Particle acceleration by relativistic shock fronts

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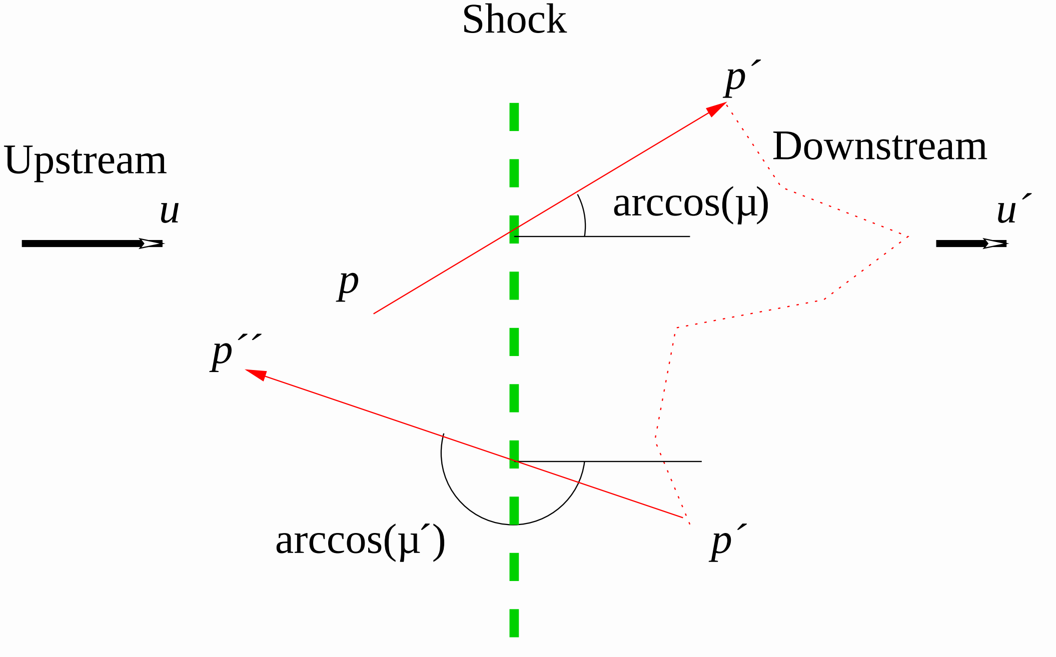
Topics

- First order Fermi processes—basics
- Diffusive shock acceleration vs. acceleration at relativistic shocks
- Shock physics
- Transport properties
- Injection

DSA (1977/8)

Scattering by (self-excited) turbulence around shock front

$$\frac{\Delta p}{p} = \frac{\Delta u}{v}\left(\mu - \mu'\right)$$



Isotropy implies

$$\frac{\langle \Delta p \rangle}{p} = \frac{4\Delta u}{3v}$$

and escape probability downstream $= 4u'/v$

DSA continued

Combining acceleration and escape gives

$$N(p) \quad \propto \quad p^{2-s} \text{ with } s \;=\; \frac{3r}{r-1} \text{ and } r = \frac{u}{u'}$$

- Power-law index a function of compression ratio r alone
- For a strong shock front $r = 4 \Rightarrow s = 4$

Comparisons

Nonrelativistic (DSA)	*Relativistic*
pitch-angle diffusion $\Rightarrow$ near-isotropy $\Rightarrow$ spatial diffusion	pitch-angle diffusion, particles in narrow, forward directed cone
solution of PDE in x, p required	solution of PDE in μ, x, p required
power-law of index $s = 3r/(r-1)$, independent of scattering law	power-law, index depends on scattering law
small escape probability, small $\langle \Delta p \rangle / p$ per cycle	escape probability ~ 0.5, $\langle \Delta p \rangle / p \sim \Gamma^2$ for first cycle, then ~ 2

Spectra

Eigenfunction expansion
$\Rightarrow$ angular dependence:

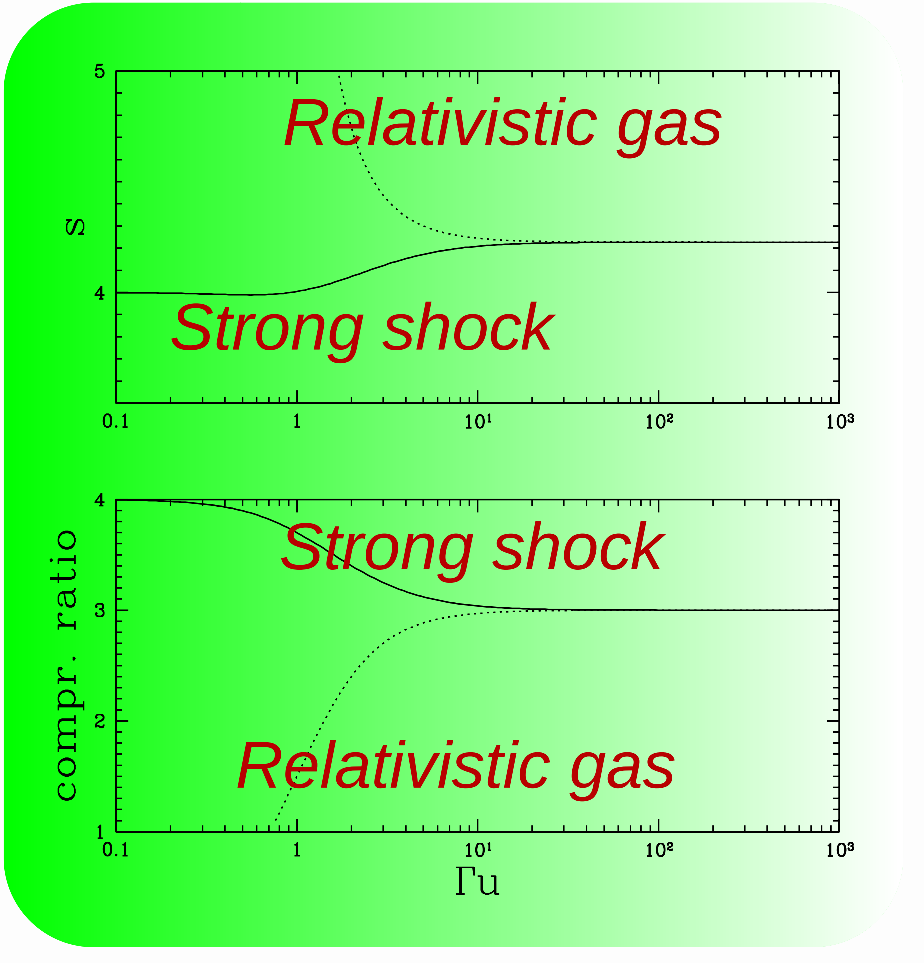
$$\frac{\exp\left(-\frac{1+\mu_{\rm s}}{1-\mu_{\rm s}u/c}\right)}{\left(1-\mu_{\rm s}u/c\right)^{s}}$$

Power-law index and compression ratio:

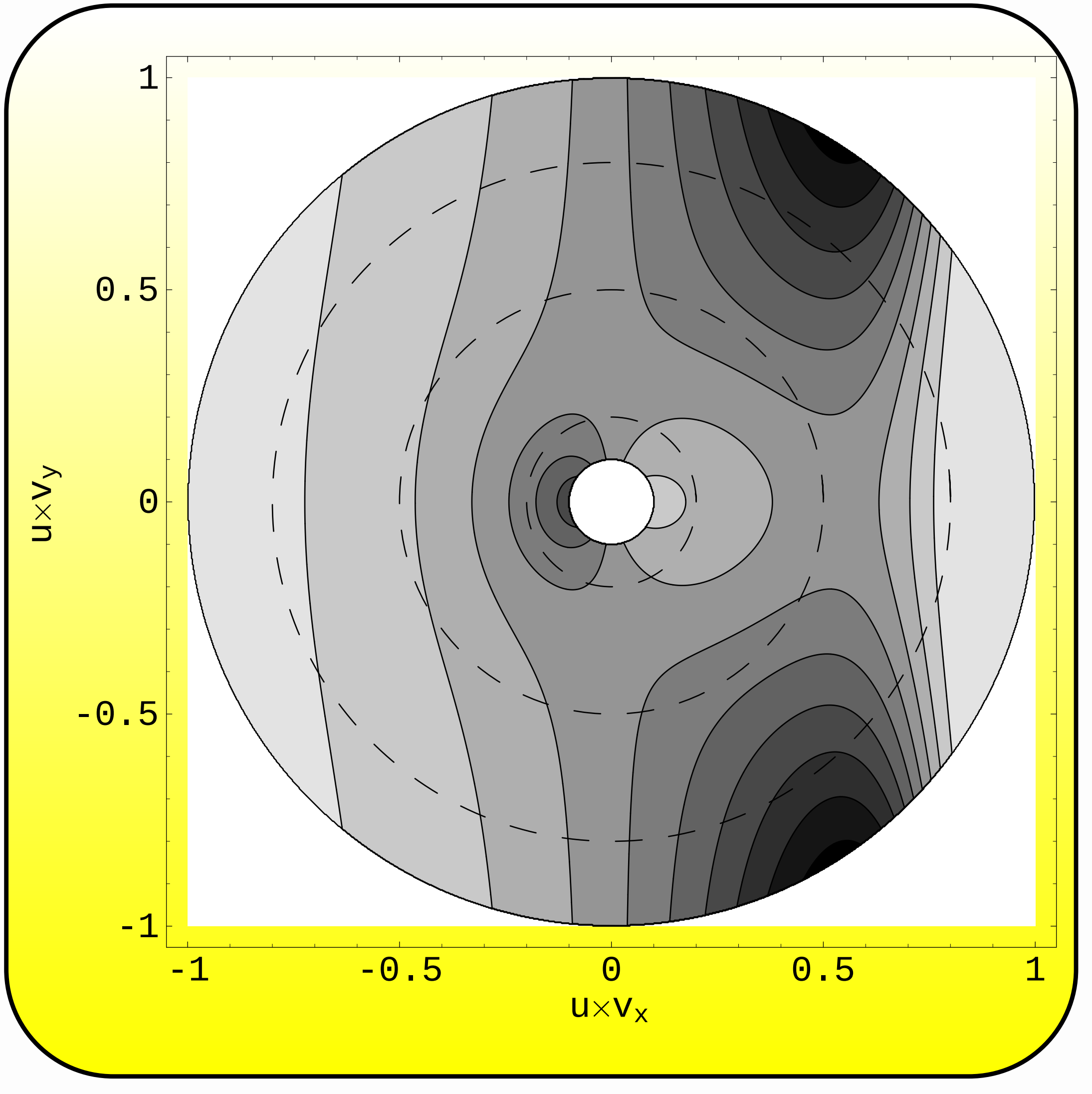
As $\Gamma \rightarrow \infty$, $s \rightarrow 4.23$

Universal index?

Kirk et al ApJ 542, 235 (2000)

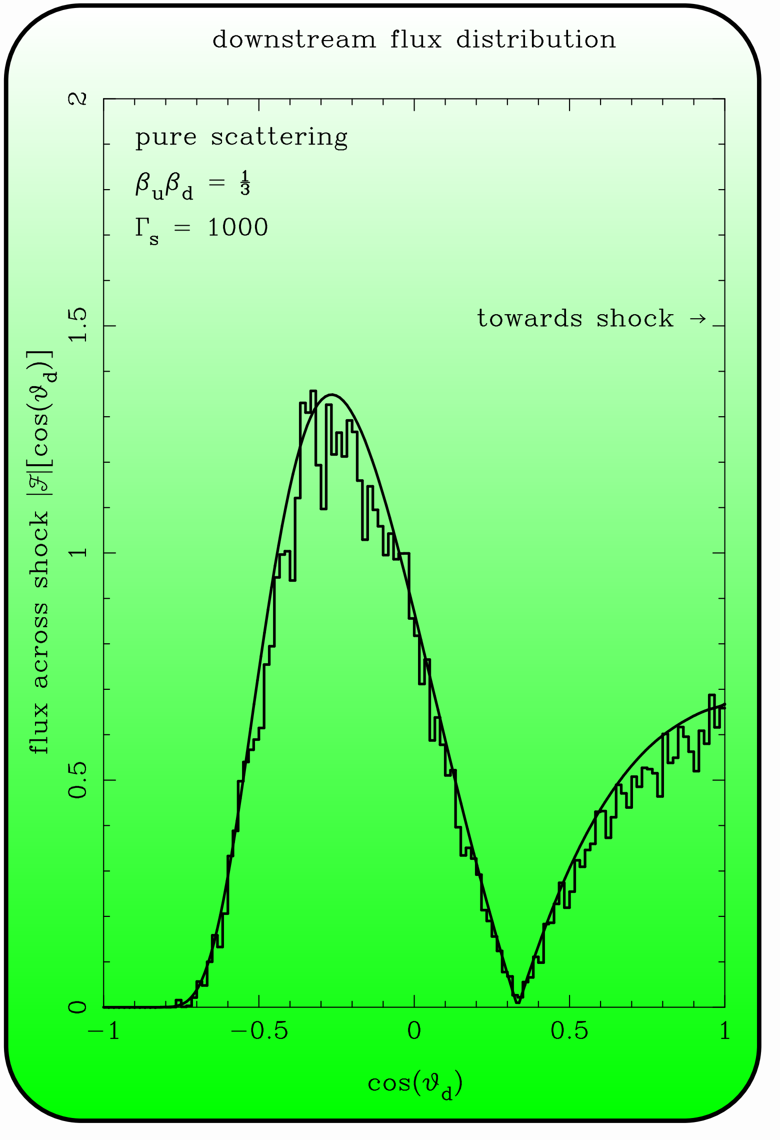


Loss cone



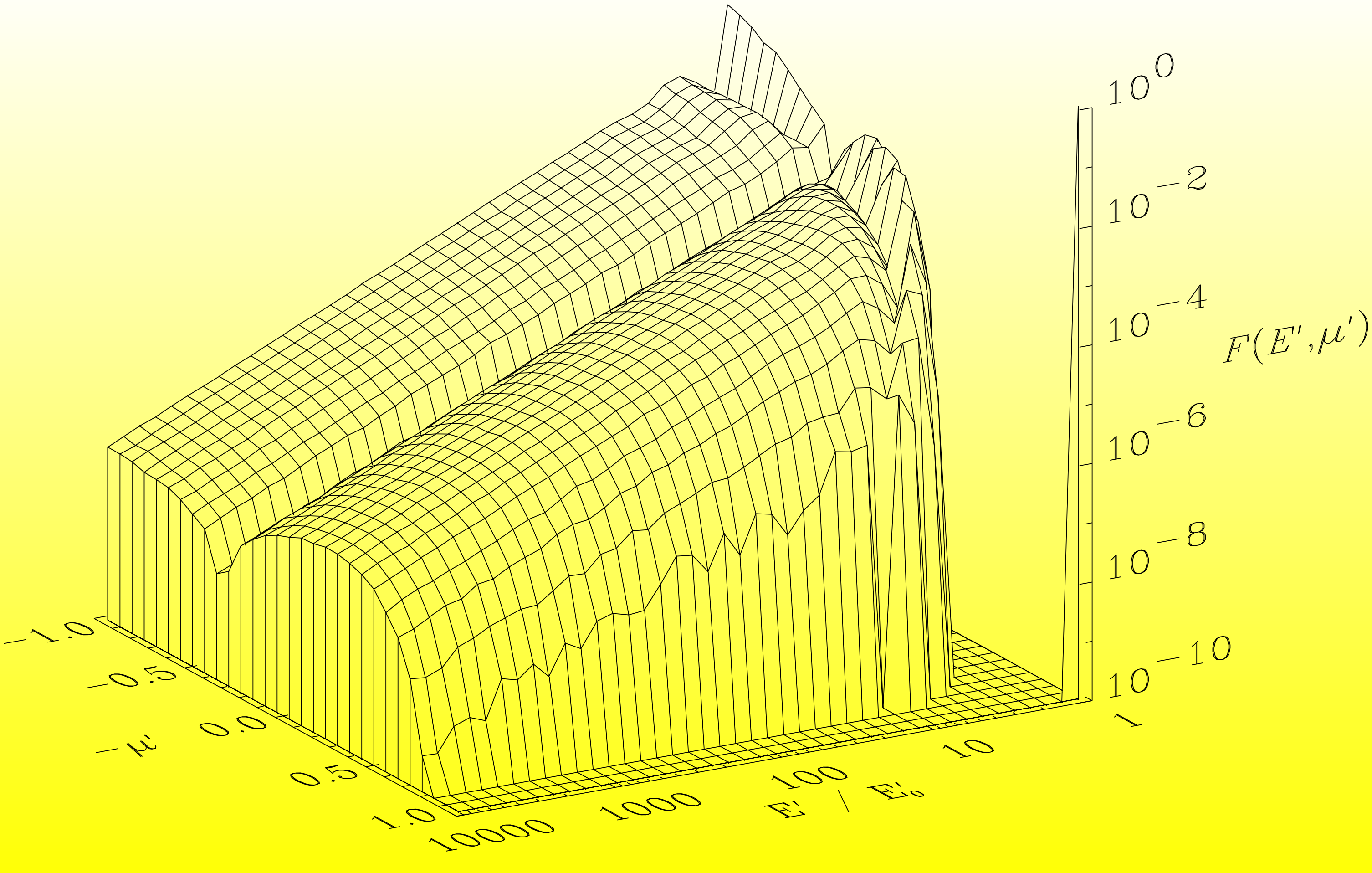
Angular distribution

Comparison of MC/analytic angular distributions



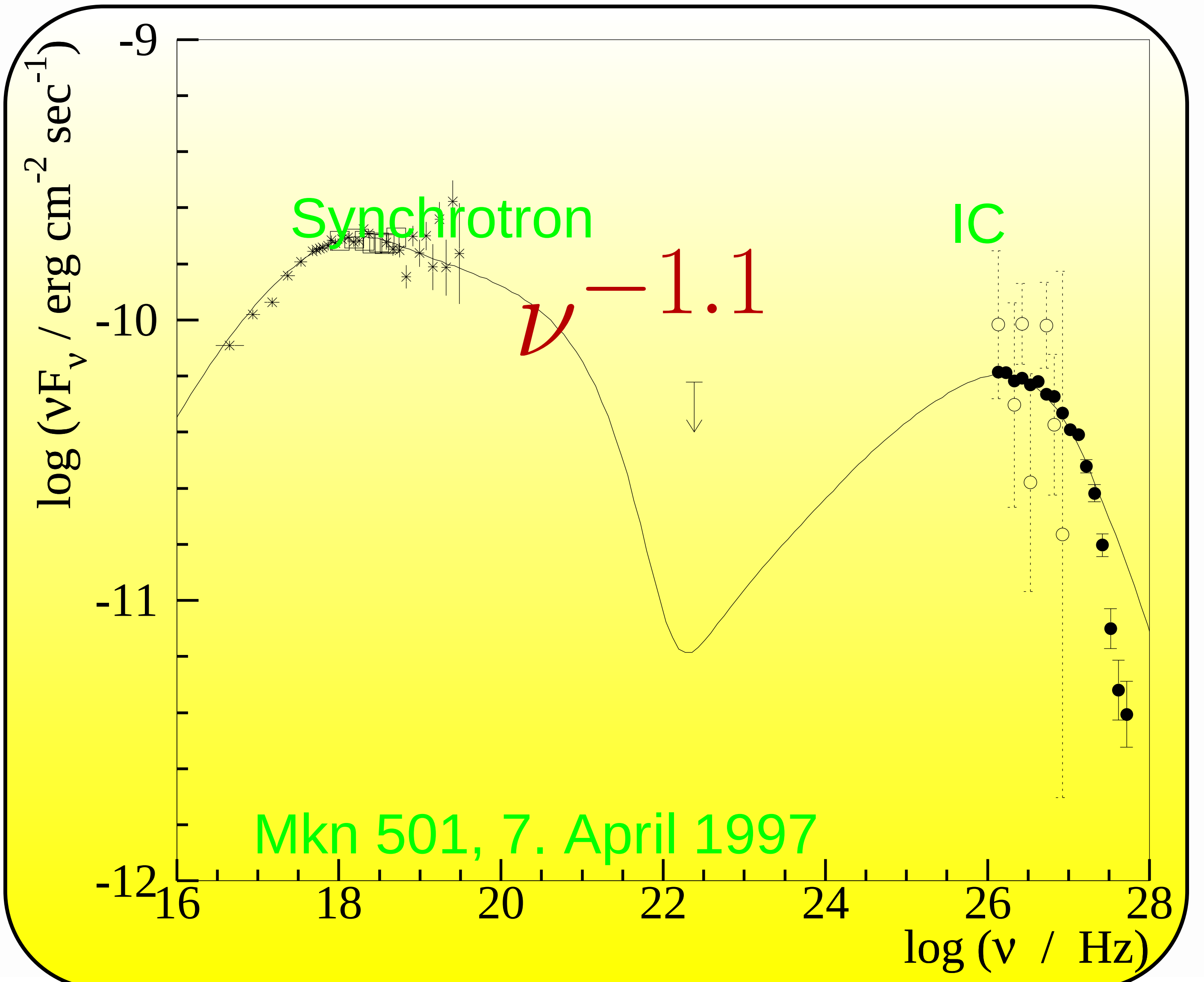
Achterberg et al
MNRAS 328, 393 (2001)

Ultra rel. MC



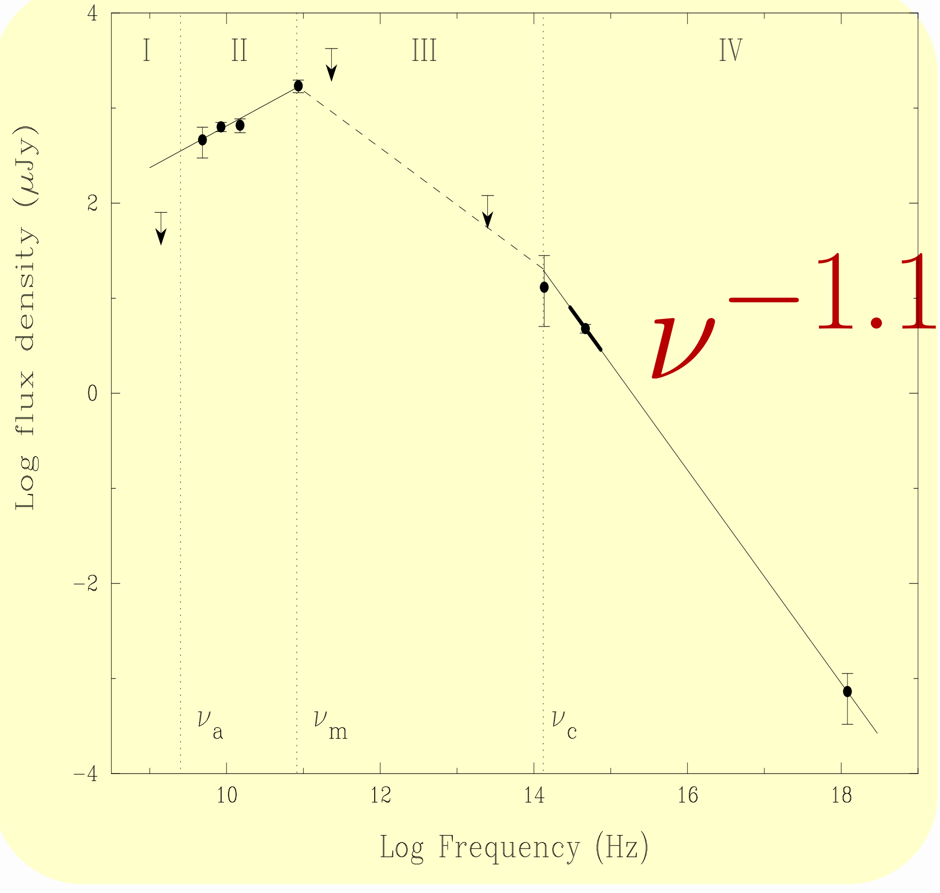
Monte-Carlo simulations in limit $\Gamma \to \infty$

Application to Blazar



and to GRB

Observations of GRB 970508 (Galama et al 1998)



$\nu^{-1.1}$ cooled electrons:

$$\frac{d \ln F}{d \ln \nu} = -\frac{s-2}{2}$$

Shock Physics 1

- Equation of state: for relativistic gas ($e \gg \rho$):

$$\frac{v_-}{v_+} \to 3 \qquad \Gamma_{\mathrm{rel}} \to \frac{\Gamma_{\mathrm{shock}}}{\sqrt{2}}$$

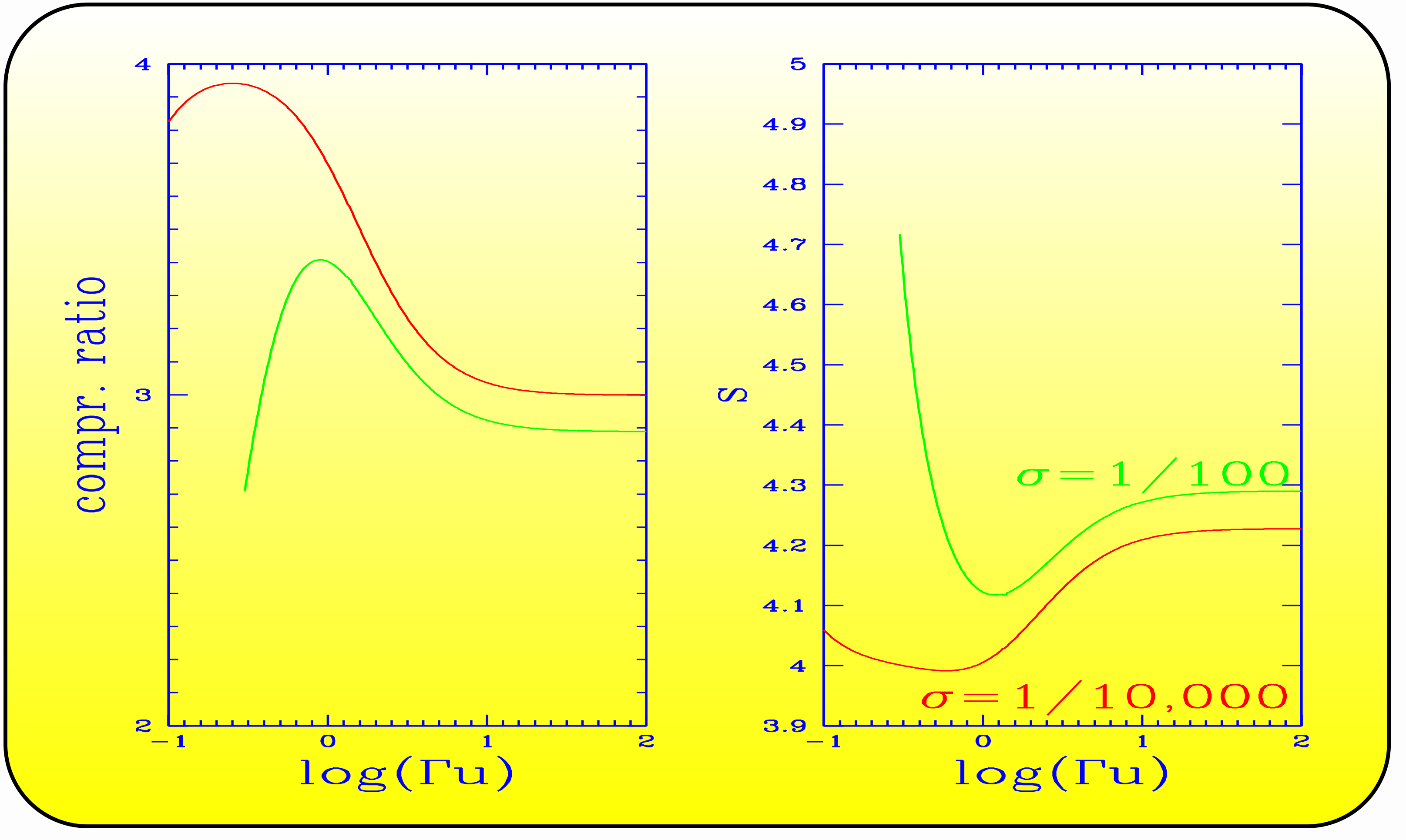
- But, inclusion of ambient magnetic field reduces compression, parameterised by

$$\sigma = \frac{B_-^2}{4\pi w} \quad \text{or} \quad M_{\mathrm{fast}} = v_- \sqrt{\frac{1+\sigma}{\sigma + c_{\mathrm{s}}^2}}$$

($w = 4e/3 = 4\langle\gamma\rangle n/3$, and $c_{\mathrm{s}} = 1/\sqrt{3}$.)

Magnetic field

Effect of ambient magnetic field



Shock Physics 2

- Field amplification (e.g., Weibel instability)

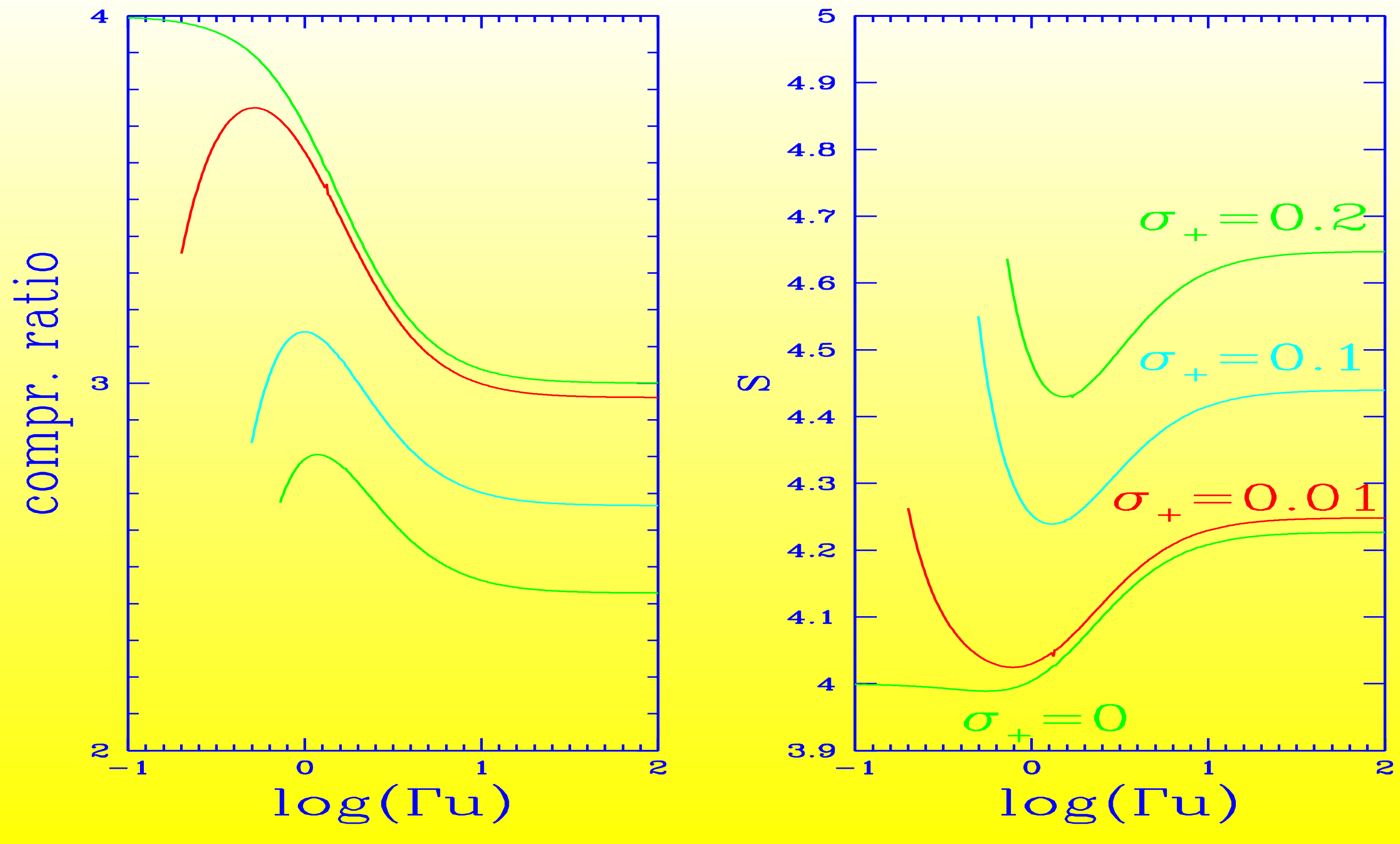
$$T^{\mu\nu} = \left(w + \frac{B^2}{4\pi}\right) u^\mu u^\nu + \left(p + \frac{B^2}{8\pi}\right) g^{\mu\nu} - \cancel{\frac{B^\mu B^\nu}{4\pi}}$$

If $\mathbf{B}$ in shock plane and $\langle \mathbf{B} \rangle = 0$,
$\gamma_{\rm eff} = 4(1+\sigma_+)/(3+2\sigma_+)$

$$\frac{v_-}{v_+} \to (\gamma_{\rm eff} - 1)^{-1} \quad \text{and} \quad \Gamma_{\rm rel} \to \Gamma_{\rm shock}\sqrt{\frac{2-\gamma_{\rm eff}}{\gamma_{\rm eff}}}$$

Downstream magnetic field

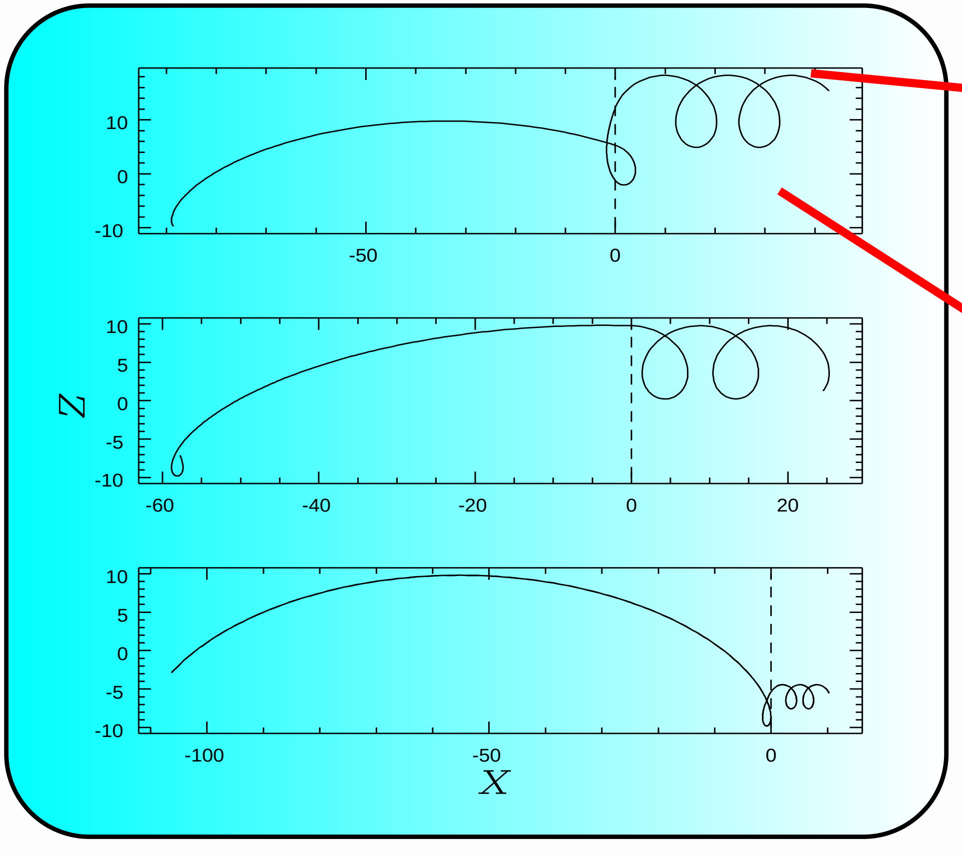
Effect of shock-generated magnetic field

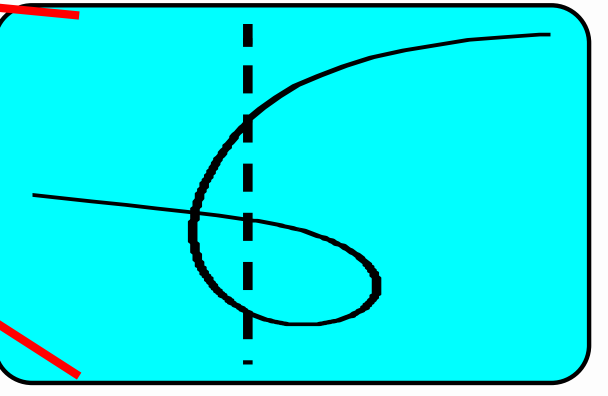


Transport properties 1

Field orientation: $B_\parallel = B'_\parallel$, $B_\perp = \Gamma_{\rm shock} B'_\perp$.

Large $\Gamma \Rightarrow$ perpendicular *superluminal* shocks.





Particle overtaken in small fraction of a gyration

Transport properties 2

- No scattering $\Rightarrow$ *no stochastic acceleration*
- Regular vs. stochastic deflection upstream—minor effect on spectrum (Monte-Carlo: Achterberg et al 2001)
- Presence/absence of downstream scattering—also a minor effect (Monte-Carlo: Ostrowski & Bednarz 2000)
- Anisotropic diffusion?

Relativistic Weibel instability

Yang et al (1993, 1994)

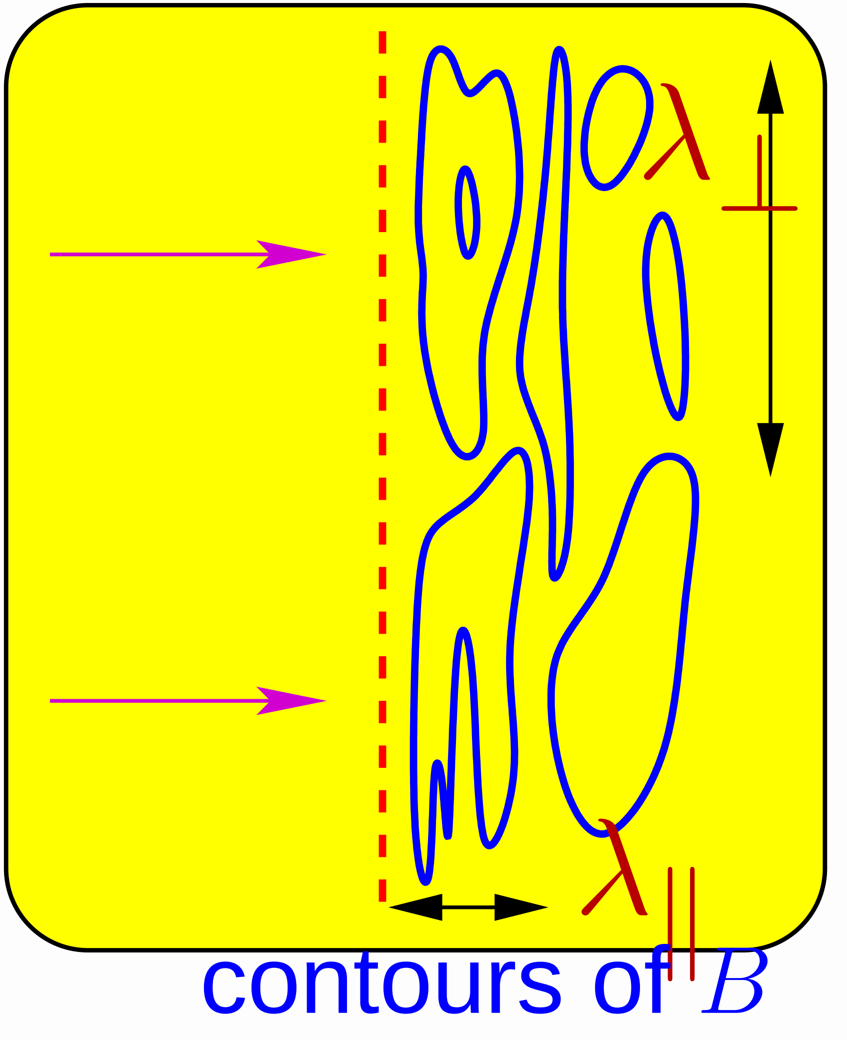
Medvedev & Loeb (1999)

Wave length:

$\lambda_\perp \approx \lambda_{\max} \approx c/\omega_{\mathrm{p}}$

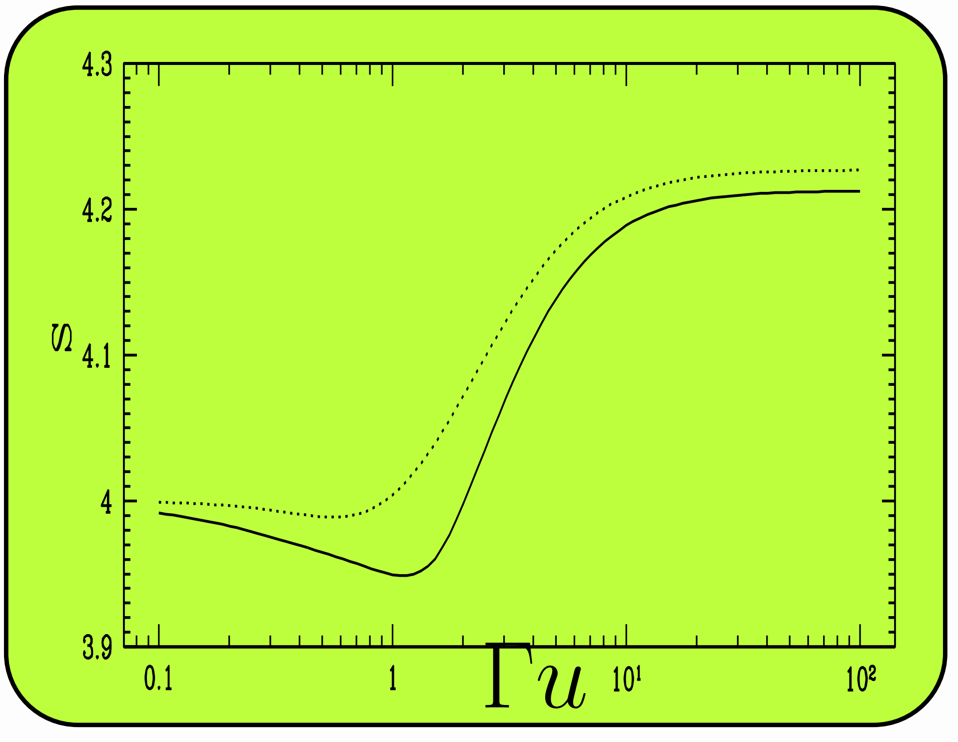
Growth-length:

$\lambda_\parallel \approx v_+/\omega_{\mathrm{p}}$



Anisotropic scattering

Effect of anisotropic scattering



$$D_{\mu\mu} \propto \frac{1-\mu^2}{\sqrt{\mu^2+\left(\lambda_{\parallel}/\lambda_{\perp}\right)^2}}$$

For large $\Gamma_{\rm shock}$
and $\lambda_{\parallel}/\lambda_{\perp} = 1/10$

$$\Delta s \approx 0.02$$

Injection

- Thermalised vs. accelerated particles: $\lambda_{\rm gyro} > \lambda_{\|}$
  $e^- e^+$-plasma $\Rightarrow \ \gamma > \text{few} \ \times \Gamma_{\rm shock}$
  $e^- p$-plasma $\Rightarrow \ \gamma > (M/m) \ \times \Gamma_{\rm shock}$
- Pre-acceleration? Synchrotron resonance for positron-ion coupling *Gallant et al (1994)*
- Soft spectrum $s > 4 \Rightarrow$ *linear* effect (in nonrelativistic theory highly nonlinear)

Conclusions

- Robust prediction of spectral slope ($s = 4.2$–4.3 for strong ultrarelativistic shock)
- Nonlinearity weak (compared to nonrelativistic case)
- Injection mechanism needed for $e^{-}p$ plasmas (synchrotron maser?)