Particle Acceleration in Astrophysical Shocks

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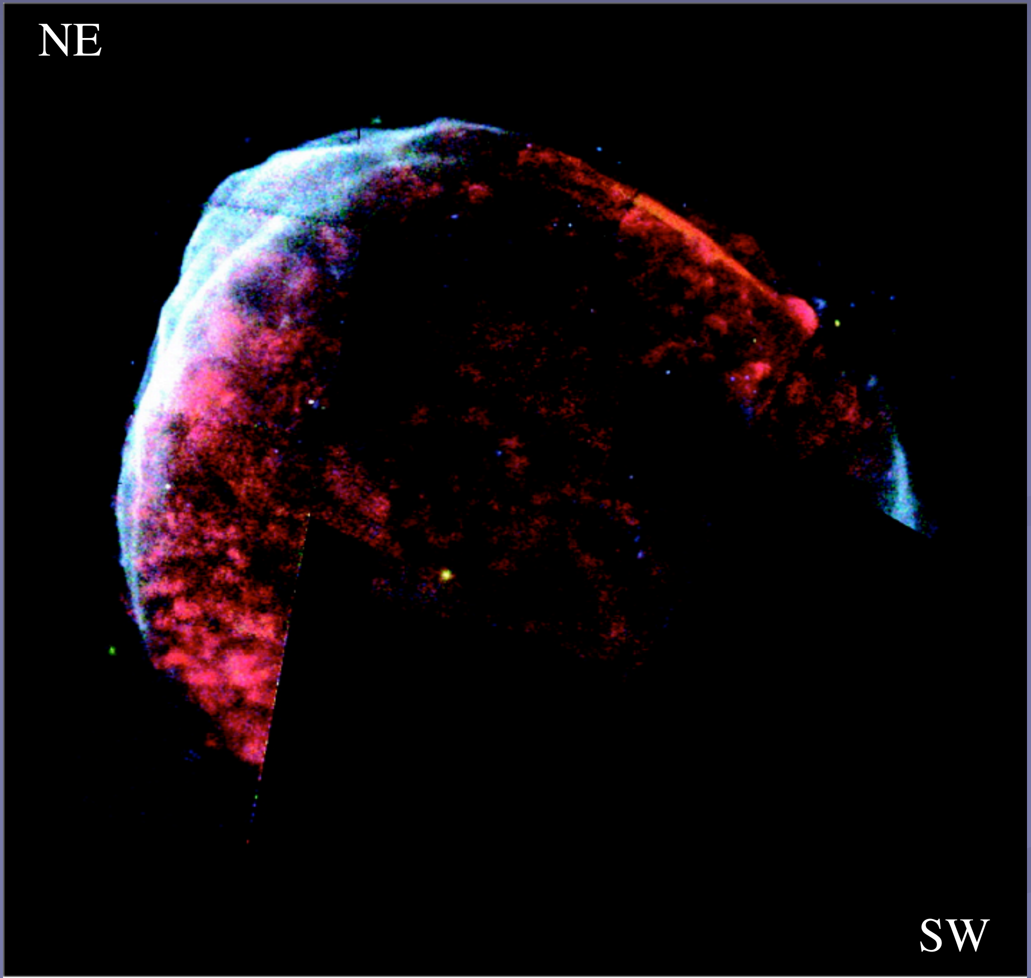
Some Key Issues

- Evidence of B field enhancement at non-relativistic, SNR shocks is growing: how are high fields generated?
- X-ray emission in SNRs is often best modeled using non-linear feedback from energetic cosmic rays: can we prove the existence of such non-linear hydrodynamic effects in SNRs [and also *relativistic shock systems*]?
- Acceleration models have difficulty in injecting electrons into the acceleration process for non-relativistic shocks: how is efficient injection driven?
- How are electrons accelerated in *relativistic shocks*? What is their distribution (non-thermal versus thermal; and at the highest energies), and abundance relative to ions?

Inferences of SNR B Fields using CHANDRA

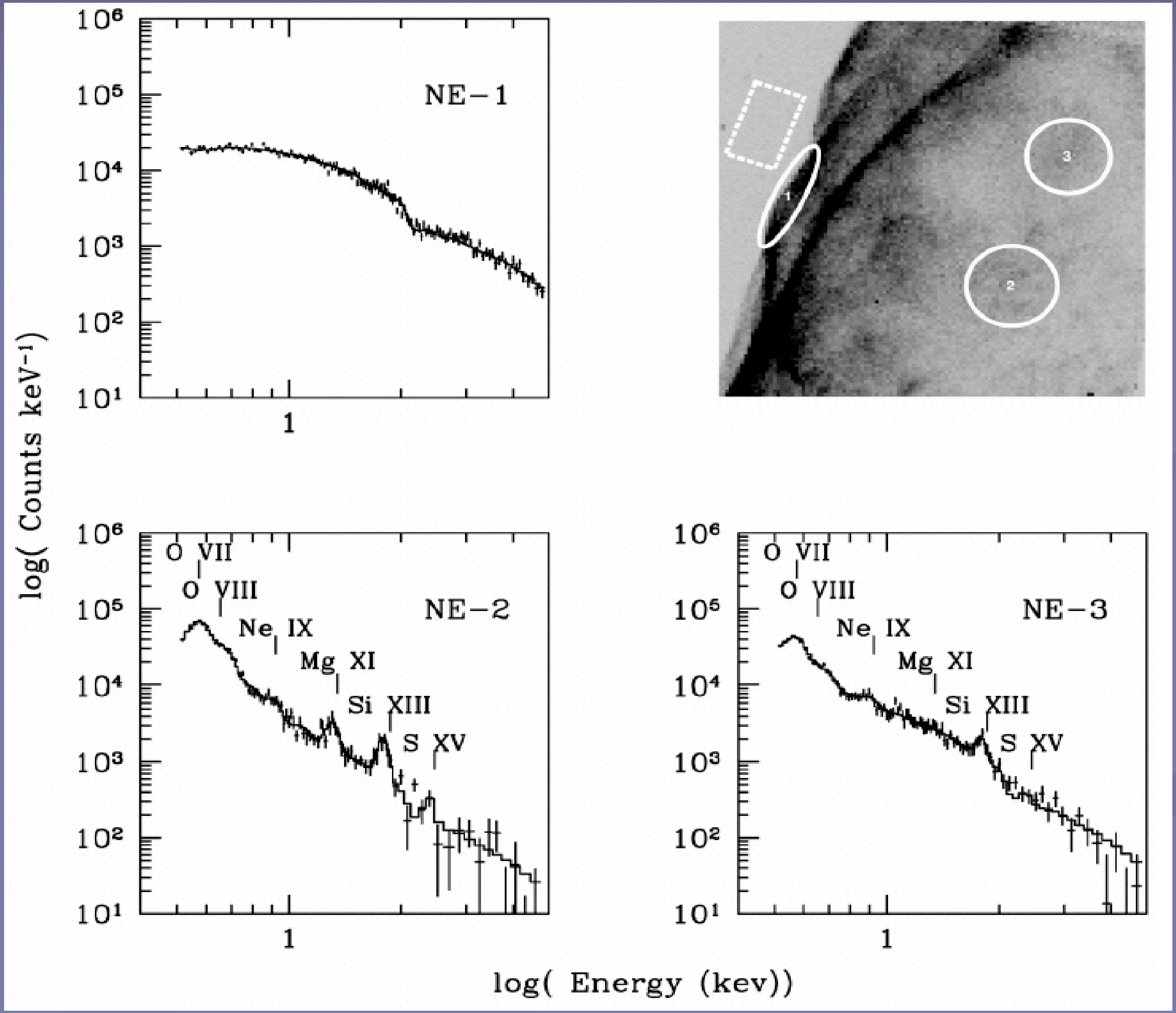
- Spatially-resolved line and continuum spectroscopy by CHANDRA X-ray Observatory permits probes of **B** field amplification in SNRs;
- Case study: SN1006 (Long et al. 2003), a clean system, i.e. early Sedov-phase (deduced from radio proper motions), simple environment (high latitude source), with well-defined shell;
- Spatial mapping of thermal (i.e. line) and non-thermal synchrotron emission details magnetic field contrast across quasi-perpendicular shock.
- Southwest rim (not shown) similar to NE image.
- Thermal interior (red) and non-thermal shell (blue).

SN1006



Red: 0.5-0.8 keV;
Green: 0.8-1.2 keV;
Blue: 1.2-2.0 keV.

Spatially-Resolved Spectroscopy with CHANDRA

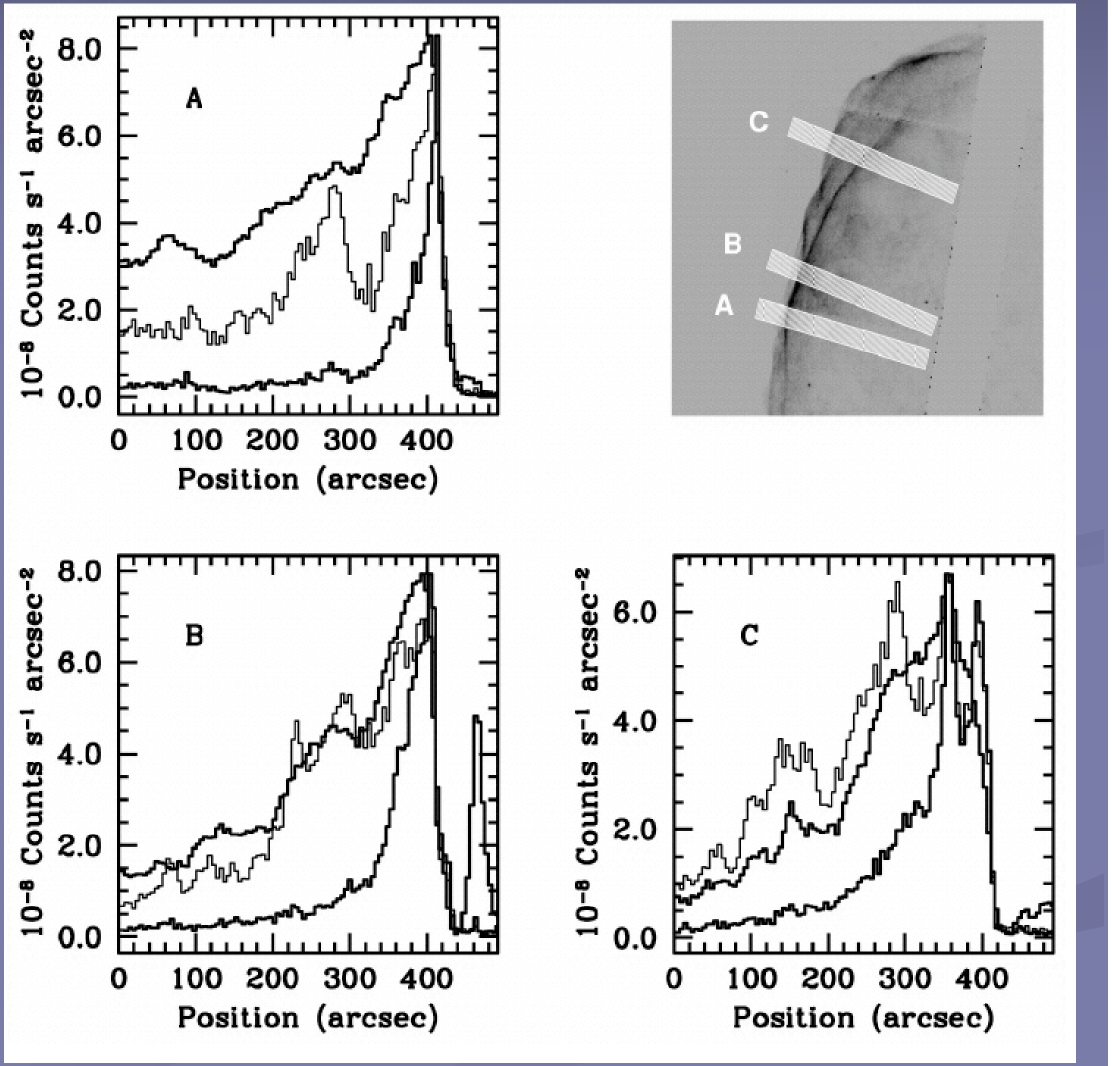


- Clear spectral evolution from non-thermal to thermal away from rim;
- Without spatial resolution, two components were confused, with the non-thermal rim dominating.

Spatial Brightness Profiles in SN1006

- Surface brightness profiles are much broader for thermal X-rays and radio synchrotron than for non-thermal X-rays;
- Narrowness of profiles along scans argues for shocks ⊥ to sky, i.e. no projectional smearing;
- Flux contrast ratio (< 1.5%) for upstream to downstream 1.2-2.0 keV suggests $B_d/B_u >> 4$, i.e. *greater than standard MHD compression in high M_S shocks* (Cas A offers similar picture: Vink & Laming 2003);
- Non-thermal X-ray width implies connection between cosmic rays and **B**-field amplification.

Long et al. 2003



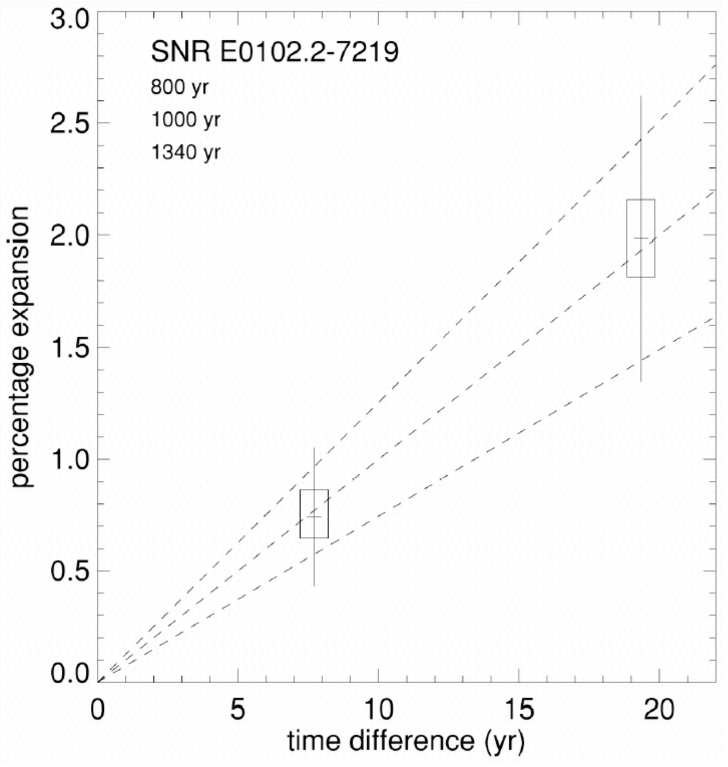
Thin black line: 0.5-0.8 keV; Black line: 1.2-2.0 keV; Grey line: 1.4 GHz radio.

Non-Linear Field Amplification by Cosmic Ray Streaming

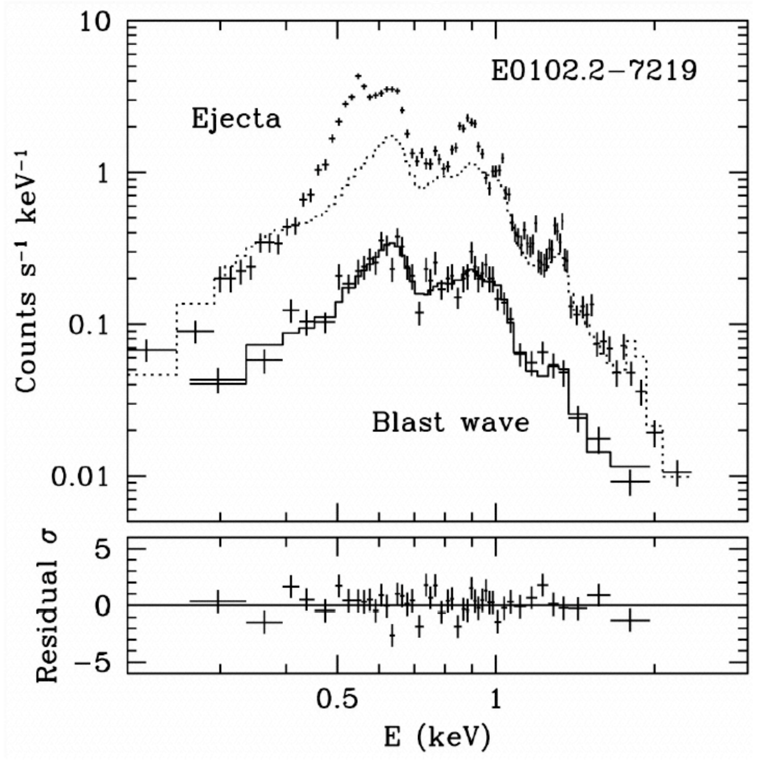
- *Lucek & Bell (2000)* proposed that high energy cosmic rays (CRs) in strong shocks could amplify B when streaming upstream;
- *Essentially an energy-budget argument*: B field and CRs take large portions of total energy flux, diminishing shock heating;
- Work done on Alfven turbulence scales as the CR pressure gradient: $dU_A/dt=v_A\, dP_{CR}/dx$;
- Field amplification should then scale as $(\delta B/B)^2 \sim M_A\, P_{CR}/\rho u^2$; works for high M_A strong shocks that generate large P_{CR};
- Mini-bandwagon has developed, with work by Berezhko, Voelk, Ellison, Bykov, Lemoine, Pelletier, and others;
- Self-consistent, simulational model for turbulent field amplification is needed.

Electron Temperatures in the Shock Layer

ROSAT/Chandra



Hughes et al. 2000

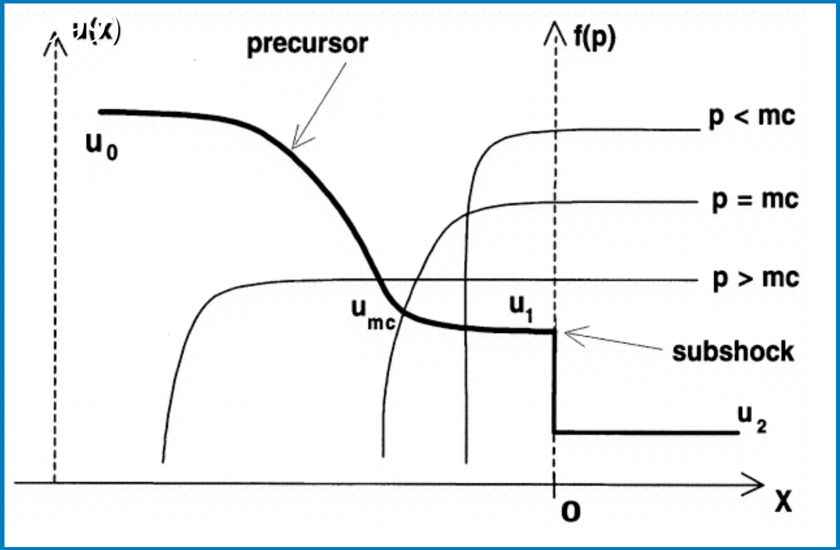


Chandra

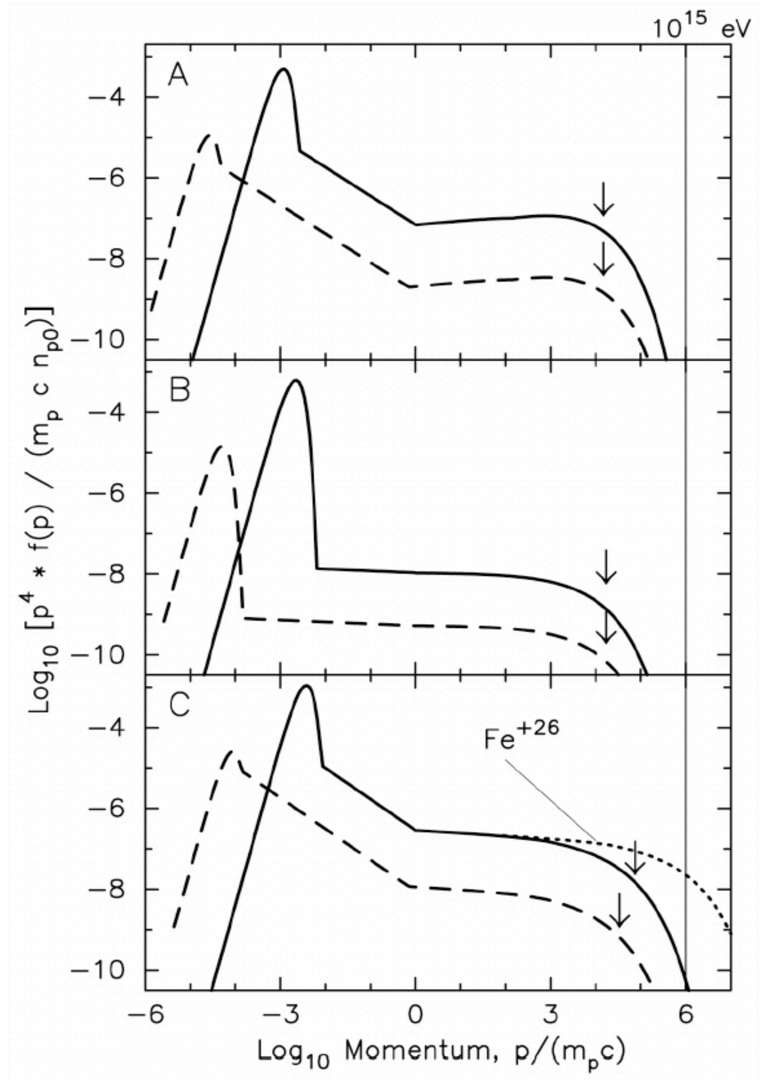
- Hughes et al. (2000; E0102.2) & Decourchelle et al. (2000; Kepler) observed that NE ionization fits to X-ray spectra (O, Ne, Fe, Mg lines) yielded T_e below hydrodynamic (HD) expectations: $3kT_e/2 < m_e(3u_1/4)^2/2$;
- Ram pressure HD quantities deduced from proper motions: usually radio, sometimes X-ray (left panel: ROSAT/Chandra);
- Concluded that low post-shock T_e and high line brightness could be produced by *non-linear* acceleration models.

Non-Linear Shock Modification

Berezhko & Ellison



Ellison & Cassam-Chenaï (2005)



NL

TP

Solid = protons, dashed = electrons

- Pressure supplied by energetic CRs slows upstream flow and reduces subshock compression ratio;
- => lower heating of ions and electrons, i.e. T_e drops below unmodified HD expectations;
- NL effects not yet demonstrated unequivocally in SNRs (e.g. Reynolds & Ellison 1992, radio data compilation for Tycho + Kepler).

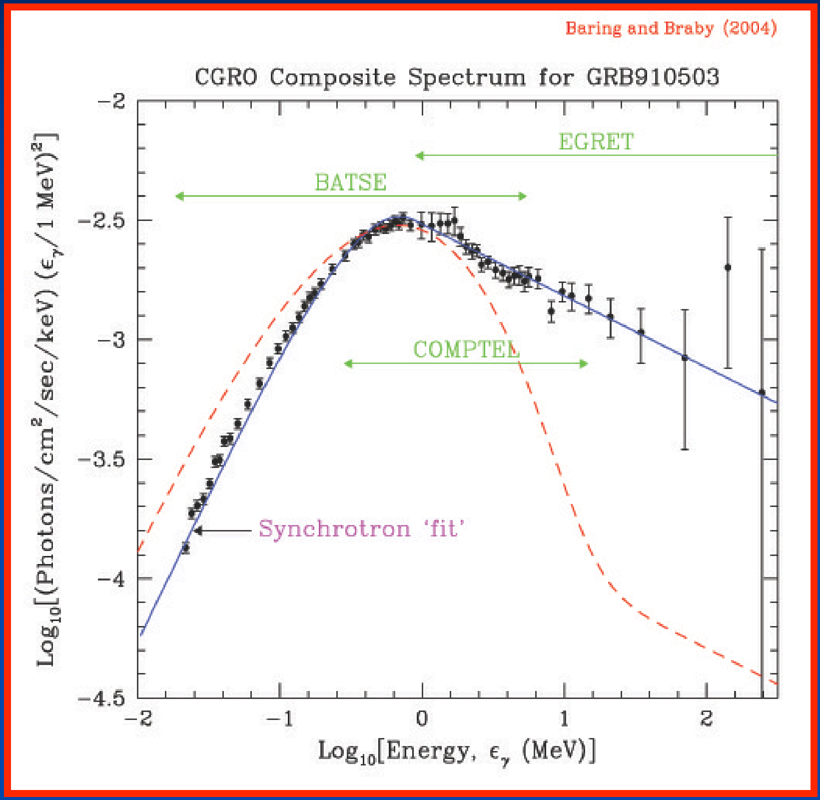
SNR Round-Up

- **B** field amplification impacts maximum energy of cosmic rays (both SNR spectral issue and CR knee issue);
- Maximum energy E_{MAX} controls P_{CR}, and therefore also **B**-field amplification;
- Maximum CR energy controls non-linear modification of shock, i.e. “sub-hydrodynamic” heating in shock layer;
- Electron-proton energy exchange in shock layer impacts inferences of heating & e^- injection efficiency,
  - i.e. modifies electron line diagnostics and ability to generate X-ray synchrotron-emitting particles;
- Complex interplay must be distilled into isolated units/problems, attacked using simulations;
- Mass ratio m_e/m_p and $E_{MAX}/m_p u^2$ are key impediments to simulational progress;
- Laboratory experiments could help span disparate scales within single systems.

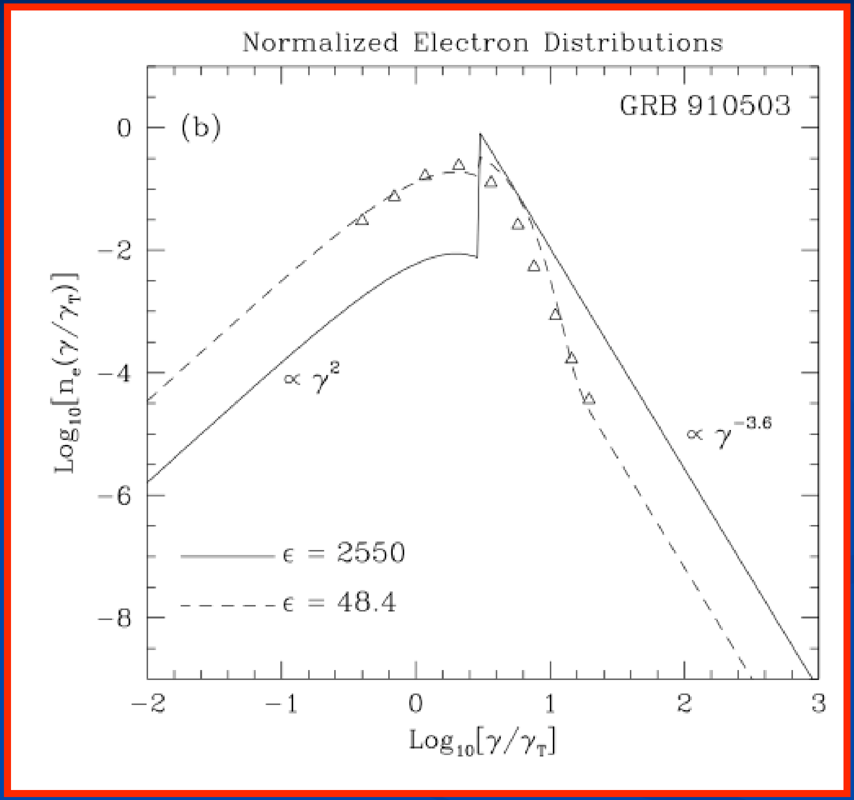
Relativistic Shocks, Gamma-Ray Bursts and Jets in Active Galaxies

- Dissipation at relativistic shocks? Application also microquasars, and pulsar winds;
- Weibel instability in shocks of low magnetization (Medvedev, Silva; Nishikawa);
- Fermi-type mechanisms: can they work in ultrarelativistic systems? - spectral index and efficiency issues (Kirk, Ostrowski, Ellison, Baring, etc.);
- Here we address a bottom line: *all have to generate the observed photon spectra*.

GRB Prompt Emission Continuum Fitting



Photon spectrum

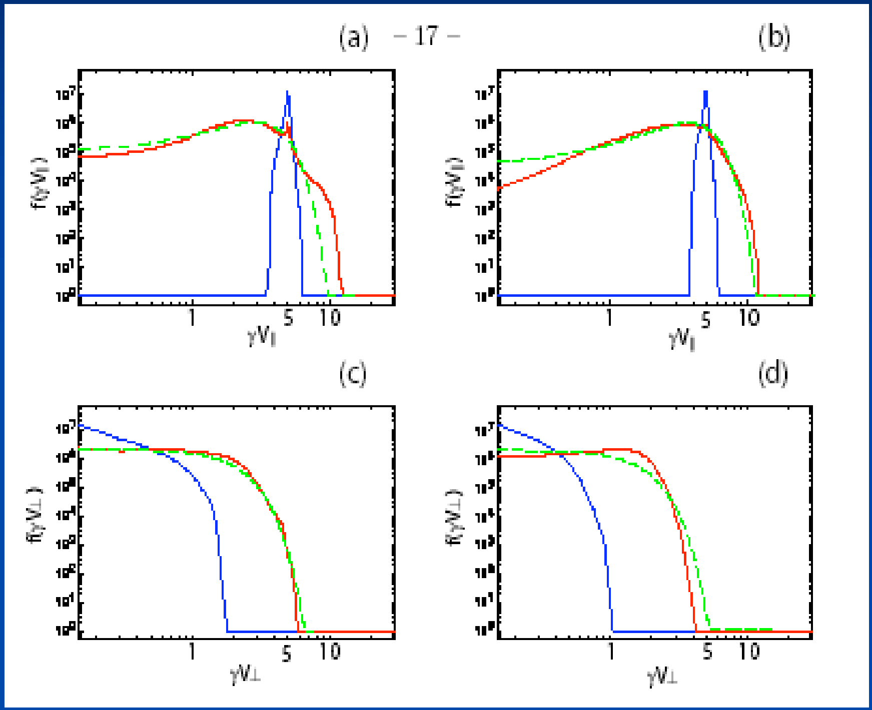


Electron Distribution

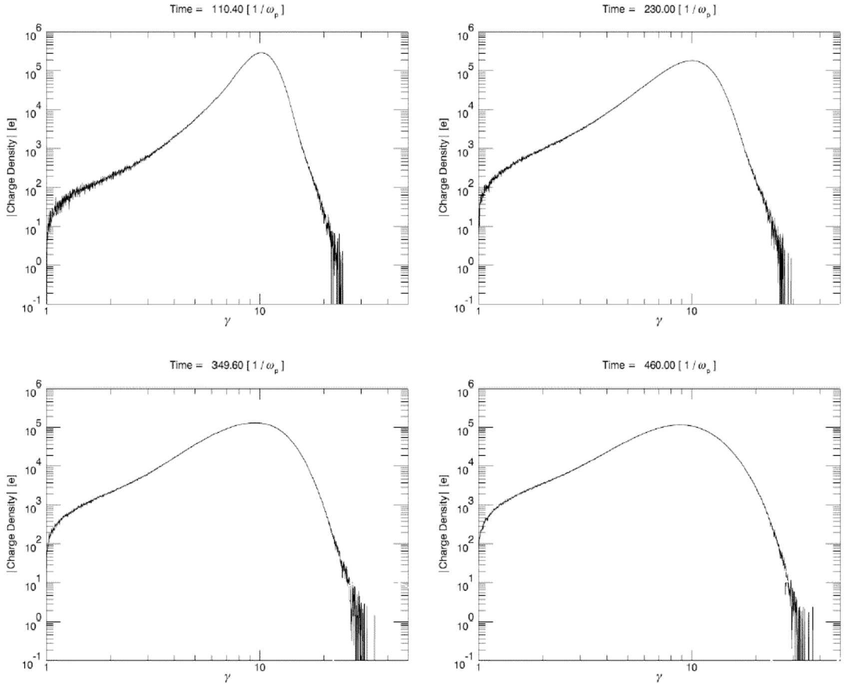
- Synchrotron radiation (preferred paradigm) fits most burst spectra - index below 100 keV is key ("line of death") issue;
- But, underlying electron distribution is predominantly non-thermal, i.e. unlike a variety of shock acceleration predictions (e.g. PIC codes, hybrid codes, Monte Carlo simulations): see Baring & Braby (2004).

3D PIC Plasma Shock Simulations

Nishikawa et al.



Medvedev

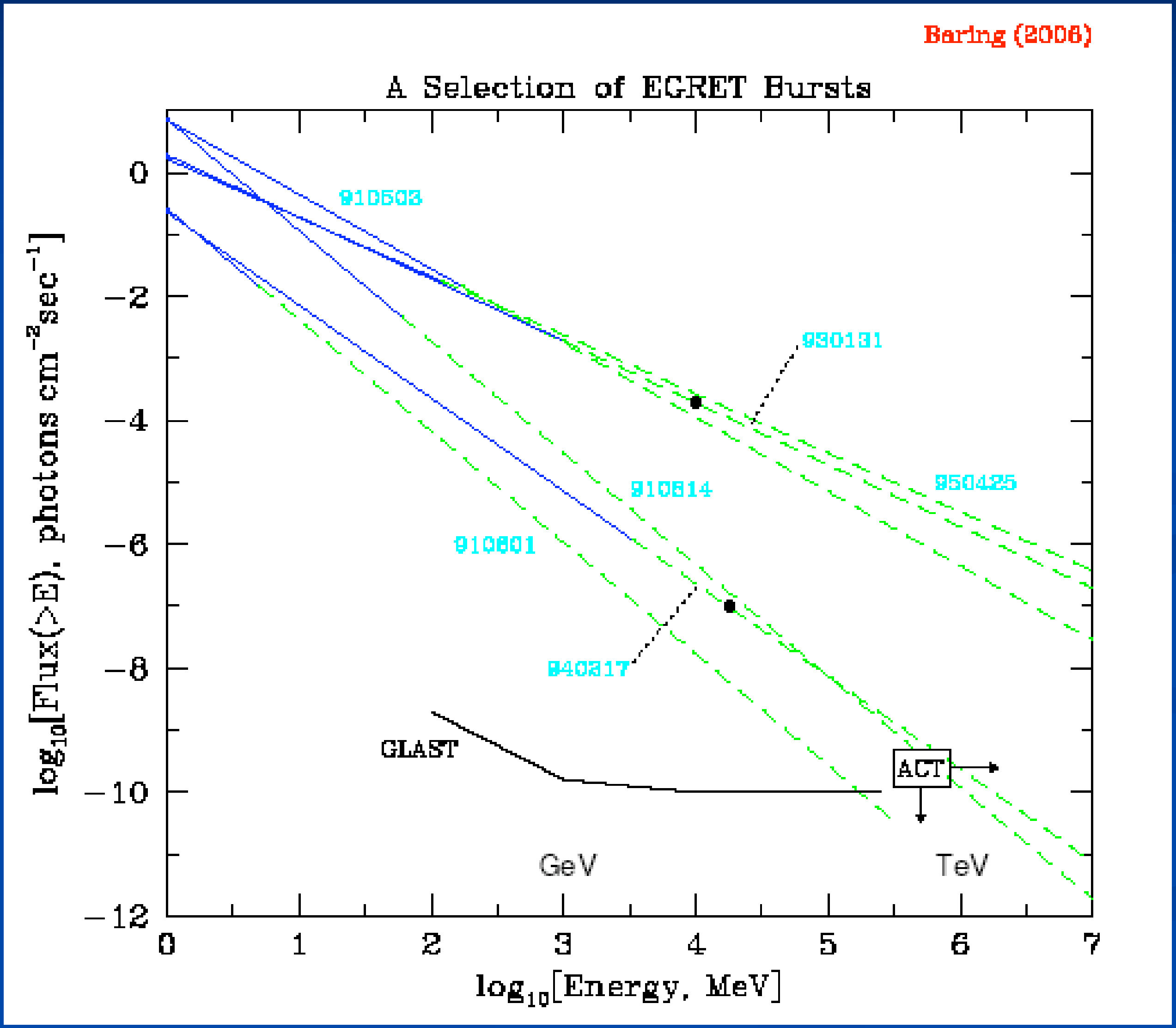


- Nishikawa et al. (ApJ 2006): e-p (left panels) and pair shocks have great difficulty accelerating particles from thermal pool (green is Lorentz-boosted relativistic Maxwellian), dominated by electromagnetic thermal dissipation;
- Medvedev (priv. comm.): Weibel instability simulation with the upper energy cutoff continuously growing in time, i.e. no steady-state;
- *In PIC simulations, non-thermal power-law is at best, not prominent.*

Escape Hatches?

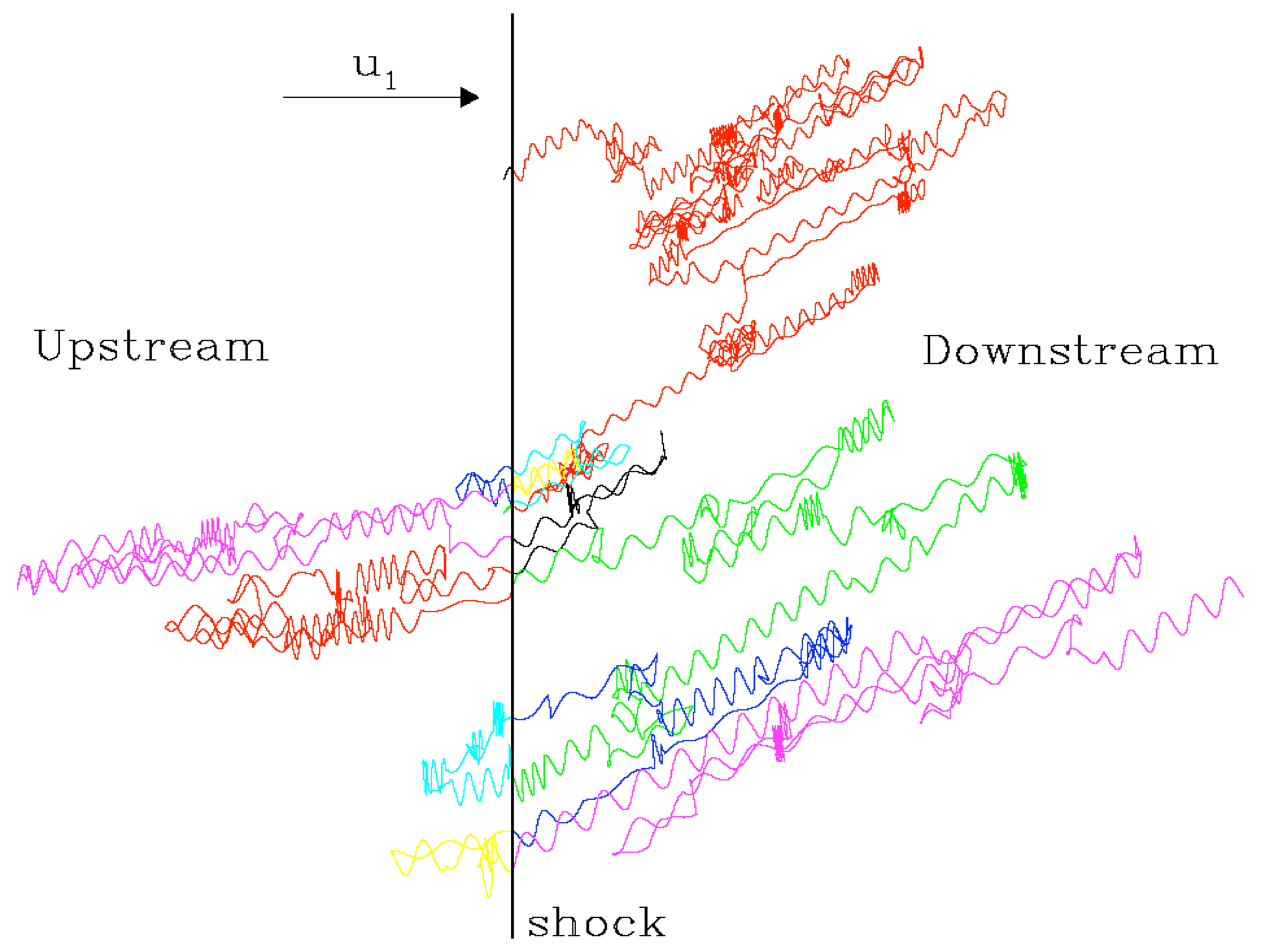
- At face value, GRB spectra indicate that acceleration models need to generate dominant non-thermal e^- distributions;
- Can laboratory experiments cast light on this?
- But, possible resolutions include:
  - other attractive radiation mechanisms:
    1. small angle synchrotron (Epstein 1973),
    2. jitter radiation (Medvedev 2000, 2006);
- Synchrotron self-absorption acting in concert with upscattering may work (Panaitescu & Meszaros 2000; Liang, Boettcher & Kocevski 2003; discussed in Baring & Braby 2004) - it removes any connection to a thermal population in the BATSE band.

High Energy Emission in EGRET Bursts



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 a strongly *increasing* function of field obliquity angle Θ_{Bn1}.

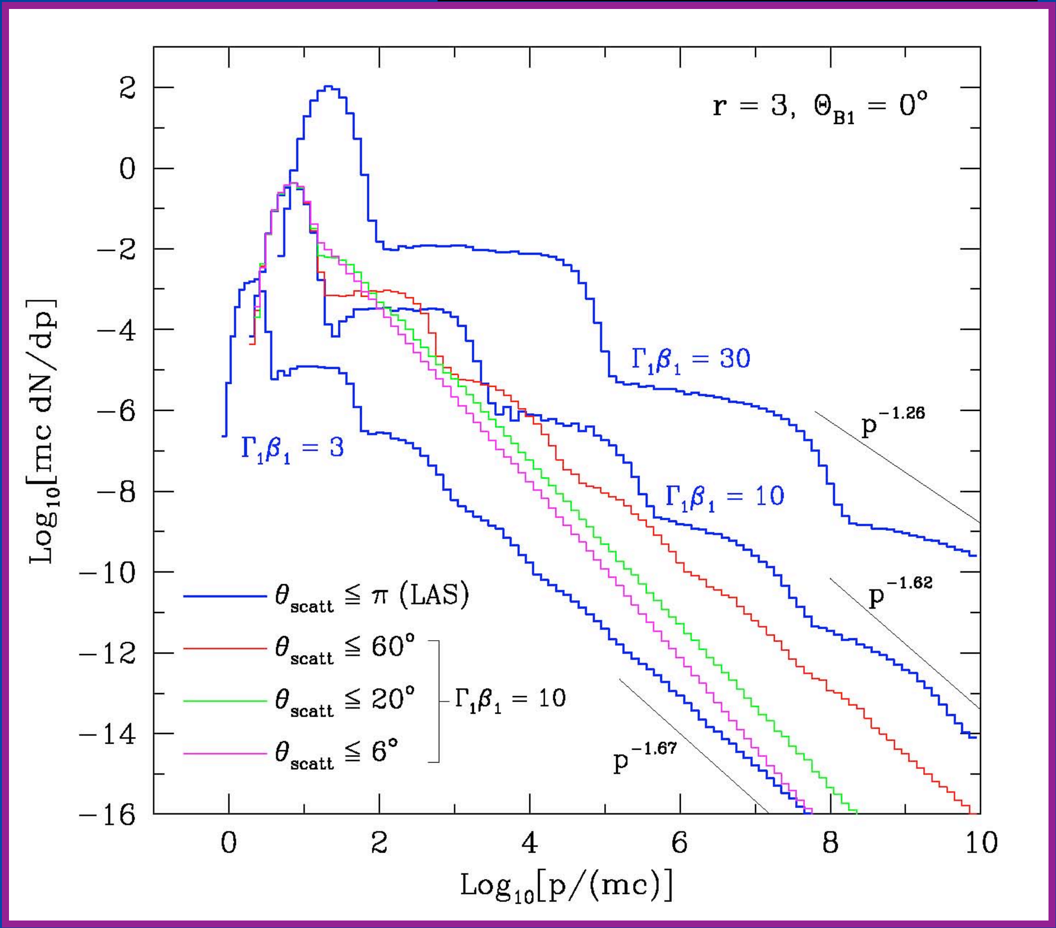


Baring & Summerlin (2006)

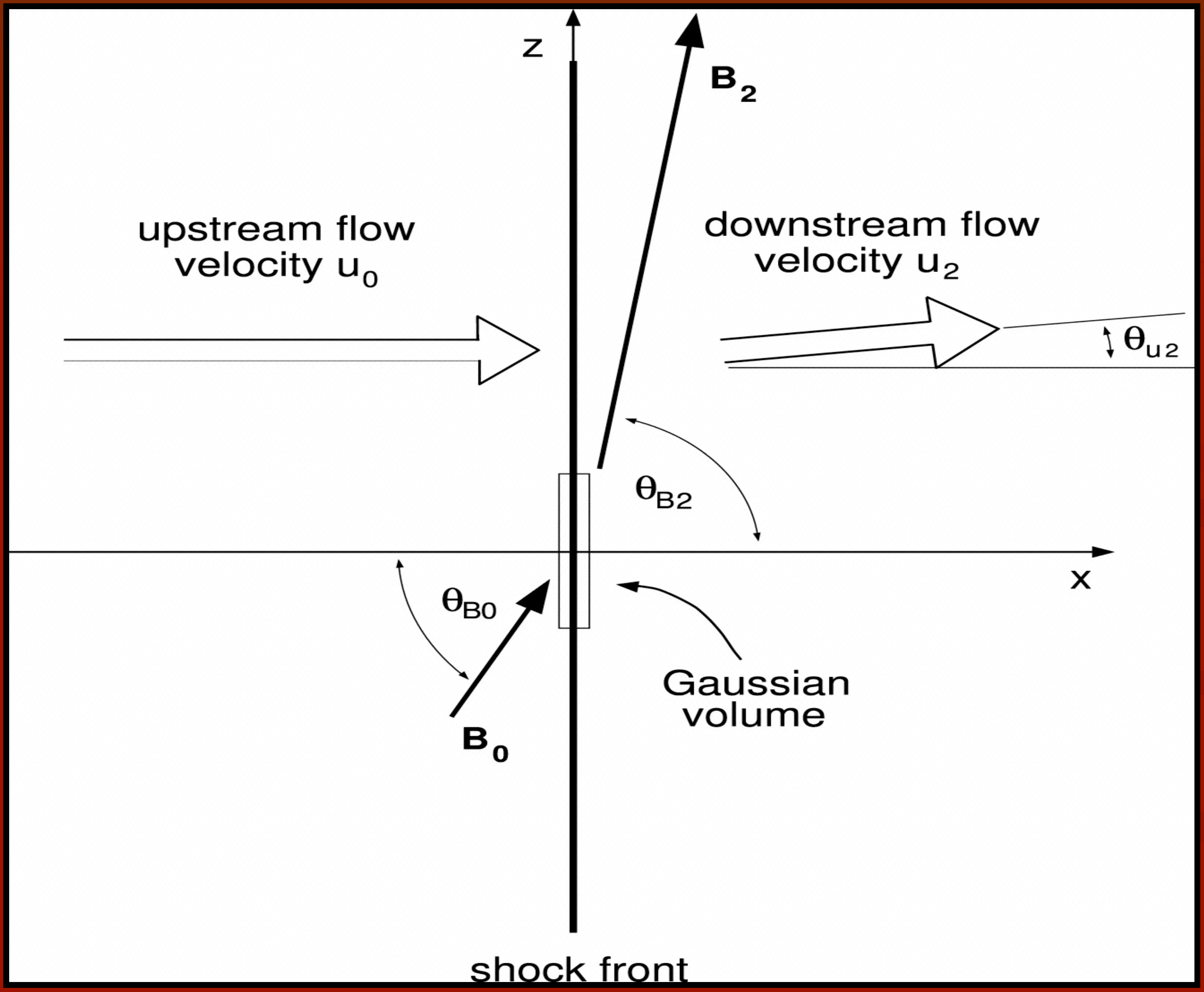
Relativistic Shocks: Spectral Dependence on Scattering

- 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)

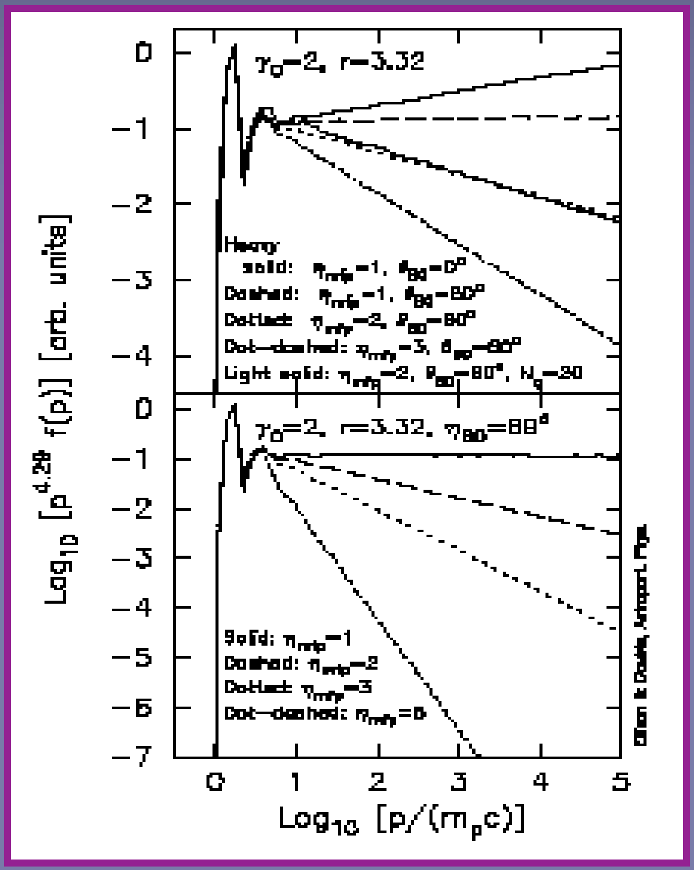
Summerlin & Baring 2007

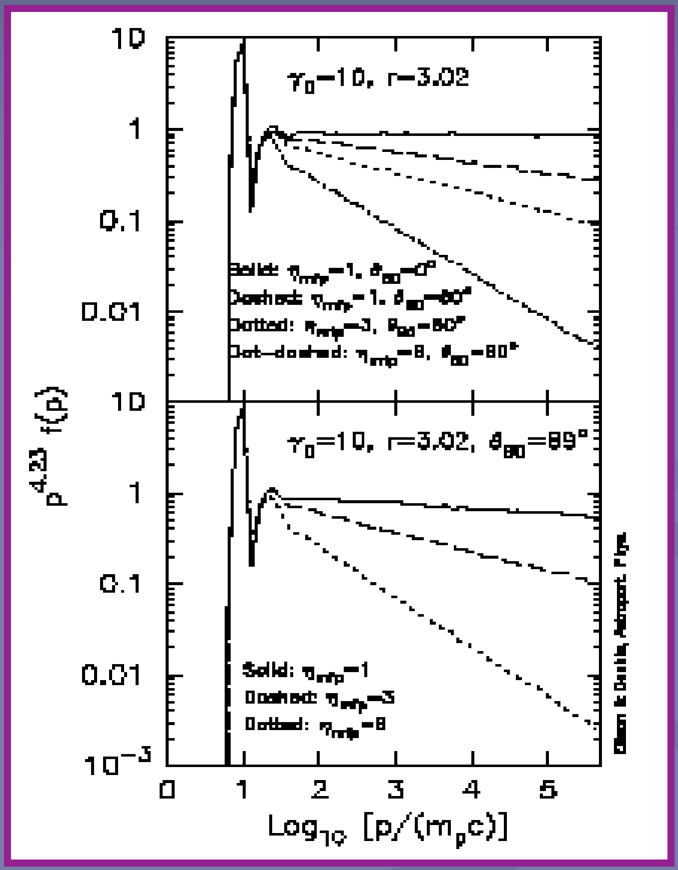


Oblique Shock Geometry



Relativistic Shocks: Spectral Dependence on Field Obliquity and Diffusion





Ellison &
Double
(2004)

- 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; see also Kirk & Heavens 1989).

Implications for Gamma-Ray Bursts

- 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;
- GRB prompt and afterglow emission more easily explained by *mildly-relativistic shocks* that are *not quasi-perpendicular* (for diffusive acceleration scenarios).

Outstanding Issues/Questions

- Evidence of magnetic field enhancement at non-relativistic, SNR shocks is growing: how are high fields generated?
- X-ray emission in SNRs can sometimes be best modeled using non-linear feedback from energetic cosmic rays in remnants: can we prove the existence of such non-linear hydrodynamic effects in SNRs? Are the relevant for relativistic shocks in GRBs and blazars?
- Acceleration models have difficulty in injecting electrons into the acceleration process in non-relativistic, electron-ion shocks: how is efficient injection driven?
- How are electrons accelerated in relativistic shocks? What is their distribution (non-thermal versus thermal), and what is their abundance relative to ions?