PLASMA PHENOMENA IN HIGH-ENERGY ASTROPHYSICS

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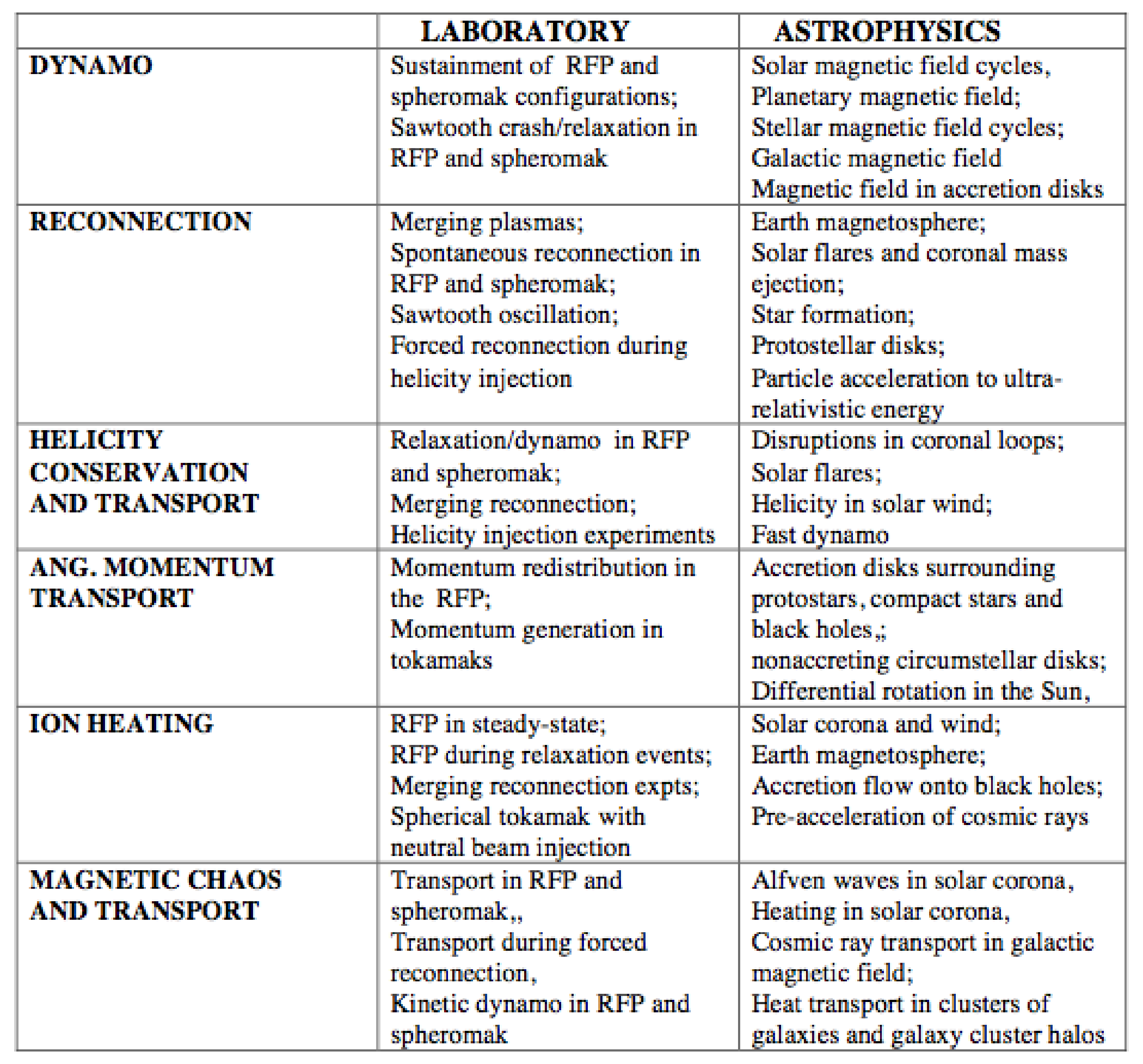
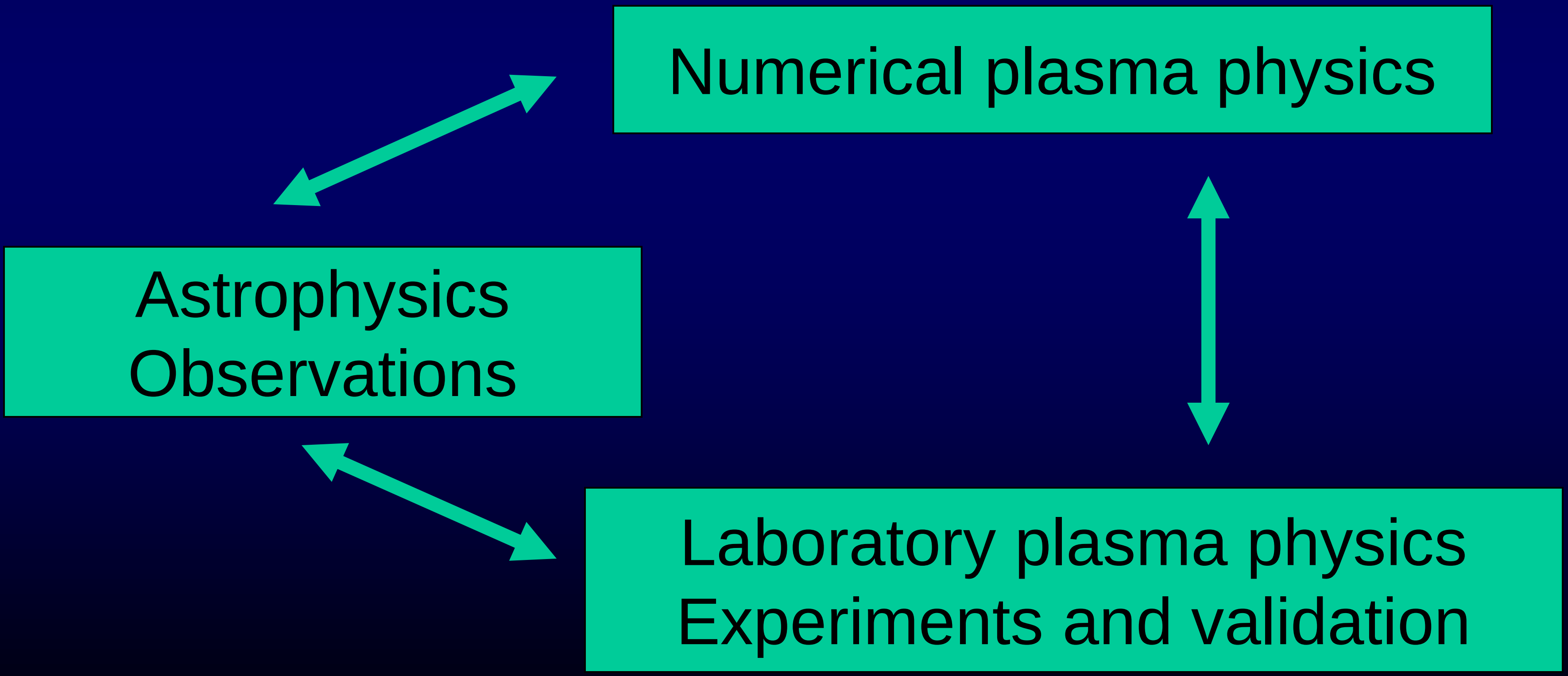
Plasma processes of astrophysical relevance



	LABORATORY	**ASTROPHYSICS**
DYNAMO	Sustainment of RFP and spheromak configurations; Sawtooth crash/relaxation in RFP and spheromak	Solar magnetic field cycles, Planetary magnetic field; Stellar magnetic field cycles; Galactic magnetic field Magnetic field in accretion disks
RECONNECTION	Merging plasmas; Spontaneous reconnection in RFP and spheromak; Sawtooth oscillation; Forced reconnection during helicity injection	Earth magnetosphere; Solar flares and coronal mass ejection; Star formation; Protostellar disks; Particle acceleration to ultra-relativistic energy
HELICITY CONSERVATION AND TRANSPORT	Relaxation/dynamo in RFP and spheromak; Merging reconnection; Helicity injection experiments	Disruptions in coronal loops; Solar flares; Helicity in solar wind; Fast dynamo
ANG. MOMENTUM TRANSPORT	Momentum redistribution in the RFP; Momentum generation in tokamaks	Accretion disks surrounding protostars, compact stars and black holes,; nonaccreting circumstellar disks; Differential rotation in the Sun,
ION HEATING	RFP in steady-state; RFP during relaxation events; Merging reconnection expts; Spherical tokamak with neutral beam injection	Solar corona and wind; Earth magnetosphere; Accretion flow onto black holes; Pre-acceleration of cosmic rays
MAGNETIC CHAOS AND TRANSPORT	Transport in RFP and spheromak,, Transport during forced reconnection, Kinetic dynamo in RFP and spheromak	Alfven waves in solar corona, Heating in solar corona, Cosmic ray transport in galactic magnetic field; Heat transport in clusters of galaxies and galaxy cluster halos

Highly nonlinear (relativistic) physics
Huge extension of physical parameters
Scalability ?

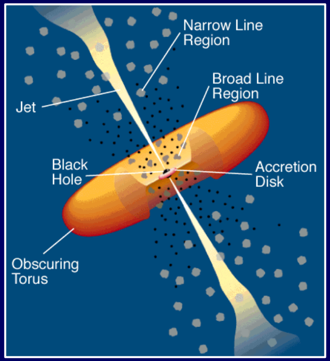


Numerical plasma physics

Astrophysics
Observations

Laboratory plasma physics
Experiments and validation

A TEST CASE
SUPERSONIC, RELATIVISTIC, COLLIMATED PLASMA JETS FROM ACCRETION DISCS



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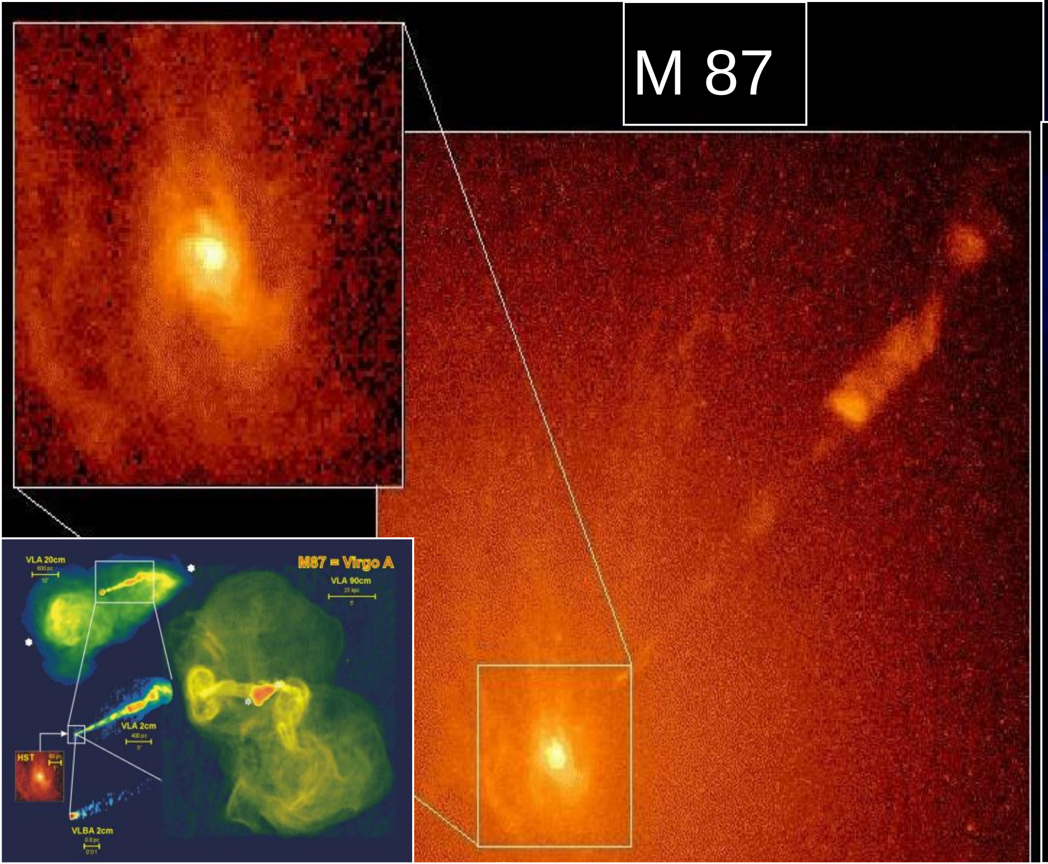
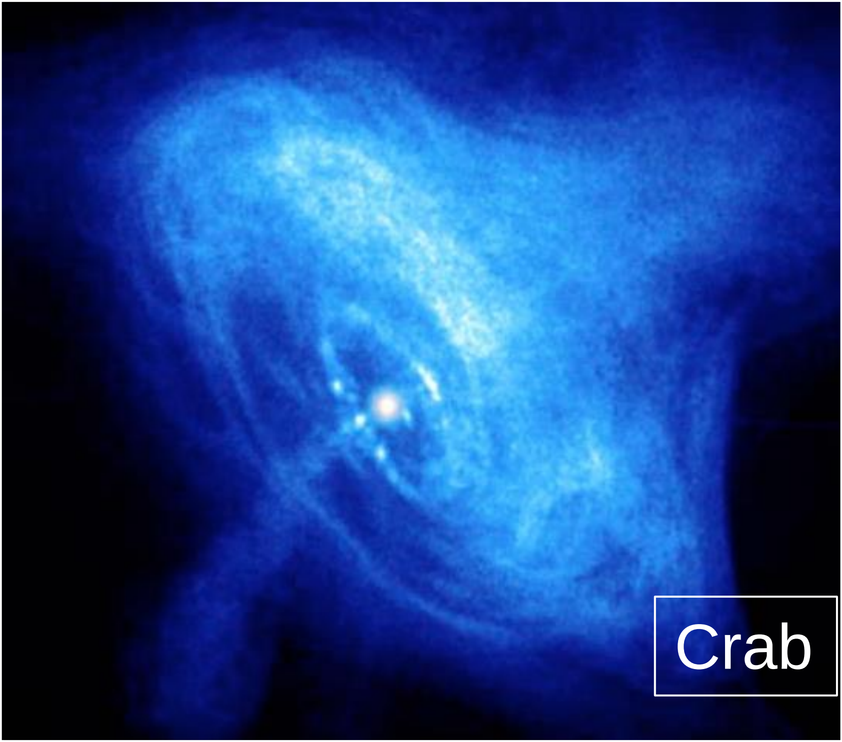
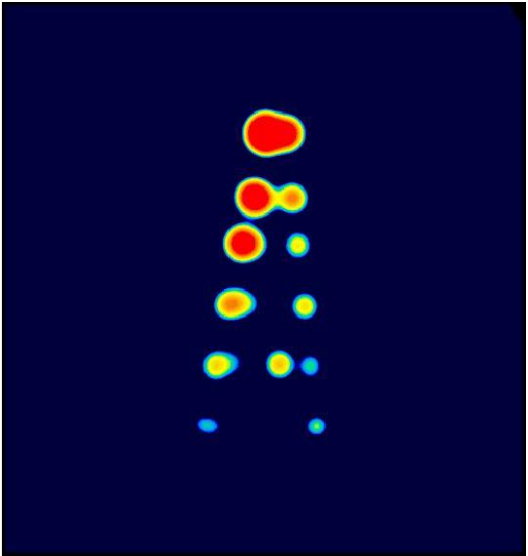
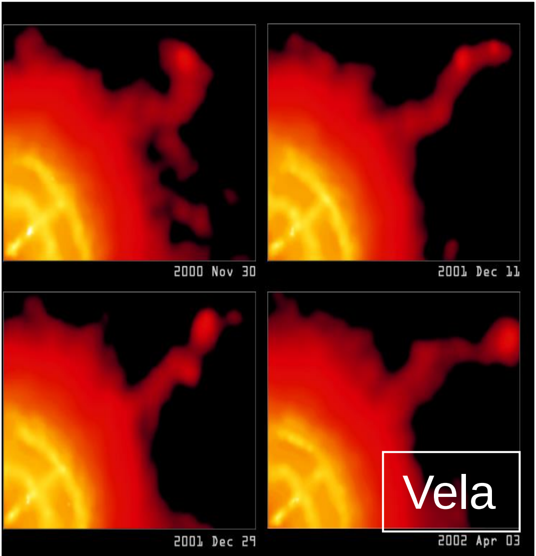
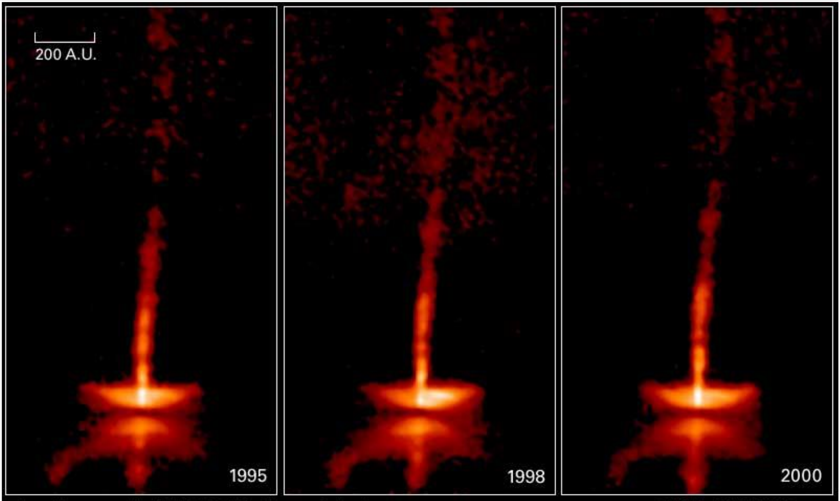
Discs and jets











The Dynamic HH 30 Disk and Jet

HST • WFPC2

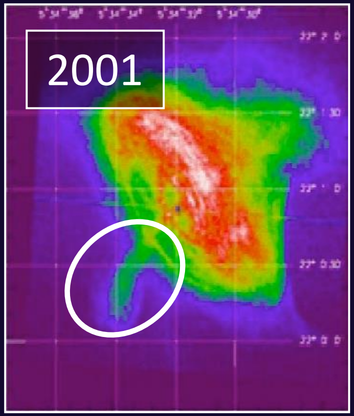
NASA and A. Watson (Instituto de Astronomía, UNAM, Mexico) • STScI-PRC00-32b

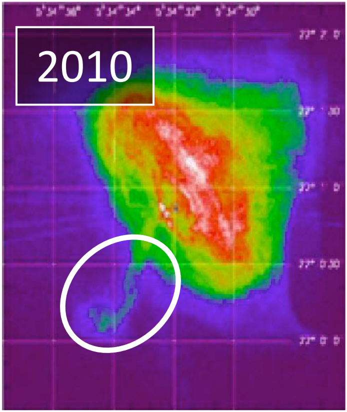
Jets and VHE Sources Variabilities

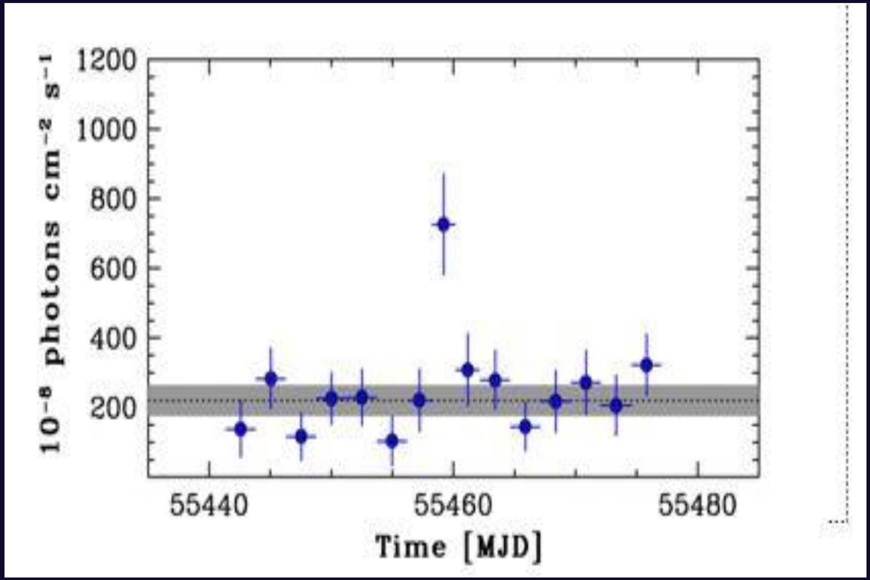
- VHE (gamma-ray) emission from blazars and rapid variabilities correlated with X rays and radio emission
    - Mkn 421 (Donnarumma et al. 2009)
    - M87 (Acciari et al. 2009)
- Doppler boosting in relativistic jets
- Jets with relativistic spine and slower sheath layer:
    - Spine produces synchrotron optical and X-ray photons, that are boosted to GeV and TeV gamma rays by inverse Compton in the sheath (e.g. Tavecchio & Ghisellini 2008)
    - Radio emission from extended (expanding) cocoon

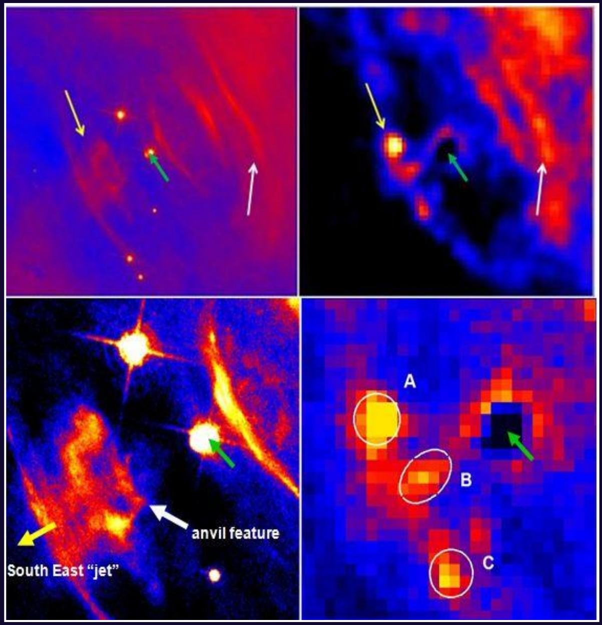
Jet Wiggling & Gamma Flares

- SE jet morphology is “S” shaped and show remarkable time variability (Weisskopf 2013)





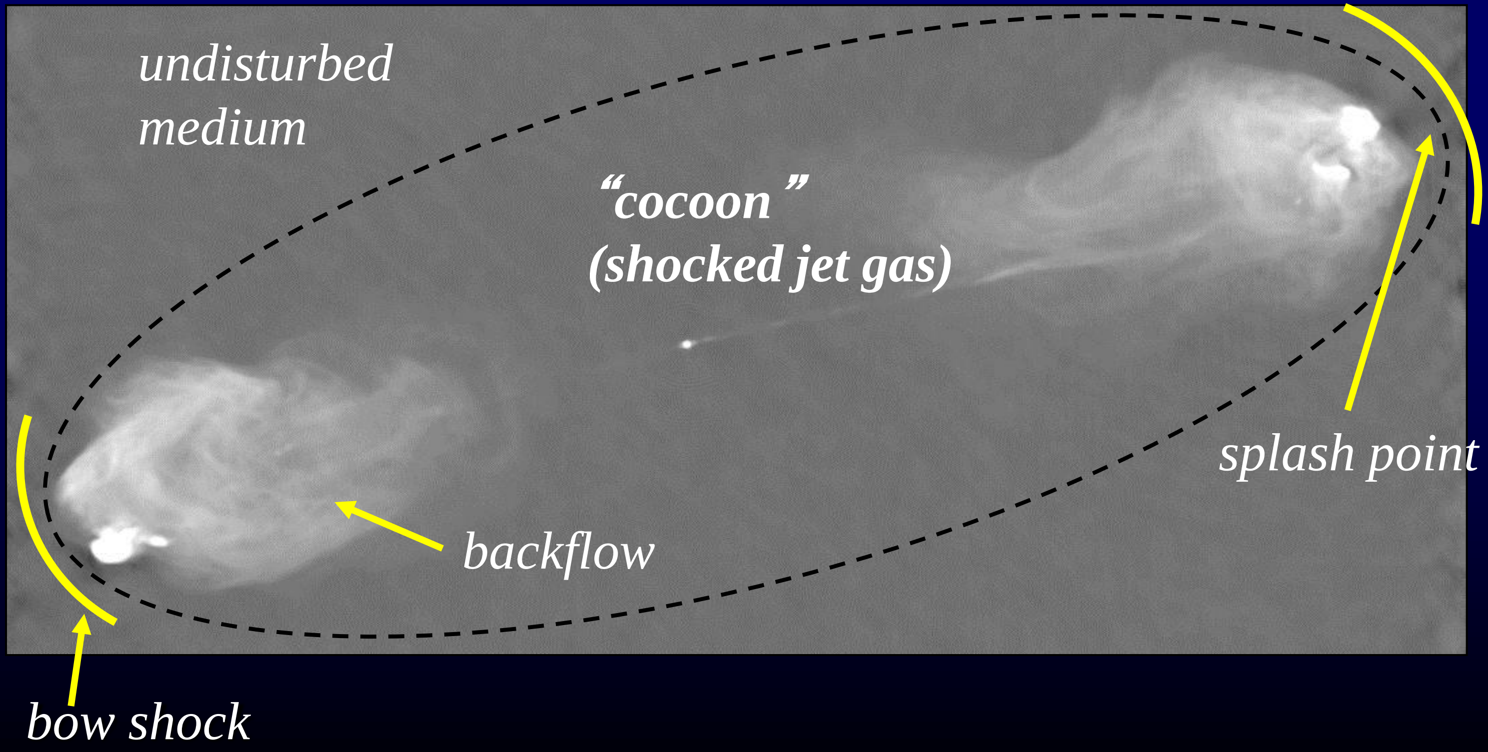




- Gamma flares correlated with X-ray emission variabilities in the anvil region and beyond

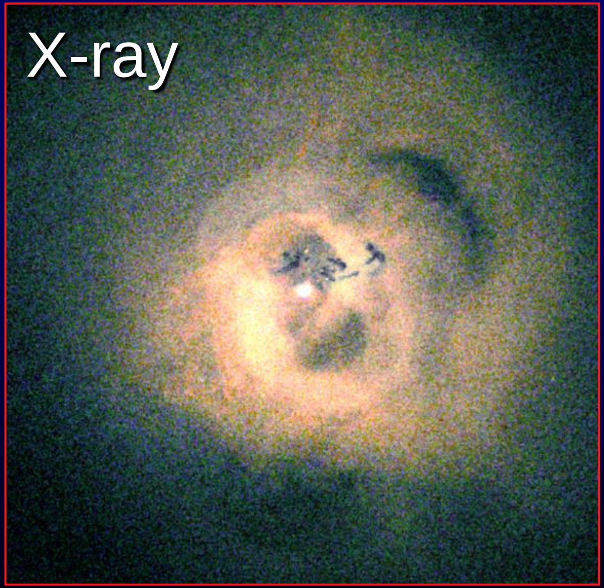
Jet propagation in ISM/IGM

- Light supersonic jets interacting with a dense medium (AGN)
- Equal density supersonic jets interacting with ISM (YSO)
- KH (shear) instabilities yield morphologies (knots, wiggles) and supra-thermal particle acceleration
- Confinement by external pressure (magnetic?)
- Activity of jet’s head and energy deposition



Remnant jets

- Clusters and groups of galaxies emit X-rays
- Thermal bremsstrahlung from hot (0.5 keV up to 10 keV) gas confined in gravitational well: hot Intra-Cluster Medium (ICM)
- Heating mechanism?
- Evidence that AGN jets affect the ICM



X-ray cavities corresponding to radio lobes

X-ray shells surround cavities

Shell temperature lower than surrounding medium: weak shocks

(Fabian et al. 2003, 2005 - CHANDRA) Perseus cluster

Accretion discs: theoretical issues

- Model of steady discs on slightly sub-Keplerian orbits accreting onto black holes or stars
- Subsonic flows (supersonic, shocks?)
- <u>Angular momentum transport by “enhanced turbulent viscosity”</u>
  - by magneto-rotational instability MRI
  - by large-amplitude vortex dissipation
  - something else ?
- Magnetic fields below equipartition
- Heating and radiation

Angular momentum equations

- Azimuthal momentum equation

$$\frac{\partial}{\partial t}\left(\rho R v_\varphi\right)+\nabla\cdot\mathbf{R}\left[\rho v_\varphi\mathbf{v}-\frac{B_\varphi}{4\pi}\left(\mathbf{B}_R+\mathbf{B}_z\right)+\left(P+\frac{B_R^2+B_z^2}{8\pi}\right)\widehat{\mathbf{e}}_\varphi\right]$$

$$-\nabla\cdot\left[\frac{\eta_V R}{3}\left(\nabla\cdot\mathbf{v}\right)\widehat{e}_\varphi+\eta_V R^2\nabla\frac{v_\varphi}{R}\right]=0$$

- Radial flux of angular momentum (no Navier-Stokes viscous terms)

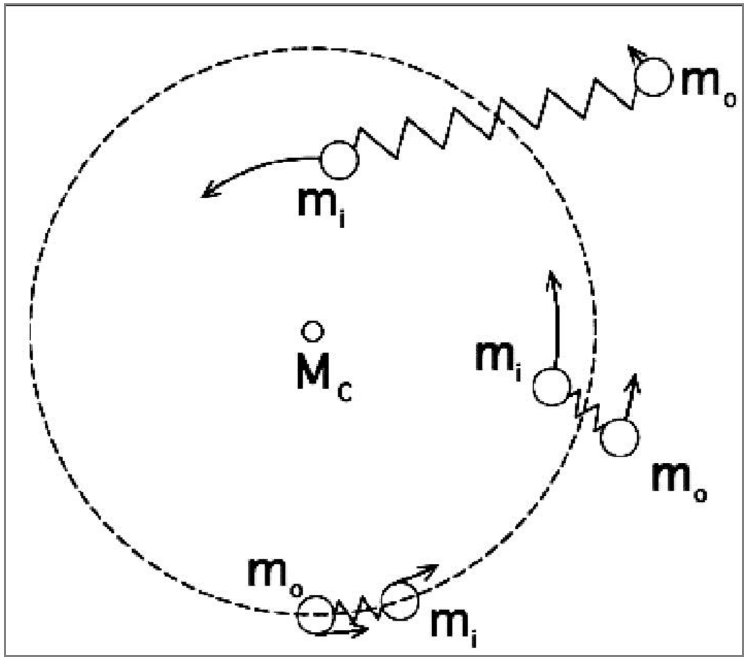
$$R\left[\rho\, u_R\,(\underbrace{R\Omega}+\underbrace{u_\varphi)-\frac{B_R B_\varphi}{4\pi}}\right]$$

  - angular momentum inflow (advected)
  - angular momentum outflow = ΣR$W_{\boldsymbol{R\varphi}}$, combination of Reynolds (velocity) and Maxwell (magnetic) stress tensors

- α-disc models $n_t = a c_s H$

Magneto-rotational instability

- Weak B-field connecting adjacent differentially rotating rings of a Keplerian disk



$$c_A^2 £ \frac{6}{p^2} c_s^2$$

Instability condition

Velikhov 1959

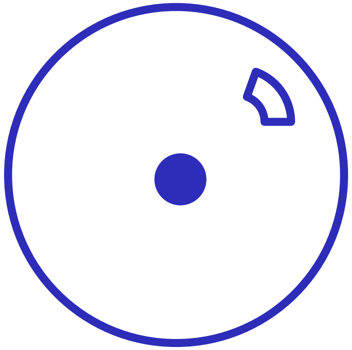
Chandrasekhar 1960

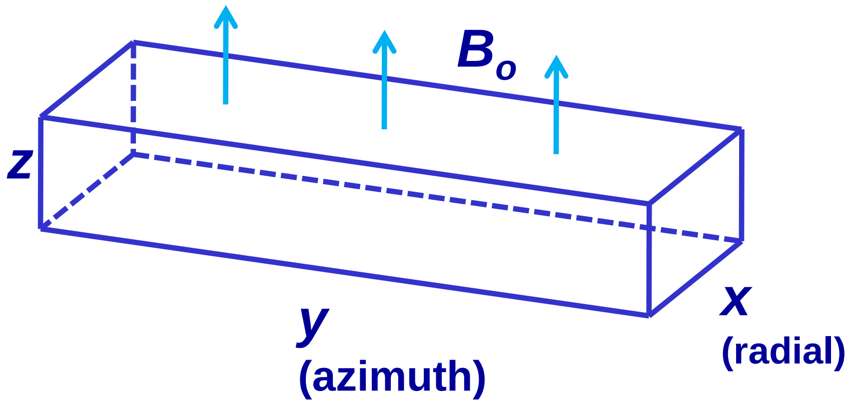
Balbus & Hawley 1991

- The inner mass m_i looses angular momentum to the outer mass m_o that gains momentum
- The process is unstable if the Alfven velocity is subthermal, as then m_i falls inward and m_o moves outward

Nonlinear MRI

- Disc turbulence driven by nonlinear development of the MRI
- Nonlinear studies of MRI turbulence rely on numerical simulations
- Most studies in term of local approximation—shearing box
- Fromang & Papaloizou 2007; Fromang et at. 2007; Pessah et al. 2007; Guan et al. 2009, Simon et al. 2009, Bodo et al. 2011





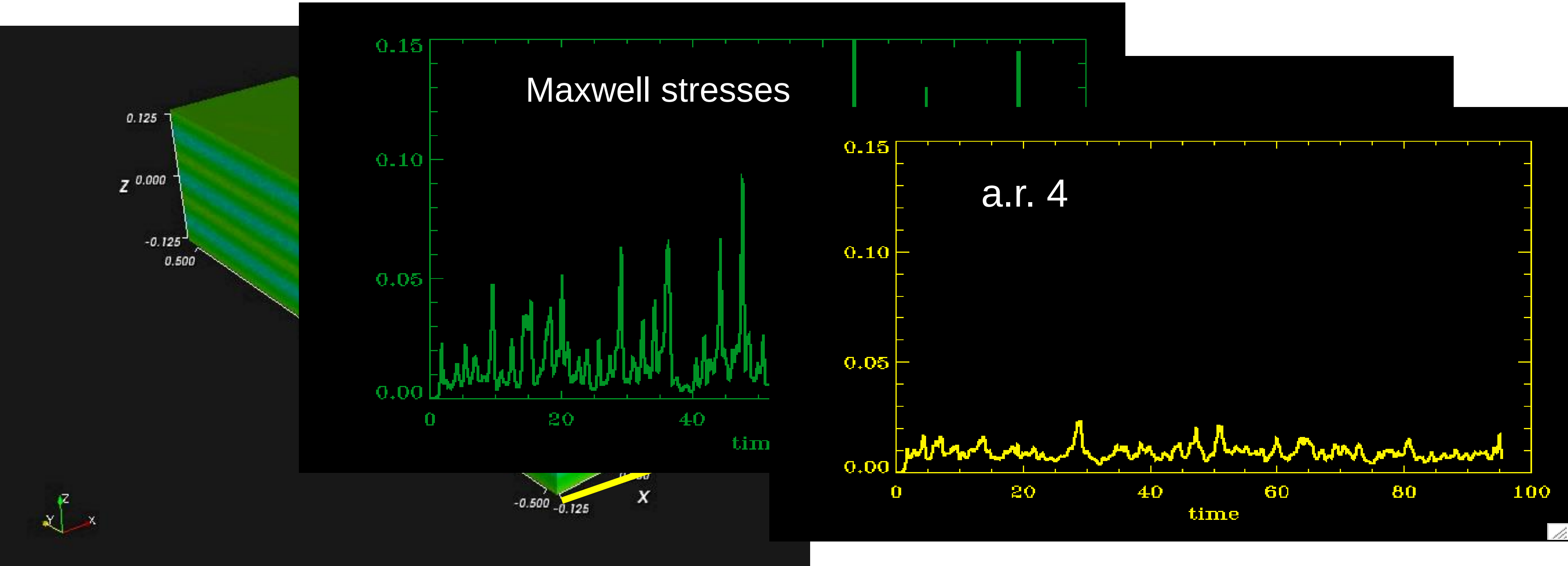
3D high-resolution simulation in shearing box approximation (Sano & Inutsuka 2001, Mignone et al 2007)

<u>Non-zero net magnetic flux</u>

The channel solution, intermittent states, transition to turbulence, calculation of Maxwell stresses

Aspect ratio dependence: large a.r. enhances the effect of parasitic instabilities destroying channel solutions

For large a.r. stresses are very small



Maxwell stresses

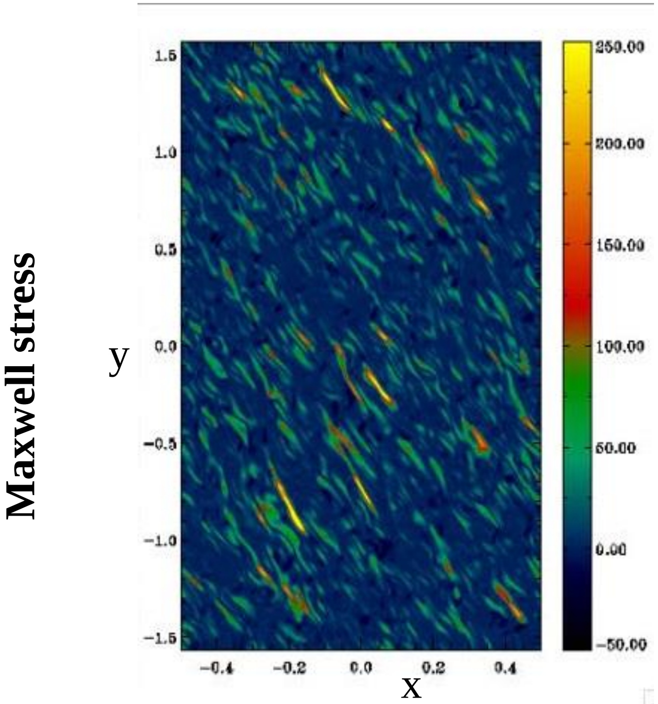
a.r. 4

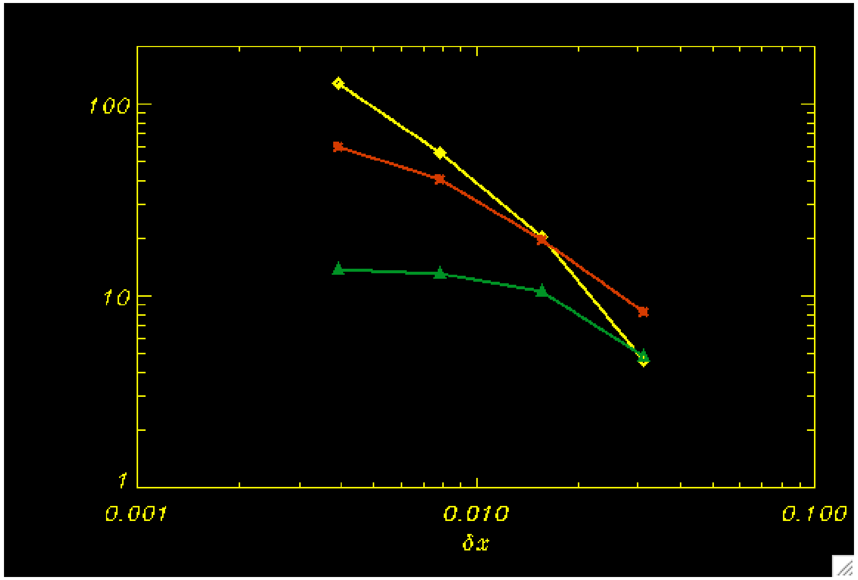
MRI turbulence and dynamos

- Work with no net flux: stationary solution with self-maintained magnetic field for MRI ?
- Even in cases in which total flux vanishes it is possible to maintain a nonzero level of turbulence
    - Turbulence generates a magnetic field (dynamo action)
    - Magnetic field drives the MRI
    - MRI maintains the turbulence
- Turbulence sets in as a subcritical nonlinear dynamo instability
- Possibility of a universal state of magnetization for all similar discs

Periodic shearing boxes

- When $B_o=0$ and $\nu=\eta=0$ the shearing box equations have no characteristic length-scale
- When $\nu\neq 0$ only length-scale is the viscous scale ($\sqrt{\nu/\Omega}$)
- $L \to \infty$? (increase resolution)
- Compute Maxwell stresses as a function of L (or $\delta x \approx 1/L$)
- Use different codes, different resolutions
  - Godunov: Piecewise linear (yellow)
  - Godunov: Piecewise quadratic (red)
  - High order (green)





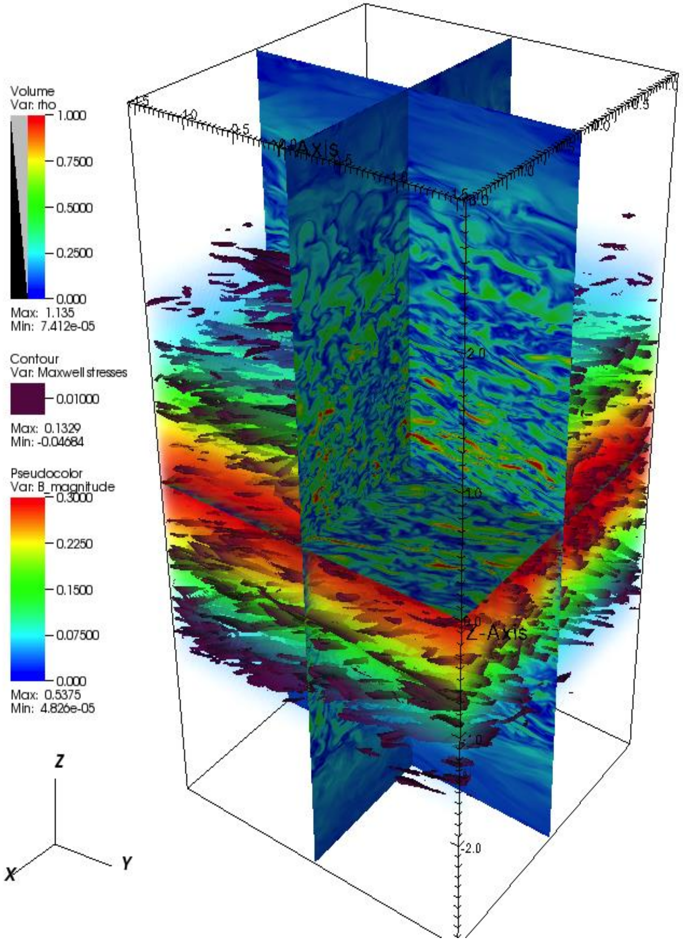
Average Maxwell Stress

- Most likely outcome is that *f(L)* → const as *L* → ∞
- Asymptotically, transport becomes a fixed ("universal") multiple of the viscous transport
- Negligible in astrophysical situations

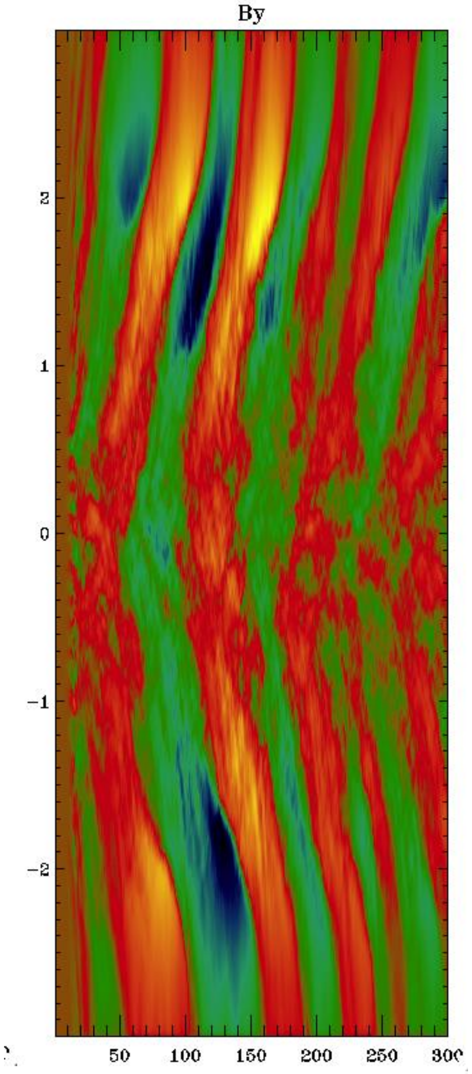
- If solution is asymptotically independent of *L* characteristic scale of magnetic structures is comparable to dissipation scale
- Solution is a *small-scale* dynamo

- In order to recover turbulent transport solution must have an efficient inverse cascade. i.e. must be a *large-scale* dynamo (*system-scale* dynamo)

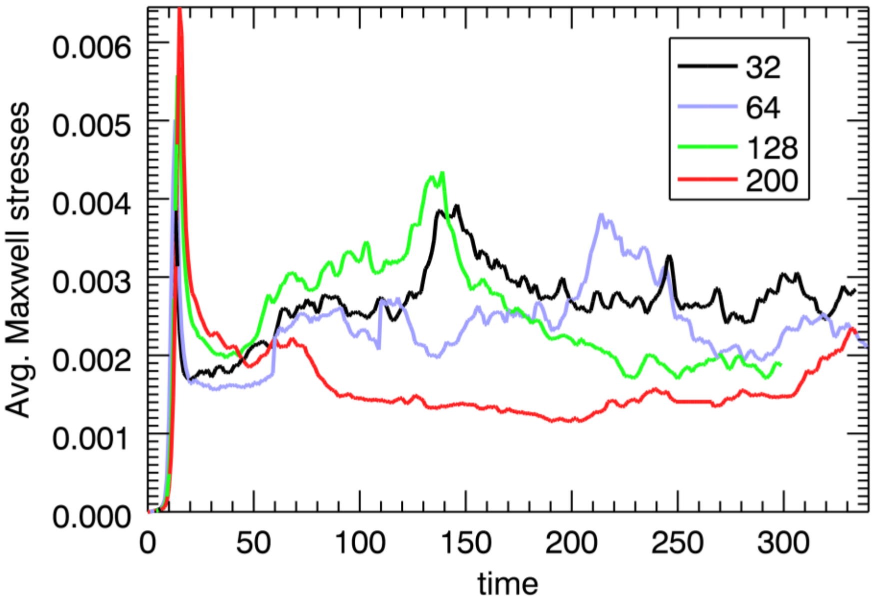
Stratified isothermal

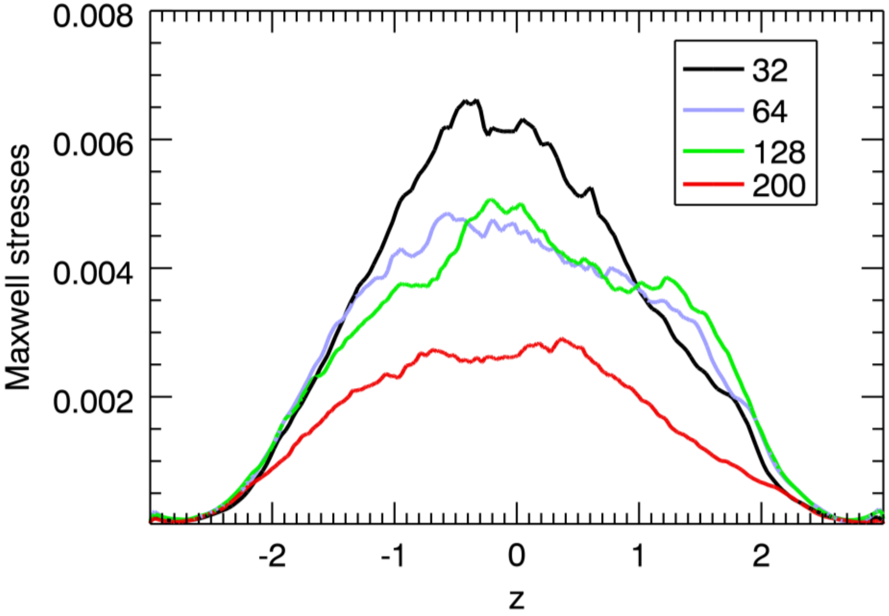


- 3 scale-heights on each side of mid-plane
- Strong evidence for pattern propagation
- Magnetic buoyancy has negligible dynamical effect
- Insensitive to b.c.'s



Stratified isothermal



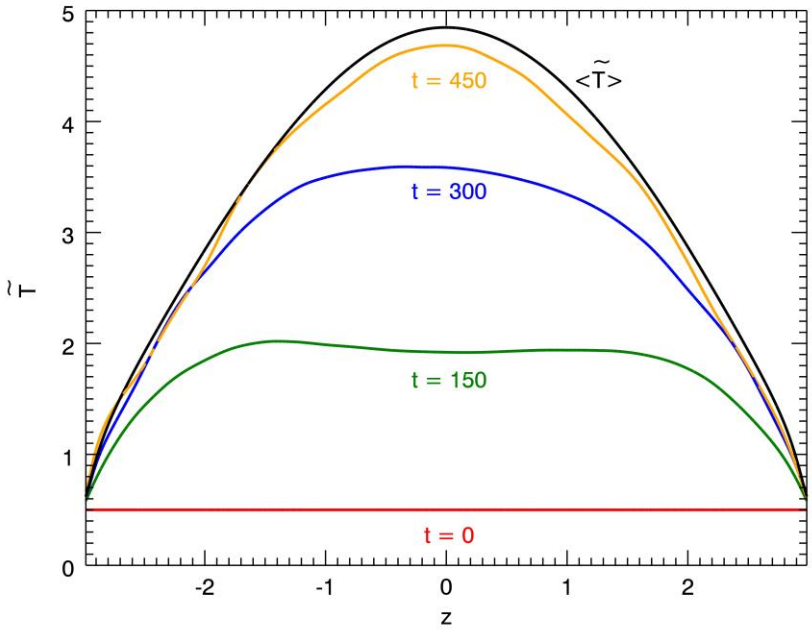


- Transport dominated by Maxwell stresses in the mid-plane region
- Little evidence of cyclic behavior in the overall transport
- <u>Overall transport decreases as the resolution increases</u>
- No convincing evidence of convergence at these resolutions

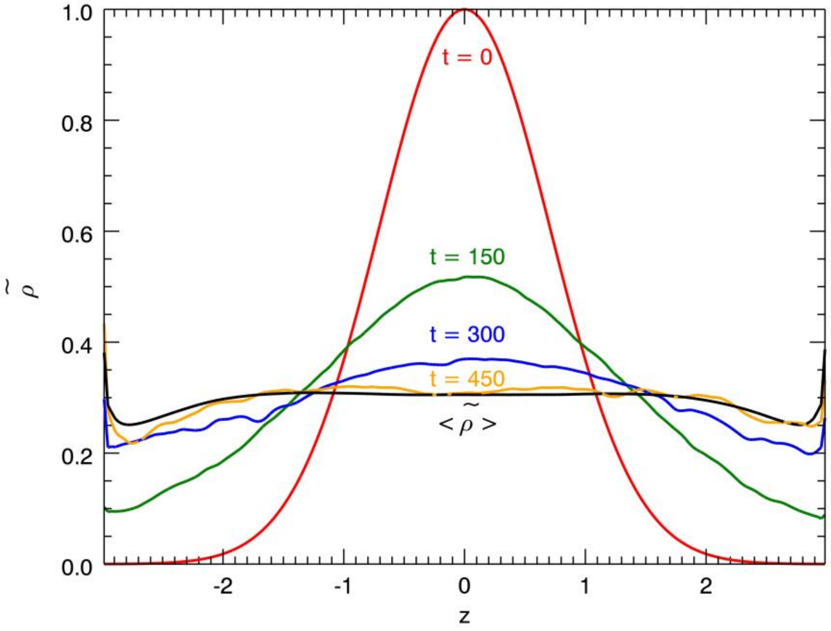
Stratified, perfect gas: evolution

- Isothermal initial state
- Viscous and Ohmic heating introduce significant departures from isothermal state
- Density becomes constant across the layer

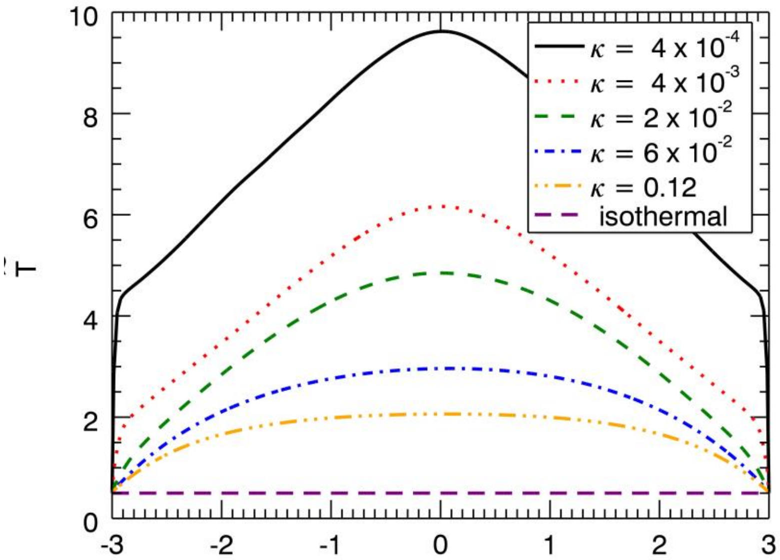
Temperature

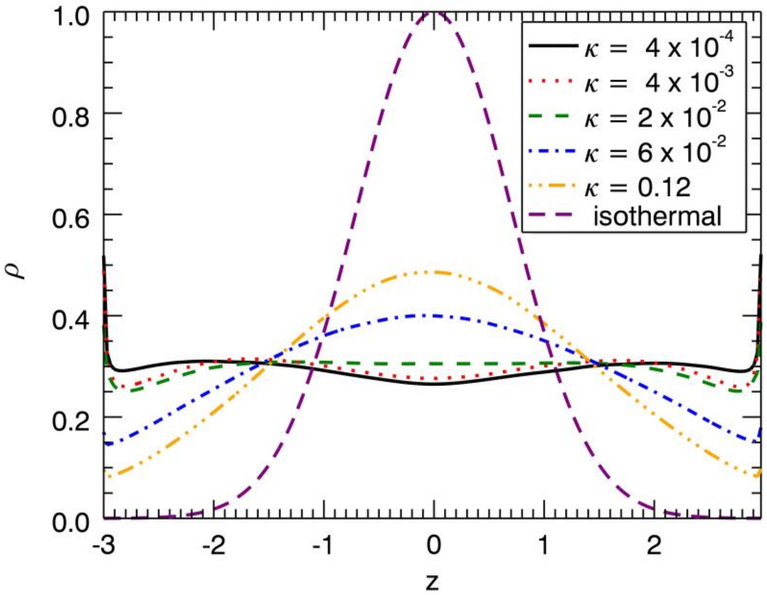


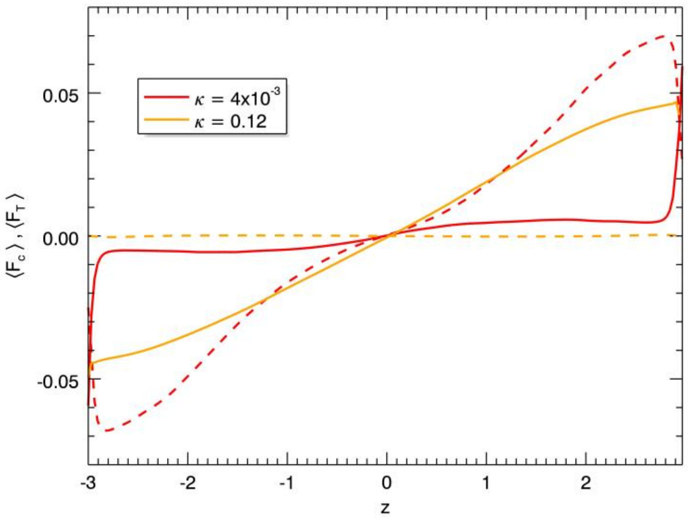
Density



Conductive and convective regimes

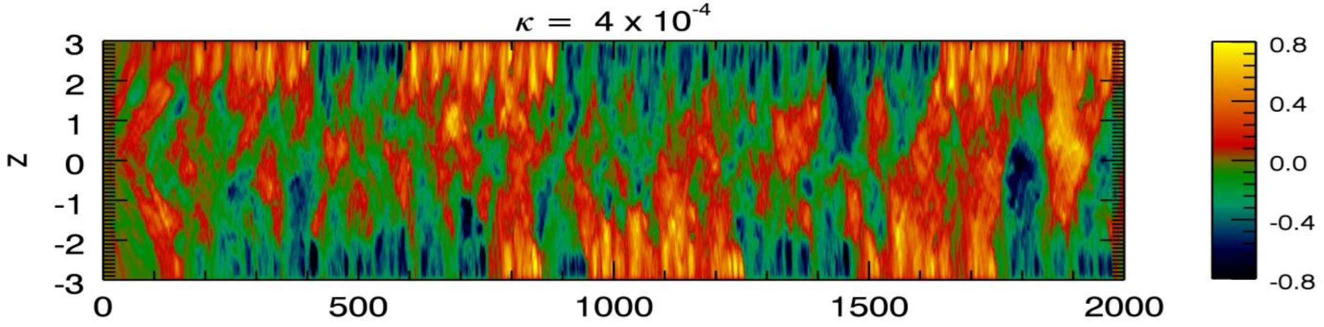

Temperature


Density

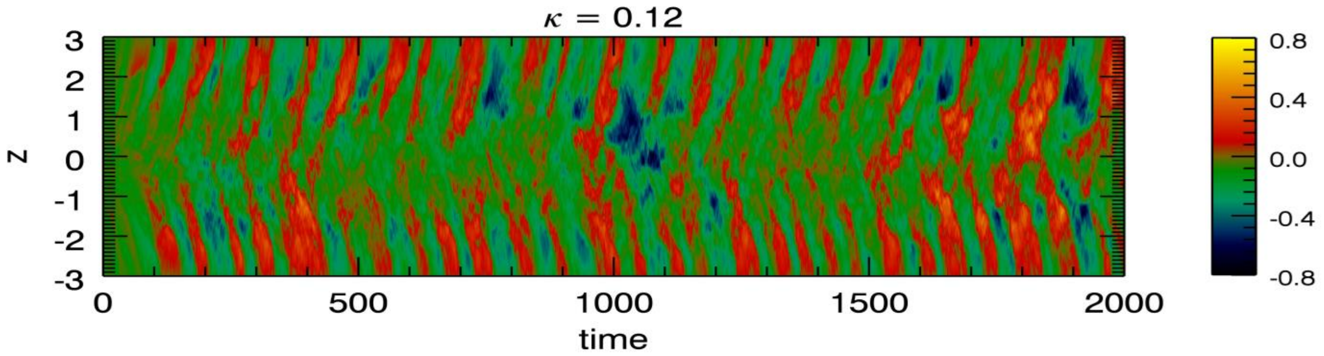

Heat flux

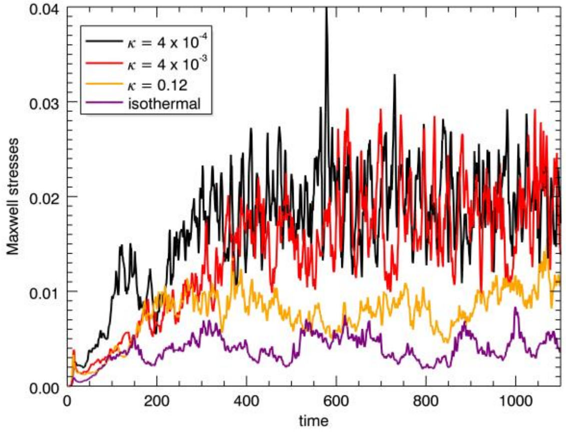
- Overturning motions lead to efficient density homogenization

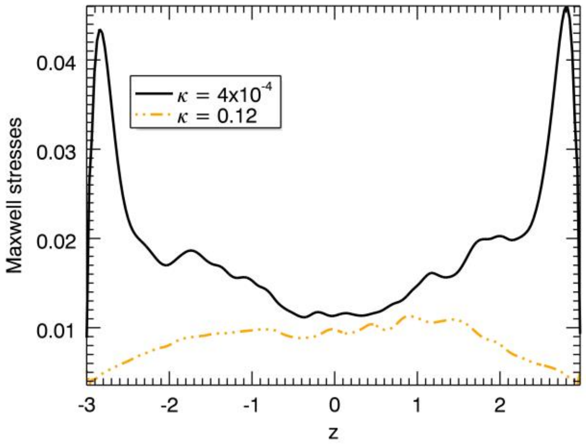
Convective



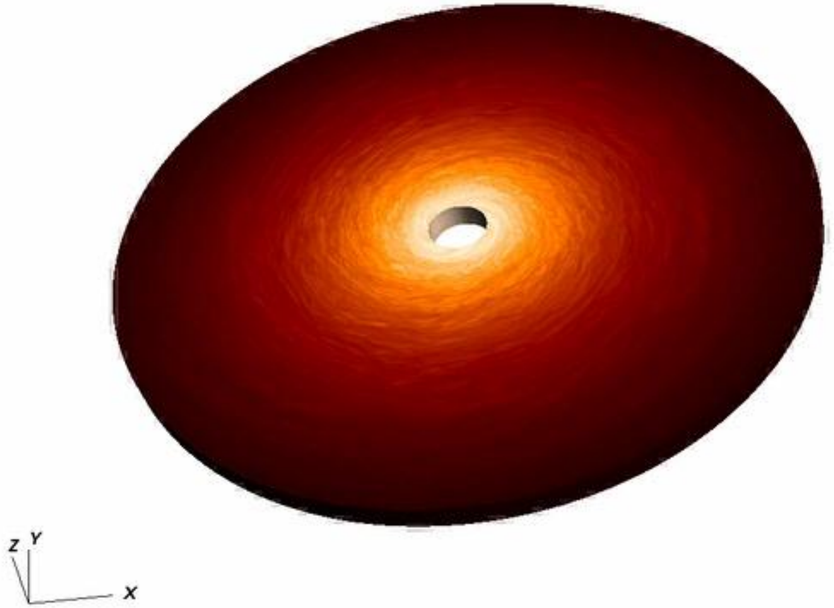
Conductive

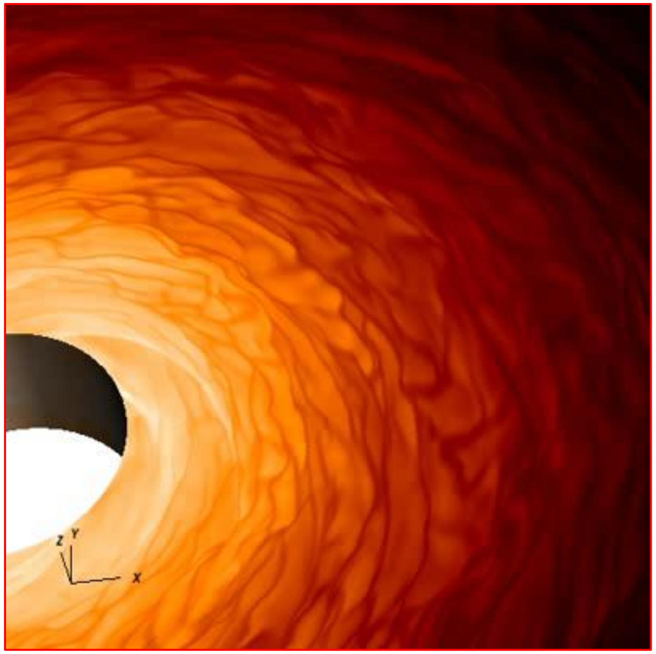


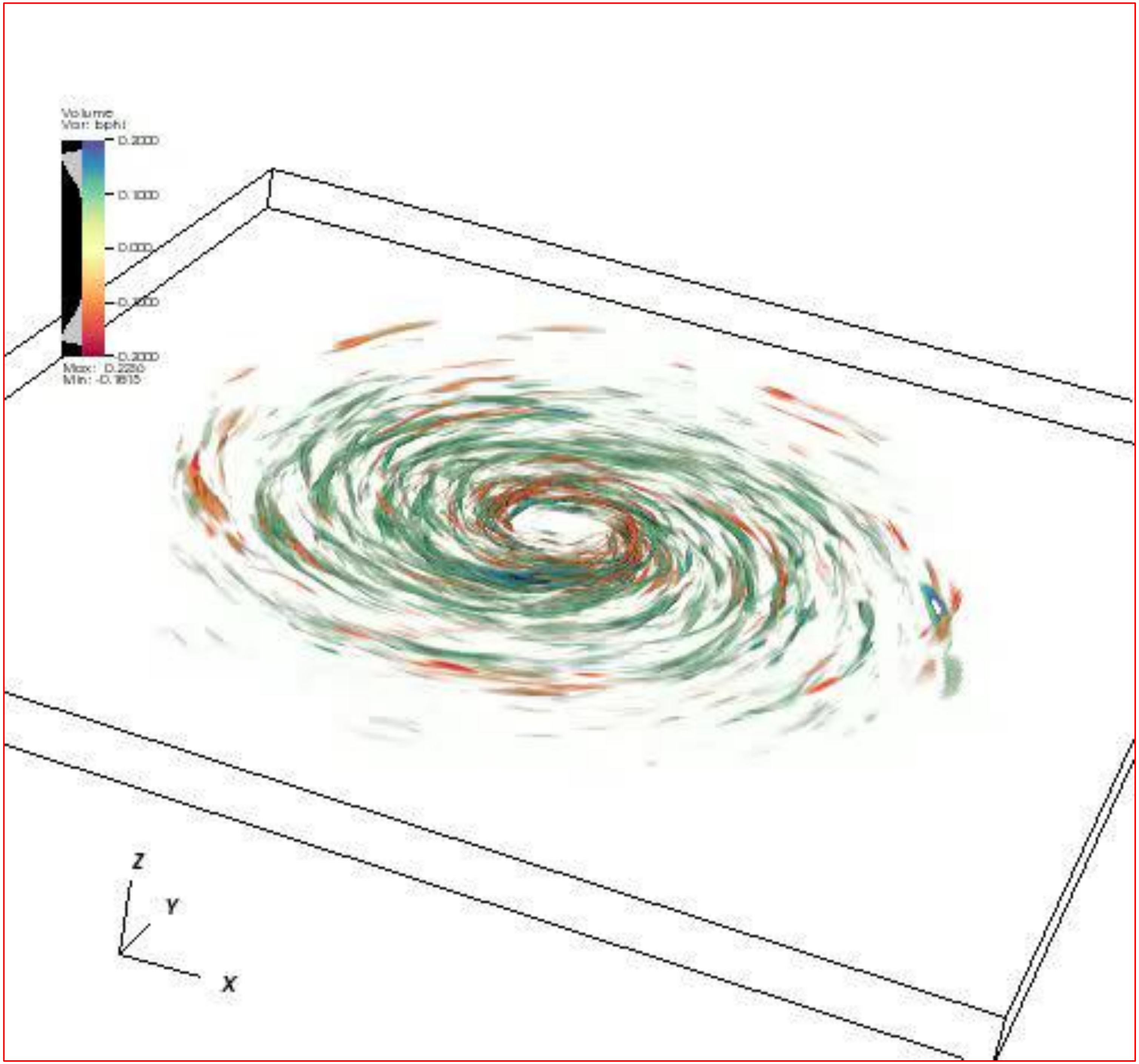




Global simulations






Volume
Var: bphi
0.2000
0.1000
0.000
-0.1000
-0.2000
Max: 0.2280
Min: -0.1815
Z
Y
X

Conclusions

- MRI provides a valuable framework to understand turbulent transport in accretion discs
- In the zero net –flux case turbulence generated by a subcritical dynamo instability
- Effective angular momentum transport depends on type of dynamo action
  - Small-scale ➔ scales with diffusivity: inefficient
  - Large-scale ➔ scales with system size: efficient
- Which type of dynamo action is observed depends on geometry, boundary conditions, stratification, eqn of state, radiative transport, etc.