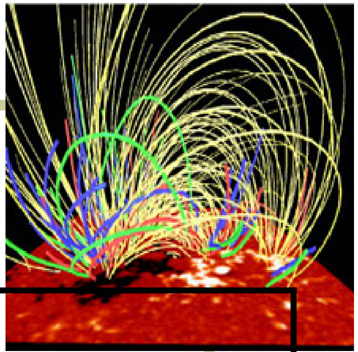
Particle acceleration and radio emission from complex active regions



Loukas Vlahos in collaboration with

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9/6/2004

Main questions

- Where are electrons accelerated?
- How are they accelerated?
- Can they all be accelerated at the loop top?

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

$$N = V n_e = L^3 n_e$$

- **For $n_e = 10^{10} cm^{-3}$**
- **$L = 2\ 10^9$ cm (0.5 arcminute!)**

Model Questions

- We need a **magnetic topology**
- We need an **energy release** mechanism.
- We need an **acceleration mechanism** with the ability to accelerate ions and electrons very efficiently
- We need **emission mechanism (s)**

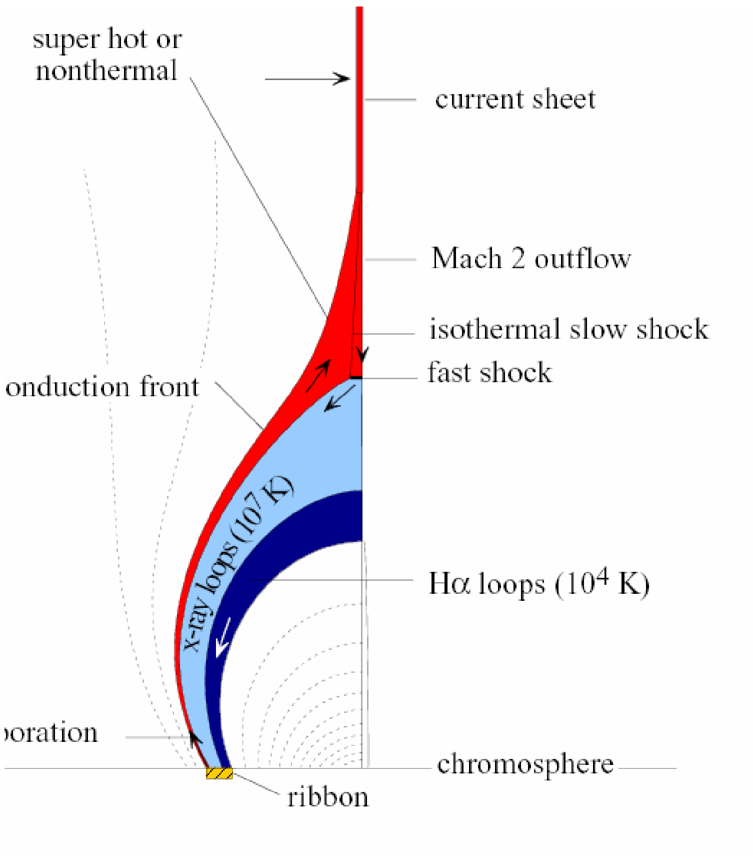
We can assume that

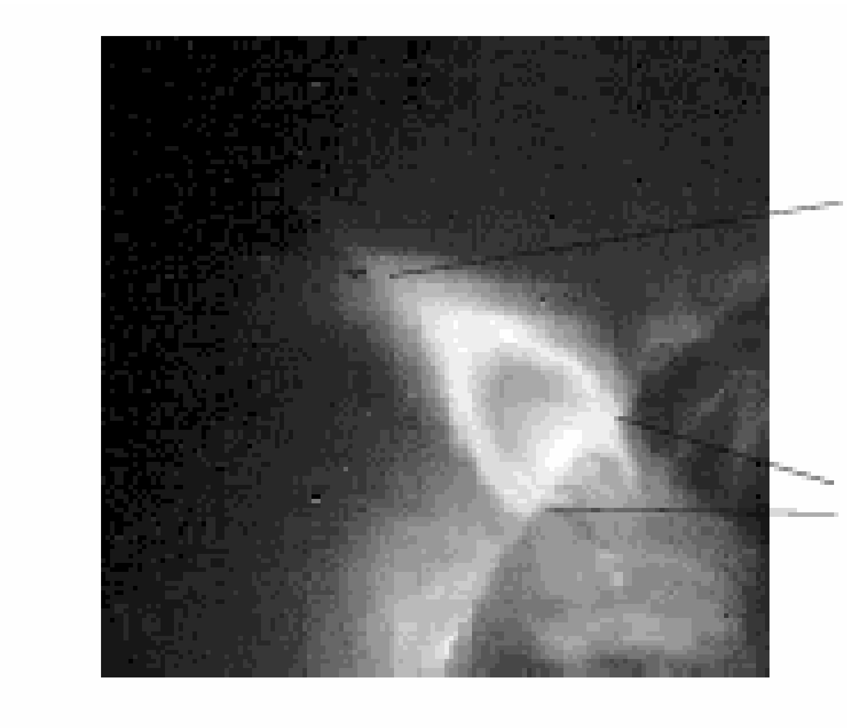
- The **magnetic topology** is simple or complex: a magnetic **loop or millions** of magnetic loops derived from the extrapolation of the magnetograms**.** (Unfortunatly this is a free parameter)
- The **energy release** is magnetic dissipation in unstable current sheets
- The emission mechanism may be : incoherent (**Bremsstrahlung or synchrotron** and/or coherent **(plasma processes (beam plasma, loss cone))**

The acceleration mechanism?

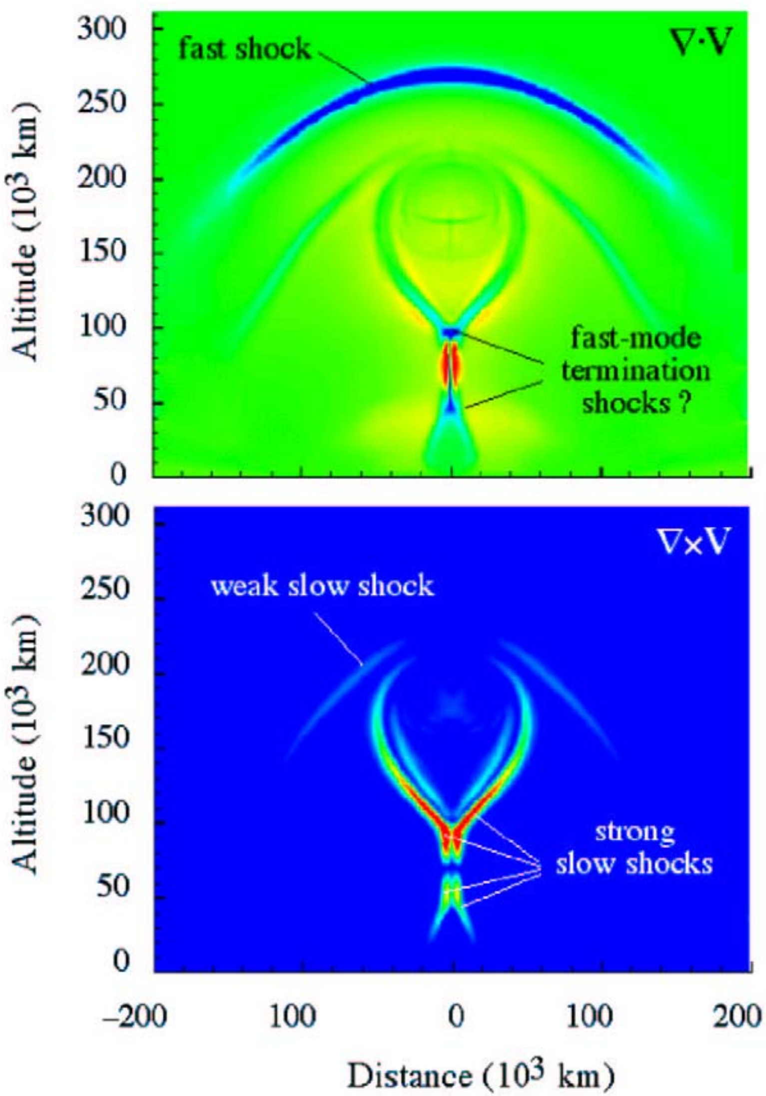
- **Electric fields** inside the current sheet or directly driven (Sub-Dreicer or super-Dreicer)
- **Shocks** supported by the energy release processe(s)
- **MHD Turbulence** excited by the energy release

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



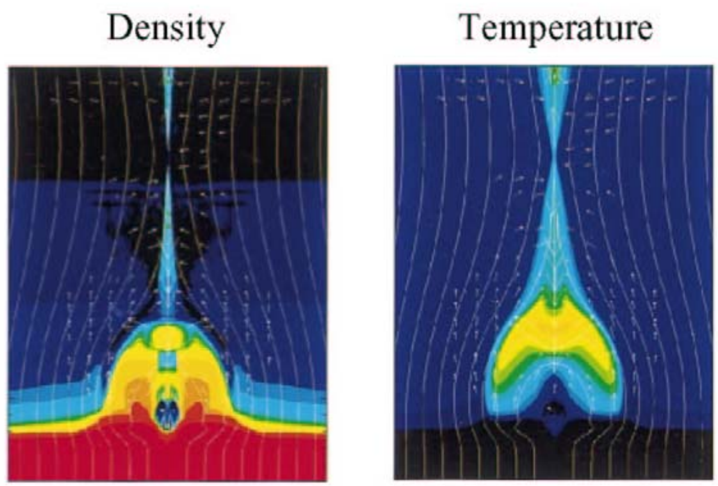


Shock Formation



Most Realistic Simulations of Flare Loops To Date

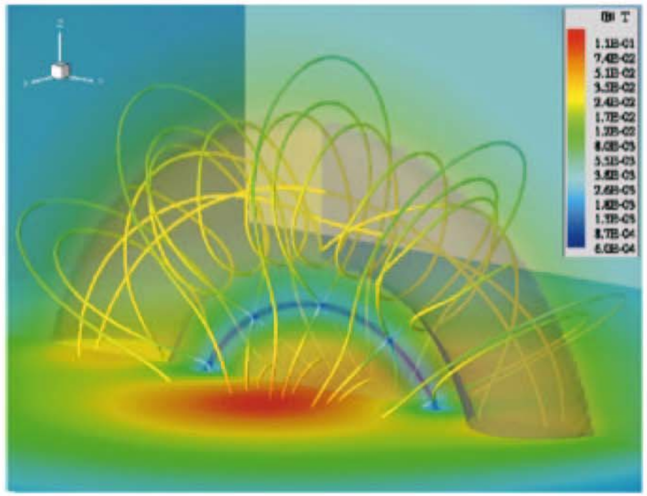
Yokoyama & Shibata (2001)



3D Flux Rope Simulation

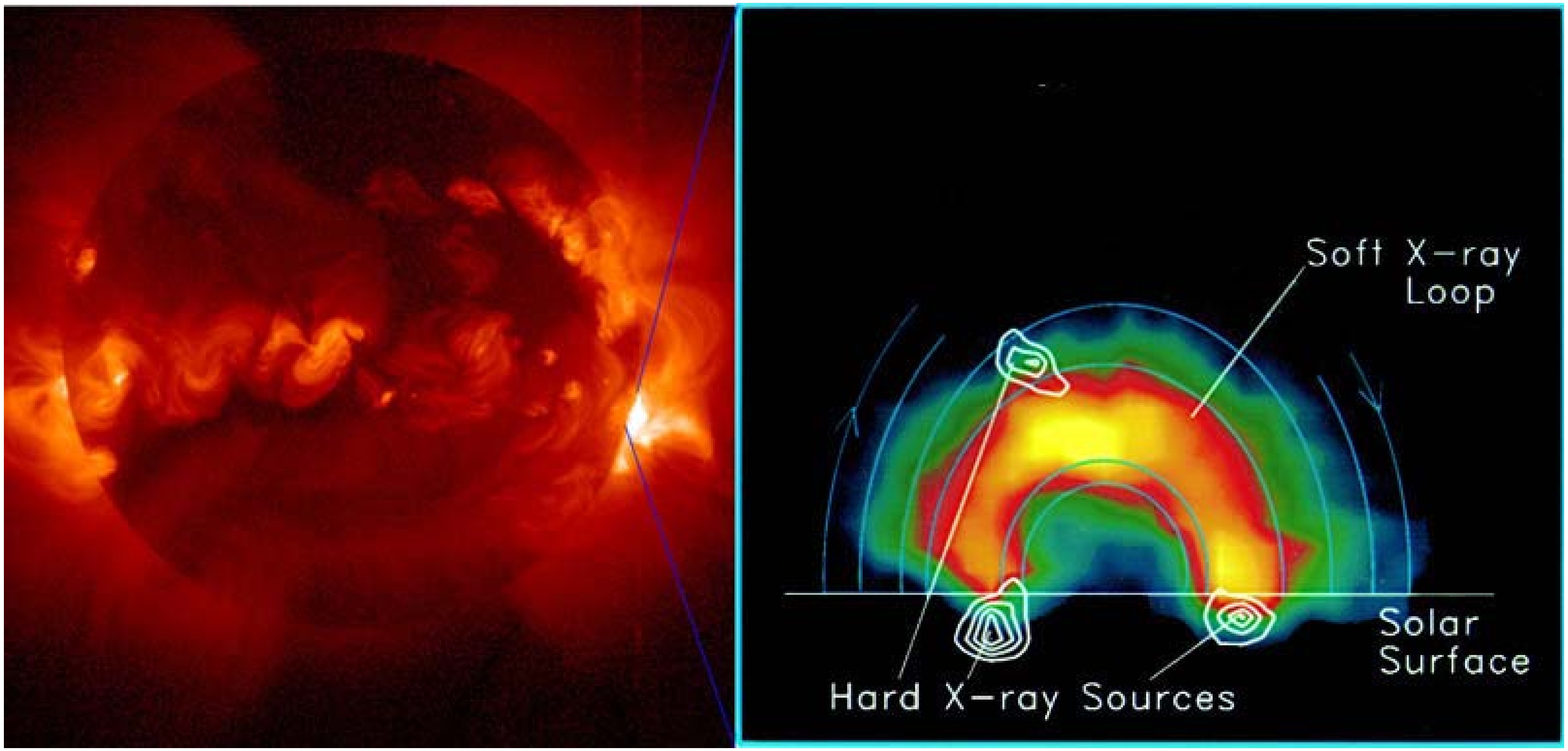
Roussev et al. (2003)

before



after

Impulsive Flare Geometry



MHD Turbulence the "standard" acceleration model

1. Alfven and fast mode waves generated at large scales (assumption)
2. Cascade to higher wave numbers (e.g., Zhou & Matthaeus 1989)
3. Fast mode waves energize electrons via transit-time acceleration (e.g., Miller 1997)
4. Alfven waves energize ions via gyroresonant acceleration (e.g., Miller & Roberts 1995)

➔ Both species accelerated by MHD turbulence

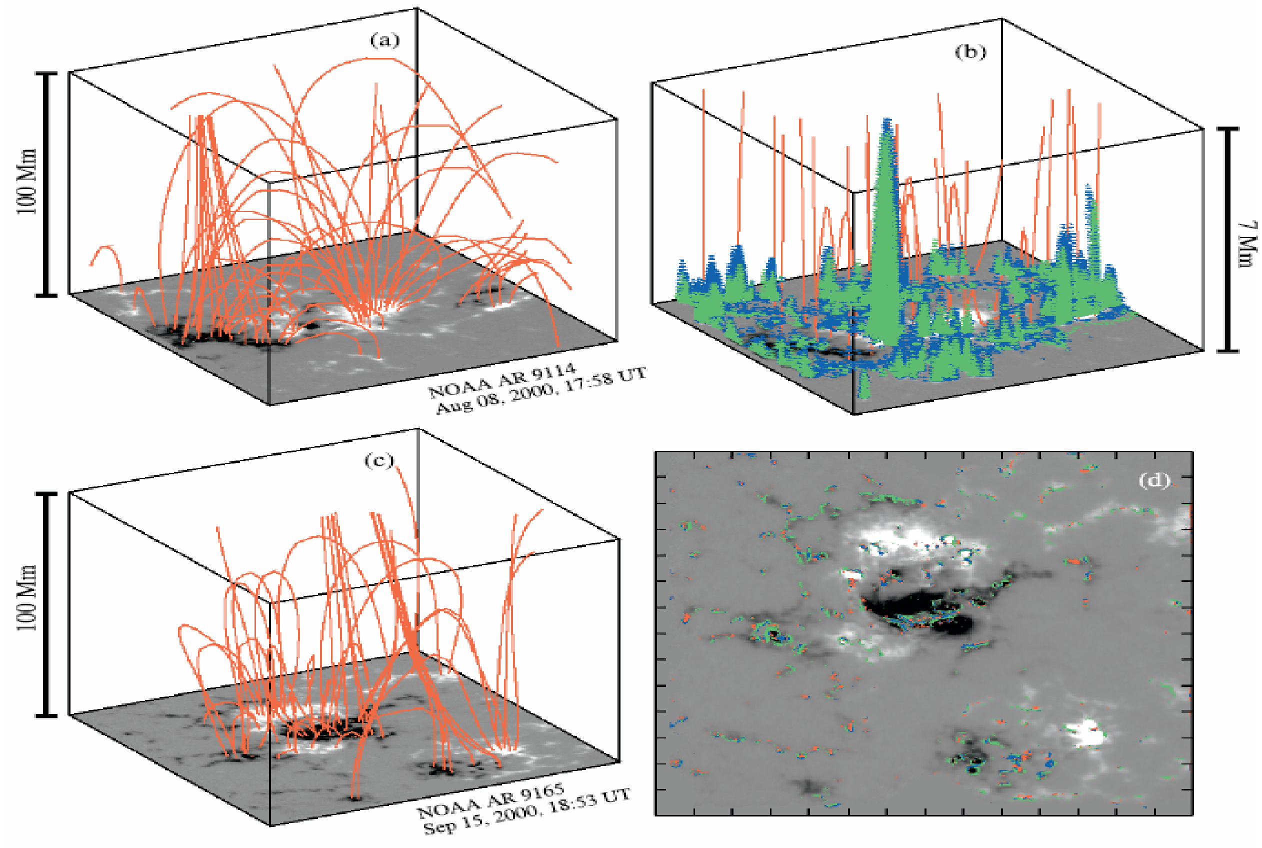
We have a problem!

- The standard model for energy release is in favor of E-field and shock acceleration
- The standard acceleration mechanism is in favor of a loop filled with MHD turbulence
- Who is correct?

For those looking for a standard model

- "Solar Flares are highly individualistic"
  - Smith and Smith, 1963
- No need for <u>the flare model</u>

Building up unstable discontinuities from the photosphere
(Vlahos+Georgoulis, ApJL, 2004)

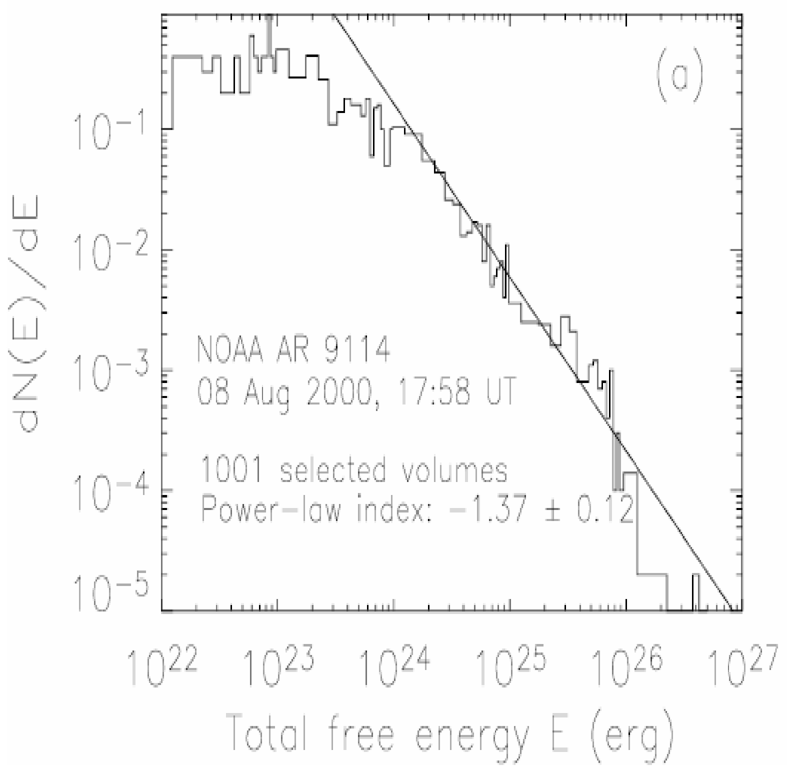


How do you define an unstable discontinuity

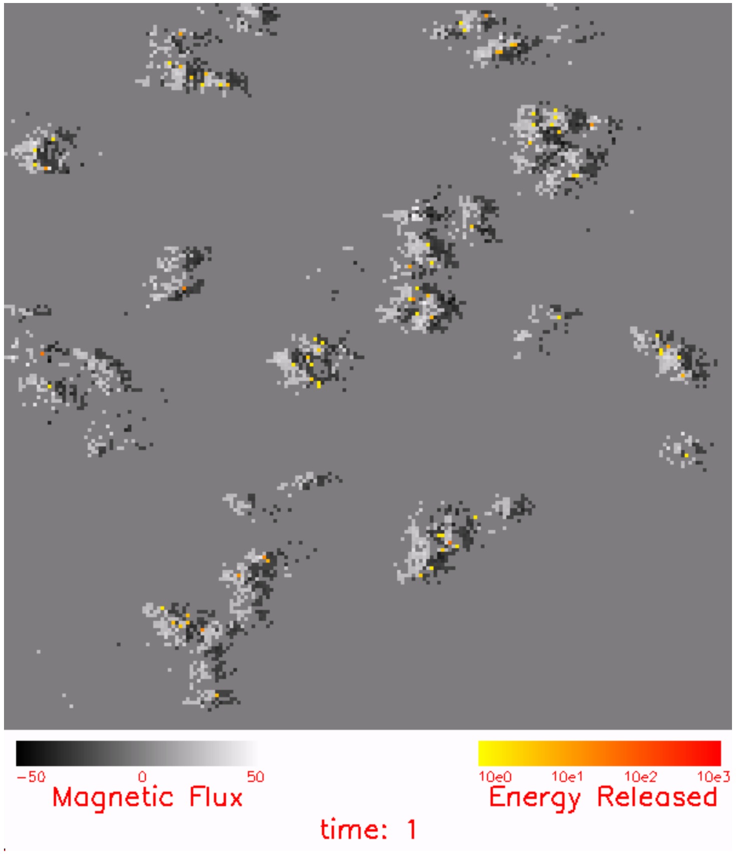
- We mark the points were (Parker's criterion)

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

is satisfied and multiply this volume with the magnetic energy in excess the potential energy



Evolving active regions build up constantly magnetic discontinuities….
(Fragos, Rantziou, Vlahos, AA, 2004)



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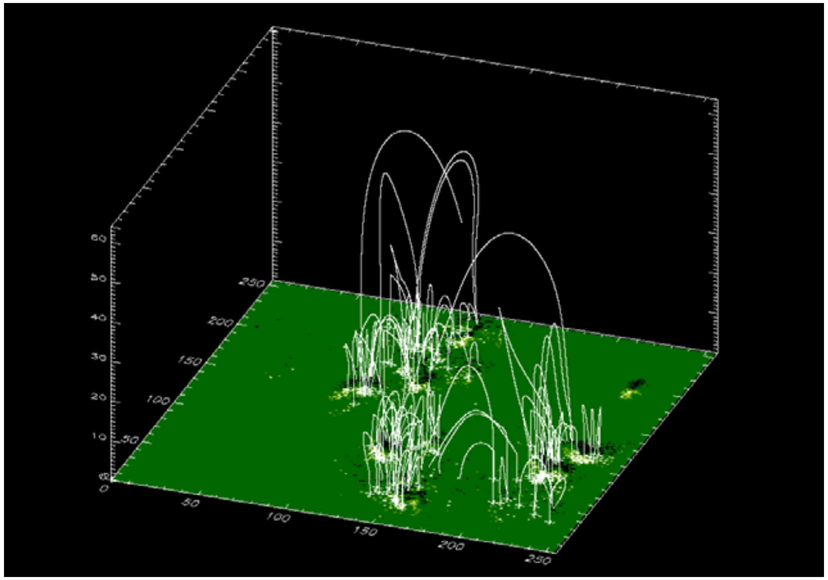
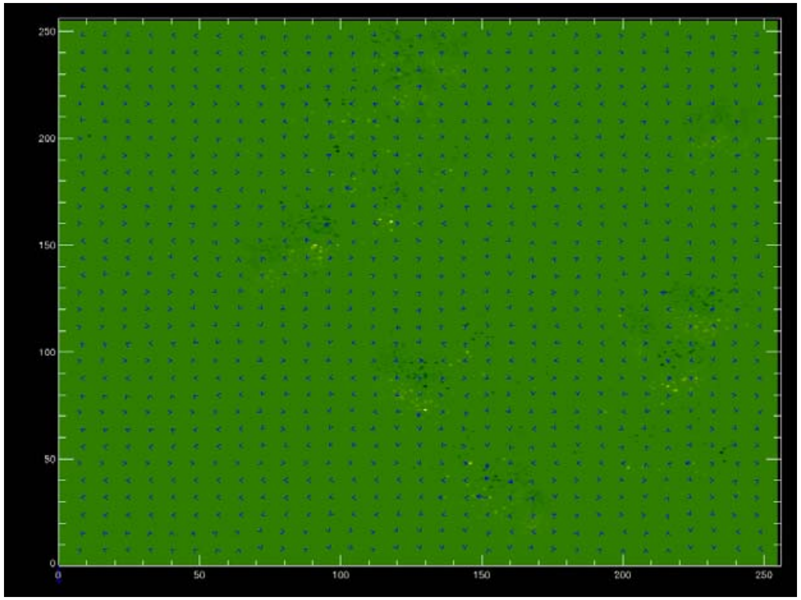
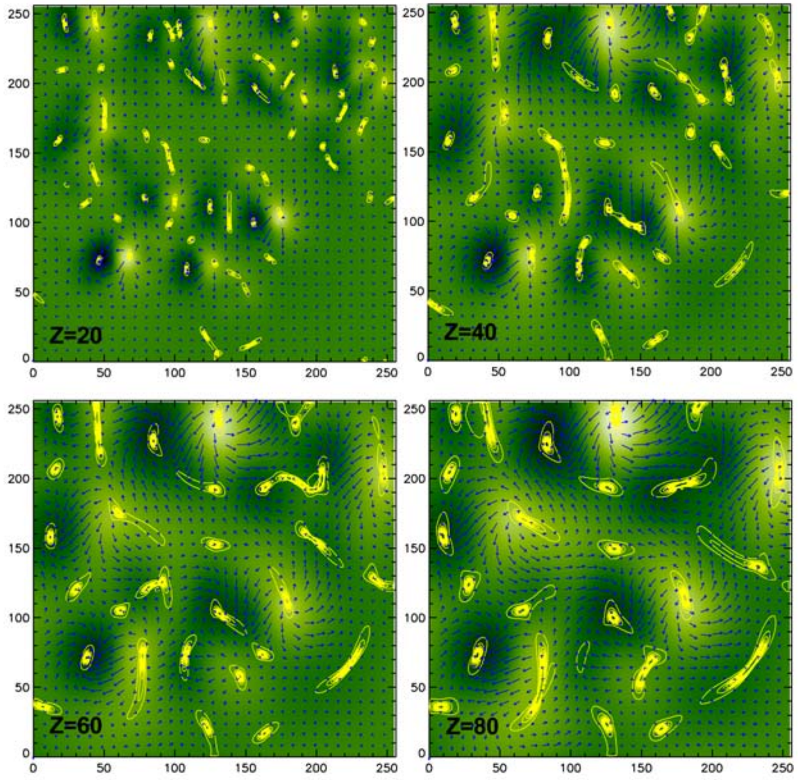
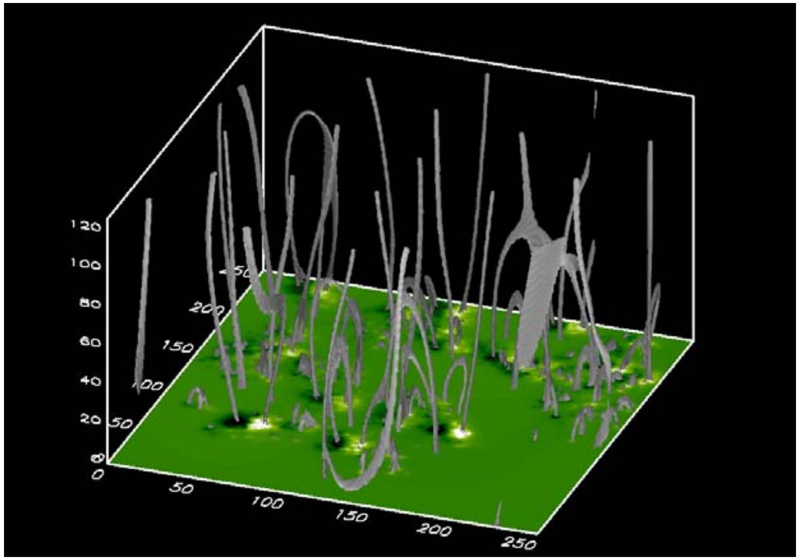




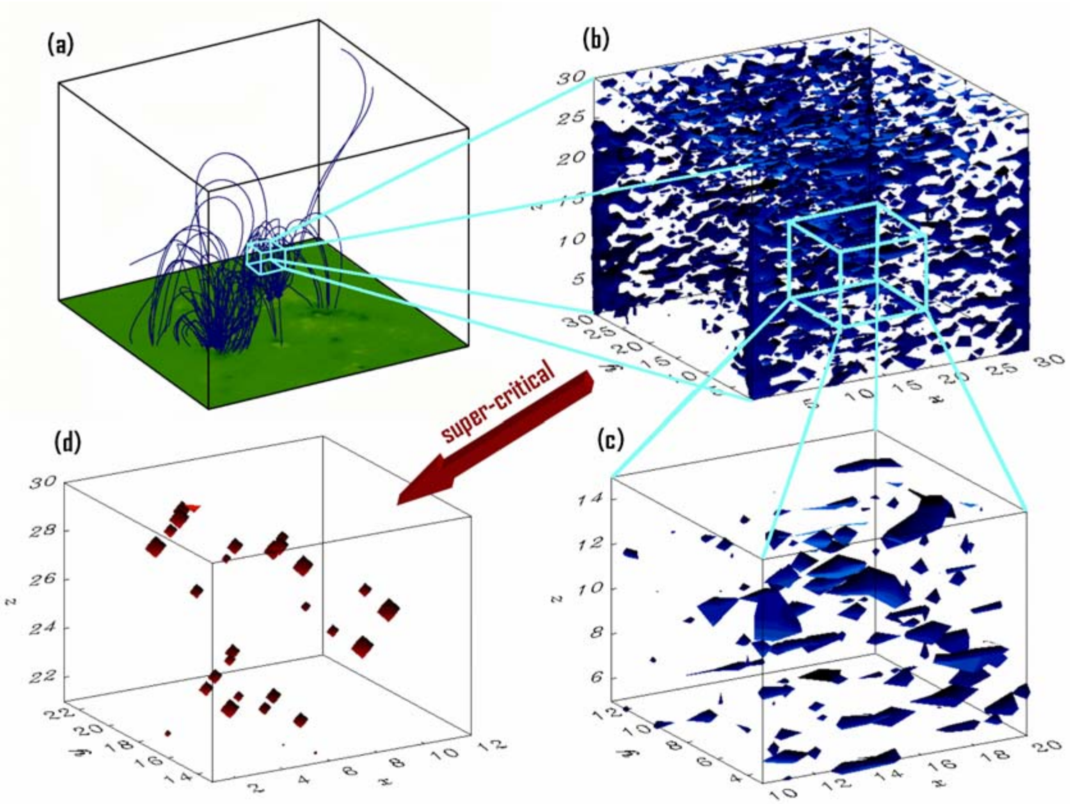
Dynamic motion of the photosphere builds constantly magnetic discontinuities
(Fragos, Rantziou, Vlahos, AA, 2004)



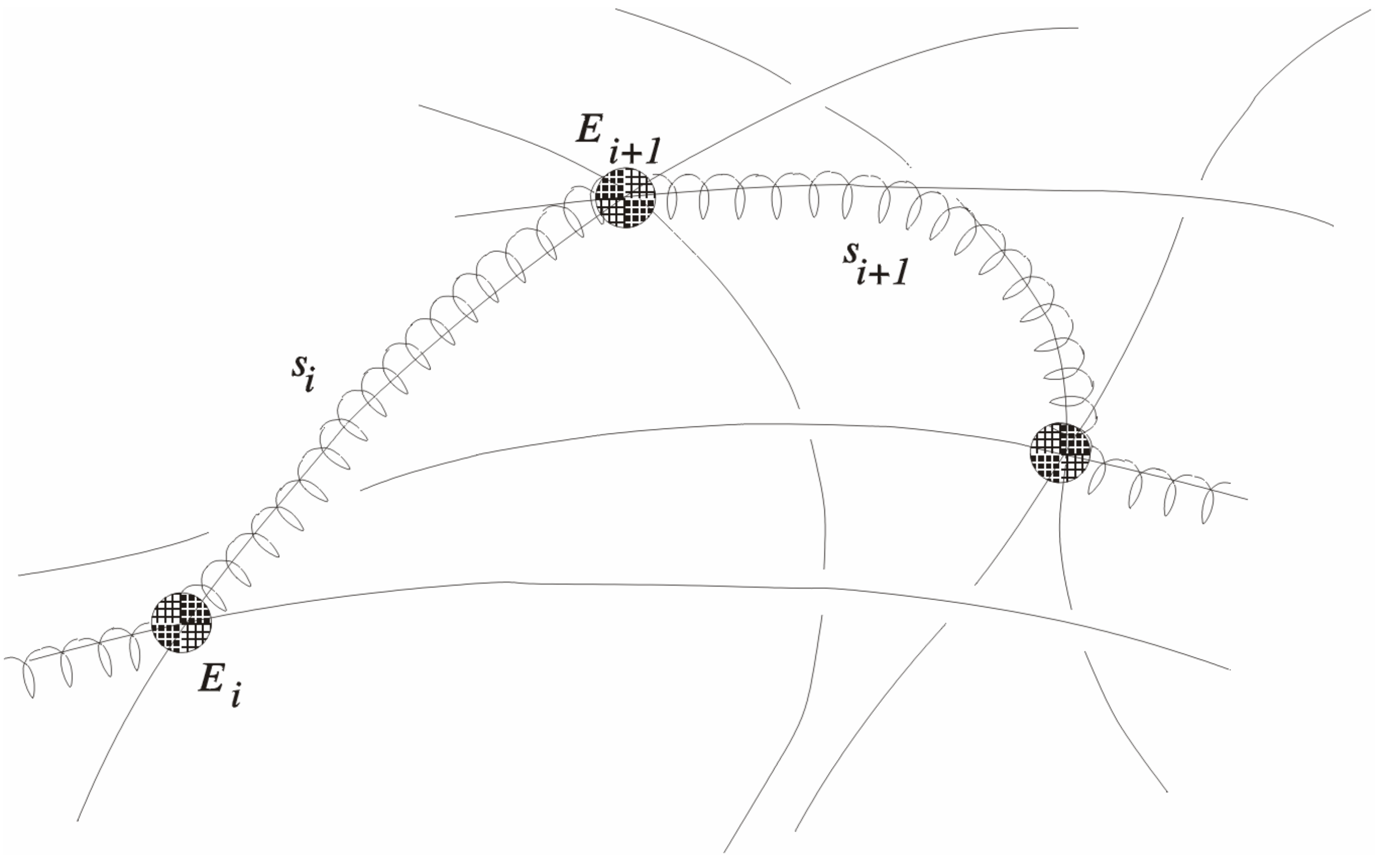


A New approach to an old problem

- From one current sheet to millions



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



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

$\mathbf{A} = \Sigma_{\mathbf{k}}\, \mathbf{a}_{\mathbf{k}} \cos(\mathbf{k}\cdot\mathbf{x} - \omega$

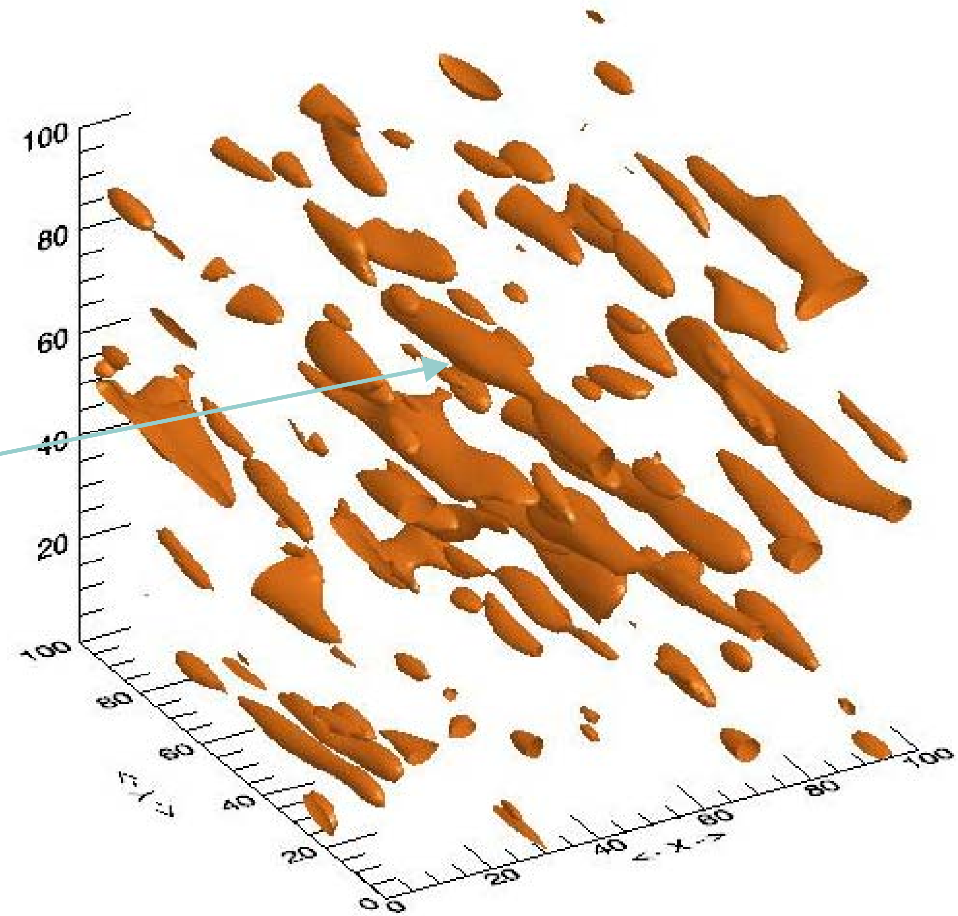
$\langle|\mathbf{a}_{\mathbf{k}}|^2\rangle \sim (1+ \mathbf{k}^T S \mathbf{k})^{-\nu}$

random $\phi_{\mathbf{k}}$

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

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

threshold j_c



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

$\partial_y << \partial_x, \partial_z$

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

Relativistic Particle Dynamics

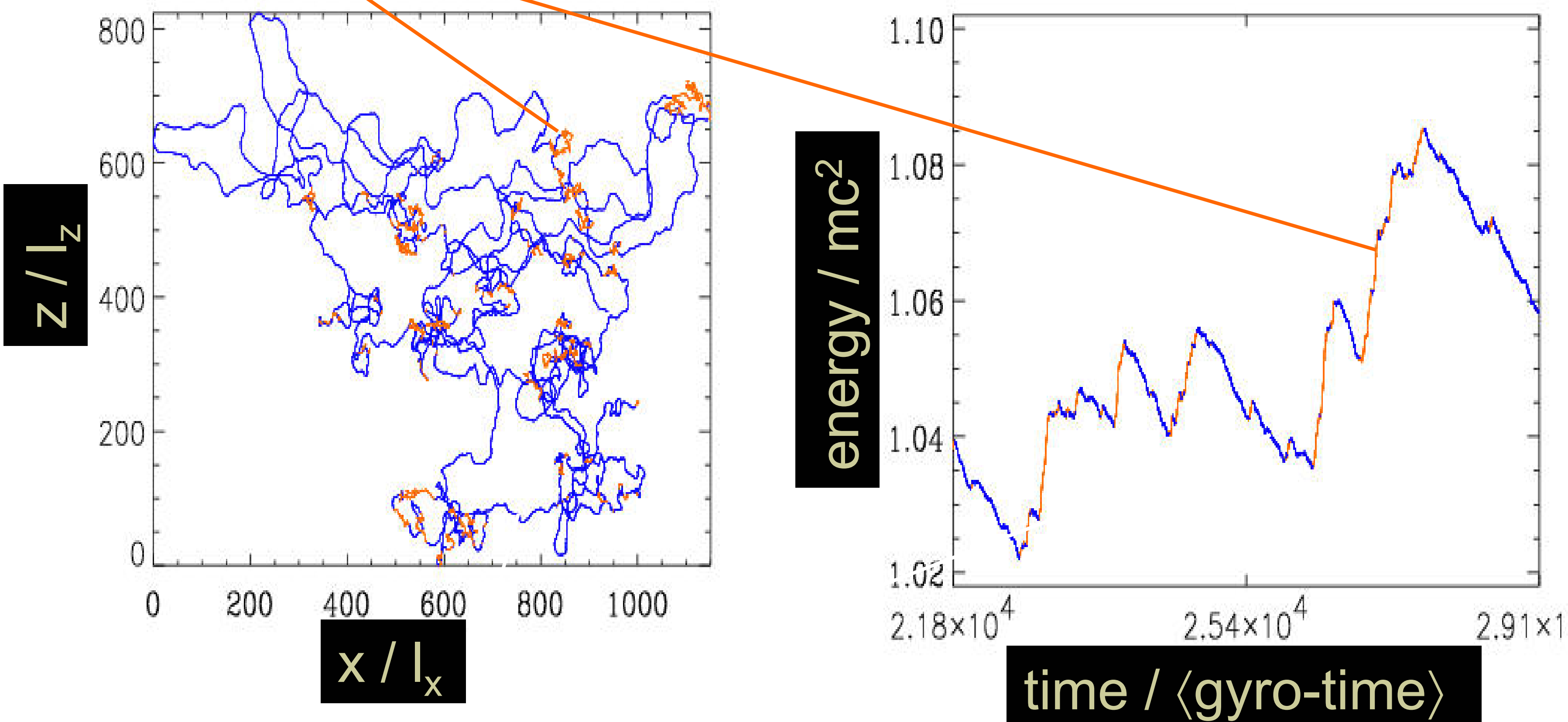
$$\frac{d\vec{r}}{dt} = \vec{v}$$

$$\frac{d\vec{p}}{dt} = e\vec{E} + \frac{e}{c}\vec{v} \times \vec{B}$$

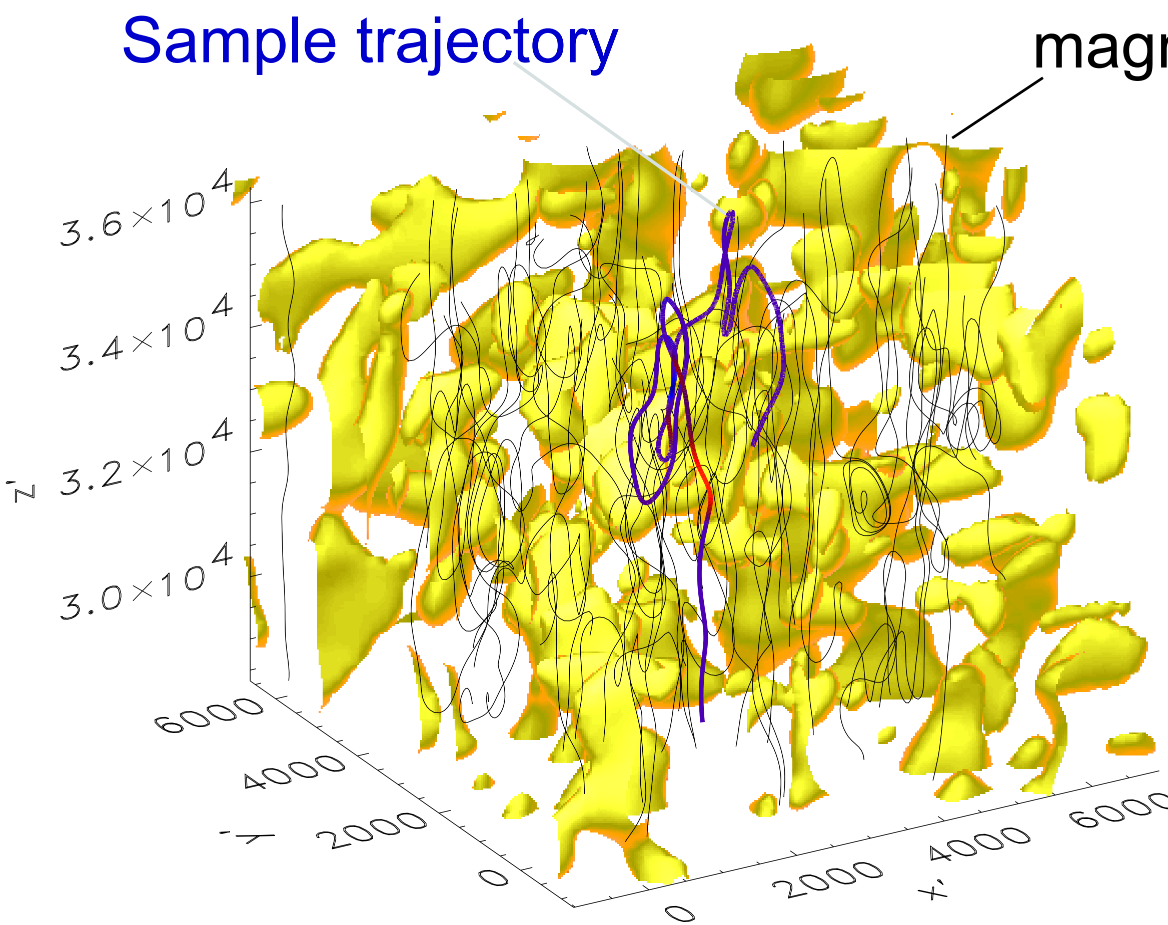
- Relativistic equations of motion are solved numerically with adaptive step-size scheme
- Magnetic and electric fields are interpolated to provide filed values in between grid-points

Finding: intermittent particle orbits

acceleration **within** local dissipation regions

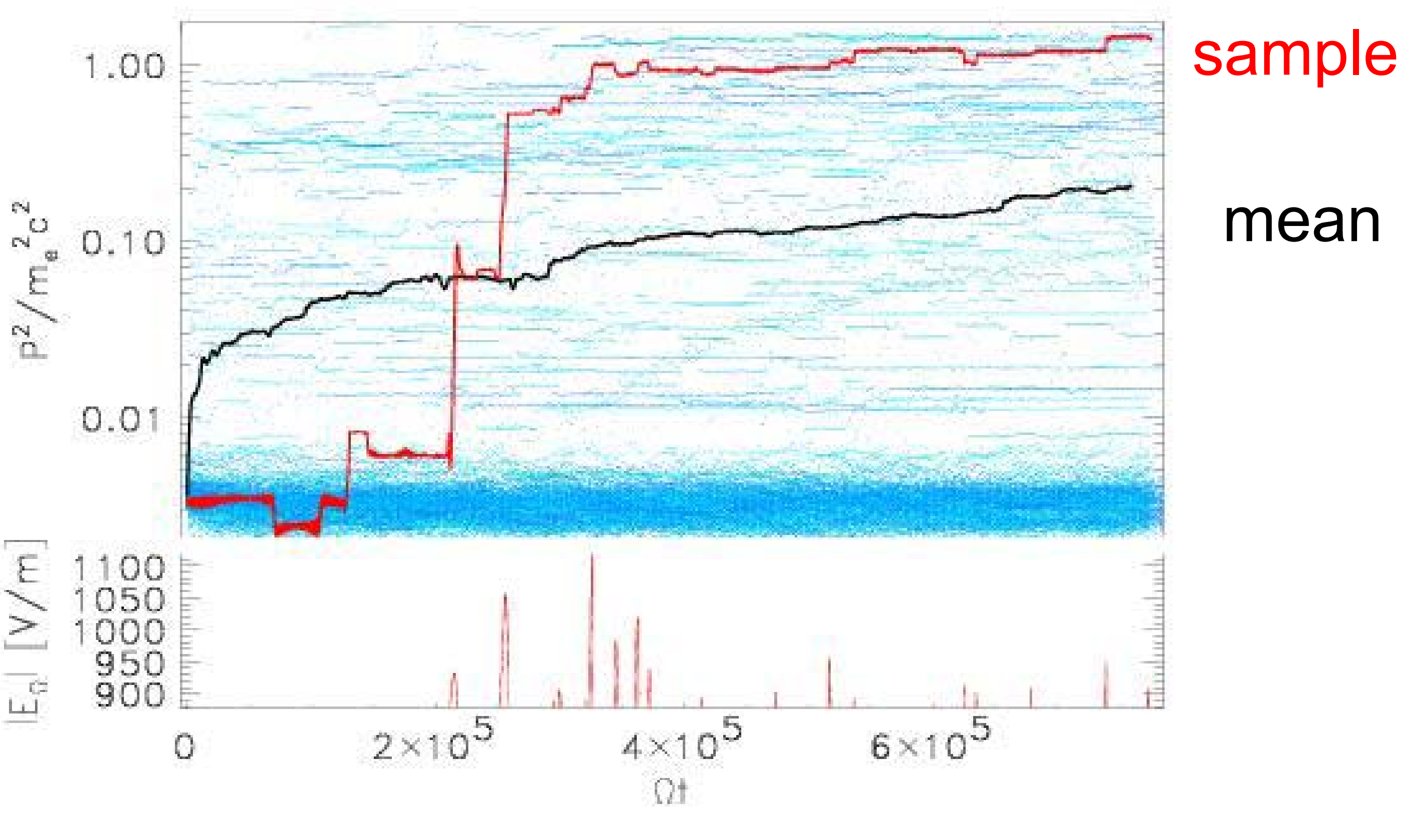


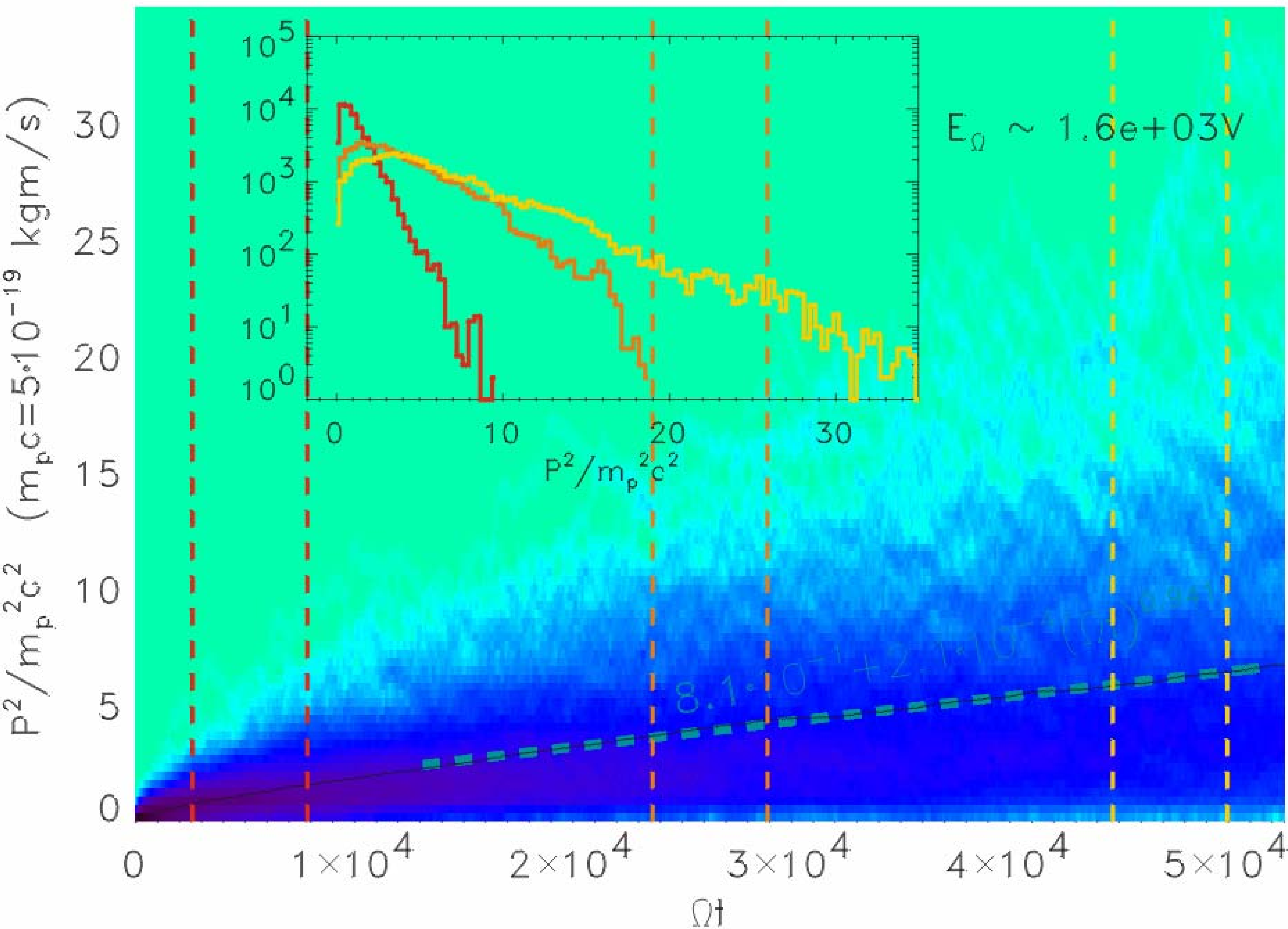
Dissipation Regions



- $B_0 = 20G$, $\delta B_X \sim \delta B_Y \sim 20G$, $\delta B_Z \sim 100G$
- Outer scales $l_X = l_Y = 1km$, $l_Z = 20km$
- Matern class PSD with index $\alpha = 1.5$
- Threshold current $j_C = enc_S$ exceeded in 5% of volume

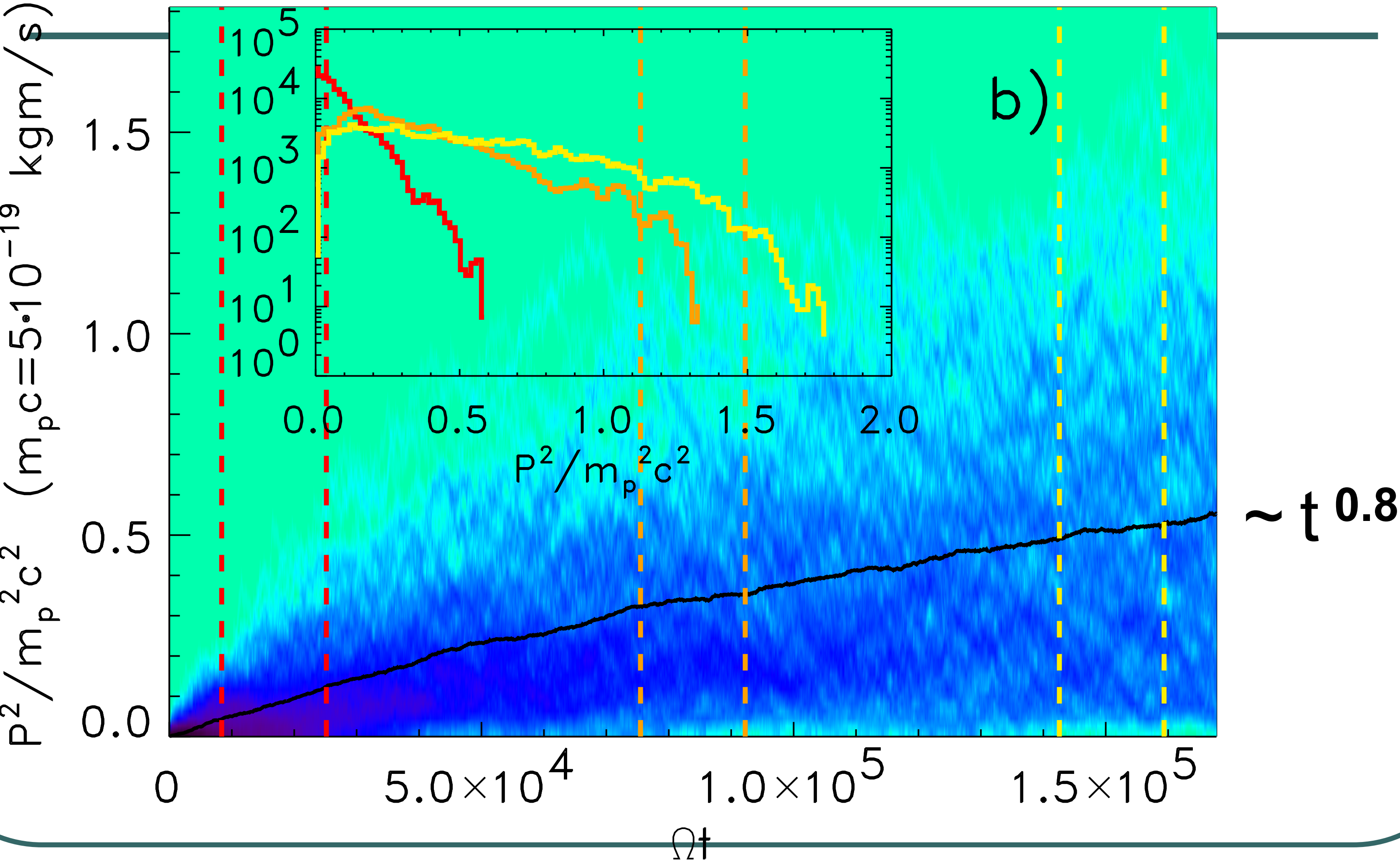
Electron Acceleration





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

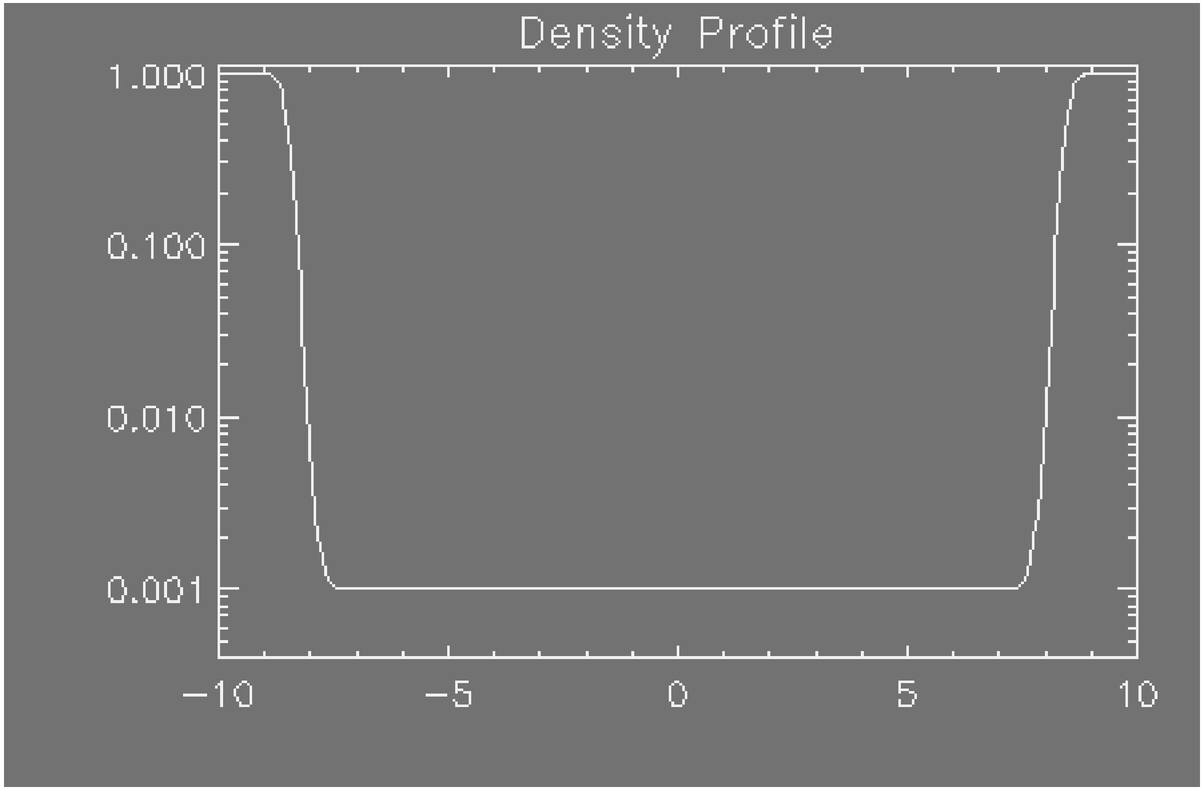
$E_\Omega / E_D = 10^5$



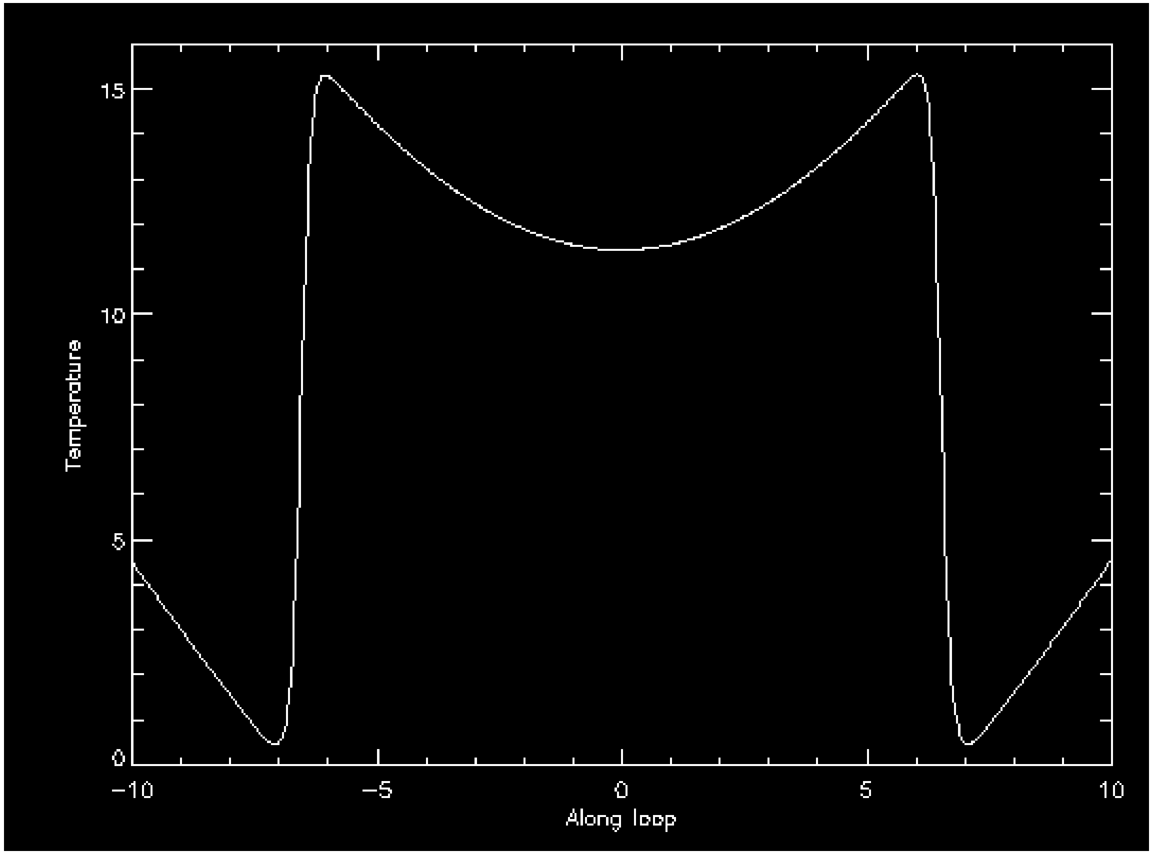
Solve the MHD equations inside a simple loop atmosphere (*Galsgaard*)

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

Density profile along the loop

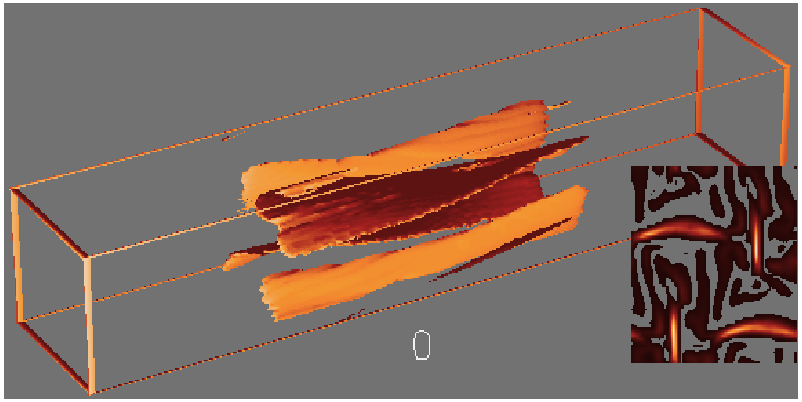


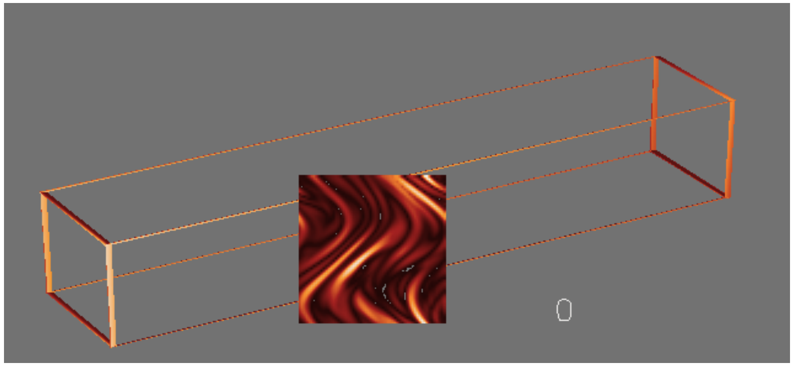
Temperature along the loop



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

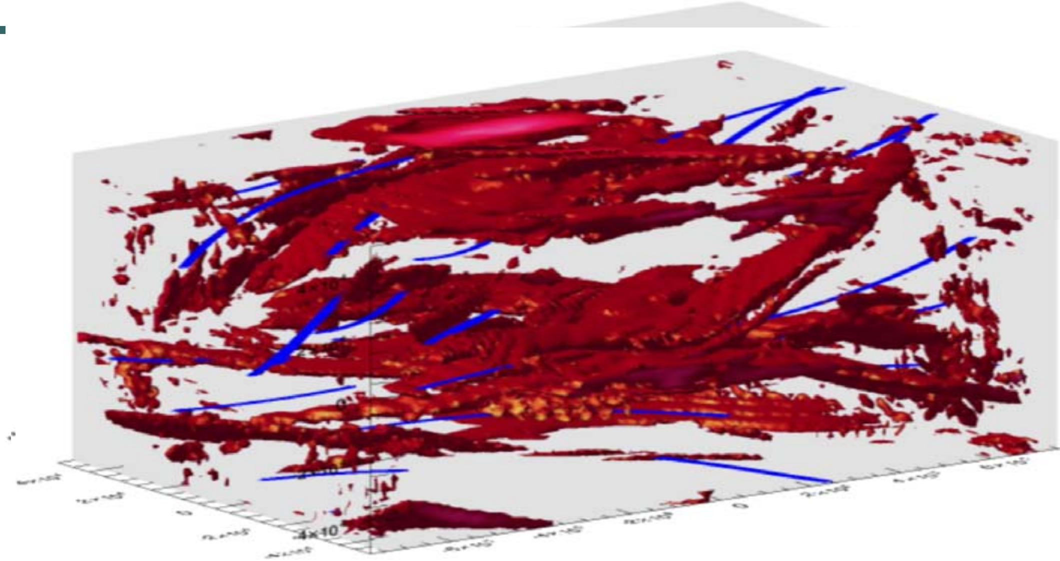




Particle acceleration in stochastic current sheets

(Rim Turkmani et al)

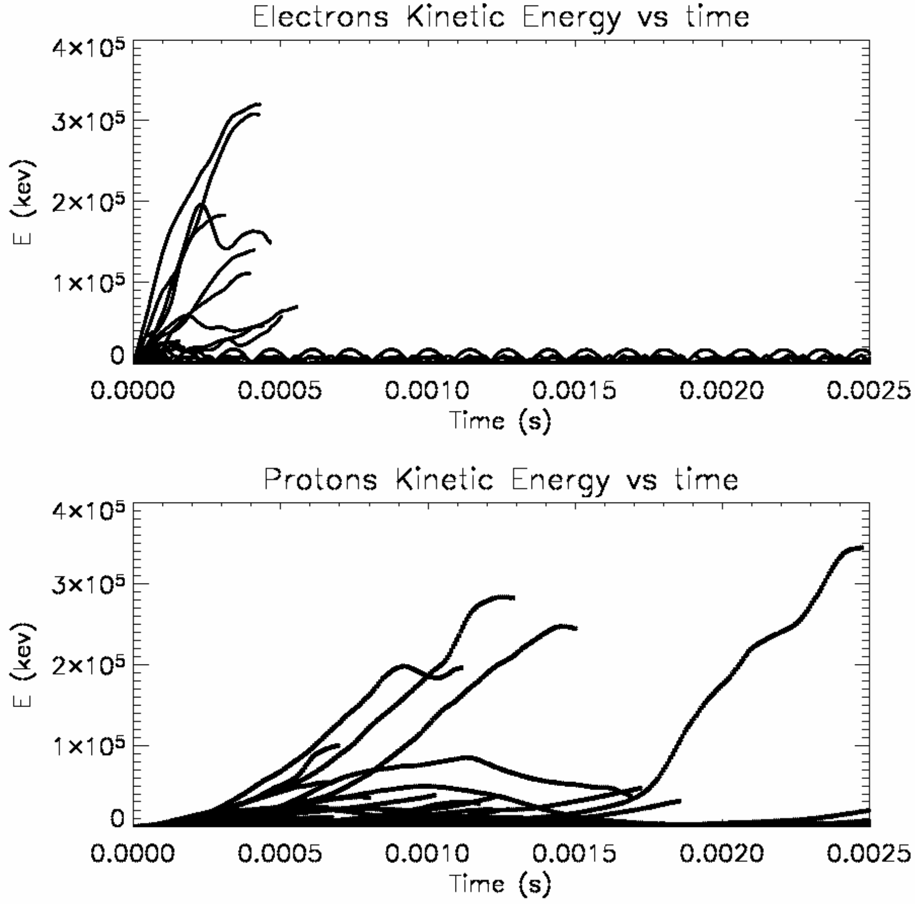
- Particles injected at random positions within an MHD box
  - Protons 0.027 kev
  - Electron 1.16 kev
- Initial velocity fixed in amplitude, random in direction



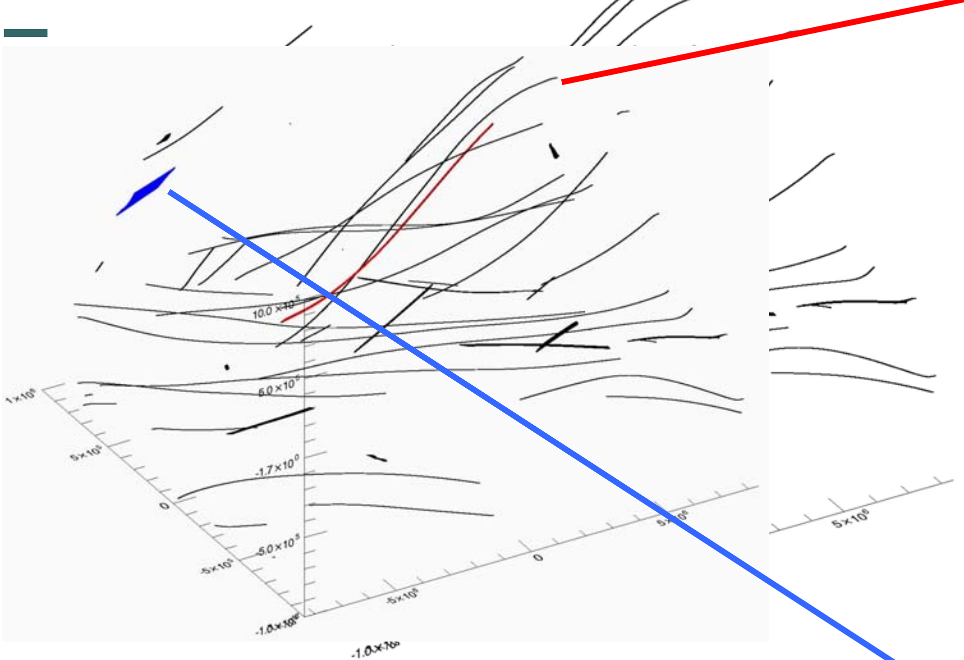
- Acceleration time scale much shorter than MHD time scale
- B and E are scaled; initial values:
  - B: Mean ~ 1.0 (0.89 – 1.08)
  - E: Mean ~ 7e-4 (e-5 – e-2)

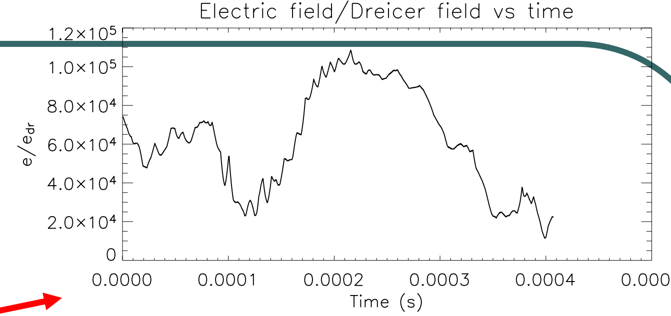
Electrons versus Protons

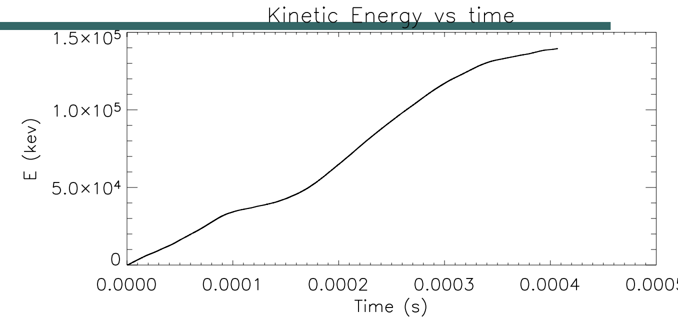
- Electrons and protons reach ~ 300 Mev in a 1.5e7 cm long loop with B=100 G within:
  - 0.5 ms for Electrons
  - 2.5 ms for Protons
- In general, electrons are accelerated ~5-6 times faster than protons

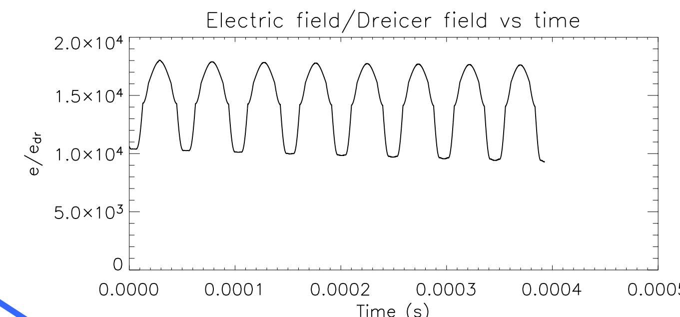


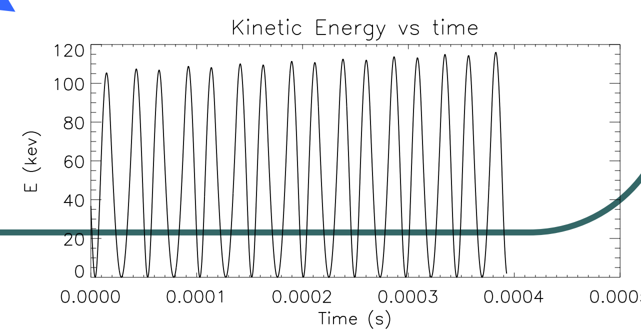
Particles motion







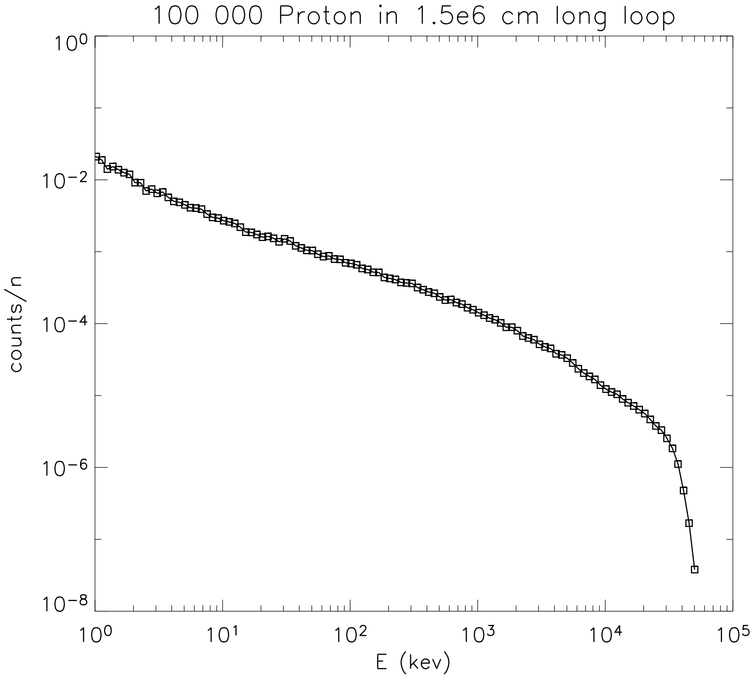


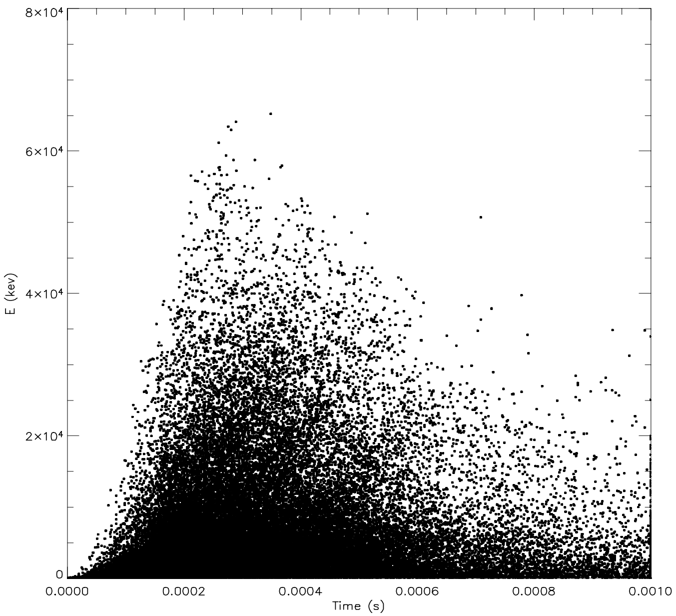


- 50 Electron run for 0.6 ms

Distribution Functions

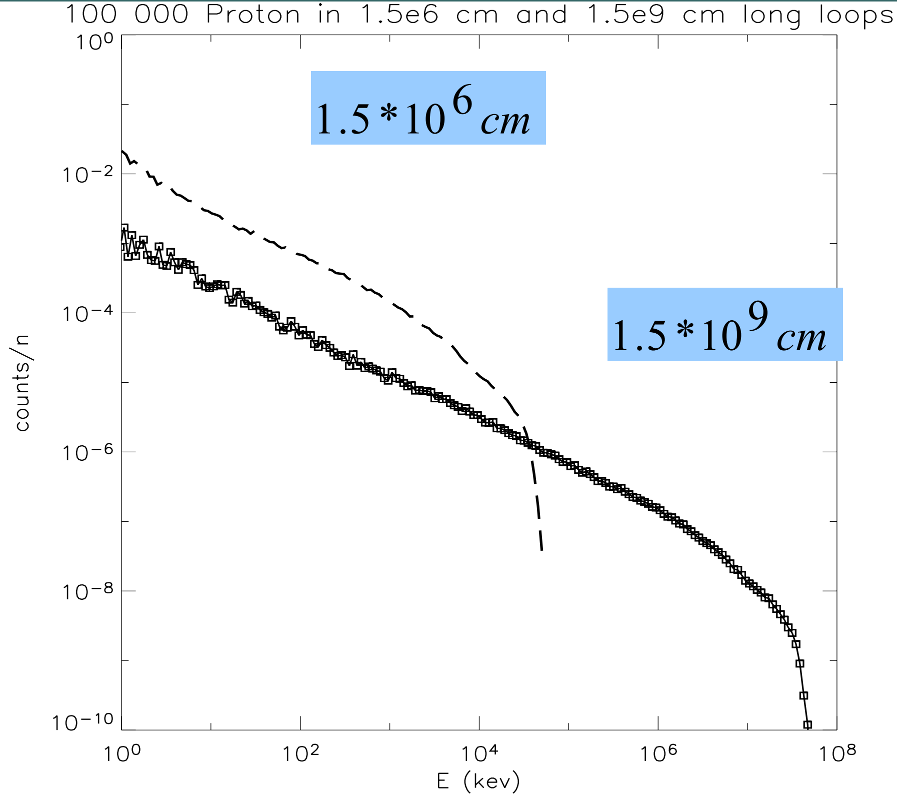
- 100,000 proton in 100 G magnetic field run for 1 ms





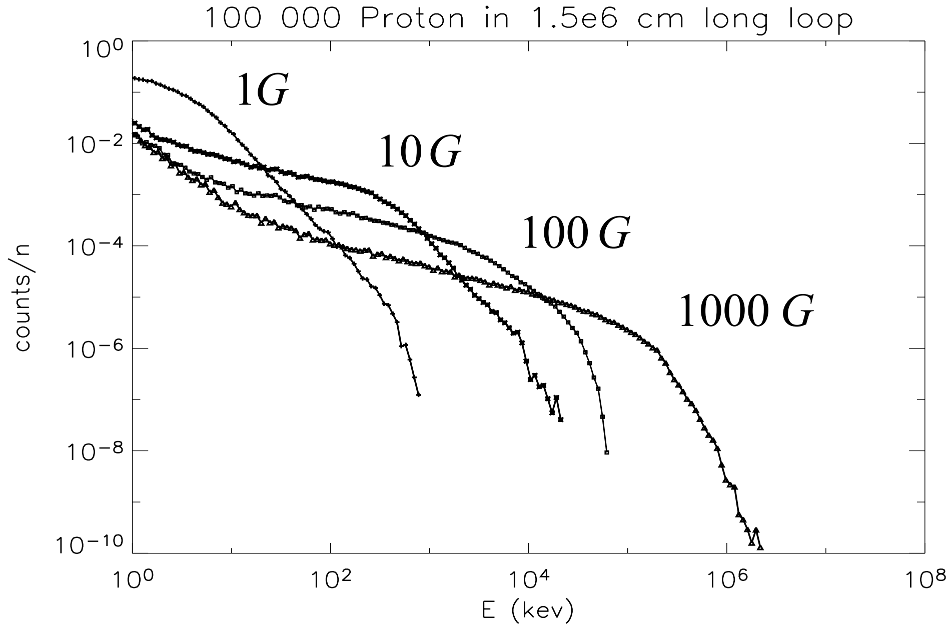
- Two parts power law
- ~ 60 Mev in 0.3 ms

Scaling with loop dimensions



Acceleration scales linearly with the spatial scale of the loop

Scaling with E and B



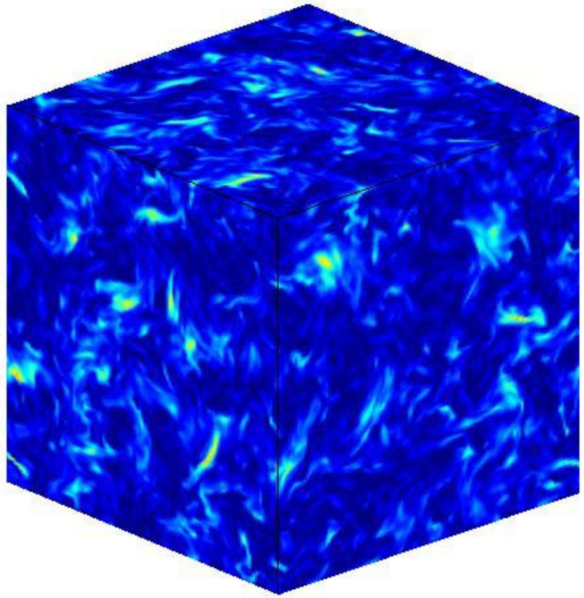
Acceleration scales almost linearly with the values of the magnetic and electric fields

Quit time acceleration: an example of MHD Turbulence (Lepreti, Isliker, Vlahos, submitted)

- The presence of electric fields in a driven magnetic field forming continuously magnetic discontinuities

$$\vec{j}(r,t) = \frac{c}{4\pi}\nabla \times \vec{B}(r,t)$$

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



My summary

- The photospheric motions drive the formation of unstable discontinuities
- Fast, slow, organized and random flows are all part of the photospheric activity
- New emerging flux adds complexity to this picture and enhances the concentration of magnetic discontinuities
- The extrapolated force free magnetogram holds important information for the activity of the complex AR.

My summary

- In the model presented the formation of critical and sub-critical discontinuities is crucial.
- The flare may start from any critical discontinuity and spread to large volumes creating an avalance
- The net result is the formation of distributed electric fields of all scales inside the magnetic field created by the extrapolated topology.

How can we observe all this?

- My proposal is that decimetric spikes are the crucial link to this model. We may be looking the accelerators in action.
- The loop like structures are going to remain and are now have a filling factor of current sheets inside.
- Particles are transported inside an electrically active environment.
- The E-fields are not aligned, so no need for return current problems. The formation of million current sheets is natural and the acceleration is stochastic.

Why loop tops

- The particles are accelerated perpendicular to magnetic fields and since they propagate in stochastic field lines are very efficiently trapped.
- Foot points are due to precipitating particles which are constantly accelerated as they propagate towards the photosphere.
- There is acceleration outside the loop (Type III)
- There is acceleration before the flare and there is acceleration long after the flare….due to the large enhancement of discontinuities
- The acceleration is going hand and hand with the formation of discontinuities so it can be present in all scales
- The foot point sources are not unique, they have internally structure but are currently unresolved