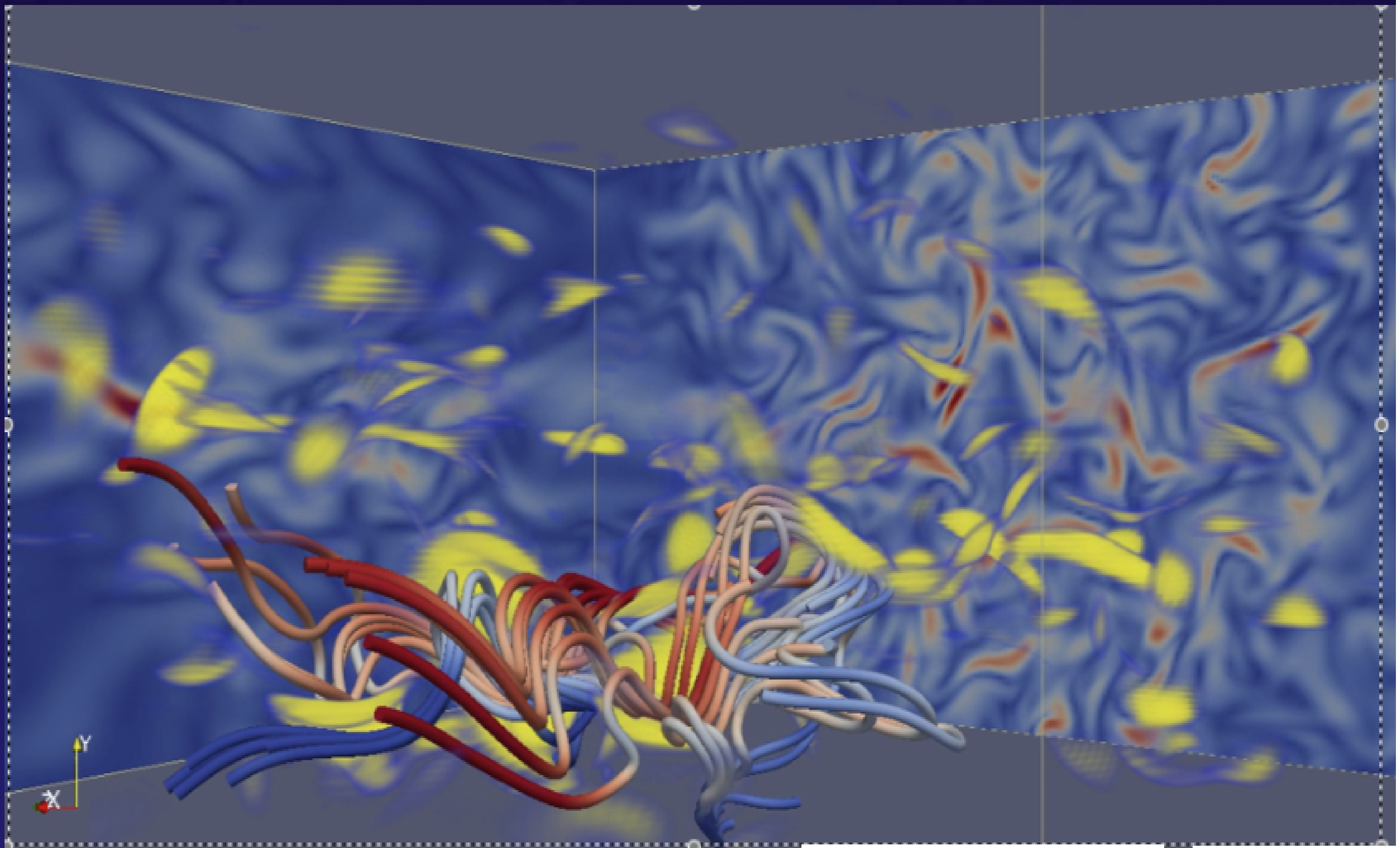
Understanding Connection between Turbulence and Energetic Particles



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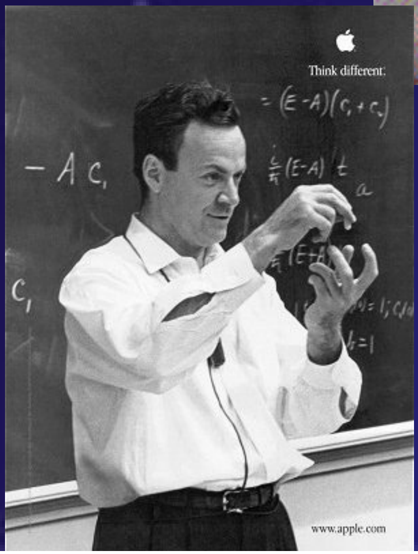
Alexander von Humboldt Stiftung/Foundation

THE UNIVERSITY of WISCONSIN MADISON

This talk shows that turbulence dramatically changes CR physics, makes 7 points:

- Turbulence is a natural state of fluids around us
- Turbulence is everywhere in astrophysical fluids
- Turbulence theory has been altered in the last decade
- Turbulence theory changes induce changes of CR paradigm
- Turbulence-precursor interaction changes shock acceleration
- Turbulence induces fast magnetic reconnection
- Turbulent reconnection induces First order Fermi acceleration

Turbulence is both dynamically and scientifically important



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

R. Feynman

7 points of the talk:

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Point I. Turbulence is natural for fluids in motion

By Jayalakshimi Satyendra

Our world depends on fluids being turbulent

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 is a chaotic order

Turbulence = Σ eddies

Reynolds number gauges the relative importance of inertia and viscous terms

- Reynolds number: $Re = VL/\nu$ ← $(V^2/L) / (\nu V/L^2)$

$$\frac{\partial \mathbf{v}}{\partial t} = -(\mathbf{v} \cdot \nabla)\mathbf{v} + \nu \nabla^2 \mathbf{v}$$

$(\mathbf{v} \cdot \nabla)\mathbf{v}$ ↑ V^2/L

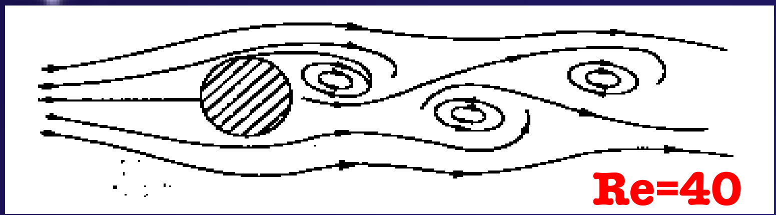
$\nu \nabla^2 \mathbf{v}$ ↑ $\nu V/L^2$

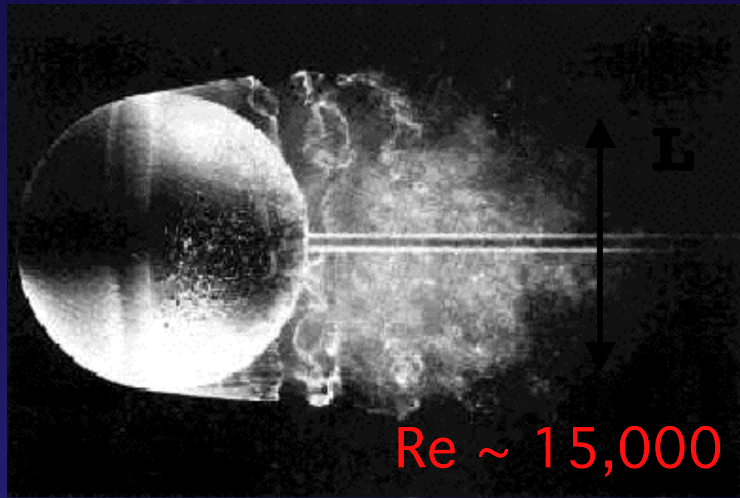
- When $Re \ll Re_{critical}$, flow = laminar

  When $Re \gg Re_{critical}$, flow = turbulent

Flows get turbulent for large Reynolds numbers

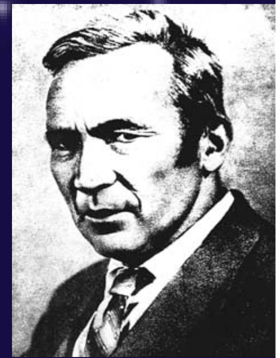
$$Re = LV/\nu = (L^2/\nu)/(L/V) = \tau_{diff}/\tau_{eddy}$$





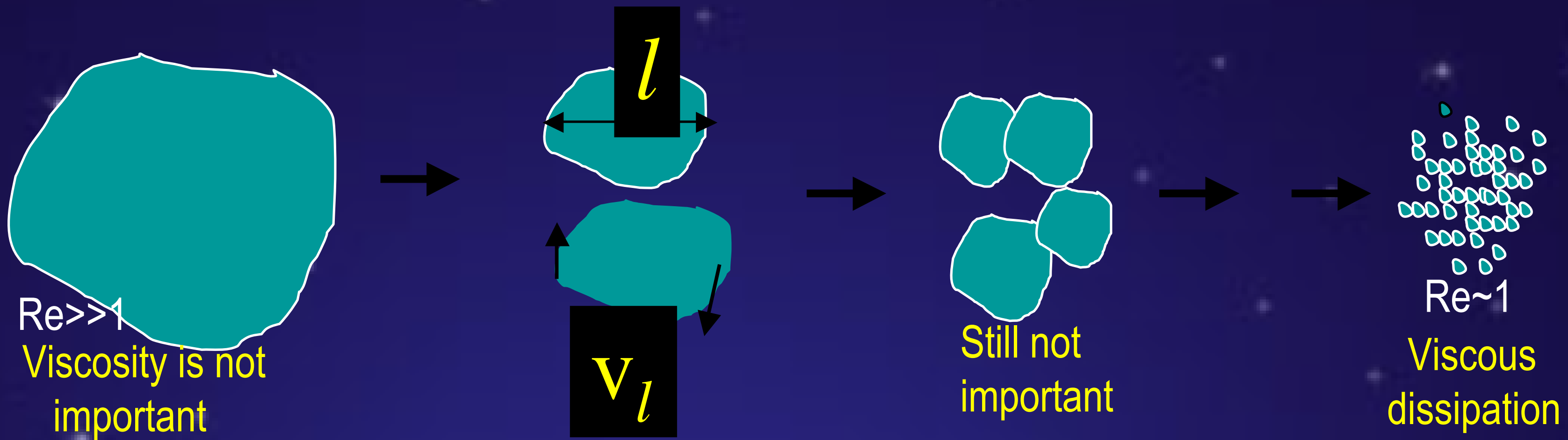
Point for numerical simulations: flows are similar for similar Re.
Numerical Re<10^{44}, while Re of astro flows > 10^{10}

Kolmogorov theory reveals order in chaos for incompressible hydro turbulence



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

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



Take home message 1:

- We live in turbulent world
- Re number is important for flows
- Statistical describtion of turbulence is possible

7 points of my talk:

- Turbulence is a natural state of fluids around us
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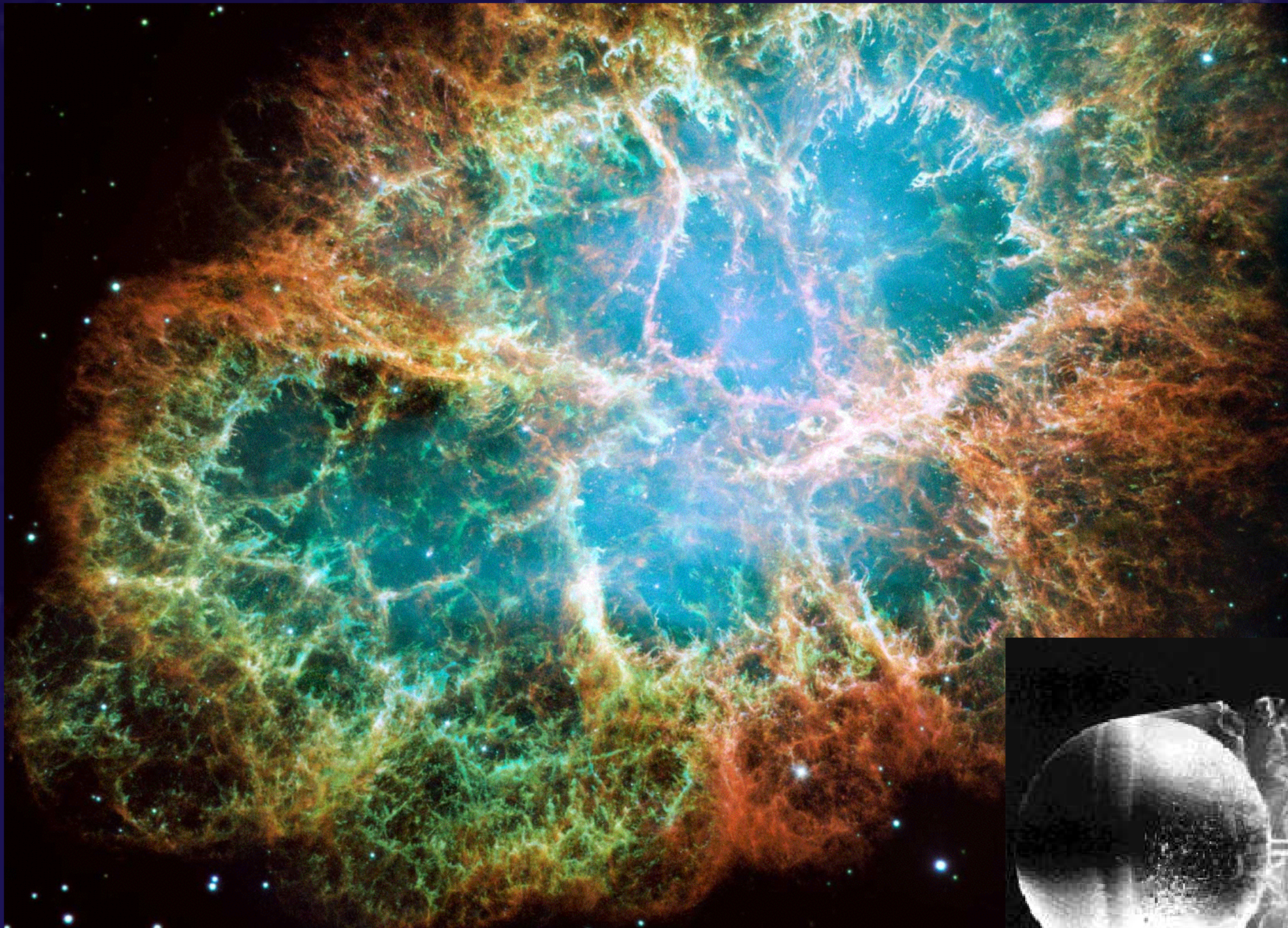
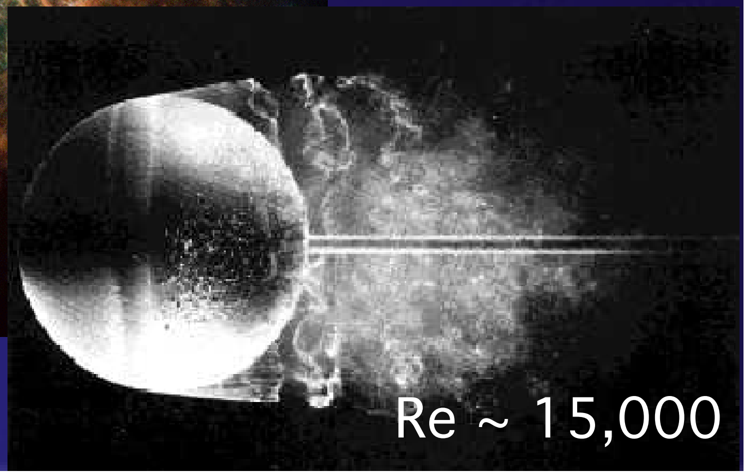
Point 2. Astrophysical fluids are turbulent as Reynolds numbers of flows are high



Astrophysical flows have Re>10^{10}.

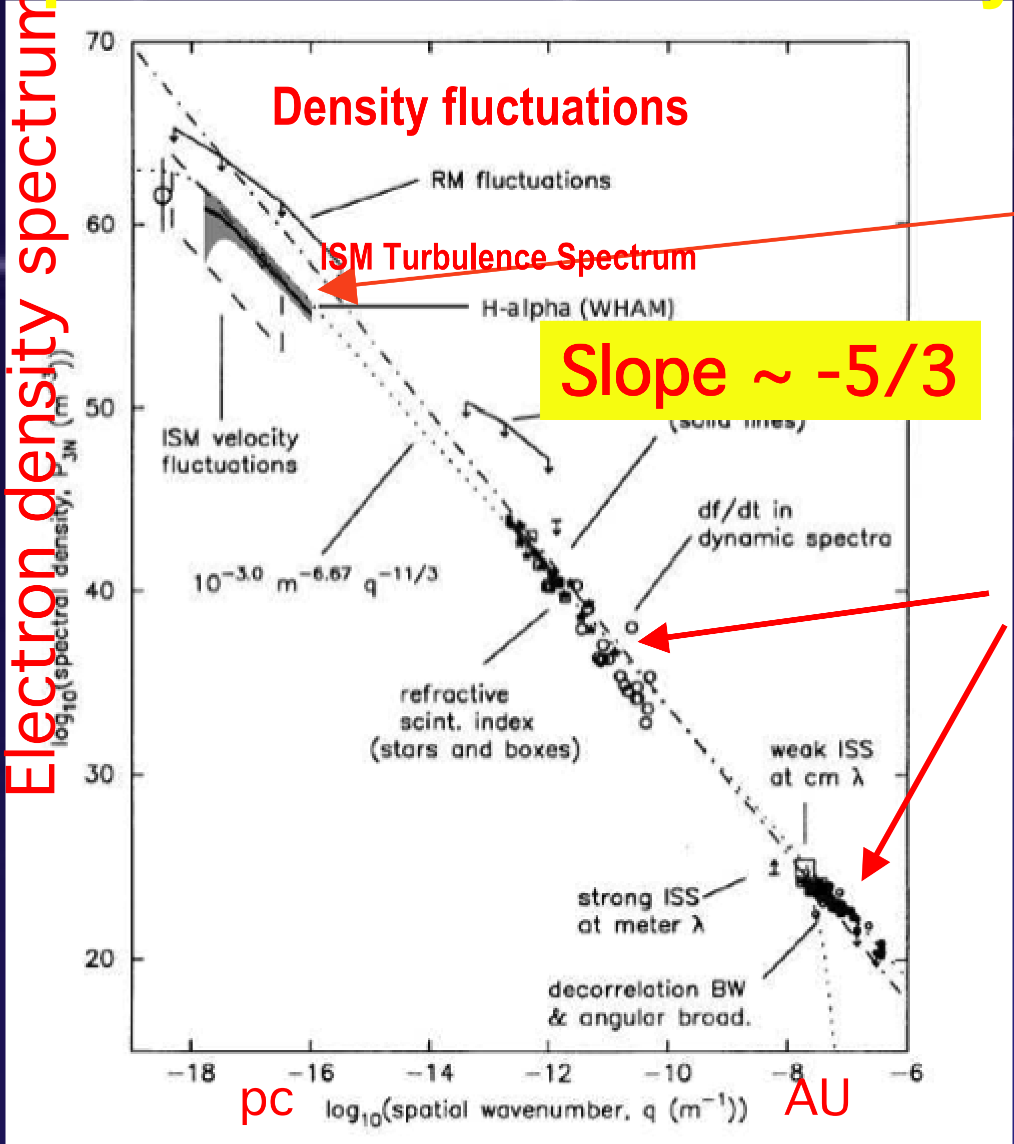


Astrophysical fluids are magnetized and turbulent, but astrophysicists resisted for years to accepting this fact

Reasons:

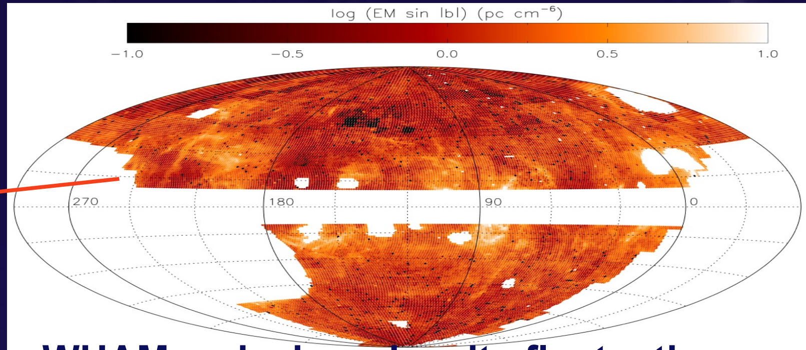
- Postulate. A theorist is able to explain any data irrespectively whether the data are right or wrong.
- Lemma 1. If something in astrophysics does not make sense the solution is through appealing to magnetic fields.
- Lemma 2. If magnetic field have been appealed to but it still does not make sense, appeal to turbulent magnetic fields.
- “Conclusion”: Try to avoid both magnetic field and turbulence!

Big Power Law in the Sky reveals Kolmogorov spectrum of electron density fluctuations



Chepurnov & Lazarian 2010

Fig. 5.— WHAM estimation for electron density overplotted on the figure of the Big Power Law in the sky figure from Armstrong et al. (1995). The range of statistical errors is marked with the gray color.



WHAM emission: density fluctuations

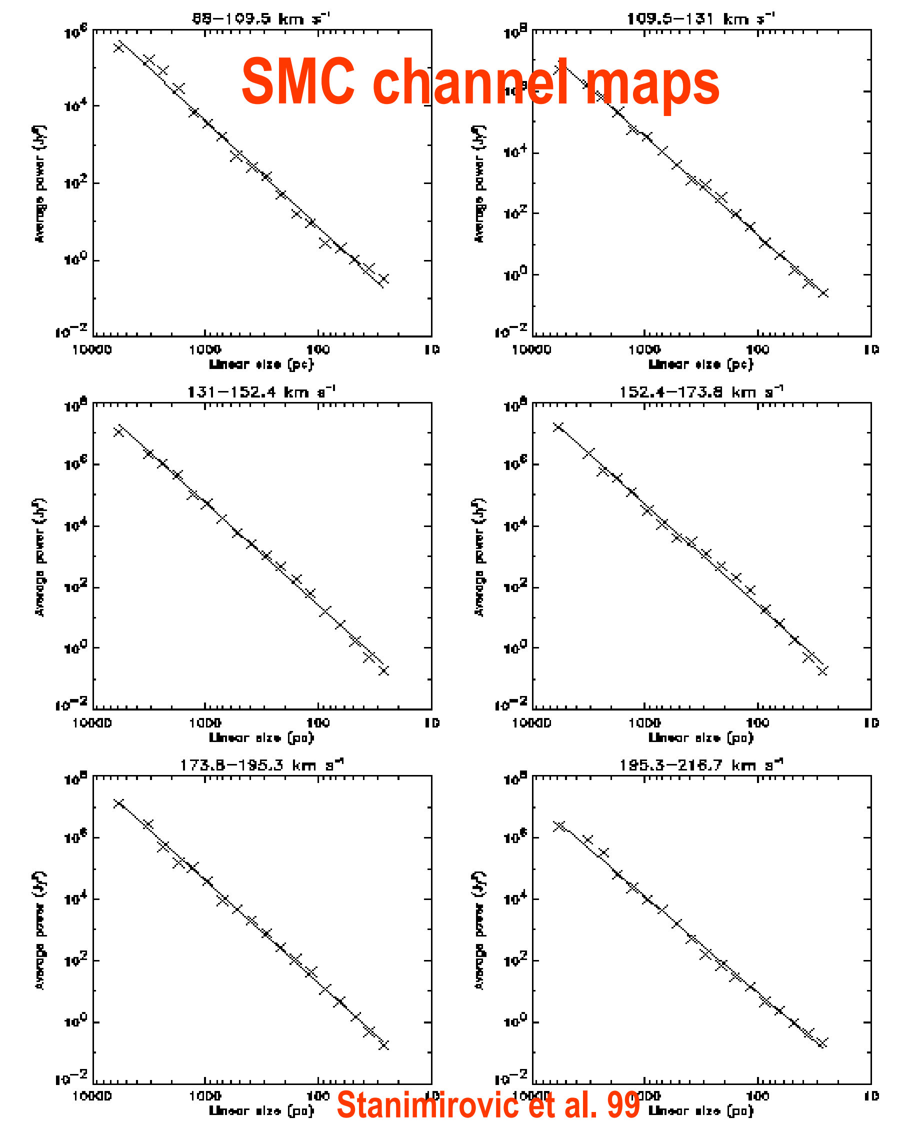
Scincillations and scattering

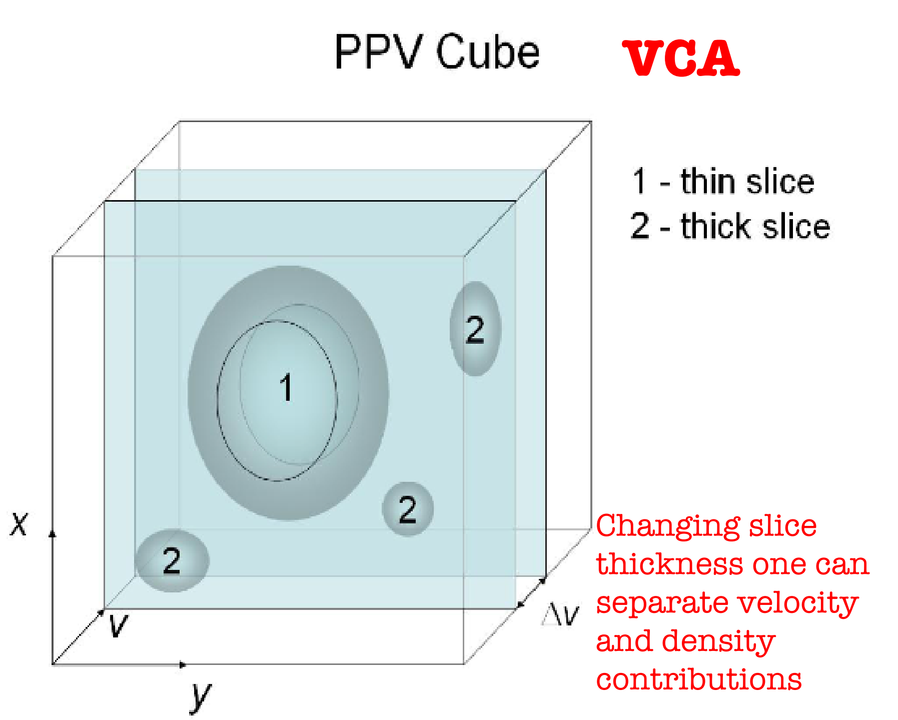
from Armstrong, Rickett & Spanger 1994

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

Kolmorogov law for turbulence

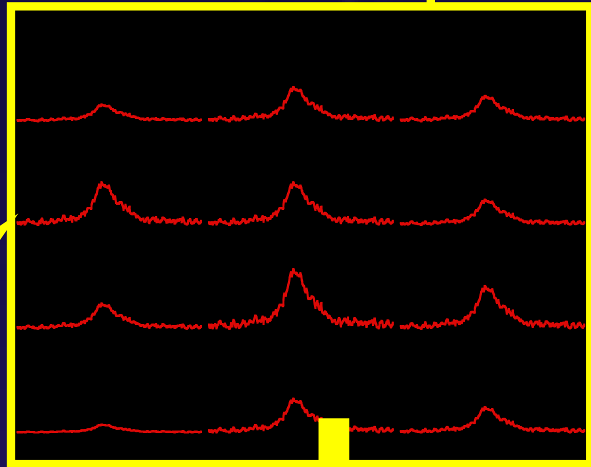
Spectra of HI channel maps reveals power law fluctuations

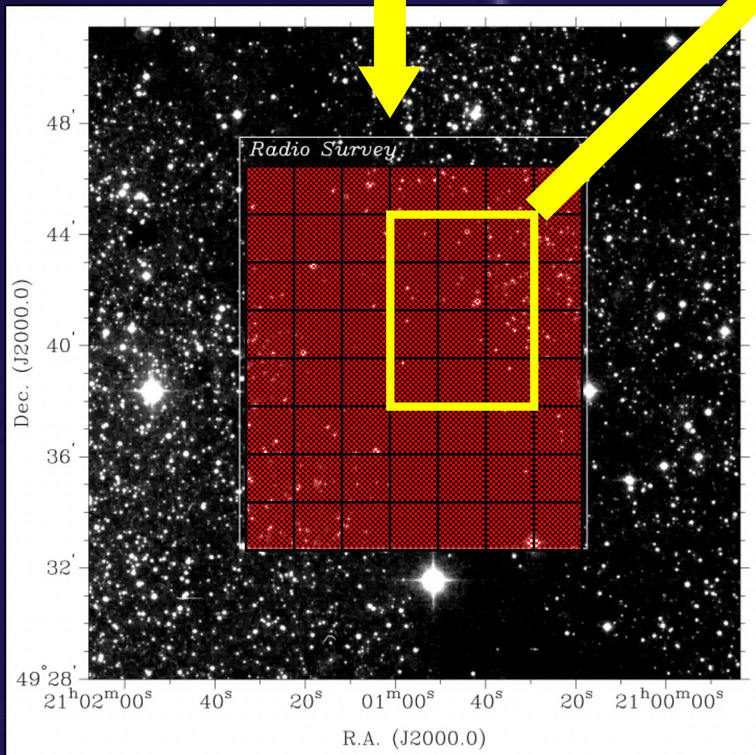


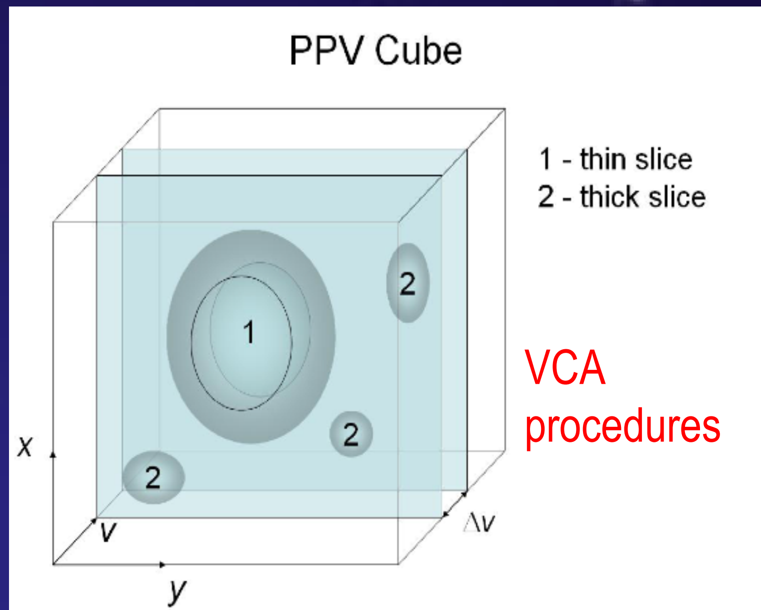


Can be dealt with the VCA technique by Lazarian & Pogosyan (00, 04)

Turbulence broadens emission and absorption lines and this can be used to study turbulence with VCA techniques

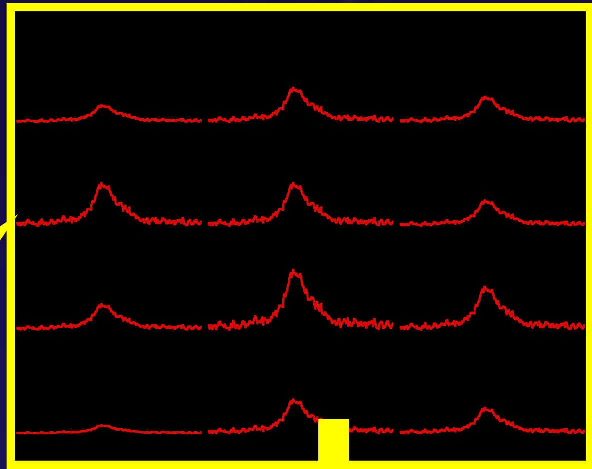


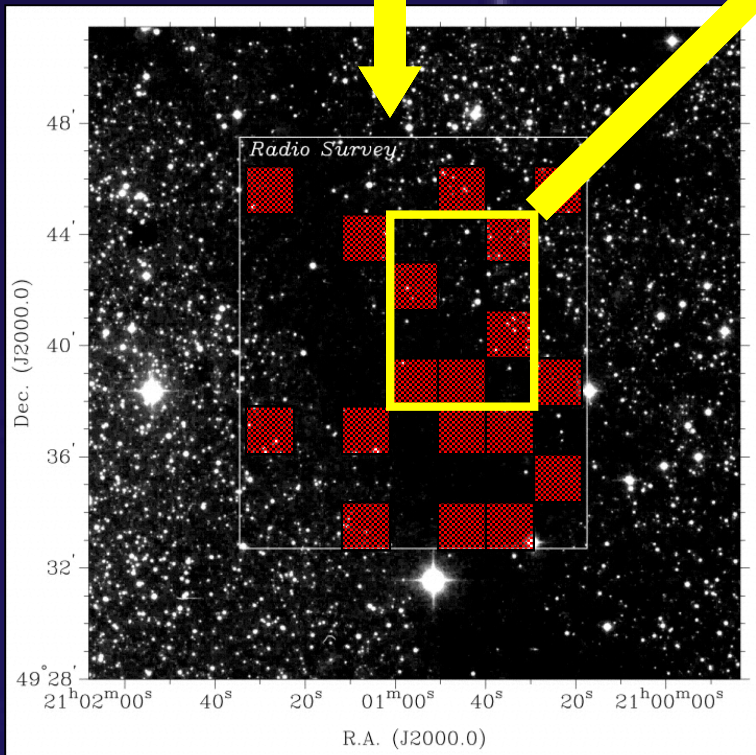


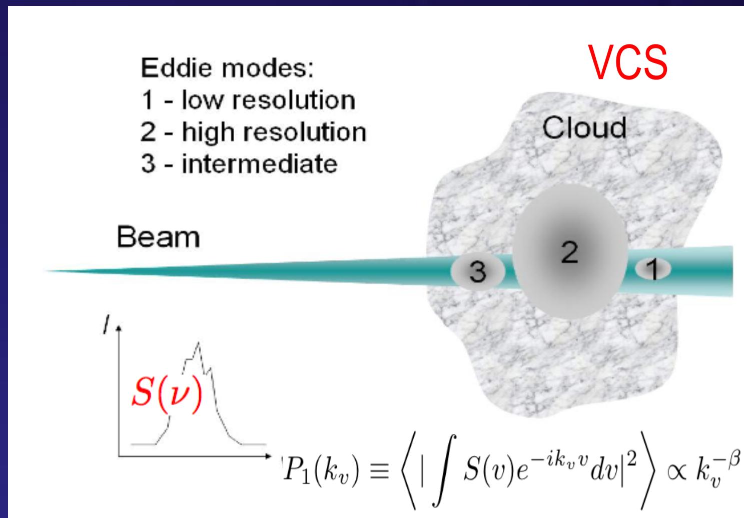


Developed in Lazarian & Pogosyan 00, 04

Sparsely sampled data can be studied with our VCS techniques

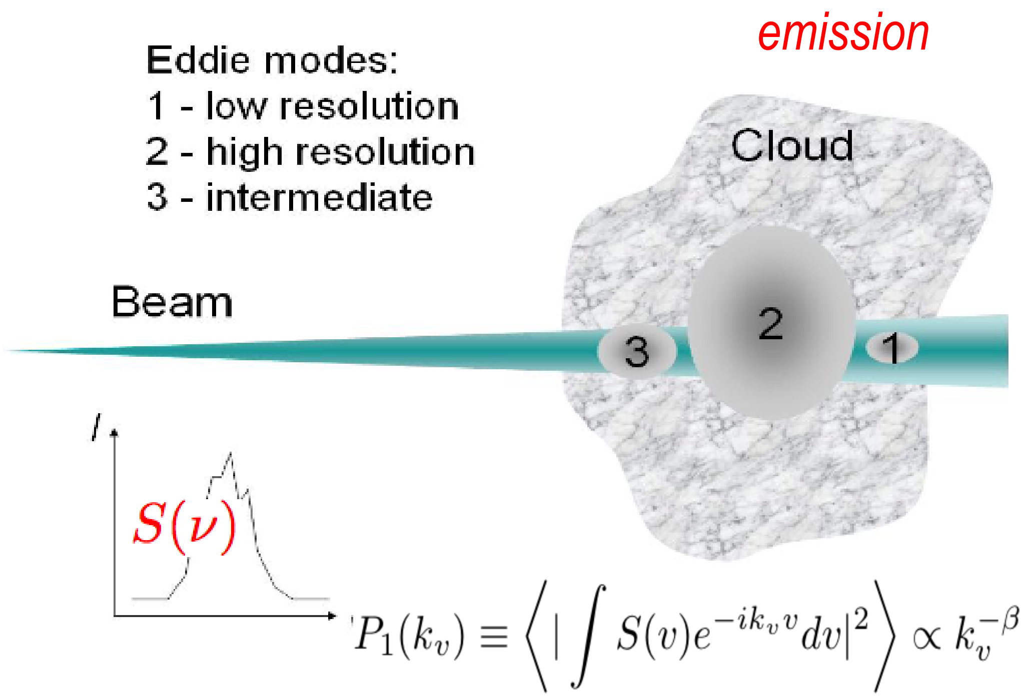






Developed in Lazarian & Pogosyan 06, 08

The relations of the spectral index of fluctuations along V-axis and the underlying velocity and density spectra were obtained



$$P_1(k_v) \equiv \left\langle \left| \int S(v) e^{-ik_v v} dv \right|^2 \right\rangle \propto k_v^{-\beta}$$

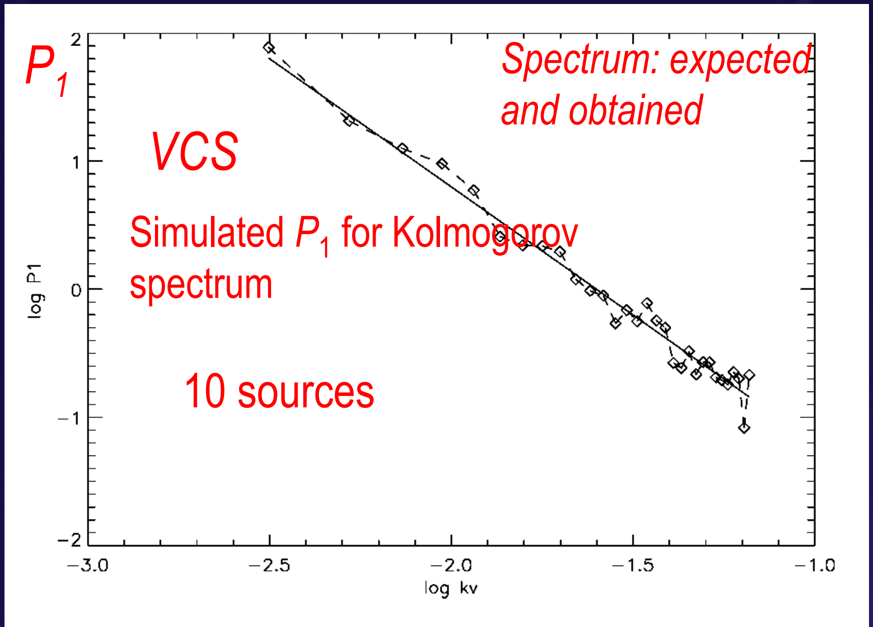
VCS is a new technique in Lazarian & Pogosyan 06, 08. Can work for resolved and unresolved objects.

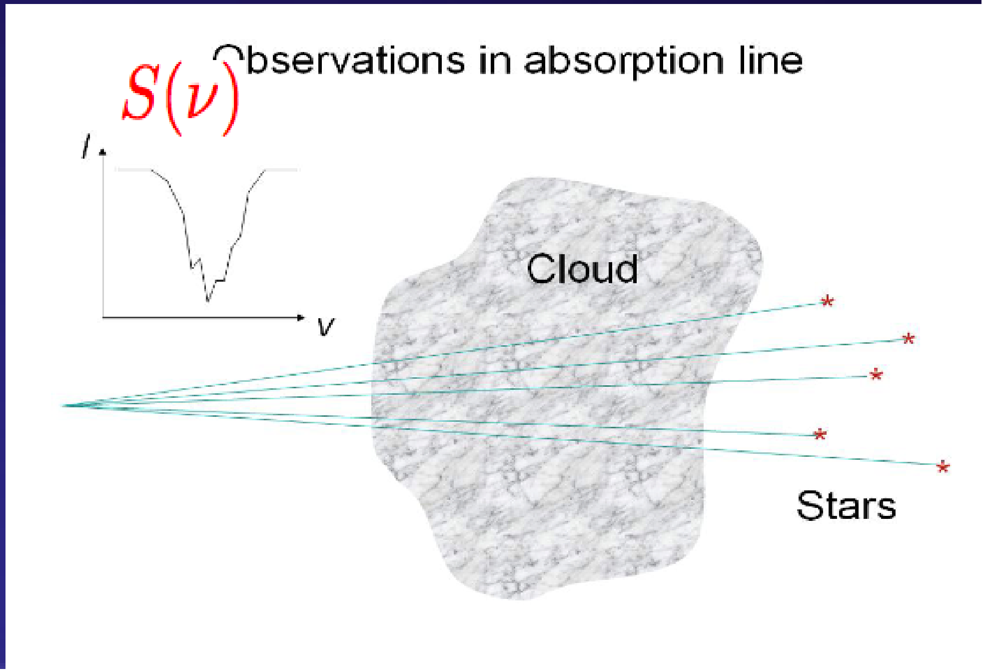
$\gamma < 0$

LOS geometry	high resolution		low resolution
	pencil beam	flat beam	
parallel	2(1+γ)/*m*	2(2+γ)/*m*	2(3+γ)/*m*
crossing	2(1+γ)/*m*	(not a power law)	2(2+γ)/*m*

$\gamma = 0$ *for steep density*

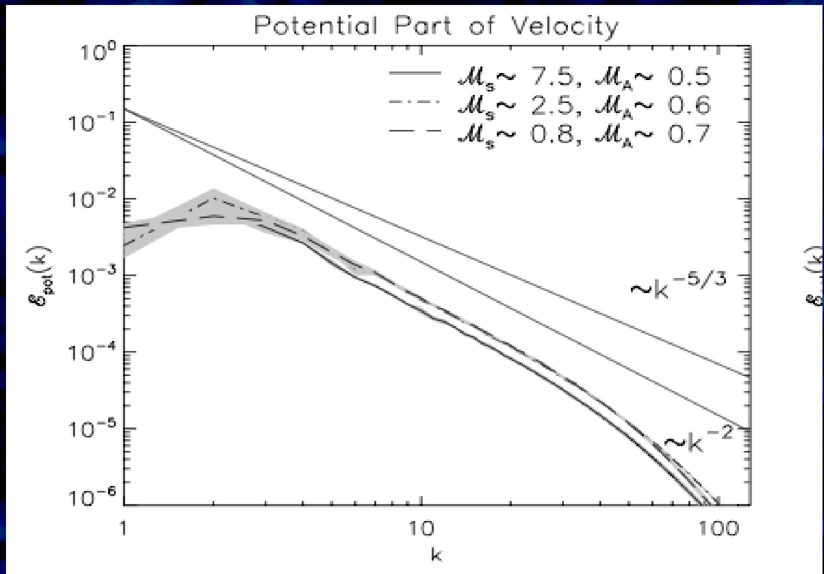
The VCA technique is also applicable to absorption lines



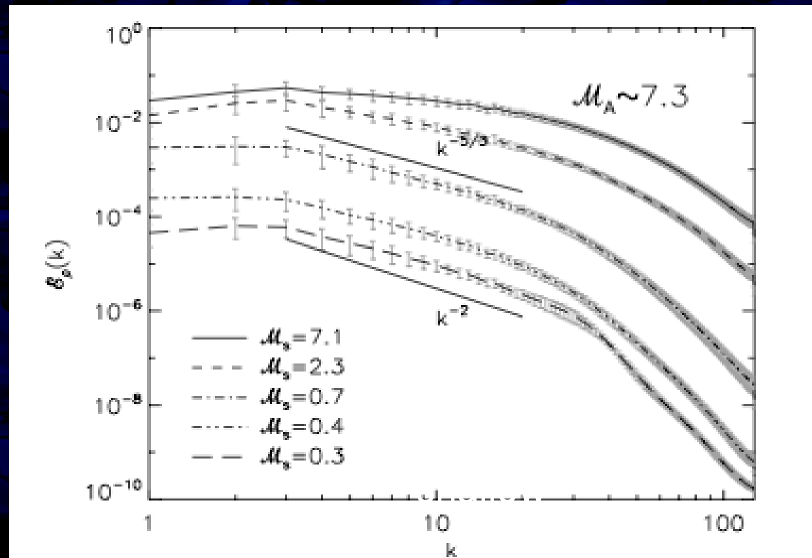


VCA and VCS techniques (Lazarian & Pogosyan 00, 04, 06, 08) reveal turbulence velocity spectra in agreement with expectations for supersonic turbulence

Expectations for supersonic turbulence



Kowal & Lazarian 2010



Kowal, Lazarian & Beresnyak 2007

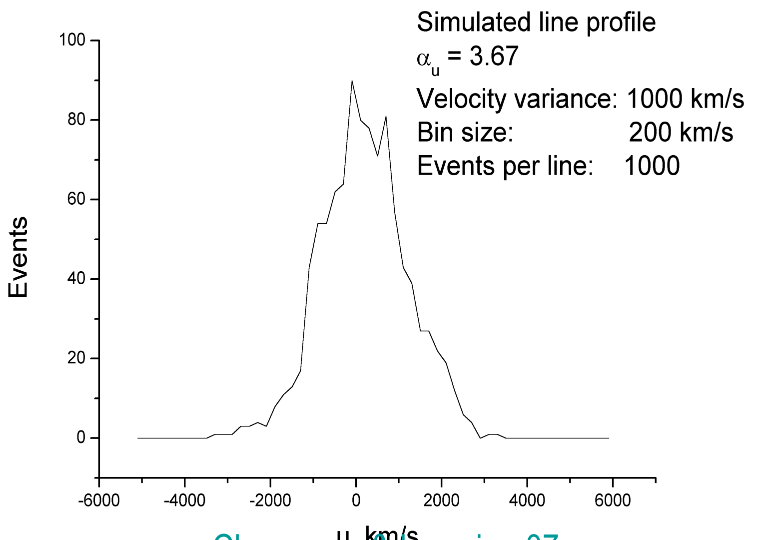
VCS gets

for high latitude galactic HI $E_v \sim k^{-1.87}$ (Chepurnov et al.08,10)

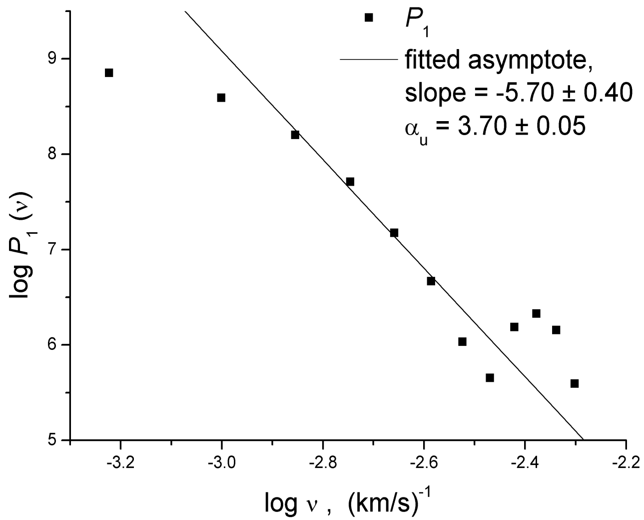
for ^{13}CO for the NGC 1333 $E_v \sim k^{1.85}$ (Padoan et al. 09)

indicating supersonic turbulence. Density is shallow $\sim k^{-08}$

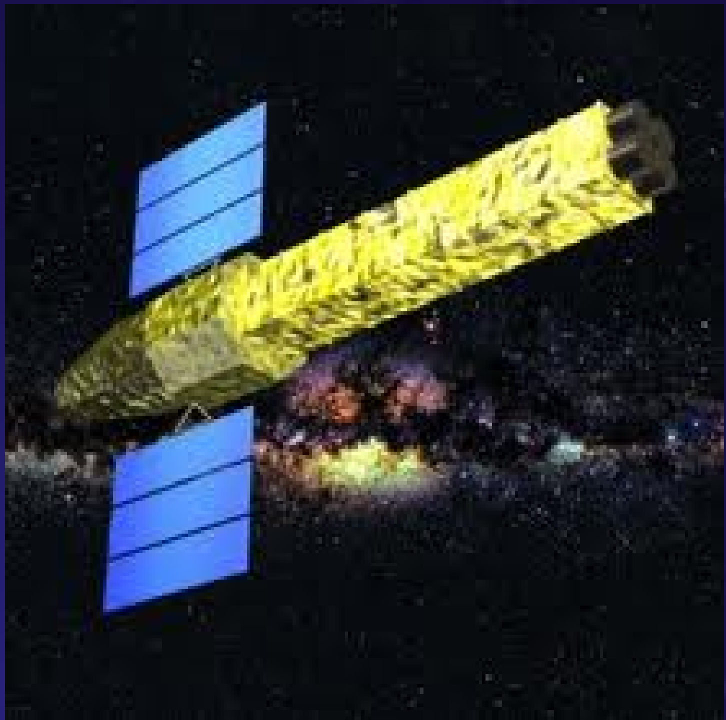
VCA technique is promising for studying galaxy clusters with Astro-H and other future X ray spectroscopic missions



Chepurnov & Lazarian 07



Lazarian & Pogosyan 2006
Chepurnov & Lazarian 2010



Astro-H would get turbulent spectra with VCS technique in 1 hour

Take home message 2:

- Astrophysical fluids are turbulent
- Turbulence is preexisting
- Turbulent velocities can be measured with new techniques

7 points of my talk:

- Turbulence is a natural state of fluids around us
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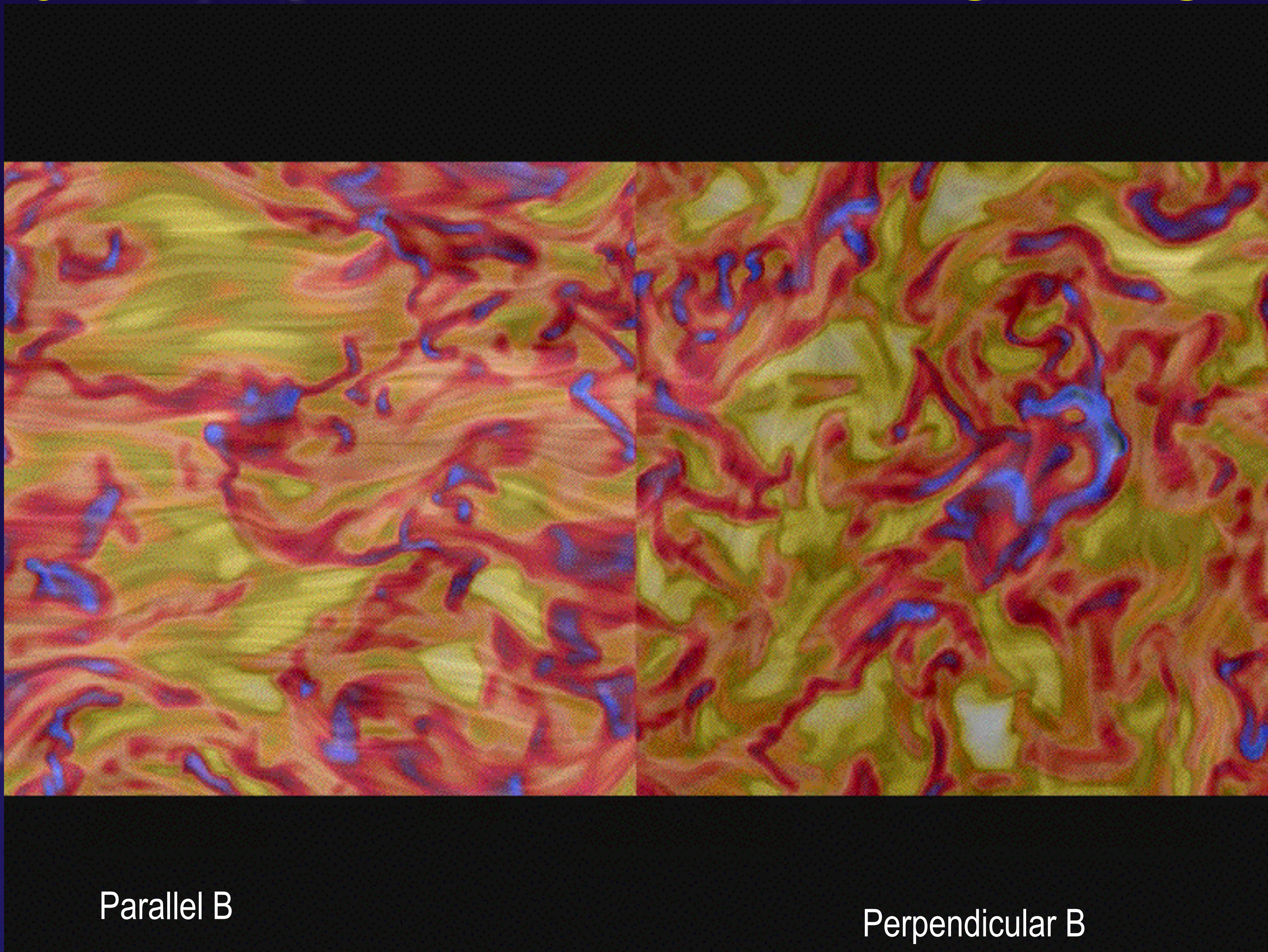
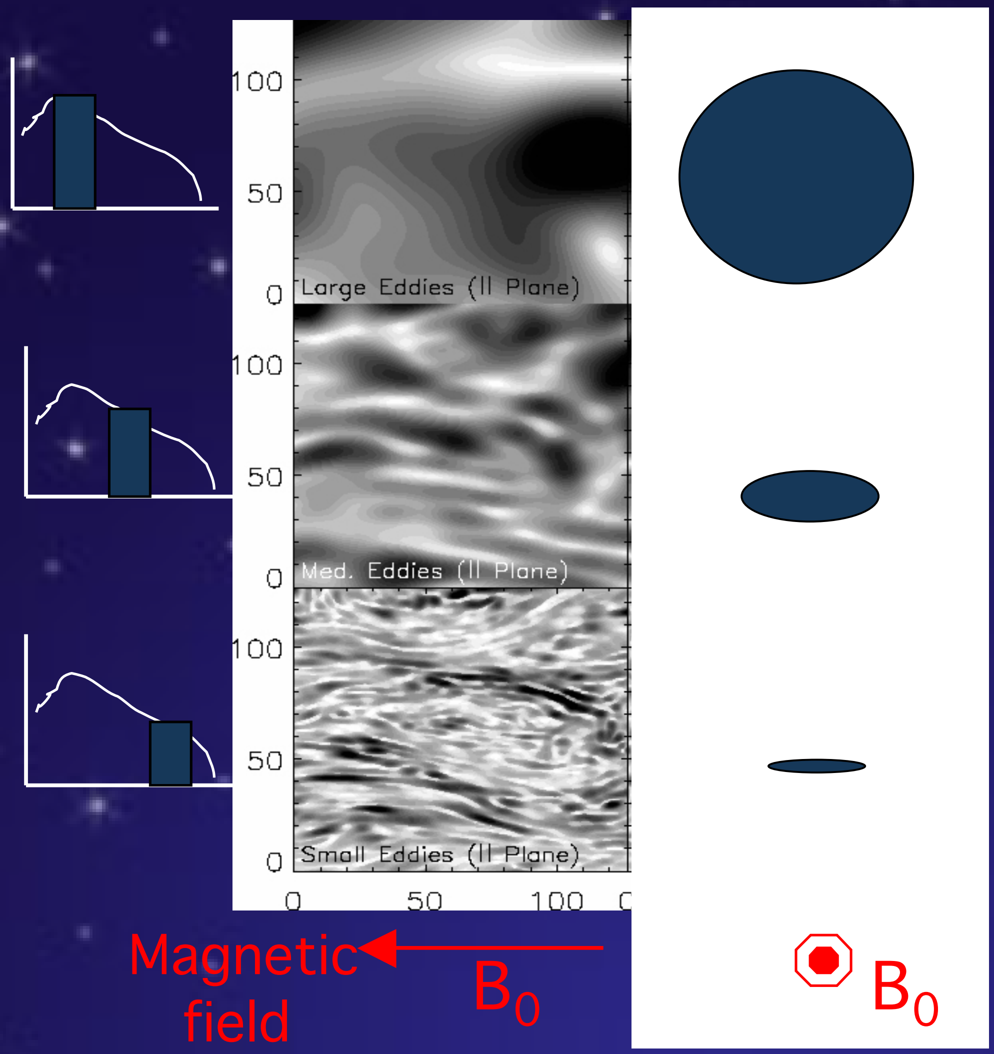
Point 3. MHD turbulence theory has been formulated recently with MHD simulations providing testing



512^3

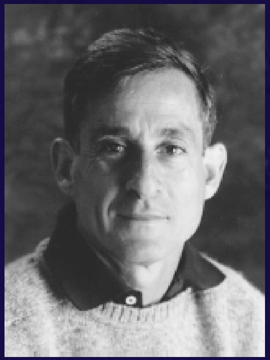
Kowal & Lazarian 2010

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



Cho, Lazarian & Vishniac 2003

Strong MHD turbulence is characterized by a “critical balance”.



- Critical balance

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

- Constancy of energy cascade rate

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

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

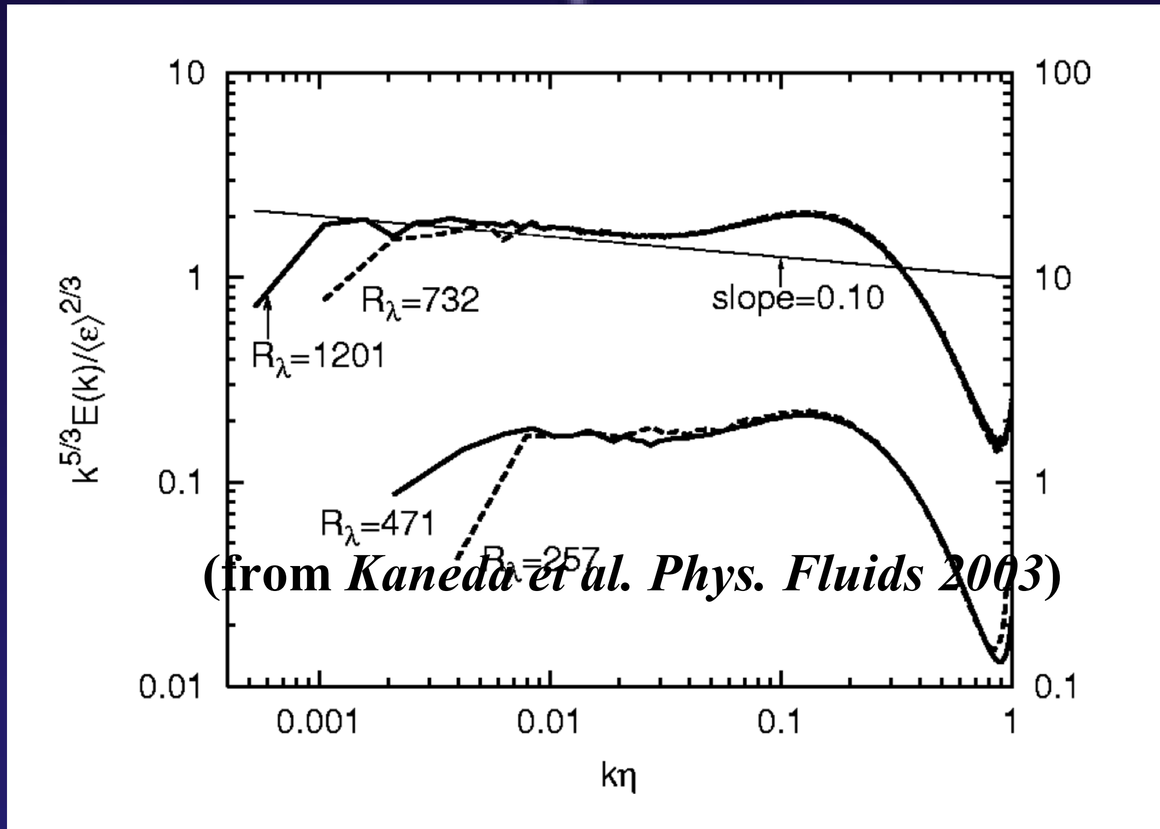
$$b_\perp \sim l_\perp^{1/3}$$

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

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

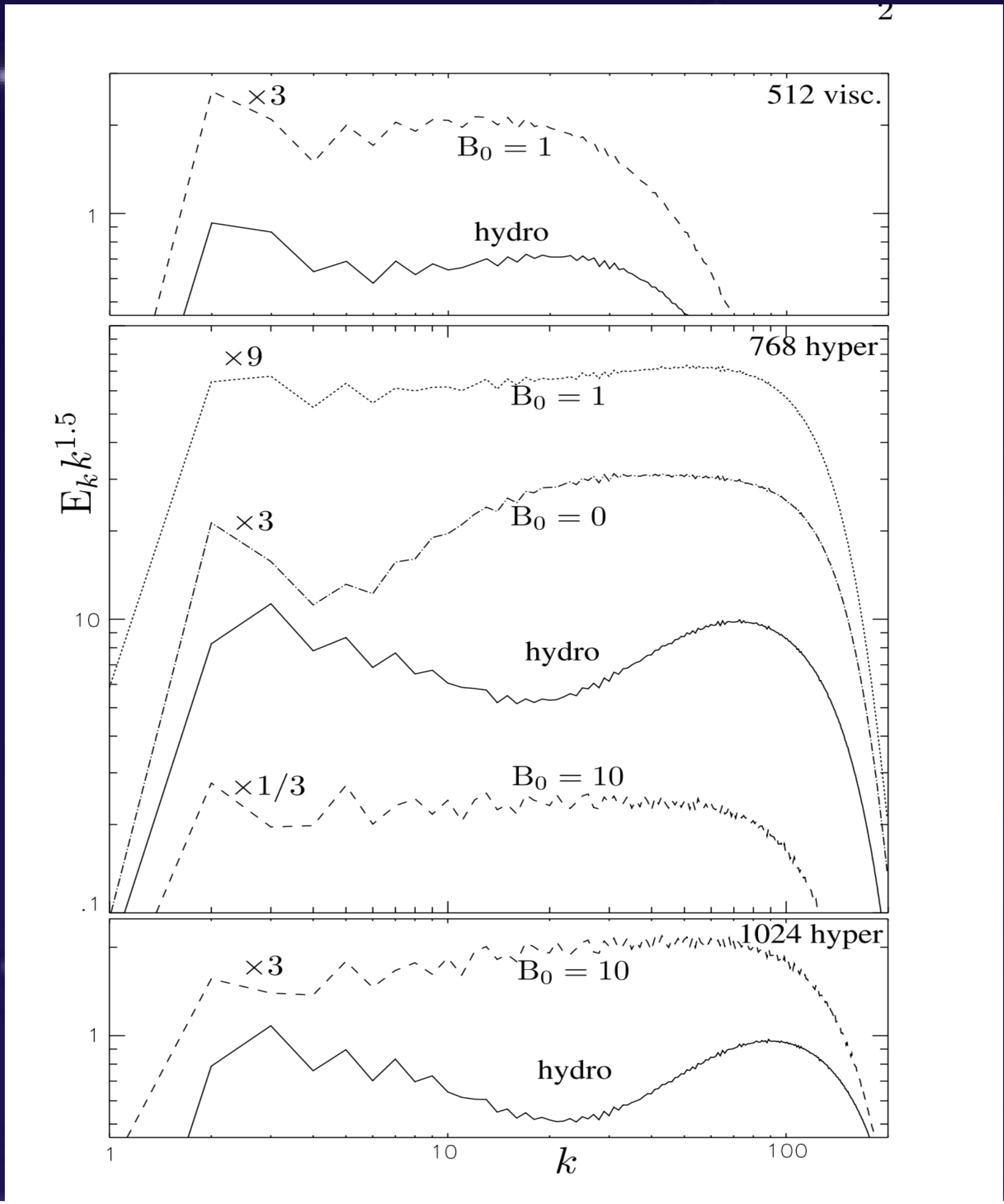
Goldreich-Sridhar model (1995)

It is difficult to find the actual spectral slope because of the bottleneck effect which is present



(from *Kaneda et al. Phys. Fluids 2003*)

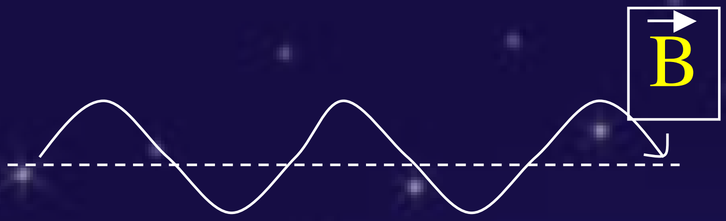
MHD simulations are broadly consistent with -5/3



GS 95 theory predicts -5/3 for incompressible MHD. Testing for compressible are in Cho & Lazarian 2002, Kowal & Lazarian 2010.

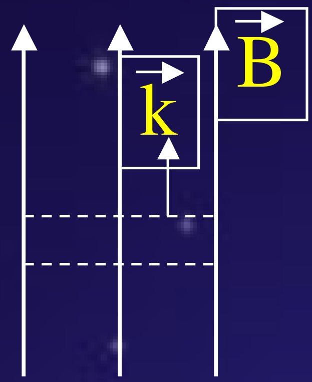
Beresnyak & Lazarian 2010

Simple considerations give hope that compressible MHD turbulence can be understood and described



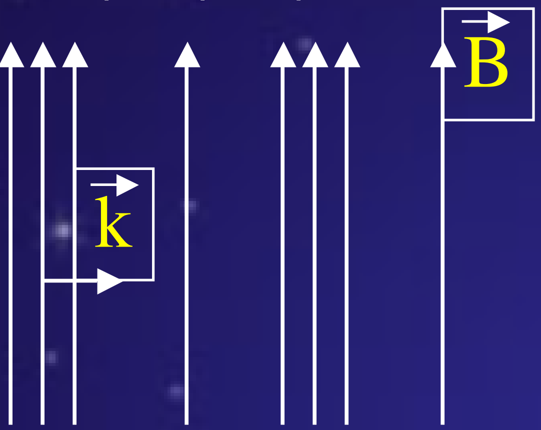
Alfven mode ($v=V_A \cos\theta$)

incompressible;
restoring force=mag. tension



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

restoring force = P_{gas}



fast mode ($v=V_A$)

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

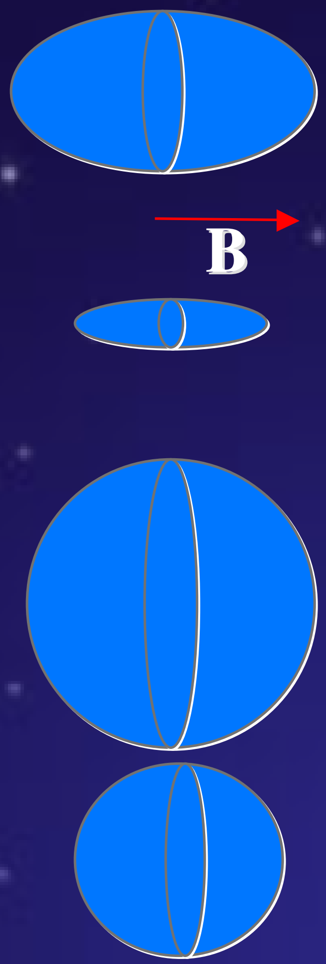
Theoretical discussion in Lithwick & Goldreich 01
Cho & Lazarian 02

For Cosmic Rays it is important that Alfvenic turbulence is anisotropic

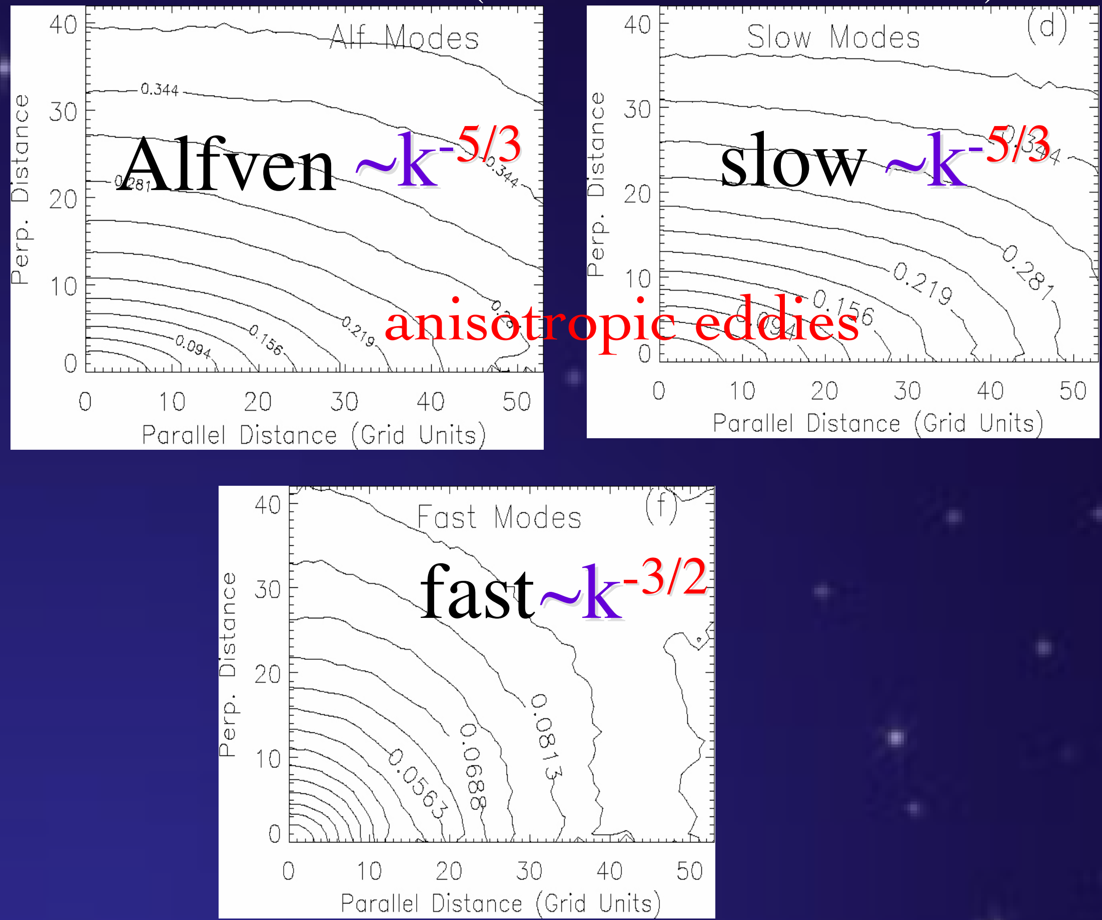
Alfven and slow modes (GS95)

$l_{||} \sim L^{1/3} l_{\perp}^{2/3}$

fast modes



Equal velocity correlation contour (Cho & Lazarian 02, 03)



Transfer of energy from Alfven modes to slow and fast modes is rather marginal for many total, i.e. $M_{total} = v/(v_A^2+v_s^2)^{1/2}$, Mach number

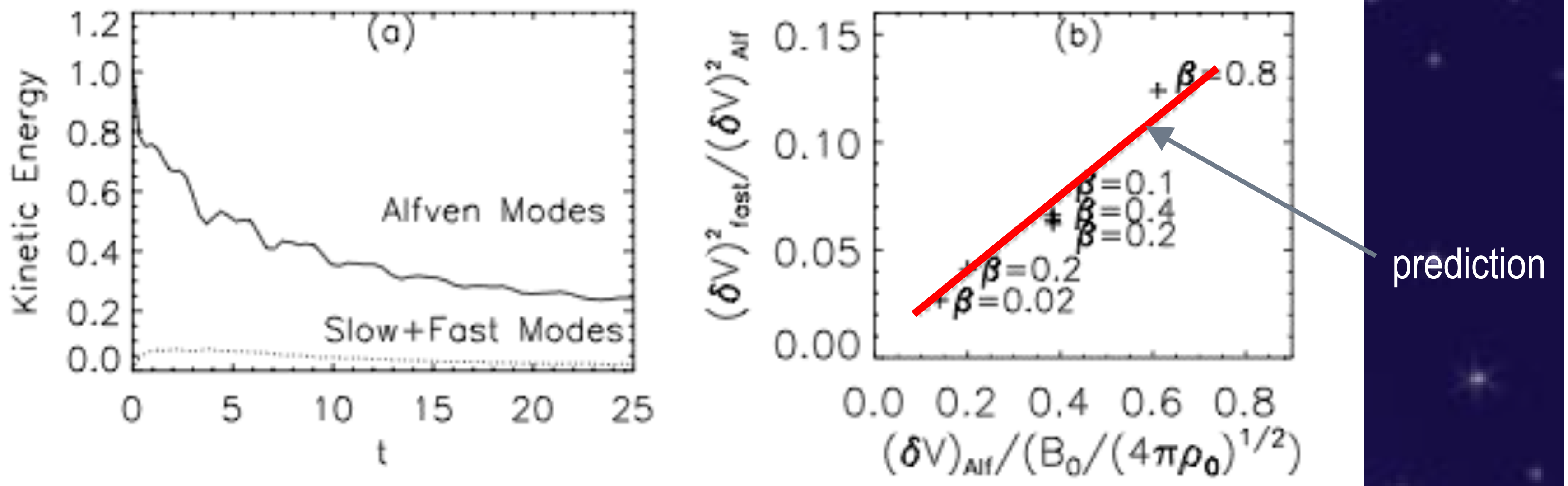


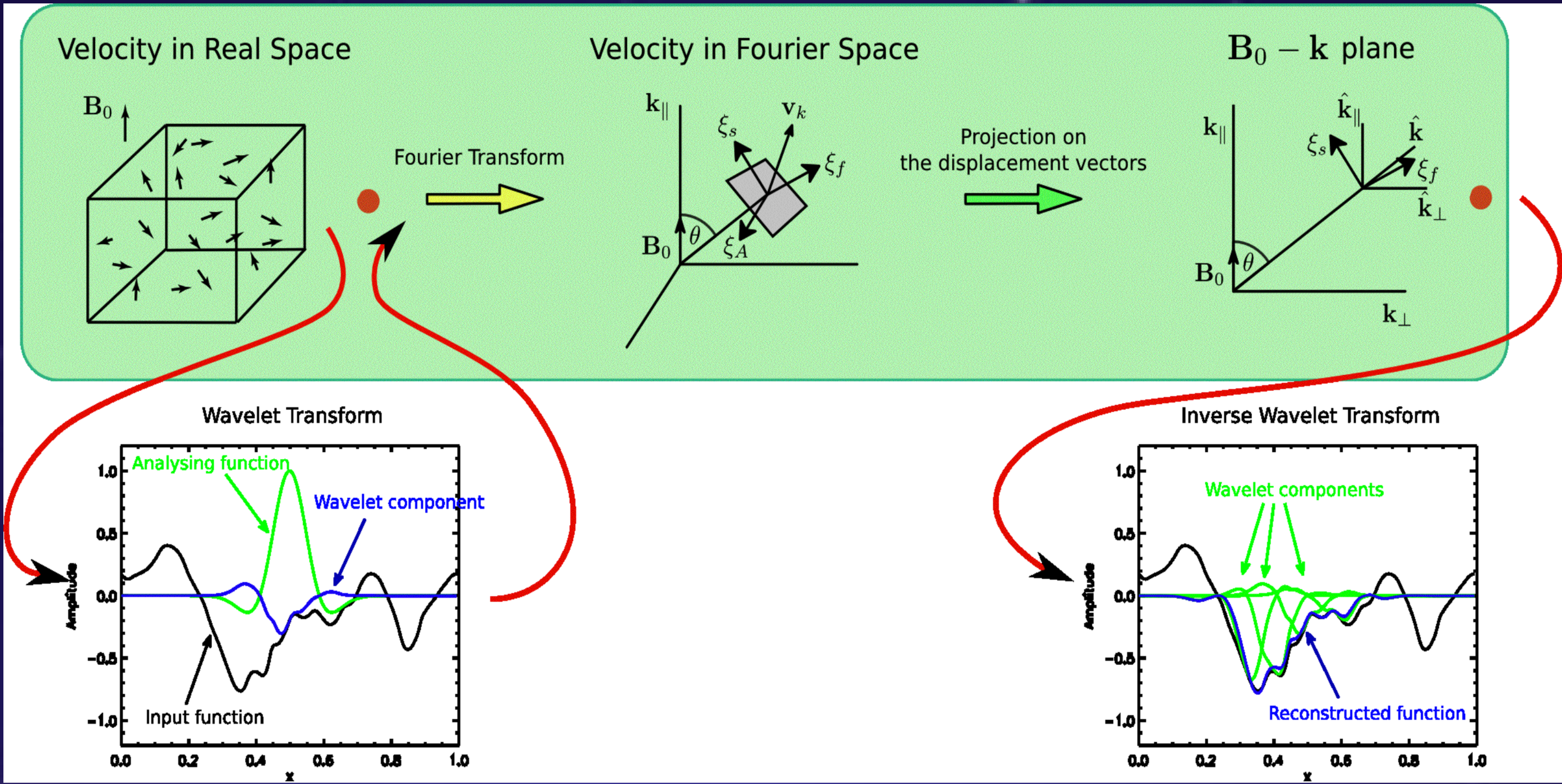
FIG. 1. (a) Decay of Alfvénic turbulence. The generation of fast and slow waves is not efficient. Initially, $\beta \sim 0.2$ and $B_0/\sqrt{4\pi\rho_0} = 1$. (b) The ratio of $(\delta V)_f^2$ to $(\delta V)_A^2$. The ratio is measured at $t \sim 3$ for all simulations. The ratio strongly depends on B_0, but only weakly on (initial) β. The initial Mach numbers span 1–4.5.

Cho & Lazarian 02

Coupling of Alfvenic, fast and slow modes is weak for M_{total}<<1 . Thus Alfvenic motions persist.

More sophisticated decomposition in Kowal & Lazarian 2010 confirms the original results by Cho & Lazarian

Kowal & Lazarian, 2010 presented an extension to Fourier-only based decomposition by Cho & Lazarian (2002) by introduction of the wavelet transformations. Before the Fourier decomposition we decompose the analyzed vector field into wavelets, then each wavelet is separated in a traditional way as described by Cho & Lazarian (2002). After the decomposition of each wavelet we obtain three sets of wavelets corresponding to the Alfven, fast and slow modes. Finally, we perform inverse wavelet transform to restore the MHD waves.



Take home message 3:

- MHD turbulence theory exists and has been tested.
- Alfven modes are very anisotropic. Fast modes are isotropic.
- GS95 theory assumes that the injection scale velocity is equal to Alfven speed. If it is less, then turbulence is initially weak up to scale l_a but gets strong. Scalings are described in Lazarian & Vishniac 1999. If the turbulence is SuperAlfenic at the injection scale, it gets Alfvenic at a smaller scale l_{trans} (see Lazarian 2006).

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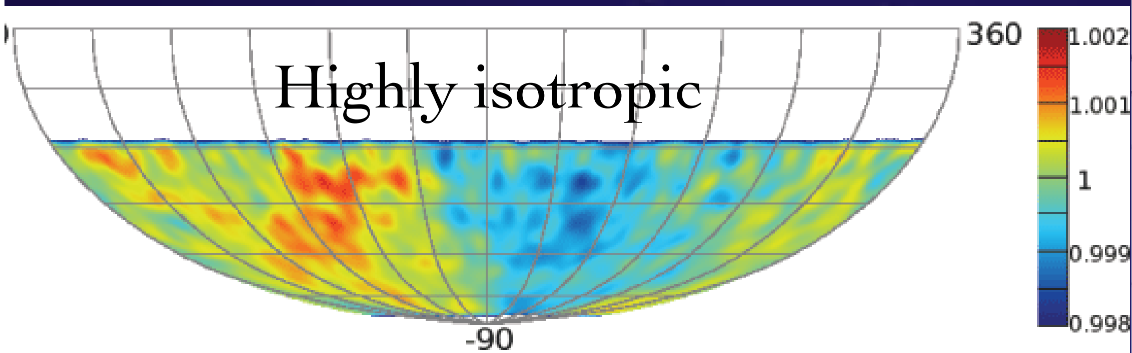
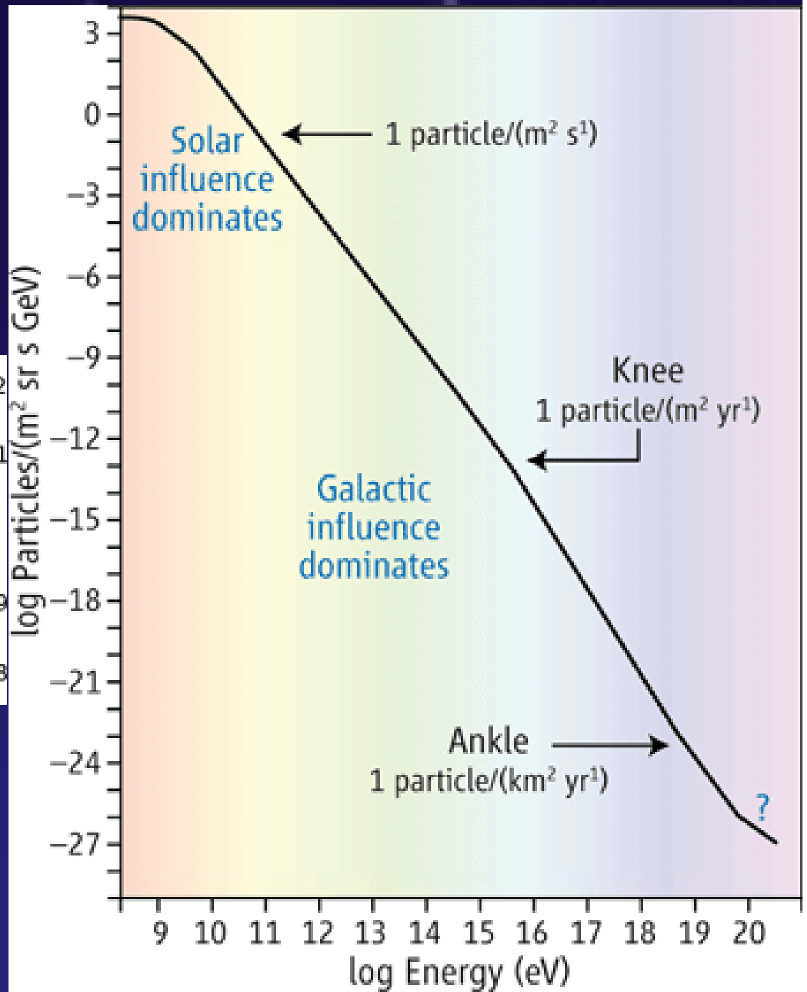
Point 4. MHD turbulence theory induces changes on our understanding of CRs propagation and stochastic acceleration



Icecube measurement 2010



M. Duldig 2006

Cosmic rays interact with magnetic turbulence

Cosmic Rays ⟷ **Magnetized medium**

In case of small angle scattering, Fokker-Planck equation can be used to describe the particles' evolution:

$$\frac{\partial F}{\partial t} + v\mu\frac{\partial F}{\partial Z} - \Omega\frac{\partial F}{\partial \phi} = S + \frac{1}{p^2}\frac{\partial}{\partial x}\left(p^2 D_{xy}\frac{\partial F}{\partial y}\right)$$

S : Sources and sinks of particles
2nd term on rhs: diffusion in phase space specified by Fokker -Planck coefficients D_{xy}

Correct diffusion coefficients are the key to the success of such an approach

$$D_{\mu\mu} \equiv \lim_{t\to\infty} \frac{1}{2t} \langle \Delta\mu(t)\Delta\mu^*(t+\tau)\rangle = \Re \int_0^\infty d\tau \langle \dot{\mu}(t)\dot{\mu}^*(t+\tau)\rangle \ ,$$

$$D_{\mu p} \equiv \lim_{t\to\infty} \frac{1}{2t} \langle \Delta\mu(t)\Delta p^*(t+\tau)\rangle = \Re \int_0^\infty d\tau \langle \dot{\mu}(t)\dot{p}^*(t+\tau)\rangle \ ,$$

$$D_{pp} \equiv \lim_{t\to\infty} \frac{1}{2t} \langle \Delta p(t)\Delta p^*(t+\tau)\rangle = \Re \int_0^\infty d\tau \langle \dot{p}(t)\dot{p}^*(t+\tau)\rangle \ ,$$

The diffusion coefficients define characteristics of particle propagation and acceleration

Propagation $\nu = 2D_{\mu\mu}/(1-\mu^2)$ $\lambda_\| = \frac{3}{4}\int d\mu \frac{v(1-\mu^2)^2}{D_{\mu\mu}}$

Stochastic Acceleration $A(E) = \frac{\partial[vp^2 D(p)]}{4p^2\partial p}$, $D(p) = \frac{1}{2}\int_{-1}^{1} D_{pp} d\mu$

$D_{\mu\mu} \longleftrightarrow \delta B$,

$D_{pp} \longleftrightarrow \delta E = \delta v \times B_0/c$

Where do δB, δv come from? MHD turbulence!

- The diffusion coeffecients are determined by the statistical properties of turbulence

For describing cosmic ray acceleration we would better use tested models of turbulence rather ad hoc ones

Ad hoc turbulence models

Slab model: Only MHD modes propagating along the magnetic field are counted.

Kolmogorov turbulence: isotropic, with 1D spectrum $E(k) \sim k^{-5/3}$

Tested models of MHD turbulence

1. Alfven and slow modes: Goldreich-Sridhar 95 scaling
2. Fast modes: isotropic, similar to accoustic turbulence

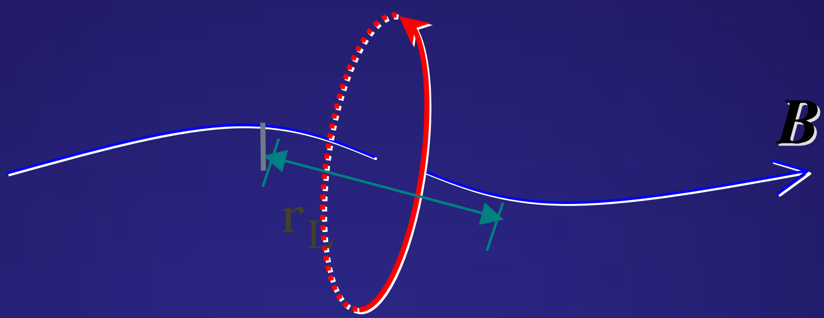
Gyroresonance scattering depends on the properties of turbulence

Gyroresonance

$\omega - k_{\parallel} v_{\parallel} = n\Omega$, $(n = \pm 1, \pm 2 \ldots)$,

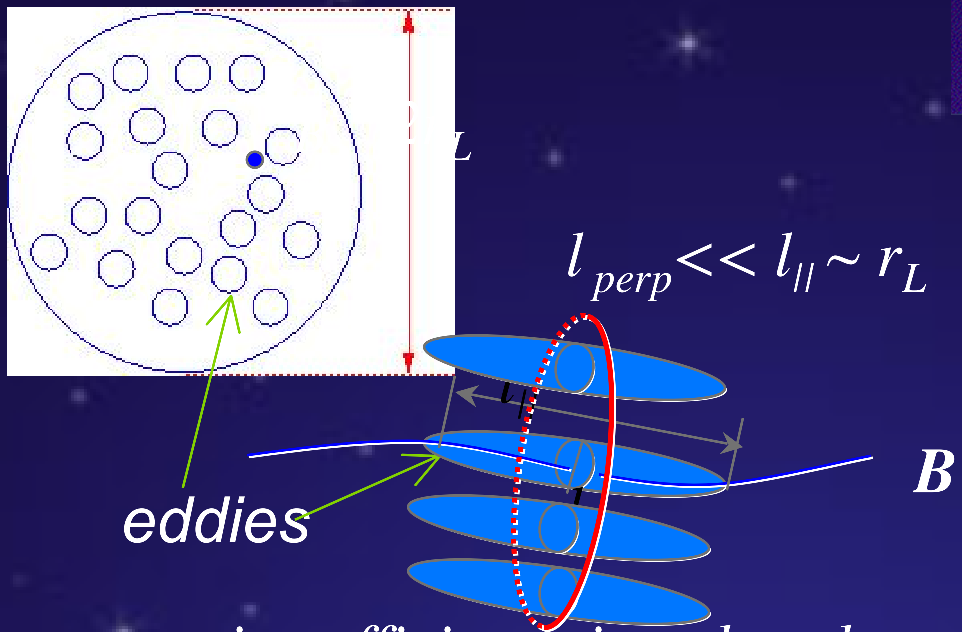
Which states that the MHD wave frequency (Doppler shifted) is a multiple of gyrofrequency of particles ($v_{\parallel}$ is particle speed parallel to B).

So, $k_{\parallel,res} \sim \Omega/v = 1/r_L$



Alfenic turbulence injected at large scales is inefficient for cosmic ray scattering/acceleration

1. "random walk"



scattering efficiency is reduced

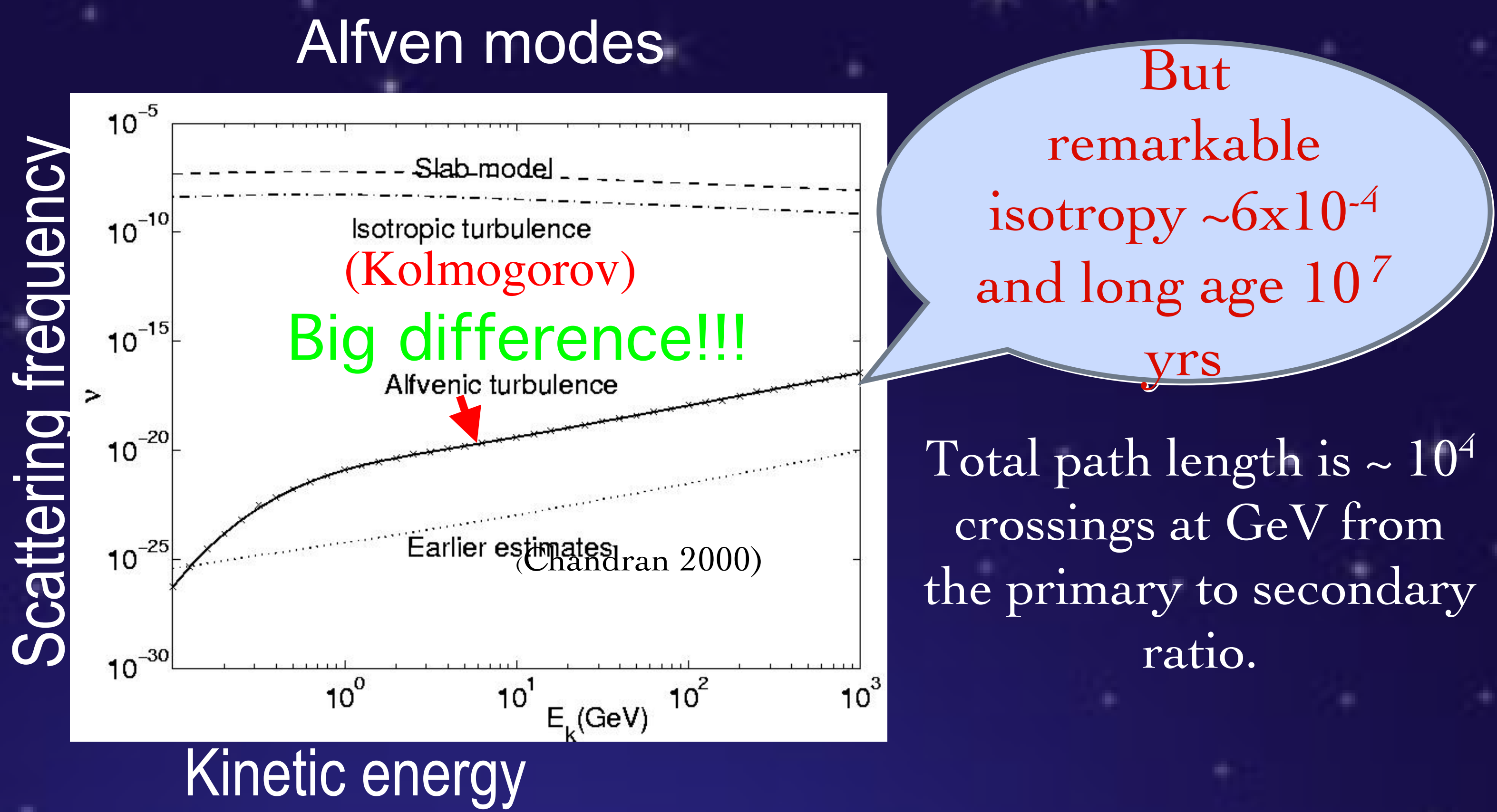
$$E(k_\perp) \sim k_\perp^{-5/3},\ k_\perp \sim L^{1/3} k_{||}^{3/2}$$

$$\Rightarrow \quad E(k_{||}) \sim k_{||}^{-2}$$

2. "steep spectrum"

⇒ *steeper than Kolmogorov! Less energy on resonant scale*

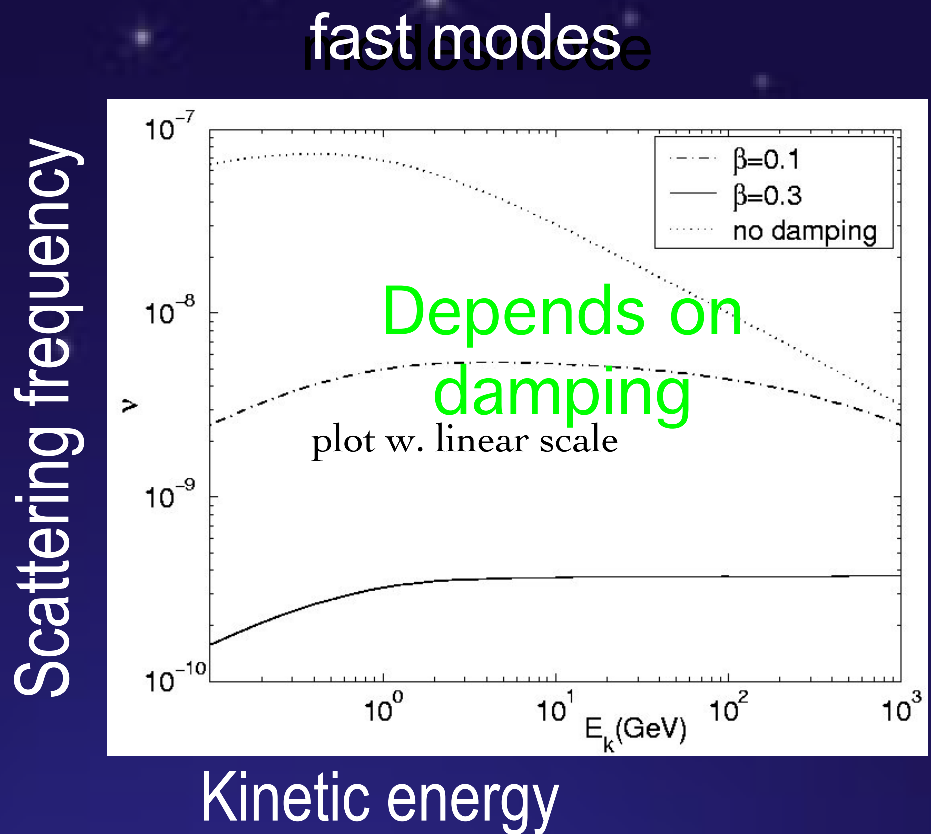
Inefficiency of cosmic ray scattering by Alfvenic turbulence is obvious and contradicts to what we know about cosmic rays



Total path length is ~ 10^4 crossings at GeV from the primary to secondary ratio.

Alternative solution is needed for CR scattering (Yan & Lazarian 02,04).

Fast modes efficiently scatter cosmic rays solving problems mentioned earlier



Fast modes are identified as the dominate source for CR scattering (Yan & Lazarian 2002, 2004).

Damping is for fast modes is usually defined for laminar fluids and is not applicable to turbulent environments

Damping increases with plasma $\beta = P_{gas}/P_{mag}$ and the angle θ between **k** and **B.**

Viscous damping (Braginskii 1965)

$$\Gamma_{\text{ion}} = \begin{cases} k_\perp^2 \eta_0 / 6\rho_i, & \beta \ll 1, \\ k^2 \eta_0 (1 - 3\cos^2\theta)/6\rho_i, & \beta \gg 1. \end{cases}$$

Collisionless damping (Ginzburg 1961, Foote & Kulsrud 1979)

$\beta \ll 1$

$$\Gamma_{\text{L}} = \frac{\sqrt{\pi\beta}}{4}\omega\frac{\sin^2\theta}{\cos\theta}\left[\sqrt{\frac{m_e}{m_{\text{H}}}}\exp\left(-\frac{m_e}{m_{\text{H}}\beta\cos^2\theta}\right) + 5\exp\left(-\frac{1}{\beta\cos^2\theta}\right)\right],$$

$\beta \gg 1$

$$\Gamma_{\text{L}} = \frac{\sin^2\theta}{\cos^3\theta}\begin{cases} 2\omega^2/\Omega_i, & k < \Omega_i/\beta V_{\text{A}}, \\ 2\Omega_i/\beta, & k > \Omega_i/\beta V_{\text{A}}, \end{cases}$$

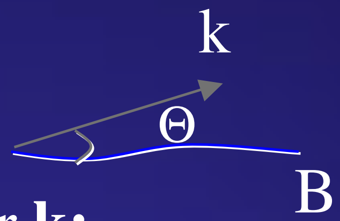
To calculate fast mode damping one should take into account wandering of magnetic field lines induced by Alfvenic turbulence

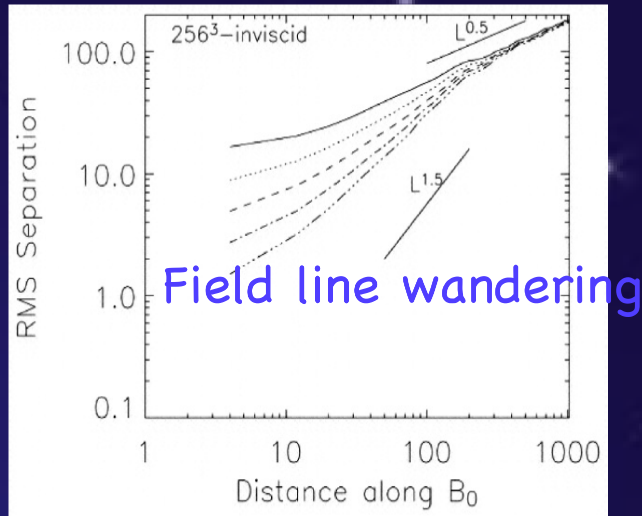
Magnetic field wandering induced by Alfvenic turbulence was described in Lazarian & Vishniac 1999

δB direction changes during cascade

Randomization of local **B:** field line wandering by shearing via Alfven modes:

$dB/B \approx (V/L)^{1/2}\, t_k^{\ 1/2}$





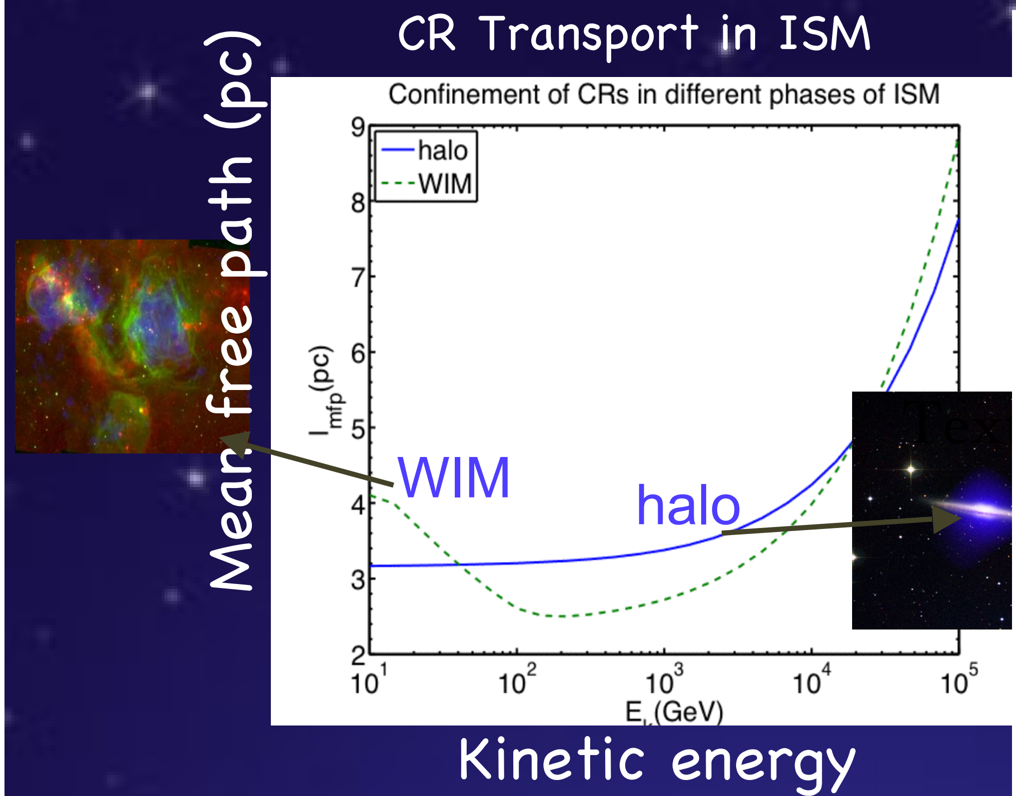
Lazarian, Vishniac & Cho 2004

Randomization of wave vector **k:**

$dk/k \approx (kL)^{-1/4}\, V/V_{ph}$

Yan & Lazarian 2004

Modeling that accounts for damping of fast modes agrees with observations



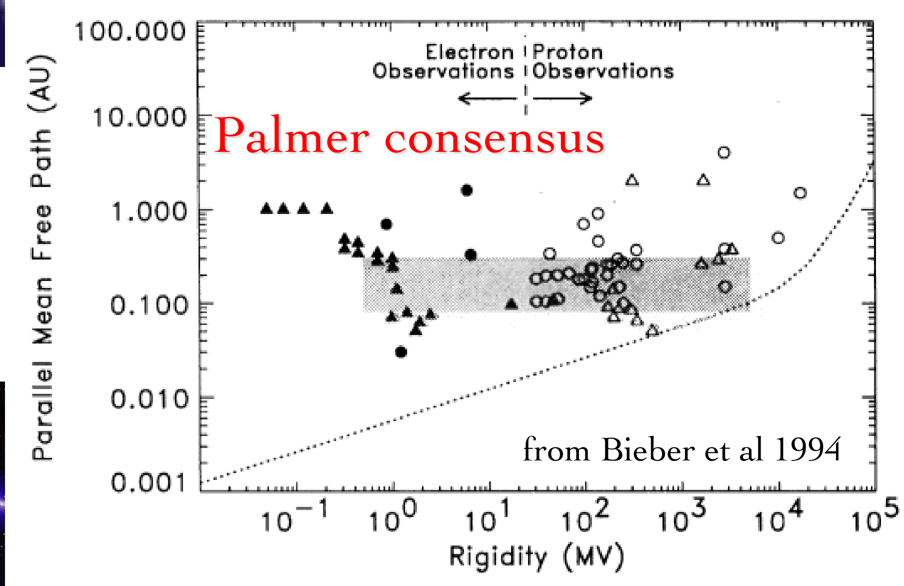
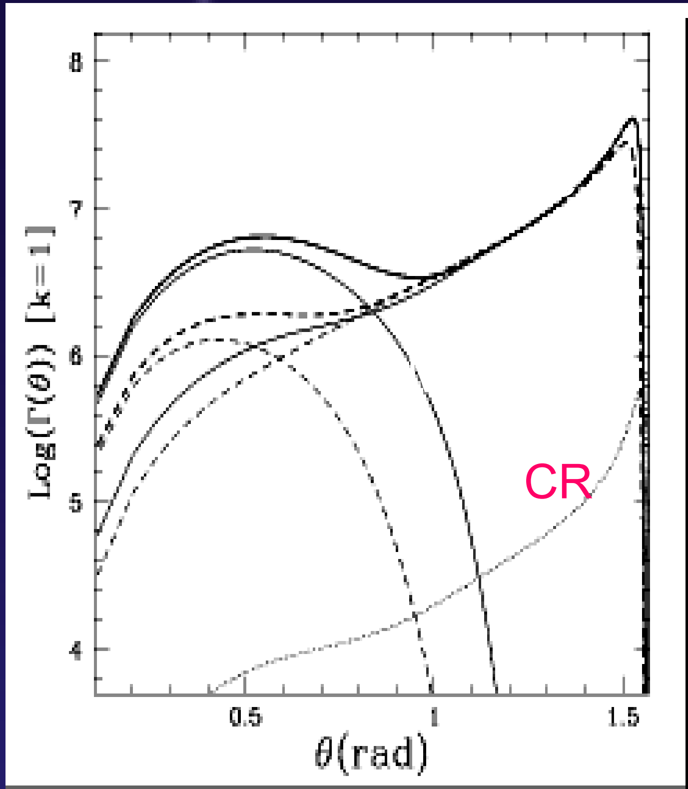


FIG. 1.—Cosmic-ray parallel mean free path vs. particle rigidity. Filled and open symbols denote results derived from electron and proton observations, respectively. See text for source references. Circles and upward-pointing triangles denote actual values and lower- limit values, respectively. The shaded band is the observational consensus enunciated by Palmer (1982). The dotted line represents the prediction of standard quasi-linear theory for magnetostatic, dissipationless turbulence with slab geometry (Jokipii 1966).

Flat dependence of mean free path can occur due to collisionless damping.

Acceleration by fast modes was also identified as major acceleration process for clusters of galaxies



The most important damping of compressive (fast) modes in the IGM is via "magnetic Landau" damping (n=0 resonance, Transit Time Damping) with **thermal electrons and protons (CR contribute for < 10%).**

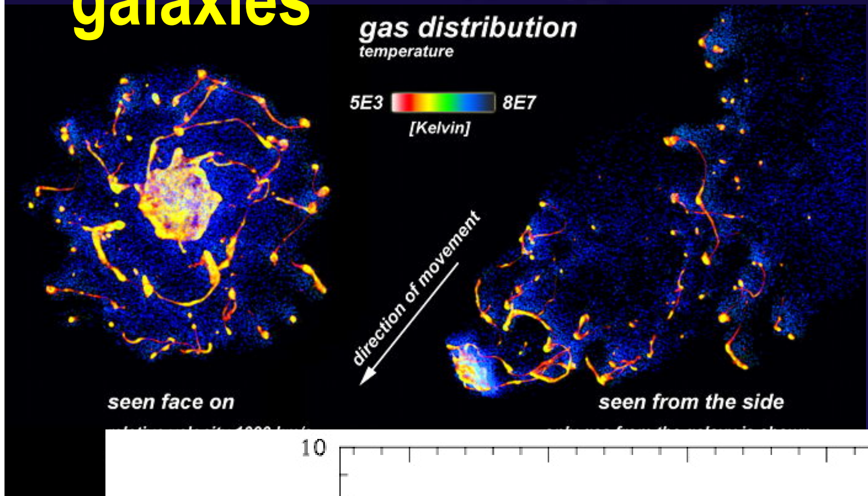
At least if the turbulence interacts with IGM in a collisionless way …

Line-bending *efficiency* >> *damping efficien*

Isotropic Effective Damping

$l_{diss} \approx 100$ pc

Fast mode acceleration is rather efficient in clusters of galaxies



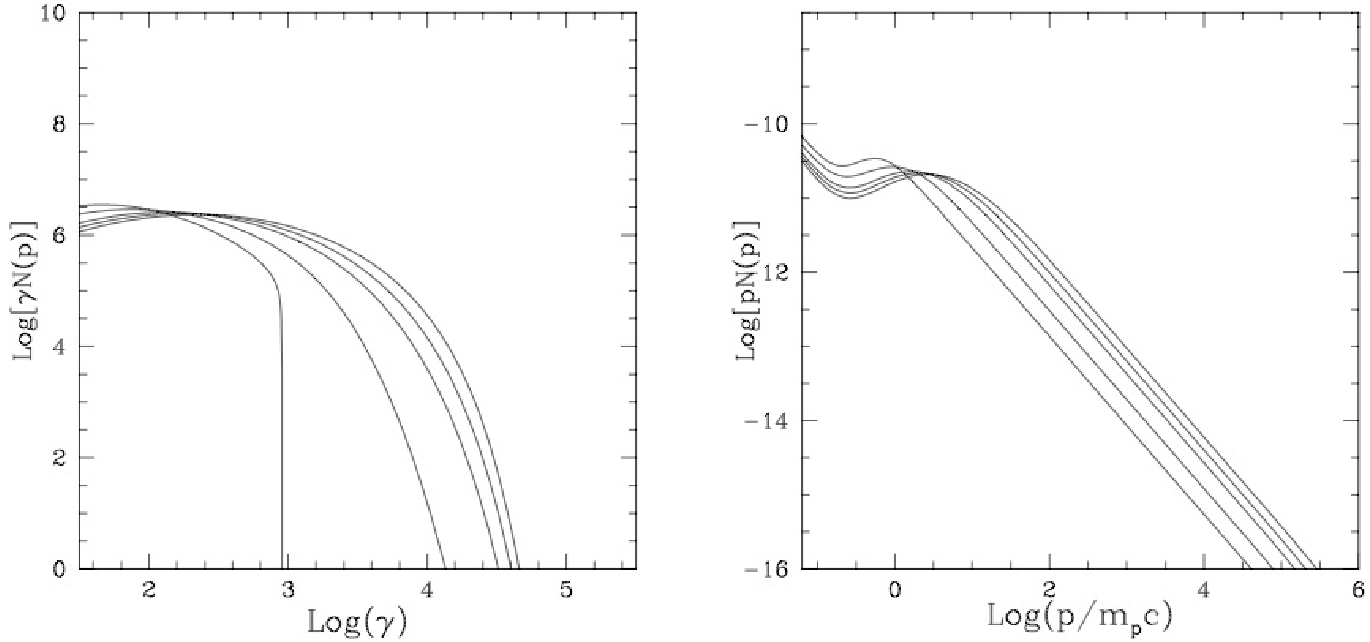
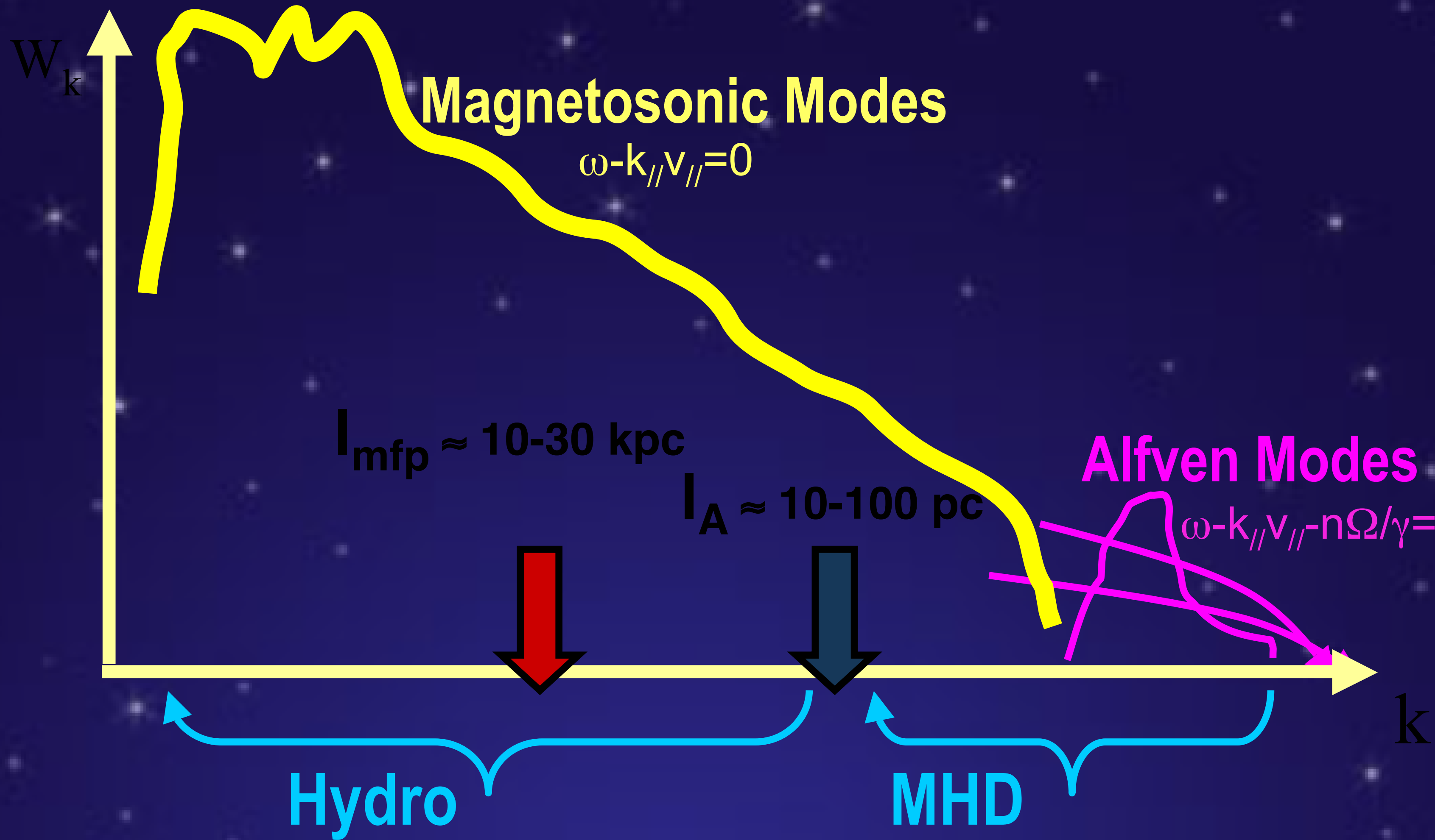


Figure 8. Left-hand panel: Time evolution of the spectrum of relativistic electrons as a function of the Lorentz factor. Right-hand panel: Time evolution of the spectrum of cosmic ray protons as a function of the particle momentum. In both panels calculations are reported for: $t = 0, 4 \times 10^{15}, 8 \times 10^{15}, 10^{16}, 1.2 \times 10^{16}$ s from the start of the re-acceleration phase. Calculations are performed assuming $(V_L/c_s)^2 = 0.18$, $L_o = 300$ kpc, $n_{th} = 10^{-3}$, $k_B T = 9$ keV, $B = 1$ μG and redshift $z = 0.1$ (for IC losses).

Brunetti & Lazarian (2007)

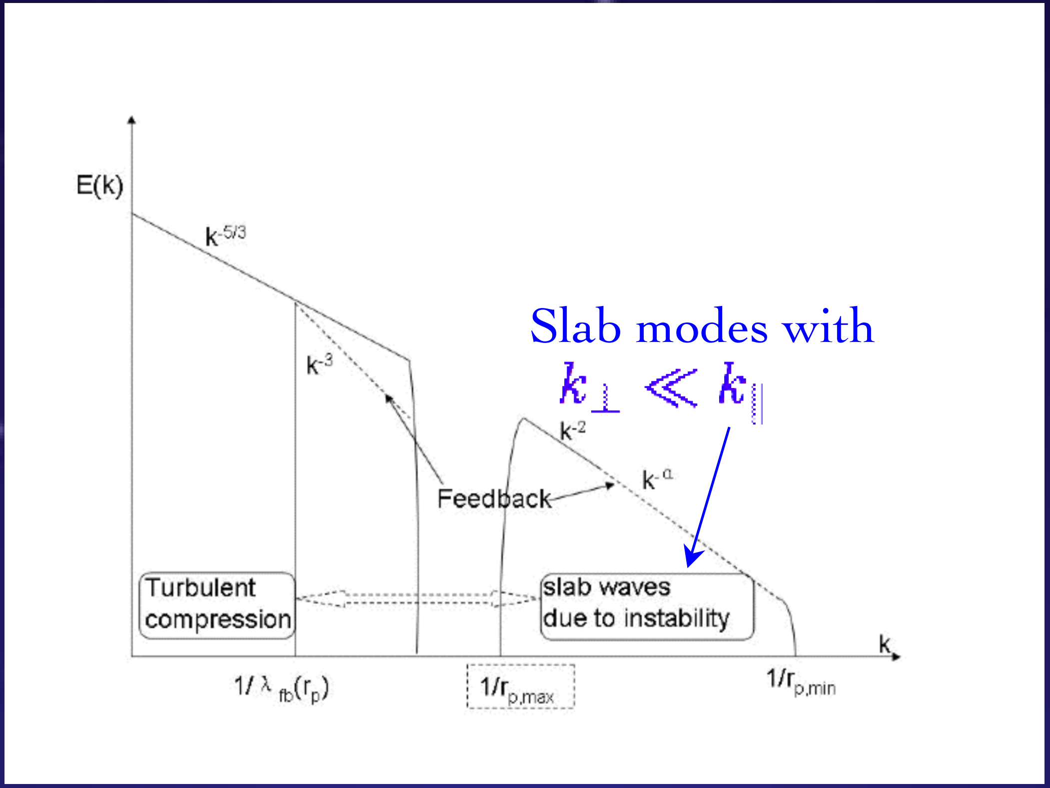
Actual turbulence may be more complex, e.g. turbulence in collisionless plasma of clusters of galaxies



The generation of small scale MHD modes in the ICM is an open issue

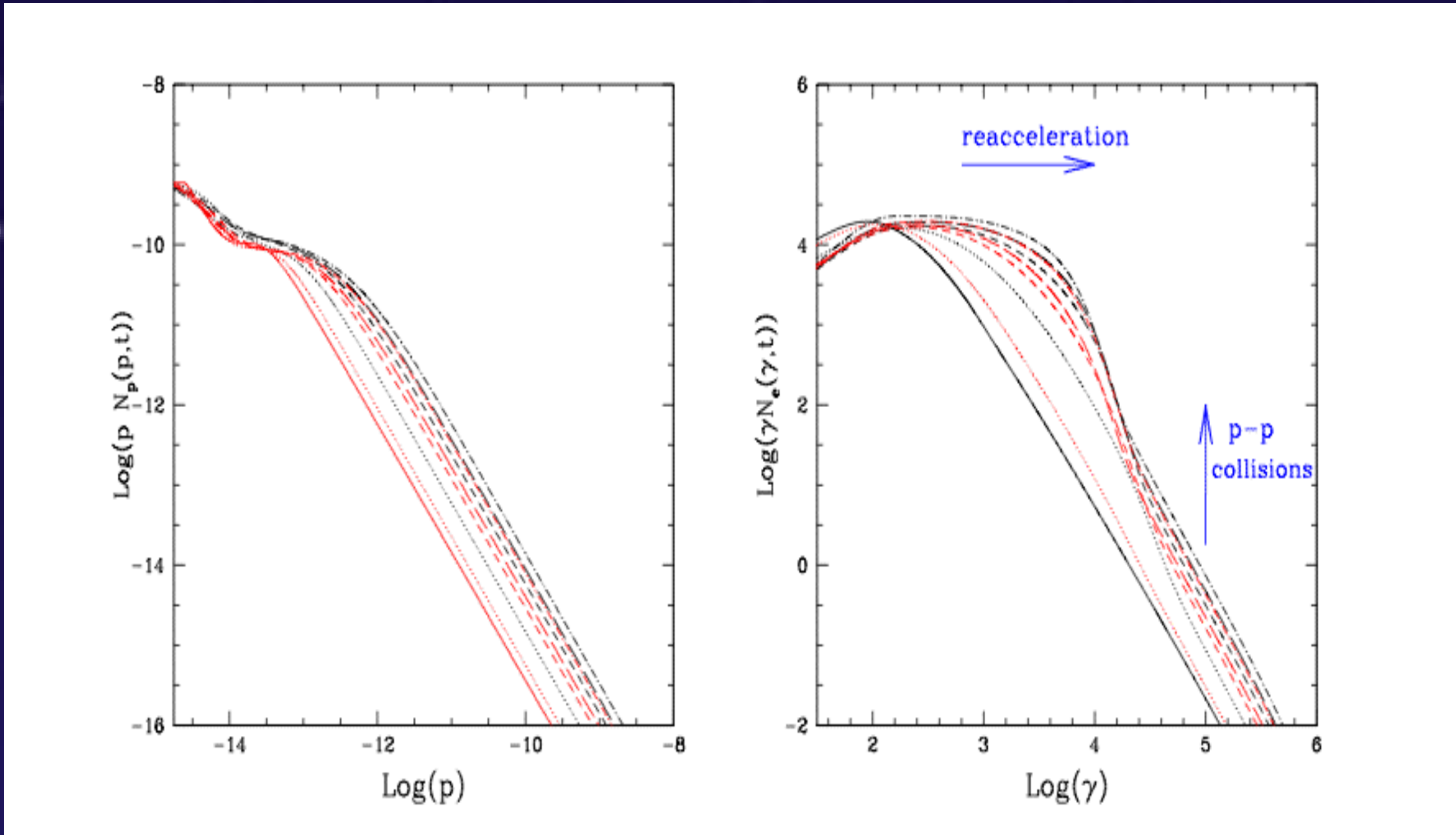
(see Schekochihin et al 2005, 09, Lazarian & Beresnyak 2006, Yan & Lazarian 2010)

Compressions of cosmic ray fluid can result in generation of additional modes



Lazarian & Beresnyak 2006 , Yan & Lazarian 2011

Effective plasma mean free path may be much smaller Coulomb mean free path decreasing collisionless damping



Most turbulent energy goes into cosmic ray acceleration (Brunetti & Lazarian 2011)

Take home message 4:

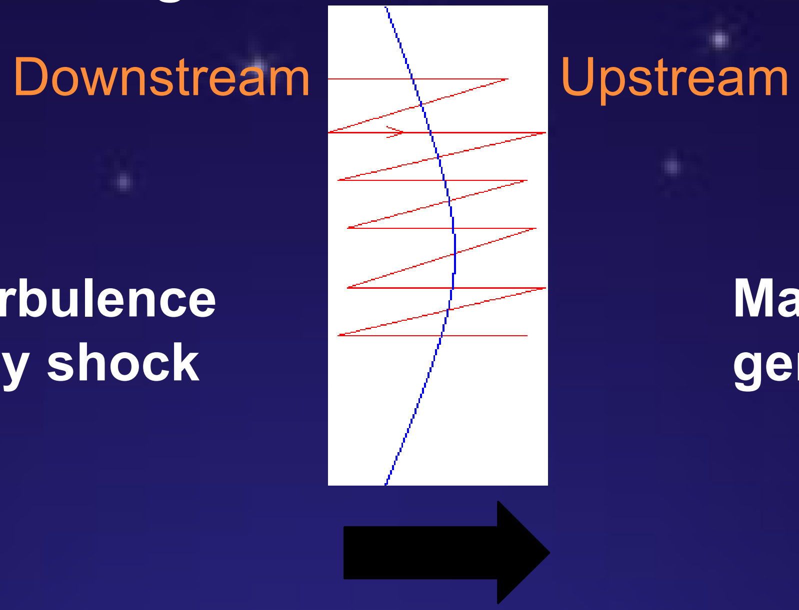
- Alfvenic turbulence is inefficient for scattering if it is generated on large scales.
- Fast modes dominate scattering, but damping of them is necessary to account for.
- Calculation of fast mode damping requires accounting for field wandering by Alfvenic turbulence.
- Scattering depends on the environment and plasma beta.
- Actual turbulence and acceleration in collisionless environments may be more complex

7 points of my talk:

- Turbulence is a natural state of fluids around us
- Turbulence is everywhere in astrophysical fluids
- Turbulence theory has been altered in the last decade
- Turbulence theory changes induce changes of CR paradigm
- Turbulence-precursor interaction changes shock acceleration
- Turbulence induces fast magnetic reconnection
- Turbulent reconnection induces First order Fermi acceleration

Point 5. Turbulence alters processes of Cosmic Ray acceleration in shocks

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



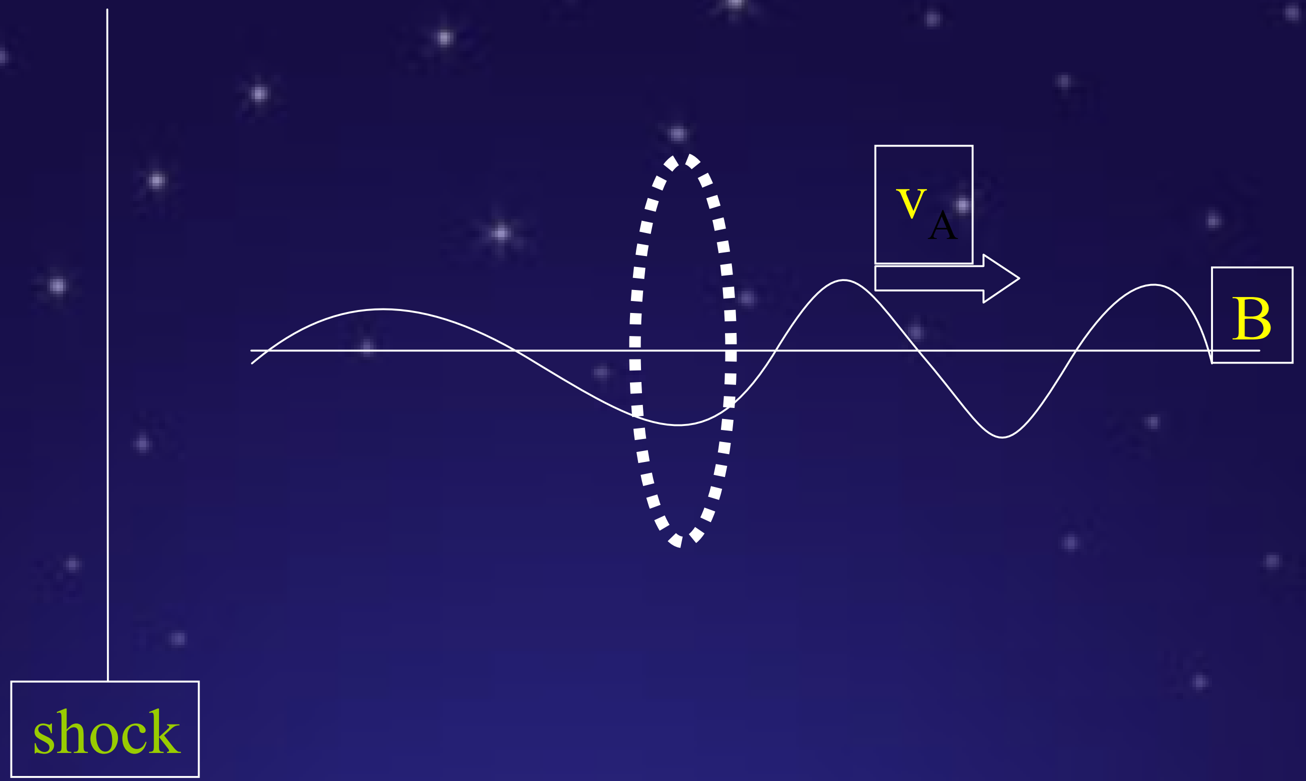
Magnetic turbulence generated by shock

Magnetic fluctuations generated by streaming

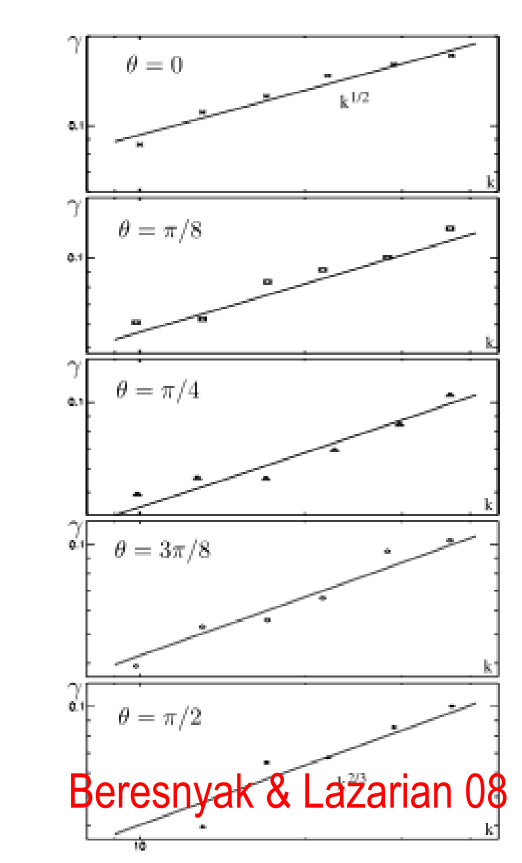
In postshock region damping of magnetic turbulence explains X-ray observations of young SNRs

Alfvenic turbulence decays in one eddy turnover time (Cho & Lazarian 02), which results in magnetic structures behind the shock being transient and generating filaments of a thickness of 10^{16}-10^{17}cm (Pohl, Yan & Lazarian 05).

Streaming instability in the preshock region is a textbook solution for returning the particles to shock region

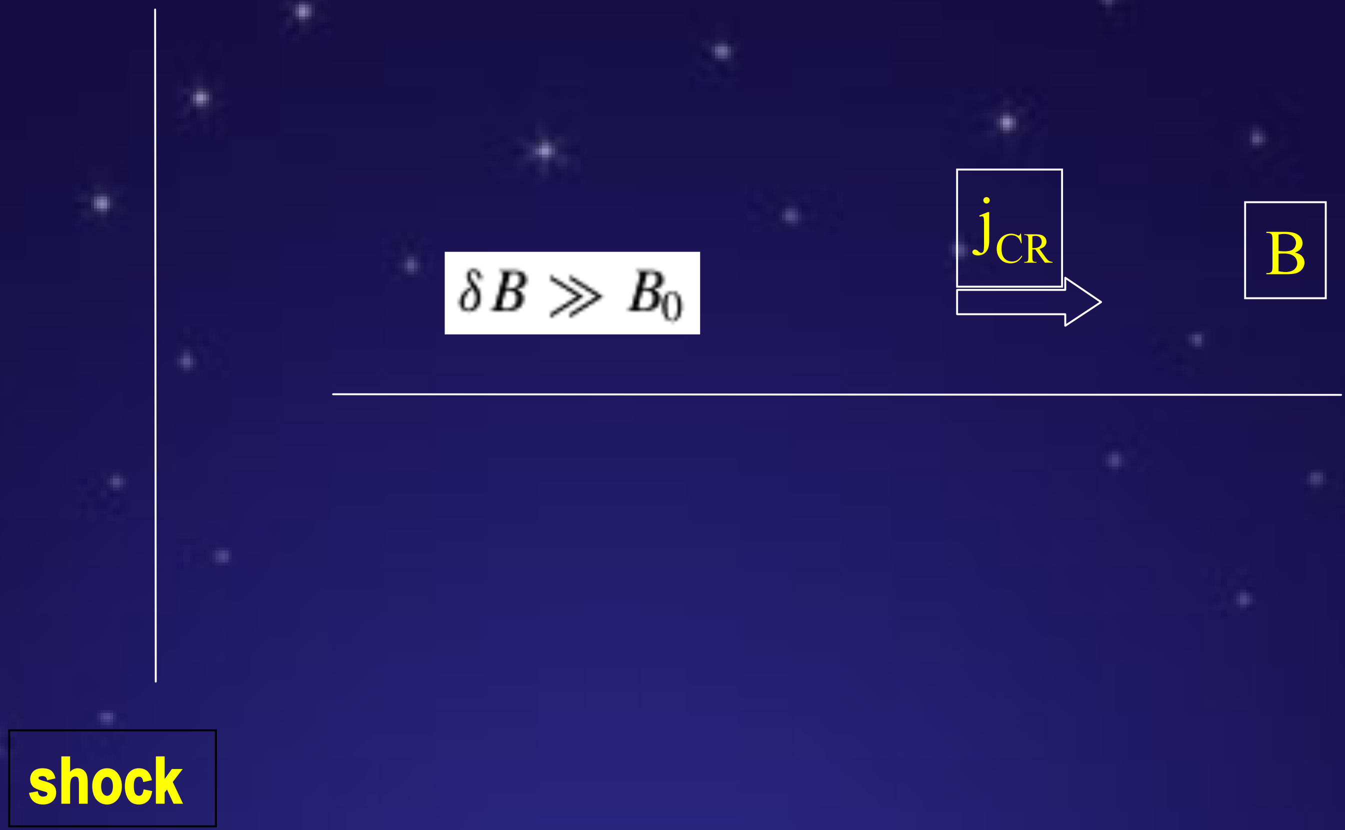


Streaming instability is inefficient for producing large field in the preshock region

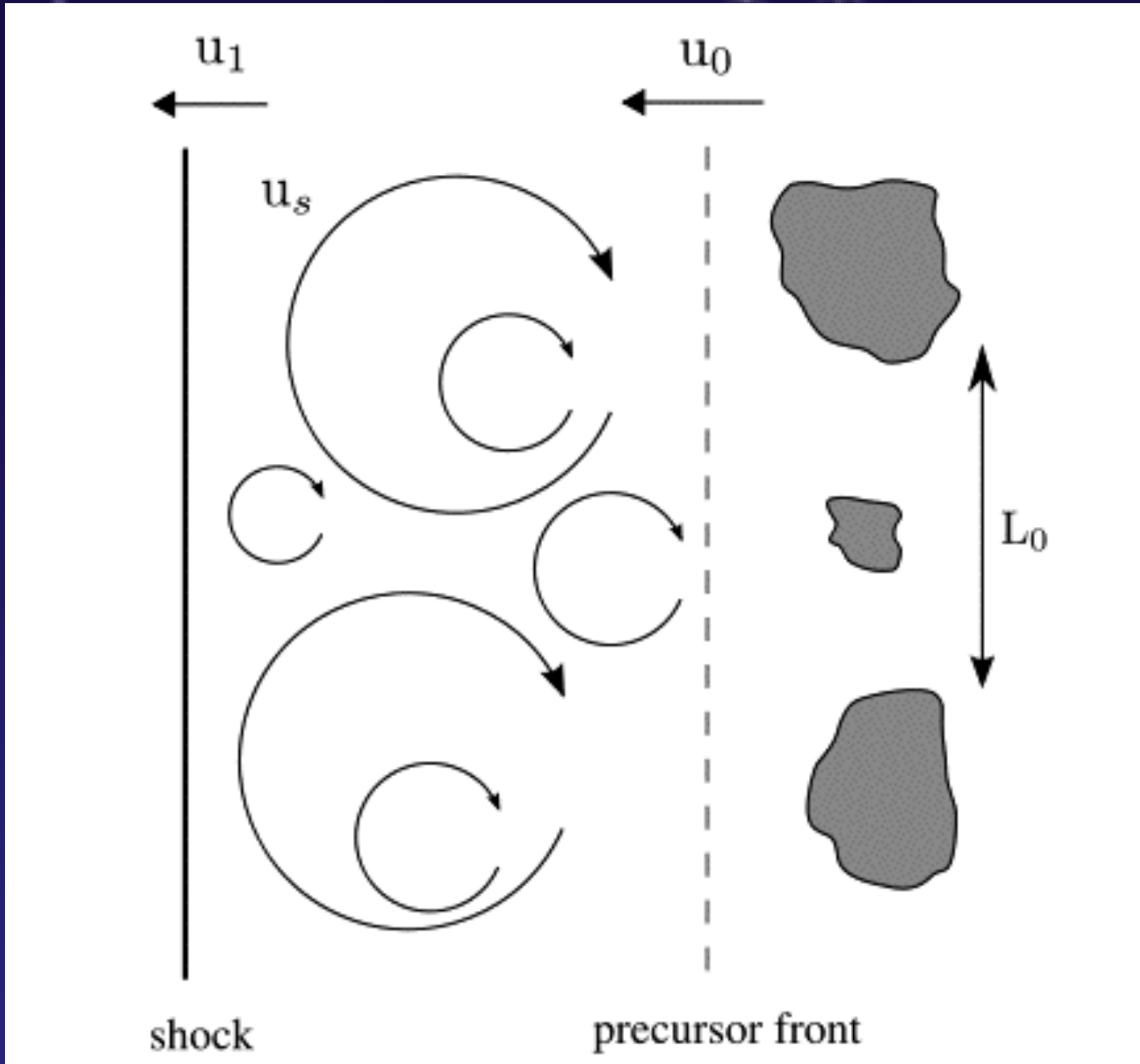


1. Streaming instability is suppressed in the presence of external turbulence (Yan & Lazarian 02, Farmer & Goldreich 04, Beresnyak & Lazarian 08).
2. Non-linear stage of streaming instability is inefficient (Diamond & Malkov 07).

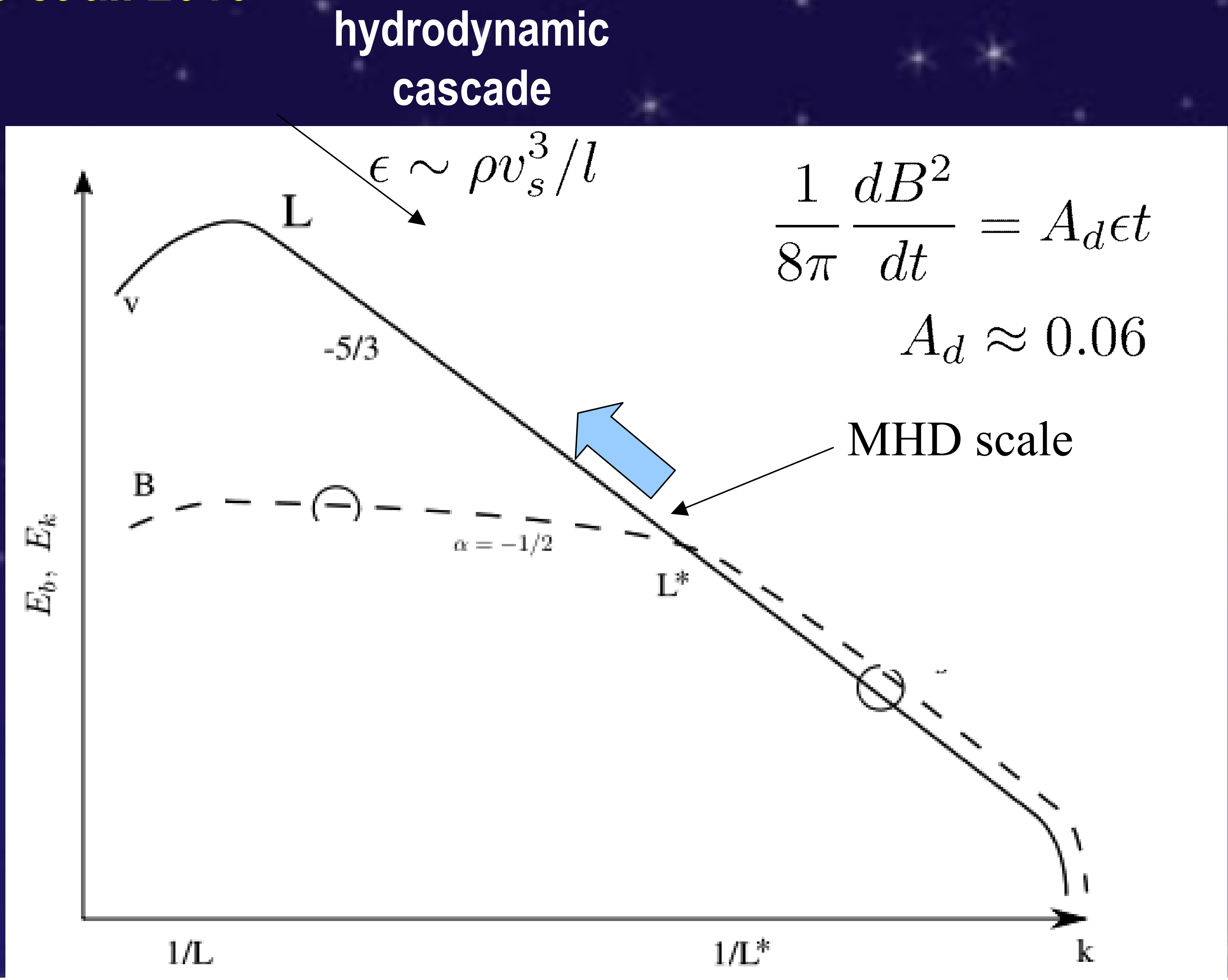
Bell (2004) proposed a solution based on the current instability



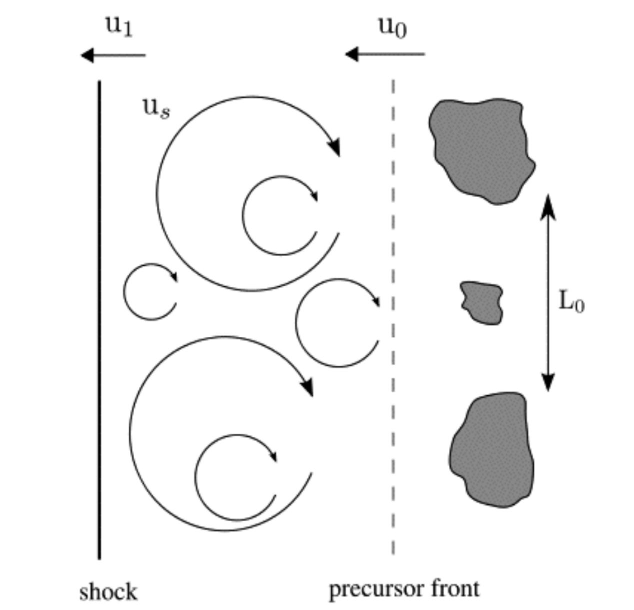
Precursor forms in front of the shock and it gets turbulent as precursor interacts with gas density fluctuation



Turbulence efficiently generates magnetic fields as shown by Cho et al. 2010



The model allows to calculate the parameters of magnetic field

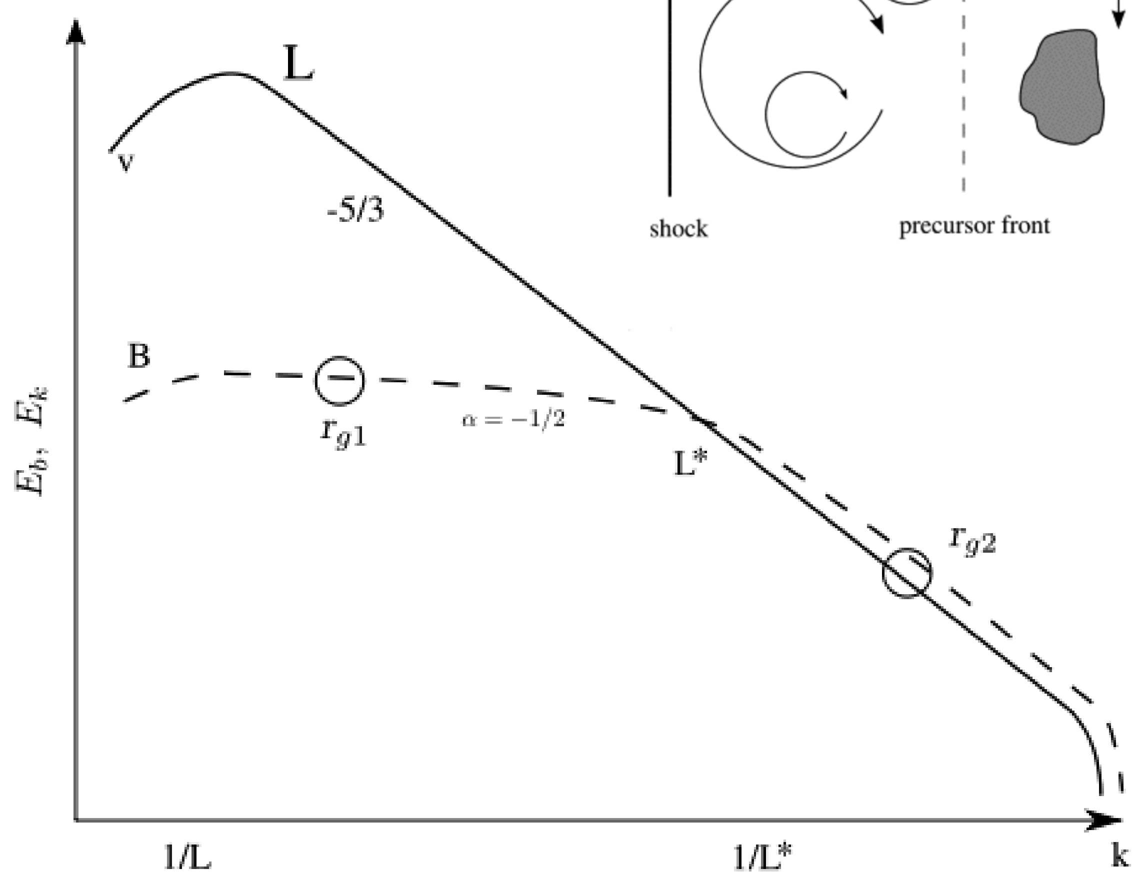


$$\delta B^2(L^*, x_1) = 8\pi A_d \epsilon \tau(x_1);$$

$$\frac{\delta B^*}{\sqrt{4\pi\rho}} = u_s \left(\frac{L^*(x_1)}{L}\right)^{1/3};$$

$$\tau(x_1) = \int_{x_1}^{x_0} \frac{dx}{u(x)};$$

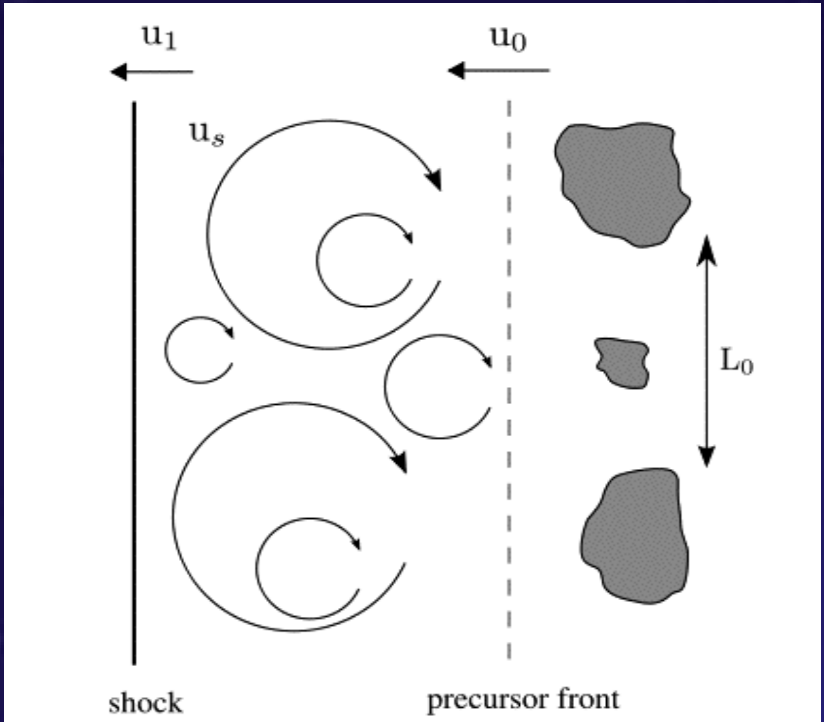
$$L^*(x_1) = (2A_d u_s \tau(x_1))^{3/2} L^{-1/2}.$$

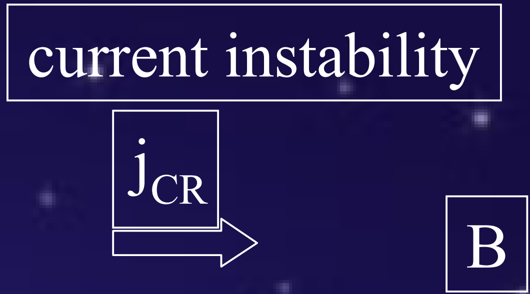


Beresnyak, Jones & Lazarian 2010

Take home message 5:

Magnetic field generated by precursor -- density fluctuations interaction might be larger than the arising from Bell's instability





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

7 points of my talk:

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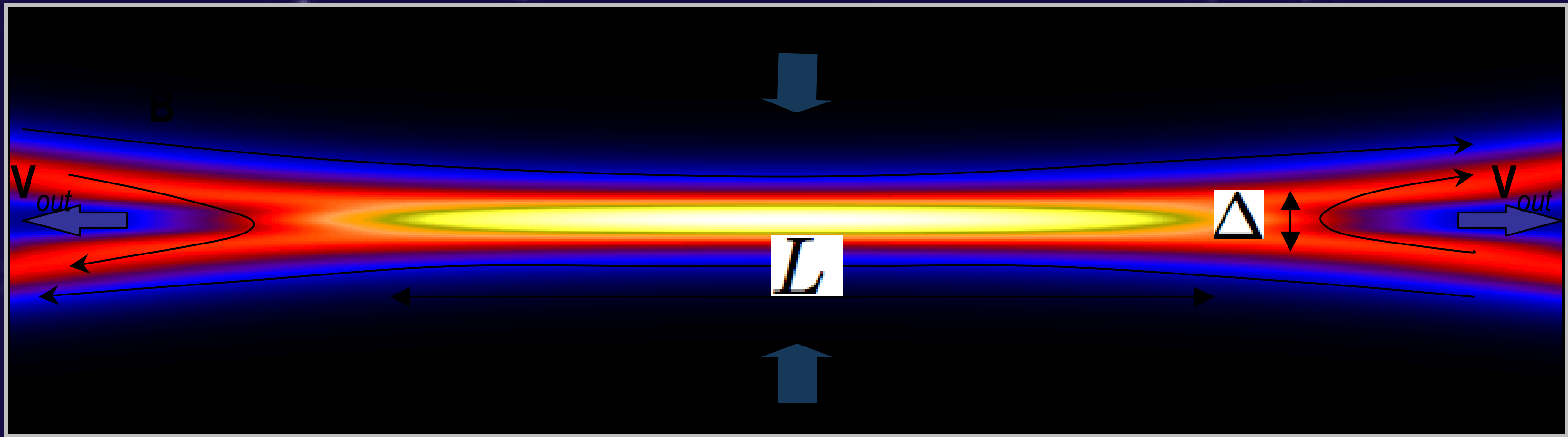
- Turbulence-precursor interaction changes shock acceleration
- **Turbulence induces fast magnetic reconnection**
- Turbulent reconnection induces First order Fermi acceleration

Point 5. Classical Sweet-Parker reconnection is too slow and turbulence is required to make it fast



Ohmic diffusion gives

$$\Delta \approx (\eta t_A)^{1/2} = L_x/(Rm)^{1/2}$$

$$Rm = \frac{L_x V_A}{\eta}$$

Lundquist number

With mass conservation: $V_{rec} L_x = V_A \Delta$

Results in the Swet-Parker expression for reconnection

$$V_{rec} \approx V_A Rm^{-1/2}$$

Theory of astrophysical reconnection: requirements are very restrictive

1. Reconnection must be both fast and slow to explain solar flares. Just one reconnection velocity, e.g. 0.1 V_A is not sufficient.
2. Reconnection rates should be consistent with the requirements of MHD turbulence theory preventing formation of magnetic knots, making magnetic spectrum shallow.
3. Reconnection mechanism is better to be applicable to different media to correspond to the principle of parsimony. E.g. satisfying both 1 and 2 for different ISM phases with different mechanisms is not natural.

Ockham's razor: "entities should not be multiplied needlessly"

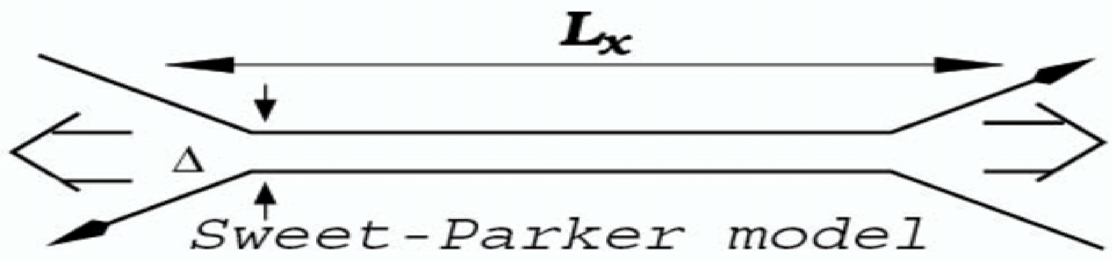
William Ockham 1288-1348

LV99 model extends Sweet-Parker model for realistically turbulent astrophysical plasmas

Turbulent reconnection:

1. Outflow is determined by field wandering.

2. Reconnection is fast with Ohmic resistivity only.



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

Key element:

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

Lazarian & Vishniac (1999)

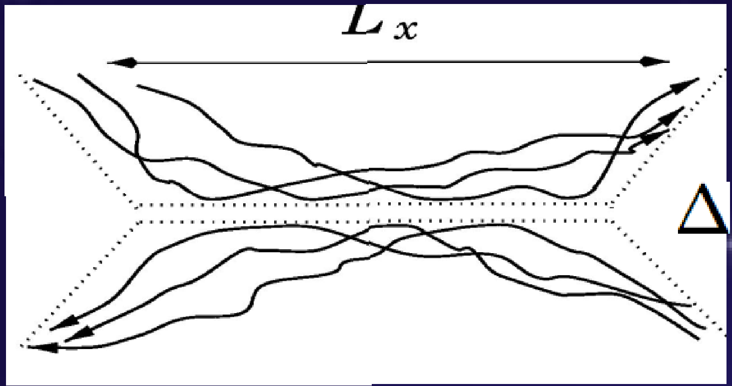
henceforth referred to as LV99

Eyink, Lazarian & Vishniac (arXiv 1103.1882) 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

Analogously, Richardson diffusion results in LV99 expression



For weak turbulence:

$$\epsilon = \frac{v_{inj}^4}{V_A L_{inj}}$$

Thus, Richardson diffusion gives

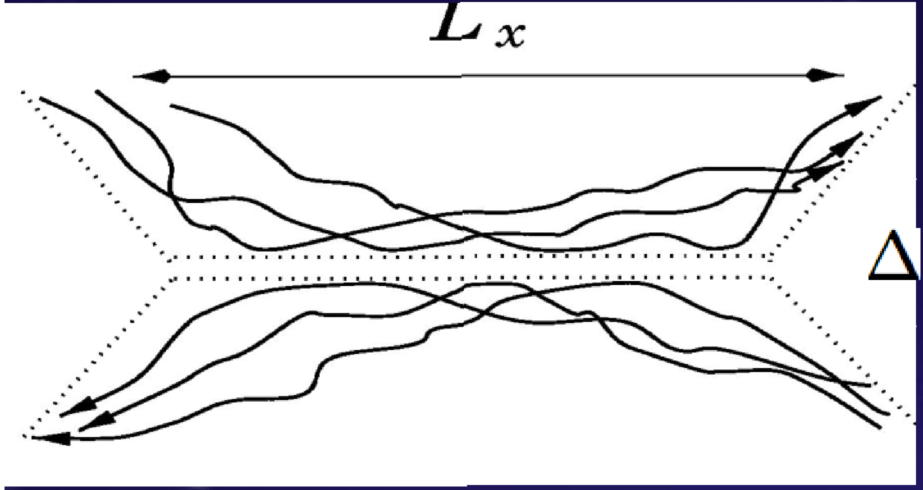
$$\Delta \approx (\epsilon t_A^3)^{1/2} \approx L_x (L_x / L_{inj})^{1/2} (v_{inj} / V_A)^2$$

With mass conservation: $V_{rec} L_x = V_A \Delta$

Results in LV99 expression for reconnection for $L_x < L_{inj}$

$$V_{rec} = V_A (L_x / L_{inj})^{1/2} (V_{inj} / V_A)^2$$

LV99 prediction can be expressed in terms of energy injection power, which is easier to measure in simulations



LV99 prediction: $$V_{rec} = V_A (L_x / L_{inj})^{1/2} (V_{inj}/V_A)^2$$

For subAlfvenic injection energy injection power: $$P_{inj} \sim V_{inj}^4 / (L_{inj} V_A)$$

Thus, $$V_{rec} \approx L_{inj} P_{inj}^{1/2}$$

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)

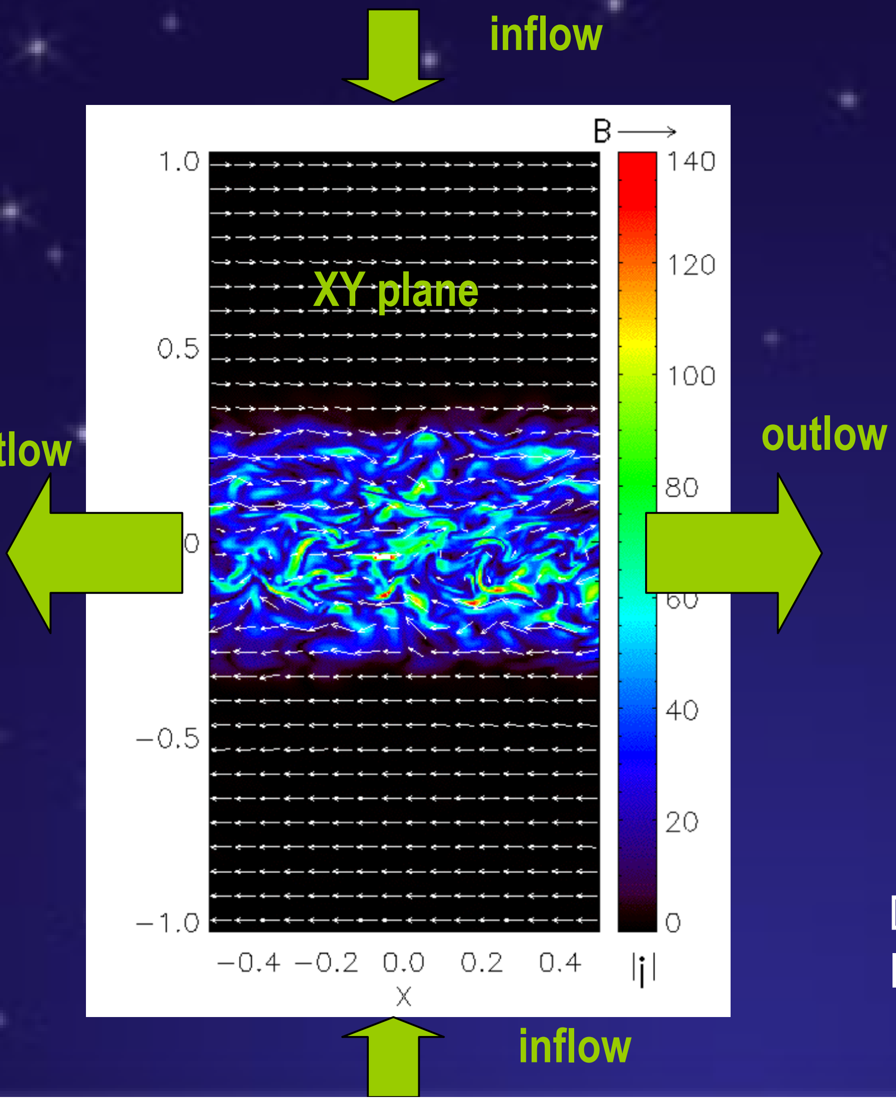
Resistivity:

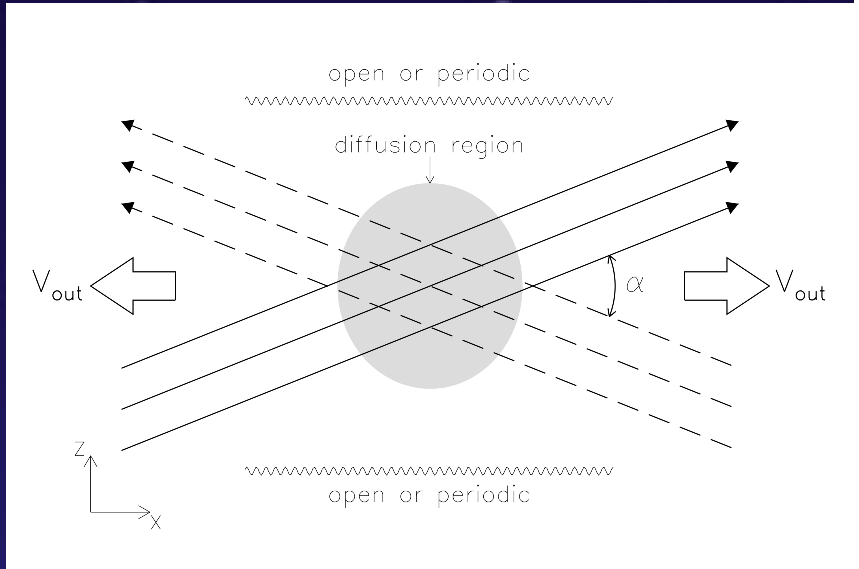
-Ohmic

-Anomalous

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

All calculations are 3D with non-zero guide field

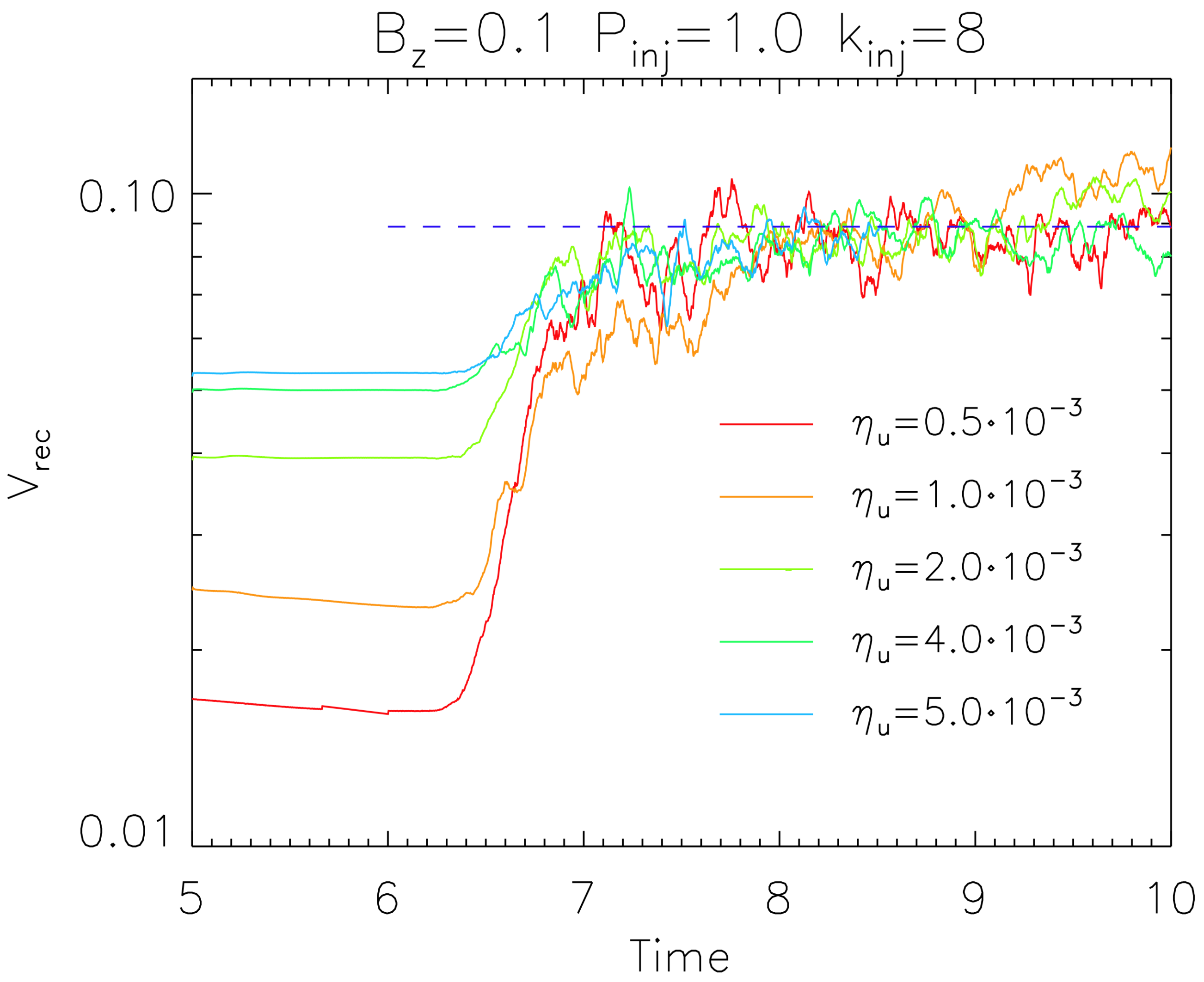




Magnetic fluxes intersect at an angle

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

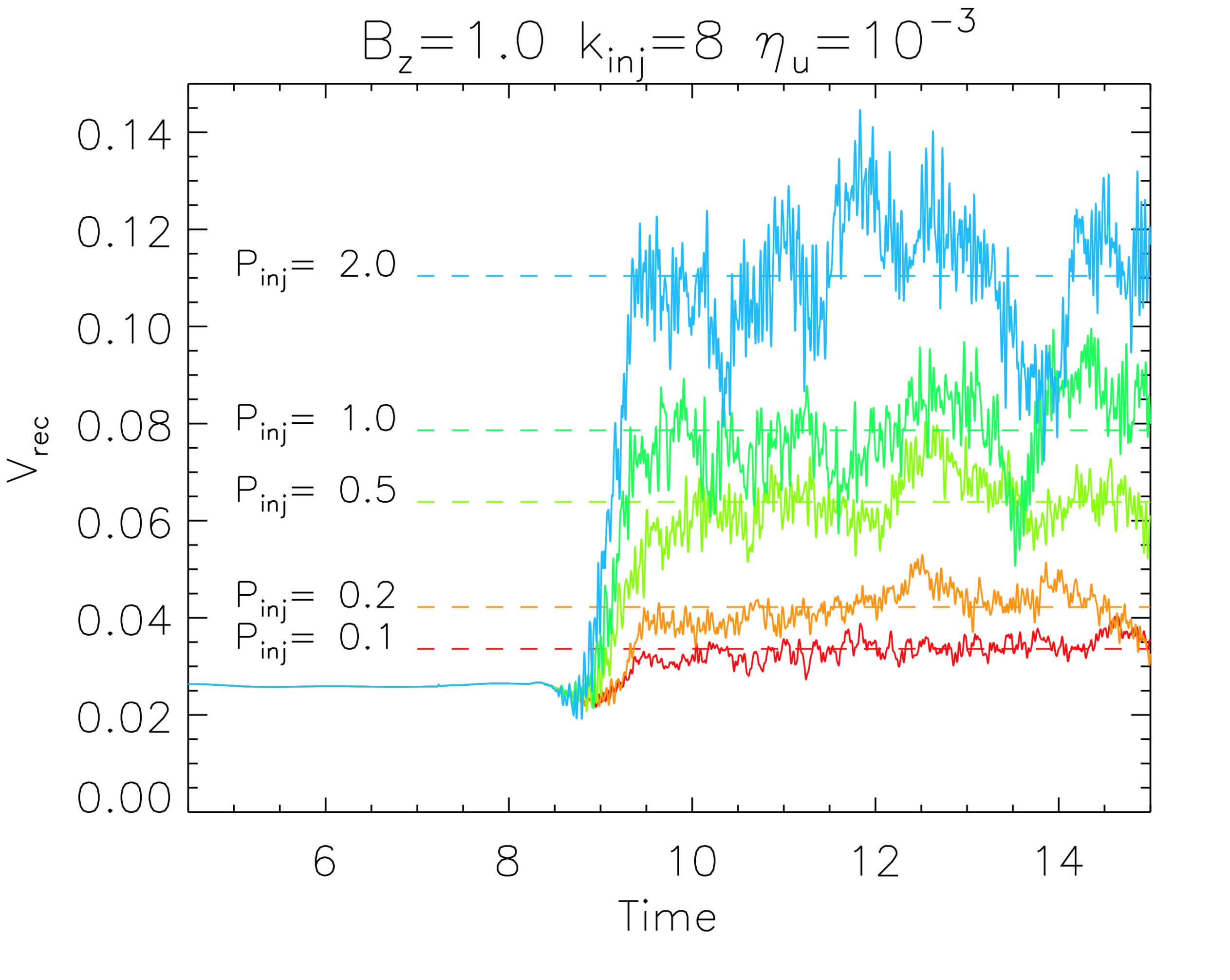
Reconnection is Fast: speed does not depend on Ohmic resistivity!



Lazarian & Vishniac 1999 predicts no dependence on resistivity

Results do not depend on the guide field

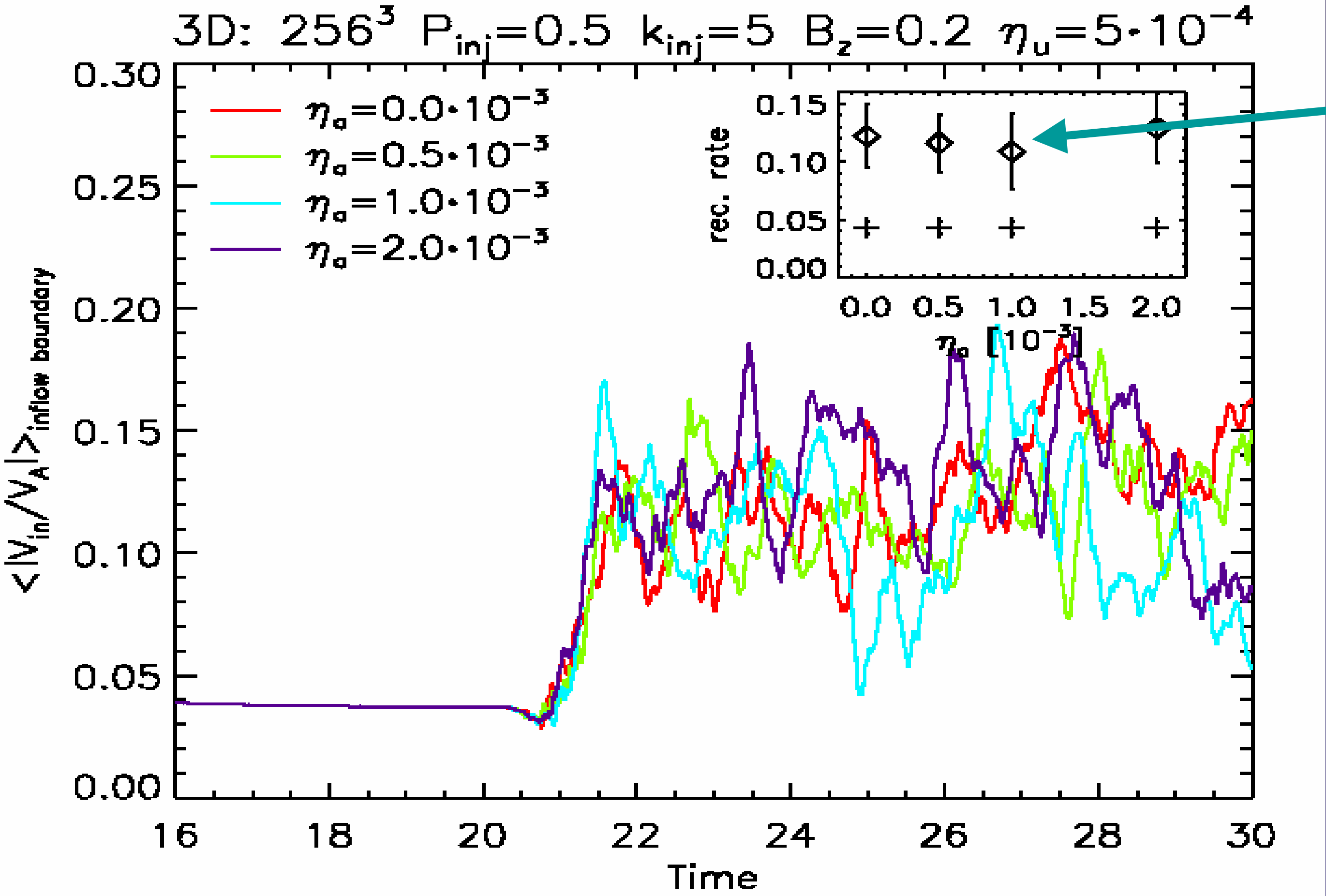
The reconnection rate increases with input power of turbulence



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

Results do not depend on the guide field

Reconnection rate does not depend on anomalous resistivity



Flat dependence on anomalous resistivity

Reconnection does not require Hall MHD

Turbulence was earlier discussed in terms of reconnection, but results were either inconclusive or negative

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

Matthaeus & Lamkin (1985) --- attempts to estimate reconnection velocities in 2D turbulence

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

Some other research directions do not compete with LV99 model, but may be complementary

1. Tearing mode: Nonlinear merging island numerical calculations are claimed to produce fast reconnection for $S>10^4$, providing velocity $<10^2 V_A$ (Loureiro et al. 2009). May be related to plasmoids by Shibata (1999).

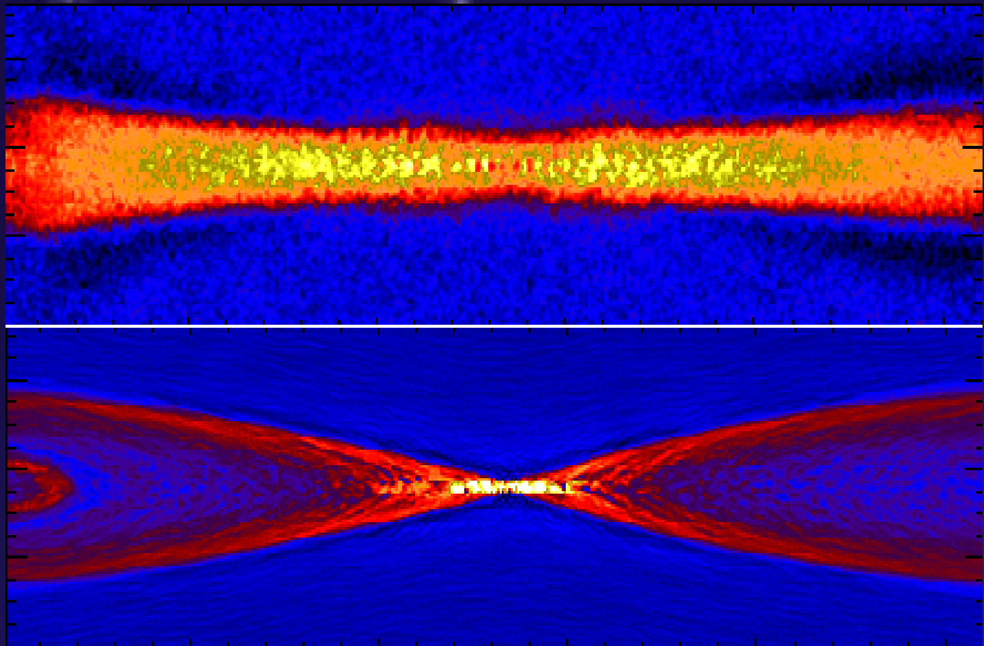
   This is too slow to disentangle magnetic field lines in turbulence, does not generate flares. But may help to initiate flares through LV99 process.

2. Explosions of reconnection were observed in MHD simulations by Lapenta (2008).

   Relation to LV99 process is to be tested.

Collisionless reconnection is very restrictive to provide an equally universal mechanism

Hall MHD



(Drake et al. '98)

Petcheck + anomalous effects

ion current

e current

Reconnection is collisional for interstellar medium, photosphere, chromosphere, accretion disks etc.

Example: Interstellar Medium

The condition for the reconnection to be "collisionless" is $\delta_{SP}/\delta_i < 1$,

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

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

and the current sheet length of sheets

$L < 10^{12}$cm

Too small!!!

Interstellar medium is example of collisional media but turbulent reconnection is not limited to such a media

System	L (cm)	B (G)	$d_i = c/\omega_{pi}$(cm)	δ_{sp} (cm)	d_i/δ_{sp}
MRX	10	100-500	1-5	0.1-5	.2-100
RFP/Tokamak	30/100	10^3/ 10^4	10	0.1	100
Magnetosphere	10^9	10^{-3}	10^7	10^4	1000
Solar flare	10^9	100	10^4	10^2	100
ISM	10^{18}	10^{-6}	10^7	10^{10}	0.001

LV99 is applicable to collisionless plasmas when the injection scale is larger than the ion inertial length!

Usual criterion for Hall term to be important is that electron flow velocity is dominated by the current. However, correlations of Hall velocity $\mathbf{u}^H = \mathbf{J}/ne = c\nabla\times\mathbf{B}/4\pi ne$ are short-ranged.

If $r^2 \gg c^2 m_i/4\pi ne^2 = \delta_i^2$, δ_i is ion inertial length, and $\langle\delta u_i(\mathbf{r})\delta u_j(\mathbf{r})\rangle \sim Ar^{2h}$

$$\langle u_i^H(\mathbf{r})u_j^H(0)\rangle \sim \left(\frac{c}{4\pi ne}\right)^2 \triangle\langle\delta B_i(\mathbf{r})\delta B_j(\mathbf{r})\rangle$$

$$\sim \left(\frac{c}{4\pi ne}\right)^2 4\pi\rho\cdot Ar^{-2(1-h)} \ll Ar^{2h} = \langle\delta u_i(\mathbf{r})\delta u_j(\mathbf{r})\rangle$$

Field wondering and magnetic field diffusion is dominated by turbulence for $r \gg \delta_i$

From Eyink, Lazarian & Vishniac 2011

Rates predicted in LV99 make magnetic turbulence self-consistent, unlike "universal" 0.1 V_A claimed by Hall MHD model

Pressure gradient — *Field line contraction*

$$l_\perp^2/l_\parallel^3 V_A^2 \sim \tau_{eject}^{-2} l_\perp^2/l_\parallel \Rightarrow \tau_{eject}^{-1} \approx V_A/l_\parallel$$

Mass conservation

$$V_{rec} l_\parallel = V_{ejec} l_\perp$$

$$V_{eject} \sim \tau_{eject}^{-1} l_\parallel$$

$$\Rightarrow V_{rec} = V_A \frac{l_\perp}{l_\parallel}$$

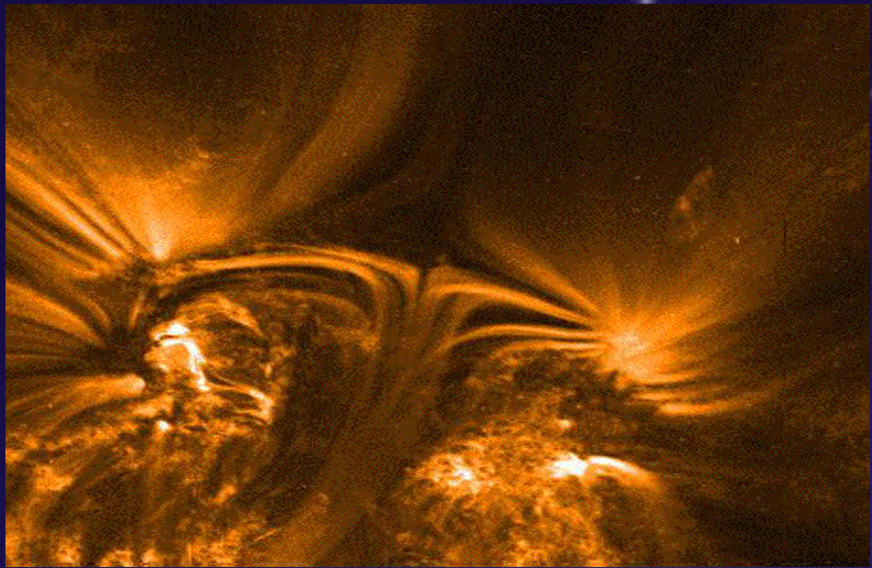
The field wandering over scale $l_\parallel$ *is* $l_\perp$.

Thus the rate of reconnection within an eddy

$$\tau_{rec}^{-1} \approx V_A/l_\parallel$$

which is equal to the GS95 cascading rate

LV99 model of reconnection gains support from 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). Level of turbulence can do this (LV99)
2. Thick current layers predicted by LV99 have been observed in Solar flares (Ciaravella, & Raymond 2008).
3. Predicted by LV99 triggering of magnetic reconnection by Alfven waves was observed by Sych et al. (2009).

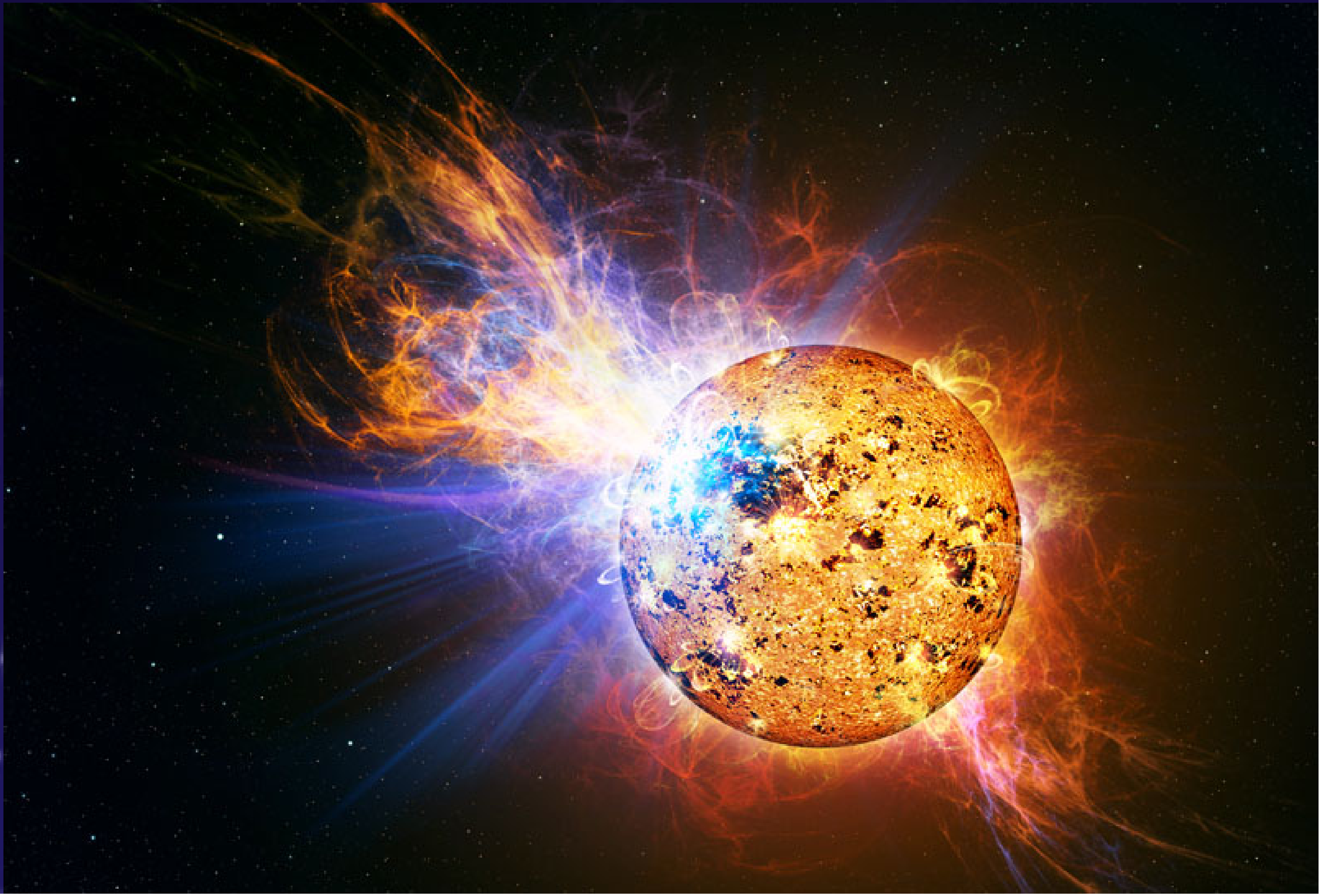
Take home message 6:

- Turbulence makes magnetic reconnection fast.
- Collisionless reconnection is very restrictive and not applicable to many astrophysical environments.
- LV99 model makes MHD turbulence theory self-consistent.

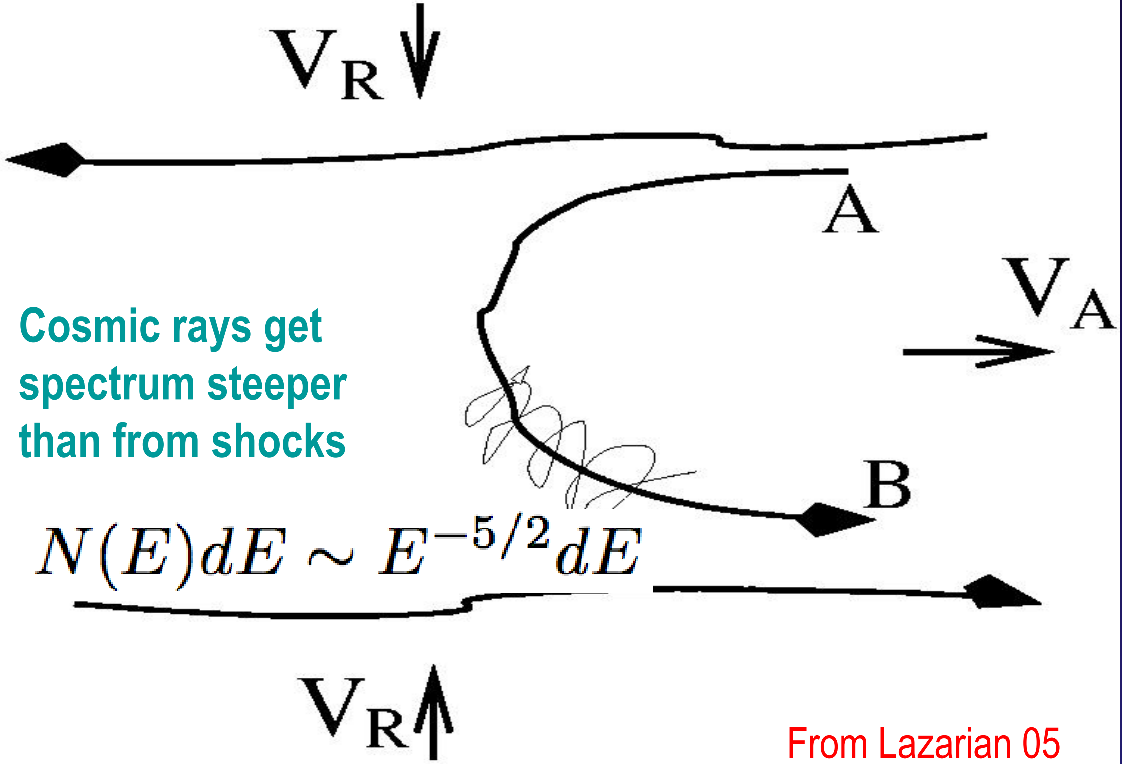
7 points of my talk:

- Turbulence is a natural state of fluids around us
- Turbulence is everywhere in astrophysical fluids
- Turbulence theory has been altered in the last decade
- Turbulence theory changes induce changes of CR paradigm
- Turbulence-precursor interaction changes shock acceleration
- Turbulence induces fast magnetic reconnection
- Turbulent reconnection induces First order Fermi acceleration

Point 7. Turbulent magnetic reconnection can accelerate energetic particles



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



Cosmic rays get spectrum steeper than from shocks

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

From Lazarian 05

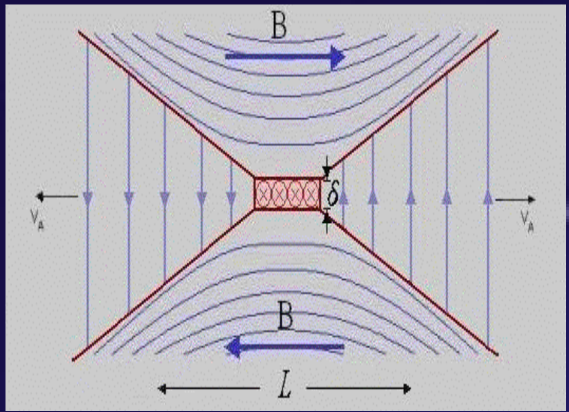
(cp. Drake 2006).

Published in De Gouveia Dal Pino & Lazarian 2003

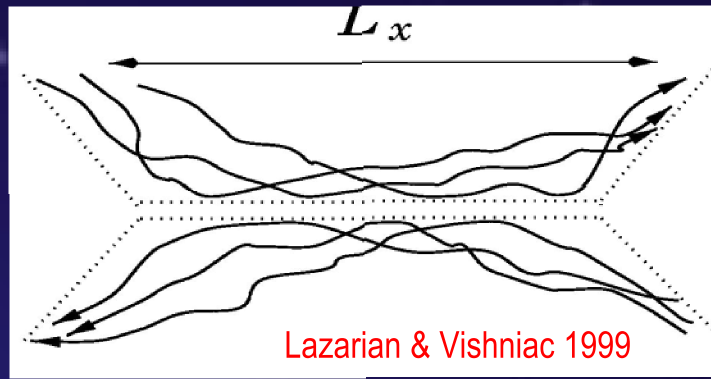
Applications to pulsars, microquasars, solar flare acceleration (De Gouveia Dal Pino & Lazarian 00, 03, 05, Lazarian 05).

The overlap between LV99 and Hall MHD happened as within the last decade convergence between the models took place

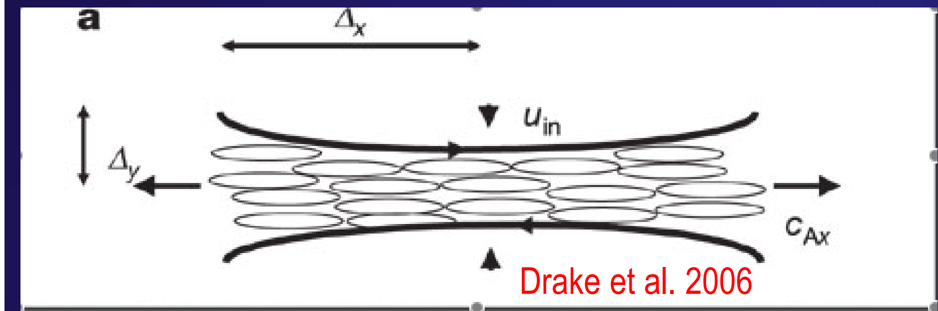
Hall MHD 1999



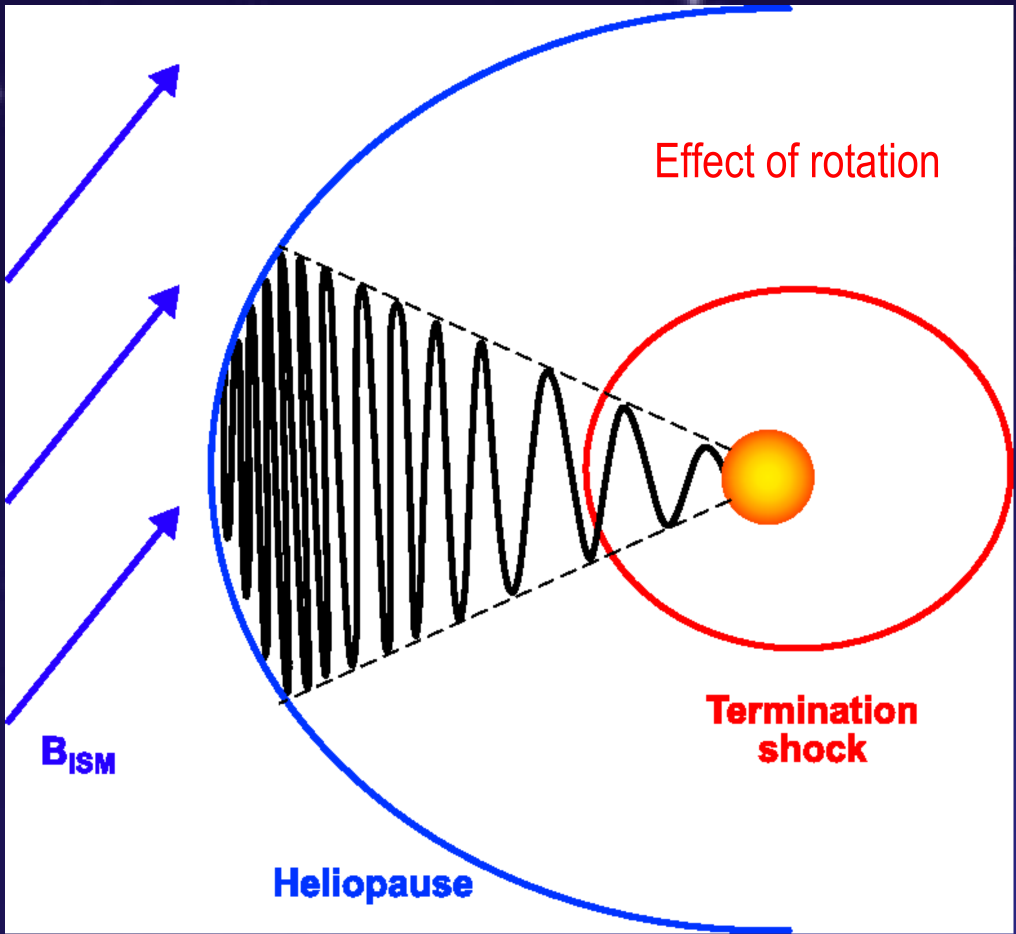
LV99 model



Hall MHD 2011



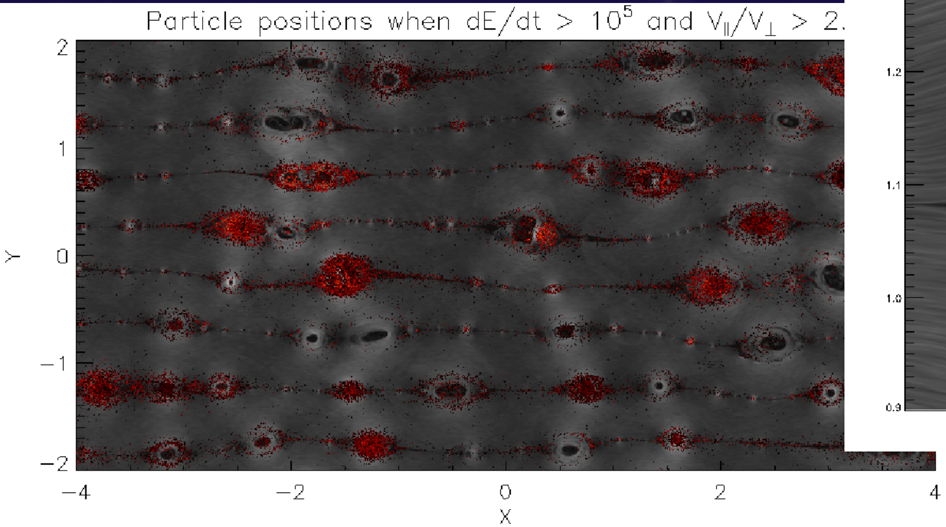
Reconnection can provide a solution to anomalous cosmic ray measurements by Voyagers

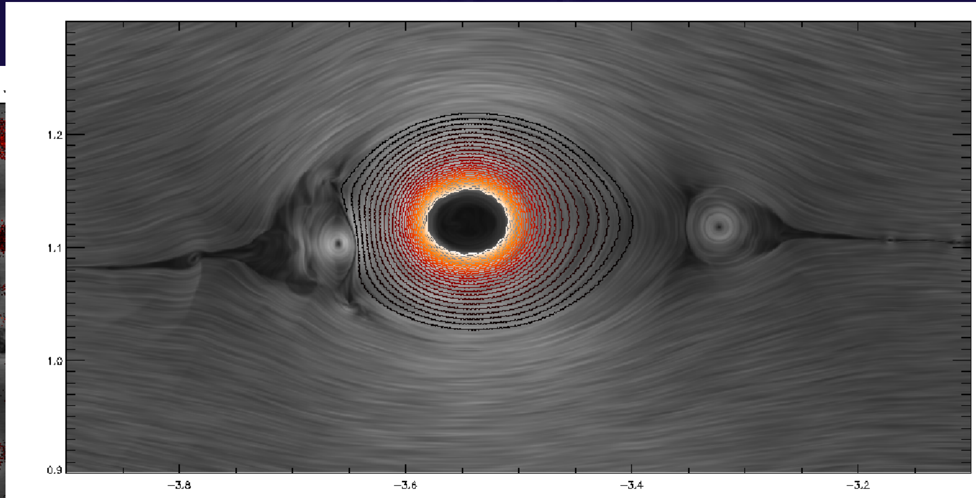


Observed anomalous CRs do not show features expected from the acceleration in the termination shock

Lazarian & Opher 2009: Sun rotation creates B-reversals in the heliosheath inducing acceleration via reconnection See also Drake et al. (2010).

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

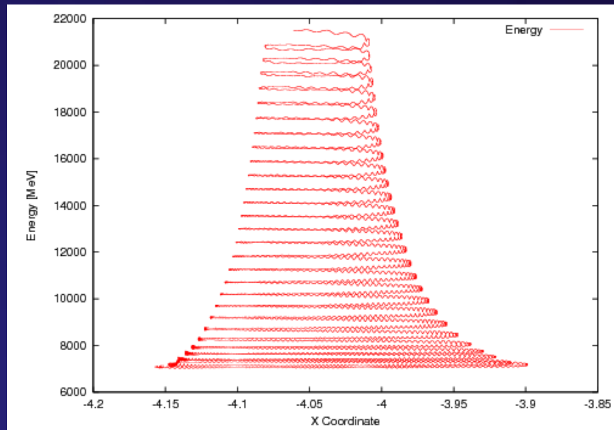




Zoom in into itrajectories

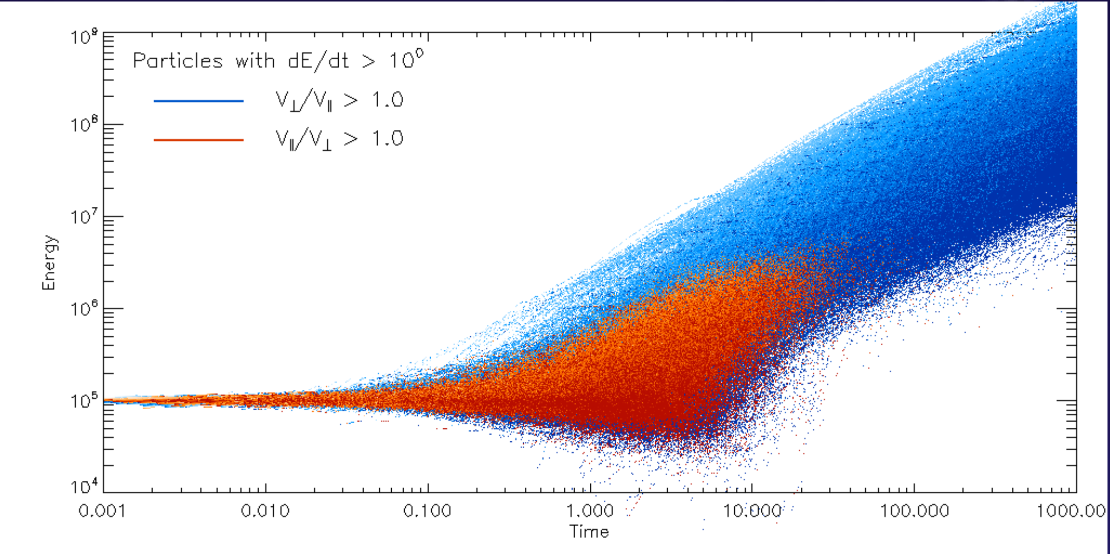
Multiple reconnection layers are used to produce volume reconnection.

Kowal, Lazarian, de Gouveial dal Pino 2011

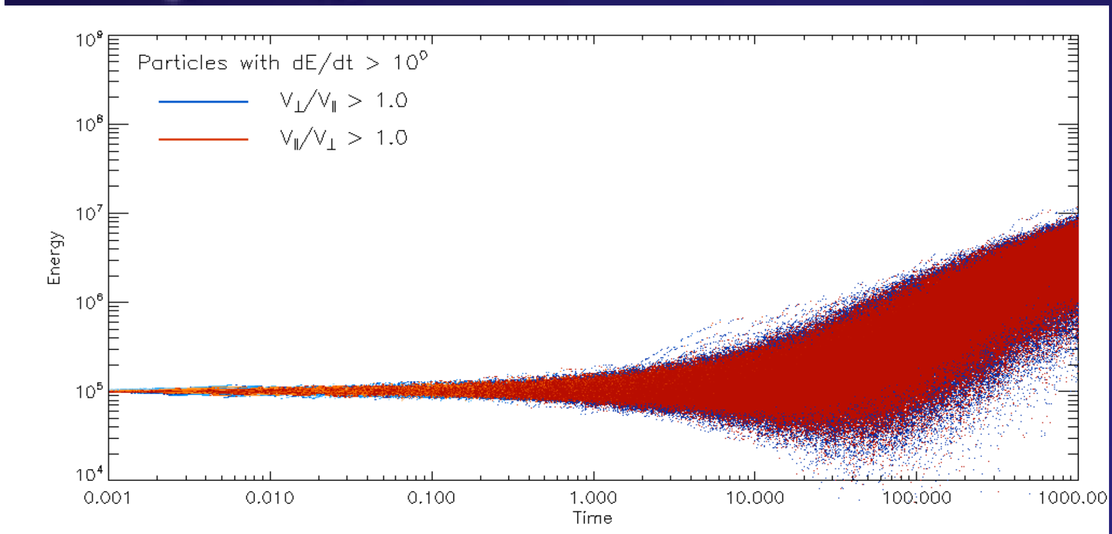


Regular energy increase

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



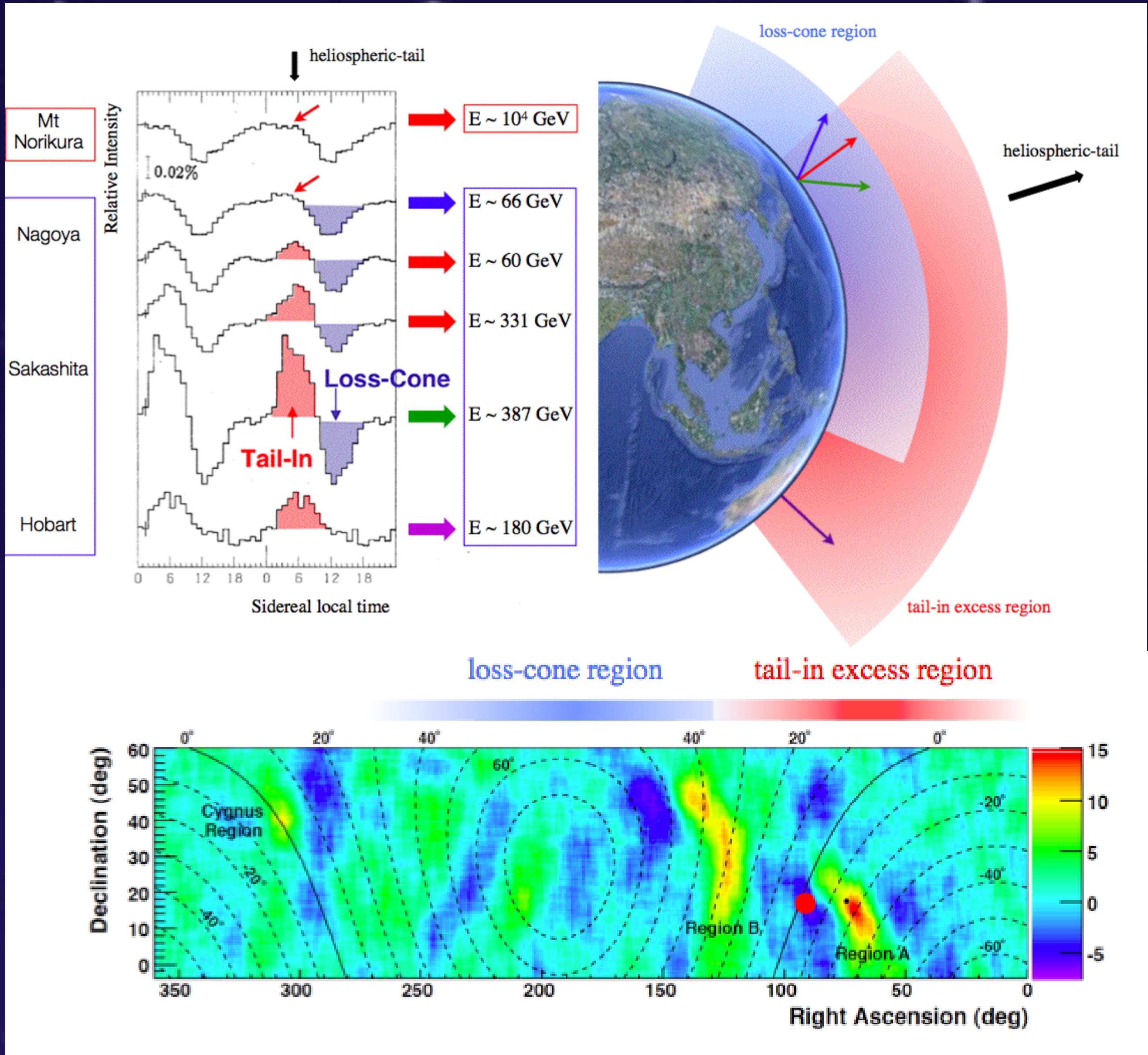
Perpendicular acceleration gets important for 2D at longer integration times



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

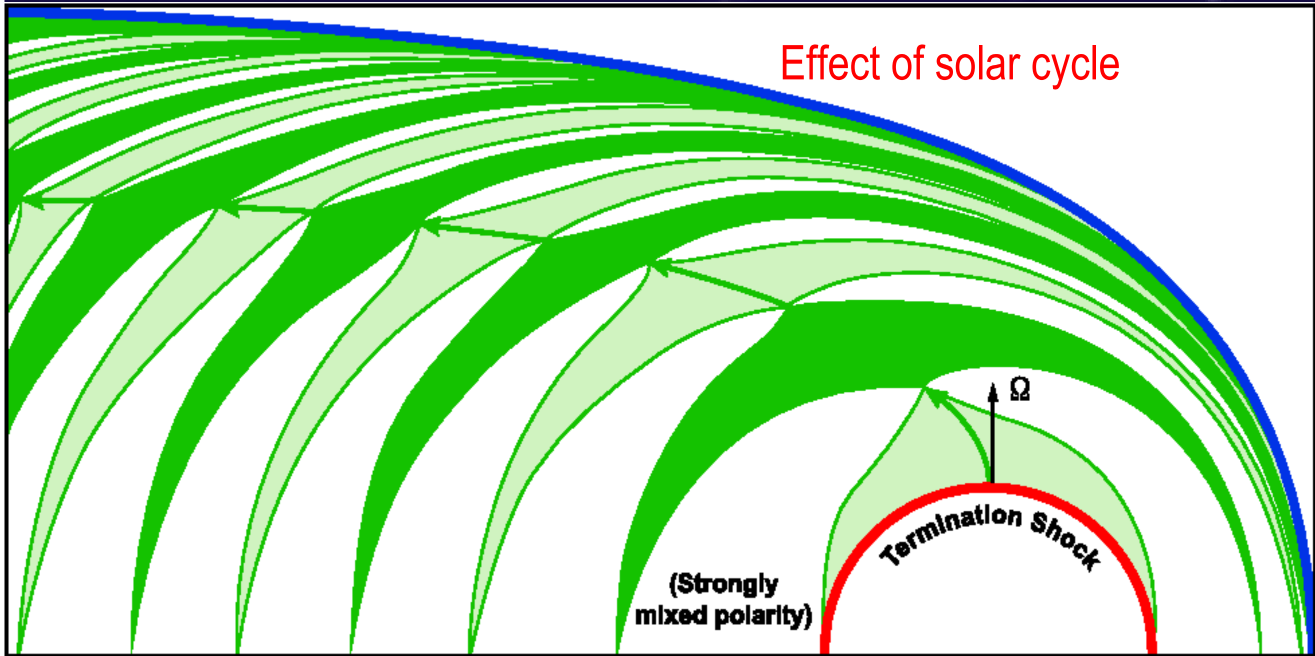


Abdo A.A. et al., 2008, Phys. Rev. Lett., 101, 221101

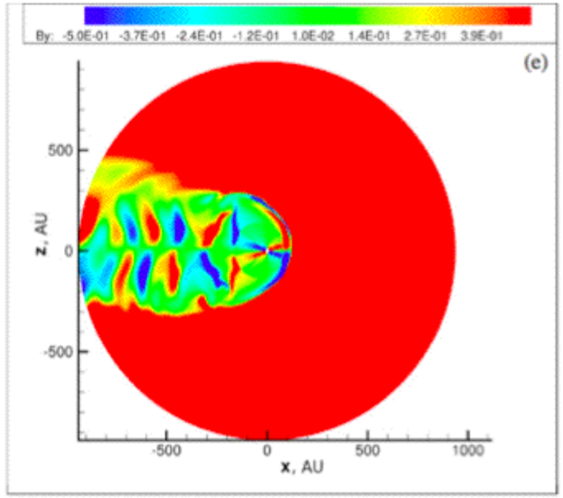
Low energy tail-in anisotropy

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



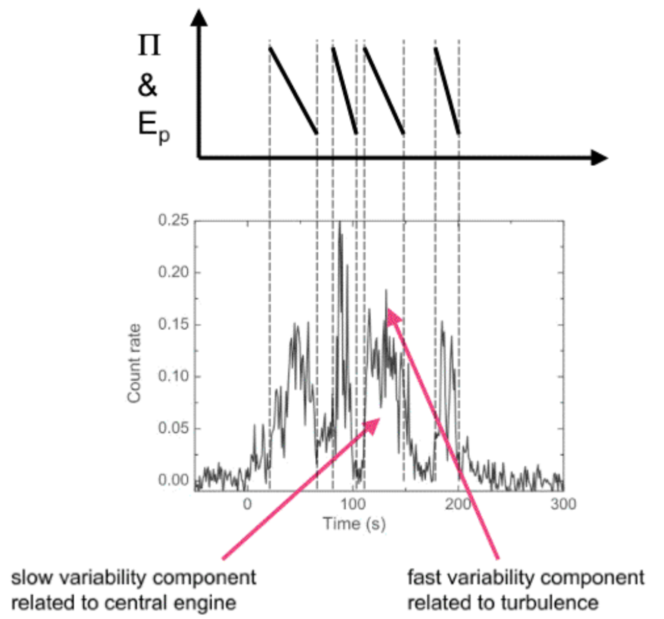
Lazarian & Desiatii 2010

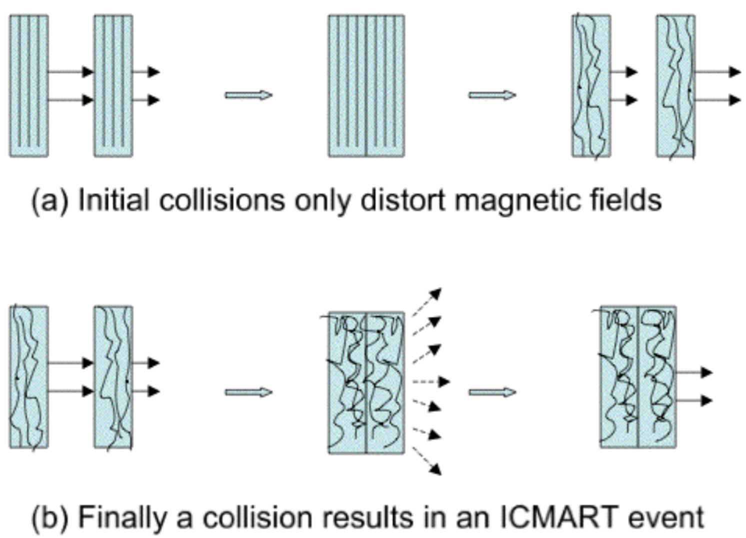
$$E_{max} \approx 10^{13}\ \mathrm{eV} \left(\frac{B}{1\ \mu\mathrm{G}}\right)\left(\frac{L_{zone}}{2\times 10^{15}\ cm}\right),$$

An important mechanism acting in gamma ray bursts, astrophysical jets, accretion disks, clusters of galaxies etc.

Example: gamma ray busts driven by turbulent reconnection are proposed in Lazarian, Yan & Petrosian 2003.

Recent detailed modeling by Zhang & Yan:



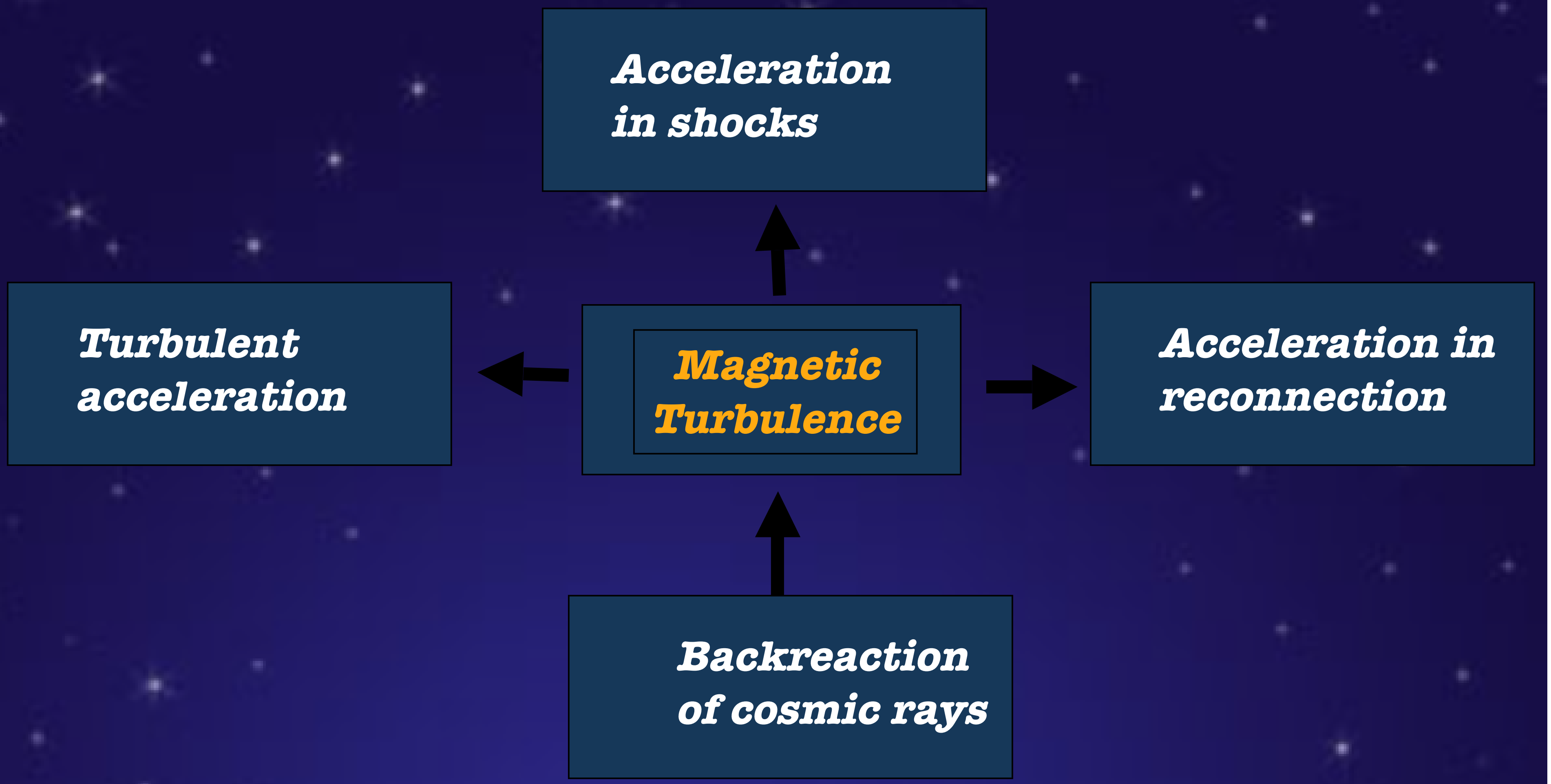


Zhang & Yan (2011)

Take home message 7:

- Turbulent reconnection accelerates CRs through first order Fermi acceleration.
- Acceleration in 2D and 3D reconnection sites is different.
- Turbulent reconnection can account for observational data.

Turbulence plays crucial role for all mechanisms of cosmic ray acceleration



There is deep connection between big power law of turbulence and big power law of cosmic rays

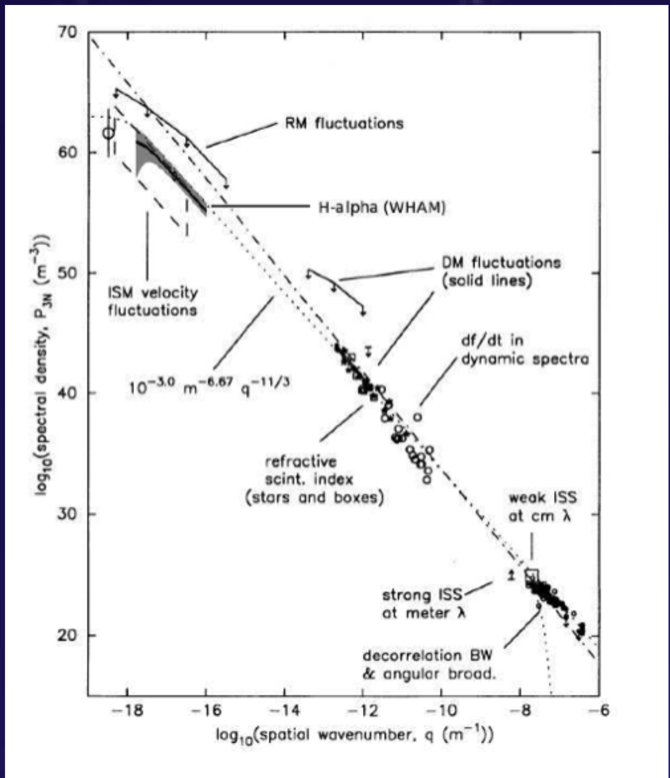
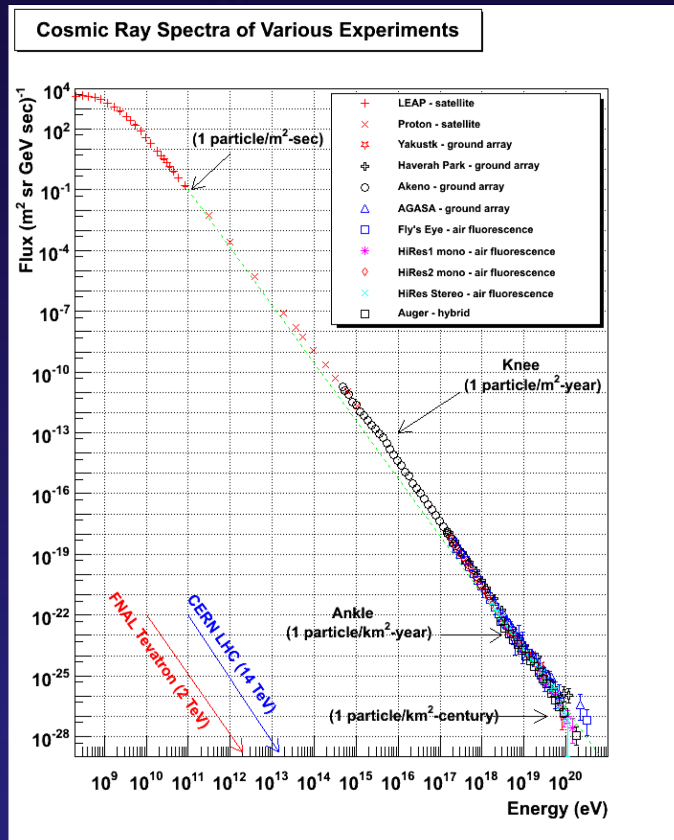
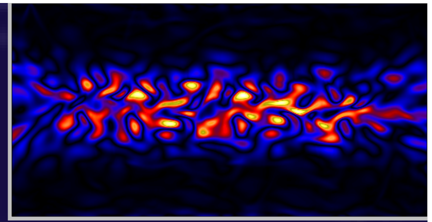
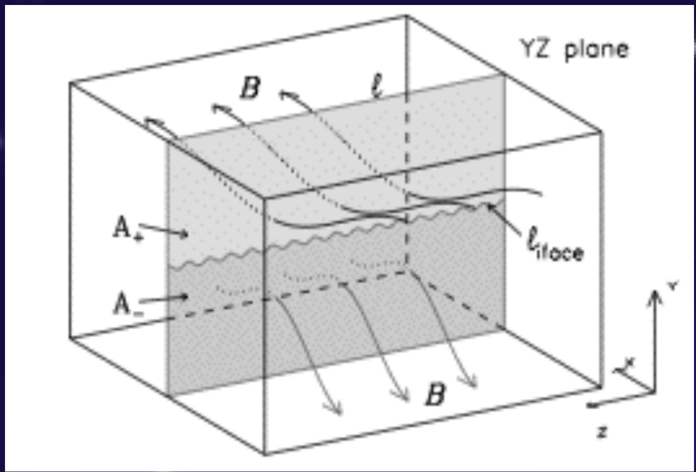


Fig. 5.— WHAM estimation for electron density overplotted on the figure of the Big Power Law in the sky figure from Armstrong et al. (1995). The range of statistical errors is marked with the gray color.



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





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

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

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

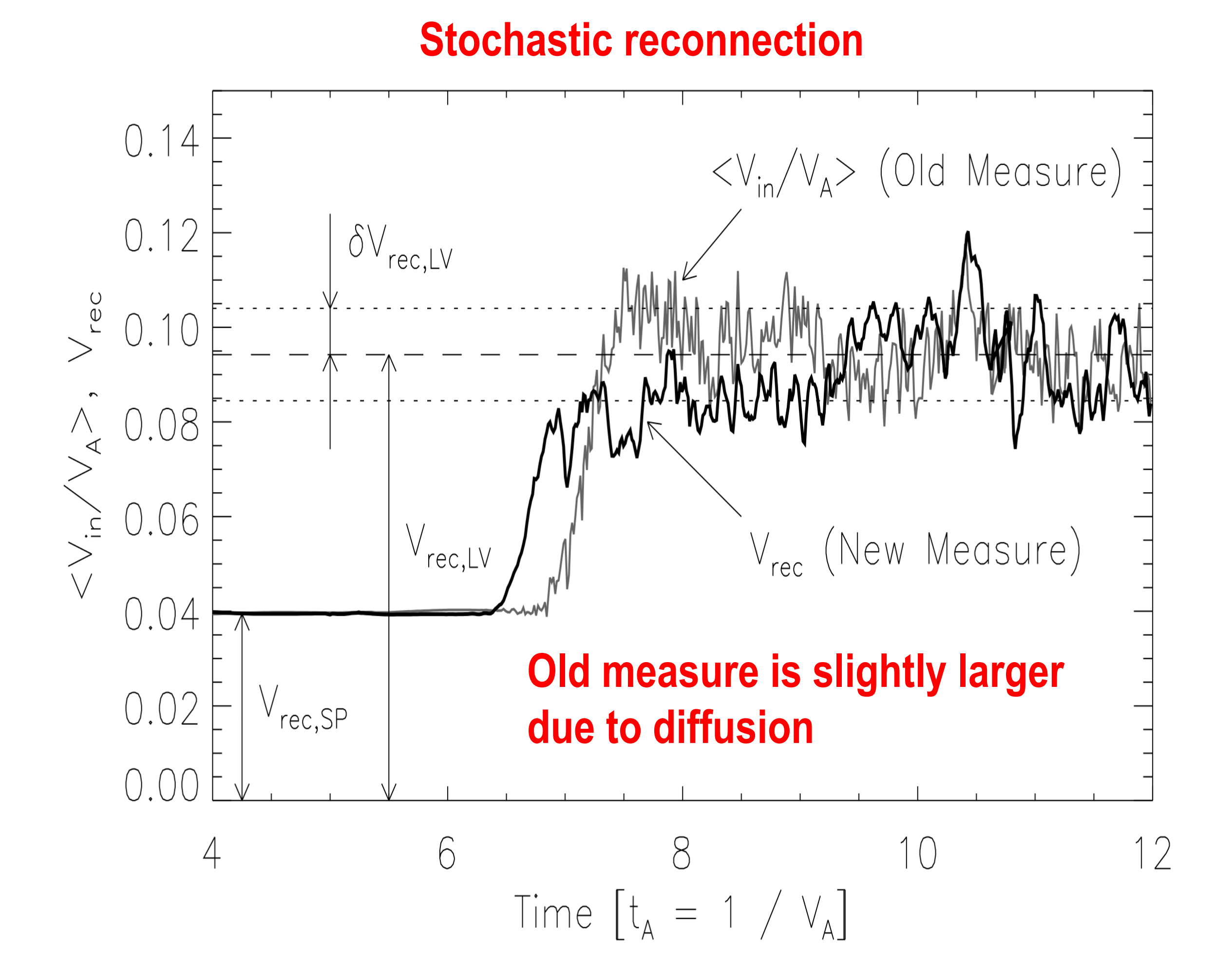
$$\int 2\vec{E}\cdot d\vec{l}_{interface} \equiv -2V_{rec}|B_{x,\infty}|L_z$$

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



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

New measure probes the annihilation of the flux

Interactions in plasmas are controlled by

$$\Lambda = 4\pi n_i \lambda_D^3 = T_i^{3/2}/[e^3(4\pi n_i)^{1/2}]$$

Table 1: *Key parameters for some typical weakly coupled plasmas.*

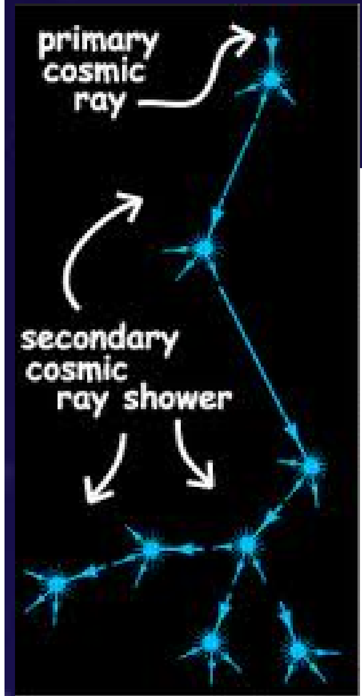
	$n(m^{-3})$	$T(eV)$	$\omega_p(sec^{-1})$	$\lambda_D(m)$	Λ
Interstellar	10^6	10^{-2}	6×10^4	0.7	4×10^6
Solar Chromosphere	10^{18}	2	6×10^{10}	5×10^{-6}	2×10^3
Solar Wind (1AU)	10^7	10	2×10^5	7	5×10^{10}
Ionosphere	10^{12}	0.1	6×10^7	2×10^{-3}	1×10^5
Arc discharge	10^{20}	1	6×10^{11}	7×10^{-7}	5×10^2
Tokamak	10^{20}	10^4	6×10^{11}	7×10^{-5}	4×10^8
Inertial Confinement	10^{28}	10^4	6×10^{15}	7×10^{-9}	5×10^4

From Fitzpatrick's lecture

Both plasma effects and turbulence may make reconnection fast, but keep in mind that astrophysical fluids are turbulent

	Plasma effects	Turbulence
Plasma effects	A lot of work on collisionless reconnection	LV99 + plasma effects on small scales
Turbulence	LV99 + plasma effects on small scales	LV99 model

Observed secondary elements supports scattering by fast modes!



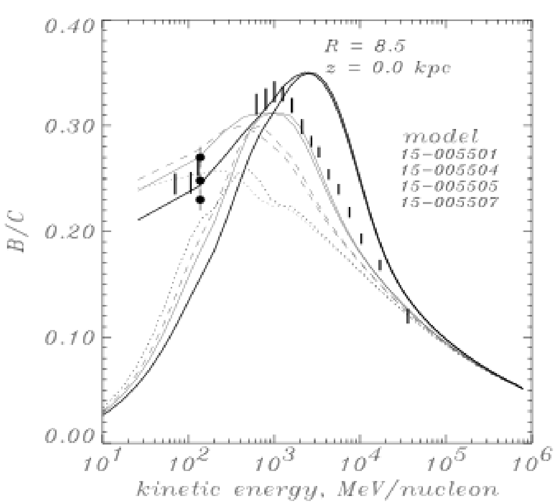
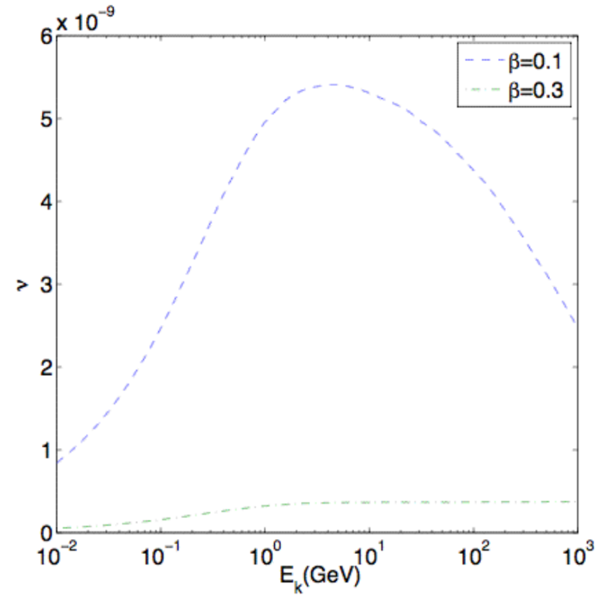


Figure 1. B/C ratio for diffusive reacceleration models with z_h = 5 kpc, $v_A = 0$ (dotted), 15 (dashed), 20 (thin solid), 30 km s^{-1} (thick solid). In each case the interstellar ratio and the ratio modulated to 500 MV is shown. Data: from Webber et al. (1996).



Scattering by fast modes

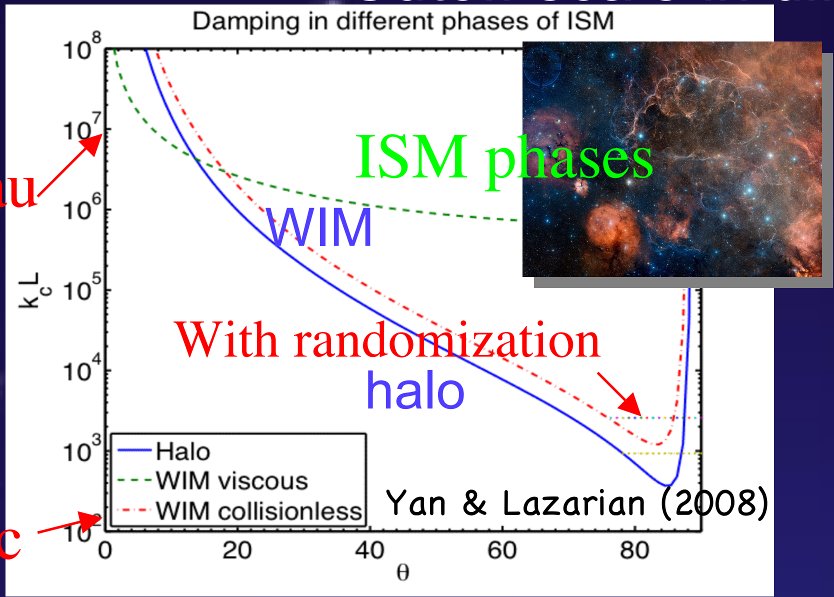
Anisotropy of fast modes arising from damping

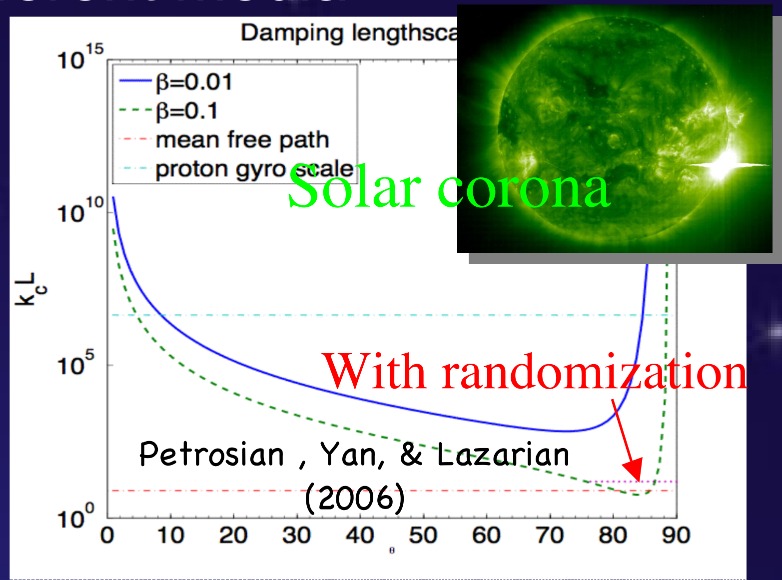
Cutoff scale in different media

$k_c L$

1au

1pc



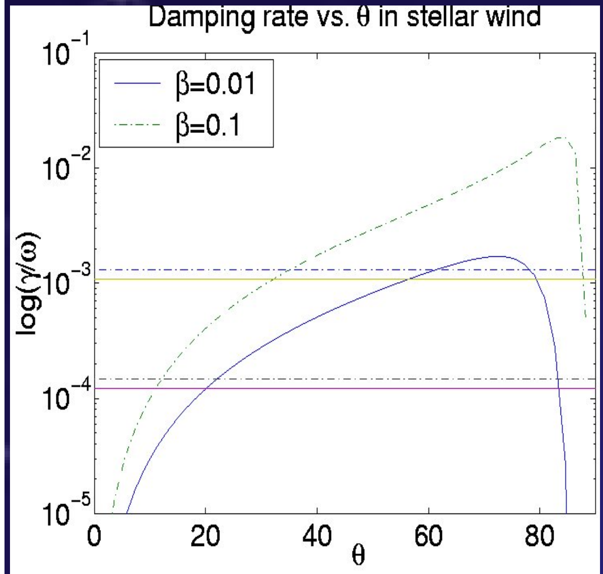


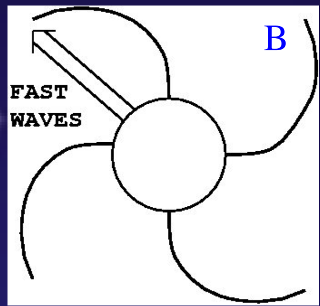
Wave pitch angle

Wave pitch angle

- Damping depends on medium.
- Anisotropic damping results in quasi-slab geometry.
- Field line wandering should be accounted for.

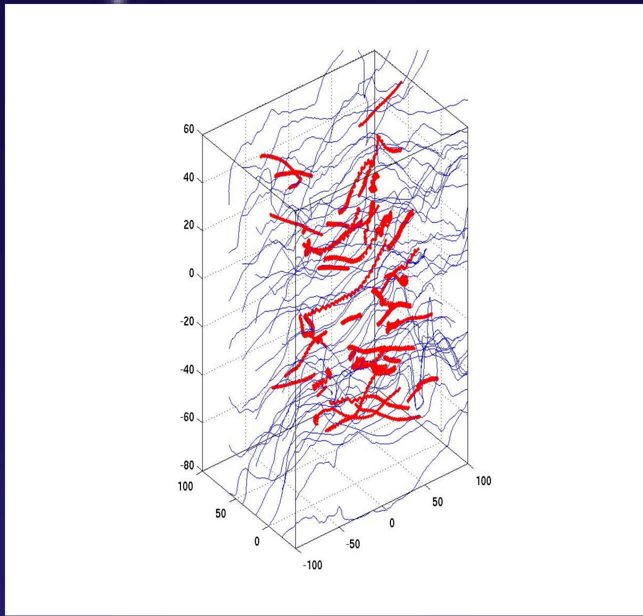
Application to stellar wind





heating by collisionless damping
is dominant in rotating stars
(Suzuki, Yan, Lazarian, & Casseneli 2005).

Comparison w. test particle simulation



– Particle trajectory

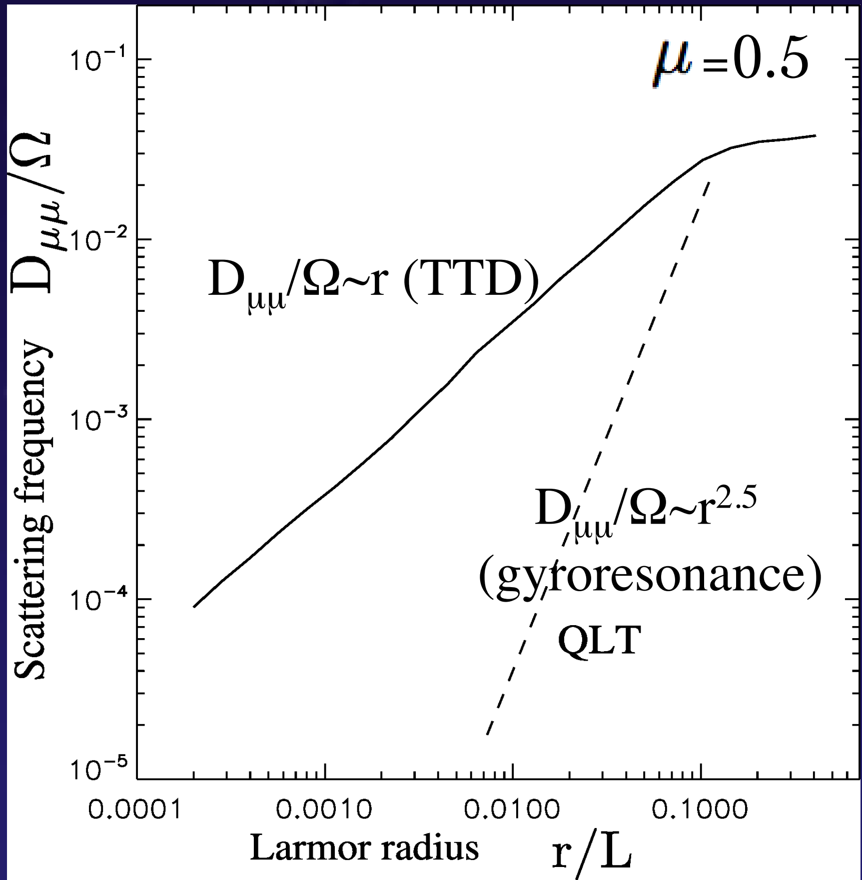
— Magnetic field

- a realistic fluctuatating **B** fields from numerical simulations

Results of Monte-Carlo simulations

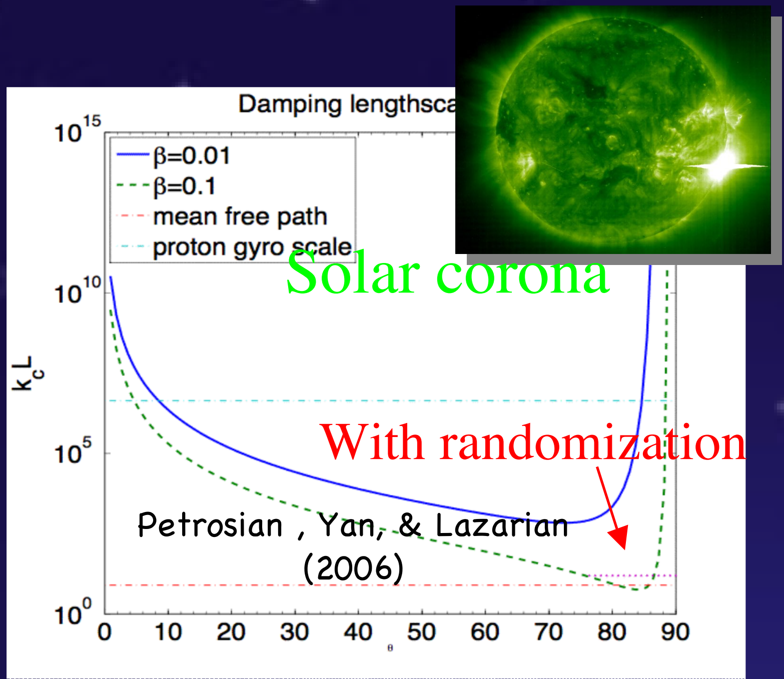
- Particle scattering in incompressible turbulence

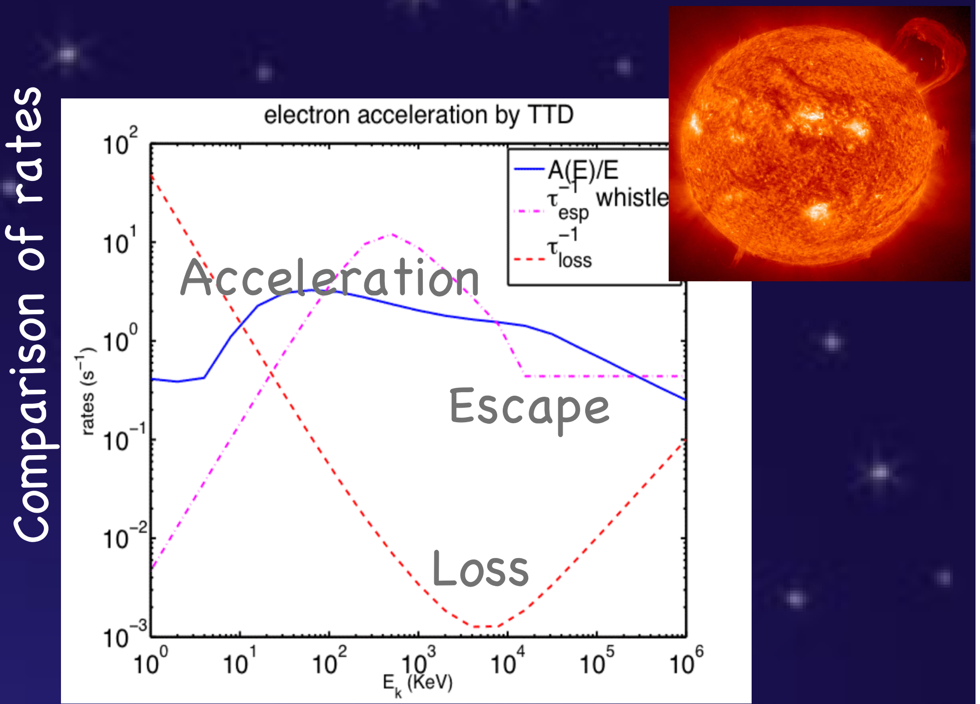
Ω— gyration frequency,
L — outer scale of turbulence.



(obtained from particle tracer, Beresnyak, Yan & Lazarian 2010)

Detailed study of solar flare acceleration must include damping, nonlinear effects



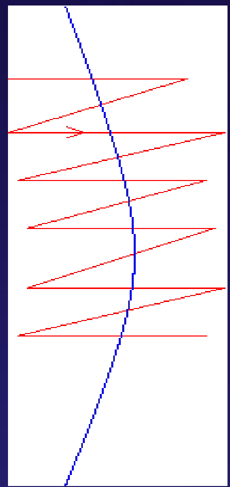


TTD Acceleration by fast modes is an important mechanism

to generate energetic electrons in Solar flares (Yan, Lazarian & Petrosian 2008).

Interaction w. small scale waves: Streaming instability

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



Downstream

Upstream

Turbulence
generated
by shock

Turbulence
generated
by streaming

Streaming cosmic rays result in formation of perturbation that scatters cosmic rays back and increases perturbation.
This is streaming instability that can return cosmic rays back to shock and may prevent their fast leak out of the Galaxy.

Streaming instability of CRs is suppressed

1. MHD turbulence can suppress streaming instability (*Yan & Lazarian 2002*).

2. Calculations for weak case ($\delta B<B$):

With background compressible turbulence (*Yan & Lazarian 2004*):

$$E_{max} \approx 1.5 \times 10^{-9} [n_p^{-1}(V_A/V)^{0.5}(Lc\Omega_0/V^2)^{0.5}]^{1/1.1} E_0$$

This gives $E_{max} \approx 20$GeV for HIM.

A similar estimate was obtained with background Alfvenic turbulence (*Farmer & Goldreich 2004*).

7 points of my talk:

- Turbulence is a natural state of fluids around us
- Turbulence is everywhere in astrophysical fluids
- Turbulence theory has been altered in the last decade
- Turbulence theory changes induce changes of CR paradigm
- Turbulence-precursor interaction changes shock acceleration
- Turbulence induces fast magnetic reconnection
- Turbulent reconnection induces First order Fermi acceleration

Alternative for UPSTREAM tubulence?

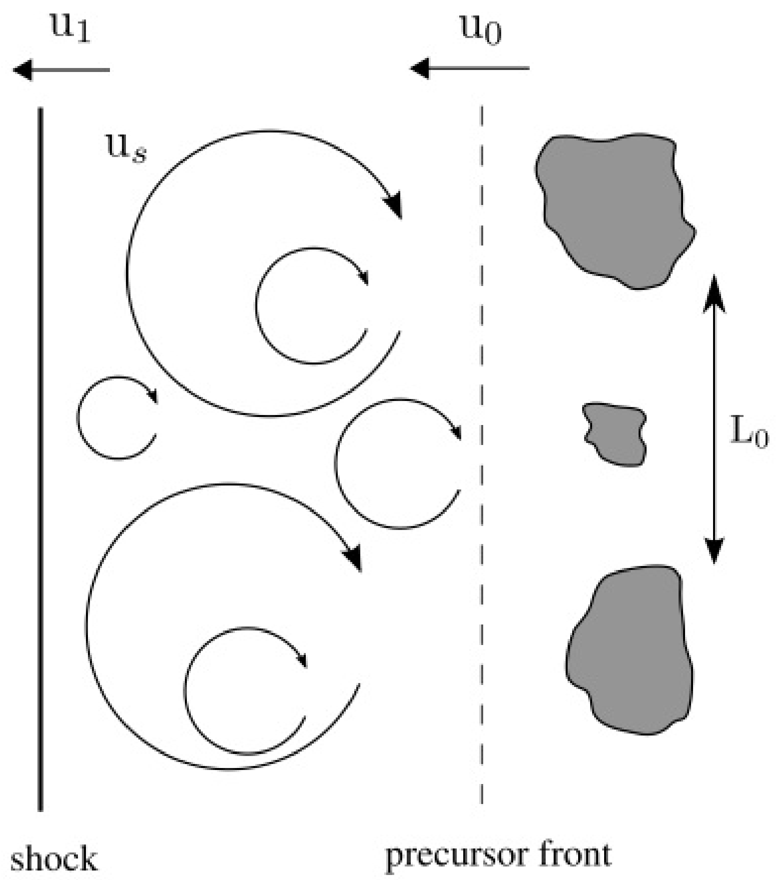


Figure 2. Solenoidal motions, excited by CR precursor (the real picture is three dimensional). In the frame of the shock the preexisting perturbations enter the precursor creating both compressive and solenoidal velocity perturbations (the last being depicted). Beresnyak, Jones & Lazaian (2009)

Implication: Magnetically limited X-ray filaments in young SNRs

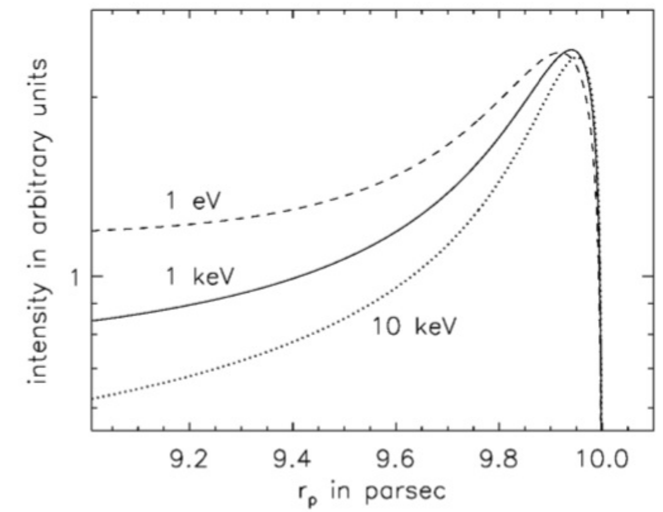


FIG. 1.—Nonthermal X-ray intensity as a function of the projected distance from the SNR center. The acceleration site is located at $r_s = 10$ pc. The solid line shows the intensity at 1 keV, and the dotted line displays the (scaled) intensity at 10 keV X-ray energy. The dashed line indicates the scaled intensity profile at very low photon energies.

Strong magnetic field produced by streaming instability at upstream of the shock, may be damped by turbulence at downstream, generating filaments of a thickness of 10^{16}-10^{17}cm (Pohl, Yan & Lazarian 2005).

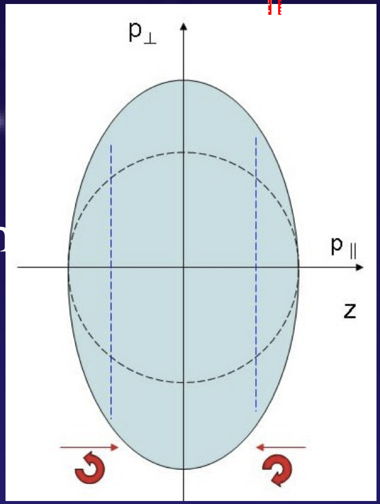
Wave Growth is limited by Nonlinear Suppression!

$$A \equiv \frac{W_\perp}{W_\parallel} - 1$$

$\frac{dA}{dt} > 0$

Turbulence compression

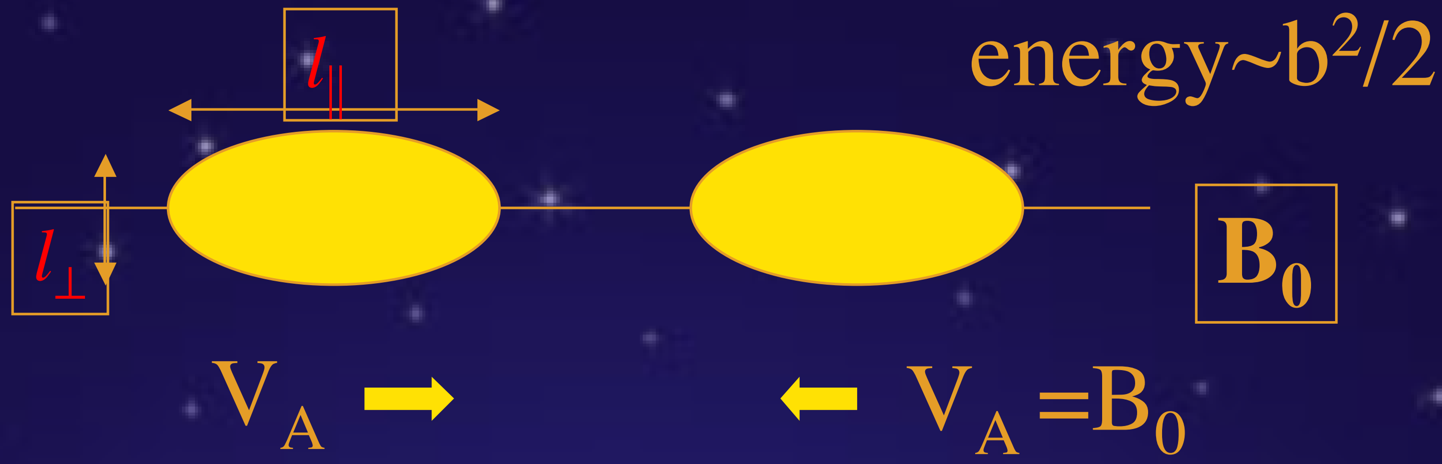
Pgas/P_{mag} < 1, fast modes (isotropic cascade +anisotropic damping)
Pgas/P_{mag} > 1 slow modes (GS95)



$\frac{dA}{dt} < 0$

Scattering by instability generated slab wave

Magnetic turbulence can be viewed in terms of interacting wave packets



When they collide, a packet loses energy of

$\Delta E \sim (dE/dt)\Delta t \sim (b^3/\, l_{\perp}\,) t_{coll} \sim (b^3/\, l_{\perp}\,)(l_{\parallel}/V_A)$.

Therefore $\Delta E\, /E \sim (b^3/\, l_{\perp}\,)(l_{\parallel}/V_A) \,/\, b^2$

$$= (b\, l_{\parallel} \,/\, l_{\perp} B_0)$$

$$= (l_{\parallel}/B_0)/(\, l_{\perp}\, /b\,)$$

$$= t_w/t_{eddy} = \chi$$

$\chi \sim 1$ strong turbulence

$\chi < 1$ weak turbulence