Particle Acceleration at Ultrarelativistic Shocks

Jacek Niemiec

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

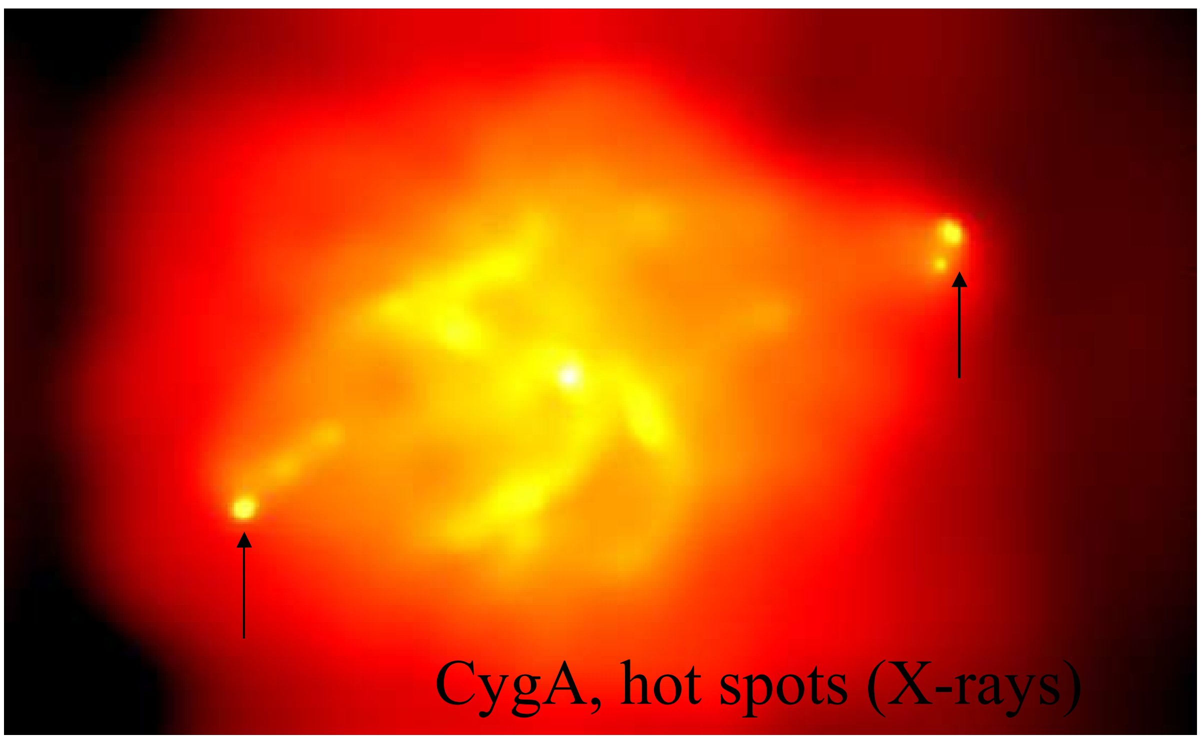
J. Niemiec, M. Ostrowski (OA UJ, Krakow, Poland), in preparation

Relativistic shocks in astrophysical objects

Relativistic plasma flows observed in:

- jets in AGN
- jets in microquasars
- GRB sources
- pulsar winds

shock waves – natural consequence of relativistic flows


CygA, hot spots (X-rays)

synchrotron radiation and/or γ rays observed

⇓

presence of energetic particles (particle acceleration)

First-order Fermi process
Nonrelativistic shocks

(test particle approach, superthermal particles)

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

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

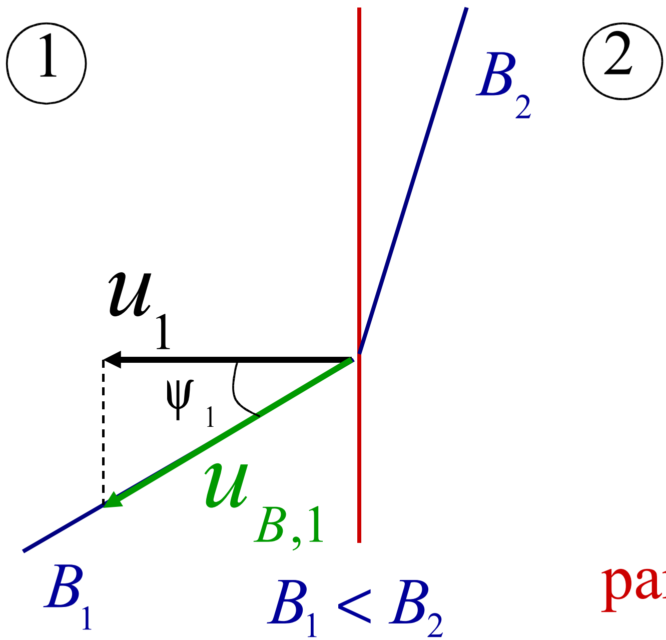
$$\alpha = \frac{3R}{R-1} \qquad (\sigma = \alpha - 2)$$

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

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

- particle spectrum independent of conditions near the shock
  ψ_1, $\delta B(k)$, $F(k)$

First-order Fermi process
Relativistic shocks



$u_{B,1} < c$ subluminal

$u_{B,1} > c$ superluminal

$u_1 \sim c$

or

$u_{B,1} \sim c$

$v_p \approx c$

particle anisotropy at shock: $\Delta\vartheta \sim 1/\gamma_1$

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

Test particle results

- parallel shocks ($\psi_1 = 0^o$):
  - semianalytic solutions of Fokker-Planck diffusion equation

    Kirk & Schneider (1987a), Heavens & Drury (1988)
  - Monte Carlo simulations

    Kirk & Schneider (1987b), Ellison, Jones, & Reynolds (1990)

spectral index differs from NR value $\alpha = 4$ and depends on the wave power spectrum of magnetic field perturbations $F(k)$

- oblique shocks ($\psi_1 \neq 0^o$):
  - semianalytic method: weakly perturbed field $\delta B/B \ll 1$, $\kappa_\perp \approx 0$, subluminal shocks

    Kirk & Heavens (1989)

flat spectra ($\alpha \approx 3$) due to particle reflections from the compressed downstream field

  - Monte Carlo simulations: finite-amplitude perturbations, $\kappa_\perp \neq 0$

    Ostrowski (1991,93), Ballard & Heavens (1992); Naito & Takahara (1995), Bednarz & Ostrowski (1996, 98)

power-law spectra for superluminal shocks in conditions of highly perturbed m

Numerical modeling of the turbulent magnetic field

- pitch-angle diffusion model

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

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

All the mentioned studies were limited to test particle approach and 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.

J. N., M. Ostrowski 2004 (ApJ 610, 851 (2004))

Monte Carlo modeling of the acceleration process by integrating particle equations of motion in turbulent magnetic field near the shock

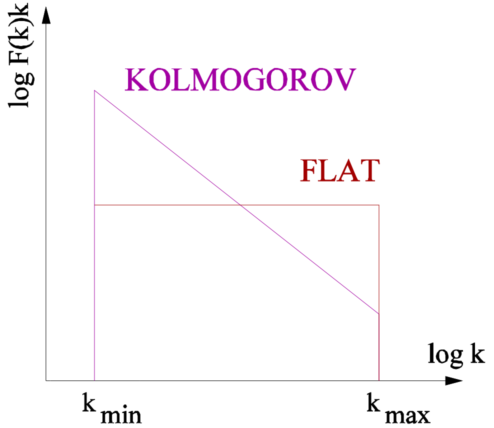
``Realistic´´ magnetic field structure

Niemiec & Ostrowski (2004)

Upstream magnetic field:

- $B = B_0 + \delta B$ uniform component + finite-amplitude perturbations (superposition of sinusoidal static waves – no Fermi II acceleration)

- perturbations in the wide wavevector range



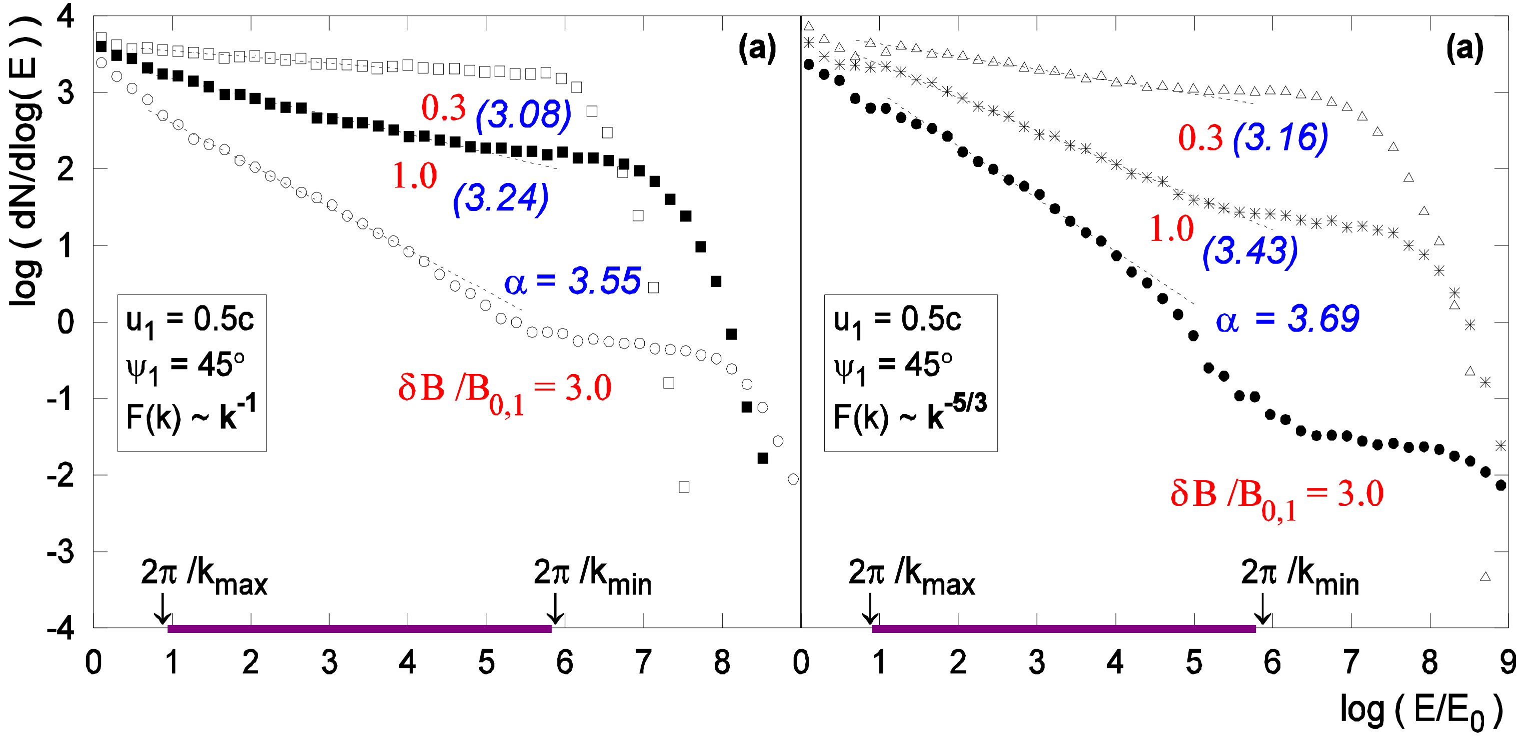
$$k_{max} / k_{min} = 10^5$$

- downstream structure: compressed upstream field

⇒ continuity of magnetic field lines across the shock

Subluminal shocks

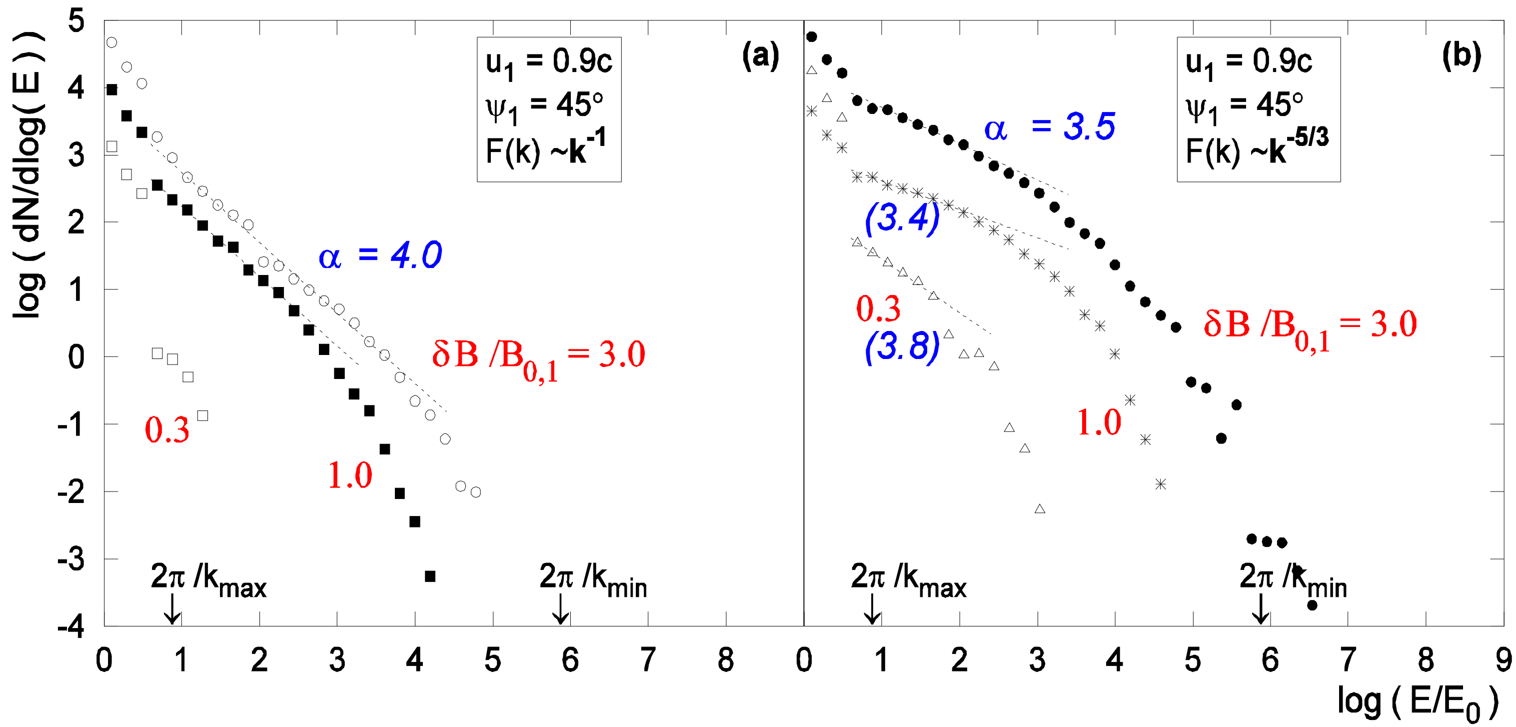
mildly relativistic shock velocity (γ_1=1.2, $u_{B,1}$=0.71c)



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

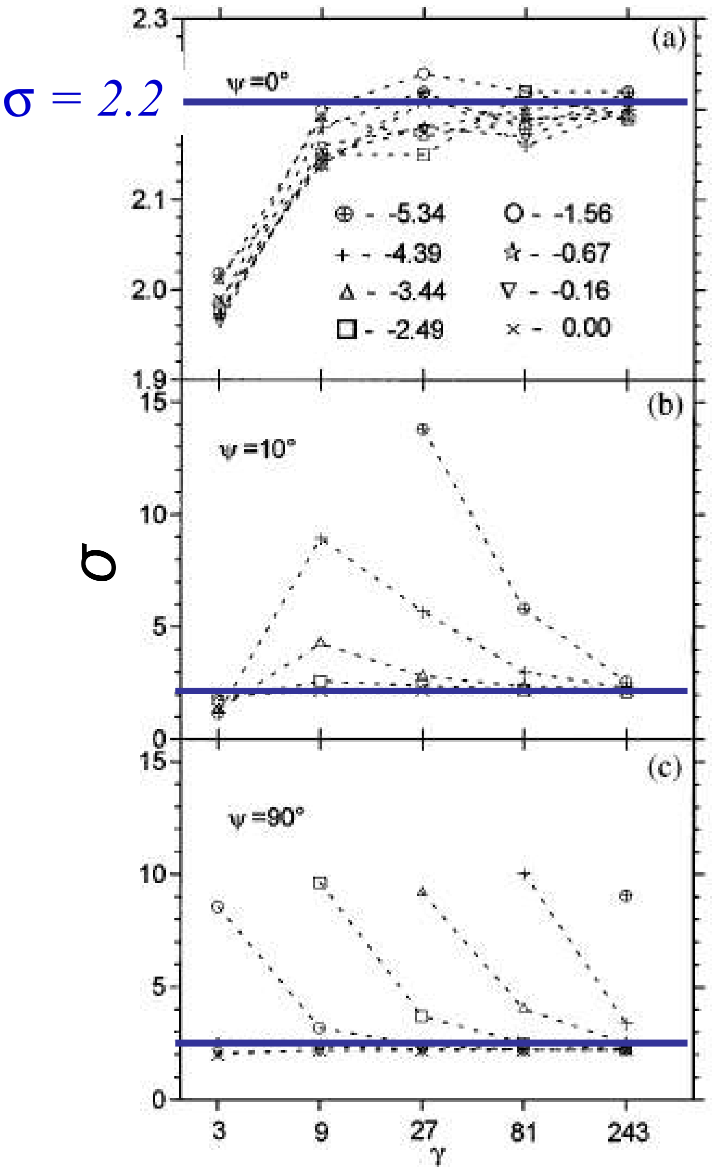
Superluminal shocks

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



- ``superadiabatic´´ compression of injected particles for low 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)



Shock Lorentz factor

Ultrarelativistic (high-γ) shocks

- 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:

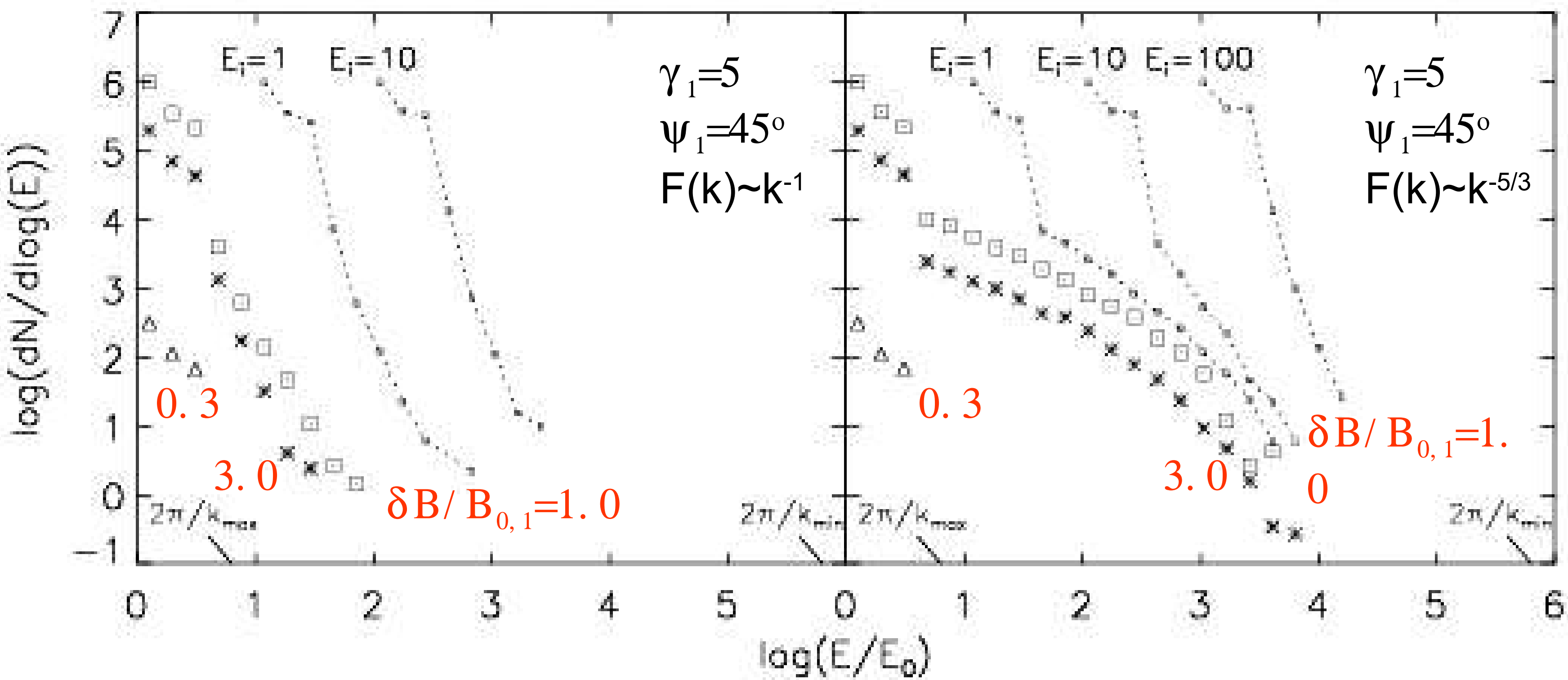
- requires strong turbulence downstream

Ostrowski & Bednarz (2002)

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

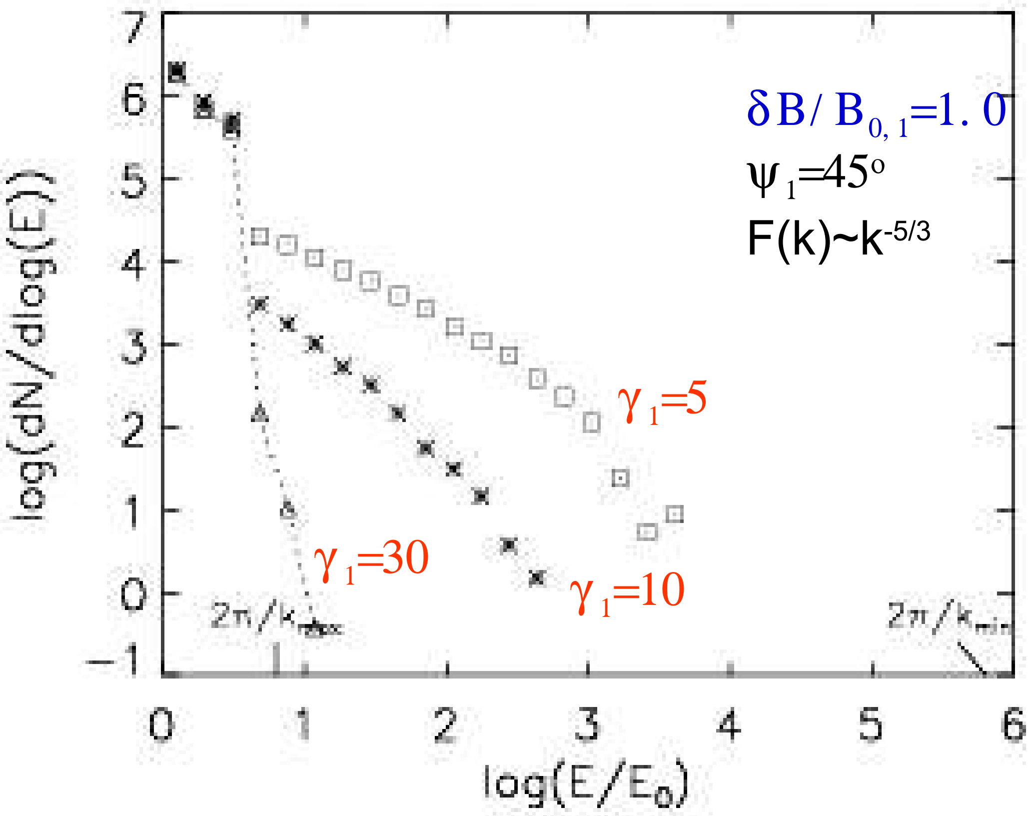
Bednarz & Ostrowski (1998)

Present approach: Superluminal high-γ shock waves



- ``superadiabatic´´ compression is the main acceleration process
- small fraction of particles forms energetic spectral tails for large amplitudes of magnetic field perturbations
- the steepening and the cut-off in the spectra occur at lower energies than in lower-γ shocks

Niemiec & Ostrowski (2005a) in preparation in all cases $u_{B,1}$~$1.4c$



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

upstream conditions for particle acceleration similar for the configurations studied

⇓

features observed are related to the character of particle transport *downstream* from the shock

Particle transport downstream of a ultrarelativistic shock:

- magnetic field structure

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

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

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

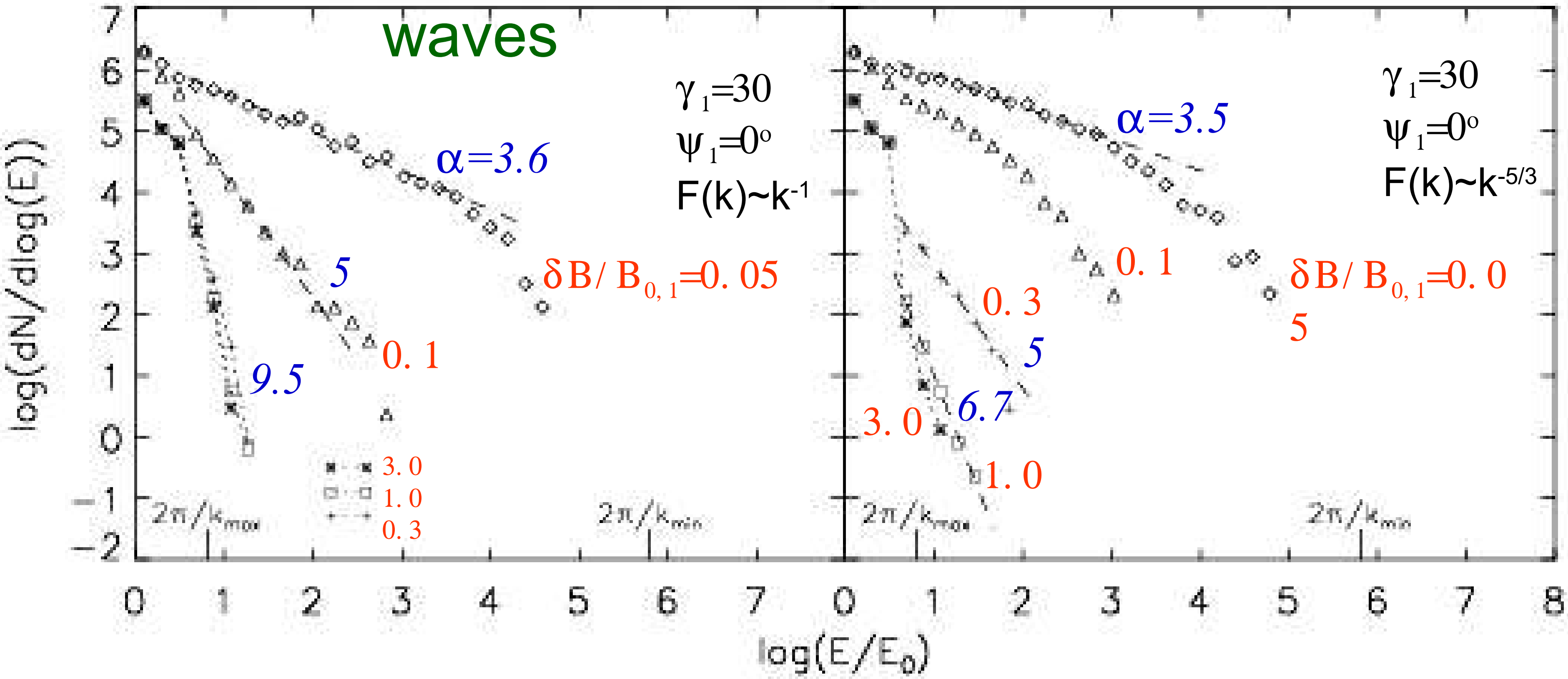
↓

- highly anisotropic 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.

Parallel high-γ shock waves



- processes of particle acceleration are inefficient for larger amplitudes of magnetic field perturbations: compression produces effectively perpendicular shock

  features analogous to those observed in superluminal shocks are recovered

- for mildly perturbed conditions particle spectra (often with the (steep) power-law parts) are generated in the limited energy range

- in conditions of weakly perturbed magnetic fields particle spectra form in the wide energy range:
    - particle spectra are non power-law in the full energy range − effects of the limited wavevector range for magnetic field turbulence
    - power-law parts of the spectra are flat − particle spectral indices deviate from the results of the pitch-angle (or ``direction angle´´) diffusion models suggesting the existence of the so-called universal spectral index $\alpha \sim 4.2$ for ultrarelativistic shocks (due to the presence of long-wave perturbations forming locally oblique field configuratuins at the shock, which enables, e.g., efficient particle reflections from the shock; Niemiec & Ostrowski (2004))
- the critical turbulence amplitude value for efficient particle acceleration to occur diminishes with the shock Lorentz factor γ_1

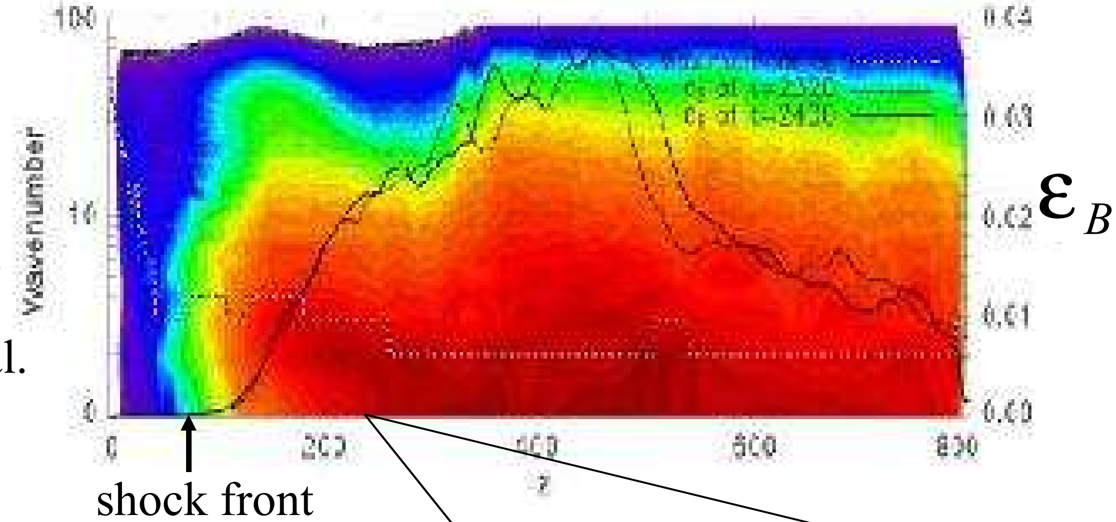
ultrarelativistic shocks are inefficient in high-energy particle production via the first-order Fermi mechanism unless additional source of turbulence exists and is able to decorrelate particle motion in the structured field near the shock

Shock generated magnetic field turbulence

PIC simulations by Frederiksen et al. 2004

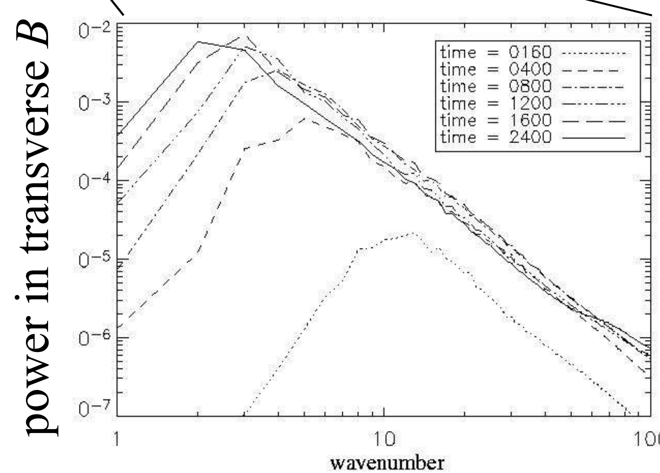
- relativistic shock generates strong small-scale turbulent magnetic field downstream by relativistic two-stream instability

Medvedev & Loeb (1999), Silva et al. (2003), Nishikawa et al. (2003, 04), Frederiksen et al. (2004)



- short-wave magnetic field structure is 2D, transversal to the shock normal, but in the nonlinear regime the perturbations should transform into isotropic 3D turbulence.

- small-scale large-amplitude fluctuations can provide efficient particle scattering, which may lead to decorrelation between particle motion and the compressed field downstream of the shock



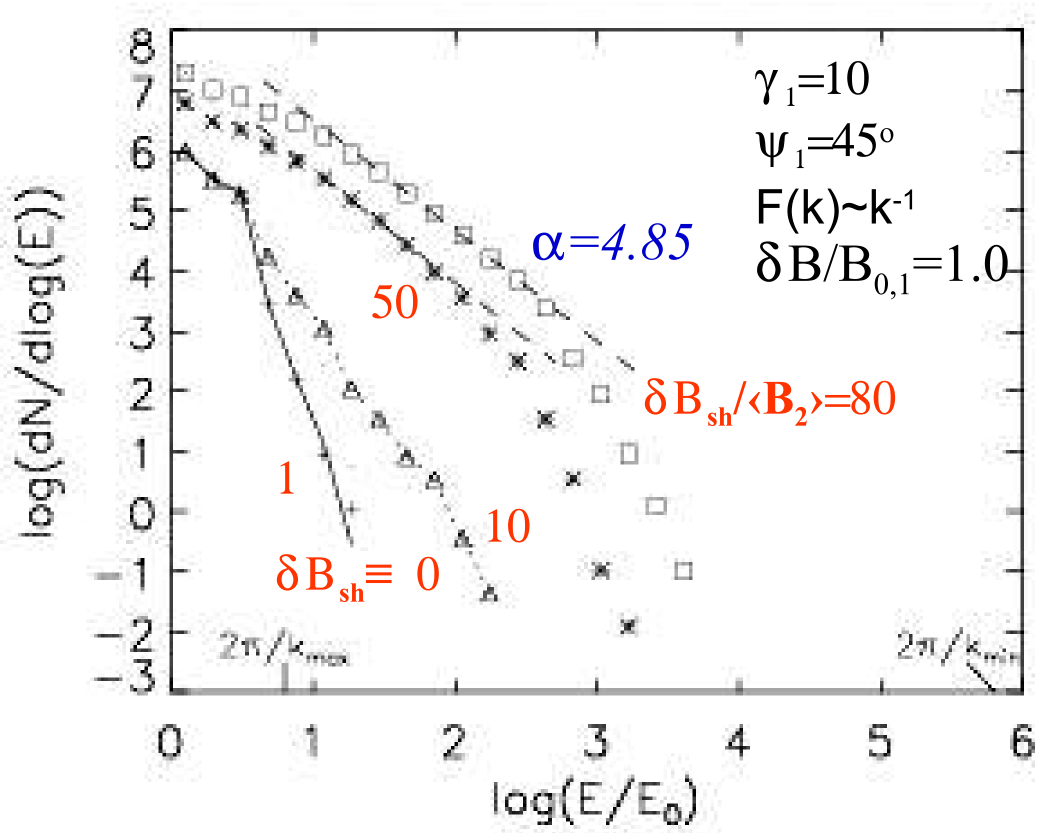
Modeling short-wave (Weibel-like) turbulence downstream

Niemiec & Ostrowski (2005b) in preparation

- 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

influence of such perturbations on particle trajectories is included as a small-amplitude momentum scattering term, with scattering probability distributions determined by a pattern of the turbulence assumed

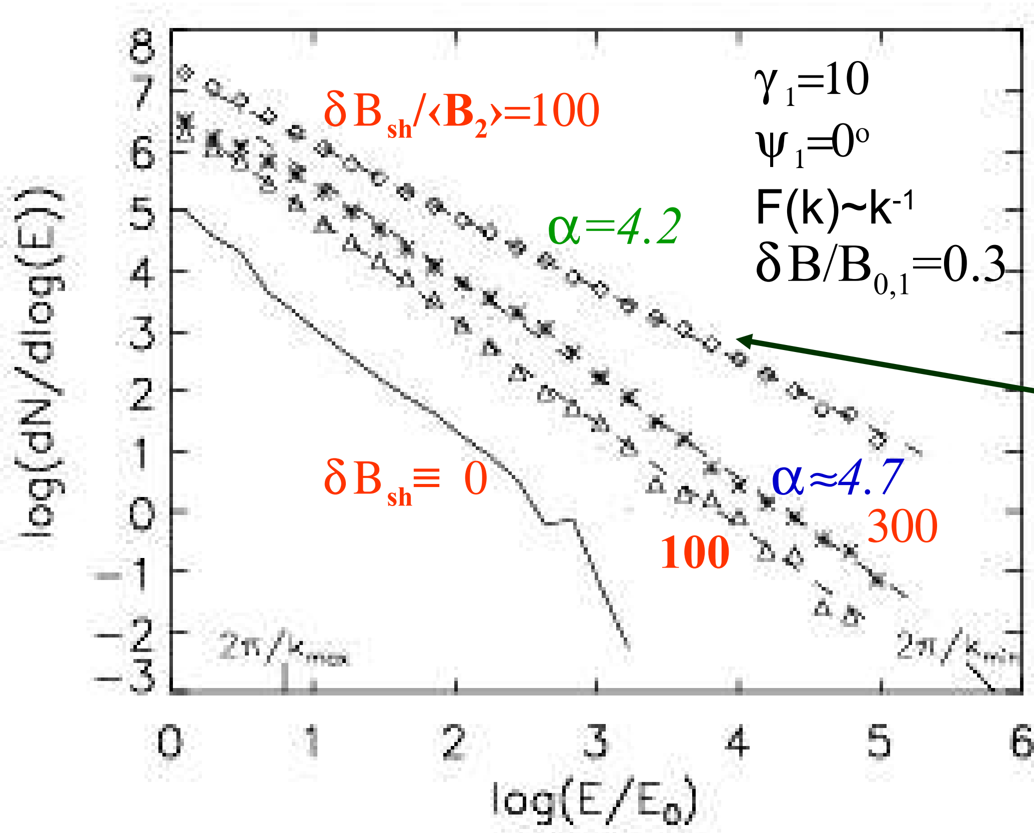
- how the existence of short-wave turbulence with various amplitudes affects particle spectra formation in high-γ shocks presented above?
- what are conditions allowing for a universal spectral index?



Oblique superluminal shocks

- for amplitudes of the short-wave turbulence much larger than the amplitude of the compressed downstream magnetic field particle spectra form in the wide energy range; they have (steep) power-law parts with spectral index which does not depend on $\delta B_{sh}/\langle B_2\rangle$ above some critical value
- efficiency of particle scattering due to small-scale perturbations depends on 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



model with particle pitch-angle scattering upstream of the shock, which does not include the effects of long-wave magnetic field perturbations.

- particle spectral index deviates from the ``universal‘‘ value $\alpha=4.2$ even in the limit of $\delta B_{sh} /\langle B2\rangle >>1$
- (long-wave) magnetic field structure upstream of the shock influences particle acceleration processes; only in the model with pitch-angle scattering upstream, particle spectrum with the ``universal‘‘ spectral index forms

Summary

- I-order Fermi process at high-γ shocks is inefficient in particle acceleration to high energies

particle spectra depart significantly from $\alpha = 4.2$ value
``universal" spectral index requires special conditions
(strong particle scattering downstream and upstream of the shock)

cf. Ellison & Double (2004)

- UHECRs production and GRB afterglow spectra?

II-order Fermi process (Virtanen & Vainio 2005)
other acceleration processes (e.g. Hoshino et. al 1992, Hededal et al. 2004)

- existing theoretical models do not allow for reliable modeling of astrophysical objects

Further progress requires:

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

need for a full plasma nonlinear description of cosmic ray acceleration process