Solar Flares and Particle Acceleration

Loukas Vlahos

In this project many colleagues have been involved

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Winter School on Turbulence, Montegufon,
Firenze, 3-7 October, 2005

Main points

- The problem
- Key Observational constrains
- Models for explosive energy release

(flares/CMEs) (break-up model, the compact flare, CA models for solar flares)

- Particle acceleration
  - Turbulent current sheet
  - Stressed magnetic topologies
  - MHD turbulence-revisited
  - The CA models
- Discussion and Summary

Role of Theory ? (Eric Priest)

- Not -- reproduce images
- Nor explain every observation
- **Understand Basic Processes**
  -- step-by-step -- simple -> sophisticated model
  - ***Listen to Observers** -- clues
  - Different Types Theory -- complement
    analytical -- computational -- data interpretation.

The problem

- Impulsive energy release and particle acceleration so far are leaving separate lives
- We all now that in nature they are a happy couple
- Our problem then is: Can we build models for particle acceleration based on the main ingredients of the impulsive energy release?
- The main reason the two problems (energy release and particle acceleration) were treated separately is very well understood. Energy release was treated with the MHD equations (large scales evolution) and particle acceleration and transport with the Kinetic equations.

The problem

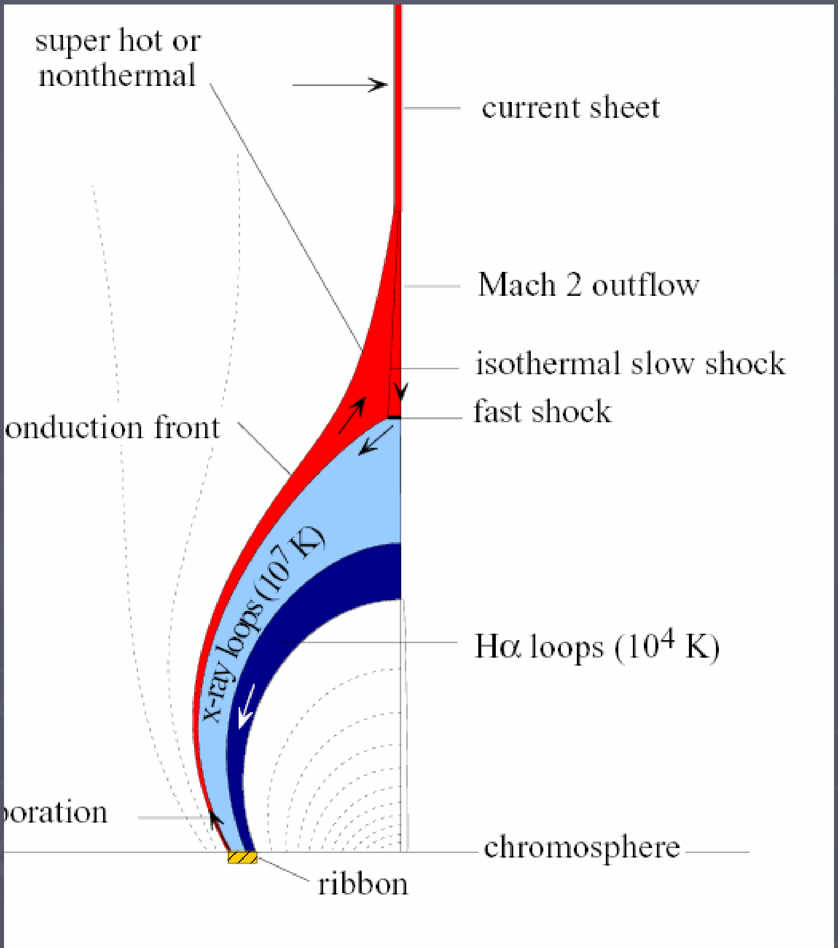
- Our main concern then is:
- How far can we push the MHD theory before Kinetic effects become extremely important and signal the break down of the MHD theory?
- Using the MHD theory, ignoring the kinetic effects, we will reach (phenomenologically) interesting but incorrect results.

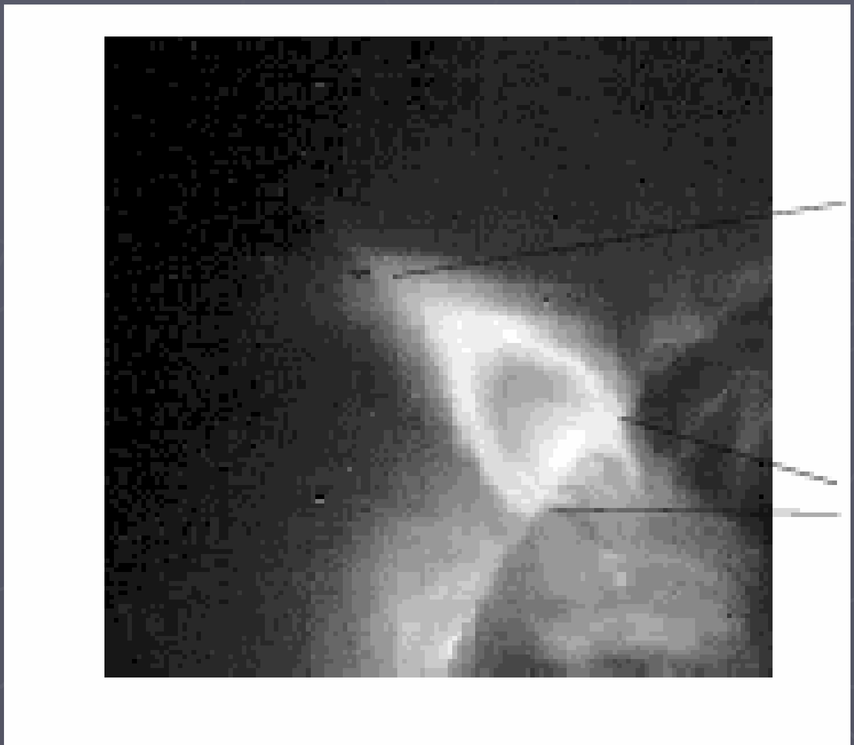
Key observational constrains

- The number of electros accelerated 10^37particles /sec above 20KeV and 10^35 ions/sec above 1MeV for 100 secs
- A very large fraction (40-50%) of the energy released in flares goes to high energy particles (E_0=10-15 KeV)
- The distribution of high energy particles (electron E_0 and ions) develop very specific power laws above a certain energy
- Some times particles accelerated in situ have a very good connection with particles in space
- Spatial characteristics... foot points and loop top sources (in a few flares).
- Motion of the foot points
- Fast time scale acceleration

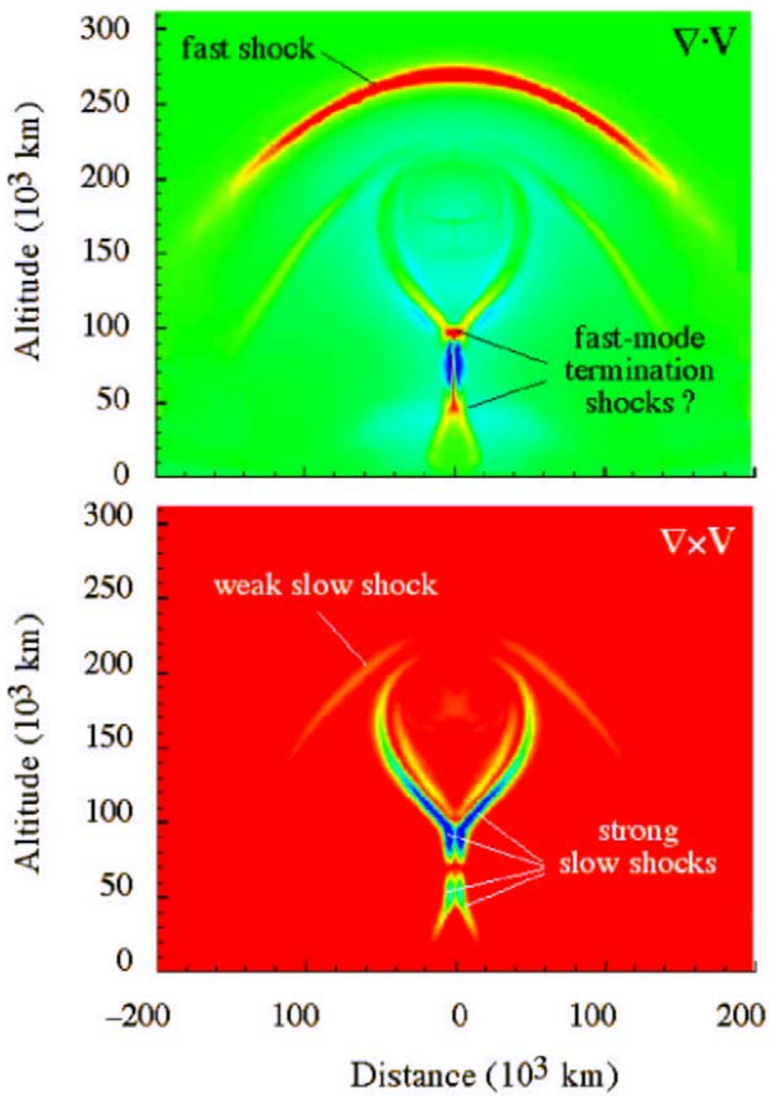
Energy release in solar active regions

The "standard(?)" solar flare model and the monolithic current sheet

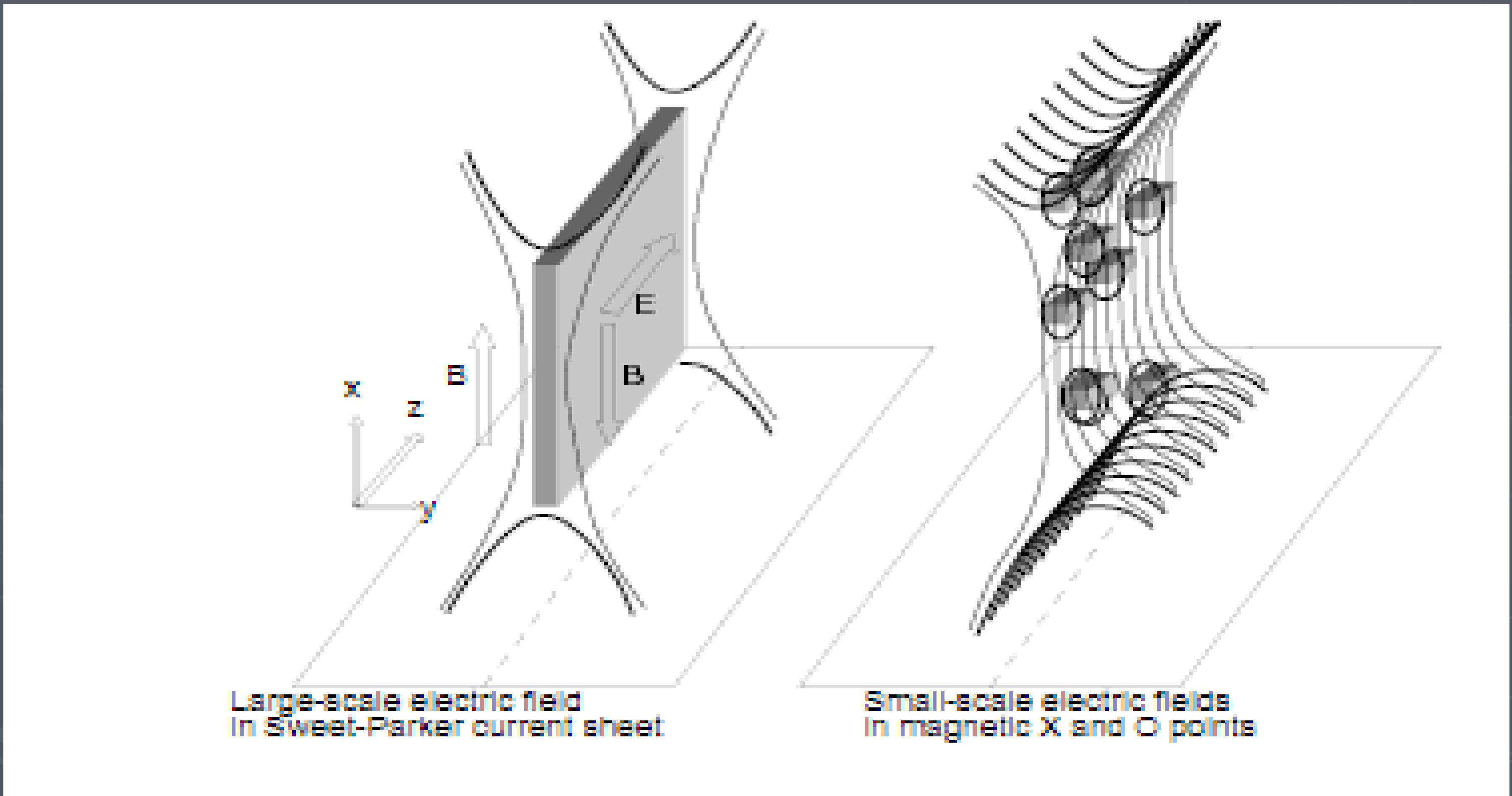




Shock Formation



Fragmented loop top current sheet



The replenishment problem!

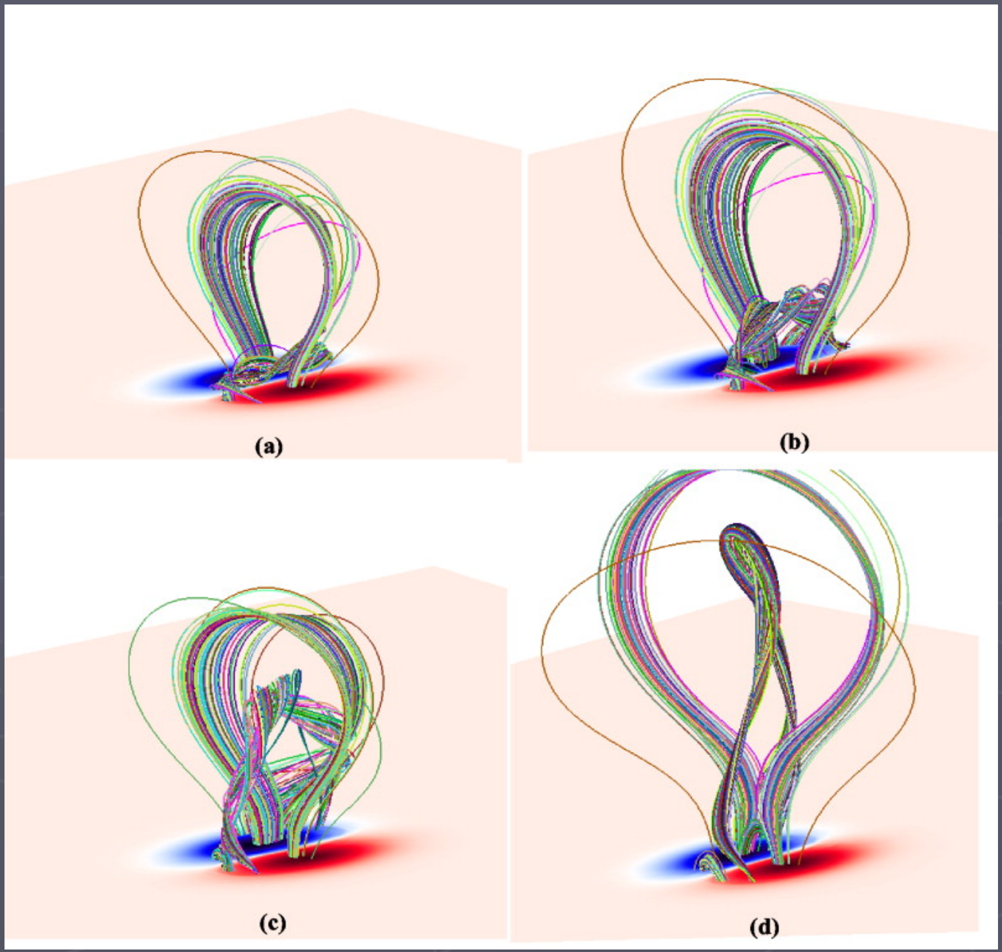
- Can they all be accelerated at the loop top?

For N = 10 ^{38} electrons in flare, where

$N = V n_e =$ $10^{10} \times 10^{10} \times 10^{5} n_e$

- **For $n_e = 10^9 cm^{-3}$**
  - **N=** 10^{34}

3D flux tube simulations (Amari et al)



Incompressible cartesian code

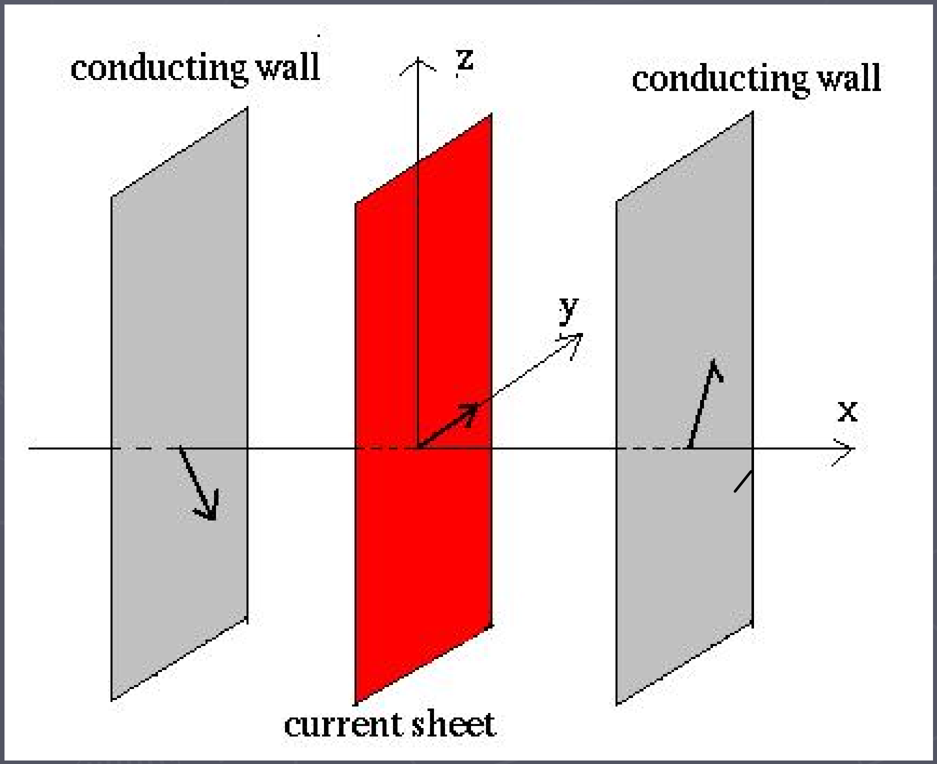
We study the magnetic reconnection in an incompressible plasma in three-dimensional slab geometry.

Different resonant surfaces are simultaneously present in different positions of the simulation domain and nonlinear interactions are possible not only on a single resonant surface, but also between adjoining resonant surfaces.

The nonlinear evolution of the system is different from what has been observed in configurations with an antiparallel magnetic field.

Geometry

The MHD incompressible equations are solved to study magnetic reconnection in a current layer in slab geometry:



Periodic boundary conditions along y and z directions

Dimensions of the domain:
$-l_x < x < l_x$, $0 < y < 2\pi l_y$, $0 < z < 2\pi l_z$

Description of the simulations: equations and geometry

Incompressible, viscous, dimensionless MHD equations:

$$\frac{\partial \mathbf{V}}{\partial t} = -(\mathbf{V}\cdot\nabla)\mathbf{V} - \nabla P + (\nabla\times\mathbf{B})\times\mathbf{B} + \frac{1}{R_v}\nabla^2\mathbf{V}$$

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

$$\nabla\cdot\mathbf{B} = 0$$

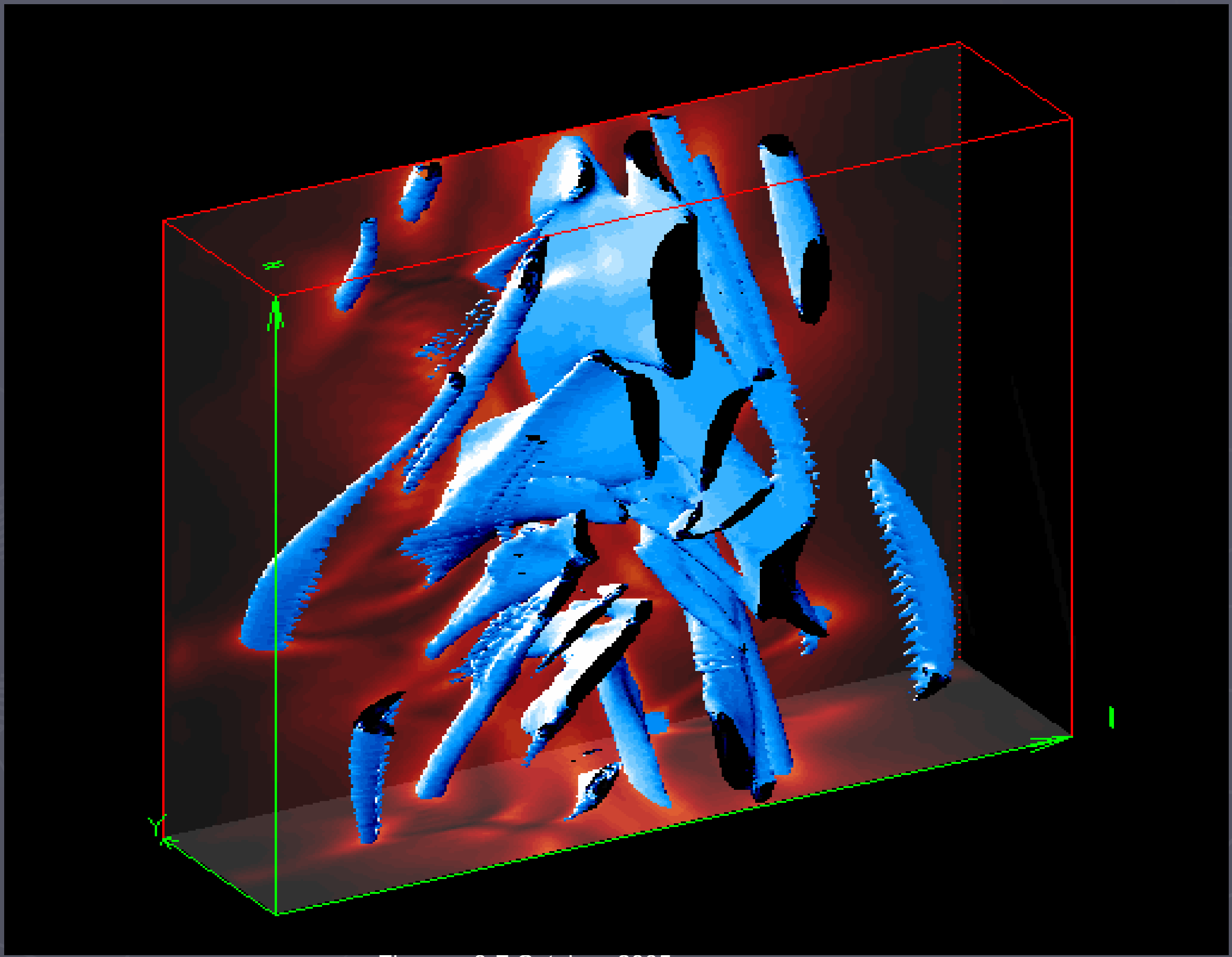
$$\nabla\cdot\mathbf{V} = 0$$

B ***is the magnetic field,*** **V** ***the plasma velocity and*** P ***the kinetic pressure.***

R_M ***and*** R_v ***are the magnetic and kinetic Reynolds numbers.***

Marco Onofri et al.

Isosurfaces of the current at t=400

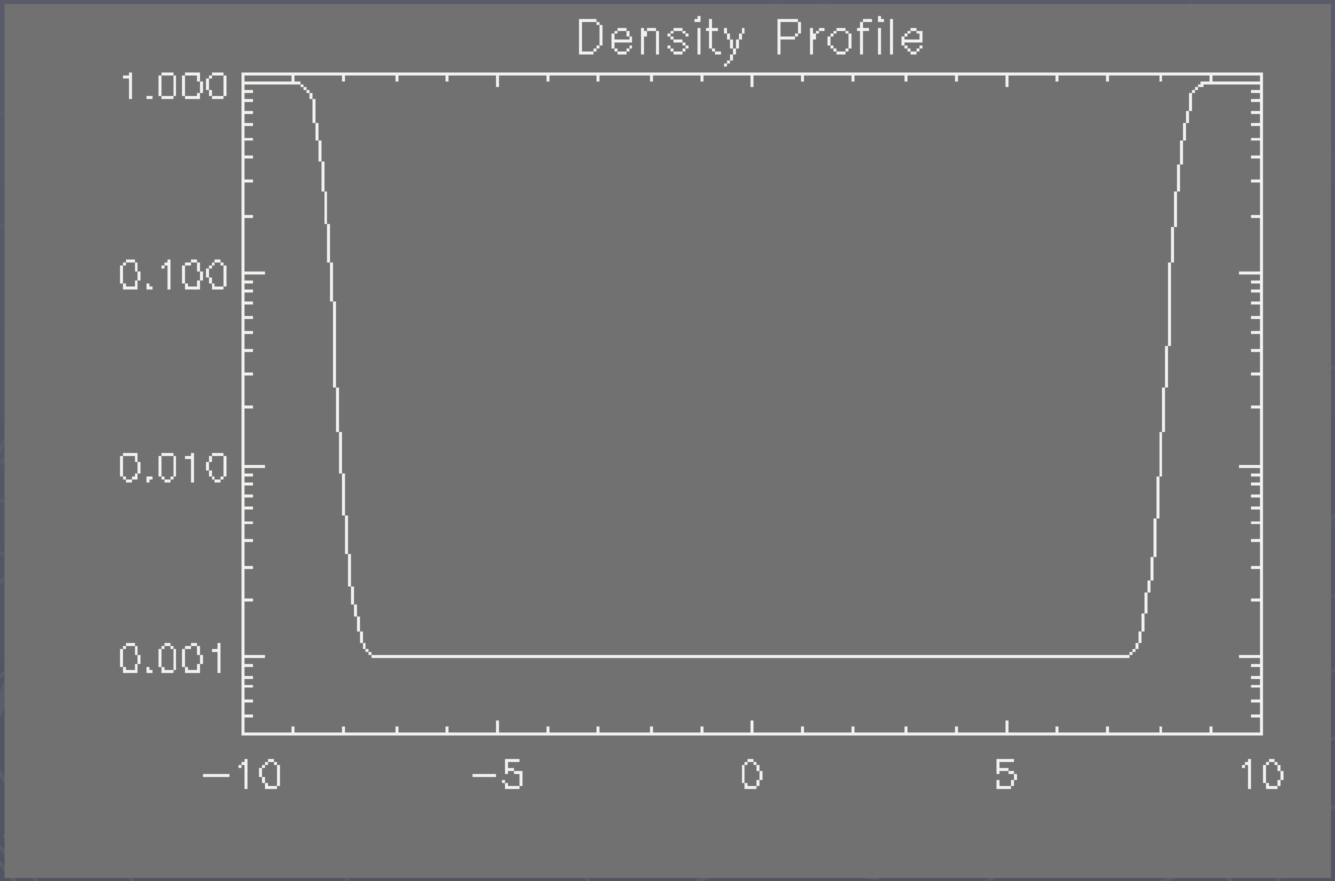


MHD Equations

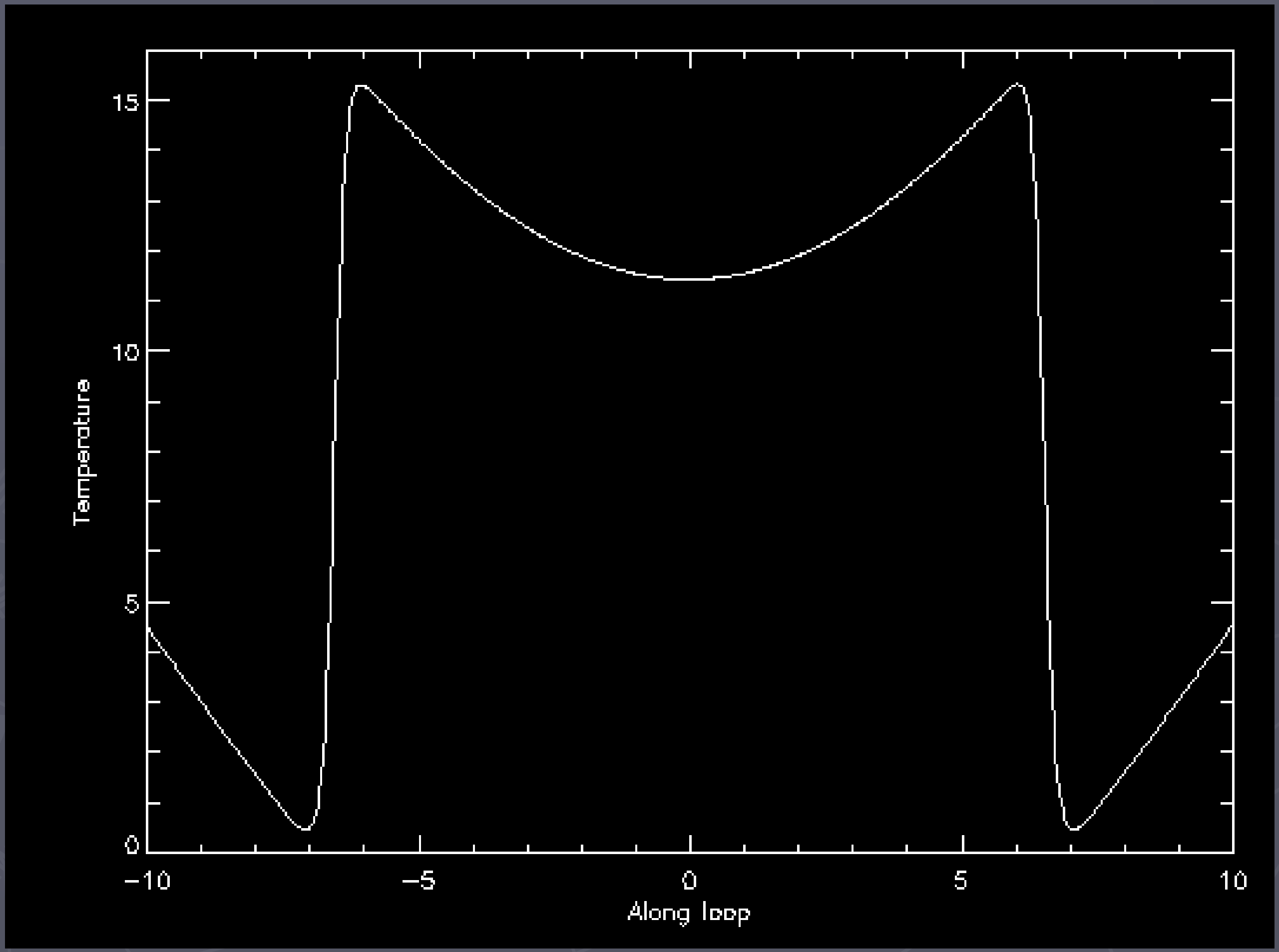
$$
\begin{aligned}
\frac{\partial \rho}{\partial t} &= -\boldsymbol{\nabla} \cdot \rho \mathbf{u}, \\
\frac{\partial \rho \mathbf{u}}{\partial t} &= -\boldsymbol{\nabla} \cdot (\rho \mathbf{u}\,\mathbf{u} + \underline{\underline{\tau}}) - \boldsymbol{\nabla} P + \mathbf{J} \times \mathbf{B} + \mathbf{F}_e, \\
\frac{\partial e}{\partial t} &= -\boldsymbol{\nabla} \cdot (e \mathbf{u}) - P\, \boldsymbol{\nabla} \cdot \mathbf{u} + Q_{\mathrm{Joule}} + Q_{\mathrm{visc}}, \\
\frac{\partial \mathbf{B}}{\partial t} &= -\boldsymbol{\nabla} \times \mathbf{E}, \\
\mathbf{E} &= -(\mathbf{u} \times \mathbf{B}) + \eta \mathbf{J}, \\
\mathbf{J} &= \boldsymbol{\nabla} \times \mathbf{B}
\end{aligned}
$$

Density profile along the loop

(Galsgaard)



Temperature along the (Galsgaard) loop



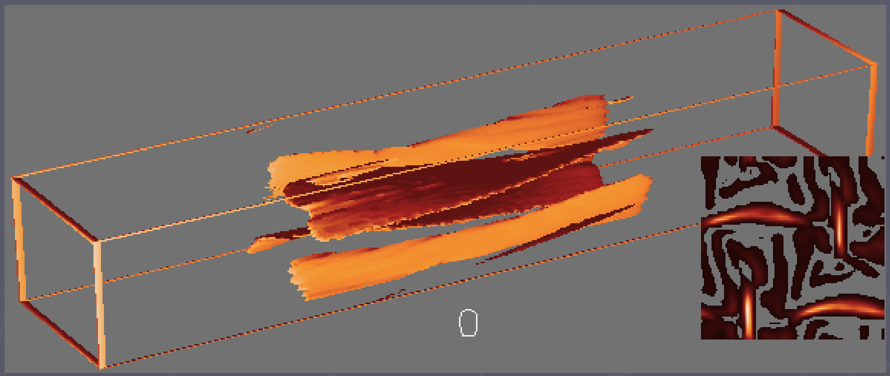
The stochastic loop model
(Galsgaard)

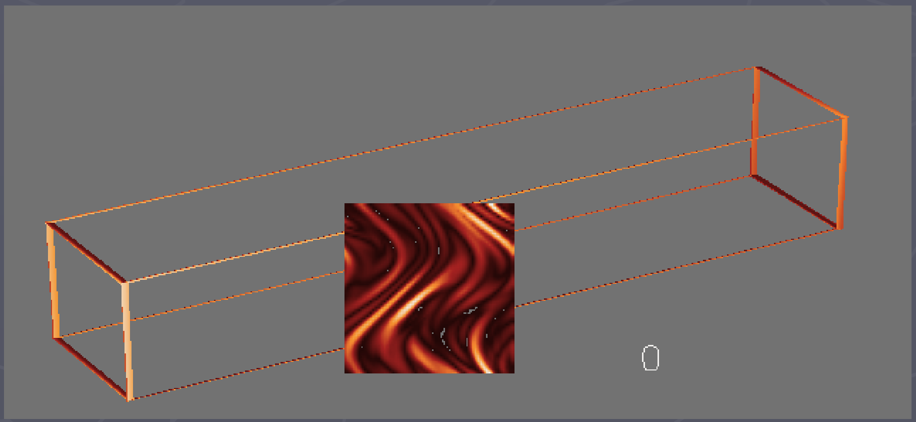
- 3D MHD experiment of photospherically driven slender magnetic flux tubes

- Continued random driving of the foot points (incompressible sinusoidal large scale shear motions)

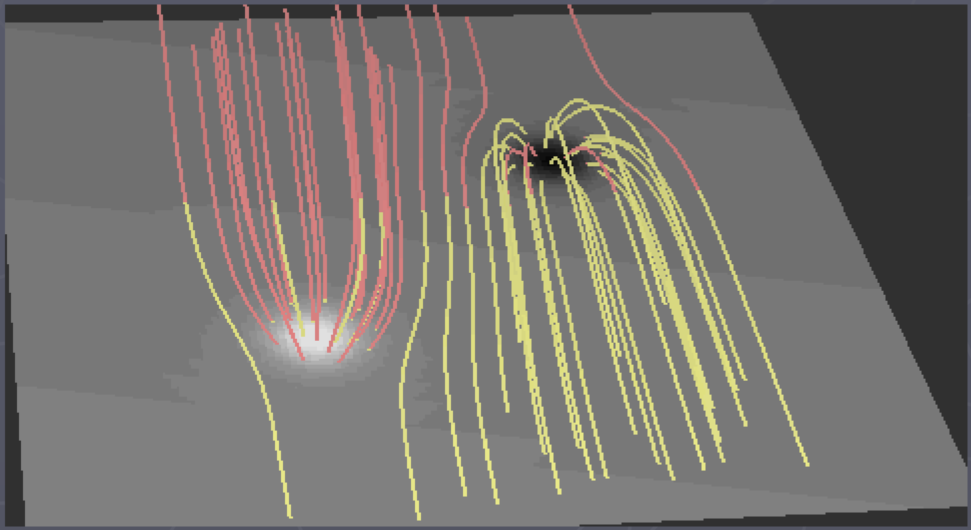
- Reconnection jets generate secondary perturbations in B

- Formation of stochastic current sheets





Dynamic Evolution of large scale current sheets



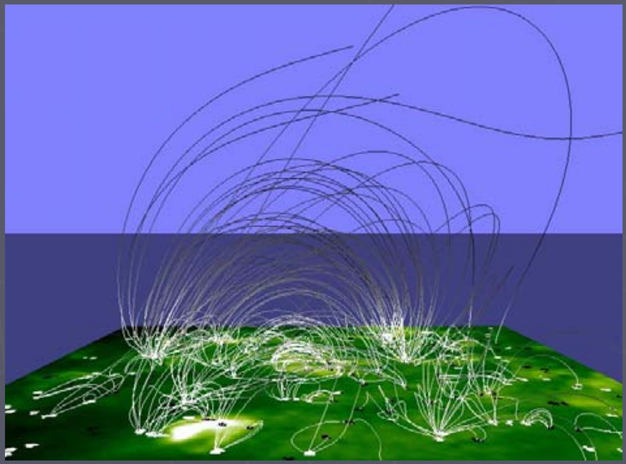
The X-CA model based on SOC

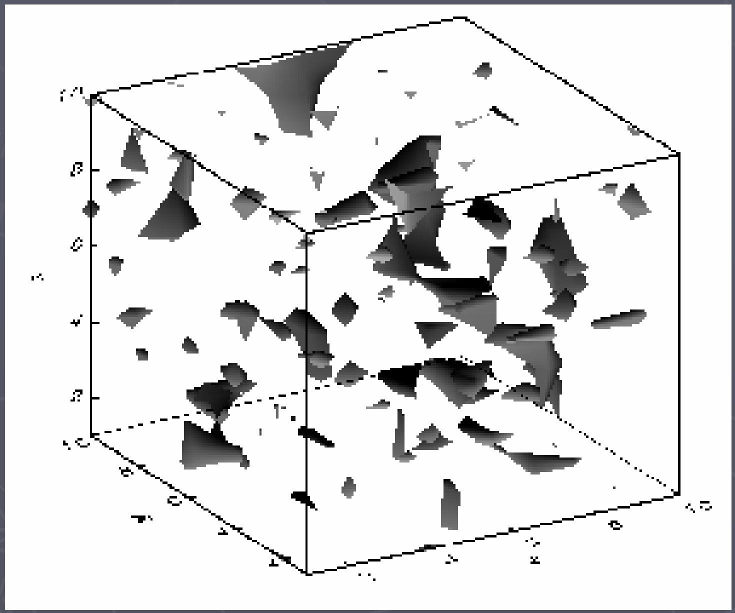
- We form a 3D box filed with magnetic fields of random values.
- We add new magnetic flux at random points and estimating the current $\vec{J} = \nabla \times \vec{B}$
- When the current exceeds a critical threshold the rearrangement of currents is automatic

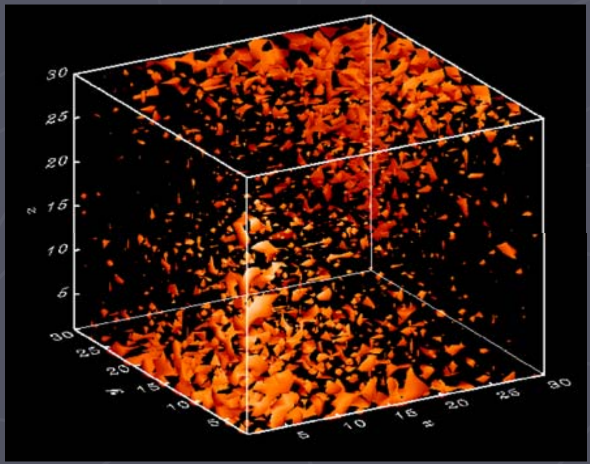
$$\frac{\partial \vec{B}}{\partial t} = \nabla \times (\vec{u} \times \vec{B}) + \eta \nabla^2 \vec{B}$$

A New approach to an old problem

- From one current sheet to millions

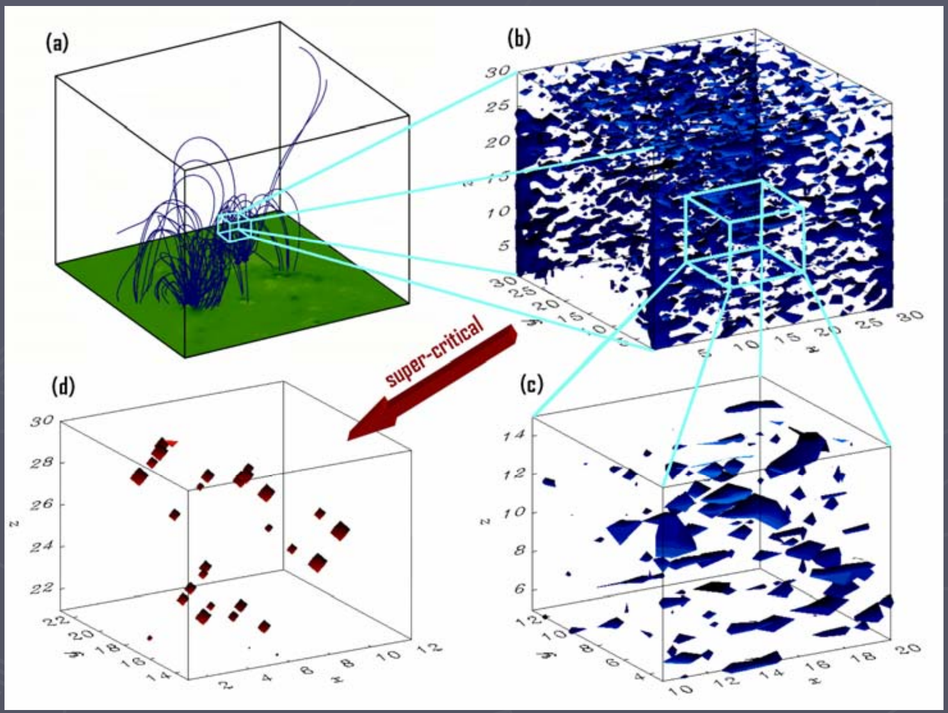




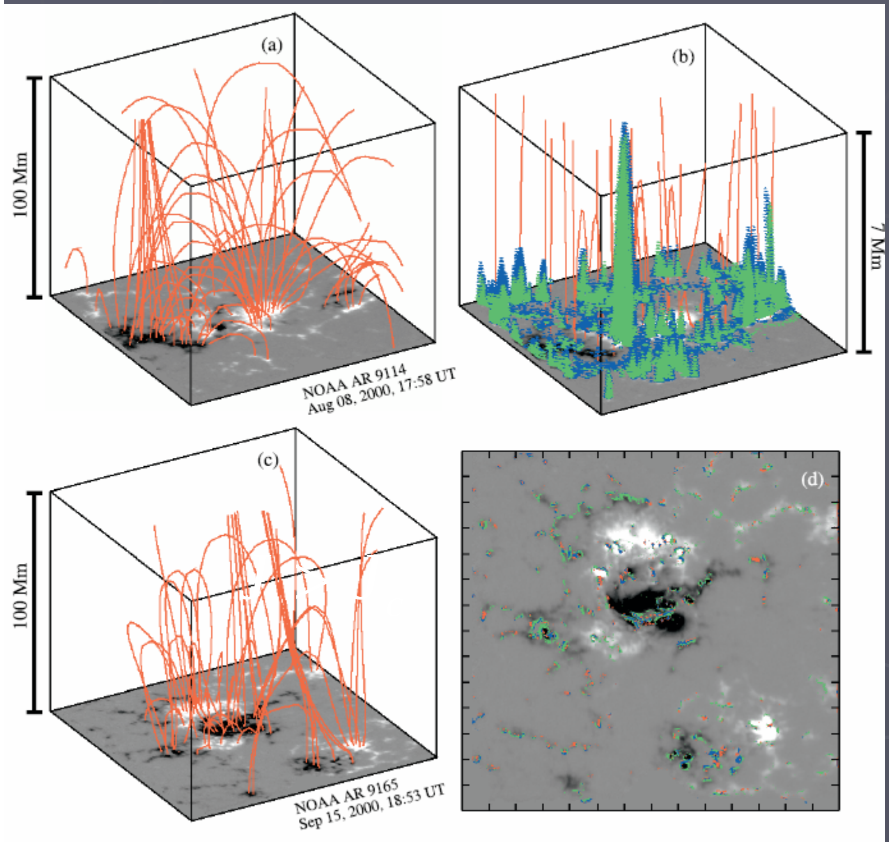


Using the X-CA model

- From one current sheet to millions



1. Active regions form and evolve by building up and releasing energy in unstable discontinuities (Vlahos+Georgoulis, ApJL, 2004)



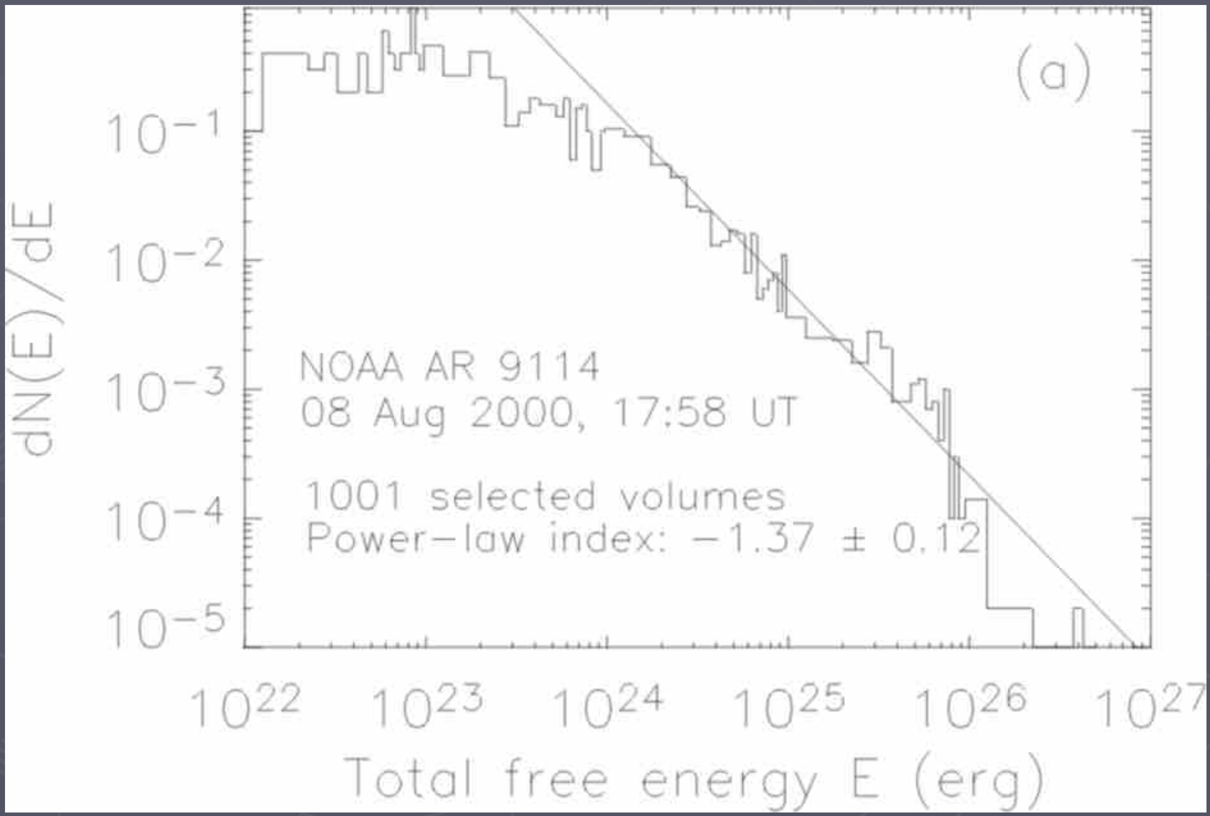
$$\vec{J} = \frac{c}{4\pi} \nabla \times \vec{B}$$

Unstable discontinuity

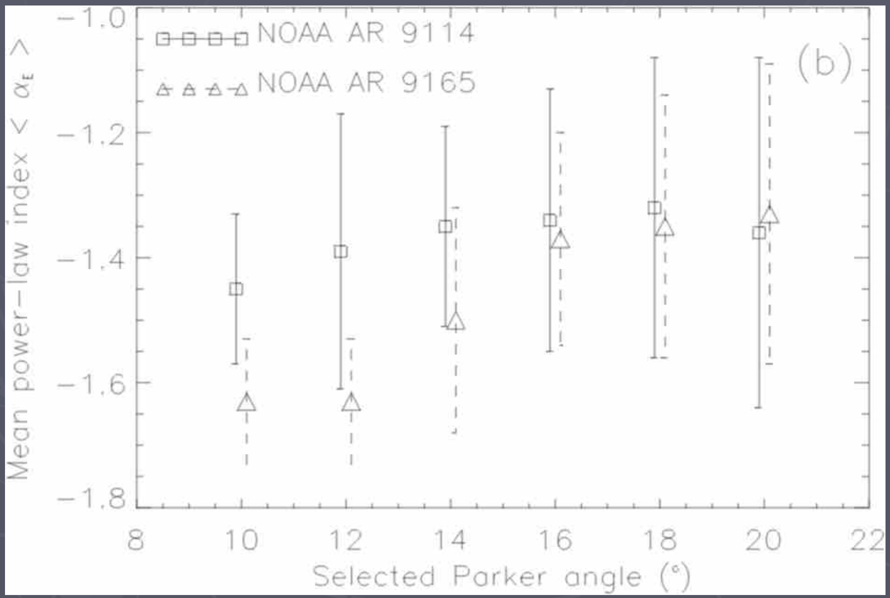
$$J > J_c$$

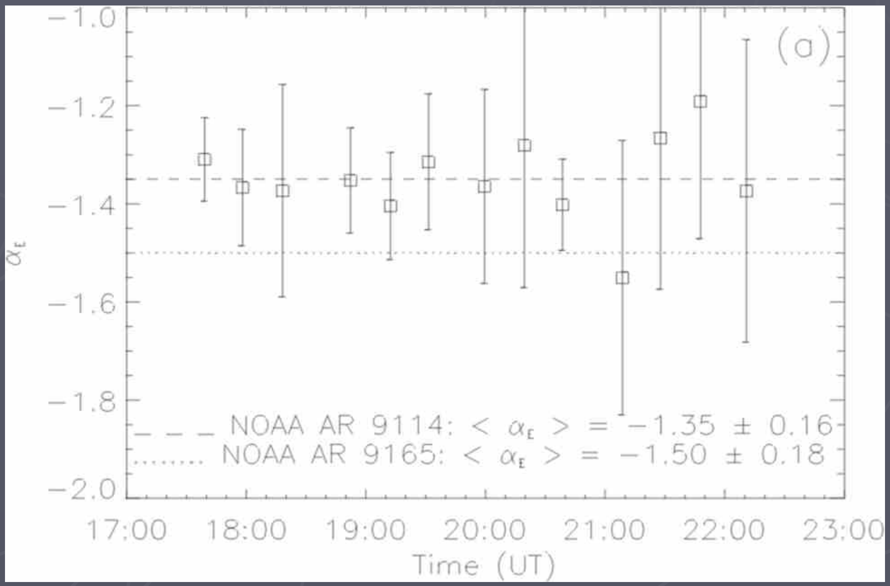
$$\vec{E} = -\frac{\vec{V} \times \vec{B}}{c} + \eta_{an} \vec{J}_c \qquad Q = \eta_{an} J_c^{\ 2}$$

PDF for the energy in the unstable discontimuities



The stability of this result on time

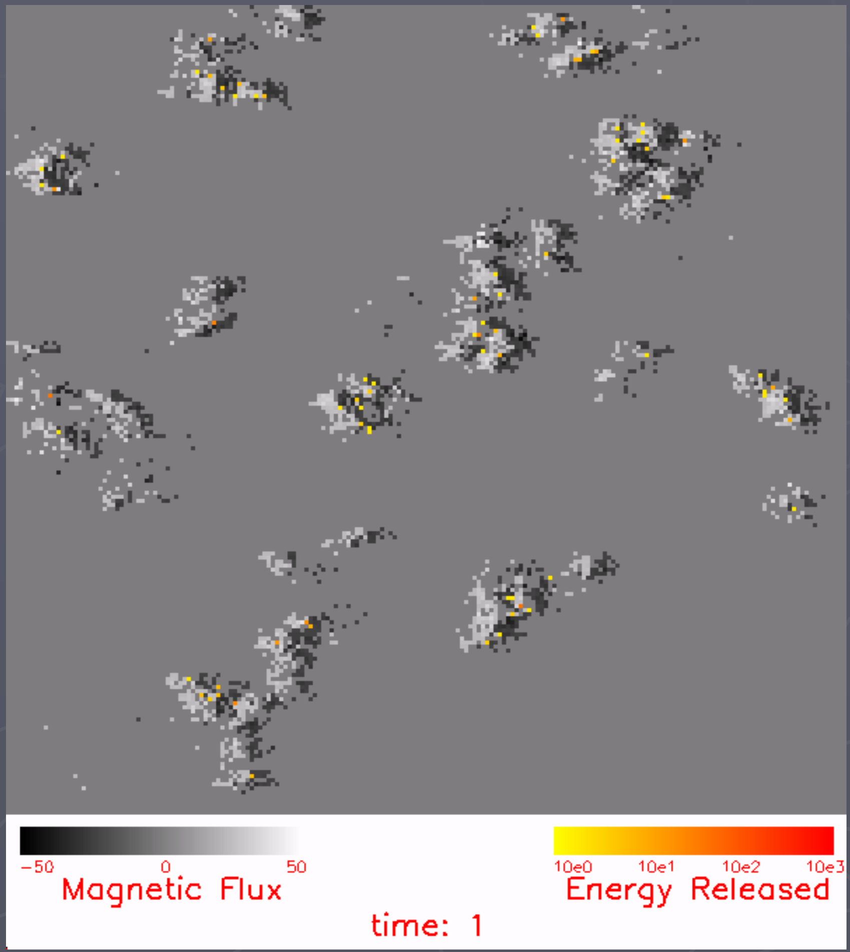




Evolving active regions build up constantly magnetic discontinuities....

(Vlahos et al., 2004, Fragos, Rantziou, Vlahos, AA, 2005)

- P=is the probability for generating new flux
- D=the probability of decaying
- E= spontaneous generation of flux



Evolving active regions build up constantly magnetic discontinuities....

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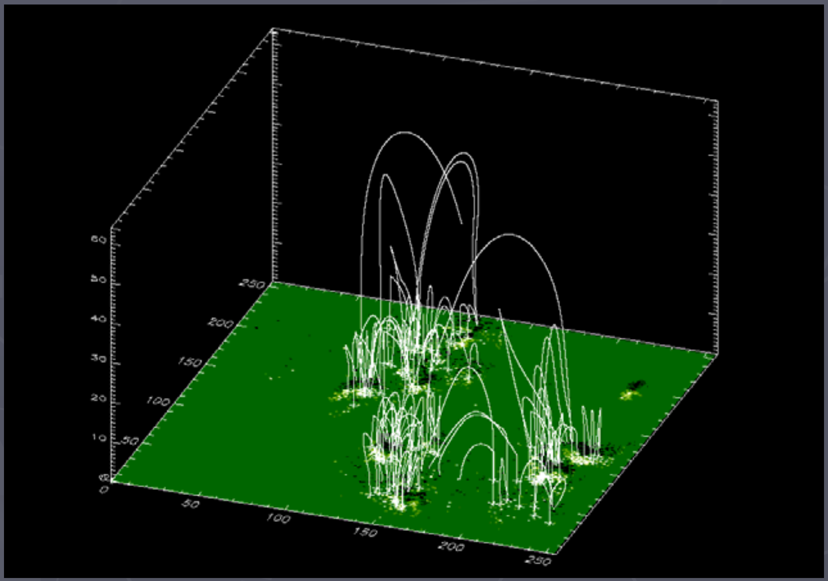
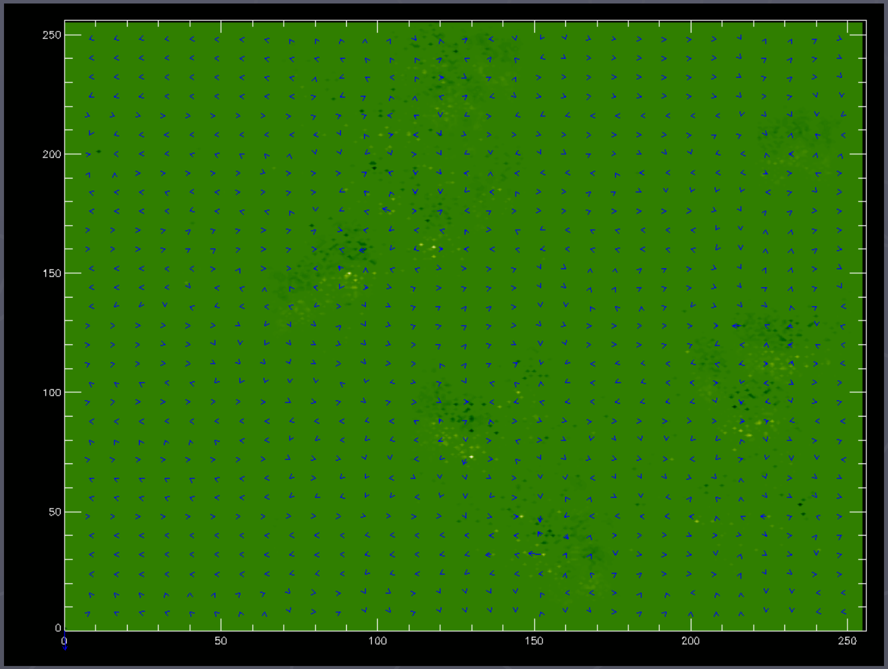
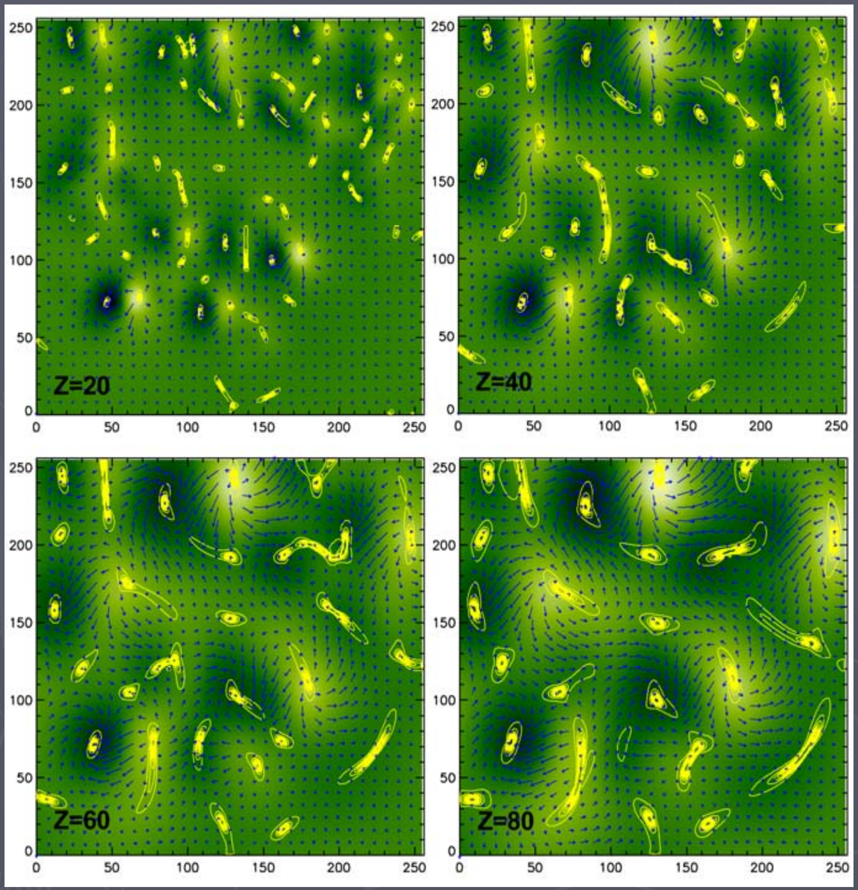
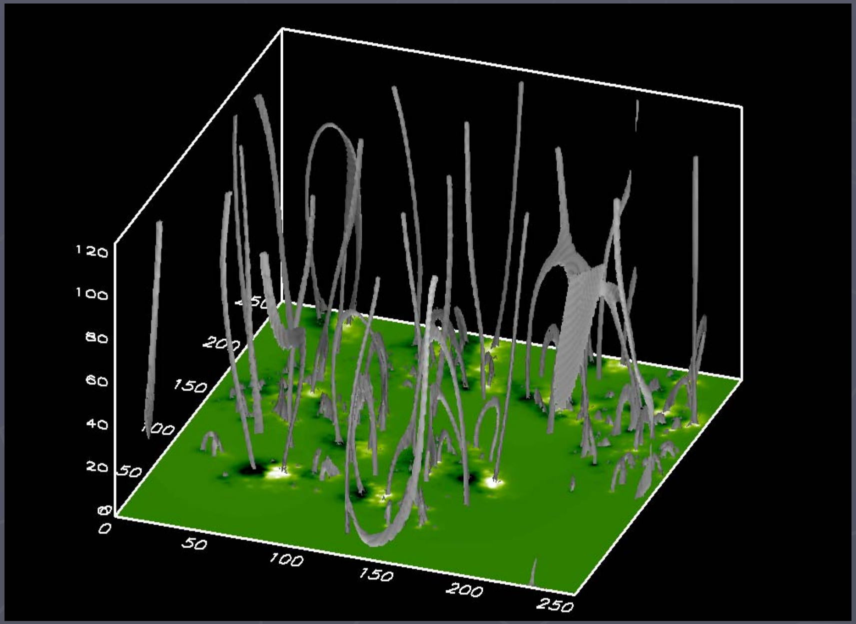




Dynamic motion of the photosphere builds constantly magnetic discontinuities

(Fragos, Rantziou, Vlahos, AA, 2004)





Dissipation of magnetic energy in 3D

- The ideal MHD is thought to be a good approximation away from the points were currents concentrate. (In the language of CA it is the loading of the system). It is a good approximation for studying the formation and evolution of large scale structures and provide the observed organization of the AR complex
- Natural formation of UCS in stressed topologies form locally currents above a critical threshold (so flares and dissipation starts, criticality and instability)
- In realistic magnetic topologies stresses which drive unstable structures appear all the time (trigger of instabilities and rearranging of field lines).
- This scenario produces the flare statistics and follows the general promisses of the SOC theory.
- The realistic photospheric structures, with a given fractal dimension, drive UCS of different size above the photosphere.
- Stochastic current sheets are formed in all stressed photospheric magnetic topologies (stable and slow changing or Unstable and rapidly changing)

Particle acceleration in Turbulent electric fields

$$\frac{d\vec{p}^{\,j}}{dt} = q_j \vec{E}(\vec{x},t) + \frac{q_j}{c}\vec{v}\times\vec{B}(x,t)$$

MHD EQUATIONS REVISITED

- Let me estimate the current

$$\vec{J} = \nabla \times \vec{B}$$

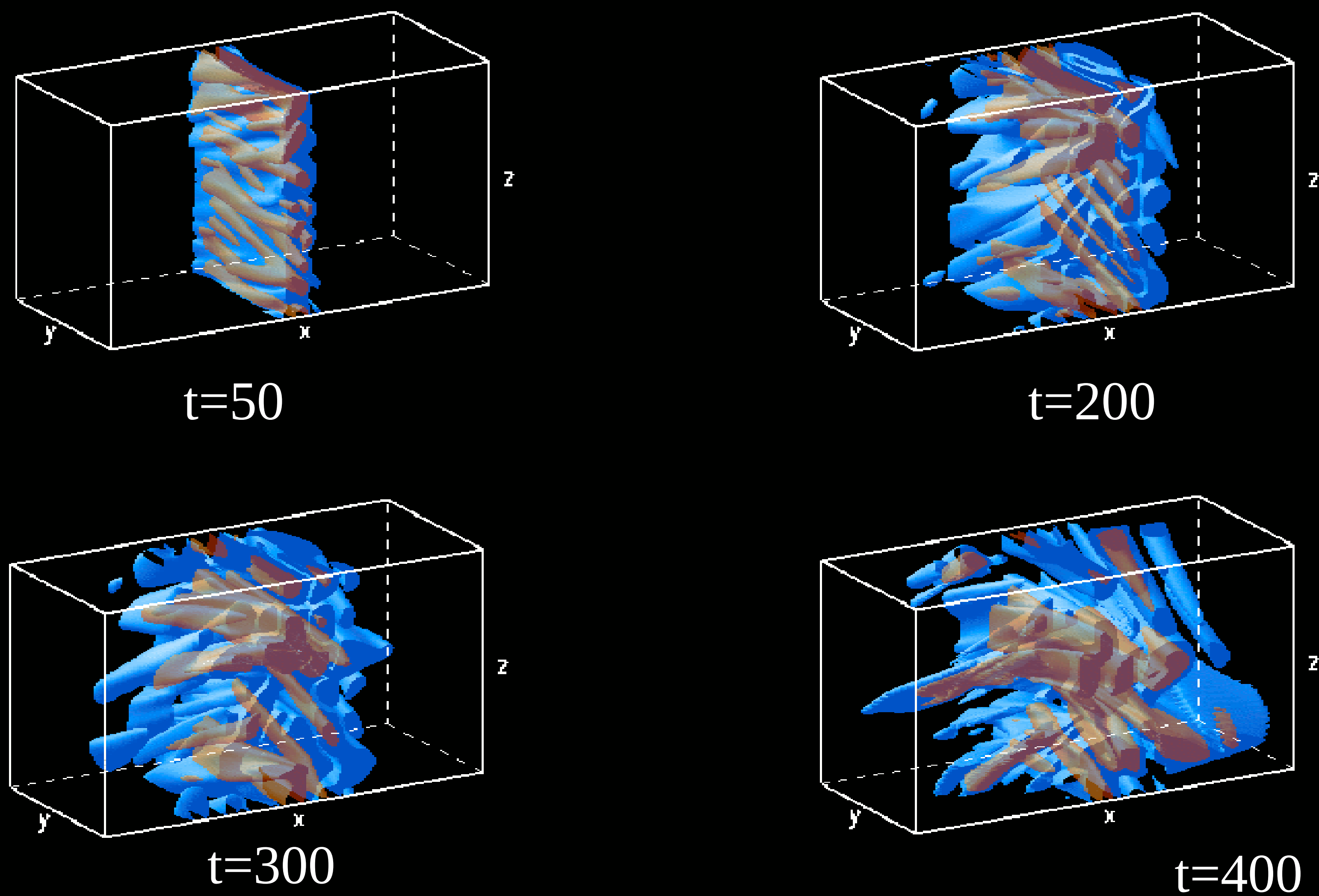
- The Electric field

$$\vec{E} = -\vec{u} \times \vec{B} + \eta \vec{J}$$

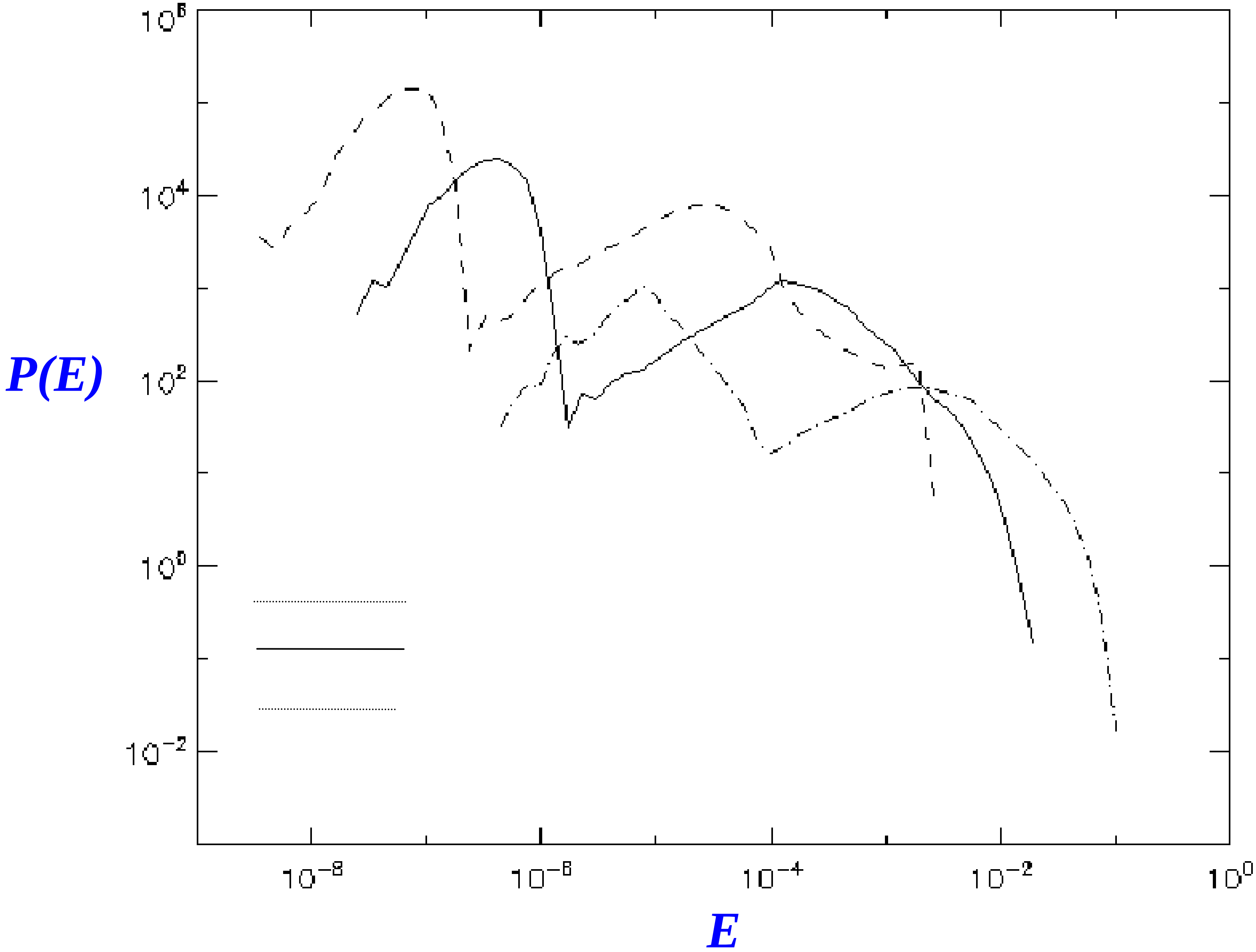
- Follow the orbits of a large number of ion and electrons

Three-dimensional structure of the electric field

Isosurfaces of the electric filed at different times

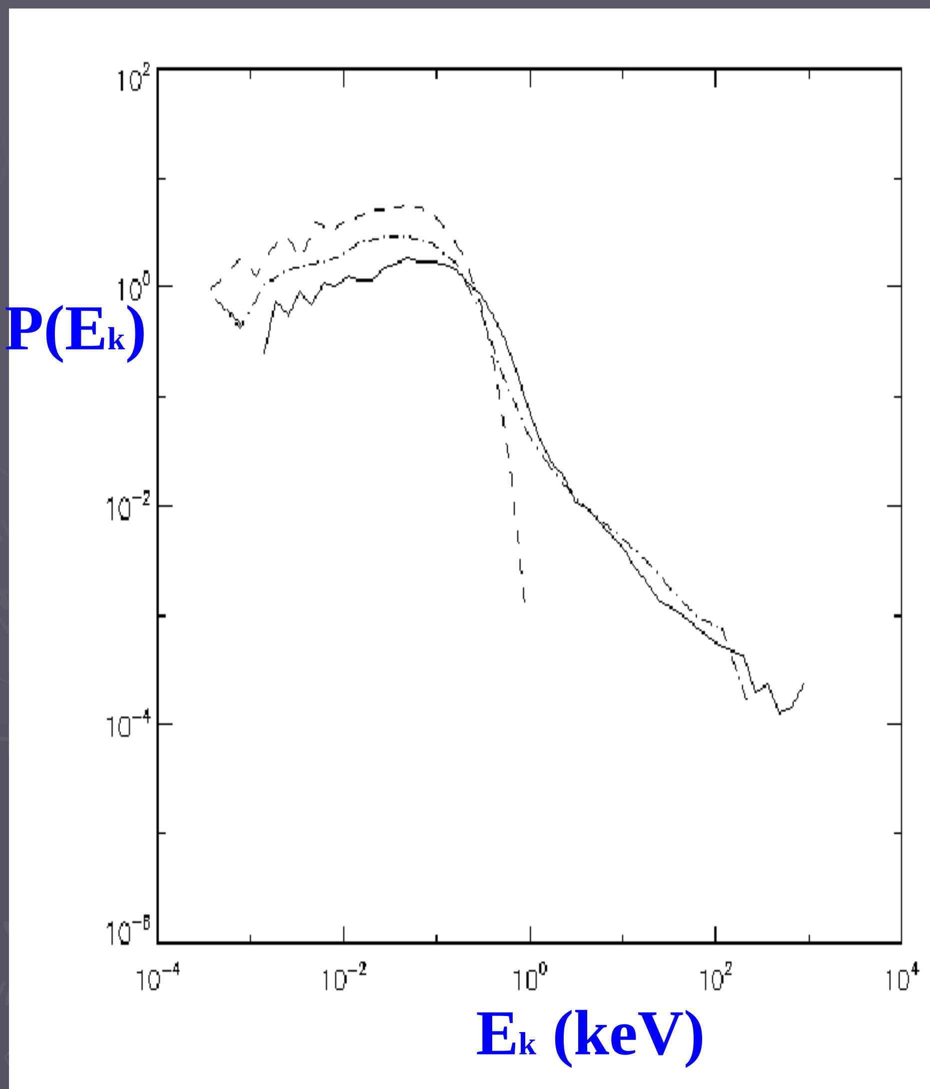


Distribution function of the electric field

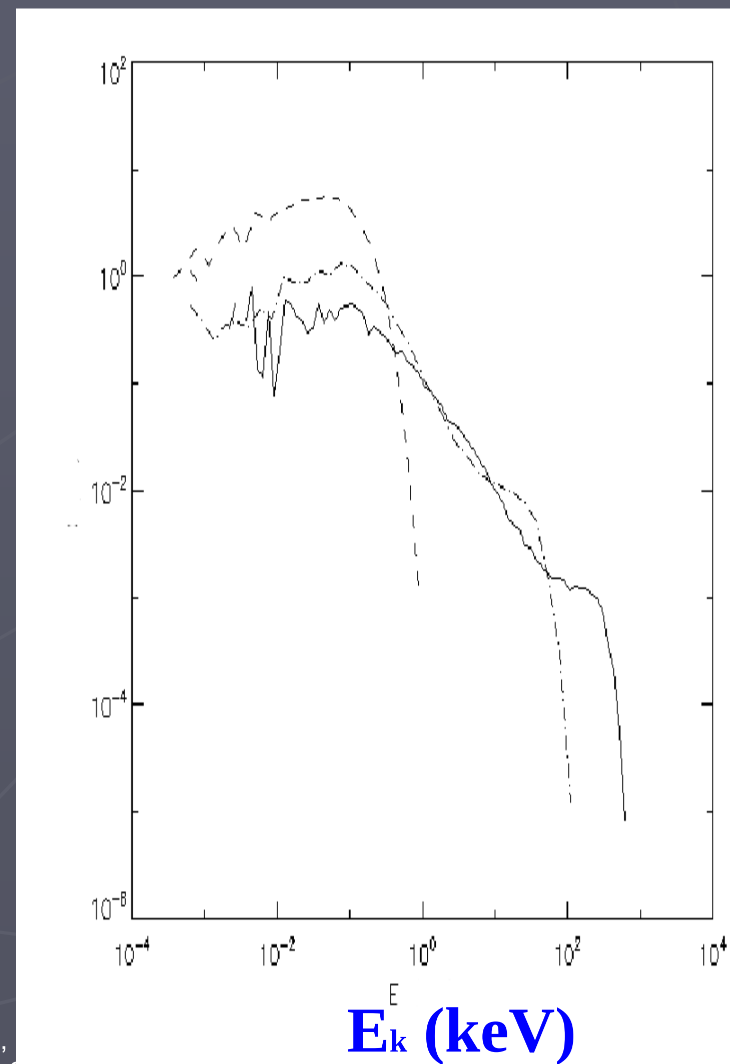


Kinetic energy distribution function of electrons

t=50 T_A

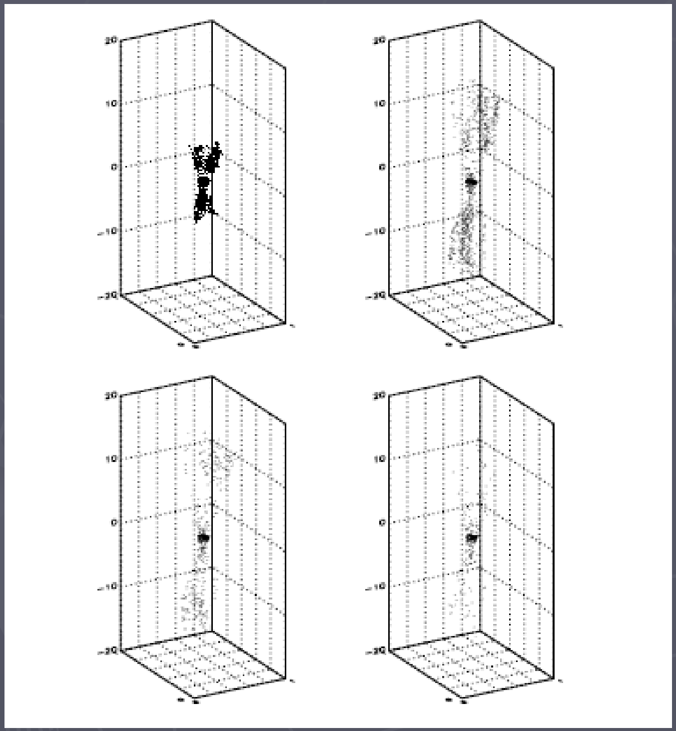


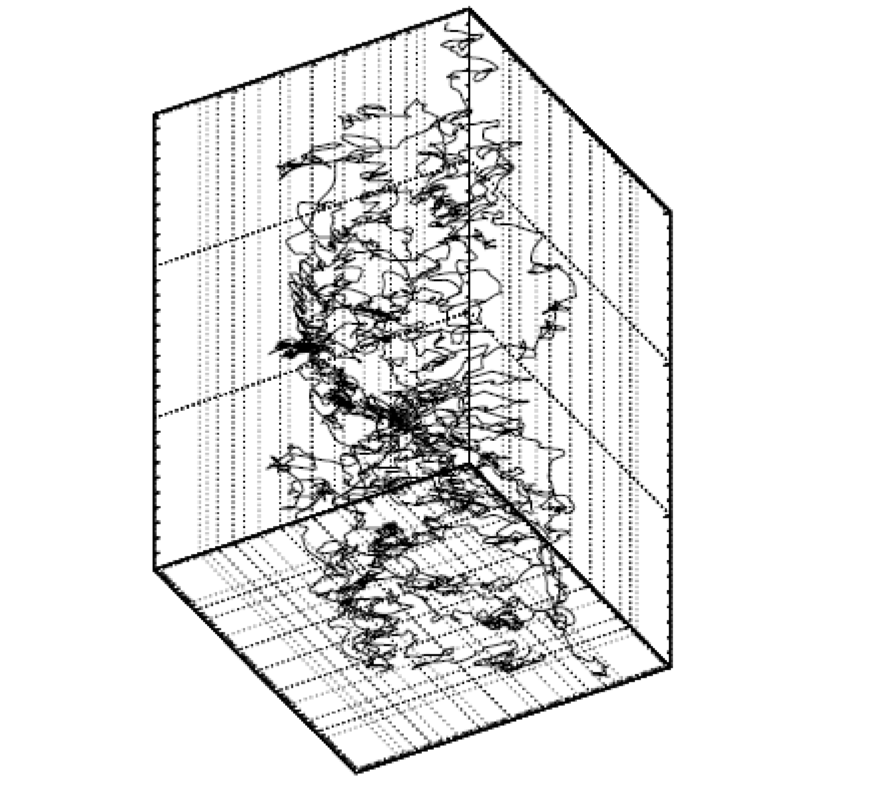
T=400 T_A



Particle motion in stochastic field lines (Gkioulidou, Zimbardo, Veltri, Vlahos, 2005)

- Magnetic field lines inside a loop





A '**Turbulent**' Field Model
(stochastic but not resonant accelerator)
(Azner+Vlahos, APJL, 2004)

$\mathbf{A} = \Sigma_\mathbf{k}\, \mathbf{a_k} \cos(\mathbf{k}\cdot\mathbf{x} - \omega(\mathbf{k})t + \phi_\mathbf{k})$

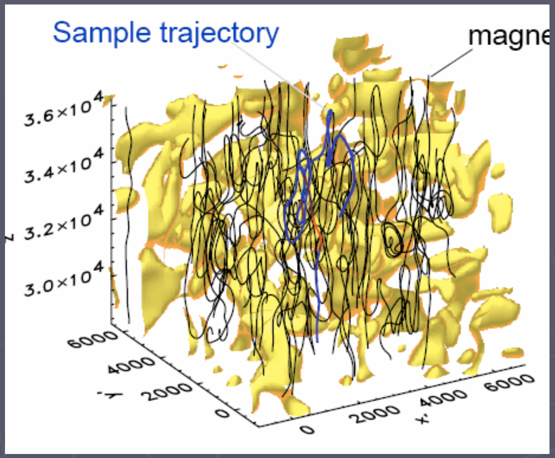
$\langle|\mathbf{a_k}|^2\rangle \sim (1+ \mathbf{k}^T S \mathbf{k})^{-\nu}$

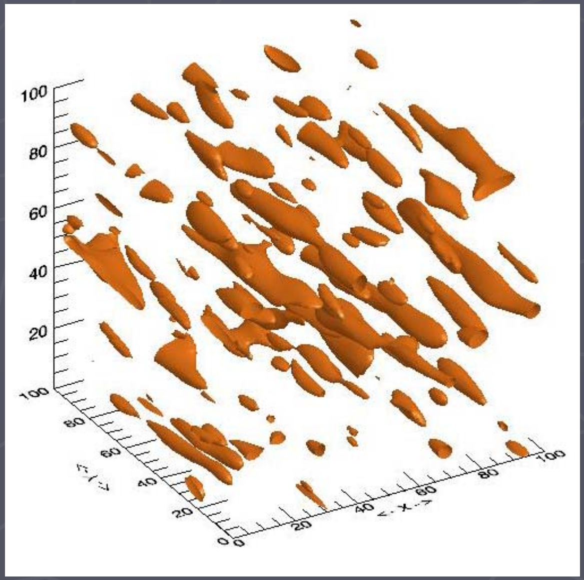
random $\phi_\mathbf{k}$

$\mathbf{B} = \nabla \times \mathbf{A}$

$\vec{J} \sim \nabla \times \vec{B}$

threshold j_c





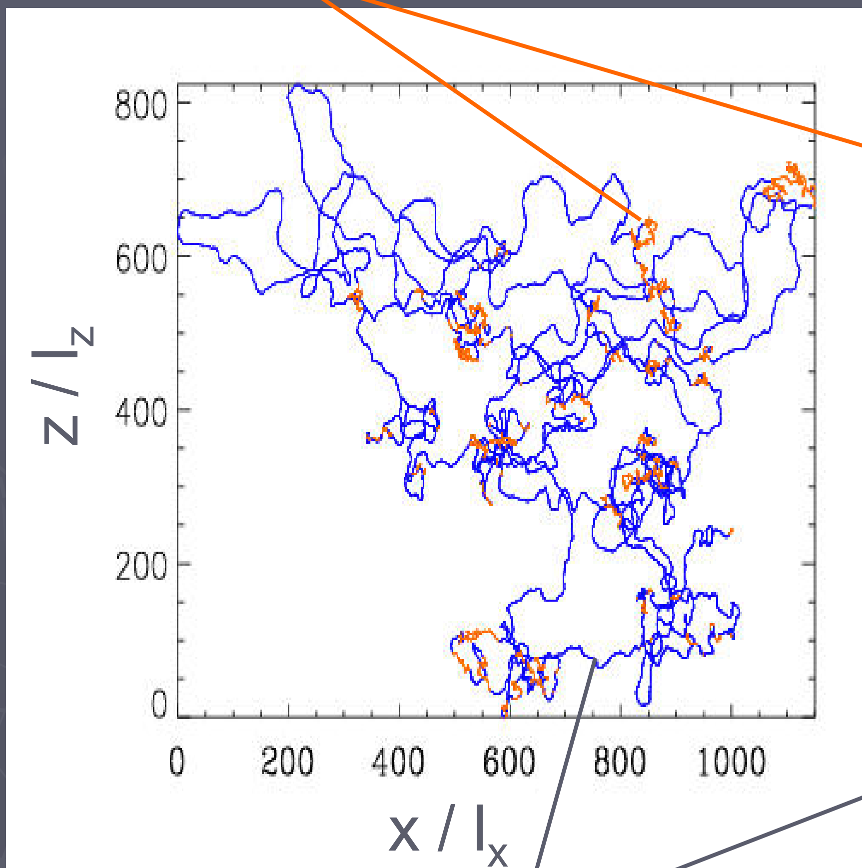
$\mathbf{E} = -\partial_t \mathbf{A} + \eta(\mathbf{j})\, \mathbf{j}$

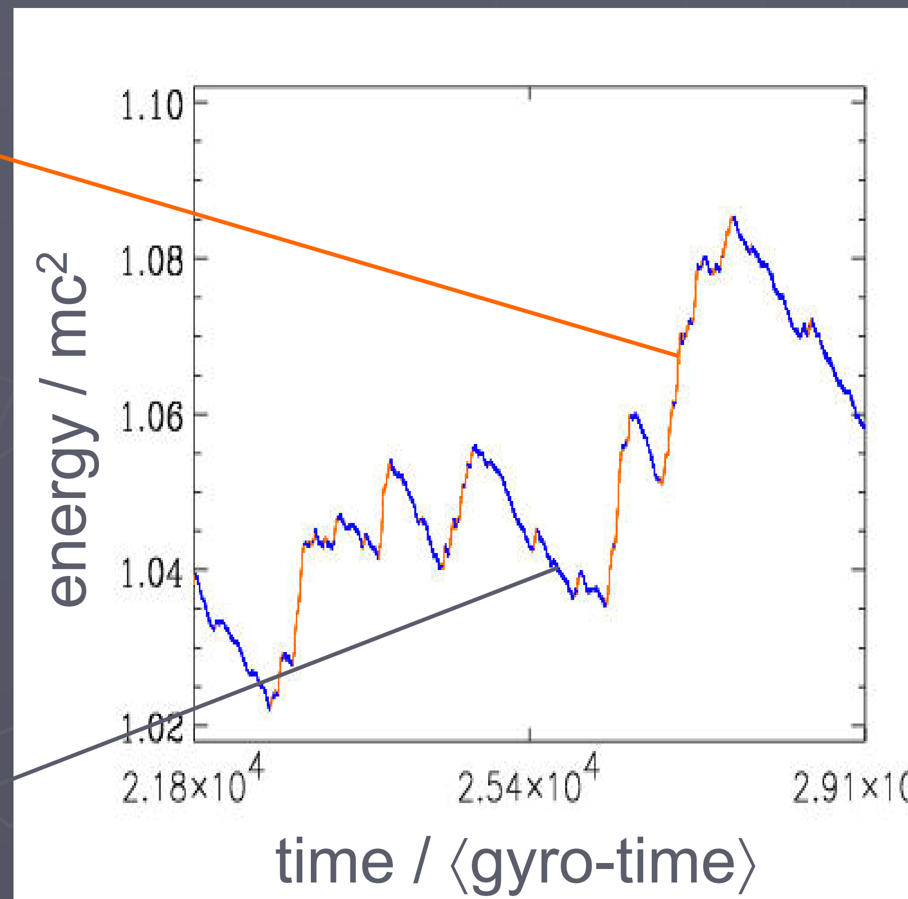
$\partial_y << \partial_x, \partial_z$

$v_{ph} << |\mathbf{v}_{ptcl}|$

Finding: intermittent particle orbits

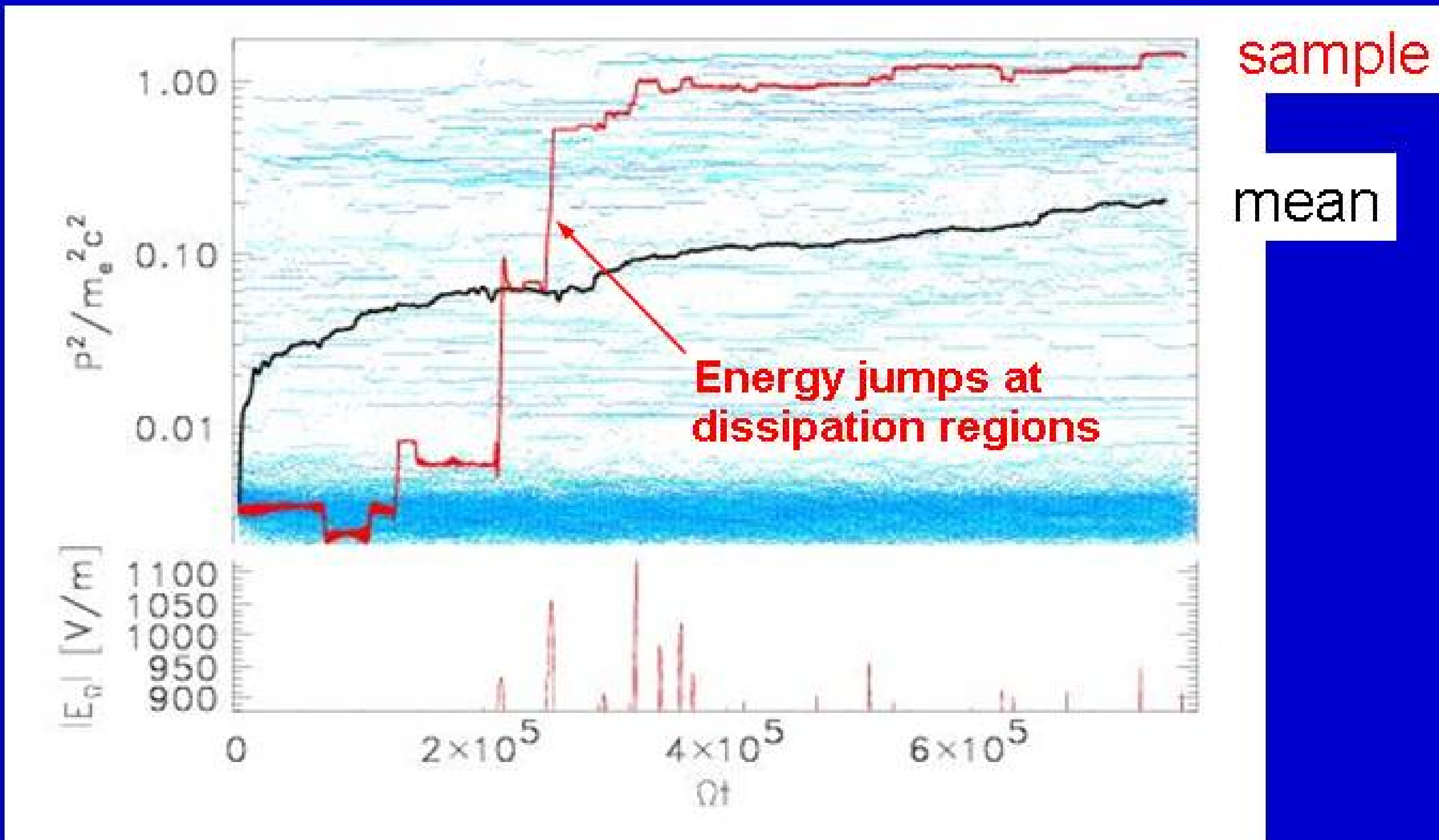
acceleration **within** local dissipation regions

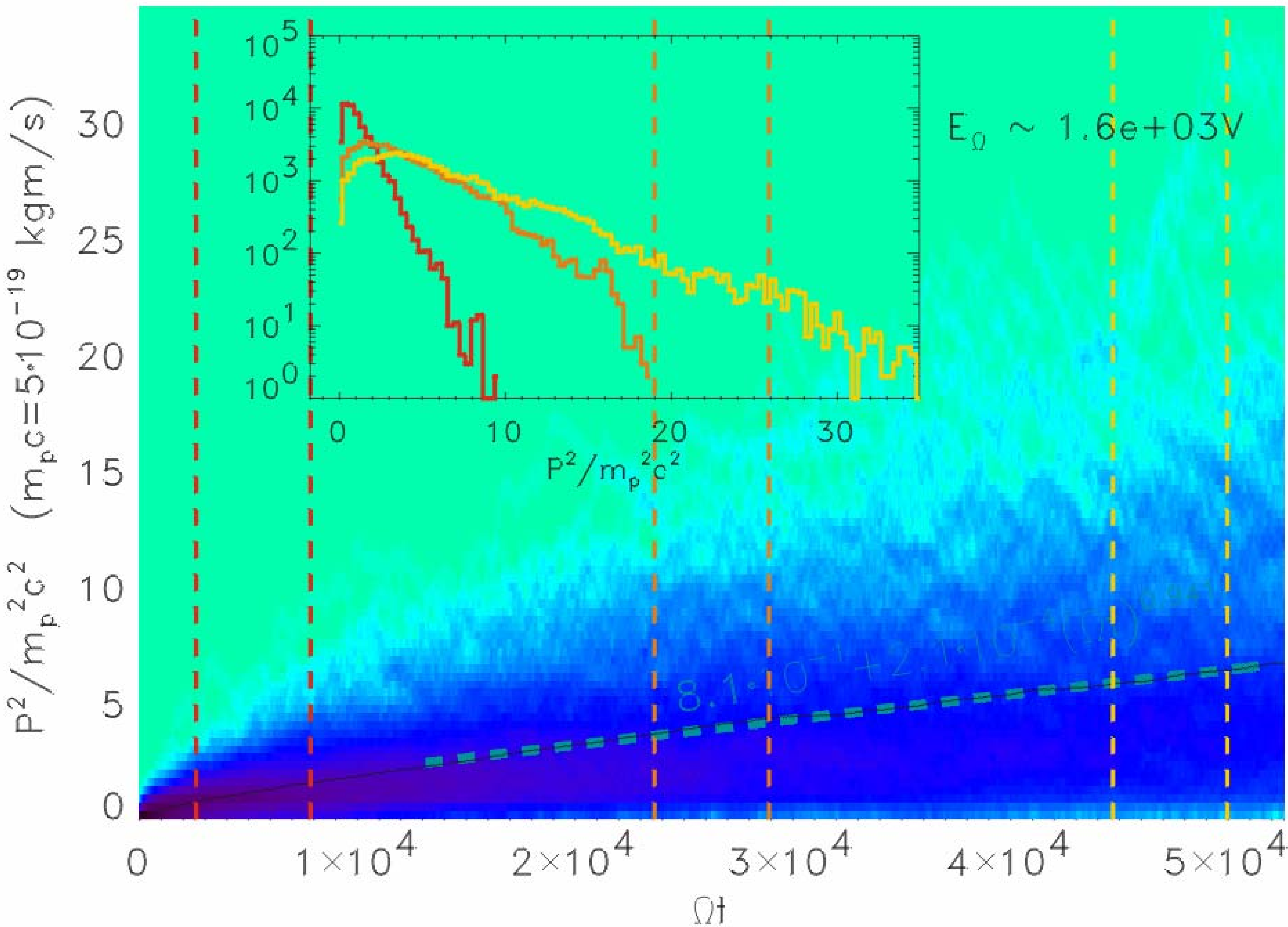




deceleration between dissipation regions

Electron Acceleration

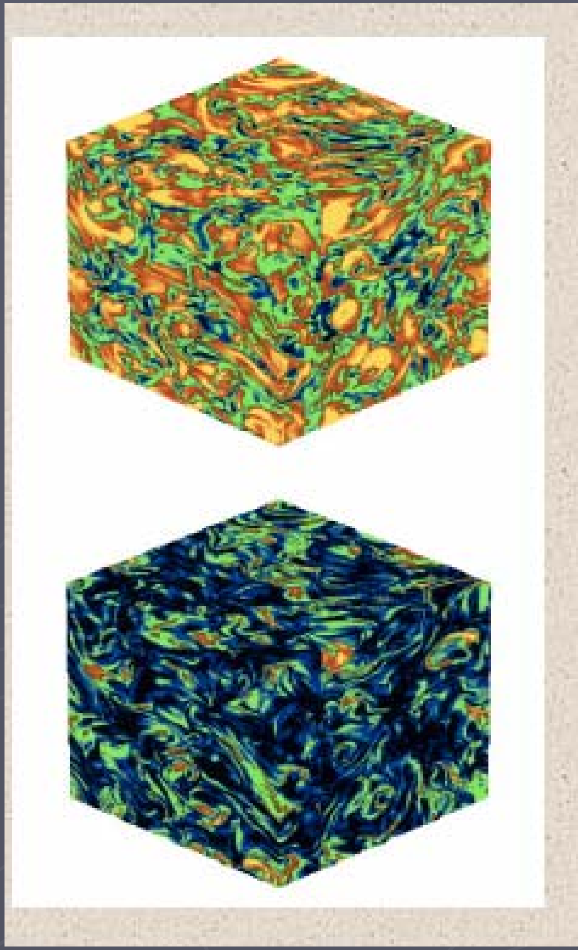




$E_\Omega \sim 1.6e+03V$
$P^2/m_p^2c^2 \quad (m_pc=5\cdot10^{-19}\ kgm/s)$
Ωt
$P^2/m_p^2c^2$
0
5
10
15
20
25
30
0
1×10^4
2×10^4
3×10^4
4×10^4
5×10^4
10^0
10^1
10^2
10^3
10^4
10^5
0
10
20
30

MHD turbulence

- Dmitruk et al ApJ, 2003, 2004
- Student appearance of current sheets and turbulent electric fields inside turbulence



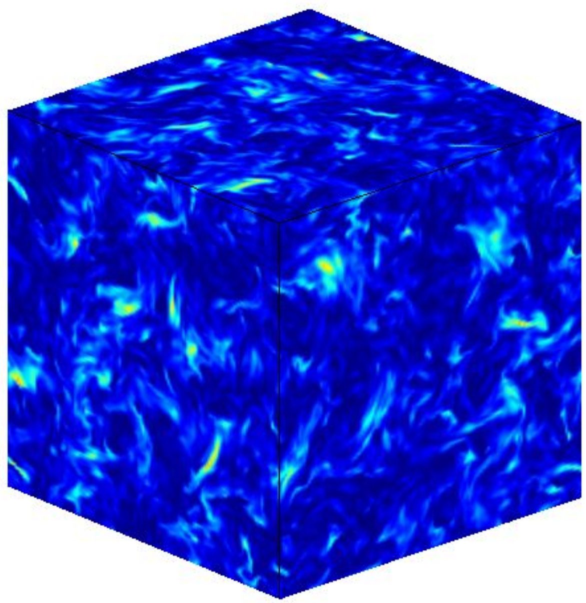
Quit time acceleration: an example of MHD Turbulence

(Lepreti, Isliker, Petraki, Vlahos, submitted)

- The presence of electric fields in a driven magnetic field forming continuously magnetic discontinuities. The simulation was done using a shell model

$$\vec{j}(r,t) = \nabla \times \vec{B}(r,t)$$

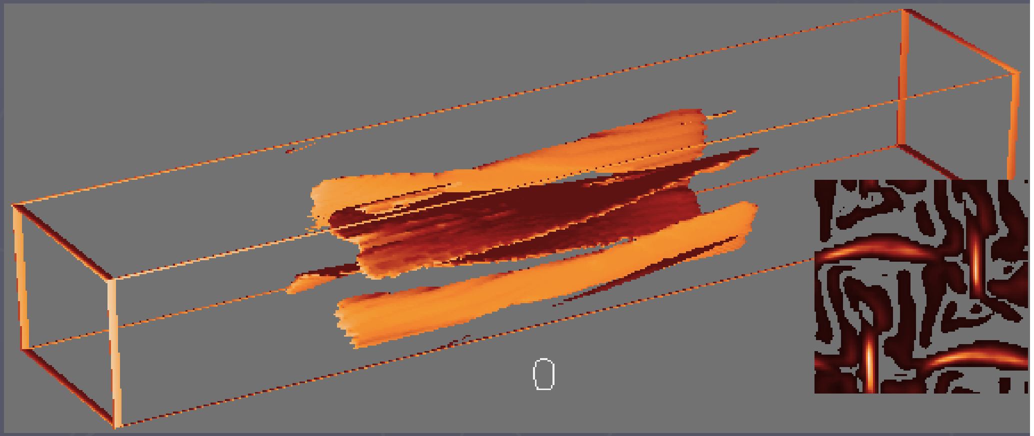
$$\vec{E}(r,t) = -\frac{\vec{v} \times \vec{B}(r,t)}{c}$$



Particle acceleration in stochastic current sheets

(Rim Turkmani et al, ApJL2004, AA 2005)

- Particles injected at random positions within an MHD box
  - Protons 0.027 kev
  - Electron 1.16 kev
- Initial velocity fixed in amplitude, random in direction

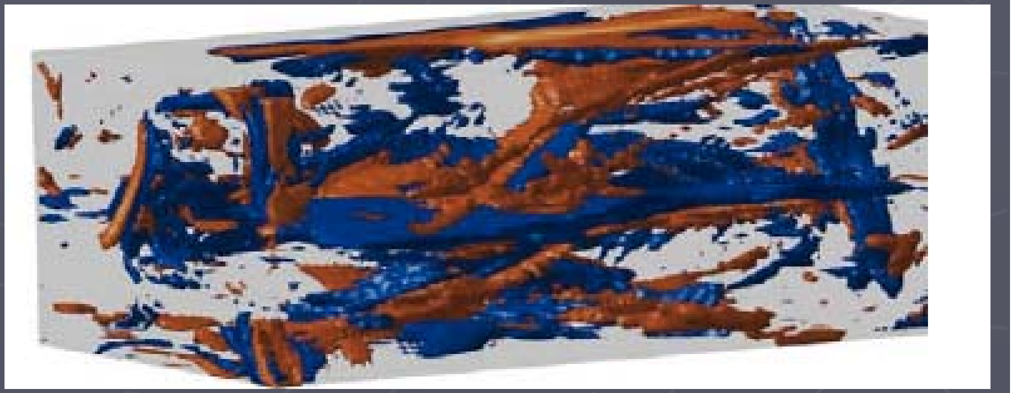


- Acceleration time scale

much shorter than

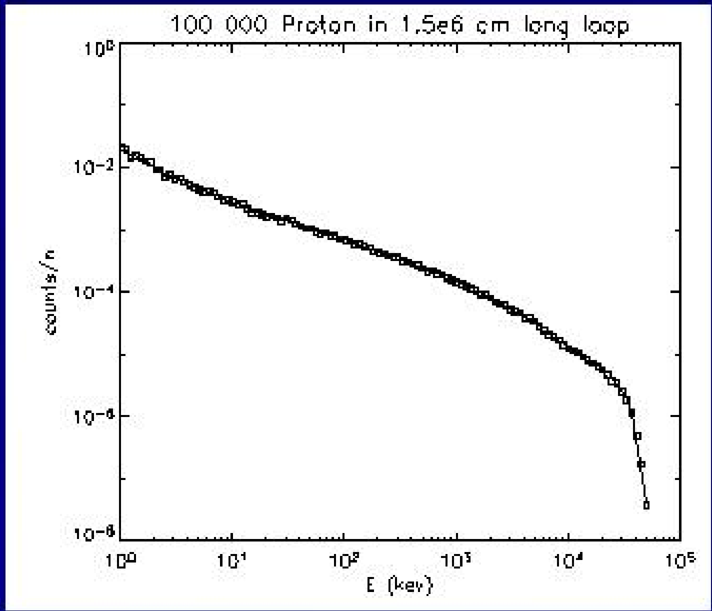
MHD time scale

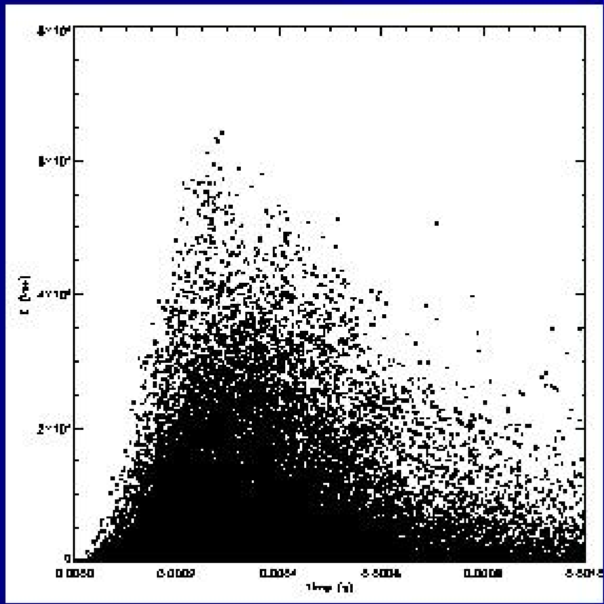
- B and E are scaled;
- initial values:
  - B: Mean ~ 1.0 (0.89 – 1.08)
  - E: Mean ~ 7e-4 (e-5 – e-2)



Distribution Functions

- 100,000 proton in 100 G magnetic field run for 1 ms

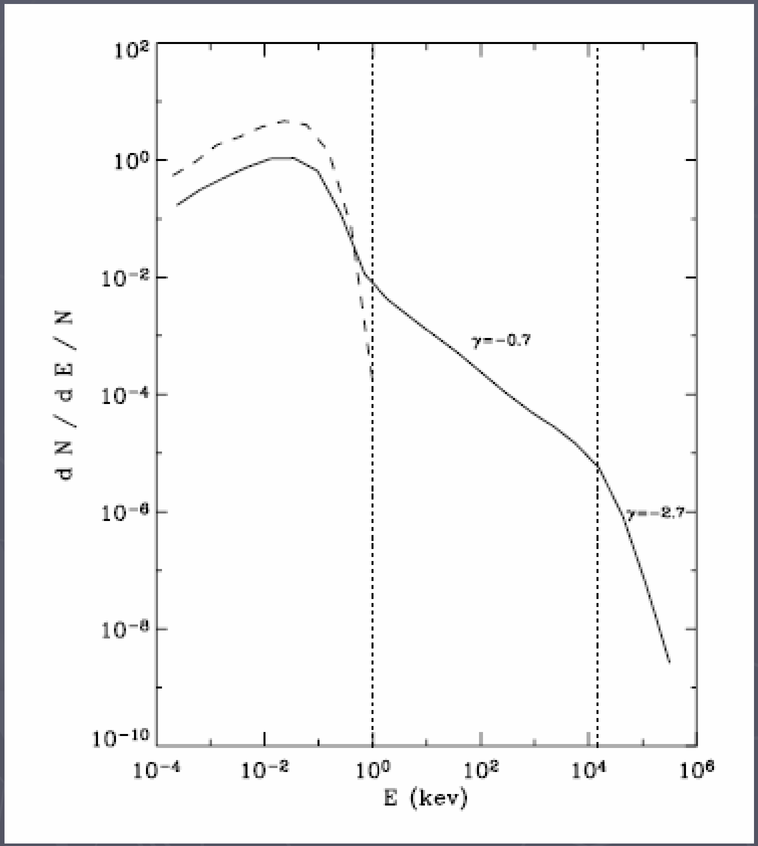




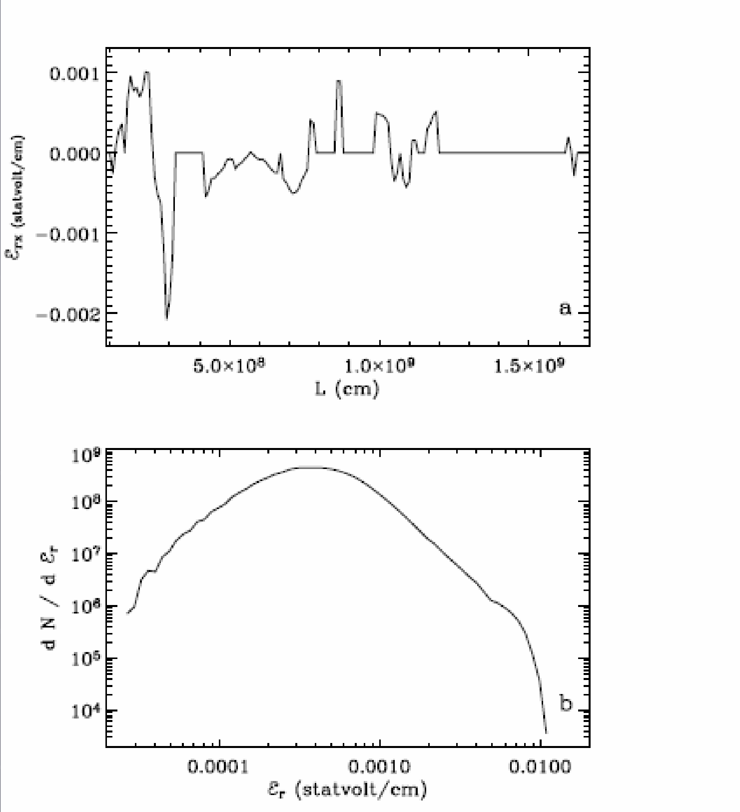
- Two parts power law

- ~ 60 Mev in 0.3 ms

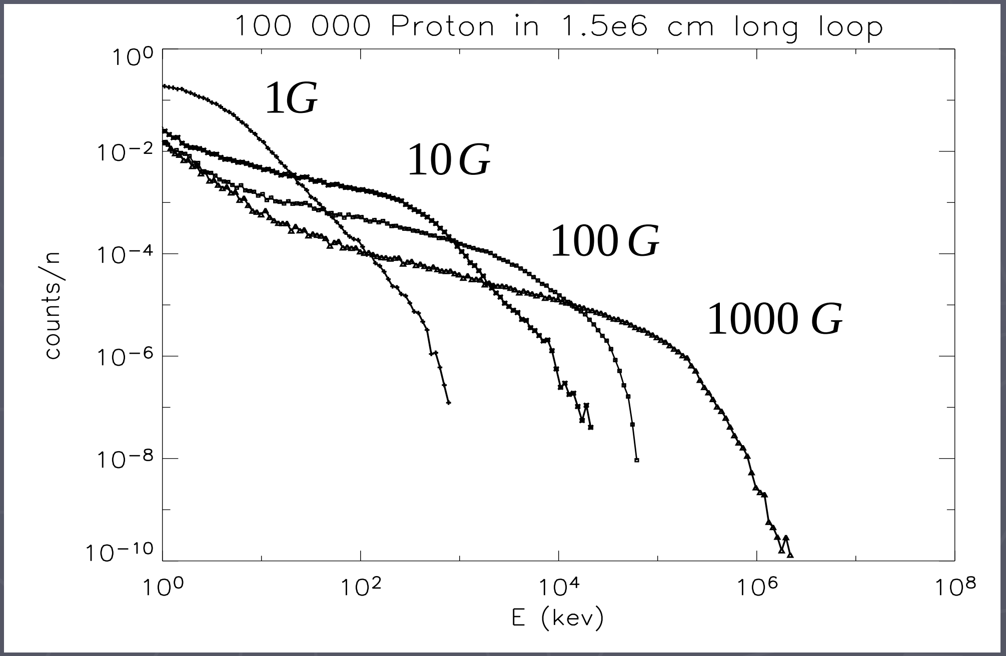
Turkmani et al



- Velocity distribution



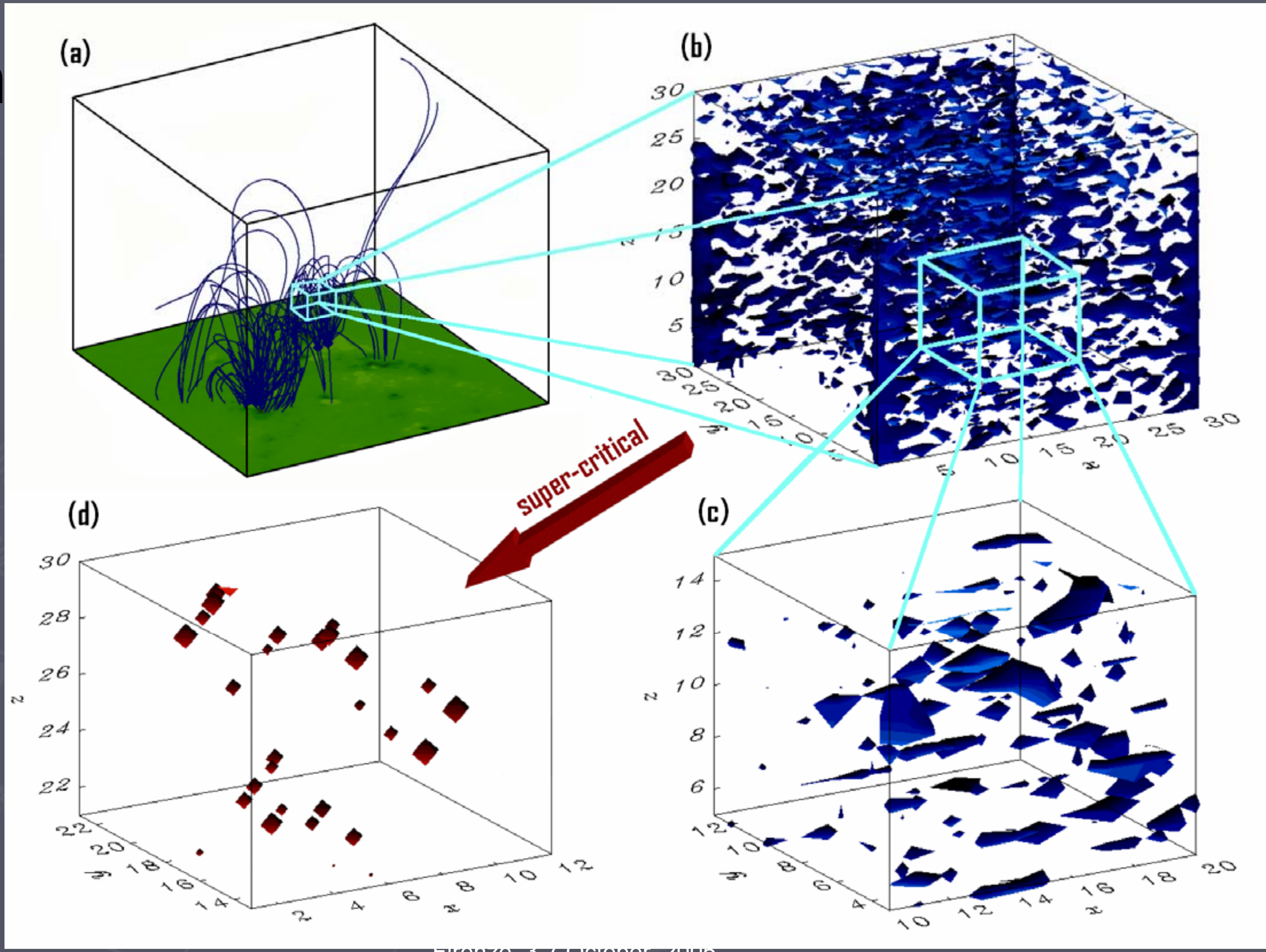
Scaling with E and B



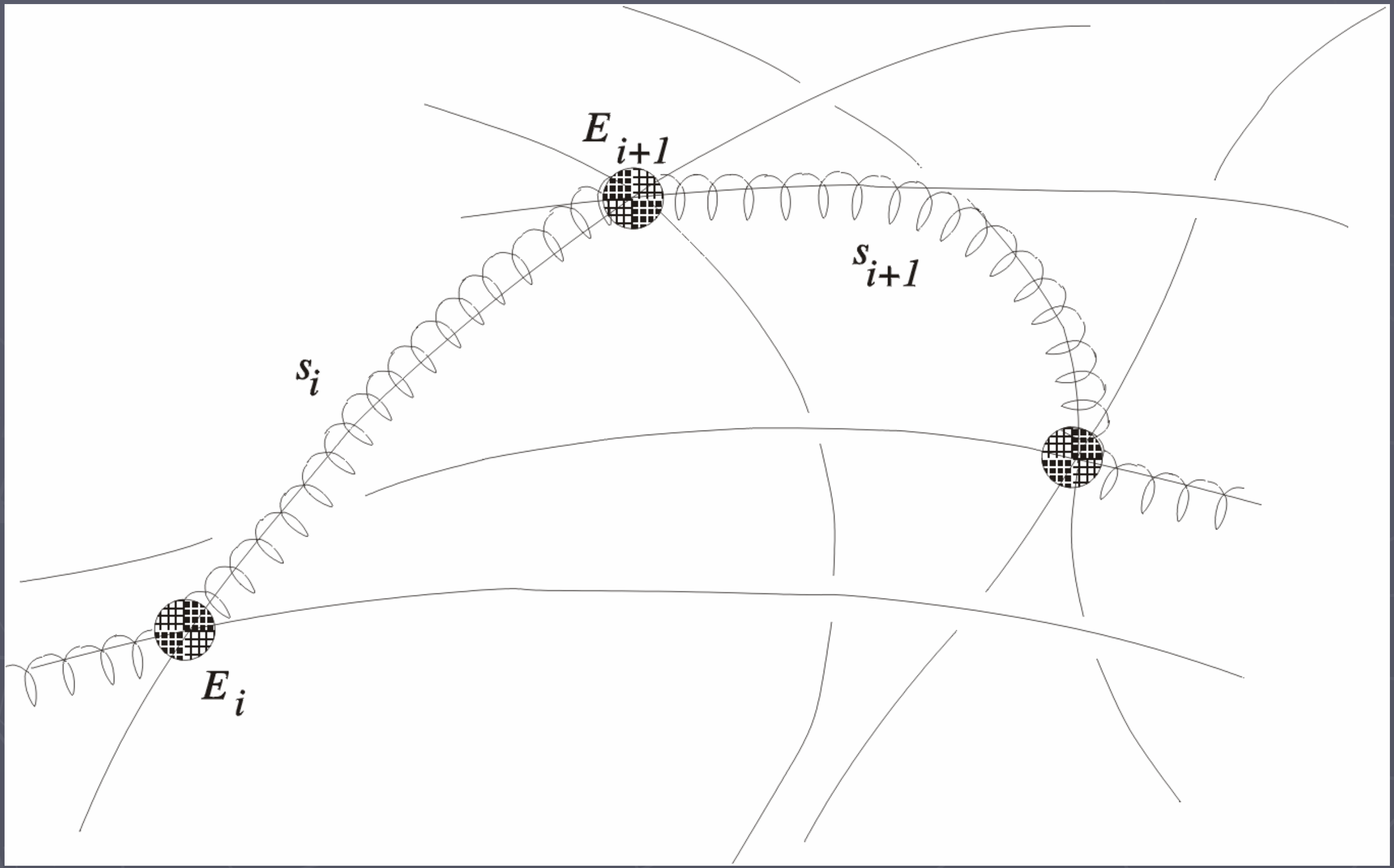
Acceleration scales almost linearly with the values of the magnetic and electric fields

Using the X-CA model

- From



Sporadic formation of current sheets
Vlahos, Isliker and Lepreti (ApJ, June 10,2004)



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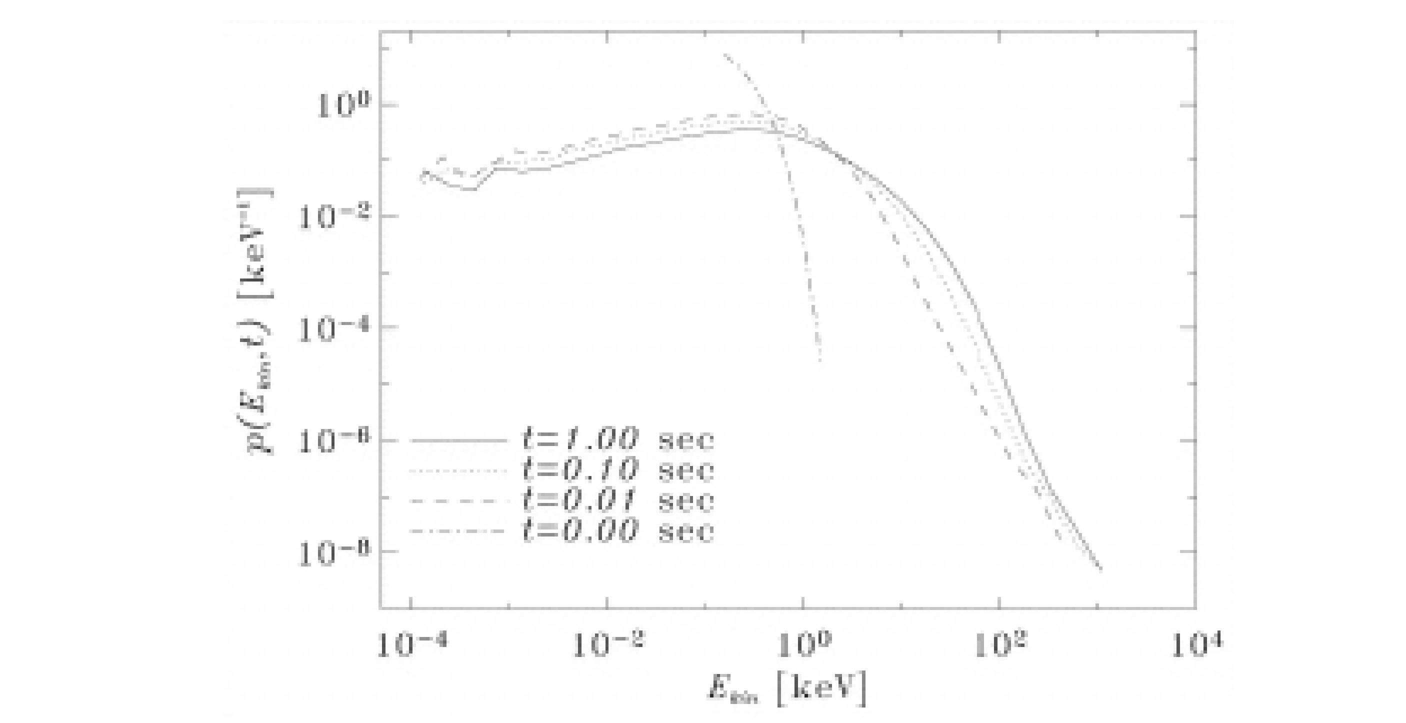
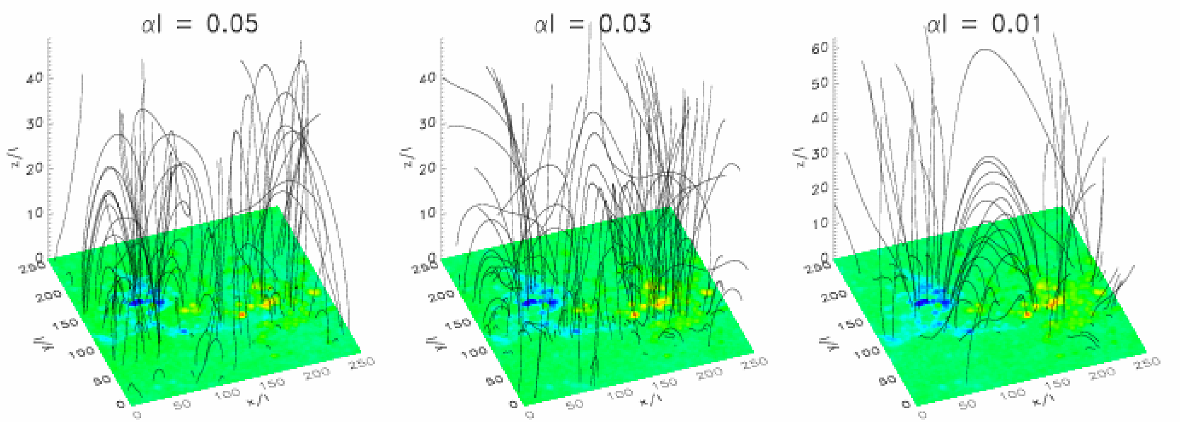


Arzner and Vlahos (2005)

5 Force-Free Extrapolation ($\nabla \times \mathrm{B} = \alpha \mathrm{B}$)

Assuming constant α, the force-free condition implies $|\mathbf{k}|^2 = \alpha^2$. Fitting the z-components of the eigenvectors $\mathrm{b}(\mathbf{k})e^{i\mathbf{k}\cdot\mathbf{x}}$ at z = 0 to the magnetogram yields

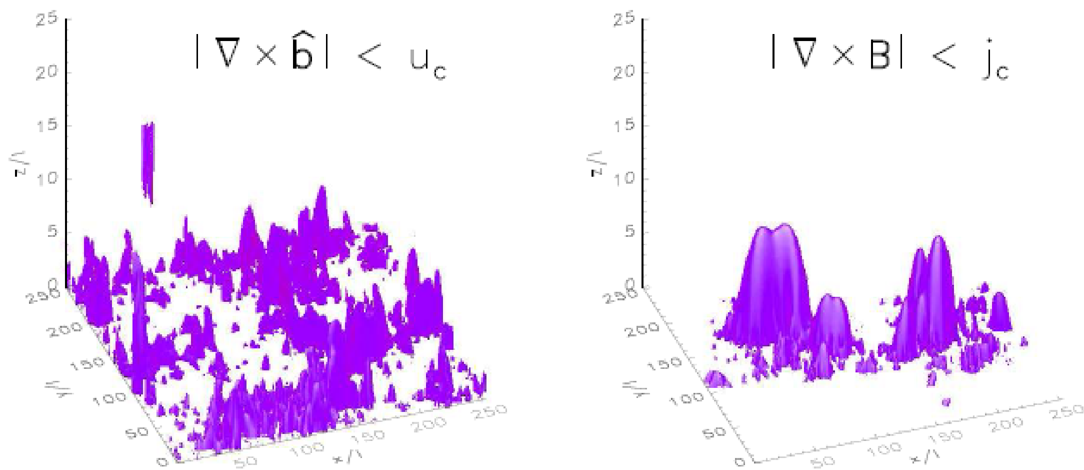


The shown fieldlines start at z = 0 at random with density $\propto |\mathrm{B}(x, y, 0)|$. The majority (>99%) of used modes decays with height (Im $k_z > 0$). Small scales decay more rapidly; the largest decaying scale is $2\pi/\alpha$.

Arzner and Vlahos (2005)

6 Anomaleous Resistivity η and Dissipative Field $\mathbf{E} = \eta \mathrm{j}$

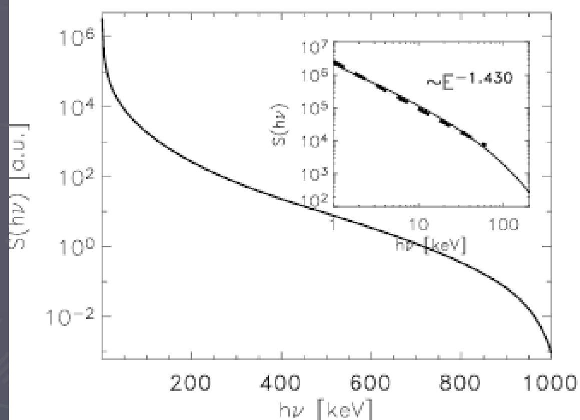
Several criteria (drift wave- or MHD kink instabilities, qualitative non-linear arguments) for the occurrence of anomaleous resistivity have been proposed; but no general and rigorous results seem available. Two plausible criteria are:

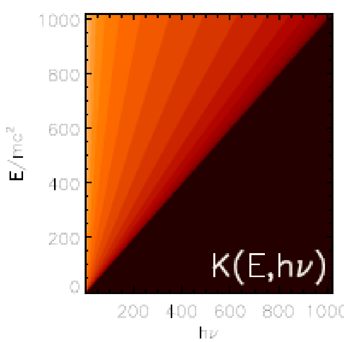


We use here the twist threshold (left, $\hat{\mathrm{b}} = \mathrm{B}/|\mathrm{B}|$), motivated by Parker's critical angle. Our u_c corresponds to a twist scale $1/u_c \sim$ 3000 km. Inside the violet regions, $\eta > 0$ and $\mathbf{E} = \eta \mathrm{j}$ exceeds E_D by about one magnitude. By the force-free assumption $\mathrm{j} = \alpha \mathrm{B}$ with $\alpha > 0$, $\mathbf{E}$ is *parallel*.

Arzner and Vlahos (2005)

13 HXR Spectrum (Thick-Target Bremsstrahlung)





The HXR spectrum $S(h\nu)$ is obtained from the electron spectrum $f(E)$ by

$$S(h\nu) = \int_{h\nu}^{\infty} K(E, h\nu) f(E)\, dE$$

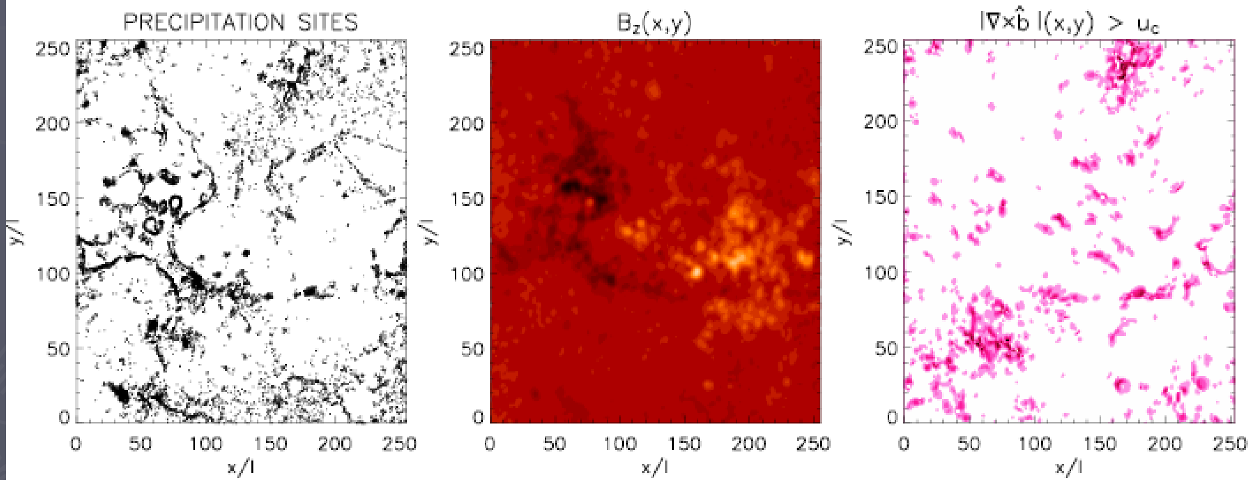
with kernel

$$K(E, h\nu) = \int_{h\nu}^{E} \sigma(E', h\nu) \frac{v'}{\dot{E}'}\, dE'$$

where $\sigma(E, h\nu)$ is the Bethe-Heitler cross section [general relativistic case, Koch & Motz (1959) 3BN, incl. Elwert's Coulomb screening], and assuming that $\dot{E} \propto v/E$ (Brown, 1971).

Arzner and Vlahos (2005)

11 Predicted Impact (HXR) Map



Absolute scaling: $l \sim 1$". Few impacting particles at positive polarity ($B_z > 0$) because of the assumption $\alpha > 0$.

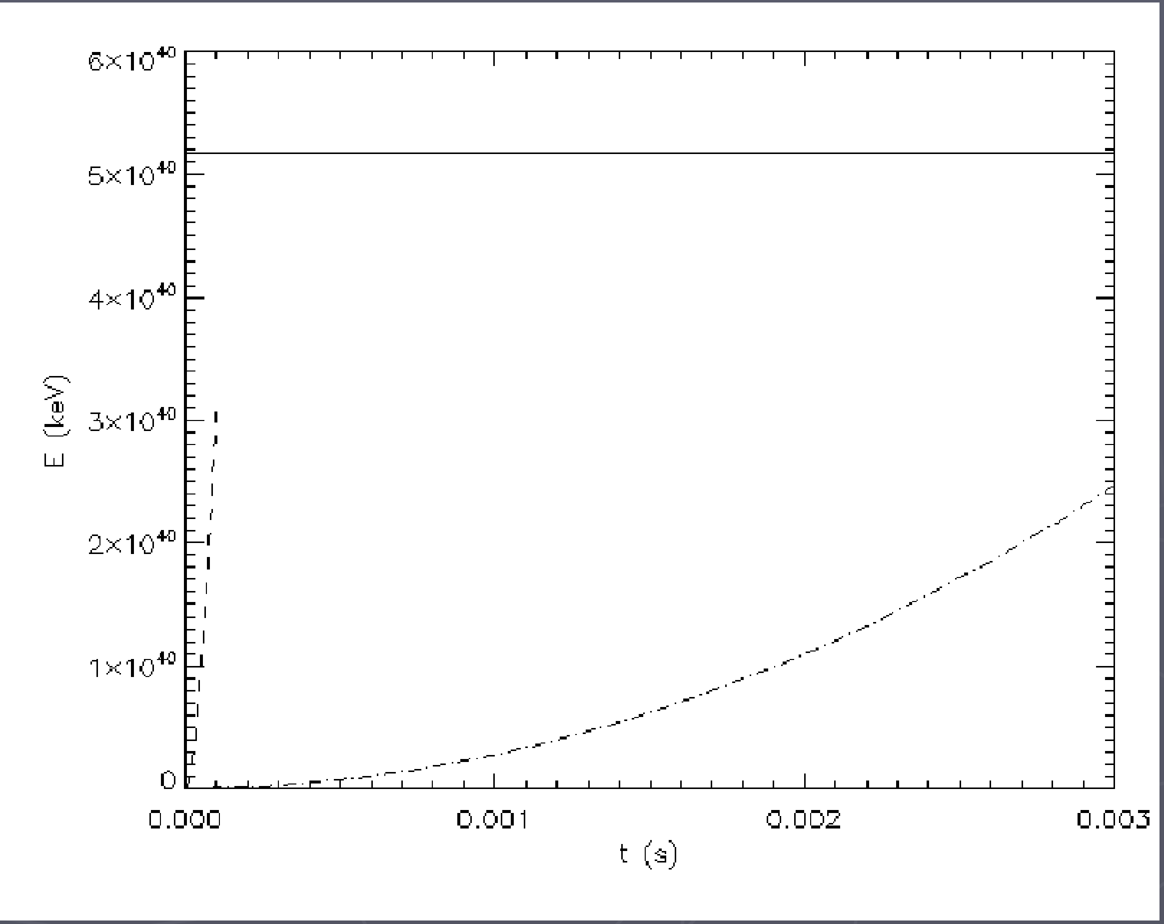
The impact map will provide a straightforward experimental test when compared with RHESSI pictures!

Why all the spectra estimated so far are not consistent with observations?
Are we reaching the limits of MHD theory?

Several resistive MHD codes existing today should be revised!

Kinetic energy as a function of time

E_k (keV)



.... protons

.... electrons

t (s)

Key observational constrains-revisited

- The number of particles accelerated 10^37particles /sec OK
- Avery large fraction (40-50%) of the energy released in flares goes to high energy particles (E_0=10-15 KeV) OK
- The distribution of high energy particles (electron and ions) develop very specific power laws above a certain energy PROBLEM
- Very good connection with particles in space OK
- Spatial characteristics... foot points and loop top sources (in a few flares). OK
- Motion of the foot points OK Dynamics of the overall structure
- Fast time scale acceleration OK

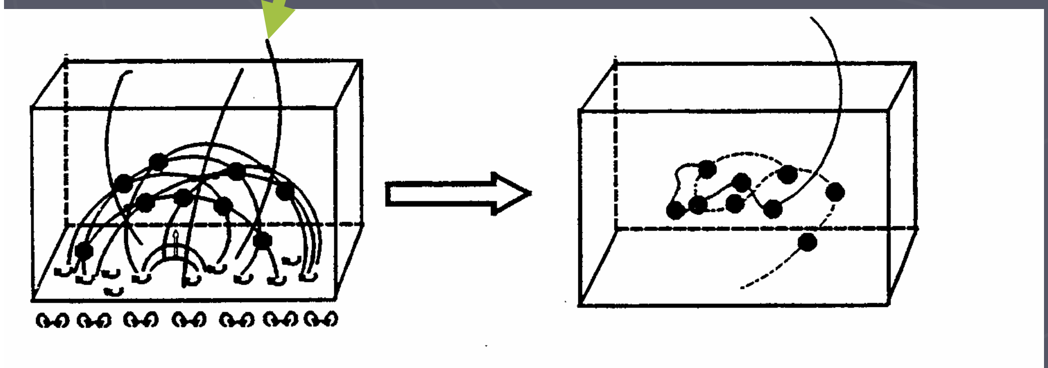
E_0

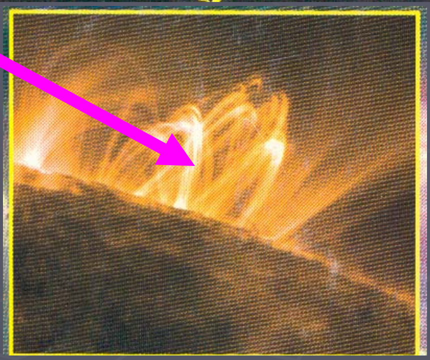
Summary

- Why the sun is so efficient accelerator?
- Do we expect loop tops and foot points in complex magnetic topologies?
- Does the sun accelerate particles all the time?
- Are flares continuous in the sun?
- Do turbulent electric fields produce hot and non thermal particles?

History....

- Vlahos(1992/1993), Vlahos and Anastasiadis (1991-92)





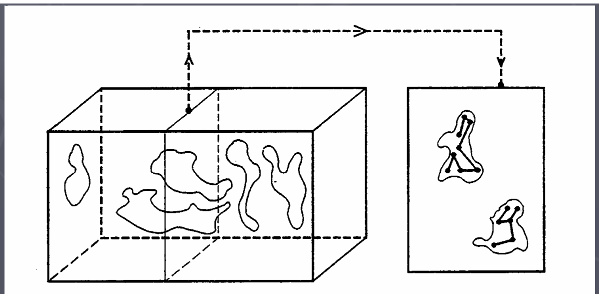


Figure 3. Formation of clusters of neutral sheets inside the active region.

Plans for the feature

- Can we combine large scale evolution using Ideal MHD and CA at the discontinuities?
- Can we develop better and more efficient extrapolation techniques so we can drive the fields from realistic photosperic magnetic fields and motions?
- Can turbulent electric fields be the answer to coronal heating and particle acceleration?