Energetic particles in Astrophysical turbulence

Huirong Yan

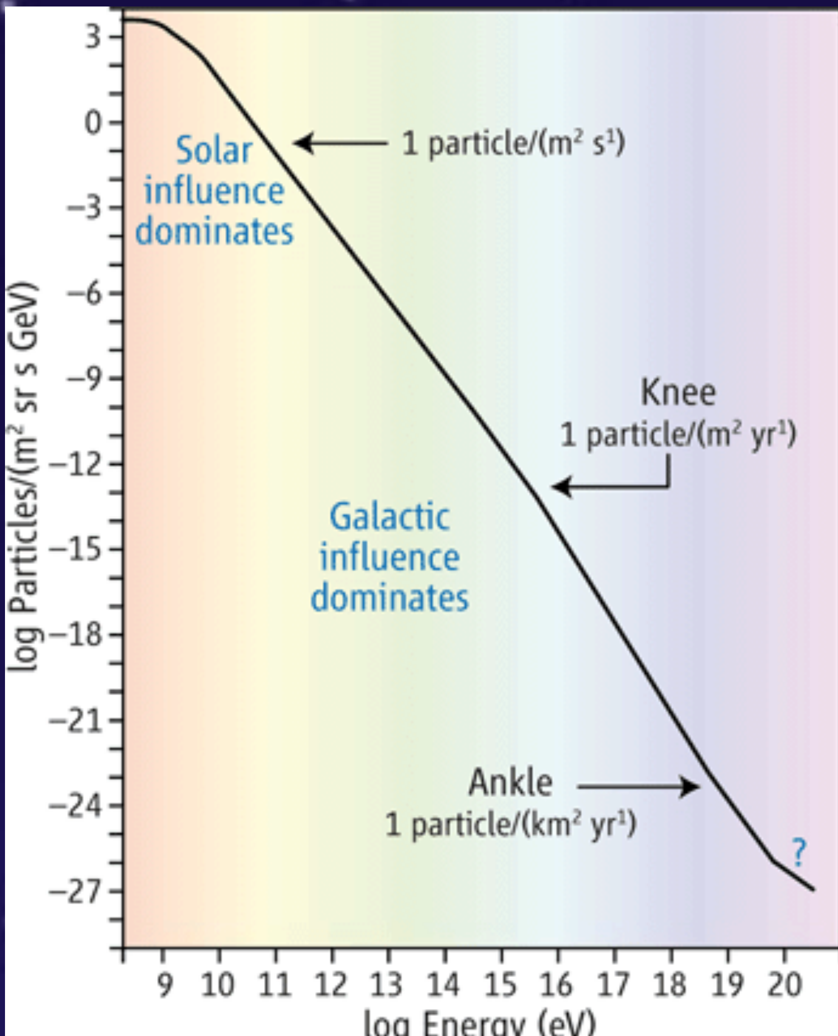
Deutsches Elektronen-Synchrotron (DESY)

& *Universität Potsdam*

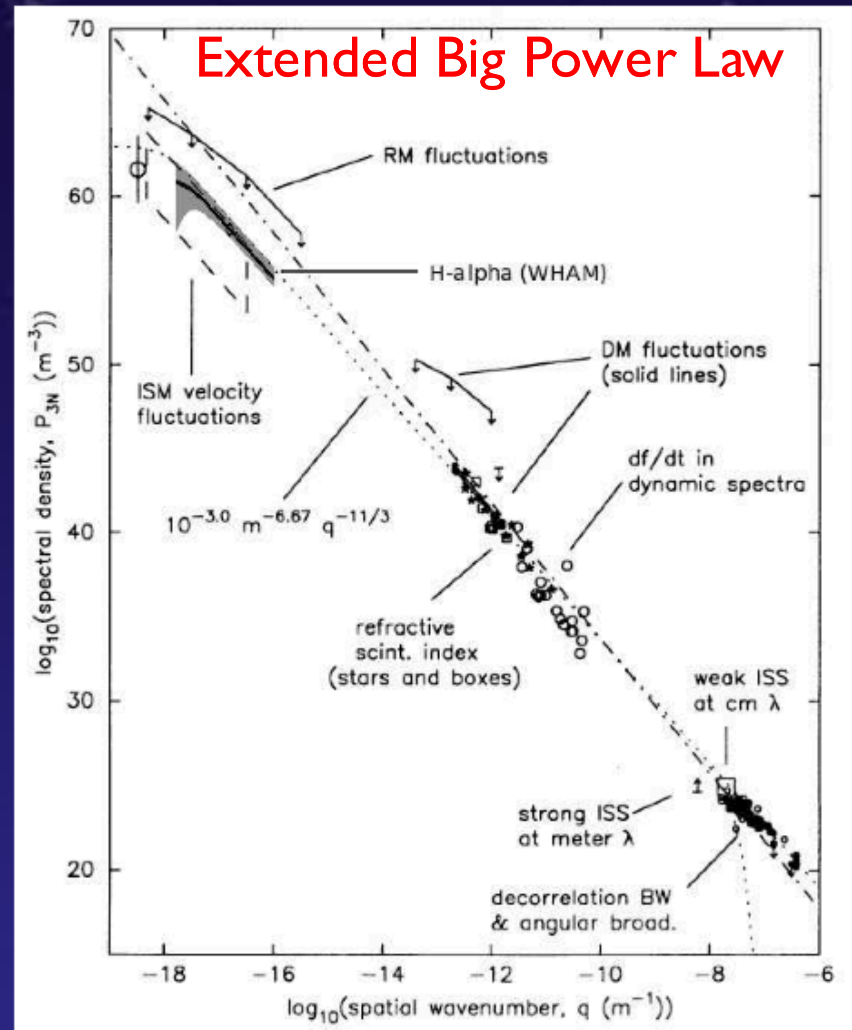
Big questions in cosmic ray physics:

- What are the sources of the high-energy particles called cosmic rays?
- How does nature accelerate particles to higher energies than is possible in man-made accelerators such as the LHC?
- What is the engine of the brightest and most violent explosion in the universe?
- Can cosmic rays provide insights about the nature of dark matter?

Cosmic Rays and turbulence

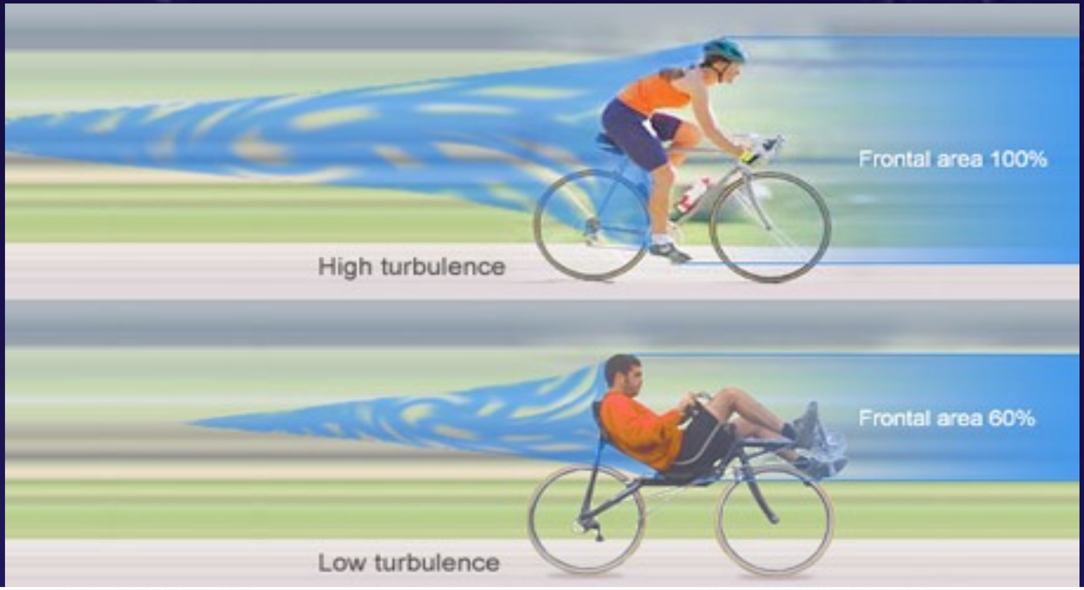


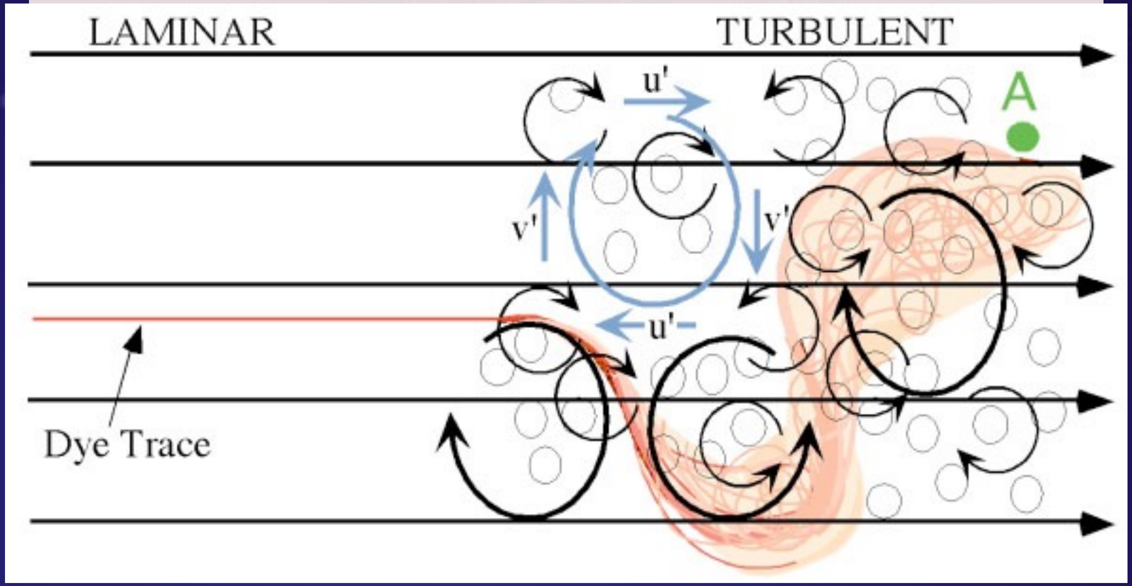
M. Duldig 2006



Armstrong et al. 1995, Chepurnov & Lazarian 2009

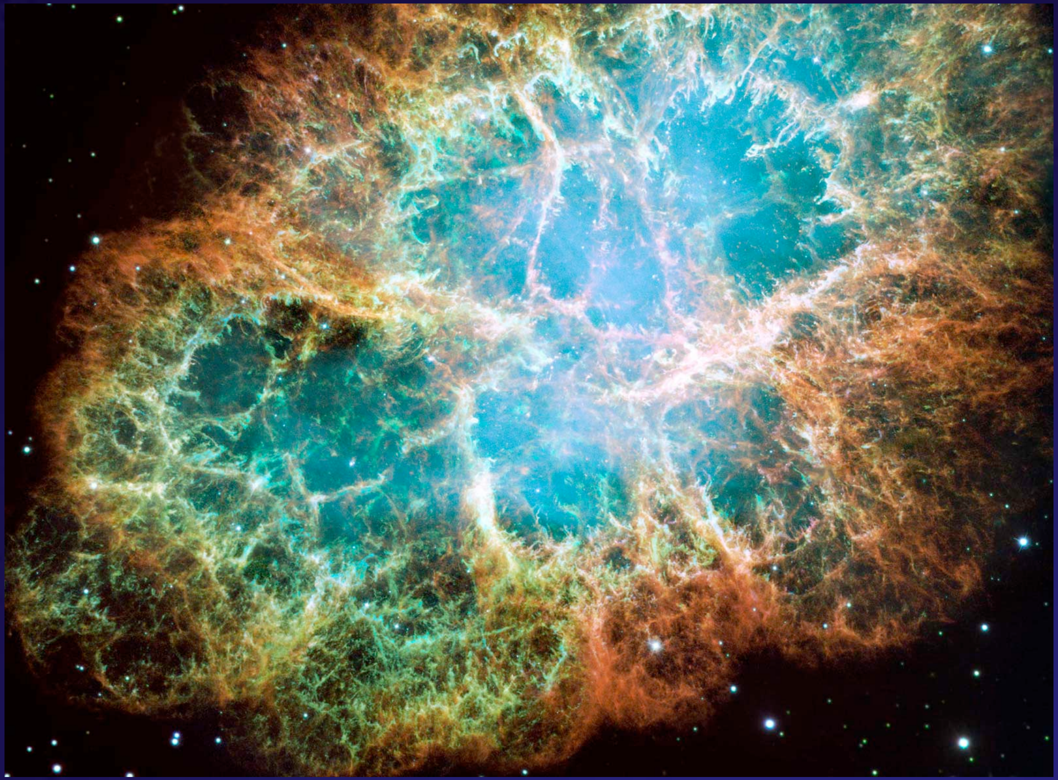
From laminar flow to turbulence cascade

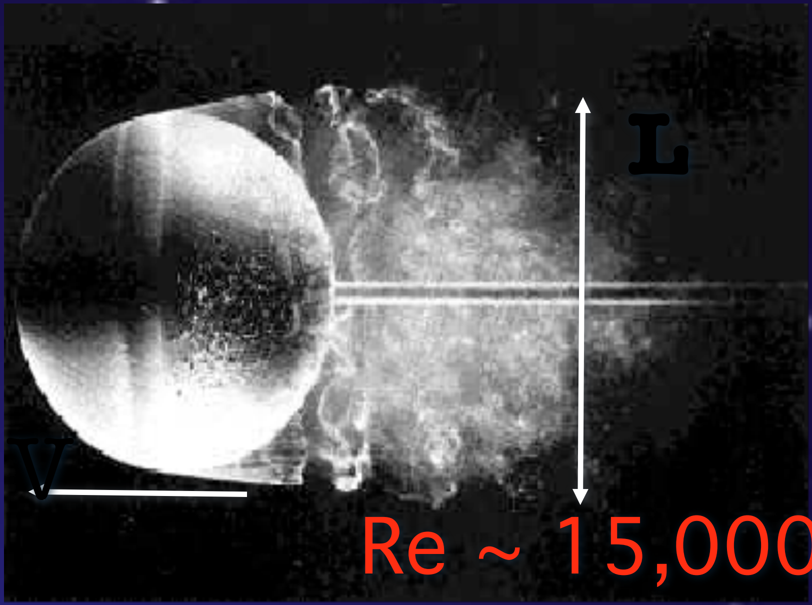




Astrophysical fluids are turbulent as Reynolds numbers of flows are high

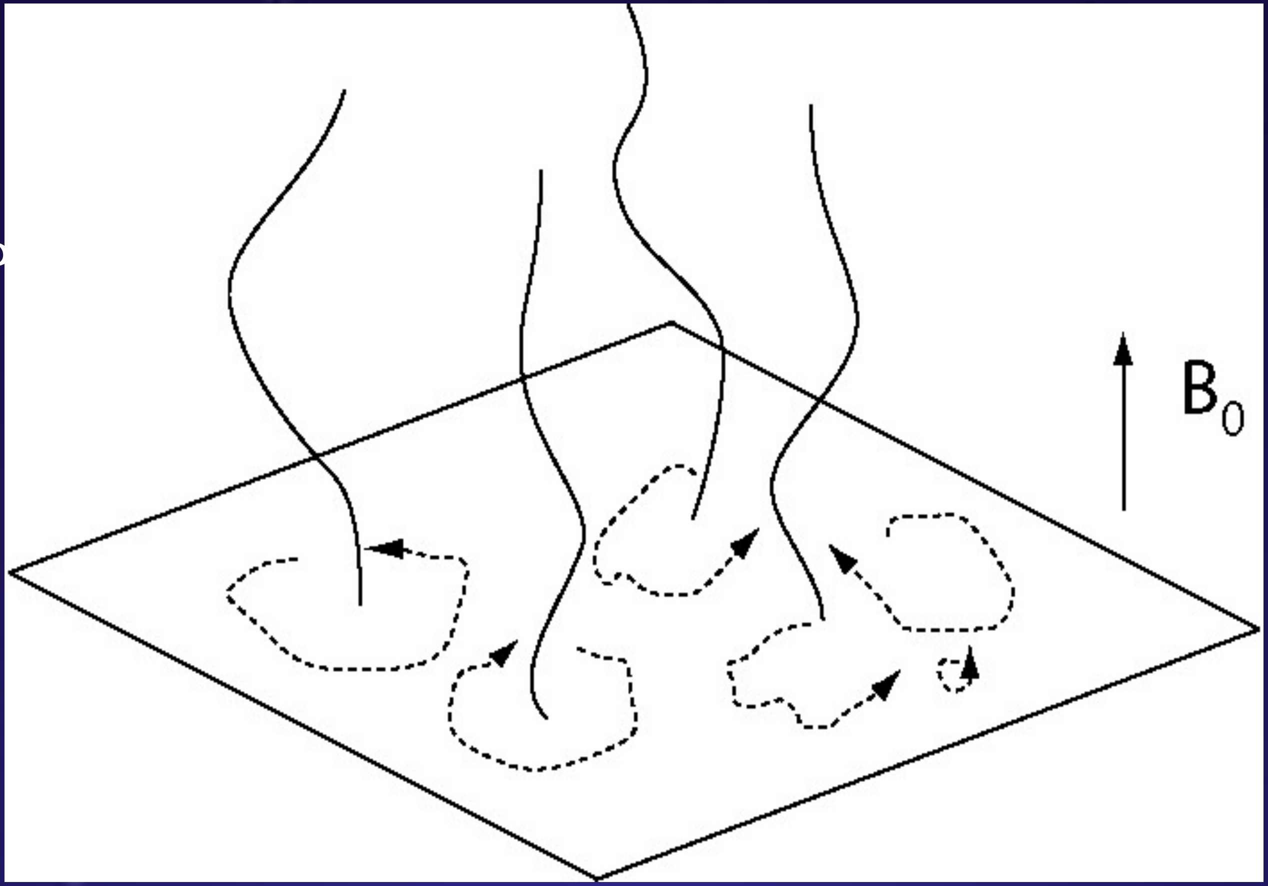
$$Re = LV/\nu = (L^2/\nu)/(L/V) = \tau_{diff}/\tau_{eddy}$$





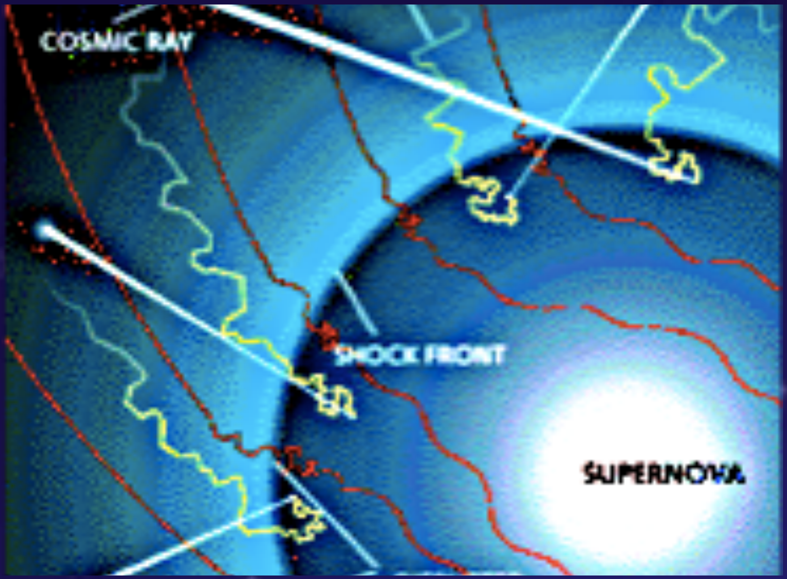
Astrophysical flows have Re>10^{10}.

B fields are frozen in and comove with astrophysical fluid!

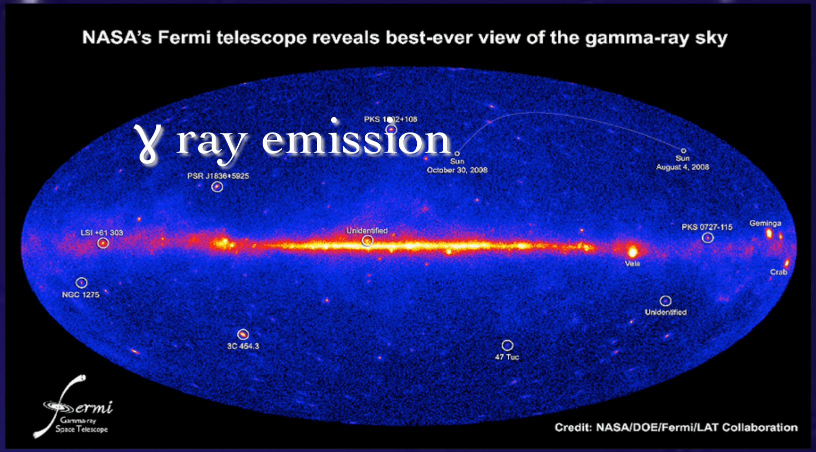


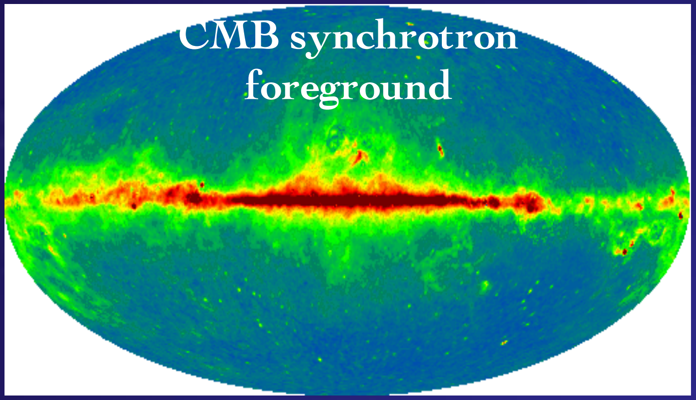
- P

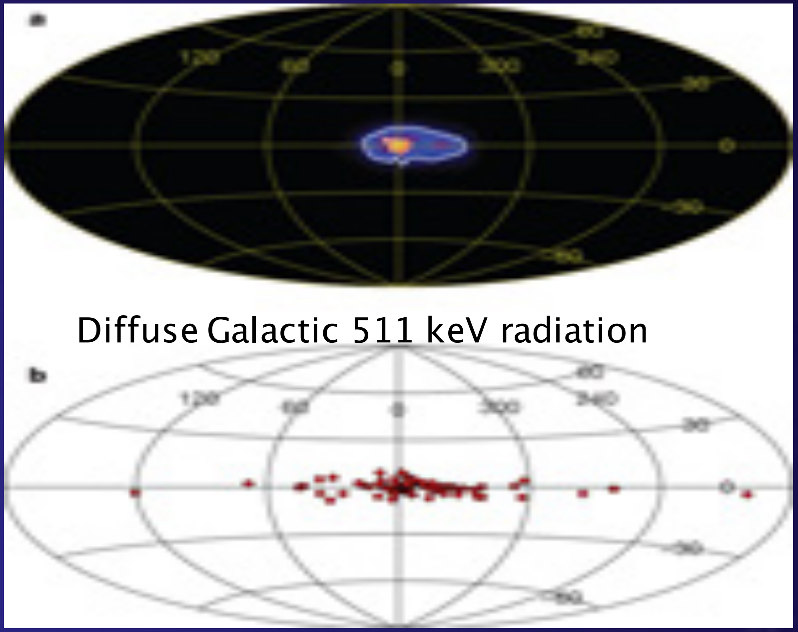
Importance I: Cosmic Ray (CR) Propagation



Particle trajectory
Magnetic field

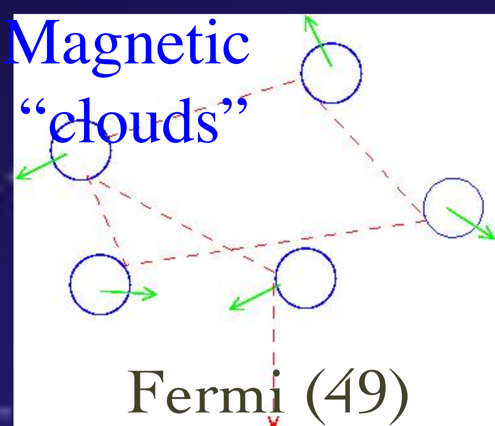




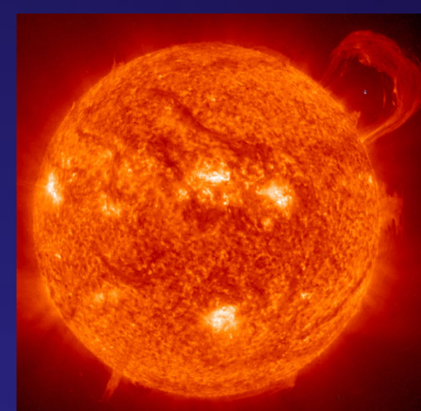


Importance of wave-particle interaction: Fermi II

Stochastic Acceleration:



Gamma ray burst



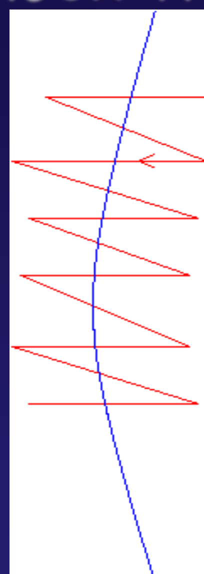
Solar Flare

Importance to Fermi I acceleration

- Shock Acceleration
- Reconnection Acceleration

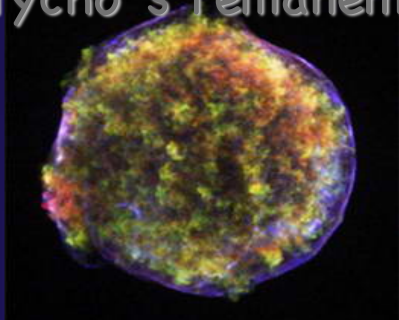
Shock front

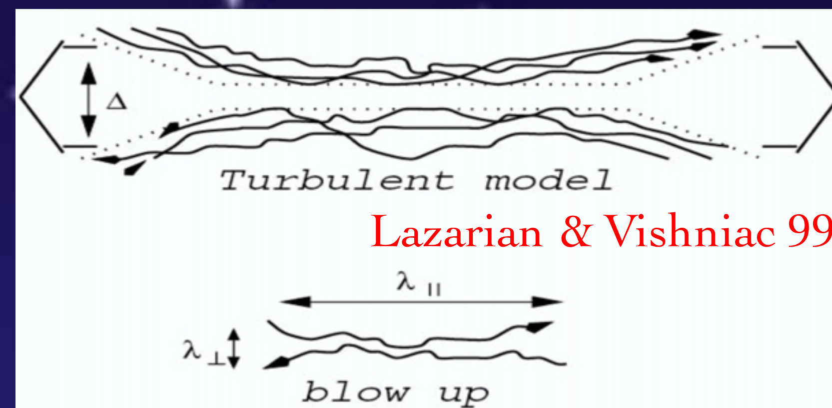
Turbulence generated by streaming

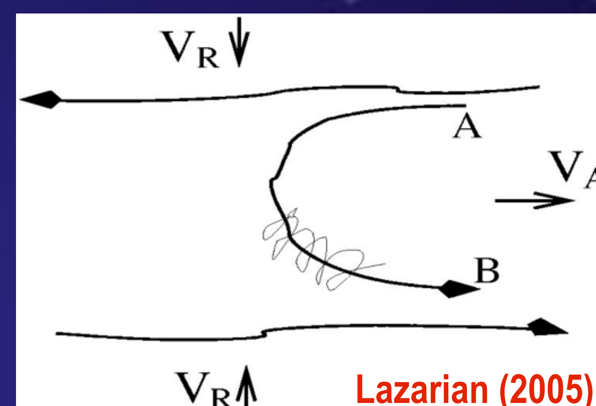


Turbulence generated by shock

Tycho's remanent







Big simulation itself is not adequate

- big numerical simulations fit results due to the existence of "knobs" of free parameters (see, e.g., http://galprop.stanford.edu/).
- Self-consistent picture can be only achieved on the basis of theory with solid theoretical foundations and numerically tested.

Outline

a. Particle Scattering in tested model of MHD turbulence

b. Cross field transport in MHD turbulence

c. Turbulent reconnection model for ϒ ray burst (GRBs)

Outline

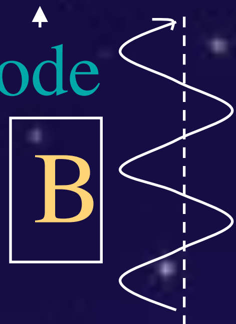
a. Particle Scattering in tested model of turbulence

b. Cross field transport in turbulence

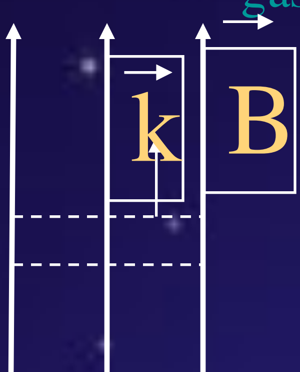
c. Turbulent reconnection model for γ ray burst (GRBs)

MHD turbulence can be decompsed

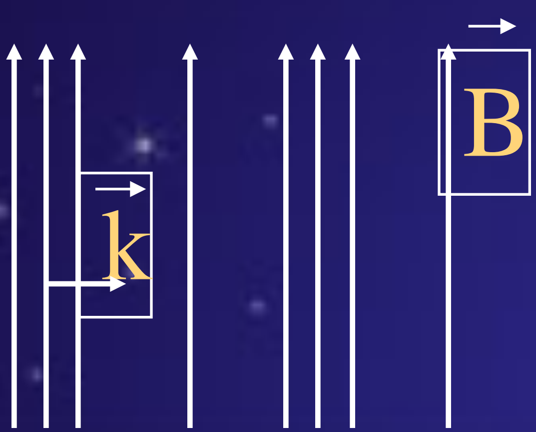
Alfven mode

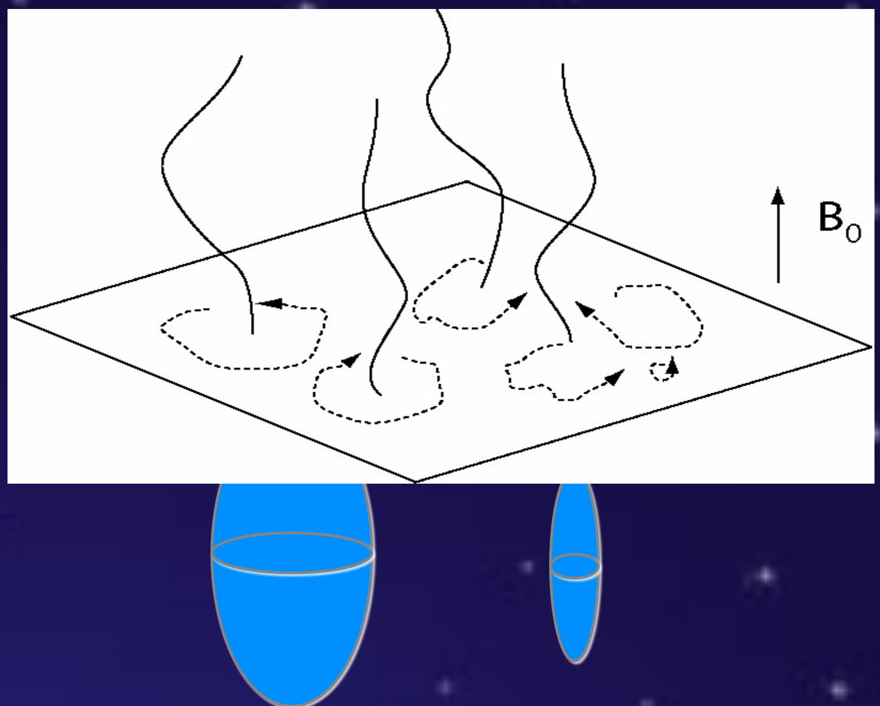


slow mode $|P_{gas}-P_{mag}|$

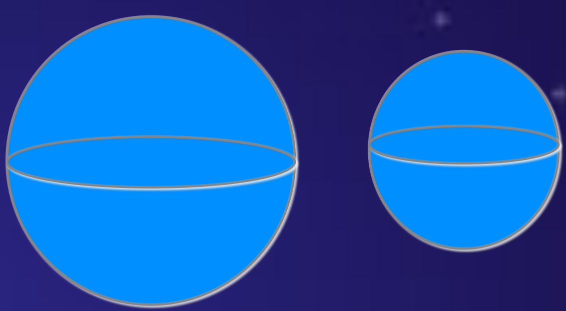


fast mode $P_{mag} + P_{gas}$





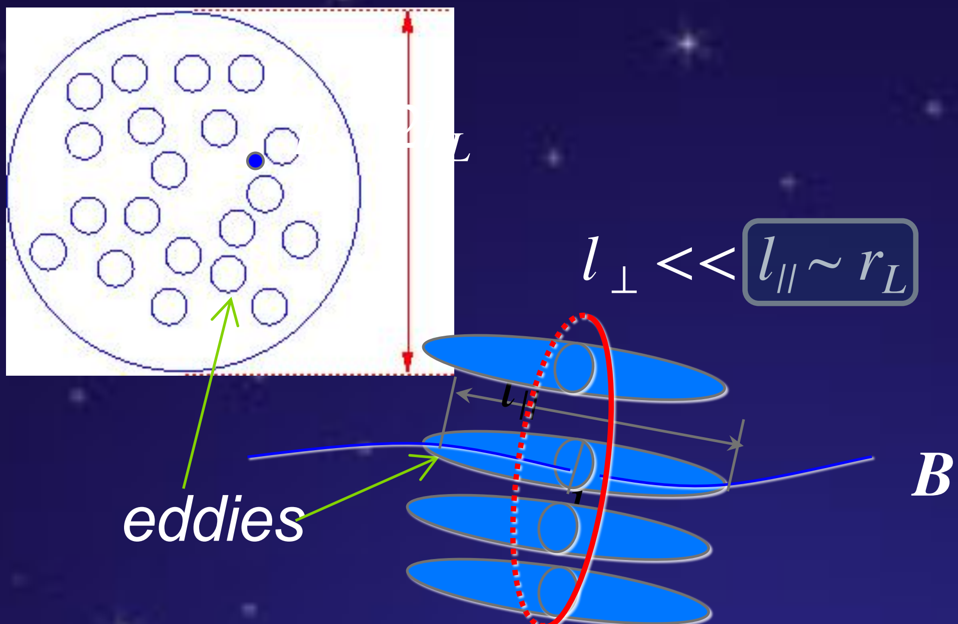
Goldreich & Sridhar 1995;
Lithwick & Goldreich 01



Cho & Lazarian 02

Contrary to common belief: Scattering in Alfvenic turbulence is negligible!

1. "random walk"



scattering efficiency is reduced

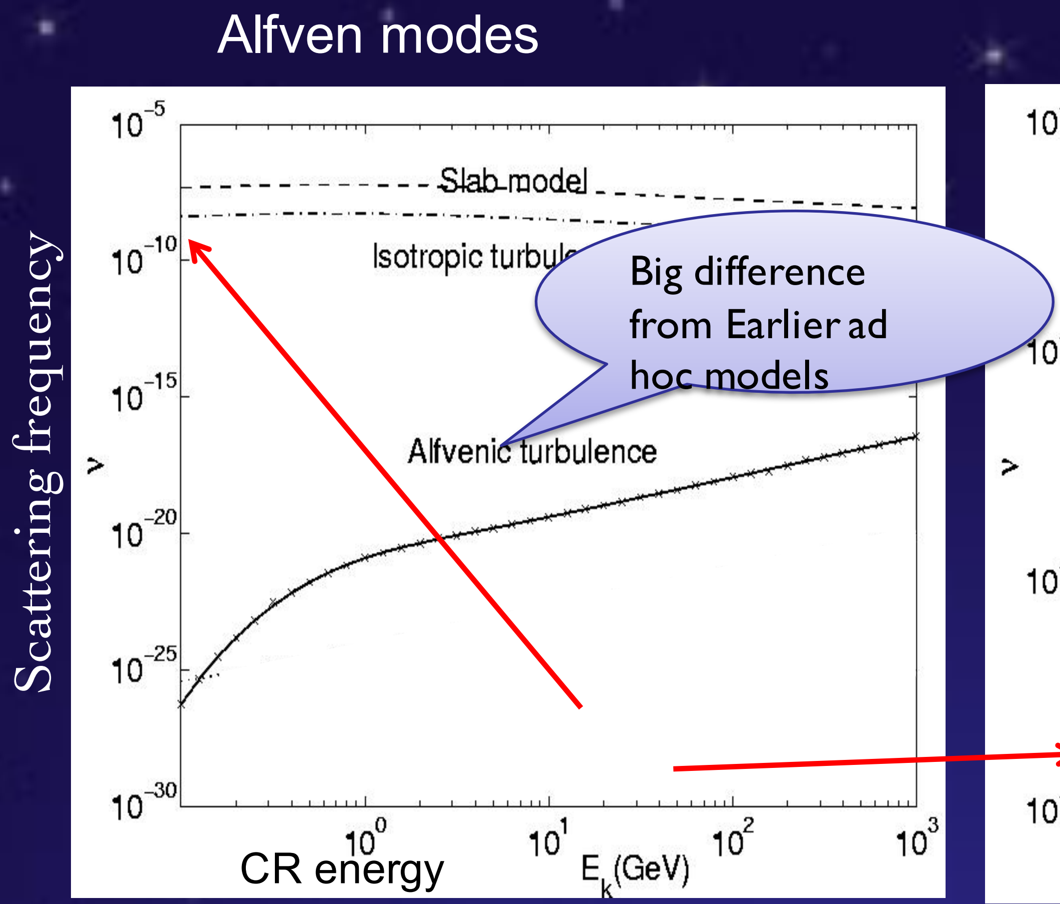
2. "steep spectrum"

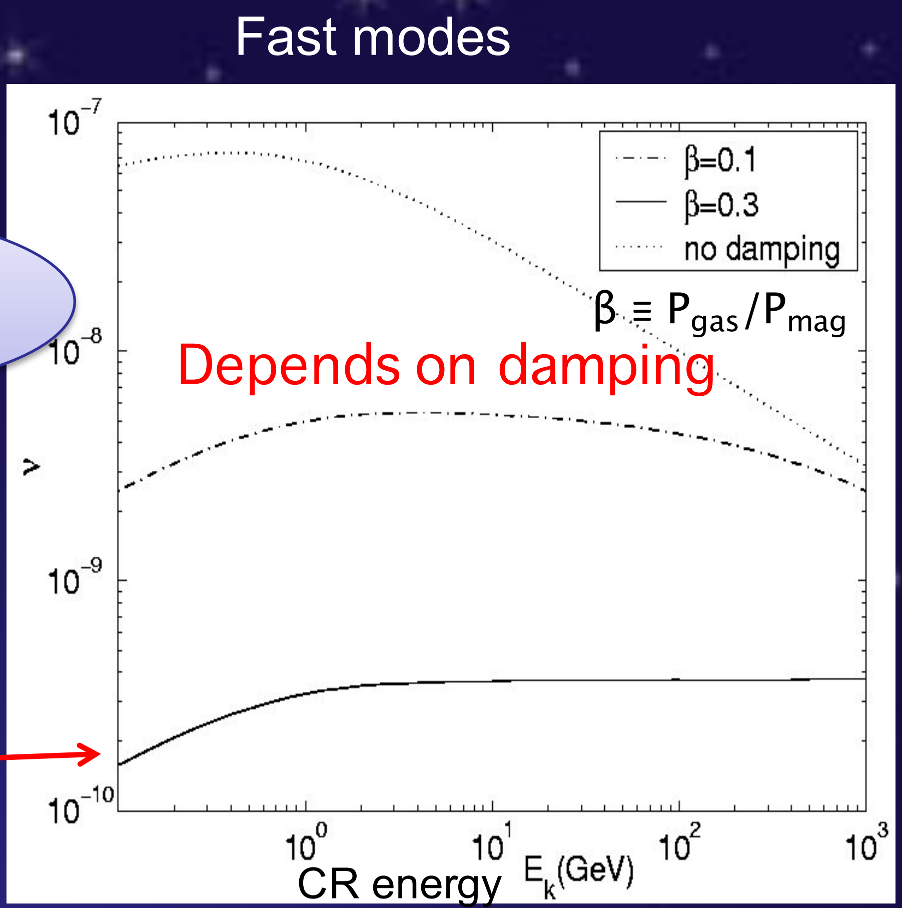
$$E(k_{\perp}) \sim k_{\perp}^{-5/3},\ k_{\perp} \sim L^{1/3} k_{||}^{3/2}$$

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

Steeper than Kolmogorov!
Less energy on resonant scale

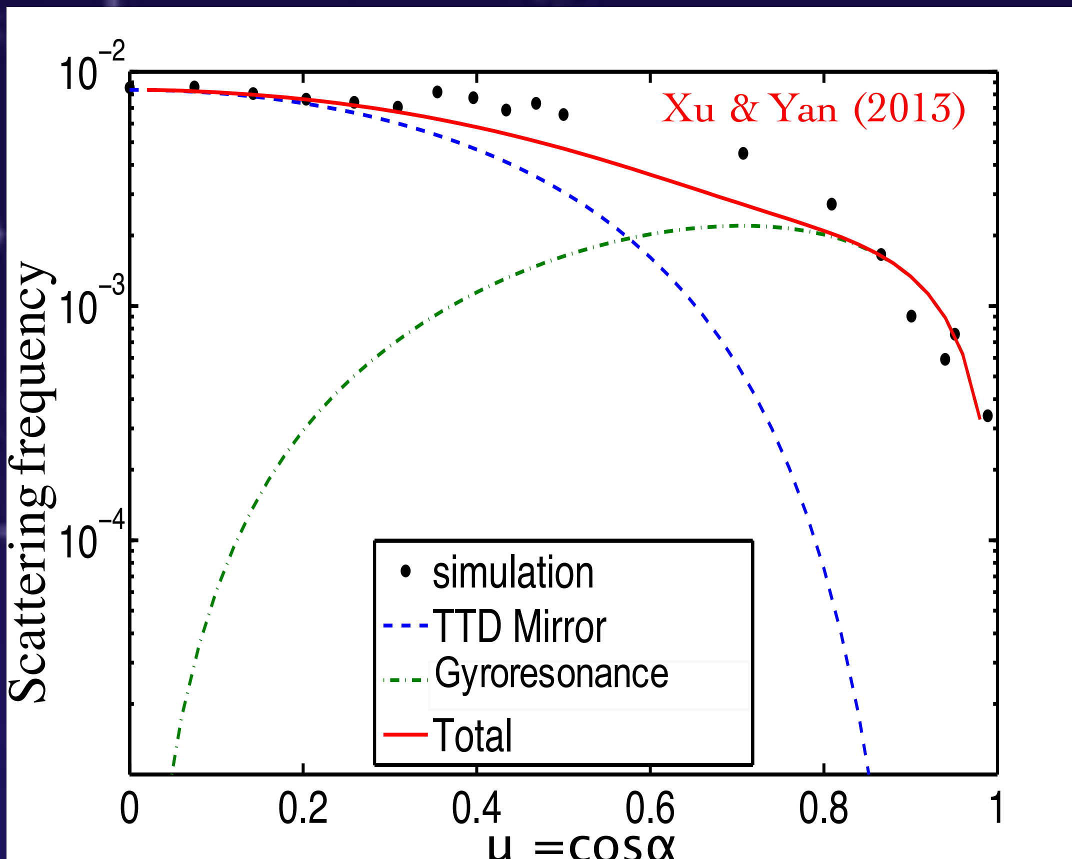
Fast modes dominate CR scattering!

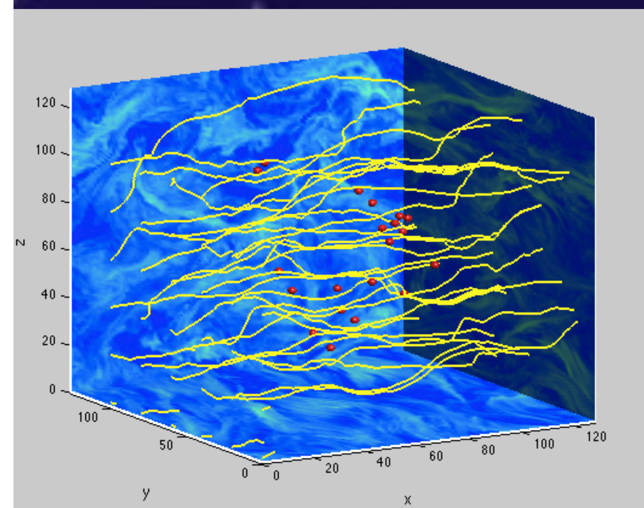




Anisotropy (Elongated eddies along the B field) makes orders of magnitude difference (Yan & Lazarian 02, 04)! Confirmed later by both Nonlinear theory (YL08) and numerical test (Xu & Yan 2013).

Prediction from NLT is confirmed by simulations

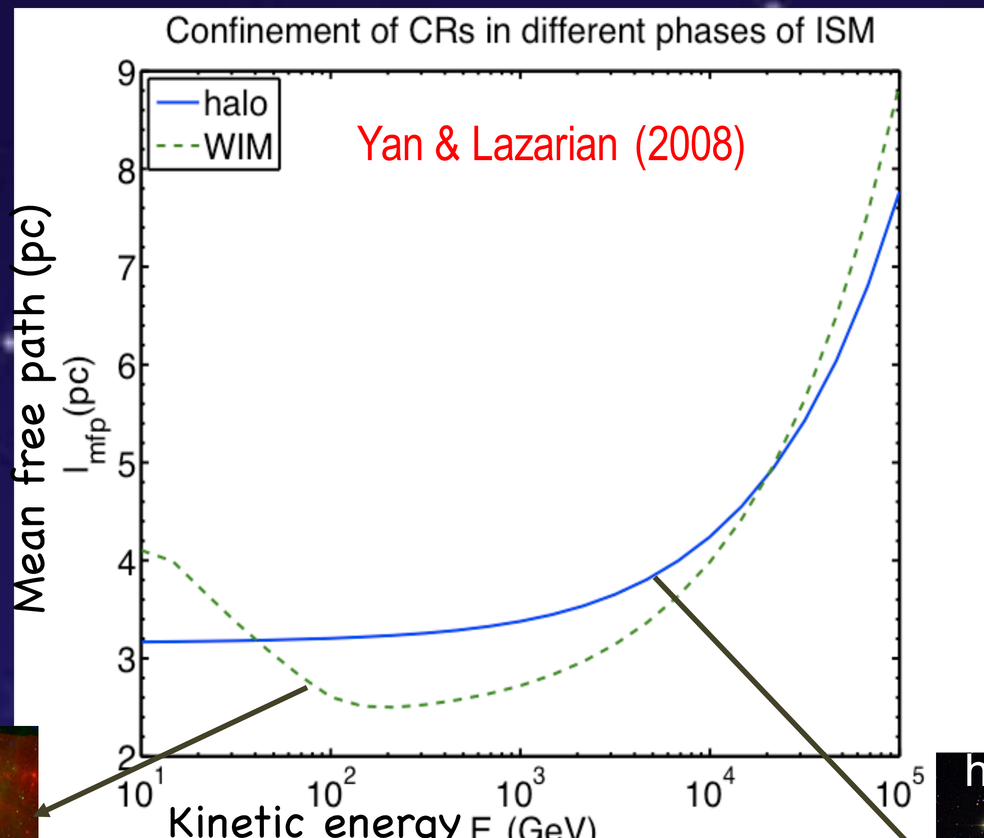




Particles
Magnetic field

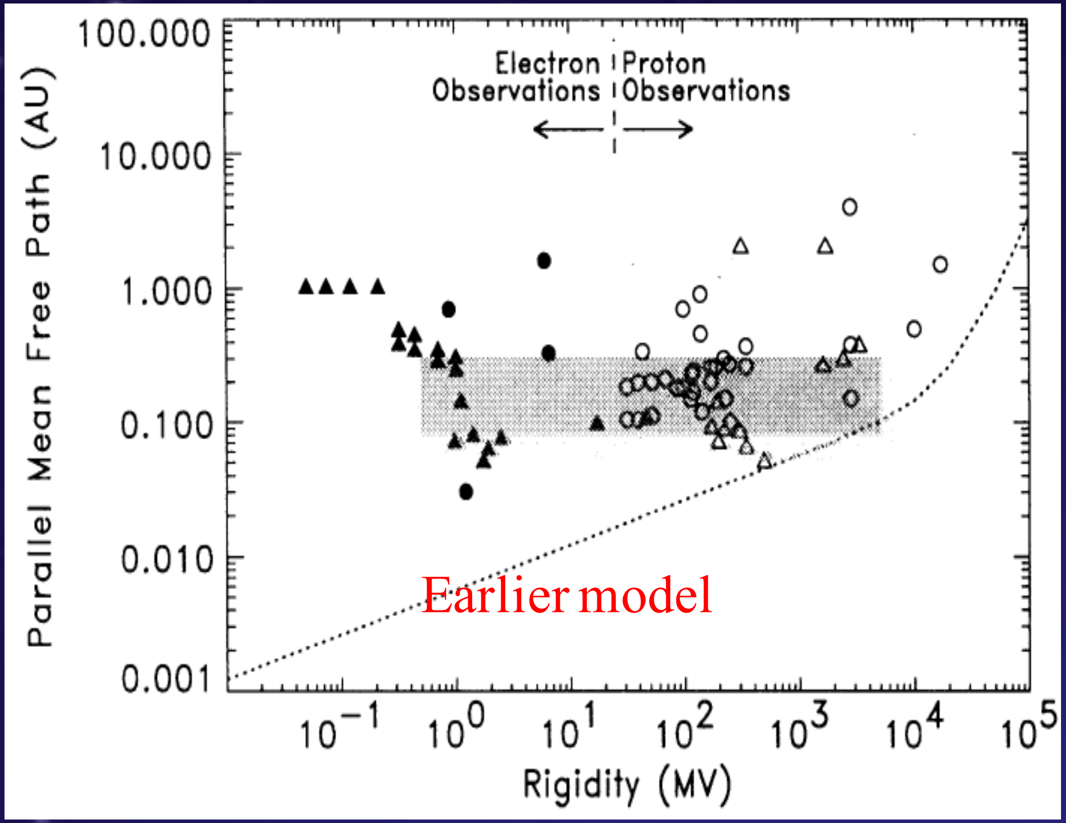
Mirror interaction dominates scattering at large pitch angles α (including 90°), and gyroresonance with fast modes is dominant for small pitch angles.

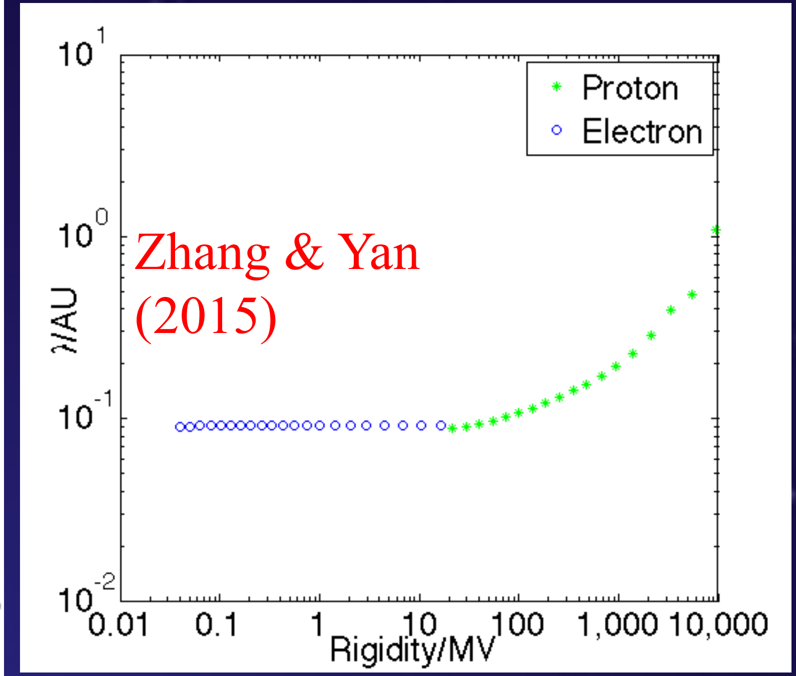
Major Implication: CR Transport varies from place to place!



Observational support on nonuniform propagation of CRs (AMS 2010; Fermi-LAT 2011,2012; PAMELA 2011):

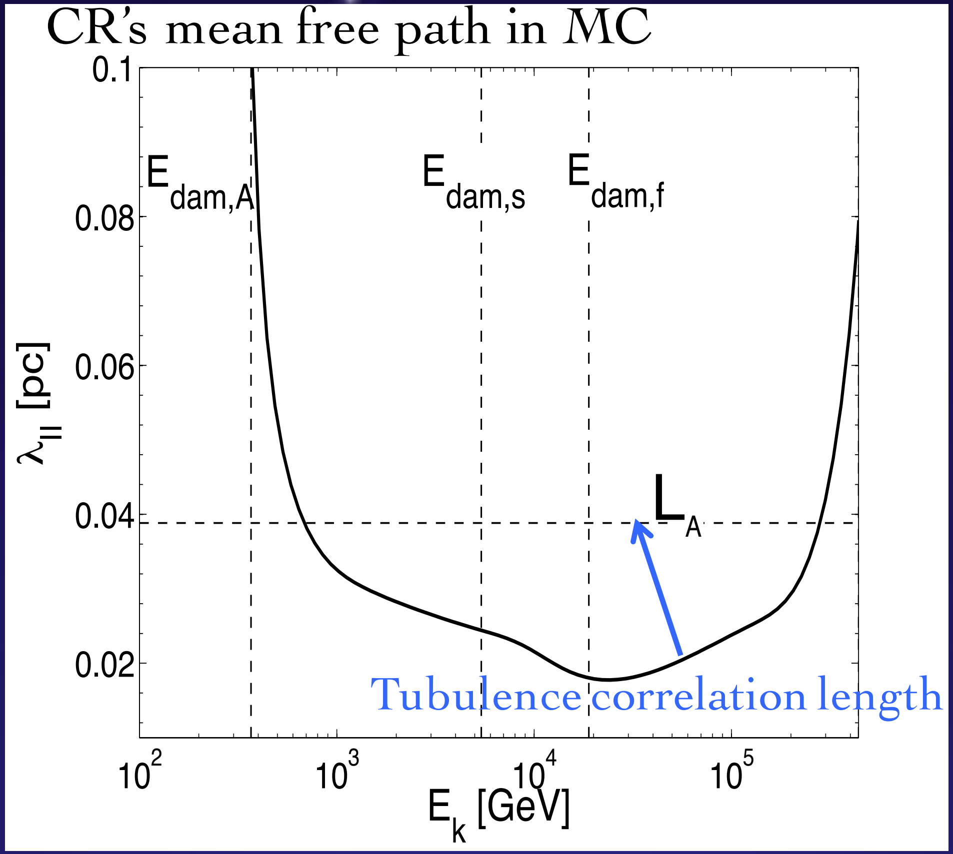
Ex II of implications: Palmer consensus explained!

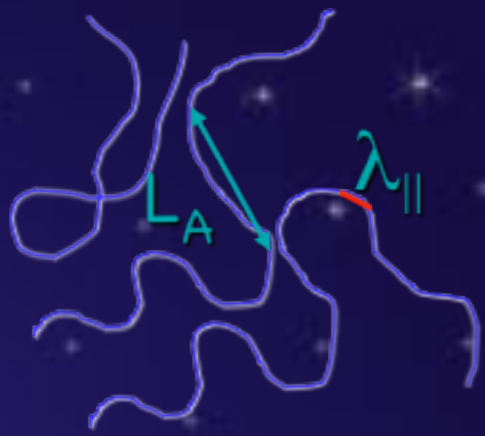




Flat dependence of mean free path can occur due to collisionless damping!

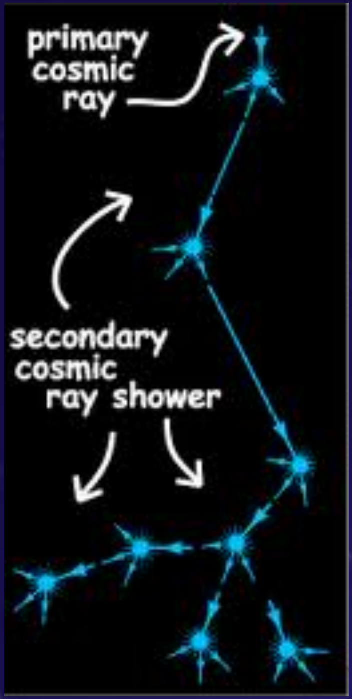
Propagation in partially ionized medium

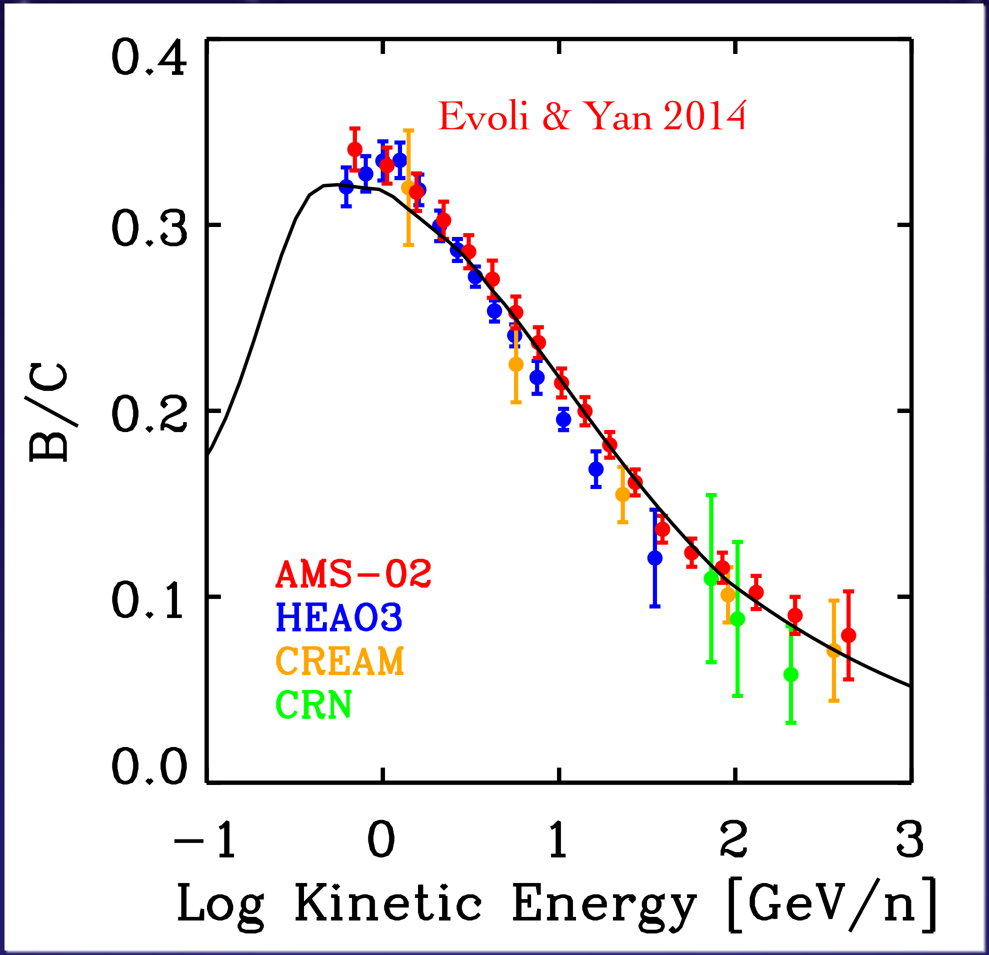




Xu et al. 2015 ApJ submitted

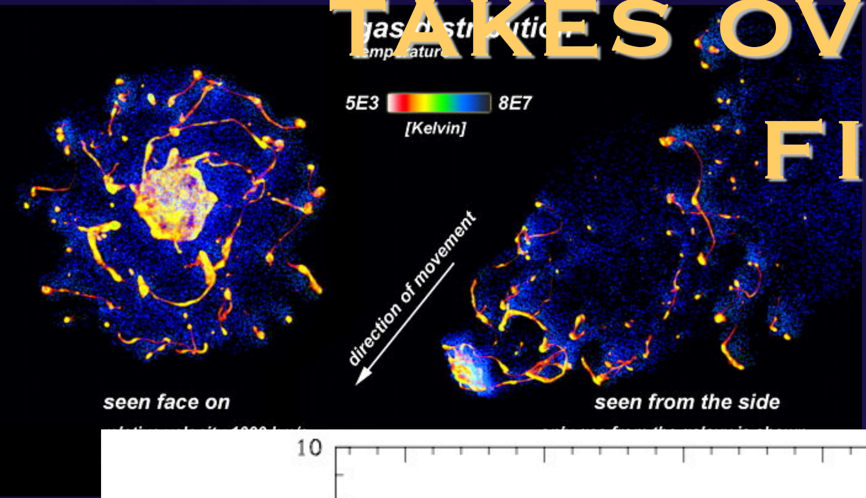
Example implication: B/C ratio





1GeV peak of B/C ratio can be produced without introducing the reacceleration!

Idea of fast modes takes over in other fields



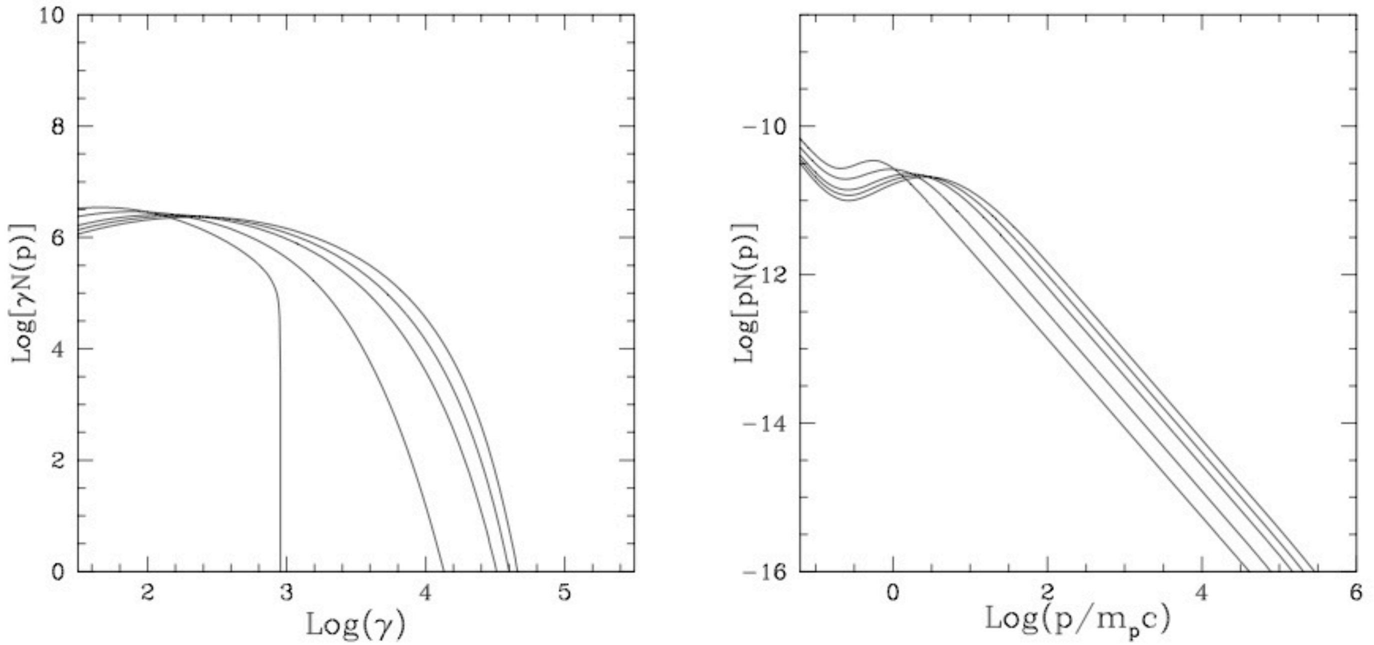
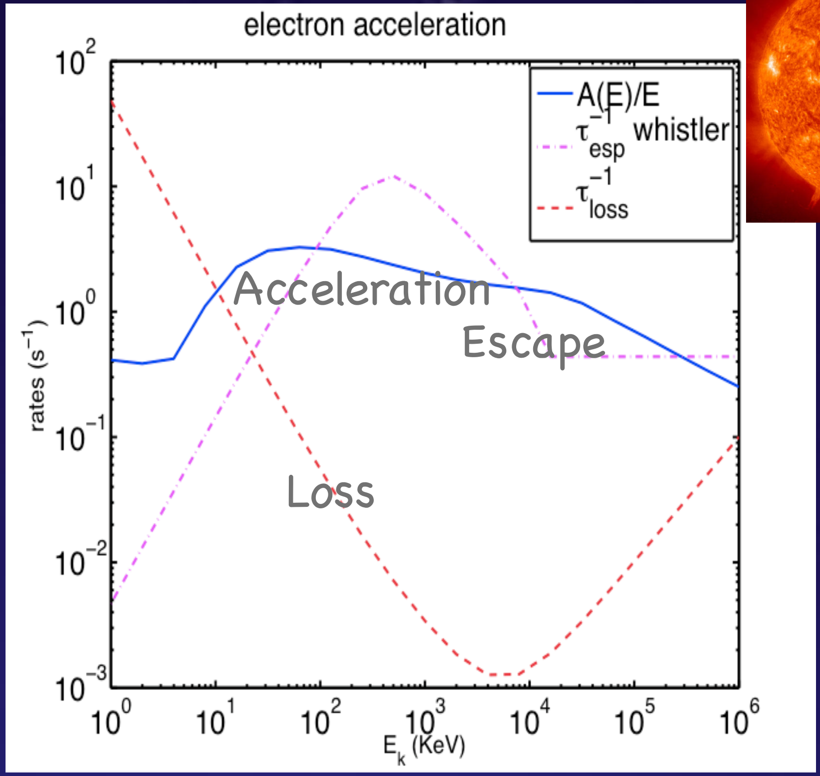


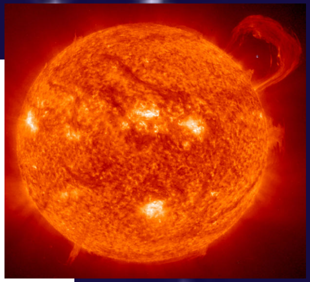
Figure 8. Left-hand panel: Time evolution of the spectrum of relativistic electrons as a function of the Lorentz factor. Right-hand panel: Time evolution of the spectrum of cosmic ray protons as a function of the particle momentum. In both panels calculations are reported for: $t = 0, 4 \times 10^{15}, 8 \times 10^{15}, 10^{16}, 1.2 \times 10^{16}$ 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, $B = 1\ \mu$G and redshift $z = 0.1$ (for IC losses).

Brunetti & Lazarian (2007)

Acceleration by fast modes is an important mechanism for electrons!

Comparison of rates

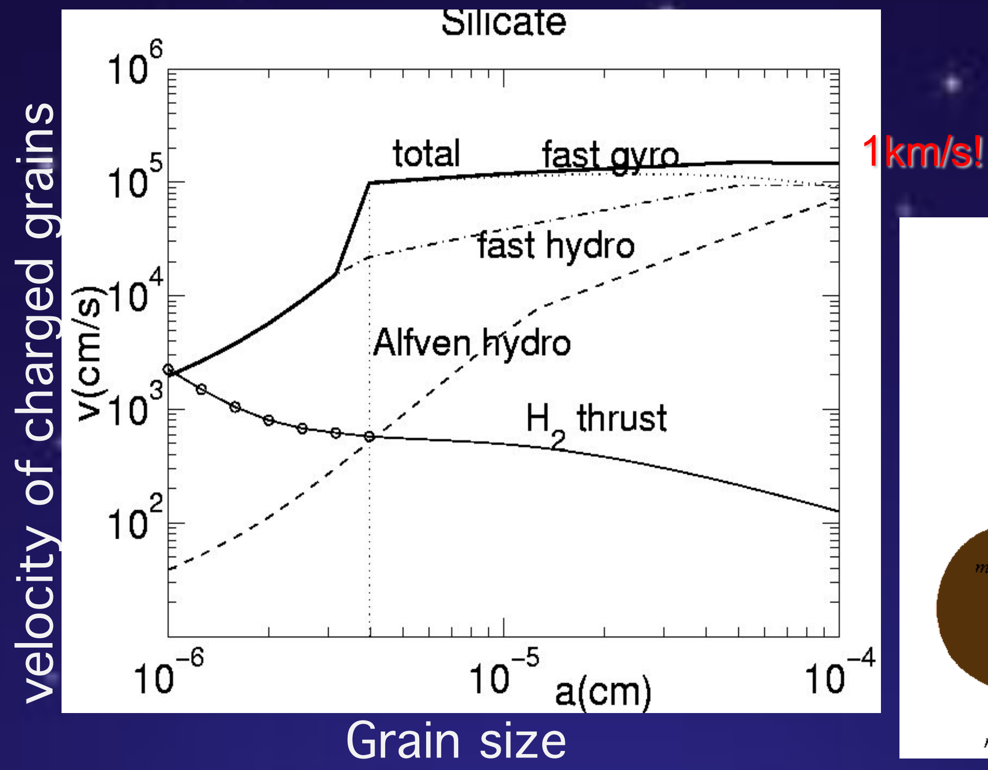


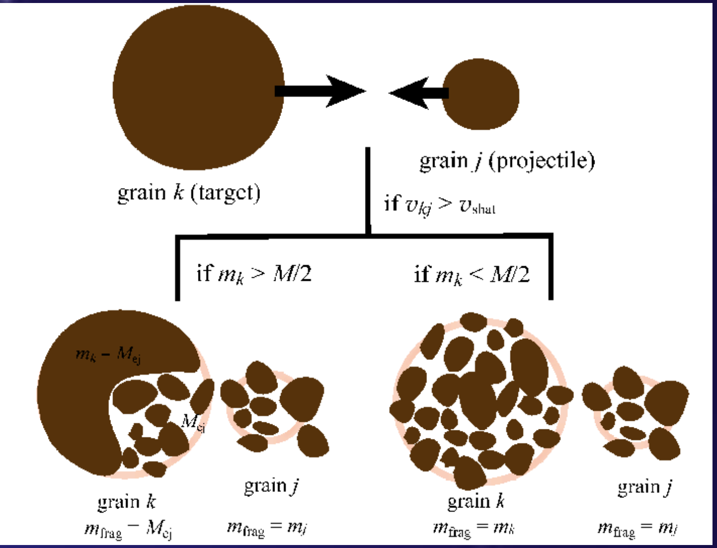


Kinetic energy

Detailed Study of solar flare acceleration must include fast modes and their damping (Yan, Lazarian & Petrosian 2008).

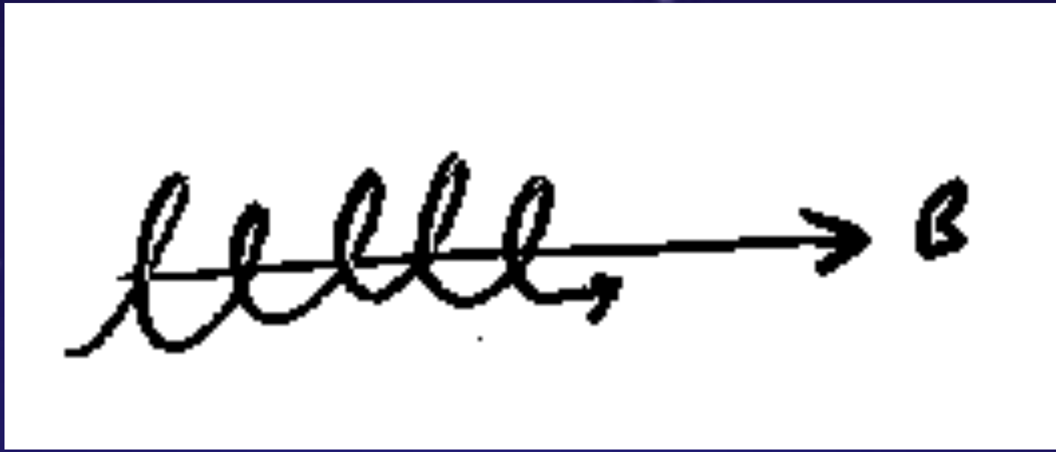
Dust dynamics is dominated by MHD turbulence!





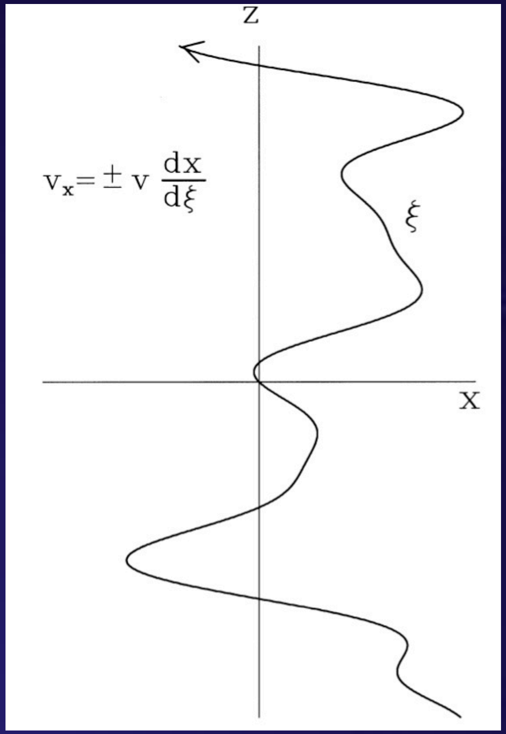
Grains can reach supersonic speed due to acceleration by turbulence and this results in more efficient shattering and adsorption of heavy elements (Yan & Lazarian 2003, Yan 2009, Hirashita & Yan 2009).

b) Cross field transport



Is there subdiffusion ($\Delta x^2 \propto \Delta t^a$, $a<1$) ?

- Subdiffusion (or compound diffusion, Getmantsev 62, Lingenfelter et al 71, Fisk et al. 73, Webb et al 06) was observed in near-slab turbulence, which can occur on small scales due to instability.



$$\Delta x^2 \propto \Delta z$$
$$\Delta z^2 \propto D_{\|} \Delta t$$

$$\boxed{\Delta x^2 \propto \sqrt{\Delta t}}$$

Diffusion is slow only if particles retrace their trajectories.

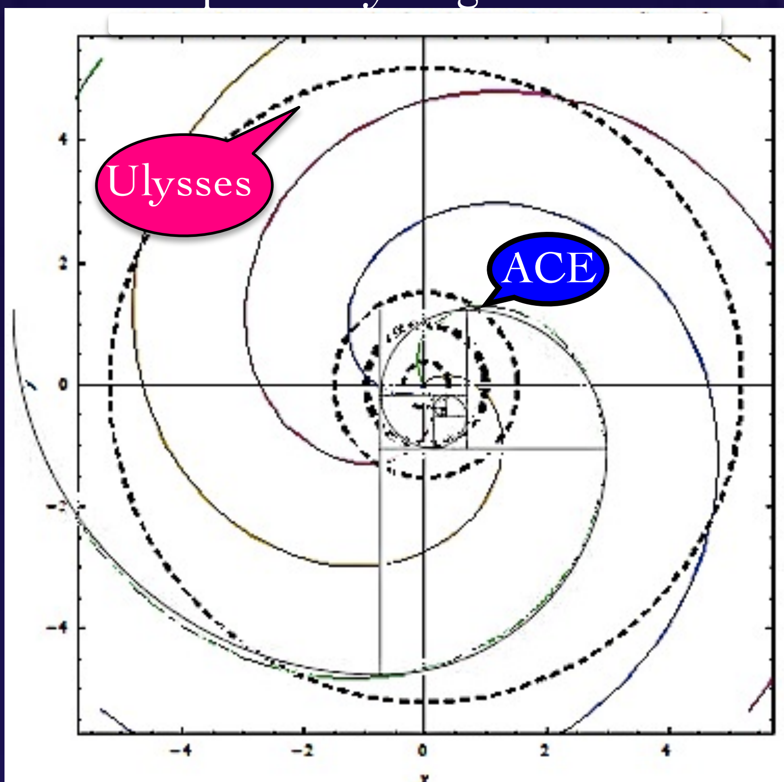
Subdiffusion is not typical!

- In turbulence, particles' trajectory become independent when field lines are separated by the smallest eddy size, $l_{\perp,min}$.

- Subdiffusion only occurs below $l_{\perp,min}$. Beyond $l_{\perp,min}$, normal diffusion applies (Yan & Lazarian 2008).

Observational evidence from solar wind

Interplanetary magnetic field



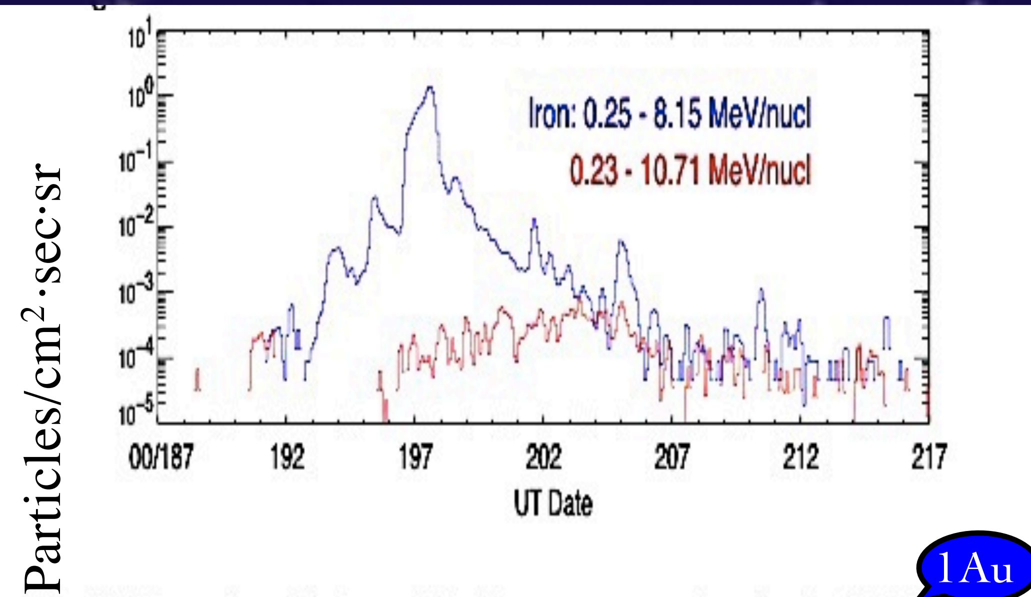
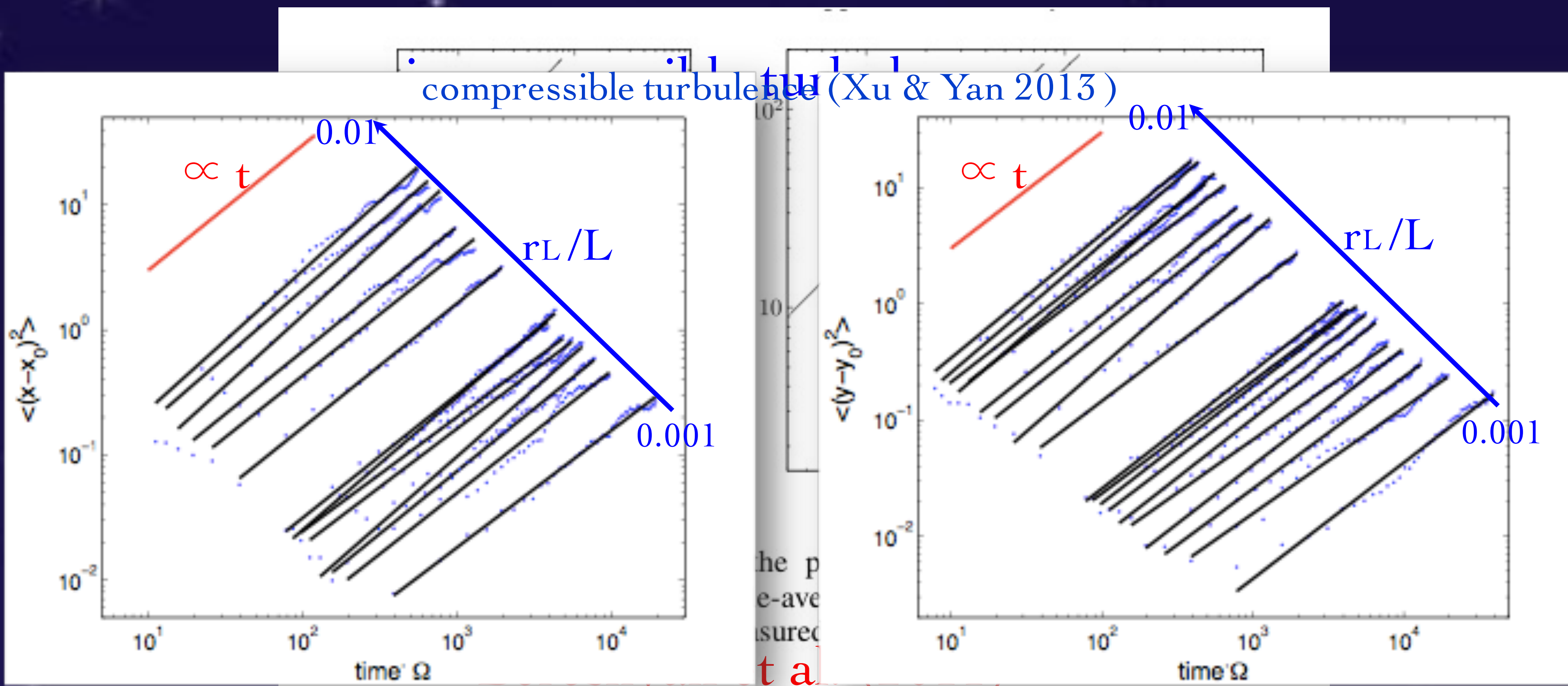


Fig. 2. Heavy ion C, O, and Fe fluxes measured on both ACE (blue) and Ulysses (red) in the July 2000 event.

from Maclennan et al. (2001)

Observations do not support the slow subdiffusion as discussed often in literatures (Getmantsev 62,Fisk et al. 73, Ko´ ta & Jokipii 2000; Mace et al. 2000; Qin at al. 2002; Webb et al 06).

General Normal Diffusion is observed in simulations!



Cross field transport in 3D turbulence is in general a normal diffusion

Cross field transport is normal diffusion on large scales

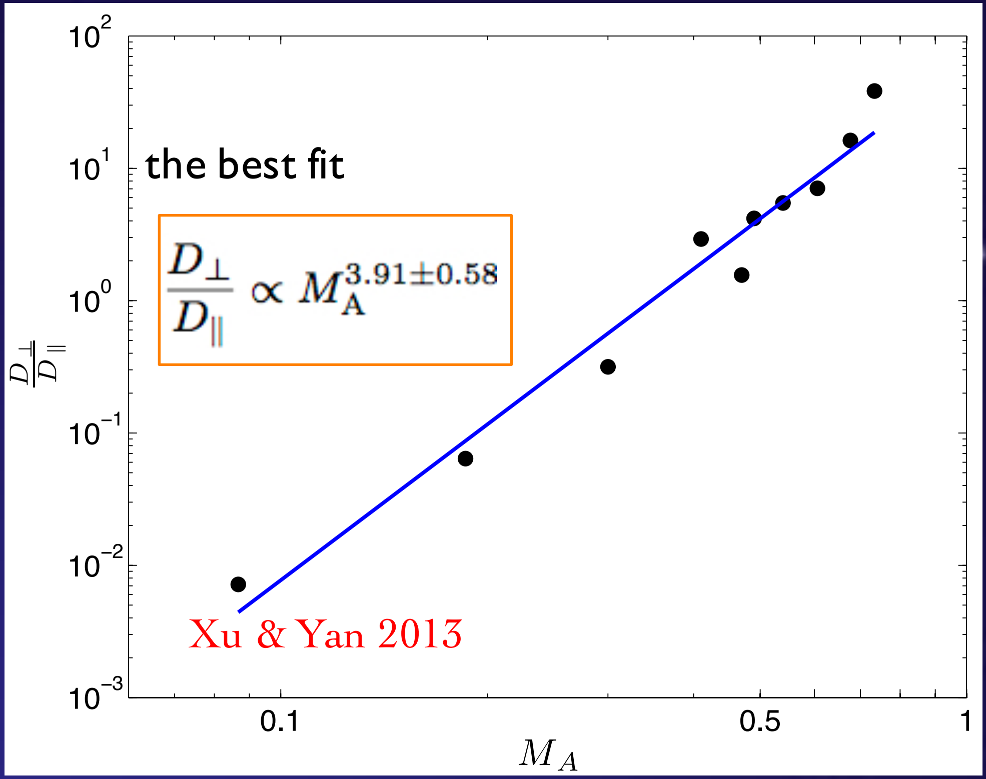
Theoretical prediction:

$$\boxed{D_\perp = D_\| M_A^4}$$

$M_A \equiv \delta B/B$

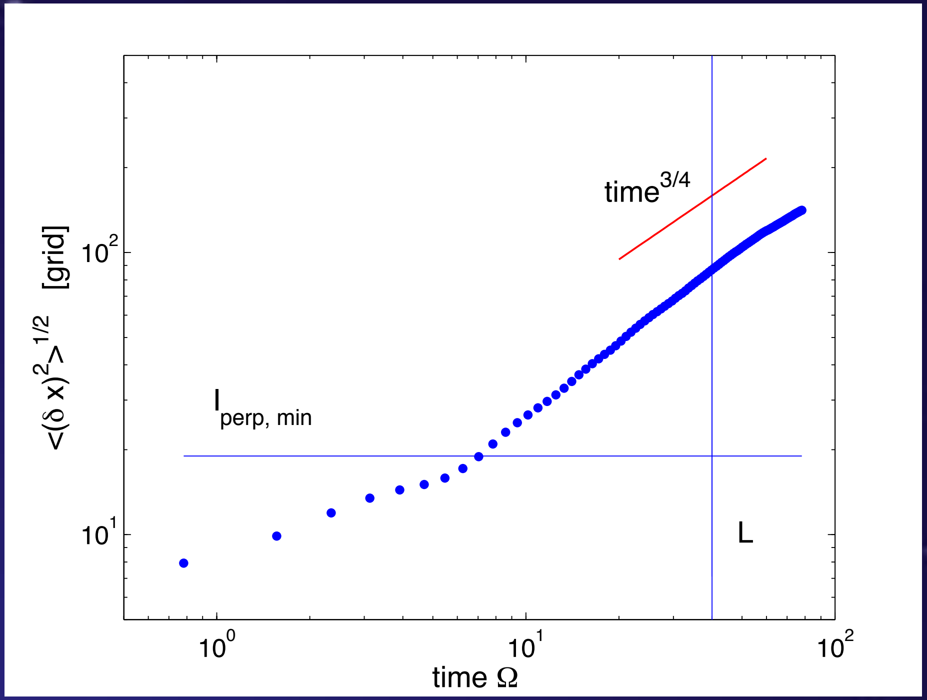
Yan & Lazarian 2008

Numerical simulation:



Field lines are superdiffusive on small scales

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



Xu & Yan 2013

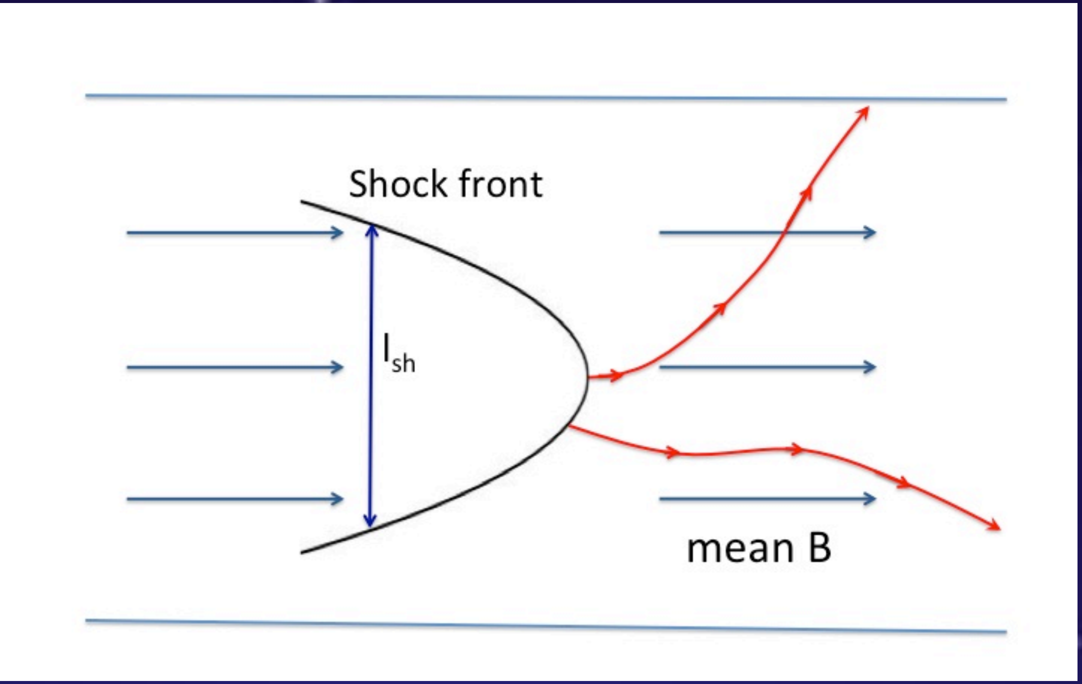
TABLE 1

Regimes of MHD turbulence and magnetic diffusion

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	Richardson	$\sim \frac{s^3}{L}$
Strong superAlfvenic	$V_L > V_A$	$[l_{min}], l_A$	$k_{\perp}^{-5/3}$	anisotropic eddy-like	numerical	Richardson	$\sim \frac{s^3}{L} M_A^3$

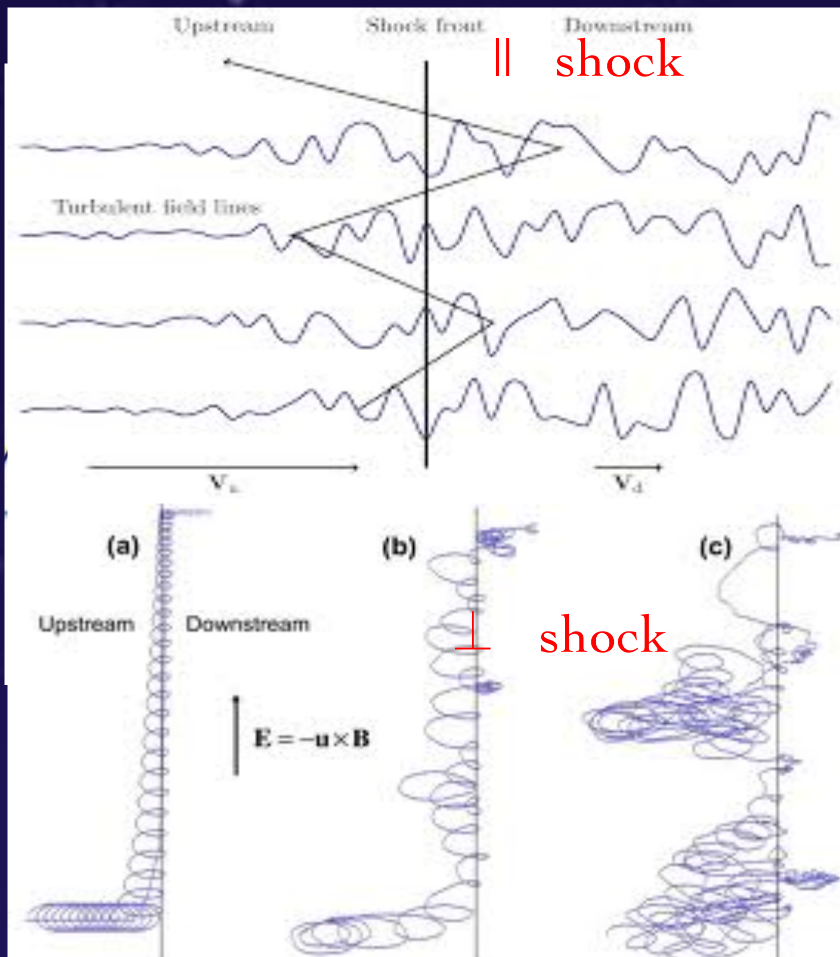
Lazarian & Yan (2014)

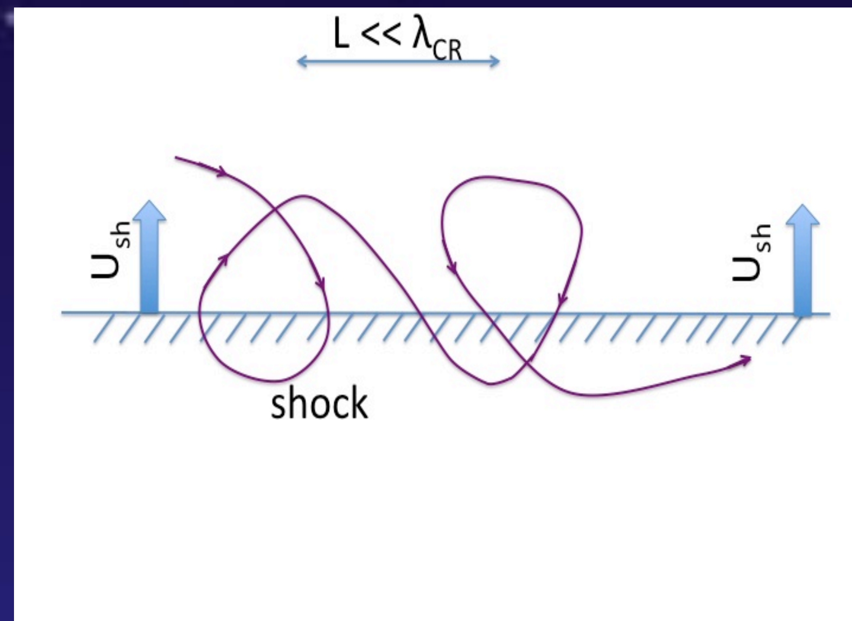
II. Acceleration at shock w. finite size



$$E_{max} = 32\left(\frac{U_1}{400\mathrm{km/s}}\right)^2 \left(\frac{L}{100\mathrm{Au}} M_A^{\zeta}\right)^{\frac{4}{3}} \left(\frac{l_{sh}}{90\mathrm{Au}}\right)^{\frac{8}{3}} \left(\frac{10Au}{\lambda}\right)^4 \mathrm{MeV}\cdot\mathrm{nuc}^{-1}.$$

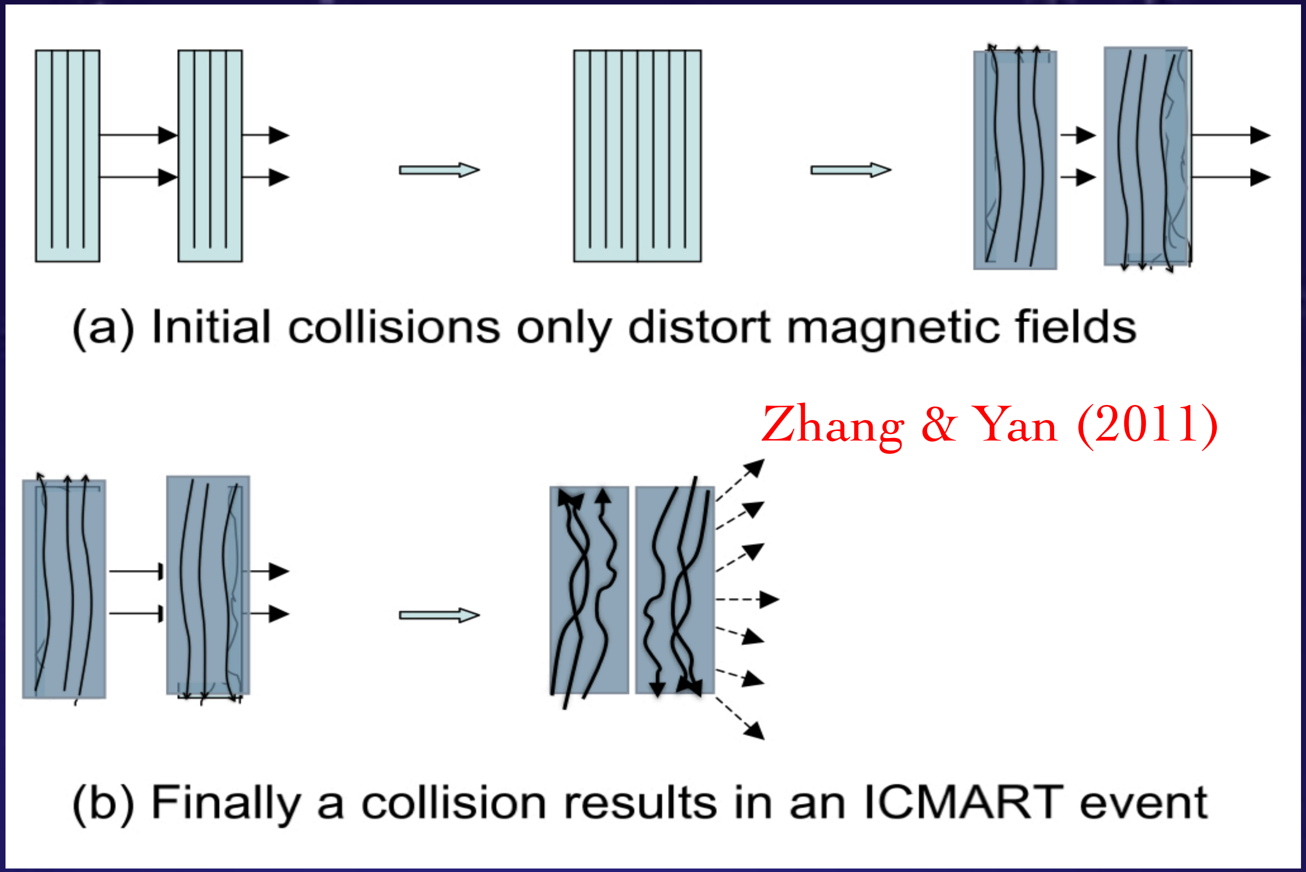
Shock acceleration is only efficient with small scale turbulence





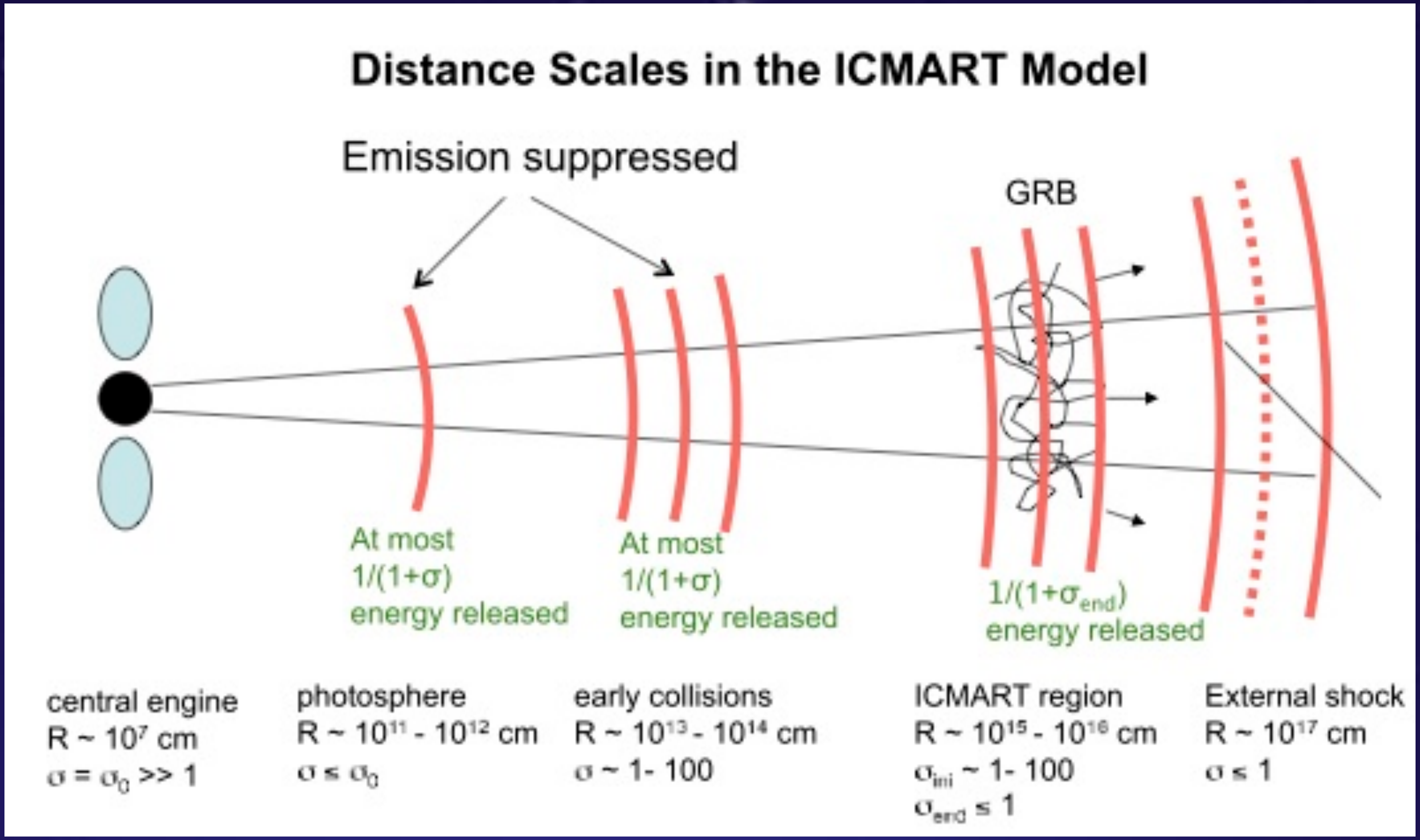
& Yan (2014)

c) Turbulent reconnection model for GRBs



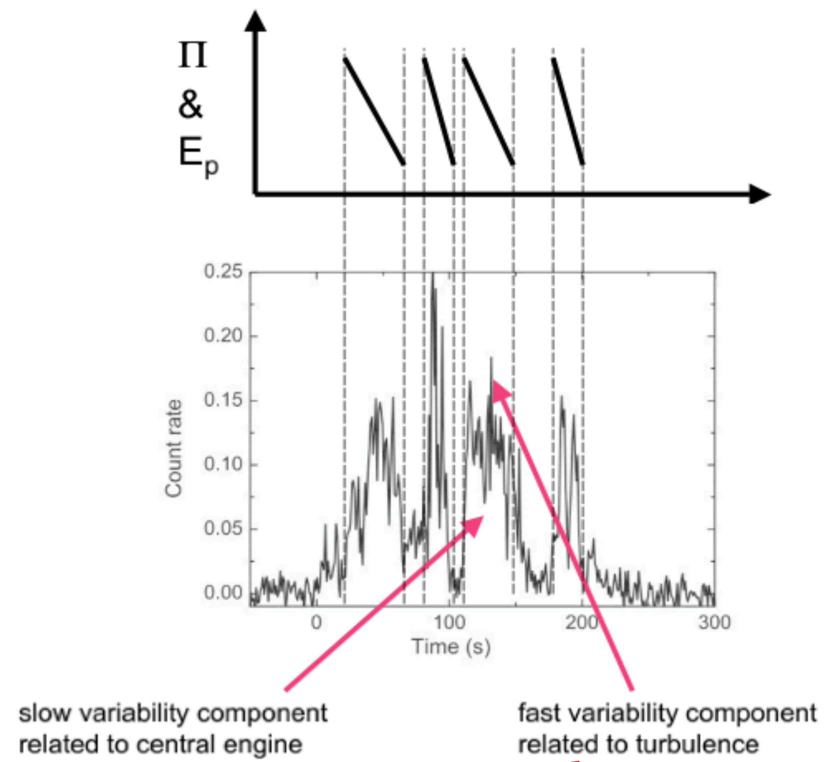
Bursty reconnection occurs as a nonlinear feedback of the increased stochasticity of B field.

Turbulent reconnection triggers a GRB at large R



Internal Collision triggered Magnetic Reconnection (ICMART) model provides a natural explanation for highly magnetized GRBs (Zhang & Yan 2011,~ 60 citation/yr)

Variabilities of light curve are naturally explained!

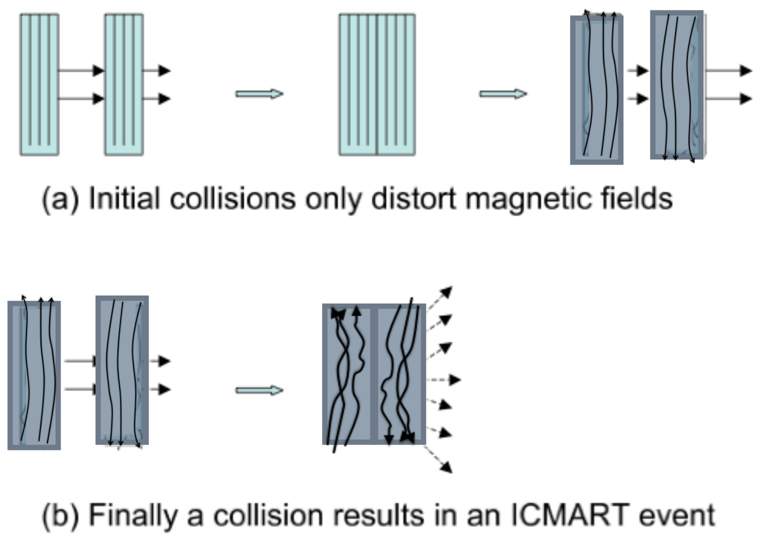


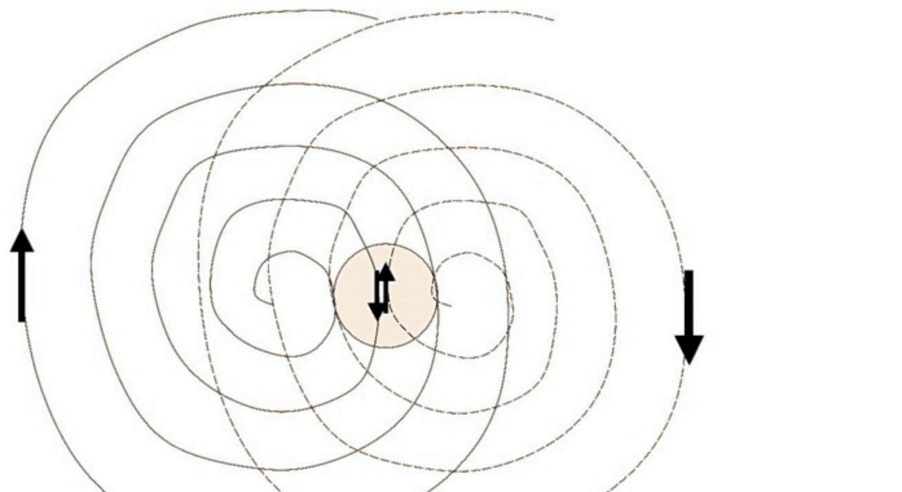
Zhang & Yan (2011)

Summary

- MHD turbulence is a key player for particle transport and acceleration.
- Compressible fast modes dominates CR. CR transport therefore varies from place to place.
- CR perpendicular transport is diffusive in large scale turbulence and superdiffusive (SD) on small scales.
- Existing codes (GalProp, Dragon, etc) are to be modified to account for these new understandings.
- In the presence of turbulence, shock acceleration is insensitive to magnetic field direction. The acceleration is only efficient if locally generated small scale turbulence dominates.
- Reconnection Acceleration in turbulence is important channel for energetic events in highly magnetized objects.

ICMART MODEL





Astrophysical systems are not perfectly symmetric systems. For example, current-driven kink instability may develop in the jet (e.g., Mizuno et al. 2009a), which would introduce a slight misalignment of the magnetic field axes in two consecutive "shells." This would result in a small cross section near the magnetic axes that have opposite orientations in the two shells