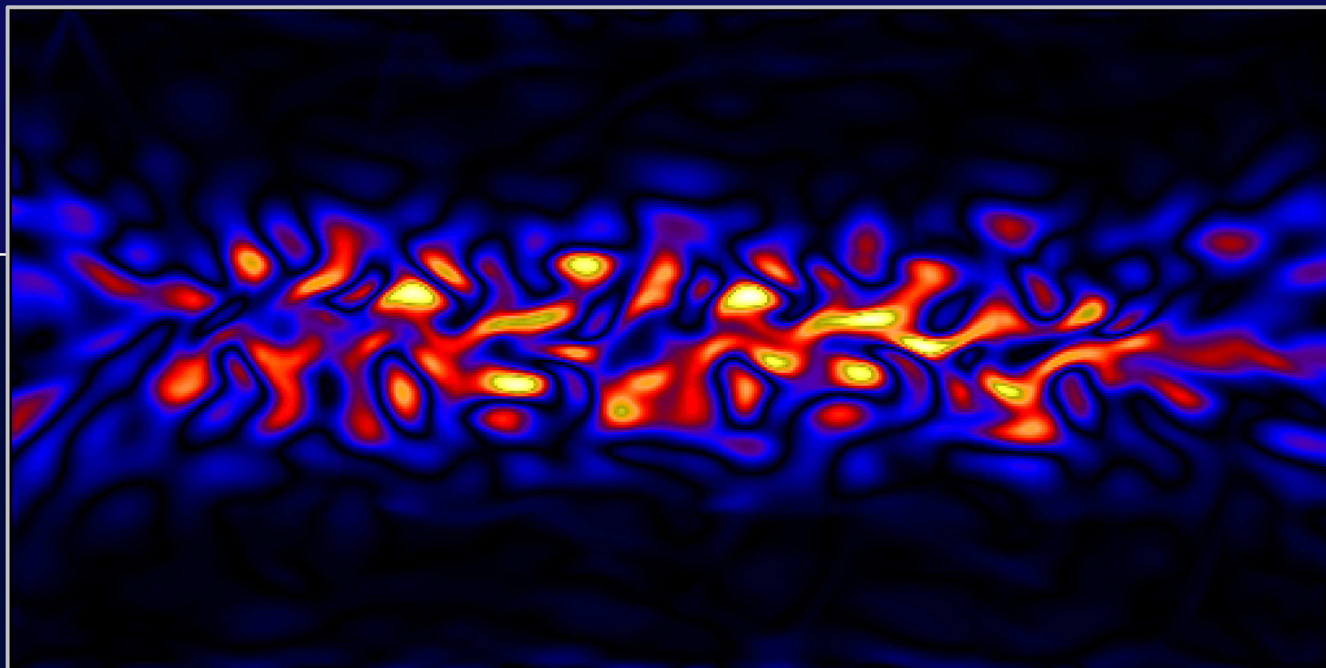
3D Reconnection of Weakly Stochastic Magnetic Field and its Implications



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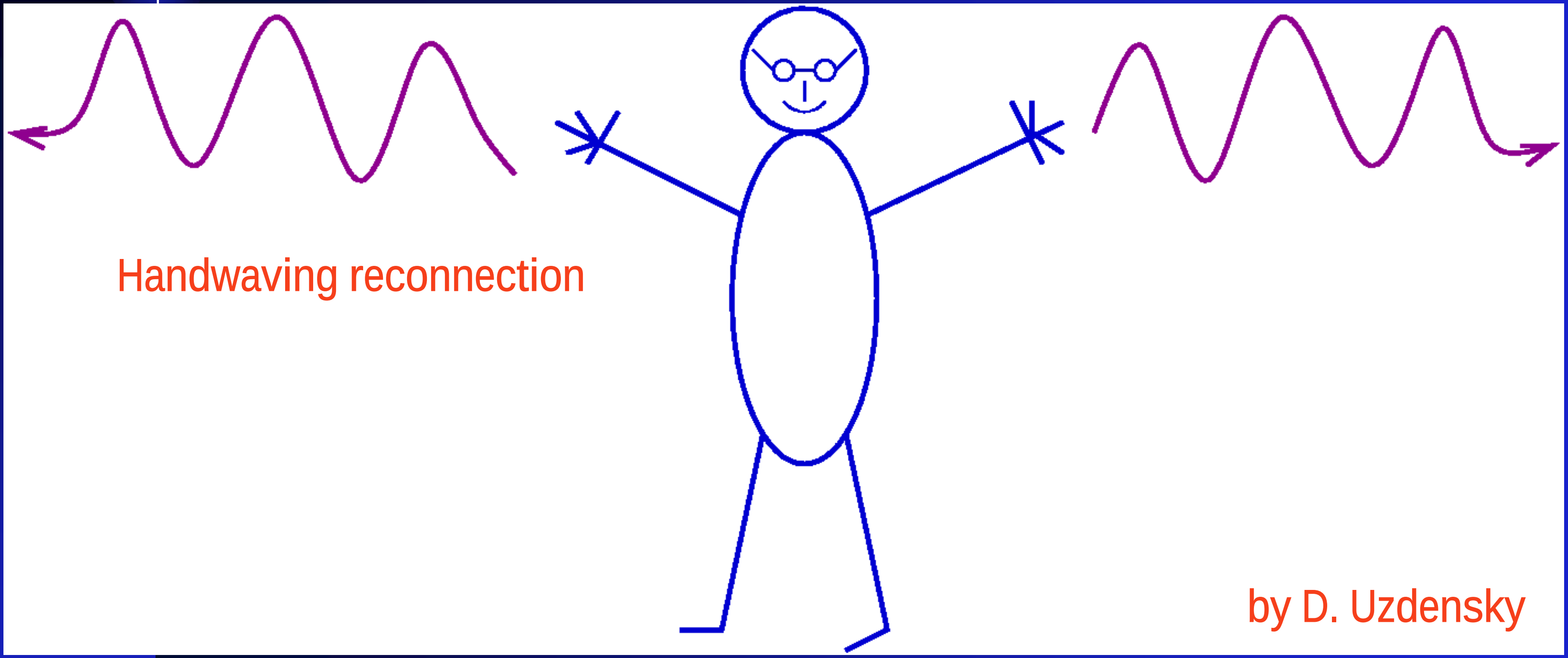
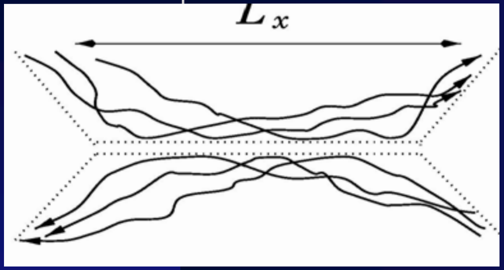
Astrophysical reconnection was always associated with a particular kind of waves



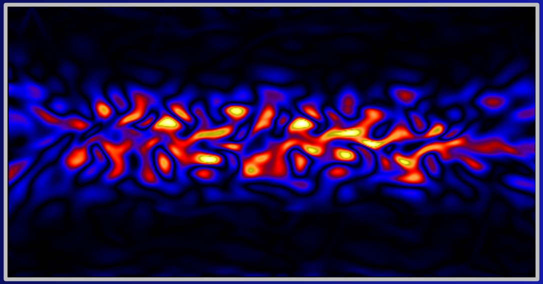
I am sure that Vahe' prefers other types of waves or non-linear interactions to do the job

The talk covers theory of reconnection, numerical testing and implications

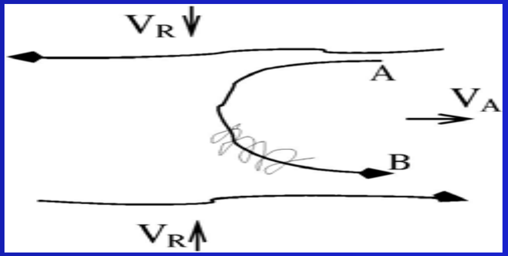
Reconnection of stochastic field



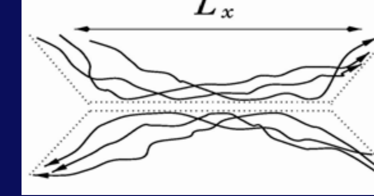
Numerical testing of reconnection

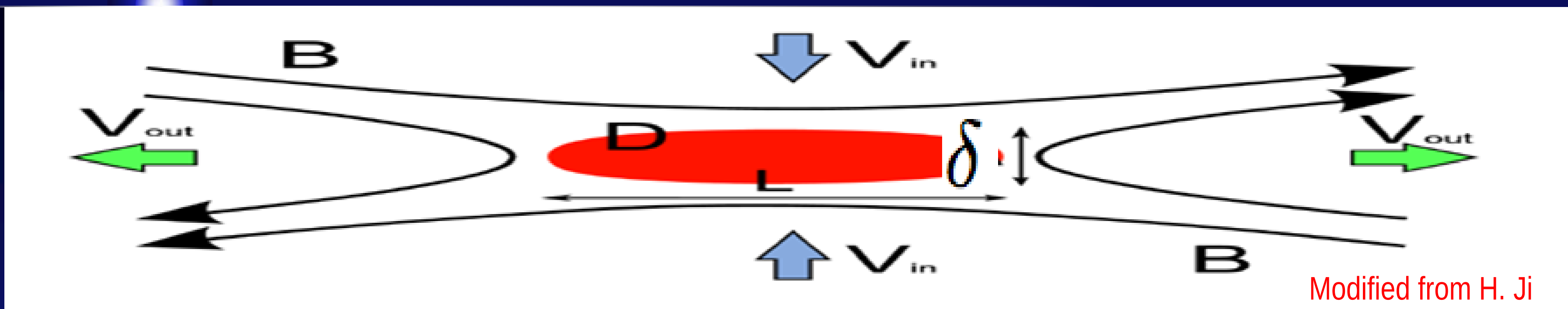


Implications of new model



Sweet-Parker model exhibits long and thin current sheets; very slow rates





$$V_{in} = \eta/\delta$$ Ohmic diffusion

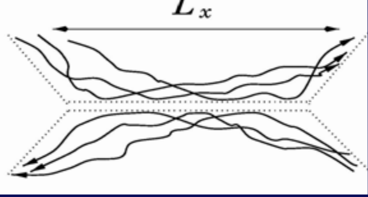
$$V_{in} L = V_{out} \delta$$ Mass conservation

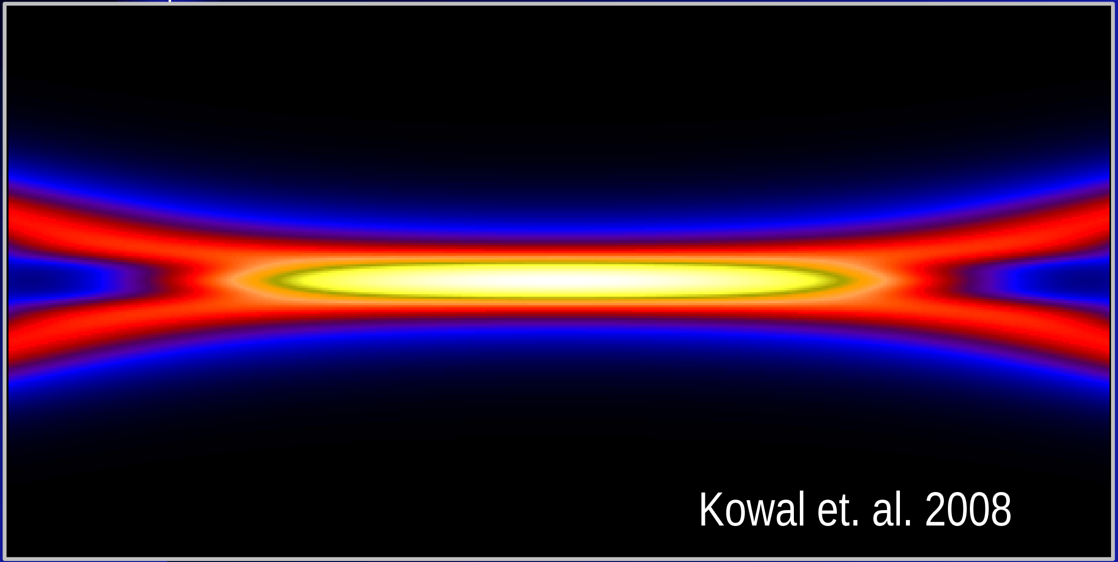
$$V_{out} = V_A$$ Free outflow

RECONNECTION RATE

$$V_{in} = V_A (L V_A/\eta)^{-1/2} = V_A Rm^{-1/2}$$

Reconnection rates for Sweet-Parker model are negligible in Astrophysics





Kowal et. al. 2008

Corresponds well to simulations, collisional lab. studies.

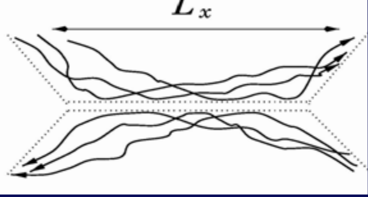
$$V_{SP} = V_A Rm^{-1/2}$$

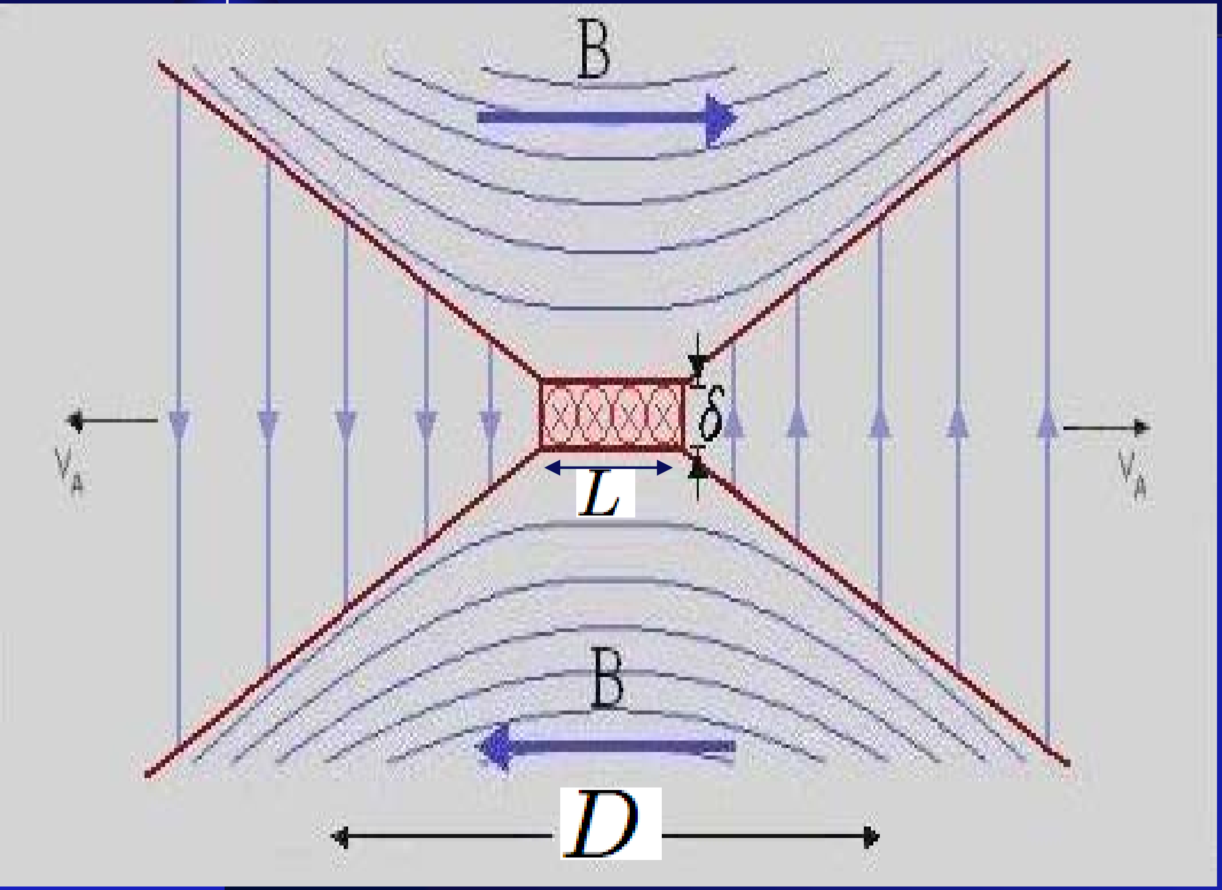
For interstellar medium

$$Rm \sim (L/d_i)\omega_{ce}\tau_e \sim 10^{16}(L/pc)$$

$$V_{SP} \sim 10^{-8} V_A$$

Petschek model does not work for uniform resistivities



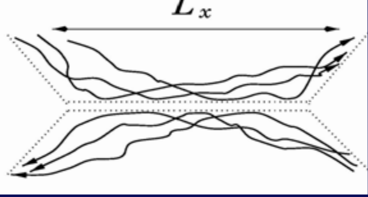


X point

Both dimensions are comparable.

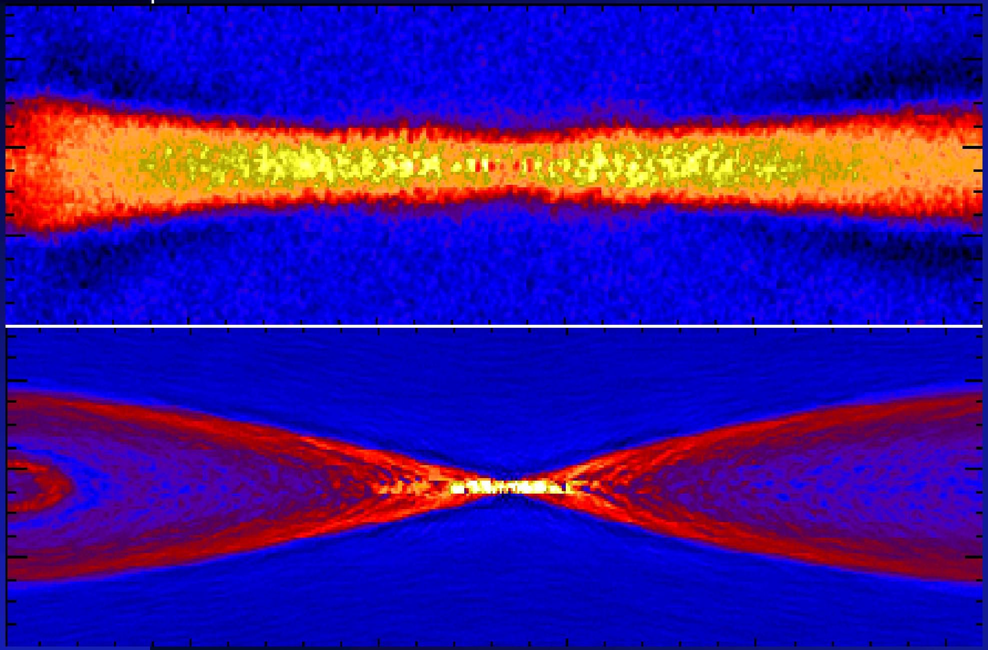
$$L \sim \delta$$

Fast reconnection $V_R \sim V_A$



Anomalous effects stabilize Petschek model, but are very restrictive

Hall MHD



Petcheck + anomalous effects

ion current

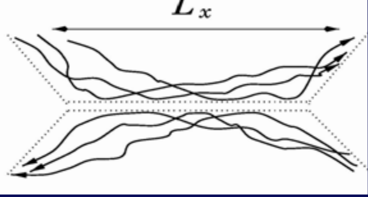
e current

(Drake et al. '98)

Very stringent requirement: mean free path of an electron is comparable with astrophysical L

Vahe' deals with both collisional and collisionless media.

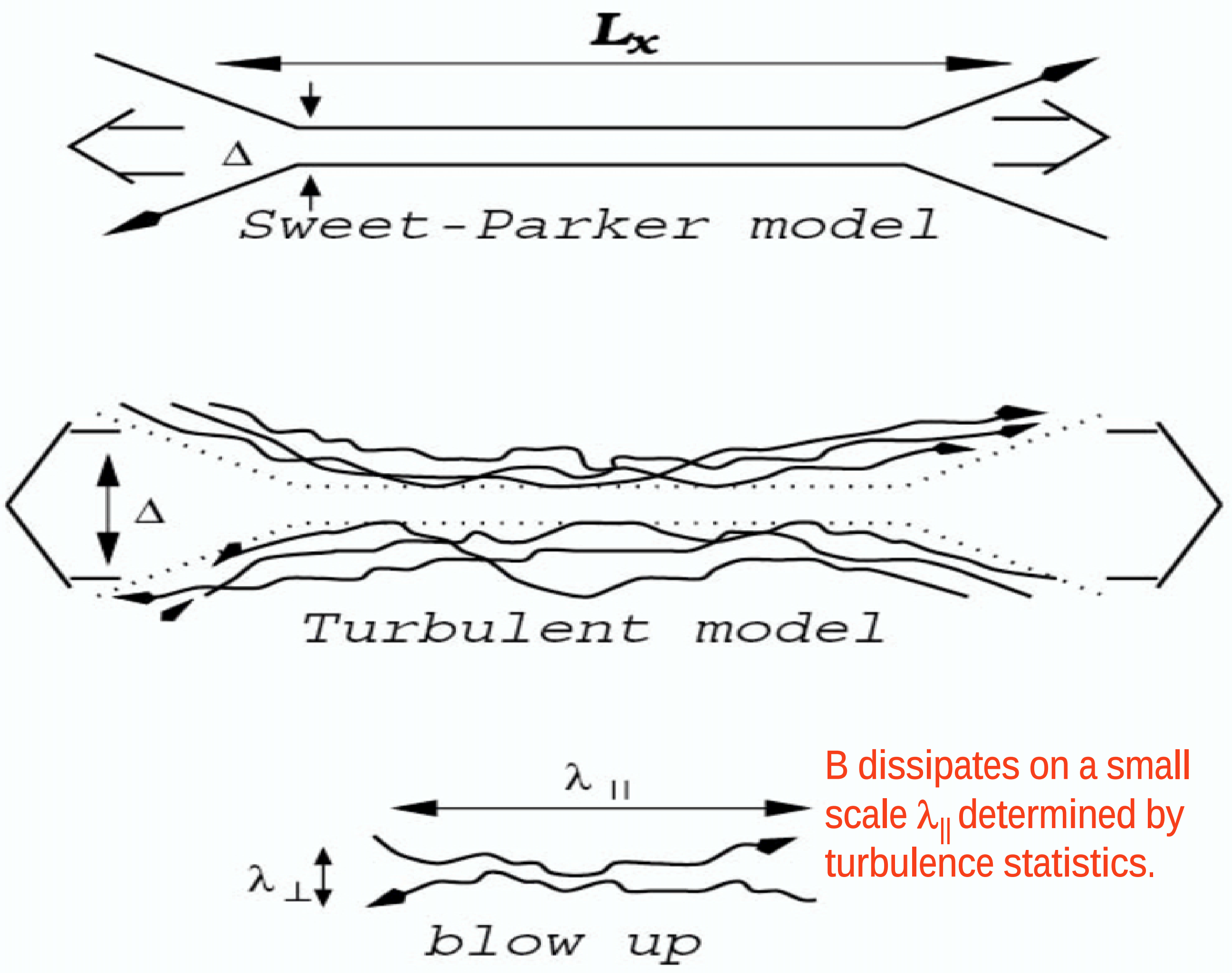
Reconnection of 3D weakly turbulent magnetic fields involves many simultaneous reconnection events



Turbulent reconnection:

1. Outflow is determined by field wandering.

2. Reconnection is fast with Ohmic resistivity only.



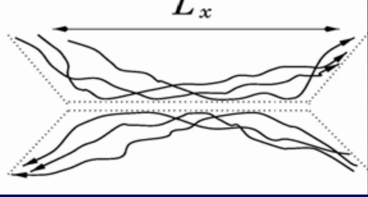
B dissipates on a small scale $\lambda_{||}$ determined by turbulence statistics.

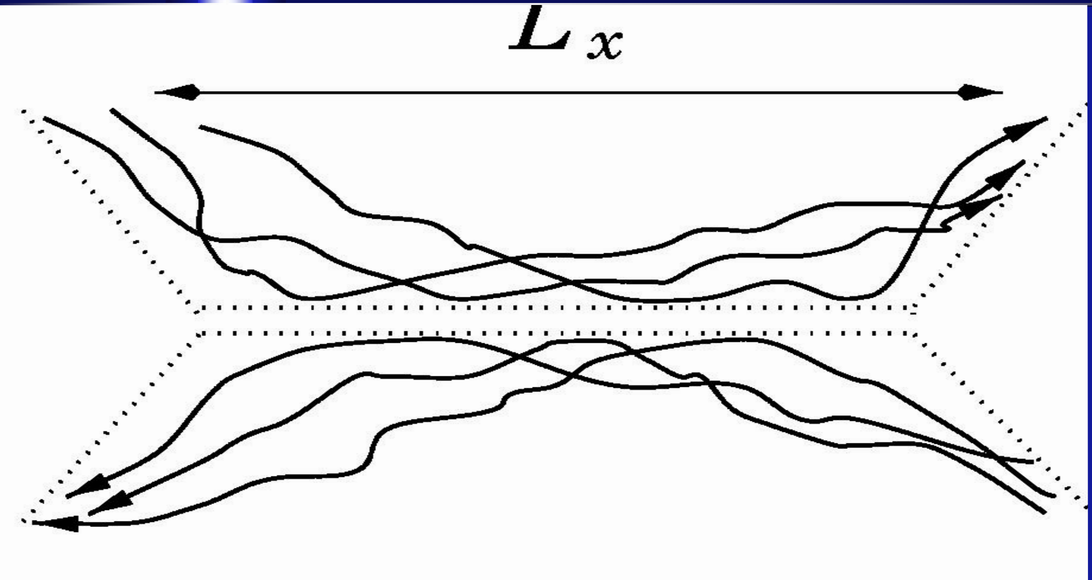
Key element:

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

Lazarian & Vishniac (1999)

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





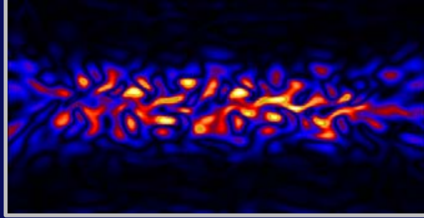
Predictions in Lazarian & Vishniac (1999):

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 $V_{rec} \sim l_{inj} P_{inj}^{1/2}$

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)

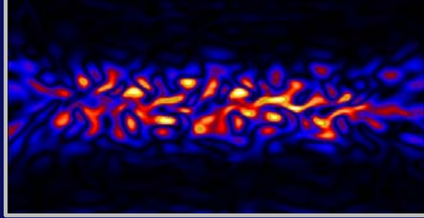
Resistivity:

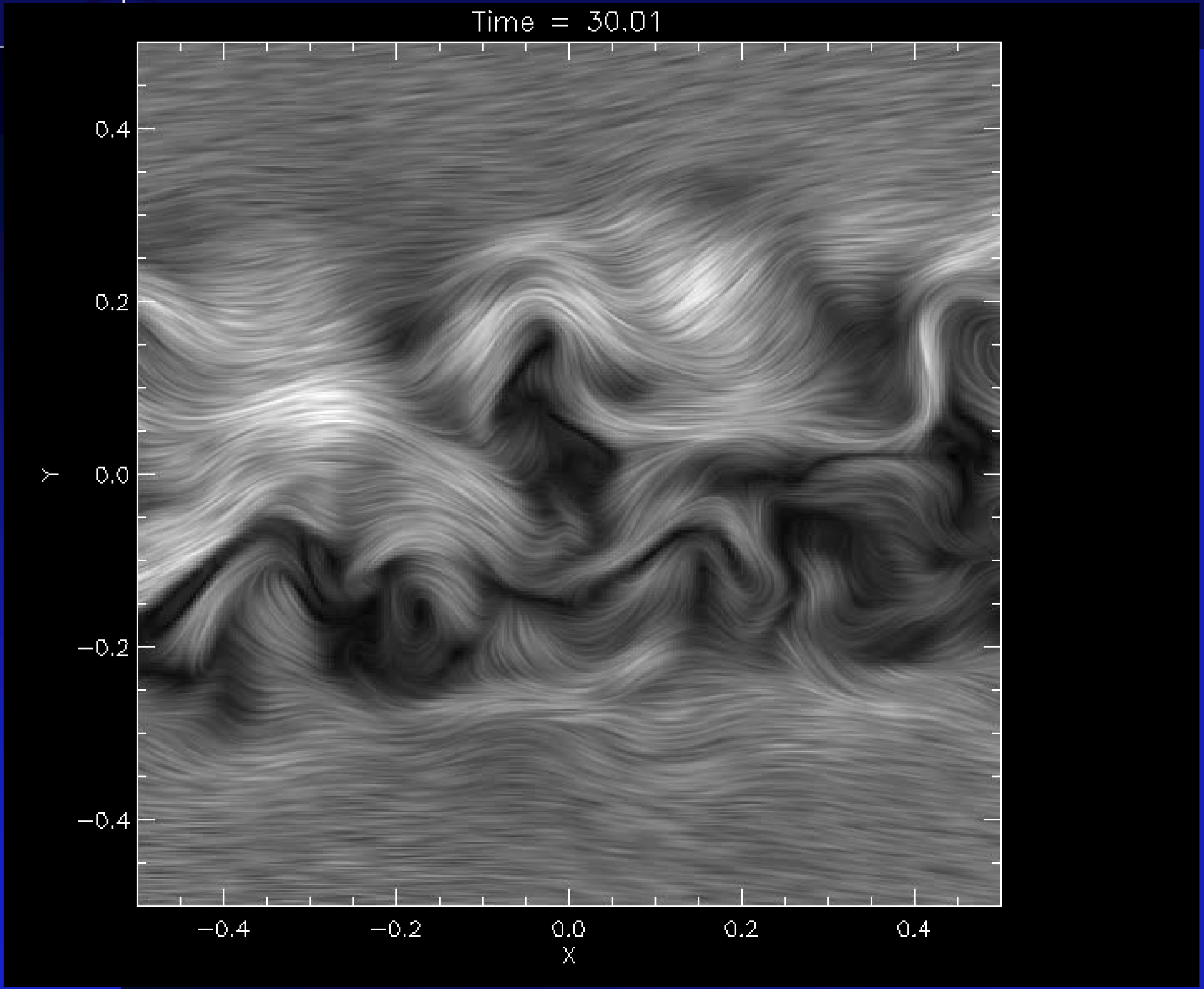
-Ohmic

-Anomalous

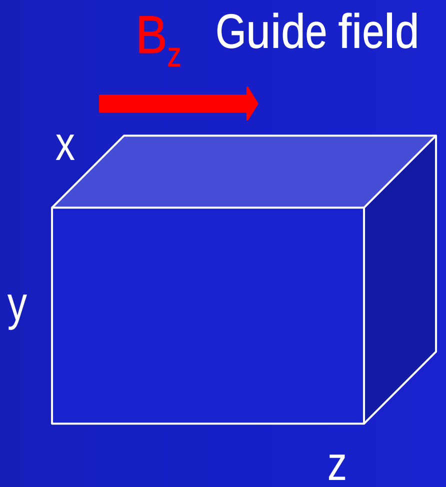
Kowal, Lazarian & Vishniac (2009) ApJ 700, 63-85

Magnetic field topology changes creating substantial component perpendicular to J



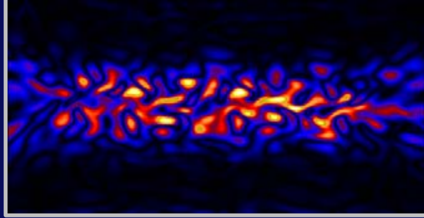


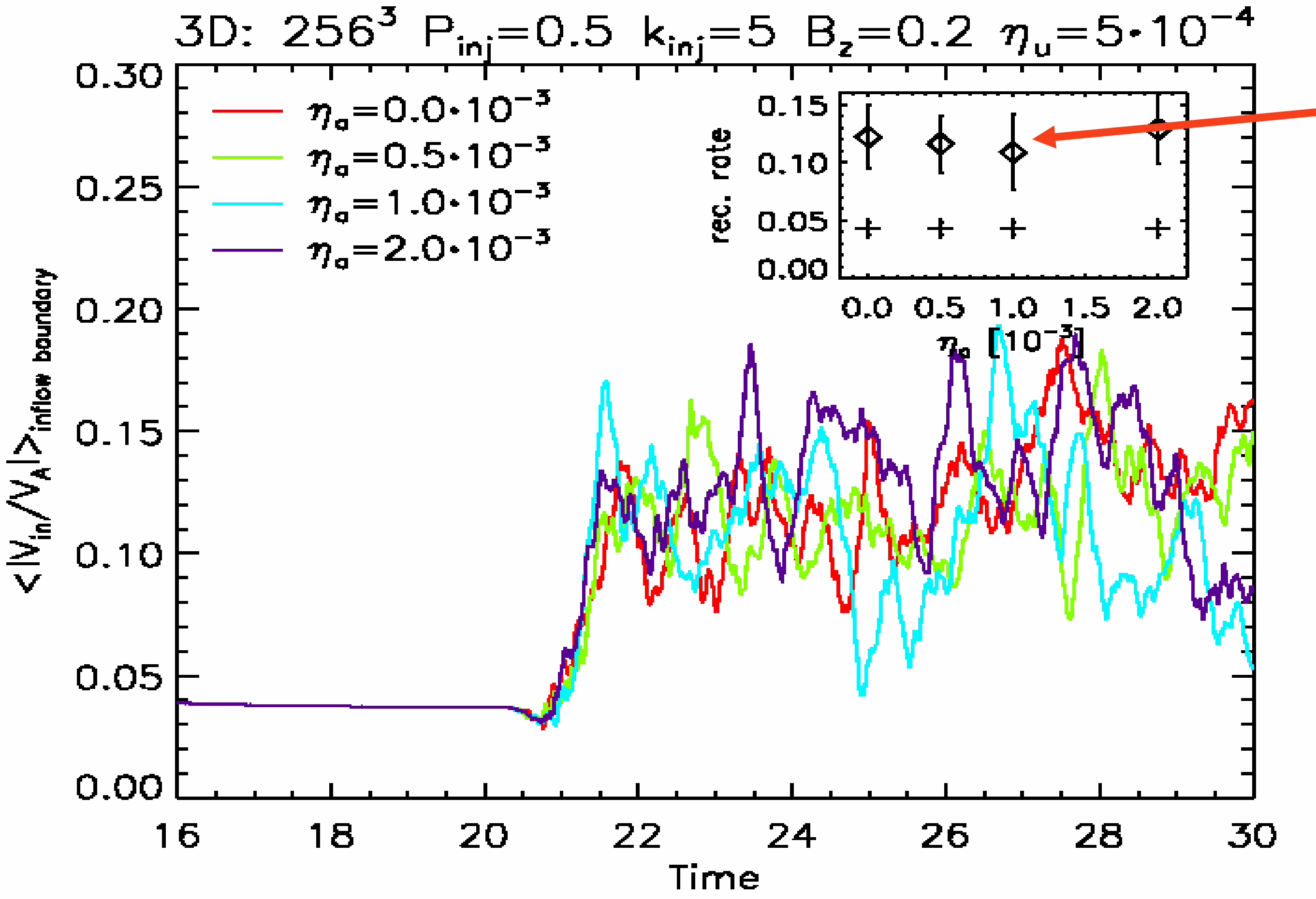
Textures reflect magnetic field topology



XY cut of simulation box

Reconnection rate does not depend on anomalous resistivity

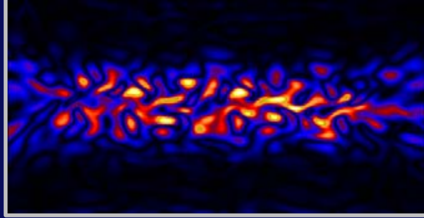


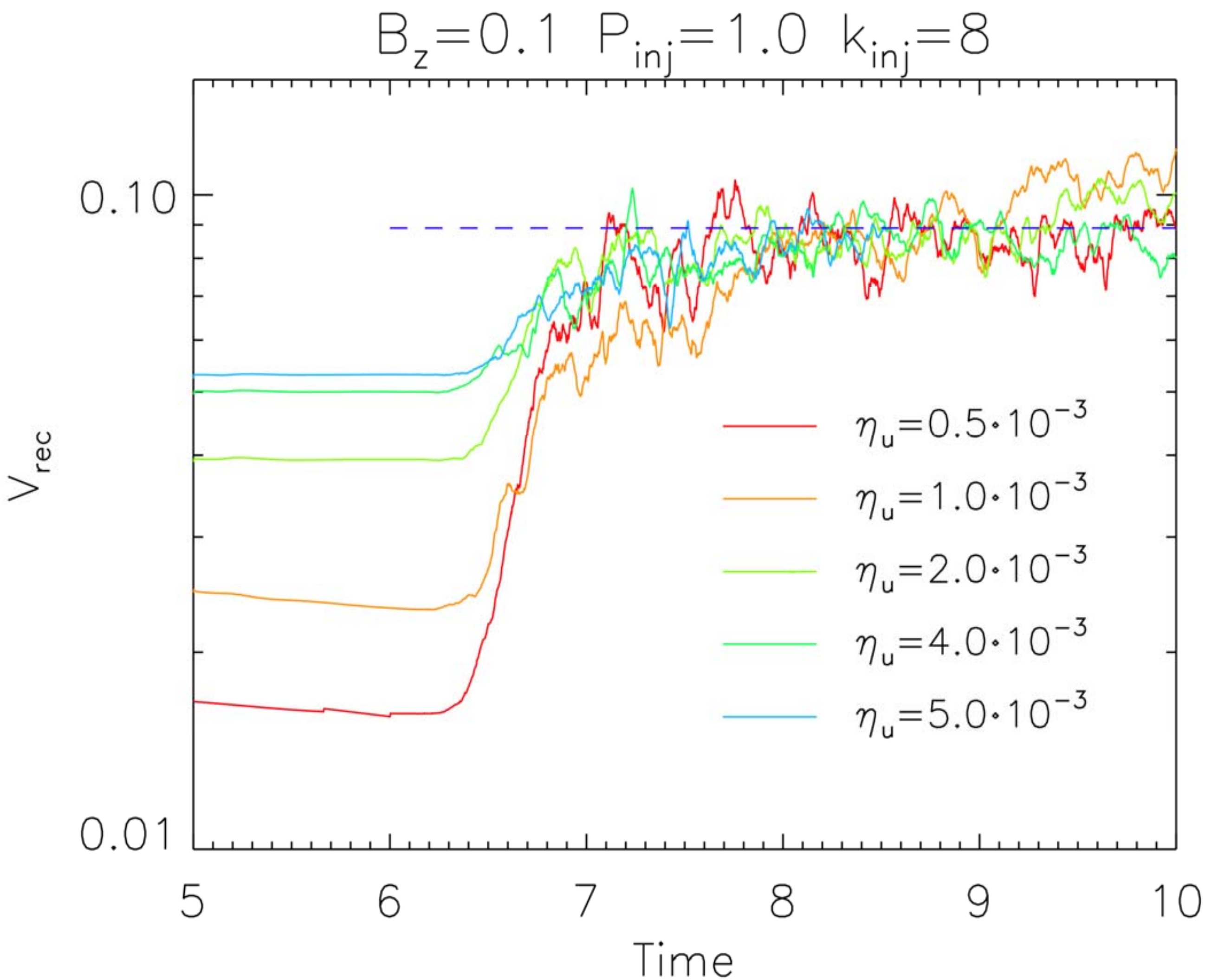


Flat dependence on anomalous resistivity

Reconnection does not require Hall MHD

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

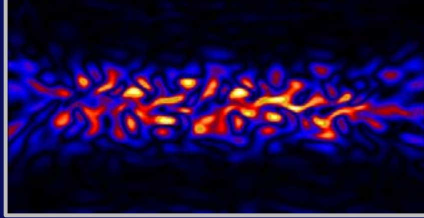


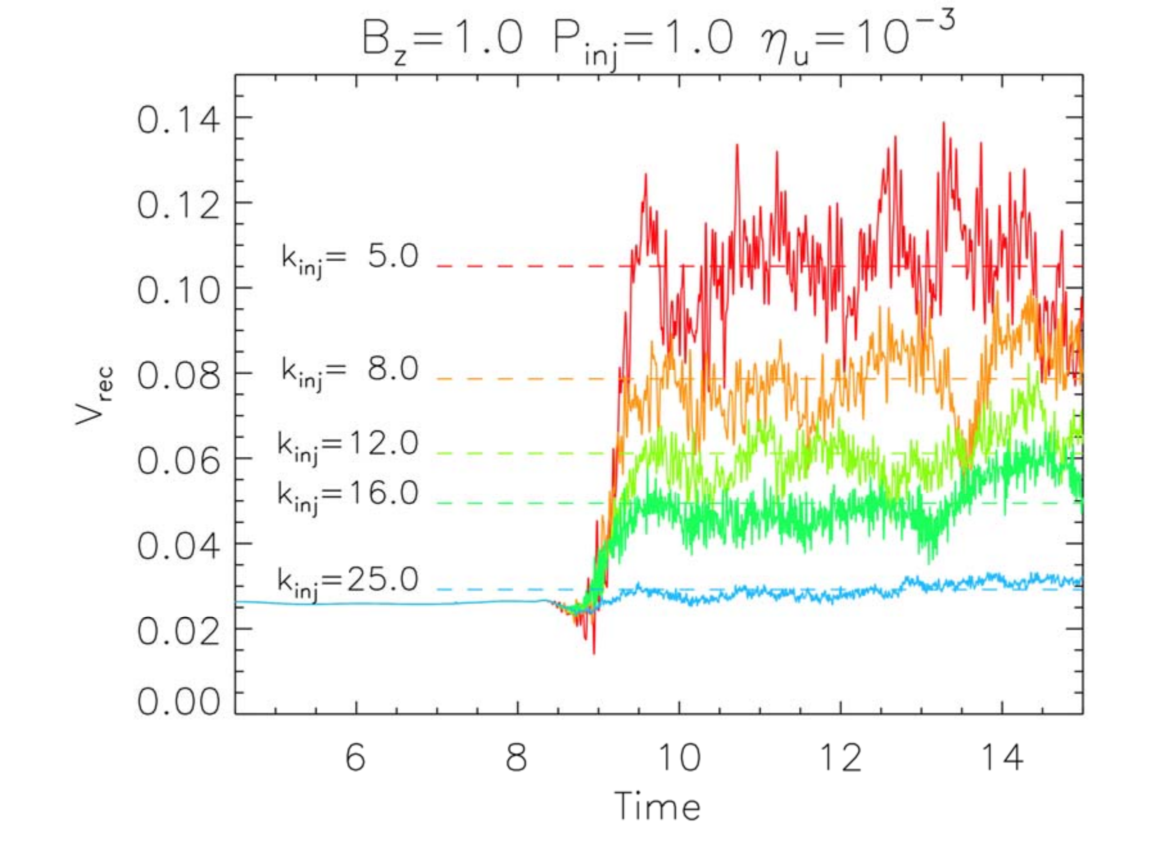


Lazarian & Vishniac 1999 predicts no dependence on resistivity

Results do not depend on the guide field

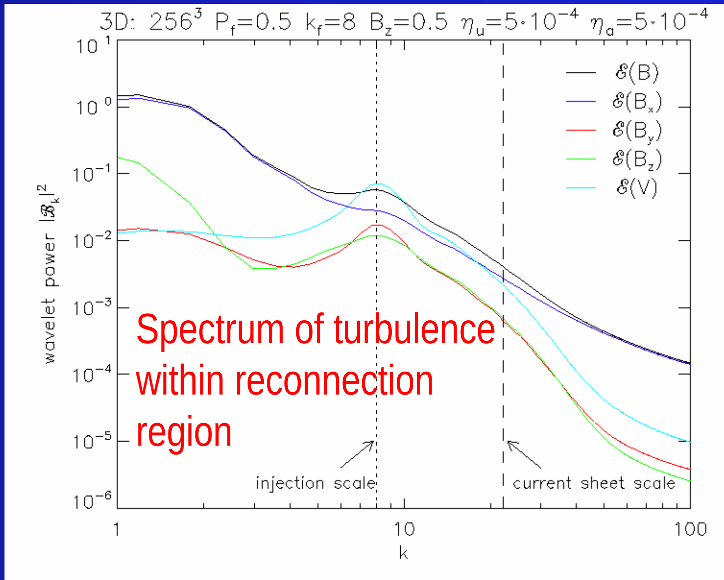
Reconnection rate increases with increase of injection scale



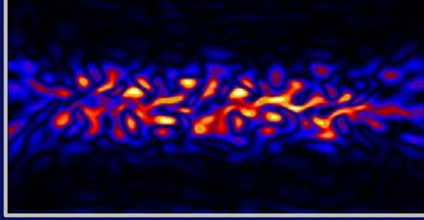


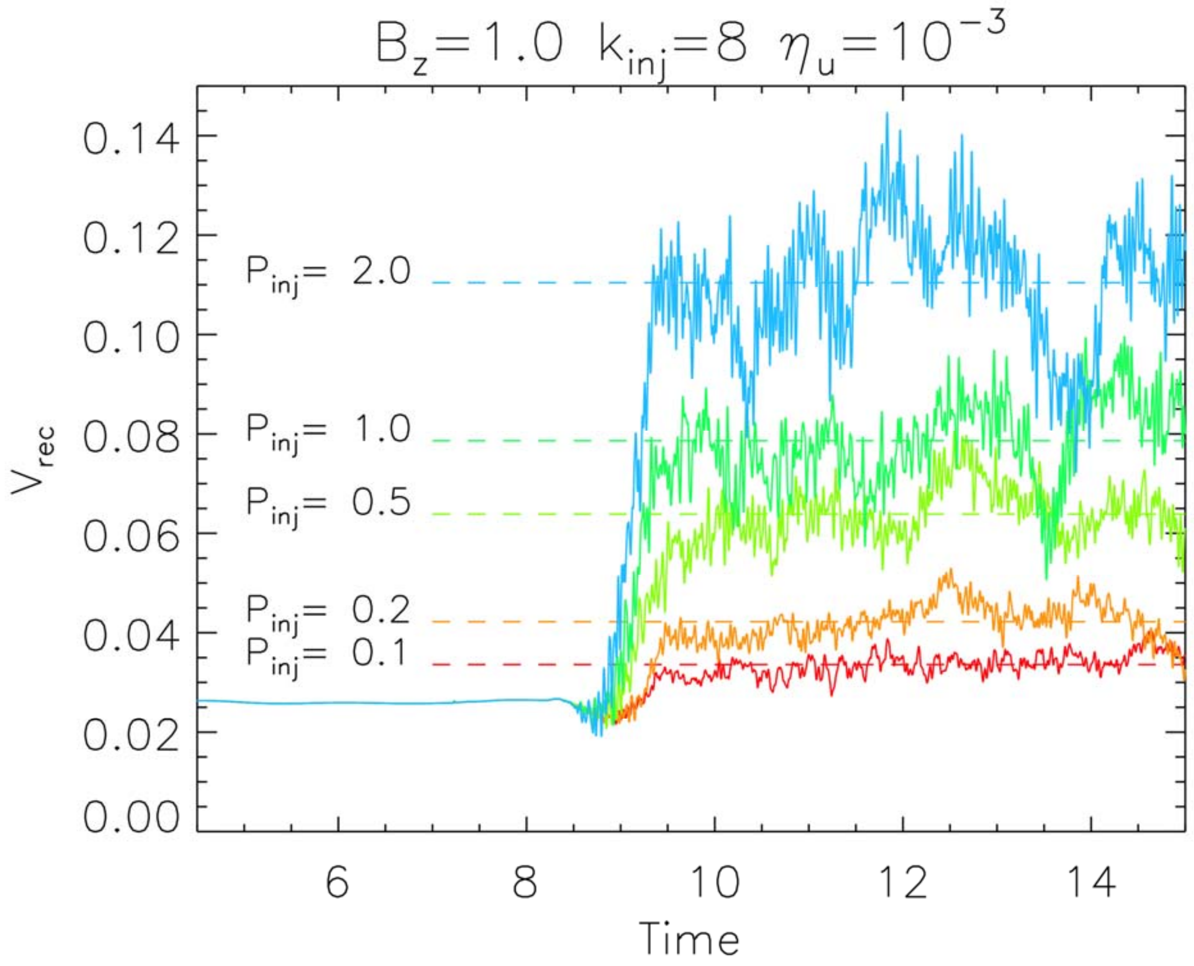
Lazarian & Vishniac (1999) prediction is $V_{rec} \sim l_{inj}^{1}$

Inverse cascade of energy



The reconnection rate increases with input power of turbulence

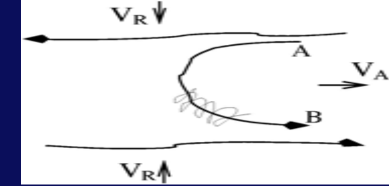


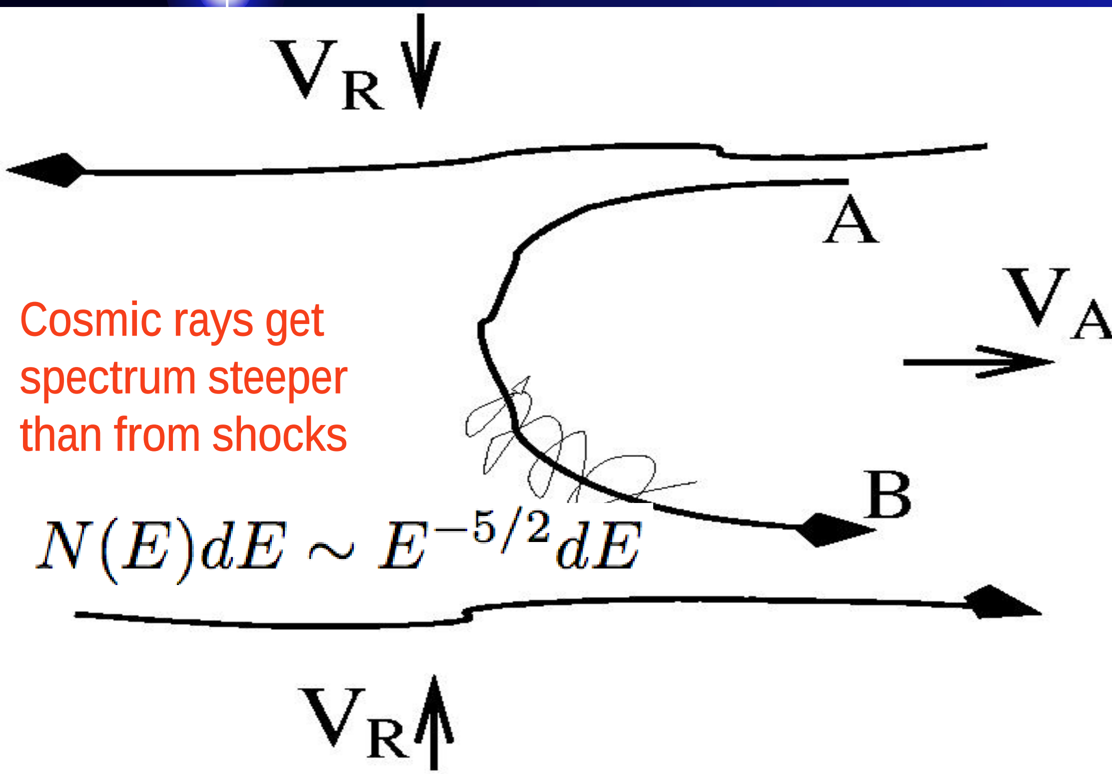


Lazarian & Vishniac (1999) prediction is $V_{rec} \sim P_{inj}^{1/2}$

Results do not depend on the guide field

Stochastic reconnection accelerates energetic particles without appealing to plasma effects





Cosmic rays get spectrum steeper than from shocks

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

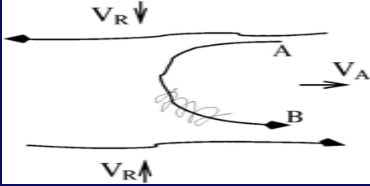
De Gouveia Dal Pino & Lazarian 2003

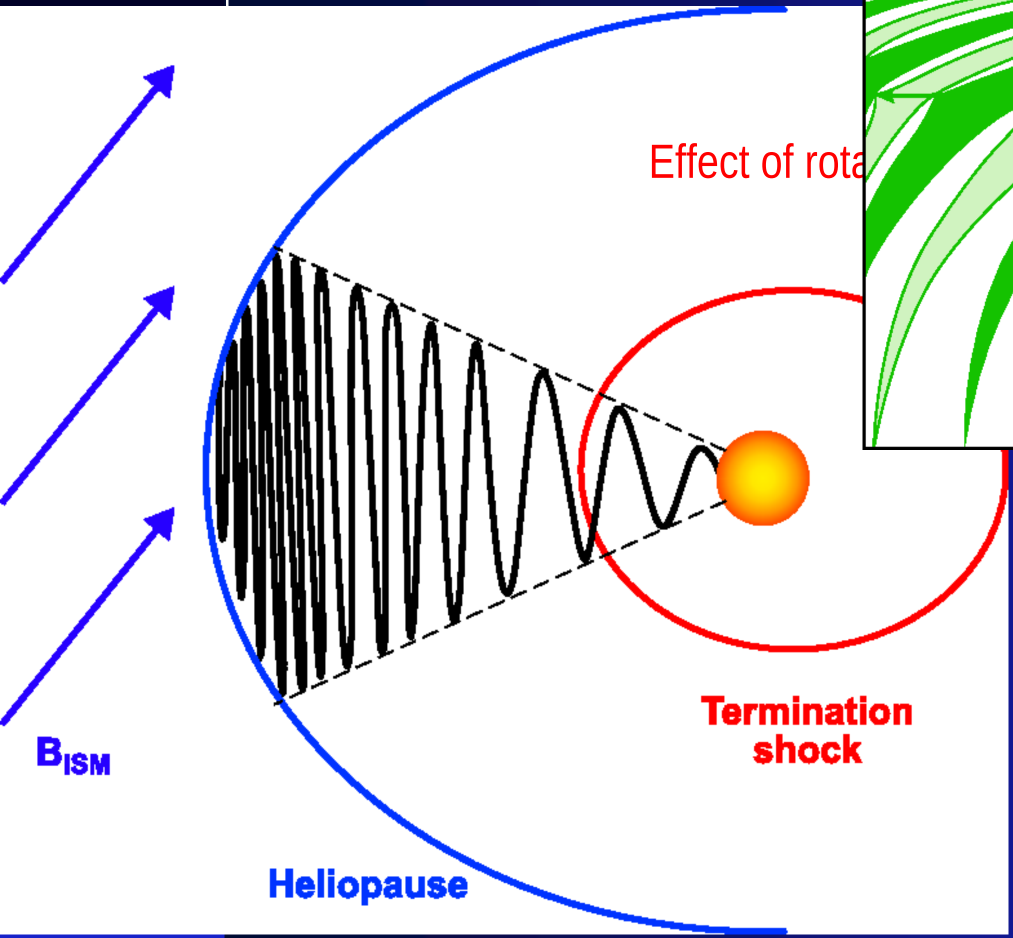
GL03 versus Drake et al. 06:

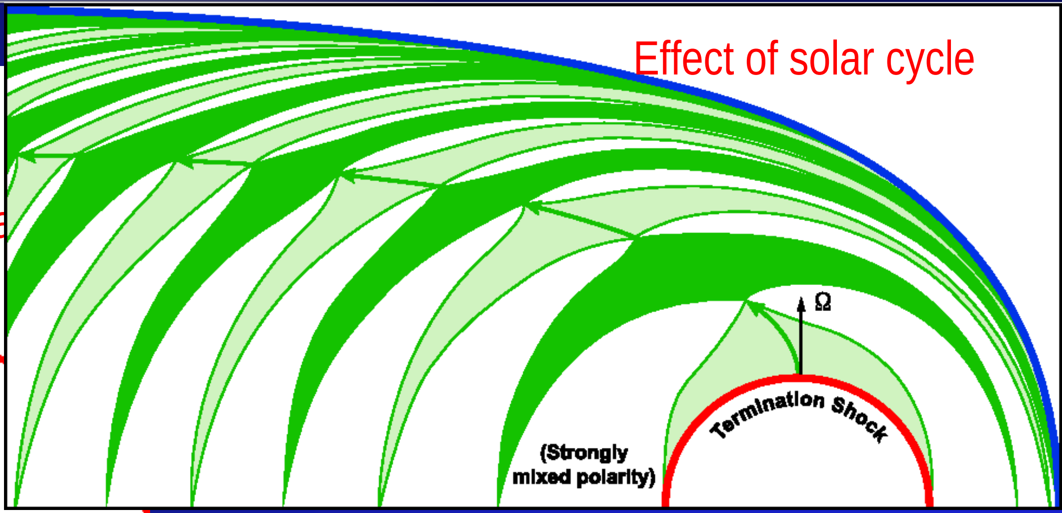
Drake et al. 2006 is 2D model with collapsing islands. The backreaction of accelerated electrons is accounted for.

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

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

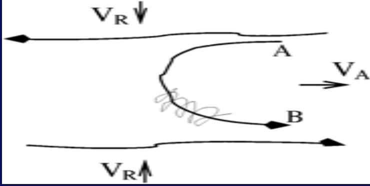






Observed anomalous CRs do not show features expected from the acceleration in the Termination shock

Lazarian & Opher 2009: both Sun rotation and Sun cycles create B-reversals in the heliosheath inducing acceleration via reconnection.

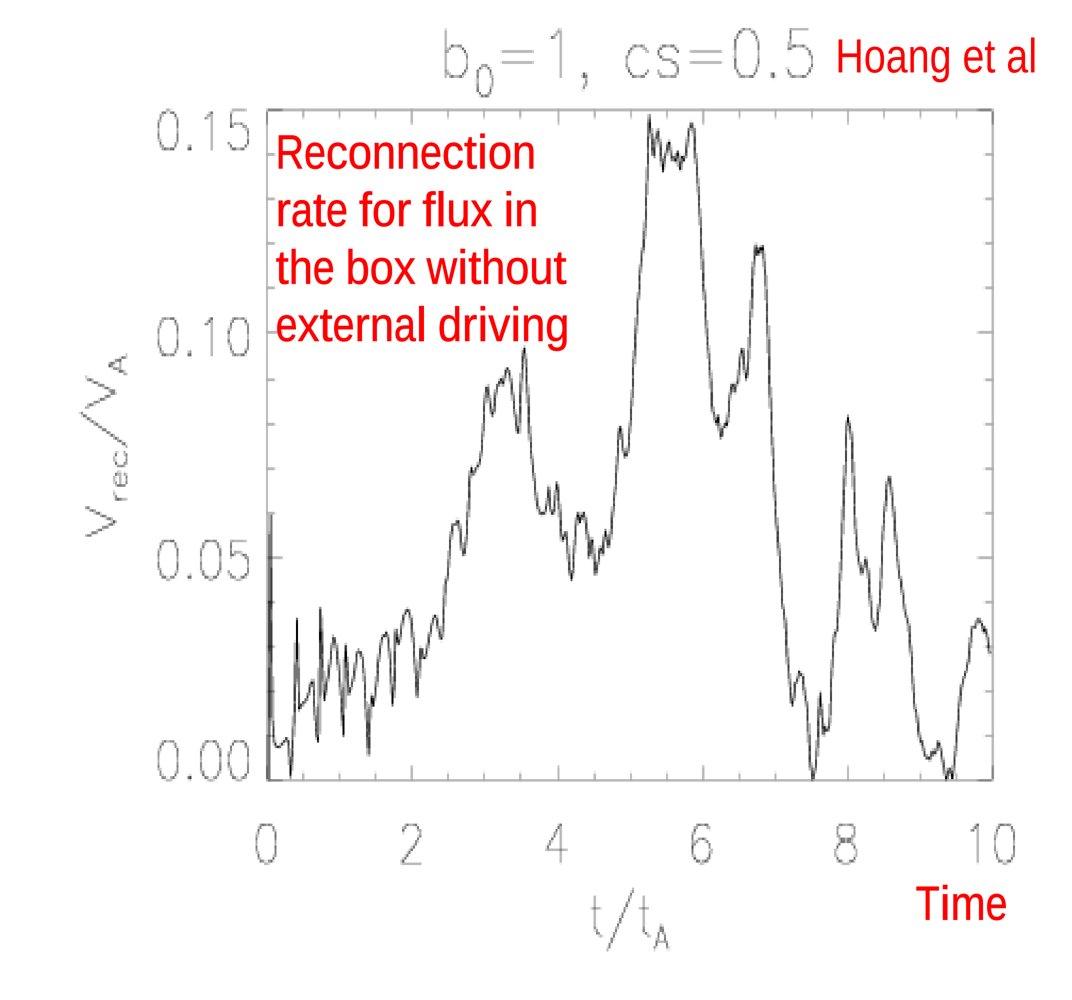


Turbulent reconnection produces flares when the initial state of field is laminar

If field is laminar, the reconnection is slow and field accumulates. As turbulence level increases, the reconnection increases enhancing turbulence further. The finite time instability develops.

$$E(t) \sim (t_0 - t)^{-2}$$

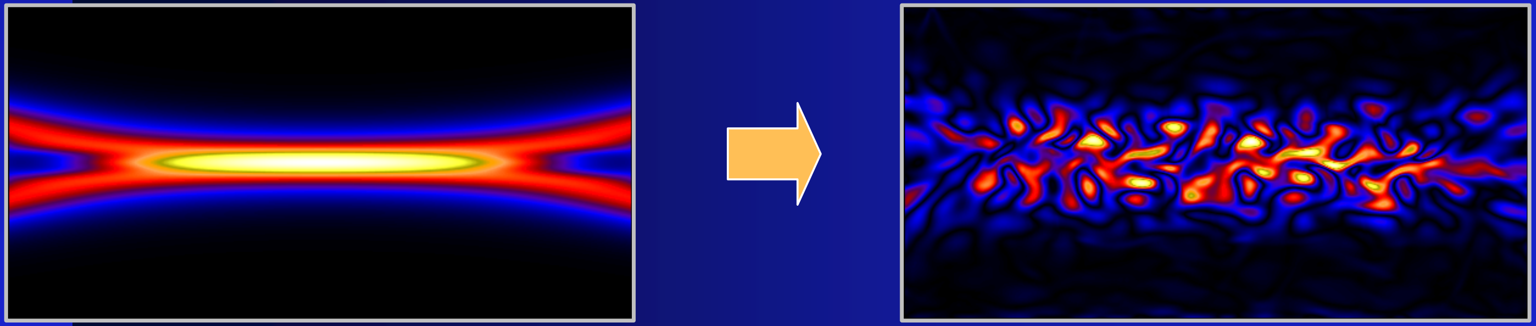
Vishniac & Lazarian 1999



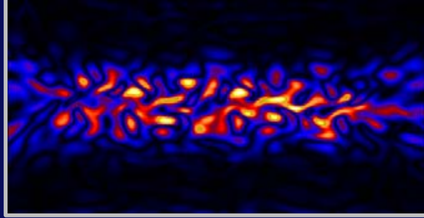
Ciaravella & Raymond 08 observed thick extended outflow regions associated with flares. Corresponds to what we expect and contradicts to Petscheck.

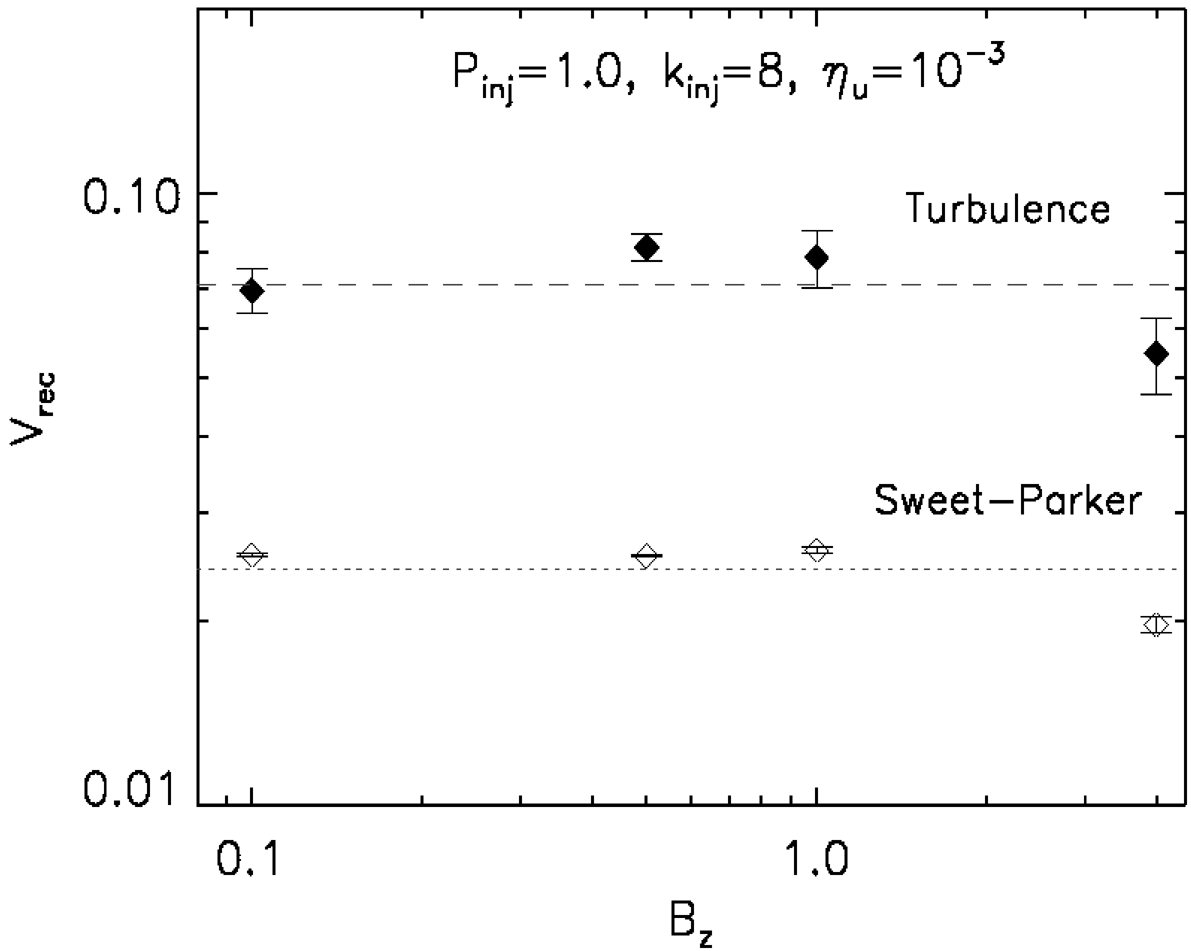
Our model of reconnection should allow Vahe’ to accelerate particles even better! This is my birthday present to Vahe’.

- Weakly stochastic magnetic fields reconnect fast.
- 3D simulations confirm predictions of Lazarian & Vishniac (1999) model of reconnection.
- Turbulent reconnection accelerates energetic particles through first order Fermi process.



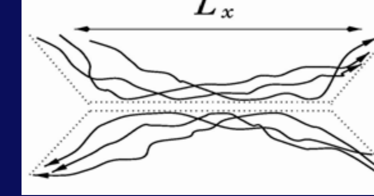
Reconnection rate marginally depends on the guide field amplitude





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

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.

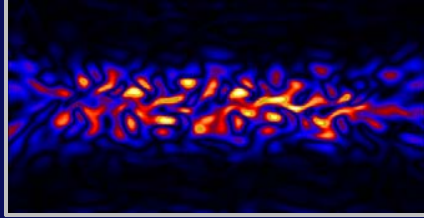
Thus the interstellar gas is in collisionless if $\frac{\delta_{SP}}{d_i} \sim \left(\frac{L}{d_i}\right)^{1/2} (\omega_{ce}\tau_e)^{-1/2}$ <1

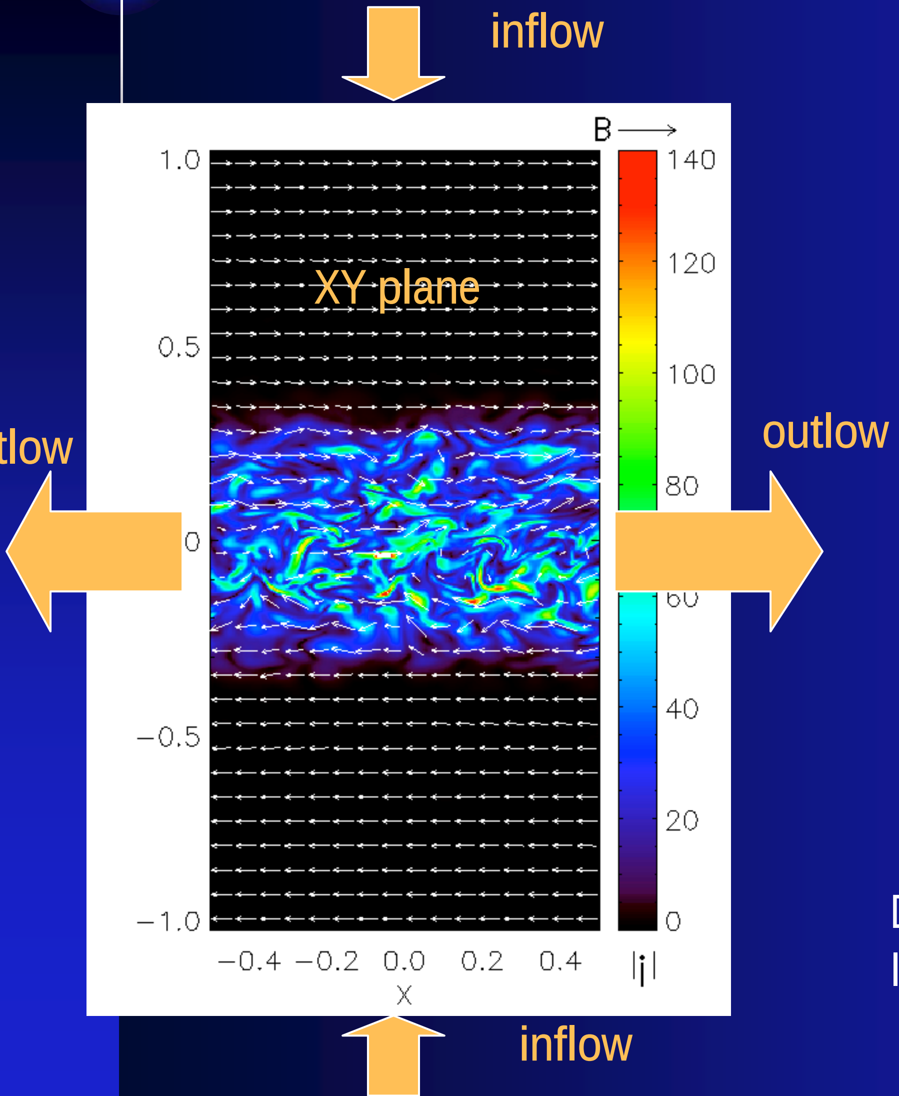
and the current sheet length of sheets

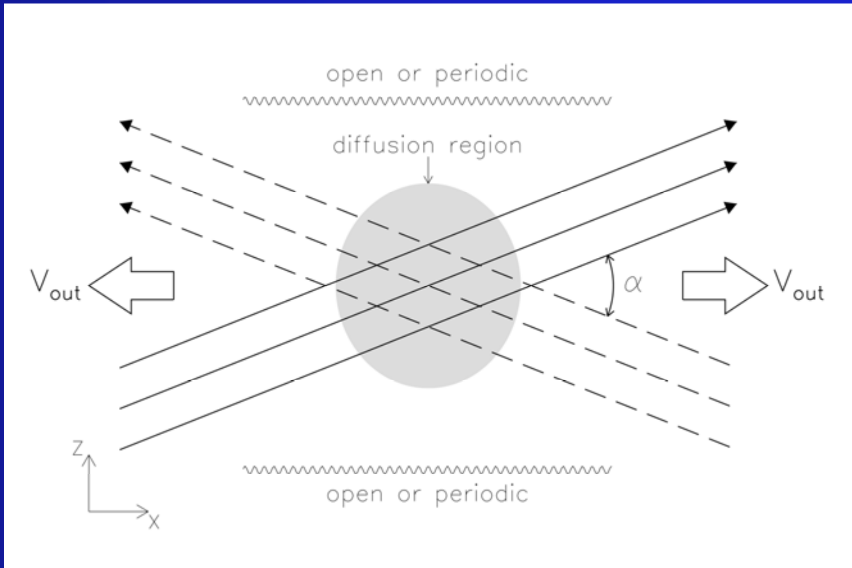
$L < 10^{12}$cm

Too small!!!

All calculations are 3D with non-zero guide field



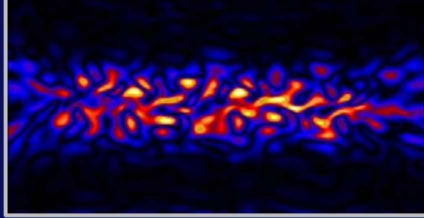


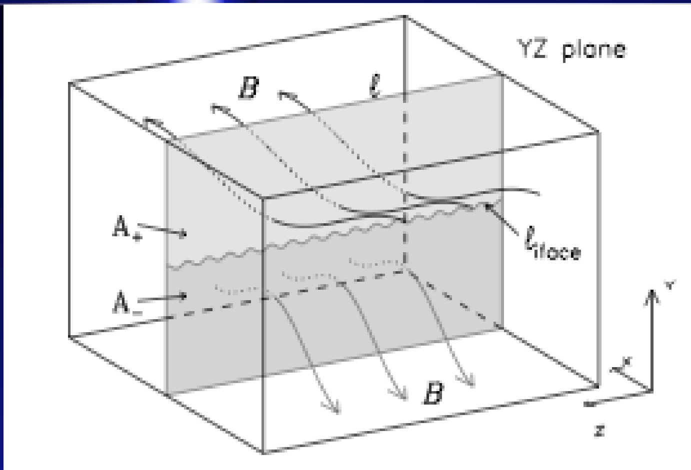


Magnetic fluxes intersect at an angle

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

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





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

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

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

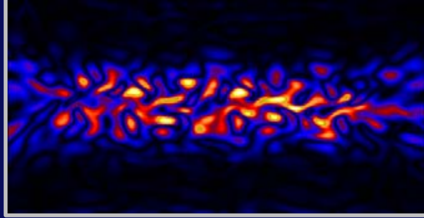
$$\int 2\vec{E} \cdot d\vec{l}_{interface} \equiv -2 V_{rec} |B_{x,\infty}| L_z$$

Asymptotic absolute value of Bx

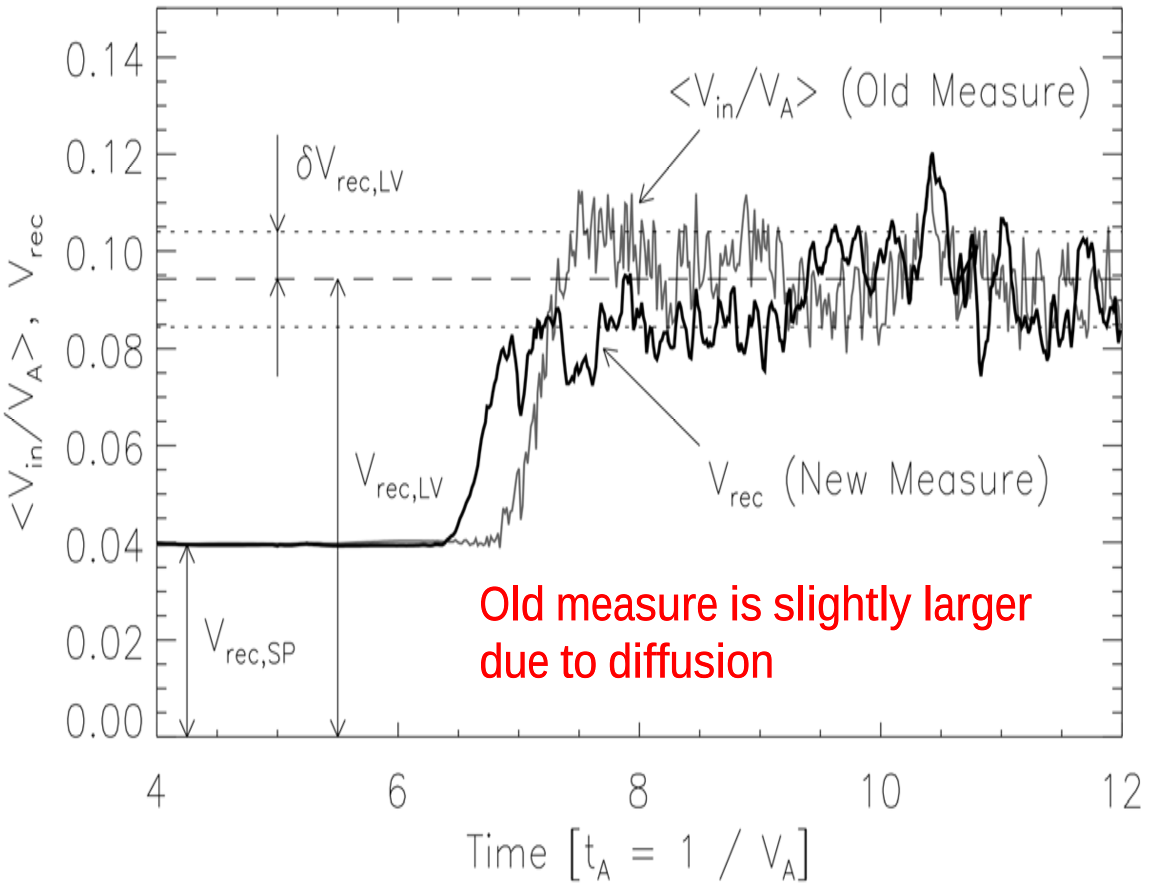
New measure:

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

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

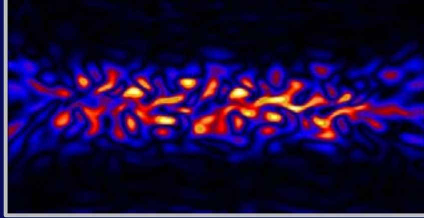
New measure probes the annihilation of the flux

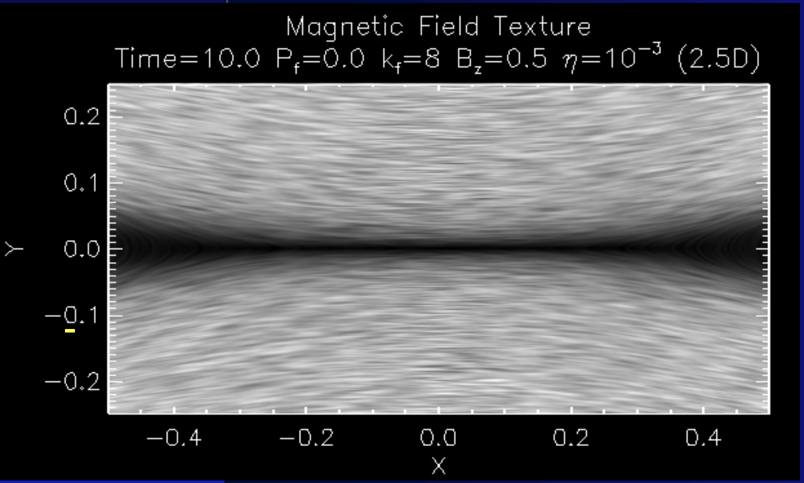
Allegoric summary: Emperor is not naked, reconnection is fast in most cases of realistically turbulent astro fluids

But, if turbulence level is low, reconnection gets slow and may be prone to bursts.

In dense partially ionized gas the reconnection speeds can be as slow as 0.01 of V_A (Lazarian et al. 04).

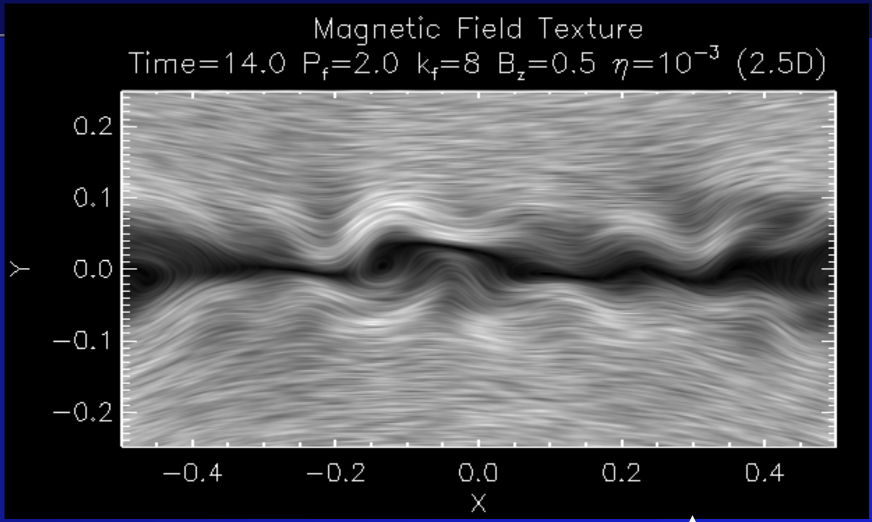
Reconnection layer structure depends on the scale of energy injection





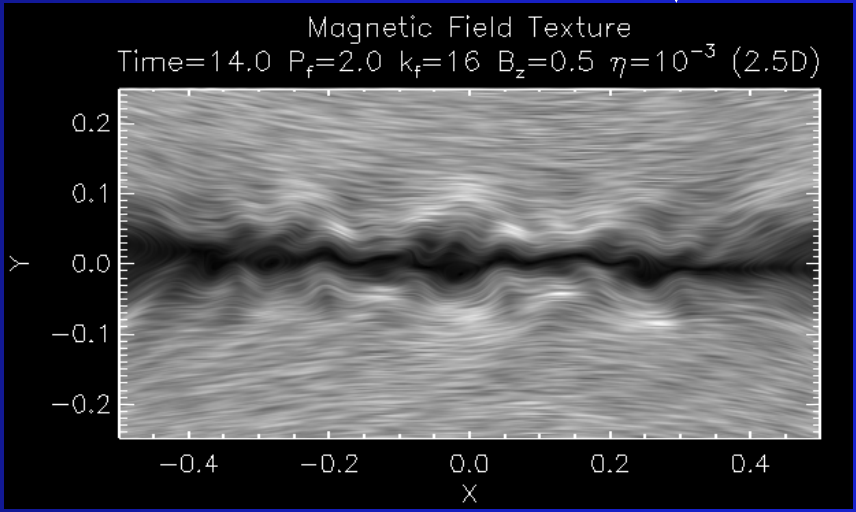
Laminar Sweet-Parker reconnection

k=8

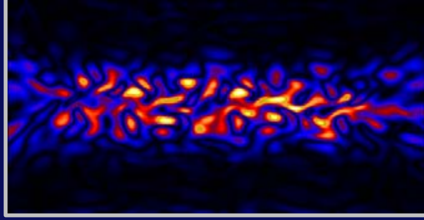


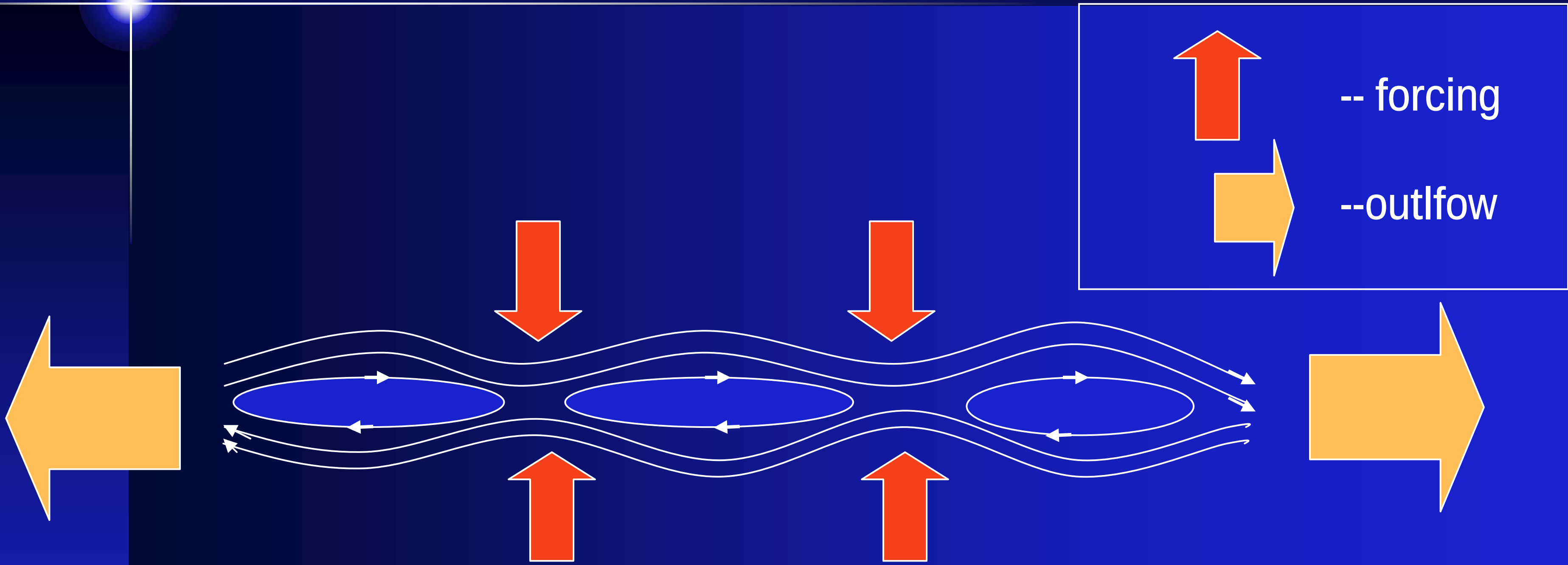
Turbulence with different scales

k=16



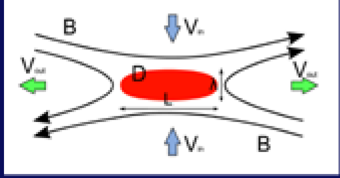
Turbulence can enhance reconnection even in 2D via ejecting of islands





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 $\delta_{SP} < d_i \equiv c/\omega_{pi}$

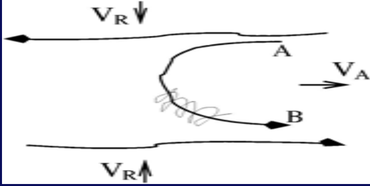
$\delta_{SP} = LRm^{-1/2} = \sqrt{L\eta/V_A}$ Sweet-Parker sheet thickness

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

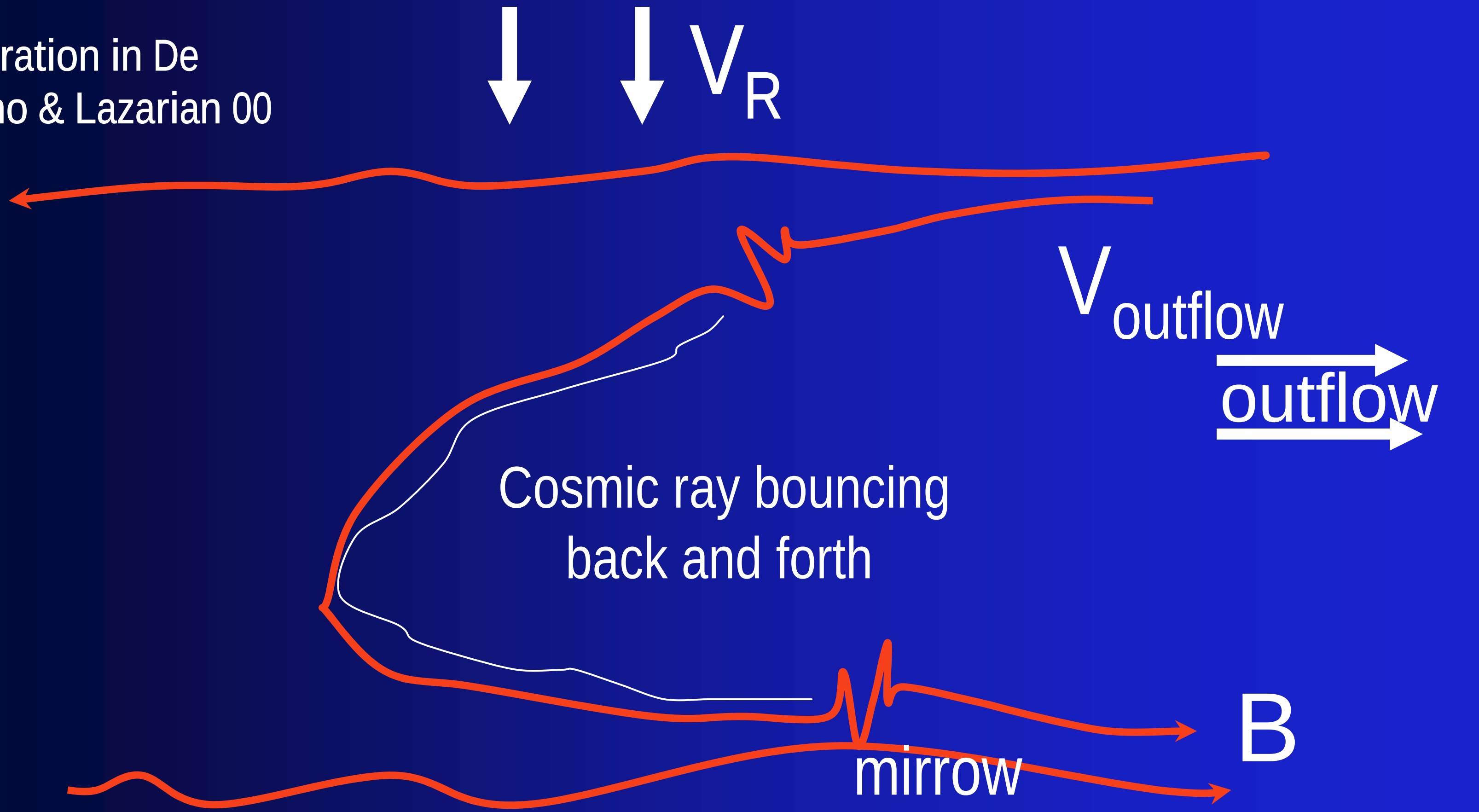
$\lambda_{e,mfp} > L/40$ Yamada et al. (2006)

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

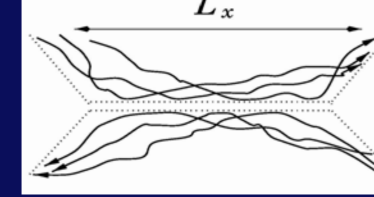


Model of acceleration in De Gouveia Dal Pino & Lazarian 00



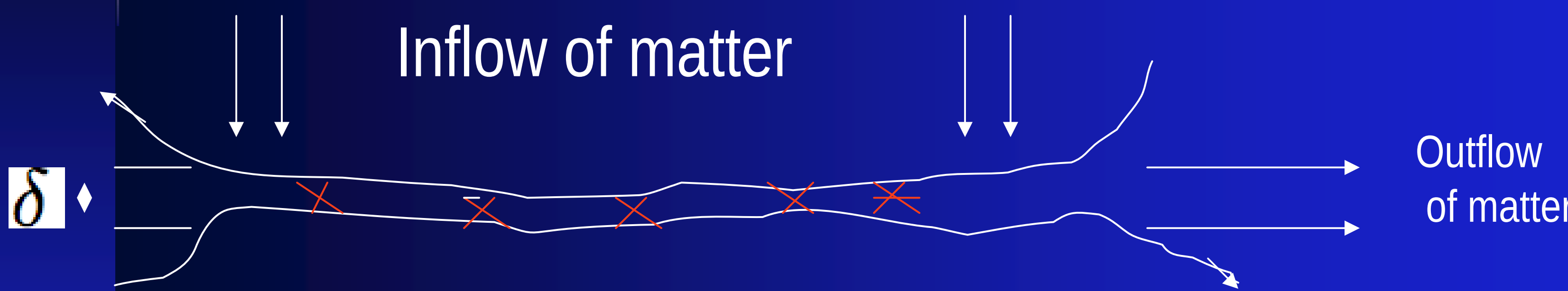
Applications to pulsars, microquasars, solar flare acceleration (De Gouveia Dal Pino & Lazarian 00, 04, Lazarian 04).

Original Petschek reconnection fails for generic astrophysical situations



Large scale fields:

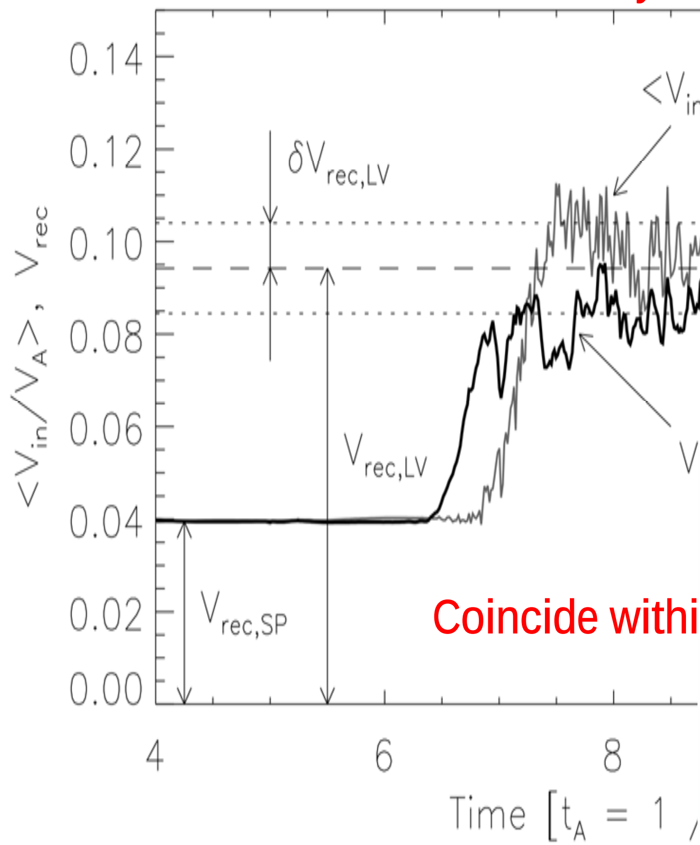
X point over many parsecs?



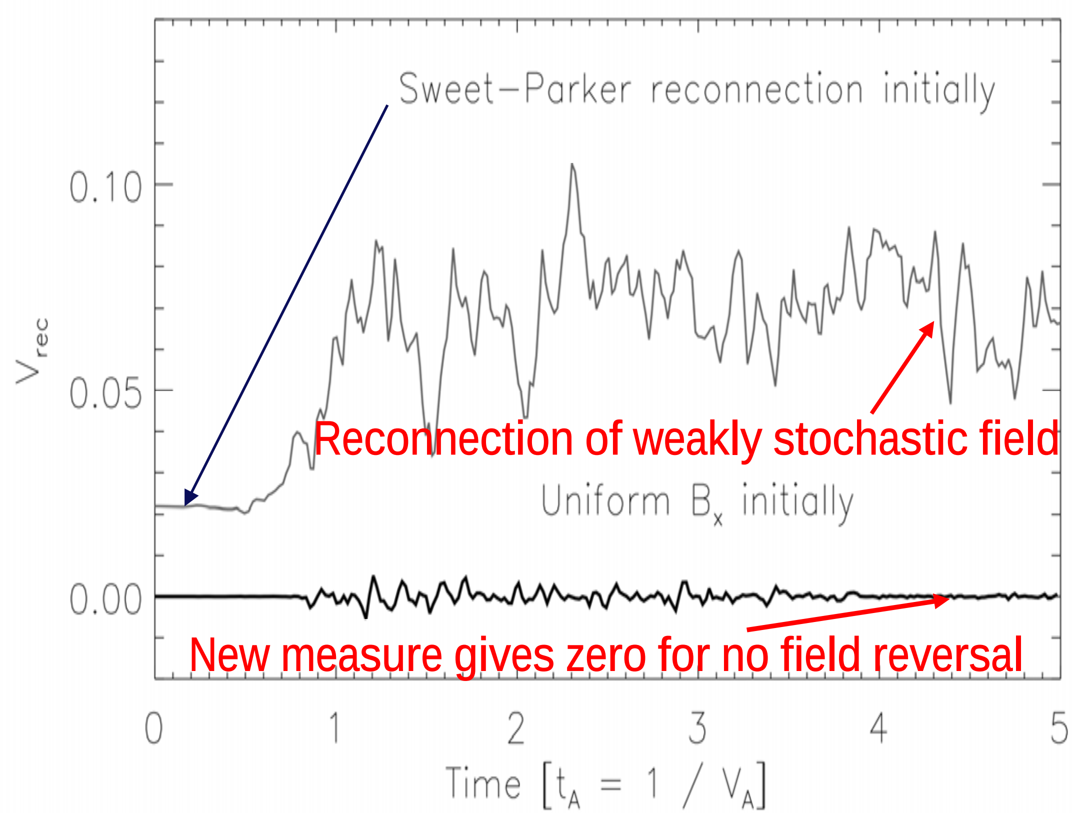
If the outflow slot δ is very small reconnection is slow because of the mass conservation constraint.

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



Without the proof of fast reconnection all MHD numerical research is a "naked emperor" from the famous tale

H.C. Andersen:"Not only was the material so beautiful, but the clothes made from it had the special power of being invisible to everyone who was stupid or not fit for his post."

Turkish version: "A turban such than one born in wedlock will see it, while the bastard will see it not"

But reconnection should be slow to explain accumulation of flux required for solar flares.