Diffusive Particle Acceleration in Relativistic Shocks

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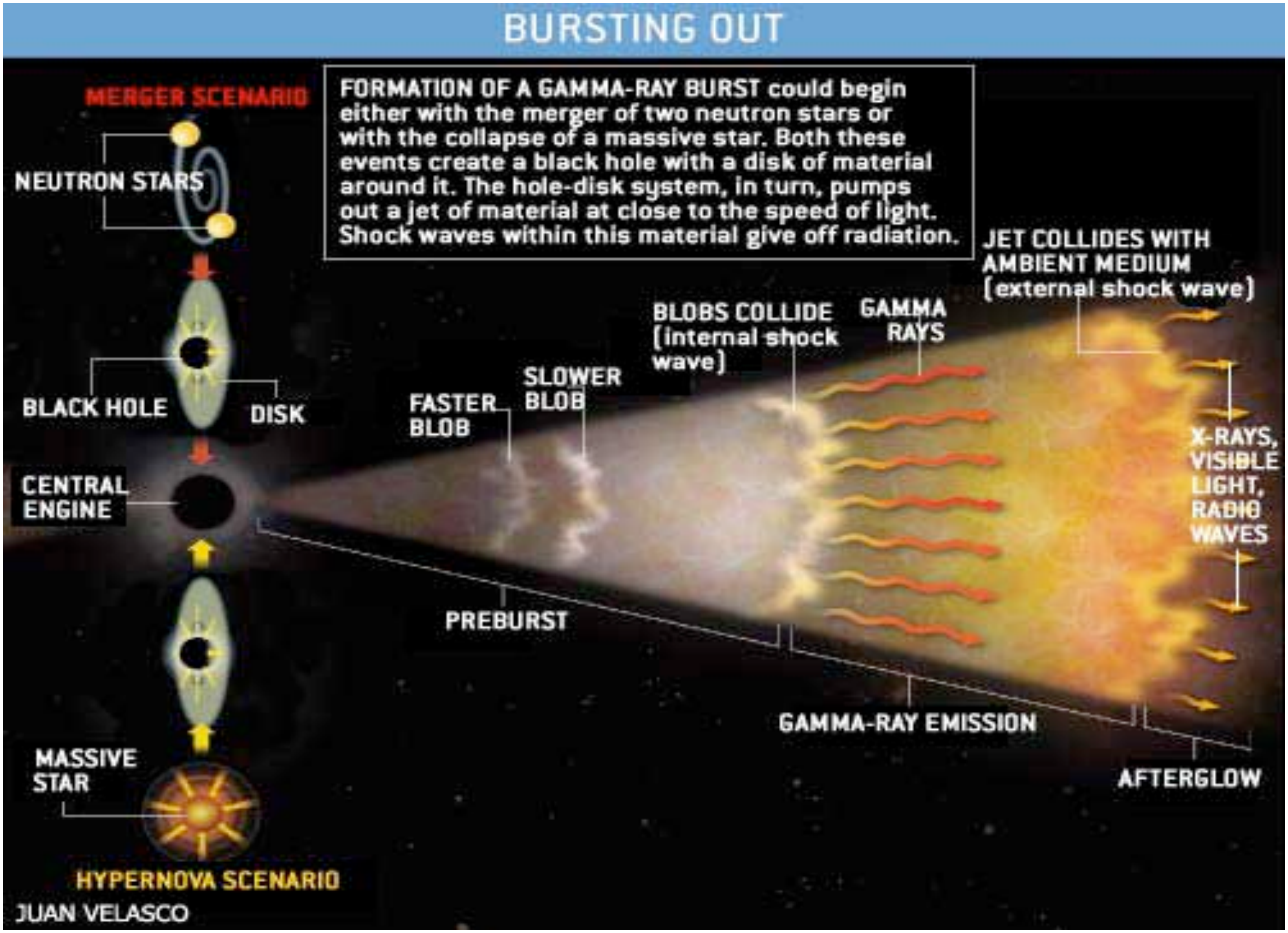
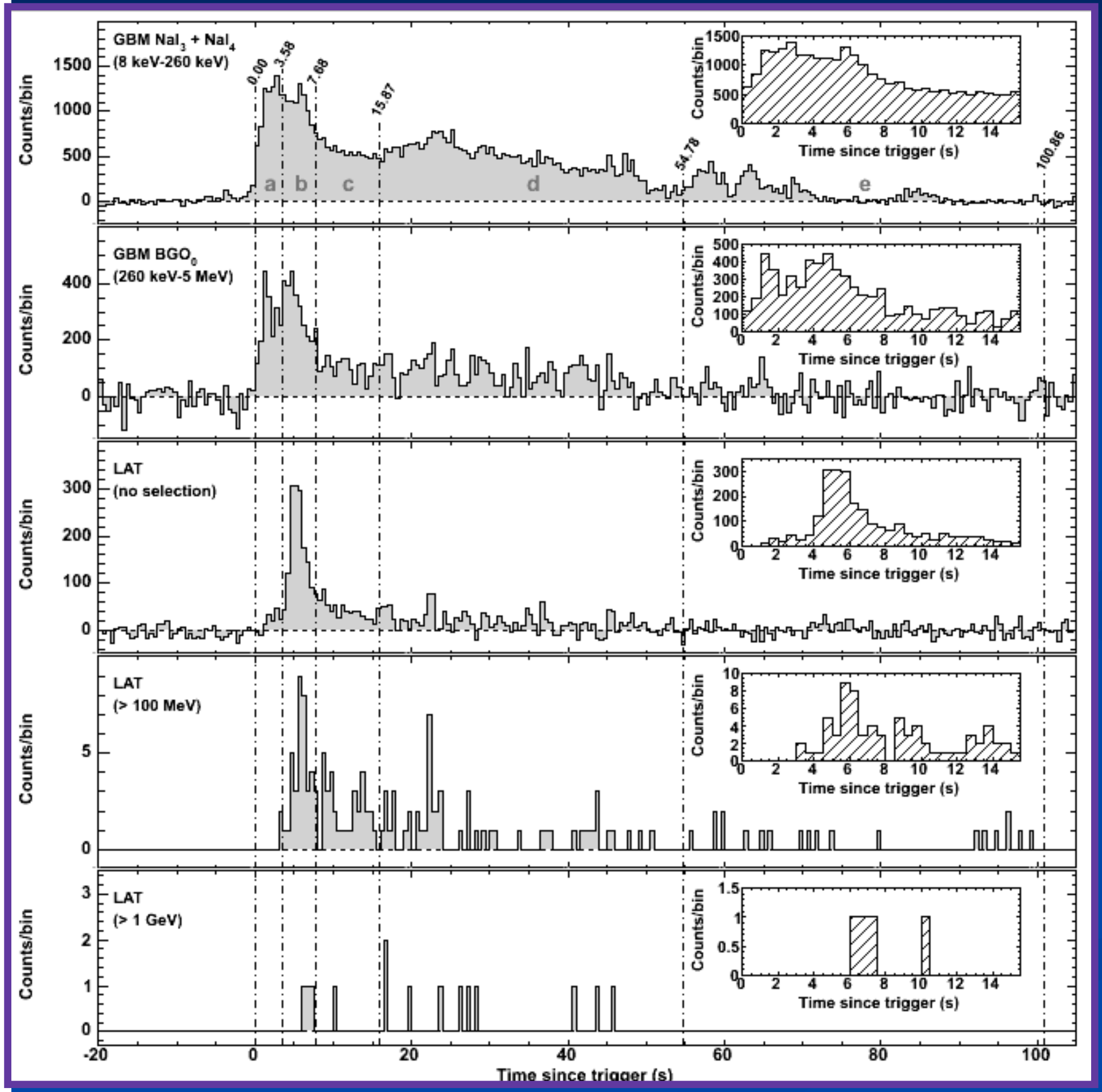
Gamma-Ray Bursts: Relativistic Outflows

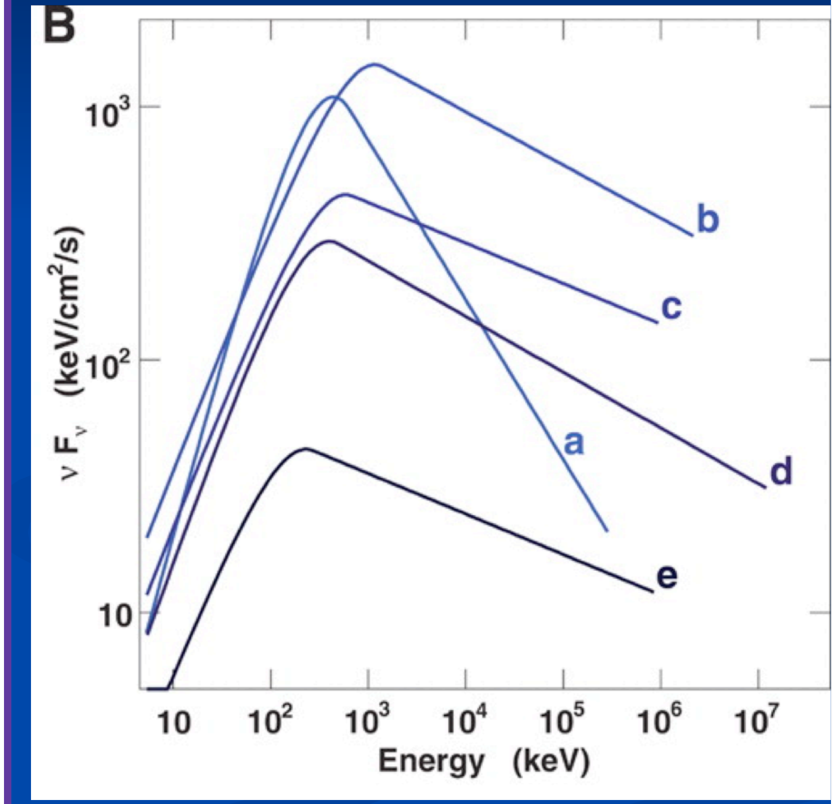


FORMATION OF A GAMMA-RAY BURST could begin either with the merger of two neutron stars or with the collapse of a massive star. Both these events create a black hole with a disk of material around it. The hole-disk system, in turn, pumps out a jet of material at close to the speed of light. Shock waves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

JUAN VELASCO

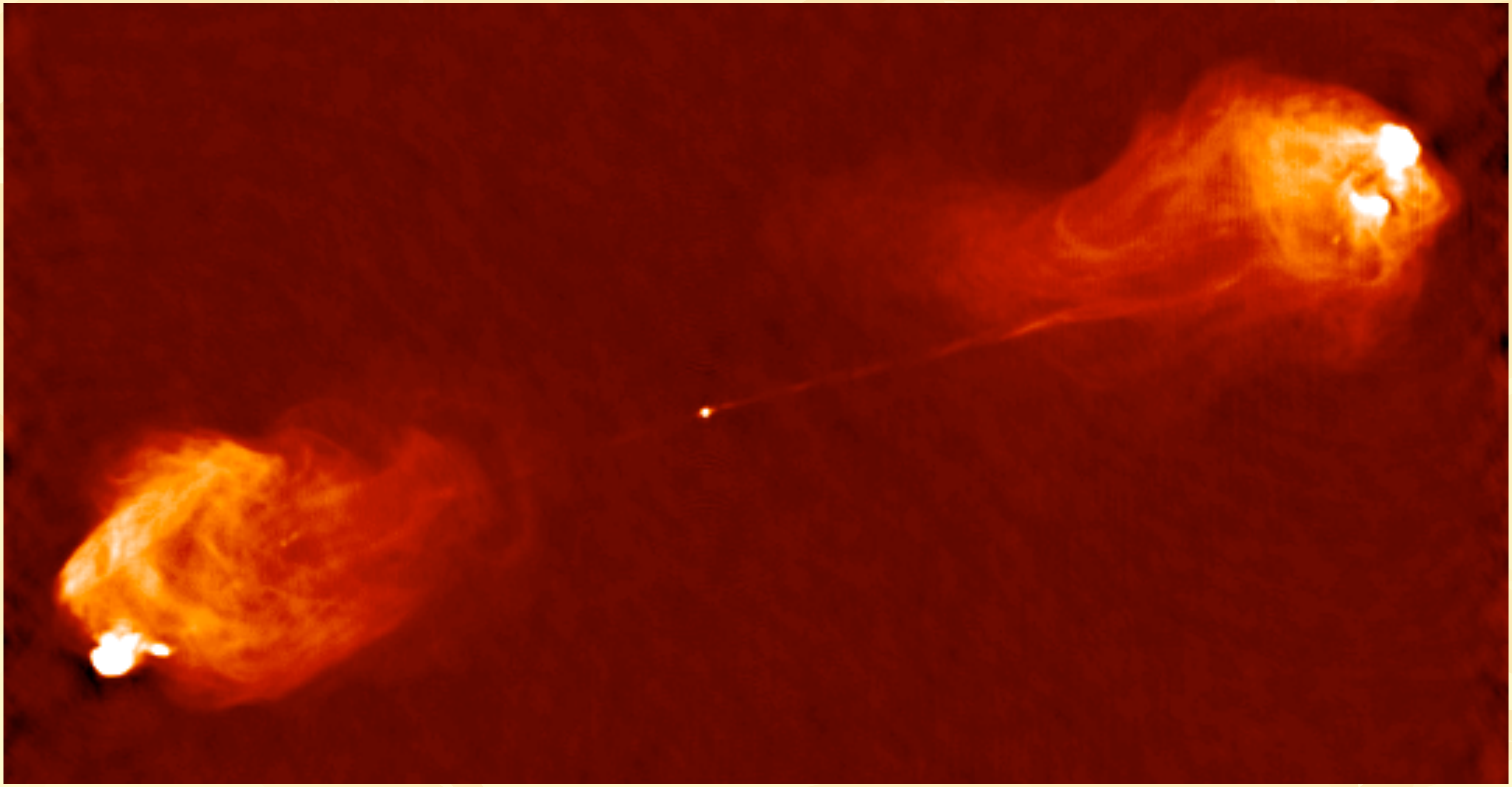
Fermi GRB 080916c
Temporal and Spectral Evolution





- Science (2009): Abdo et al.

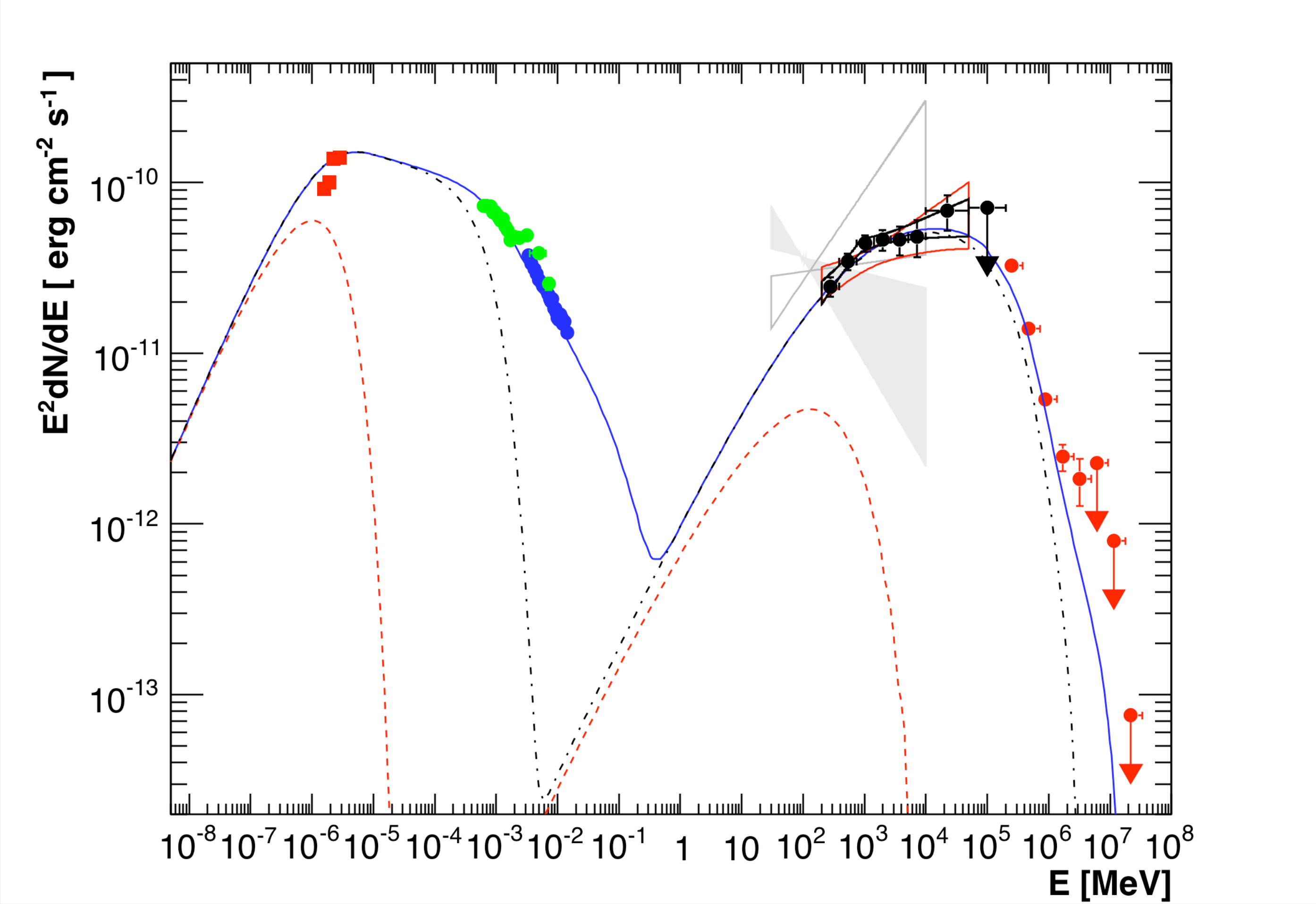
High Energy Cosmic Ray Accelerators: Radio Galaxies like Cygnus A



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

z=0.116

Abdo et al. (2009)

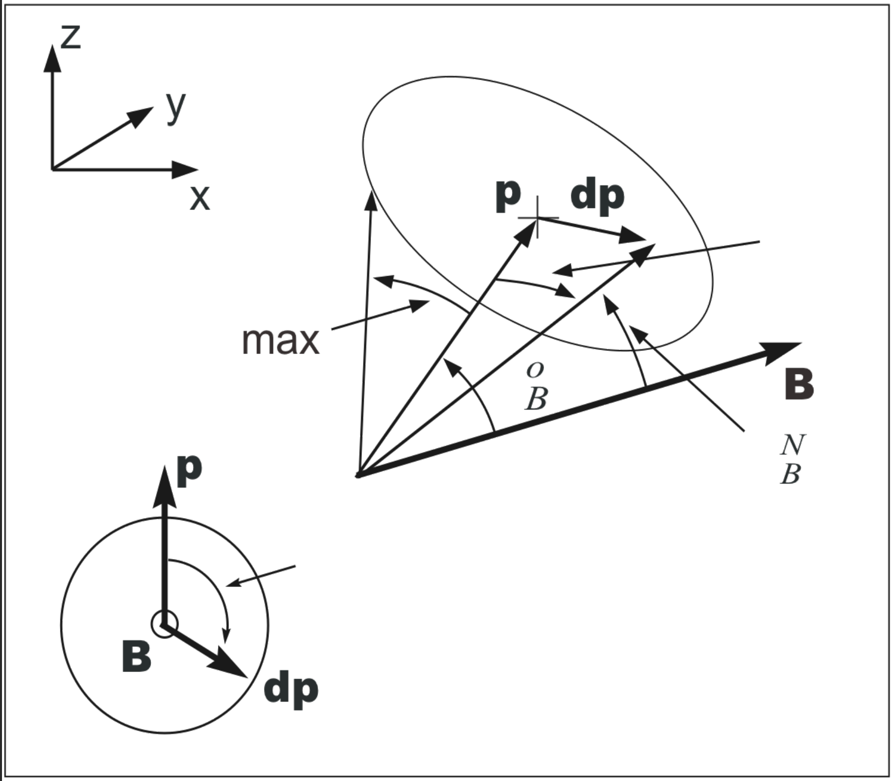


HBLs vs. FSRQs

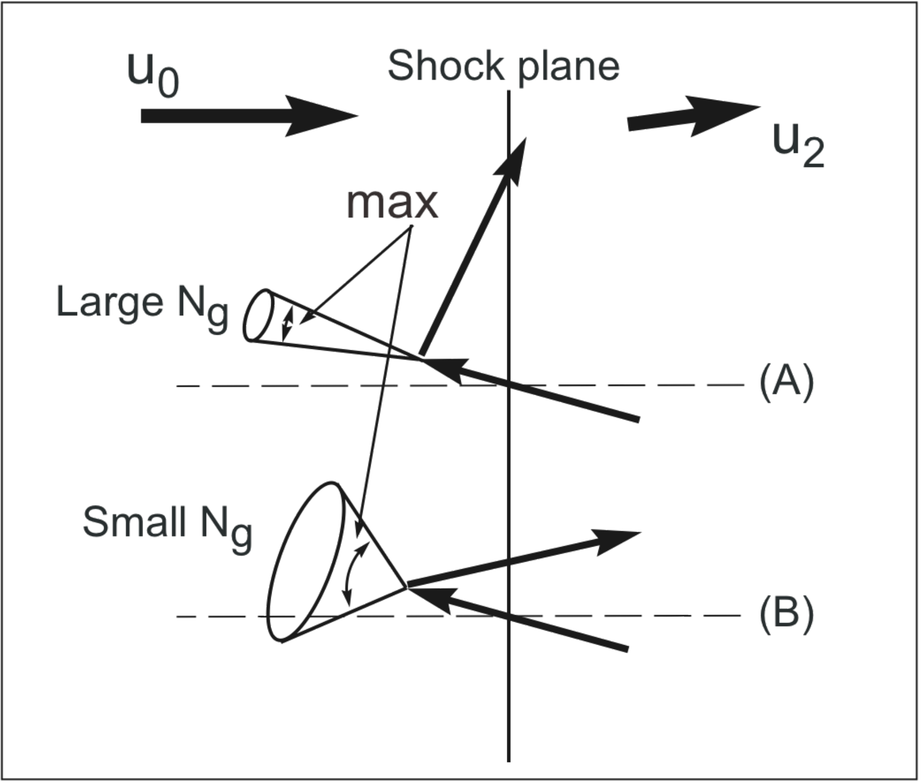
Shock Acceleration: Monte Carlo Simulations

- 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.

Scattering Geometry

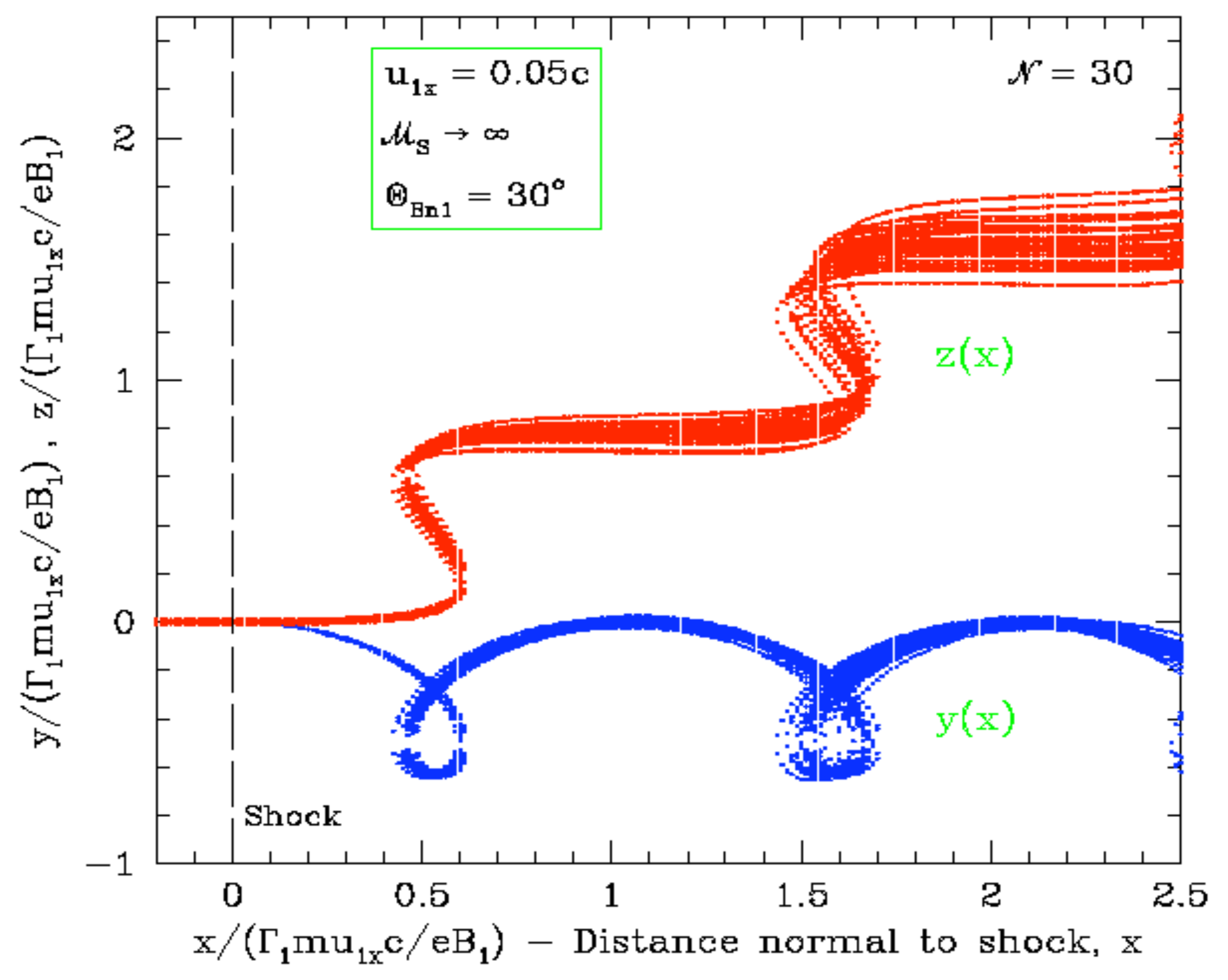


Ellison & Double, Astropart. Phys.



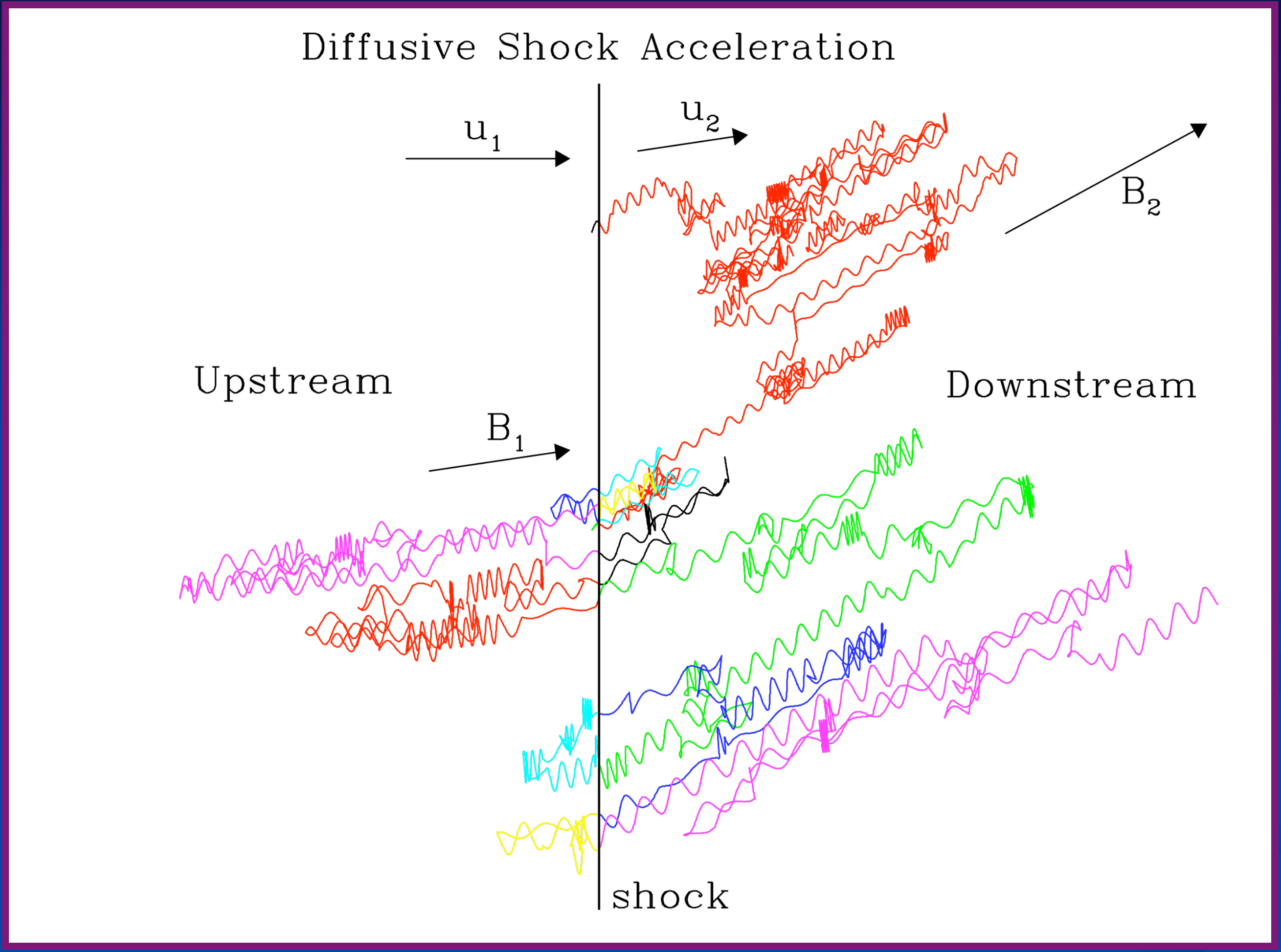
Ellison & Double, Astropart. Phys.

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.

Monte Carlo Simulation Particle Trajectories

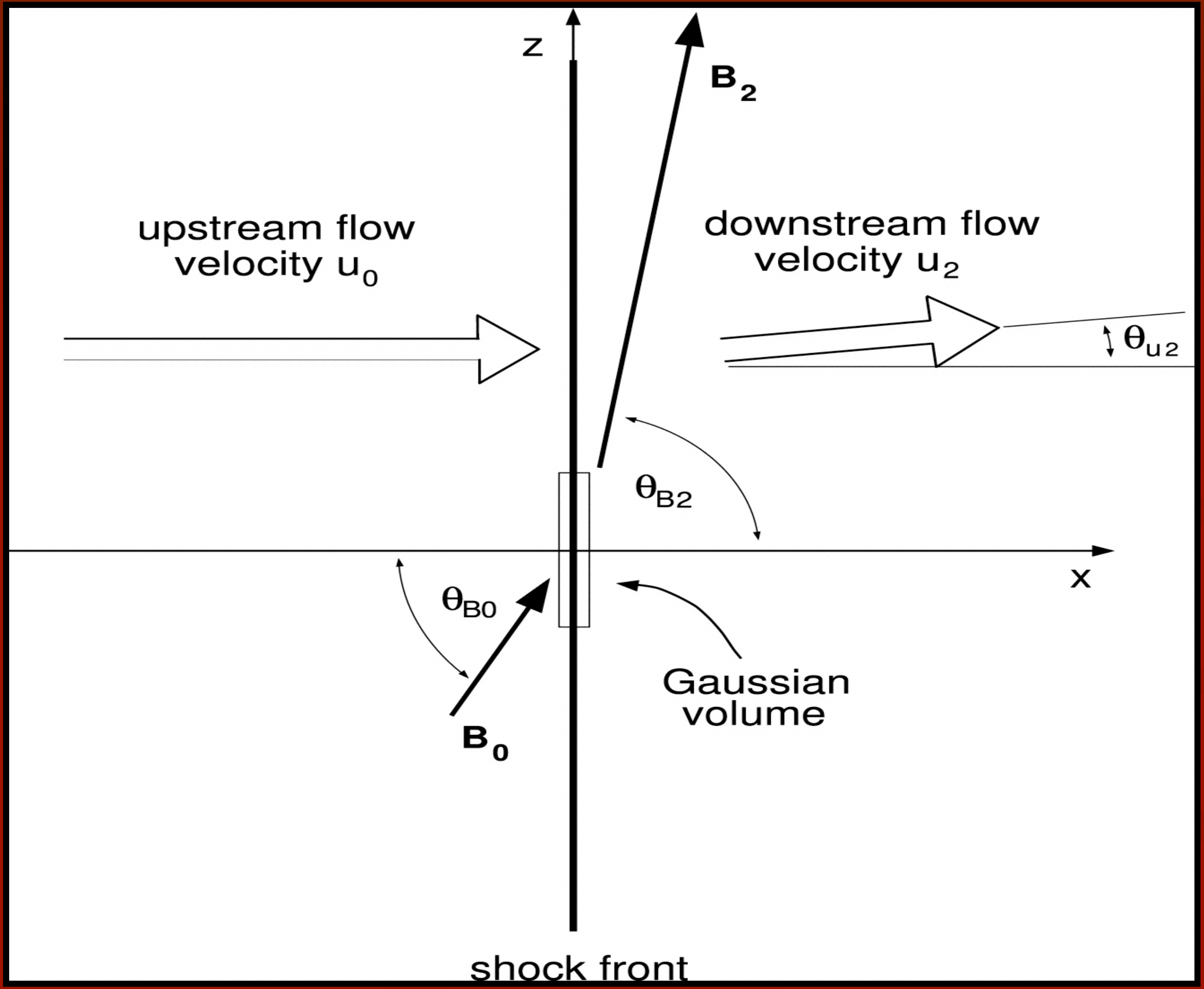


- Gyration in B-fields and diffusive transport modeled by a Monte Carlo technique; color-coded in Figure according to fluid frame energy.
- Shock crossings produce net energy gains (evident in the increase of gyroradii) according to principle of first-order Fermi mechanism.

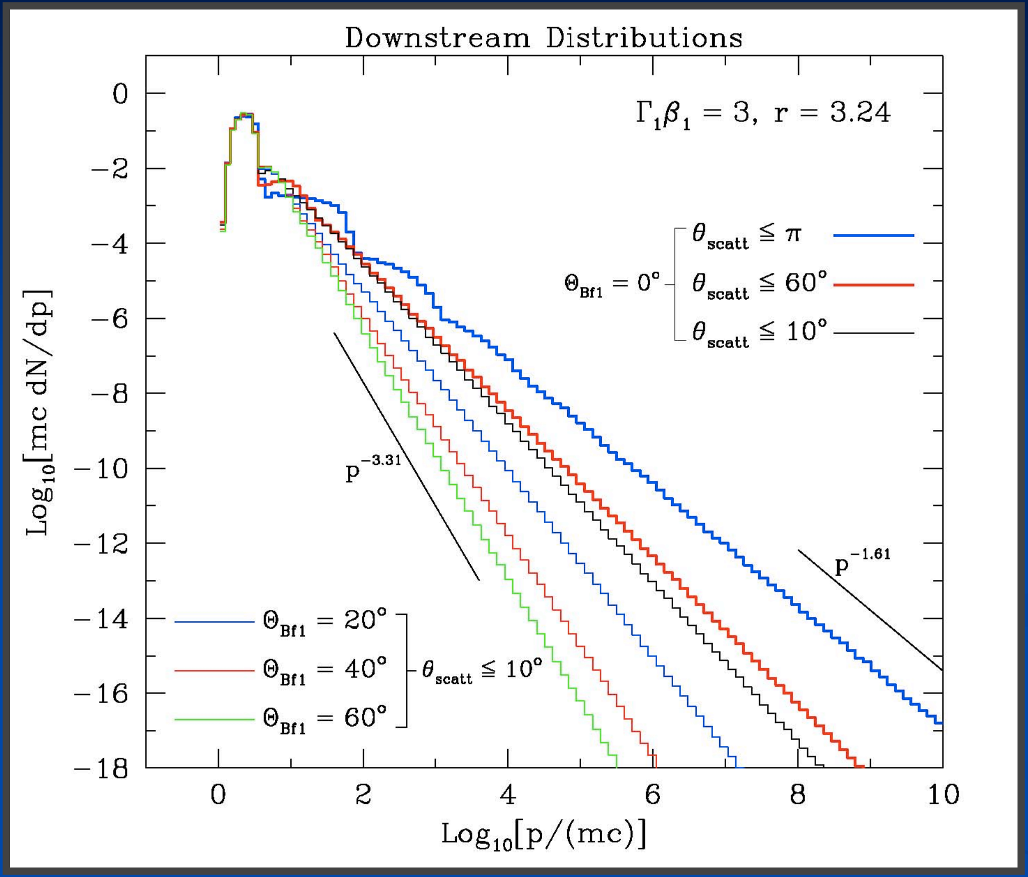
Spectral Properties of Diffusive Relativistic Shock Acceleration

- 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}.

Oblique Shock Geometry



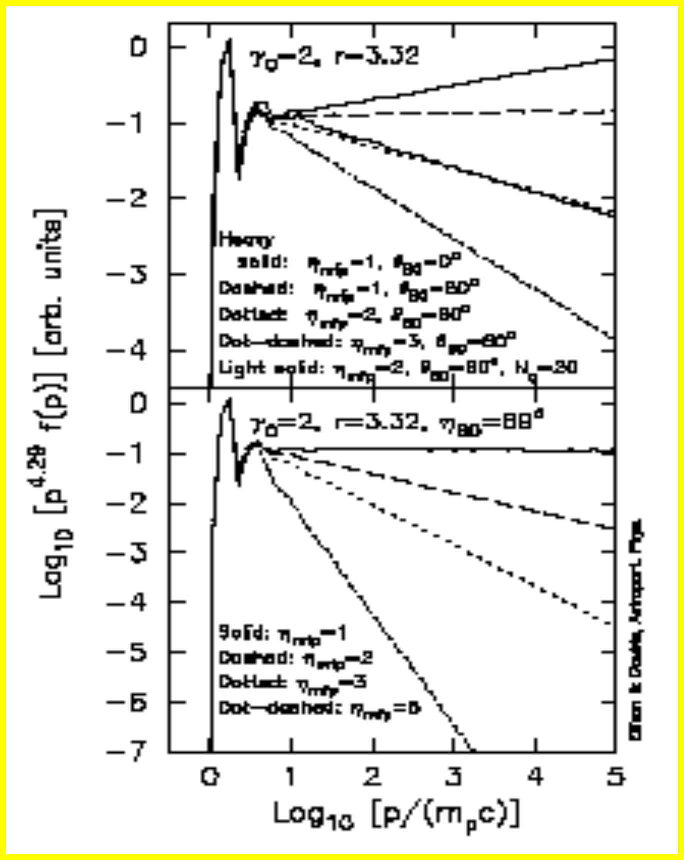
Spectral Dependence on Field Obliquity

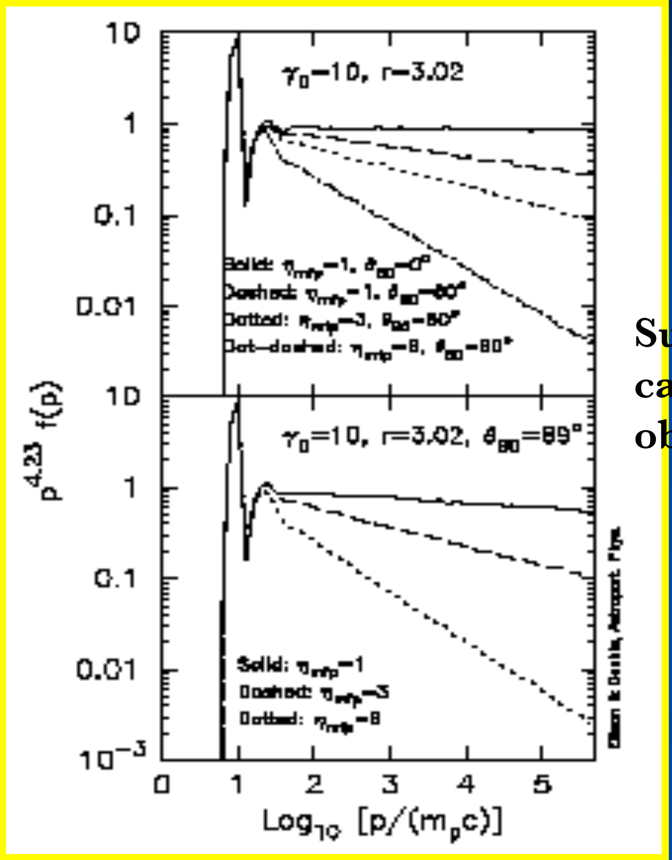


Superluminal cases ->

- 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 2008 [in prep]; Kirk & Heavens 1989).

Relativistic Shocks: Spectral Dependence on Field Obliquity and Diffusion





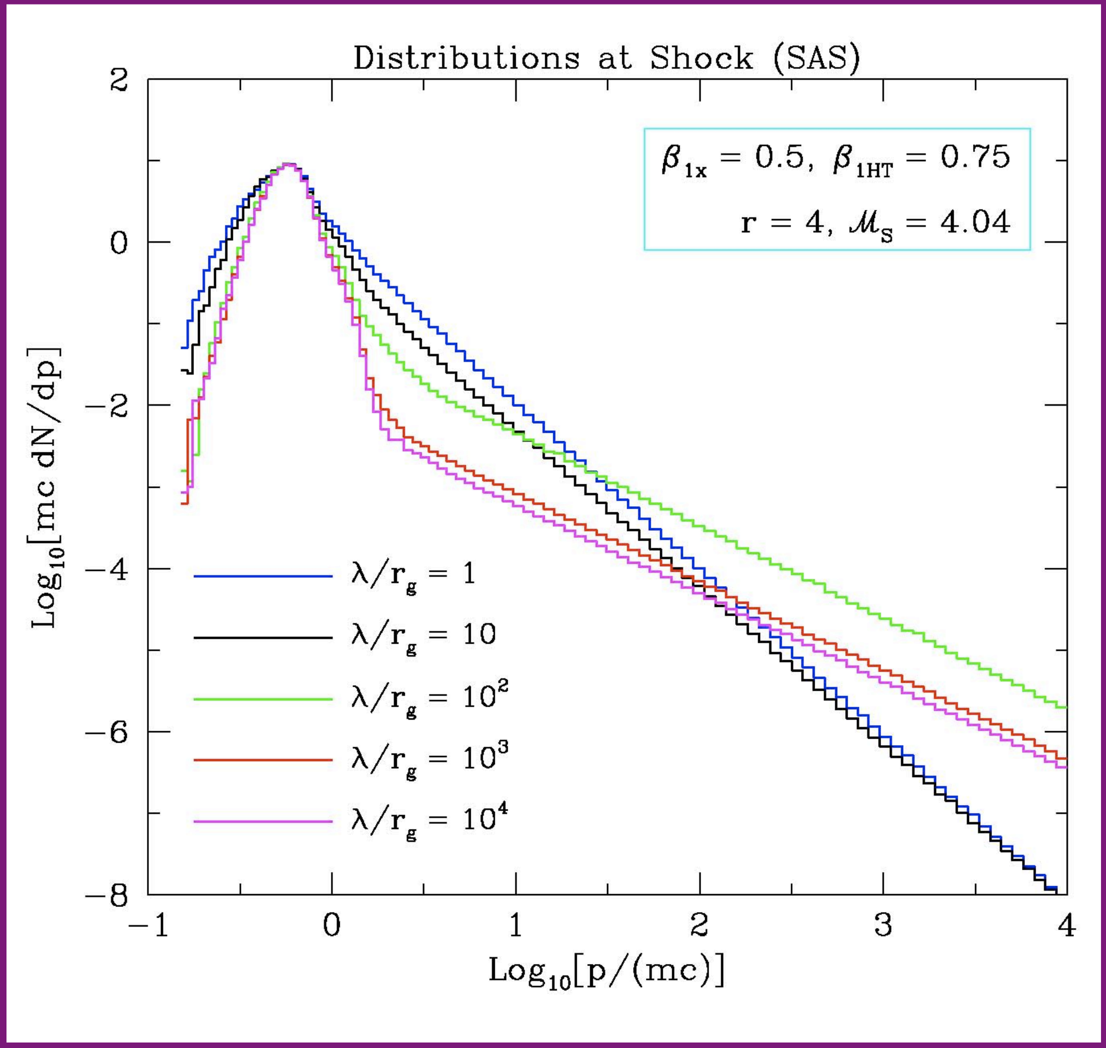
Ellison & Double (2004)

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

Shock Acceleration Injection Efficiencies

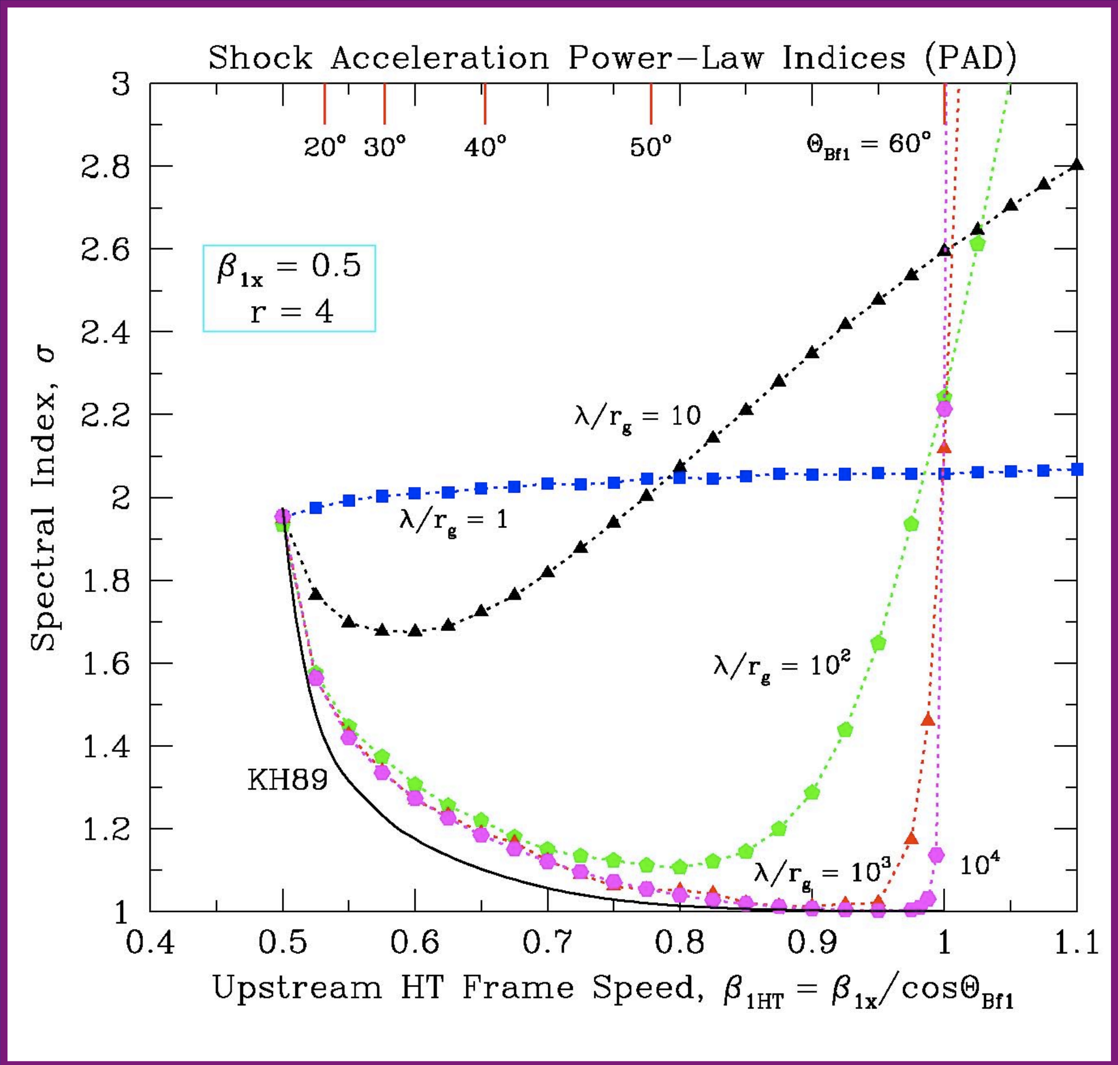
- Complete particle spectra in the limit of small angle scattering (SAS: pitch angle diffusion: PAD) **range considerably**;
- In cases of strong cross field diffusion, the index is **around two** and the injection is efficient;
- Gyro-orbit simulations for $\lambda/r_g \to \infty$ that give flat power-law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



Baring & Summerlin 2009, in prep.

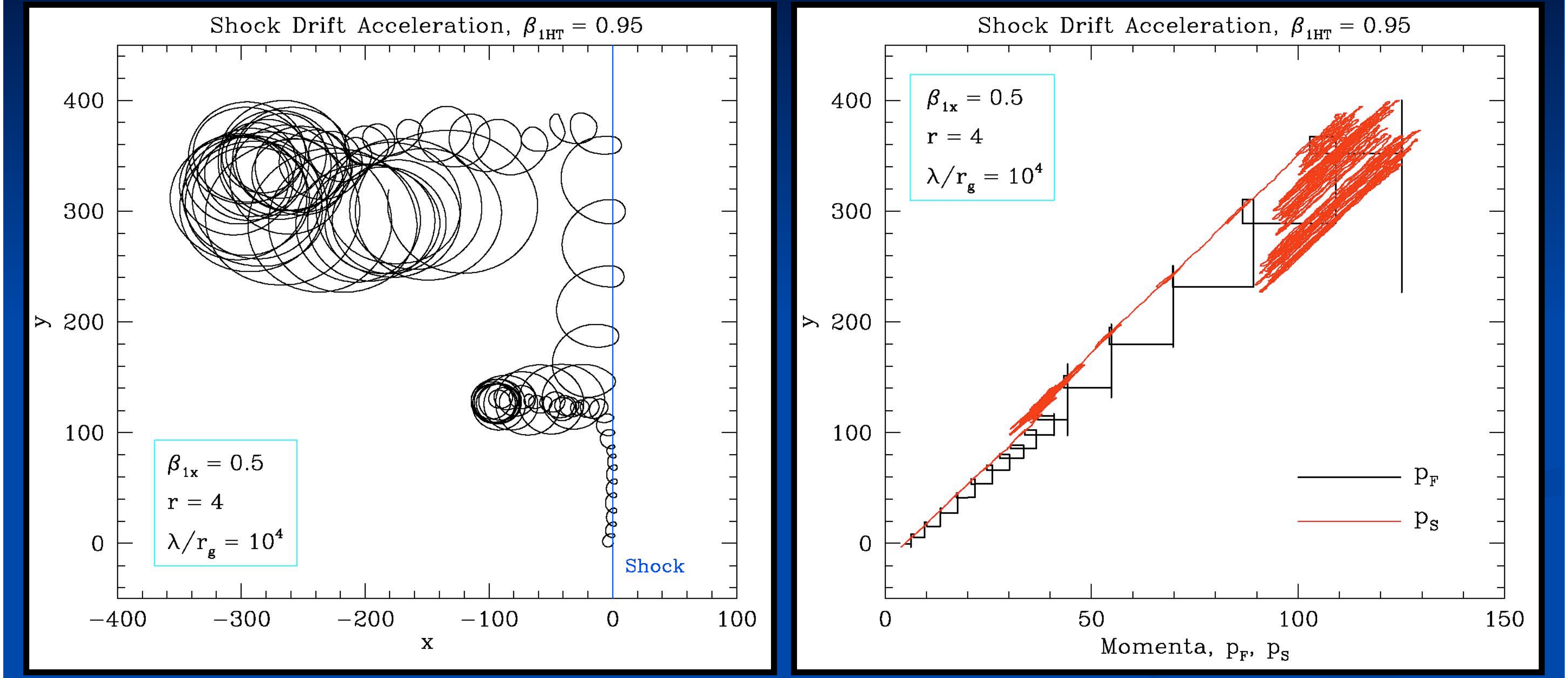
Shock Acceleration Spectral Indices

- 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 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)

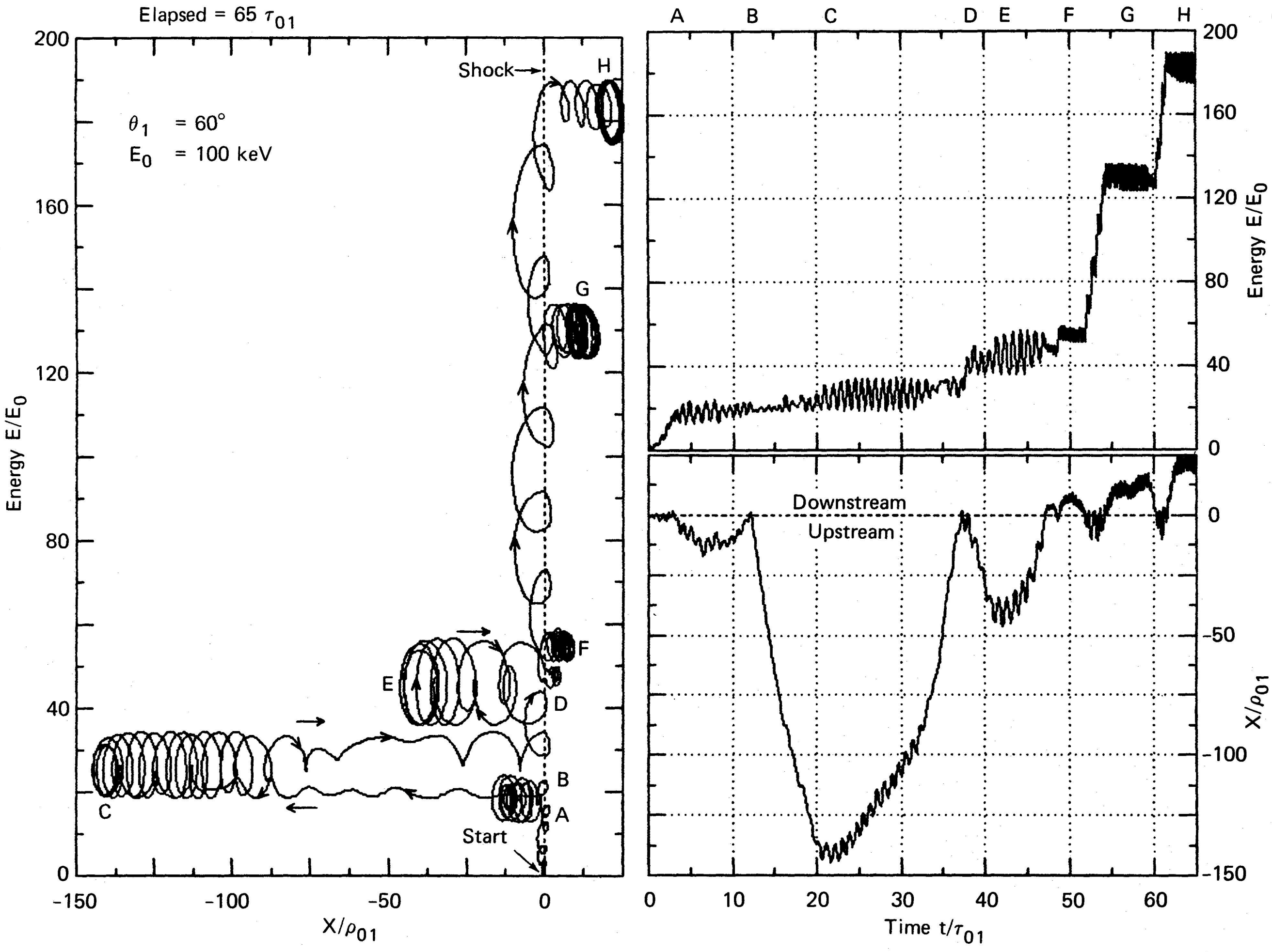


FIG. 6.—Sample for quasi-perpendicular shock $\theta_1 = 60°$. See Fig. 5 caption and text for details.

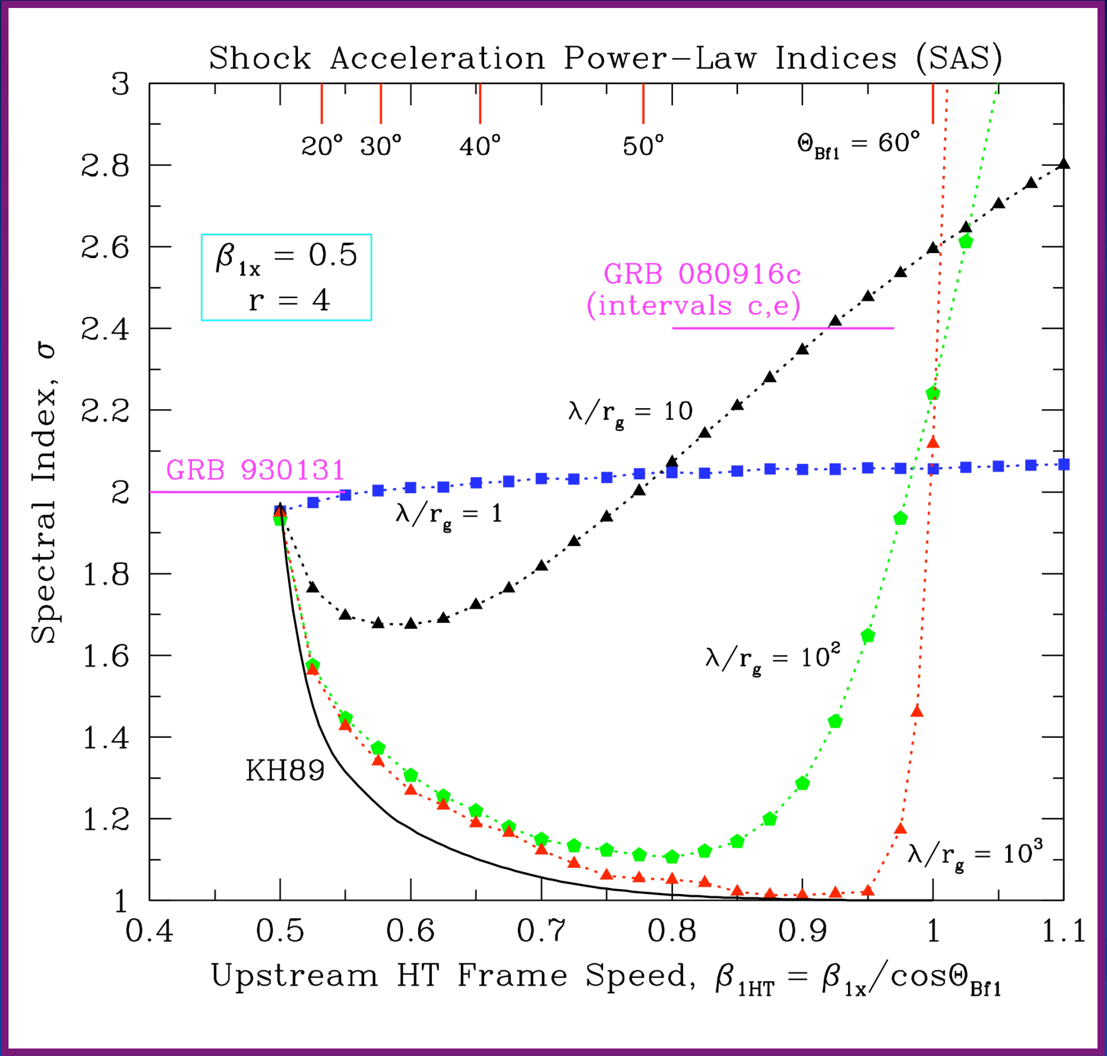
$$\mathbf{p}.\frac{d\mathbf{p}}{dt} = q\mathbf{p}.\left\{\mathbf{E}+\frac{\mathbf{v}}{c}\times\mathbf{B}\right\} \equiv q\mathbf{p}.\mathbf{E}$$

Connecting to Source Gamma-ray Observations

- GRBs: coupling between particle acceleration index σ for $dn/dp \propto p^{-\sigma}$ and observed photon index β ($dn_\gamma/d\varepsilon_\gamma \propto \varepsilon_\gamma^{-\beta}$) depends on whether in situ cooling is efficient or not.
  - Uncooled synchrotron or IC: $\beta=(\sigma+1)/2 \Rightarrow \sigma=2\beta-1$
  - Strongly-cooled synchrotron or IC: $\beta=(\sigma+2)/2 \Rightarrow \sigma=2\beta-2$
- Uncooled hadronic emission: $\beta\sim\sigma$
- Blazars: uncooled synchrotron self-Compton (SSC) is generally invoked to explain gamma-rays:
  - Uncooled SSC: $\beta=(\sigma+1)/2 \Rightarrow \sigma=2\beta-1$
- Hadronic scenarios: $\beta\sim\sigma$
- => Great diagnostics potential in *Fermi* era!

Shock Acceleration Spectral Indices

- Power-law indices in the limit of small angle scattering range considerably;
- GRBs and blazars generally require $\sigma>1.5$;
- Cooled GRB scenarios and blazars require either strong turbulence, or subluminal shocks;
- GRB emission is uncooled synchrotron/IC, then superluminal shock regime is preferred.



Baring & Summerlin (2009)

Conclusions

- Shock acceleration particle indices depend on several parameters: **field obliquity**, the **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 hadronic and leptonic models.
- Index parameter space dichomatizes into sub-luminal (flat) and super-luminal (steep) regimes.
- **Extremely flat spectra realized in sub-luminal shocks with minimal cross field diffusion**: retention of particles in shock layer permits action of shock drift acceleration.
  - **Unlikely to be realized in Nature: shock environs are turbulent; injection is inefficient, and spectra not commensurate with source photon signals ($\sigma > 1.5$).**