Coronal reconnection: Microphysics and photospheric B

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Corona physics - key questions:

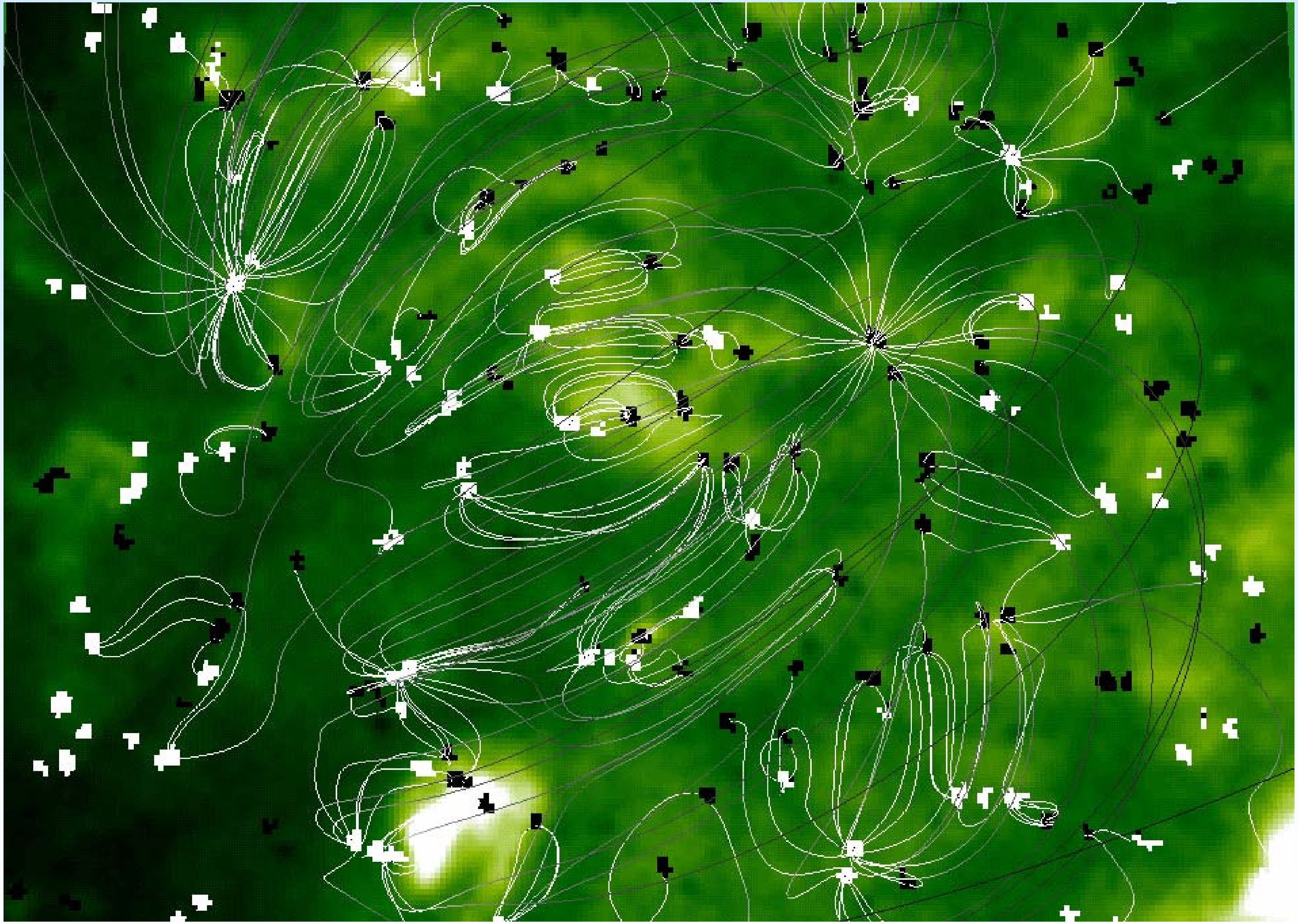
- **How and when are eruptions triggered ?**
- **How are micro- and macro-physics coupled in these processes ?**
- **What accelerates particles ?**

-> ***Reconnection is fundamental,***

but what can we measure?

The complexity of solar field calls for numerical simulation to specify the questions to be addressed by SOLAR-B!

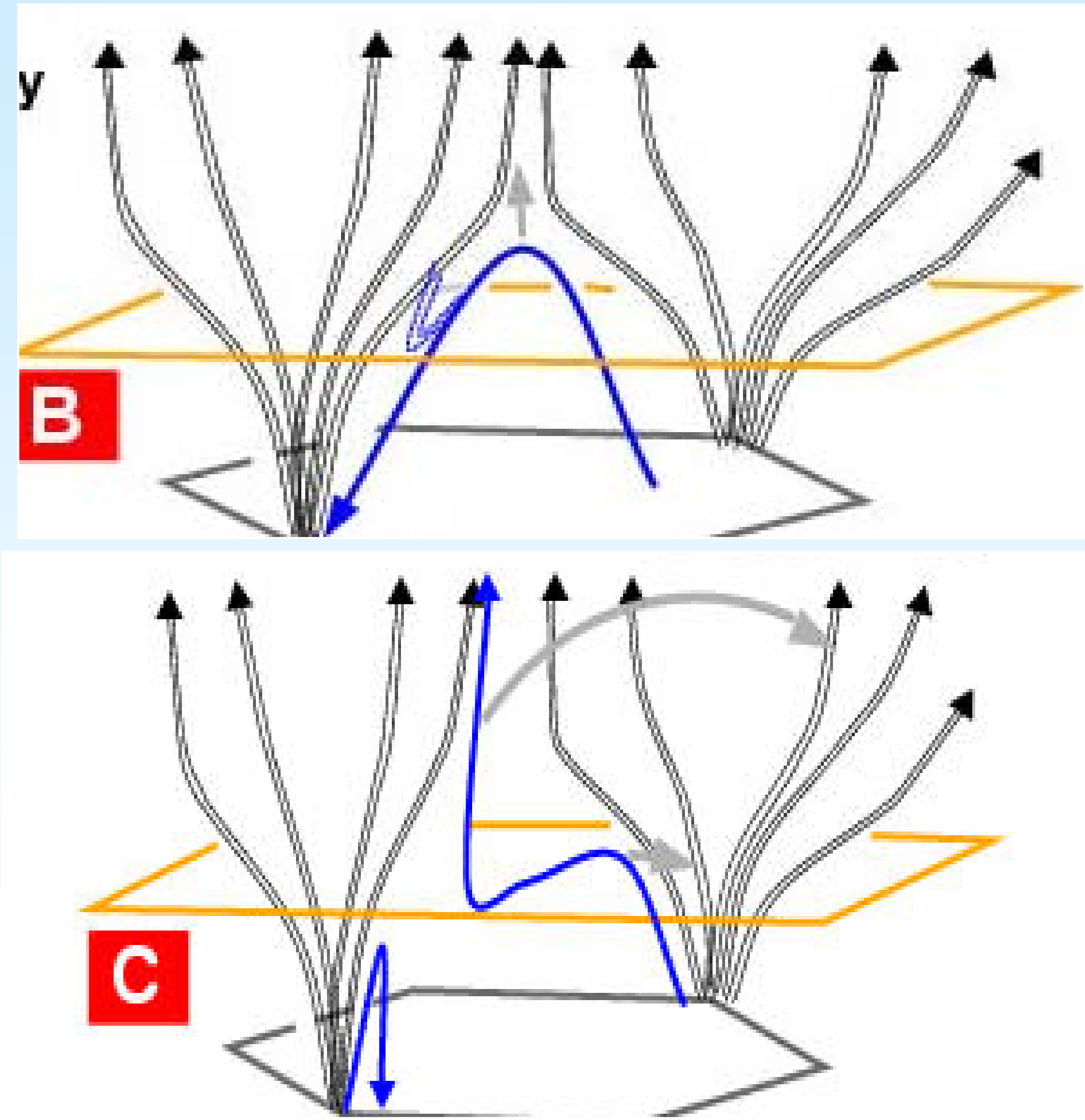
Field complexity: magnetic carpet



... obtained by potential-B-extrapolation of the line-of-sight - component (Bz) of the photospheric magnetic field, as observed by MDI / SOHO (see, e.g., Title & Schrijver, 1998)

-> Where in the corona does reconnection take place ?

Reconnection – the essence



Most generally, reconnection is „a change of magnetic connectivity through a region of non-ideal plasma“ (see, e.g., Axford, 1984).

Key open questions:

- **What makes the coronal plasma non-ideal?**
- **Where are these regions located?**

(Emerging flux model, Fisk et al., 1999)

Non-idealness of the plasma

Criterion for non-idealness:

A magnetic Reynolds number ->

of the order of unity

$$\boxed{R_m = \frac{\mu_0 \, l \, v}{\eta}}$$

For Spitzer (Coulomb-collision based) resistivity + typical plasma velocities and sizes: $R_m \sim 10^{10}$!

For Spitzer resistivity and typical plasma velocities R_m becomes ~ 1 in current sheets thinner than 1 cm!

while the (Coulomb-) collisional mean free path is

$$l_{mfp} = \frac{1}{n}\left(\frac{kT}{e^2}\right)^2 \approx 10^8 cm \left(\frac{T}{10^6 K}\right)^2 \left(\frac{n}{10^9 cm^{-3}}\right)^{-1}$$

-> Additional, non-Coulomb resistivity is needed!

Particle scattering by fluctuations

The ensemble averaging of the Vlasov equation for $f_j = f_{0j} + \delta f_j.$

with $\langle \delta f_j \rangle = \left\langle \delta \vec{E} \right\rangle = \left\langle \delta \vec{B} \right\rangle = 0.$

reveals

$$\boxed{\begin{aligned}\frac{\partial f_{0j}}{\partial t} + \vec{v}\cdot\frac{\partial f_{0j}}{\partial \vec{r}} + \frac{e_j}{cm_j}\left(\vec{v}\times\vec{B}\right)\cdot\frac{\partial f_{0j}}{\partial \vec{v}} &= \left(\frac{\partial f_j}{\partial t}\right)_{an} \\ &= -\frac{e_j}{m_j}\left\langle\left(\delta\vec{E} + \frac{\vec{v}\times\delta\vec{B}}{c}\right)\cdot\frac{\partial \delta f_j}{\partial \vec{v}}\right\rangle.\end{aligned}}$$

$$\left(\frac{\partial}{\partial t} n_j m_j v_{y,j}\right)_{an} = \left\langle \delta E_y \delta\rho_j + \frac{\delta j_{z,j}\delta B_x - \delta j_{x,j}\delta B_z}{c}\right\rangle.$$

and for the „collision frequency“:

$$\boxed{\nu_{eff,j} = \frac{1}{\langle n_j m_j v_{y,j}\rangle}\left(\frac{\partial}{\partial t} n_j m_j v_{y,j}\right)_{an}.}$$

Theoretical (quasilinear) estimates of the anomalous (effective) „collision frequency“:

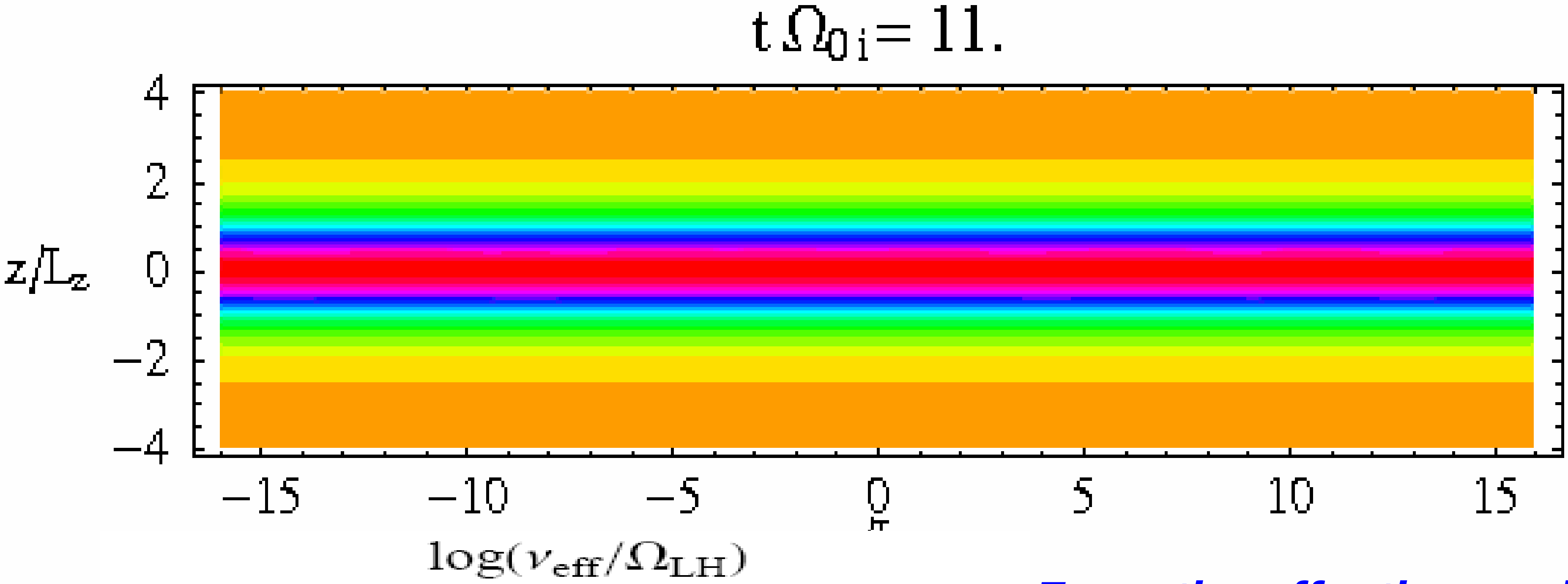
$$\nu = \sum_k \frac{\Delta k |\delta E(k)|^2 \omega_{pe}}{k v_{te}^2 m_e n v_d} Im \xi_e Z(\xi_e)$$

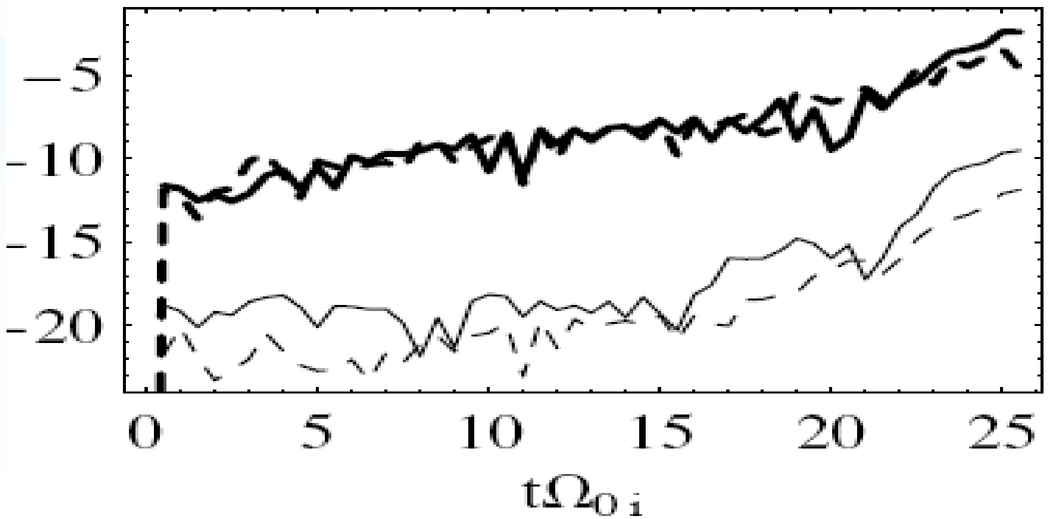
But what is the wave energy at sun? Invisible ! –> kinetic simulations needed!

In a simulation one also can directly determine the effective “ collision frequency“

$$\nu(t+\delta t/2) = \frac{2}{\delta t}\frac{p(t+\delta t) - p(t)}{p(t+\delta t) + p(t)}$$

Scattering for Jerp (LHD)

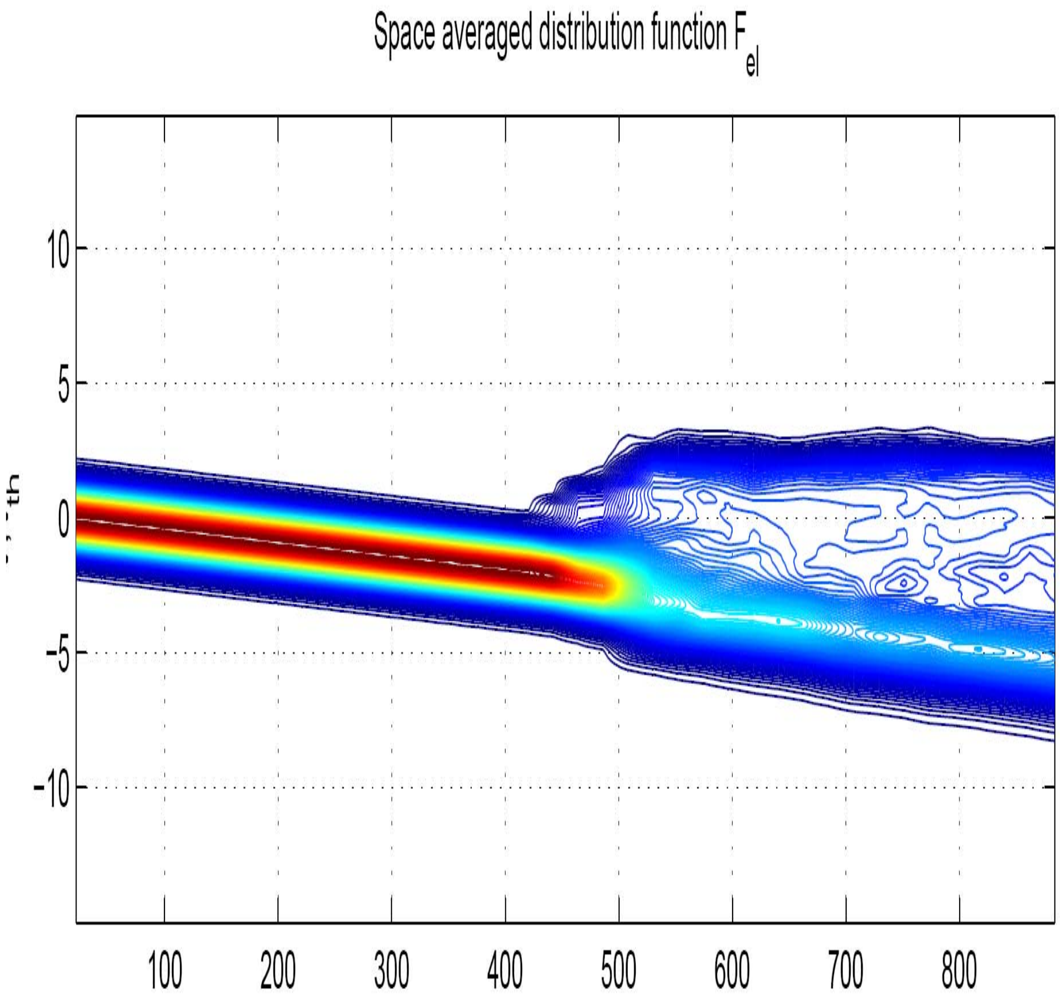


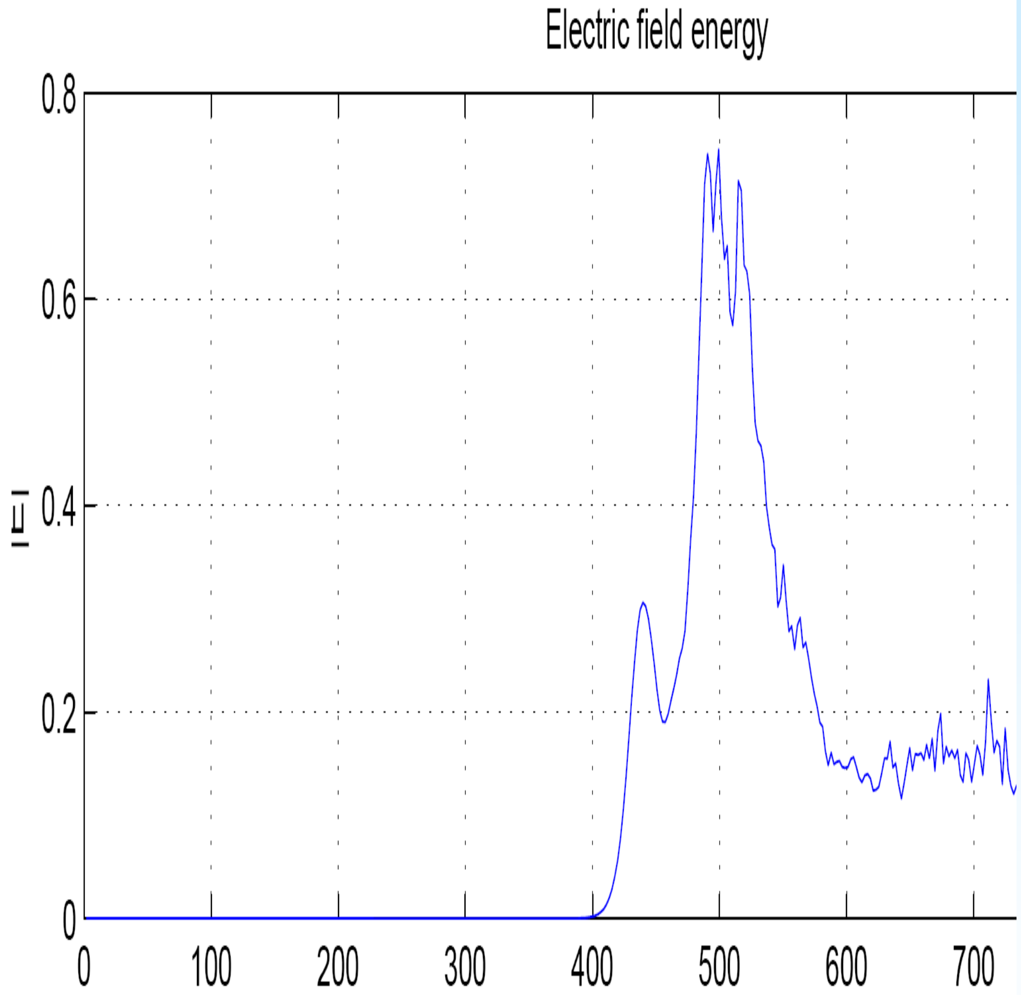


From the effective „collision rate“ follows the „effective, (turbulent) resistivity“:

$$\boxed{\eta_{eff} = \nu_{eff} \frac{m_e}{\epsilon_o e^2}}$$

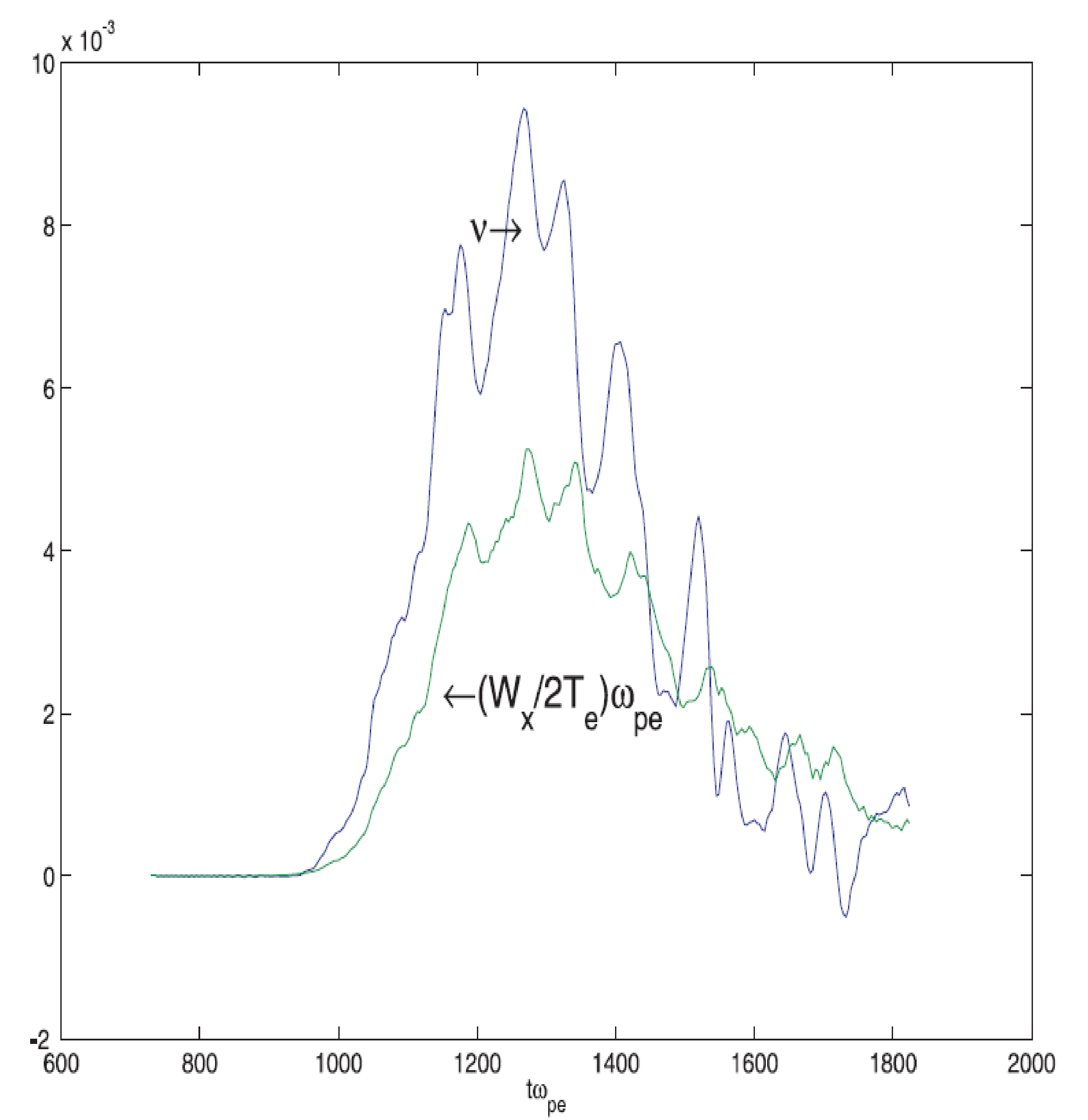
Scattering for Epar = const. (IA)





-> electric currents in the transition region are limited and dissipated due to wave-particle scattering in self-generated potential wells

„Collision frequency“ for Epar



← **Blue: momentum exchange rate (simulation result):**

$$\nu(t+\delta t/2) = \frac{2}{\delta t}\frac{p(t+\delta t)-p(t)}{p(t+\delta t)+p(t)}$$

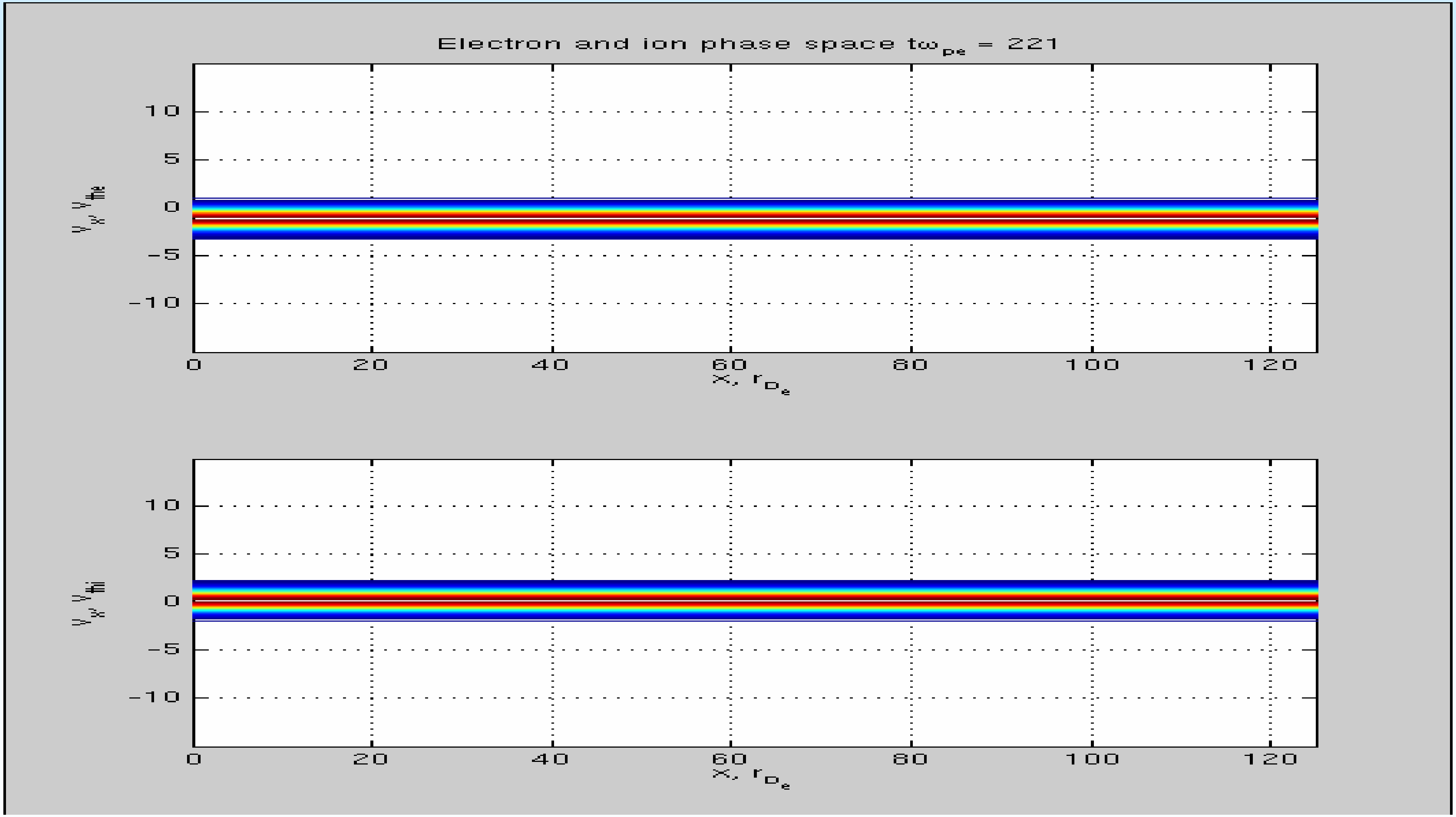
← **green: the theoretical estimate, using E^2**

$$\nu = \sum_k \frac{\Delta k |\delta E(k)|^2 \omega_{pe}}{k v_{te}^2 m_e n v_d} Im \xi_e Z(\xi_e)$$

is much smaller, also the Sagdeev-formula estimate

$$\left(\frac{c}{\omega_e}\right)^2 \omega_e \frac{\epsilon_0 \delta E^2}{2nT}$$

Scattering in case of Jpar=const.



In this most nonlinear case of permanent energy supply (open simulation boundaries!) phase space structures (electron holes) strongly scatter

Sub-summary: Microphysics

The anomalous resistivity in the solar atmosphere can be either Jperp, Epar, or Jpar – driven:

1.) scattering of Jperp -> nonlinear LHD-type-instability
[PIC: Büchner&Kuska,1999; Vlasov: Silin&Büchner, 2005]

2.) scattering in case of Epar:
-> weak, quasi-linear ion-acoustic instability
[Sagdeev and Galeev, 1967; PIC: Dum, 1970, Vlasov:Büc05]

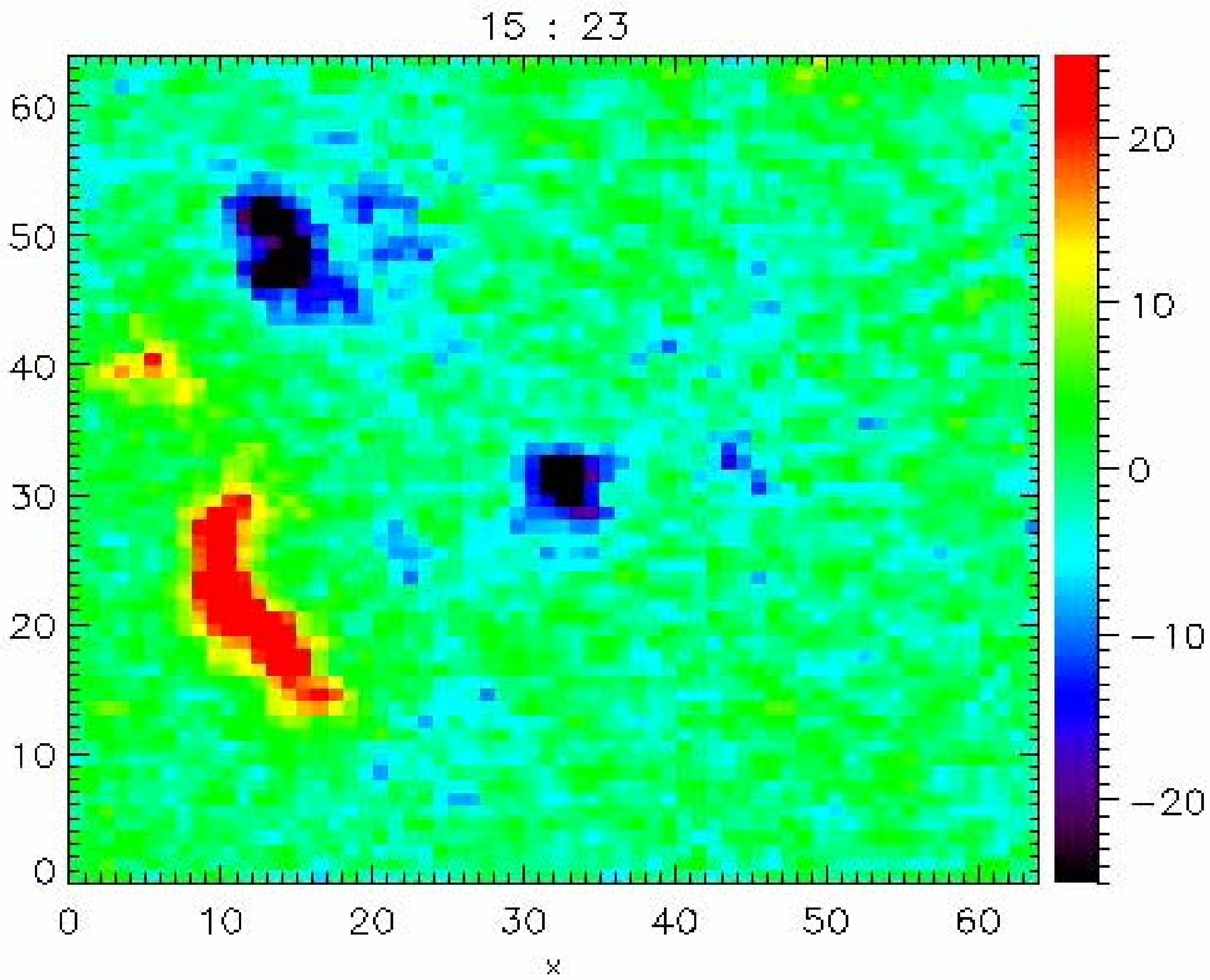
3.) Most efficient, however, is scattering in case of Jpar:
-> nonlinear ion-acoustic electron-hole instabilities
[Büchner 2005; Elkina & Büchner, 2006]

Model for MHD
[Shibata, 1999]
possible,

$$\eta = \begin{cases} \eta_0 \min\left(1, \left|\frac{v_d}{v_c}\right| - 1\right) & |v_d| \geq v_c \\ 0 & , |v_d| < v_c \end{cases}$$

but V_c and Eta_0 do strongly depend on the configuration!

Photospheric Bn-field dynamics

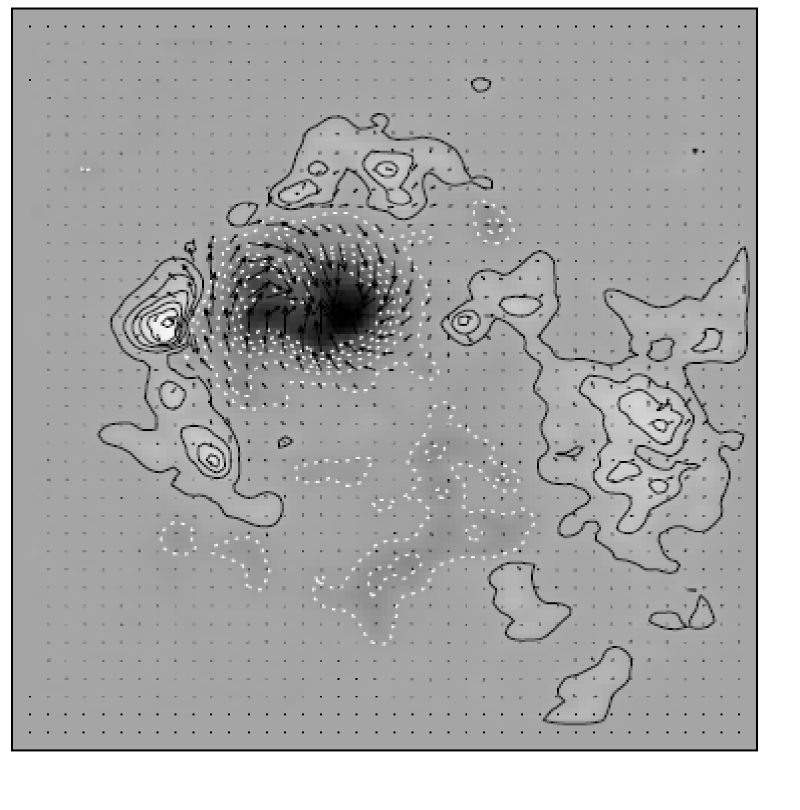


It is necessary to find out, which one of the kinetic current flow models applies.

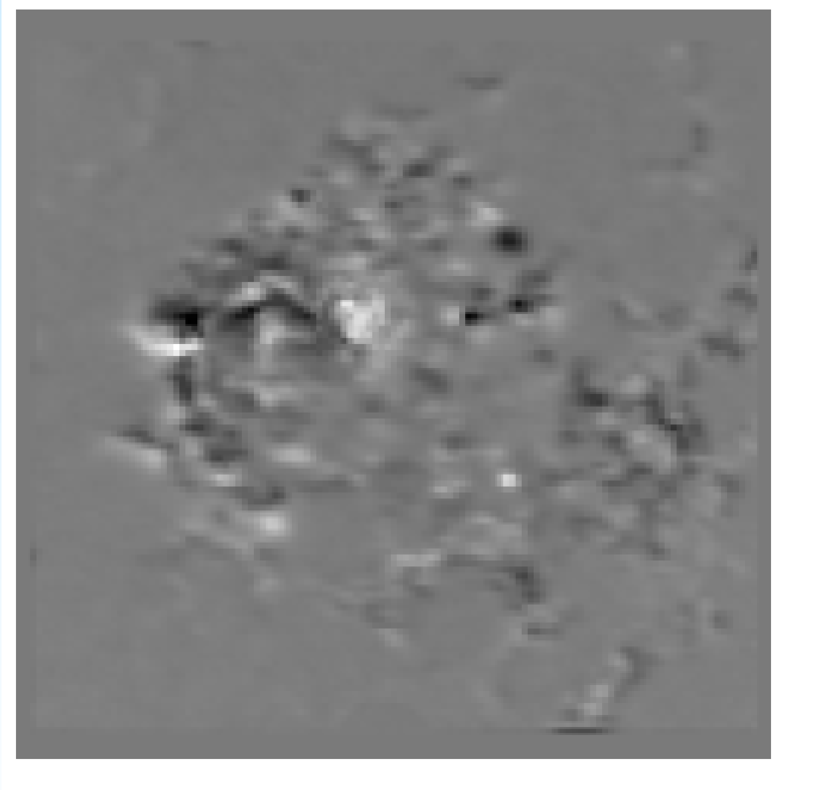
An appropriate starting point are the observed dynamically varying photospheric magnetic fields.

SOHO/MDI 17.-18.10.1996; area 40” x 40” ~ 23 Mm x 23 Mm

Horizontal velocity, estimated by local correlation tracking (LCT)



Vector magnetogram AR8210
May 1st 1998, 17:13UT



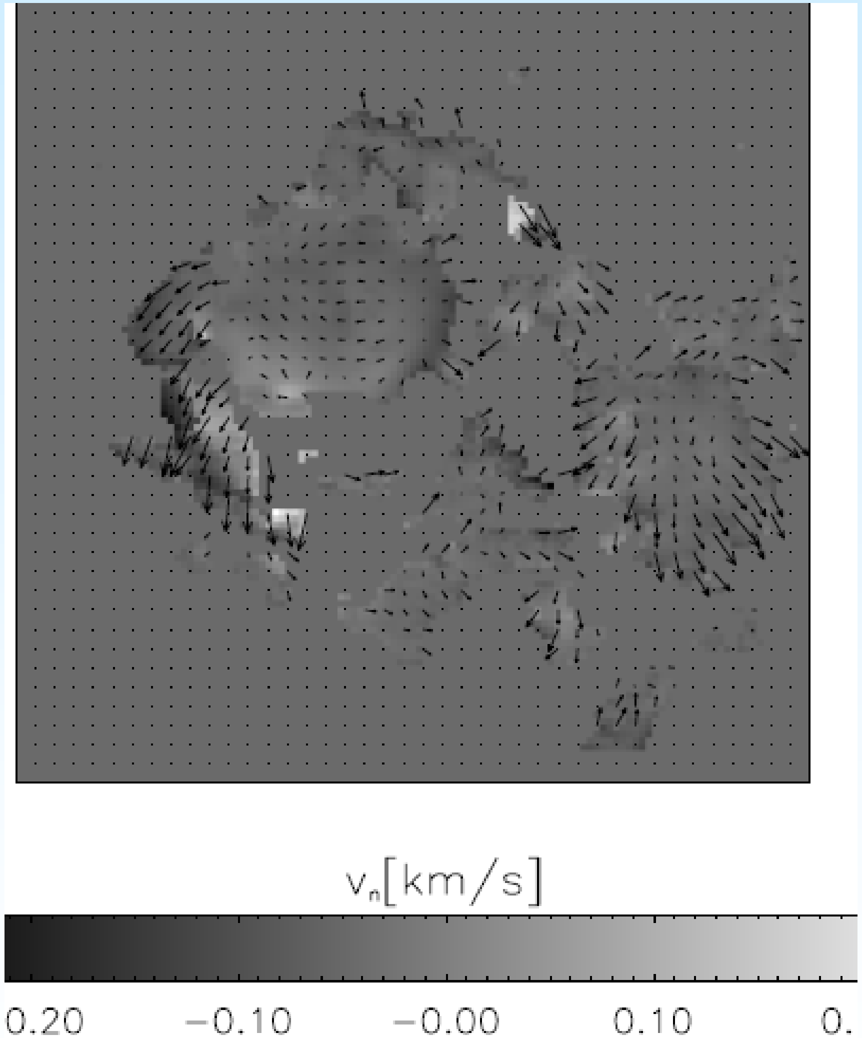
Variation of the Bz component between 17:13UT and 21:29 UT

$$C(\vec{\delta},\vec{x}) = \int J_t(\epsilon - \frac{\delta}{2}) J_{t+\tau}(\epsilon + \frac{\delta}{2}) W(x-\epsilon)\partial\epsilon$$

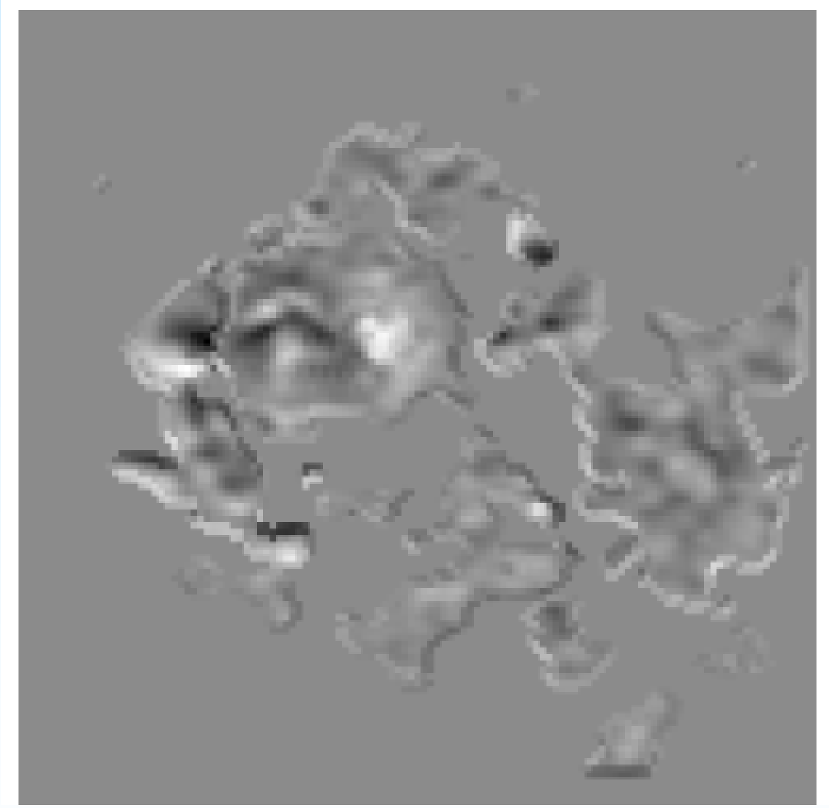
[Chang et al., Santos et al., 2005]

LCT + induction equation for the vertical velocities Vn and Bn:

$$\frac{\partial B_n}{\partial t} = \vec{\nabla}_t \cdot (v_n \vec{B}_t - B_n \vec{v}_t)$$



Velocities obtained by ILCT



Bn variation, consistent with Bt & V

[Welsh et al., 2004; Santos et al., 2005]

MHD simulation with eta(j)

$$\frac{\partial \rho}{\partial t} = -\nabla \cdot \rho \mathbf{u} - \nu(\rho - \rho_0)$$

$$\frac{\partial \rho \mathbf{u}}{\partial t} = -\nabla \cdot \rho \mathbf{u}\mathbf{u} - \frac{1}{2}\nabla p + \mathbf{j} \times \mathbf{B} - \mu\rho(\mathbf{u} - \mathbf{u}_0)$$

$$= -\nabla \cdot \left[\rho \mathbf{u}\mathbf{u} + \frac{1}{2}\left(p + B^2\right)\underline{\underline{1}} - \mathbf{B}\mathbf{B}\right] - \mu\rho(\mathbf{u} - \mathbf{u}_0)$$

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{u} \times \mathbf{B} - \eta \mathbf{j})$$

$$\frac{\partial p}{\partial t} = -\nabla \cdot p\mathbf{u} - (\gamma - 1)p\nabla \cdot \mathbf{u} + 2(\gamma - 1)\eta \mathbf{j}^2 - \kappa n k_B(T - T_0)$$

with

$$\mathbf{E} = -\mathbf{u} \times \mathbf{B} + \eta \mathbf{j}$$

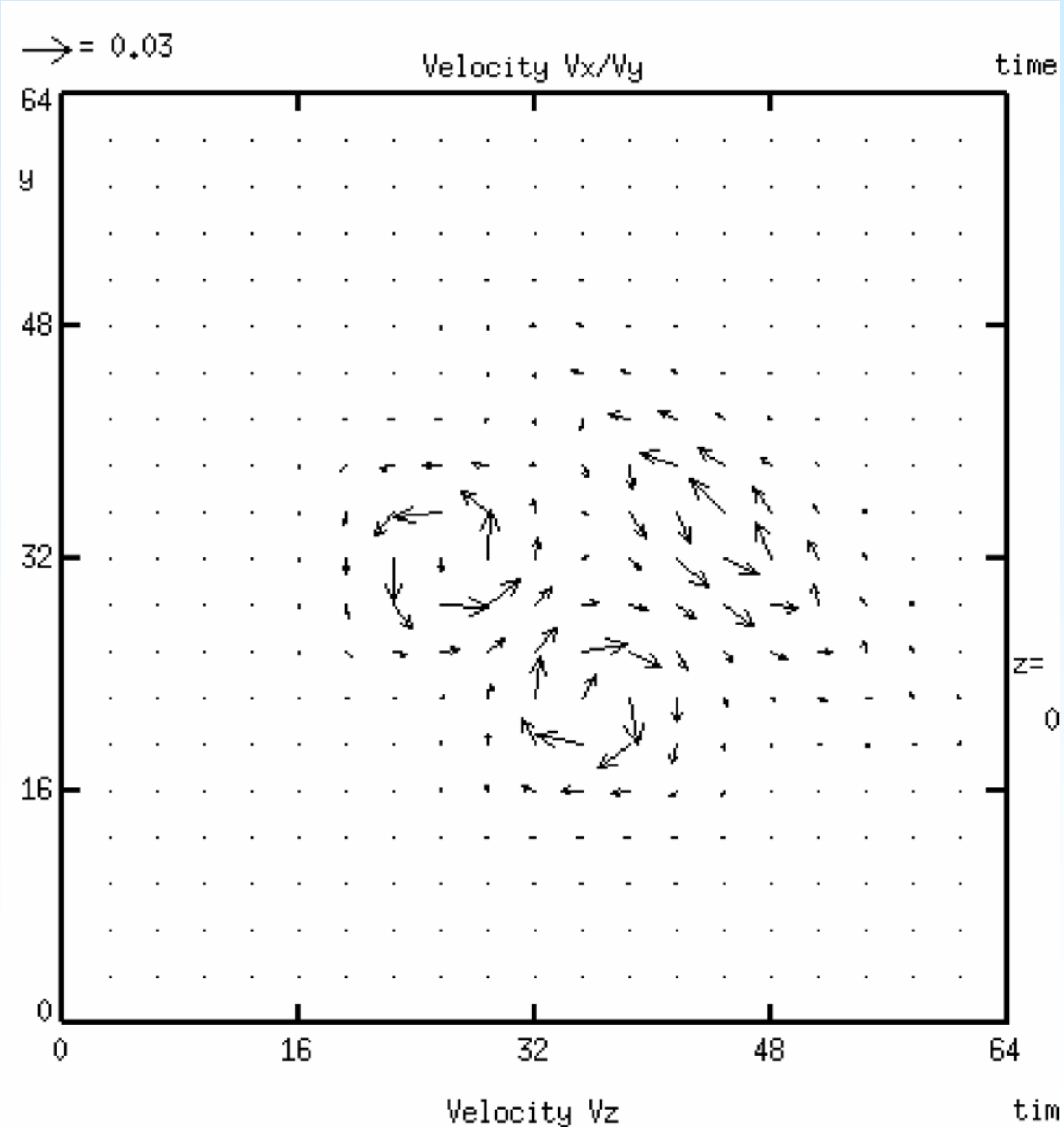
$$\nabla \times \mathbf{B} = \mathbf{j}$$

Neutral gas in the chromosphere:

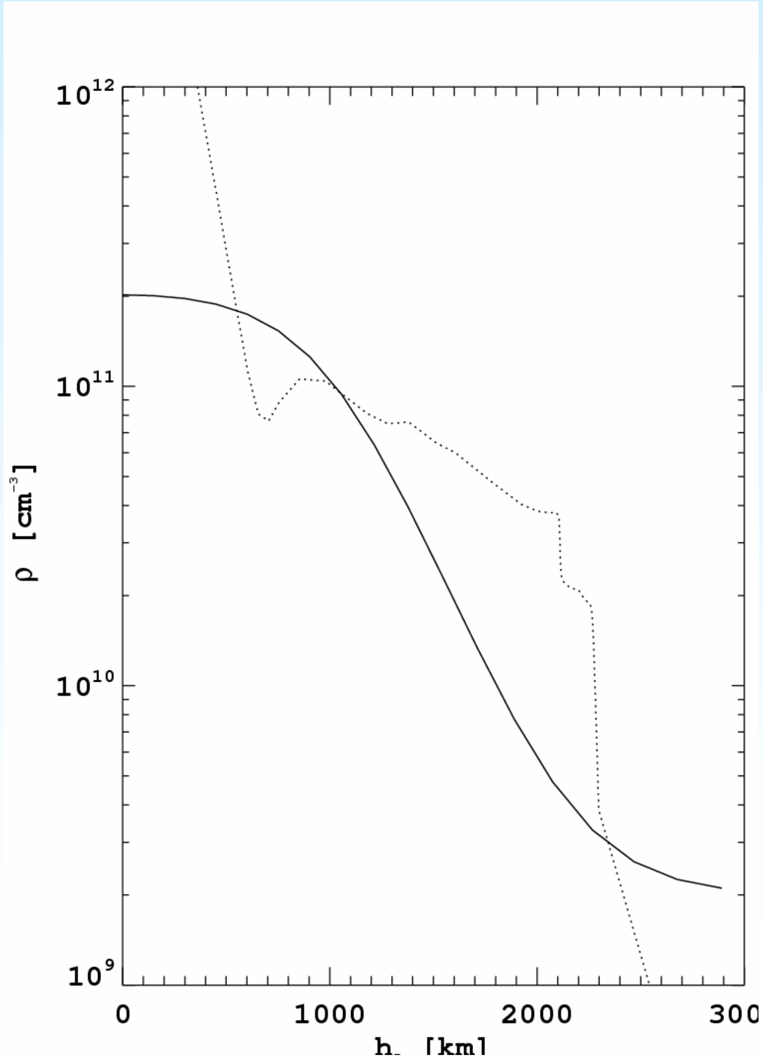
$$U = u_0 / \cosh\left(\frac{x - y + c_0}{L_0}\right) / \cosh\left(\frac{x + y + c_1}{L_1}\right)$$

$n_n \approx 10^{13}\, to\, 10^{14}\ \mathrm{cm}^{-3}$. $v_{th} = 7 \cdot 10^3\ \mathrm{m/s}$ $\nu_{in} = n_n \sigma_n v_{th}$ with $\sigma_n \approx 10^{-15}\ \mathrm{cm}^2$.

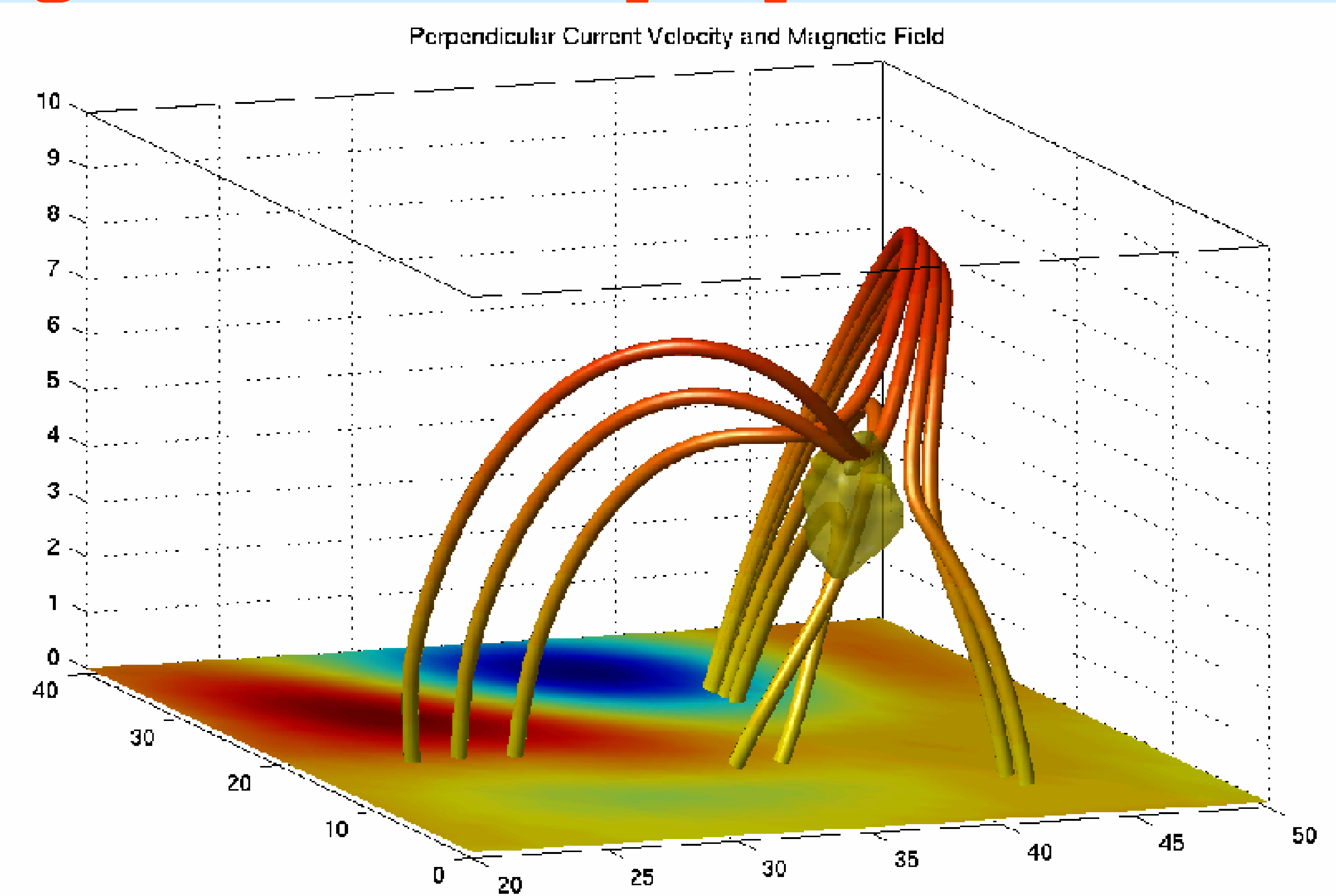
Boundary condition: photospheric motion



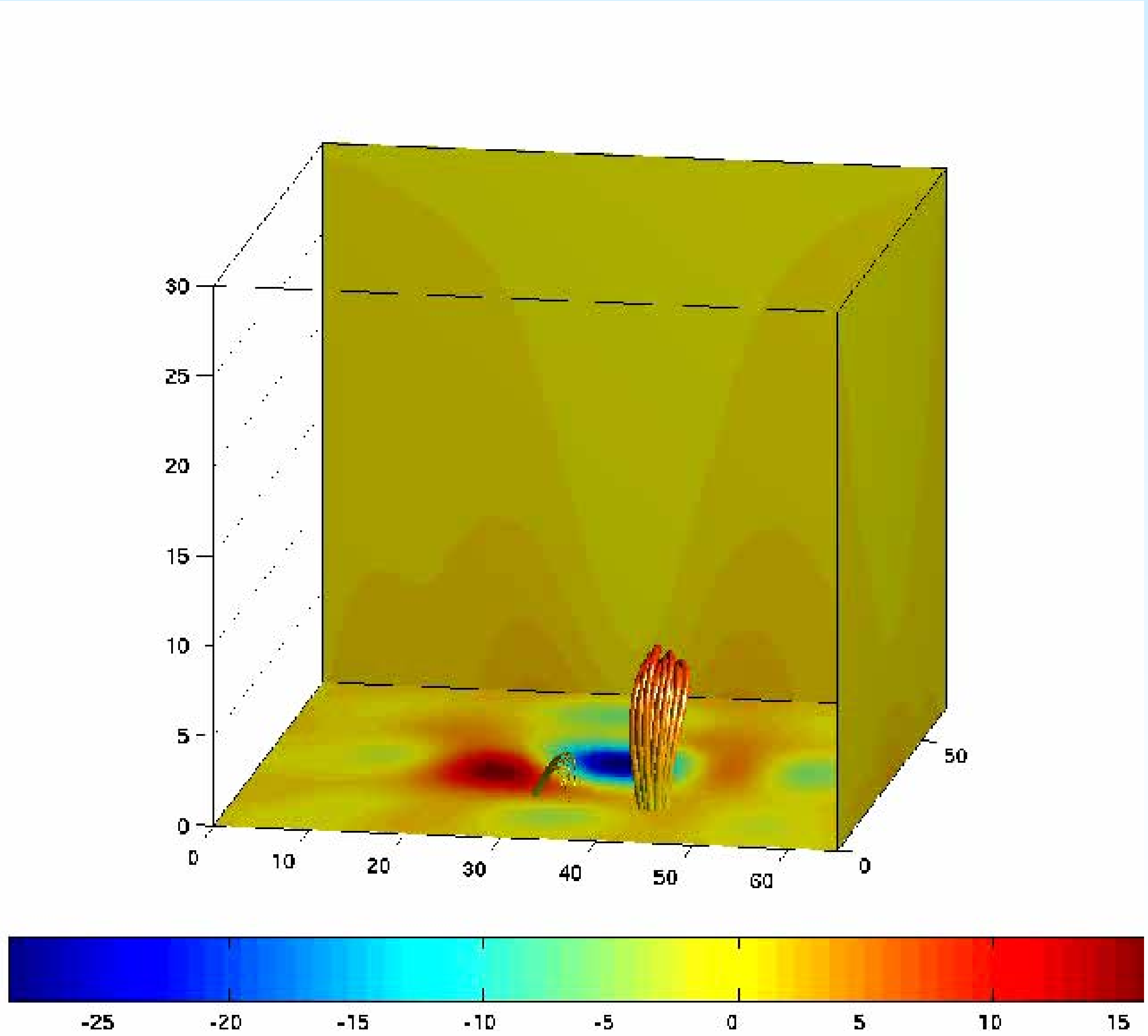
Initial cond. n (VAL) , T ...



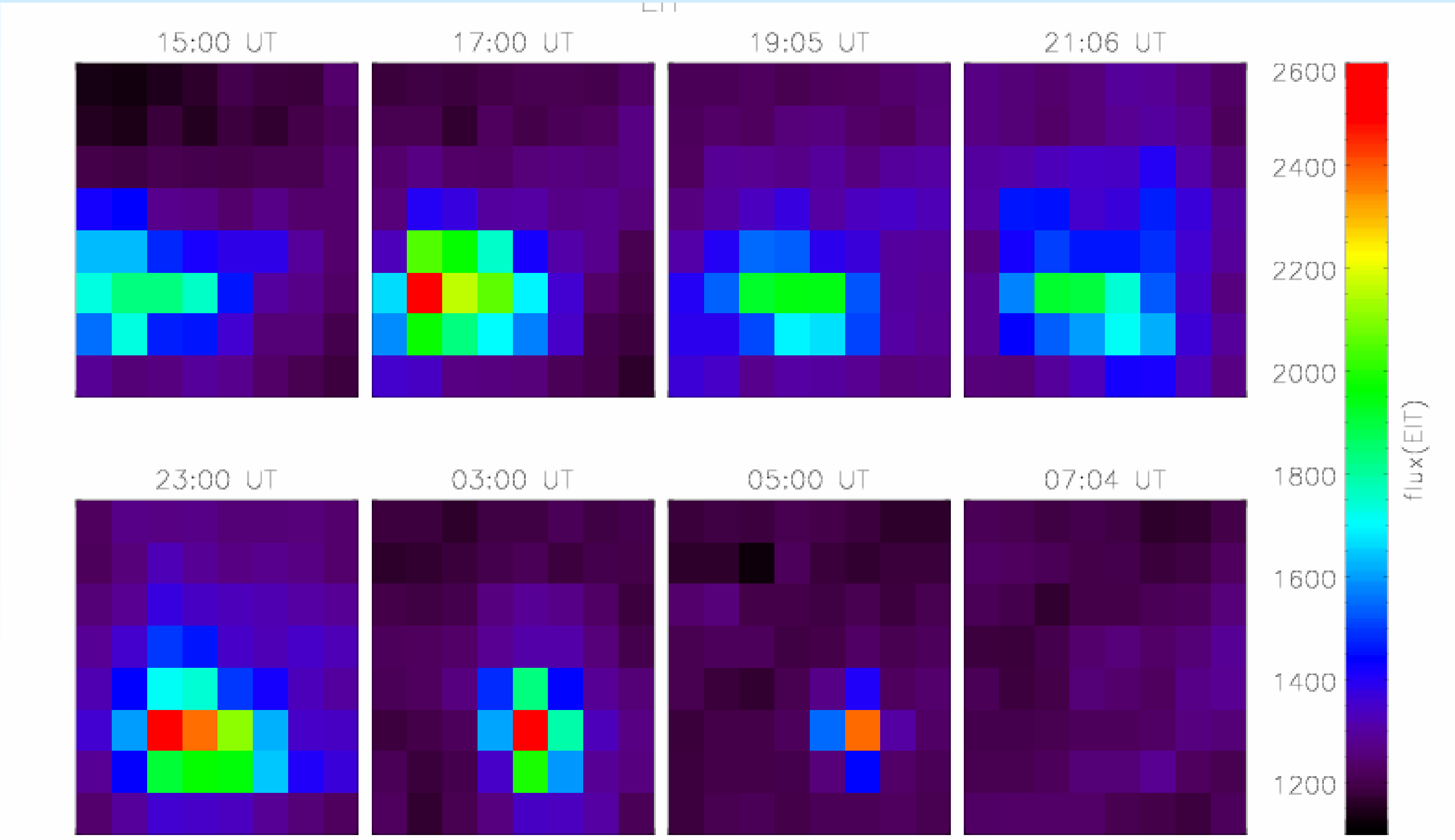
Reconnection type 1:
Magnetic nulls: Jperp current sheet



Dynamics of transition region reconnection due to enhanced Jperp:

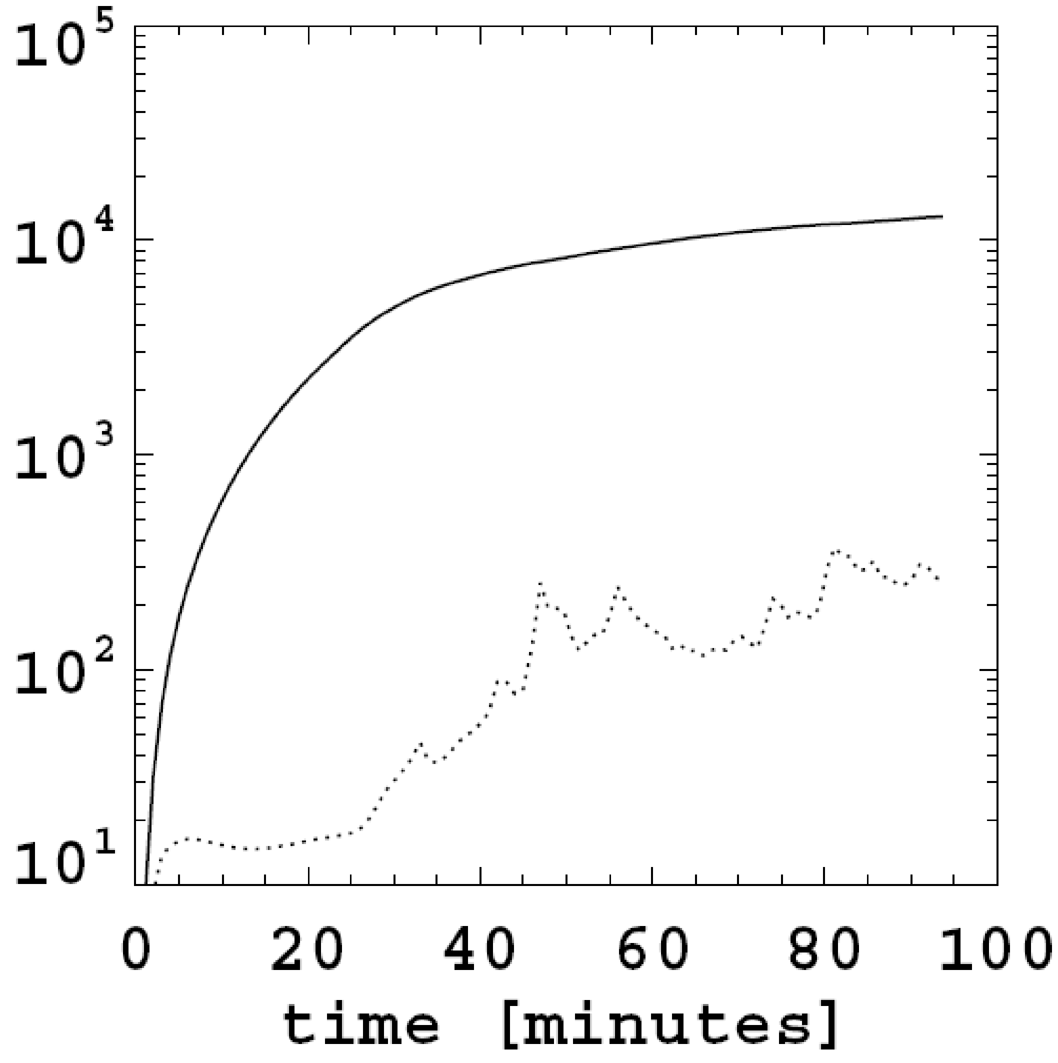


Result: SOHO-EIT (195 A) BP:



EUV BP of 17-18.10.1996 **(M. Madjarska et al., A & A, 398, 775, 2003)**

Current evolution in the corona



Solid line:

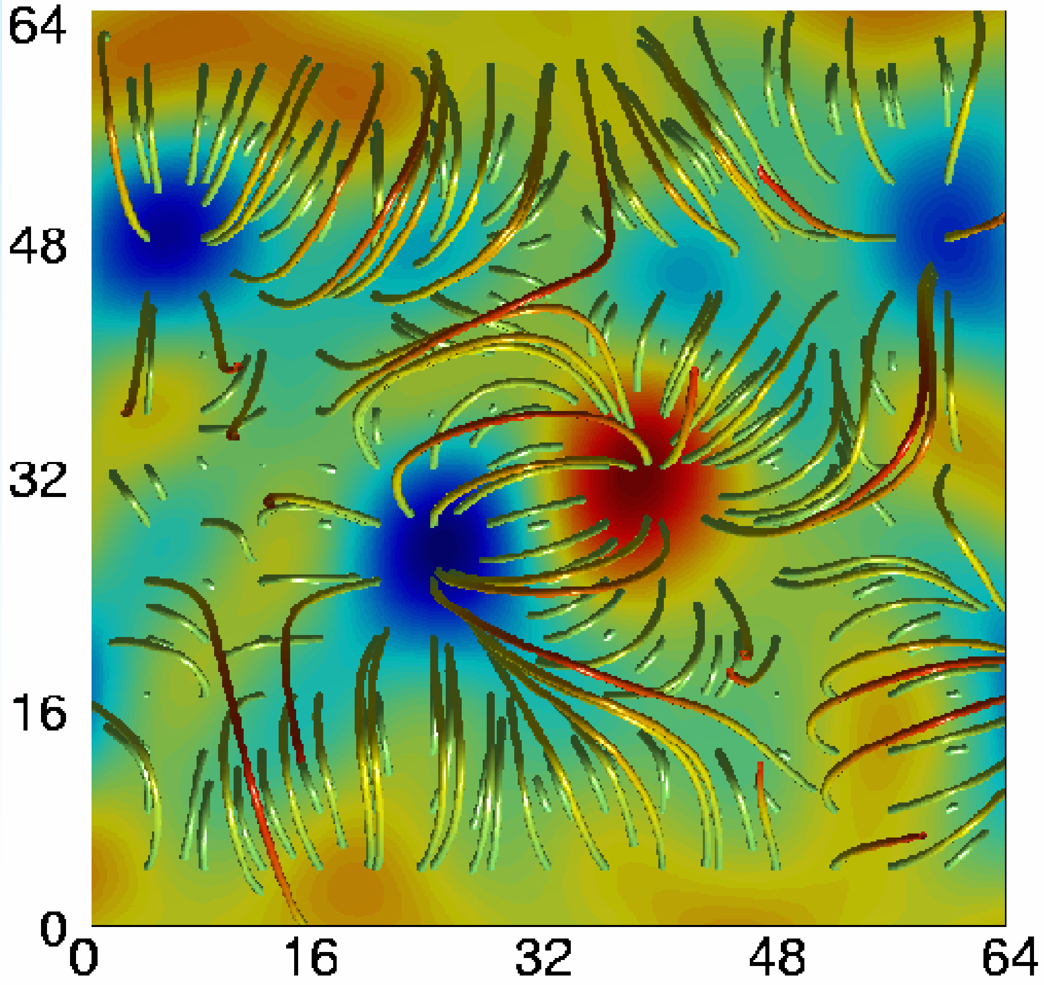
$$\int j_{||}^2 dV$$

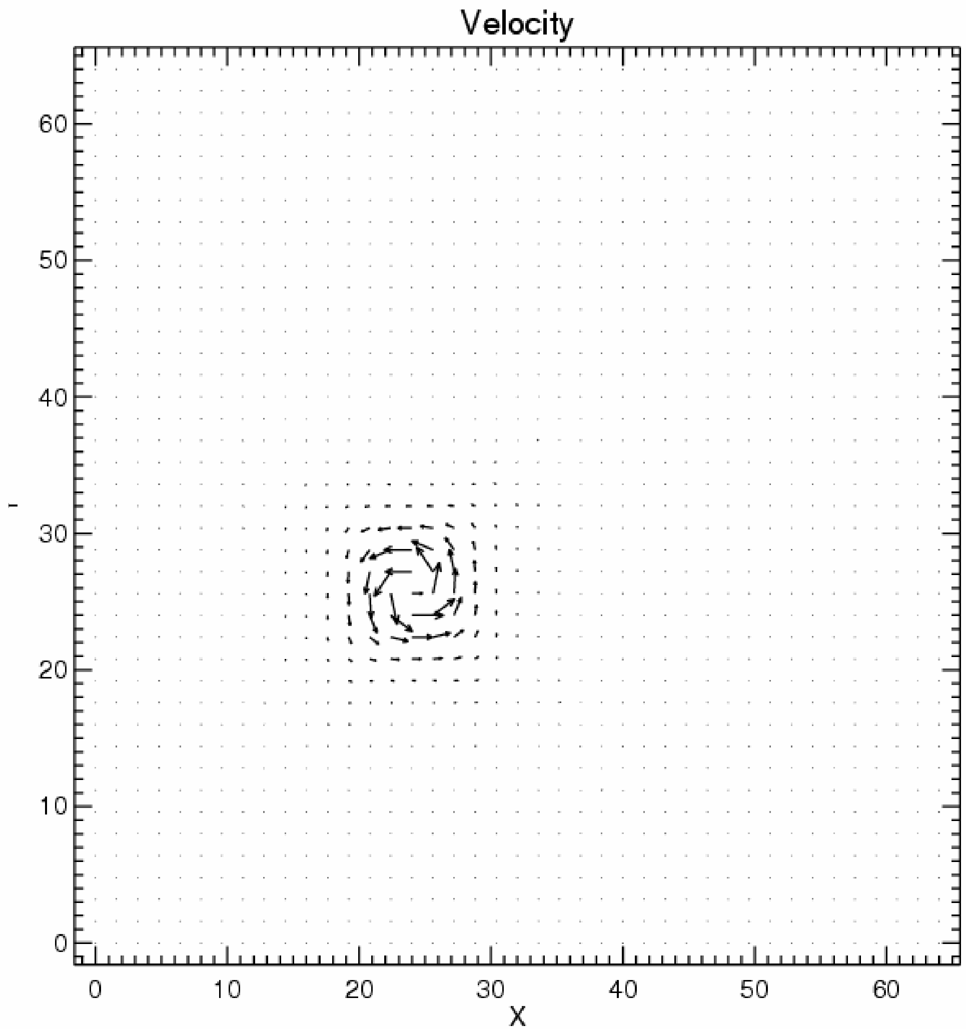
Dashed line:

$$\int j_{\perp}^2 dV$$

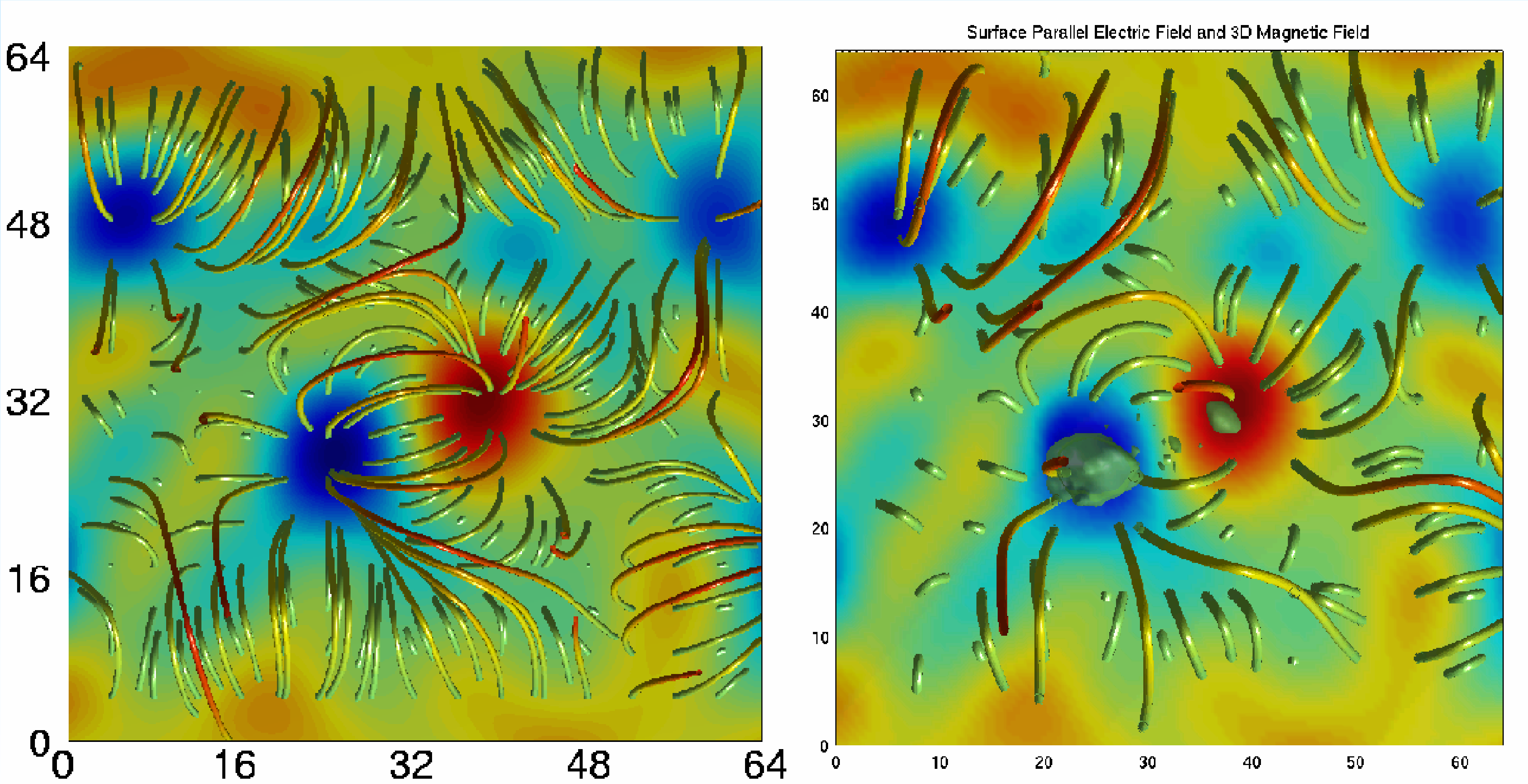
Reconnection type 2: No null, but footpoint twisting

(EUV BP, 14.6.98, 14:00 UT, Brown et al. 2000)

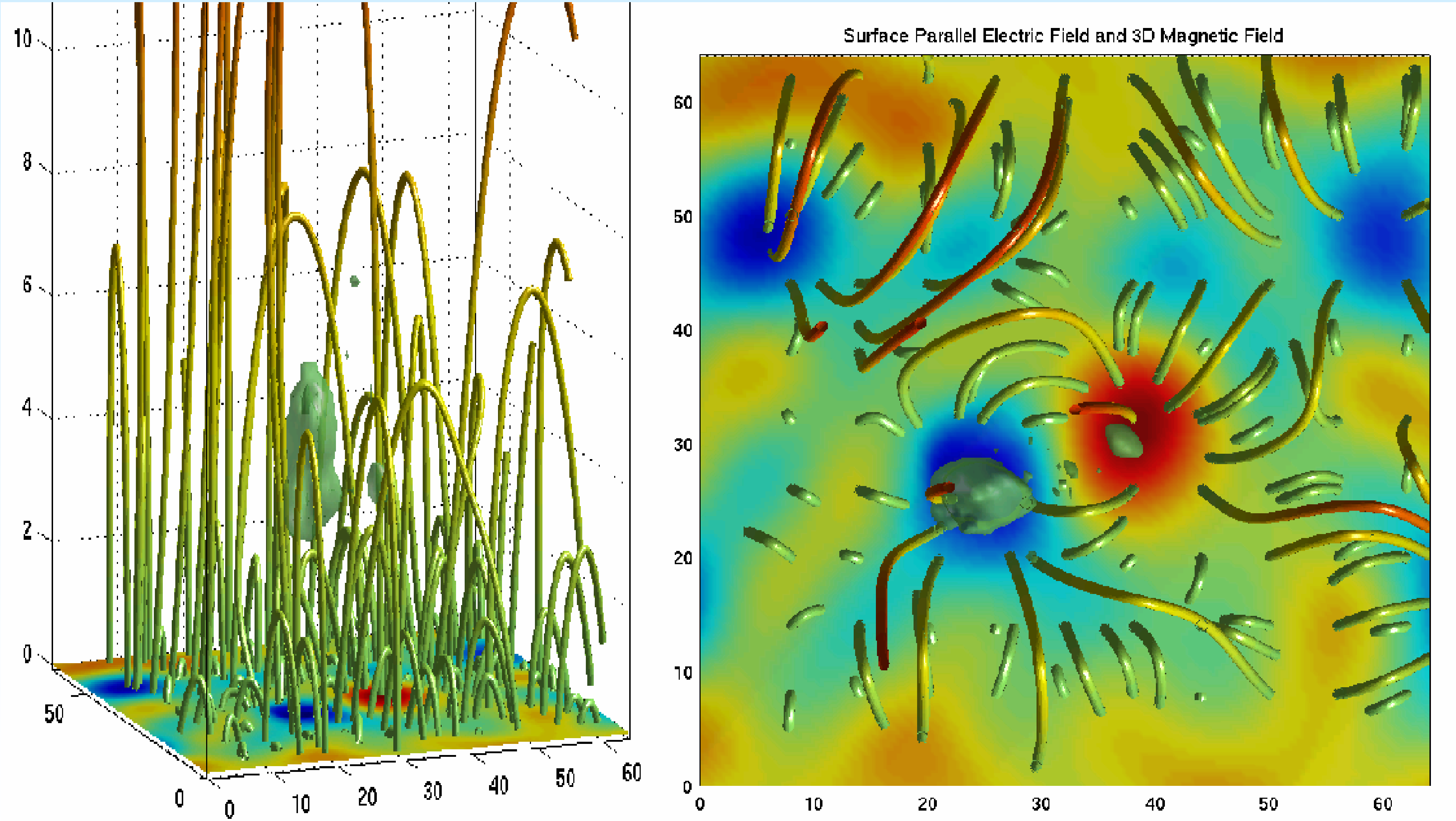




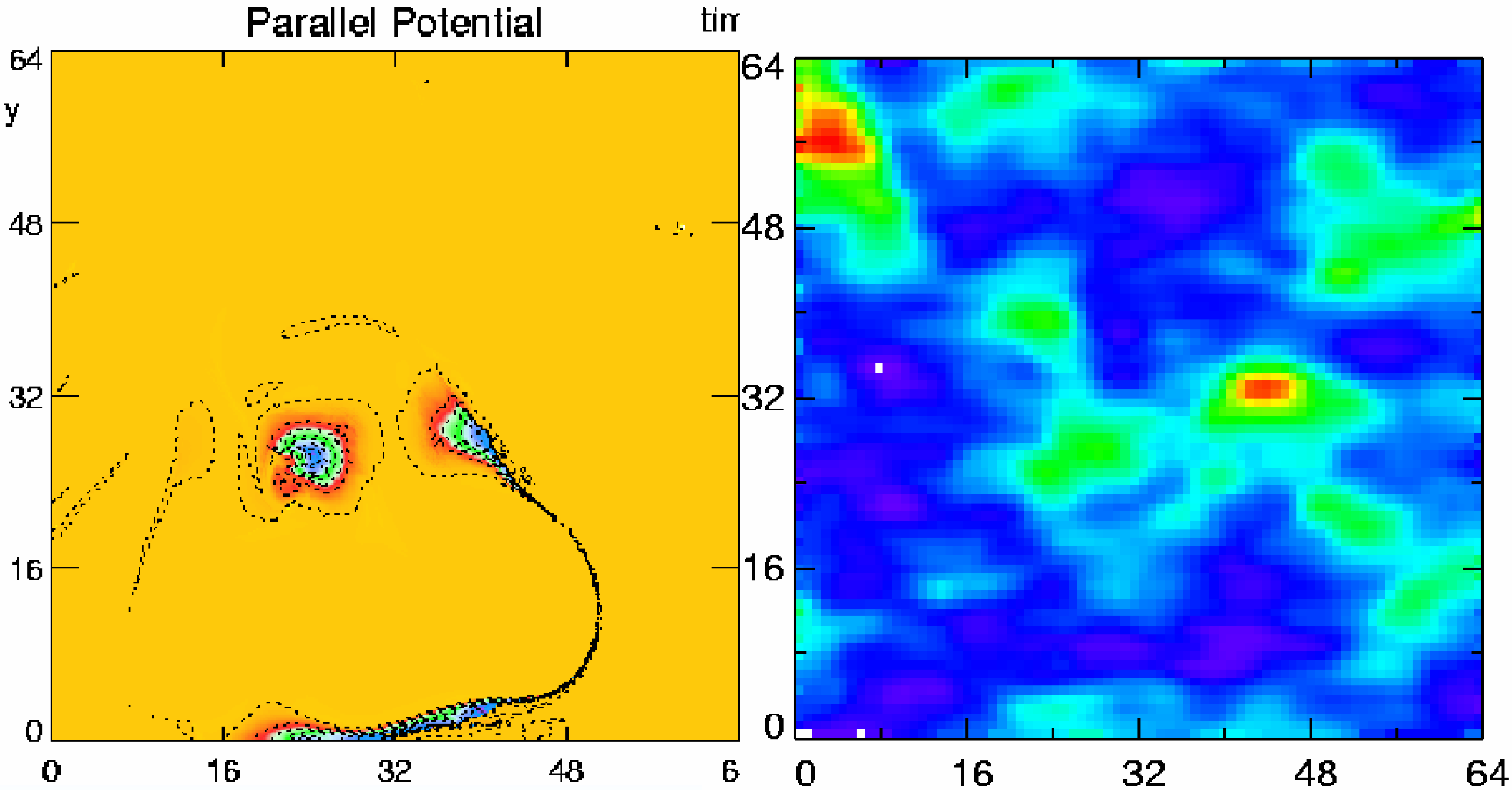
Generation of Jpar->Epar



Jpar - threshold exceeded:
-> transition region reconnection

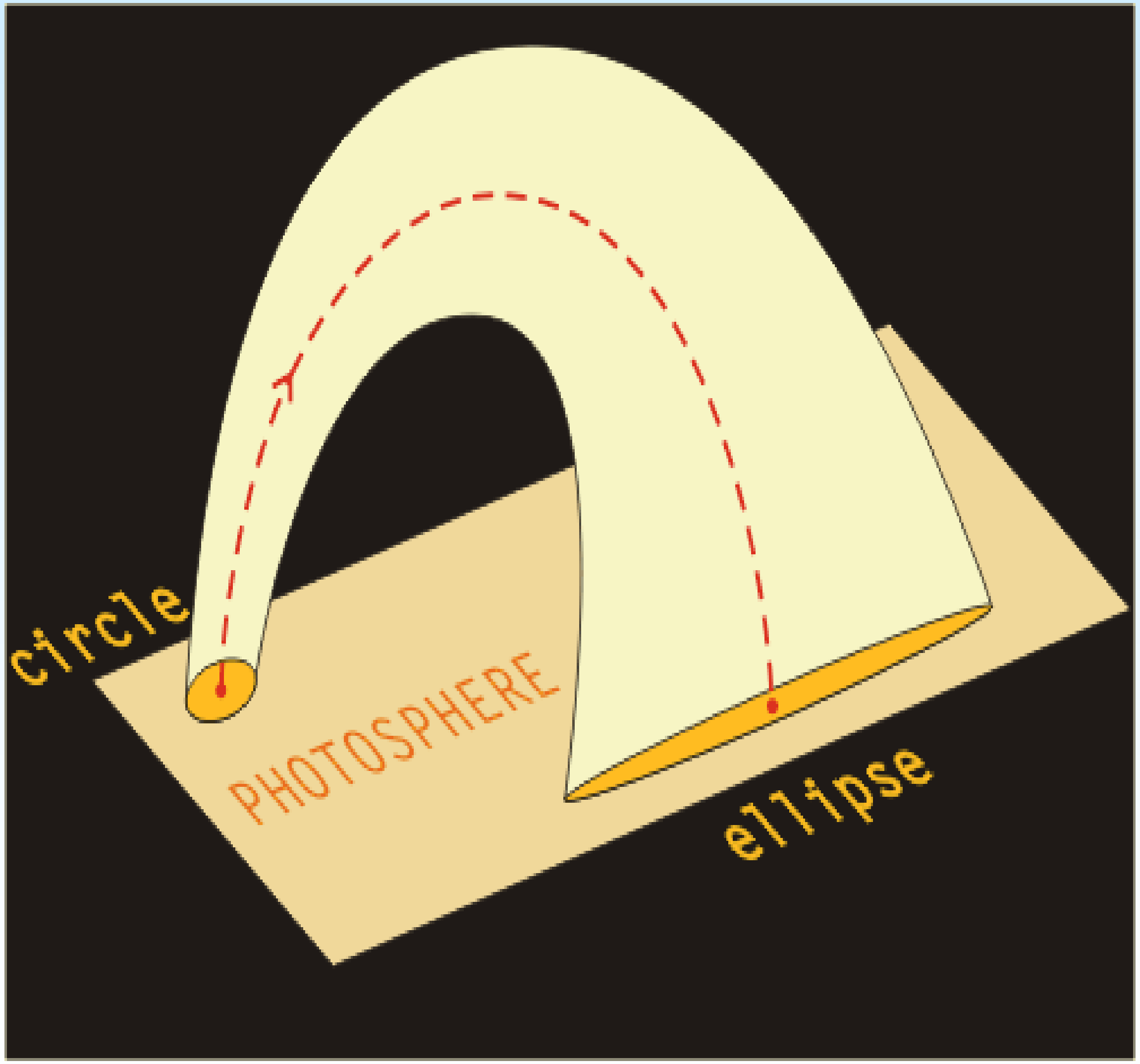


Epar vs. TRACE-EUV



The parallel electric field Epar accelerates electrons to MeV energies

Independent on coronal nulls Jpar are formed in QSL:



Quasi-separatrix layers (QSL) form if the magnetic connectivity in the complex coronal B-field changes consierably -> Measure: Q

$$Q = \frac{(a^2 + b^2 + c^2 + d^2)}{|ad - bc|}$$

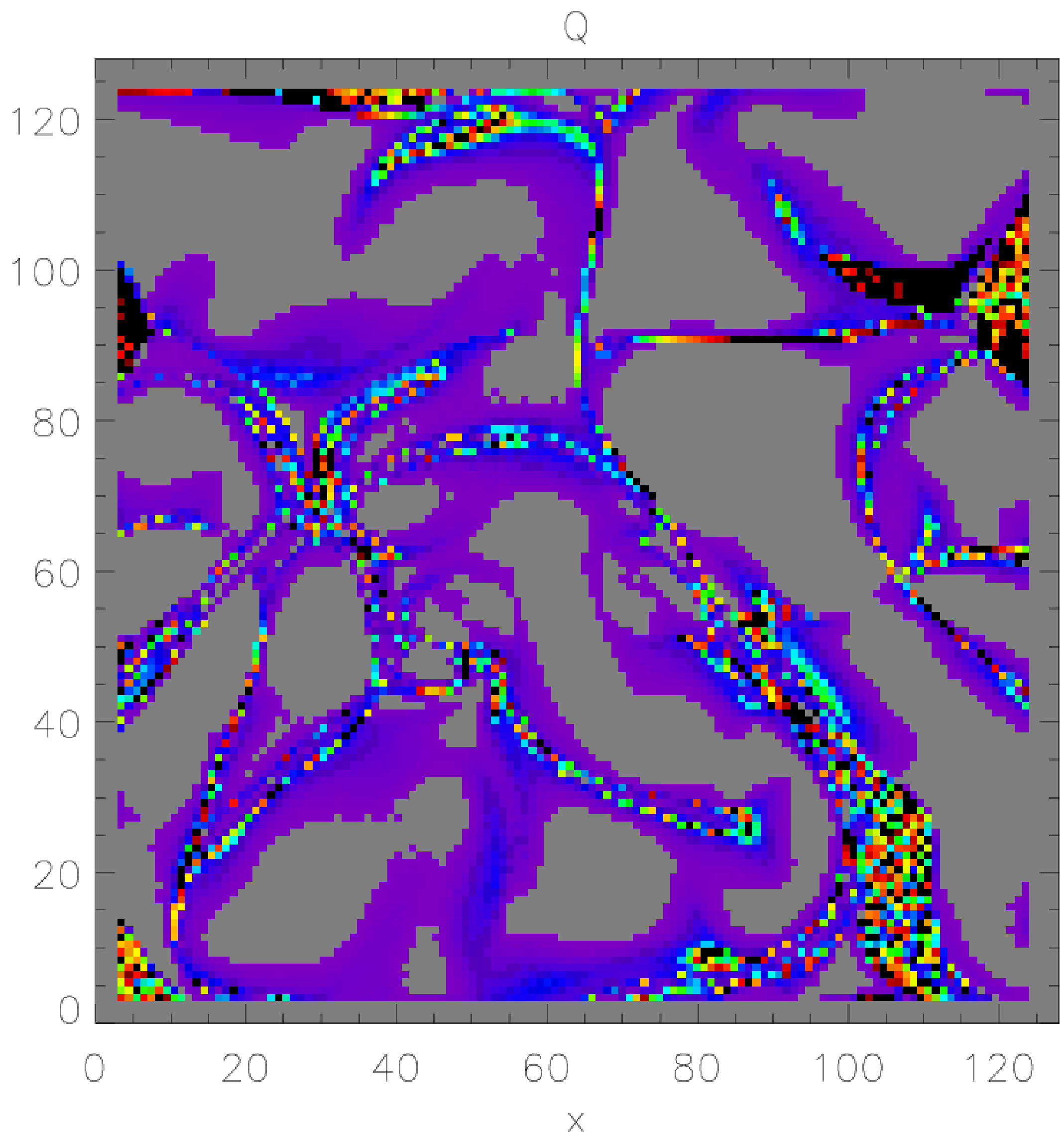
where a,b,c,d are the elements of the Jacobian:

$$D = \begin{pmatrix} \frac{\partial X}{\partial x} & \frac{\partial X}{\partial y} \\ \frac{\partial Y}{\partial x} & \frac{\partial Y}{\partial y} \end{pmatrix} = \begin{pmatrix} a & b \\ c & d \end{pmatrix}$$

[Titov et al. 2003]

(Q is practically the aspect ratio of the ellipse conjugate to a circle)

Q predicts Epar-> particle acceleration



Epar is maximum, where (1) Q >>1 and (2) plasma moves accross the QSL

Summary and Outlook

We investigated the microphysics of coronal current dissipation and used this information to obtain conditions and sites of reconnection based on time-dependent photospheric vector magnetic field observations as initial and boundary conditions of numerical simulations which included also the plasma-neutral gas coupling in the chromosphere.

Perspectives in the Solar-B era:

- Start with the SOT vector magnetic fields
- Predict current concentrations with Q(potential fields)
- Calculate Vn and Vt by ILCT to be used in the
- Dynamical simulation of J starting with potential field
- Switch on resistivity after the microphysical model
- Obtain heating -> compare with brigthenings in EIS
- Obtain E_par and electron energies -> compare XRT
- Still to be developed: Line-of sight integration of radiation fluxes and energetic electron fluxes