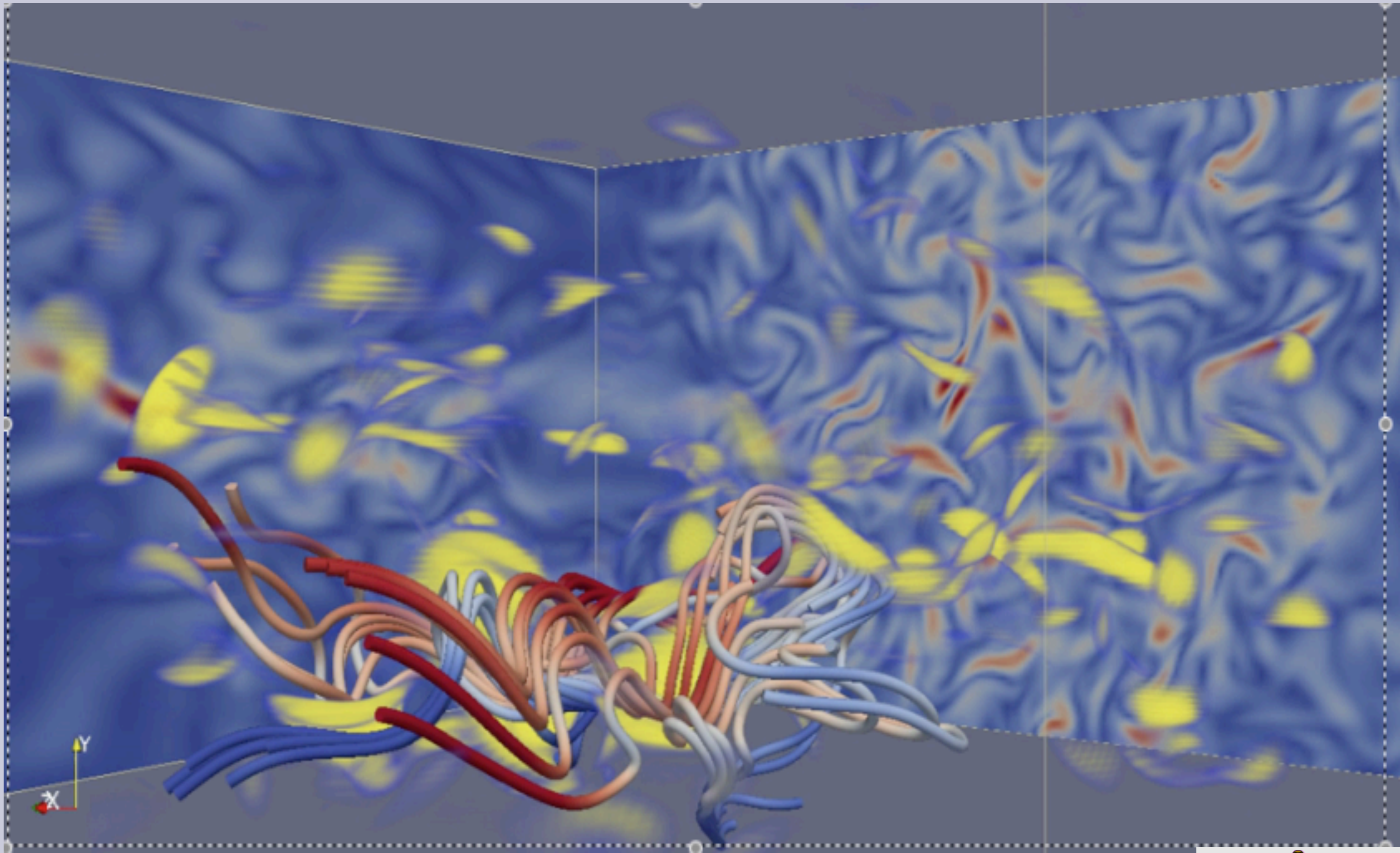
Magnetic Turbulence, Reconnection and CR Perpendicular Diffusion



Alex Lazarian (Astronomy and Physics)

THE UNIVERSITY of WISCONSIN MADISON

Special thanks to E. Vishniac, H. Yan and G. Kowal

Plan of the talk

Properties of turbulence and magnetic reconnection
CR perpendicular transport
Implications for CR acceleration

Plan of the talk

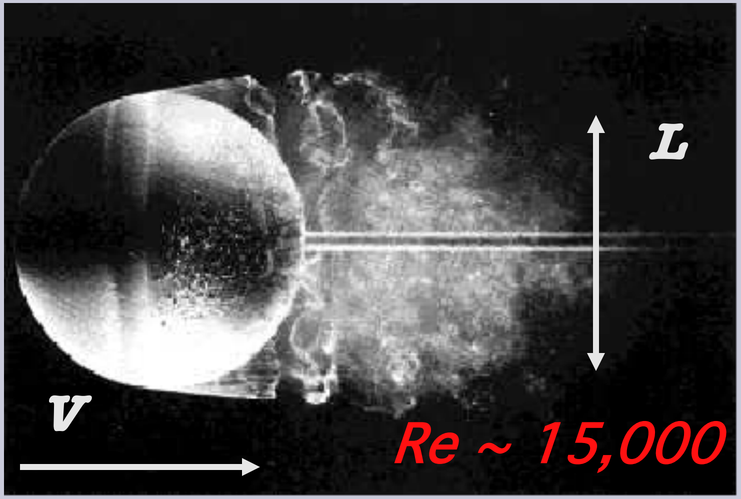
Properties of turbulence and magnetic reconnection

CR perpendicular transport

Implications for CR acceleration

Astrophysical flows are turbulent due to large Reynolds numbers

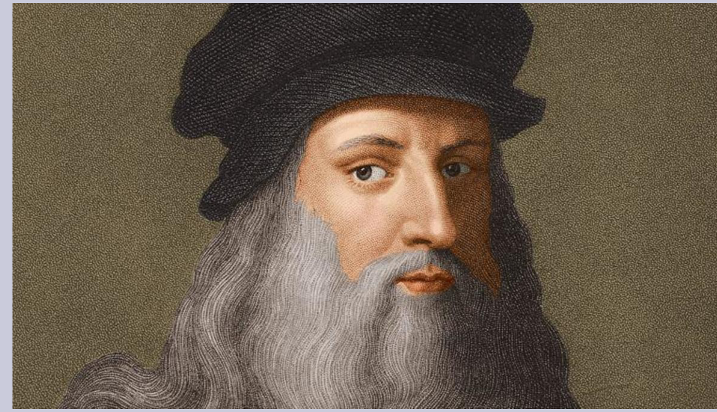
$$Re = LV/\nu = (L^2/\nu)/(L/V) = \tau_{diff}/\tau_{eddy}$$



Astrophysical flows have Re> 10^{10}

For reference: Numerical Re<10^4 and this is a problem of brute force approach.

Turbulence is a chaotic order



L. Da Vinci

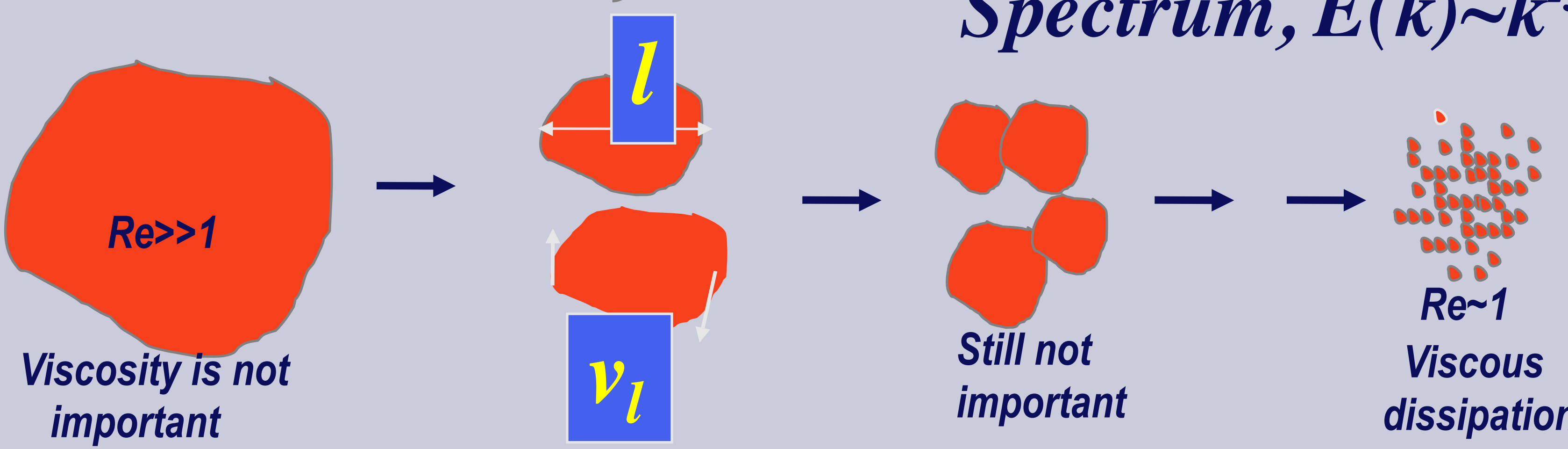
It is important to know the laws of this order and use them

Kolmogorov theory reveals order in chaos for incompressible hydro turbulence

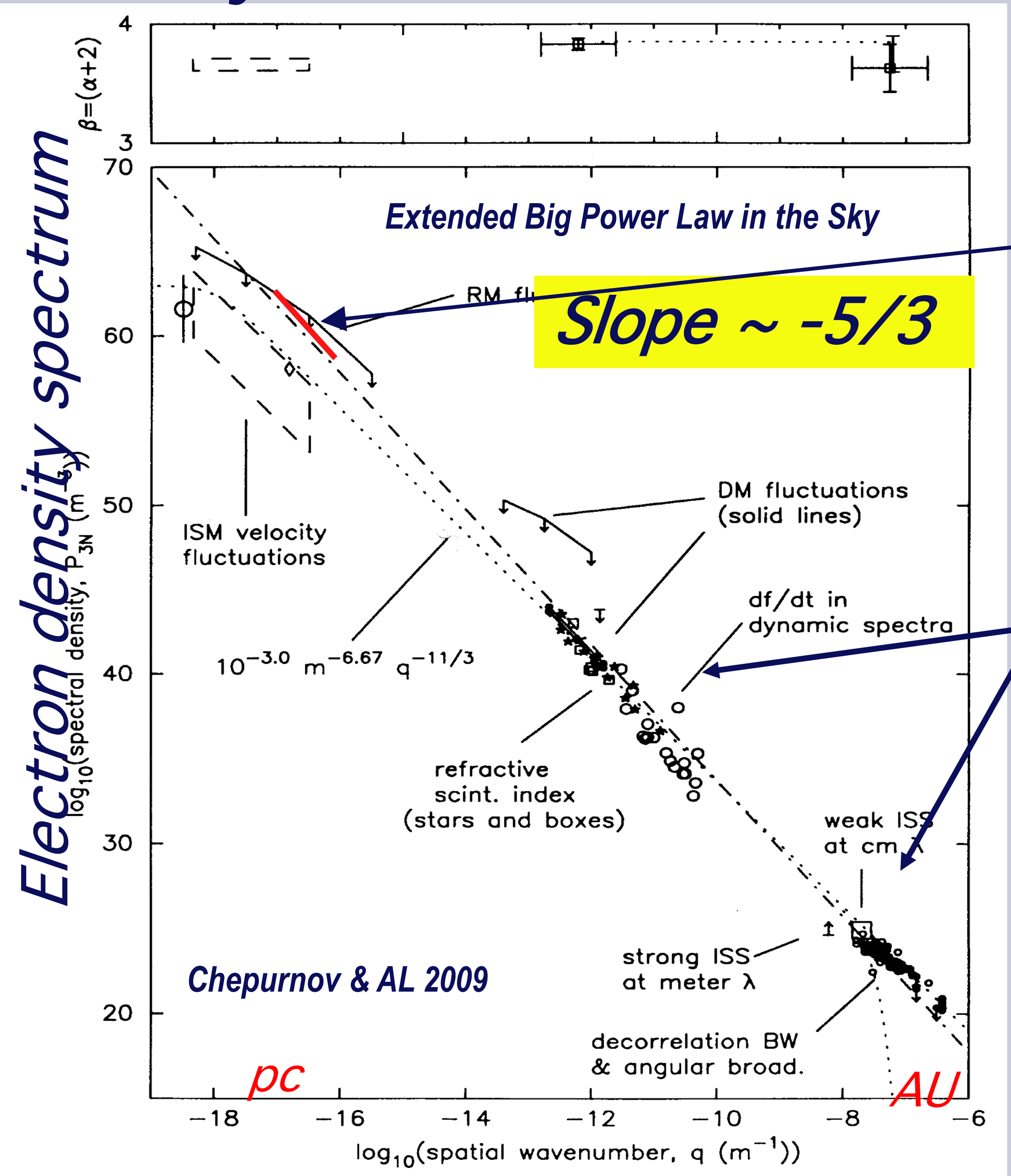
A. Kolmogorov

$$\left.\begin{aligned} \frac{V_l^2}{t_{cas,l}} &= const \\ t_{cas,l} &= l/V_l \end{aligned}\right\} \frac{V_l^3}{l} = const, \; V_l \sim l^{1/3}$$

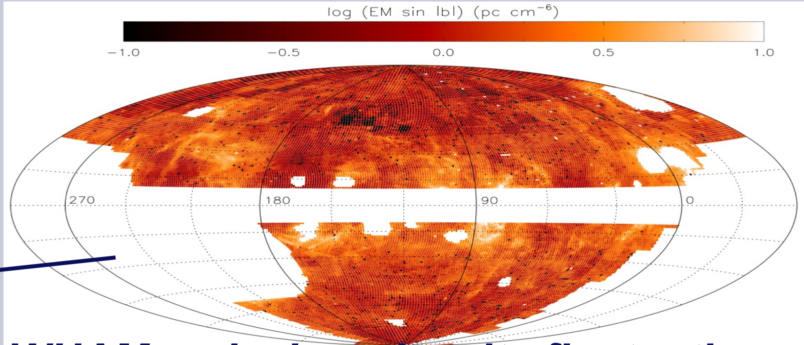
$$Spectrum, \; E(k) \sim k^{-5/3}$$



ISM reveals Kolmogorov spectrum of electron density fluctuations



Slope ~ -5/3

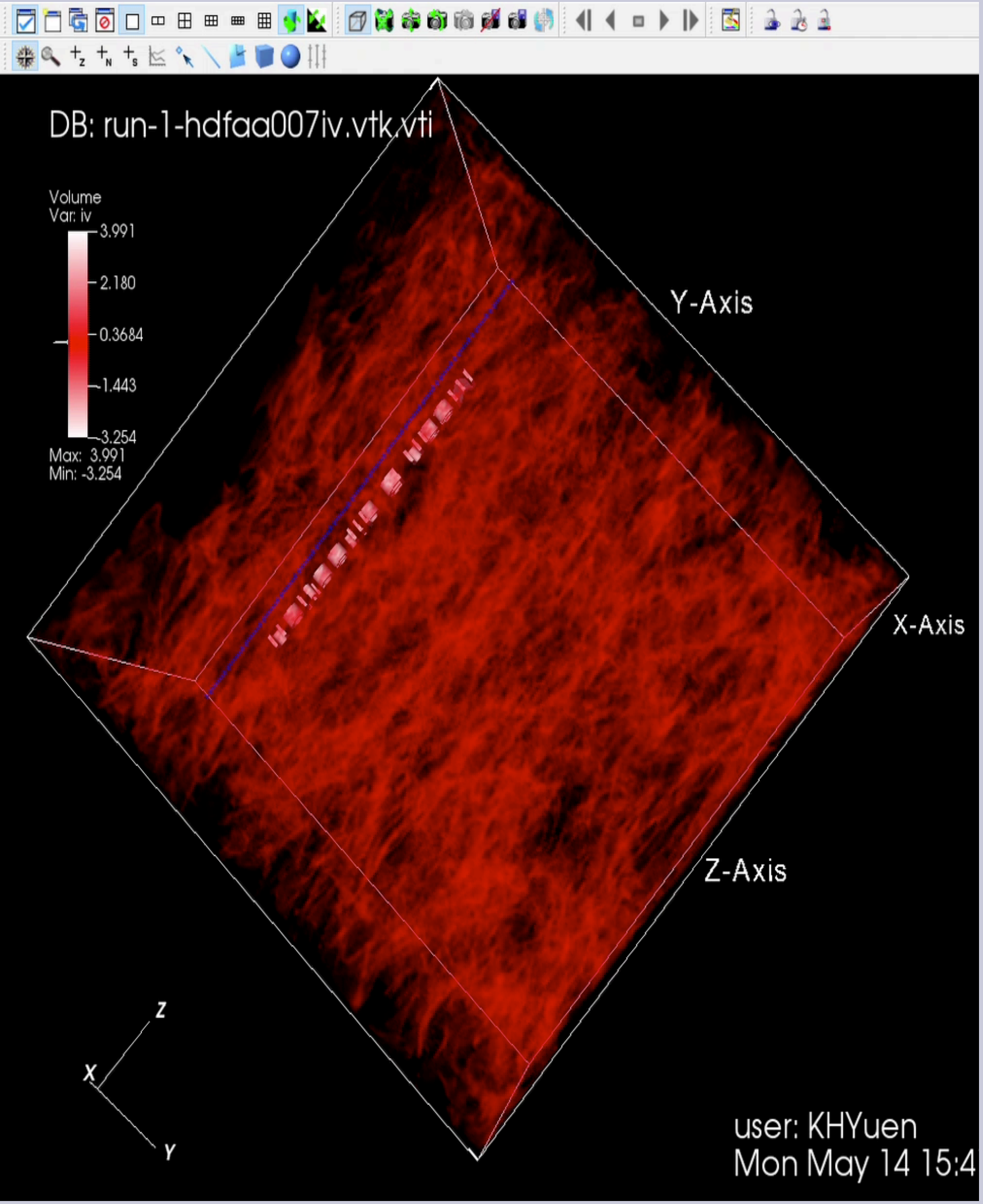


WHAM emission: density fluctuations

Scincillations and scattering

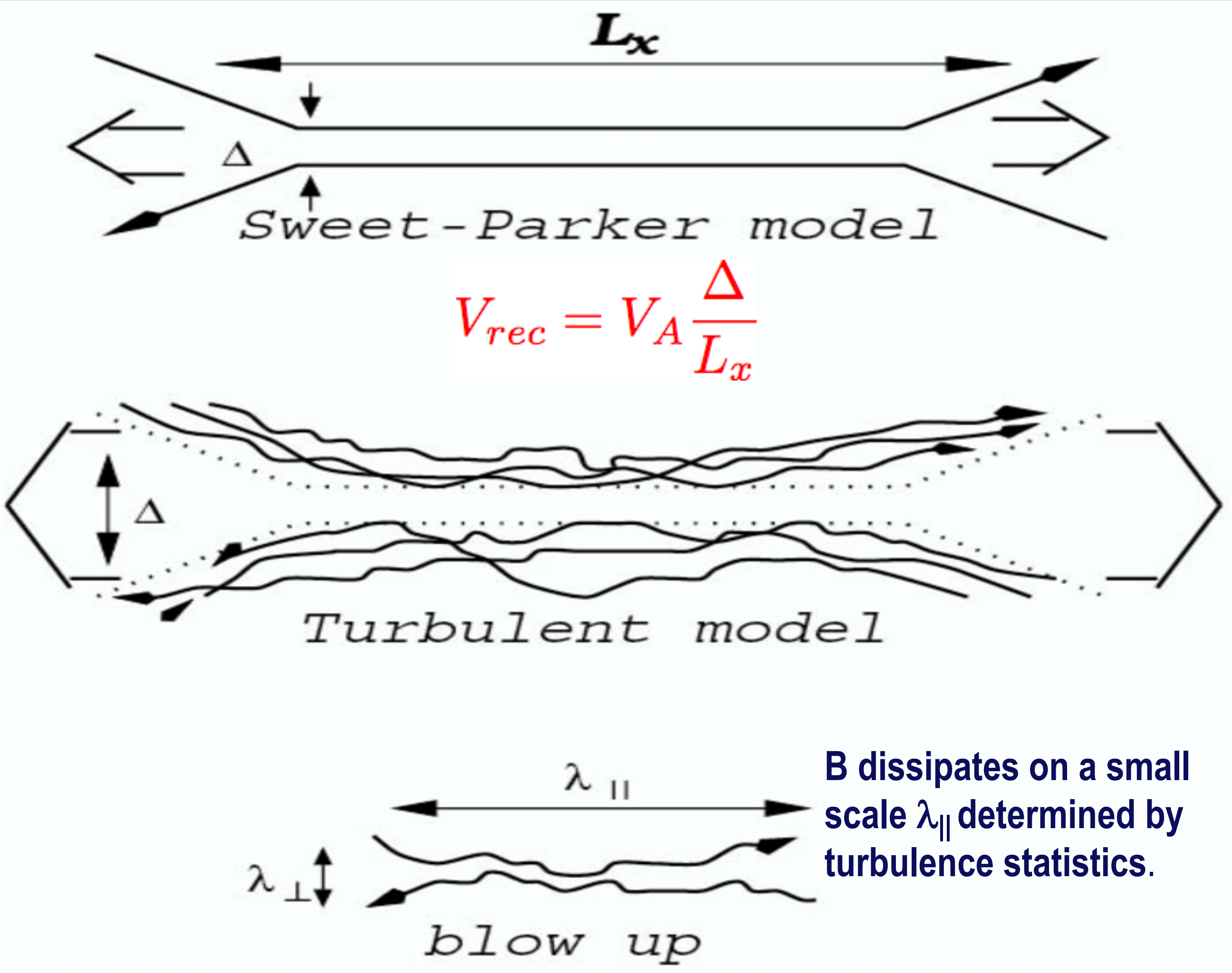
Armstrong, Rickett & Spangler(1995)

MHD turbulence is anisotropic: contours of turbulent velocities are aligned parallel to B



In contrast to isotropic Kolmogorov turbulence

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



Outflow is determined by field wandering.

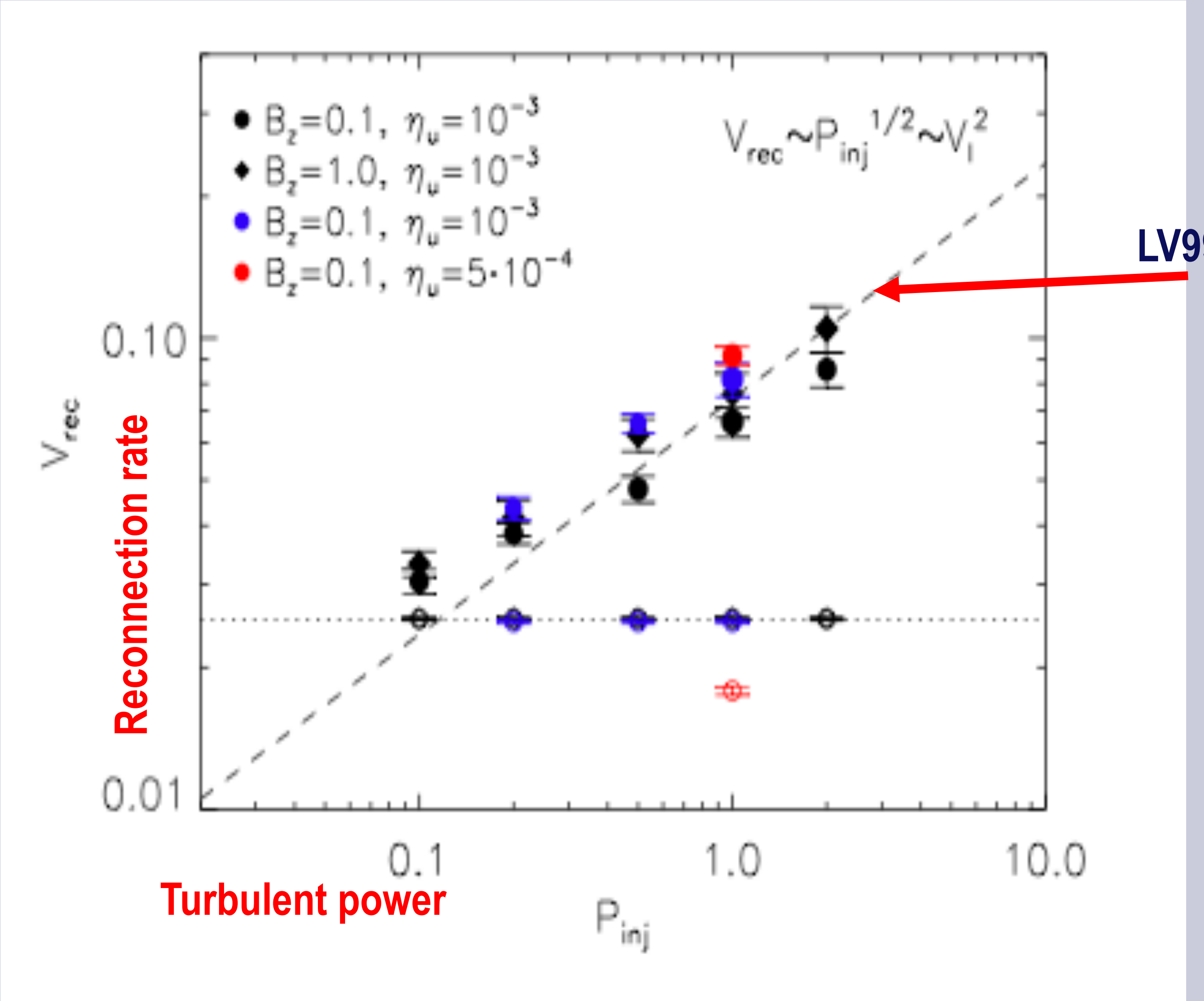
B dissipates on a small scale $\lambda_{||}$ determined by turbulence statistics.

More theoretical works on turbulent reconnection:

AL, Vishniac & Cho 2004
Eynik, AL, Vishniac 2011
Eyink 2015

AL & Vishniac (1999)

Testing of LV99 predictions: rate of reconnection versus the level of turbulence

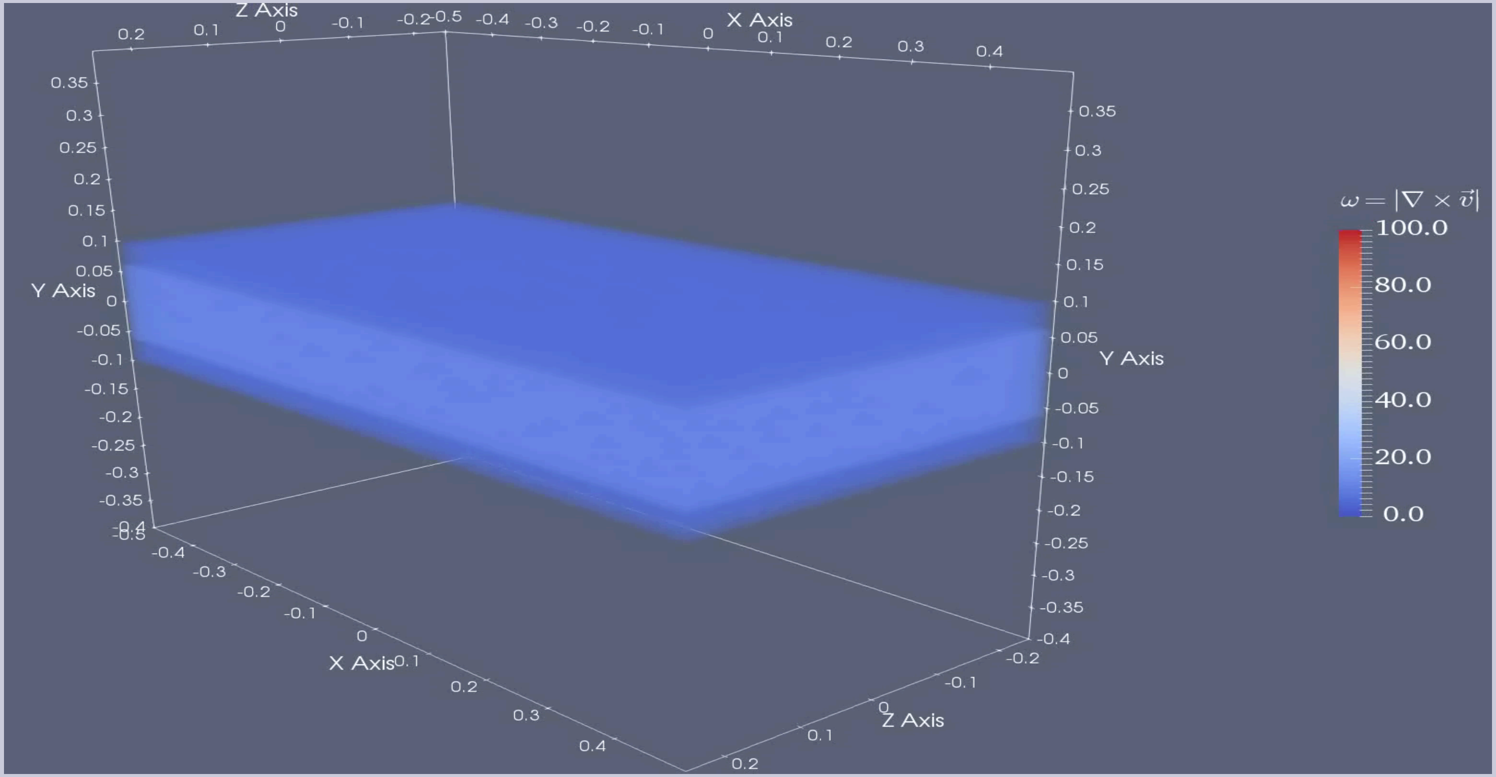


LV99 prediction is $V_{rec} \sim P_{inj}^{1/2}$

Kowal et al. 2012

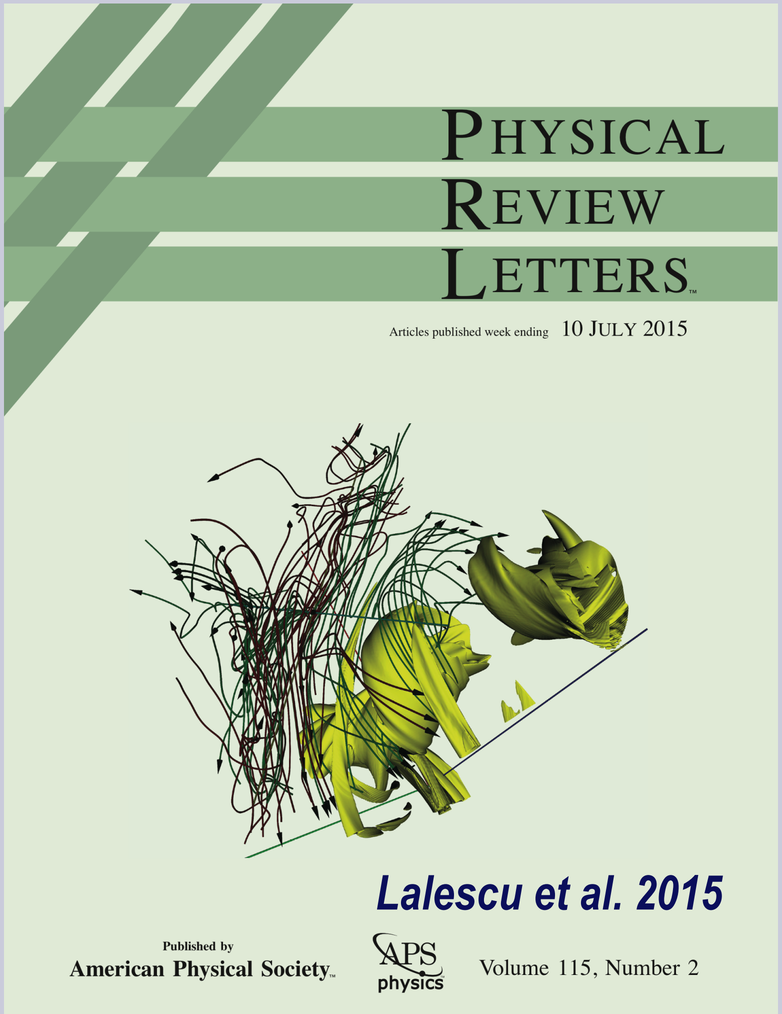
Self-reconnection corresponds to the expectations

Kowal et al.17



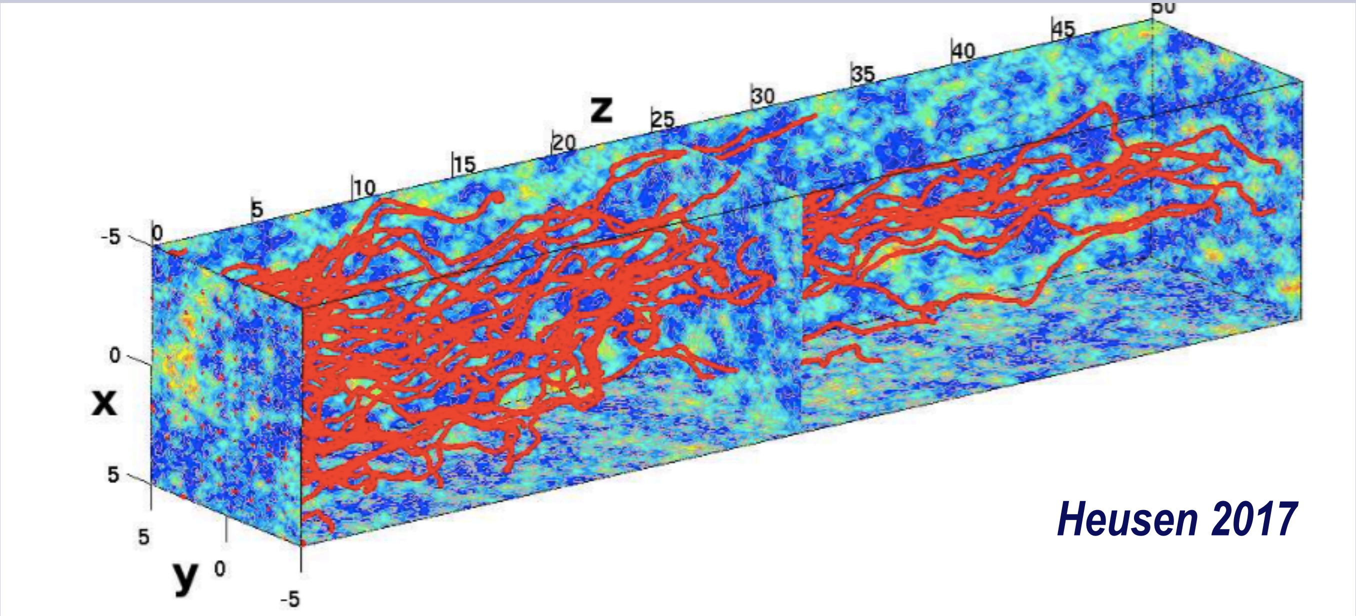
Simulations by Kowal 2019 are 2048 x 8192 x 2048

Turbulent reconnection explains solar wind data

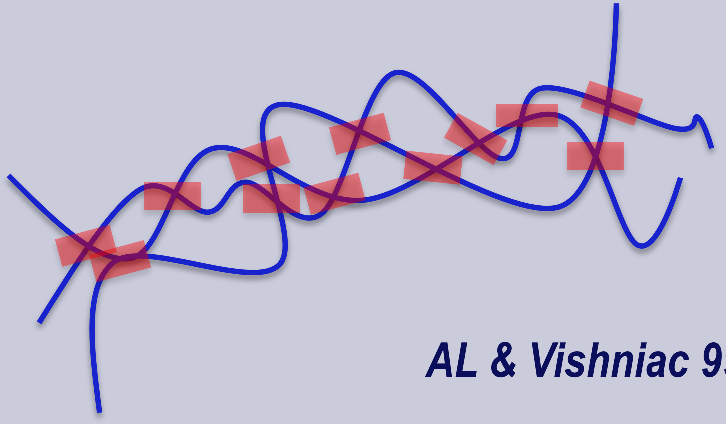


Solar flares also correspond to the predictions of turbulent reconnection theory (Chitta & AL 2019)

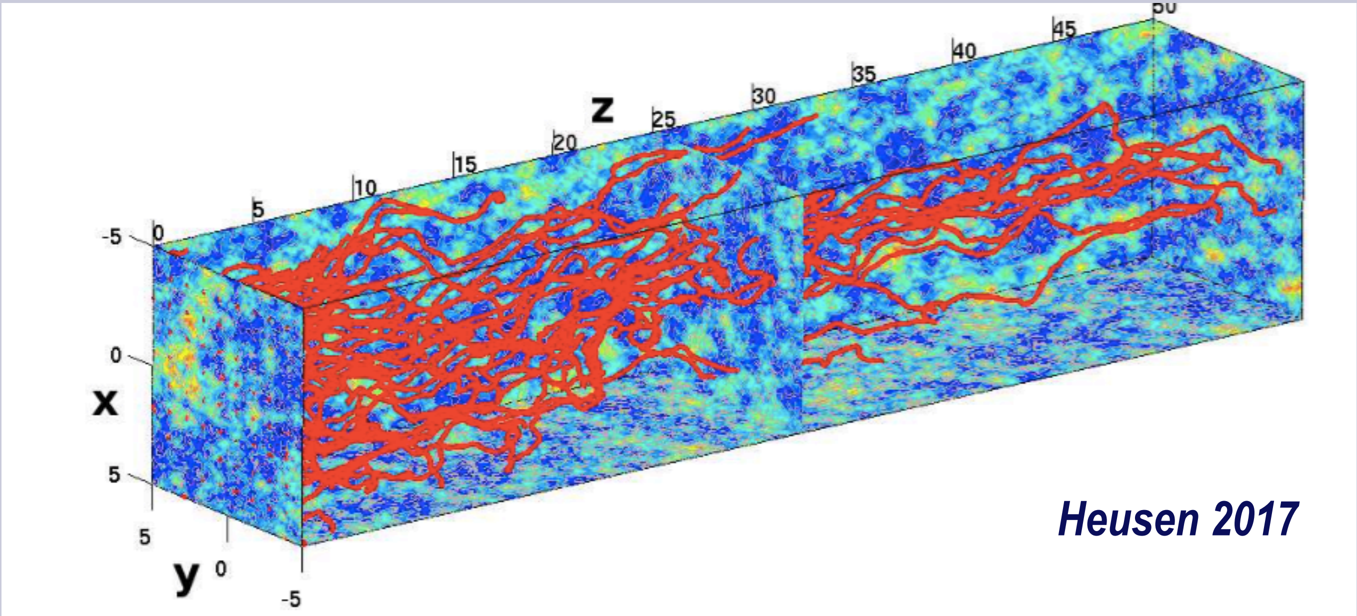
Without turbulent reconnection magnetic fields would create knots



Turbulent reconnection allows mixing of magnetic field perpendicular to B-direction



AL & Vishniac 99



Heusen 2017

Derivation of MHD turbulence spectrum assuming turbulent reconnection

- Critical balance

$$\frac{l_\perp}{V_{\perp l}} = \frac{l_{//}}{V_A}$$

- Constancy of energy cascade rate

$$\frac{V_{\perp l}^2}{t_{cas}} = const$$

$$\frac{V_{\perp l}^2}{(l_\perp / V_{\perp l})} = const$$

$$V_\perp \sim l_\perp^{1/3}$$

$$Or, E(k) \sim k^{-5/3}$$

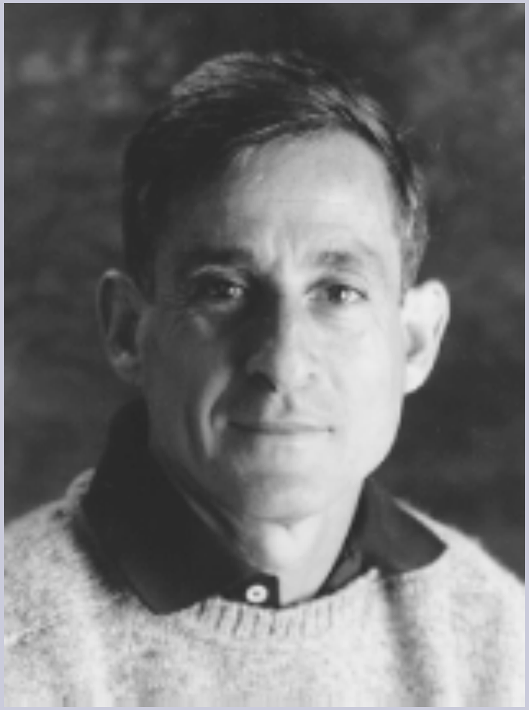
$$l_{||} \sim l_\perp^{2/3}$$

Kolmogorov perpendicular spectrum and more and more elongated eddies at small scales

$$V_\perp \sim l_\perp^{1/3}$$

$$l_{||} \sim l_\perp^{2/3}$$

are Goldreich-Sridhar 1995 relations derived in the frame of mean field



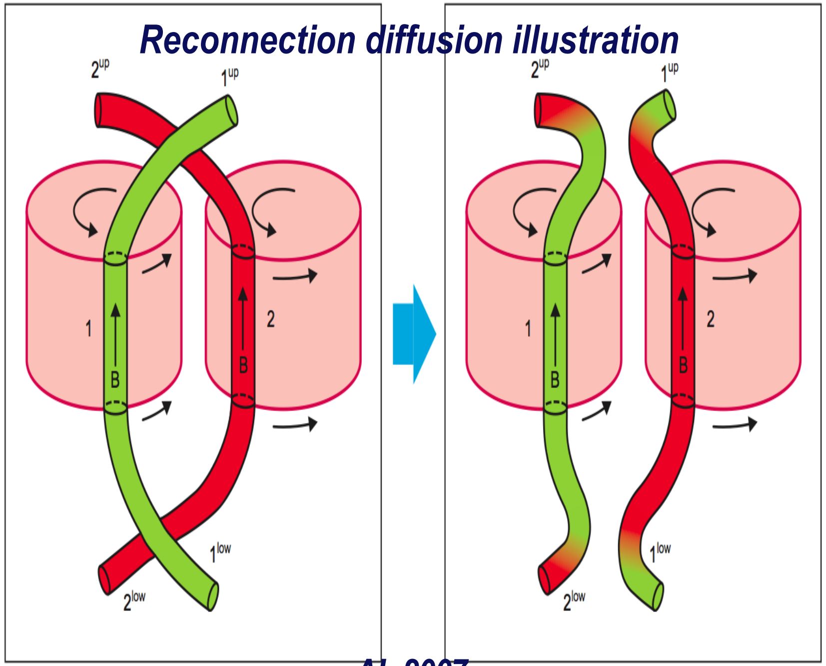
P. Goldreich

Numerical simulations show that the GS95 relations (Cho & Vishniac 2000, Maron & Goldreich 2001, Cho, AL & Vishniac 2002) are not valid in the mean magnetic field reference system.

Local system of reference must be adopted

Note in passing: turbulent reconnection is the violation of the textbook flux freezing

Reconnection diffusion illustration



AL 2007

H. Alfven

Alfven theorem is violated in turbulent media!

Confirmed by Eyink et al (2013 numerical paper in Nature)

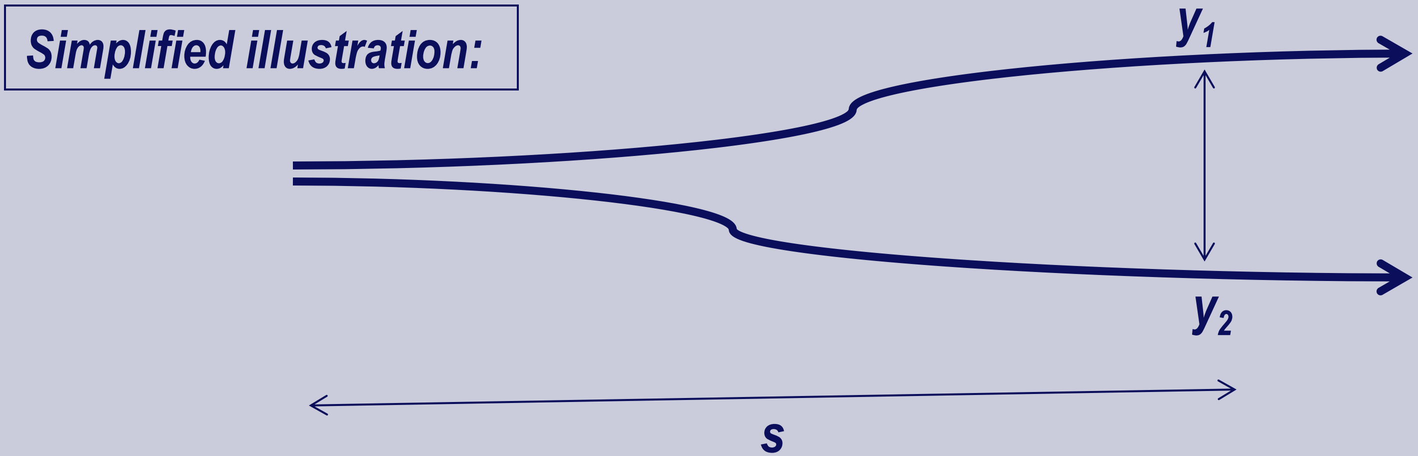
Plan of the talk

Properties of turbulence and magnetic reconnection

CR perpendicular transport

Implications for CR acceleration

AL & Vishniac 1999 predicted that particles moving along magnetic field lines get separated as $s^{3/2}$



$$\langle |y_1(s) - y_2(s)|^2 \rangle \sim s^3$$

This law was termed in Eyink, AL & Vishniac (2011) *Richardson spatial diffusion law*

In the presence of turbulence dynamically important B-field its lines stochastic separate in proportion s^3 $M_A{}^4$

Moving along magnetic field lines distance $l_{\|}$ one gets the mean squared separation $\langle\delta^2\rangle^{\frac{1}{2}}$

$$\frac{d\langle\delta^2\rangle}{ds} \sim \frac{\langle\delta^2\rangle}{l_{\|}} \qquad (1)$$

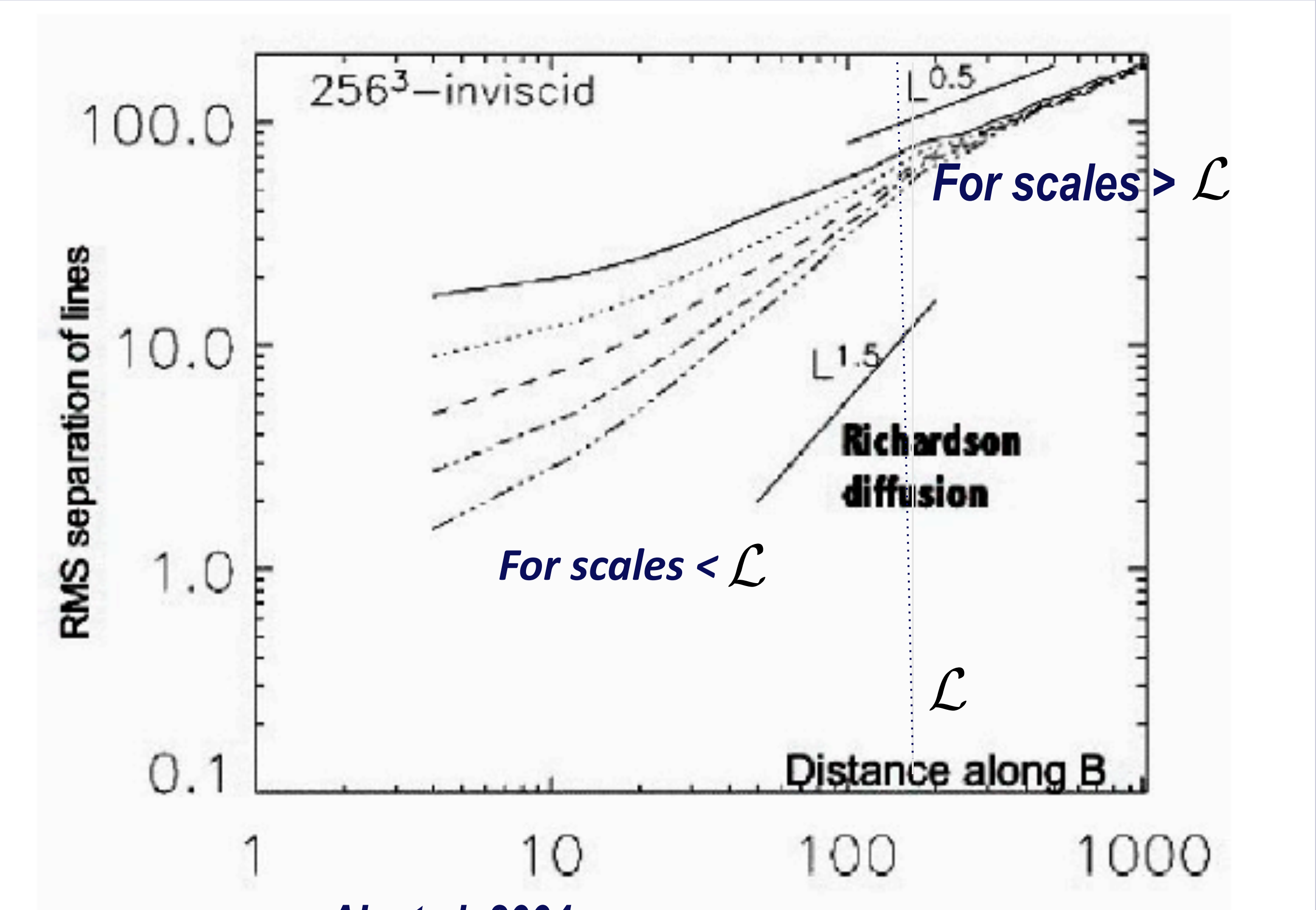
For subAlfvenic turbulence magnetic field lines at distance $l_{\|}$ are mixed by turbulent eddies with parallel size

$$l_{\|} \sim L(\frac{\delta}{L})^{2/3} M_A^{4/3} \qquad (2)$$

Comgining with Eqs. (1) and (2) one gets (AL & Vishniac 1999):

$$\langle\delta^2\rangle \sim \frac{s^3}{L} M_A^4$$

The predicted fast divergence of magnetic fields was confirmed with MHD turbulence simulations

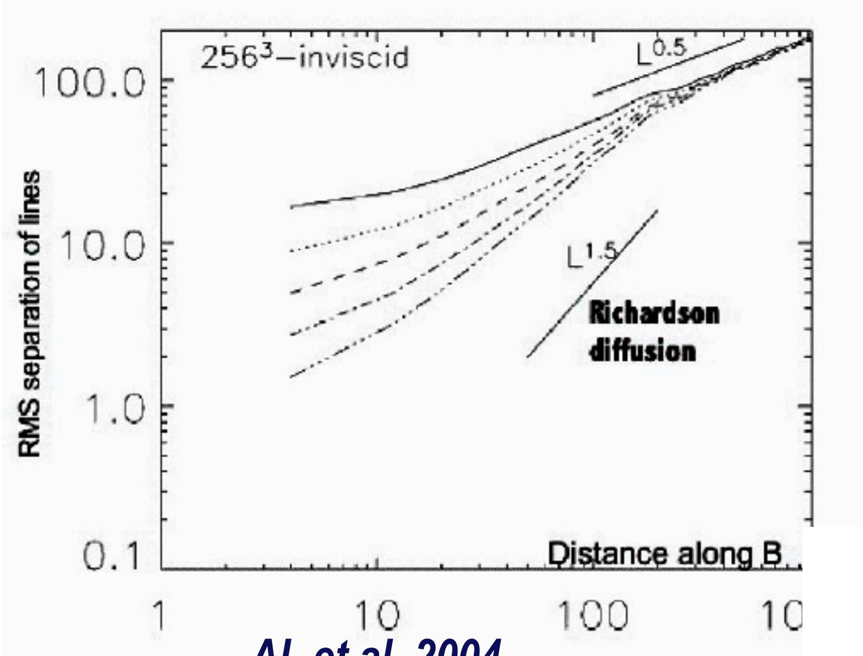


AL et al. 2004

ℒ is turbulence injection scale

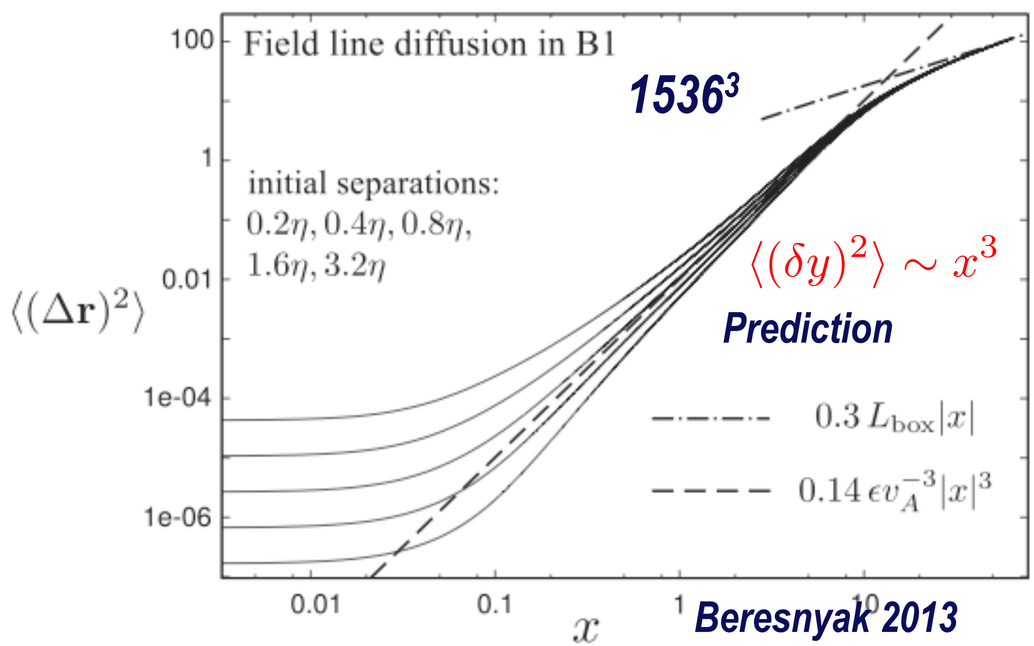
See also simulations in Maron & Chandran (2004)

Higher resolution made it more obvious



AL et al. 2004

More recent simulations



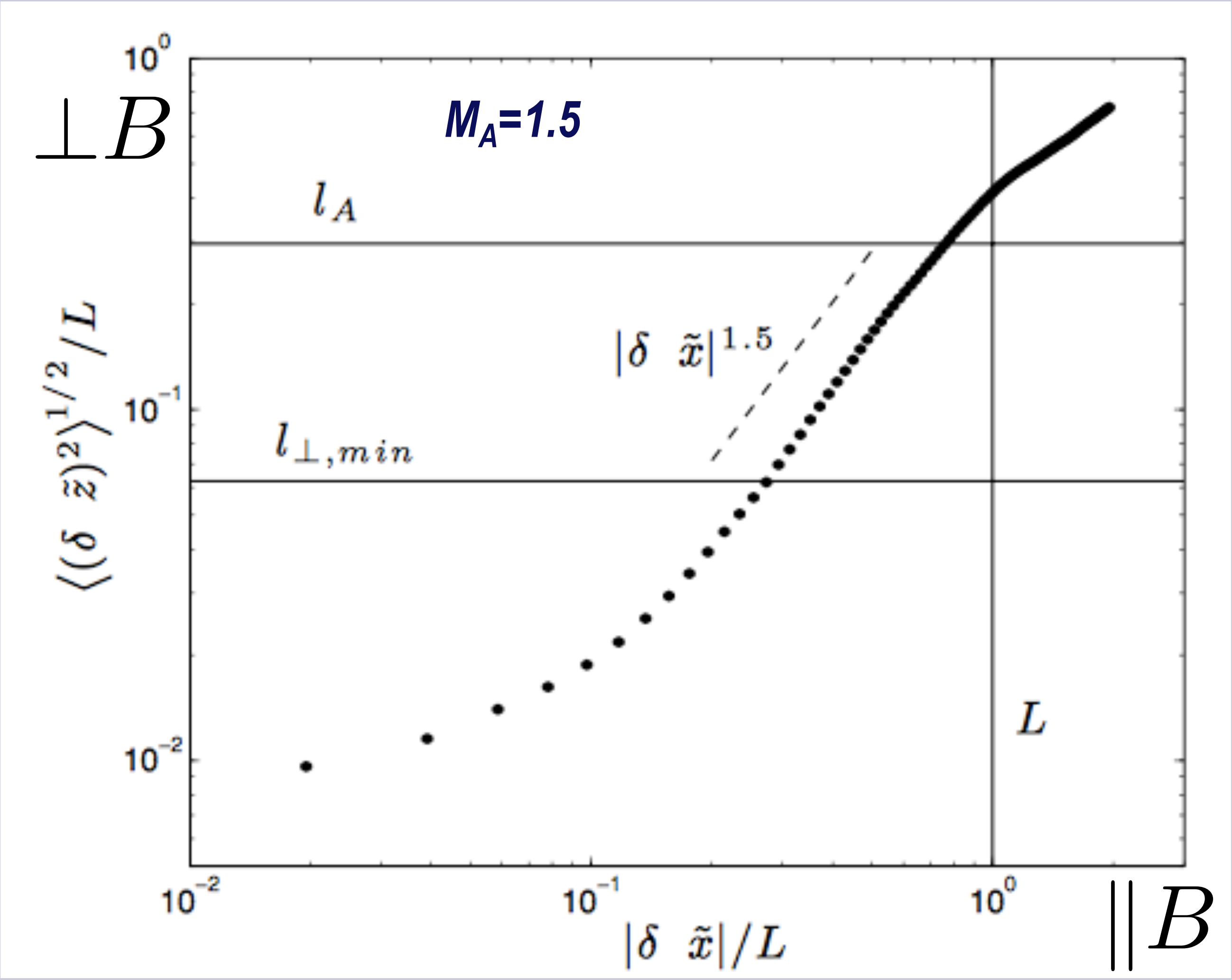
1536^3

$\langle(\delta y)^2\rangle \sim x^3$

Prediction

Beresnyak 2013

Naturally, particles streaming freely along magnetic field lines show the same superdiffusion as magnetic field lines



Xu & Yan 2013

Different regimes of Alfvenic turbulence provide different regimes of B-field line separation

Type of MHD turbulence	Injection velocity	Range of scales	Spectrum E(k)	Motion type	Ways of study	Magnetic diffusion	Squared separation of lines
Weak	$V_L < V_A$	$[l_{trans}, L]$	$k_{\perp}^{-2}$	wave-like	analytical	diffusion	$\sim sLM_A^4$
Strong subAlfvenic	$V_L < V_A$	$[l_{min}, l_{trans}]$	$k_{\perp}^{-5/3}$	anisotropic eddy-like	numerical	Richardson	$\sim \frac{s^3}{L} M_A^4$
Strong superAlfvenic	$V_L > V_A$	$[l_A, L]$	$k_{\perp}^{-5/3}$	isotropic eddy-like	numerical	diffusion	$\sim s l_A$
Strong superAlfvenic	$V_L > V_A$	$[l_{min}], l_A$	$k_{\perp}^{-5/3}$	anisotropic eddy-like	numerical	Richardson	$\sim \frac{s^3}{L} M_A^3$

L and l_{min} are the injection and perpendicular dissipation scales, respectively. $M_A \equiv \delta B/B$, $l_{trans} = LM_A^2$ for $M_A < 1$ and $l_A = LM_A^{-3}$ for $M_A < 1$. For weak Alfvenic turbulence $\ell_{\parallel}$ does not change. s is measured along magnetic field lines.

AL & Yan 2014

If cosmic rays diffuse along B-field lines, it is still superdiffusion in terms of perpendicular displacement

Substitute parallel displacement $s^2 = D_{\|} \delta t$

In the expression for the magnetic field perpendicular displacement $\langle \delta^2 \rangle \sim \frac{s^3}{L} M_A^4$

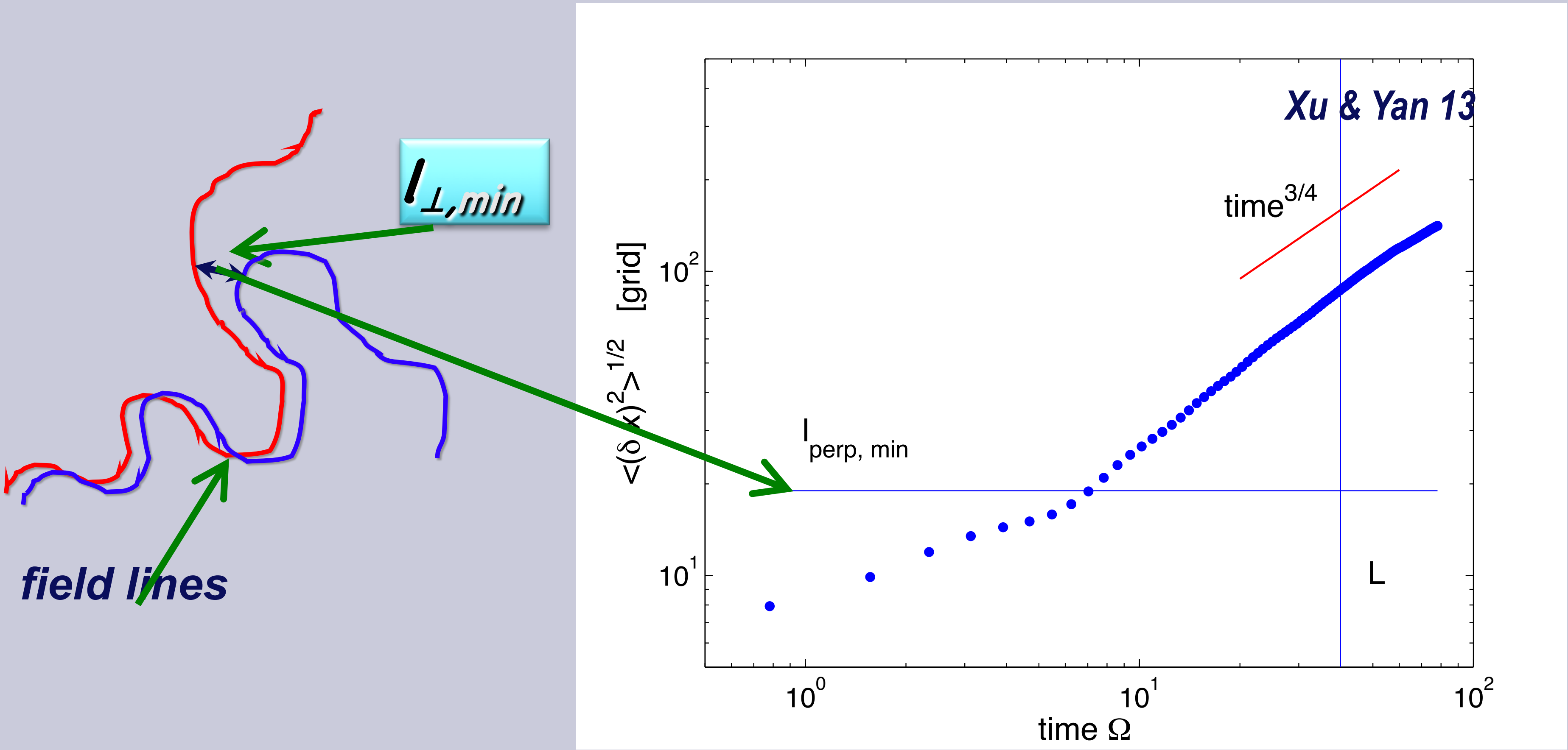
One gets

$$\langle \delta_{CR}^2 \rangle \sim \frac{(D_{\|} \delta t)^{3/2}}{L} M_A^4$$

Which means

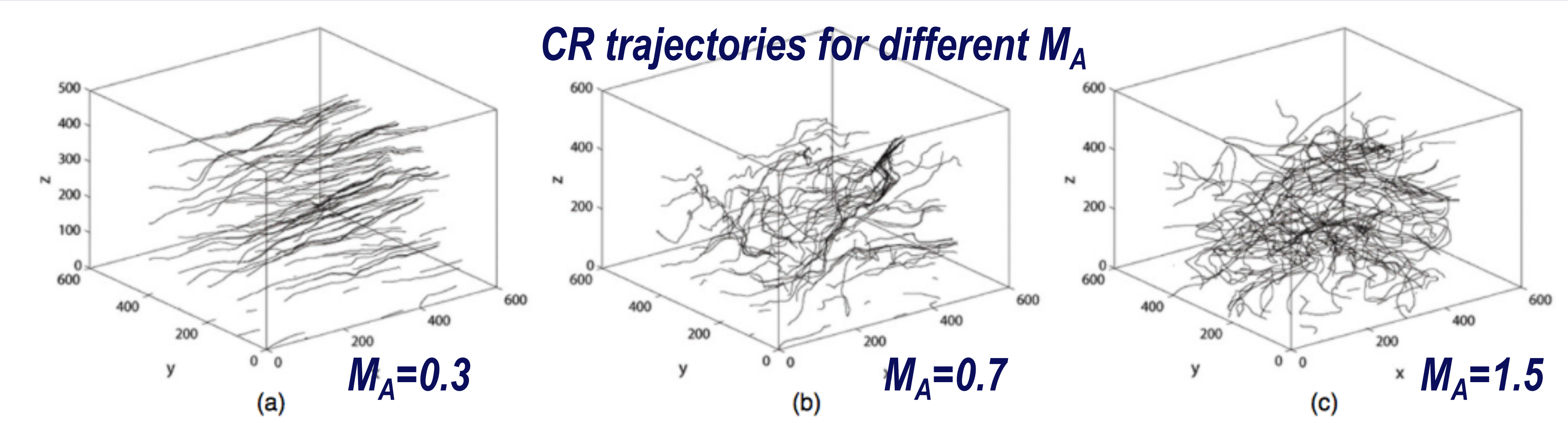
$$\langle \delta_{CR}^2 \rangle^{1/2} \sim \delta t^{3/4}$$

For CR diffusing along magnetic field lines the perpendicular displacement is superdiffusive ~ $t^{3/4}$



Prediction: $$\langle \delta_{CR}^2 \rangle^{1/2} \sim \delta t^{3/4}$$

The predicted dependence on $M_A{}^4$ has been carefully tested by Xu & Yan (2013)



SubAlfvenic turbulence: forth power of Alfven Mach number

On scales s > L and s>> mfp the ordinary diffusion is present (AL06, Yan & AL08)

$$D_{\perp,\mathrm{global}} \approx D_{\parallel} M_A^4,$$

On scales < L and s< mfp, CRs trace magnetic field divergence

$$\ell_{\perp}^2 \sim \frac{s^3}{27L} M_A^4,$$

On scales < L and s >> mfp, CRs trace magnetic field divergence, s is covered in diffusion process

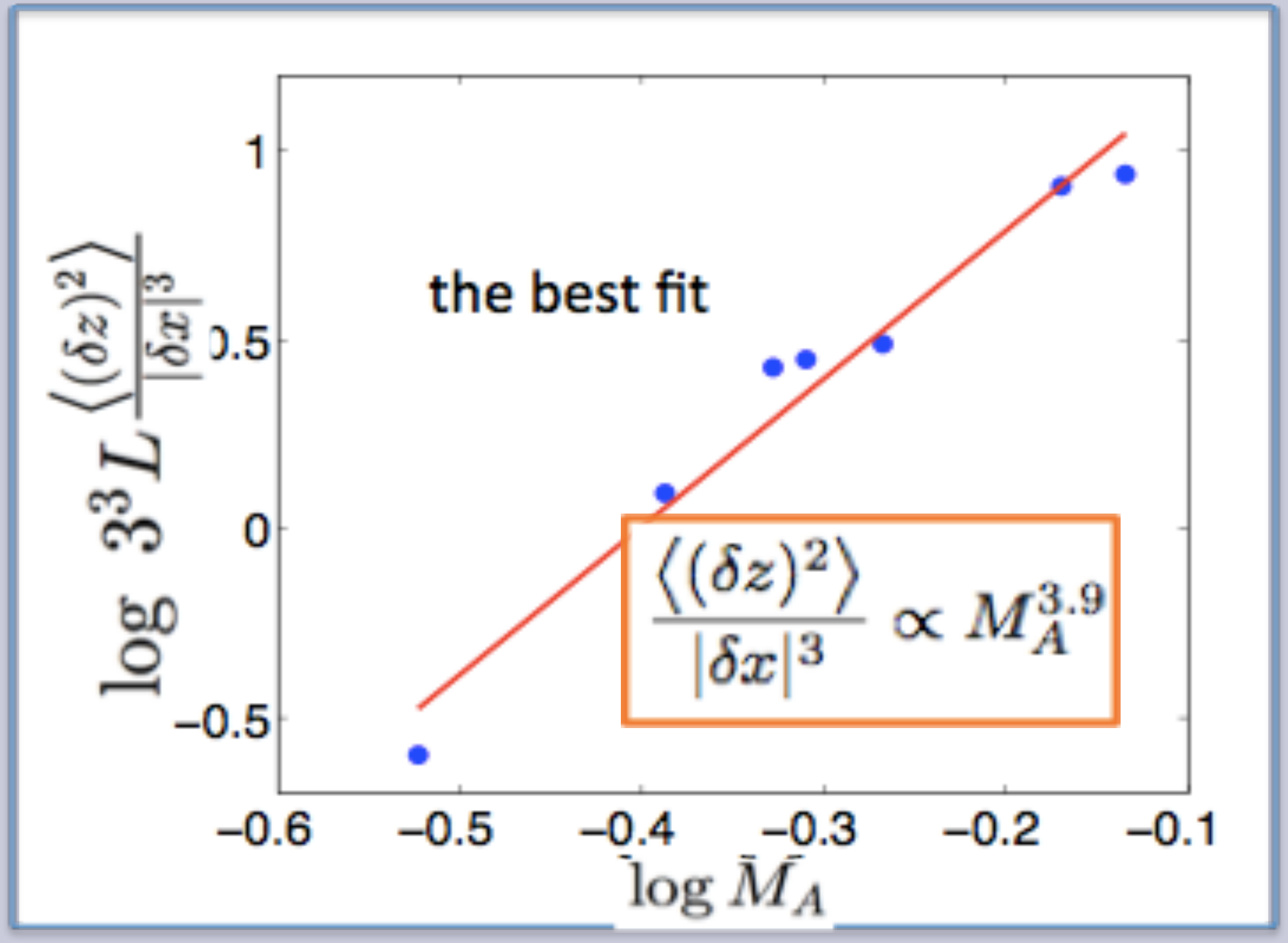
$$l_{\perp,\mathrm{CR}}^2 \sim \frac{(D_{\parallel}\delta t)^{3/2}}{27L} M_A^4, \quad M_A < 1,$$

Differs from the textbook (see Jokipii & Parker 69) M_A^2 dependence

For free streaming along B-field lines the dependence on M_A^4 is confirmed

LV99 prediction

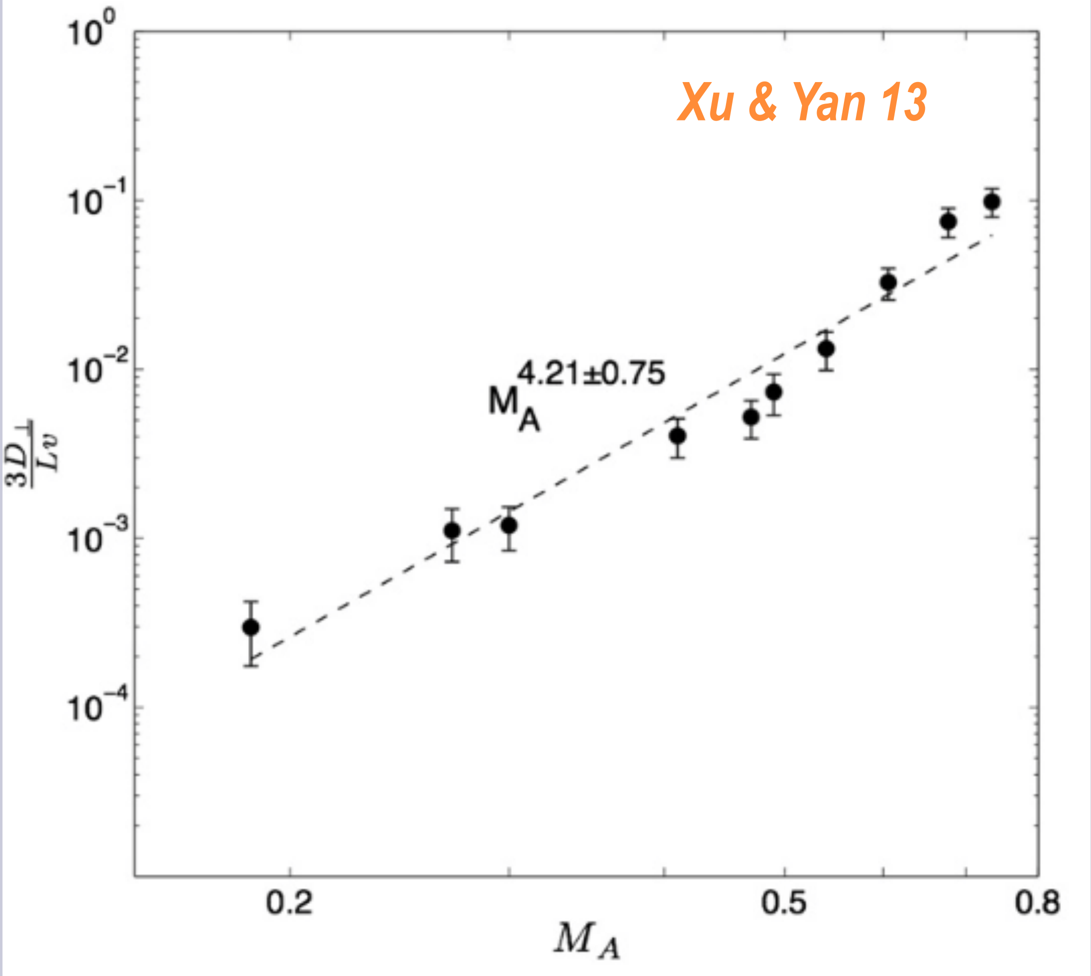
$$< (\delta z)^2 >= \frac{|\delta x|^3}{3^3 L} M_A^4$$



Xu & Yan 13

On scales >> L the parallel and perpendicular diffusion are related through M_A^4

Diffusive regime



To compare with $D_{\perp,\mathrm{global}} \approx D_\| M_A^4,$ *in AL06, Yan & AL08*

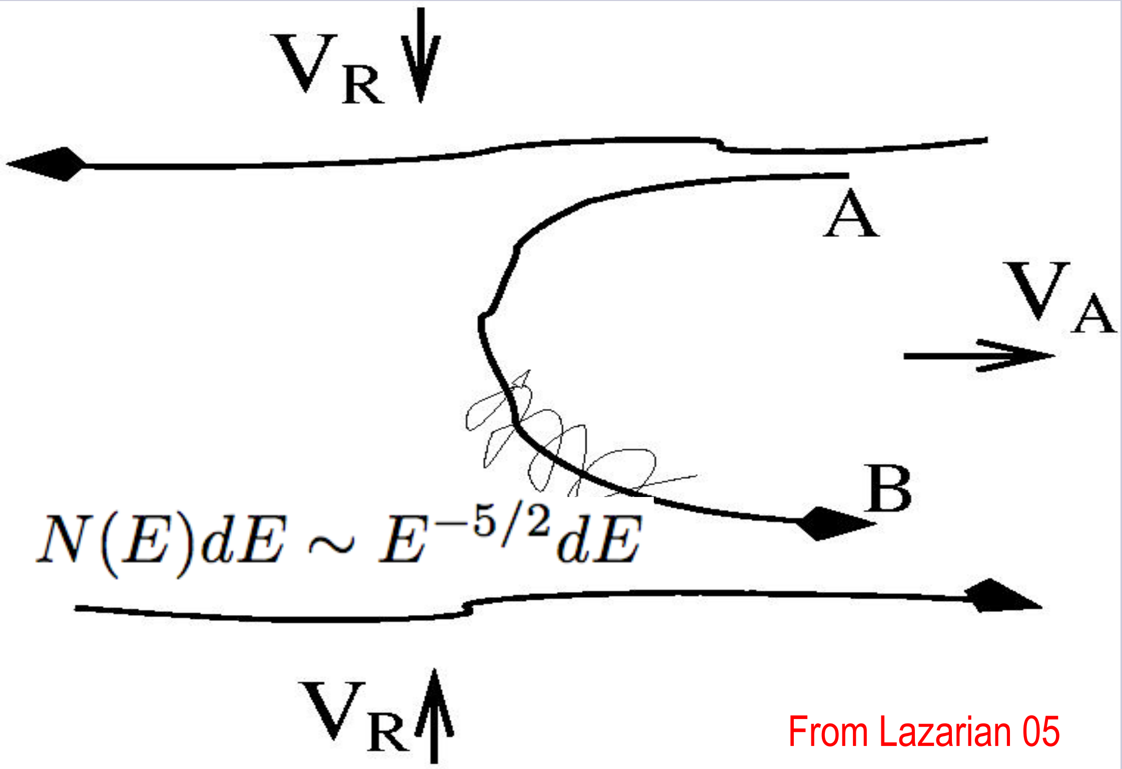
Plan of the talk

Properties of turbulence and magnetic reconnection

CR perpendicular transport

Implications for CR acceleration

Turbulent reconnection induces First Order Fermi acceleration



De Gouveia Dal Pino & Lazarian 2005

(similar mechanism but in 2D is proposed in Drake et al. 2006).

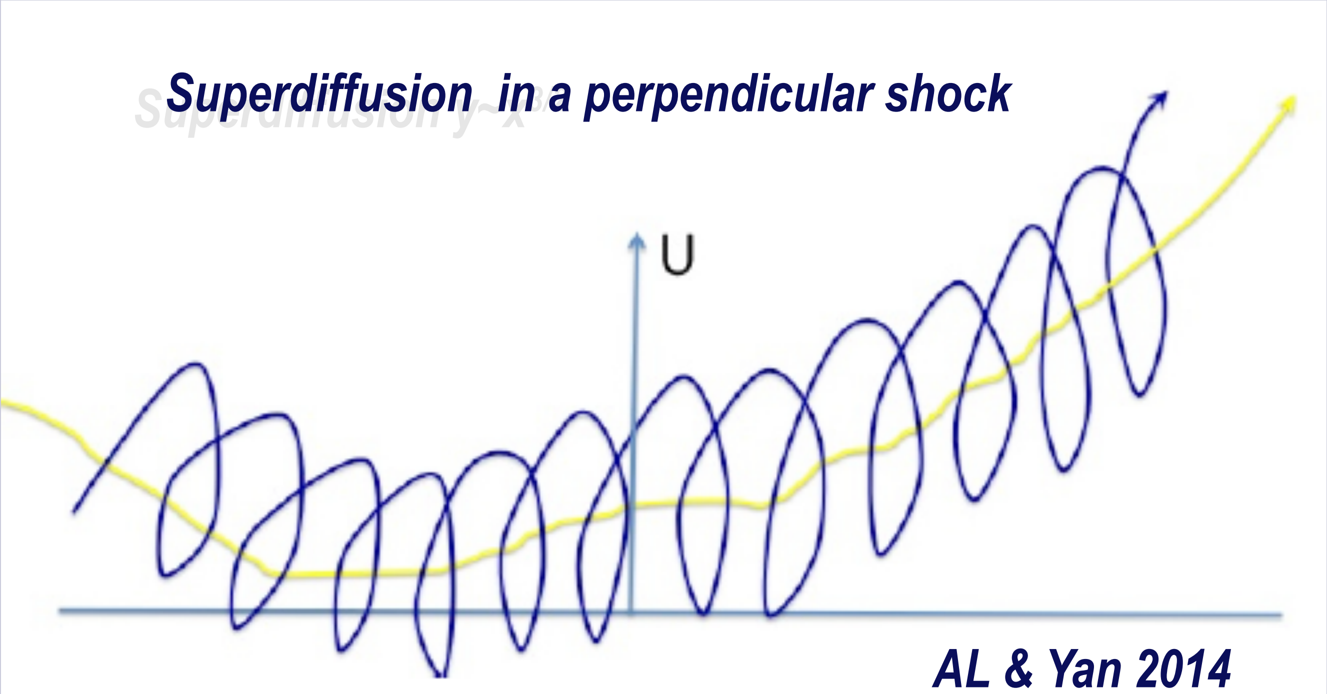
In 3D there are no islands thus the acceleration is more efficient

Superdiffusion prevents the particles to return back to a perpendicular shock

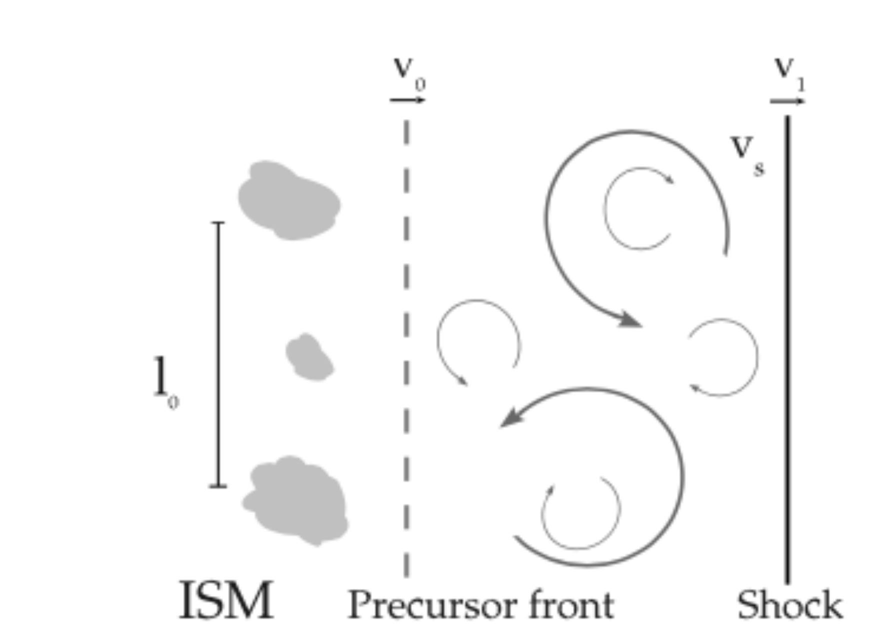
$$\frac{\kappa_\perp}{\kappa_\parallel} = \frac{1}{1 + (\lambda_{CR}/r_L)^2}$$

Accepted expression

In reality



Precursor forms in front of the shock and it gets turbulent as precursor interacts with gas density fluctuation



Much more efficient than Bell's mechanism

$$\frac{dB_{\rm cur}^2}{dB_{\rm dyn}^2} = 1.6\times10^{-4}\left(\frac{10^{15}\ {\rm eV}}{E_{\rm esc}}\right)\left(\frac{\eta_{\rm esc}}{0.05}\right)\left(\frac{L}{1\ {\rm pc}}\right) \times\left(\frac{B_0}{5\ \mu{\rm G}}\right)\left(\frac{v_{A0}}{12\ {\rm km\ s^{-1}}}\right)\left(\frac{0.5u_{\rm sh}}{A_s(u_0-u_1)}\right)^3$$

Beresnyak, Jones & AL 2009, de Valle, AL & Santos-Lima 2016, Xu & AL 2018

Numerical simulations support predictions of turbulent dynamo in a precursor

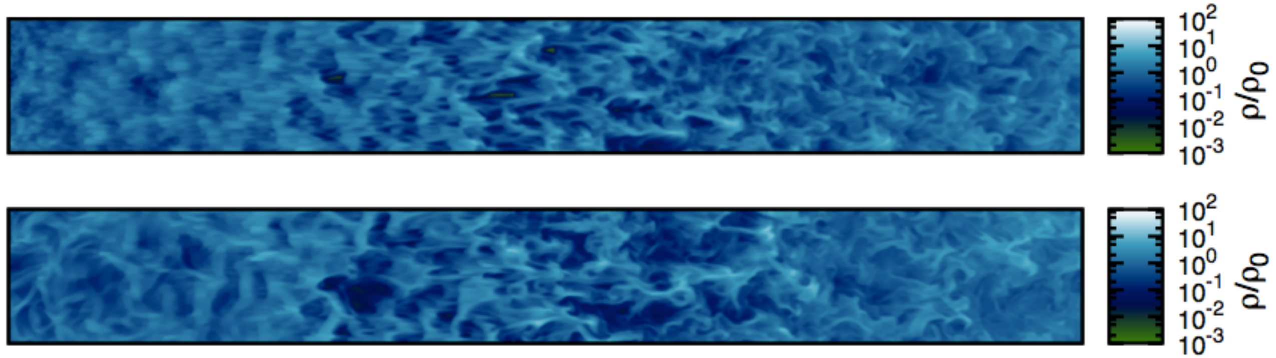


Figure 4. Final density distribution in a central cut of the xy-plane of the computational box for Model AI (upper panel) and for Model BI (bottom panel). The parameters of the models are listed in Table 1.

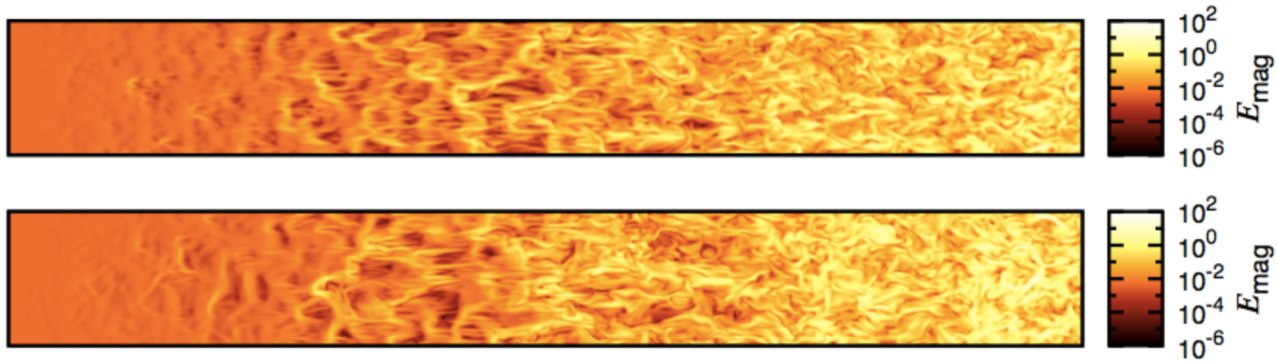
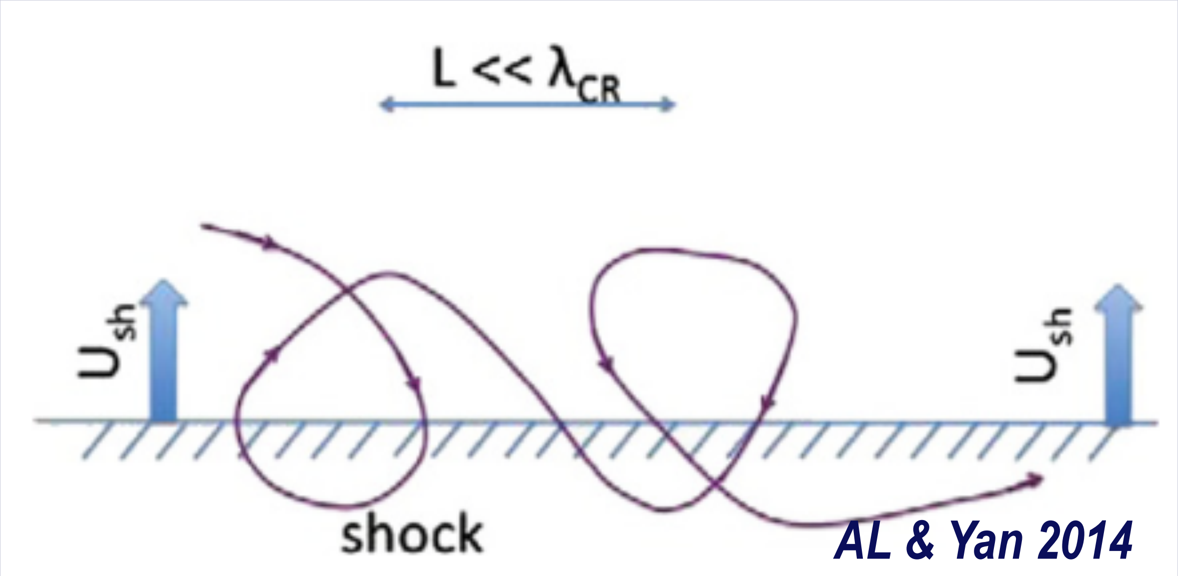


Figure 5. Final distribution of the magnetic energy in a central cut of the xy-plane of the computational box for Model AI (upper panel) and for Model BI (bottom panel). The parameters of the models are listed in Table 1.

Del Valle, AL, Santos-Lima 2016

First simulations supporting the model are Drury & Downes 2012

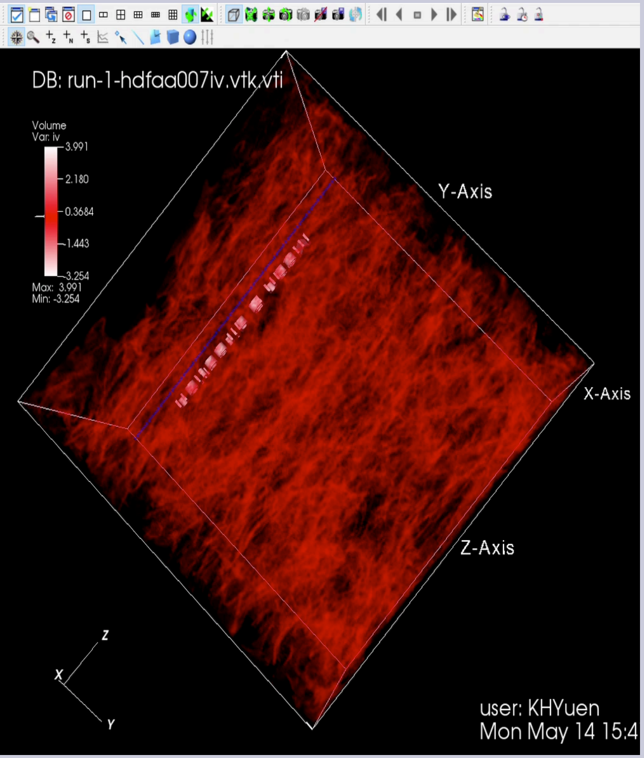
Turbulent dynamo makes parallel and perpendicular shocks similar with particles returning to shocks with precursors



Synthesis: dynamo and magnetic field structure theories

Summary:

Actual properties of MHD turbulence must be accounted for CR transport and acceleration



Divergence of turbulent magnetic field lines makes CRs transport superdiffusive

Turbulent dynamo makes shock acceleration much very different from the accepted DSA