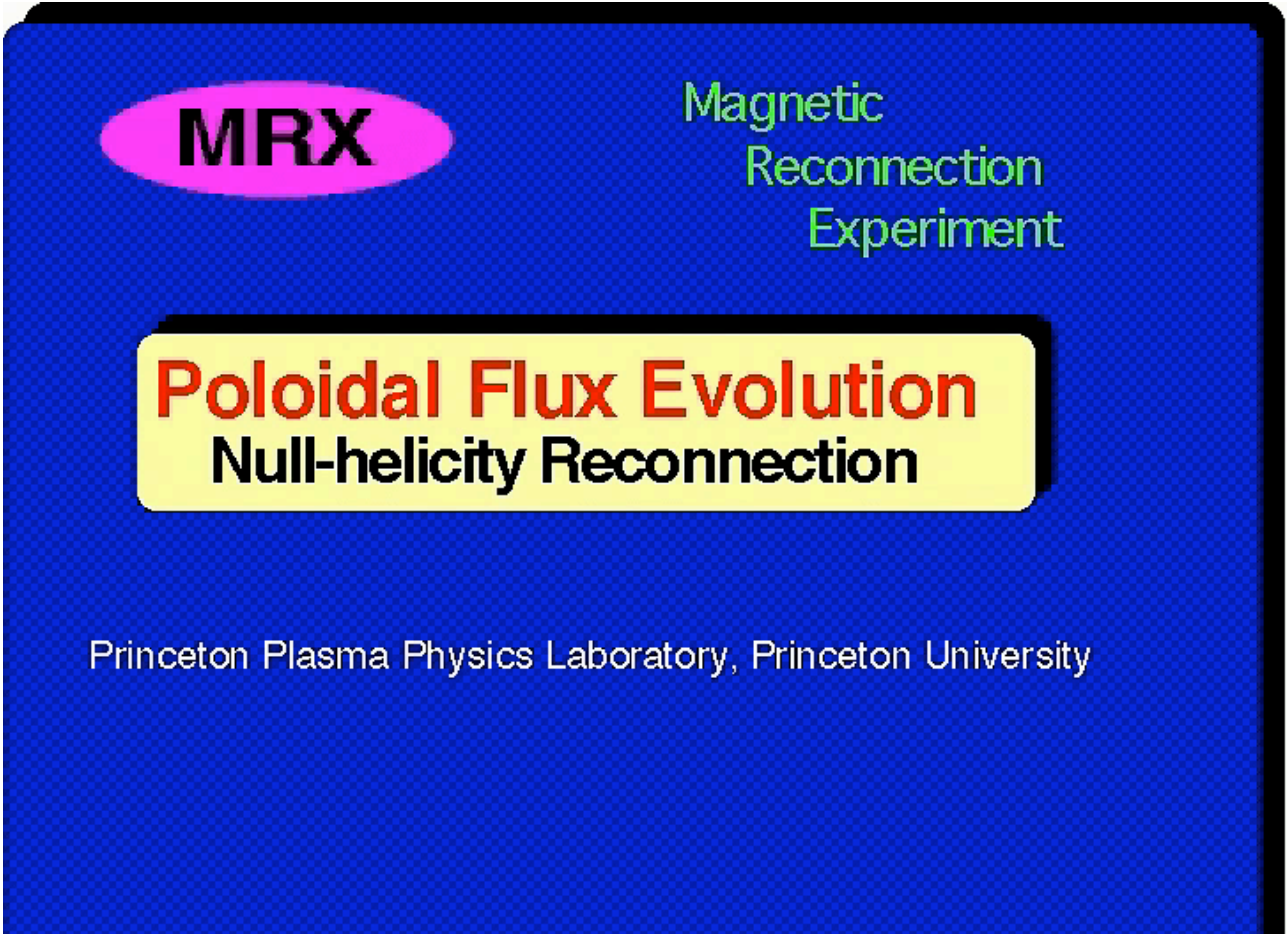
Experimental documentation of magnetic reconnec

Experimentally measured flux evolution



Laboratory experiments available for dedicated study of magnetic reconnection

Device	*Where*	*Since*	*Geometry*	*B_g/B_rec*	*Main Issues*
3D-CS	Russia	1970	Linear	0-20	Heating
LPD, LAPD	UCLA	1980	Linear	1-10	Heating, waves
TS-3/4	Tokyo	1990	Merging	0-10	Rate, heating
MRX	Princeton	1995	Toroidal, merging	0-20	Rate, heating, waves, boundary, scaling, impulsive
SSX	Swarthmore	1996	Merging	0-1	Heating
VTF	MIT	1998	Toroidal	>~15	Trigger/impulsive, heating
RSX	Los Alamos	2002	Linear	2-40	Boundary, impulsive
RWM	Wisconsin	2002	Linear	10-30	Boundary

Recent Progress in Study of Reconnection Layer and Rate

M. Yamada, PPPL

- **Major progress made in**
  1) Numerical simulations
  2) Space observations
  3) Lab experiments
  - **Profiles of reconnection layer documented**
  - **Reconnection rate measured quantitatively**
    Enhanced resistivity was measured
- **Identified possible causes of fast reconnection**
  - Two fluid physics dominant in the collisionless regime.
    Hall effects verified
  - Turbulence/ fluctuations in the sheet
- **Recognized main issues for global reconnection**
  - 3-D MHD modes trigger fast reconnection toroidal pinch systems
  - Impulsive reconnection studied

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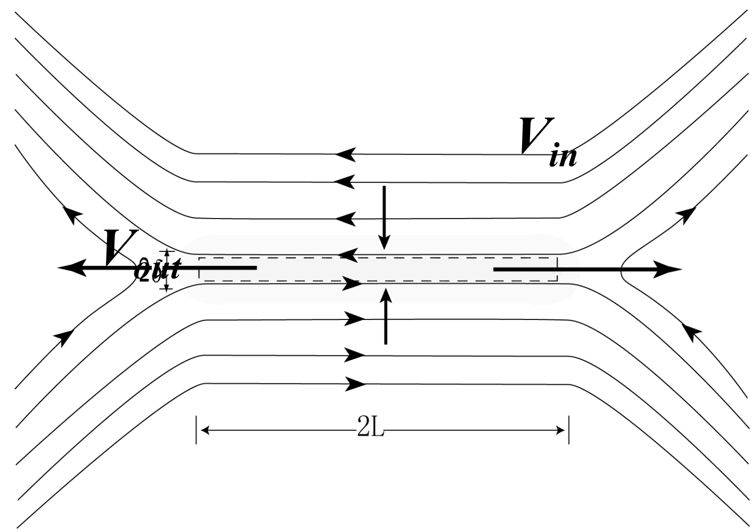
The Sweet-Parker 2-D MHD Model for Magnetic Reconnection

Assumptions:

- 2D
- Steady-state
- Incompressibility
- Classical Spitzer resistivity



Mass conservation
+ Pressure balance

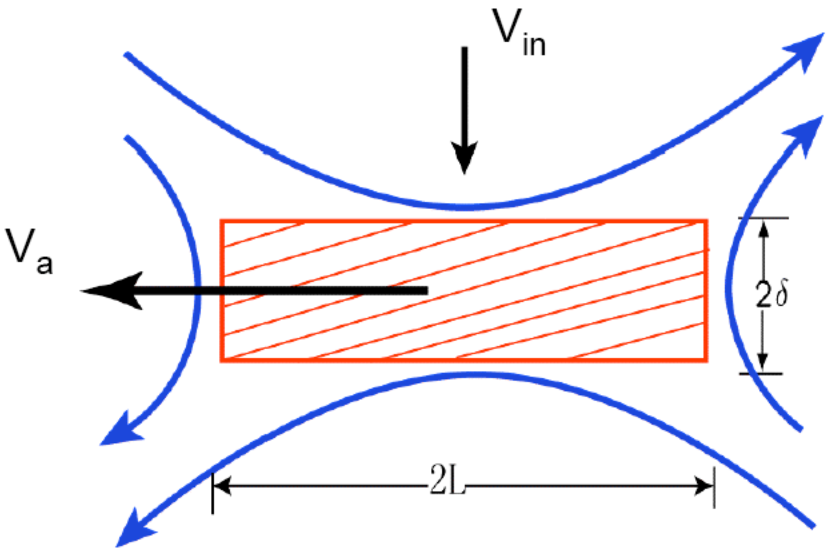
$$\boxed{\frac{V_{in}}{V_A} = \frac{1}{\sqrt{S}}}$$

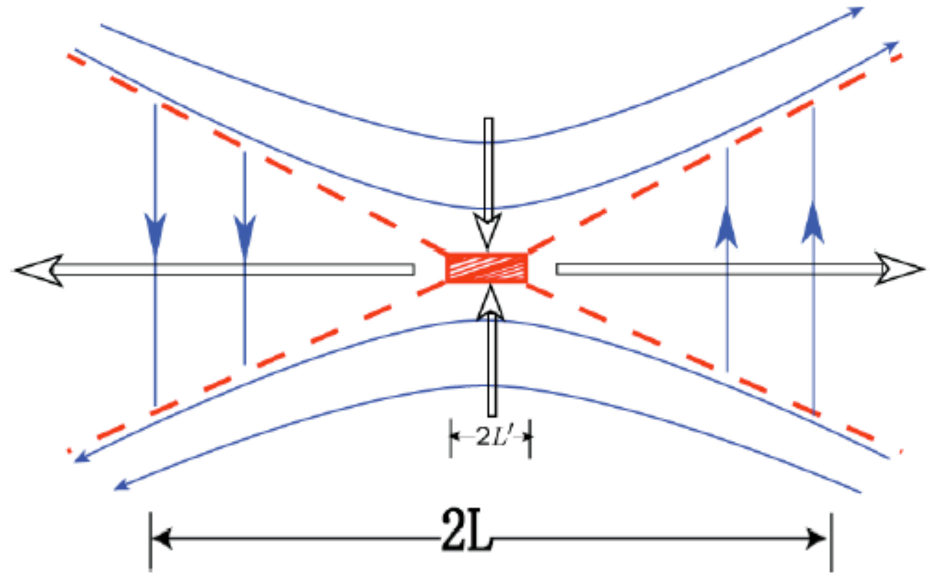
$$S = \frac{\mu_0 L V_A}{\eta_{Spitz}}$$

S=Lundquist number

$\tau_{reconn} \ll \tau_{SP} \sim$ 3-10 months

Models for Fast Reconnection





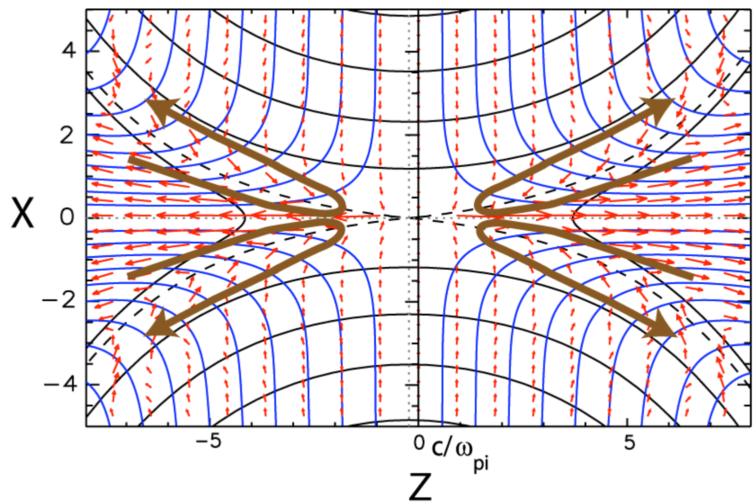
Generalized Sweet-Parker model with enhanced resistivity caused by turbulence.

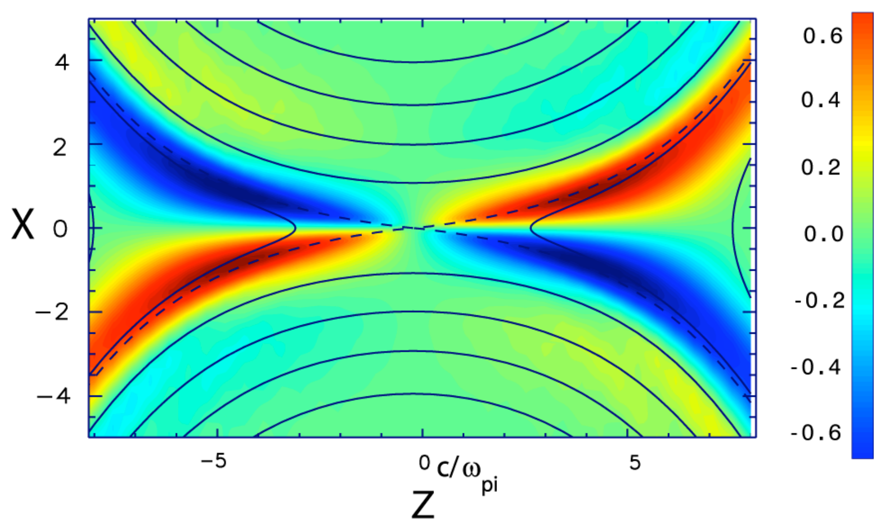
Two-fluid model in which electrons and ions decouple in the diffusion region (~ c/ω_{pi})

=> Generalized Ohm's law

$$\mathbf{E} + \mathbf{V} \times \mathbf{B} = \eta \mathbf{J} + \frac{\mathbf{J} \times \mathbf{B} - \nabla p}{en} + \frac{m_e}{e^2} \frac{\mathrm{d}\mathbf{V}_e}{\mathrm{d}t}$$

The Hall Effect During Reconnection Shown in 2D Simulation





- **Black lines →magnetic flux.**
- **Blue lines → ion flow streamlines.**
- **Red arrows → electron flow velocity vectors.**
- **Brown arrows → In-plane current.**

Different motions of ions and electrons

↓

In-plane current

↓

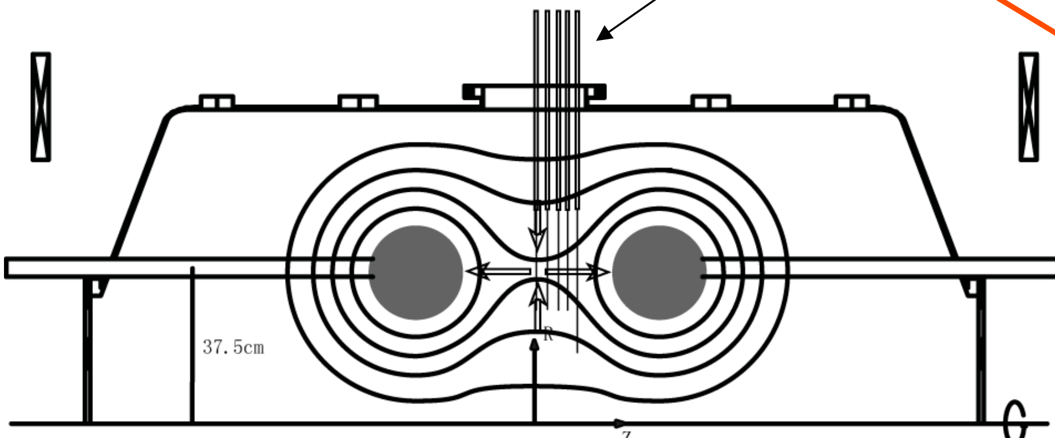
An out-of-plane quadrupole magnetic field

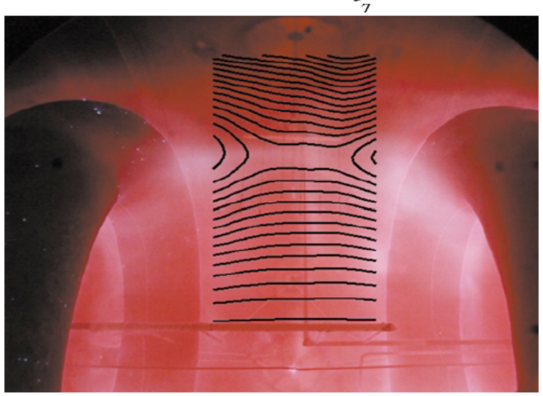
In color code

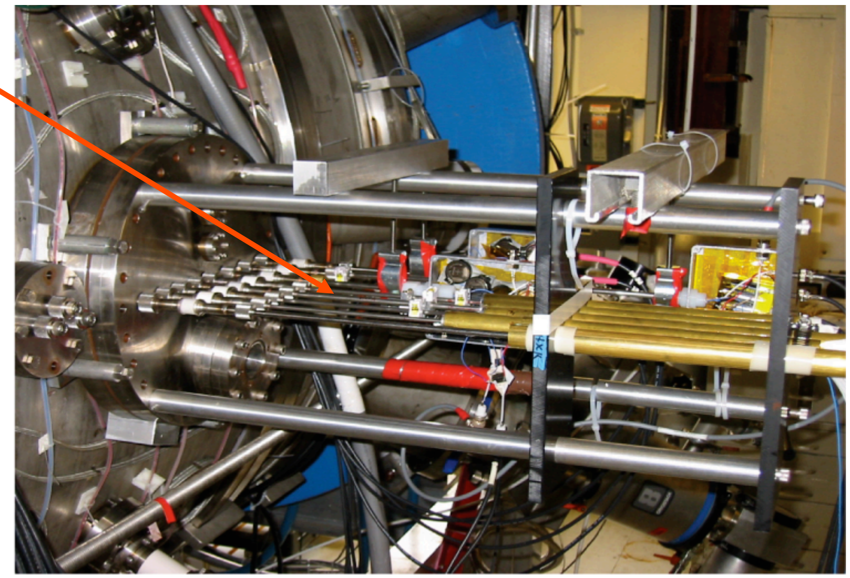
by J. Breslau

Dedicated lab experiments systematically studied reconnection layer and rate

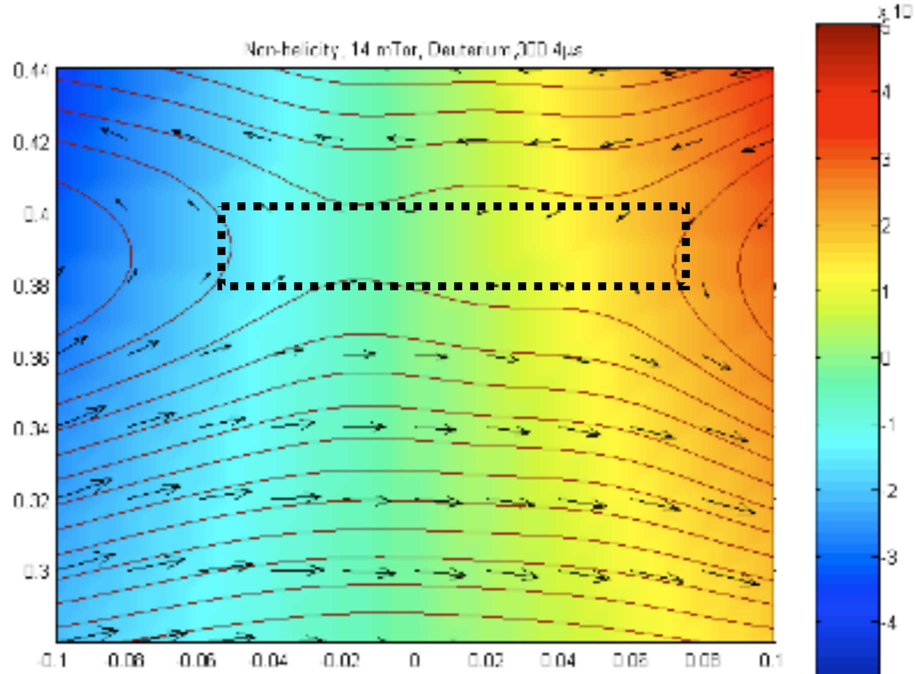
Linear probe arrays







- Five fine structure probe arrays with resolution up to Δx= 2.5 mm in radial direction are placed with separation of Δz= 2-3 cm



Change of Neutral sheet Profile

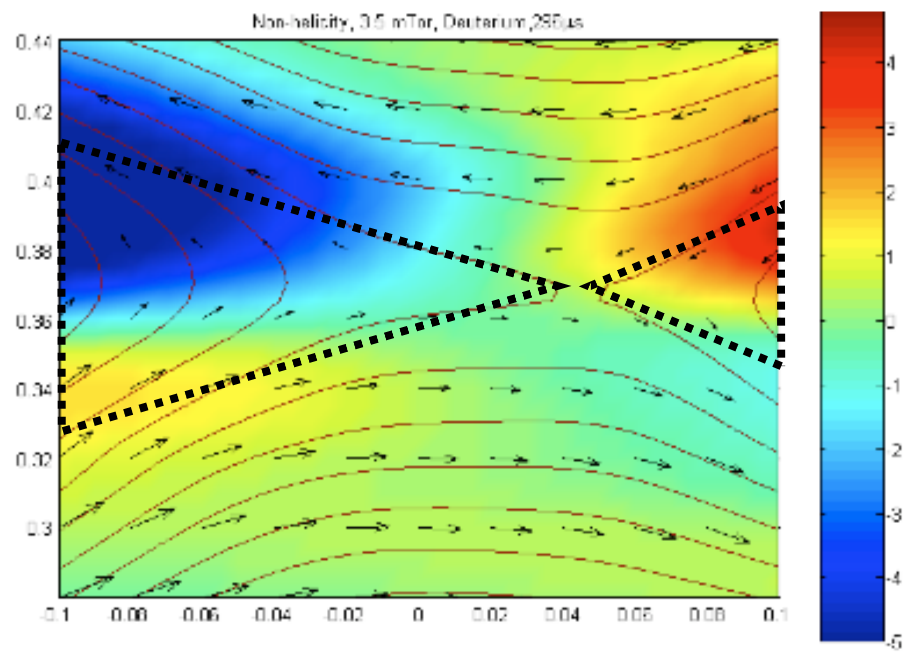
from “Rectangular S-P” type to “Double edge X” shape as collisionality is reduced

Rectangular shape

Collisional regime: $[illegible]_{mfp}$ < [illegible] [illegible]

Slow reconnection

No Q-P field



X-type shape

Collisionless regime: $[illegible]_{mfp}$ > [illegible] [illegible]

Fast reconnection

Q-P field present

Ma and Bhattacharjee, GRL 1996

Cassak et al PRL 2005

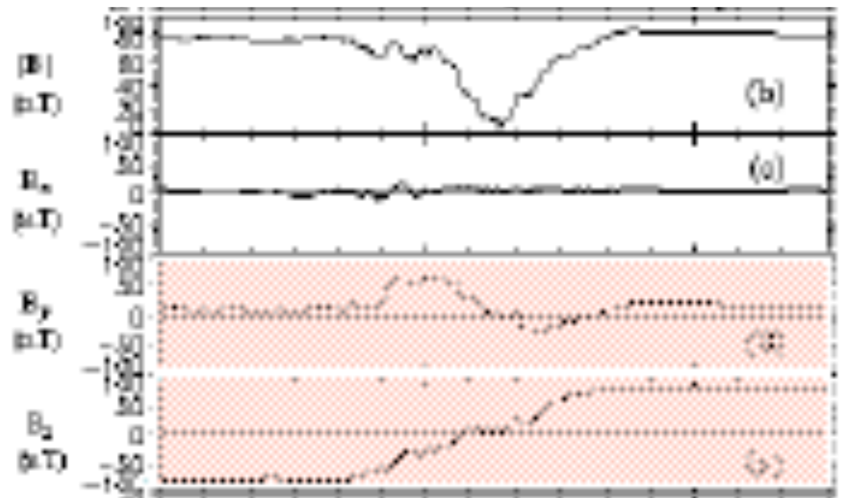
Magnetic Reconnection in the Magnetosphere

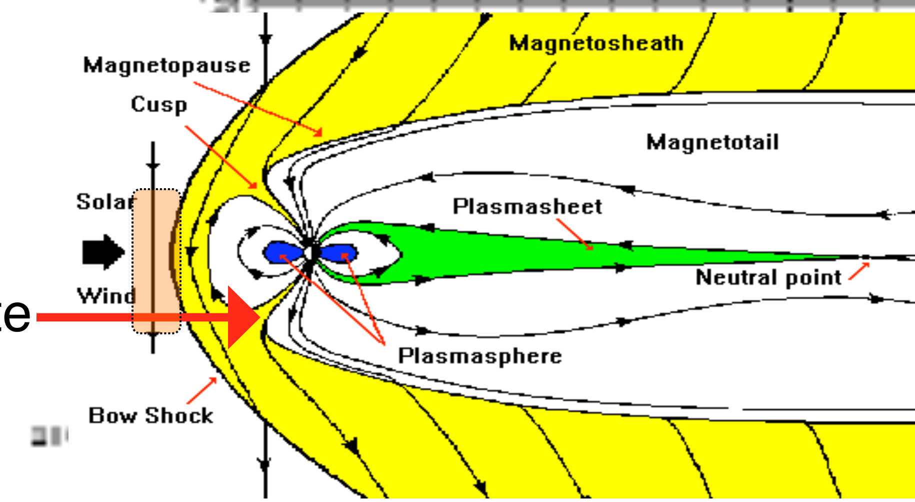
A reconnection layer has been documented in the magnetopause

d ~ c/w_{pi}

Measurements of Diffusion Region with a Hall effect signature

Mozer et al., PRL 2002





POLAR satellite

Fast Reconnection <=> Large E_{rec}
=> Enhanced effective resistivity

We have observed:

- **Hall MHD Effects create a large E field** (no dissipation)
- **Electrostatic Turbulence**
- **Electromagnetic Fluctuations**
- **Electron diffusion region identified**

How does energy dissipation occur?

How is the reconnection rate really determined?

What is role of the pressure tensor in Gen-Ohm's law?

=> ***Next level of intensive study***

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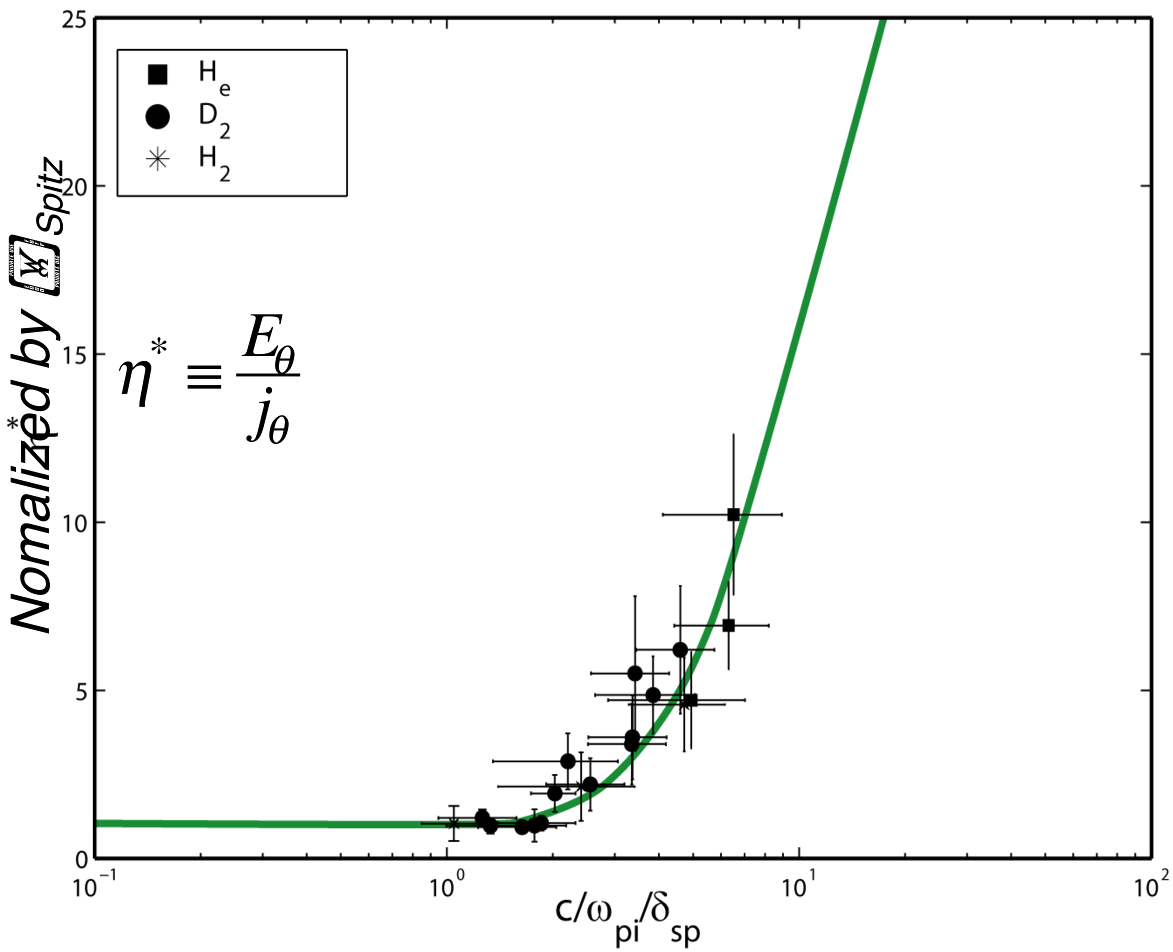
MRX Scaling:

A linkage between space and lab on reconnection



$\square_{eff} \sim 20\ (\square_{mfp}/L)$

$\sim\ (c/\square_{pi})^2/\ \square\square_{SP}$

Atransition from the MHD to 2 fluid regime when $(c/\square_{pi}) \sim \square_{sp}$

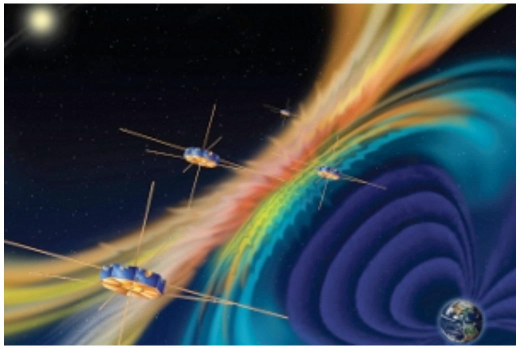
Major issues for future reconnection layer research

- ***How is the reconnection rate determined?***
  - *Hall effects + Pressure Tensor + Turbulence*
  - *Turbulence*
  - *Multiple reconnection layers*
  - *Impulsive reconnection*
  - *Effects of boundaries*

- ***What is a key mechanism for energy conversion (dissipation)?***
  => *Particle acceleration and heating*

- ***How does it affect global magnetic self-organization?***

Major opportunities for magnetic reconnection research



- ***<u>Space satellite missions:</u>***

  MMS cluster satellite mission

  Study multi-scale reconnection regions with kinetic information

  Solar satellite missions

  IRIS, Solar Probe Plus, Chromosphere reconnection, effects of weakly ionized plasmas, impulsive reconnection

- ***<u>Advanced computer simulations</u>***

  3-D large S simulation, multiple reconnection layers, kinetic effects

=> <u>Larger laboratory experiments [<= NRC 2010 report]</u>

Multiple reconnection layers
Particle heating and acceleration
Impulsive reconnection
Effects of boundary