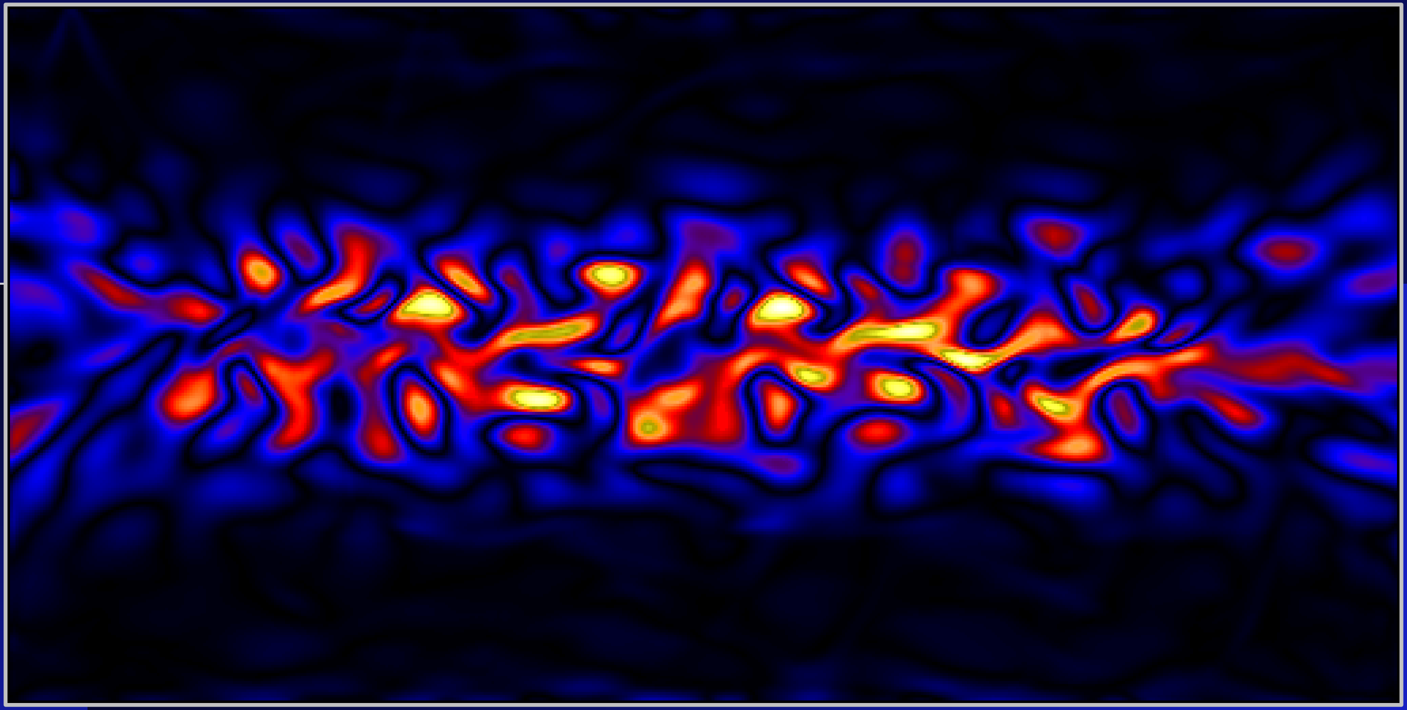
Fast Reconnection of Weakly Stochastic Magnetic Field and Cosmic Ray Acceleration



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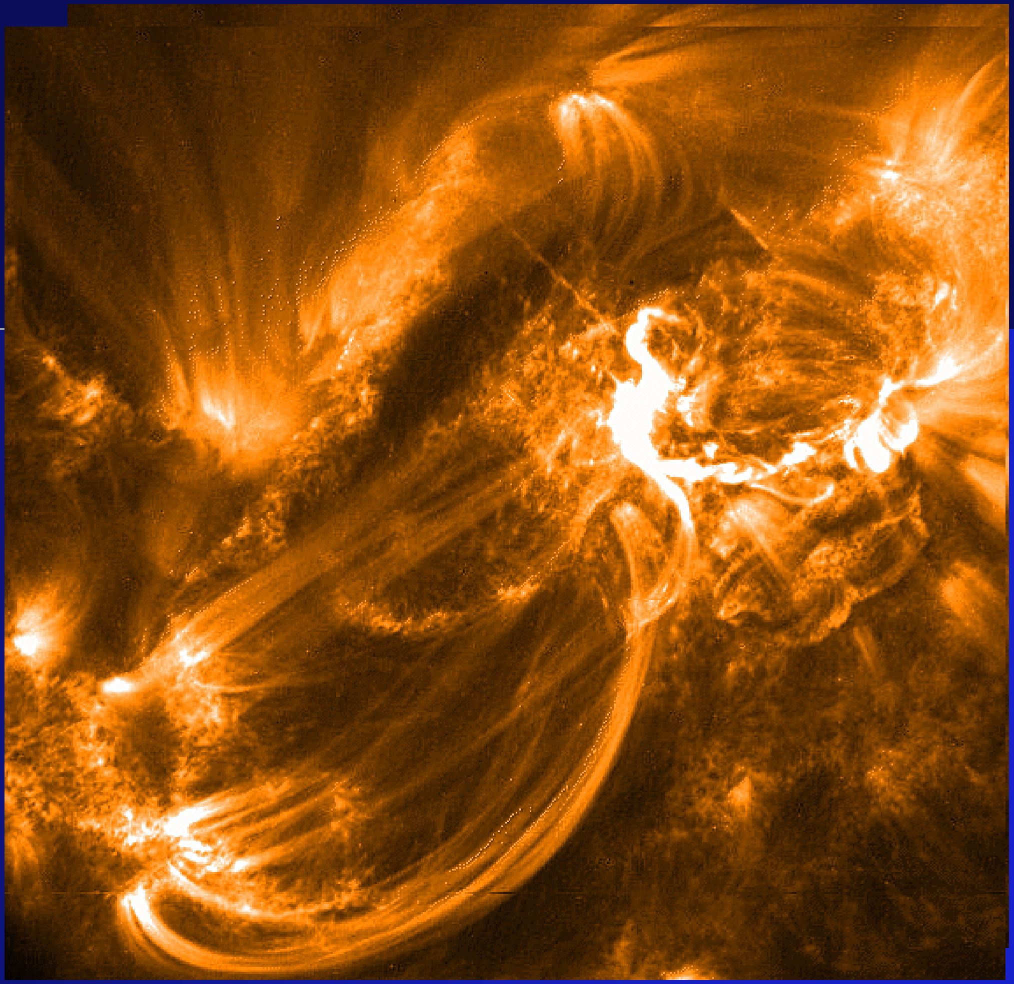
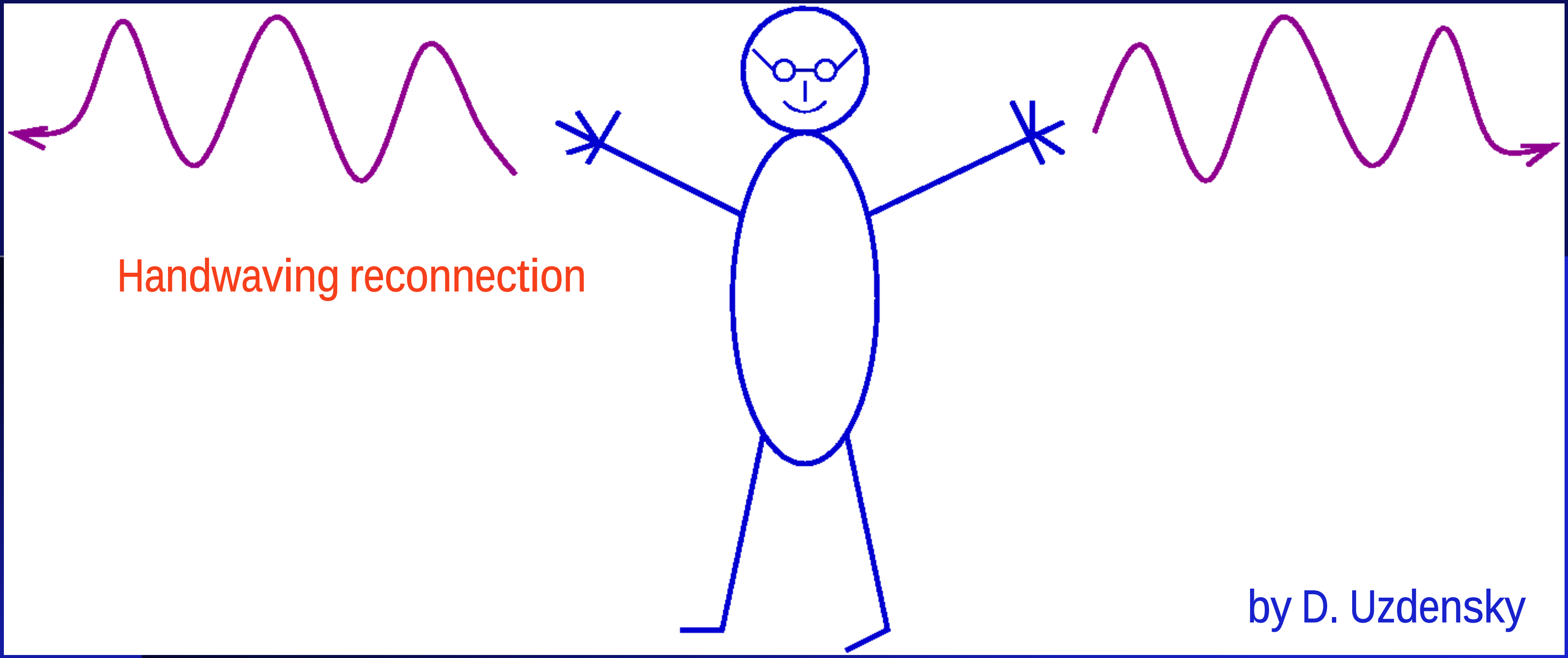
Requirement to good theory: Reconnection should better be fast, but in some cases we know that it is slow!

Magnetic reconnection is slow for the field to accumulate prior to Solar flare.

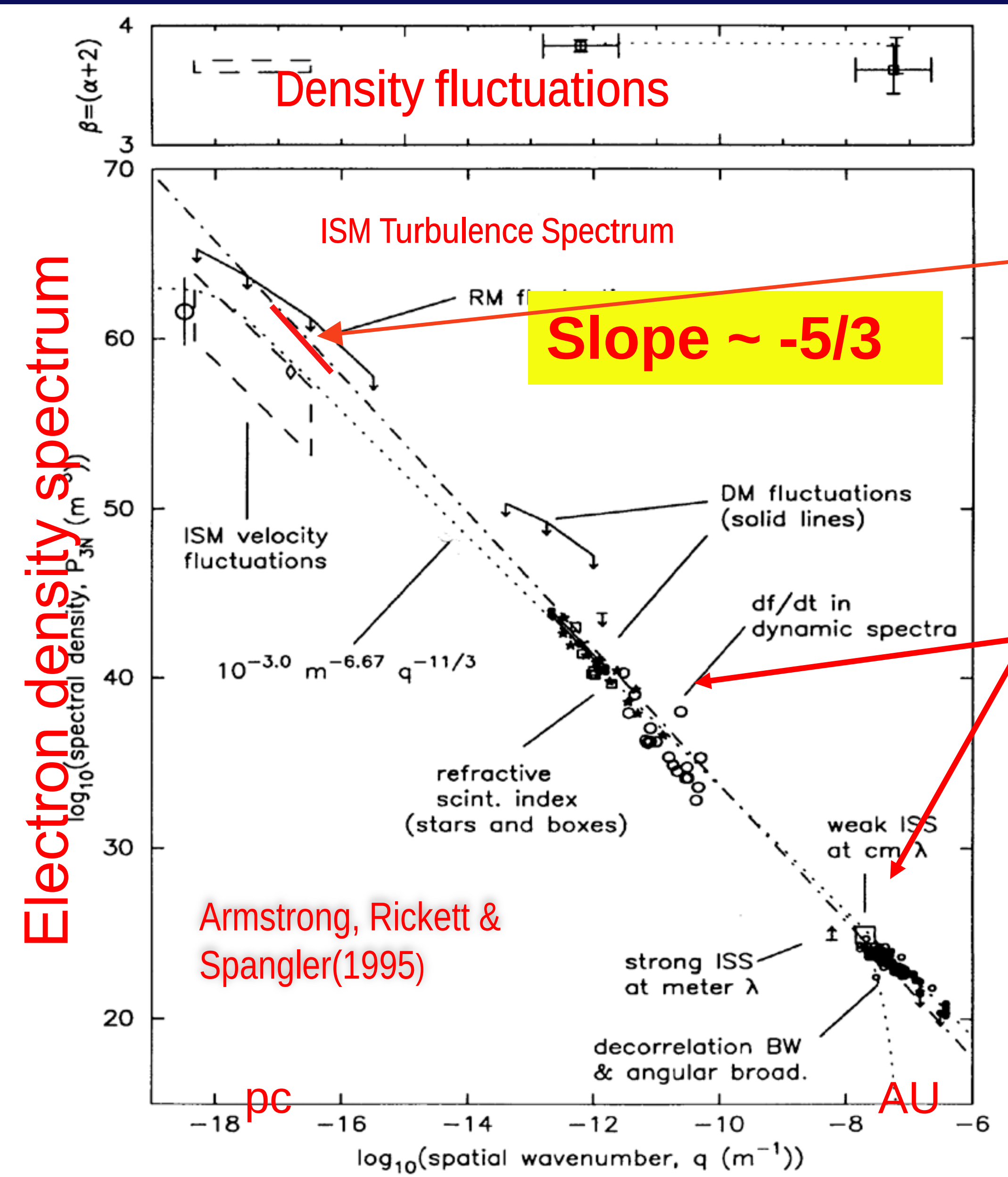


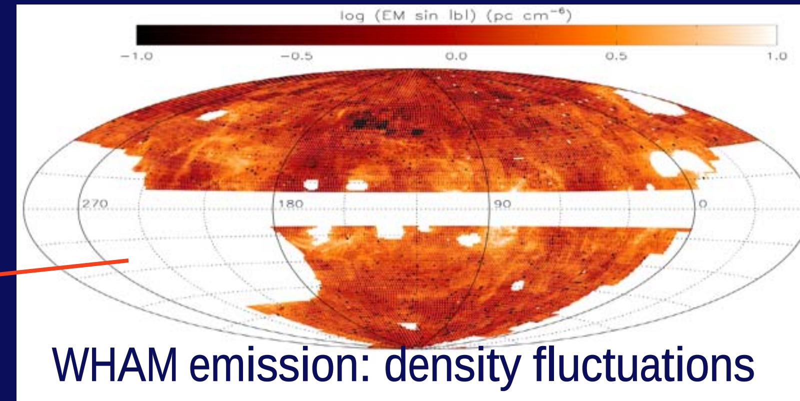
Astrophysical reconnection was always associated with a kind of waves



It is good to see whether other types of waves or non-linear interactions can do the job

Astrophysical fluids are turbulent and magnetic field lines are not laminar





Chepurnov & Lazarian 2009

Scincillations and scattering

Also ubiquitous Doppler shifting and broadening of emission lines testifies of interstellar turbulence with Kolmogorov or a bit steeper spectrum (see Lazarian & Pogosyan 2000, Chepurnov et al. 2009).

Reconnection of 3D weakly turbulent magnetic fields involves many simultaneous reconnection events

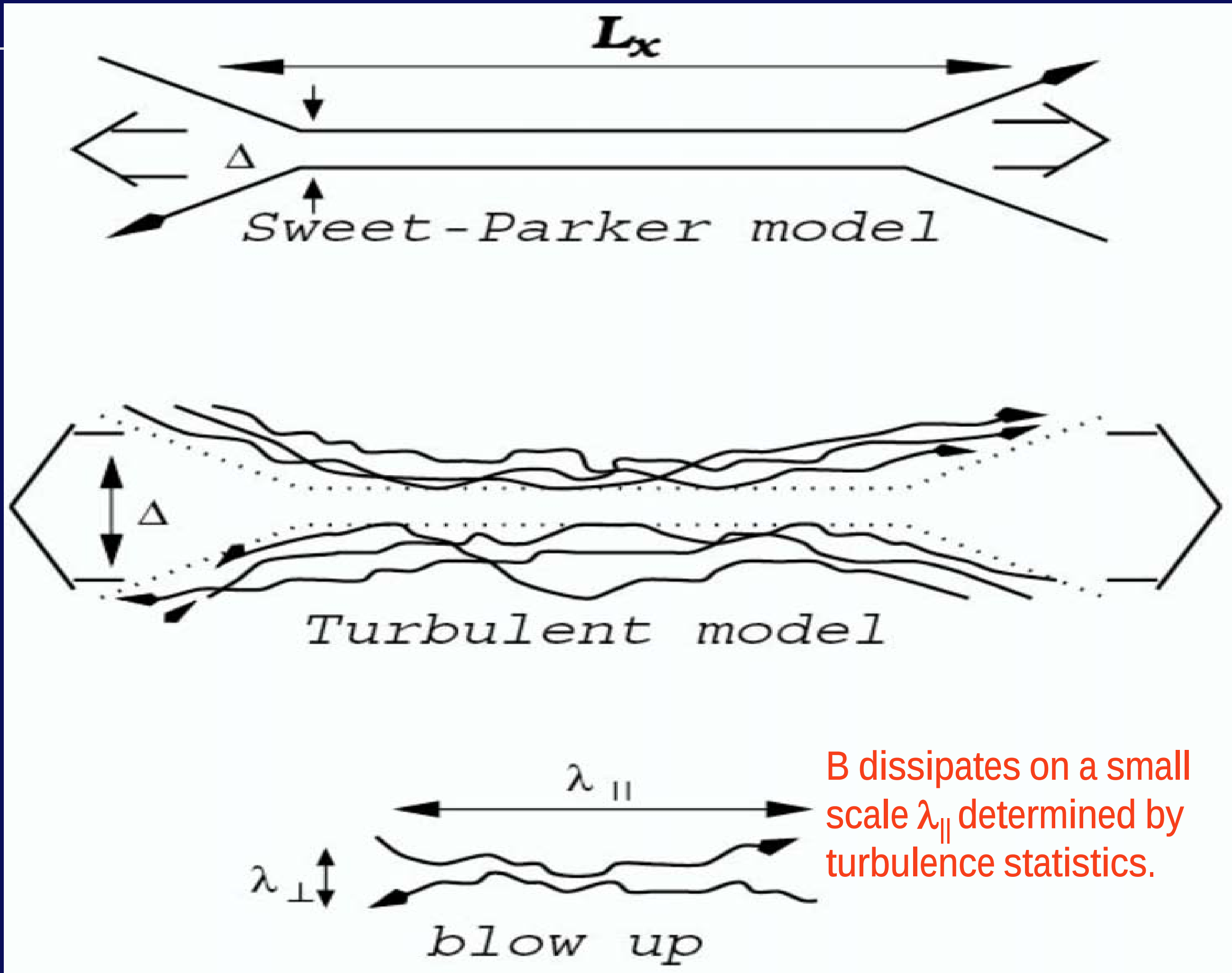
Turbulent reconnection:

1. Outflow is determined by field wandering.

2. Reconnection is fast with Ohmic resistivity only.

Key element:

$L/\lambda_{||}$ reconnection simultaneous events



B dissipates on a small scale $\lambda_{||}$ determined by turbulence statistics.

Lazarian & Vishniac (1999)

Turbulence was discussed in terms of reconnection, but results were inconclusive

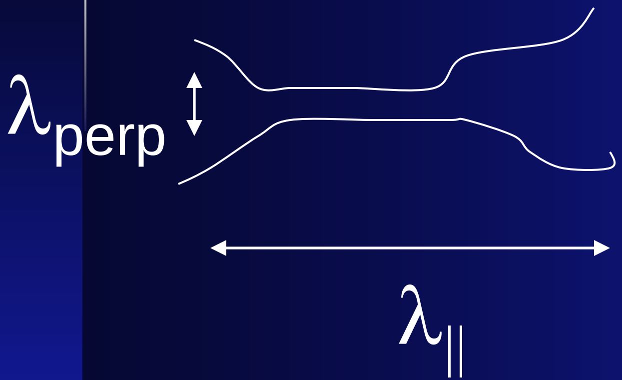
Microturbulence affects the effective resistivity by inducing anomalous effect

Some papers which attempted to go beyond this:

Speizer (1970) --- effect of line stochasticity in collisionless plasmas
Jacobs & Moses (1984) --- inclusion of electron diffusion perpendicular mean B
Strauss (1985), Bhattacharjee & Hameiri (1986) --- hyperresistivity
Matthaeus & Lamkin (1985) --- numerical studies of 2D turbulent reconnection

Constraints on processes of turbulent 2.5D reconnection are in Kim & Diamond (2001)

Local reconnection rate is slow for Alfvenic turbulence due to eddy anisotropy



Conservative scenario:

Local reconnection is Sweet-Parker

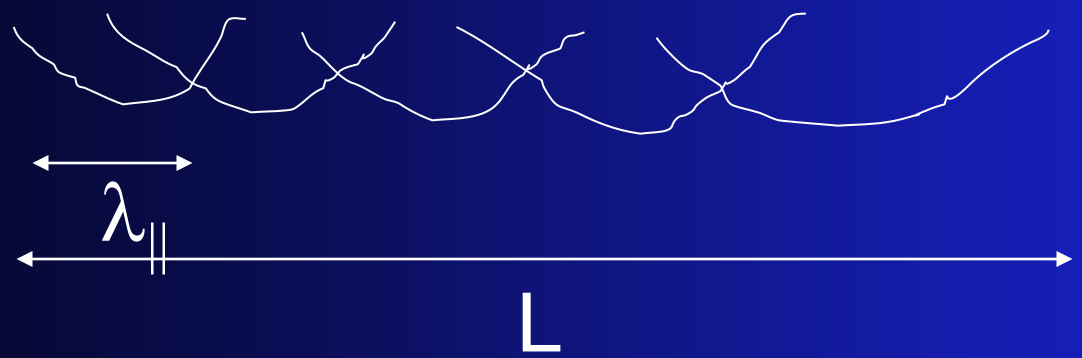
$$V_{rec,\ local} \quad \lambda_{||} = V_{alfen} \quad \lambda_{perp}$$

$$V_{rec,\ local} = \eta / \lambda_{perp}$$

$$V_{rec,\ local} = V_l\ Rm^{-1/4}$$

if $\lambda_{||}$ scales as $\lambda^{2/3}{}_{perp}$ (as in Goldreich-Sridhar 95)

Constraint due to Ohmic diffusion provides reconnection velocity faster than V_A

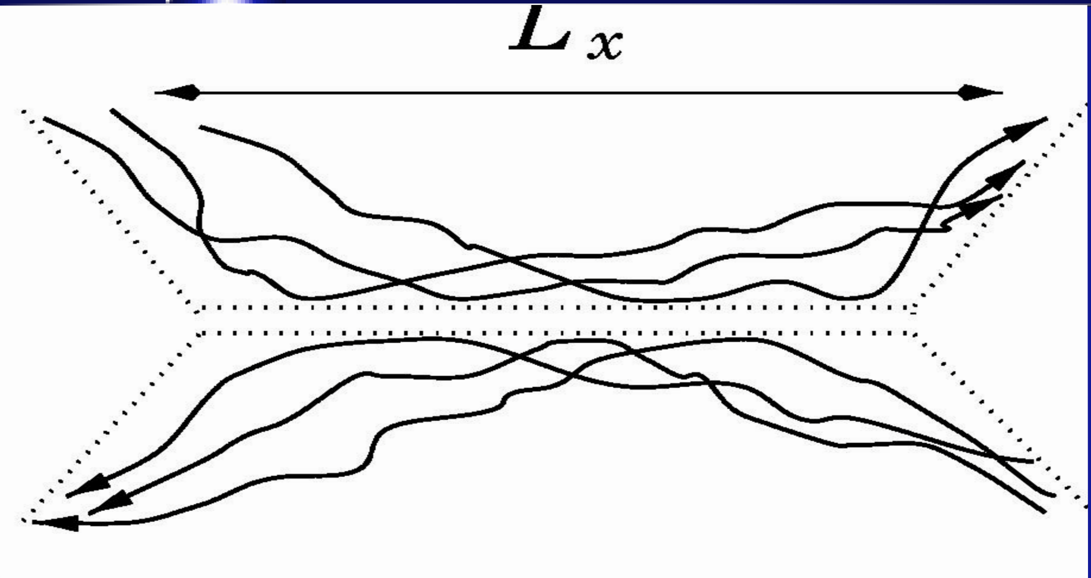


$$V_{rec,\ global} = L/\lambda_{||}\, V_{rec,\ local}$$

For Goldreich-Shridhar 95 model of MHD turbulence the reconnection rate is

$$V_{rec,\ global} = V_{alfven}\, Rm^{1/4} > V_{alfven} \quad !!!!!!$$

Bottle neck is the outflow width: field wandering determines the reconnection rate



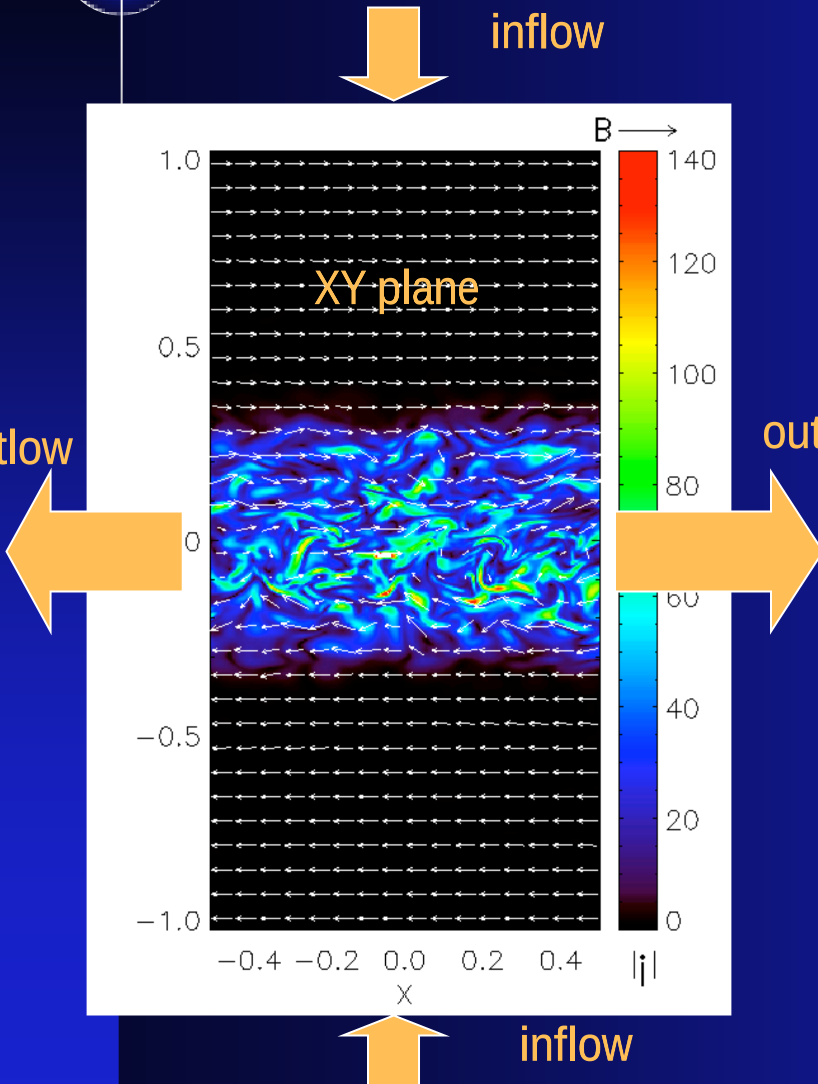
Definitive predictions in Lazarian & Vishniac (1999):

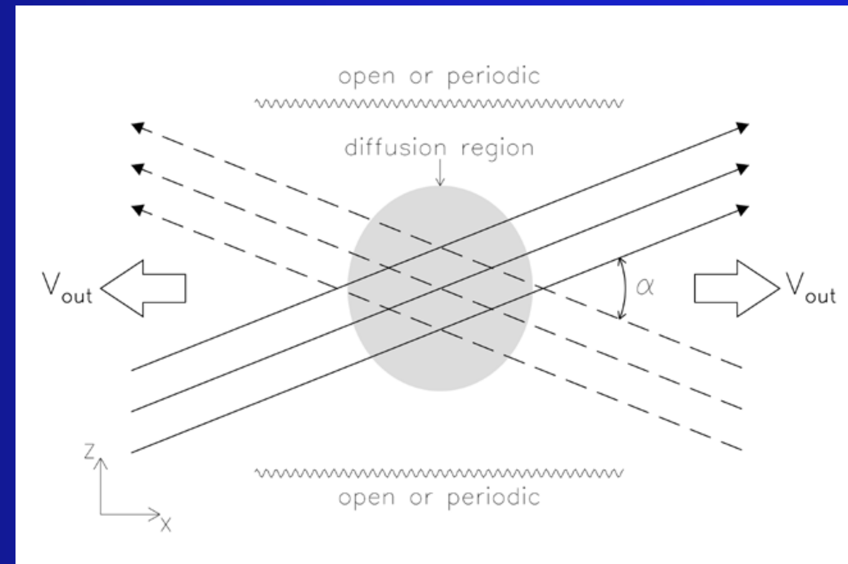
No dependence on anomalous or Ohmic resistivities!

$$V_{rec} = V_A \left(\frac{l_{inj}}{L_x}\right)^{1/2} \left(\frac{v_{inj}}{V_A}\right)^2$$

As $P_{inj} \sim v_{inj}^4/(lV_A)$ it translates into $V_{rec} \sim l_{inj} P_{inj}^{1/2}$

All calculations are 3D with non-zero guide field





Magnetic fluxes intersect at an angle

Driving of turbulence: r_d=0.4, h_d=0.4 in box units.
Inflow is not driven.

We solve MHD equations with outflow boundaries

MHD equations with turbulence forcing:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}) = 0$$

$$\frac{\partial \rho \vec{v}}{\partial t} + \nabla \cdot \left[\rho \vec{v} \vec{v} + \left(c_s^2 \rho + \frac{B^2}{8\pi} \right) \vec{I} - \frac{1}{4\pi} \vec{B} \vec{B} \right] = \rho \vec{f}$$

$$\frac{\partial \vec{B}}{\partial t} = \nabla \times \left(\vec{v} \times \vec{B} + \eta \nabla \times \vec{B} \right), \nabla \cdot \vec{B} = 0$$

isothermal EOS

Forcing:

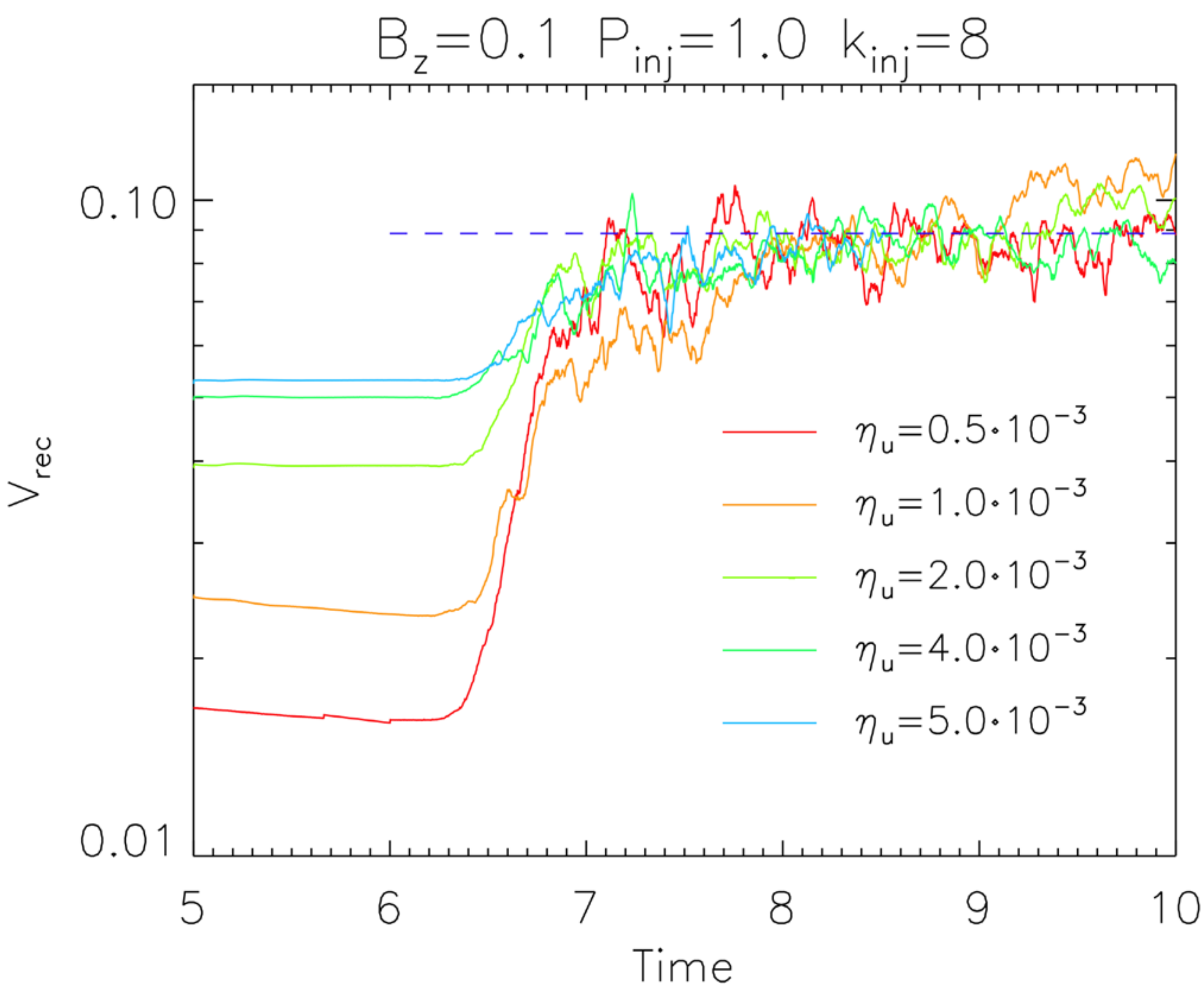
- random with adjustable injection scale (k_f~8 or 16)
- divergence free (purely incompressible forcing)

Resistivity:

-Ohmic

Kowal, Lazarian & Vishniac (2009)

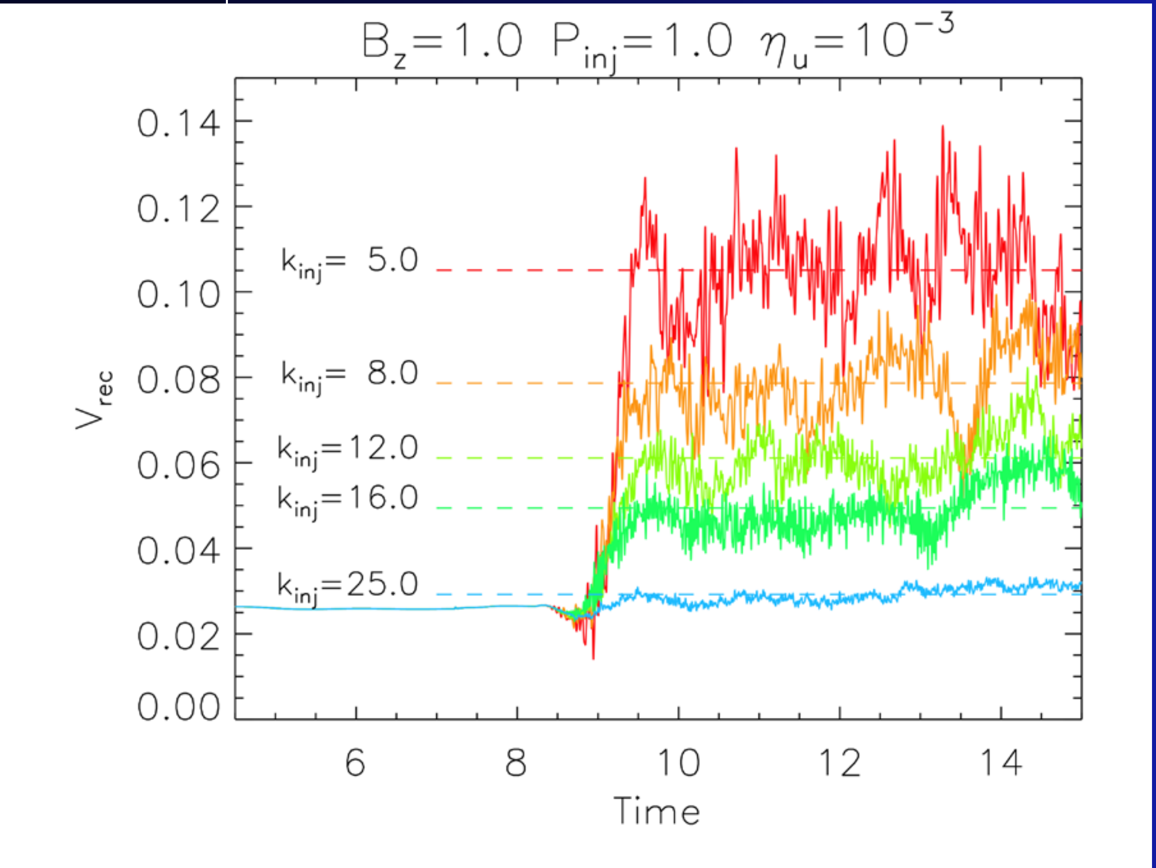
Reconnection is Fast: speed does not depend on Ohmic resistivity!



Lazarian & Vishniac 1999 predicts no dependence on resistivity

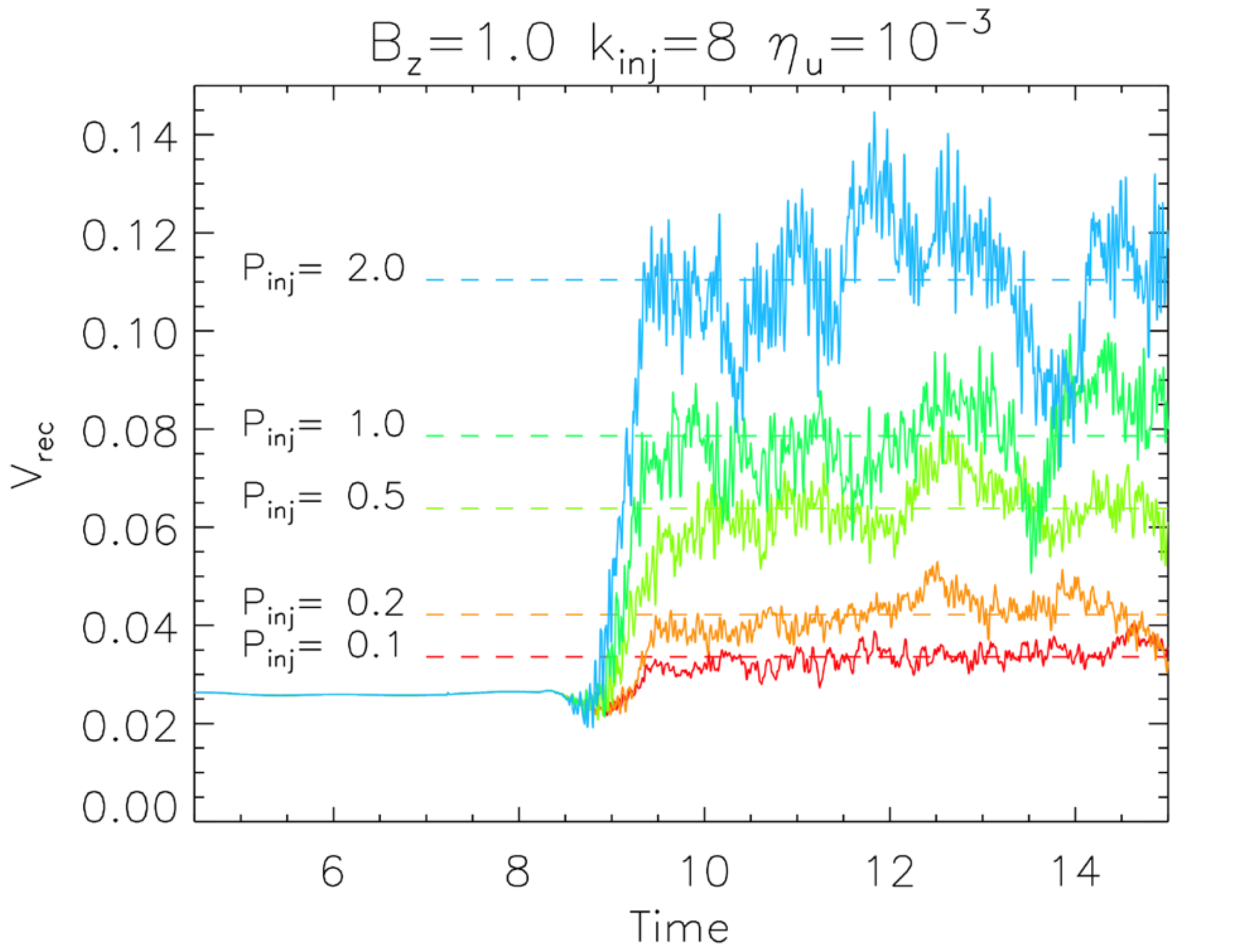
Results do not depend on the guide field

Reconnection rate increases with increase of injection scale



Lazarian & Vishniac (1999) prediction is $V_{rec} \sim l_{inj}^{1}$

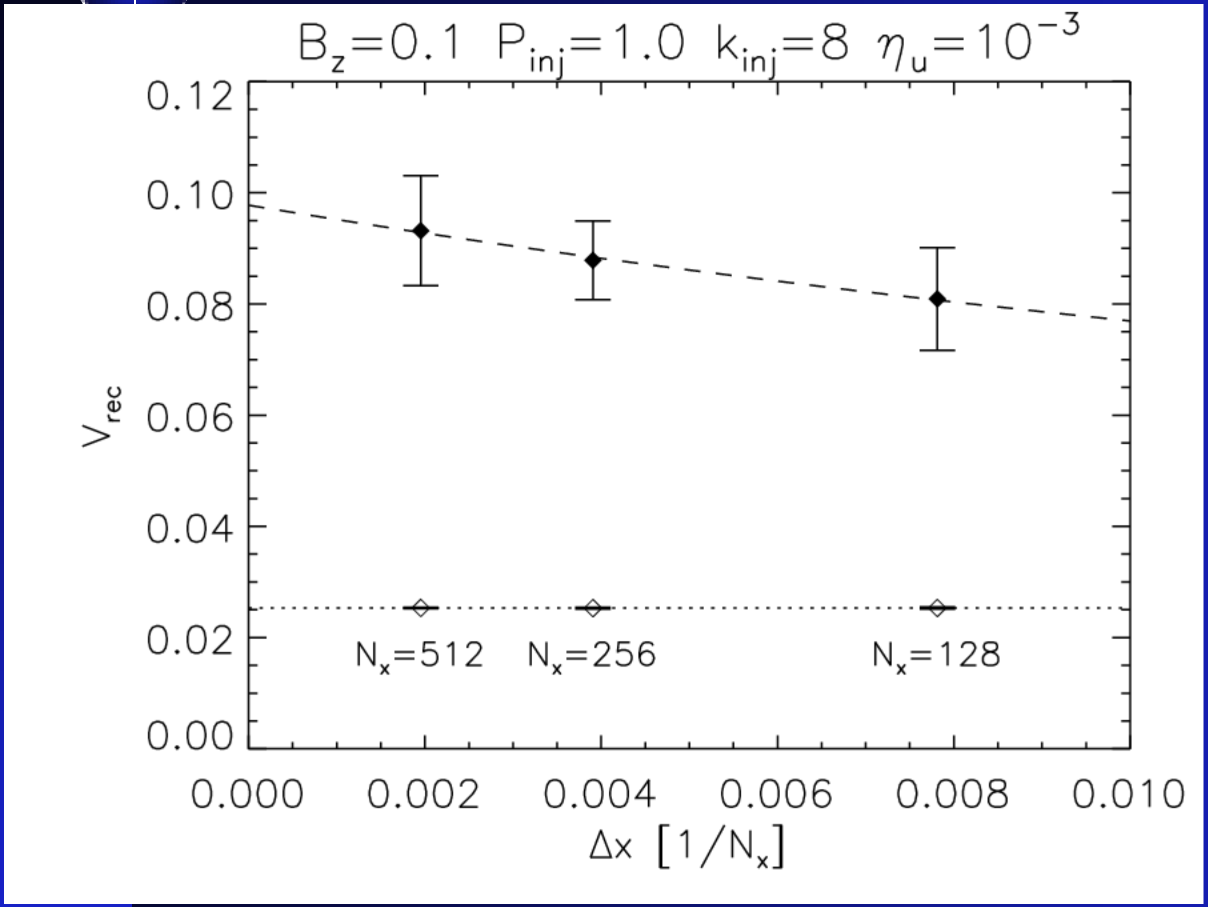
The reconnection rate increases with input power of turbulence



Lazarian & Vishniac (1999) prediction is $V_{rec} \sim P_{inj}^{1/2}$

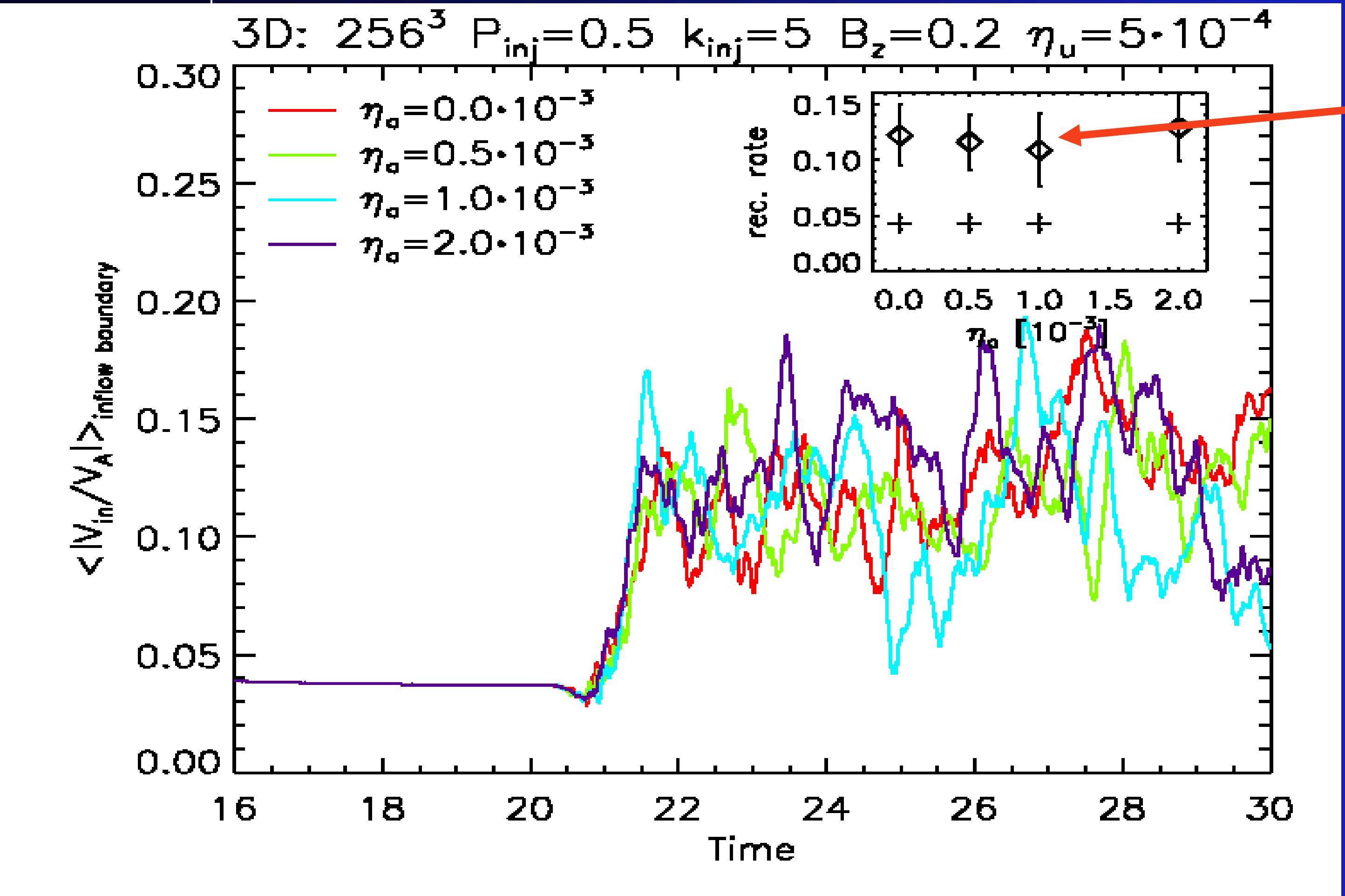
Results do not depend on the guide field

Reconnection rate marginally depends on resolution: fast reconnection is not due to numerical resistivity



Numerical resistivity effects are more important at low resolution

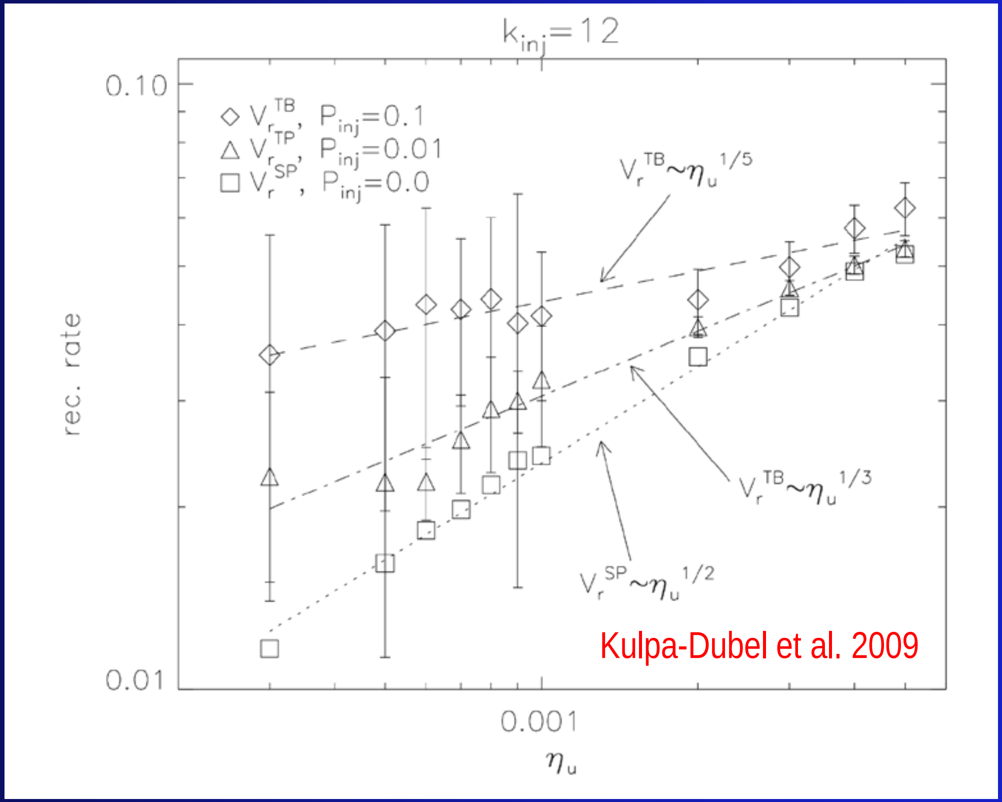
Reconnection rate does not depend on anomalous resistivity



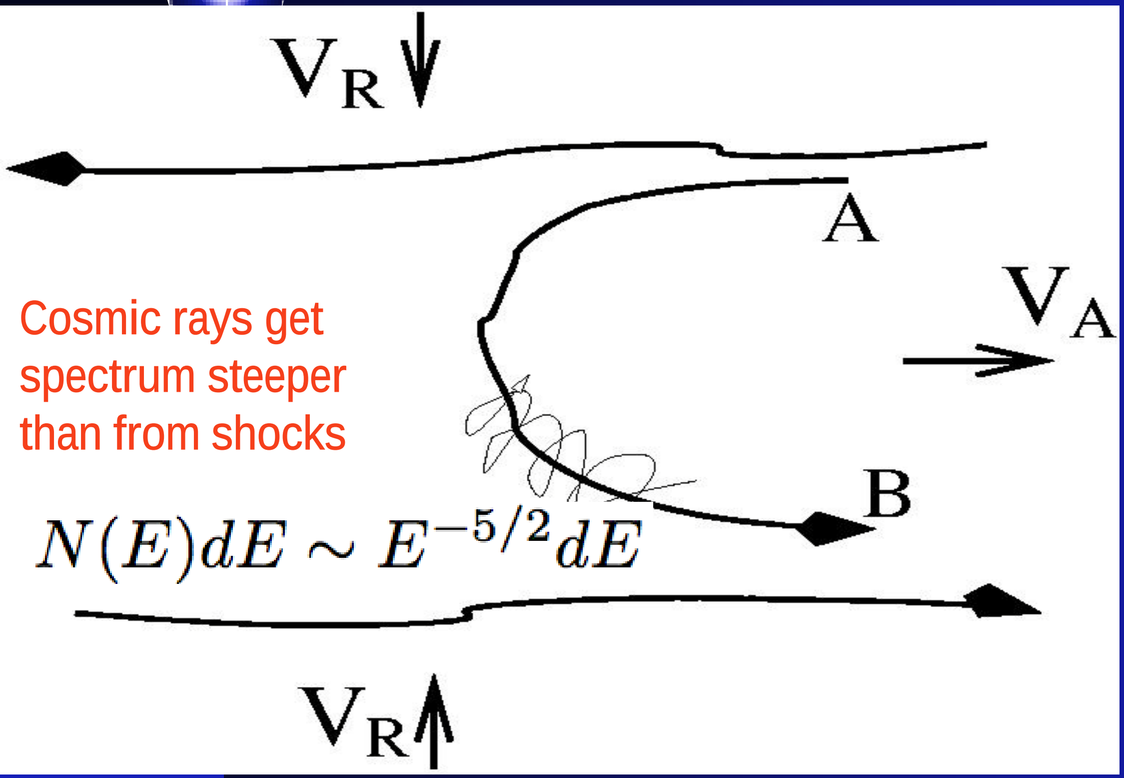
Flat dependence on anomalous resistivity

Reconnection does not require Hall MHD

Reconnection in 2D is different from our scheme, it is not fast. Fortunately we live in 3D world!!!



In our reconnection model energetic particles get accelerated by First Order Fermi mechanism



Cosmic rays get spectrum steeper than from shocks

$$N(E)dE \sim E^{-5/2}dE$$

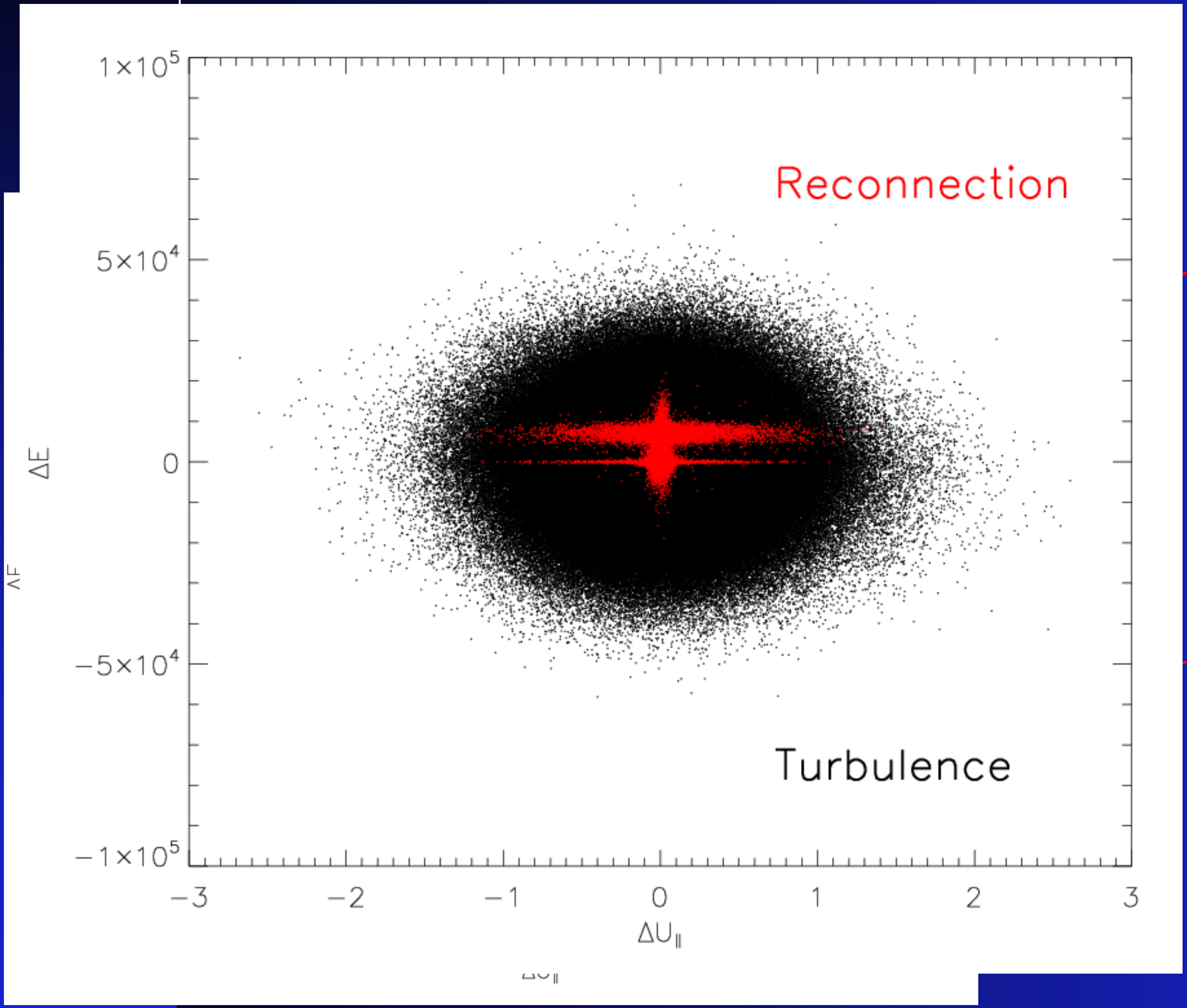
(cp. Drake 2006).

De Gouveia Dal Pino & Lazarian 2003

(ping pong acceleration according to Pat)

Applications to pulsars, microquasars, solar flare acceleration (De Gouveia Dal Pino & Lazarian 00, 03, 05, Lazarian 05).

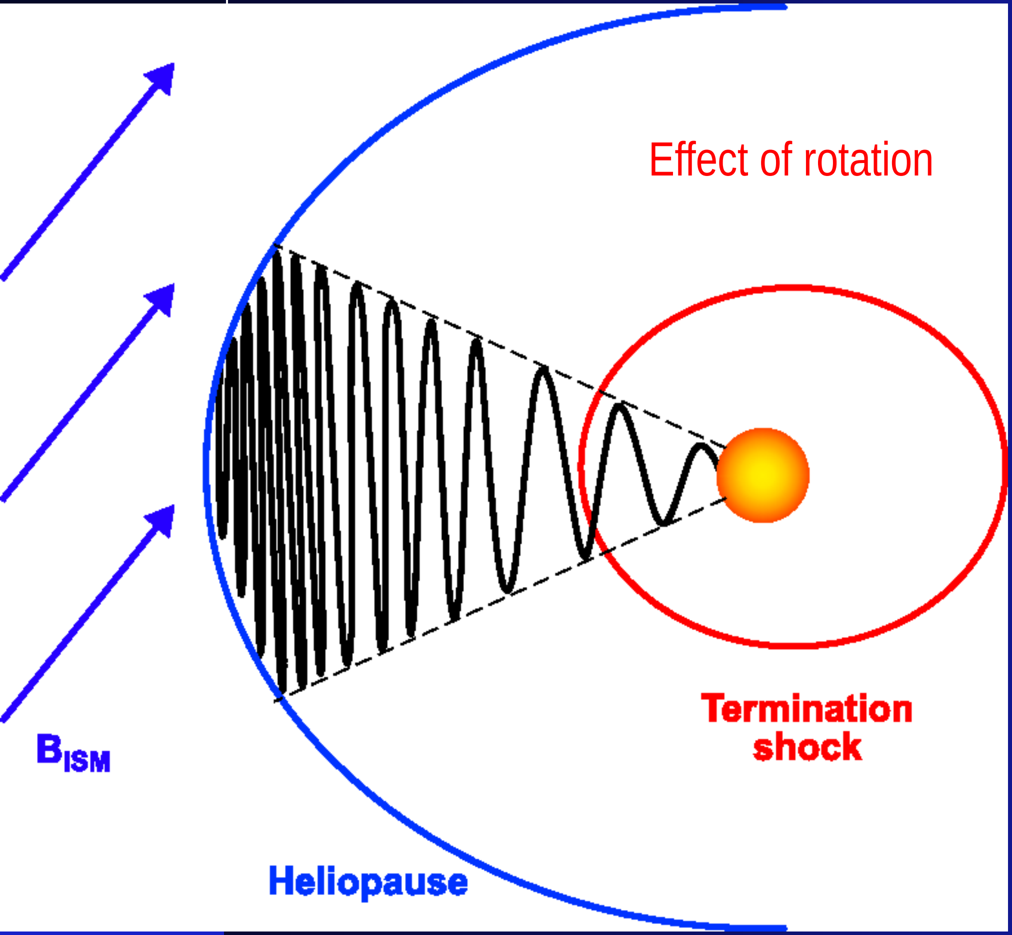
In the presence of reconnection regular increase of energy is clearly seen

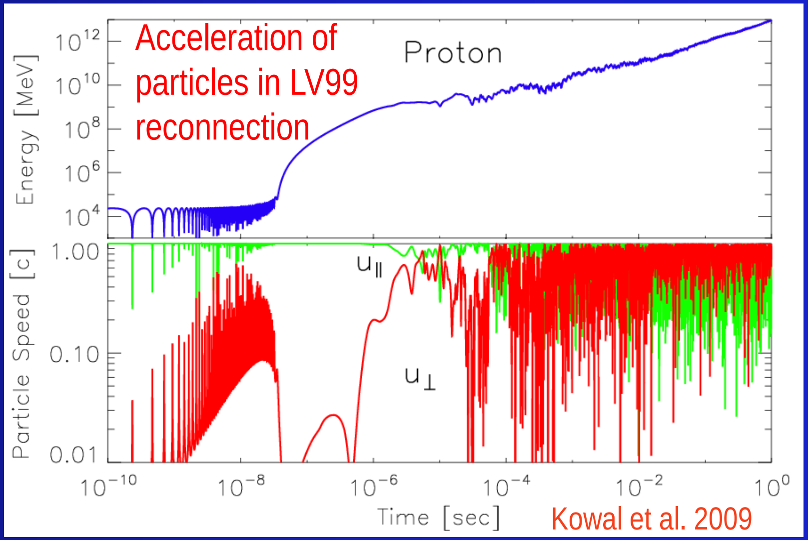


3D turbulent reconnection

Pure Turbulence

Reconnection can provide a solution to anomalous cosmic ray measurements by Voyagers

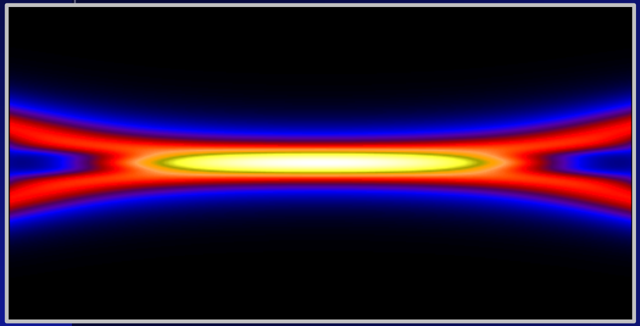


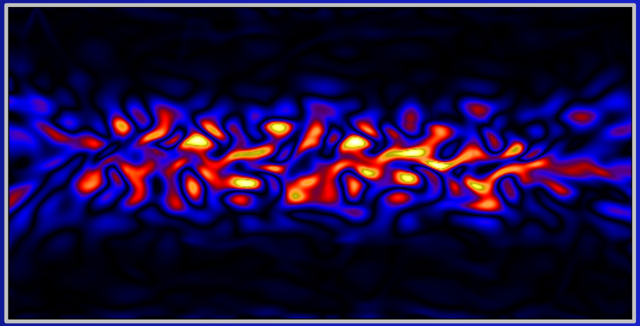


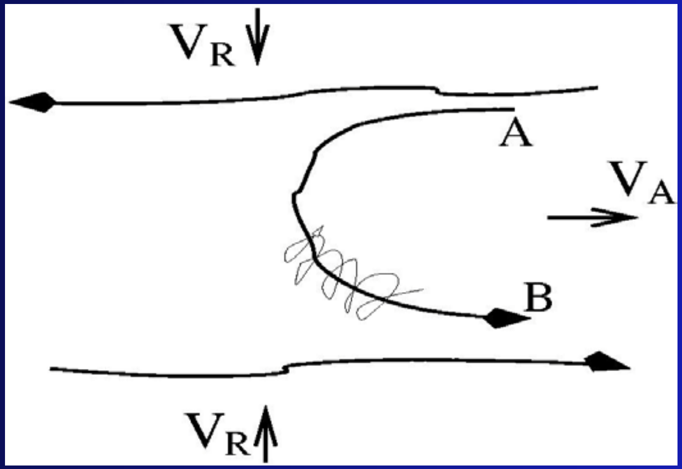
Observed anomalous CRs do not show features expected from the acceleration in the termination shock

Lazarian & Opher 2009: Sun rotation creates B-reversals in the heliosheath inducing acceleration via reconnection.

3D reconnection of weakly stochastic magnetic fields is fast; it efficiently accelerates CRs

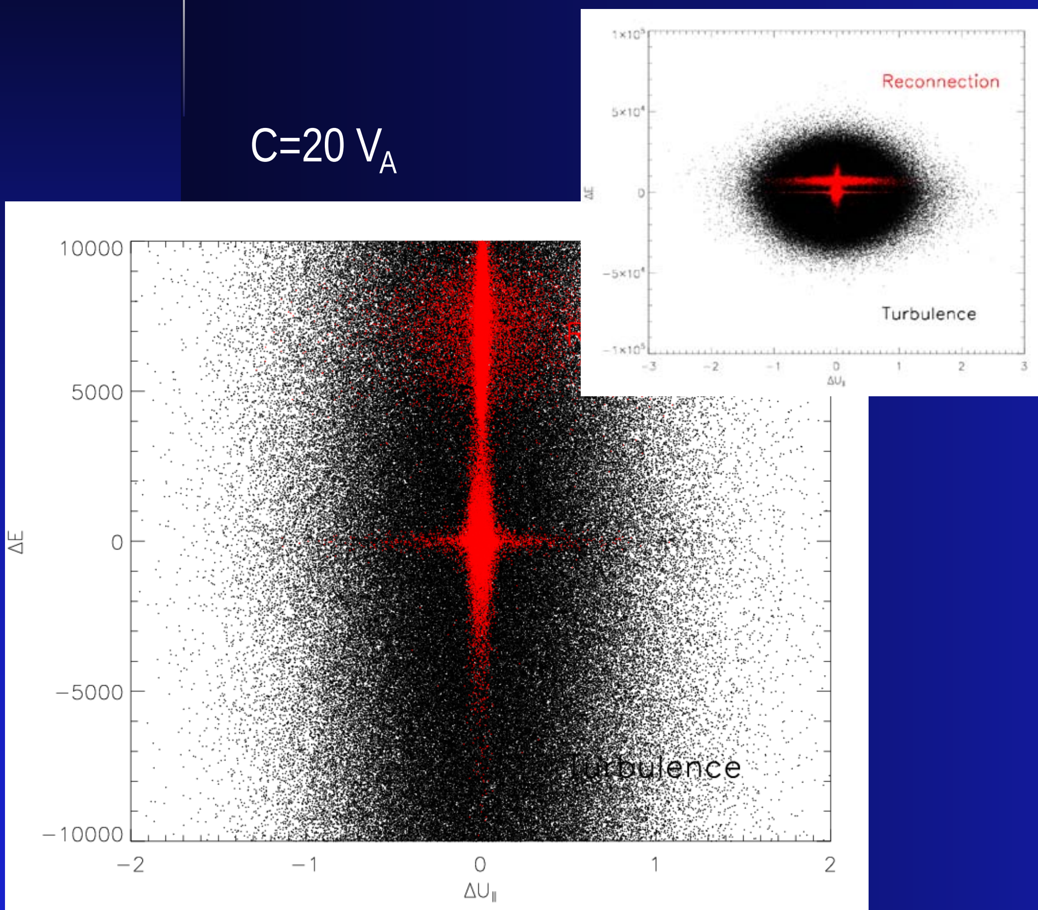




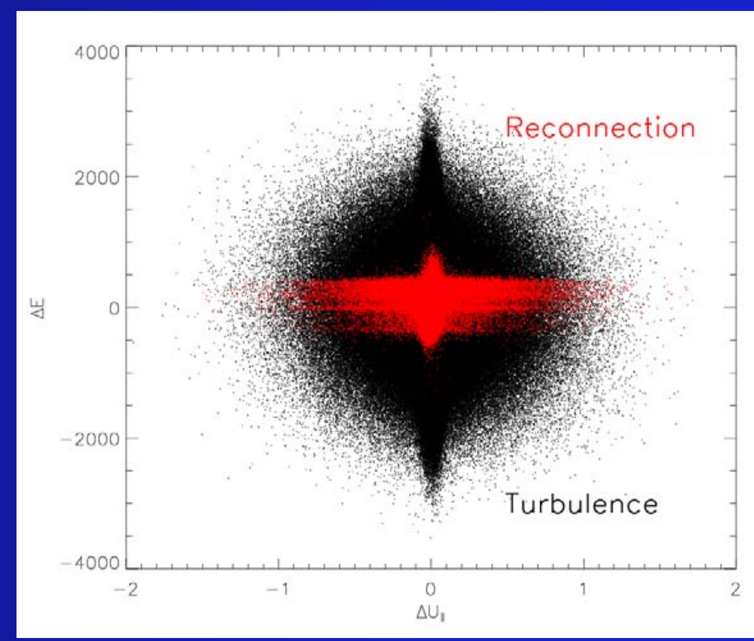


It also explains observed phenomena: Solar flares, removal of magnetic flux in star formation etc.

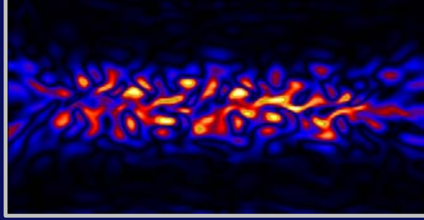
C=20 V_A

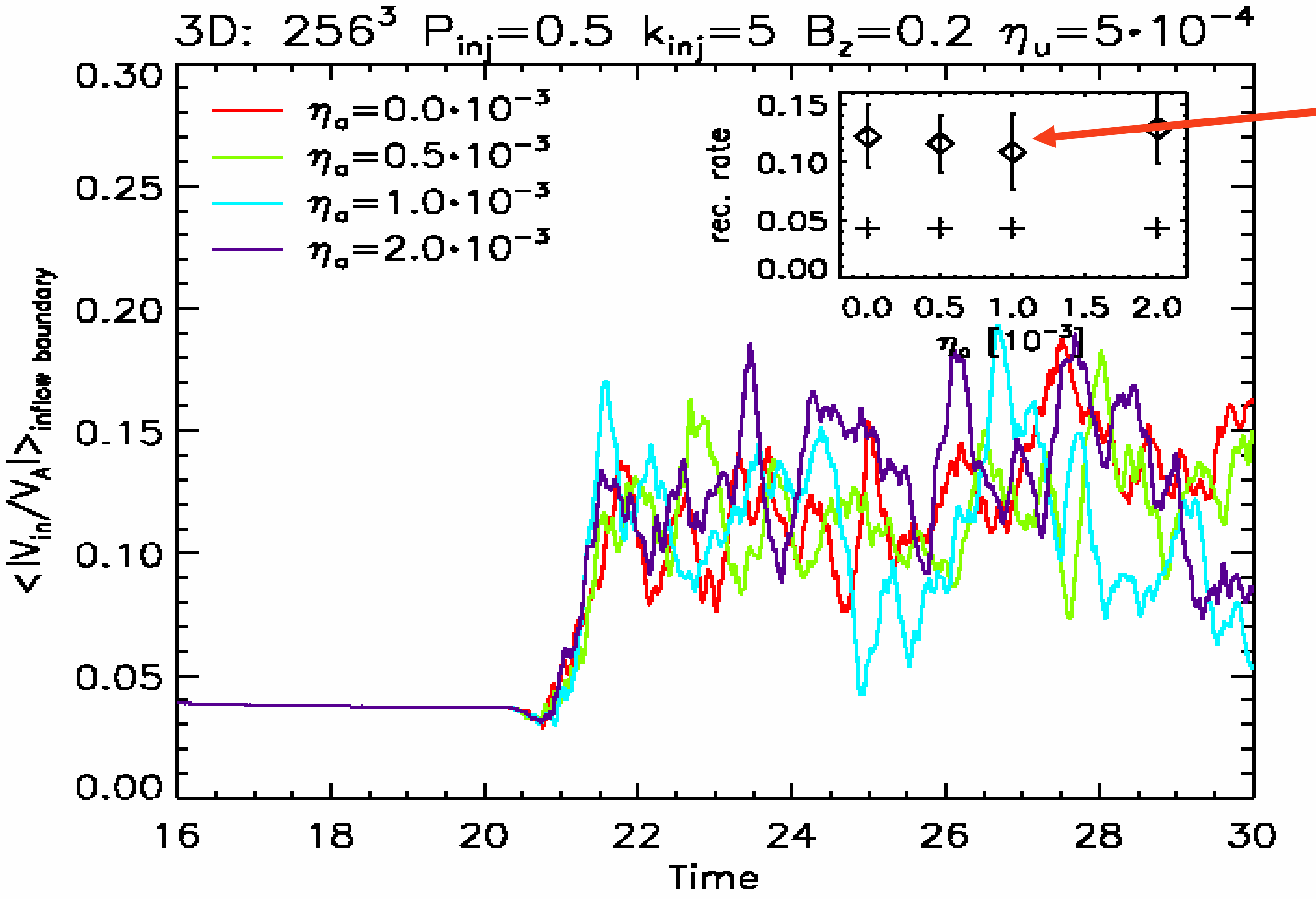


C=100 V_A



Reconnection rate does not depend on anomalous resistivity

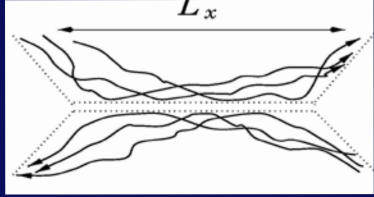




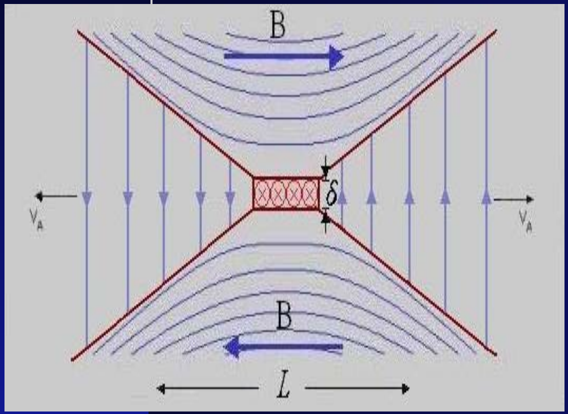
Flat dependence on anomalous resistivity

Reconnection does not require Hall MHD

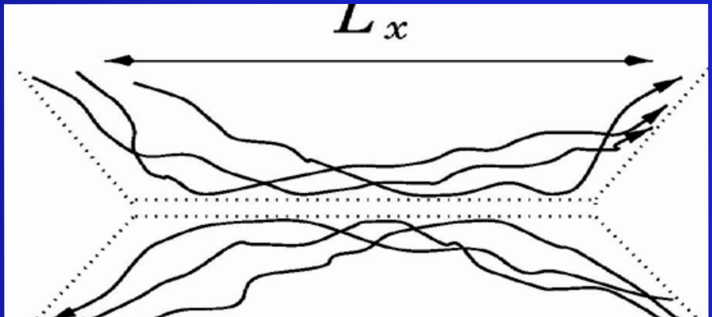
In 10 years a substantial convergence between the models took place



Hall MHD 1999

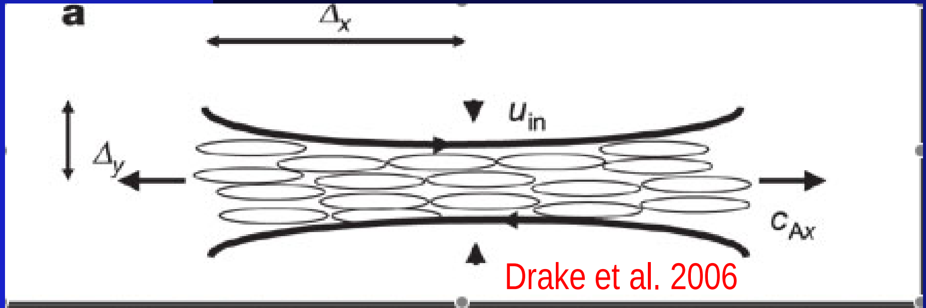


Our model



Lazarian & Vishniac 1999

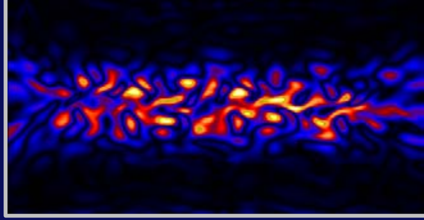
Hall MHD 2009



Drake et al. 2006

Our model is the one of volume filled reconnection. John Raymond attempted to test our model, confirmed its predictions, but by that time the Hall MHD model evolved…

We solve MHD equations with outflow boundaries



MHD equations with turbulence forcing:

$$\frac{\partial \rho}{\partial t} + \nabla\cdot(\rho \vec{v}) = 0$$

$$\frac{\partial \rho\vec{v}}{\partial t} + \nabla\cdot\left[\rho\vec{v}\vec{v} + \left(c_s^2\rho + \frac{B^2}{8\pi}\right)\vec{I} - \frac{1}{4\pi}\vec{B}\vec{B}\right] = \rho\vec{f}$$

$$\frac{\partial \vec{B}}{\partial t} = \nabla\times\left(\vec{v}\times\vec{B} + \eta\nabla\times\vec{B}\right), \nabla\cdot\vec{B} = 0$$

isothermal EOS

HLLD solver
Field interpolated
constrained transport

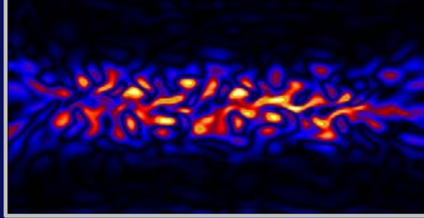
Forcing:

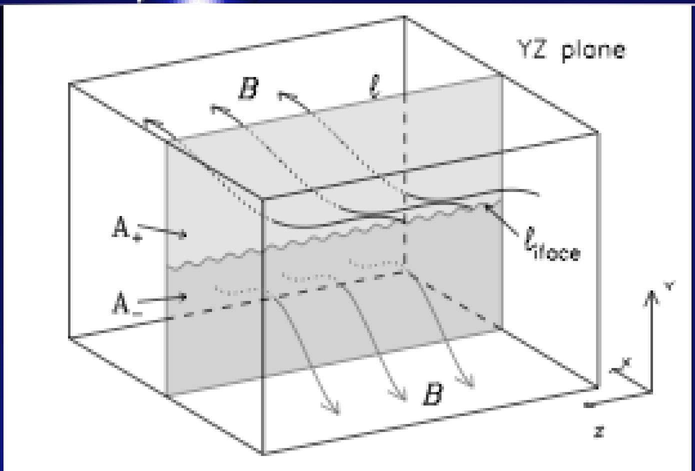
- random with adjustable injection scale (k_f~8 or 16)
- divergence free (purely incompressible forcing)

Resistivity:
-Ohmic
-Anomalous

Kowal, Lazarian, Vishniac & Otmianowska-Mazur (2009, ApJ, 700,63)

We used both an intuitive measure, V_{inflow}, and a new measure of reconnection





$$\partial_t \Phi = -\oint \boldsymbol{E}\cdot d\boldsymbol{l} = \oint (\boldsymbol{v}\times\boldsymbol{B} - \eta\boldsymbol{j})\cdot d\boldsymbol{l}$$

$$\partial_t\Phi_+ - \partial_t\Phi_- = \partial_t \int |B_x| dA,$$

$$\partial_t \int |B_x| dS = \oint \vec{E}\cdot d\vec{l}_+ - \oint \vec{E}\cdot d\vec{l}_- = \oint sign(B_x)\vec{E}\cdot d\vec{l} + \int 2\vec{E}\cdot d\vec{l}_{interface}$$

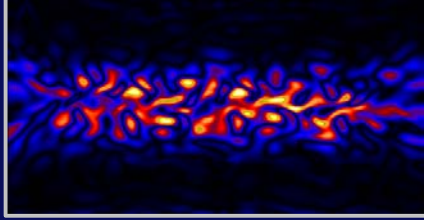
$$\int 2\vec{E}\cdot d\vec{l}_{interface} \equiv -2V_{rec}|B_{x,\infty}|L_z$$

Asymptotic absolute value of Bx

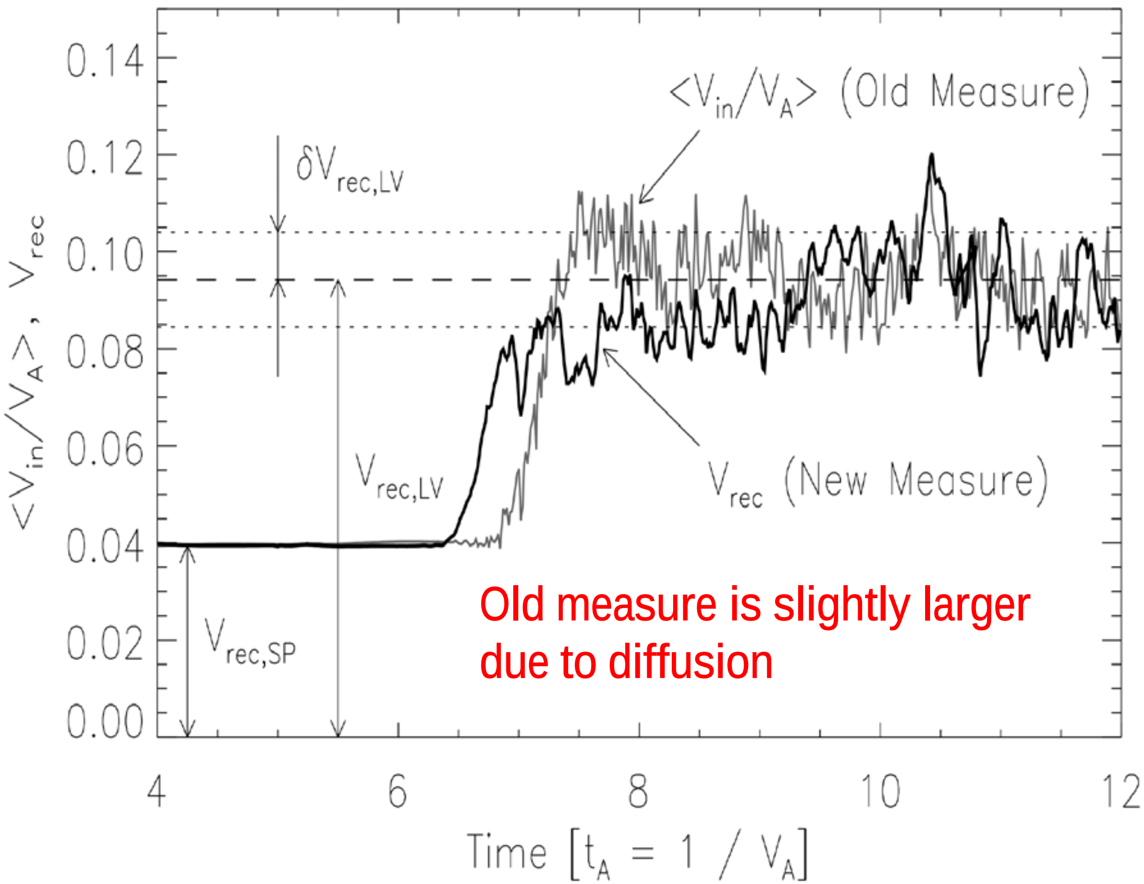
New measure:

$$V_{rec} = -\frac{1}{2|B_{x,\infty}|L_z}\left[\partial_t \int |B_x| dA - \oint sign(B_x)\vec{E}\cdot d\vec{l}\right]$$

Calculations using the new measure are consistent with those using the intuitive one



Stochastic reconnection

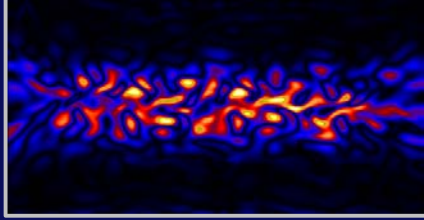


Old measure is slightly larger due to diffusion

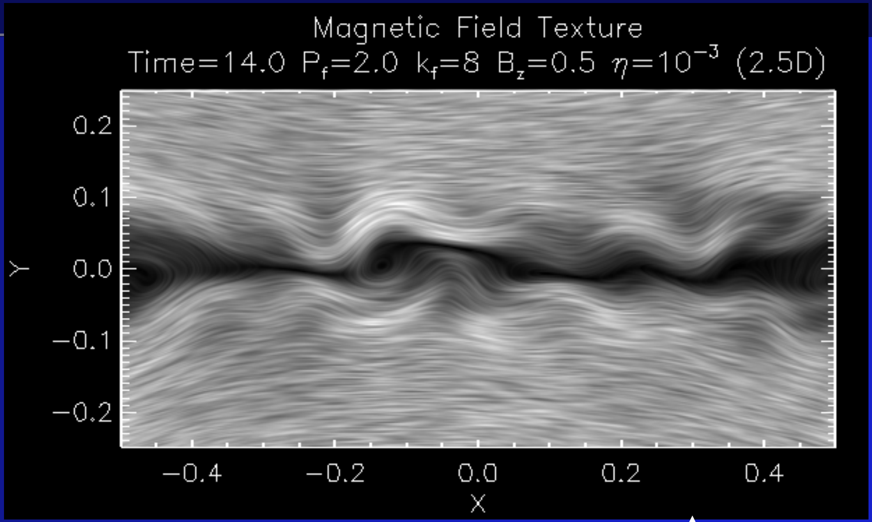
Intuitive, "old" measure is the measure of the influx of magnetic field

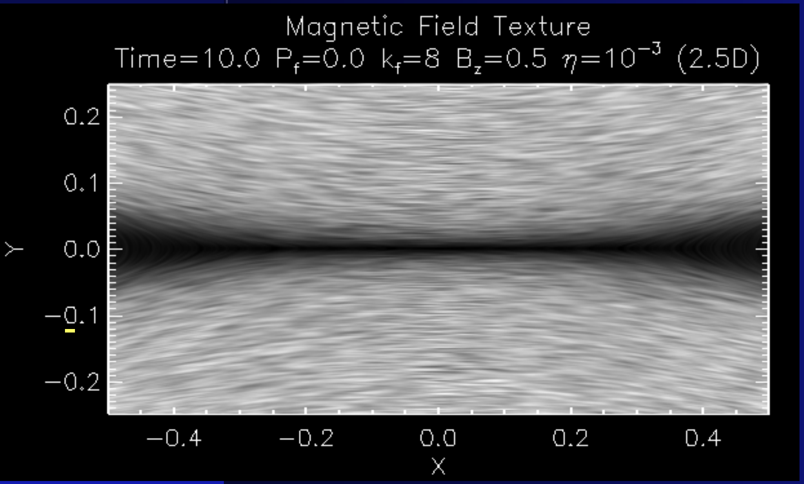
New measure probes the annihilation of the flux

Reconnection layer structure depends on the scale of energy injection

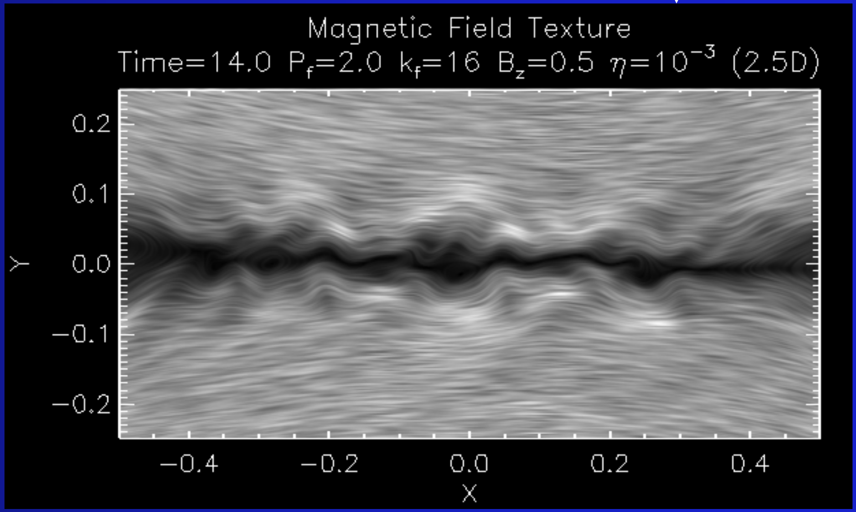


k=8





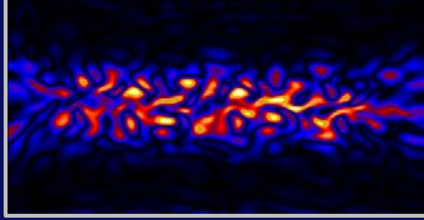
Turbulence with different scales

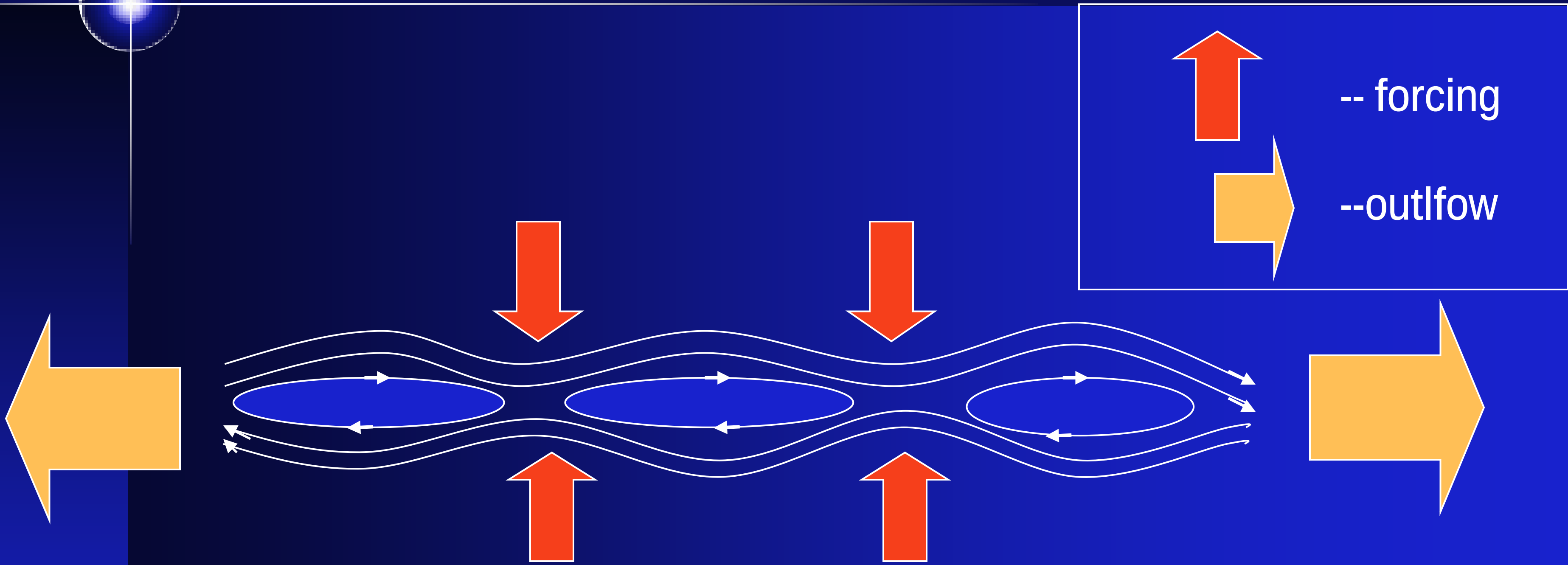


Laminar Sweet-Parker reconnection

k=16

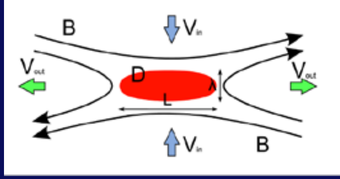
Turbulence can enhance reconnection even in 2D via ejecting of islands





Slower than in 3D as no multiple reconnection events are possible. The rate depends on both forcing and resistivity.

The range of direct applicability of collisionless reconnection is rather limited



Reconnection is collisionless if $\delta_{SP} < d_i \equiv c/\omega_{pi}$

$$\delta_{SP} = LRm^{-1/2} = \sqrt{L\eta/V_A}$$

Sweet-Parker sheet thickness

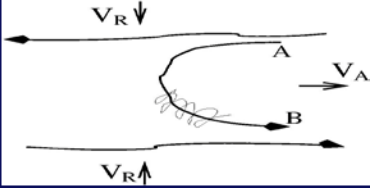
Which translates into a restrictive: for $\beta \approx 1$

$$\lambda_{e,mfp} > L/40$$

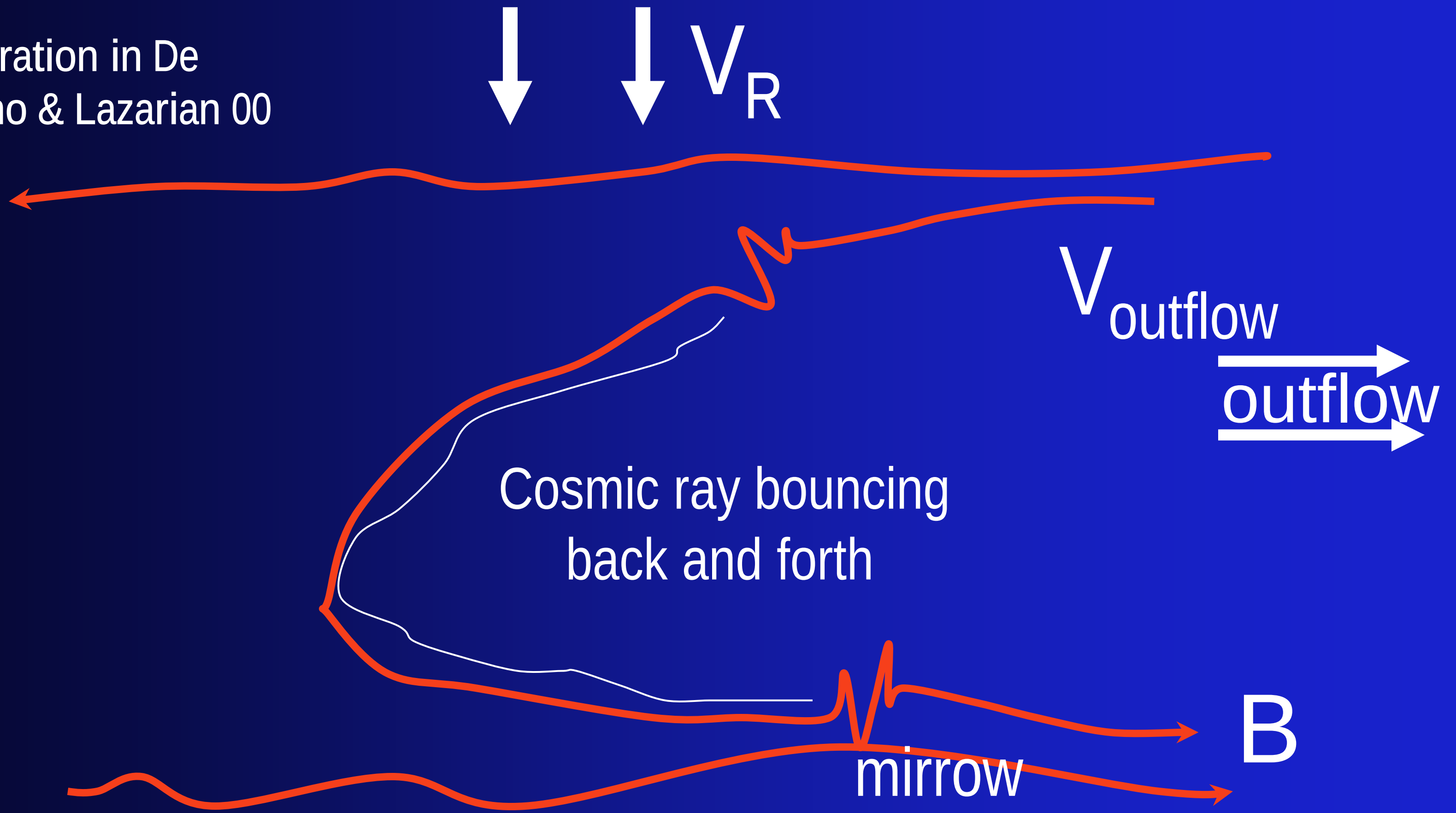
Yamada et al. (2006)

Which makes a lot of astrophysical environments, e.g. ISM, disks, stars collisional! Does it mean that all numerics in those fields is useless?

Turbulent reconnection efficiently accelerates cosmic rays by first order Fermi process

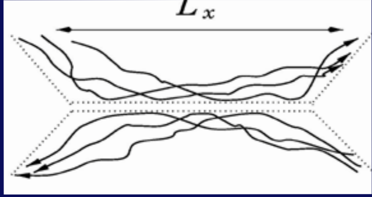


Model of acceleration in De Gouveia Dal Pino & Lazarian 00



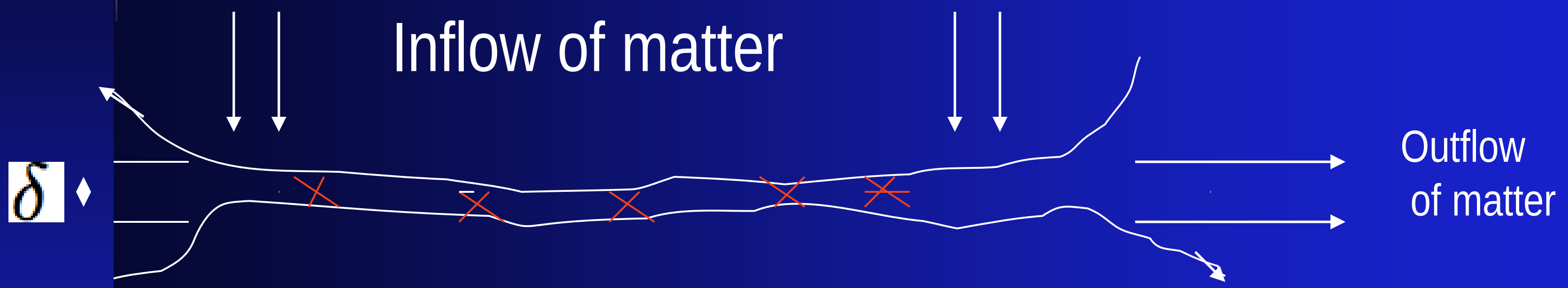
Applications to pulsars, microquasars, solar flare acceleration (De Gouveia Dal Pino & Lazarian 00, 04, Lazarian 04).

Original Petschek reconnection fails for generic astrophysical situations



Large scale fields:

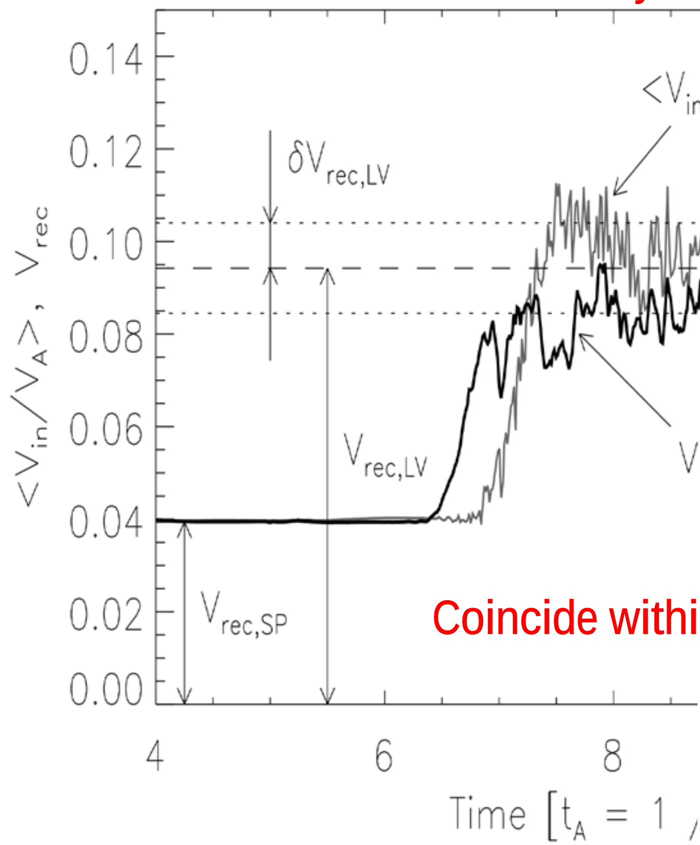
X point over many parsecs?



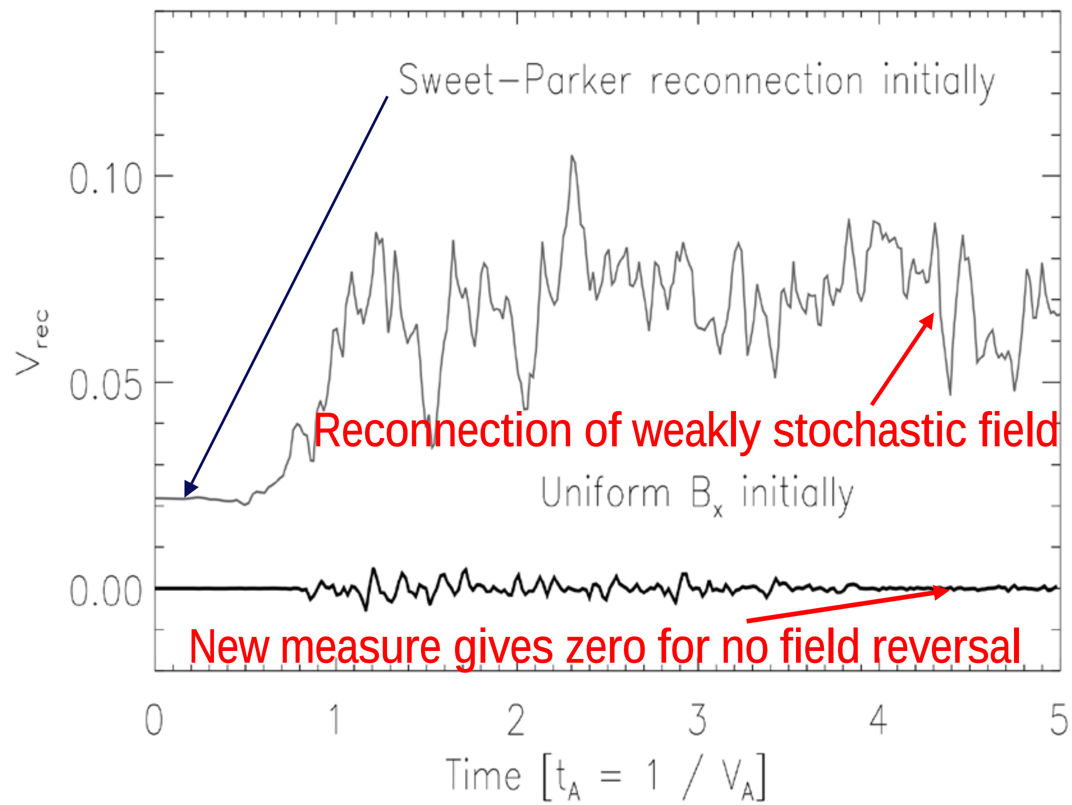
If the outflow slot δ is very small reconnection is slow because of the mass conservation constraint.

Observations suggest that Solar reconnection layers are thick and not X-points (Raymond et al. 07). Also in most of ISM, stars, protostellar disks the reconnection is in collisional regime.

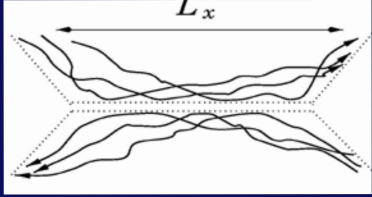
Reconnection of weakly stochastic field



Tests of new measure: no effect of flux diffusion



While electrons make many gyrations over a collision time, reconnection is collisional for interstellar medium



For ISM the collisionality parameter is $\omega_{ce}\tau_e \sim 10^5 BT^{3/2}/n_e \sim 10^5$ >> 1.

But the condition for the reconnection to be "collisionless" is different, i. e. $\delta_{SP}/d_i < 1$,

$d_i \sim 200/\sqrt{n_i}$ km is ion inertial length and $\delta_{SP} = (Ld_i/\omega_{ce}\tau_e)^{1/2}$ is resistive width.

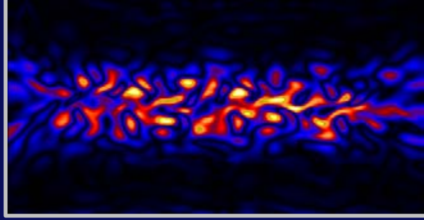
Thus the interstellar gas is in collisionless if $$\frac{\delta_{SP}}{d_i} \sim \left(\frac{L}{d_i}\right)^{1/2} (\omega_{ce}\tau_e)^{-1/2}$$

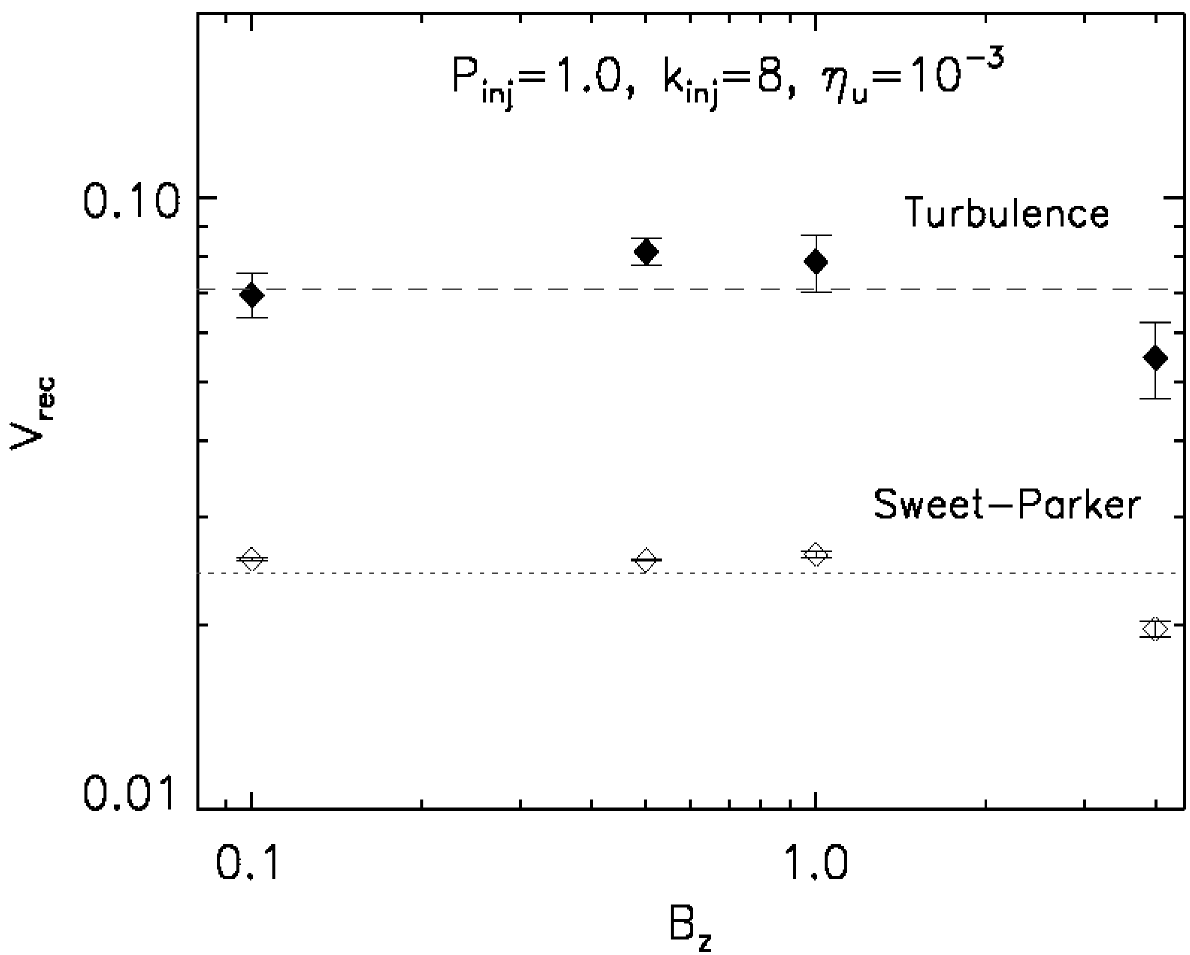
and the current sheet length of sheets

$L < 10^{12}$ cm

Too small!!!

Reconnection rate marginally depends on the guide field amplitude





Lazarian & Vishniac 1999 model predicts the dependence on field wandering, but not on the amplitude of guide field