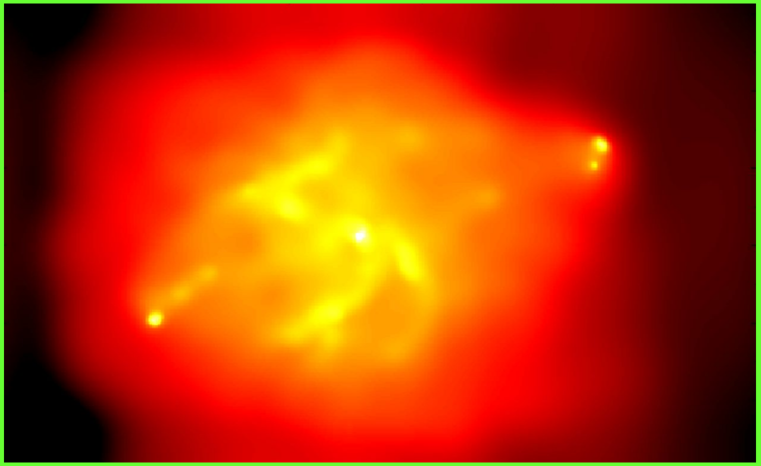
Shock acceleration models – personal review



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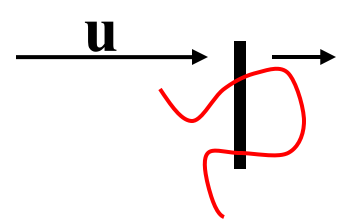
Particle acceleration in the interstellar MHD medium

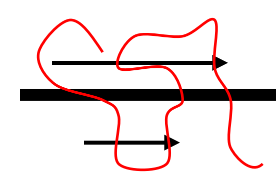
Inhomogeneities of the magnetized plasma flow lead to energy changes of energetic charged particles due to electric fields

$$\delta \mathbf{E} = \delta \mathbf{u}/c \times \mathbf{B}$$

$$\mathbf{B} = \mathbf{B}_0 + \delta \mathbf{B}$$

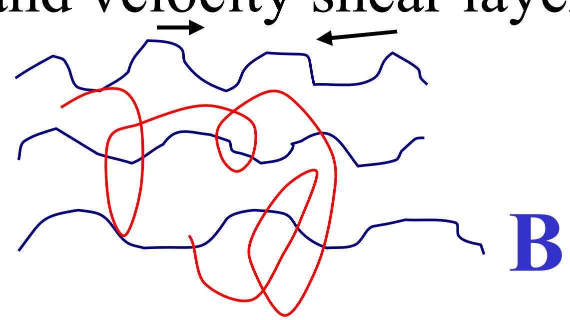


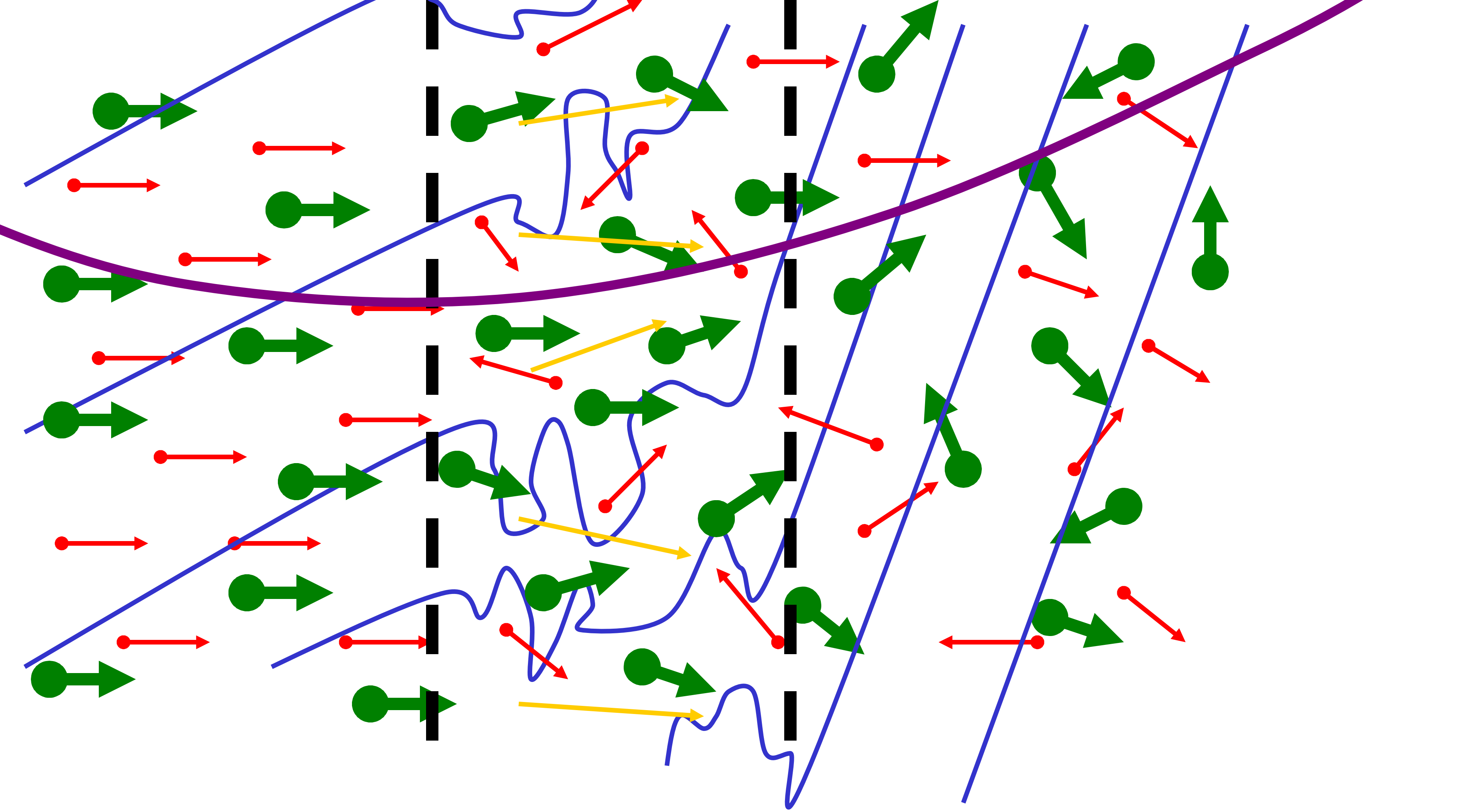
- compressive discontinuities: shock waves



- tangential discontinuities and velocity shear layers

- MHD turbulence





Shock transition

layer

PIC simulations

Shock transition layer internal structure

compression and thermalization of the ambient plasma

Microscopic approach required:

usually Particle-In-Cell simulations for shocks propagating in

-magnetized (e^-, e^+) plasmas

-magnetized (e, p) or (e, ion) plasmas

e.g. papers by Hoshino et al. 1992, Nishikava et al. 2003, Frederiksen at el.2004, Spitkovsky 2006

The **3D simulations** are still unable to study long time behaviour of individual particles to be able to analyse the injection process to the Fermi acceleration of high energy particles.

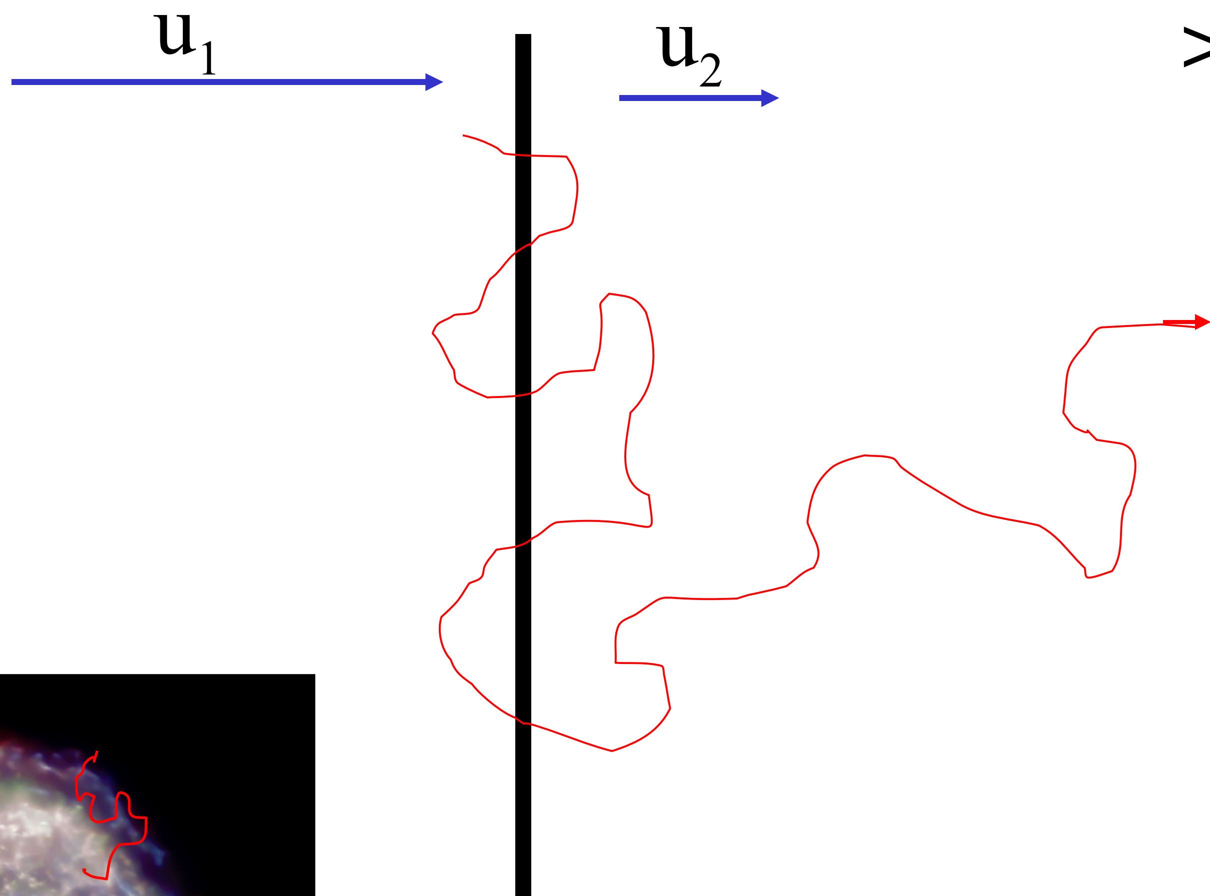
They describe nicely formation of relativistic Maxwellians for (e^-, e^+) plasmas or ions in (e, ion) plasmas, plus the **electron acceleration** processes in the energy range **($\Gamma m_e c^2$, $\Gamma m_{ion} c^2$)**. Also substantial insight into formation of intermittent small-scale magnetic field structures and related currents was achieved.

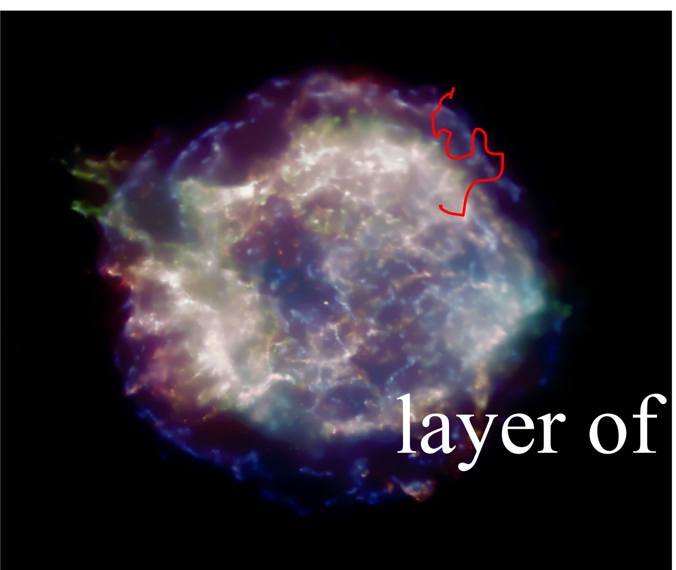
It is still a substantial step to be done in order to follow with the microscopic physics approach the CR particle energy evolution between these "thermal", **$\Gamma m c^2$,** and the CR scales **>> $\Gamma m c^2$**

(→ *a talk by Anatoly Spitkovsky*)

I order Fermi acceleration

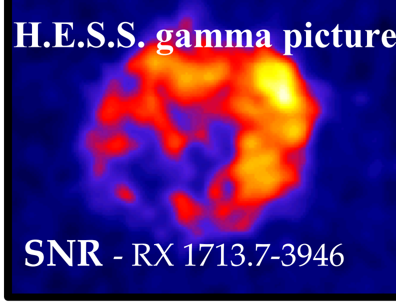
$$E \gg E_{th} \gg \Gamma mc^2$$





layer of plasma compression

Acceleration at non-relativistic (NR) shock waves



Cosmic rays with $v >> u_1$ are nearly **ISOTROPIC** at the shock. This fact and particle **diffusive** propagation are the main factors responsible for relative **independence** of the accelerated particle spectrum on the background conditions.

In the **test particle** approach

$$n(p) \propto p^{-\sigma}, \quad \text{where} \quad \sigma = \frac{R+2}{R-1}$$

and the only parameter defining the spectral index is the shock compression **$R = u_1/u_2$.**

Below we use often □ □ □

index "1" – upstream, "2" – downstream of the shock

NR shock:

Spectral index does not depend on, e.g.,

- turbulence character (with $V_A << u_1$)*
- mean value and inclination of B (if $u_B << v$)
- shock velocity (for $M >> 1$)

if only boundary conditions are not important in the considered energy range and nonlinear effects or other acceleration processes are negligible.

* II order Fermi can be important for $V_A > 0.1\, u_1$

Relativistic shock acceleration:

Particle velocity: $V \sim u_{shock}$

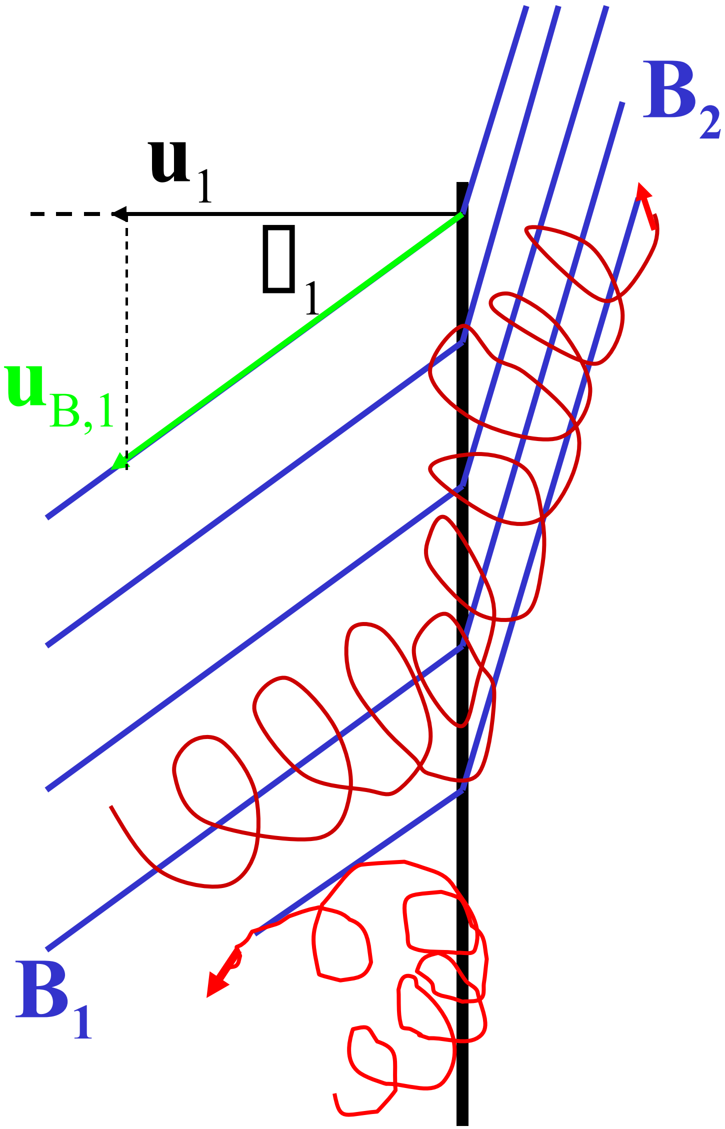
→ **Particle anisotropy** in the shock: □□ $\sim \boldsymbol{\gamma}^{-1}$

shock Lorentz factor

Significant influence of the **background conditions** at the resulting particle spectrum:

- the mean magnetic field
- MHD turbulence
- the shock Lorentz factor

Sub- and super-luminal shocks



$$u_{B,1} = \frac{u_1}{\cos \theta_1}$$

➡ $u_{B,1} < c$ - subluminal

particle reflections possible

➡ $u_{B,1} > c$ - superluminal

only transmissions 1→2

History of the I order Fermi acceleration studies

Peacock 1981 -- simple angular form for the distribution function

Kirk & Schneider 1987 -- Fokker-Planck equation, **parallel shocks** **($\square_1 = 0$)**

Kirk & Heavens 1989 -- FP equation **oblique shocks** **($\square_1$ □ 0)**

Begelman & Kirk 1990 -- acceleration at superluminal shocks

since 1991 (Ostrowski, Ellison et al., Takahara et al., Heavens et al., et al.)
-- numerical simulations allow for studies of **□B ~ B**

since 1998 (Bednarz & Ostrowski, Gallant & Achterberg, Kirk et al., et al.)
-- ultrarelativistic shock waves **$\gamma >> 1$**

All these studies were limited to the test particle approximation and apply simplified models for turbulent MHD medium near the shock

Niemiec & O. 2004, 2006, & Pohl 2006 – slightly more realistic field structure

Let us consider

mildly relativistic shocks

with, say, $u \sim 0.3 - 0.9\ c$

or the shock Lorentz factors $\boldsymbol{\gamma}$ in the range

$1.05 - 2.3$

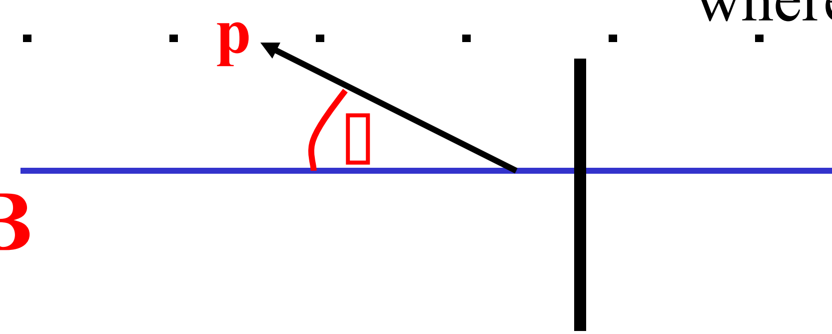
the Fokker-Planck approach of Kirk & Schneider for stationary acceleration at a parallel shock

pitch angle diffusion coefficient

$$\gamma(u+\mu v)\frac{\partial F}{\partial x}=\frac{\partial}{\partial \mu}\left((1-\mu^{2})D_{\mu}\frac{\partial F}{\partial \mu}\right)$$

where $F = F(x, p, \mu)$

pitch angle cosine



Solution:

2. general solutions are obtained upstream and downstream of the shock by solving the eigenvalue problem
2. by matching the two solutions at the shock, the spectral index and anisotropic distribution is found by taking into account a sufficient number of eigenfunctions

At **oblique subluminal shocks** the same procedure works,

but one has to assume

$$\mathbf{p_{\perp}^2 / B = const}$$

$\delta B << B_o$

for particle interactions with the shock

↓

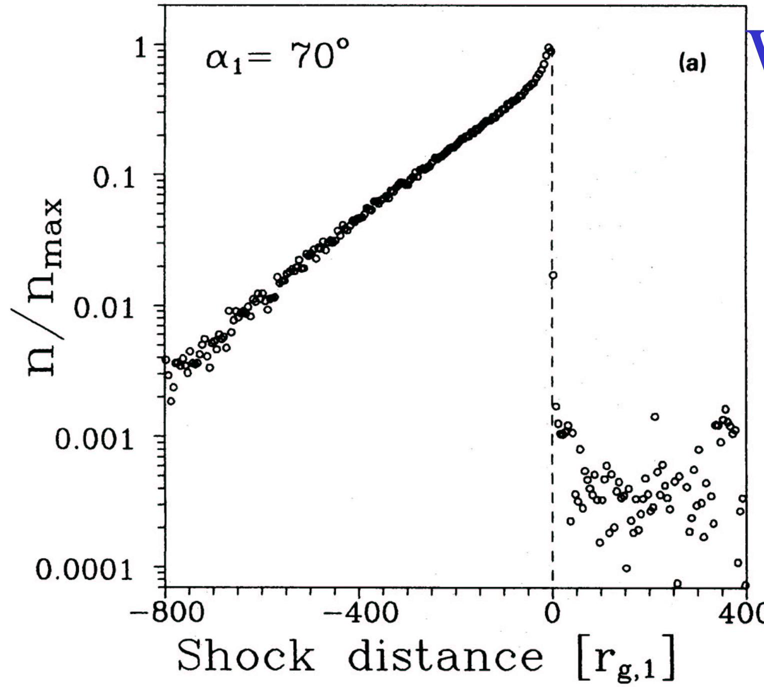
Even a slight inclination of the mean magnetic field leads to substantial (qualitative) changes in the acceleration process

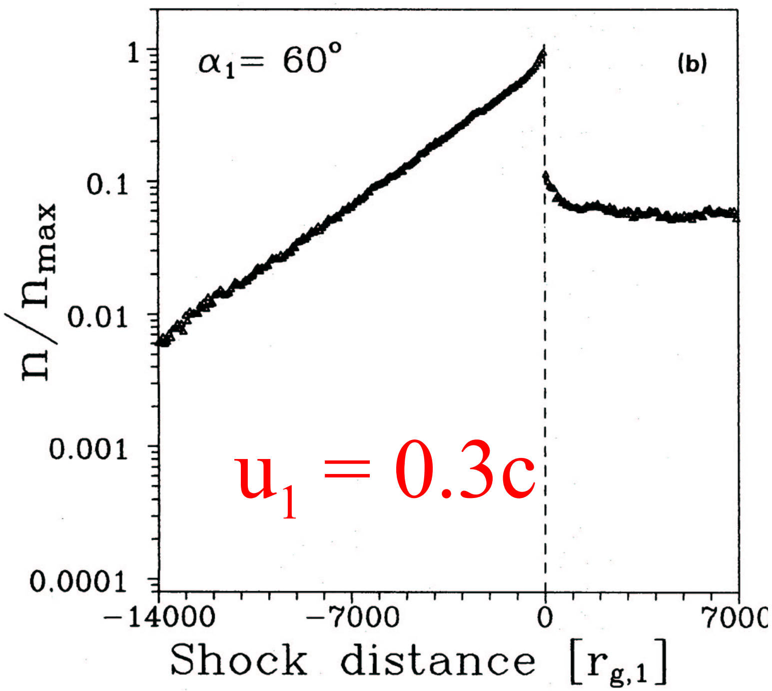
particle density jump at the shock

very flat spectra

(Kirk & Heavens 1989)

Weakly perturbed oblique shocks





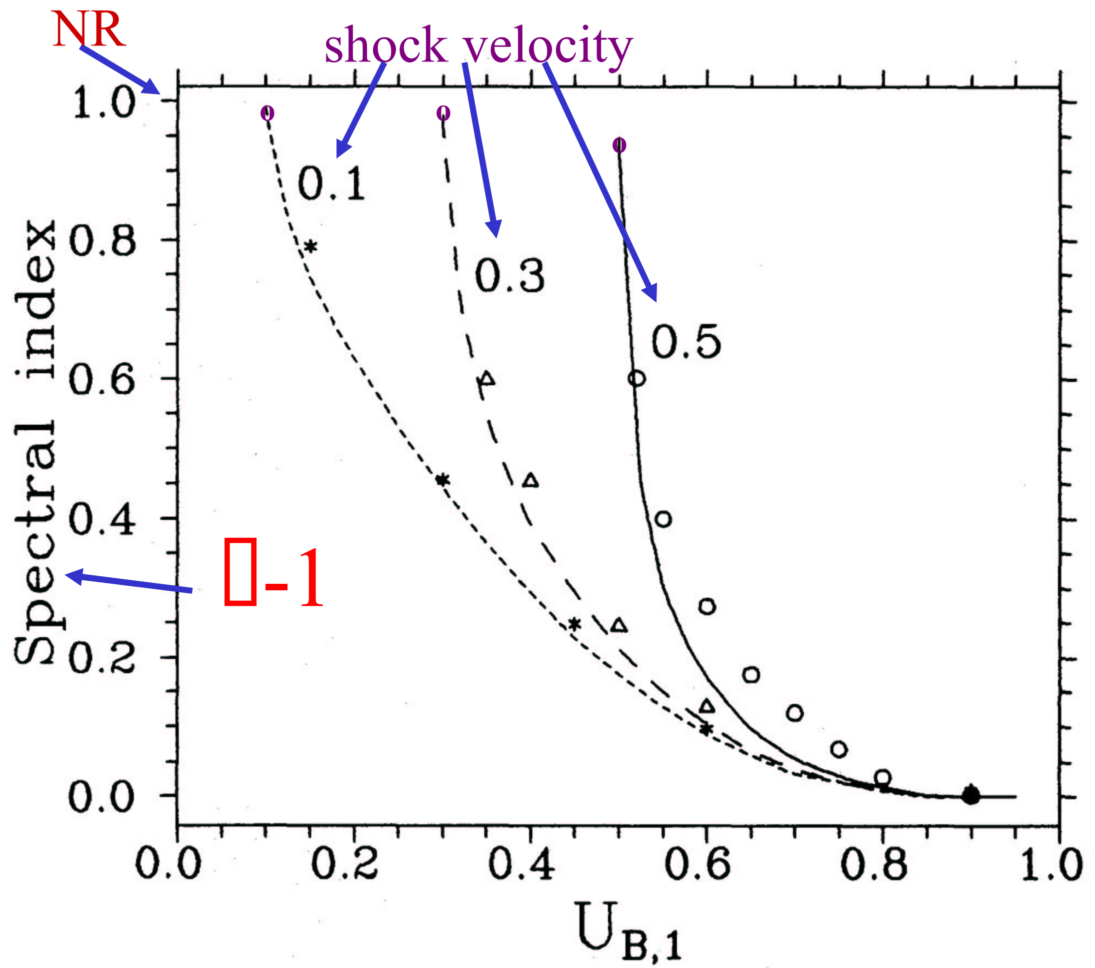
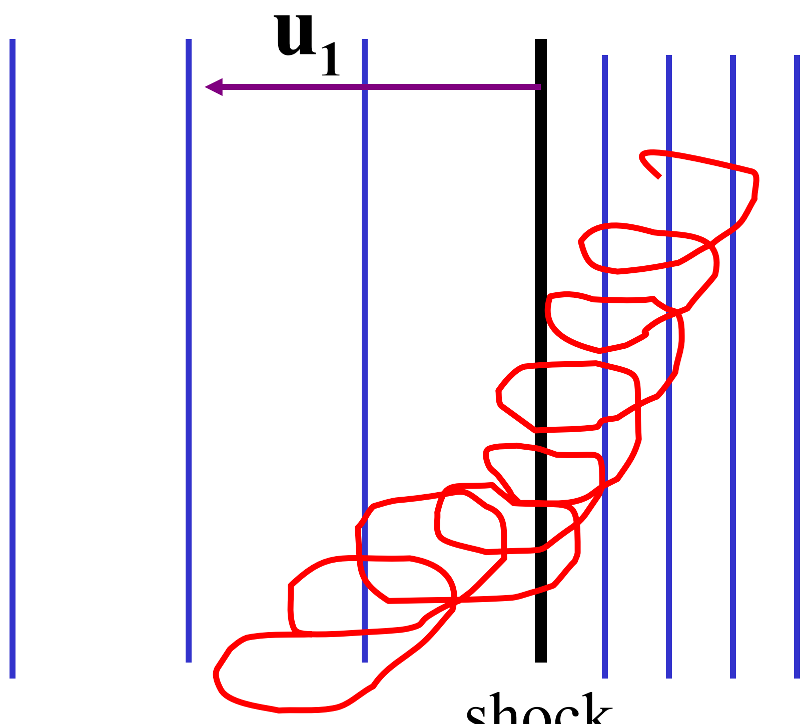


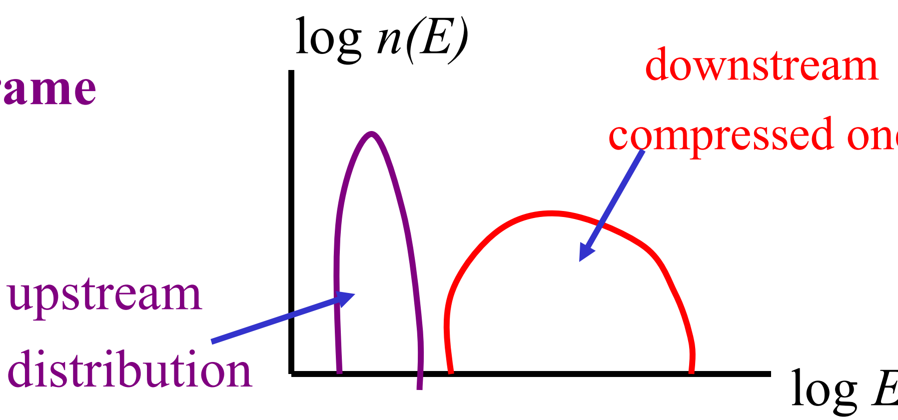
Figure 3. Spectral indices of accelerated particles versus the shock velocity along the magnetic field. The simulations were performed in the conditions of negligible magnetic field perturbations, $\eta \cong 0$, for three shock velocities and the compression $R = 4$. The lines represent the analytical results of Kirk & Heavens (1989); the respective values of u_1 are given near the curves.

Superluminal shock wave $u_{B,1} > c$



particle trajectory in the shock frame

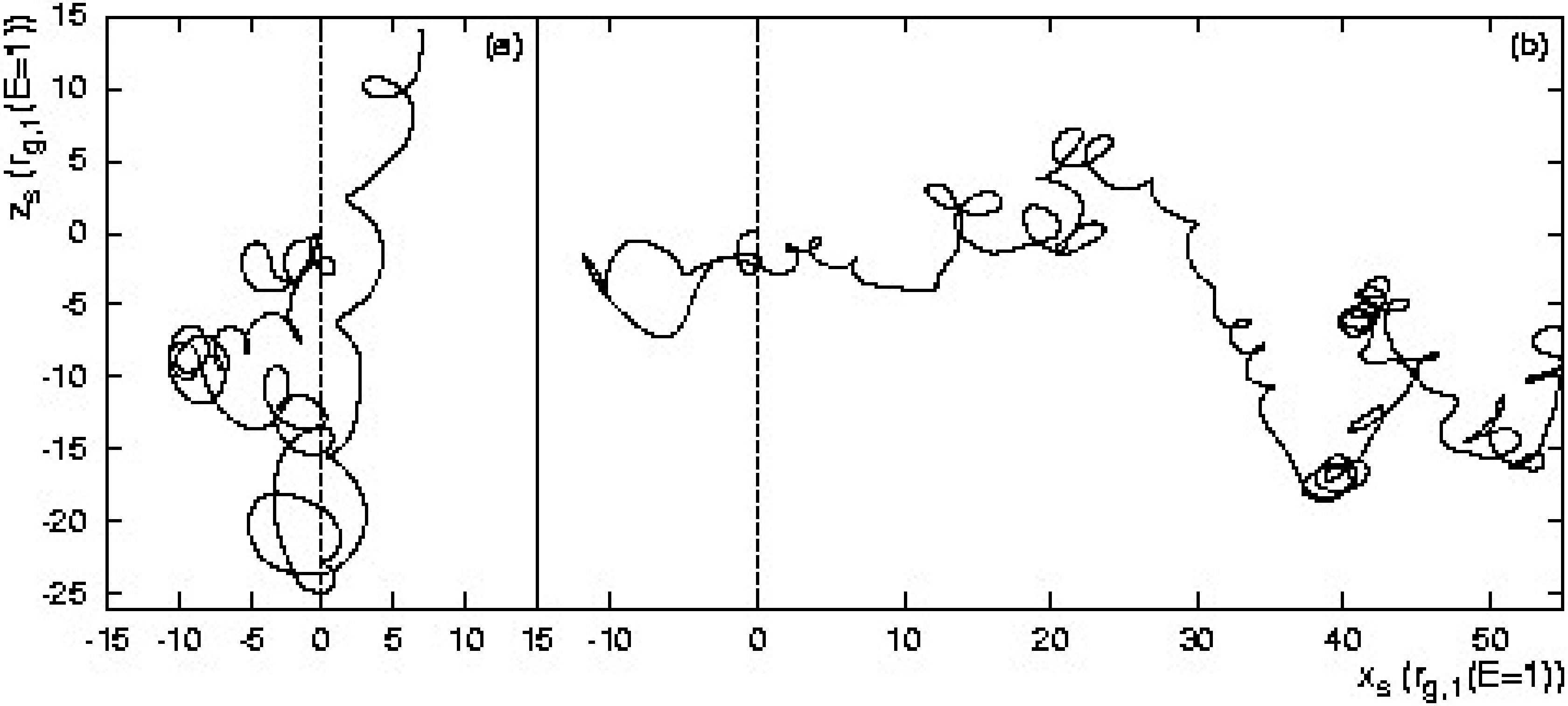
For $\delta B \ll B_o$ only transmissions upstream -downstream possible



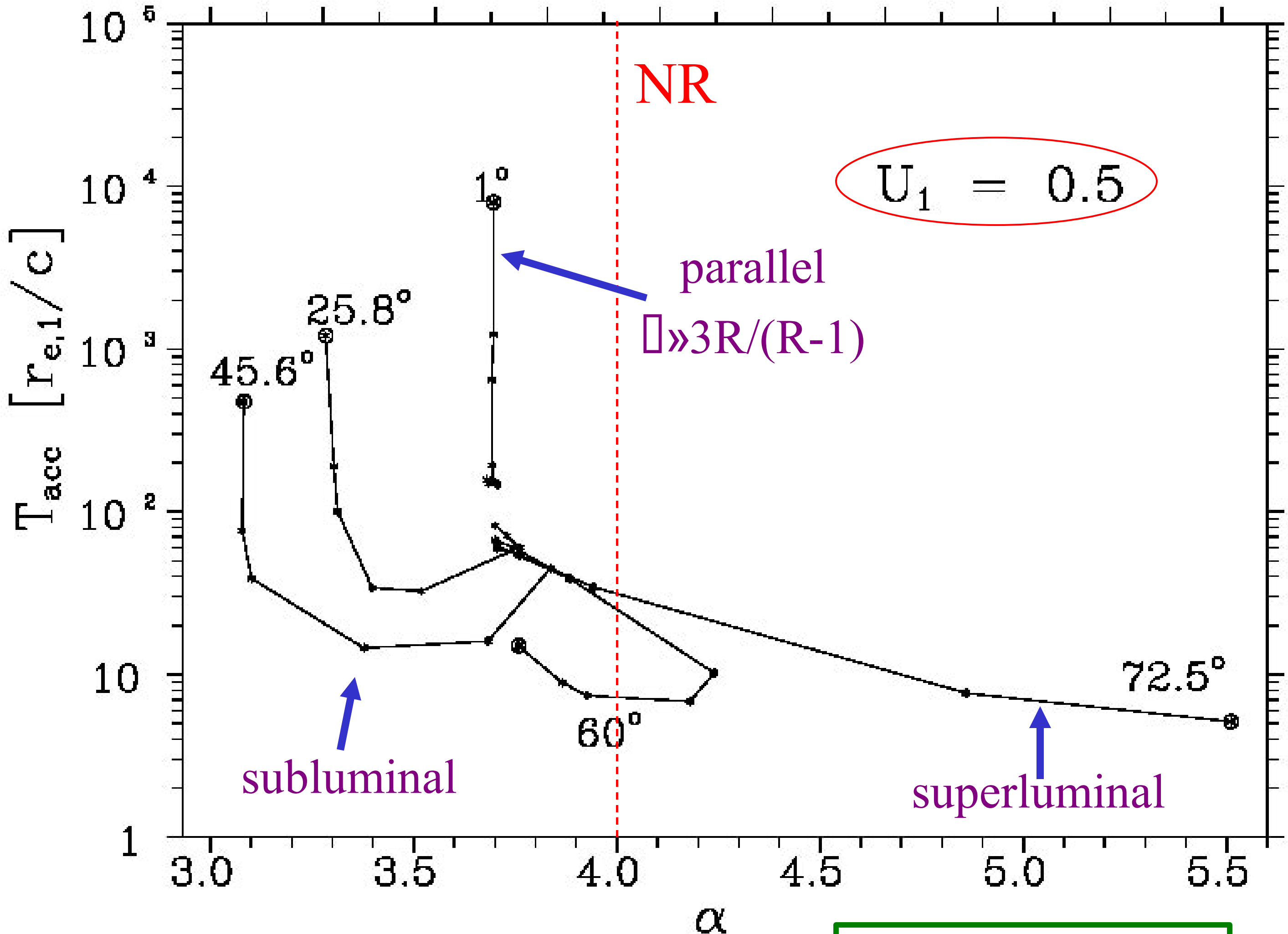
Begelman & Kirk 1990

For $\delta B \sim B$ numerical modelling

often **Monte Carlo** simulations



„Summary" of results for mildly relativistic shocks



$$\frac{u_1}{\cos 60^\circ} = 1$$

$\alpha = \sigma + 2$

Bednarz & O. 1996

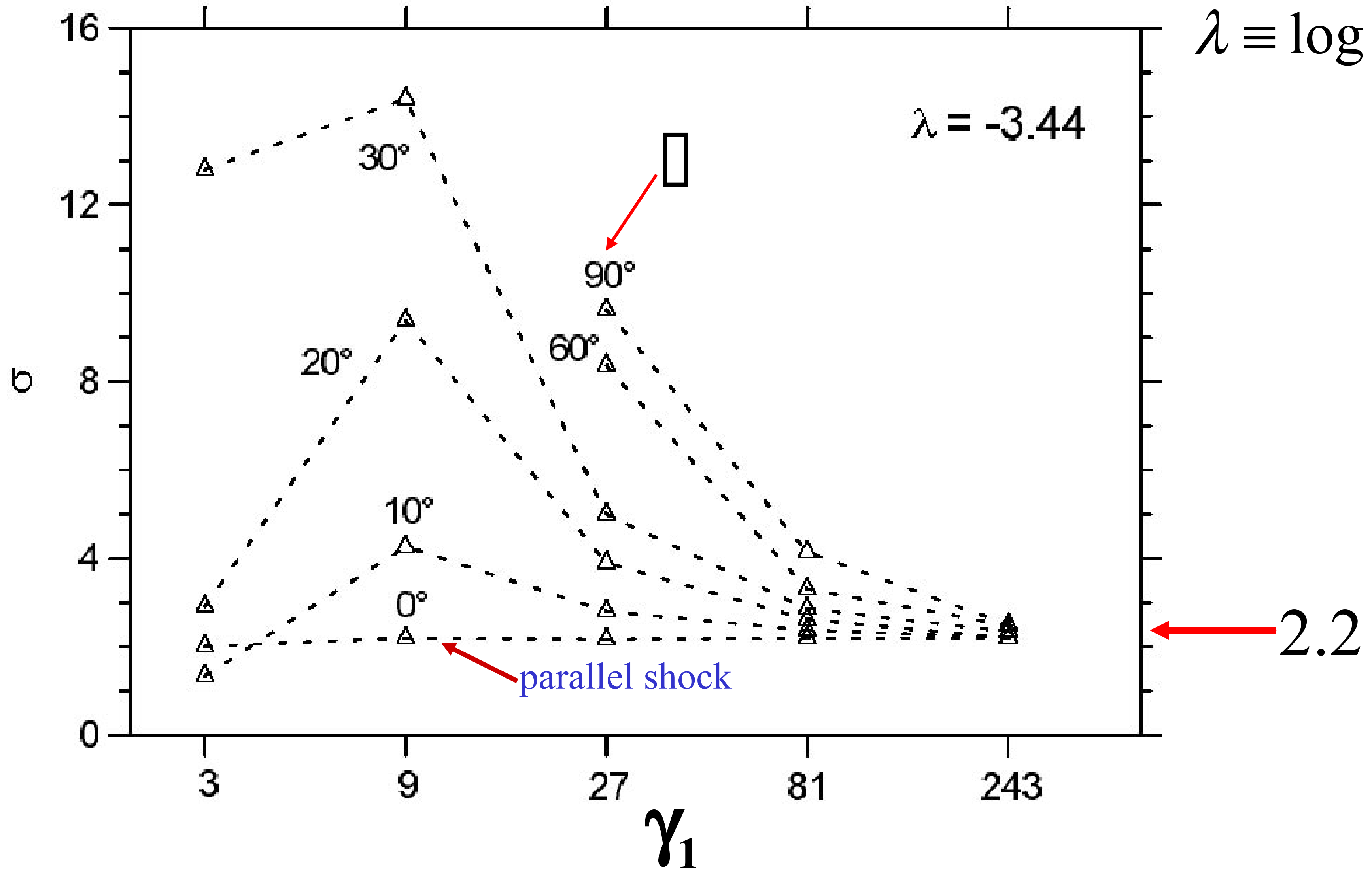
Ultra-relativistic shock waves

$$\gamma_1 >> 1$$

superluminal (perpendicular) shocks, $u_{B,1} > c$

Spectral index for particles accelerated at ultrarelativistic shocks

(pitch angle diffusion modelling - Bednarz & Ostrowski 1998)



$\lambda \equiv \log \frac{\kappa_{\perp}}{\kappa_{\parallel}}$

The same value of □ » 2.2 was derived for ultra-relativistic shocks by Gallant, Achterberg, Kirk, Guthmann, Vietri, Pelletier, Lemoine, et al. (1999 – 2006)

Does there exist an universal spectral index for relativistic shocks ?

.

O&Bednarz 2002:

The opinion saying that spectra of particles accelerated at relativistic shocks are the power-laws (+ a cut off) with the spectral index close to 2.2 was (and it is still) prevailing in the astrophysical literature.

This erroneous opinion comes from misinterpretation of the papers discussing the Fermi I acceleration at relativistic shock waves, which effectively consider parallel shocks, while the real ones are perpendicular.

Thus, what spectra are expected to be generated at relativistic shocks?

A role of realistic background conditions in CR acceleration at relativistic and ultra-relativistic shocks we attempted to consider in a series of papers:

Niemiec & O. (ApJ: 2004, 2006, & Pohl 2006).

→ ***a talk of Niemiec***

In the Monte Carlo simulations:

-shock Lorentz factors between 2 and 30

-different inclinations of B_0

-different spectra of the background long wave MHD (static – no Fermi II accel.) turbulence

-possibility of generation of highly nonlinear turbulence at the shock (like in PIC simulations)

The obtained results **do not** reproduce the often claimed universal **σ** ≈ 2.2 power-law.

They show:

-**no** power-law spectra

-**cut-off** within the considered range of energies

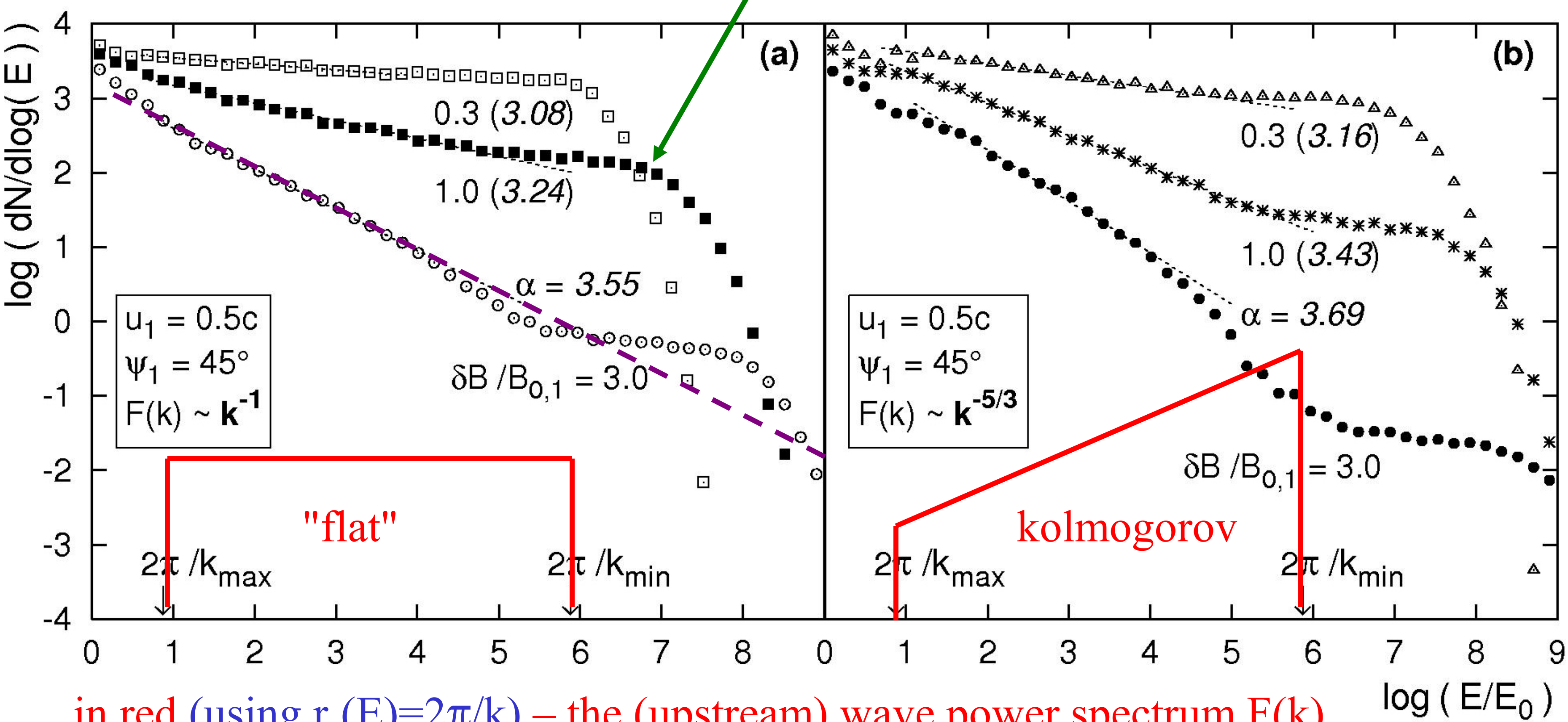
-wide **variety** of spectral indices

Mildly relativistic shocks

oblique *subluminal* shock:

$$\delta B^2 = \int_{k_{min}}^{k_{max}} F(k)dk$$

hard component before the cut off

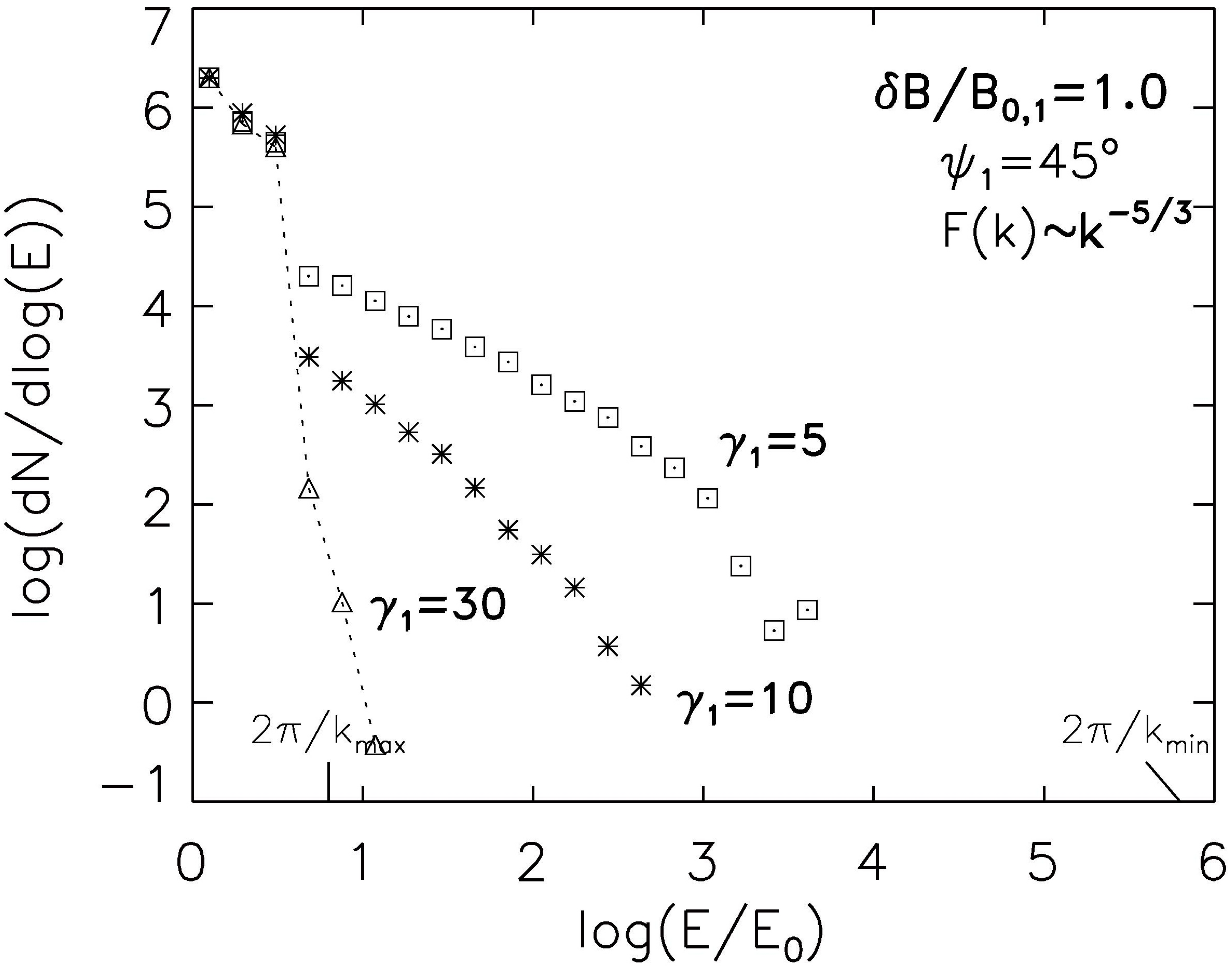


in red (using $r_g(E)=2\pi/k$) – the (upstream) wave power spectrum F(k)

$\gamma_1 = 5, 10, 30$

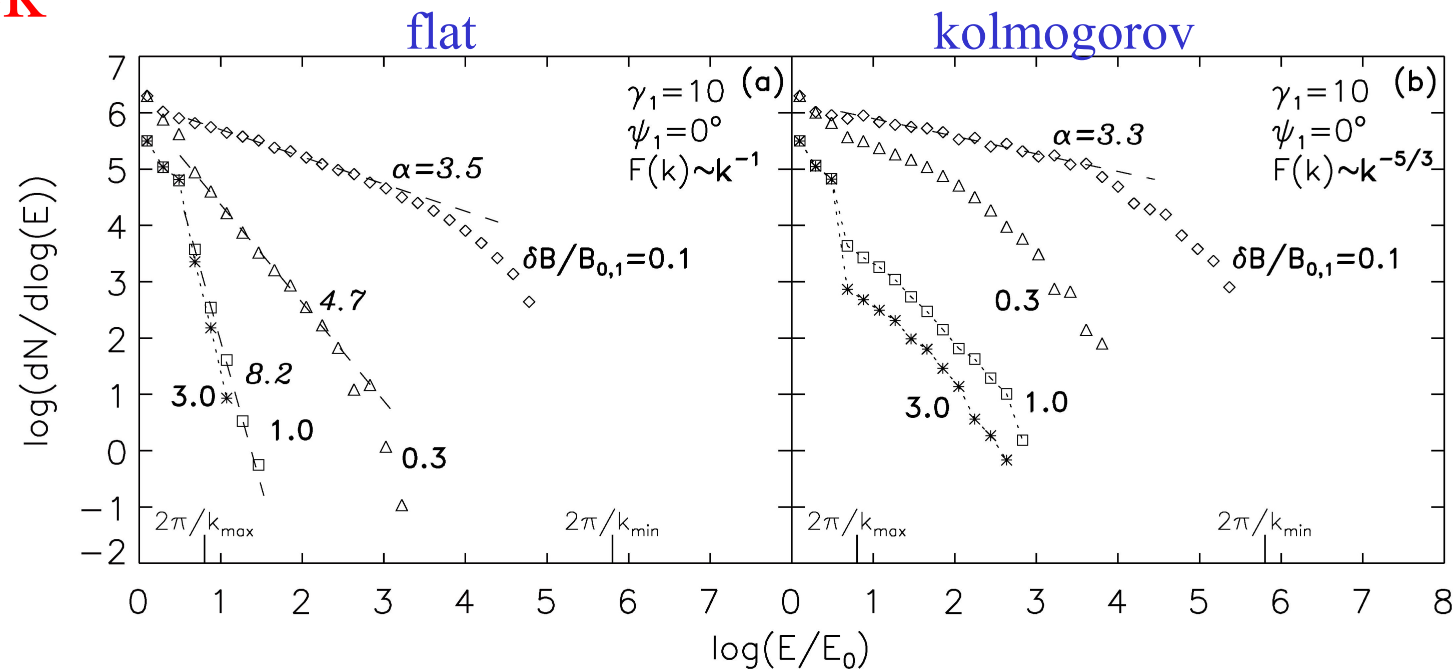
$u_1 = 0.98c, 0.995c, 0.9994c$

$u_{B,1} \approx 1.4c$

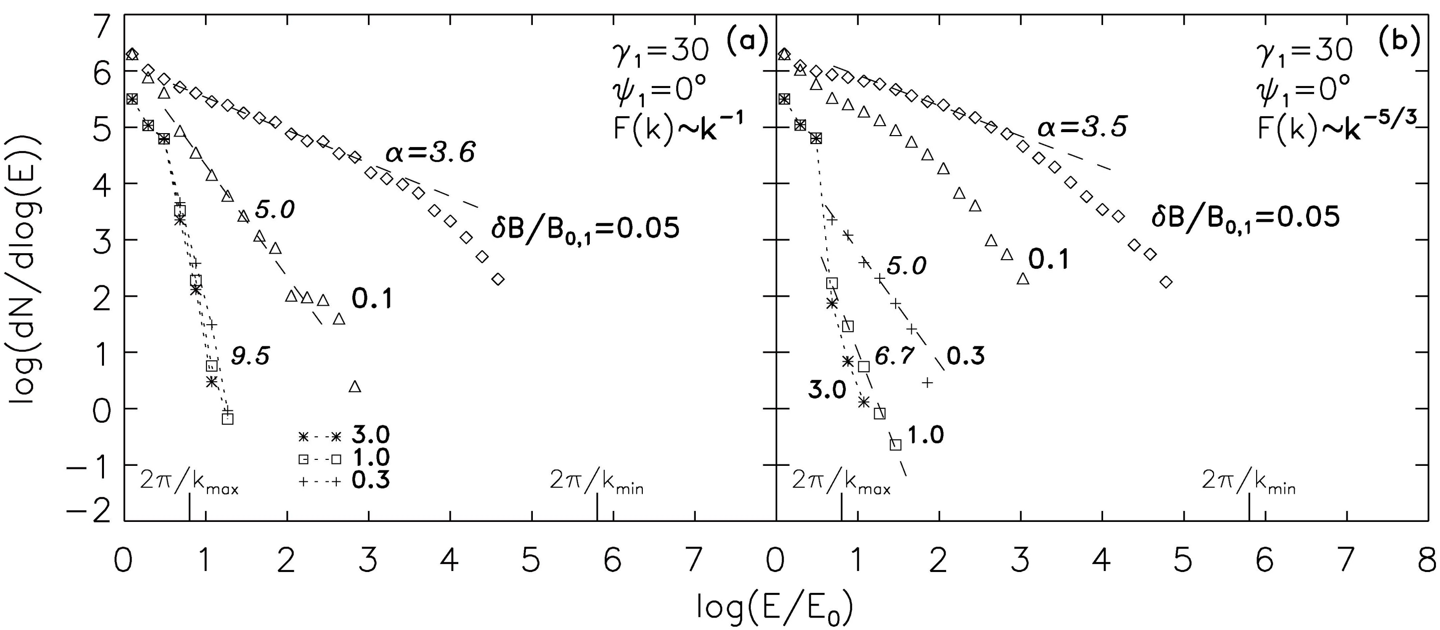


Parallel shock

$\gamma_1 = 10$



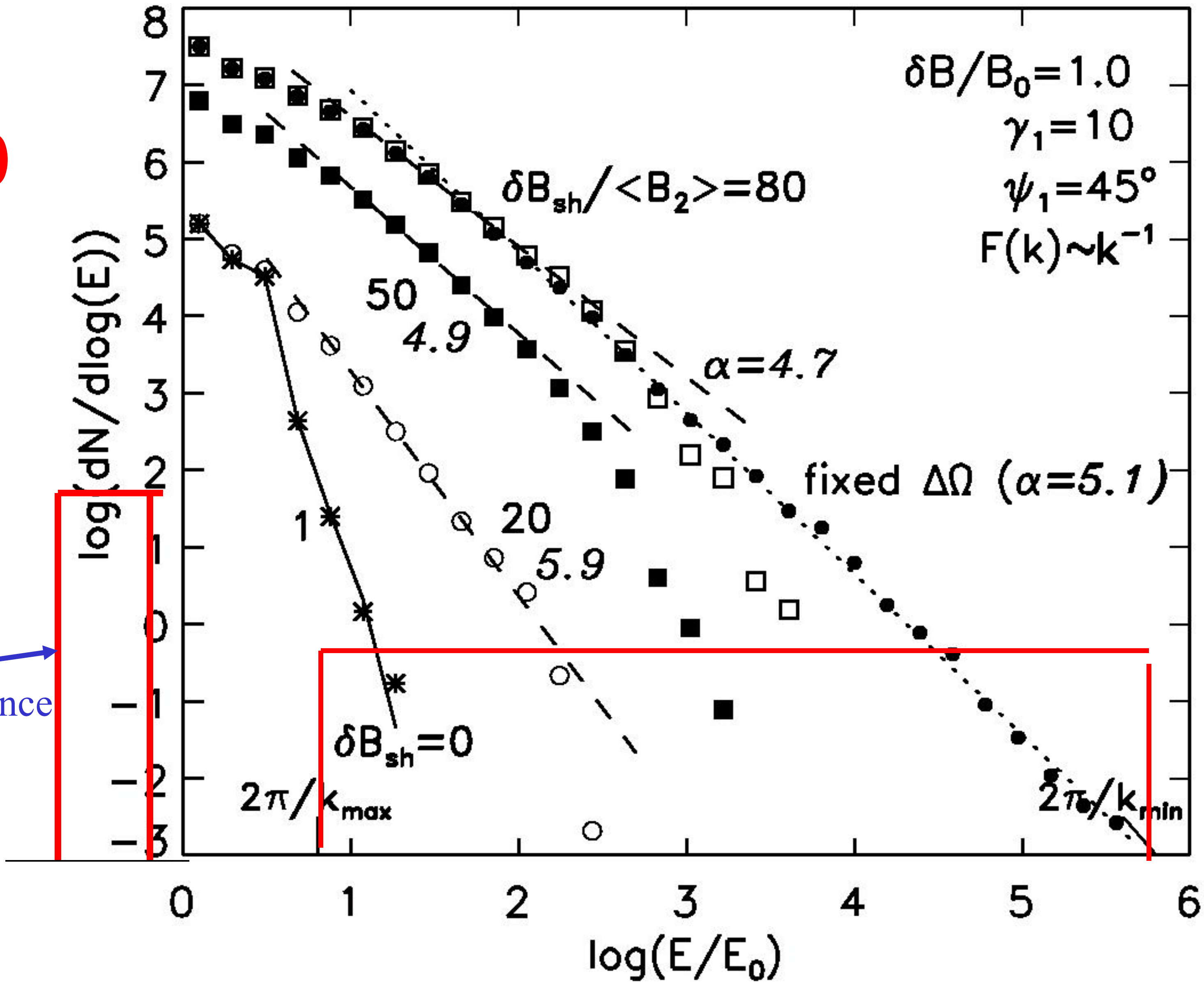
$\gamma_1 = 30$



Ultrarelativistic shock waves with "shock generated" downstream short-wave turbulence

$\gamma_1 = 10$

short wave
MHD turbulence



Some proposals of

non-standard or **non-Fermi**

relativistic shock acceleration processes

„Microscoping" studies of relativistic shock structure

For example:

- Hoshino et al., 1992, „Relativistic magnetosonic shock waves in synchrotron sources - Shock structure and nonthermal acceleration of positrons", ApJ, 390, 454

  PIC 1D modelling of the perpendicular wind terminal shock in Crab

- Pohl at al., 2002, „Channeled blast wave behavior based on longitudinal instabilities", A&A, 383, 309

  Analytic modelling of macroscopic instabilities and wave generation

- Medvedev & Loeb, 1999, „Generation of Magnetic Fields in the Relativistic Shock of Gamma-Ray Burst Sources", ApJ, 526, 697

  Instability in the shocked magnetized plasma for generation of short wave magnetic field perturbations

Derishev et al., 2003, „Particle Acceleration through Multiple Conversions from Charged into Neutral State and Back”, Phys.Rev. D 68, 043003

Boris Stern, 2003, „Electromagnetic Catastrophe in Ultrarelativistic Shocks and the Prompt Emission of Gamma-Ray Bursts”, MNRAS 345, 590

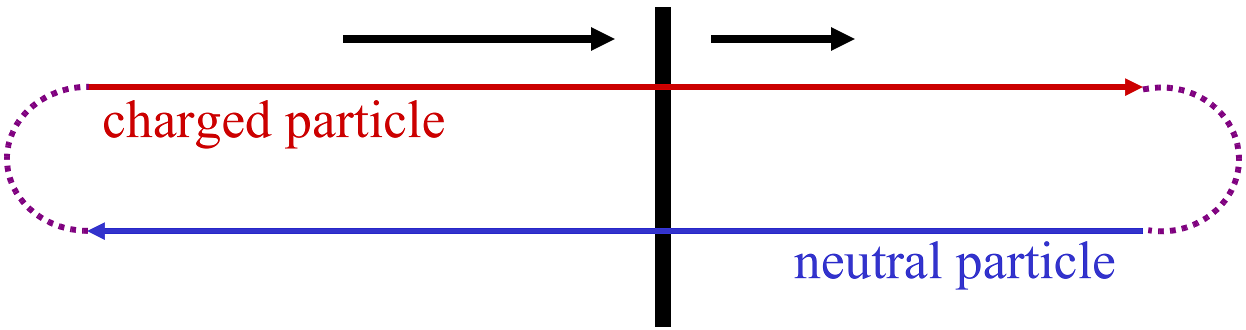
Pisin Chen et al., 2002, „Plasma Wakefield Acceleration for Ultrahigh Energy Cosmic Rays”, Phys.Rev.Lett. 89, 1101 and others

Interaction of a relativistic particle beam with plasma

Ucer & Shapiro 2001, "Unlimited Relativistic Shock Surfing Acceleration", PRL 87 and others

Acceleration at perpendicular shock wave with strong electric potential drop

Works of Derishev et al. and Stern for ultrarelativistic shock waves - $\Gamma >> 1$



$$\frac{\Delta E}{E} \sim \Gamma^2$$

upstream shock downstream

NUCLEONS

$n + \gamma \rightarrow p + \pi^-$ $\qquad$ $p + \gamma \rightarrow n + \pi^\pm$

(or decay of n)

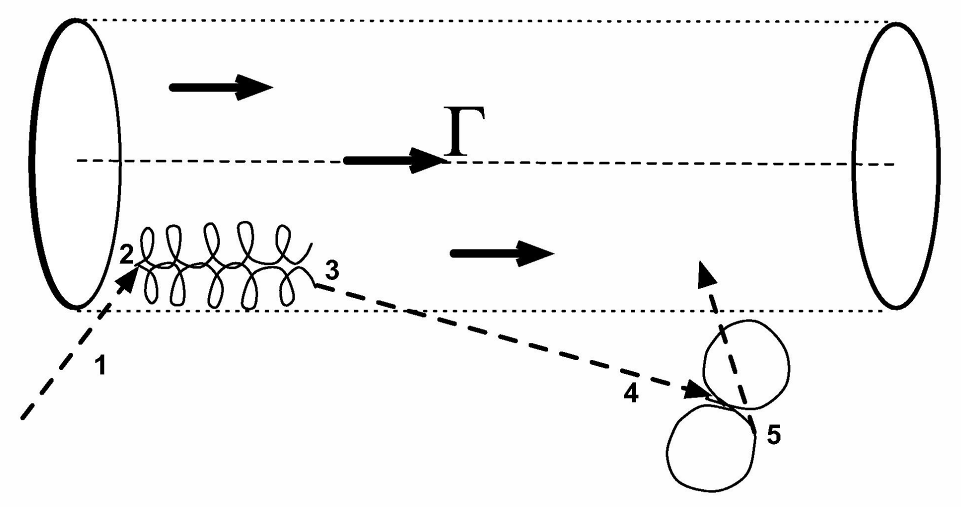
PAIRS (e^+, e^-)

$\gamma' + \gamma \rightarrow e^+ + e^-$ $\qquad$ $e^\pm + \gamma \rightarrow e^\pm + \gamma'$

Recently: Stern & Poutanen astro-ph/0604344 Poster 39

A photon breeding mechanism for the high-energy emission of relativistic jets

claim, that such mechanism can effectively work at the jet side boundary for $\Gamma >> 1$, leading to unstable photon production.



Numerical study shows that the process can become unstable by draining energy of the jet bulk flow. However possible constraints/limitations for its action are still unclear for me.

Conclusions

- theory of cosmic ray acceleration at relativistic shocks is not sufficiently developed to enable realistic modelling of astrophysical sources, at most qualitatively

- wide range of the studied physical conditions at relativistic shocks **do not allow** for generation of the accelerated particle spectra which are wide range power-laws and/with the universal spectral index $\sigma \approx 2.2$

- cosmic ray spectra generated at ultrarelativistic shock waves are not expected to extend to very high energies. Thus, postulating such shocks to be sources of UHE CR particles is doubtful

A few more remarks

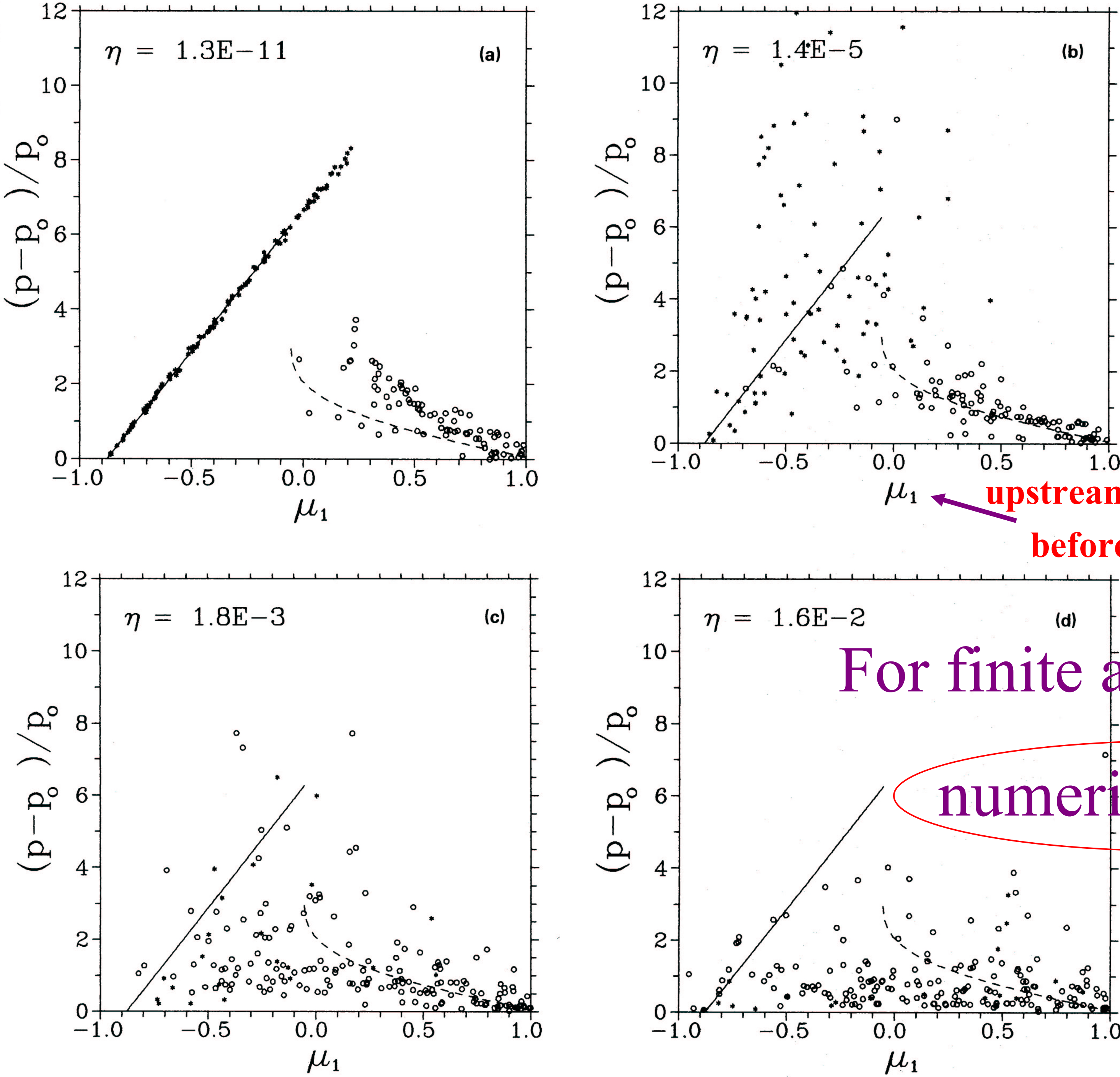
- **observational results** and **numerical simulations** still play an essential role in developing the theory of relativistic shock acceleration

- in my opinion the full picture requires consideration of the second order Fermi acceleration acting in the relativistic MHD turbulence near (downstream of) the shock

- PIC simulations are unable to study higher CR energies

-interesting non-standard proposals by Derishev et al., Stern, & Poutanen should be critically verified

$$\eta \equiv \log \frac{\kappa_{\perp}}{\kappa_{\parallel}}$$



$u_1 = 0.5\ c$

$\theta_1 = 55^o$

upstream particle pitch angle before hitting the shock

For finite amplitude δB → numerical methods

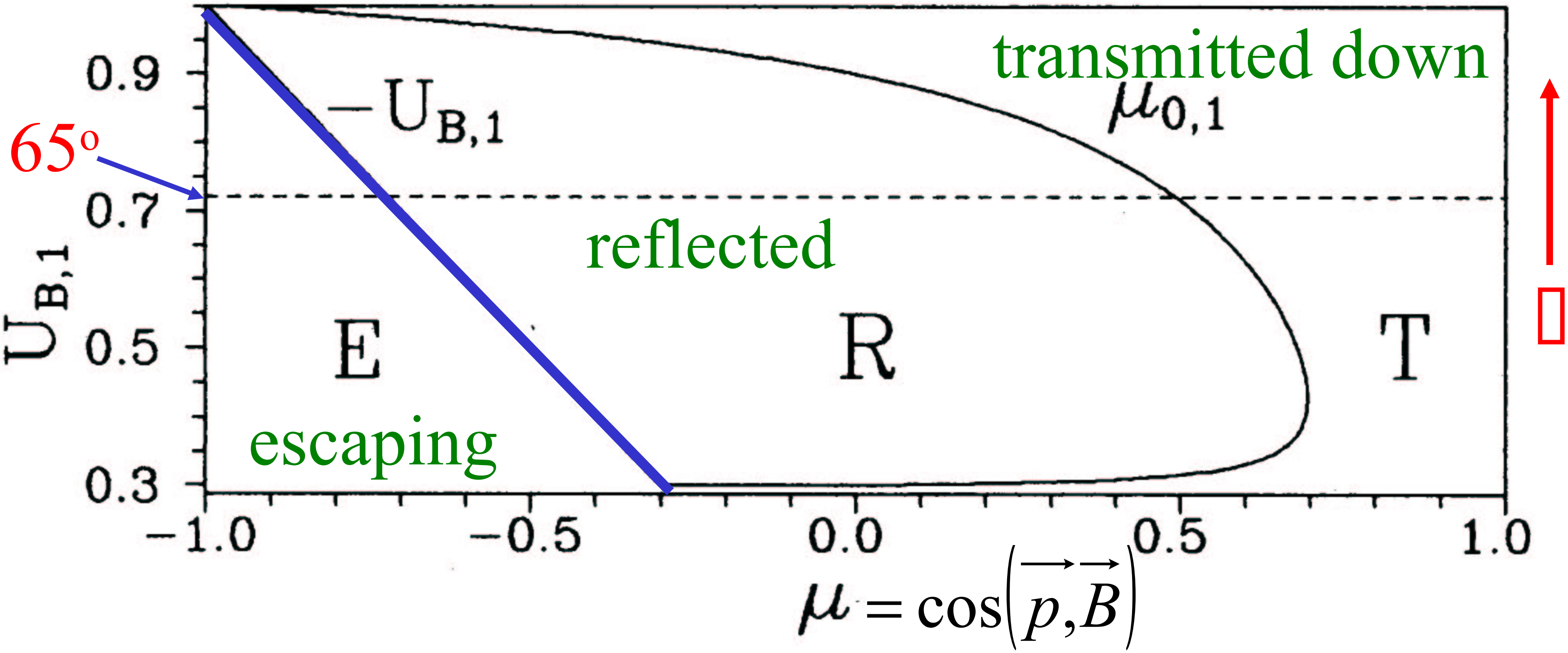
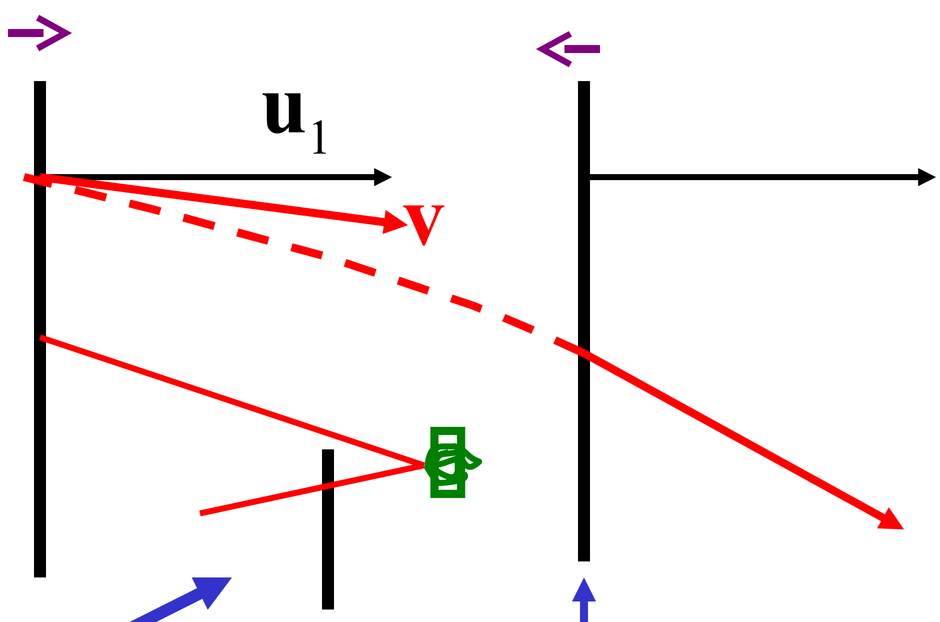


Figure 5. The division of particle pitch angles for upstream particles in oblique shocks based on the assumption of the particle magnetic moment conservation. For $\mu < -U_{B,1}$ (region E) most reflected particles escape upstream from the shock, for higher values of μ the particles approach the shock and can be reflected (region R) or transmitted downstream (region T). The plot is given for a shock wave with the velocity $u_1 = 0.3$ and $R = 5.28$. An auxiliary dashed line is for $U_{B,1} = 0.72$.

Warning: the large angle scattering model applied sometimes for description of CR acceleration at relativistic shocks is unphysical

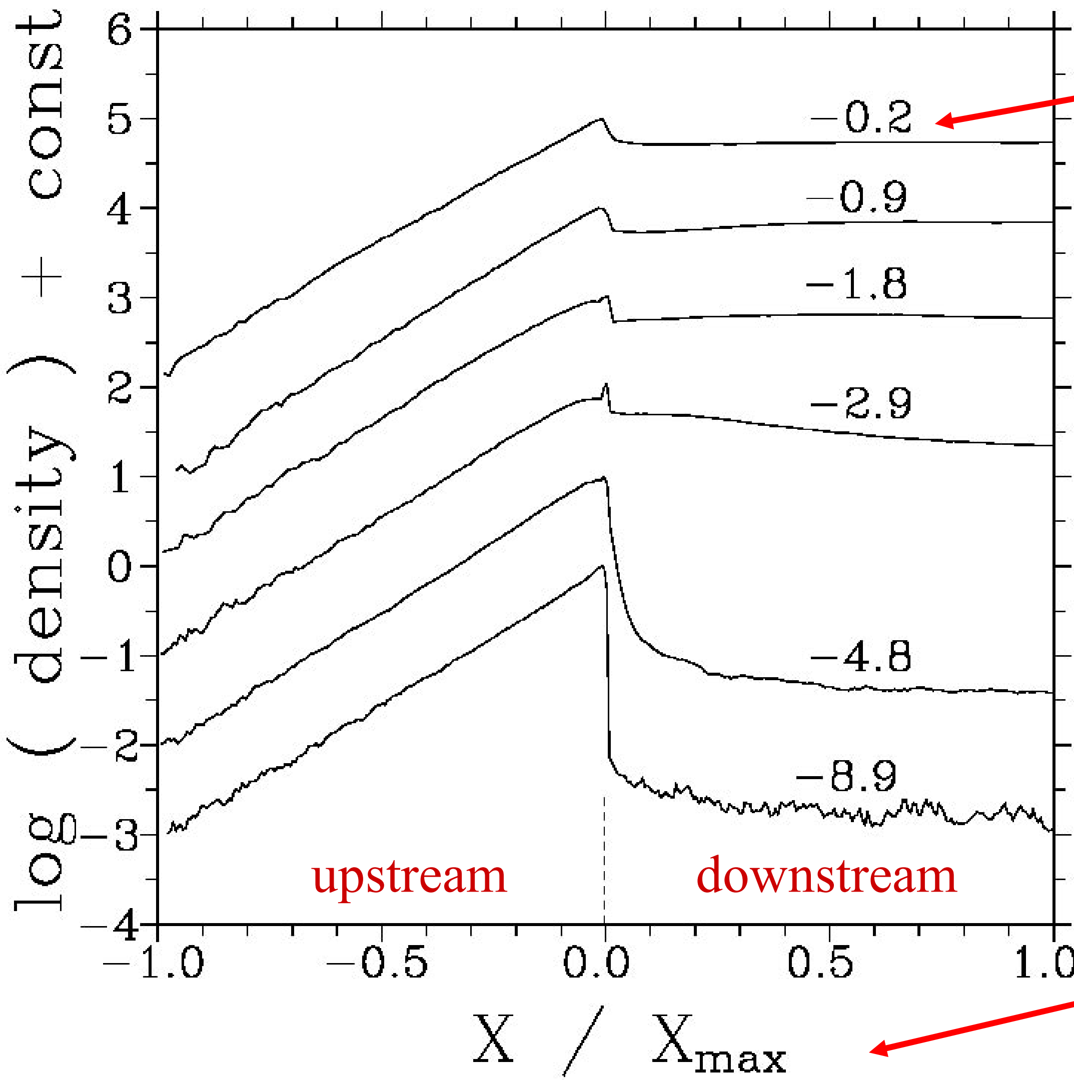
In the upstream plasma rest frame:



there are no such scattering centres within the MHD medium

the shock overruns an escaping particle

Cosmic ray density across an oblique subluminal shock



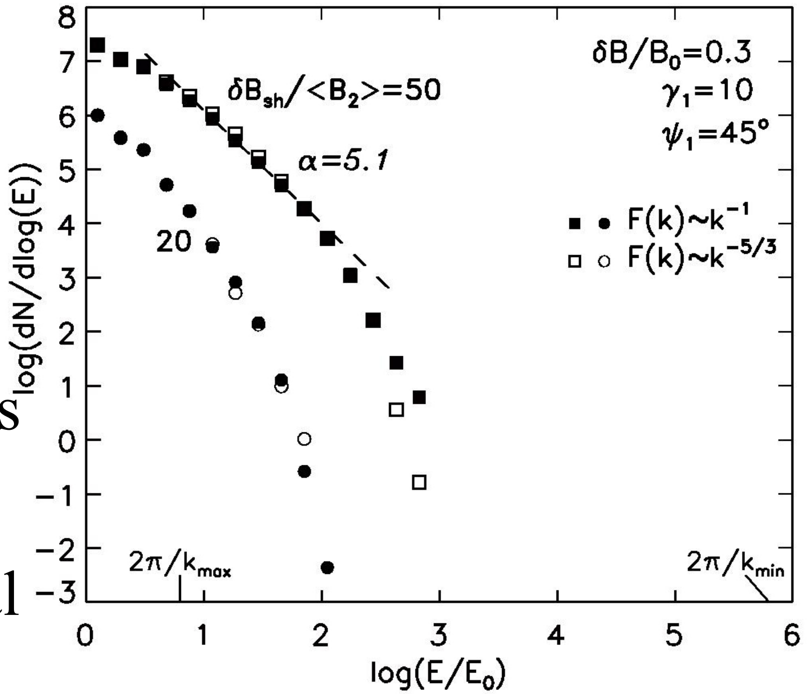
~ log (turbulence amplitude □B/B)

□B~B

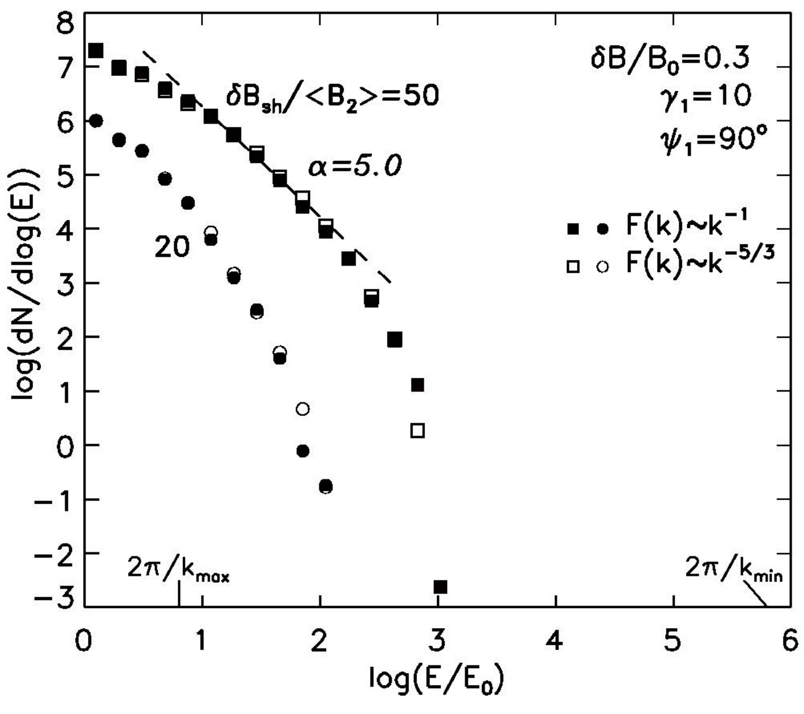
□B□B

Distance to the shock in units of X_{max}

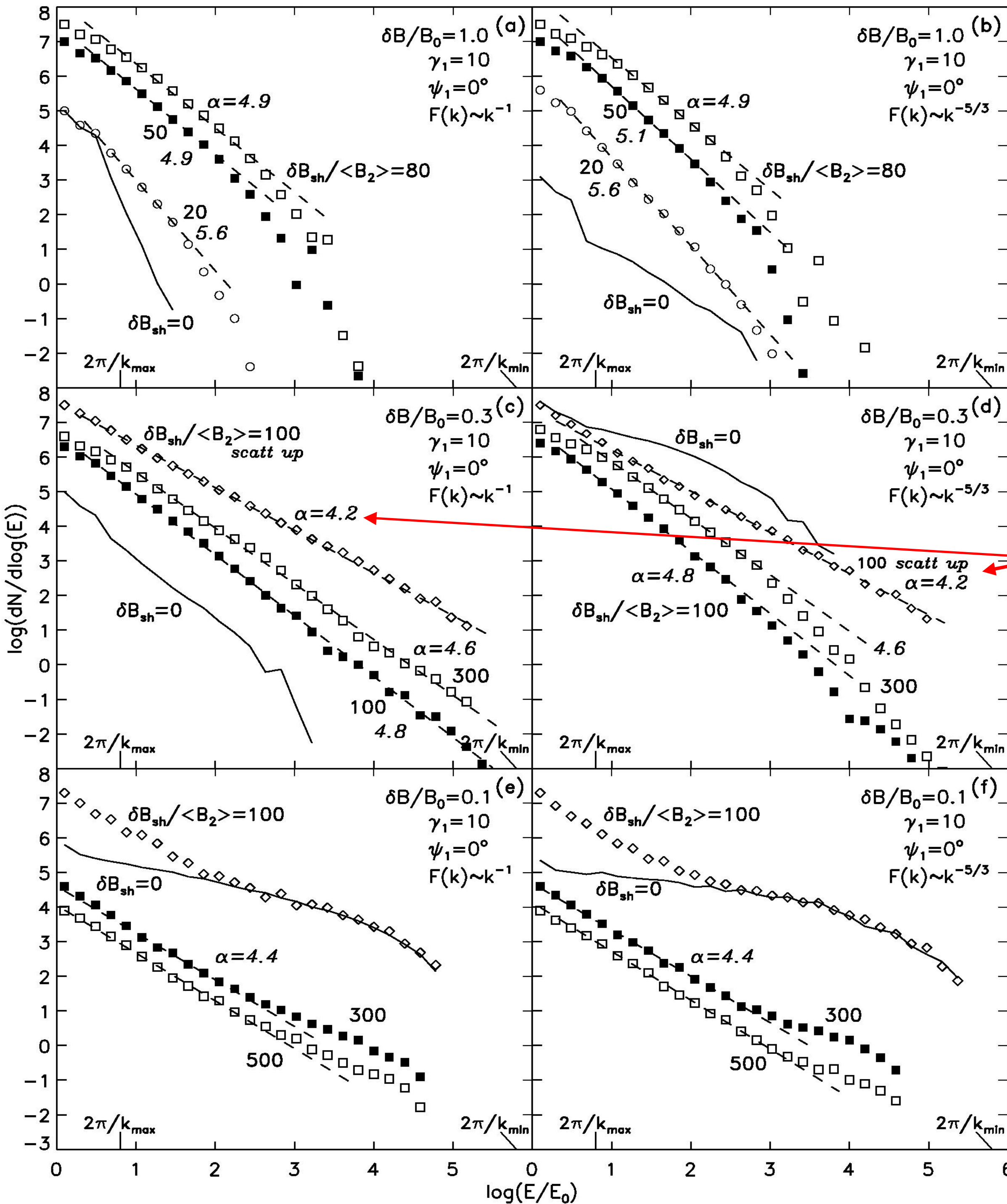
Short wave turbulence perturbs particle trajectory (pitch angle) $\Delta\Omega_{sh} \propto E^{-1/2}$ in a time interval given in the simulations as $\Delta t \propto E$, while the regular and long wave B-components in such time interval lead to $\Delta\Omega_{reg} \approx const$.



Thus the role of short wave turbulence in perturbing particle trajectories decreases with growing particle energy.



Parallel shock



universal spectral index