ENERGY RELEASE AND PARTICLE ACCELERATION IN STRESSED AND COMPLEX MAGNETIC TOPOLOGIES

Loukas Vlahos
Department of Physics University of Thessaloniki,
Greece

Topics

- Motivation: The “standard” model for solar flares and the “best” acceleration mechanism are not compatible….
- Formation of active regions and building up stresses in complex active regions
- Stochastic current sheets formation in complex magnetic topologies
- The mixing of acceleration mechanisms in complex magnetic topologies
- Discussion and summary

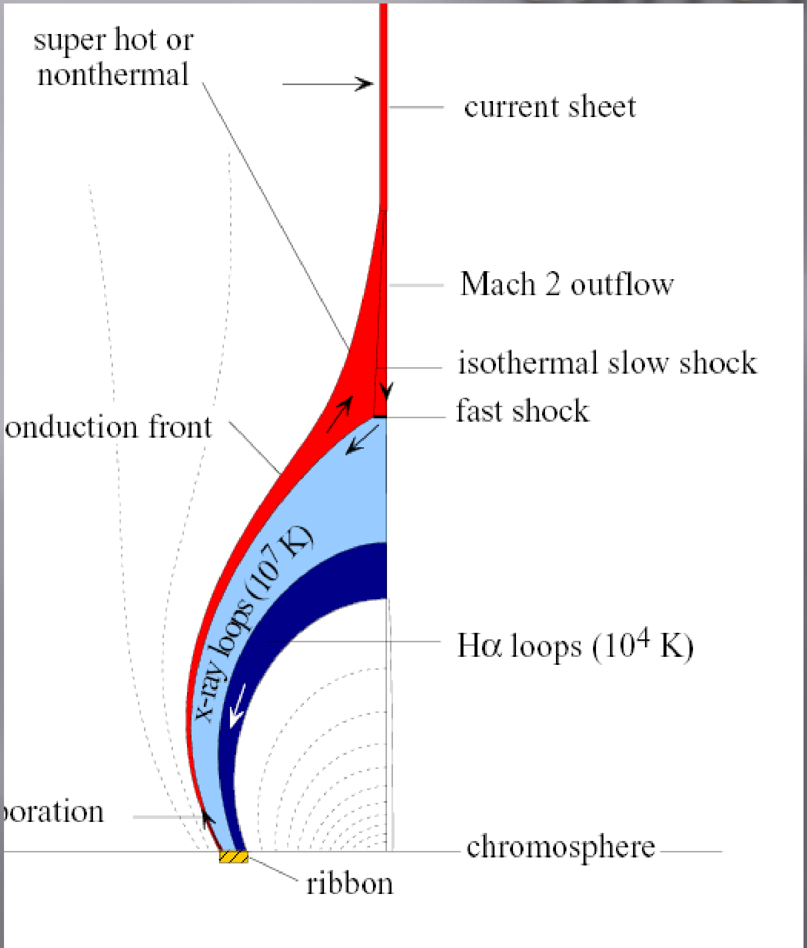
Motivation for this study

- The single large scale current sheet, if ever formed, will be unstable and collapse in sub-second time scales to many smaller scale structures.
- Acceleration in the sun is a wider phenomenon, extended much beyond the impulsive flare.
- The energy release and particle acceleration must be consistent with the statistical properties of flares. Power laws are all over the dominant characteristics of the formation and energy release in the sun.

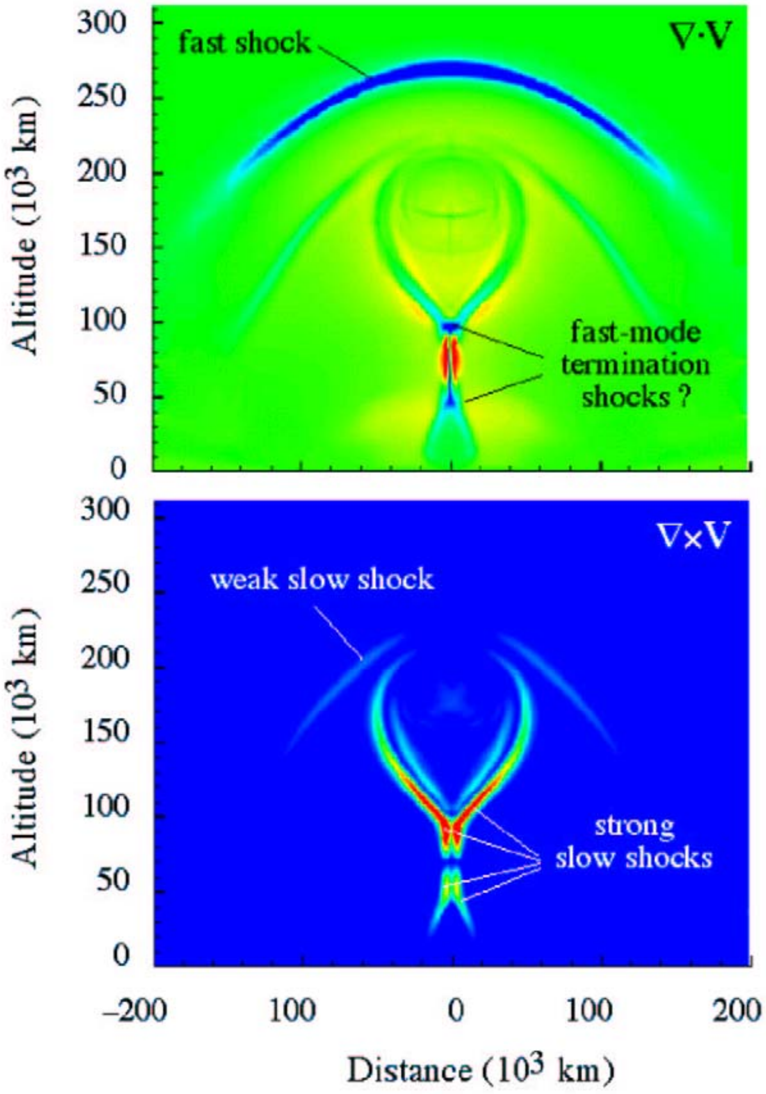
The "pure" acceleration mechanism is a theoretical simplificationany realistic topology will mix the accelerators

- **Electric fields** inside the current sheet or directly driven (Sub-Dreicer or super-Dreicer electric filed)
- **Shocks:** CME or flare driven
- **MHD Turbulence**: How are set in? How they are connected to the flare models?
- All the above mechanisms are mixed in realistic magnetic topologies!

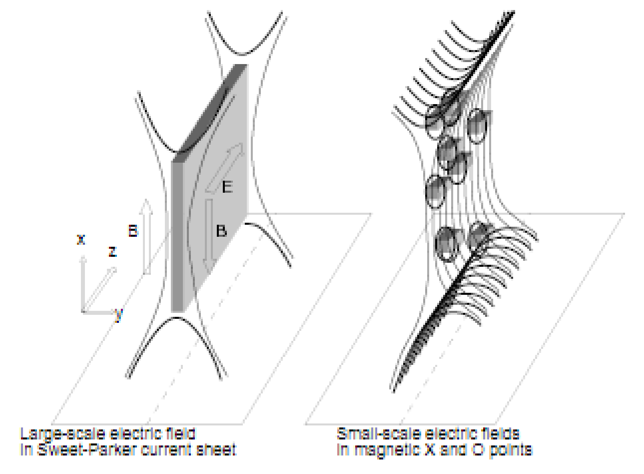
The "standard(?)" solar flare model and the monolithic current sheet



Shock Formation



Fragmented loop top current sheet



Large-scale electric field
in Sweet-Parker current sheet

Small-scale electric fields
in magnetic X and O points

The number problem and the loop top model

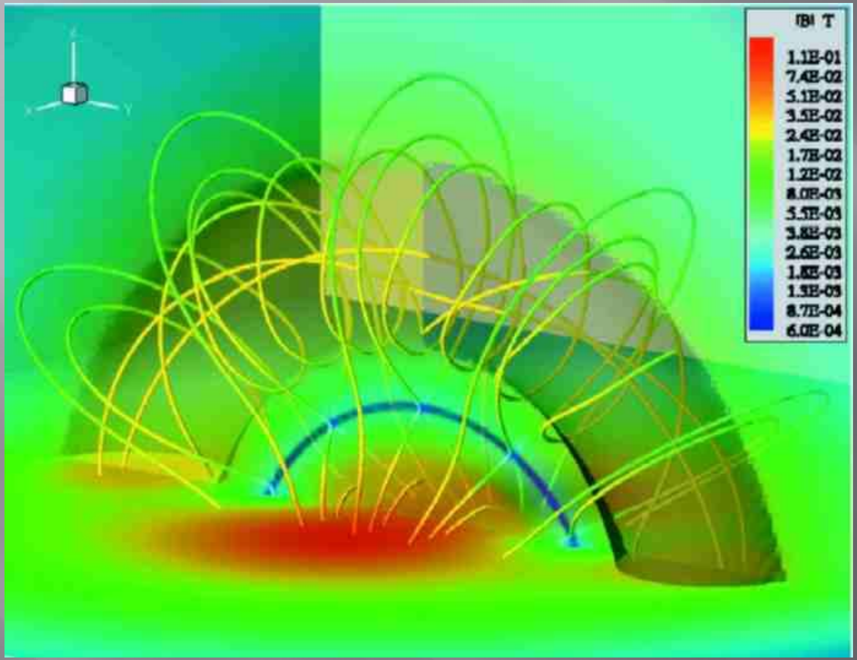
- Can they all be accelerated at the loop top?

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

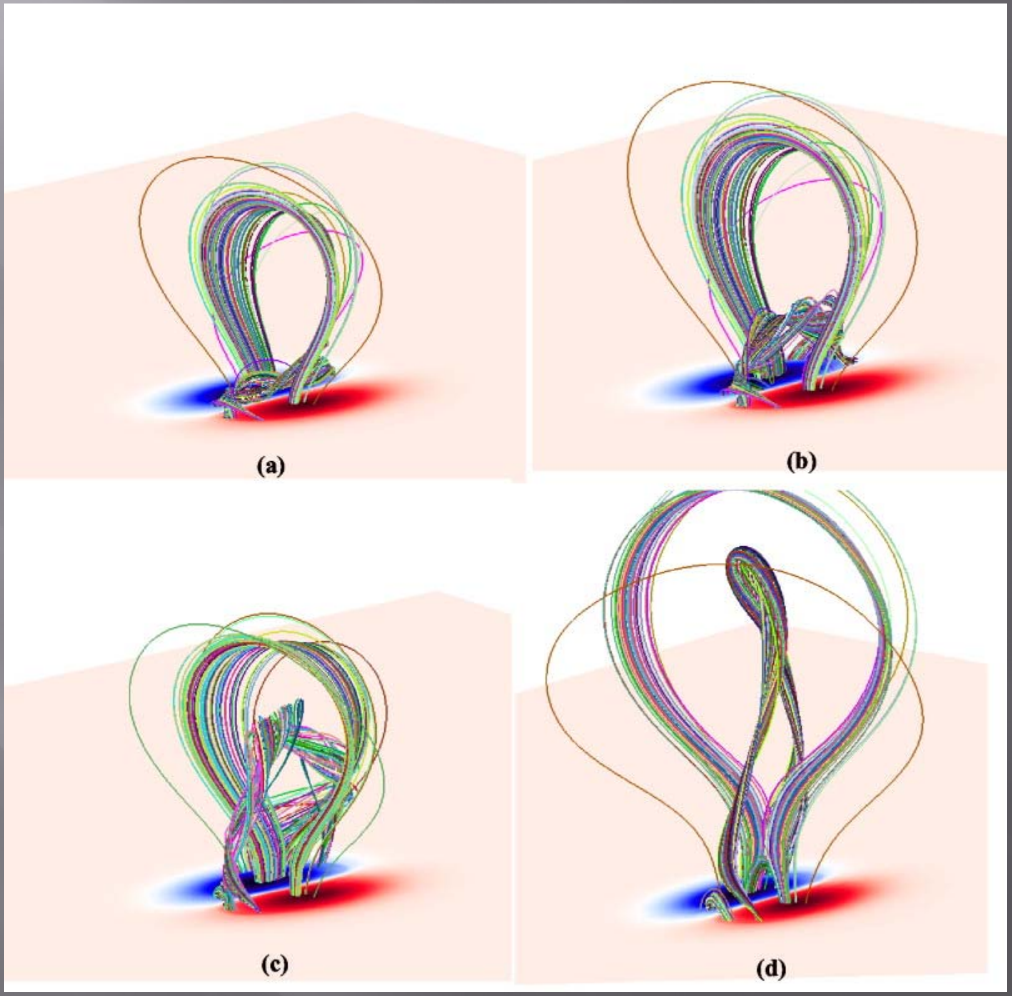
$N = V n_e = L^3 n_e$

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

3D flux tube simulations
(Roussev et al)



3D flux tube simulations (Amari et al)



MHD Turbulence the "standard" acceleration model

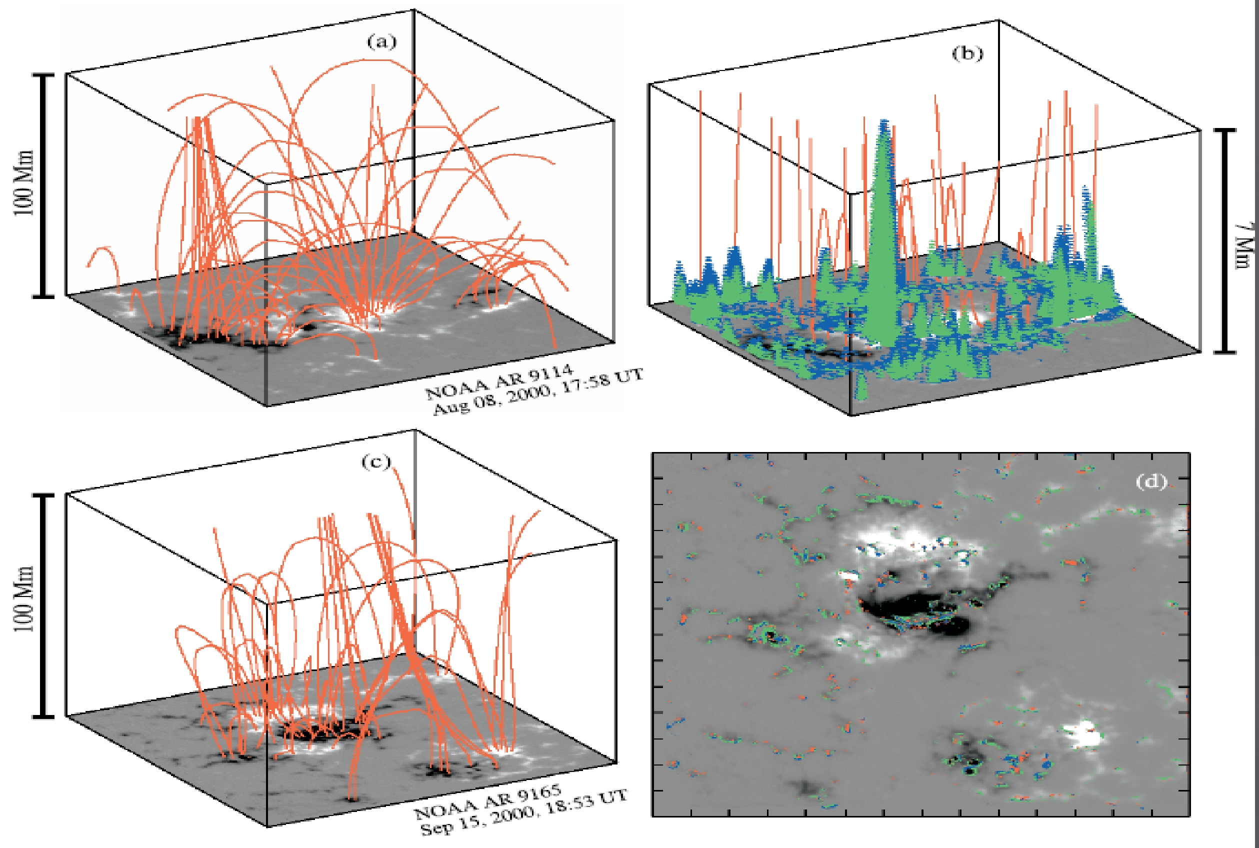
1. Alfven and fast mode waves generated at large scales (assumption)
2. Cascade to higher wave numbers (e.g., Zhou & Matthaeus 1989)
3. Fast mode waves energize electrons via transit-time acceleration (e.g., Miller 1997)
4. Alfven waves energize ions via gyroresonant acceleration (e.g., Miller & Roberts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

➔ Both species accelerated by MHD turbulence

We have a problem!

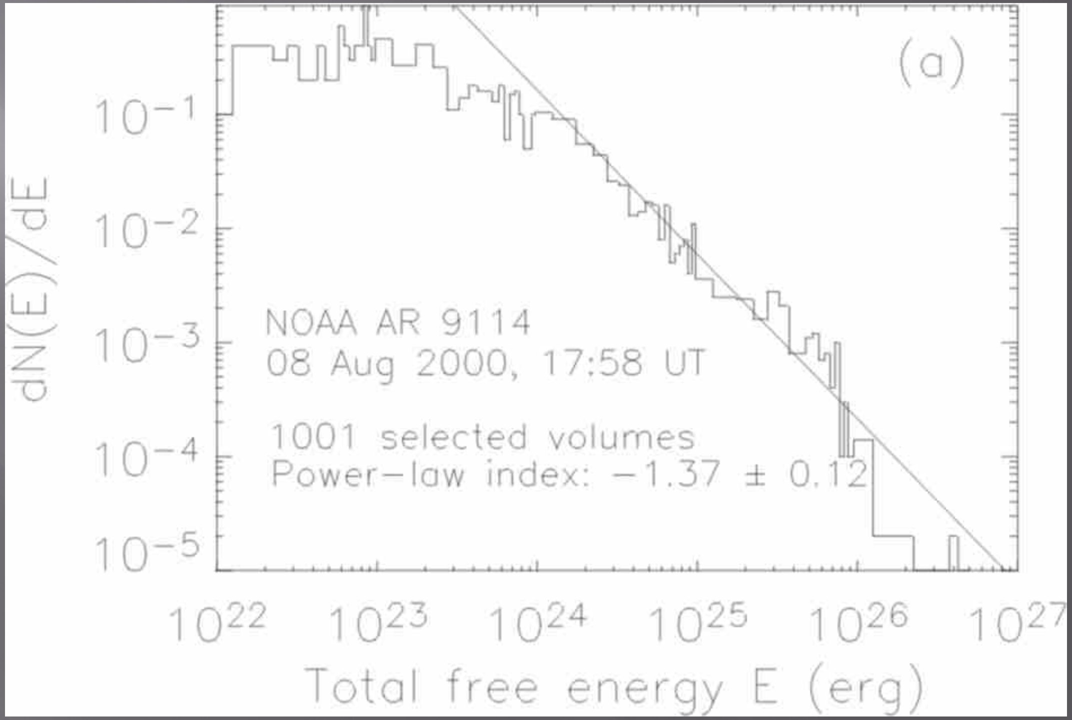
- The standard model for energy release is in favor of E-field and shock acceleration
- The standard acceleration mechanism is in favor of a loop filled with MHD turbulence
- Who is correct?

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



Unstable discontinuities

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

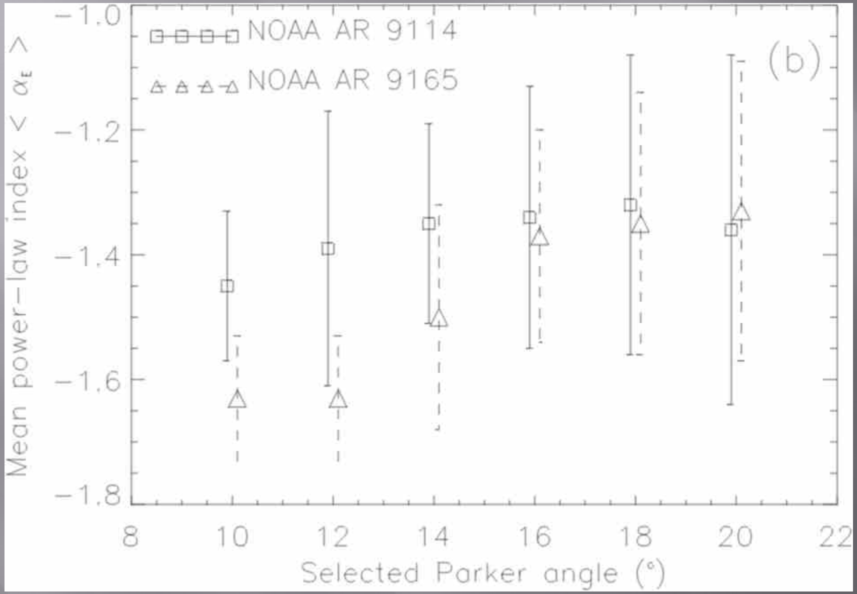


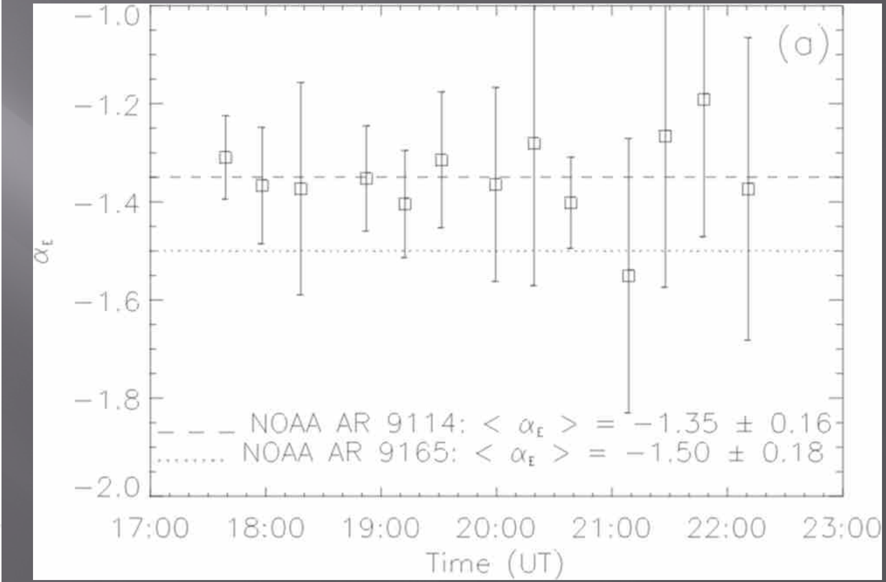
Unstable discontinuity

$$J > J_c$$

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

The stability of this result on time

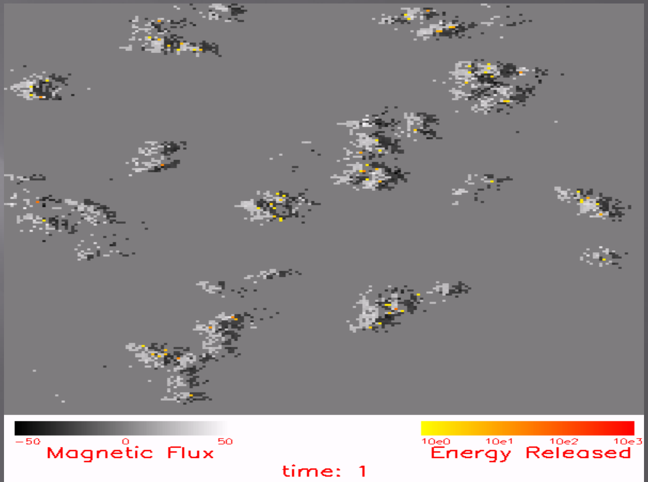




Evolving active regions build up constantly magnetic discontinuities….

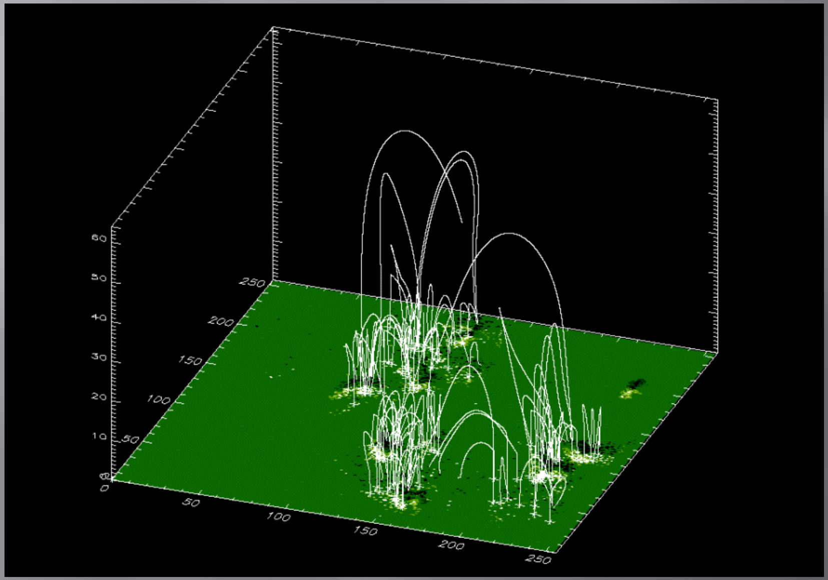
(Fragos, Rantziou, Vlahos, AA, 2004)

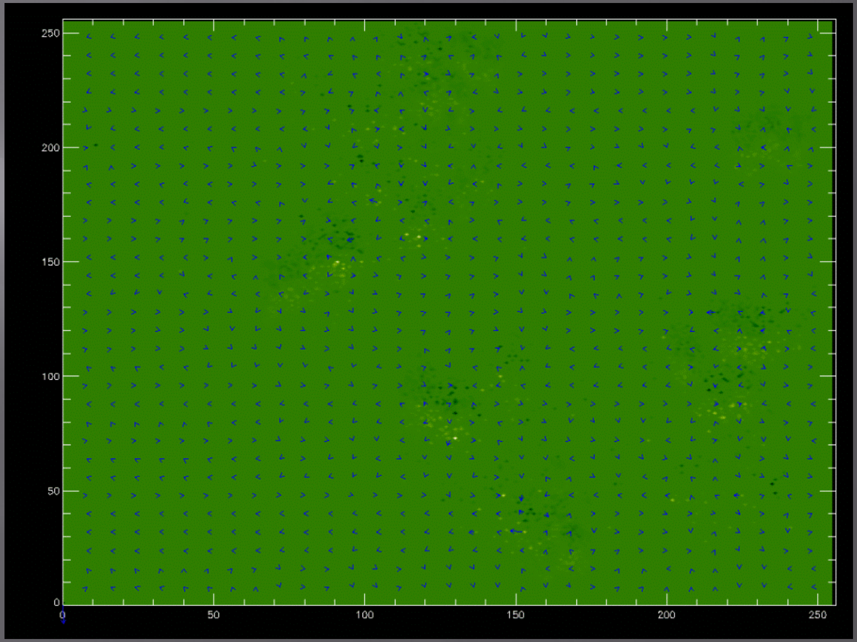
- P=is the probability for generating new flux
- D=the probability of decaying
- E= spontaneous generation of flux



Evolving active regions build up constantly magnetic discontinuities….

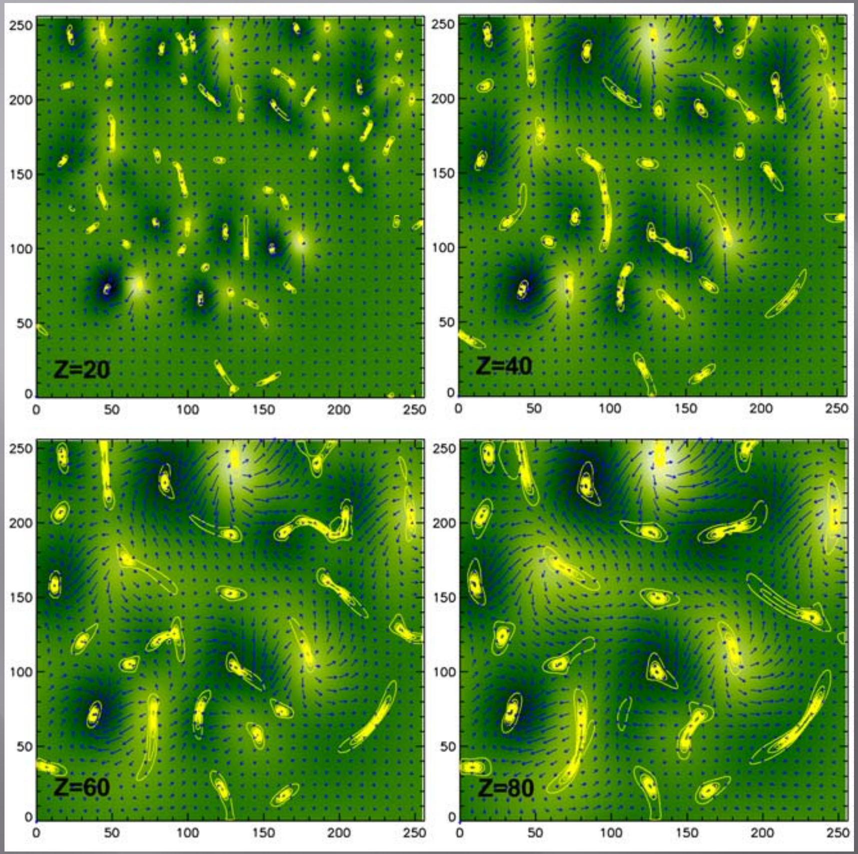
(Fragos, Rantziou, Vlahos, AA, 2004)

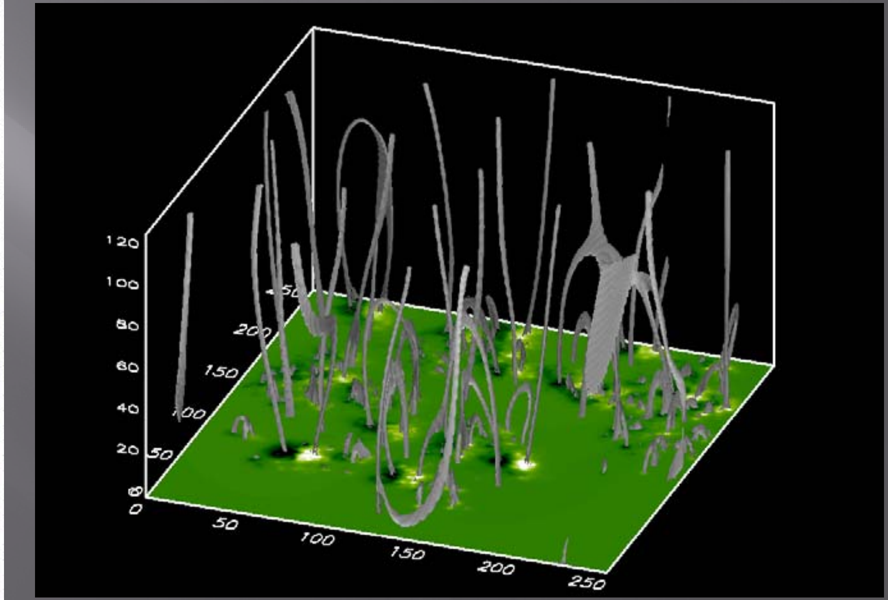




Dynamic motion of the photosphere builds constantly magnetic discontinuities

(Fragos, Rantziou, Vlahos, AA, 2004)

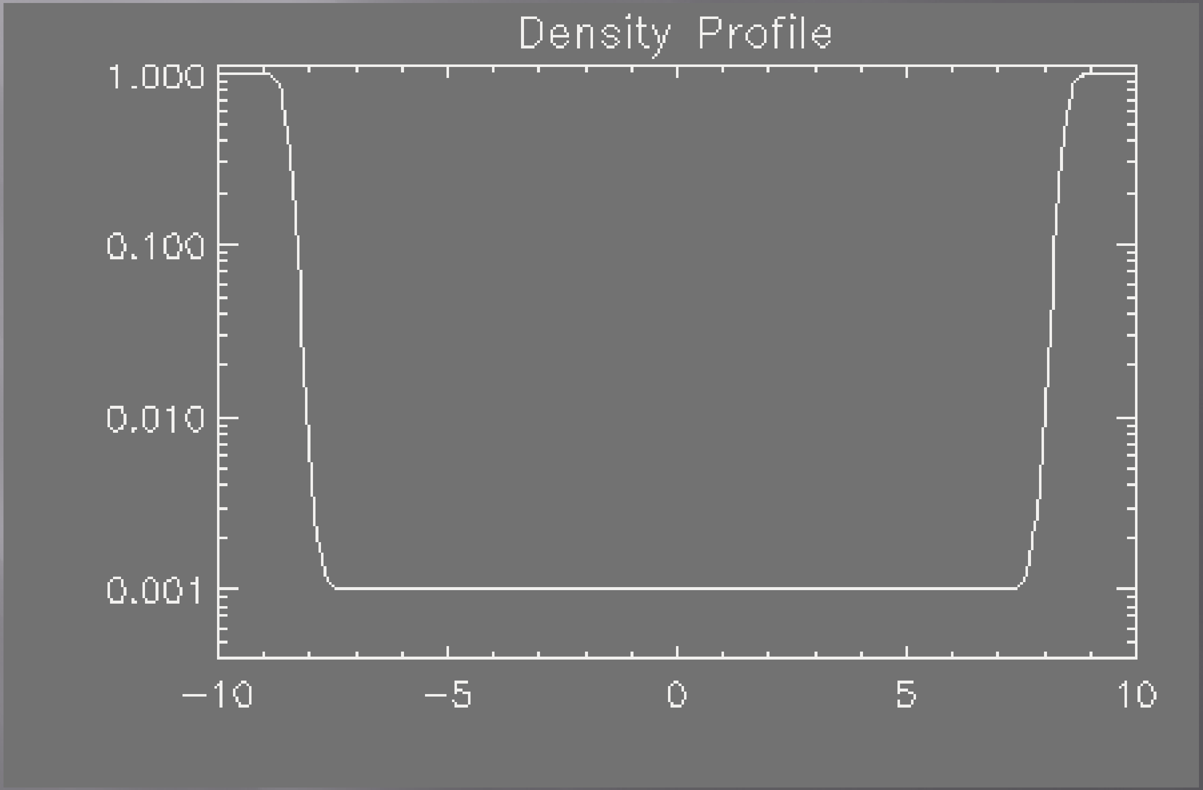




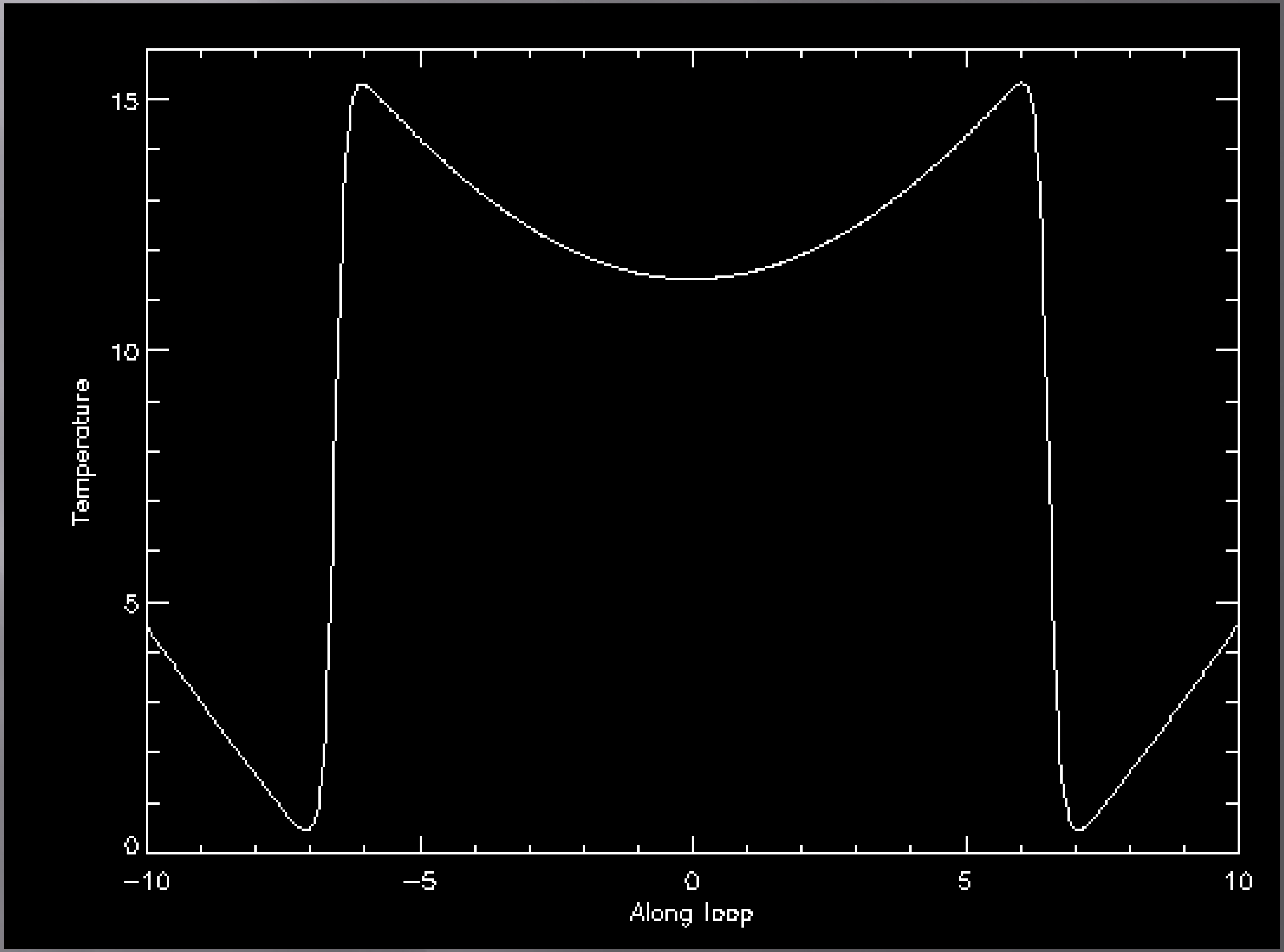
Solve the MHD equations inside a simple loop atmosphere (*Galsgaard)*

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

Density profile along the loop

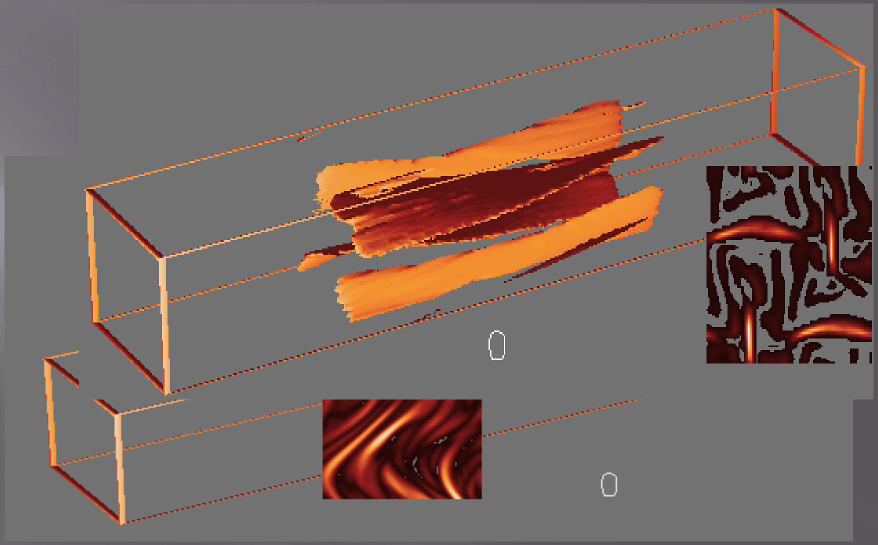


Temperature along the loop



The stochastic loop model (Galsgaard)

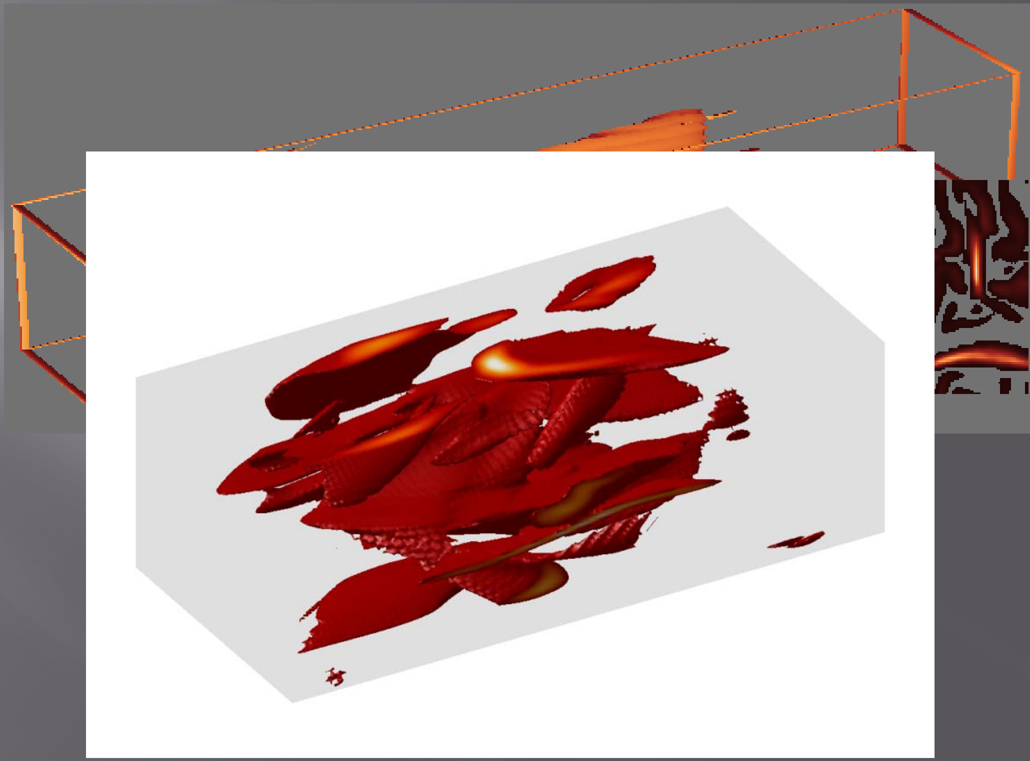
- 3D MHD experiment of photospherically driven slender magnetic flux tubes
- Continued random driving of the foot points (incompressible sinusoidal large scale shear motions)
- Reconnection jets generate secondary perturbations in B
- Formation of stochastic current sheets



Particle acceleration in stochastic current sheets

(Rim Turkmani et al, submitted to ApJL)

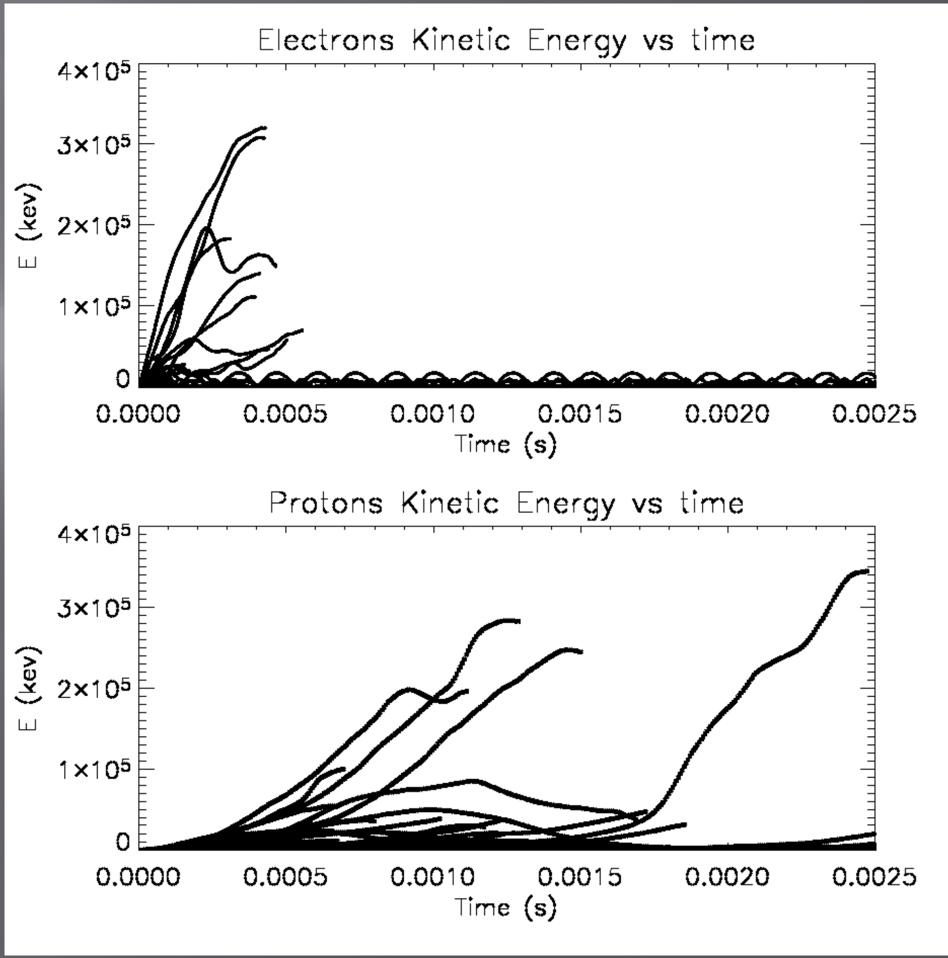
- Particles injected at random positions within an MHD box
  - Protons 0.027 kev
  - Electron 1.16 kev
- Initial velocity fixed in amplitude, random in direction



- 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



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

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

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

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

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

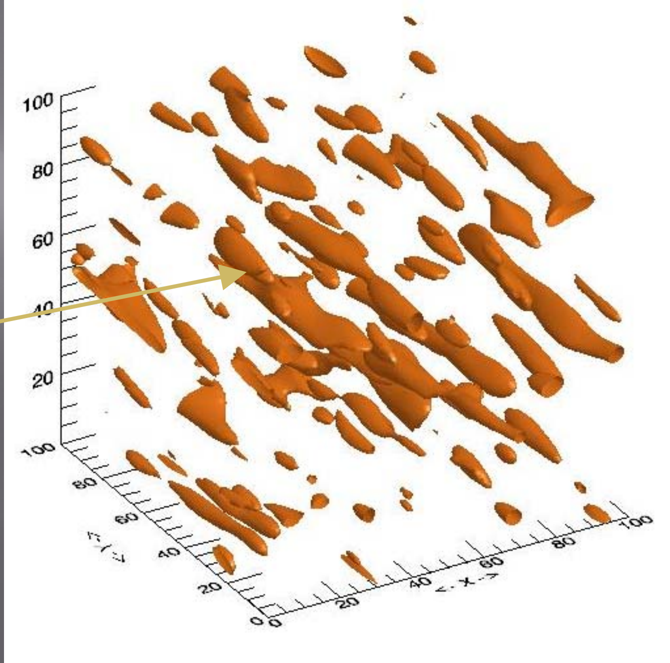
$\vec{J} \sim \nabla \times \vec{B}$

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

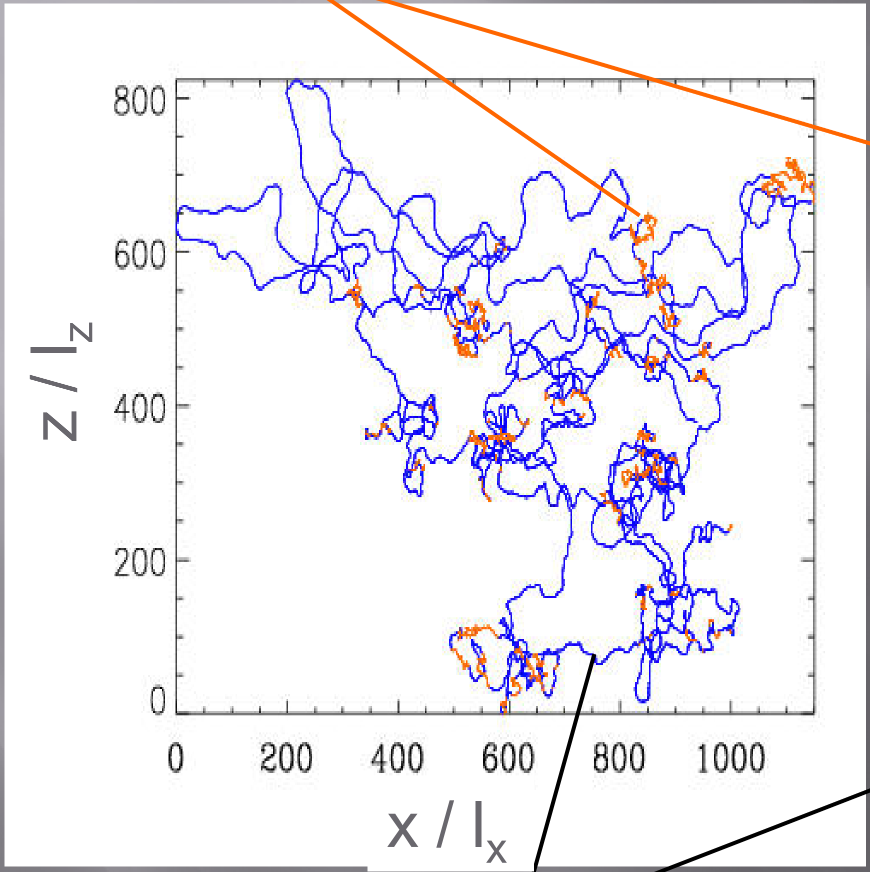
$$\frac{d\vec{r}}{dt} = \vec{v}$$

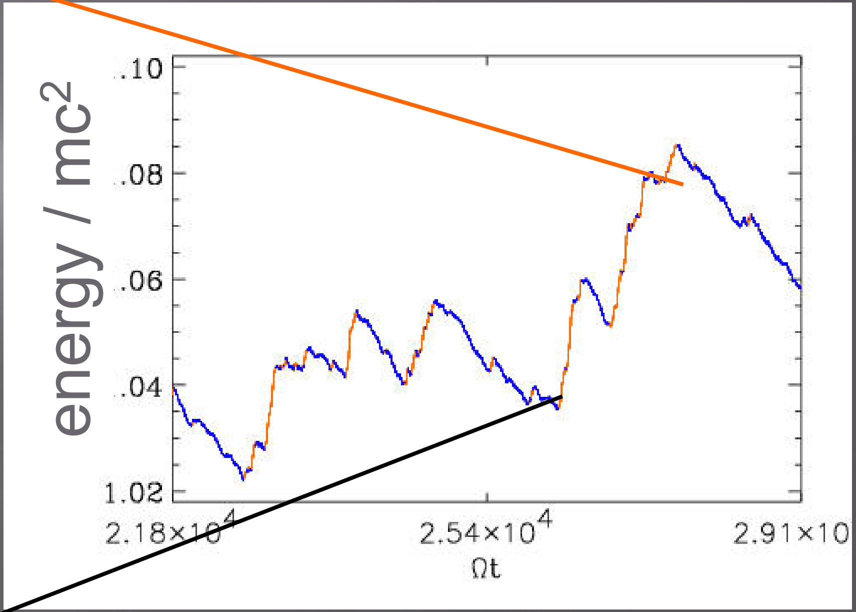
$$\frac{d\vec{p}}{dt} = e\vec{E} + \frac{e}{c}\vec{v} \times \vec{B}$$

- 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

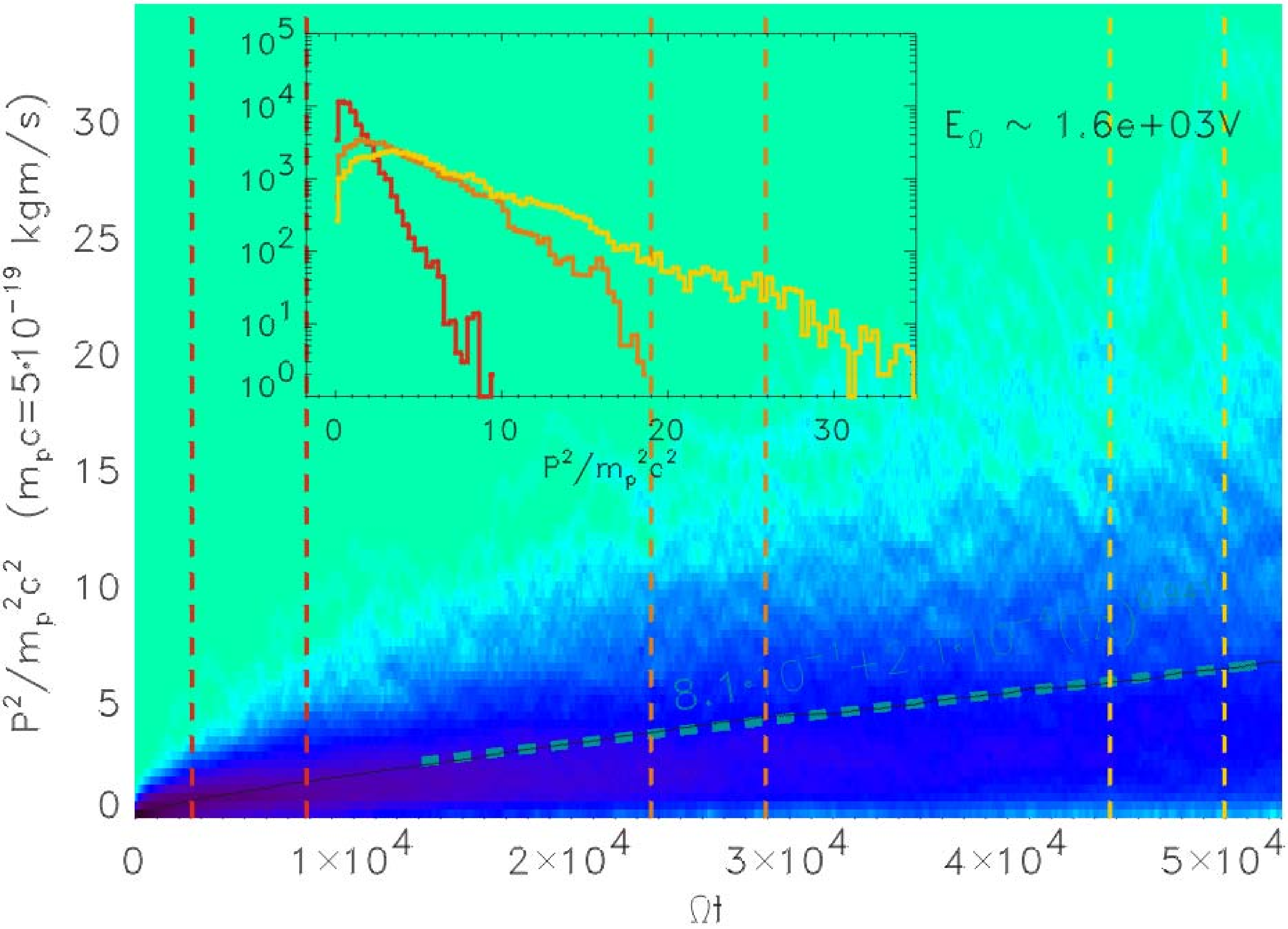
acceleration **within** local dissipation regions



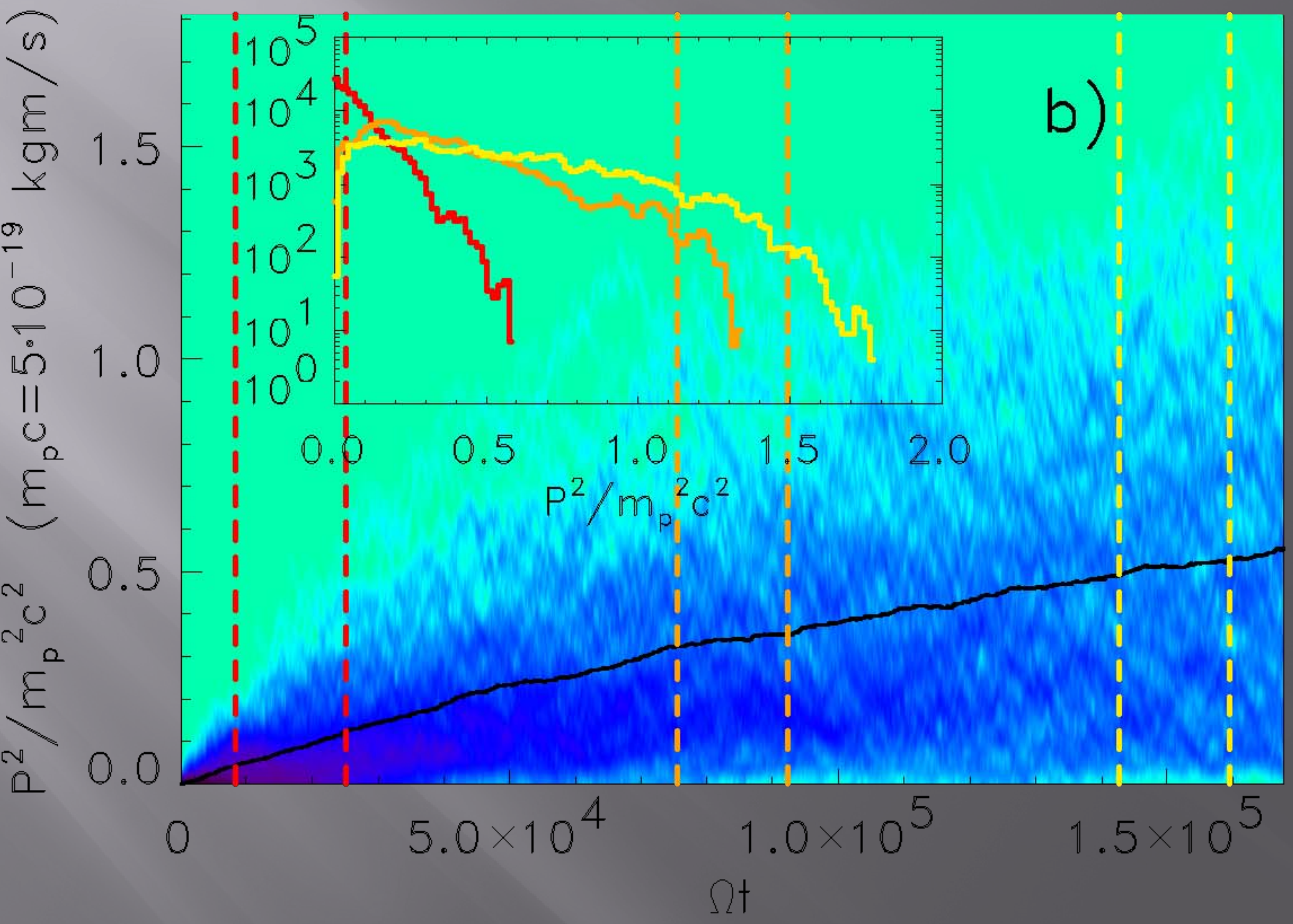


time / ⟨gyro-time⟩

deceleration **between** dissipation regions


E_Ω ~ 1.6e+03V
$P^2/m_p^2c^2$ $(m_pc=5\cdot10^{-19}$ kgm/s)
0
5
10
15
20
25
30
0
1×10^4
2×10^4
3×10^4
4×10^4
5×10^4
Ωt
$8.1\cdot10^{-1}+2.1\cdot10^{-4}(\Omega t)^{0.941}$
10^5
10^4
10^3
10^2
10^1
10^0
0
10
20
30
$P^2/m_p^2c^2$

$E_\Omega / E_D = 10^5$



$\sim t^{0.8}$

Summary

1. Solar flares are released in stressed completed magnetic topologies and are associated with stochastic current sheets
2. Particle acceleration mechanisms are not simple but are mixed (e.g. stochastic short lived E-fields and shocks appear impertinently inside turbulent plasma)
3. Long current sheets, if ever formed, are quickly collapsing to thousands of non linear smaller structures (shocks, current sheets) of all sizes (this may be true in loop tops magnetic topologies as well)
4. In break out flares, shocks, current sheets, turbulence are possibly all present, covering different parts of energy spectrum.