Particle acceleration and high energy emission from the Sun

Loukas Vlahos

Main topics

- Introductory remarks
- Observational constrains for the accelerated particles
- Basic mechanisms for particle acceleration
- The sun as particle accelerator
- Open problems

Introduction

- In astrophysics Hydrodynamics and MHD are the dominant tools for almost all the problems.
- There are good reasons for this and most of them have been outlined from several speakers this week.
- But…. There are several problems, one of them is the topic of my talk, which falls outside the domain of the MHD theory.
- Physicists, as more scientists, are pragmatic people and search not were the problem is but only were there is light so they can find something.

The velocity distribution and the Vlassov equation

- The velocity distribution $f_j(\vec{v}, \vec{r}, t)$
- The evolution of the velocity distribution

$$\frac{\partial f_j}{\partial t} + \vec{v} \cdot \nabla f_j + (\vec{E} + \vec{v} \times \vec{B}/c) \cdot \nabla_{\vec{v}} f_j = \left(\frac{\partial f}{\partial t}\right)_{coll}$$

- Maxwell's Equations witch evolves E and B using

$$\rho = e(\int (f_i - f_e) d\vec{v}$$
$$\vec{j} = e \int (f_i - f_e) \vec{v} d\vec{v}$$

Forms of velocity distributions

- Plasma in Equilibrium
  - Maxwellian (minimum energy state)
- Non Equilibrium plasma
  - Two Mawellians with different temperatures and densities
  - Non-Thermal plasma Maxwellian+ power law tail

‘Anomalous’ Collisions and Diffusion Equation

- Diffusion of particles inrandom E-fields. Particles executing random walks inside such environment (see more on Kaspar’s talk)
- Fokker Planck (the simplest form)

$$\frac{\partial f}{\partial t} = \frac{\partial}{\partial v} D_{vv} \frac{\partial f}{\partial v}$$

$$D = \frac{< v(t) v(t+\tau) >}{\tau}$$

What current observations can tell to the theorists

- In fact.. a lot… so much that scared most solar physics theorists and are currently doing something else…. accretion disks, black holes AGN’s (remember that physicist are pragmatic people…)

Electrons (large flare)

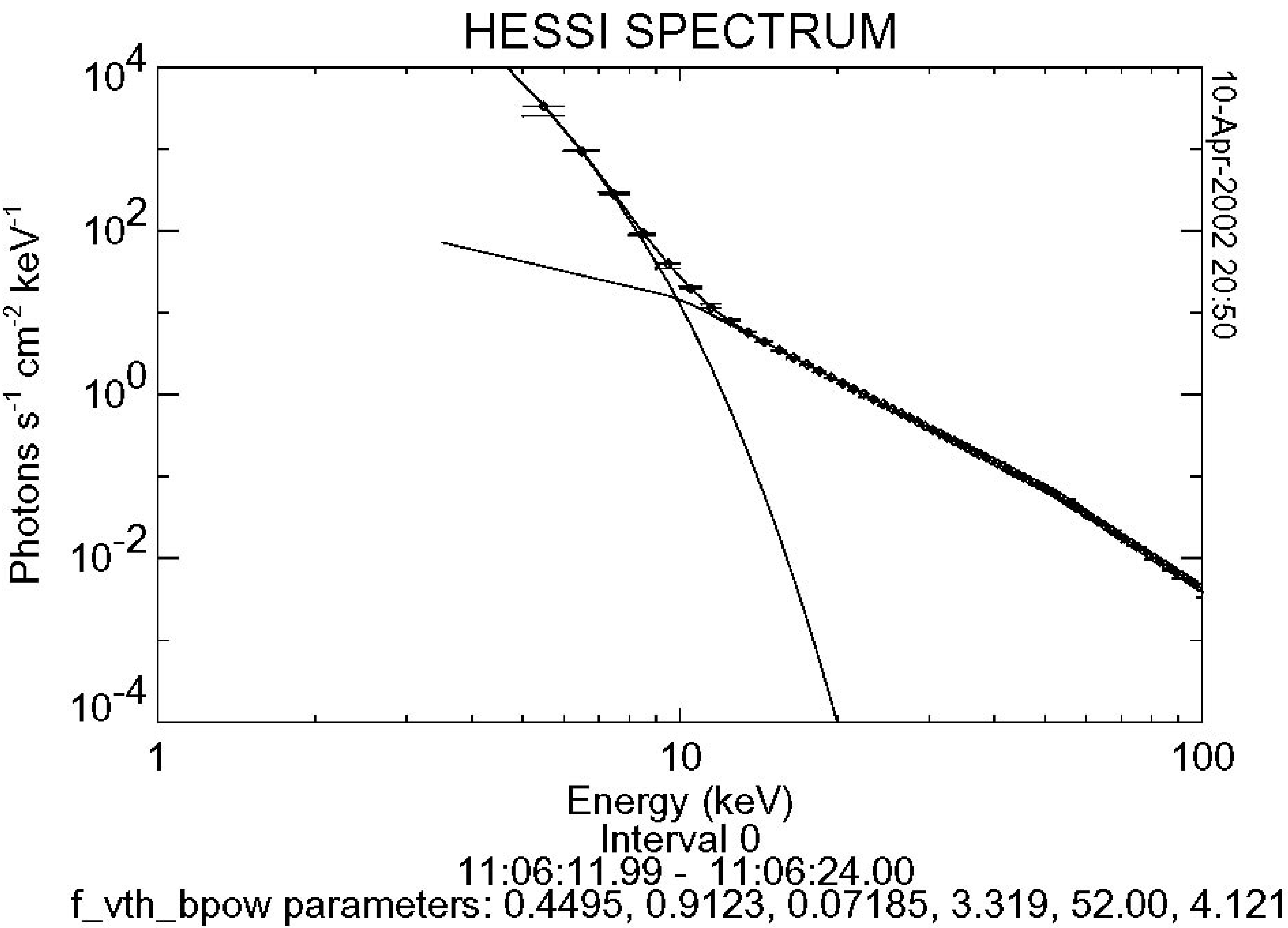
- 10^{37} e s^{-1} > 20 keV
- for ~ 100 s
- 100 MeV maximum
- $3x10^{31}$ ergs > 20 keV
- Energy equipartition
- Simultaneous with ions
- Acceleration from thermal distribution
- Replenishment

Ions (large flare)

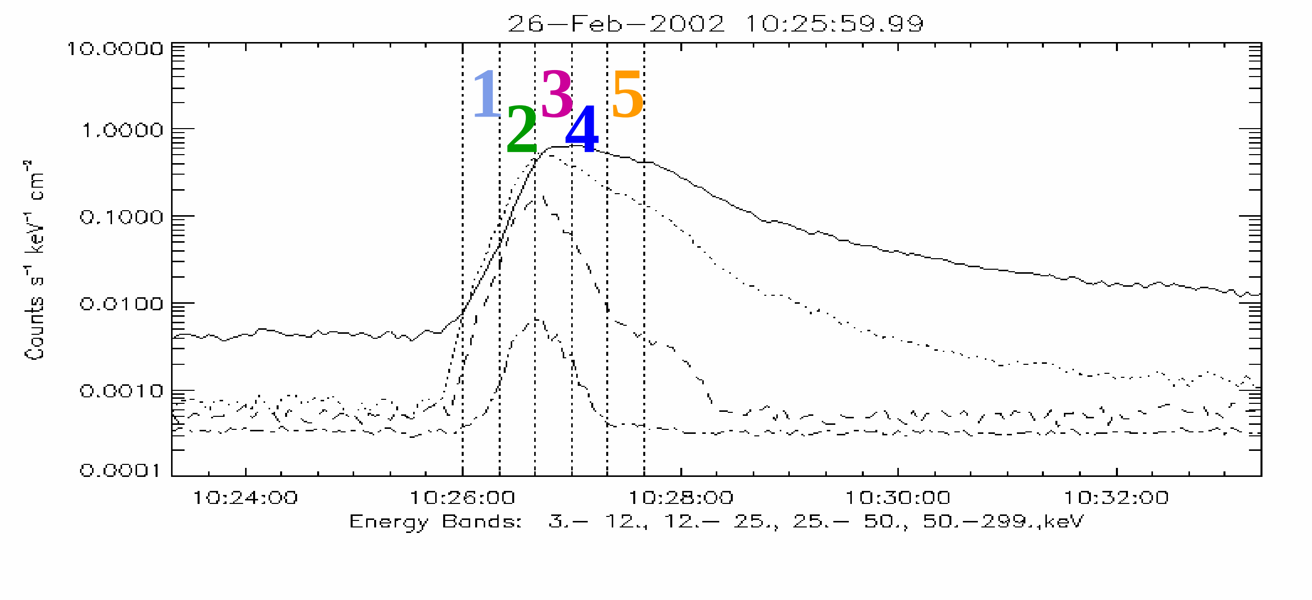
- 10^{35} p s^{-1} > 1 MeV
- for ~ 100 s
- 1 GeV maximum
- 3×10^{31} ergs > 1 MeV/n
- Energy equipartition
- Simultaneous with electrons
- Acceleration from thermal distribution
- Abundance enhancements
- Replenishment

More…

- Energy is released in footpoints (ususaly two or more..)
- Ions and Electrons seem to choose different footpoints-diferent loops?
- Radio emission suggest the presence of beams (type III), shocks (type II), microwaves (trapped particles in complex topologies?)
- Acceleration prior to the flare and long after

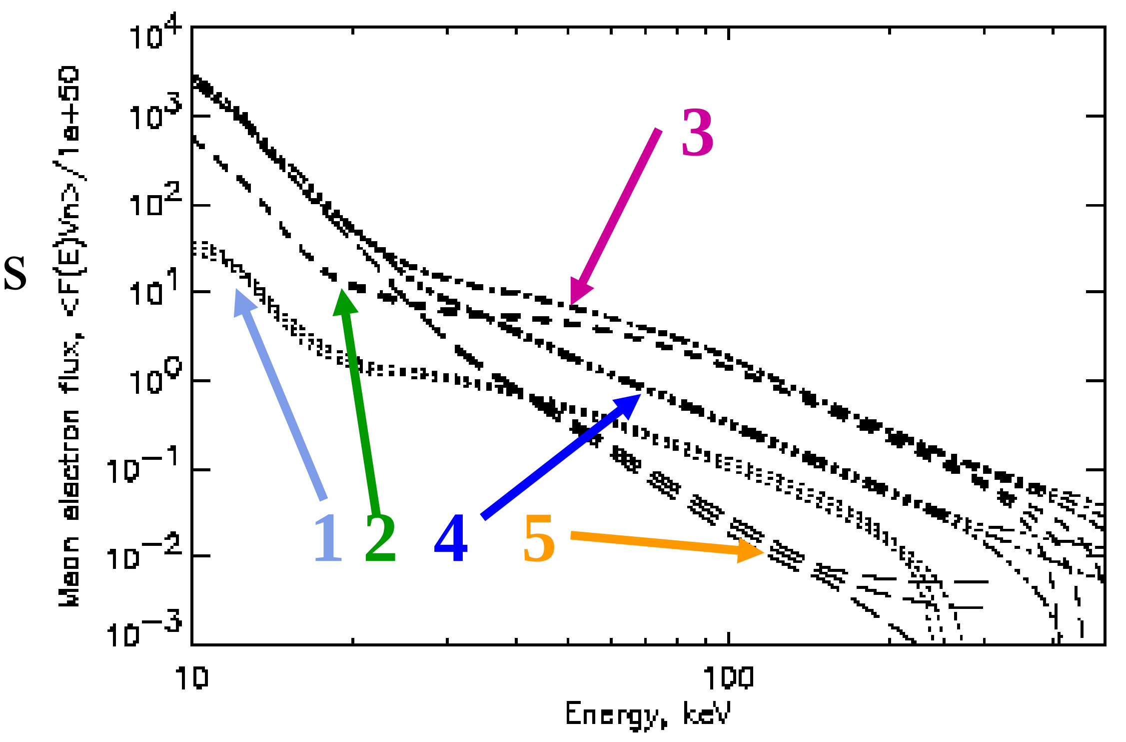

HESSI SPECTRUM
10-Apr-2002 20:50
Photons s-1 cm-2 keV-1
10^4
10^2
10^0
10^-2
10^-4
1
10
100
Energy (keV)
Interval 0
11:06:11.99 - 11:06:24.00
f_vth_bpow parameters: 0.4495, 0.9123, 0.07185, 3.319, 52.00, 4.121

Mean Electron Spectrum: Temporal evolution

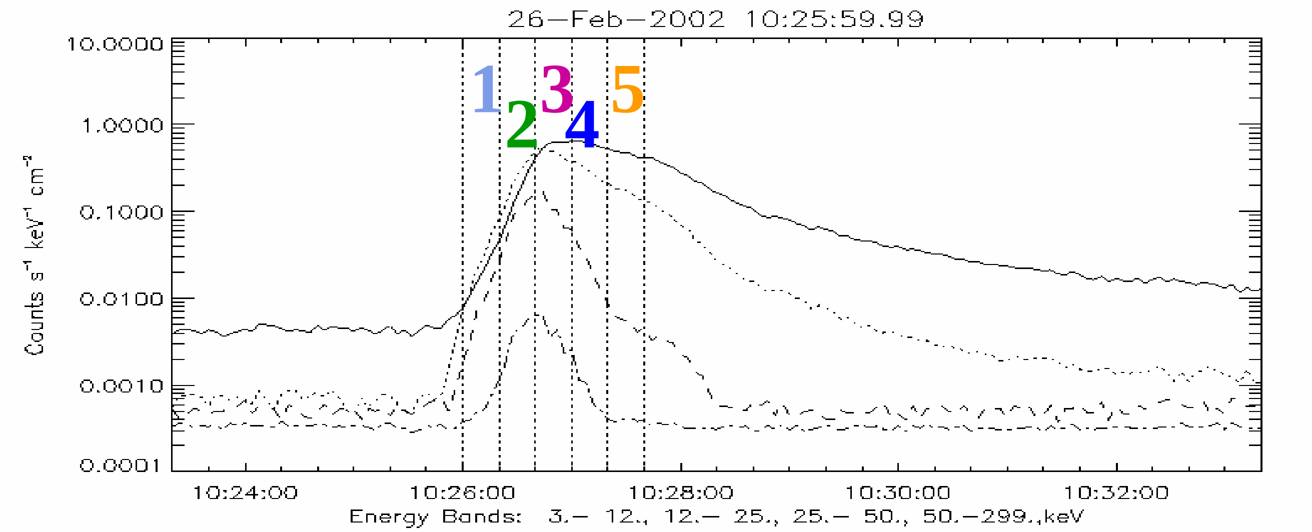


RHESSI Light curves
3-12keV;
12-25keV;
25-50keV;
50-300keV

Temporal evolution of the Regularized Mean Electron Spectrum (20s time intervals



Mean Electron Spectrum: Temporal evolution



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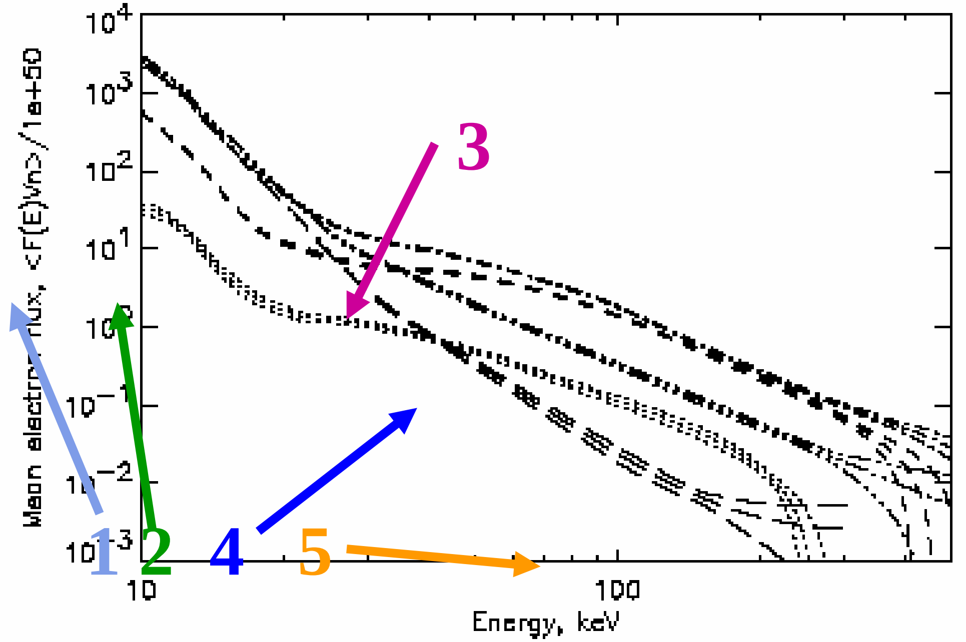
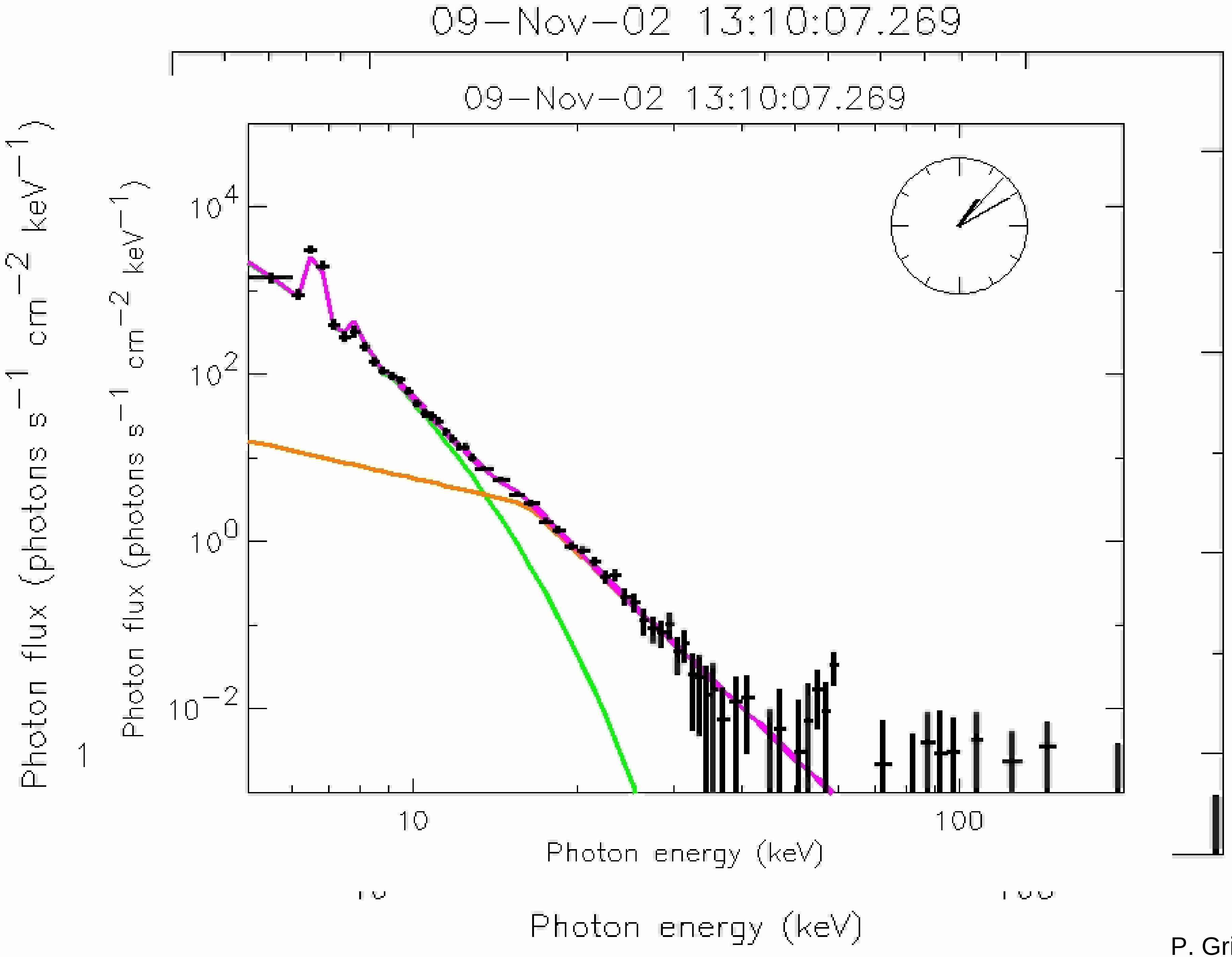
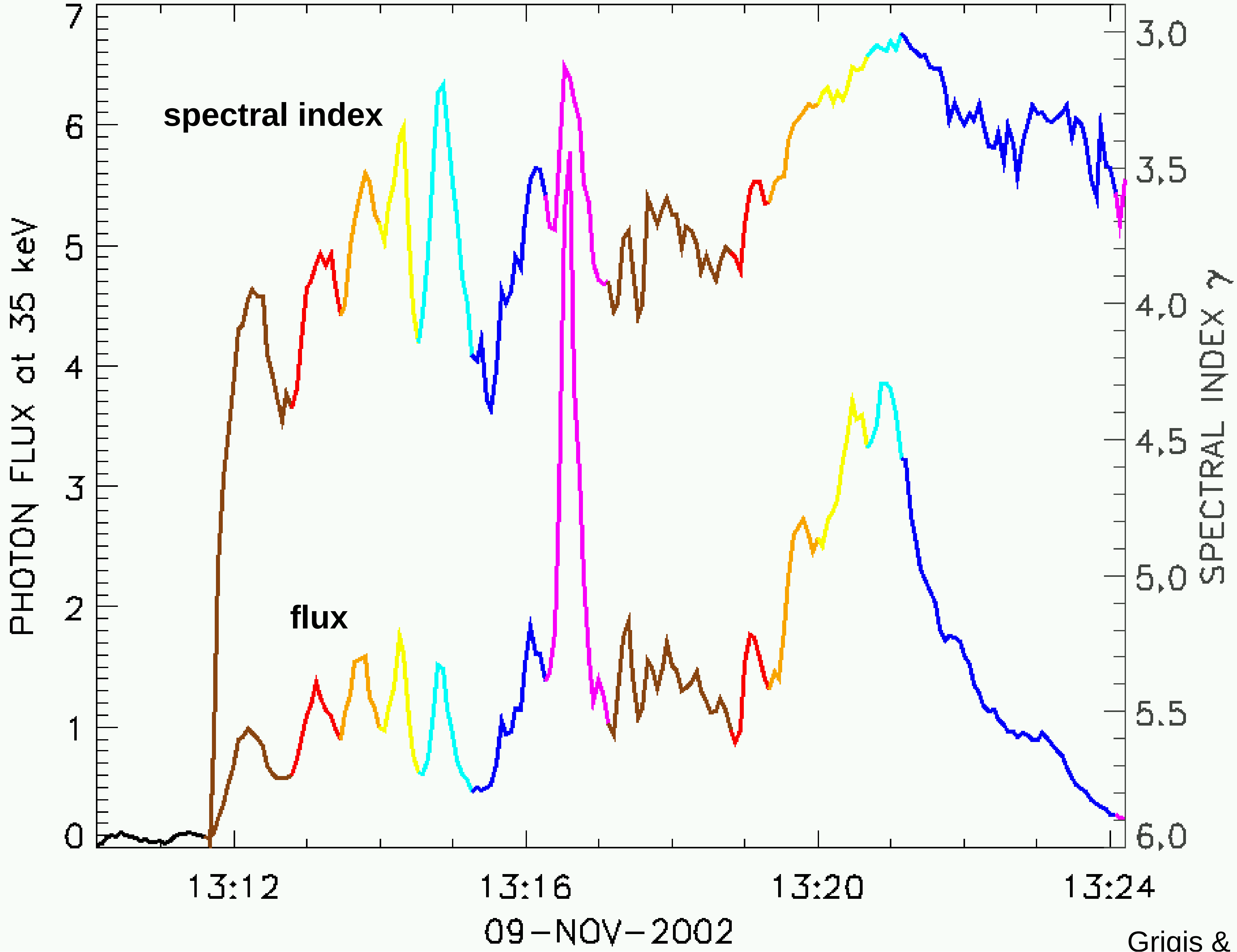




09-Nov-02 13:10:07.269
Photon flux (photons s^{-1} cm^{-2} keV^{-1})
10^4
10^2
10^0
10^{-2}
10
100
Photon energy (keV)

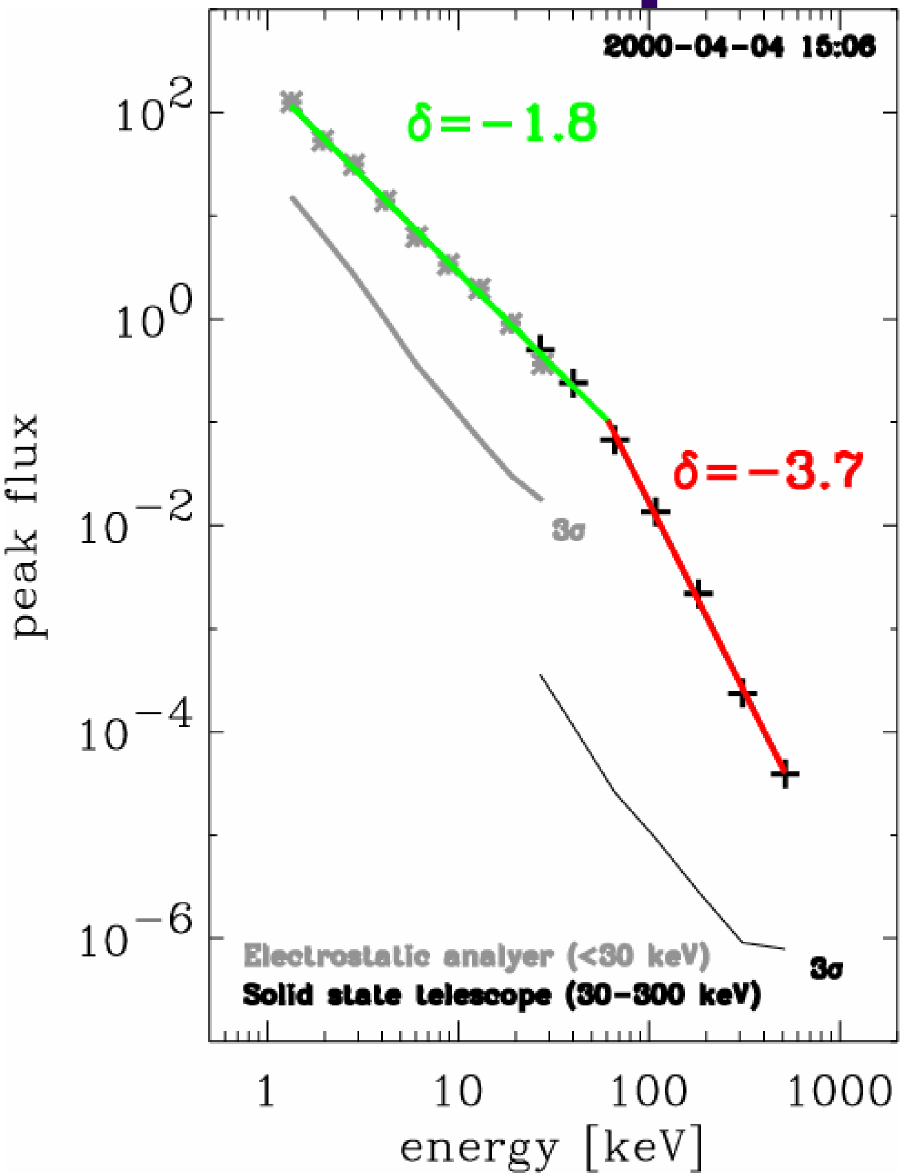
P. Grigis



spectral index
flux
PHOTON FLUX at 35 keV
SPECTRAL INDEX γ
13:12
13:16
13:20
13:24
09−NOV−2002
0
1
2
3
4
5
6
7
3,0
3,5
4,0
4,5
5,0
5,5
6,0

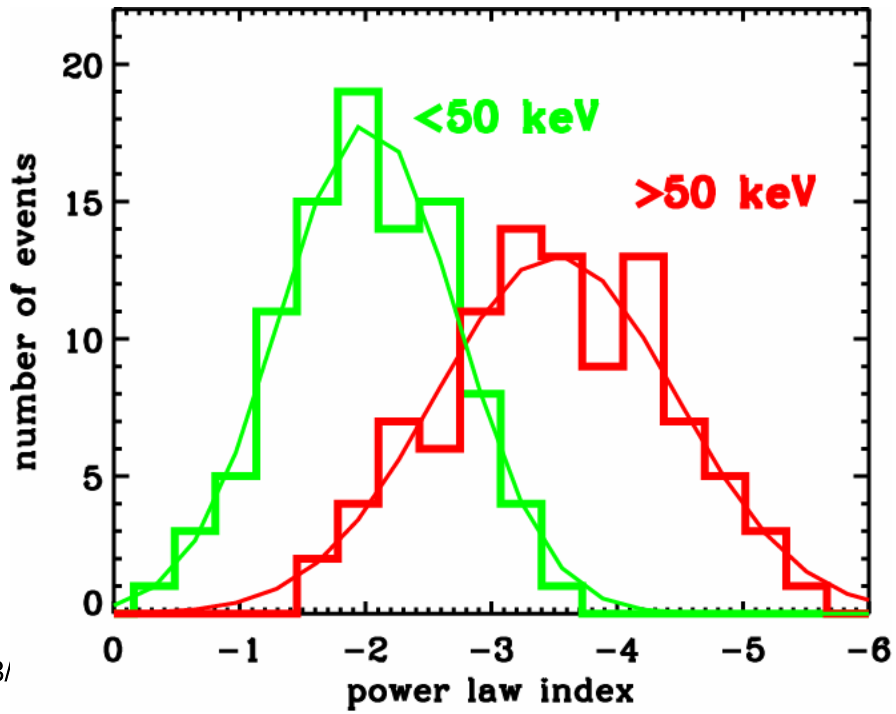
Grigis & B.

Electron spectrum at 1AU



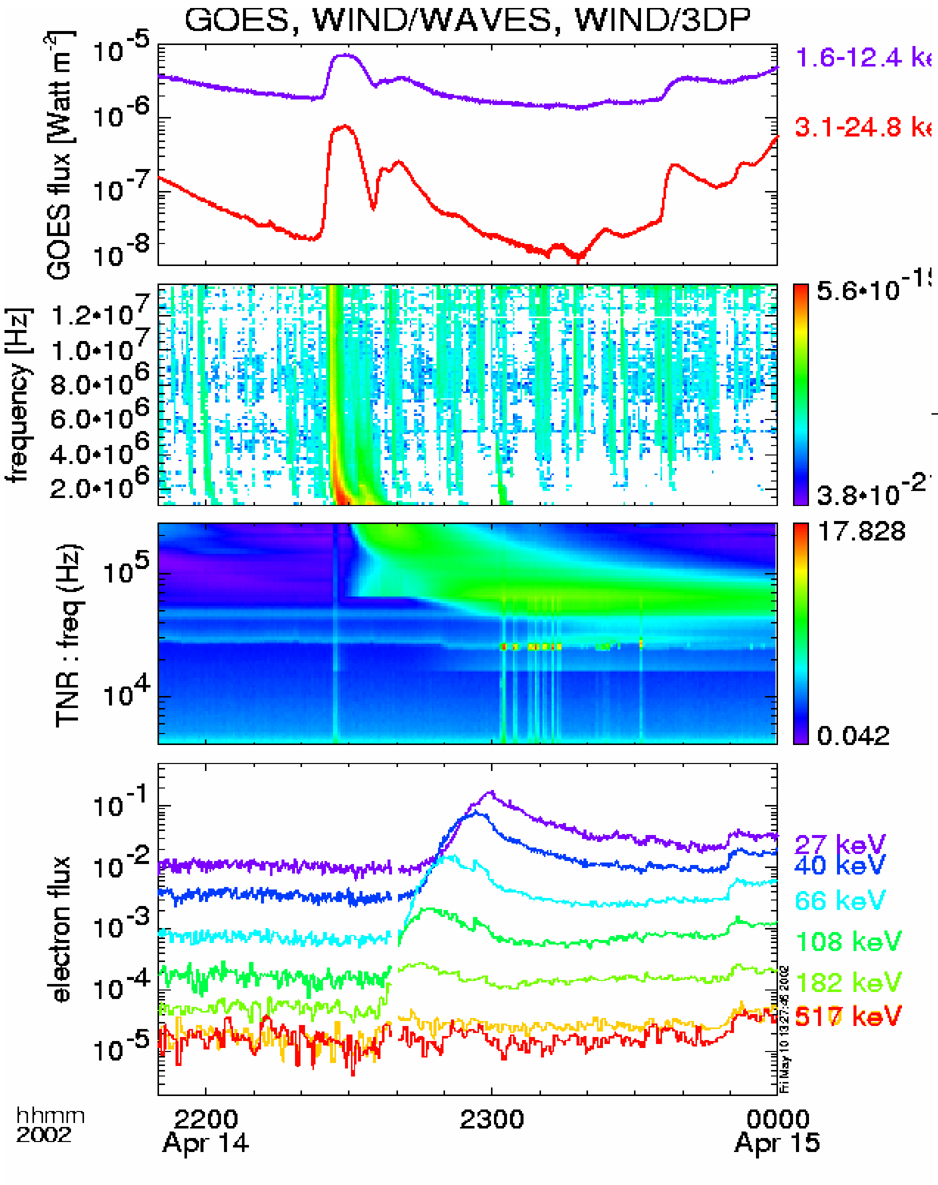
Typical electron spectrum can be fitted with broken power law:

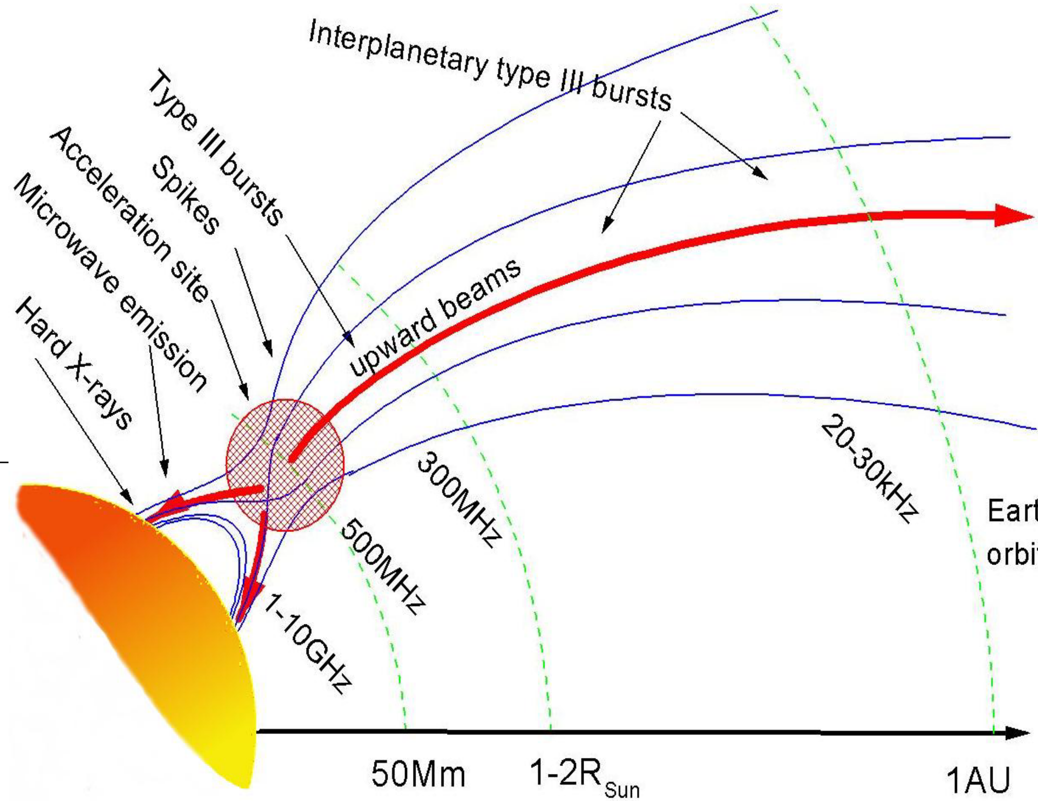
Break around: 30-100 keV
Steeper at higher energies



Oakley, Krucker, & Lin 2004

Solar energetic particles at 1AU (Krucker-Kontar)





Abundance Enhancements

Ion	Ambient Abundance Relative to H	Mass Number A	Charge-to-mass Ratio Q/A	Observed Enhancement in SEPs Relative to Coronal
H	1	1	1.0	
^3He	$\approx 5 \times 10^{-4}$	3	0.67	≈2000
^4He	0.036	4	0.5	normal
C	2.96×10^{-4}	12	0.5	normal
N	7.90×10^{-5}	14	0.5	normal
O	6.37×10^{-4}	16	0.5	normal
Ne	9.68×10^{-5}	20	0.40	≈3
Mg	1.25×10^{-4}	24	0.42	≈3
Si	9.68×10^{-5}	28	0.43	≈3
Fe	8.54×10^{-5}	56	0.23	≈10
Kr	1.41×10^{-8}	85 (mean)	0.13	≈100
Xe	8.66×10^{-10}	128 (mean)	0.11	≈1000

(work by Reames et al.)

What the observation do not say

- Magnetic topology in the corona
- Location of energy release
- How to connect the magnetic energy release mechanisms with particle acceleration?
- What is the role of MHD in predicting the evolution of a flare, if most energy goes to energetic particles?

Acceleration Mechanisms

- Direct E-fields-Reconnection?
- Stochastic acceleration by Waves (MHD and whistlers) ?
- Shocks wave acceleration?

- Does any of these work for the Sun?

Basic equation for non relativistic particles

$$m_j \frac{d\vec{v}}{dt} = q_j \left(\vec{E}(\vec{r},t) + \frac{\vec{v} \times B(\vec{r},t)}{c} \right) - \nu m \vec{v}$$

$$m_j \vec{v} \cdot \frac{d\vec{v}}{dt} = q_j \vec{v} \cdot \vec{E}(\vec{r},t) - \nu m v^2$$

1. Sub-Dreicer Electric Fields

- Uses: Long ($\sim 10^9$ cm) weak ($< 10^{-4}$ V cm^{-1}) fields
- Geometry: Field-aligned in the loop or normal to an arcade
- Mechanism: Runaway acceleration (Dreicer 1960; Knoepfel & Spong 1979)

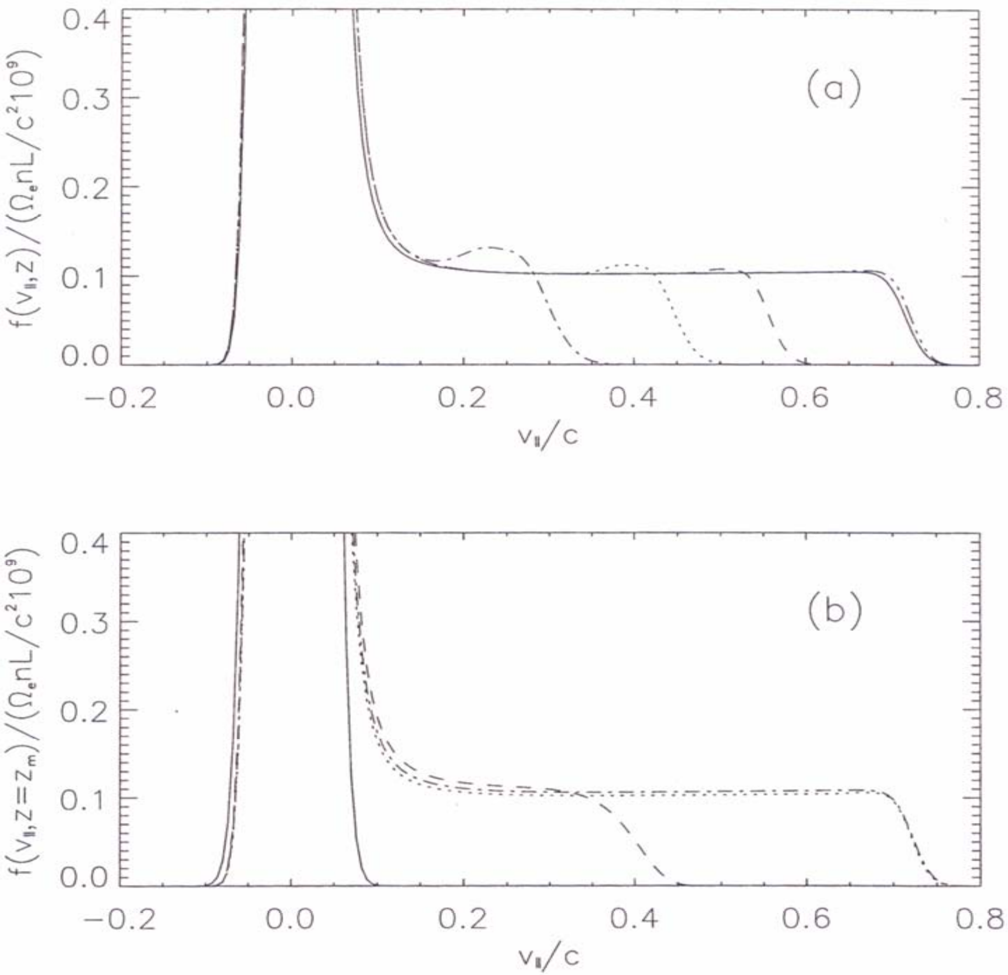
Strengths

- Runaway physics well understood (Fuchs et al. 1986)
- Models have been successful for HXR and radio emission (Holman & Benka 1992)

Weaknesses

- Maximum electron energy ~100 keV
- Need lots (~10^{12}) of current channels
- Replenishment is difficult (Emslie & Henoux 1995)
- Ion acceleration is untenable (Holman 1995)
- Native distributions are flat
- Current Channel formation/stability ?

Runaway Distributions

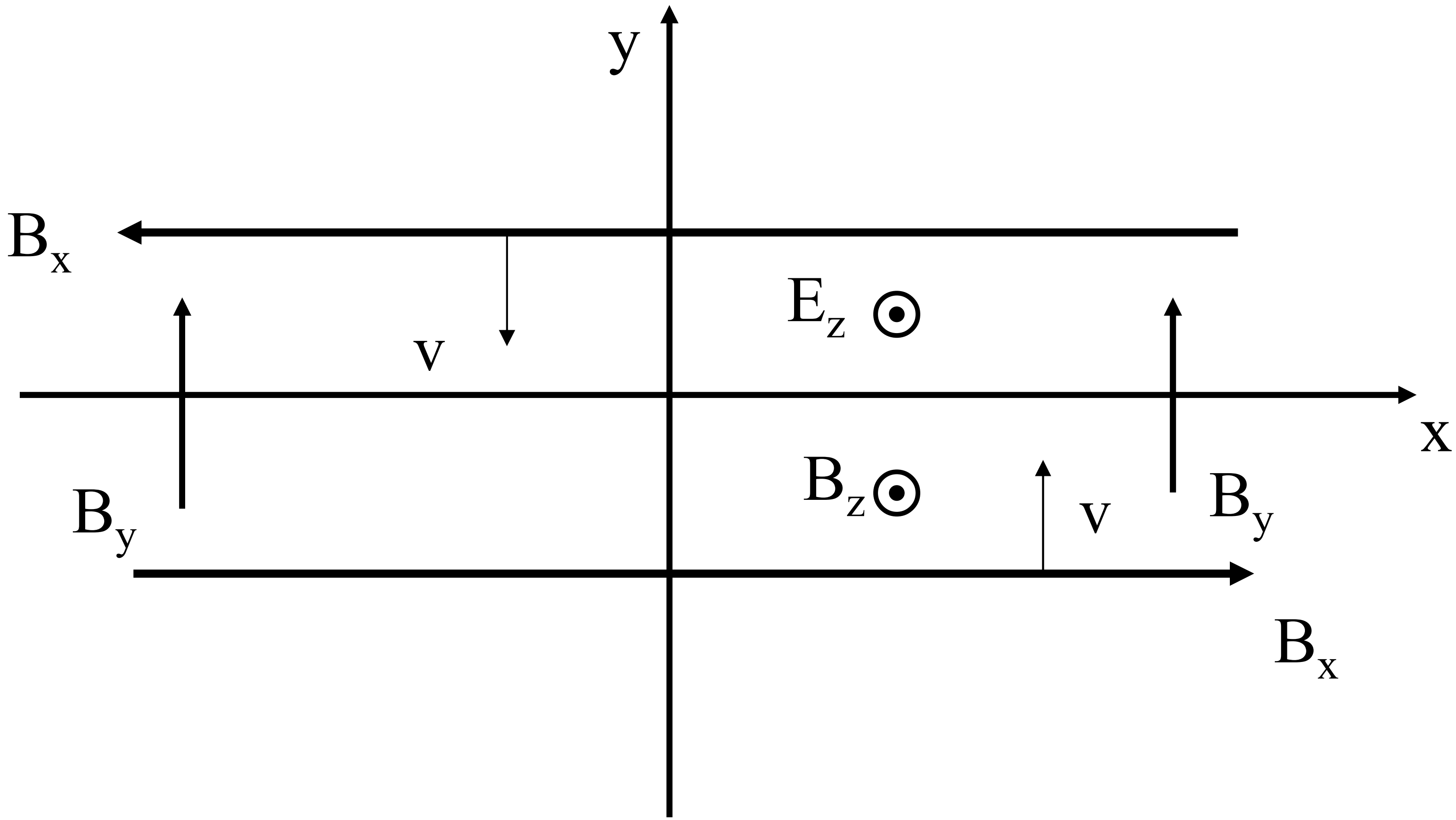


(Sommer 2002)

2. Super-Dreicer Electric Fields

- Uses: Long (~10^9 cm) strong (>>1 V cm^{-1}) fields
- Geometry: Large (thin!) current sheet above an arcade of loops
- Mechanism: Direct acceleration with drift escape

Magnetic Field Configuration



$$v = 10^8\, cm/s, B = 10^3\, G \Rightarrow E_z = 10^3\, V/cm$$

Strengths

- Hopeful for HXR emission (e.g., Litvenenko 1996; Martens 1988)
- Maximum electron energy ~1 GeV
- Simple geometry
- Replenishment is natural

Weaknesses

- Ion acceleration very questionable
- Particle distributions not calculated
- Electron holes are actually doing the acceleration (Drake et al.)
- Stability of very thin sheet ?

3. Shocks

- The mechanism for gradual events; prime importance at astrophysical sites
- Uses: Large-scale (Ellison & Ramaty 1985) or an ensemble of smaller shocks (Anastasiadis & Vlahos 1991)
- Geometry: In or around the loop(s)
- Mechanism: Diffusive or shock drift

Strengths

- Actual acceleration mechanism is well studied
- Ion acceleration (a few MeV) is possible (Decker & Vlahos 1986)

Weaknesses

- Distributions mostly unknown (Ellison & Ramaty 1985)
- Replenishment ?
- Ion abundance enhancements not likely
- Type II emission not typical
- Generation unspecified

4. Fermi Acceleration (Stochastic)

- Uses: Large-amplitude $(\delta B / B \approx 1)$ plasma waves, or magnetic “blobs”
- Geometry: Waves distributed throughout the loop(s), on both open and closed field lines.
- Mechanism: Adiabatic collisions with moving scattering centers (Fermi 1949; Davis 1956)

Strengths

- Oldest flare acceleration mechanism (Parker & Tidman 1958)
- Energizes ions (Ramaty 1979; Miller et al. 1990) and electrons (Gisler 1992; LaRosa et al. 1994)
- Simple geometry (cospatial return currents)

Weaknesses

- No ion abunance enhancements
- Maximum electron energy ?
- Consistent modeling parameters not used
- “outdated”
- Formation of turbulence ?

5. Resonant Acceleration (Stochastic)

- Uses: low-amplitude $(\delta B / B << 1)$ plasma waves
- Geometry: Waves distributed throughout the loop, on both open and closed field lines
- Mechanism: Resonance with either the transverse wave E-field (cyclotron) or the parallel B-field (Landau)

Quasilinear Simulation

$$\frac{\partial N_e}{\partial t} = -\frac{\partial}{\partial E}\left\{\left[A_e + \left(\frac{dE}{dt}\right)_{\mathrm{Ce}}\right] N_e\right\} + \frac{1}{2}\frac{\partial^2}{\partial E^2}\left[(D_e + D_{\mathrm{Ce}})N_e\right] - \frac{N_e}{T_e} + S_e \quad ,$$

$$\frac{\partial N_i}{\partial t} = -\frac{\partial}{\partial E}\left\{\left[A_i + \left(\frac{dE}{dt}\right)_{\mathrm{Ci}}\right] N_i\right\} + \frac{1}{2}\frac{\partial^2}{\partial E^2}\left[(D_i + D_{\mathrm{Ci}})N_i\right] - \frac{N_p}{T_p} + S_p \quad ,$$

$$\frac{\partial W_{\mathrm{TFM}}}{\partial t} = \frac{\partial}{\partial k}\left[k^2 D_{\mathrm{FM}} \frac{\partial}{\partial k}\left(k^{-2} W_{\mathrm{TFM}}\right)\right] - \gamma_{\mathrm{FM}} W_{\mathrm{TFM}} + S_{\mathrm{FM}} \quad ,$$

$$\frac{\partial W_{\mathrm{TA}}}{\partial t} = \frac{\partial}{\partial k_{\|}}\left(D_{\|\|}\frac{\partial W_{\mathrm{TA}}}{\partial k_{\|}}\right) - \gamma_{\mathrm{A}} W_{\mathrm{TA}} + S_{\mathrm{A}}$$

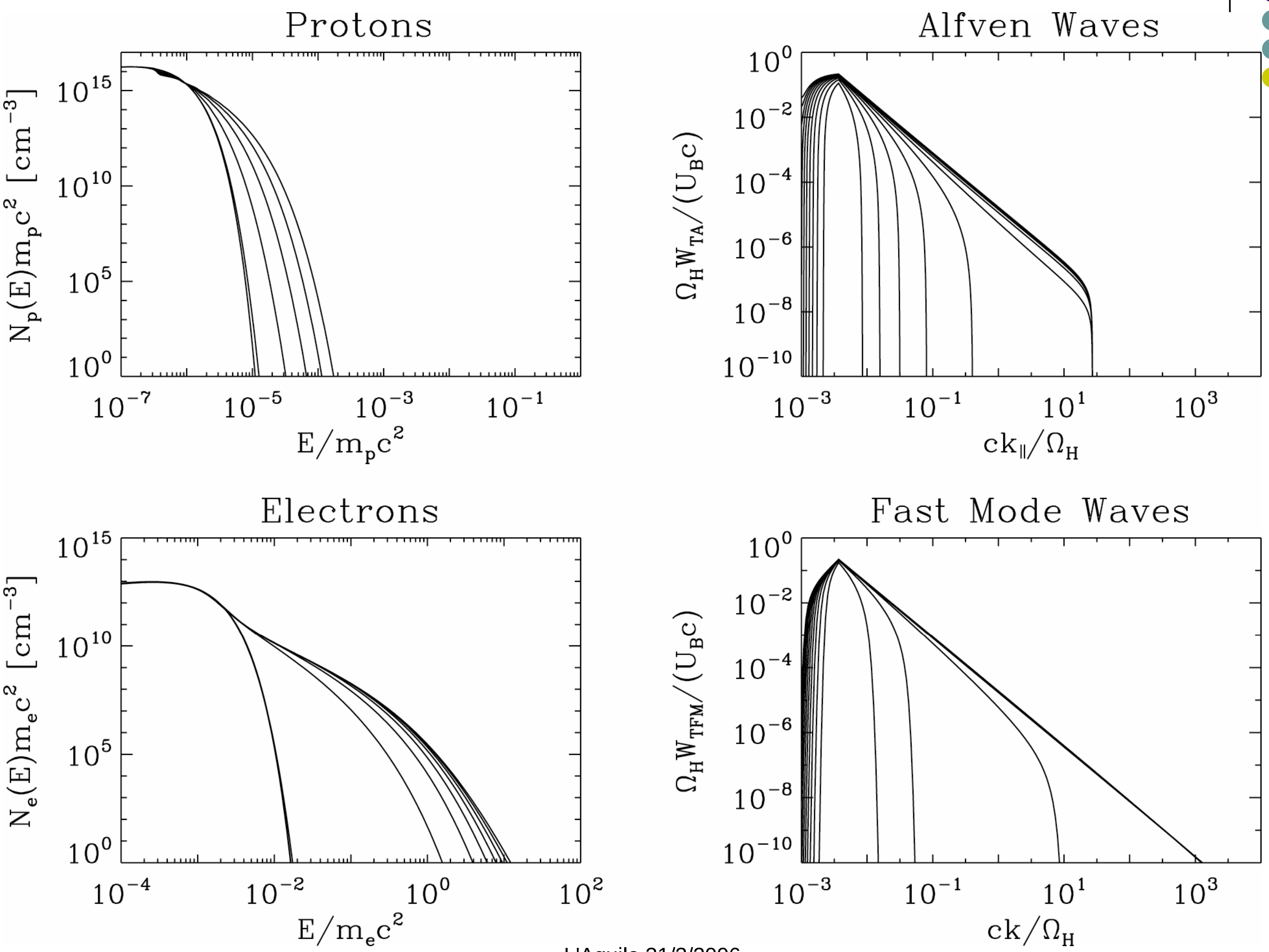
Strengths

- Employs low-amplitude waves
- Successful for both ions (e.g., Barbosa 1979) and electrons (e.g., Petrosian et al.)
- Simple geometry (cospatial return currents)
- *Required* for ^{3}He enhancement
- Unified ion/electron acceleration model possible (Miller 1998)

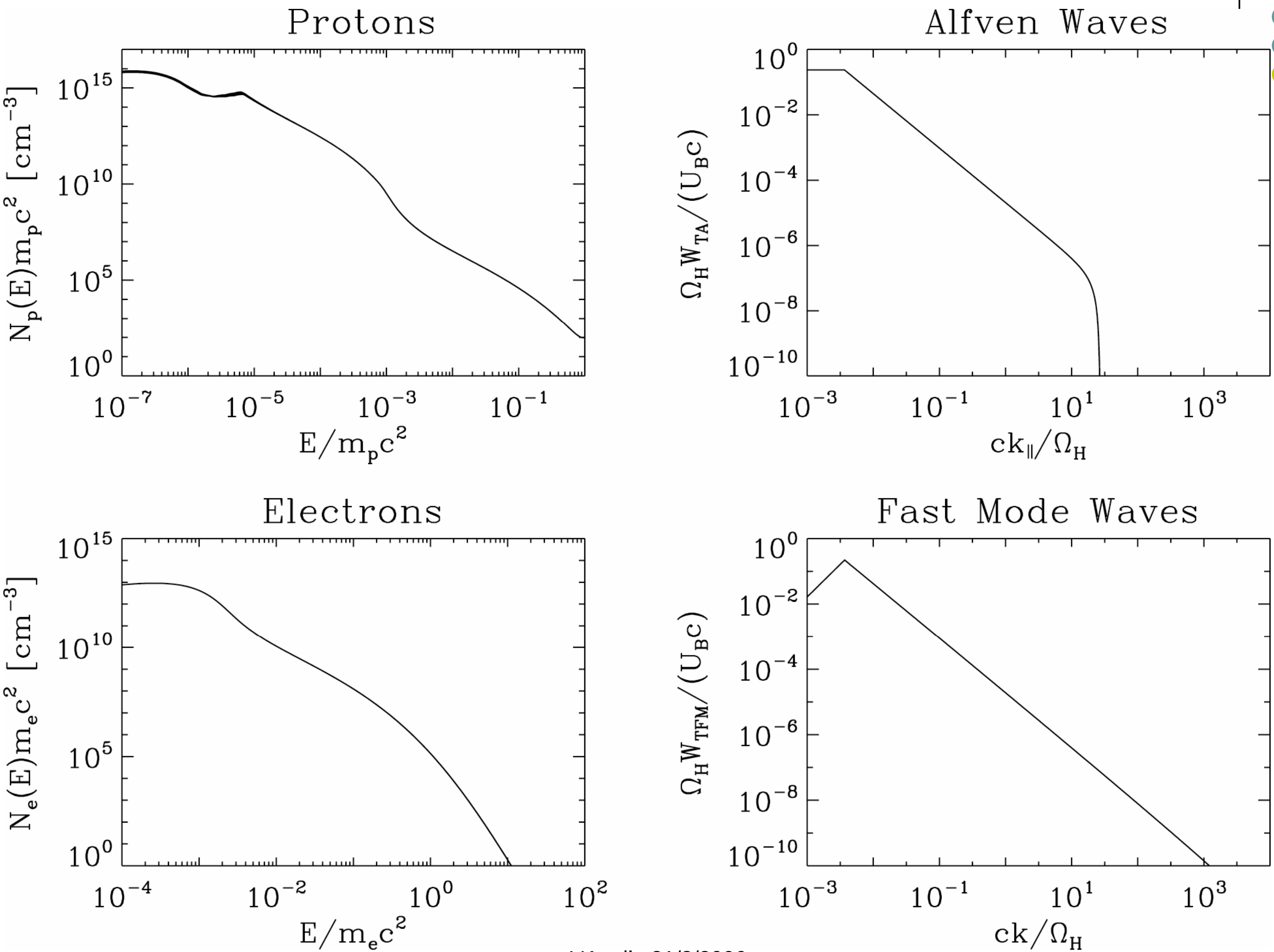
Weaknesses

- Source of turbulence is not firmly established
- Plasma wave zoo => collection of unrelated (?) models
- Fast variation of the wave amplitude to accomplish many peaks with changing slopes
- Connectivity to the energy release (reconnection)

Example



$t = 0 - 0.1$ s



T = 2 – 4 s ➔ Equilibrium

An important statment

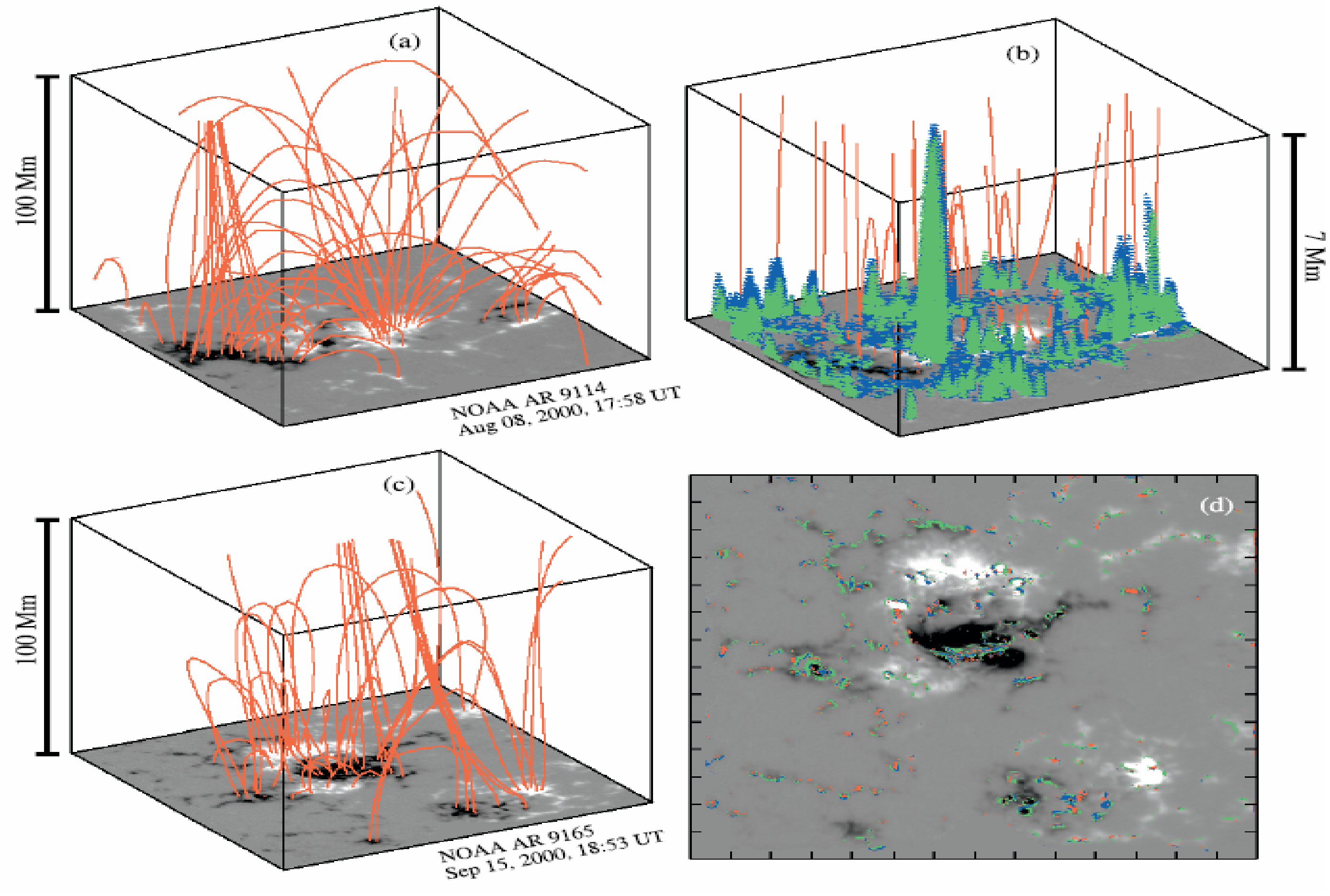
- None known theory ca capture all the details known to us from the current observations
- All theories seem to have partial success.
- What is missing?

A new look….on an old problem

- Flares are symptoms of the construction and evolution of active region.
- Known Particle acceleration are lucking the global stressed magnetic magnetic topology to host them.

- So we come back to the missing link of MHD and Kinetic effects

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

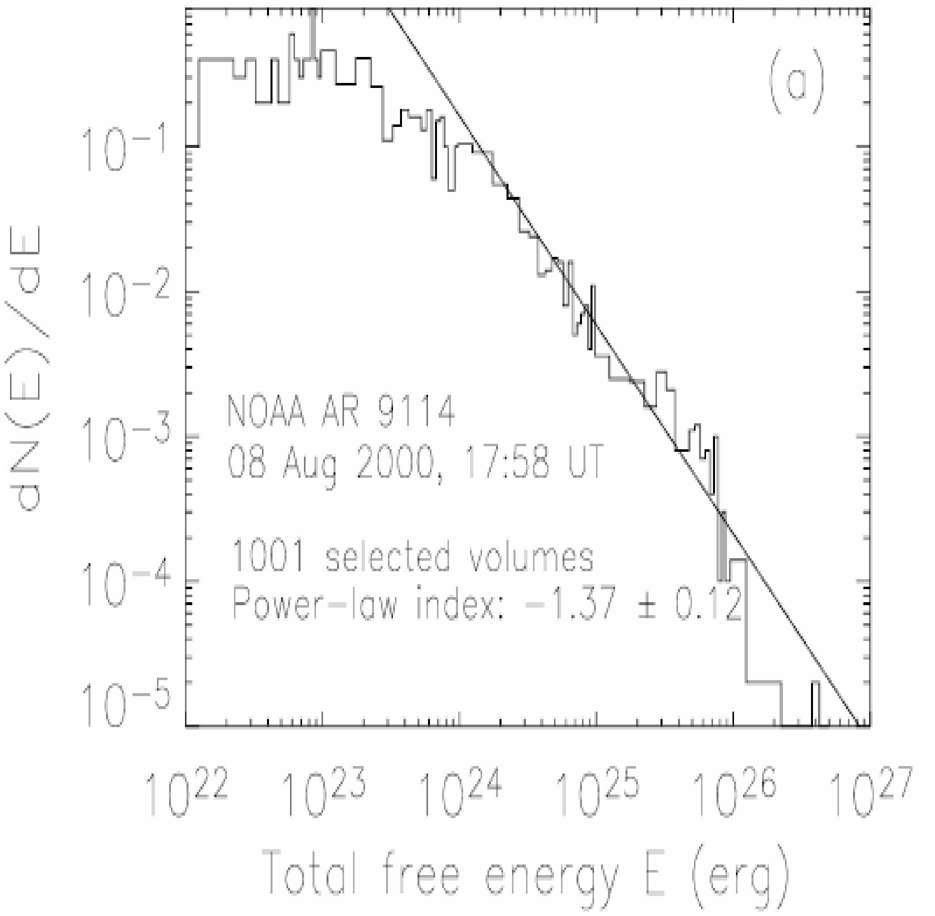


How do you define an unstable discontinuity

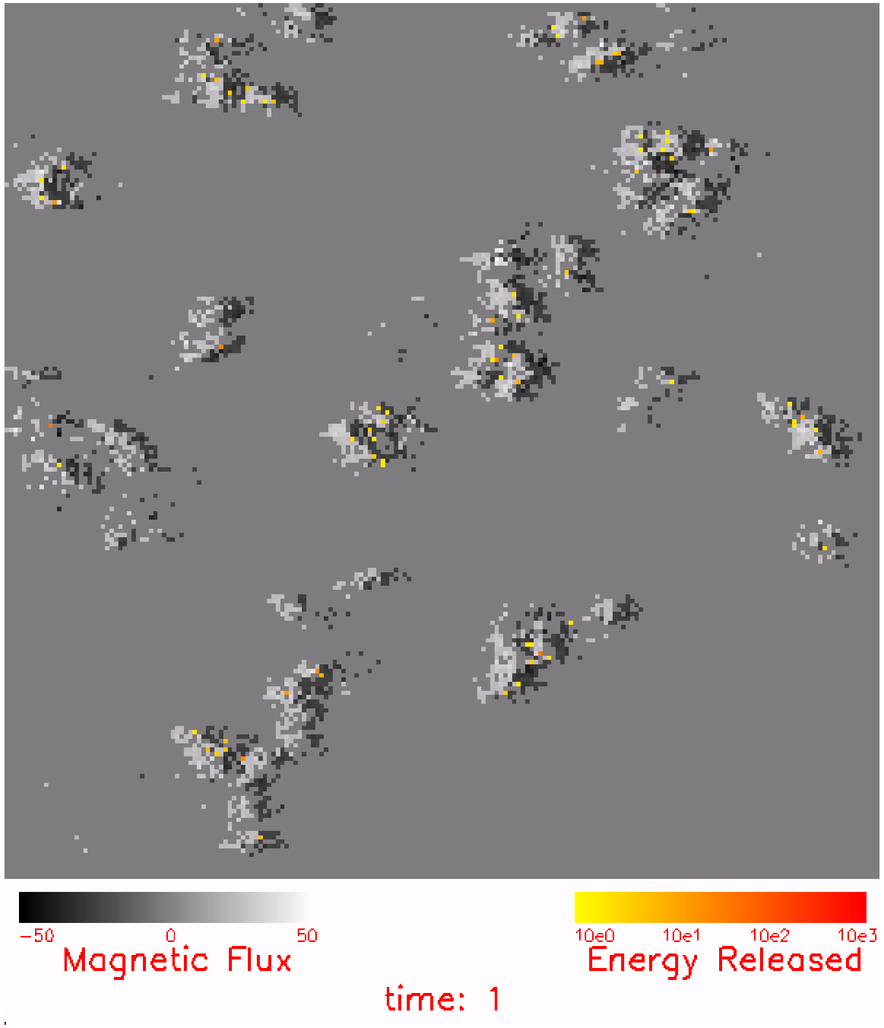
- We mark the points were (Parker's criterion)

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

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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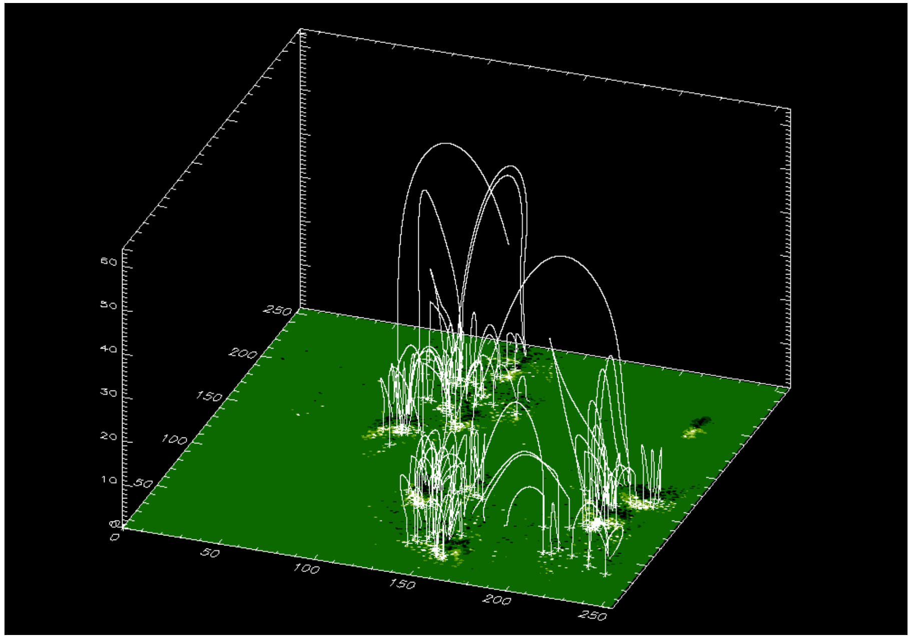
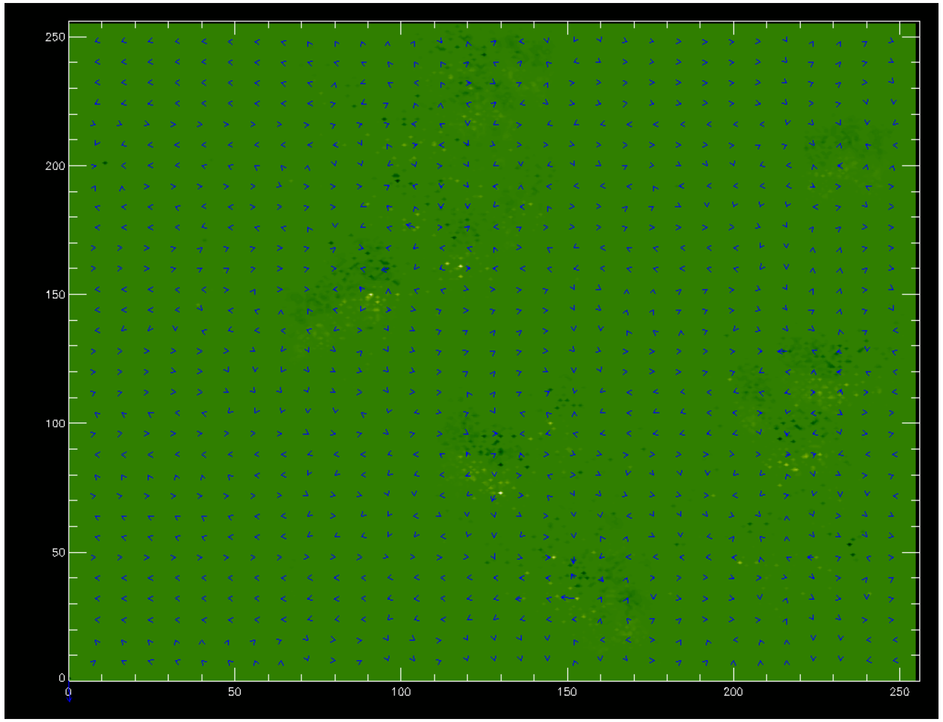
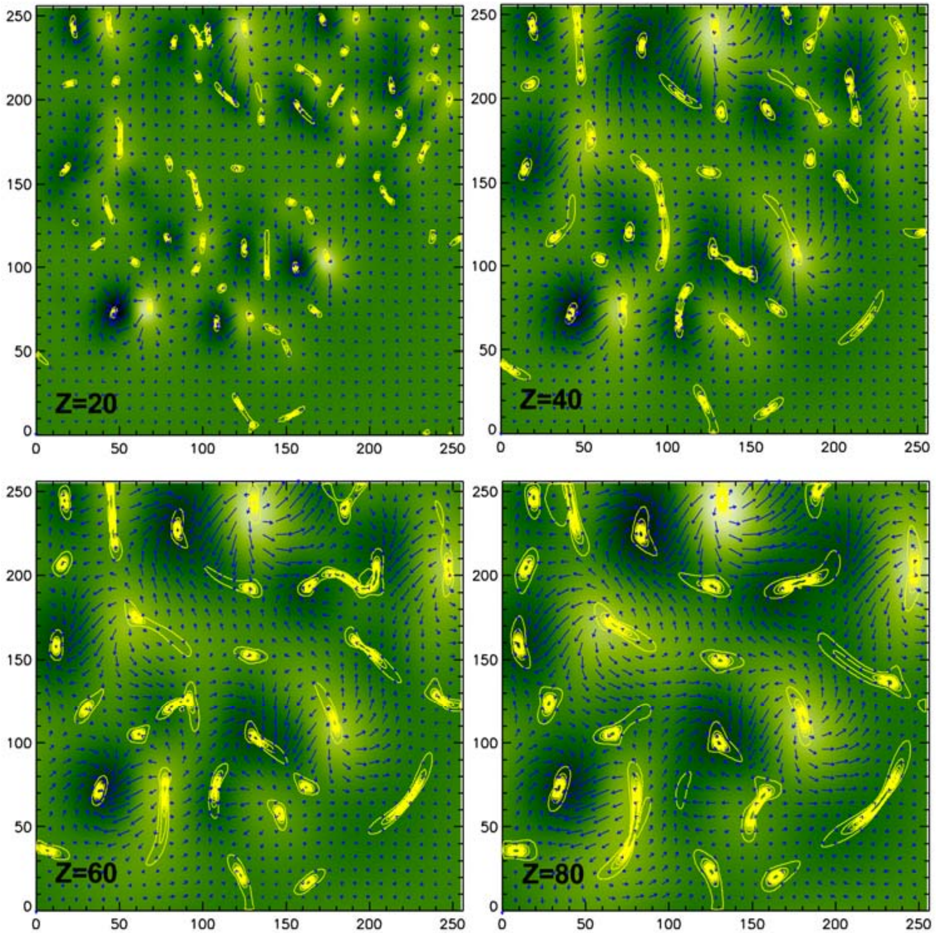
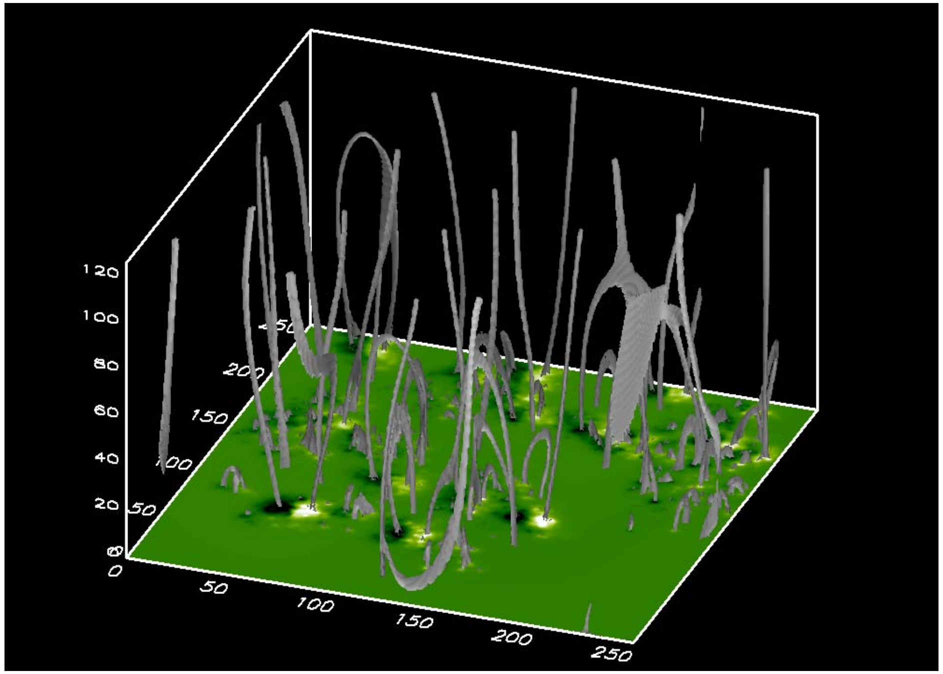




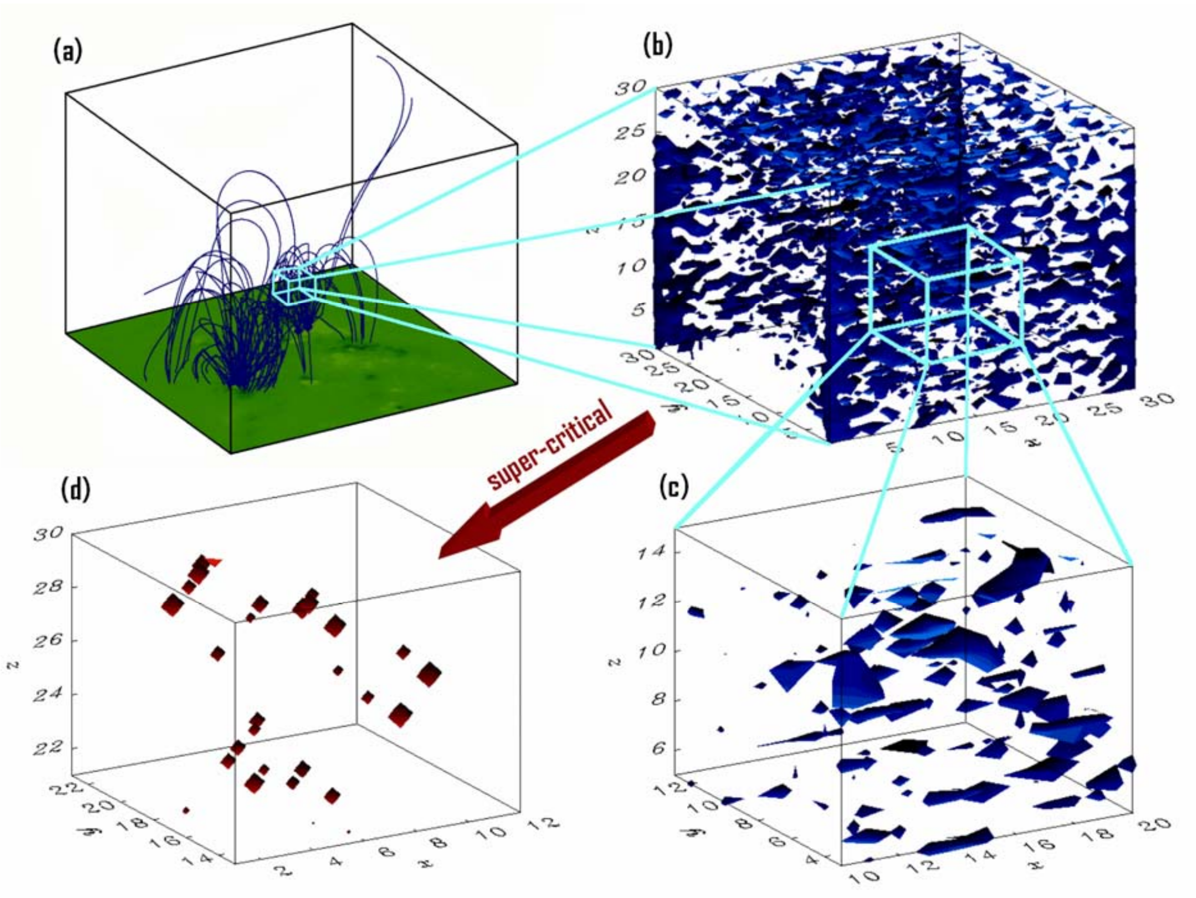
Dynamic motion of the photosphere builds constantly magnetic discontinuities
(Fragos, Rantziou, Vlahos, AA, 2004)



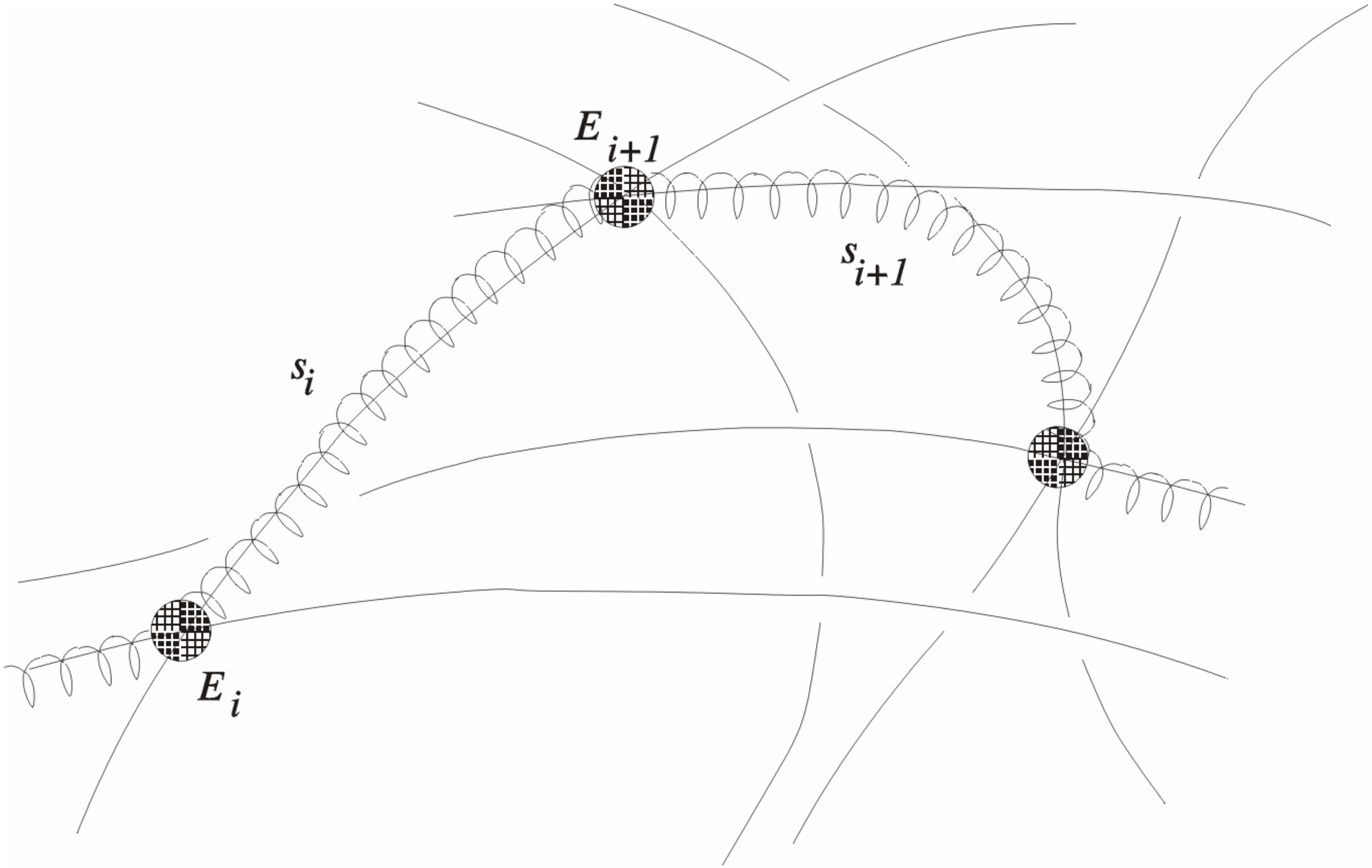


A New approach to an old problem

- From one current sheet to millions

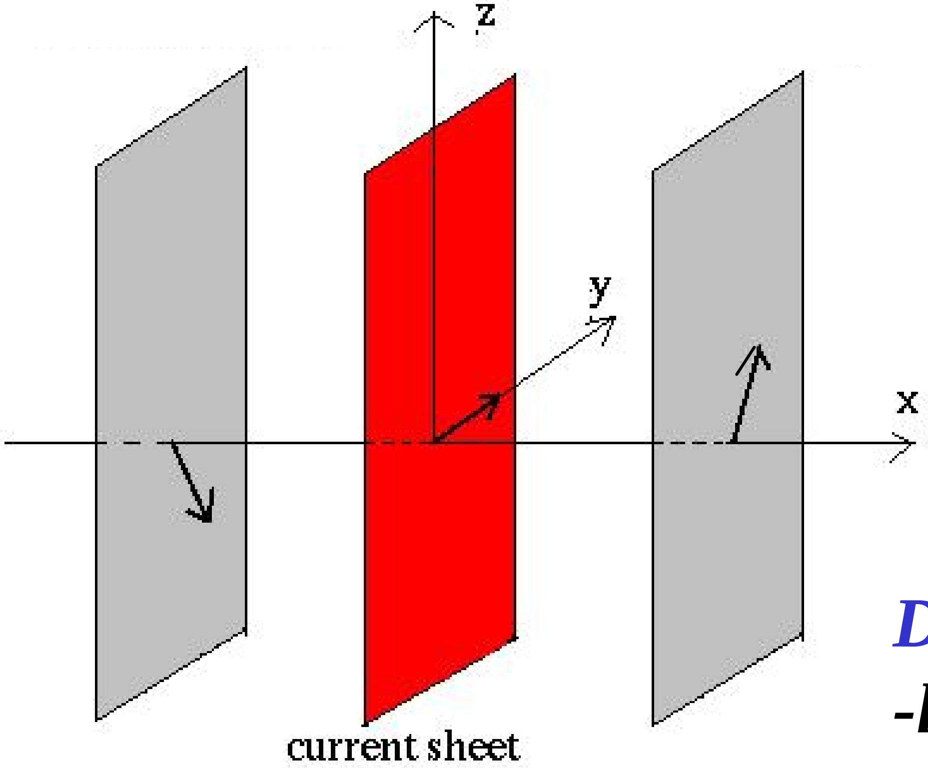


Sporadic formation of current sheets
Vlahos, Isliker and Lepreti (ApJ, June 10,2004)



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

Incompressible, viscous, dimensionless MHD equations:

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

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

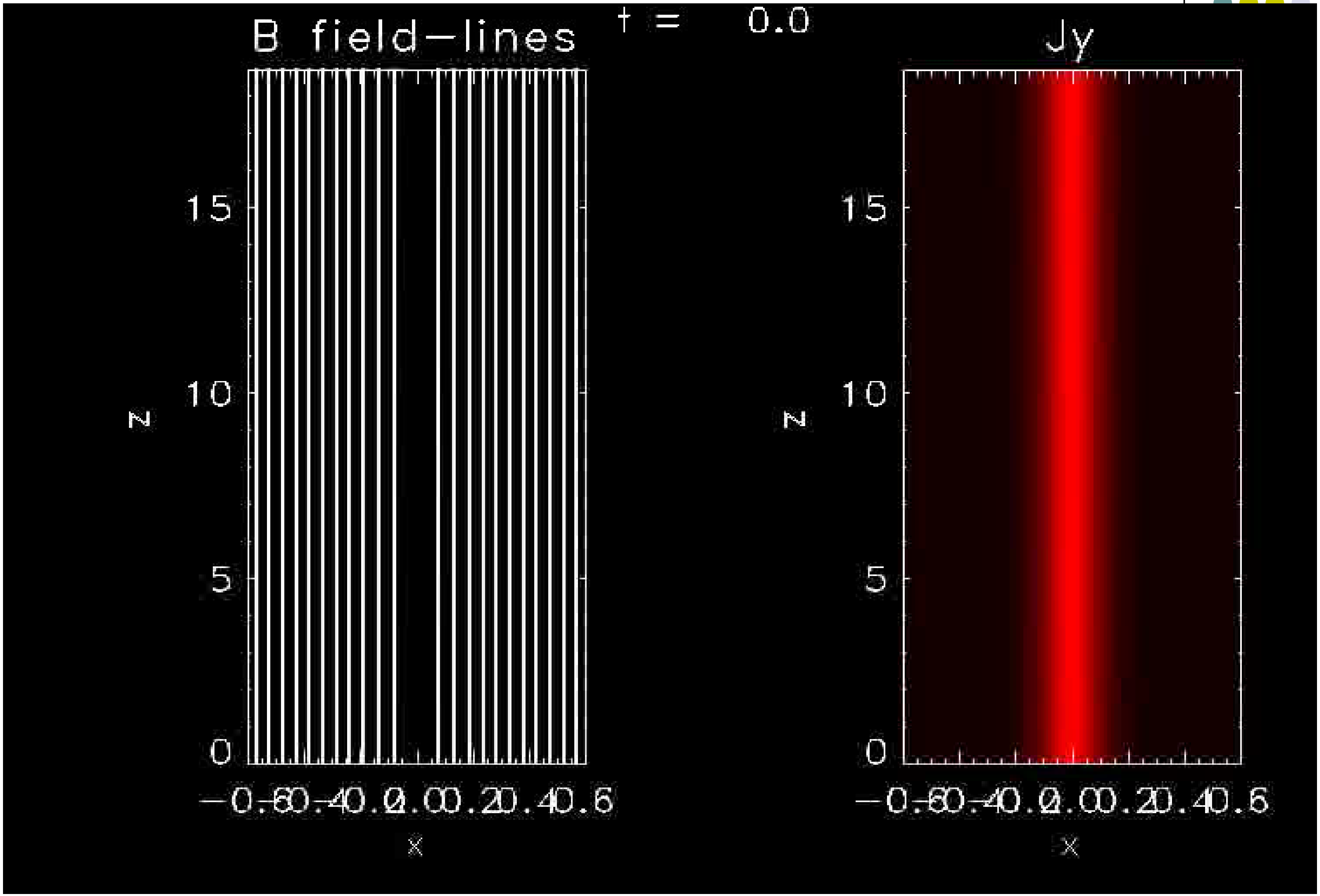
$$\nabla \cdot \mathbf{B} = 0$$

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

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

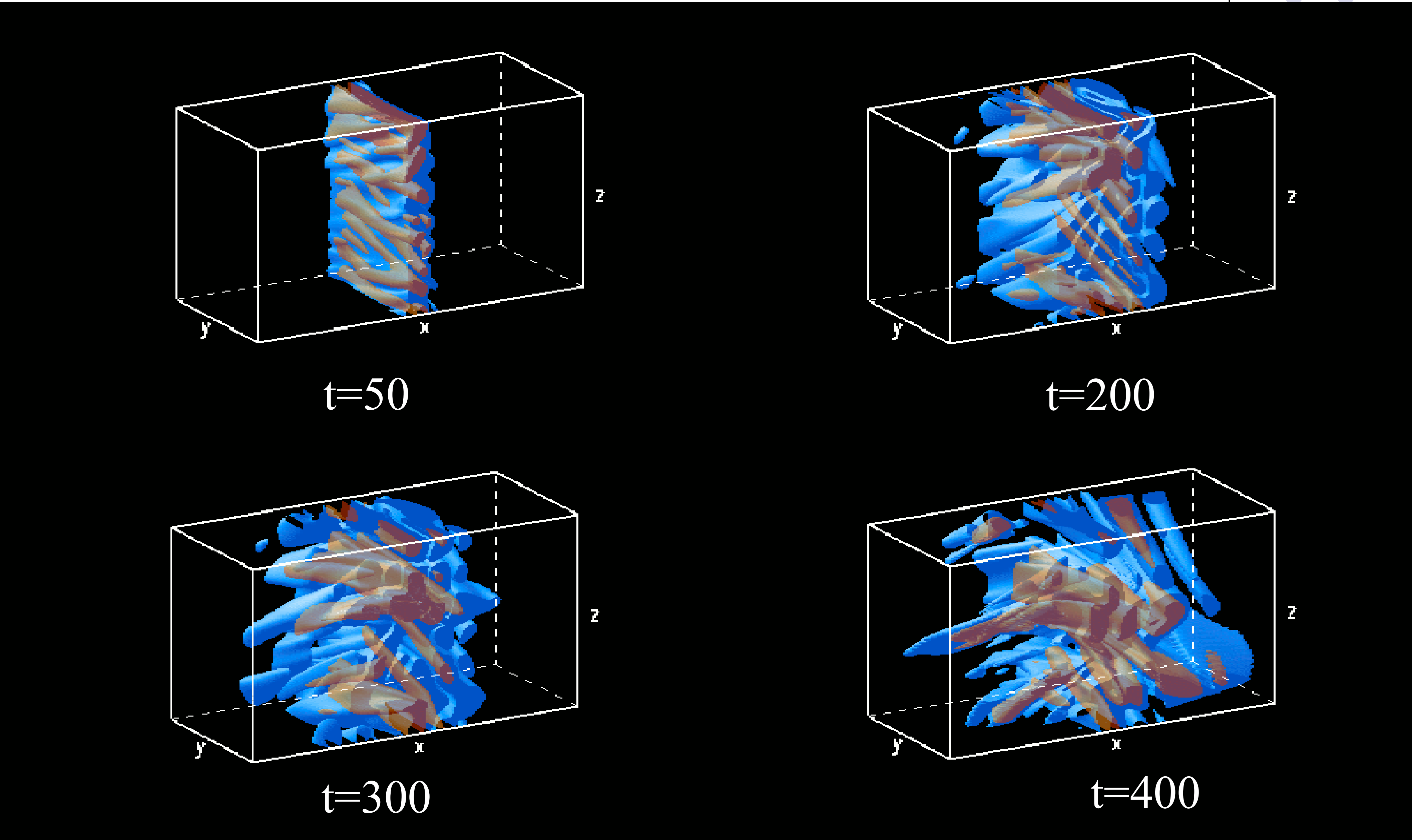
R_M ***and*** R_v ***Are the kinetic and magnetic Reynolds numbers.***

Numerical results: reconnection of magnetic field lines



Three-dimensional structure of the electric field

Isosurfaces of the electric field at different times



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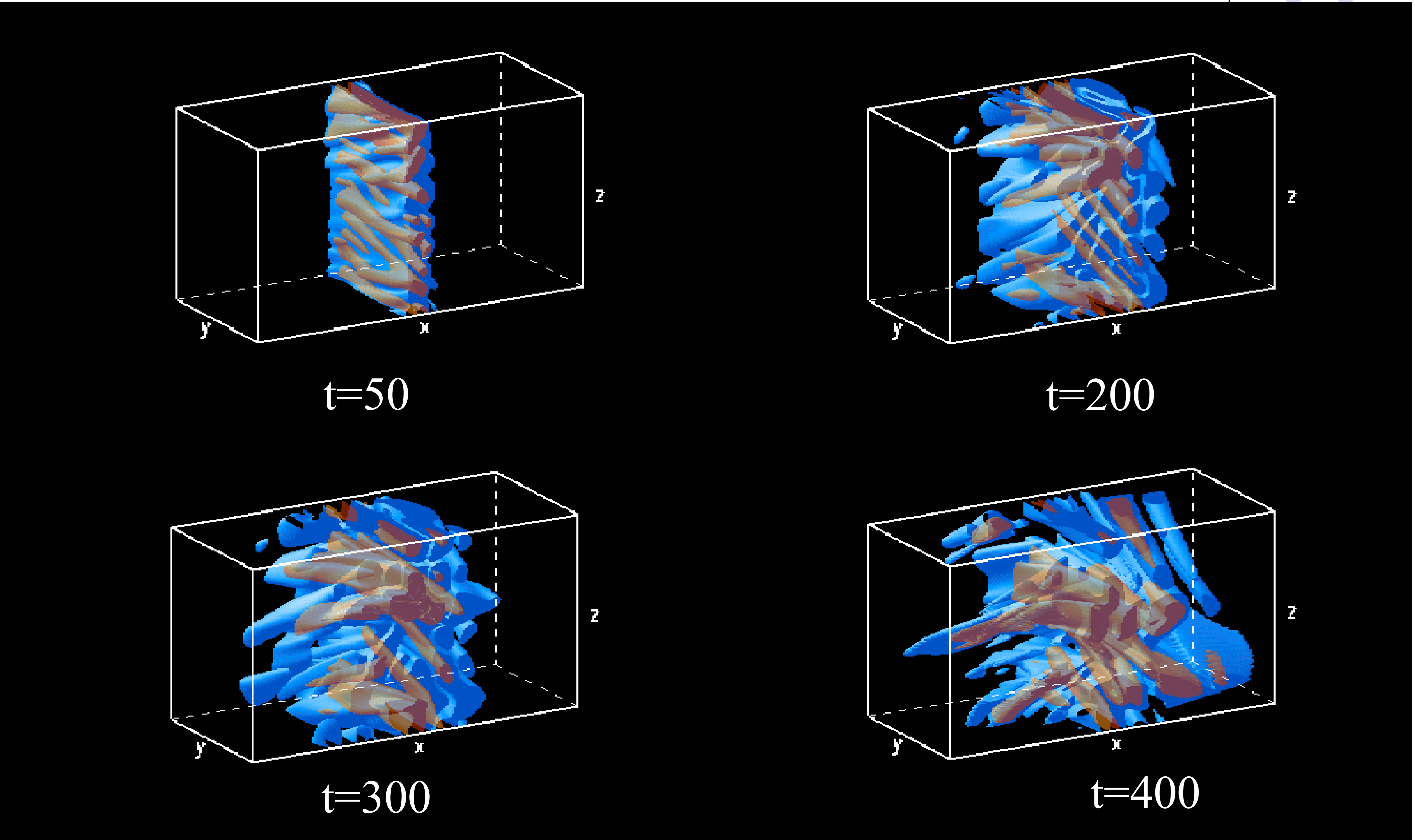
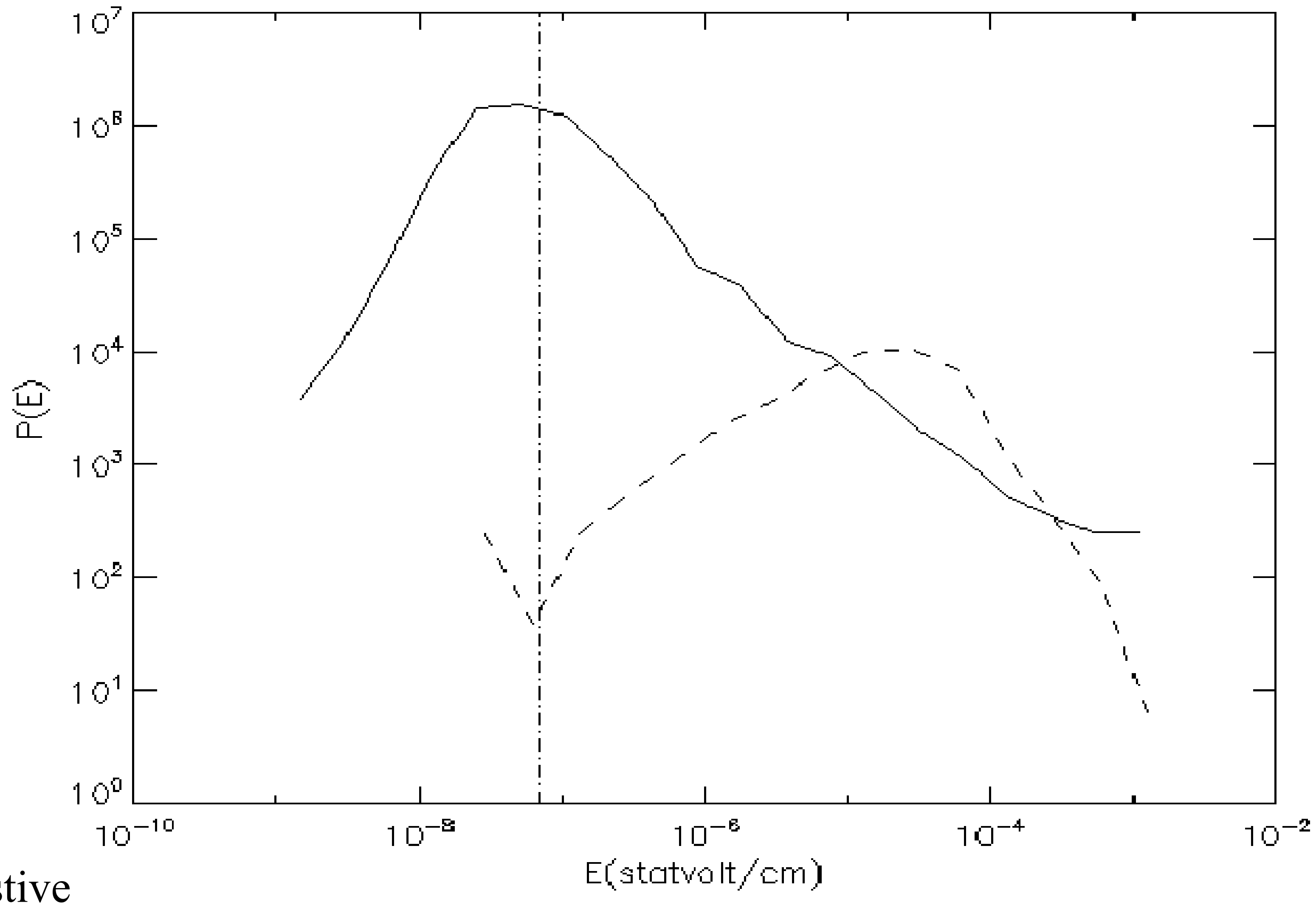


Distribution function of the electric field at t=50

P(E)



E

resistive

convective

Particle acceleration

Relativistic equations of motions:

$$\frac{d\mathbf{r}}{dt} = \mathbf{v} \qquad \frac{d\,\mathbf{p}}{d\,t} = e\,\mathbf{E} + \frac{e}{c}\,\mathbf{v}\ x\ \mathbf{B}$$

$$\mathbf{p} = \gamma m \mathbf{v} \qquad \gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}}$$

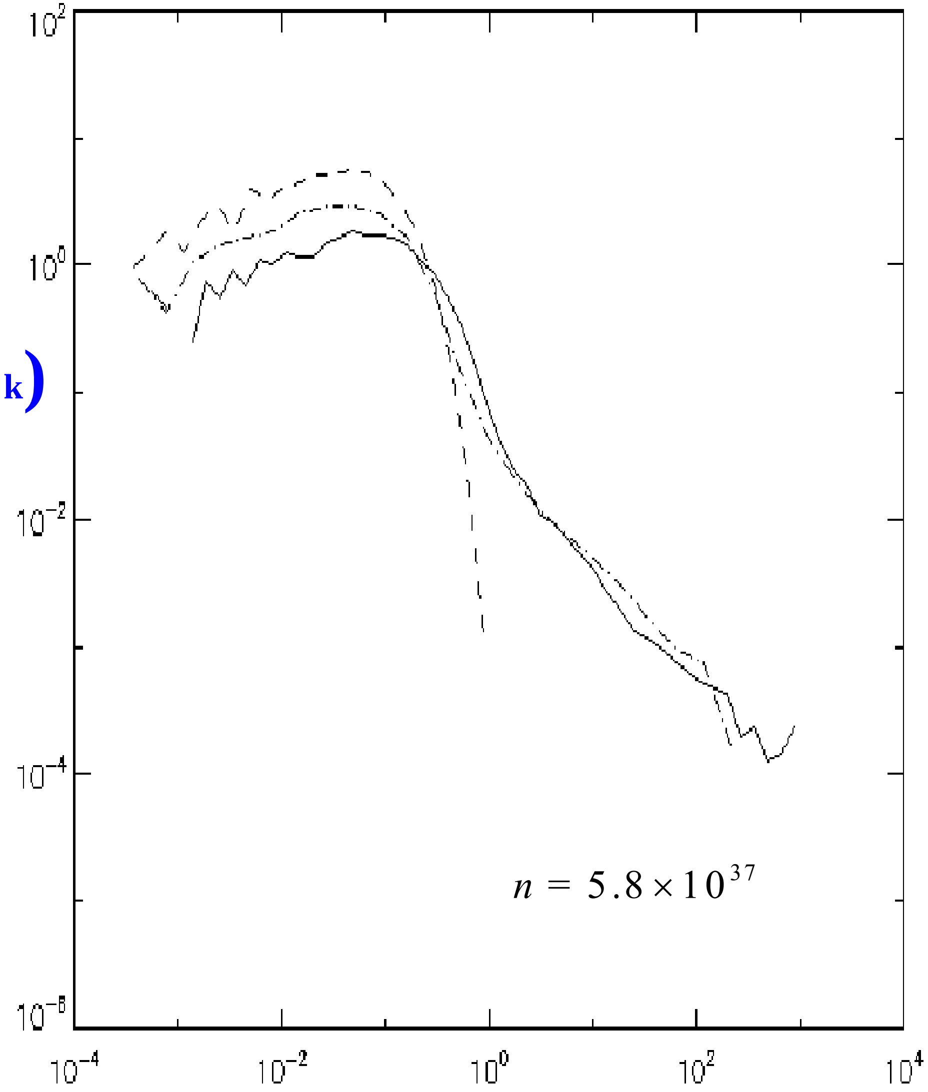
The equations are solved with a fourth-order Runge Kutta adaptive step-size scheme.

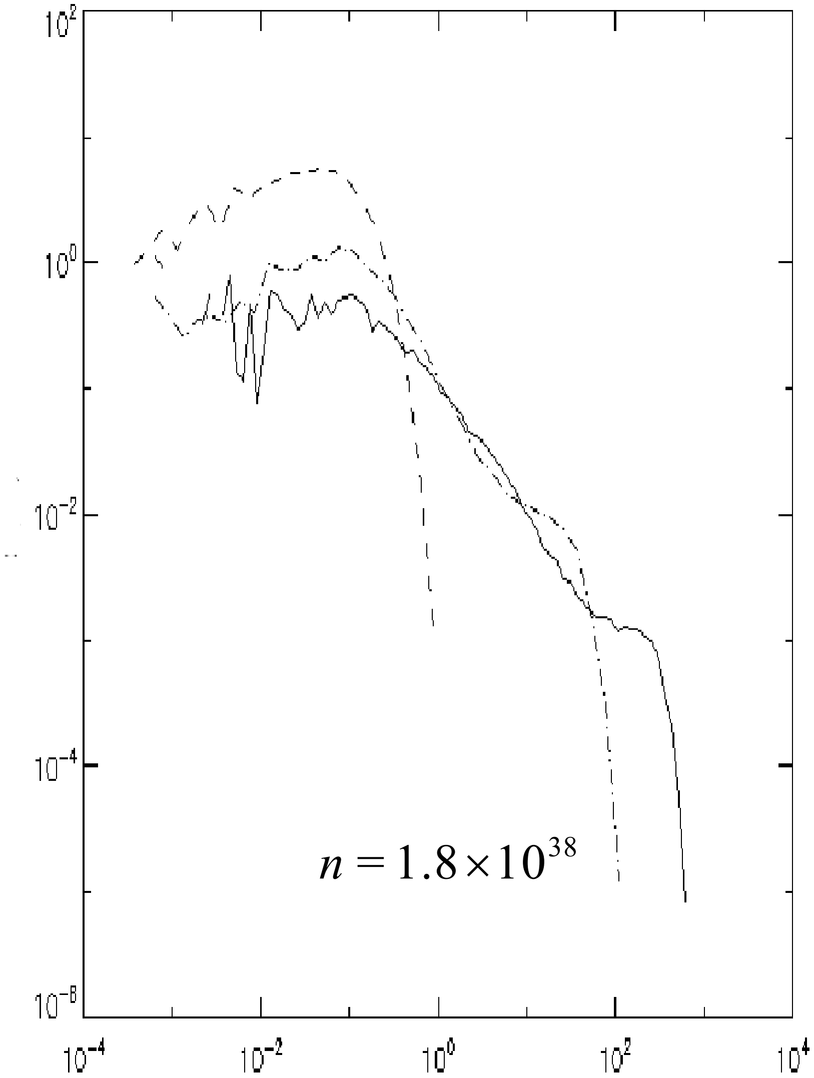
The electric and magnetic field are interpolated with local 3D interpolation to provide the field values where they are needed

Kinetic energy distribution function of electrons

t=50 T_A T=400 T_A

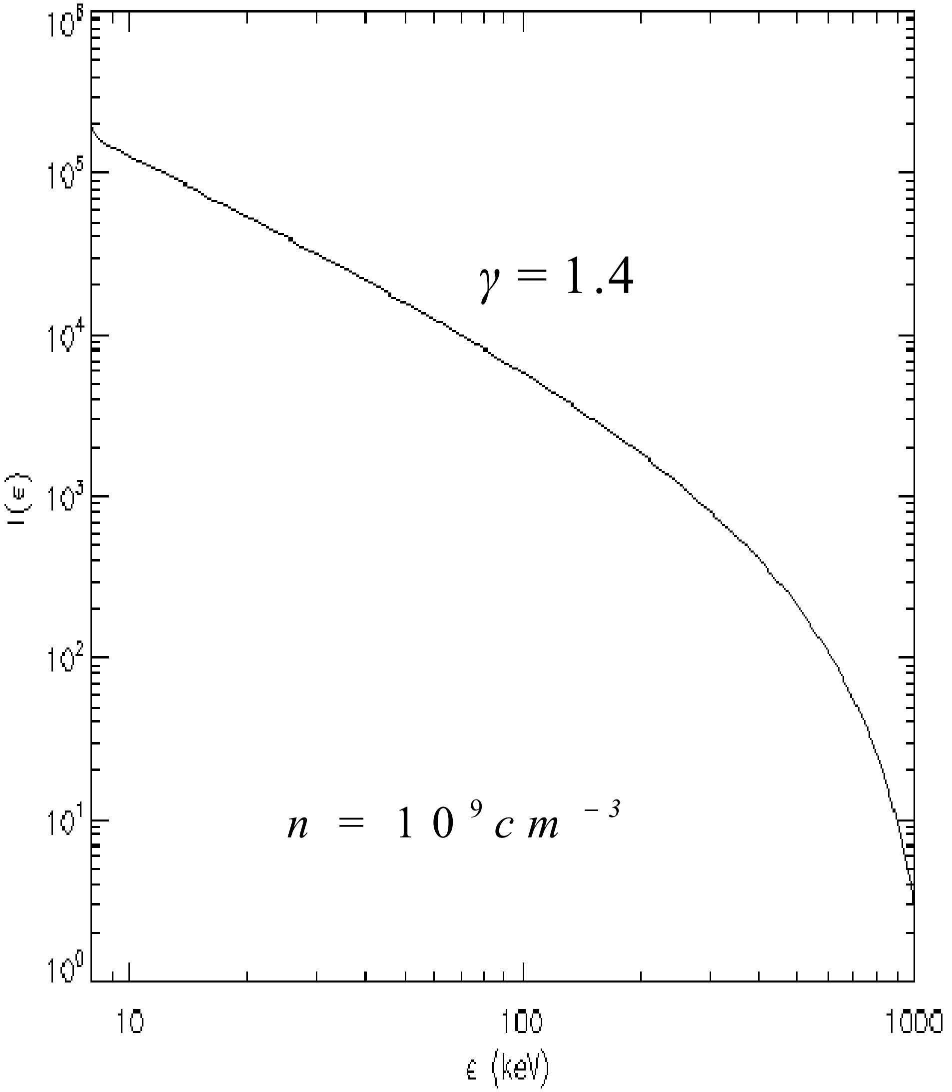
P(E_k)

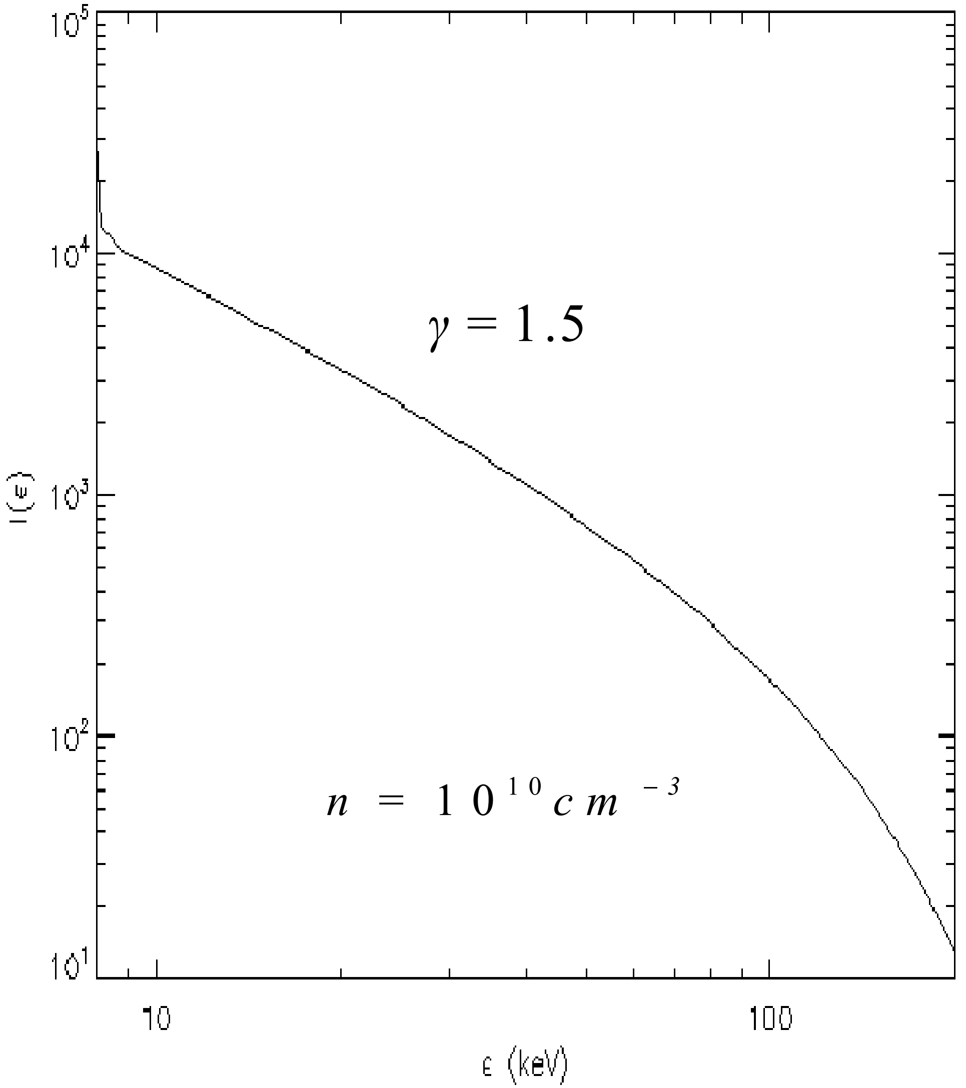




E_k (keV) E_k (keV)

HXR bremsstralung spectrum

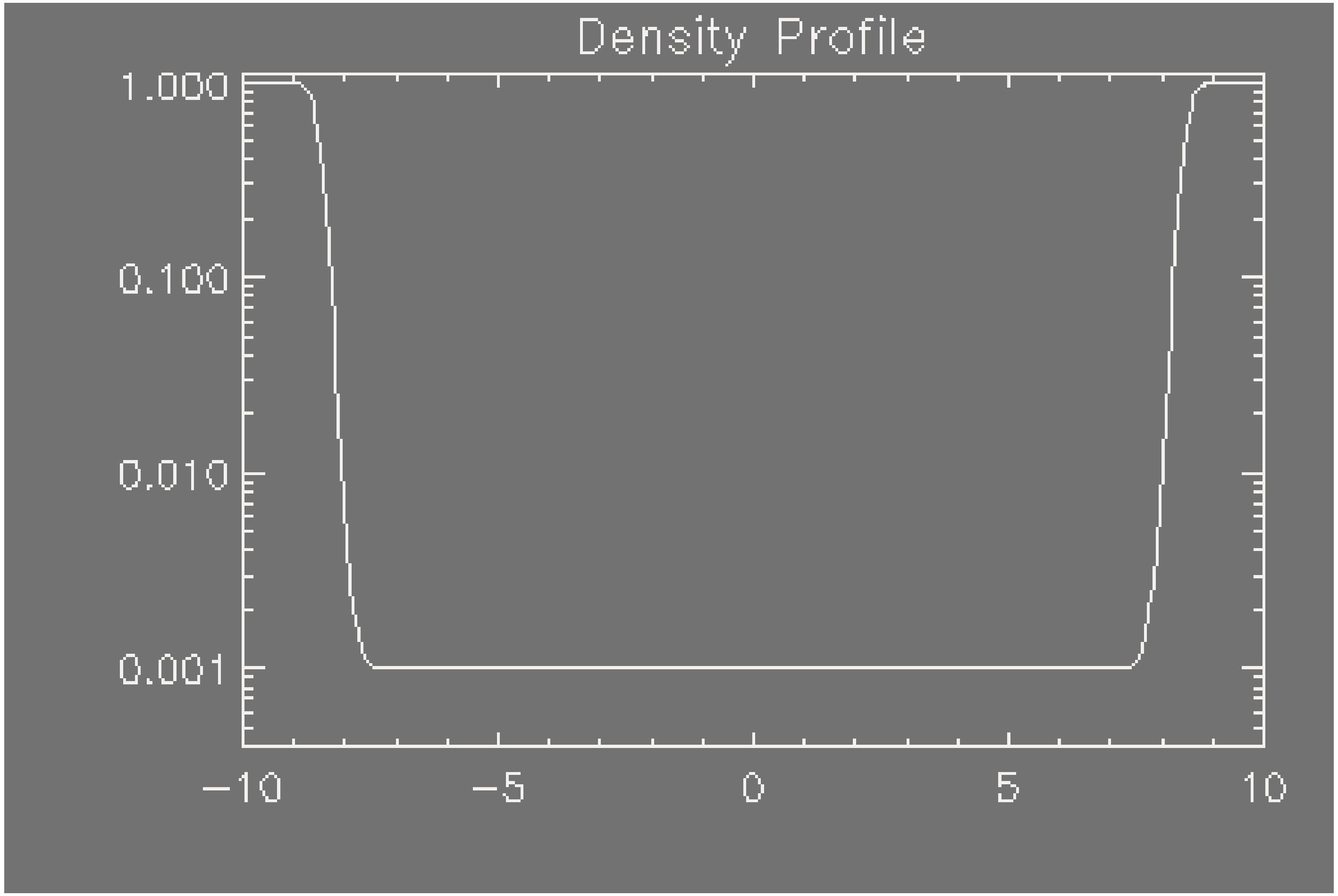




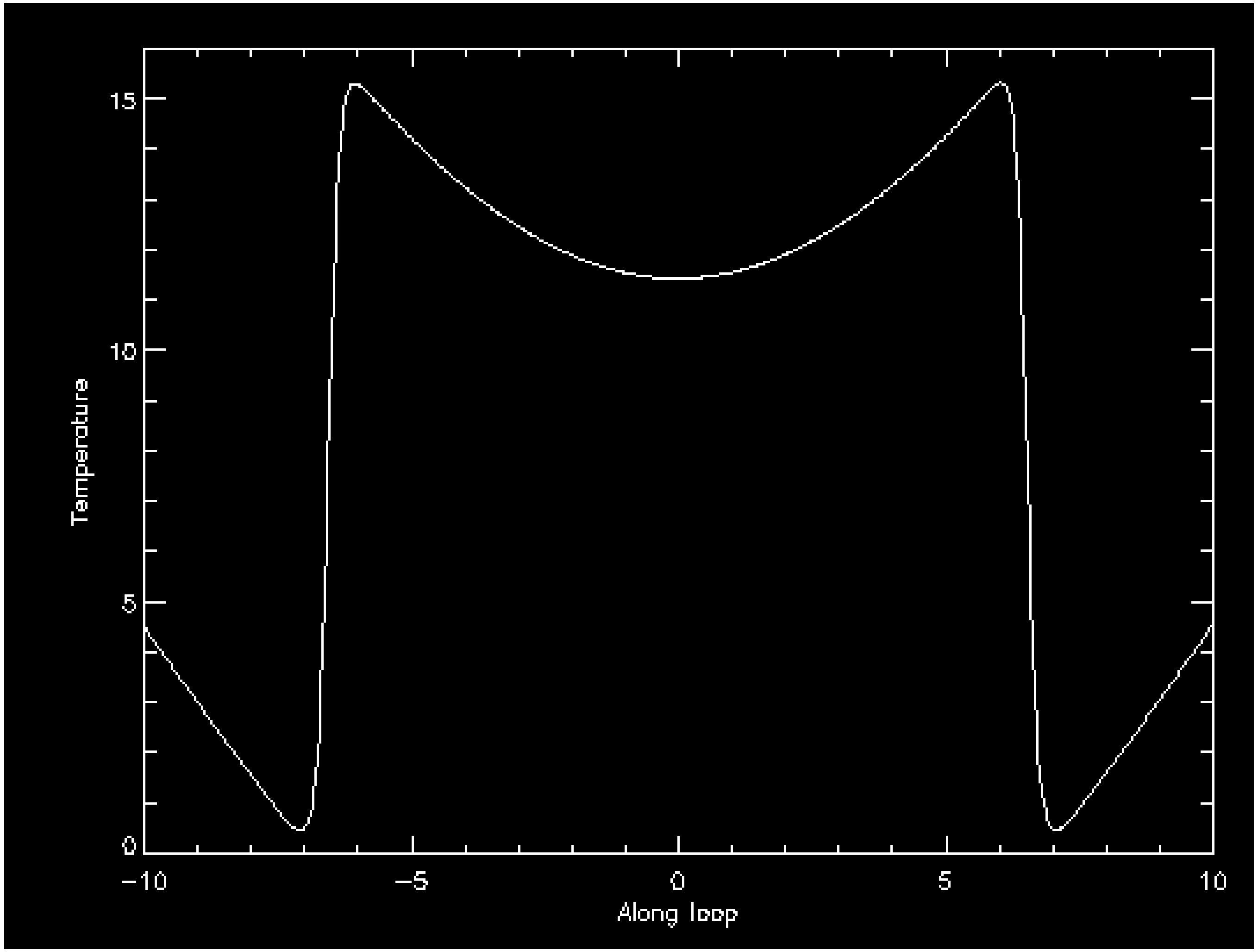
Solve the MHD equations inside a simple loop atmosphere (*Galsgaard*)

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

Density profile along the loop

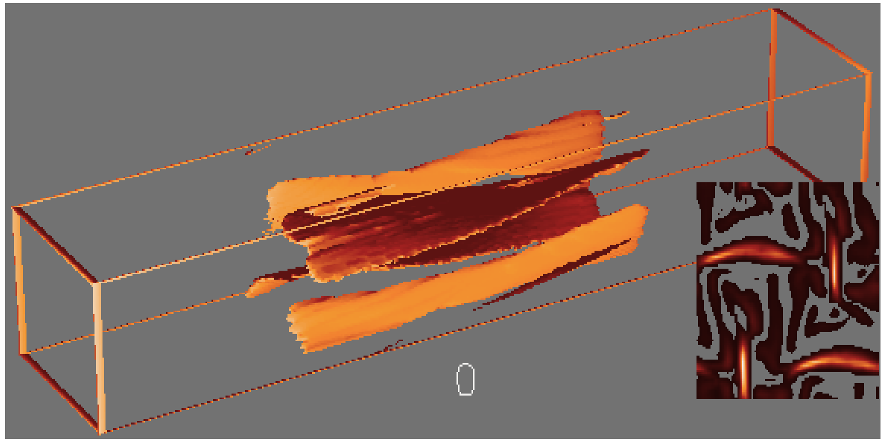


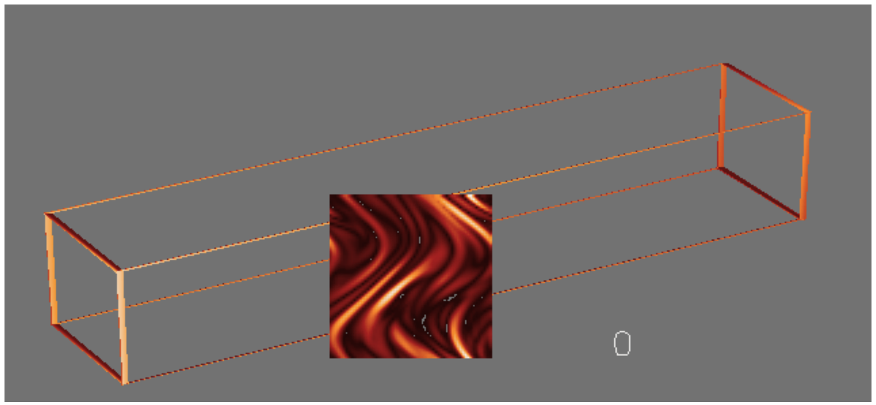
Temperature along the loop



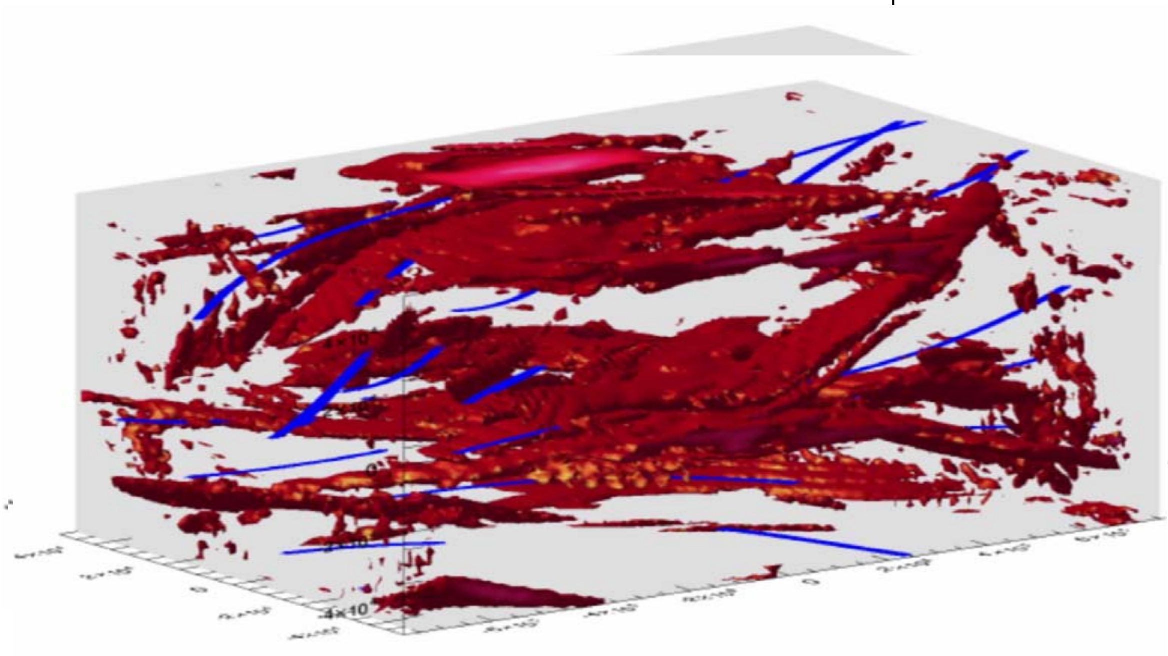
The stochastic loop model (Galsgaard)

- 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



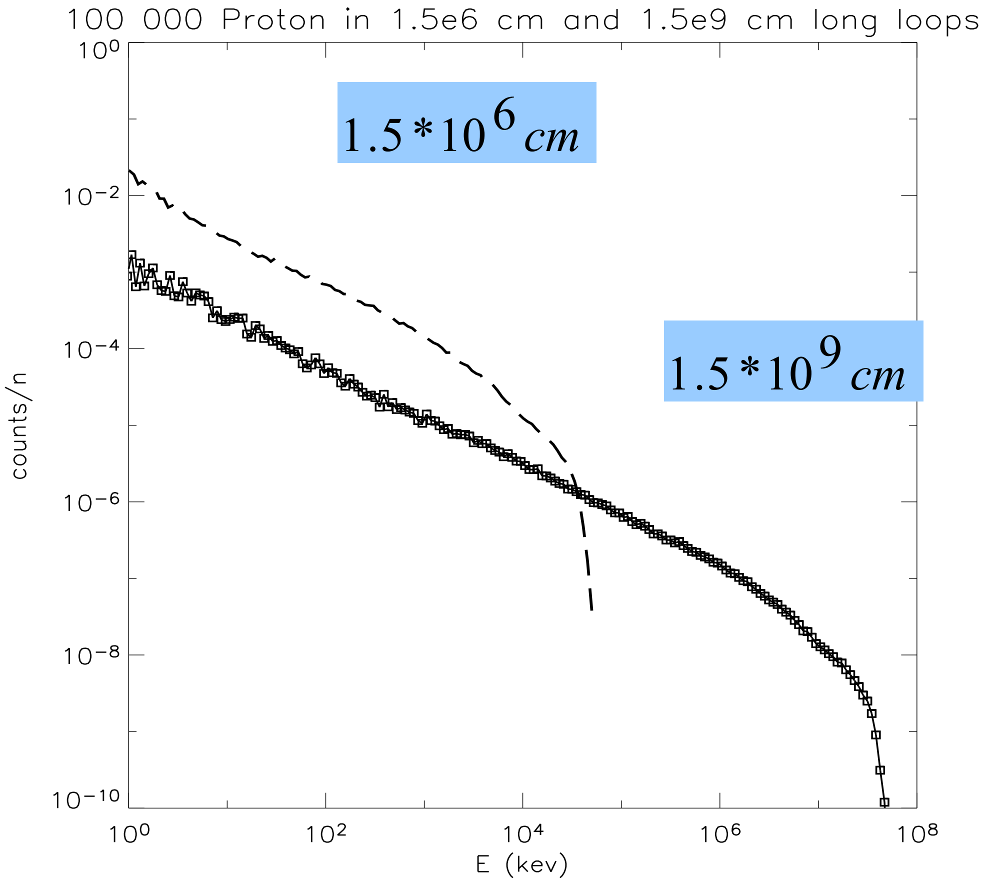


Particle acceleration in stochastic current sheets
(Rim Turkmani et al)



- 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)

Scaling with loop dimensions



Acceleration scales linearly with the spatial scale of the loop

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.