Collisionless reconnection and its interscale coupling to plasma turbulence

Jörg Büchner

collaborators: Patricio Munoz, Fabien Widmer

Max-Planck-Institute for Solar System Research Göttingen, Germany and

Collaborative Research Center „Astrophysical Flow Instabilities and Turbulence" Göttingen University

thanks also to: F. Jenko and D. Told (UCLA)

N. Yokoi and M. Hoshino (University Tokyo)

Outline

Large scale consequences of magnetic reconnection for the dynamics of the Solar corona, but:

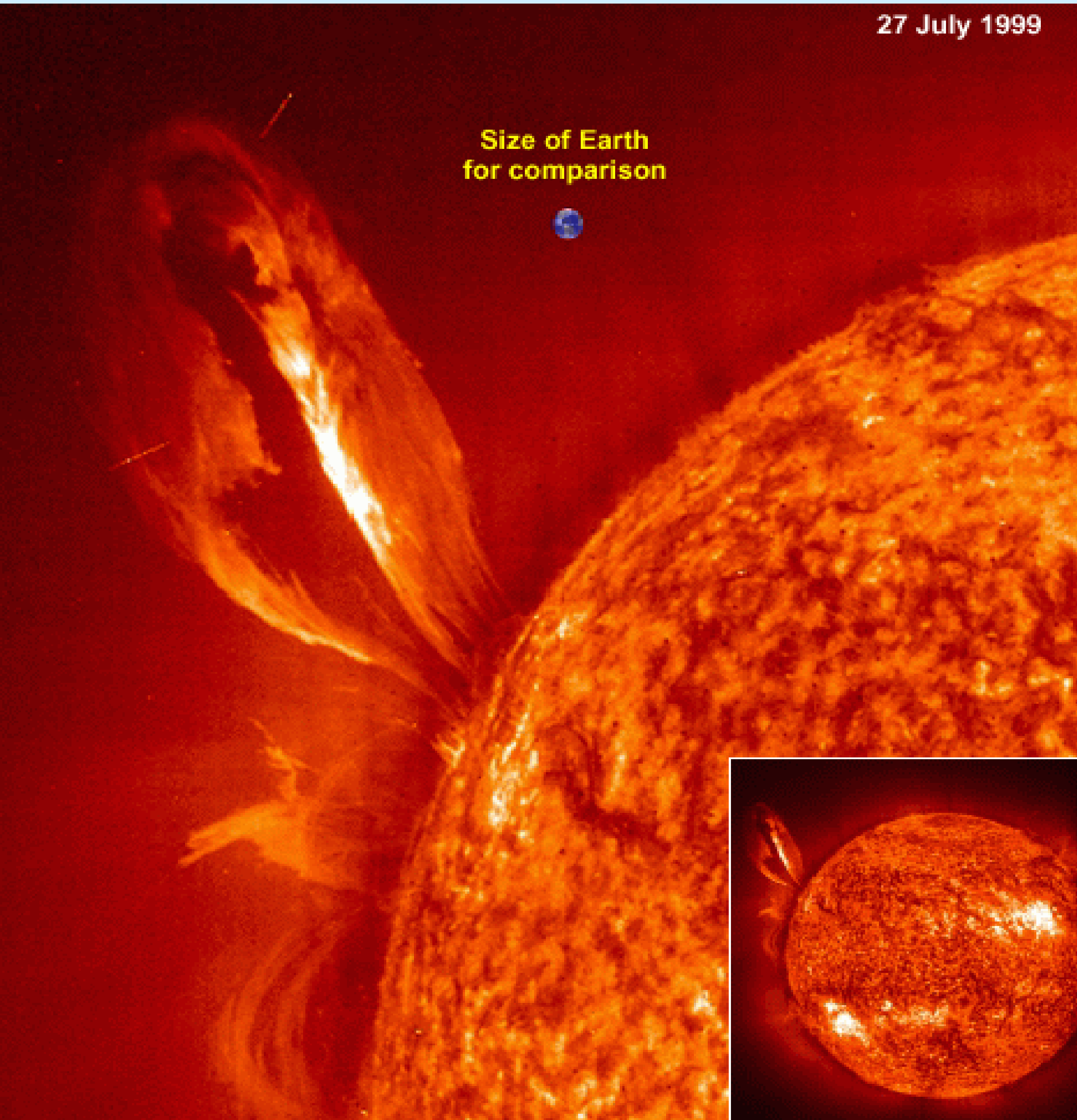
- **the coronal plasma is collisionless while**
- **the plasma beta differs a lot, mostly < 1**

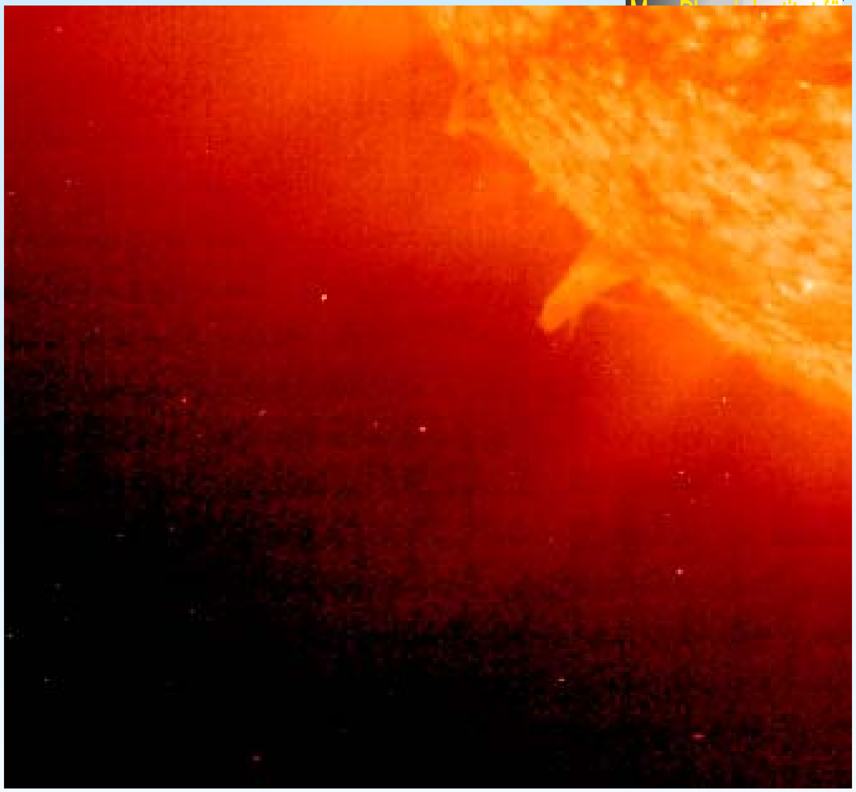
-> Dissipation, balancing of electric fields et c.: kinetic processes in dependence on beta (PIC code results).

-> SGS models might bridge the gap between the scales, e.g. a Reynolds averaged turbulence approach

-> But: differences to the real kinetic turbulence, dependence on plasma beta (gyrokinetic and PIC code simulation results)

Observed large scale phenomena





Solar coronal plasma, prominences (confined cold plasmas) rest until they suddenly erupt causing flares and CMEs

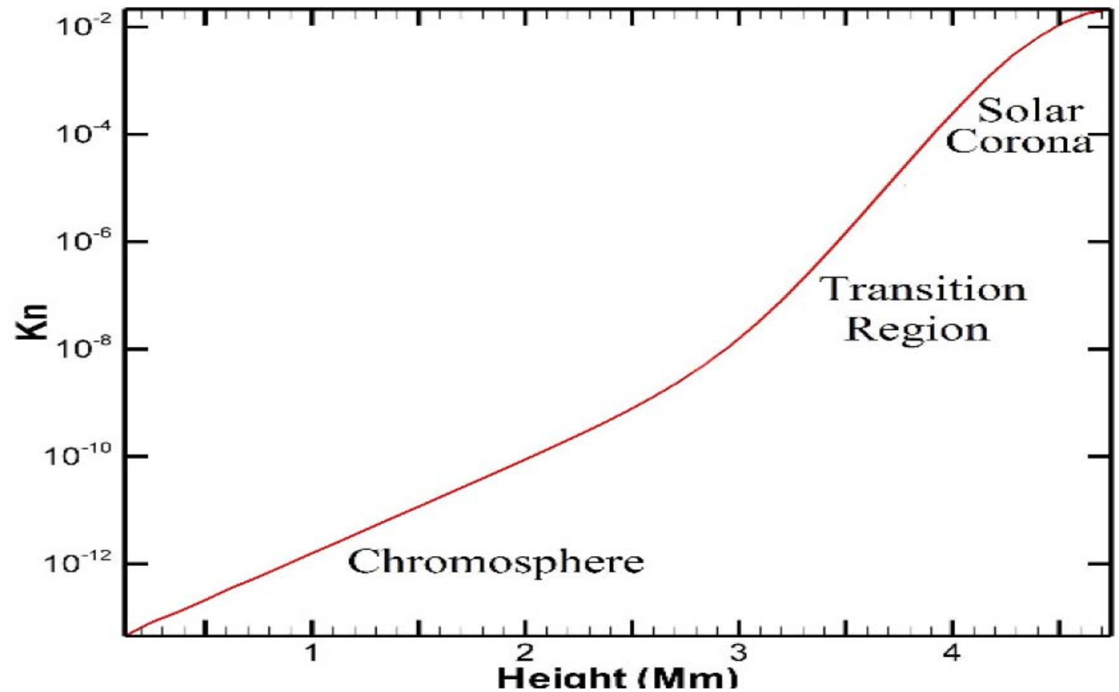
Collisionless coronal plasma

Debye length/sphere:

$\lambda_{de} \ll L, \qquad \Lambda = n\lambda_{de}^3 \gg 1$

Knudsen number:

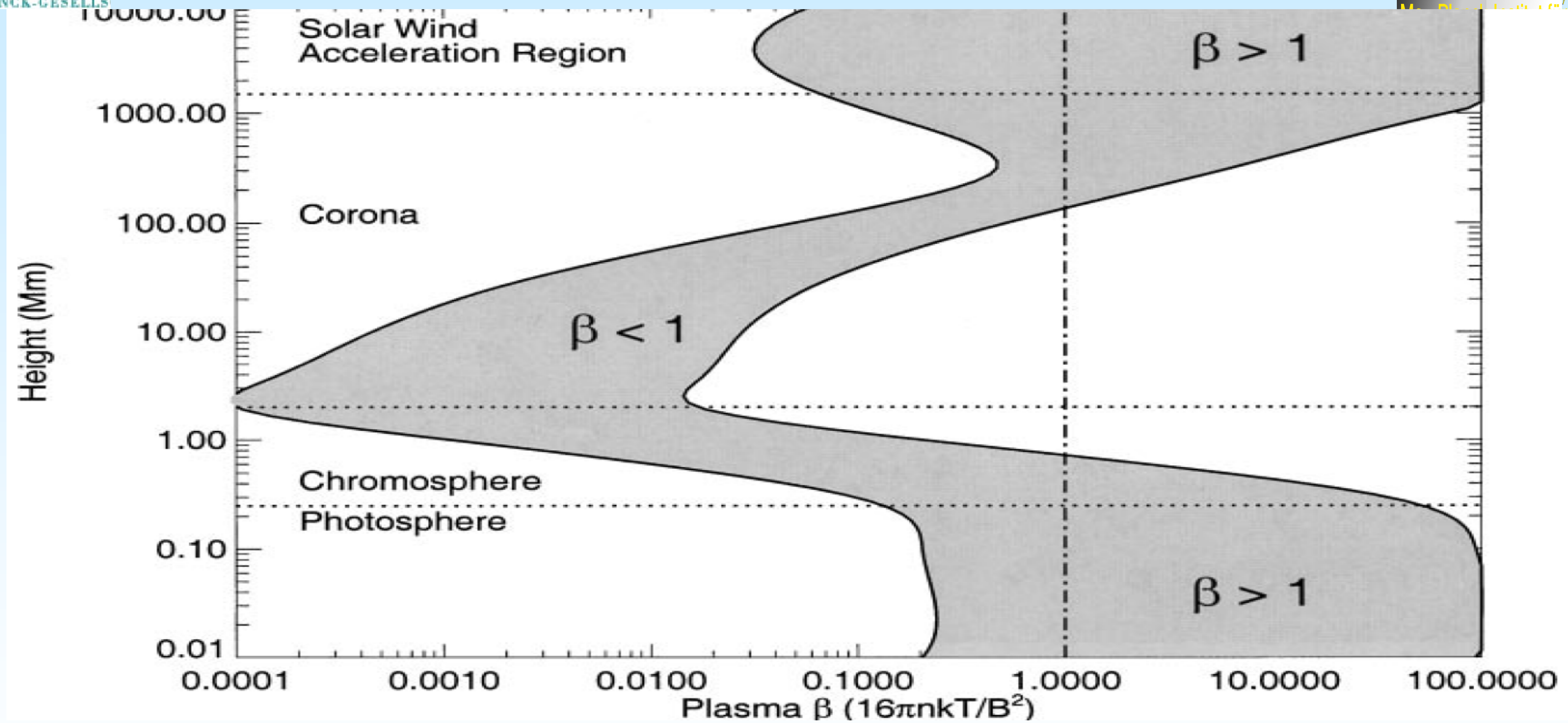
$K_N = \lambda_{\mathrm{mfp}}/L \gtrsim 0.1$



The plot to the right is obtained by means of GOEMHD3 solar eruption-MHD simulations, with $\lambda_{mfp} \propto T_e^2/(n_e \ln\Lambda)$ and $L = (T_e/\nabla T_e)$. Approx.: $\ln\Lambda \propto T^{3/2}/n_e^{1/2}$. From S. Silva.

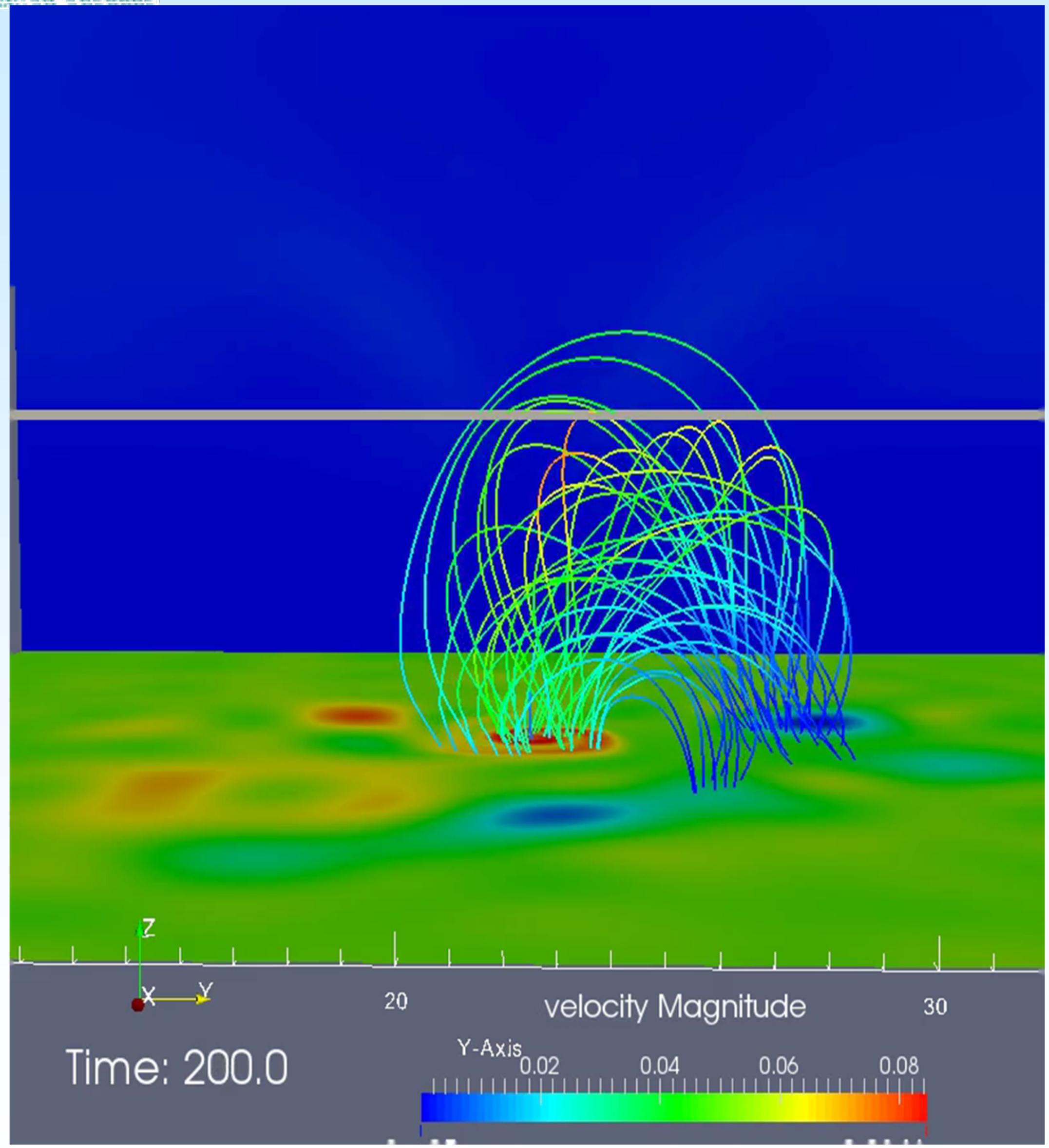
-> the solar coronal plasma is by all means collisionless

Coronal plasma -β



β =16 πn k_BT / B^2 varies from << 1 (strong force free B-field), to, locally,β ~ 1 or even larger near magnetic Nulls (infinity) !

Usually: anomalous resistivity



Solar eruption simulation, e.g. by the MHD code GOEMHD3
[Skala & Büchner, 2015]

$$\frac{\partial(\rho \boldsymbol{u})}{\partial t} + \nabla \cdot \left[\rho \boldsymbol{u}\boldsymbol{u} + \frac{1}{2}(p + B^2)\boldsymbol{I} - \boldsymbol{B}\boldsymbol{B}\right] = -\nu\rho(\boldsymbol{u} - \boldsymbol{u}_0) + \chi\nabla^2\rho\boldsymbol{u}$$

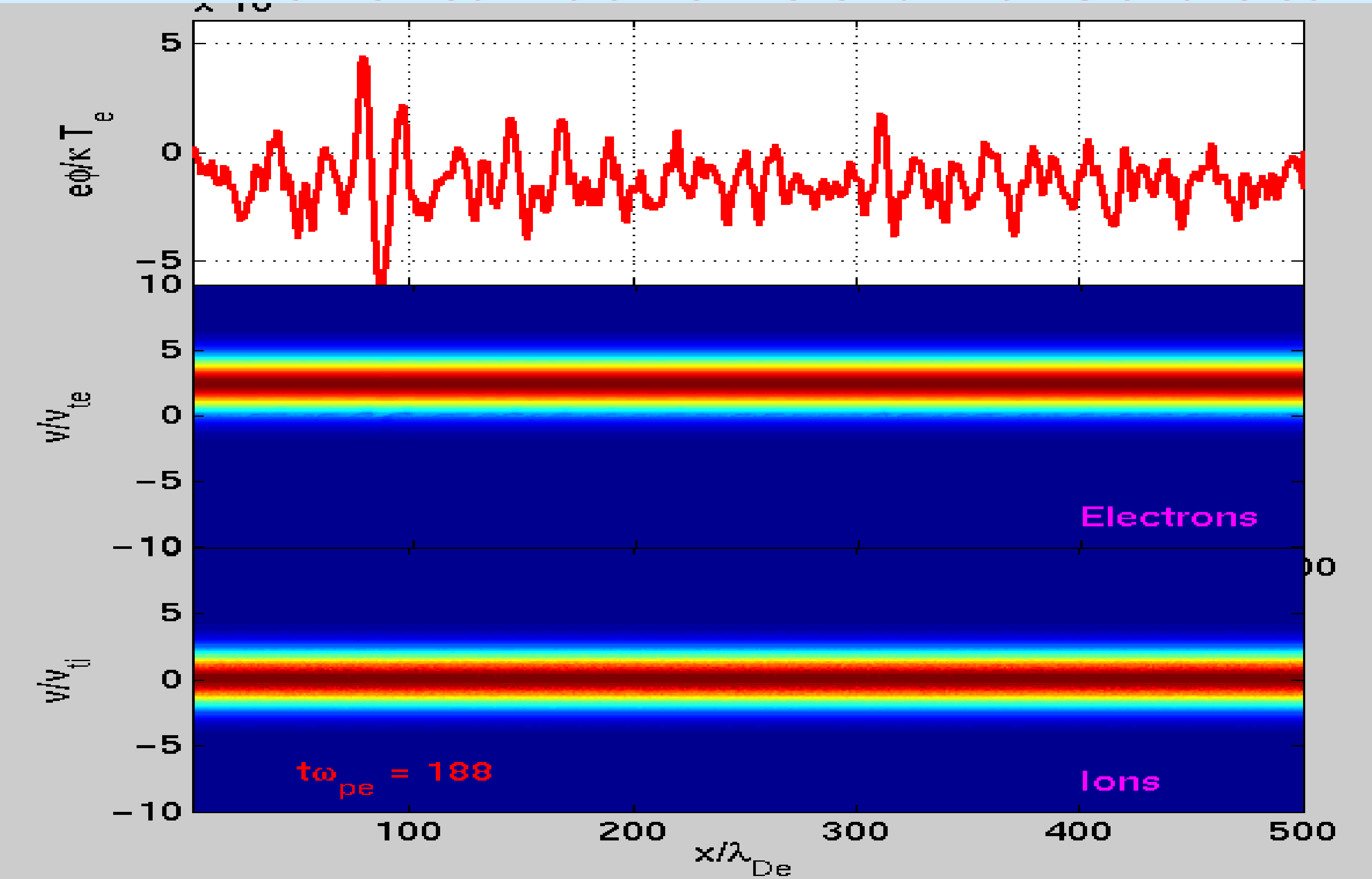
$$\frac{\partial \boldsymbol{B}}{\partial t} = \nabla \times (\boldsymbol{u} \times \boldsymbol{B}) - (\nabla\eta) \times \boldsymbol{j} + \eta\nabla^2\boldsymbol{B}$$

$$\frac{\partial h}{\partial t} + \nabla \cdot h\boldsymbol{u} = \frac{(\gamma - 1)}{\gamma h^{\gamma-1}}\eta \boldsymbol{j}^2 + \chi\nabla^2 h,$$

$$\eta = \eta_0 + \begin{cases} 0, & if |j| < j_{crit} \\ \eta_0(\frac{|j|}{j_{crit}} - 1)^2 & if |j| \geq j_{crit} \end{cases}$$

$$\eta = \eta_0 + \begin{cases} 0, & \text{if } |u_{ccv}| < u_{crit} \\ \eta_{eff}\left(\frac{|u_{ccv}|}{u_{crit}} - 1\right), & \text{if } |u_{ccv}| \geq u_{crit} \end{cases}$$

Indeed: for small beta fast field aligned electron currents cause micro-turbulence and structures



electric potential -> double layer

Vlasov code simulation: [Büchner & Elkina, 2006]

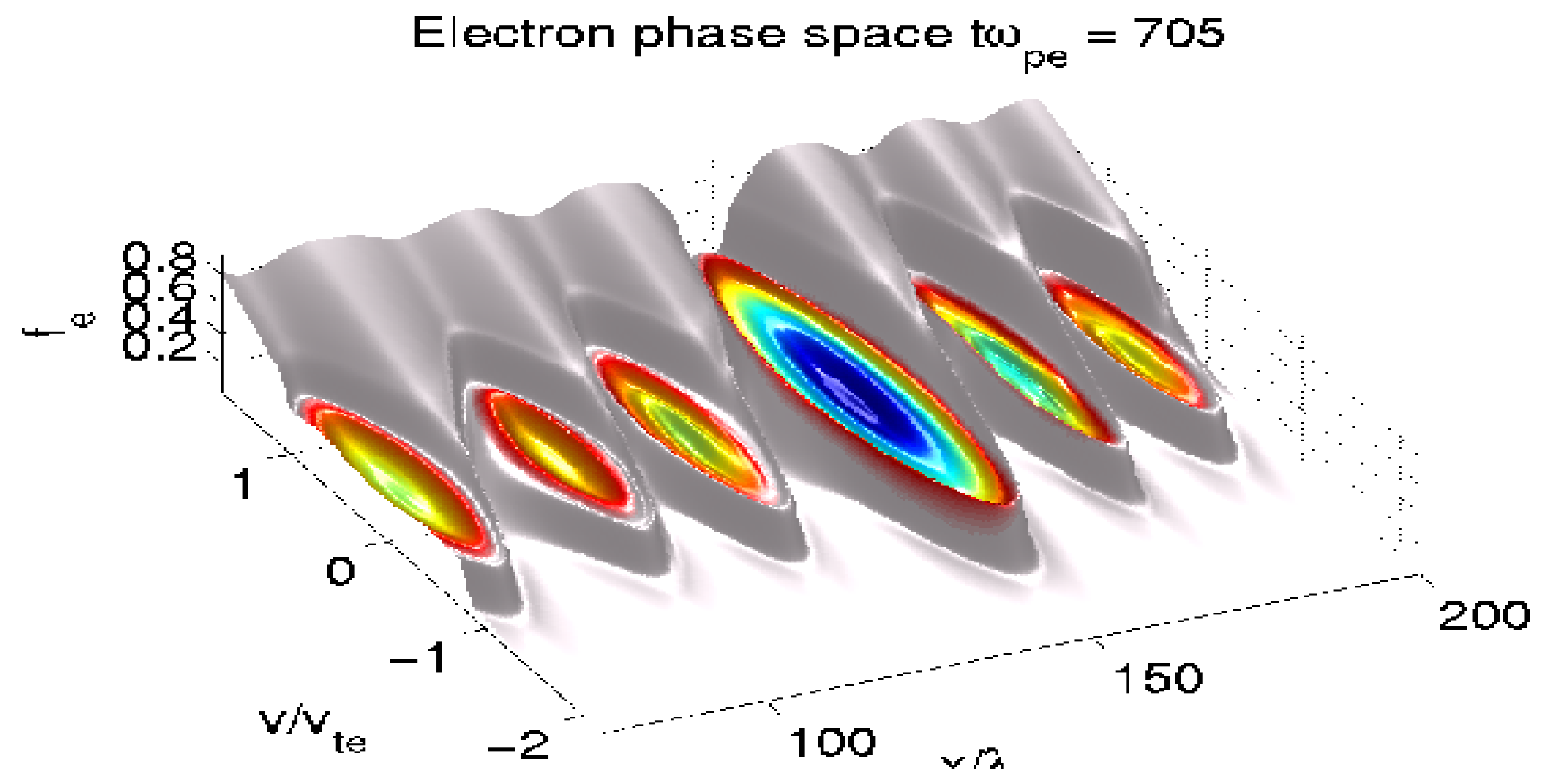
Observation: by Cluster, [Wang et al. 2010, 2014]

<- fe (electron current)

<- fi

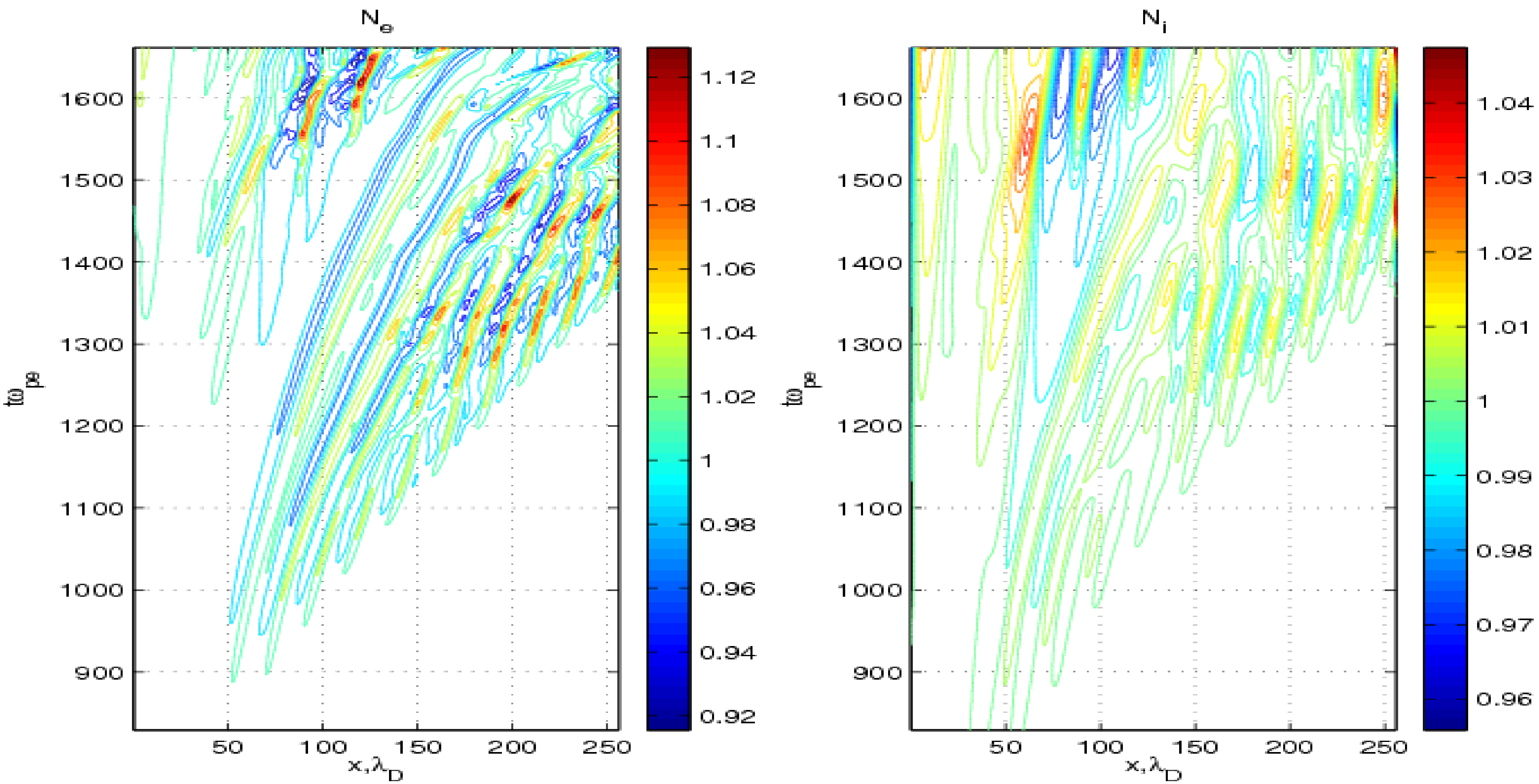
How to link this to the observed macro-scale phenomena?

Behind: electron phase space holes



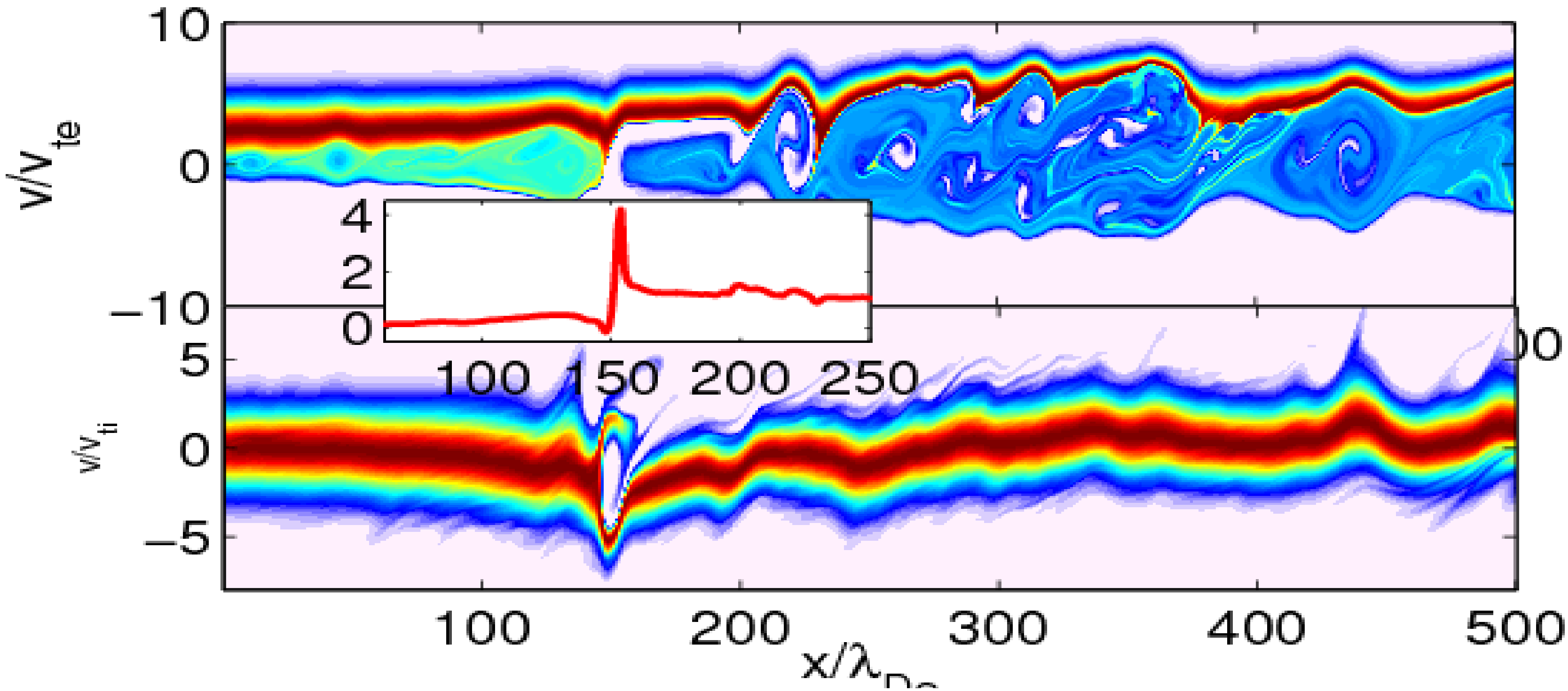
Electron phase space holes -> They grow and finally balance electric fields beyond the quasi-linear weak turbulence level.

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).

Double layer and turbulence -> effective (macroscopic) resistivity



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].

Quantification by „collision rates“

Using the definition:
the „anomalous“ re

$$E_{||} = \eta_{an} j_{||} = \eta_{an} ne \left(v_i - v_e\right)$$

$$\eta_{an} = \frac{E_{||}}{j_{||}} = \frac{1}{ne(v_i - v_e)} \left(-\frac{m_e}{ne}\frac{d(nv_e)}{dt} - \frac{1}{ne}\frac{dp_e}{dx_{||}} + \frac{1}{ne} f_{eff} \right)$$

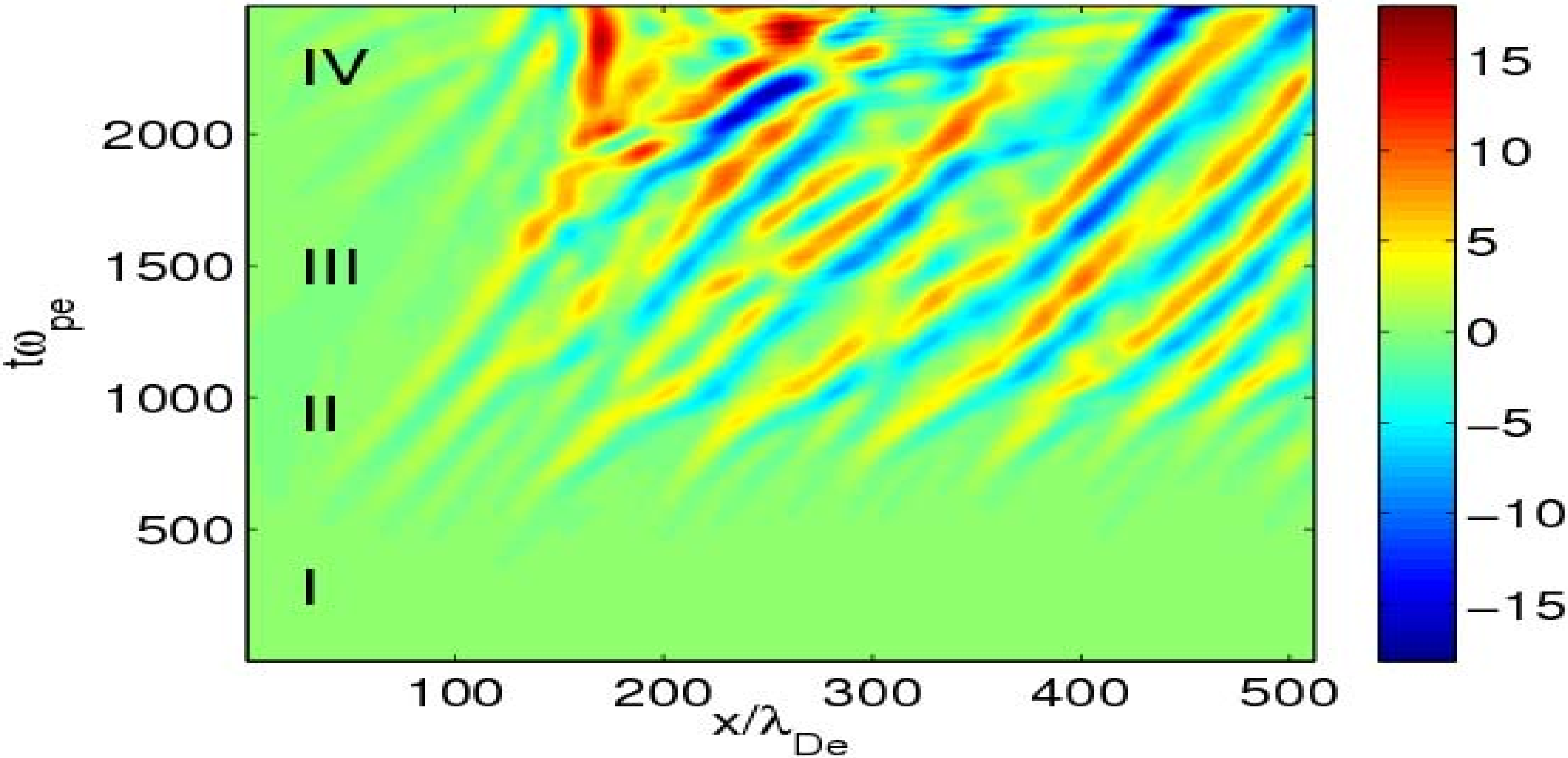
with .....
where

$$\eta_{an} = \frac{m_e}{ne^2}\nu_{an} = \left(\epsilon_0 \omega_{pe}^2\right)^{-1} \nu_{an}$$

$$\nu_{an} = -\nu_{in} - \nu_{pg} + \nu_{eff}$$

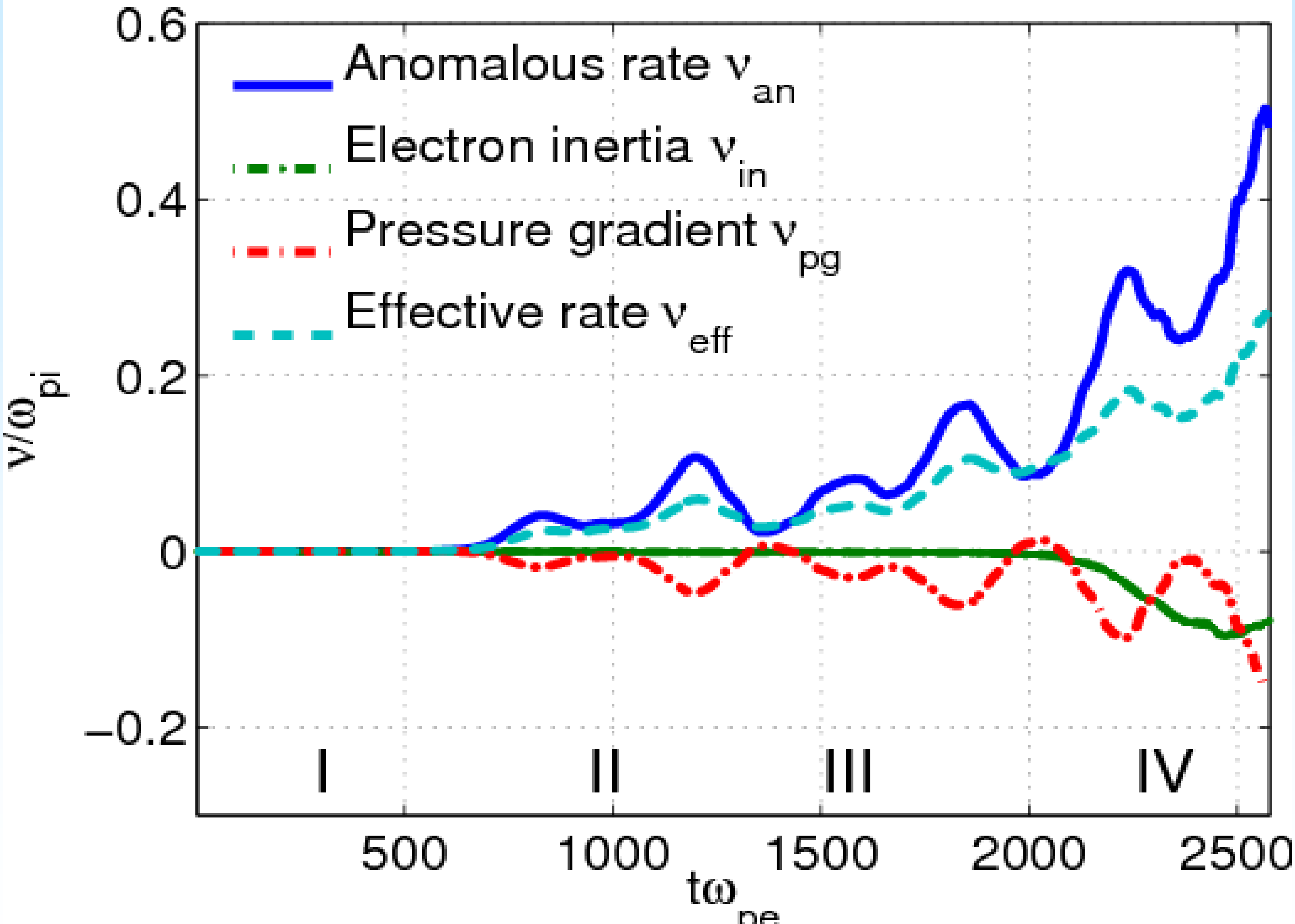
$$\nu_{in} = \frac{1}{n(v_i - v_e)}\frac{d(nv_e)}{dt} \qquad \nu_{pg} = \frac{1}{nm_e(v_i - v_e)}\frac{dp_e}{dx_{||}} \qquad \nu_{eff} = \frac{f_{eff}}{ne(v_i - v_e)}$$

Local „anomalous“ collision rates



„Anomalous“ collisions at phase space holes / DLs while locally particles can also gain enery -> the average matters!

Average „collision rates“

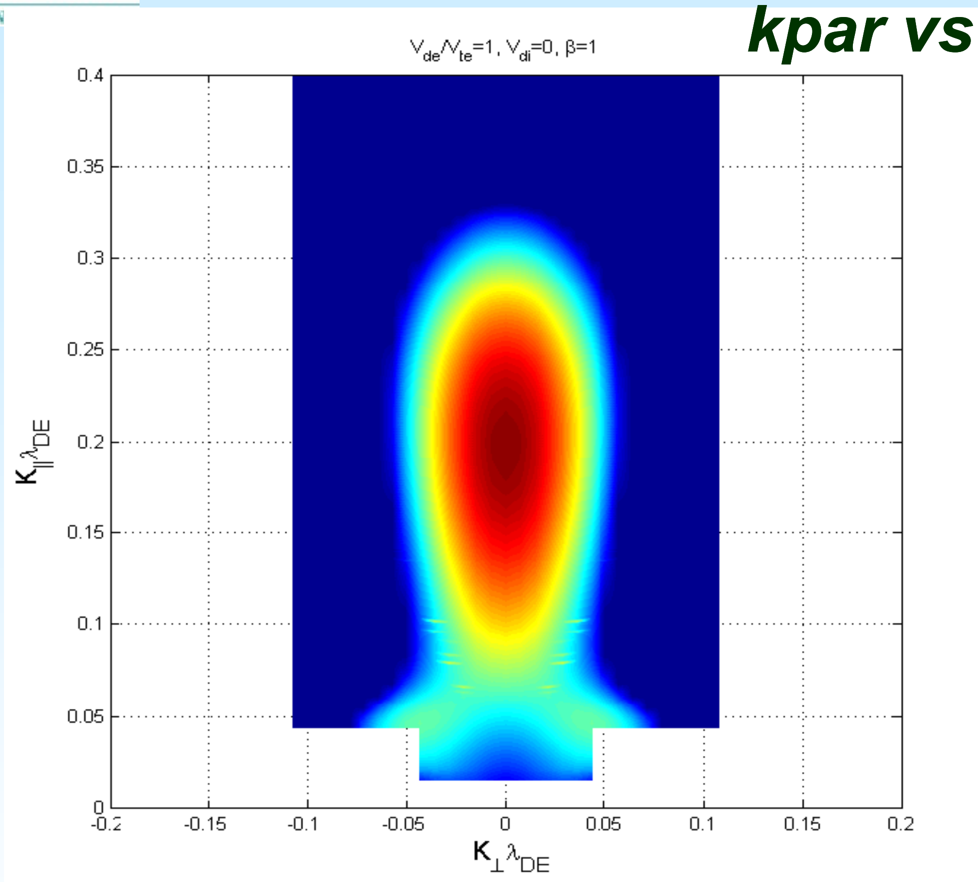


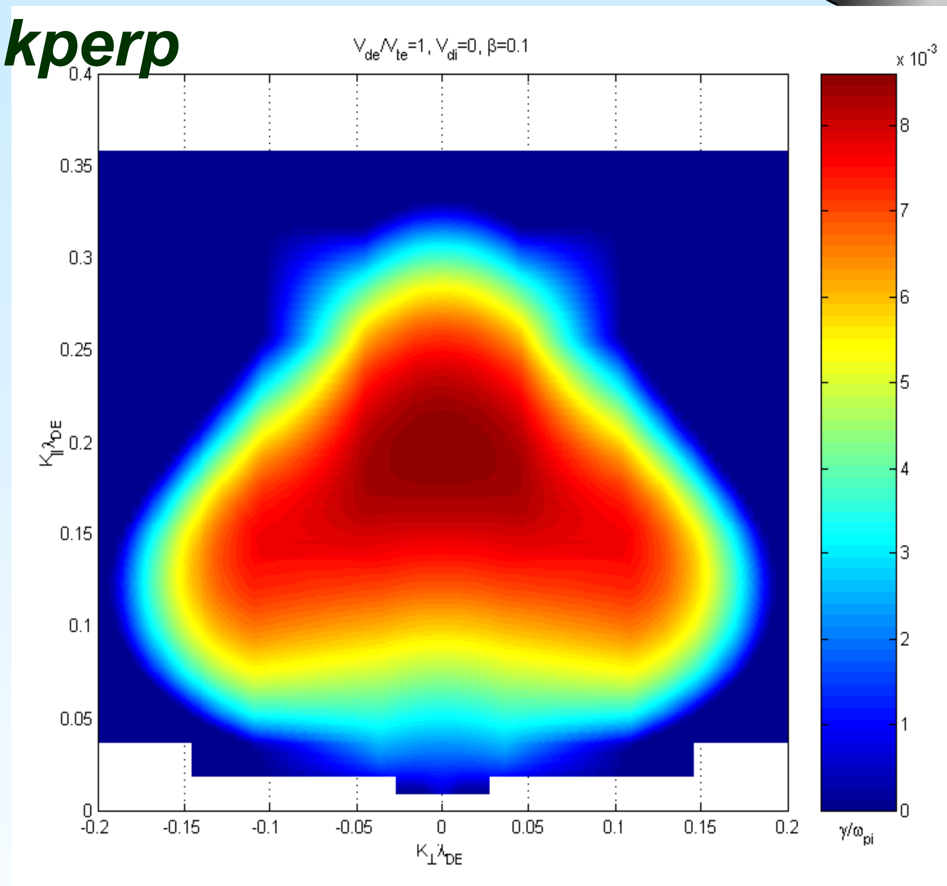
[Büchner and Elkina, 2006]:

The Rm, which corresponds to the threshold Uccv > Vte for the instability l = c / ω_pi = 20 m, V= 20 km/s and Nu=0.5 ω_pi is Rm ~ 1!

Larger beta: LH(perp) instabilities

kpar vs kperp



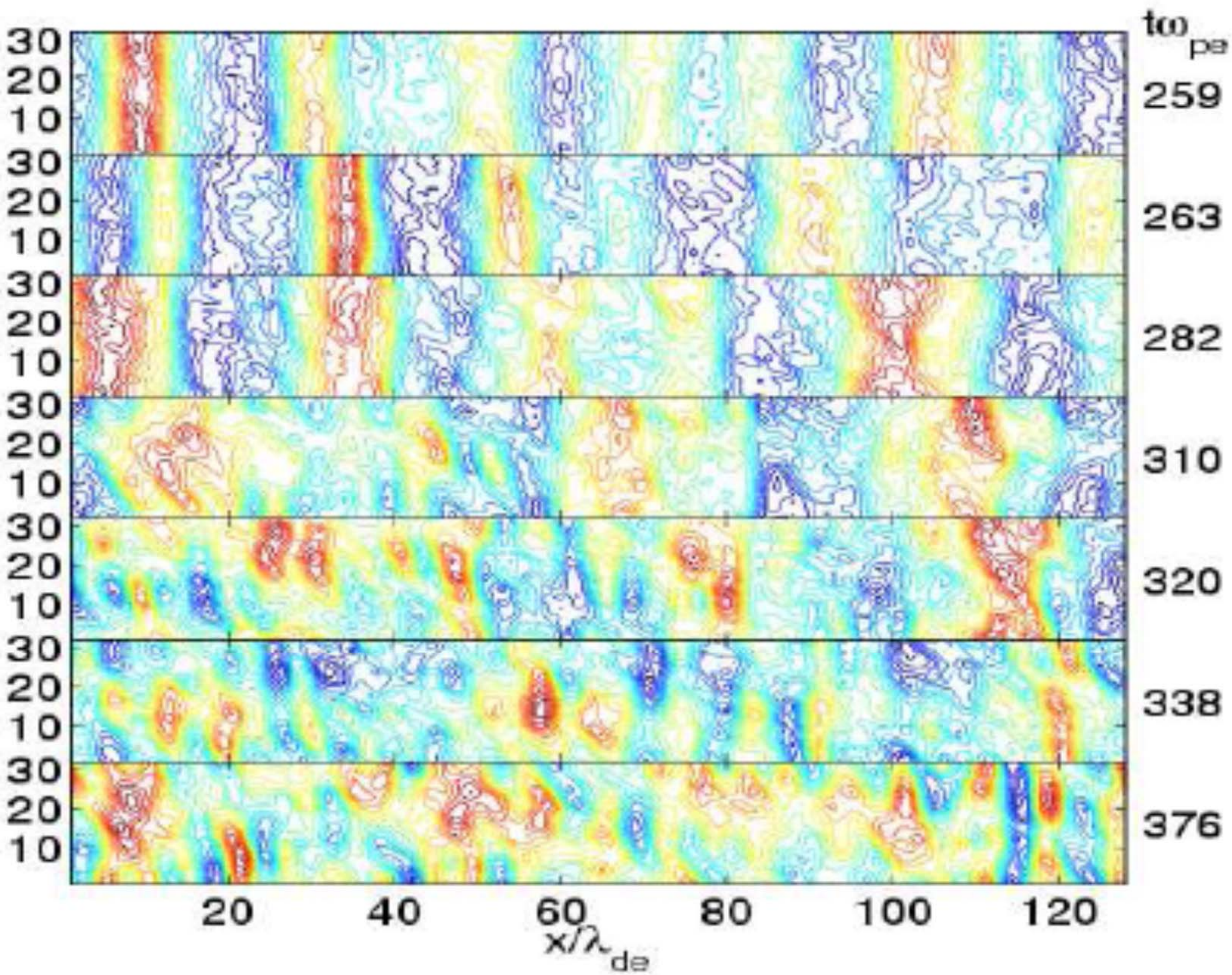


β = 0.01 | **β = 0.1**

Linearily unstable modes γ > 0 (colors) in kpar vs. k⊥

For small β the most unstable waves are B-field aligned, in the solar coronae often β ~ 0.1 - 1 -> oblique waves

Larger beta: 2D LH turbulence



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 & Elkina, 2010]

Dissipation in collisionless CS

Ensemble averaging <fo> < E> … -> slowly varying parts + fluctuations:

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

-> Modified Vlasov equation for the slowly varying quantities with a non-linear term in the r.h.s.:

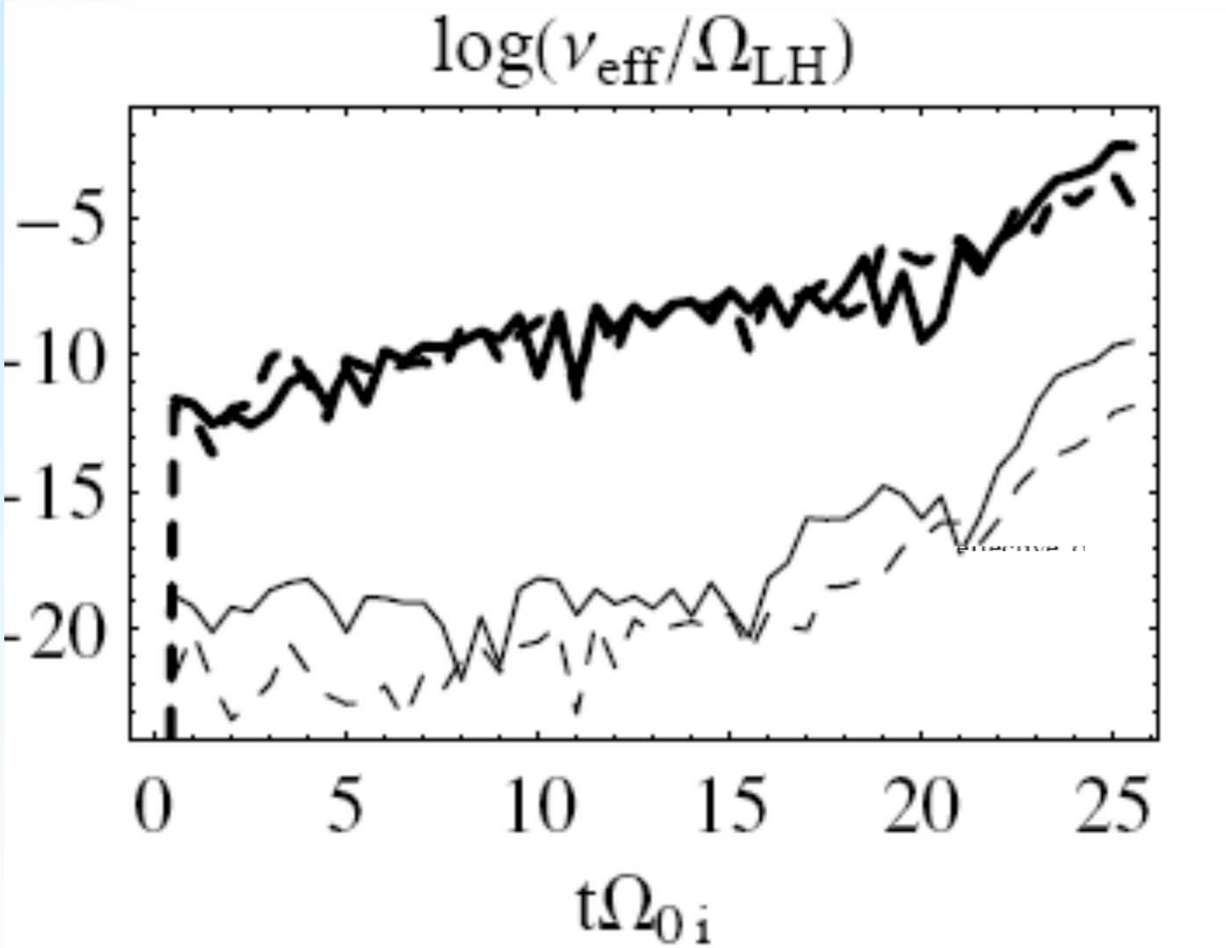
$$\frac{\partial f_{0e}}{\partial t} + \vec{v} \cdot \frac{\partial f_{0e}}{\partial \vec{r}} + \frac{e}{m_e} \vec{E} \cdot \frac{\partial f_{0e}}{\partial \vec{v}} = \boxed{-\frac{e}{m_e} \left\langle \left(\delta \vec{E} + \vec{v} \times \delta \vec{B} \right) \cdot \frac{\partial \delta f_e}{\partial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

r.h.s.: correlation of fluctuations of e/m fields, plasma and current densities

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

These non-linear terms can be calculated quasi-linearily for small amplitudes but, in general, only by kinetic simulations

2D Current sheet „collision rates“



Tested for the collisionless magnetospheric plasma where these rates exceed those of the 1D turbulence by a factor of about 6 [Silin, Büchner and Vaivads, 2005; Panov, Büchner et al., 2008]

Effective „collision rates“: Solid (electric) $\delta\rho\delta E_{\shortparallel}$ and dashed (magnetic fluctuations) $\delta j \times \delta B$ lines;
(Upper - thicker lines: electrons; Lower - thinner lines: ions

Result for solar conditions

Magnetic diffusivity expressed via an effective „collision frequency“:

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

Neglible: binary particle collision [Spitzer 56, Härm–Braginski 63]

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

There is no indication for the estimate of [Bunemann 1958] in the solar corona

$$\cancel{\nu_{eff} \simeq \omega_{pe}/2\pi}$$

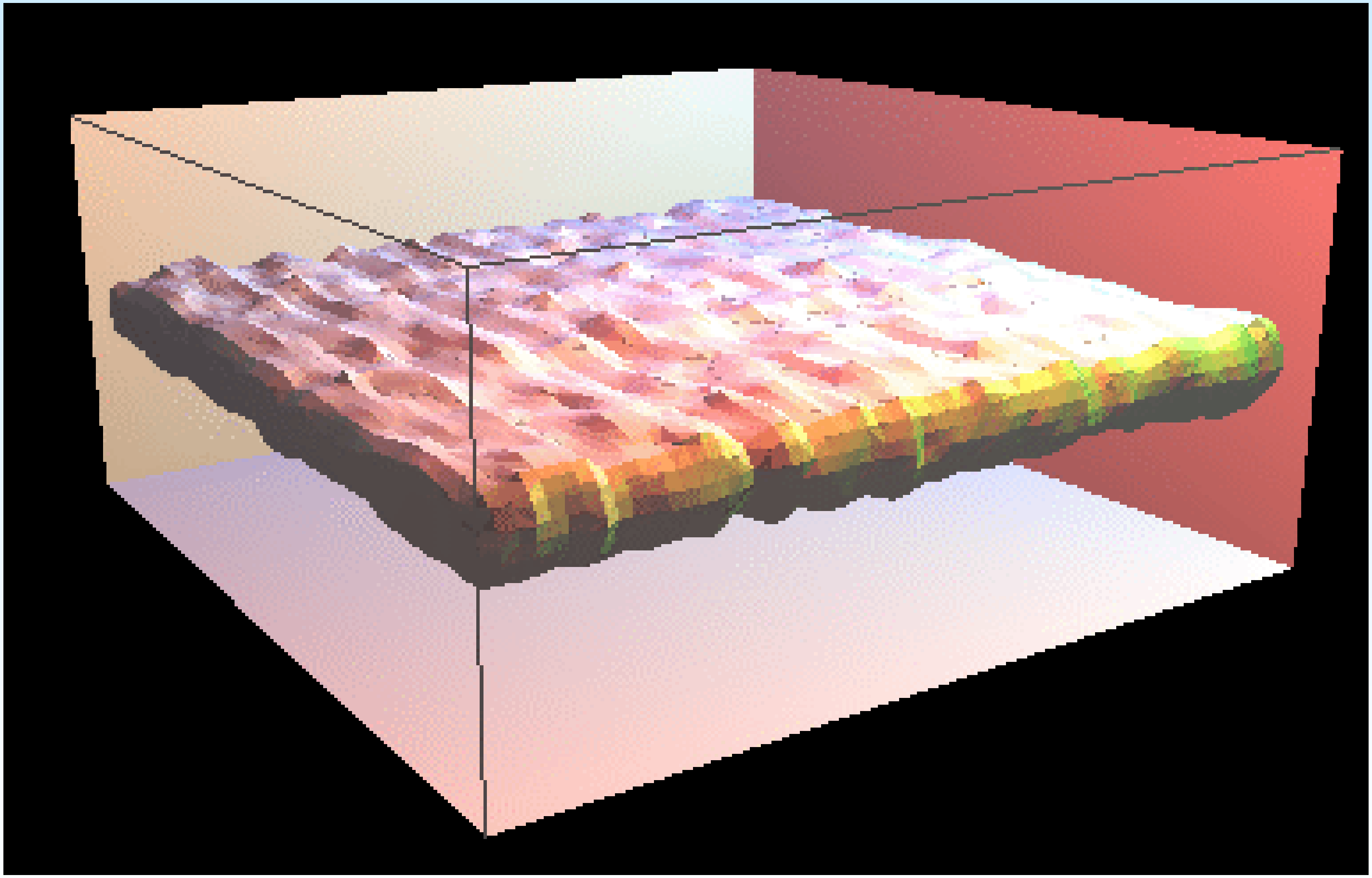
PIC and Vlasov code simulations revealed for the solar corona: [Büchner, Kuska, Panov, Silin, Elkina, 2005-08]

→ 1D small beta: IA / double layers $\quad \nu_c \approx \omega_{pi}/2\pi$

→ 2D higher beta – LH turbulence $\quad \nu_c \sim \omega_{LH}$

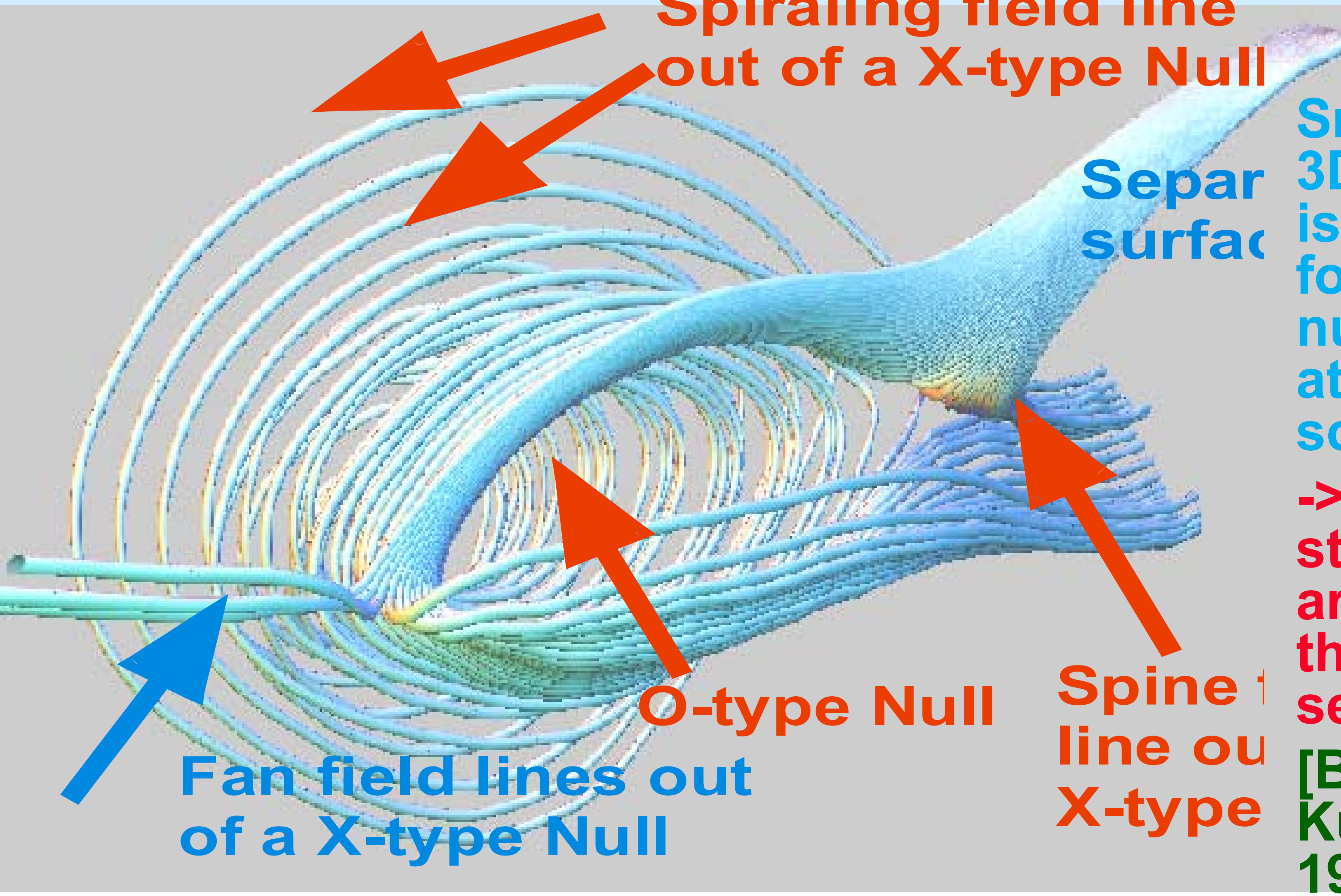
- But: what about larger beta cases (Nulls?)

Larger beta-> 3D instabilities



3D PIC-code simulation result: A sausage mode instability causes 3D small scale reconnection with Nulls [Büchner&Kuska, 1999]

Beta > 1: 3D kinetic reconnection, Nulls

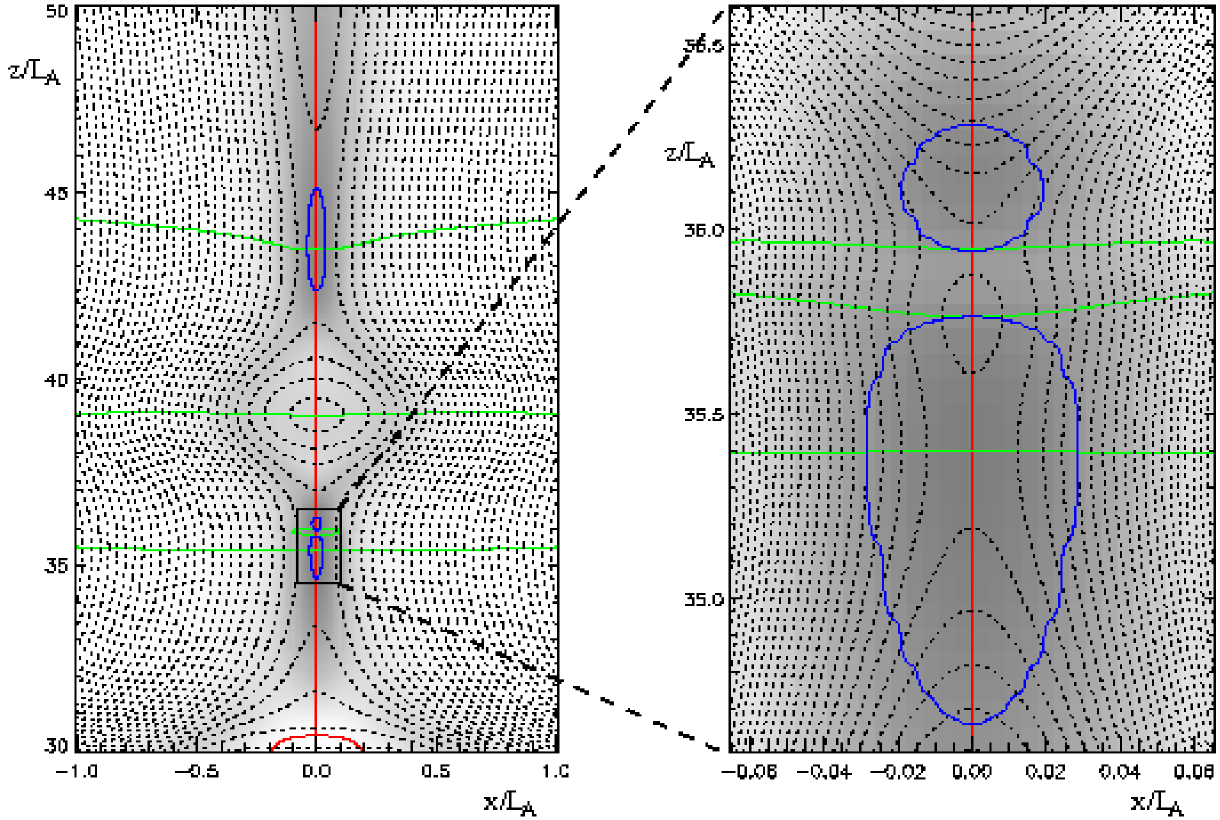


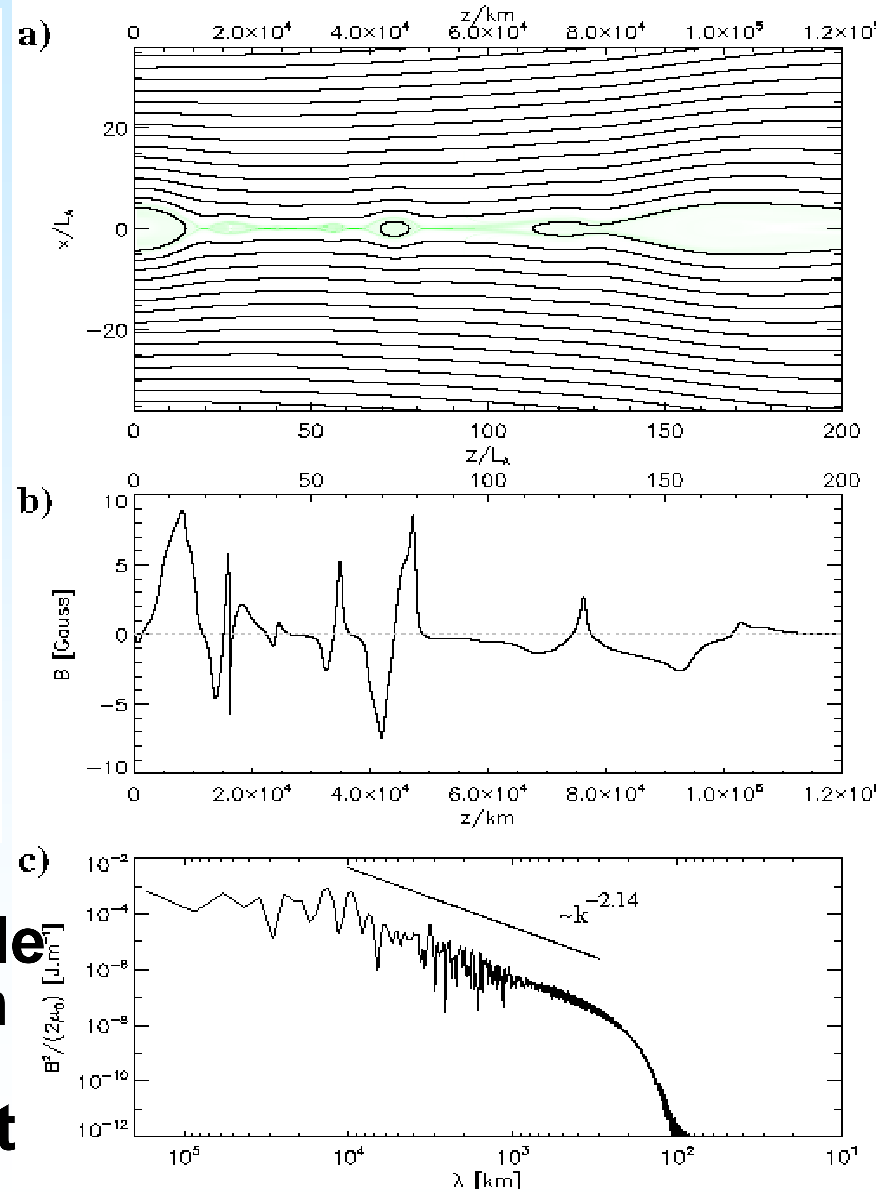
Small scale 3D B-field islands form with nulls form at plasma scales,

-> macro-structures arise from the micro-seeds.

[Büchner& Kuska, 1999]

Linking scales by MHD-AMR





By adaptive mesh refinement MHD simulations the MHD turbulence cascade can be followed down to the dissipation scale. Spectral index of the island size distribution in the inertial range is abo1t 2.14 from [Barta, Büchner, Skala, 2012].

Model: Reynolds-averaged SGS terms for MHD turbulence

$$\mathbf{E}_{\mathrm{M}} = -\beta\mathbf{J} + \gamma\boldsymbol{\Omega} + \alpha\mathbf{B}$$

Reynolds averaging
Mean field approach,
[Yokoi et al, 2010]

where

$$\beta = \frac{5}{7}\nu_{\mathrm{K}} = C_\beta \tau K,$$

$$\gamma = \frac{5}{7}\nu_{\mathrm{M}} = C_\gamma \tau W,$$

$$\alpha = C_\alpha \tau H,$$

with the turbulent energy

$$K (\equiv \langle \mathbf{u}'^2 + \mathbf{b}'^2 \rangle / 2)$$

the turbulent cross-helicity and

$$W (\equiv \langle \mathbf{u}' \cdot \mathbf{b}' \rangle)$$

the turbulent residual helicity

$$H (\equiv \langle -\mathbf{u}' \cdot \boldsymbol{\omega}' + \mathbf{b}' \cdot \mathbf{j}' \rangle)$$

For details: See the talk by N. Yokoi later today

MHD: SGS-turbulence model in 2D

$$\frac{\partial \rho}{\partial t} = -\boldsymbol{\nabla}\cdot(\rho \boldsymbol{U}) + \chi \nabla^2 \rho$$

$$\frac{\partial \rho \boldsymbol{U}}{\partial t} = -\nabla \cdot \left[\rho \boldsymbol{U} \otimes \boldsymbol{U} + \frac{1}{2}(p + B^2)\boldsymbol{I} - \boldsymbol{B} \otimes \boldsymbol{B}\right] + \chi \nabla^2 (\rho \boldsymbol{U})$$

$$\frac{\partial \boldsymbol{B}}{\partial t} = \nabla \times (\boldsymbol{U} \times \boldsymbol{B}) - (\nabla(\eta + \beta)) \times \boldsymbol{J} + (\eta + \beta)\nabla^2 \boldsymbol{B}$$
$$+\nabla \times (\gamma \sqrt{\rho}\Omega)$$

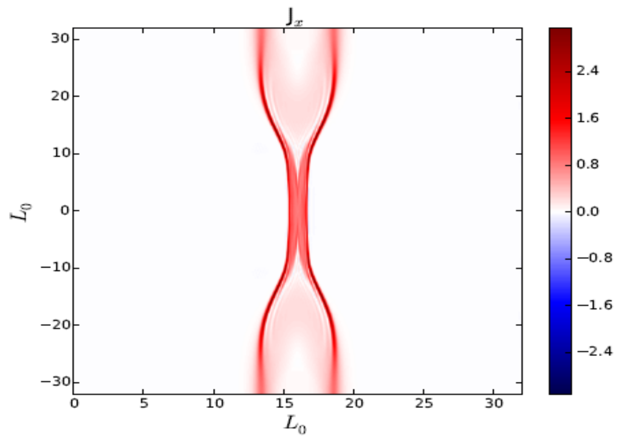
$$\frac{\partial h}{\partial t} = -\nabla \cdot (h\boldsymbol{U}) + \frac{\gamma - 1}{\gamma h^{\gamma-1}}(\eta \boldsymbol{J}^2 - \frac{\rho K}{\tau_t}) + \chi \nabla^2 h$$

$$\frac{\partial K}{\partial t} = -\boldsymbol{U} \cdot \nabla K + C_\beta \tau_t K \frac{\boldsymbol{J}^2}{\rho} - C_\gamma \tau_t W \frac{\boldsymbol{\Omega} \cdot \boldsymbol{J}}{\sqrt{\rho}} + \frac{\boldsymbol{B}}{\rho} \cdot \nabla W - \frac{K}{\tau_t}$$

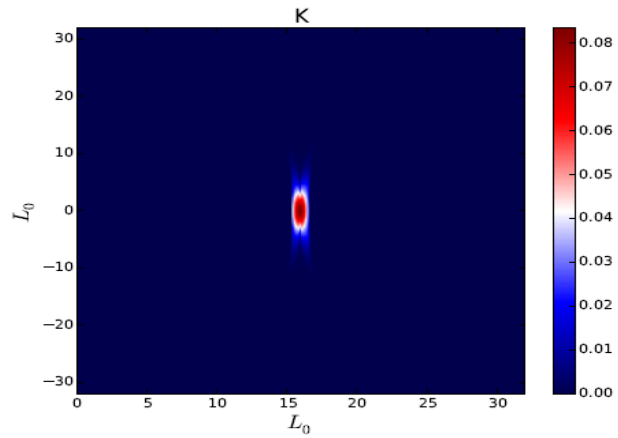
$$\frac{\partial W}{\partial t} = -\boldsymbol{U} \cdot \nabla W + C_\beta \tau_t K \frac{\boldsymbol{\Omega} \cdot \boldsymbol{J}}{\sqrt{\rho}} - C_\gamma \tau_t W \boldsymbol{\Omega}^2 + \frac{\boldsymbol{B}}{\sqrt{\rho}} \cdot \nabla K - C_W \frac{W}{\tau_t}$$

For more details: See the talk by N. Yokoi later today

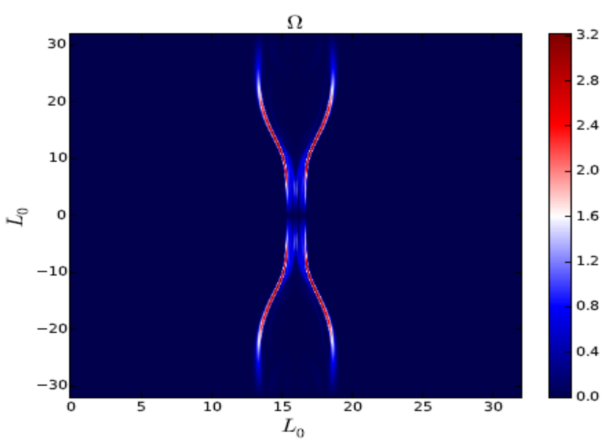
SGS turbulence as modeled for Harris-current-sheet reconnection



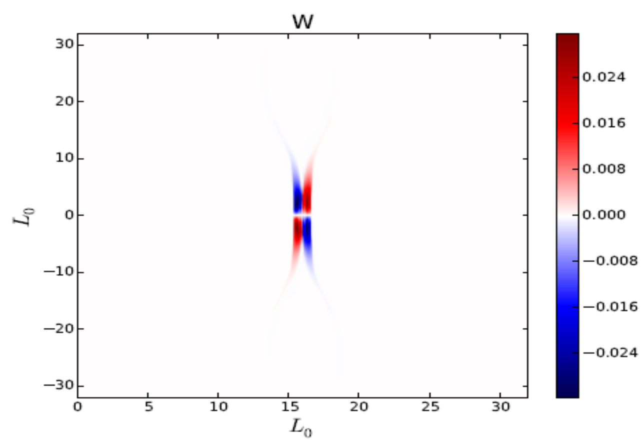
(a) Mean current density J



(b) Turbulent energy K



(c) Mean vorticity Ω

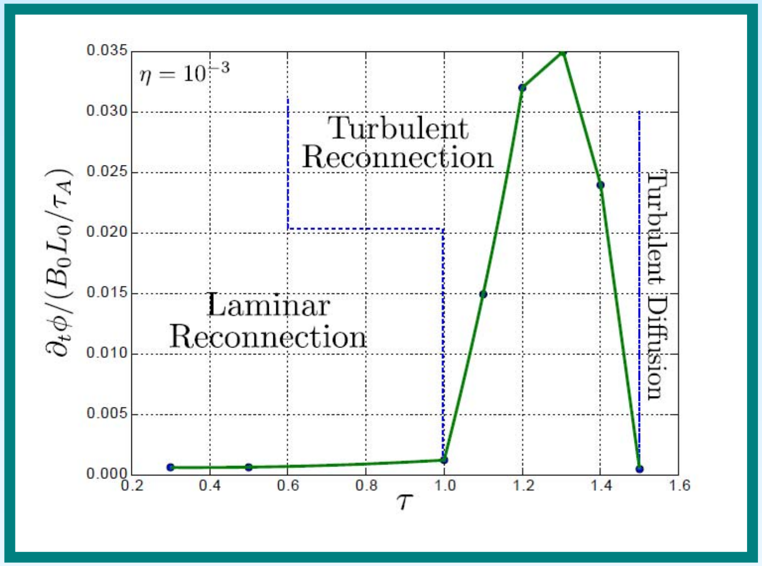


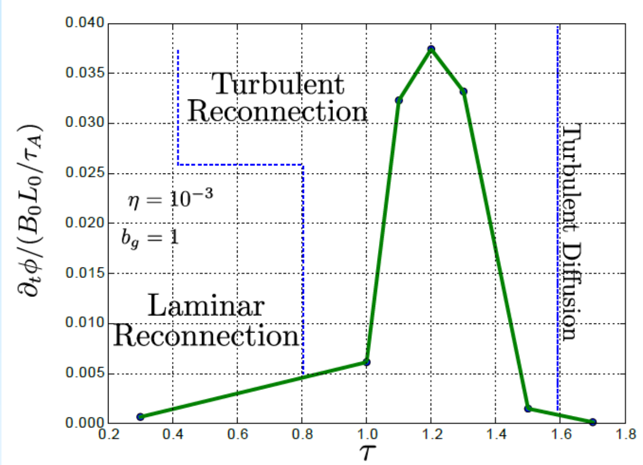
(d) Turbulent cross-helicity W

Enhanced energy of the turbulence (b) near the X-point increases the reconnection rate, the more the smaller the backgrund resistivity.

For more details see the talk by F. Widmer tomorrow.

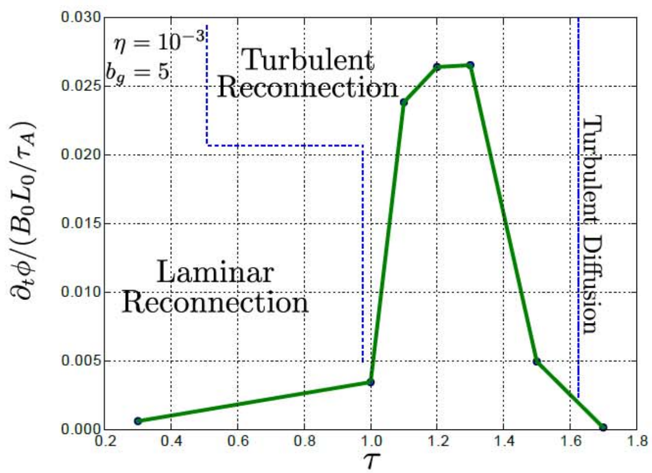
SGS turbulence enhances reconnection but: minimum influence of guide fields



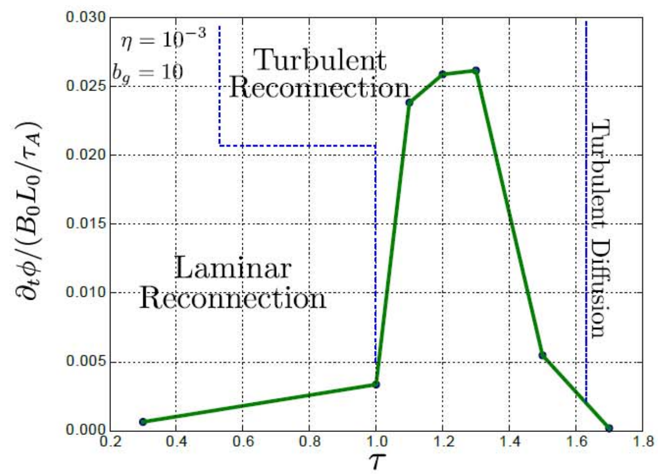


(a) Guide field $b_g = 1$, time $245\tau_A$

Higashimori et al, 2013 for Bg=0: the reconnection rate is enhanced by SGS-modeled turbulence.



(b) Guide field $b_g = 5$, time $245\tau_A$



(c) Guide field $b_g = 10$, time $245\tau_A$

But not much influence of the guide field!

For more details see the talk by F. Widmer tomorrow.

Gyrokinetics to bridge scales

Gyrokinetic Vlasov/Maxwell system eliminates fast gyromotion ($6D \rightarrow 5D$)
$\Rightarrow$ Simulations less resource-demanding.

Gyrokinetics requires very strong guide fields ($b_g \rightarrow \infty$), i.e., ordering ϵ parameter:

$$\boxed{\epsilon \sim \omega/\Omega_{ci} \sim \rho_i/L \sim k_{\parallel}/k_{\perp} \ll 1}$$

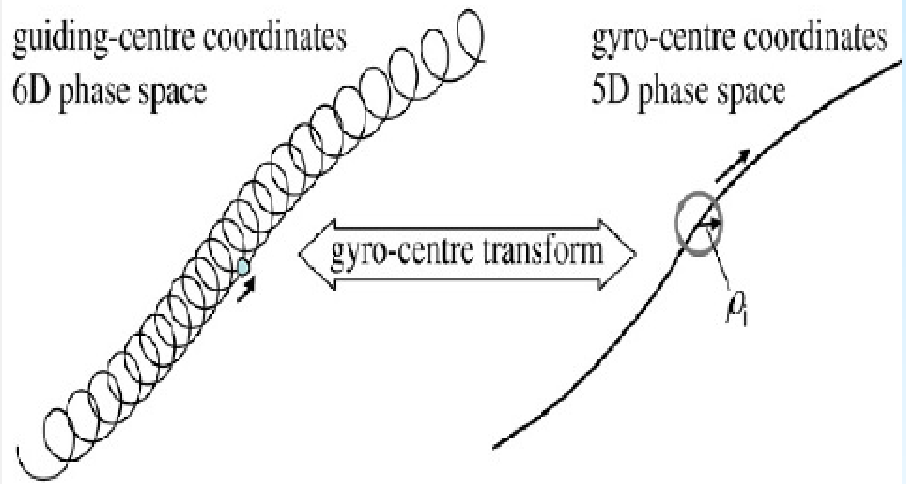
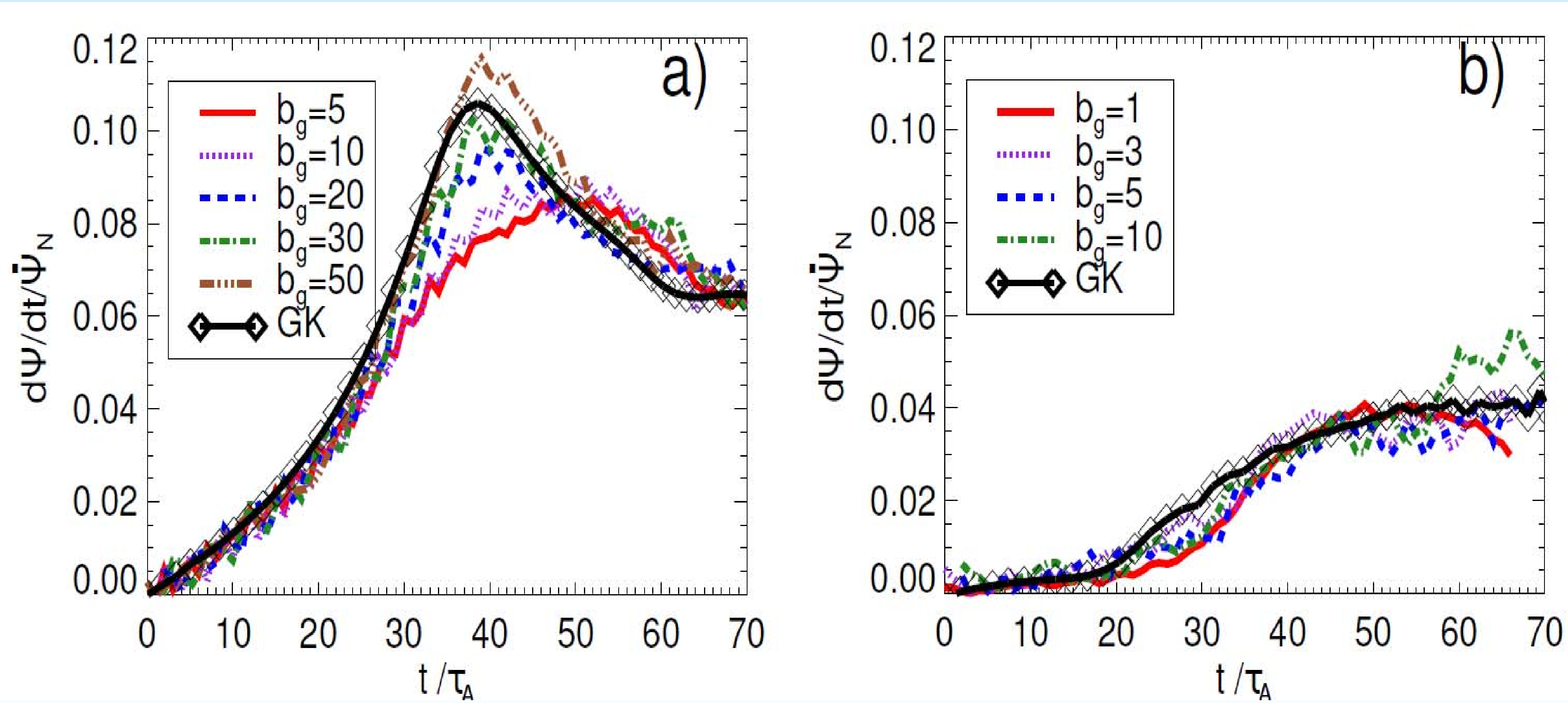


Figure 9 : Gyro-transformation [Garbet et al., 2010]

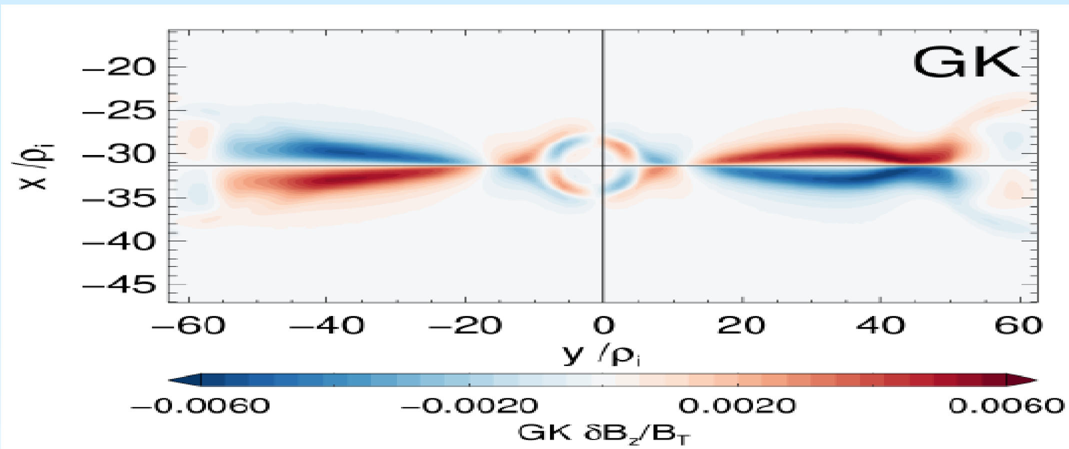
We used the gyrokinetic code GENE"Gyrokinetic Electro-magnetic Numerical Experiment" [Jenko et al. 2000]

PIC vs gyrokinetics – β dependence

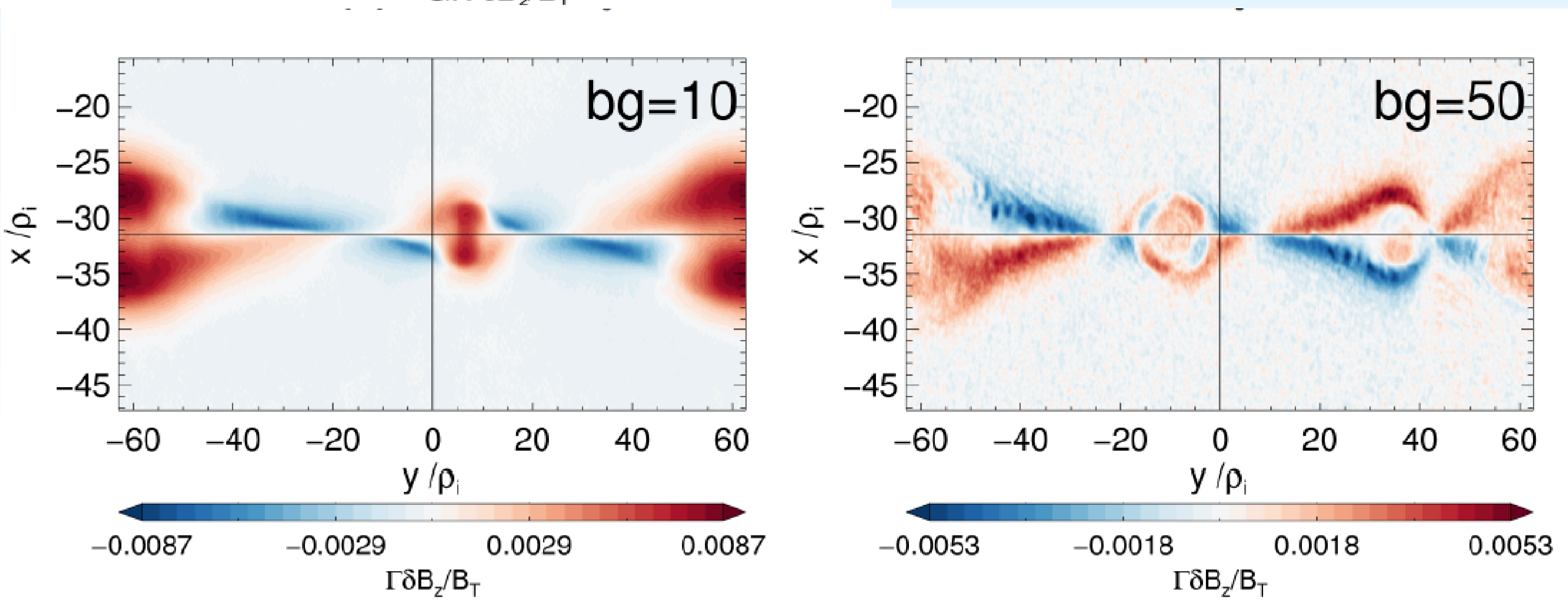


Reconnection rates dψ/dt for different guide field strength (1-50) by PIC-simulations (ACRONYM code) and GK (black line) a) βi = 0.01 b) βi = 1.0 from [Munoz et al., 2015]

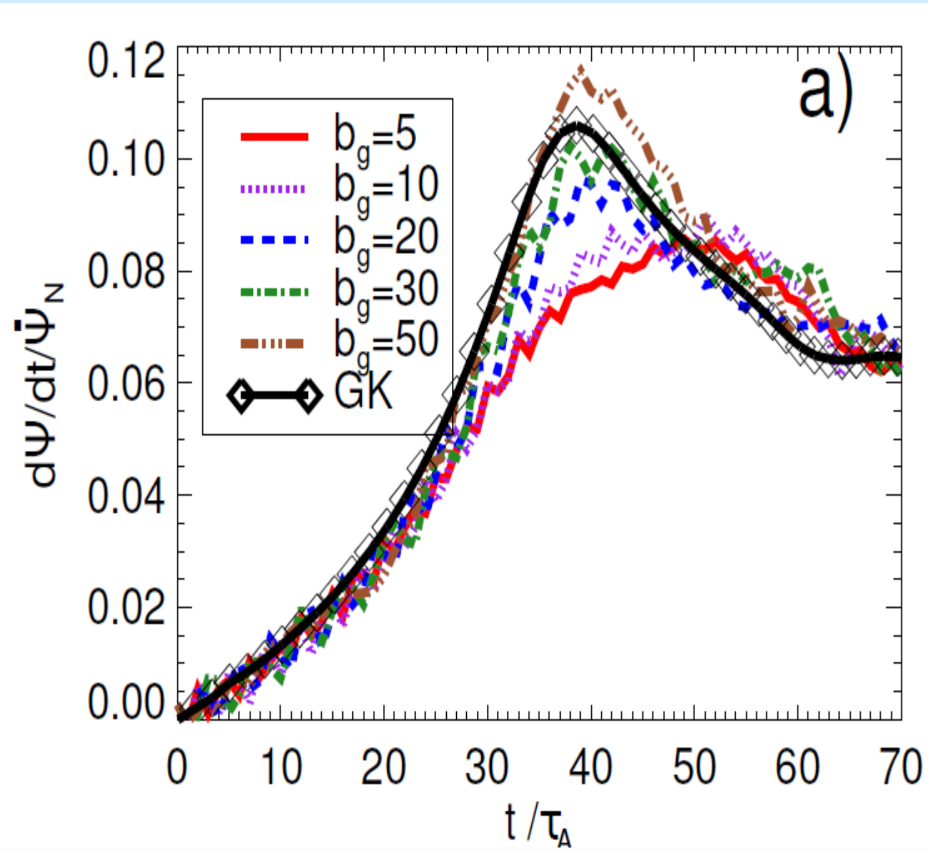
But: not well described by GK: the turbulence at the reconnection site

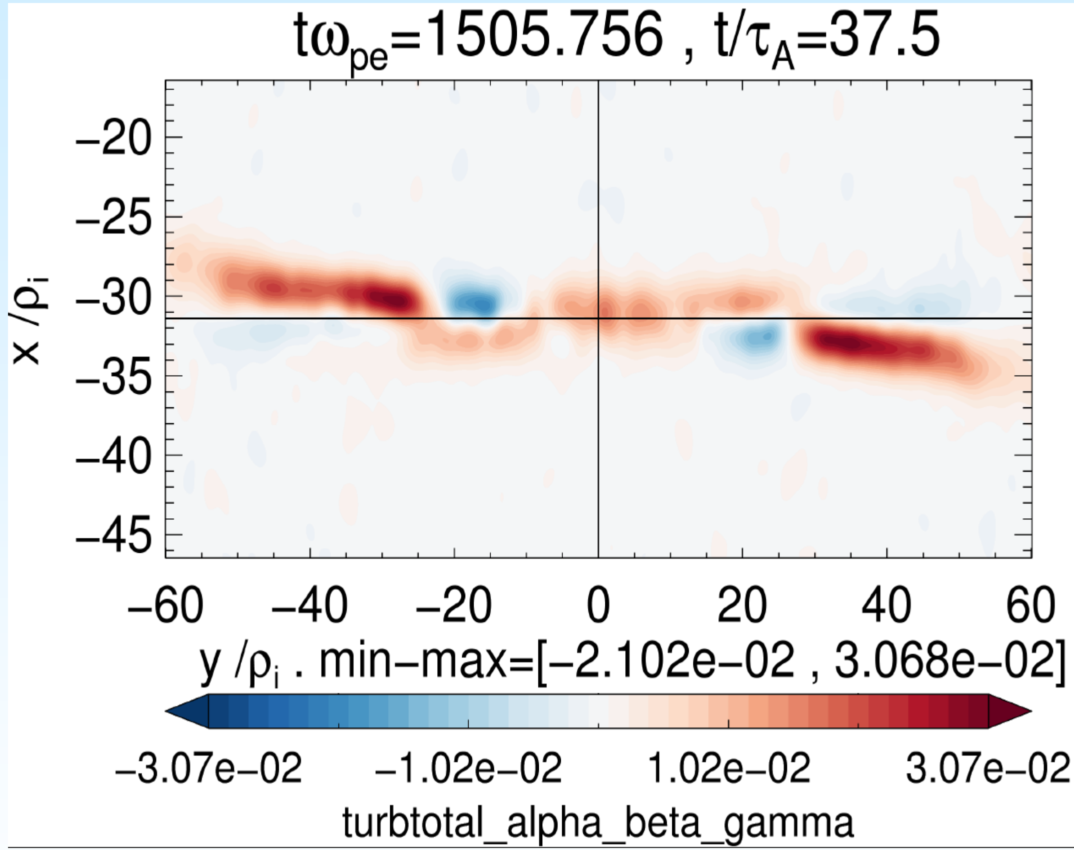


Microturbulence in gyrokinetics (left) and PIC simulations (below, left: Bg=10, right: Bg=50), from [Munoz et al, 2015]



For large scale evolution: gyrokinetics
Here: calibration of gyrokinetics on PIC





Left: reconnection rates dψ/dt for different guide field strengths (1-50) by PIC and GK (black line) simulations (βi = 0.01) and right: turbulence energy distribution [Munoz et al., 2015]

Balancing the E-field in 2D reconnection – zero guide field case

$$E_i + \overbrace{\underbrace{\epsilon_{ijk} V_j B_k}_{\text{ideal/convective}} - \underbrace{\frac{1}{en}\epsilon_{ijk} J_j B_k}_{\text{Hall e-i scales}}}^{\epsilon_{ijk} V_{e,j} B_k} = - \underbrace{\frac{1}{en}\frac{\partial P_{e,ij}}{\partial x_i}}_{\text{pressure/ambipolar}} - \underbrace{\frac{m_e}{e^2 n}\frac{dJ_i}{dt}}_{\text{inertia}} - \underbrace{\eta_{ij} J_j}_{\text{anomalous}}$$

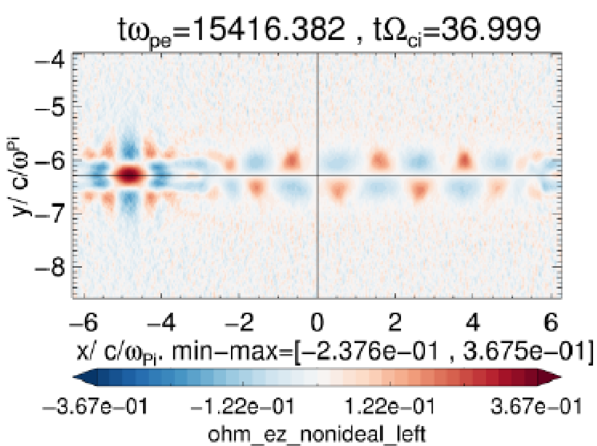


Figure 36 :
$E_{\mathrm{LHS}} = E_z + E_{z,\mathrm{convective}}$

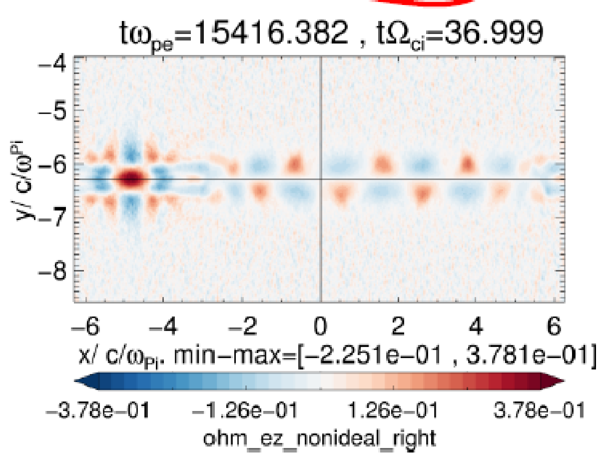


Figure 37 :
$E_{\mathrm{RHS}} = E_{z,\mathrm{pressure}} + E_{z,\mathrm{inertia}}$

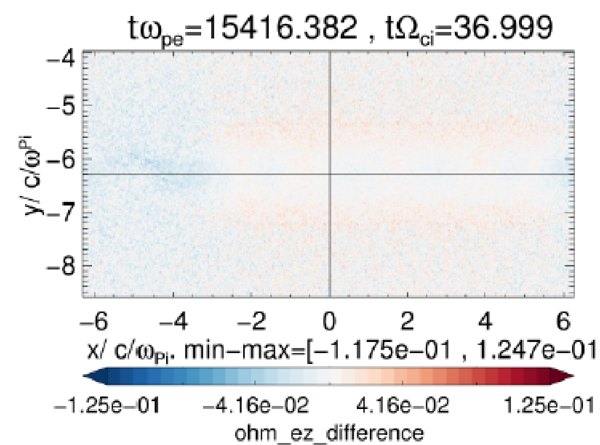


Figure 38 : $E_{\mathrm{RHS}} - E_{\mathrm{LHS}}$

Guide field kinetic reconnection -> "anomalous" balance of the E-field

$$E_i + \overbrace{\underbrace{\epsilon_{ijk} V_j B_k}_{\text{ideal/convective}} - \underbrace{\frac{1}{en}\epsilon_{ijk} J_j B_k}_{\text{Hall e-i scales}}}^{\epsilon_{ijk} V_{e,j} B_k} = -\underbrace{\frac{1}{en}\frac{\partial P_{e,ij}}{\partial x_i}}_{\text{pressure/ambipolar}} - \underbrace{\frac{m_e}{e^2 n}\frac{dJ_i}{dt}}_{\text{inertia}} - \underbrace{\eta_{ij} J_j}_{\text{anomalous}}$$

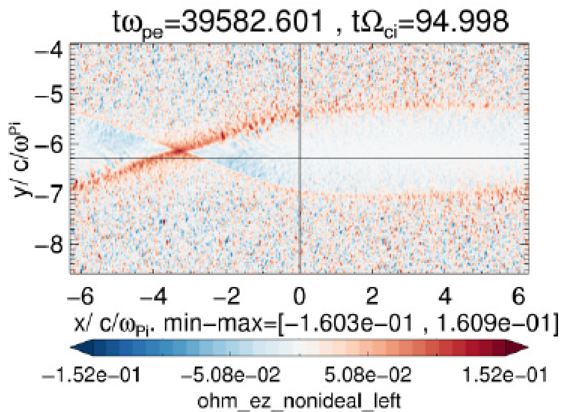


Figure 33 : $E_{\text{LHS}} = E_z + E_{z,\text{convective}}$

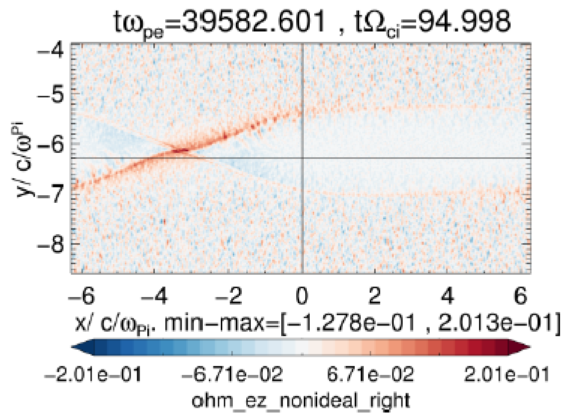


Figure 34 : $E_{\text{RHS}} = E_{z,\text{pressure}} + E_{z,\text{inertia}}$

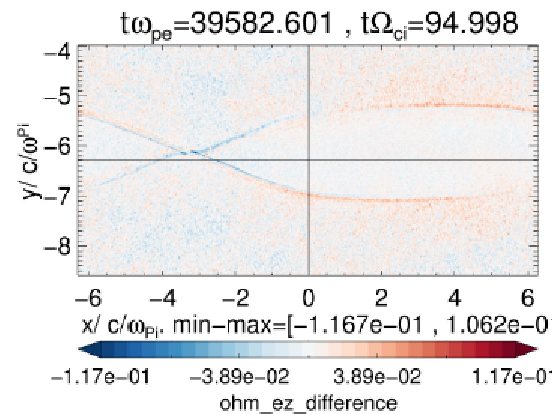
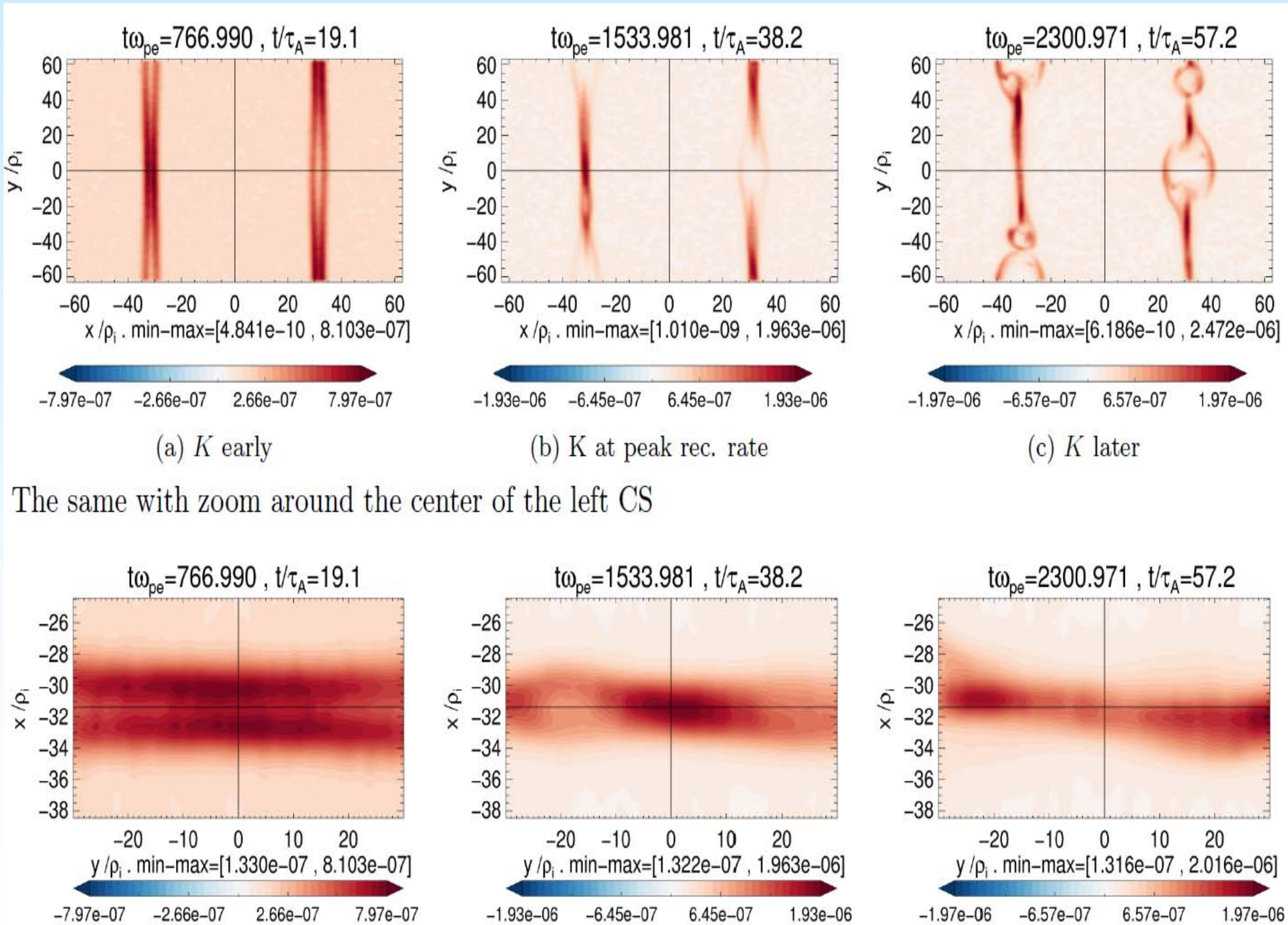


Figure 35 : $E_{\text{RHS}} - E_{\text{LHS}}$

Turbulence causes anomalous "collisions" in the reconnection region [Munoz et al., 2015]

PIC: micro-turbulent energy K(t)



For v = the bulk velocity and

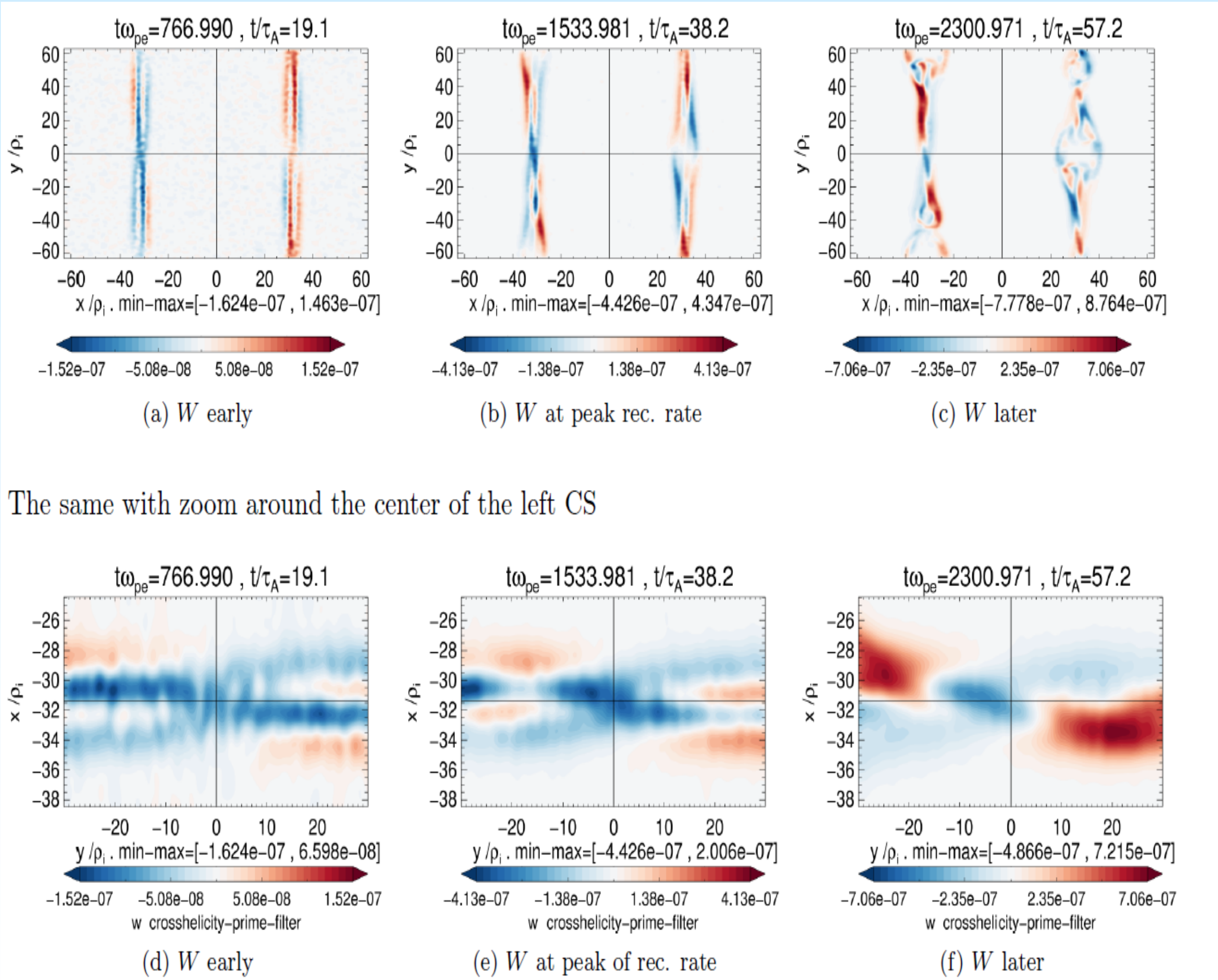
$$\vec{b} = \frac{\vec{B}}{\sqrt{\mu_0 \bar{\rho}}}$$

To compare with Reynolds decomposition results the turbulent cross-helicity

$$K = \frac{1}{2}\langle \vec{V}'^2 + \vec{b}'^2 \rangle$$

is calculated

PIC: turbulent cross-helicity W(t)



For v = bulk velocity and

$$\vec{b} = \frac{\vec{B}}{\sqrt{\mu_0 \bar{\rho}}}$$

To compare with Reynolds decomposition results the turbulent cross-helicity

$$W = \langle \vec{V}' \cdot \vec{b}' \rangle$$

is calculated

Summary

- In the Solar corona collisionless magnetic reconnection takes place but at very different plasma beta conditions, with scales to bridge of many orders of magnitude.
- For very small plasma beta -> 1 D turbulence due to concentrated field aligned currents -> ion acoustic type turbulence -> double layers -> phase space holes -> anomalous resistivity
- For moderately small beta–> 2 D effects become important, LH turbulence -> resistivity enhanced
- Order unity plasma beta or larger near magnetic nulls –> 3 D effects become important
- SGS models may help but have to include kinetic effects.

The Solar Orbiter Mission