# Cosmic ray acceleration mechanism

Yutaka Ohira ( Aoyama Gakuin University )

## Contents

# Acceleration of charged particles

In order to accelerate charged particles,
there has to be an electric field.

**Motional electric field, $E = u \times B$**

diffusive shock acceleration, 2nd order acceleration

**Induced electric field, $\mathrm{rot}\, E = -\partial B/\partial t$**

acceleration at reconnection regions

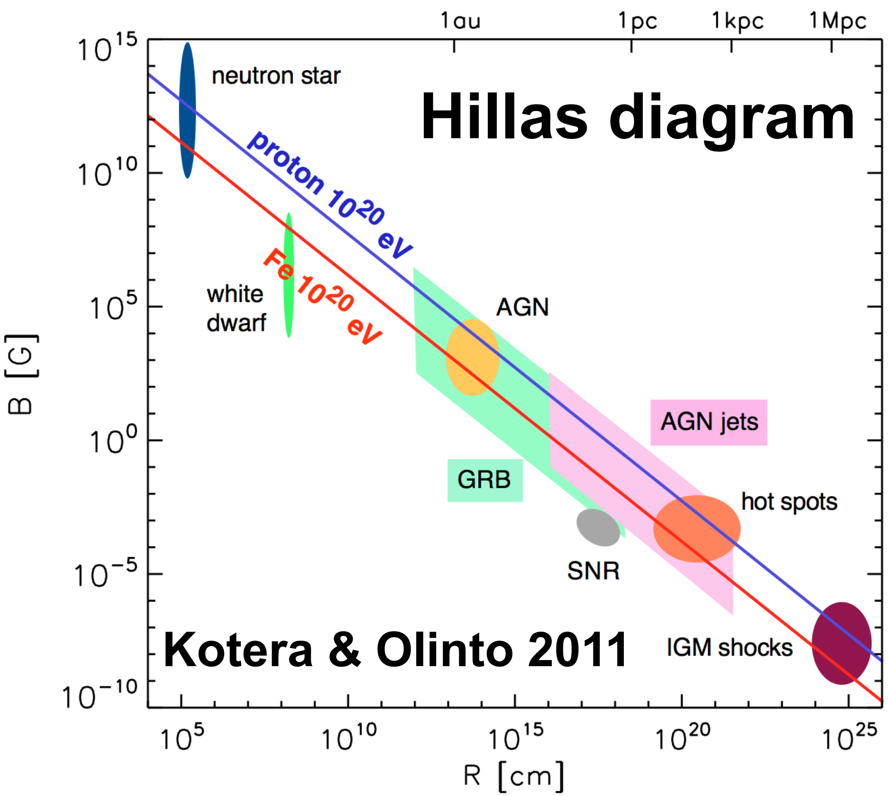
**Electric field produced by charge separation, $E = -\nabla \phi$**

wake field acceleration,
acceleration in pulsar magnetosphere
(strong radiation or rotating magnetized neutron star are needed)

To create the electric fields, a magnetic field is needed.

To accelerate CRs, there has to be a magnetic field.

# Maximum energy




**Larmor radius ($r_L = E_{max}/ZeB$) is smaller than source size, R.**

**← $r_L = R$**

**$E_{max}$ is limited by a finite acceleration time, escape from the accelerator, and cooling**

**If we specify the acceleration mechanism of CRs, we can write a more strict condition on the Hillas diagram, but magnetic fields of the source have a large ambiguity.**

**Therefore, a constraint on magnetic fields is most important.**

# Particle accelerations

Diffusive shock acceleration (1st order Fermi)

Turbulent acceleration (2nd order Fermi)

Shear acceleration

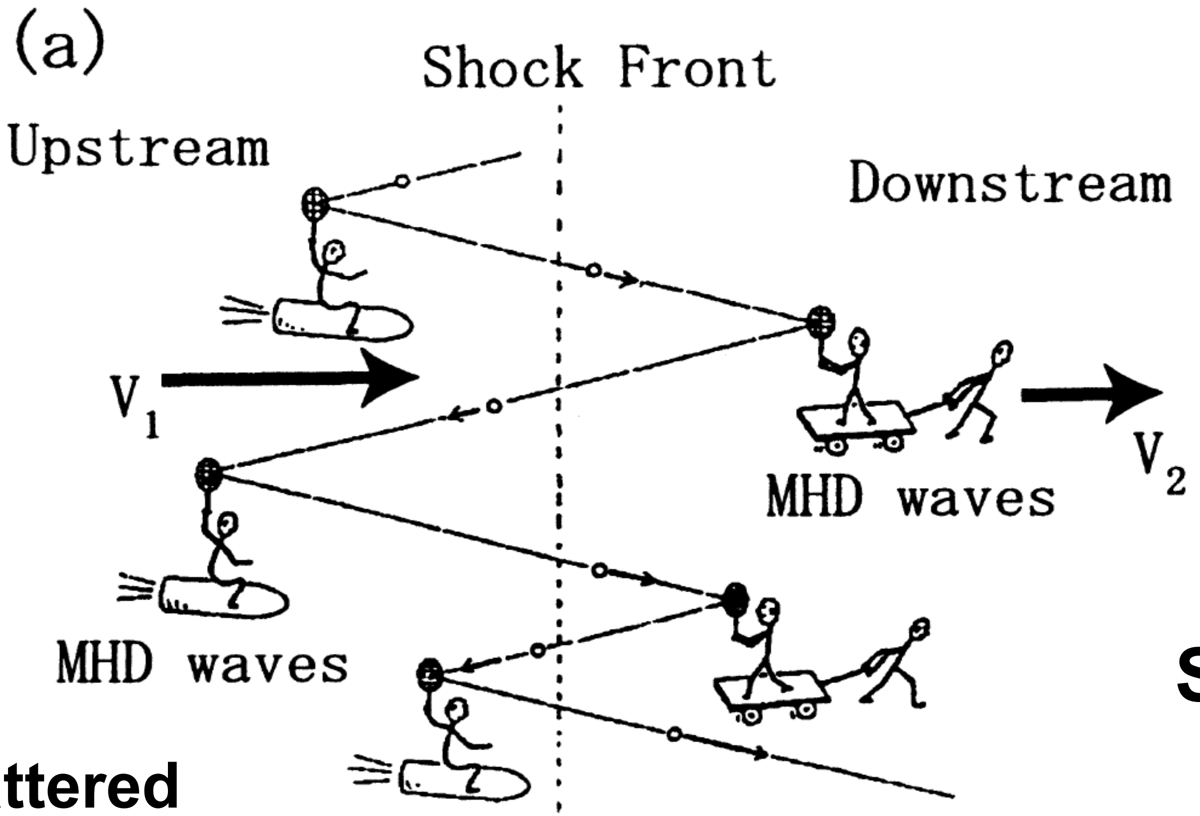
Surfing acceleration

Shock drift acceleration

Acceleration in the magnetic reconnection

Direct acceleration by electric fields and so on.

# Diffusive Shock Acceleration(DSA)




**Scholer**

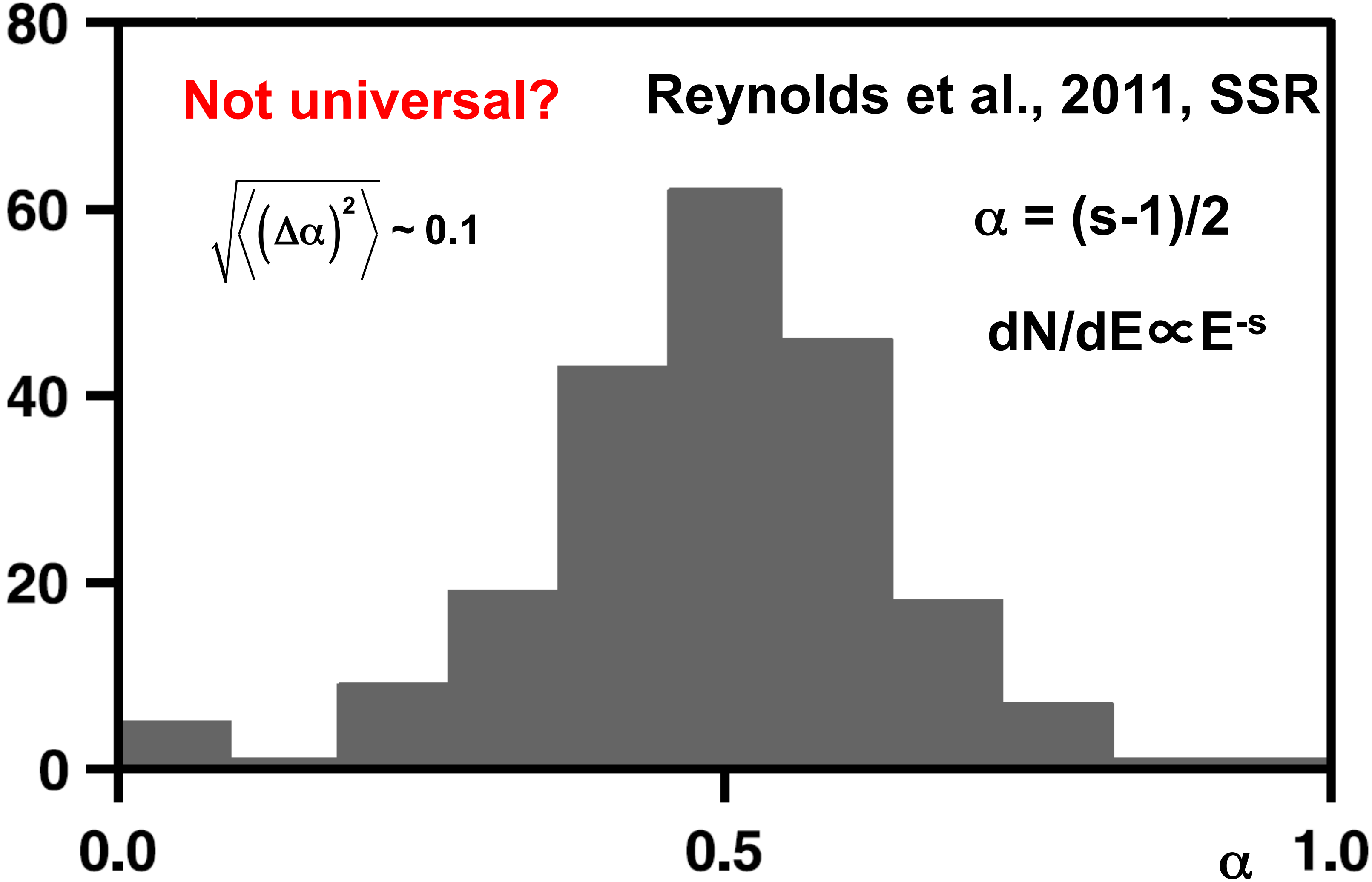
**CRs are scattered by MHD waves.**

**CRs excite the MHD waves.**

$$dN/dE \propto E^{-s} \quad s = \frac{u_1/u_2 + 2}{u_1/u_2 - 1} = 2$$

**Axford 1977, Krymsky 1977, Blandford&Ostriker 1978, Bell 1978**

## Spectral index of radio synchrotron flux, $f_\nu \propto \nu^{-\alpha}$




The standard DSA predicts $s = 2$ $(\alpha = 0.5)$

CR observations require $s_{source} \sim 2.4$ $(\alpha \sim 0.7)$

# Spectral index in Cas A (radio)

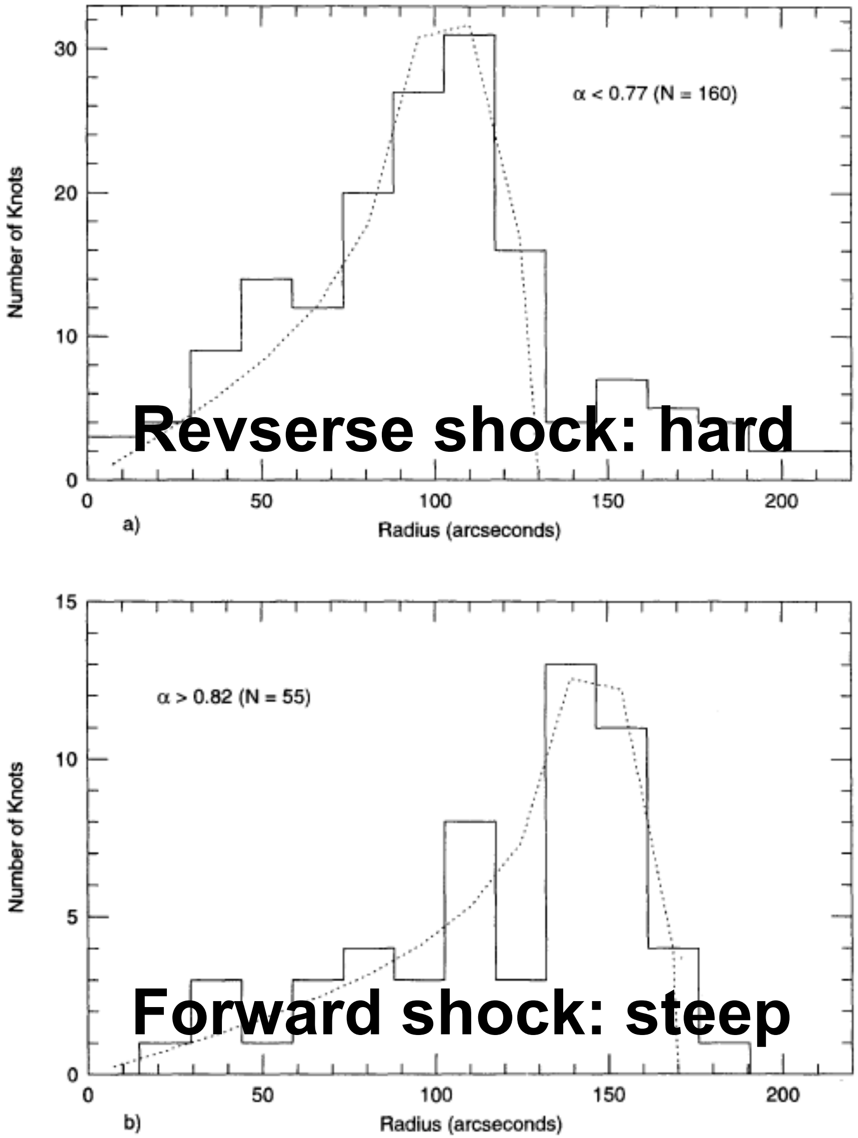
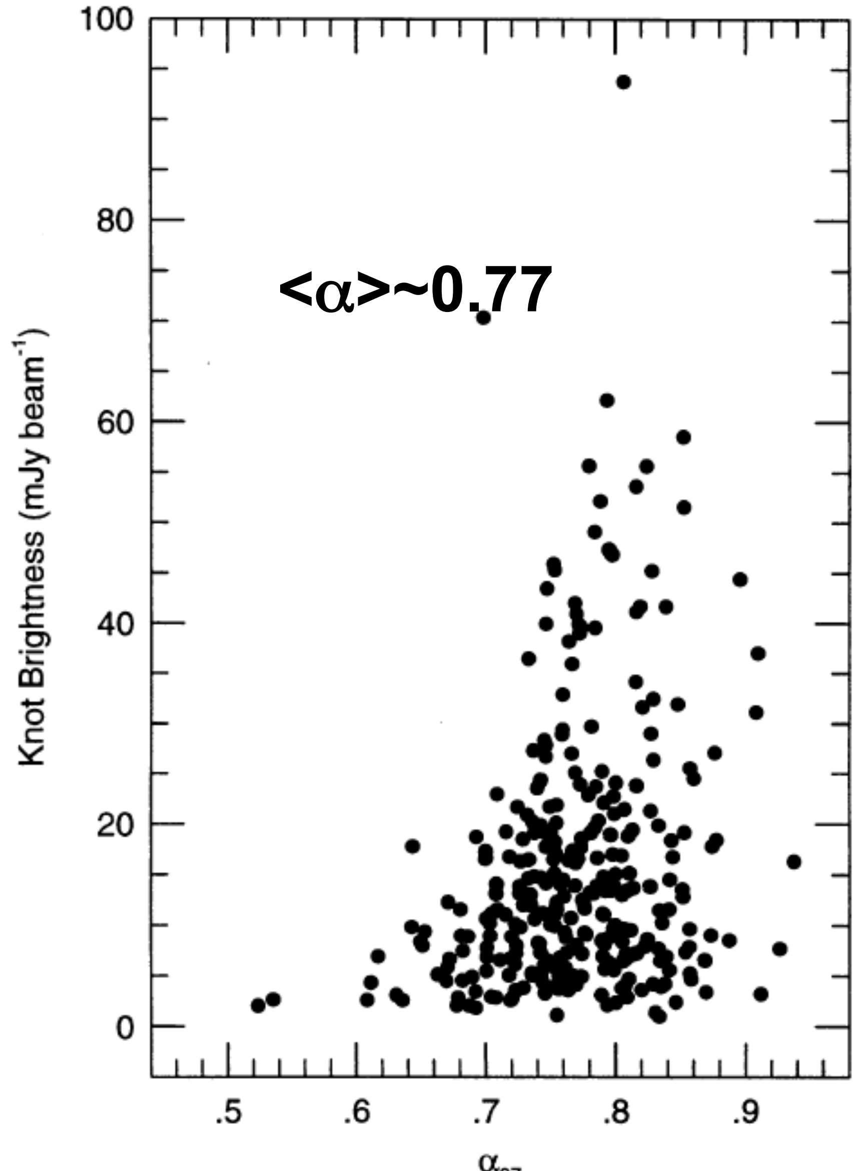



FIG. 4.—Histograms of projected radial position for (*a*) knots flatter than $\alpha = 0.77$ and (*b*) knots steeper than $\alpha = 0.82$. Overlain in dotted lines, for comparison, are models of shells with uniform knot distributions and inner




**Anderson & Rudnick 1996**

# Diffusive shock acceleration(DSA)

DSA only needs a shock, so it is very simple.

However, there are many types of shocks ( ~ 100 types ).

Non-relativistic shock or Relativistic shock

e-/e+ plasma or e-/ion plasma

or e-/e+/ion plasma

Strongly magnetized plasma or Weakly magnetized plasma

Parallel shock ($B \parallel V_{sh}$) or Perpendicular shock ($B \perp V_{sh}$)

Test particle DSA or Nonlinear DSA

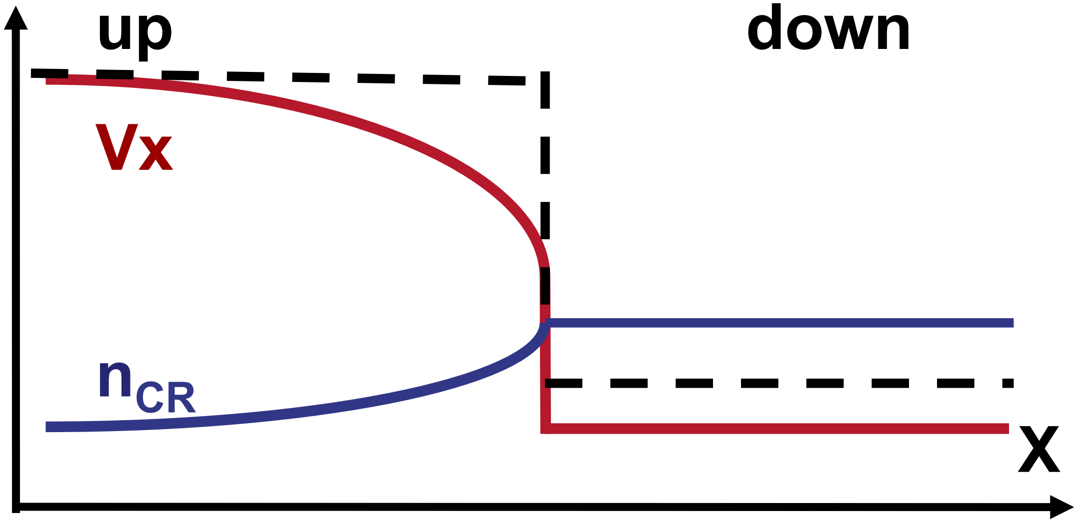
Fully ionized plasma or Partially ionized plasma

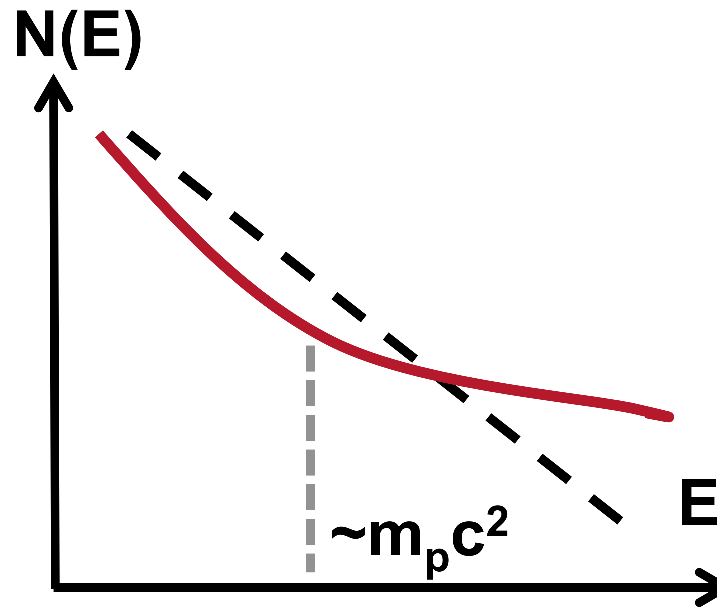
Adiabatic shock or Radiative shock

Non-radiation mediated shock or Radiatiion mediated shock

# Nonlinear DSA

Shock rest frame




The upstream plasma is pushed by the CR pressure.

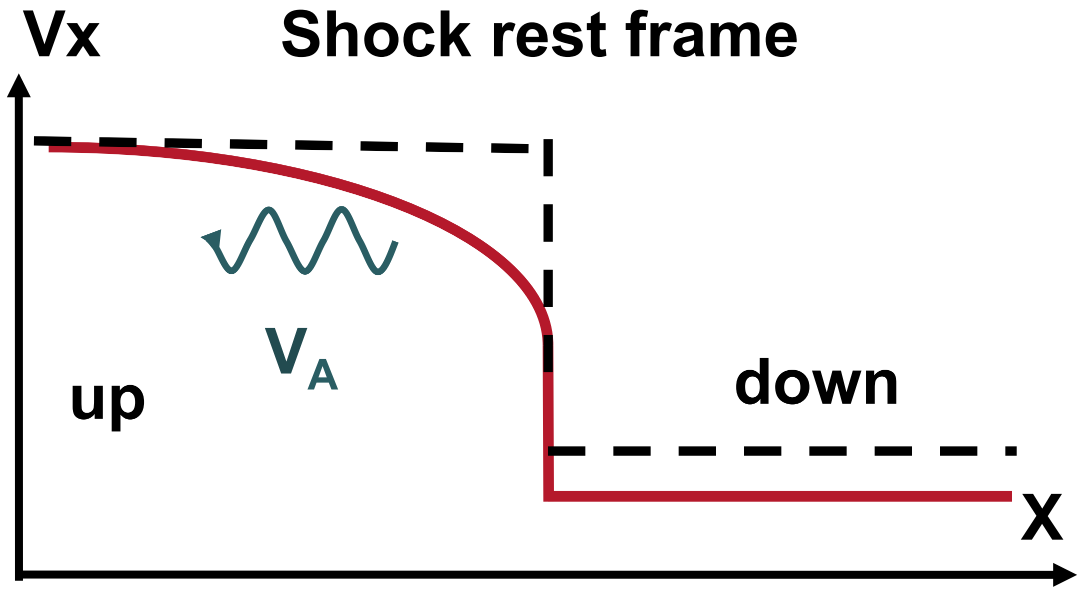
The total compression ratio becomes large.

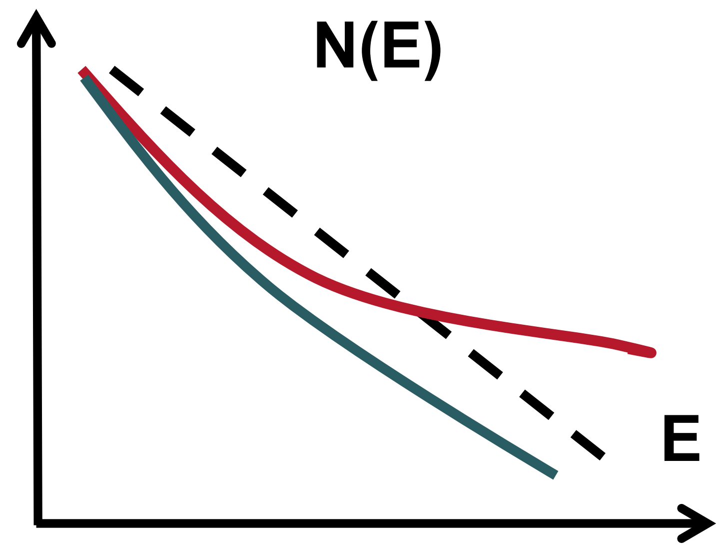
The CR spectrum is not a single power law form.

This is inconsistent with GCR and SNR observations.

e.g., Drury & Volk (1981), Malkov & Drury (2001)

# Recent nonlinear DSA Model




MHD Waves excited by CRs go to the upstream.

The velocity of scattering centers is $V_1 - V_A$.

$V_A$ is comparable to $V_{sh}$ because of the strong magnetic field.

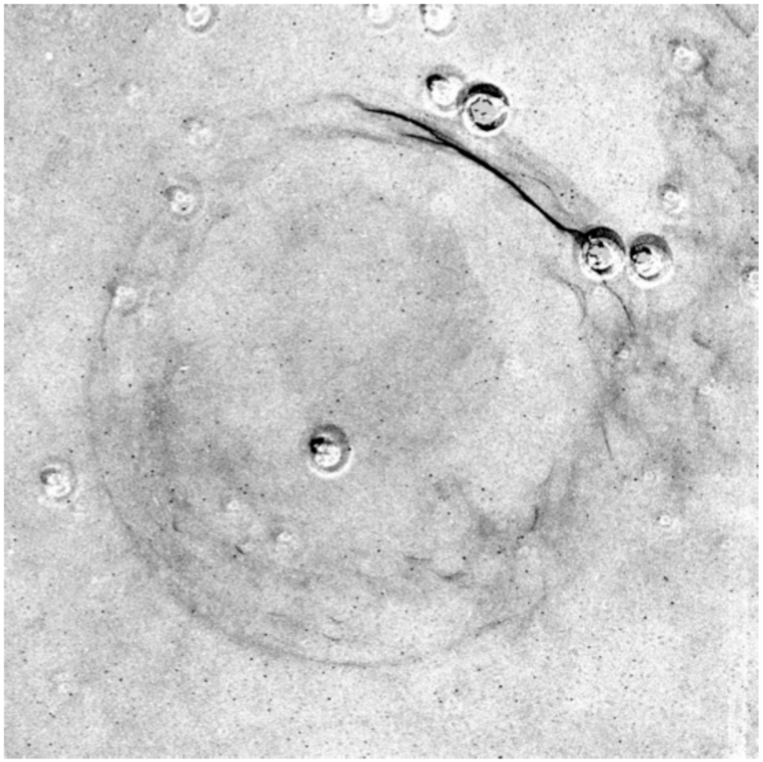
The jump of the scattering velocity becomes small.

As the result, the CR spectrum becomes steep and consistent with observations.

e. g., Ptuskin & Zirakashvili (2008)

# ISM is not a fully ionized plasma

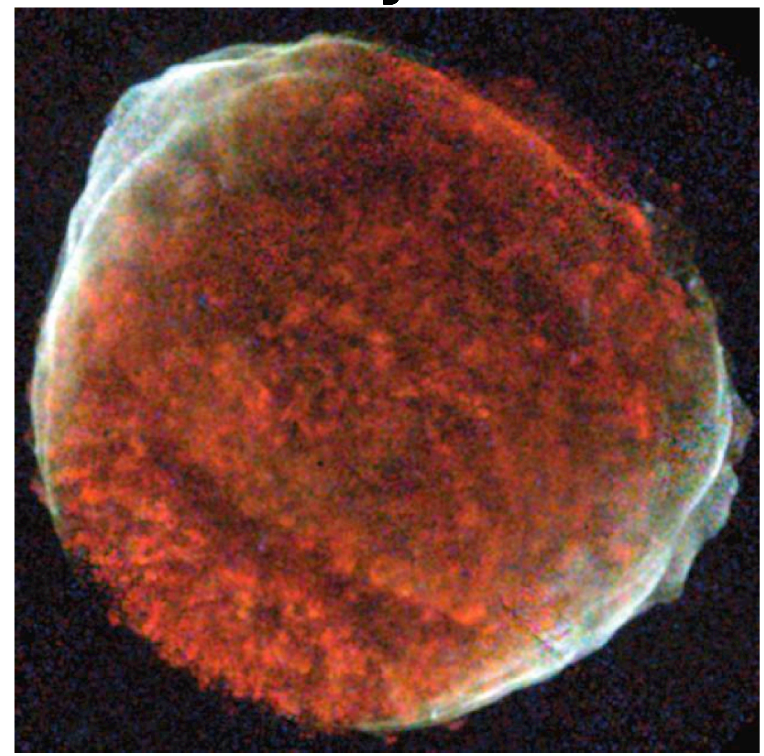
**Hα**



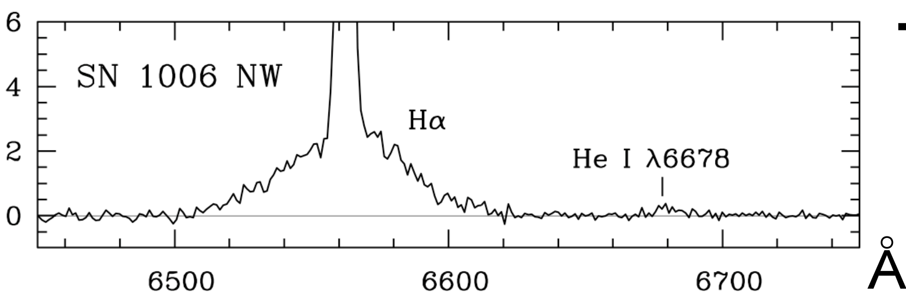
**Winkler et al. ApJ 2003**

**SN1006**

**X ray**



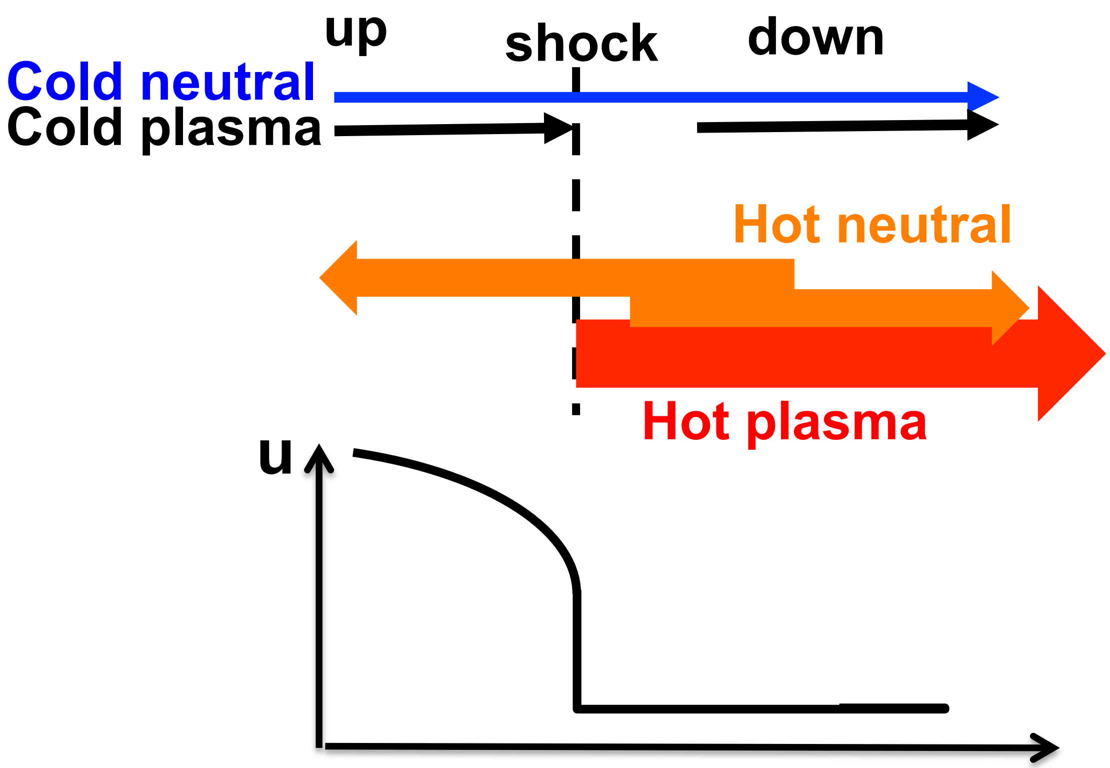
**Cassam-Chenai et al. ApJ 2008**




**The neutral fraction is of the order of unity.**

**Ghavamian et al. ApJ 2000, 2002**

# DSA in partially ionized plasma




Downstream neutral particles leak into the upstream region.

The upstream flow is decelerated in the neutral precursor.

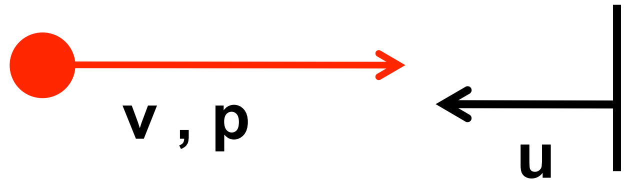
DSA in the precursor region makes a spectrum steeper than $E^{-2}$, which is consistent with observations. (Ohira 2012,Blasi et al. 2012)

Leaking neutral particles could be important for injection into DSA and B field amplification. (Ohira et al., 2009, Ohira, 2013)

Ionization fraction is a important parameter for CR acceleration.

# $E_{max}$ of DSA

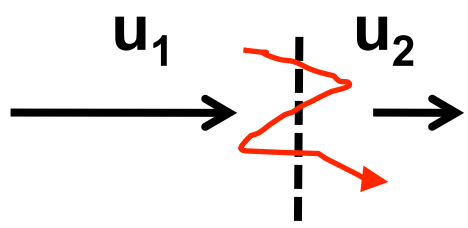
**Momentum change by particle scattering**




After scattering,

$$\Delta p = 2\frac{u}{v}\,p$$

For a shock,




$\Delta p$ per one cycle is

$$\Delta p = \frac{4(u_1 - u_2)}{3v}\,p$$

Time of one cycle, $\Delta t = (\lambda_{mfp,1}/u_1 + \lambda_{mfp,2}/u_2)$

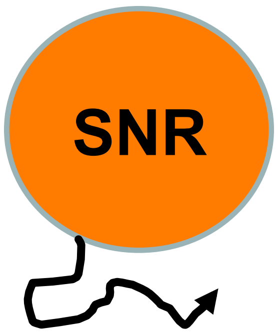
$t_{acc} = p\,\Delta t/\Delta p \sim \lambda_{mfp} v / u_{sh}^2$ (Krymsky et al. 1979, Drury 1983)

$t_{acc} = t_{Sedov}$ and $\lambda_{mfp} = r_g$

$\rightarrow E_{max} \sim 10^{14}\mathrm{eV}\, B_{\mu G}$

**To accelerate to the knee energy, B field has to be amplified.**

# Time evolution of $E_{max}$ for SNRs



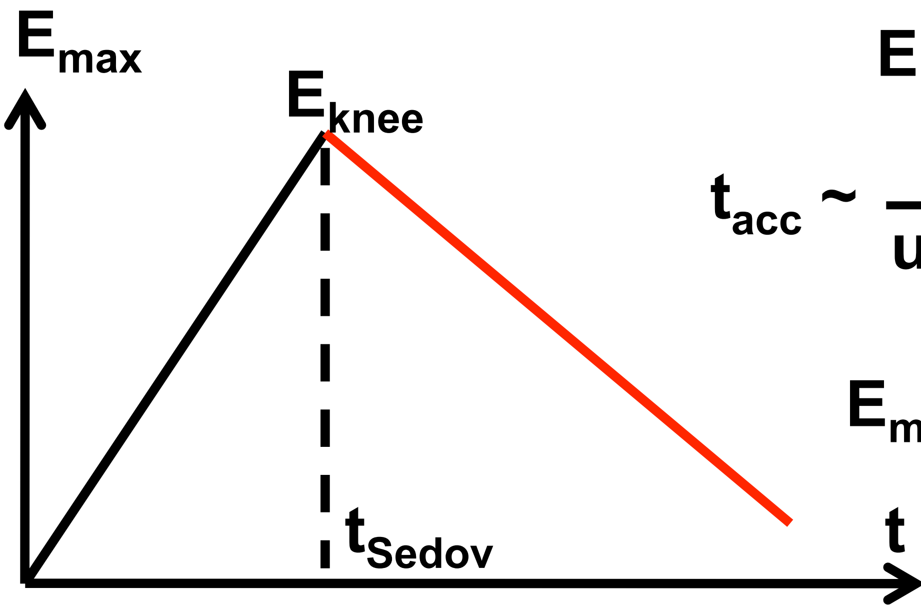

$$R_{sh} = R_{Sedov} \times \begin{cases} (t_{age} / t_{Sedov}) & (t < t_{Sedov}) \\ (t_{age} / t_{Sedov})^{2/5} & (t > t_{Sedov}) \end{cases}$$

$$R_{diff} \propto (Dt)^{1/2}$$

**Free expansion phase ( t < 200yr ): age limited**

$$E_{max} = E_{knee} ( t / t_{Sedov} )$$ (B should be amplified and $\lambda_{mfp}=r_L$)

**Sedov phase ( $t < 10^5$ yr ) : escape limited**




$E_{max}$ is obtained from $t_{esc} = t_{acc}$

$$t_{acc} \sim \frac{D}{u_{sh}^2} \quad , \quad t_{esc} \sim \frac{R_{sh}^2}{D} \quad , \quad D = \eta_g \frac{cE}{3eB}$$

$$E_{max} \propto \frac{B(t)t^{-1/5}}{\eta_g(t)} = E_{knee} (t / t_{Sedov})^{-\alpha}$$

**$E_{max}$ decreases with time**

# DSA in relativistic shocks

**The angular distribution of accelerated particles is highly anisotropic, so the return probability is not the same as that of non-relativistic shocks.**
**The velocity jump at relativistic shocks and the energy gain per cycle are different from that of non-relativistic shocks.**

$dN/dE \propto E^{-s}$

**Keshet & Waxman 2005**

$$s = \frac{2 + \beta_1/\beta_2 - 2\beta_1\beta_2 + \beta_2^2}{\beta_1/\beta_2 - 1} \rightarrow \sim 2.22 \quad (\beta_1 = 1,\ \beta_2 = 1/3)$$

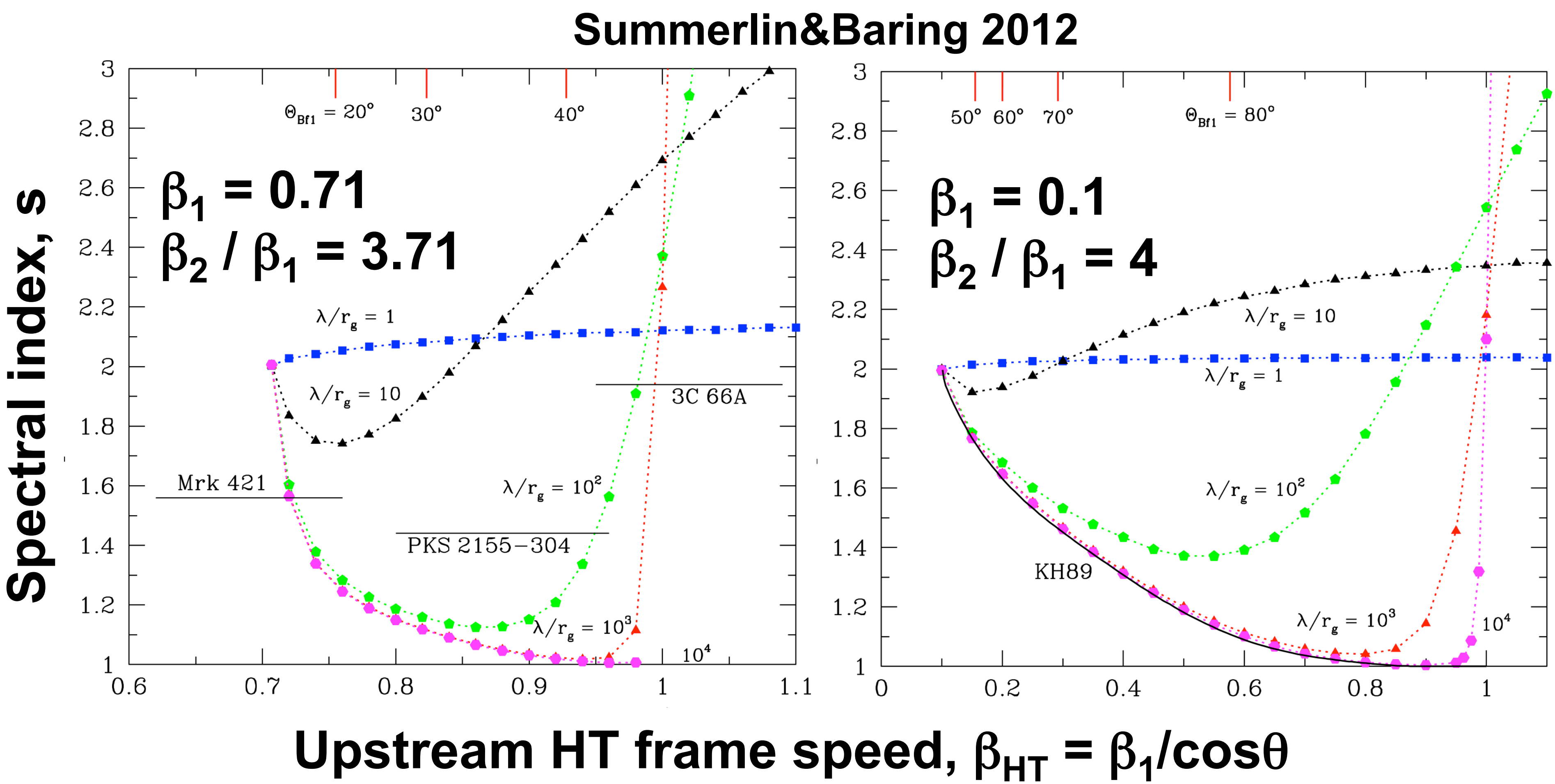
**for relativistic shocks & isotropic diffusion**

s depends on diffusion property

$$s = \frac{u_1/u_2 + 2}{u_1/u_2 - 1} \rightarrow 2 \ (u_1/u_2 = 4)$$

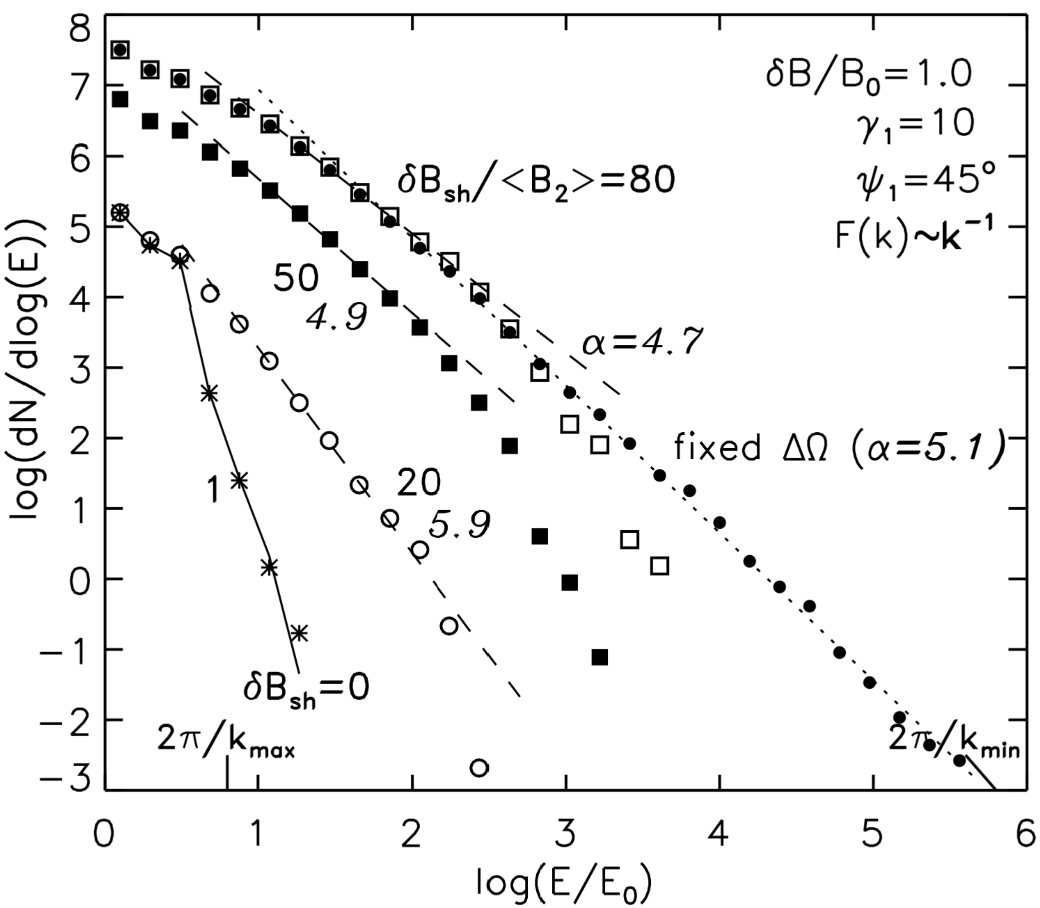
**for non-relativistic shocks & any diffusion**

# Spectral index in test particle simulations




**For relativistic shocks, the spectral index depends on magnetic field fluctuations and magnetic field orientation.**

# Test particle studies of relativistic DSA




Niemiec et al. 2006

**To return to the shock from the downstream region, there has to be small scale magnetic fluctuations in the downstream region.**

$$\lambda_{\delta B} < r_{L,CR}$$

**(Lemoine et al. 2006)**

**→ $D_{xx} \sim c r_{L,CR}^2/\lambda_{\delta B} \propto E^2$**

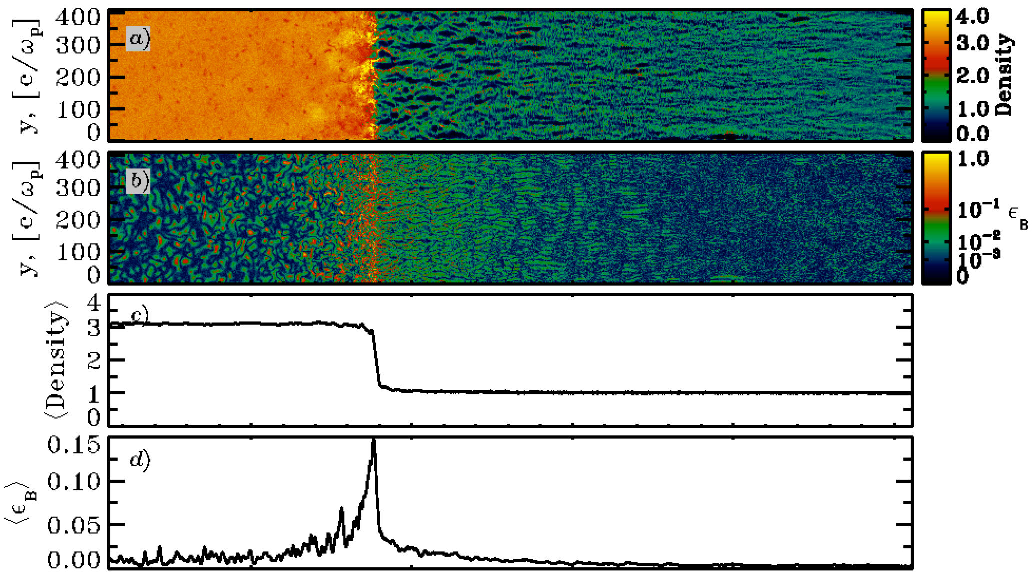
**Not Bohm**

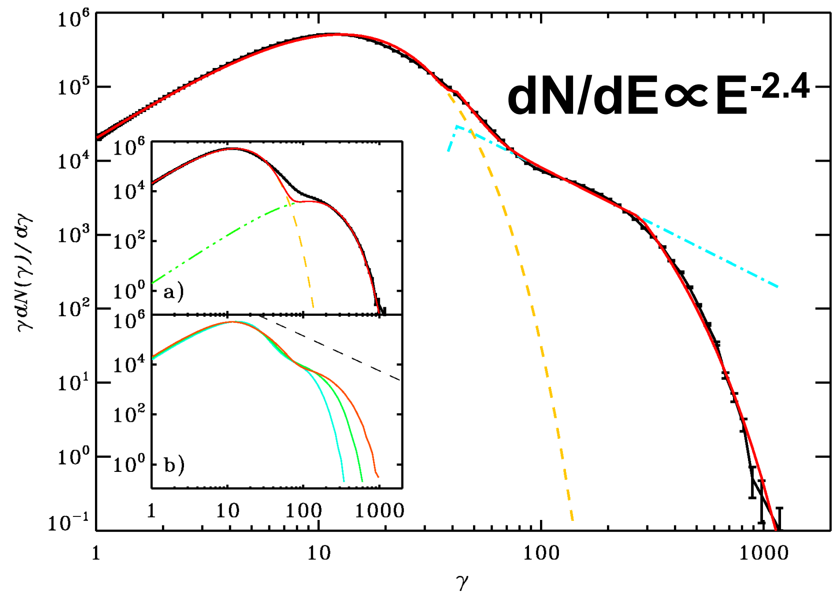
**→ Relativistic shock cannot accelerate CRs upto $10^{20}$eV**

**(e.g. Lemoine&Pelletier 2010)**

# PIC simulations of relativistic shocks

**Particle in cell simulations solve Maxwell equations and equation of motion of many charged particles.**




**Spitkovsky 2008**

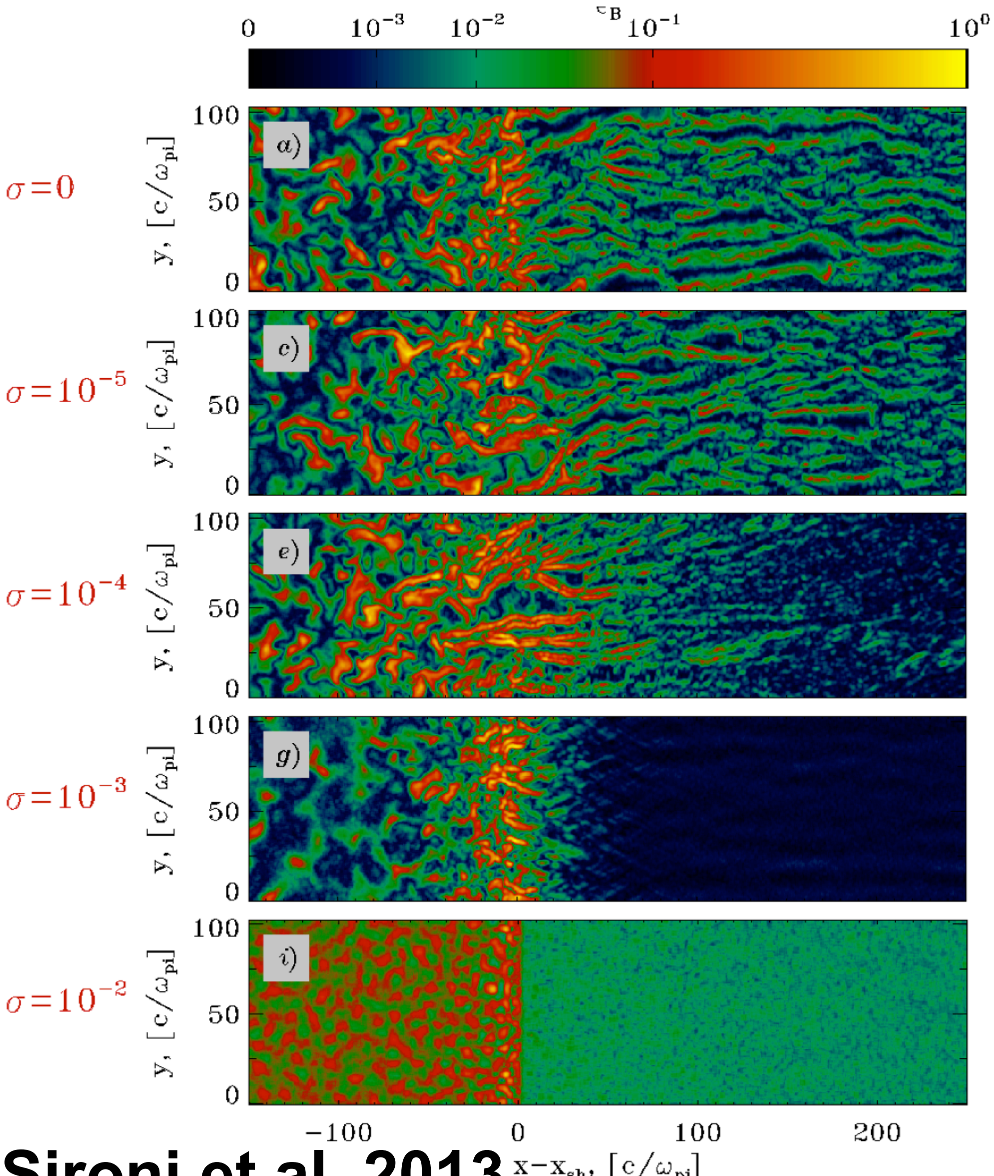
**For very weakly magnetized relativistic shocks,**

**Upstream particles are thermalized by the Weibel instability.**

**$\lambda_{\delta B} \sim c/\omega_p \ll r_{L,CR} \rightarrow$ The injection condition is satisfied.**

**Spectral index ~ 2.4 ≠ 2.2**

# $E_{max}$ of Weibel mediated shocks




Sironi et al. 2013

**PIC simulations show**

$\lambda_{\delta B} \sim c/\omega_{pp}$ ( $\ll r_{L,CR}$ ).

→ Small angle scattering

→ $D_{\theta\theta} \sim (\delta\theta)^2 / \delta t$

$\sim (\lambda_{\delta B}/r_{L,CR})^2 / (\lambda_{\delta B}/c)$

→ $D_{xx} \sim c\lambda_{mfp} \sim c\,(c/D_{\theta\theta})$

$\sim c r_{L,CR}^2/\lambda_{\delta B} \propto E^2$

Not Bohm

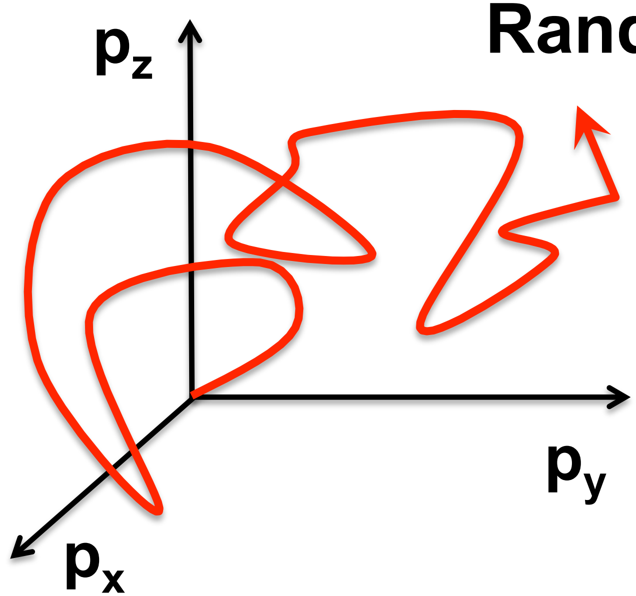
$R_{turb} \sim r_{L,sh}$

→ $E_{max}$ is limited by

$R_{turb} \sim R_{diff} \sim D_{xx}/c$

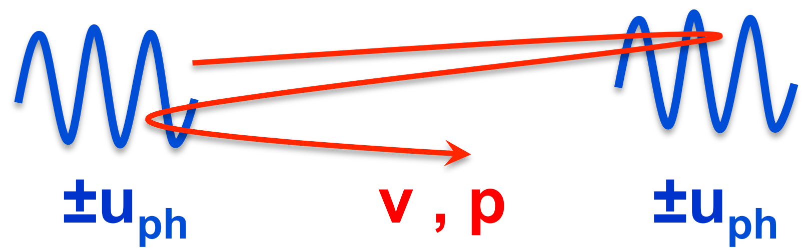
→ $E_{max} \sim 10^{17}$eV for GRB

# Second order acceleration




Random walk in the 3D momentum space

$$\frac{\partial f}{\partial t} = \frac{1}{p^2}\frac{\partial}{\partial p}\left(p^2 D_{pp}\frac{\partial f}{\partial p}\right) \qquad D_{pp} = \left\langle \frac{\Delta p \Delta p}{\Delta t} \right\rangle$$




The momentum change is $\Delta p \sim (u_{ph}/v)p$

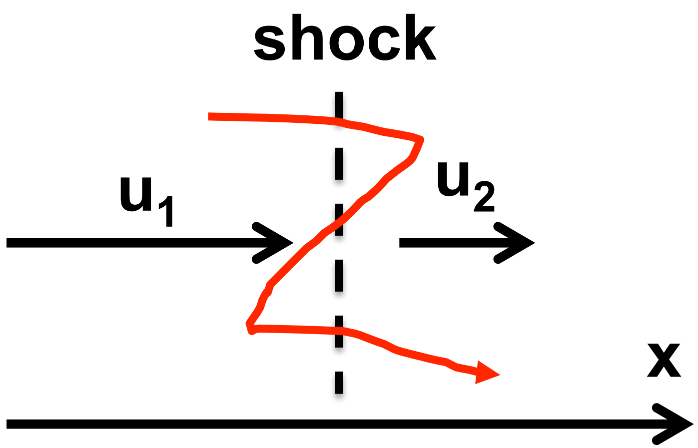
$$D_{pp} \sim \frac{\Delta p \Delta p}{\tau_{sc}} \sim p^2 \frac{u_{ph}^2}{\tau_{sc} v^2} \sim p^2 \frac{u_{ph}^2}{\kappa_{xx}}$$

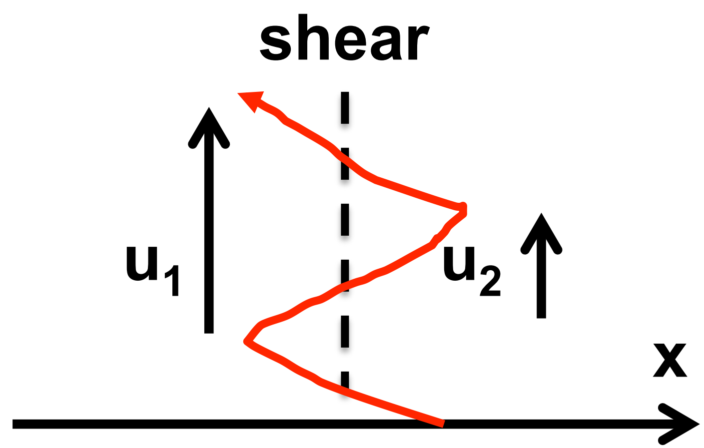
For $\kappa_{xx} \propto p^{\alpha}$ and no escape, $dN/dp \propto p^{\alpha-1}$ $\quad \alpha \geqq 0 \rightarrow$ very hard!

If particles escape, the spectrum is not always power law.

# Shear acceleration

Berezhko&Krymsky 1981, Earl et al.1988
Webb 1989, Ostrowsky 1990, Rieger&Duffy 2006




Spectral index = 2

The spectral index depends on the escape process.

All particles cross the shock.

Some particles cross the shear boundary.

Shock is usually stable.

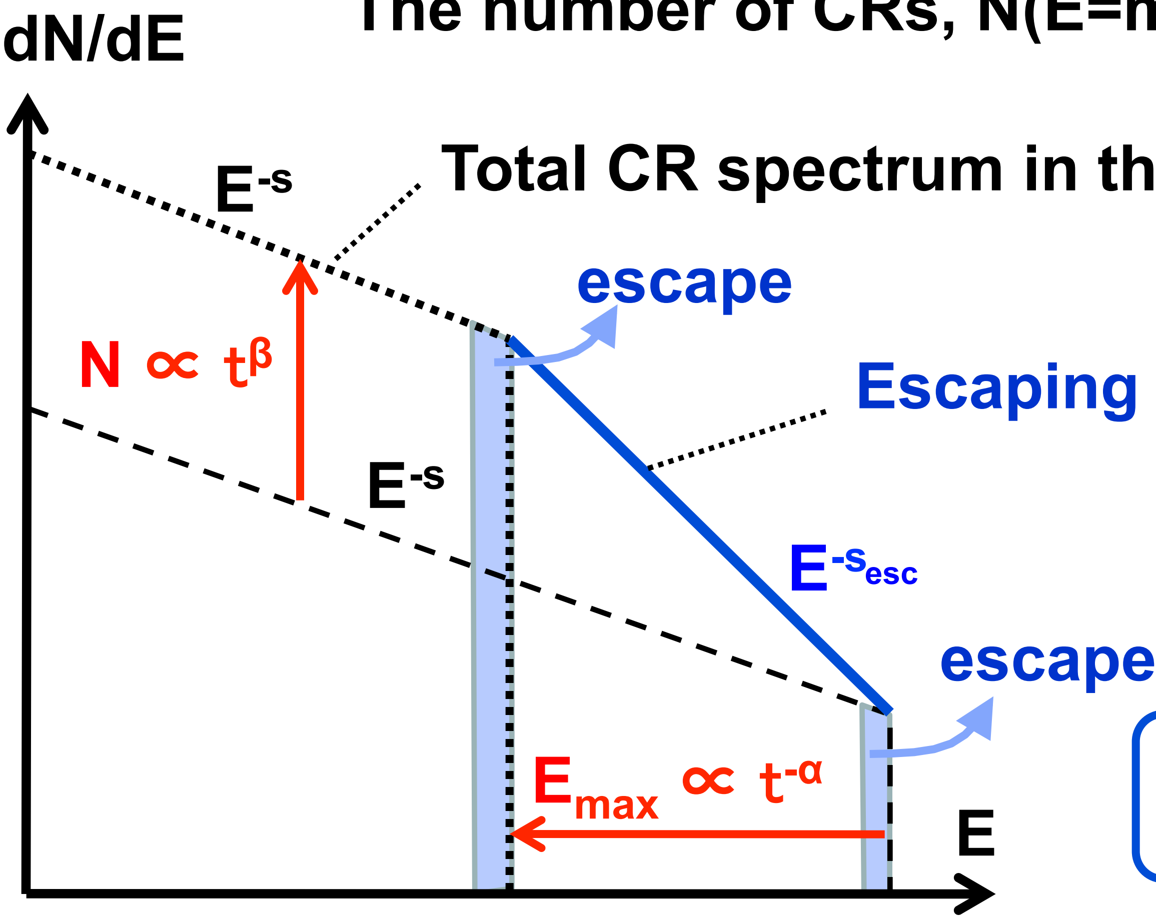
Shear is usually unstable.

→ Turbulent shear acceleration (Ohira 2013)

# Spectrum of escaping CRs from the source

Maximum energy, $E_{max} \propto t^{-\alpha}$ , $\alpha > 0$

The number of CRs, $N(E=mc^2) \propto t^{\beta}$ , $\beta > 0$




$(dN/dE)_{esc} \propto E^{-s_{esc}}$

$$\boxed{s_{esc} = s + \frac{\beta}{\alpha}}$$

$s \neq s_{esc}$

Y. Ohira, K. Murase, R. Yamazaki, 2010, A&A, 513, A17

(Ptuskin&Zirakashvili(2005), Ohira&Ioka(2011), Caprioli et al.(2010), Drury(2011))

# Summary

DSA is widely though to be the acceleration mechanism of CRs.
However, there are several problems.

For Galactic CRs,

observations show that the spectral index of accelerated particles inside SNRs is not always just 2.
There are several theoretical ideas. Which is right?

For UHECRs,

recent simulations of relativistic collisionless shocks show that the turbulent region is too small to accelerate UHECRs.
Even if the turbulent region is sufficiently large, $D_{xx} \propto E^2$ cannot accelerate UHECRs.

To understand the spectral index of CRs, escape is important.

$$dN/dE \propto t^{\beta} E^{-s},\ E_{max} \propto t^{-\alpha} \rightarrow \quad s_{esc} = s + \frac{\beta}{\alpha}$$