Monte Carlo simulations of the first-order Fermi process

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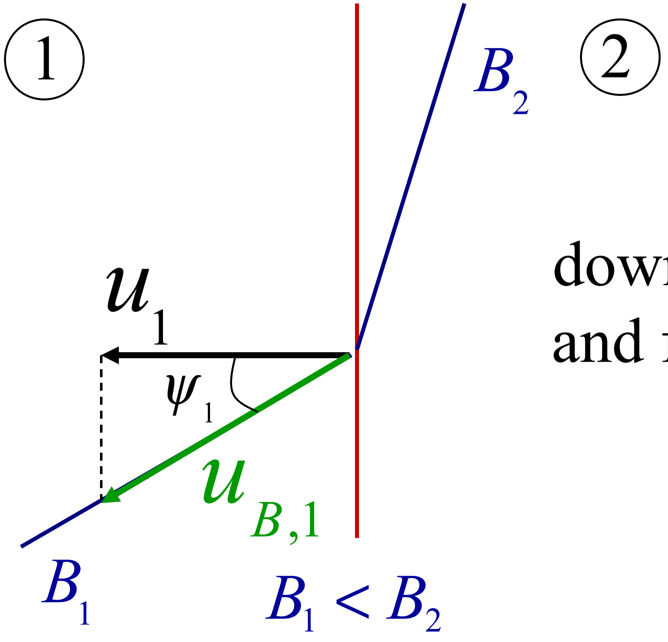
Niemiec & Ostrowski (2004) ApJ **610**, 851
Niemiec & Ostrowski (2006) ApJ **641**, 984
Niemiec, Ostrowski & Pohl (2006) ApJ accepted (astro-ph/0603363)

Collisionless shock wave front structure

Test particle approach

$r_g(E) » r_g^{ion}$



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

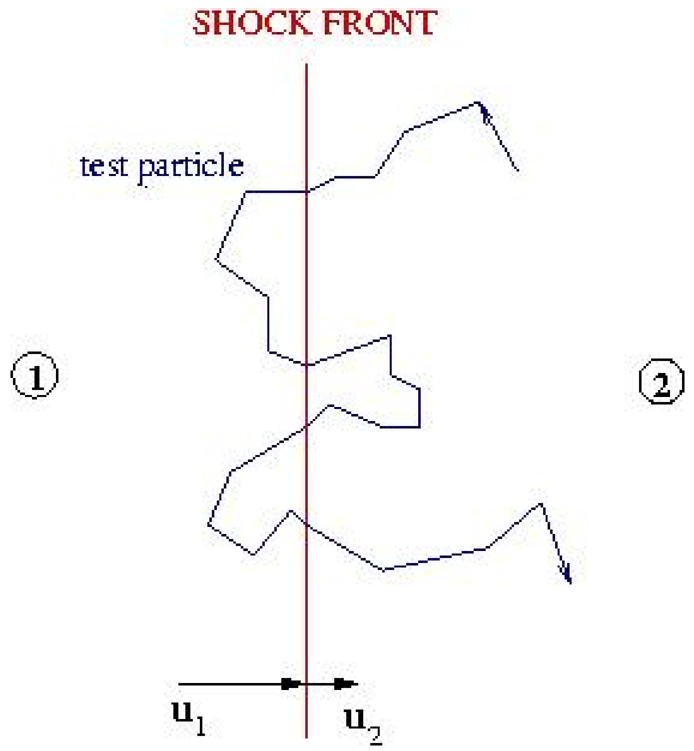
$u_{B,1} < c$ subluminal

$u_{B,1} > c$ superluminal

$\Psi_1 = 0^o$ – parallel shock

$\Psi_1 \neq 0^o$ – oblique shock

First-order Fermi process



energy gains ⟺ escape from the shock

(diffusion, advection with plasma flow)

⬇

(power-law) particle spectrum

First-order Fermi process

Nonrelativistic shocks

(test particle approach, superthermal particles)

$$u_1 << \mathrm{v}_p$$

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

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

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

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

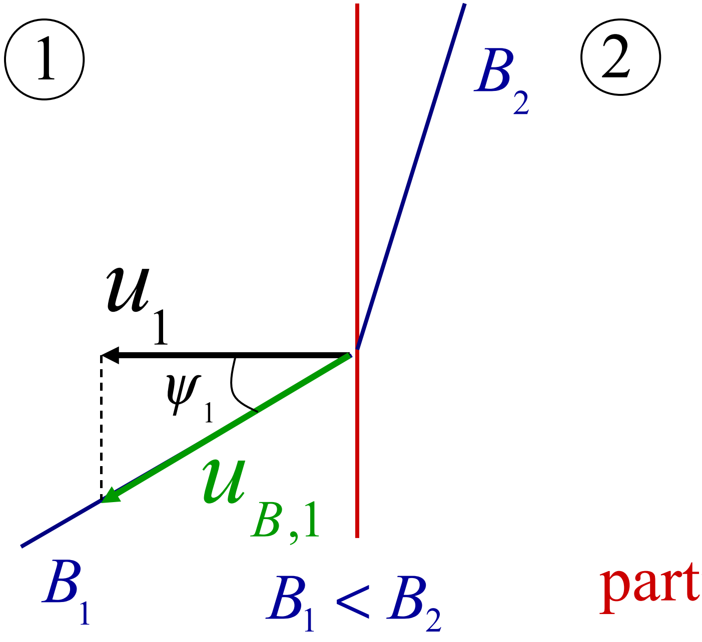
$$\alpha = 2\gamma_{\mathrm{syn}} + 3 \approx 4.0 - 4.2$$

- particle spectrum independent of conditions near the shock

ψ_1, $\delta B(k)$, $F(k)$

First-order Fermi process

Relativistic shocks



$u_1 \sim c$

or

$u_{B,1} \sim c$

$\mathrm{v_p} \approx c$

particle anisotropy at shock: $\Delta\vartheta \sim {}^{1}\!/_{\gamma_1}$

⇓

- 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.

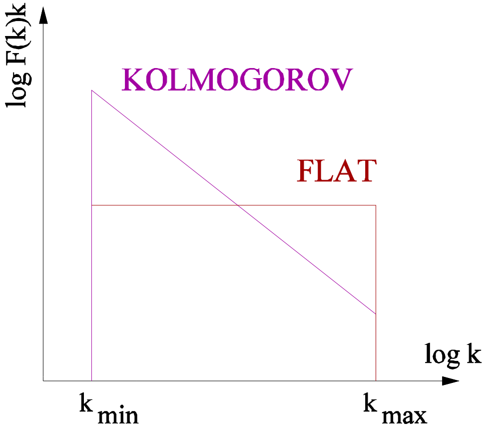
``Realistic´´ magnetic field structure

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



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

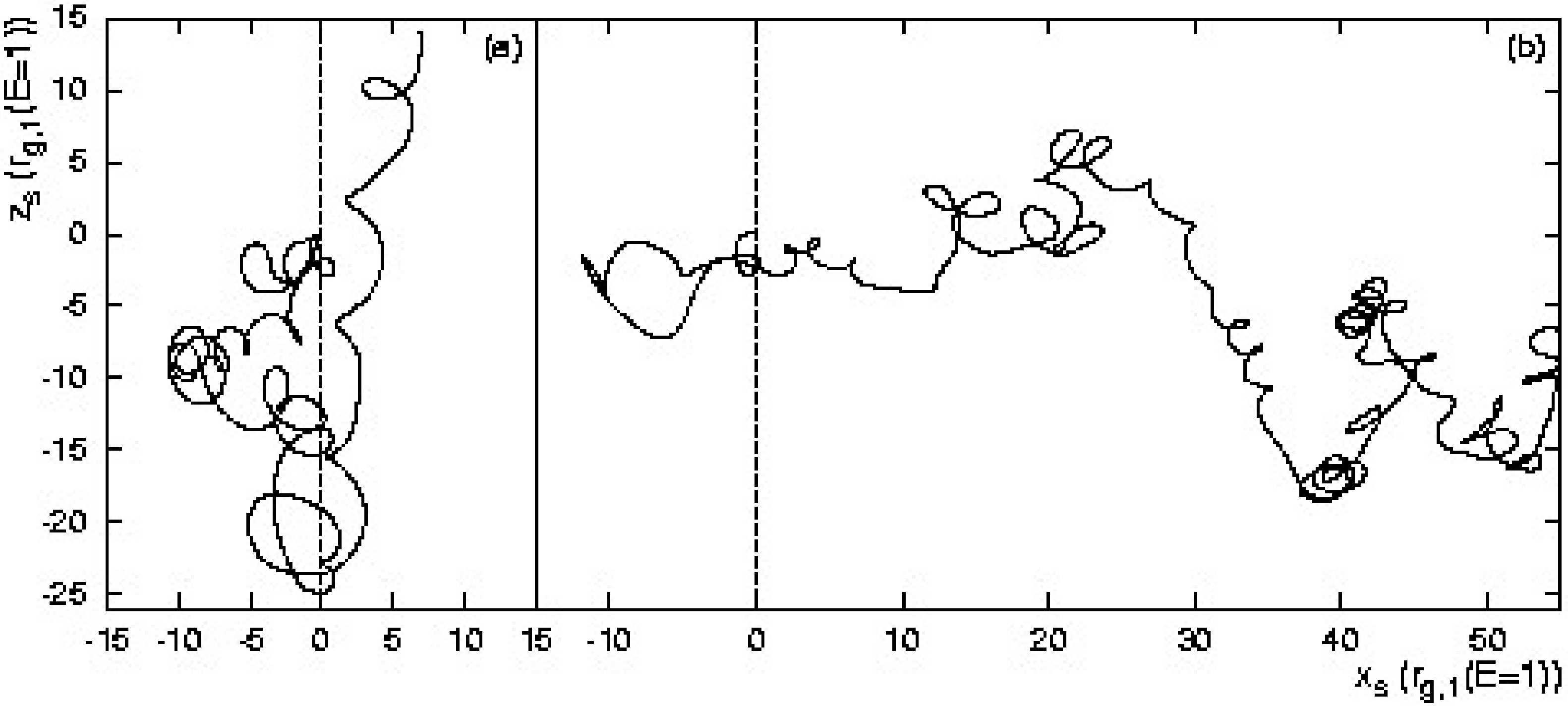
- downstream structure: compressed upstream field

⇨ continuity of magnetic field lines across the shock

``Realistic´´ magnetic field structure

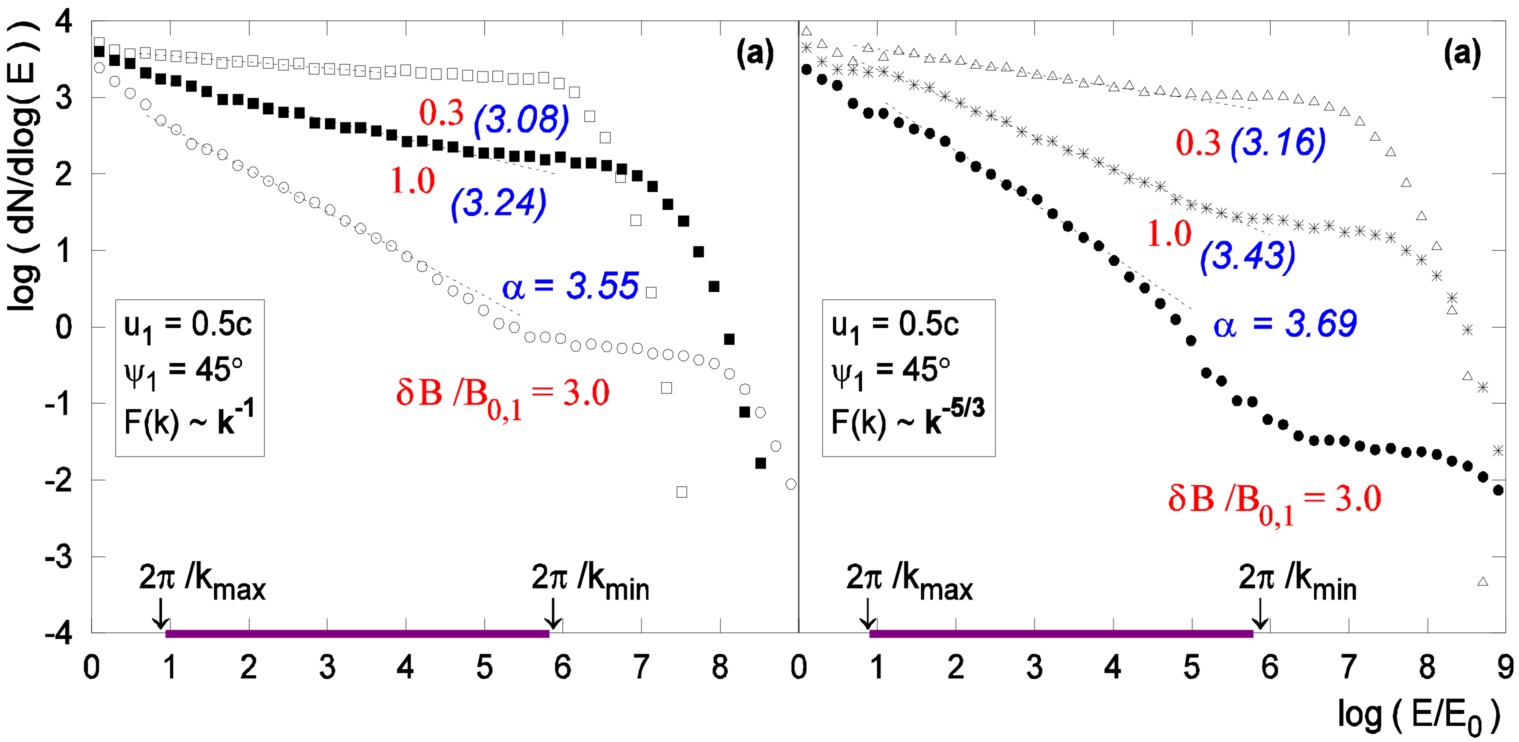
Niemiec & Ostrowski (2004, 2006) & Pohl (2006)

- 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

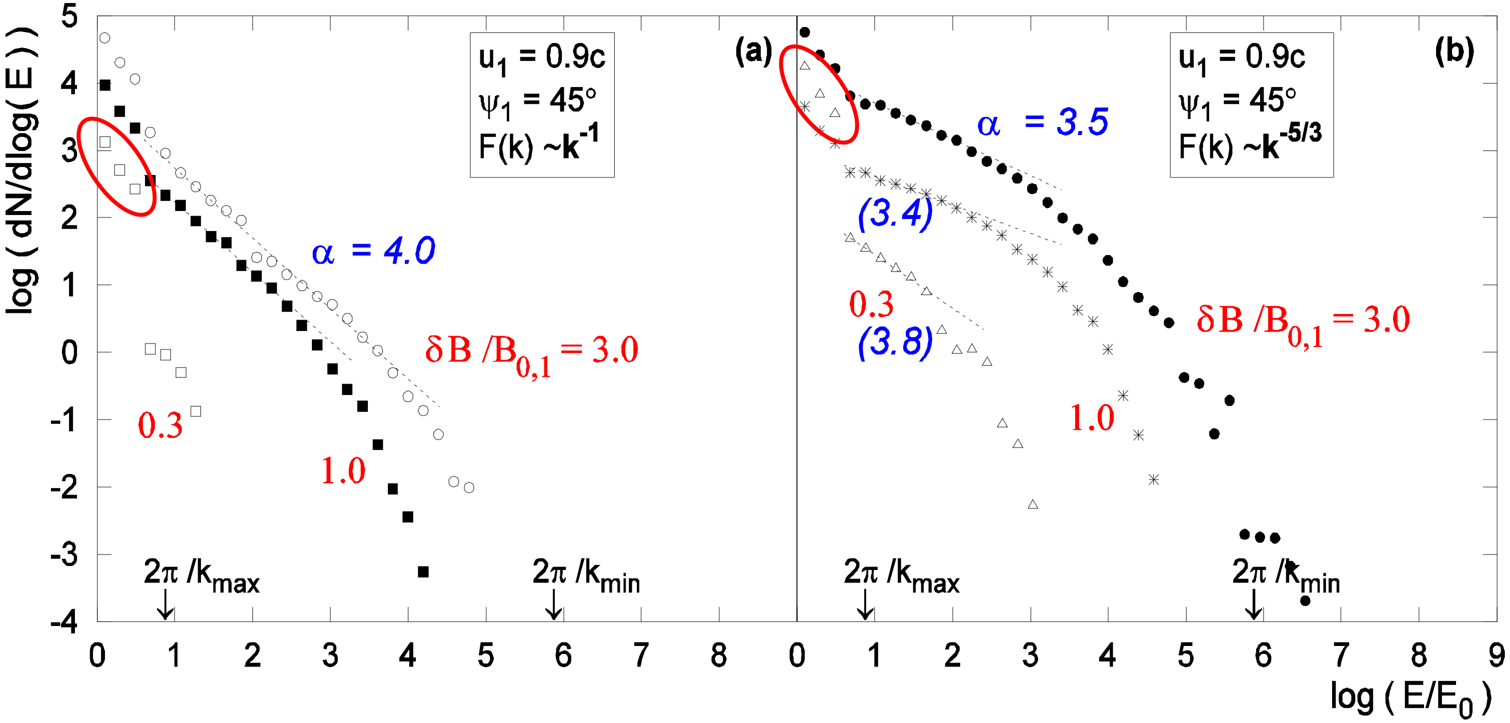
(due to limited dynamic range of magnetic field perturbations – scattering conditions vary with particle energy)

- cut-offs due to lack of magnetic turbulence at relevant scales

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

Superluminal shocks

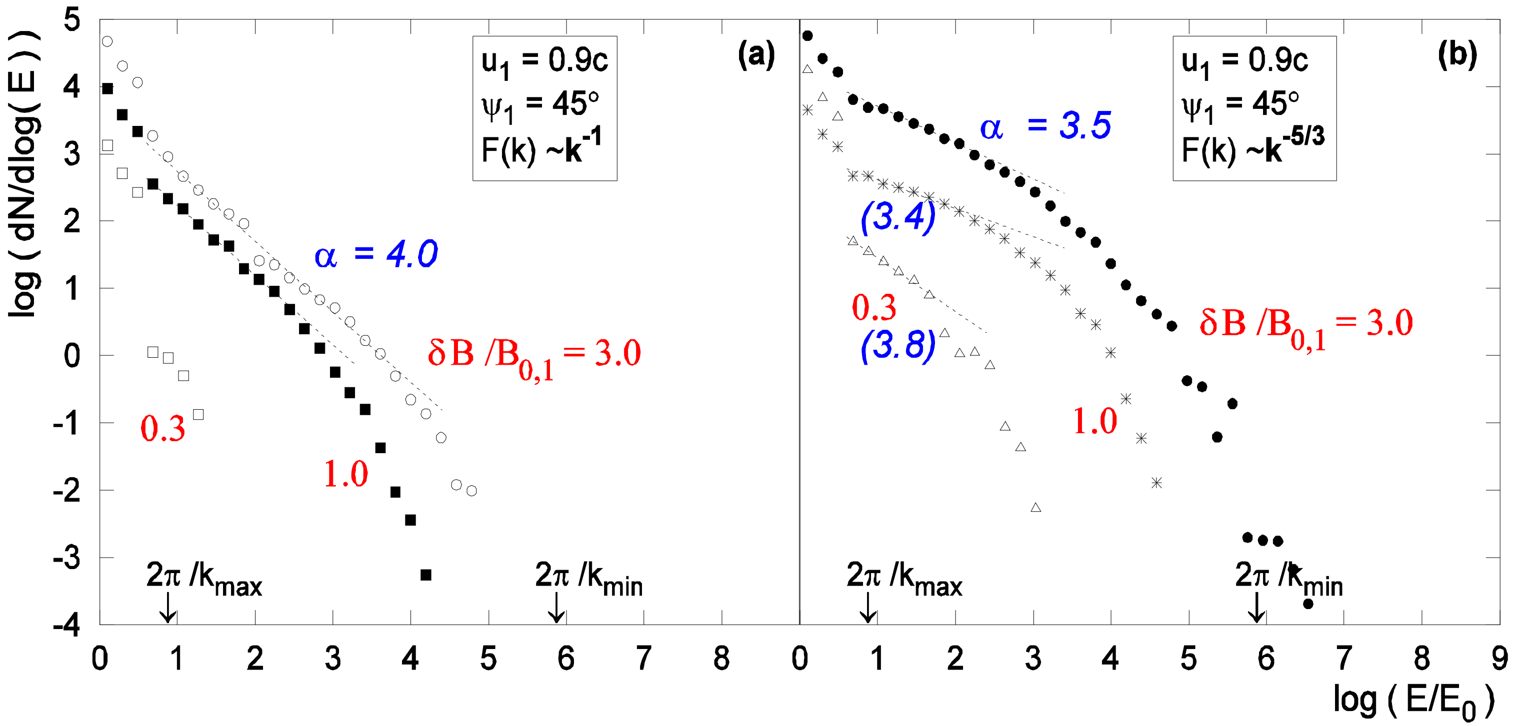
mildly relativistic shock velocity ($\gamma_1=2.3$, $u_{B,1}=1.27c$)



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

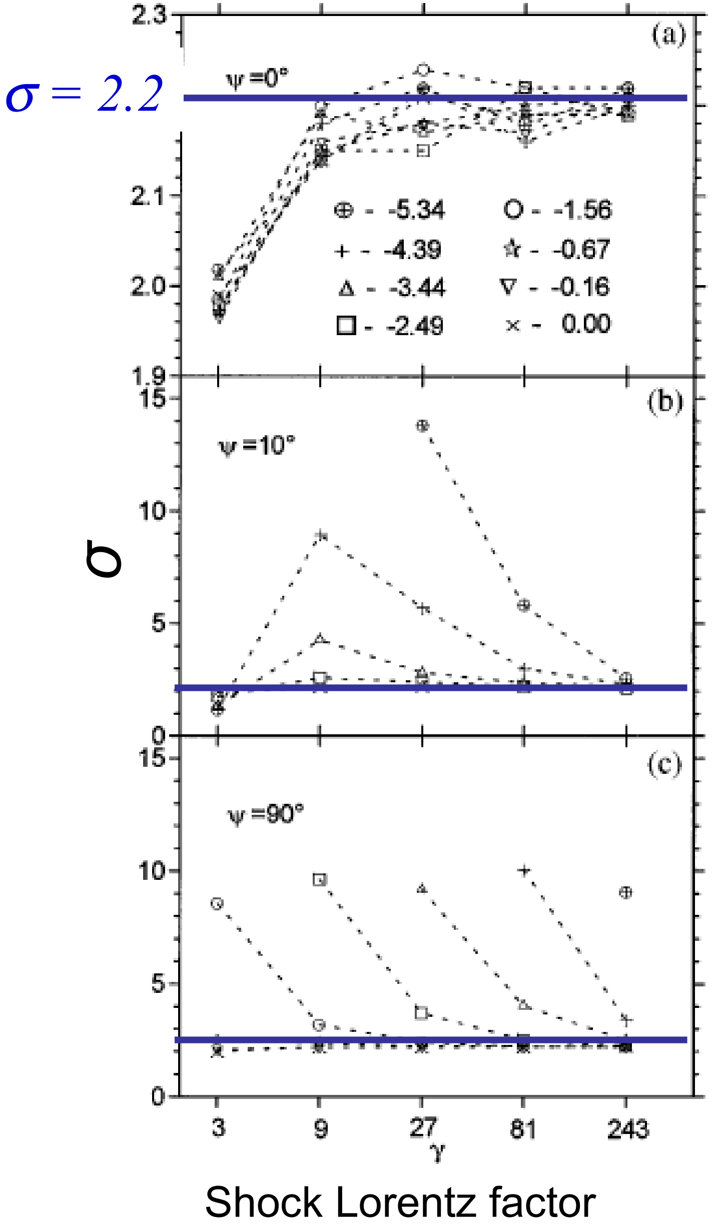
Superluminal shocks

mildly relativistic shock velocity ($\gamma_1=2.3$, $u_{B,1}=1.27c$)



- \`\`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-γ) 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:

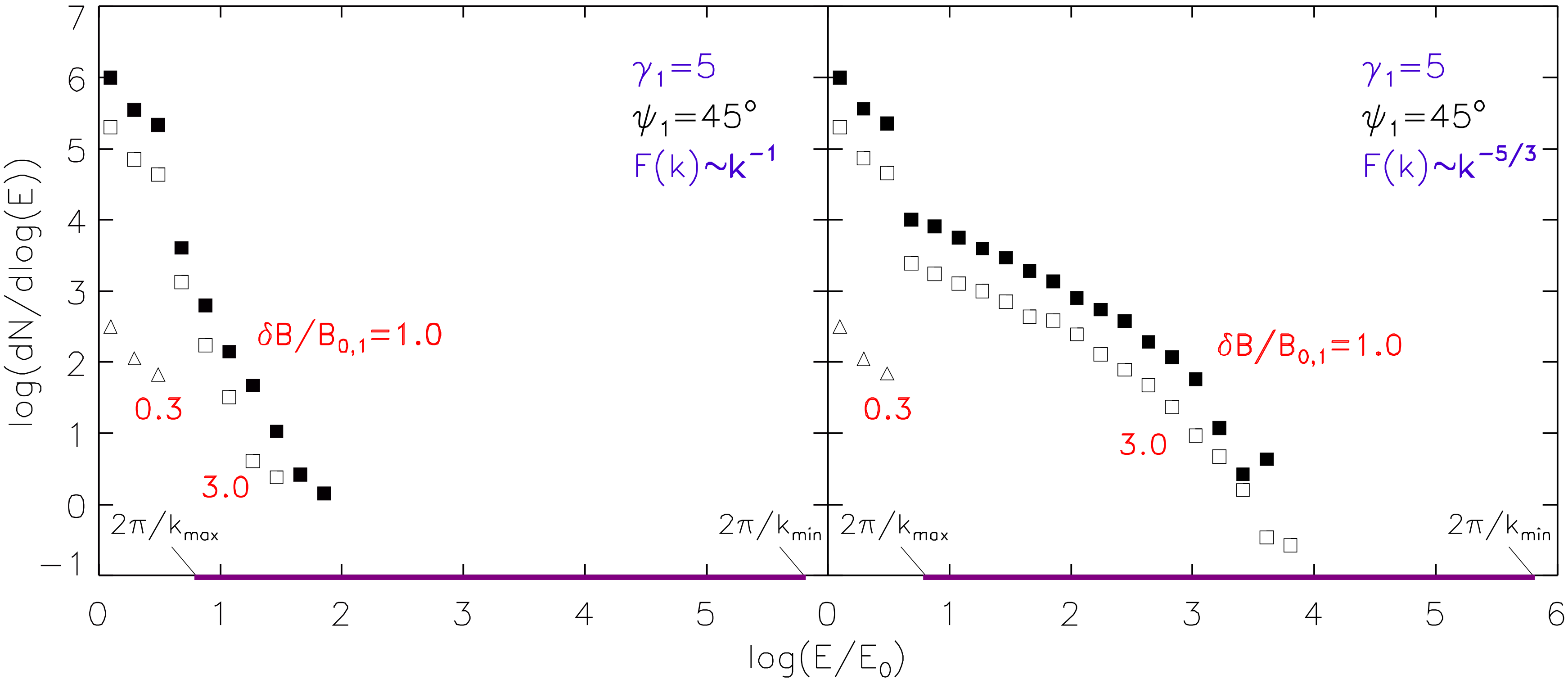
- requires strong turbulence downstream

Ostrowski & Bednarz (2002)

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

Bednarz & Ostrowski (1998)

Superluminal high-γ shock waves Niemiec & Ostrowski (2006)

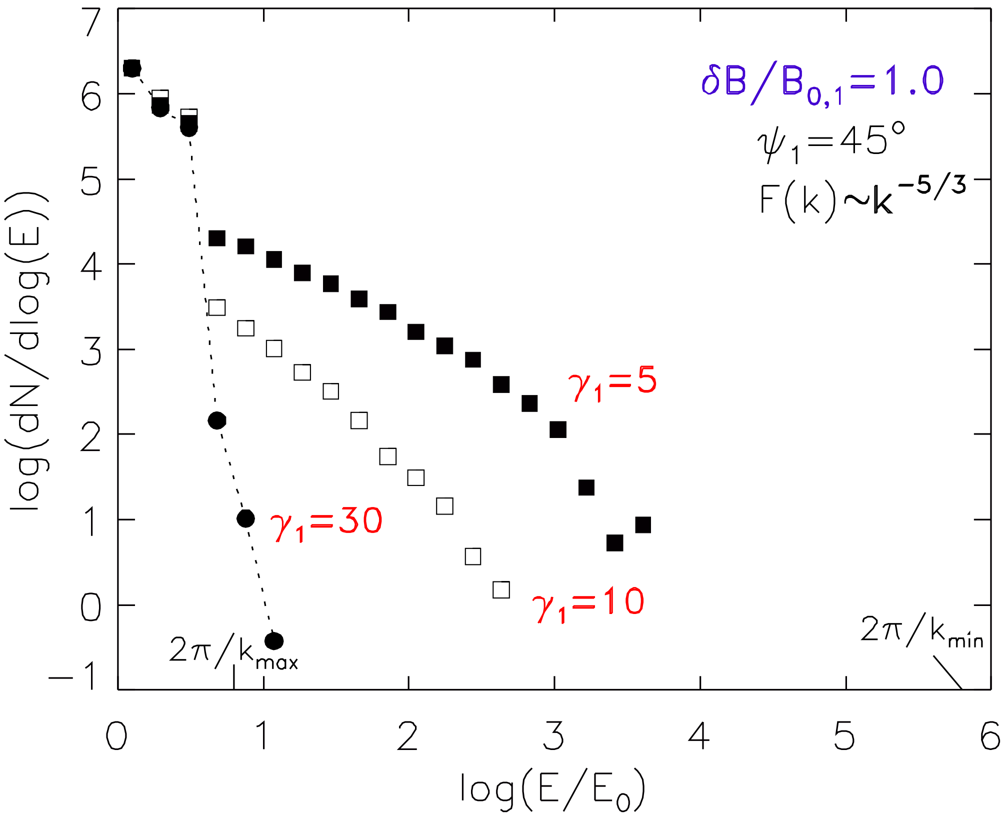


- ``superadiabatic´´ particle compression is the main acceleration process
- small fraction of particles forms energetic spectral tails for large-amplitude magnetic field perturbations

strong dependence on *F(k)*
non–power-law spectral form

- cut-offs in the spectra occur within resonance energy range

For all configurations $u_{B,1} \sim 1.4c$



- the cut-off energy decreases with growing shock Lorentz factor γ_1

Particle transport near a ultrarelativistic shock wave

- downstream magnetic field structure

$$B_{||,2} = B_{||,1}$$

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

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

⇩

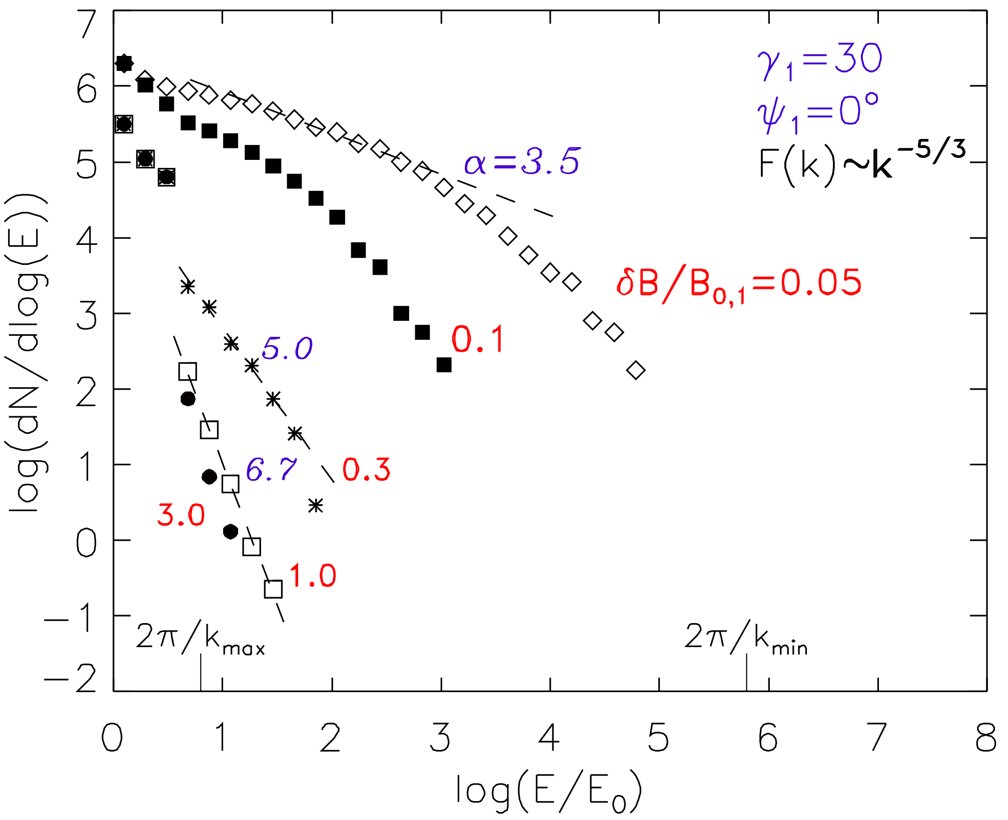
highly anisotropic downstrean particle diffusion:

diffusion coefficient along shock normal $\kappa_{||} \ll \kappa_{\perp}$

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-γ 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

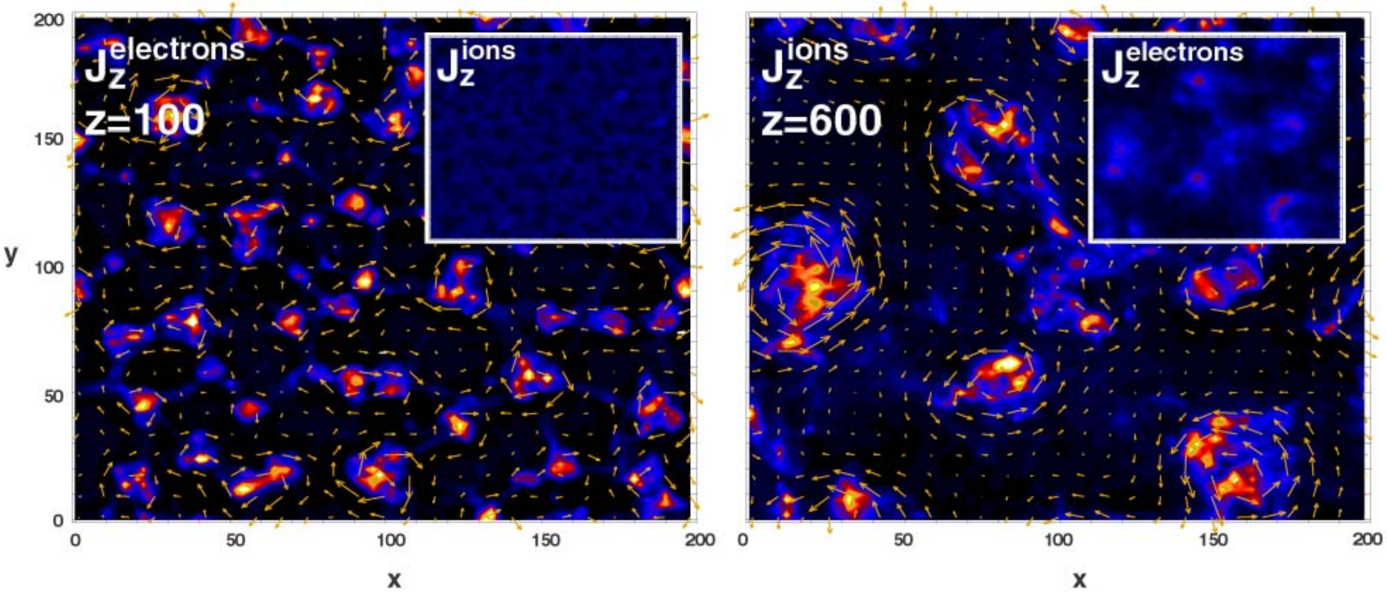
- spectral indices depart from $\alpha = 4.2$ value

- 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 „uniwersal“ 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

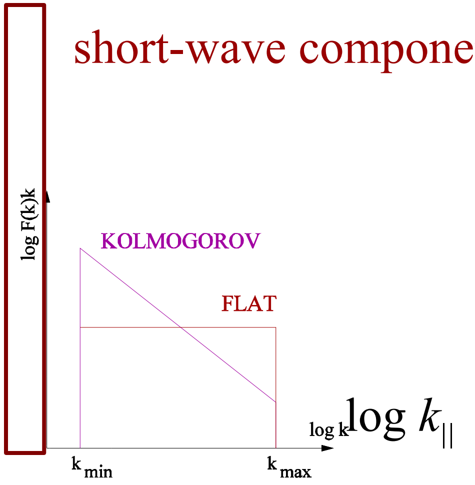


- relativistic shock generates strong small-scale turbulent magnetic field downstream by relativistic two-stream instability (Medvedev & Loeb 1999; Silva et al. 2003; Nishikawa et al. 2003, 2005; Frederiksen et al. 2004) *talk by A. Spitkovsky*
- short-wave magnetic field structure is 2D, transversal 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

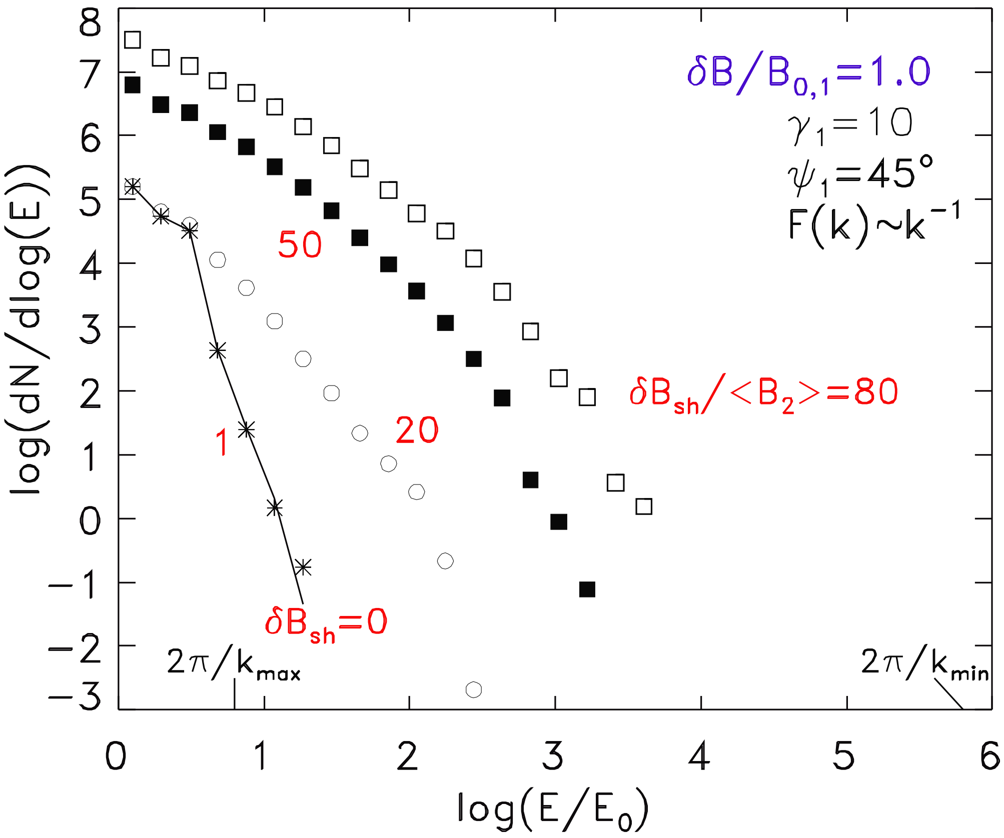
Niemiec, Ostrowski & Pohl (2006)

- 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


short-wave component

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

Superluminal shocks with short-wave perturbations downstream

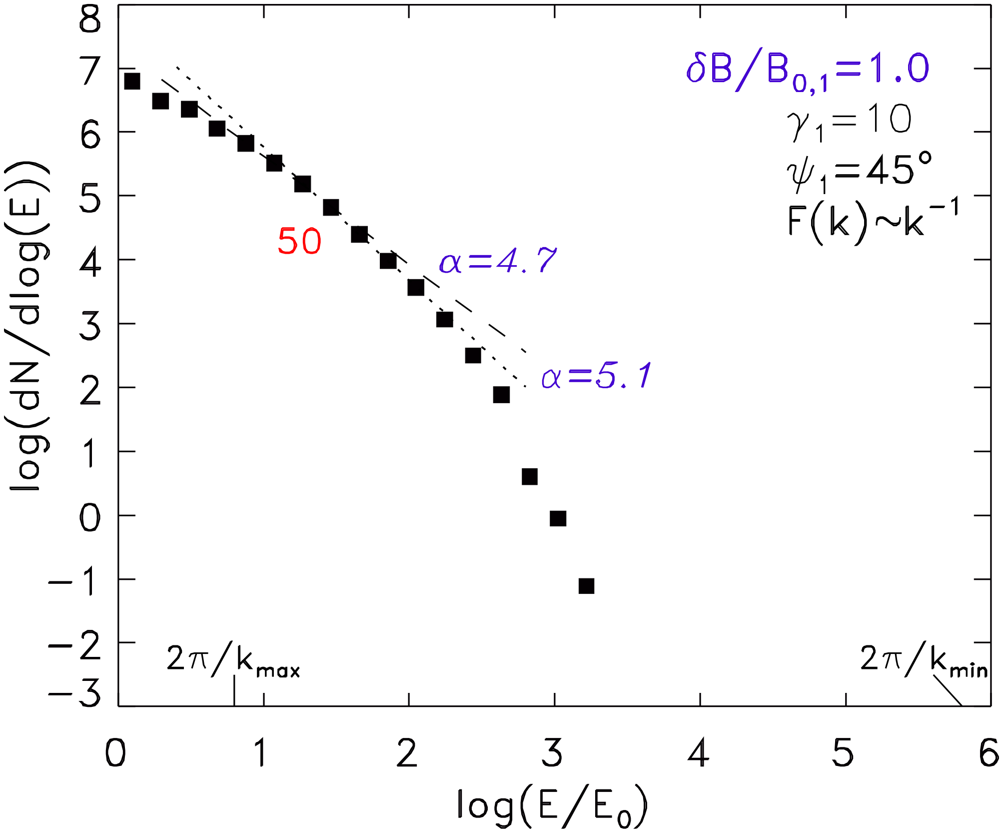


- for energy densities in short-wave turbulence much larger than the energy density in the compressed downstream magnetic field energetic particle spectral tails are formed

non–power-law spectral form (convex spectra)

similar spectral shape for different $\delta B/B_{0,1}$, F(k) (and γ_1)

Superluminal shocks with short-wave perturbations downstream



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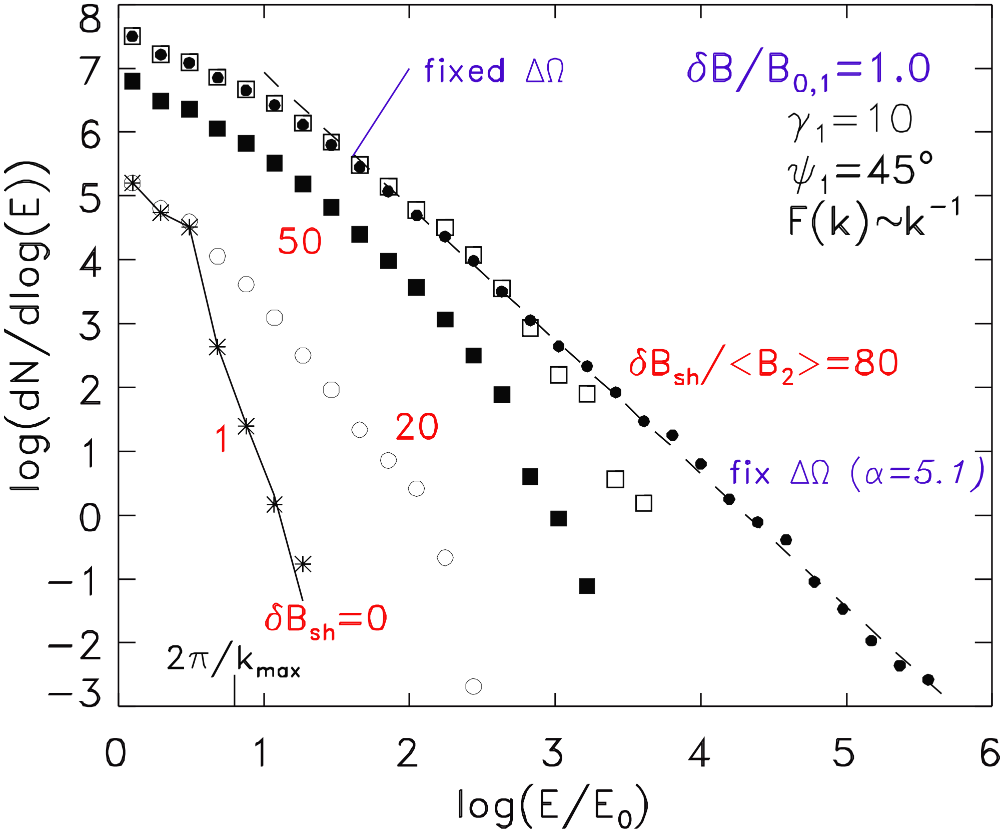

Superluminal shocks with short-wave perturbations downstream

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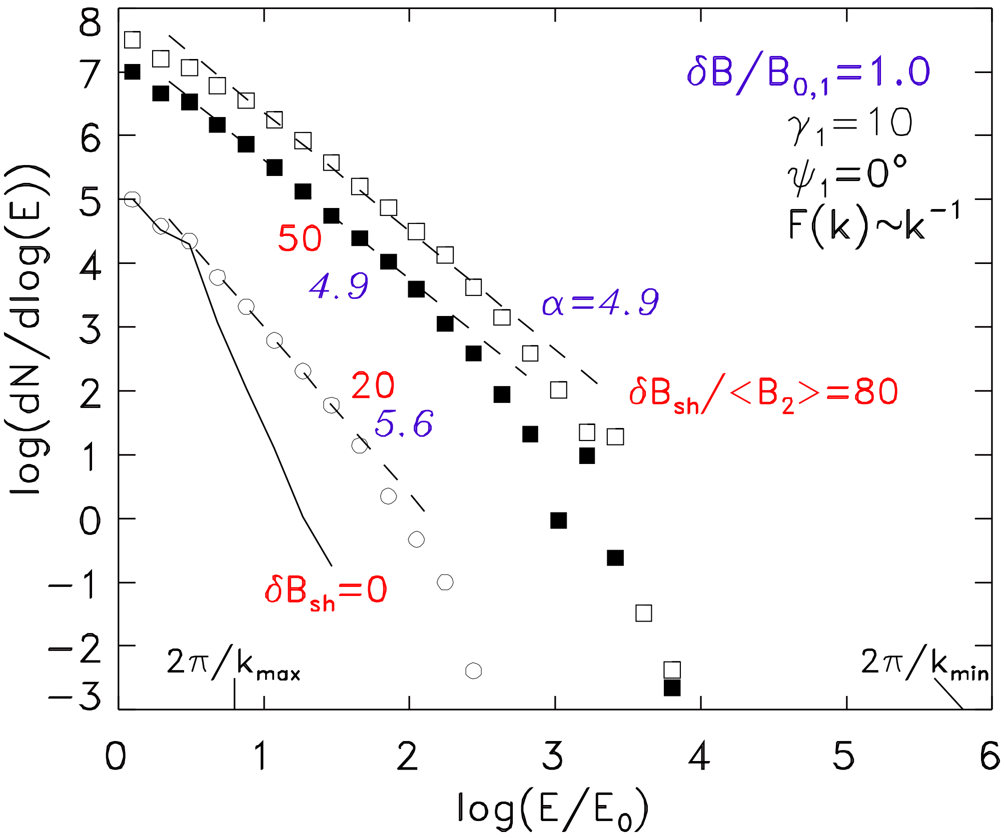
  non–power-law spectral form (convex spectra)

  similar spectral shape for different $\delta B/B_{0,1}$, F(k) (and γ_1)

- efficiency of particle scattering (scatt. angle ΔΩ) 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

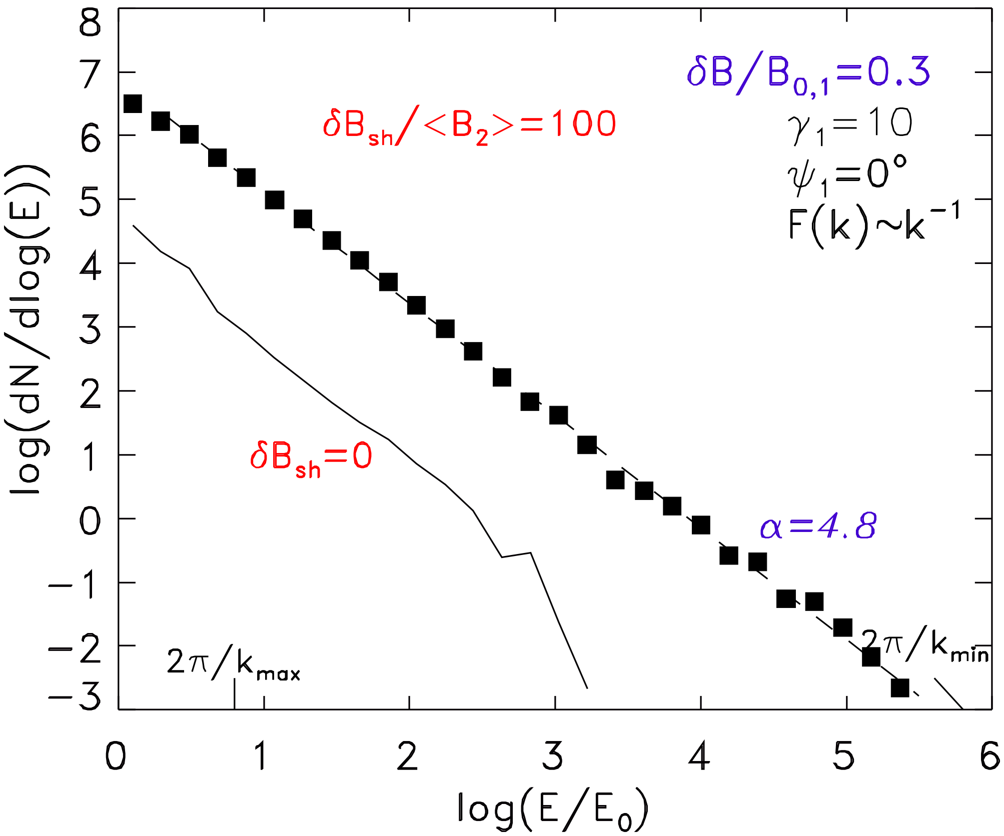
Parallel shocks with short-wave perturbations downstream



- for larger amplitudes of the compressed field ($\delta B/B_{0,1}$) spectra qualitatively similar to those formed at superluminal shocks

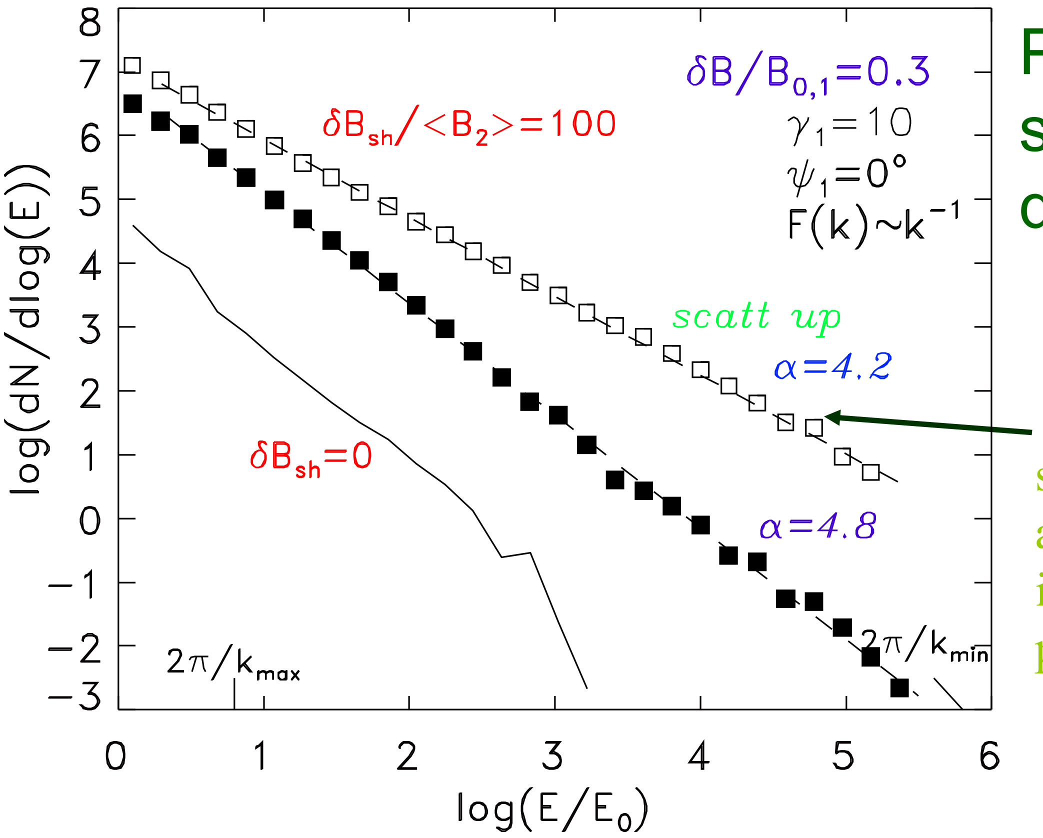
  (large-amplitude long-wave perturbations provide locally superluminal conditions that lead to spectral cut-offs when particle scattering in short-wave turbulence decreases with particle energy)
- particle spectral index deviates from the ``universal“ value *α=4.2* even in the limit of $\delta B_{sh}/\langle B_2\rangle \gg 1$

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-γ 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 γ 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)