Cosmic Ray Acceleration in Relativistic Astrophysical Shocks

Matthew G. Baring

Rice University

baring@rice.edu

Thesis Student:
Errol J. Summerlin

SOCOR Conference, Trondheim, Norway, 16th June, 2009

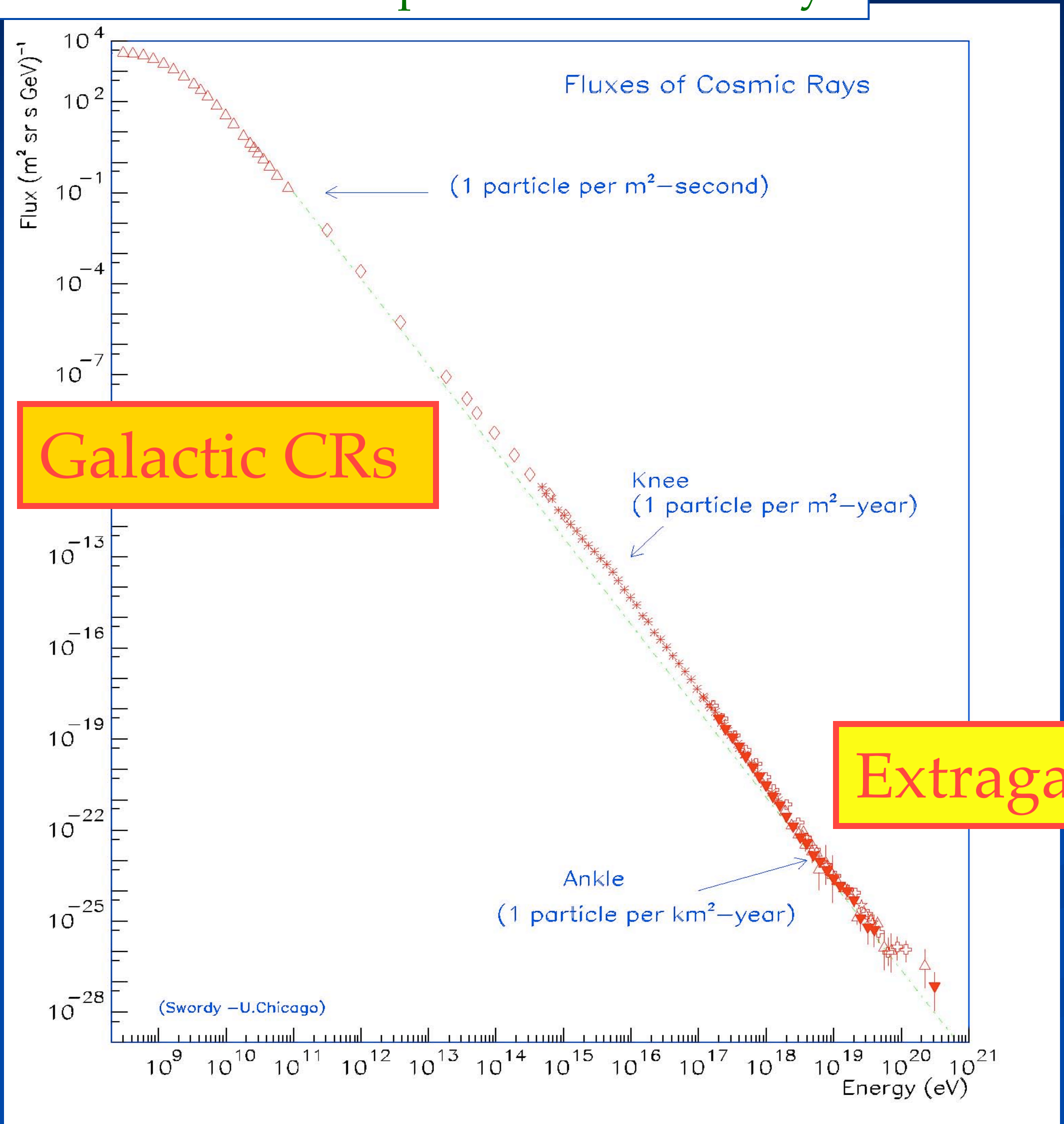
Talk Layout

- Astrophysical context; gamma-ray bursts, and active galaxies (radio galaxies and blazars) as sources of 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).

Complete Cosmic Ray Spectrum

Balloon + satellite expts ← | → EAS arrays

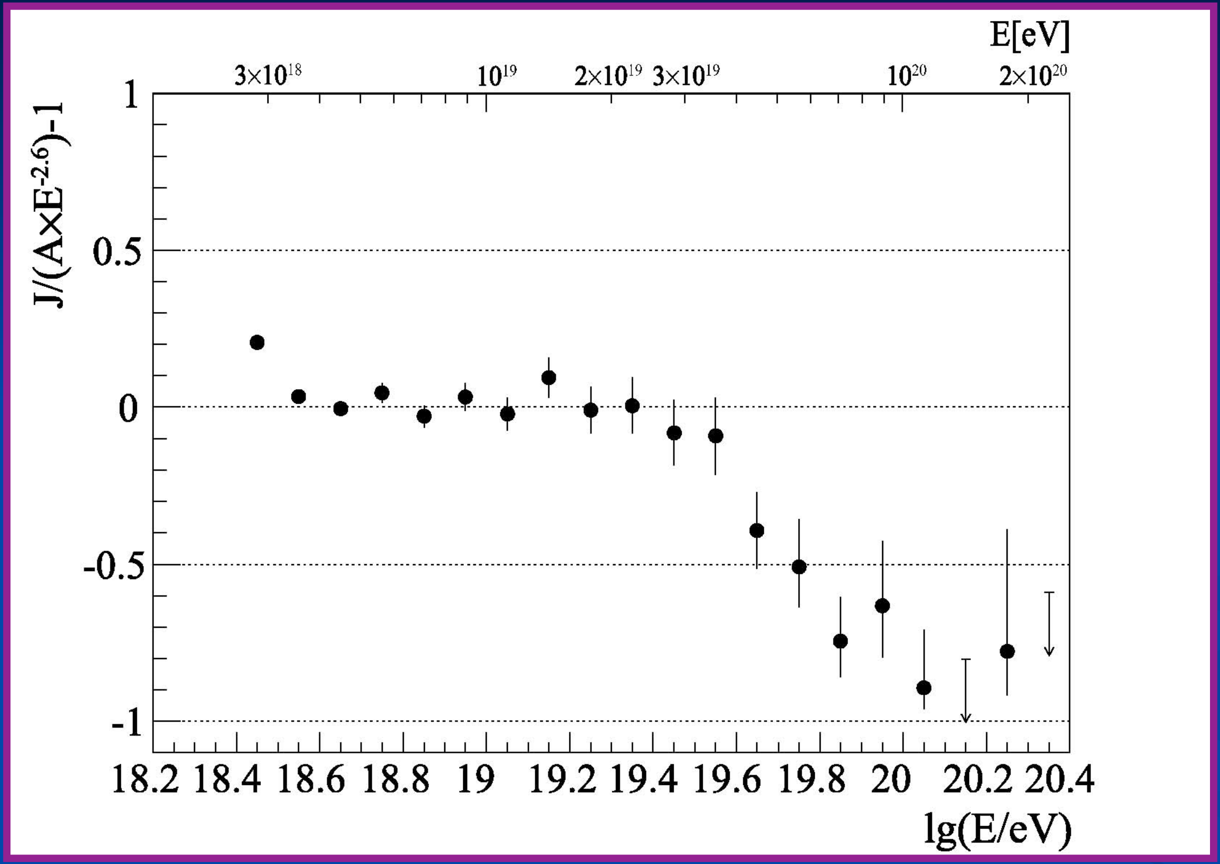
Discovered in 1912 by V. Hess



Galactic CRs

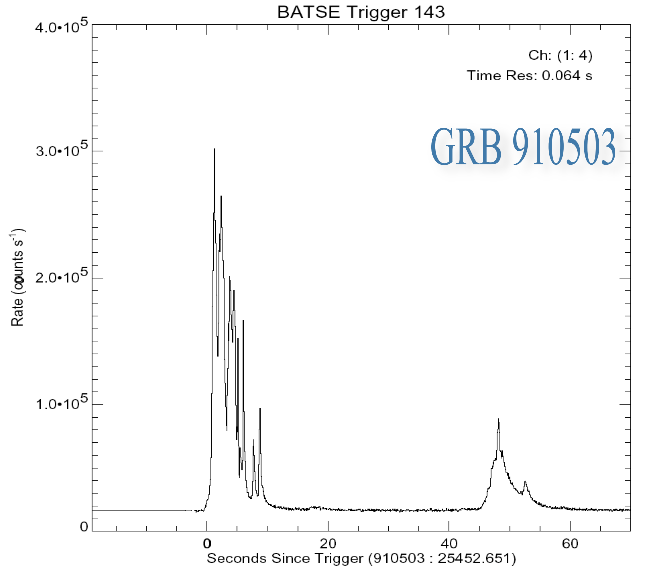
Extragalactic CRs

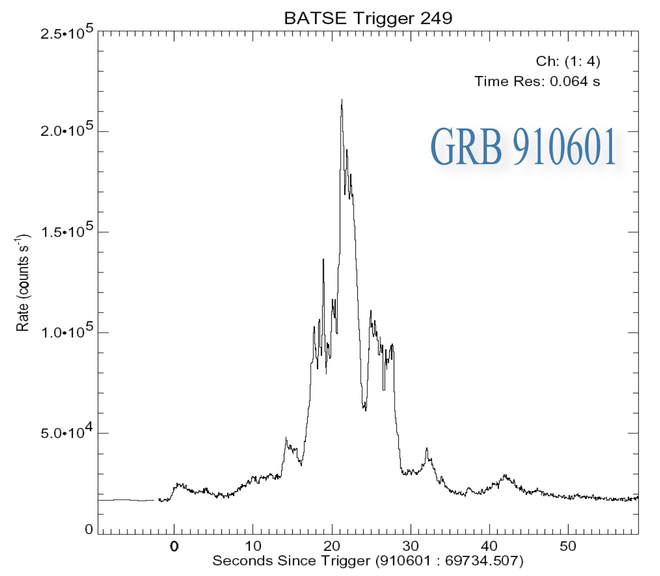
Pierre Auger UHECR Spectrum (2007)

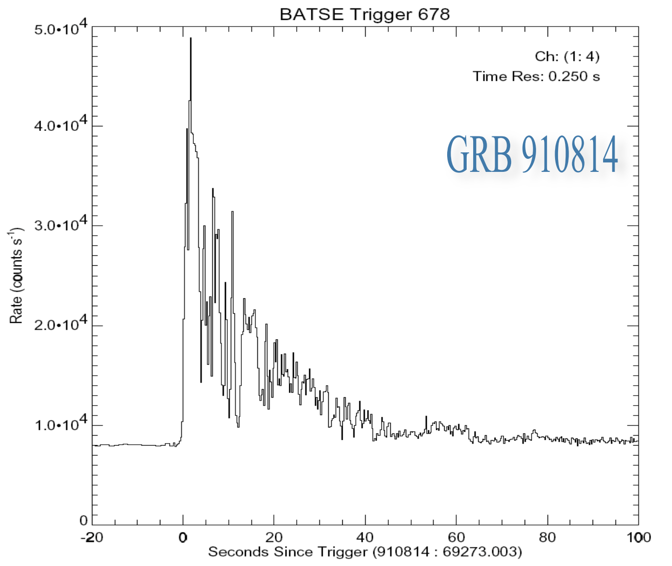


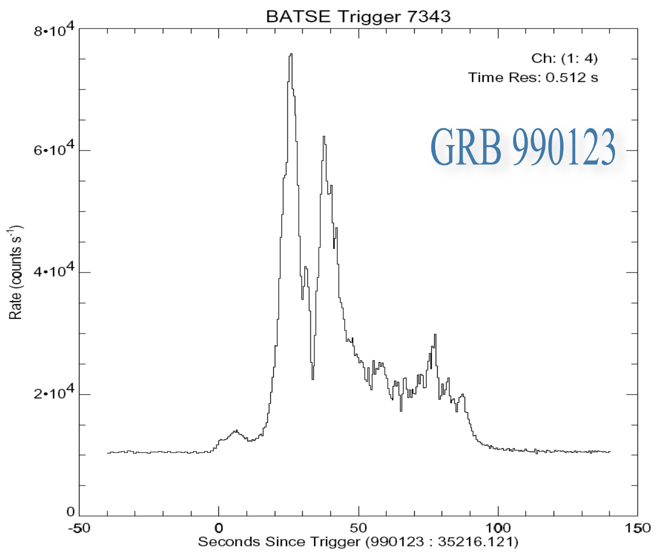
- Pierre Auger Array determination of UHECR spectrum (x $E^{2.6}$ above) ***reveals GZK turnover*** at 60 EeV (Roth et al. 2007).
- Confirms Fly’s Eye and later HIRES observations; contradicts AGASA results;
- => UHECR sources must be further than around 30-50 Mpc.

BATSE Gamma-Ray Burst Lightcurves

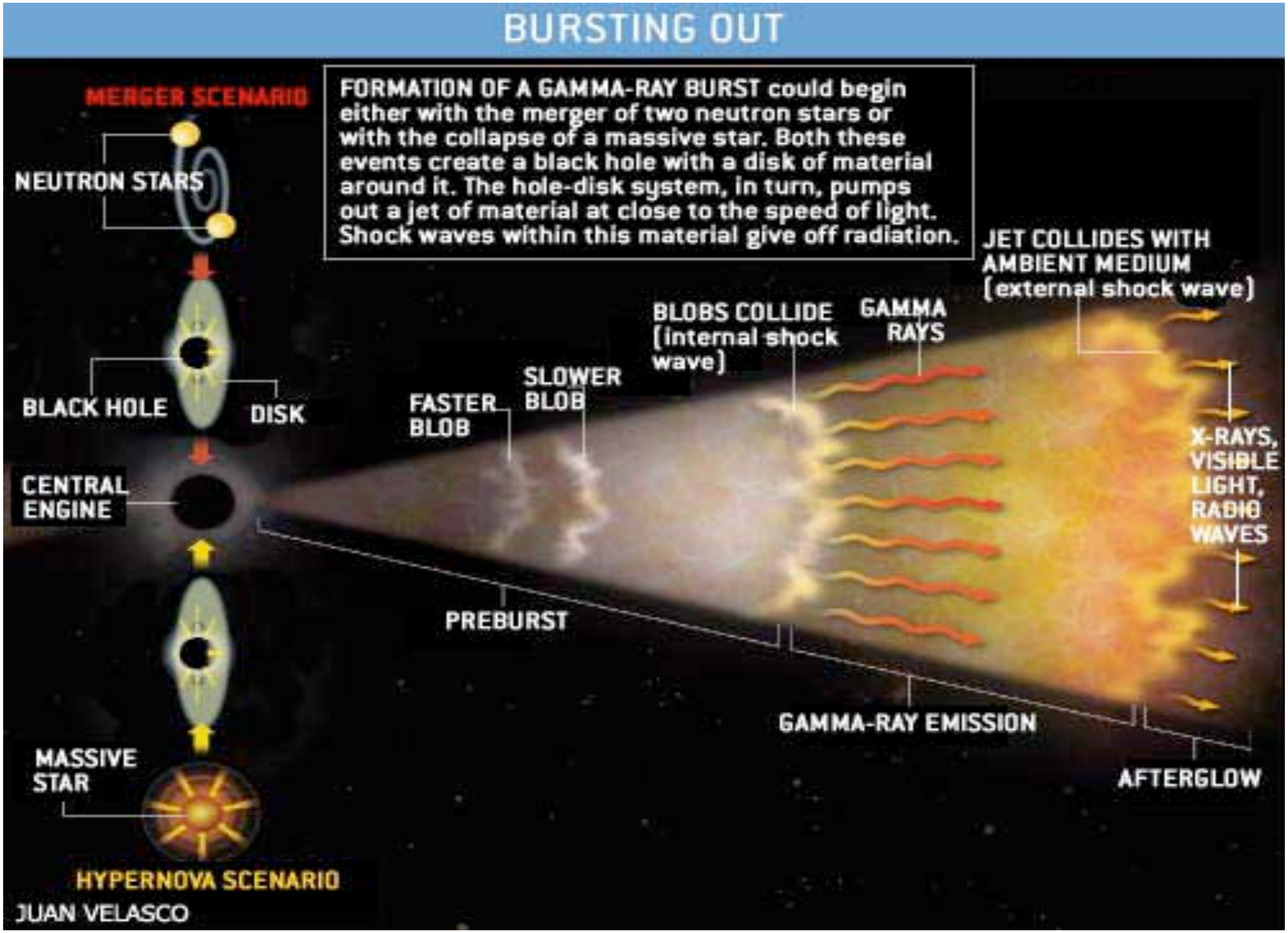








Gamma-Ray Bursts: Relativistic Outflows

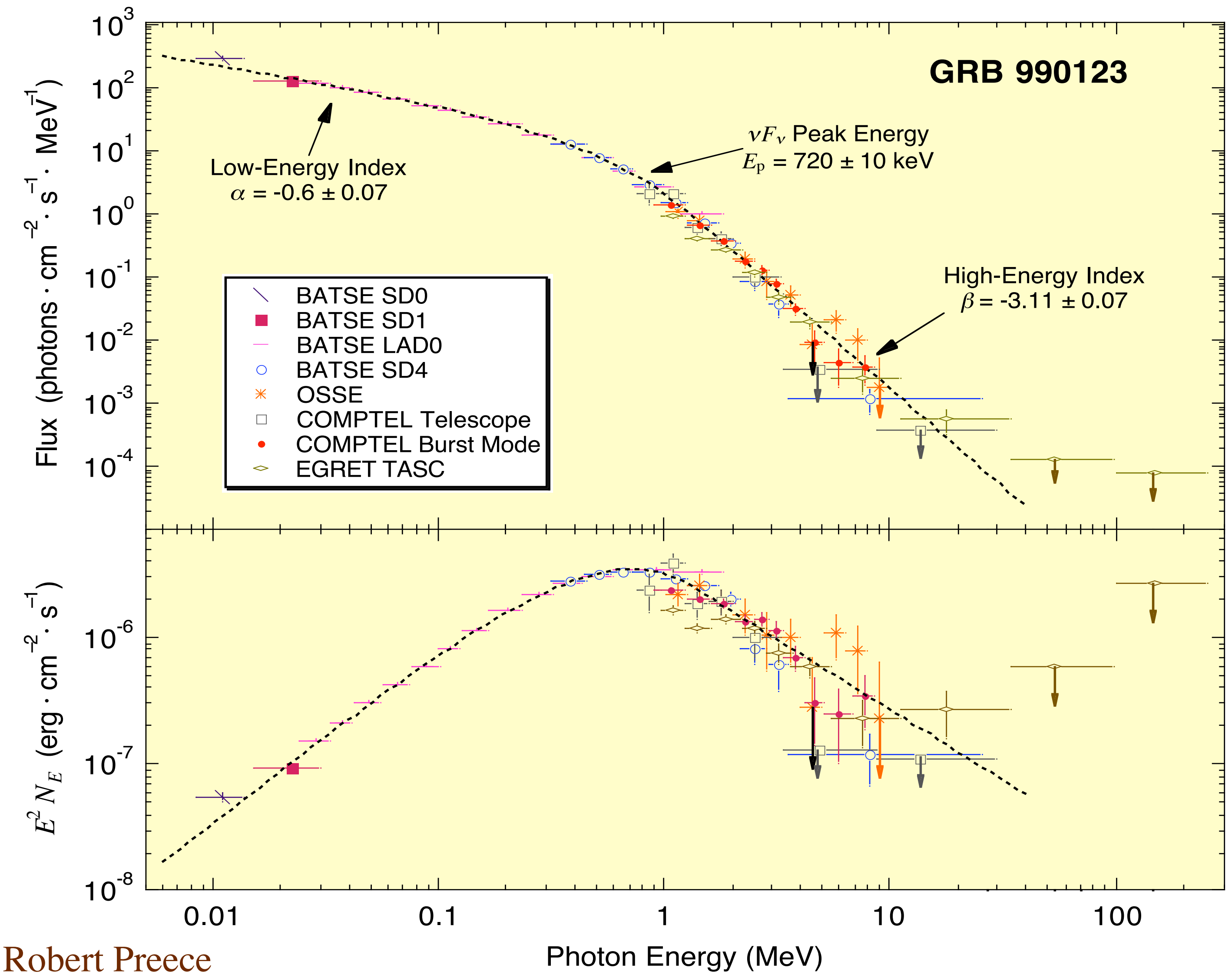


BURSTING OUT

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.

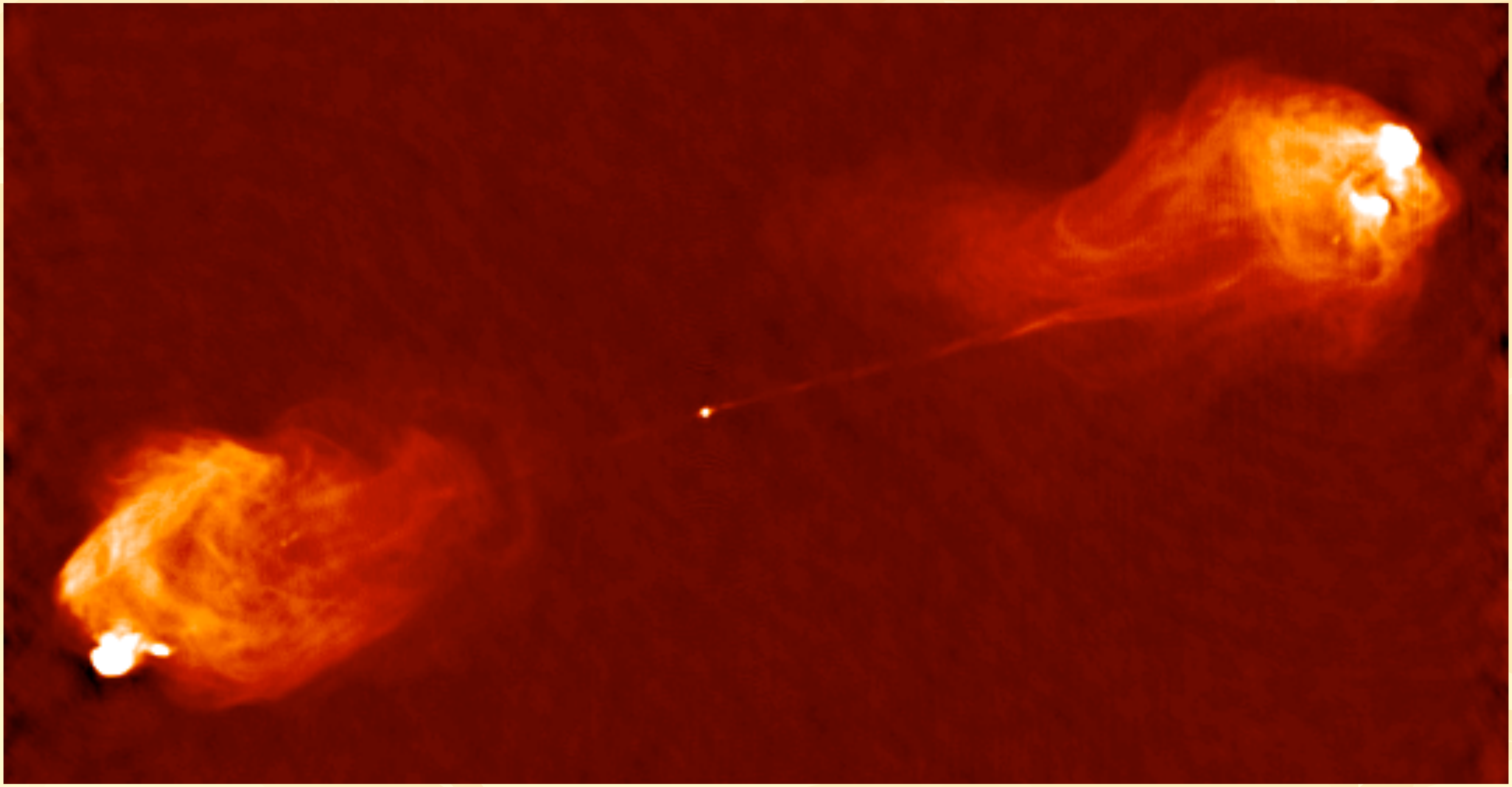
JUAN VELASCO

Spectral Character: GRB990123



Credit: Robert Preece

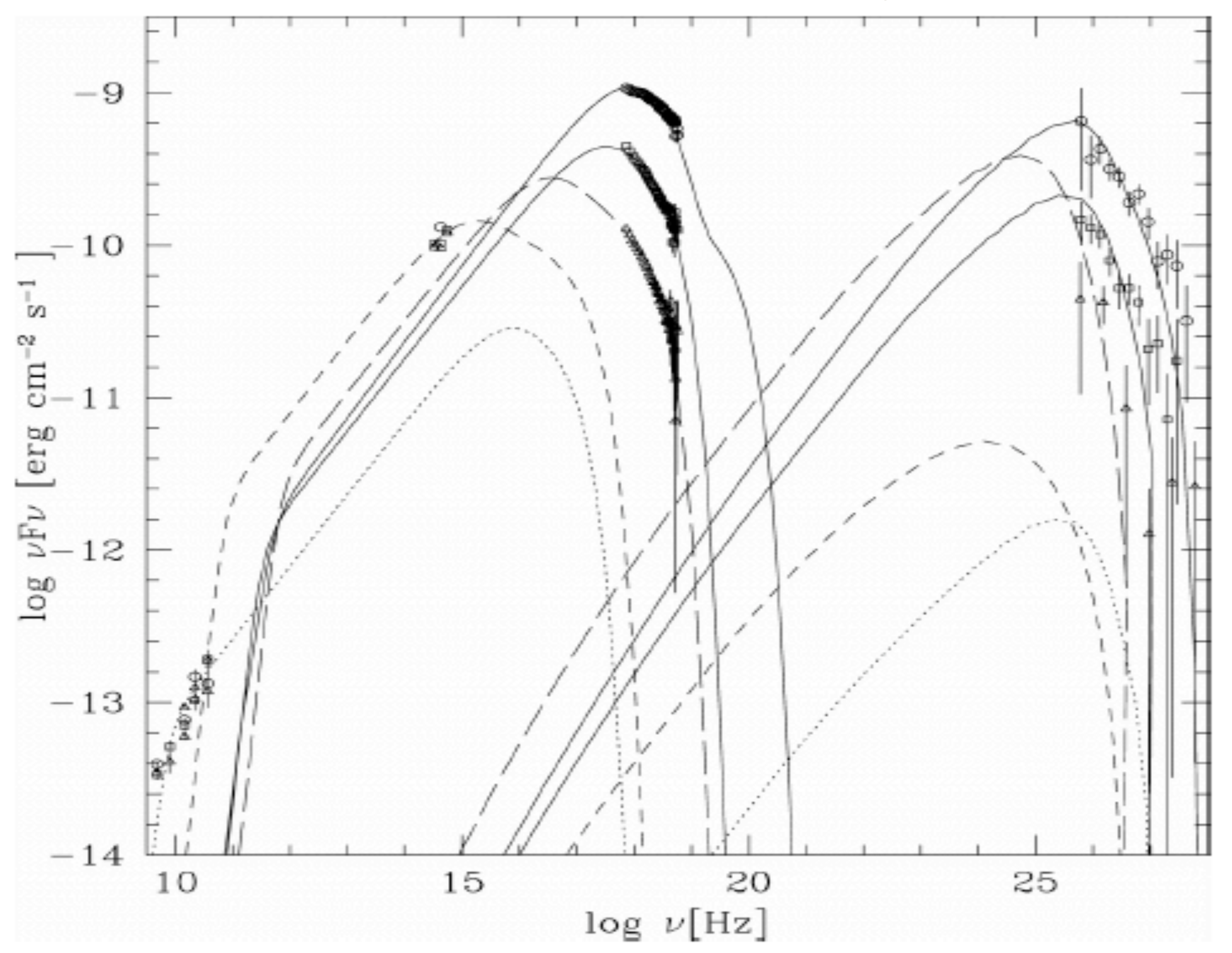
High Energy Cosmic Ray Accelerators: Radio Galaxies like Cygnus A



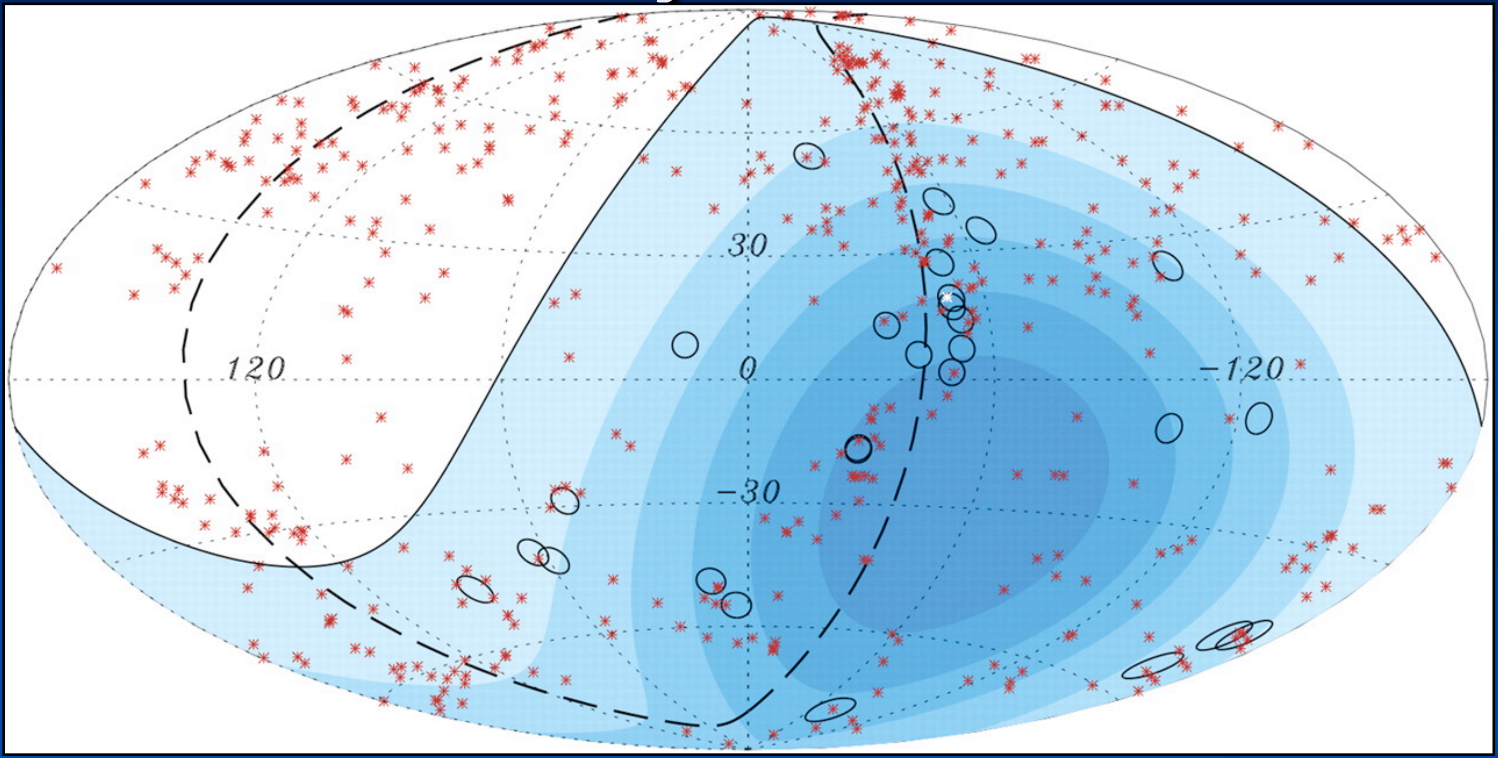
Multi-wavelength Flaring in the Blazar Markarian 421

z=0.031

Blazejowski et al. (2005)



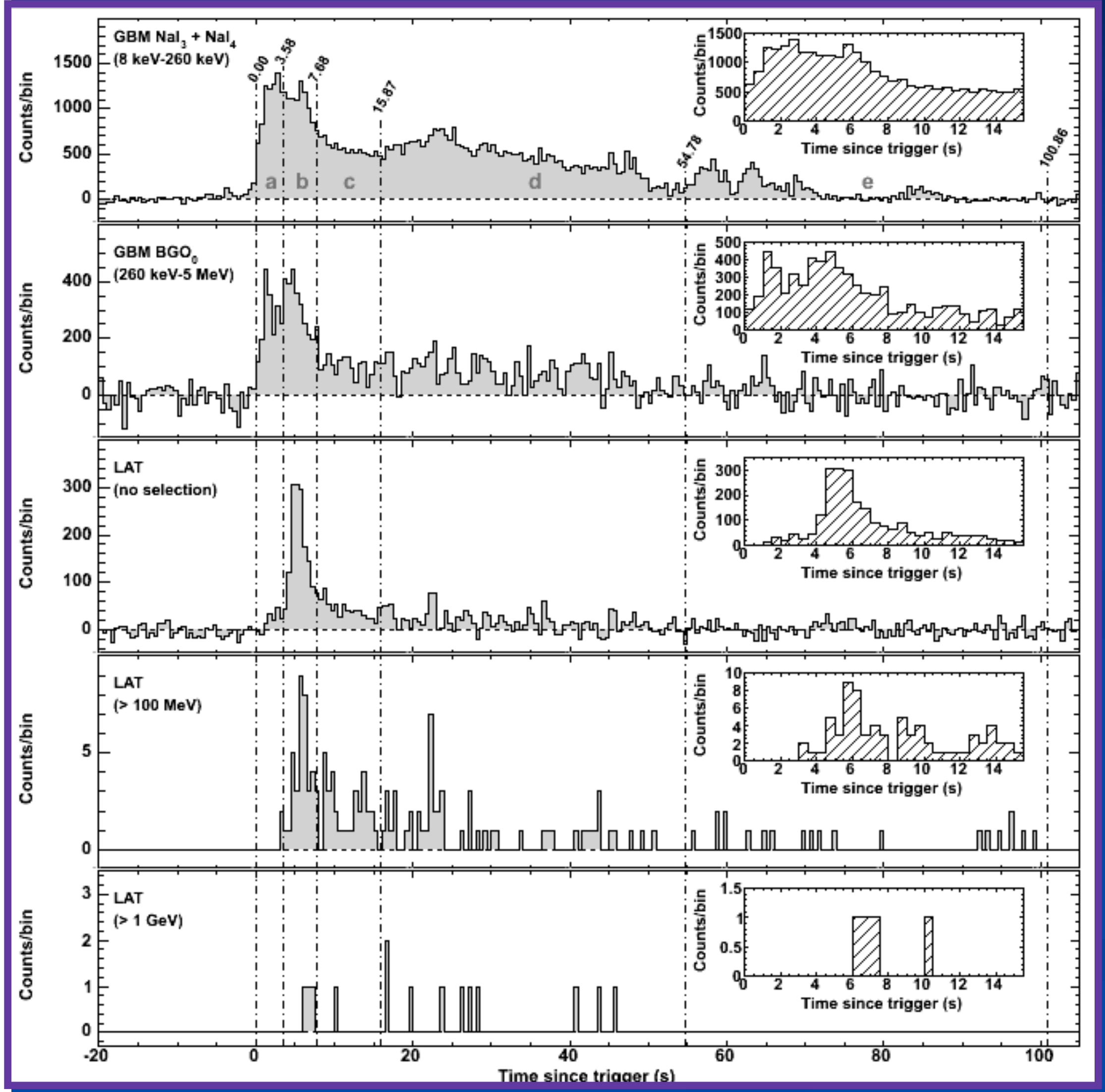
Correlation of UHECR Directions with nearby (z<0.02) AGNs

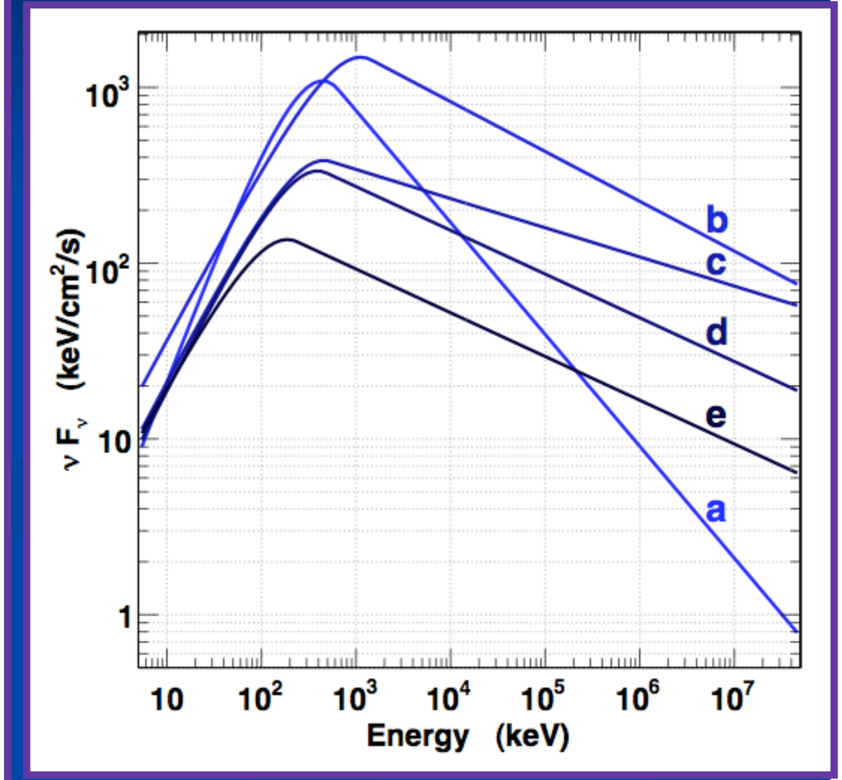


- **Science (2007) 318, 938**: Pierre Auger Collaboration announces correlation of arrival directions on Celestial Sphere (Aitoff proj.) of the 27 cosmic rays (1.2 year's data) with highest energy (E>57 EeV) with the positions of the 472 AGN (318 in the field of view of the Observatory) with redshift *z* < 0.018 (*D* < 75 Mpc Veron-Cetty 2006 catalog). The dashed line marks the Supergalactic plane.

Fermi GRB 080916c

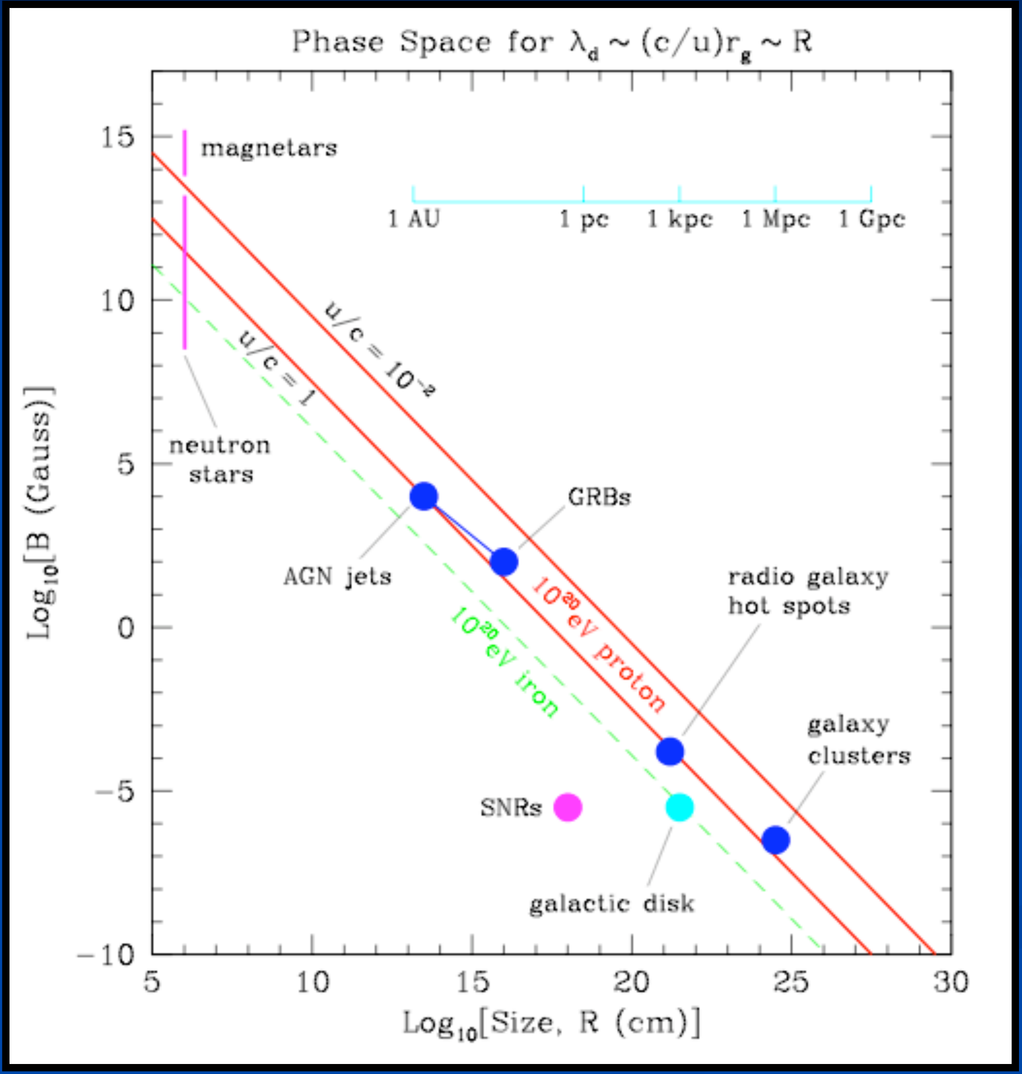
Temporal and Spectral Evolution





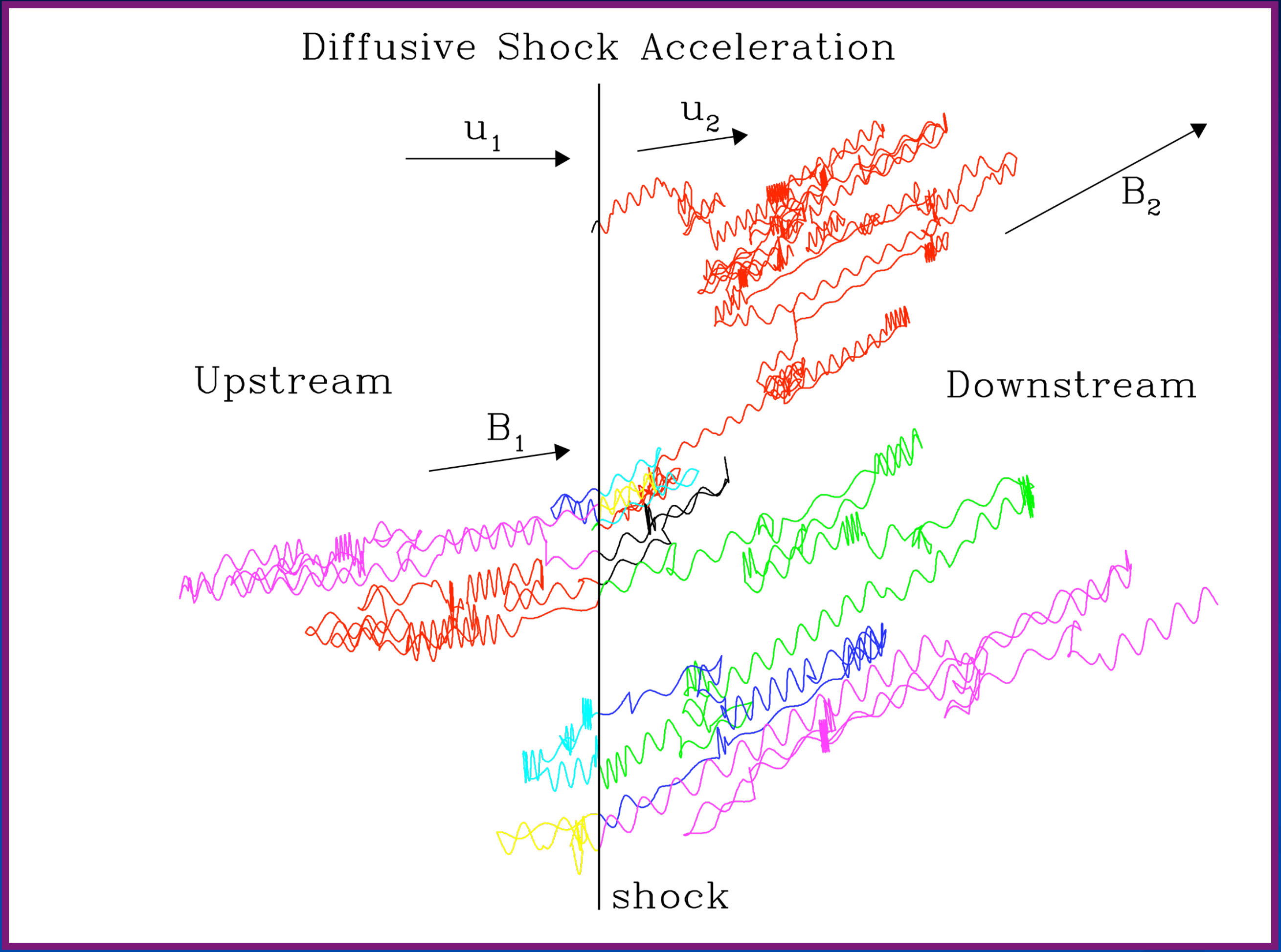
- Science (2009): Abdo et al.

Cosmic Ray Acceleration: Fields and Spatial Scales



- B-R phase space - after Hillas (1984);
- Based on diffusion theory at non-rel. shock using Bohm limit (mfp $\lambda \sim c\, r_g/u$);
- Gyroresonant interactions operate;
- AGN jets, GRBs and magnetars are best candidates for UHECR production.

Monte Carlo Simulation Particle Trajectories

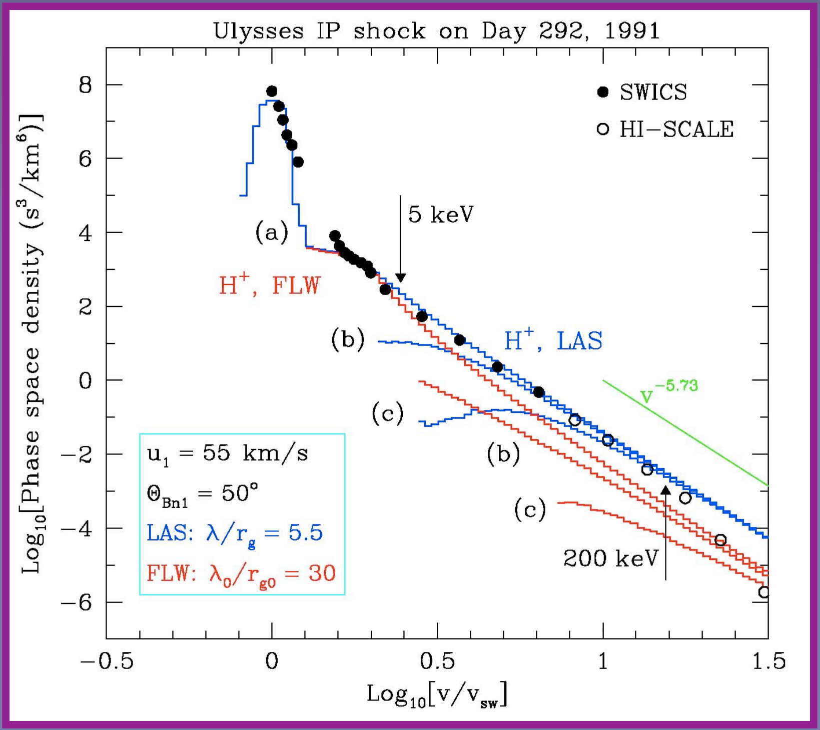


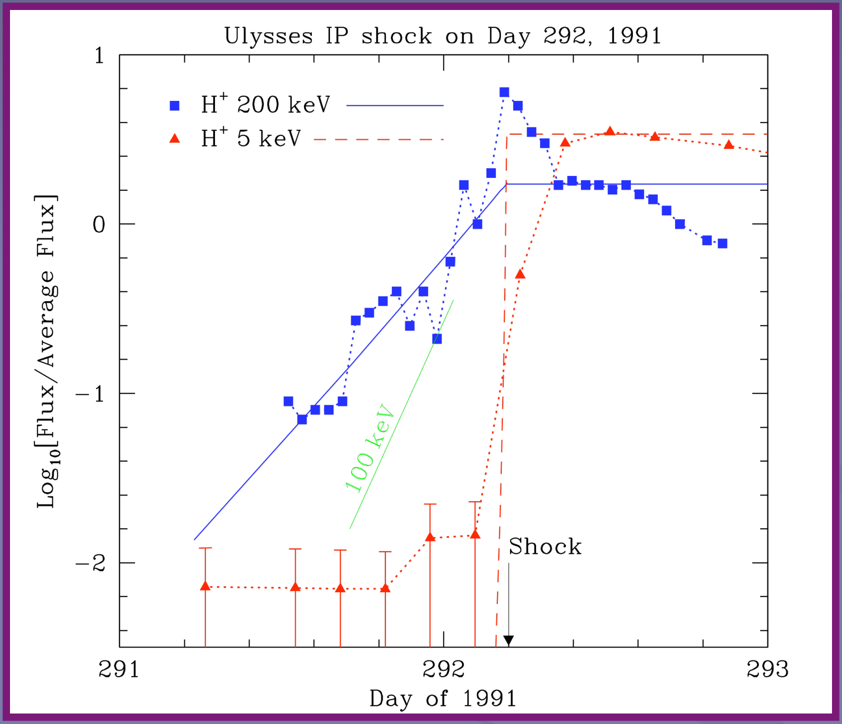
- Gyration in B-fields and diffusive transport modeled by a Monte Carlo technique; color-coded in Figure according to fluid frame energy.
- Shock crossings produce net energy gains (evident in the increase of gyroradii) according to principle of first-order Fermi mechanism.

Shock Acceleration: Monte Carlo Simulations

- The Monte Carlo simulations use a kinetic description of convection and diffusion in MHD shocks (after Bell 1978);
- 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.

Ulysses 1991 Day 292 Shock: Spectral and Spatial Comparison





- ***Left Panel***: Ulysses SWICS and HI-SCALE downstream data from Gloeckler, et al. (1994), together with MC simulation fit (upper blue histogram) to data from Baring & Summerlin (2008).
- ***Right Panel***: Spatial/temporal profiles for 5 keV (SWICS) and 200 keV (HI-SCALE) protons. MC model for LAS in strong field turbulence matches 200 keV ramp scale *for same turbulence parameter λ/r_g that fits downstream spectrum*.

Expectation Uncertainties for UHECRs

- Population statistics + source energetics:
  - Space distribution of source population;
  - Duty cycle of transient or flaring sources;
  - Non-thermal hadronic luminosity distribution function of candidate sources (i.e. AGNs and GRBs);
  - Relativistic beaming reductions of intrinsic source luminosity;
- Spectral form: power-law "lever arm" critical to fluxes predicted in *HIRES/Auger/AGASA* window;
  - shock acceleration expectations;
  - Tying cosmic ray spectra to candidate source gamma-ray spectra - a central role for *Fermi* science;
- Hadronic vs. leptonic acceleration efficiency:
  - non-thermal population abundances possess the biggest uncertainty: they are products of the acceleration environment.

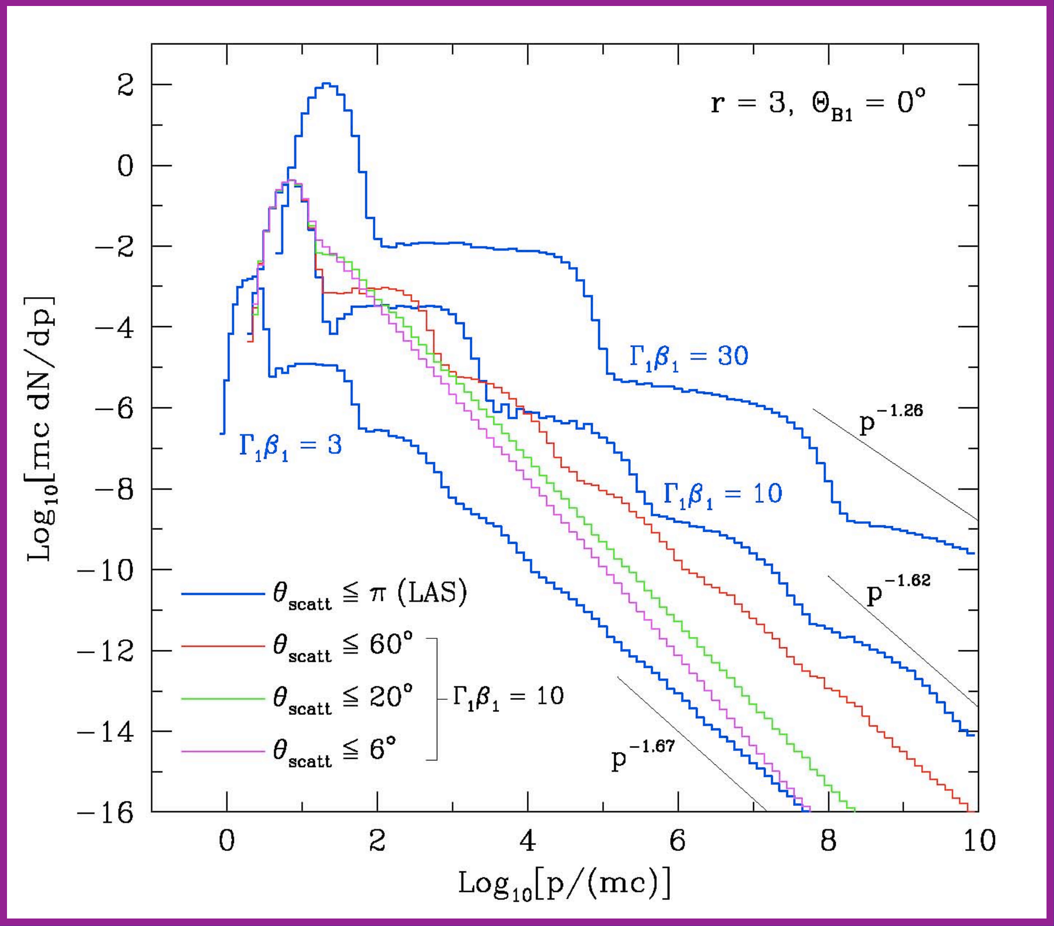
Spectral Properties of Diffusive Relativistic Shock Acceleration

- 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;
- Spectral index is generally (but not always) a strongly *increasing* function of field obliquity angle Θ_{Bn1}.

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)

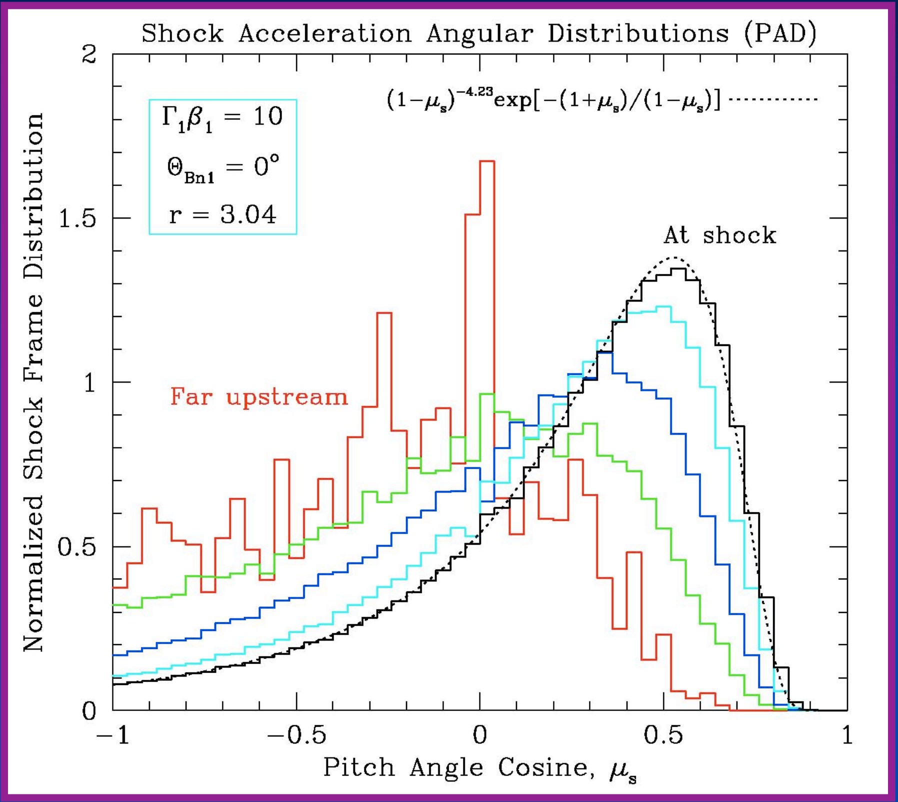
Stecker, Baring & Summerlin 2007

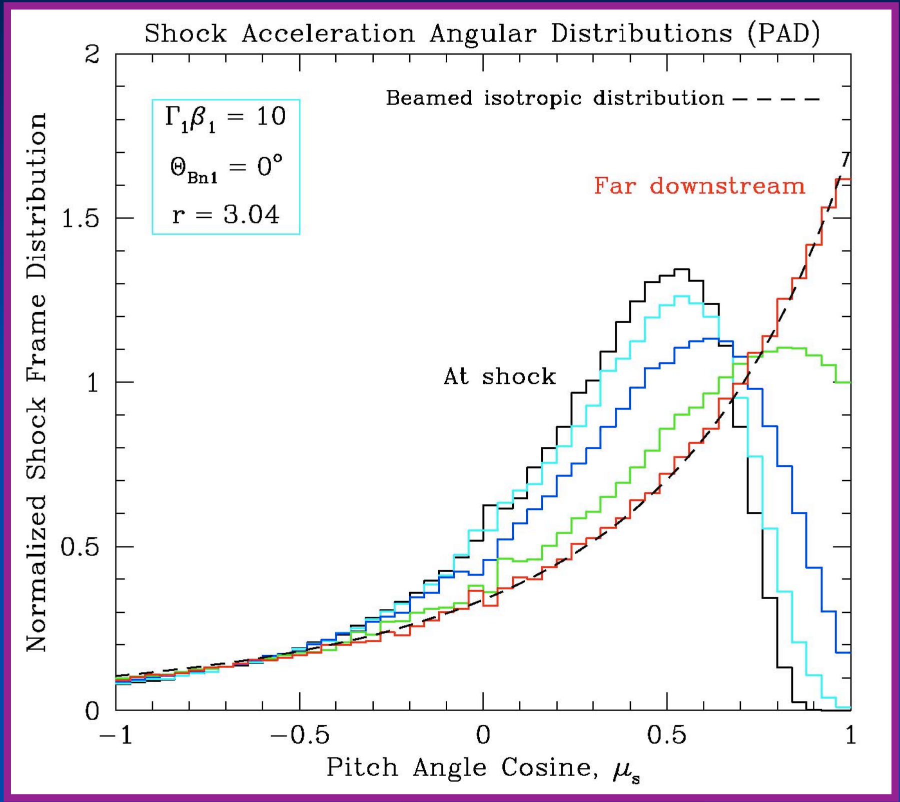


The Character of Relativistic Shocks

- 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).

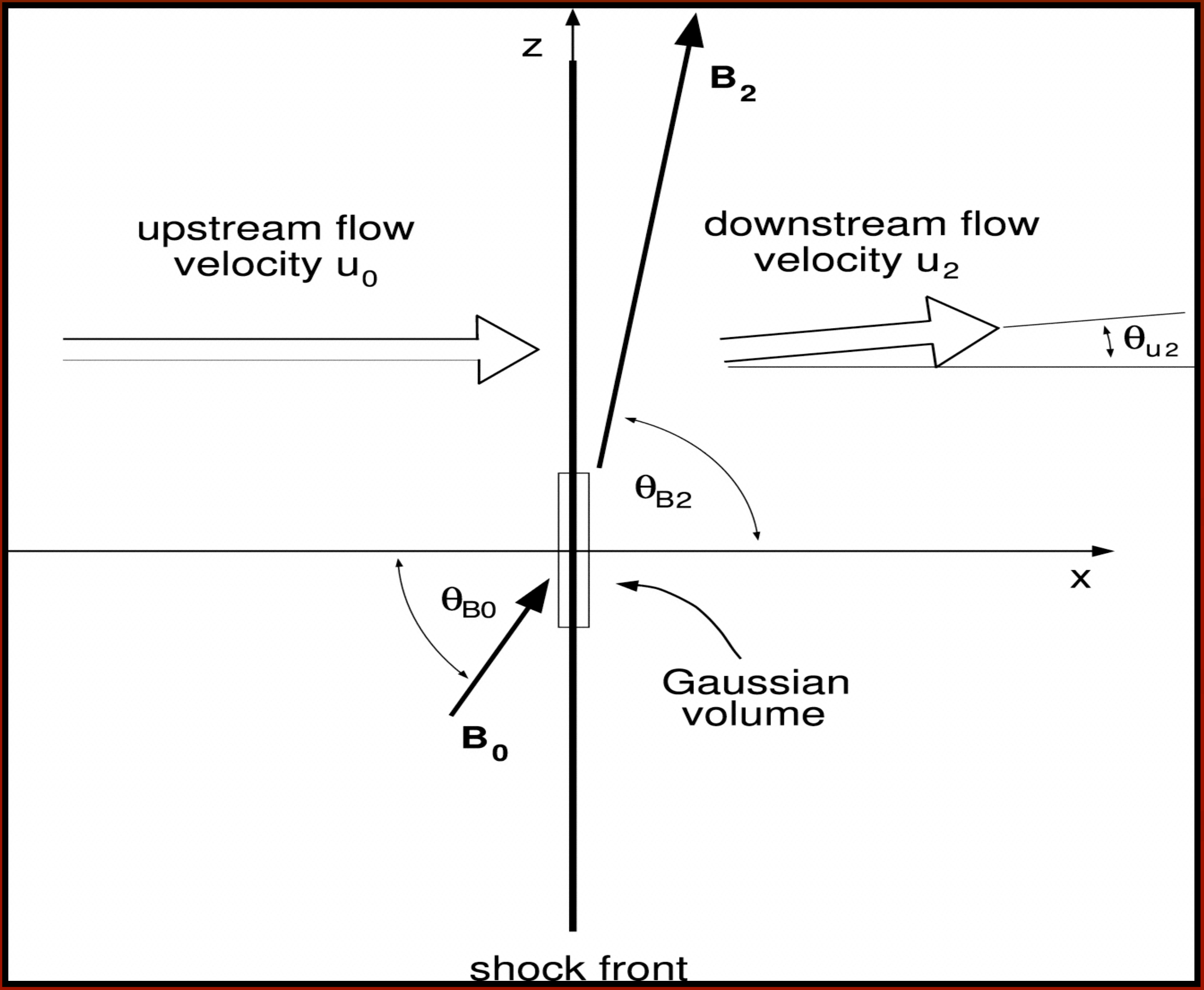
Upstream and Downstream Angular Distributions



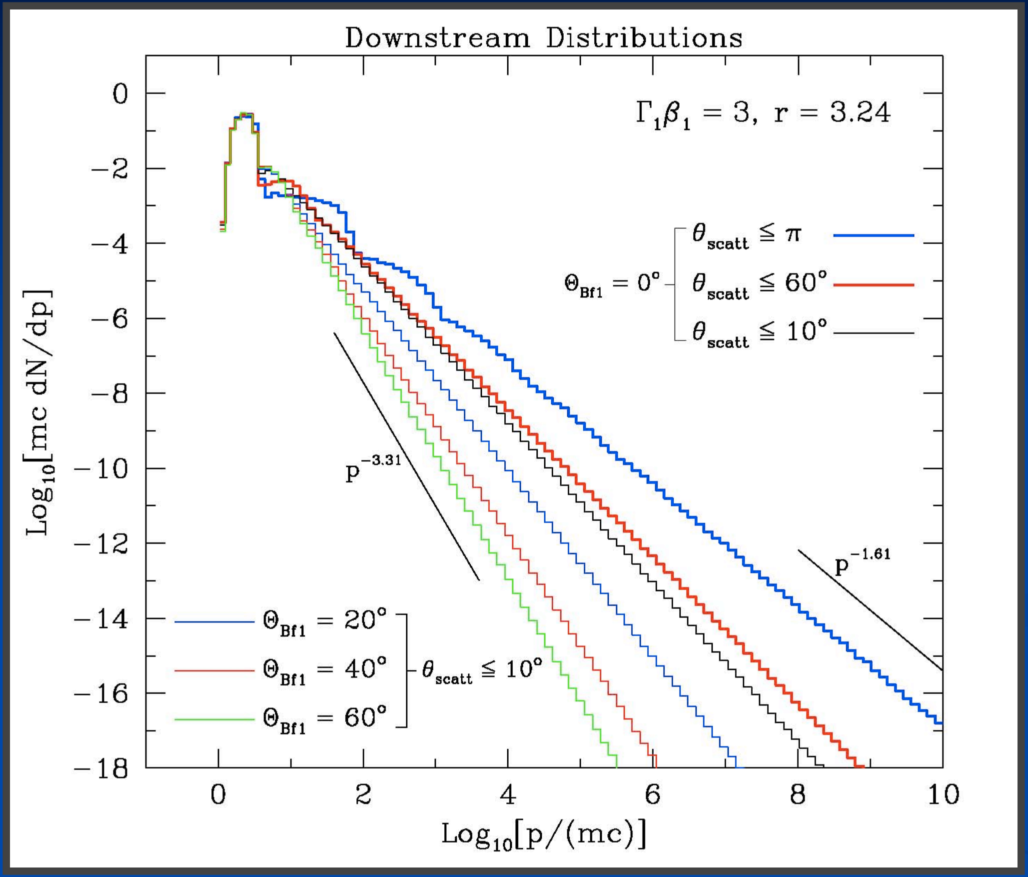


- Pitch angle diffusion (PAD) simulation shock frame distributions for a parallel, relativistic shock with $\Gamma_1\beta_1$=10.
- *Left Panel*: different distances upstream. At the shock (black), simulation results closely approximate the asymptotic ($\Gamma_1\beta_1$>>1) analytic form of Kirk et al. (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



Spectral Dependence on Field Obliquity

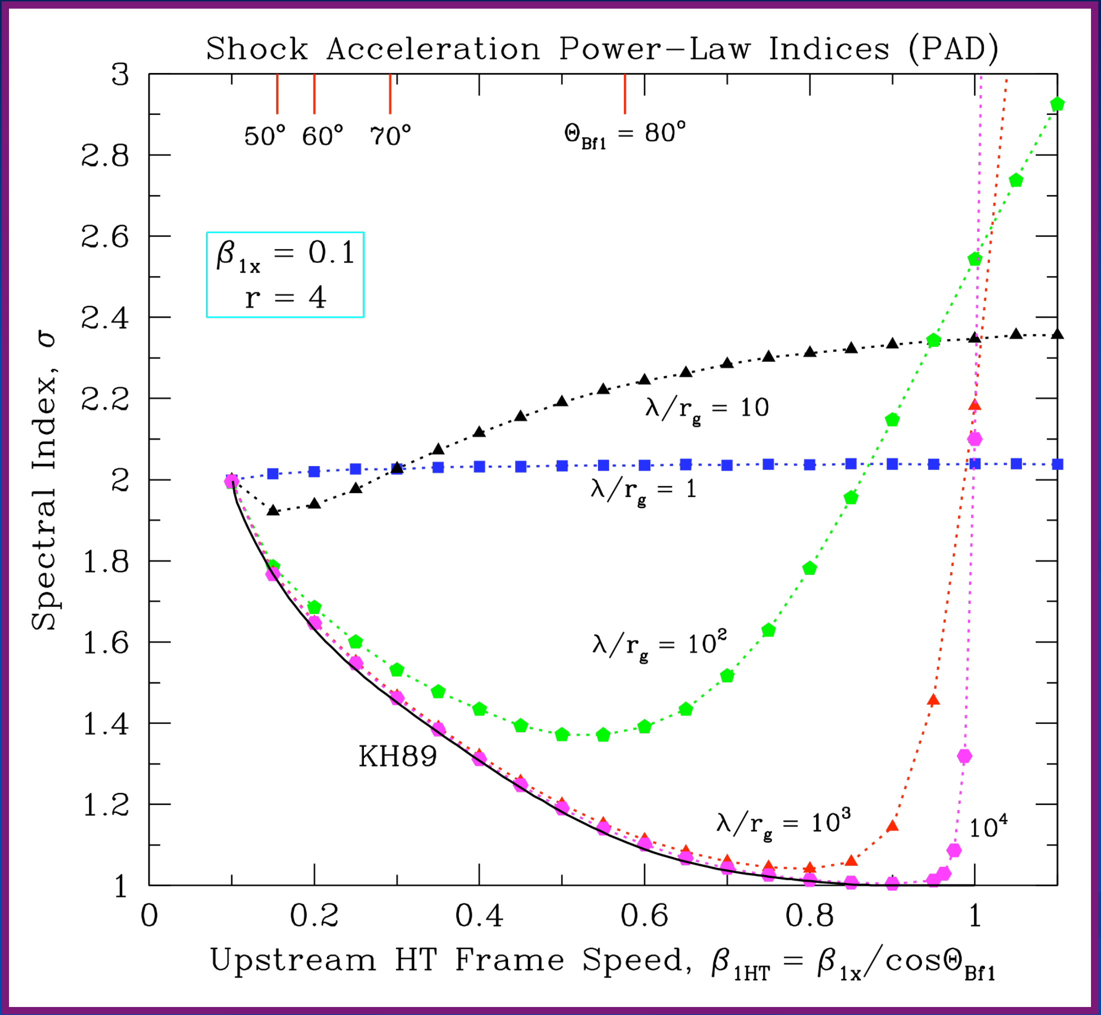


Superluminal Cases ->

- 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 2009 [in prep]; Kirk & Heavens 1989).

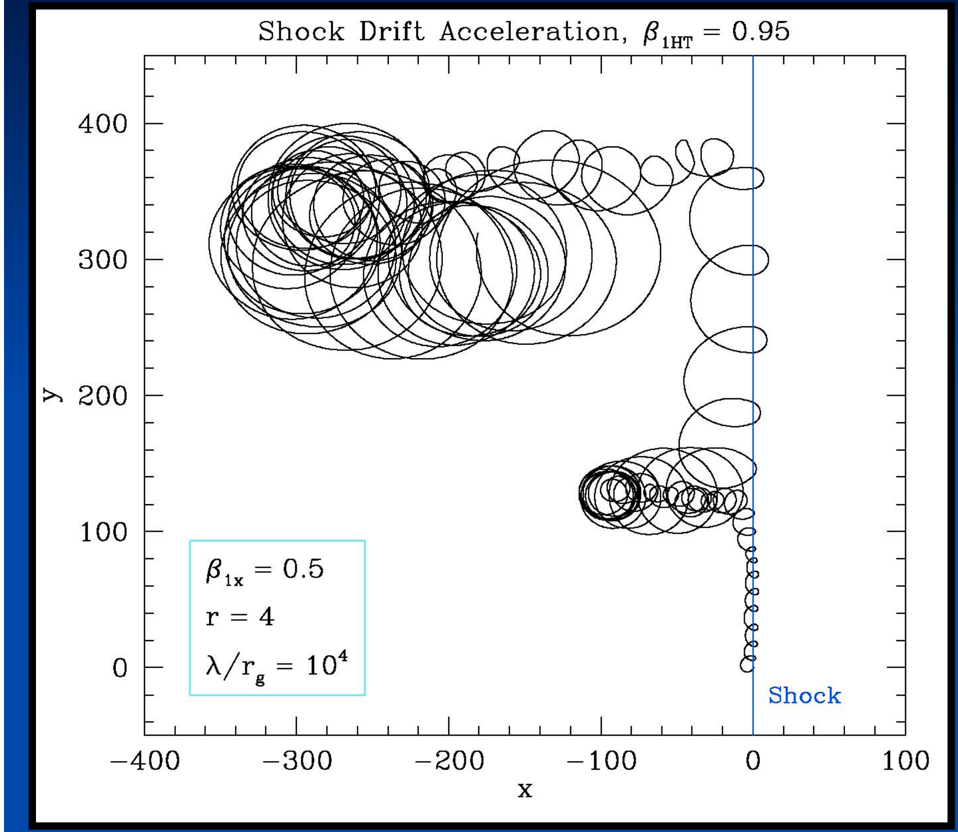
Shock Acceleration Spectral Indices

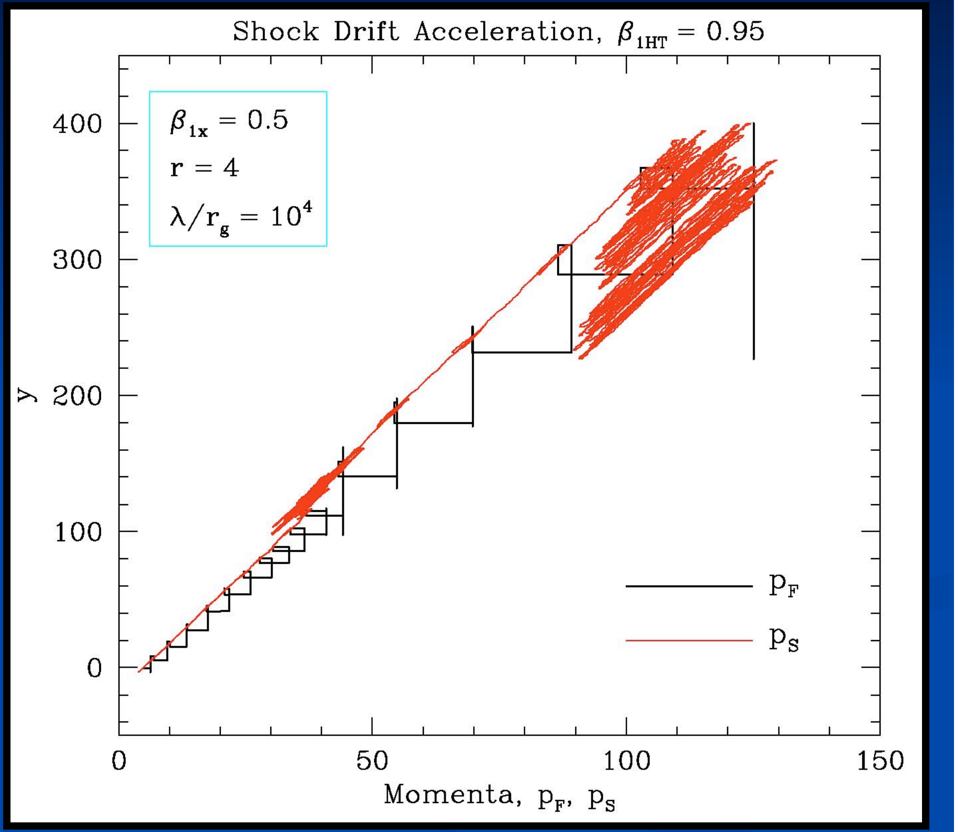
- To compare with Kirk & Heavens (1989) solutions of convection-diffusion equation (oblique shocks).
- Power-law indices in the limit of small angle scattering (pitch angle diffusion: PAD) range considerably;
- For absolutely no cross field diffusion ($\lambda/r_g \to \infty$), the index is as low as unity and the distribution is extremely flat:
- Such regimes correspond to pure shock drift acceleration, and are extremely unlikely.



Baring & Summerlin 2009, in prep.

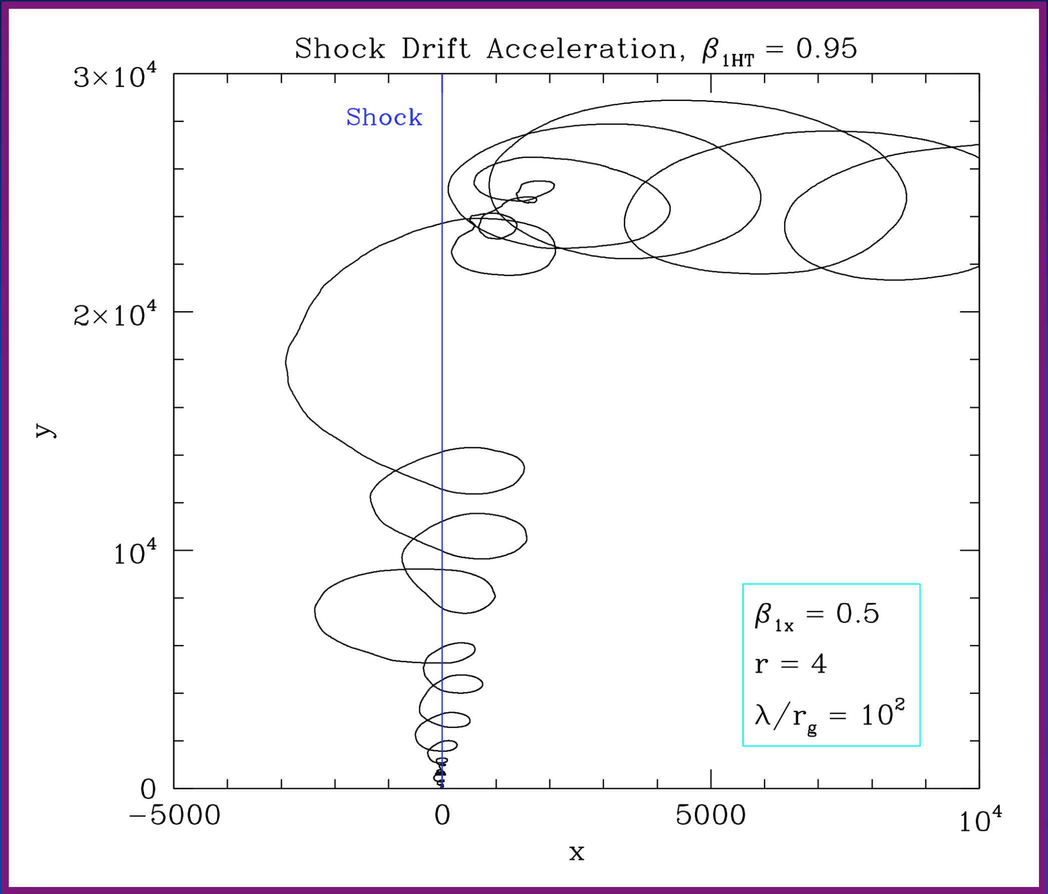
Shock Drift in Action: $\lambda/r_g=10^4$





- *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.

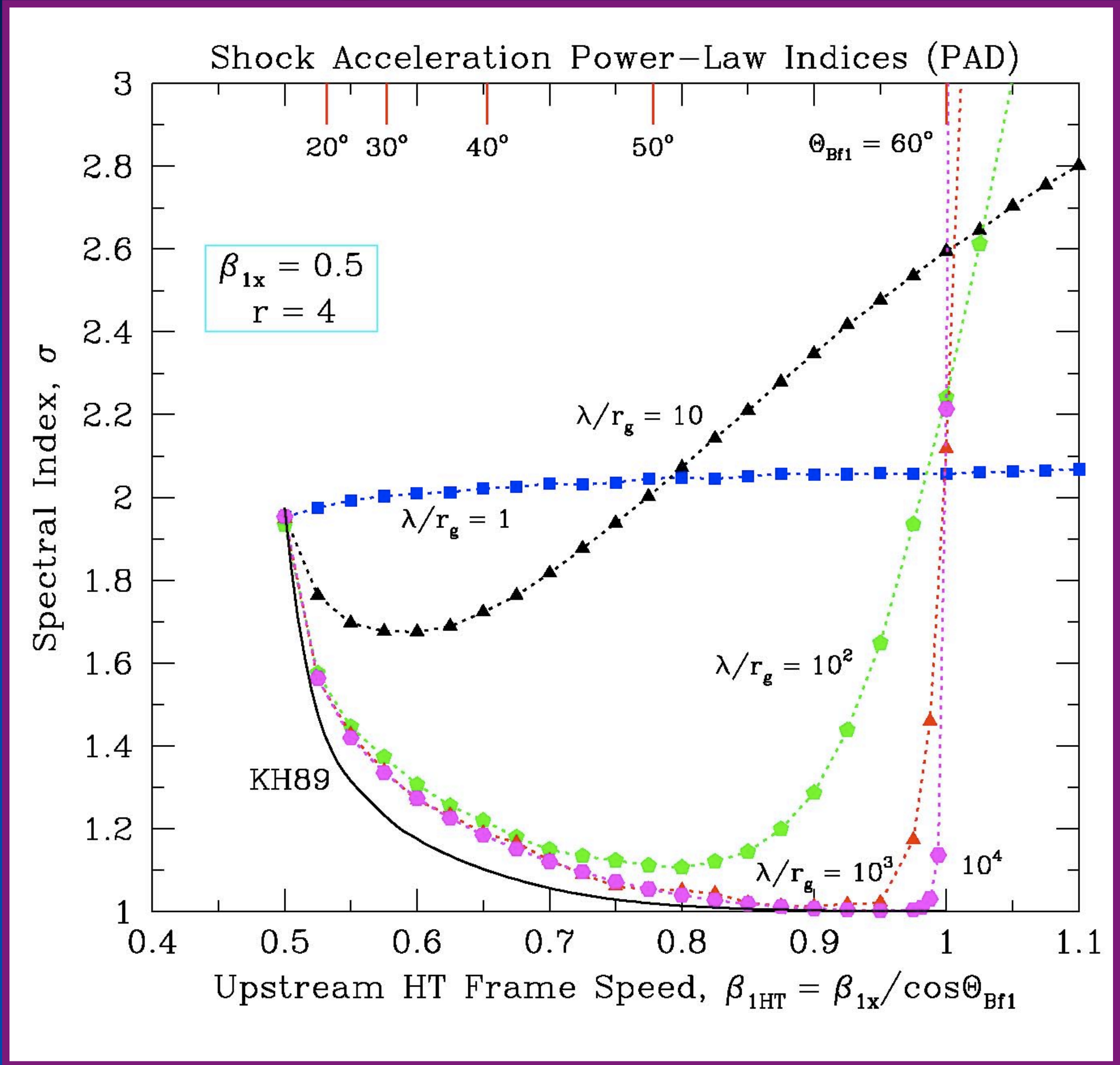
Disrupted Shock Drift: $\lambda/r_g=10^2$



- 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

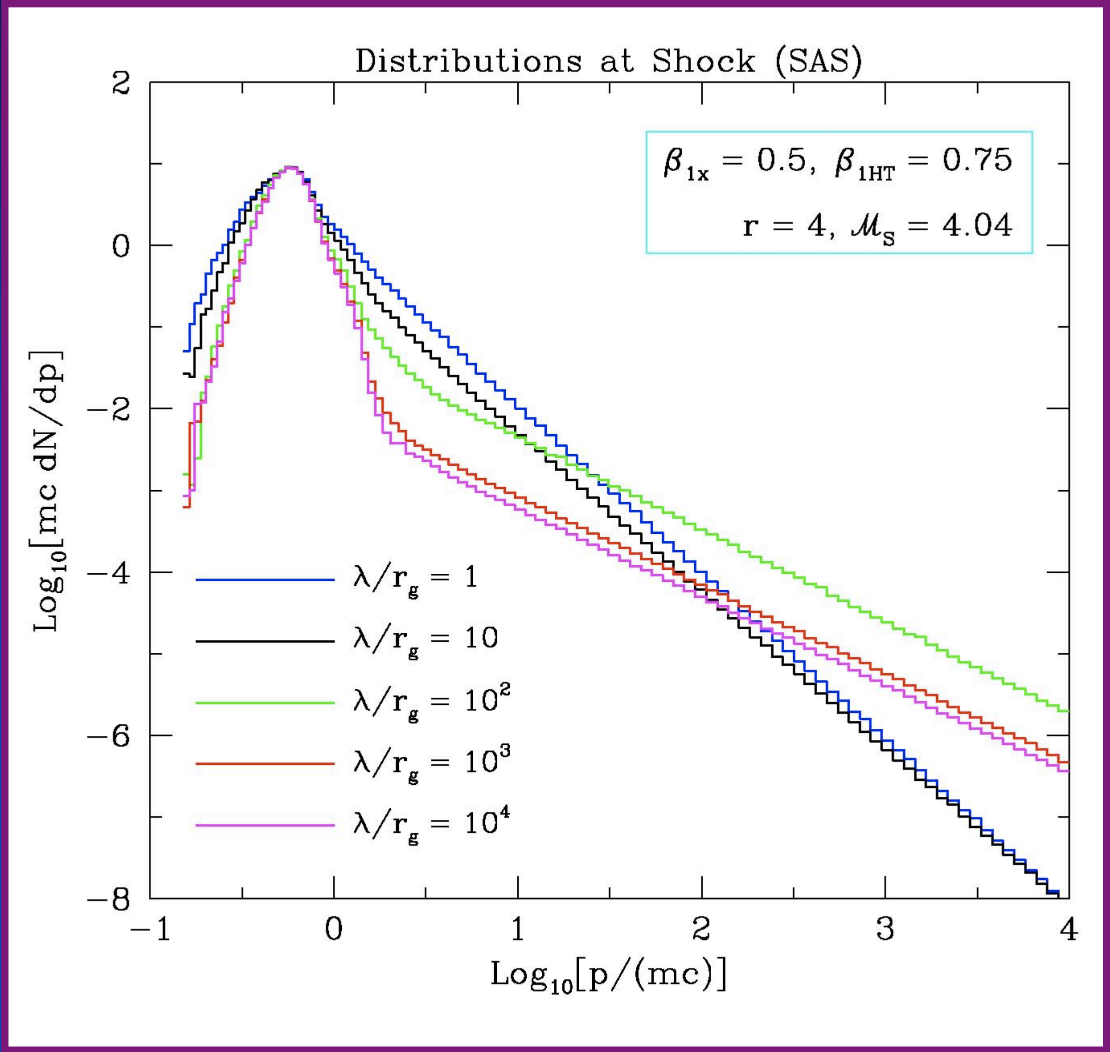
- Power-law indices in the limit of small angle scattering (pitch angle diffusion: PAD) range considerably;
- In cases of absolutely no cross field diffusion, the index is as low as unity and the distribution is extremely flat;
- Gyro-orbit simulations for $\lambda/r_g \rightarrow \infty$ do not quite 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, in prep.

Shock Acceleration Injection Efficiencies

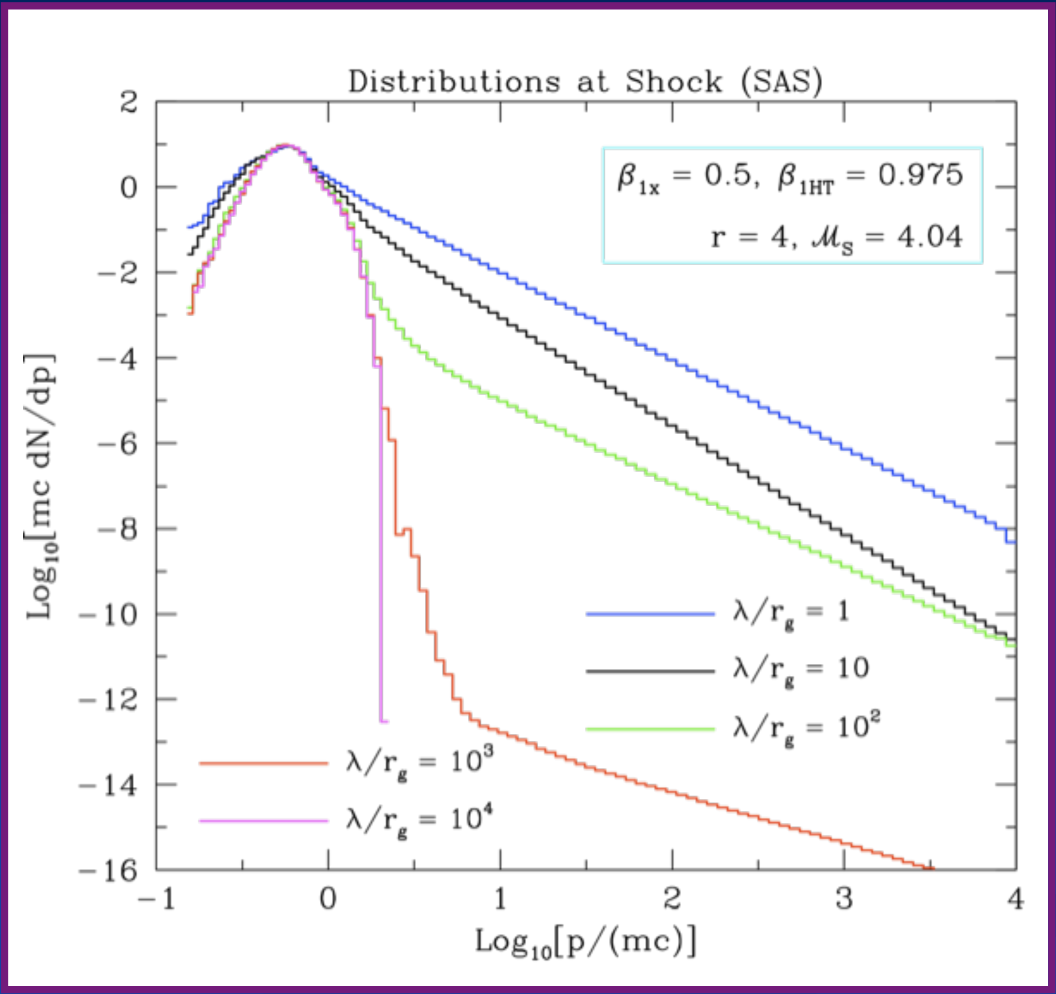
- Complete particle spectra in the limit of small angle scattering (pitch angle diffusion: PAD) range considerably;
- In cases of strong cross field diffusion, the index is around two and the injection is efficient;
- Gyro-orbit simulations for $\lambda/r_g \to \infty$ that give flat power-law indices are poor injectors – this becomes far more extreme as HT frame speed approaches c.



Baring & Summerlin 2009, in prep.

Injection Efficiencies: Near Luminality

- When shocks are nearly luminal, the injection efficiency precipitously drops in gyro-orbit simulations as $\lambda/r_g \to \infty$.
- => 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, in prep.

Implications for sources of UHECRs

- Relativistic shocks can generate a multitude of spectral forms: power-law indices depend on shock parameters and scattering properties;
- => **Non-canonical spectral index**
- Distinct contrast to non-relativistic case [depends on *r* only];
- Spectrum is only flat for quasi-parallel shocks *or* strong turbulence, **if shocks are superluminal**;
- GRB prompt and afterglow emission more easily explained by *mildly-relativistic shocks* that are *not quasi-perpendicular* (for diffusive acceleration scenarios). True also perhaps for radio galaxies.

Conclusions

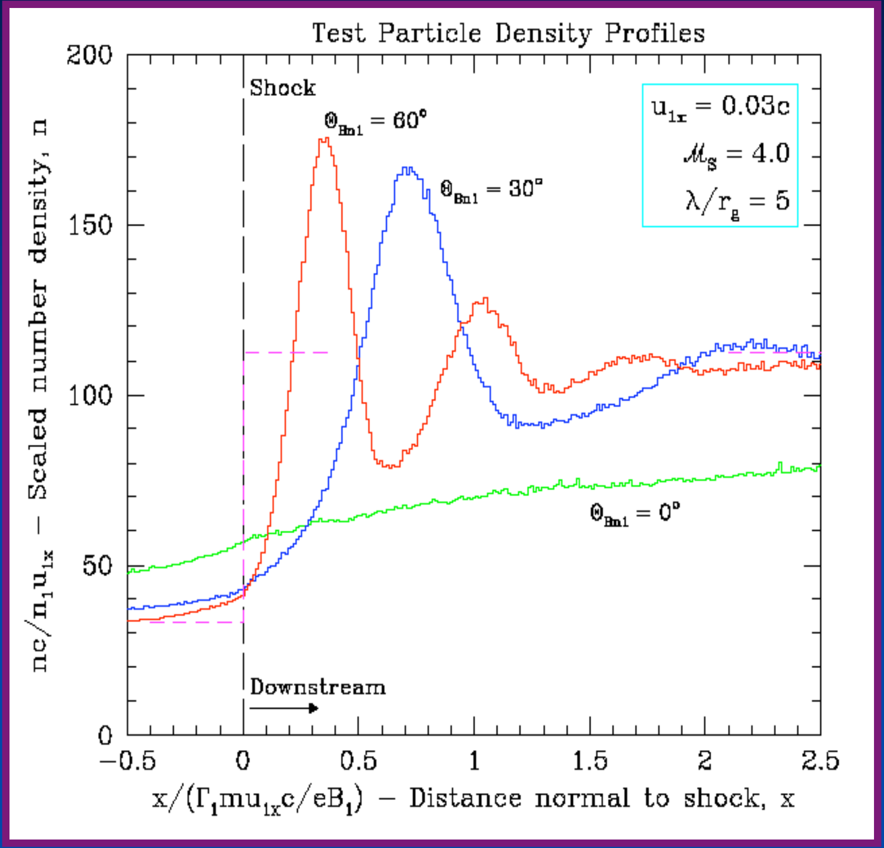
- Shock acceleration particle spectral indices depend on several shock parameters: field obliquity to the shock normal, scattering strength or level of MHD turbulence, amount of diffusion across B;

  => there is no canonical spectral index.
- Unless source shocks are superluminal and only modestly turbulent, UHECR spectral generation is easily realized for a variety of conditions in relativistic shocks.
- The *e-p* abundance ratio, a key parameter for the UHECR and neutrino cosmic flux budget, is still a critical unknown – a goal for future simulation probes.
- GRB and AGN 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: efficient retention of particles in the shock layer permits efficient action of shock drift acceleration.
  - Unlikely to be realized in Nature! And not commensurate with source photon signals.

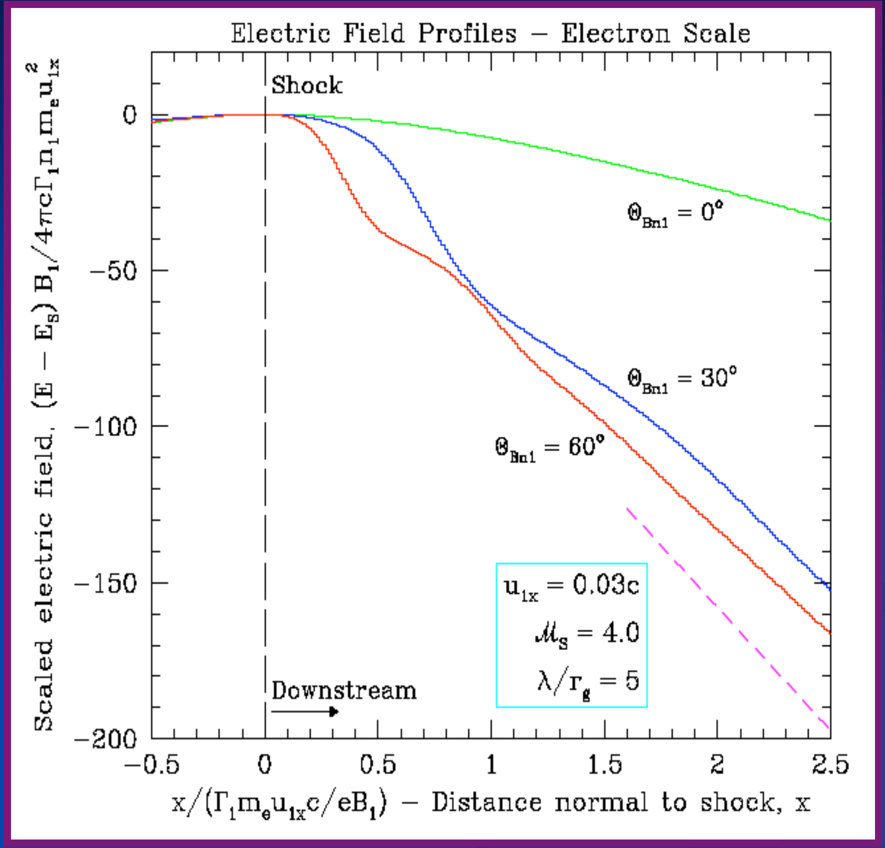
Power-Law Normalizations: the big Unknown

- For single component species, the downstream thermal population is heated to momentum ~$\Gamma_1\beta_1$mc. This effectively establishes the power-law normalization;
- For relativistic *e-p* shocks, this introduces a temperature ratio $T_e/T_p \sim m_e/m_p$ that effects a normalization ratio $\varepsilon_e \sim (m_e/m_p)^\sigma$ of n_e/n_p in the power-law domain;
- For σ~2, this offset is large: $\varepsilon_e \sim 10^{-8}$;
- In most source modeling to date, this unknown is chosen.
- Need to consider:
  - the effect on ε_e by heating of thermal electrons in plasma shocks via *e-p* charge separation potentials in the shock layer [e^+-e^- pair shocks don't exhibit such separations];
  - Turbulent heating modifications to ε_e in PIC simulations.
- These can increase ε_e by several orders of magnitude.
- Relevant both for UHECR and VHE neutrino flux budgets, as well as *Fermi* gamma-ray sources.

Density and Electric Field Profiles - low M_s



(Density profiles apply to e or p)



- Heating the beam smooths out the gyrational influence on density and E-field profiles. Correlation of gyrational peaks with field obliquity is marked.
- Efficient acceleration in parallel shocks diminishes density compression on sub-diffusive scales (i.e. $|x| < 5$ here).
- Dashed magenta lines mark Rankine-Hugoniot densities and (maximal) E.

Shock Drift in Oblique, Non-Relativistic Systems

DECKER AND VLAHOS

(DV 1986)

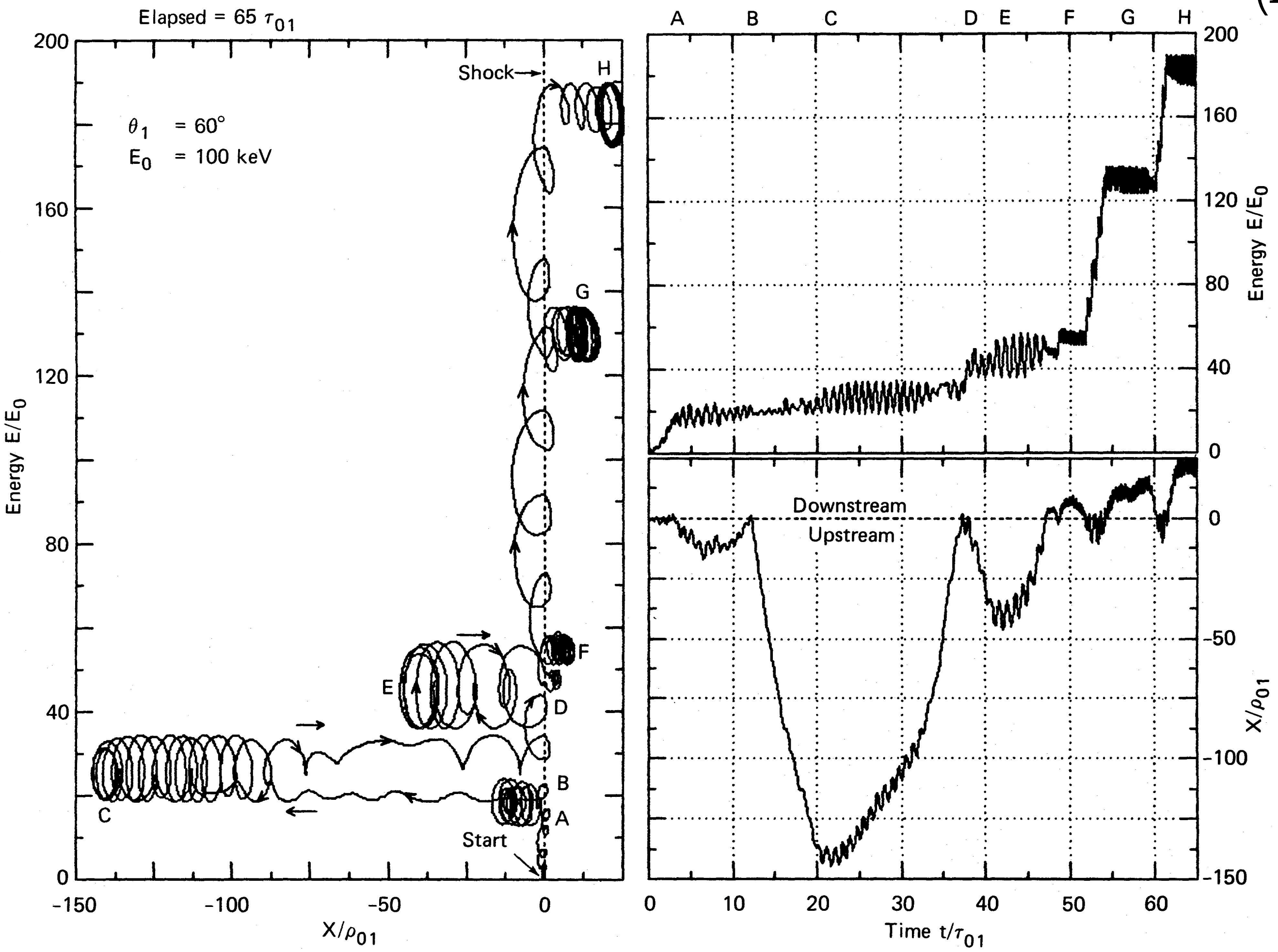
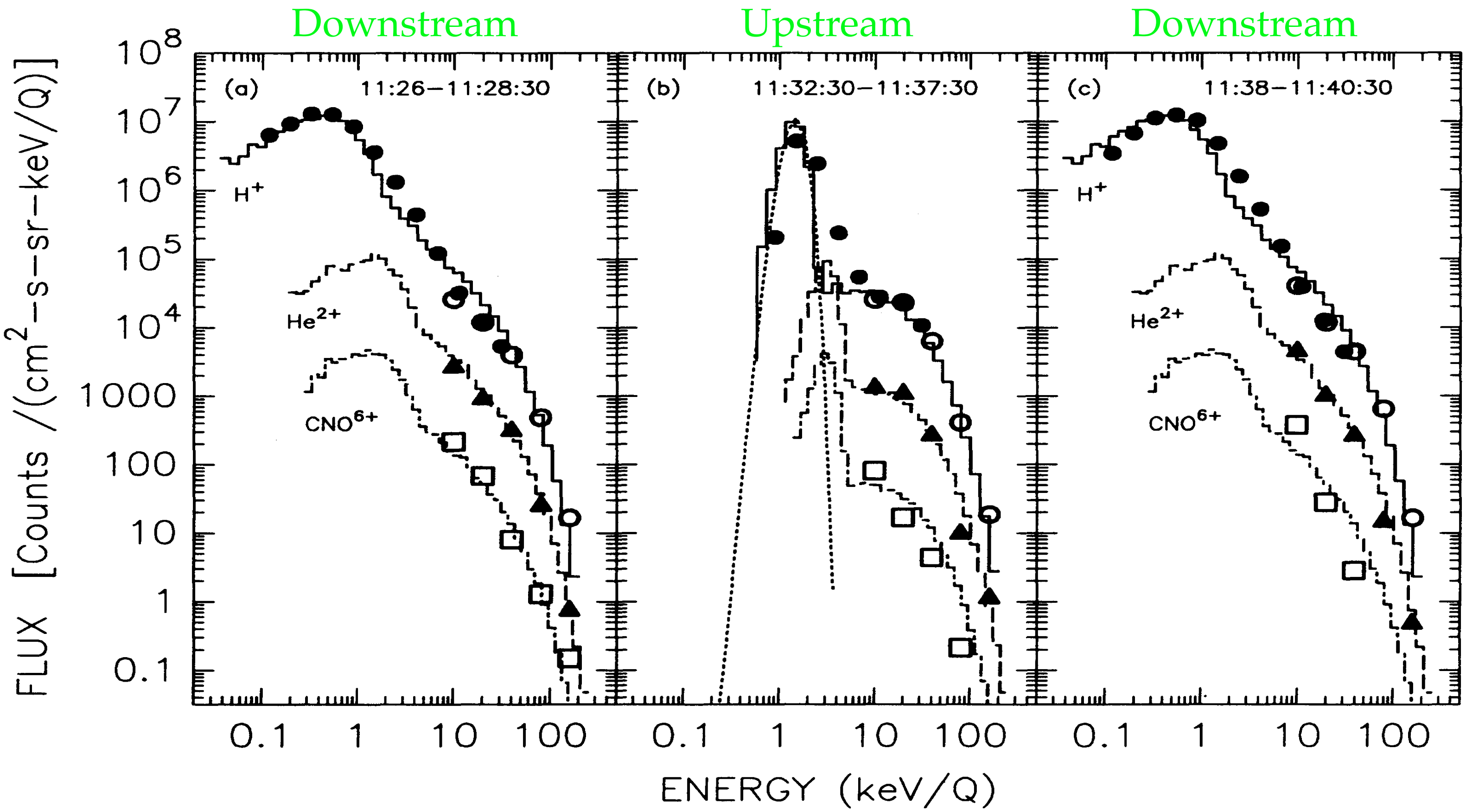


FIG. 6.—Sample for quasi-perpendicular shock $\theta_1 = 60°$. See Fig. 5 caption and text for details.

Ion Acceleration at Earth's Bow Shock

Ellison, Moebius & Paschmann (1990)



- AMPTE observations of diffuse ions at Q-parallel Earth bow shock H^+, He^{2+} and CNO^{6+} observed during time when solar wind magnetic field was nearly radial;
- Efficient acceleration (25%) in high MS shock; model fits work only for non-linear model that exhibits A/Q enhancements; Scholer, Trattner & Kucharek (1992) found similar results with hybrid PIC simulations.

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

Kirk, Guthmann, Gallant & Achterberg (2000)