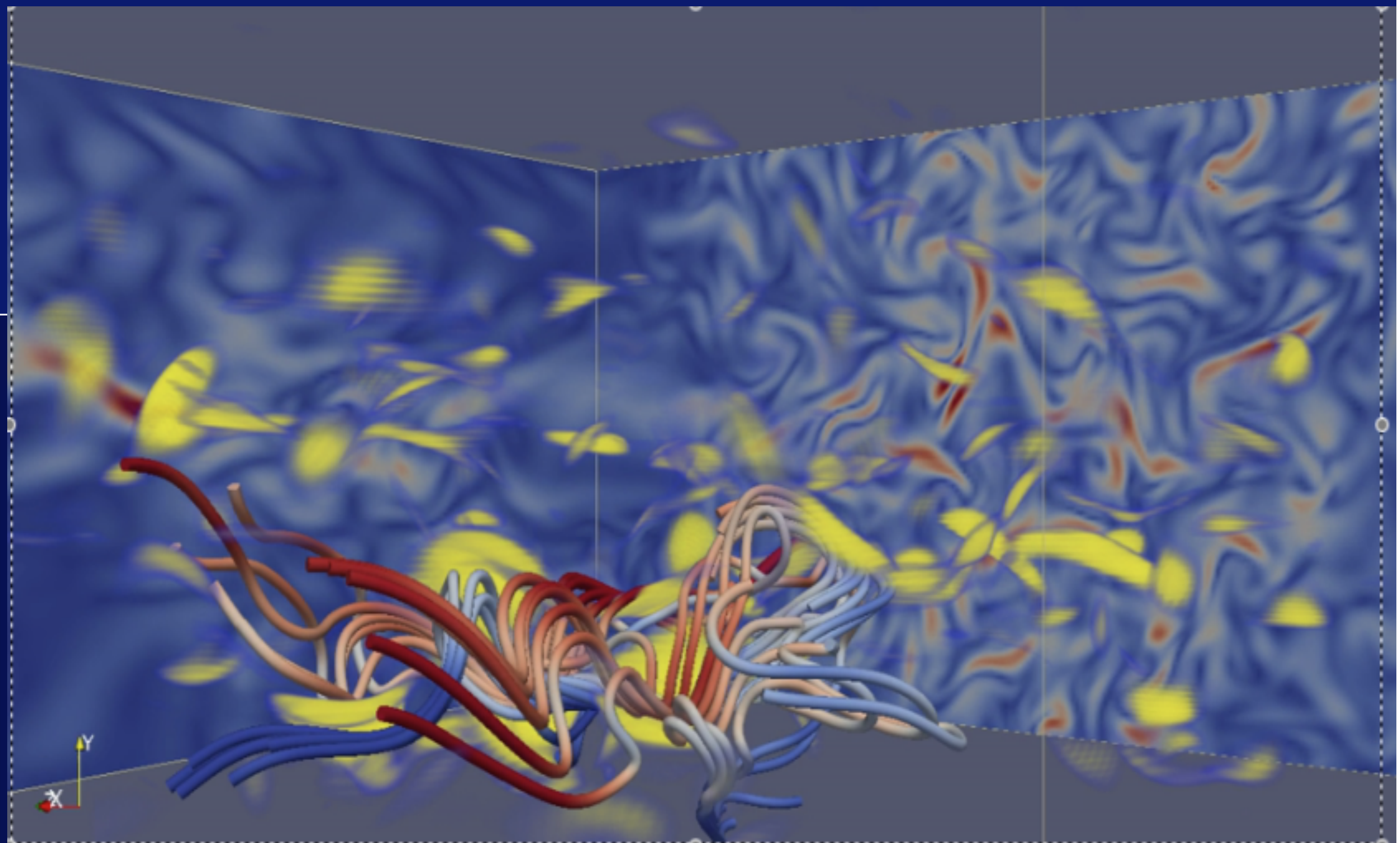
Effects of Alfvenic Turbulence on Cosmic Rays in Astrophysical Plasmas



Alex Lazarian (Astronomy and Physics)

THE UNIVERSITY of WISCONSIN MADISON

Plan of the talk

1. Turbulent Astrophysical Plasmas
2. Turbulent reconnection and violation of flux freezing
3. Theory of Alfvenic turbulence
4. CR superdiffusion
5. CR acceleration in shocks
6. CR acceleration in reconnection sites
7. Damping of streaming instability by Alfvenic turbulence

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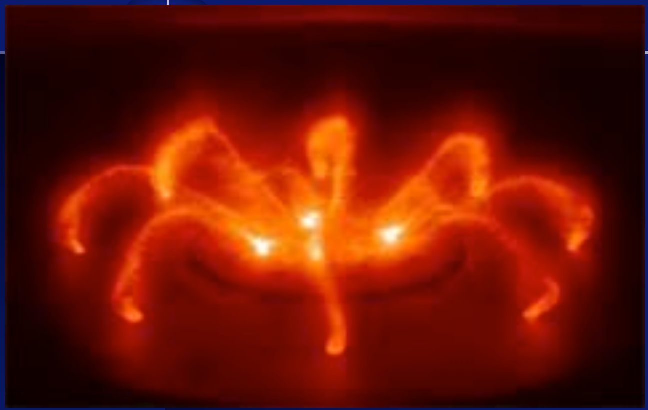
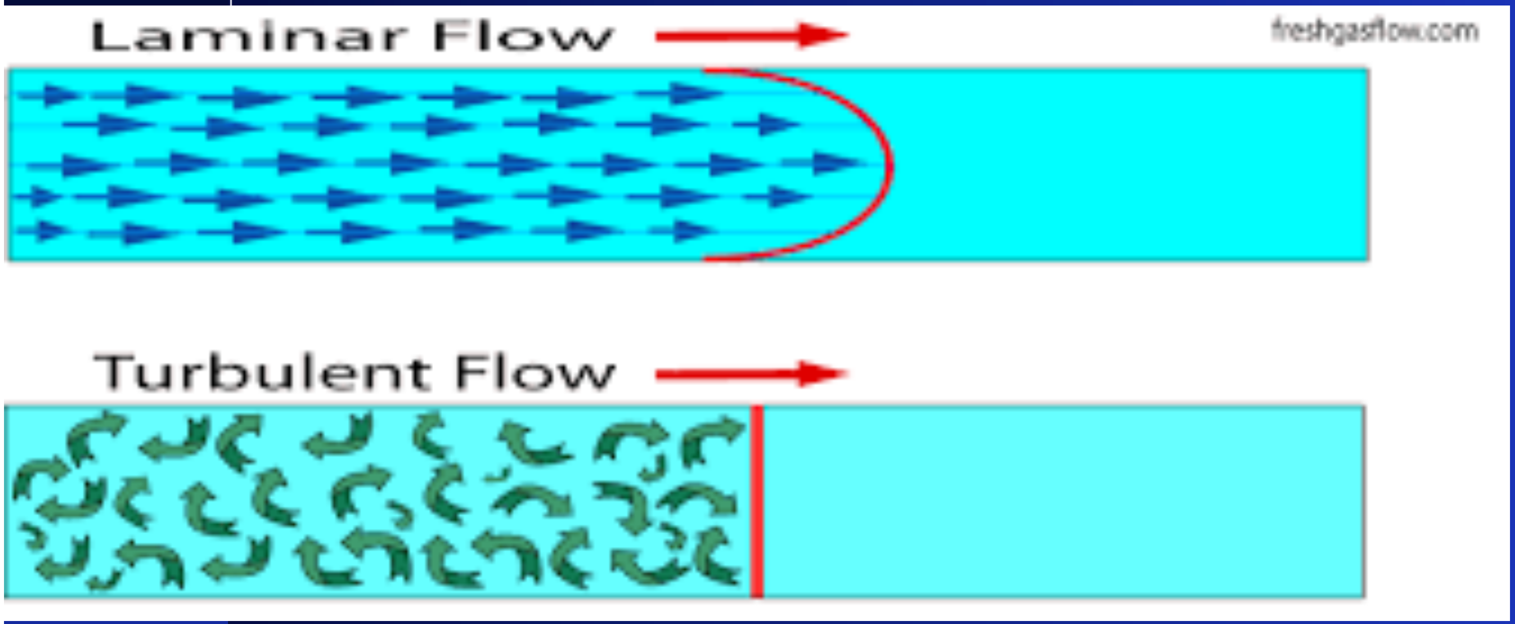
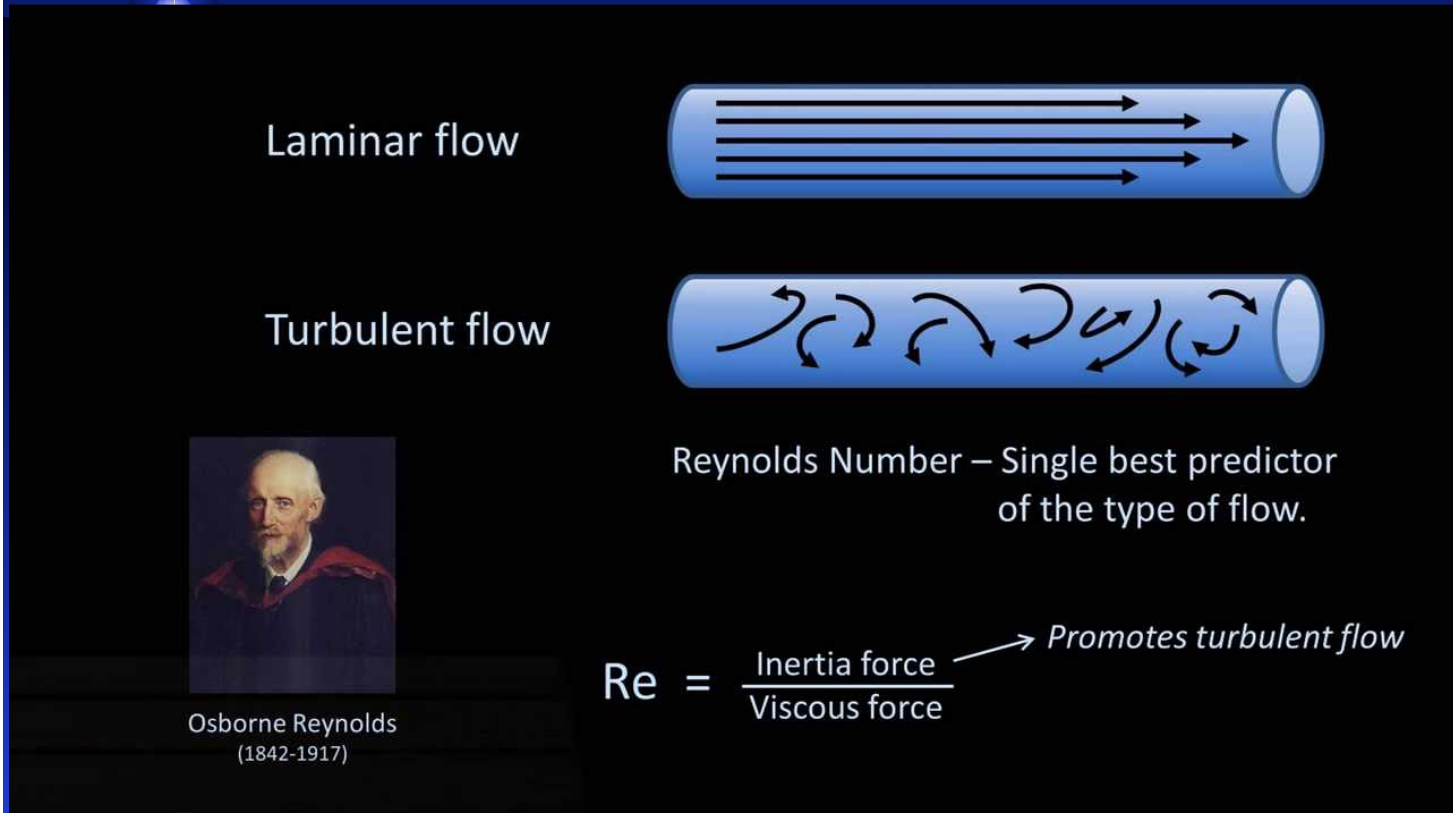
Plasma fills astrophysical space



Plasmas are turbulent in astrophysics

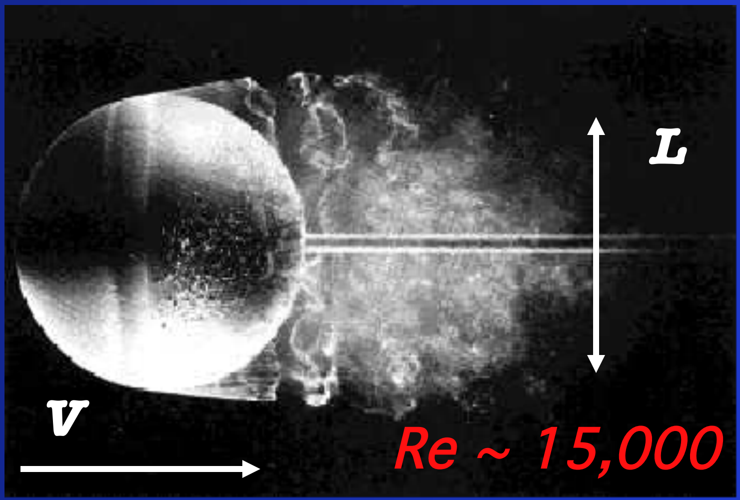


Reynolds number of astrophysical flows is usually >10^8



Flows get turbulent for large Reynolds numbers

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



Point for numerical simulations: flows are similar for similar Re. Numerical $Re<10^4$, while Re of astro flows > 10^{10}

Turbulence radically changes the properties of fluids

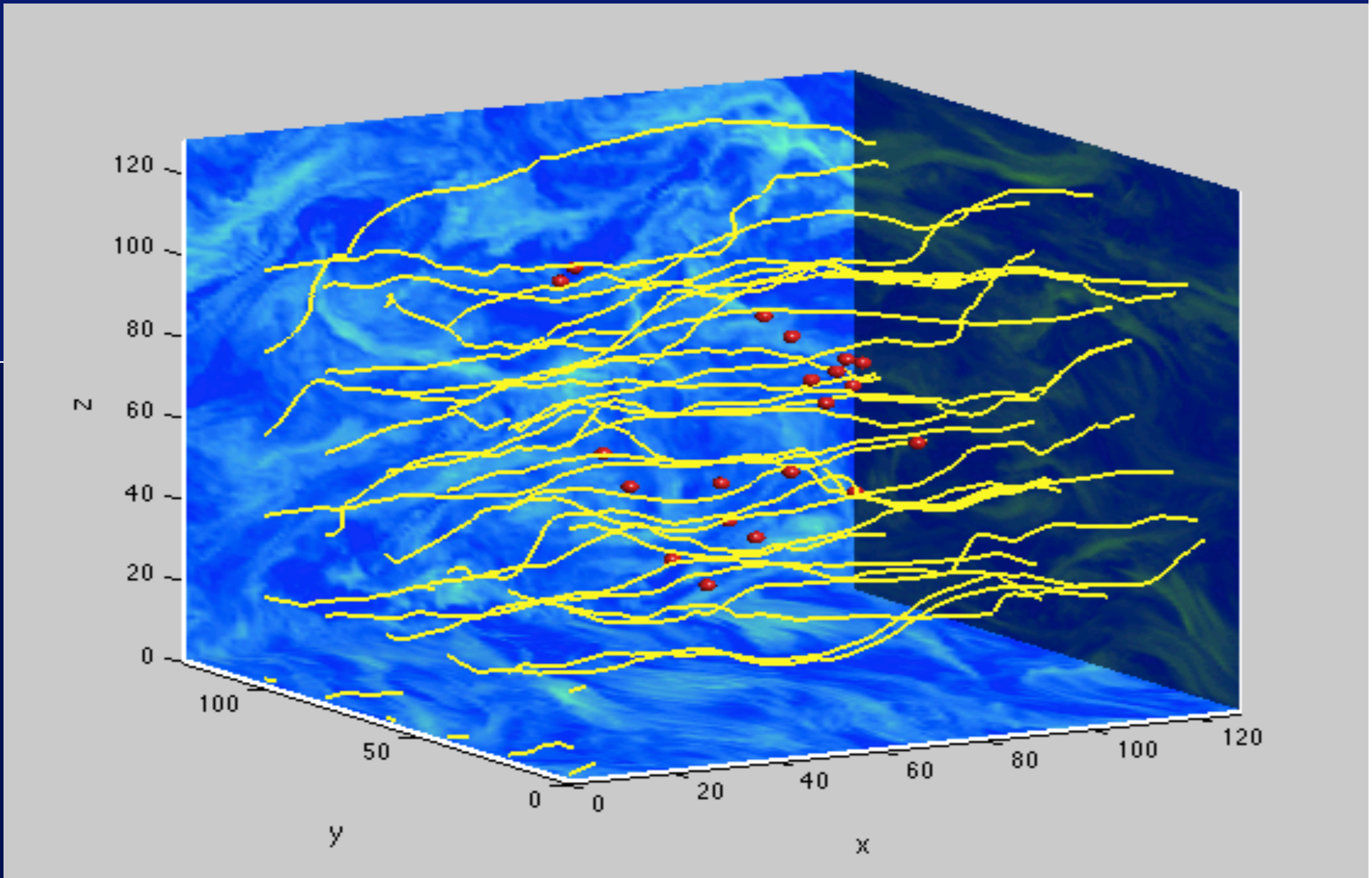
Without turbulence:

molecular diffusion coefficient D $\sim 10^{-5}$ cm^2/sec

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

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

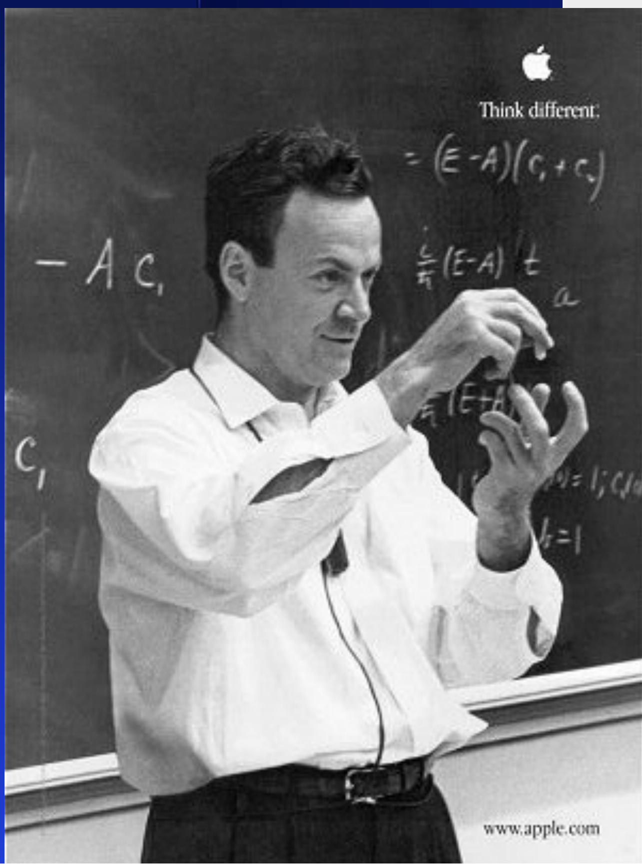
Turbulence radically changes perpendicular diffusion of CRs



Effect was pointed out by Parker and Jokipii and was my inspiration for the idea of turbulent reconnection.

Turbulence is powerful

Due to turbulence DC-8 plane lost its engine



"Turbulence is the last great unsolved problem of classical physics"

R. Feynman

Turbulence as mysterious as quantum mechanics

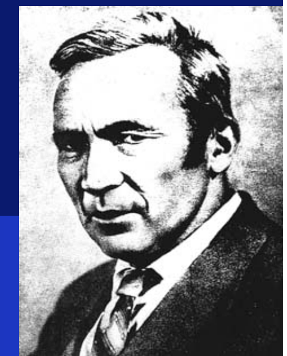
Werner Heisenberg believed that turbulence is more mysterious than quantum mechanics.
What do we know about turbulence?

But we can do quantum mechanical calculations!

Turbulence is a chaotic order

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

Kolmogorov theory reveals order in chaos for incompressible hydro turbulence

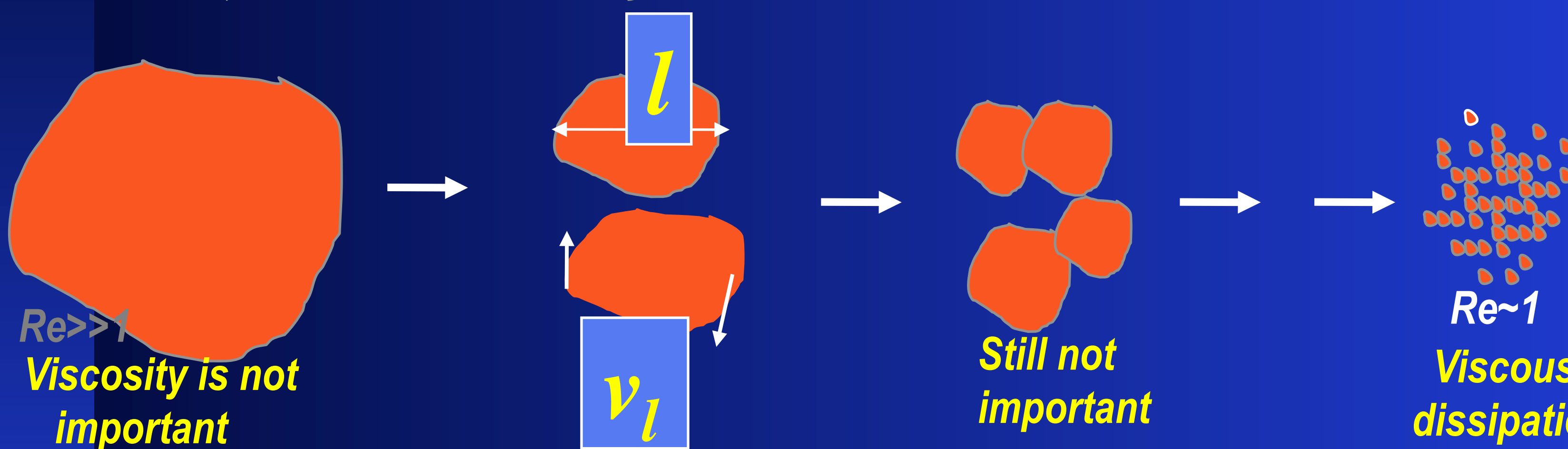


$$\frac{V_l^2}{t_{cas,l}} = const$$

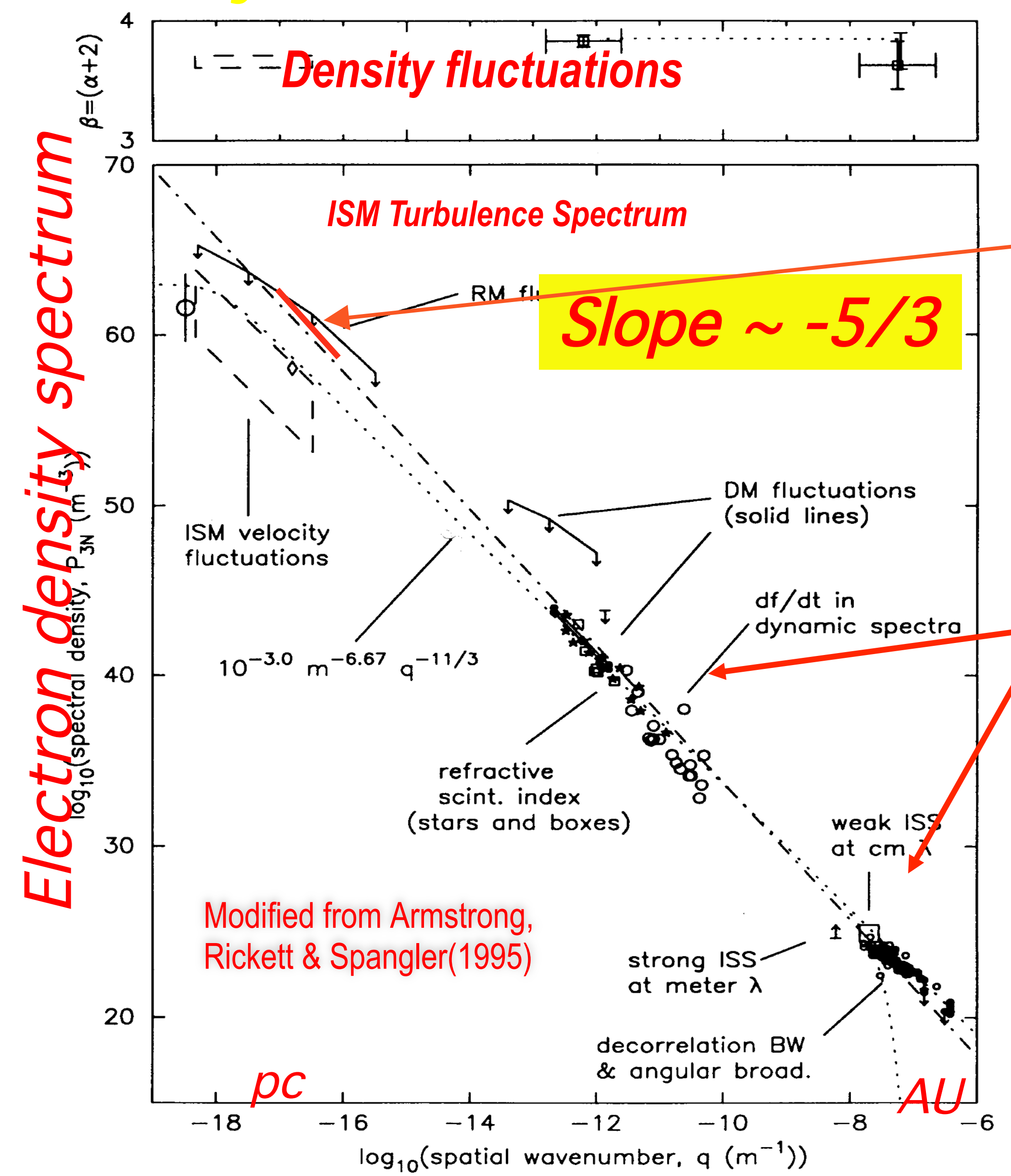
$$t_{cas,l} = l/V_l$$

$$\frac{V_l^3}{l} = const, \; V_l \sim l^{1/3}$$

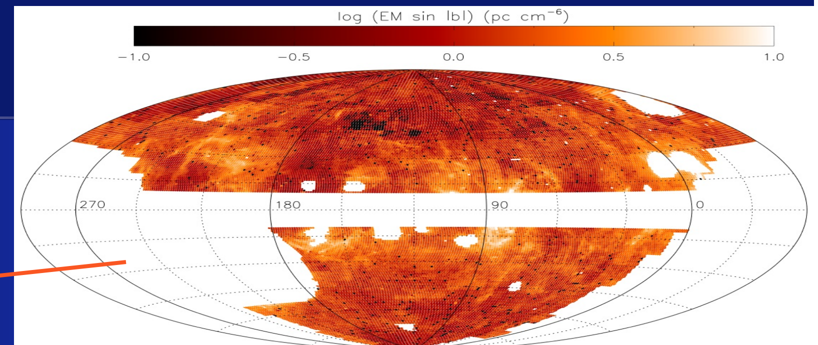
Or, $E(k) \sim k^{-5/3}$



ISM reveals Kolmogorov spectrum of electron density fluctuations



Scincillations and scattering



WHAM emission: density fluctuations

Chepurnov & Lazarian 2009

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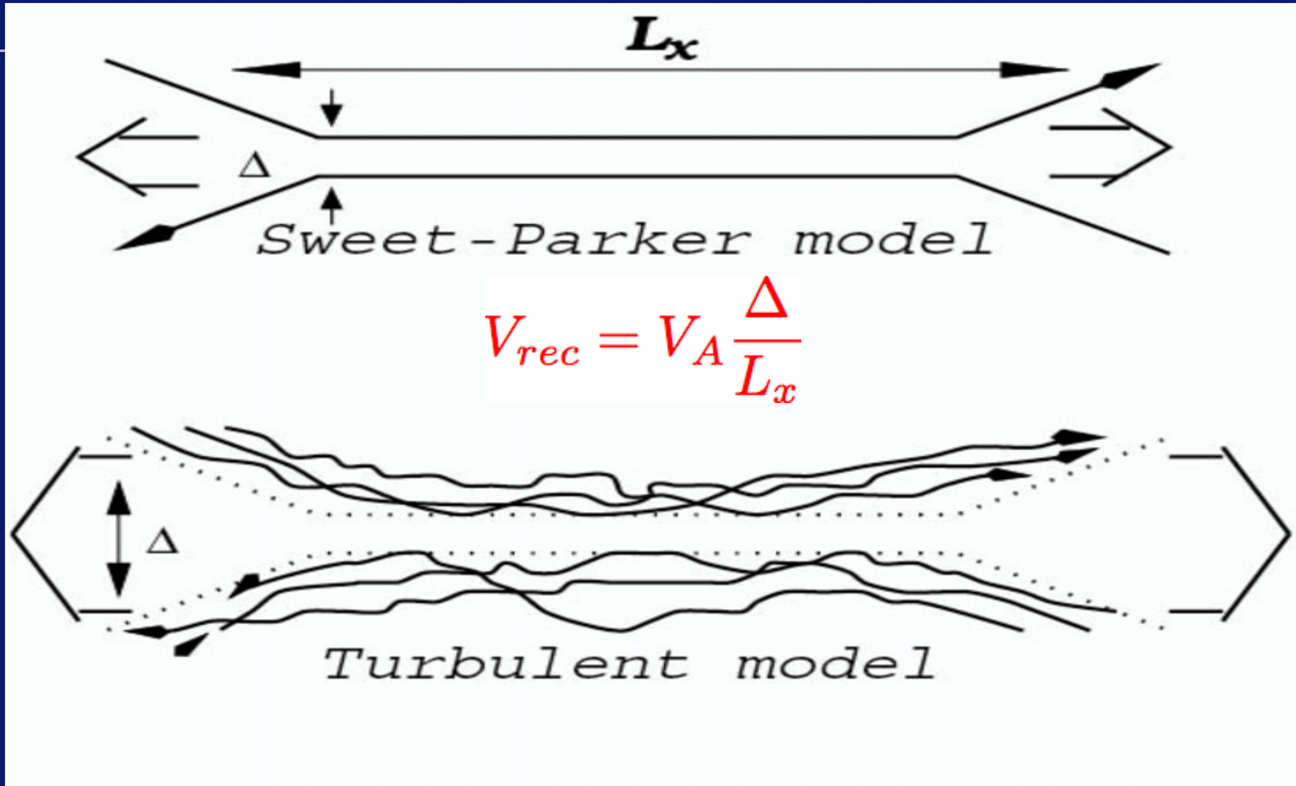
Turbulence makes magnetic reconnection fast!

Turbulent reconnection:

Outflow is determined by field wandering.



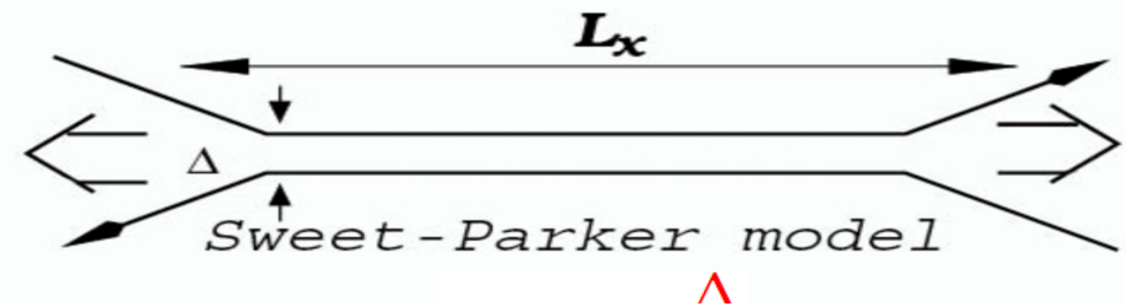
AL & Vishniac (1999)

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 fiel wandering.



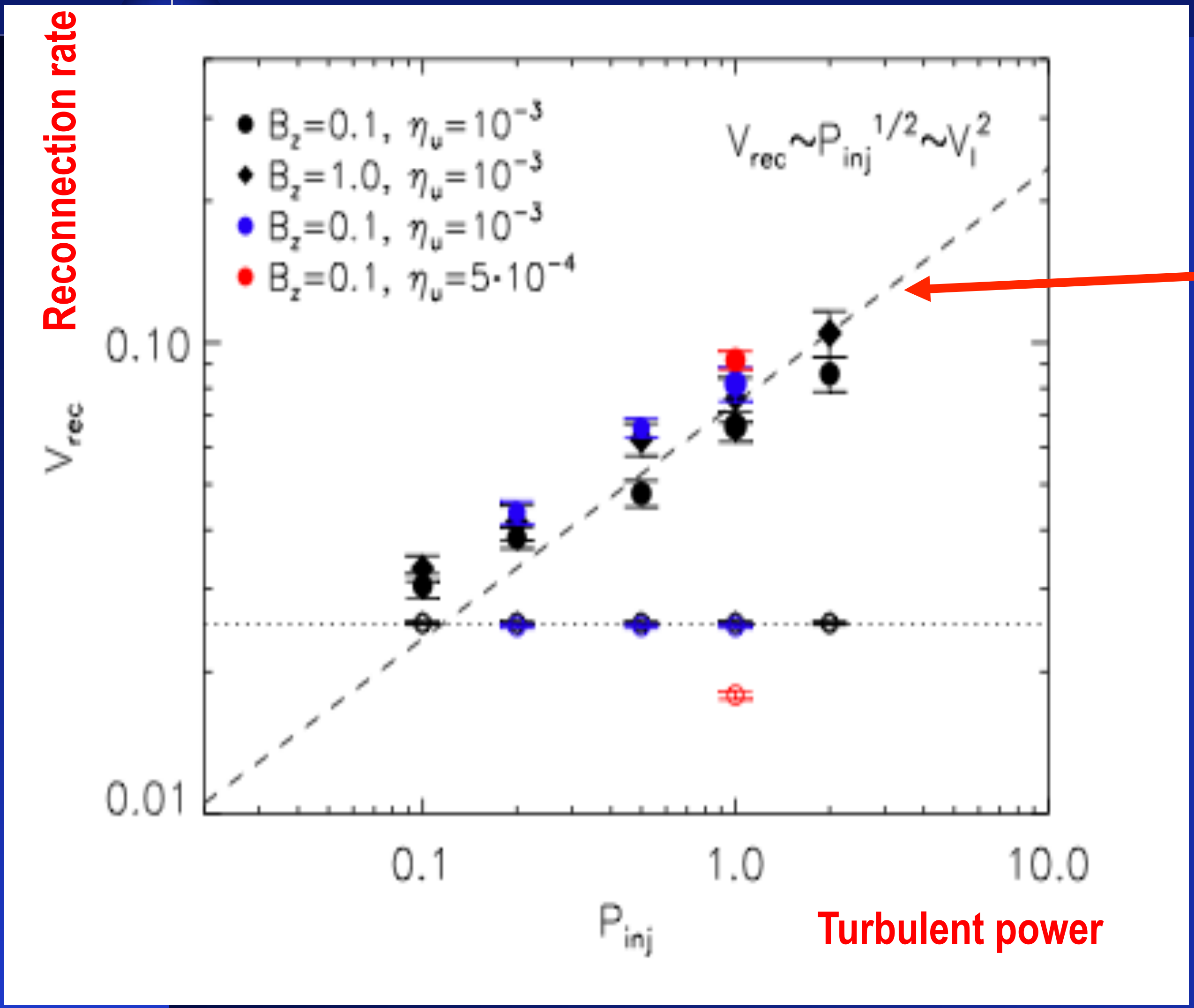
Without turbulence:

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 !

Numerics confirms that turbulence makes reconnection fast



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

More recent studies:

Oishi, Mac Low, Collins, Tamura 2015

Takamoto, Inue, AL 2016

Kowal et al. 2017 a b

Kowal et al. 2012

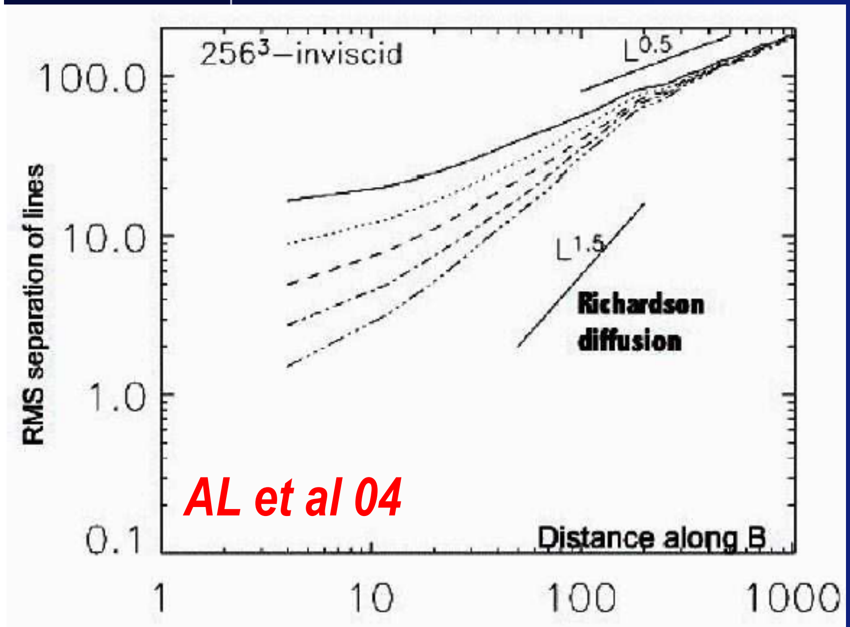
Eyink, AL & Vishniac 2011 related LV99 to the well-known concept of Richardson diffusion

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

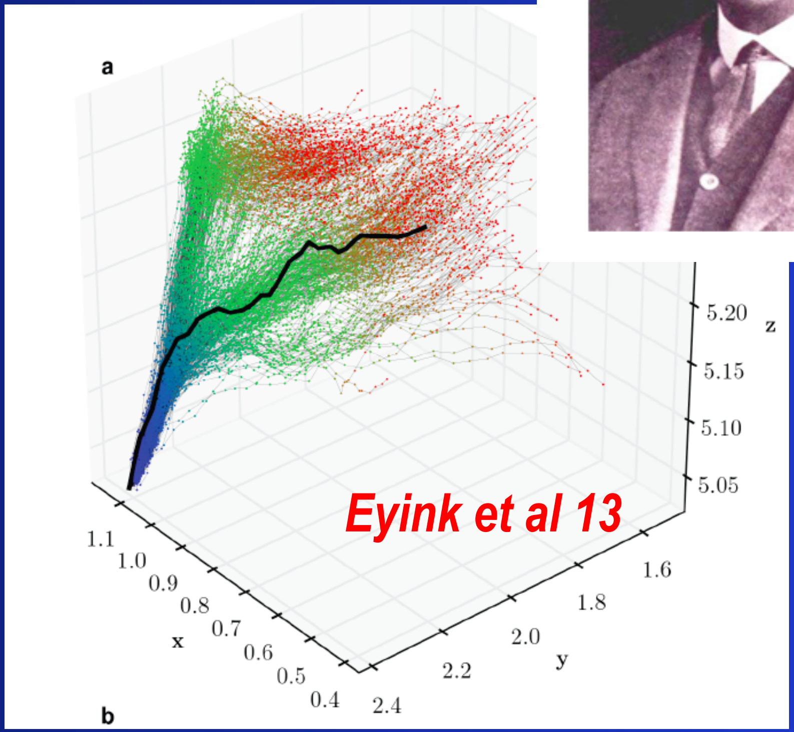
Richardson's law

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

Richardson diffusion measured in MHD

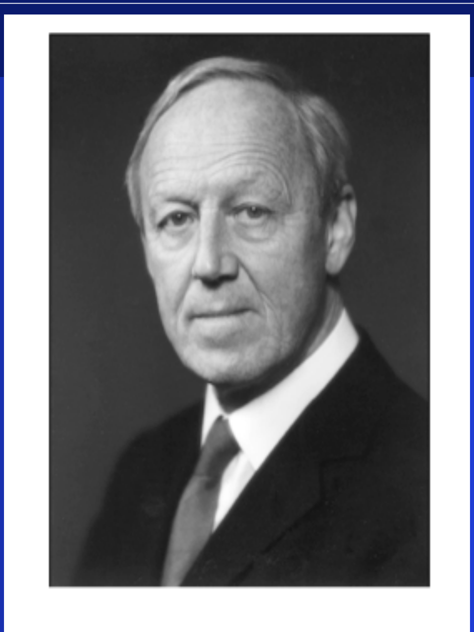


Diffusion in space



Diffusion in time

Big Implication: LV99 means that magnetic field in *turbulent fluids* is not frozen in



Hannes Alfven

Turbulent reconnection and violation of flux freezing was shown by comparison of simulations and Solar wind data

Lalescu et al. 2015

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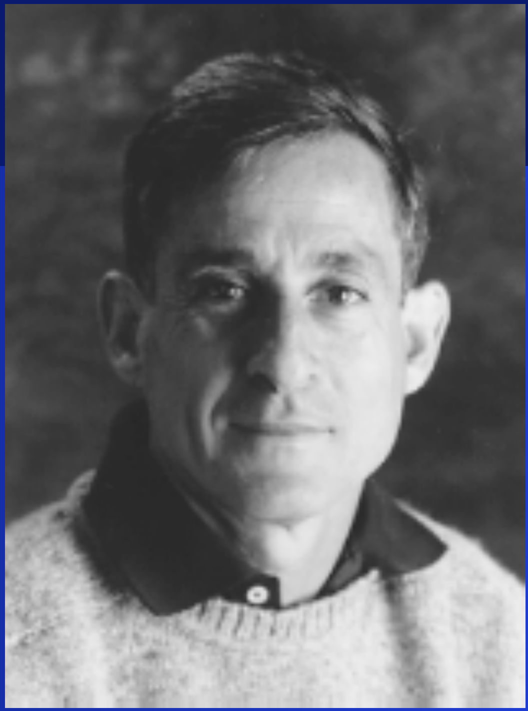
Goldreich-Sridhar 1995 turbulent model was derived using closure relations that are valid in global system of reference



Numerical simulations (Cho & Vishniac 2000, Maron & Goldreich 2001, Cho, AL & Vishniac 2002 show that the local system of reference must be used instead

Derivation of GS95 scalings based on the LV99 reconnection theory

- Critical balance

$$\frac{l_\perp}{V_{\perp l}} = \frac{l_\|}{B_0}$$

- Constancy of energy cascade rate

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

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

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

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

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

Local system is used!

In addition, LV99 defines the scaling for subAlfvenic turbulence

GS95 is transAlfvenic with $M_A=(V_L/V_A)=1$

Weak turbulence

For $M_A<1$, spectrum ~ $k_\perp^{-2}$ from the injection scale L_i to $L_i M_A^2$ (see also Galtier 2000)

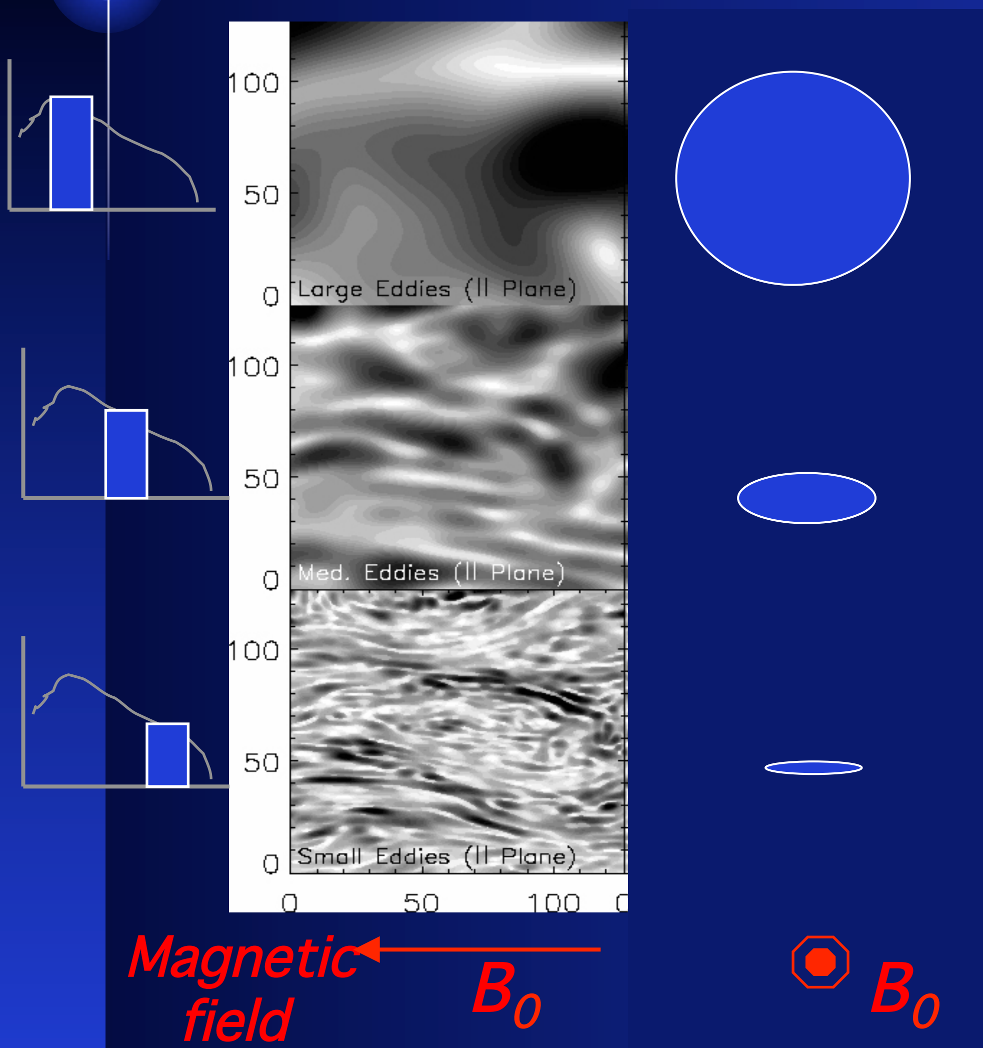
Strong turbulence

For scales less than $L_i M_A^2$ the spectrum ~ $k_\perp^{-5/3}$

$$\ell_\parallel \approx L_i \left(\frac{\ell_\perp}{L_i}\right)^{2/3} M_A^{-4/3},$$

$$\delta u_\ell \approx u_L \left(\frac{\ell_\perp}{L_i}\right)^{1/3} M_A^{1/3},$$

Alfvenic eddies get more and more elongated with the decrease of the scale



Cho, Lazarian & Vishniac 2003

Spectra $k^{-5/3}$ versus $k^{-3/2}$

Kraichnan 1962 model has $k^{-3/2}$ spectrum (assumes isotropy), This spectral slope was very dear to pundits of MHD theory.

GS95 is suggested by outsiders from the MHD turbulence community and provided $k^{-5/3}$

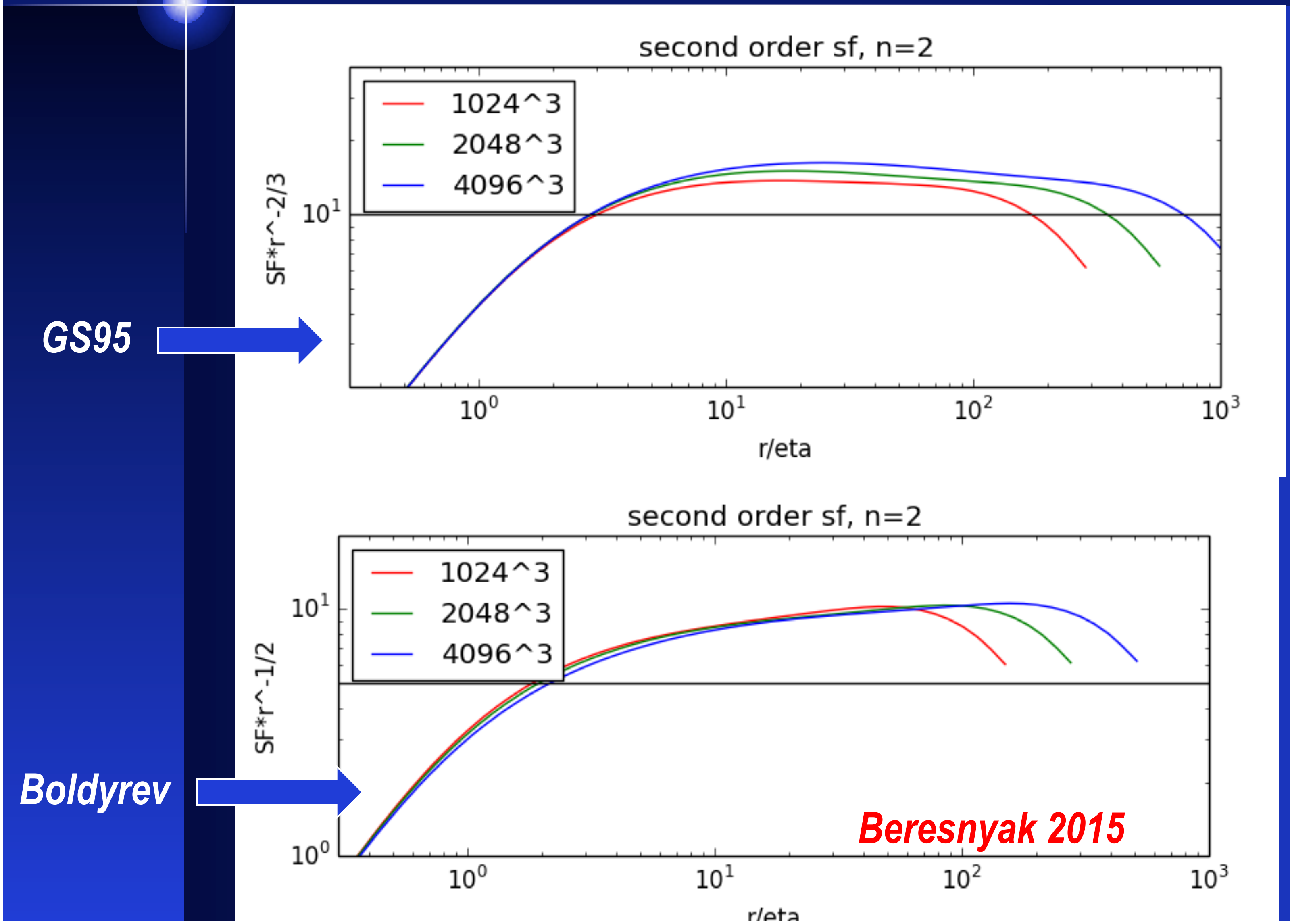
Numerical simulations were suggesting more like $k^{-3/2}$

Boldyrev 2005, 2006 provided a theory predicting $k^{-3/2}$

Beresnyak & AL 2010 suggested that the spectrum that the MHD turbulence is less local than hydro and its spectrum of $k^{-5/3}$ is affected by an extended bottleneck

What is right?

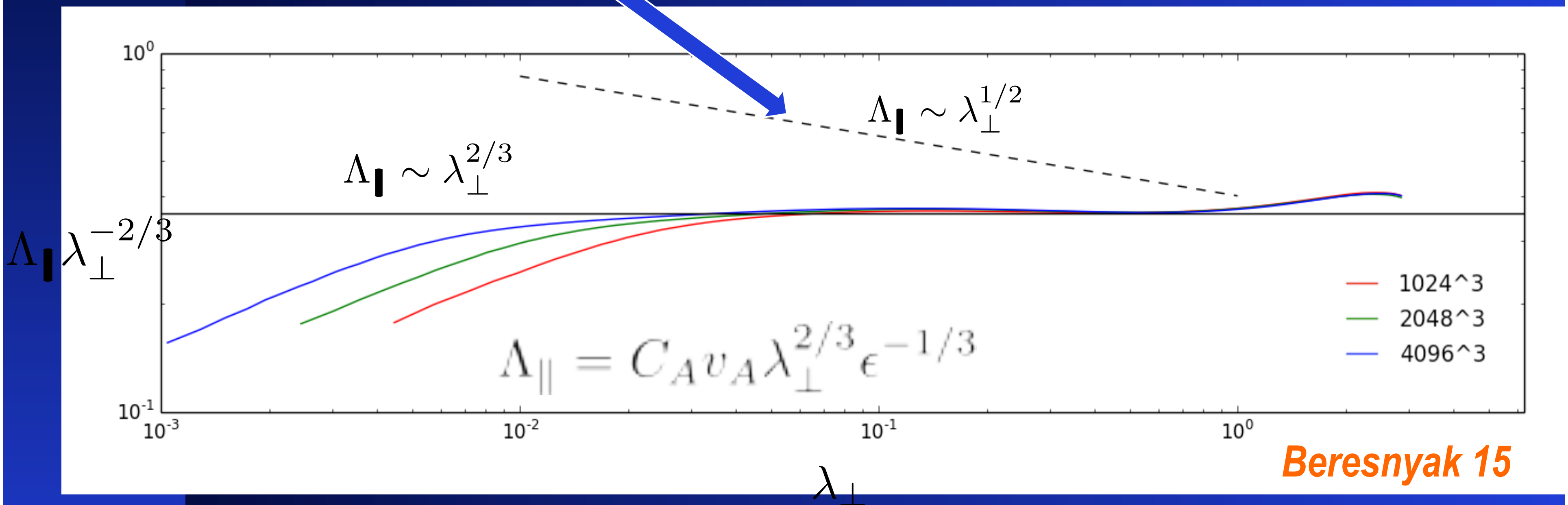
Second order SF demonstrates $r^{2/3}$ scaling



Anisotropy in SF agrees well with GS95 predictions

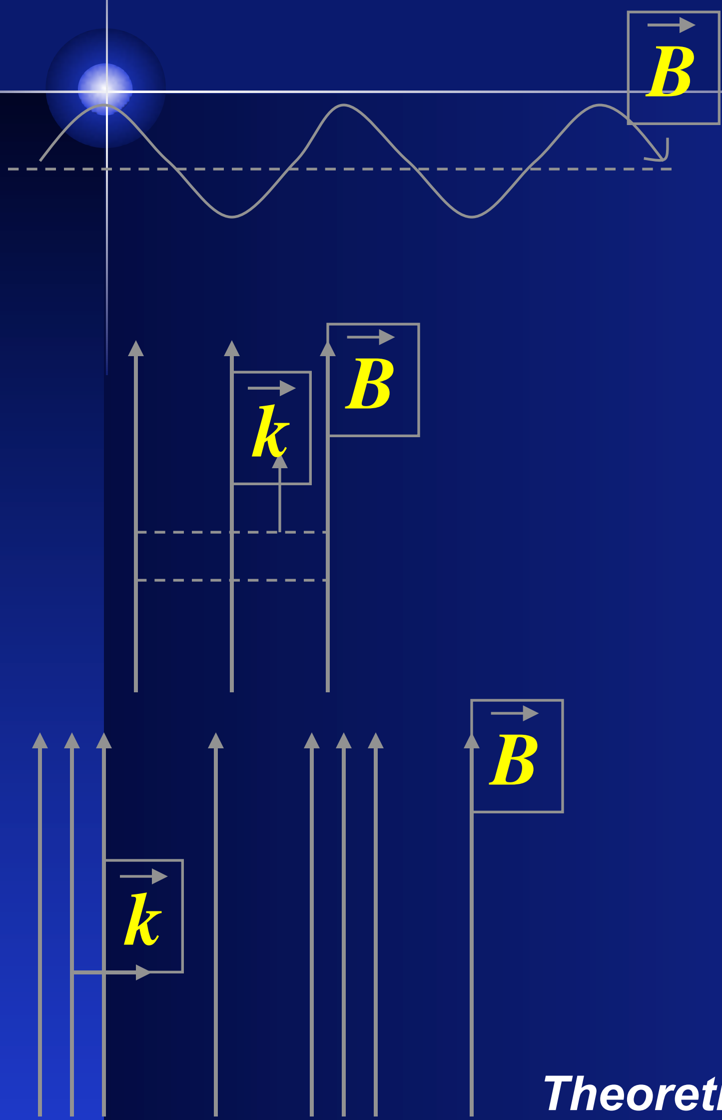
GS95: $l_{||} \sim l_{\perp}^{2/3}$

Boldyrev $l_{||} \sim l_{\perp}^{1/2}$



Beresnyak 15

Alfven, Slow and Fast cascades do not exchange energy



Alfven mode ($v=V_A \cos\theta$)

incompressible;
restoring force=mag. tension

slow mode ($v=c_s \cos\theta$)

restoring force = P_{gas}

fast mode ($v=V_A$)

restoring force = $P_{mag} + P_{gas}$

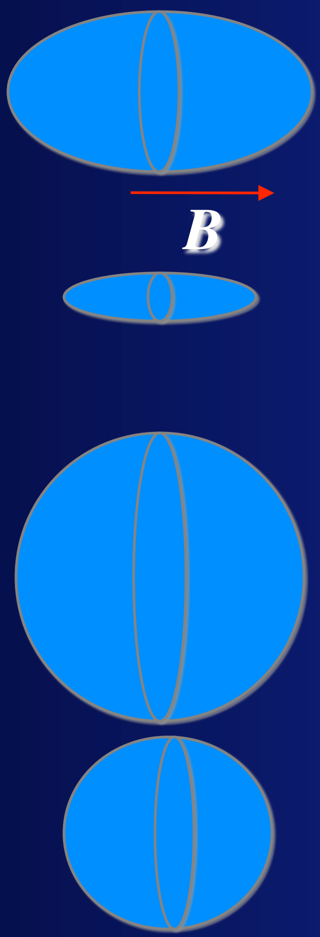
Theoretical discussion is in Lithwick & Goldreich 01
Cho & AL 02

Credit: Francesca Grifo

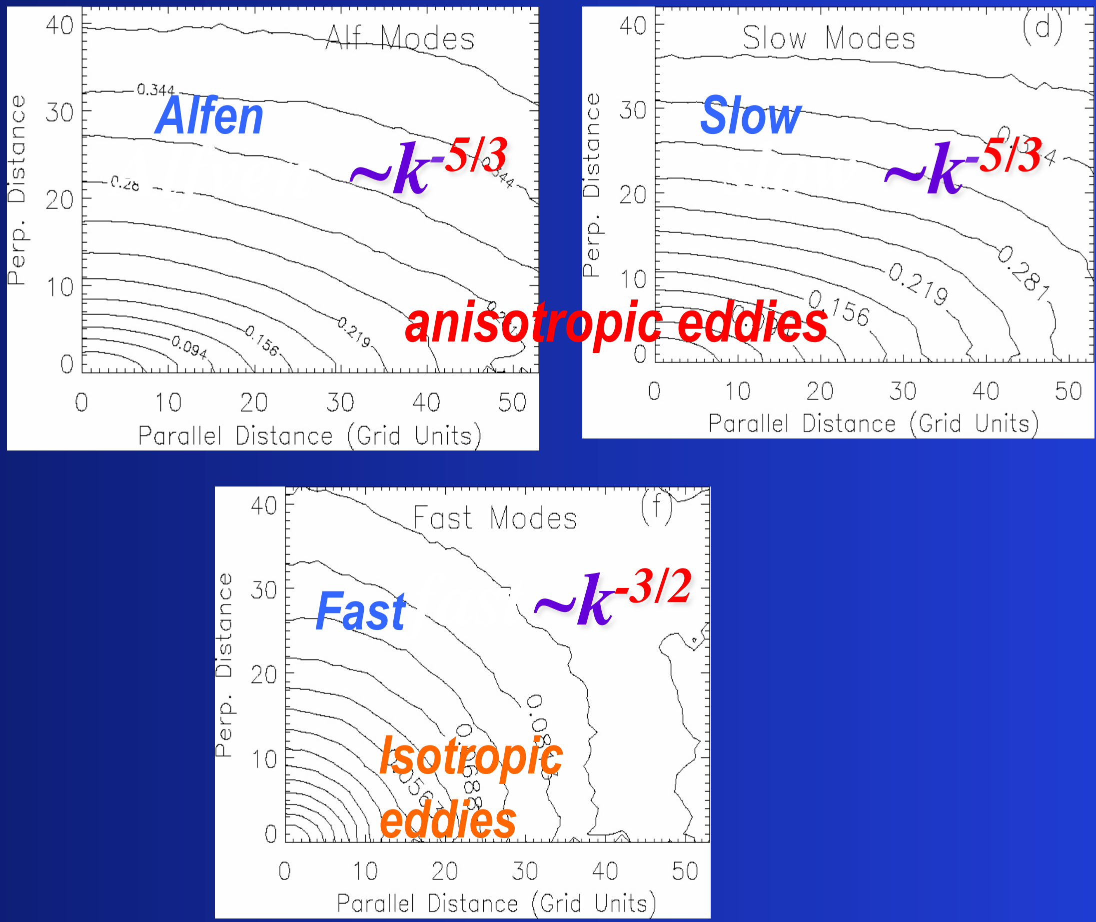
Modes are different, Alfven mode is the same as in incompressible MHD

Alfven and slow modes (GS95)

fast modes



Equal velocity correlation contour (Cho & AL02)



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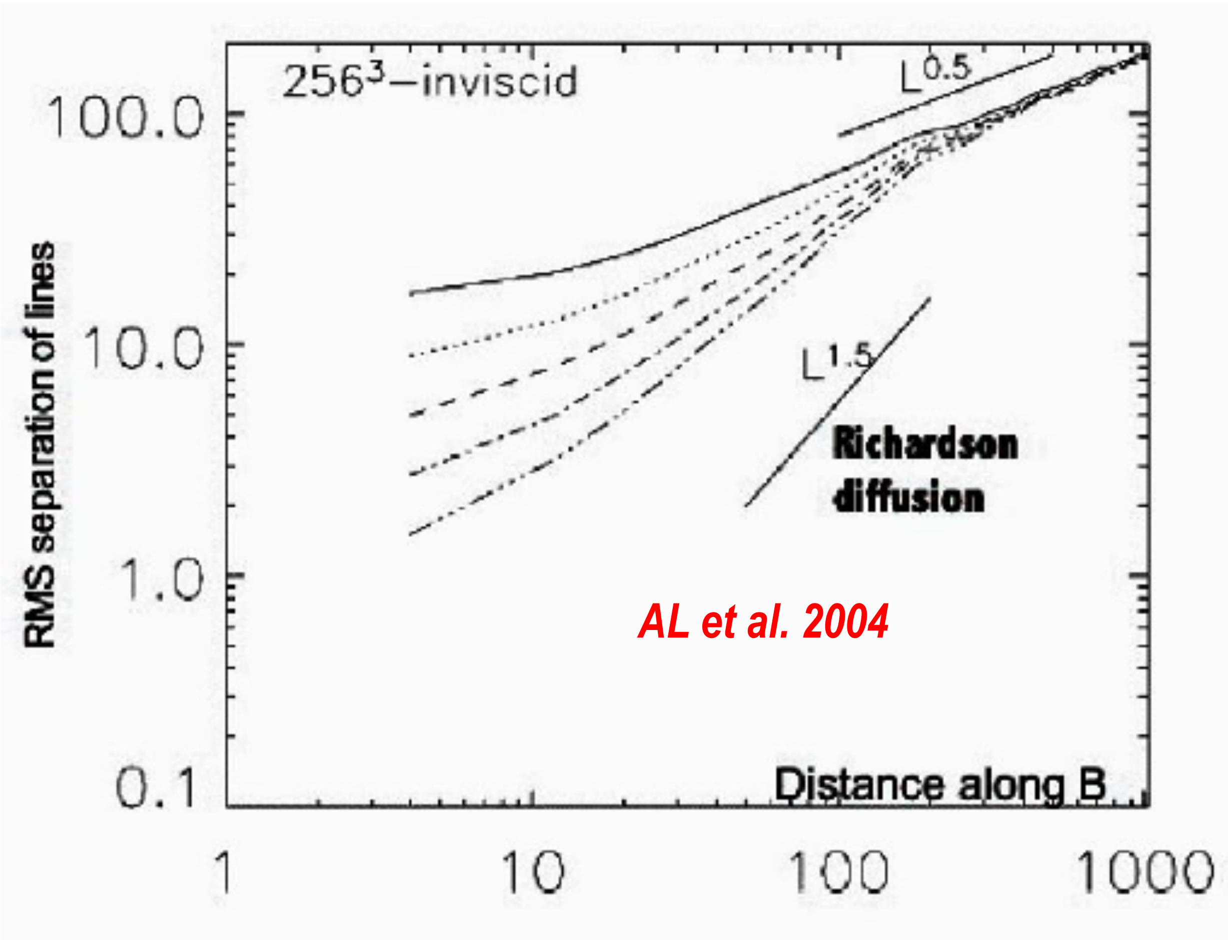
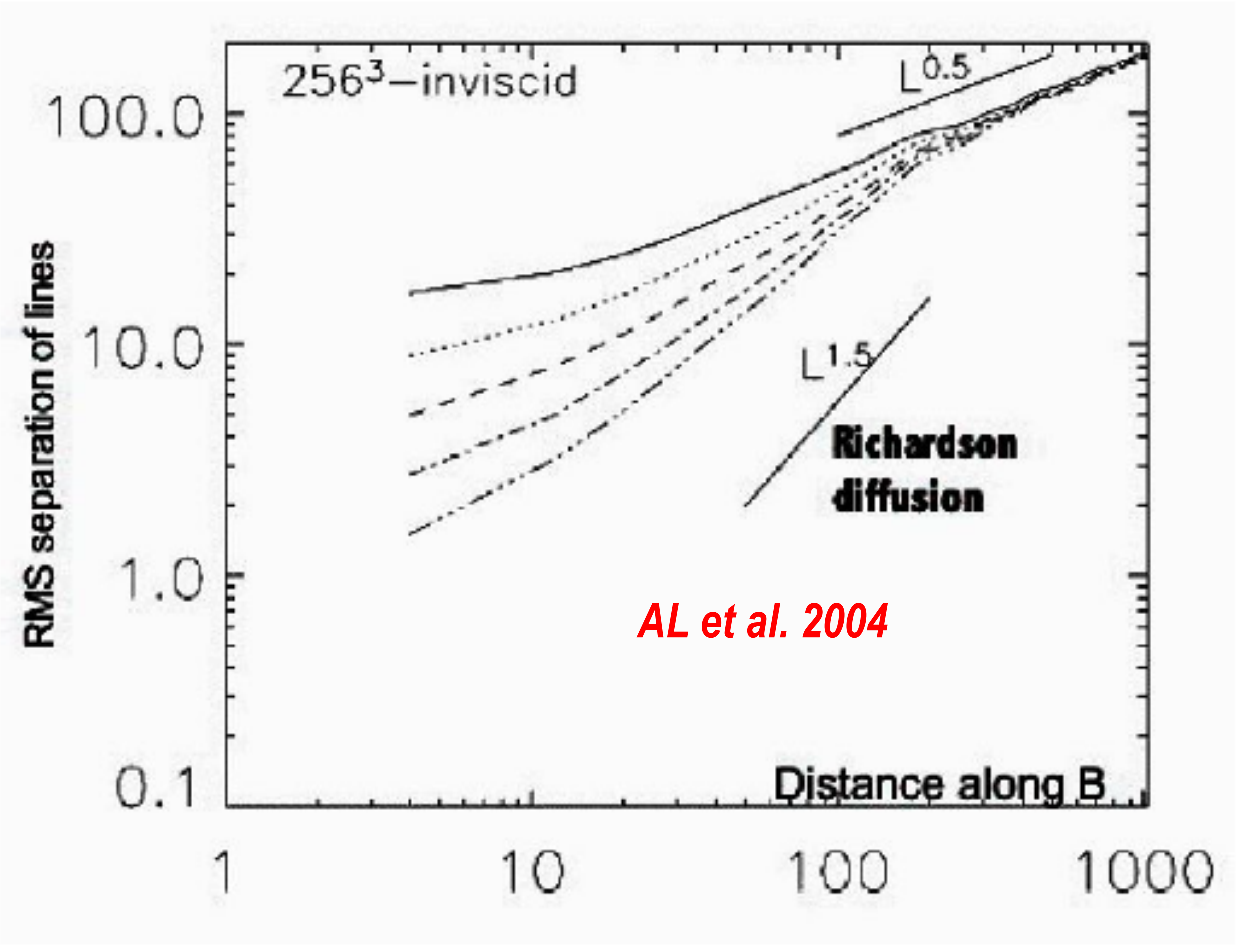
Alfvenic turbulence induces Richardson dispersion, i.e. superdiffusive separation of magnetic field lines



For scales < L

Explosive separation of magnetic field lines is described analytically in AL & Vishniac 1999.
Separation ~ $X^{3/2}$

Alfvenic turbulence induces Richardson dispersion, i.e. superdiffusive separation of magnetic field lines



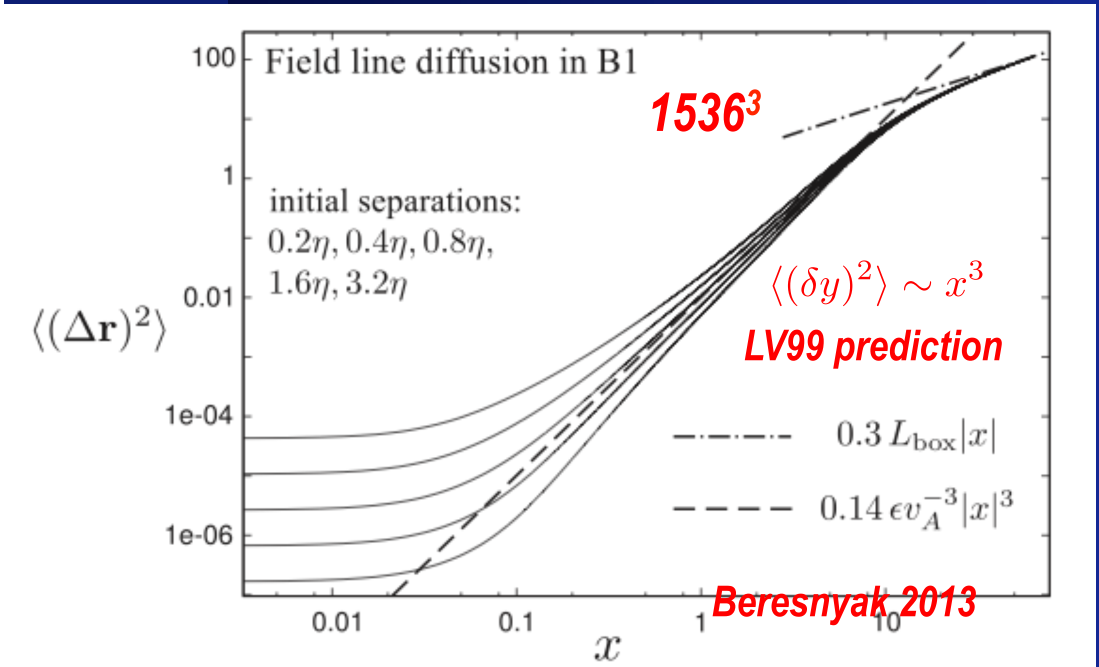
For scales < L

Explosive separation of magnetic field lines is described analytically in AL & Vishniac 1999. Separation ~ $X^{3/2}$

Richardson diffusion in space means superdiffusion (superballistic behavior) for CRs following magnetic field

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

Superdiffusion acts on scales x less than the injection scale of MHD turbulence



Injection scale of turbulence in the Galaxy is about 100 pc

Diffusion perpendicular to mean magnetic field direction is determined by magnetic field line wandering

Realized by Jokipii & Parker 69, Jokipii 73 but turbulence model was not right

In fact, this motivated my work in turbulent magnetic reconnection

The study with modern understanding of MHD turbulence is in AL& Vishniac 99

Strong subAlfvenic turbulence at scales $s<l_{trans}$ results in superdiffusion:

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

At scales $s>l_{trans}$ results in ordinary diffusion:

$$\ell_{\perp}^{2} \sim sLM_{A}^{4}.$$

Superdiffusive behavior is confirmed in AL et al. 04, Maron & Chandran 04, Beresnyak 15

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

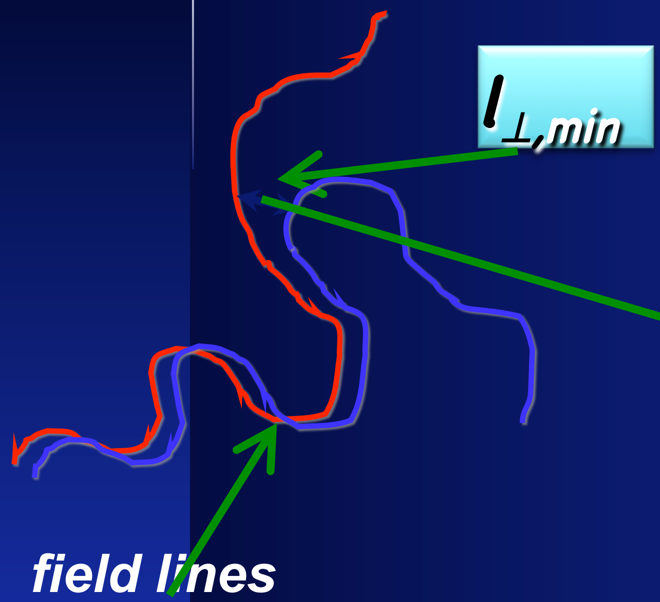
$$\ell_{\perp}^2 \sim \frac{s^3}{27L} M_A^4,$$

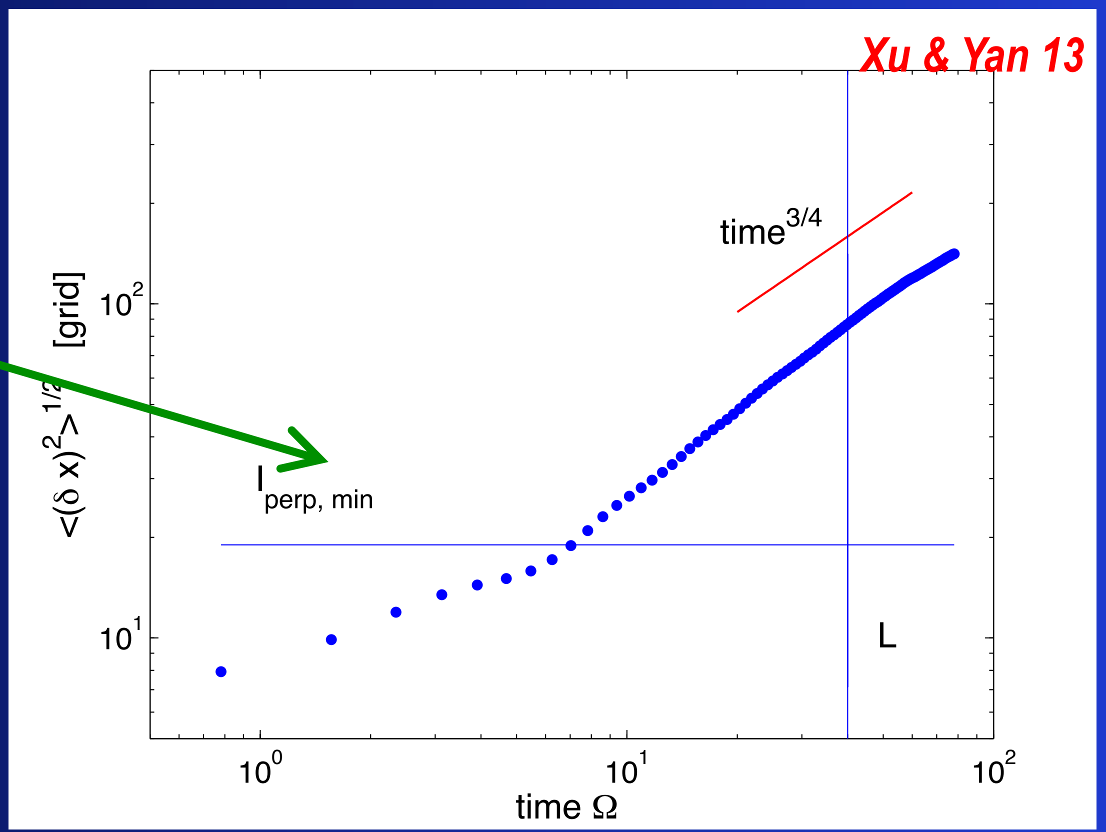
On scales < L and s >> mfp, CRs trace magnetic field divergence, s is covered in diffusion process

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

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

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



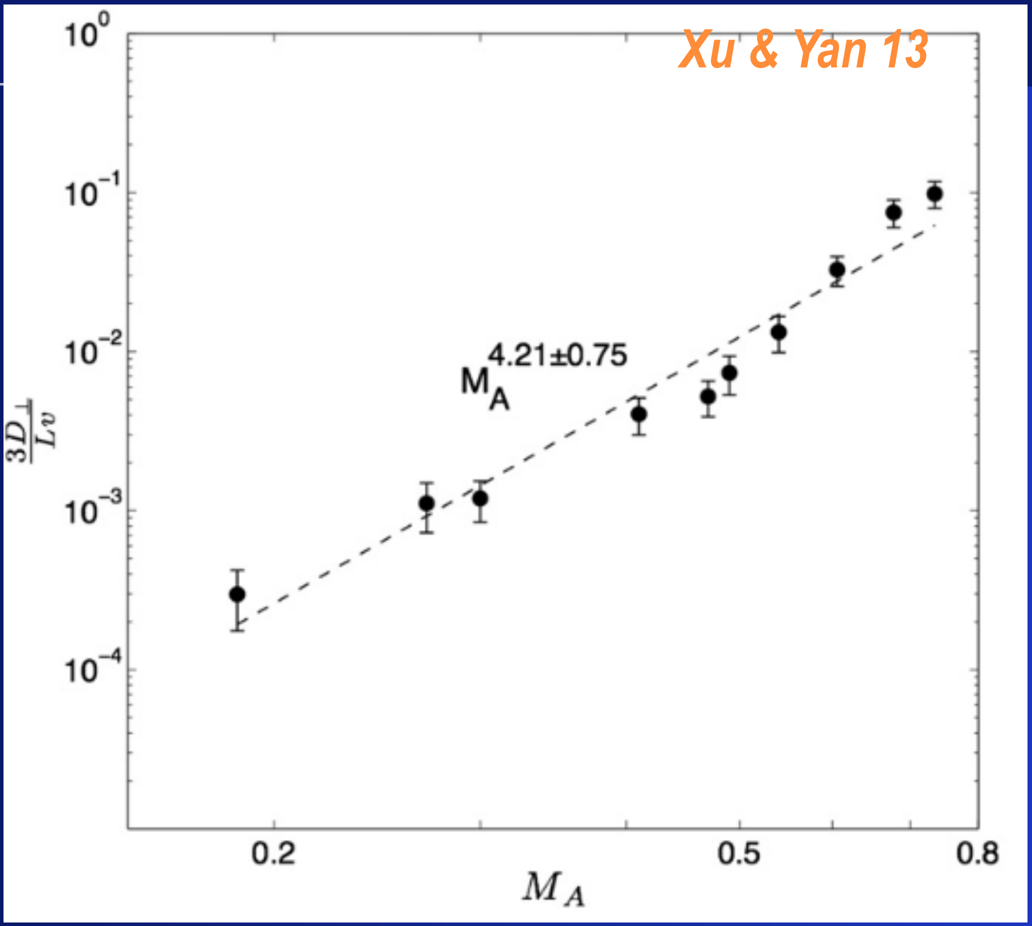


Prediction:

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

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

Diffusive regime

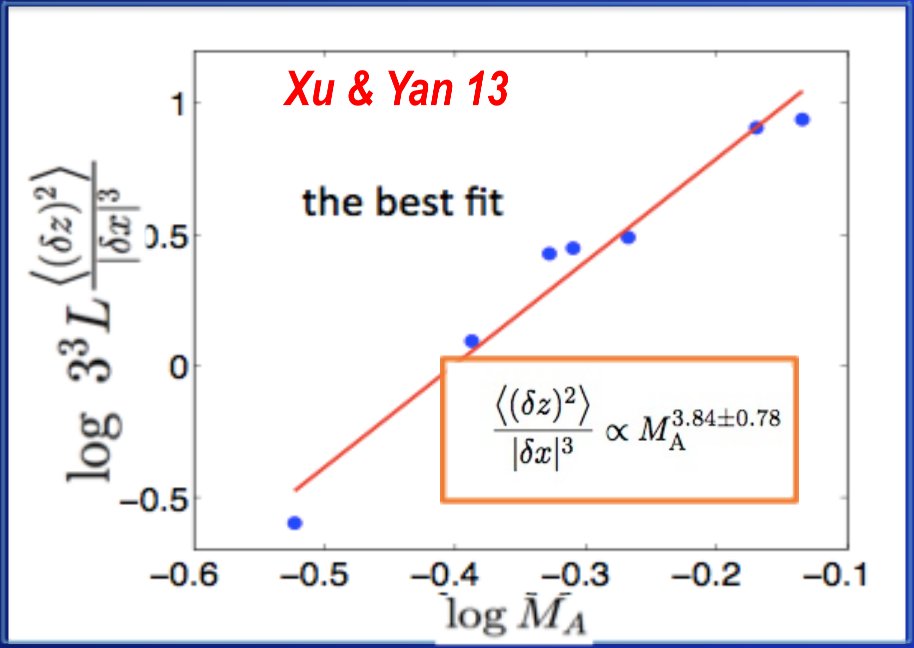


To compare with $D_{\perp,\mathrm{global}} \approx D_\parallel M_A^4,$ *in AL06, Yan & AL08*

The dependence on forth power of Alfven Mach number is also confirmed

Superdiffisive regime

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



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

AL & Vishniac 1999; Yan & AL 2008

Different regimes of Alfvenic turbulence and field line divergence

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	$\sim sLM_A^2$
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	$\sim sl_A$
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

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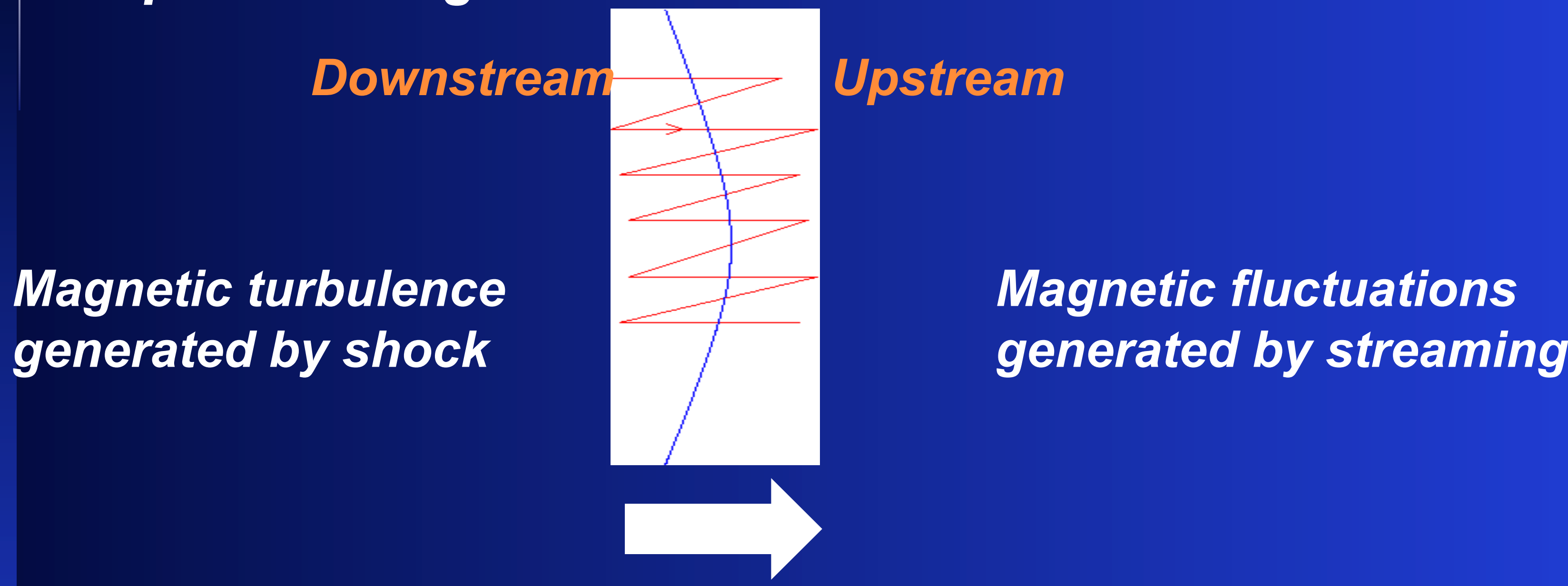
Turbulence strongly affects the processes of cosmic ray acceleration in shocks

Acceleration in shocks requires scattering of particles back from the upstream region.

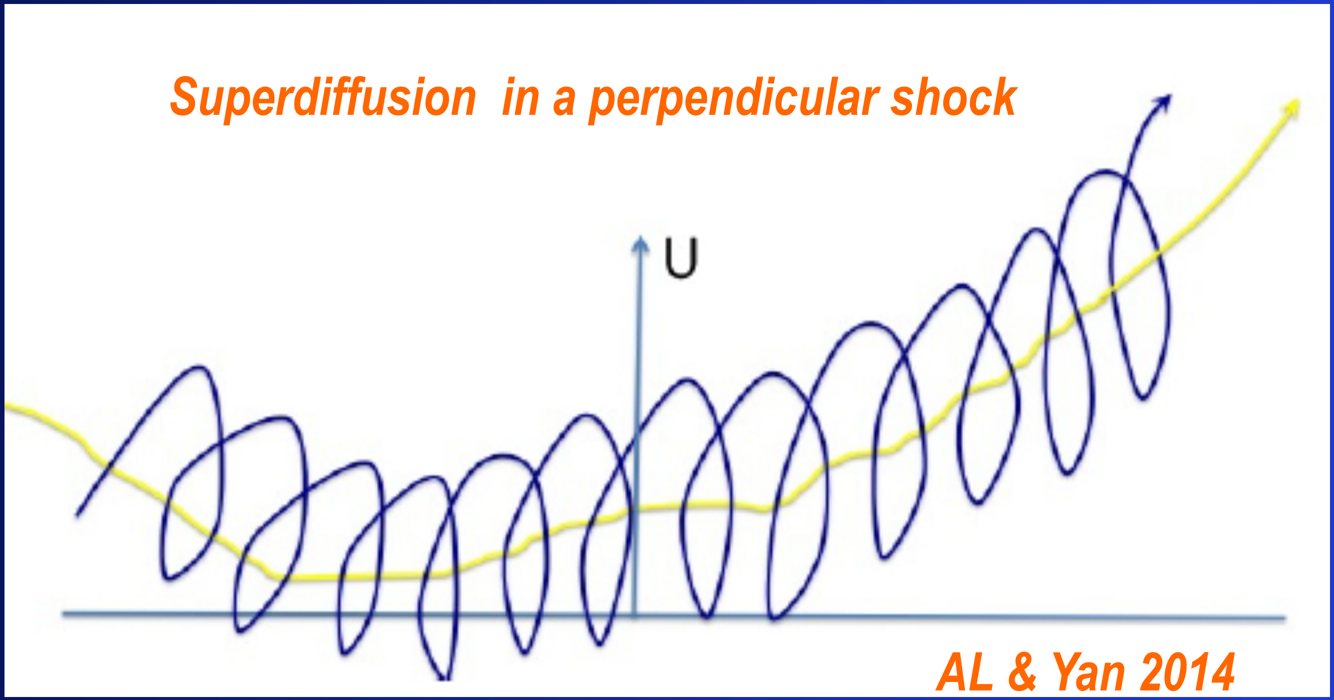


Superdiffusion prevents the particles to return back to a perpendicular shock

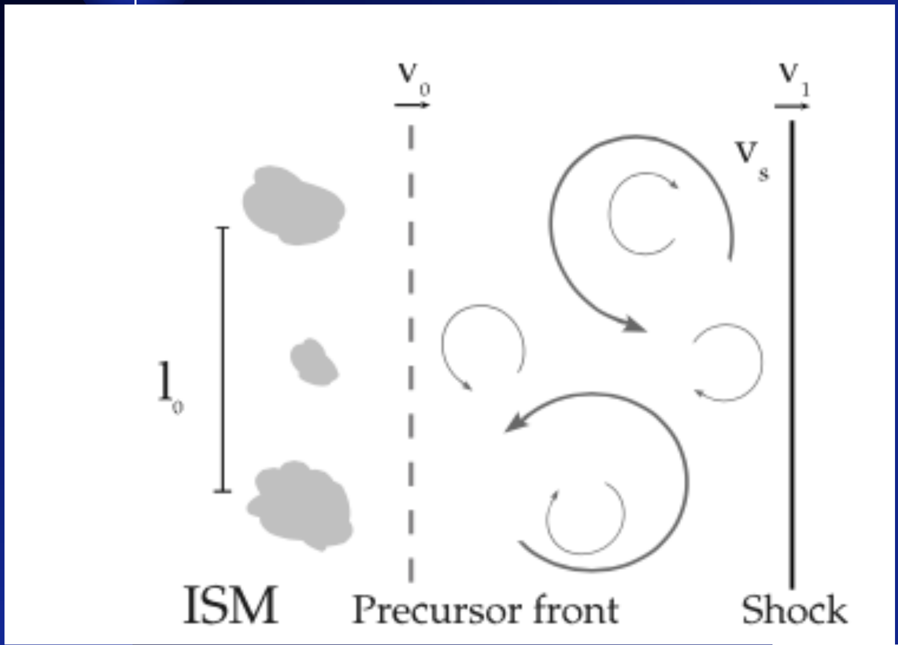
$$\frac{\kappa_{\perp}}{\kappa_{\parallel}} = \frac{1}{1 + (\lambda_{CR}/r_L)^2}$$

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

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

Beresnyak, Jones & AL 2009, de Valle, AL & Santos-Lima 2016, Xu & AL 2017

Numerical simulations support predictions of turbulent dynamo in a precursor

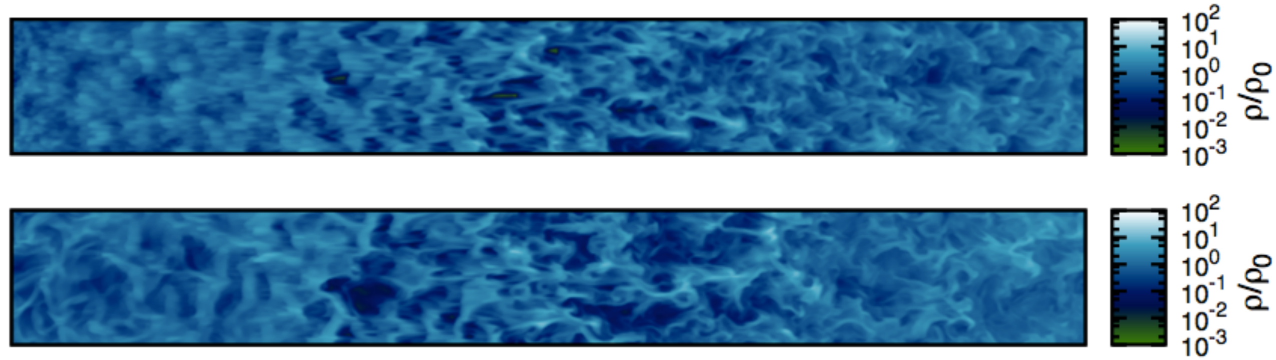


Figure 4. Final density distribution in a central cut of the xy-plane of the computational box for Model AI (upper panel) and for Model BI (bottom panel). The parameters of the models are listed in Table 1.

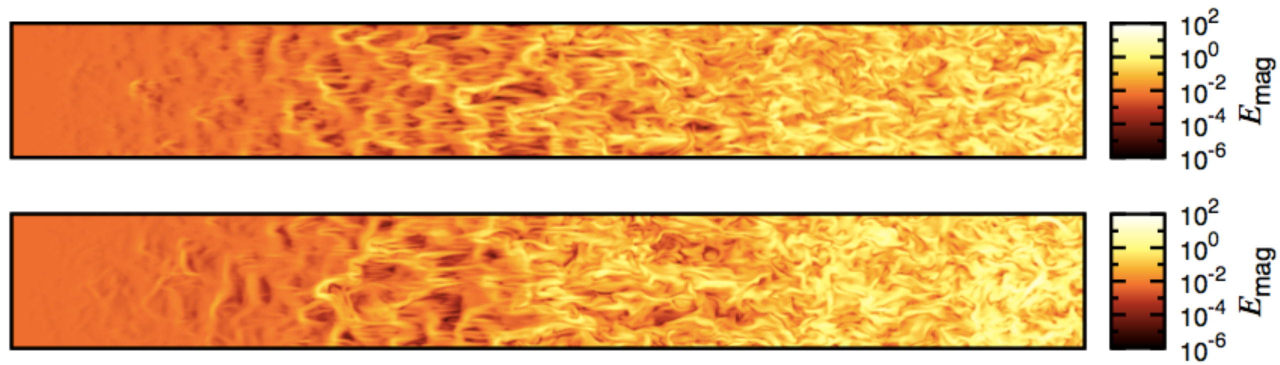
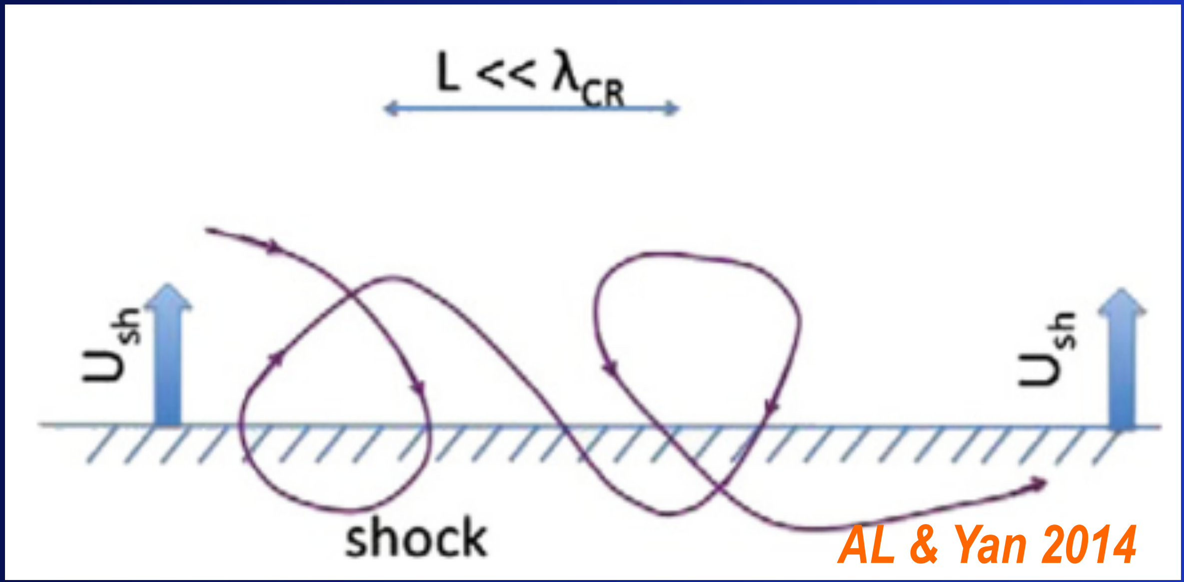


Figure 5. Final distribution of the magnetic energy in a central cut of the xy-plane of the computational box for Model AI (upper panel) and for Model BI (bottom panel). The parameters of the models are listed in Table 1.

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

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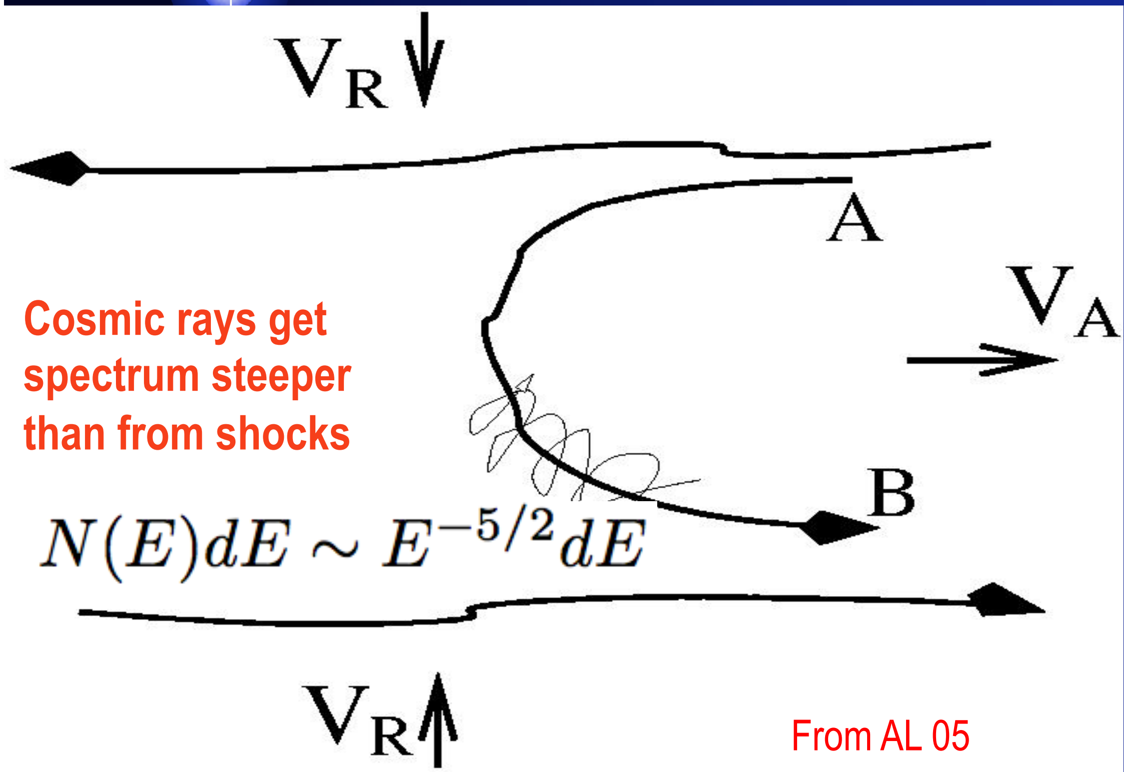
In LV99 reconnection model energetic particles get accelerated by First Order Fermi mechanism



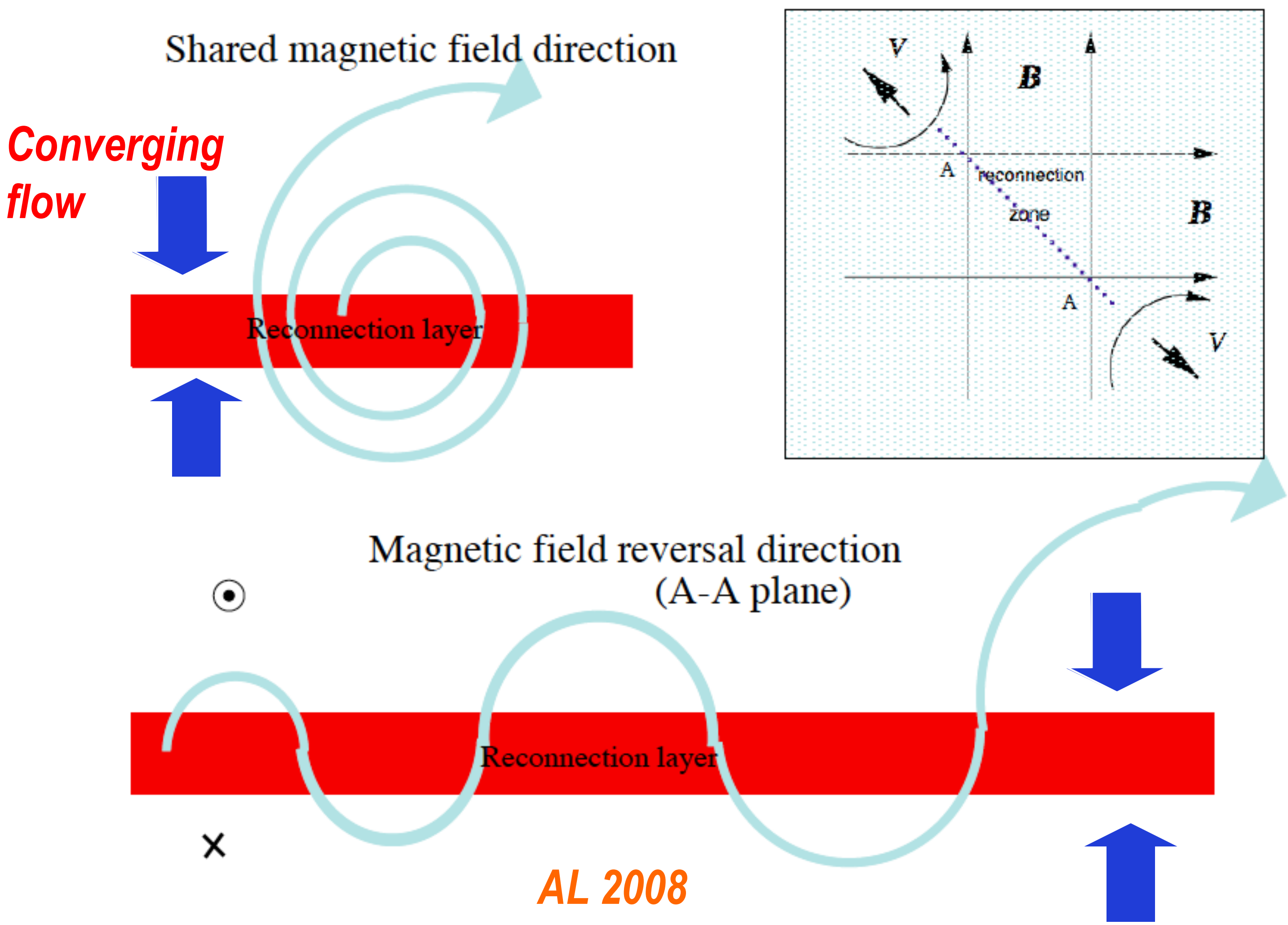
Cosmic rays get spectrum steeper than from shocks

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

(cp. Drake et al. 2006).

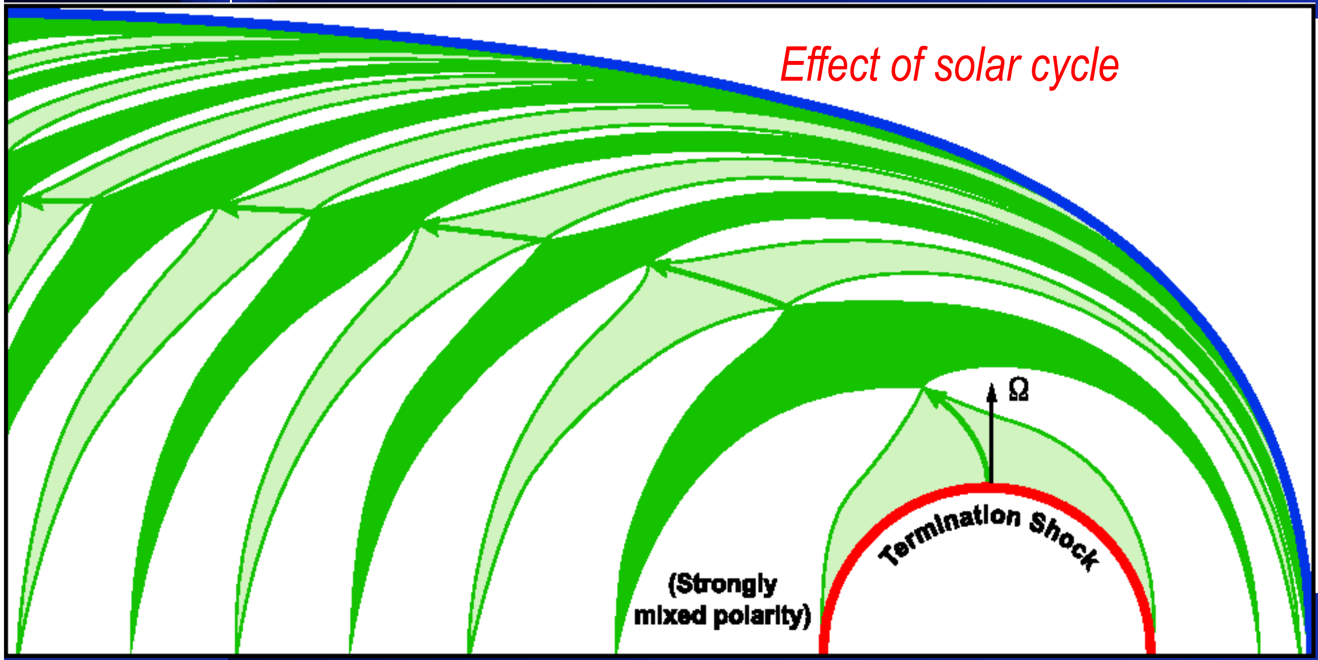
Published in De Gouveia Dal Pino & AL 2003, 2005

First order Fermi acceleration happens also for perpendicular components

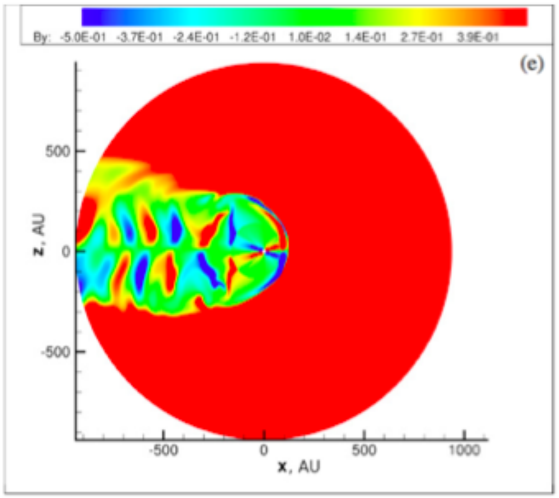


AL 2008

Magnetic reconnection expected in magnetotail is important for TEV anisotropies and lower energy excess observed



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



AL & Desiatii 2010

Plan of the talk

1. *Turbulent Astrophysical Plasmas*
2. *Turbulent reconnection and violation of flux freezing*
3. *Theory of Alfvenic turbulence*
4. *CR superdiffusion*
5. *CR acceleration in shocks*
6. *CR acceleration in reconnection sites*
7. *Damping of streaming instability by Alfvenic turbulence*

Streaming instability damping by Alfvenic turbulence is suggested by Yan & AL 02 and quantified by Farmer & Goldreich 04

$$\Gamma_{cr} \approx \Omega_B \frac{n_{cr}(>\gamma)}{n_i}\left(\frac{v_{stream}}{V_A} - 1\right),$$

Streaming instability growth rate

FG04 considered damping by strong turbulence and assumed M_A=1. Their conclusion is that streaming instability is suppressed in the Galaxy. This entails expectations of CR anisotropies >> 10^{-4} observed.

"streaming catastrophe"

Results in FG04, however, do not cover all important regimes of turbulence

$$M_A \equiv \frac{V_L}{V_A} = \frac{\delta B}{B}$$

AL16

Type of MHD turbulence	Injection velocity	Range of scales	Spectrum E(k)	Instability damping rate and r_L range
Weak	$V_L < V_A$	$[l_{trans}, L]$	$k_\perp^{-2}$	$\frac{V_A M_A^{8/3}}{r_L^{2/3} L^{1/3}}$, $LM_A^4 < r_L < LM_A$
Strong subAlfvenic	$V_L < V_A$	$[l_{min}, l_{trans}]$	$k_\perp^{-5/3}$	$\frac{V_A M_A^2}{r_L^{1/2} L^{1/2}}$, $\frac{l_{min}^{4/3}}{L^{1/3}} < r_L < LM_A^4$
Hydro-like superAlfvenic	$V_L > V_A$	$[l_A, L]$	$k^{-5/3}$	$\frac{V_A M_A}{r_L^{2/3} L^{1/3}}$, $l_A < r_L < L$
Strong superAlfvenic	$V_L > V_A$	$[l_{min}, l_A]$	$k_\perp^{-5/3}$	$\frac{V_A M_A^{3/2}}{r_L^{1/2} L^{1/2}}$, $\frac{l_{min}^{4/3}}{L^{1/3}} M_A < r_L < l_A$

For subAlfvenic turbulence the range for the strong turbulence damping is limited to $<LM_A^4$, It extends from LM_A^4 to LM_A for weak turbulence

As for the suppression of streaming in the Galaxy FG04 uses a number of assumptions

1. The level of turbulent dissipation is estimated assuming that all the heating of halo gas is due to turbulent damping.

This is not true as in the presence of streaming: additional heating comes from CRs.

2. Streaming instability damping is induced by strong turbulence in the halo.

M_A in the halo <1, even heating over-estimates in FG04 suggest M_A=0.2

3. A over-simplified relation between the streaming velocity and degree anisotropy is assumed.

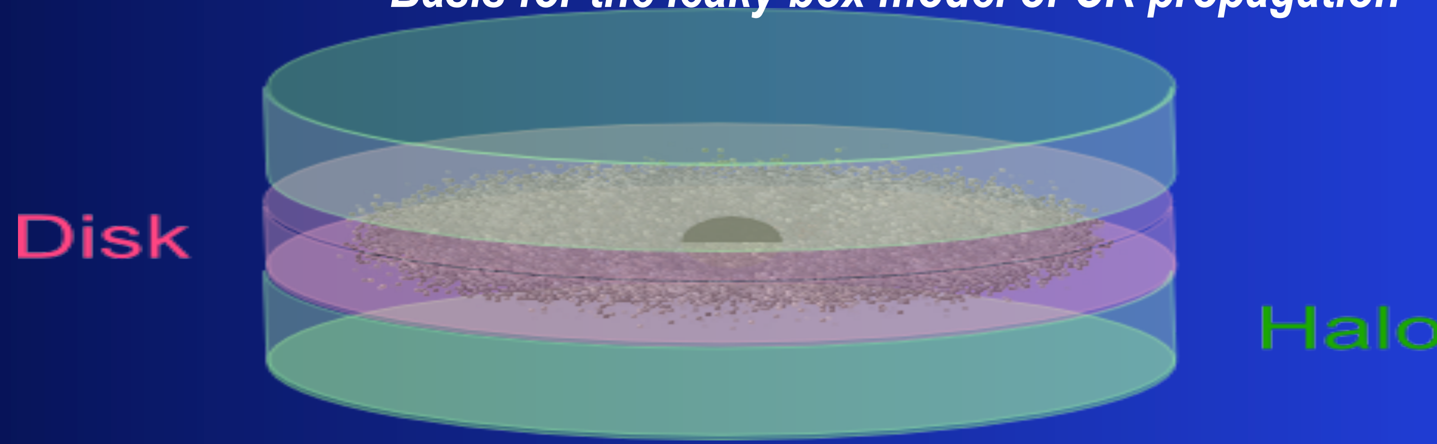
This ignores superdiffusion of magnetic field lines that we discussed.

Streaming instability damping by Alfvenic turbulence is suggested by Yan & AL 02 and quantified by Farmer & Goldreich 04

$$\Gamma_{cr} \approx \Omega_B \frac{n_{cr}(>\gamma)}{n_i}\left(\frac{v_{stream}}{V_A} - 1\right),$$

Streaming instability

Basis for the leaky box model of CR propagation



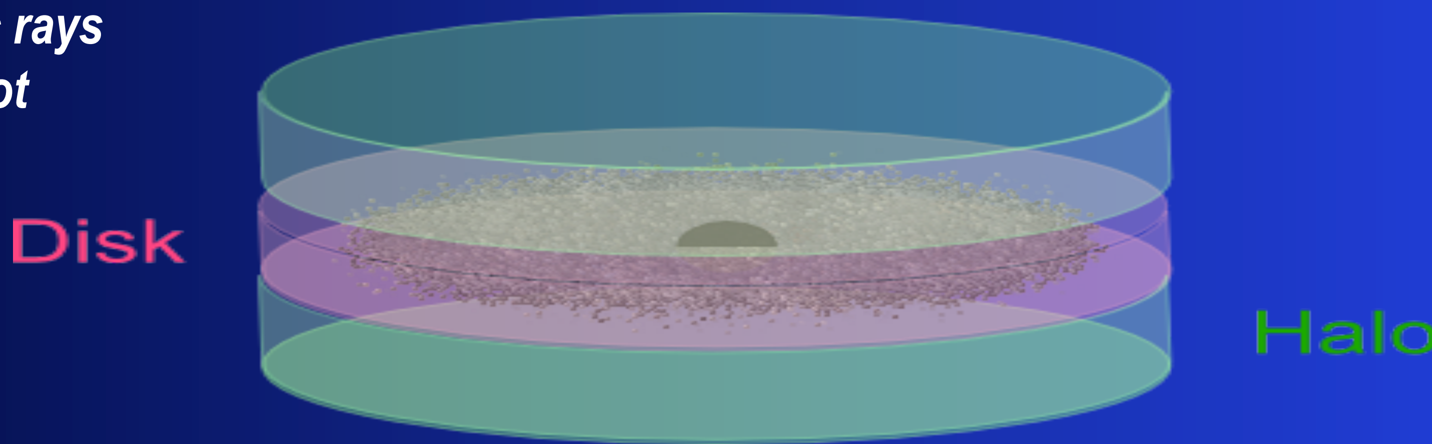
Quantified in Farmer & Goldreich 04 for strong transAlfvenic turbulence

Farmer & Goldrech 2004 challenged the "leaky box" for CR confinement and isotropization claiming that streaming instability cannot exist in the presence of turbulence

The model of damping by strong turbulence is used

The turbulence level was estimated using $\epsilon_{turb.dissipation} = radiation \;\; cooling$

Problem: cosmic rays stream and do not isotropize

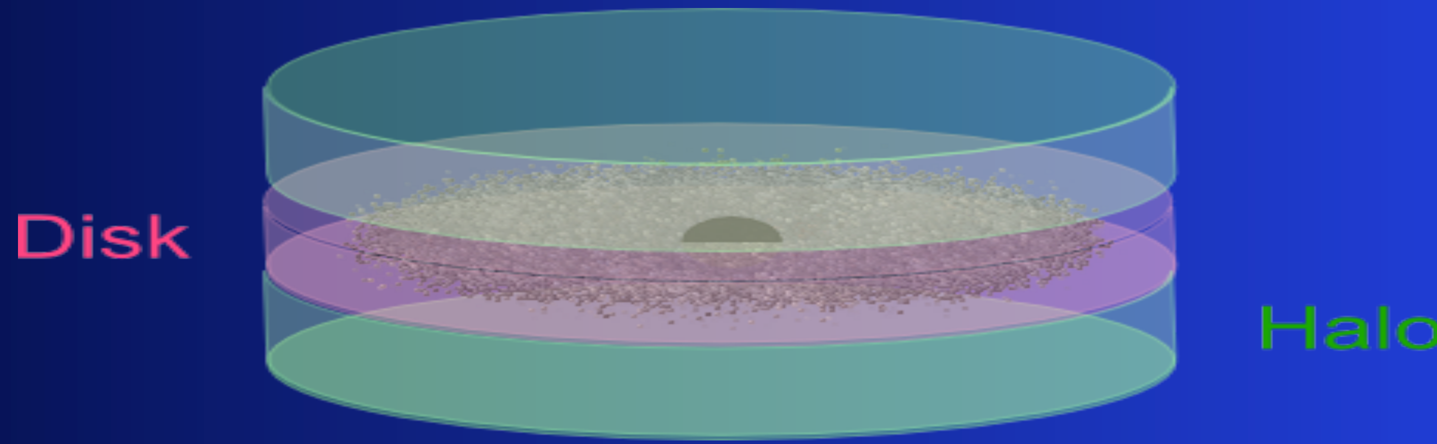


The work meant the crisis of the existing models of CR isotropization!

Detailed calculations in AL16 show that "leaky box" model is valid if it is accounted that scattering is by weak turbulence and the level of turbulence in Halo is small

The model of damping by weak turbulence is used

The turbulence level was estimated using $\epsilon_{turb.dissipation} < radiation\ \ cooling$



CRs stream in the disk where turbulence is transAlfvenic and randomize by streaming instability in the halo. Streaming CR and not turbulence dissipation is the source of halo healing.

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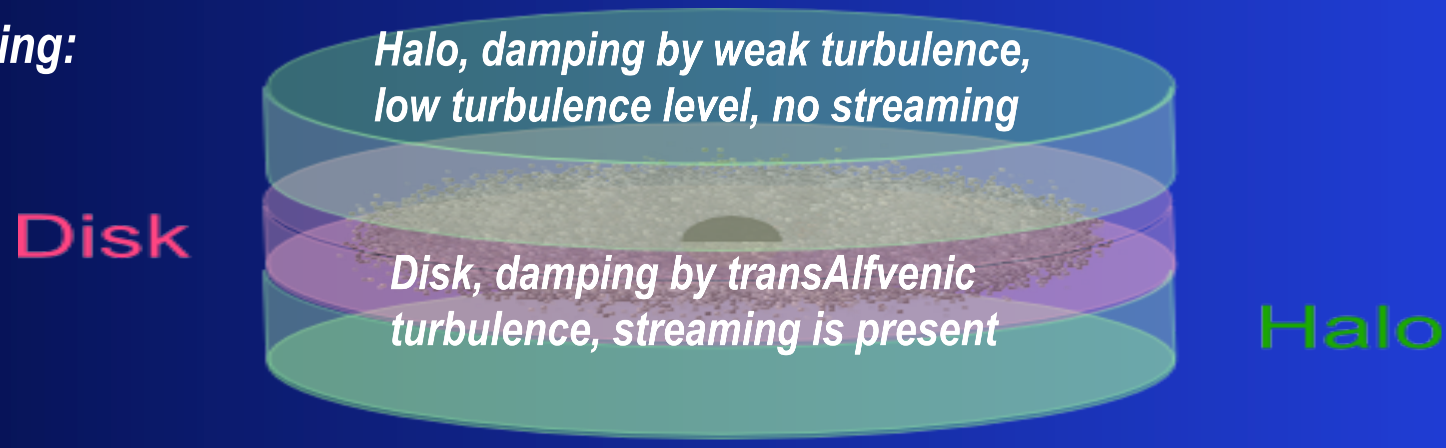
New understanding:



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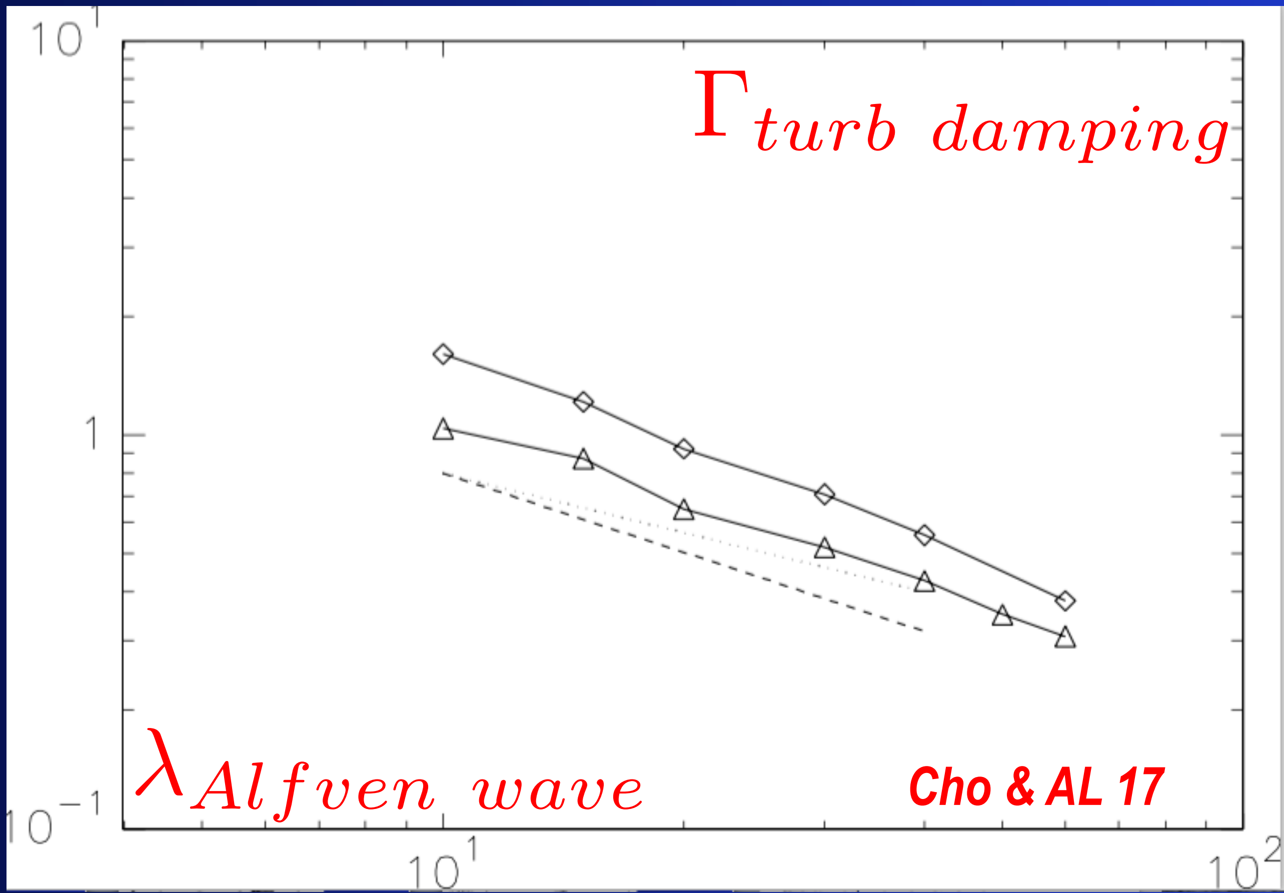
Numerical simulations confirm the AL16 scaling of the Alfven wave damping



Summary

1. *Alfvenic turbulence, turbulent reconnection, superdiffusion, turbulent damping of Alfven waves, turbulent dynamo are closely interrelated processes*
2. *For CRs these processes change radically the existing paradigms*
3. *Theories of propagation and acceleration of CRs is subject to serious revisions*