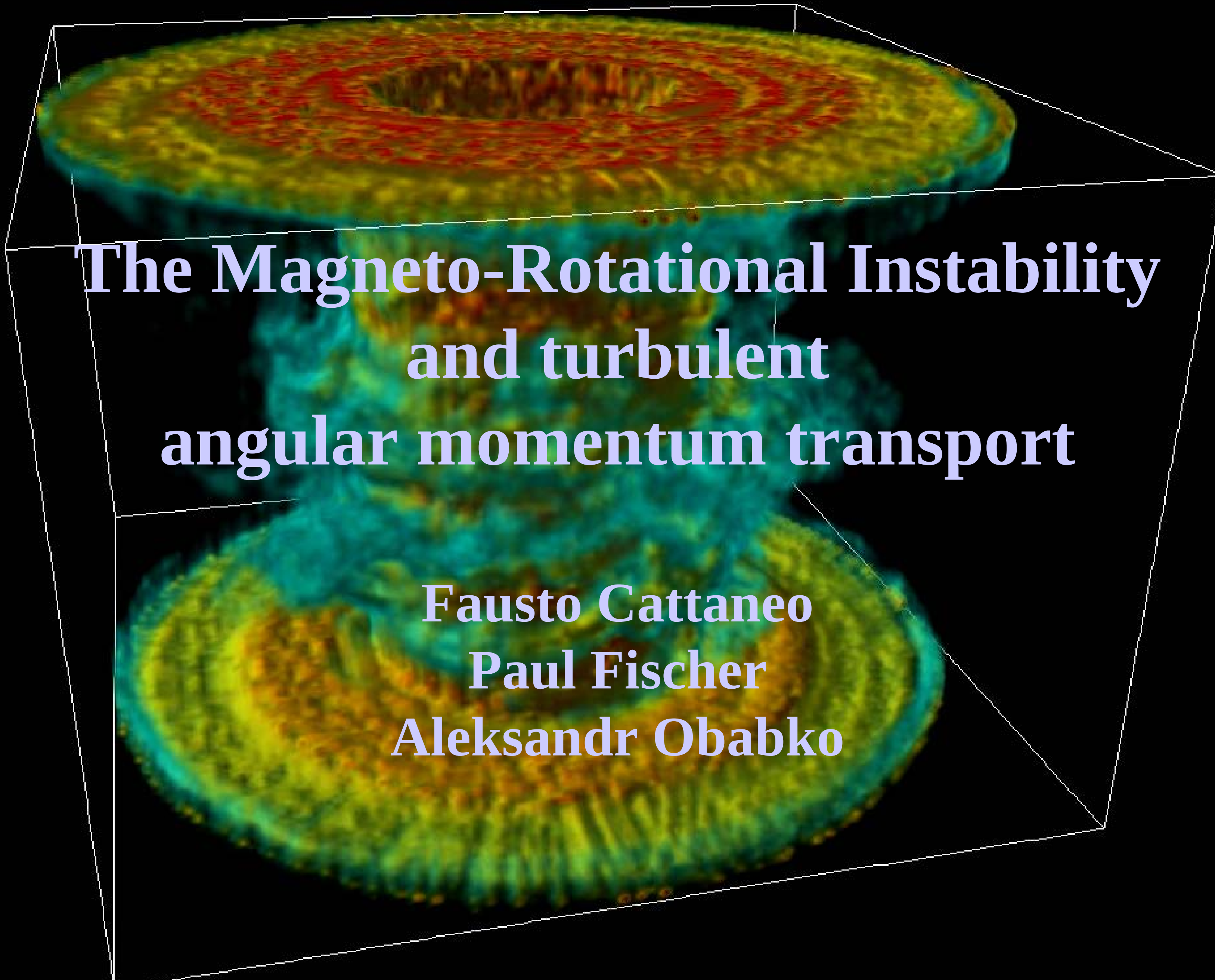
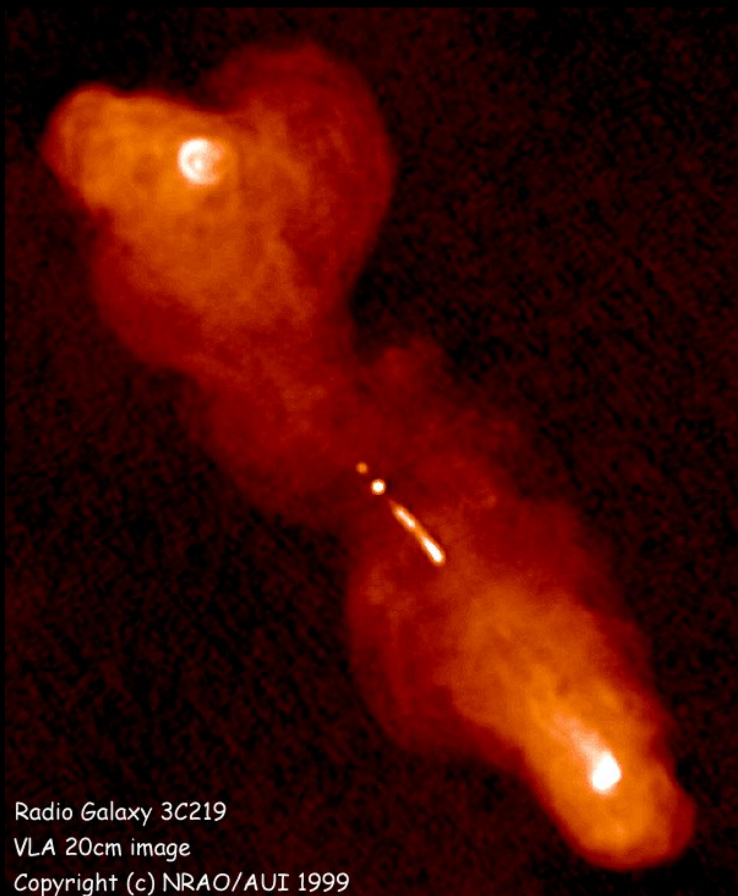


The Magneto-Rotational Instability and turbulent angular momentum transport

Fausto Cattaneo
Paul Fischer
Aleksandr Obabko

Accretion



300 Kp

Accretion onto a central compact object is believed to power some of the most energetic phenomena in the universe

Black hole accretion

(Lynden-Bell 1969)

- **Central mass ~10^8-10^{10} $M_\odot$**
- **Accretion rate ~1 $M_\odot$/yr**
- **Total luminosity ~10^{47} $L_\odot$**

Angular momentum transport

- If angular momentum is conserved matter just orbits the central object
- Accretion rate is determined by the outward transport of angular momentum

- Frictional or viscous transport too inefficient to explain observed luminosities
- Something many orders of magnitude more efficient is needed

Turbulent transport

Shakura & Sunyaev (1973) assumed transport was due to turbulence in the disc. For reasonable transport rates assumption gave

Reasonable disc structures

Reasonable accretion rates

In a turbulent flow effective diffusivity

$$D \approx U\ell = \nu\left(\frac{U\ell}{\nu}\right) = \nu\,\mathrm{Re}$$

characteristic length scale (ℓ)

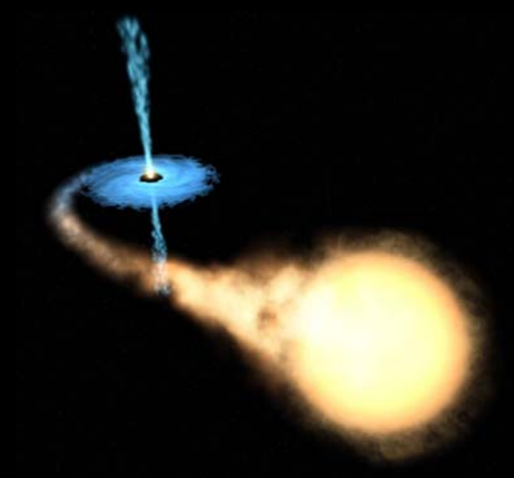
characteristic velocity (U)

What is the physical origin of the turbulence?

Keplerian discs

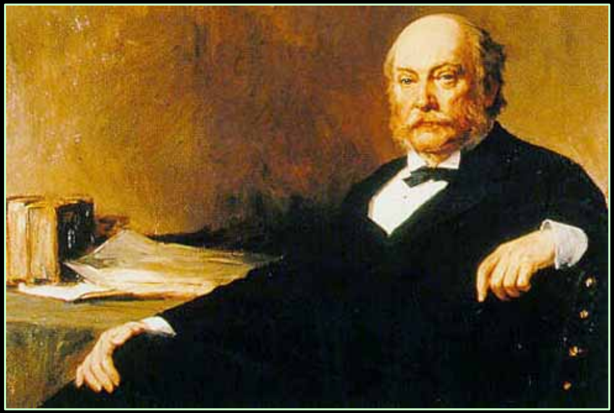
Most astrophysical discs are close to Keplerian

- nearly circular
- angular velocity profile $\Omega \propto r^{-3/2}$
  - angular velocity increases inwards
  - angular momentum $(r^2\Omega)$ increases outwards



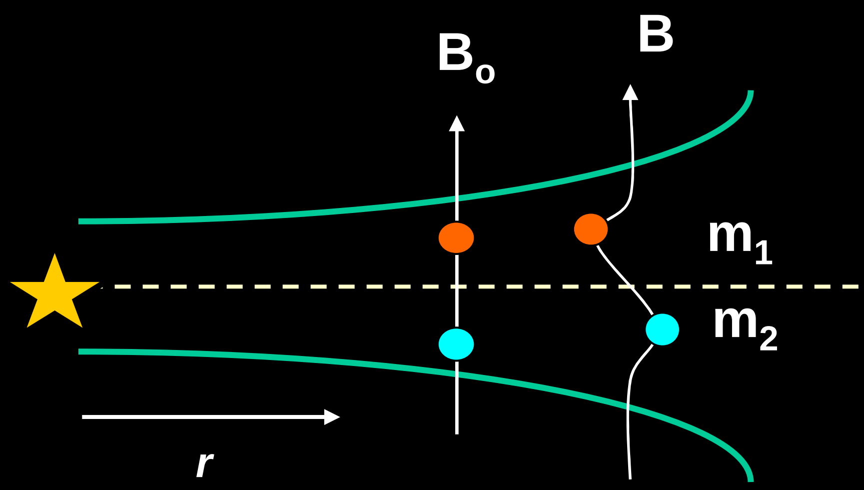
Stable to axi-symmetric disturbances

(Rayleigh criterion)



The Magneto-Rotational Instability

Stability changes dramatically if disc is even weakly magnetized (Velikov 1959; Balbus & Hawley 1991)



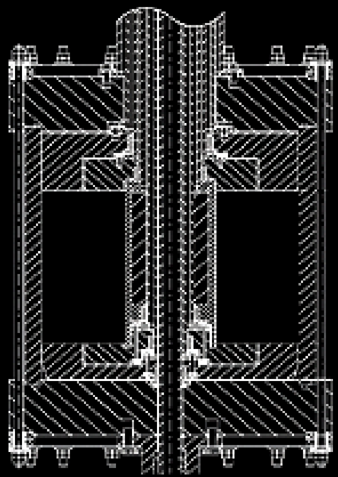
- **New instability criterion is that angular velocity increases inwards**
- **Effect of instability is to transport angular momentum outwards**

Laboratory experiments

- Instability depends on velocity profile, not gravitational force
- Can be studied in Couette flow between concentric cylinders using liquid metals (Na, Ga)
- Spin cylinders so that basic state has circular streamlines and

$$\frac{d\Omega}{dr} \leq 0 \quad \text{and} \quad \frac{d(r^2\Omega)}{dr} > 0$$

New Mexico exp: S. Colgate



Princeton exp: J. Goodman & H. Ji

Laboratory experiments

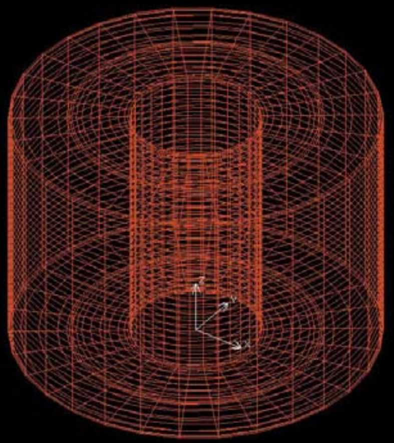
Three basic questions

- What is the effect of the endplates?
  - secondary Ekman circulation
  - Stewartson layers
- Can the MRI be demonstrated?
  - basic state not purely Couette flow
  - enhanced angular momentum transport due to Ekman turbulence
- What does the nonlinear state look like?
  - flow visualization in liquid metals difficult
  - what contributes to the angular momentum flux?

Numerical simulations

- Solve incompressible MHD equations for a viscous, electrically conducting fluid

- Cylindrical geometry with different endplates
  - periodic
  - lids (same Ω as outer cylinder)
  - rings (two: rotating at intermediate Ω's)



- Use spectral-elements method optimized for highly parallel machines (based on Nekton 5000)

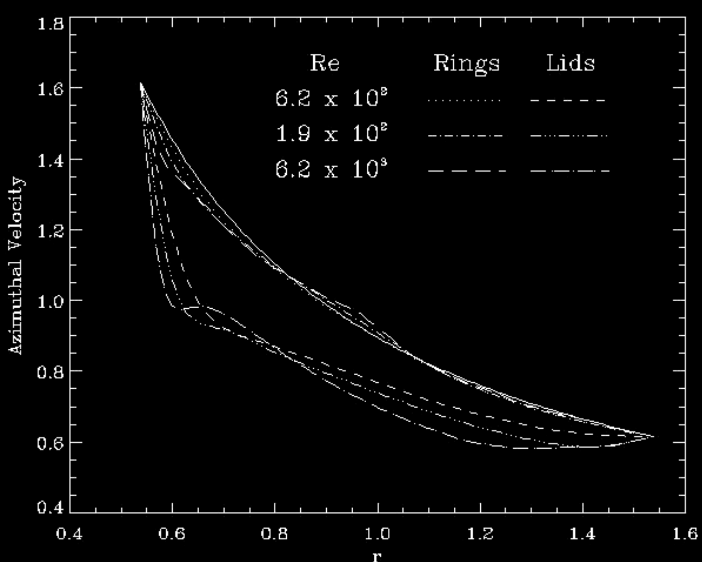
- Vary magnetic field strength

End effects: simulations

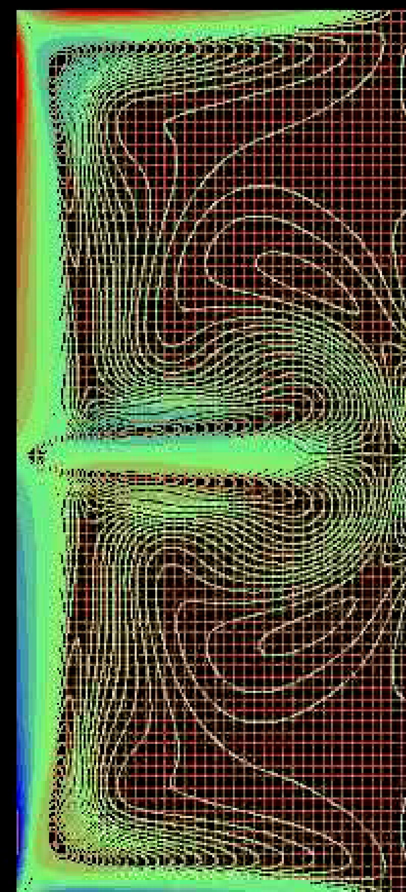
vorticity

<u>**Configurations:**</u>

- **Periodic**
- **Lids**
- **Rings**
-

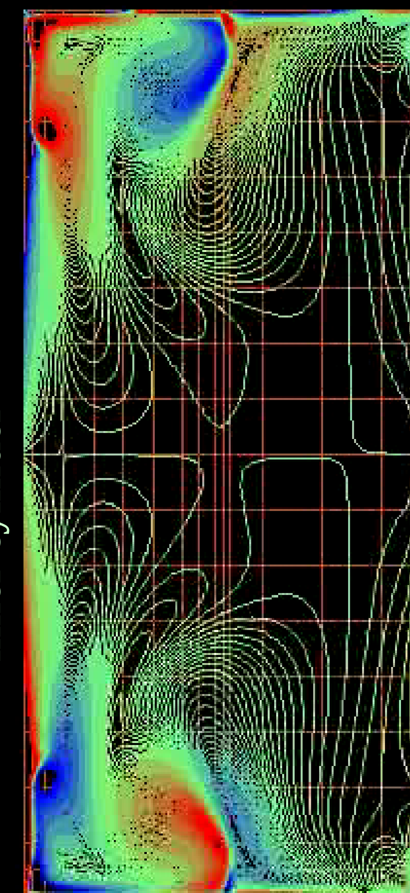


inner cylinder



lids

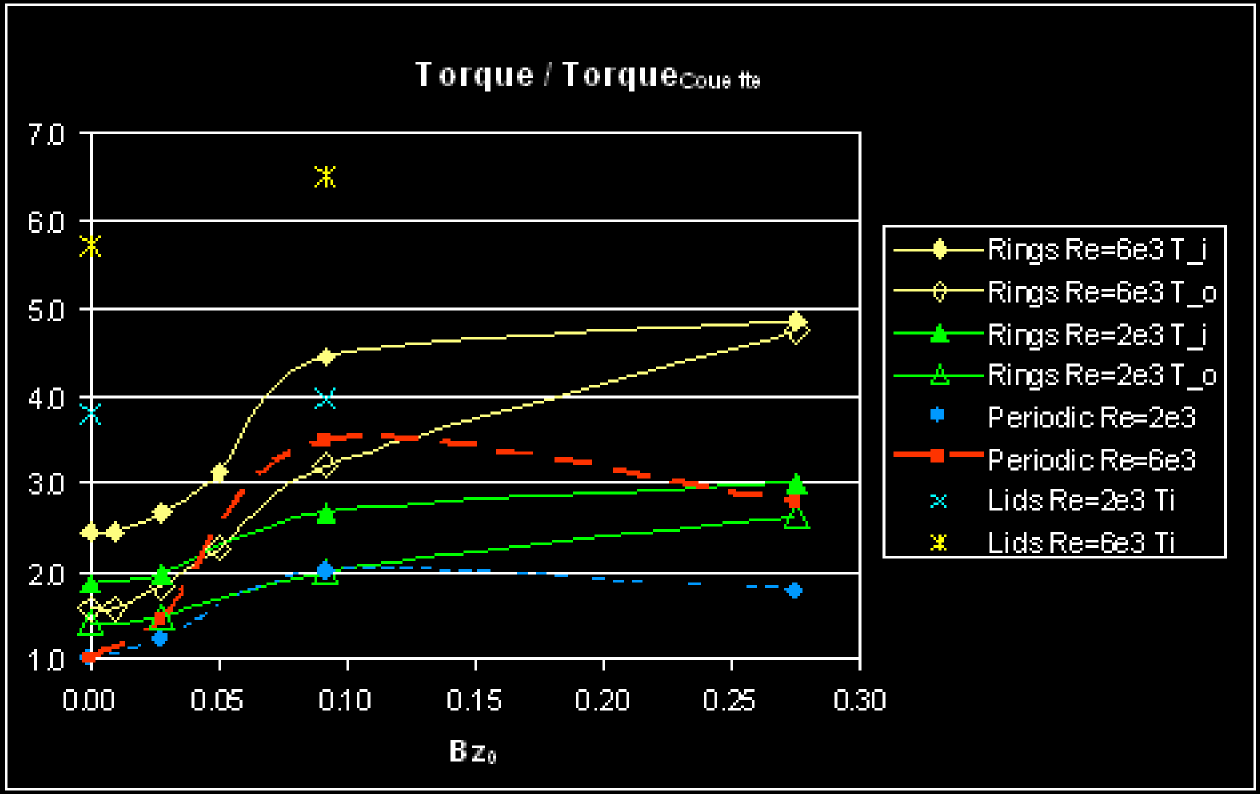
inner cylinder



rings

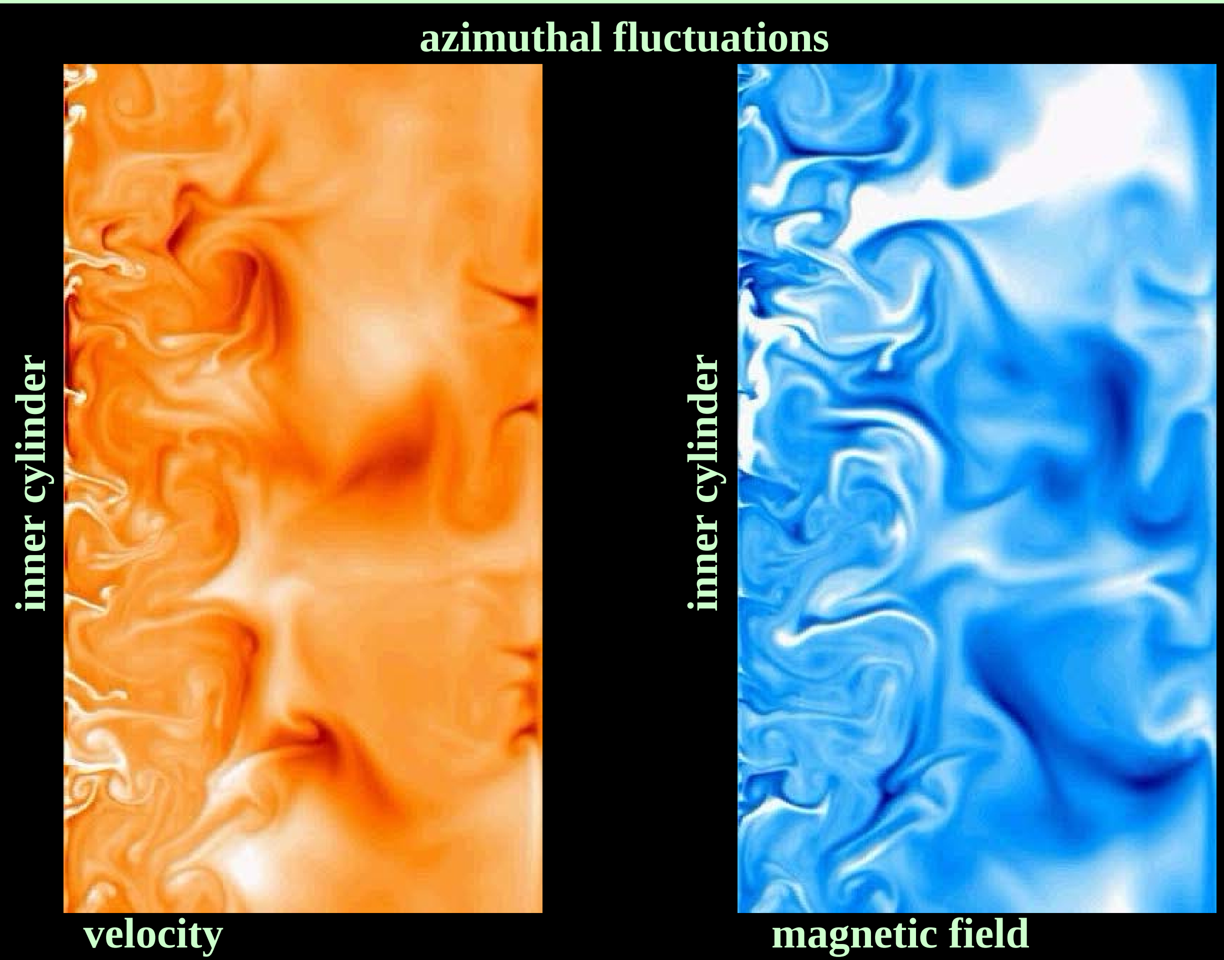
Torque measurements: simulations

- Instability enhances angular momentum transport
- To keep same rotation rate <u>torque</u> on cylinders must be increased



applied magnetic field strength

Flow structure: simulations

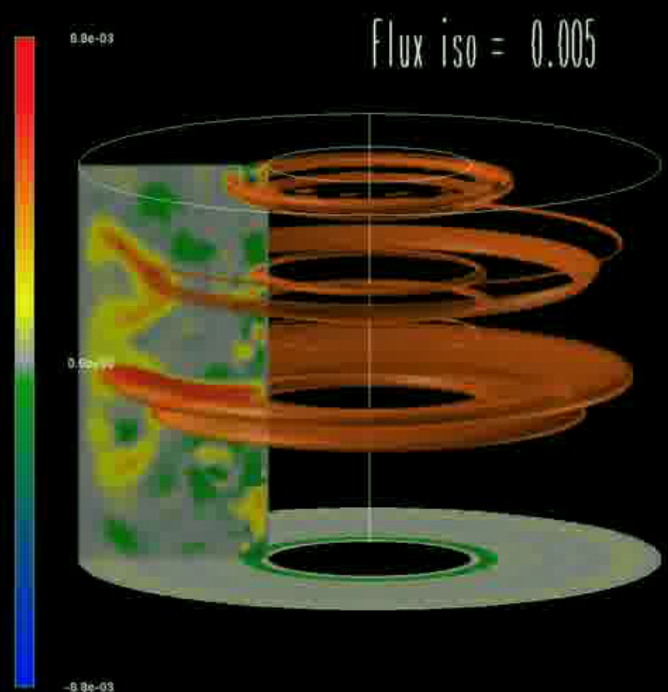


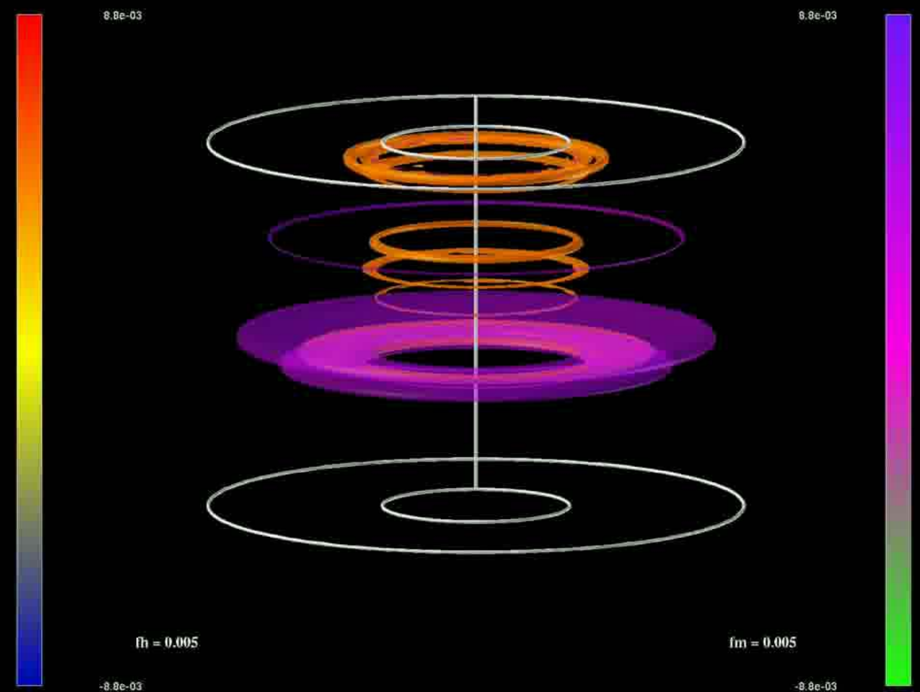
- Magnetic field expelled to outer regions
- Inner part dominated by eddy motions – plumes
- Outer part dominated by waves (magneto-inertial)

Angular momentum flux: simulations

$$F_{rz} = r\left[\left(u_\theta - \bar{u}_\theta\right)u_r - B_\theta B_r\right]$$

- Transport by coherent structures (cf. convection)
- Reynolds stresses dominant in the inner part
- Maxwell stresses dominant in the outer part





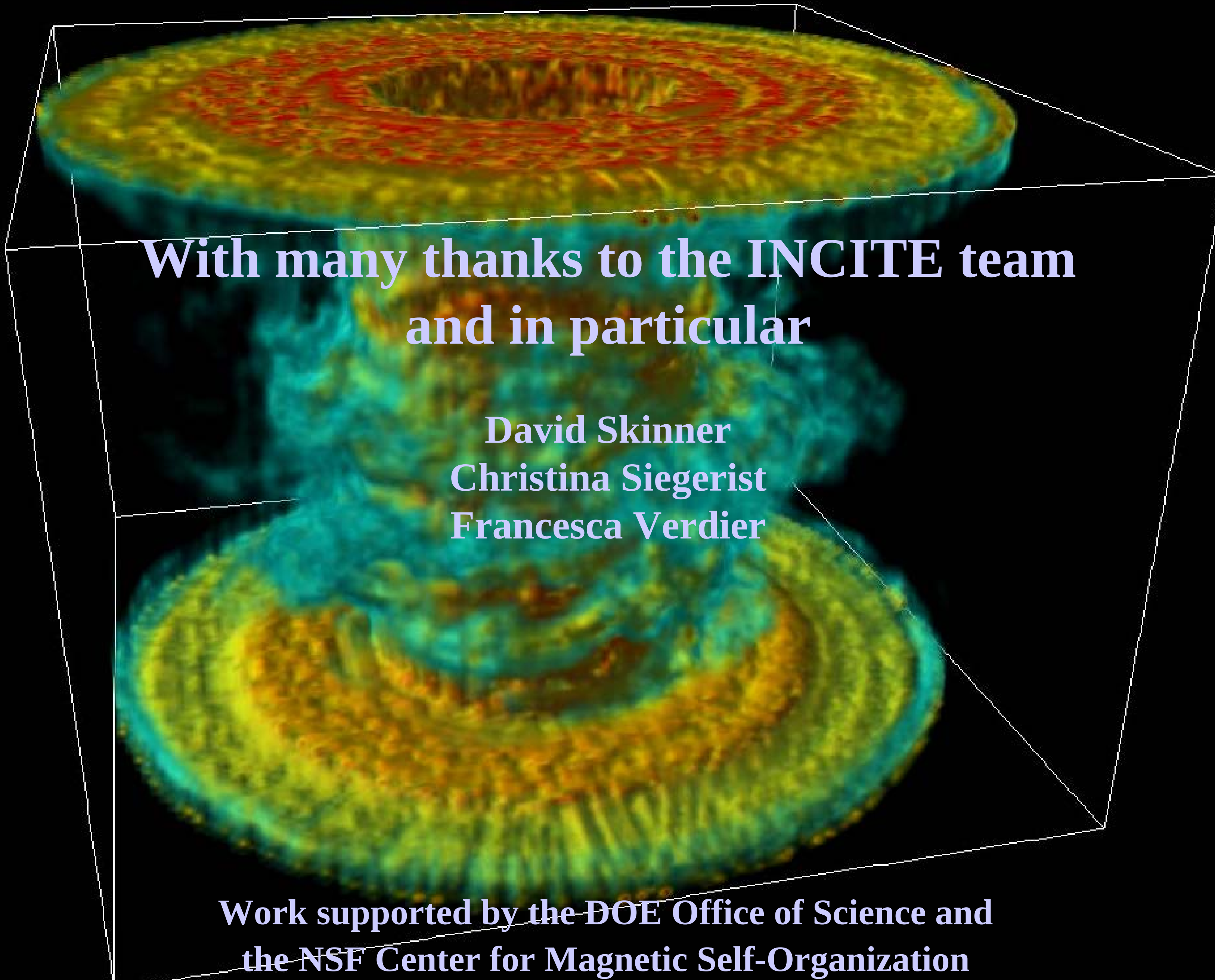
Conclusion

- Using INCITE resources it is possible to demonstrate numerically the existence of the MRI in realistic (laboratory) geometry

- Numerical simulations complement experiment
  - allow more flexible boundary conditions
  - can explore different parameter regimes (eg. high *Rm* limit)
  - afford superior flow visualization

- Numerical simulations can guide design of future laboratory experiments

- Results of numerical simulation provide basis for formulation of phenomenological models of MRI turbulence and enhanced angular momentum transport



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Francesca Verdier

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