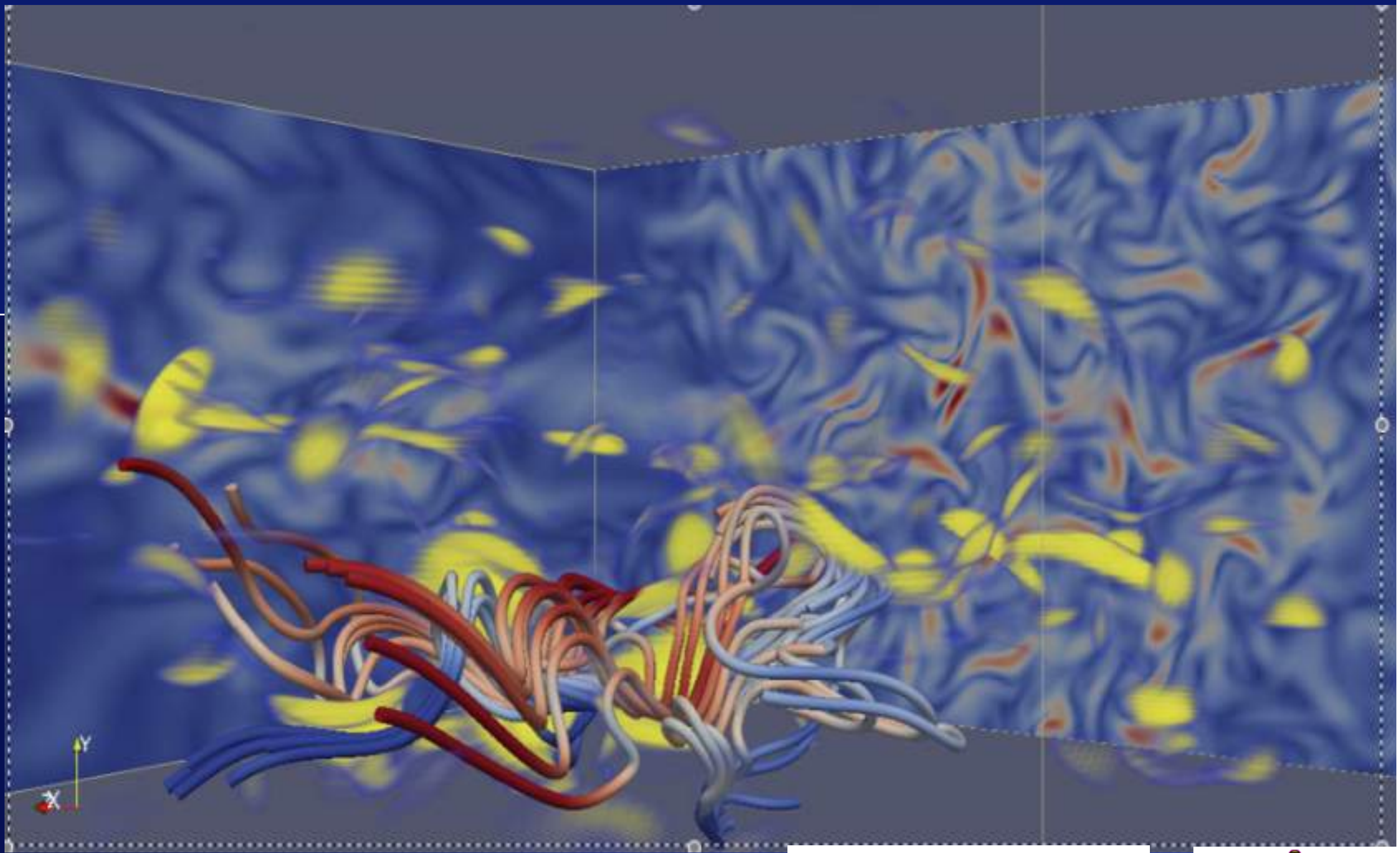
Non-relativistic and relativistic turbulent reconnection



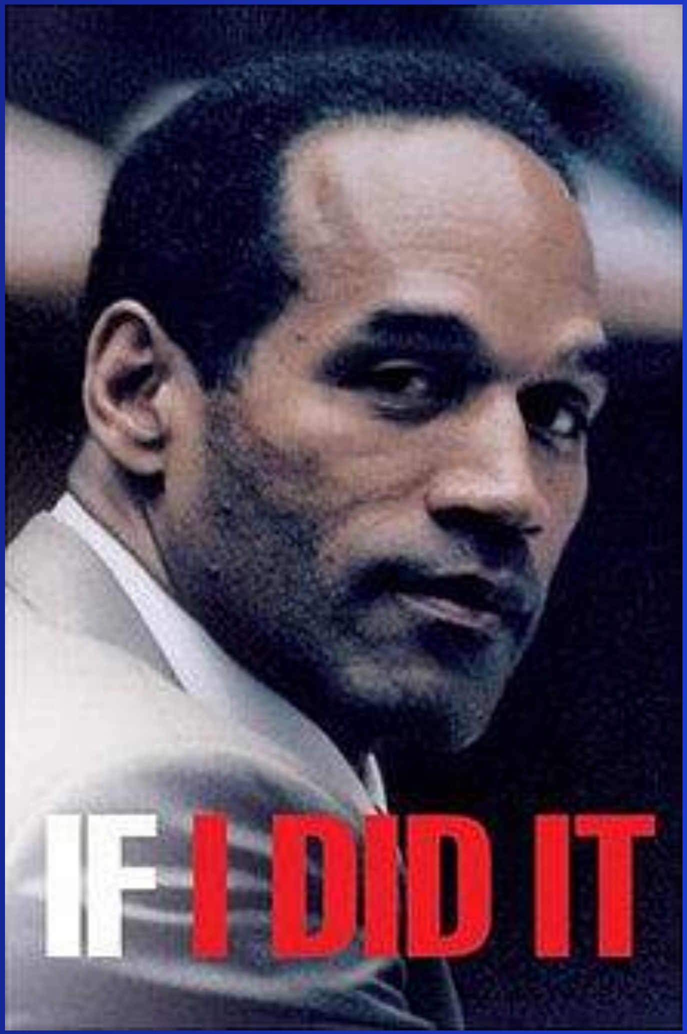
Alex Lazarian

Special Thanks to G. Eyink, G. Kowal, M. Takamoto, E. Vishniac

Alexander von Humboldt Stiftung / Foundation

THE UNIVERSITY of WISCONSIN MADISON

O.J. Simpson wrote the book “If I did it” after the jury found him not guilty in spite of DNA evidence (I believe for political correctness reasons)

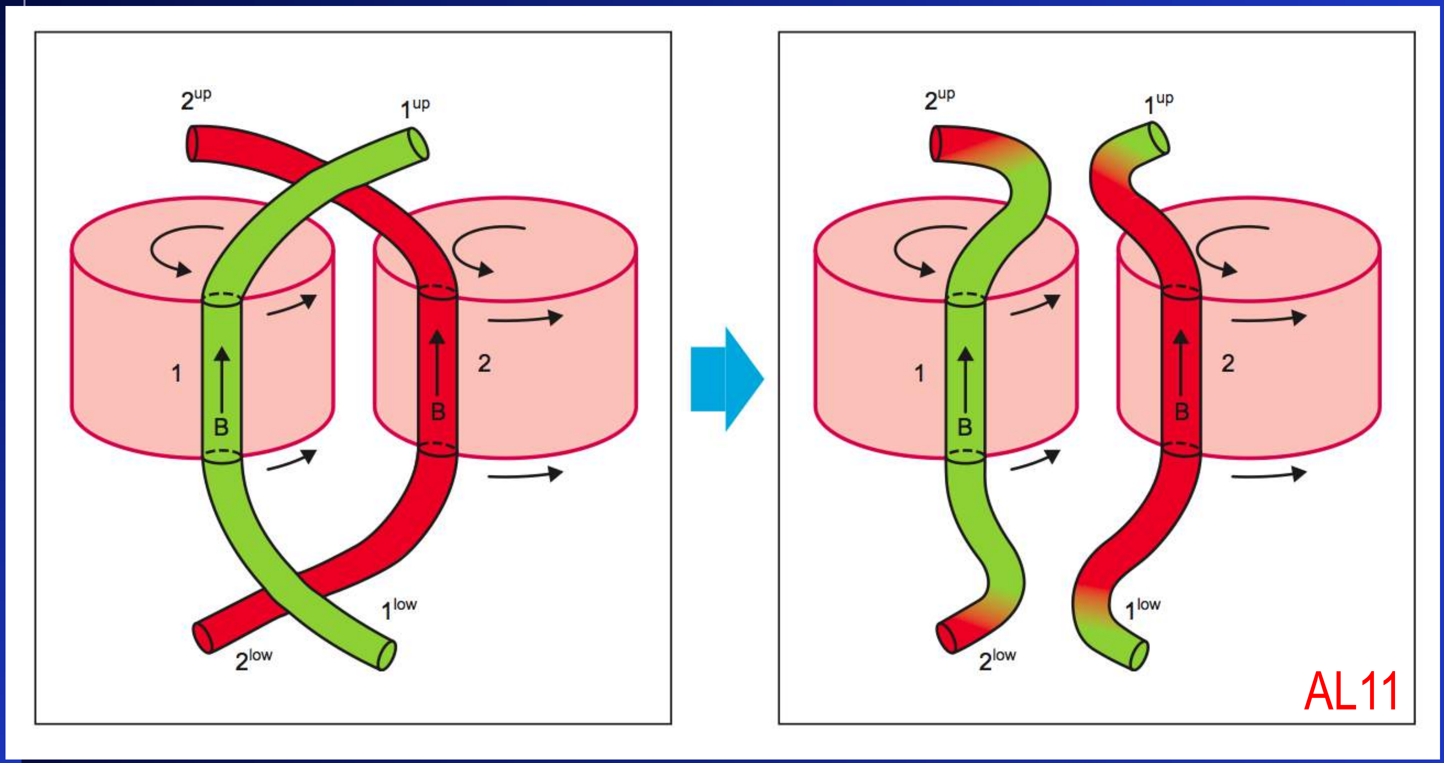


O. J. Simpson

We start with the similar note: If Turbulent Reconnection did it

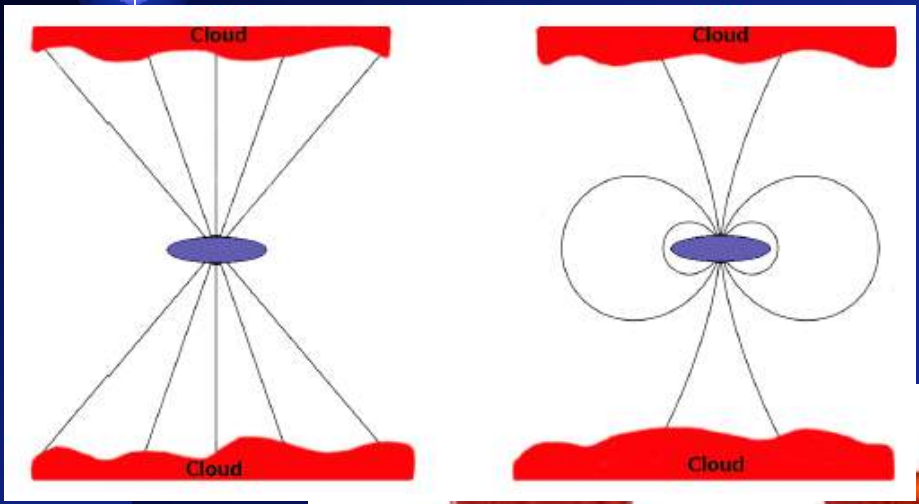
If there were a way to make reconnection fast irrespective of plasma parameters but only depend on the level of turbulence, this would naturally explain a lot of observational data.

If reconnection did it: Reconnection would provide diffusion with the turbulent diffusion rates which essential for star formation



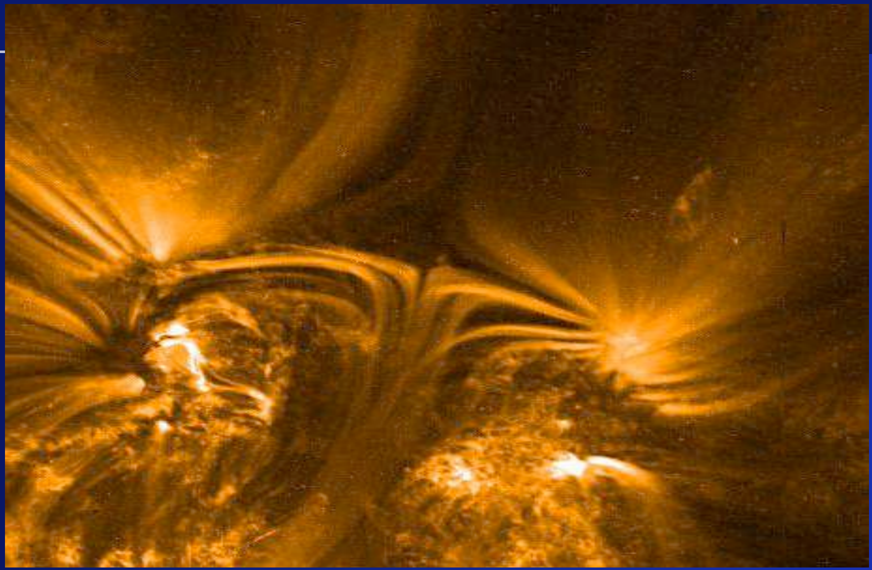
AL 05, 11, 14, Santos-Lima et al. 10, 12, 13

If Turbulent Reconnection did it: there would be a way to solve "magnetic braking catastrophe"



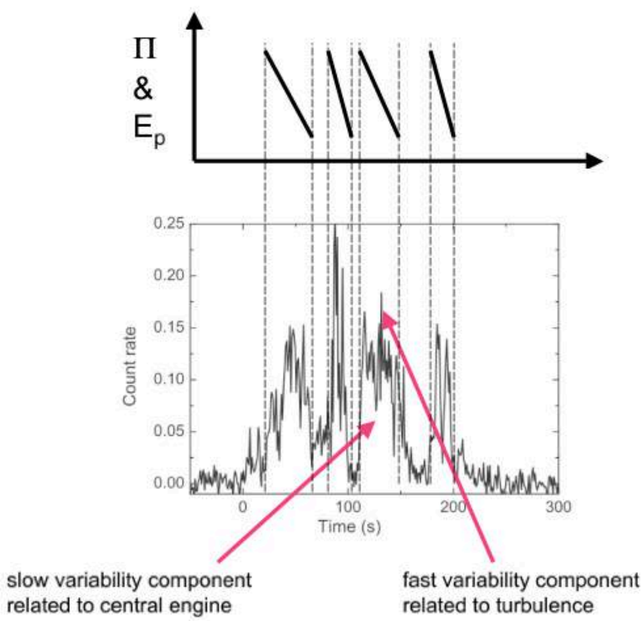
Casanova, AL, Santos-Lima 15

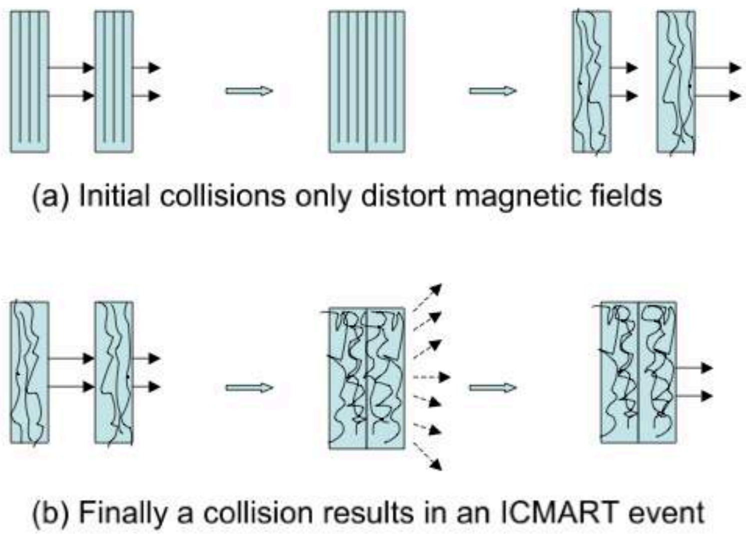
If turbulent reconnection did it: there would be a way to explain Solar flare observations



1. Solar flares can only be explained if magnetic reconnection can be initially slow (to accumulate flux) and then fast (to explain flares).
2. Reconnection is fast in collisional and collisionless plasmas (Shibata et al. 2012)

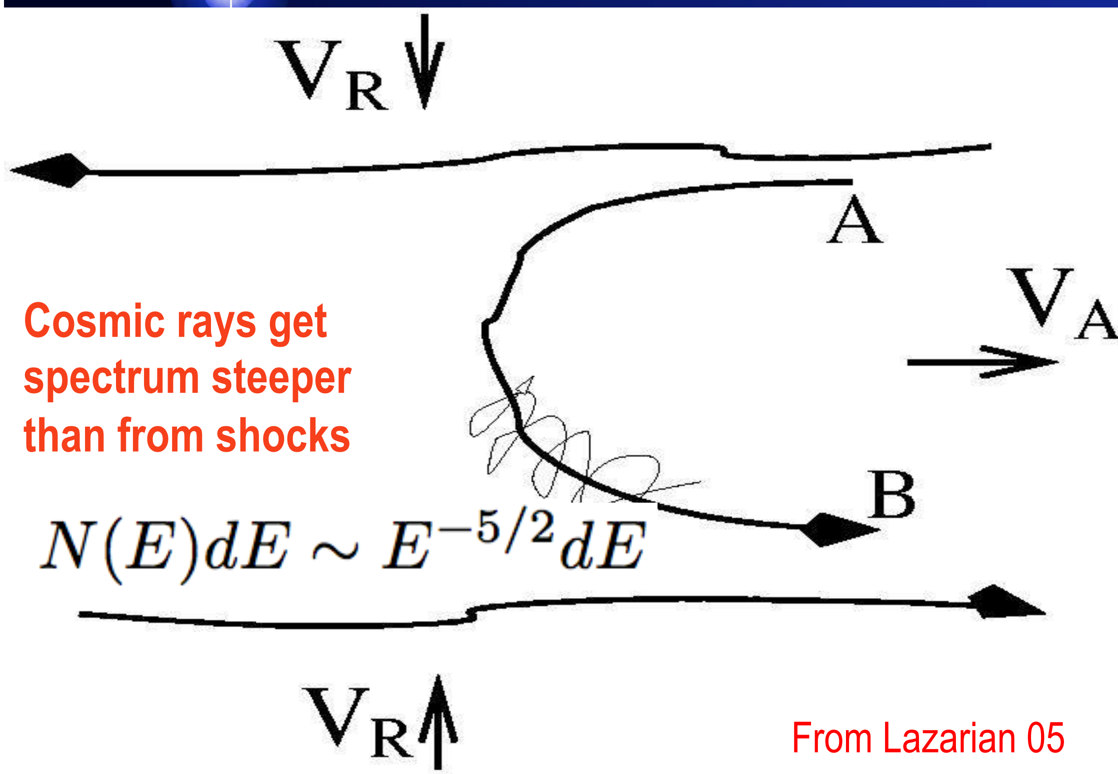
If turbulent reconnection did it: there would be a way to explain gamma ray bursts





Zhang & Yan 11

If reconnection did it: energetic particles would get accelerated by First Order Fermi mechanism

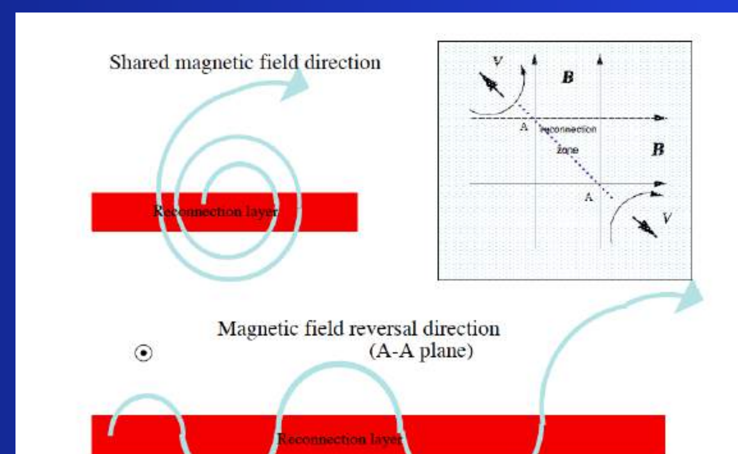


Cosmic rays get spectrum steeper than from shocks

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

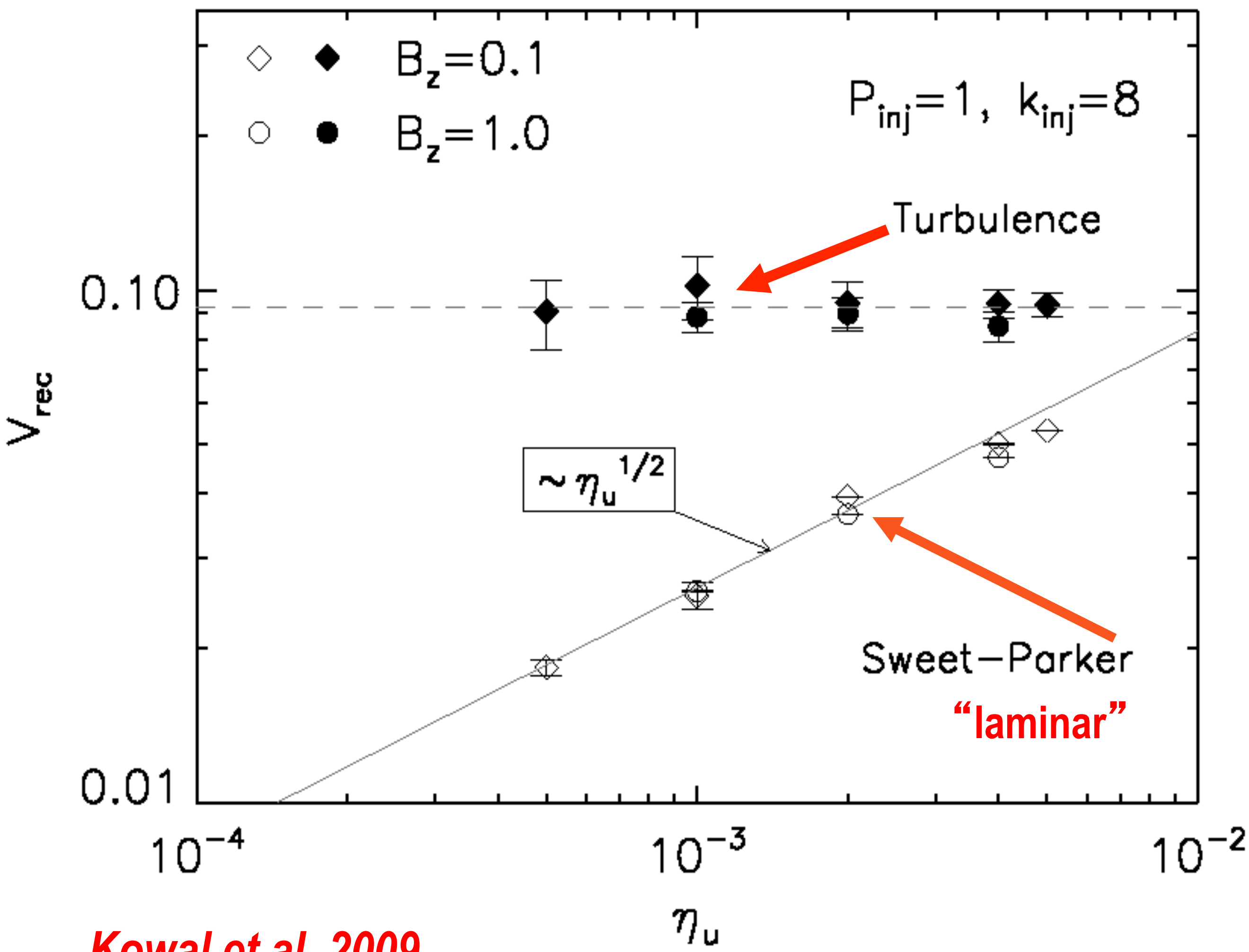
From Lazarian 05

(cp. Drake 2006).

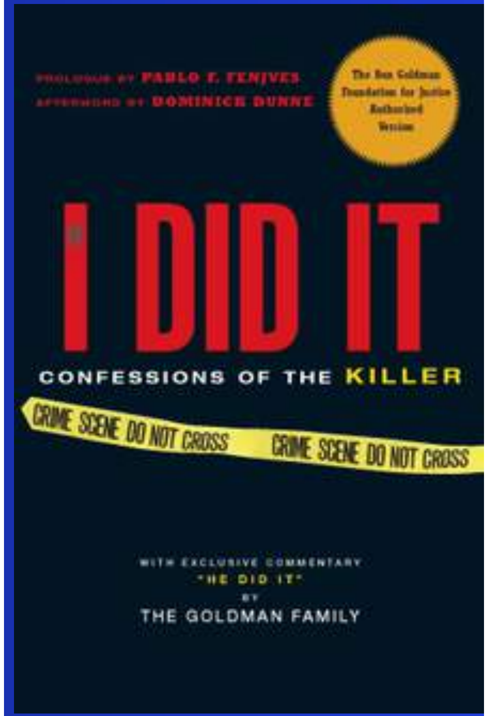


Lazarian et al. 2010

Plasma pandits jury may still be out, but we have convincing evidence that turbulence did it!



Kowal et al. 2009



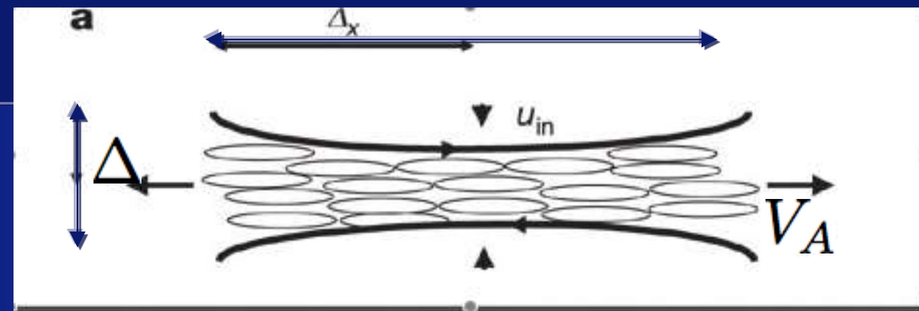
Plasmoids/tearing is a transient regime transferring to fully turbulent reconnection in 3D

$$S = \frac{LV_A}{\eta}$$

$$Re = \frac{\Delta V_A}{\nu}$$

$$\Delta = L\frac{V_{rec}}{V_A}, \text{ i.e. } \Delta \propto S$$

$$S \to \infty \text{ means } Re \to \infty$$



- Sweet-Parker happened to be a transient reconnection up to $S=10^4$. After that tearing happens. Fast reconnection means that the outflow thickness Δ grows in proportion to S. Thus the Reynolds number $Re = \frac{\Delta V_A}{\nu}$ of the outflow grows as S. This entails to the transition to turbulent regime.

- Turbulence is known to suppress the instabilities and therefore one expects tearing to be suppressed. If turbulence does not make reconnection fast then Delta will stop growing after a critical Re is achieved. Thus reconnection would not be fast and would scale as 1/S.

- Many phenomena require reconnection larger that the 0.01 or even 0.1 of $V_{A.}$ Tearing cannot provide this!

Ubiquitous turbulence controls non-relativistic and relativistic magnetic reconnection

- Turbulent reconnection in compressible fluids
- Relativistic turbulent reconnection
- Turbulent self-sustained reconnection

Ubiquitous non-relativistic and relativistic turbulence controls magnetic reconnection

- Turbule ... ds
- Relativis
- Turbule

Turbulence was considered in terms of reconnection, with interesting possibilities discussed

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

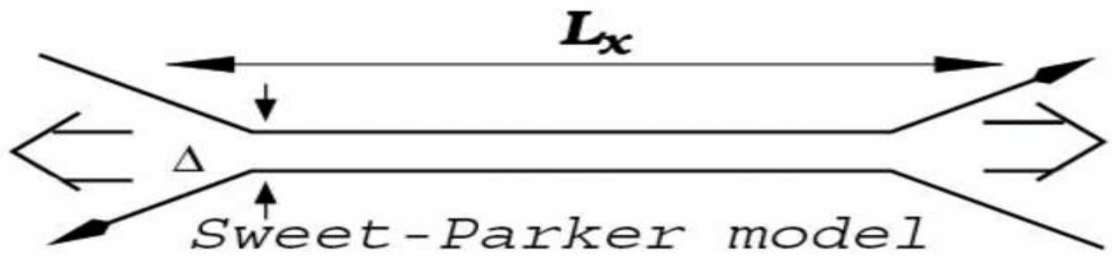
On the contrary, Kim & Diamond (2001) conclude that turbulence makes any reconnection slow, irrespectively of the local reconnection rate

Boozer (2013) claim about 3D requirement for fast reconnection

LV99 model extends Sweet-Parker model for turbulent astrophysical plasmas and makes reconnection fast

Turbulent reconnection:

Outflow is determined by field wandering.



$$V_{rec} = V_A \frac{\Delta}{L_x}$$

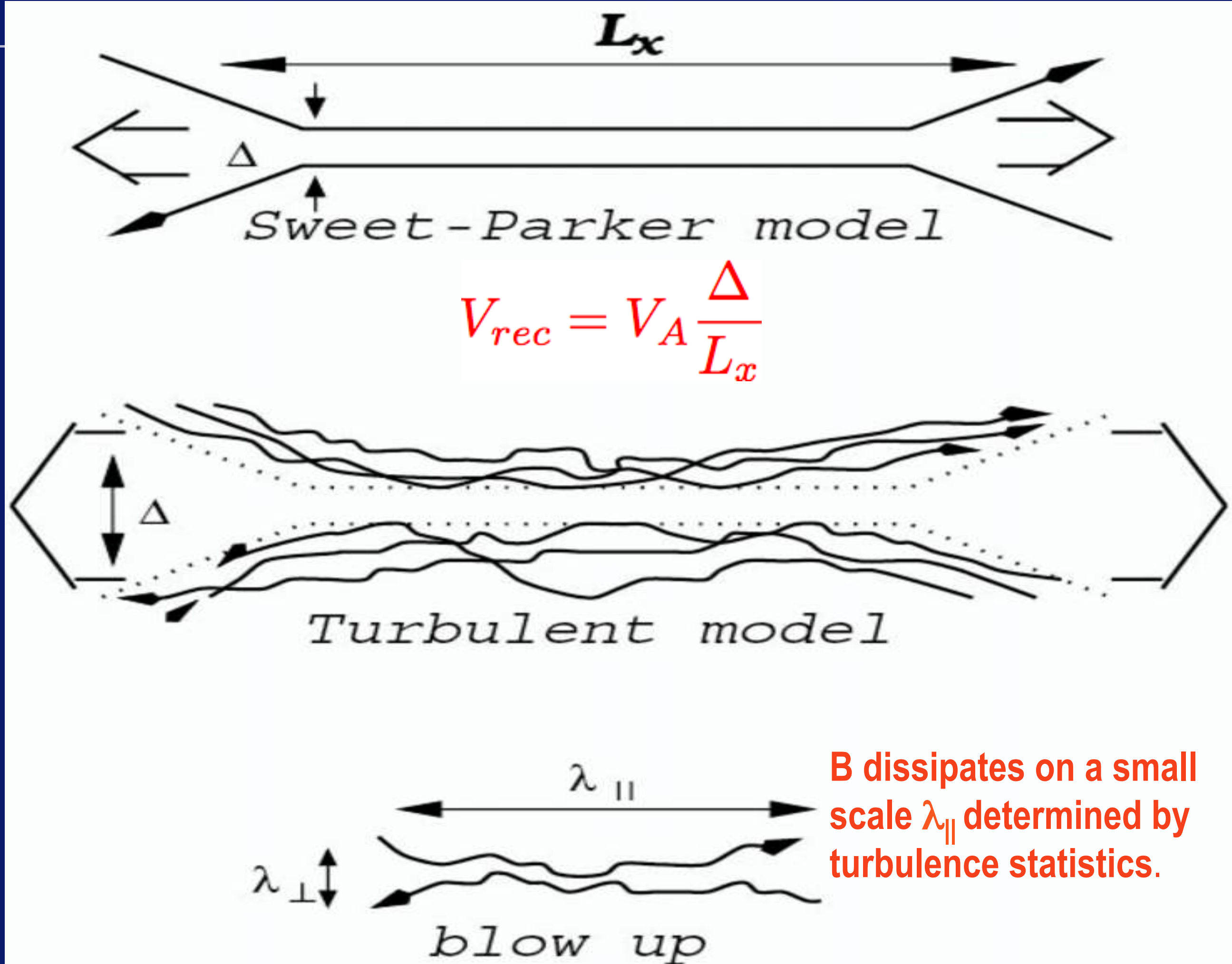
AL & Vishniac (1999)

henceforth referred to as LV99

LV99 model extends Sweet-Parker model for turbulent astrophysical plasmas and makes reconnection fast

Turbulent reconnection:

Outflow is determined by field wandering.



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

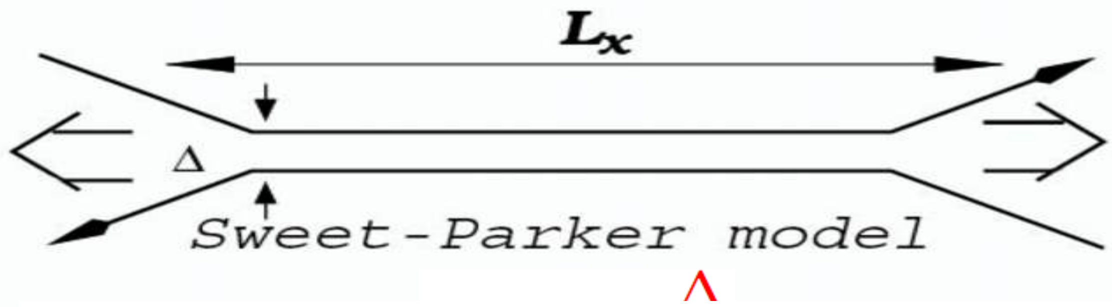
AL & Vishniac (1999)

henceforth referred to as LV99

LV99 model extends Sweet-Parker model for turbulent astrophysical plasmas and makes reconnection fast

Turbulent reconnection:

Outflow is determined by field wandering.



Without turbulence:

molecular diffusion coefficient D ~10^{-5} cm^2/sec

(← It's for small molecules in water.)

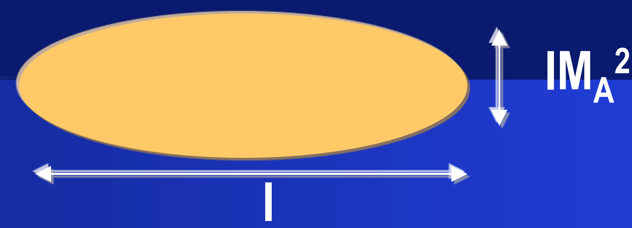
➔ Mixing time ~ (size of the cup)^2/D ~ 10^7 sec ~ 0.3 year !

AL & Vishniac (1999)

henceforth referred to as LV99

The outflow region is determined by wandering magnetic field lines

For subAlfvenic turbulence eddies are elongated



If injection scale l is less than L_x then the magnetic field lines undergo random walk with lM_A^2 and outflow thickness is

$$\Delta = (L_x/l)^{1/2} l M_A^2 = (L_x l)^{1/2} (v_l/V_A)^2$$

Mass conservation

$$\rho_{in} V_{rec} L_x = \rho_s v_s \Delta$$

Which gives

$$V_{rec} = (\rho_s/\rho_{in})(l/L_x)^{1/2}(v_l/V_A)^2$$

For incompressible fluid LV99 provide:

$$V_{rec} = min[(L_x/l)^{1/2}, (l/L_x)^{1/2}](v_l/V_A)^2$$

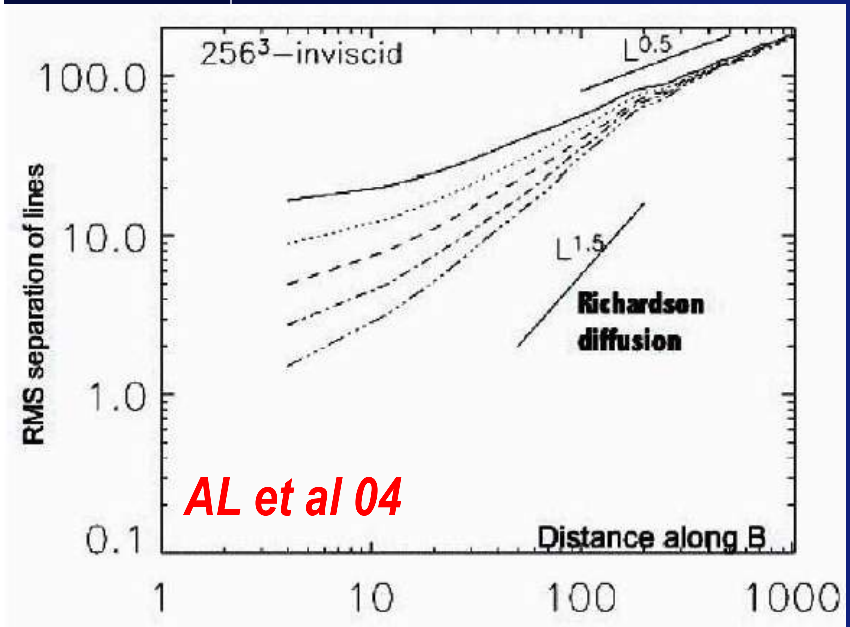
Eyink, AL & Vishniac 2011 related LV99 to the well-known concept of Richardson diffusion

$$\langle|\mathbf{x}_1(t) - \mathbf{x}_2(t)|^2\rangle \sim t^3$$

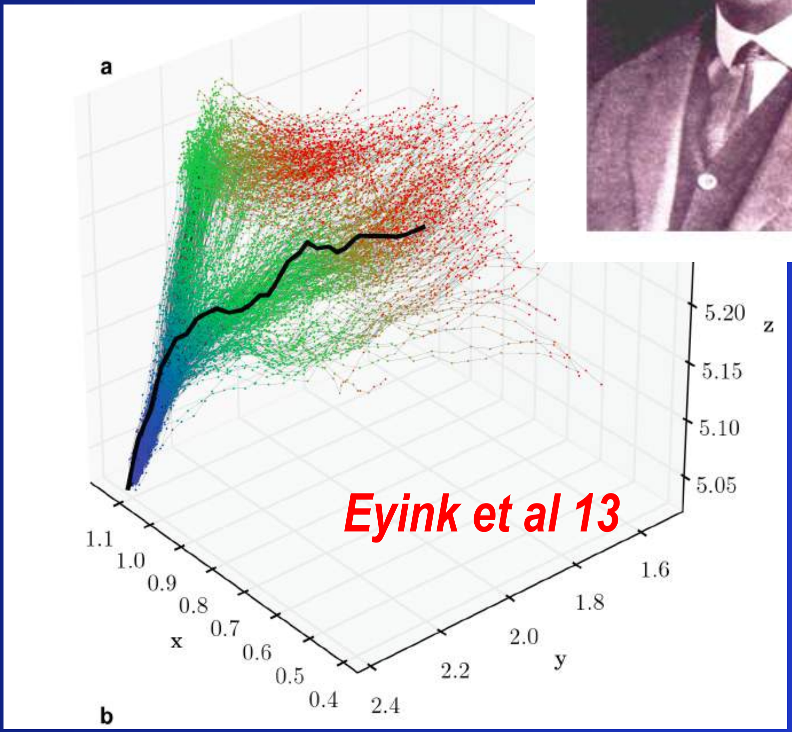
Richardson's law

Eyink, AL & Vishniac 2011 related LV99 to the well-known concept of Richardson diffusion

Richardson diffusion measured in MHD



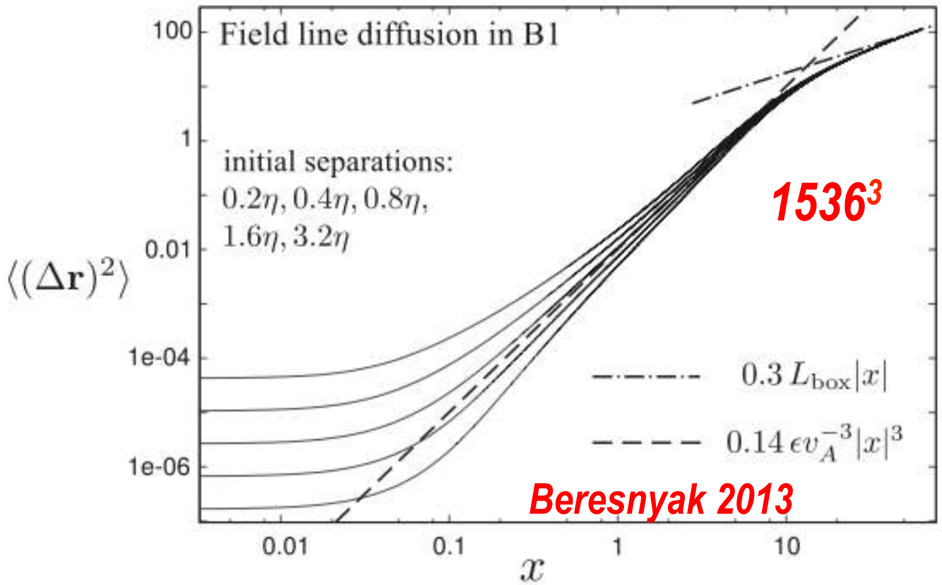
Diffusion in space



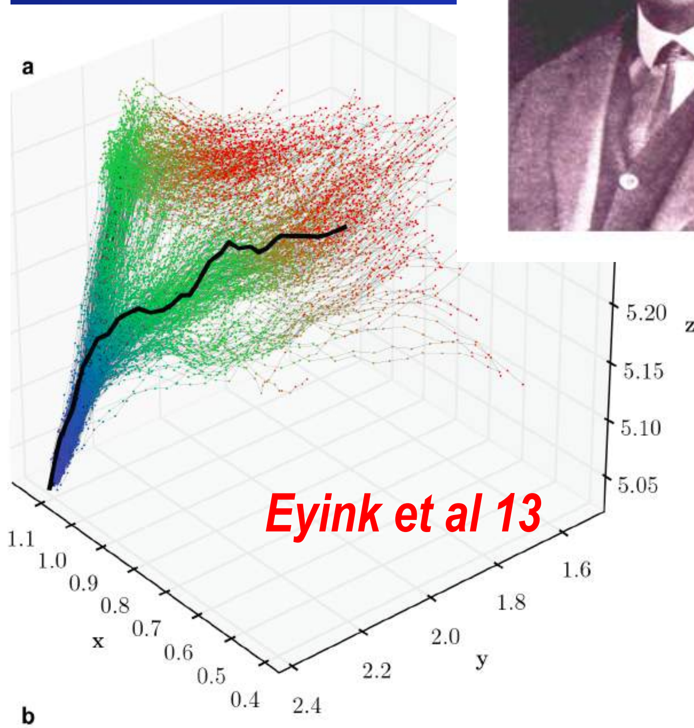
Diffusion in time

Eyink, AL & Vishniac 2011 related LV99 to the well-known concept of Richardson diffusion

Richardson diffusion measured in MHD



Diffusion in space



Diffusion in time

New theoretical study of Eyink derives LV99 relations, formulates Generalized Ohm's Law and shows that effects of turbulence dominate those of plasma microphysics

Turbulent General Magnetic Reconnection

G. L. Eyink

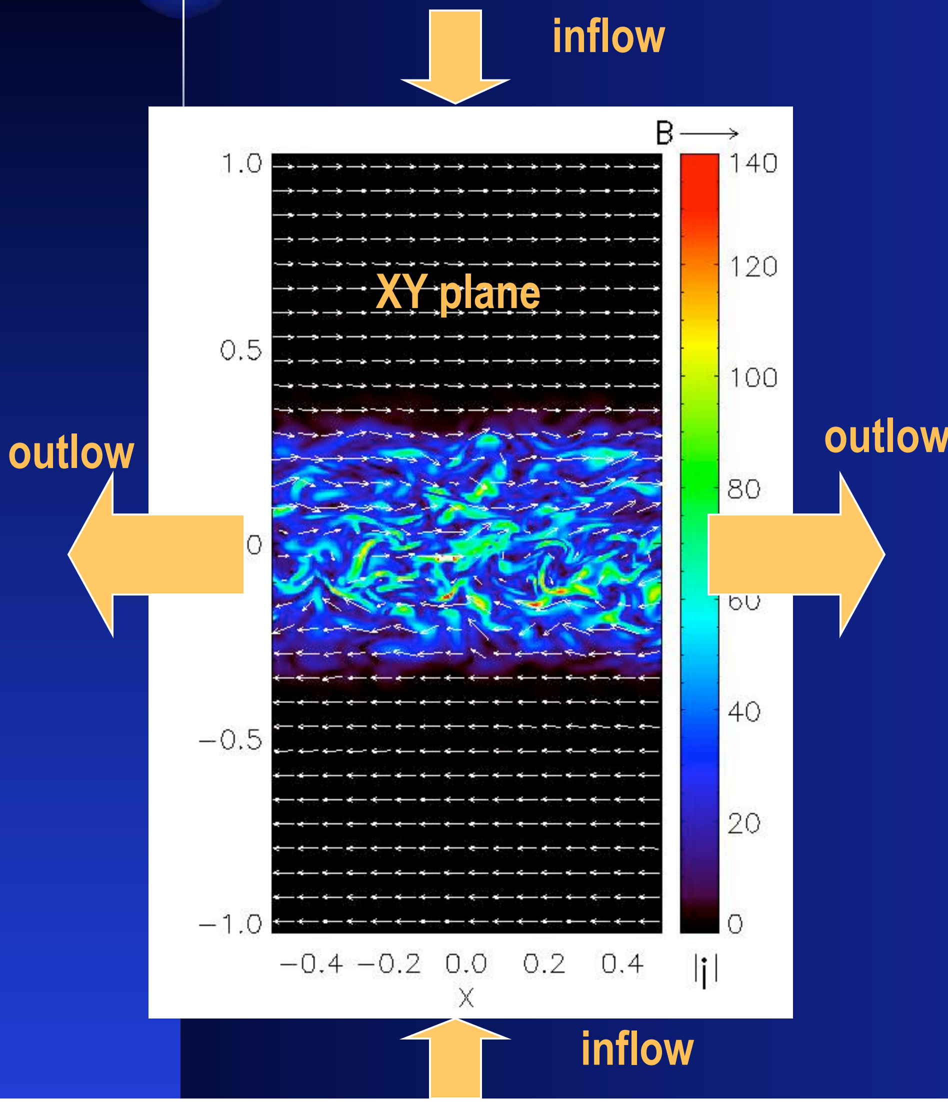
Department of Applied Mathematics & Statistics and Department of Physics & Astronomy, The Johns Hopkins University, Baltimore, MD 21218

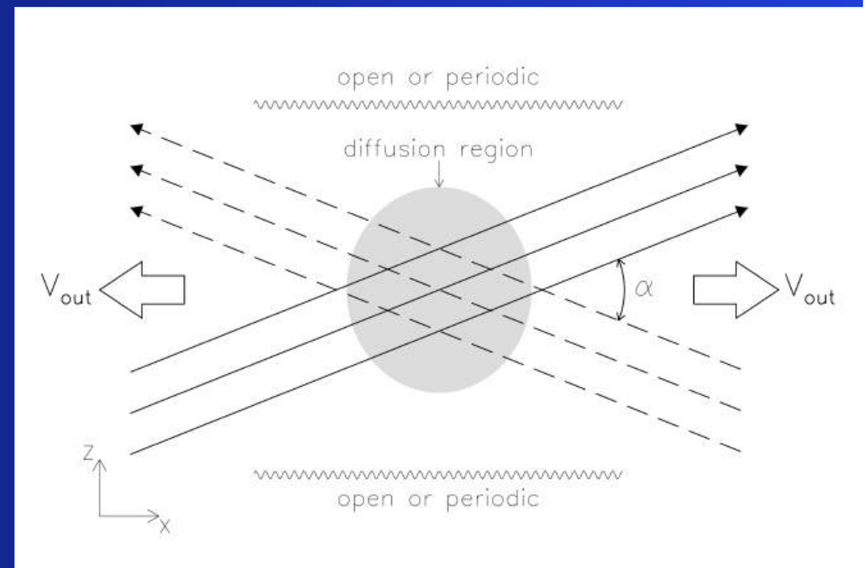
ABSTRACT

Plasma flows with an MHD-like turbulent inertial range, such as the solar wind, vitiate many assumptions of standard theories of magnetic reconnection. In particular, the "roughness" of turbulent velocity and magnetic fields implies that magnetic field-lines are nowhere "frozen-in" in the usual sense. This situation demands an essential generalization of the so-called "General Magnetic Reconnection" (GMR) theory. Following ideas of Axford and Lazarian & Vishniac, we identify magnetic field-lines by "tagging" them with plasma fluid elements and then determine their slip-velocity relative to the plasma fluid by integrating in arc-length along the wandering field-lines. The main new concept introduced here is the *slip-velocity source vector*, which gives the rate of development of slip-velocity per unit arc-length of field line. The slip-source vector is the ratio of the curl of the non-ideal electric field $\boldsymbol{R}$ in the Generalized Ohm's Law and the

Eyink 15

NUMERICAL TESTING:
All calculations are 3D with non-zero guide field

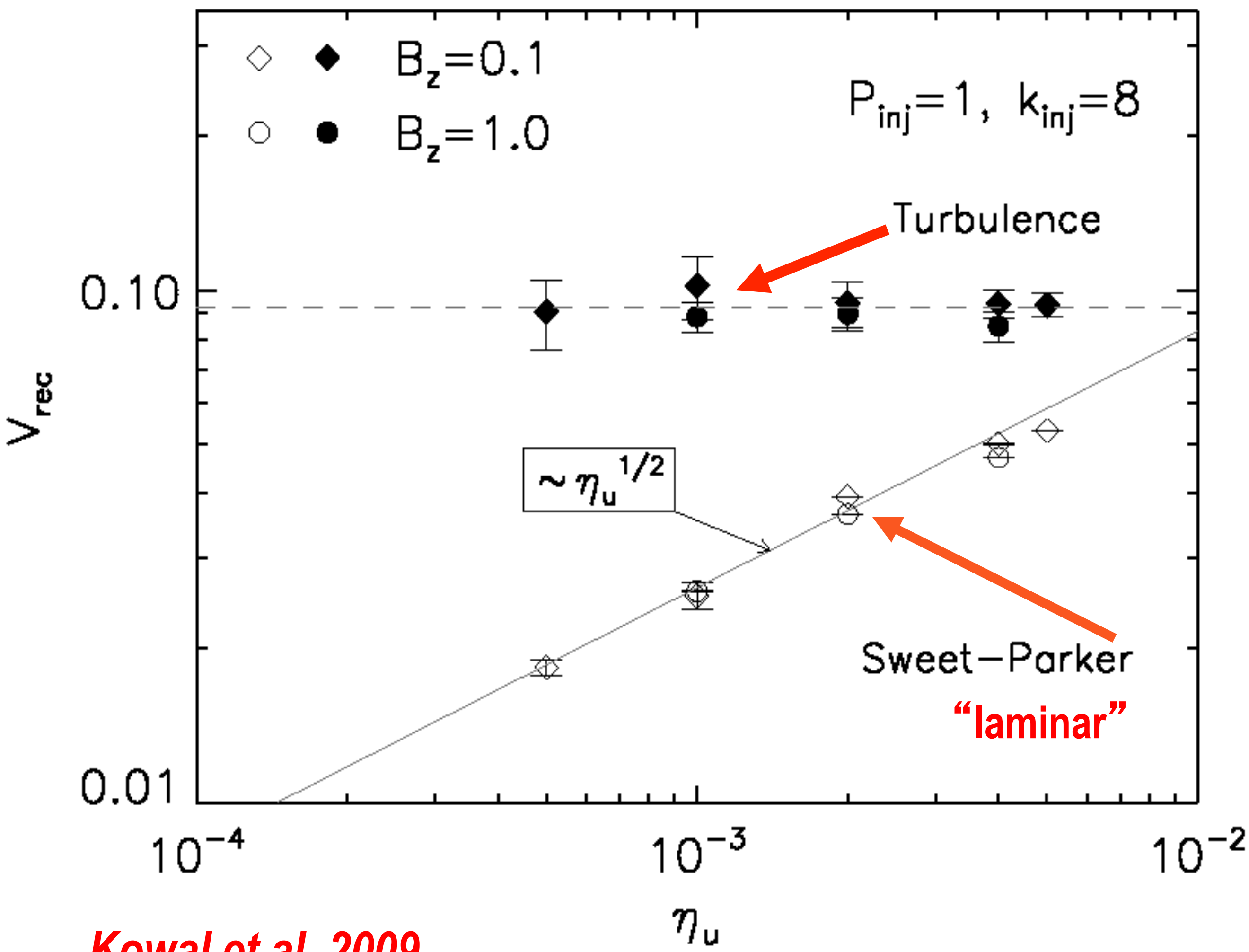




Magnetic fluxes intersect at an angle

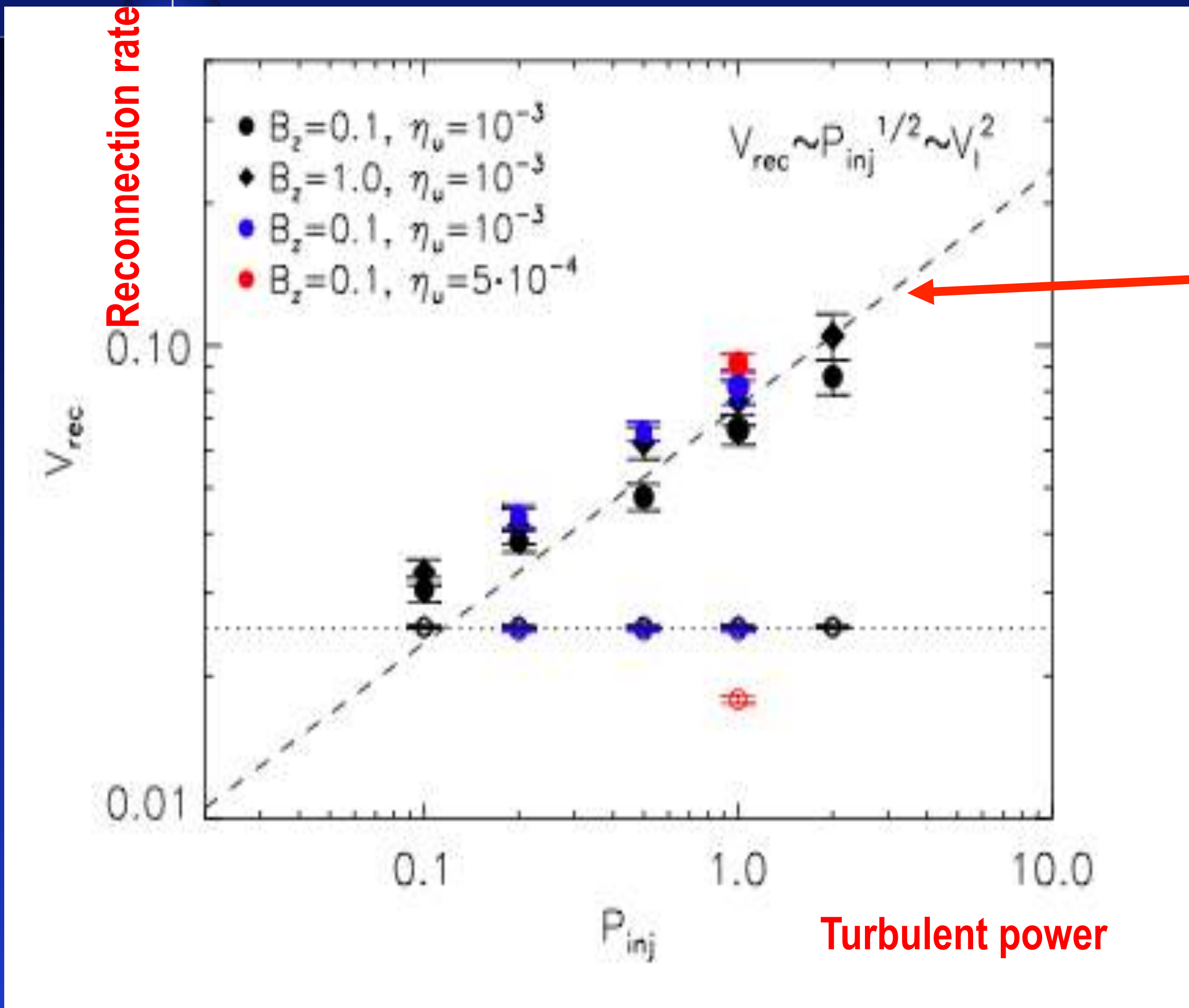
Driving of turbulence: r_d=0.4, h_d=0.4 in box units.
Inflow is not driven.

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



Kowal et al. 2009

The reconnection rate increases with input power of turbulence



LV99 prediction is $V_{rec} \sim P_{inj}^{1/2}$

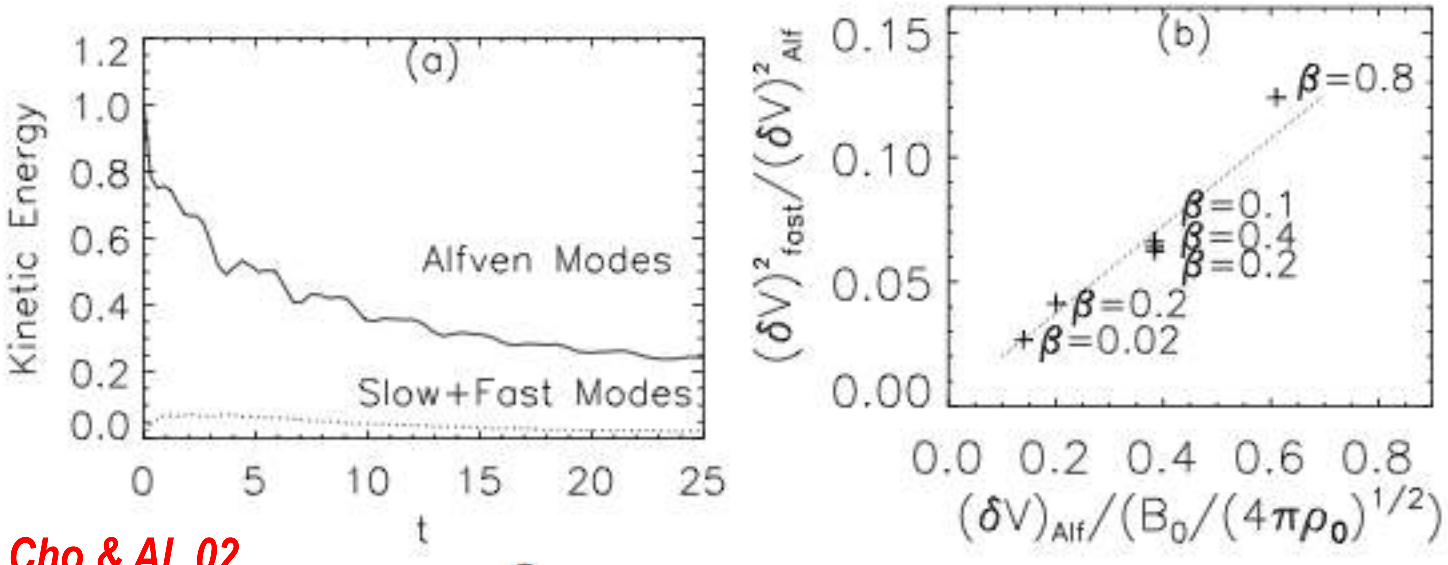
Kowal et al. 2012

BACK to THEORY. In compressible media V_{rec} changes with plasma density and energy in Alfvenic component

For compressible media with injection scale l less tha L_x LV99 expressions can be generalized:

$$V_{rec} = v_s(\rho_s/\rho_{in})(l/L_x)^{1/2}\frac{(v_{total}^2 - v_{comp}^2)}{V_{Alf}^2}$$

Generation of compressible modes happens for incompressible driving



Cho & AL 02

$$\frac{v_{comp}^2}{V_{Alf}^2} \propto \frac{v_{inj}}{V_{Alf}}$$

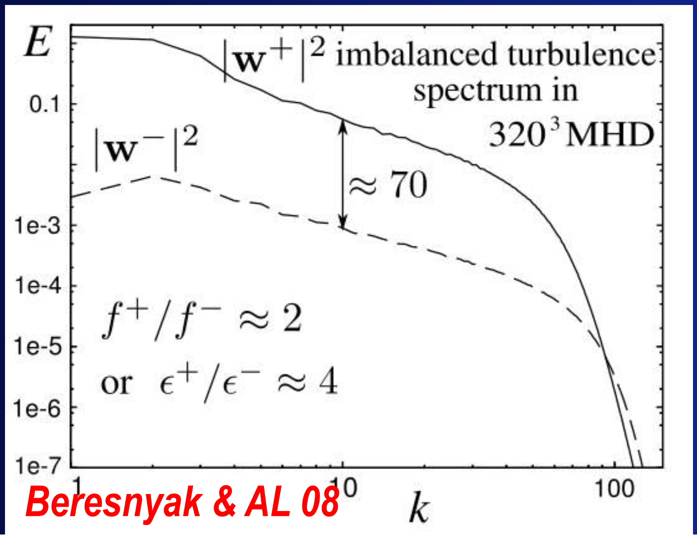
Thus

$$\epsilon = \frac{v_l^4}{l V_{Alf}} = \frac{v_{inj}^2}{t_{inj}} \Rightarrow v_{inj} \propto v_l^2$$

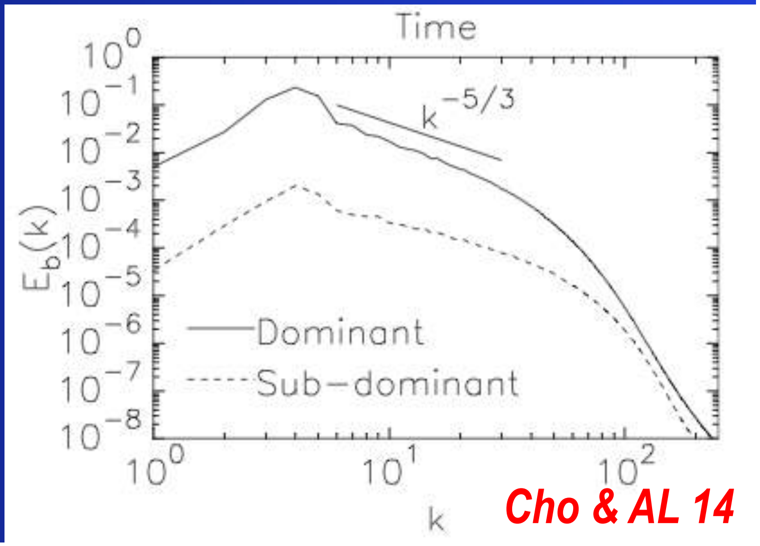
$$v_{total}^2 - v_{comp}^2 \approx v_l^2(1 - C_2(v_{inj}/V_{Alf})] \propto v_{inj}(1 - C_2(v_{inj}/V_{Alf})]$$

TOWARDS RELATIVISTIC RECONNECTION: Good correspondence between turbulence in relativistic and non-relativistic limits

	Non-relativistic	*Relativistic*
Balanced Turbulence	*Theory: Goldreich & Sridhar 95* *Numerics: Cho & Vishniac 00* *Maron & Goldreich 01, Cho & AL 02*	*Theory: Thompson & Blaes 98* *Numerics: Cho 05*
Imbalanced Turbulence	*Theory: Beresnyak & AL 08*	



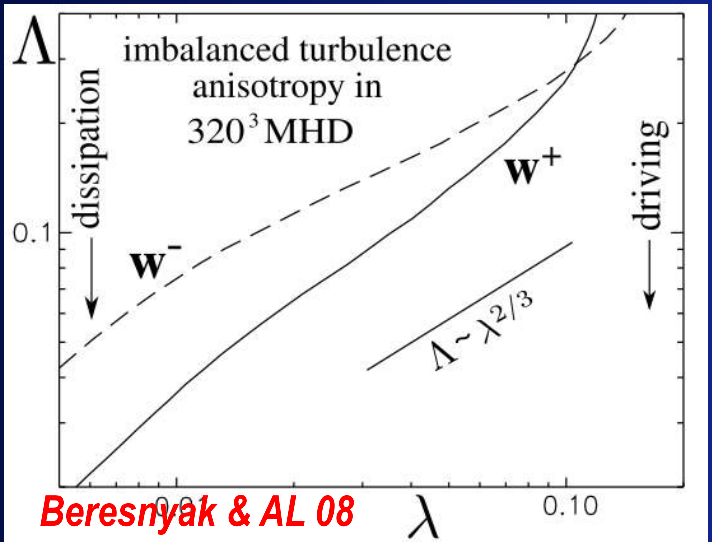
Beresnyak & AL 08



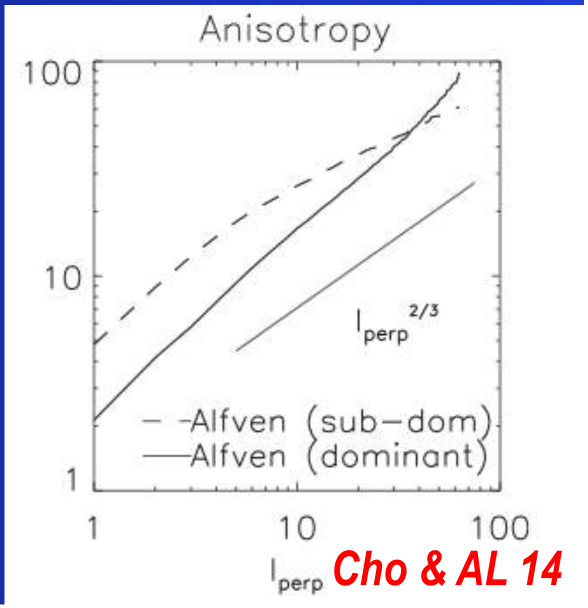
Cho & AL 14

Good correspondence between turbulence in relativistic and non-relativistic limits

	Non-relativistic	Relativistic
Balanced Turbulence	*Theory: Goldreich & Sridhar 95* *Numerics: Cho & Vishniac 00* *Maron & Goldreich 01, Cho & AL 02*	*Theory: Thompson & Blaes 98* *Numerics: Cho 05*
Imbalanced Turbulence	*Theory: Beresnyak & AL 08*	

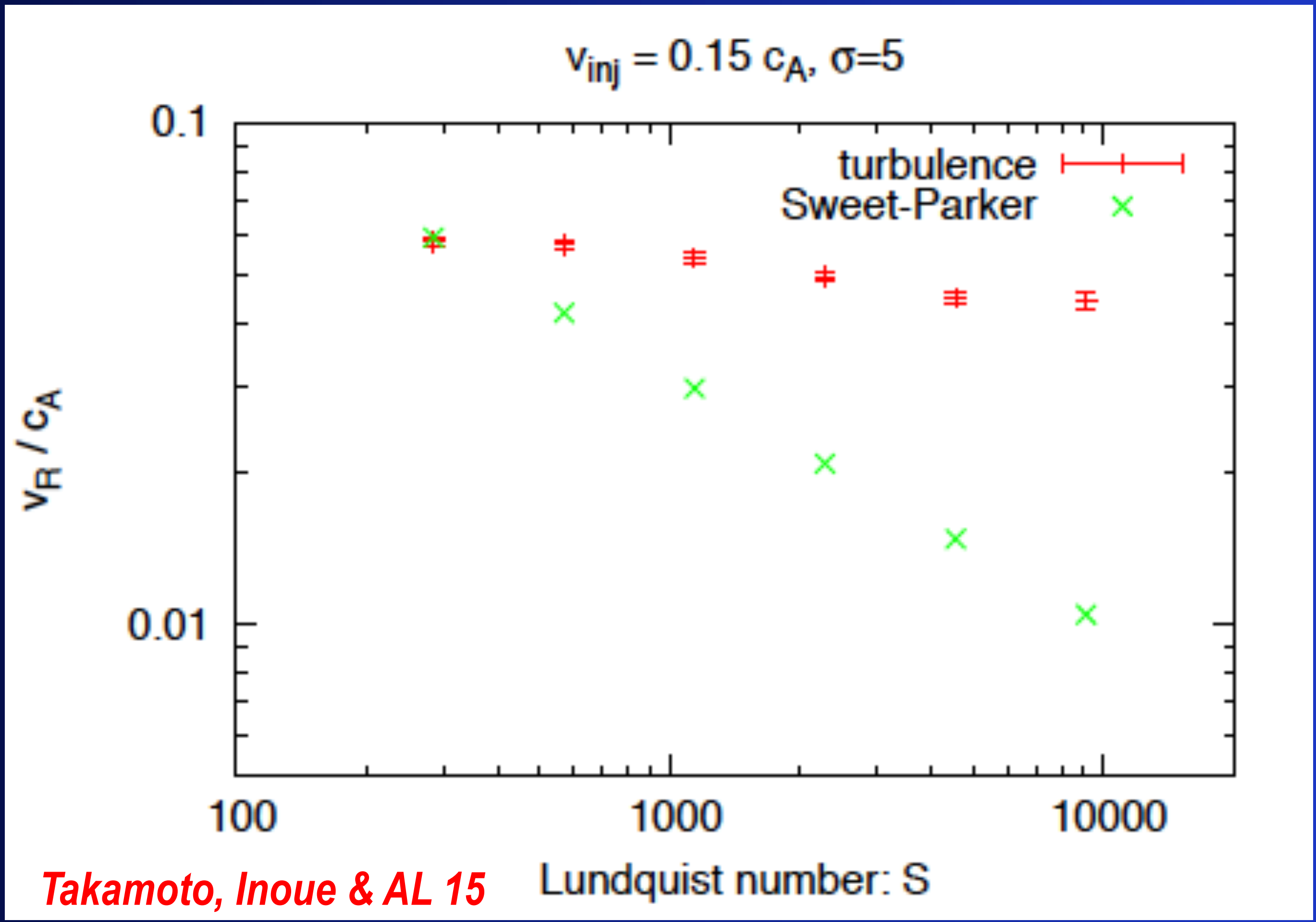


Beresnyak & AL 08



Cho & AL 14

Simulations show that the relativistic turbulent reconnection is fast, i.e.does not depend on S



Will LV99 expression be applicable to relativistic reconnection?

For compressible media with injection scale l less than L_x LV99 expression:

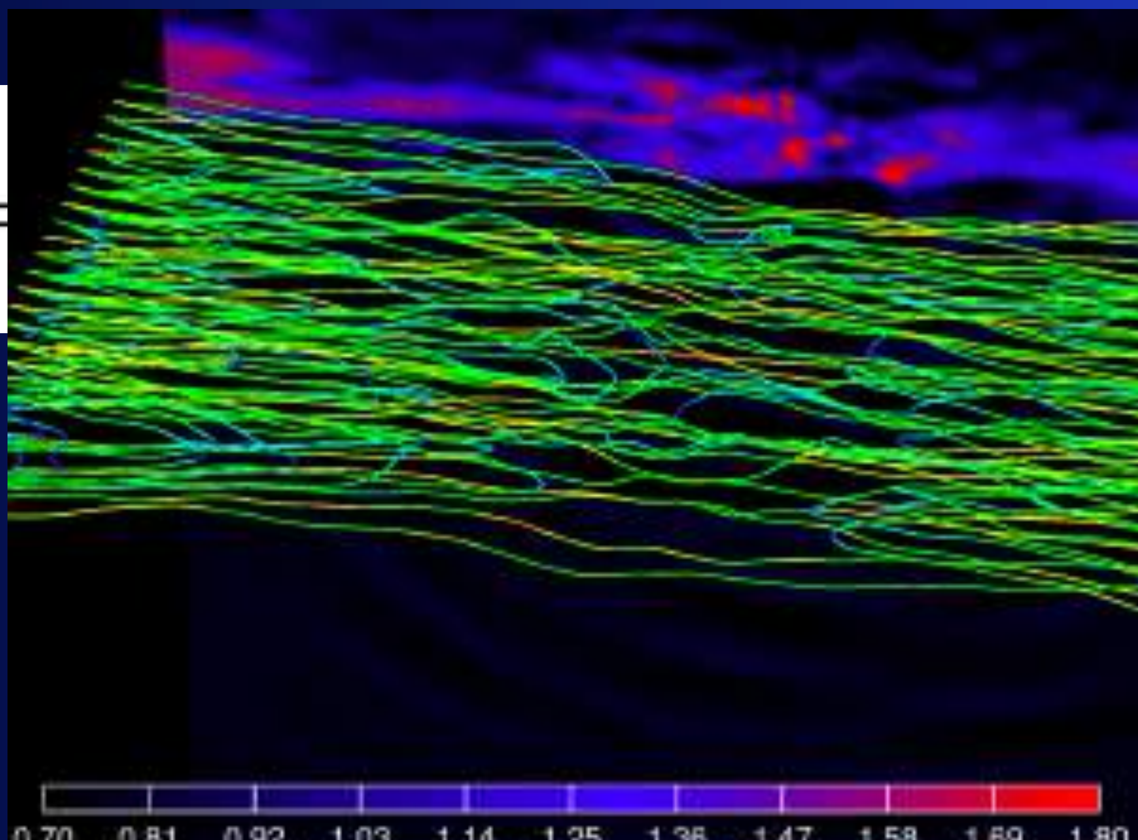
$$V_{rec} = v_s(\rho_s/\rho_{in})(l/L_x)^{1/2}\frac{(v_{total}^2 - v_{comp}^2)}{c_A^2}$$

⇧ *changes* ⇧ *changes*

Will LV99 expression be applicable to relativistic reconnection?

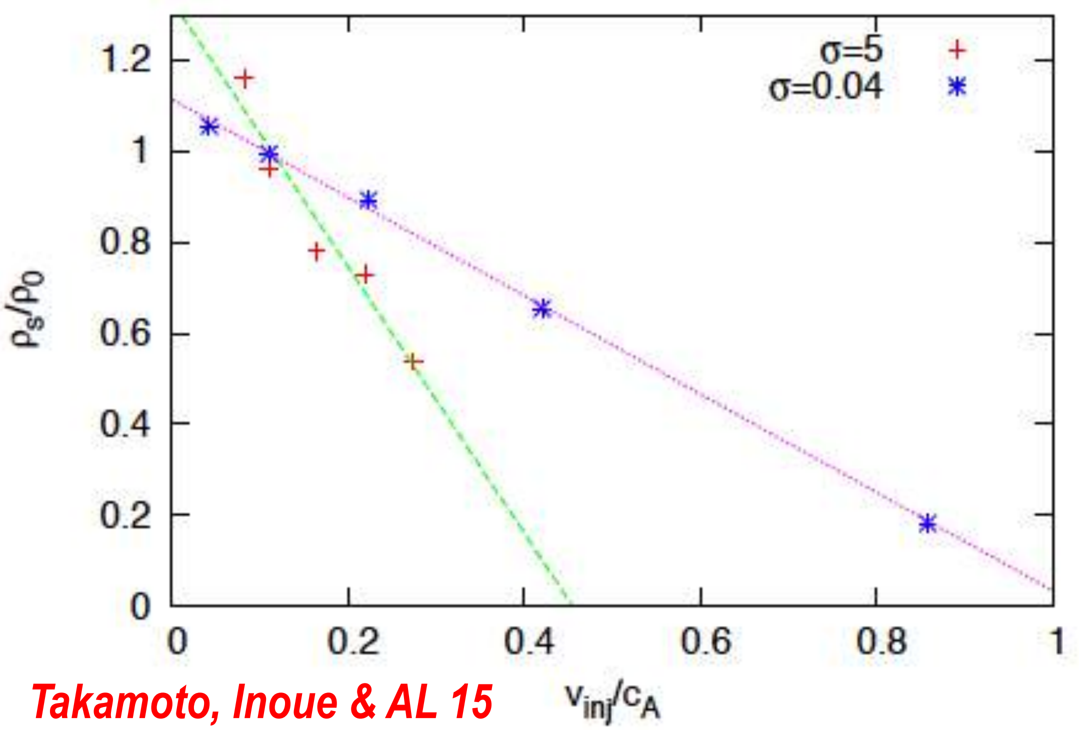
For compressible media with injection scale l less than L_x LV99 expression:

$$V_{rec} = \quad \ldots \quad - v_{comp}^2) \,/\, c_A^2$$



anges

Density in reconnection region decreases with increasing turbulent velocity



Takamoto, Inoue & AL 15

The density decrease decreases reconnection speed

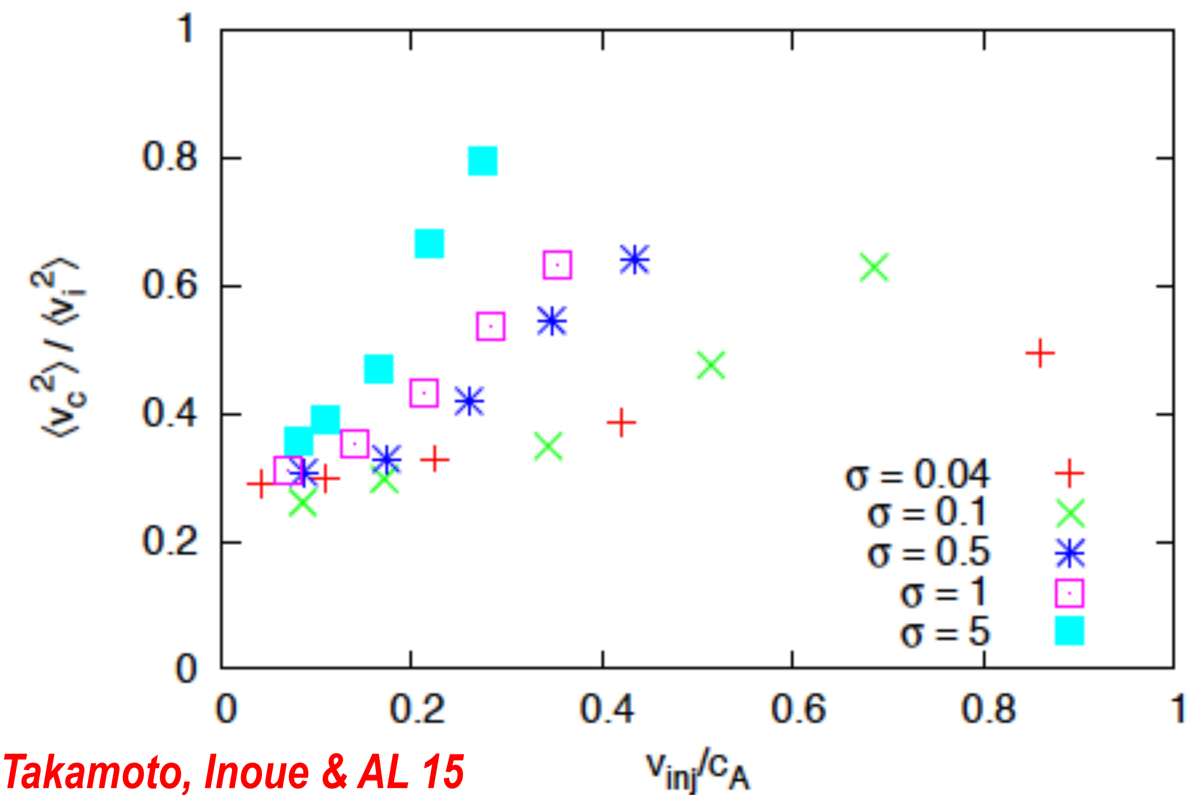
Conservation of energy flux

$$\rho_{\rm in} c^2 (1+\sigma) v_{\rm in} L + \rho_{\rm in}(1+2\sigma)\epsilon_{\rm inj} l_x l_z = \left(\rho_{\rm s} h_{\rm s} c^2 \gamma_{\rm s}^2 + \frac{B_{\rm s}^2}{4\pi}\right) v_{\rm s}\delta.$$

$$\Rightarrow \quad \rho_{\rm s}/\rho_{\rm in} = \alpha(1-\beta v_{\rm inj})$$

The transfer of energy to compressible modes also decreases reconnection speed

$$v_{total}^2 - v_{comp}^2 \approx v_l^2[1 - C_2(v_{inj}/c_A)]$$



Takamoto, Inoue & AL 15

With

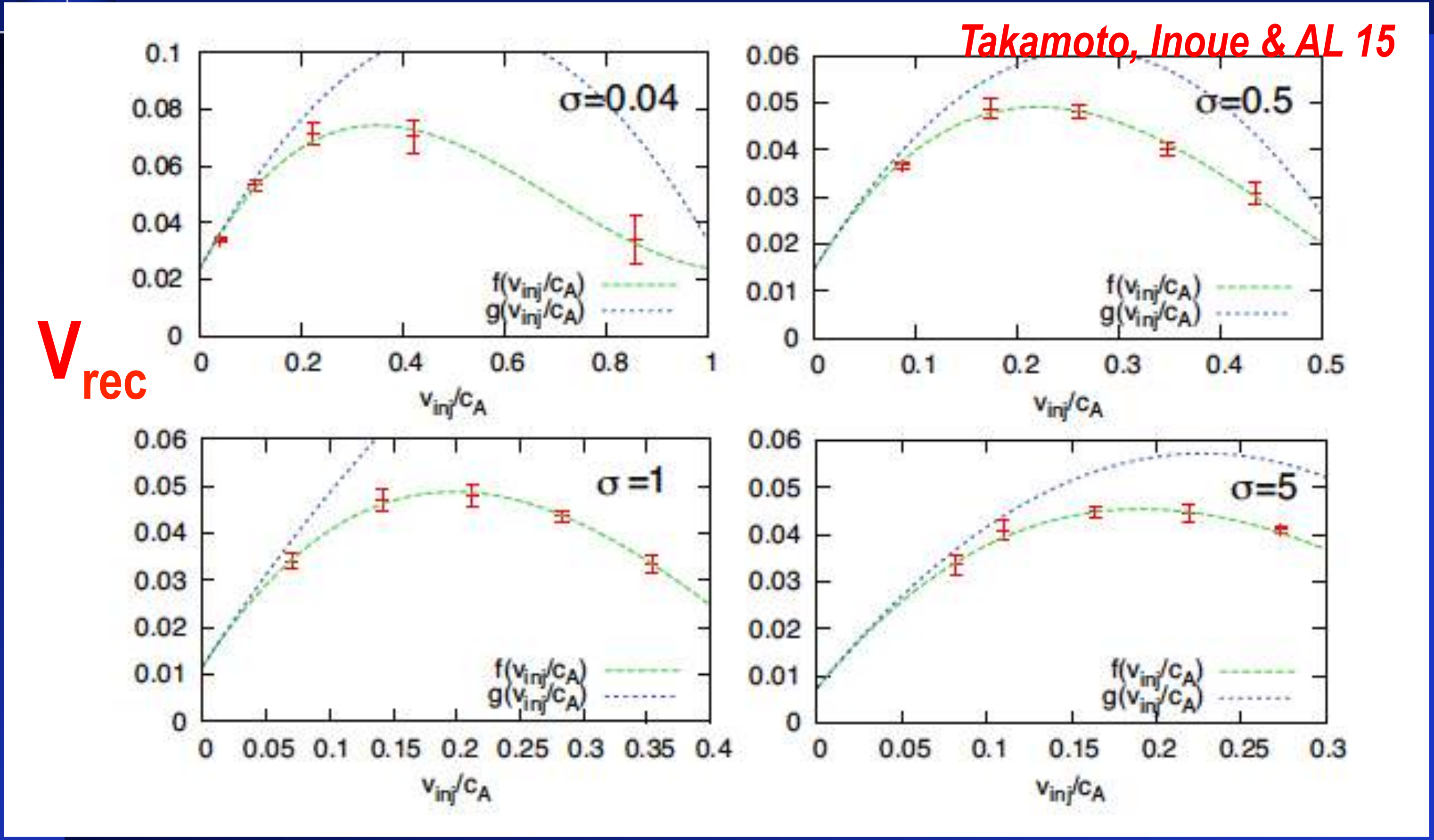
$$\epsilon = \frac{v_l^4}{lc_A} = \frac{v_{inj}^2}{t_{inj}}$$

$$v_{inj} \propto v_l^2$$

And squared Alfvenic compoent

$$\propto v_{inj}[1 - C_2(v_{inj}/c_A)]$$

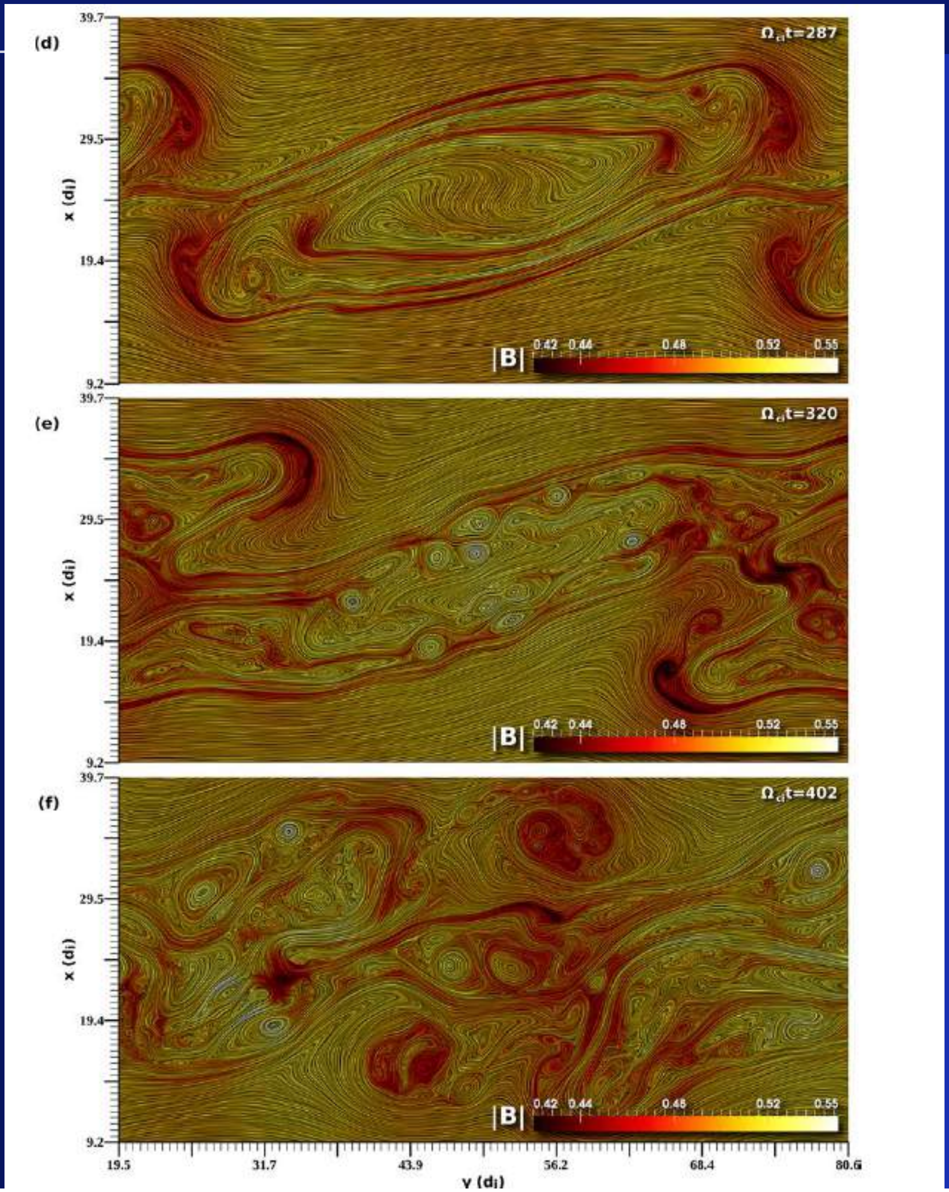
Relativistic simulations agree well with compressible turbulent reconnection prediction



$$V_{rec} \approx 0.3 c_A (\rho_s/\rho_{in})(l/L_x)^{1/2} \frac{v_{inj}(1 - C_2 v_{inj}/c_A)}{c_A}$$

Max reconnection $\sim 0.3\, c_A$

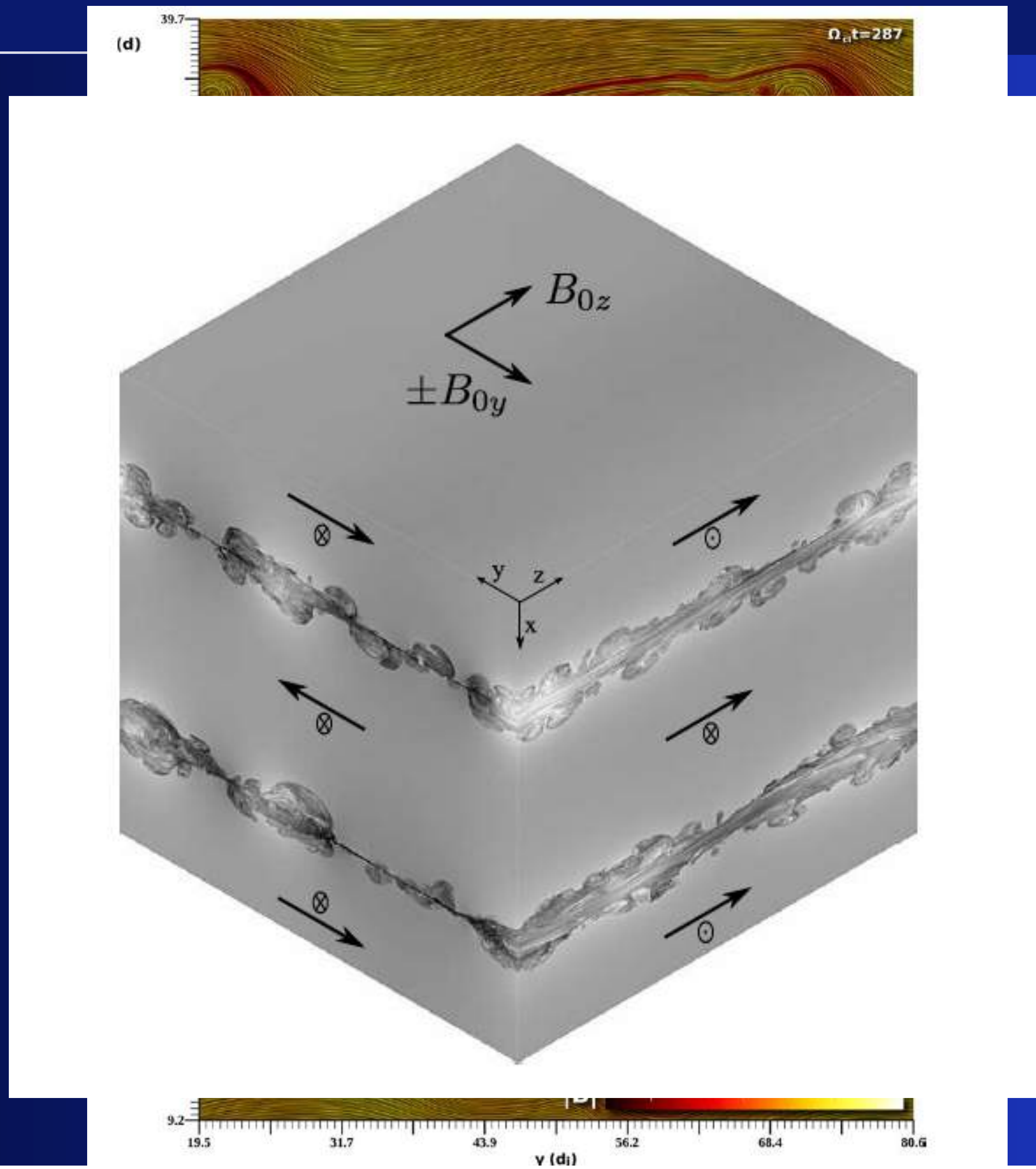
TURBULENCE INDUCED BY REONNECTION: Reconnection in 3D PIC simulations results development of turbulence



Karimabadi et al. 13

Reconnection in 3D PIC simulations results development of turbulence

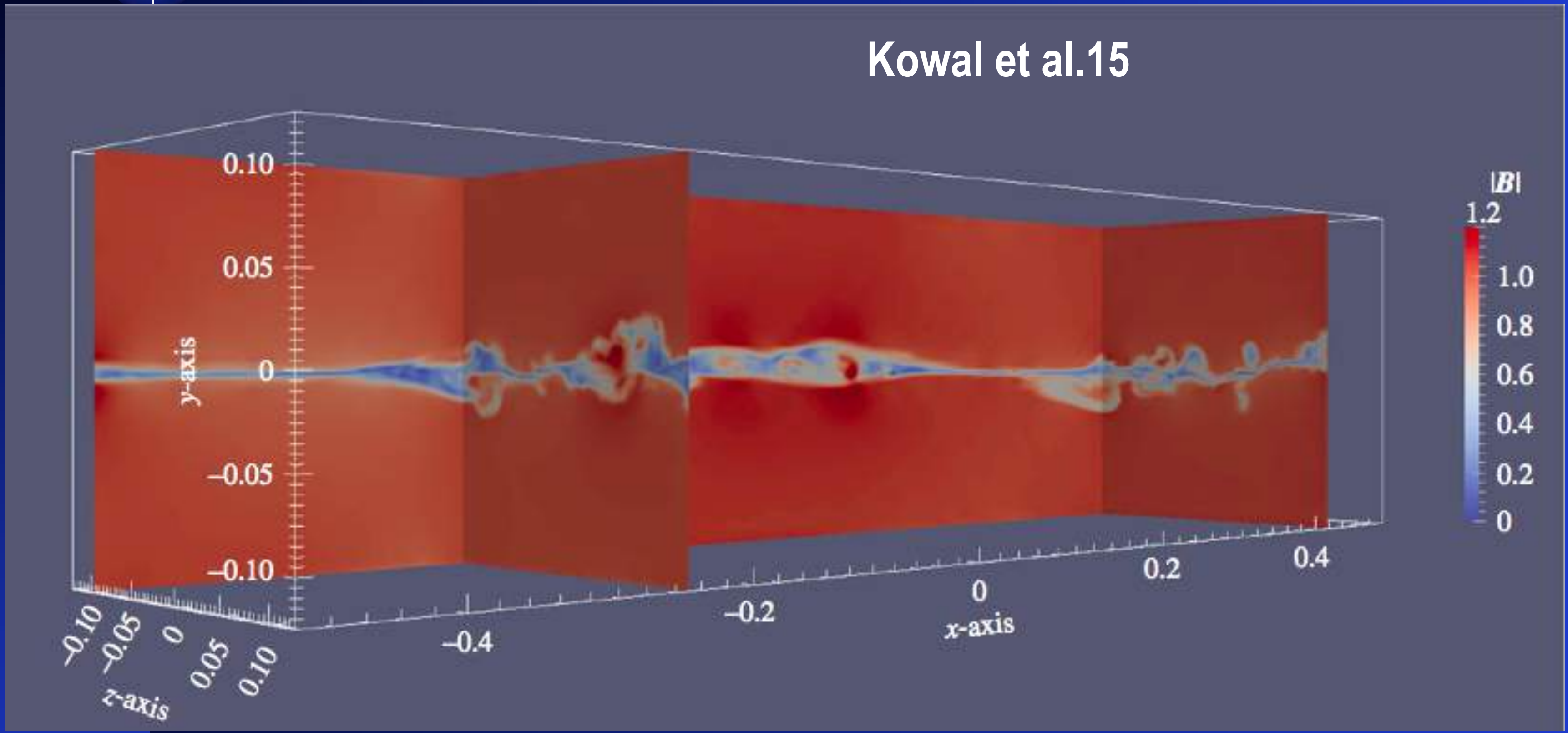
Development of MHD turbulence is observed in 3D reconnection simulations by Beresnyak 13



Also Oishi et al. 15 confirmed LV99 predictions

Karimabadi et al. 13

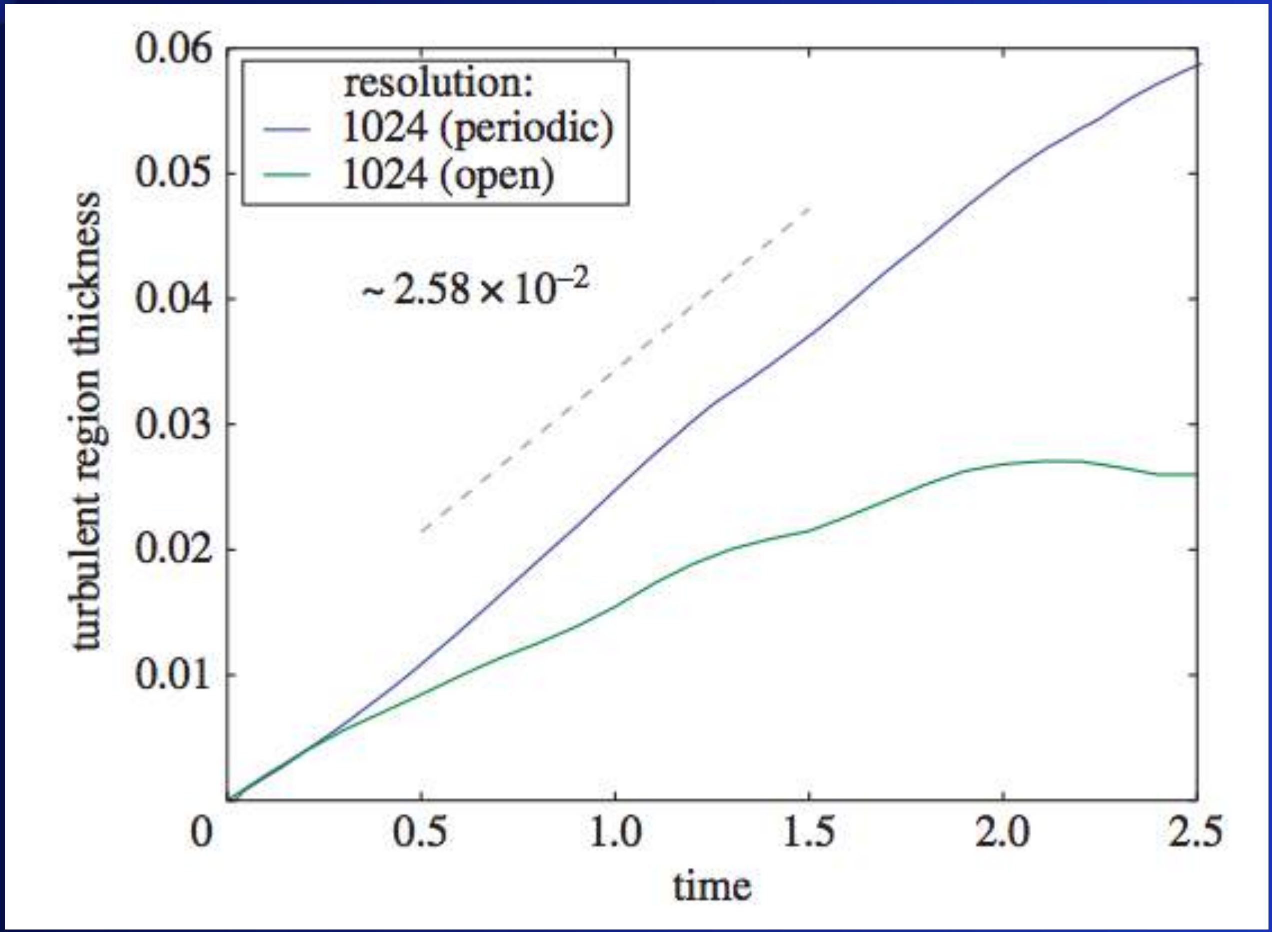
Simulations demonstrate the development of turbulence through Kelvin-Helmholz instability



$$V_\Delta \approx (C_K r_A)^{3/4} V_{Ay} \beta^{1/2}$$

Expected reconnection rate, Ck is Kolmogorov constant, r_A is magnetization

Self-sustained reconnection exhibits rates consistent with the the predictions based on the extension of LV99 theory



$V_{REC} \sim 0.02 V_A$

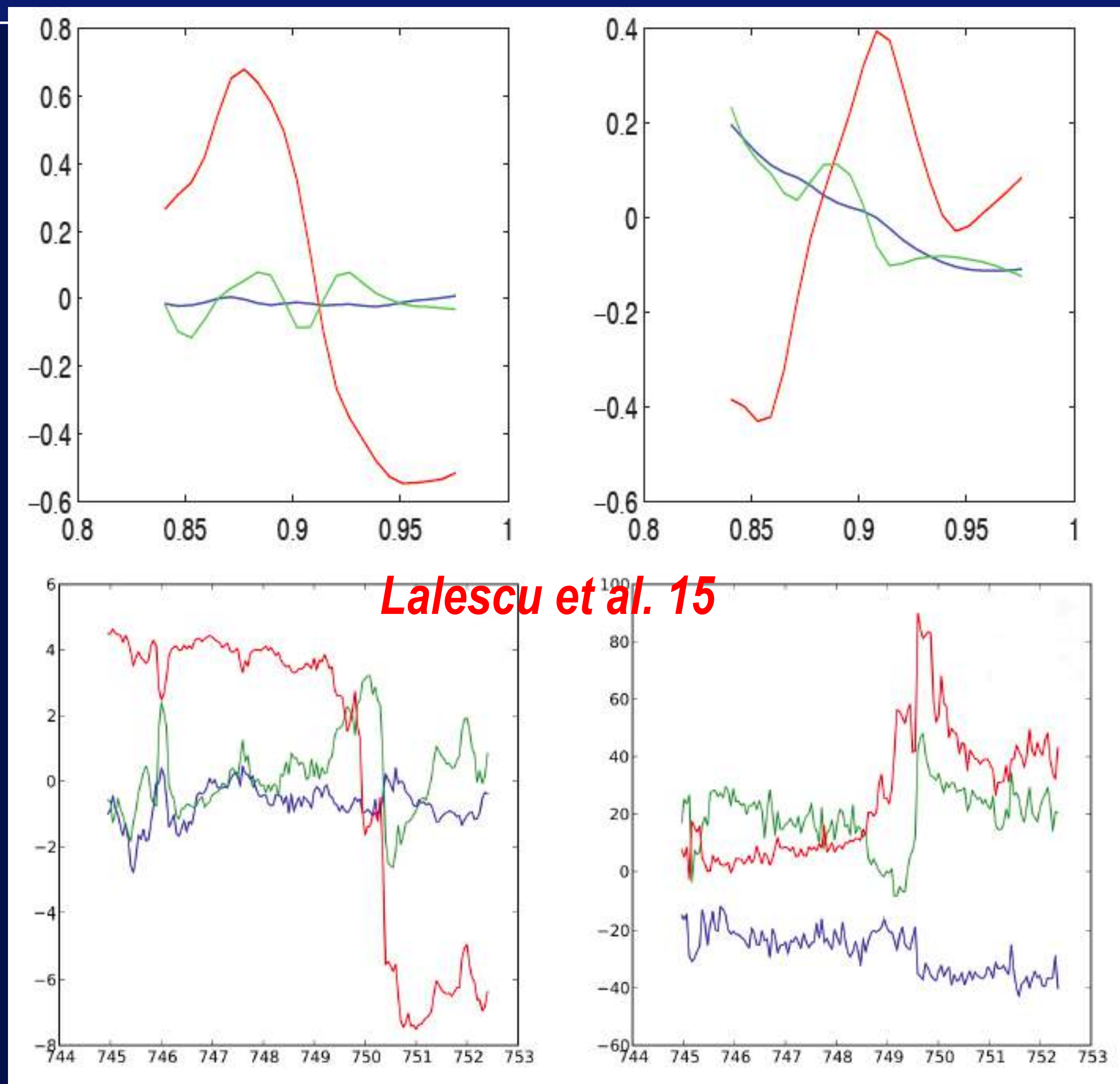
Slower growth and saturation are predicted with open boundary conditions

Correcting a claim in Karimabadi & Lazarian (2014) review on no evidence of LV99 reconnection signatures in Solar Wind

The complex structure of magnetic reconnection similar to one in solar wind is revealed in simulations of MHD turbulence

Lalescu et al. 2015

Turbulent reconnection is consistent with Solar wind measurements (cf. Karimabadi & AL 14)

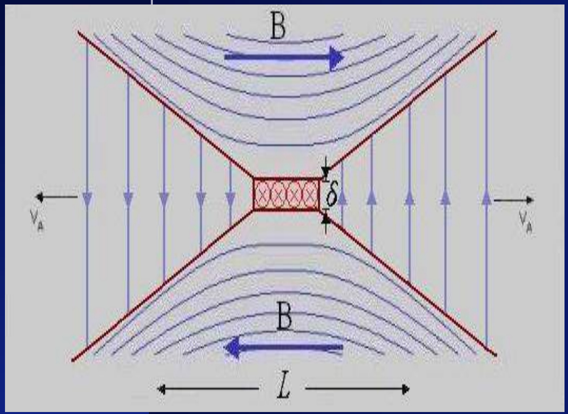


MHD turbulence data set events

Solar wind reconnection events

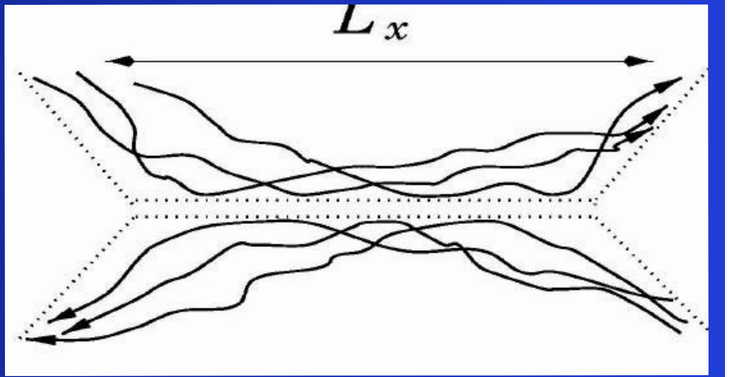
Convergence between the plasma-based reconnection and turbulent model is evident!

Paradigm 1999



Hall effect is **required**

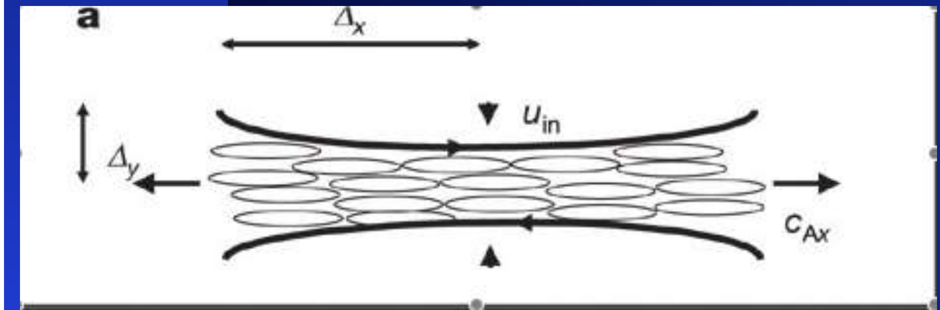
LV99 model



Hall effect is **not required**

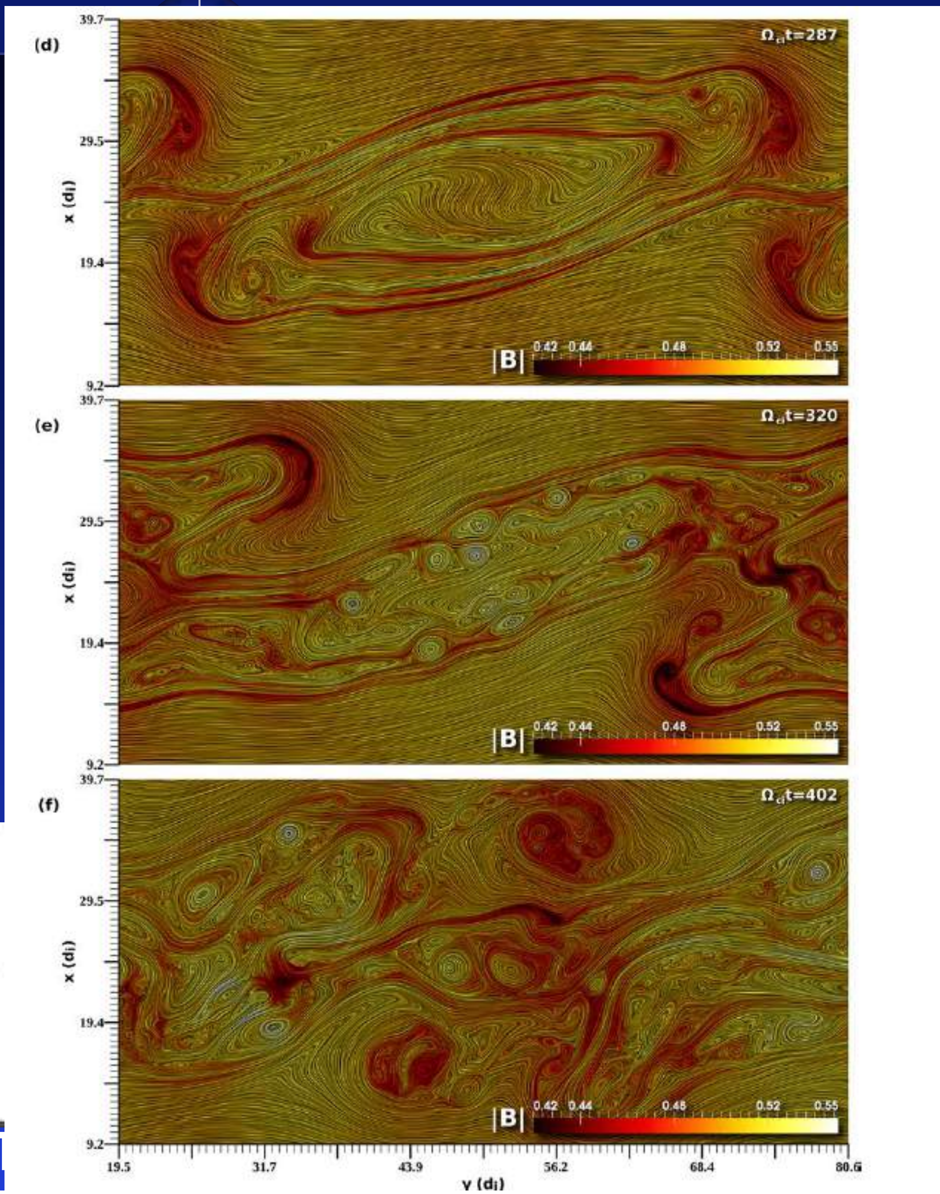
(Fully 3D, turbulence)

Paradigm 2015



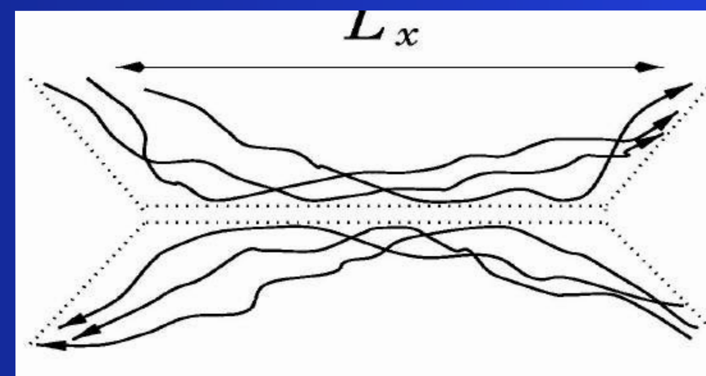
Tearing reconnection (Hall effect is **not required**)

Convergence between the plasma-based reconnection and turbulent model is evident!



ed)

LV99 model

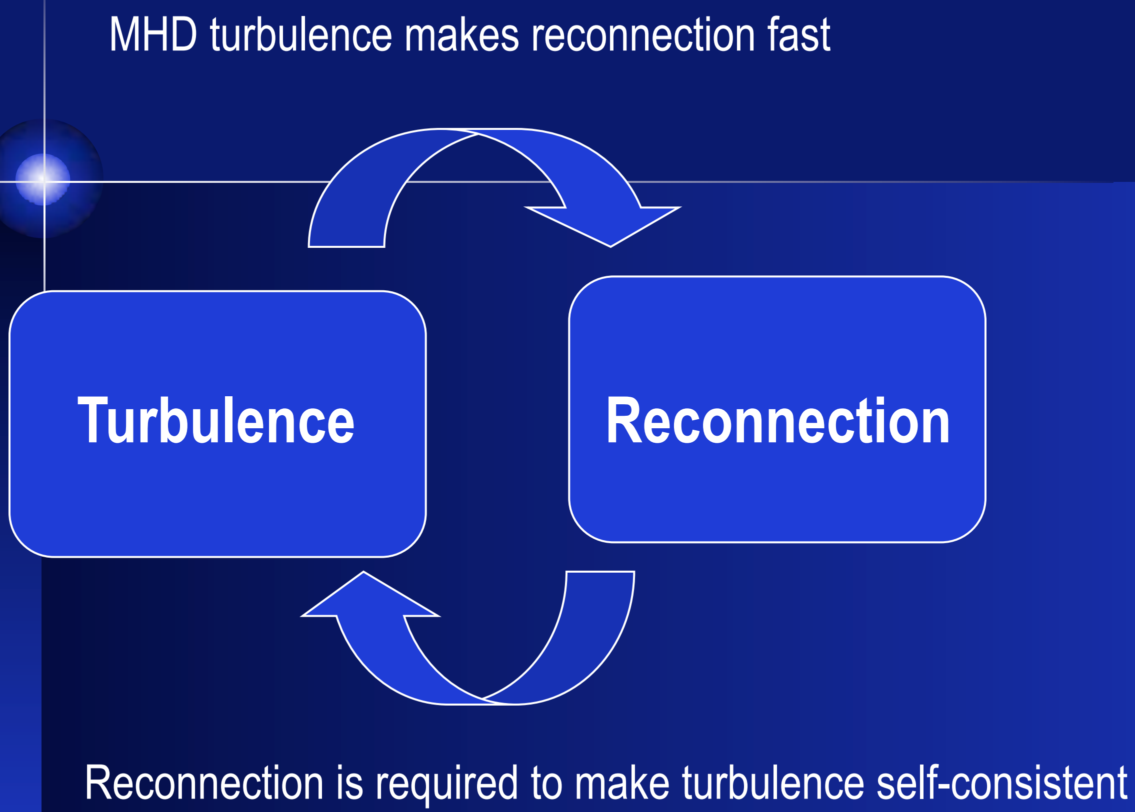


Hall effect is not required

(Fully 3D, turbulence)

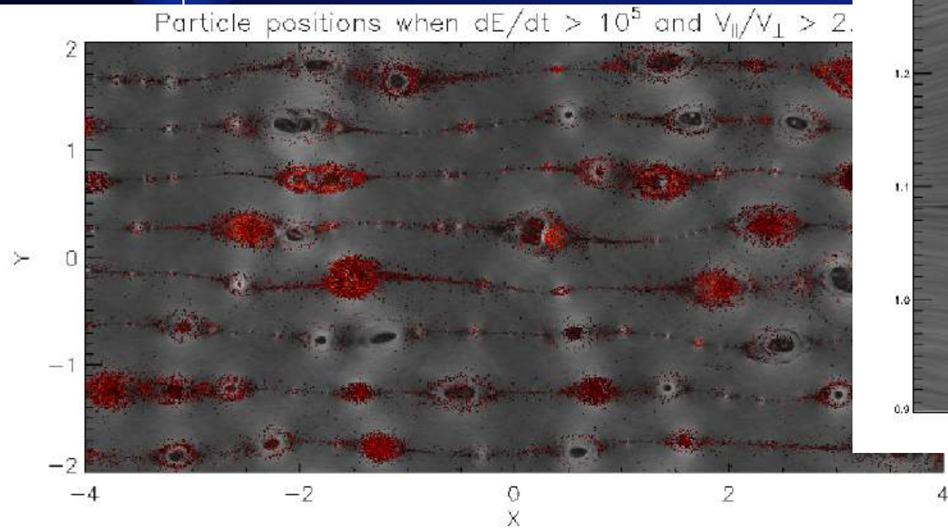
3D simulations without turbulence show transfer to turbulent state (e.g. Karimabadi 2012)

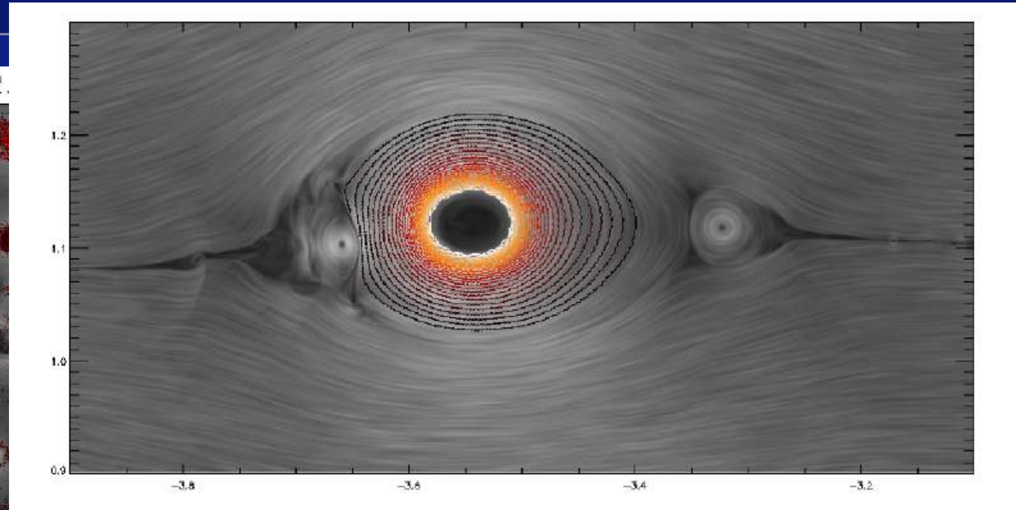
Turbulence and fast astrophysical reconnection are interconnected. Relativistic and non-relativistic cases are similar.



EXTRA SLIDES FOLLOW

MHD calculations reproduce 2D PIC calculations by Drake et al and go beyond

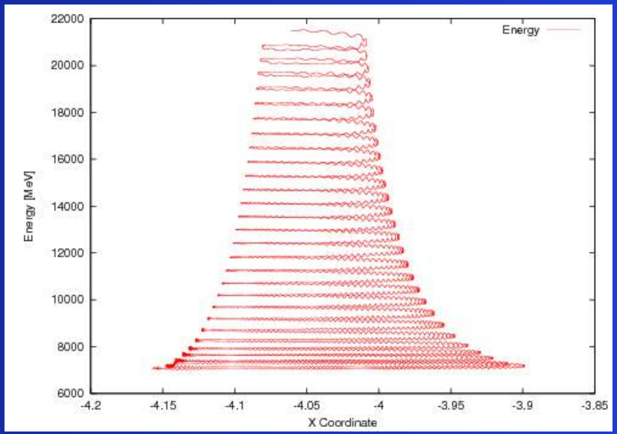




Zoom in into itrajectories

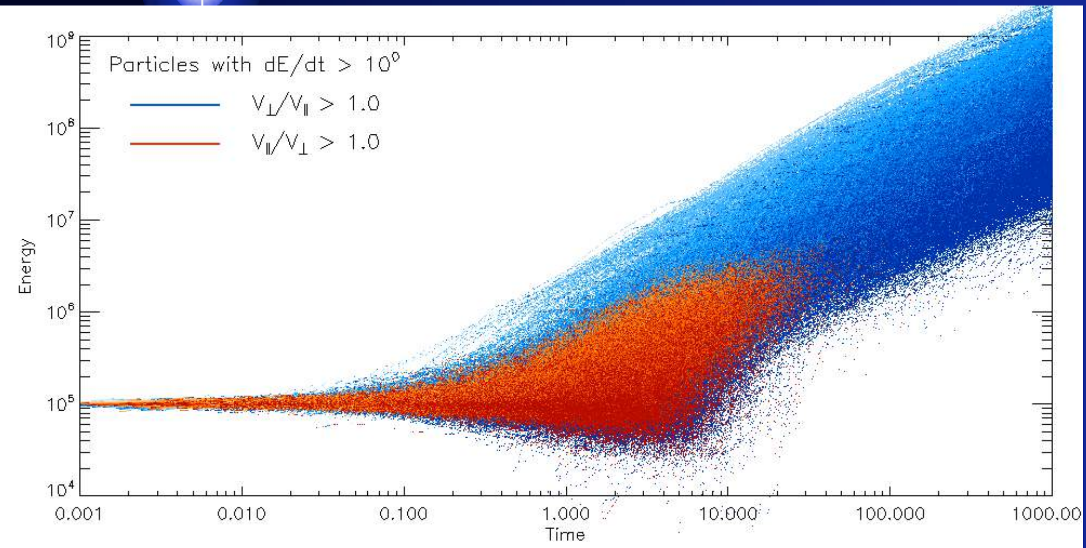
Multiple reconnection layers are used to produce volume reconnection.

Kowal, Lazarian, de Gouveial dal Pino 2011

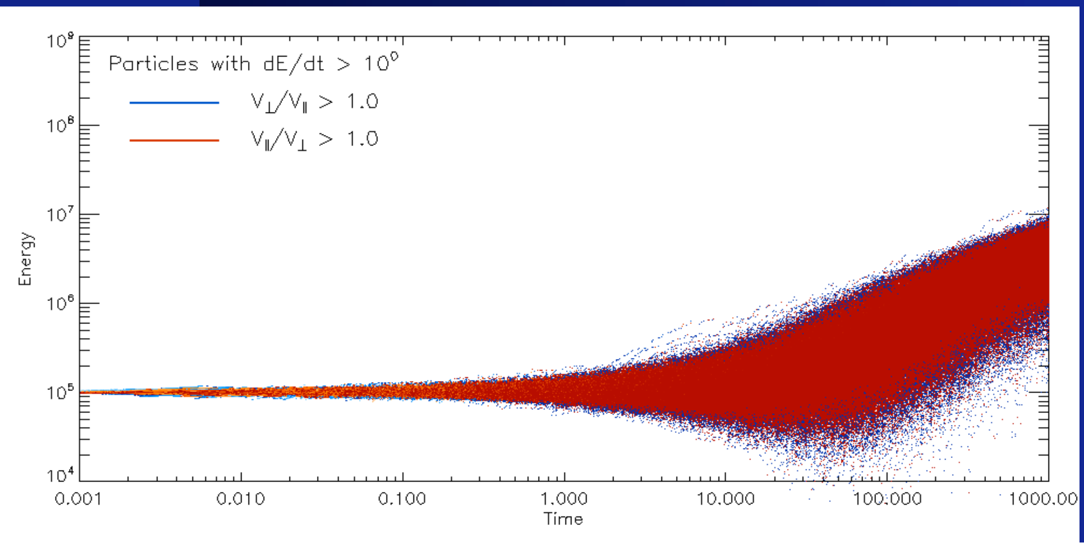


Regular energy increase

2D and 3D reconnection accelerates particles very differently: Loops and spirals behave differently!



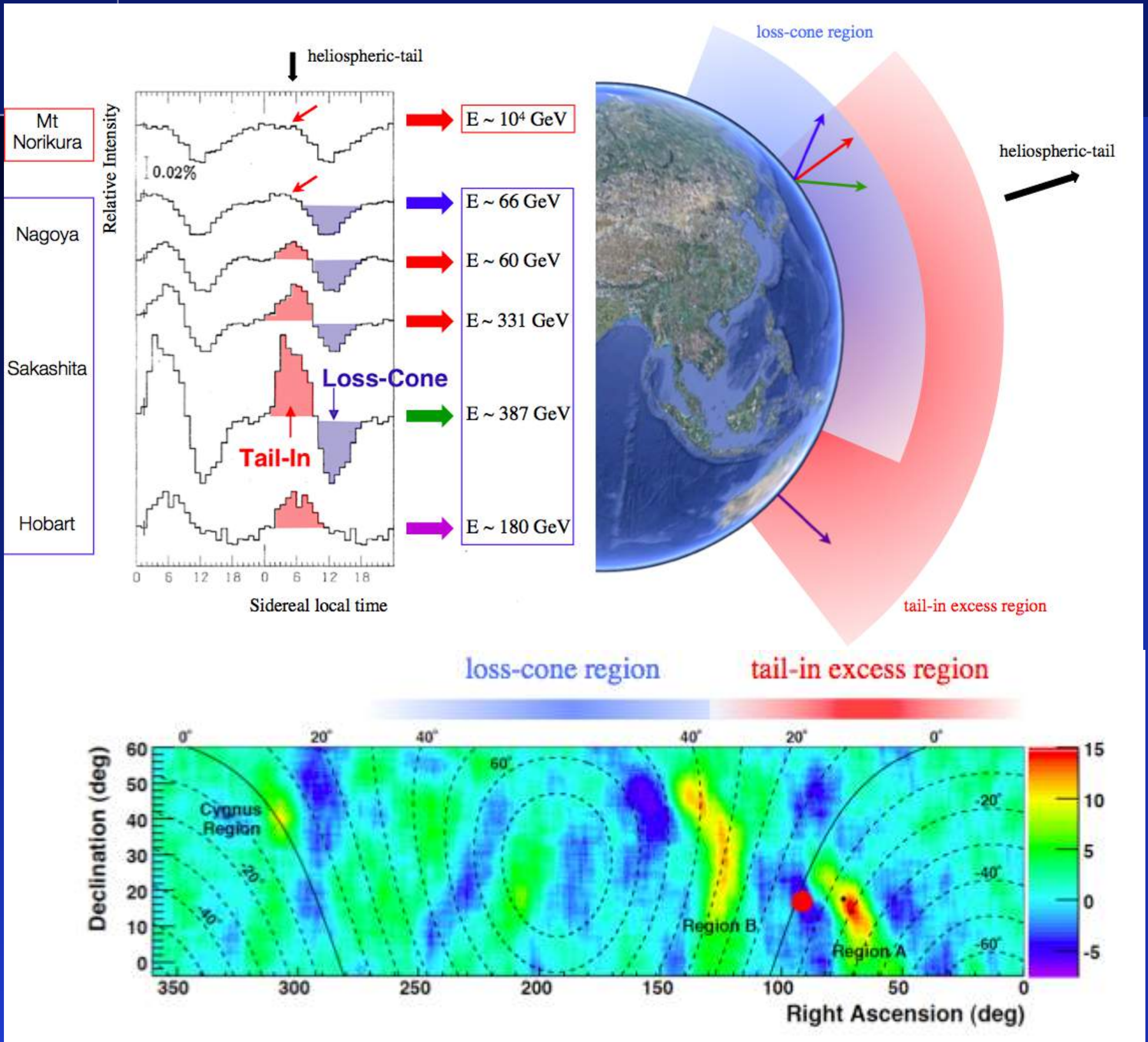
Perpendicular acceleration gets important for 2D at longer integration times



Parallel momentum mostly increases for the acceleration in 3D

Kowal, Lazarian, de Gouveial dal Pino 2010

Excess of cosmic rays is observed in the tail in region

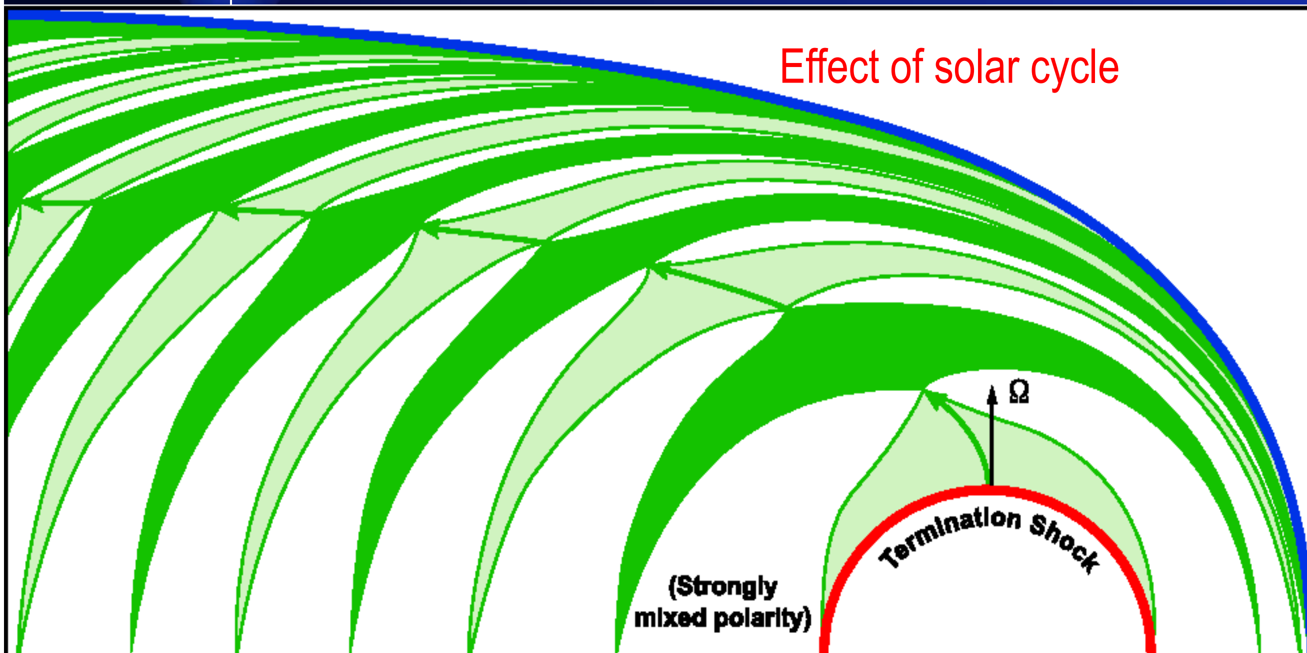


Abdo A.A. et al., 2008, Phys. Rev. Lett., 101, 221101

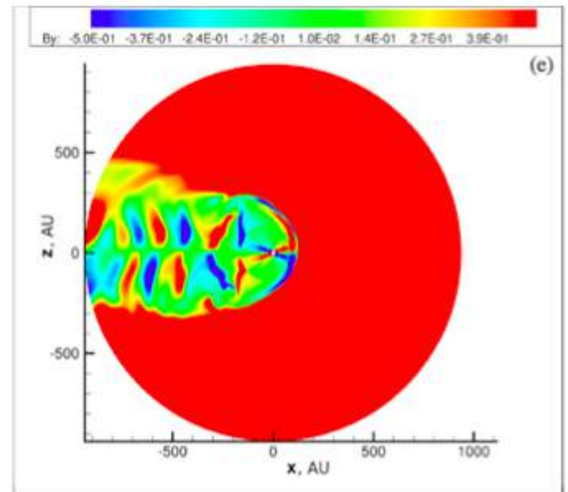
Low energy tail-in anisotropy

1-10Tev from Milagro, TibetIII, AGRO-YBJ and ICECUBE

MILAGRO data: Magnetic reconnection expected in magnetotail can explain both the TeV and lower energy excess observed



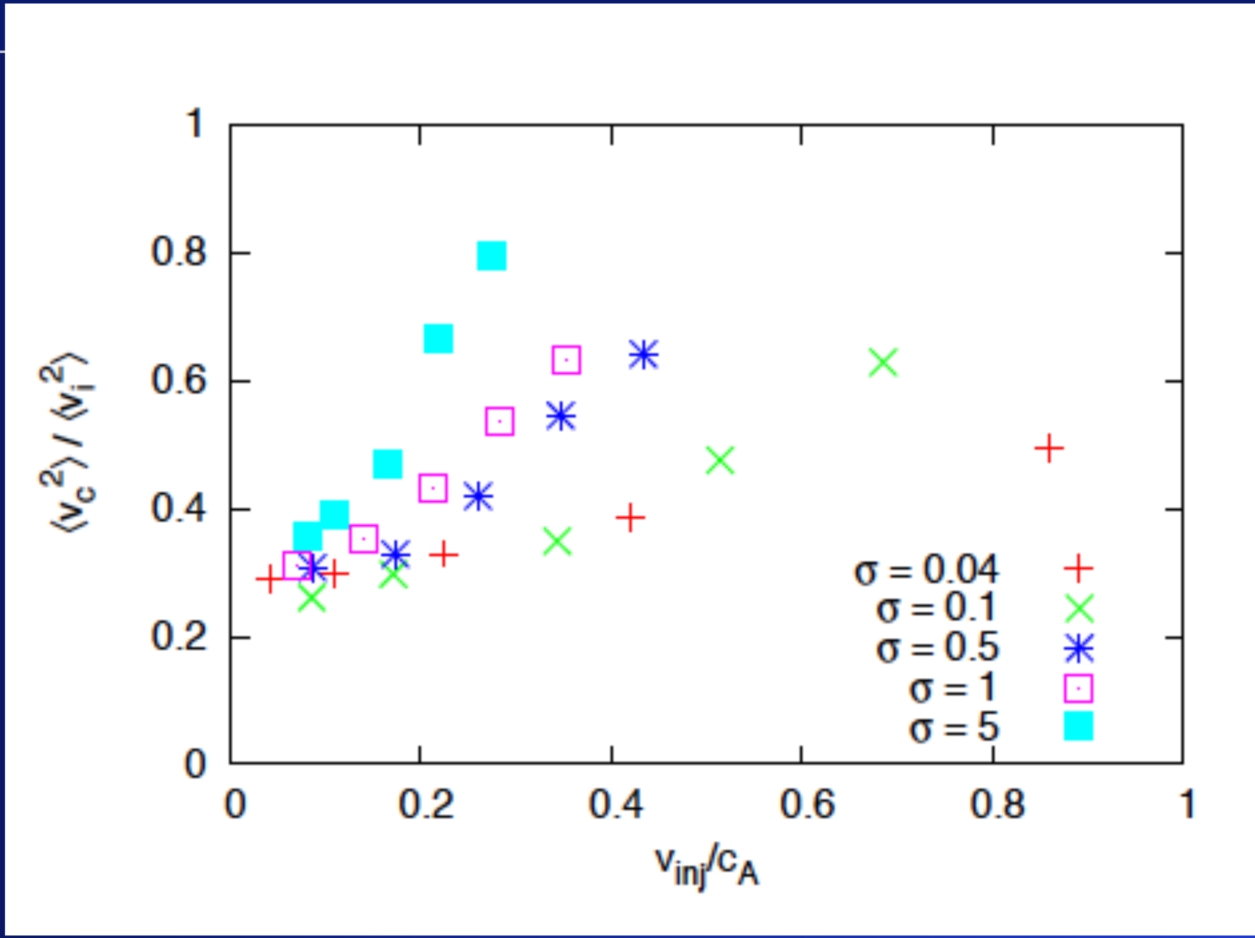
Pogorelov et al., ApJ, 696, 1478, 2009



Lazarian & Desiatii 2010

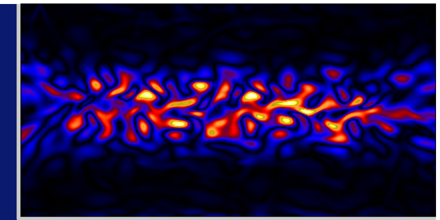
Compressible modes drain energy from Alfvenic ones

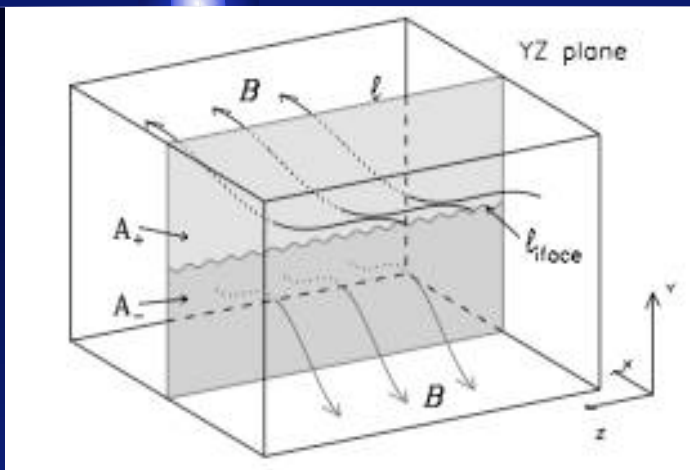
$$\frac{v_{comp}^2}{c_A^2} \propto \frac{v_{inj}}{c_A}$$



$$v_{total}^2 - v_{comp}^2 \approx v_l^2(1 - C_2(v_{inj}/c_A)] \propto v_{inj}(1 - C_2(v_{inj}/c_A]$$

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





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

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

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

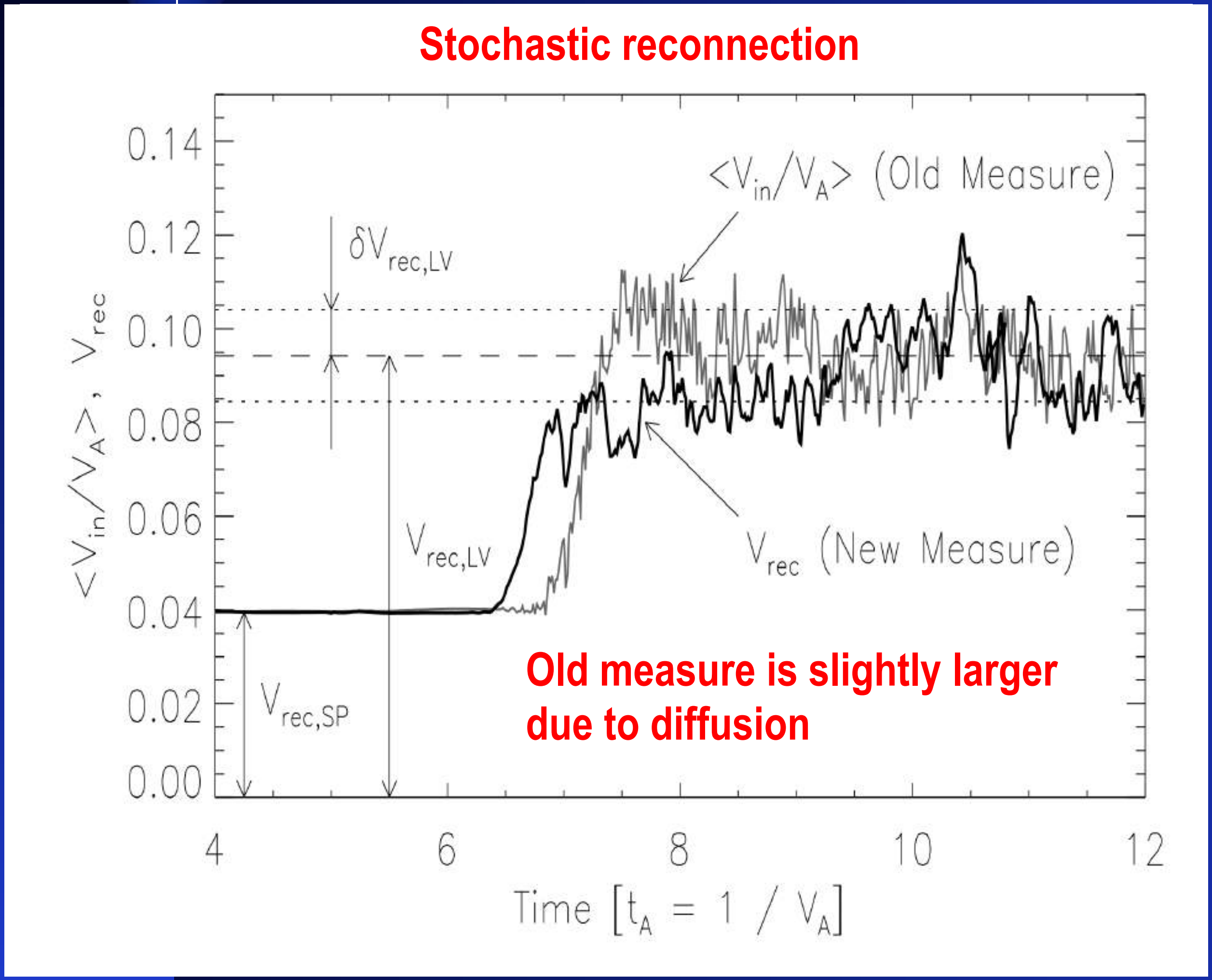
$$\int 2\vec{E}\cdot d\vec{l}_{interface} \equiv -2V_{rec}|B_{x,\infty}|L_z$$

Asymptotic absolute value of Bx

New measure:

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

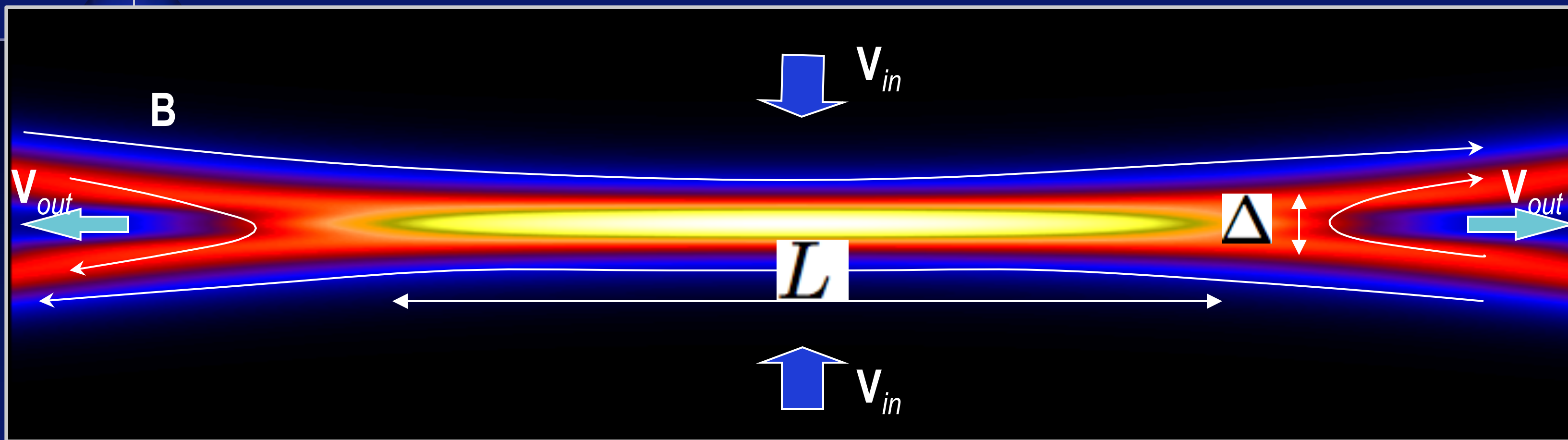
Calculations using the new measure are consistent with those using the intuitive one



Intuitive, “old” measure is the measure of the influx of magnetic field

New measure probes the annihilation of the flux

Turbulence is expected to change Sweet-Parker reconnection and its tearing extension



1. *Magnetic field lines get not straight.*
2. *Tearing instability gets suppressed when the eddy turnover rate is larger than the instability rate.*
3. *The outflow gets inevitably turbulent for sufficiently large Re numbers of the outflow*

$$R_\Delta = \frac{\Delta V_A}{\nu}$$

   a. *if turbulence suppresses instability, then Δ gets constant and reconnection rate start dropping as 1/S*
   b. *Turbulence induces a transfer to a new regime of reconnection*