Diffusive Shock Acceleration: Some Ongoing Issues

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Thanks to many!

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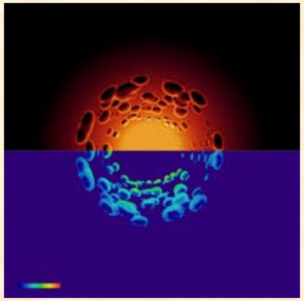
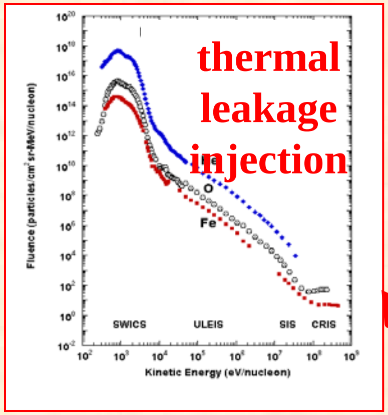
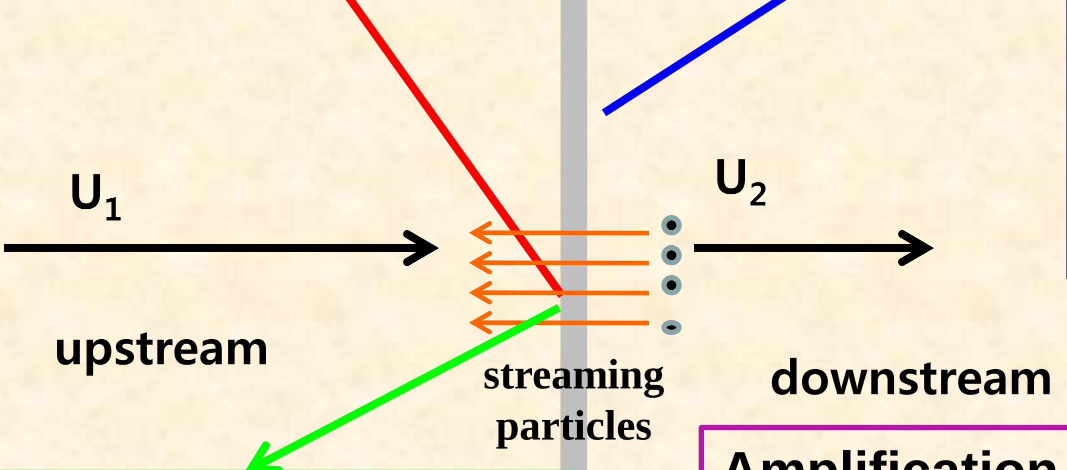
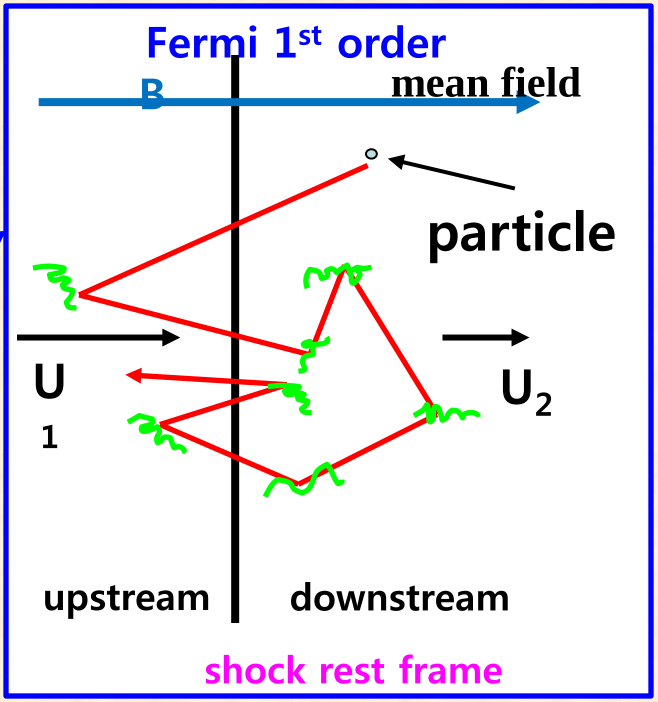
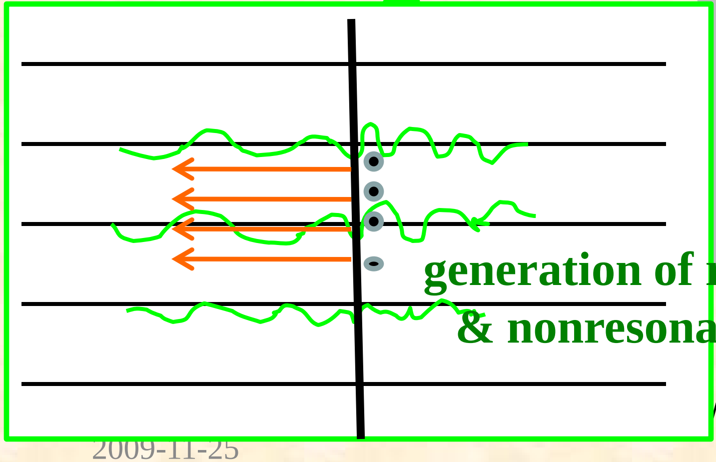


Cartoon of DSA









Amplification of B fields
→ Higher $P_{\max}$

Scattering of particles
Dissipation of waves

Spatial (& Momentum)
Diffusion: κD(p)

Some Key Ongoing Issues:

- Physics of suprathermal particle “injection”
- DSA efficiency & spectrum of CRs
  - (internal & escaping)
  - $p_{max} \propto qBR(U_s/c)$
- Amplification of scattering magnetic fields
  - (instabilities), field PDF($k \sim 1/l$)
    - CR diffusion properties
    - influence on shock structure
- Modeling approaches (shocks are highly nonlinear)

Modeling approaches to nonlinear DSA:

•“Full” Microphysics: (PIC, “hybrid plasma”)
  >e.g., Giacalone & Jokipii, Spitkovsky et al, Nishikawa et al, Hoshino et al
    injection physics, self-consistent evolution
    of fields & particle distributions, scattering behaviors

•Hybrid PIC-MHD simulation:
  >e.g., Lucek & Bell
    self-consistent coupling between CRs and (MHD) turbulence

•Monte Carlo simulation:
  >e.g., Ellison et al
    internally self-consistent steady state
    user-defined scattering, field structures

•Analytic modeling:
  >e.g., Malkov et al, Blasi et al
    steady state, user-defined scattering, field structures

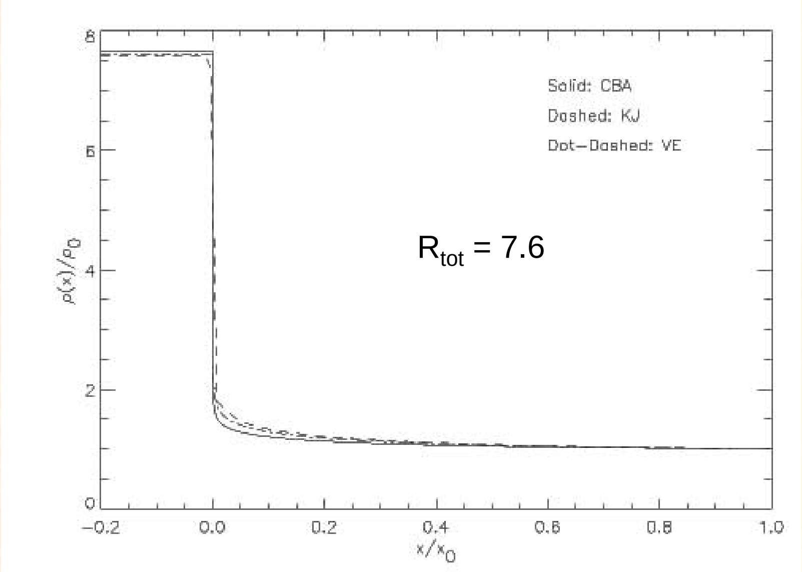
•Hybrid kinetic-equation-CFD:
  >e.g., Kang et al, Berezhko et al
    dynamical evolution on multiple scales, multi-dimensional applications

Comparison of some DSA modeling approaches:

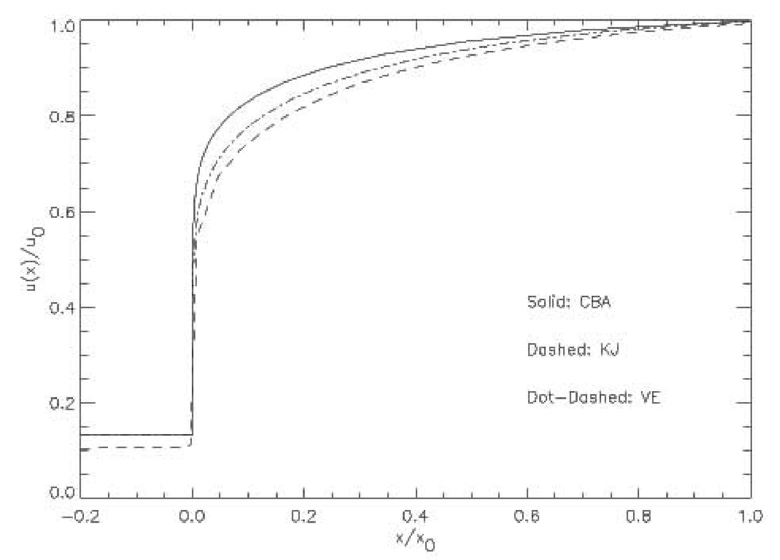
MC, Analytic (steady), & Kinetic/CFD (evolving)

Mach 30 parallel, plane shock:
U_s = 5000 km/s
Bohm-like diffusion, $D \propto p$, $B_0 = 3\mu G$
QL, resonant streaming instability, balanced by dissipation
"FEB" @ $x/x_0 = 1$, $x_0 = D(p = 10^3\, m_p c)/U_s$
"Distinct" injection models

$$\frac{dU_A}{dt} = v_A \frac{dP_{CR}}{dz},$$



$R_{tot} = 7.6$

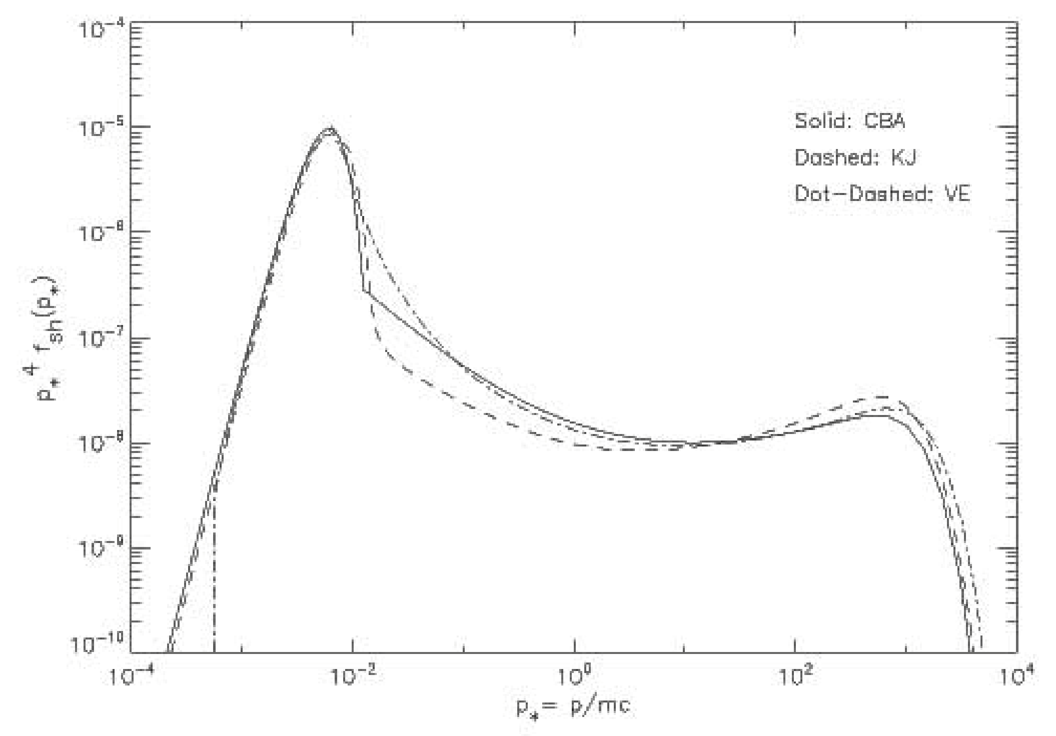


CBA: Caprioli, Blasi & Amato (analytic)
KJ: Kang & Jones (kinetic & CFD, AMR)
VE: Vladimirov & Ellison (Monte Carlo)

Preliminary:
Caprioli, et al (in prep)

Comparison of some DSA modeling approaches:

MC, Analytic (steady), & Kinetic/CFD (evolving)



Acceleration “efficiency” ≈ 60%

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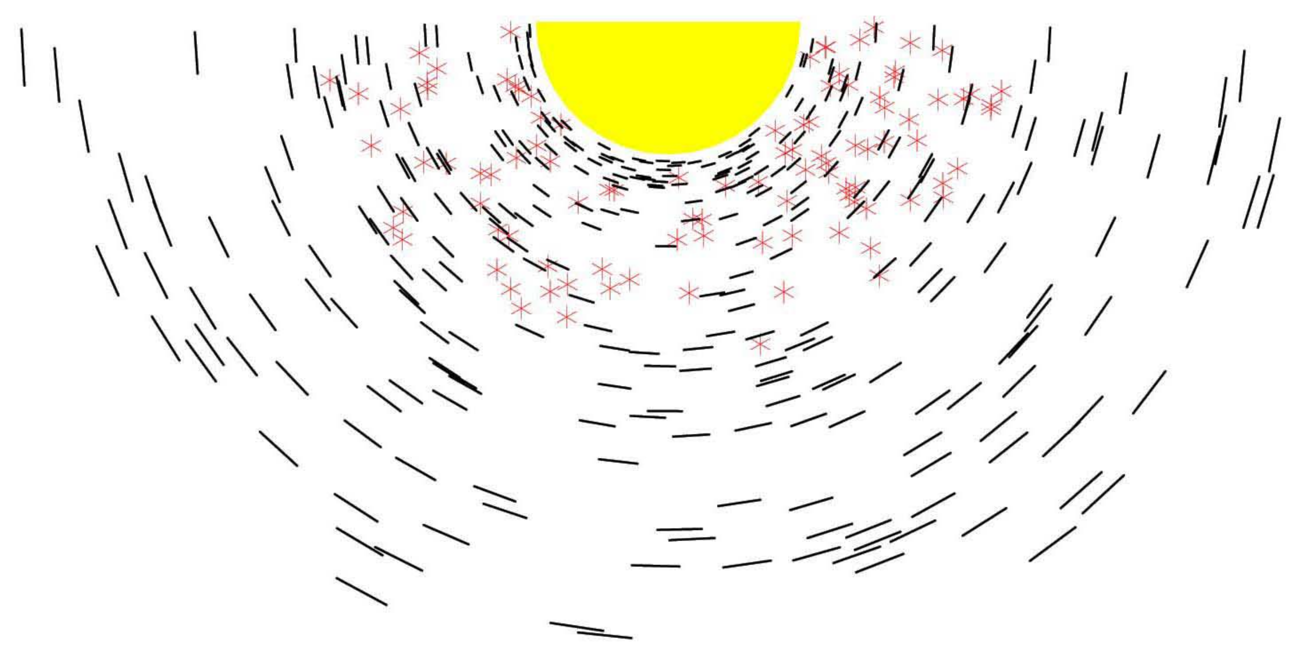
Need for nonlinear, multi-scale DSA modeling of inherently multi-D astrophysics:

Example: clumpy, irregularly shocked O star winds

Hydrodynamical model of ζ Pup (Hamann et al 2009)
Shocks indicated by red stars



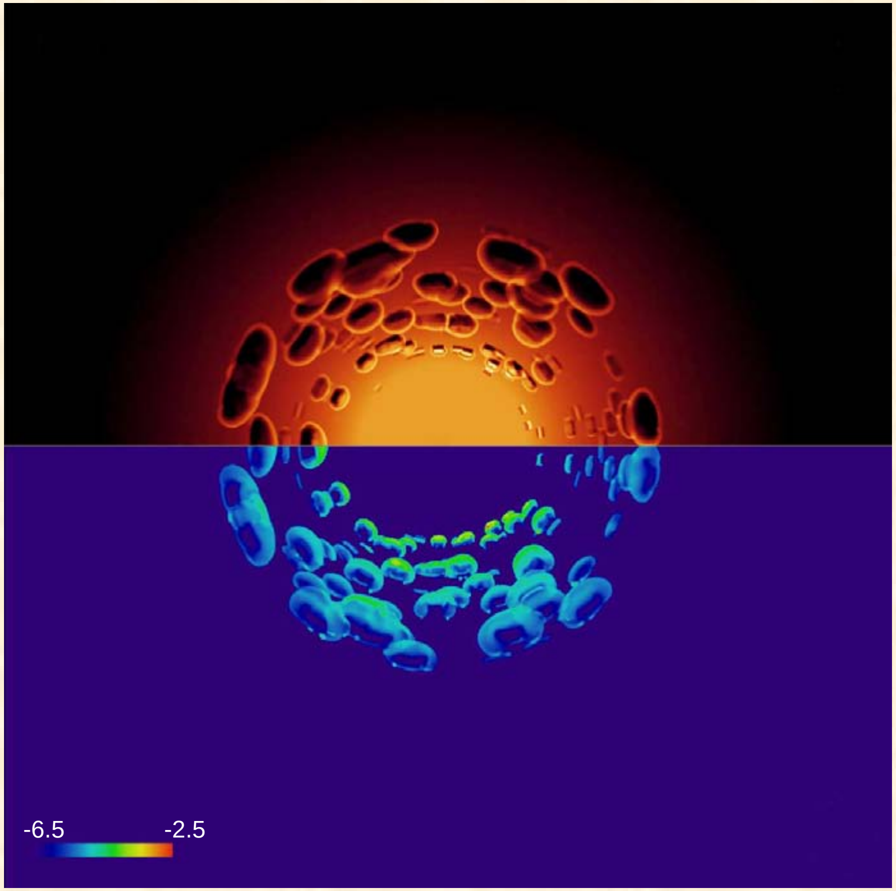
U_w ~ 2000 km/s
T_{wind} ~ 10^4 K
R ~ AU
t_{dyn} ~ days

Nonlinear DSA Simulation:

Hybrid kinetic-equation-MHD
AstroBEAR AMR with CGMV CRs

$R_* \approx 10\ R_{sun}$
$R_{in} = 50\ R_*$
$B \sim .01\ R_{in}/R$
Thermal leakage
injection
Bohm diffusion

Edmon et al
(in prep)



t = 3 days

log density

log P_c

$E_{max} \sim$ GeV

Amplification of scattering fields:

Fields in SNRs apparently >> B_{ISM}

Shocks in inhomogeneous media generate post shock turbulence

1D CR shocks unstable to amplification of field fluctuations
- resonant streaming instability (Alfven waves)
- nonresonant, current instability

Precursors of modified shocks dynamically unstable
- 1D acoustic instability (Drury, Zank et al)
- multi-D, R-T like instabilities

Hydrodynamical post shock turbulence:

Shocks in inhomogeneous media generate post shock vorticity:
($\omega \sim U_s (\rho_2 / \rho_1)/R_s$) => stretch-fold B field growth

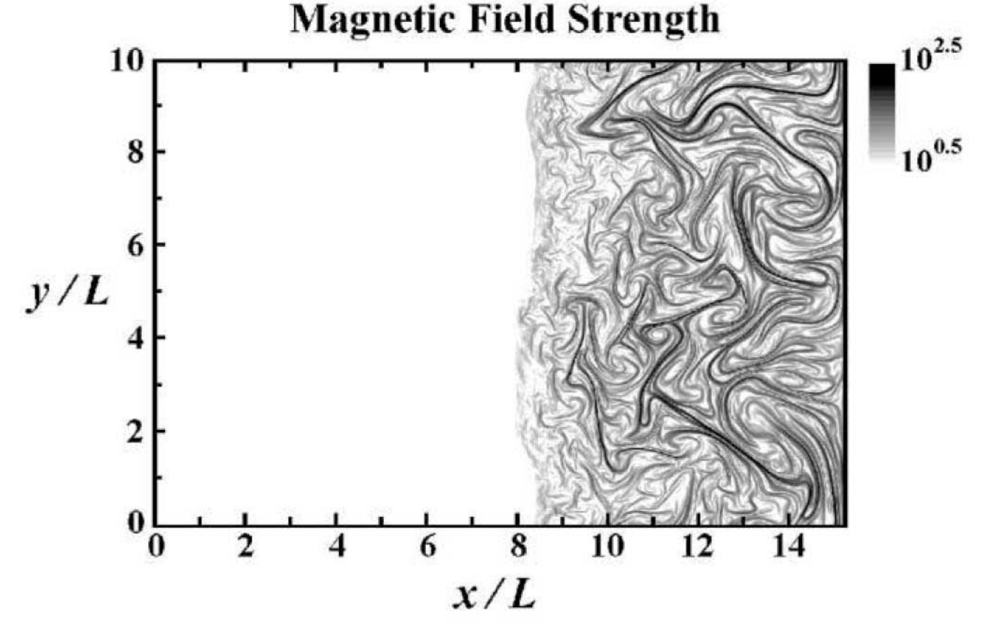


FIG. 2.—More results from run 7. Shown is the gray-scale representation of the magnitude of the magnetic field over the entire simulation domain. White represents values below $3.16B_0$, black represents values larger than $316B_0$, and the shades between these two extremes are equally spaced in a logarithm of B/B_0.

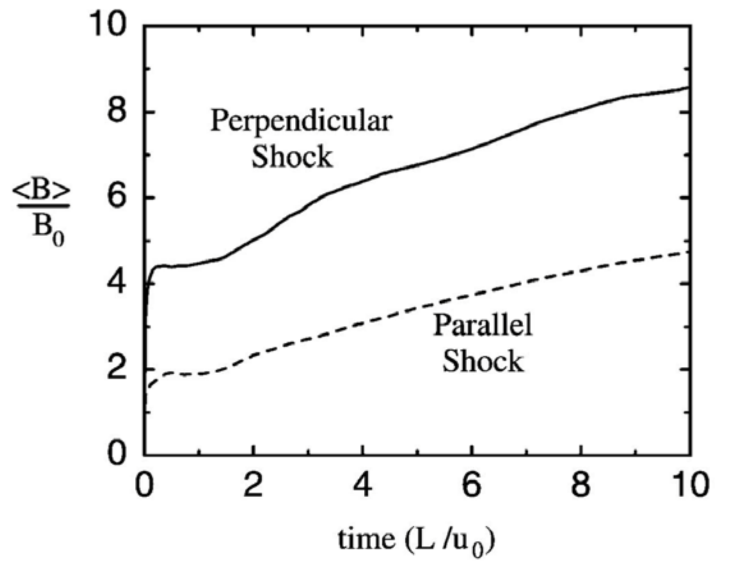


FIG. 3.—Results from runs 3 and 6. Plotted is the magnetic field, averaged over the entire downstream region, which increases as the shock moves away from the wall, as a function of time. The only difference between these two simulations is the angle between the upstream mean magnetic field and the plasma flow velocity, as indicated.

Giacalone & Jokipii 2007

Especially for large compression: e.g., radiative & CRs?

Clumpy warm ISM

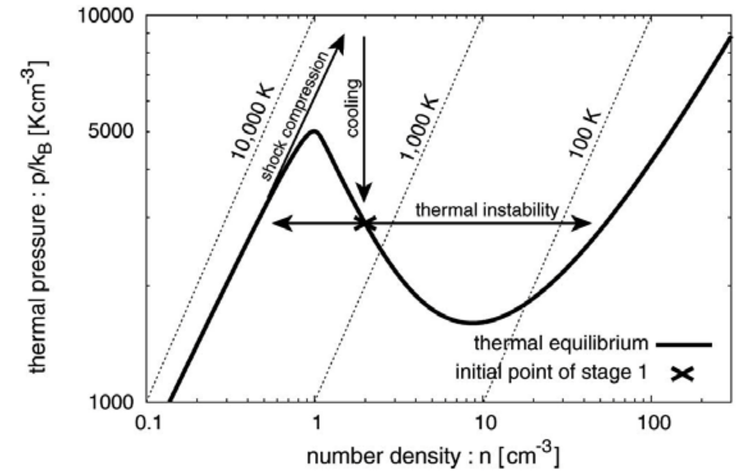


Figure 1. Thermal equilibrium state of the cooling function (thick solid line). The isothermal lines of 10,000 K, 1000 K, and 100 K are plotted as dashed lines. The evolutionary track of diffuse WNM that is compressed by a shock wave and cooled by following radiative cooling to form thermally unstable gas is illustrated as allows. We also illustrate the evolutionary tracks of the thermal instability that are simulated in Stage 1. The initial unperturbed state of Stage 1 is plotted as a cross.

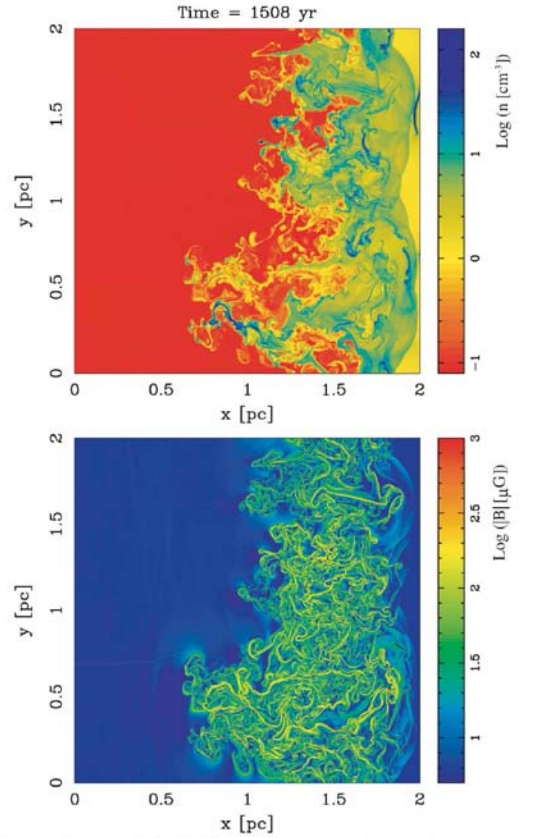
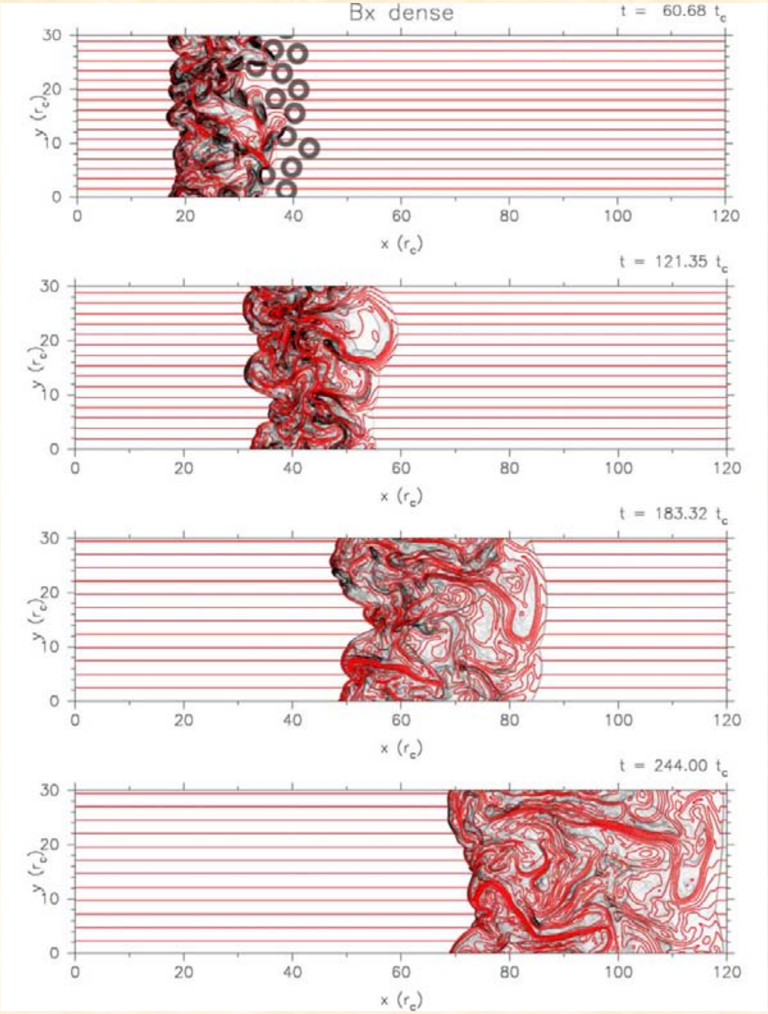


Figure 4. Results of Model 2. The top and bottom panels respectively represent the structure of the number density and magnetic field strength. The color scale is the same as Figure 3.

Inoue et al 2009

Especially for large compression: e.g., radiative & CRs?



Radiative clumps

Cunningham et al (in prep)

Field amplification though streaming Instabilities

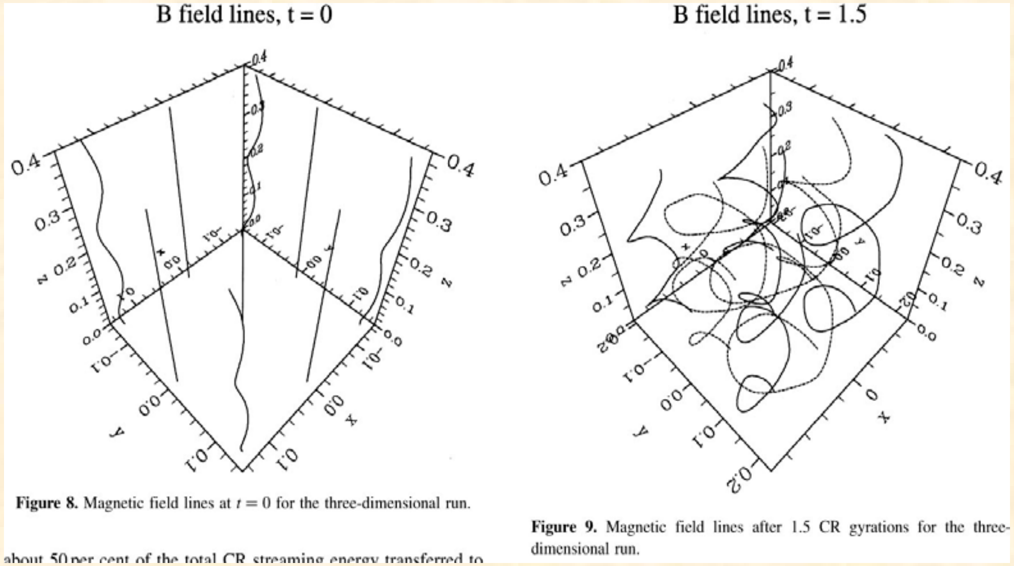


Figure 8. Magnetic field lines at $t = 0$ for the three-dimensional run.

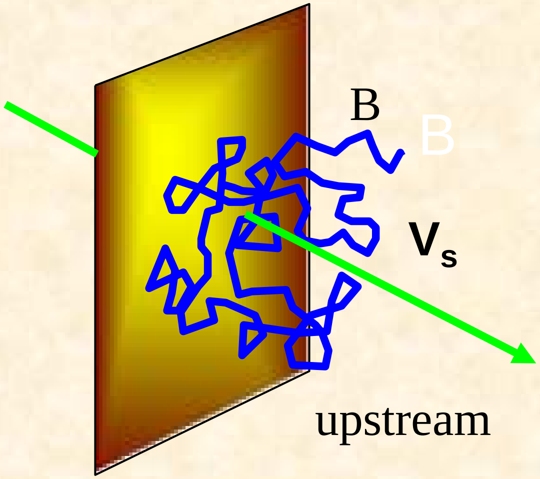
Figure 9. Magnetic field lines after 1.5 CR gyrations for the three-dimensional run.

about 50 per cent of the total CR streaming energy transferred to

$$\frac{\mathrm{d}U_\mathrm{A}}{\mathrm{d}t} = v_\mathrm{A}\frac{\mathrm{d}P_\mathrm{CR}}{\mathrm{d}z},$$

wave energy density

- **-streaming CRs upstream of parallel shocks**
- **- resonant amplification of Alfven waves on scales r_g**
- **- amplify B field (Lucek & Bell 2000)**



Bell 2004

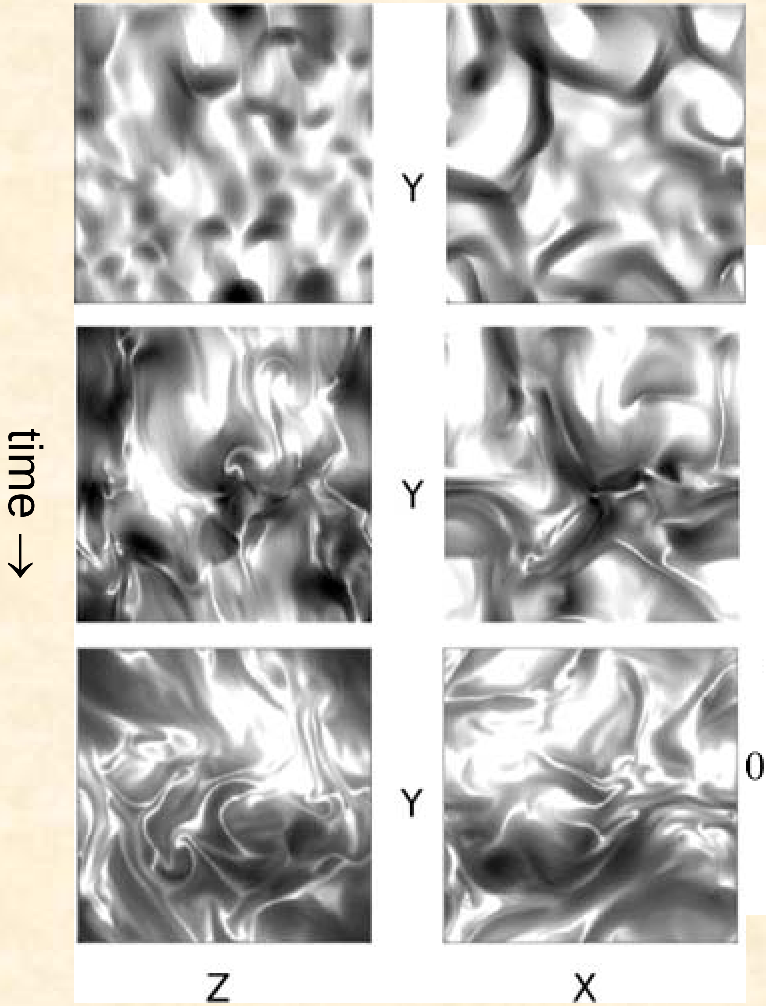
non-resonant, current driven, purely growing mode

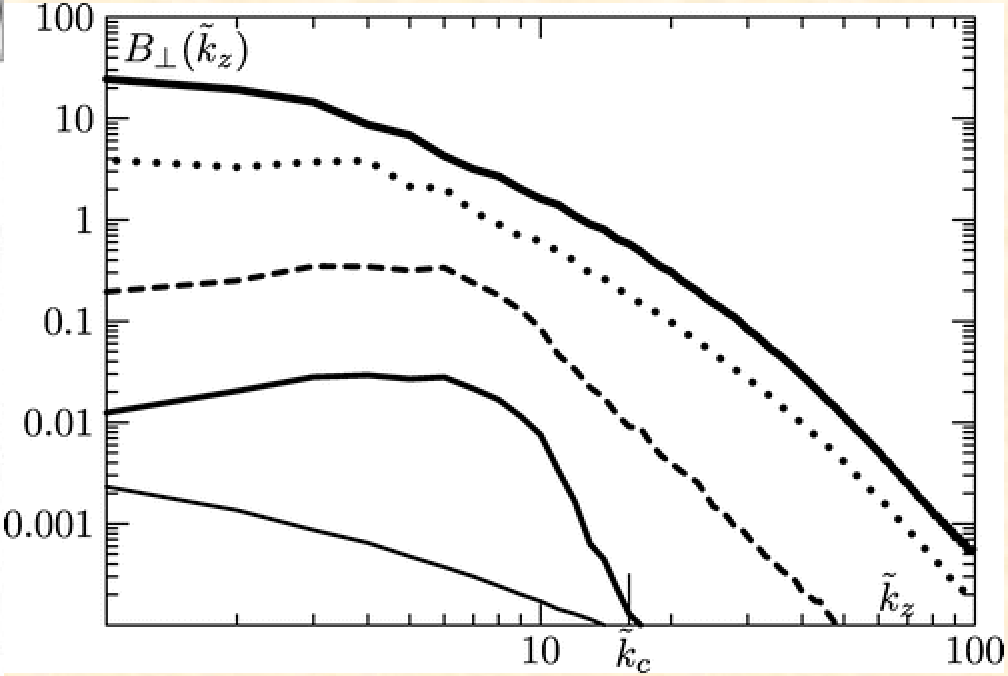
$$\delta B^2 \approx (u_s/c)P_{CR} \approx (u_s/c)\rho_0 u_s{}^2$$

$$\frac{\delta B^2}{B_0^2} = M_A^2 \frac{u_s}{c}\frac{P_{CR}}{\rho_0 u_s{}^2} \qquad \frac{\delta B}{B_0} \sim 30-300 \quad \text{for SNRs}$$

Nonresonant instability, fixed j_{cr}:

Field fluctuations predominantly smaller than r_g; motions become fairly stochastic; $\lambda_{mfp} \sim E^2/((q\delta B)^2 L)$



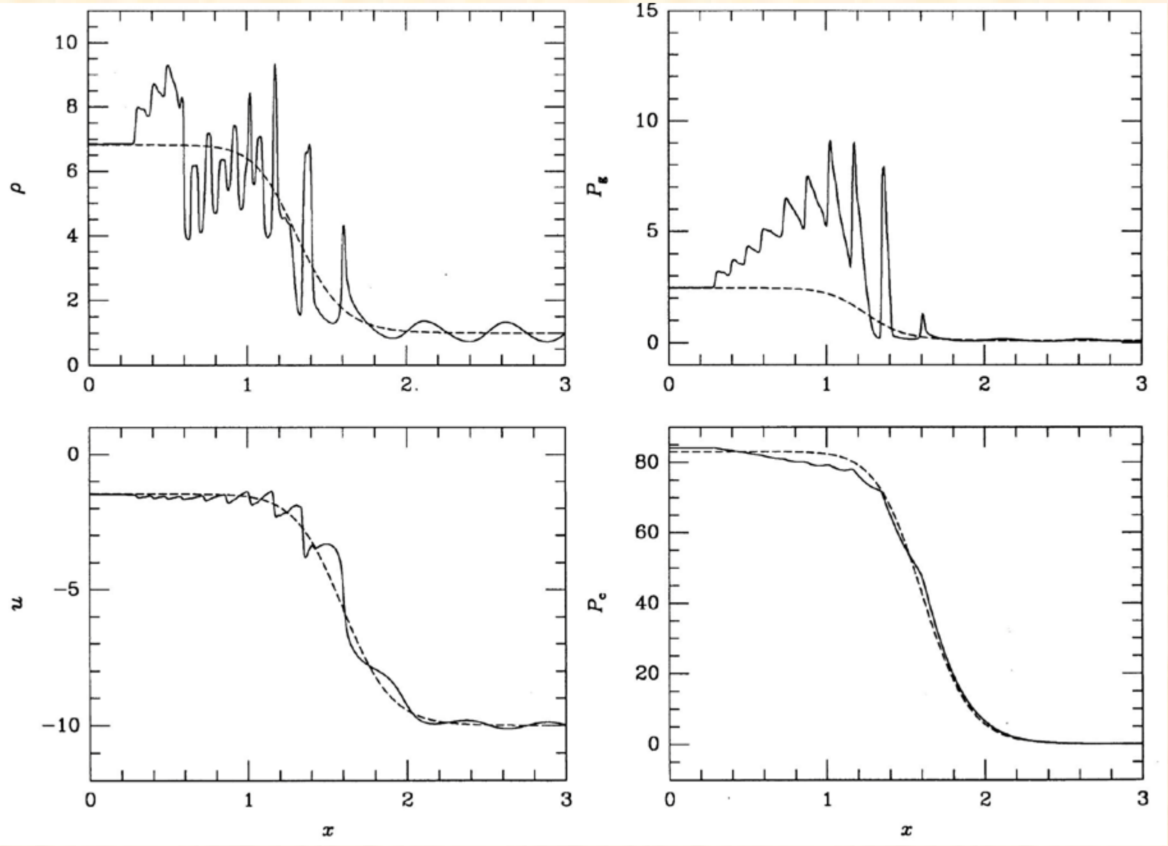


Zirakashvili et al 2008

Precursor instabilities due to smooth $P_{c,}$

Weak dynamical coupling of CRs with fluid:

a $\propto \nabla P_t/\rho$, if $P_t \sim P_c$ enhances compressions => acoustic instability in 1D generates mini-shocks in precursor



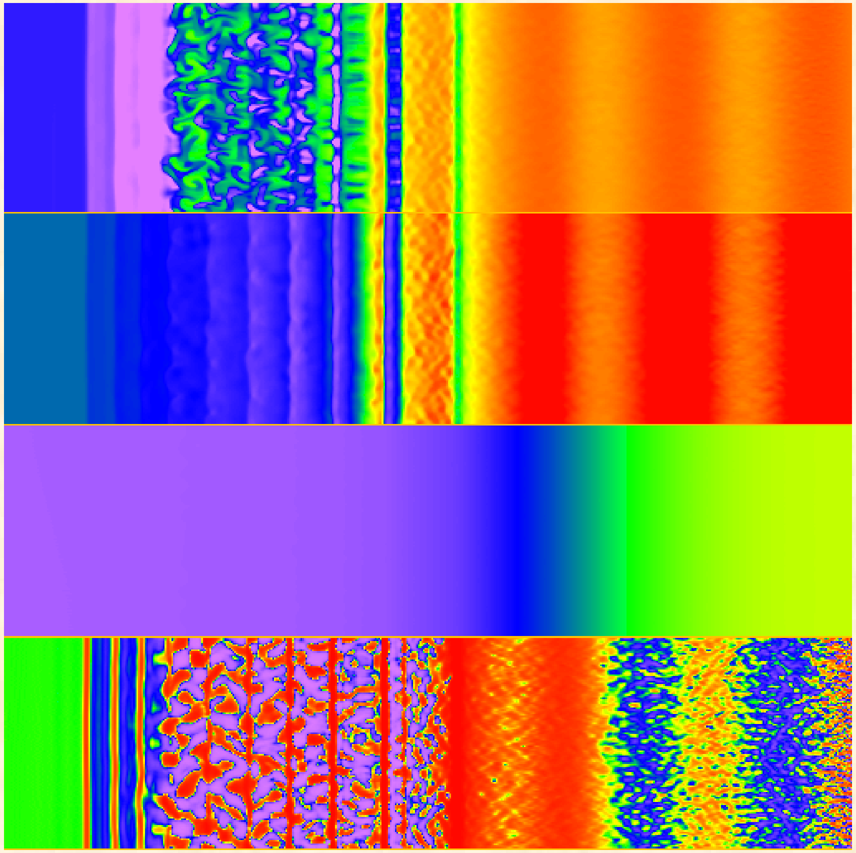
e.g., Drury & Falle
Kang et al
Malkov & Diamond

Ryu et al 1993

Diffusive P_c also leads to R-T like instabilities

In presence of density variations,

$\nabla P \cdot \nabla \rho < 0$ locally



density, ρ

P_g

P_c

div u

Ryu et al 1993

Smooth P_c in precursor of shocked turbulence:

Local $\nabla P \cdot \nabla \rho < 0$ condition amplifies precursor turbulence

=> small scale dynamo

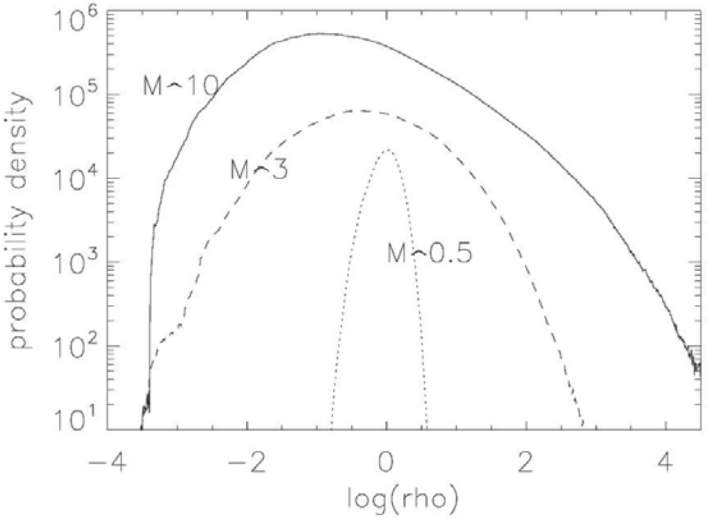


FIG. 1.— PDF of density of the inflow fluid is approximately log-normal due to the ambient turbulence in the ISM. Pictured is PDF of density from simulations with different sonic Mach numbers (Beresnyak, Lazarian & Cho, 2005).

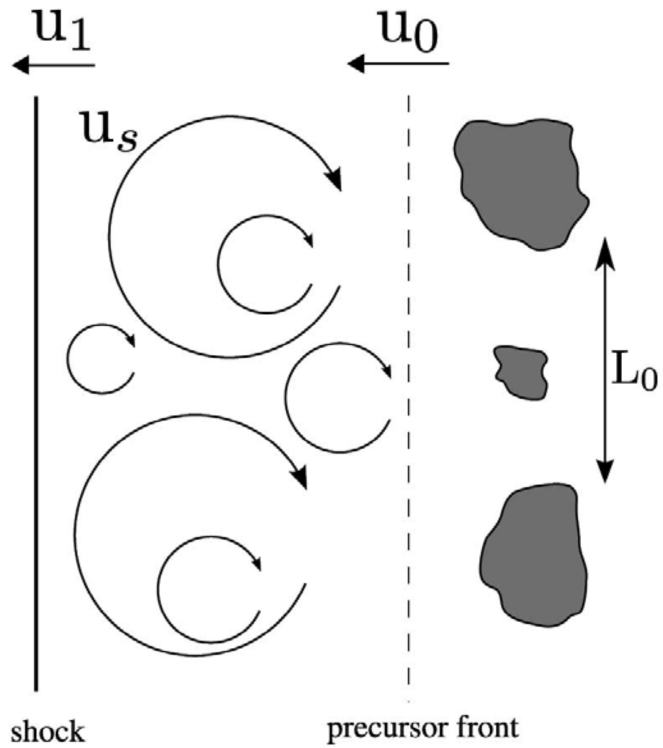


FIG. 2.— Solenoidal motions, exited by CR precursor (the real picture is three-dimensional). In the frame of the shock the preexisting perturbations enter the precursor creating both compressive and solenoidal velocity perturbations (the last being depicted).

Beresnyak et al 2009

Schematic of expected PDFs & diffusion properties

E_b saturates on scales < L*< L

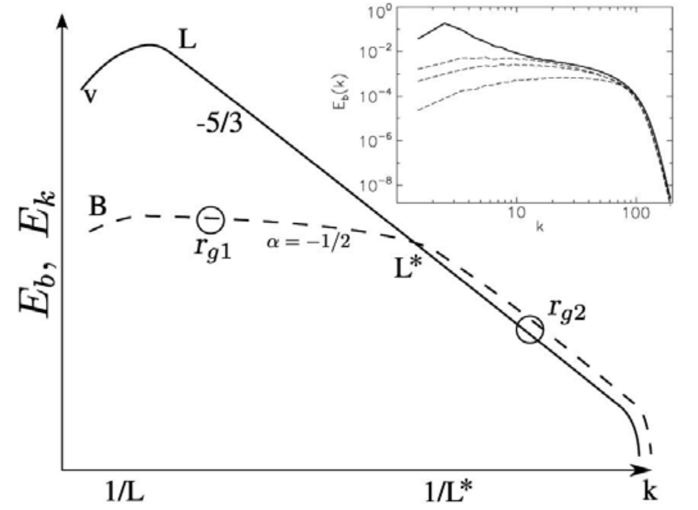


FIG. 3.— Magnetic field spectrum (dashed), generated by small-scale dynamo induced by solenoidal velocity motions (solid). L^* is an equipartition scale of magnetic and kinetic motions, it plays a central role in particle scattering. Upper panel: magnetic and velocity fields from simulations (Cho et al 2009) with different dashed lines corresponding to magnetic spectra at different times.

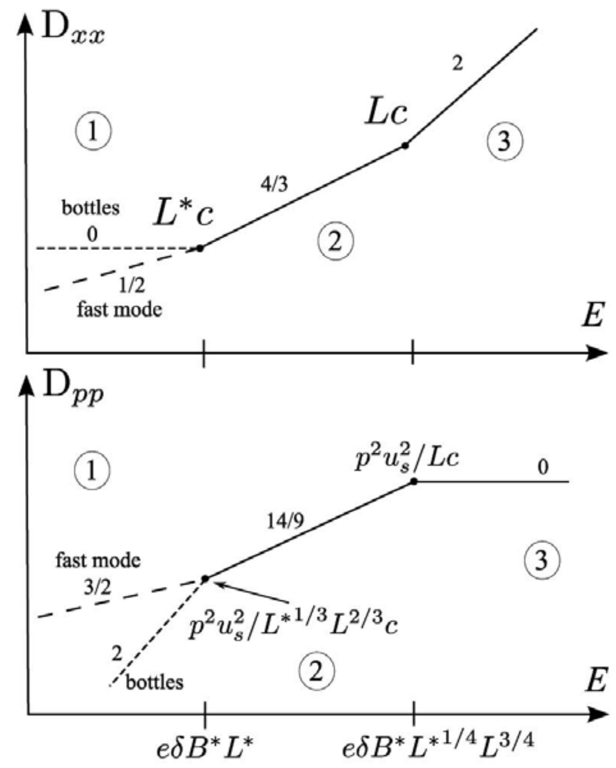


FIG. 4.— Scattering coefficients as they depend on energy. The scattering has three principal regimes: (1), a low-energy scattering, which depends on the properties of small-scale MHD turbulence, two cases where fast modes are present (dashed) and absent (dotted) are shown; (2), the strong scattering, where particles are scattered efficiently by the large magnetic fields, generated by small-scale dynamo; (3), high-energy scattering, where particles are only weakly scattered.

Beresnyak et al 2009

Summary

- Detailed modeling will be a challenge for some time

- The underlying physics is robust

- Strong, CR shocks subject to multiple instabilities

- Magnetic field amplification is likely
  in both precursor & post shock regions

- Injection physics is critical (espec. efficiency), hard problem