In situ observations of magnetic reconnection in near-Earth space

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Outline

- Magnetic reconnection
- In situ observations of reconnection in near-Earth space
- A few key open issues:
  - non-thermal particle acceleration
  - reconnection & turbulence
  - microphysics
- Future spacecraft data relevant for reconnection
- Summary

Magnetic reconnection

- Violation of the frozen-in condition in thin boundaries (current sheets)

- Consequences:
  - magnetic topology change ($E_{||}$)
  - plasma transport across boundaries
  - plasma acceleration (alfvenic jets)
  - plasma heating
  - non-thermal particle acceleration

- Importance of scales (collisionless):

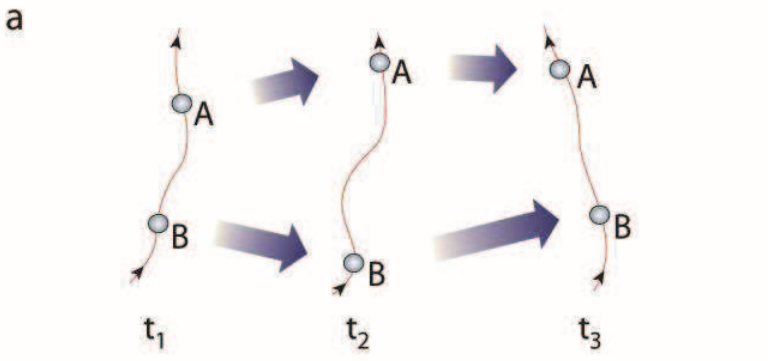
$$\mathbf{E}+\mathbf{u}\times\mathbf{B}=\frac{\mathbf{J}}{\sigma_*}+\frac{\mathbf{J}\times\mathbf{B}}{ne}-\frac{\nabla\cdot\mathbf{P_e}}{ne}+\frac{m_e}{ne^2}\frac{\partial\mathbf{J}}{\partial t}$$

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

MHD (>> ρ_i) ~ 10^3 km

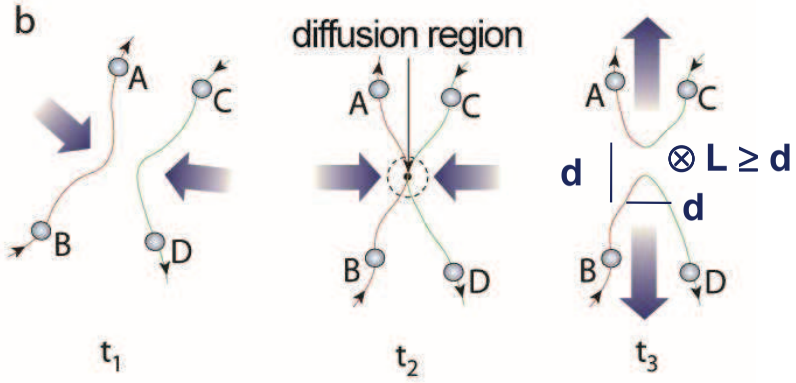
ion (~ ρ_i) ~ 50 km

electron(~ ρ_e) ~ 1 km



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

$E_{||}=0$

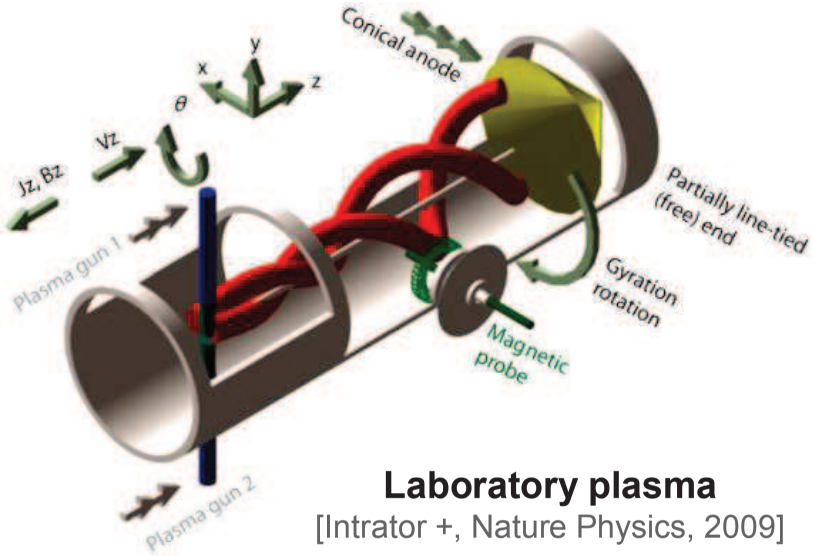


$\mathbf{E'} = \mathbf{E}+\mathbf{u}\times\mathbf{B} \neq 0$

$E_{||}\neq 0$

[adopted from Paschmann, Nature, 2006]

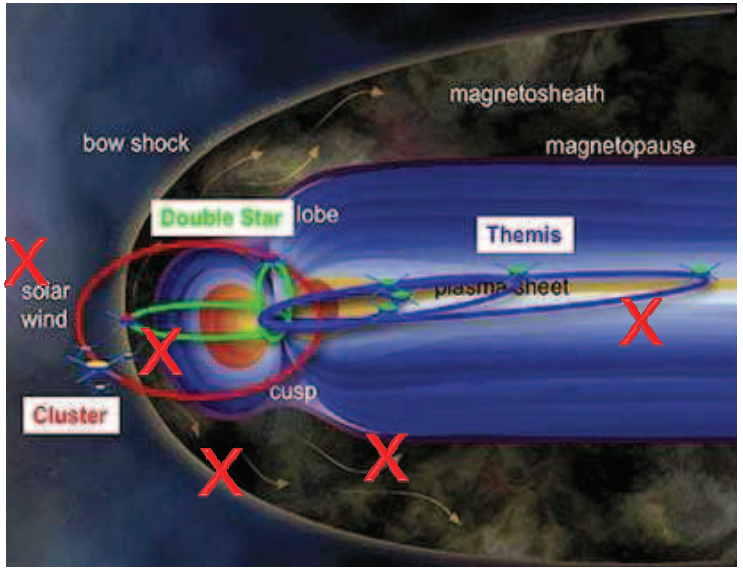
Reconnection in the plasma Universe



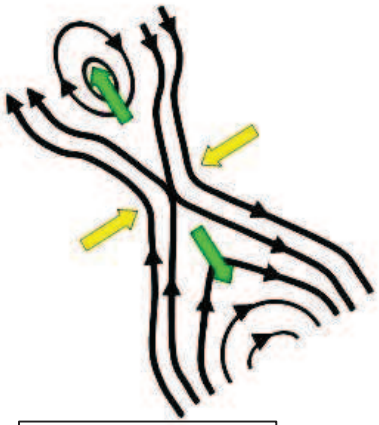
Laboratory plasma
[Intrator +, Nature Physics, 2009]

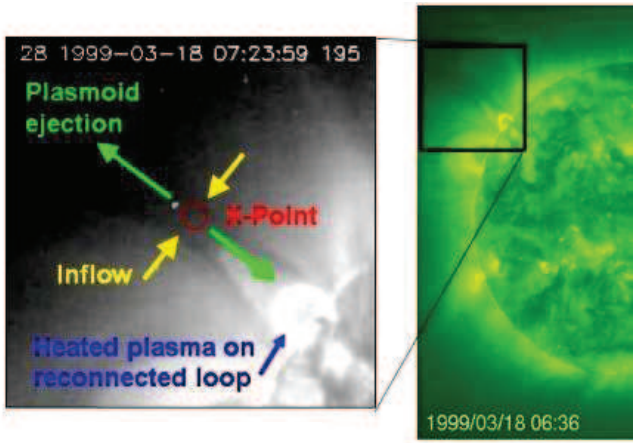
L ~ 10^{-2} m

L ~ 10^{7} m



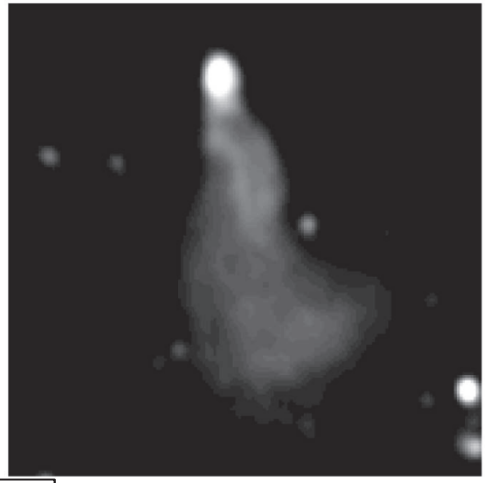
Near-Earth space
[Paschmann, 2008]





Solar corona
[Yokoyama+, ApJL, 2001]

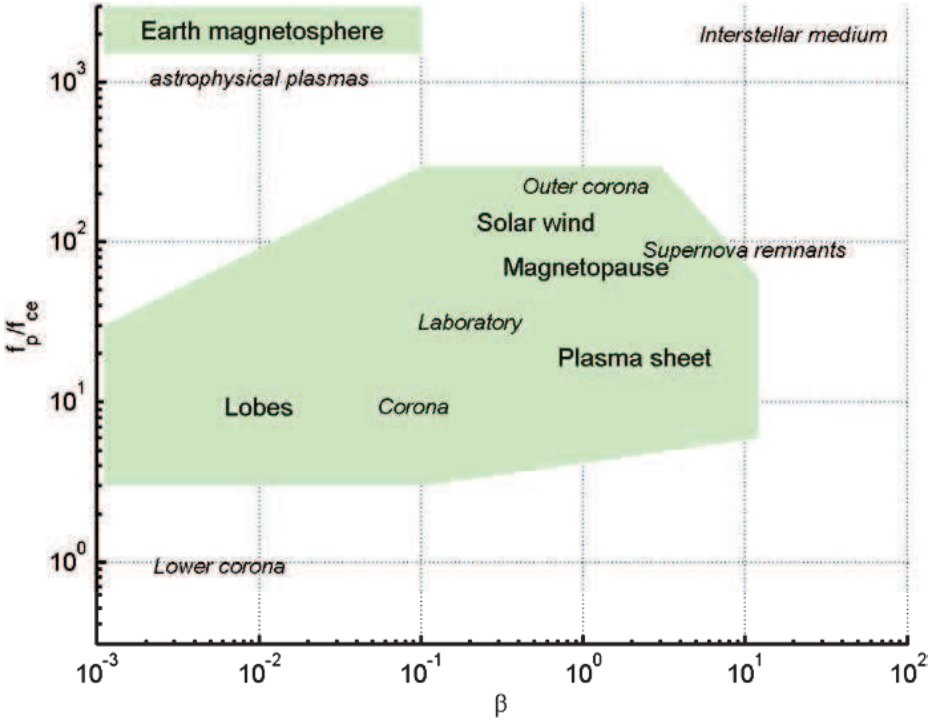
L ~ 10^{8} m



Radio galaxy lobes
[Kronberg +, ApJ, 2004]

L ~ 10^{16} m (?)

Near-Earth space as *plasma laboratory*



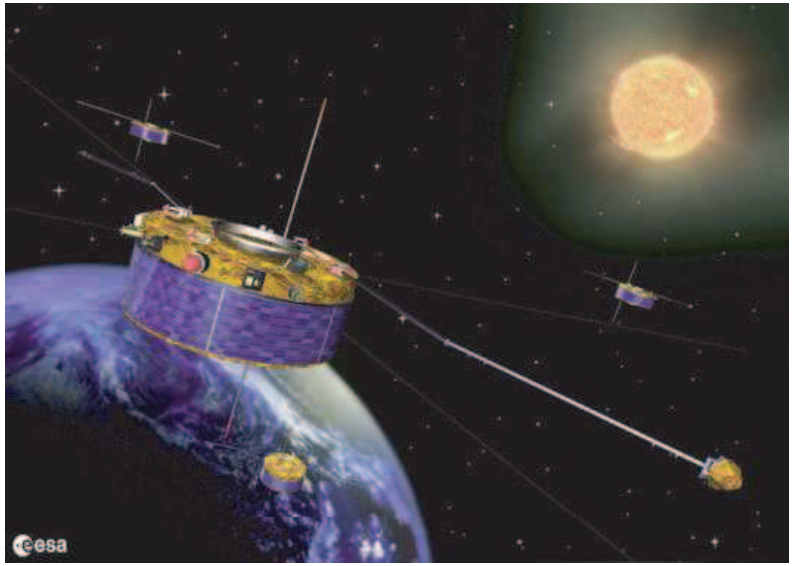
[Vaivads+, Plasma Phys. Contr. Fus., 2009]

Near-Earth plasma typically is:

- fully ionized
- mainly H^+ and e^-
- not relativistic
- collisionless

	LAB	NEAR-EARTH	SUN	ASTRO
In situ measur. E & B	**yes**	**yes**	no	no
In situ measur. f(v)	no	**yes**	no	no
Imaging	**yes**	**yes**	**yes**	**yes**
Boundary conditions	artificial	**natural**	**natural**	**natural**
Repeatability	**yes**	no	no	no

Current multi-spacecraft missions

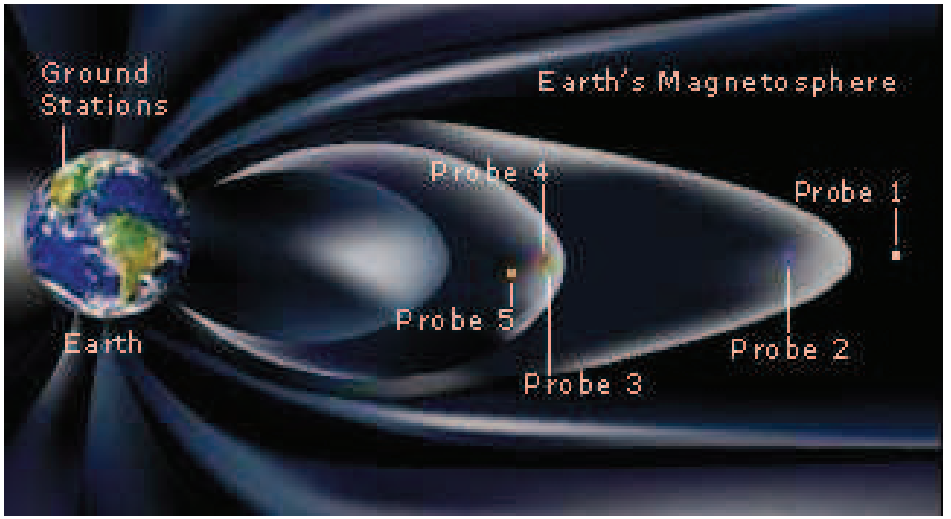


ESA/Cluster: 2000 - 2014 [http://sci.esa.int/cluster]

- **first 4 spacecraft mission**
- distinguish temporal/spatial variations
- measurement of 3D quantities: $\mathbf{J}=(1/\mu_0)\ \nabla \mathrm{x}\mathbf{B}$, $\nabla\cdot\mathbf{B} = 0$, $\mathbf{E}\cdot\mathbf{J}$, etc.
- tetrahedrical configuration with changeable separation 100-10000 km -> measurements at different scales
- 4 sets of 11 identical instruments to measure electromagnetic fields and particle distribution functions

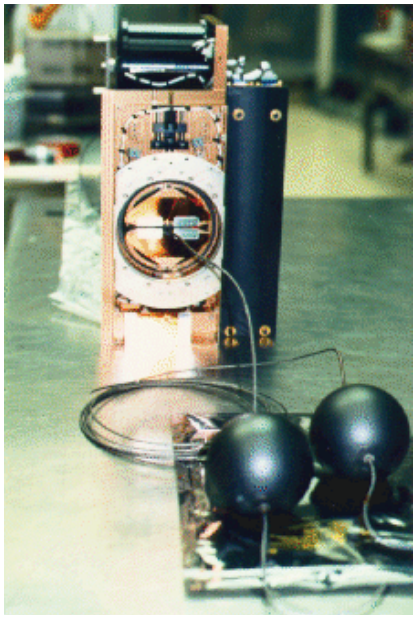
NASA/Themis: 2007 – 2012 [http://themis.ssl.berkeley.edu]

- tailored for studying substorms at large scales
- configuration with changeable separation 500-10000 km
- 5 sets of 6 identical instruments



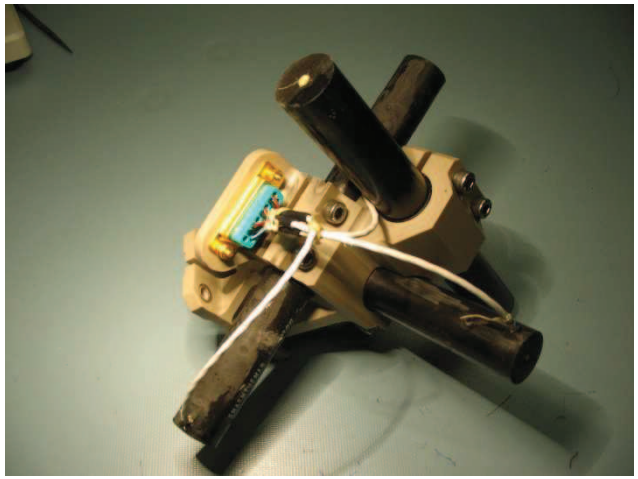
In situ spacecraft instrumentation

Fluxgate (DC) magnetometer onboard ESA/Cluster

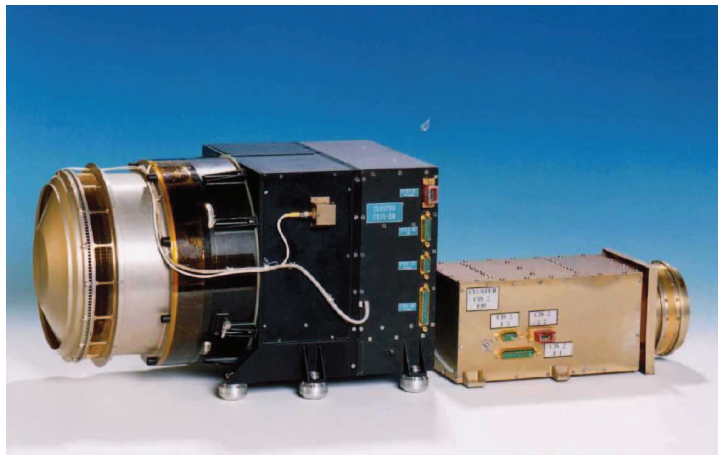


Langmuir probe for electric field measurements onboard NASA/Fast

@ LPP



Search coil (AC) magnetometer onboard NASA/Themis



Ion spectrometer onboard ESA/Cluster

A few key open issues

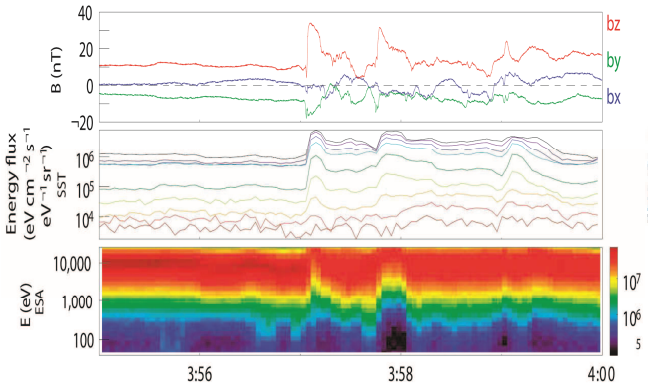
1. Supra-thermal particle acceleration
   Why? Only way to study reconnection in remote objects (e.g. solar flares through emitted radiation)

2. Relationship reconnection – turbulence
   Why? Two mayor ingredients of lab-space-astro plasmas

3. Microphysics (proton scales and below)
   Why? The basic physics of reconnection (e. g. onset)

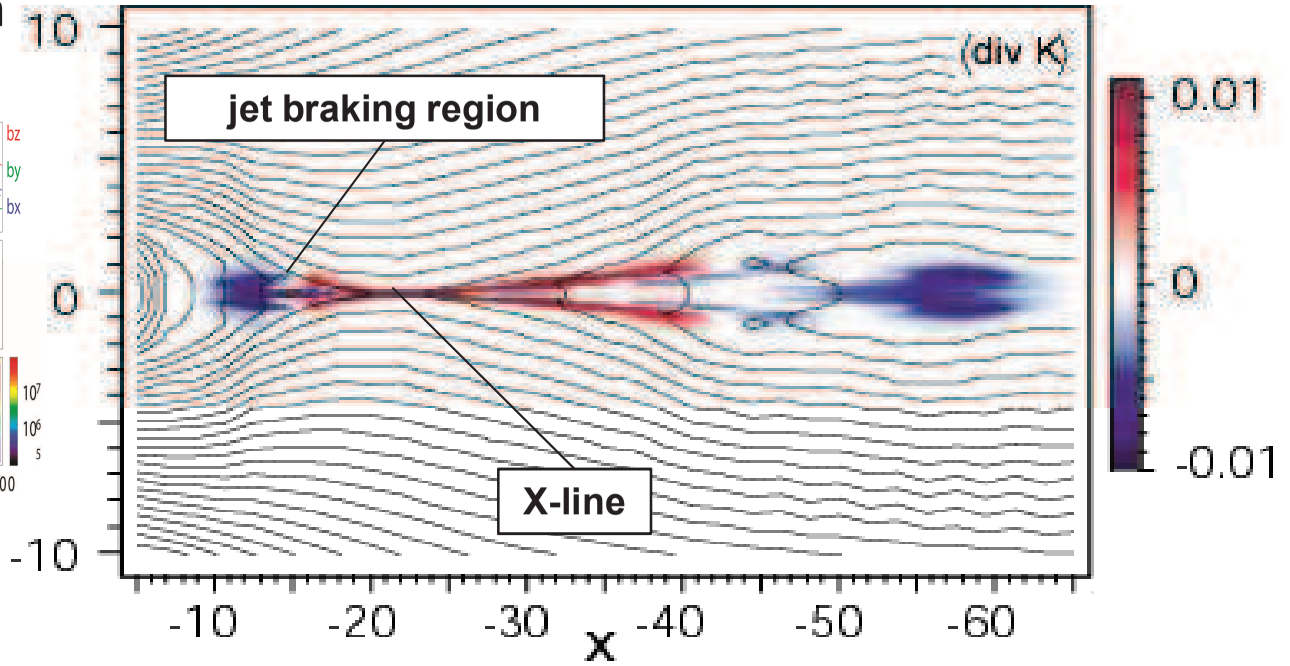
Particle acceleration during magnetotail reconnection

Betatron at reconnection jet fronts (B gradients)

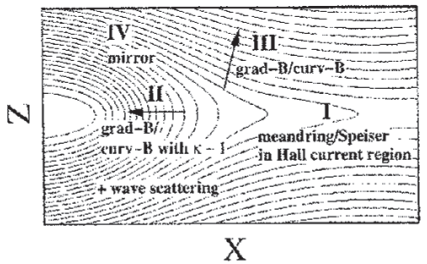


[Ashour-Abdalla+, Nature Physics, 2011]

[adopted from Birn+, AnnGeo, 2005]

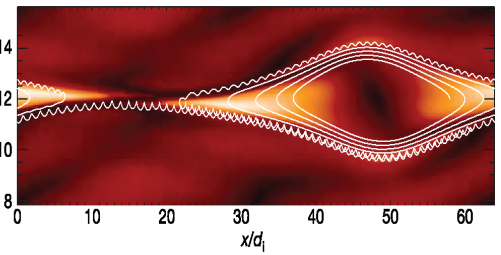


B pile-up region



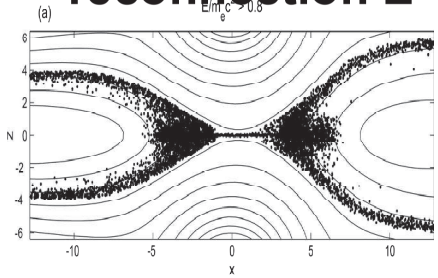
[Hoshino+, JGR, 2001]
[Imada+, JGR, 2007]

small-scale islands



[Drake+, Nature, 2006]
[Chen+, Nature Phys, 2008]

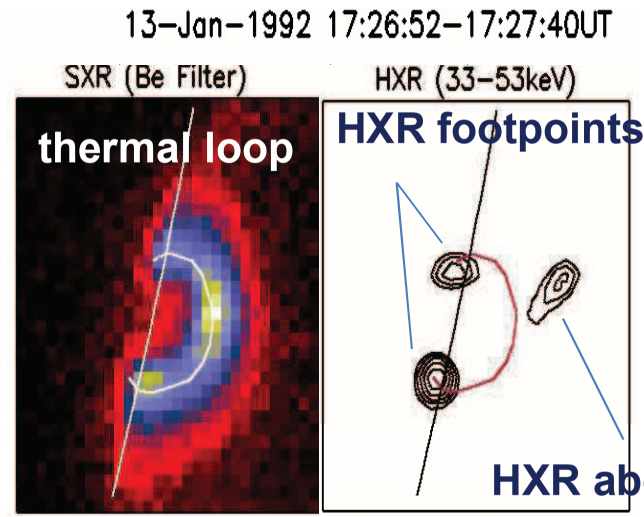
reconnection E



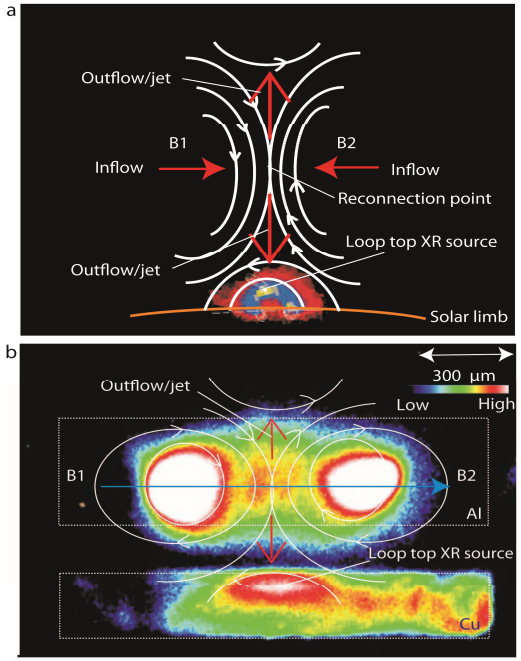
[Pritchett+, GRL, 2006]
[Retinò+, JGR, 2008]

Jet braking regions in lab and astro plasmas

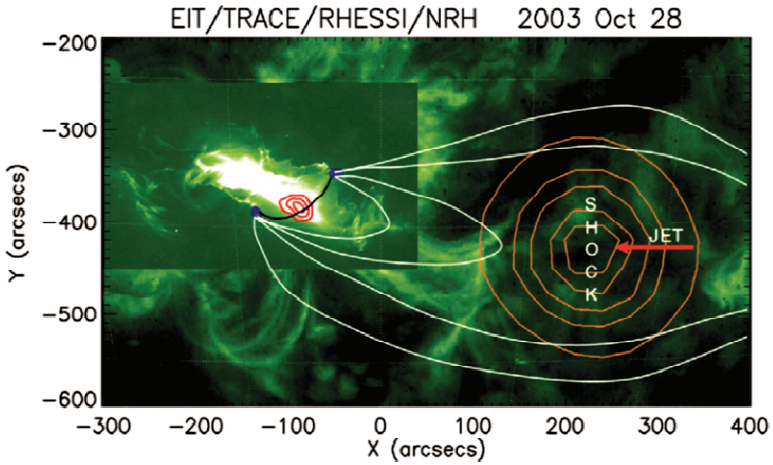
Above-the-loop-top HXR source (YOHKOH)



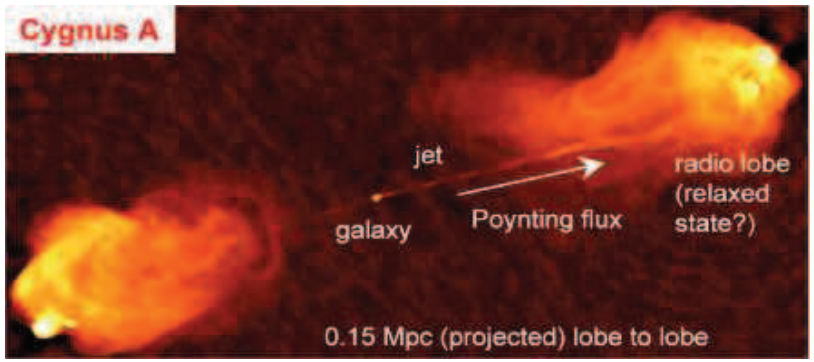
[courtesy S. Krucker, UC Berkeley]



[Zhong+, Nature Physics, 2010]

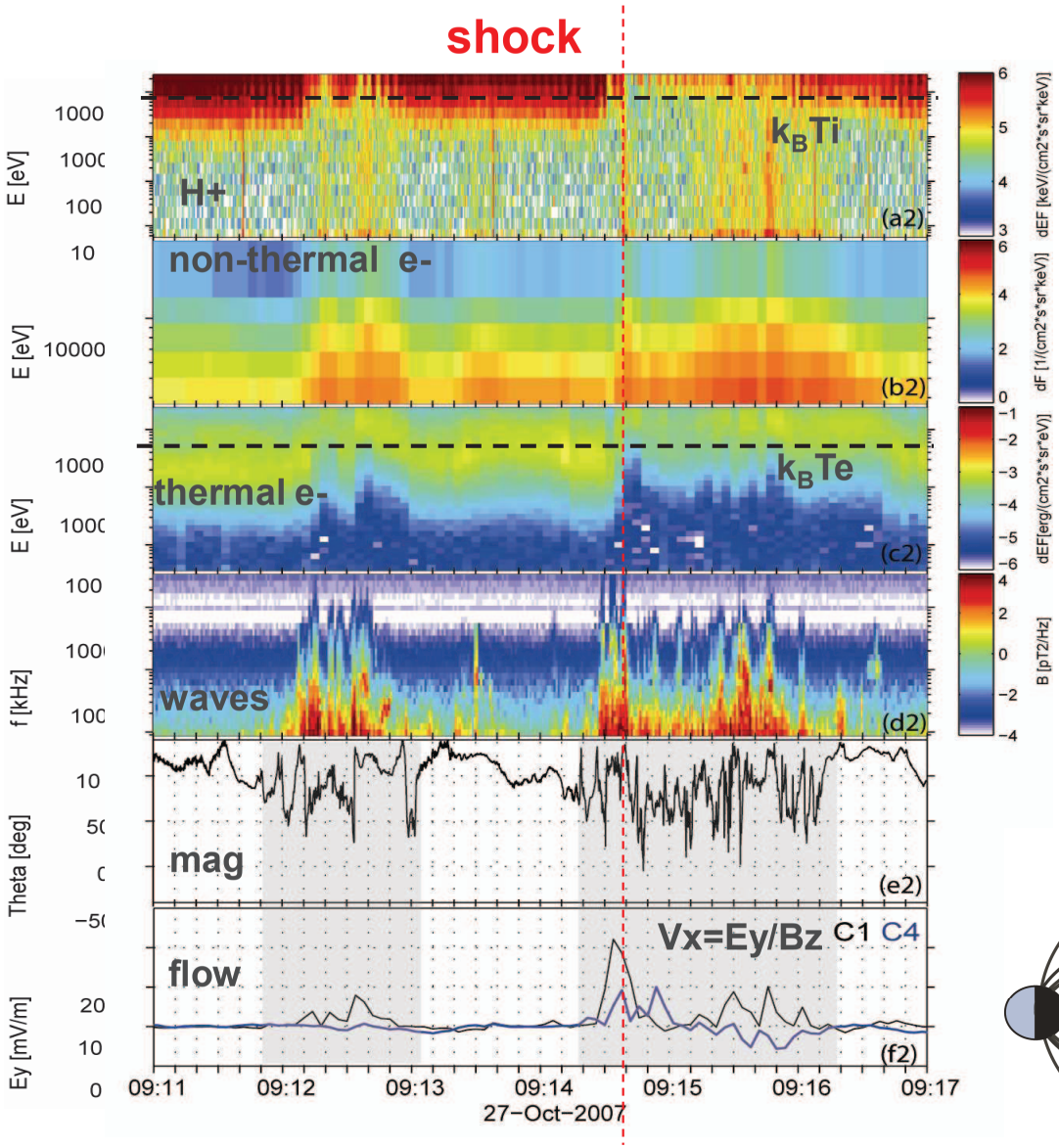


[Mann+, A&A, 2009]

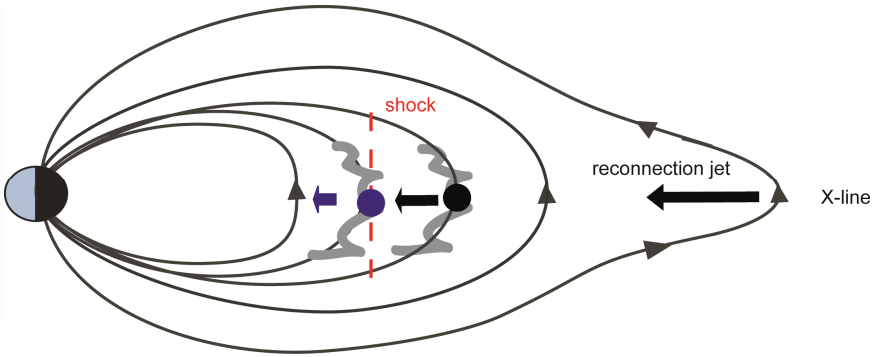


Radio galaxy [adopted from http://www.ece.unm.edu/~plasma/Space/jets.htm]

Electron acceleration in the jet braking region (I)

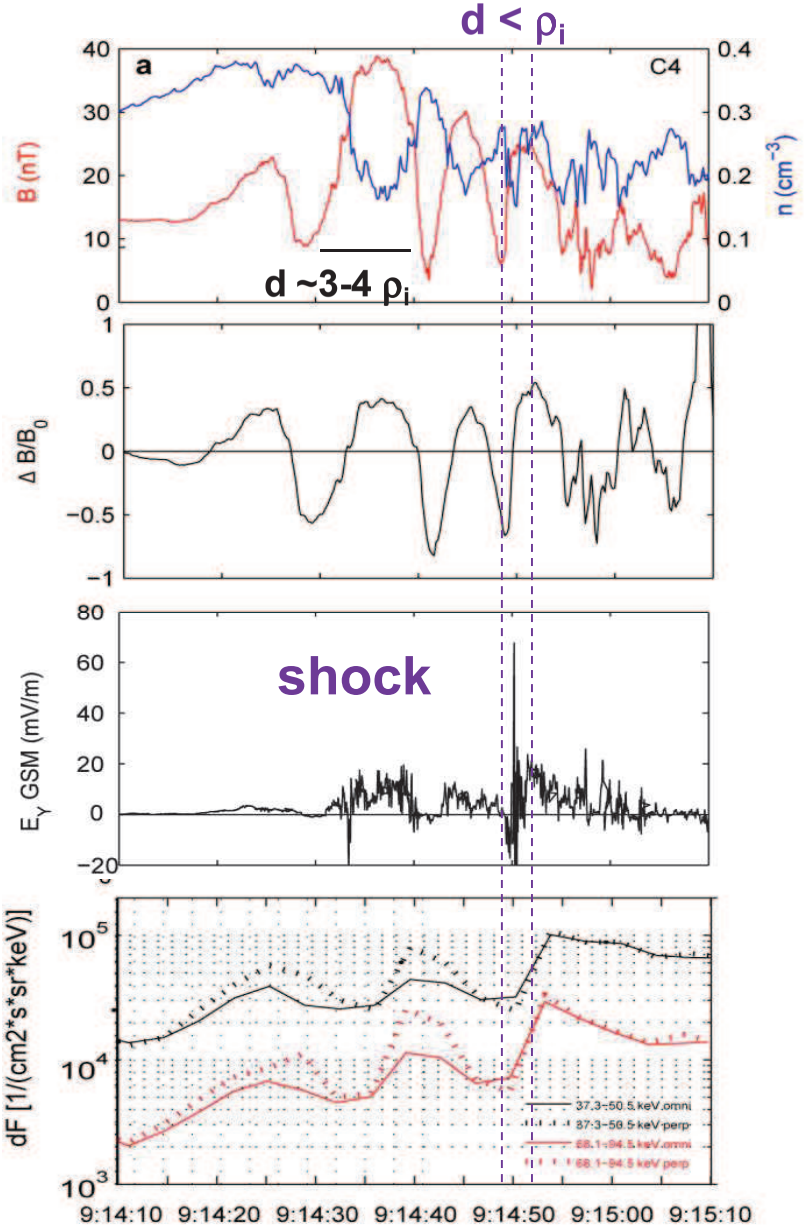


- Turbulence compised of large-amplitude magnetosonic waves (dB/B~1)
- Betatron electron acceleration in sub-proton scale current layers
- Non-adiabatic (stronger) acceleration in sub-proton scale shock



[Retinò+, JGR, under review]
[Zieger+, GRL,under review]

Electron acceleration in the jet braking region (II)



N & B anticorrelated
(except at shocklet)

dB/B ~1

strong electric fields
and waves in LH range

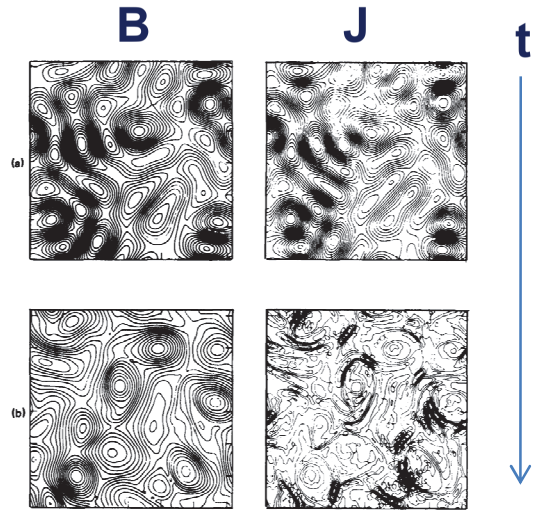
acceleration of supra-thermal
electrons (~100 keV)

[Zieger+, GRL, under review]

Relationship reconnection - turbulence

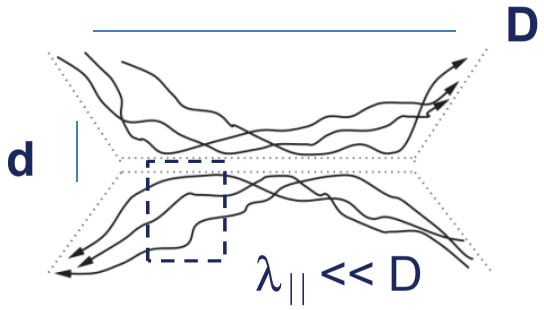
Small-scale current sheets in turbulent plasma

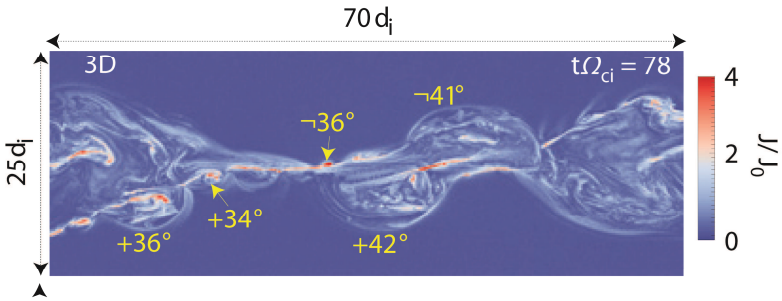
[Matthaeus & Lamkin, Phys. Fluids,1986; Dmitruk & Matthaeus, Phys; Plasmas, 2006; Servidio +, Phys. Plasmas, 2010]



Turbulent current sheet

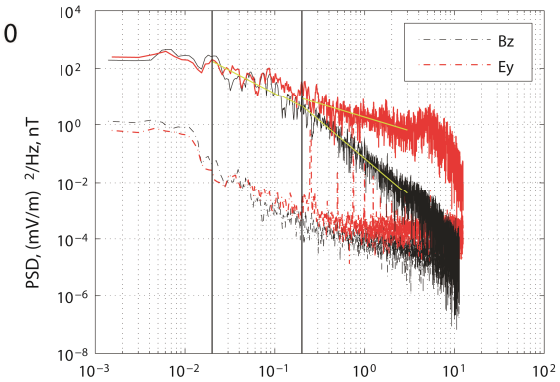
[Lazarian & Vishniac, ApJ, 1999; Lapenta, PRL, 2008; Loureiro+, MNRAS, 2009; Eyink, JMP, 2009; Daughton+, Nature Physics, 2011]





Turbulence/waves in current sheets

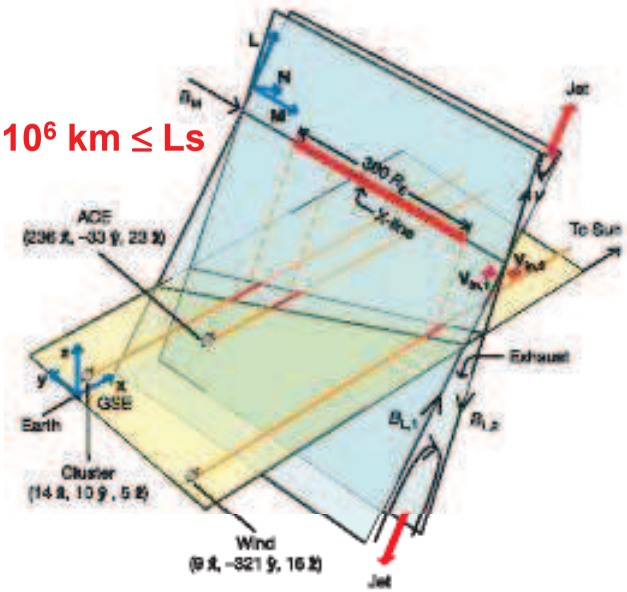
[Bale+, GRL, 2002; Vaivads+, GRL, 2004; Khotyaintsev+, Ann Geo, 2004; Retinò+, GRL, 2006; Eastwood+,PRL, 2009; Huang+, JGR, 2010; Che+, Nature, 2011]



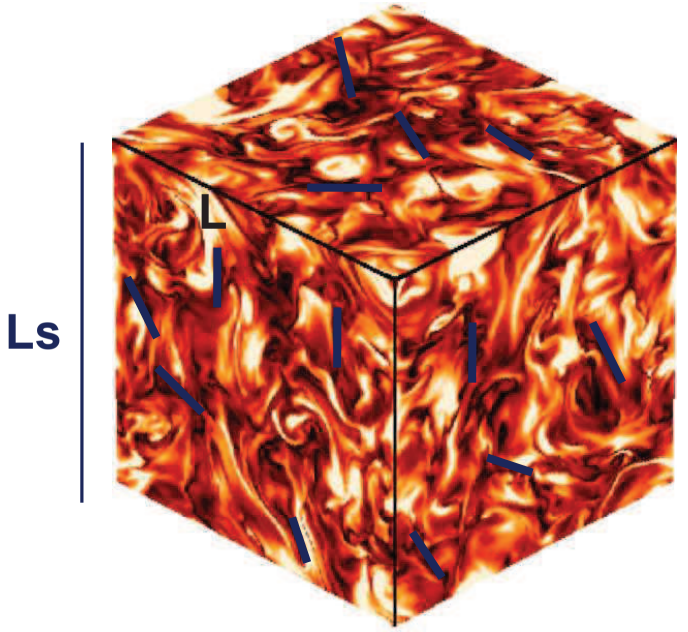
Reconnection in turbulent plasma

Large-scale/laminar vs small-scale/turbulent current sheets

L ~ 3 ·10^6 km ≤ Ls

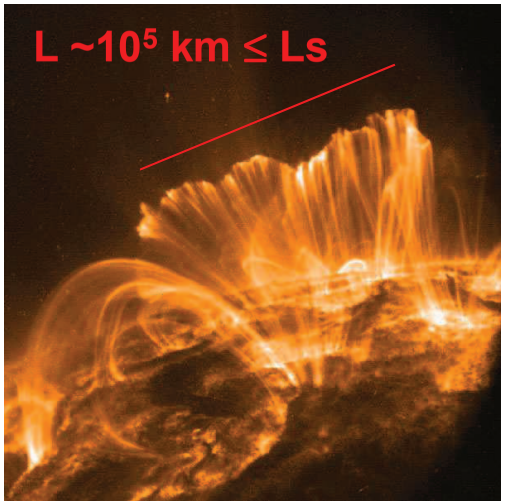


[Phan+, Nature, 2006]



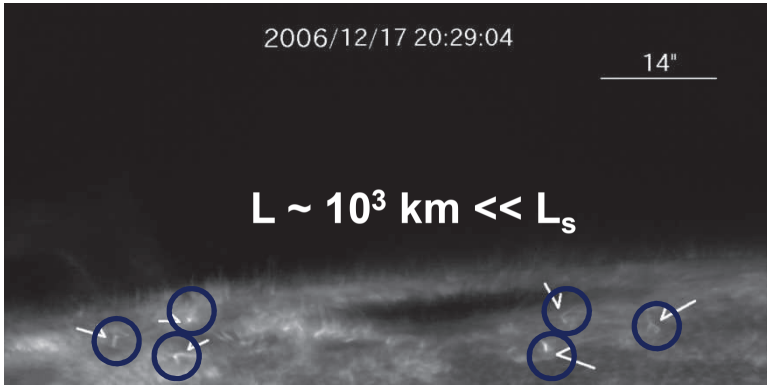
L << Ls

[Dmitruk & Matthaeus, Phys. Plasmas, 2006]



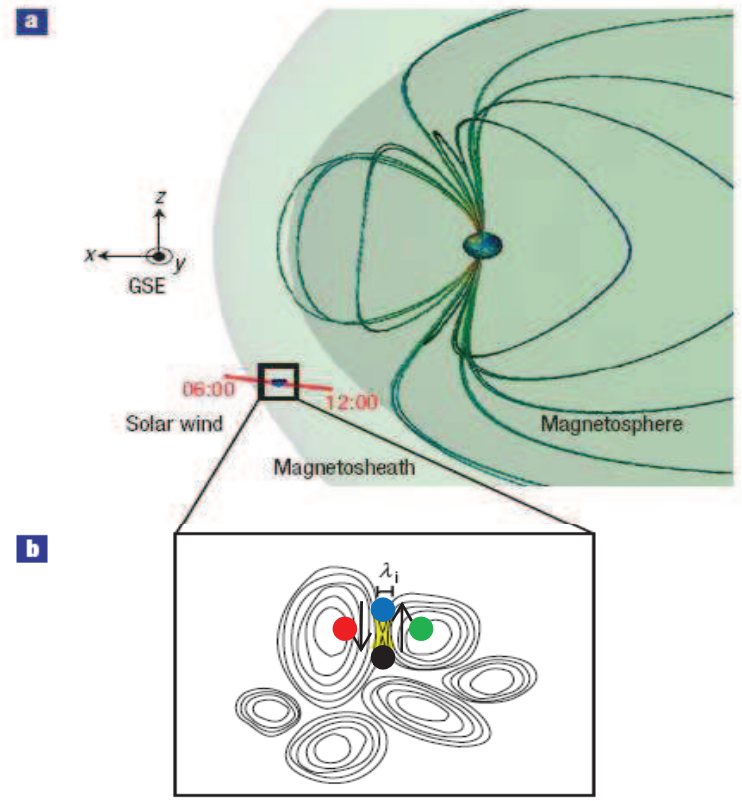
Coronal loop observed by NASA/TRACE (UV ~10^6 K)

Ca II image from Hinode - SOT

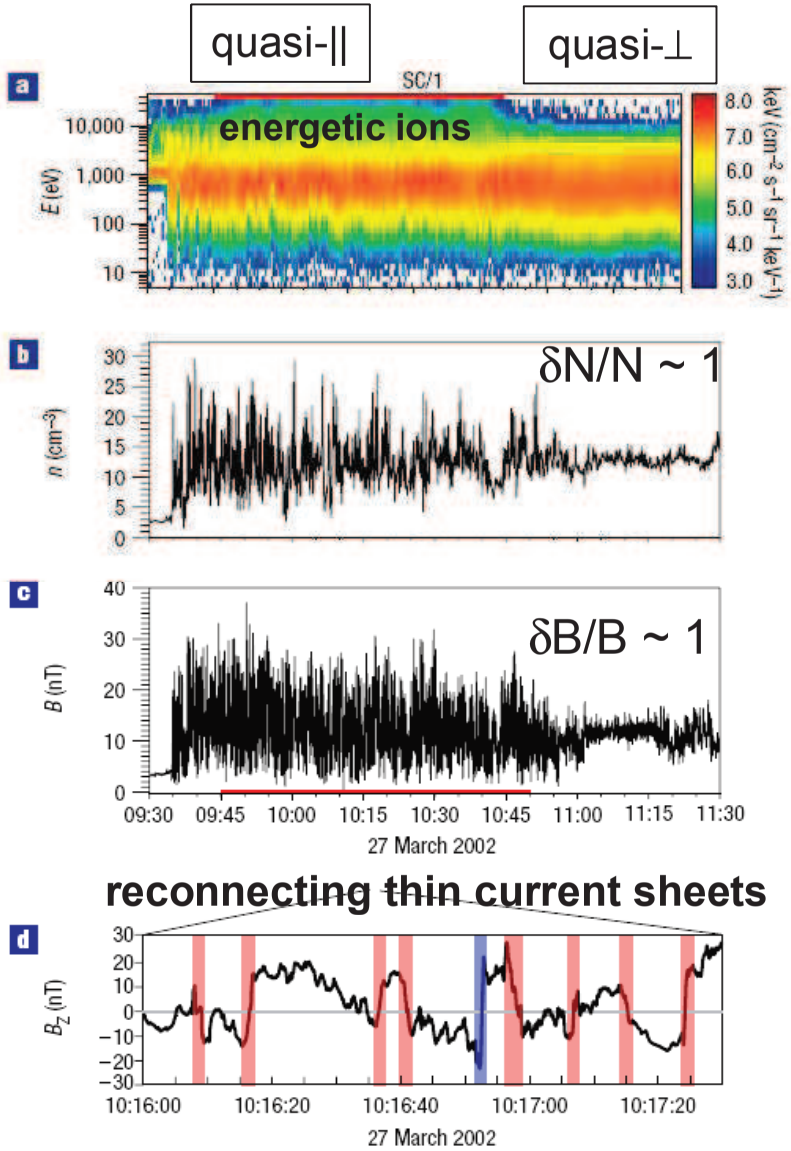


[Shibata +, Science, 2007]

In situ evidence of reconnection in turbulent plasma (I)

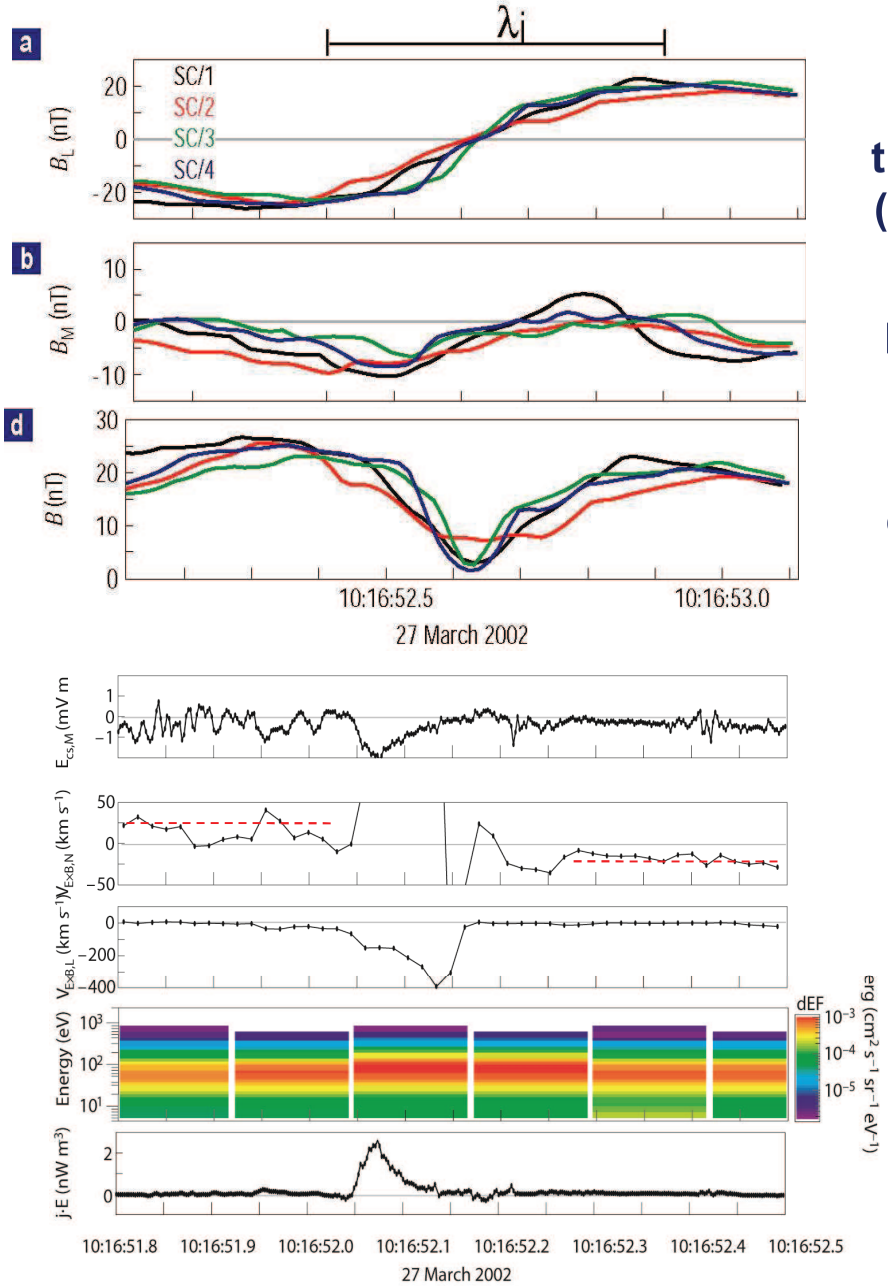


cartoon of small-scale current sheets formation in turbulent plasma



[Retinò+, Nature Physics, 2007]
also [Gosling+, ApJL, 2007; Chian+, ApJL, 2011] in solar wind

In situ evidence of reconnection in turbulent plasma (II)



thin current sheet
(from 4-point B measurements)

Hall field

energy dissipation

LH turbulence

rate ~ 0.1 (fast)

plasma acceleration

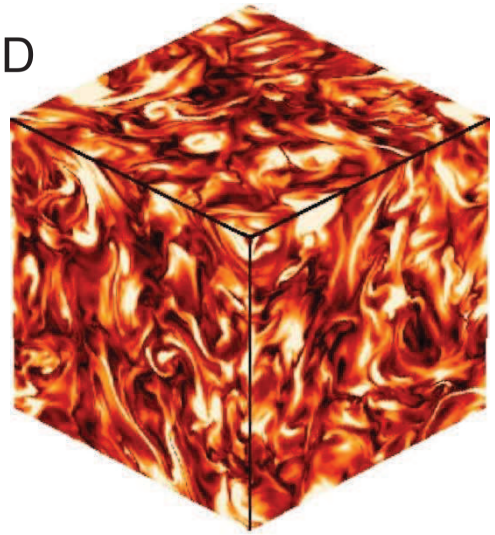
electron heating

energy dissipation

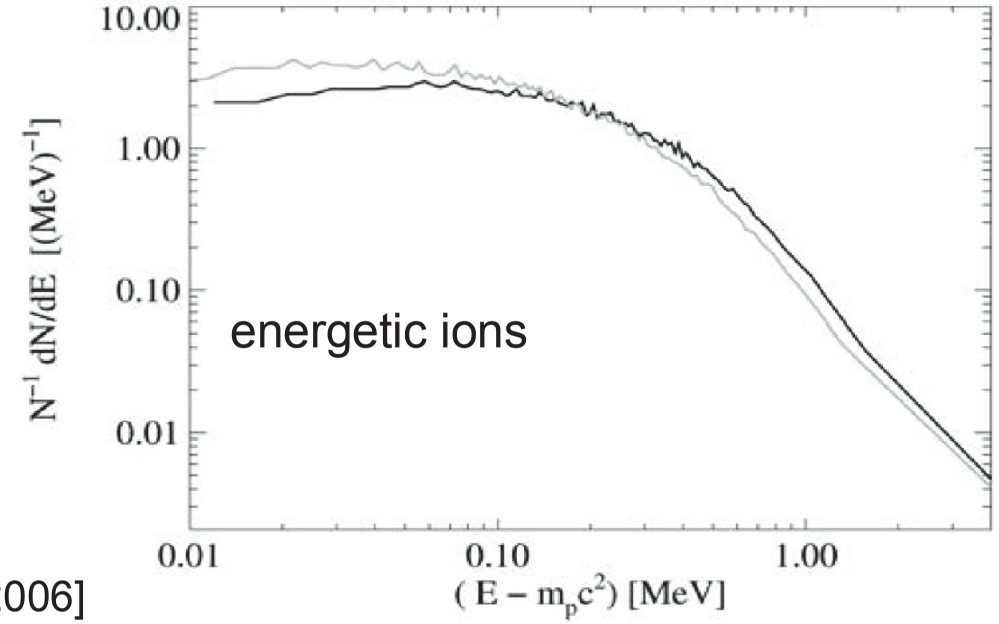
[Retinò+, Nature Physics, 2007]

Non-thermal particle acceleration during reconnection in turbulent plasma

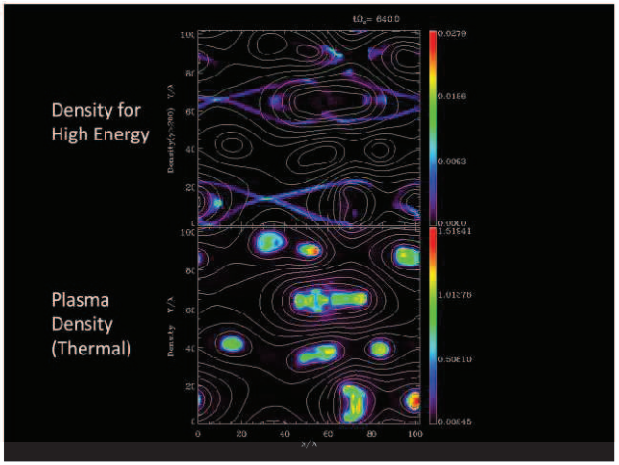
|B|
Hall MHD



[Dmitruk & Matthaeus, Phys. Plasmas, 2006]



PIC



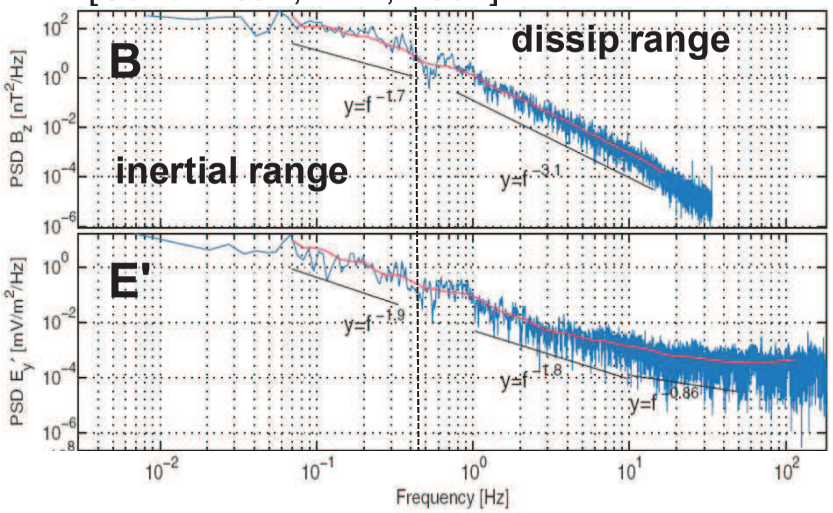
[courtesy of M. Hoshino]

- reconnection occurring in many small-scale current sheets
- non-thermal particles accelerated in the current sheets

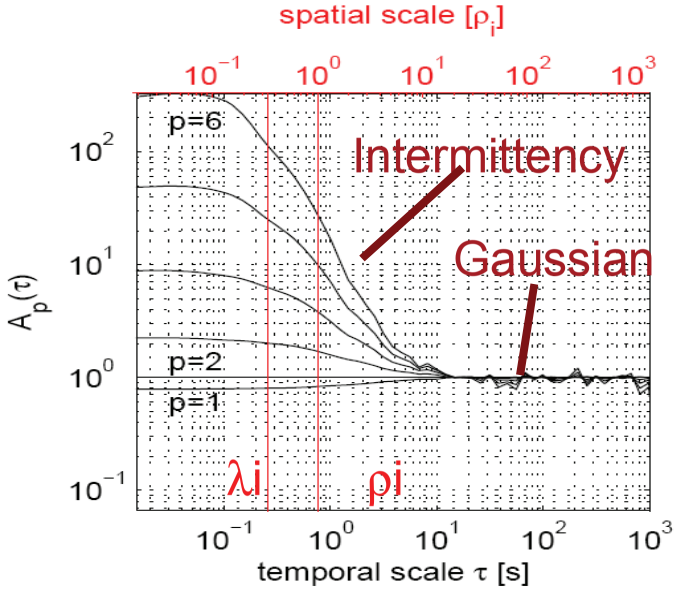
[also mechanism proposed by Lazarian&Opher, ApJ,2009]

Properties of turbulence

[Sundkvist +, PRL, 2007]



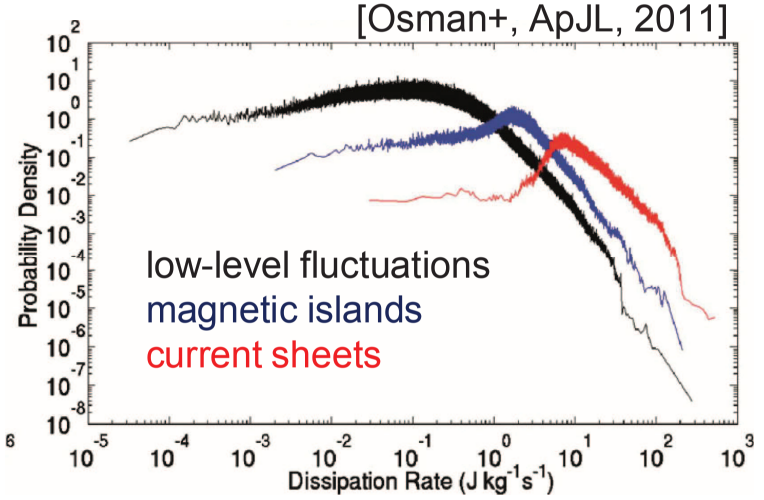
alfvenic turbulence
(-5/3 in inertial range)



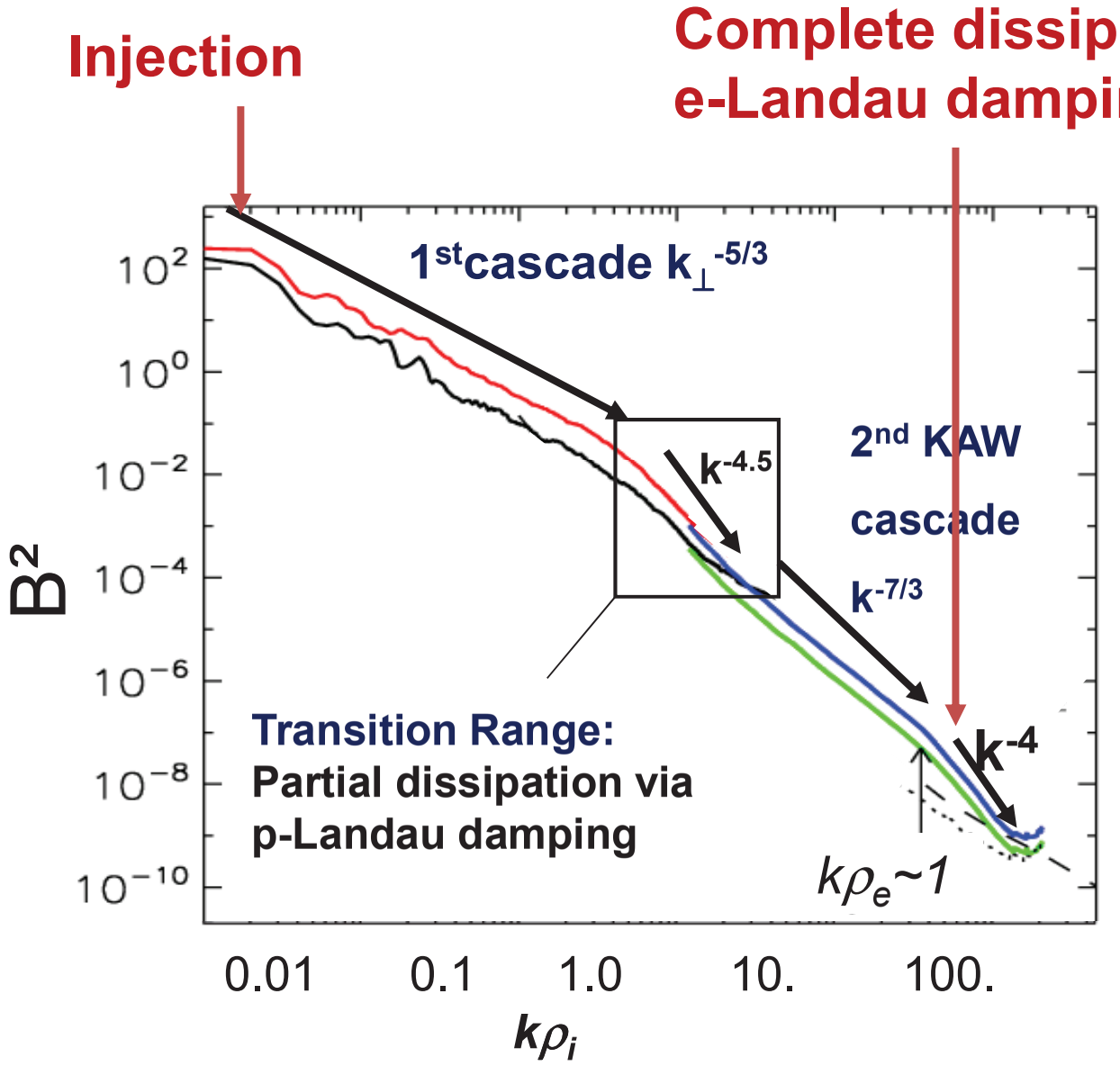
intermittency at scales λ_i - ρ_i (close to dissip. range) -> presence of coherent structures

dissipation in current sheets with d~ λ_i larger than wave damping around ω_{ci} -> turbulent reconnection important mechanism for energy dissipation at ion scales

[Osman+, ApJL, 2011]



Turbulence cascade in solar wind



Importance:

- **Turbulence**
- **Particle heating & acceleration**
- **Reconnection**

Dissipation range

[Sahraoui+, PRL, 2009]
[Sahraoui+, PRL, 2010]

Possible applications of turbulent reconnection to lab and astro plasmas

- sawtooth oscillations in tokamaks
- coronal heating
- particle acceleration in solar flares
- dissipation in accretion disks
- cosmic rays acceleration

Future spacecraft data relevant for reconnection & turbulence

NASA/MMS [http://mms.gsfc.nasa.gov]: **2014 --** near-Earth space
Goal: the physics of reconnection at electron scales (also turbulence, particle acceleration)

ESA/SolarOrbiter [http://sci.esa.int/solarorbiter]: **2017 --** near-Sun corona (62 Rs/0.28 AU). **Goals**: solar wind acceleration, coronal heating, production of energetic particles (turbulence, reconnection)

NASA/SolarProbePlus [http://solarprobe.gsfc.nasa.gov]: **2018 --** near-Sun corona (8.5 Rs). **Goals**: similar to SolarOrbiter

Summary

- Near-Earth space unique laboratory to study the physics of reconnection through *in situ* measurements (in particular multi-point)
- Non-thermal acceleration, turbulent reconnection and microphysics key open issues of reconnection that can be studied with in situ measurements
- Possible applications of results from in situ observation (with caution): sawtooth oscillations in tokamaks, coronal heating, particle acceleration in flares, dissipation in accretion disks, cosmic ray acceleration etc.
- Future missions will improve our understanding of particle acceleration, turbulent reconnection and reconnection at electron scales. Current missions (Cluster, Themis) very important for preparation (lots of data!)
- Synergy between lab-astro-space crucial to understand magnetic reconnection in the plasma Universe