Laboratory Plasma Astrophysics:

Magnetic Reconnection, Angular Momentum Transport, and Dynamos

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Contents

- Workshop on Opportunities in Plasma Astrophysics (WOPA)
- Roles of laboratory experiments in understanding space and astrophysical plasmas
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Workshop on Opportunities in Plasma Astrophysics (WOPA)

- Community activity to identify a unified set of major challenges and associated new opportunities
  - 10 working groups
  - > 70 members
  - From 3 communities: lab plasma physics, space physics, and astrophysics

- Worked before, during, and after the meeting, spanning over 1 year period to produce a first comprehensive report

http://www.pppl.gov/conferences/2010/WOPA

10 Major Plasma Astrophysics Questions

http://www.pppl.gov/conferences/2010/WOPA

1. How do magnetic explosions work?
2. How are cosmic rays accelerated to ultrahigh energies?
3. What is the origin of coronae and winds in virtually all stars, including Sun?
4. How are magnetic fields generated in stars, galaxies, and clusters?
5. What powers the most luminous sources in the universe?
6. How is star and planet formation impacted by plasma dynamics?
7. How do magnetic field, radiation and turbulence impact supernova explosions?
8. How are jets launched and collimated?
9. How is the plasma state altered by ultra-strong magnetic field?
10. Can magnetic fields affect cosmological structure formation?

10 Major Plasma Topics

http://www.pppl.gov/conferences/2010/WOPA

1. Magnetic Reconnection (J. Drake)
2. Collisionless Shocks and Particle Acceleration (M. Lee)
3. Waves and Turbulence (A. Bhattacharjee)
4. Magnetic Dynamos (E. Zweibel & F. Cattaneo)
5. Interface and Shear Instabilities (D. Ryutov & M. Pound)
6. Angular Momentum Transport (E. Quataert)
7. Magnetized Dusty Plasma (E. Thomas)
8. Radiative Hydrodynamics (B. Remington)
9. Relativistic, Pair-Dominated, Strongly Magnetized Plasmas (E. Liang)
10. Jets and Outflows Including Structure Formation (H. Li)

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David Schultz

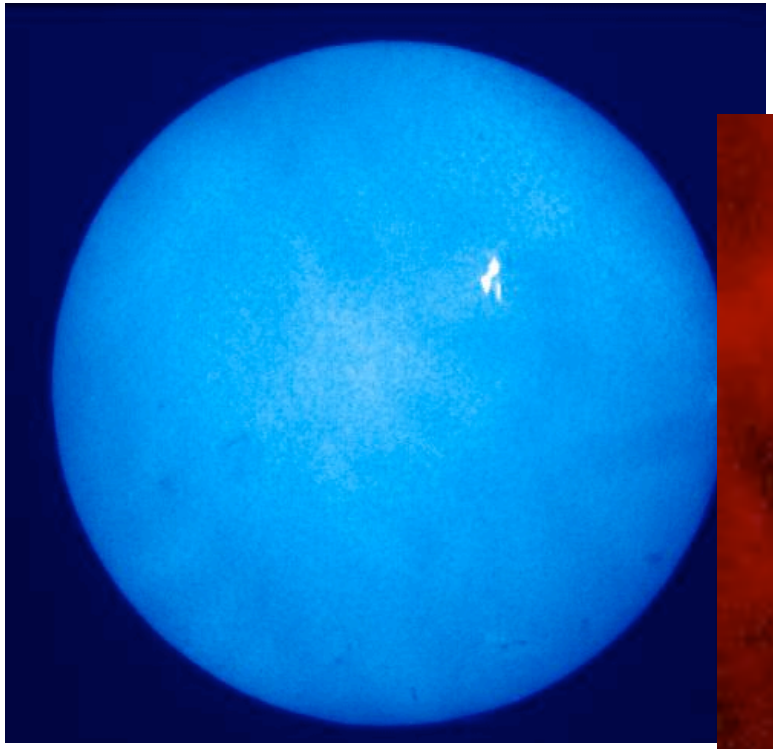
Roles of Laboratory Experiments in Understanding Astrophysical Plasmas

- **Laboratory plasma physics has advanced significantly in terms of physics, technology, and diagnostics, partnering with theory and modeling.**
  - **Capable of providing *both* in-situ and remote sensing measurements**
- **Motivated by space and astrophysical observations**
- **Verify/confront theory**
- **Benchmark/challenge simulation; unique opportunity to validate codes**
- **Compare with observations; support space mission**
- **Discover new physics**

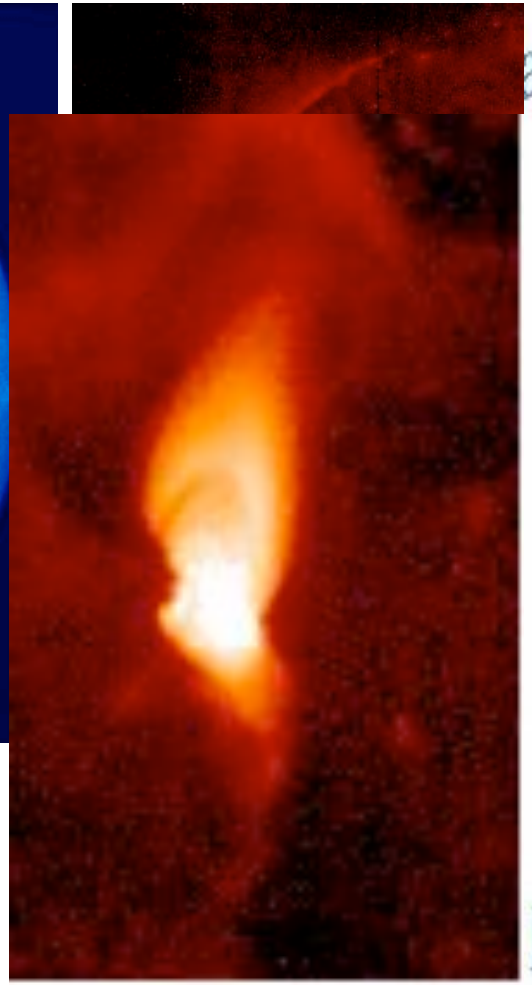
Laboratory plasma experiments can support space missions by helping achieve their science goals

Magnetic Reconnection:
How to explosively release magnetic energy?

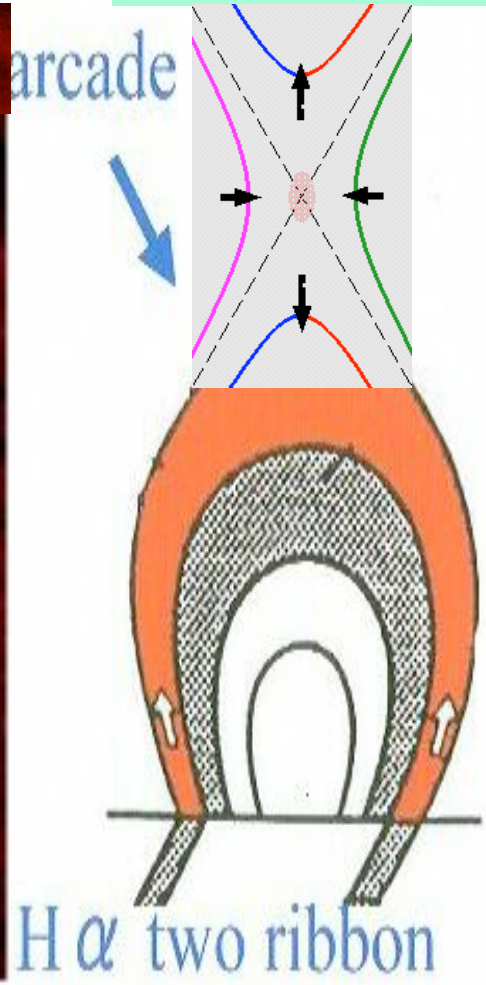
Hα



X-rays



Magnetic Reconnection



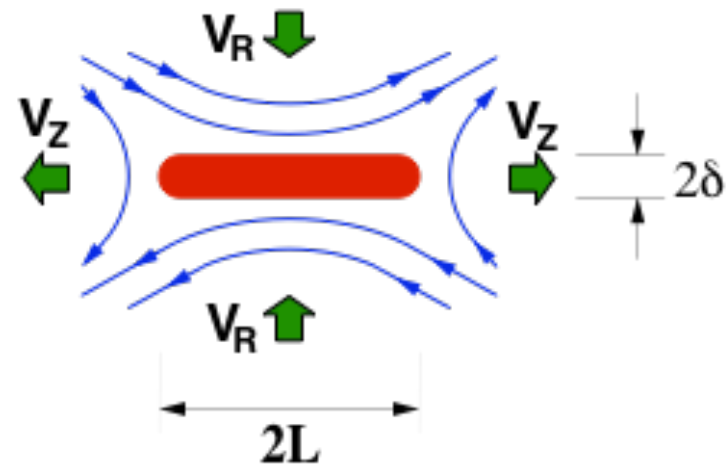
Outstanding Questions on Magnetic Reconnection

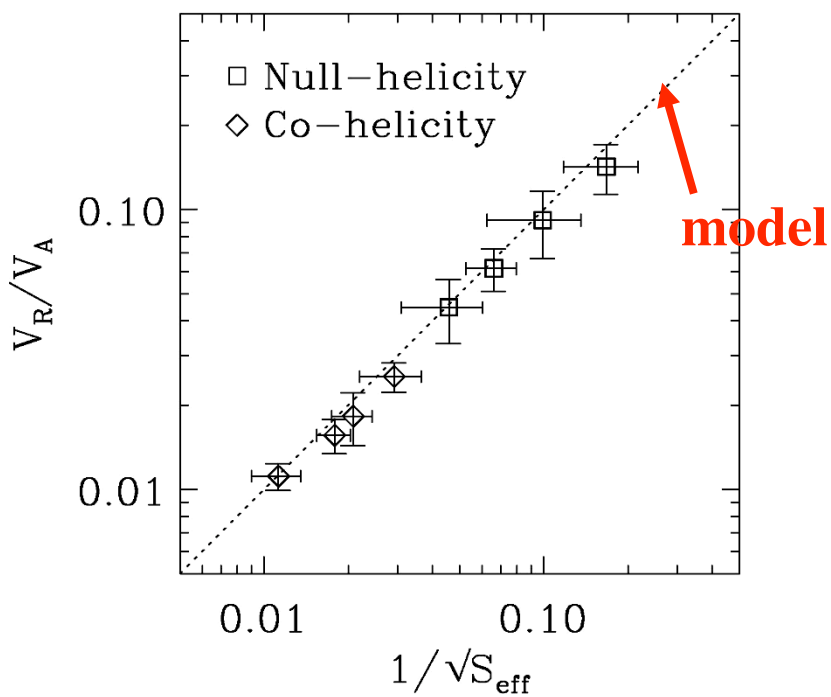
- **Why reconnection is so fast?**
- **How does reconnection take place in 3D?**
- **How does reconnection start?**
- **How are particles energized?**
- **How do boundary conditions affect reconnection process?**
- **How to apply local reconnection physics to a large system?**

Testing Sweet-Parker Model
(Petschek-like reconnection still unseen)

Ji et al. PRL (1998) PoP (1999)

- Classical S-P model predicts reconnection rate at $\frac{V_R}{V_A} = \frac{1}{\sqrt{S}}$





- First quantitative tests were done in the lab (MRX); correct only with modifications:

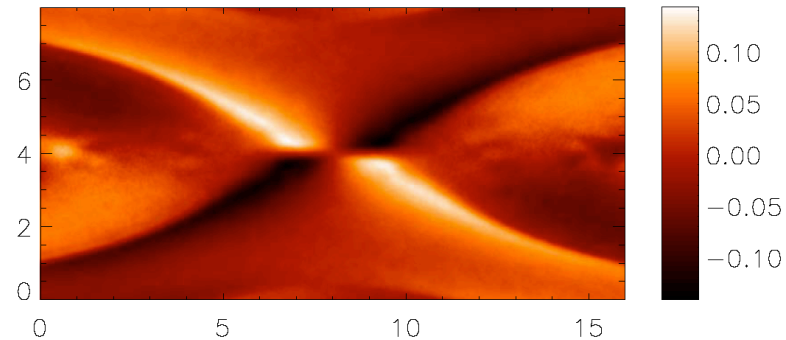
$$S_{\text{eff}} = \frac{\mu_0 L V_A}{\eta^*} \cdot \frac{1}{1 + L\dot{n}/nV_Z} \cdot \frac{V_Z}{V_A}$$

- Importance of resistivity enhancement and boundaries

Two-fluid Effects for Fast Reconnection

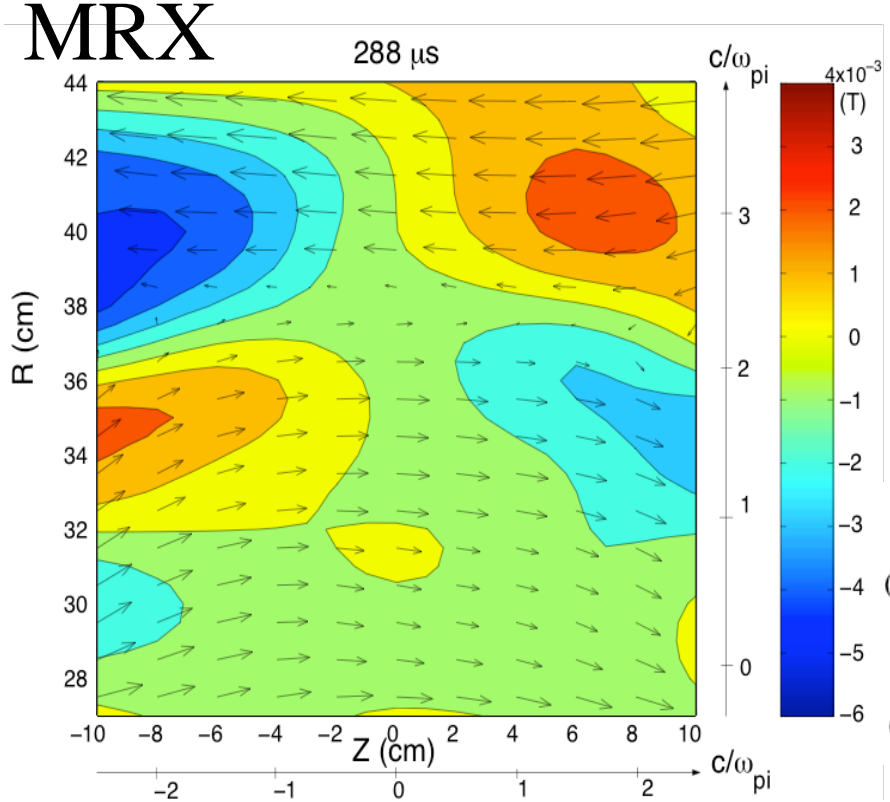
Ren et al. PRL (2005) Yamada et al. PoP (2006)
Matthaeus et al. GRL (2005), Brown et al. POP (2006)

- Numerical prediction of quadrupole out-of-plane field

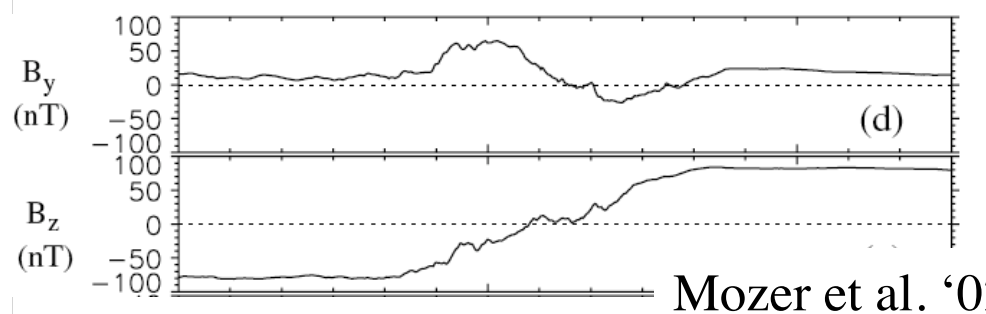


(e.g. Drake et al. '98)

MRX



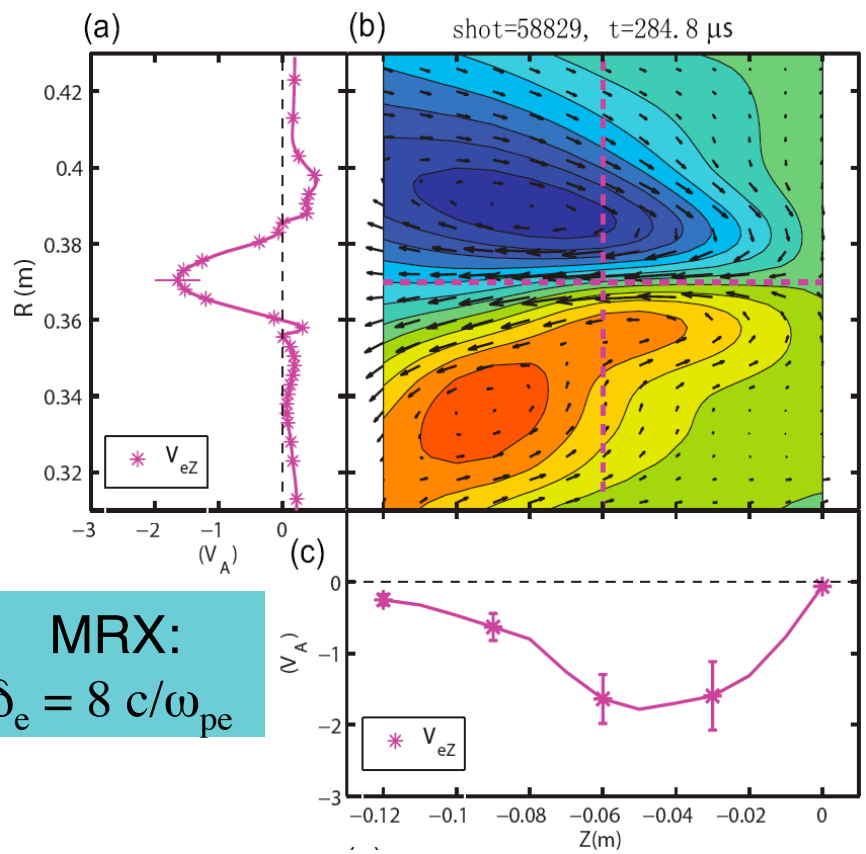
- Definite confirmation in the lab, with theoretically expected dependence on the collisionality
- Consistent with 1D space data



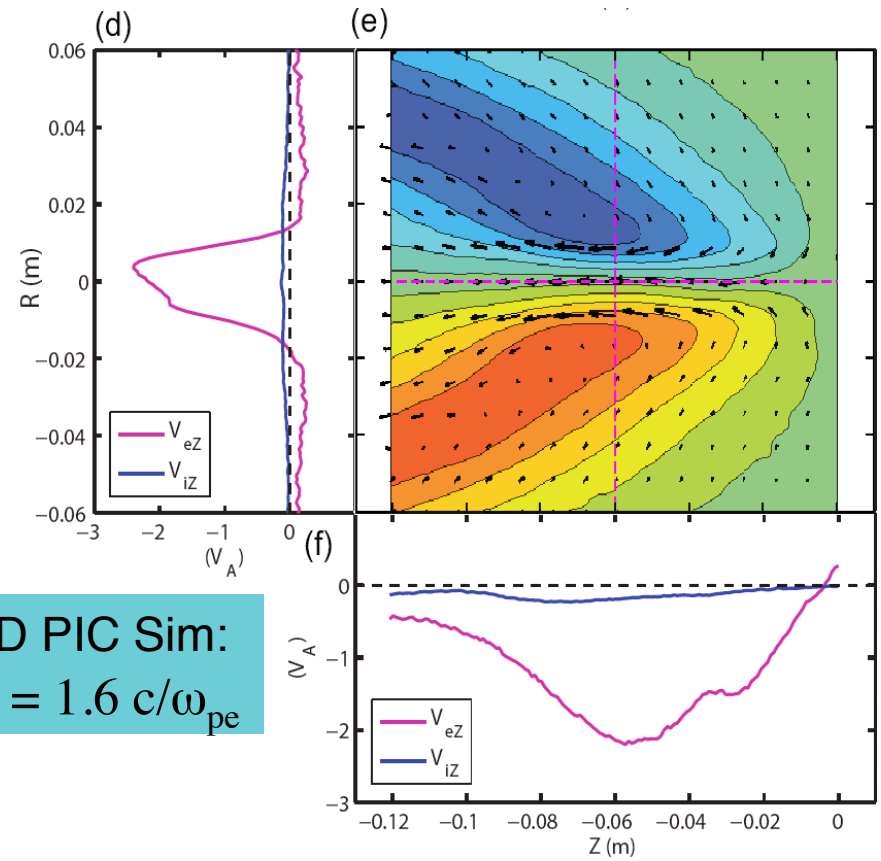
Mozer et al. '02

Detection of Electron Diffusion Region

Ren et al. PRL (2008) Ji et al. GRL (2008)
Dorfman et al. PoP (2008) Royteshteyn et al. POP (2010)



MRX:
$\delta_e = 8\ c/\omega_{pe}$

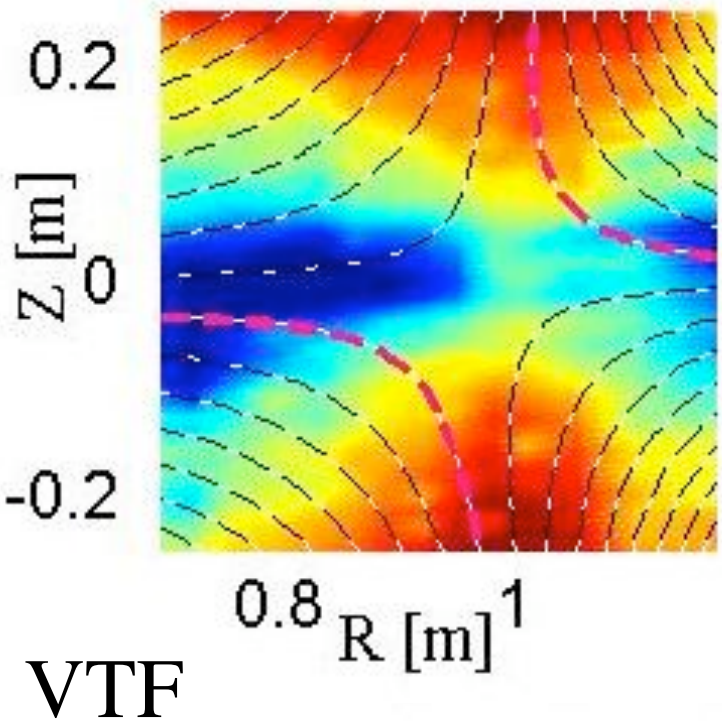


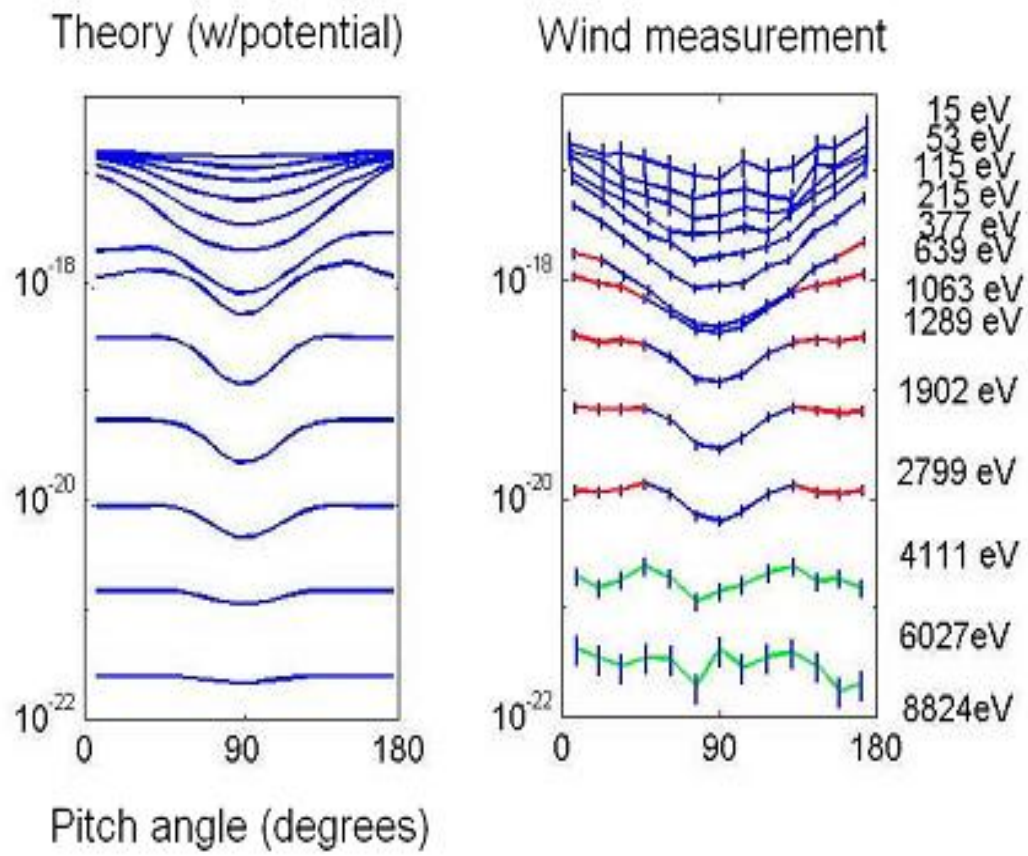
2D PIC Sim:
$\delta_e = 1.6\ c/\omega_{pe}$

- All ion-scale features reproduced, but e-layer is thicker in MRX; 3D important?: Supporting Magnetospheric MultiScale (MMS) mission

Potential Well and Electron Kinetics

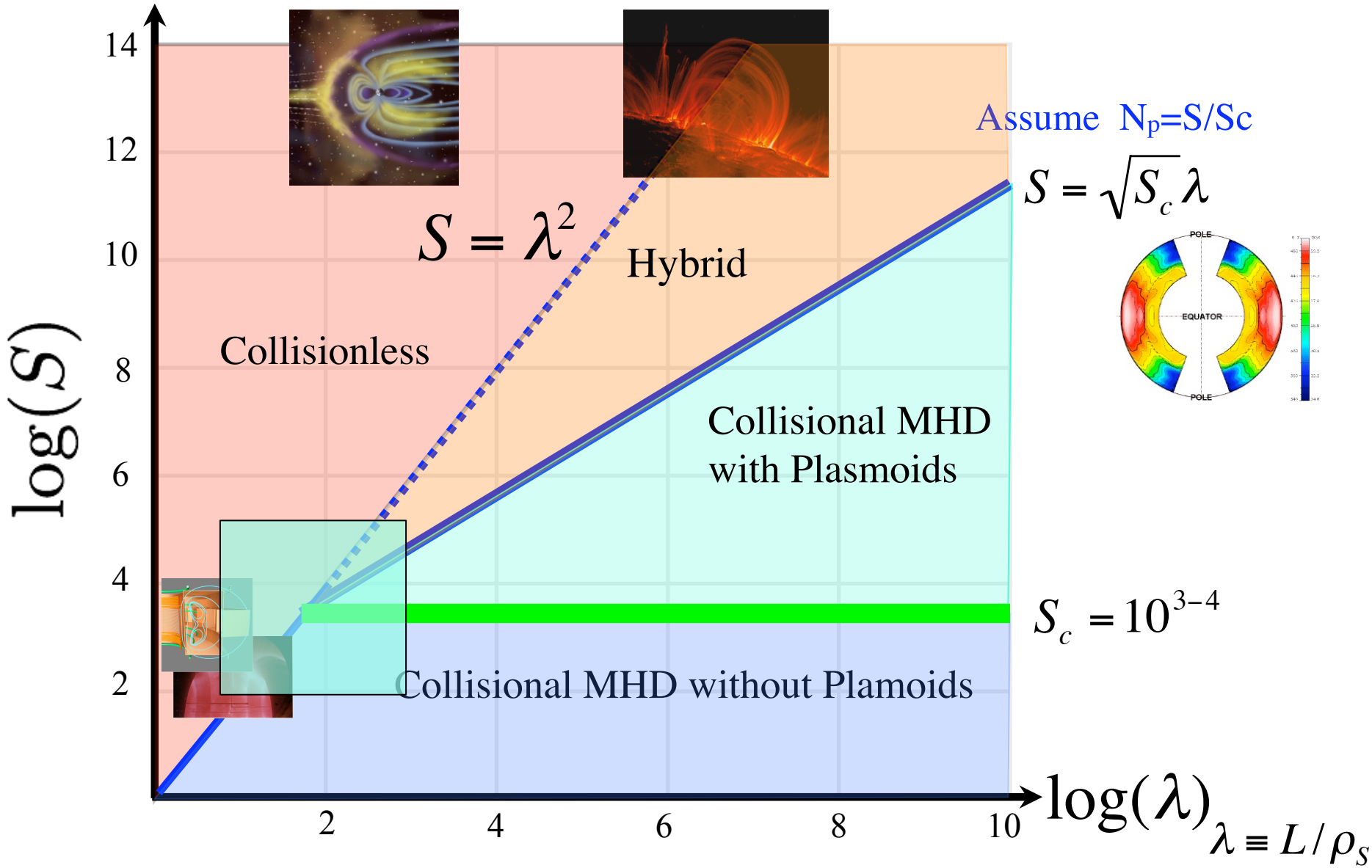
Egedal et al. PRL (2005)





- Potential well around X-line, based on results from VTF experiment, can explain measured electron distribution function in space

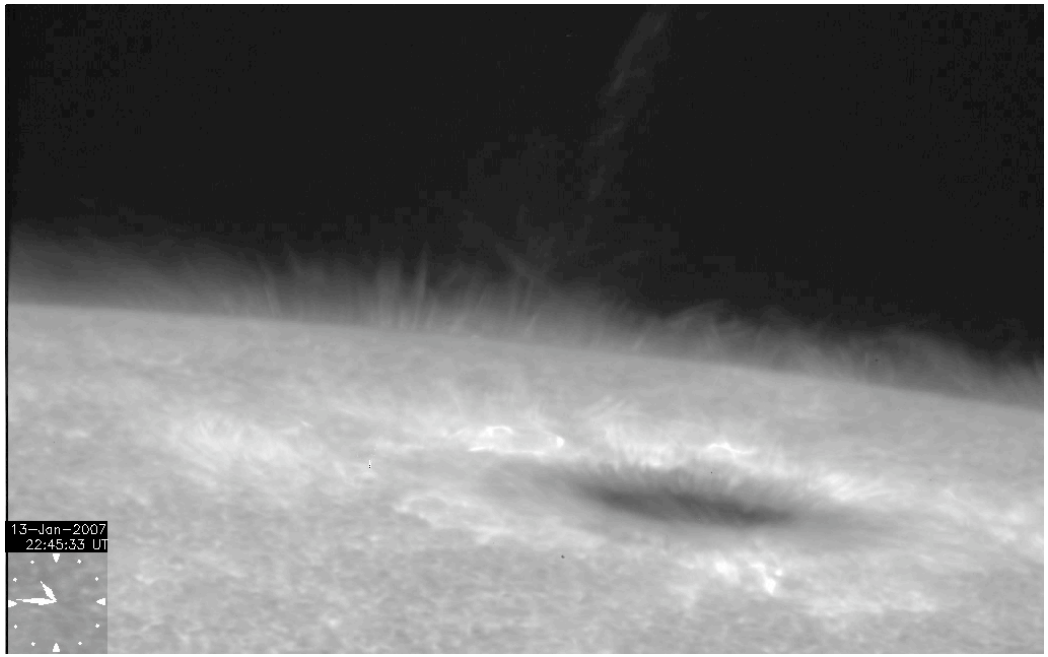
Future: next generation experiment to access different reconnection phases at high-S in large plasmas



Future: reconnection in partially ionized plasmas

Interface Region Imaging Spectrograph (IRIS) mission (2012 launch)

Ion Spectrum	λ	Δλ	Log T
	Å	mÅ	K
UV Spectra (effective area of 2.8 cm^2 fo			
†: Count rates for Mg II wing, h and k ar			
Si I (3P) Cont	1335	12.5	3.7
Mg II wing	2820	25	3.7-3.9
O I	1356	12.5	3.8
Mg II h	2803	25	4.0
Mg II k	2796	25	4.0
C II	1335	12.5	4.3
C II	1336	12.5	4.3
Si IV	1403	12.5	4.8
Si IV	1394	12.5	4.8
O IV	1401	12.5	5.2
O IV	1400	12.5	5.2
Fe XII	1349	12.5	6.2
Fe XXI	1354	12.5	7.0



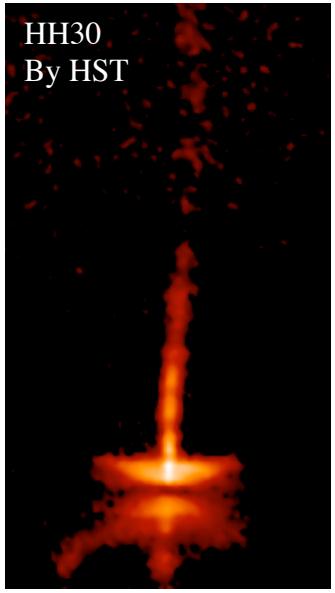
Reconnection on solar chromosphere (by Hinode)

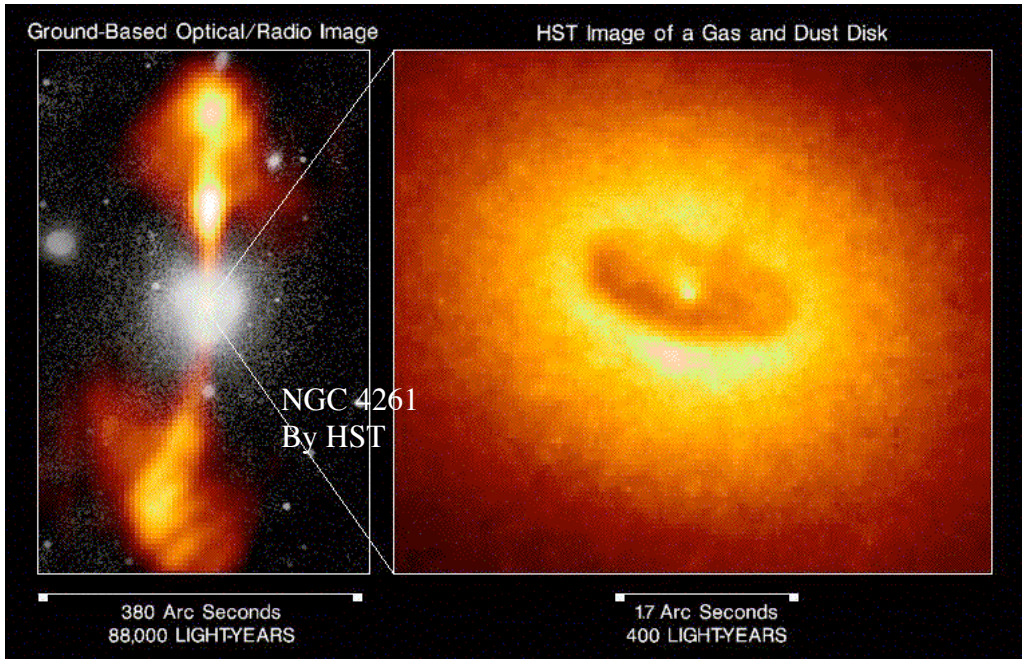
Also being studied in the lab, with planned spectral measurements

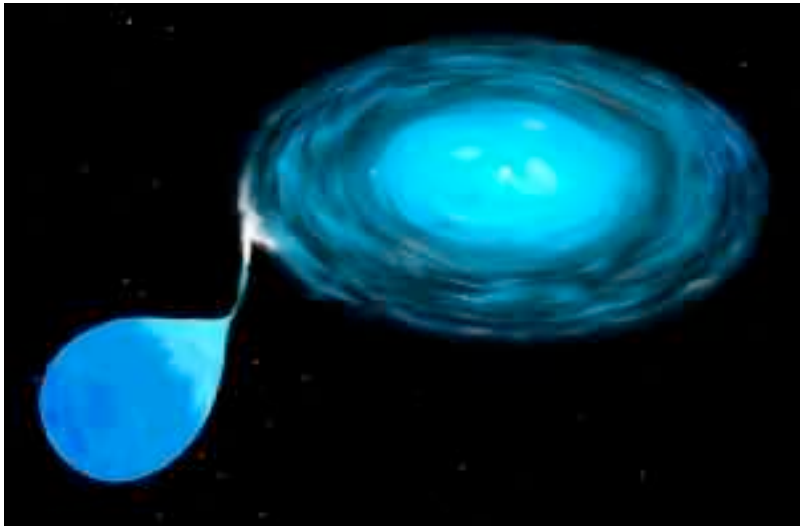
Angular Momentum Transport: Why Accretion Is Fast?

Fast accretion is observed in:

- Formation of stars and planets in proto-star systems
- Mass transfer and energetic activity in binary stars
- Release of energy in quasars and Active Galactic Nuclei







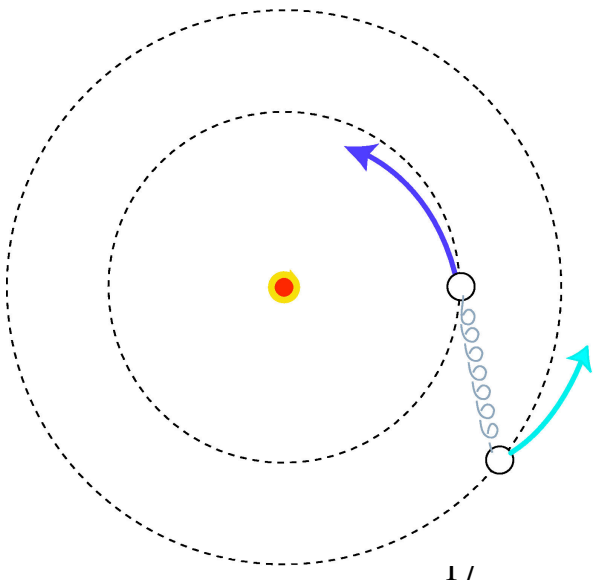
Two Main Candidate Mechanisms to Generate Turbulence for Fast Accretion

- **Nonlinear hydrodynamic instabilities in cool, poorly ionized disks**
  - **Zeldovich (1981)**
  - **Richard & Zahn (1999) based on Wendt (1933) and Taylor (1936)**
  - **Richard (2001)**

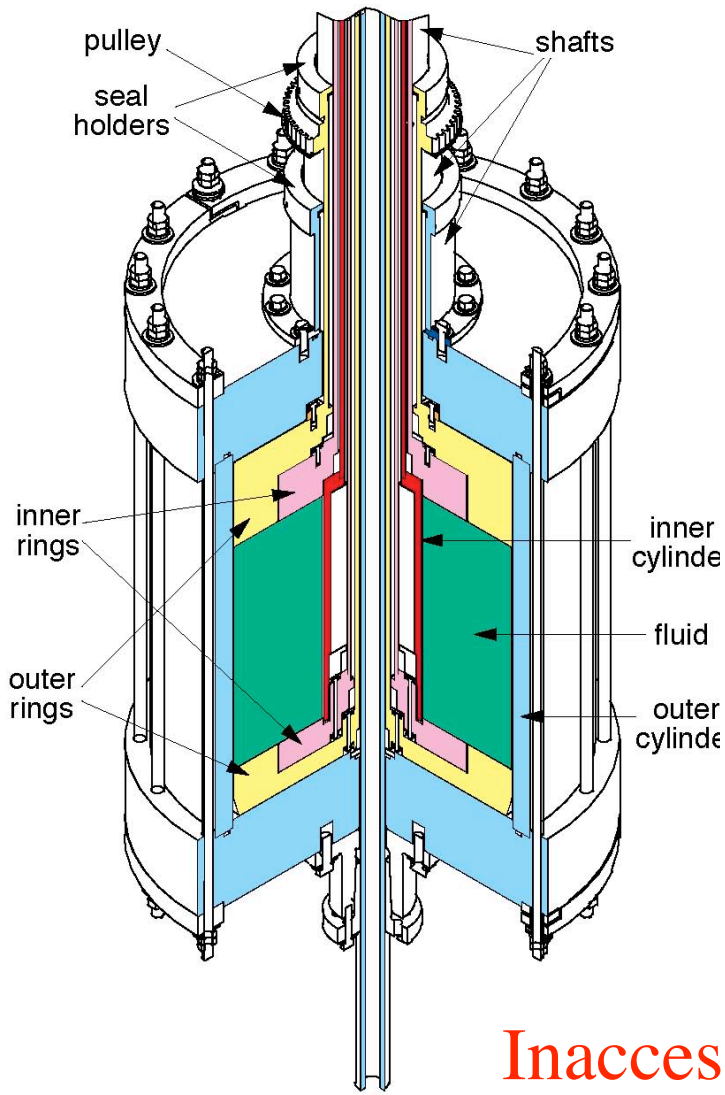
Terrestrial flows are almost always unstable if $Re > 10^2$-10^4.

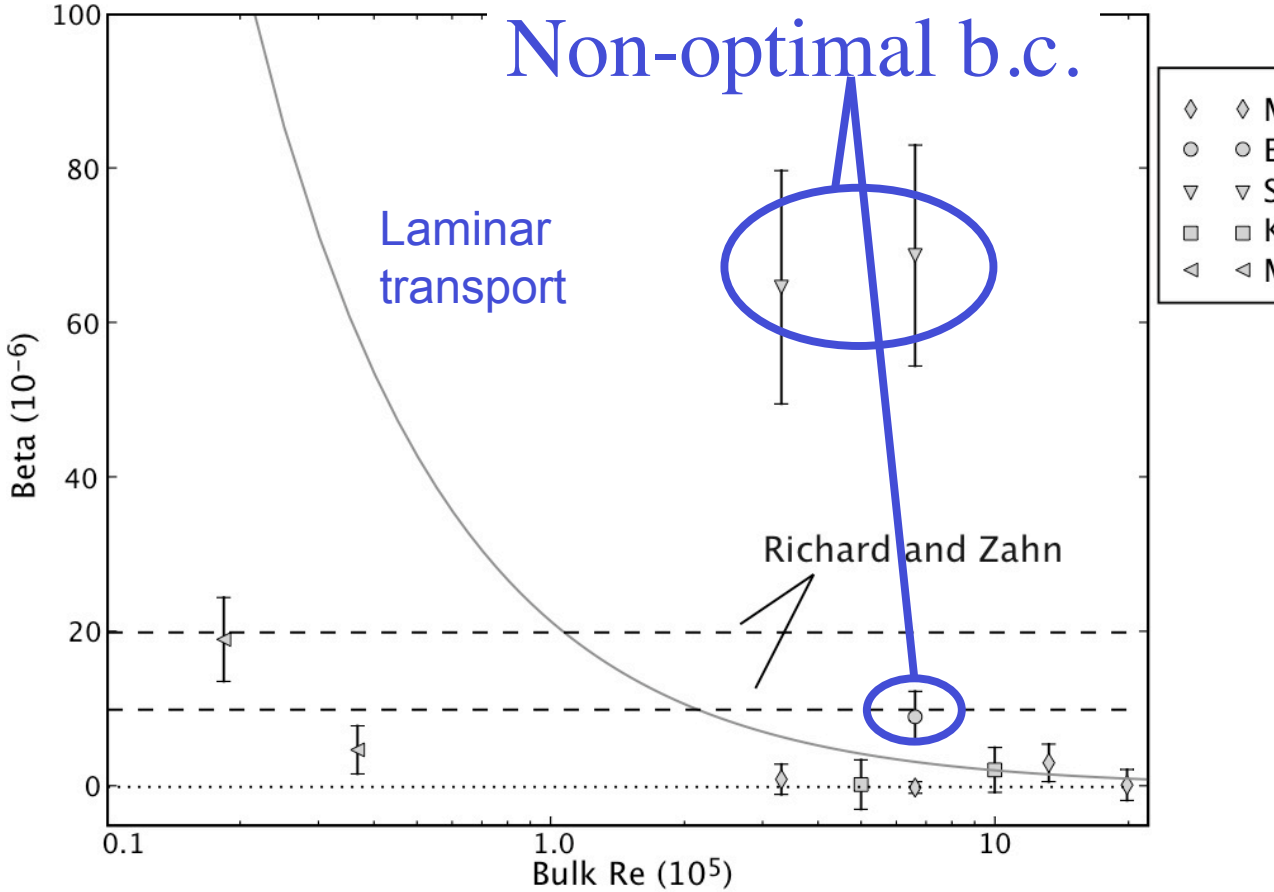
- **Magnetorotational Instability (MRI) in hot, highly conducting disks**
  - **Velikhov (1959) and Chandrasekhar (1960)**
  - **Shakura & Sunyaev (1973)**
  - **Balbus & Hawley (1991)**

Magnetic field can destabilize otherwise stable flows.



Negligible Angular Momentum Transport In Hydrodynamic Flows Even at Re>1e6





Inaccessible numerically

Ji et al. Nature (2006)
Schartman et al. (2010)

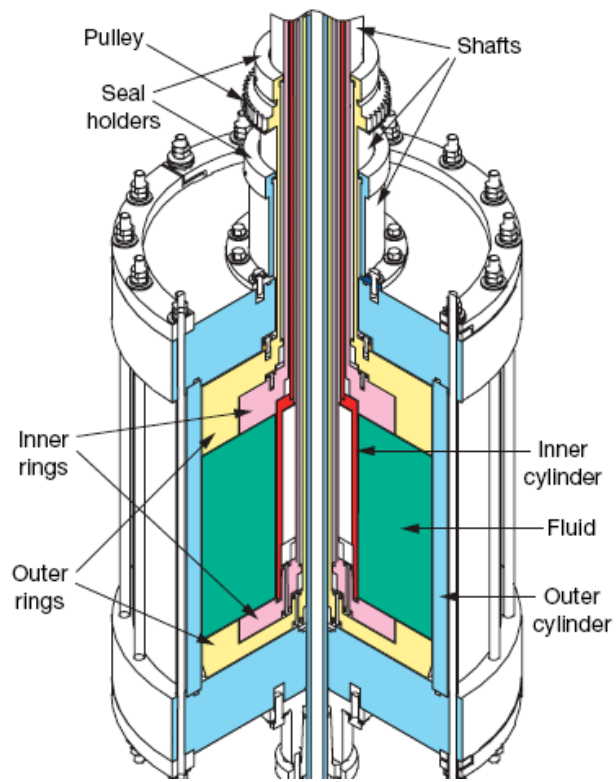
Vol 444|16 November 2006|doi:10.1038/nature05323

LETTERS

Hydrodynamic turbulence cannot transport angular momentum effectively in astrophysical disks

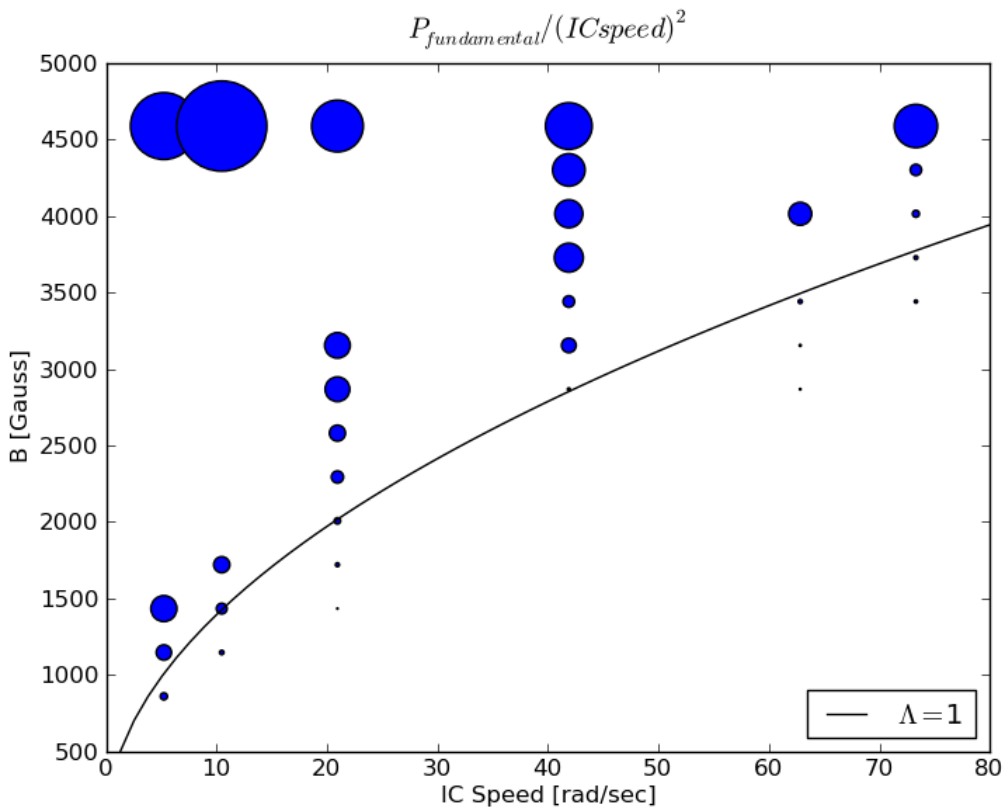
Hantao Ji[1], Michael Burin[1]†, Ethan Schartman[1] & Jeremy Goodman[1]

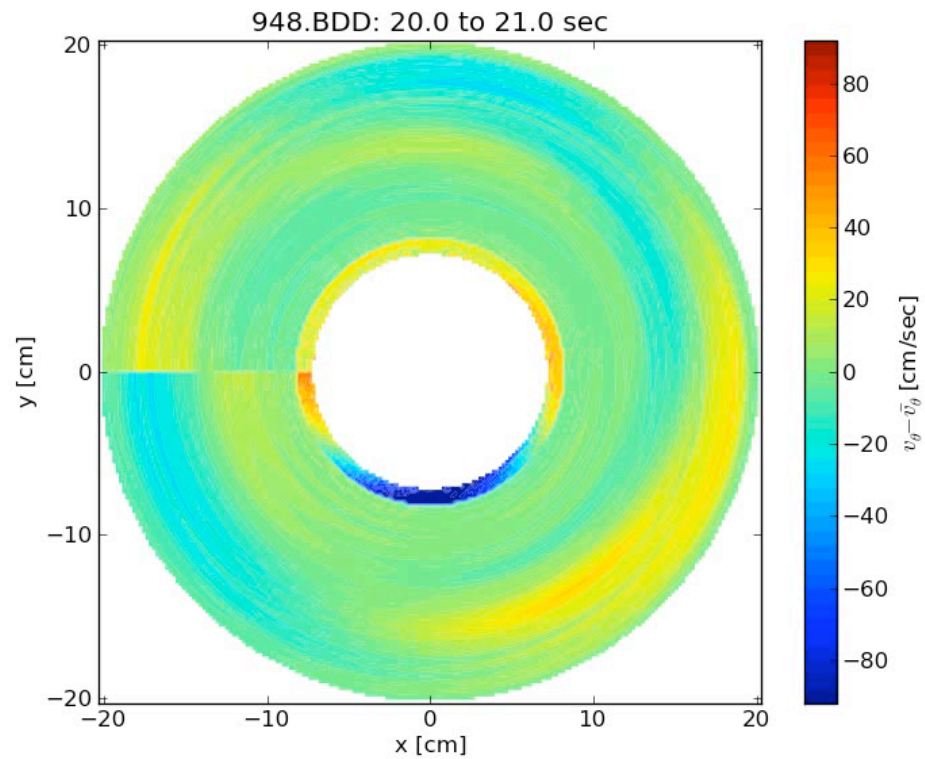
The most efficient energy sources known in the Universe are accretion disks. Those around black holes convert 5–40 per cent of rest-mass energy to radiation. Like water circling a drain, inflowing mass must lose angular momentum, presumably by vigorous turbulence in disks, which are essentially inviscid[1]. The origin of the turbulence is unclear. Hot disks of electrically conducting plasma can become turbulent by way of the linear magnetorotational instability[2]. Cool disks, such as the planet-forming disks of protostars, may be too poorly ionized for the magnetorotational instability to occur, and therefore essentially unmagnetized and linearly stable. Nonlinear hydrodynamic instability often occurs in linearly stable flows (for example, pipe flows) at sufficiently large Reynolds numbers. Although planet-forming disks have extreme Reynolds numbers, keplerian rotation enhances their linear hydrodynamic stability, so the question of whether they can be turbulent and thereby transport angular momentum effectively is controversial[3–15]. Here we report a laboratory experiment, demonstrating that non-magnetic quasi-keplerian flows at Reynolds numbers up to millions are essentially steady. Scaled to accretion disks, rates of angular momentum transport lie far below astrophysical requirements. By ruling out purely hydrodynamic turbulence, our results indirectly support the magnetorotational instability as the likely cause of turbulence, even in cool disks.



Large-amplitude, Coherent Velocity Oscillations Observed Only When Elsasser # $\Lambda = V_A^2/\eta\Omega > 1$

Ultrasonic Doppler Velocimetry



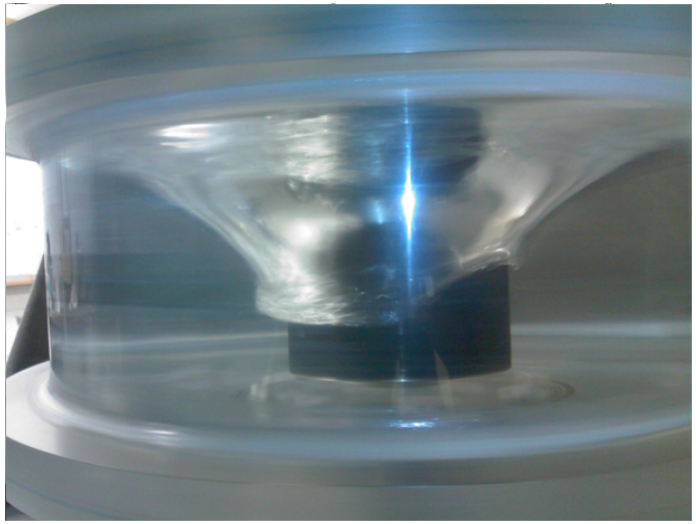


- More than 20% of background velocity
- Saturated modes exhibit a spiral structure
- A global manifest of MRI?
- Saturated modes exhibit a spiral structure

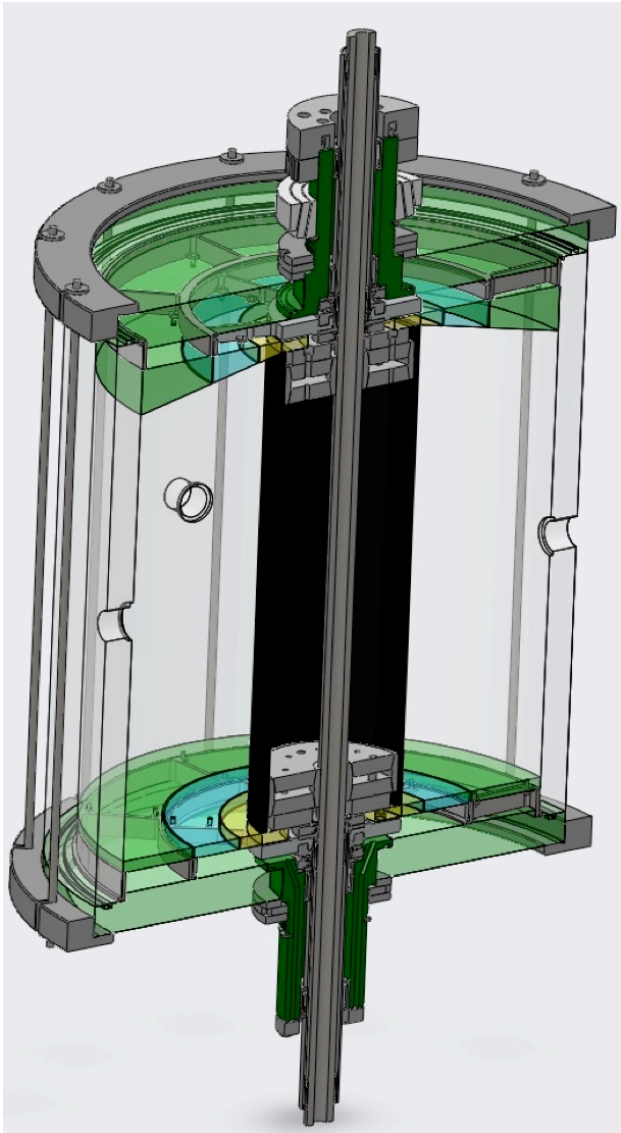
Roach et al (2010)

Future: Hydrodynamic and Liquid Metal Experiments

- **Hydrodynamic experiments**
  - **Why Keplerian flows are so stable? Resemble stability of hurricanes? How about Rossby waves?**

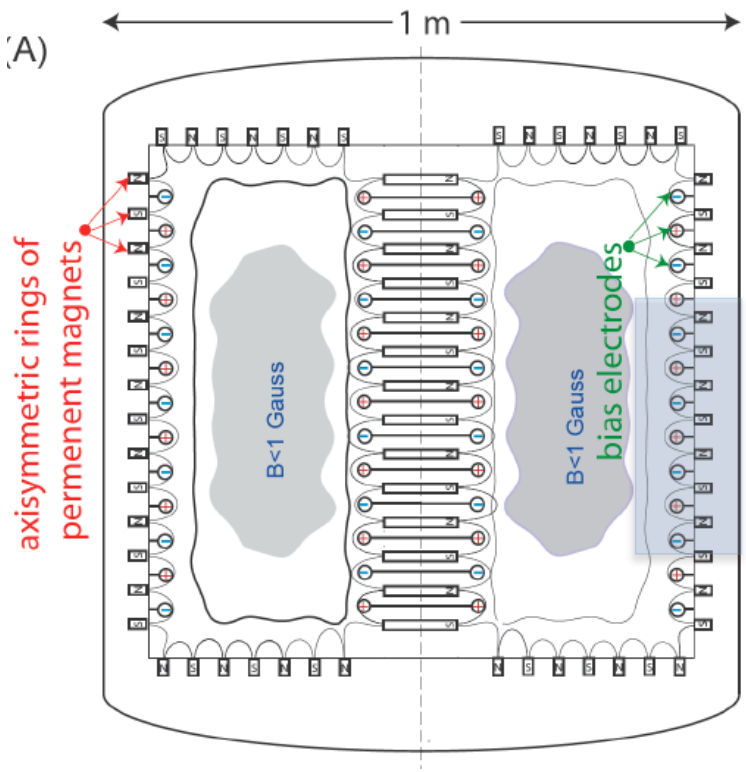


- **Liquid metal experiments**
  - **AMT scaling by an upgraded experiment**



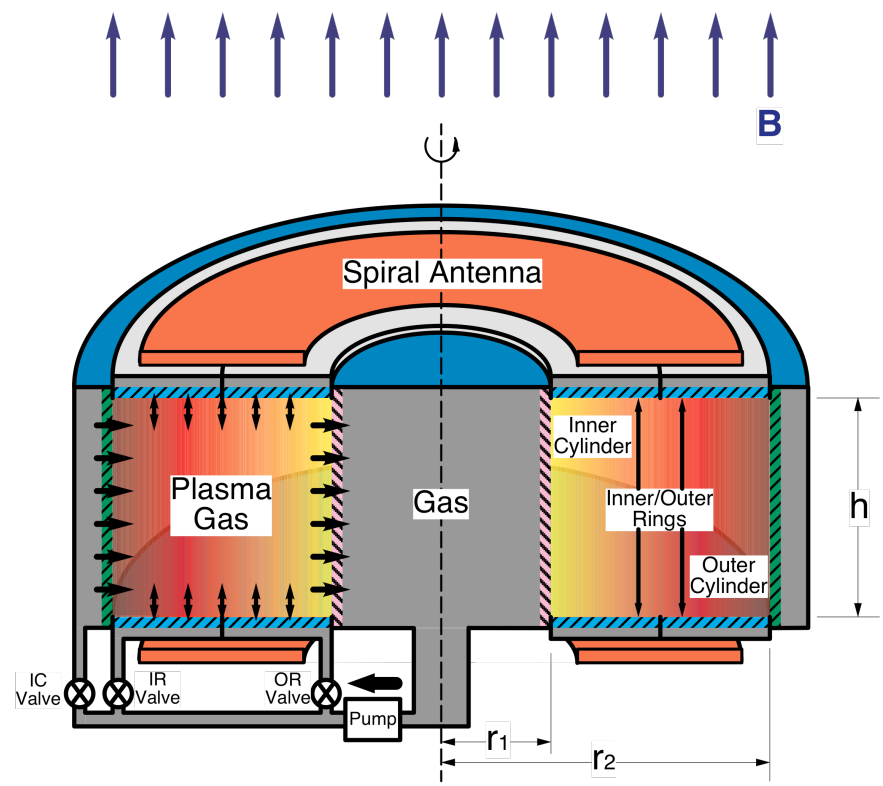
Future: Gas and Plasma Experiments

Plasma Couette flow (U. Wisconsin)



- Driven by E×B flow at edge

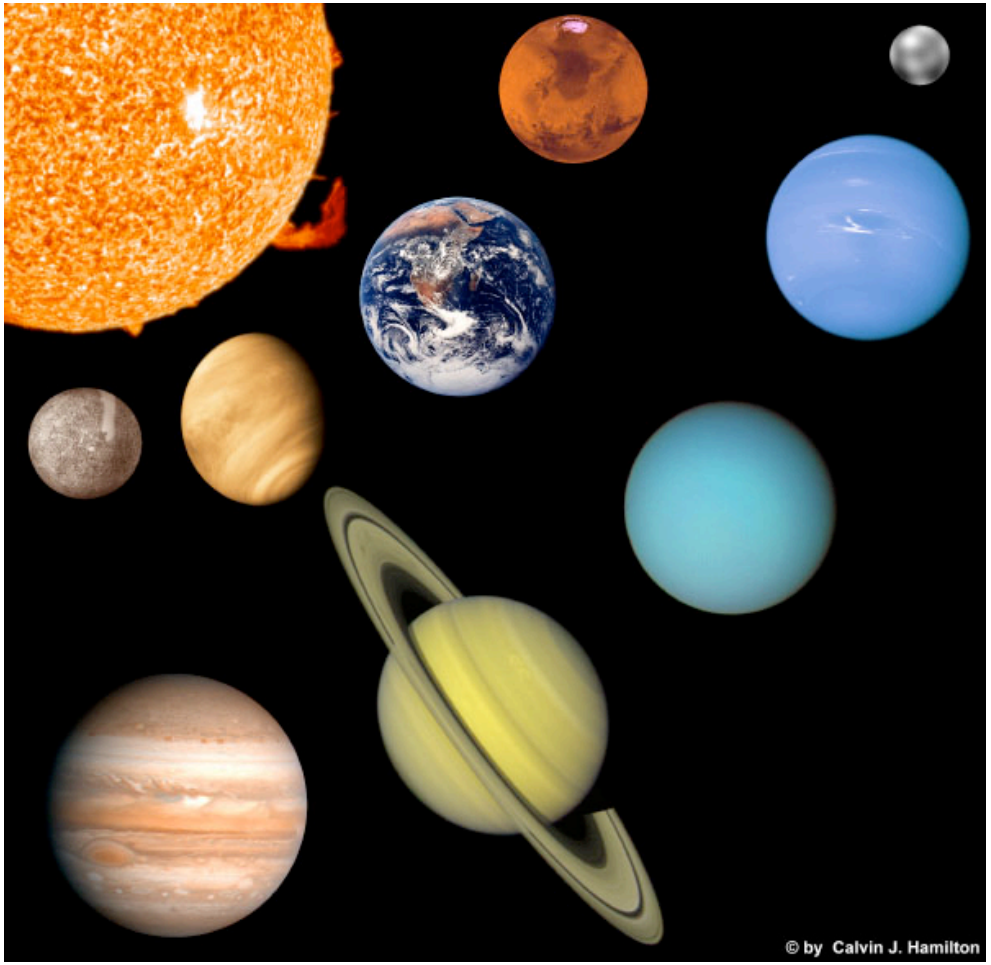
Swirling Gas and Plasma Experiment (Princeton)

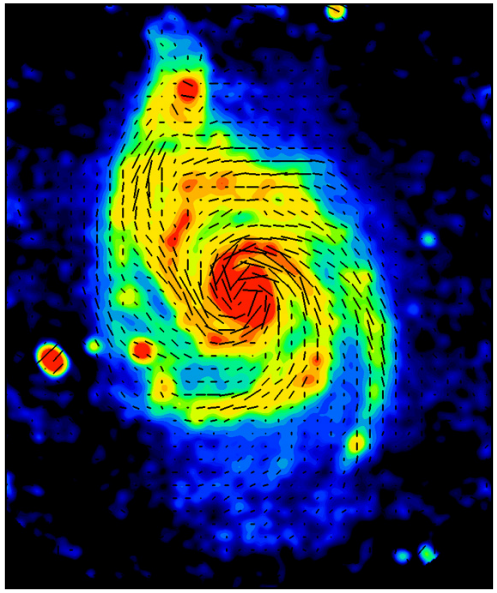


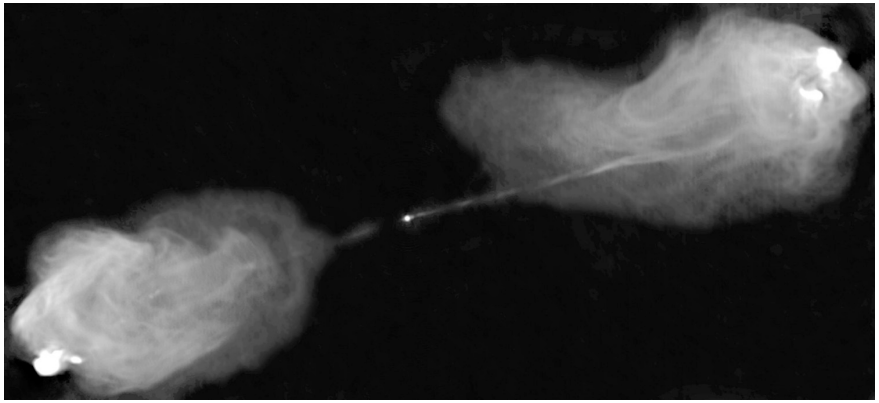
- Inject and pump out gas radially
- Plasma made by spiral antenna(s)
- Possibly mix proper chemicals

Dynamos:
How Is Magnetic Field Generated?

Magnetic fields exist wherever there are conducting fluids or plasmas

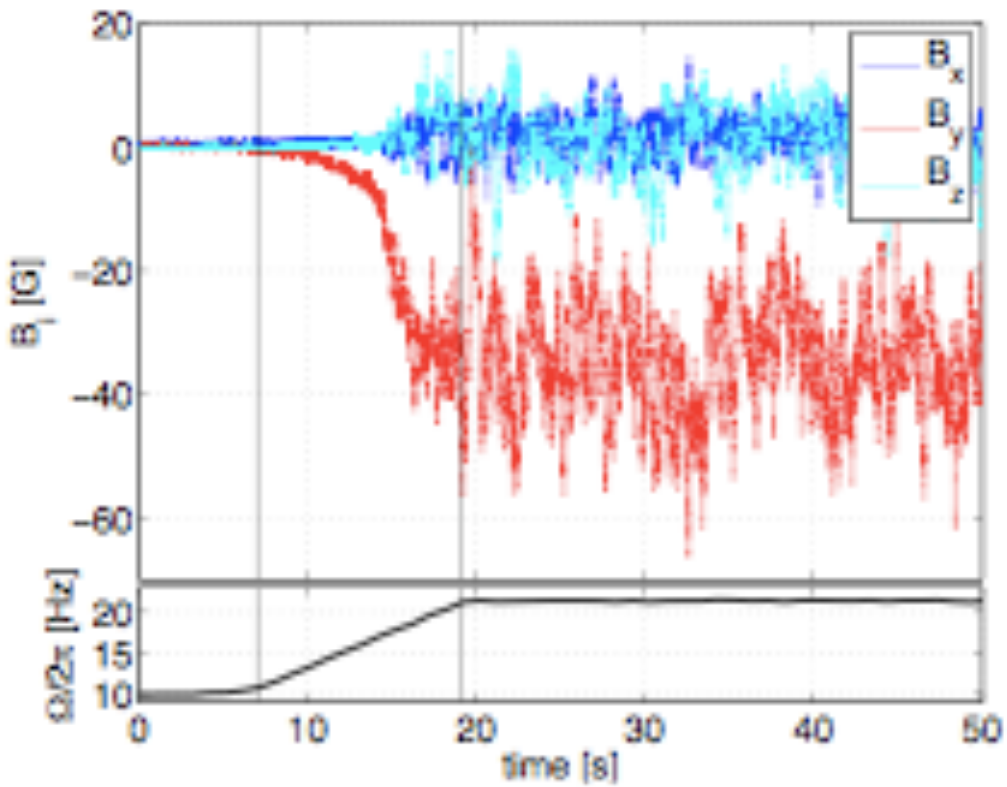


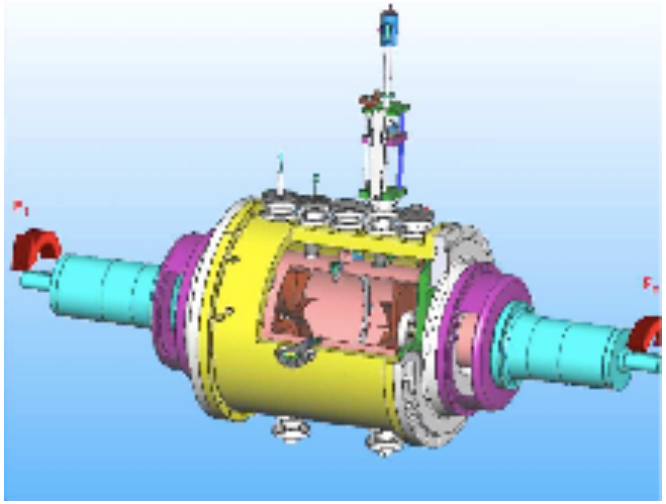




Kinematic Dynamo Model

- Growth of magnetic field from a seed in a sufficiently conducting fluid





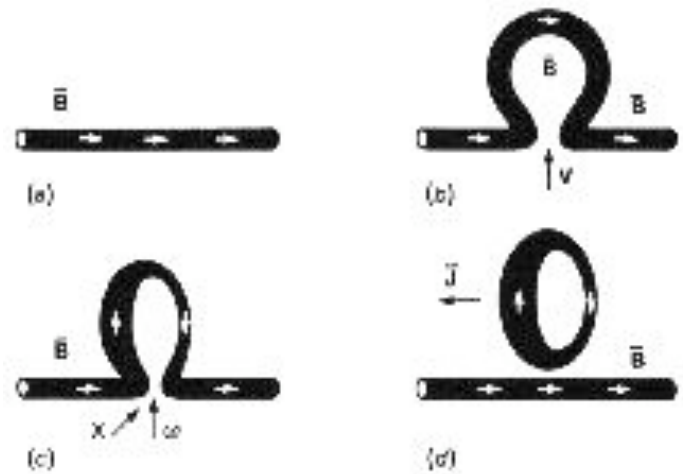
French VKS Experiment but with iron propellers

Monchaux et al. (2009)

Parker's α-ω Model

Differential rotation increases Bt from Bp: ω-effect.

Rising/sinking plumes reinforce Bp from Bt: α effect.

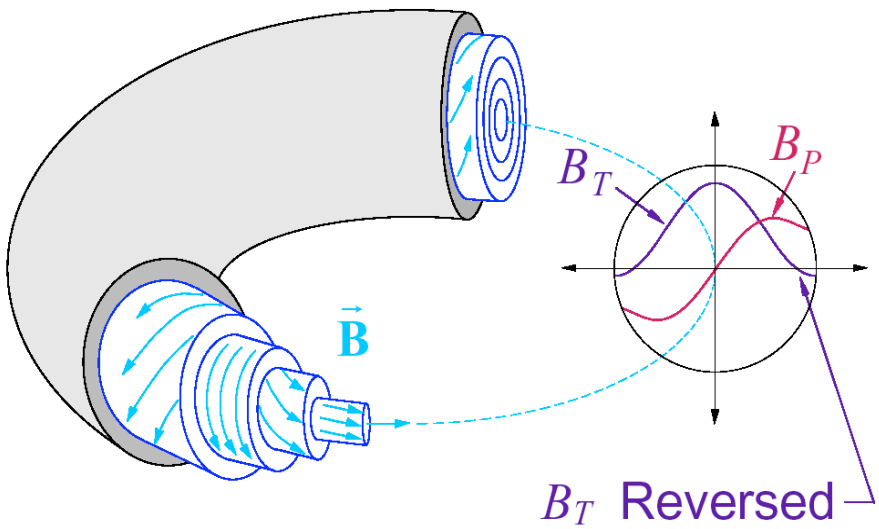


β-effect:

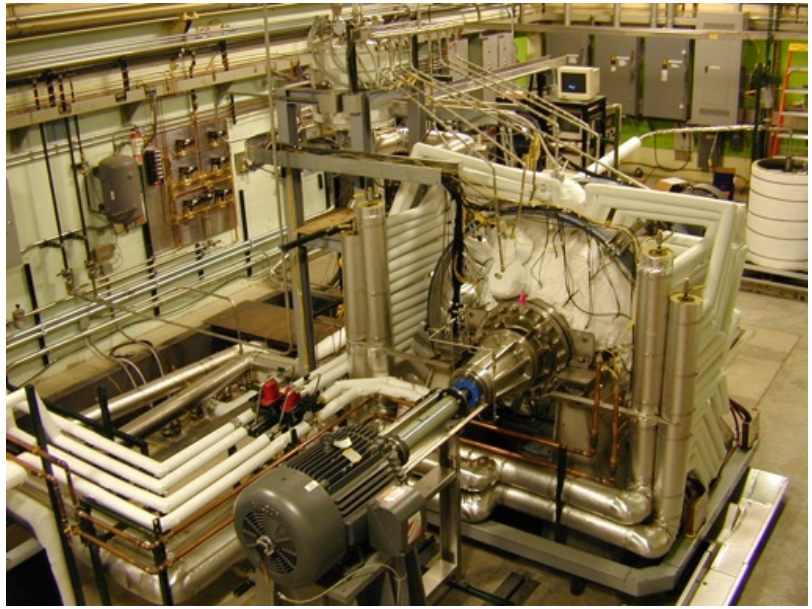
Turbulent mixing of magnetic field

α-effect and β-effect Detected, But Separately

MST plasma experiment



MDE liquid metal experiment



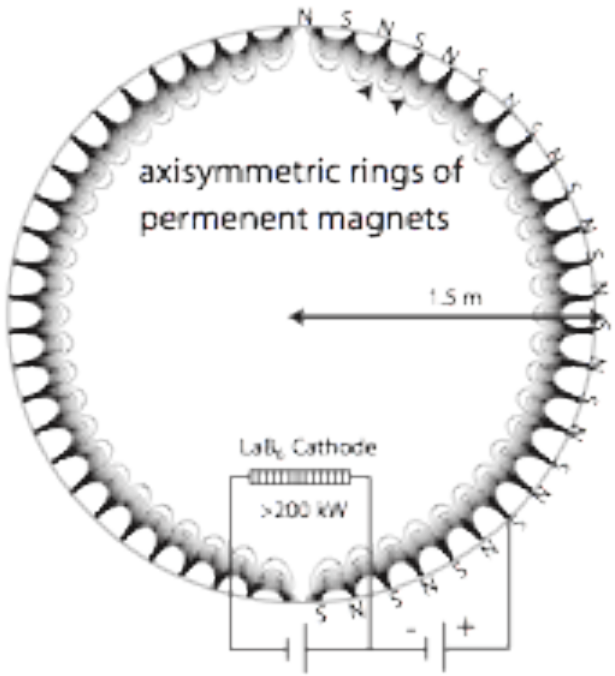
α-effect converts one component to another

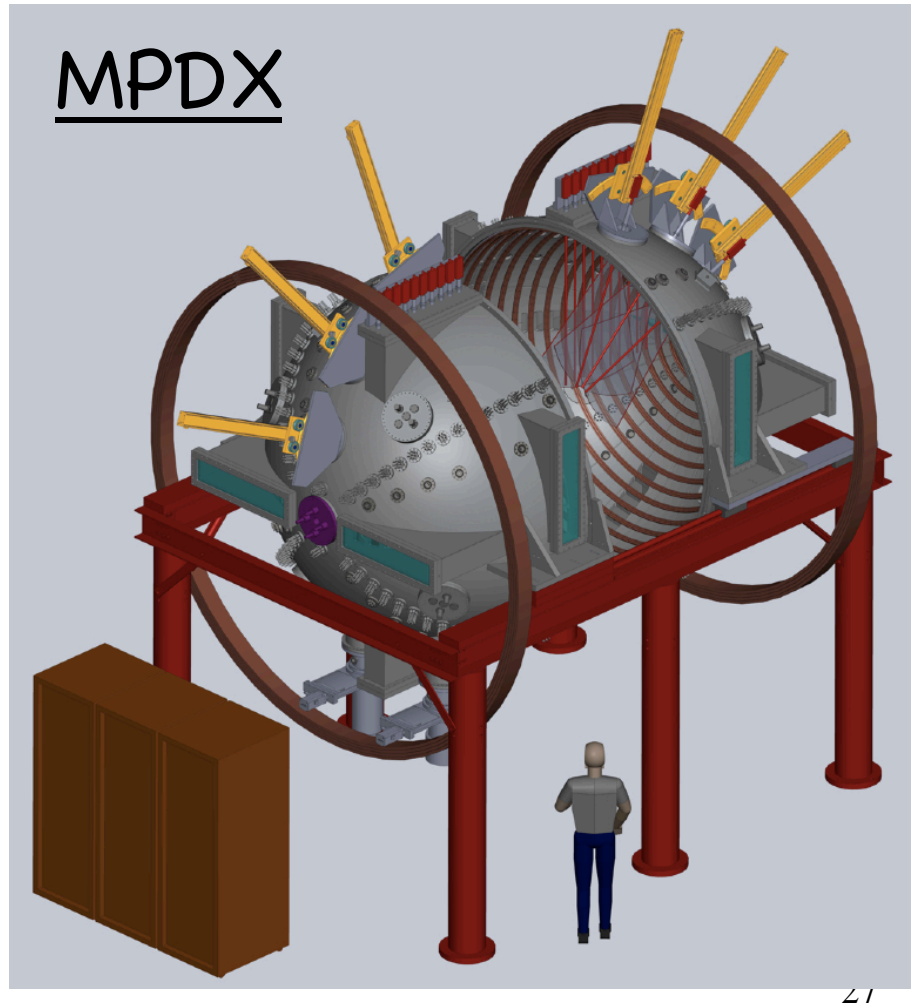
Ji et al. (1994), Fontana et al. (2000)

β-effect delays dynamo onset

Nornberg et al. (2006), Spence et al. (2008)

Future: more controlled liquid metal experiments; plasma dynamo experiment





More versatile than liquid metal; more plasma physics

Poster by M. Nornberg

Summary

- Laboratory plasma experiments play increasingly important roles to study space and astrophysical plasmas; they are becoming a necessity rather than a luxury especially for theory and modeling.

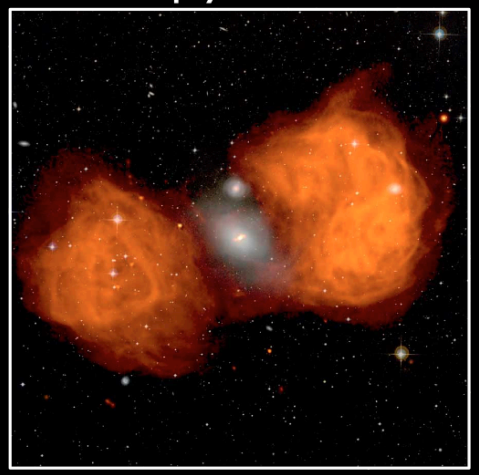
- In the area of magnetic reconnection, next generation experiments are ready to be initiated to access new phases in large-sized and high-S plasmas, as well as reconnection in partially ionized plasmas

- In the area of angular momentum transport, hydrodynamic turbulence was shown to be insignificant for fast accretion; MRI is promising in liquid metal experiment. Gas and plasma experiments are just beginning, and should explore new regimes

- In the area of dynamos, theoretical models are just beginning to be seriously tested in the liquid metal experiments. New experiment based on plasma is being built to explore dynamo with extended parameters and with more physics.

Report of the Workshop on Opportunities in Plasma Astrophysics

Research Opportunities in Plasma Astrophysics



Report of the Workshop on Opportunities in Plasma Astrophysics
Princeton, New Jersey — January 18-21, 2010

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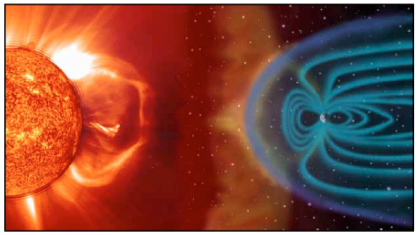
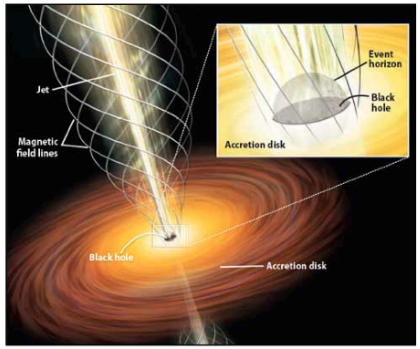
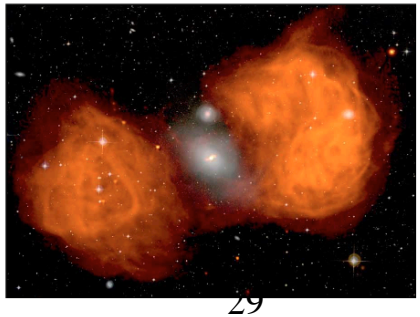
10 MAJOR QUESTIONS

- ***How do magnetic explosions work?***
- ***How are cosmic rays accelerated to ultra-high energies?***
- ***What is the origin of coronae and winds in virtually all stars, including the Sun?***
- ***How are magnetic fields generated in stars, galaxies, and clusters?***
- ***What powers the most luminous sources in the universe?***
- ***How is star and planet formation impacted by plasma dynamics?***
- ***How do magnetic fields, radiation, and turbulence impact supernova explosions?***
- ***How are jets launched and collimated?***
- ***How is the plasma state altered by strong magnetic fields?***
- ***Can magnetic fields affect cosmic structure formation?***

10 MAJOR TOPICS

Magnetic Reconnection
Collisionless Shocks and Particle Acceleration
Waves and Turbulence
Magnetic Dynamos
Interface and Shear-flow Instabilities
Angular Momentum Transport
Dusty Plasmas
Radiative Hydrodynamics
Relativistic, Pair-dominated and Strongly Magnetized Plasmas
Jets and Outflows

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