Characteristics of Diffusive Acceleration at Relativistic Shocks

Matthew G. Baring
Rice University
baring@rice.edu

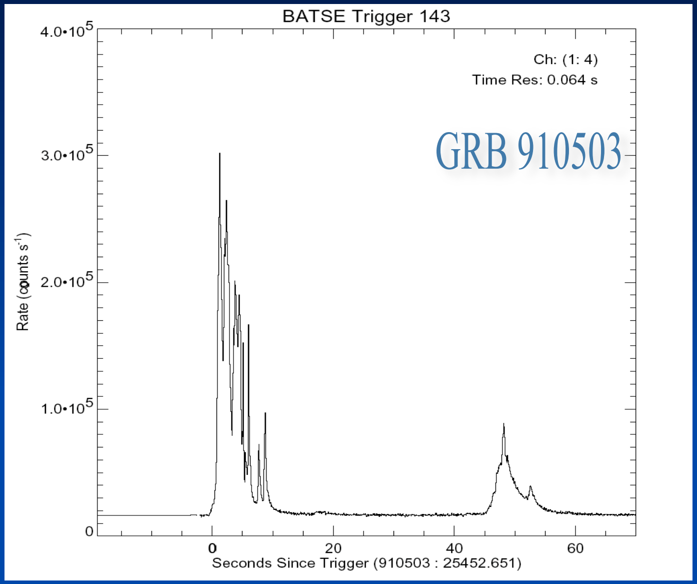
Former Thesis Student:
Errol J. Summerlin

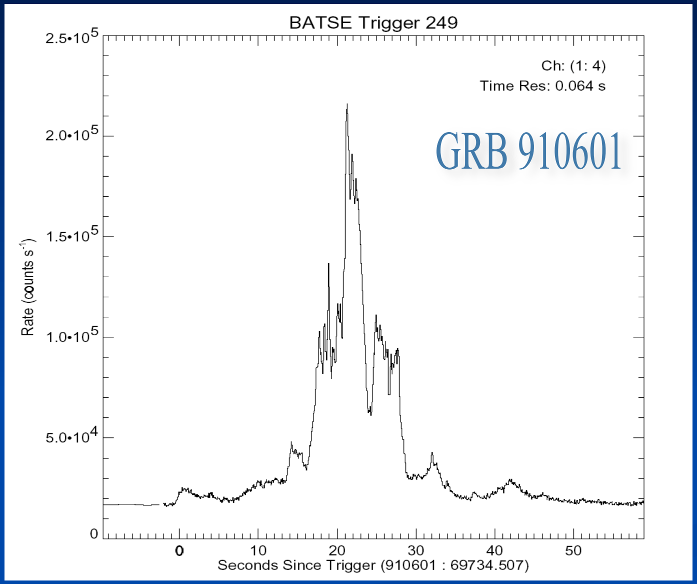
Particle Acceleration in Astrophysical Plasmas, KITP/UCSB 18th September, 2009

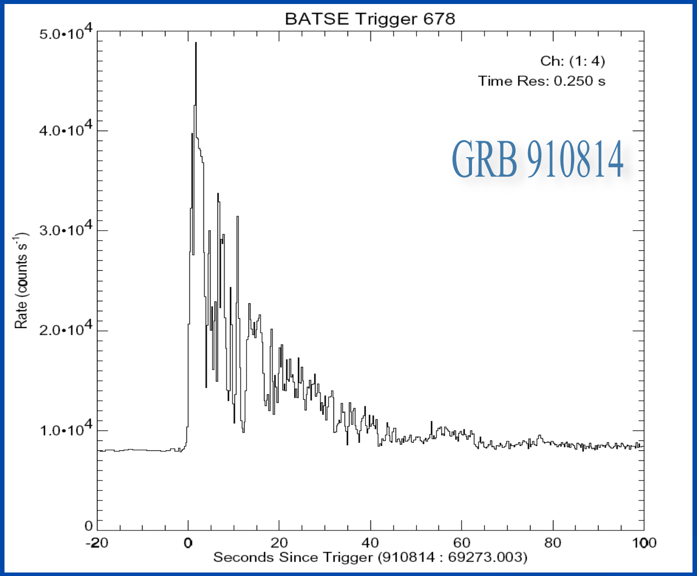
Talk Layout

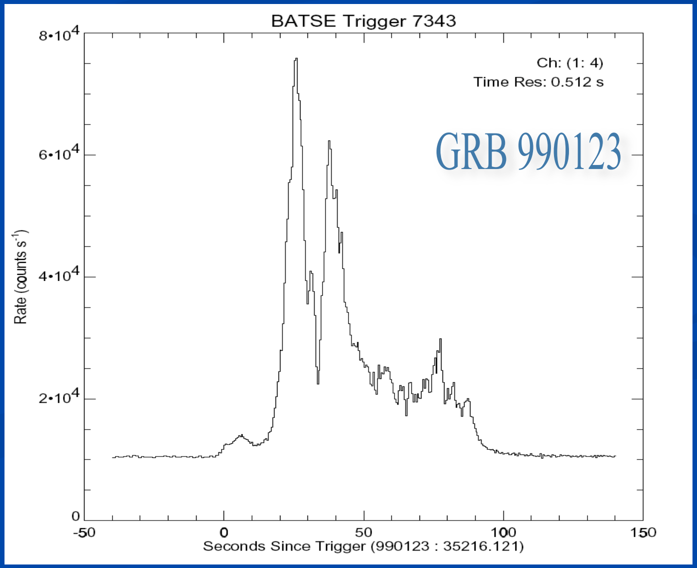
- Astrophysical context; gamma-ray bursts, blazars (active galaxies) and ultra-high energy cosmic rays (UHECRs);
- Monte Carlo simulation technique;
- Plane-parallel relativistic shocks;
- Oblique shocks;
- Bottom line: a plethora of possibilities (=everyone can have their flavor of coffee).

BATSE Gamma-Ray Burst Lightcurves

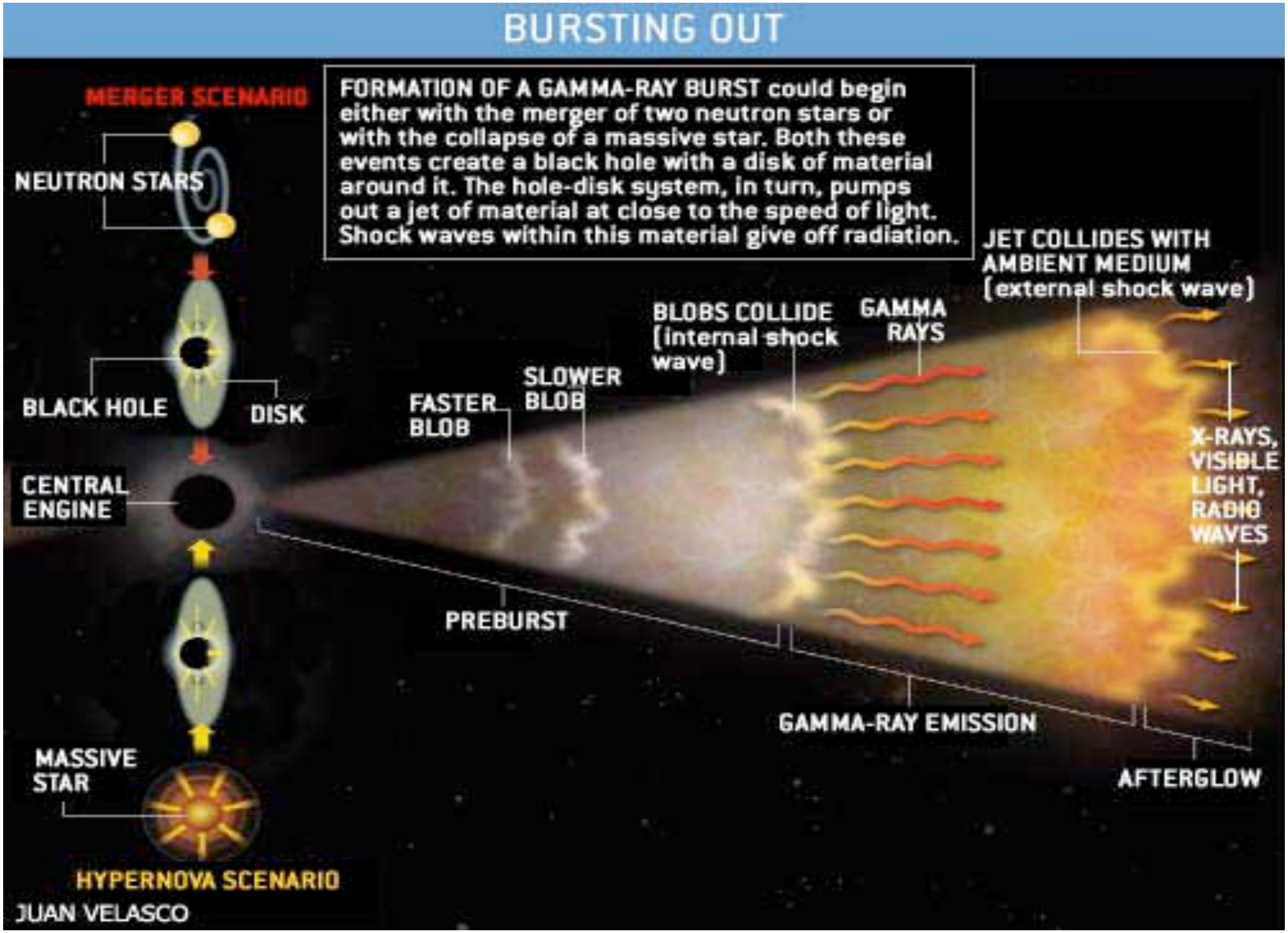






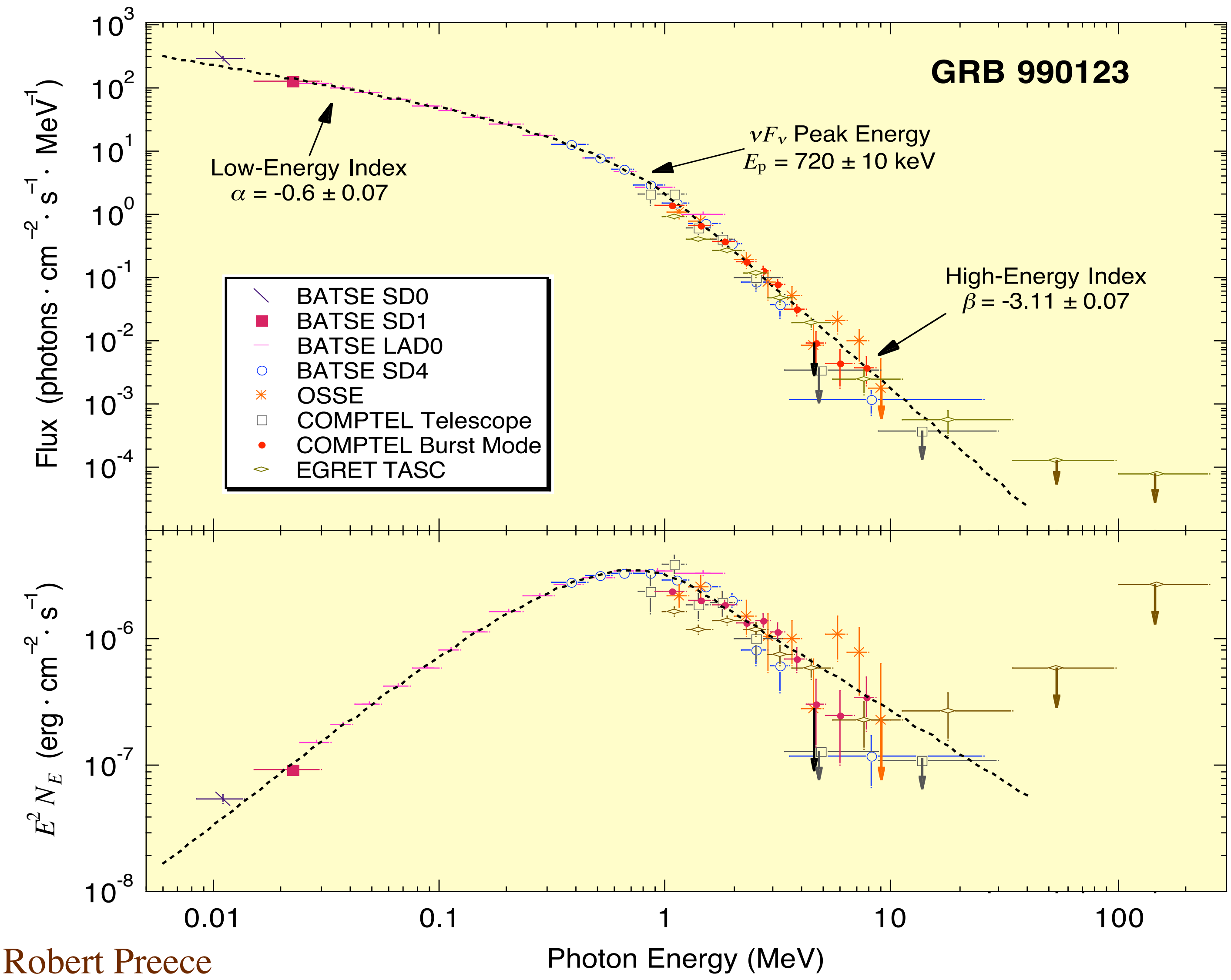


Gamma-Ray Bursts: Relativistic Outflows



FORMATION OF A GAMMA-RAY BURST could begin either with the merger of two neutron stars or with the collapse of a massive star. Both these events create a black hole with a disk of material around it. The hole-disk system, in turn, pumps out a jet of material at close to the speed of light. Shock waves within this material give off radiation.

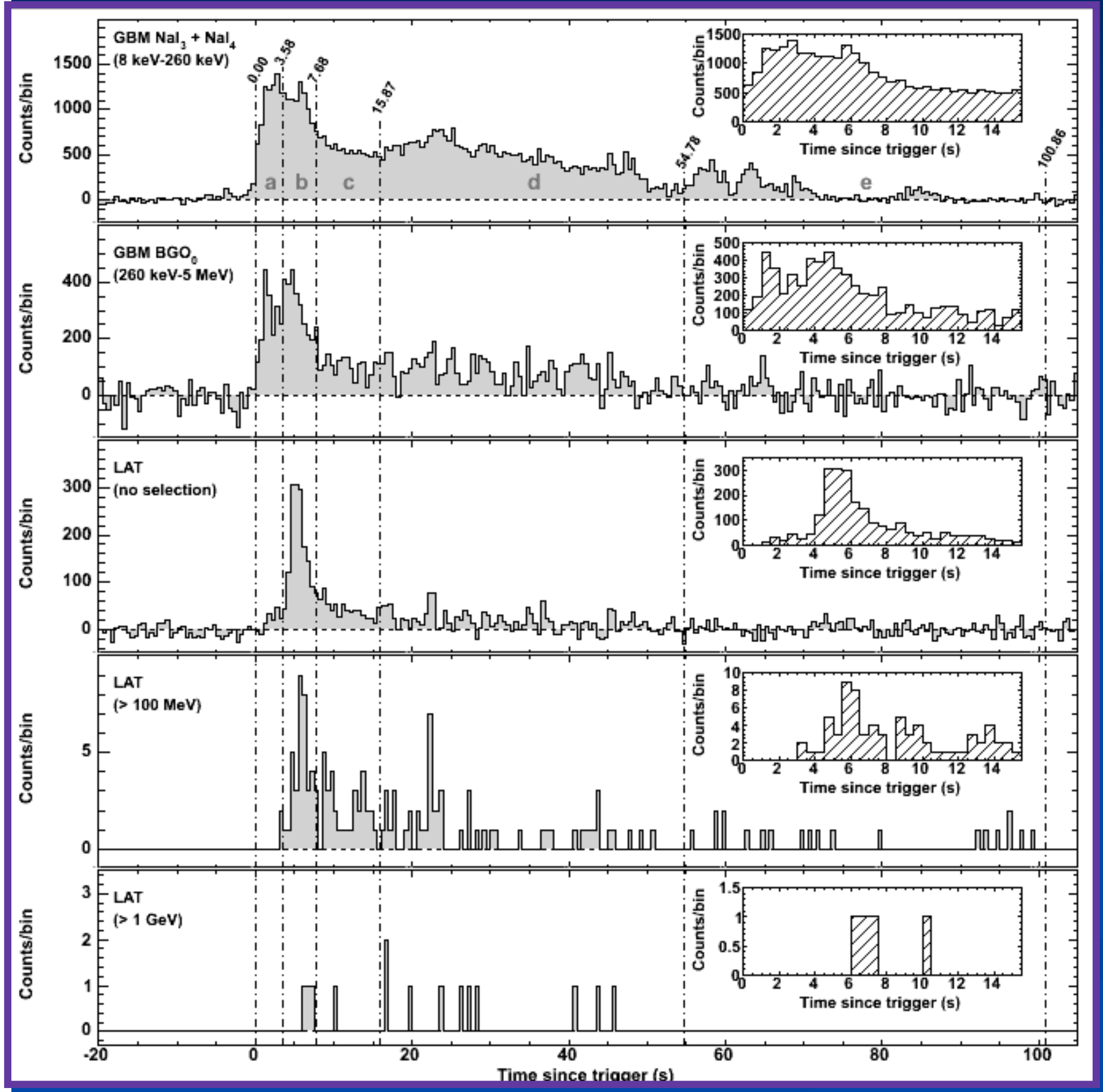
Spectral Character: GRB990123

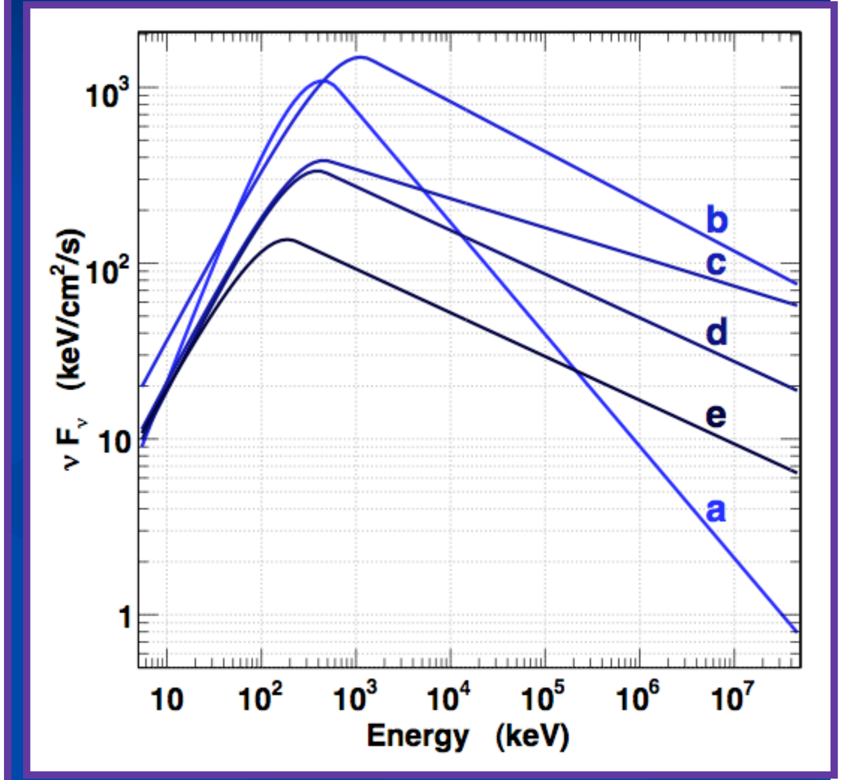


Credit: Robert Preece

Fermi GRB 080916c

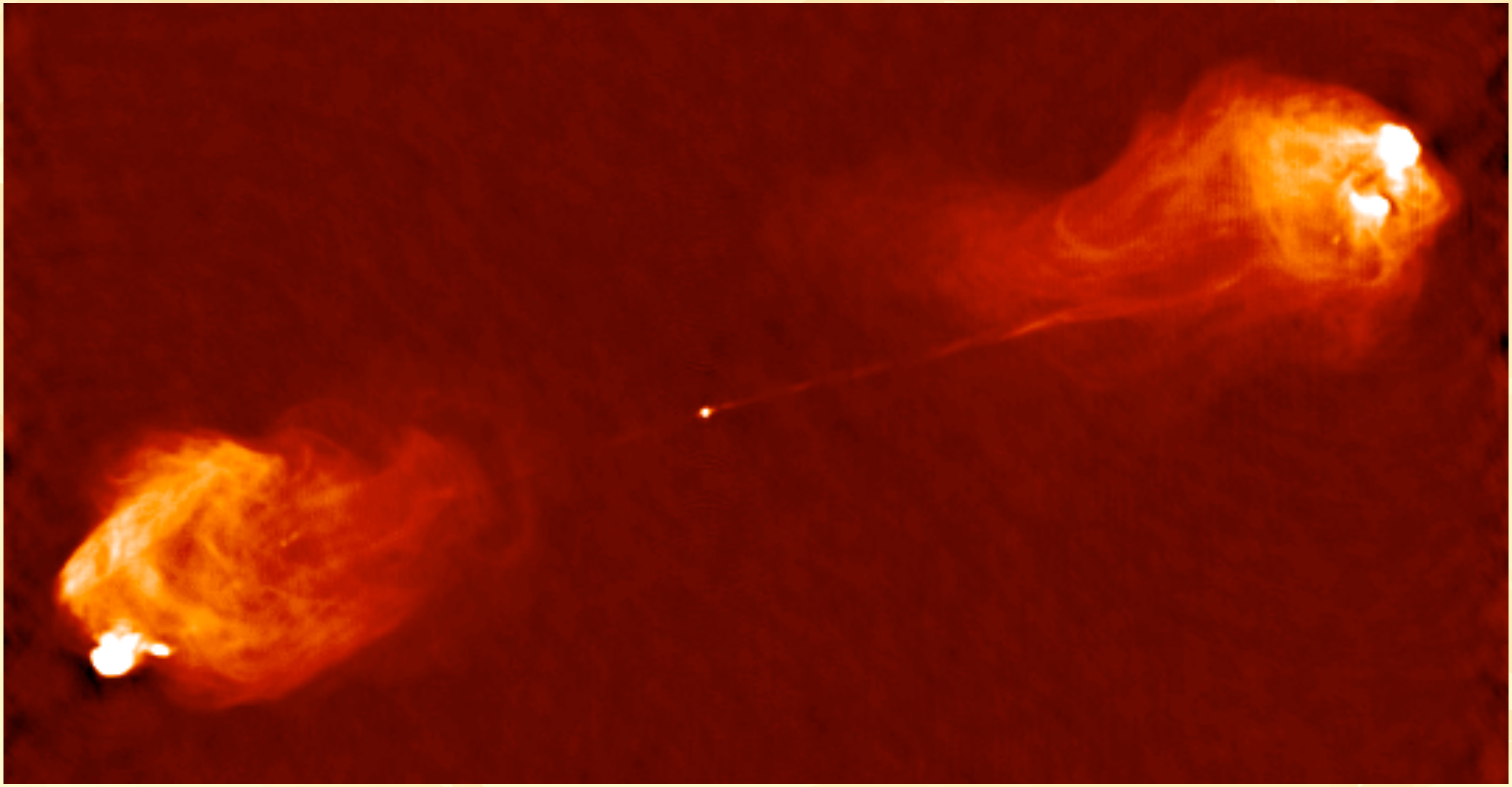
Temporal and Spectral Evolution





- Science (2009): Abdo et al.

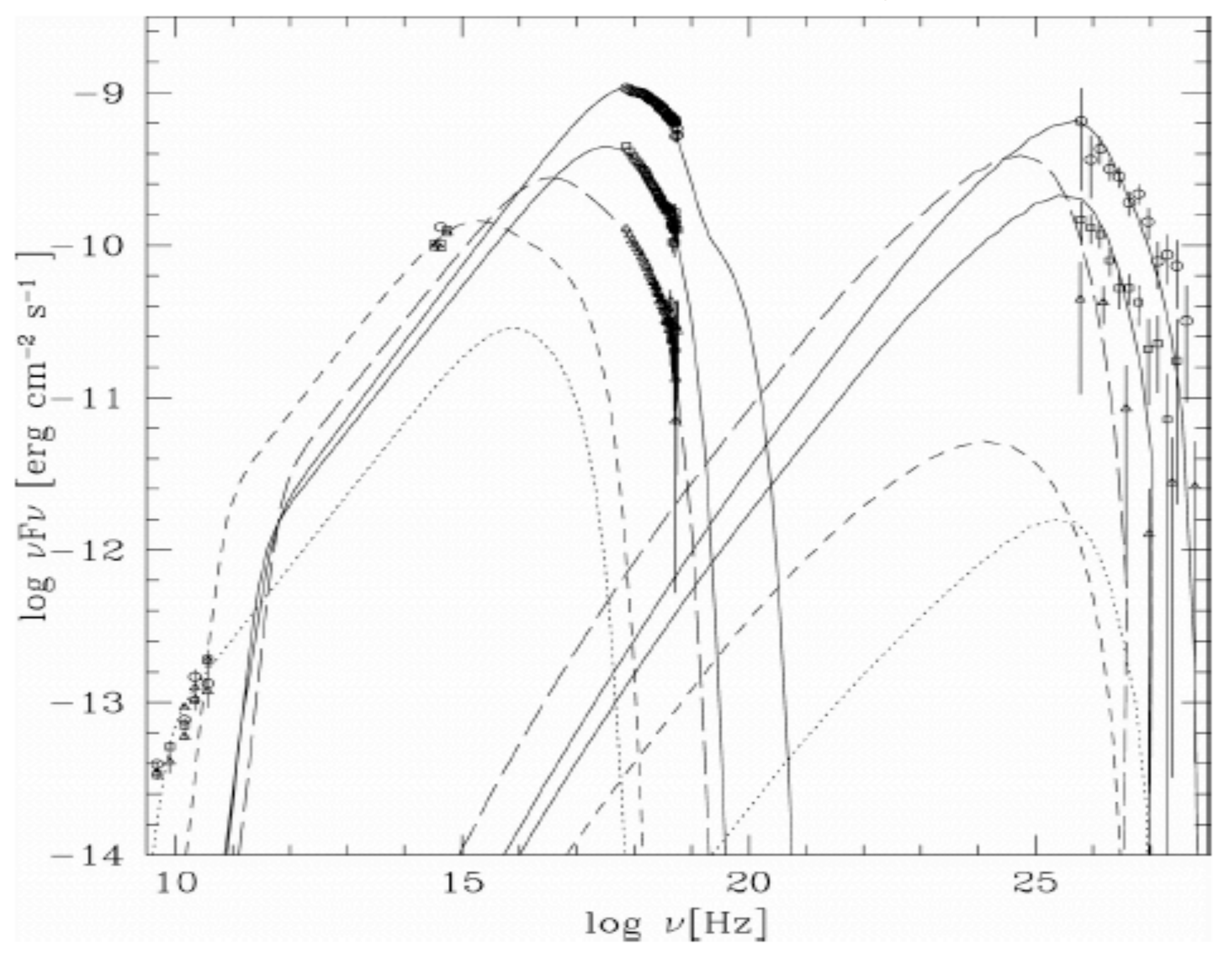
High Energy Cosmic Ray Accelerators: Radio Galaxies like Cygnus A



Multi-wavelength Flaring in the Blazar Markarian 421

z=0.031

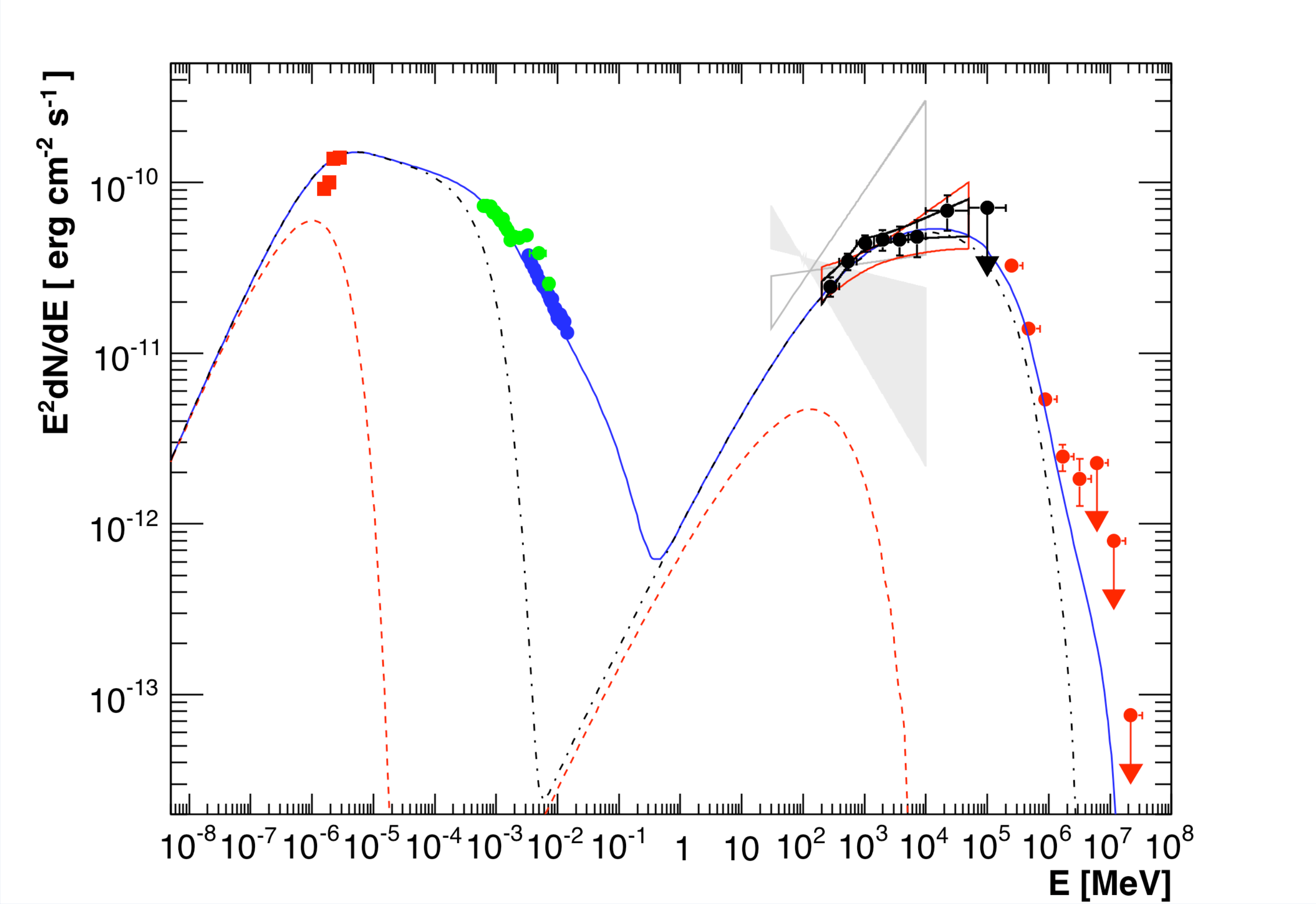
Blazejowski et al. (2005)



Multi-wavelength Low-state SED: *Fermi*-LAT Blazar PKS 2155-304

z=0.116

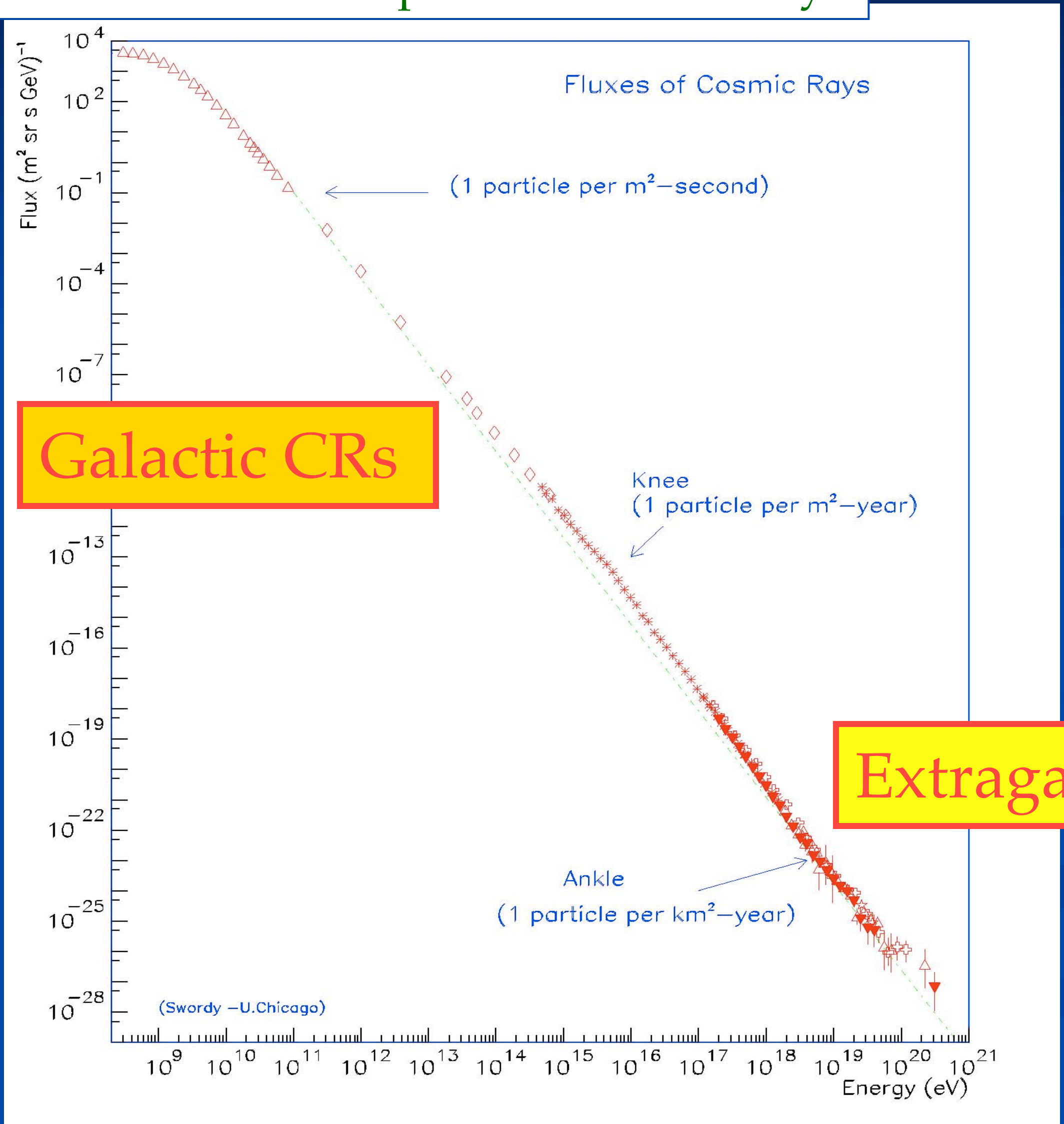
Abdo et al. (2009)



Complete Cosmic Ray Spectrum

Balloon + satellite expts ← | → EAS arrays

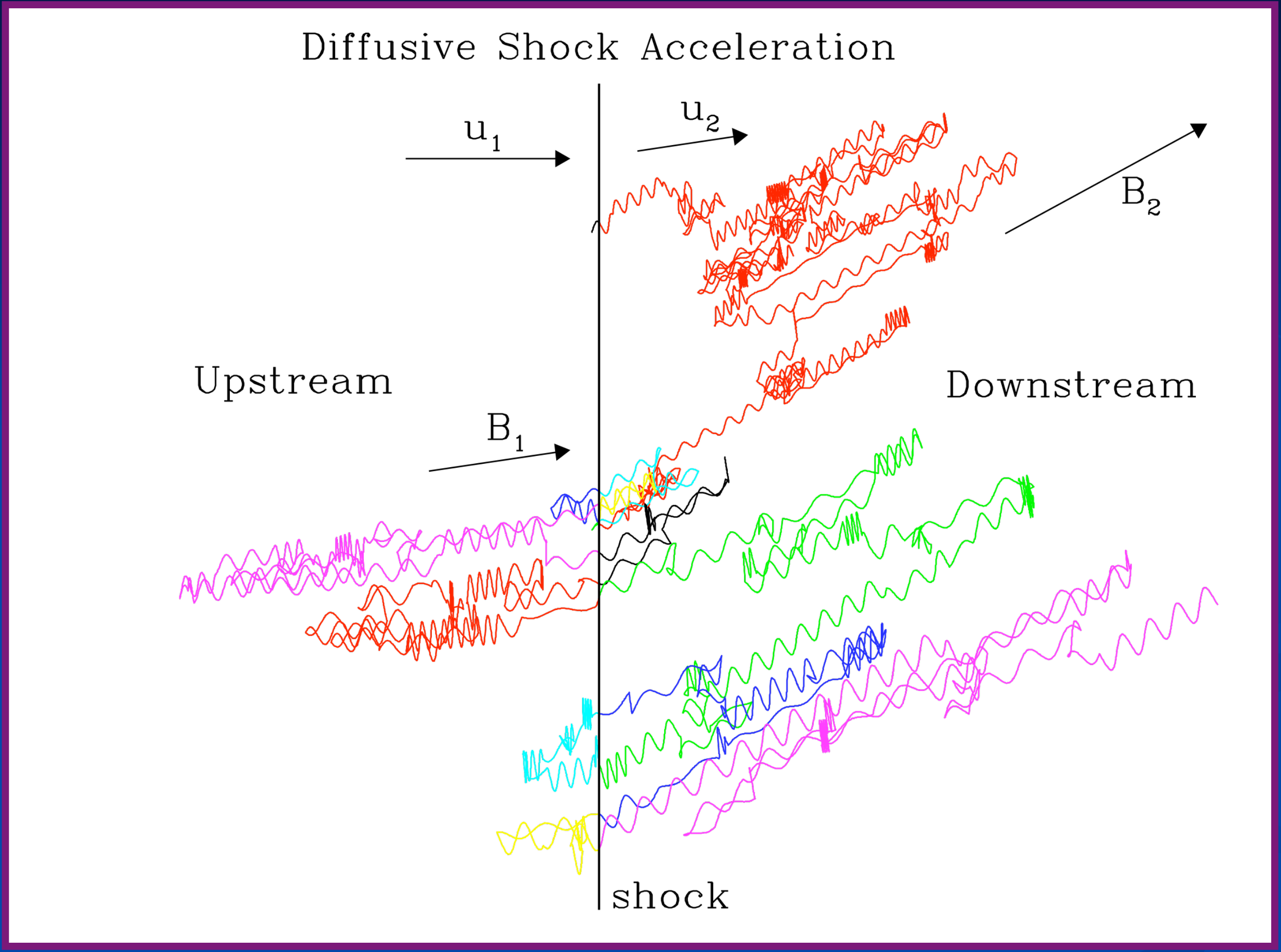
Discovered in 1912 by V. Hess



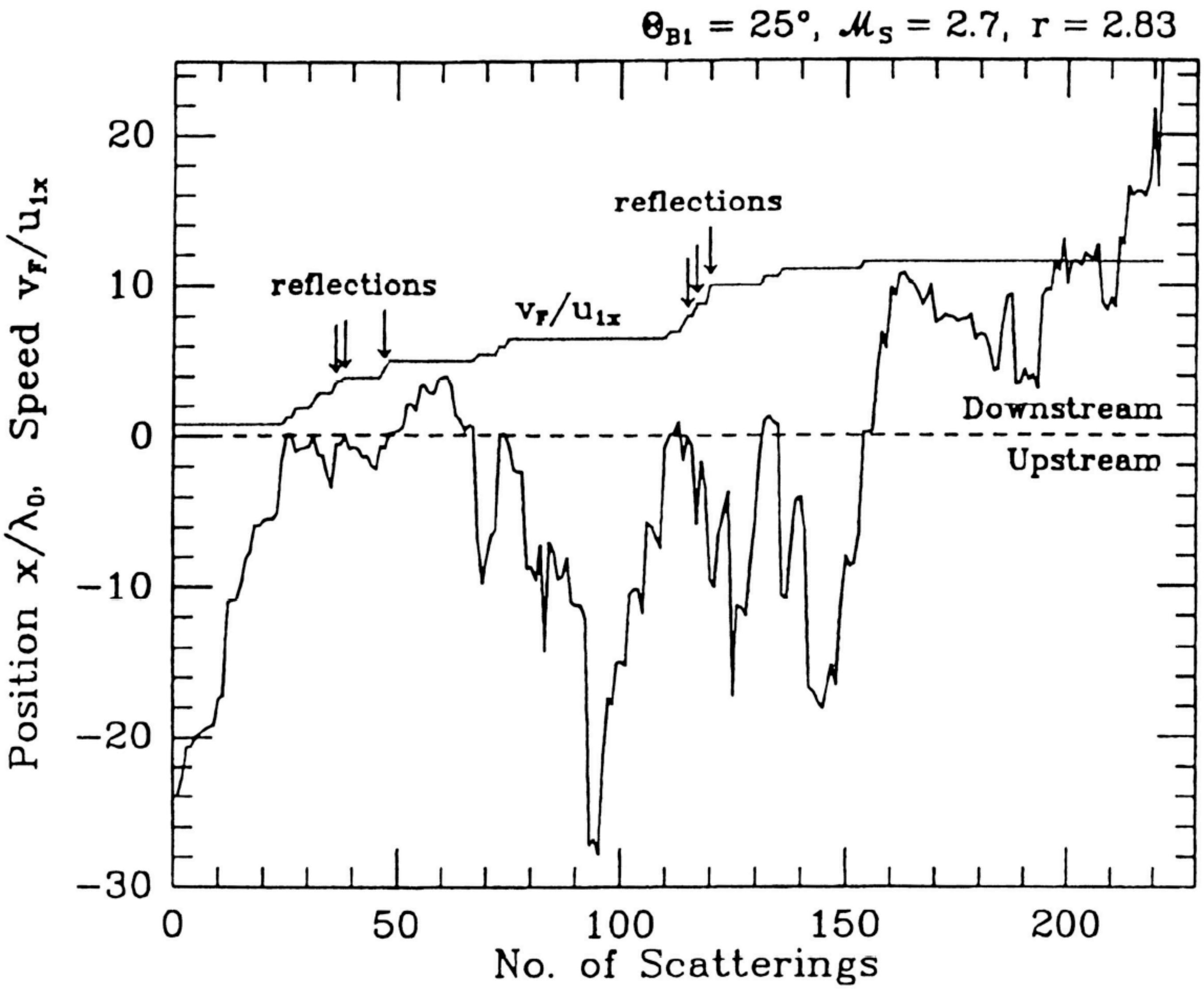
Galactic CRs

Extragalactic CRs

Monte Carlo Simulation Particle Trajectories

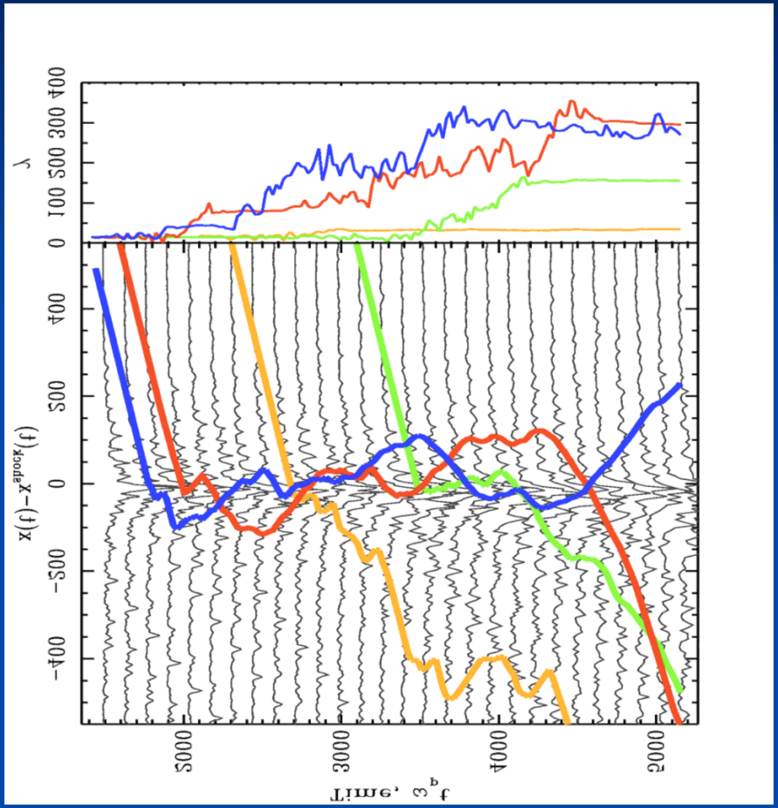


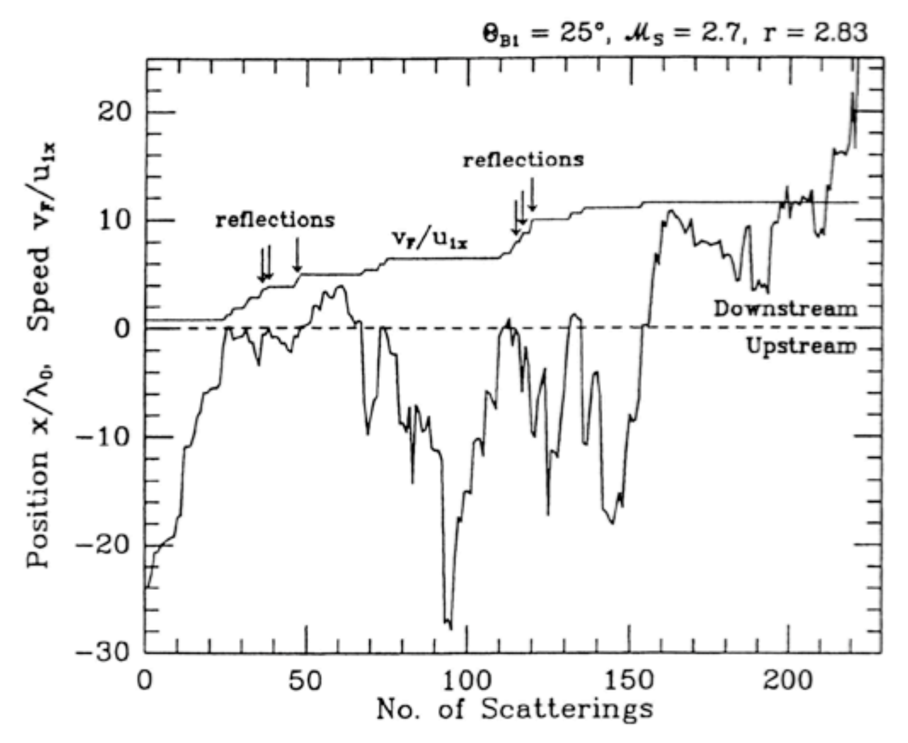
- Gyration in B-fields and diffusive transport modeled by a Monte Carlo technique; color-coded in Figure according to fluid frame energy.
- Shock crossings produce net energy gains (evident in the increase of gyroradii) according to principle of first-order Fermi mechanism.



Baring, Ellison & Jones (1994)

Diffusive Acceleration in PIC Simulations



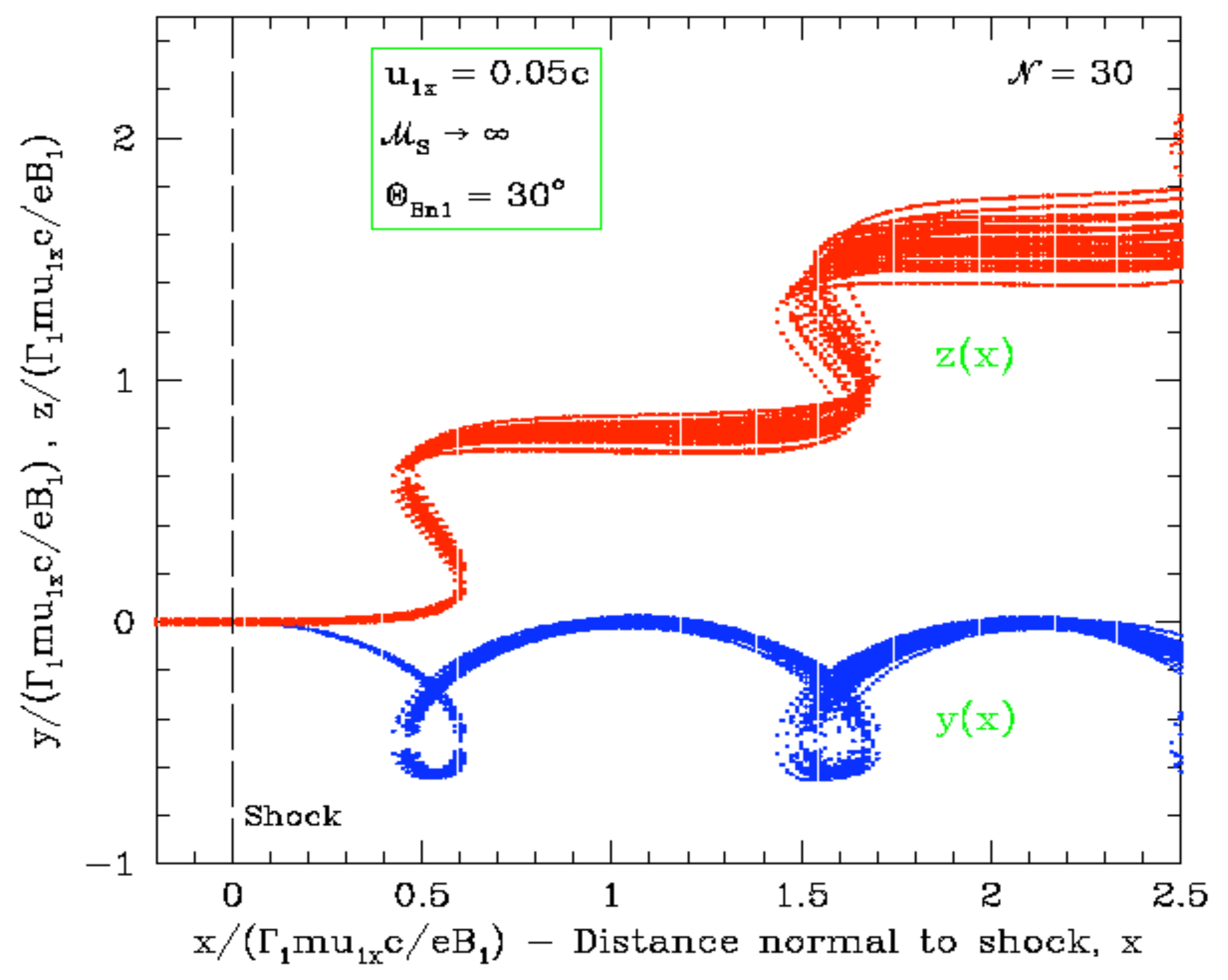


- *Left panel*: Spitkovsky (2008): starting to see the evidence of diffusive transport on scales larger than the inertial length + associated energization to form a power-law.
- *Right panel*: Monte Carlo simulation diffusive energization.

Shock Acceleration: Monte Carlo Simulations

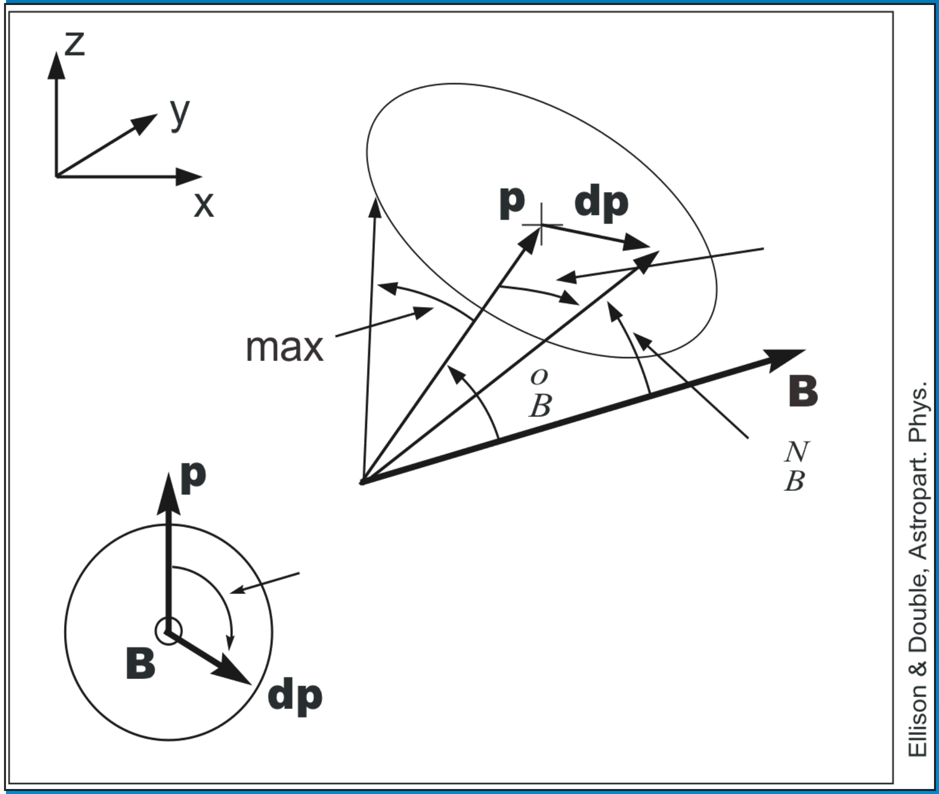
- The Monte Carlo simulations use a kinetic description of convection and diffusion in MHD shocks;
- Thermal ions and e^- are injected far upstream of shock;
- Particle diffusion in MHD turbulence is phenomenologically described via the mean free path λ being some power of its gyroradius r_g: same prescription for both thermal and non-thermal particles, and for electrons and protons;
- Principal advantages include addressing large momentum ranges => **excellent for astrophysical problems**.
- Simulations are fully relativistic, and not restricted to subluminal shocks, and include shock drift acceleration;
- Technique has been well-tested in heliospheric contexts of acceleration at the Earth's bow shock (Ellison et al. 1990) and interplanetary shocks (Baring et al. 1997; Summerlin & Baring 2006) using *in-situ* spacecraft data.

Shock Layer Particle Trajectories - high M_S

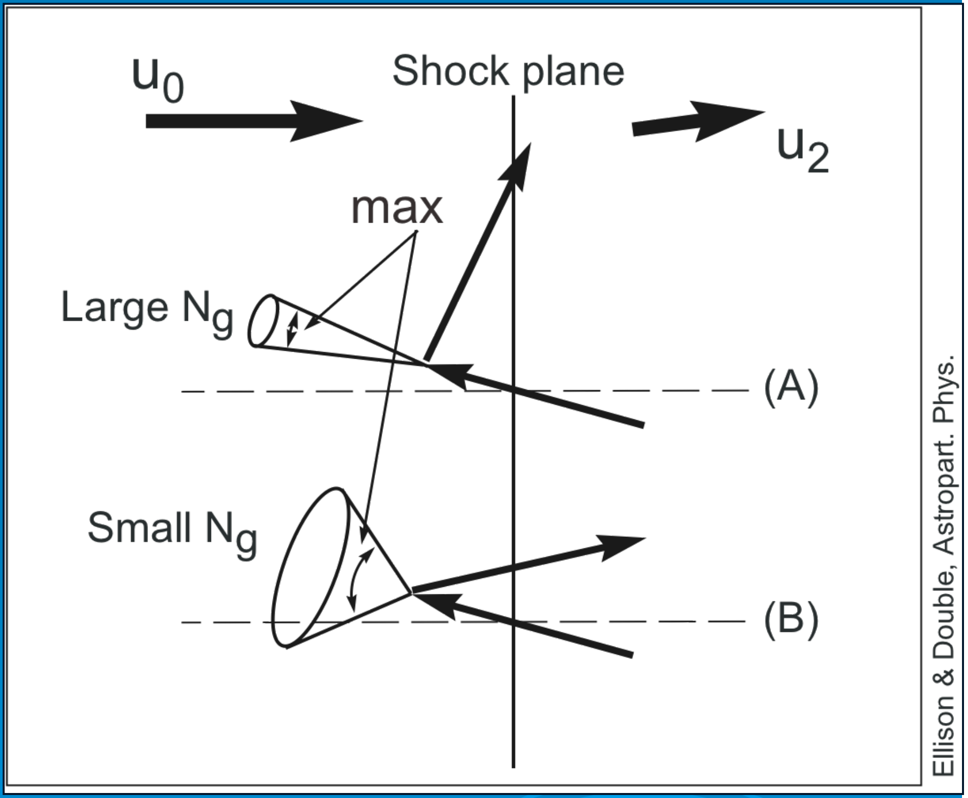


Gyrational concentration of particles in x-direction yields obvious density enhancements and cusp structure. Co-ordinates y and z are parallel to shock plane.

Scattering Geometry



Ellison & Double, Astropart. Phys.

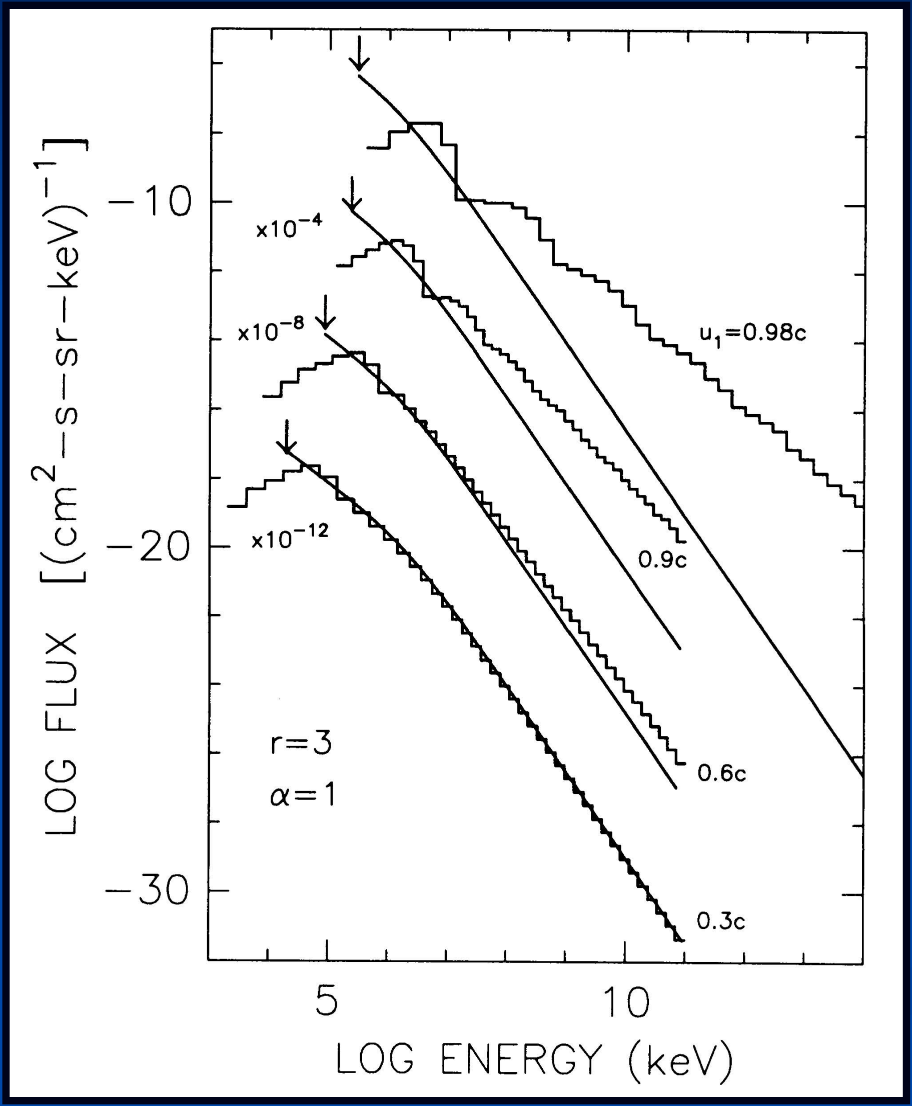


Ellison & Double, Astropart. Phys.

Spectral Properties of Diffusive Relativistic Shock Acceleration

- For small angle scattering, ultra-relativistic, parallel shocks have a power-law index of 2.23 (Kirk et al. 2000);
- Result obtained from solution of diffusion/convection equation and also Monte Carlo simulations (Bednarz & Ostrowski 1996; Baring 1999; Ellison & Double 2004);
- Power-law index is **not universal**: scattering angles larger than Lorentz cone flatten distribution;
- Large angle scattering yields kinematic spectral structure;
- In *superluminal* shocks, spectral index is generally a strongly *increasing* function of field obliquity angle Θ_{Bn1}.

Ellison, Jones & Reynolds (1990): Large Angle Scattering

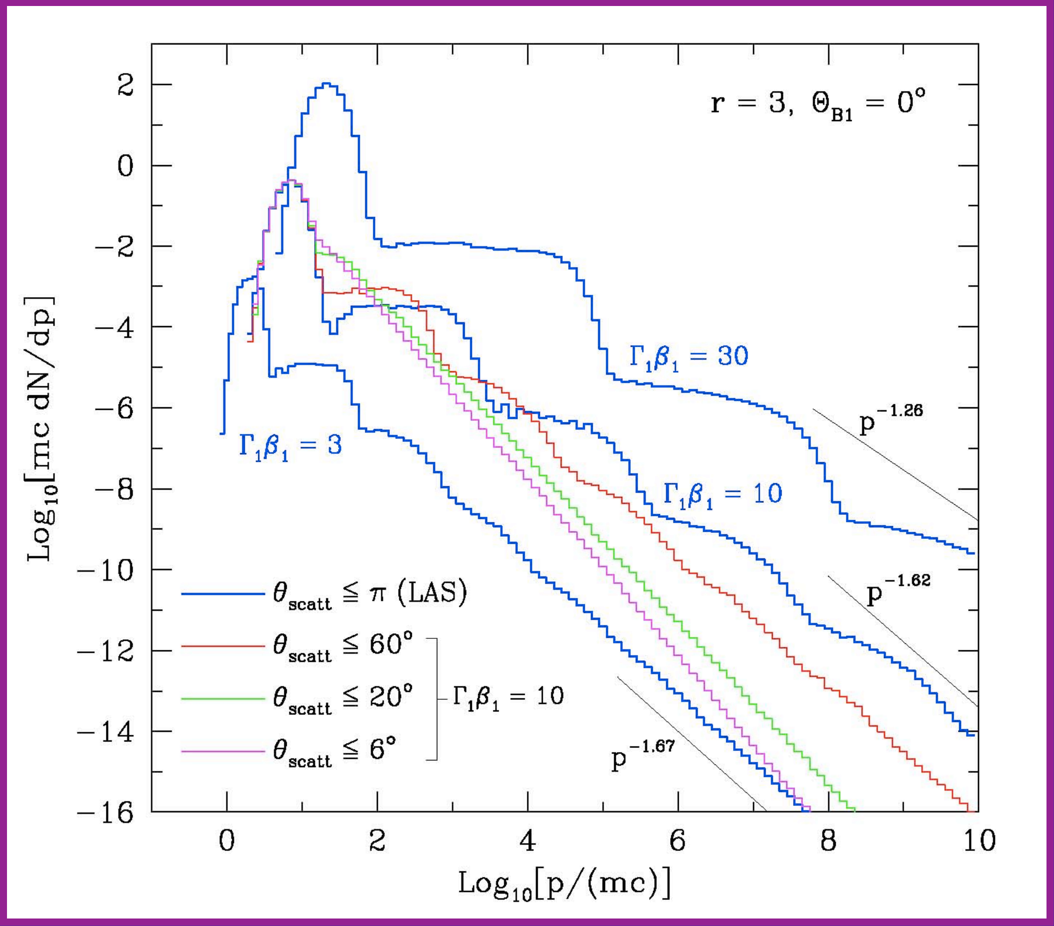


- Monte Carlo results for parallel shocks;
- Spectrum flattens and becomes more structured as $u_1 \rightarrow c$;
- Relativistic kinematics increases energy gains in shock crossings (a la inverse Compton scattering).

Relativistic Shocks: Spectral Dependence on Scattering

- Deviations from ``canonical'' index of 2.23 (Bednarz & Ostrowski 1998; Kirk et al. 2000; Baring 1999) occur for scattering angles $> 1/\Gamma_1$, i.e. *outside Lorentz cone*;
- Large angle scattering yields kinematically structured distributions;
- (e.g., Ellison, Jones & Reynolds 1990; Ellison & Double 2004; Baring 2005)

Stecker, Baring & Summerlin 2007

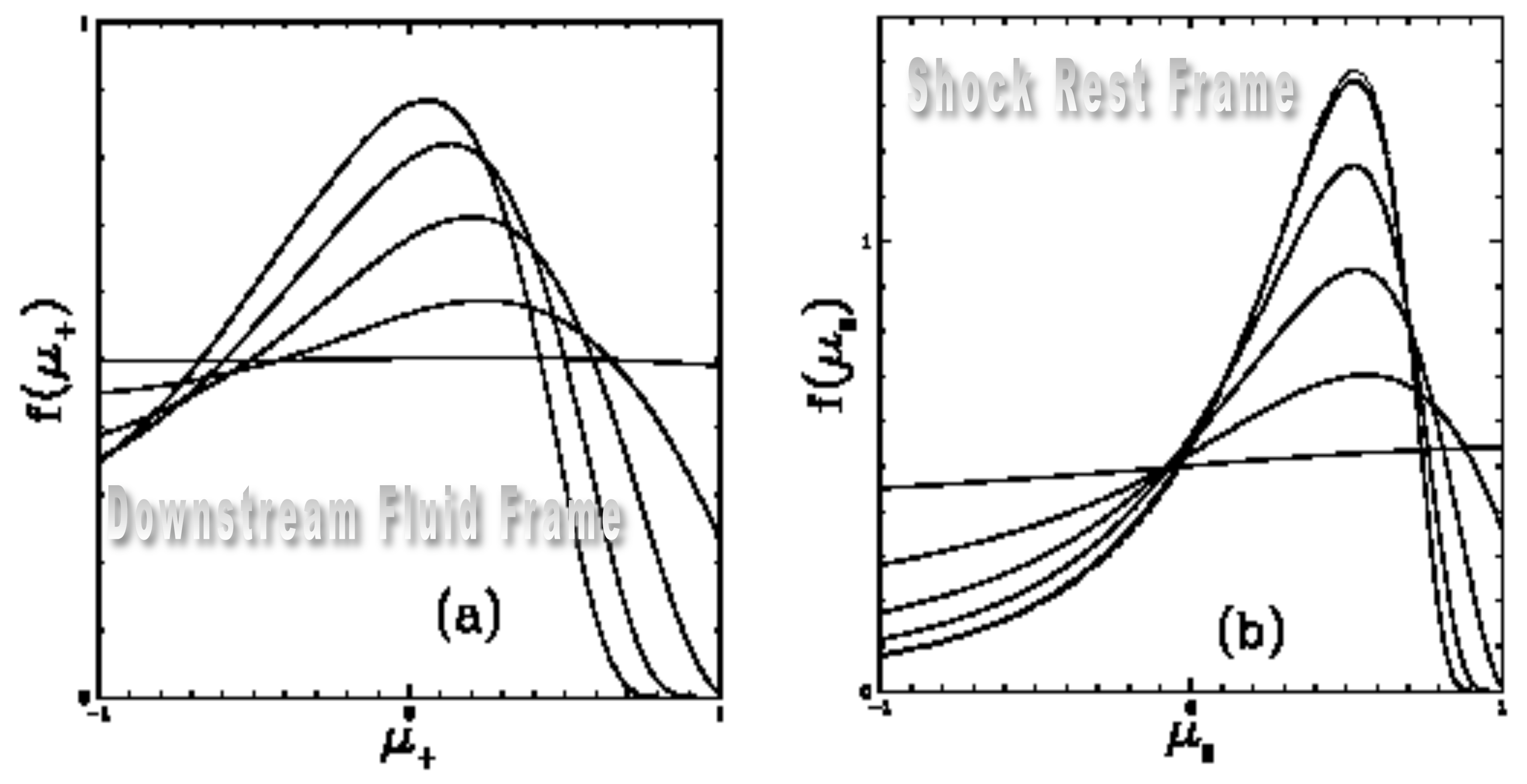


The Character of Relativistic Shocks

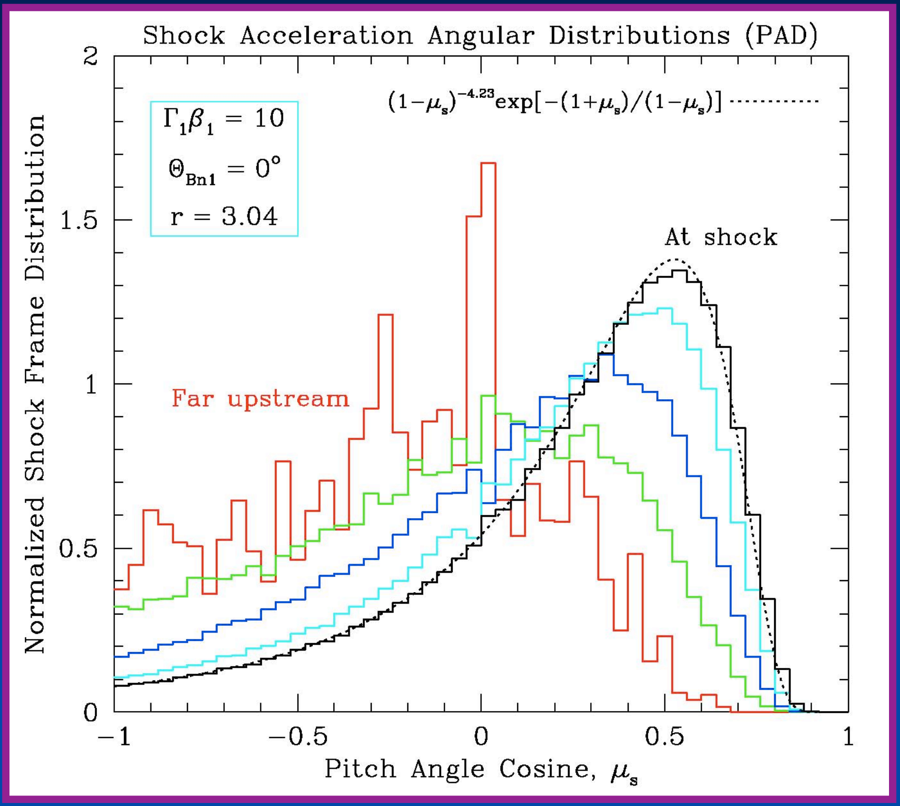
- Character of relativistic shocks defined by their intrinsic anisotropy: convective influence is profound, particularly for superluminal cases;
- Escape downstream is a *strong function* of shock speed and field obliquity: convective loss rates are high;
- Acceleration times are not modified strongly by relativistic effects (EJR90, Baring 2002).

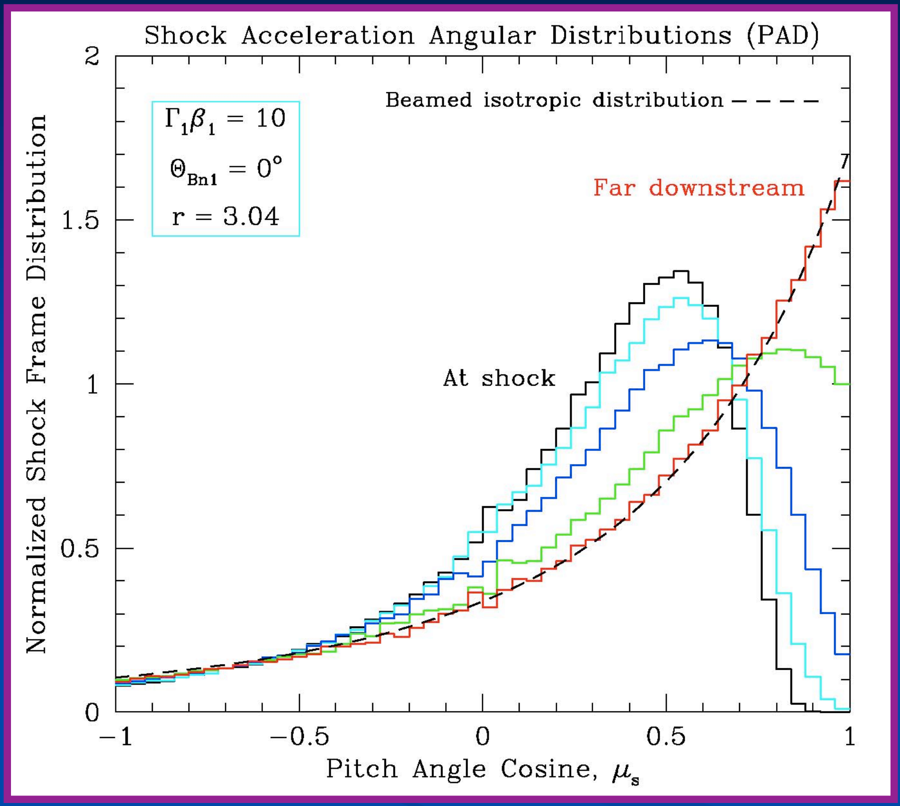
Anisotropies in Relativistic Shocks: Pitch Angle Diffusion, $0.1c < u_1 < c$

Kirk, Guthmann, Gallant & Achterberg (2000)



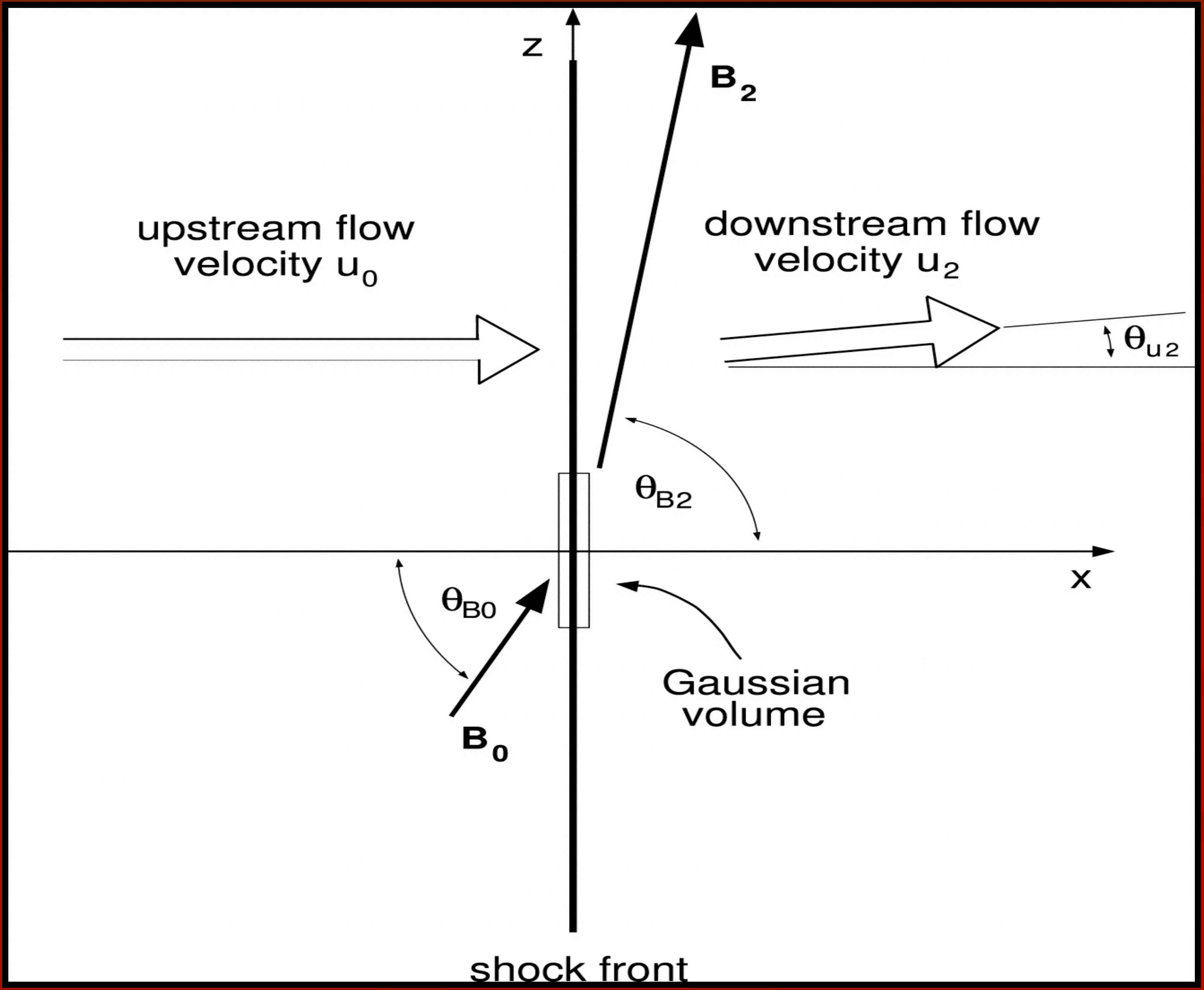
Upstream and Downstream Angular Distributions



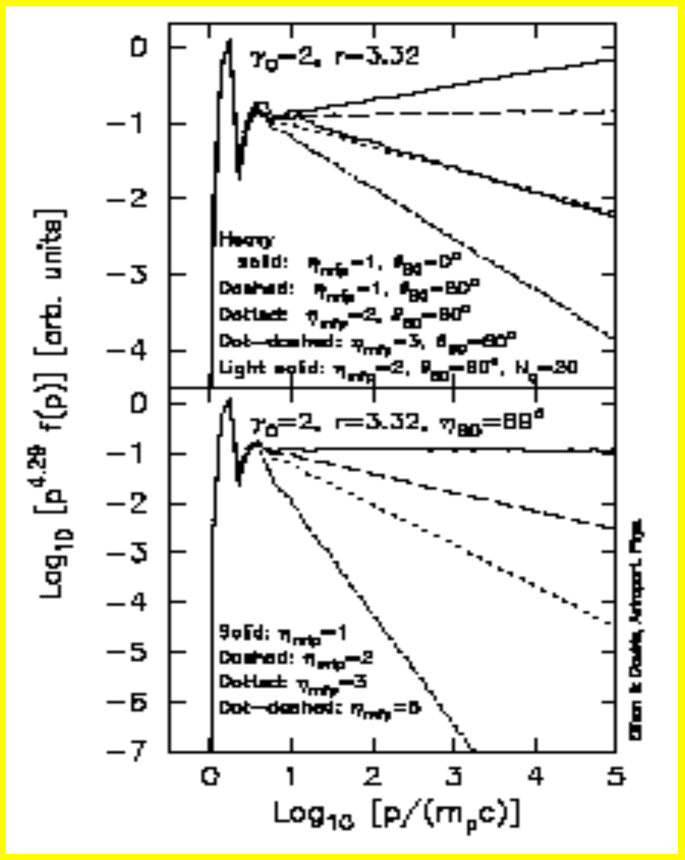


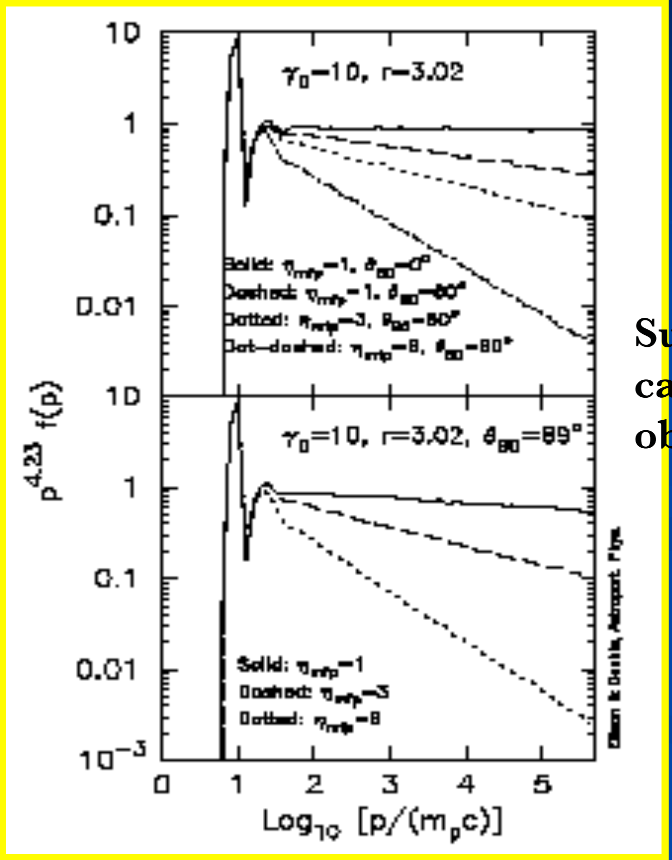
- Pitch angle diffusion (PAD) simulation shock frame distributions for a parallel, relativistic shock with $\Gamma_1\beta_1$=10.
- *Left Panel*: different distances upstream. At the shock (black), simulation results closely approximate the asymptotic ($\Gamma_1\beta_1$>>1) analytic form of Kirk et al. (2000).
- *Right Panel*: different distances downstream of the shock. Far downstream, the distribution approximates that for an isotropic fluid boosted by β_2=1/3.

Oblique Shock Geometry



Relativistic Shocks: Spectral Dependence on Field Obliquity and Diffusion



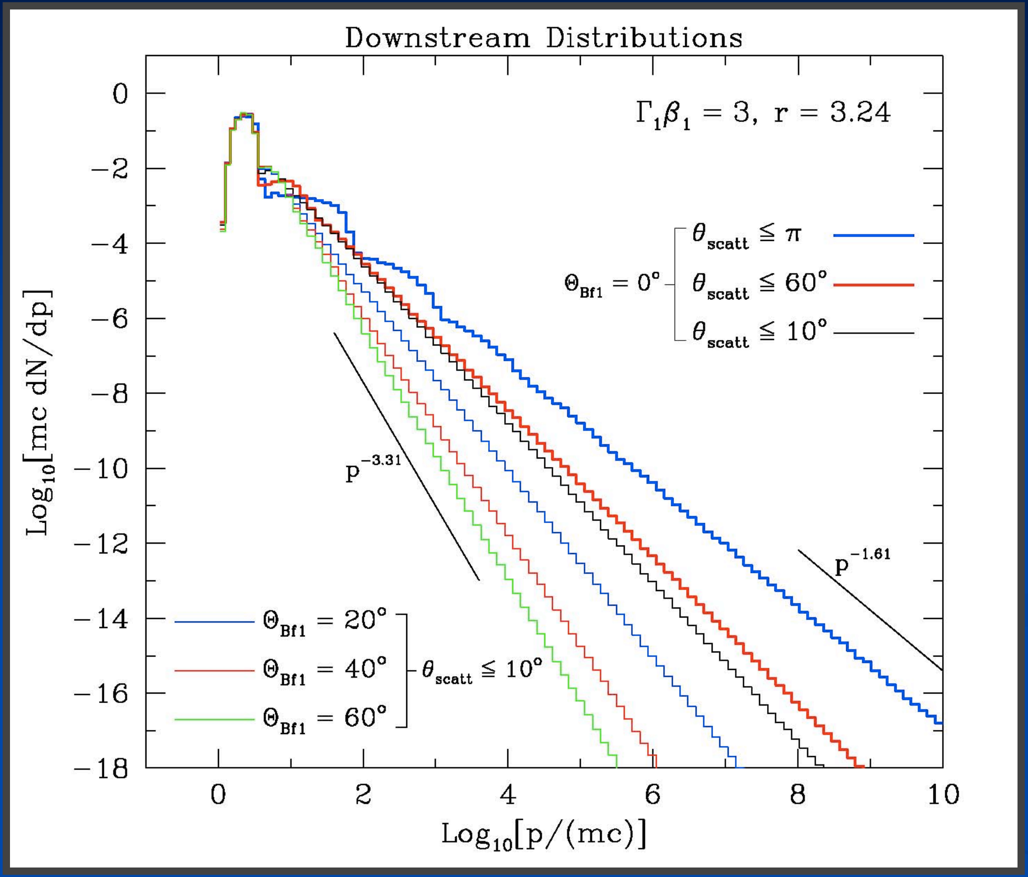


Ellison &
Double
(2004)

Superluminal cases for oblique shocks

- Increasing upstream B-field obliquity and/or ratio of mean free path to gyroradius steepens the continuum (e.g. Bednarz & Ostrowski 1998; Ellison & Double 2004; Summerlin & Baring 2008 [in prep]; Kirk & Heavens 1989).

Spectral Dependence on Field Obliquity

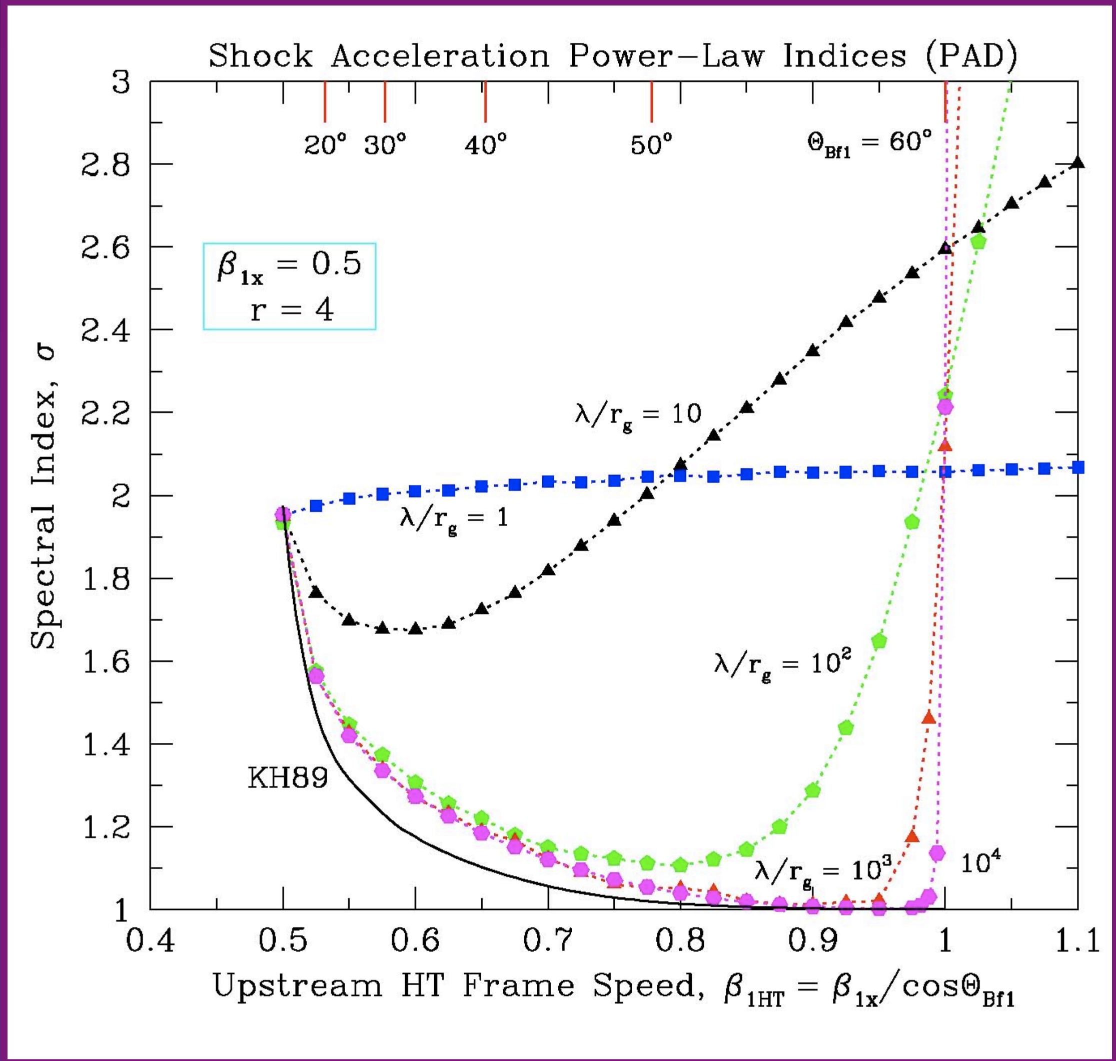


Superluminal cases ->

- Increasing upstream B-field obliquity and/or ratio of mean free path to gyroradius steepens the continuum (e.g. Bednarz & Ostrowski 1998; Ellison & Double 2004; Summerlin & Baring 2008 [in prep]; Kirk & Heavens 1989).

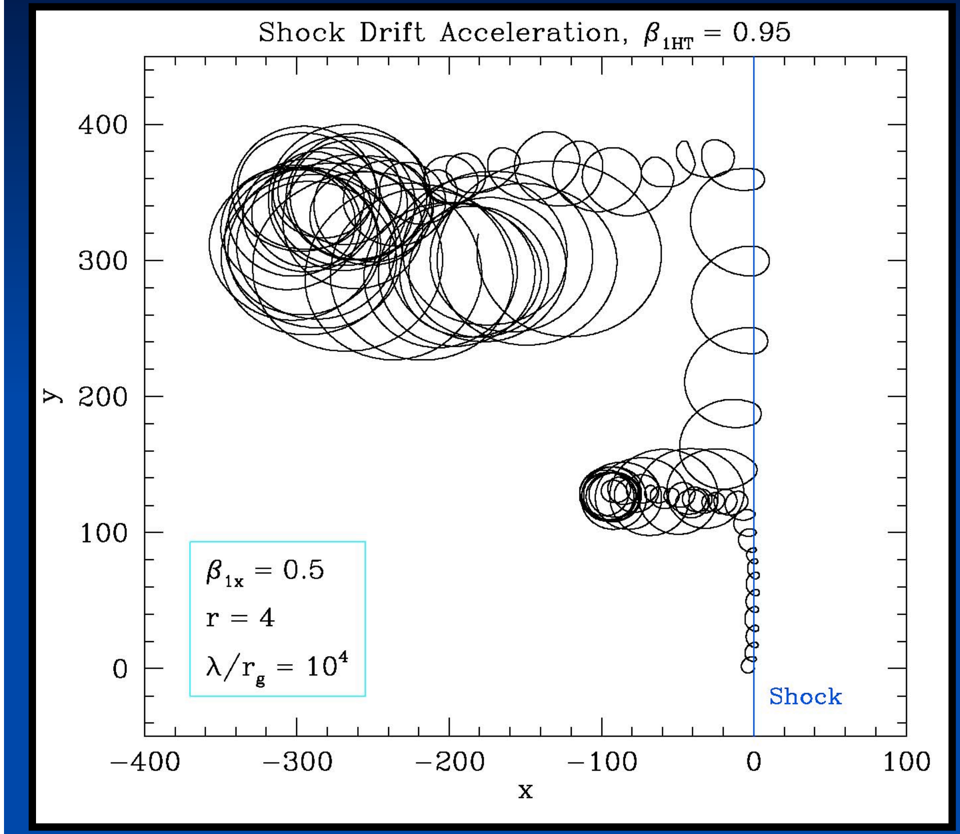
Shock Acceleration Spectral Indices

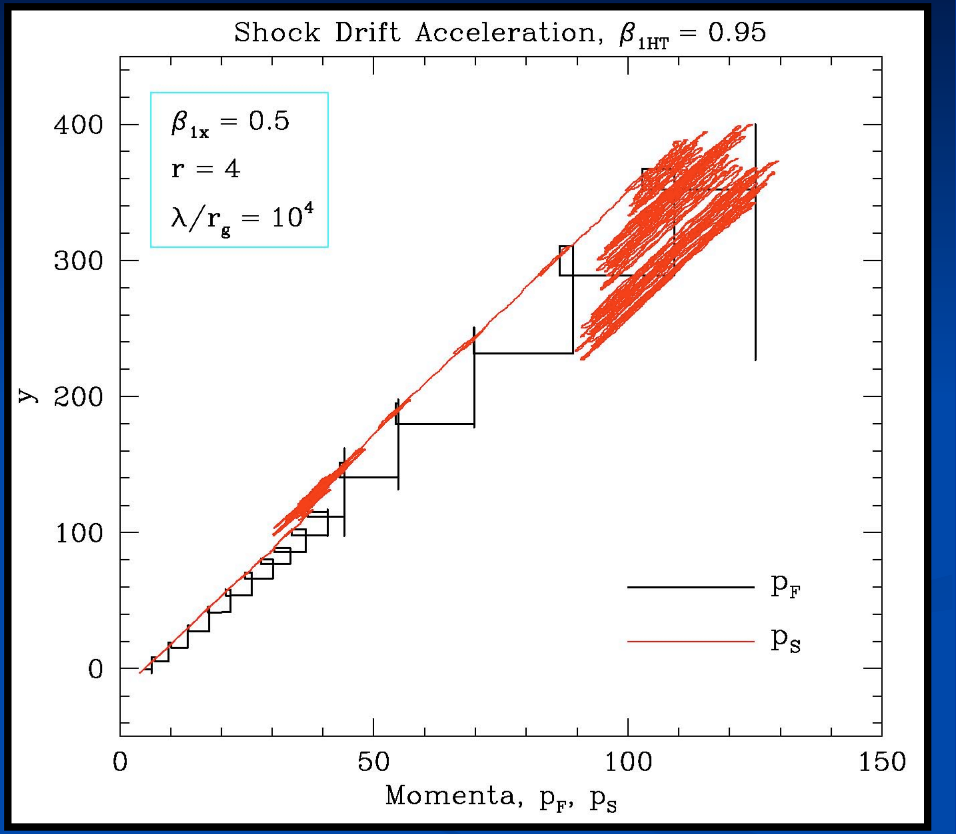
- Power-law indices in the limit of small angle scattering (pitch angle diffusion: PAD) range considerably;
- In cases of absolutely no cross field diffusion, the index is as low as unity and the distribution is extremely flat;
- Gyro-orbit simulations for $\lambda/r_g \to \infty$ do not quite match Kirk & Heavens (1989, KH89) solutions to diffusion-convection equation, since KH89 assumes conservation of adiabatic moment for particles interacting with the shock.



Baring & Summerlin 2009, in prep.

Shock Drift in Action: $\lambda/r_g=10^4$





- *Left Panel*: projection of a selected ion orbit onto the x-y plane, exhibiting drifting in the shock layer. *Right Panel*: evolution of magnitudes of momentum in fluid (p_F) and shock (p_S) frames versus y, indicating shock drift episodes interspersed with upstream diffusive hiatuses in energy gain;
- Lowering λ/r_g rapidly degrades the contribution of shock drift, enables particle convection downstream, and steepens spectrum.

Shock Drift in Oblique, Non-Relativistic Systems

DECKER AND VLAHOS

(DV 1986)

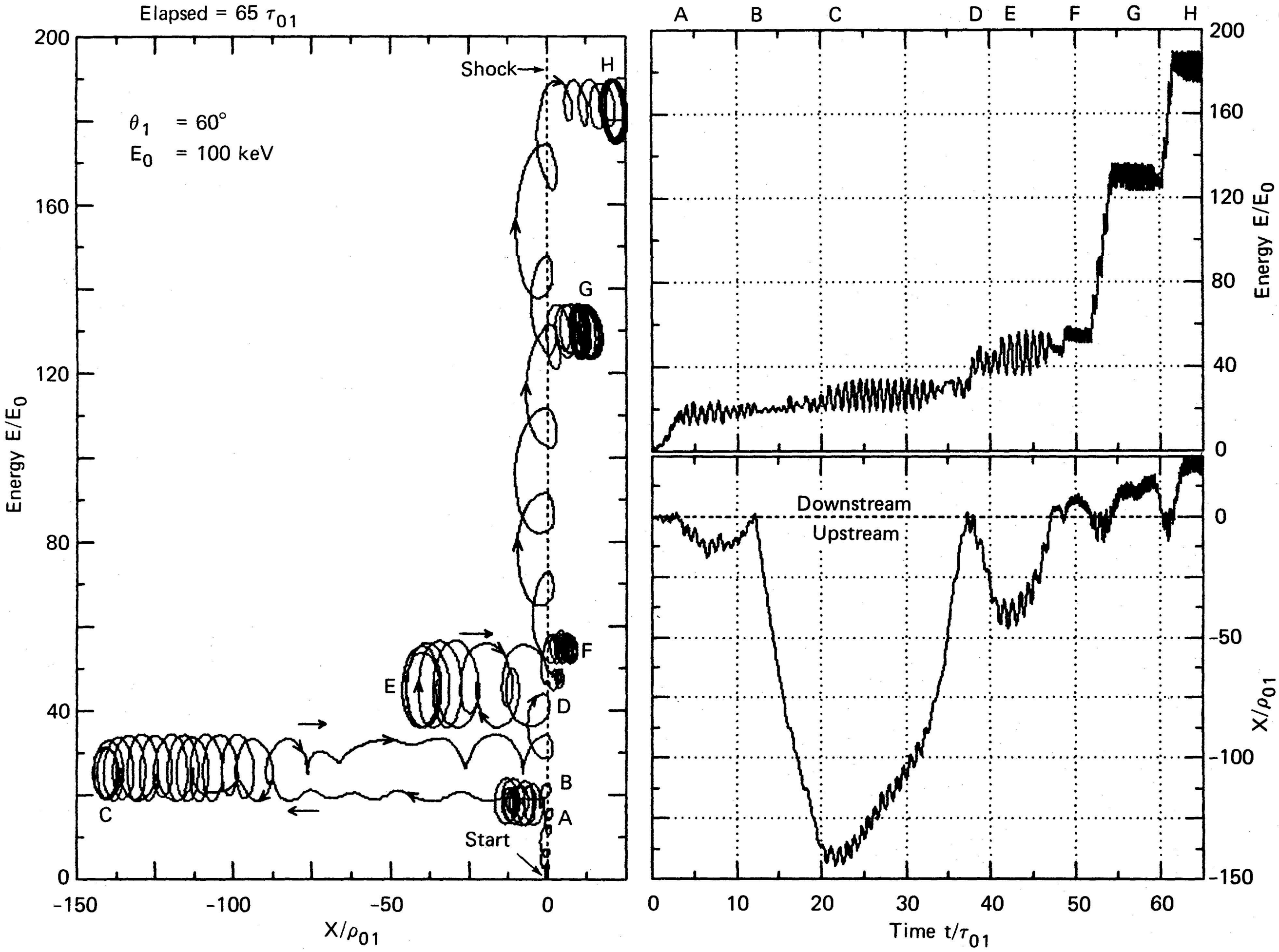
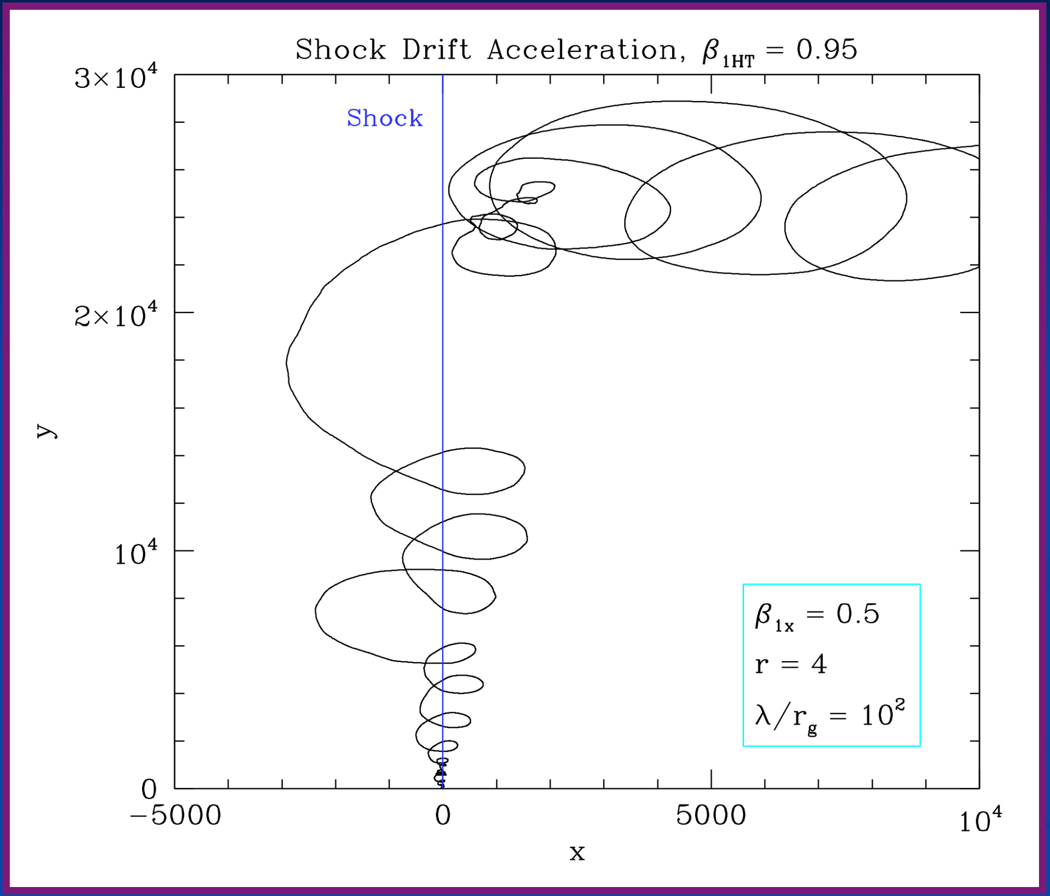


FIG. 6.—Sample for quasi-perpendicular shock θ_1 = 60°. See Fig. 5 caption and text for details.

$$\mathbf{p}.\frac{d\mathbf{p}}{dt} = q\mathbf{p}.\left\{\mathbf{E}+\frac{\mathbf{v}}{c}\times\mathbf{B}\right\} \equiv q\mathbf{p}.\mathbf{E}$$

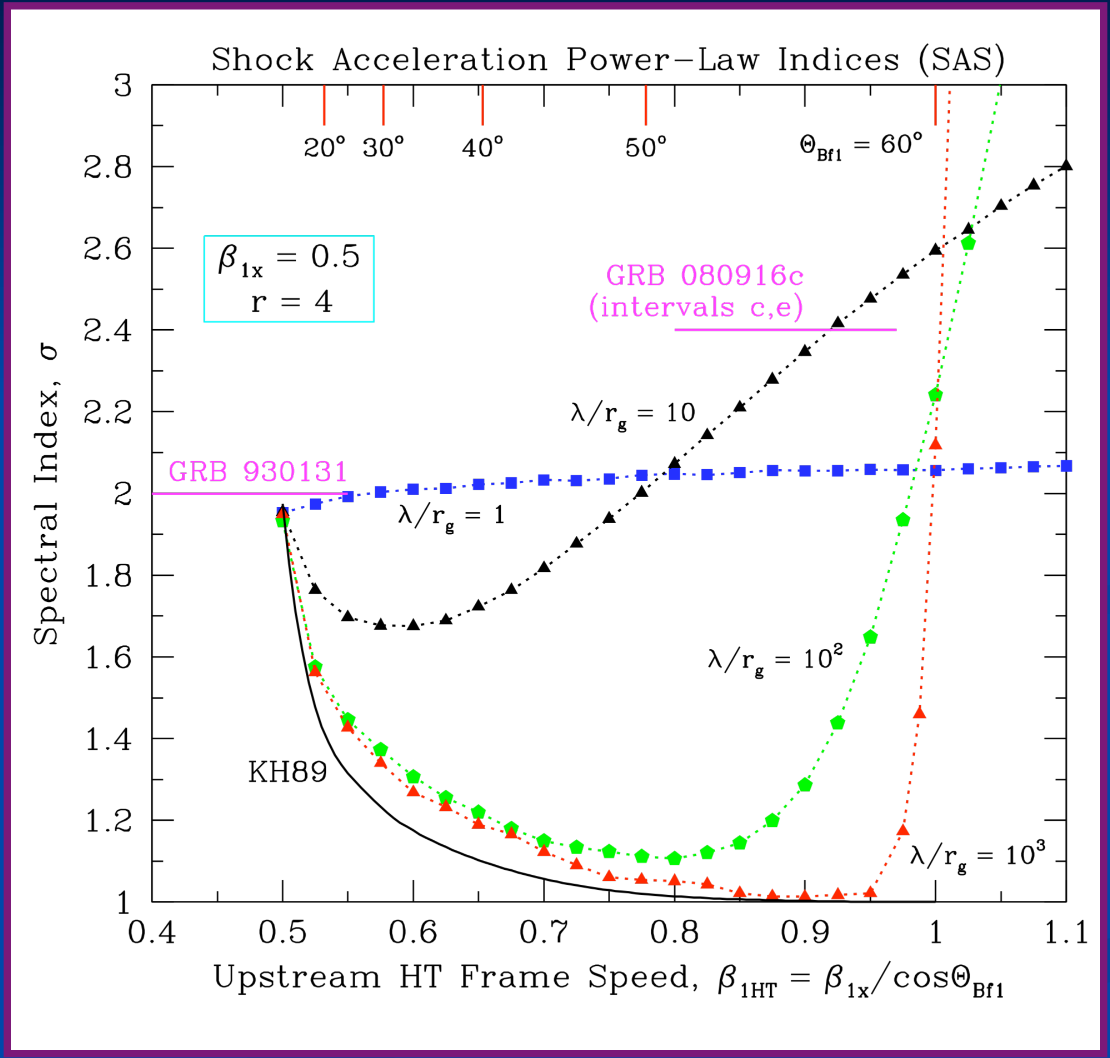
Disrupted Shock Drift: $\lambda/r_g = 10^2$



- Projection of a selected ion orbit onto the x-y plane, exhibiting drifting in the shock layer. Exhibits "wonky drift."
- Lowering λ/r_g rapidly degrades the contribution of shock drift, enables particle convection downstream, and steepens spectrum.

Shock Acceleration Spectral Indices

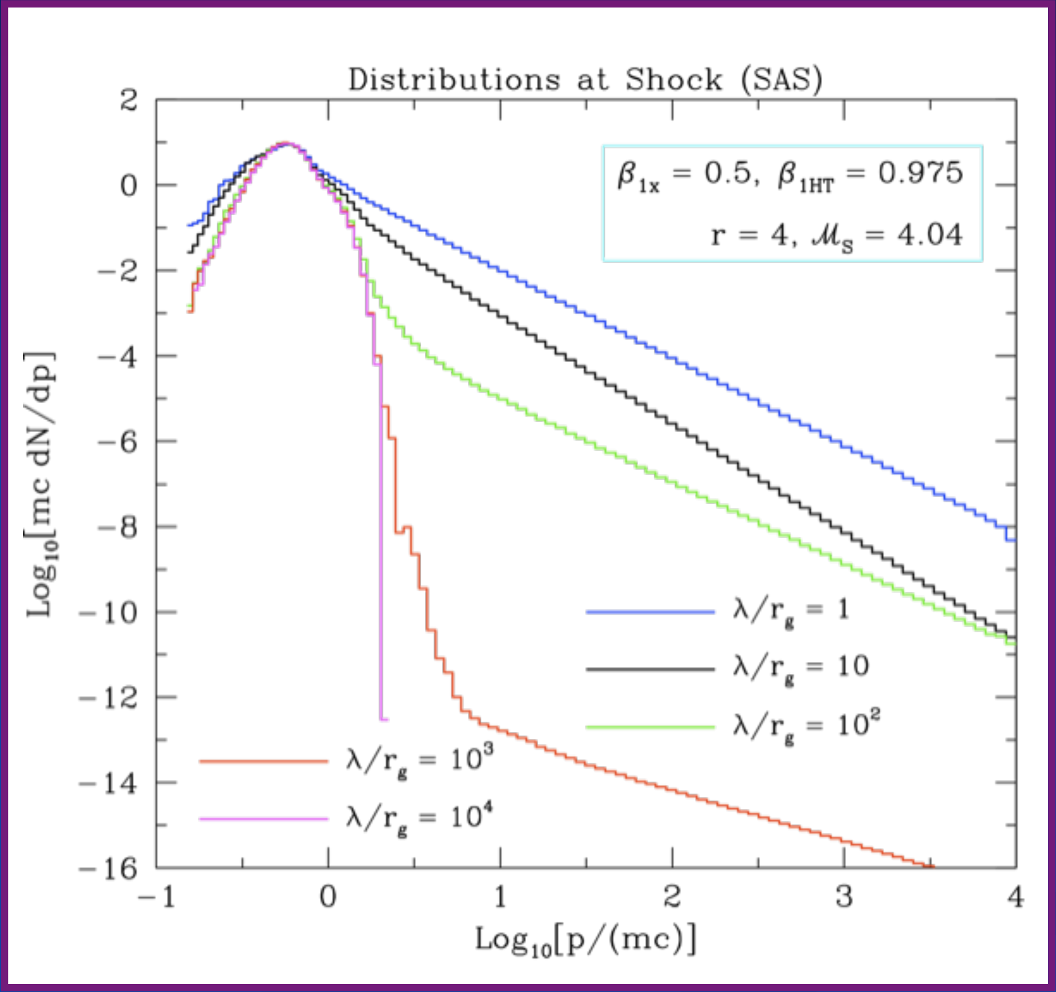
- Power-law indices in the limit of small angle scattering (pitch angle diffusion: PAD) range considerably;
- In cases of absolutely no cross field diffusion, the index is as low as unity and the distribution is extremely flat;
- Gyro-orbit simulations for $\lambda/r_g \rightarrow \infty$ do not quite match Kirk & Heavens (1989, KH89) solutions to diffusion-convection equation, since KH89 assumes conservation of adiabatic moment for particles interacting with the shock.



Baring & Summerlin (2009)

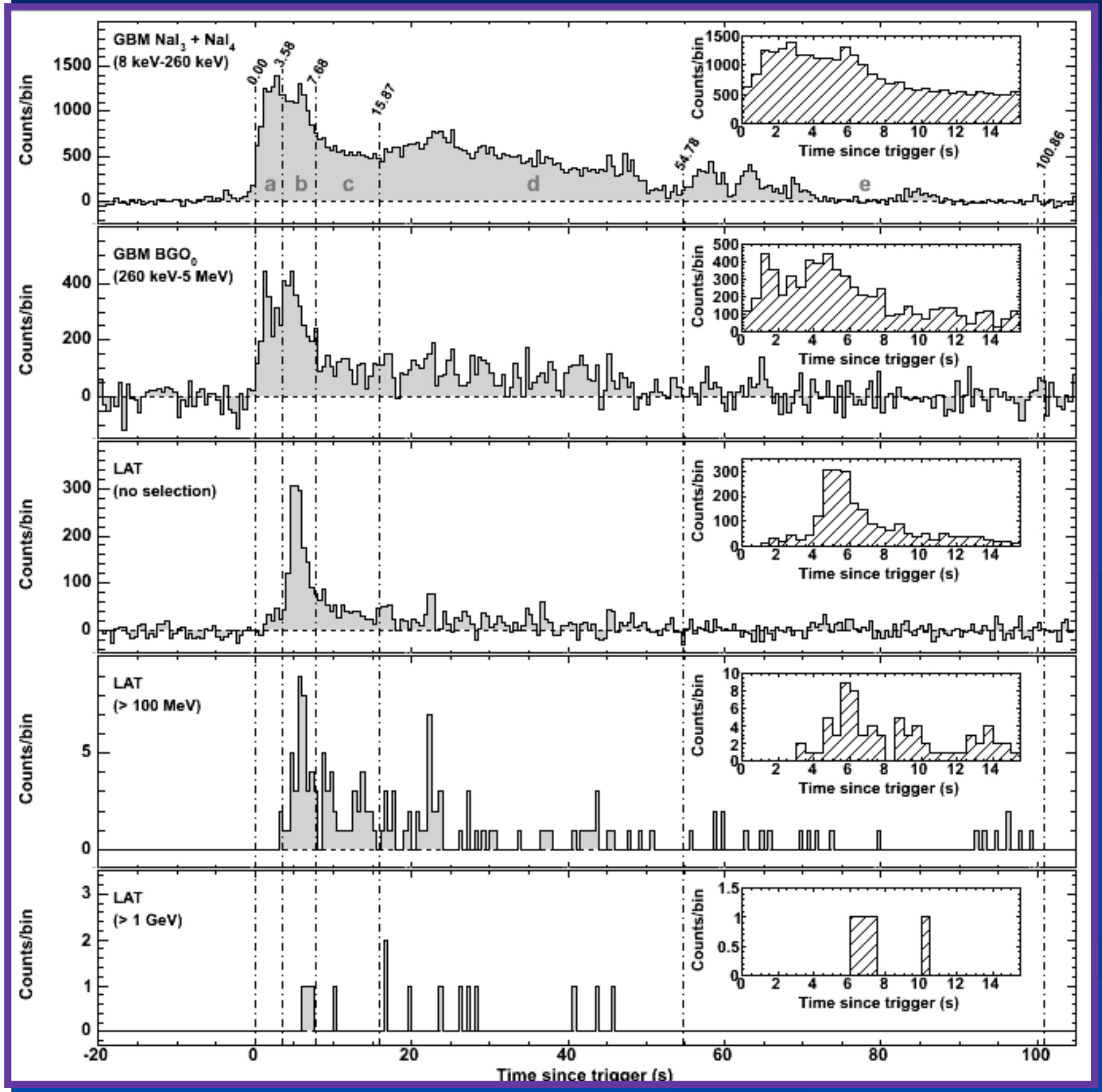
Injection Efficiencies: Near Luminality

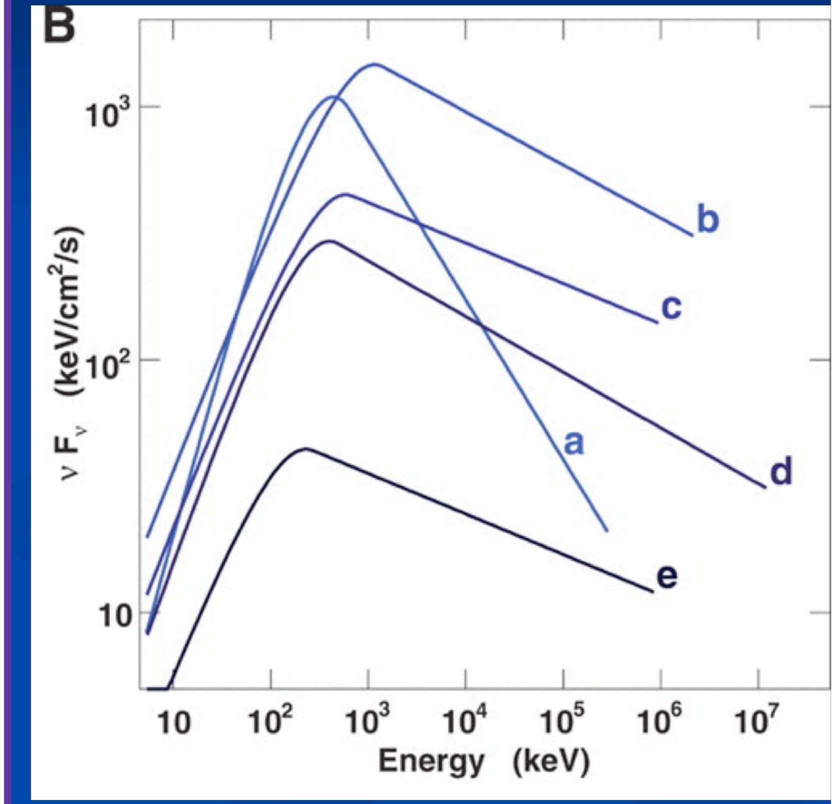
- When shocks are nearly luminal, the injection efficiency precipitously drops in gyro-orbit simulations as $\lambda/r_g \rightarrow \infty$.
- => flat power-law index cases are poor injectors – this becomes far more extreme as HT frame speed approaches c.
- Rapid convection downstream inhibits suprathermal injection.
- Stochastic heating can aid injection: only modestly.
- Astrophysical requirements of moderate turbulence and injection efficiency advocate spectra steeper than $E^{-1.5}$.



Baring & Summerlin 2009.

Fermi GRB 080916c
Temporal and Spectral Evolution





- Science (2009): Abdo et al.

Conclusions

- Shock acceleration particle spectral indices depend on several shock parameters: field obliquity to the shock normal, scattering strength or level of MHD turbulence, amount of diffusion across B;
  - => there is no canonical spectral index.
- So, GRB and blazar spectra are intimately connected to detailed shock parameters =>*Fermi* role for gamma-ray spectral diagnostics for both hadronic and leptonic models.
- **Extremely flat spectra can be realized in sub-luminal shocks with minimal cross field diffusion**: extremely efficient retention of particles in the shock layer (c.f. Ostrowski 2000 cocoons) permits efficient action of shock drift acceleration.
  - Unlikely to be realized in Nature! And not commensurate with source photon signals (σ>1.5).