Major Scientific Challenges and Opportunities in Understanding Magnetic Reconnection and Related Explosive Phenomena in Self-Organizing Plasmas

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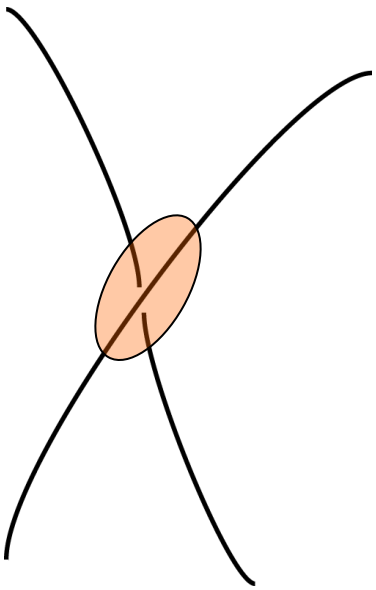
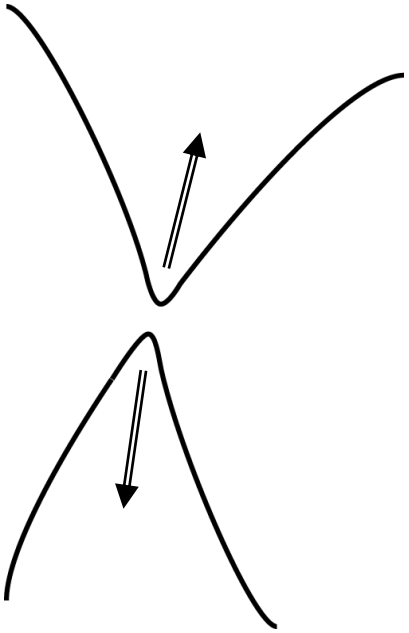
Outline

- Magnetic reconnection as a fundamental plasma process
  - What is magnetic reconnection?
  - Where does it occur and why is it important?
- Major scientific challenges in understanding reconnection and related explosive phenomena
- Major research opportunities in meeting scientific challenges
  - Theory and numerical simulation
  - Observations
  - Laboratory experiments
- Summary

Magnetic Reconnection



Before reconnection



After reconnection

- **Topological rearrangement of magnetic field lines**
- **Magnetic energy => Kinetic energy**

Magnetic Reconnection Occurs Throughout Heliophysical Plasmas

- Solar interior
  - Part of solar dynamo which requires changes in magnetic topology
- Solar chromosphere & corona
  - Solar flares, Coronal Mass Ejection, likely important for coronal heating
- Solar wind
  - Solar wind turbulence and current sheet dissipation
- Planetary magnetospheres
  - Plays a key role in plasma transport and magnetic storms, likely important for aurora activity
- Interface with local galactic plasma
  - Dissipation in heliospheric sheath and pause

Magnetic Reconnection Occurs Throughout Astrophysical Plasmas

- Normal Stars:
  - Same as in the heliospheric plasma.
- Non-accreting (isolated) neutron stars (NSs):
  - pulsar magnetospheres, winds, pulsar wind nebulae (PWN), e.g., the Crab;
  - magnetar flares.
- Accretion disks, their coronae, and jets/winds:
  - Newly-born stars (Young Stellar Objects);
  - Compact objects (white dwarfs, NSs, black holes), e.g., in X-ray binaries;
  - Central engines and jets of gamma-ray bursts (GRBs);
  - Super-massive black holes in centers of galaxies, including Sagittarius A* (our Galactic center), quasars, blazars, and giant extragalactic radio lobes.
- Interstellar and intergalactic medium:
  - part of ISM turbulence, including star formation in molecular clouds;
  - Galactic magnetic field and galactic wind;
  - galaxy clusters.

Magnetic Reconnection Occurs in Laboratory Fusion Plasmas

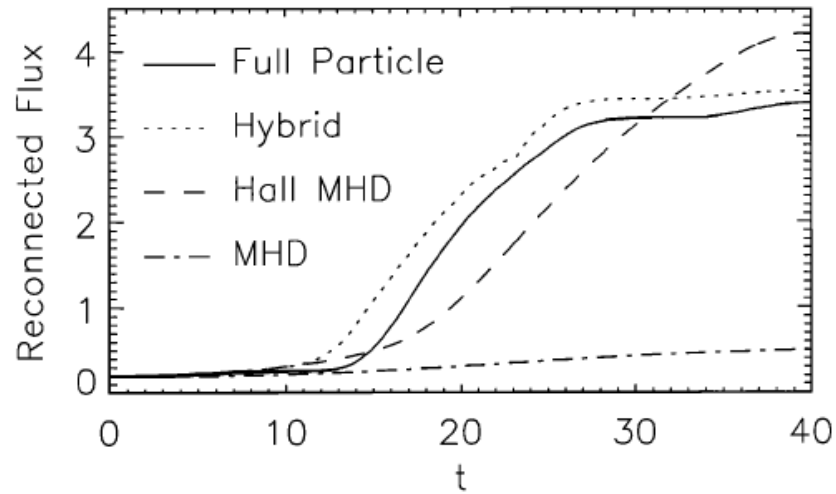
- Magnetic fusion plasmas
  - Sawtooth oscillations in tokamaks
  - (Neoclassic) tearing mode growth
  - Disruptive activity such as disruptions, possibly edge-localized modes
  - Magnetic self-organization (relaxation) events in low-q current-driven systems such as reversed field pinches and spheromaks
  - Formation of FRCs based on plasma merging
- Inertial fusion plasmas
  - Possibly in Z-pinch plasmas, in which magnetic drive dominates
  - Possible even in laser-driven plasmas, in which magnetic field is applied to improve the energy confinement, or magnetic fields could spontaneously arise and then saturate by reconnection

Magnetic reconnection is a fundamental process in the Universe and in laboratory fusion plasmas.

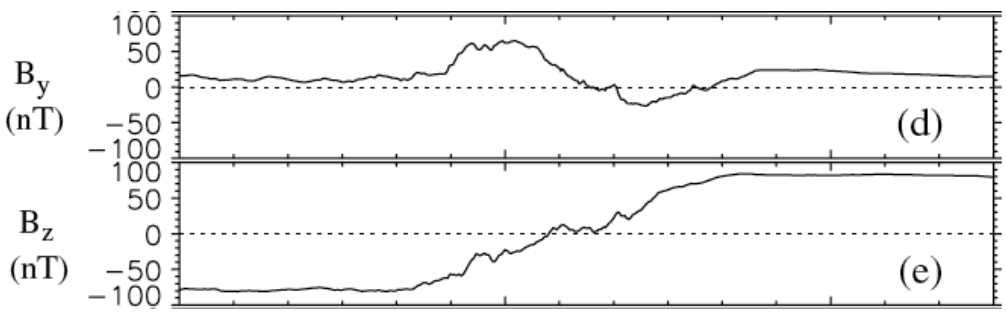
Significant Progress Made in the Past Decades in Understanding Reconnection

Example:

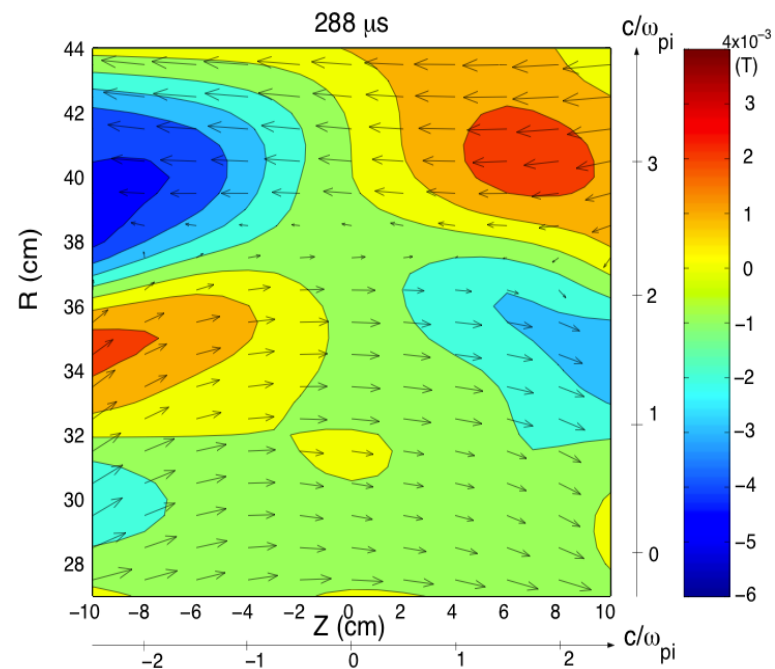
Fast reconnection due to **two-fluid effects**



Results from modeling
Birn et al, JGR (2001)



Results from POLAR satellite
Mozer et al., PRL (2002)



Results from MRX experiment
Ren et al, PRL (2005)

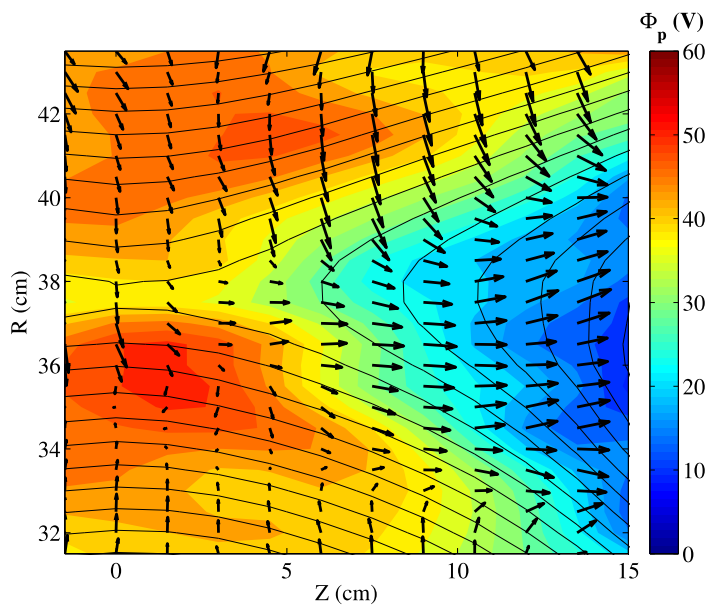
Major Scientific Challenges in Understanding Magnetic Reconnection (I)

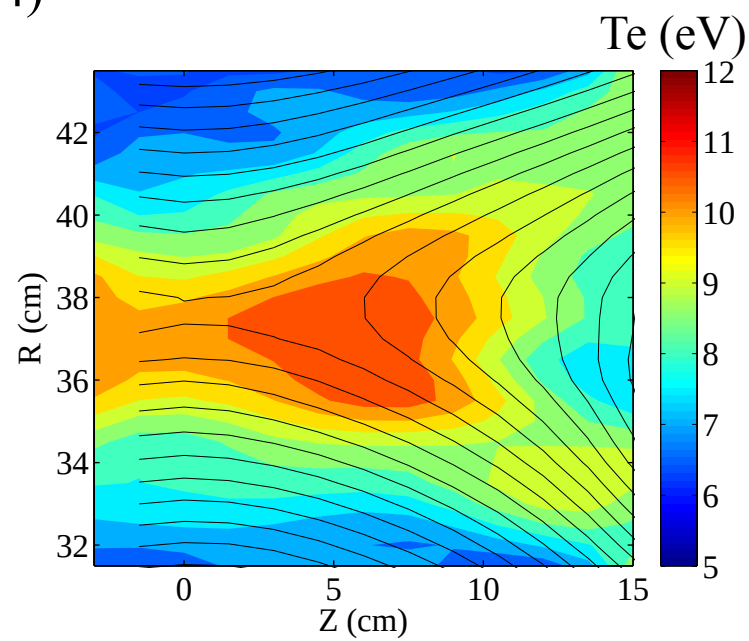
1. **How is reconnection rate determined?** ***(The rate problem)***
   - Two-fluid effects shown to facilitate fast reconnection
   - Associated dissipation, especially on electron scales, is still elusive.

2. **How are particles energized?** ***(The energy problem)***
   - Heating versus (bulk and nonthermal) acceleration
   - Electrons versus ions (versus neutrals)

Energy Converted from Magnetic Field to Ion and Electrons: Ion Flow Acceleration, Electron/Ion Heating

Yoo et al. PRL (2013)
Yamada et al. Nature Communications (2014)





- 1/2 of magnetic energy goes to plasma
  - 2/3 to ion flow energy and heating
  - 1/3 to electron heating

The inventory of enthalpy flow is consistent with the recent space data (Eastwood '13)

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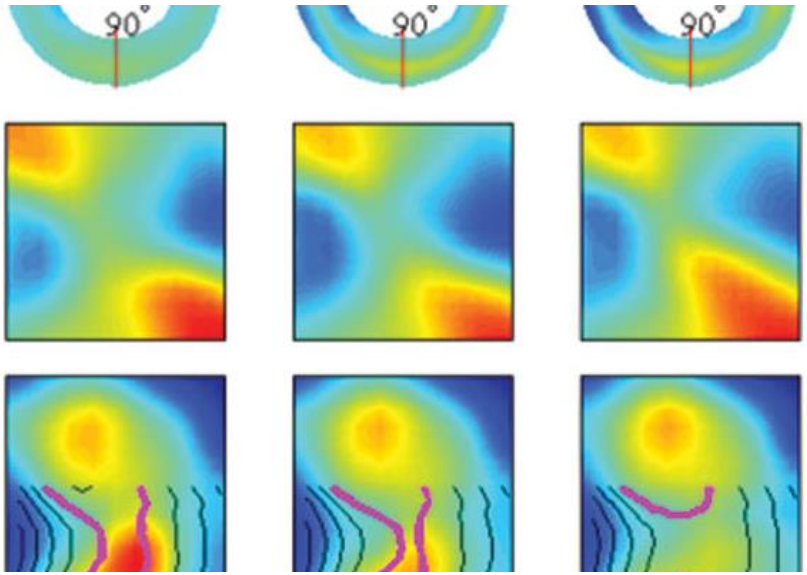
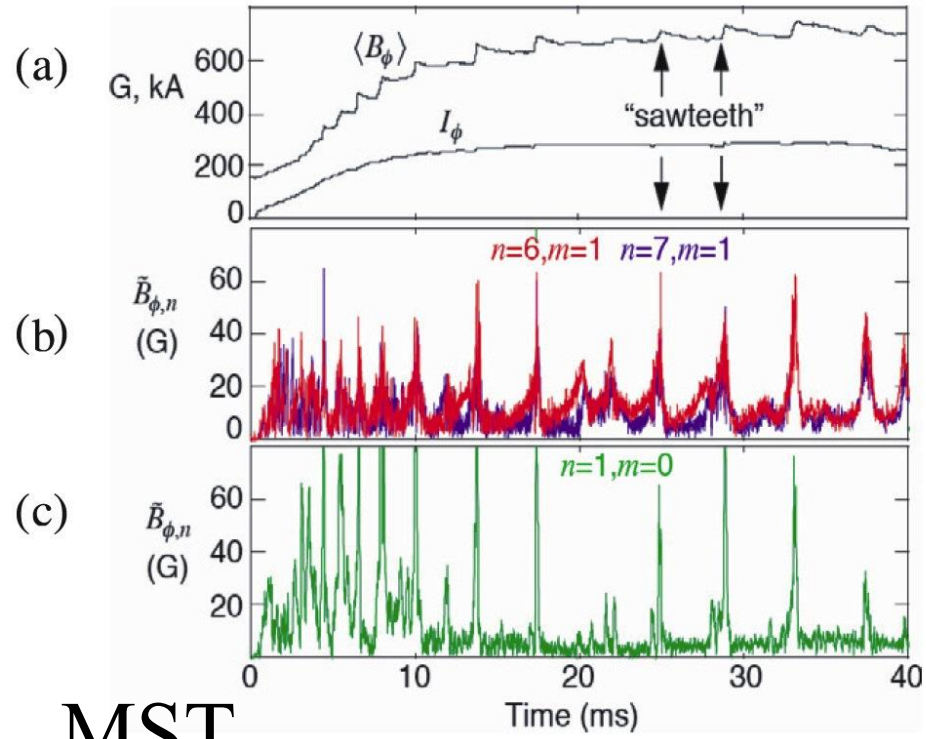
3. **How does reconnection take place in 3D?** ***(The 3D problem)***
   - 3D fundamentally different different from 2D?
   - Effects due to magnetic stochasticity or turbulence?
   - Roles of reconnection in the self-organization phenomena such as Taylor relaxation due to accumulation and conservation of magnetic helicity?

Global 3D: Cause of the Reconnection Onset in Periodic Systems



VTF



MST

Katz et al. (2010)

Prager et al. (2005)

Major Scientific Challenges in Understanding Magnetic Reconnection (II)

4. **How do boundary conditions affect reconnection process?** ***(The boundary problem)***
   - Periodic versus Open
   - Line-tied

5. **How does reconnection start?** ***(The onset problem)***
   - Why reconnection is always impulsively? How magnetic energy is accumulated?
   - Is onset local or global, 2D or 3D?

6. **How does partial ionization affect reconnection?** **(*The partial ionization problem*)**
   - Fast reconnection occurs also in weakly ionized plasmas, as in chromosphere and molecular clouds.
   - Increased friction or enhanced two-fluid effect?

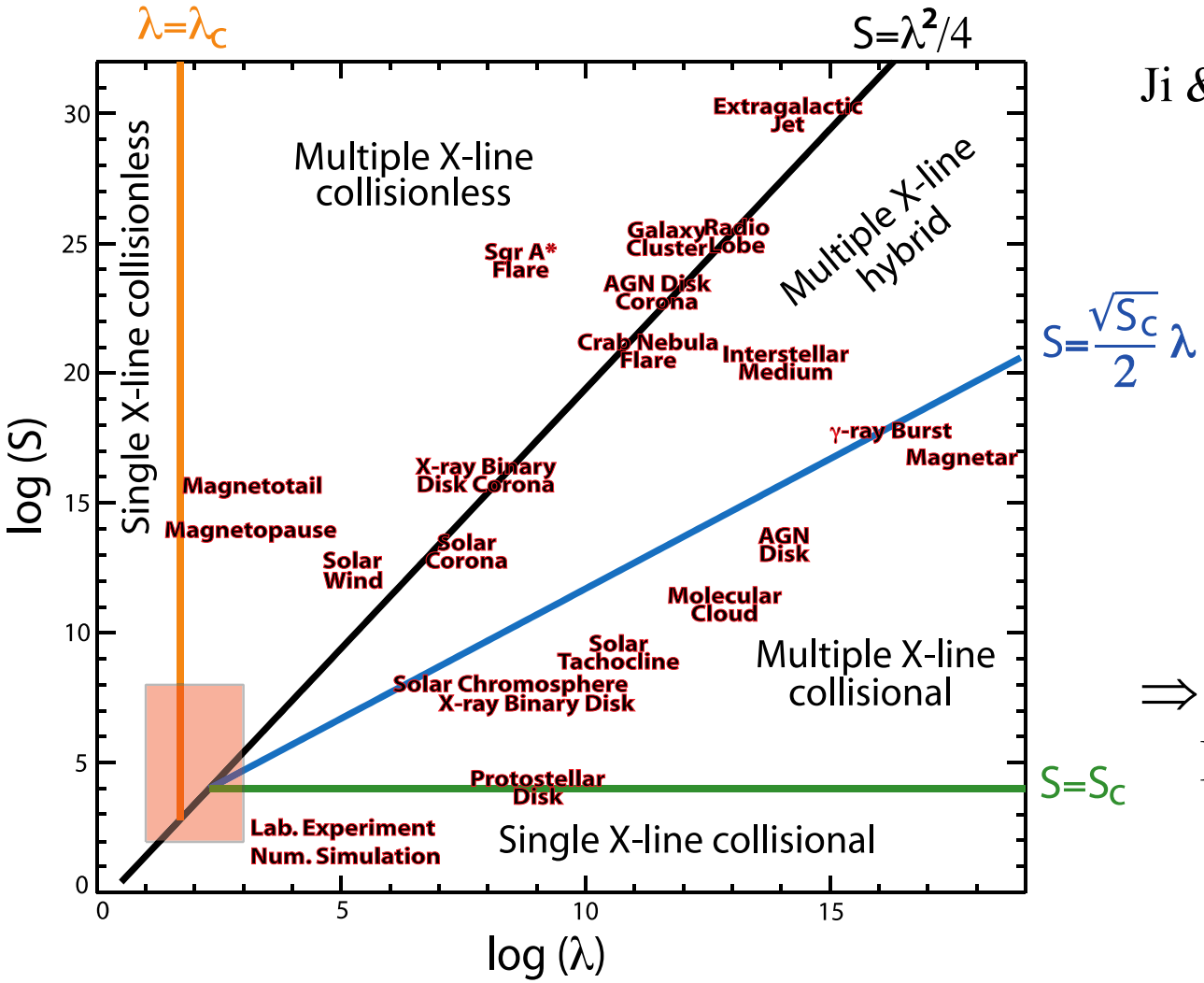
Major Scientific Challenges in Understanding Magnetic Reconnection (III)

7. **What roles does reconnection play in flow-driven systems? *(The flow-driven problem)***
   - As a mechanism to saturate or regulate dynamo
   - How does reconnection occur in preexisting turbulence?

8. **How does reconnection occur in extreme physical conditions? (*The extreme problem*)**
   - How does radiation or relativity affect reconnection?

9. **How to apply local reconnection physics to a large system? *(The multi-scale problem)***
   - Different coupling mechanisms between local dissipation scale or kinetic scale to global MHD scales: "reconnection phase diagram"
   - Do plasmoid instabilities in reconnecting current sheets exist in real plasmas?

"Phase Diagram" for Different Coupling Mechanisms during Reconnection in Large Plasmas



Ji & Daughton (2011)

⇒ Larger devices
FLARE, TREK

Further updates exist, such as on effects due to electron anisotropic pressure
[Le et al. J. Plasma Phys. (2014)]

Each scientific question can be studied by multiple, complementary approaches

Questions	Theory & Simulation	Space observations		Laboratory Experiments		
		in situ	Remote-sensing	Magnetized Basic	Magnetic Fusion	High Energy Density
Multi-Scale						
Rate						
Partial Ionization						
3D						
Boundary						
Onset						
Energy						
Flow-driven						
Extreme						

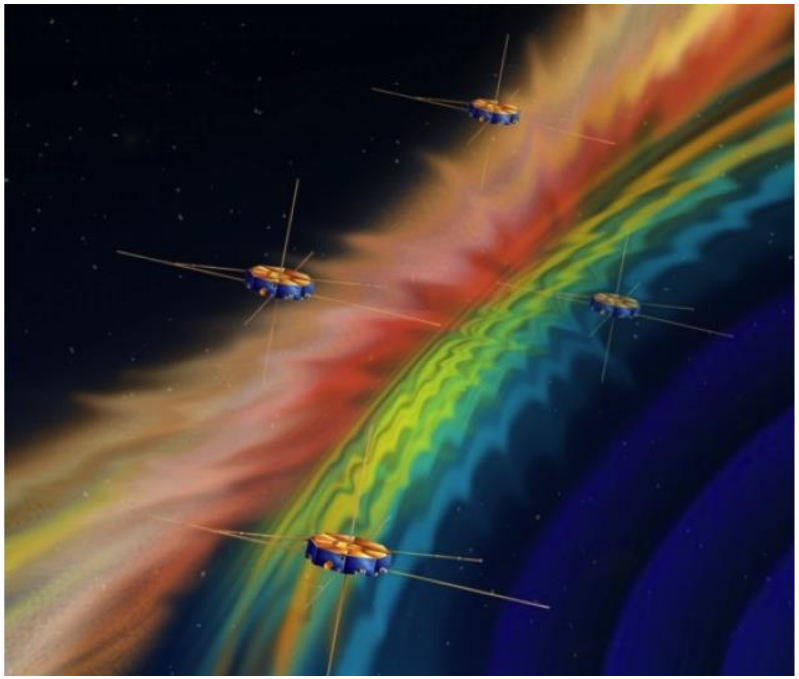
Green: capabilities in place or can be available upon investment
Yellow: capabilities difficult to achieve in the near future

Theory & Simulation

- All major questions will be studied by theory and simulations using fluid, kinetic and hybrid models, and multi-fluid models that include kinetic effects through physics-based closure equations.
- **Simulations can verify and validate lab experiments.**
- Petascale computing resources have enabled modeling of 2D reconnection processes with realistic plasma parameters and system geometries.
- The exascale era promises to enable more realistic issues in 3D reconnection studies.

Dahlin et al,
Daughton et al,

Observations



- Magnetospheric Multi-Scale mission and the scheduled Solar Probe Plus mission will provide unprecedented *in situ* measurements of magnetic reconnection and its related phenomena, such as coronal heating.
- The state-of-the-art remote sensing satellites such as Solar Dynamics Observatory and Fermi satellite continue to surprise us with new observations of explosive phenomena.

- These observations are intrinsically **either local *in situ* or global** morphological, but not simultaneously both, so that the problems such as multi-scale coupling are difficult to attack.
- Nonetheless, observations provide the ground truth of magnetic reconnection and its related phenomena in nature.

Laboratory Experiments

- With diversity in geometries and parameter regimes, experiments will continue to address some of the forefront questions in reconnection physics.
- The dedicated magnetized basic experiments are most mature, and their next generation facilities are poised to provide accessibilities in new reconnection phases with direct relevance to heliophysics and astrophysics.
- Magnetic fusion experiments provide accesses to collisionless reconnection in periodic geometries.
- High energy density plasmas by laser or Z pinch are emerging as a new platform, which can be used to uniquely attack a subset of the major reconnection problems.
- All of these experiments require adequate diagnostics and modeling in order to effectively contribute to solving reconnection problems.

Dedicated Laboratory Experiments on Reconnection

Device	*Where*	*Since*	*Who*	*Geometry*	*Focus*
3D-CS	Russia	1970	Syrovatskii, Frank	Linear	3D, energy
LPD, LAPD	UCLA	1980	Stenzel, Gekelman, Carter	Linear	Energy, 3D
TS-3/4	Tokyo	1990	Katsurai, Ono	Merging	Rate, energy
MRX	Princeton	1995	Yamada, Ji	Toroidal, merging	Rate, 3D, energy, partial ionization, boundary, onset
SSX	Swarthmore	1996	Brown	Merging	Energy, 3D
VTF	MIT	1998	Fasoli, Egedal	Toroidal	Onset, 3D
Caltech exp	Caltech	1998	Bellan	Planar	Onset, 3D
RSX	Los Alamos	2002	Intrator	Linear	Boundary, 3D
RWX	Wisconsin	2002	Forest	Linear	Boundary
Laser plasmas	UK, China, Rochester	2006	Nilson, Li, Zhong, Dong, Fox, Fiksel	Planar	Flow-driven, extreme
VINETA II	Max-Planck	2012	Grulke, Klinger	Linear	3D
TREX	Wisconsin	2013	Egedal, Forest	Toroidal	Energy
FLARE	Princeton	2013	Ji +	Toroidal	All
HRX	Harbin,China	2015	Ren +	3D	3D, energy

Summary

- Magnetic reconnection is a fundamental process throughout the universe and in laboratory fusion plasmas.
- Major scientific questions are identified to understand magnetic reconnection and to predict related explosive phenomena.
- Theory/simulations, observations, and laboratory experiments should work synergistically to solve these major questions.
- Multiple communities, **with cross-agency support**, should collaborate effectively through appropriate forms of partnership to maximize scientific productivity: DoE-NASA collaboration is desirable.
- Progress in understanding magnetic reconnection will also benefit fusion research as well as space weather research.