Particle Energization

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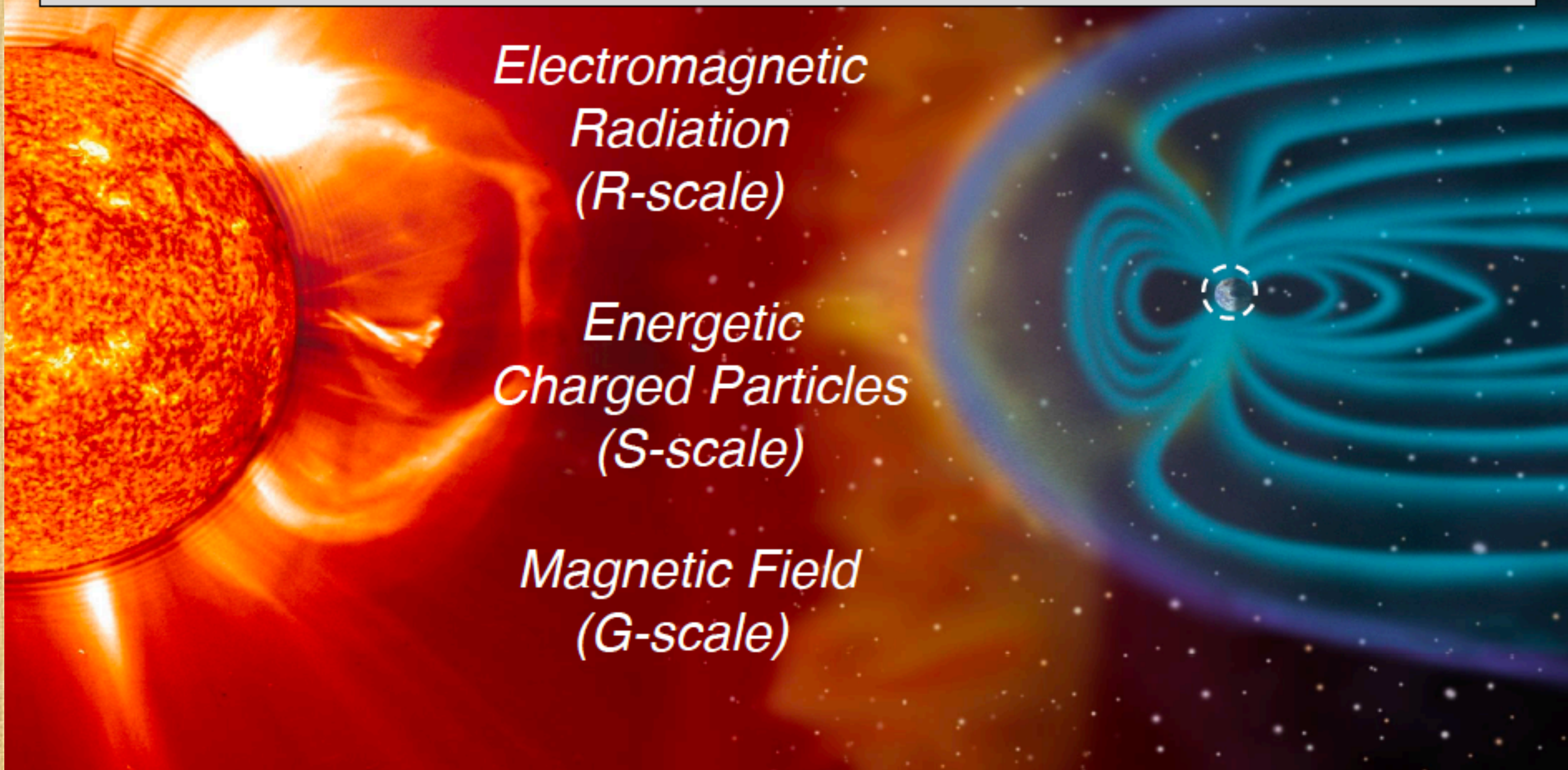
Drivers of space Weather

Space weather refers to the variable conditions on the Sun and in space that can influence performance and reliability of space and ground-based technological systems, and endanger life or health



Courtesy: W. Murtagh, this school

Particle acceleration: physical mechanisms

- Shocks
- Wave-particle interactions
- Reconnection and turbulence

Why are shocks important?

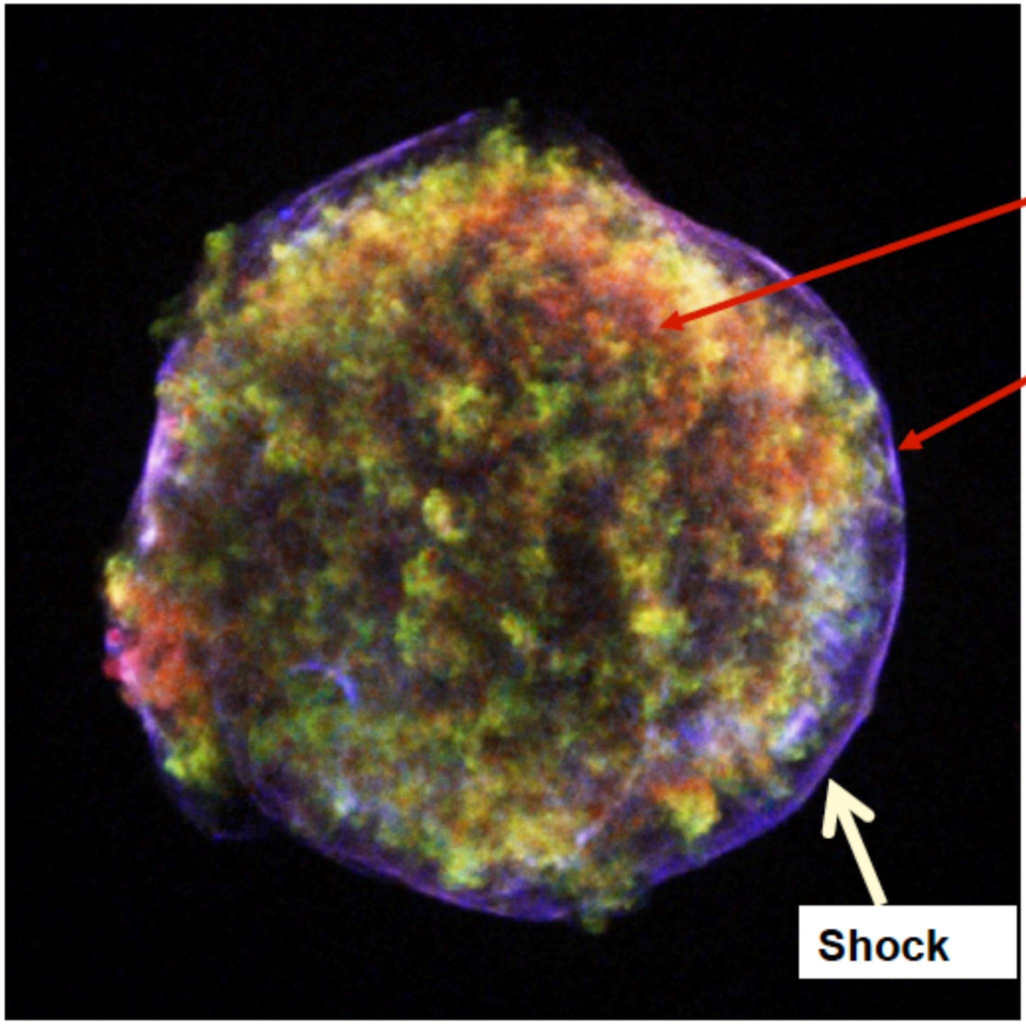
➔ Collisionless shocks are common in astrophysics

➔ Shocks are known to produce strongly non-thermal particle distributions

➔ Note that the concept, and even the existence, of a "collisionless" shock is not obvious

Until the Earth bow shock was detected by spacecraft there was debate as to whether or not a "shock" in the solar wind would exist.

Tycho's Supernova Remnant



http://chandra.harvard.edu/photo/2005/tycho/

Exploded in 1572 and studied by Tycho Brahe

This is a Chandra X-ray image

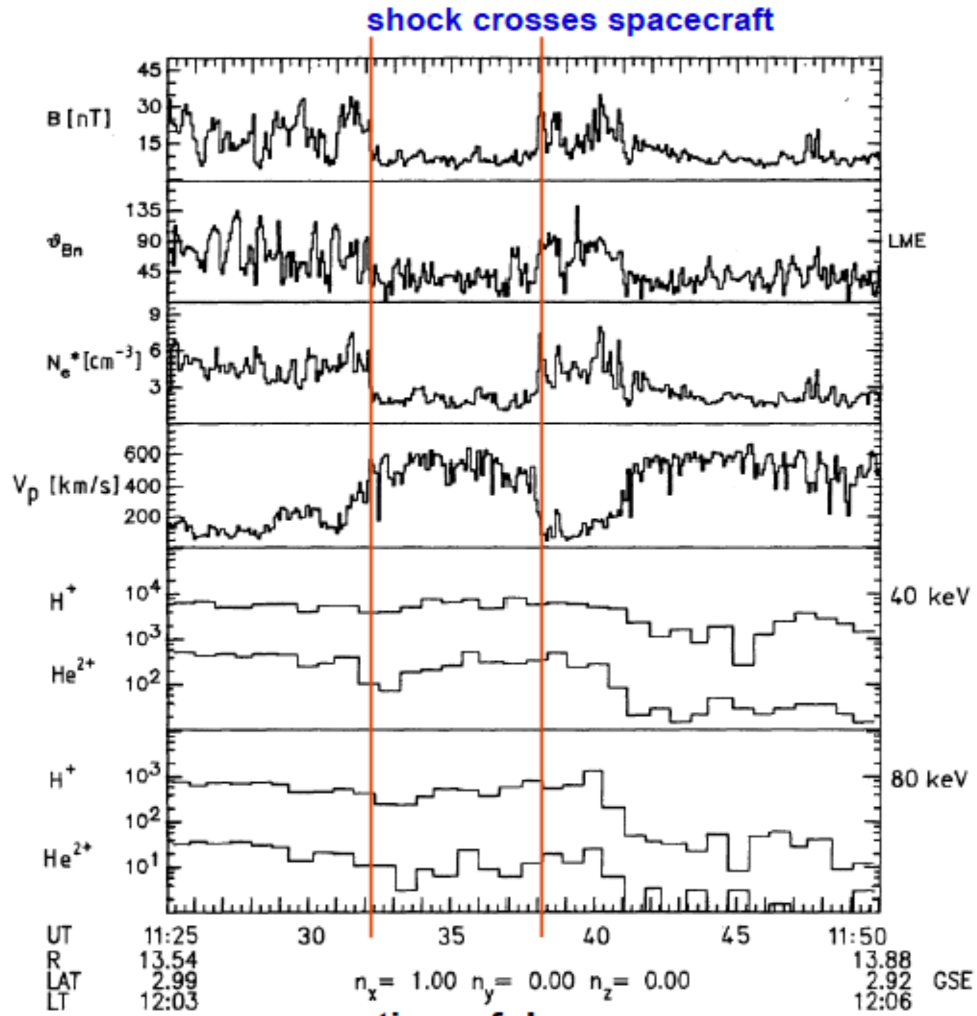
Shock heated gas inside 3000 km/s blast wave (filamentary blue)

Blue is nonthermal X-ray emission (synchrotron) from shock accelerated relativistic electrons.

No doubt that TeV electrons are produced by this shock !!

Evidence for TeV ions is less direct but very strong.

What does a heliospheric shock look like?

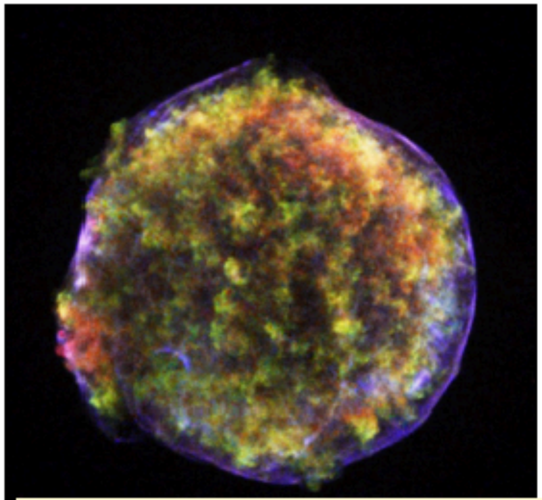


Earth bow shock observed by AMPTE spacecraft

(Ellison, Moebius & Paschmann 1990)

Spacecraft give a great deal of information at one point. Global information much harder to determine.

SNR shock (Tycho)



Great global info, but no detailed plasma information

Heliosphere

Many collisionless shocks, ALL accelerate particles !

Can study shock accel. In detail with in-situ spacecraft observations

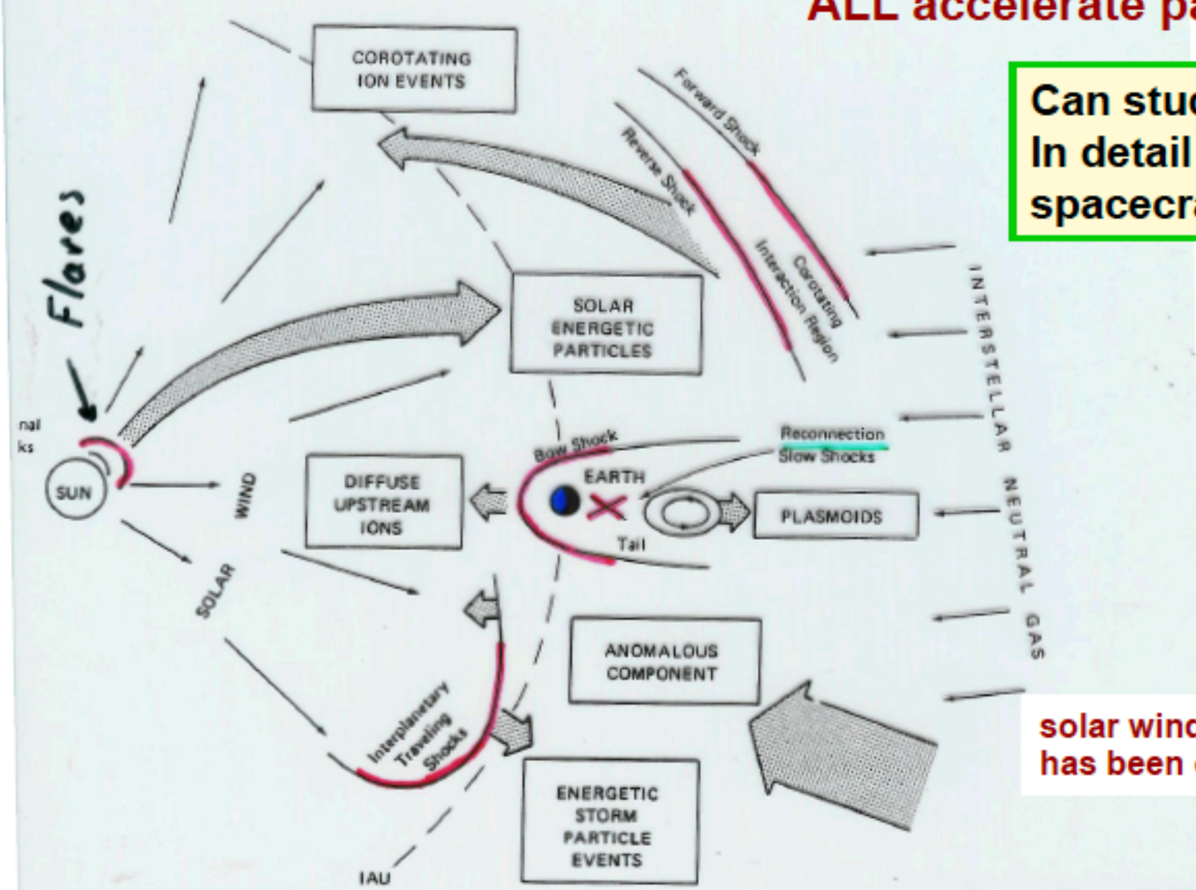


Fig. 2. Various particle acceleration sites within the heliosphere (adapted from [262]).

solar wind termination shock has been observed !

e.g. Scholer 84

Collisionless plasmas :

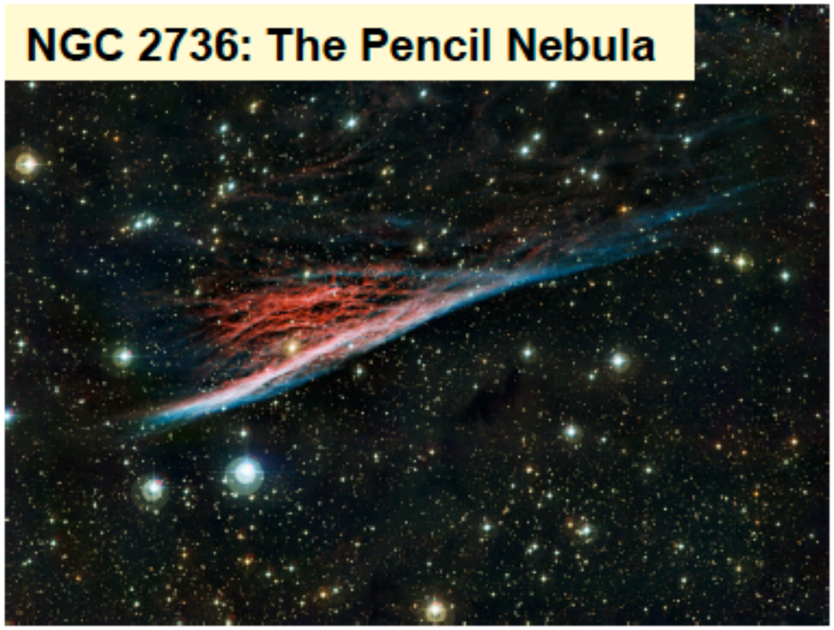
1) Density, ρ, is low enough so particle-particle collisions are rare
   ➔ e.g., in solar wind, particle-particle mean-free-path, L_ρ, is on the order of Sun-Earth distance

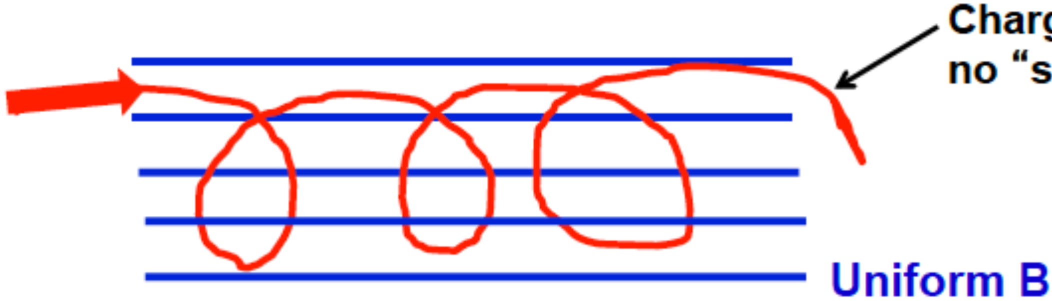
2) Turbulent magnetic field
   ➔ Charged particles pitch-angle scatter in turbulence and have effective mfp, $L_B << L_\rho$

We see "thin" structures in solar wind and interstellar medium :

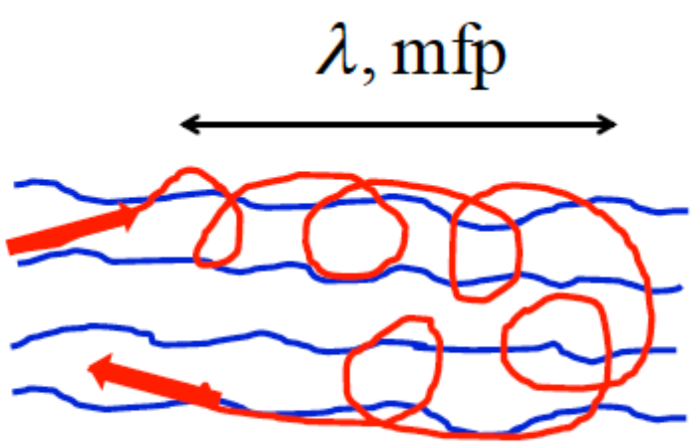
e.g., planetary bow shocks and SNR shocks

The length scale of these structures can be orders of magnitude smaller than the collisional mfp



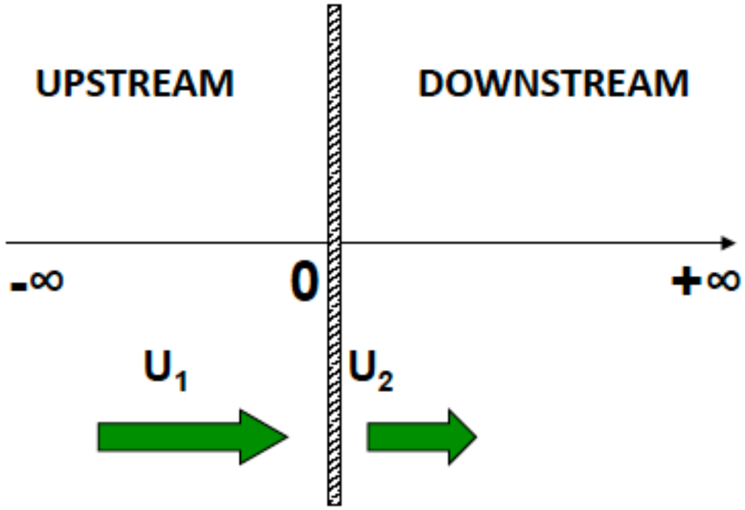


If B-field is weak enough, and particle flux large enough, particles will distort the field :



Particles pitch-angle scatter and turn around ➔ can define a collisionless mean free path.
This "collision" is nearly elastic in frame of B-field

Shock Solutions



Let us sit in the reference frame in which the shock is at rest and look for stationary solutions

$$\frac{\partial}{\partial x}(\rho u) = 0$$

$$\frac{\partial}{\partial x}(\rho u^2 + P) = 0$$

$$\frac{\partial}{\partial x}\left(\frac{1}{2}\rho u^3 + \frac{\gamma}{\gamma - 1}uP\right) = 0$$

It is easy to show that aside from the trivial solution in which all quantities remain spatially constant, there is a discontinuous solution:

$$\frac{\rho_2}{\rho_1} = \frac{u_1}{u_2} = \frac{(\gamma+1)M_1^2}{(\gamma-1)M_1^2+2}$$

M_1 is the upstream Fluid Mach number

$$\frac{p_2}{p_1} = \frac{2\gamma M_1^2}{\gamma+1} - \frac{\gamma-1}{\gamma+1}$$

$$\frac{T_2}{T_1} = \frac{[2\gamma M_1^2 - \gamma(\gamma-1)][(\gamma-1)M_1^2+2]}{(\gamma+1)^2 M_1^2}$$

Strong Shocks $M_1^2 >> 1$

In the limit of strong shock fronts these expressions get substantially simpler and one has:

$$\frac{\rho_2}{\rho_1} = \frac{u_1}{u_2} = \frac{\gamma + 1}{\gamma - 1}$$

$$\frac{p_2}{p_1} = \frac{2\gamma M_1^2}{\gamma + 1}$$

$$\frac{T_2}{T_1} = \frac{2\gamma(\gamma - 1)}{(\gamma + 1)^2} M_1^2, \quad T_2 = 2\frac{\gamma - 1}{(\gamma + 1)^2} m u_1^2$$

ONE CAN SEE THAT SHOCKS BEHAVE AS VERY EFFICENT HEATING MACHINES IN THAT A LARGE FRACTION OF THE INCOMING RAM PRESSURE IS CONVERTED TO INTERNAL ENERGY OF THE GAS BEHIND THE SHOCK FRONT…

THE ASTROPHYSICAL JOURNAL

AN INTERNATIONAL REVIEW OF SPECTROSCOPY AND ASTRONOMICAL PHYSICS

VOLUME 119 JANUARY 1954 NUMBER 1

Fermi's 1954 paper

GALACTIC MAGNETIC FIELDS AND THE ORIGIN OF COSMIC RADIATION*

E. FERMI
Institute for Nuclear Studies, University of Chicago
Received September 11, 1953

Fermi talks of regions of large field strength with sharp discontinuities "jaws of the trap"

A particle that finds itself between two such regions will be trapped on the stretch of line of force comprised between them. When this happens, the energy of the particle will change with time at a rate much faster than usual. It will decrease or increase according to whether the jaws of the trap move away from or toward each other.

Recently de Hoffmann and Teller[5] have discussed the features of magnetohydrodynamic shocks. They show, in particular, that at a shock front sudden variations in direction and intensity of the field are likely to occur. One is tempted to identify the boundaries of many clouds of the galactic diffuse matter with shock fronts. If this is correct, we have a source of magnetic discontinuities.

Fermi postulated that shocks could "trap" particles. This is first-order Fermi acceleration but Fermi did not derive the famous "Universal" power law

First-order Fermi acceleration mechanism
Also called Diffusive Shock Acceleration (DSA)

Some review papers:
Axford 1981, Drury 1983, Blandford & Eichler 1987, Jones & Ellison 1991, Berezhko & Ellison 1999, Malkov & Drury 2001, Bykov 2004

Fermi 1949 ➔ response to Hannes Alfven's solar model
Fermi 1954 ➔ connection to shocks

➔ **Discovery papers for first-order Fermi mechanism in shocks:**
Krymskii (1976), Axford, Leer & Skadron (1977), Bell (1978), Blandford & Ostriker (1978)

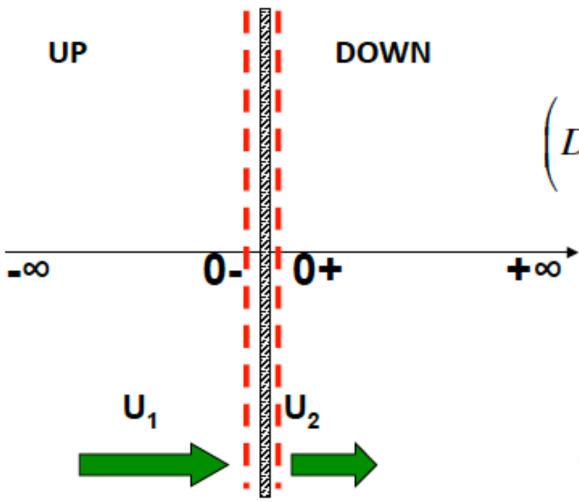
➔ $$f(p) \propto p^{-4}$$

So called "Universal" power law for relativistic particles (in momentum)

THE TRANSPORT EQUATION APPROACH

$$\frac{\partial f}{\partial t} = \frac{\partial}{\partial x}\left[D\frac{\partial f}{\partial x}\right] - u\frac{\partial f}{\partial x} + \frac{1}{3}\frac{du}{dx}p\frac{\partial f}{\partial p} + Q(x,p,t)$$

DIFFUSION ADVECTION COMPRESSION INJECTION



Integrating around the shock:

$$\left(D\frac{\partial f}{\partial x}\right)_2 - \left(D\frac{\partial f}{\partial x}\right)_1 + \frac{1}{3}(u_2 - u_1)p\frac{df_0(p)}{dp} + Q_0(p) = 0$$

Integrating from upstr. infinity to 0-:

$$\left(D\frac{\partial f}{\partial x}\right)_1 = u_1 f_0$$

and requiring homogeneity downstream:

$$p\frac{df_0}{dp} = \frac{3}{u_2 - u_1}(u_1 f_0 - Q_0)$$

Parker 1965: convection-diffusion (aka “confusion-defection”) equation

THE TRANSPORT EQUATION APPROACH

INTEGRATION OF THIS SIMPLE EQUATION GIVES:

$$f_0(p) = \frac{3u_1}{u_1 - u_2} \frac{N_{inj}}{4\pi p_{inj}^2} \left(\frac{p}{p_{inj}} \right)^{\frac{-3u_1}{u_1 - u_2}}$$

DEFINE THE COMPRESSION FACTOR
$r = u_1/u_2 \rightarrow 4$ (strong shock)

THE SLOPE OF THE SPECTRUM IS

$$\frac{3u_1}{u_1 - u_2} = \frac{3}{1 - 1/r} \rightarrow 4 \quad \text{if r} \rightarrow 4$$

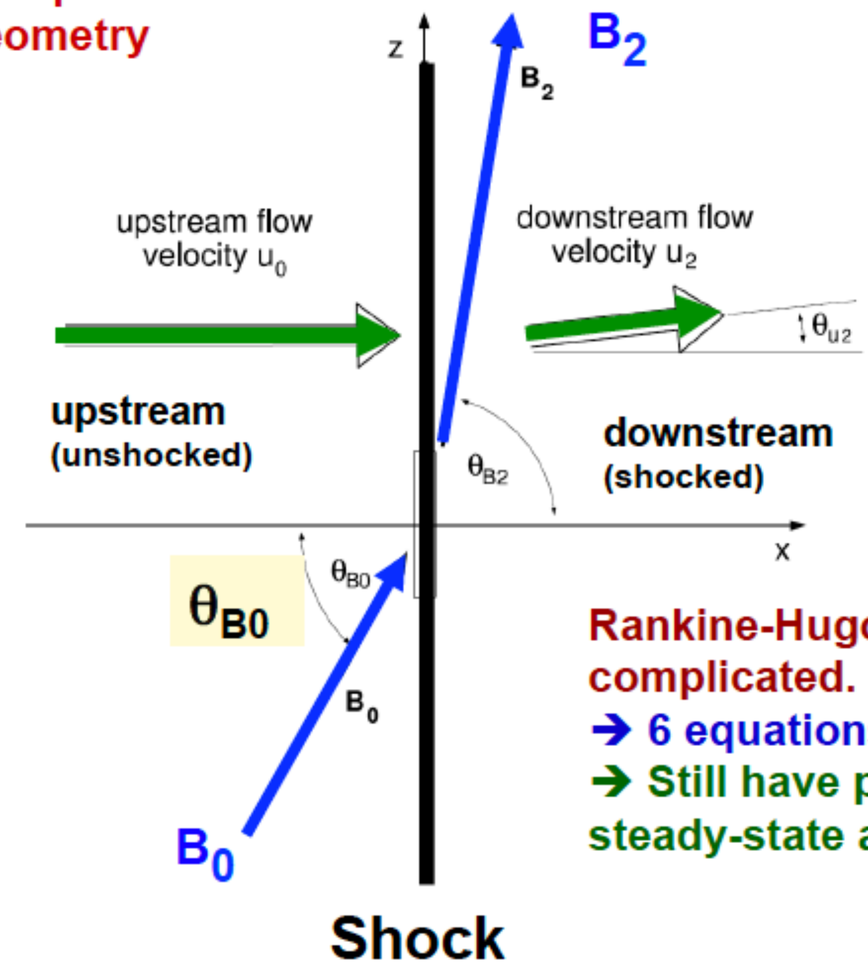
NOTICE THAT: $N(p)dp = 4\pi p^2 f(p)dp \rightarrow N(p) \propto p^{-2}$

1. **THE SPECTRUM OF ACCELERATED PARTICLES IS A POWER LAW EXTENDING TO INFINITE MOMENTA**

2. **THE SLOPE DEPENDS UNIQUELY ON THE COMPRESSION FACTOR AND IS INDEPENDENT OF THE DIFFUSION PROPERTIES**

3. **INJECTION IS TREATED AS A FREE PARAMETER WHICH DETERMINES THE NORMALIZATION**

Oblique Shock geometry



Parallel Shocks: $\theta_{B0} = 0^o$

Perpendicular: $\theta_{B0} = 90^o$

Rankine-Hugoniot relations more complicated. B-field does not drop out

➔ 6 equations instead of 3

➔ Still have plane shock and steady-state approximations

Quasilinear Theory

(Yakimenko 1963; Kennel & Engelmann 1966; Stix 1992)

$$\frac{\partial f}{\partial t} + \boldsymbol{v} \cdot \nabla f + \frac{q}{m}\left(\boldsymbol{E} + \frac{1}{c}\boldsymbol{v} \times \boldsymbol{B}\right) \cdot \nabla_v f = 0 \tag{1}$$

$$f = f_0(\boldsymbol{x}, \boldsymbol{v}, t) + f_1(\boldsymbol{x}, \boldsymbol{v}, t) \qquad \boldsymbol{B} = \boldsymbol{B}_0 + \boldsymbol{B}_1(\boldsymbol{x}, t) \qquad \boldsymbol{E} = \boldsymbol{E}_1(\boldsymbol{x}, t)$$

B_0 is a uniform background magnetic field.

f_0 is the background or equilibrium plasma distribution function

E_1 and B_1 represent a collection of waves, which could be slowly growing or slowly decaying. We're going to treat E_1 and B_1 as known.

f_1 represents the response of the plasma to these waves

Our goal is to find how f_0 varies over times much longer than the wave periods.

Quasilinear Theory

(Yakimenko 1963; Kennel & Engelmann 1966; Stix 1992)

$$\frac{\partial f}{\partial t} + \boldsymbol{v} \cdot \nabla f + \frac{q}{m}\left(\boldsymbol{E} + \frac{1}{c}\boldsymbol{v} \times \boldsymbol{B}\right) \cdot \nabla_v f = 0 \tag{1}$$

$$f = f_0(\boldsymbol{x}, \boldsymbol{v}, t) + f_1(\boldsymbol{x}, \boldsymbol{v}, t) \qquad \boldsymbol{B} = \boldsymbol{B}_0 + \boldsymbol{B}_1(\boldsymbol{x}, t) \qquad \boldsymbol{E} = \boldsymbol{E}_1(\boldsymbol{x}, t)$$

$$\frac{\partial f_0}{\partial t} + \boldsymbol{v} \cdot \nabla f_0 + \frac{q}{mc}(\boldsymbol{v} \times \boldsymbol{B}_0) \cdot \nabla_v f_0 = 0 \rightarrow f_0(\boldsymbol{x}, \boldsymbol{v}, t) = f_0(v_\perp, v_\parallel)$$

Here, we are using cylindrical coordinates $(v_\perp, v_\parallel, \theta)$ in velocity space, where the cylindrical axis is aligned with $\boldsymbol{B}_0$. Soon, we will set $\boldsymbol{B}_0 \rightarrow B_0\hat{\boldsymbol{z}}$, and $v_\parallel$ will become v_z.

(technically, f_0 varies in time over time scales much longer than the wave periods. But here the variable *t* describes time variations over times comparable to the wave periods, and f_0 doesn't vary on this "fast" time scale.

Quasilinear Theory

(Yakimenko 1963; Kennel & Engelmann 1966; Stix 1992)

$$\frac{\partial f}{\partial t} + \boldsymbol{v} \cdot \nabla f + \frac{q}{m}\left(\boldsymbol{E} + \frac{1}{c}\boldsymbol{v} \times \boldsymbol{B}\right) \cdot \nabla_v f = 0 \tag{1}$$

$$f = f_0(\boldsymbol{x}, \boldsymbol{v}, t) + f_1(\boldsymbol{x}, \boldsymbol{v}, t) \qquad \boldsymbol{B} = \boldsymbol{B}_0 + \boldsymbol{B}_1(\boldsymbol{x}, t) \qquad \boldsymbol{E} = \boldsymbol{E}_1(\boldsymbol{x}, t)$$

$$\frac{\partial f_0}{\partial t} + \boldsymbol{v} \cdot \nabla f_0 + \frac{q}{mc}(\boldsymbol{v} \times \boldsymbol{B}_0) \cdot \nabla_v f_0 = 0 \rightarrow f_0(\boldsymbol{x}, \boldsymbol{v}, t) = f_0(v_\perp, v_\parallel)$$

$$\frac{\partial f_1}{\partial t} + \boldsymbol{v} \cdot \nabla f_1 + \frac{q}{mc}(\boldsymbol{v} \times \boldsymbol{B}_0) \cdot \nabla_v f_1 = -\frac{q}{m}\left(\boldsymbol{E}_1 + \frac{1}{c}\boldsymbol{v} \times \boldsymbol{B}_1\right) \cdot \nabla_v f_0$$

Difficult-looking equation. How do we solve this equation for $f_1(\boldsymbol{x},\boldsymbol{v},t)$ if we know $\boldsymbol{E}_1$, $\boldsymbol{B}_1$, $\boldsymbol{B}_0$, and f_0?

Method of characteristics!

Quasilinear Theory

(Yakimenko 1963; Kennel & Engelmann 1966; Stix 1992)

$$\frac{\partial f}{\partial t} + \boldsymbol{v} \cdot \nabla f + \frac{q}{m}\left(\boldsymbol{E} + \frac{1}{c}\boldsymbol{v} \times \boldsymbol{B}\right) \cdot \nabla_v f = 0 \qquad (1)$$

$$f = f_0(\boldsymbol{x}, \boldsymbol{v}, t) + f_1(\boldsymbol{x}, \boldsymbol{v}, t) \qquad \boldsymbol{B} = \boldsymbol{B}_0 + \boldsymbol{B}_1(\boldsymbol{x}, t) \qquad \boldsymbol{E} = \boldsymbol{E}_1(\boldsymbol{x}, t)$$

$$\frac{\partial f_0}{\partial t} + \boldsymbol{v} \cdot \nabla f_0 + \frac{q}{mc}(\boldsymbol{v} \times \boldsymbol{B}_0) \cdot \nabla_v f_0 = 0 \rightarrow f_0(\boldsymbol{x}, \boldsymbol{v}, t) = f_0(v_\perp, v_\parallel)$$

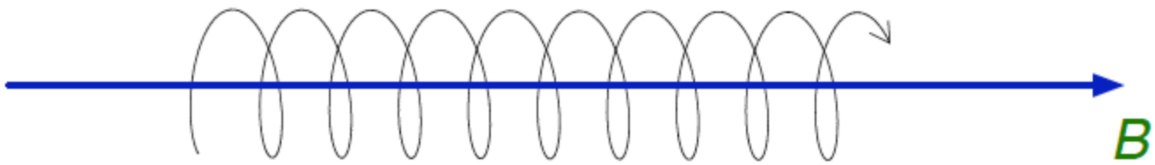
$$\frac{\partial f_1}{\partial t} + \boldsymbol{v} \cdot \nabla f_1 + \frac{q}{mc}(\boldsymbol{v} \times \boldsymbol{B}_0) \cdot \nabla_v f_1 = -\frac{q}{m}\left(\boldsymbol{E}_1 + \frac{1}{c}\boldsymbol{v} \times \boldsymbol{B}_1\right) \cdot \nabla_v f_0$$

Let $f_1(\boldsymbol{x}, \boldsymbol{v}, t) = f_1(\boldsymbol{x}(t), \boldsymbol{v}(t), t)$, where $d\boldsymbol{x}/dt = \boldsymbol{v}$, $d\boldsymbol{v}/dt = (q/mc)(\boldsymbol{v} \times \boldsymbol{B}_0)$:

$$\frac{\mathrm{d}f_1}{\mathrm{d}t} = -\frac{q}{m}\left(\boldsymbol{E}_1(\boldsymbol{x}(t), t) + \frac{1}{c}\boldsymbol{v}(t) \times \boldsymbol{B}_1(\boldsymbol{x}(t), t)\right) \cdot \nabla_v f_0 \qquad (2)$$

Solve for $\boldsymbol{x}(t)$ and $\boldsymbol{v}(t)$; integrate (2) to find f_1; plug f_1 into 3$^{\text{rd}}$ term in (1); and average.

Single Particle Motion in a Uniform Magnetic FIeld



$$\frac{\mathrm{d}\boldsymbol{x}}{\mathrm{d}t} = \boldsymbol{v}$$

$$\frac{\mathrm{d}\boldsymbol{v}}{\mathrm{d}t} = \frac{q}{mc}(\boldsymbol{v} \times \boldsymbol{B}_0)$$

$$\boldsymbol{B}_0 = B_0\hat{\boldsymbol{z}} \longrightarrow v_z = \text{ constant} \qquad v_\perp = \sqrt{v_x^2 + v_y^2} = \text{ constant}$$

Helical motion. Cyclotron frequency $\Omega = \dfrac{qB_0}{mc}$, gyroradius $= \rho = v_\perp/\Omega$.

Quasilinear Theory

(Yakimenko 1963; Kennel & Engelmann 1966; Stix 1992)

$$\frac{\partial f}{\partial t} + \boldsymbol{v}\cdot\nabla f + \frac{q}{m}\left(\boldsymbol{E} + \frac{1}{c}\boldsymbol{v}\times\boldsymbol{B}\right)\cdot\nabla_v f = 0, \qquad (1)$$

$$f = f_0(\boldsymbol{v}) + f_1(\boldsymbol{x},\boldsymbol{v},t) \qquad \boldsymbol{B} = \boldsymbol{B}_0 + \boldsymbol{B}_1 \qquad \boldsymbol{E} = \boldsymbol{E}_1$$

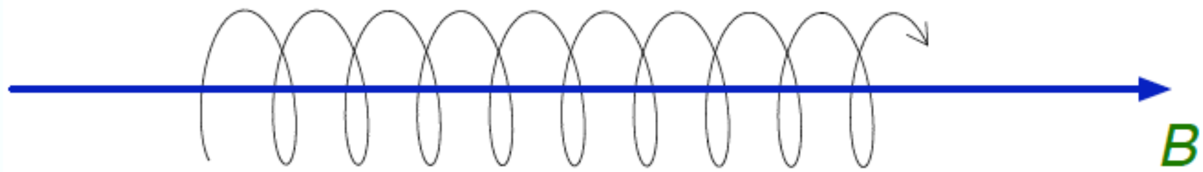
Solve for f_1 in terms of f_0, $\boldsymbol{E}_1$, $\boldsymbol{B}_1$; plug f_1 into 3rd term in (1); average:

$$\frac{\partial f}{\partial t} = \lim_{V\to\infty}\sum_{n=-\infty}^{\infty}\frac{\pi q^2}{m^2}\int\frac{d^3k}{(2\pi)^3 V v_\perp} G\, v_\perp \boxed{\delta(\omega_{kr} - k_\parallel v_\parallel - n\Omega)}\, |\psi_{n,k}|^2 G\, f,$$

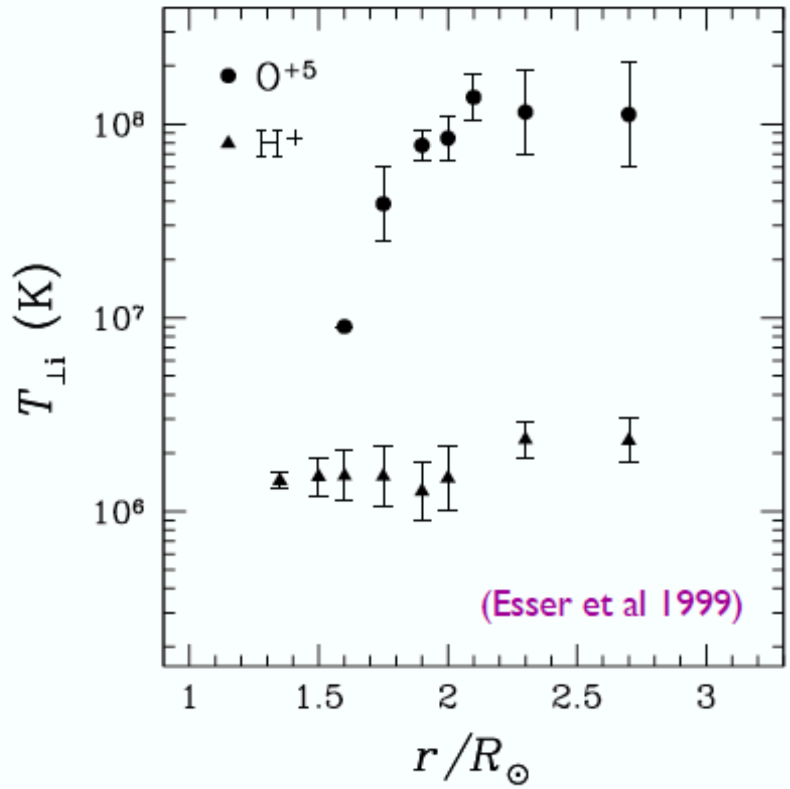
$$G \equiv \left(1 - \frac{k_\parallel v_\parallel}{\omega_{kr}}\right)\frac{\partial}{\partial v_\perp} + \frac{k_\parallel v_\perp}{\omega_{kr}}\frac{\partial}{\partial v_\parallel}$$

$$\psi_{n,k} = \frac{1}{\sqrt{2}}\left[E_{k,r}e^{i\phi}J_{n+1}(\sigma) + E_{k,l}e^{-i\phi}J_{n-1}(\sigma)\right] + \frac{v_\parallel}{v_\perp}E_{kz}J_n(\sigma) \qquad \sigma = k_\perp v_\perp/\Omega$$

Wave-Particle Resonance Condition



- Consider $\delta\vec{E} = \delta\vec{E}_0 \cos(\vec{k}\cdot\vec{x} - \omega t)$
- Let $\vec{x} = \vec{x}' + v_{\parallel}\hat{b}t$, where $\hat{b} = \vec{B}_0/B_0$
- Primed frame moves with particle guiding center
- Consider $\delta\vec{E} = \delta\vec{E}_0 \cos[\vec{k}\cdot\vec{x}' - (\omega - k_{\parallel}v_{\parallel})t]$, where $k_{\parallel} = \vec{k}\cdot\hat{b}$
- $\omega - k_{\parallel}v_{\parallel}$ = Doppler-shifted frequency in guiding center frame
- Wave-particle resonance when $\omega - k_{\parallel}v_{\parallel} = n\Omega$



- These are *perpendicular* temperatures inferred from line widths observed at the Sun's limb.
- Protons in the corona and low-β fast-solar-wind streams satisfy $T_\perp > T_{||}$

What is Magnetic Reconnection?

If a plasma is perfectly conducting, that is, it obeys the ideal Ohm's law,

$$E + v \times B = 0$$

B-lines are frozen in the plasma, and no reconnection occurs.

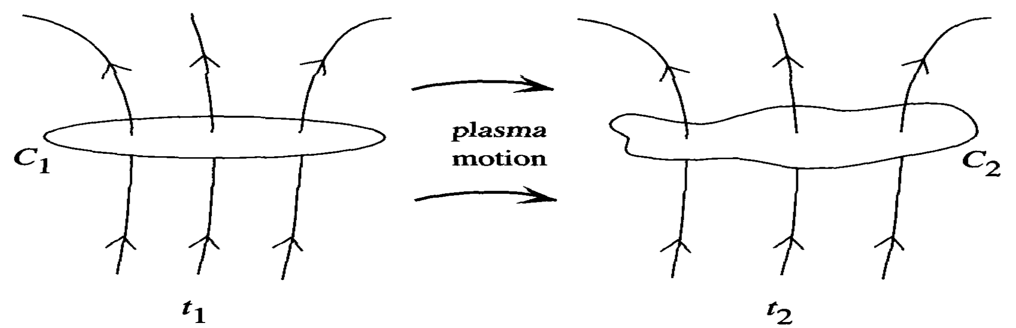


Fig. 1.6. Magnetic flux conservation: if a curve C_1 is distorted into C_2 by plasma motion, the flux through C_1 at t_1 equals the flux through C_2 at t_2.

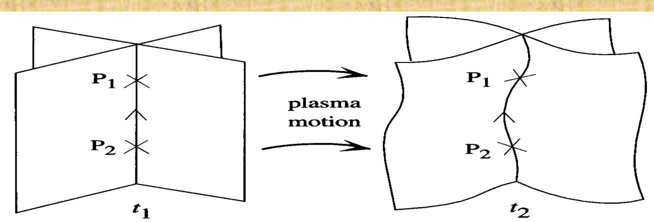


Fig. 1.7. Magnetic field-line conservation: if plasma elements P_1 and P_2 lie on a field line at time t_1, then they will lie on the same line at a later time t_2.

Magnetic Reconnection: Mathematical Definition

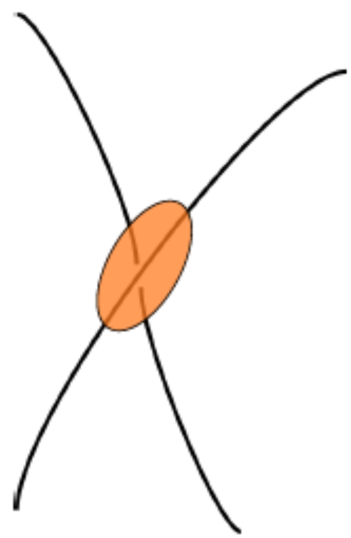
Departures from ideal behavior, represented by

$$\mathrm{E} + \mathrm{v} \times \mathrm{B} = \mathrm{R}, \quad \mathrm{B} \cdot \nabla \times \mathrm{R} = 0$$

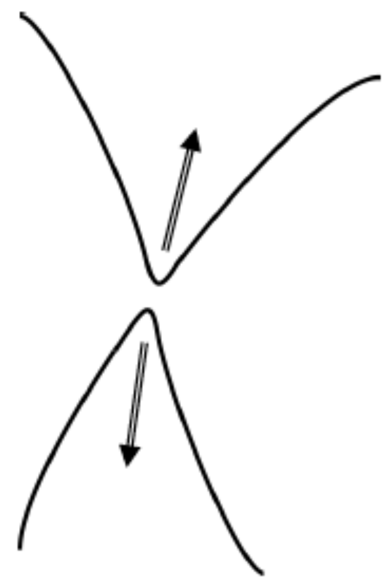
break ideal topological invariants, allowing field lines to break and reconnect.

In the generalized Ohm's law for weakly collisional or collisionless plasmas, **R** contains resistivity, Hall current, electron inertia and pressure.

Magnetic Reconnection



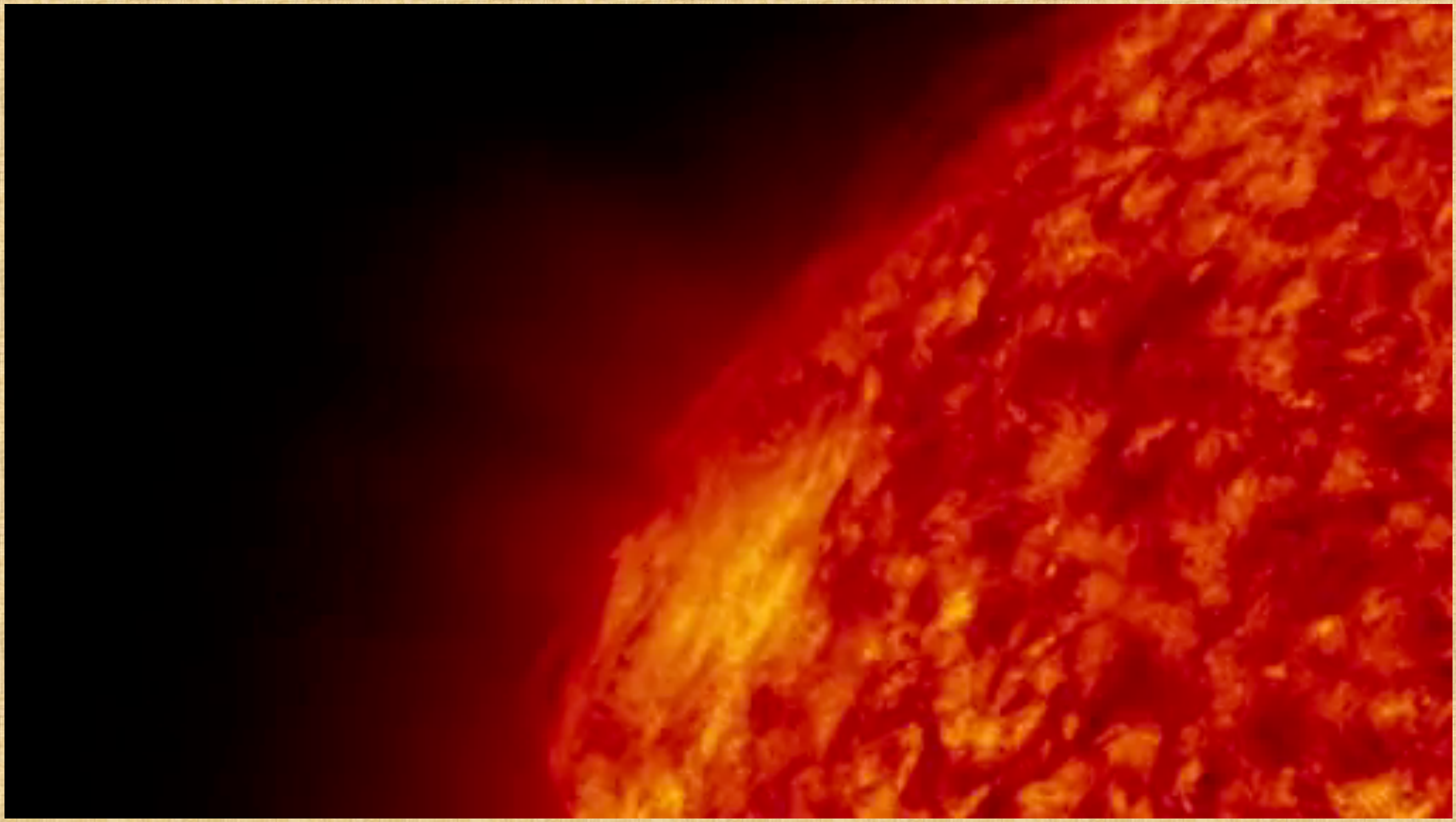
Before reconnection



After reconnection

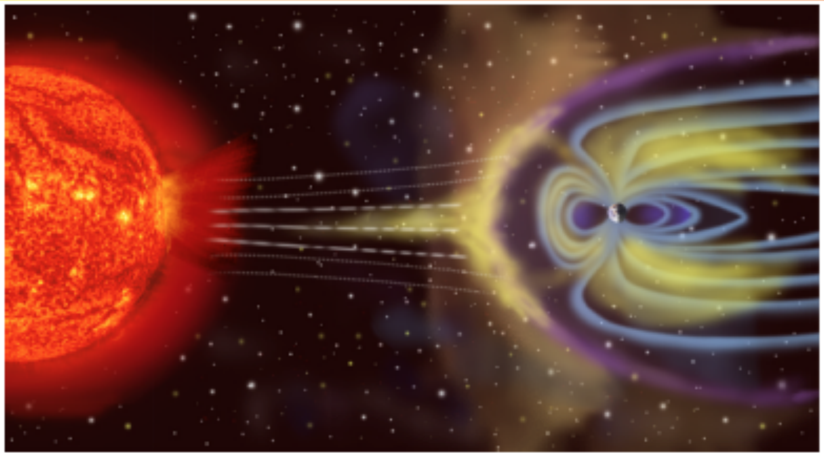
- Topological rearrangement of magnetic field lines
- Magnetic energy => Kinetic energy

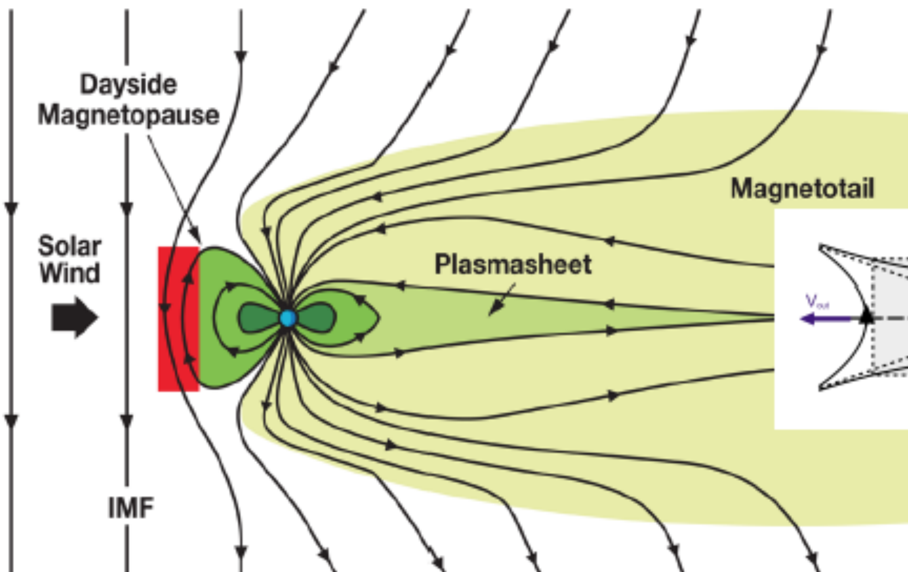
The Flaring Sun

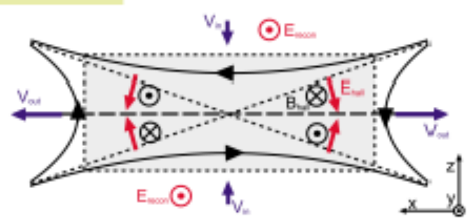


Courtesy: The Solar Dynamics Observatory

Magnetic reconnection layers in the magnetosphere





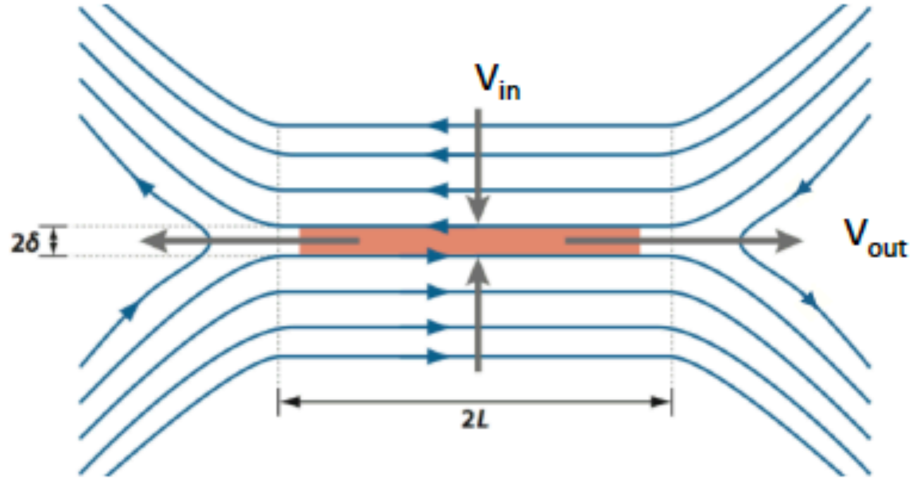


Data is available to evaluate inventory of energy flows

The Sweet-Parker Model for Magnetic Reconnection

Assume;

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



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

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

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

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

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

S = Lundquist number

In solar flares, $\tau_{SP} \sim$ 1 year $\gg \tau_{reconn}$

Impulsive Reconnection: The Onset/Trigger Problem

Dynamics exhibits an impulsiveness, that is, a sudden change in the time-derivative of the reconnection rate.

The magnetic configuration evolves slowly for a long period of time, only to undergo a sudden dynamical change over a much shorter period of time.

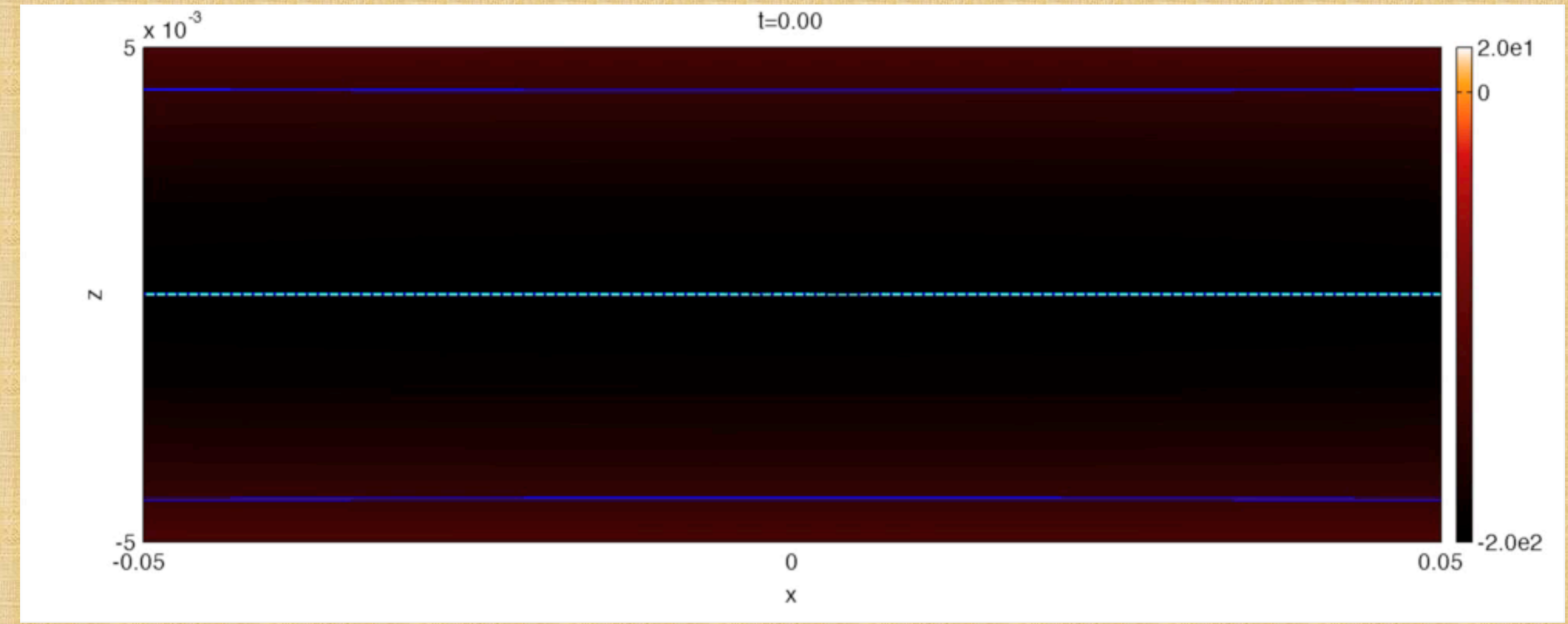
Dynamics is characterized by the formation of near-singular current sheets which need to be resolved in computer simulations: a classic multi-scale problem coupling large scales to small.

Examples

Magnetospheric substorms

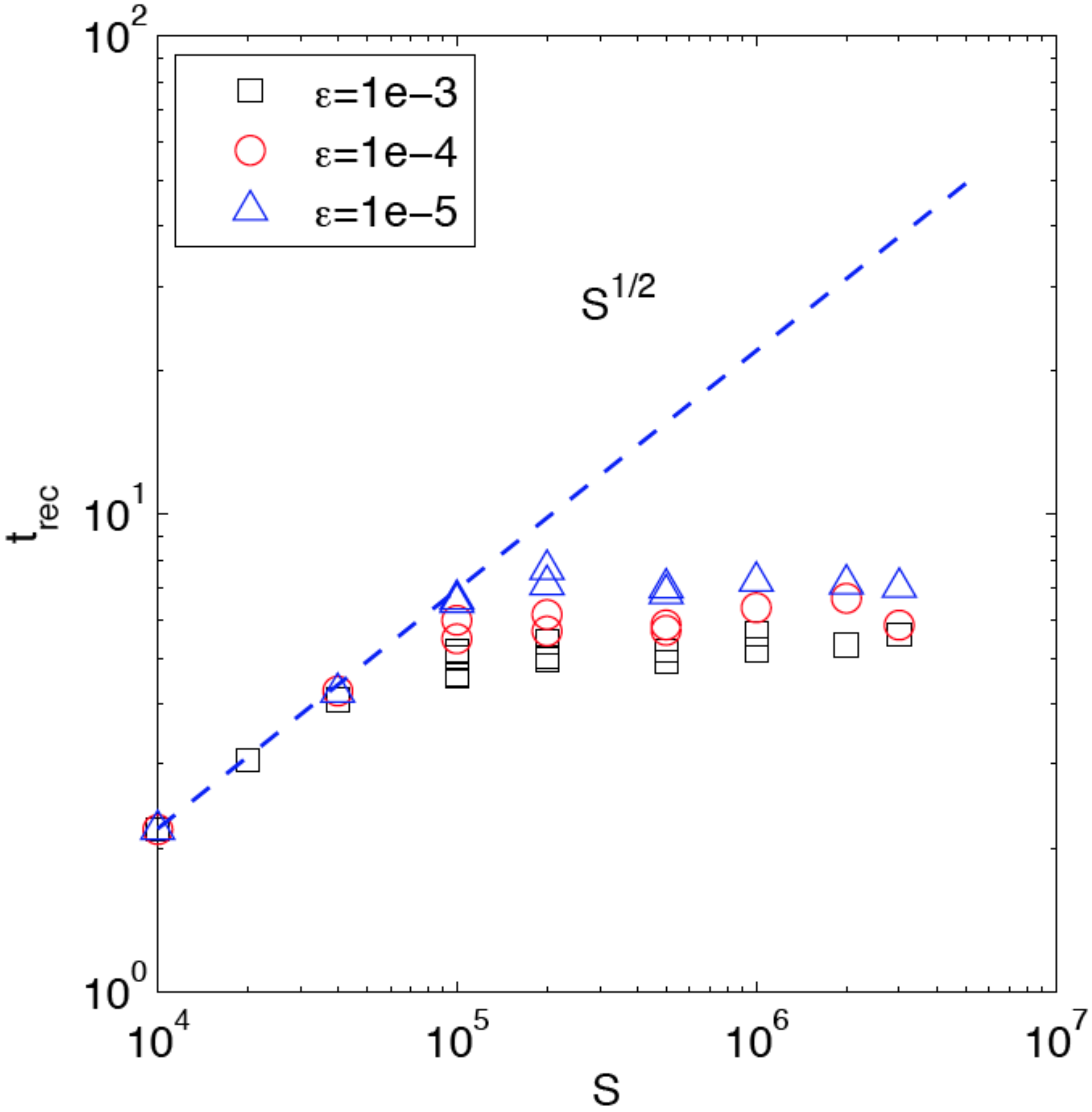
Impulsive solar/stellar flares

The thin current sheet is explosively stable if we exceed a critical Lundquist number, S_c forming, ejecting, and coalescing a hierarchy of plasmoids.



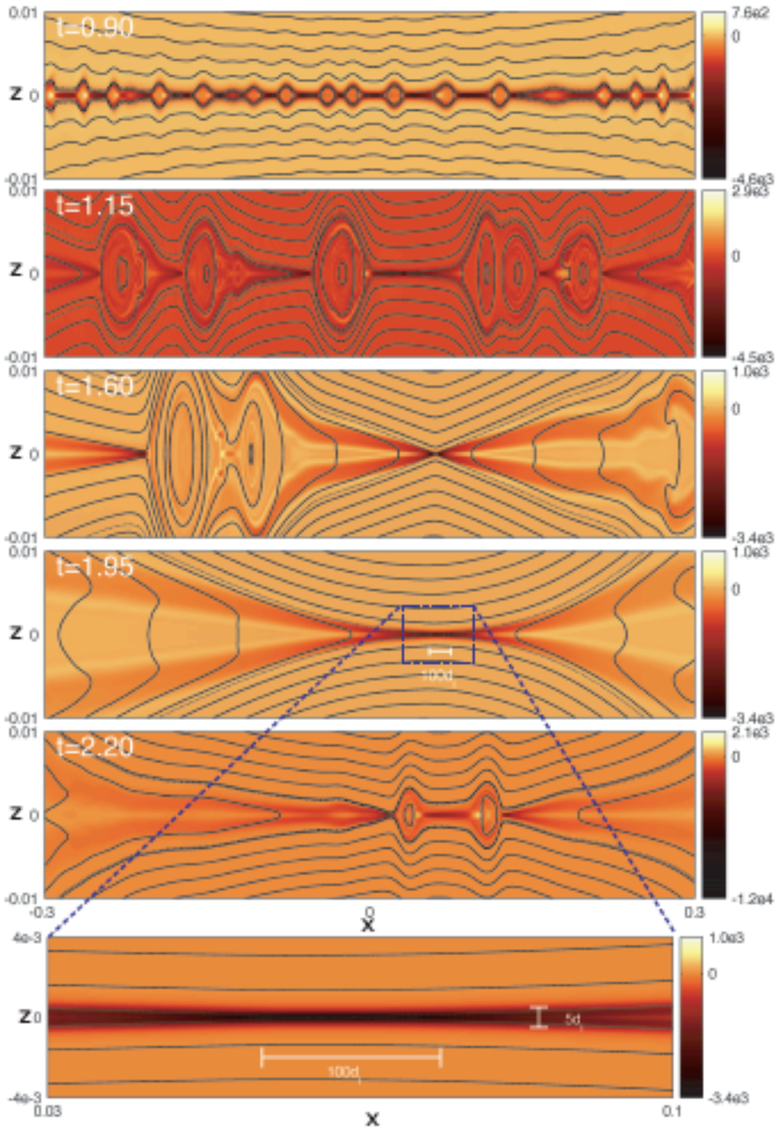
B. et al. 2009, Huang and B. 2010, Uzdensky et al. 2010

Reconnection Time of 25% of Initial Flux

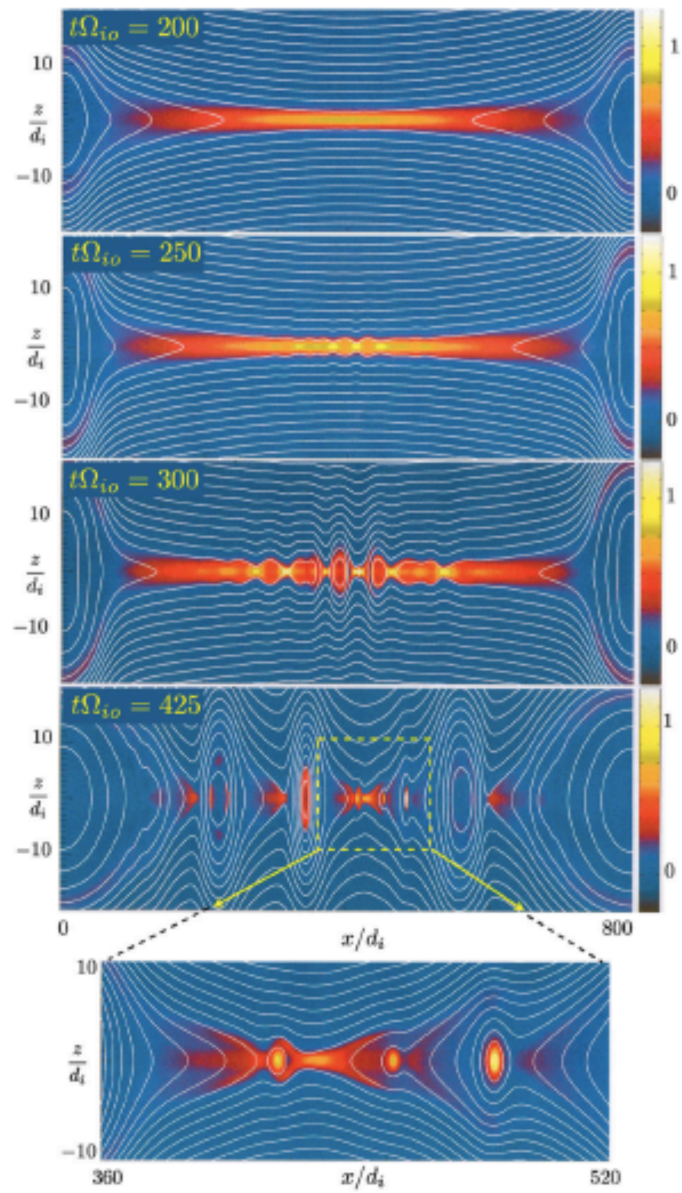


$$< \frac{1}{V_A B}\frac{d\psi}{dt} >\sim 0.01$$

$$< u_i >\sim 0.01 V_A$$



Run B, resistive Hall

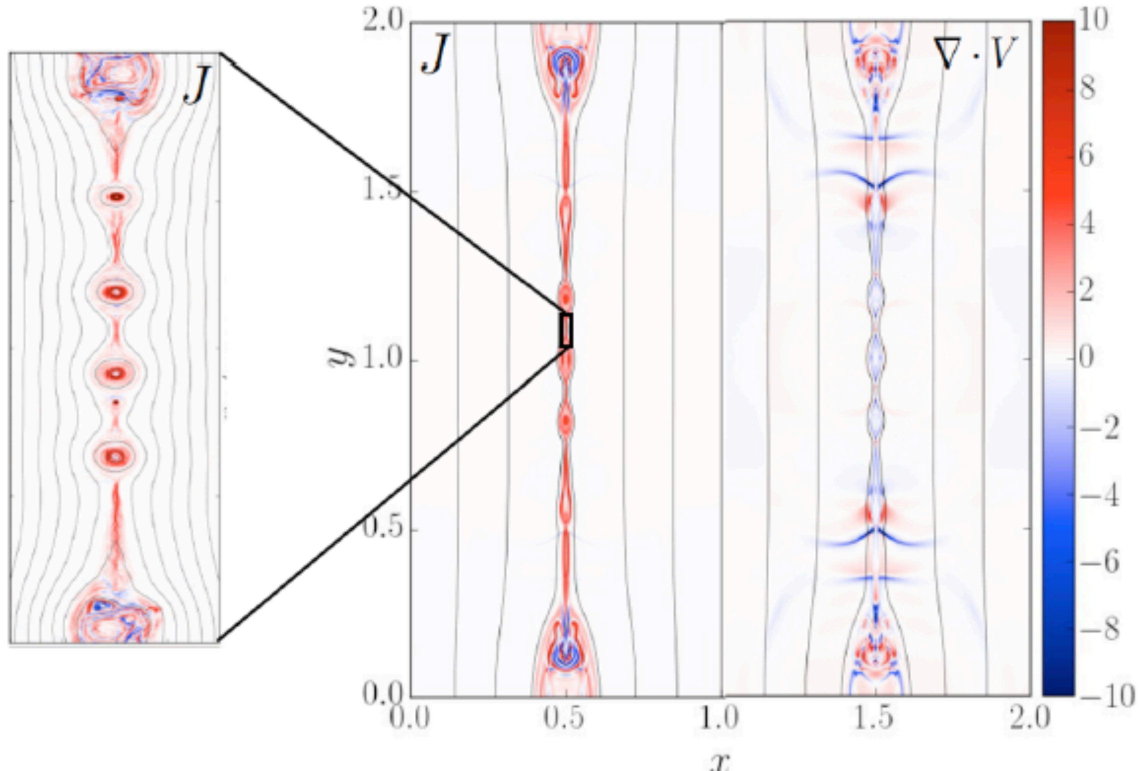


Daughton et al. (2009), PIC

Multi-scale problem, but with an underlying unity

L~1 km

Kinetic

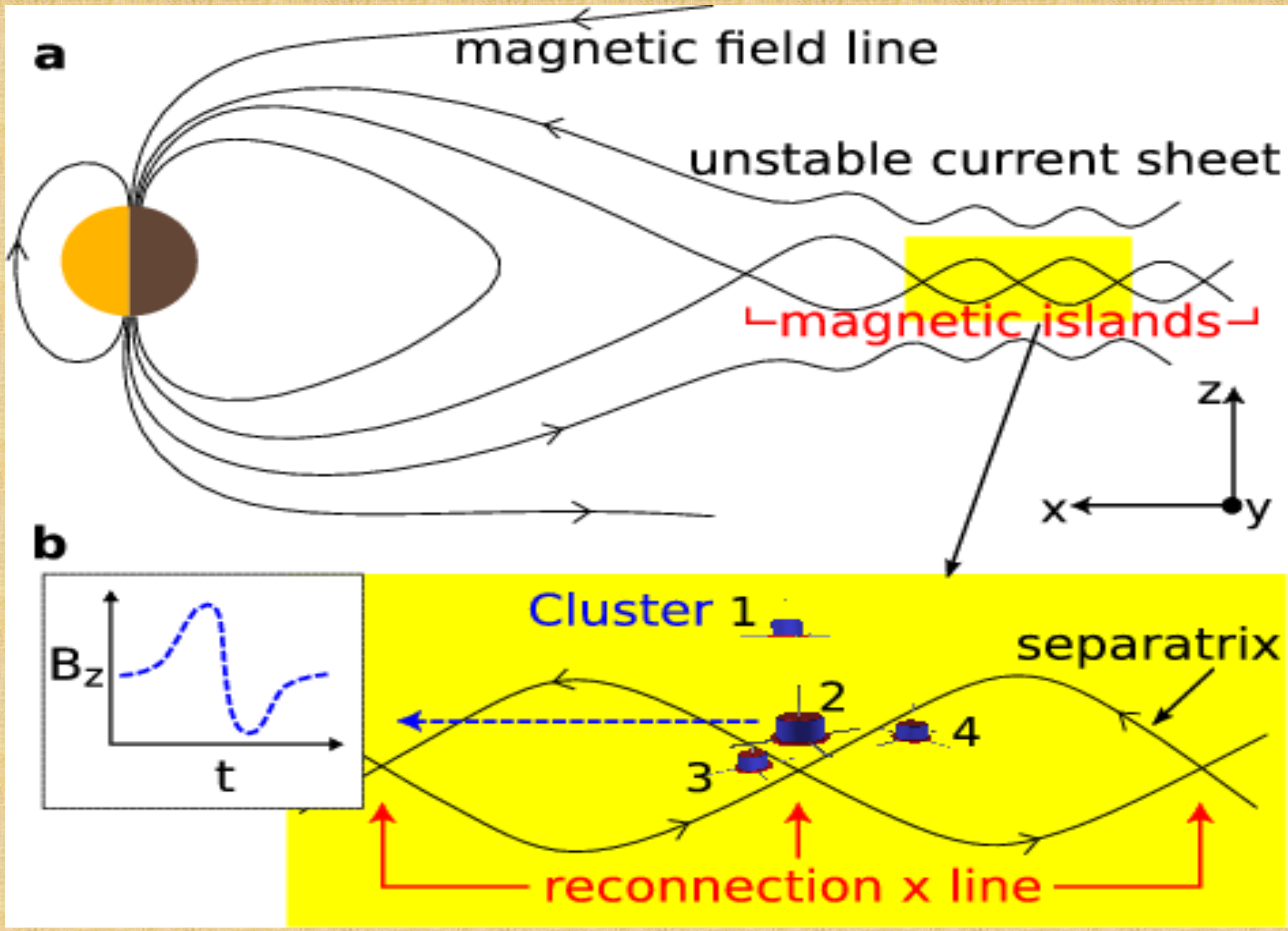


L~10^5 km

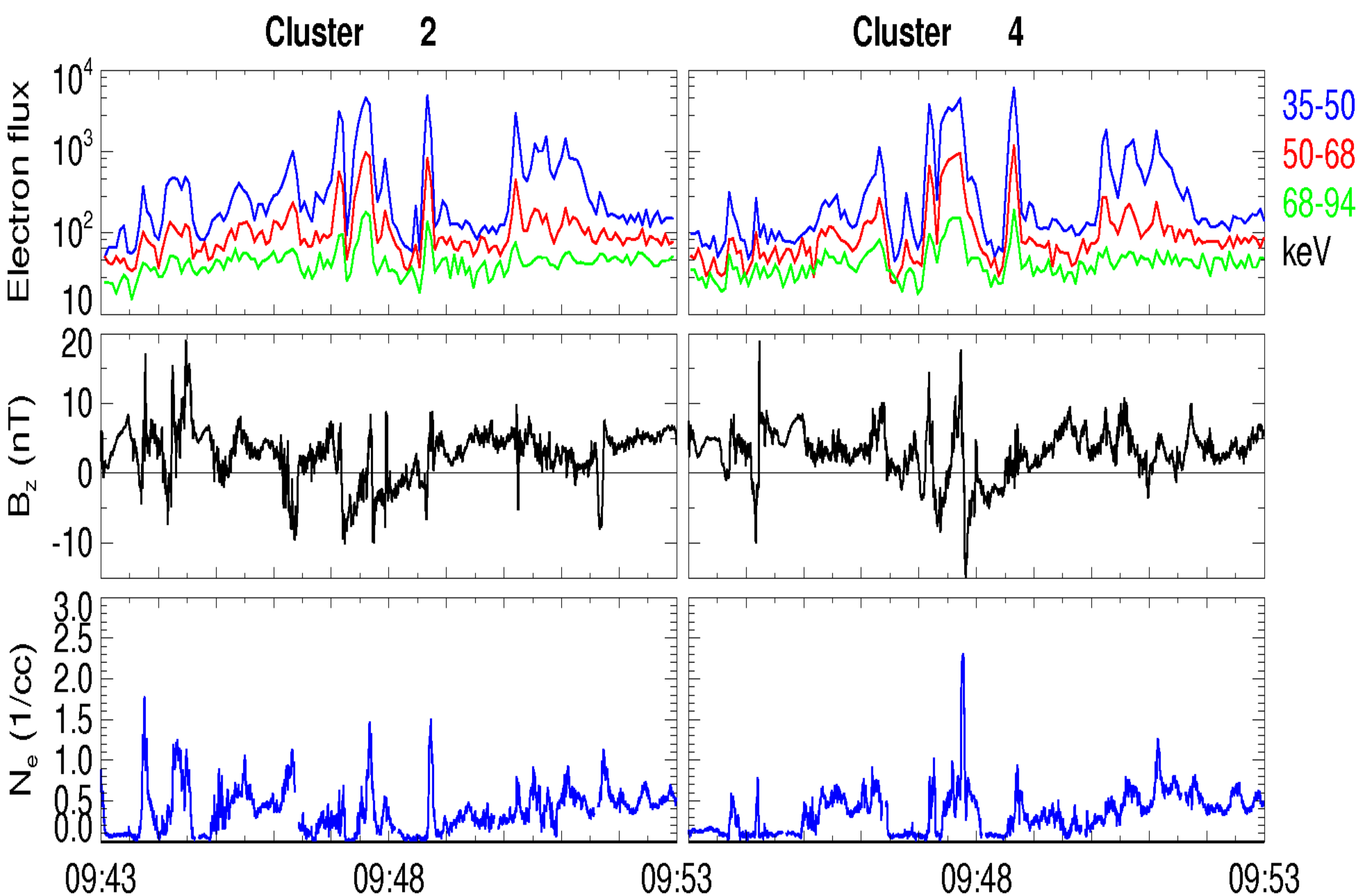
MHD

Observations of energetic electrons within magnetic islands

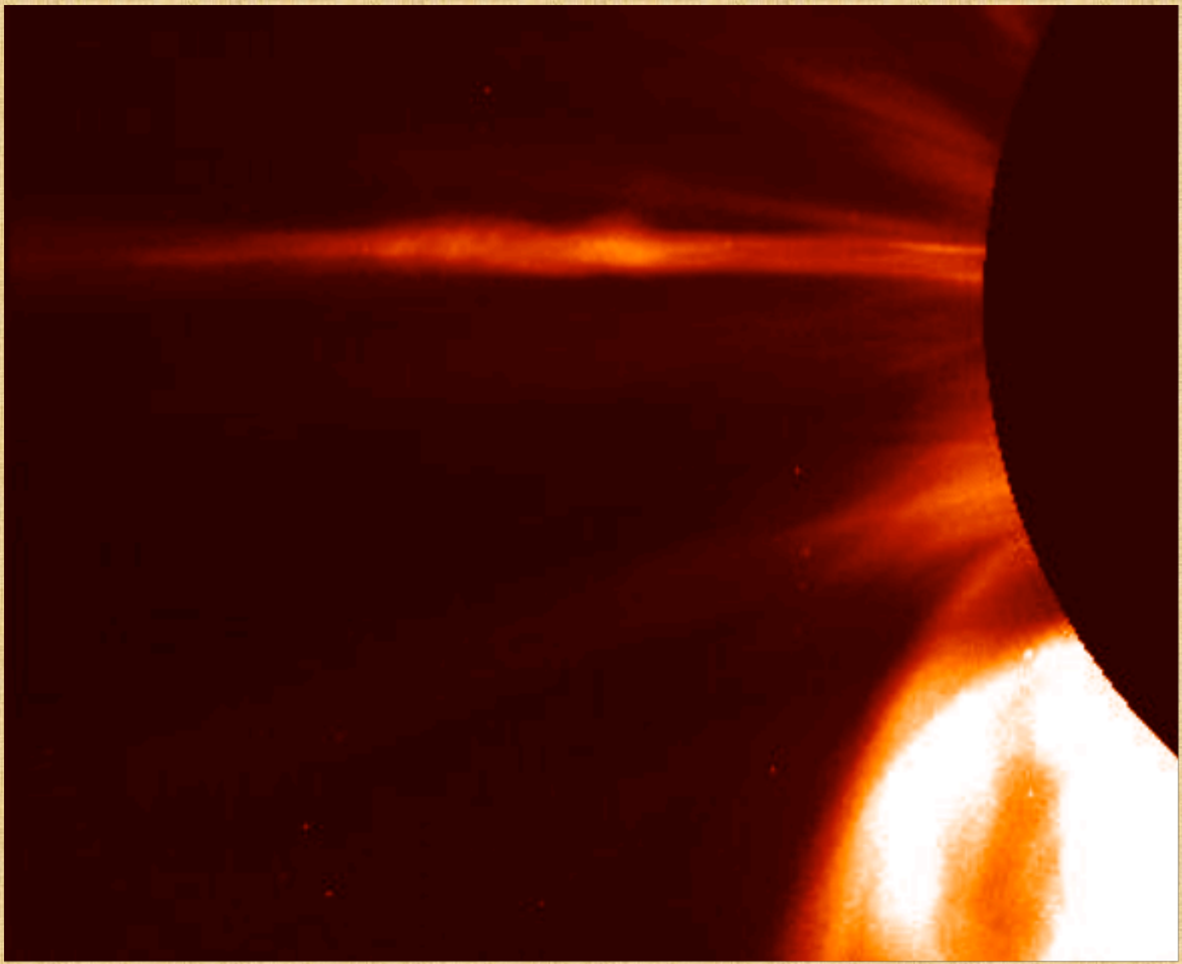
[Chen et al., Nature Phys., 2008, PoP 2009]



e bursts & bipolar Bz & Ne peaks
~10 islands within 10 minutes

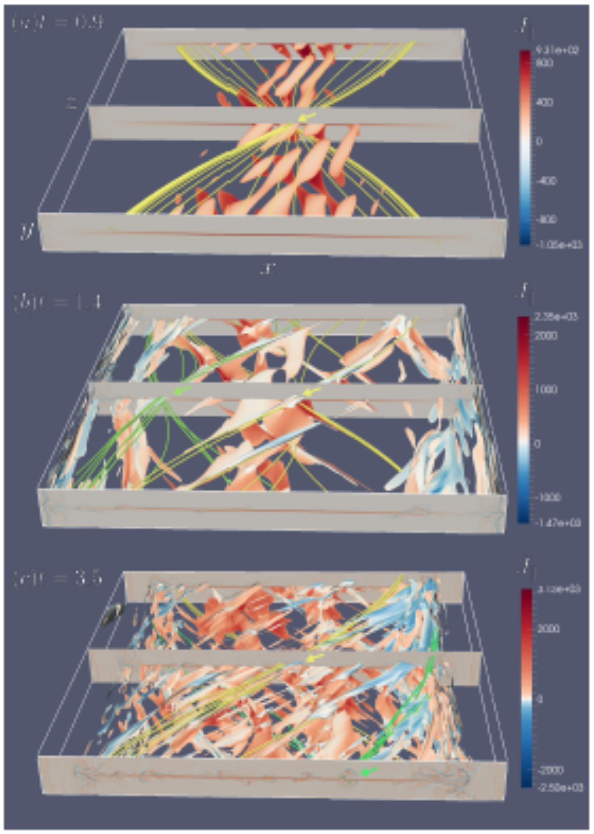


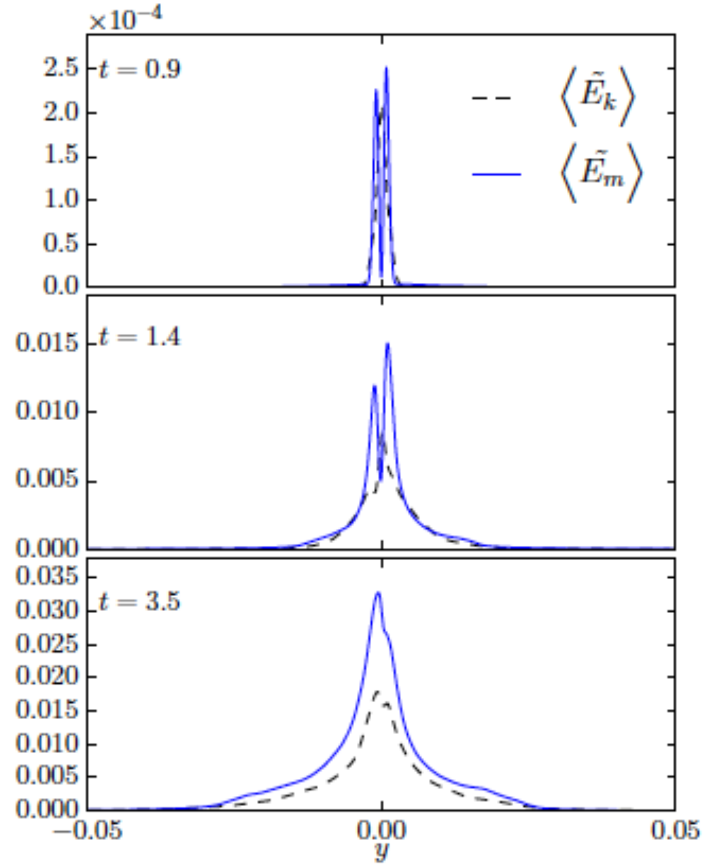
Post CME Current Sheet



Courtesy: Lijia Guo

Turbulent Region Broadens as Instabilities Evolve

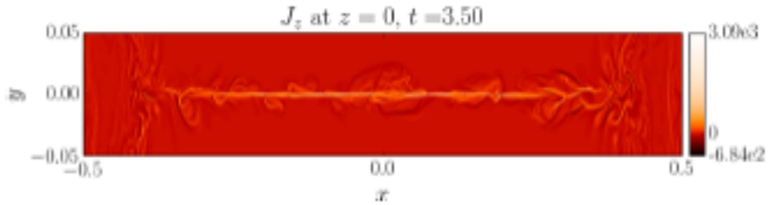




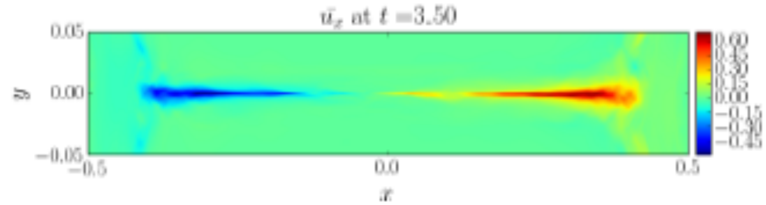
- In fully developed turbulent state, approximately 70% of turbulence energy is in $y = [-0.01, 0.01]$.

Plasmoid-Induced Turbulent Reconnection

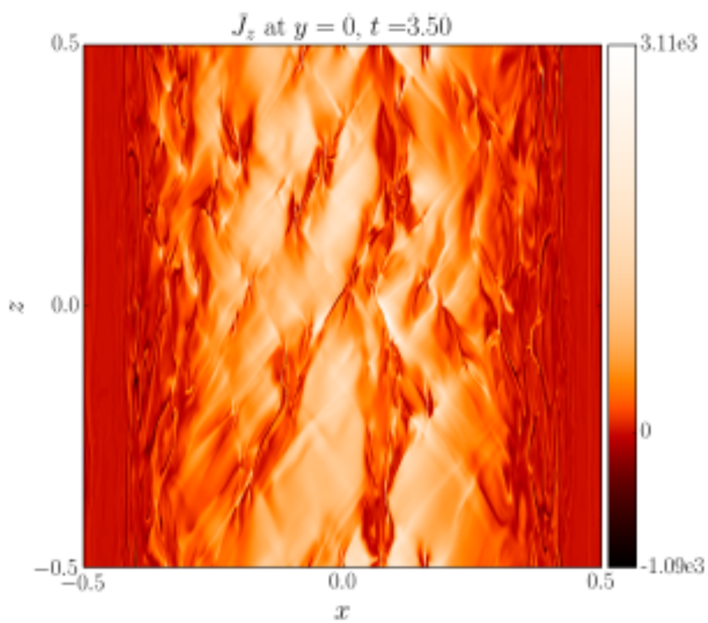
$x - y$ slice of J_z at $z = 0$



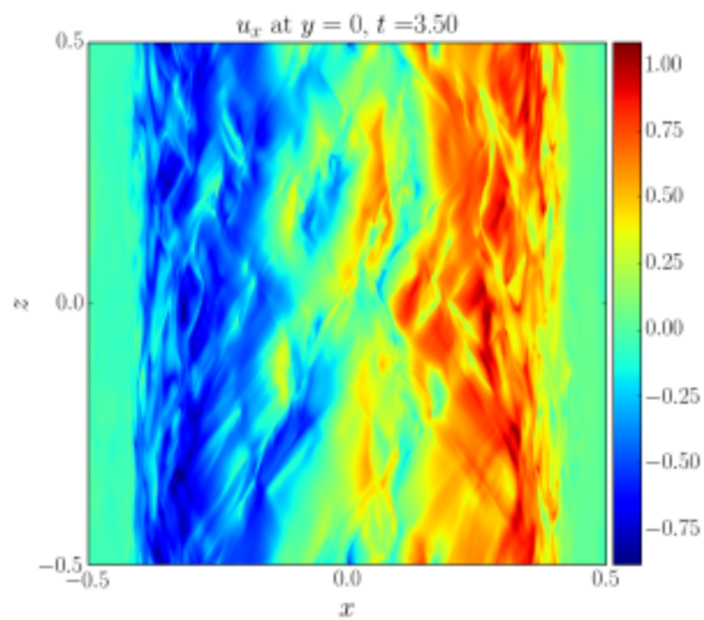
Mean field of outflow $\bar{u_x}$



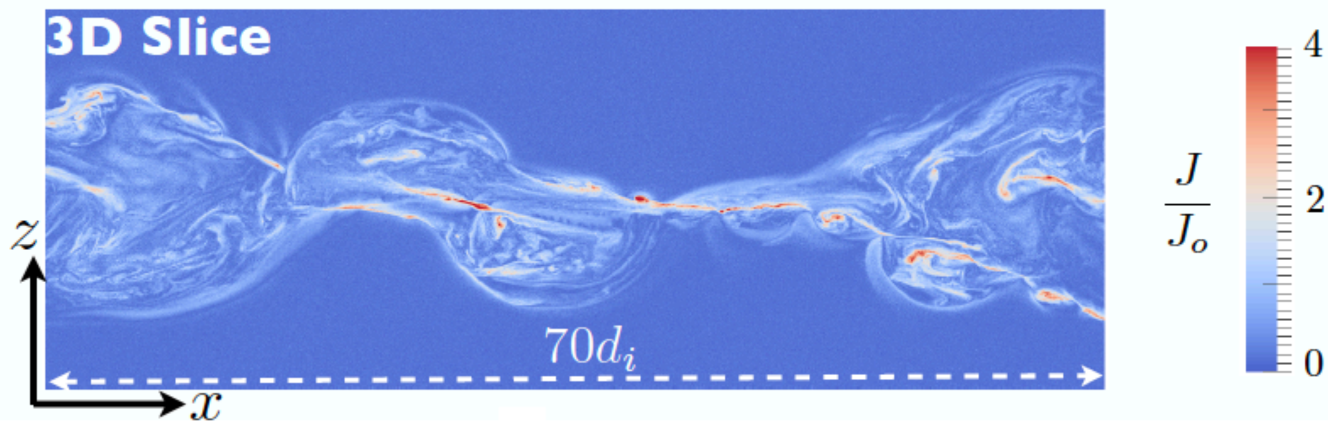
$x - z$ slice of J_z at $y = 0$

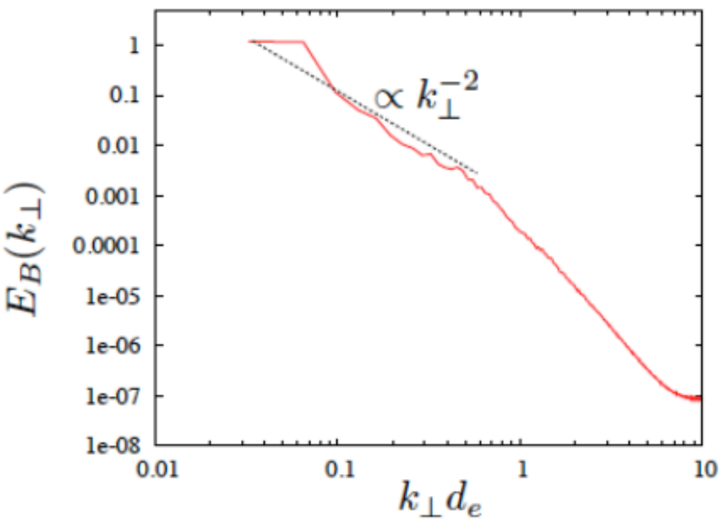


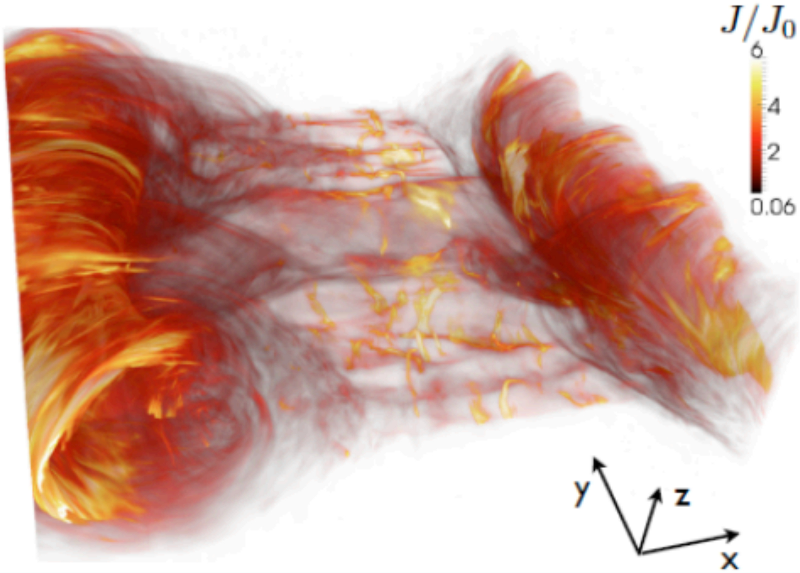
$x - z$ slice of u_x at $y = 0$



Recent development: 3D Magnetic Reconnection

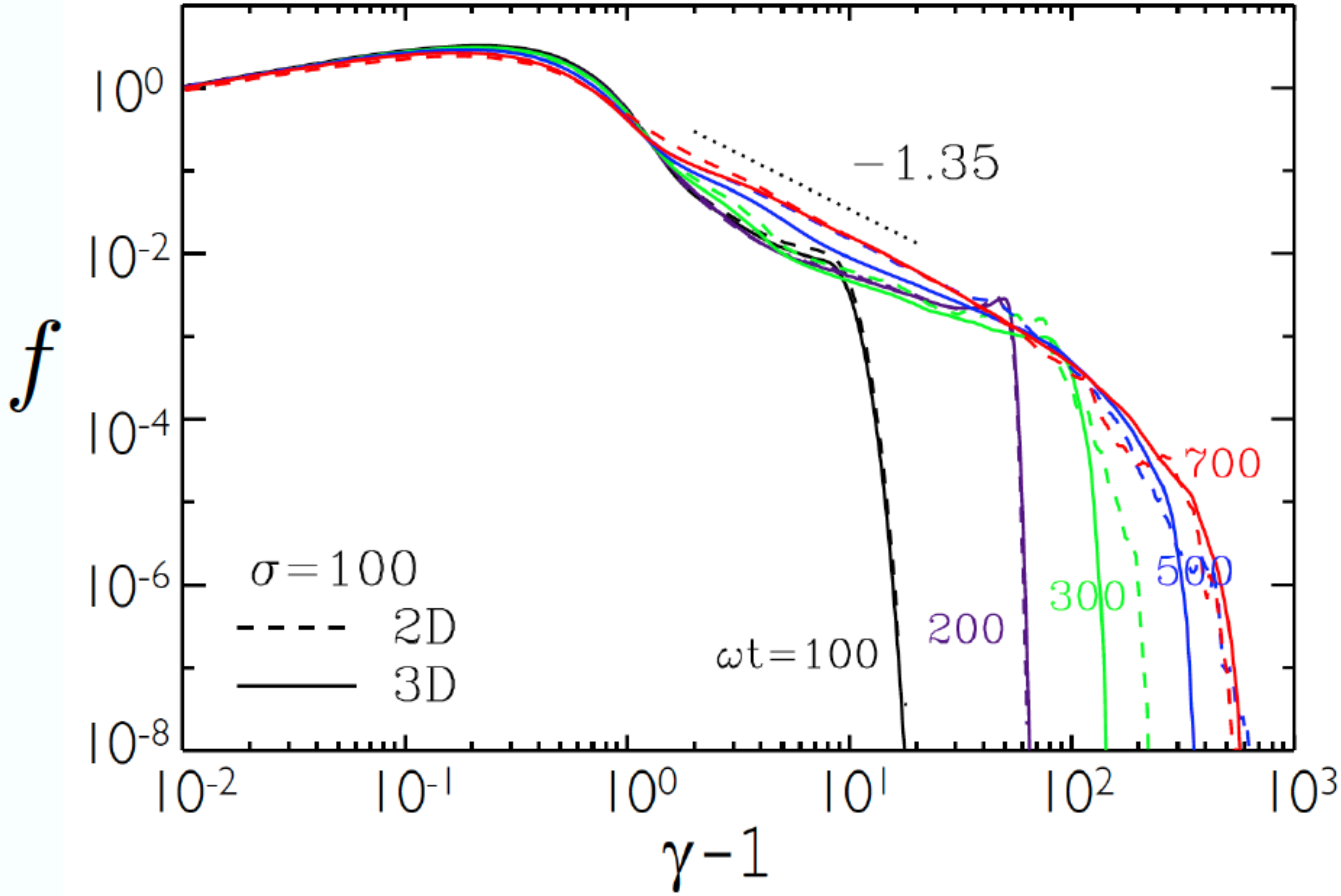






Daughton et al, Nature Physics, 2011, Guo et al. 2014 PRL, 2015 ApJ

Energy spectra from 2D and 3D PIC simulations



Guo et al. 2014 PRL, 2015 ApJ, 2016 PoP

- 2D and 3D kinetic simulations for relativistic magnetic reconnection show that the reconnection layer is dominated by development of flux ropes, and generates strong particle acceleration.
- Despite turbulence in the reconnection layer, nonthermal particles are efficiently generated and form power-law distributions.
- Using a number of diagnostics, we show the contributions from different acceleration mechanism. For anti-parallel case, the acceleration is dominated by Fermi acceleration, and this leads to power-law distribution. Acceleration by parallel electric field is important for reconnection with a strong guide field.
- The acceleration mechanism and power-law formation are quite robust and general.