Magnetic turbulence in the shock precursor and CR acceleration

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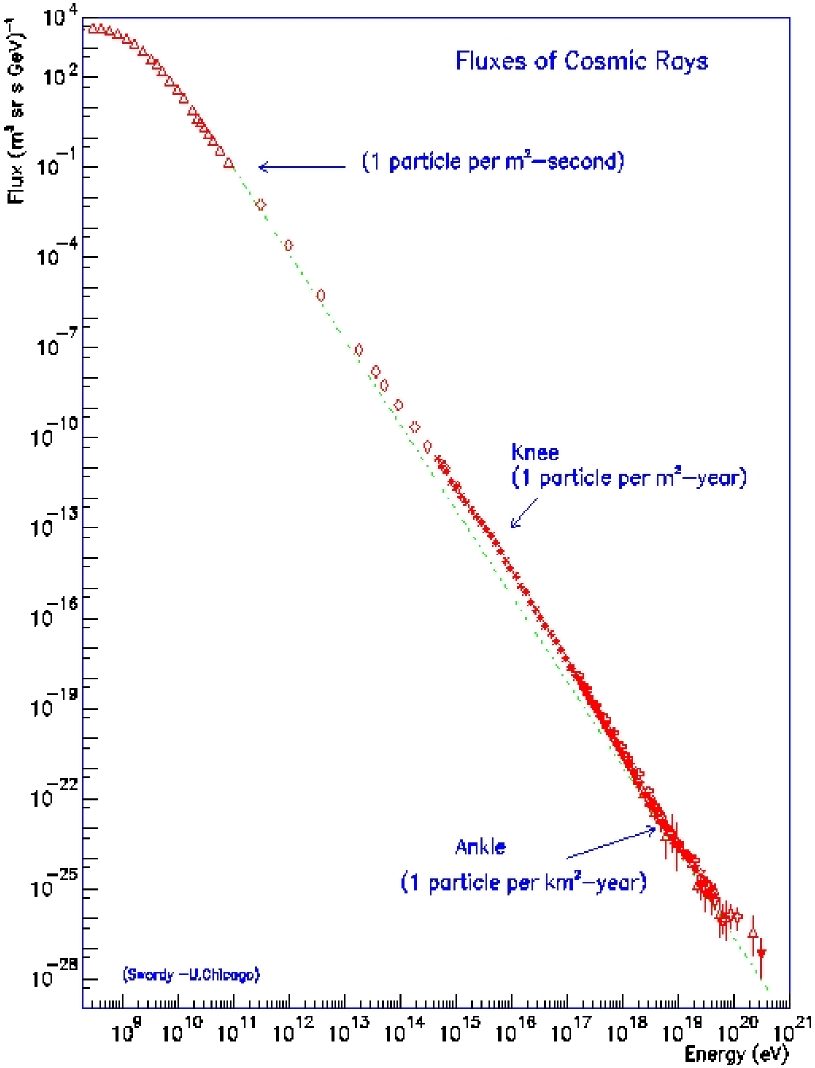
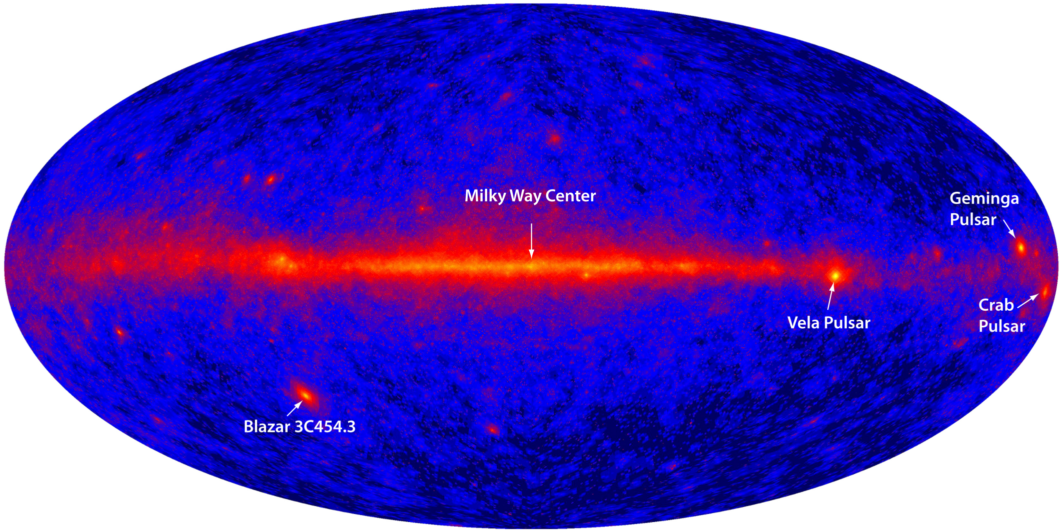
CRISM 2011

CR spectrum observed on Earth (mostly isotropic):



Cosmic rays are possibly produced by supernova explosions: Baade & Zwicky 1934; Shklovskii 1953; etc.

Fermi gamma-ray sky:



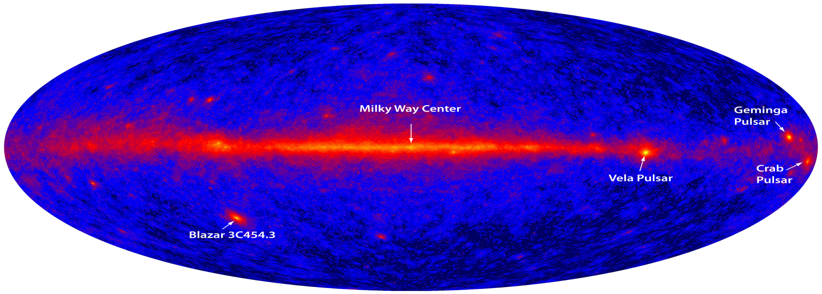
There is a correlation between diffuse gamma rays and density of supernova remnants. This is actually a correlation with matter density.

CRs in the Galaxy

Energy density in our Galaxy $w_B \sim w_{CR} \sim w_{\mathrm{kin.}} \sim 1\mathrm{eV/cm}^3$

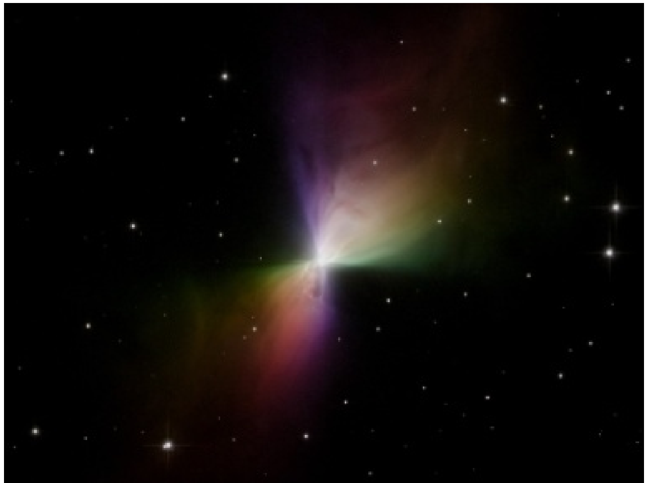
Lifetime in the disk ~ 3 My, in corona 20 My (from C/B and ^{10}Be)

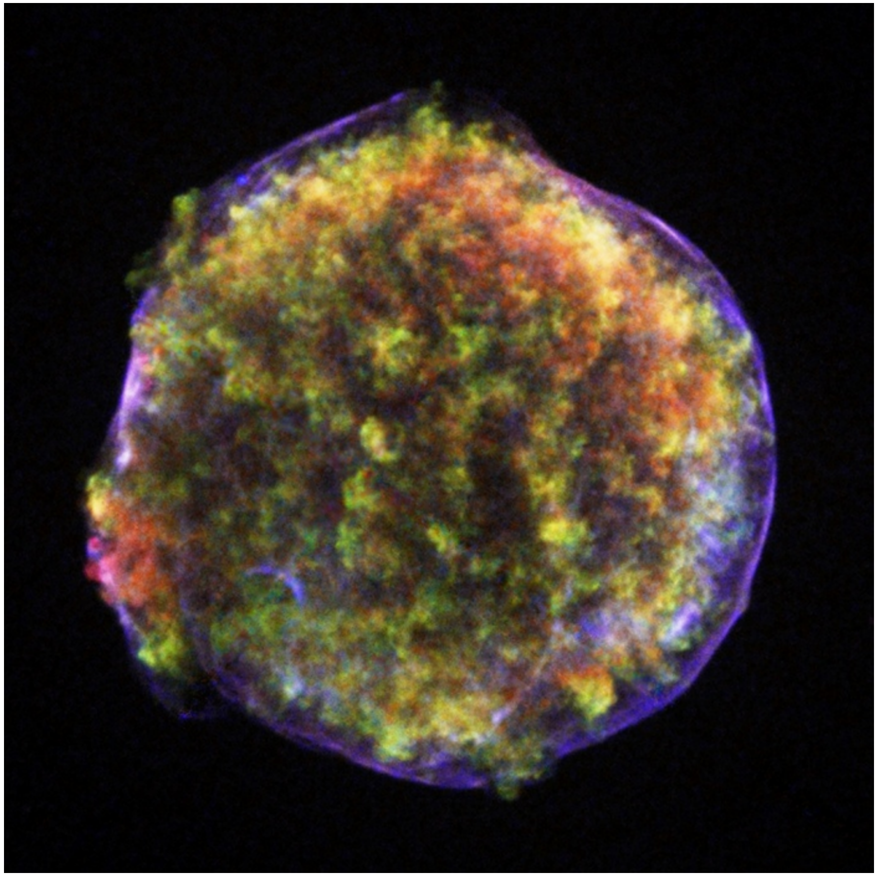
P_{CR}~10% of supernova energy



Turbulent reacceleration (second order), e.g.:

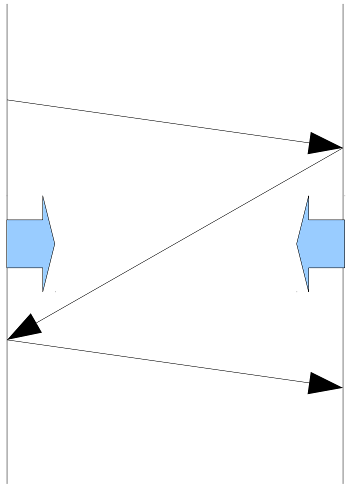
Stellar winds vs Supernovae





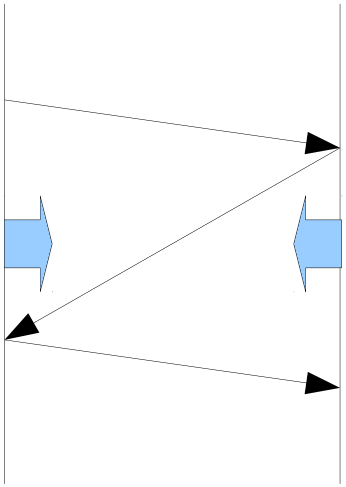
Tycho supernova in X-rays, *Chandra observatory, 2002*

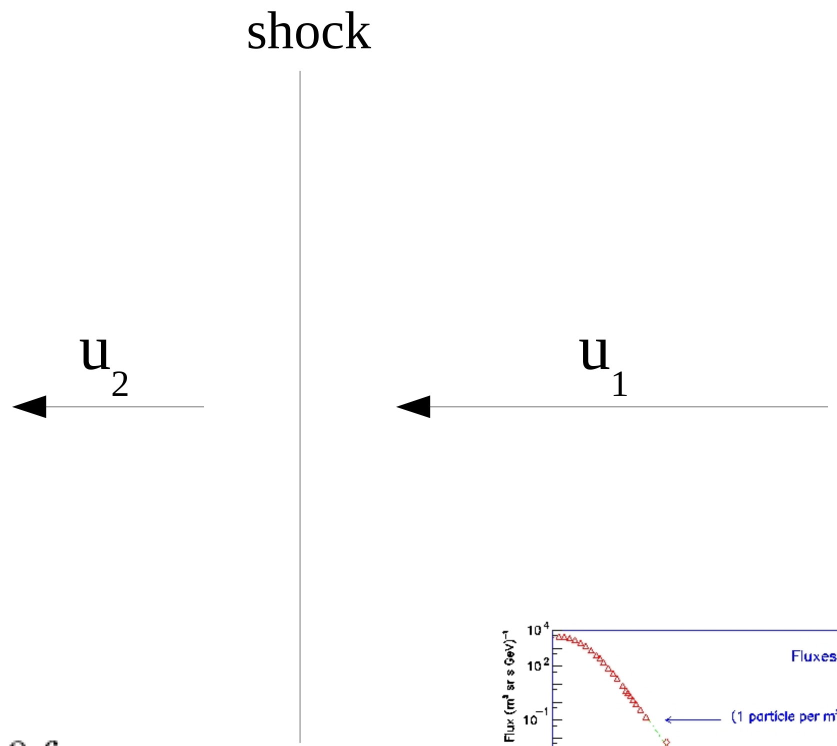
1-st order Fermi: acceleration by converging mirrors
Fermi 1949



Diffusive Shock Acceleration

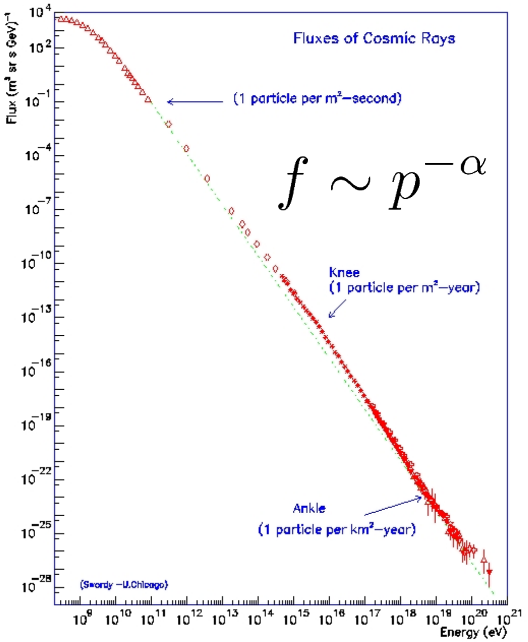
1-st order Fermi: acceleration
by converging mirrors
Fermi 1949





$$\frac{\partial f}{\partial t} + u\frac{\partial f}{\partial x} = \frac{\partial}{\partial x}\left(D_{xx}\frac{\partial f}{\partial x}\right) + \frac{p}{3}\frac{\partial u}{\partial x}\frac{\partial f}{\partial p}\,.$$

Krymsky, 1977
Axford et al, 1977
Bell, 1978
Blandford & Ostriker 1978



$$f \sim p^{-\alpha}$$

Diffusive Shock Acceleration

shock

Post-shock turbulence

Fluid doesn't know about the shock

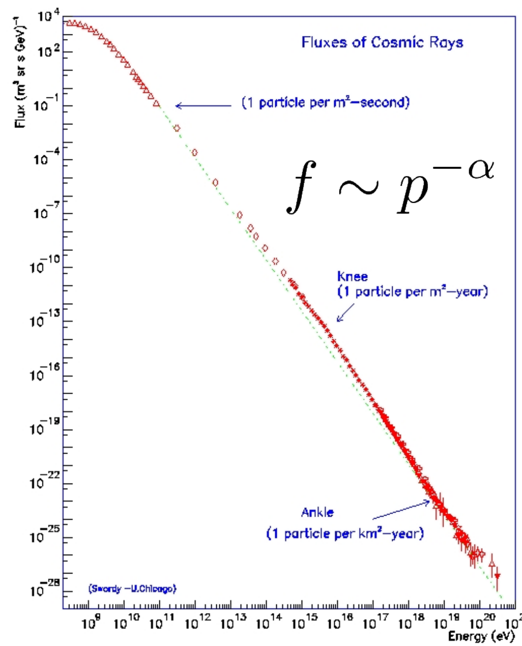
Test particle models actually predict almost no acceleration!

u_2

u_1

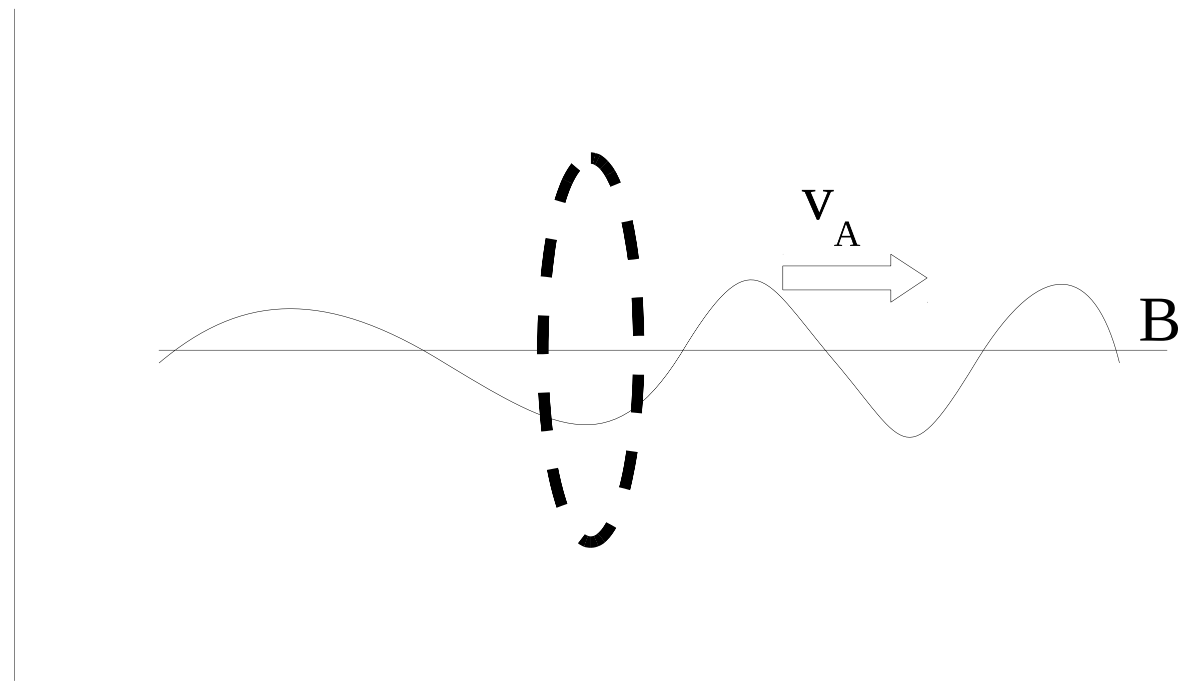
Key: lifetime of the shock vs diffusion coefficient D.

$$\frac{\partial f}{\partial t} + u\frac{\partial f}{\partial x} = \frac{\partial}{\partial x}\left(D_{xx}\frac{\partial f}{\partial x}\right) + \frac{p}{3}\frac{\partial u}{\partial x}\frac{\partial f}{\partial p}$$



$$f \sim p^{-\alpha}$$

Streaming Instability in Front of the Shock

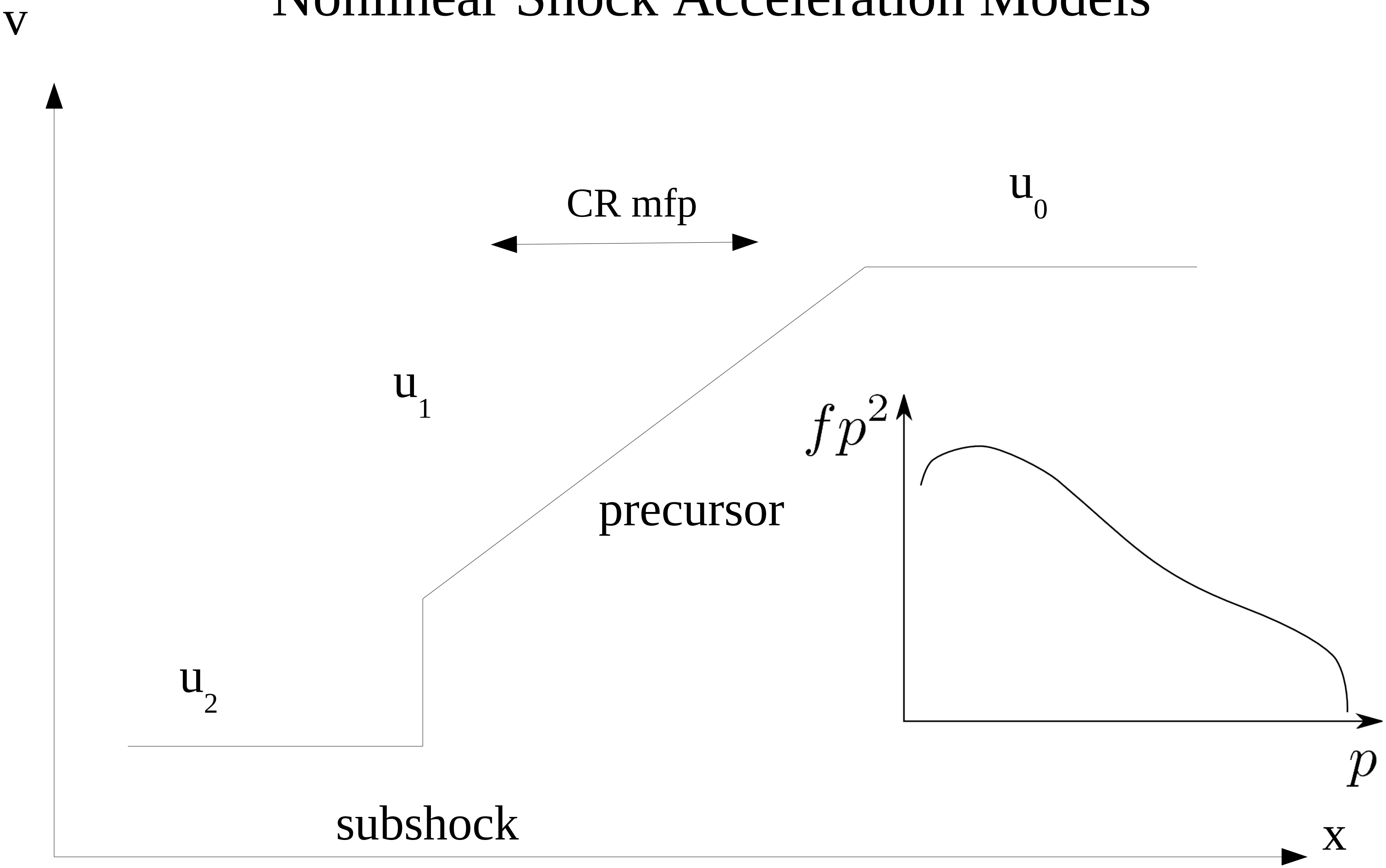


shock

$$\frac{\partial f}{\partial t} + u\frac{\partial f}{\partial x} = \frac{\partial}{\partial x}\left(D_{xx}\frac{\partial f}{\partial x}\right) + \frac{p}{3}\frac{\partial u}{\partial x}\frac{\partial f}{\partial p} + \frac{1}{p^2}\frac{\partial}{\partial p}\left(p^2 D_{pp}\frac{\partial f}{\partial p}\right)$$

See Elena Amato's talk

Nonlinear Shock Acceleration Models



See, e.g., review by Malkov & Drury (2001)

Challenge of the problem:

1) Strongly nonlinear, supersonic fluid dynamics
2) Disparity of scales:
- Ratio of outer to dissipation scales of turbulence
- Ratios of r_L of thermal particle (<1eV), low energy CR (~1GeV), high energy CR (~10^7GeV)

Codes:

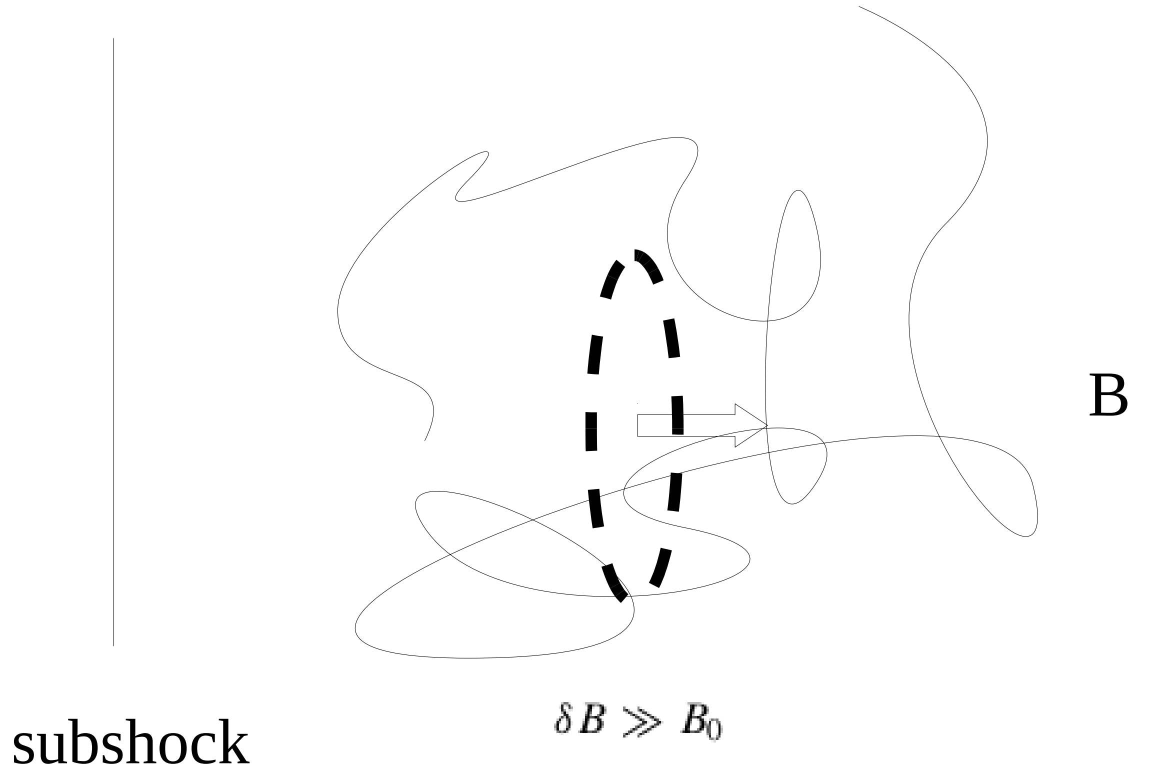
Fluid codes have limited resolution, PIC codes have both limited resolution and limited statistics at high energies.

Observations:

One observation worth 1000 theories, but its not easy to make the trade.

Nonlinear Streaming Instability

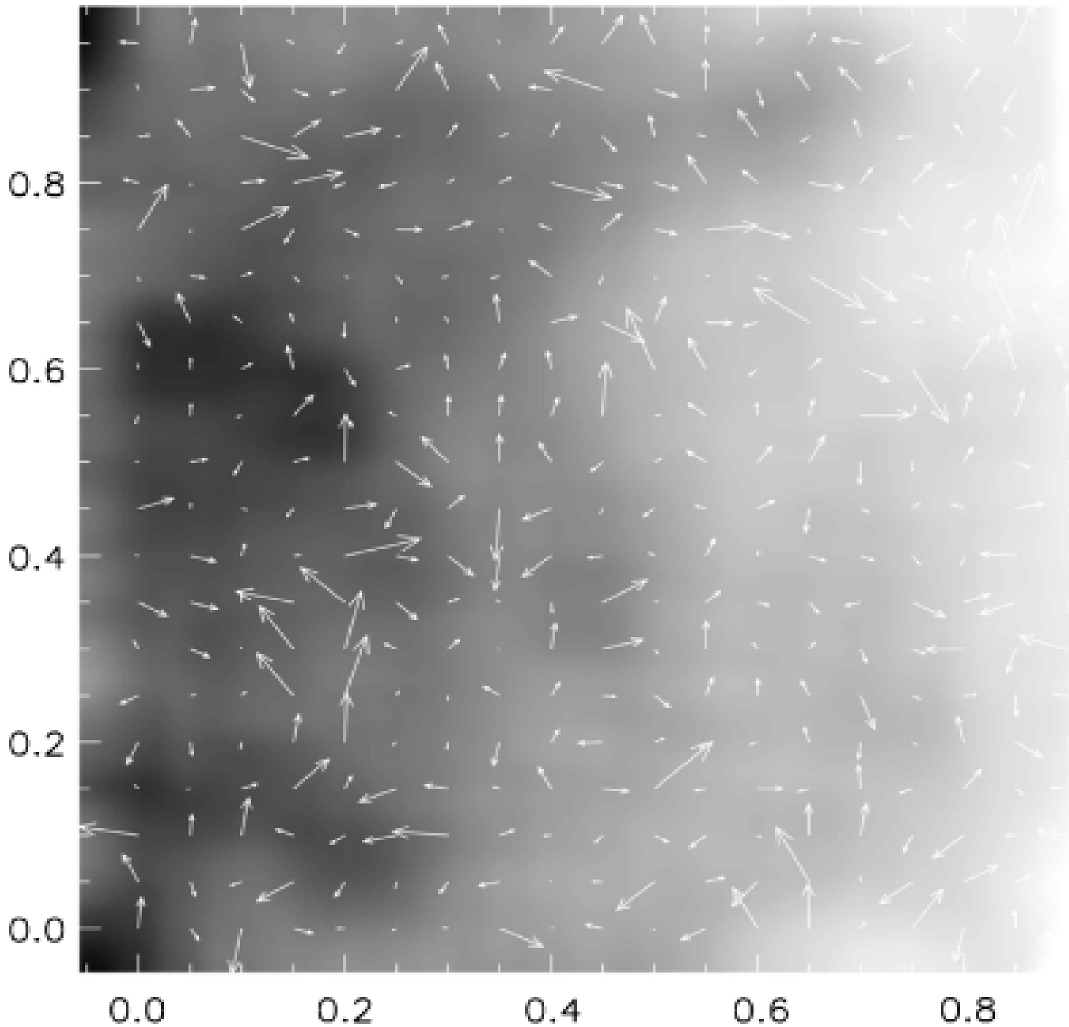
The free energy of CRs will easily generate magnetic fields higher than the ISM field (5μG).



Diamond & Malkov (2007)

Particle Tracing in Turbulent Fields

particles injected



particles escape

(slice from 3D)

Current Instability (Bell 2004)

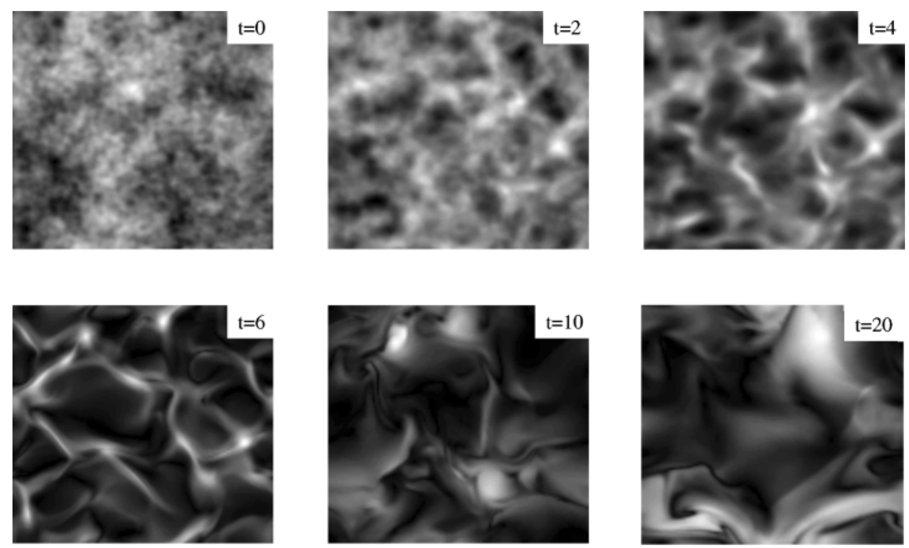
j_{CR}

B

$\delta B \gg B_0$

subshock

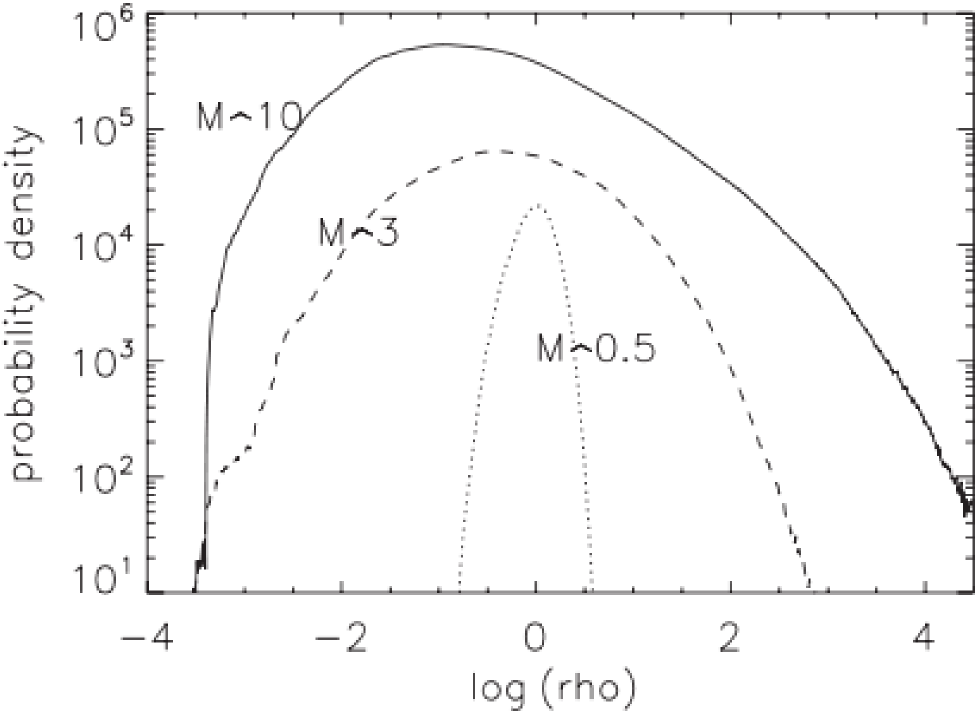
inflowing fluid has small
magnetic perturtabions



from Bell (2004)

Alternative to current or streaming instability

Density inhomogeneities in the ISM or stellar wind



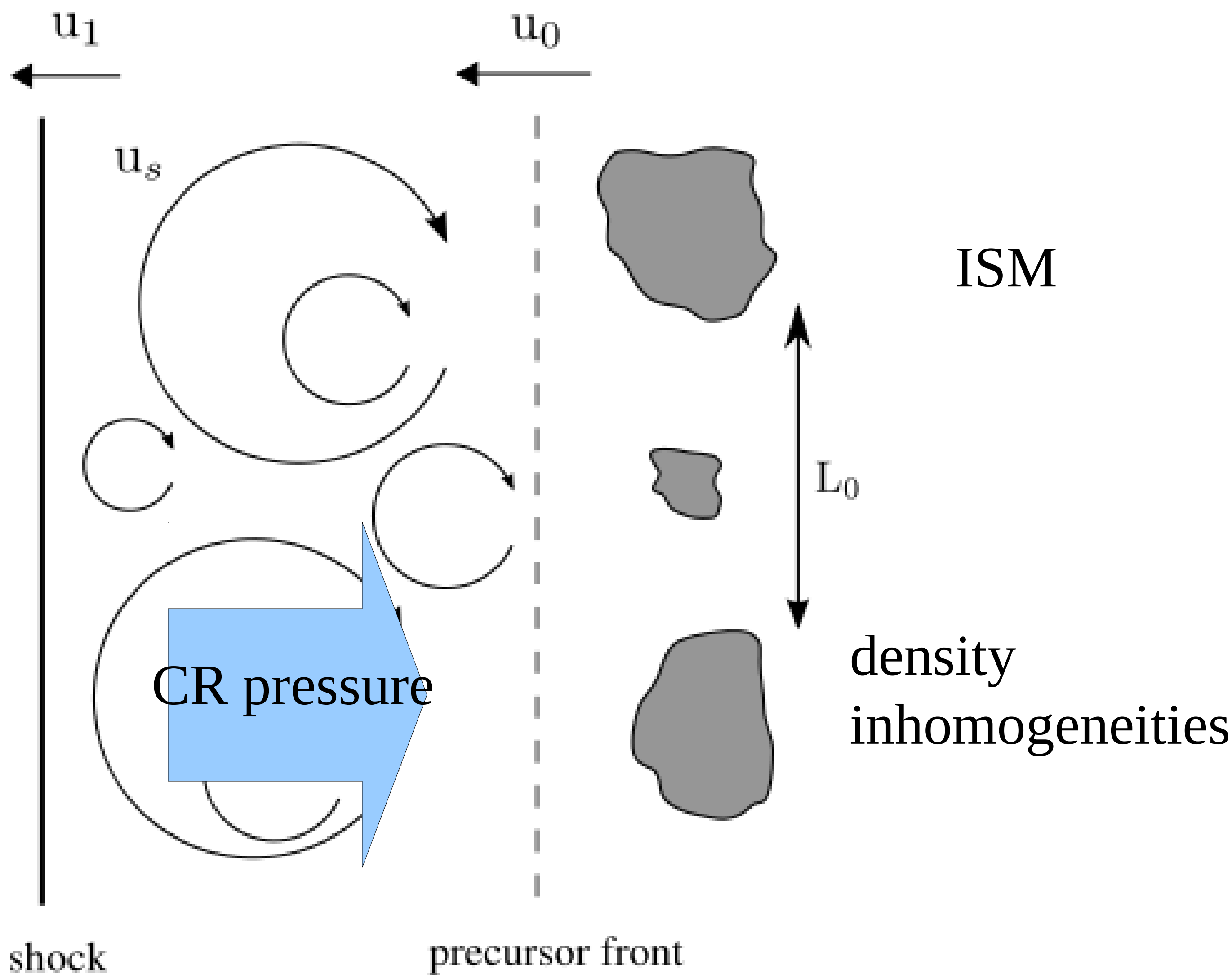
Crab Nebula (*NASA*, *HST*)

On the density scalings see, e.g. Patrick Hennebelle's talk

Precursor Turbulence will generate magnetic fields

$$\nabla \rho \times \nabla P$$

directly produce vorticity

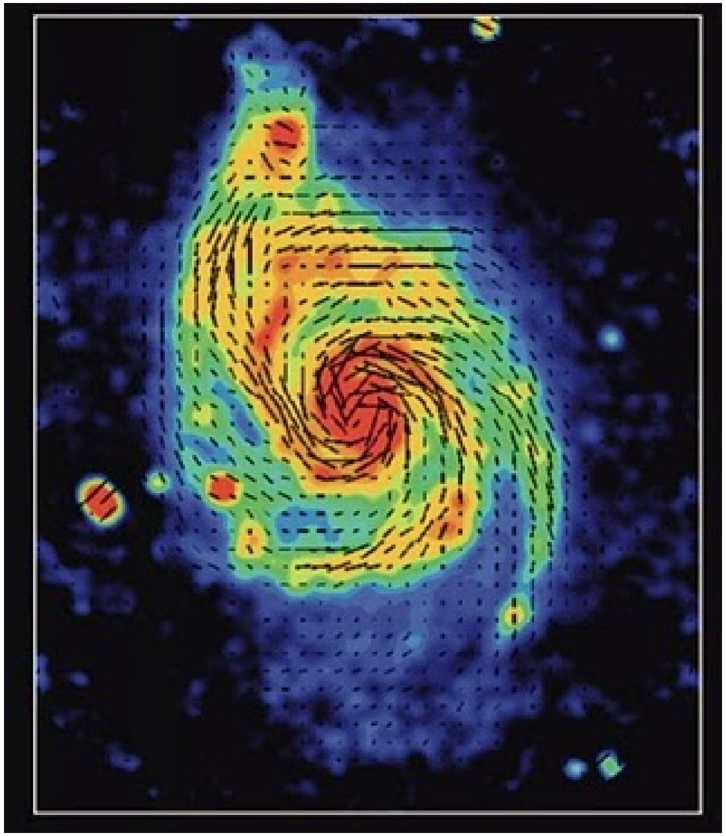


MHD Dynamo

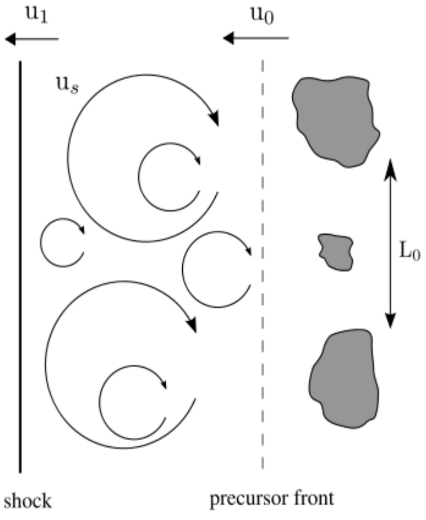
Large-scale dynamo $L(B)>L_t$
require special conditions and slow.

Small-scale dynamo $L(B)<L_t$
very generic in three-dimensional dynamics and fast

Disk galaxies:

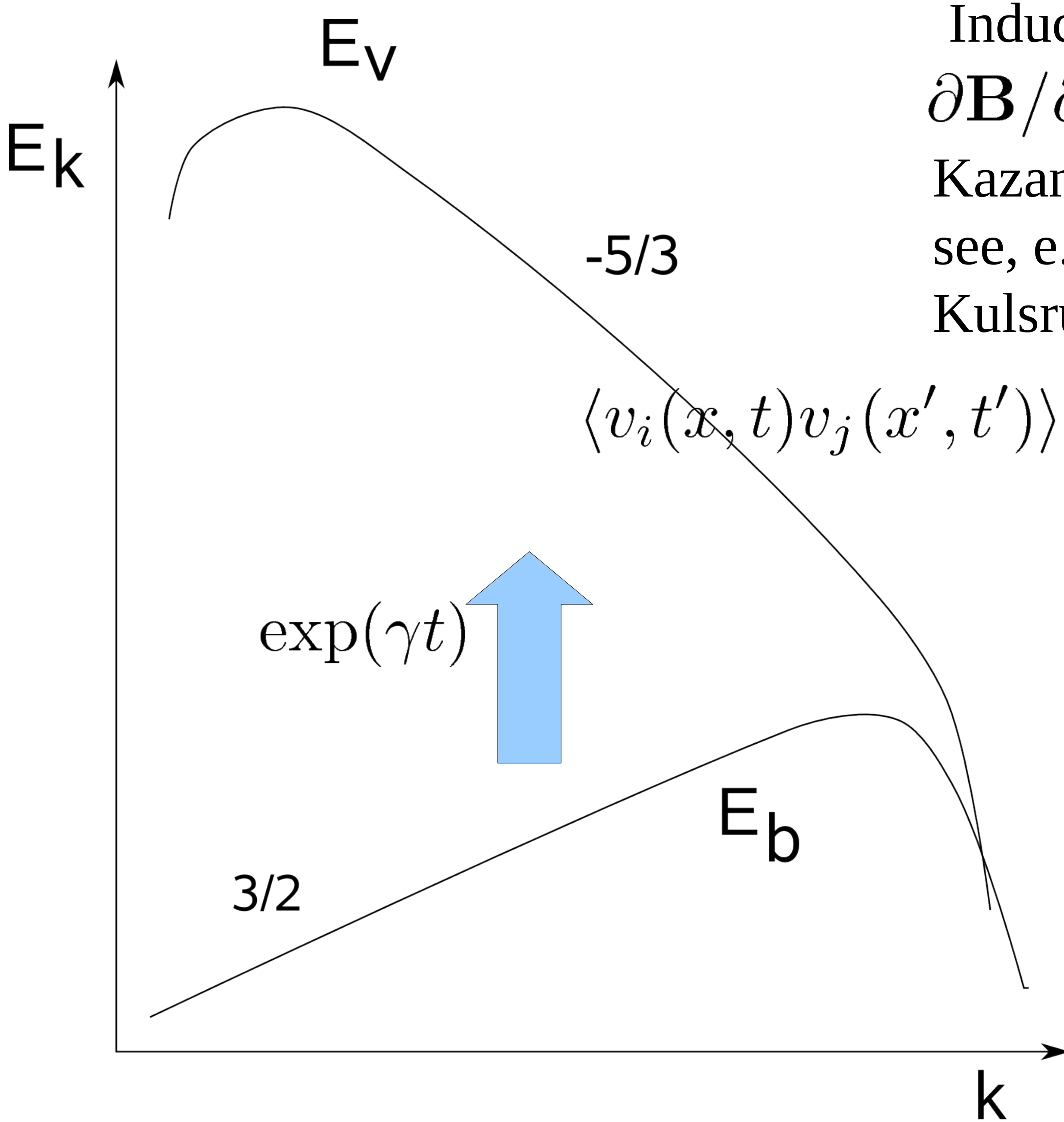


CR shocks:



Clusters

Kinematic Dynamo



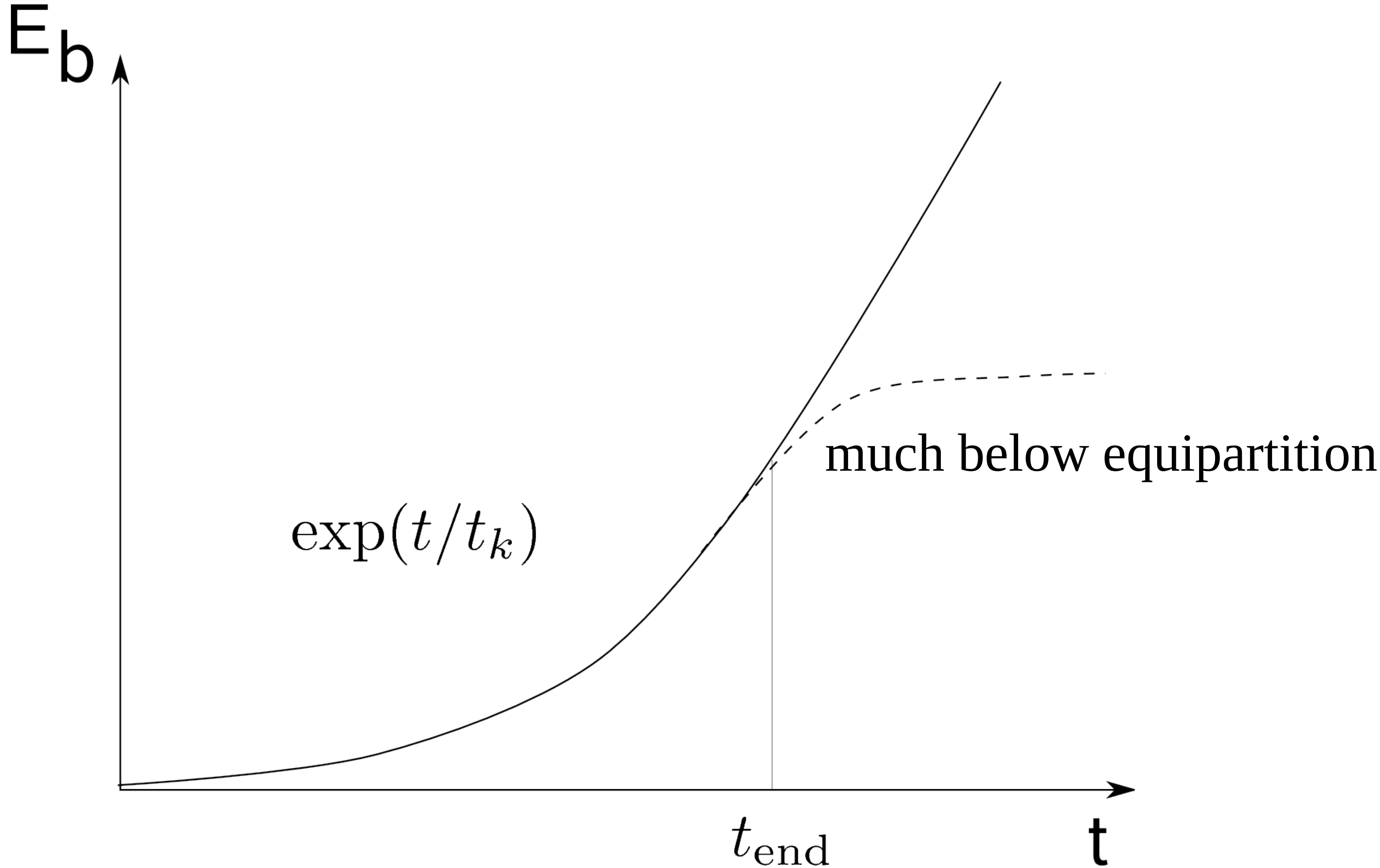
Induction eq-n is linear

$$\partial \mathbf{B}/\partial t = \nabla \times (\mathbf{v} \times \mathbf{B})$$

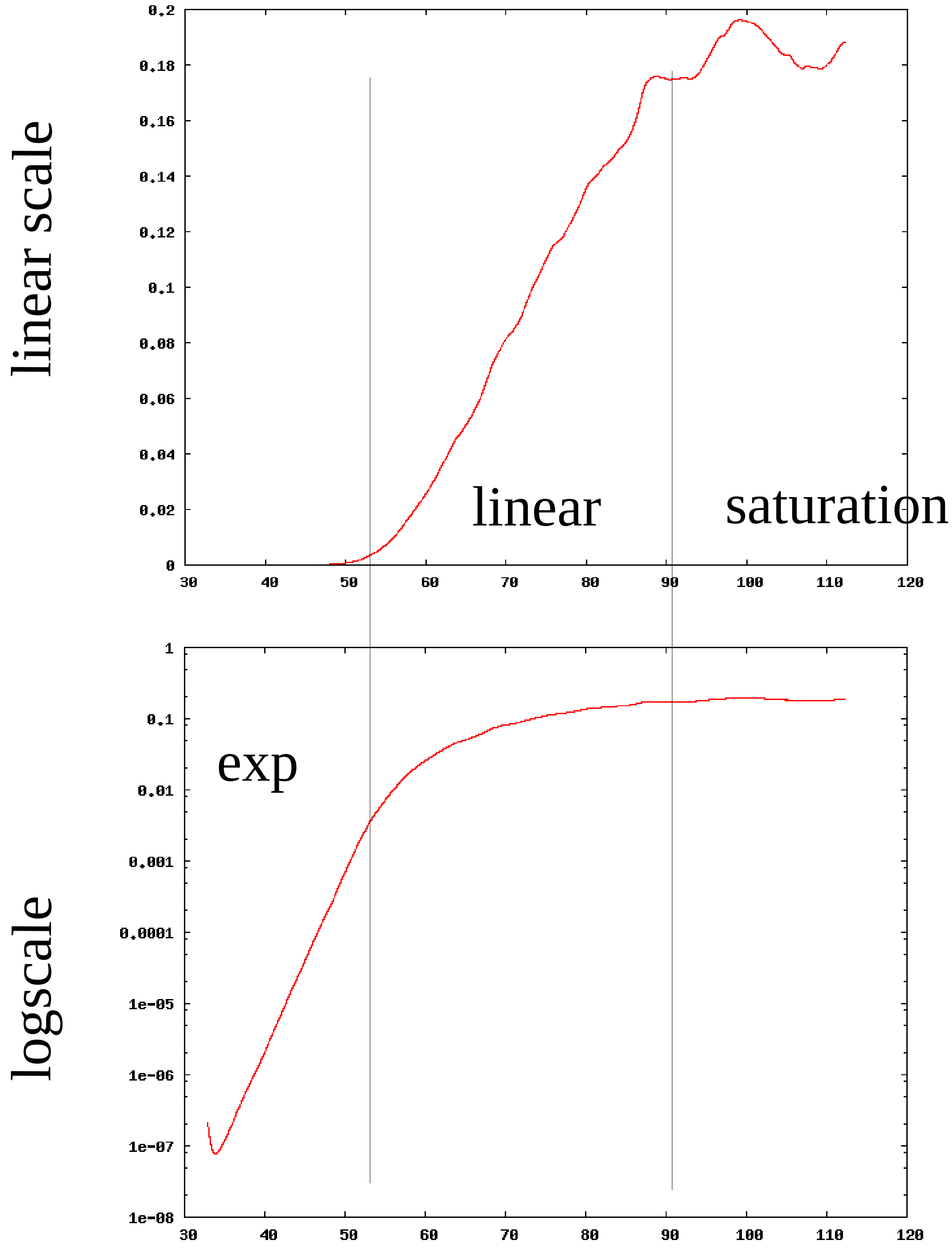
Kazantsev-Krachnan model, see, e.g. Kazantsev, 1967, Kulsrud & Anderson 1992:

$$\langle v_i(x,t) v_j(x',t')\rangle = \kappa_{ij}(x-x')\delta(t-t')$$

Nonlinear Dynamo



Evolution of total magnetic energy

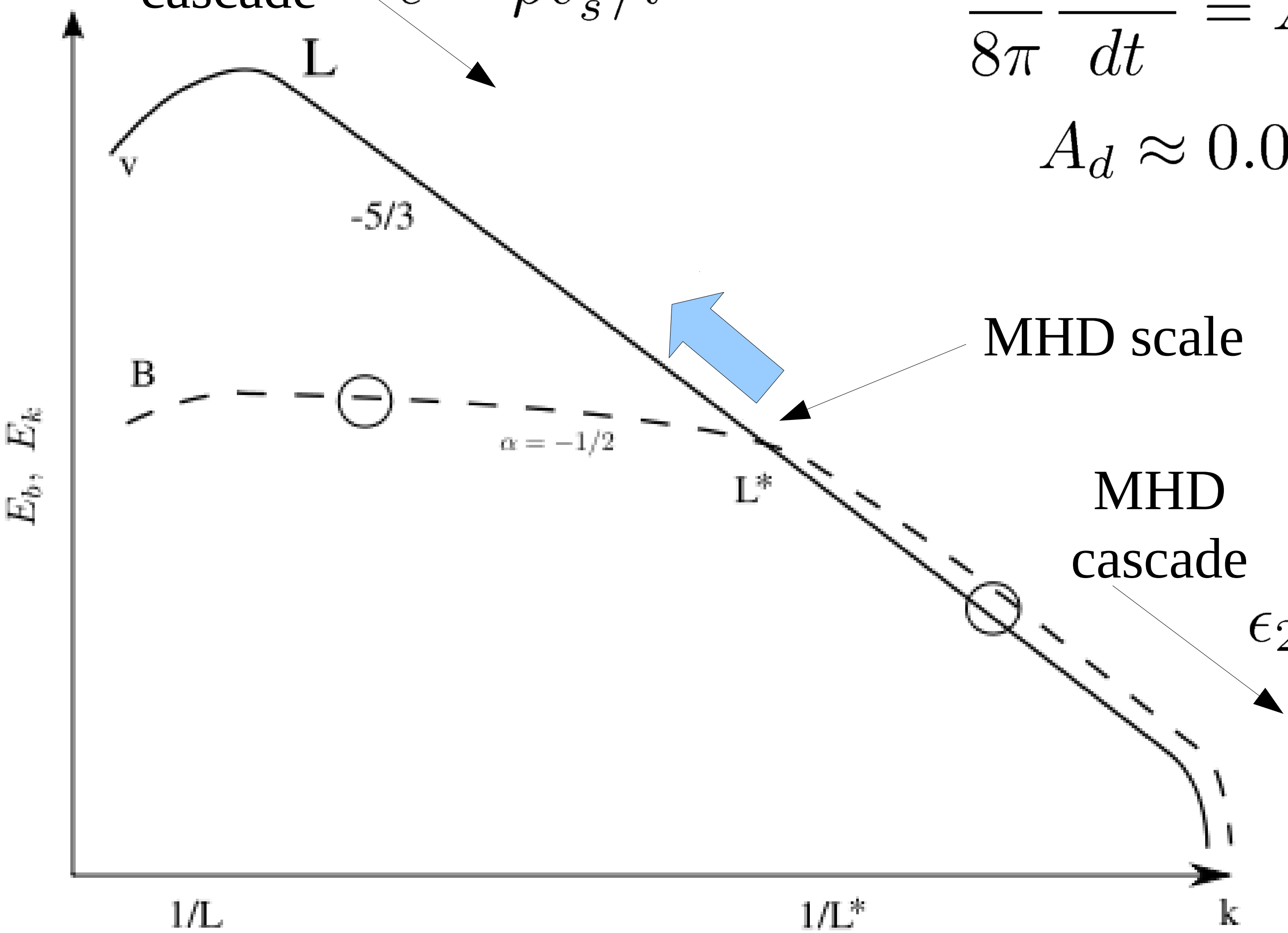


Astrophysical Small-Scale Dynamo

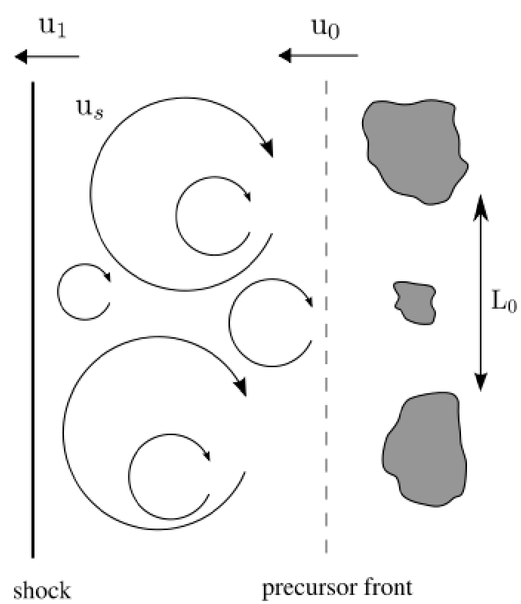
hydrodynamic cascade $\epsilon \sim \rho v_s^3/l$

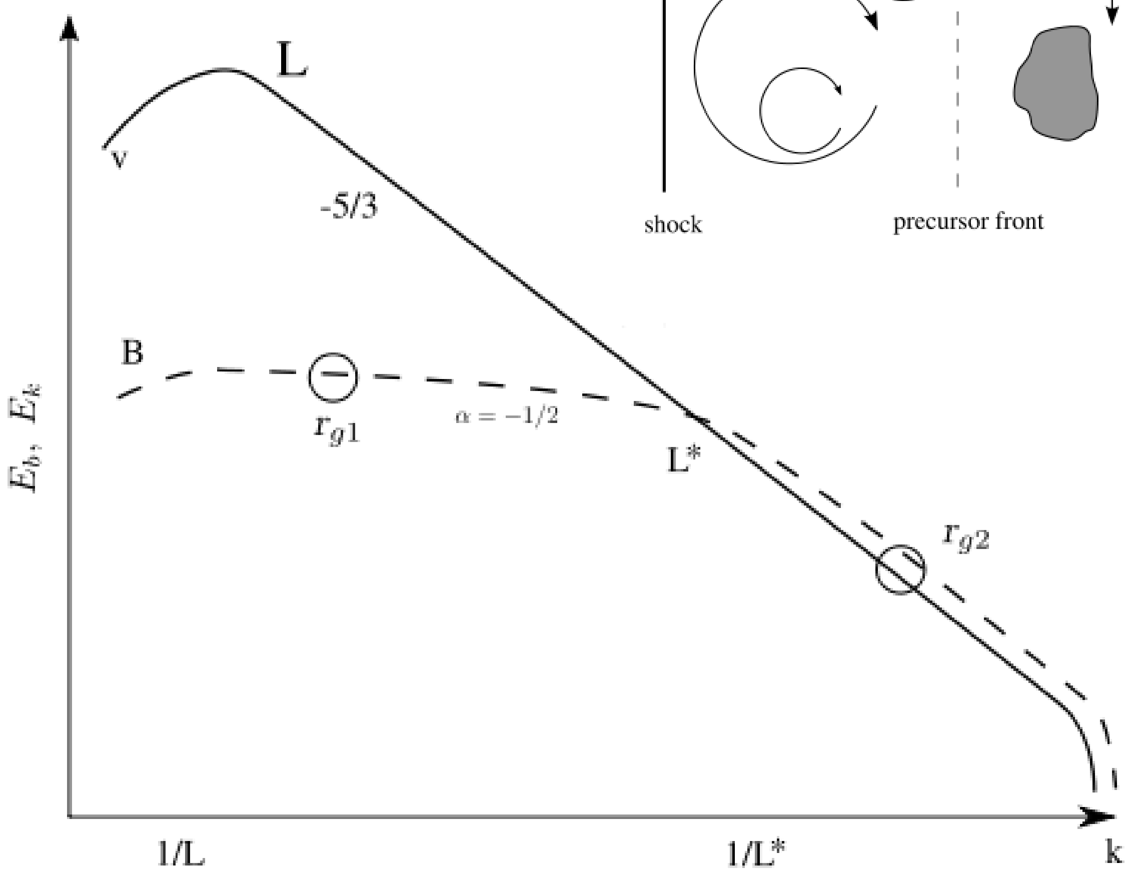
$$\frac{1}{8\pi}\frac{dB^2}{dt} = A_d \epsilon t$$

$$A_d \approx 0.06$$



Dynamo in the shock precursor





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

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

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

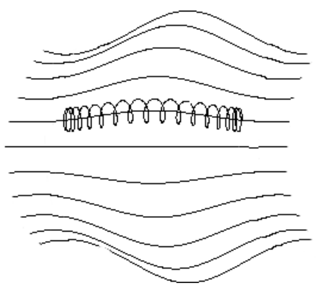
$$L^*(x_1) = (2A_d u_s \tau(x_1))^{3/2} L^{-1/2}.$$

Concepts in scattering

Scattering by existing fields

Self-scattering(instabilities), e.g. streaming instability.

Regular field



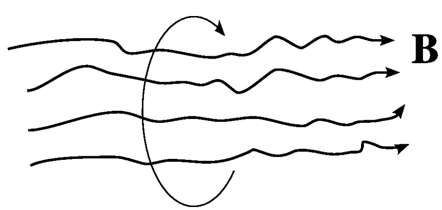
Magnetic mirrors

$D_{\mu\mu}$~const

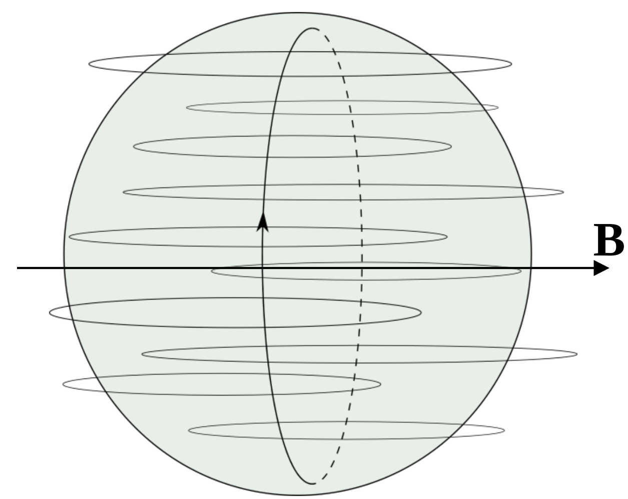
$D_{\mu\mu}/\Omega$~r

Anisotropic B perturbations are inefficient scatterers:

Random field



Resonant scattering

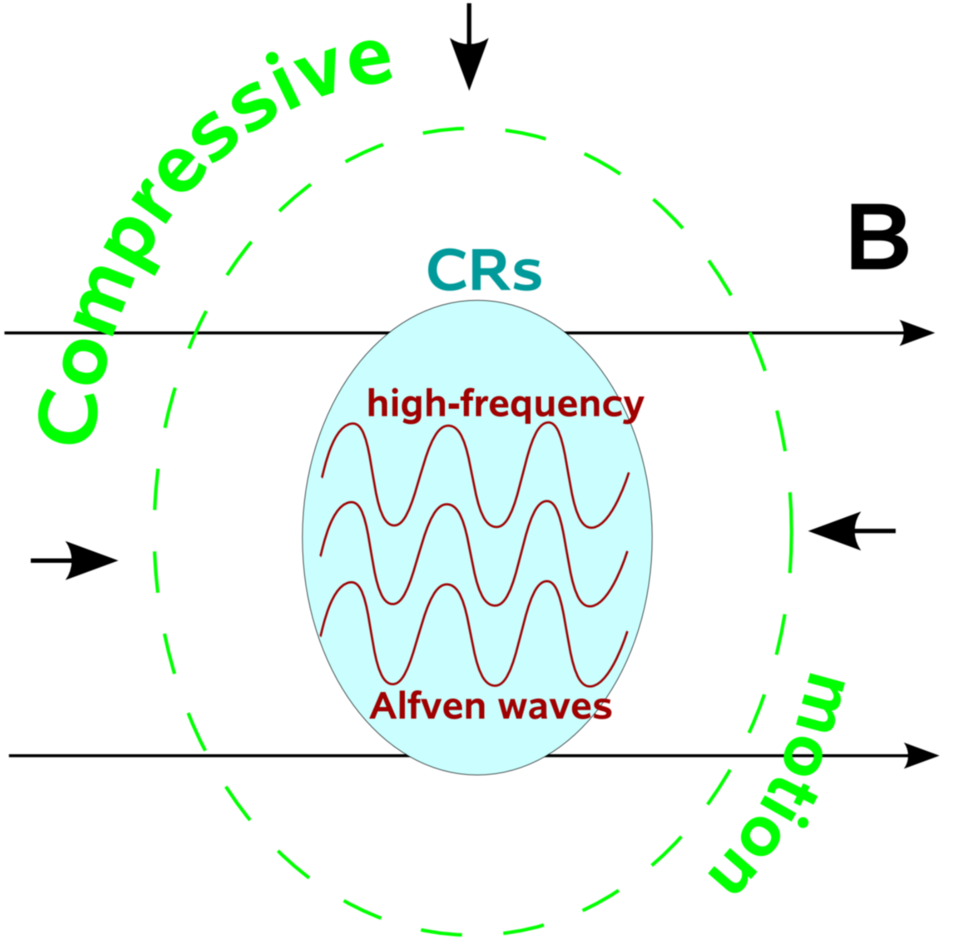


$$\langle B_i(\mathbf{k}) B_j^*(\mathbf{k}')\rangle / B_0^2 = \delta(\mathbf{k} - \mathbf{k}') M_{ij}(\mathbf{k})$$

“QLT” Jokipii 1966, NLT

$D_{\mu\mu}/\Omega$ ~$r^{2.5}$

The instability between circularly polarized Alfven wave and the anisotropic distribution of fast particles (CRs)

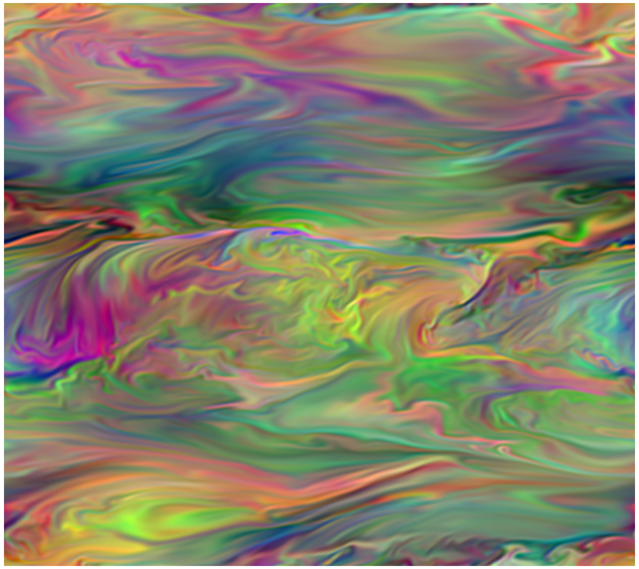


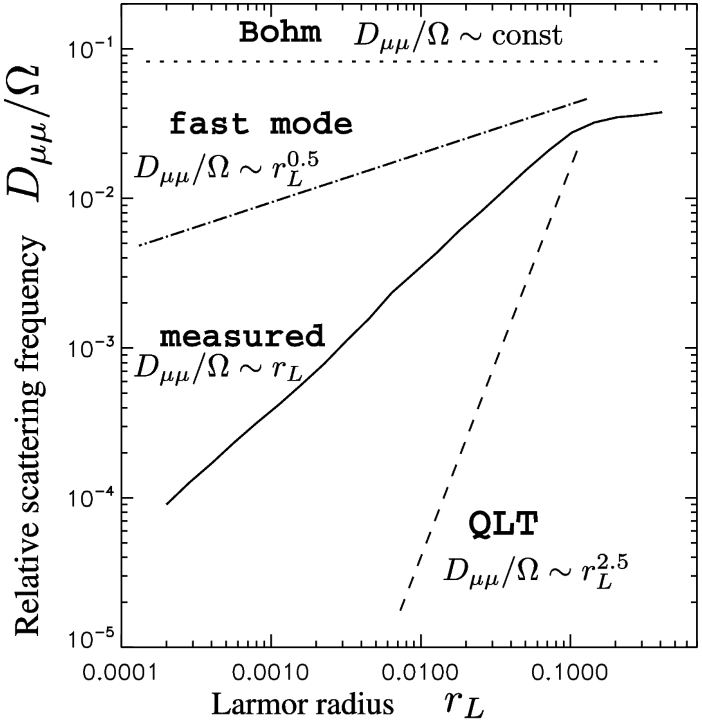
$$\gamma_{\mathrm{CR}} = \pi^2 e^2 v_A \int \frac{v_\perp^2}{c^2} \left(\frac{\partial F}{\partial p_\parallel} - \frac{v_\parallel}{v_\perp} \frac{\partial F}{\partial p_\perp} \right) \delta(k_\parallel v_\parallel \pm \omega_C)\, d^3\mathbf{p}$$

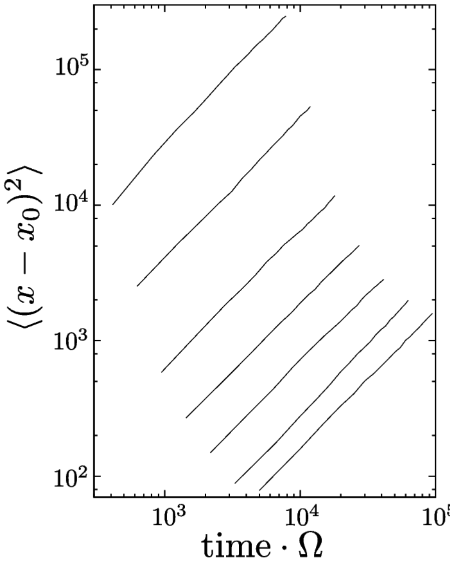
See MNRAS 373, 1195

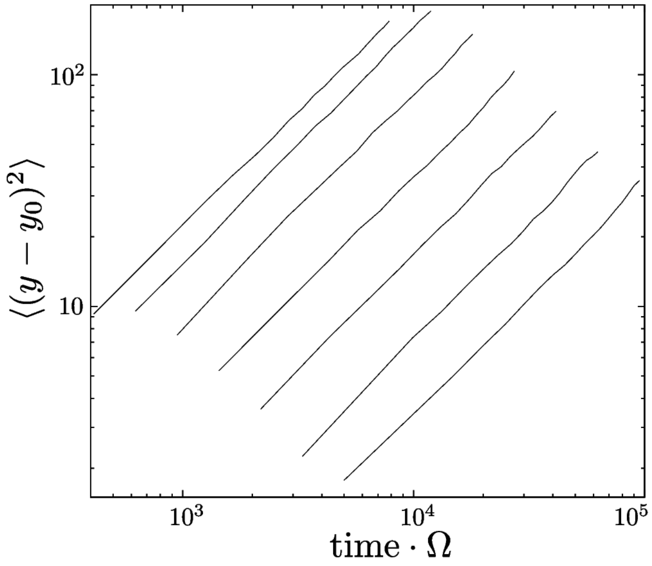
Particle scattering and diffusion in a magnetic turbulence with outer scale

incompressible MHD simulations
+ particle tracing code
(Beresnyak et al 2011, ApJ)



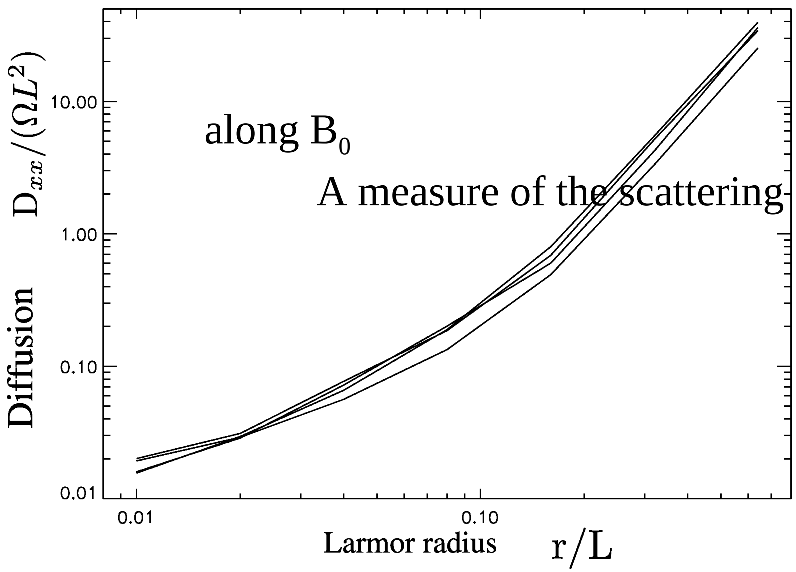




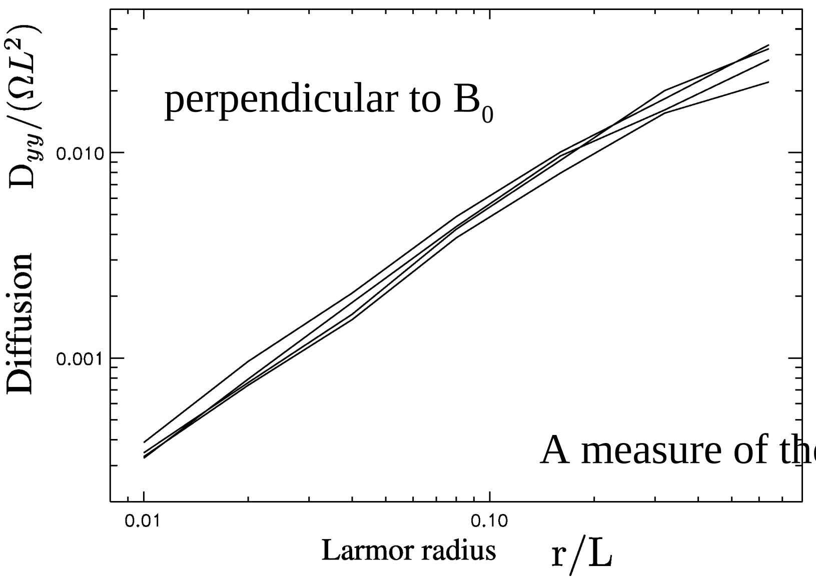


Space diffusion

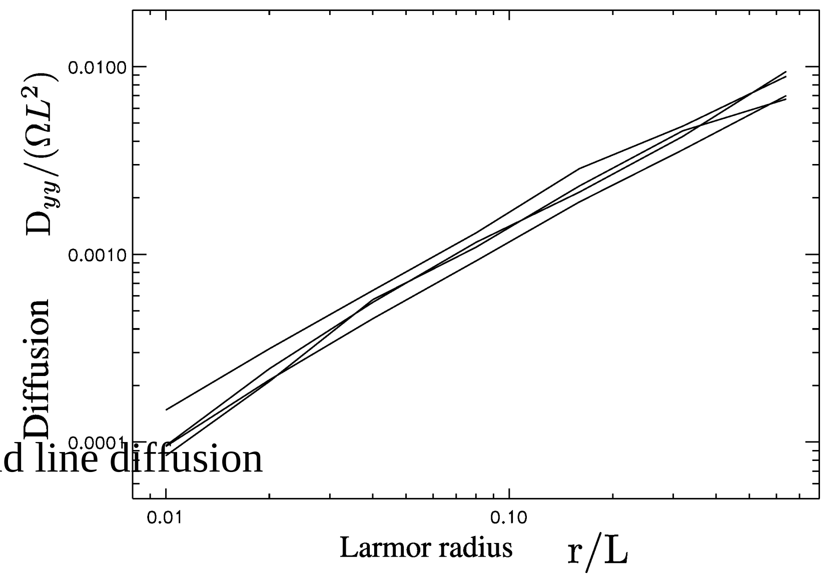
transAlfvenic $\delta B \sim B_0$



NB: We made highest resolution MHD simulations ever performed (up to 3072^2x1024), data cubes are available upon request, soon might be available in a public database.



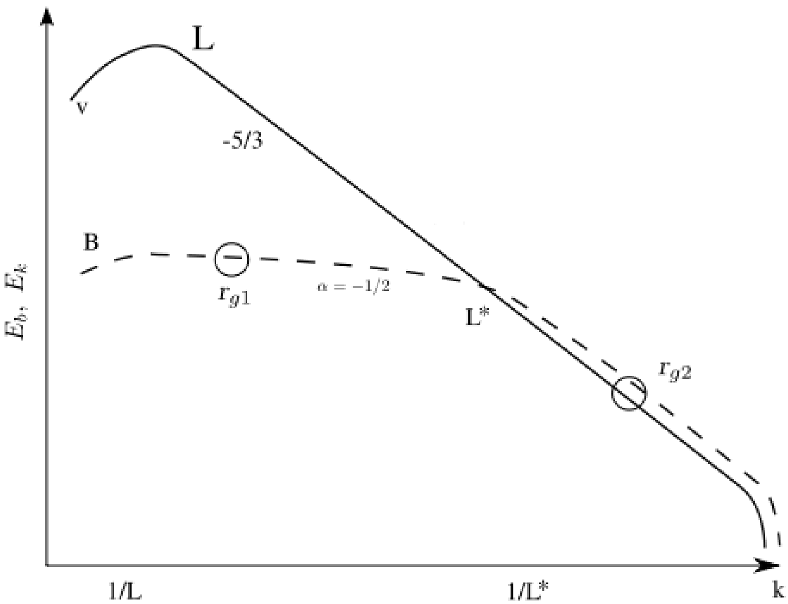
subAlfvenic $\delta B \sim B_0/10$

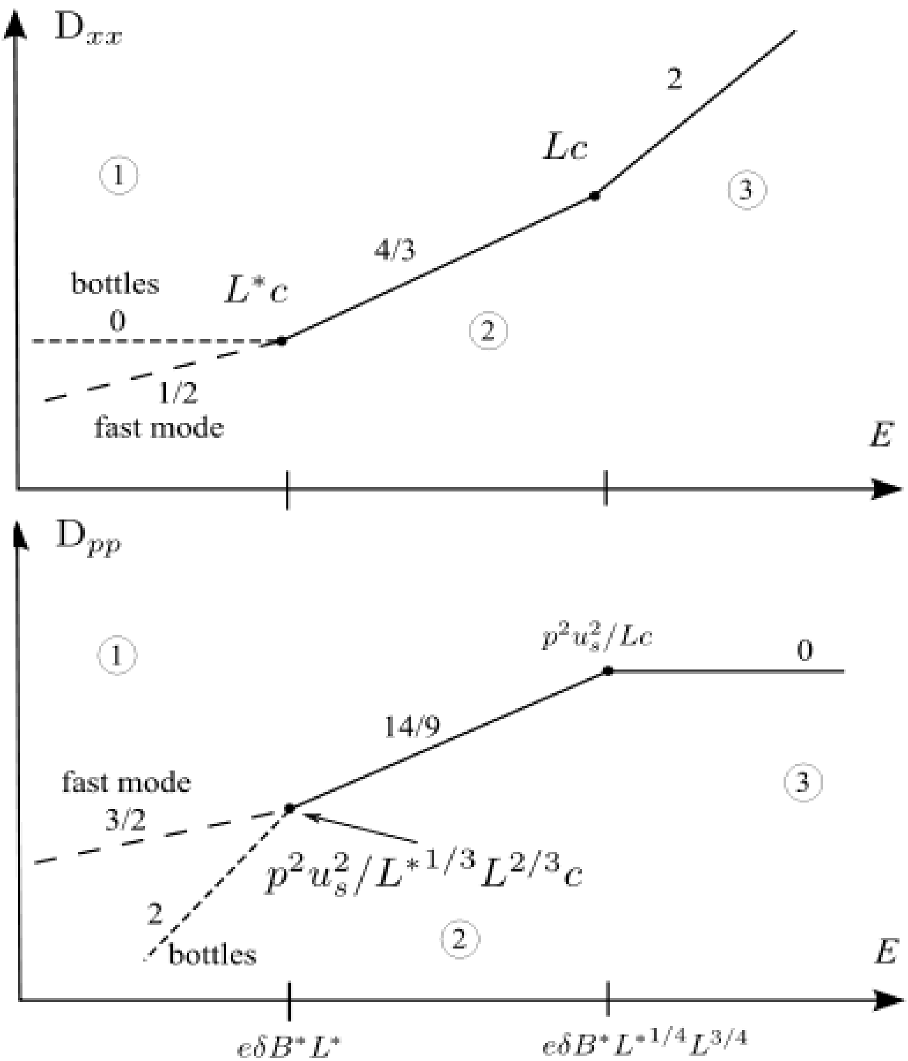


A measure of the field line diffusion

Particle scattering in a precursor

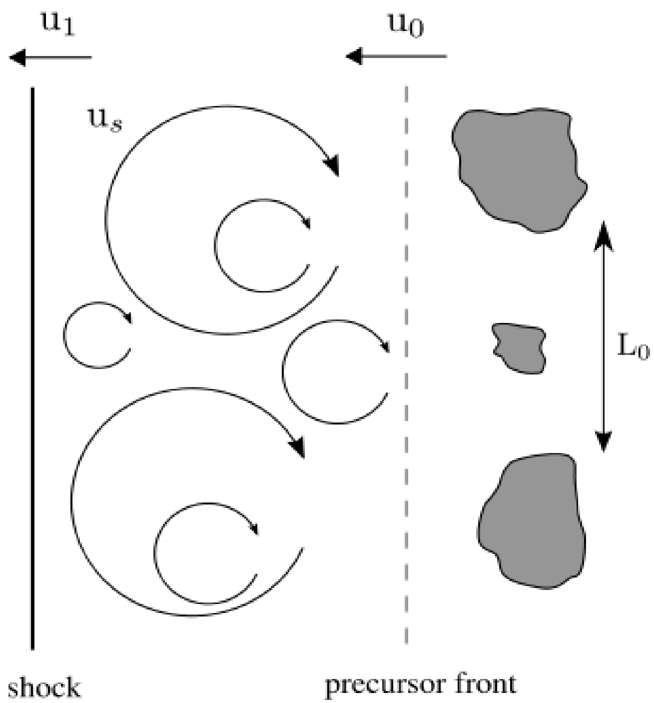
Three regimes of scattering:

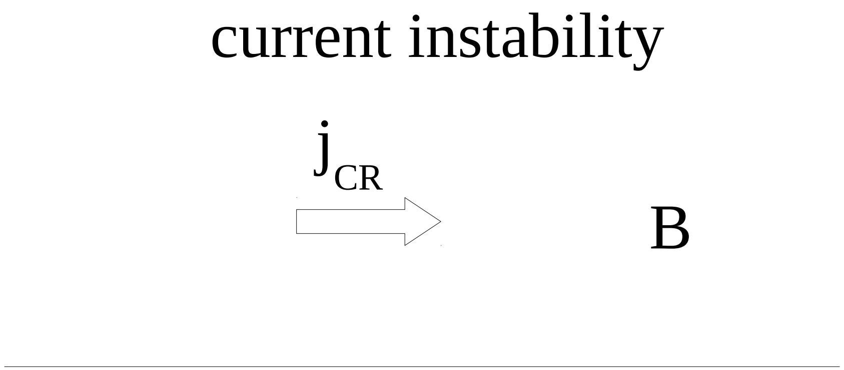




Beresnyak et al 2009, ApJ 707

Comparison Between Small-Scale Dynamo and Current Instability





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

Summary

- Cosmic Rays in the Galaxy can be explained by diffusive acceleration in supernova shocks.
- The only efficient acceleration is nonlinear acceleration
- If ISM has density inhomogeneities (and it does!), precursor develops turbulence and generates fairly strong magnetic fields
- This mechanism is more efficient than previously suggested current instability
- Future work will quantify u_s with higher precision using MHD simulations and calculate the CR spectra using diffusion-advection equation.