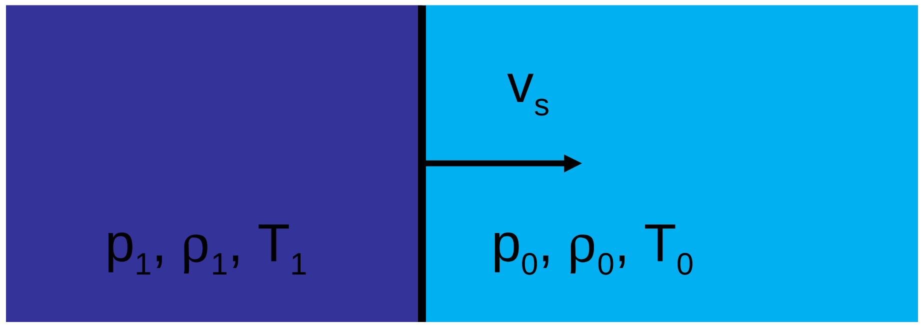
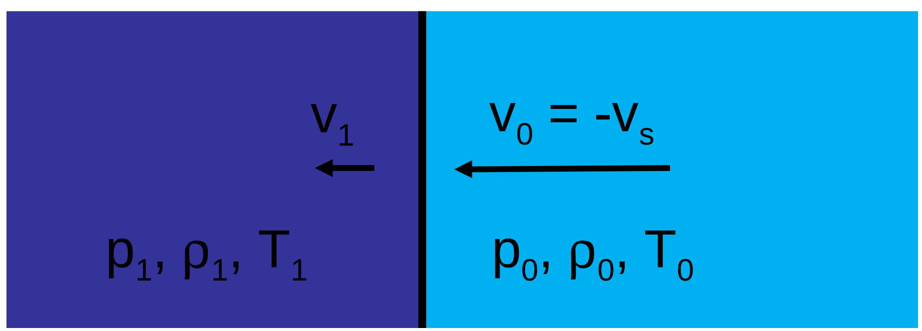
Shocks and Fermi-I Acceleration

Non-Relativistic Shocks

Stationary Frame



Shock Rest Frame

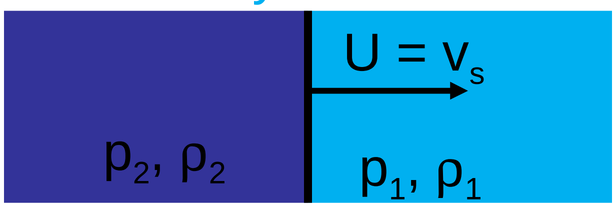


Particle Acceleration at Strong Shocks

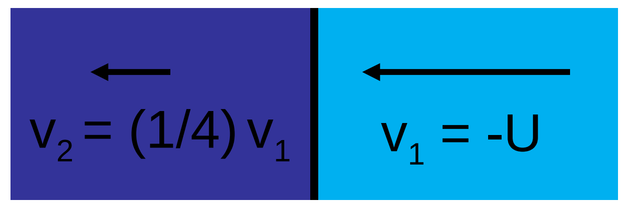
General Idea:

Particles bouncing back and forth across shock front:

Stationary frame of ISM

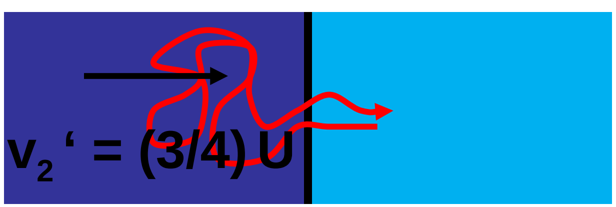


Shock rest frame

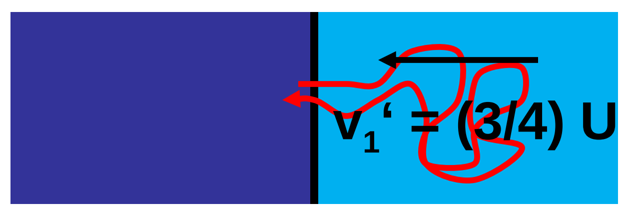


$v_1 \rho_1 = v_2 \rho_2$

$\rho_1 / \rho_2 = 1/4$



Rest frame of shocked material

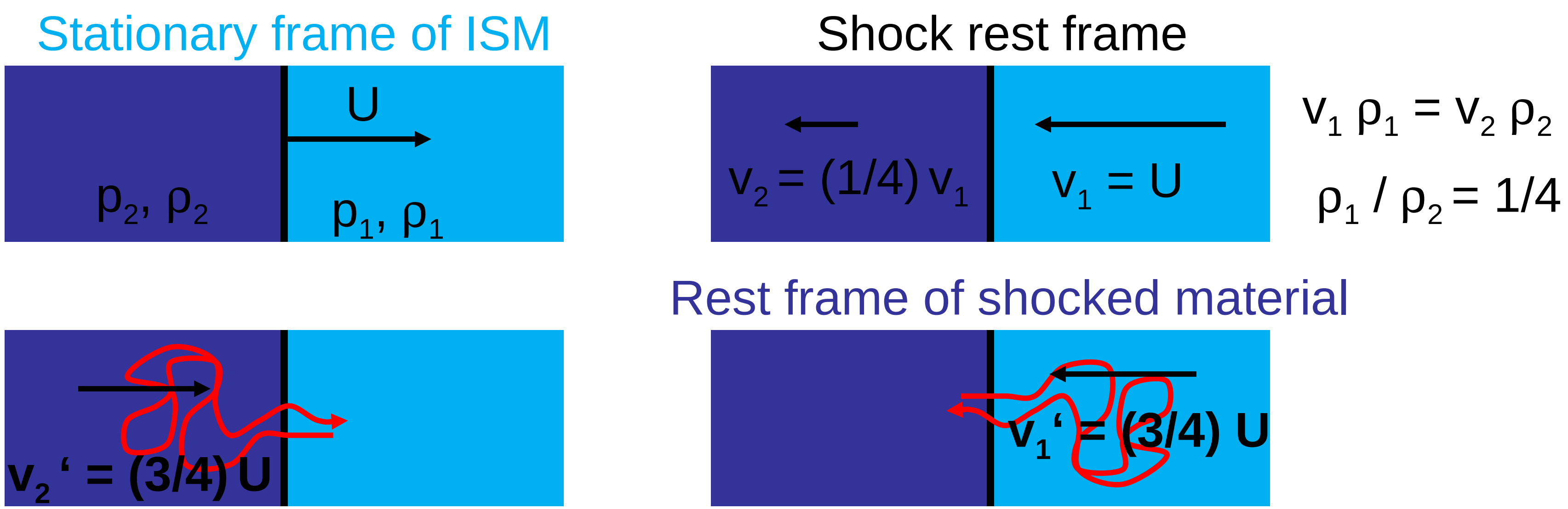


At each pair of shock crossings, particles gain energy

$$\langle \Delta E / E \rangle = (4/3)\, V/c = U/c$$

Write $E = \beta E_0 = (1 + U/c) E_0$; $\beta = 1 + U/c$

Particle Acceleration at Strong Shocks (cont.)



Flux of particles crossing the shock front in either direction:

$$F_{cross} = \tfrac{1}{4} Nc$$

Downstream, particles are swept away from the front at a rate :

$$NV = \tfrac{1}{4} NU$$

Probability of particle to remain in the acceleration region:

$$P = 1 - (\tfrac{1}{4} NU)/(\tfrac{1}{4} Nc) = 1 - (U/c)$$

Particle Acceleration at Strong Shocks (cont.)

Energy of a particle after k crossings:

$$E = \beta^k E_0$$

Number of particles remaining:

$$N = P^k N_0$$

$$\Rightarrow \ln(N[>E]/N_0) / \ln(E/E_0) = \ln P / \ln\beta = -1$$

or $N(>E)/N_0 = (E/E_0)^{\ln P/\ln\beta}$

$$\boxed{\Rightarrow N(E)/N_0 = (E/E_0)^{-2}}$$

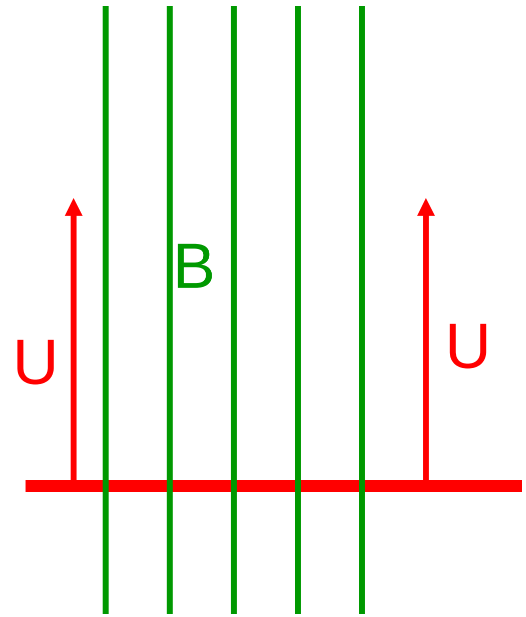
More General Cases

Weak nonrelativistic shocks

$p > 2$

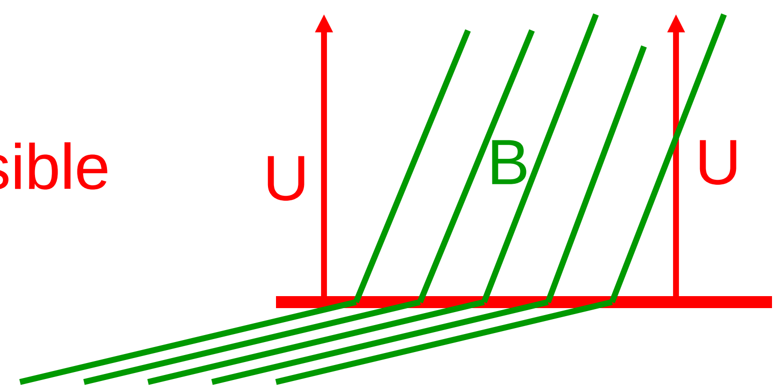
Relativistic parallel shocks:

$p = 2.2 – 2.3$

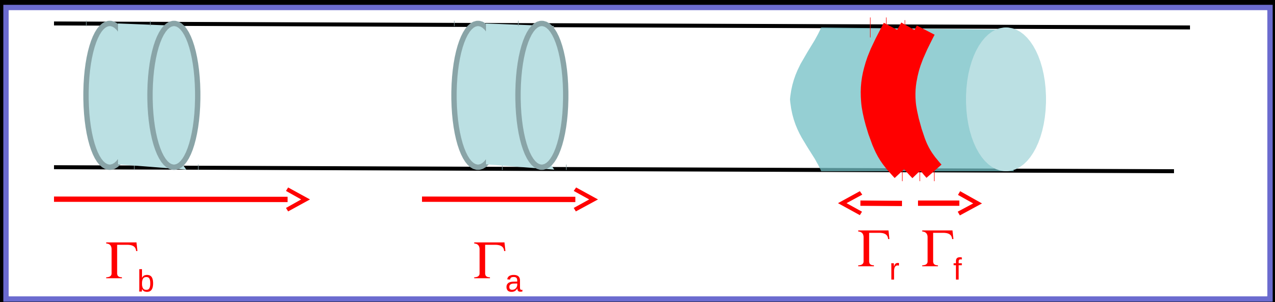


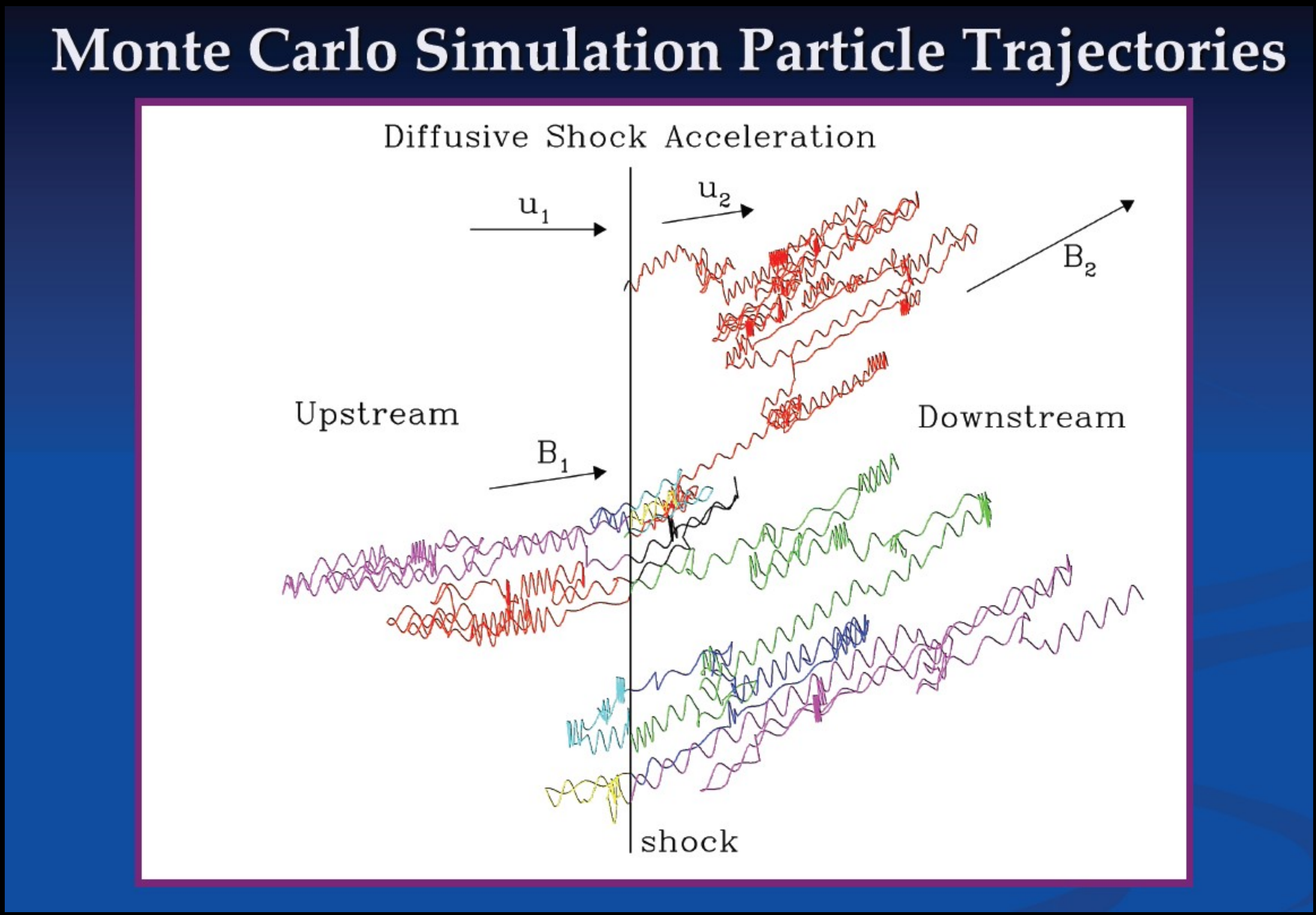
Relativistic oblique shocks:

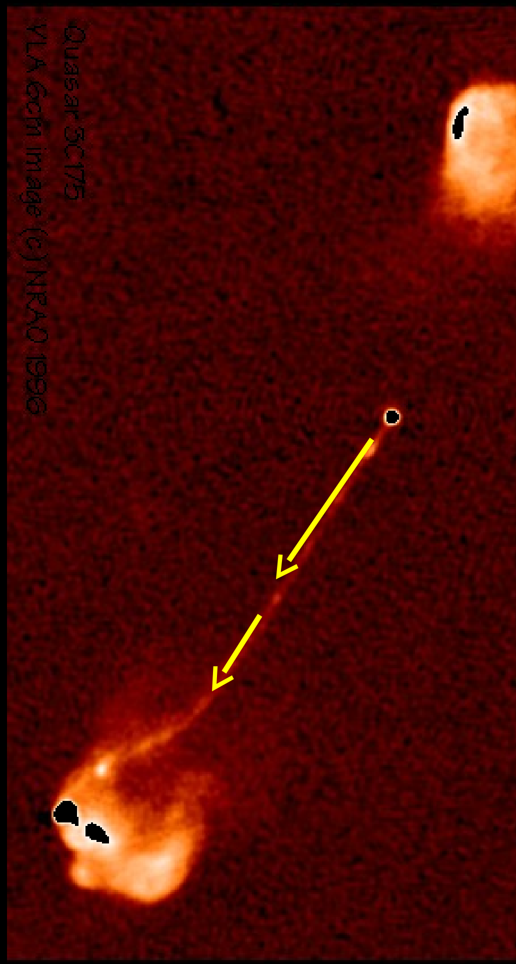
Almost any spectral index possible



Diffusive Shock Acceleration

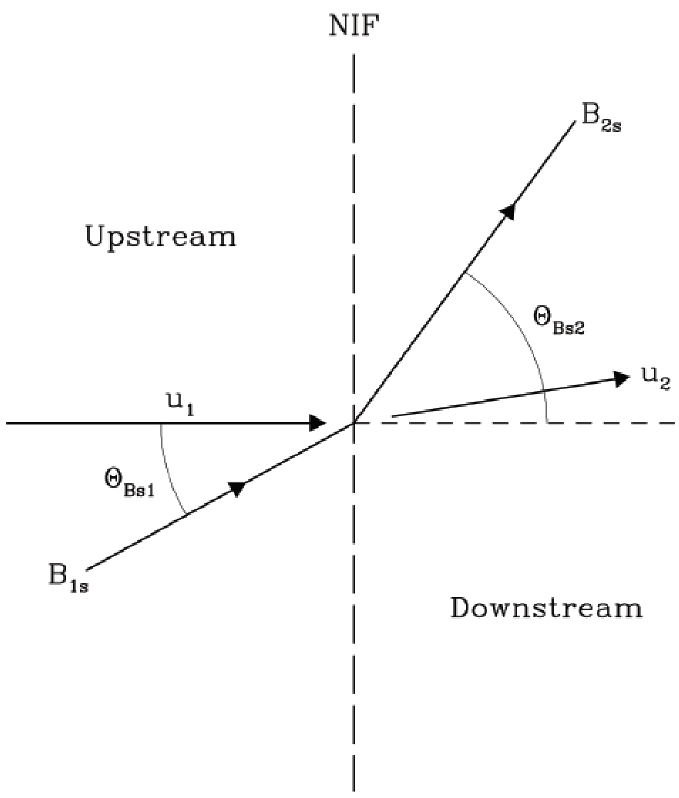




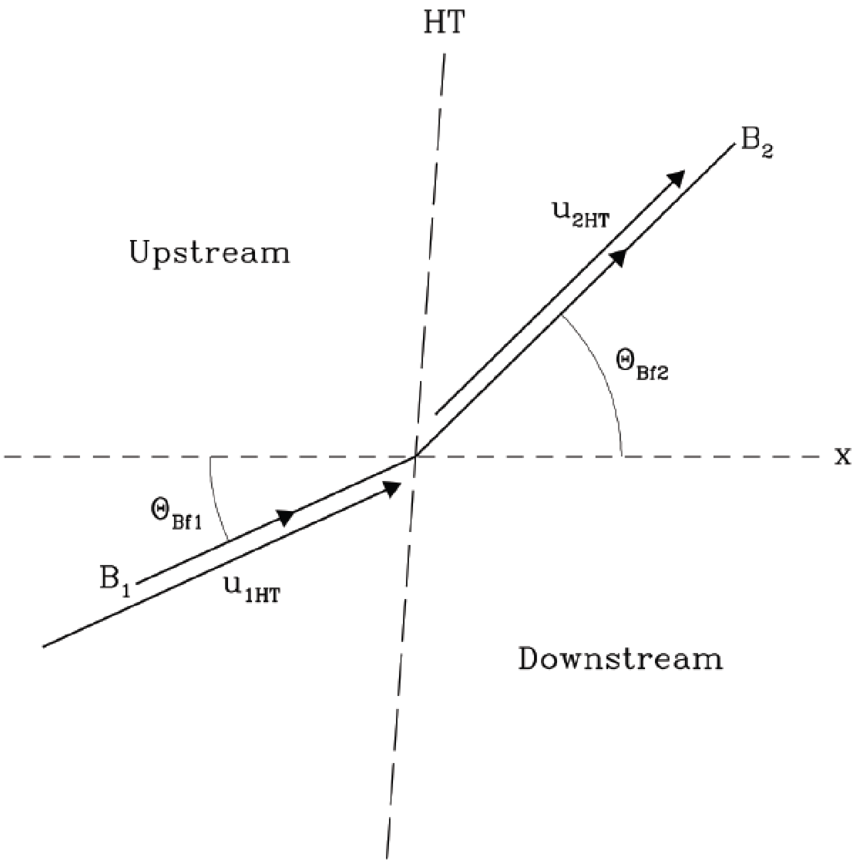


Diffusive Shock Acceleration

Particle retention in the shock layer is extremely sensitive to the magnetic field angle w.r.t. the shock normal in relativistic shocks.



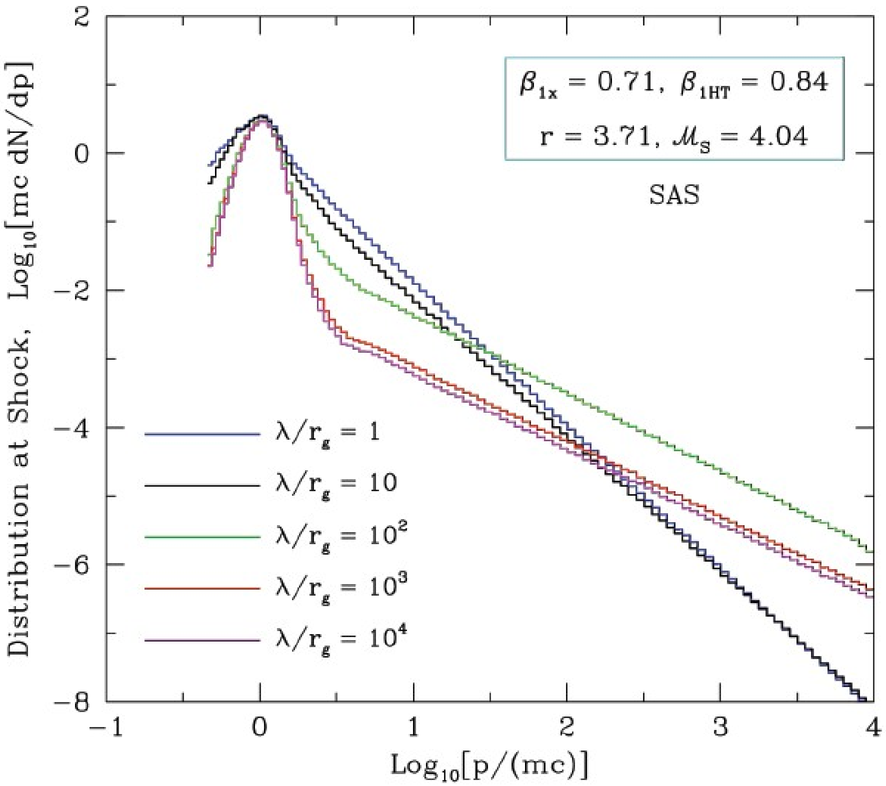
Normal Incidence Frame (NIF)



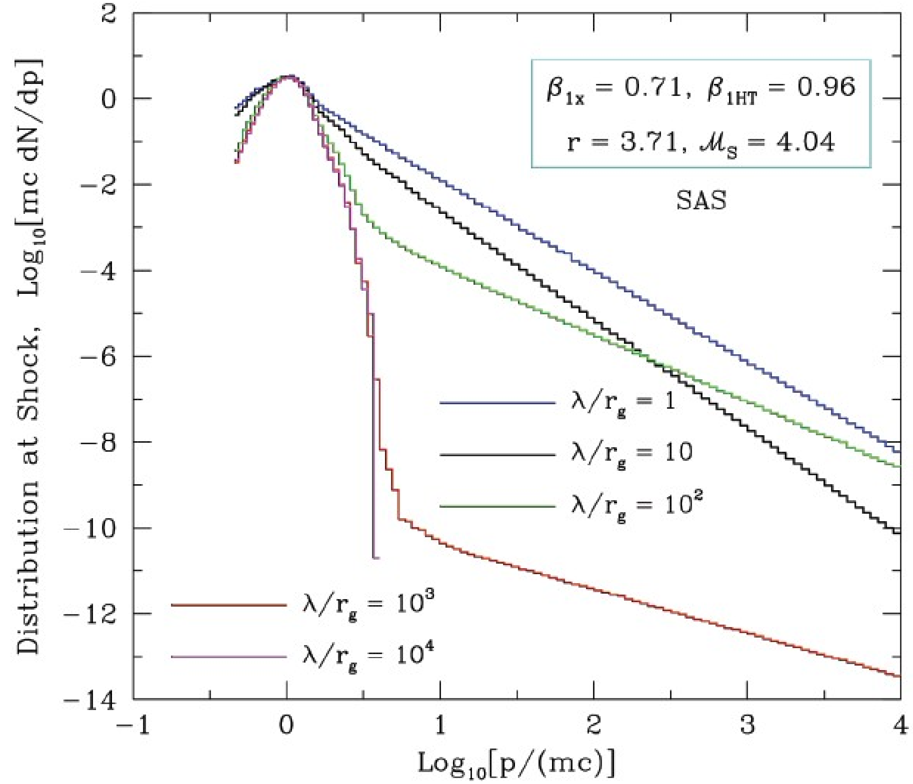
de Hoffmann-Teller frame (HT)

Electron Spectra from Diffusive Shock Acceleration

$\lambda = \eta * r_g$ = Pitch-angle scattering mean free path



Moderately sub-luminal
($\beta_{1HT} = \beta_{1x}/\cos\Theta_{Bf1} < 1$)

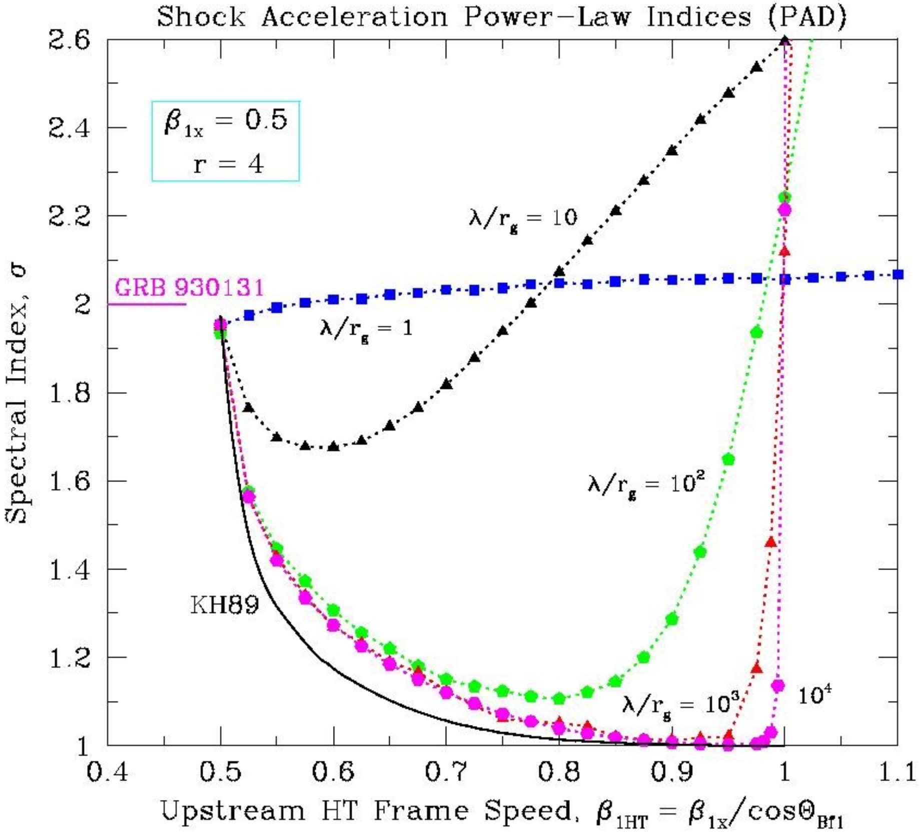


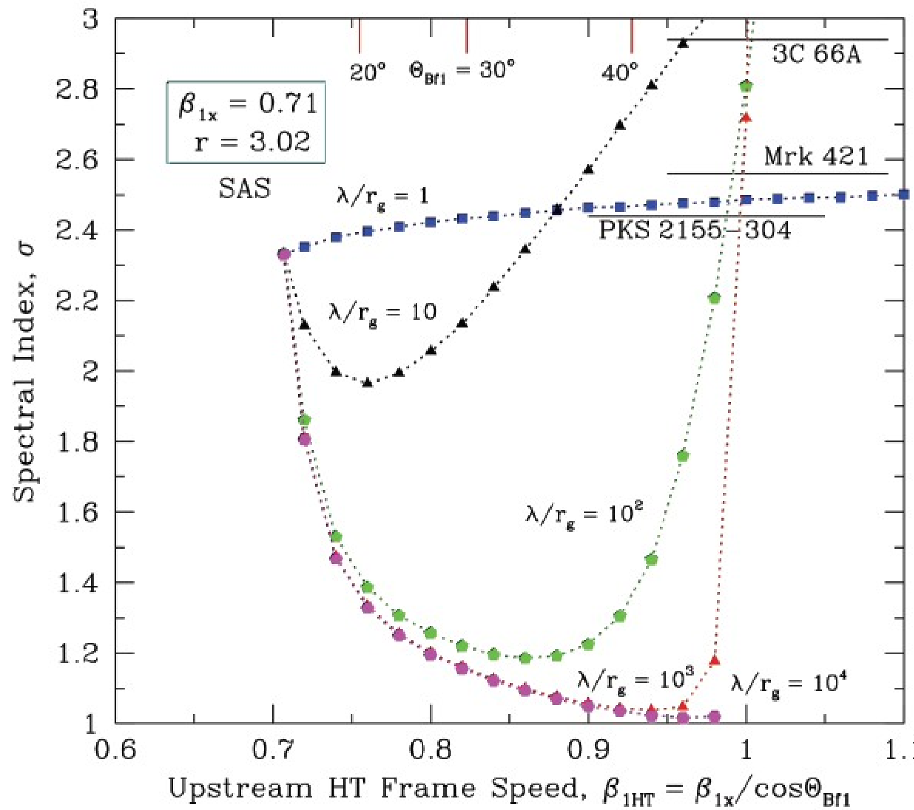
Marginally sub-luminal
($\beta_{1HT} = \beta_{1x}/\cos\Theta_{Bf1} \sim 1$)

(Summerlin & Baring 2012)

Asymptotic Particle Spectral Index

$n(\gamma) \sim \gamma^{-\sigma}$





(Summerlin & Baring 2012)

Effects of Cooling and Escape

Evolution of particle spectra is governed by the Continuity Equation:

$$\frac{\partial n_e(\gamma,t)}{\partial t} = -\frac{\partial}{\partial \gamma}(\dot{\gamma}\, n_e) + Q_e(\gamma,t) - \frac{n_e(\gamma,t)}{t_{esc,e}}$$

Radiative and adiabatic losses

Particle injection (acceleration on very short time scales)

Escape

Effects of Cooling and Escape (cont.)

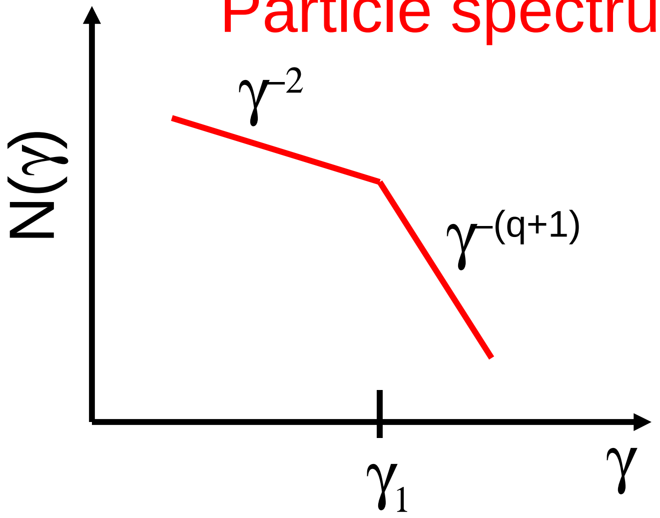
Assume rapid particle acceleration:

$Q(\gamma, t) = Q_0\, \gamma^{-q}$ $\quad\quad$ $\gamma_1 < \gamma < \gamma_2$

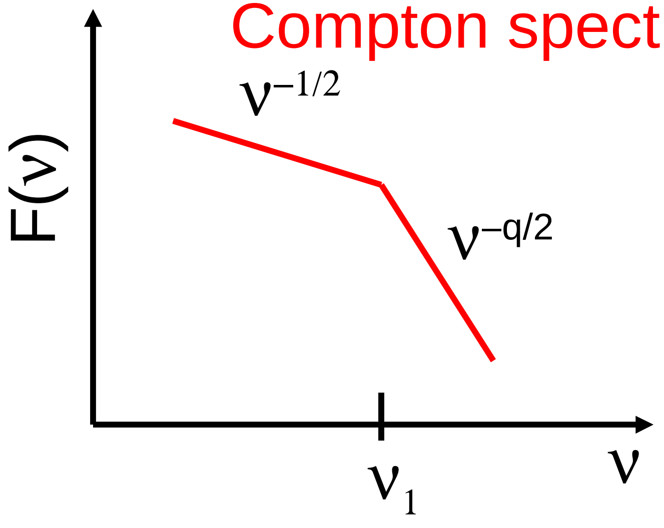
Fast Cooling :

$t_{cool} \ll t_{dyn}, t_{esc}$ for all particles

Particle spectrum:



Synchrotron or Compton spectrum:



Effects of Cooling and Escape (cont.)

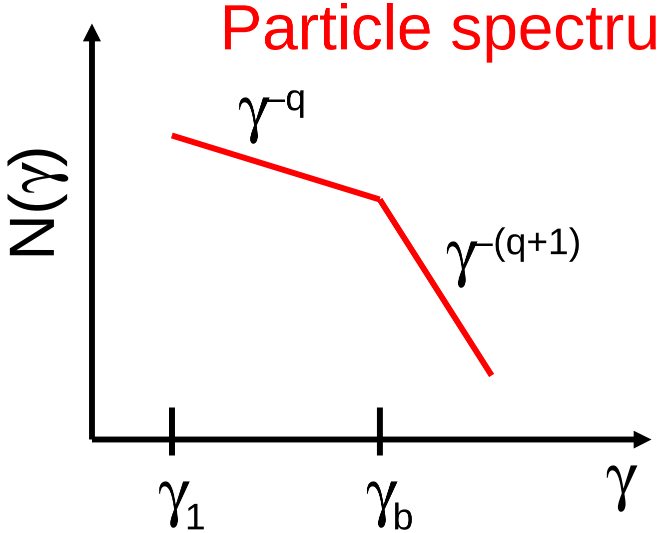
Assume rapid particle acceleration:

$Q(\gamma, t) = Q_0\, \gamma^{-q}$ $\qquad \gamma_1 < \gamma < \gamma_2$

Slow Cooling :

$t_{cool} \ll t_{dyn}, t_{esc}$ only for particles with $\gamma > \gamma_b$

Particle spectrum:



Synchrotron or Compton spectrum: