On magnetic reconnection in space plasmas: current and future perspectives from multipoint & multiscale missions

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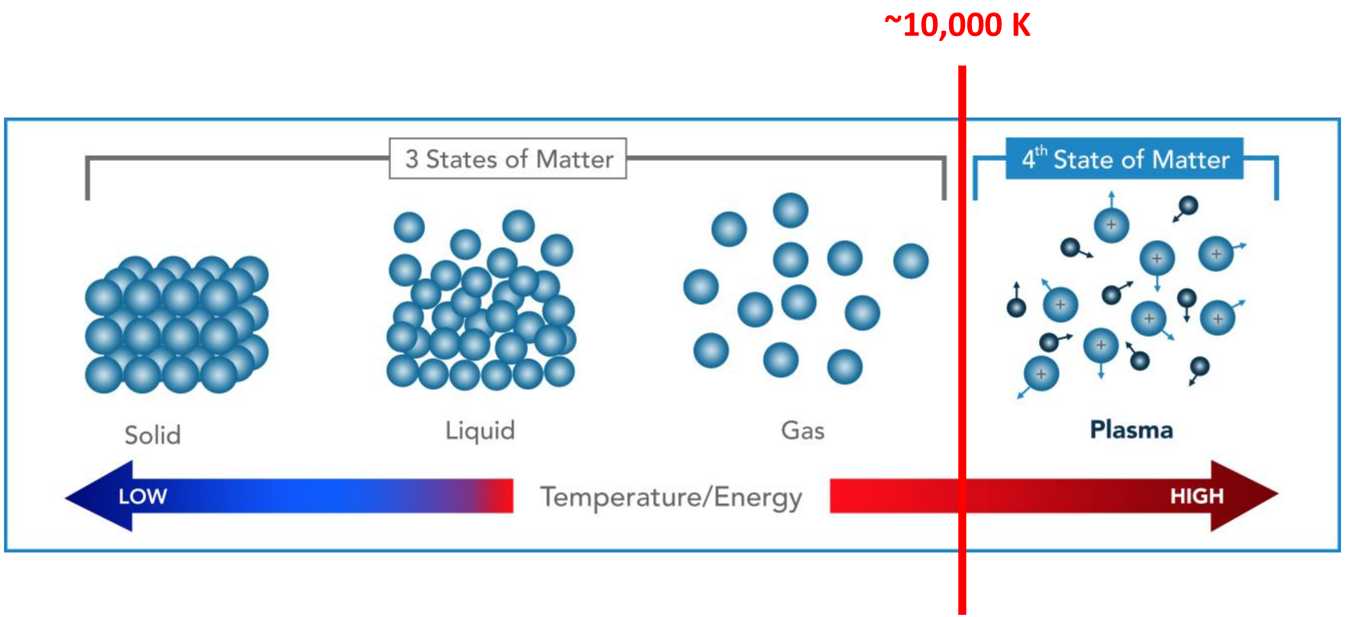
Outline

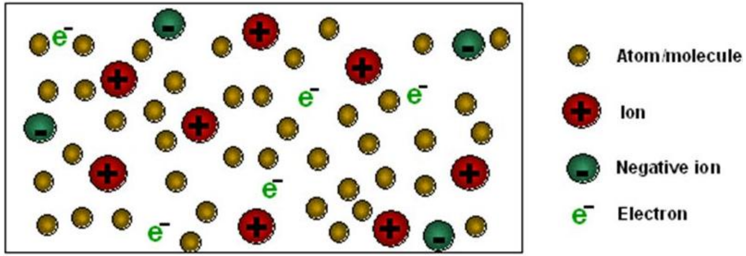
- Some basics of plasmas
- Examples of space and astrophysical collisionless plasmas
- Basic physics of collisionless magnetic reconnection
- The heliosphere as laboratory to study collisionless reconnection:
  - Near-Sun corona, interplanetary space & planetary magnetospheres: exploratory
  - Near-Earth space: fundamental
- In situ observations of reconnection in near-Earth space: the importance of multi-point measurements
- Reconnection & turbulence
- Particle energization by reconnection
- Future perspective: multi-scale science

Basics of plasmas



Plasma shows **collective behavior**: the force on a charged particle is due to E and B fields that in their turn are generated **self-consistently** by all other charged particles

Ionization and collisionality



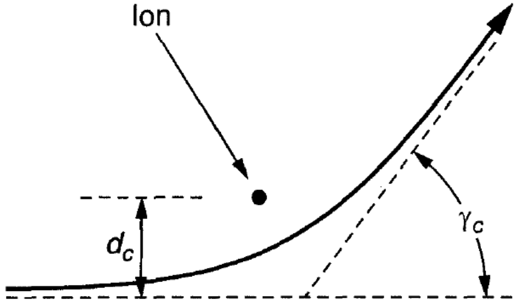


Fig. 4.1. Electron orbit during a Coulomb collision with an ion.

Plasma can be partially or fully ionized.
However plasma is always quasi-neutral.

Plasma can be collisional or collisionless

Many heliospheric are **fully ionized**, **electron-ion, collisionless** plasmas and this seminar will focus on them. However important examples of partially ionized and/or collisional space plasmas exist: solar chromosphere, planetary ionospheres.

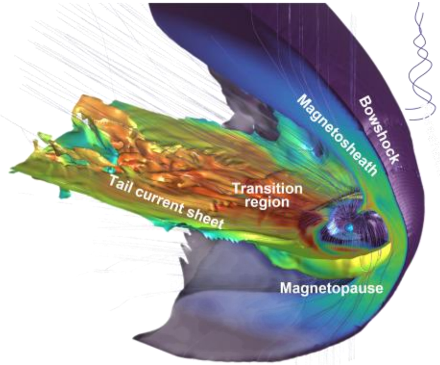
Examples of heliospheric plasmas

Electron	Chromosphere	Corona (1 R_S)	Solar wind (1 AU)
Density (cm^3)	10^{10}	10^7	10
Temperature (K)	$(6–10) \times 10^3$	$(1–2) \times 10^6$	10^5
Free path (km)	10	10^3	10^7

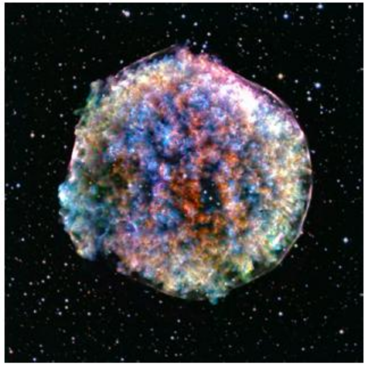
[Marsch, Ann. Geophys., 2018]

The Plasma Universe (Alfvén, 1987): 99% of the visible matter

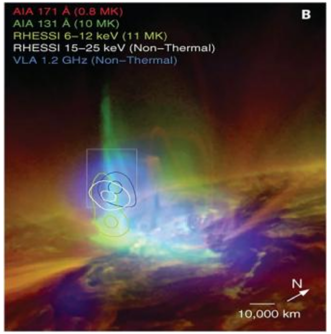
Examples of helio and astro collisionless plasmas: solar and stellar coronae; interplanetary, interstellar and intergalactic media; planetary and exoplanetary magnetospheres; supernova remnant shocks, accretion disks, astrophysical jets.



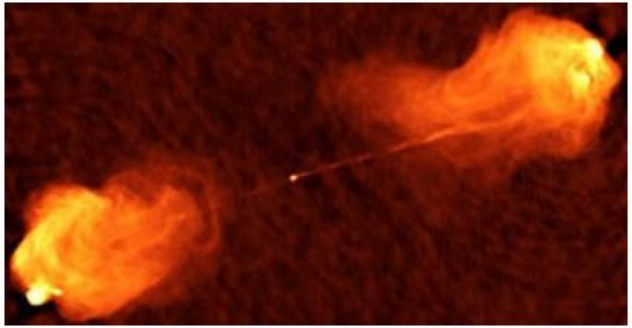
Near-Earth space. Global Vlasov simulations.



Tycho supernova remnant shock. Composite image. X-ray: NASA/CXC/RIKEN&GSFC/T. Optical: DSS.



Solar corona. Radiation emitted by energized particles in a solar flare. From Chen+, Science, 2015.

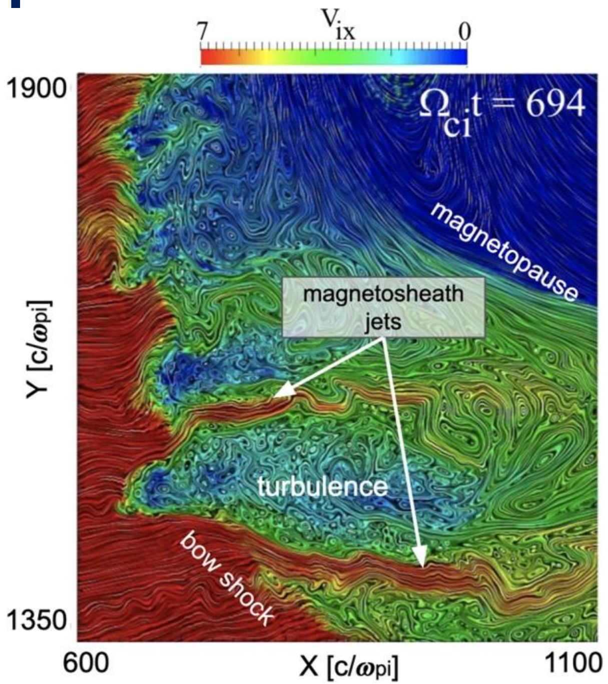


Galaxy Cygnus A jet and radio lobes. The 'hot spots' mark the shock fronts between the jet and the interstellar medium. Radio image.

Strong energy conversion/dissipation and plasma energization produced by fundamental plasma processes

Fundamental plasma processes

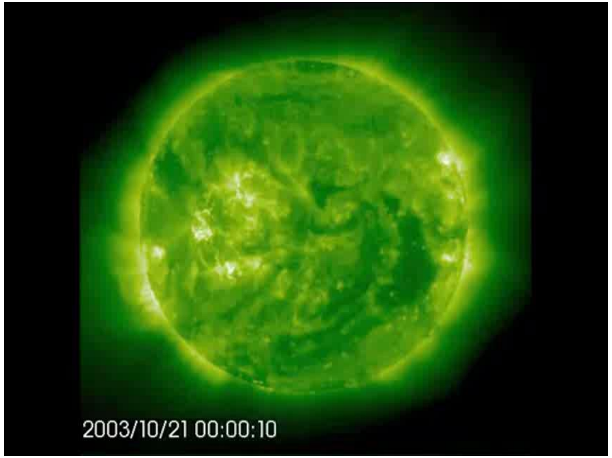
- Shocks
- **Magnetic reconnection**
- Turbulence
- Jets generation
- Combination of them



Numerical simulation of the terrestrial bow shock where shock, turbulence, reconnection, and jets all couple together. Color scale is the ion velocity, which has a turbulent behavior with the formation of jets and small-scale reconnection regions. Adopted from Karimabadi+, Phys. Plasmas, 2014]

see [Retinò et al., Experimental Astronomy, 2021]

Basics of reconnection



Solar flare recored from the Extreme Ultraviolet Imager on ESA/ SOHO in the 195A emission line

- Magnetized plasma everywhere in Universe
- Formation of current sheets
- Dissipation of electric currents in current sheets leads to plasma energization
- R. G. Giovanelli, *A Theory of Chromospheric Flares*, Nature, 1946

The frozen-in condition

MHD approximation(L>>ρ_i):

$$\mathbf{E}' = \mathbf{E} + \mathbf{V} \times \mathbf{B} = \frac{\mathbf{J}}{\sigma}$$

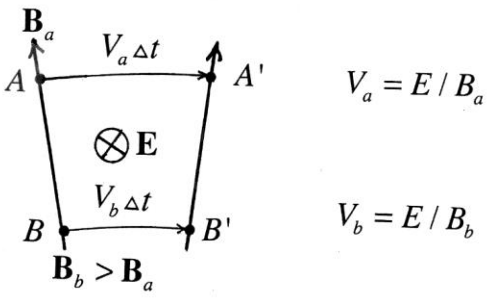
$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{V} \times \mathbf{B}) + \frac{1}{\mu_0 \sigma} \nabla^2 \mathbf{B}$$

For infinitely conductive plasma ($R_m=\mu_0\sigma LV>>1$): :

$$\mathbf{E}' = \mathbf{E} + \mathbf{V} \times \mathbf{B} = 0$$

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{V} \times \mathbf{B})$$

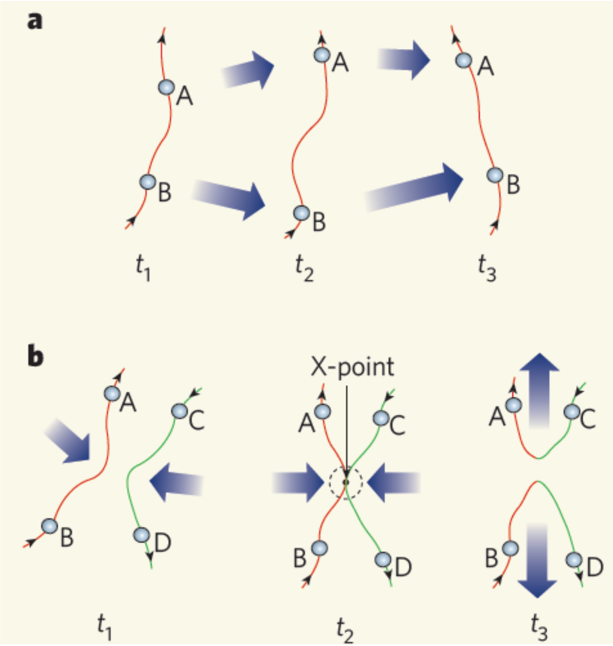
Frozen-in flux theorem (Alfvén, 1942):
The total magnetic flux through a surface delimited by a closed curve moving with an infinitely conducting plasma is constant



Implications:

- All plasma elements and magnetic flux contained at a given time in a magnetic flux tube will remain in the same flux tube at all later times
- We can define unique flux tube velocity $W=ExB/B^2$ so that $W=V_\perp$

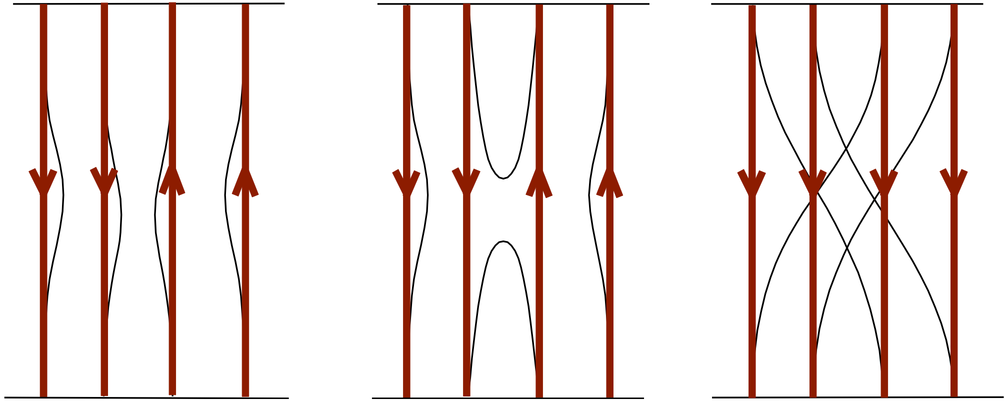
Reconnection: breaking of the frozen-in condition



[Adopted from Paschmann, Nature, 2006]

- E'≠ J/σ (finite conductivity within the diffusion region)
- $E_{||} \neq 0$
- $\mathbf{V}_{\perp} \neq \mathbf{W}$

Magnetic topology



t1 < t2

$E_{||}=0$

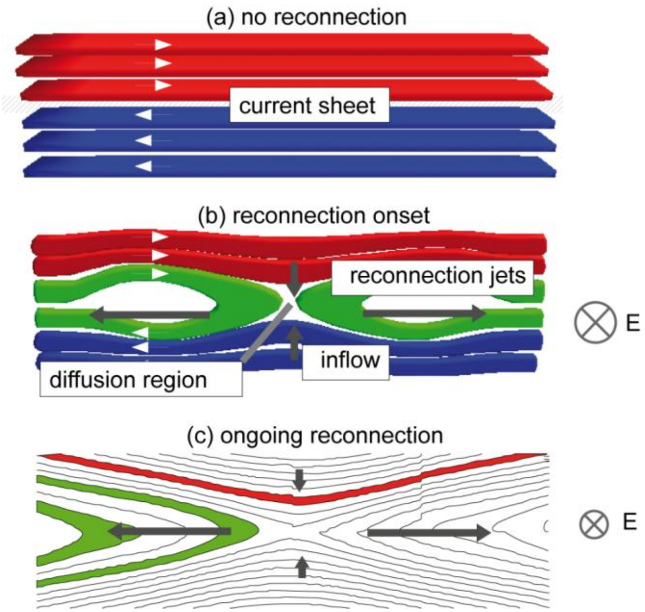
$B=0$

$E_{||}\neq0$

Topology conserved

Topology not conserved

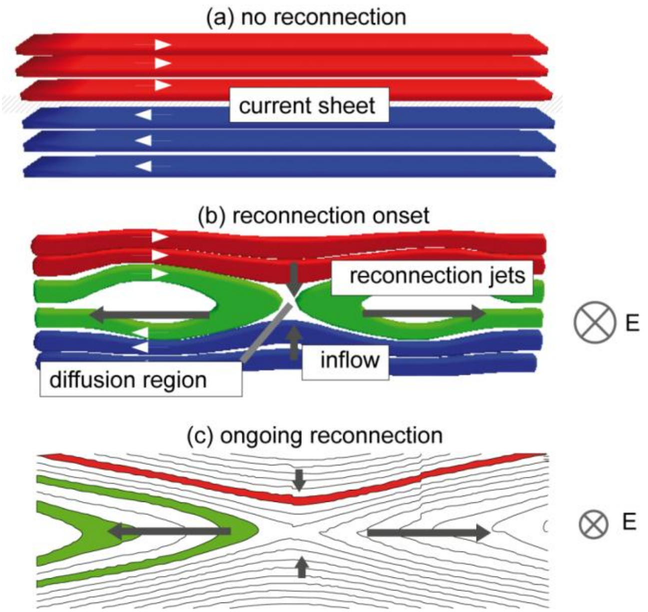
Key reconnection quantities (I)



[Adopted from Vaivads et al., Space Sci. Rev, 2006] .

- **Current sheet**: (locally) planar region of strong current
- **Reconnection plane**: plane containing reconnecting magnetic field
- **X-point/reconnection site**: region where reconnection starts
- **X-line**: line connecting X-points
- **Guide field**: B field along X-line
- **Onset**: time when reconnection starts
- **Diffusion region**: region where frozen-in condition breaks (containing X-point)

Key reconnection quantities (II)



[Adopted from Vaivads et al., Space Sci. Rev, 2006] .

- **Reconnection electric field**: out-of-plane E field due to non ideal-terms
- **Inflow**: magnetic flux tubes motion towards X-point
- **Rate R**: how fast flux tube reconnect
- **Normal component B_N**: component of B perpendicular to reconnecting filed in reconnecting plane
- **Reconnecting jets**: accelerated plasma flows

$$\mathbf{J}\times\mathbf{B} = -\nabla\left(\frac{B^2}{2\mu_0}\right) + \frac{1}{\mu_0}\nabla(\mathbf{B}\cdot\mathbf{B})$$

- **Reconnection bulge:** reconnected flux tube associated to increased R
- **Flux rope/magnetic island**: closed magnetic flux tube between to X-points

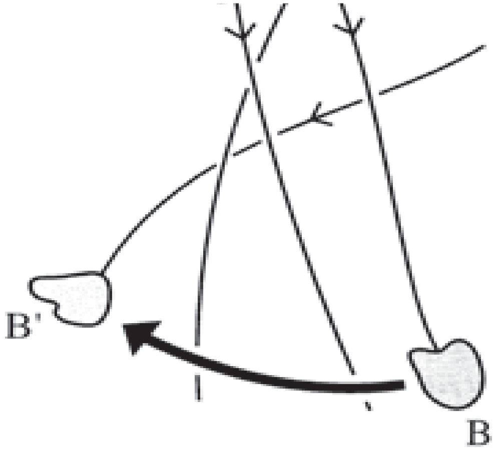
Definition(s) of reconnection

General Magnetic Reconnection (3D):
“*breakdown of magnetic connection due to a localized non-idealness* “
Necessary and sufficient condition:

$$\int_{D_R} E_{\|} ds \neq 0$$

2D definitions:

- X-point where two separatrices meet
- **E** along the X-line
- change in magnetic connectivity (violation of frozen-in condition)
- plasma flow across separatrices



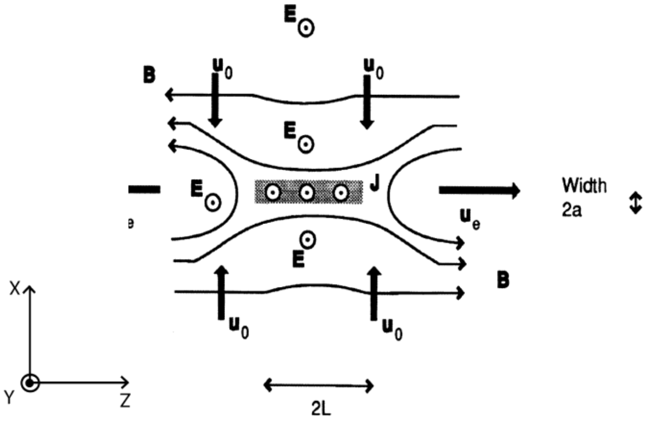
(b)

[Priest, 2000]

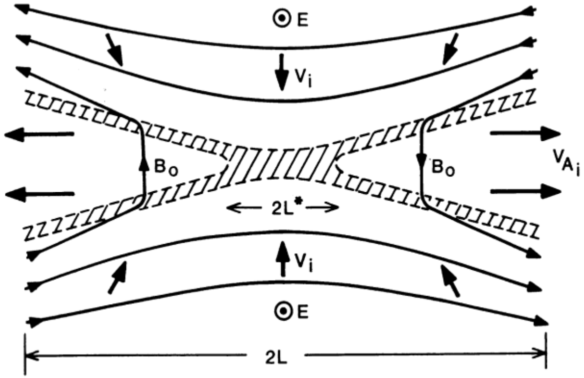
Operational definition of reconnection

- **Change of magnetic field topology**:
  - $\int E_{||} \neq 0$
  - $B_N \neq 0$
- **Change in plasma connectivity** : $W = E \times B/B^2 \neq V_\perp$
- **Plasma transport across current sheet**
- **Energy conversion/dissipation**:
  - $E \cdot J > 0$
  - plasma acceleration (reconnection jets)
  - plasma heating
  - non-thermal particle acceleration

First theoretical models



Sweet-Parker
[Parker,1958; Sweet,1958]

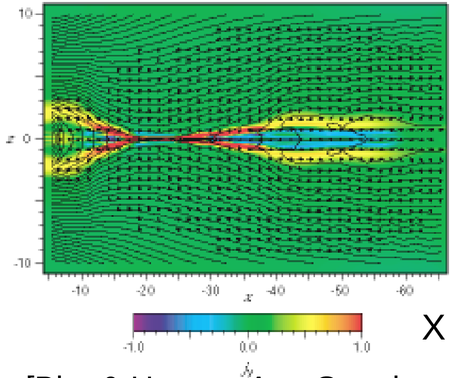


Petschek
[Petschek, 1964]

- Reconnection rate = $(u_0/u_{A0})^{1/2}$ / $R_{m0}^{1/2}$
- Alfvenic outflow: u_e=u_{A0}
- Energy conversion: WB = ½ W_K + ½ W_T
- Reconnection too slow to explain solar flares occurring on time scale ~ 100 s

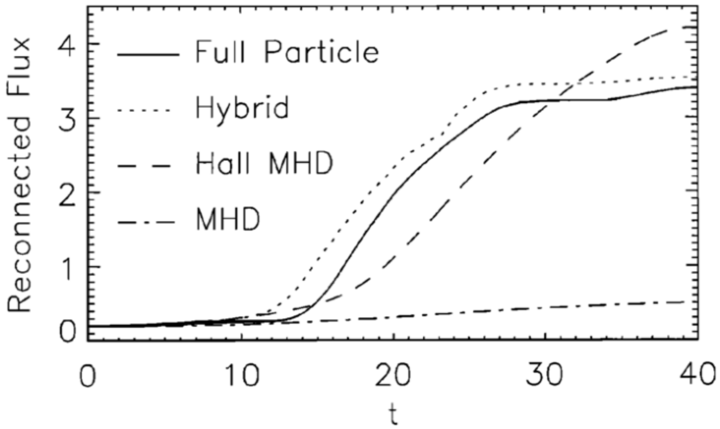
- Smaller diffusion region
- Plasma accelerated at slow shocks
- Higher reconnection rate ≈ 1/log(R_{m0})

Numerical simulations

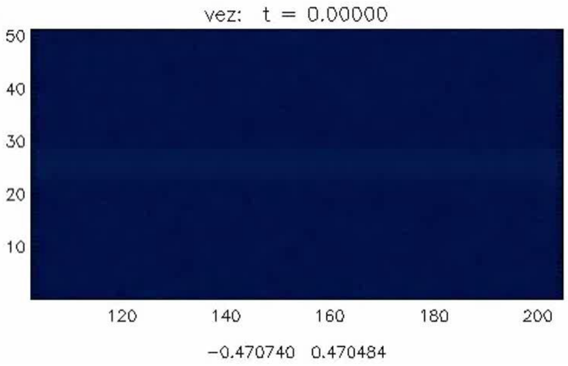


MHD simulation

[Birn & Hesse., Ann.Geophys., 2005]



[Birn et al., JGR, 2001]



PIC simulation

Courtesy M. Shay

GEM challenge:

- Reconnection fast (R ~ 0.1) for all models except MHD
- Fast reconnection due to Hall physics
- Fast collisionless reconnection (space plasma)

Collisionless reconnection: scales

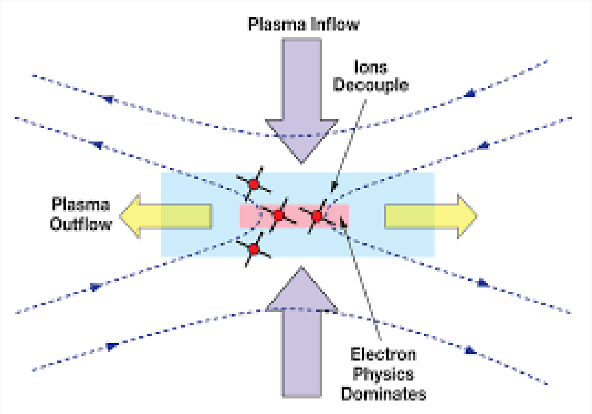
Generalized Ohm's law:

$$\mathbf{E} + \mathbf{u} \times \mathbf{B} = \frac{\mathbf{J}}{\sigma} + \frac{\mathbf{J} \times \mathbf{B}}{ne} - \frac{\nabla \cdot \mathbf{P_e}}{ne} + \frac{m_e}{ne^2}\frac{\partial \mathbf{J}}{\partial t}$$

MHD | anomalous conductivity | Hall | electron pressure | electron inertia

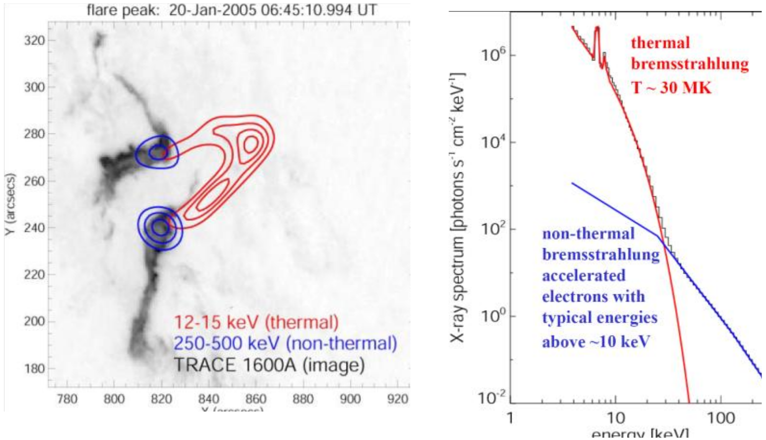
Three scales:

- MHD scales (>> ρi)
- ion scales (~ ρ_i)
- electron scales (~ ρ_e)



Observations of reconnection: *remote* in solar corona

Hard X-Rays emission from a solar flare (RHESSI)



[Courtesy of S. Krucker]

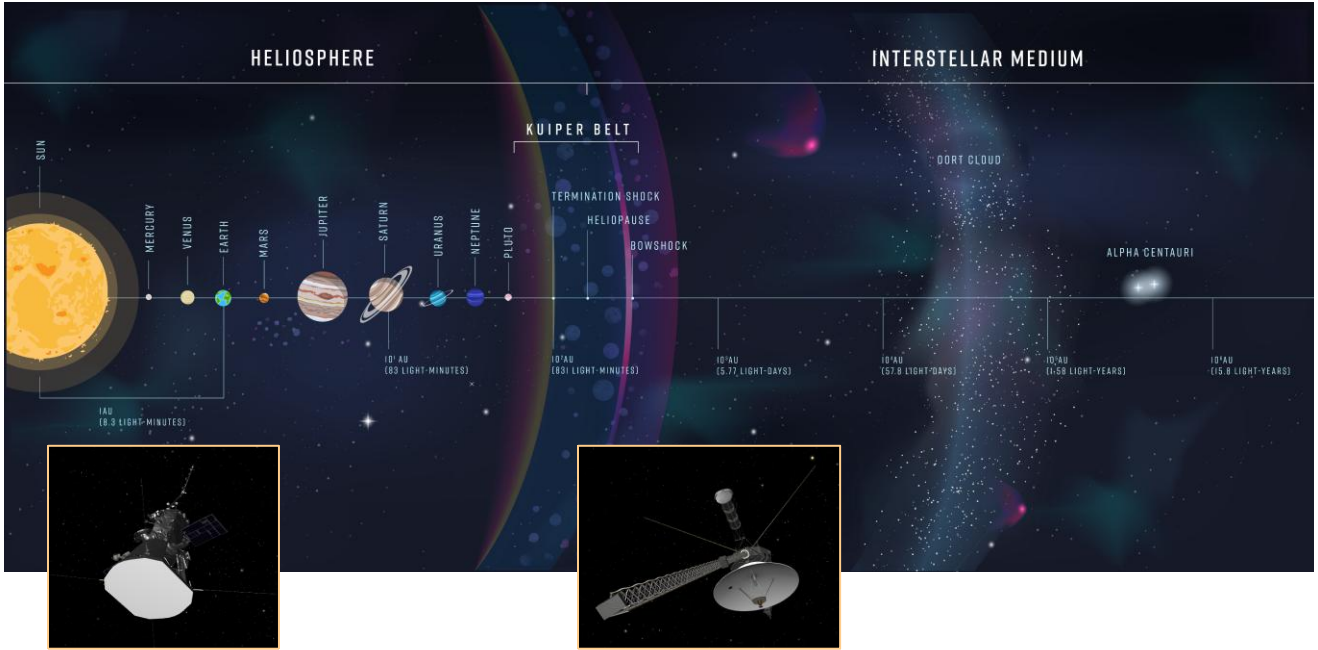
Spacecraft :

- JAXA/Yohkoh
- NASA/Rhessi
- NASA/TRACE
- ESA/SOHO
- NASA/SDO
- JAXA/Hinode
- NASA/ParkerSolarProbe
- ESA/Solar Obiter

Measurement technique: spectroscopic imaging by space telescopes

- White light (images, magnetograms and dopplergrams of photosphere and chromosphere)
- UV-EUV (heated plasma)
- Soft X-ray (heated plasma)
- Hard X-ray (accelerated particles)
- Gamma ray (accelerated particles)

The heliosphere: a natural laboratory to study space plasmas *in situ*



Parker Solar Probe 2018-

Voyager 1,2 1977-

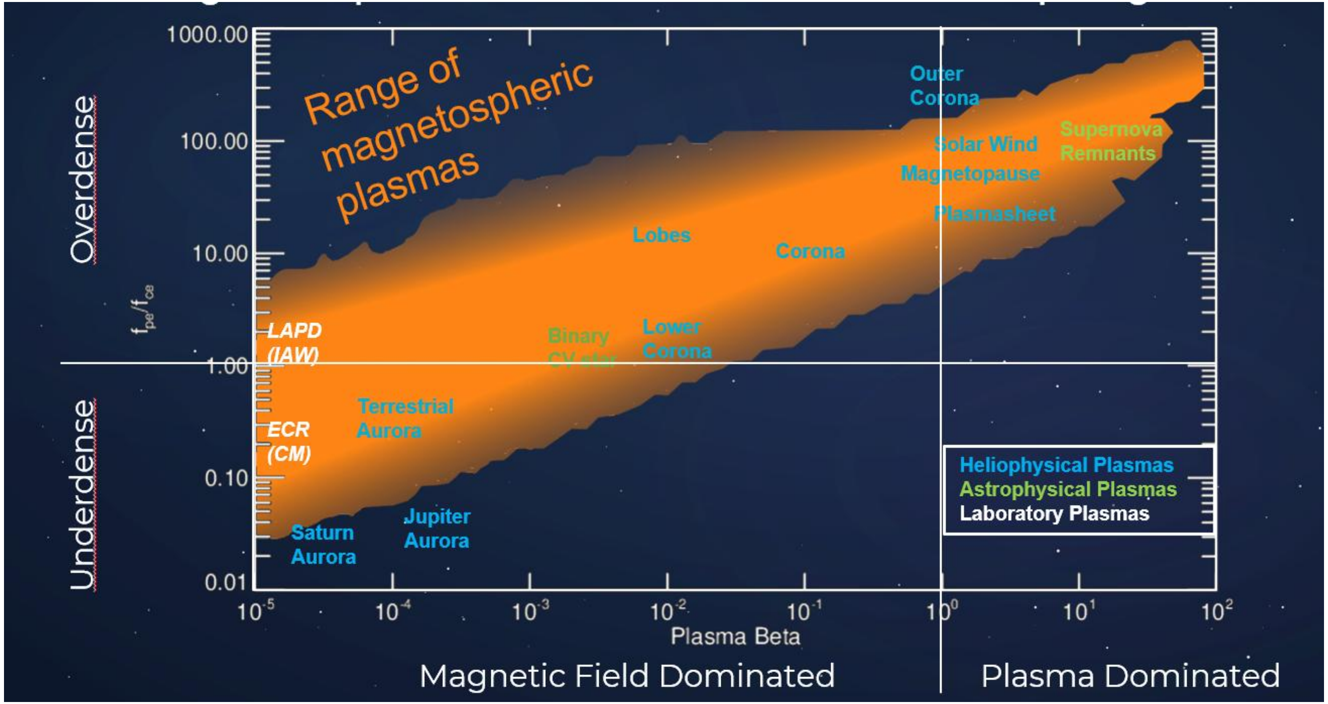
Fundamental:

- Multi-point
- High accuracy/sensitivity (EMC, spinning spacecraft, ...)
- High resolution (kinetic scales)
- High telemetry (large volumes of data)

Exploratory:

- Lower accuracy/sensitivity/resolution measurements (technical challenges)
- New or poorly studied regions (plasma conditions)

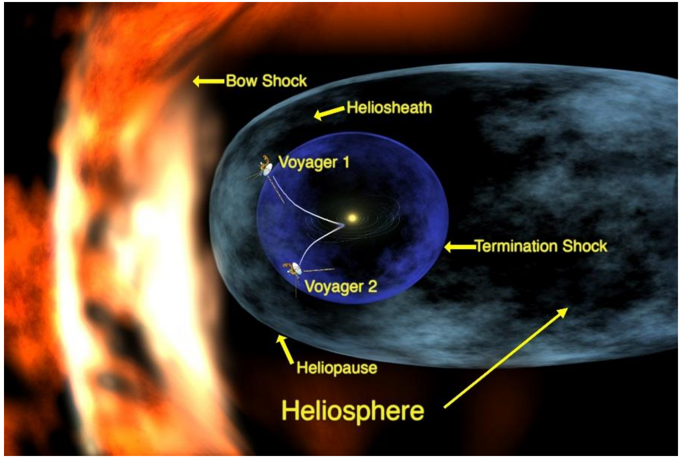
The Plasma Universe (Alfvén, 1987): 99% of the visible matter



From Alfvén (1987): information about the plasma universe can also be obtained by extrapolation of laboratory experiments and magnetospheric *in situ* measurements of plasmas. This approach is possible because it is likely that the *basic* properties of plasmas are the same everywhere.

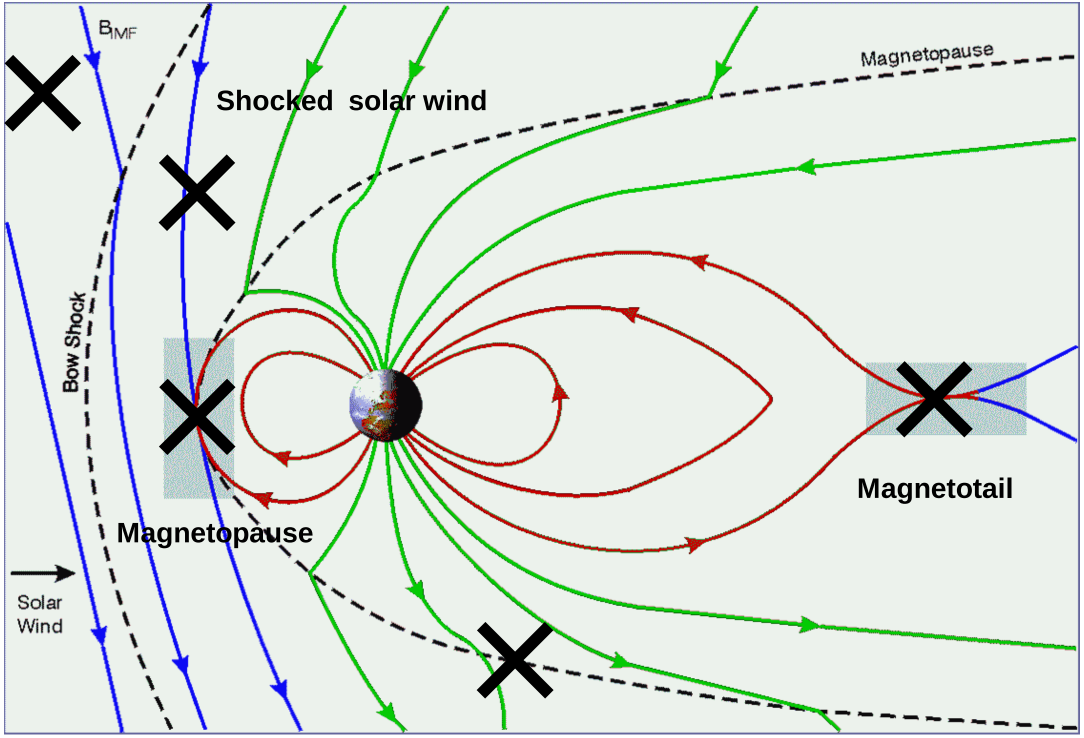
In situ observations in the heliosphere

- **Solar wind & magnetosheath**: Gosling et al., 2005; Phan et al., 2006; Gosling et al., 2007; Retino et al., 2007; Phan et al. 2018
- **Earth's magnetosphere**:
  - Magnetopause: Paschmann et al., 1986; Phan et al., 2002; Mozer et al., 2002; Vaivads et al., 2004; Retino et al. 2006, Burch et al, 2016
  - Magnetotail; Hones et al., 1985; Øieroset et al., 2001; Chen et al., 2008; Retino et al., 2008; Fu et al., 2013; Fu et al., 2015; Torbert et al., 2018
  - Kelvin-Helmoltz vortexes: Hasegawa et al., 2009; Eriksson et al, 2016
- **Planetary magnetospheres**: Mercury (Slavin et al. 2009), Jupiter (Huddleston et al., 1997), Saturn (Arridge et al., 2016); Uranus (Masters et al., 2014)
- **Comet tail**: Russell et al., 1986
- **Heliopause**: Swisdak et al., 2013



In situ observations: near-Earth space

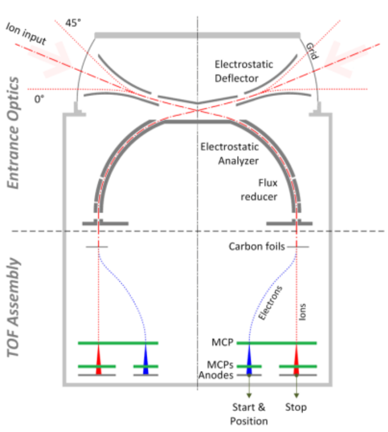
Pristine solar wind



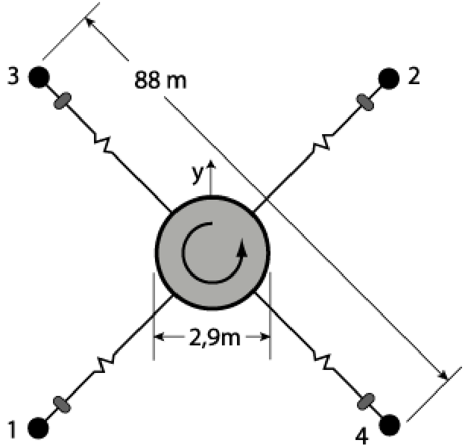
Kelvin-Helmoltz vortexes

Best available in situ measurements !!!

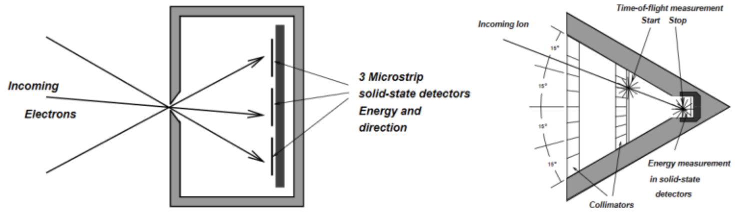
In situ observations: instrumentation



Electrostatic Analyzer (ions and electrons)

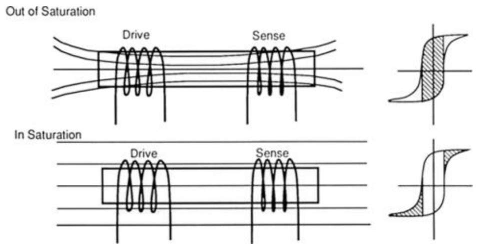


Langmuir probes (**E** field)

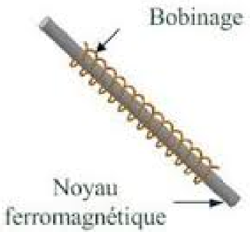


Solid state detectors (energetic ions and electrons)

Magnetometers



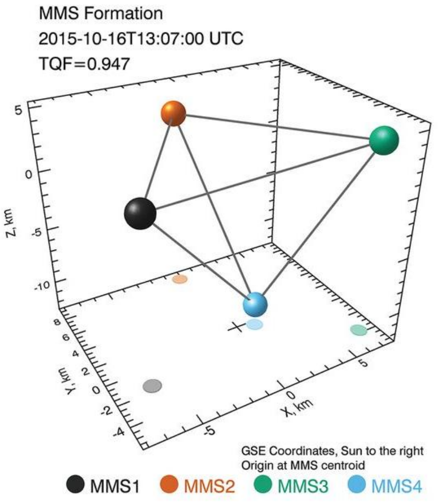
Fluxgate (DC)



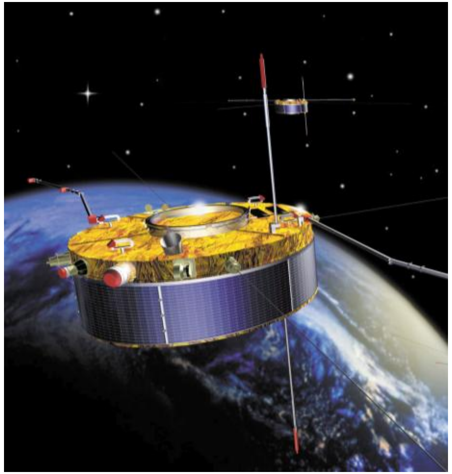
Search-coil (AC)

Cornerstone four spacecraft missions

System	~100,000 km
Fluid (MHD)	>5,000 km
ion	100-1000 km
electron	1-10 km

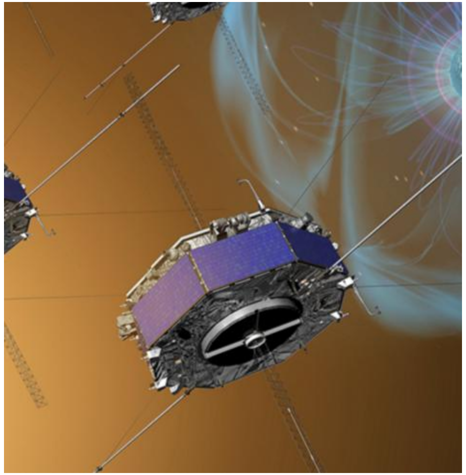


Cluster/ESA (2000-2026)
polar orbit, apogee $20R_E$



Spacecraft separation
on ion or fluid scales

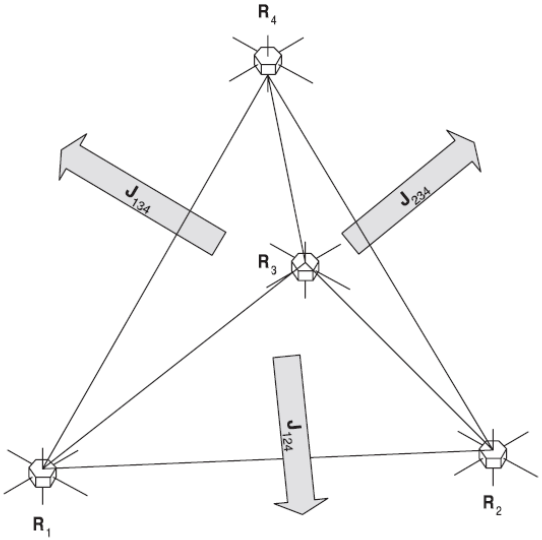
MMS/NASA (2015-)
equatorial orbit, apogee $25R_E$



Spacecraft separation
on electron or ion scales

Why 4 spacecraft ?

Direct estimates of gradients



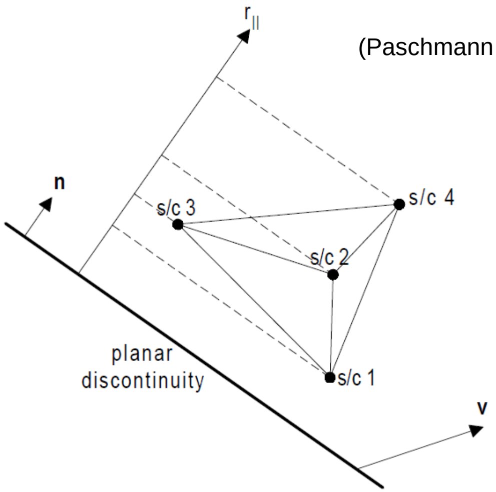
(Dunlop et al., JGR 2002)

Curlometer

$$\nabla \times \mathbf{B} = \mu_o \left(\mathbf{J} + \varepsilon_o \frac{\partial \mathbf{E}}{\partial \mathbf{t}} \right)$$

Direct estimates of phase velocities

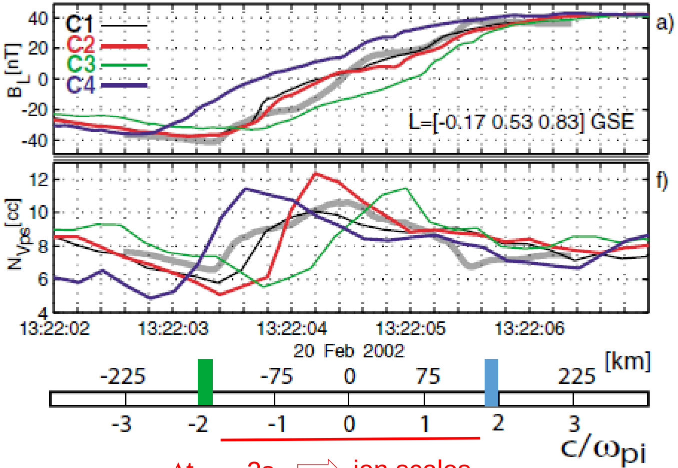
(Paschmann & Daly, 1998)



Boundaries, plasma waves

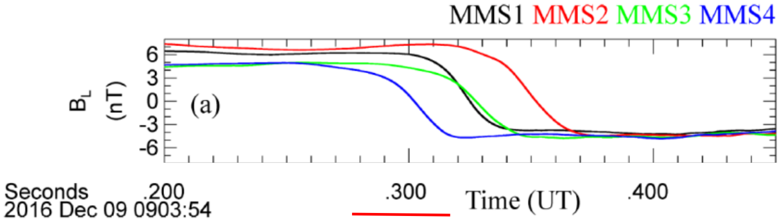
Example: 4-point measurements of current sheets

Cluster spacecraft
magnetopause current sheet crossing
[adopted from Vaivads et al., *Phys. Rev. Lett.*, 2004]

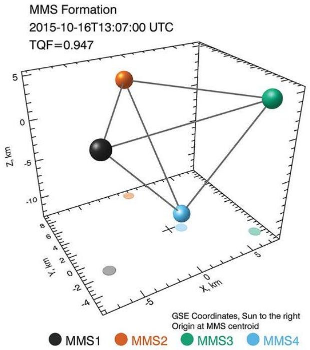


$\Delta t_{CS} \sim 2s$ ⇨ ion scales

MMS spacecraft
magnetosheath current sheet crossing
[adopted from Phan et al., *Nature*, 2018]



$\Delta t_{CS} \sim 50$ ms ⇨ electron scales



Tetrahedrical configuration
ESA/Cluster: 100s -1000s km
NASA/MMS: 10s – 100s km

- **n** and V_{cs} from four-point measurements (timing method)
- Current sheet thickness = $V_{cs} \cdot \Delta t_{CS}$
- electric current **J** density from four-point measurements of **B** (curlometer method)
- Knowledge of spatial structure and temporal evolution can be obtained at given scale assuming planarity, stationarity and linearity

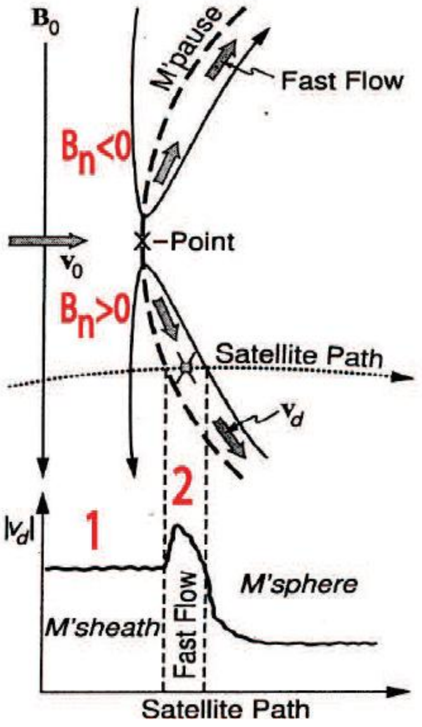
However:

- 4-points methods not valid for non-planar, non-stationary and non linear structures at a given scale
- No information about scale coupling: only one scale at a time (fluid or ion for Cluster / ion or electron for MMS)

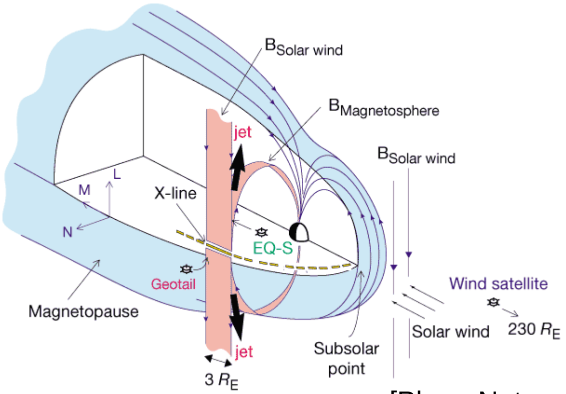
In situ observations of reconnection: *the ages*

- **BC -** *Before Cluster* (ISEE, AMPTE, Geotail, WIND, Equator-S)*:* single-point/single-scale
- **C -** *Cluster 2000:* 4-points / ion or fluid scales
- **AC -** *After Cluster* (MMS 2015): 4-points / electron or ion scales
- **LAC -** *Long after Cluster* (HelioSwarm 2030, Plasma Observatory ? 2037): ≥ 7 points / multi-scale

BC age. In situ evidence of reconnection at fluid scales: reconnection jets



Expected signatures away from X-point



[Phan, Nature, 2000]

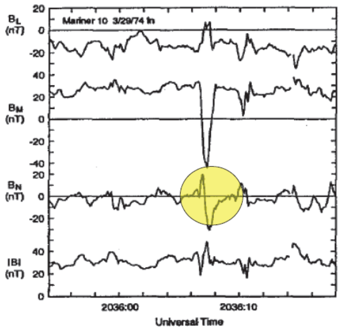
- First evidence: Paschmann et al., Nature, 1986
- Tangential stress balance:

$$\Delta \mathbf{V}_{th} = \mathbf{V}_{t2} - \mathbf{V}_{t1} = \pm(\mu_0 \rho_1)^{-1/2}(\mathbf{B}_{t2} - \mathbf{B}_{t1})$$

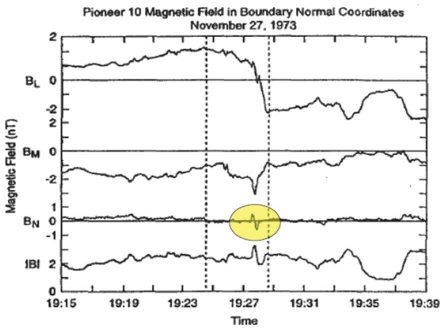
$$\mathbf{v} - \mathbf{V}_{HT} = \pm(1-\alpha)\mathbf{B}[\mu_0 \rho_1 (1-\alpha_1)]^{-1/2}$$

BC age. In situ evidence of reconnection at fluid scales: flux transfer events

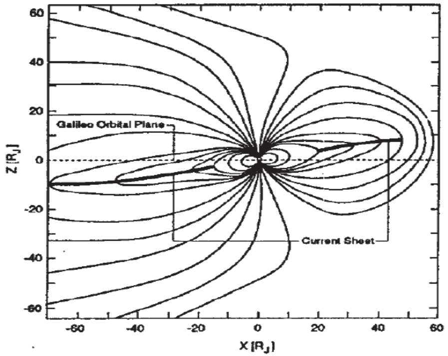
Jupiter



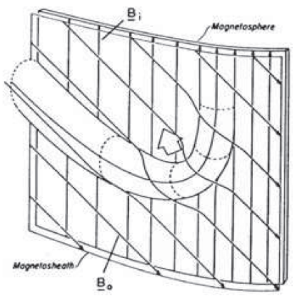
Mercury



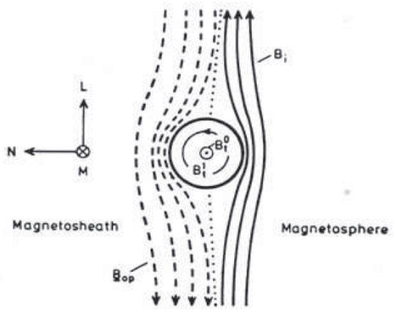
- ✔ Flux Transfer Events - unsteady reconnection
- ✔ Bipolar Bn signature



[Russell 2000, ASR]



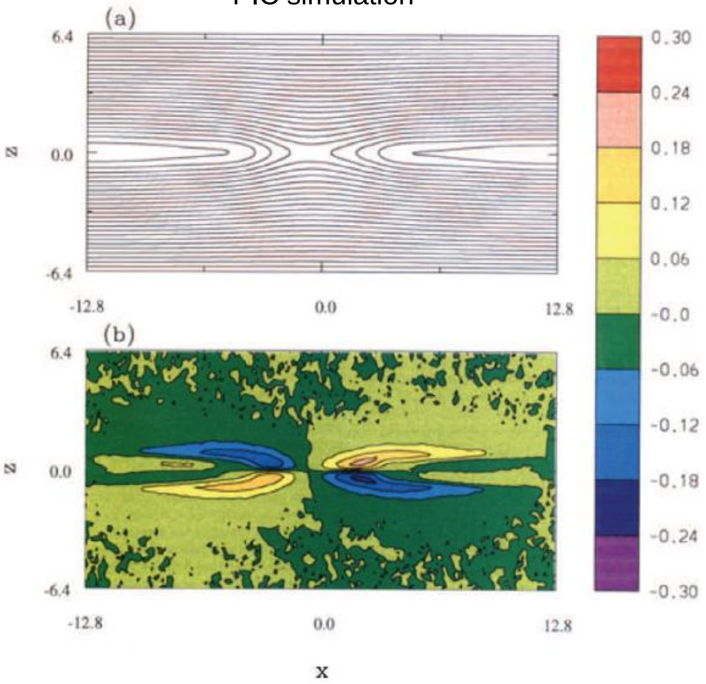
(a)



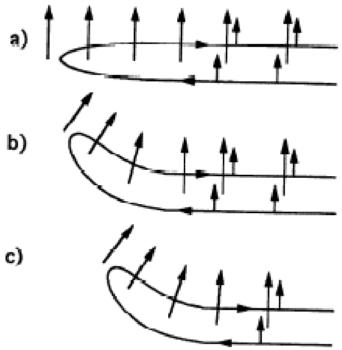
(b)

C age. Reconnection at ion scales: Hall reconnection

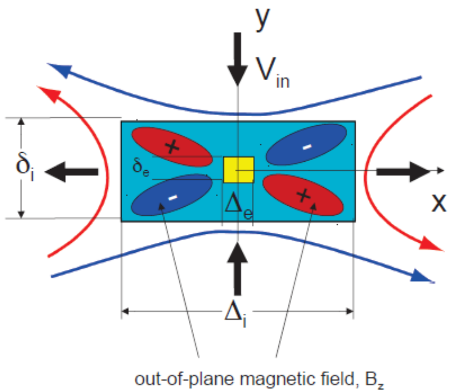
PIC simulation



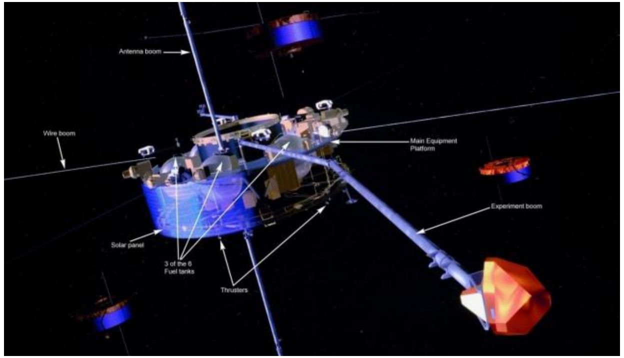
[Pritchett et al., JGR, 2001]



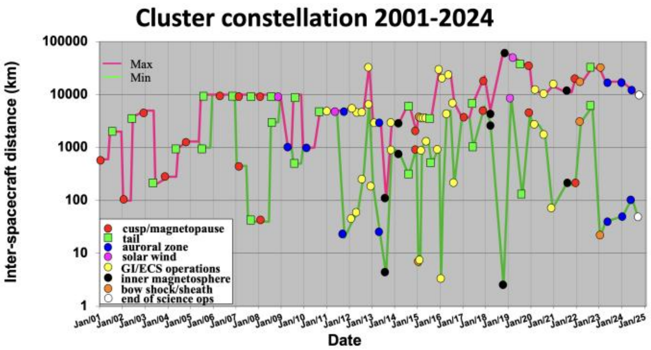
[Mandt et al. GRL, 1994]



The ESA/Cluster mission (2000-2026)

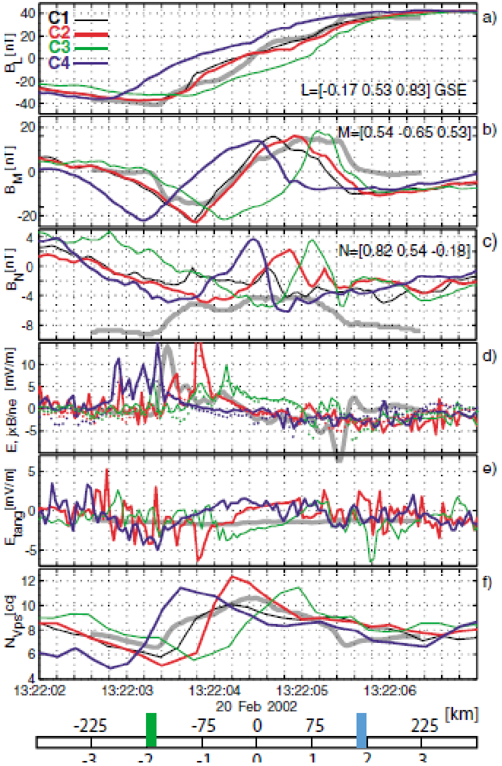


- **First ever 4-point mission to study the near-Earth space**
- distinction between spatial and temporal variations
- measurement of 3D quantities
- tetrahedrical configuration with variable separation from 100 to 10000 km: observations at different scales

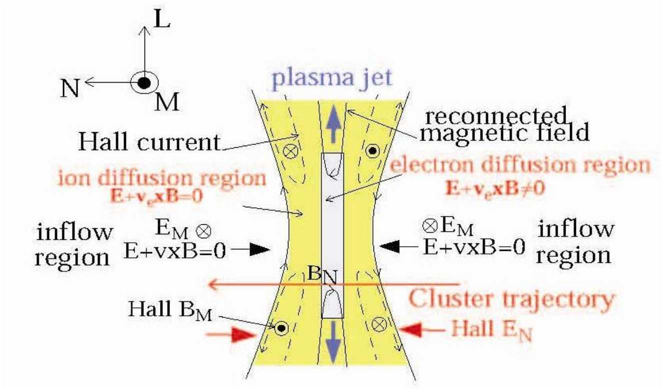


C age. Cluster observations of Hall reconnection (ion scales)

Cluster 4 point measurements

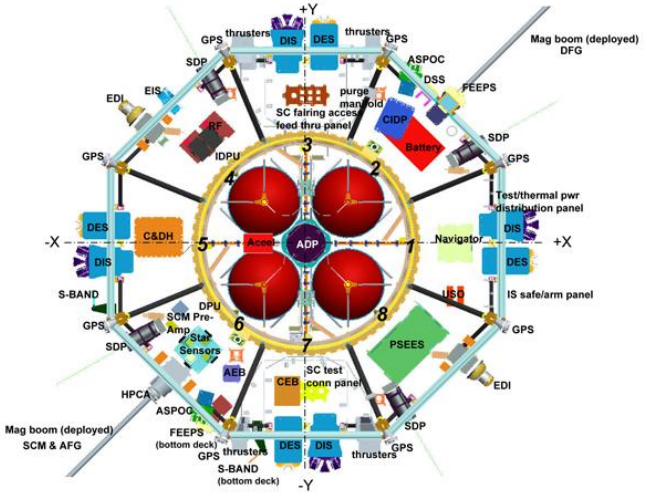


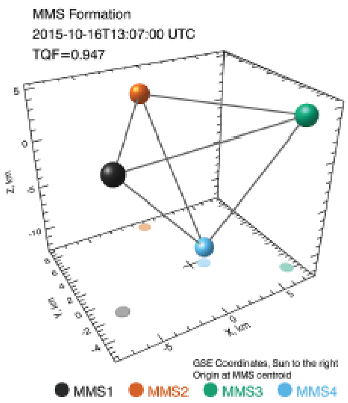
[Vaivads et al., PRL, 2004]



- Quadrupolar Hall Magnetic field
- Bipolar Hall electric field balanced by (1/N·e) **J**x**B**
- Reconnection rate R ~ 0.1 (fast reconnection)
- Resolution of plasma data not sufficient to resolve ion scales

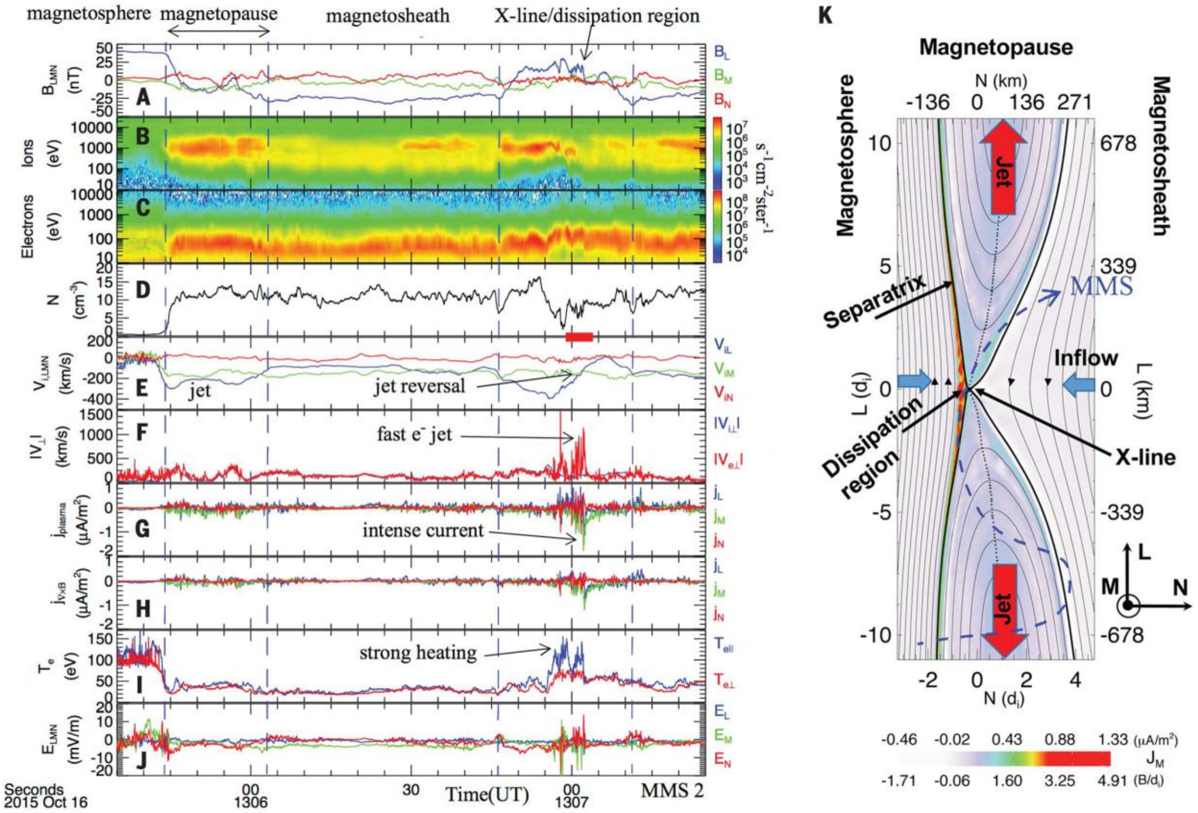
The NASA/MMS mission (2015-)





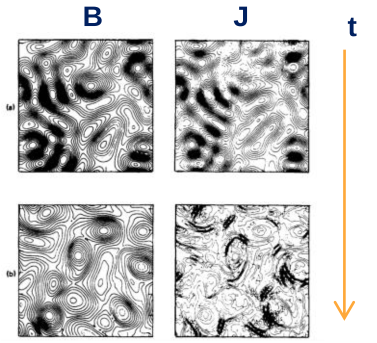
- 4 SC mission fully dedicated to study reconnection at electron scales
- tetrahedrical configuration with variable separation down to 7 km -> sub-ion/electron scales
- High temporal resolution of plasma measurements: 30 ms for electrons, 150 ms for ions

AC age. MMS first electron-scale observations of reconnection



[Burch et al., Science, 2016 at magnetopause; see also Torbert et al., Science, 2018 in magnetotail]

Reconnection & Turbulence

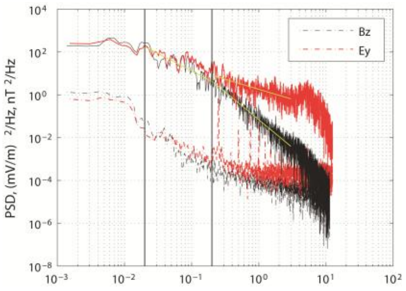


Reconnection in turbulent plasmas

[Matthaeus & Lamkin, Phys. Fluids,1986; Dmitruk & Matthaeus, Phys; Plasmas, 2006; Servidio +, PRL 2009]

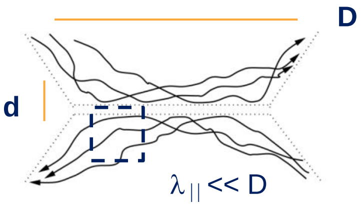
Turbulence/waves in current sheets

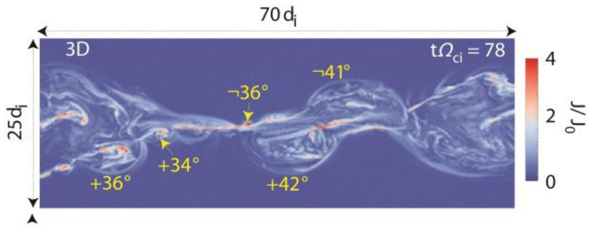
[Bale+, GRL, 2002; Vaivads+, GRL, 2004; Khotyaintsev+, Ann Geo, 2004; Retinò+, GRL, 2006; Eastwood+; PRL, 2009; Huang+, JGR, 2010]



Turbulent current sheet

[Lazarian & Vishniac, ApJ, 1999; Lapenta, PRL, 2008; Loureiro+, MNRAS, 2009; Daughton+, Nature Physics, 2011; Che+, Nature, 2011]

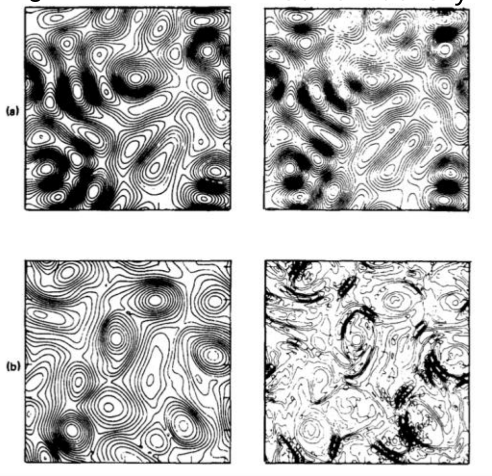




Reconnection in turbulent plasma

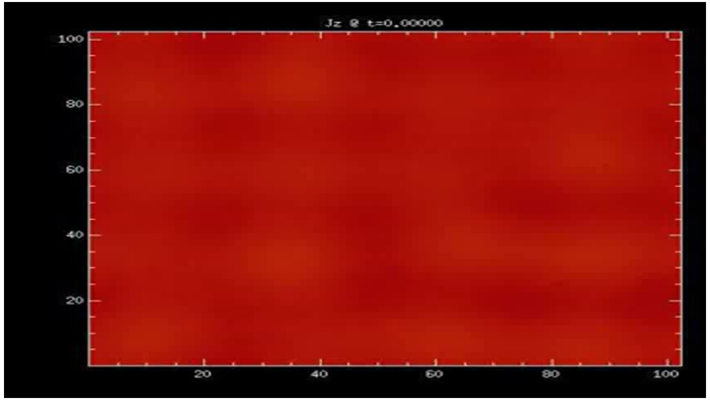
2D MHD simulation

Magnetic field lines　Current density



[Matthaeus & Lamkin, Phys. Fluids, 1986]

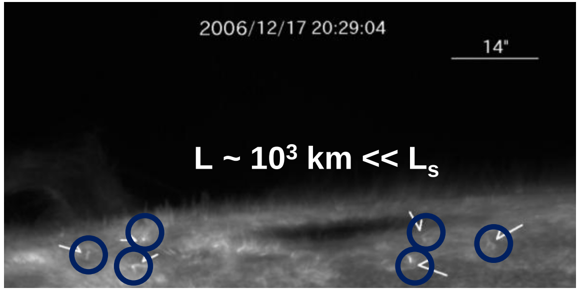
PIC simulation



[from Wu et al., 2013]

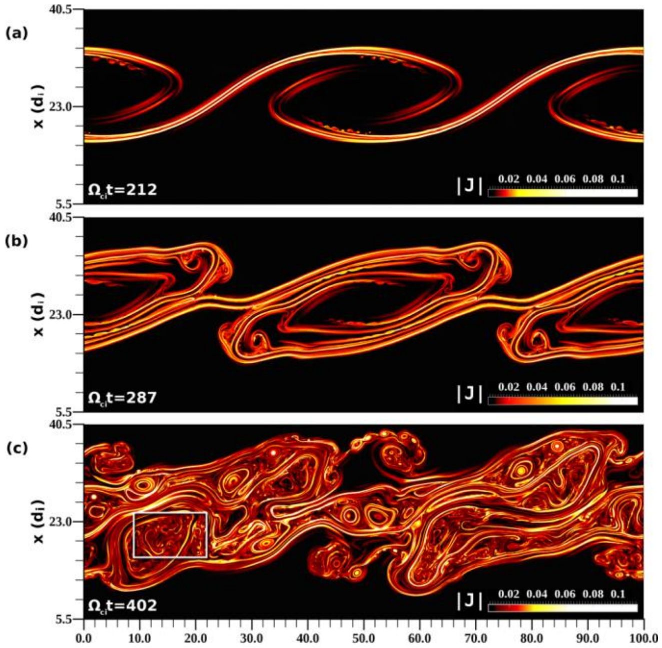
Many different simulations supports this scenario (MHD, Hall-MHD, PIC, Vlasov):
Servidio 2009, Servidio 2011, Camporeale2011, Wan 2012, Karimabadi 2013, Haynes 2014, Valentini2014, Wan 2015)

In situ data scarce

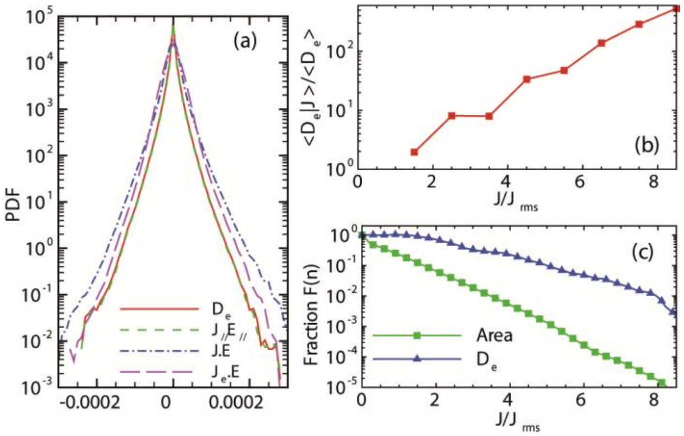


[Shibata +, Science, 2007]

Intermittent dissipation and particle energization



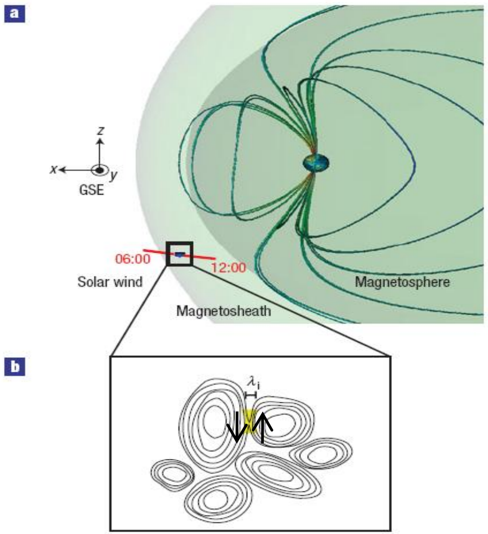
[Karimabadi+, Phys. Plasmas, 2013]

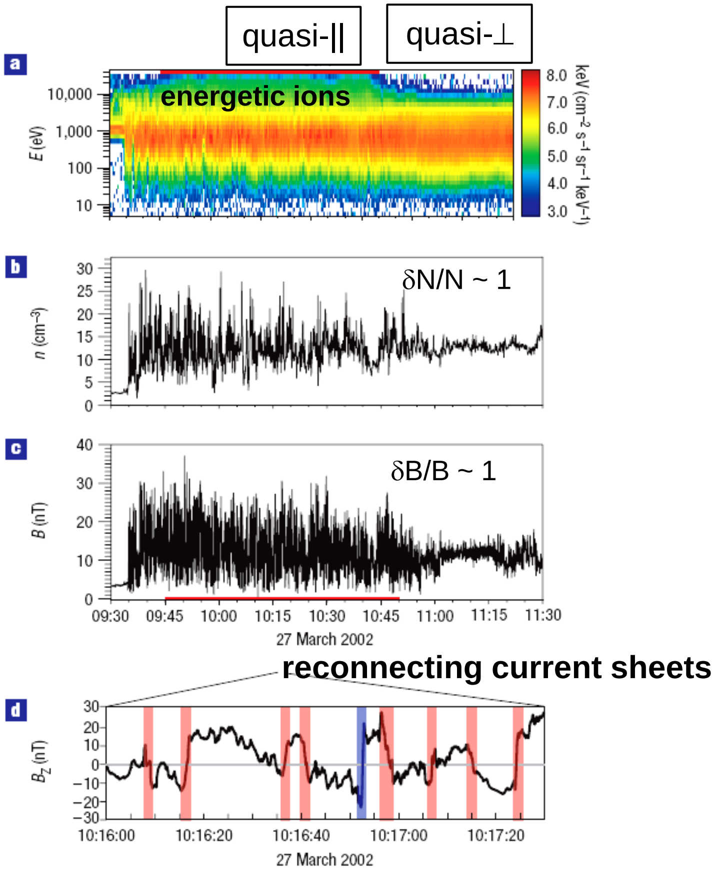


[Wan+,PRL, 2012]

Heating strongly intermittent heating at kinetic scales

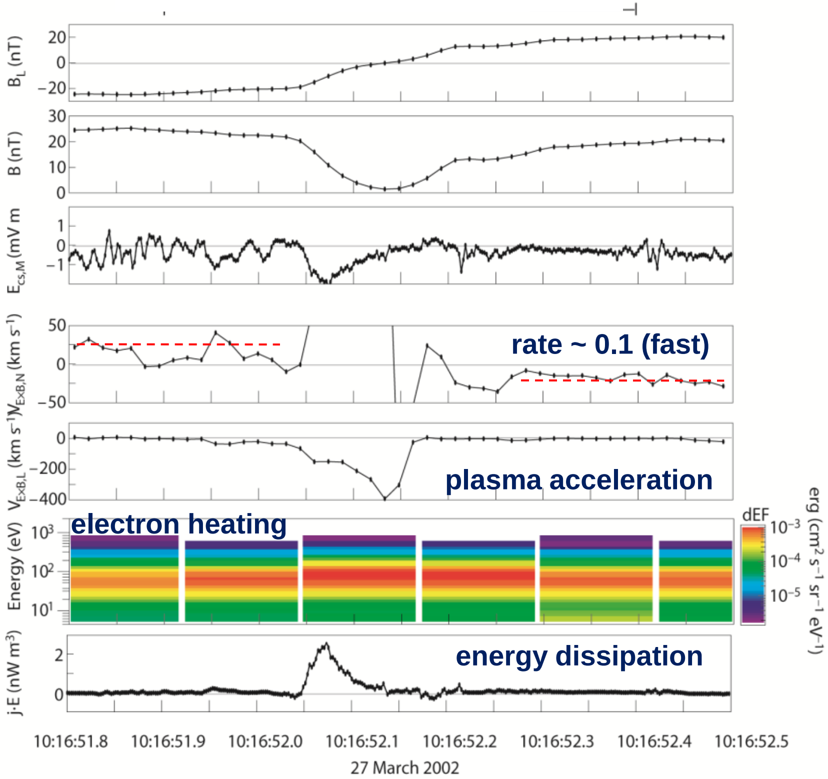
Reconnection in turbulence





[Retinò et al., Nature Physics, 2007]

Reconnection in turbulence: in situ evidence

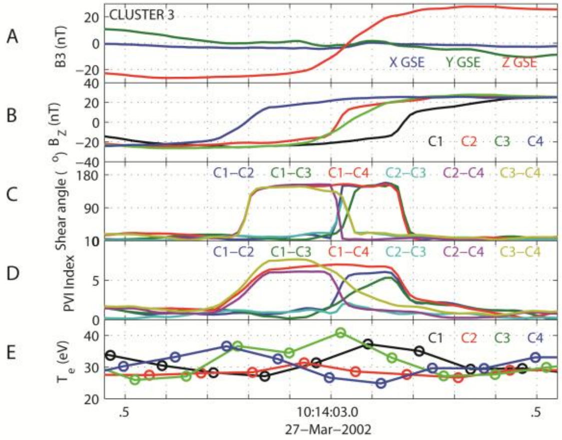


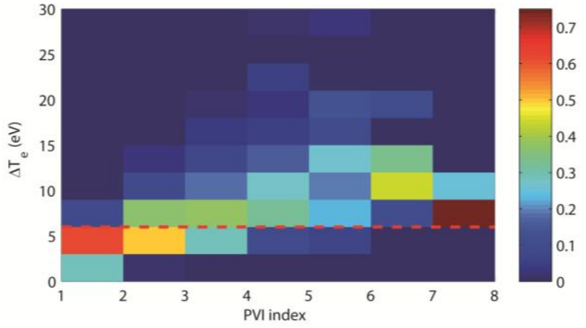
[Retinò+, Nature Physics, 2007]

Electron heating in thin current sheets

PVI [Greco+, GRL, 2008]

$$\mathcal{I}(s, \Delta s) = \frac{|\Delta \boldsymbol{b}(s, \Delta s)|}{\sqrt{\langle |\Delta \boldsymbol{b}(s, \Delta s)|^2 \rangle}}.$$

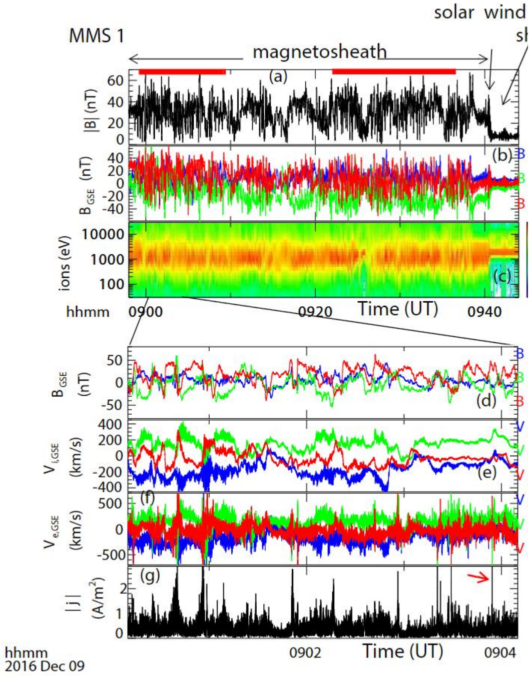


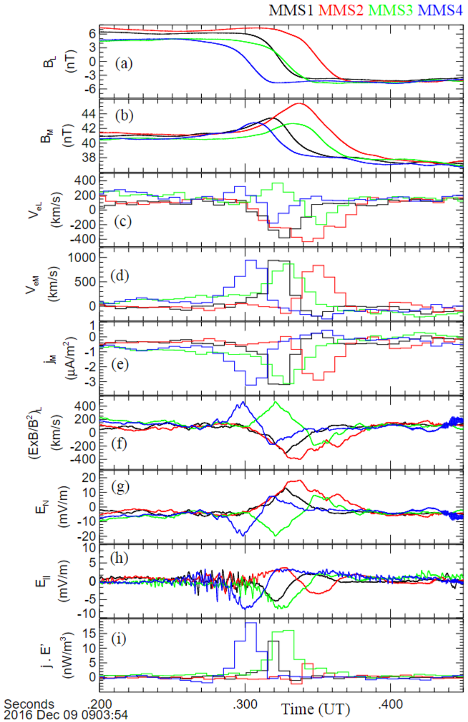


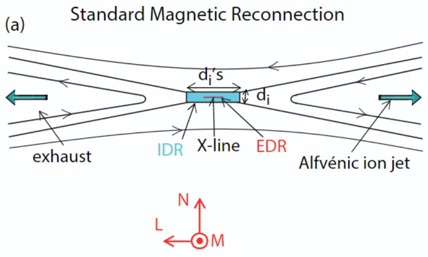
[Chasapis+, ApJLett., 2015]

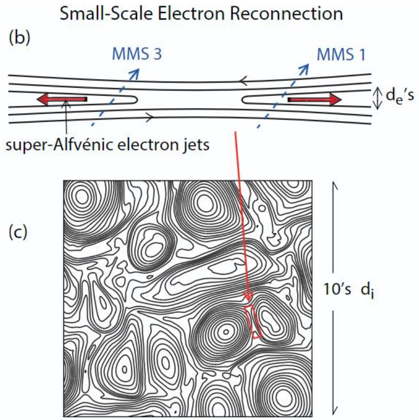
First evidence of local electron heating in thin cureent sheets within turbulence. Current sheets have scales $\leq d_i$. Cluster results later confirmed by MMS (e.g. Chasapis et al, ApJ Lett., 2017)

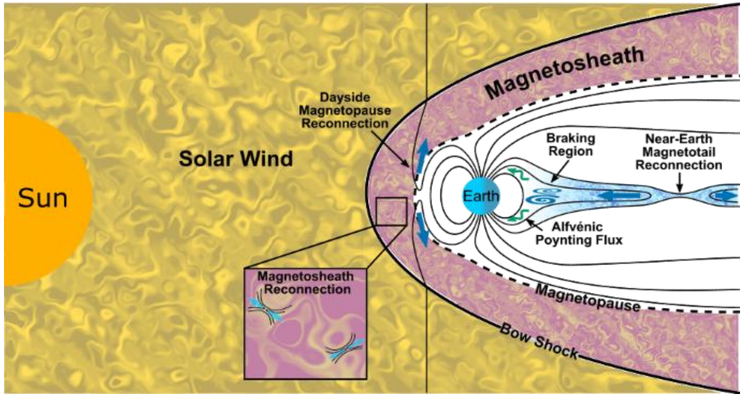
Electron-only reconnection (MMS)









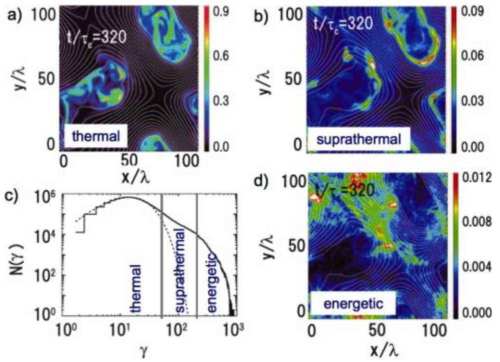


Discovery: Phan et al. , Nature, 2018
No Ion Jets: current sheets are too thin for ion coupling to occur.
Role in Turbulence: current sheets can be broken up before ions have the time to react to the reconnection electric fields
Energy Dissipation: most of magnetic energy goes into heating the electrons

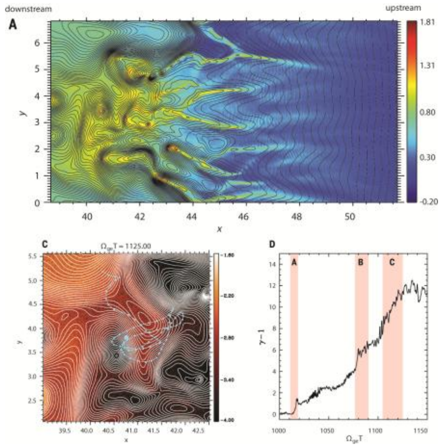
See also review by J. Stawarz, The Interplay Between Collisionless Magnetic Reconnection and Turbulence, Space Science Reviews, 2024

Reconnection & turbulence: (some) open questions

- What is the role of reconnection for energy dissipation in turbulence dissipation range?
- How the relative role between reconnection and wave-like dissipation depends on the properties of trbulence (e.g. weak vs strong, 2D vs 3D, etc.)?
- Can turbulence enhance reconnection rate? (Lazarian &Vishniac, ApJ,1999; Servidio et al., PRL,2009)
- What is the role of turbulent reconnection for accelerating energetic particles ?



[adopted from Hoshino, PRL, 2012]

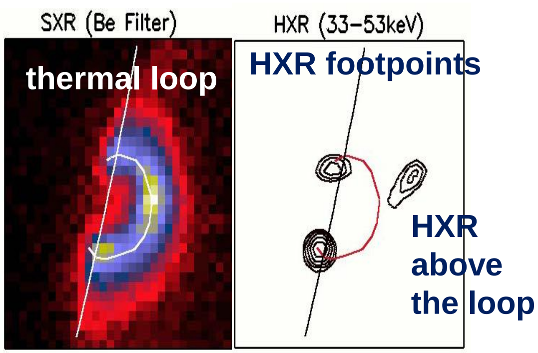


[Matsumoto+, Science, 2015]

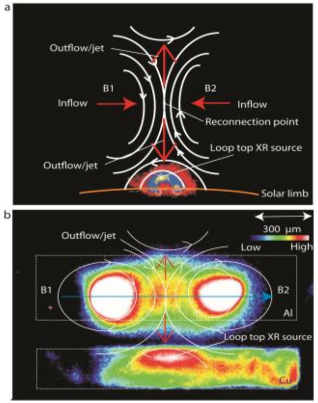
Answering all these reconnection questions requires resolving multi-scale physics !

Non-thermal particle acceleration

SUN



LAB



[Zhong+, Nature Physics, 2010]

- reconnection main process invoked to explain solar flares [Giovanelli, Nature, 1946] and other astrophysical energetic phenomena
- observed X-rays produced by accelerated particles during reconnection
- accelerated particles only available tool to study reconnection in distant objects (through emitted radiation)
- accelerated particles in the magnetosphere account for only a few % of dissipated magnetic energy but acceleration mechanisms can be studied in situ (estimated 50% in flares and even more in astrophysical objects)

Definitions (not firm)

- *acceleration* vs *heating*

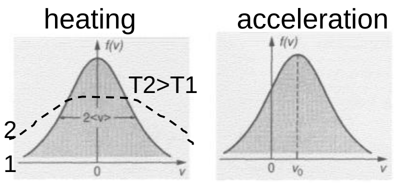
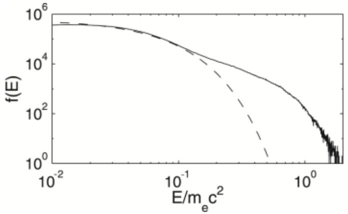


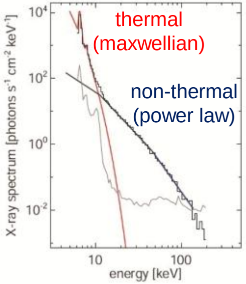
Fig. 6.5. Maxwellian and drifting Maxwellian velocity distributions.

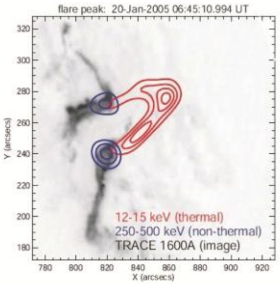
collisional plasma
(f(v) maxwellian)



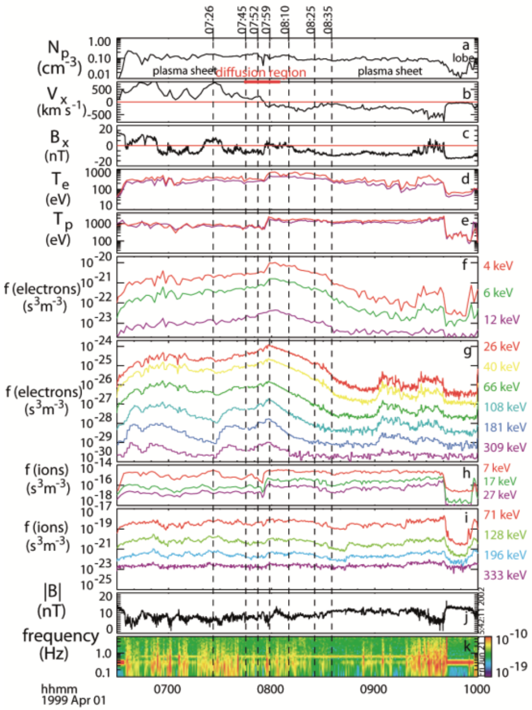
collisionless plasma
(f(v) not maxwellian)

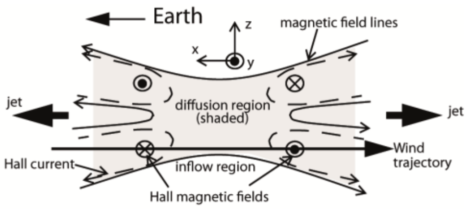
- *thermal* vs *non-thermal*

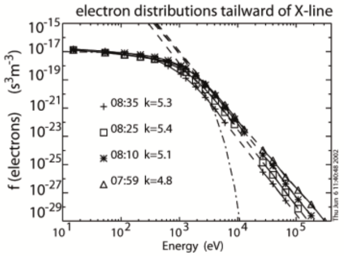


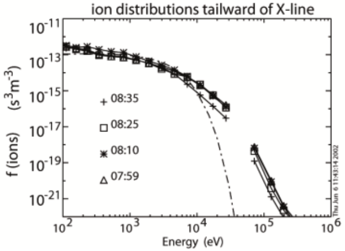


In situ evidence of non-thermal particle acceleration





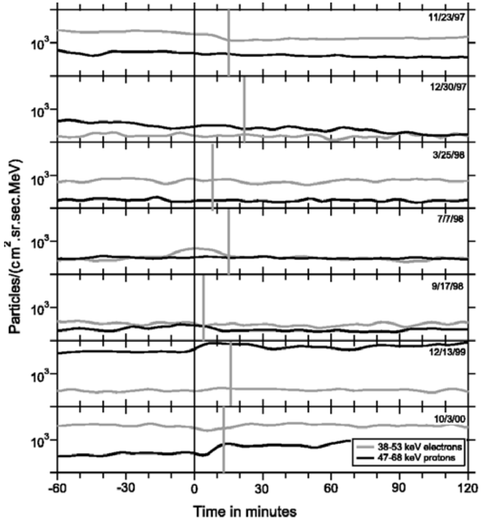




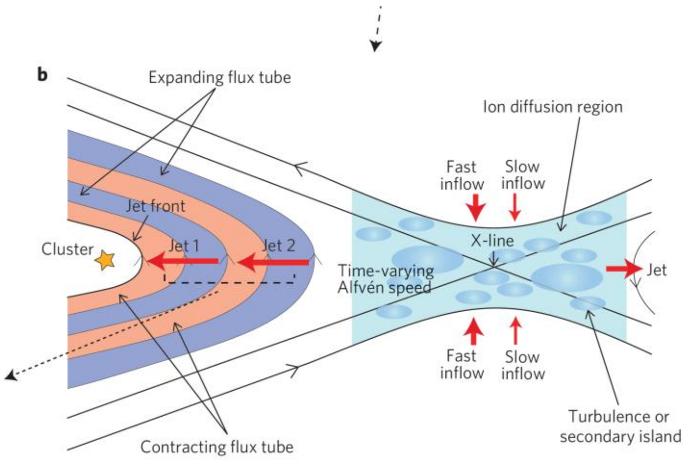
- in situ evidence in the magnetotail
- non-thermal electrons f(E)~$E^{-\gamma}$ with γ~5 for E> 2 keV
- no clear ion acceleration

[adopted from Øieroset et al., PRL,2002]

Particle acceleration is always efficient ?



[adopted from Gosling+,GRL, 2005]



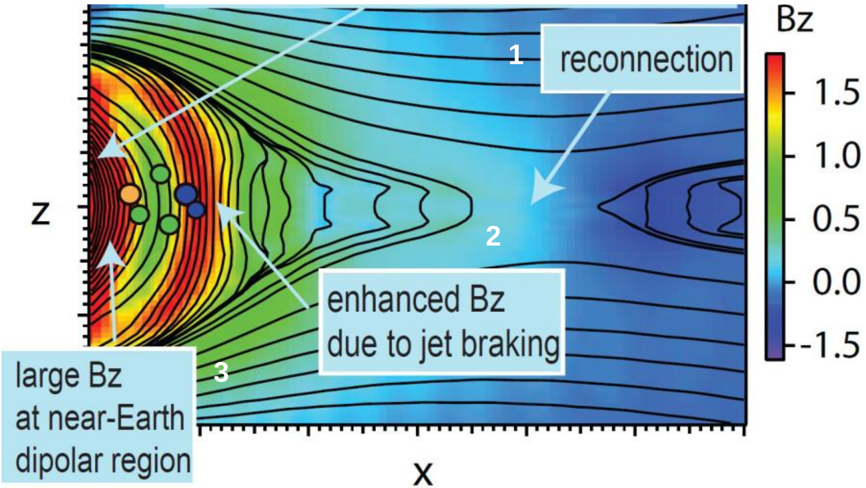
[Fu et al. Nature Physics,2013]

absence of energetic particles
in solar wind reconnection events
(steady reconnection)

Strong particle acceleration in
magnetotail (unsteady reconnection)

particle acceleration depends on reconnection conditions: steady vs unsteady, beta, laminar vs turbulent, etc.

Where does particle acceleration occur ?

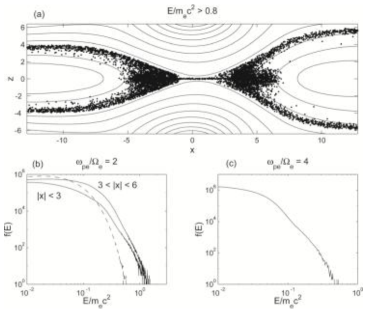


[Birn et al., JGR, 2011]

Three regions important for acceleration:

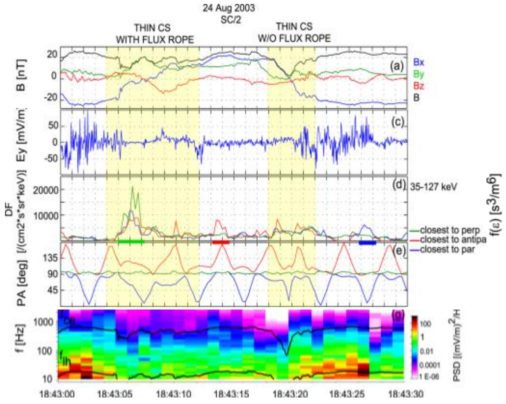
1. **X-line** [Øieroset+, PRL, 2002; Imada+, JGR,2007; Retinò+, JGR,2008;Chen+,Nature Physics, 2008]
2. **Outflow/jet fronts** [Fu+, GRL,2011; Ashour-Abdalla+, Nature Physics,2011]
3. **Interaction with dipolar field and obstacles** [Sergeev+, GRL, 2009; Zieger+, GRL, 2011]

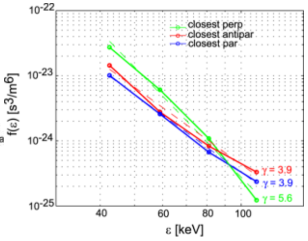
Acceleration by reconnection electric field at X-line



[Pritchett+,GRL, 2006]

- 3D full PIC simulations
- acceleration by reconnection electric field up to relativistic energies; non-thermal electrons $f(E) \sim E^{-g}$ with g~5
- unsteady reconnection
- acceleration by $E_{||}$ in the case of guide field [Pritchett+, JGR, 2006]



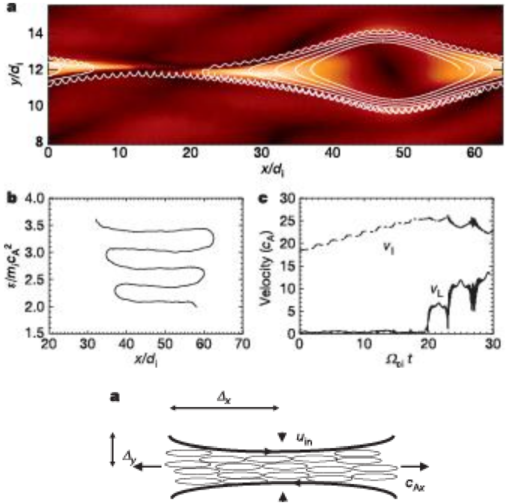


[Retinò+, JGR, 2008]

- direct X-line acceleration by Ey ~ 7 mV/m (unsteady reconnection)
- further acceleration within magnetic island

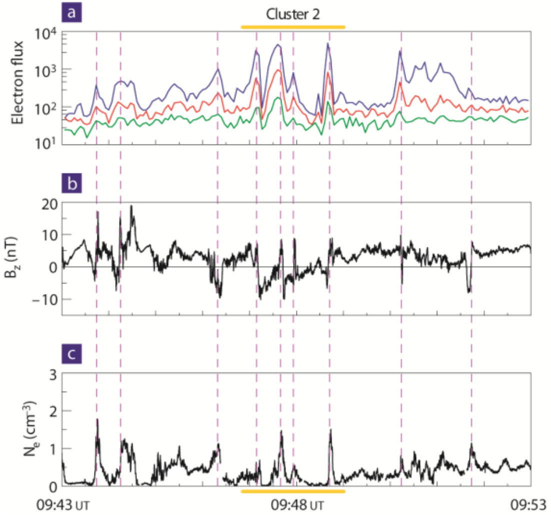
Acceleration in magnetic islands

acceleration in small-scale islands



[adopted from Drake+, Nature, 2006]

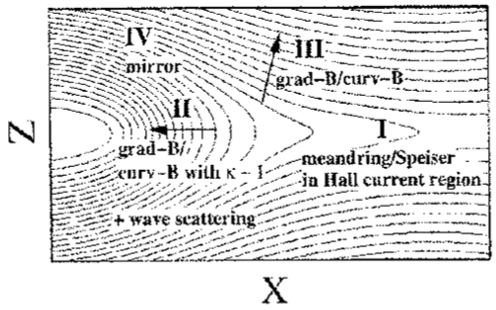
In situ observations

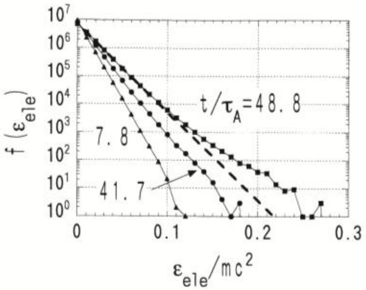


[adopted from Chen+, Nature Physics, 2008]

Acceleration at magnetic flux pile-up

PIC simulation

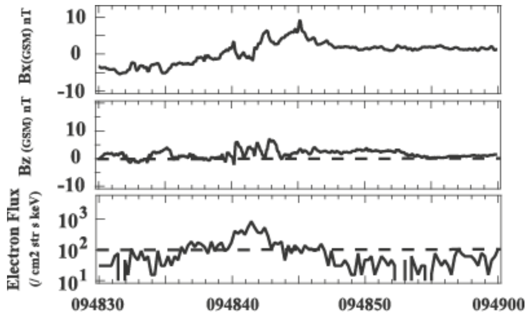


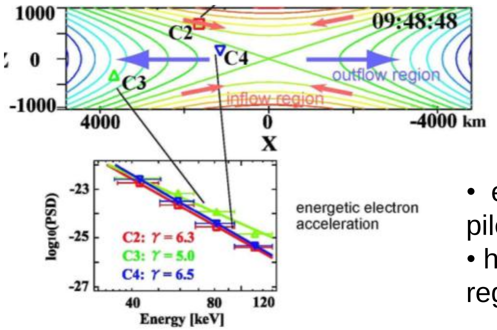


[adopted from Hoshino+, JGR, 2001]

- acceleration by Ey in strong B-gradient region (« magnetic flux pile-up »)
- magnetic mirror and ∇B / curvB drift keep particles in acceleration region
- non-adiabatic mechanism (gyroradius comparable to B-gradients + wave scattering)

in situ evidence

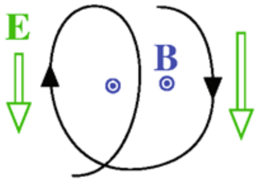




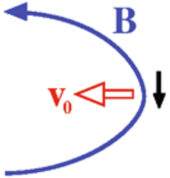
[adopted from Imada+, JGR, 2007]

- electron acceleration at B pile-up
- harder spectrum in pile-up region than at X-line

Betatron/Fermi acceleration at jet fronts



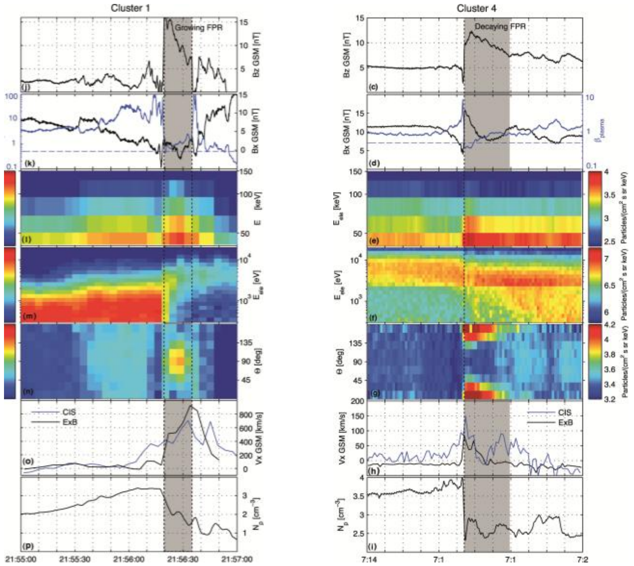
betatron



Fermi

[adopted from Birn+, 2012]

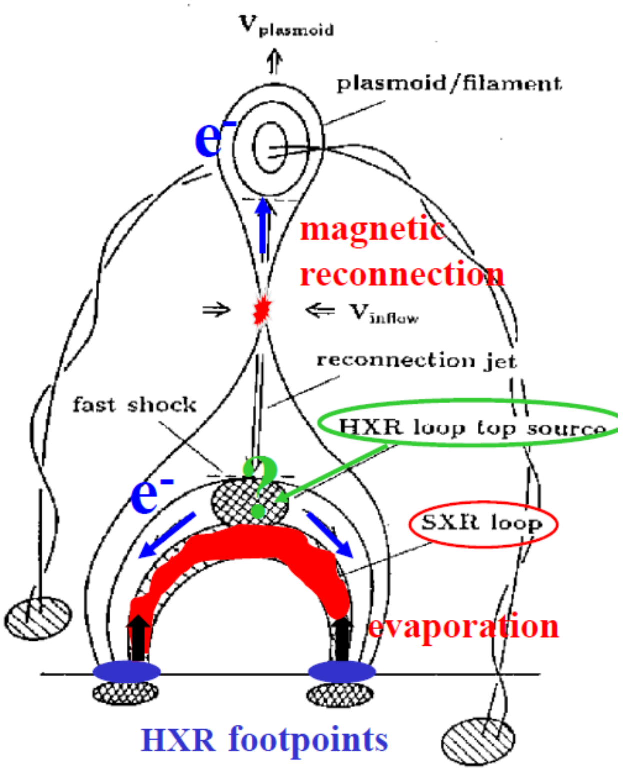
PA 90°



[adopted from Fu+, 2011]

PA 0° & 180°

The flare *Standard Model*



[Courtesy: K. Shibata, Univ. Kyoto]

1)Release of magnetic energy by reconnection

2)Particle are accelerated (not understood) + heating

3)Accelerated electrons produce HXR emission (mostly footpoints)

4) Above loop top HXR source not understood

5)collisional loses of accelerated electrons heat plasma

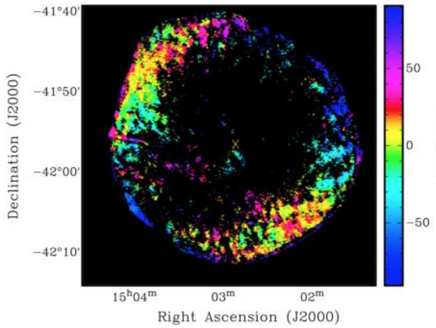
6)“evaporation” fills loop

Particle acceleration: (some) open questions

1. How particle acceleration depends on plasma parameters, boundary conditions, stages of reconnection etc.
2. Which reconnection regions produce the strongest acceleration ?
3. What is the role of turbulent reconnection for particle acceleration?
4. How energy is partitioned among energetic electrons, protons and heavy ions

Answering all these reconnection questions requires resolving multi-scale physics !

[Reynoso+, AJ, 2013]



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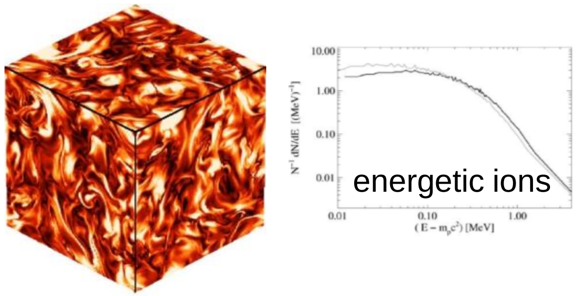
most efficient particle acceleration and generation of magnetic turbulence at quasi-par shocks



[Dmitruk & Matthaeus, Phys. Plasmas, 2006]

Current and future spacecraft measurements relevant for in situ reconnection

Exploratory physics (single-point):

- ESA/BepiColombo (2018-): Mercury's magnetosphere
- NASA/ParkerSolarProbe (2018-): near-Sun corona (8.5 Rs)
- ESA/SolarOrbiter (2020-): near-Sun corona (62 Rs)
- ESA/JUICE (2023-): Jupiter's and Ganymede's magnetosphere

Fundamental physics (multi-point, beyond Cluster, THEMIS and MMS):

- NASA/HelioSwarm (2030): multi-scale measurements in solar wind (mainly)
- ESA/PlasmaObservatory ? (2037): multi-scale measurements in terrestrial magnetosphseric system (mainly)

HelioSwarm: see talk by K. Klein

Plasma Observatory: see talk by M. F. Marcucci on Friday 22nd

Next logical step in *fundamental* space plasma physics