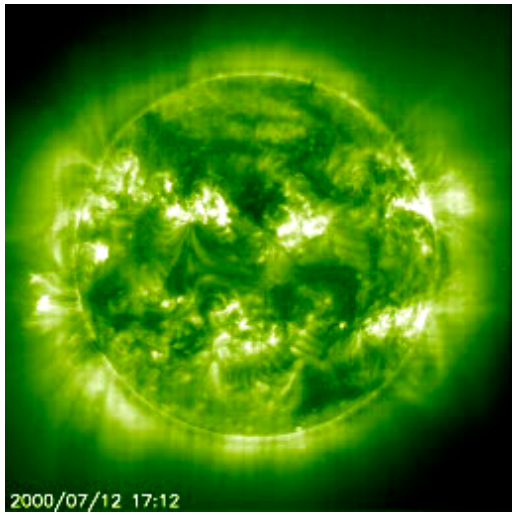
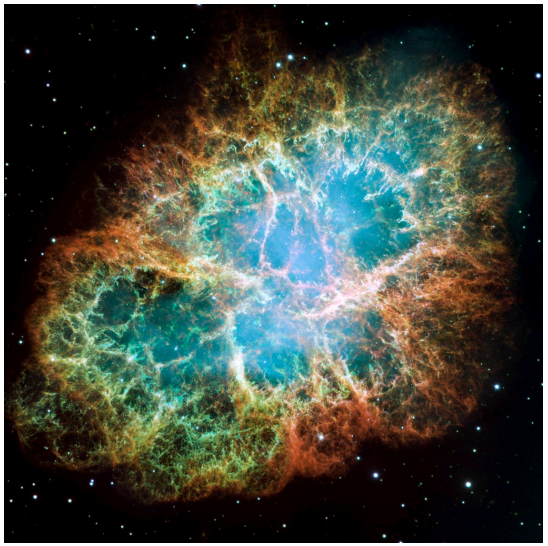


# Magnetic reconnection, a key self-organization mechanism in laboratory and astrophysical plasmas

**Masaaki Yamada**

Princeton Plasma Physics laboratory
Princeton University

Meeting at U. Rochester
February 13-14, 2012

# Outline

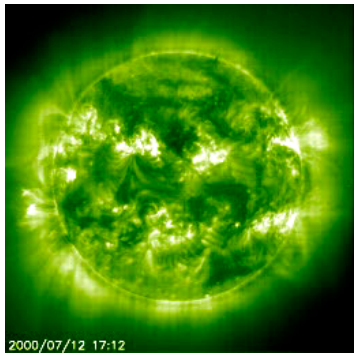
- **Magnetic reconnection**
  - Why does it occur so fast compared with the classical MHD theory?
- **Classical MHD (magneto-hydrodynamic) analysis**
  - Sweet-Parker model for reconnection layer and its generalization
  - Fast reconnection <=> Resistivity enhancement
- **Local analysis based on two-fluid physics**
  - **Lower collisionality => faster reconnection**
  - **Collision-free reconnection => an X-shaped neutral sheet**
  - **Hall effect and experimental verification**
  - **Identification of fluctuations (EM-LHDW)**
- **Global reconnection issues**

  **Magnetic self-organization**
  - **Sawtooth phenomena in tokamak**
- **A new scaling in transition from MHD to 2-fluid regime**

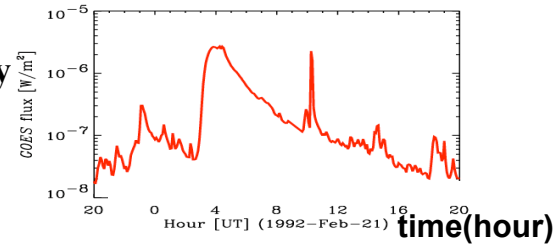
⇒ *M. Yamada, R. Kulsrud, H.Ji, Rev. Mod. Phys. v.82, 603 (2010)*
*E. Zweibel & M. Yamada, Ann. Rev. AA, AA47-8, 291 (2009)*

# Magnetic Reconnection: $B^2 \Rightarrow W_p$

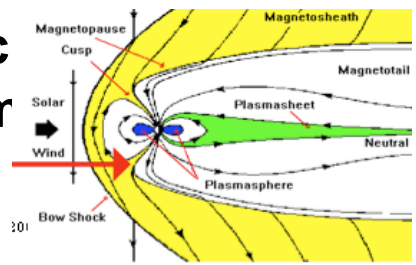
**Solar flare**



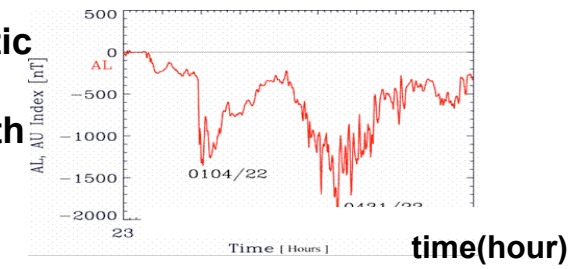

**X-ray intensity**



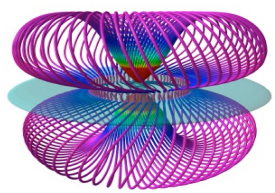

**Magnetospheric Aurora-substorm**



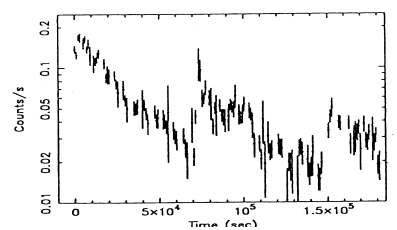

**Magnetic Field strength**



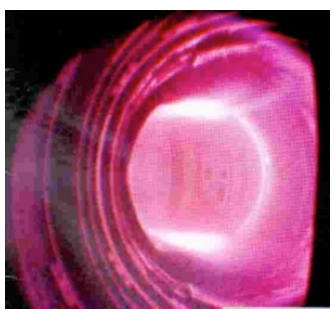

**Protostellar flare**



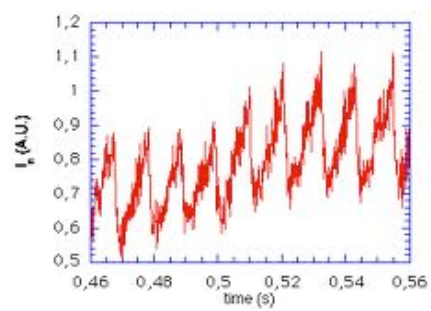
**X-ray intensity**




**Tokamak disruption**



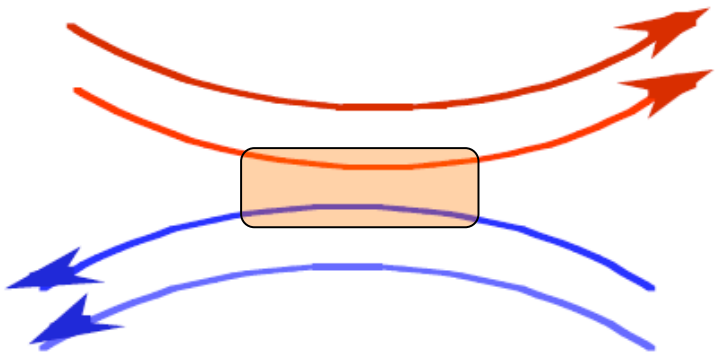
**Electron temperature**



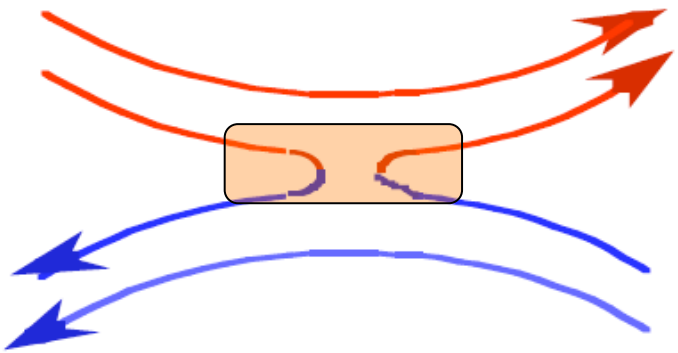

**Reconnection occurs very fast ($\tau_{reconn} \ll \tau_{SP}$)**

# Magnetic Reconnection

- **Topological rearrangement of magnetic field lines**
- **Magnetic energy => Kinetic energy**
- **Key to stellar flares, coronal heating, particle acceleration, star formation, energy loss in lab plasmas**

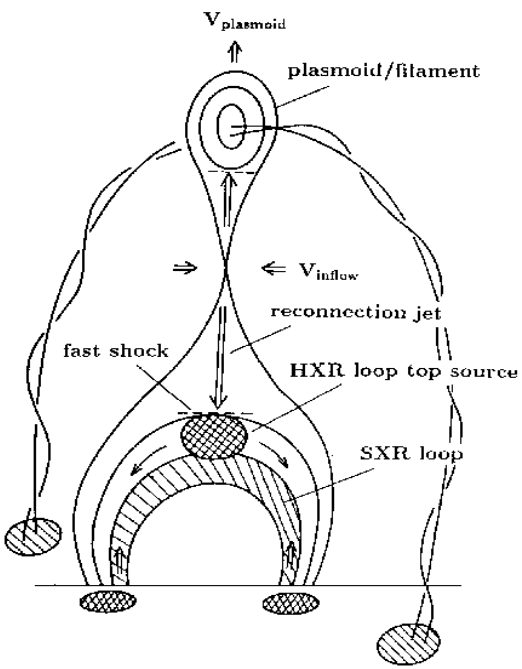


Before reconnection

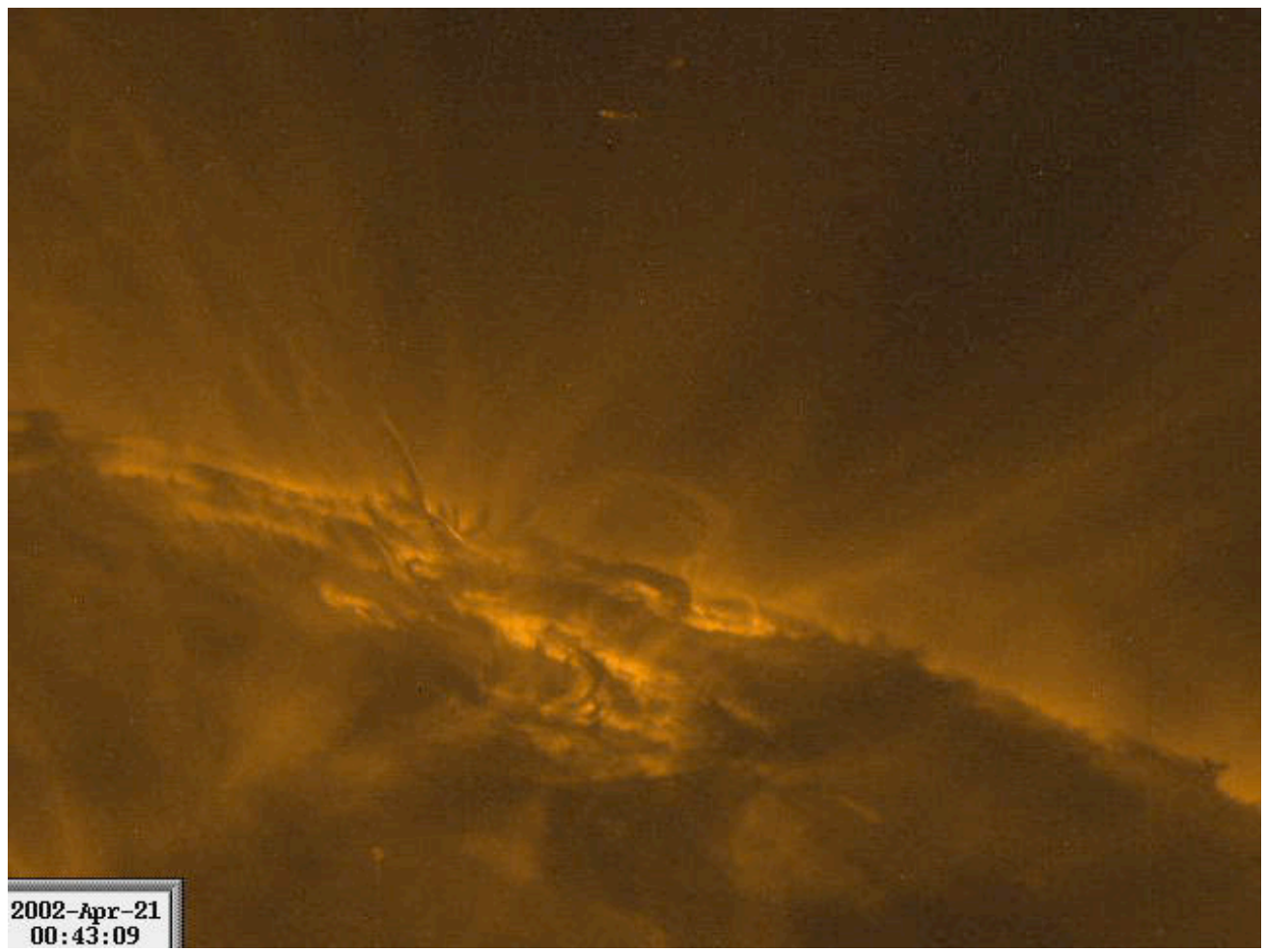


After reconnection

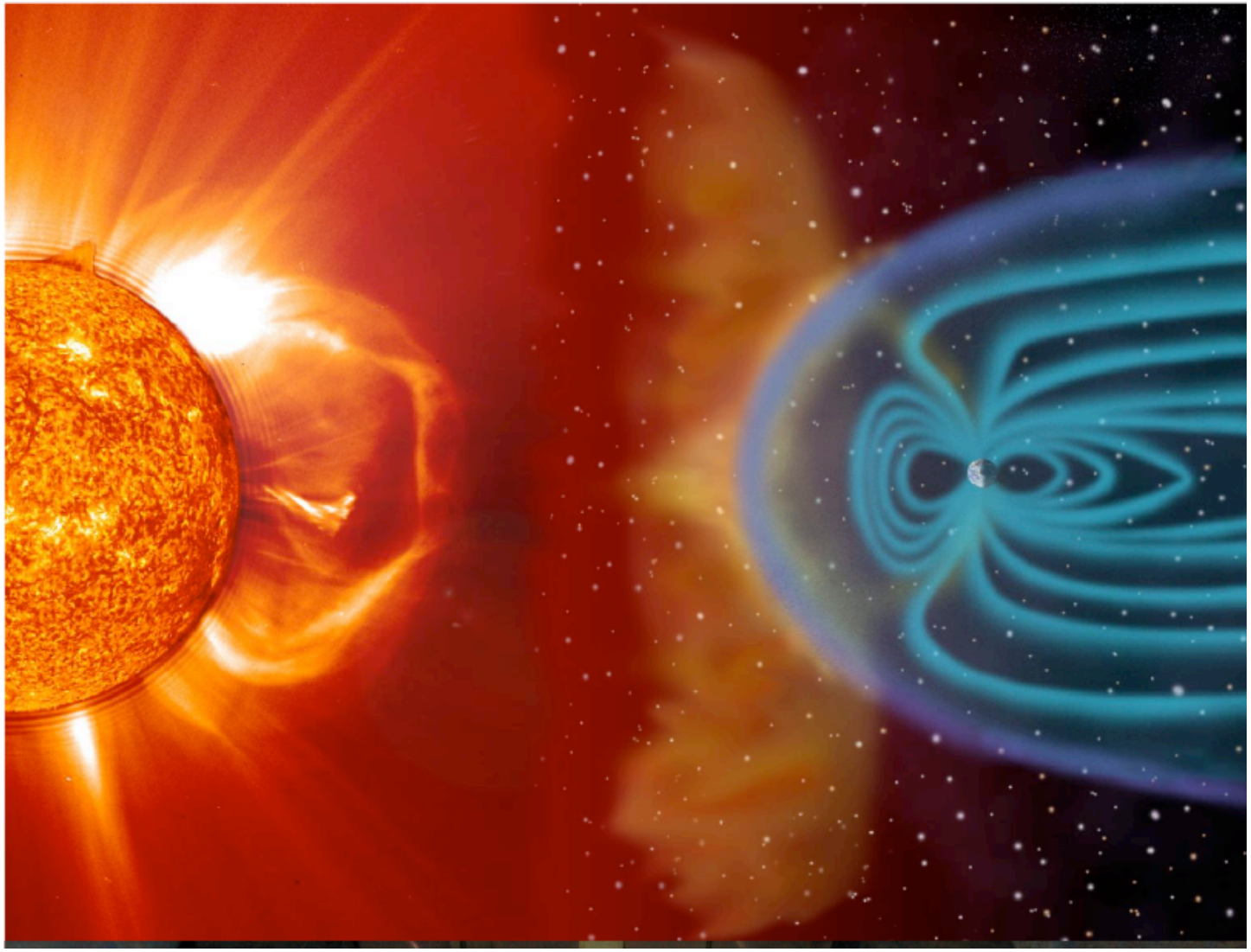
# Reconnection in Coronal Mass Ejection



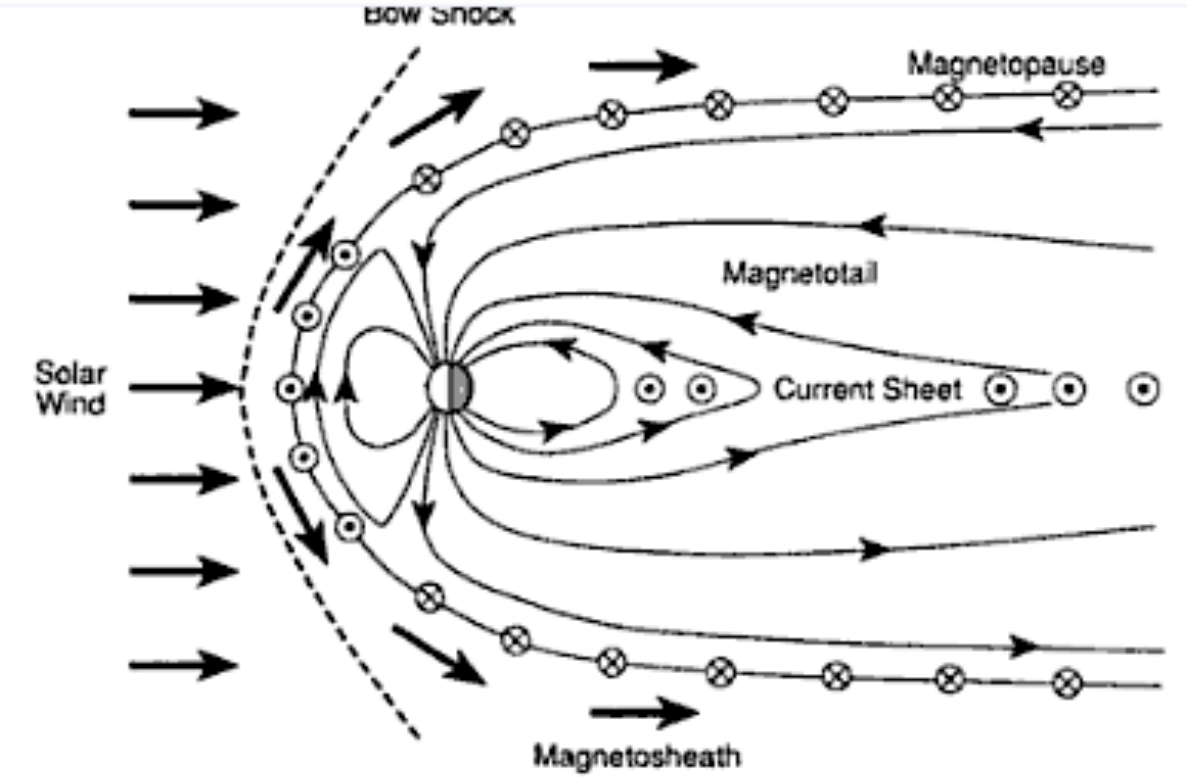

***Shibata***
***Unified model***

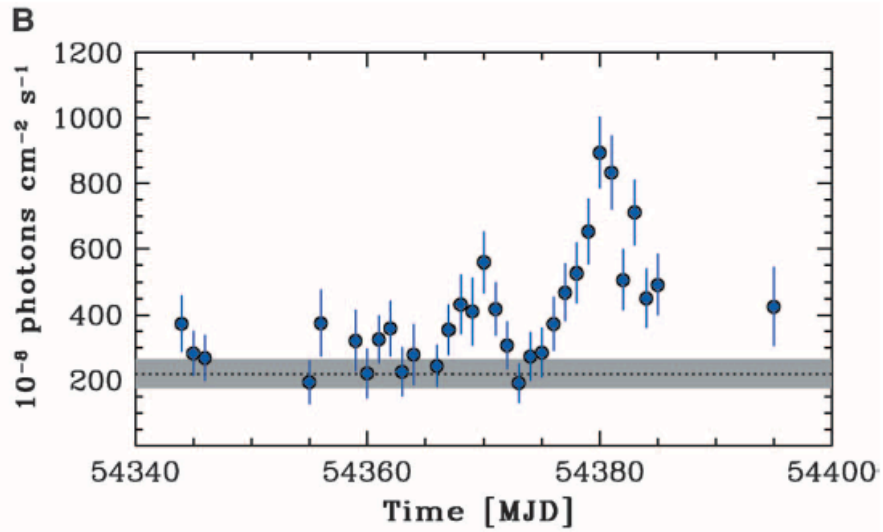


# 太陽風と地磁気の相互作用



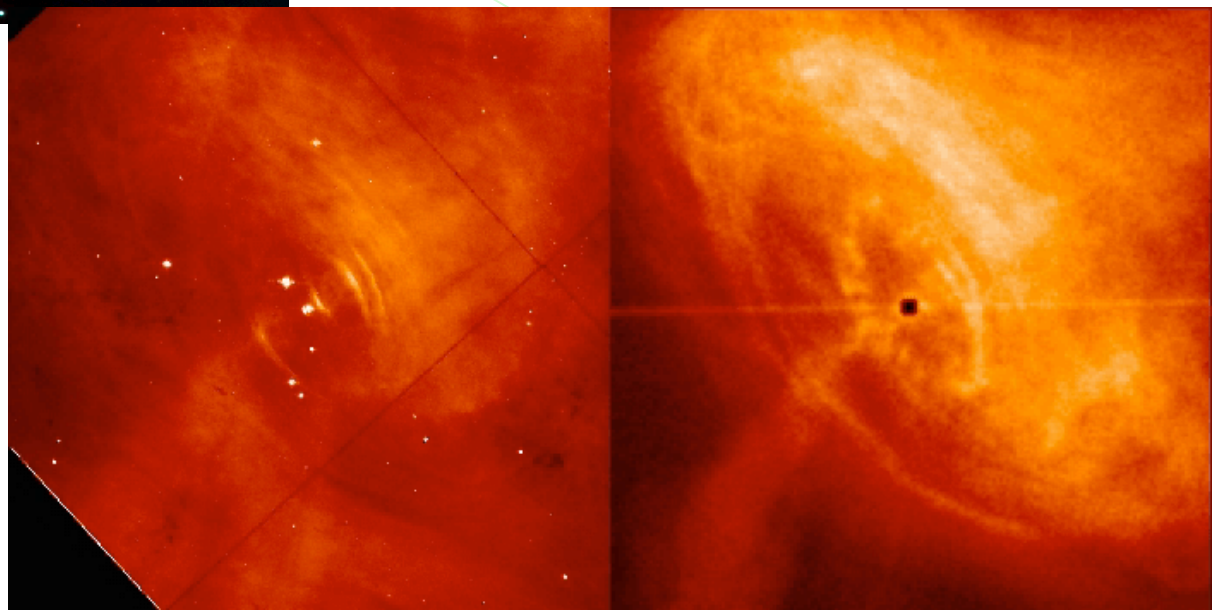
# 地球磁気圏: Magnetosphere



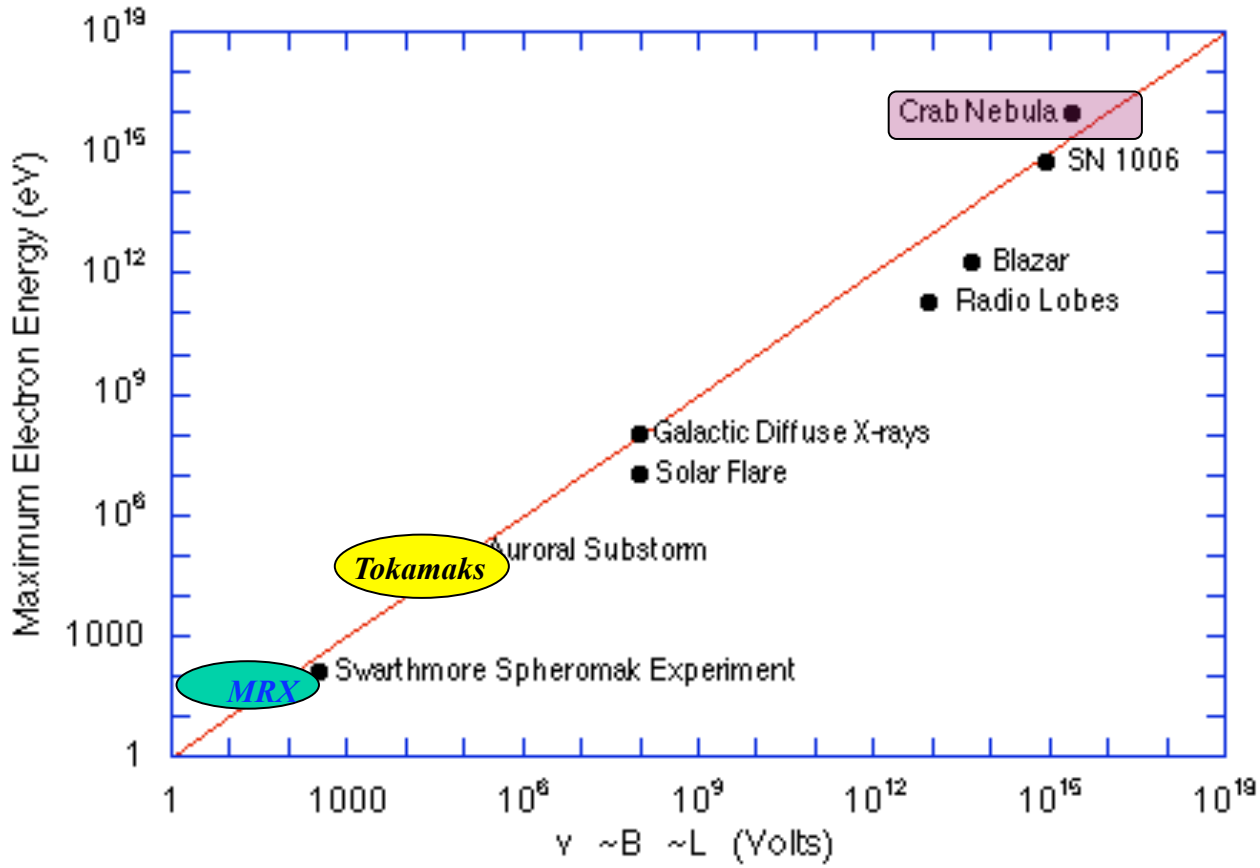



***Gamma ray flares in Crab Nebura***

*Reconnection could explain high energy gamma ray emission from the center of Crab Nebula (J. Arons, R. Blandford, et al) Uzdensky et al 2011*



# *Maximum particle energy in astrophysical and laboratory systems [by K. Makishima]*




where v is the typical velocity, B is the typical magnetic field, and L is the typical system size

from K. Makishima, "Energy non-equipartition processes in the Universe."

# A. Local Reconnection Physics

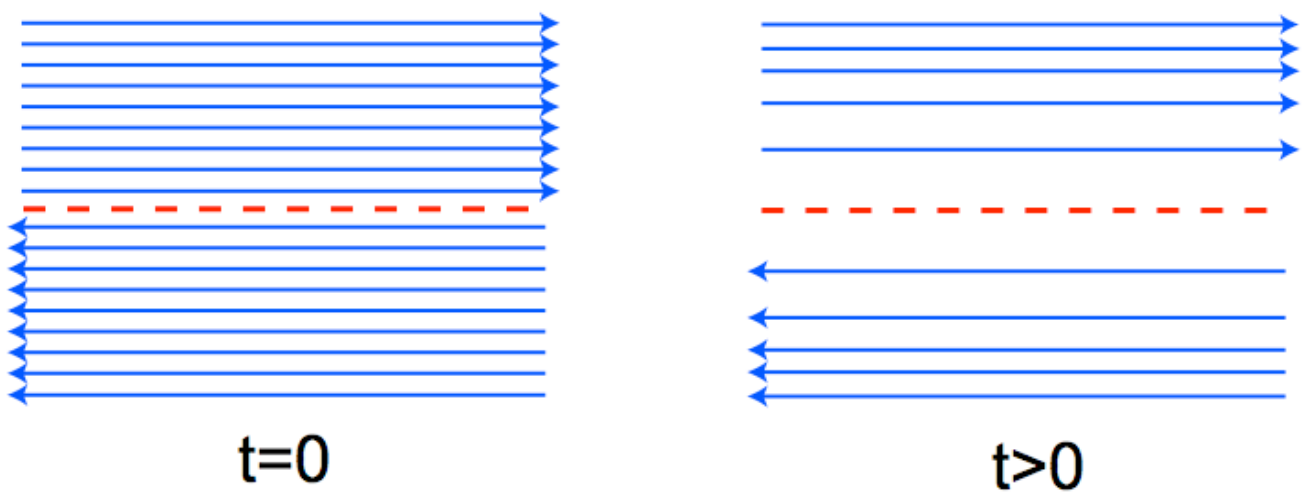
1. **MHD analysis**
2. Two-fluid analysis

# How do magnetic field line reconnect? (1)

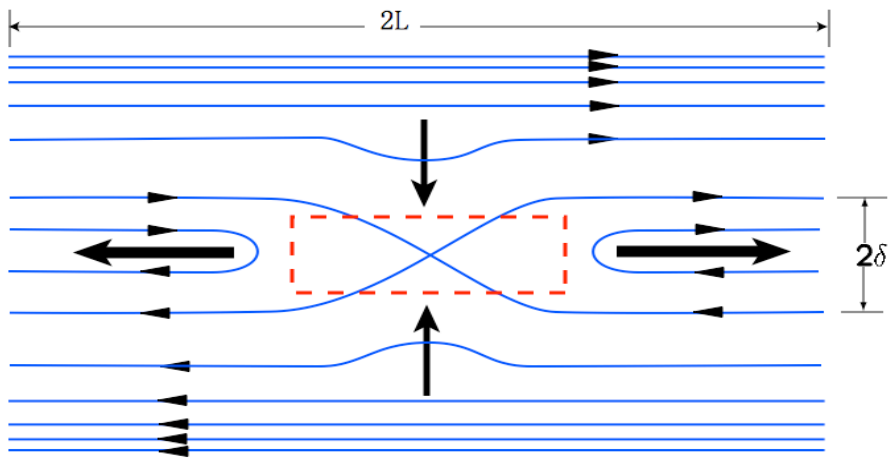
## 1-D Diffusion of Magnetic Field Lines

$$t_D \approx \frac{\mu_0 l^2}{\eta}$$

*~$10^6$ years for solar coronae*



# How do magnetic field lines reconnect? (2D)




- In 2D picture, magnetic field lines should reconnect faster because newly reconnected field lines move out of the diffusion region quickly due to a tension force

$$\mathbf{E} + \mathbf{v} \times \mathbf{B} = \eta \mathbf{j}$$

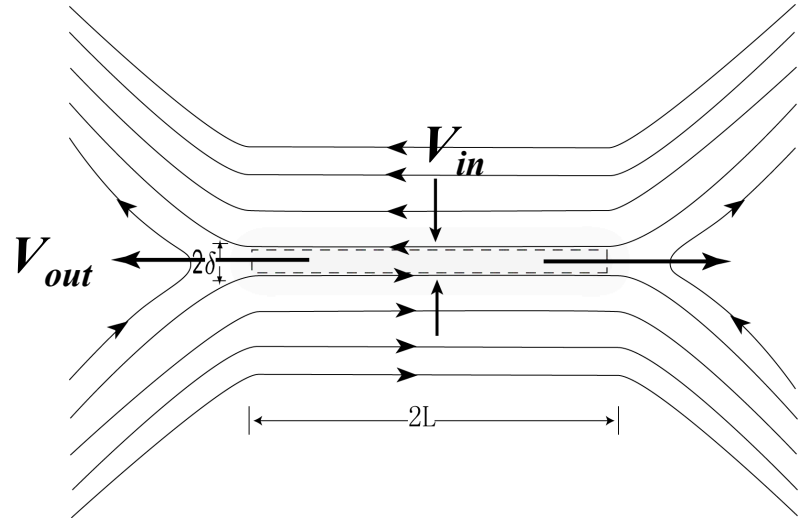
$$\frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \mathbf{E} \qquad => \qquad \frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}) + \frac{\eta}{\mu_0} \nabla^2 \mathbf{B}$$

$$\nabla \times \mathbf{B} = \mu_0 \mathbf{j}$$

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

Assumptions:

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




B is resistively annihilated in the sheet

$\tau_{reconn} \ll \tau_{SP} \sim 6-9$ months

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}) + \frac{\eta}{\mu_0} \nabla^2 \mathbf{B} \Rightarrow V_{in} B = \frac{\eta_{Spitz}}{\mu_0} \frac{B}{\delta}$$

Mass conservation: $V_{in} L \approx V_{out} \delta$

Pressure balance: $\frac{1}{2} \rho V_{out}^2 \approx \frac{B^2}{2\mu_0} \Rightarrow V_{out} \approx V_A$

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

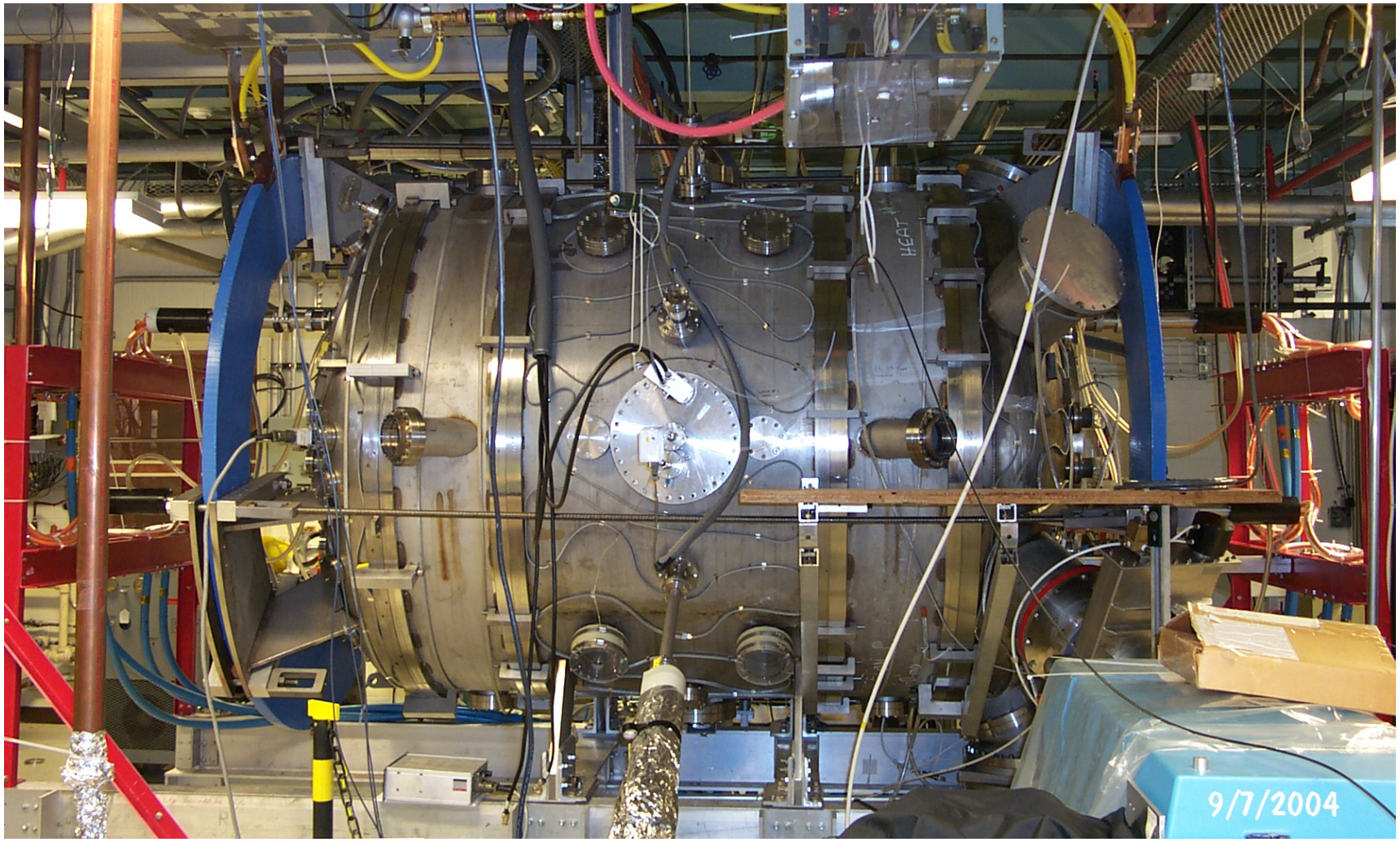
$$S = \frac{\mu_0 L V_A}{\eta_{Spitz}}$$

***S=Lundquist number***

# Dedicated Laboratory Experiments on Reconnection

| *Device* | *Location* | *Start* | *Investigators* | *Geometry* | *Issues* |
|---|---|---|---|---|---|
| 3D-CS | Russia | 1970 | Syrovatskii, Frank | Linear | 3D, heating |
| LPD, LAPD | UCLA | 1980 | Stenzel, Gekelman | Linear | Heating, waves |
| TS-3/4 | Tokyo | 1990 | Ono, Inomoto | Merging | Rate, heating |
| MRX | Princeton | 1995 | Yamada, Ji | Toroidal, merging | Rate, heating, scaling |
| SSX | Swarthmore | 1996 | Brown, Grey | Merging | Heating |
| VTF | MIT | 1998 | Egedal | Toroidal with guide B | Trigger |
| RSX | Los Alamos | 2002 | Intrator | Linear | Boundary |
| RWX | Wisconsin | 2002 | Forest | Linear | Boundary |

# Magnetic Reconnection Experiment (MRX)



# Objectives of Magnetic Reconnection Experiment

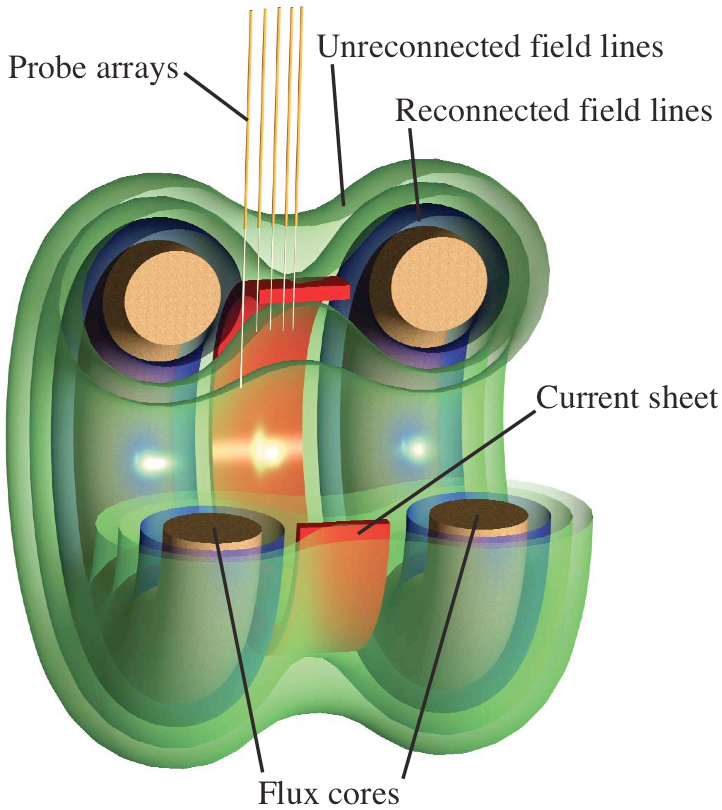
**We learn from plasmas the fundamental physics of magnetic reconnection** by generating **this elementary process in a controlled laboratory environment**

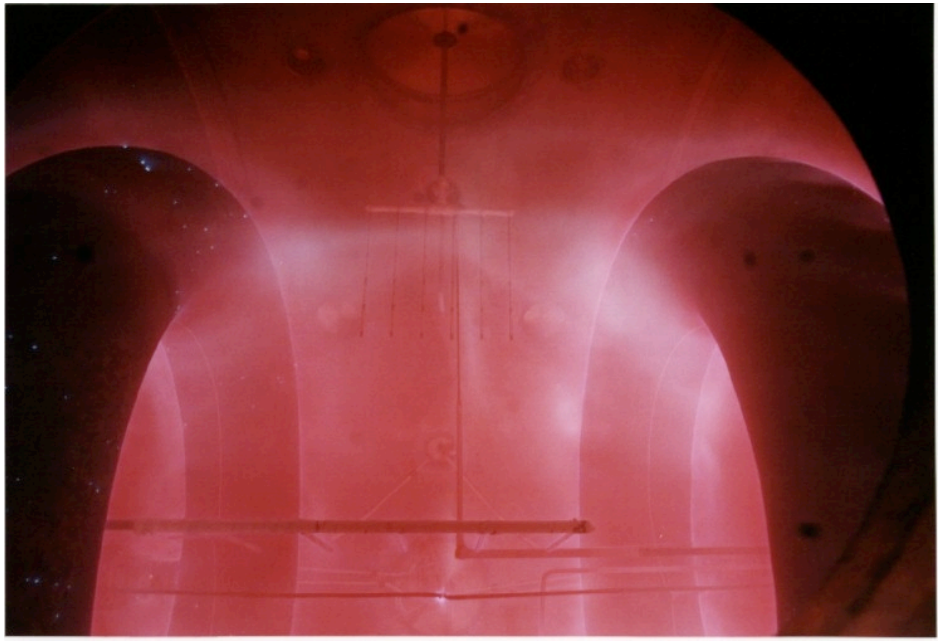
**The primary issues;**

- **Study non-MHD effects in the reconnection layer; [two-fluid physics, turbulence, new physics]**
- **How magnetic energy is converted to plasma flows and thermal energy,**
- **How local reconnection determine global phenomena**
  - **Global 2-D and 3-D MHD effects on reconnection**
  - **Effects of boundary**

- **Why does reconnection occur so fast?**

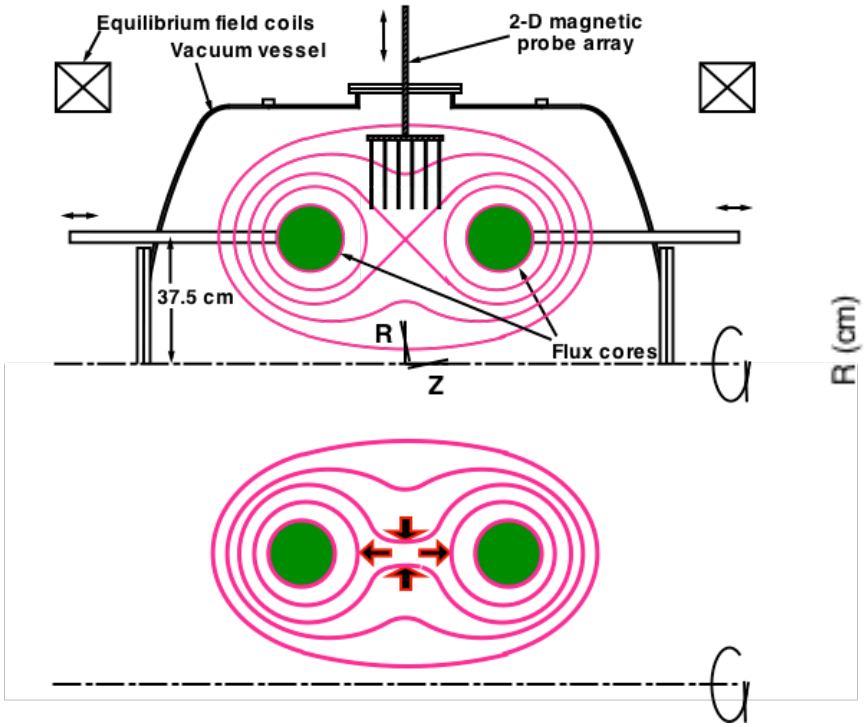
# Plasma Production in MRX



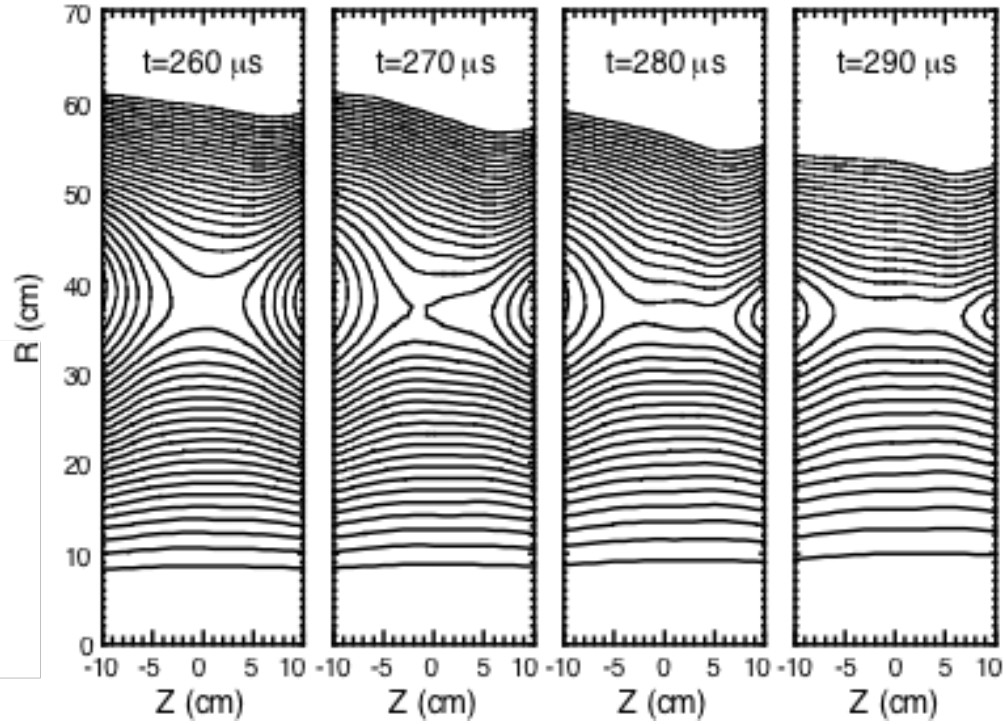



1) ***Gas is injected into the vacuum vessel.***
2) ***Currents through the "flux cores" ionize plasma and drive reconnection.***

# Experimental Setup and Formation of Current Sheet




**Experimentally measured flux evolution**

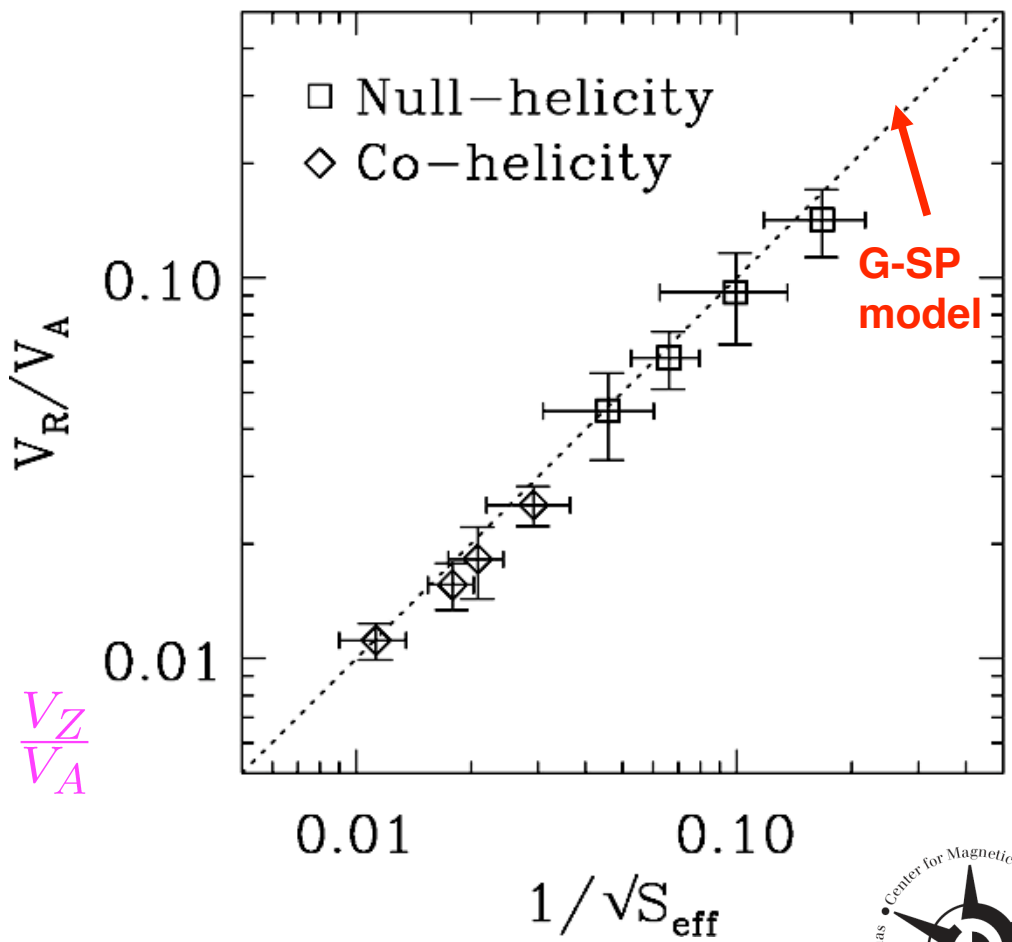



***$n_e$= 1-10 x$10^{13}$ $cm^{-3}$,***
***$T_e$~5-15 eV,***
***B~100-500 G,***

# Agreement with a Generalized Sweet-Parker Model

(Ji et al. PoP '99)

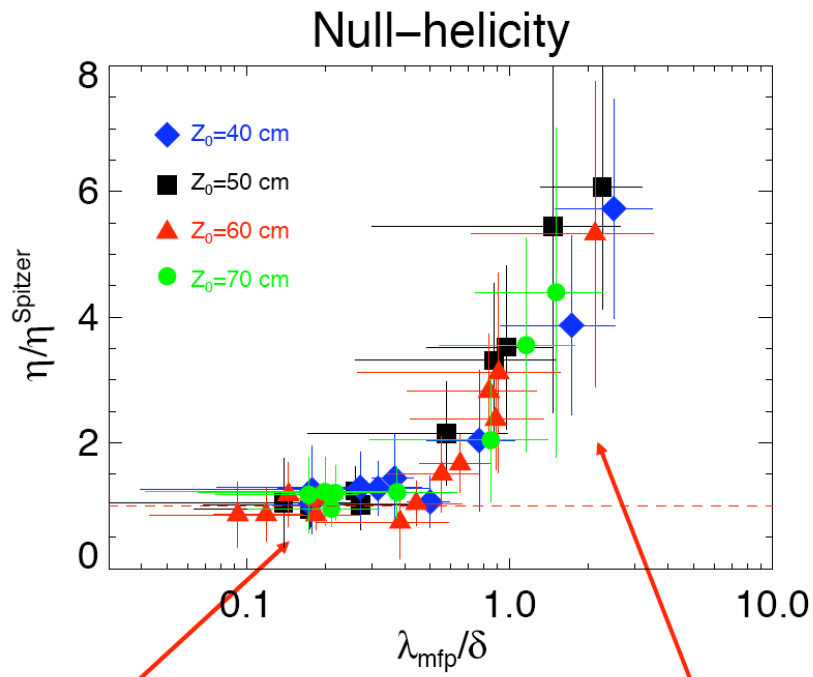
- **The model modified to take into account of**
  - **Measured enhanced resistivity**
  - Compressibility
  - High plasma pressure in downstream than upstream




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

# Resistivity increases as collisionality is reduced in MRX

***Effective resistivity***




Close to classical Spitzer

$$\eta_{\perp}^{Spitzer} = 1.03\times10^{-4} T_e^{-3/2} Z \ln\Lambda$$

Enhanced in low collisional plasma

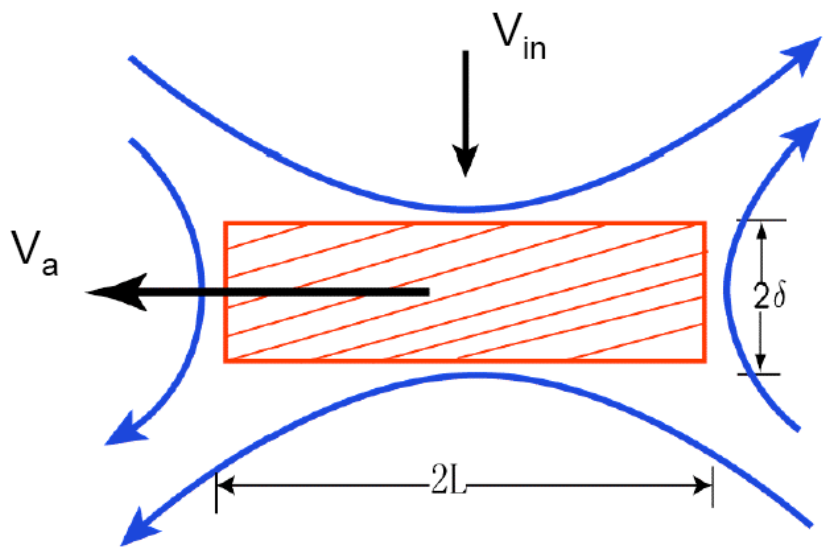
$$E_\theta + V_R \times B_Z = \eta j_\theta \qquad \eta^* \equiv \frac{E_\theta}{j_\theta}$$

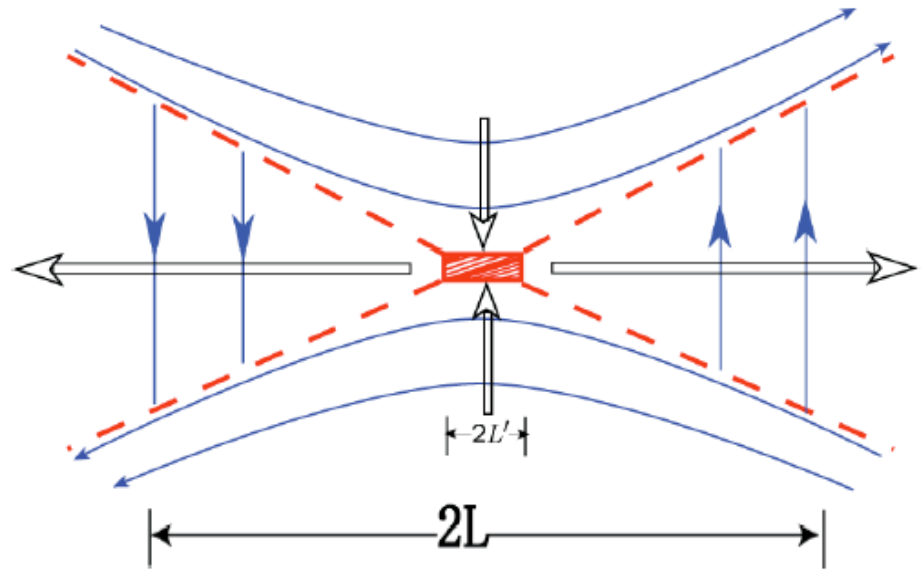
**But the cause of enhanced η was unknown.**

# Local Reconnection Physics

1. MHD analysis
2. **Two-fluid analysis**

# Descriptions of Fast Reconnection



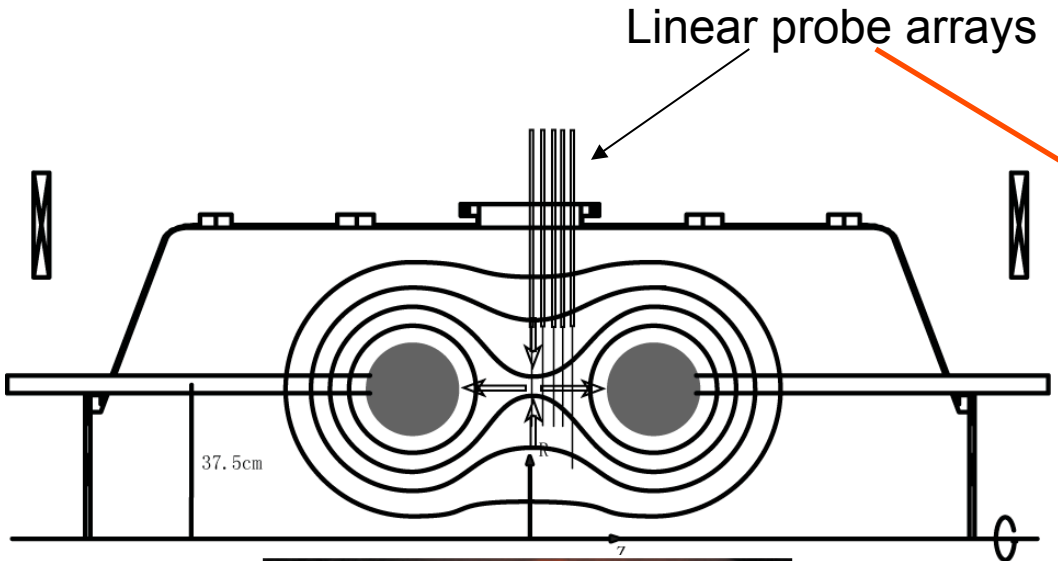

Generalized Sweet-Parker model with enhanced resistivity

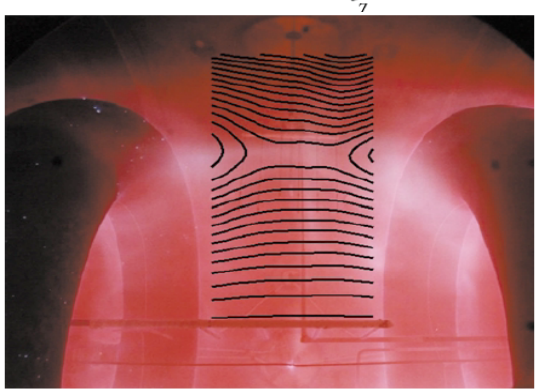
$$\mathbf{E} + \mathbf{V} \times \mathbf{B} = \eta \mathbf{J}^*$$

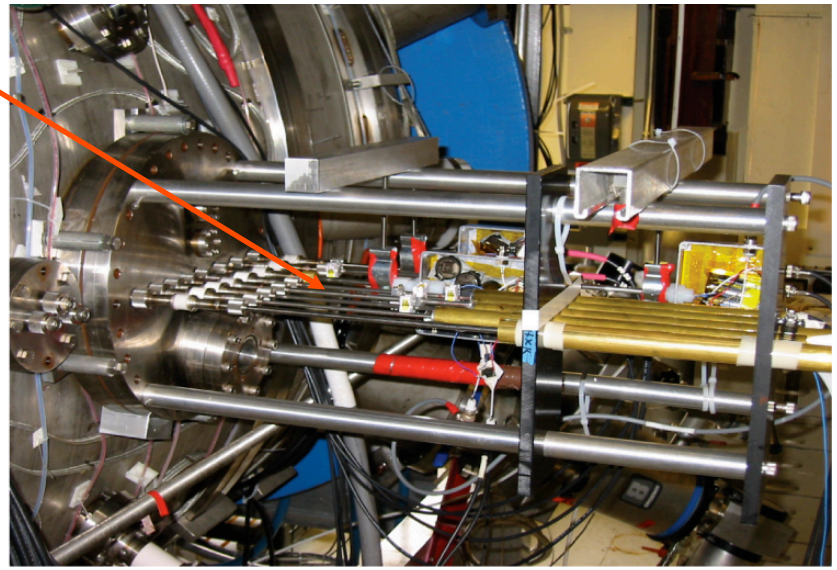
Two-fluid MHD model in which electrons and ions decouple in the diffusion region ($\sim c/\omega_{pi}$).

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

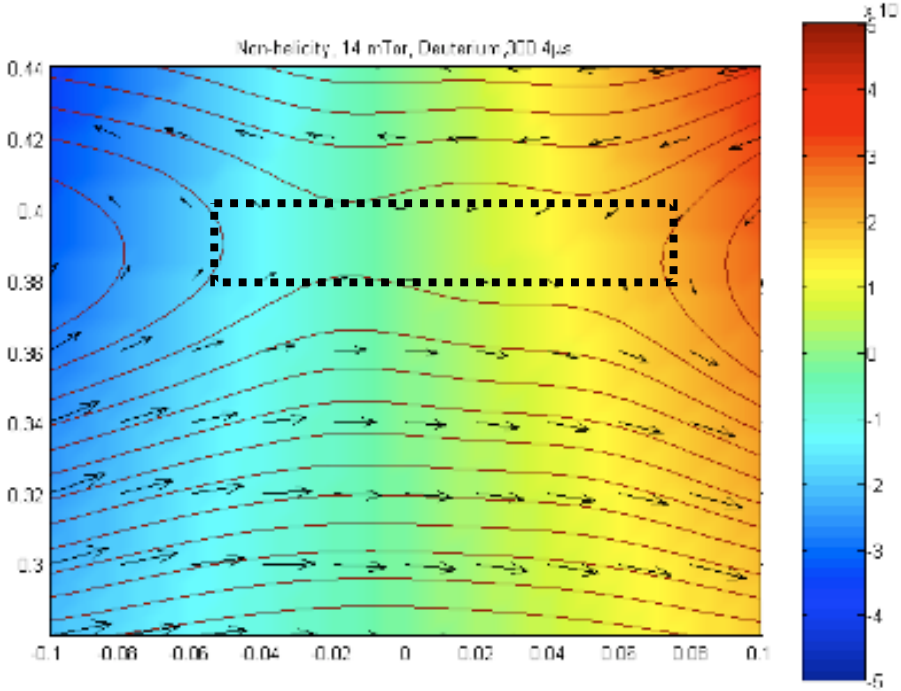
# MRX with fine probe arrays

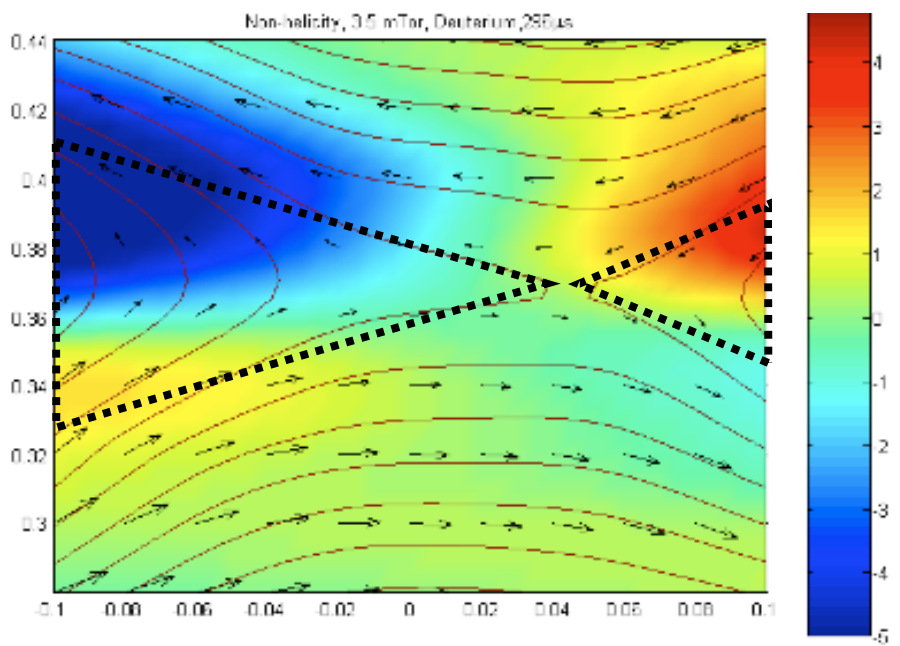




- Five fine structure probe arrays with resolution up to Δx= 2.5 mm in radial direction are placed with separation of Δz= 2-3 cm




# Neutral sheet Shape in MRX

Changes from "Rectangular S-P" type to "Double edge X" shape as collisionality is reduced

*Rectangular shape*

Collisional regime: $\lambda_{mfp} < \delta$
Slow reconnection

No Q-P field

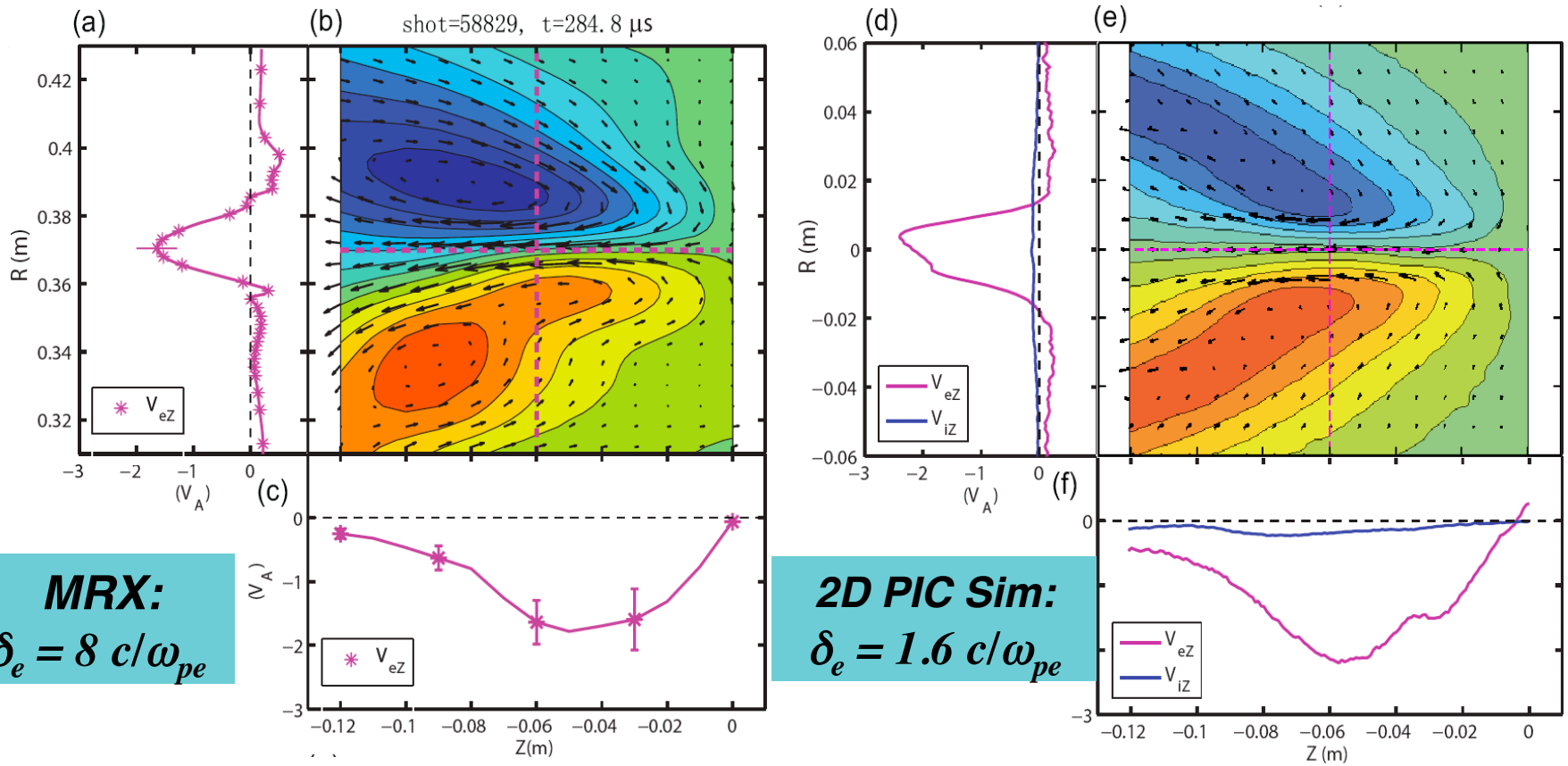
*X-type shape*

Collisionless regime: $\lambda_{mfp} > \delta$
Fast reconnection

Q-P field present

*Yamada et al, PoP 2006*

# First Detection of Electron Diffusion Layer Made in MRX: Comparison with 2D PIC Simulations

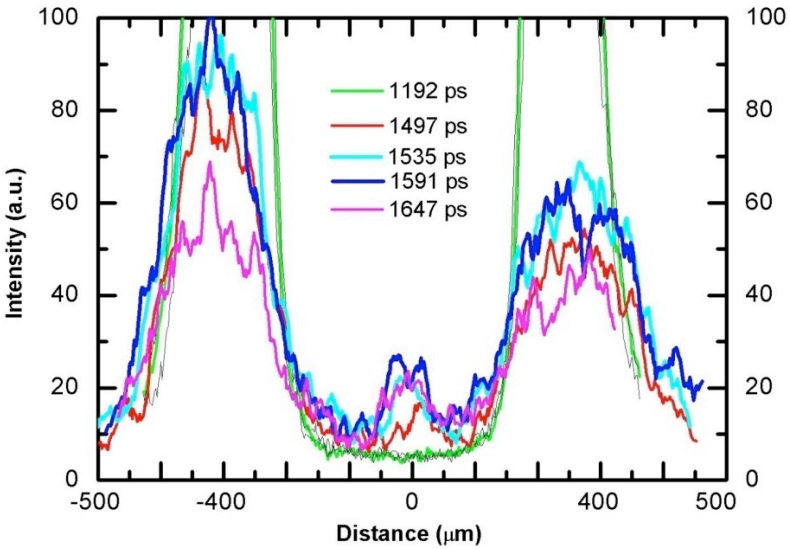


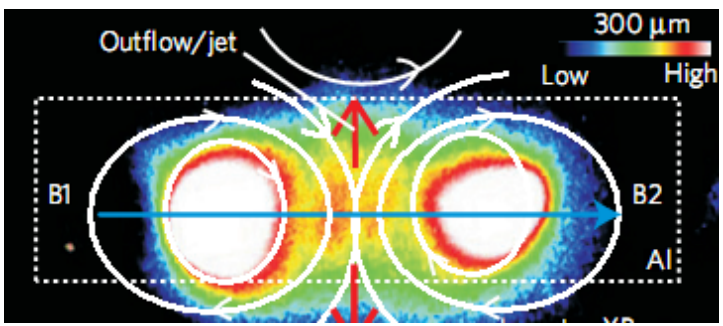

**MRX:**
$\delta_e = 8\ c/\omega_{pe}$

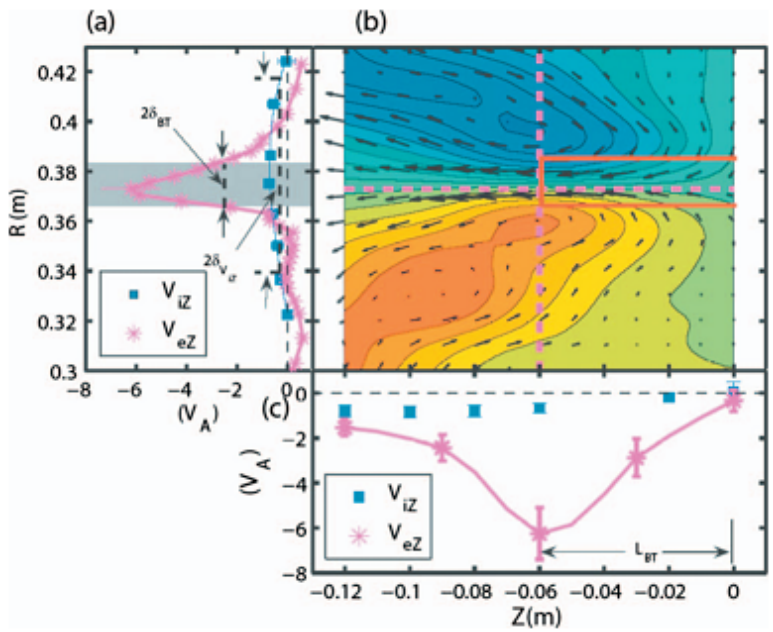
**2D PIC Sim:**
$\delta_e = 1.6\ c/\omega_{pe}$

***All ion-scale features reproduced; but electron-layer is 5 times thicker in MRX Þ importance of 3D effects***

# *Recent study of reconnection region in a laser plasma*



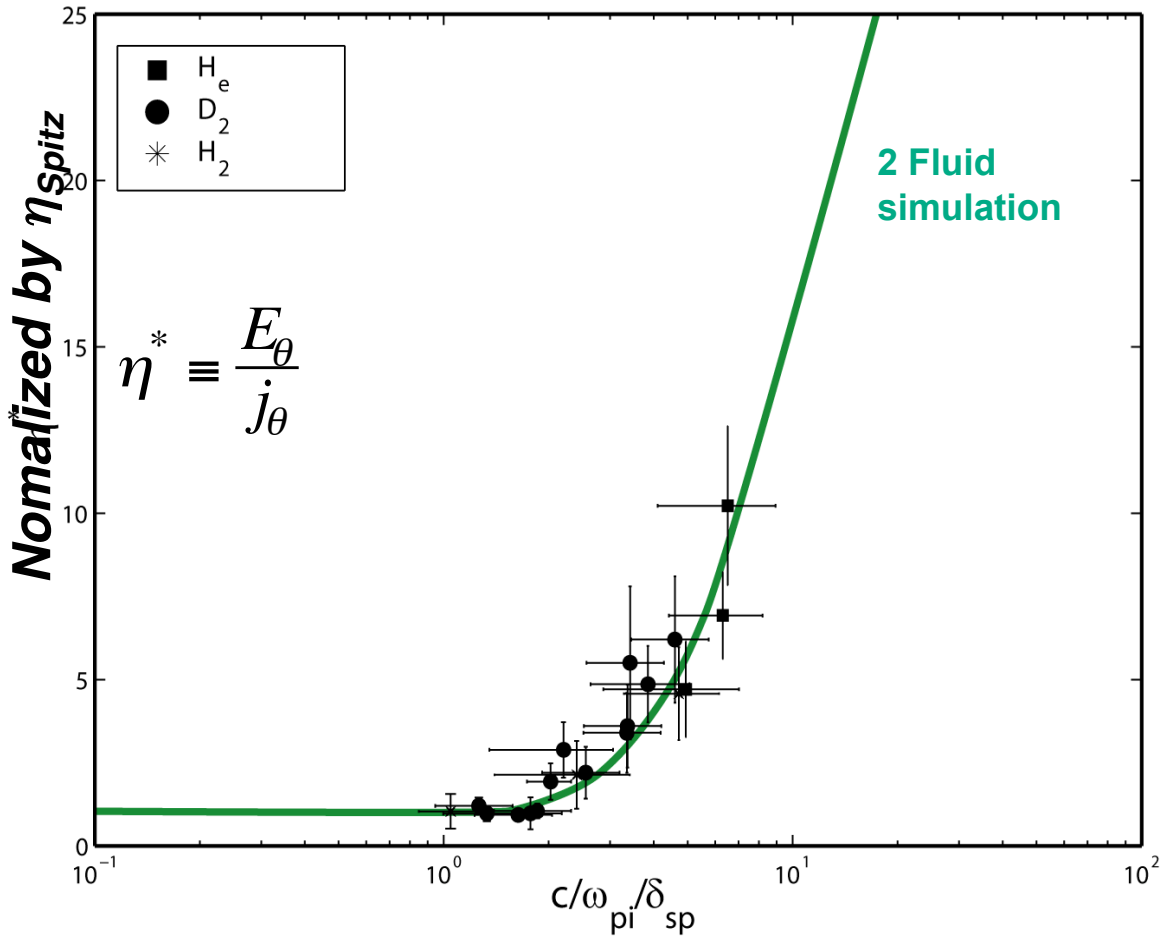




*Ren, et al. PRL. 101,085003(2008)*

- *Ion difussion region with the width of ~$d_i$*
- *Electron difussion region with the width of ~$10d_e$*

# Enhanced resistivity: MRX Scaling: $\eta^*$ vs $(c/\omega_i)/\delta_{sp}$

## A linkage between space and lab on reconnection




$(c/\omega_{pi})/\delta_{sp}$
$\sim 5(\lambda_{mfp}/L)^{1/2}$

*Yamada et al, PoP, 2006*

**MRX scaling shows a transition from the MHD to 2 fluid regime based on $(c/\omega_{pi})/\delta_{sp}$**

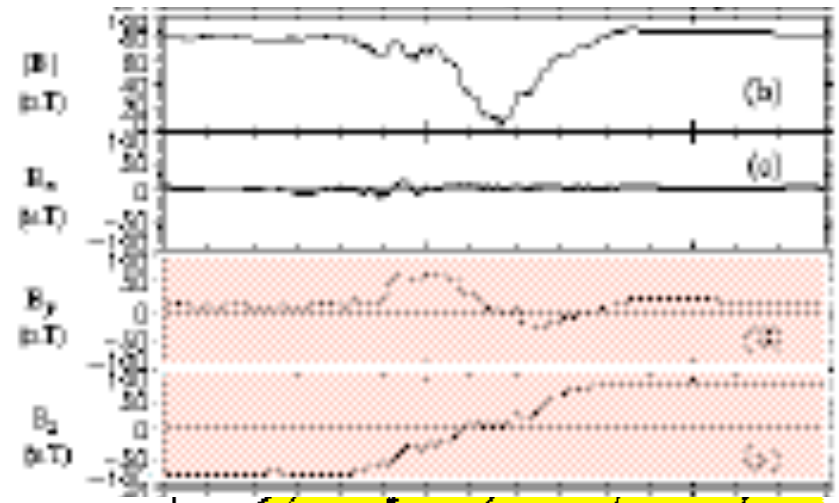
# Magnetic Reconnection in the Magnetosphere

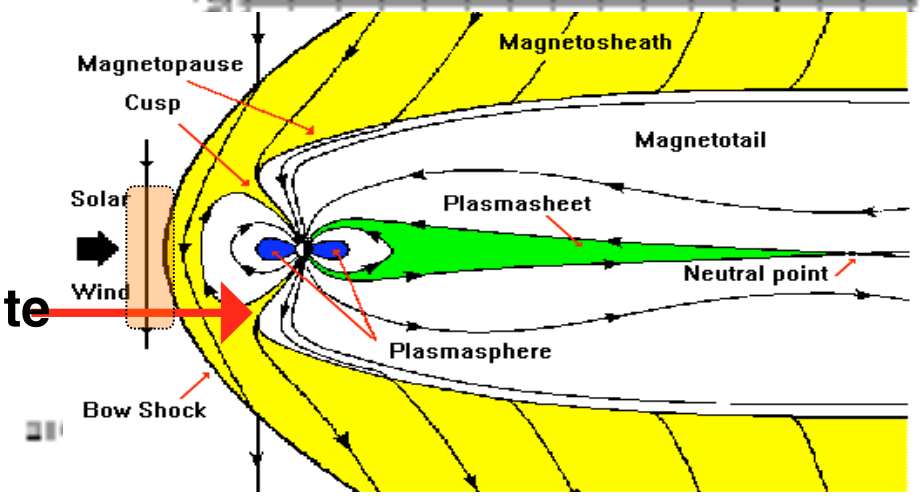
**A reconnection layer has been documented in the magnetopause**

$\delta \sim c/\omega_{pi}$

Measurements of Diffusion Region with a Hall effect signature

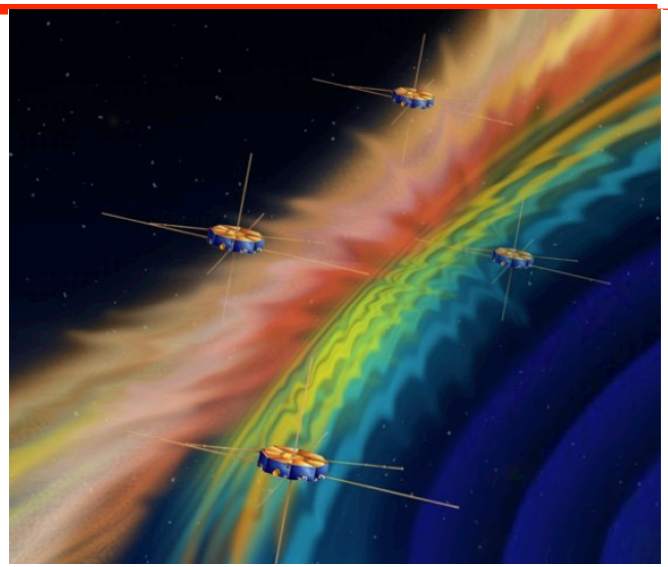
**Mozer et al., PRL 2002**



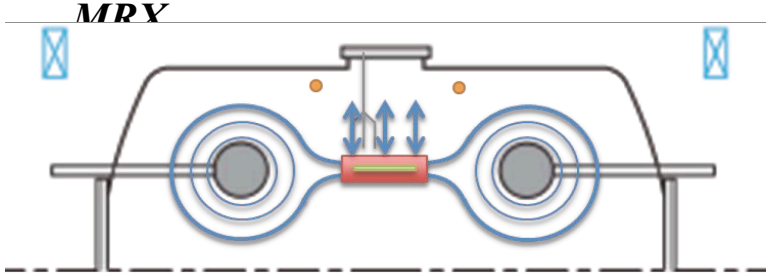



**POLAR satellite**

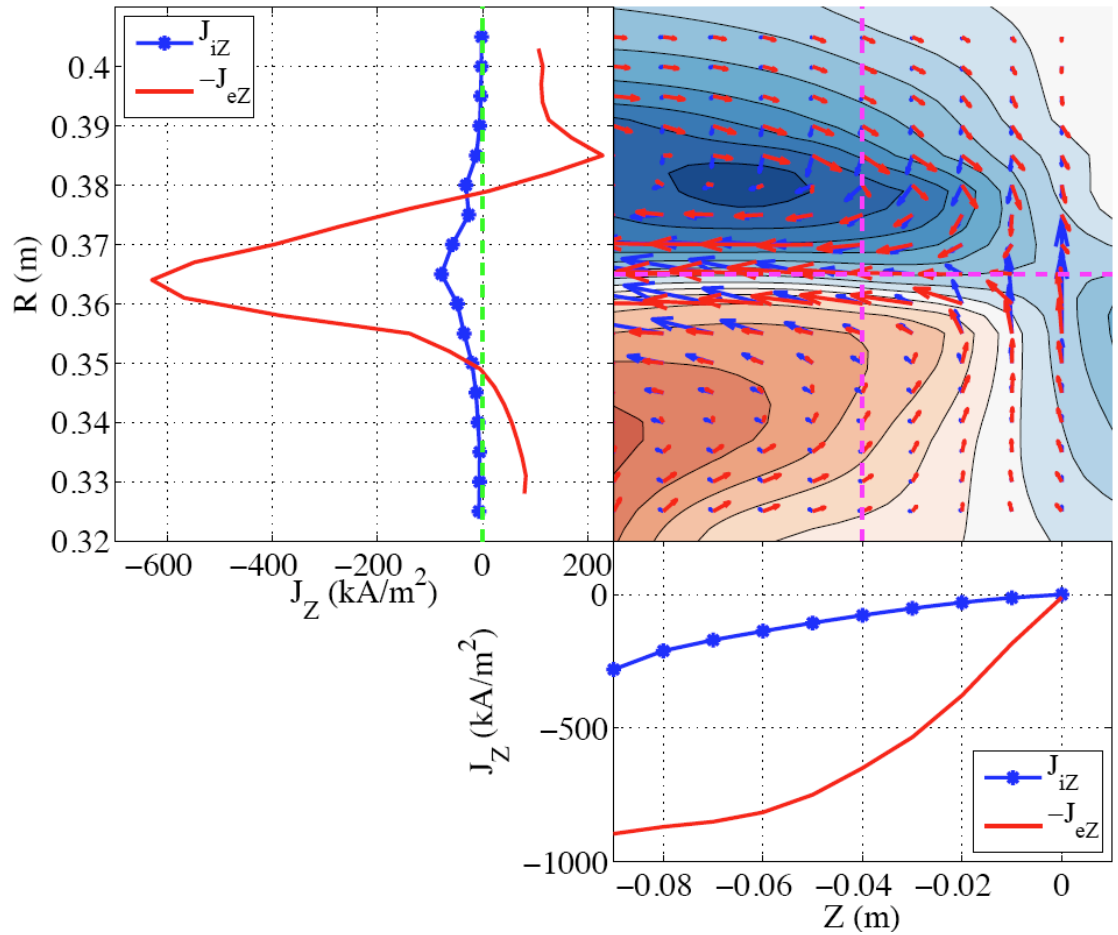
# Study of the two-fluid dynamics by plasma jogging, has started on MRX in collaboration with MMS



*Plasma can be jogged (swept) around the diagnostic region of MRX*



*Ion flow vectors are magnified by 5*




*Test ground for MMS (Magnetosphere Multi-Scale mission) data analysis*

*With Goddard, SWI, UNH, UC-Berkeley*

# Summary

Good progress has been made in the research of magnetic reconnection <= collaboration between laboratory physics and astrophysics communities

- Transition from collisional to collisionless regime documented
- A scaling found on reconnection rate

- Notable progress made for identifying causes of fast reconnection
  - Two fluid MHD physics plays dominant role in the collisionless regime. Hall effects have been verified through a quadrupole field
  - Electron diffusion region identified.
  - Effects of turbulence
  - Causal relationship between these processes for fast reconnection is yet to be determined

- Universal principles yet to be found for mechanisms of particle acceleration and heating and for global reconnection phenomena
  - Magnetic self-organization
  - Global forcing
  - Impulsive reconnection