Laboratory Study of Angular Momentum Transport in Astrophysically Relevant Flows

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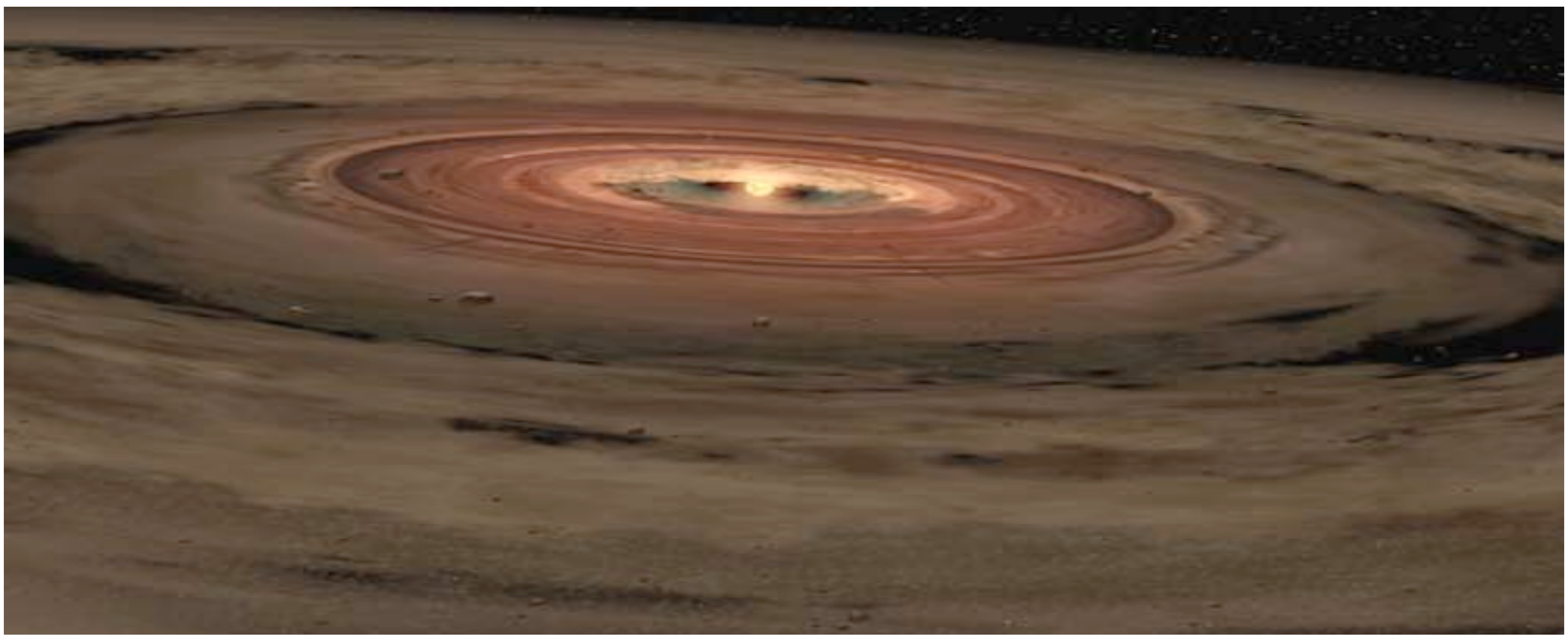
Plasma Science Committee
National Research Council

This talk represents a case where astrophysical questions can be answered by laboratory experiments.

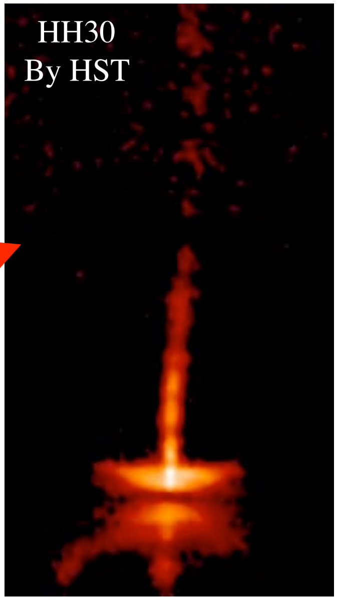


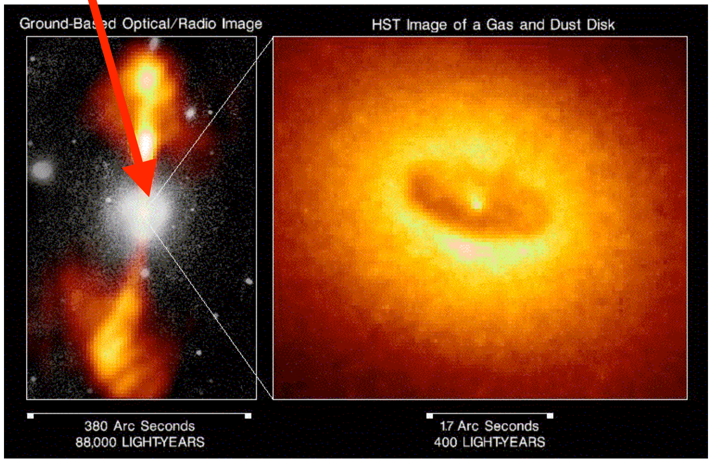
Outline

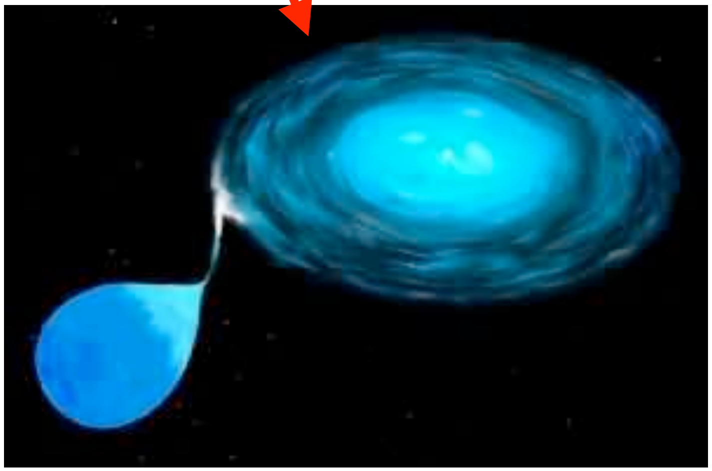
- Motivations
- The basic idea
- Experimental adventure
- Hydrodynamic stability at large Reynolds numbers
- Preliminary results from MHD experiments
- Summary and outstanding questions

Accretion Disks

- An accretion disk consists of gas, dust and plasmas rotating around and slowly falling onto a central point-like object.
- Many important astrophysical processes happen in accretion disks:
  - Formation of stars and planets in proto-star systems
  - Mass transfer and energetic activity in binary stars
  - Release of energy (as luminous as 10^{15} of Sun) in quasars and Active Galactic Nuclei







The Problem: why accretion is fast?

- **Equivalent to the question why the angular momentum outward transport is fast**

compared to:

- **The transport which can be supported by molecular (classical) viscosity**

therefore:

- **Turbulence is required to generate enhanced "viscosity"**

however:

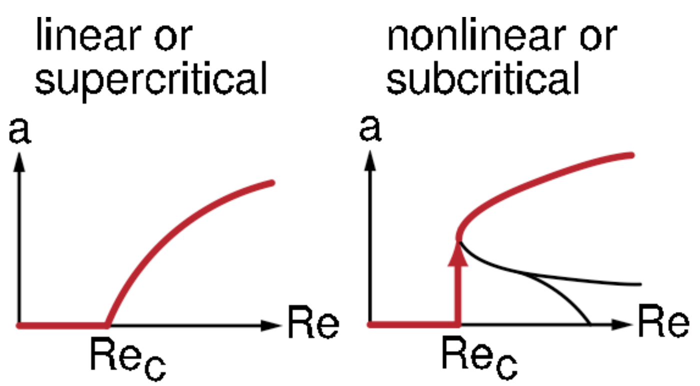
$$\Omega \propto R^{-q}; q = 1.5$$

- **Hydrodynamically the steady state disks (Keplerian disks) are linearly stable satisfying Rayleigh's criterion $d(R^2\Omega)/dR>0$**

Two Main Candidate Mechanisms to Generate Turbulence for Fast Accretion

- **Nonlinear hydrodynamic instabilities in cold disks, insufficiently ionized for MHD effects but essentially inviscid (large Re's)**
  - **Zeldovich (1981)**
  - **Richard & Zahn (1999) based on Wendt (1933) and Taylor (1936)**
  - **Richard (2001)**

Terrestrial flows are often nonlinearly unstable at *Re* > 10^2-10^4 despite linear stability.

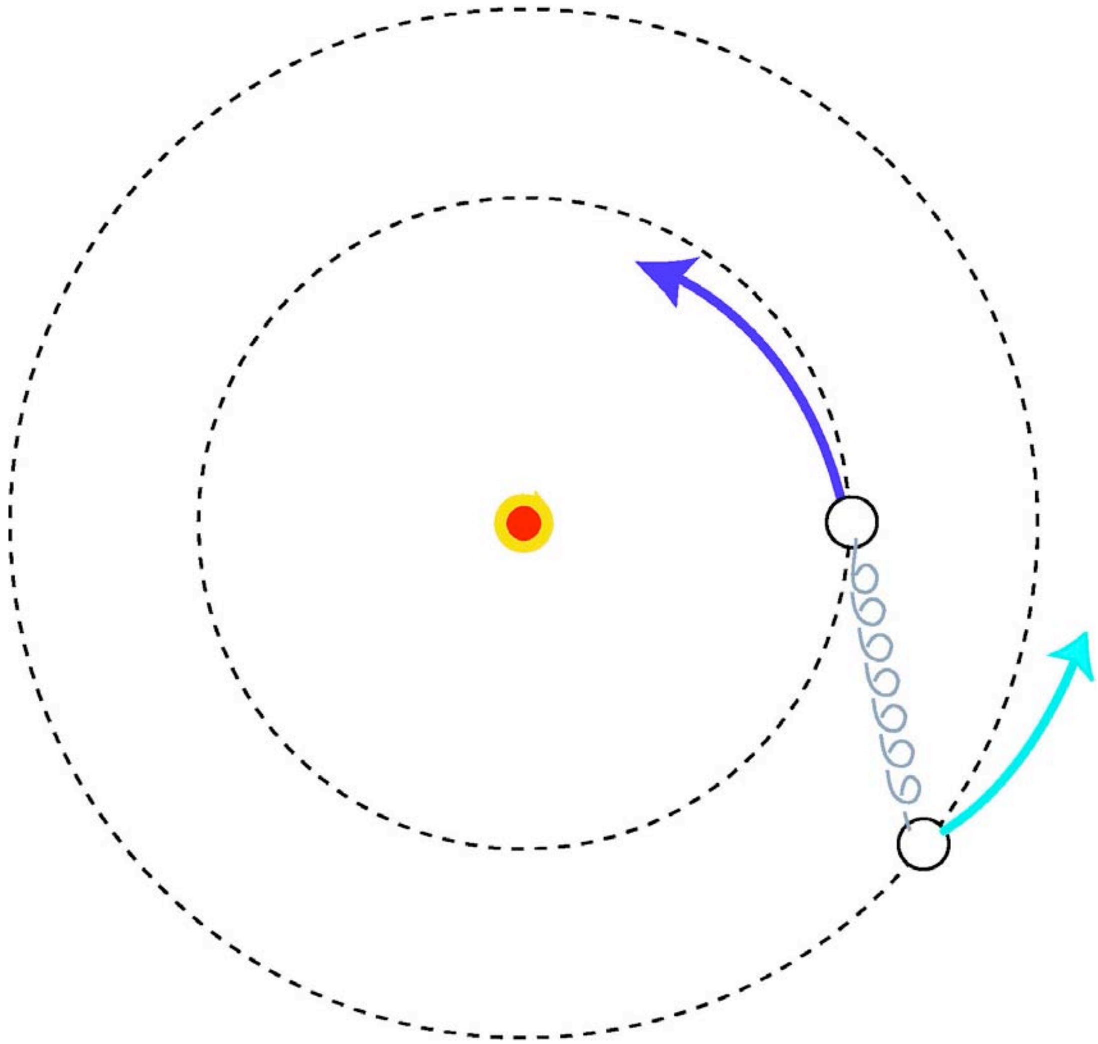


$$\nu_{turb} = \beta R^3 \left| \frac{\partial \Omega}{\partial R} \right|$$

- **Magnetorotational Instability (MRI) in hot disks, which are highly electrically conducting**
  - **Velikhov (1959) and Chandrasekhar (1960)**
  - **Shakura & Sunyaev (1973)**
  - **Balbus & Hawley (1991)**

$$\nu_{turb} = \alpha C_s H$$

Physical Picture of MRI



Understanding Turbulent Transport

Mechanism (parameter)	MRI (α)	Nonlinear Hydro (β)
Observations Hueso & Guillot (2005)	e.g. 10^{-3}-10^{-1}	e.g. 2×10^{-5}-4×10^{-4}
Theoretical arguments	No predictions?	Inward transport if any ($\beta<0$) Balbus & Hawley (1998)
Numerical simulations	10^{-3}-10^{-1}	None-existing for Keplerian flows
Previous lab experiments	Controversial Sisan et al. (2004) Stefani et al. (2006)	$\beta=(1\text{-}2)\times10^{-5}$ based on Wendt('33), Taylor ('36); Richard ('01), Beckley ('02)

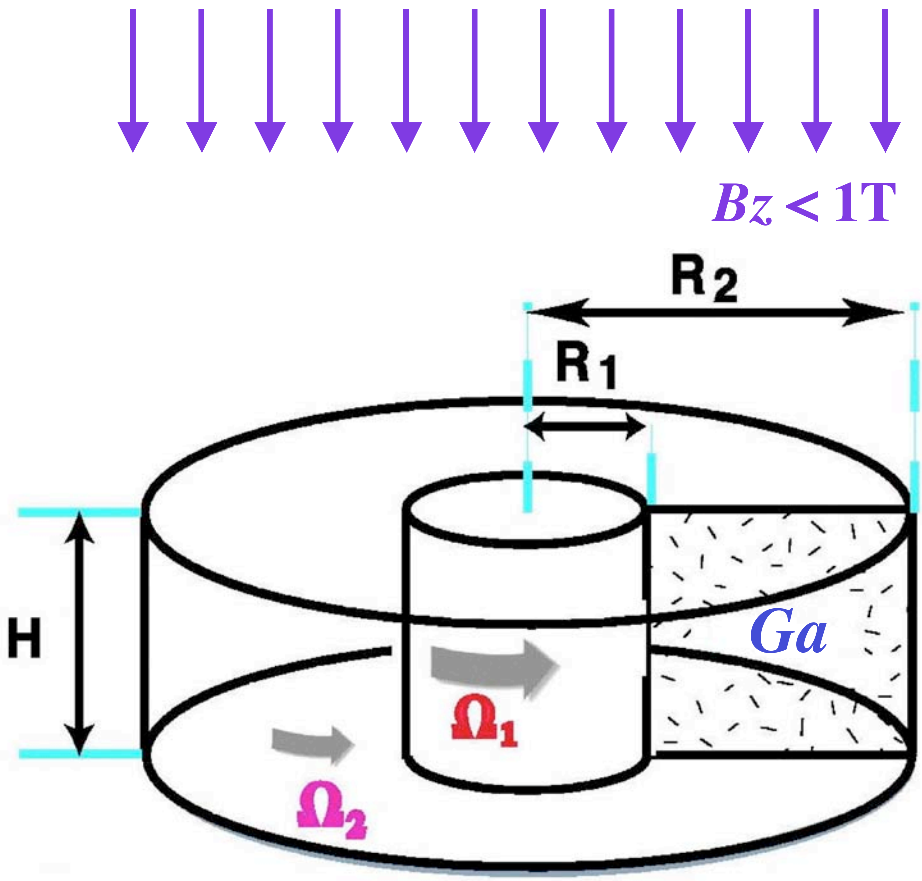
The Basic Idea

Magnetized Taylor-Couette Flow of Liquid Gallium

- **MRI destabilized with appropriate Ω_1, Ω_2 and B_z in a table-top size.**

- **Identical dispersion relation as in accretion disks in incompressible limit**

- **Centrifugal force balanced by pressure force from the outer wall**



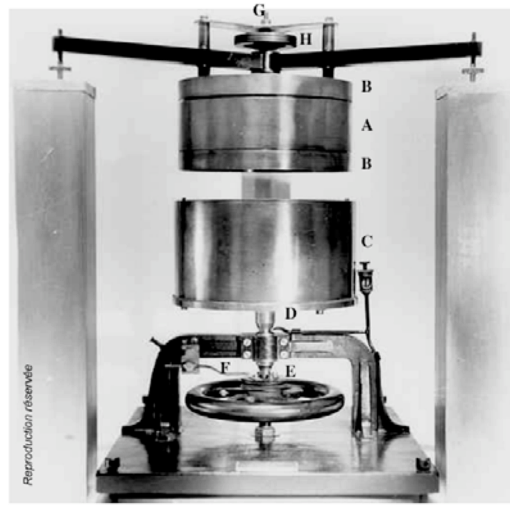
Not to simulate accretion disks, but to study basic physics

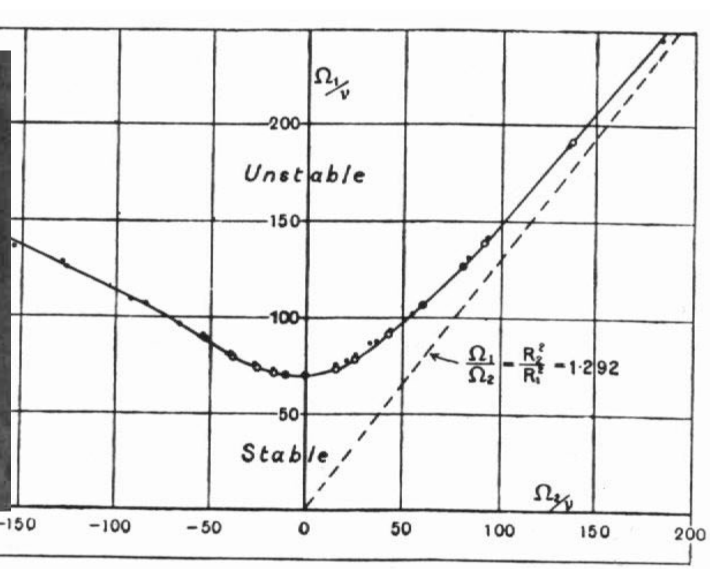
Taylor-Couette Flows

- Maurice Couette conceived first device to measure water viscosity (1890)

- Lord Rayleigh's criterion (1916): stable if angular momentum increases with radius

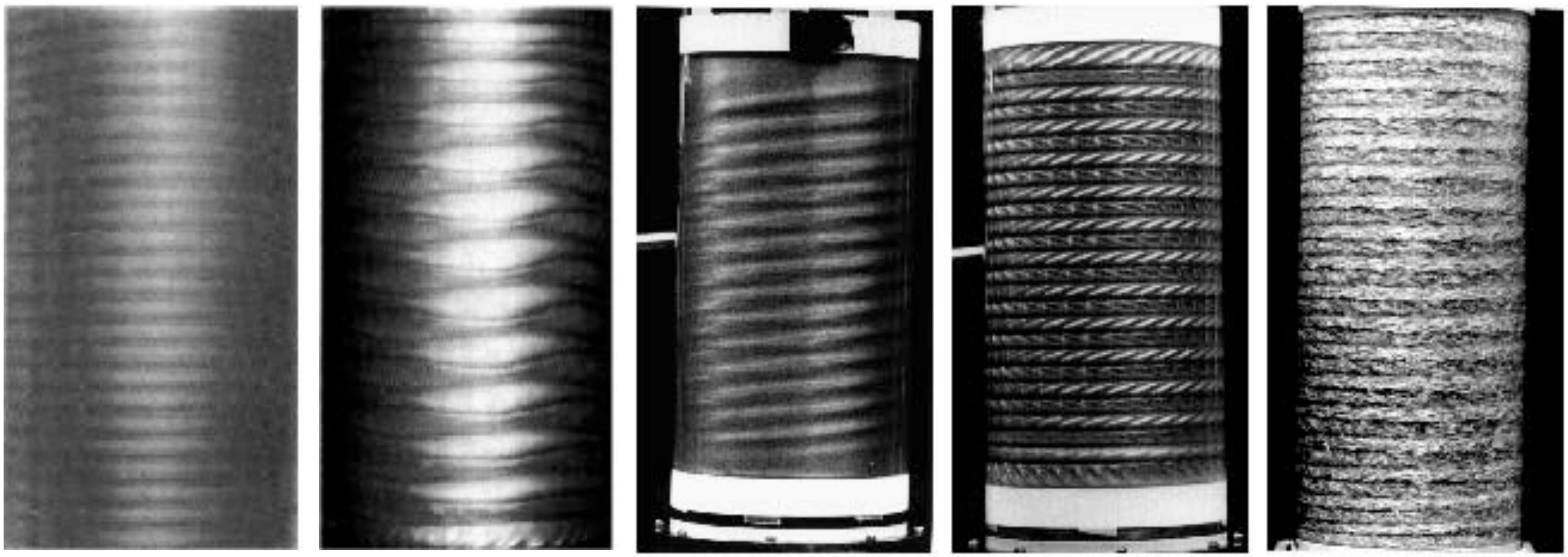
- G.I. Taylor (1923) included viscosity, leading to quantitative agreements





Taylor-Couette Flows (Cont'd)

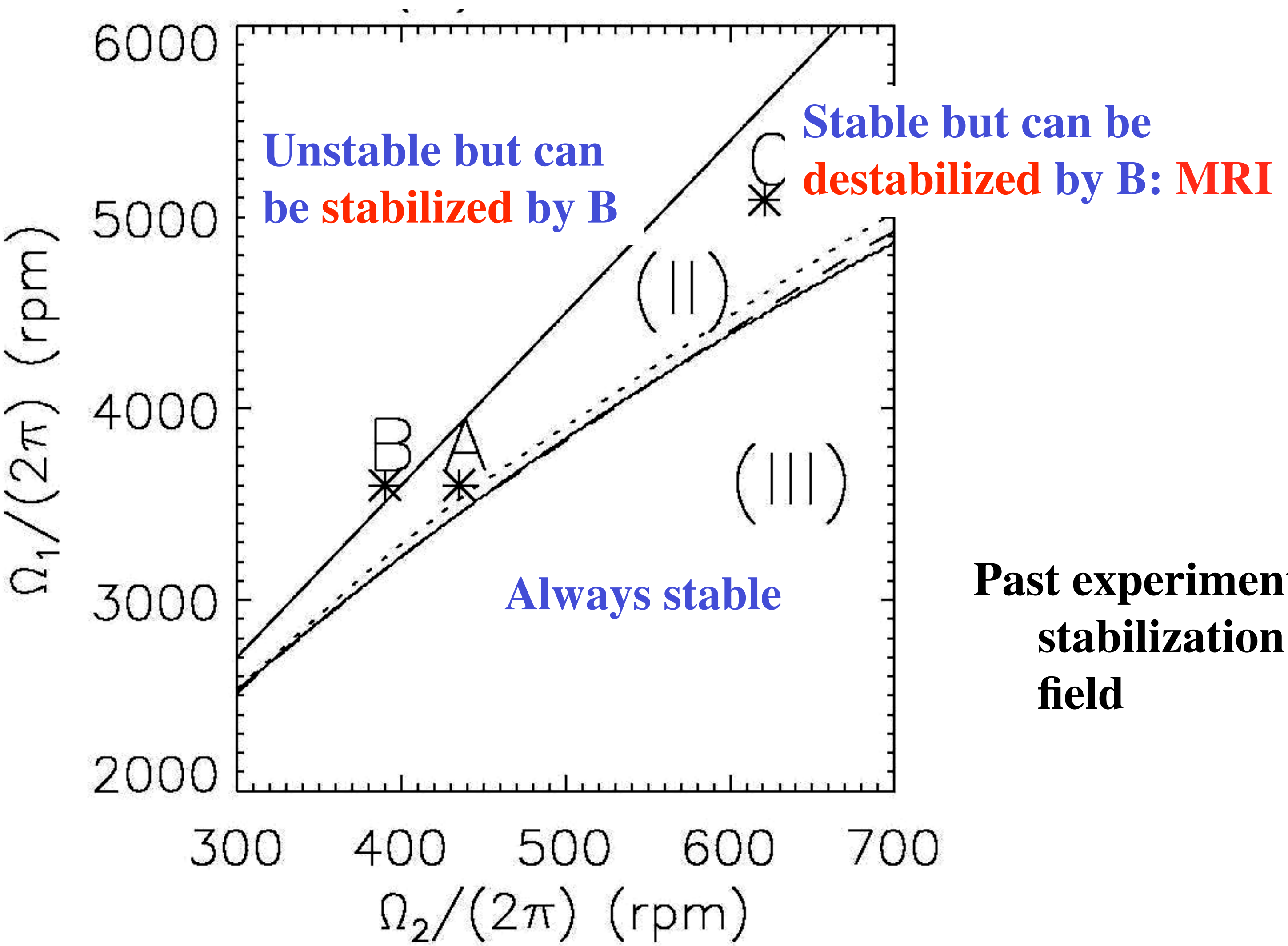
- **Most modern work focused on nonlinear dynamics: bifurcations and transition to turbulence**



Taylor Vortex | **Wavy** | **Spirals** | **Twists** | **Turbulent**

Stability Diagram of Magnetized Taylor-Couette Flow

Ji, Goodman, and Kageyama, MNRAS (2001)



Past experiments focused on stabilization by magnetic field

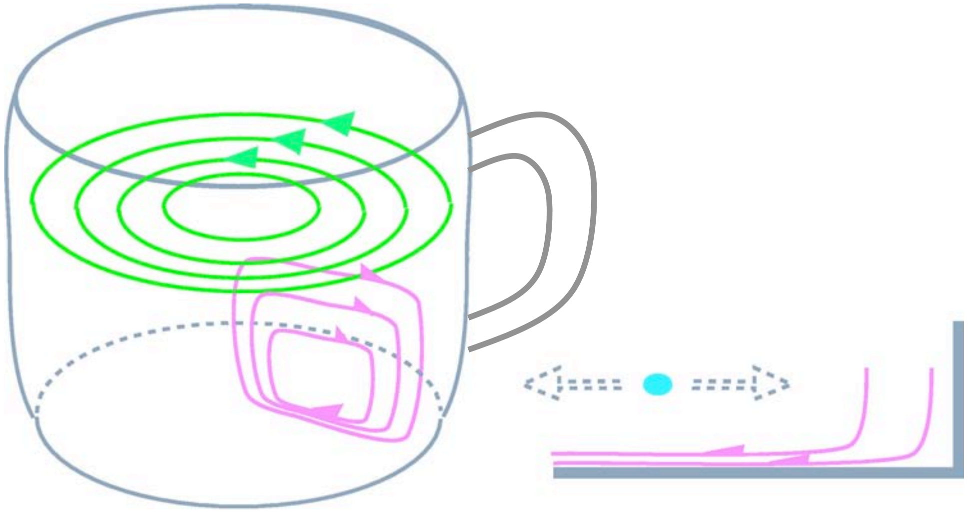
Experimental Adventure

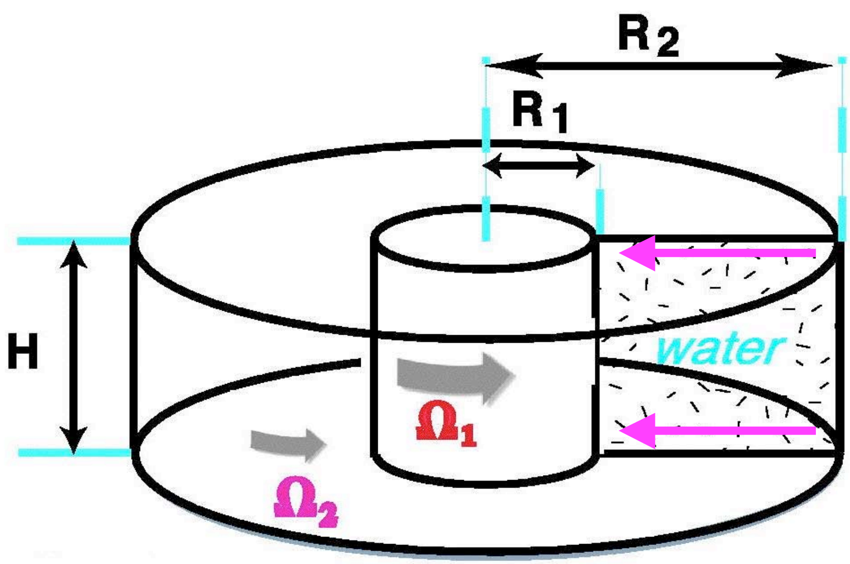
A Prototype Experiment

- **Seed particles to monitor stability and to measure flow**

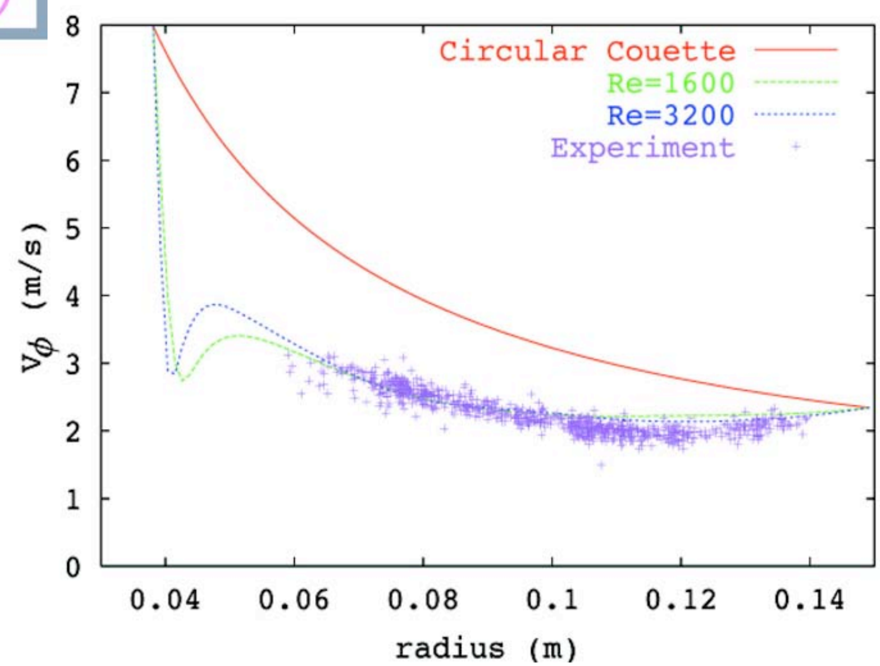
Potter's wheel

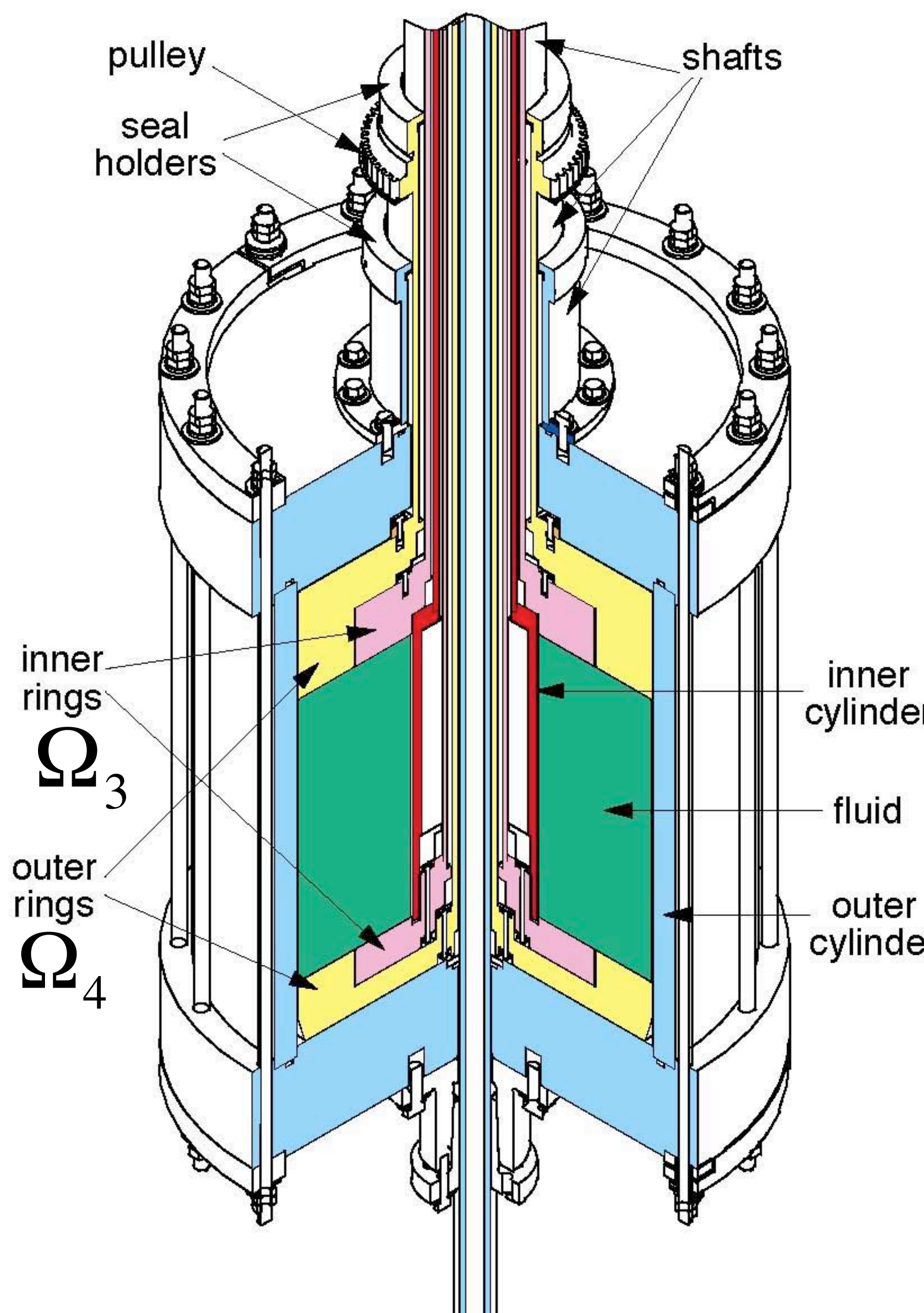
Prototype Experiments: *Ekman Effects* due to Axial Boundaries are Important

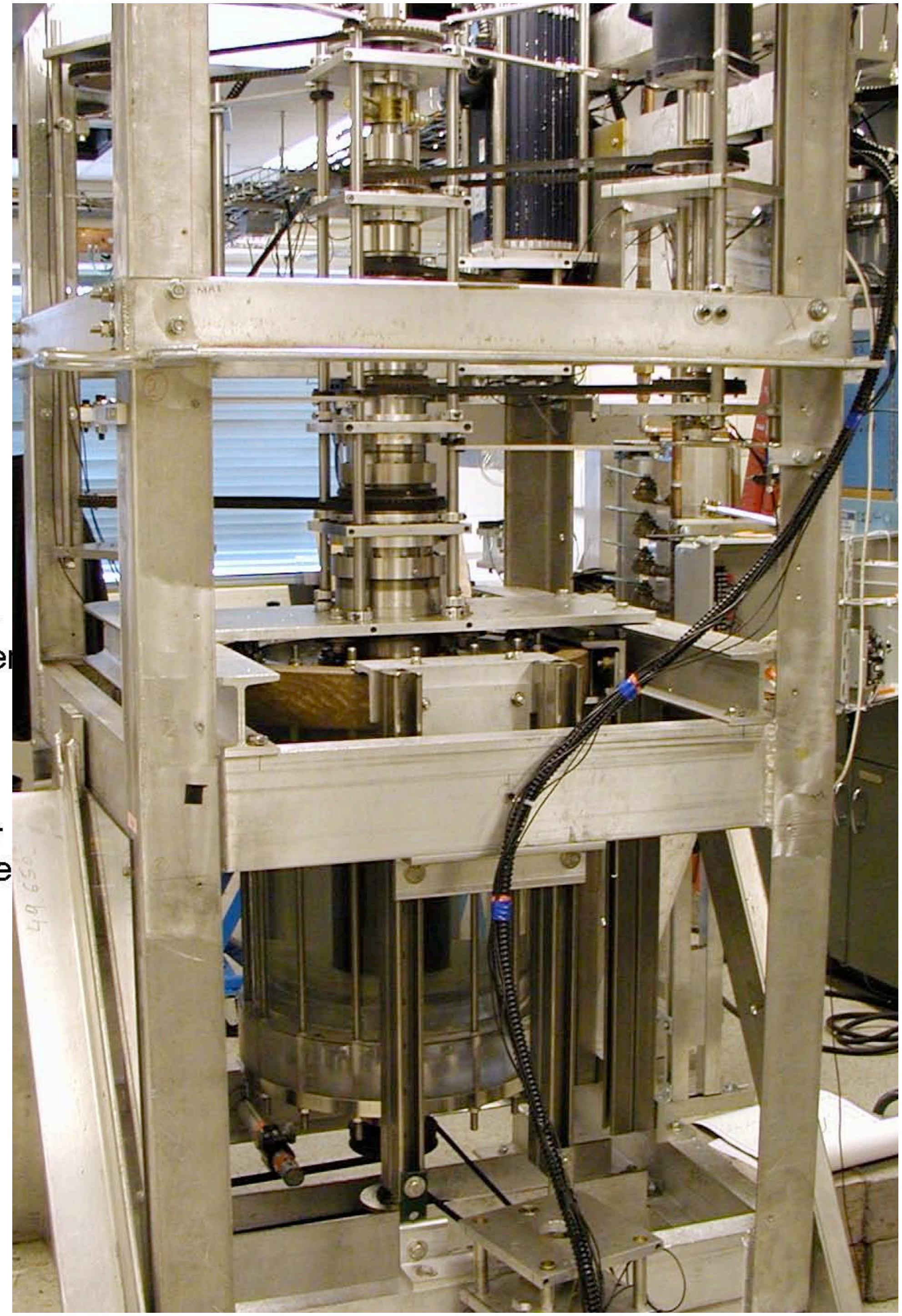




Kageyama et al. (2004)





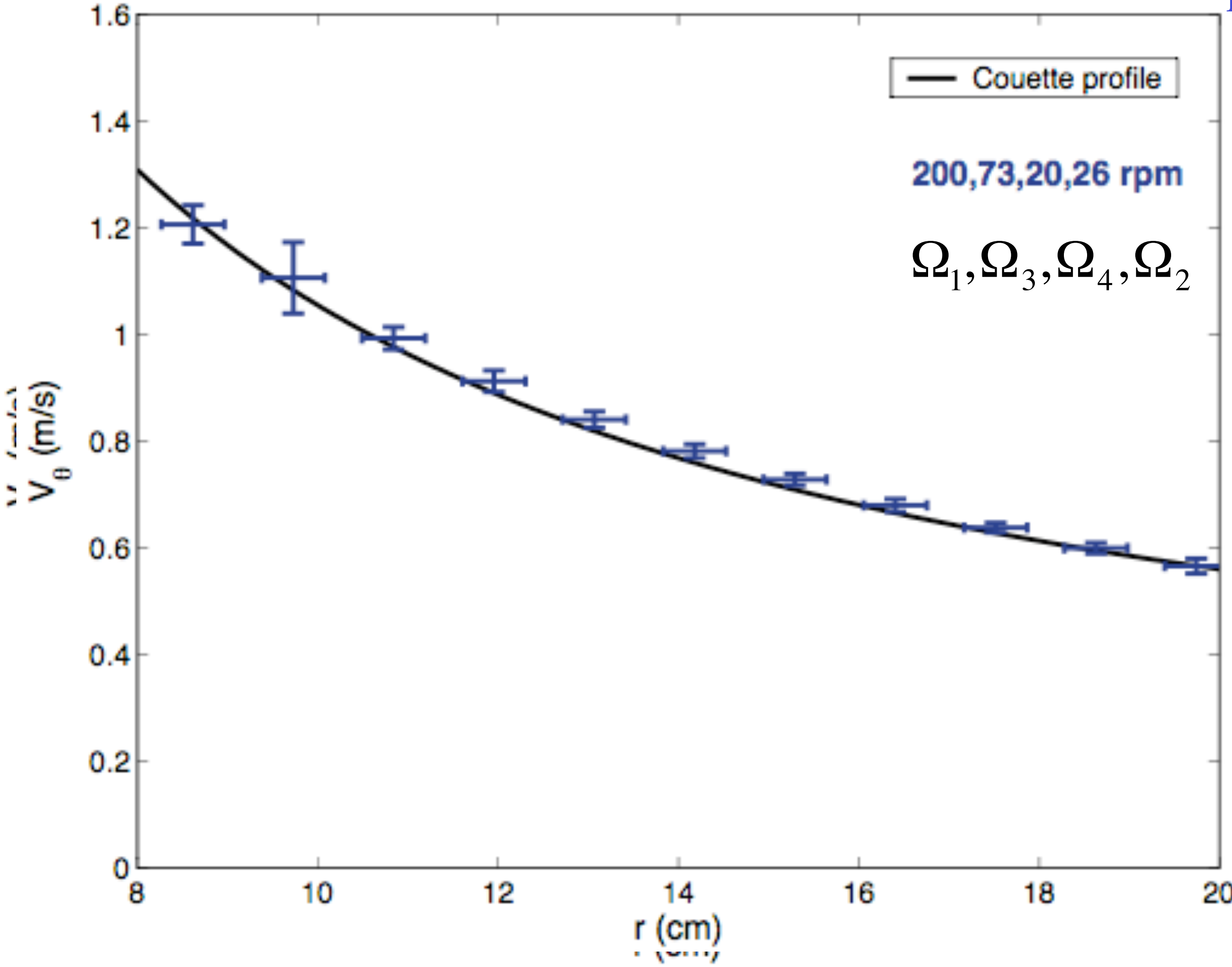


To control Ekman effects

Hydrodynamic Stability
At Large Reynolds Numbers

Fine Profile Controls by Rings

Burin et al. (2006)



Guess #0

Guess #1

Guess #2

Guess #3

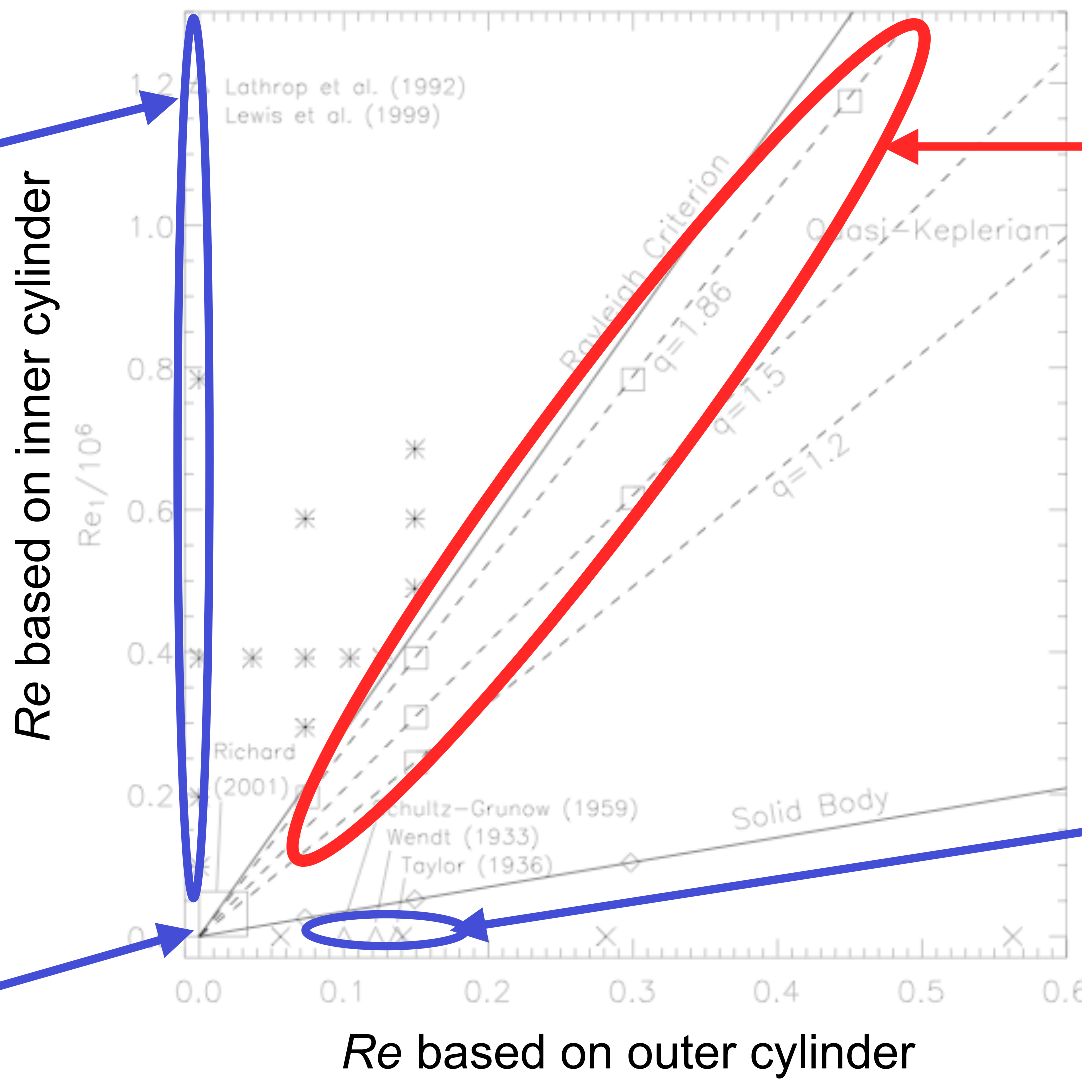
Guess #4

Guess #5

Guess #6

Various Types of Flows Explored at Much Larger Reynolds Numbers (> 10^6)

most Taylor-Couette exp's explore along this line

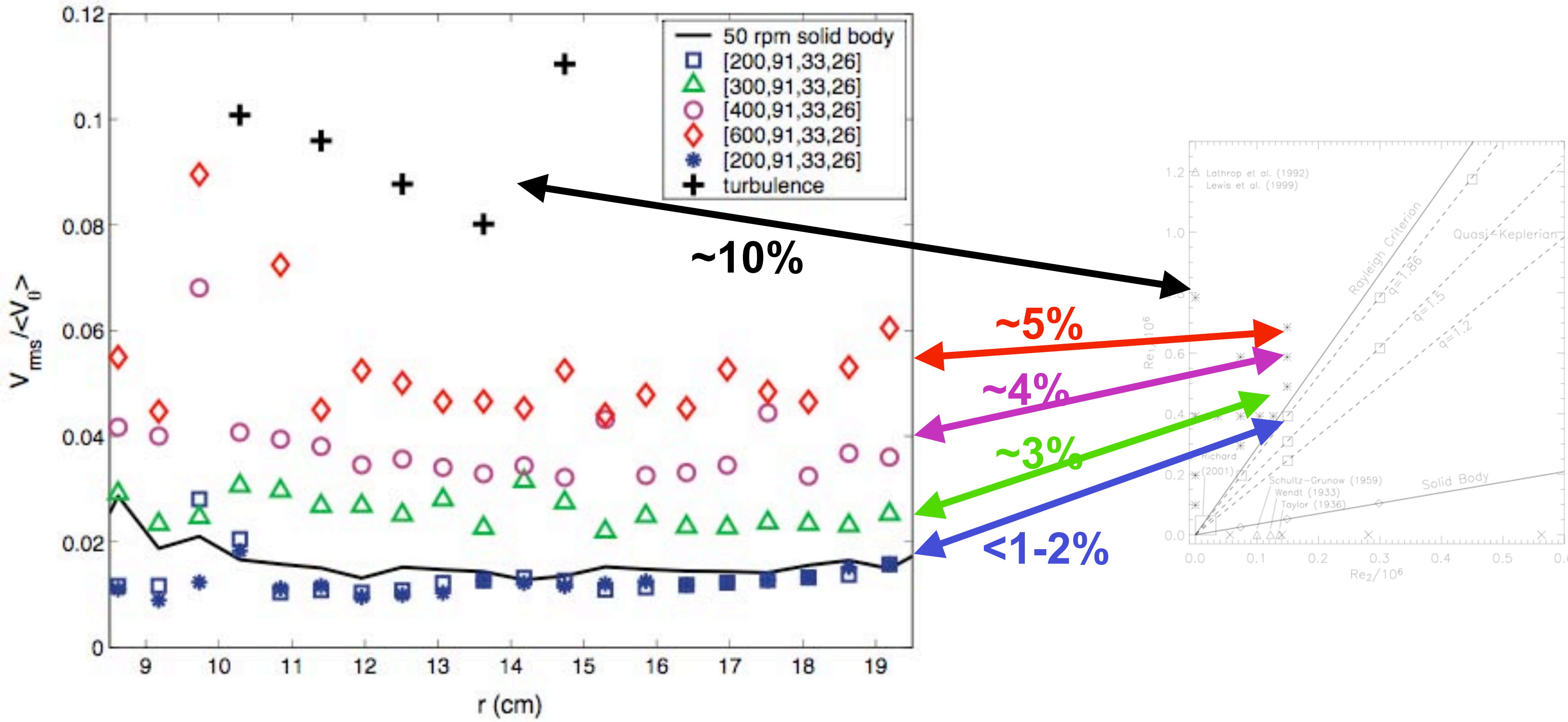


quasi-Keplerian flows: *as quiet as solid-body flows*

Exp's used to derive β

Richard 2001

Flow Becomes as Quiet as Solid-body When Entering Linearly Stable Regime Even at Re > 10^6



No hysteresis

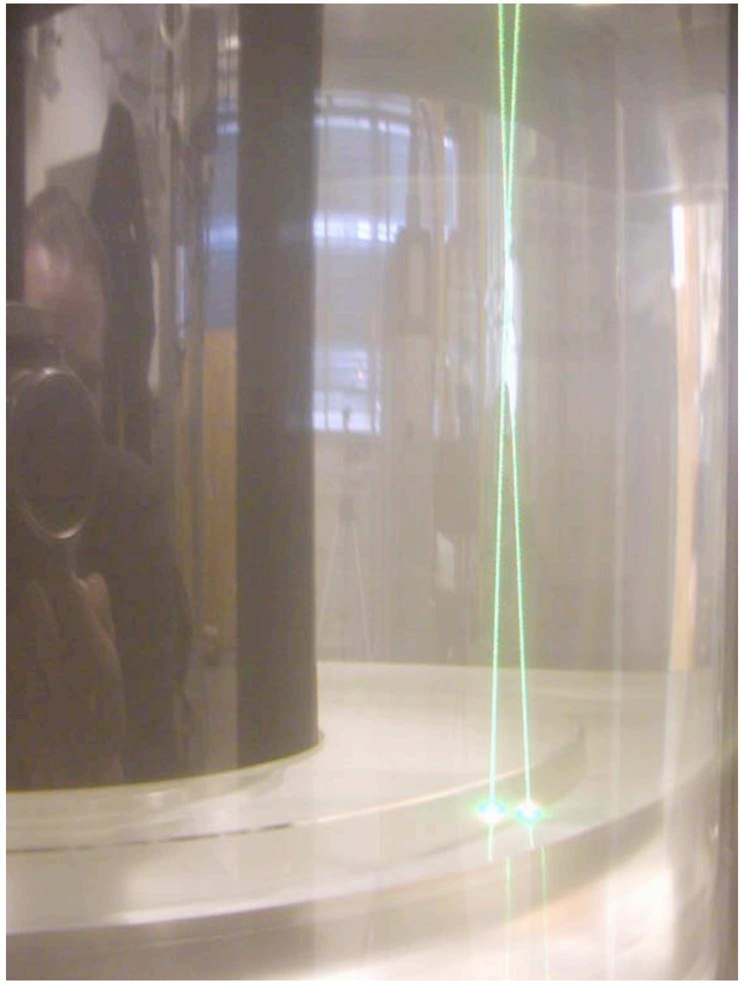
Direct Measurement of Reynolds Stress

- Quantifying transport:

$$\nu_{turb} = \beta R^3 \left| \frac{\partial \Omega}{\partial R} \right| \qquad \beta \equiv \frac{\langle \tilde{V}_r \tilde{V}_\theta \rangle}{q^2 \langle V_\theta \rangle^2}$$

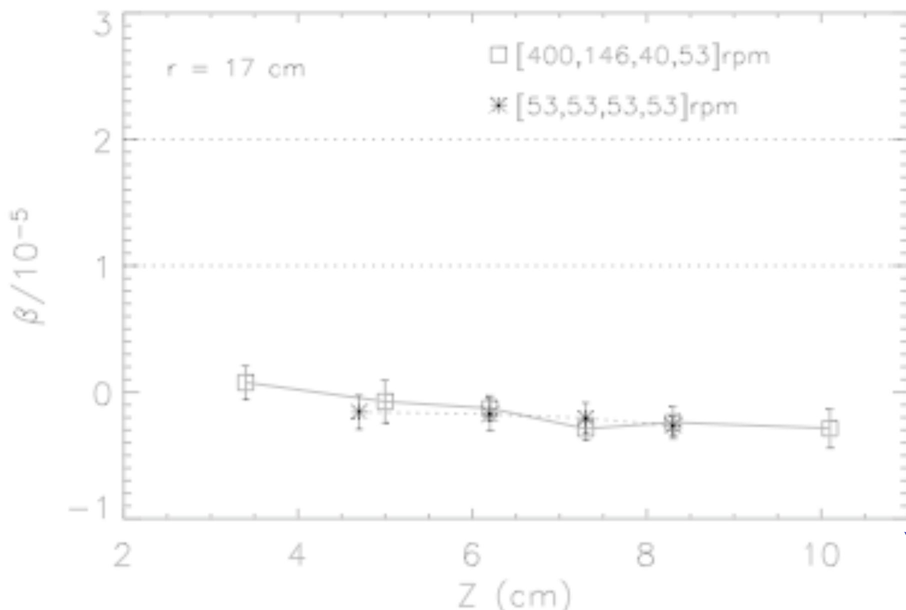
  Proposed value: $\beta = (1-2) \times 10^{-5}$

- Simultaneous measurement of V_r and V_θ by a dual synchronized Laser Doppler Velocimetry
  - Random errors are reduced by large number statistics
  - Systematic errors are removed by comparing with solid-body flows
- Benchmarked in hydrodynamically unstable cases

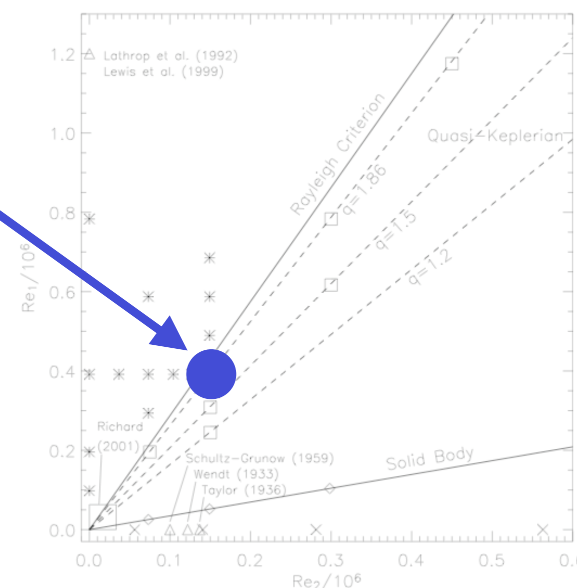


V_r measured by a pair of lasers

Negligible Reynolds Stress in Quasi-Keplerian Flows -- with Optimal Boundary Conditions

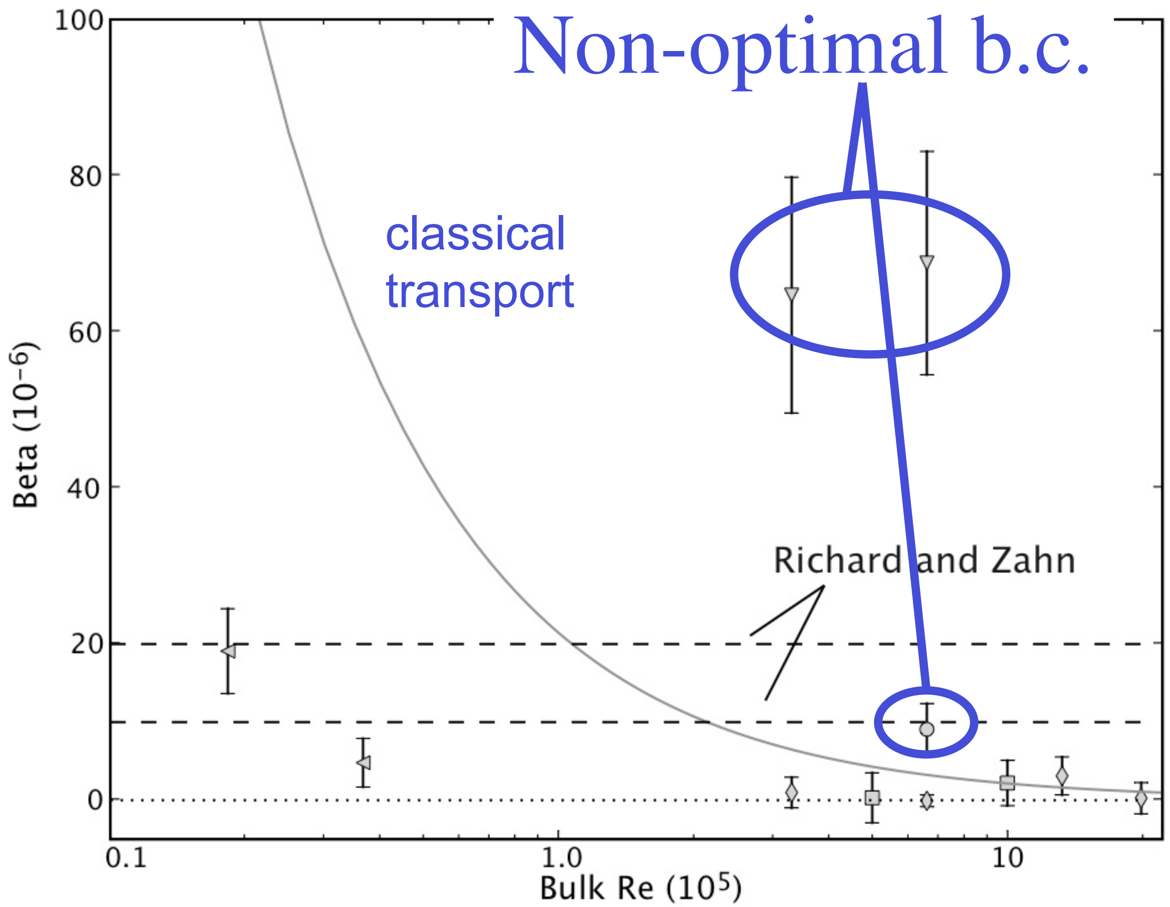


proposed value



No Signs of Turbulence up to Re=2×10^6

- Remarkable from experience on terrestrial flows
- Large Reynolds stress when
  - Boundary conditions not optimum, or
  - At smaller Re's
- $\beta<3.4\times10^{-6}$ with 98% confidence



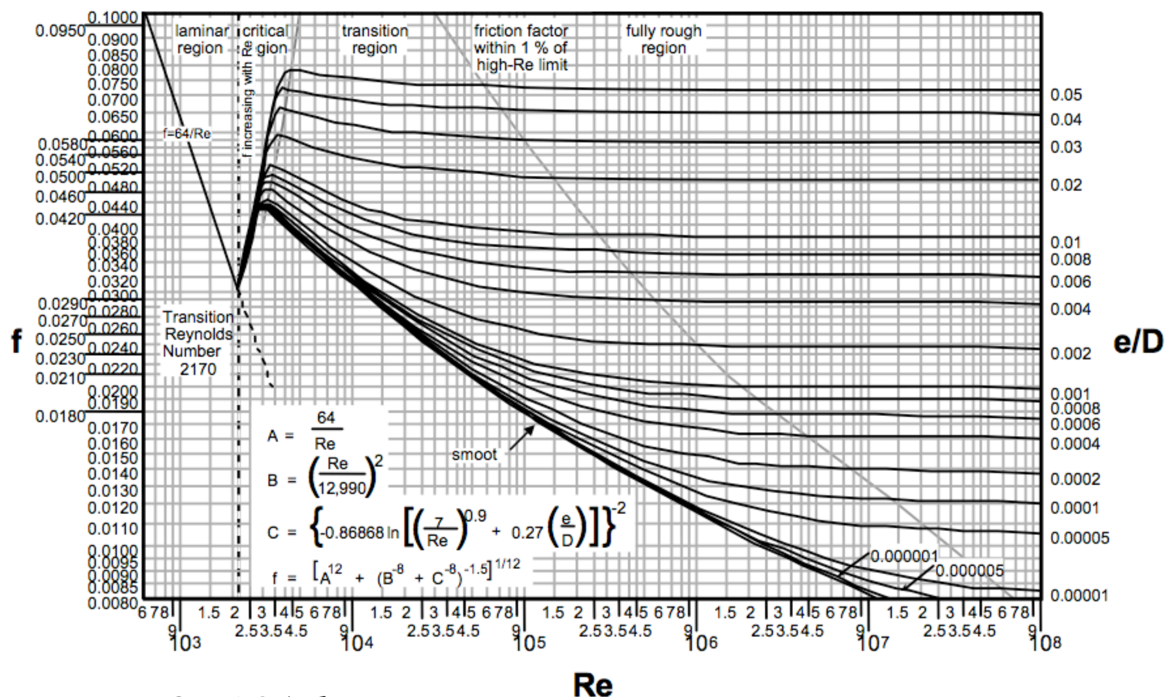
H. Ji et al., Nature (2006)
E. Schartman et al., to be submitted to A&A (2008)

Nonlinear Instabilities Very Unlikely Important in Accretion Disks where $Re \geq 10^{12}$

- Transition has happened at Re < 2×10^6, but turbulence was undetectable
  - Turbulence unlikely important at larger Re's

Turbulent transitions in pipe flows at different wall roughness: "Moody Diagram"

$$f \equiv -D\frac{dP}{dx}\Big/\frac{1}{2}\rho\overline{U}^2$$

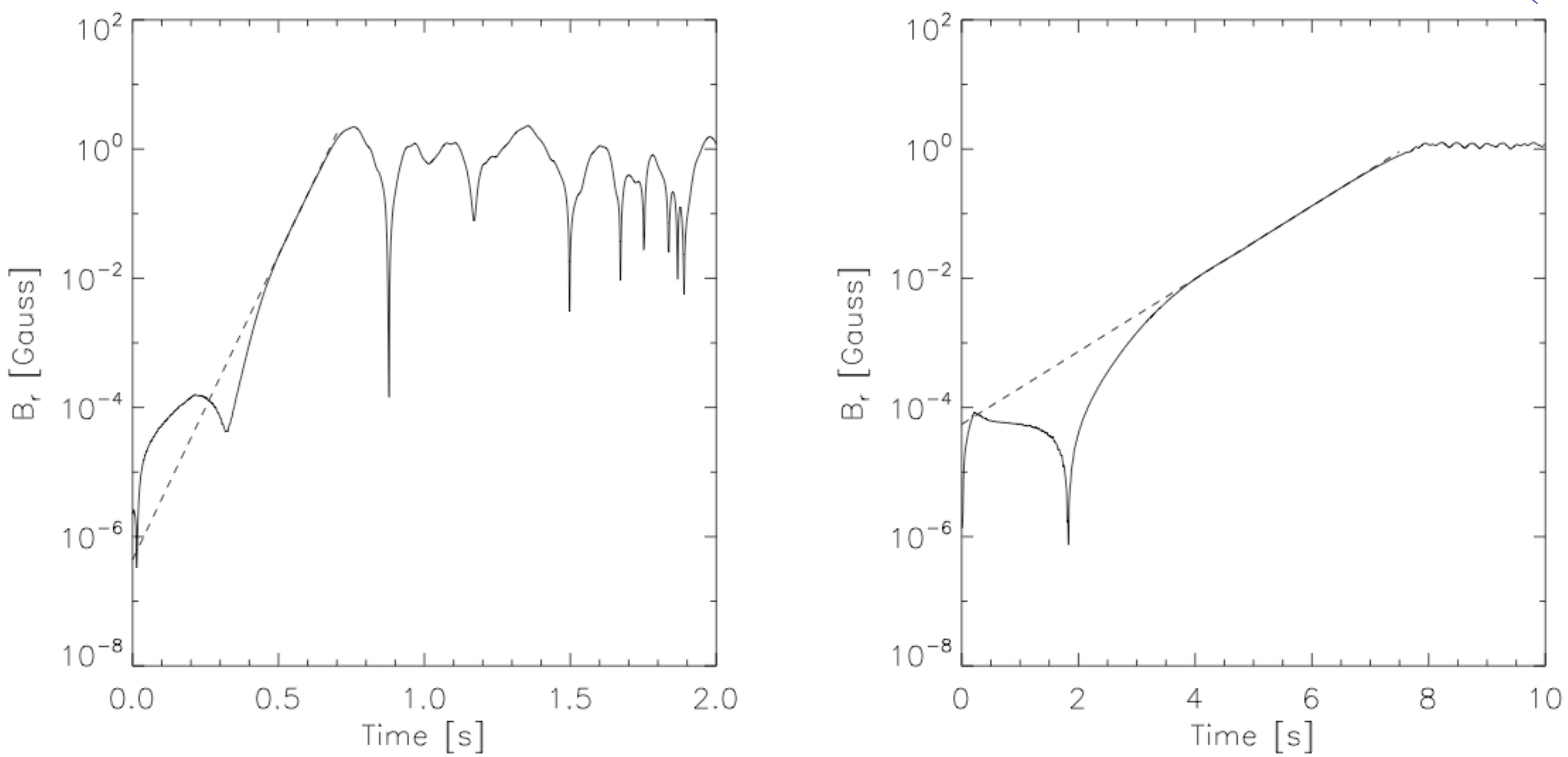


- Transition happens at Re > 2×10^6
  - Turbulence unlikely important, since larger Re_crit ⟹weaker turbulence above transition

Initial Liquid Gallium Experiments

Predictions by 2D Simulation with Realistic Boundaries

Liu (2008)



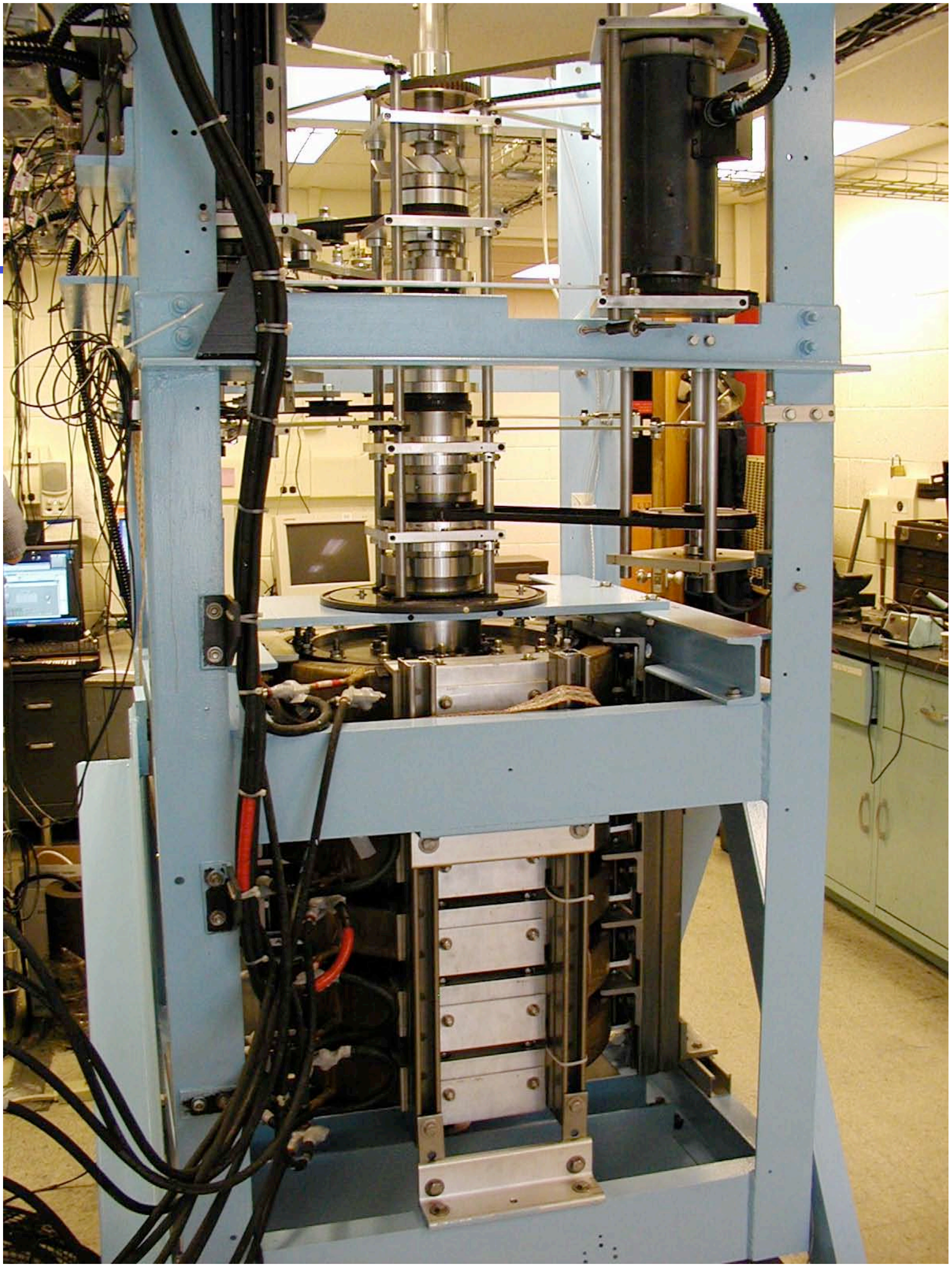
100% speeds, B≈2.5kG
γ≈21.7/s

45% speeds, B≈1.9kG
γ≈1.3/s

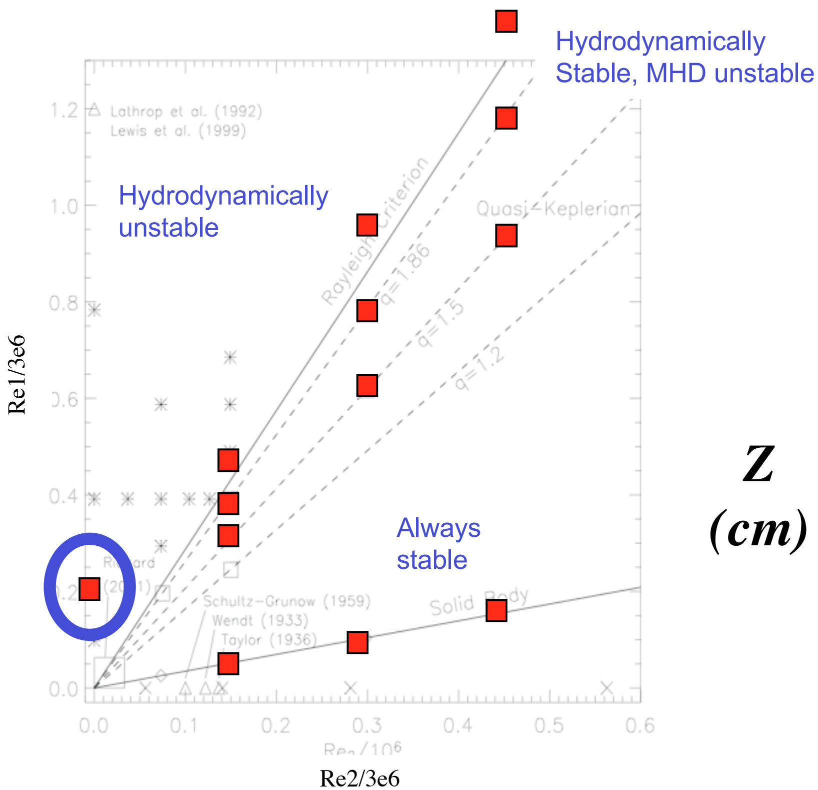
So far: 65% in water
30% in liquid metal

Liquid Metal Exp'ts Have Begun

- **Transition to liquid metal experiment**
  - Prevention of slow oxidization
  - Upgrade of motor powers
- **Axial field up to 5 kG**
- **Initial Diagnostics**
  - 4×9 array of pickup coils on surface
  - Radial flux loops

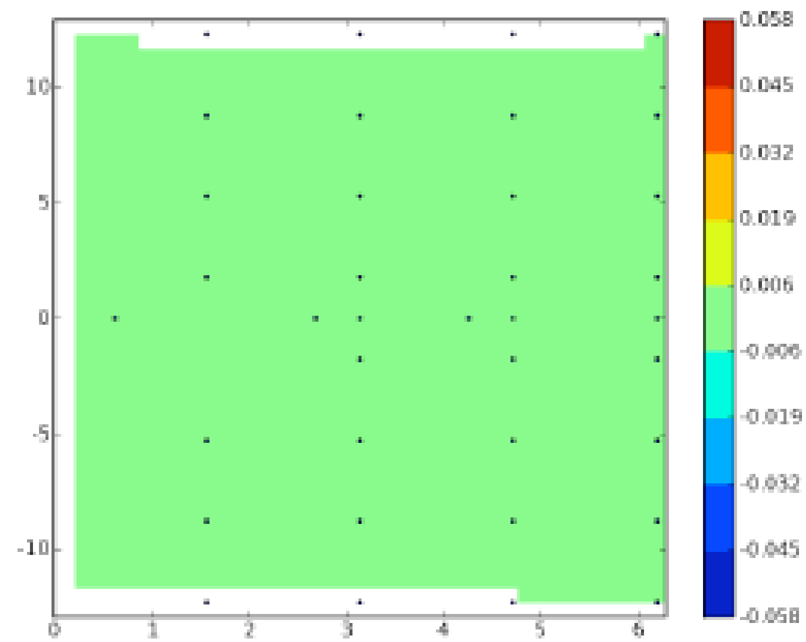


Non-axisymmetric Modes Appear When Imposing Bz on Hydro-unstable Flows



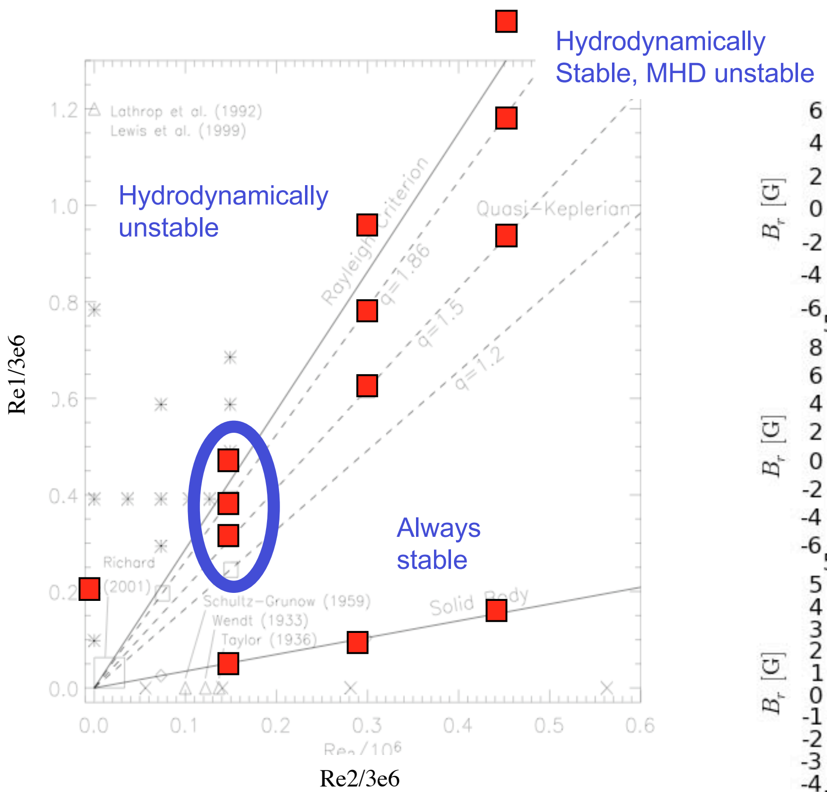
B~2.5kG

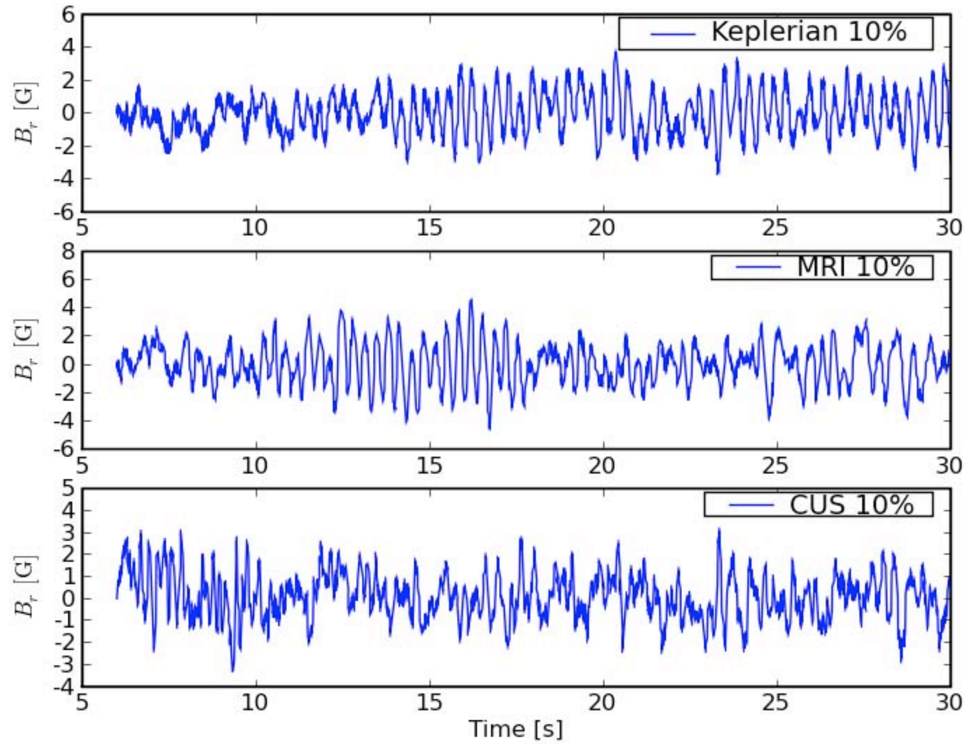
Br measurements at surface



Magneto-coriolis waves?

Non-axisymmetric Modes Also Appear When Imposing Bz on Hydro-stable Flows





B~2.5kG

Signs of MRI ?

Summary

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Observations Hueso & Guillot (2005)	e.g. 10^{-3}-10^{-1}	e.g. 2×10^{-5}-4×10^{-4}
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Princeton MRI experiments	Liquid Ga exp underway; A plasma MRI prototype exp to study non-MHD effects	$\beta<3.4\times10^{-6}$ (98% conf.) Ji et al. (2006) Schartman et al. (2008)

Astrophysical Questions Addressed in Laboratory

- Nonlinear hydrodynamic turbulence for fast accretion? Effectively ruled out

- Why quasi-Keplerian flows are so robustly stable at large Re's?
  - Resembles stability of Hurricanes/Typhoons?
  - Interactions between turbulence and large-scale shear, resembling multi-scale dynamics in plasma turbulence?

- Does MRI exist in pure MHD form transporting angular momentum?
  - Importance of boundary conditions

- How does physics beyond dissipative MHD affect MRI and angular momentum transport?
  - Two-fluid effects, ambipolar diffusion (three-fluid effects), kinetic effects

→ An Exciting Time for Laboratory Astrophysics