Astrophysical plasma
Part I

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Introduction

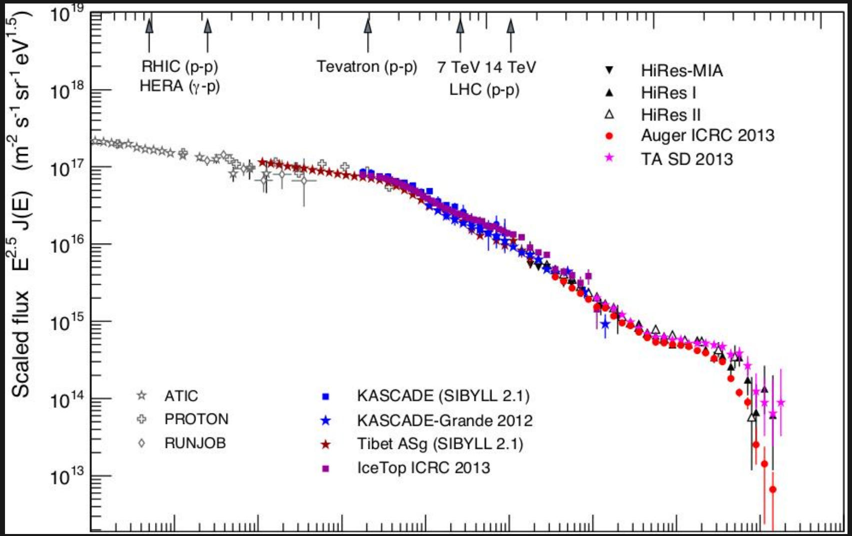
Cosmic rays: Energetic charged particles

Energy equipartition in Galaxy:

$U_{CR} = U_{mag} = U_{rad} = U_{th}$

Energy distribution is far from “fair share”

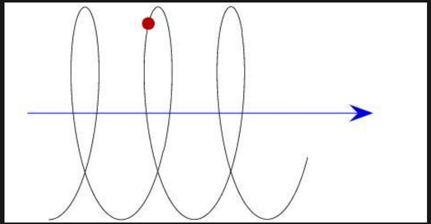
How can nature accelerate particles
to much higher energy than does the LHC?



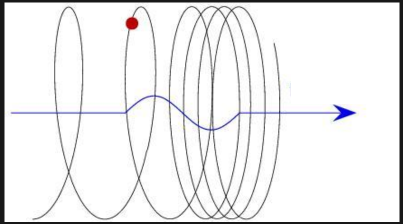
10 TeV 10 PeV 1 Joule

Introduction

Cosmic magnetic field is necessary for particle acceleration



Charged particle
in magnetic field



Turbulent field determines scattering and confinement

→ a collisionless medium!

Dynamics of field provides accelerating E field

Introduction

Turbulent magnetic field → Ensemble of waves

In rest frame of an EM wave $E/B = \omega/k = 0$ → No E field

One rest frame for all waves → No acceleration

Decisive is field at location of particle

Resonance → Constant Lorentz force
→ Scattering

Introduction: Resonances

Assume a homogeneous magnetic field, $B_0 = B_z$

Field of a circularly polarized EM wave $B_x = b \cos(kz - \omega t)$

Trajectory of a charged particle $z = v_z\, t \quad v_y = v_{perp} \cos(\Omega t)$

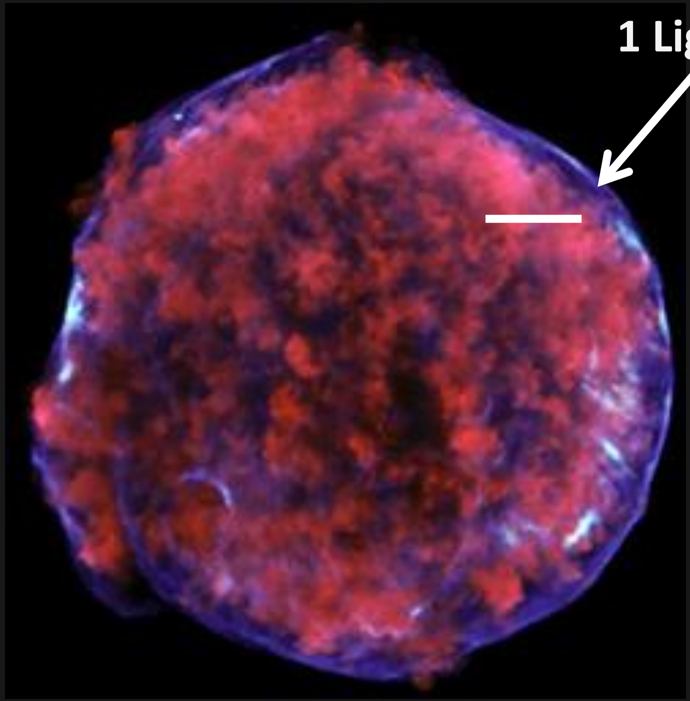
Lorentz force $v_y\, B_x =$ constant, if $k v_z - \omega = +/- \Omega$

This is a resonance. Particle can pick their waves!

Introduction

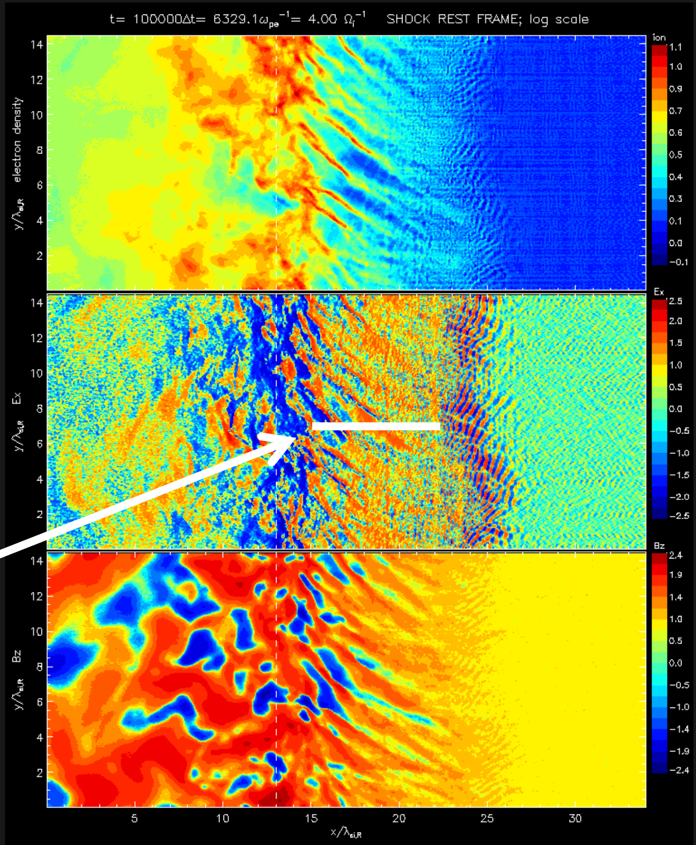
- Introduction
- Shock acceleration
- Turbulence at shocks

What is so difficult?



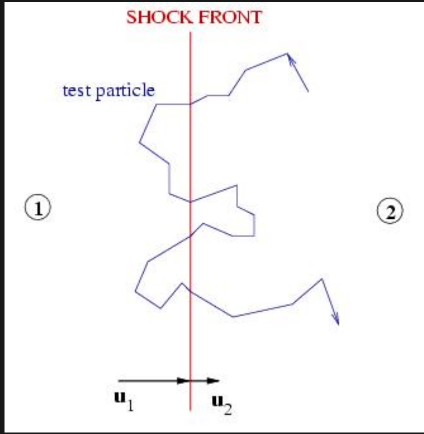
1 Light-year

1 Light-millisecond



Shock acceleration

Elastic scattering on both sides of shock



→ Pre-acceleration required (Injection)

→ Energy gain per cycle $\delta E/E = C\, v_s$

→ Acceleration rate depends on scattering rate on both sides

→ How is the magnetic turbulence produced?

Shock acceleration

Technically, we solve a cosmic-ray transport equation

$$\frac{\partial N}{\partial t} = \nabla(D\nabla N - \vec{v}N) - \frac{\partial}{\partial p}\left((N\dot{p}) - \frac{\nabla\vec{v}}{3}Np\right) + Q$$

D: Coefficient for spatial diffusion

v: Velocity of background plasma (technicaly the scattering centers)

d*p*/d*t*: Rate of momentum loss or gain

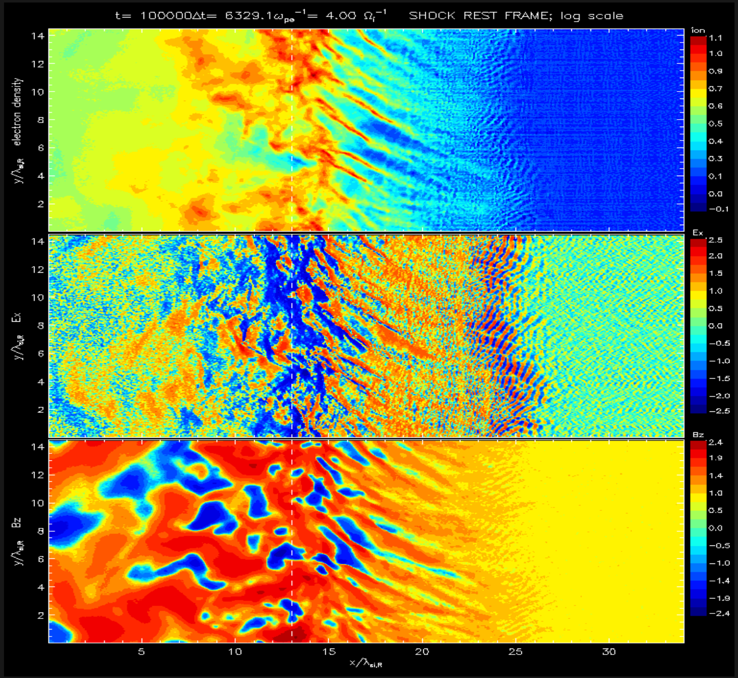
Q: Rate of injection

Need for injection

Ion density

E_x

B_z



Particles must cross the shock

→ Lecture 2

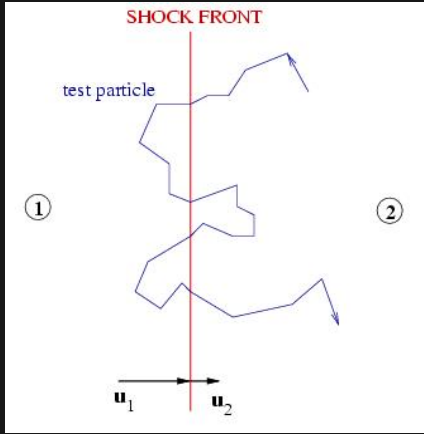
Structure of a perpendicular shock

Thickness: Ion Larmor radius

2.5D PIC Simulation
(Wieland et al.)

Energy gain per cycle

Nonrelativistic shocks



Particle distributions are locally isotropic

Shock crossing → half-sphere distribution

Isotropization on the other side

Lorentz-transform energy and average over half-sphere distribution

$$\Delta E = \frac{4}{3}\frac{u_1 - u_2}{c} E = \frac{4}{3}\frac{v_s}{c}\frac{r-1}{r} E$$

r is compression ratio, u_1/u_2

Escape and spectrum

Constant downstream density, *n*

Advection rate downstream, *n* u_2, and shock crossing rate, *n c/4*

If no other way of escape, the ratio *4* u_2/c is escape probability, *P*

Have *l* cycles: $\ln\frac{E_l}{E_0} = l\frac{\Delta E}{E_0}$ $\ln P_l = -4l\frac{u_2}{c} = -\frac{3u_2}{u_1-u_2}\ln\frac{E_l}{E_2}$

Integral spectrum

$$\int_E du\, N(u) \propto P(E) \propto E^{\frac{-3u_2}{u_1-u_2}} \qquad N(E) \propto E^{-s} \qquad s = \frac{2u_2+u_1}{u_1-u_2} = \frac{r+2}{r-1}$$

Acceleration rate

Homogeneous solution to spatial part of transport equation

$$vn - D\frac{\partial n}{\partial x} = \text{const.} \qquad \rightarrow \qquad n \propto \exp\left(\int^{x} dz \frac{v}{D}\right)$$

Going against the flow (upstream) leads to exponential suppression

Scale D/v indicates how far particles get before returning or escaping

Takes time $\Delta t = 2D/vc$ for a relativistic particle to travel

Acceleration rate $\frac{\Delta E}{\Delta t} = 8\frac{4}{3}\frac{r-1}{r}\frac{v_s^2}{D}E = 8\frac{v_s^2}{D}E$

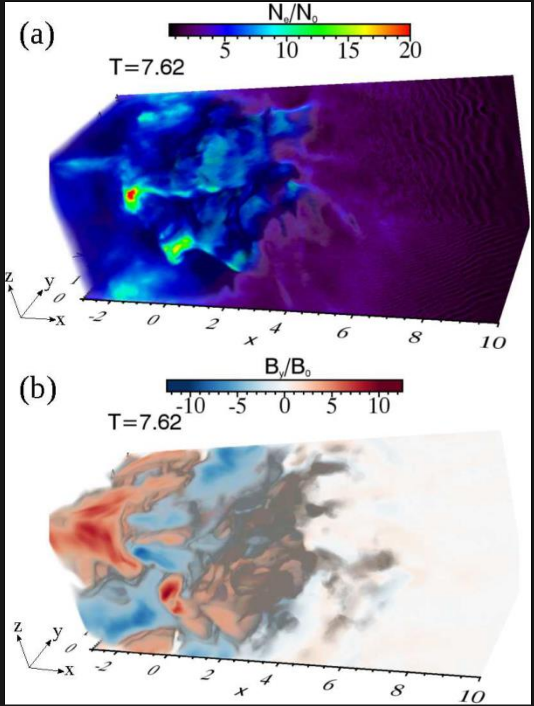
Is this real?

Simulations suggest that the process actually works

... at least under certain conditions

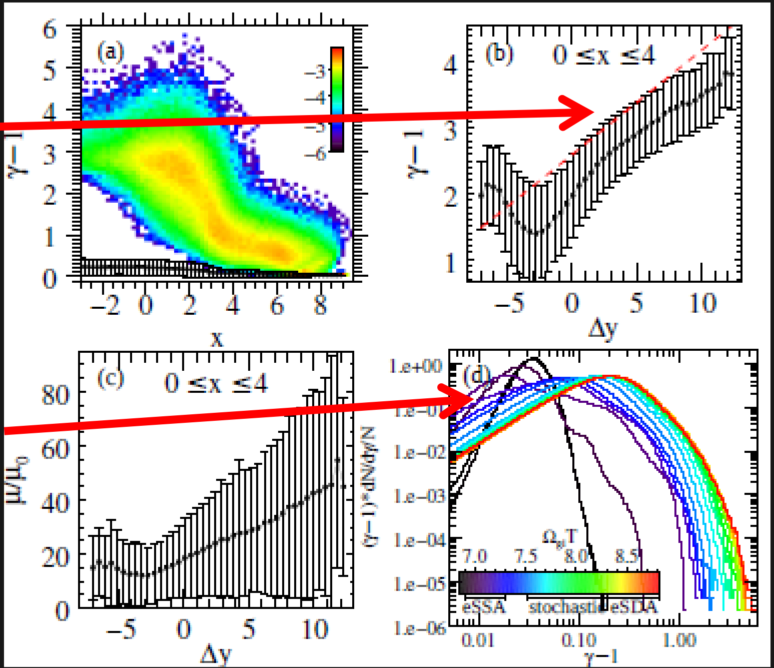
Shock acceleration

First 3D simulation: Matsumoto et al. 2017



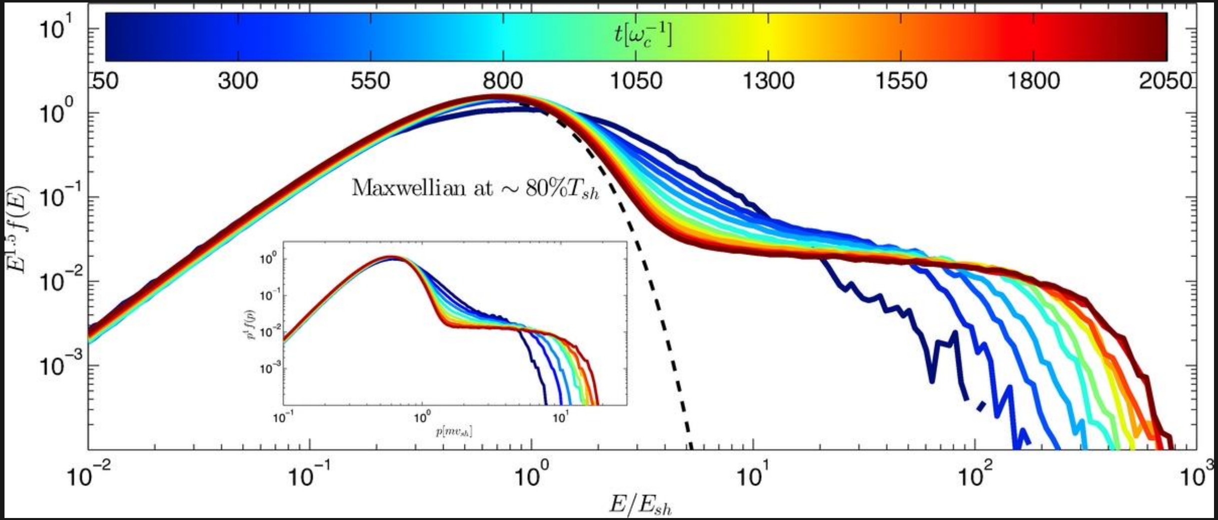
Shock drift acc.

following
shock surfing acc.



Shock acceleration

Full PIC can be done for about 20 ion Larmor times, too short for ion acceleration



Ion acceleration at 100 Larmor times

Nonrelativistic hybrid simulations of parallel shock

Caprioli & Spitkovsky 2014

Shock acceleration

But what of reality?

Diffusion requires turbulence upstream

$$\frac{\partial N}{\partial t} = \nabla(D\nabla N - \vec{v}N) - \frac{\partial}{\partial p}\left((N\dot{p}) - \frac{\nabla\vec{v}}{3}Np\right) + Q$$

Magnetic turbulence

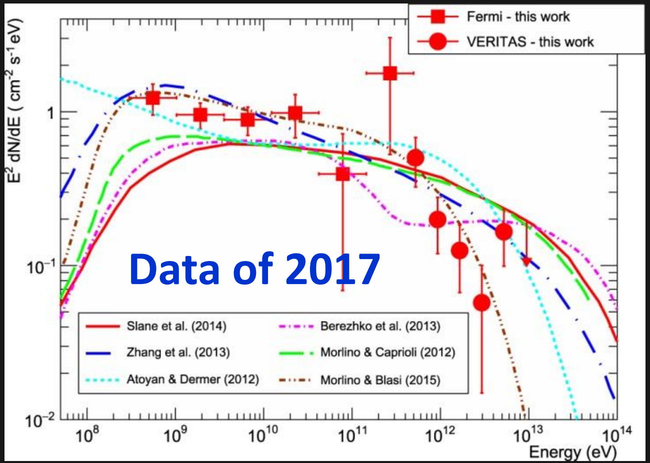
Acceleration

Magnetic-field amplification

Is there evidence for strong magnetic turbulence?

Tycho‘s SNR

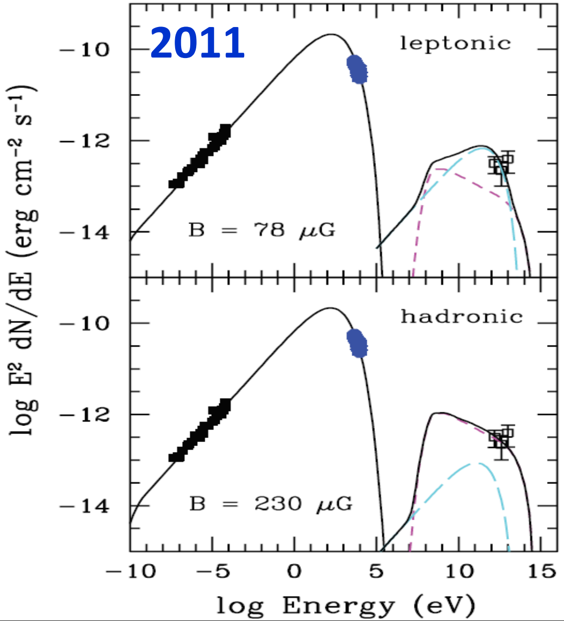
γ-ray / X-ray ratio → magnetic field



With damping

B>300 μG

VERITAS papers



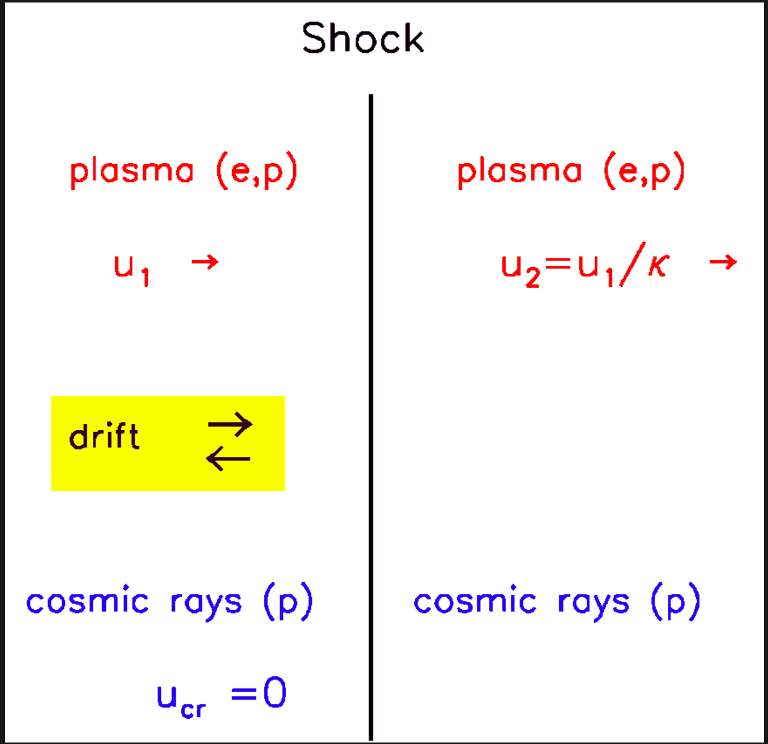
Magnetic turbulence

Relative drift upstream

→ Magnetic turbulence upstream
→ Needed for efficient acceleration

Interactions at shock

→ Magnetic turbulence downstream
→ Needed for radiation modeling



Shock acceleration

Radiation modelling indicates (turbulently) amplified magnetic field

Most radiation is produced downstream

→ a strong magnetic field downstream is sufficient

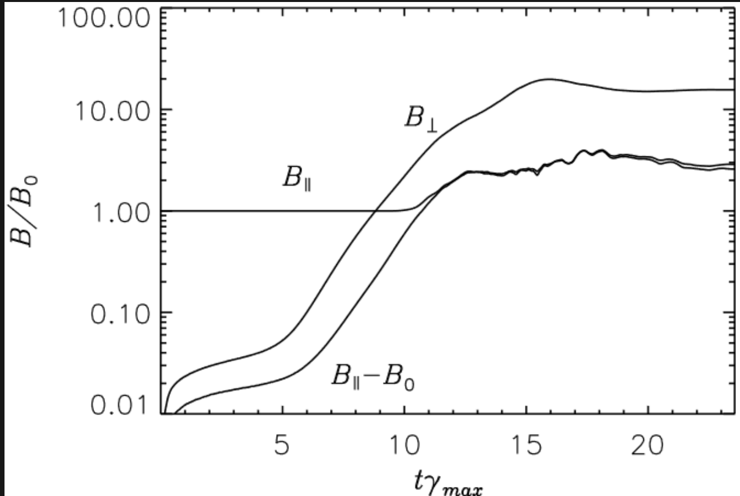
Shock acceleration relies on turbulent magnetic field upstream

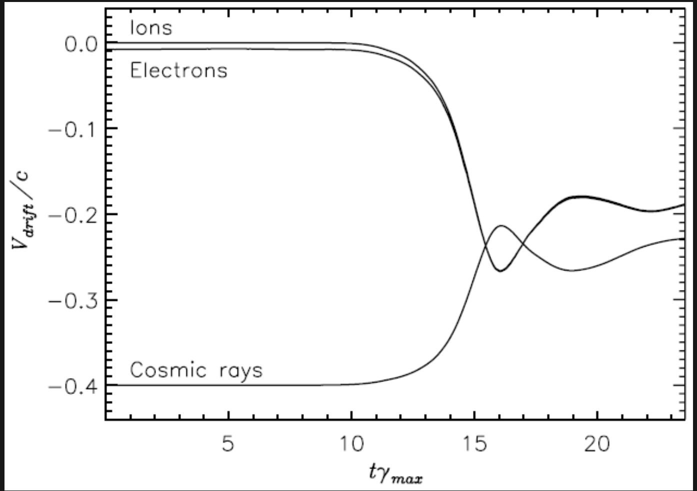
Magnetic turbulence

Resonant amplification of Alfven waves is not very fast

Maybe nonresonant magnetic-field amplification by, e.g., Bell's mode

CR streaming is energy source → Turbulence (Stroman et al.)

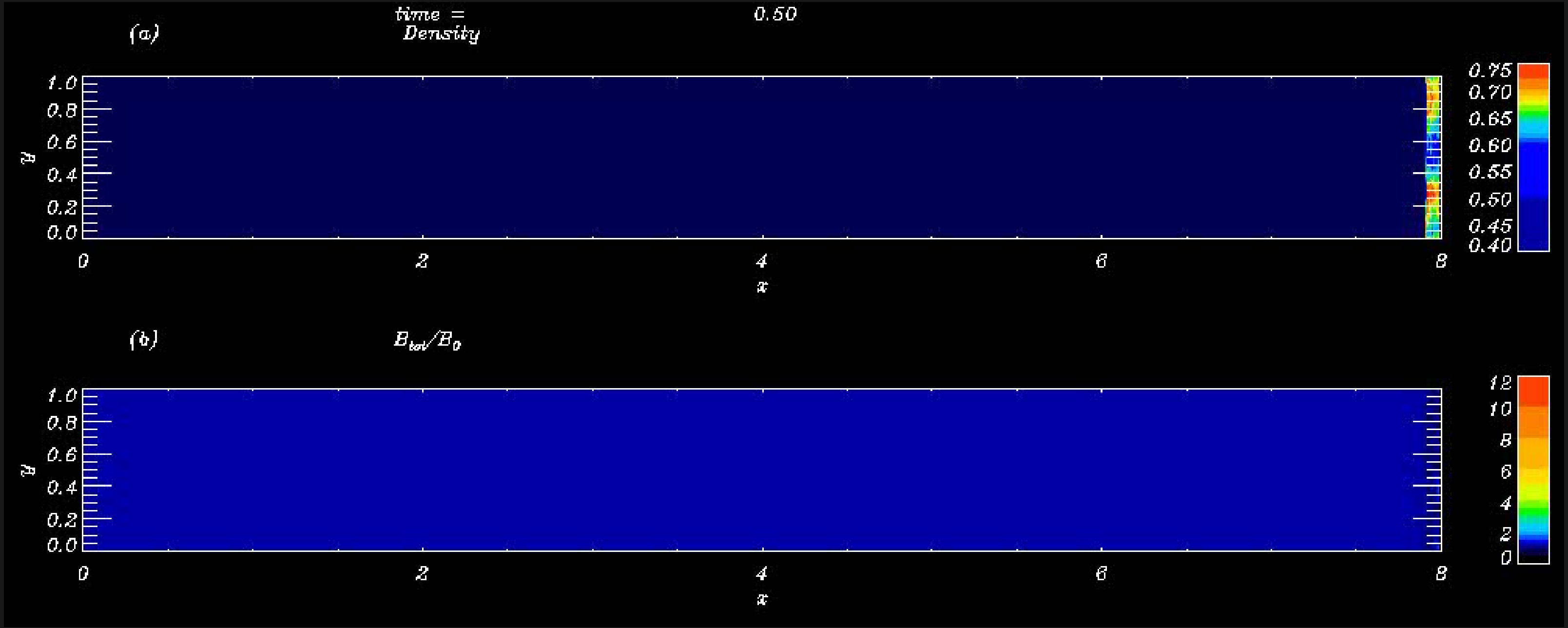




Magnetic turbulence

Turbulence behind the shock arises from dynamo effects

(Mizuno et al.)



Summary Part I

Efficient shock acceleration requires

- Pre-acceleration at the shock
- Build-up of turbulence far upstream
- High scattering efficiency of the turbulence
- Very rapid build-up of turbulence