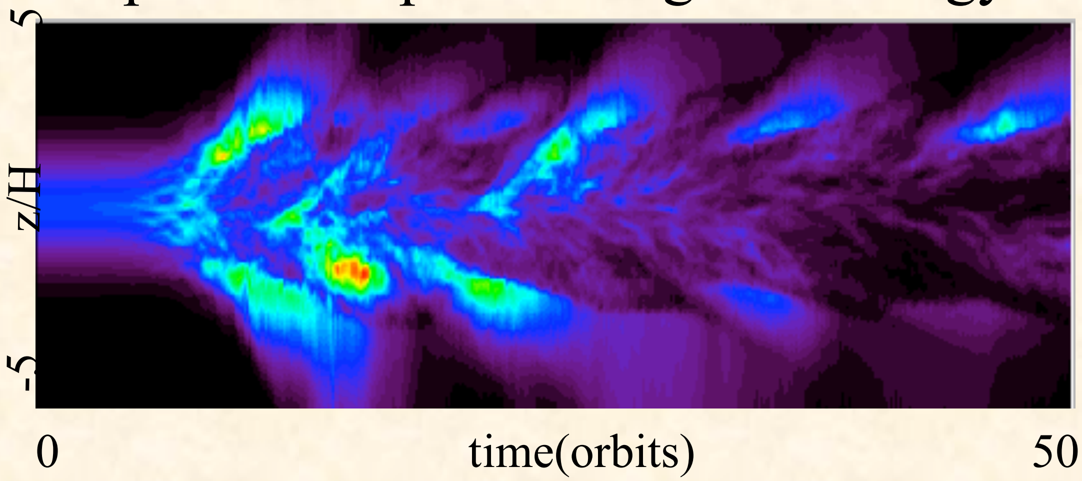
Time-evolution of volume-averaged quantities:



Also note: Sustained amplification of B indicates dynamo action

In vertically stratified disks, MRI generates magnetized corona.

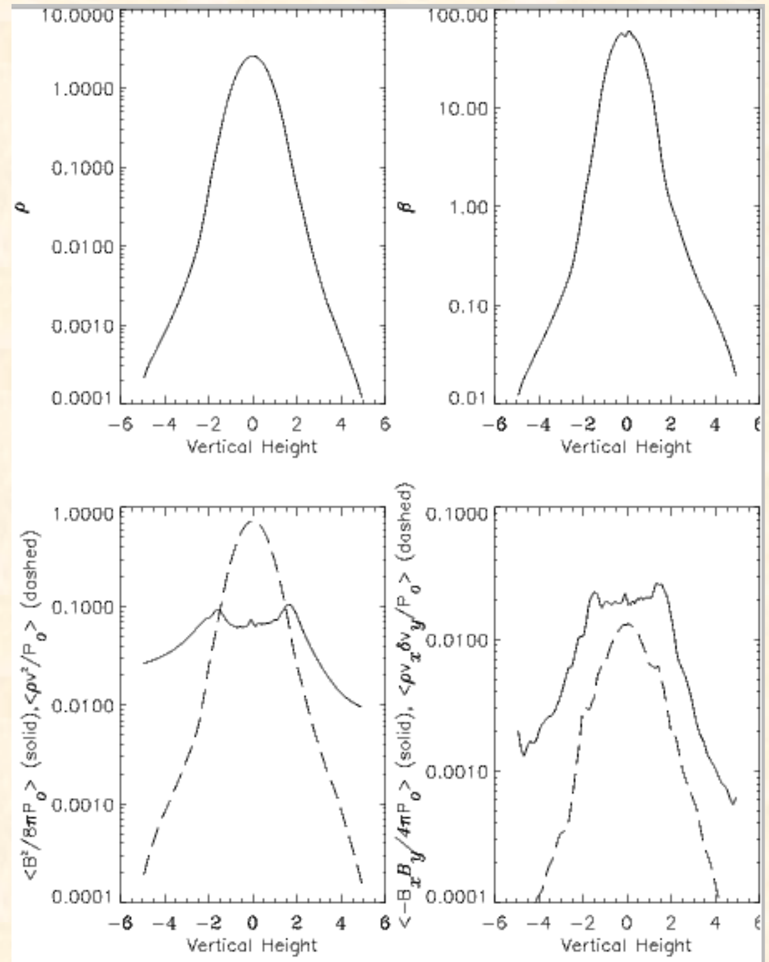
“spacetime” plot of magnetic energy



Clearly shows how buoyant field rises into corona.

$$F(z,t) = \frac{\int\int f(x,y,z,t)\,dx\,dy}{\int\int dx\,dy}.$$

Vertical profiles of t-averaged quantities.



Numerical simulations have established:

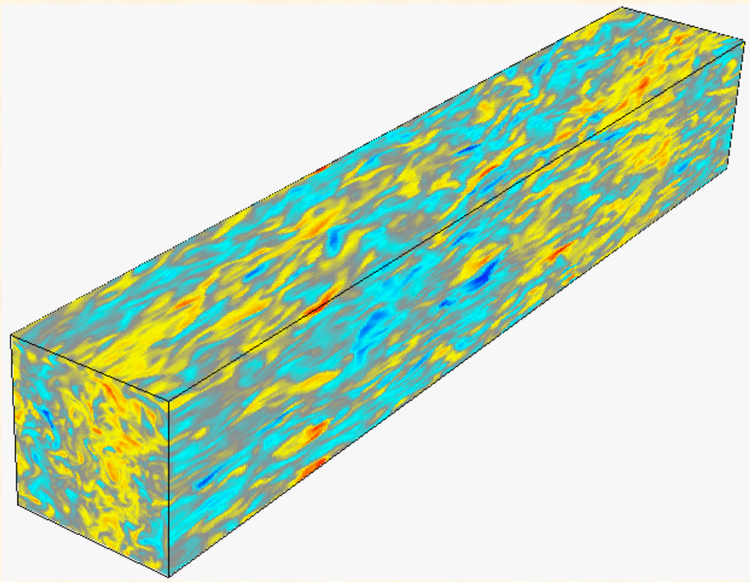
- In 3D MRI saturates as MHD turbulence with significant Maxwell stress.
- Turbulence amplifies field for much longer than the dissipation time => drives MHD dynamo
- Power spectrum is nearly Kolmogorov but anisotropic => most of the energy on largest scales

Directions for future work:

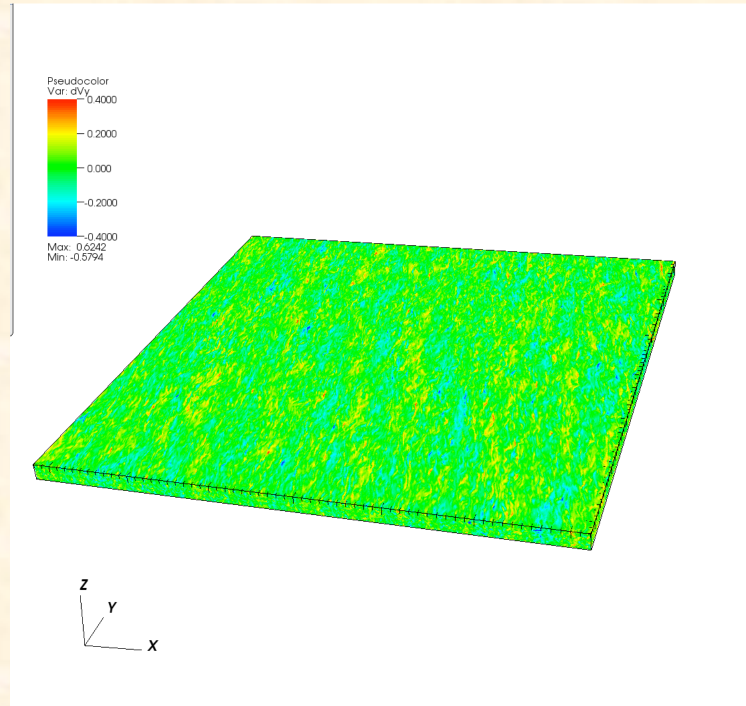
- Effect of increasing radial extent in shearing box.
- Effect of magnetic Prandtl number $P_m = \nu/\eta > 1$
- Effect of anisotropic (Braginskii) viscosity.
- Structure of vertically stratified disks including radiation.
- Global calculations of entire disk including radiative transfer

New studies of MRI: *effect of increasing boxsize.*

Almost all 3D simulations of the MRI to date use very narrow domain in the radial (x) direction.



Thin box: H x 4H x H

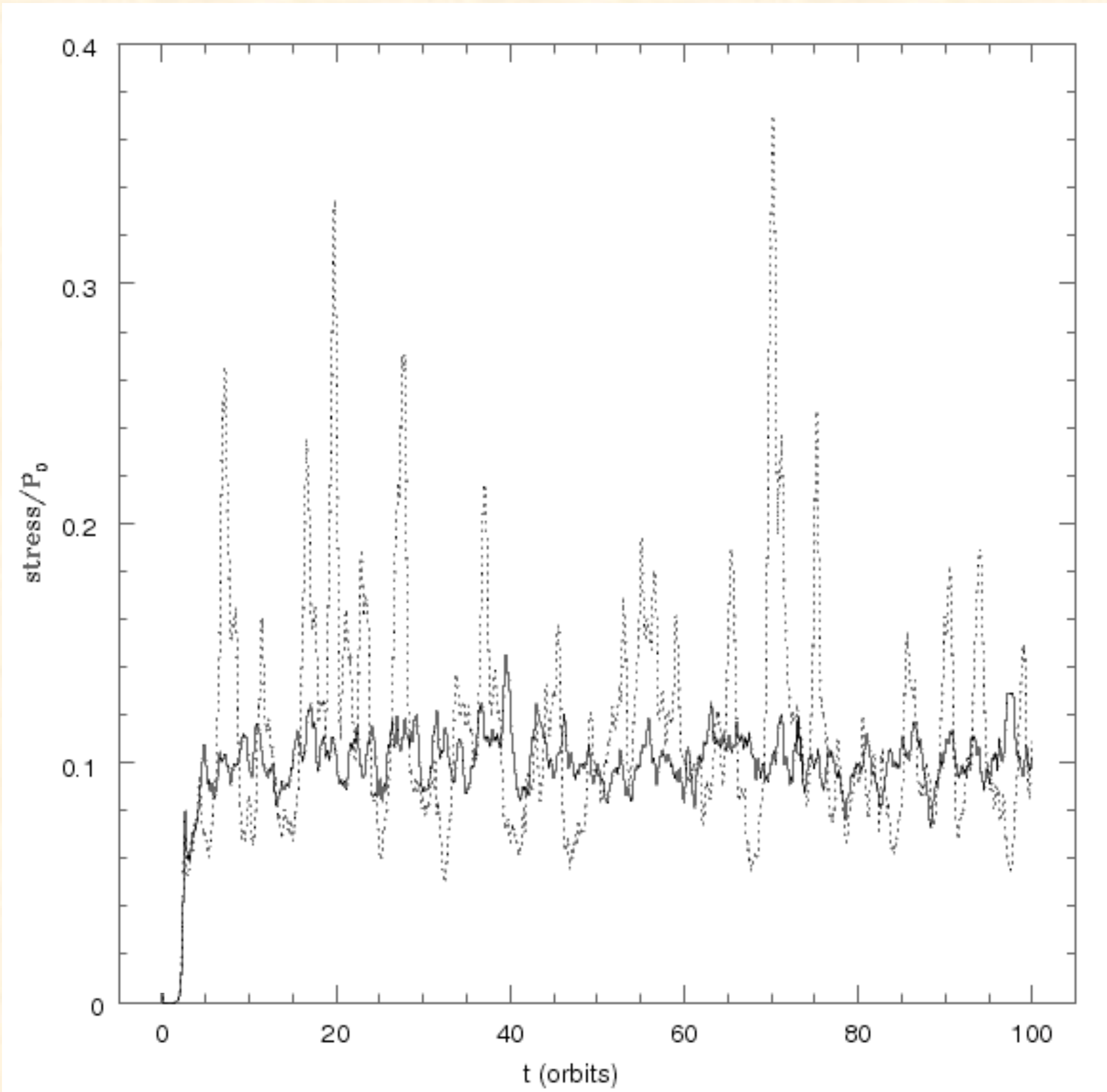


Wide box: 32H x 32H x H

Is the saturation level the same in wide boxes?

(Requires novel algorithms for circumventing CFL condition on orbital velocity.)

Preliminary results: net flux.



$B_z = B_0$
$\beta = 2P_0/B_0^2 = 1600$

Domain size either:
H x 8H x H
or 8H x 8H x H

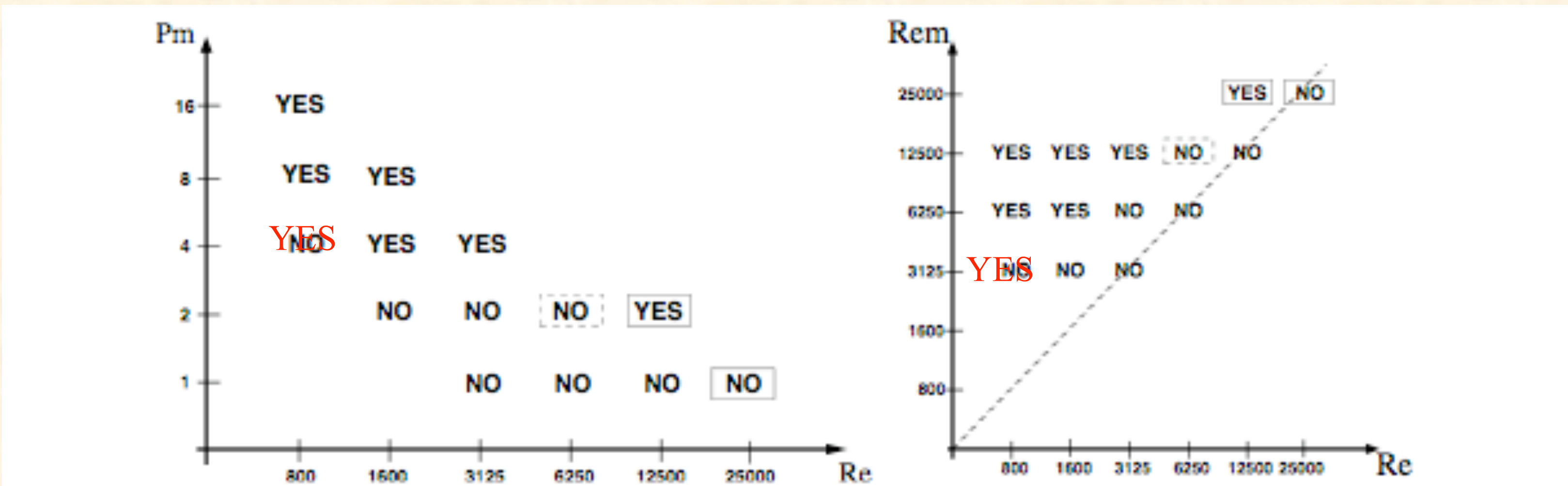
Resolution 64/H

See Bodo et al (2008) for extensive analysis of this problem.

Also talk by A. Mignone.

New studies of MRI: *effect of finite dissipation.*

Fromang et al. (2007) have found that MRI-driven turbulence dies away in the shearing box with no net field at low magnetic Prandtl number Pr = ν/η, and low Reynolds number Re = cH/ν.



YES = sustained turbulence

NO = turbulence eventually dies away… WHY?

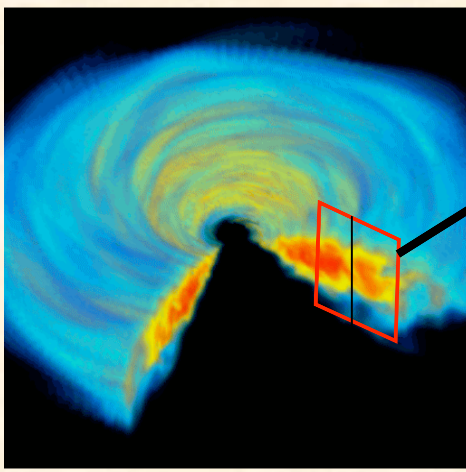
Exact YES/NO boundary seems to depend on boxsize.

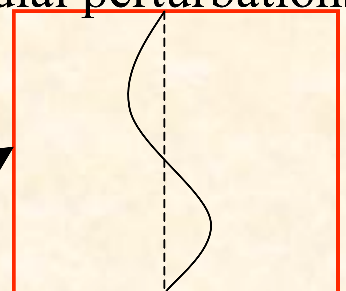
New studies of MRI: *effect of anisotropic viscosity.*

In a weakly colisional plasma, viscous transport is only along magnetic field lines (Braginskii 1964). Relevant to inner regions of AGN disks.

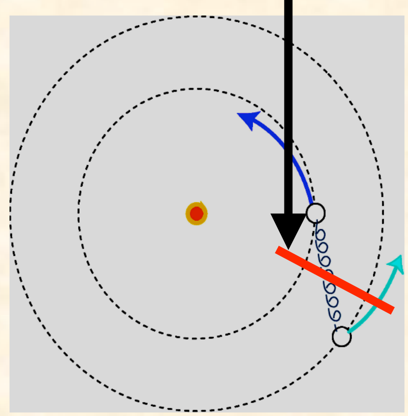
This leads to the magneto-viscous instability in disks (Islam & Balbus 2008). Mechanism is identical to MRI, except viscosity (rather than Maxwell stress) transports angular momentum!

Radial perturbations to vertical B





Side view
(r-z plane)

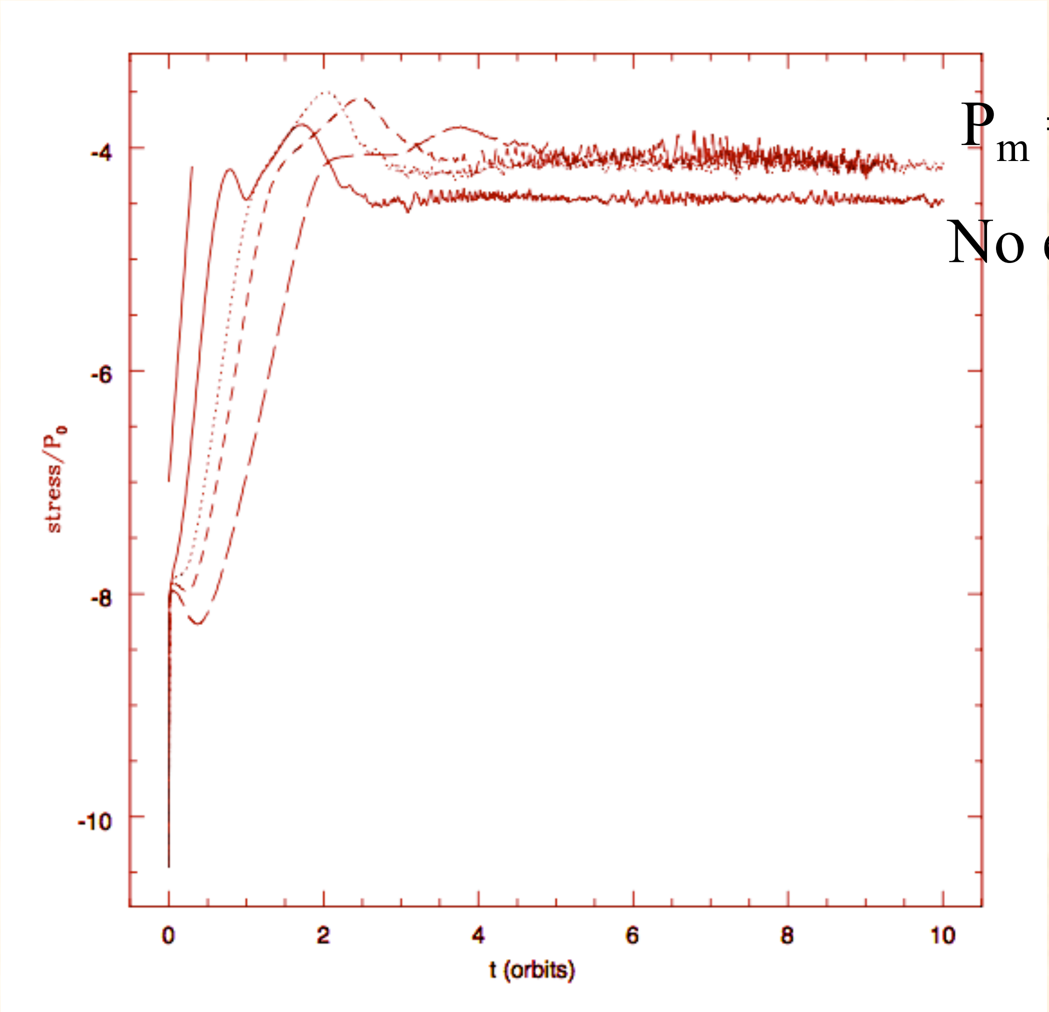


Will the saturation of the MRI be different when the MVI is also present?

Instability when

$$(\mathbf{k} \cdot \mathbf{V_A}) \le \sqrt{3}\Omega$$

Reynolds stress in MVI unstable disk.

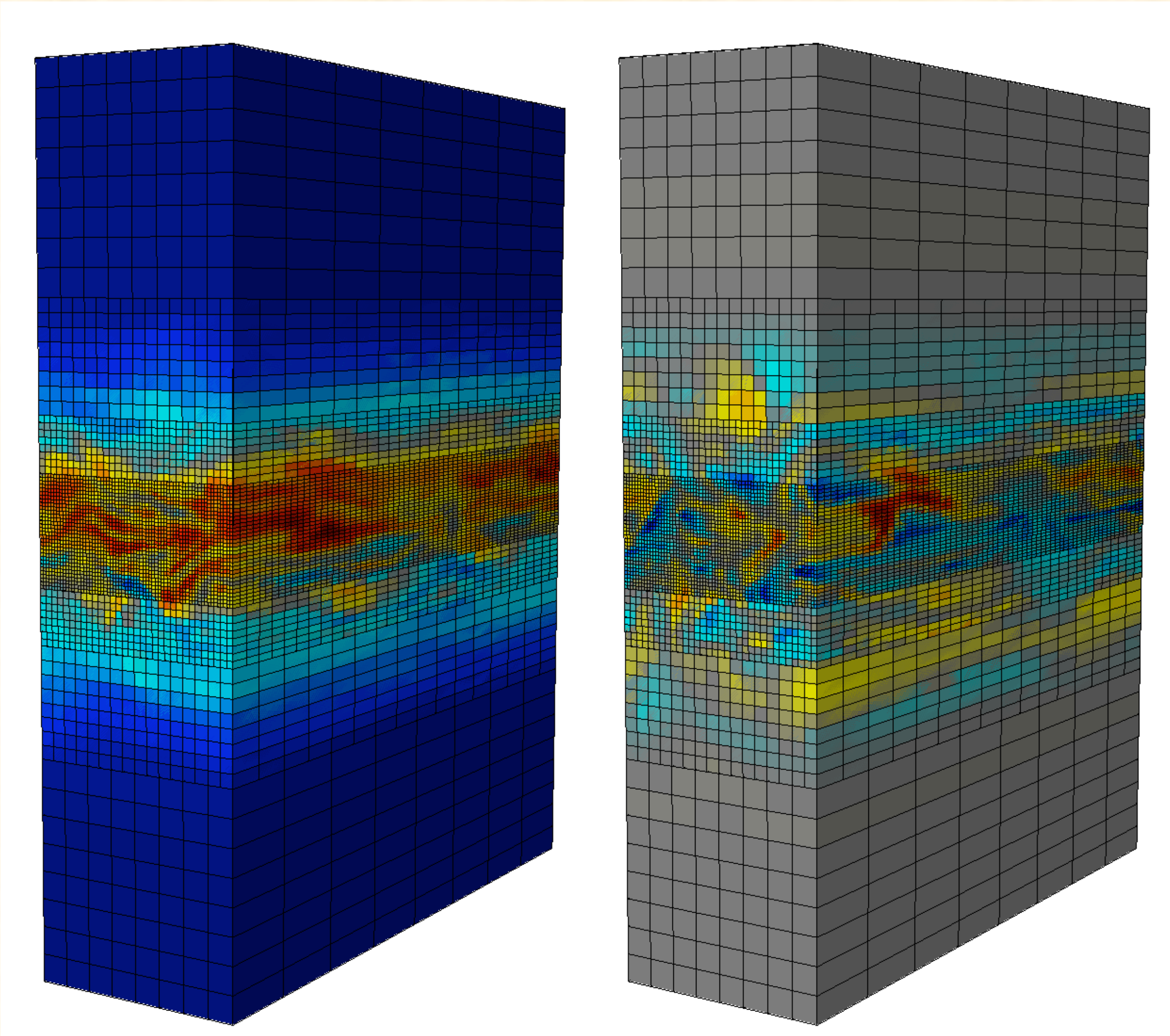


$P_m = \nu/\eta = 2, 5, 10$

No explicit resistivity

Saturation independent of P_m

New studies of MRI: *stratified disks with cooling*.



Density

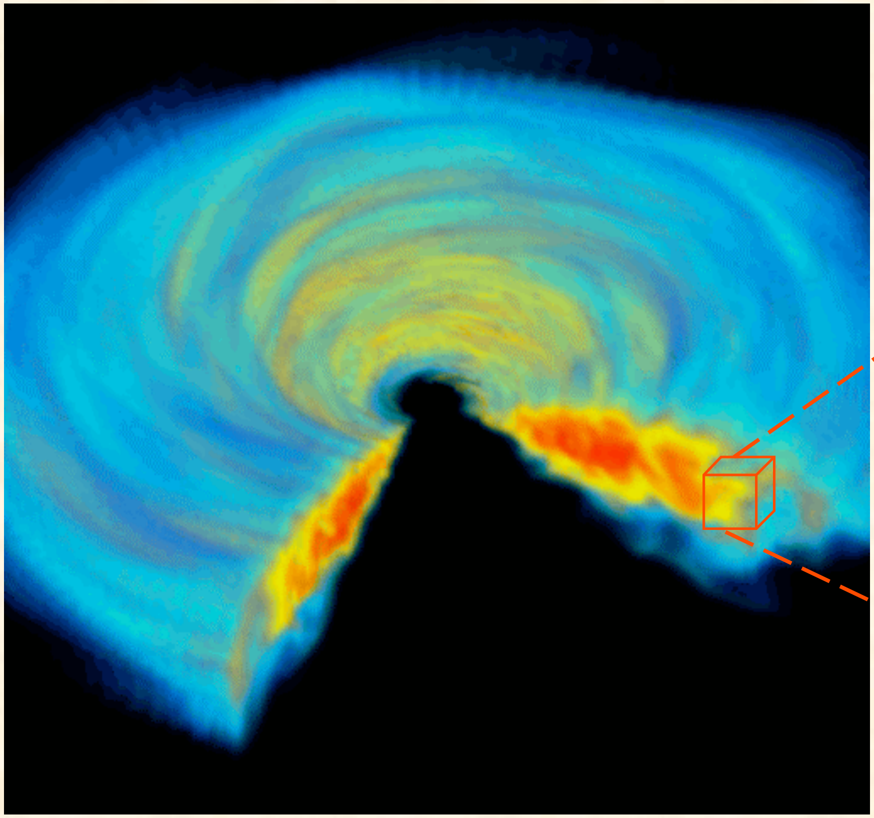
Angular momentum fluctuations

Current simulations of stratified disks use isothermal EOS.

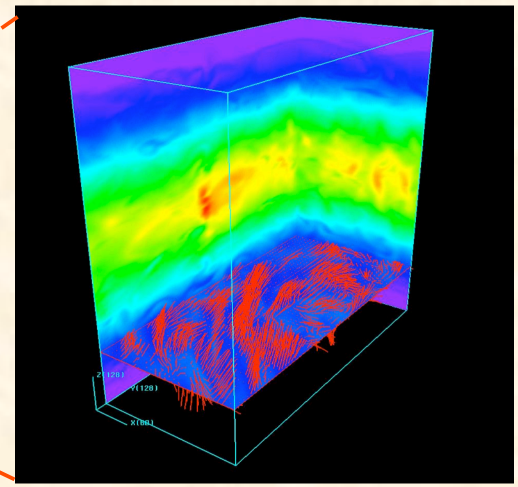
Vertical flux of ME might depend on stratification.

Now using static nested-grids to refine midplane of thin disks *with cooling* in shearing box

From local to global



Global simulation (H/r ~ 1)

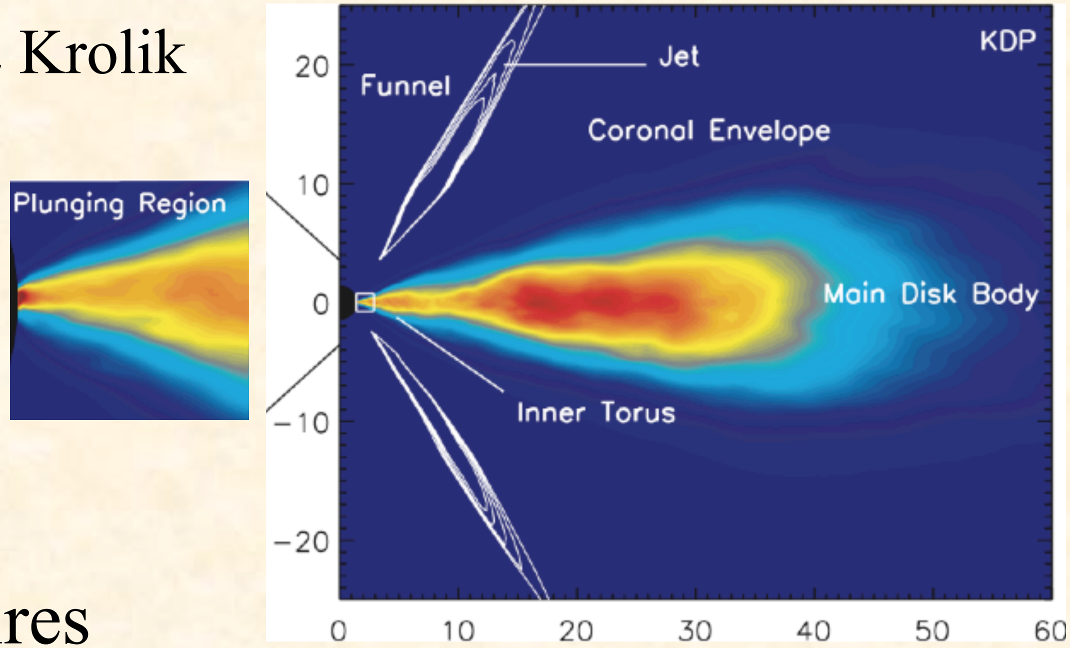


Local simulation

Hawley, Balbus, & Stone 2001; Miller & Stone 1999

Powerful jets are produced in global disk simulations of accretion onto rotating black hole.

de Villiers, Hawley, & Krolik



Jet production requires

- Net vertical field in inner region
- Rotating black hole

Unbound winds are not observed from larger radii

- Perhaps net flux is needed?

New studies of MRI: *weakly ionized protostellar disks.*

Start with generalized Ohm's Law:

$$\boxed{\mathbf{E} = \mathbf{V} \times \mathbf{B} - \frac{4\pi\eta\mathbf{J}}{c} - \frac{\mathbf{J} \times \mathbf{B}}{n_e e} + \frac{(\mathbf{J} \times \mathbf{B}) \times \mathbf{B}}{c\gamma\rho_i\rho}}$$

where $\mathbf{J} = [c/4\pi]\nabla \times \mathbf{B}$

Inductive(I) – Ohmic(O) – Hall(H) +Ambipolar diffusion(A)

For instability (MRI), need:

(O/I) < 1 } (Jin 1996; Sano & Miyama 1999; Sano et al. 1998; Fleming, Stone, & Hawley 2000)

(A/I) < 1 } (Blaes & Balbus 1994; Brandenburg et al 1995; MacLow et al. 1997; Hawley & Stone 1998)

Which terms dominate in a proto-stellar disk?
(Salmeron & Wardle 2007; Wardle 2007)

Must adopt a disk model:

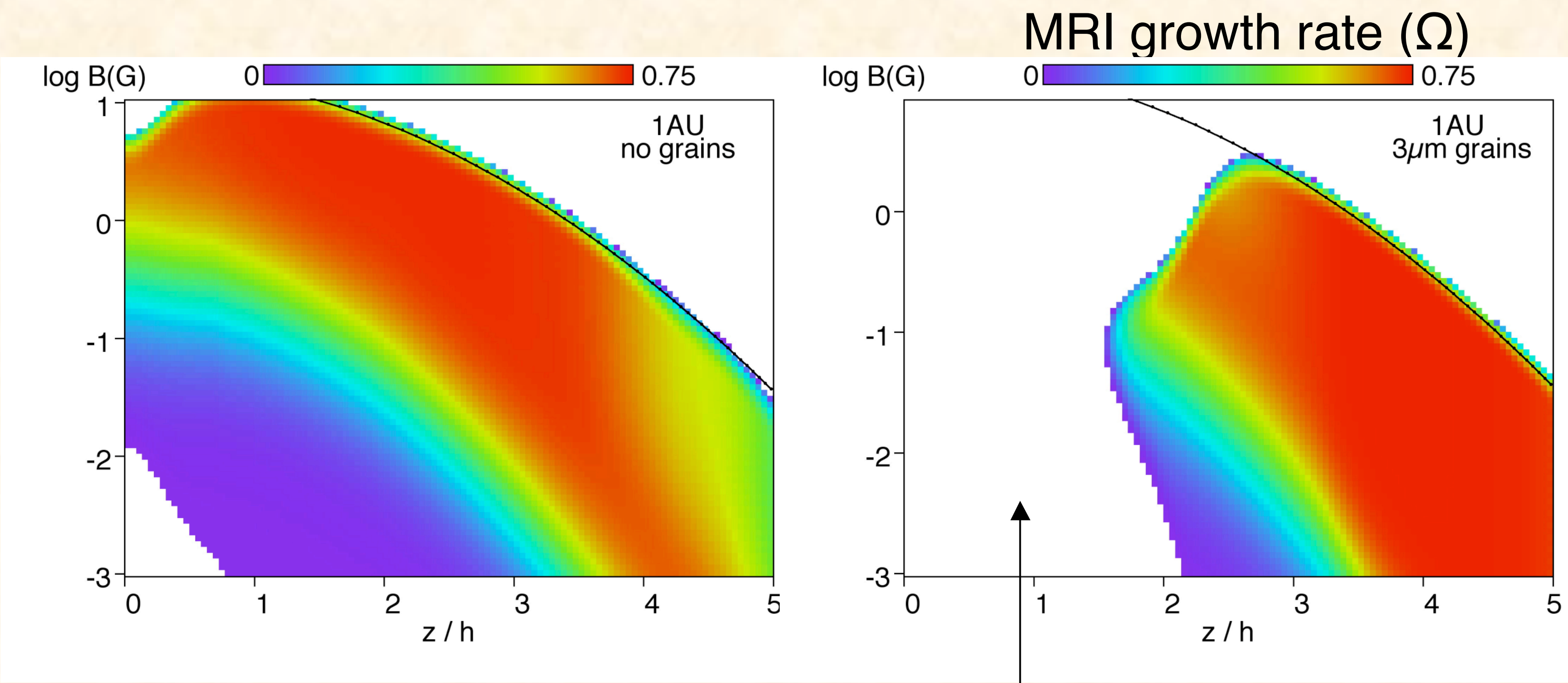
- Minimum-mass solar nebula, $\Sigma = \Sigma_0 \, r^{-3/2}$, with $\Sigma_0 = 1700$ g/cm^2
- Non-thermal source of ionization (e.g. X rays)
- multi-species ion chemistry model including grains.

Find that (e.g., Wardle 2007):

– No grains: coupling can be maintained even at the midplane at 1AU
  - Hall diffusion dominates
  - $\Sigma_{active} \approx 1700$ g cm^{-2}

– Grains increase magnetic diffusion
  - 1 AU: 0.1 μm $\Sigma_{active} \approx 2$ g cm^{-2} *(not zero!)*
    – 3 μm $\Sigma_{active} \approx 80$ g cm^{-2}
  - 5 AU: 1 μm $\Sigma_{active} \approx \Sigma_{total}$

MRI unstable regions of a proto-stellar disk (depends on assumed field strength).



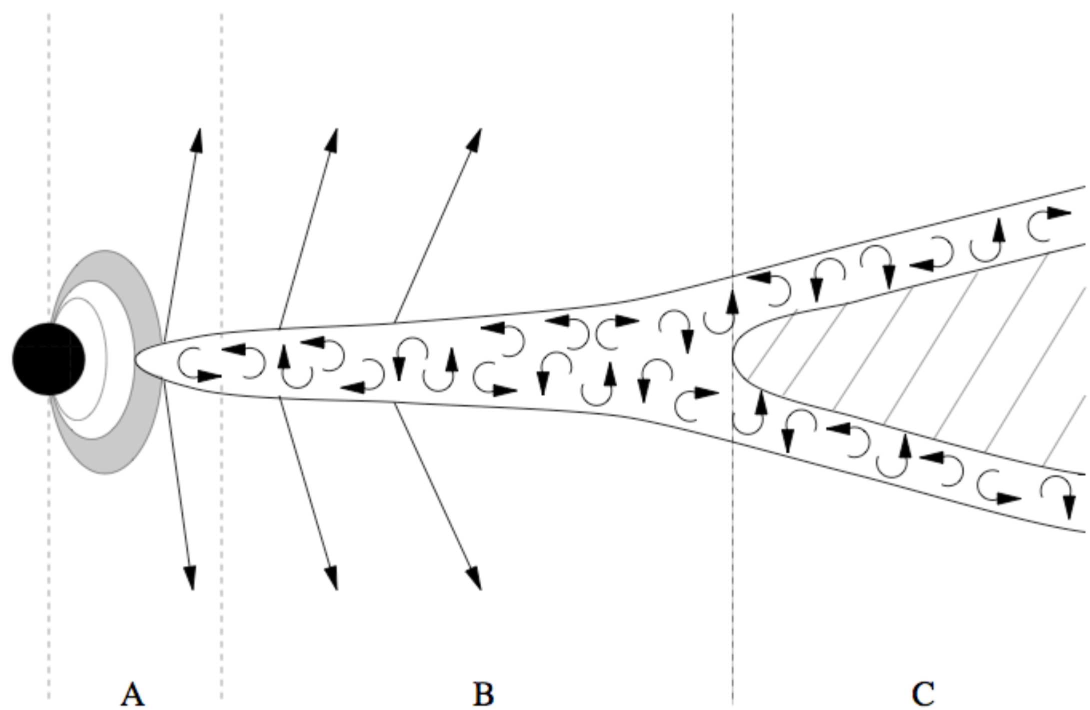
Grains produce a “dead zone”

See poster by R. Salmeron.

Wardle 2007

Leads to a layered structure for proto-planetary disks.

Gammie 1996



Disk-star interaction region

(X-wind?)

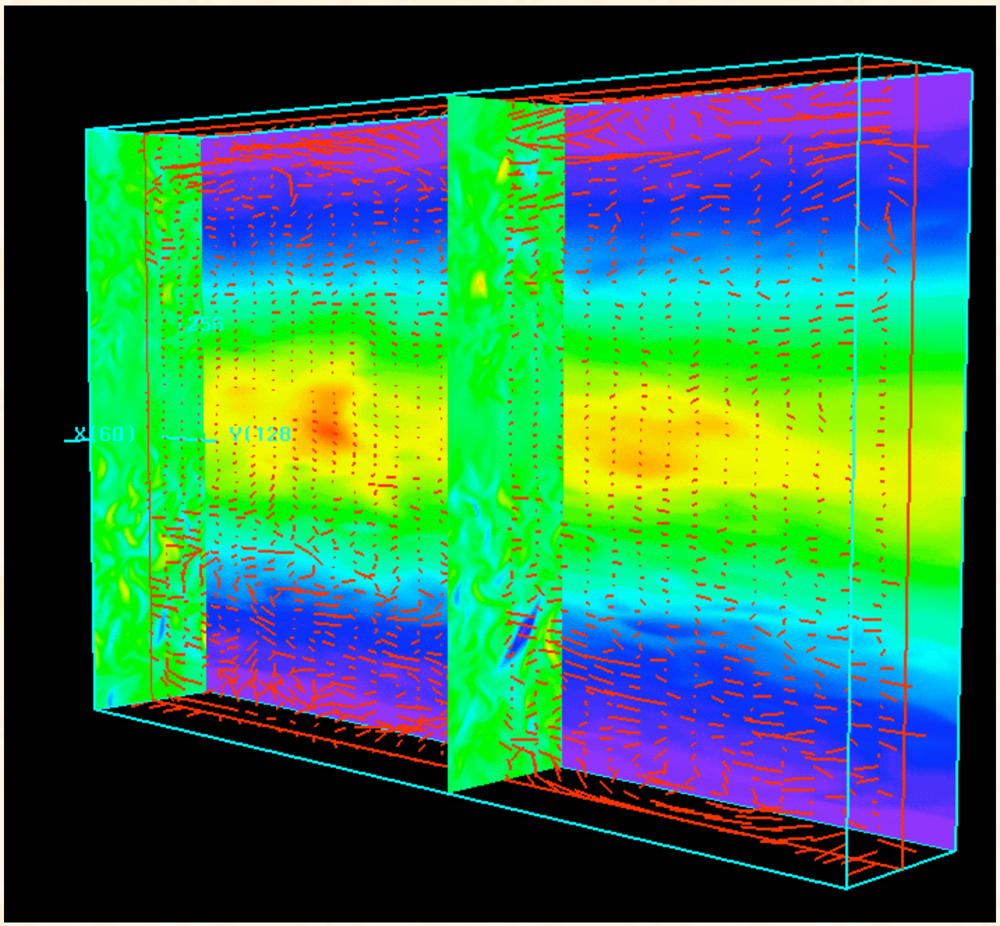
Disk completely turbulent, but Hall MHD (disk wind?)

Layered disk region.

Layered disks

(Gammie 1996; Igea & Glassgold 1998)

• Studied using 3-D simulations of stratified disks with non-uniform resistivity $\eta = \eta(z)$ (Fleming & Stone 2003)



Low η (active layer)

High η (dead zone)

Low η (active layer)

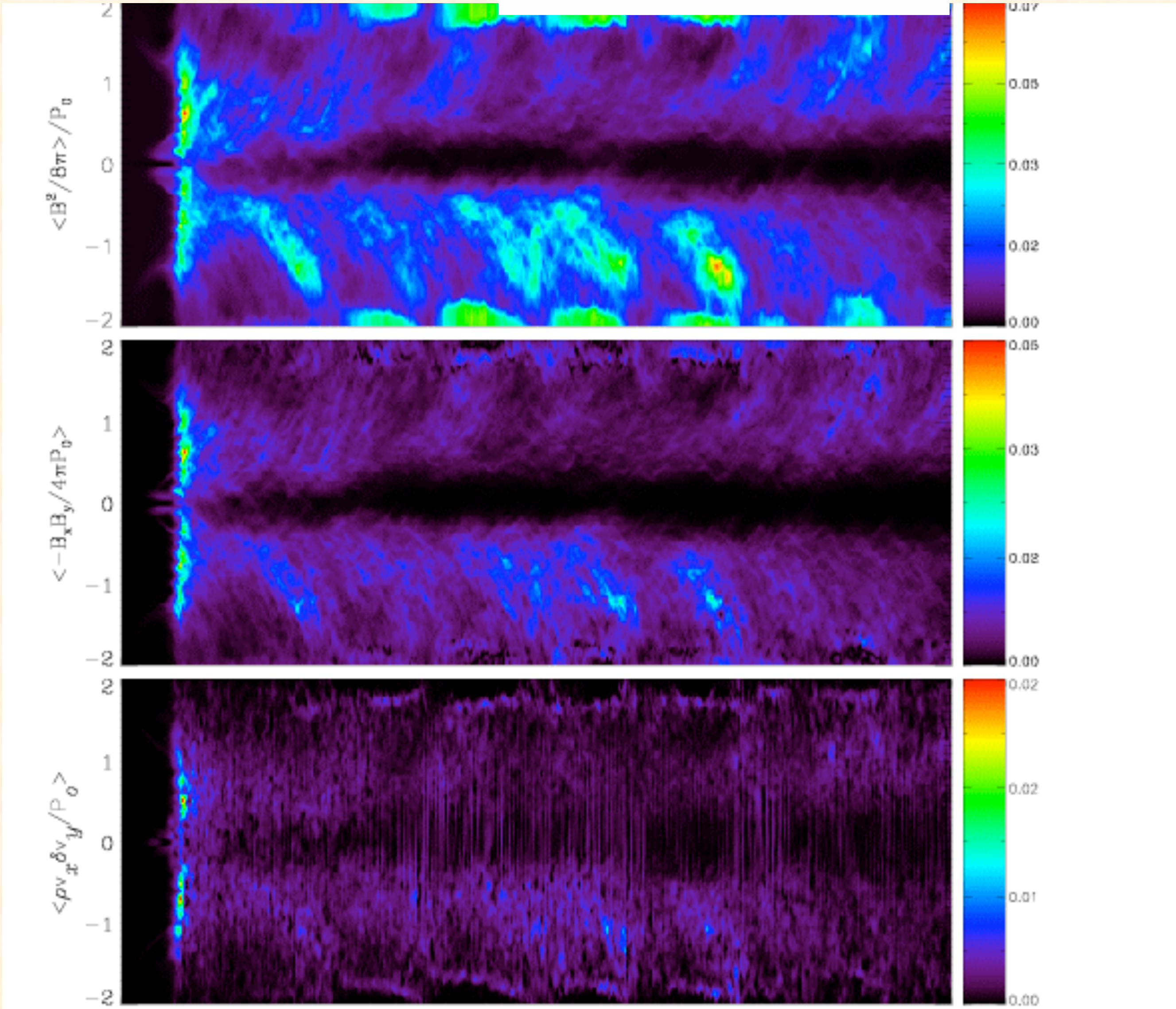
Development of dead zone is evident in *space-time* plots from 3-D simulations (64 x 128 x 256)

$$F(z,t) = \frac{\int\int f(x,y,z,t)\,dx\,dy}{\int\int dx\,dy}.$$

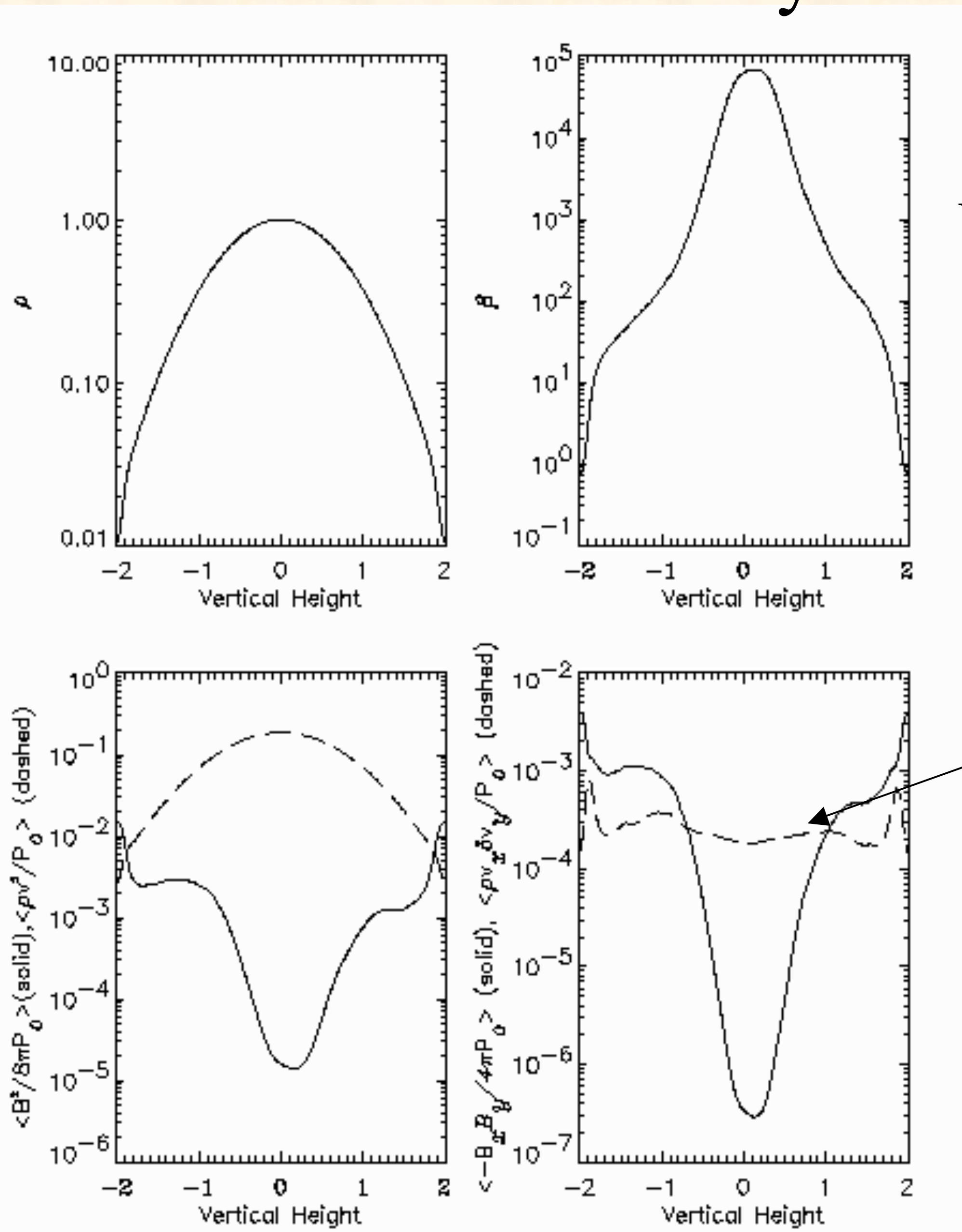
Magnetic pressure

Maxwell stress

Reynolds stress



But dead zone more dynamic than expected:



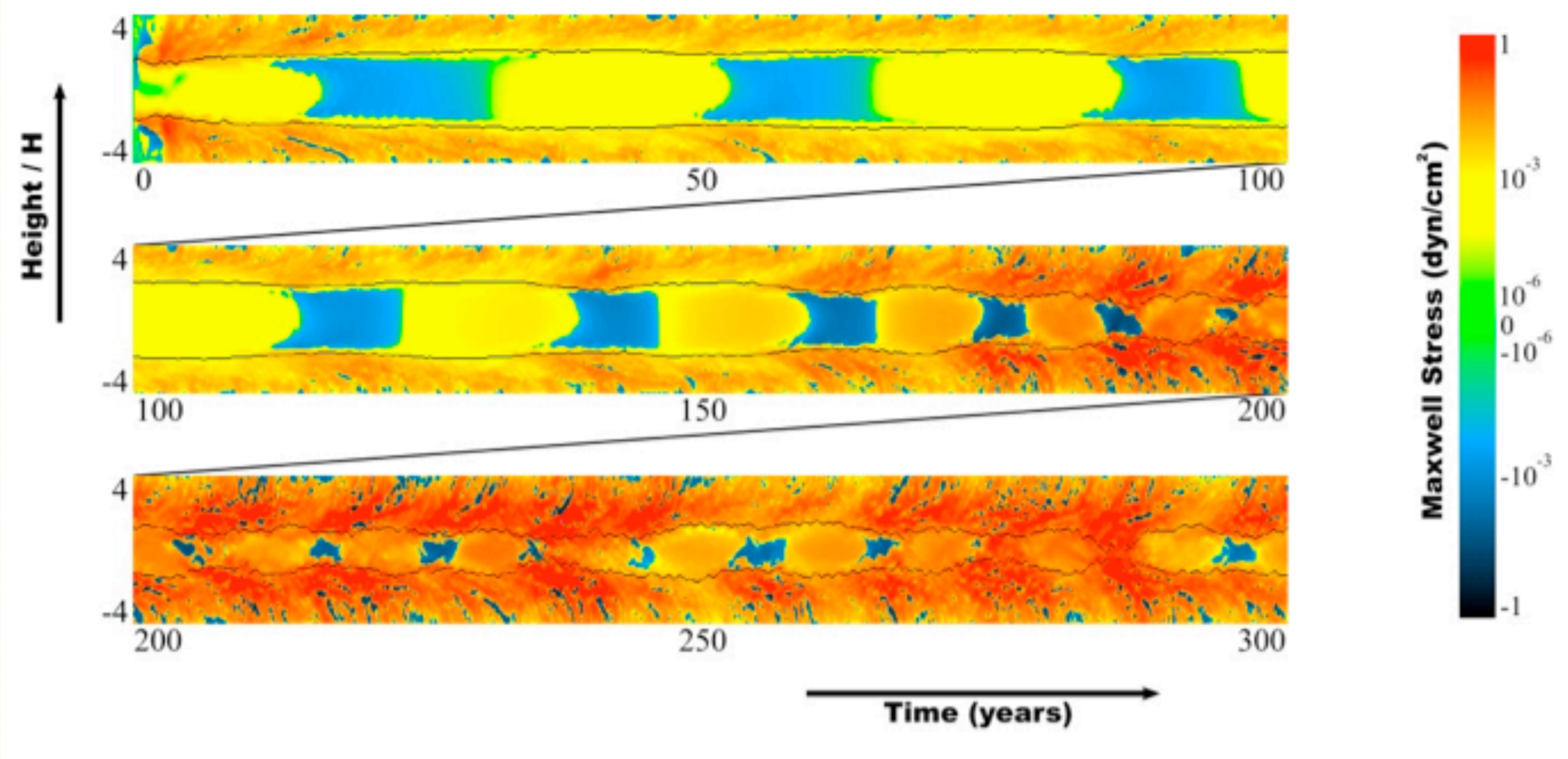
Vertical profiles of time-averaged quantities

Reynolds stress large in dead zone

Associated with density waves driven by turbulence in active layers

More recently, layered disks studied with non-equilibrium ionization recombination.

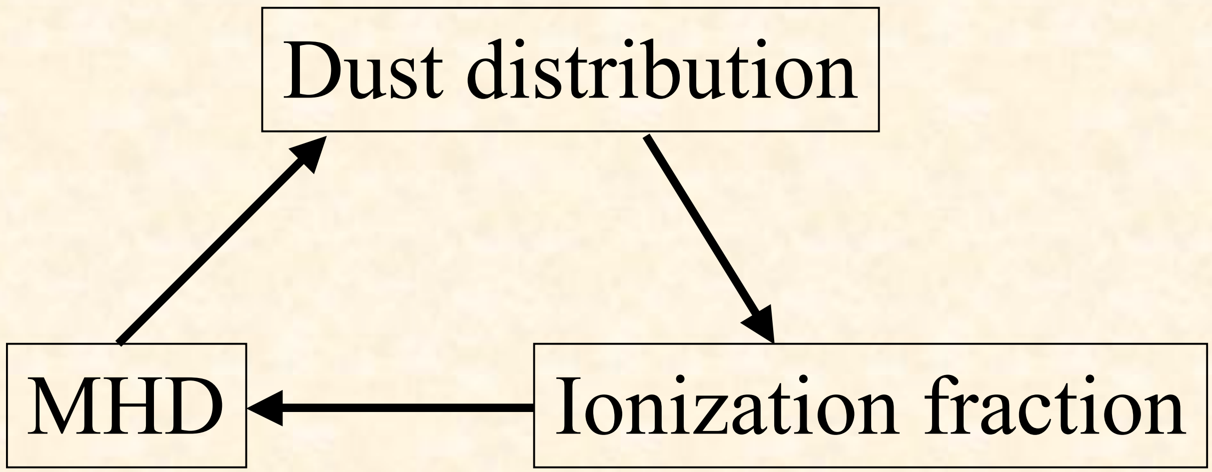
Turner & Sano 2007



Magnetic field diffuses into dead zone.

With nonzero Reynolds and Maxwell stress, it has become an "undead" zone.

The distribution of grains *must* be computed self-consistently with the MHD



Various groups now undertaking studies of the motion of a large number of grains simultaneously with MHD to study:

(1) turbulent mixing and sorting
(2) streaming instabilities
(3) gravitational settling of grains
(4) Feedback of grains on ionization structure

Hydrodynamic turbulence in disks.

- *Long-standing question:* Can hydrodynamic nonlinear shear instabilities produce turbulence?
- Recent work has renewed interest in evolution of vortices in disks, especially transient amplification of leading --> trailing waves

  2D incompressible

  Umurhan & Regev 2004; Yecko 2004;
  Mukhopadhyay/Afshordi/Narayan 2005

  2D compressible

  Johnson & Gammie 2005

  3D anelastic in stratified disks

  Barranco & Marcus 2005

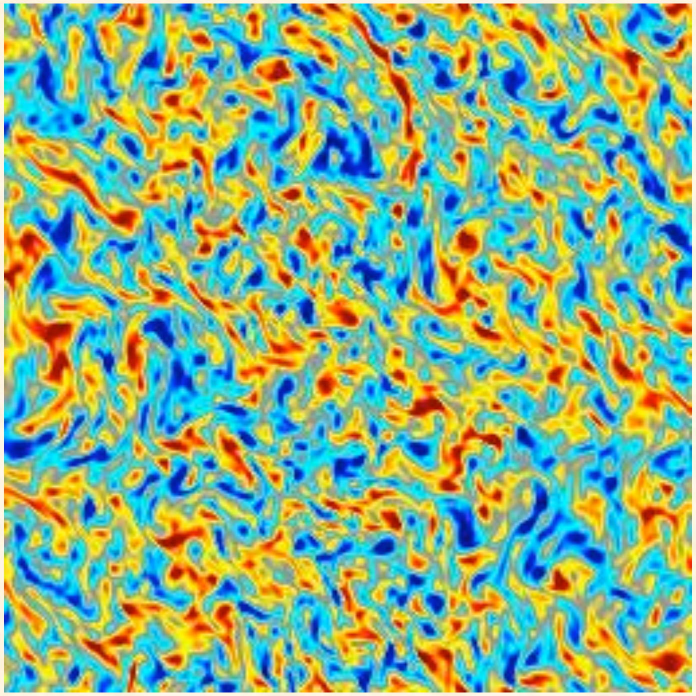
Study evolution of vortices in 3D compressible disks at the highest resolutions possible.

Comparison of evolution in 2D and 3D

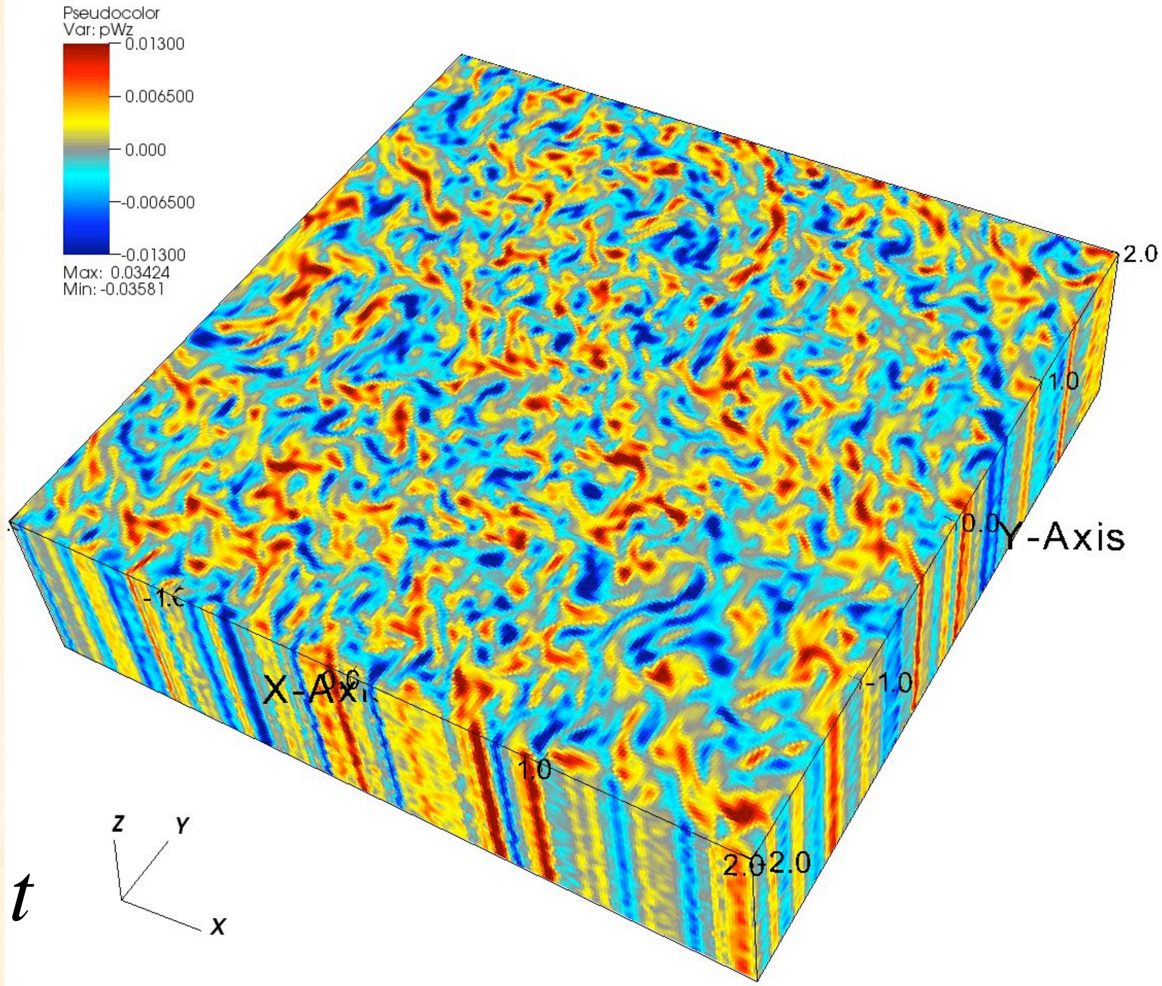
Initial vorticity distribution identical in 2D and 3D

Random V_z added in 3D

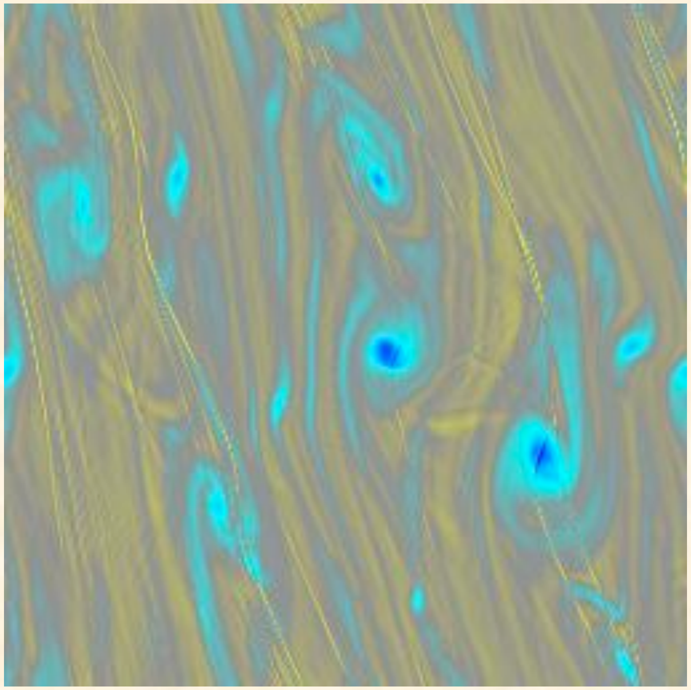
2D grid: 256^2 (4Hx4H) 3D grid: 256^2x64 (4Hx4Hx1H)

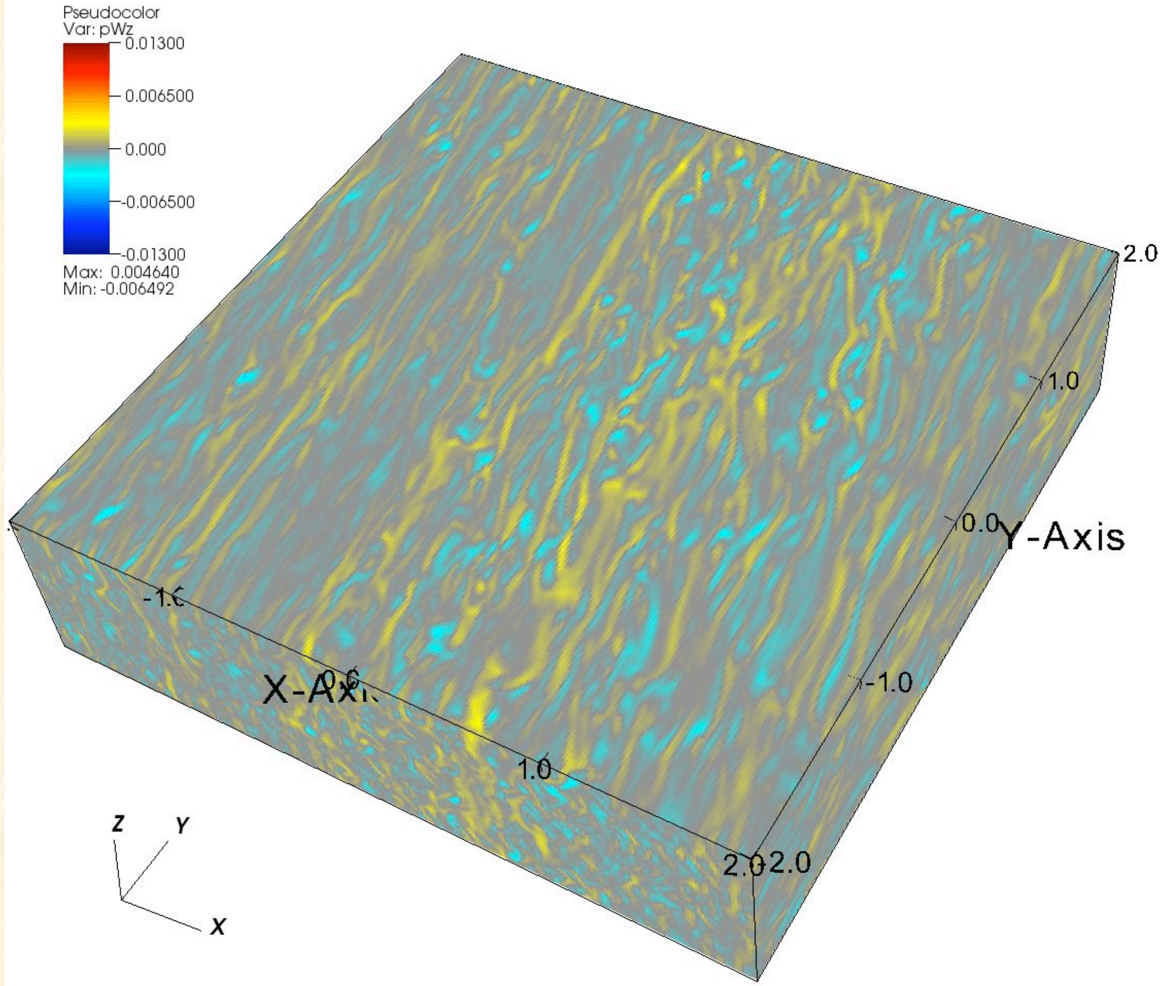


2D simulation



$$T = 0.5\Omega\, t$$



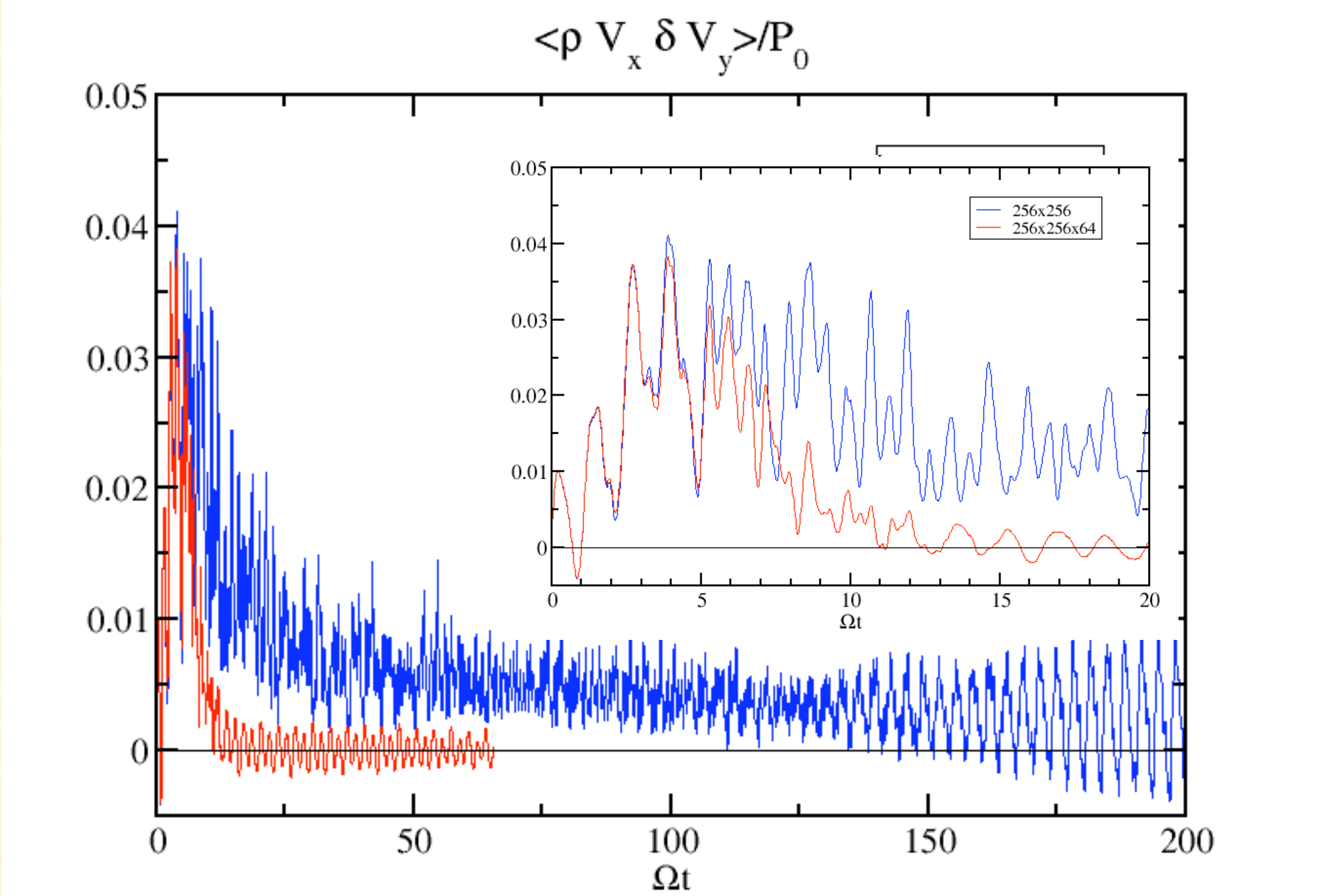


$$\mathrm{T} = 20\,\Omega\, t$$

In 2D, long-lived vortices emerge

In 3D, vorticity and turbulence decays much more rapidly

Evolution of Stress: 2D versus 3D



In 3D, KE and stress decays much more rapidly.

Stress at late times dominated by largest vortices.

NB: Ji et al (2006) report no hydrodynamic instability for Re ~ 10^6 in recent experiments of Cuoette flow

Conclusions

I. The time-dependent MHD of protostellar disks is complex and still being understood.

II. Powerful jets are observed in global simulations of MRI-unstable accretion onto rotating black holes.

III. Why aren't powerful winds produced in global simulations of MRI unstable disks? Need net vertical flux? Better thermodynamics? Non-ideal MHD?

Global simulations of an *MRI unstable* thin disk, including interaction with central star, are warranted.