Collisionless reconnection in space and solar physics

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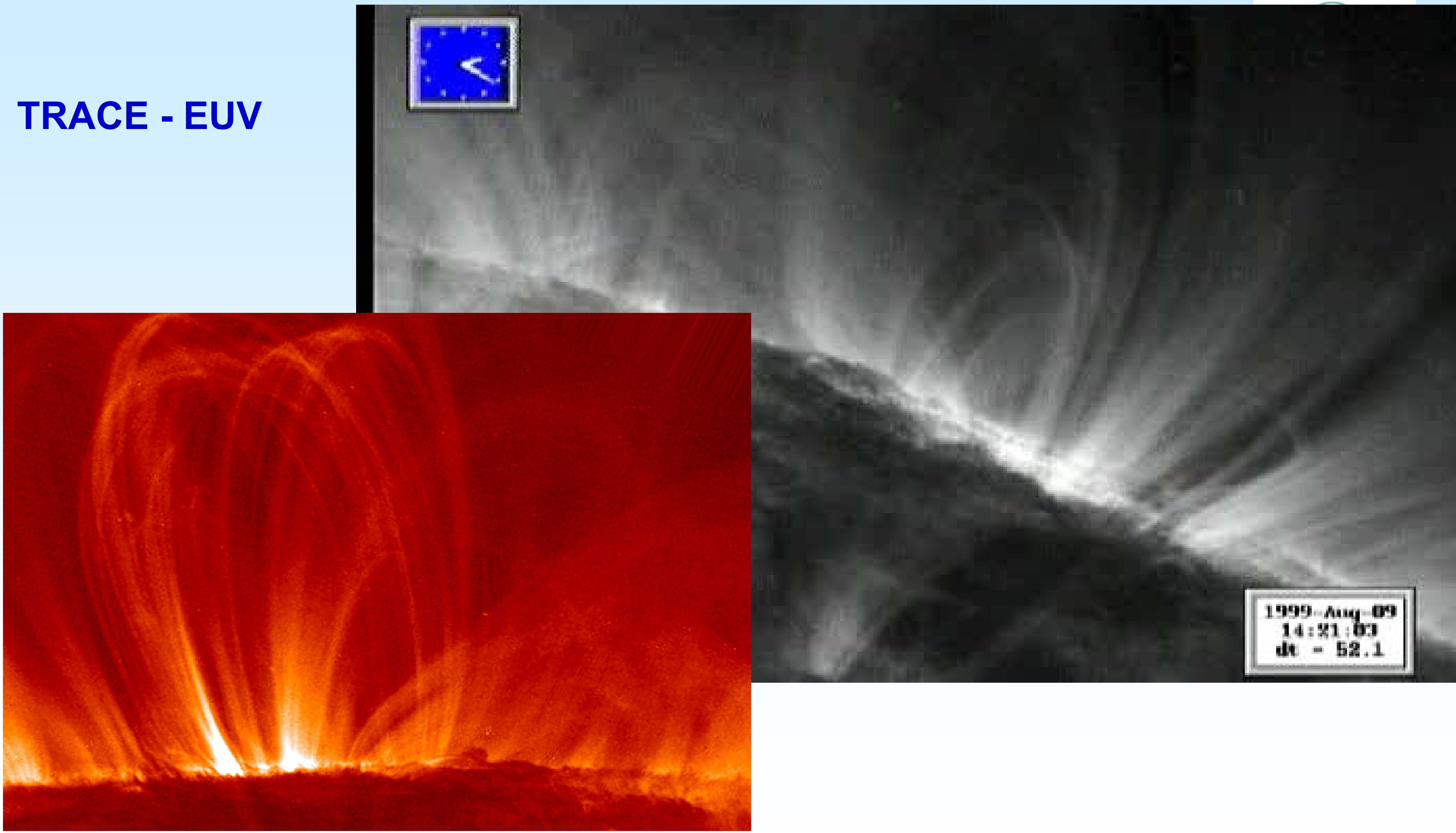
Topics

- Scales
  - Large (fluid) scales: system sizes cause Rm = 10^6-10^8
  - Small (plasma) scales: Nanoflares/mini flux transfers
- Geometry (from 2D to 3D reconnection)
  - Null points (high beta) and
  - „Finite-B reconnection“ -> low-beta
- Balance of the reconnection E-field

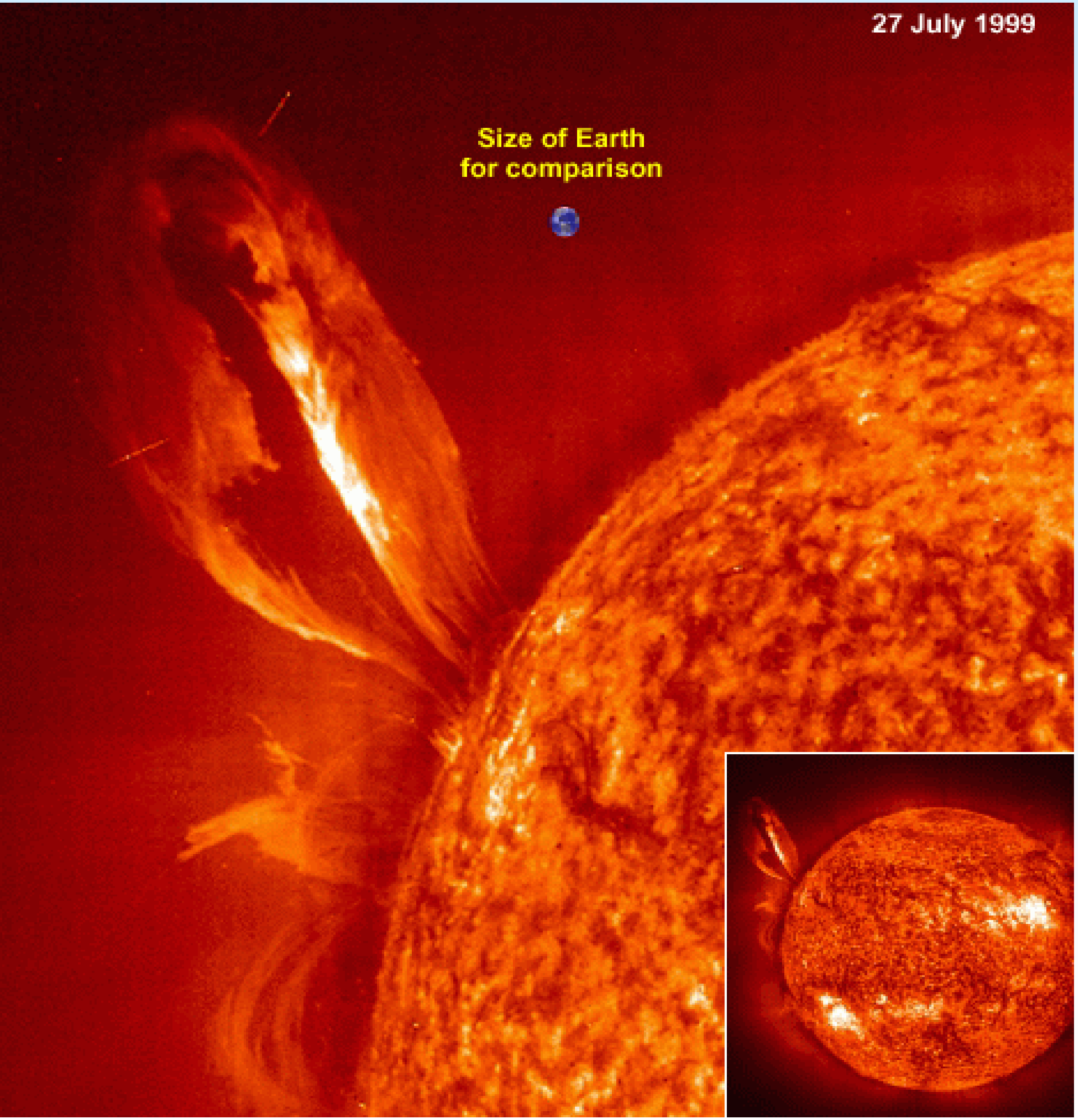
  (plasma non-idealness, inner current layer ...)
  - MHD using „anomalous“ resisitivity if strong current concentrations / thin current sheets are formed
  - Multi-fluid: the generalized Ohms law rpvide more possibilties, but still thin current sheets are required
  - Kinetic: Even more ways, but: thin sheets still required

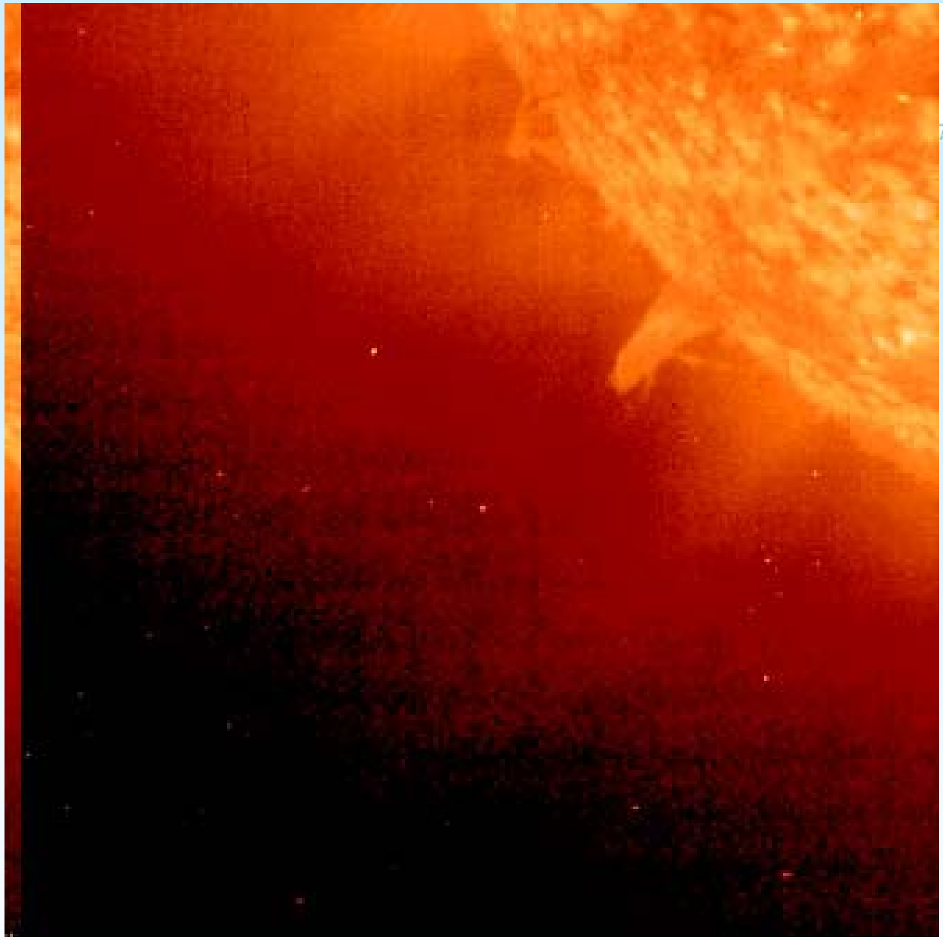
Scales: Exploding arcs at sun

TRACE - EUV



Prominence eruptions





Prominence eruptions -> CMEs

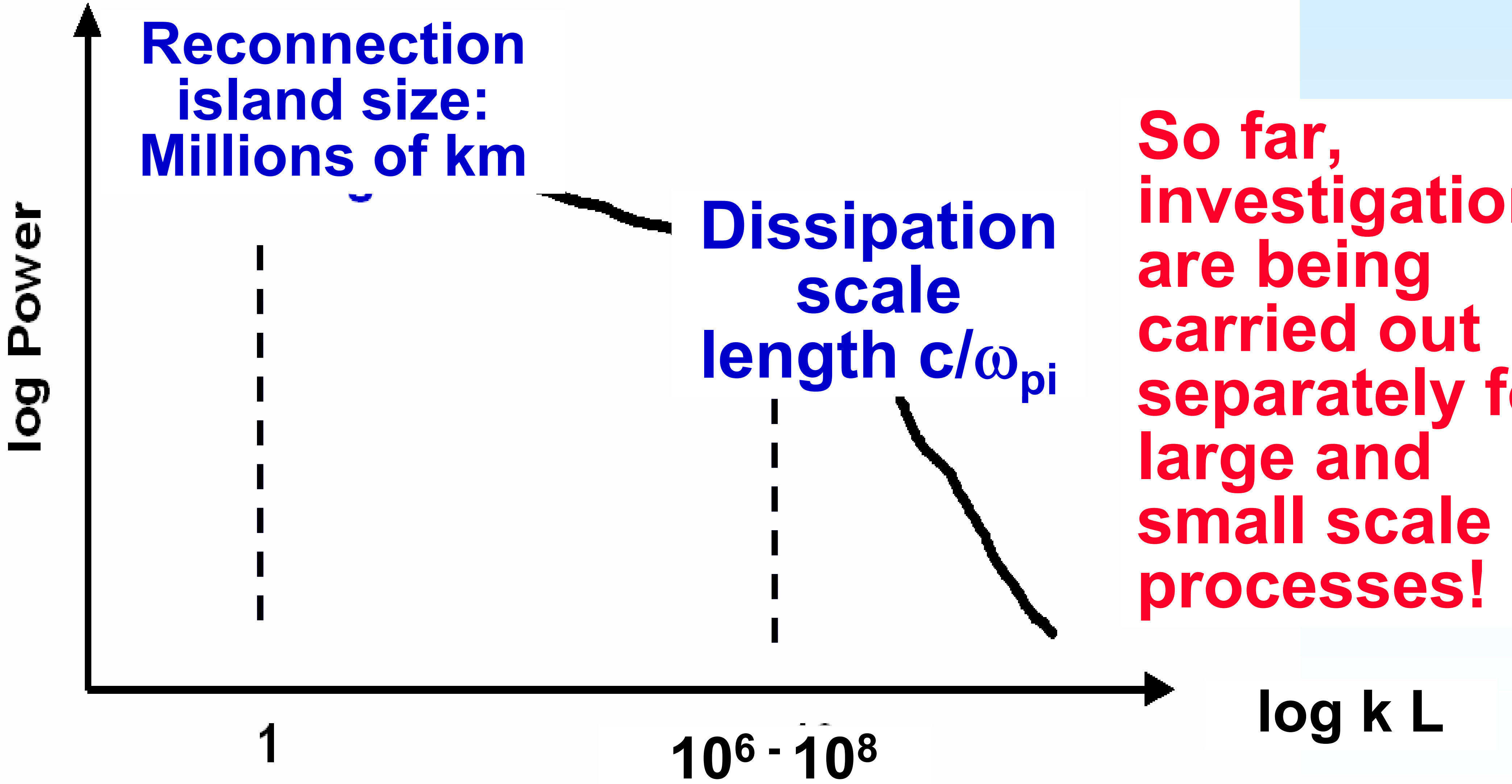
Collisonless coronal plasma: Dissipation scales vs structure sizes

Plasma temperature Te ~ Ti ~ 10^6 K

n	λ_{De}	c/ω_{pi}
10^8 cm^{-3}	0.7 cm	20 m
10^{11} cm^{-3}	0.02 cm	0.7 m

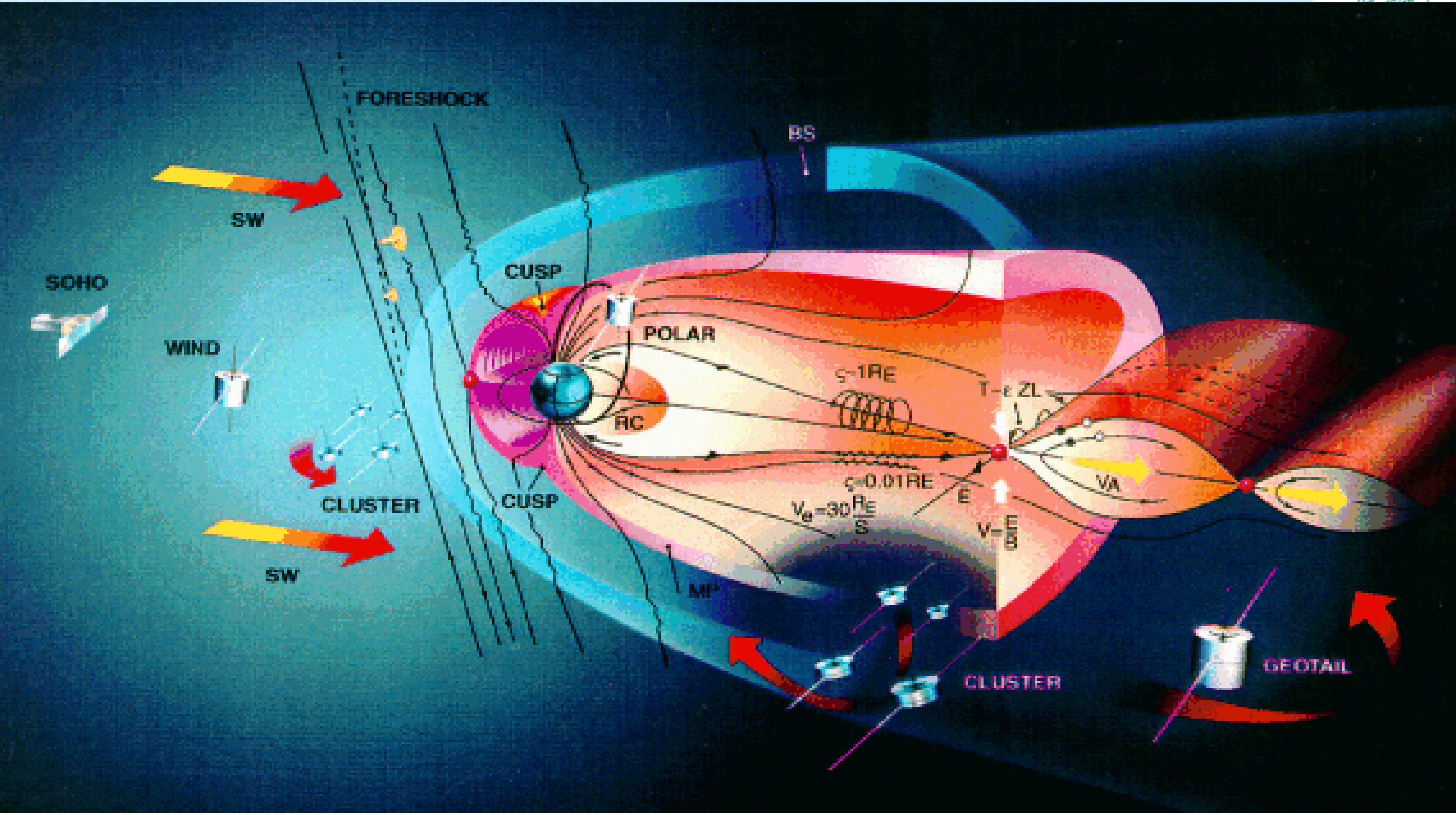
While the size of observed objects is: L ~ 10^7 m !

Large scale of collisionless reconnection in astrophysics, e.g. at Sun

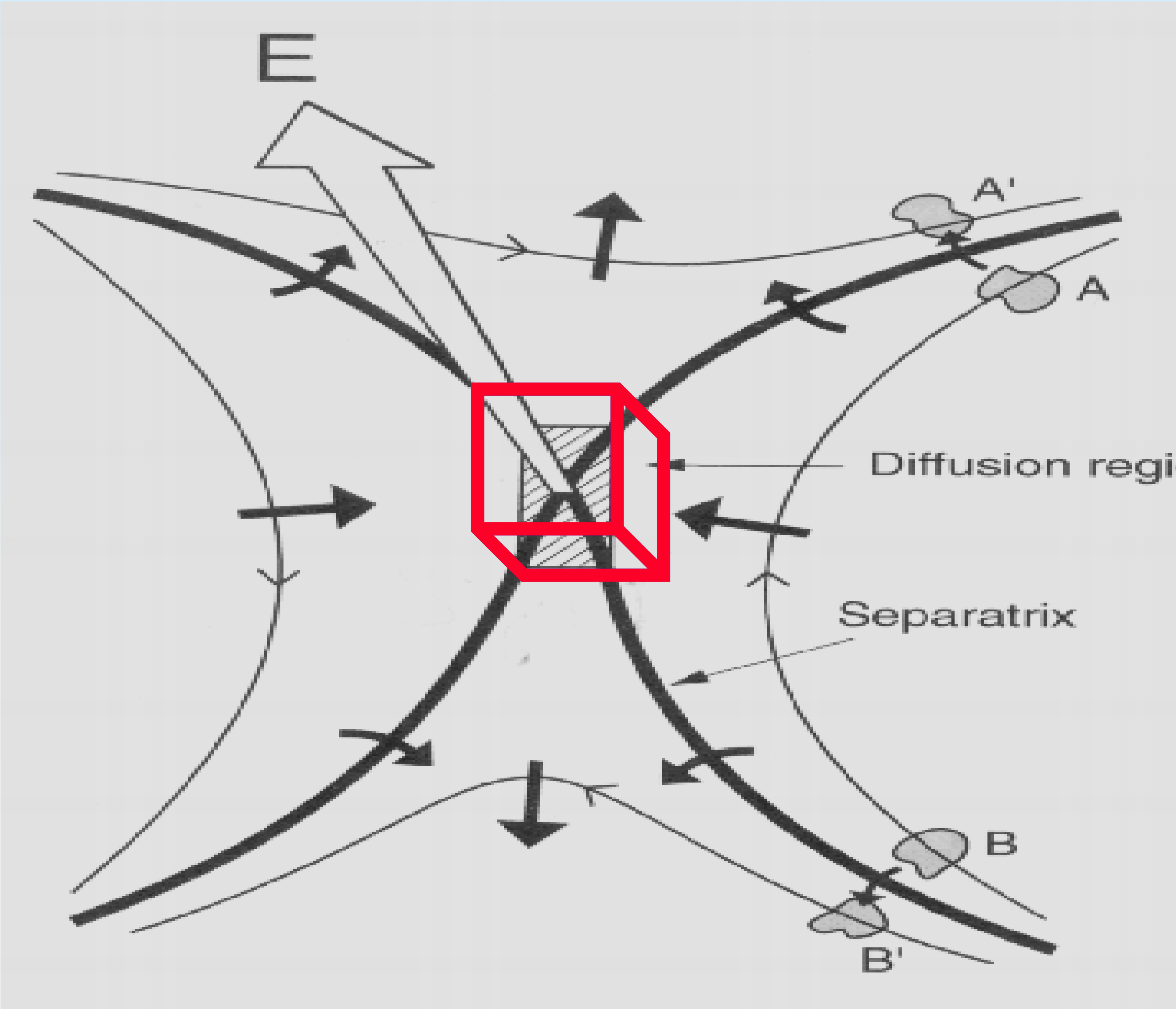


So far, investigations are being carried out separately for large and small scale processes!

Reconnection observations by s/c

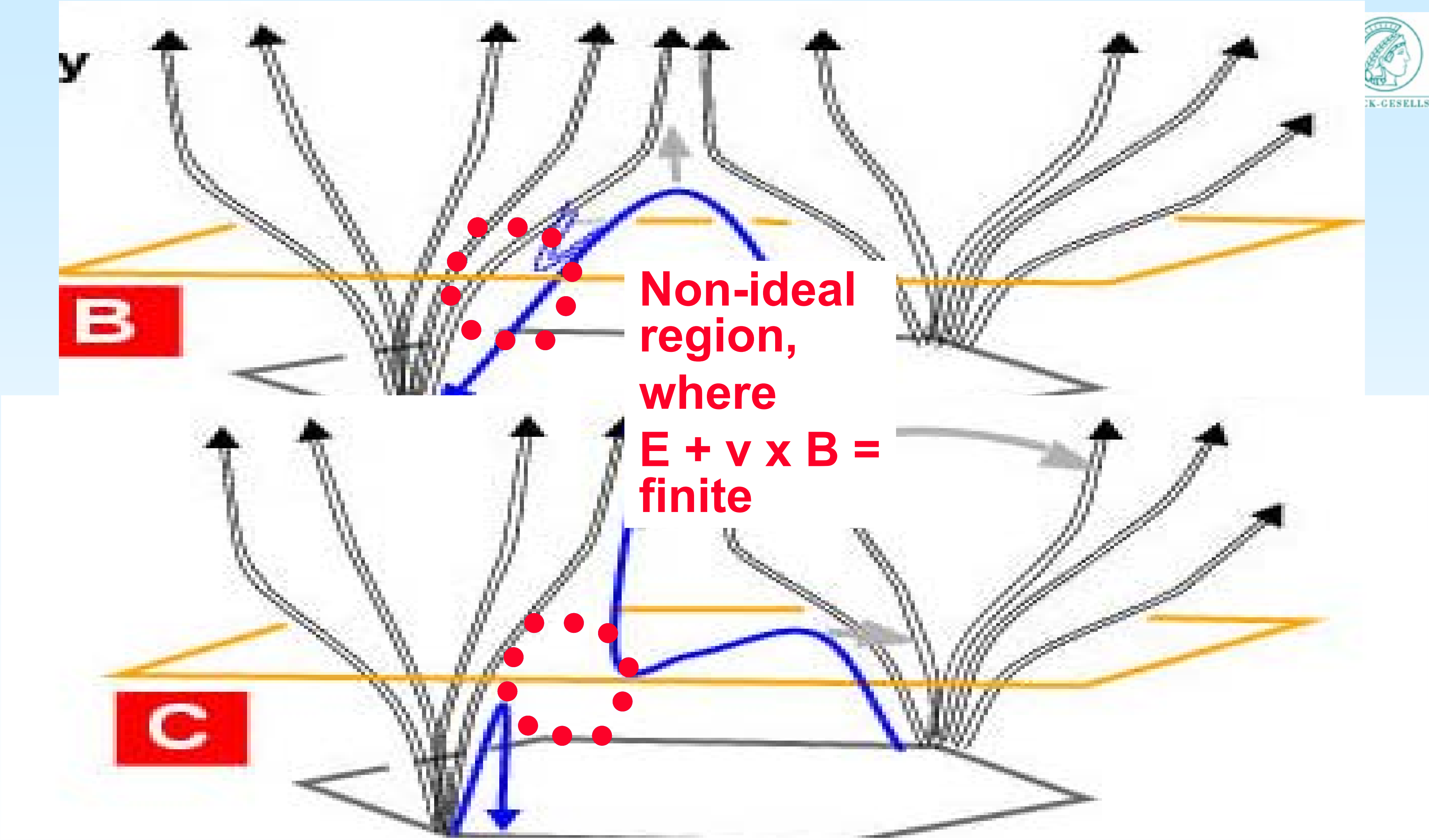


Reconnection geometry in 2D



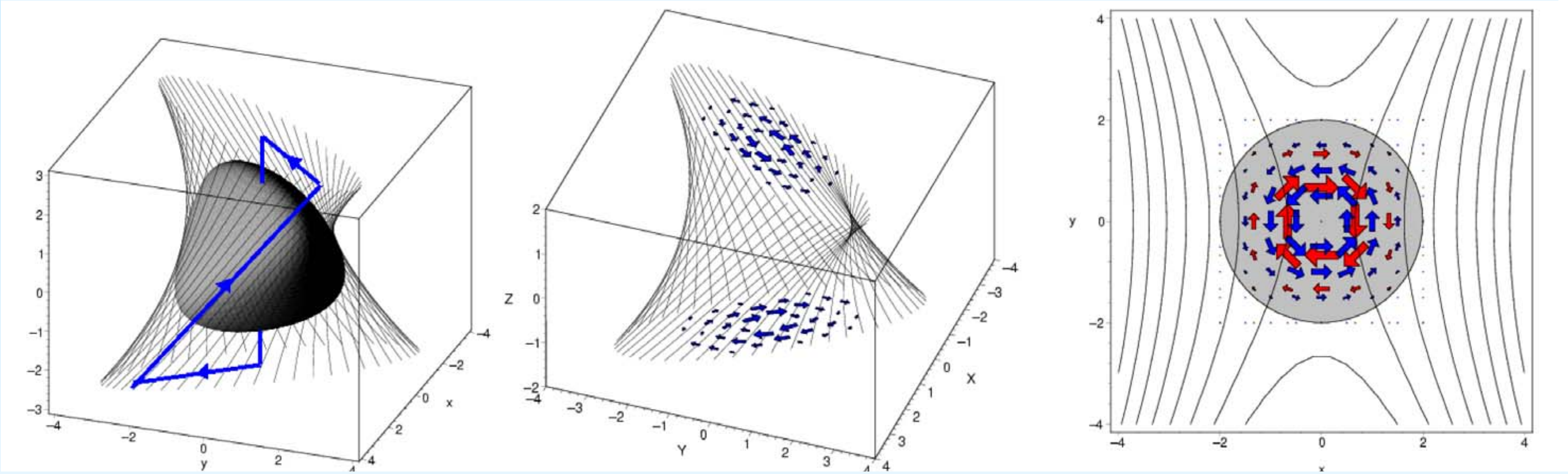
Reconnection in two dimensions:
Non-ideal region, where E + v x B = finite

Reconnection in three dimensions



Non-ideal region, where E + v x B = finite

3D-case of hyperbolic B fields



Selfconsistent solution: Counter-Rotation of plasma -> The reconnection rate is the 'mismatch' of flux due to the difference of the plasma velocities above and below the reconnection region of non-ideal plasma:

$$\frac{d\Phi_{mag}}{dt} = \int_L \mathbf{E} \cdot d\mathbf{l} = \int_R \left(\mathbf{w}^{in} - \mathbf{w}^{out}\right) \times \mathbf{B} \cdot d\mathbf{r}$$

Non-idealness by resistivity

Induction equation

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

... reveals scales -> magnetic Reynolds number

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

For reconection R_m must become ~ 1, hence, e.g. in the solar atmosphere:

1.) l ~ 1 km

2.) η ~ 10^8 times that of collisions

-> Collisions will no make it

Balance of E_{rec} by electrons & ions

Two-fluid-description (e-i) ->„generalized Ohm`s law"

$$\frac{4\pi}{\omega_{pe}^2}\frac{d\vec{J}}{dt} = \boxed{\vec{E} + \vec{v}_i \times \vec{B}} - \frac{1}{ne}\vec{J}\times\vec{B} + \frac{1}{ne}\nabla p_e - \eta\vec{J}$$

c/ω_{pe} <- spatial -> <- scales -> ρ_i c/ω_{pi} ^

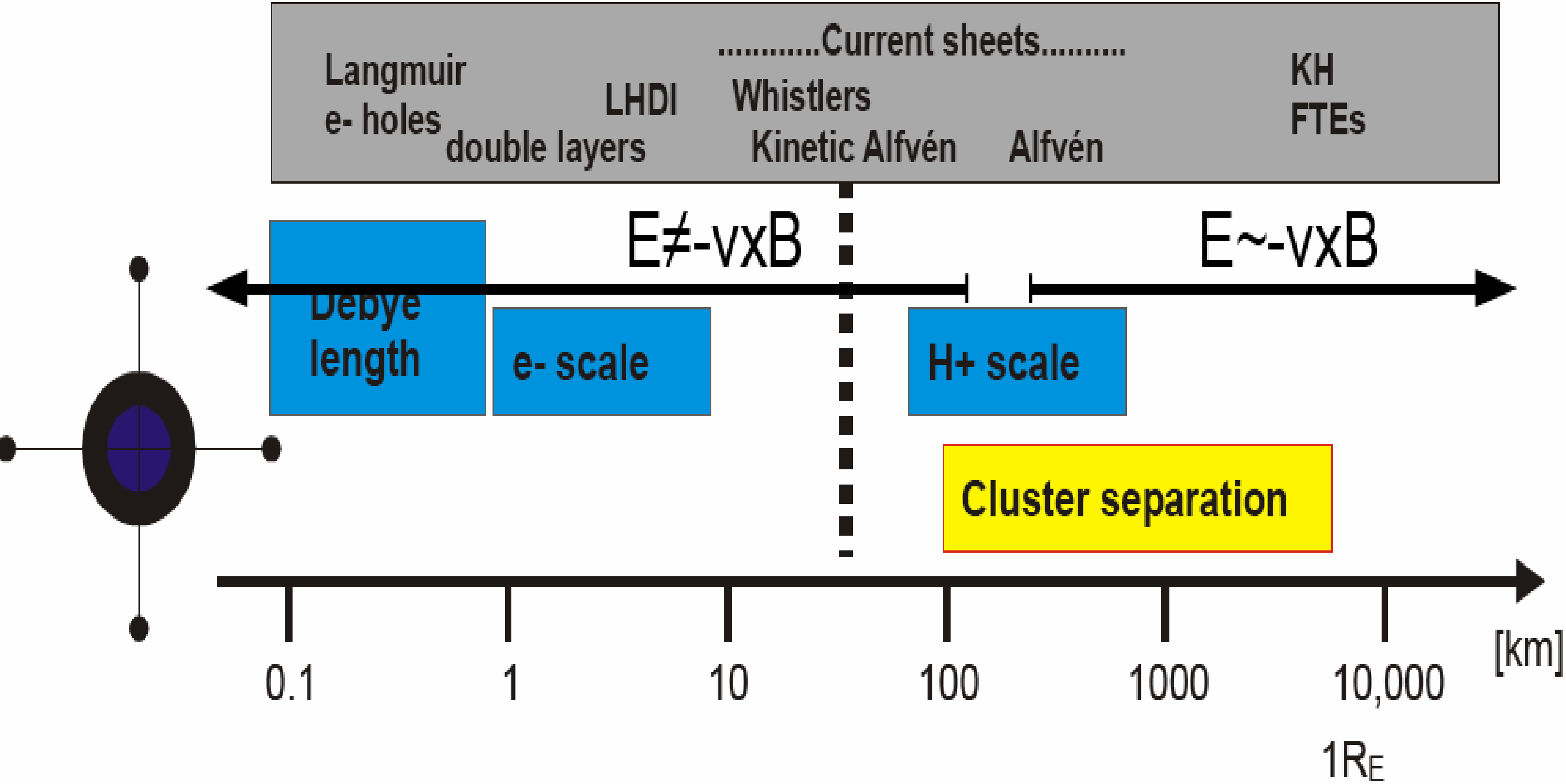
electron inertia

elektrons - ions decoppled, „Hall" term"

off-diagonal elements of the pressure tensor

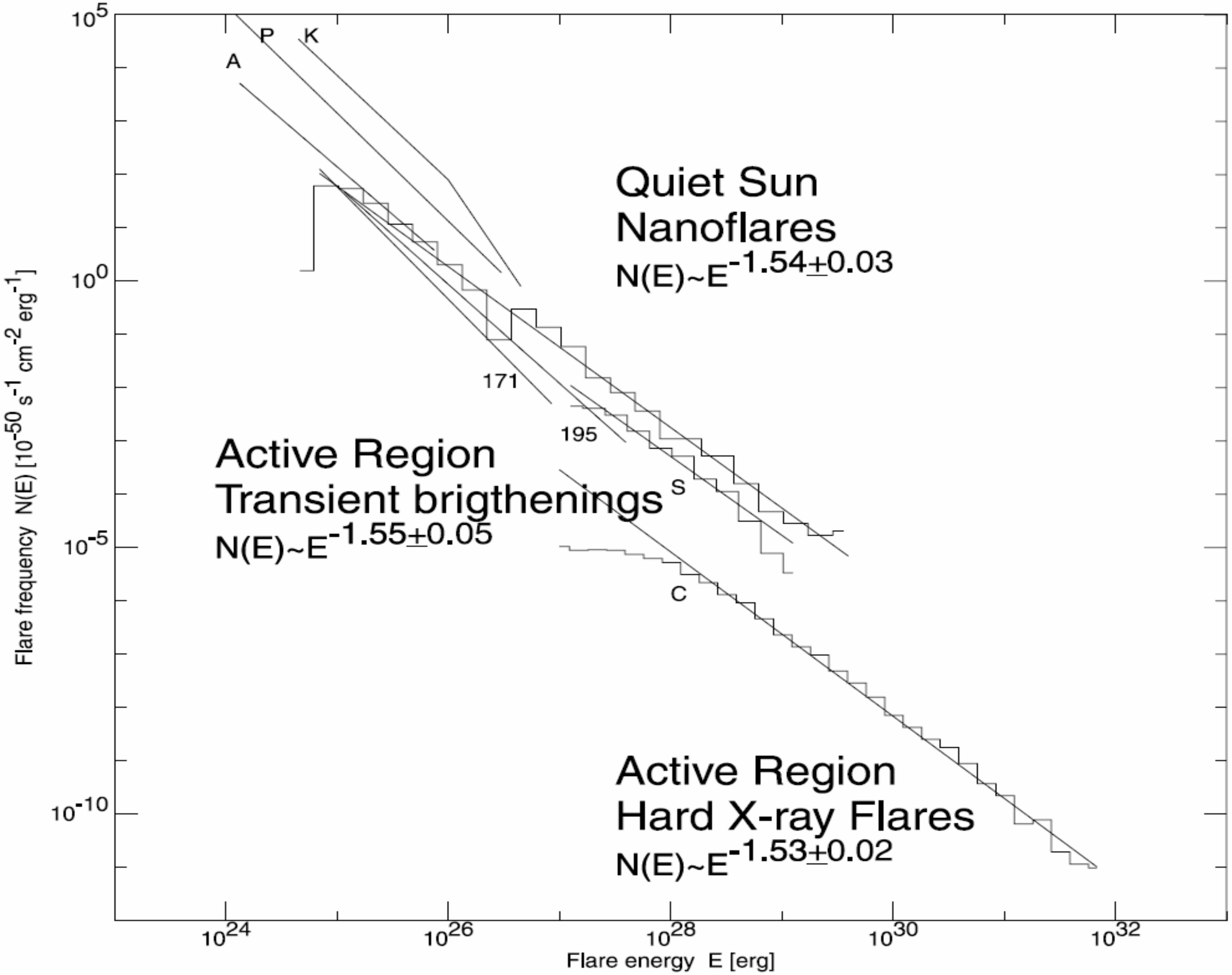
dissipation due to high-frequency turbulence

Scales observable by CLUSTER



In 2007 a sensational 17 km separation was reached!!

Perhaps also small scale reconnection

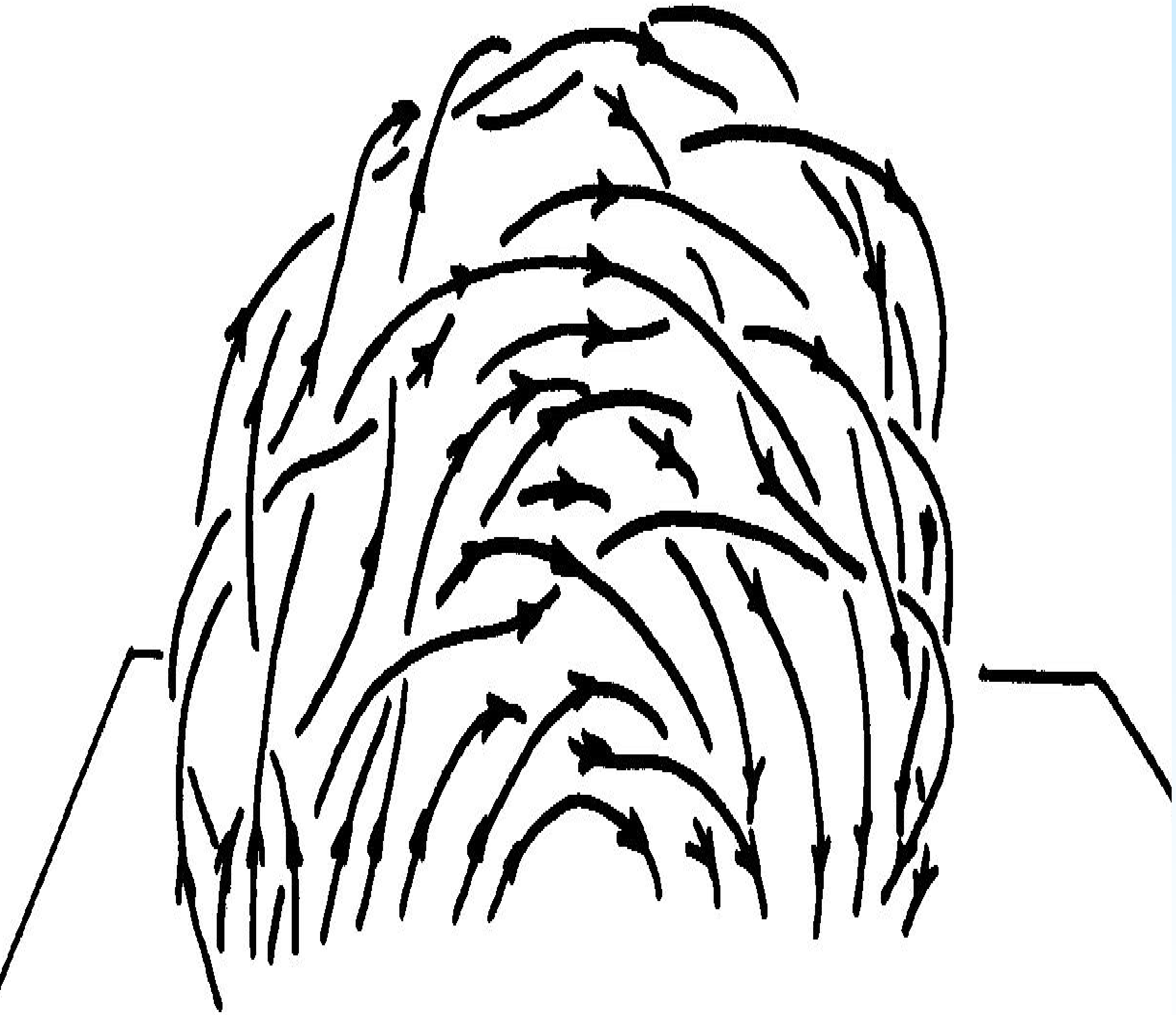


N(E) is the probability of an energy release event in the range dE dA dt

So that the total energy releas is the integral over N(E) dE dA dt.

[Aschwanden and Parnell 2008]

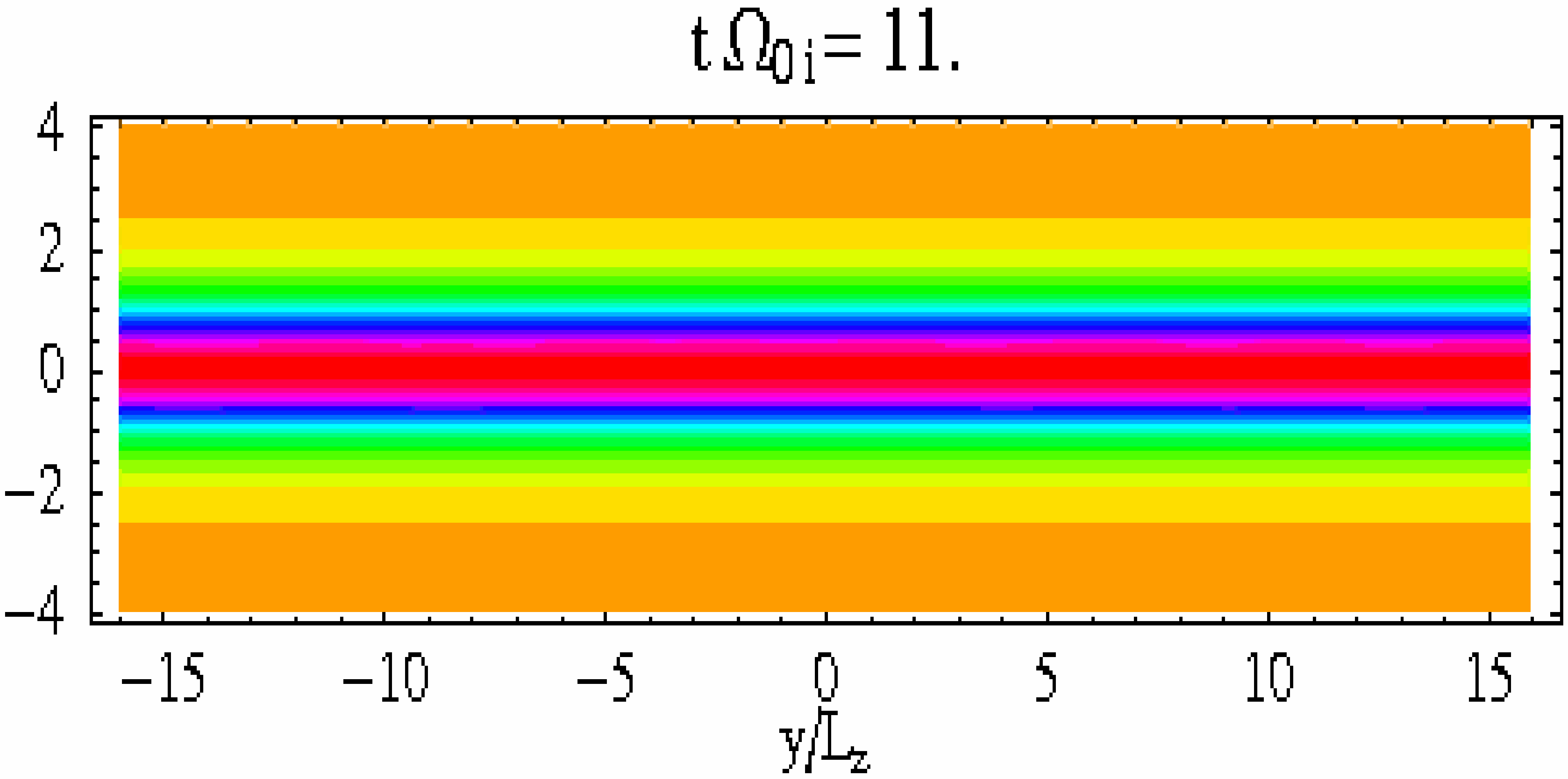
Nanoflare hypothesis



Many small tangential discontinuities form due to footpoint motion of magnetic flux tubes (e.g. in the solar photosphere) -> small scale reconnection may cause '*Nano-Flares*' $E \sim 10^{24}$ ergs, t ~1s [Parker, 1988]

Note: At Sun not observable in principle!!

High beta (~1) case: thin current sheets -> gradient drift LHDI -> kink/sausage



At microscales (kinetic effects)

MPS

Ensemble averaging:

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

$$f_j = f_{0j} + \delta f_j \qquad E_{||} = \left\langle E_{||} \right\rangle + \delta E_{||}$$

-> Modified Vlasov equation, after velocity averaging

-> momentum exchange in the parallel direction

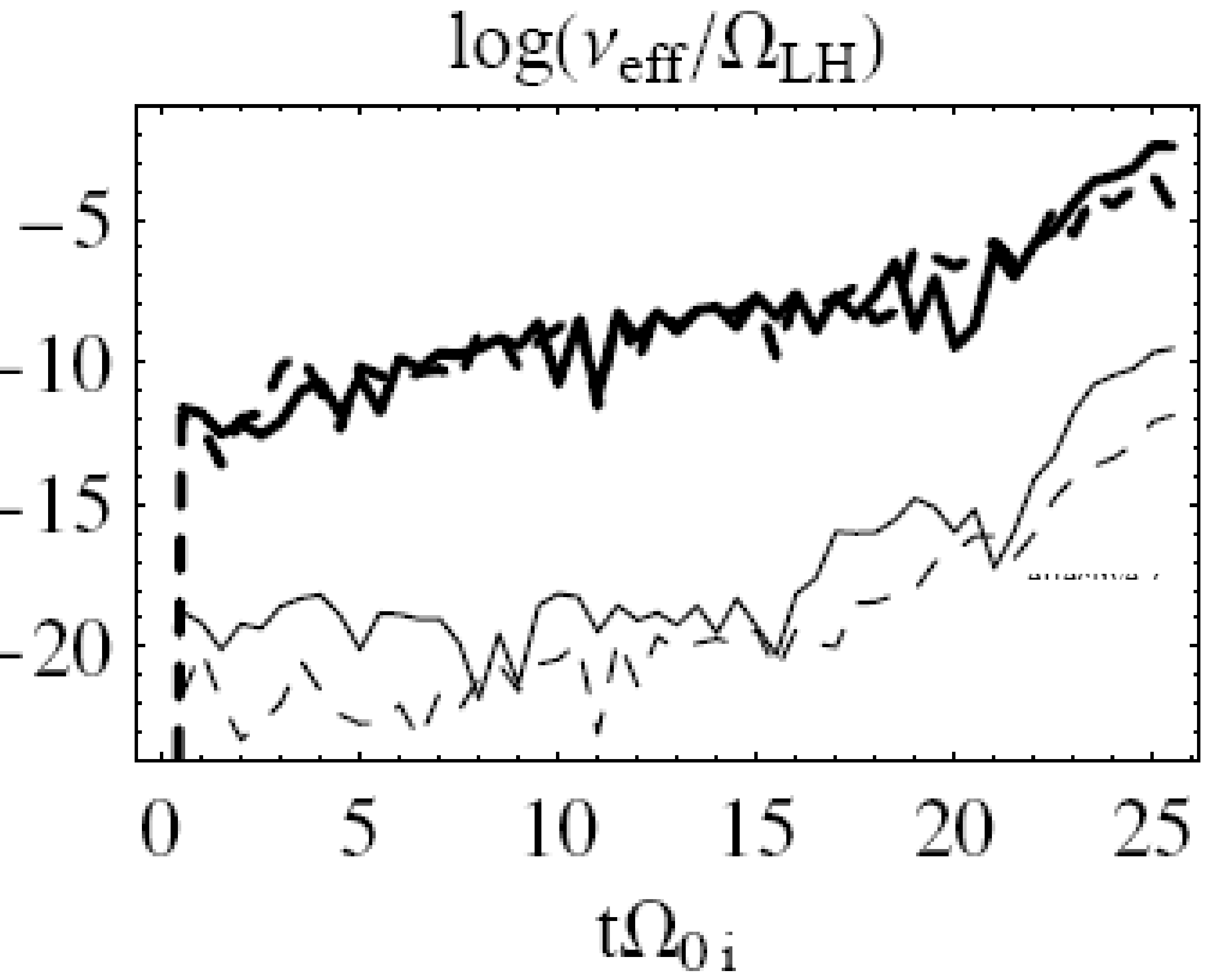
$$\frac{\partial f_{0e}}{\partial t} + \vec{v} \cdot \frac{\partial f_{0e}}{\partial \vec{r}} + \frac{e}{m_e} \vec{E} \cdot \frac{\partial f_{0e}}{\partial \vec{v}} = -\frac{e}{m_e} \left\langle \left(\delta \vec{E} + \vec{v} \times \delta \vec{B} \right) \cdot \frac{\partial \delta f_e}{\partial \vec{v}} \right\rangle$$

-> correlation of e/m fluctuations and plasma density /current fluctuations

$$\left(\frac{d}{dt} n m_e v_{y,e} \right)_{eff} = \langle \delta E_y \delta \rho_e + \delta j_{z,e} \delta B_x - \delta j_{x,e} \delta B_z \rangle$$

-> The correlations can be taken from theory (e.g. quasilinear), from observations, from simulations

Corresponding quasi-collisions

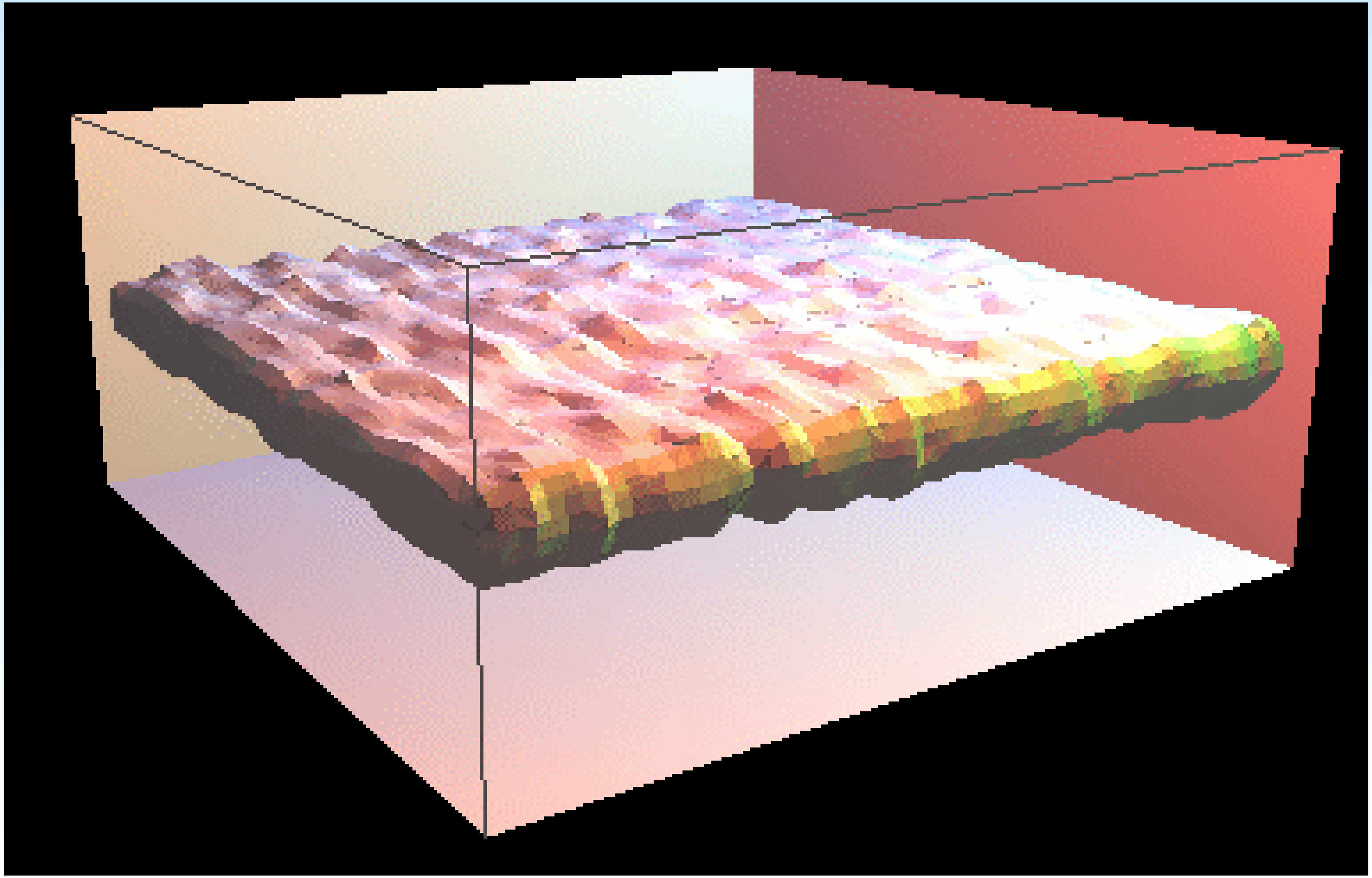


In the solar coronal plasma these rates exceed those of the 1D instability by a factor of about 6

What are the consequences for 3D reconnection?

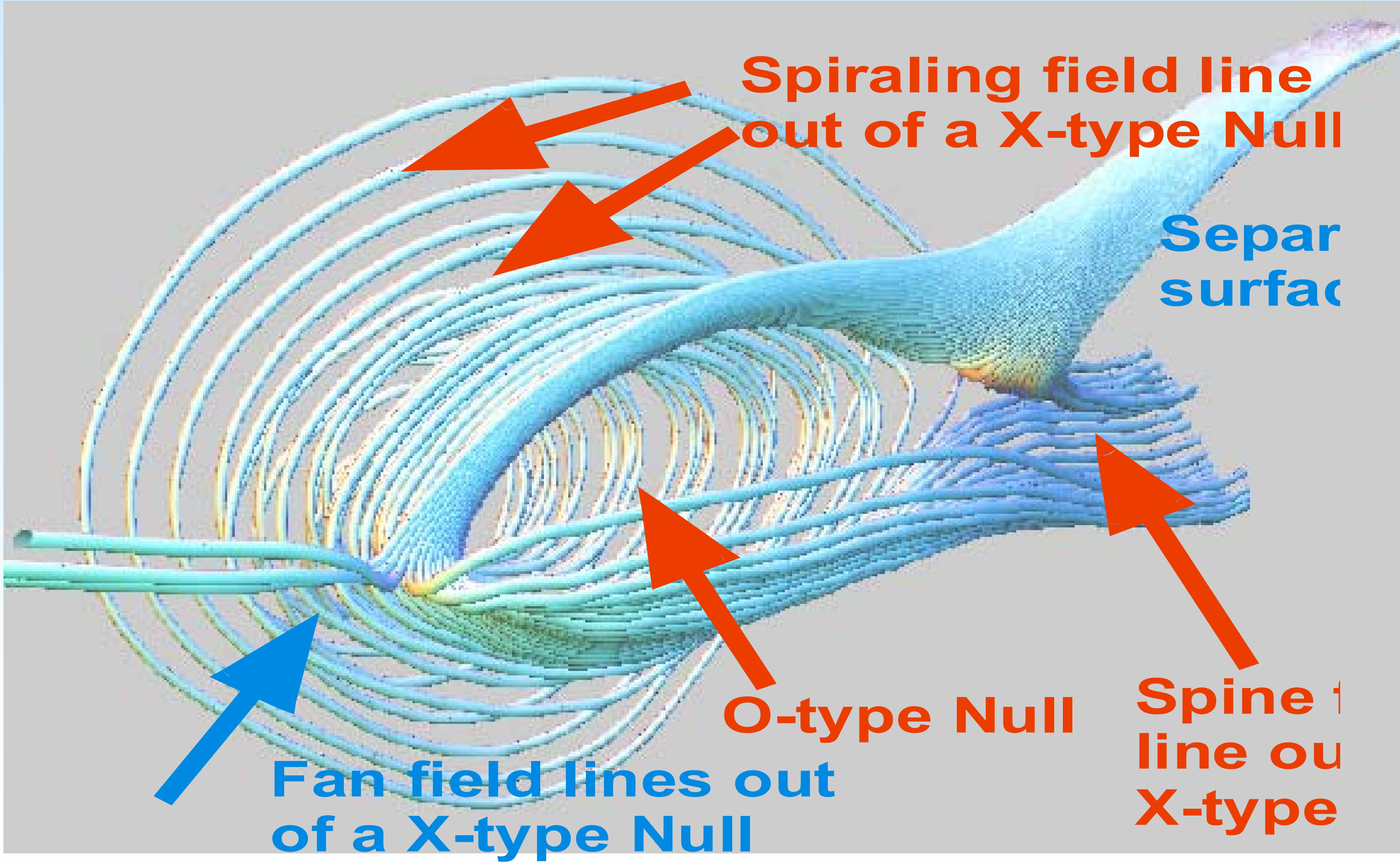
The collision rates are shown as solid (elec$\delta\rho\delta E_{\parallel}$ and $\delta j \times \delta B$ (magnetic fluctuations) lines by thick lines for the electron-contribution and thin lines for the Ions

3D current sheet instability

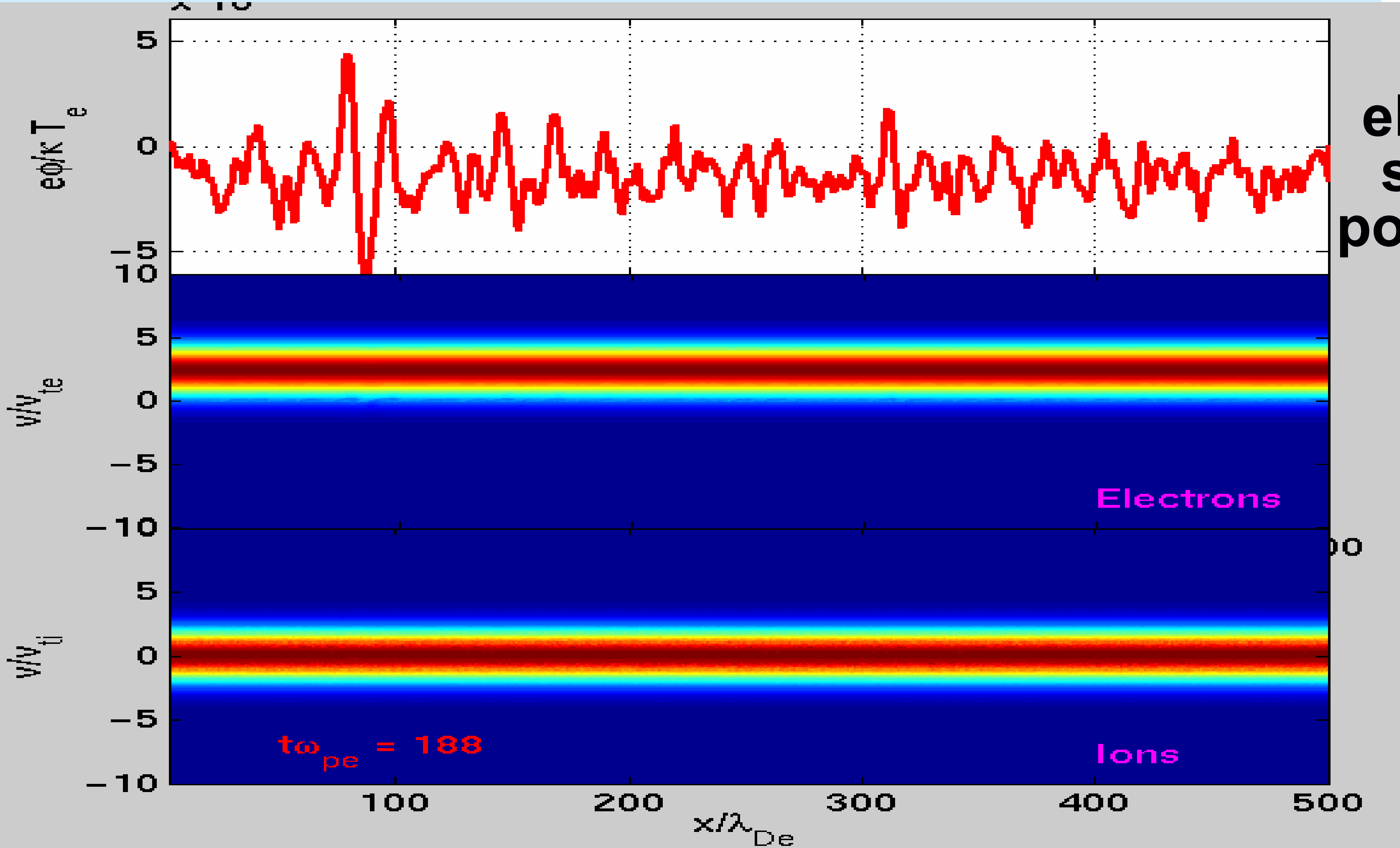


3D PIC-code simulation [Büchner & Kuska]

3D micro-reconnection



Low beta -> Quasi 1D solutions of the Vlasov equation

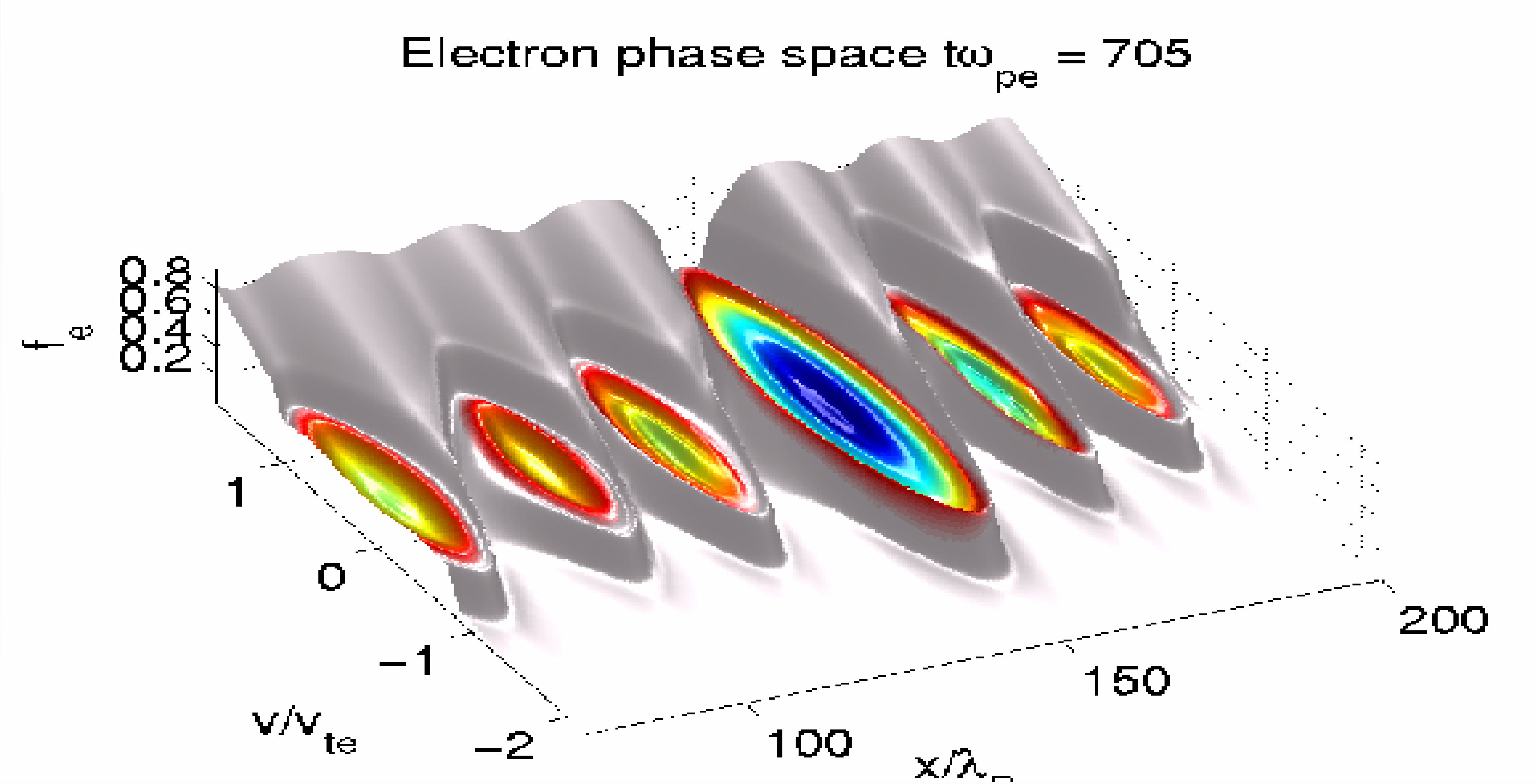


electro static potential

f_e

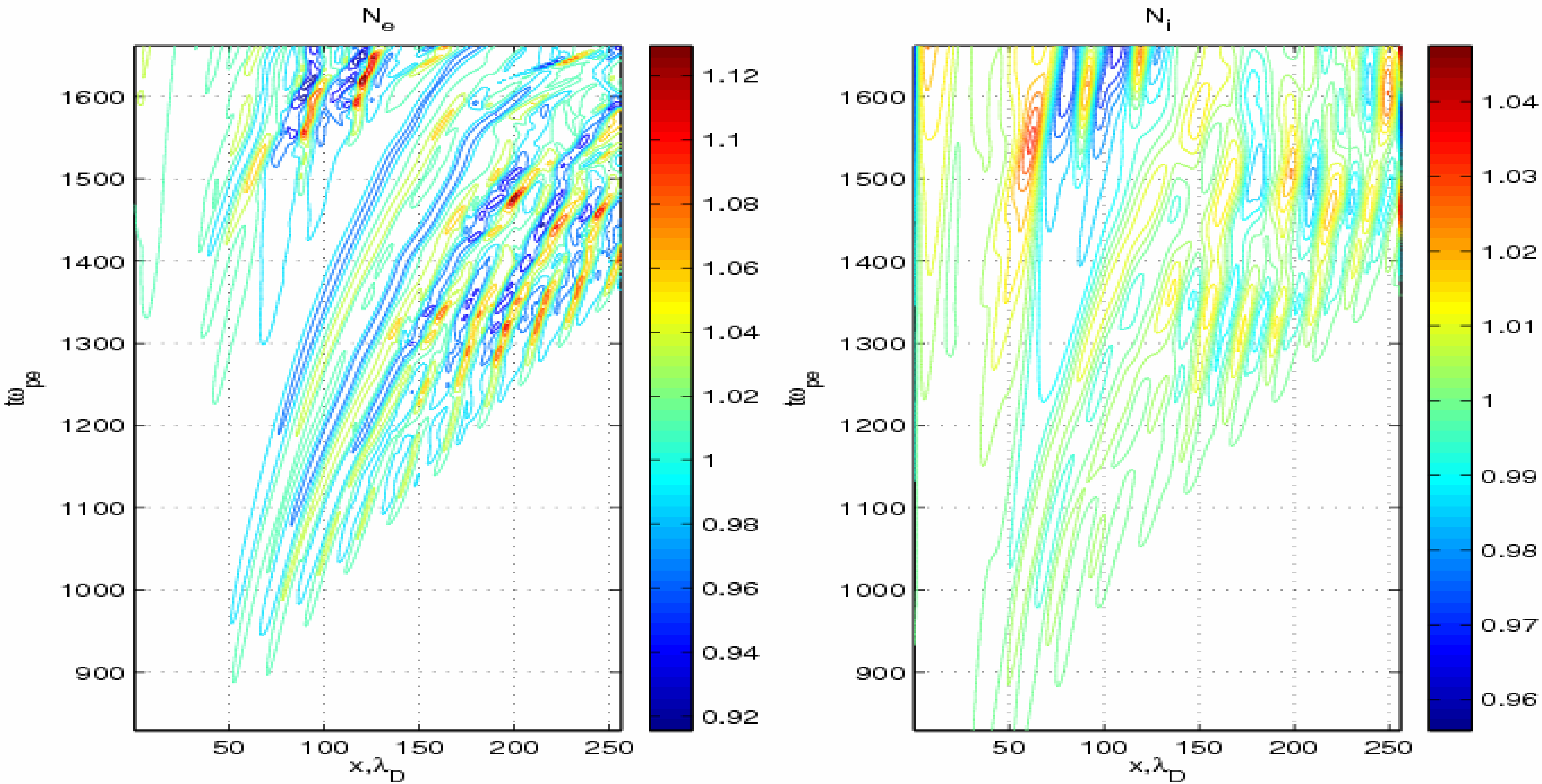
f_i

Electron phase space holes



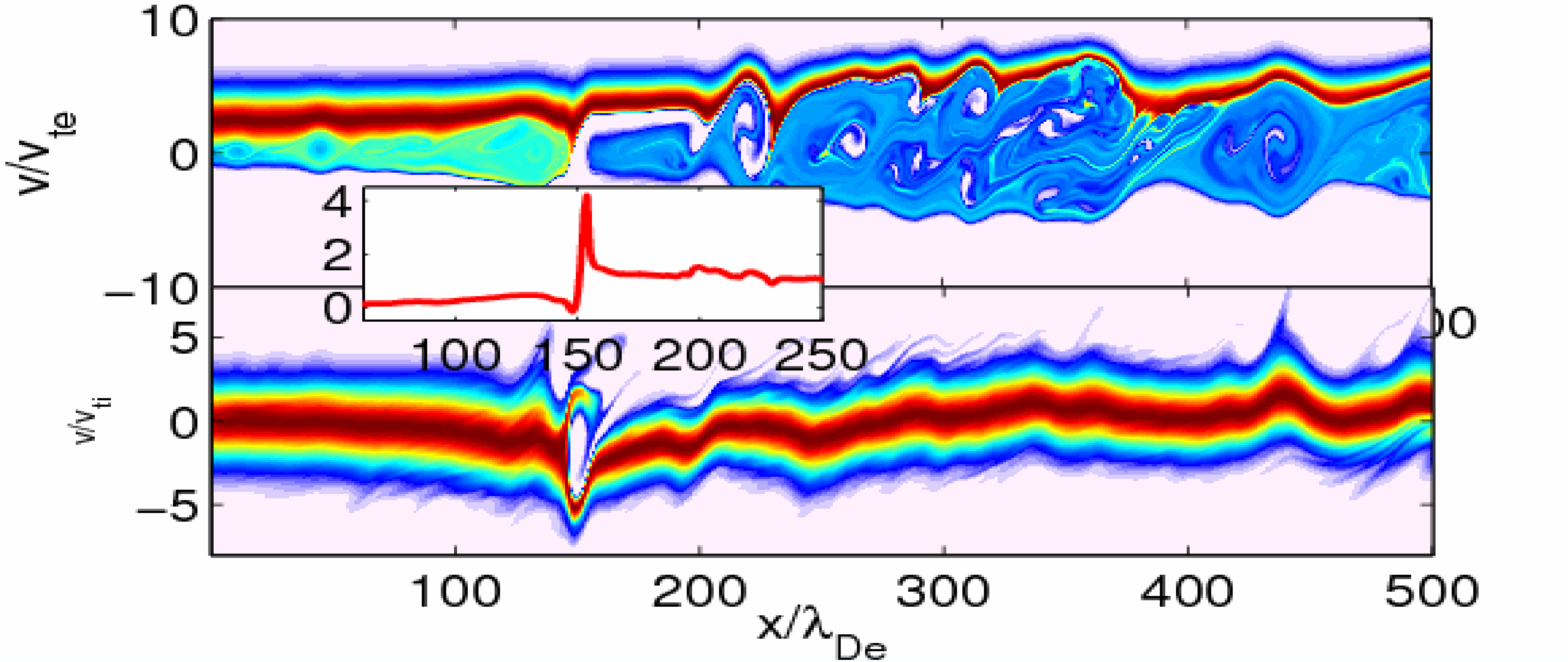
Electron phase space holes -> They grow and lead beyond the quasi-linearl (QL), weak turbulence theory level.

Later also ion density holes



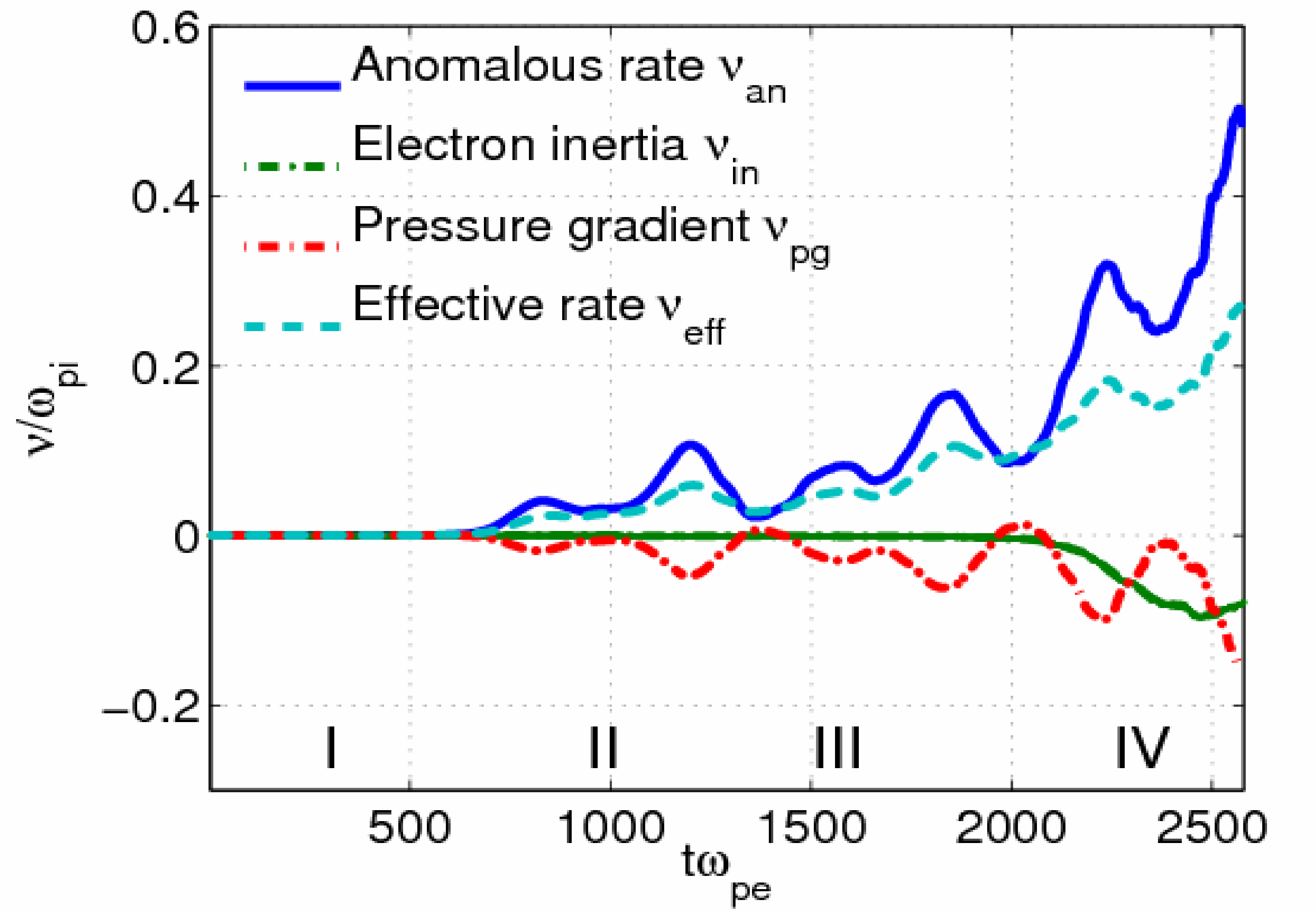
In case of open boundary conditions after electron density holes are formed (left plot) also ion holes are formed (right plot).

Finally – the ion holes merge into electrostatic double layers



Inset: electrostatic potential around the double layer. The ion holes merge into the double layer while the electron motion becomes highly turbulent behind the layer [from Büchner & Elkina, 2006].

Effective „collision rates“



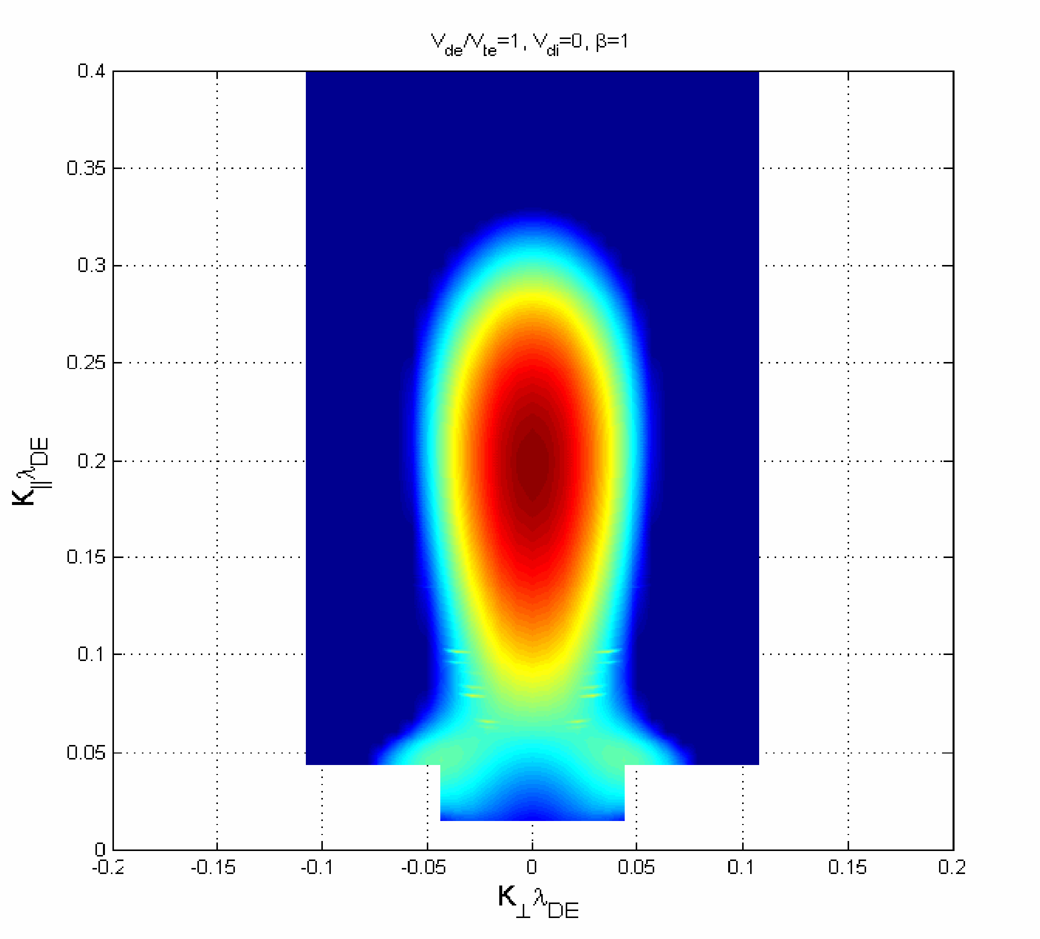
2D Vlasov & 1D fluid simulation

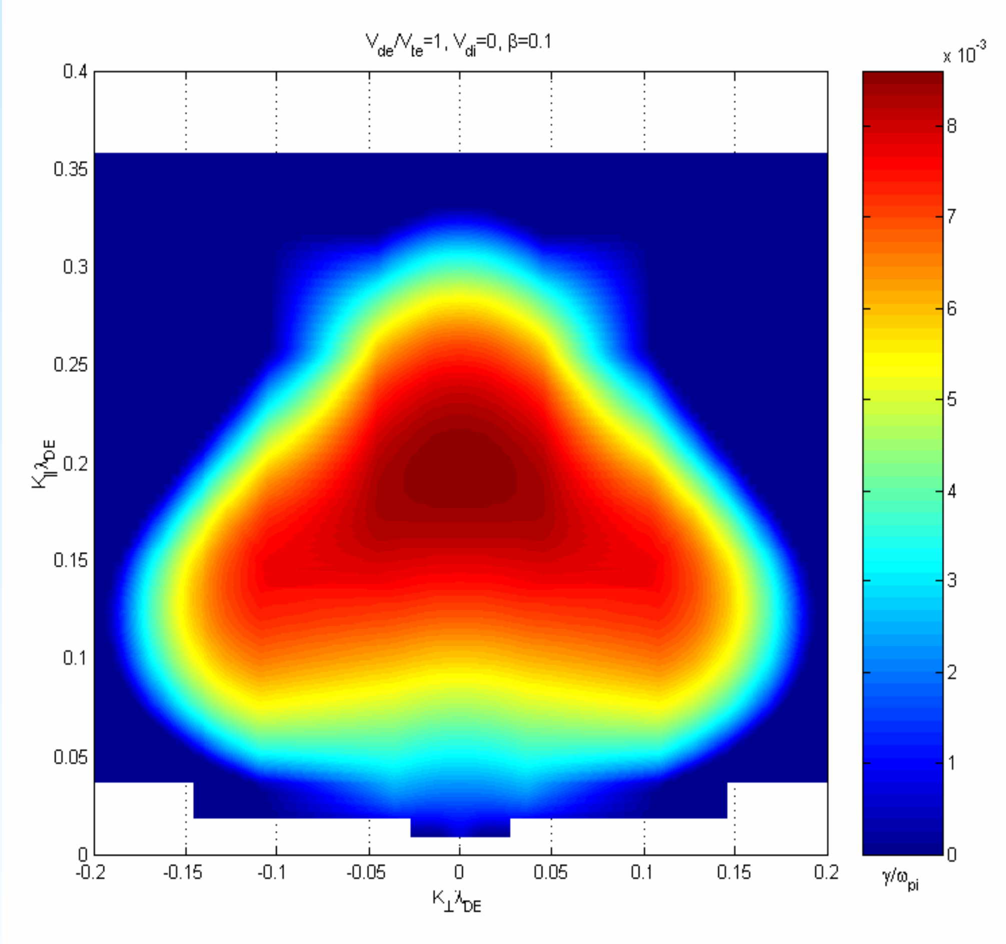
$$\frac{\partial f}{\partial t} + v_x \frac{\partial f}{\partial x} + v_y \frac{\partial f}{\partial y} + \frac{q_\alpha}{m_\alpha} \vec{F} \frac{\partial f_\alpha}{\partial \vec{v}} = 0$$

$$\frac{\partial n u_z}{\partial t} + \nabla (n_\alpha u_z u_z) = \frac{q_\alpha}{m_\alpha} \left[E_z + (u_x B_y - u_y B_x) \right]$$

- **Unsplit finite volume, conservative central scheme**
- **Velocity and real space grid (Debye length resolution) (32-128) x 128 x 128 x 128 x 128 x 128**
- **Mass ratios Mi/me = 25, 100, 1800**
- **on the Altix 4700 with its 9728 Montecito dual-core CPUs**
- **Performance 62.3 TFlop/s and 17 TBytes shared memory**

Transition to 2D, LH, kpar vs kperp



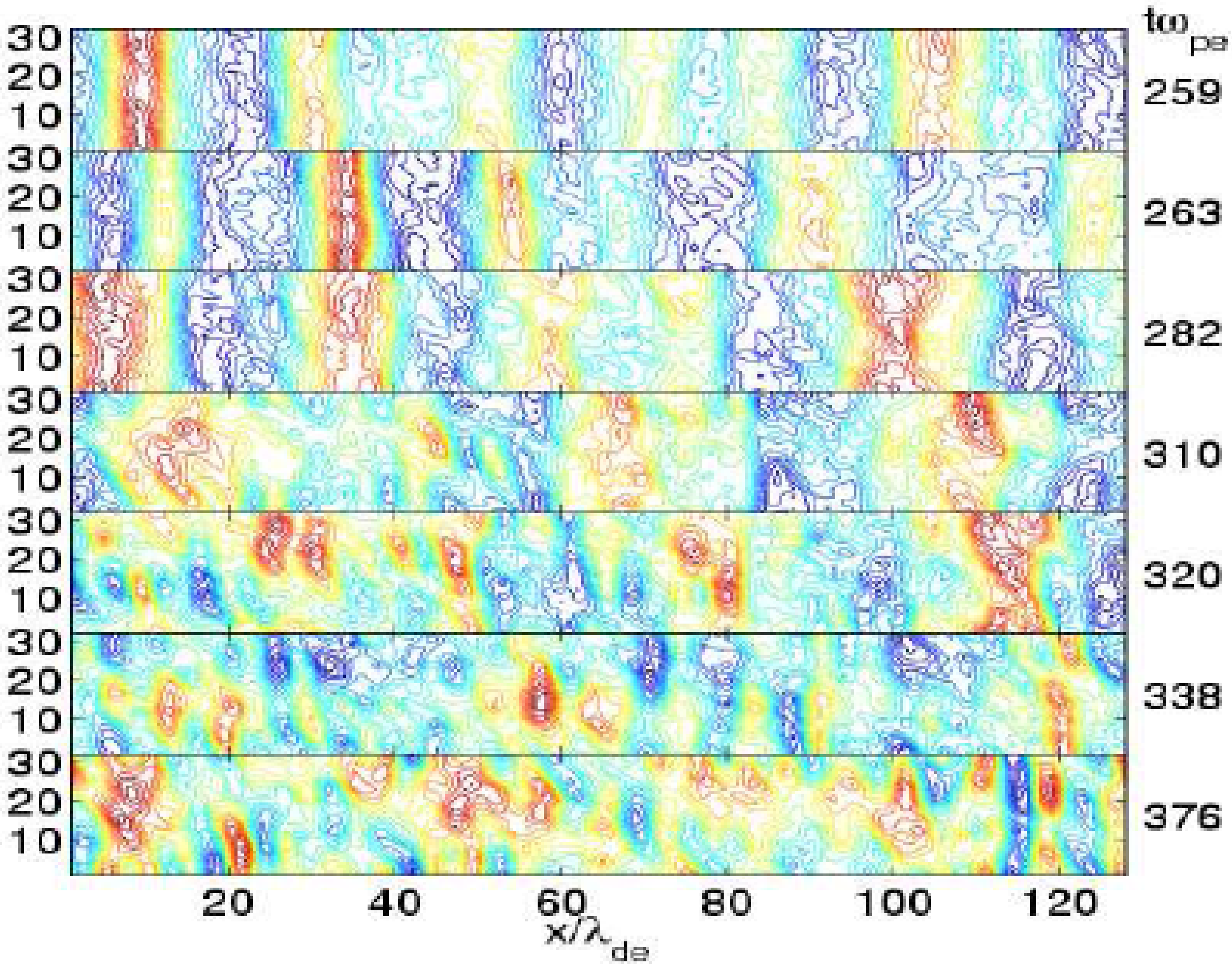


$\beta = 0.01$ $\beta = 0.1$

Linearily unstable modes $\gamma > 0$ (colors) in kpar vs. $k\perp$

Only for very small β the most unstable waves are B-field aligned, but in the corona often $\beta \sim 0.1 - 1$

Evolution -> LH waves take over



Time-evolution of the parallel electric wave-field Ex(x,y). First ion-acoustic field-aligned modes are excited. After t ω_pe ~ 300 oblique LH modes take over [Büchner et al. 2008] .

Balancing reconnection E-field at Sun

If one scales the Ohm‘s law by an „effective resisitivty“, i.e. „effective collision frequency“,

$$\boxed{\eta = \frac{\nu}{\epsilon_0 \omega_{pe}^2}}$$

then the orders of magnitude are

1.) in the (lower) chromosphere:
binary particle collisions dominate
[Spitzer, Härm & Braginski 1958-63]

$$\nu_{coll} \cong \frac{\omega_{pe}}{n\lambda_D^3}$$

2.) in the corona (collisionless effects, e.g. high frequency plasma turbulence , from Vlasov code simulations for coronal conditions, (e.g. Te~Ti):
[Büchner & Elkina 2006-2008]
- for low beta conditions -> 1D: IA double layers
- for higher beta plasma –> 2D: LH turbulence

$$\nu_c \approx \omega_{pi}/2\pi$$

But: large velocities *j/ne* > v_te needed -> thin sheets

$$\nu_c \approx \omega_{pi}$$

- for null-points (largest beta) -> LHD, kink/sausage