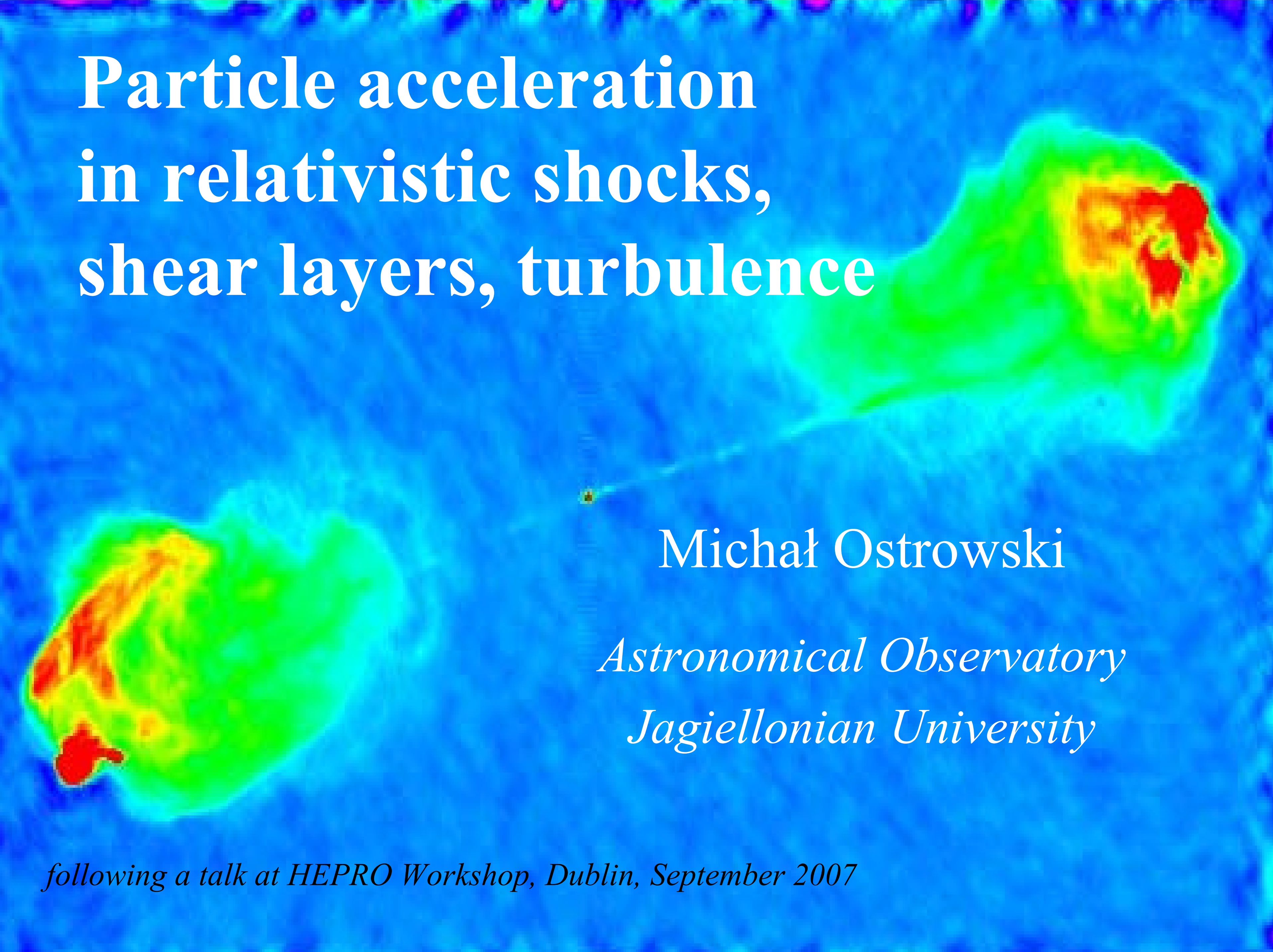

Particle acceleration in relativistic shocks, shear layers, turbulence

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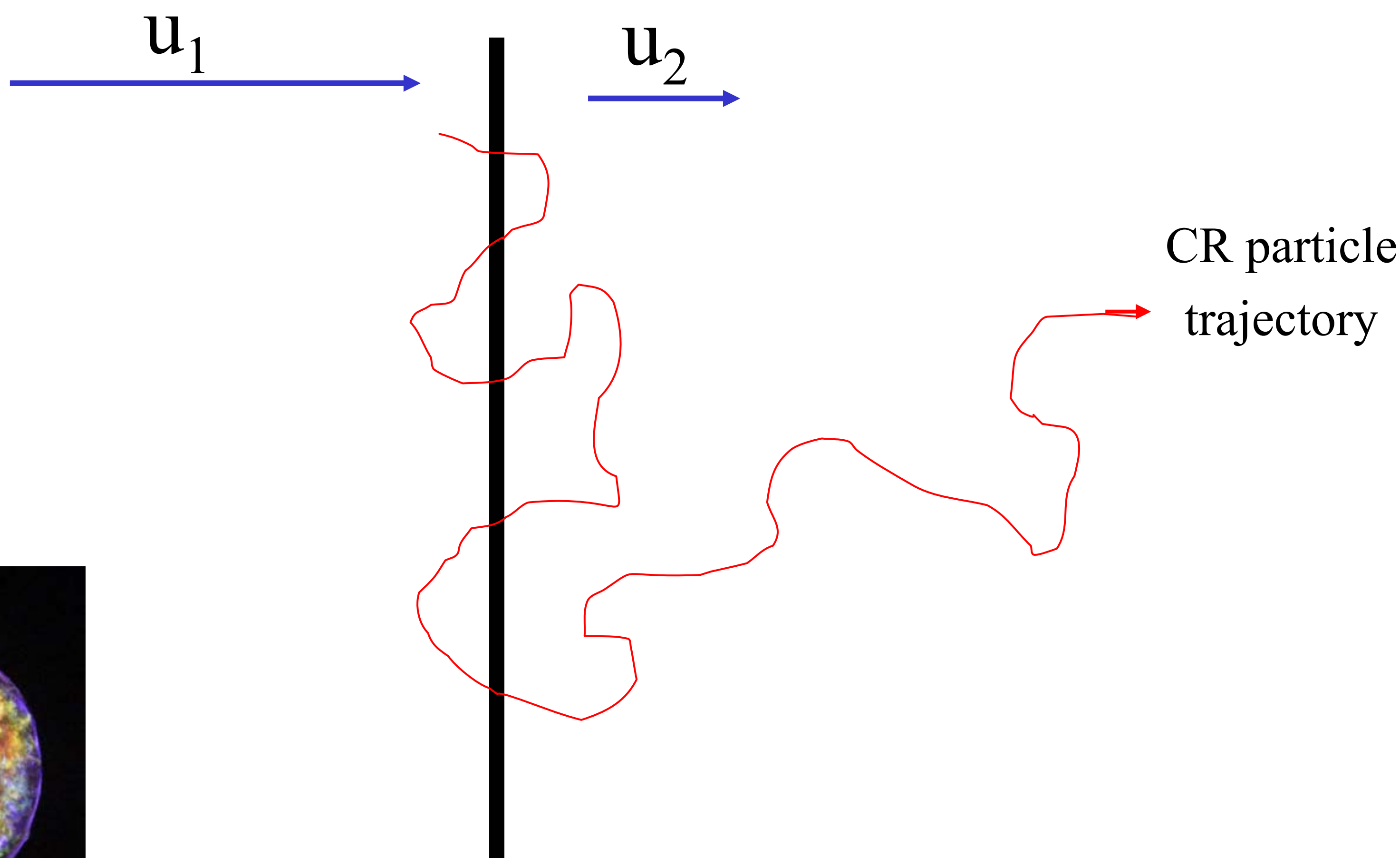
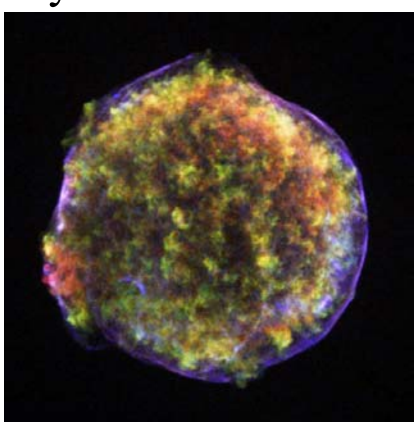
following a talk at HEPRO Workshop, Dublin, September 2007

I order Fermi acceleration



Tycho SNR

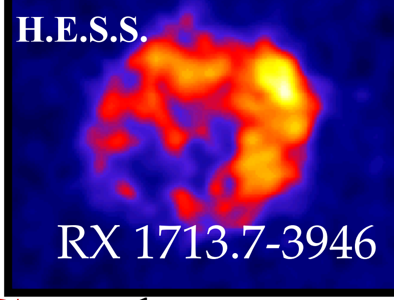


shock

layer of plasma compression

(*PIC* modelling)

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

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

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

Below we use often $\alpha = \sigma + 2$

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

Relativistic shock:

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

→ Particle anisotropy in the shock: $\Delta\theta \sim \gamma^{-1}$

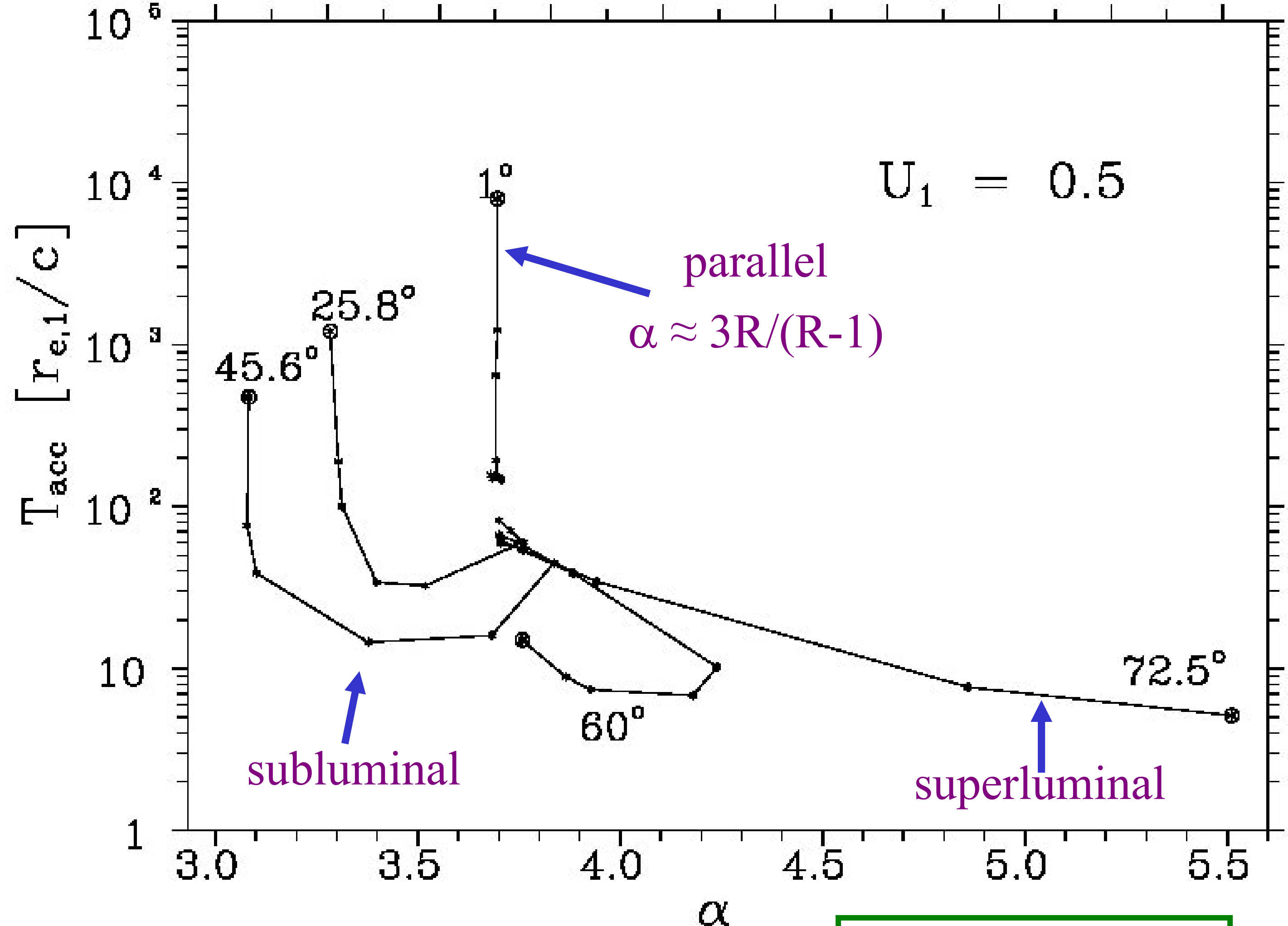
shock Lorentz factor

Significant influence of the background conditions near the shock at the resulting particle spectrum:

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

„Summary” of results for mildly relativistic shocks in 80th-90th

(simplified analytic and numerical models usually required power-law outputs)



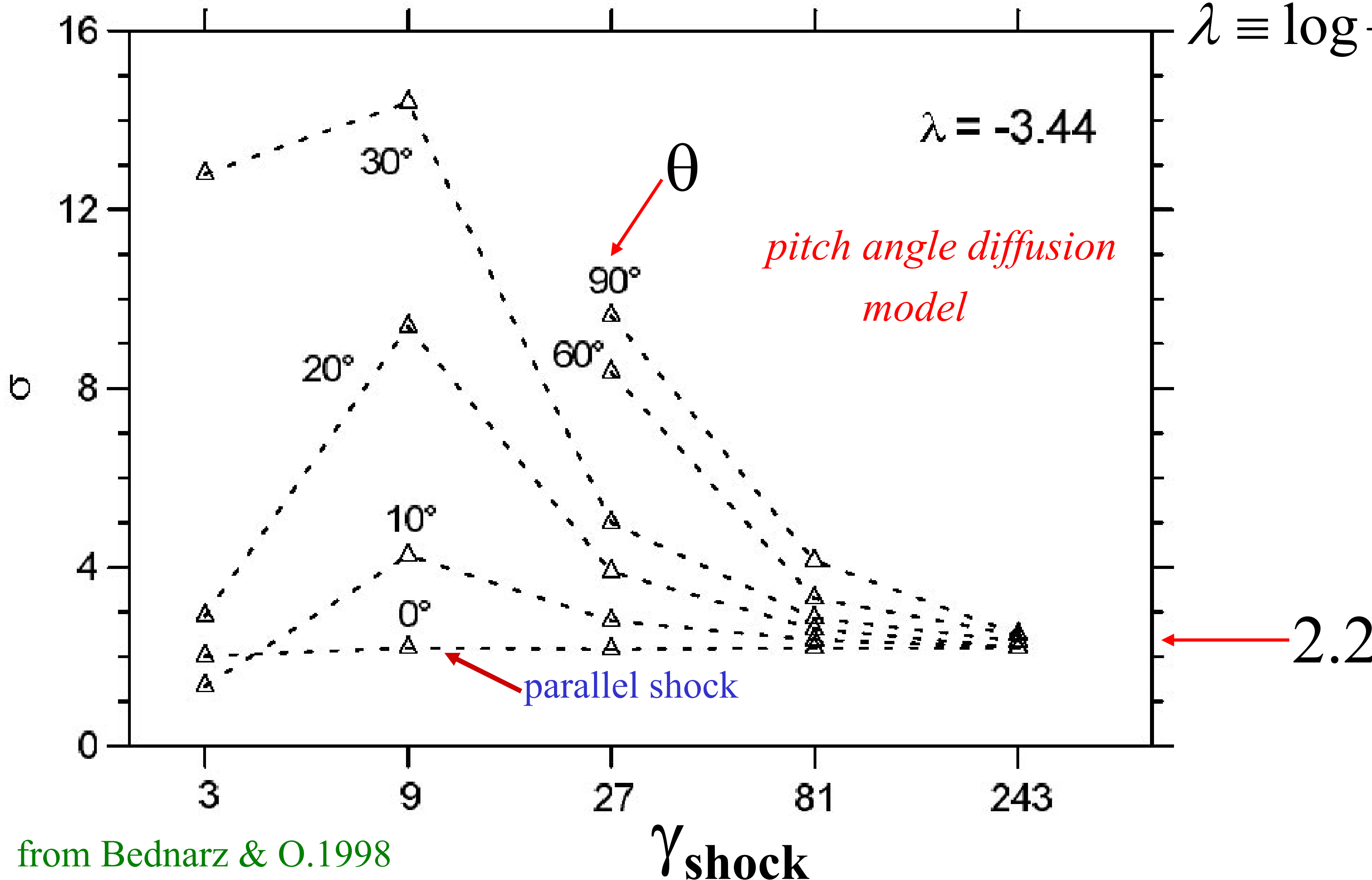
$$\frac{u_1}{\cos 60^\circ} = 1$$

$$\boxed{\alpha = \sigma + 2}$$

from Bednarz & O. 1996

Universal spectral index for particles accelerated at **ultrarelativistic** shocks

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



from Bednarz & O.1998

The same value of $\sigma \approx 2.2$ 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 ?

Discussion by O. & Bednarz (2002) concluded that it

requires strong turbulence

downstream of the shock.

Is it enough ? Do such conditions really exist in shocks ?

. *Niemiec et al. 2004-6:* No !

Below $\sigma = 2.2 \Rightarrow \alpha = 4.2$

Realistic background conditions:

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

In the Monte Carlo simulations:

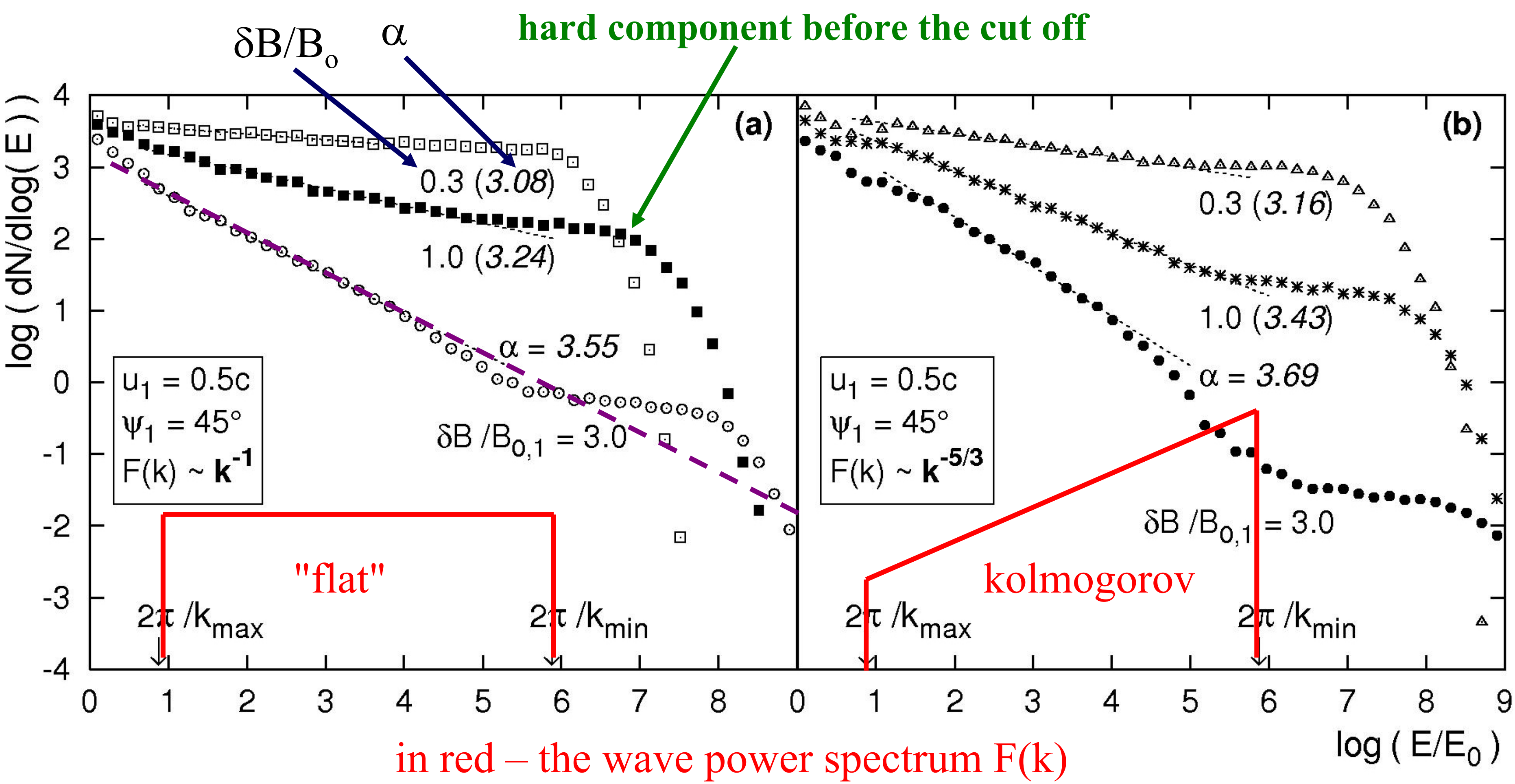
- ***shock Lorentz factors between 2 and 30***
- ***different inclinations of B_0***
- ***different spectra of the 3D background long wave MHD (static – no Fermi II accel.) turbulence***
- ***possibility of generation of highly nonlinear turbulence at the shock (like in PIC simulations)***

Mildly relativistic shocks

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

oblique *subluminal* shock:

E $\longrightarrow$ $k = 2\pi/r_g(E)$

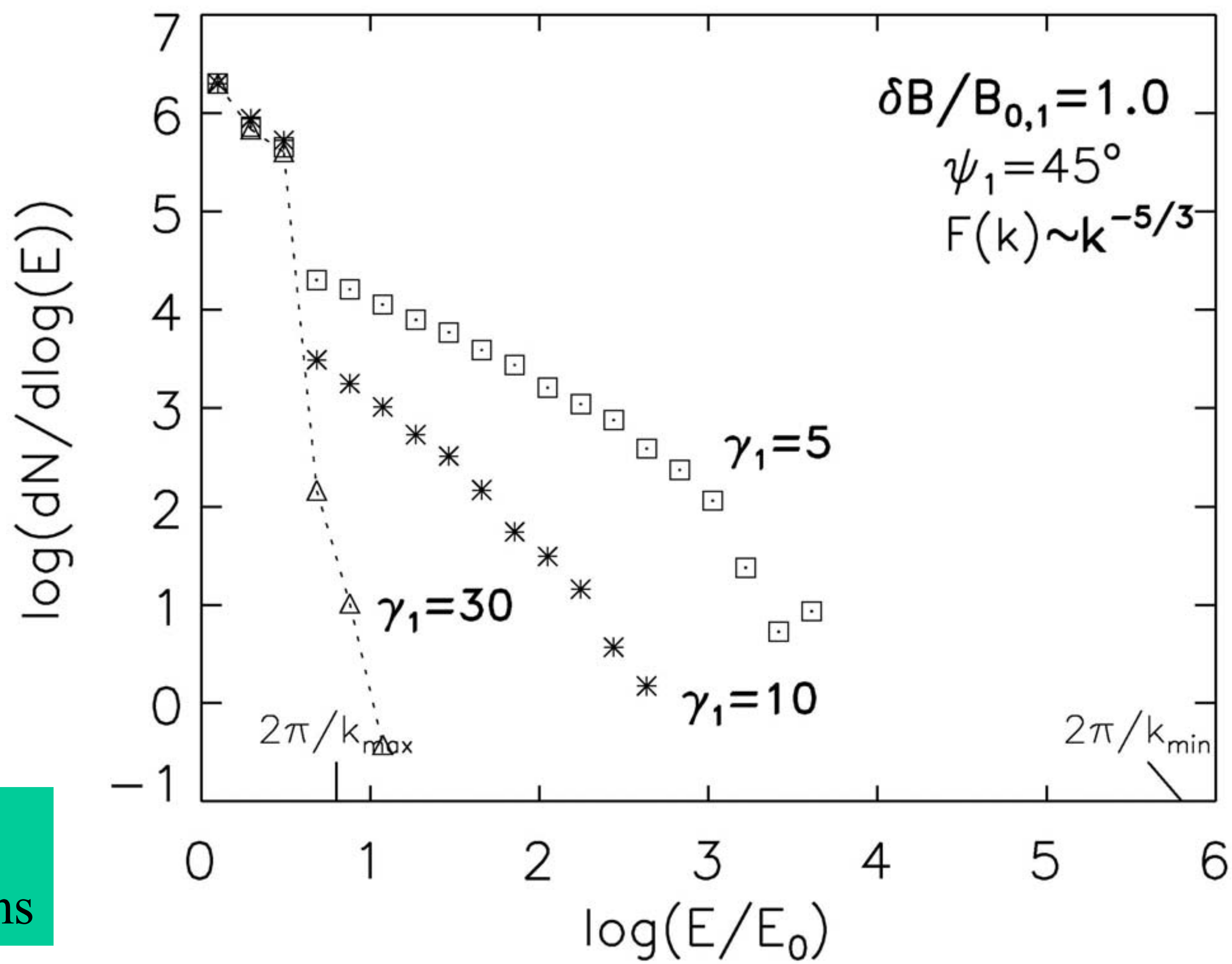


in red – the wave power spectrum F(k)

Ultrarelativistic shock waves

$$\gamma_{\mathbf{shock}} \equiv \gamma_1 = \mathbf{5, 10, 30}$$

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

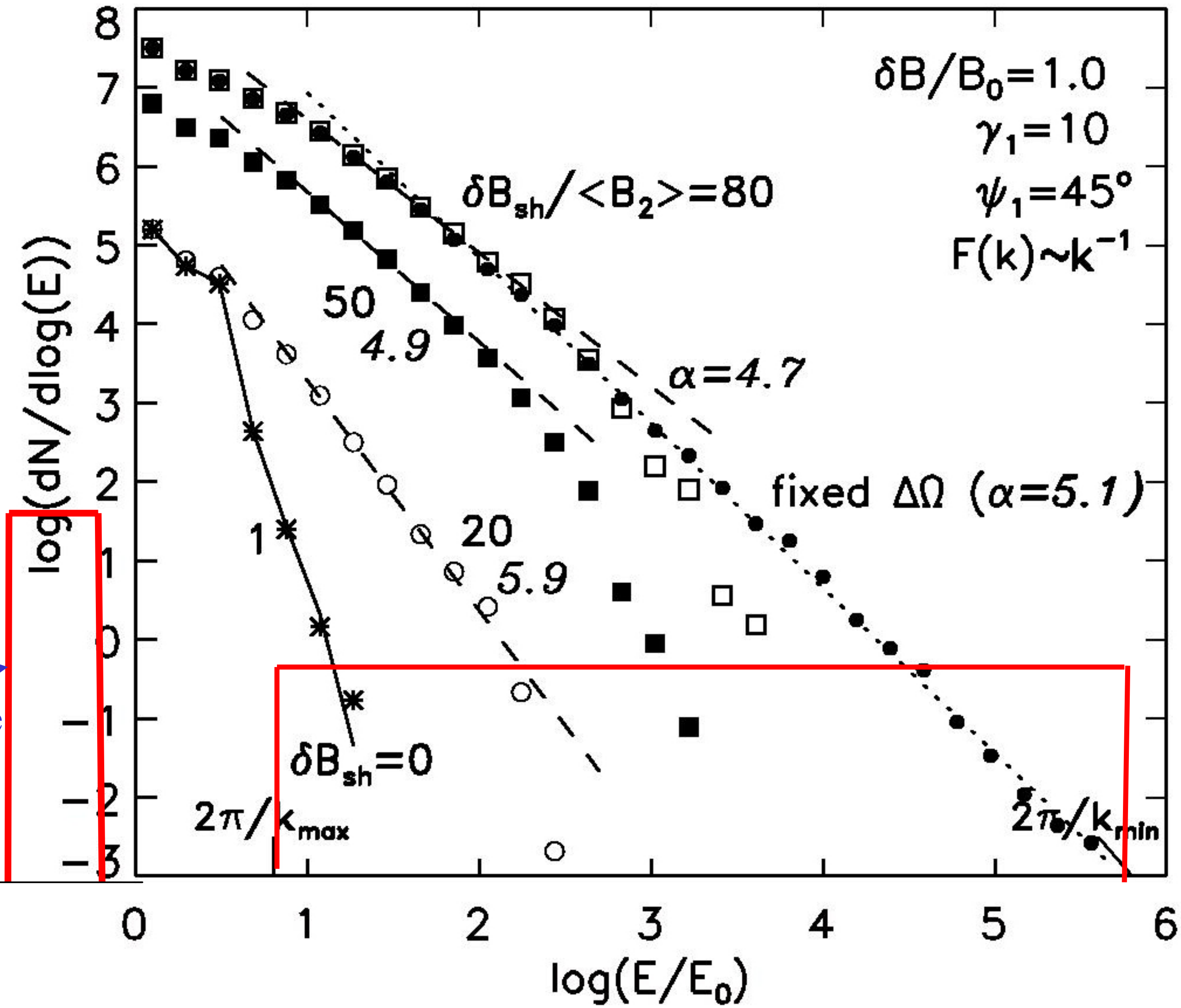


No spectra with $\sigma \approx 2.2$ appeared in these simulations

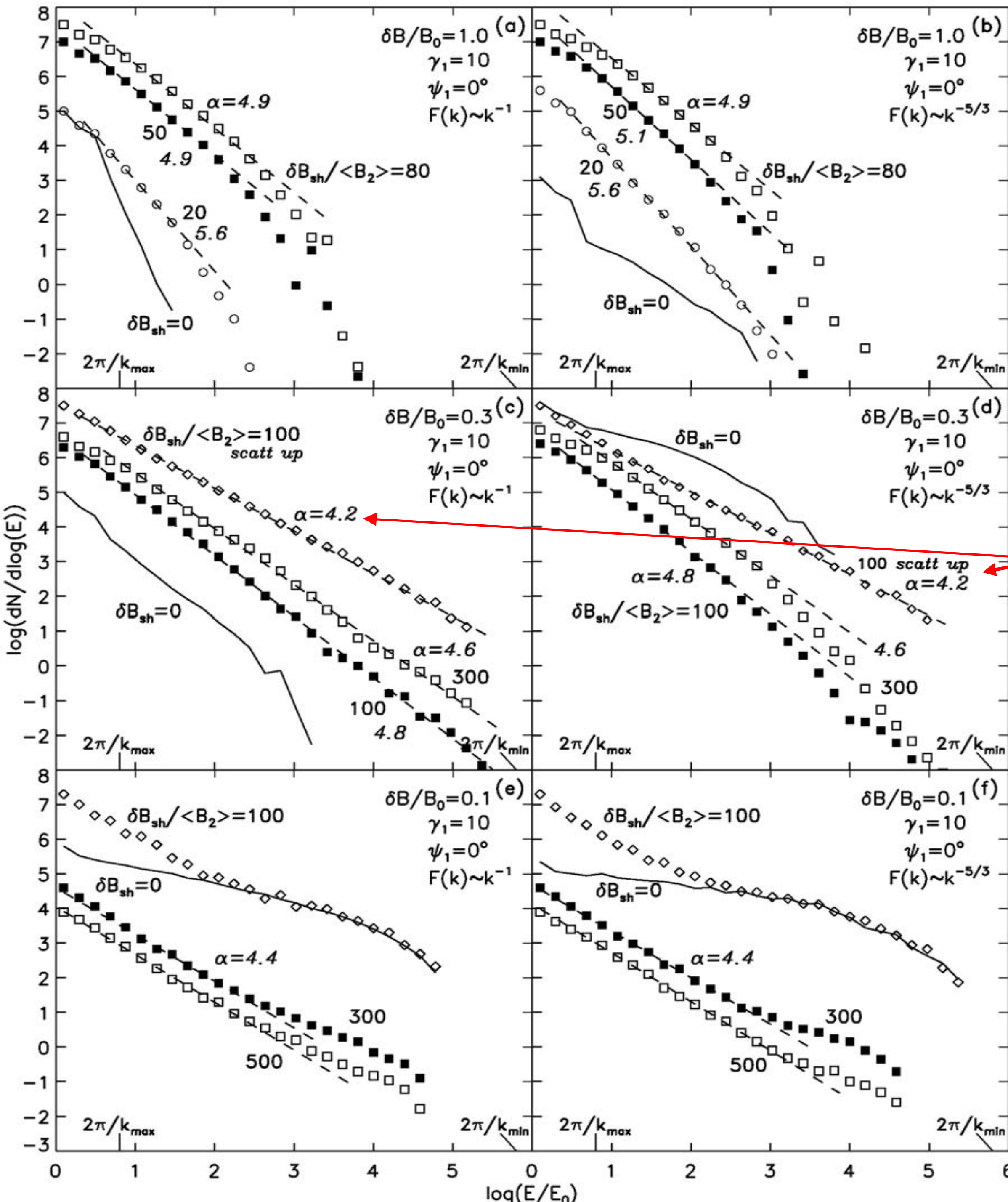
Ultrarelativistic shock waves with "shock generated" downstream short-wave turbulence

$\gamma_1 = 10$

short wave
MHD turbulence



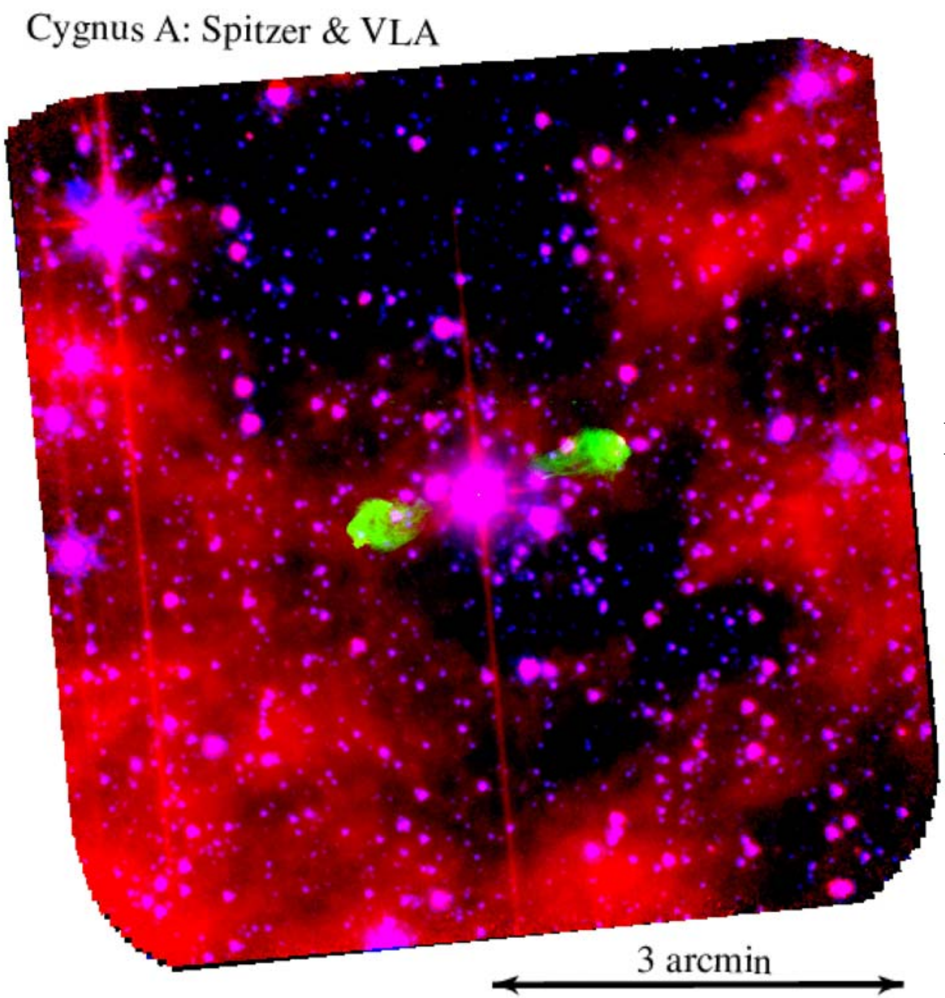
Parallel shock ?

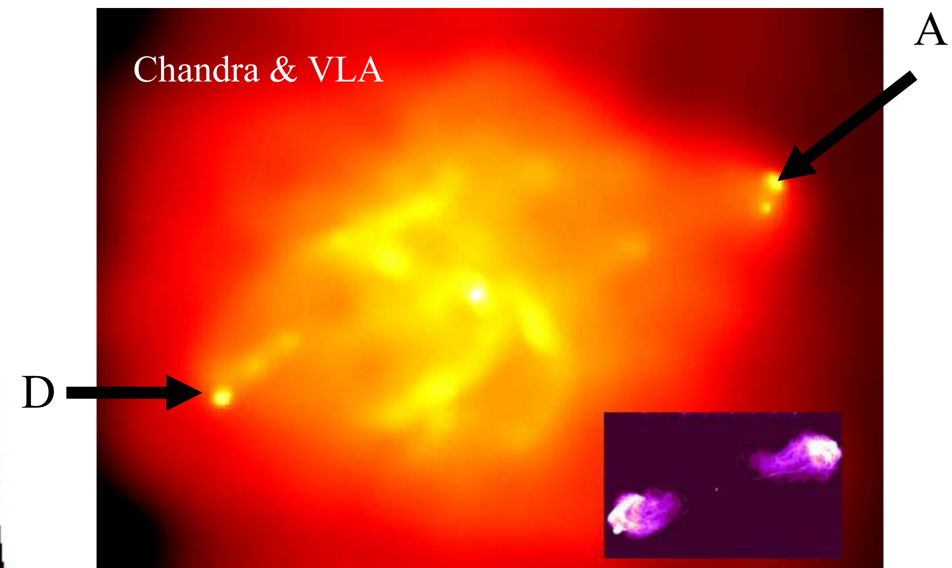


universal spectral index for unphysical scattering

No "universal" spectral index recovered !

Observational constraints for relativistic shock acceleration: Cygnus A hot spots



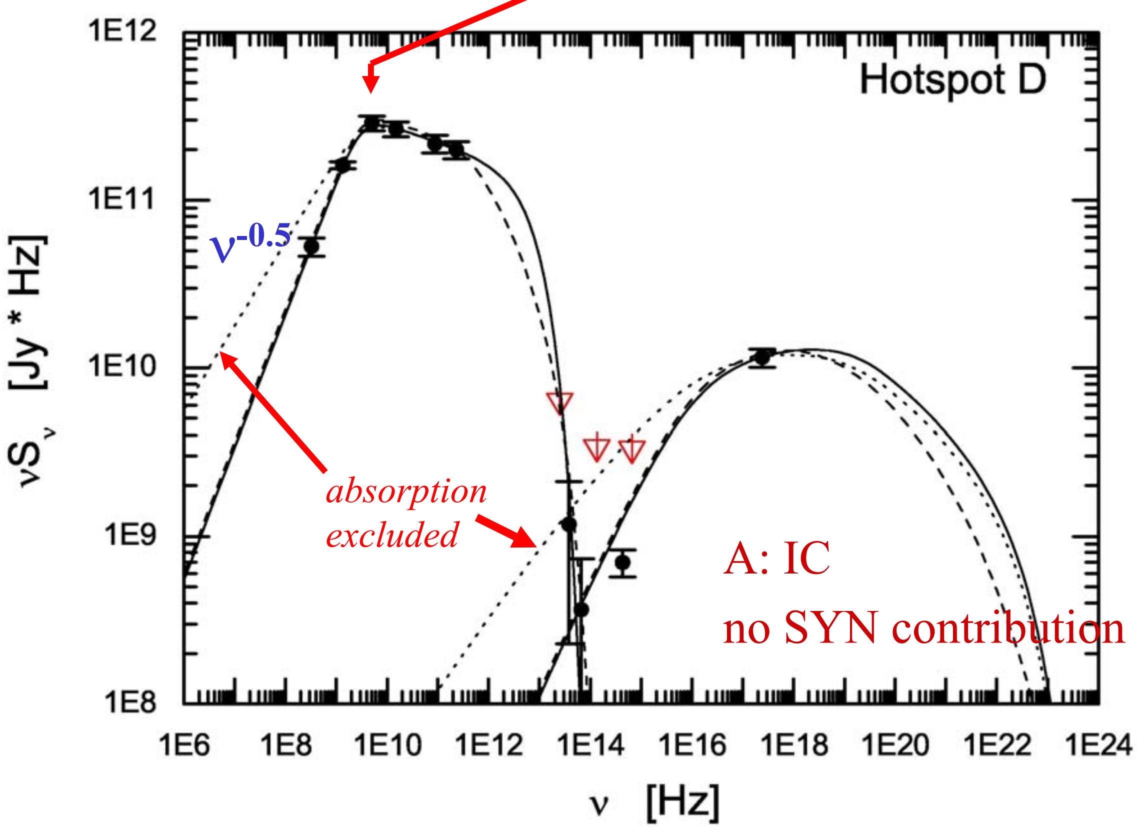


from Stawarz et al. (*ApJ 2007*)

$$S_\nu^{syn} \propto \begin{cases} \nu^{-\alpha_1} & \text{for} \quad \nu_{\min} < \nu < \nu_{cr} \\ \nu^{-\alpha_2} \exp(-\nu/\nu_{\max}) & \text{for} \quad \nu > \nu_{cr} \end{cases}$$

or with the second break with Δα=0.5 (dashed line)

α_1=0.21 , α_2 = 1.1 , ν_{cr} = 3.1 GHz , ν_{max} = 0.9 10^{13} Hz

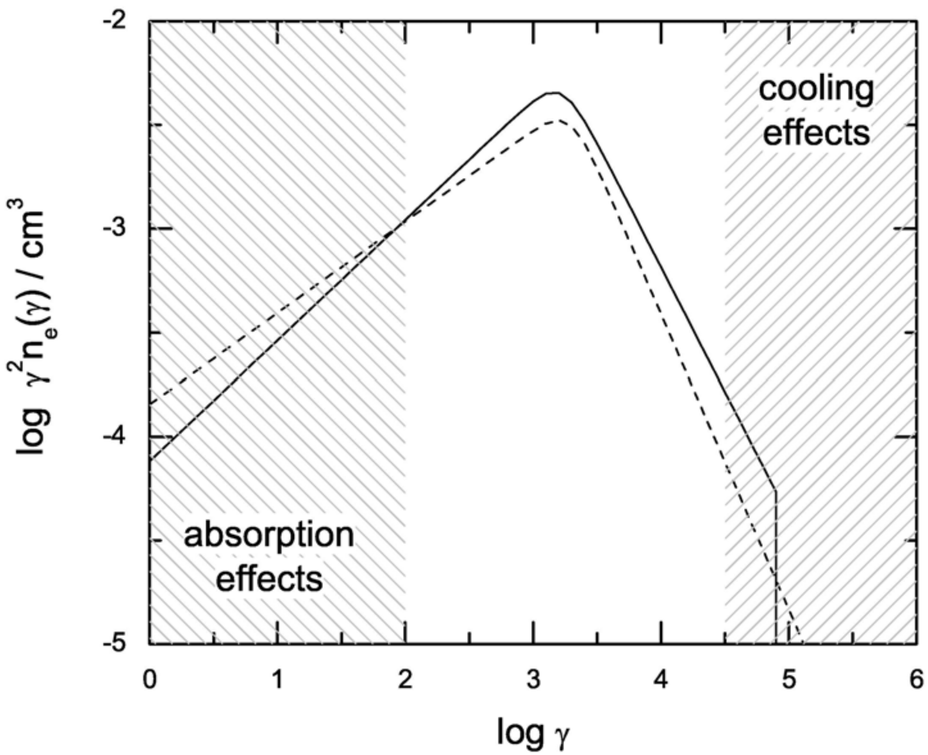


$$\nu_{\min} = \frac{3eB}{4\pi m_e c} \gamma_{\min}^2 \approx 4.2\, B_{\mu G}\, \gamma_{\min}^2$$

$$\gamma_{\min} \leq 300$$

B_{IC} = 270 μG

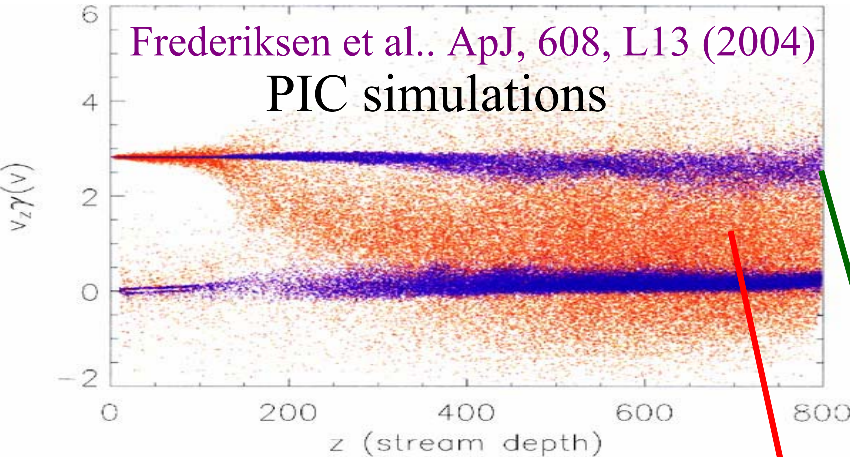
Electron spectra in Cyg A hotspots

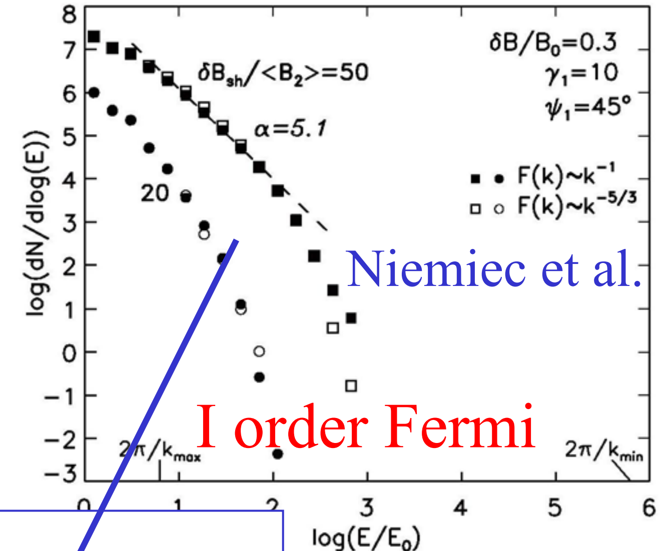


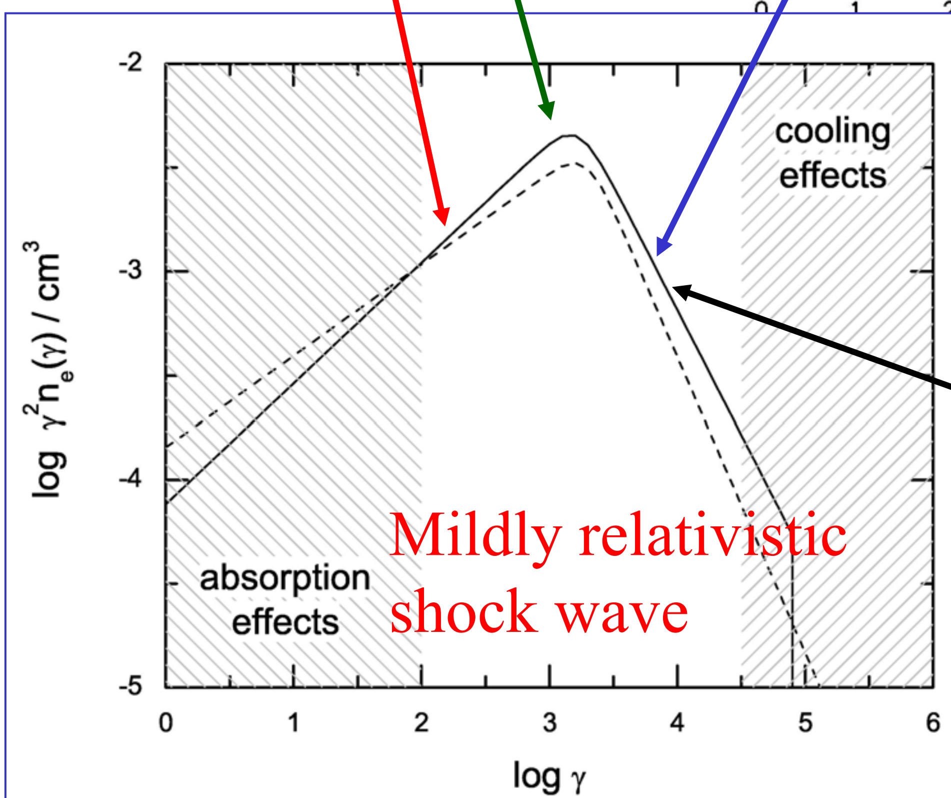
Electron energy distribution in Cygnus A hotspots: 'standard' electron spectrum $n_e(\gamma) \propto \gamma^{-2}$ is apparently absent

- the critical break energy corresponds almost exactly to the mass ratio between protons and electrons, $\approx m_p/m_e$;
- the low-energy segment of the electron distribution continues down to at least $\sim 0.1\, m_p/m_e$, with flat power-law slopes of $\boxed{s \approx 1.5}$;
- the high-energy part of the electron continuum is very steep, with $\boxed{s > 3}$ and maximum energies $\gtrsim 50\, m_p/m_e$;
- curved spectrum is not likely to result from absorption/cooling effects, but seems to be intrinsic to the hotspots.

Simple interpretation (*figures for illustration only*):







or II order (?)

Relativistic shock acceleration - conclusions

Wide range of the studied physical conditions **do not allow** for generation of particle spectra, which are

1.) wide range power-laws

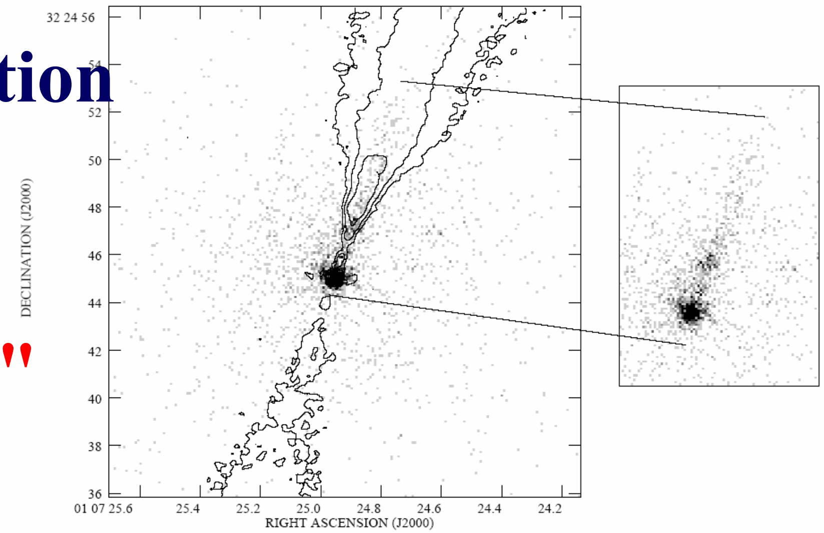
2.) with the universal spectral index $\sigma \approx 2.2$ (usually much steeper)

Remark:

CR spectra generated at ultrarelativistic shocks **are not** expected to extend to very high energies – thus postulating such shocks (with Fermi I acceleration) to be sources of UHE CR particles is doubtful

Relativistic shear layer acceleration at boundary of relativistic jet:

II order Fermi or "CR viscosity"



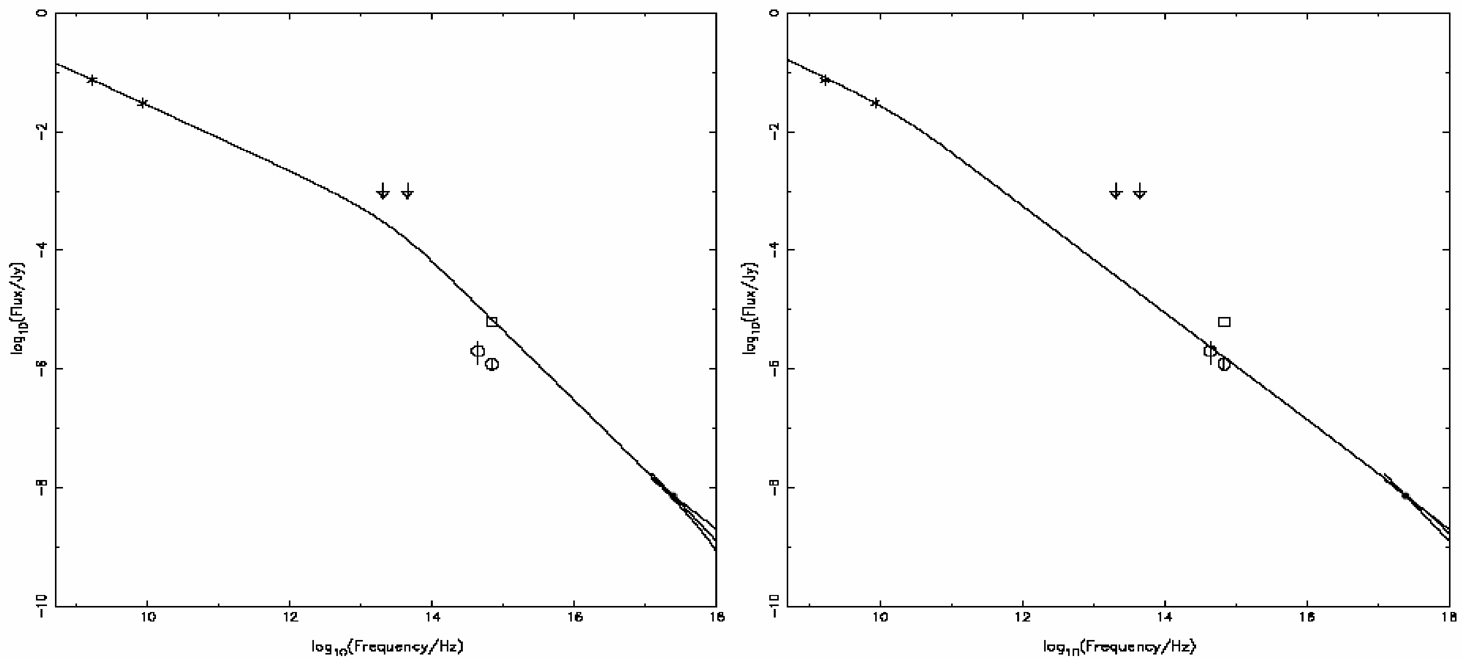


Figure 2. The radio-to-X-ray spectrum of the jet of 3C 31, based on the whole 6-arcsec region of the jet detected with *Chandra*. Radio points (stars) are taken from the data of Laing & Bridle (2002a); the infra-red data points (crosses) are upper limits derived from our ISO observations (Tansley et al. 2002); the high optical data point (box) is the flux density of Butcher et al. (1980), while the lower optical data points (open circles) are the data of Croston et al. (in preparation); the filled circle is the X-ray flux density reported in the text. The 'bow tie' around the X-ray flux density illustrates the 1σ range of spectral index in the power-law fit to the jet spectrum. The solid lines show broken power-law synchrotron models of the kind discussed in the text: left, the model fitting the Butcher et al. optical flux, with a spectral break in the infra-red; right, the model fitting the Croston et al. optical fluxes, with a break in the mm-wave region.

II order Fermi acceleration in shocks and shear layers

- *jet terminal shocks* generate a lot of turbulence within hot-spots
- *plasma velocity shear* (e.g. at the jet side boundaries) generates turbulence
- B *reconnection processes* generate waves in jets, hot-spots and radio lobes
- CR *scattering within a velocity shear* layer is equivalent (for small λ) to the II order acceleration

Characteristic wave velocities, V ,

acceleration time scales, τ_{acc} ,

and maximum electron energies, γ_{max}

$$V = \frac{B}{\sqrt{4\pi\rho}}$$

$$\tau_{acc,\min} \approx T_g \frac{c^2}{V^2}$$

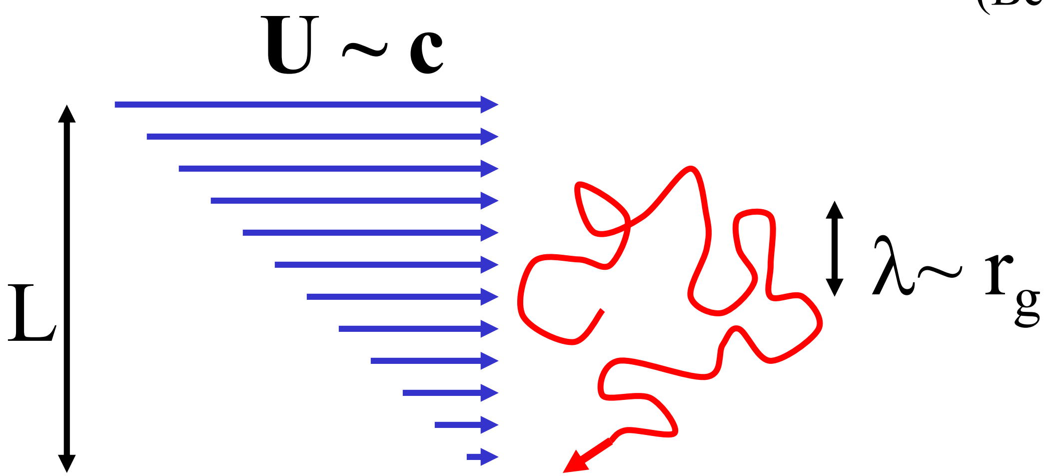
$$\tau_{syn}(\gamma_{\max}) = \tau_{acc,\min}(\gamma_{\max}) \longrightarrow \gamma_{\max} \approx 4 \cdot 10^8 \frac{V_8}{\sqrt{B_{\mu G}}}$$

For illustration with $\rho = n_p m_p$:

Small scale jet	$B \sim 1$ G	$n_p \sim 10^6$	$V \sim 0.01$ c	γ_{max} $\sim 10^6$ (1 TeV)	$\tau_{acc,min} \sim 10^3$ s
equipartition →		10^2	c	10^7	1 s
Large scale jet	0.1 mG	10^{-4}	0.1 c	10^9 (10^3 TeV)	10^2 yr
Hot spot	1 mG	10^{-4}	c	10^9	10^2 yr
Radio source lobe	10 μG	10^{-5}	0.03 c	10^9	10^3 yr

Shear layer acceleration (CR viscosity acceleration)

(Berezhko et al., beginning of 1980th)



$$\Delta U = U\frac{\lambda}{L}$$

$$\tau_{shear} \sim \frac{\lambda}{c}\left(\frac{c}{\Delta U}\right)^2 \sim \mathrm{T_g}\left(\frac{\mathrm{L}}{\mathrm{r_g}}\right)^2 \quad \text{for } \Delta U << c$$

$$\frac{\tau_{II}}{\tau_{shear}} \sim \left(\frac{c}{V}\frac{r_g}{L}\right)^2$$

For illustration: L = 100 pc , V = 0.01 c , B = 0.1 mG

$\sim 10^{-26}\,\gamma^2$ for electrons

$= 1$ for $\gamma \sim 10^{13}$ **(~ 10^4 TeV)** ⟶ **protons !**

II order Fermi acceleration

(or CR viscosity acceleration at higher particle energies),

and/or acceleration in the magnetic field reconnection regions

should be considered to be an interesting possible alternative for the I order shock acceleration, acting continuously within

- (downstream) regions near the shocks,
- radiosource hot spots
- small and large scale jets (boundary layers)
- radio lobes

even facing substantial mathematical and physical difficulties in the analysis.