

# Monte Carlo simulations of the first-order Fermi process

*Jacek Niemiec*

*Department of Physics and Astronomy, Iowa State University, Ames, USA*

*Institute of Nuclear Physics PAN, Kraków, Poland*

Niemiec & Ostrowski (2004) ApJ **610**, 851

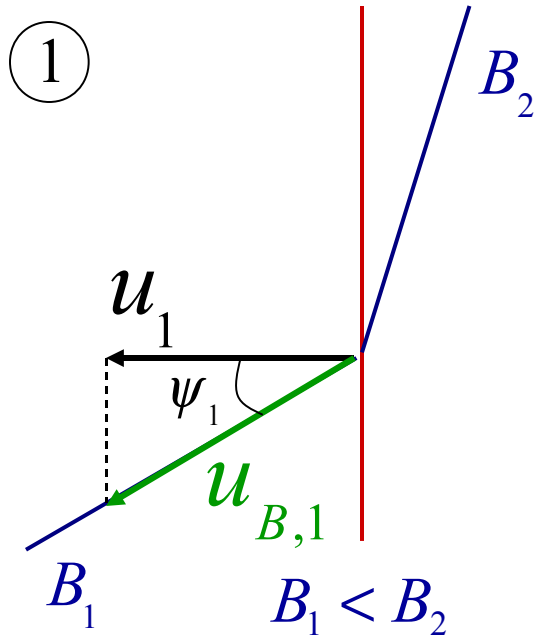
Niemiec & Ostrowski (2006) ApJ **641**, 984

Niemiec, Ostrowski & Pohl (2006) ApJ accepted (astro-ph/0603363)

# Collisionless shock wave front structure

## Test particle approach

$$r_g(E) \gg r_g^{ion}$$



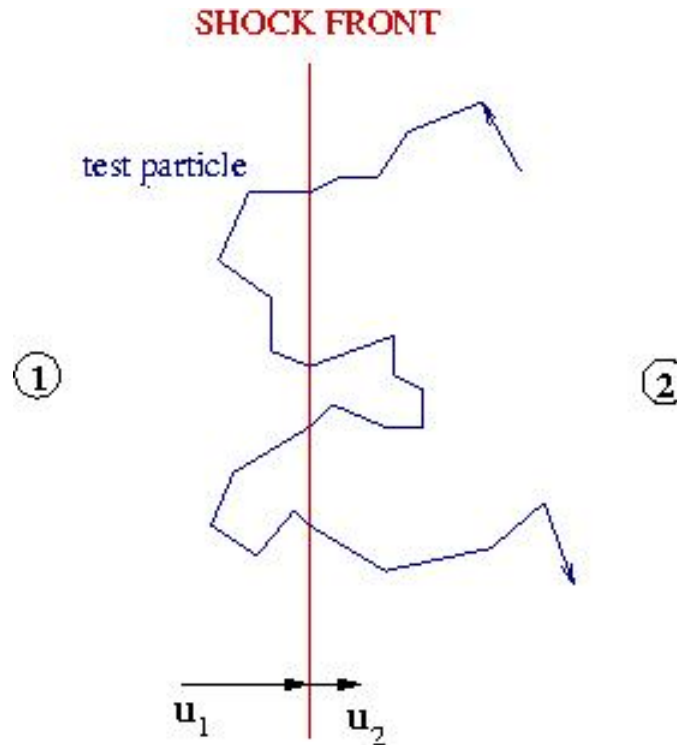
downstream compression of upstream plasma  
and frozen-in magnetic field determined from  
MHD jump conditions

$u_{B,1} < c$  subluminal  
 $u_{B,1} > c$  superluminal

$\Psi_1 = 0^\circ$  – parallel shock

$\Psi_1 \neq 0^\circ$  – oblique shock

# First-order Fermi process



energy gains  $\longleftrightarrow$  escape from the shock  
(diffusion, advection with plasma flow)



(power-law) particle spectrum

# First-order Fermi process

## Nonrelativistic shocks

(test particle approach, superthermal particles)

$$u_1 \ll v_p$$

- particle distribution function **isotropic**:  $f(p) \sim p^{-\alpha}$  ( $N(E) \sim E^{-\sigma}$ )

$$\alpha = \frac{3R}{R-1} \quad (\sigma = \alpha - 2)$$

$$R = \frac{u_1}{u_2} \text{ compression ratio}$$

high Mach numbers:  $R = 4$  and  $\alpha = 4$  ( $\sigma = 2$ )

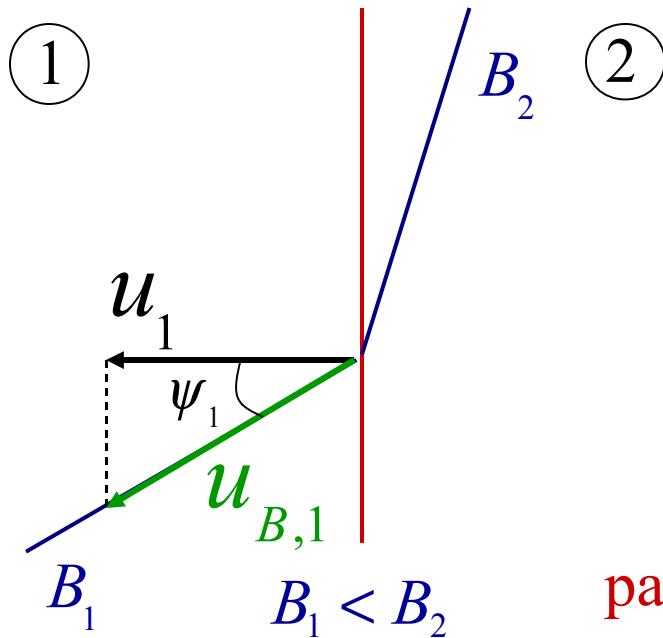
$$\alpha = 2\gamma_{\text{syn}} + 3 \approx 4.0 - 4.2$$

- particle spectrum independent of conditions near the shock

$$\psi_1, \delta B(k), F(k)$$

# First-order Fermi process

## Relativistic shocks



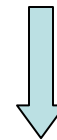
or

$$u_1 \sim c$$

$$u_{B,1} \sim c$$

$$V_p \approx c$$

particle anisotropy at shock:  $\Delta v \sim \frac{1}{\gamma_1}$



- acceleration process is very sensitive to the background conditions and details of particle-wave interactions, which are poorly known

# Numerical modeling of the turbulent magnetic field

- pitch-angle diffusion model

$\Delta\theta$ ,  $\Delta t_{scatt}$  scattering parameters

- ``realistic`` magnetic field – integration of particle equations of motion

Studies of the I-order Fermi process – *M. Ostrowski's talk* –  
apply **simplified models** for the turbulent MHD medium near the shock.

In particular they neglect:

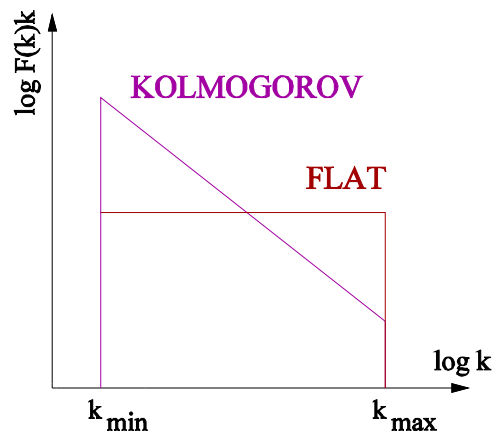
- presence of long wave perturbations (mean field)
- continuity of magnetic field across the shock –  
correlations in particle motion on both sides of the shock.

# “Realistic” magnetic field structure

Niemiec & Ostrowski (2004, 2006) & Pohl (2006)

Upstream magnetic field:

- $\vec{B} = \vec{B}_0 + \delta\vec{B}$  uniform component + finite-amplitude perturbations (superposition of sinusoidal static waves – no Fermi II acceleration)
- perturbations in the wide wavevector range



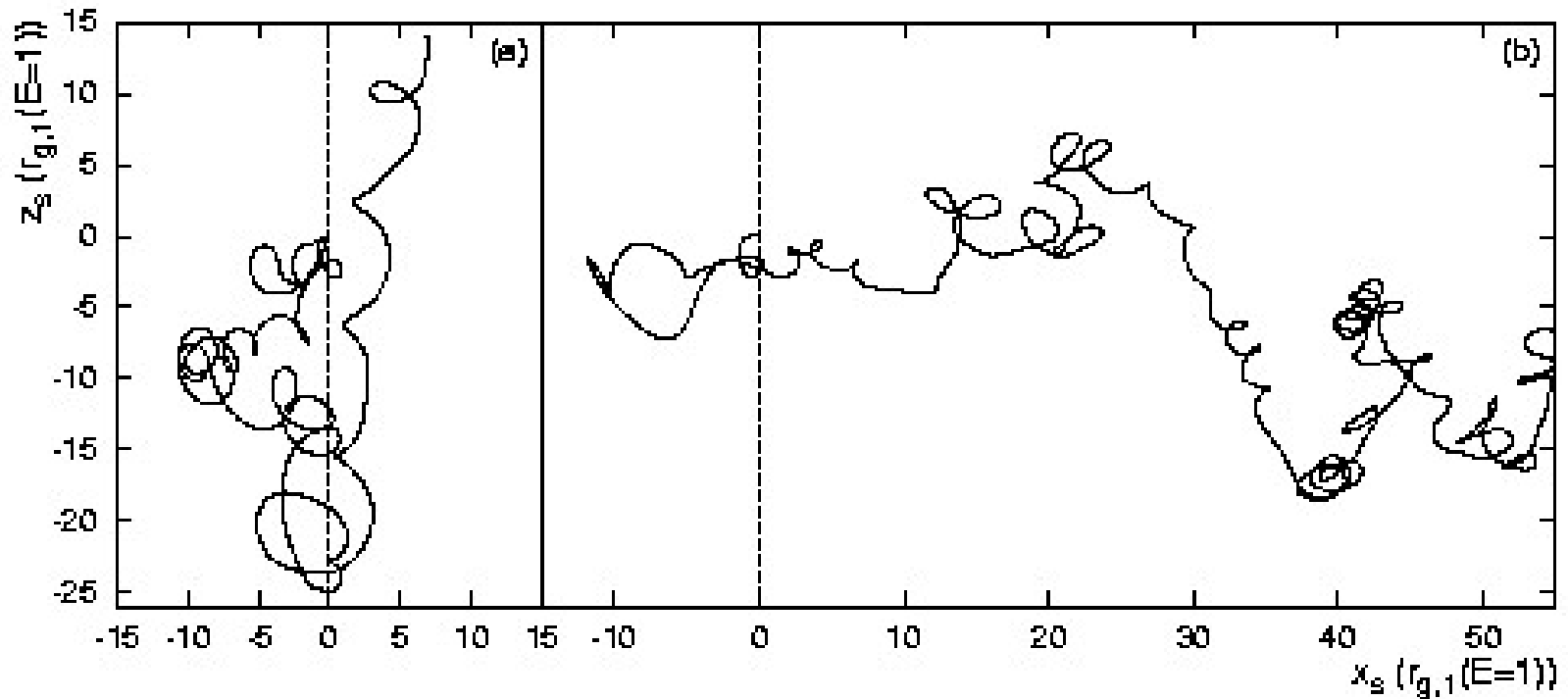
$$k_{\max} / k_{\min} = 10^5$$

- downstream structure: compressed upstream field  
→ continuity of magnetic field lines across the shock

# “Realistic” magnetic field structure

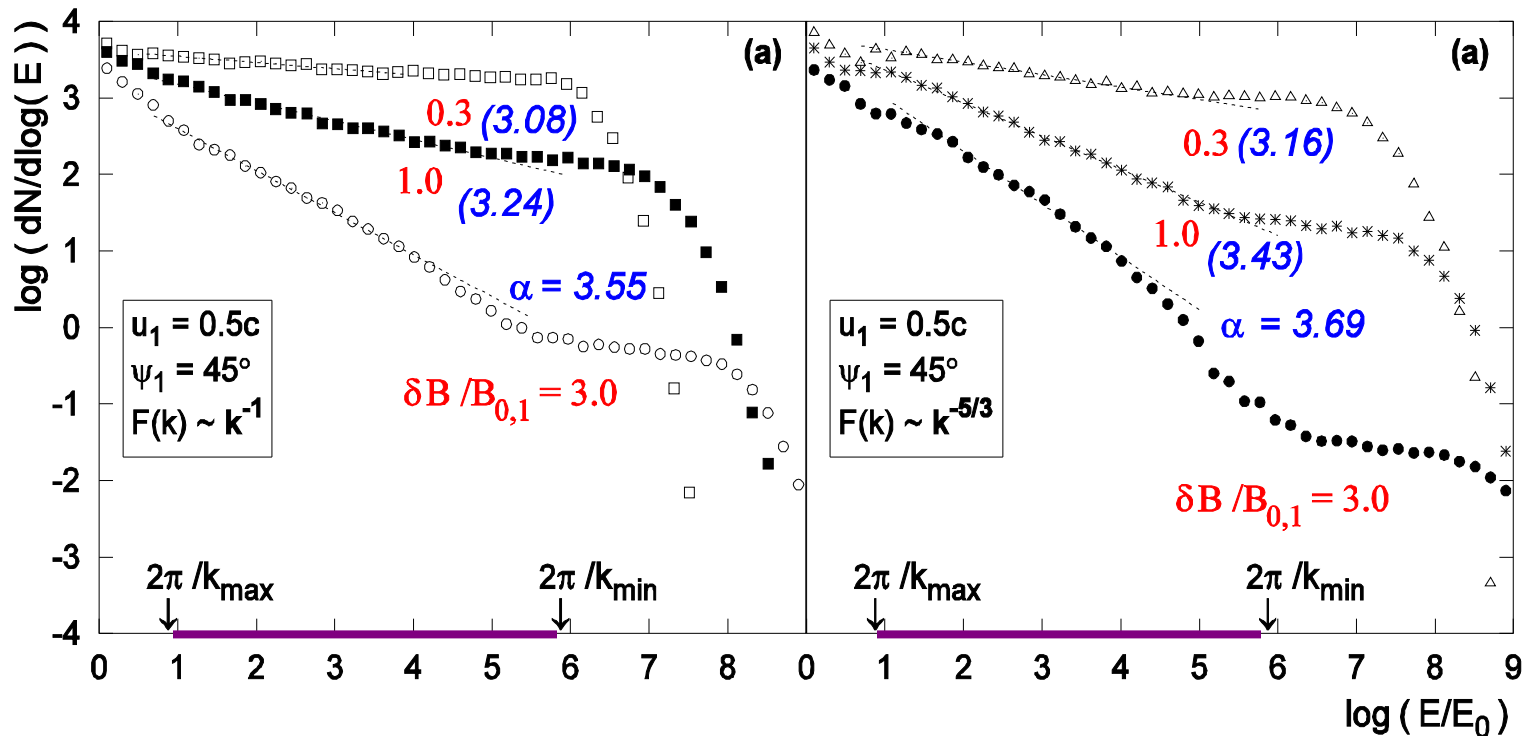
Niemiec & Ostrowski (2004, 2006) & Pohl (2006)

- integrate particle equations of motion in the turbulent magnetic field



# Subluminal shocks Niemiec & Ostrowski (2004)

mildly relativistic shock velocity ( $\gamma_1=1.2$ ,  $u_{B,1}=0.71c$ )

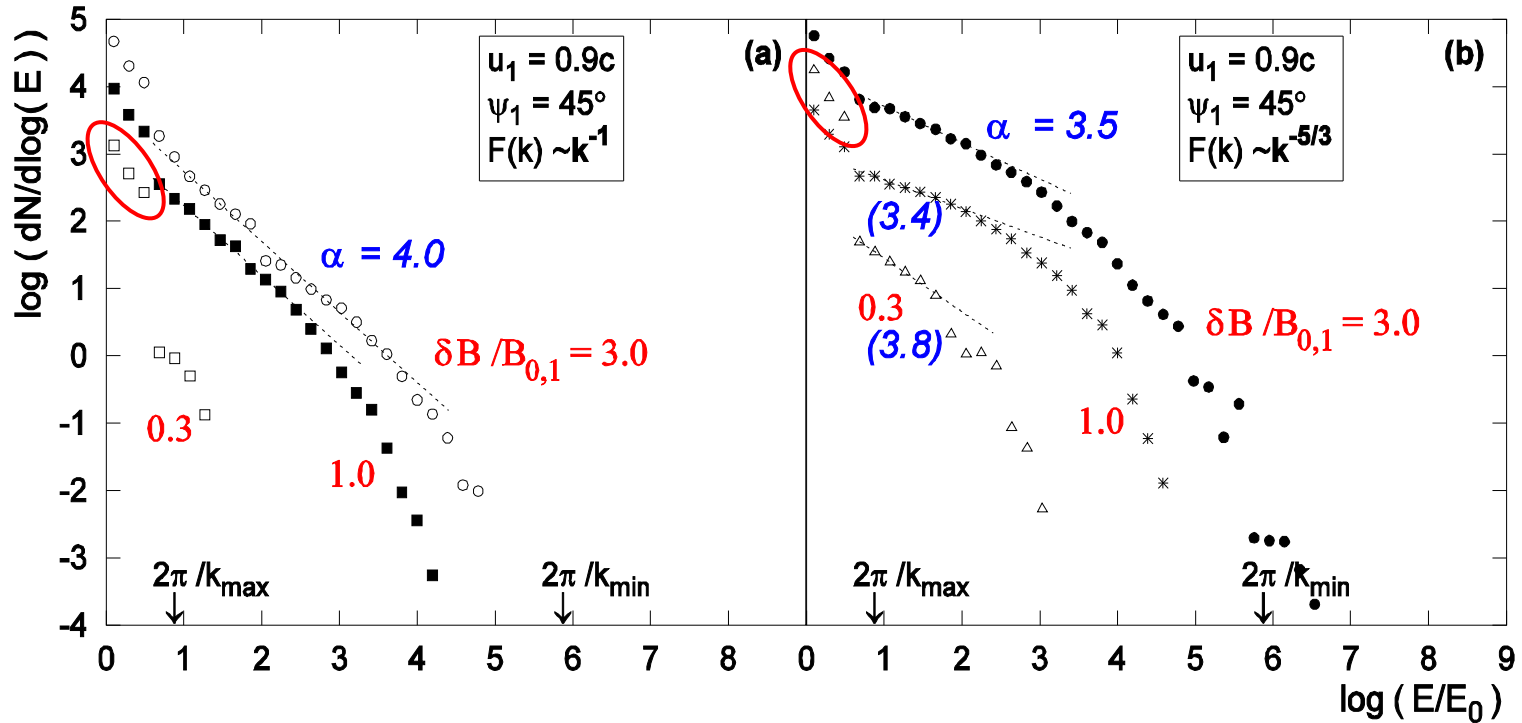


- non power-law spectrum in the full energy range  
(due to limited dynamic range of magnetic field perturbations – scattering conditions vary with particle energy)
- cut-offs due to lack of magnetic turbulence at relevant scales

$$k_{res} \approx 2\pi / r_g(E)$$

# Superluminal shocks

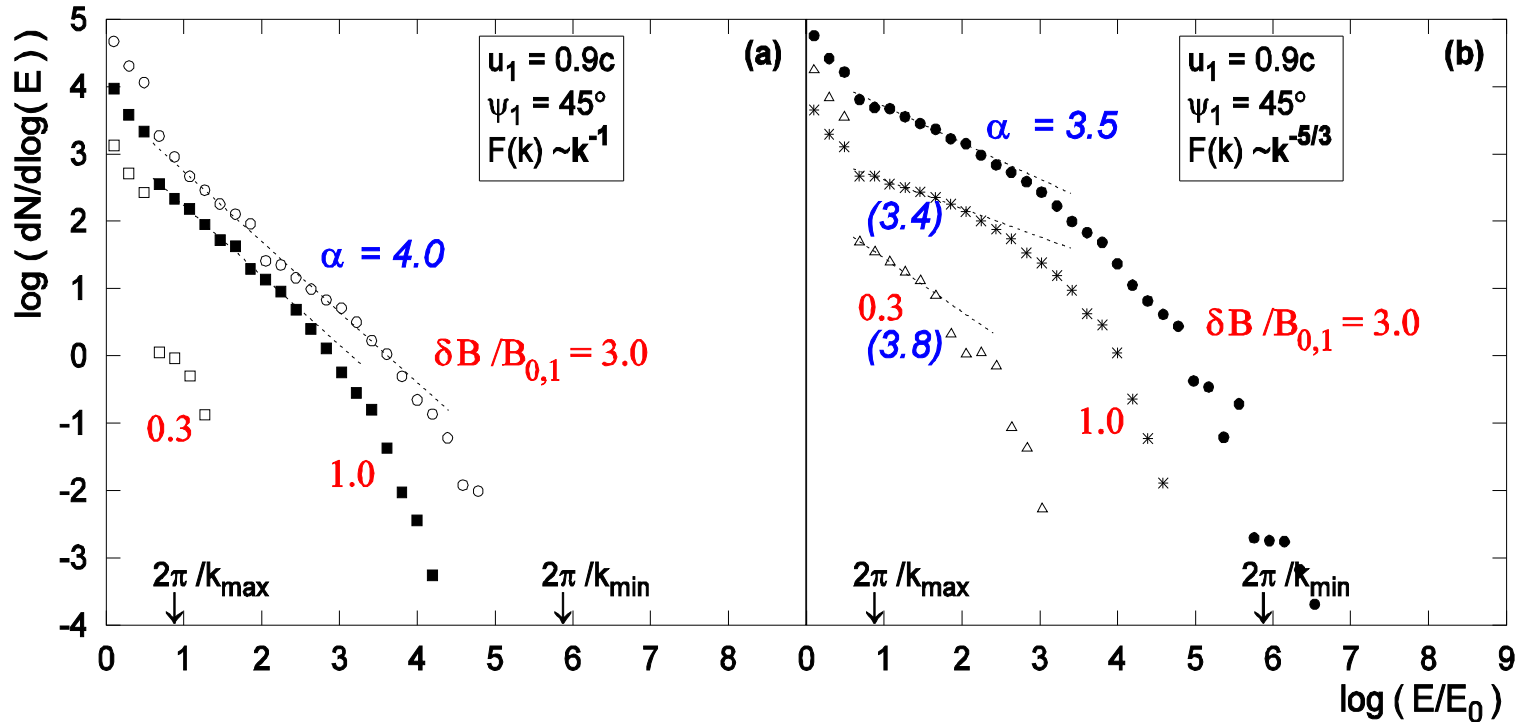
mildly relativistic shock velocity ( $\gamma_I=2.3$ ,  $u_{B,I}=1.27c$ )



- “superadiabatic” compression of injected particles for small turbulence amplitude  $\delta B/B_{0,1}=0.3$  (Begelman & Kirk, 1990)

# Superluminal shocks

mildly relativistic shock velocity ( $\gamma_I=2.3$ ,  $u_{B,I}=1.27c$ )



- "superadiabatic" compression of injected particles for small turbulence amplitude  $\delta B/B_{0,1}=0.3$  (Begelman & Kirk, 1990)
- power-law sections in the spectra form at larger perturbation amplitudes (due to locally subluminal field configurations and respective magnetic field compressions formed at the shock by long-wave perturbations)
- steepening and cut-off occur in the resonance energy range

Bednarz & Ostrowski (1998)

## Ultrarelativistic (high- $\gamma$ ) shocks

- almost always **superluminal** conditions
- **asymptotic spectral index ( $\gamma_1 \gg 1$ )**

$$f(p) \sim p^{-\alpha} \quad (N(E) \sim E^{-\sigma})$$

$$\alpha = 4.2 \quad (\sigma = 2.2)$$

Achterberg, Bednarz, Gallant, Guthmann  
Kirk, Ostrowski, Pelletier, Vietri, et al.

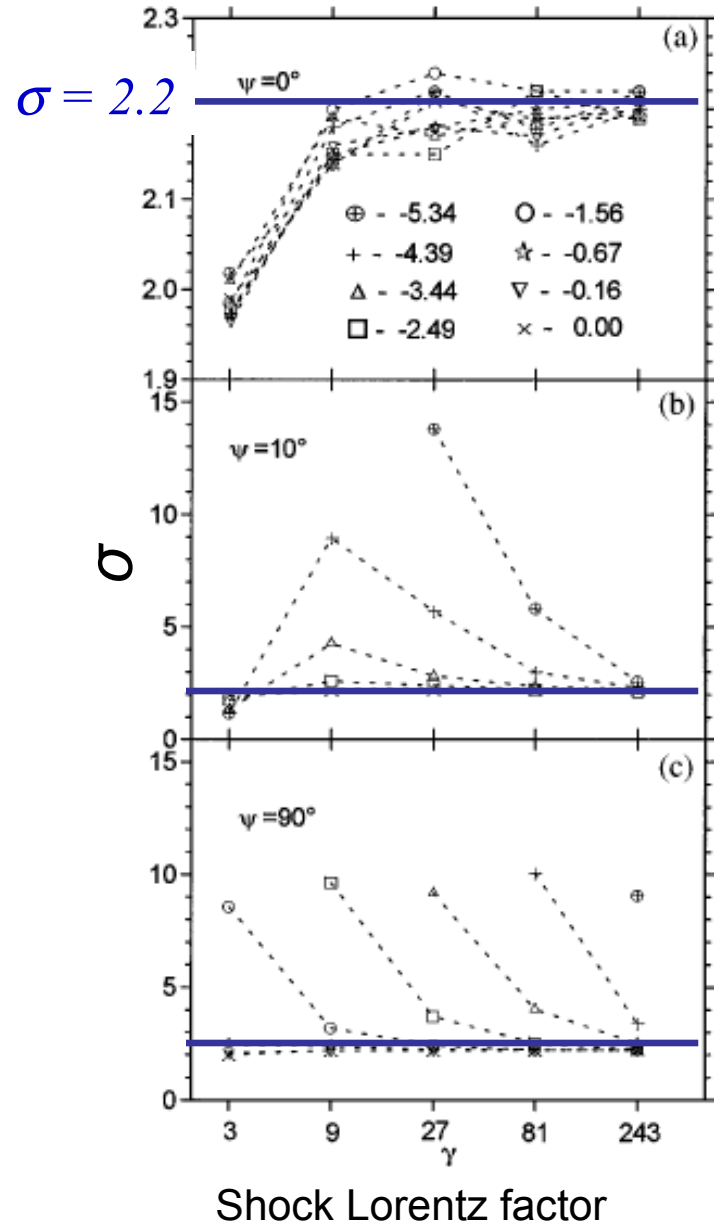
For oblique shocks:

- **requires strong turbulence downstream**

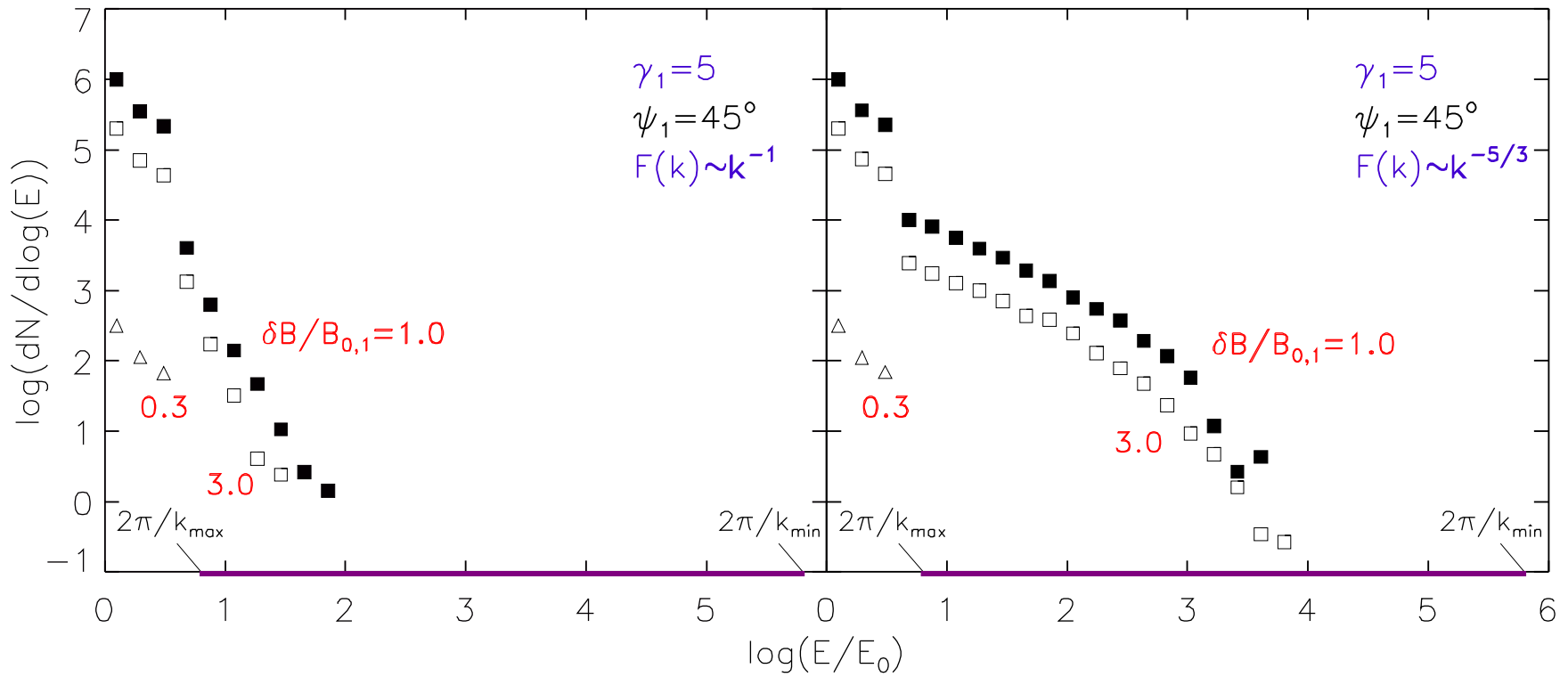
Ostrowski & Bednarz (2002)

- for medium turbulence amplitude and  $\gamma_1 \sim 10-100$  **much steeper particle spectra**

Bednarz & Ostrowski (1998)

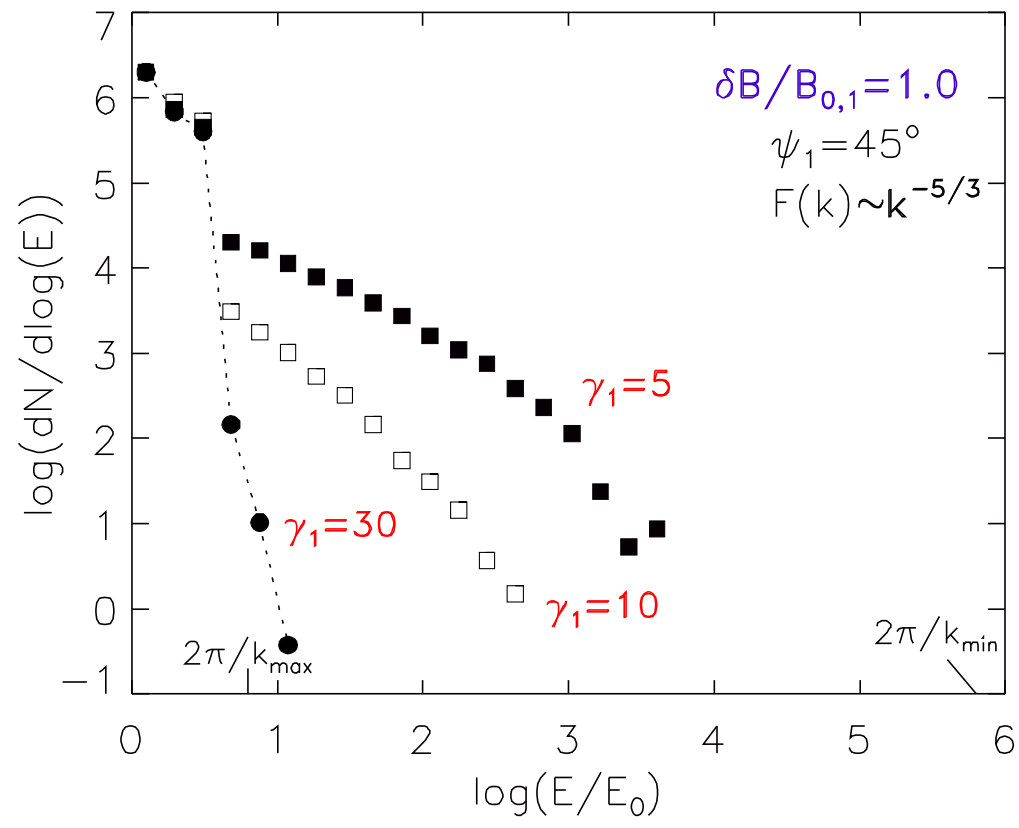


# Superluminal high- $\gamma$ shock waves Niemiec & Ostrowski (2006)



- “superadiabatic” particle compression is the main acceleration process
- small fraction of particles forms energetic spectral tails for large-amplitude magnetic field perturbations
  - strong dependence on  $F(k)$
  - non-power-law spectral form
- cut-offs in the spectra occur within resonance energy range

For all configurations  $u_{B,I} \sim 1.4c$



- the cut-off energy decreases with growing shock Lorentz factor  $\gamma_1$


# Particle transport near a ultrarelativistic shock wave

- downstream magnetic field structure

$$B_{\parallel,2} = B_{\parallel,1}$$

$$B_{\perp,2} = r B_{\perp,1} \text{ compression of tangential field components}$$

compression factor:  $r = R \gamma_1/\gamma_2$  ( $R \approx 3$ )



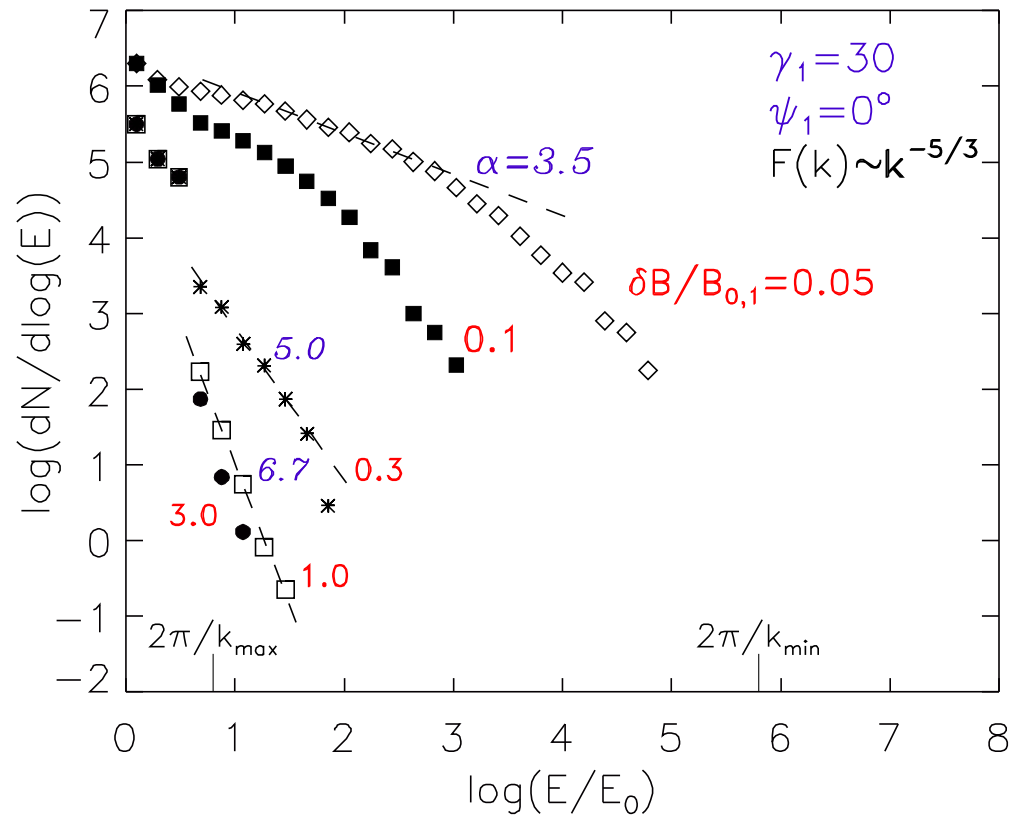
highly anisotropic downstream particle diffusion:

diffusion coefficient along shock normal  $K_{\parallel} \ll K_{\perp}$

Downstream magnetic field structure becomes effectively 2D, perpendicular to the shock normal. Due to inefficient cross-field diffusion, advection of particles with the general downstream flow leads to high particle escape rates, which results in steep particle spectra.

- large-amplitude long-wave perturbations can form locally subluminal conditions at the shock leading to the more efficient particle acceleration (Kolmogorov turbulence)

# Parallel high- $\gamma$ shock waves

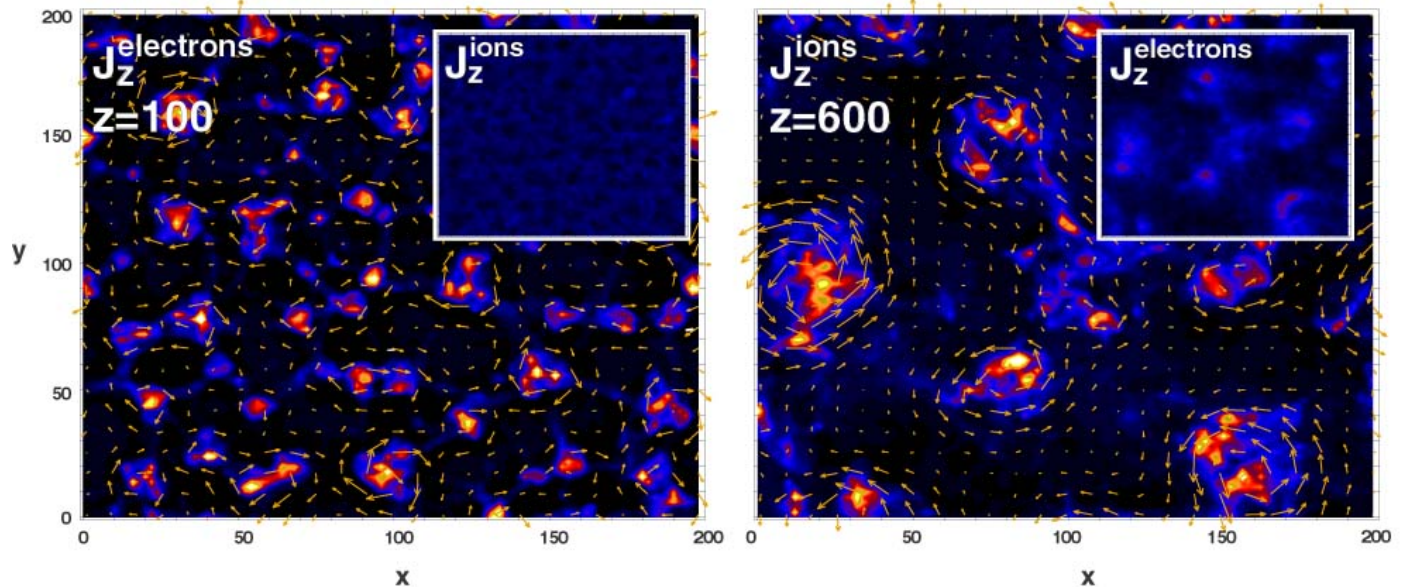


- processes of particle acceleration are inefficient for larger amplitudes of magnetic field perturbations:
  - compression produces effectively perpendicular shock configuration and features analogous to those observed in superluminal shocks are recovered
- spectral indices depart from  $\alpha = 4.2$  value

- turbulent conditions near the shock which are consistent with the shock jump conditions can lead to substantial modifications of the acceleration picture with respect to the (simplified) models producing wide-range power-law spectra, often with the „universal“ spectral index
- ultrarelativistic shocks are inefficient in high-energy particle production via the first-order Fermi mechanism (unless additional source of turbulence exists and is able to decorrelate particle motion in the structured field near the shock ?)

# Shock generated magnetic field turbulence

PIC simulations by Frederiksen et al. 2004

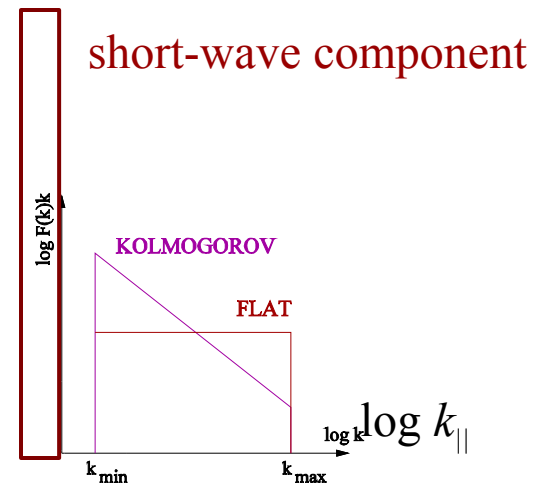


- relativistic shock generates **strong small-scale** turbulent magnetic field **downstream** by relativistic two-stream instability (Medvedev & Loeb 1999; Silva et al. 2003; Nishikawa et al. 2003, 2005; Frederiksen et al. 2004) *talk by A. Spitkovsky*
- short-wave magnetic field structure is 2D, transversal to the shock normal, but in the long-time nonlinear regime the perturbations should transform into **isotropic 3D turbulence**.
- small-scale large-amplitude fluctuations can possibly provide efficient particle scattering, which may lead to **decorrelation between particle motion and the compressed field downstream of the shock**

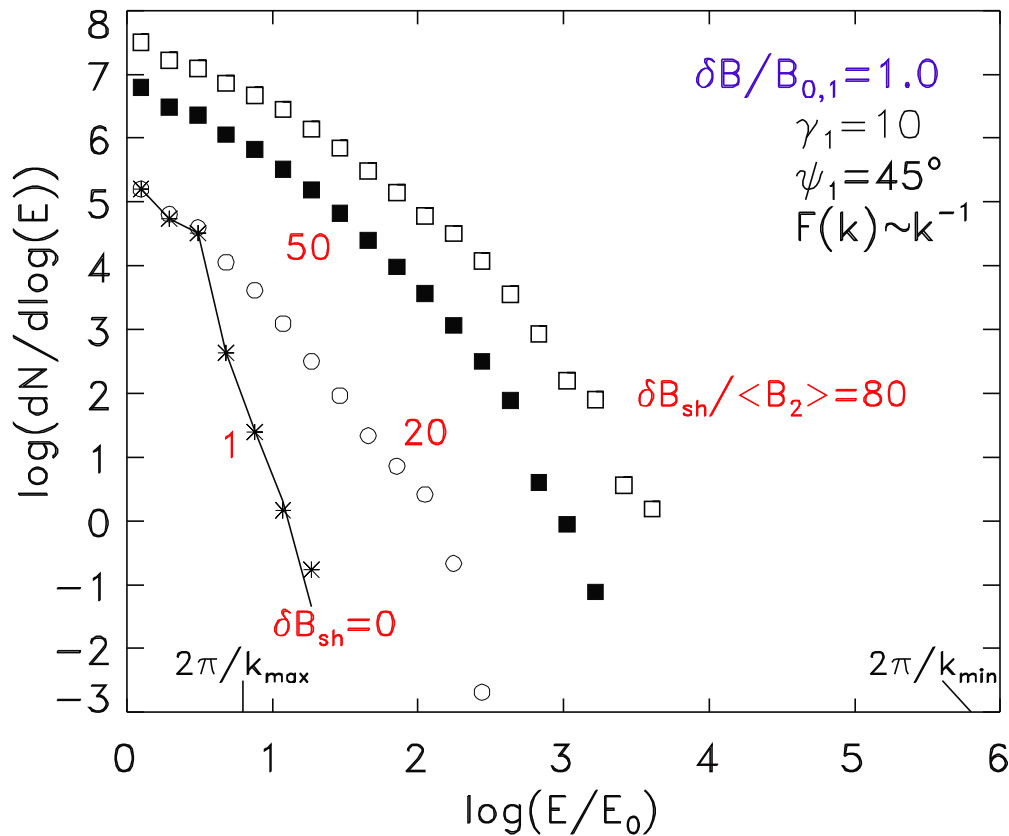
# Modeling short-wave (Weibel-like) turbulence downstream

Niemiec, Ostrowski & Pohl (2006)

- analytic model for **3D Weibel-like turbulent component downstream of the shock** (superposition of large-amplitude sinusoidal static waves with flat power spectrum in the wavevector range  $(10 k_{max} r, 100 k_{max} r)$ , where  $r=R\gamma_1/\gamma_2$ )
- short-wave turbulence imposed on the compressed downstream field
- hybrid method used: exact particle trajectories in long-wave compressed field and small-angle scattering ( $\Delta\Omega$ ) in short-wave component

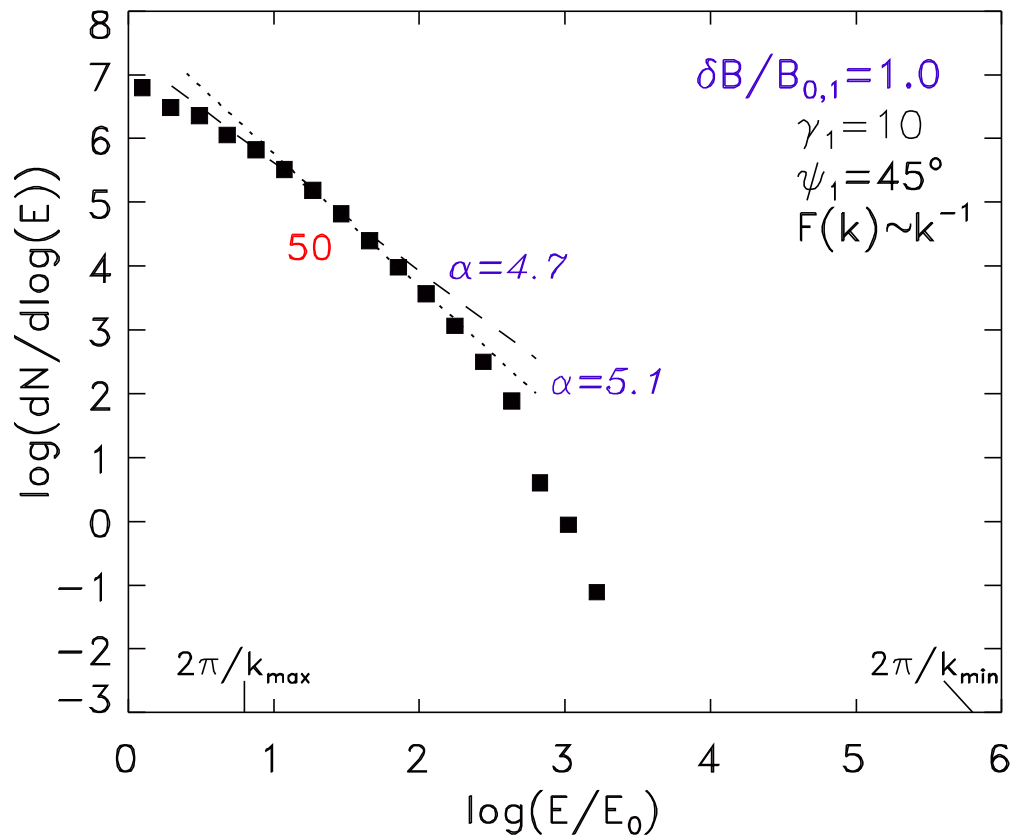


- how the existence of short-wave turbulence with various amplitudes affects particle spectra formation in high- $\gamma$  shocks presented above?
- what are conditions allowing for a “universal” spectral index?



## Superluminal shocks with short-wave perturbations downstream

- for energy densities in **short-wave** turbulence much larger than the energy density in the compressed downstream magnetic field energetic particle spectral tails are formed
  - non-power-law spectral form (convex spectra)
  - similar spectral shape for different  $\delta B / B_{0,1}$ ,  $F(k)$  (and  $\gamma_1$ )

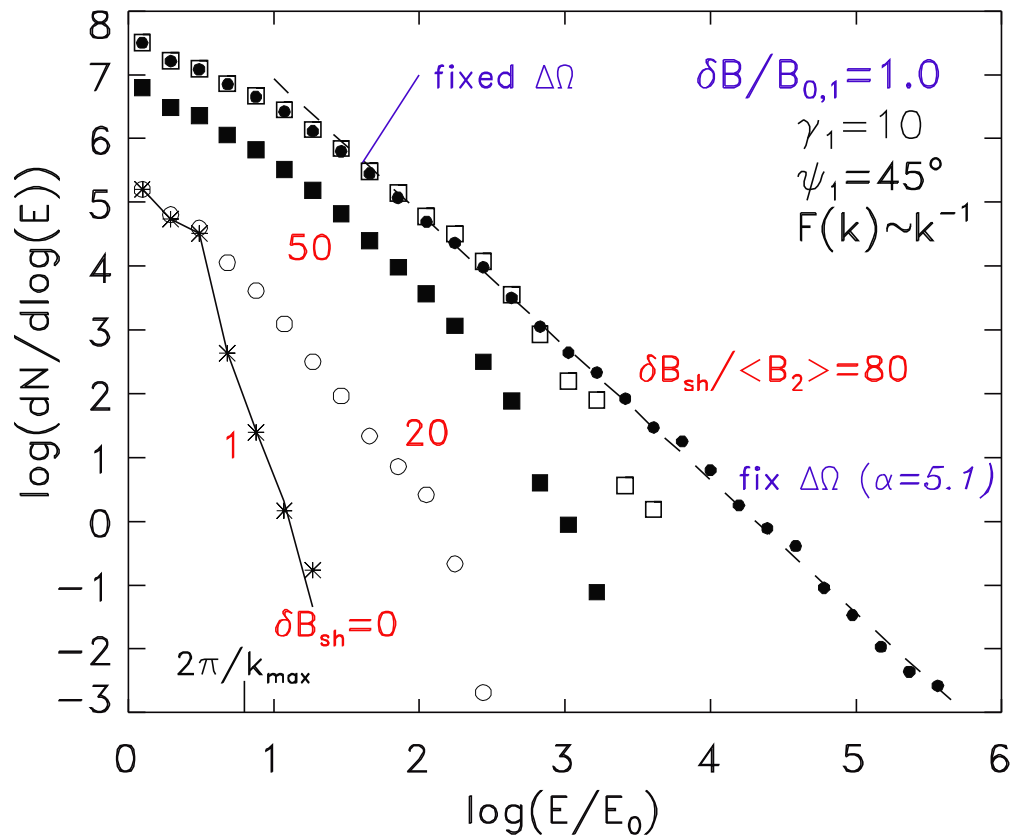


## Superluminal shocks with short-wave perturbations downstream

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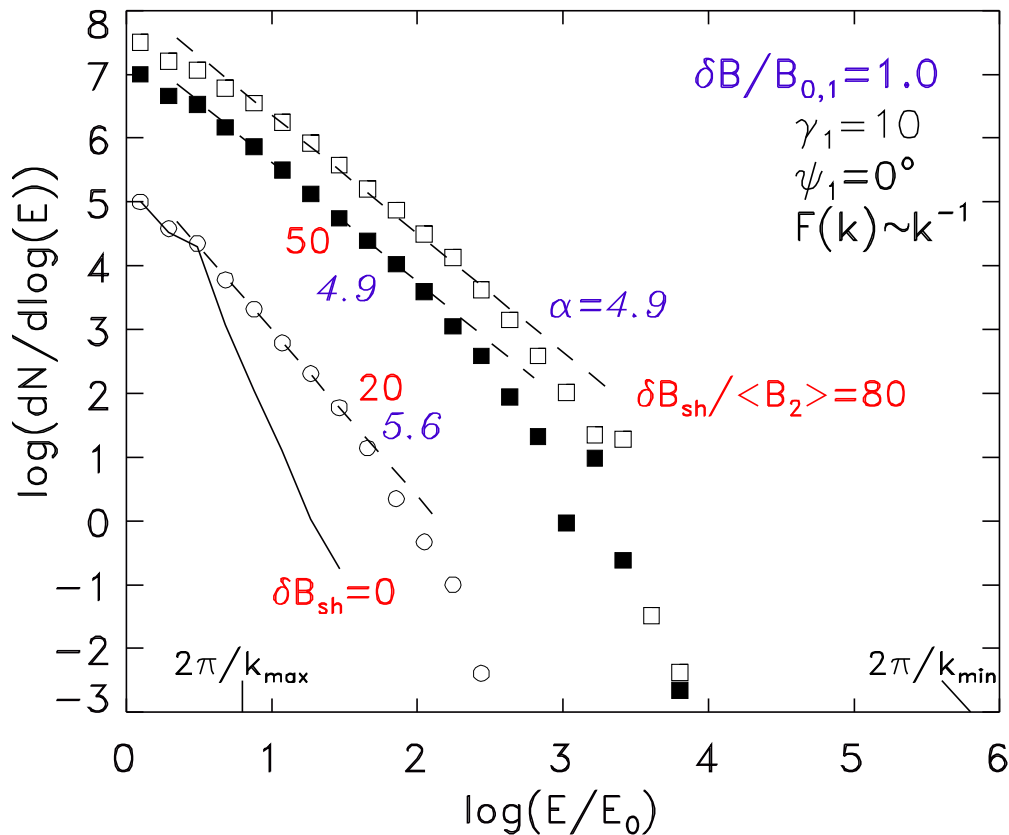
non-power-law spectral form (convex spectra)

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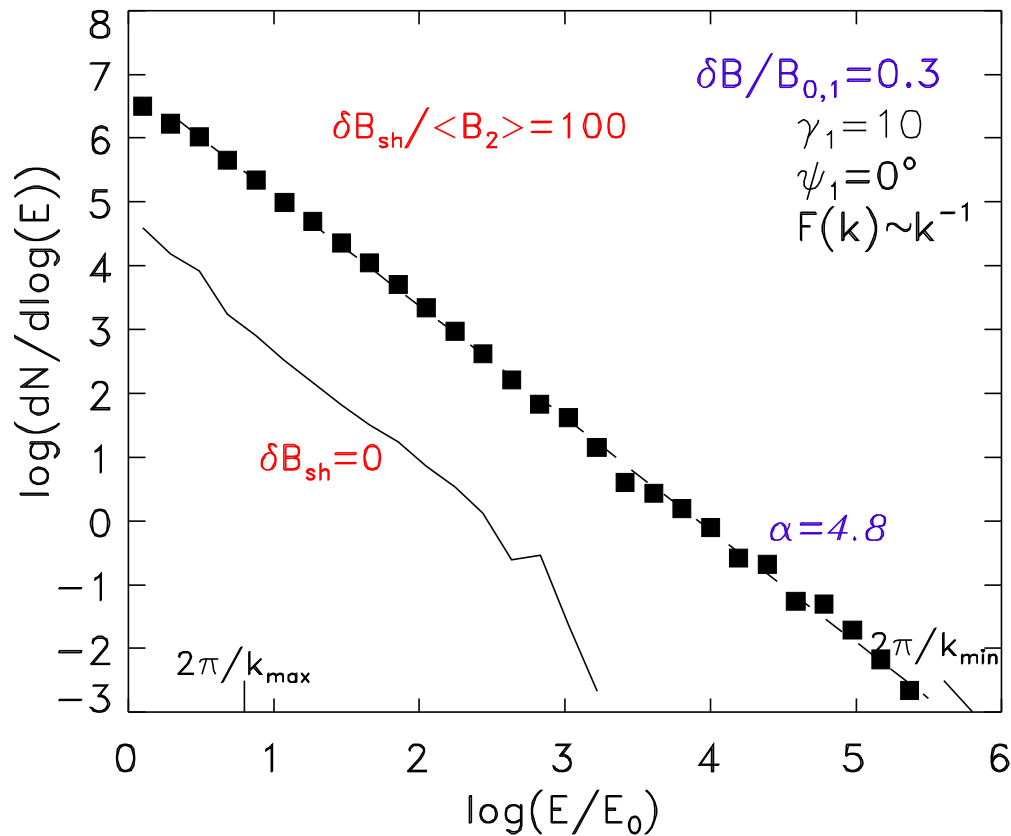
## Superluminal shocks with short-wave perturbations downstream

- for energy densities in short-wave turbulence much larger than the energy density in the compressed downstream magnetic field energetic particle spectral tails are formed
  - non-power-law spectral form (convex spectra)
  - similar spectral shape for different  $\delta B/B_{0,1}$ ,  $F(k)$  (and  $\gamma_1$ )
- efficiency of particle scattering (scatt. angle  $\Delta\Omega$ ) due to small-scale perturbations decreases with particle energy:  $\delta B_{sh}/\langle B_2 \rangle$  must be extremely large to decorrelate motion of high-energy particles from the compressed field downstream of the shock



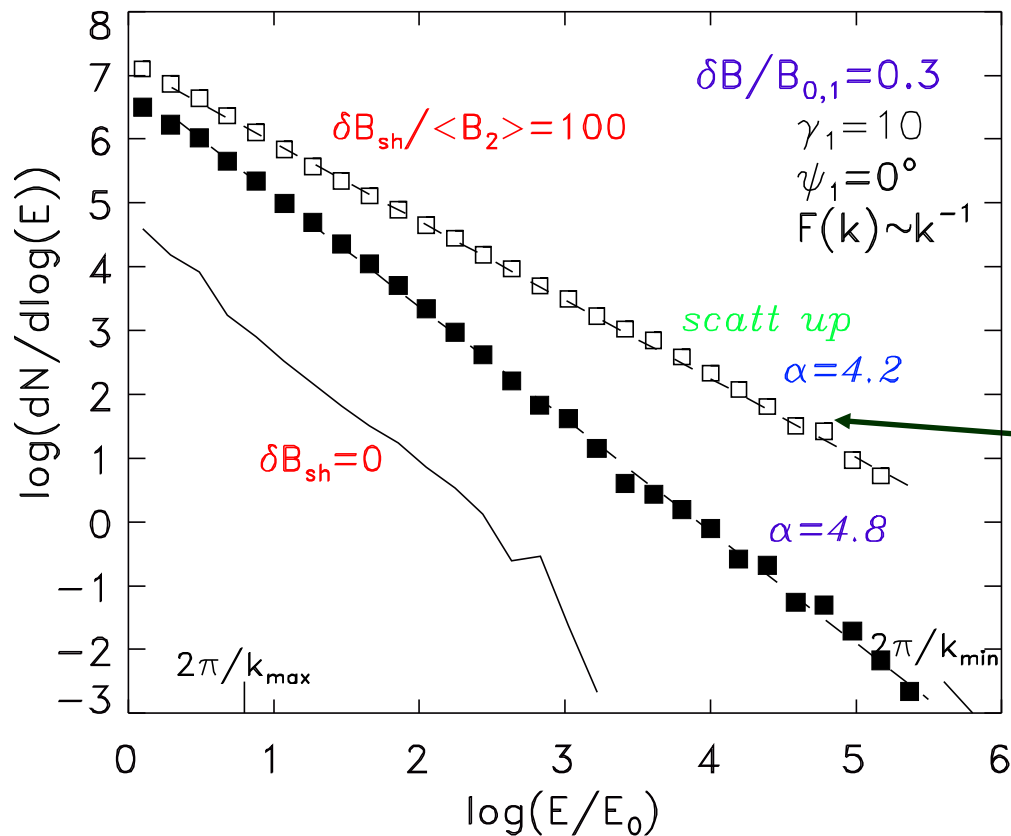
Parallel shocks with short-wave perturbations downstream

- for larger amplitudes of the compressed field ( $\delta B / B_{0,1}$ ) spectra qualitatively similar to those formed at superluminal shocks (large-amplitude long-wave perturbations provide locally superluminal conditions that lead to spectral cut-offs when particle scattering in short-wave turbulence decreases with particle energy)
- particle spectral index deviates from the “universal” value  $\alpha = 4.2$  even in the limit of  $\delta B_{sh} / \langle B_2 \rangle \gg 1$



Parallel shocks with short-wave perturbations downstream

- for smaller amplitudes of the long-wave field, scattering on the short-wave turbulence can dominate up to the highest energies – wide-energy power-law spectra
- particle spectra steeper than the expected “universal” spectrum  $\alpha=4.2$



Parallel shocks with short-wave perturbations downstream

short-wave component both downstream and upstream of the shock removes the influence of long-wave magnetic field perturbations

- for smaller amplitudes of the long-wave field, scattering on the short-wave turbulence can dominate up to the highest energies – wide-energy power-law spectra
- particle spectra steeper than the expected “universal” spectrum  $\alpha = 4.2$
- (long-wave) magnetic field structure upstream of the shock influences particle acceleration processes; only in the model with short-wave component both downstream and upstream, particle spectrum with the “universal” spectral index forms

# Concluding remarks

- I-order Fermi process at high- $\gamma$  shocks is inefficient in particle acceleration to high energies
  - particle spectra substantially depend on the form of the magnetic turbulence near the shock; spectral indices depart significantly from  $\alpha=4.2$  value
  - for the same background conditions, shocks with larger  $\gamma$  produce steeper spectra with lower cut-off energies
  - “universal” spectral index requires special conditions (strong particle scattering downstream and upstream of the shock)

The role of the I-order Fermi process in explaining the observational properties of astrophysical sources hosting relativistic shocks requires serious reanalysis

- UHECRs production, hot spots’ and GRB afterglows’ spectra?
  - II-order Fermi process (Virtanen & Vainio 2005)
  - other acceleration processes (e.g. Hoshino et. al 1992, Hededal et al. 2004)

Further progress requires:

- observational results
- numerical simulations (PIC simulations (magnetic field turbulence generation & particle injection) – background conditions for Monte Carlo methods)