Diffusive Particle Acceleration (DSA) in Relativistic Shocks

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1) **Monte Carlo simulation of Diffusive Shock Acceleration (DSA) in collisionless shocks of arbitrary speed.**

2) **Includes non-linear feedback of particle pressure on shock structure, and consistent thermal injection model**

3) **Can do all shock speeds but emphasize trans-relativistic shocks**
   a) **GRB afterglows**
   b) **Type Ibc supernovae with long-duration X-ray transients and mildly relativistic ejecta**

4) **Here, only consider protons in parallel, steady-state shocks**

5) **Don Warren in next talk discusses electron acceleration**

For details and references to extensive literature on relativistic shocks, see Ellison, Warren & Bykov, ApJ 2013

1) Non-relativistic shocks (flow speed << c) are known to be efficient particle accelerators. Famous test-particle power law : → $f(p) \propto p^{-3r/(r-1)}$

2) Relativistic shocks are harder to study mathematically because they have highly anisotropic particle distributions ➔ Require Simulations
   a) Particle-In-Cell (PIC)
   b) Monte Carlo

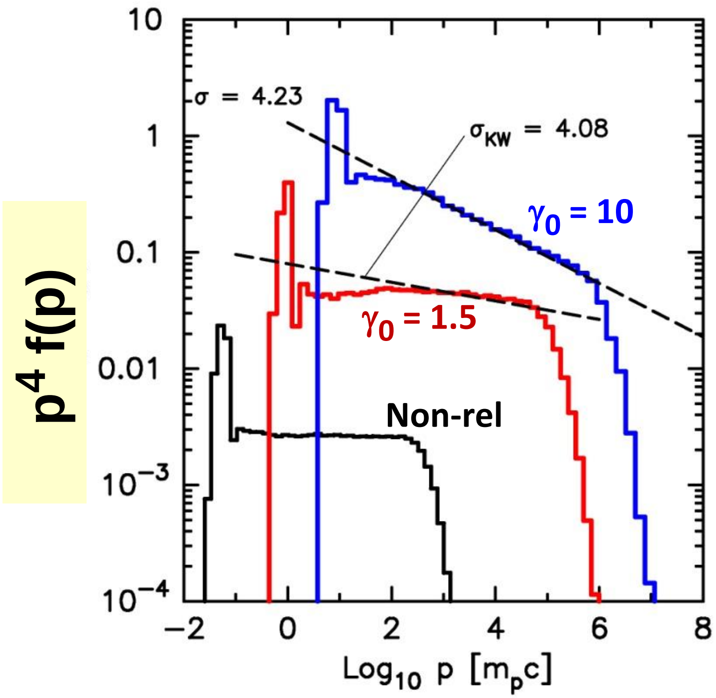
3) PIC has great advantage in that the plasma physics is done consistently:
➔ shock creation, B-field generation, particle diffusion & acceleration, for electrons and protons, all done self-consistently

4) However, computation time strong limit for PIC, particularly with 3-D requirement for cross-field diffusion ➔ small dynamic range

5) Monte Carlo assumes scattering law ($\lambda \propto$ gyro-radius) ➔ allows large dynamic range but must parameterize plasma physics

6) Use Monte Carlo to investigate non-linear effects from efficient DSA for applications that require large dynamic range, e.g., ultra-high-energy CRs

Test-Particle results :



Test-particle results:

1) For $V_{sk} << c$, strong shock has compression ratio $r \sim 4$ and $f(p) \propto p^{-4}$ (phase-space)

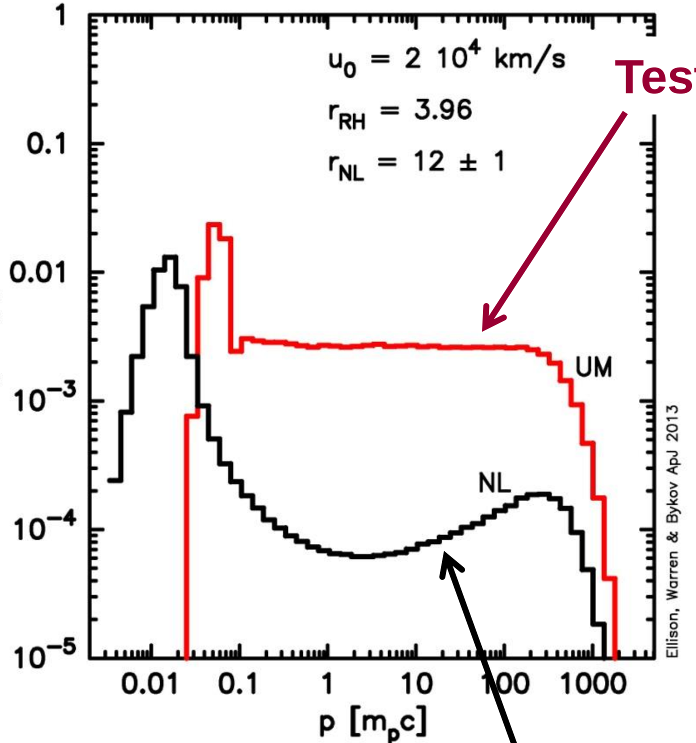
2) For $V_{sk} \sim c$, $r \sim 3$ and $f(p) \propto p^{-4.23}$

3) Trans-rel. shock ($\gamma_0 \sim 1.5 - 3$) $f(p)$ in between

1) For trans-relativistic & fully relativistic speeds, all results depend on details of plasma physics, i.e., wave-particle interactions in self-generated magnetic turbulence ➔ parameterize in Monte Carlo

2) BUT, if application assumes acceleration is efficient (e.g., GRBs) ➔ Cosmic Rays must modify shock structure ➔ Non-linear shock structure calculated in Monte Carlo

Non-relativistic shock

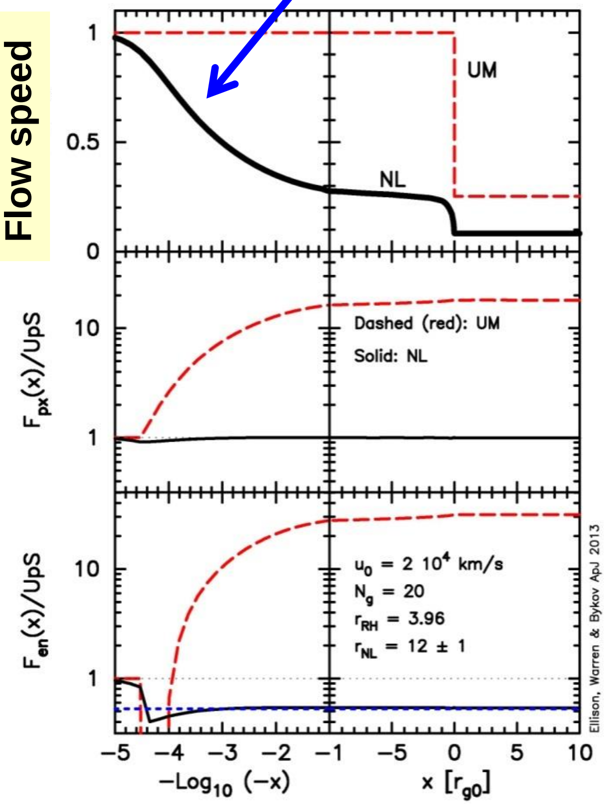


p⁴ f(p)

Test-particle f(p)

Shock structure modified by CR backpressure

Flow speed

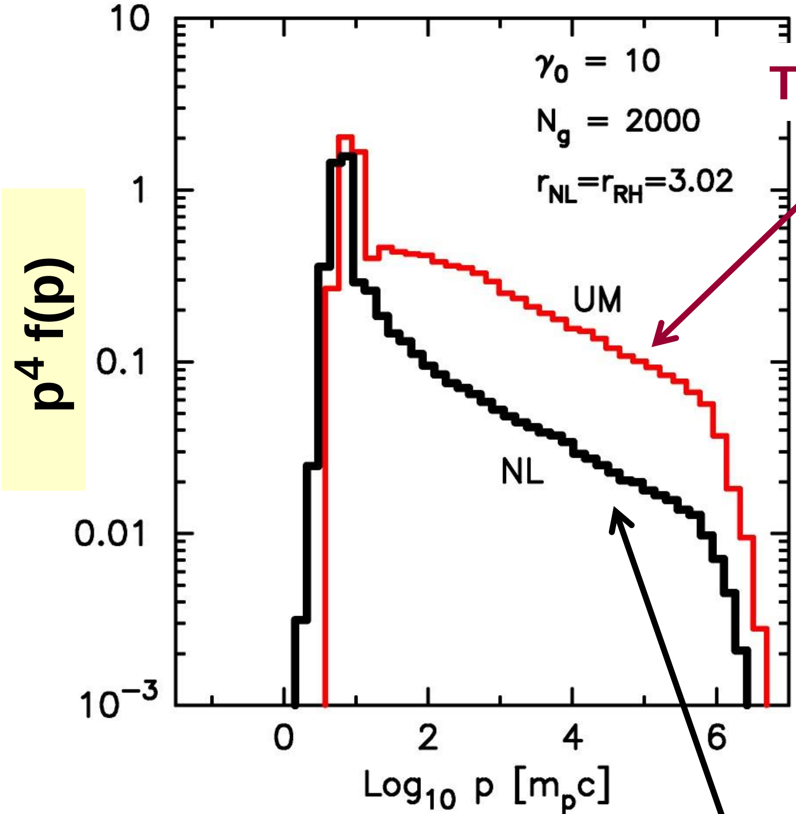


Position, x

Energy & momentum conserving non-linear f(p)

Cosmic ray acceleration can strongly modify shock structure in non-relativistic shocks

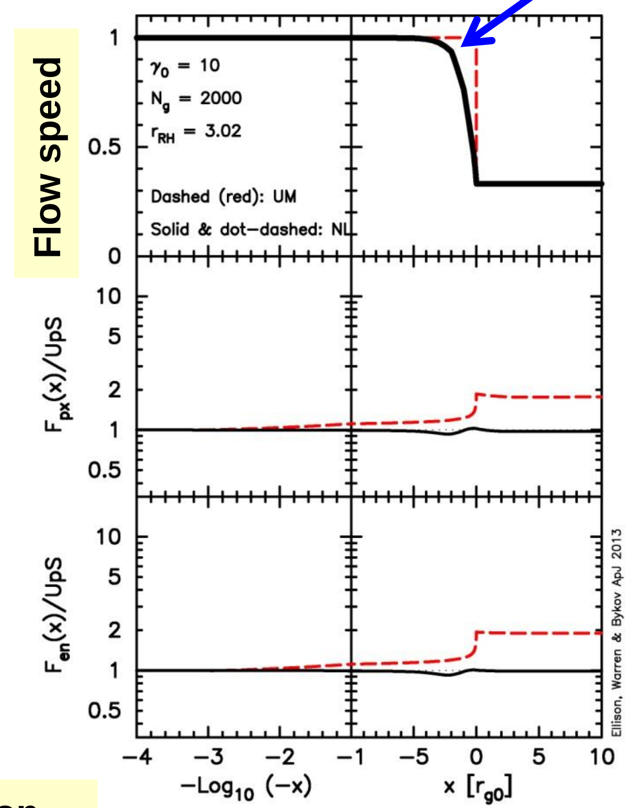
Fully relativistic shock, $\gamma_0 = 10$



Test-particle f(p)

Energy & momentum conserving non-linear f(p)

Shock structure modified by CR backpressure



Position, x

Amount of shock modification depends on injection efficiency and strength of B-field turbulence.

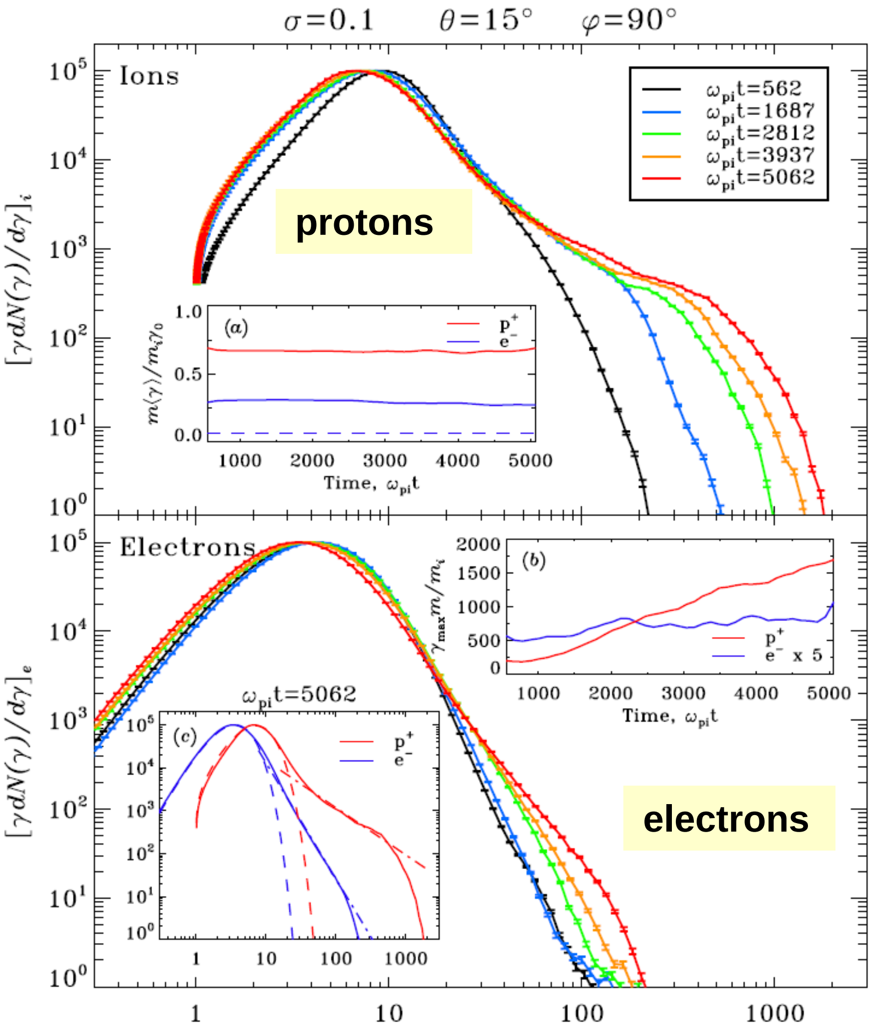
Are approximations required by Monte Carlo too extreme to yield useful results?

Look at direct comparison between Monte Carlo results and Particle-in-Cell (PIC) simulation of Sironi & Spitkovsky 2011

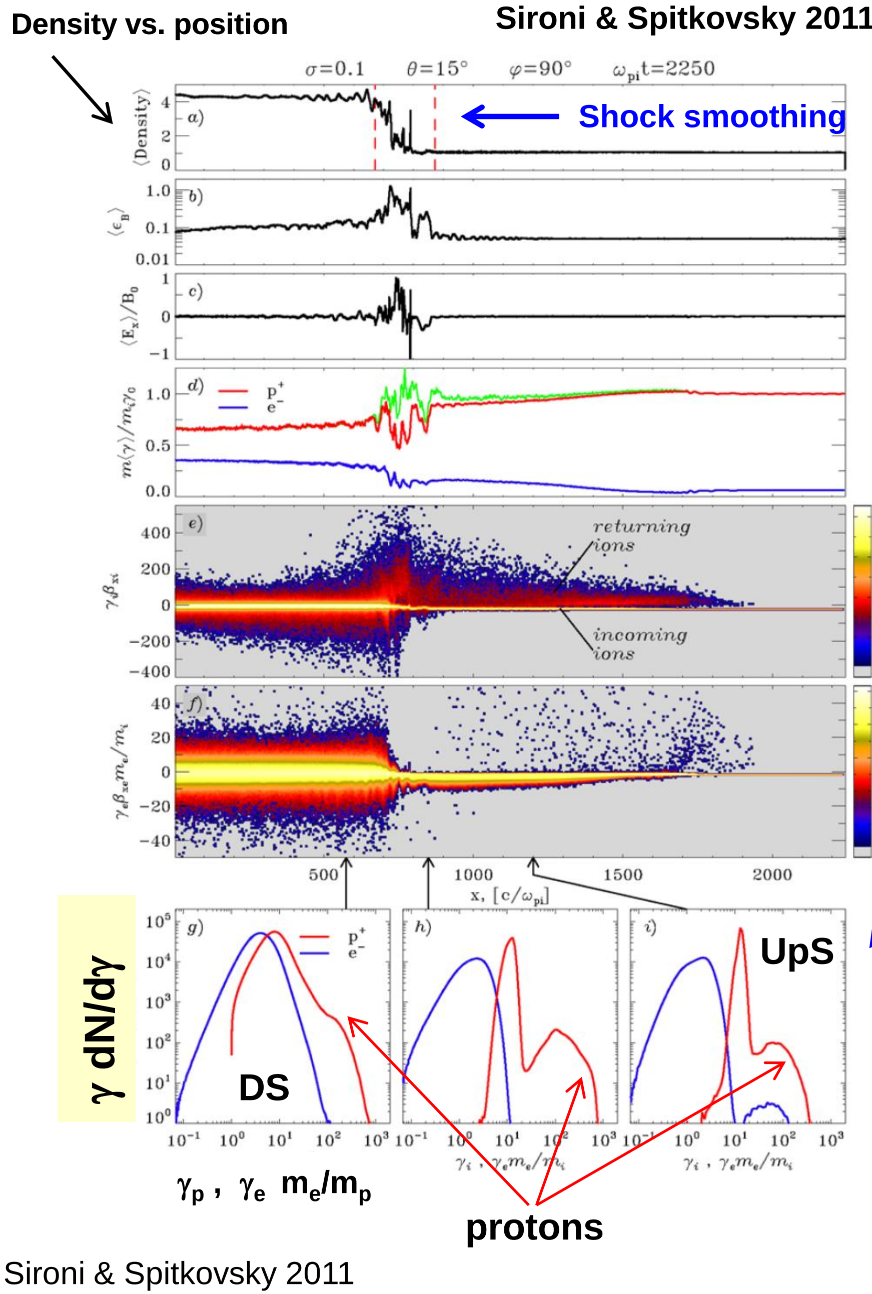
Quasi-parallel PIC simulation: Angle between shock normal and B-field: $\theta = 15^0$

Shock Lorentz factor: $\gamma_0 = 15$

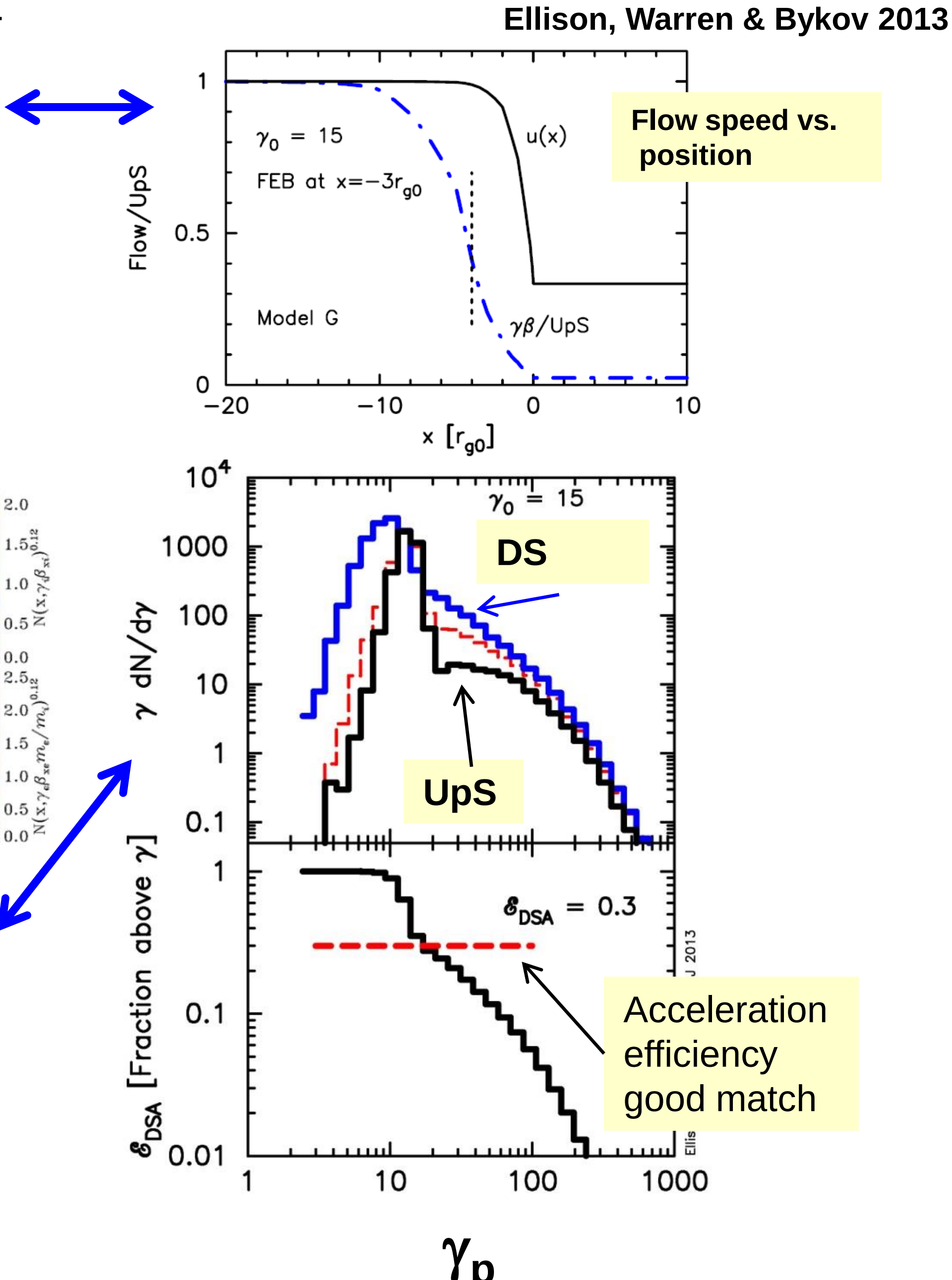
Sironi & Spitkovsky 2011



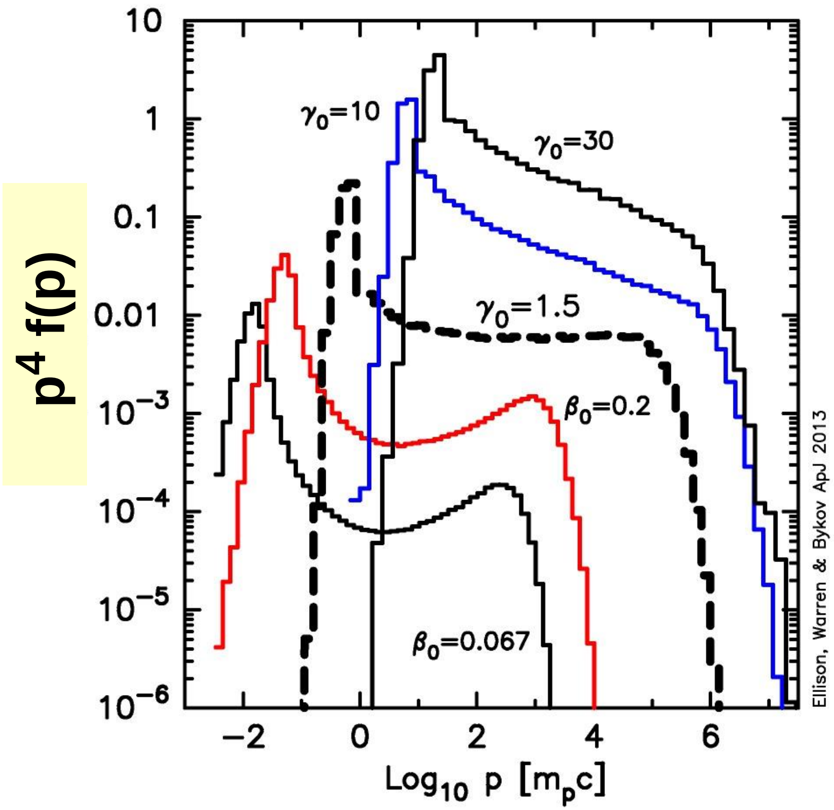
γ_p , γ_e m_e/m_p



Density vs. position
Sironi & Spitkovsky 2011
Shock smoothing
protons
DS
UpS
γ dN/dγ
γp , γe me/mp
Sironi & Spitkovsky 2011



Ellison, Warren & Bykov 2013
Flow speed vs. position
Flow/UpS
u(x)
γβ/UpS
Model G
x [rg0]
DS
UpS
γ dN/dγ
Acceleration efficiency good match
γp



If shock slows from fully relativistic to trans-relativistic to non-relativistic (as in GRB afterglow), expect transition from soft power law to highly modified concave spectrum

Basic assumptions:

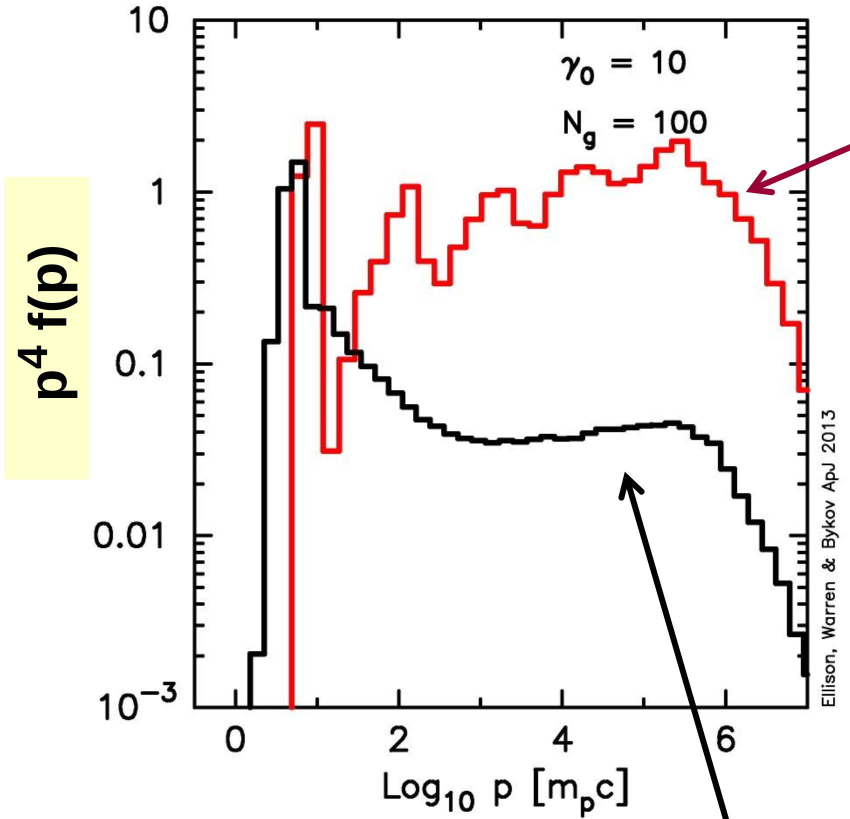
➔ **Magnetic turbulence, with required scales, can be generated by accelerated particles in shock precursor**

➔ **Simple description of wave-particle interactions used in MC ($\lambda \propto$ gyroradius) is a reasonable approximation**

➔ **Plane-parallel shock geometry OK for first-step (suggested by quasi-parallel PIC results)**

➔ **Enough particles are injected to have efficient acceleration**

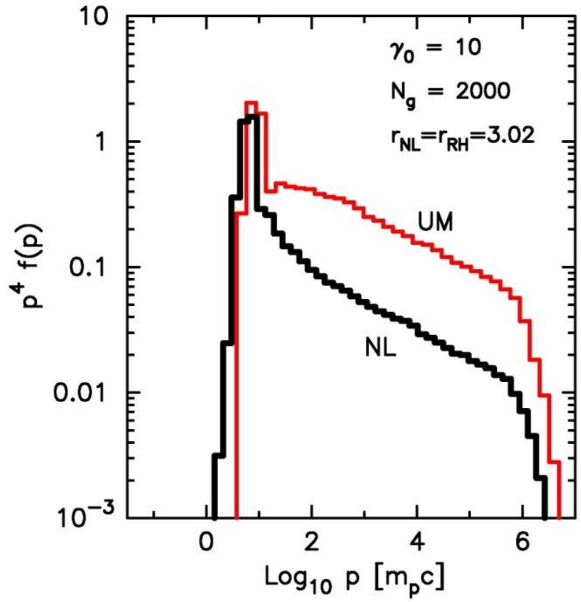
Fully relativistic shock with Large-Angle-Scattering



Test-particle f(p)

Energy & momentum conserving non-linear f(p)

Fully relativistic shock with "fine" scattering



Assumptions for plasma physics strongly impact results, BUT, independent of any assumption, if acceleration is efficient, non-linear effects must be taken into account

Conclusions:

1) **If relativistic shocks accelerate particles efficiently, non-linear back reaction of cosmic rays (CRs) on shock must be taken into account**

2) **Assuming efficient CR production, there must be a transition between non-relativistic shocks with hard, concave spectra, and fully relativistic shocks with softer spectra**

3) **Trans-relativistic shocks ($\gamma_0 \sim 1.5 – 3$) may be important for GRB afterglows and subclass of Type Ibc supernova with relativistic ejecta speeds (e.g., Soderberg et al 2006)**

4) **To model observations must accelerated electrons consistently with ions and calculate radiation transformed to observer frame**

Stay for talk by Don Warren with preliminary work applying non-linear DSA to GRB afterglow emission

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