Particle Acceleration in Astrophysical Shocks

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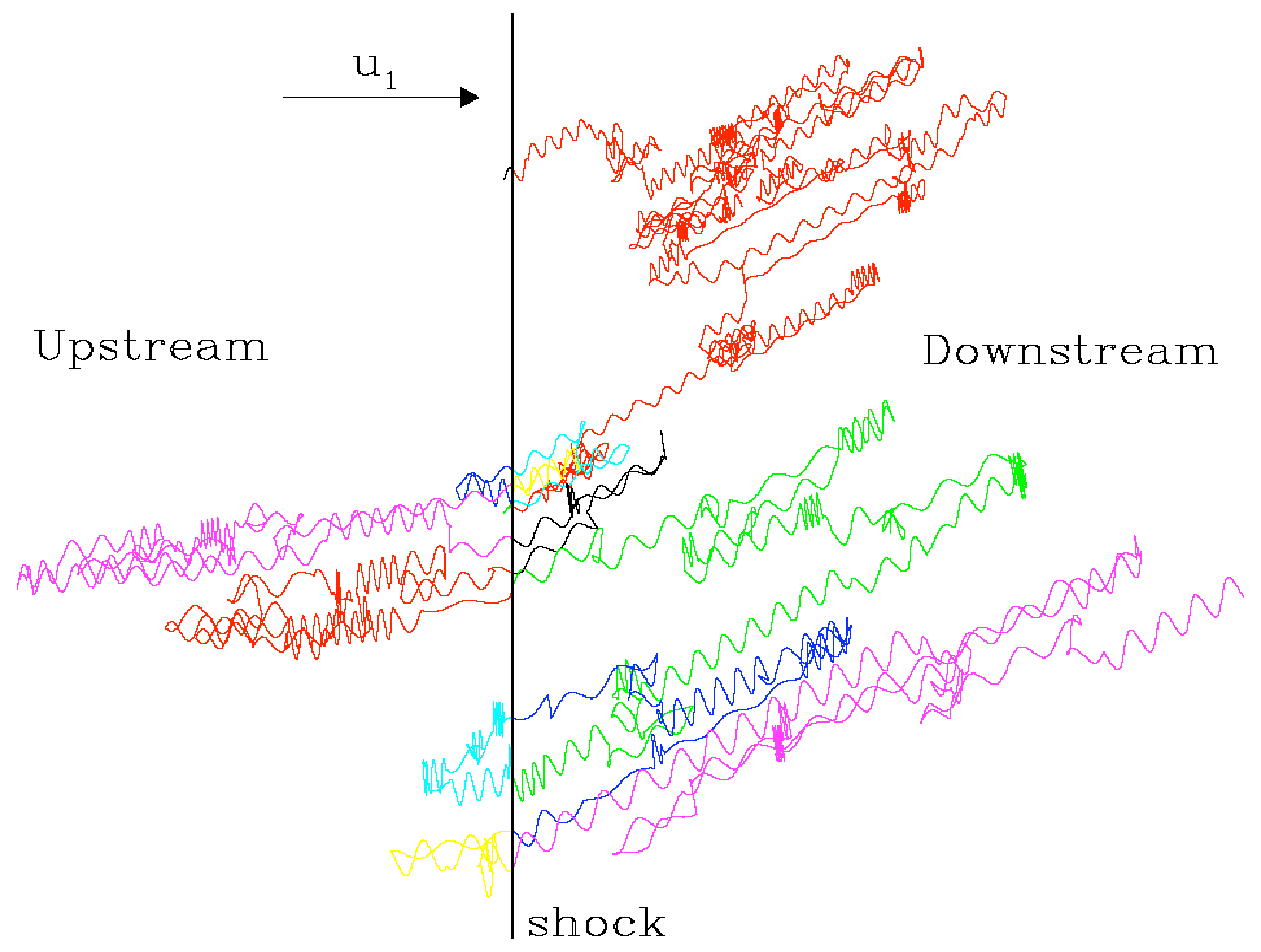
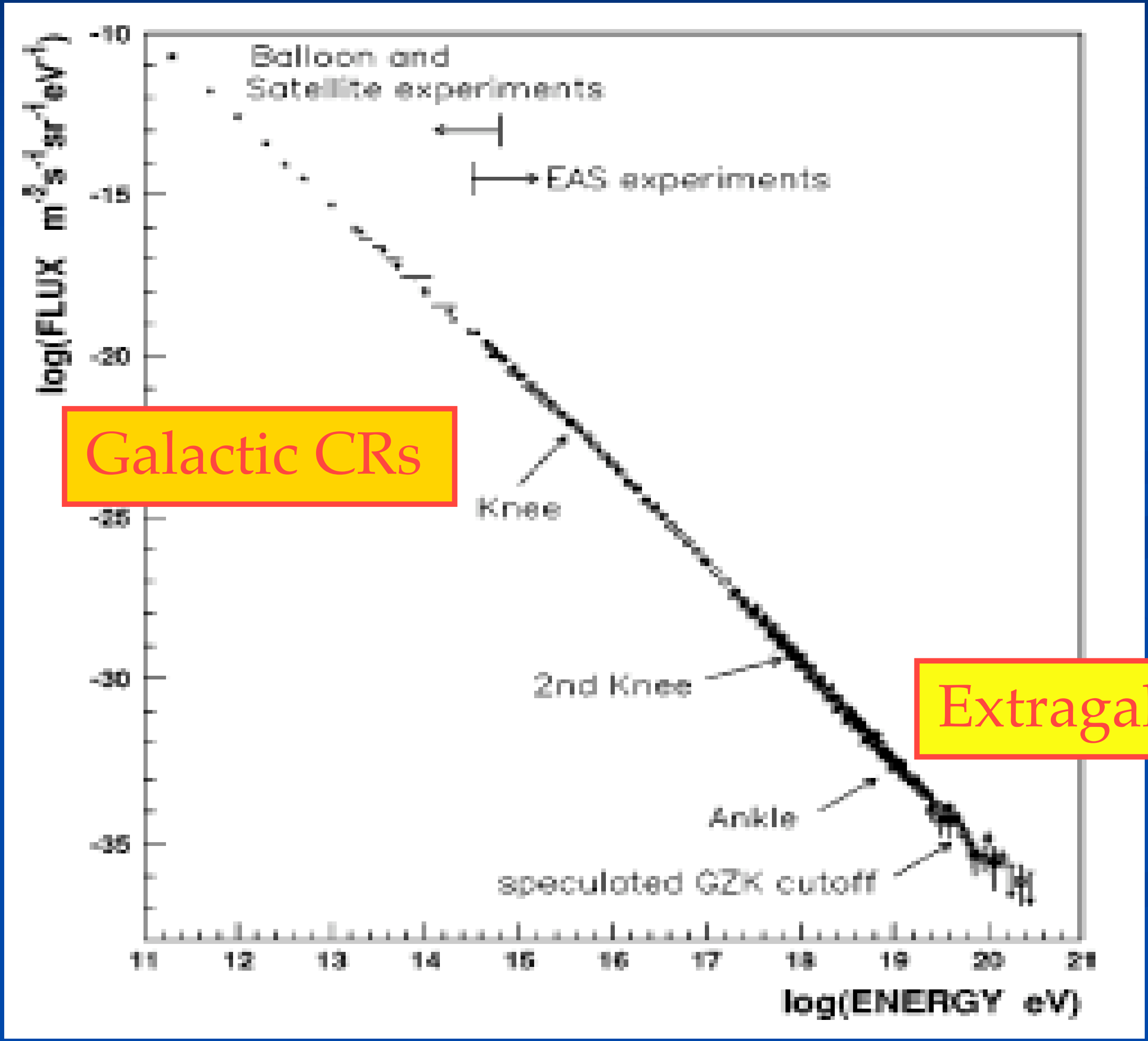
Topics Covered

- Overview of shock acceleration and its cosmic sites;
- Achieving the energy for UHECRs;
- Population constraints: global energetics;
- Spectral issues: can acceleration models generate the right distributions?
- *If time permits*: Testing grounds for shock acceleration theory: the heliosphere.



Baring & Summerlin (2006)

Complete Cosmic Ray Spectrum

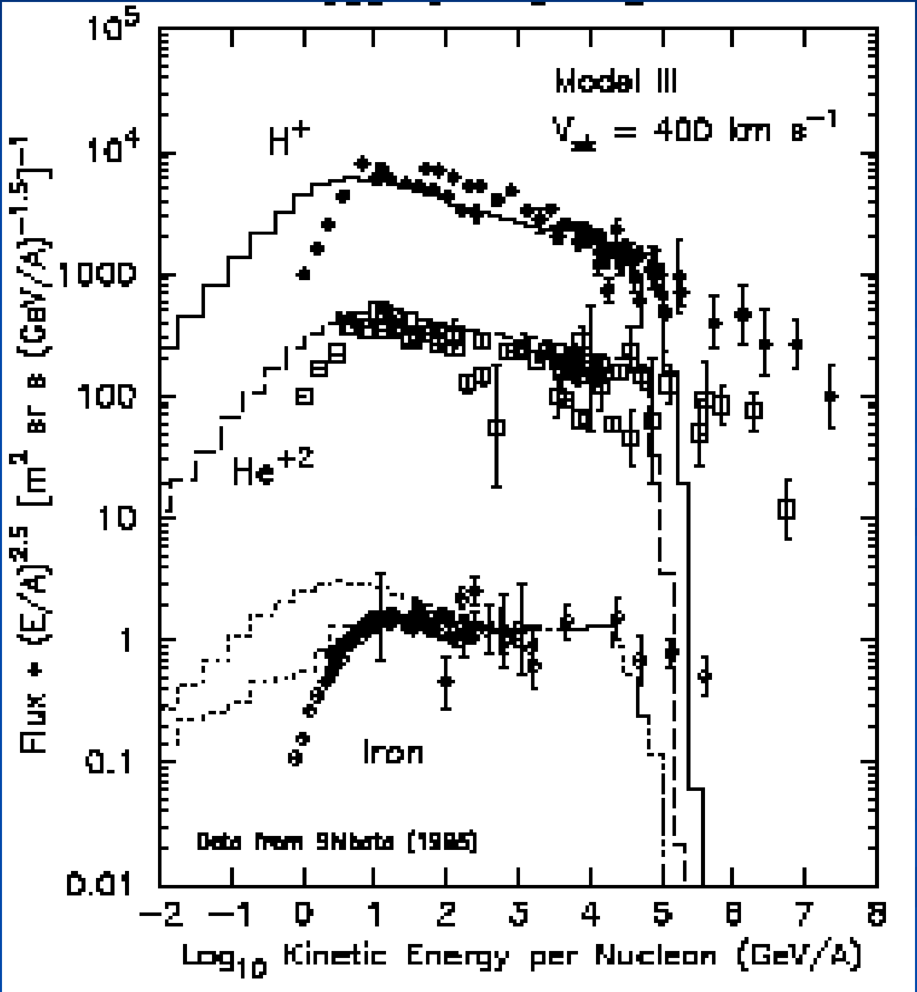


Galactic CRs

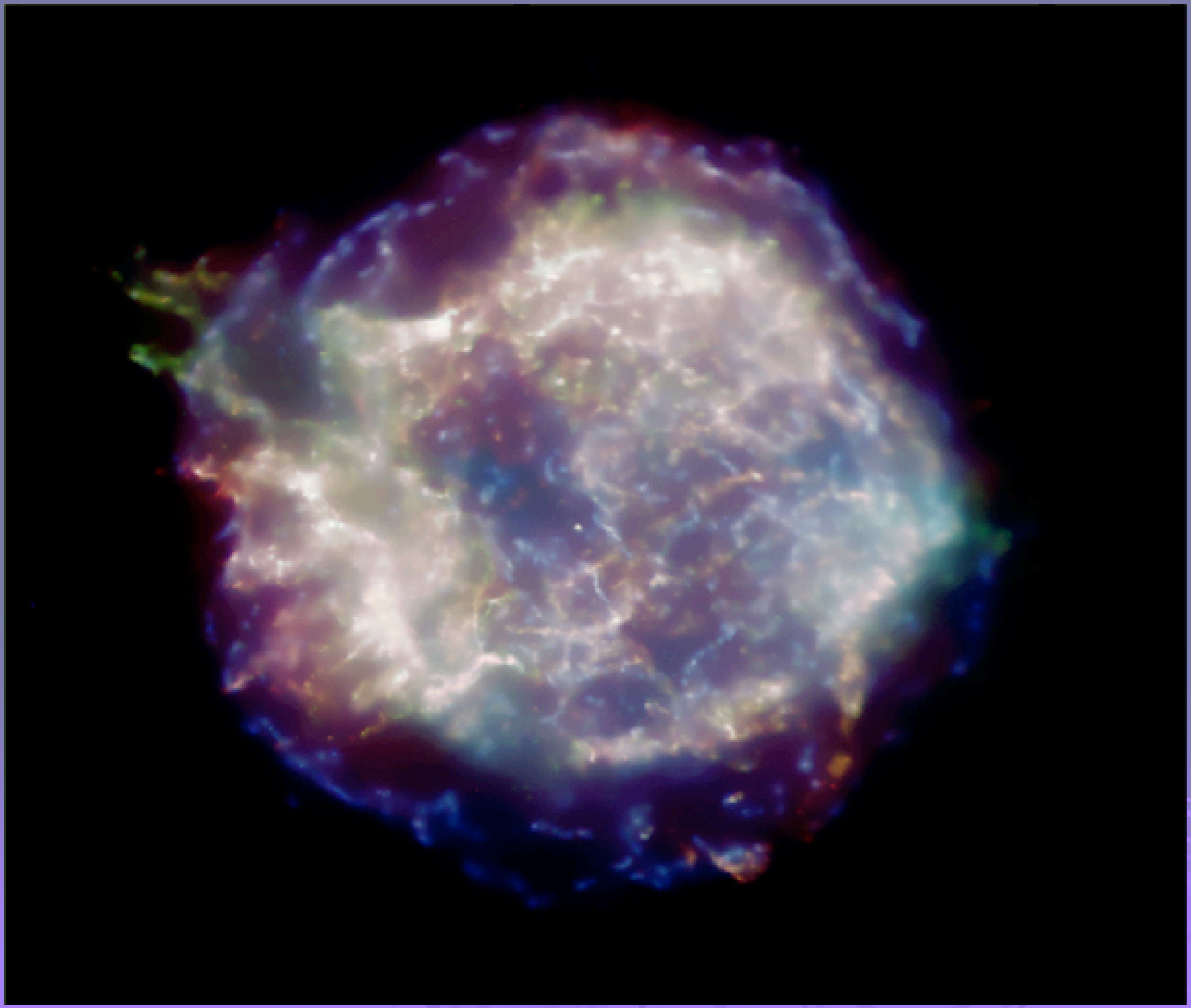
Extragalactic CRs

Galactic Cosmic Rays

- SNR origin?
- Solar modulation reduces flux below 1 GeV/nucleon;
- Instrumental data spread increases near CR knee;
- Non-linear models of acceleration required for SNRs: abundances are not solar;
- [Ellison et al. 1997]

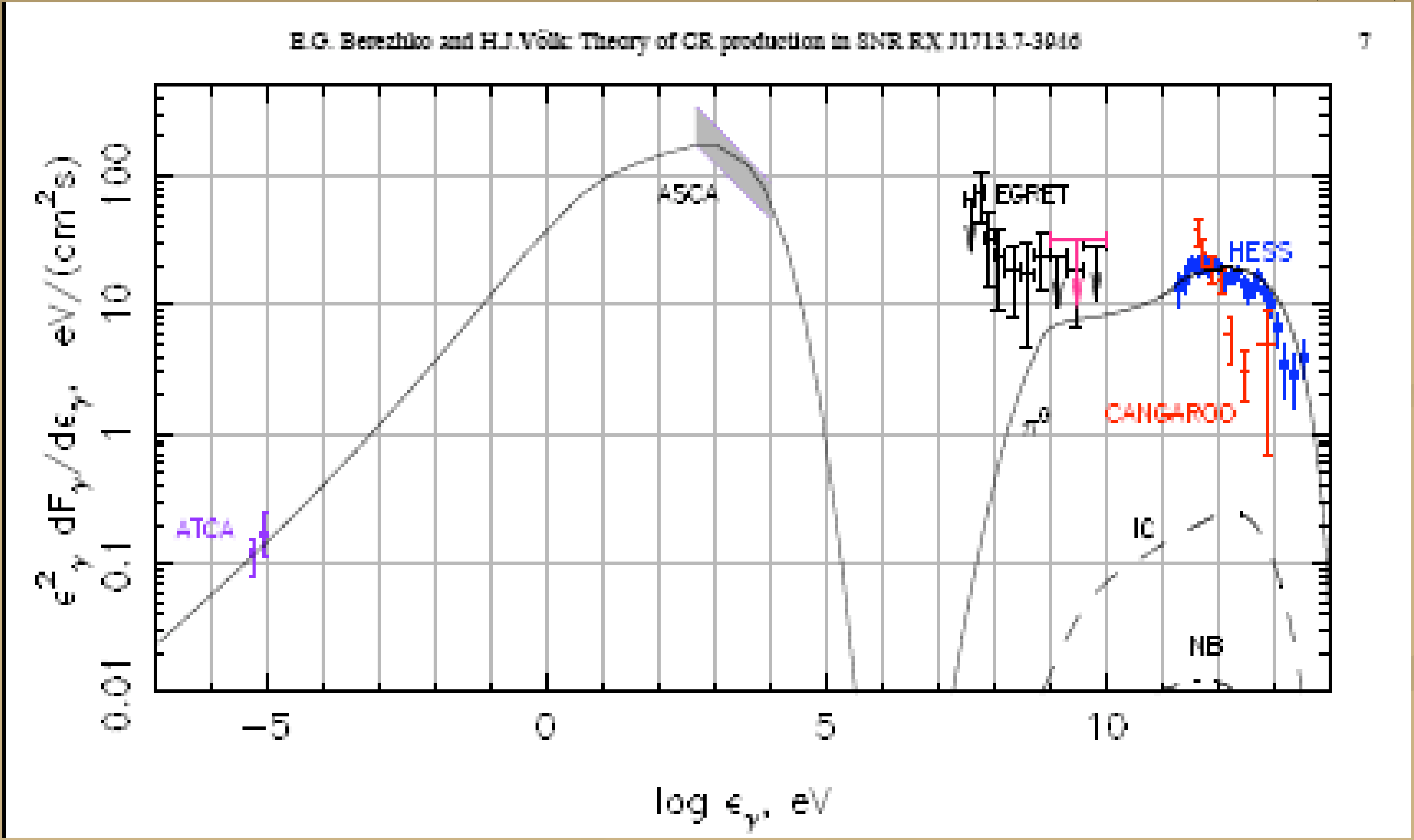


Cassiopeia A Supernova Remnant



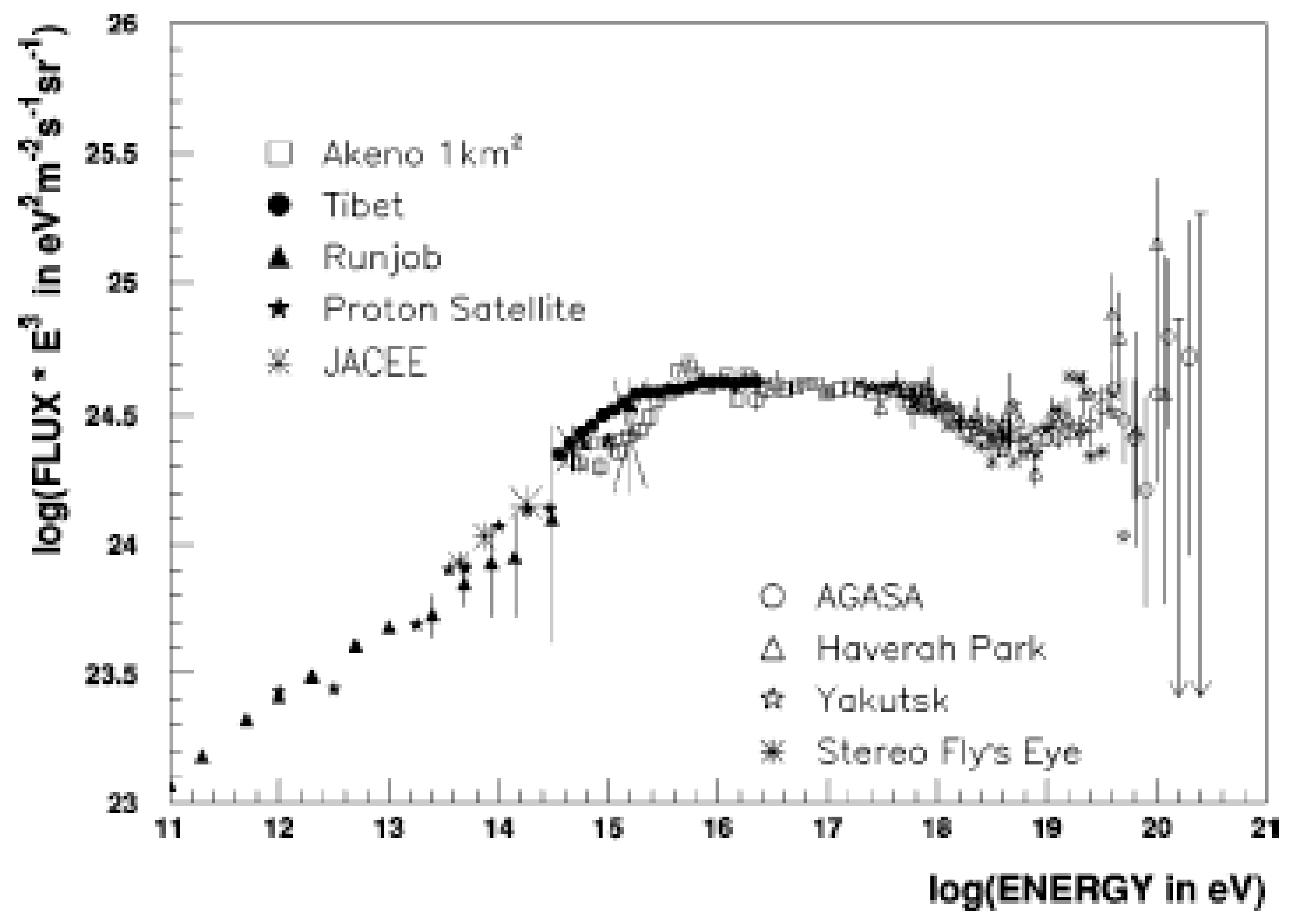
Spectral Modeling of SNR Shell Emission

Berezhko & Voelk (2006)



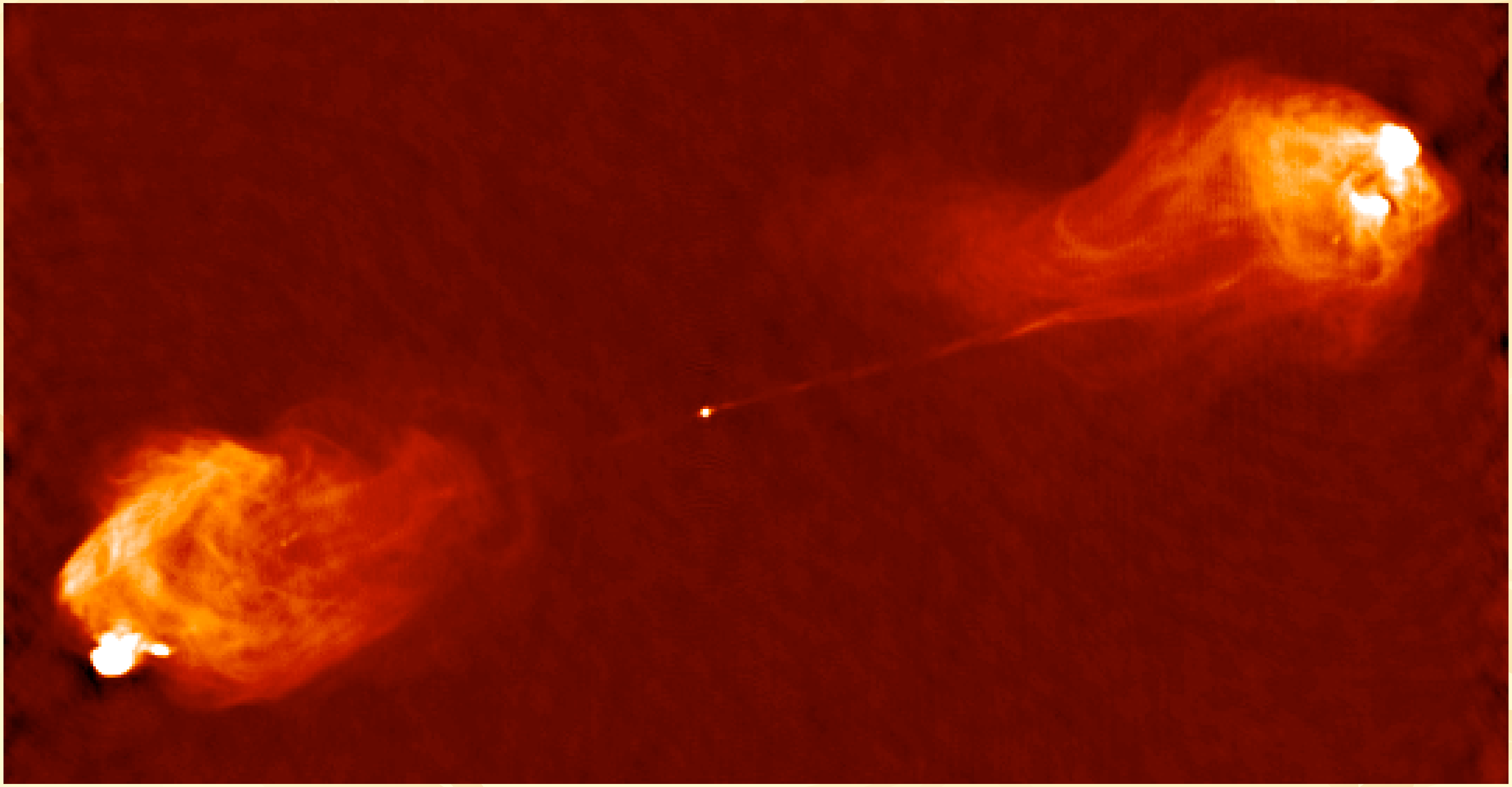
E.G. Berezhko and H.J. Völk: Theory of CR production in SNR RX J1713.7-3946 7

High Energy Cosmic Ray Spectrum



From Nagano & Watson (2000)

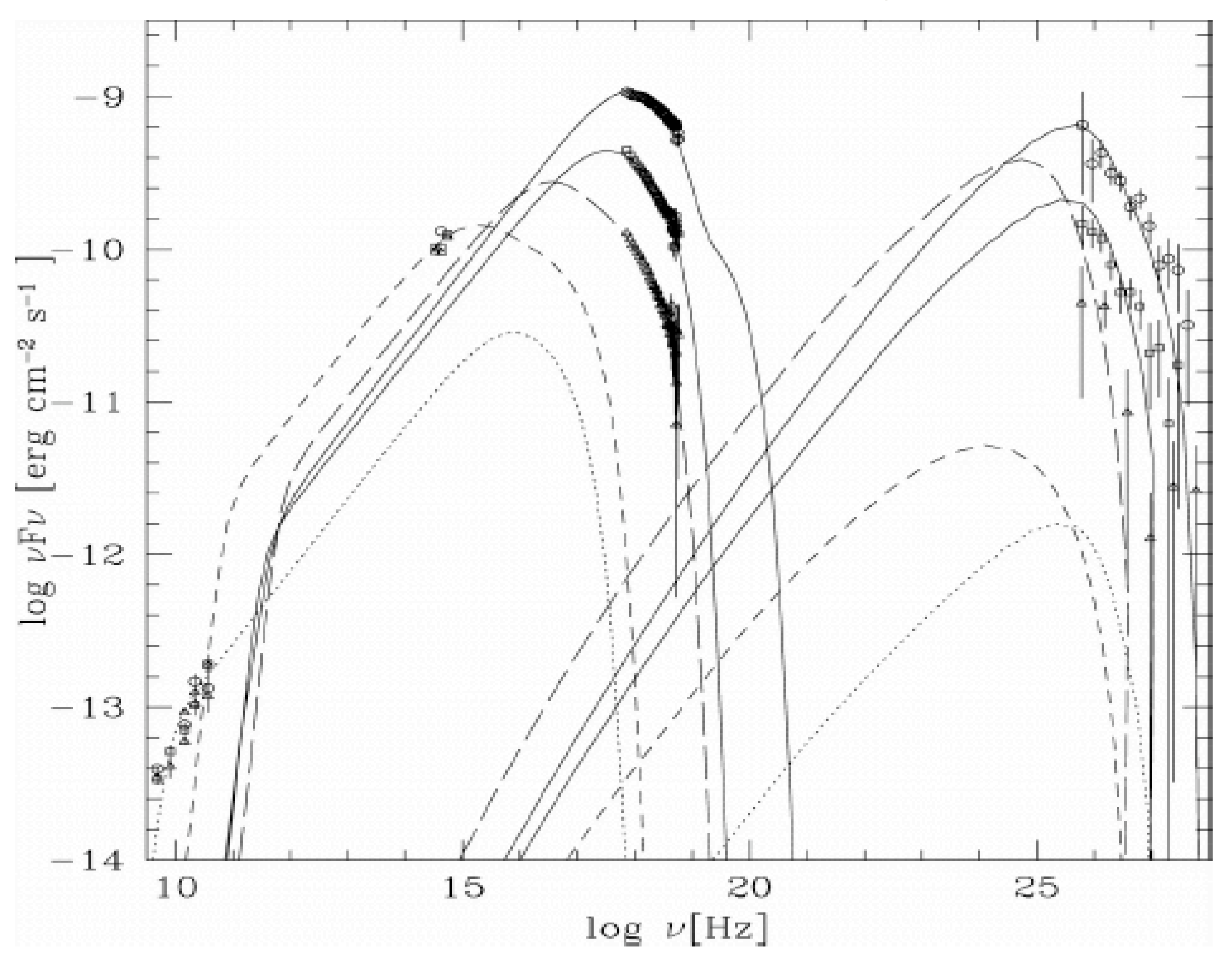
High Energy Cosmic Ray Accelerators: Radio Galaxies like Cygnus A



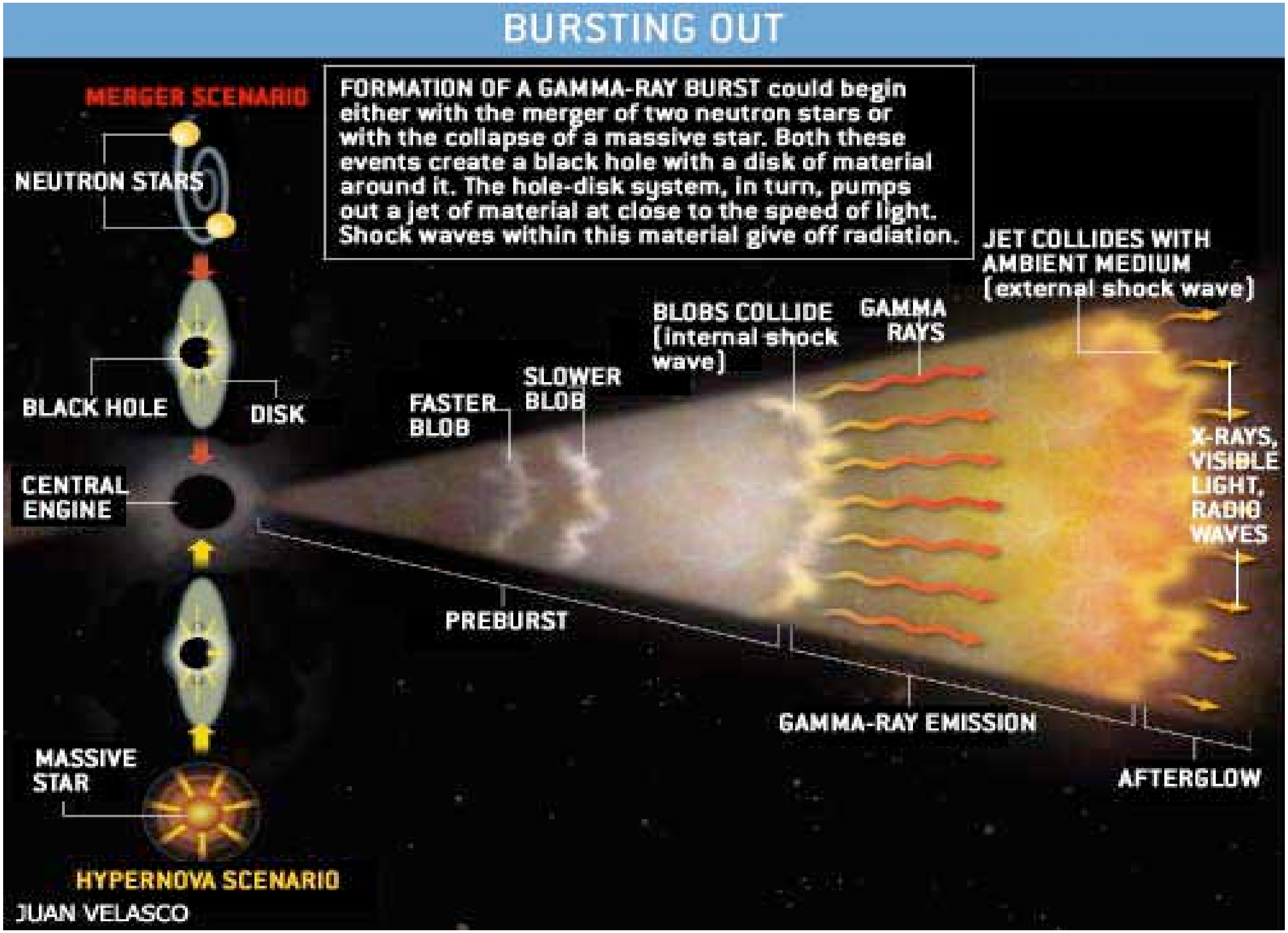
Multi-wavelength Flaring in the Blazar Markarian 421

z=0.031

Blazejowski et al. (2005)



Gamma-Ray Bursts: Relativistic Outflows

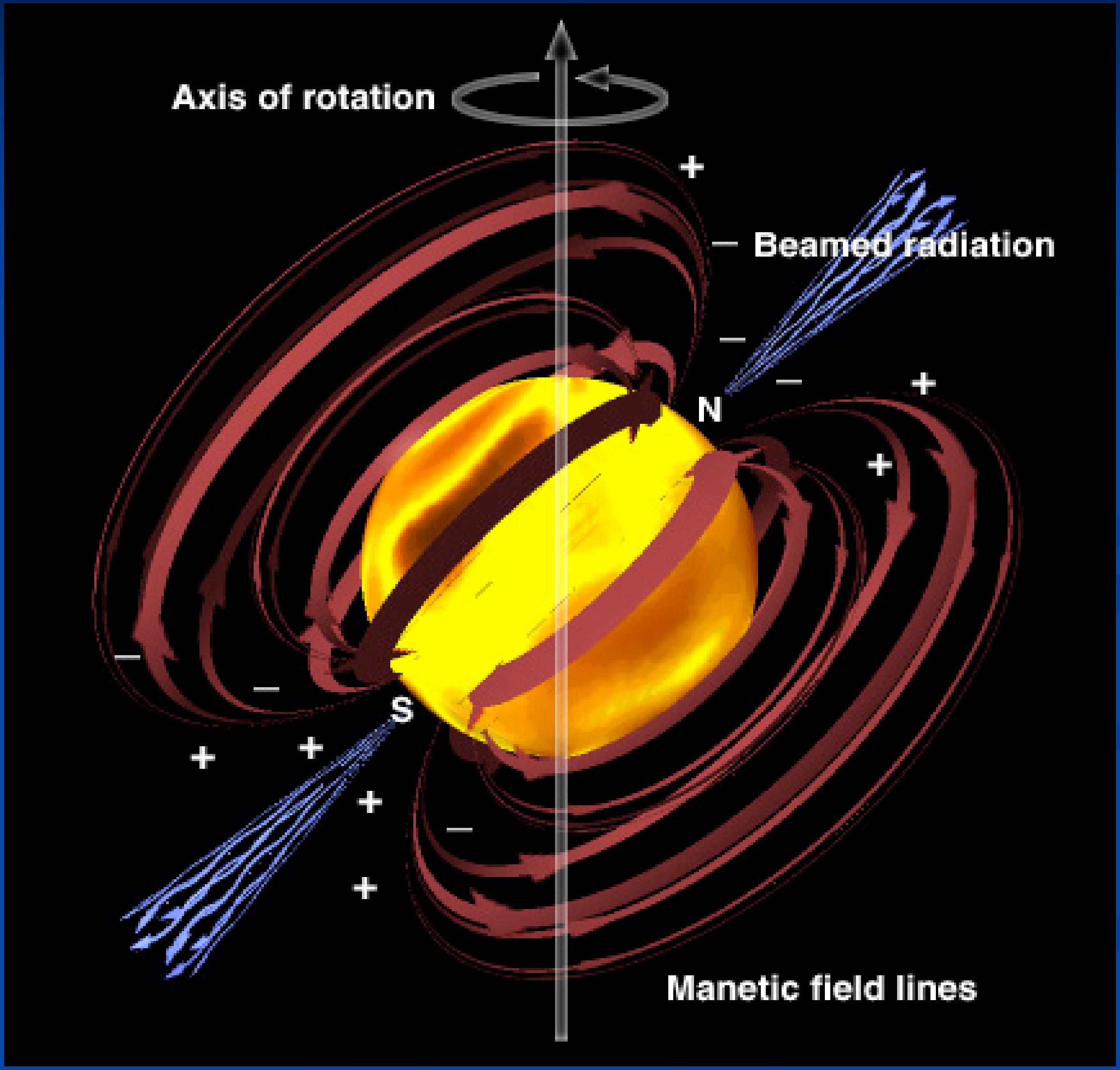


BURSTING OUT

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

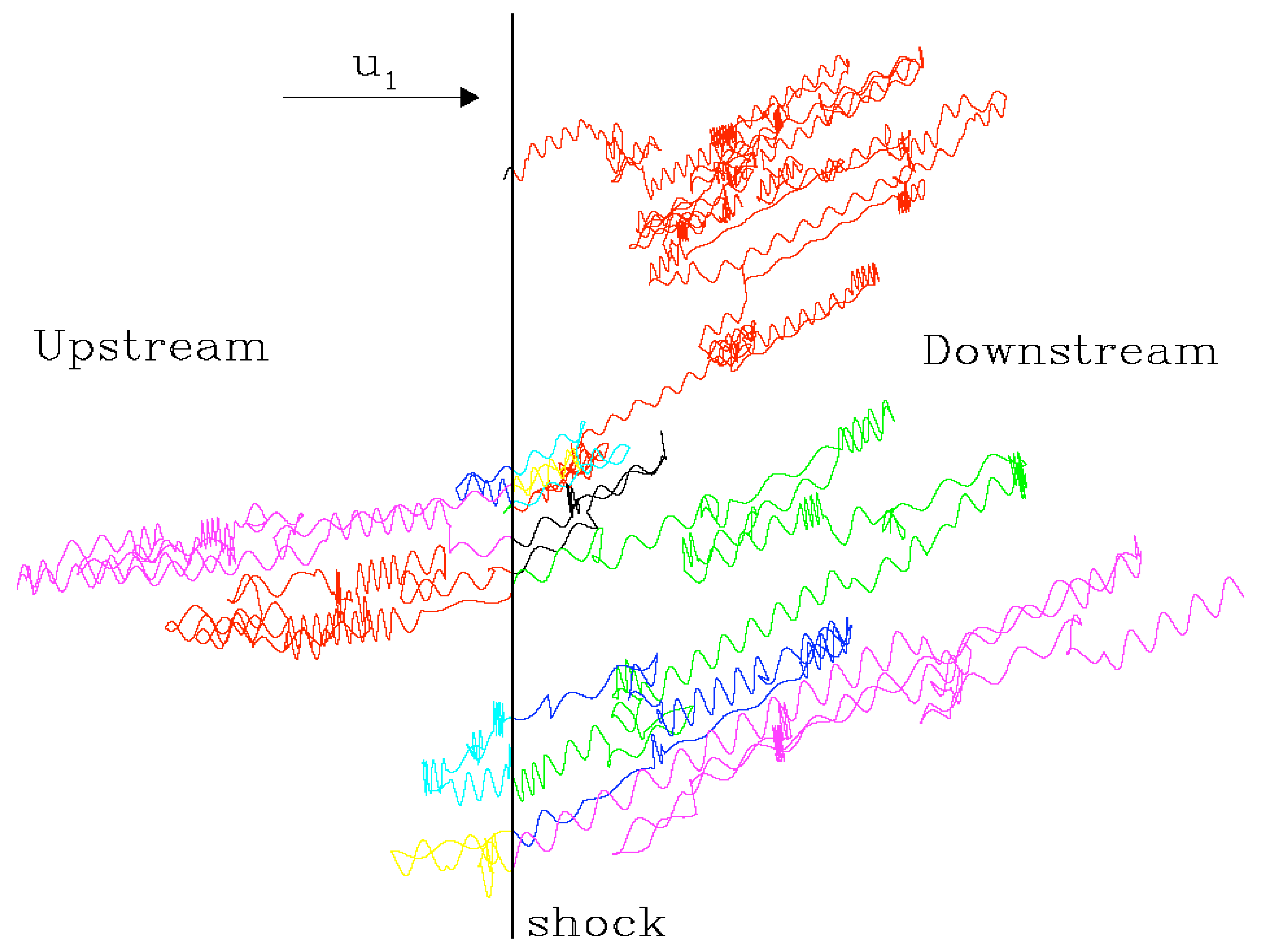
Magnetars - high B Neutron Stars



Good for UHECR production since high B guarantees very large induced E fields + small gyroradii.

Achieving the 10^{20} Energies of UHECRs

- First criterion for viability of bottom-up acceleration models:
- What conditions are required in sources in order to accelerate up to the observed UHECR energies?



Baring & Summerlin (2006)

Acceleration Times + Maximum Energies

- For non-relativistic parallel ($\Theta_{\mathrm{Bn1}} = 0°$) shocks, in the diffusion approximation (= isotropy), the acceleration time is (e.g. Forman, Jokipii & Owens 1974)

$$\boxed{\tau_{acc}^{NR} = \frac{3}{u_1 - u_2} \int_{p_i}^{p} \left(\frac{\kappa_1}{u_1} + \frac{\kappa_2}{u_2} \right) \frac{dp'}{p'} \quad ,}$$

so that

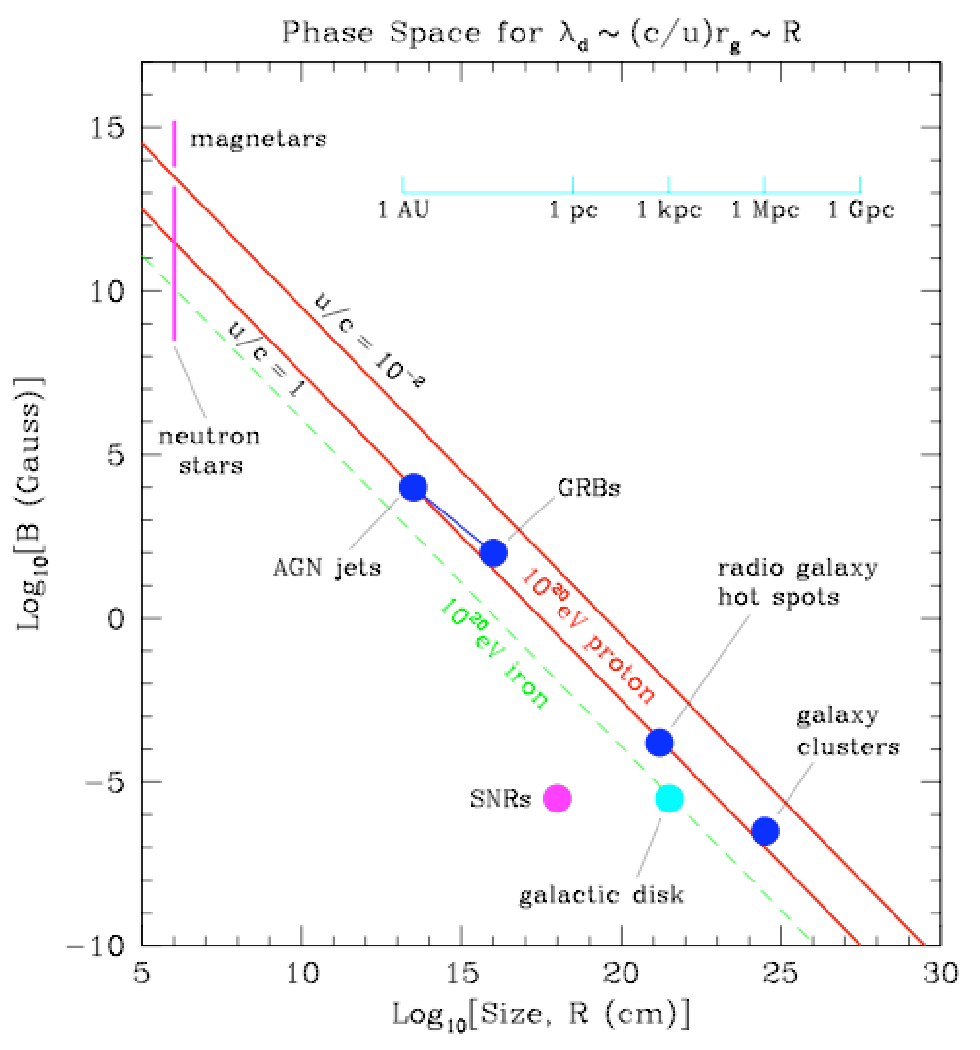
$$\tau_{acc}^{NR} \approx \frac{0.1}{\beta_1^2} \frac{E_{\mathrm{TeV}}}{B_{\mathrm{Gauss}}} \ \mathrm{sec.}$$

- Hence AGNs can accelerate to UHECRs energies in days if $B \sim 100$ Gauss.
- For GRBs, the variability timescale is much shorter, thereby requiring much higher fields, $B \sim 10^4$ Gauss.

Note: kappa is spatial diffusion coefficient

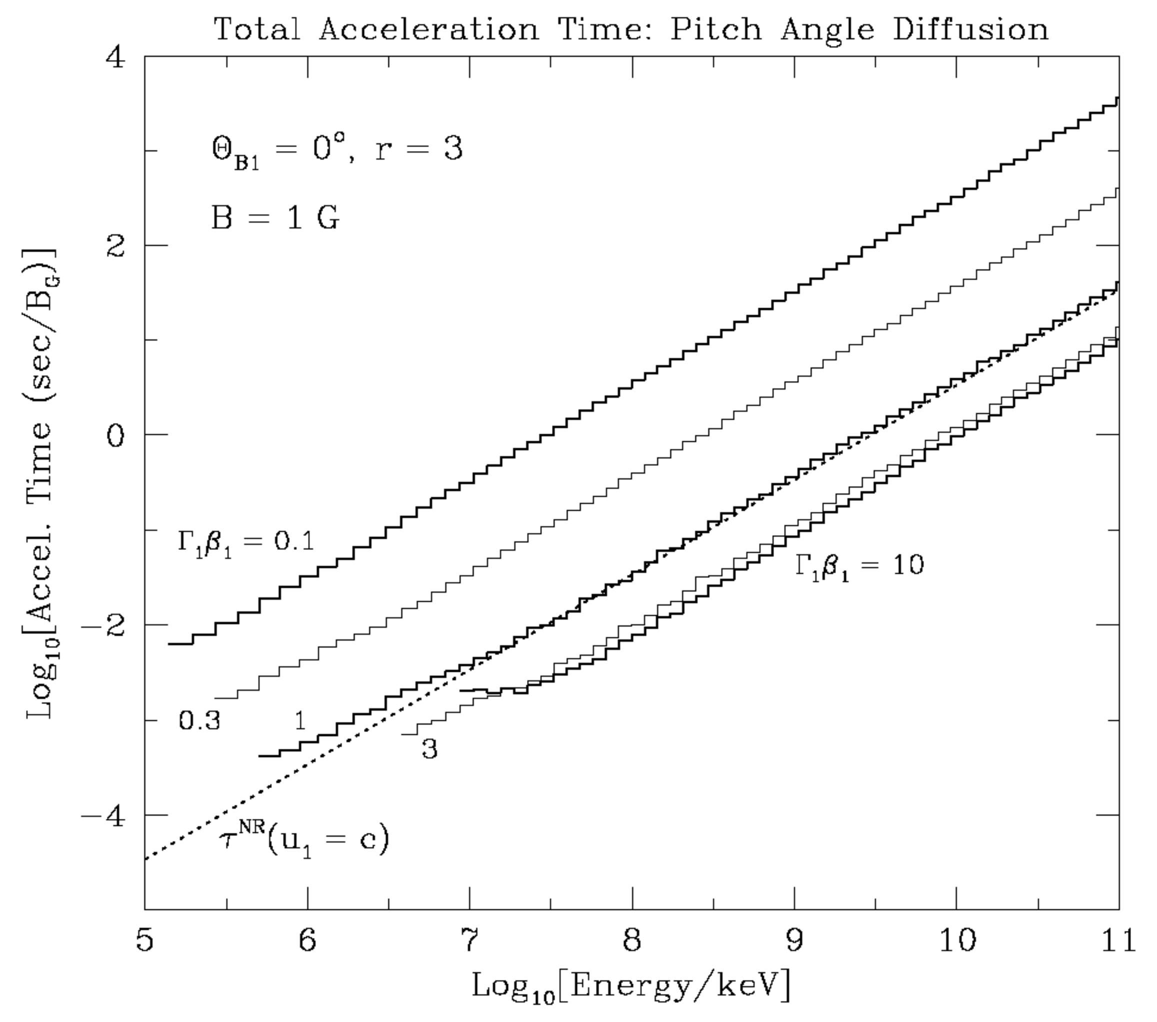
$$\boxed{\kappa = \frac{1}{3} \lambda v}$$

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 ~ c r_g / u);
- Gyroresonant interactions operate;
- AGN jets, GRBs and magnetars are best candidates for UHECR production.

Acceleration Times: Pitch Angle Diffusion

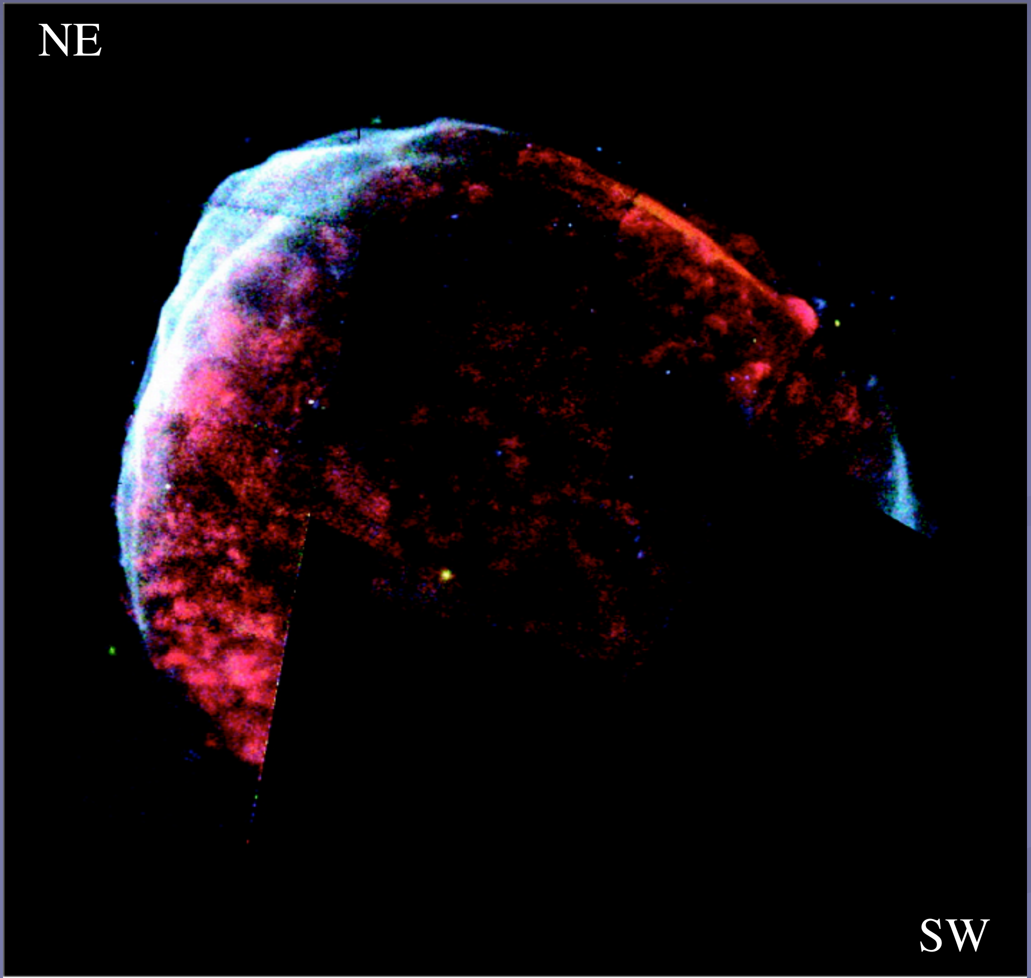


(see Baring 2002)

Inferences of SNR B Fields using CHANDRA

- Spatially-resolved line and continuum spectroscopy by CHANDRA X-ray Observatory: probes **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 non-thermal synchrotron emission details magnetic field contrast across quasi-perpendicular shock.
- Thermal interior (red) and non-thermal shell (blue).

SN1006

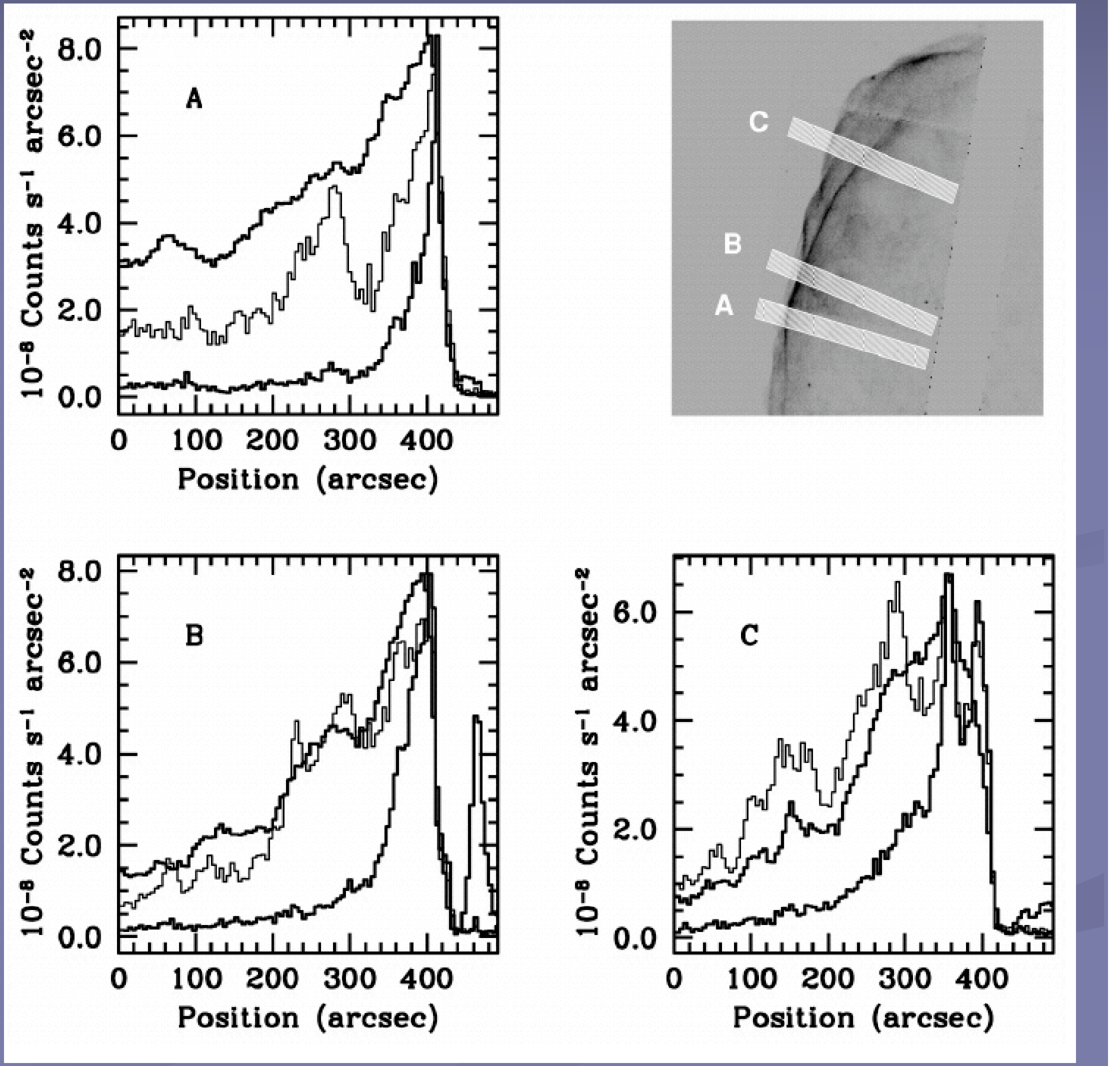


Red: 0.5-0.8 keV;
Green: 0.8-1.2 keV;
Blue: 1.2-2.0 keV.

Spatial Brightness Profiles in SN1006

- 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 $\perp$ 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.

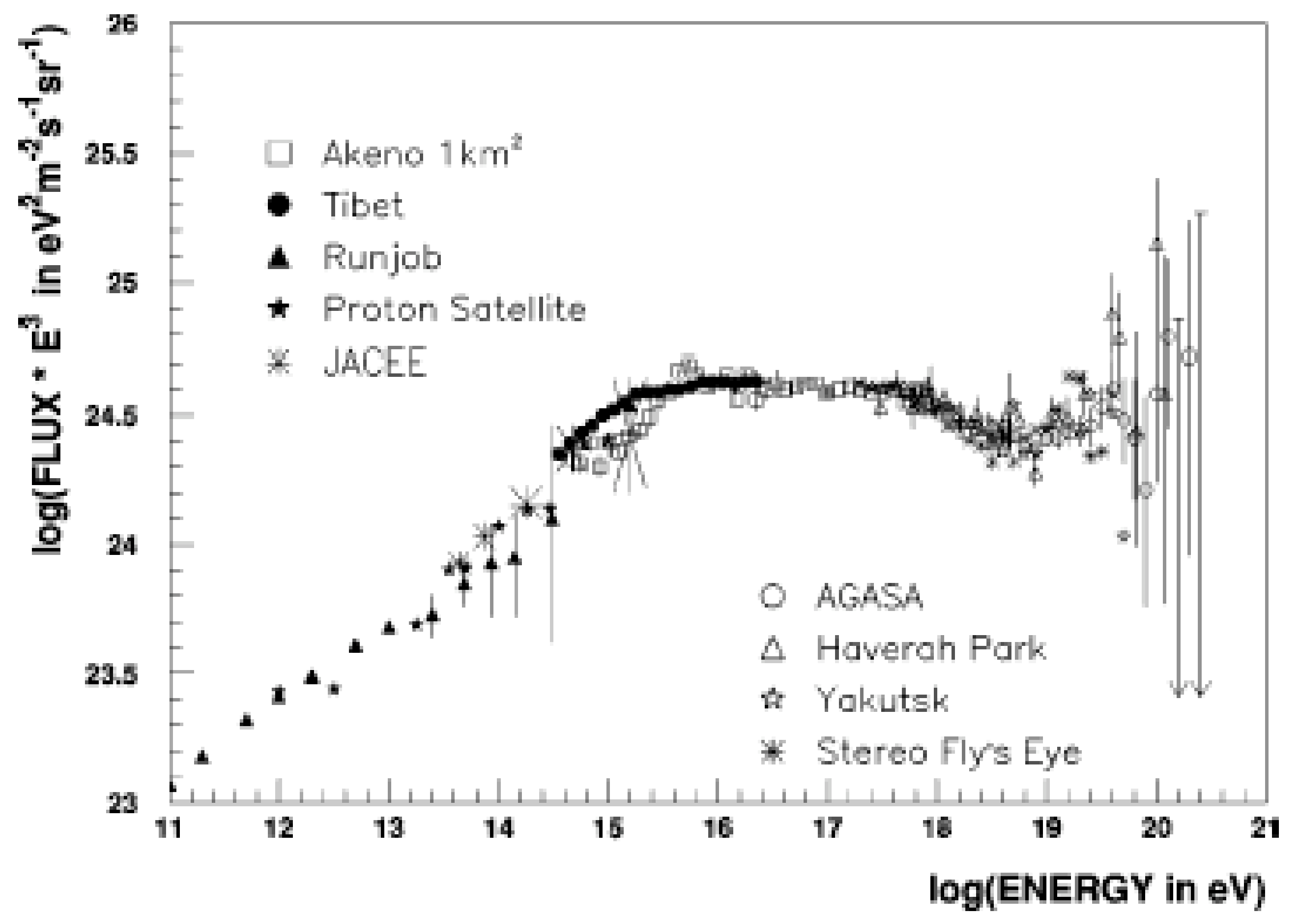
Modeling Field Amplification

- *Lucek & Bell (2000)* proposed that high energy cosmic rays (CRs) in strong shocks could non-linearly amplify B when streaming upstream;
- 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 $(dB/B)^2 \sim M_A\ P_{CR}/\rho u^2$; works for high M_A strong shocks that generate large P_{CR};
- Idea needs simulational vindication. Bell has been working on this, but progress is needed.

Population Constraints: Global Energetics

- Second criterion for viability of bottom-up acceleration models:
- Can the putative sources/sites for acceleration provide UHECRs in sufficient numbers?
- And within the GZK horizon, if needed?

High Energy Cosmic Ray Spectrum



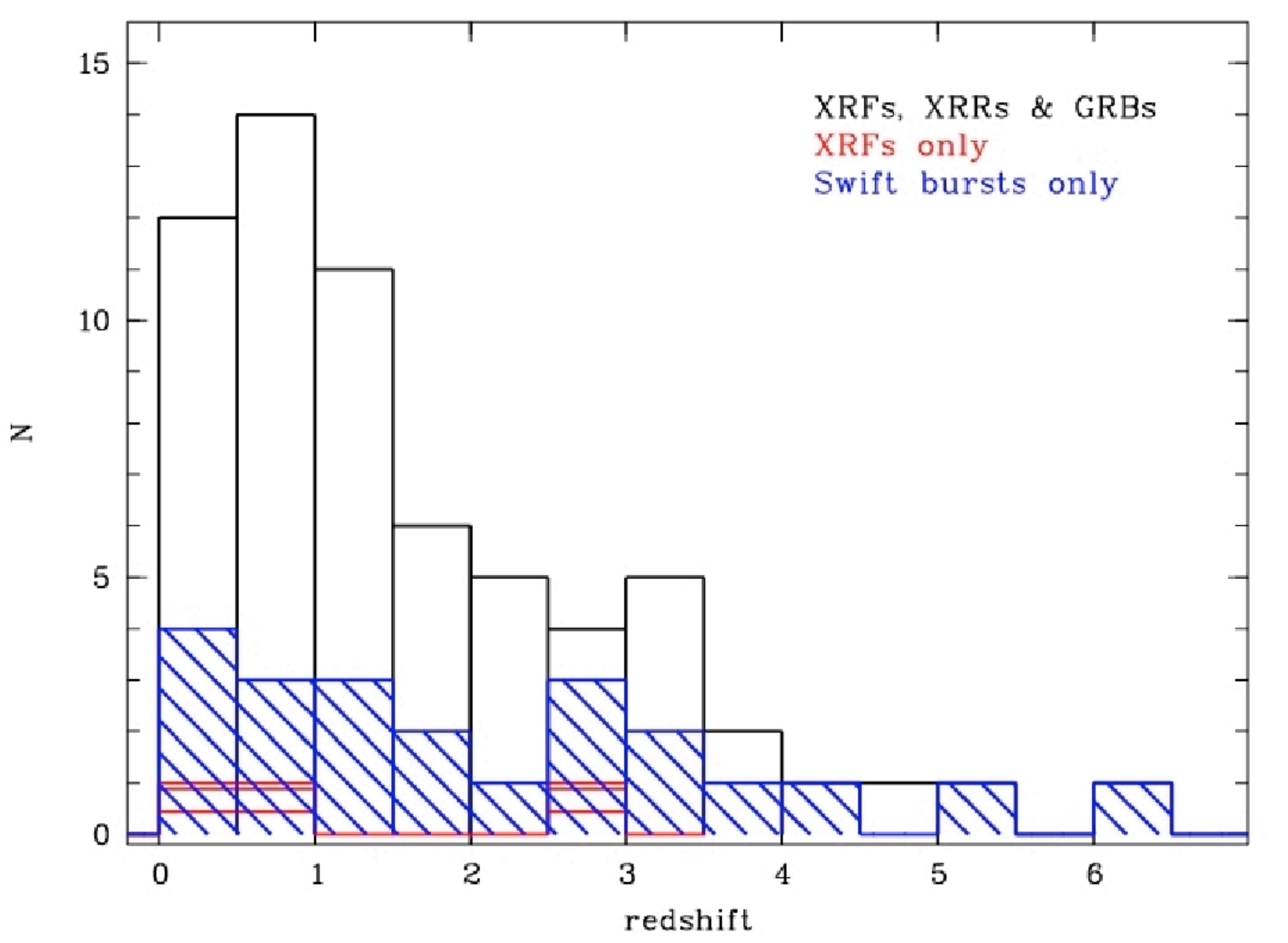
From Nagano & Watson (2000)

Gamma-Ray Bursts and UHECRs

- Possibility of GRBs generating UHECRs was raised by Milgrom & Usov (1995), Waxman (1995) and explored in later papers;
- Need to match the UHECR flux at 10^{20} eV
  - $E^3\, dn/dE \sim 1.2 \times 10^{21}$ eV^3 cm^{-2} s^{-1};
- UHECR energy density is:
  - $U_{CR} = 2 \times 10^{-21}$ ergs cm^{-3};
- GRBs liberate $L_{ph} \sim 10^{51}$ ergs in photons, and perhaps $L_{CR} \sim f_{CR}\, L_{ph}$ in UHE cosmic rays;
- Since $f_{CR}=f(E_{CR})$, both $f<1$ and $f>1$ are possible;
- GRBs occur at rate of 1/galaxy/10^7 years;

Gamma-Ray Burst Redshift Distribution

BeppoSax, HETE, INTEGRAL + Swift October 2005



Gamma-Ray Bursts and UHECRs (ctd.)

- Redshift distribution sets spatial density of GRB hosts; short bursts are fewer, but on average nearer;
- In the GRB volume of ~(10 Gpc)^3 in a Hubble time, the produced cosmic ray energy
  - $U_{CR,GRB} = 4.7 \times 10^{-21} f_{CR}$ ergs cm^{-3};
- => GRBs can populate UHECRs at the required rate if their luminosity in each source is comparable to L_{ph}, i.e. 0.1% of total explosion energy budget;
- Very reasonable constraint: $L_{CR} > L_{ph}$ follows from radiation if $n_{CR} \sim n_e$, and then UHECR budget depends on acceleration spectrum;
- GLAST will probe energetics of GRB population.

Active Galaxies and UHECRs

- AGNs (Seyferts, blazars, radio galaxies, quasars) have $L_{ph} \sim 10^{42} - 10^{47}$ erg/sec; [10^{44} erg/sec now assumed]
- In the GZK volume of ~(30 Mpc)^3 in a Hubble time, the AGN-produced cosmic ray energy density is
  - $U_{CR,AGN} = 1.7 \times 10^{-24} f_{CR}$ ergs cm^{-3} per AGN;
- => need at least 10^3 AGNs per GZK volume $(z=0.01)^3$ for them to populate UHECRs if $L_{CR} \sim 10^{44}$ erg/sec;
- N.B. flaring duty cycle reduces f_{CR};
- Less than Hubble time available? Higher z quasars generally have higher L_{ph};
- Energetic AGN populations (blazars and quasars), their number densities and duty cycles will be surveyed by GLAST after launch, late 2007.

Spectral Issues for UHECR Generation

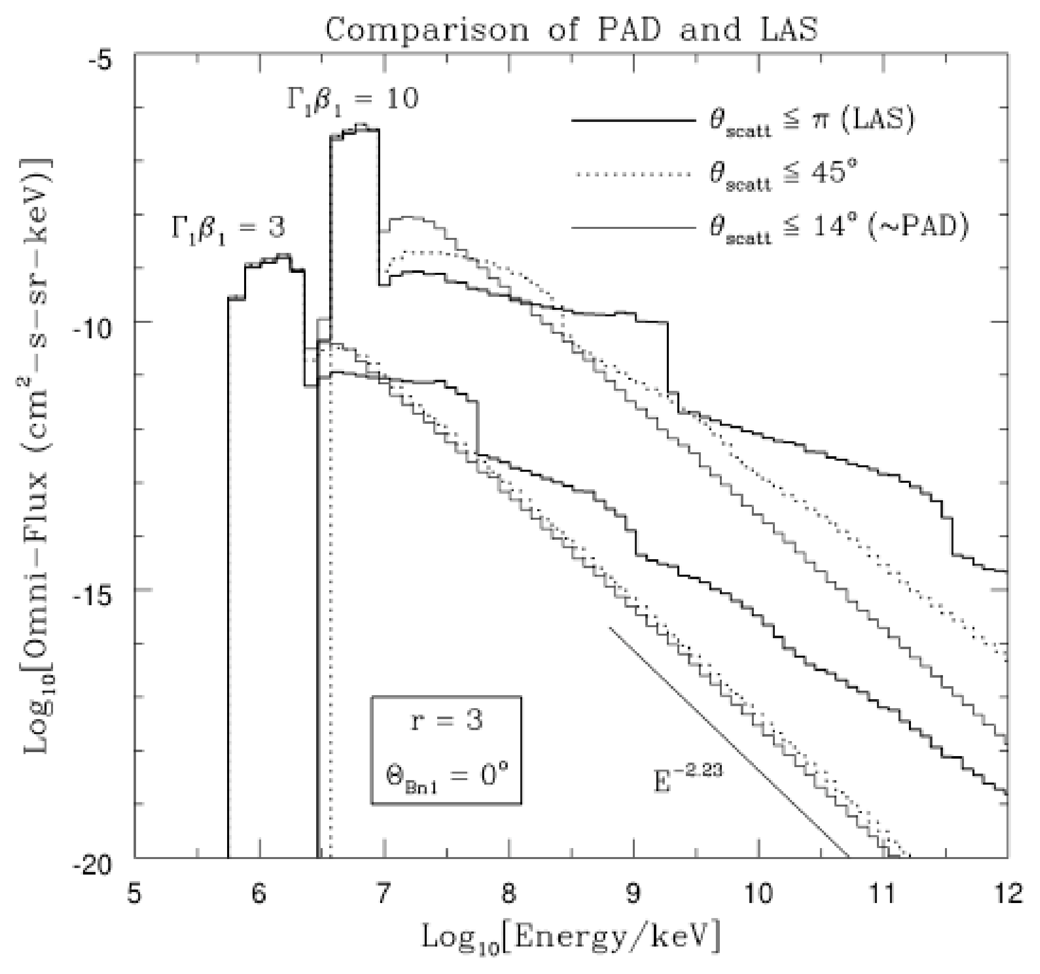
- Third criterion for viability of bottom-up acceleration models:
- Can shock acceleration in putative sources generate particle distributions commensurate with the UHECR spectrum, *and* in concord with radiation signatures for the sources?

Distinguishing Properties of Relativistic Shocks

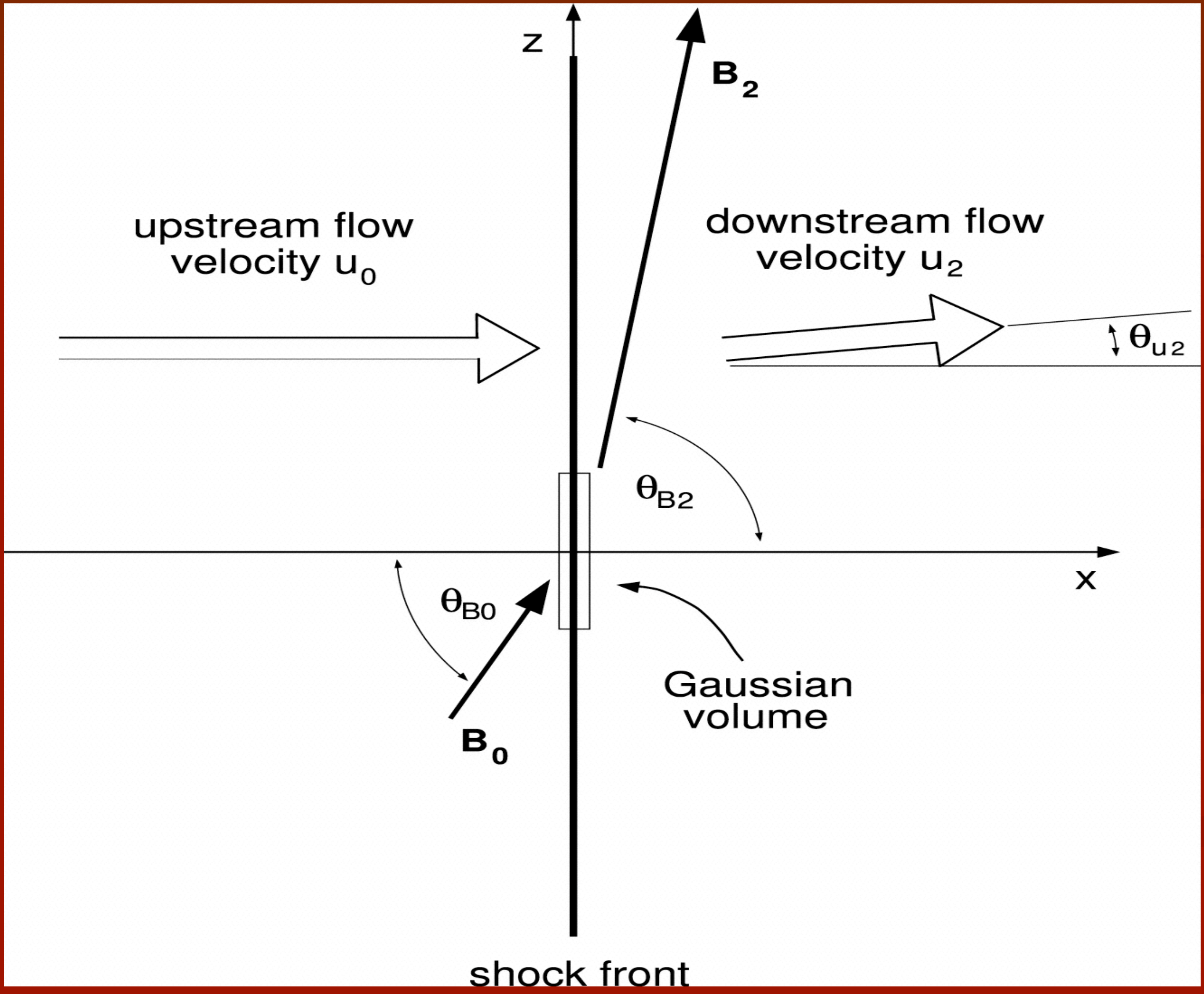
- For small angle scattering, ultra-relativistic, parallel shocks have a power-law index of 2.23 (Kirk et al. 2000);
- Result obtained from solution of diffusion/convection equation and also Monte Carlo simulations (Bednarz & Ostrowski 1996; Baring 1999; Ellison & Double 2004);
- Power-law index is **not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

Relativistic Shocks: Spectral Dependence on Scattering

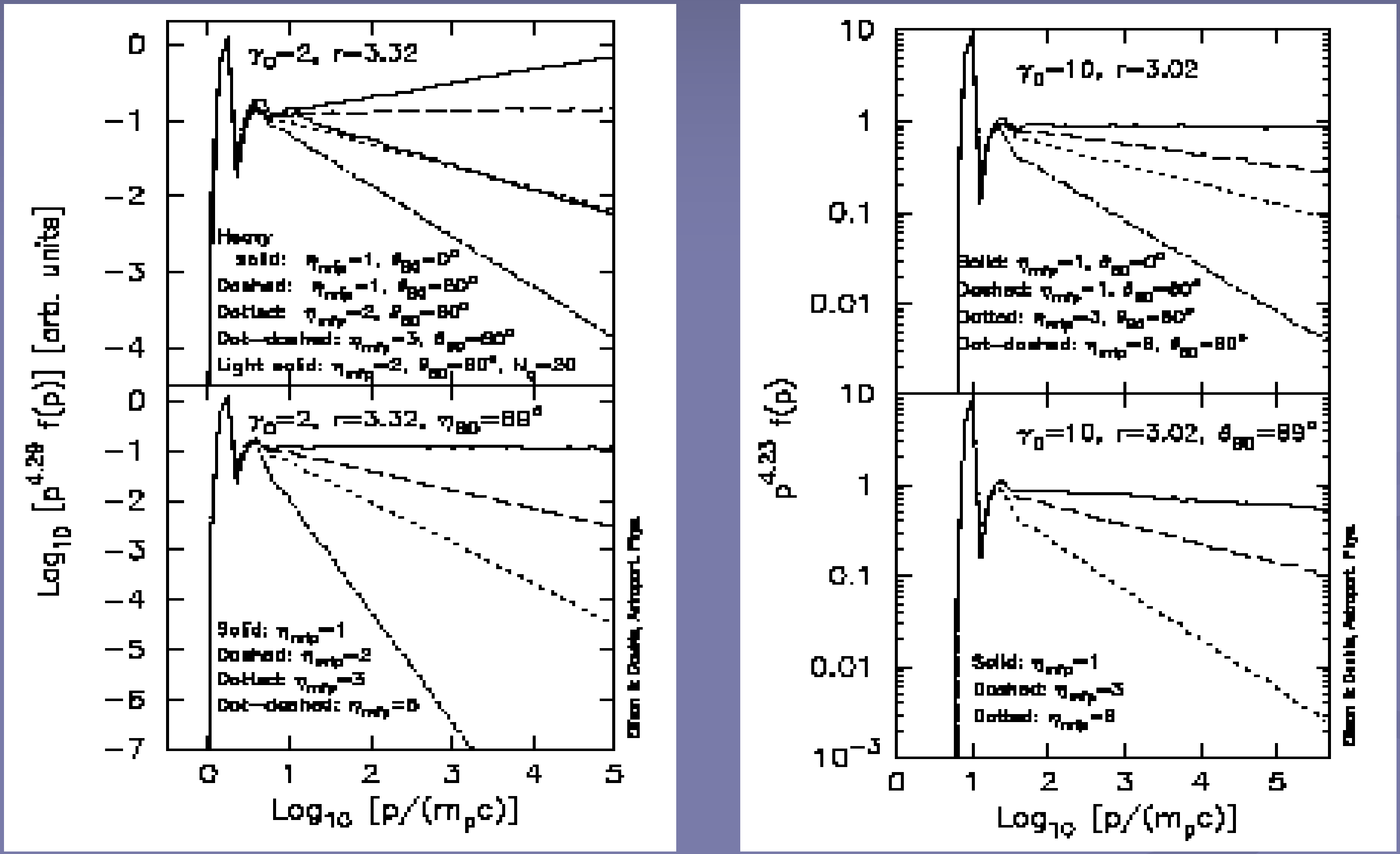
- Deviations from ``canonical'' index of 2.23 (Bednarz & Ostrowski 1998; Kirk et al. 2000; Baring 1999) occur for scattering angles outside Lorentz cone;
- Large angle scattering yields kinematically structured distributions;
- (e.g., Baring 2005)



Oblique Shock Geometry



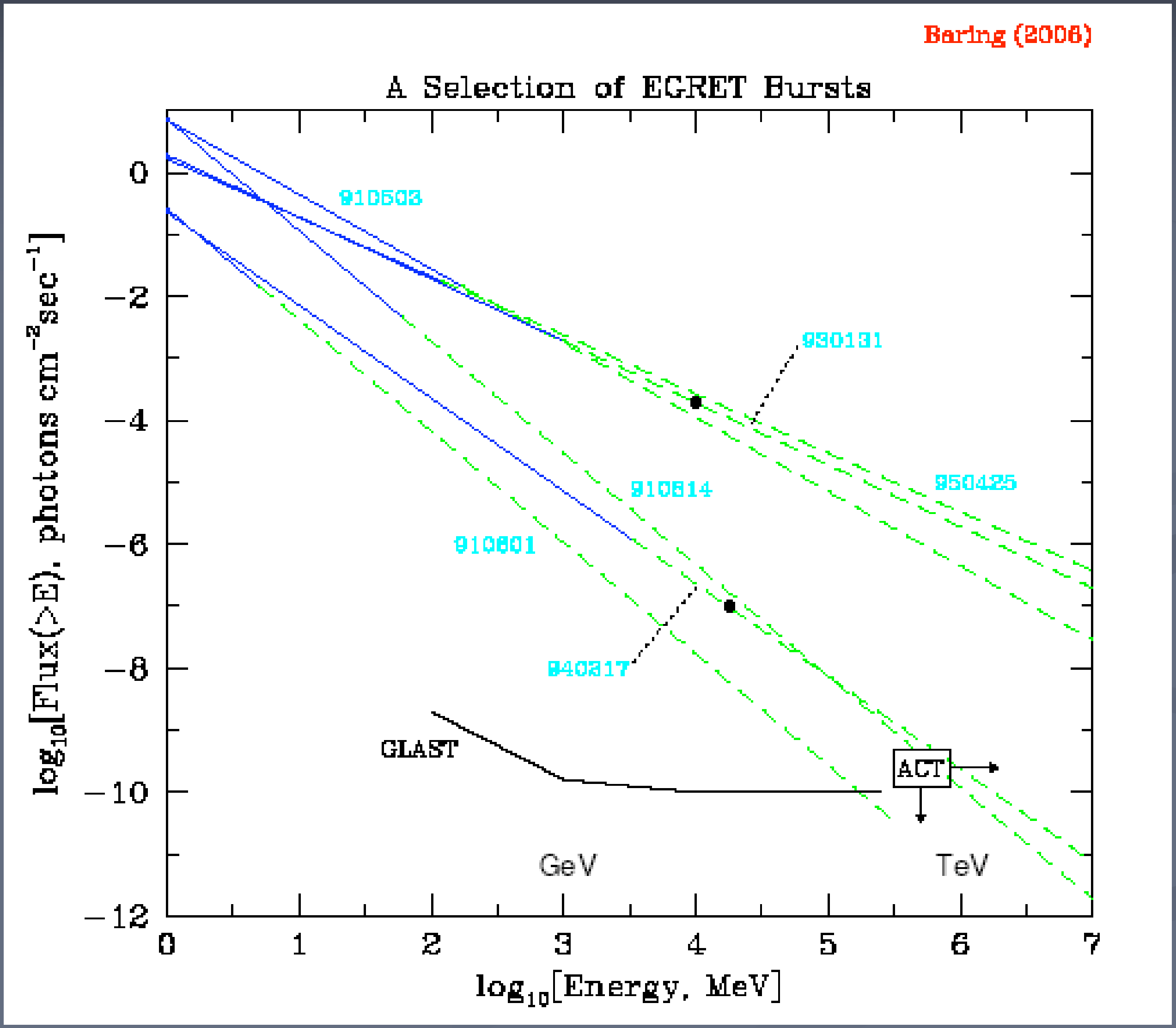
Relativistic Shocks: Spectral Dependence on Field Obliquity and Diffusion



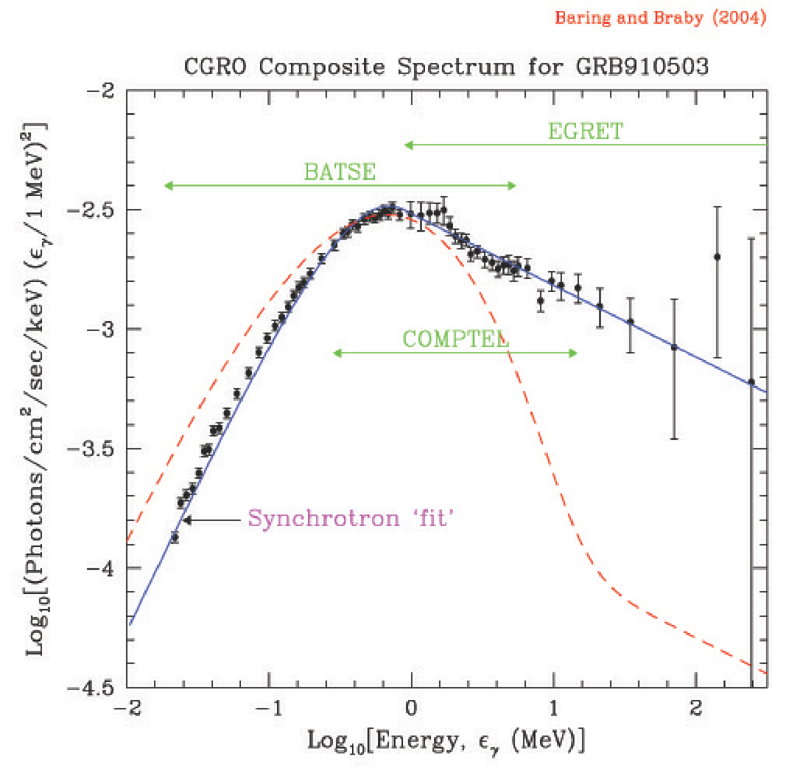
Ellison &
Double
(2004)

- 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).

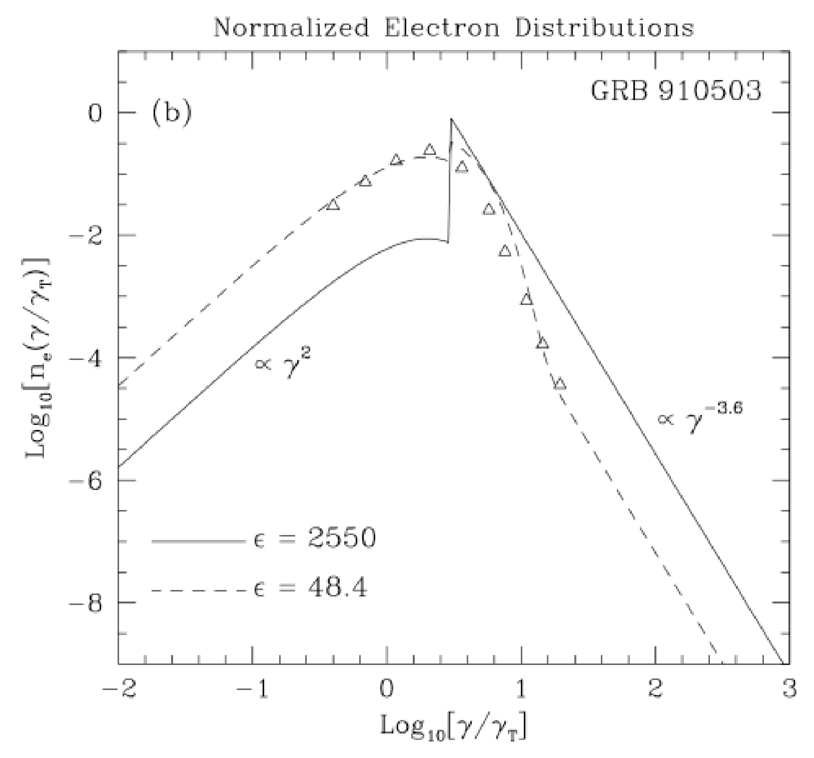
High Energy Emission in EGRET Bursts



GRB Prompt Emission Continuum Fitting



Photon spectrum

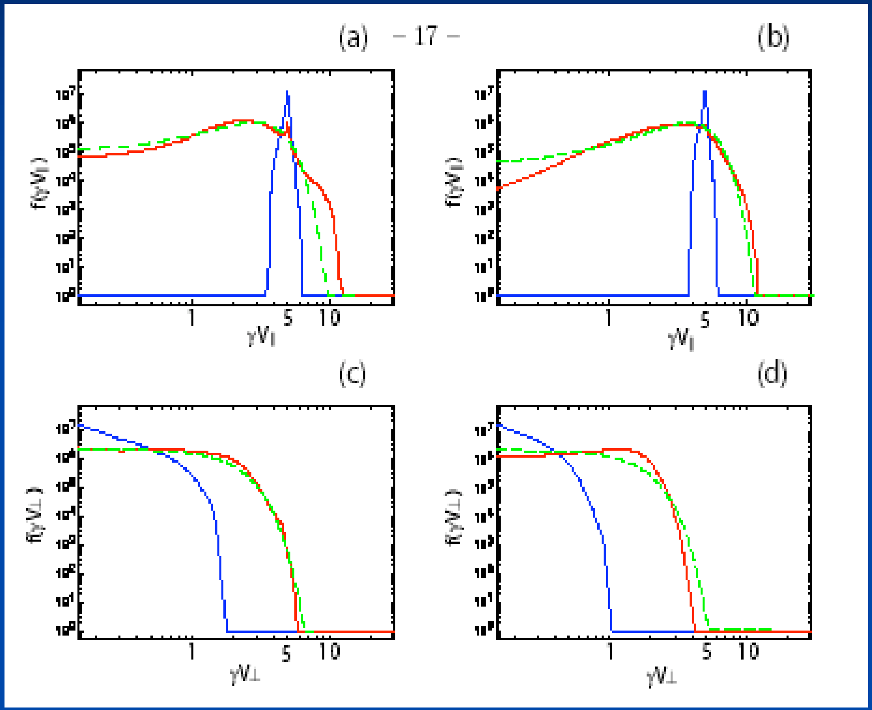


Electron Distribution

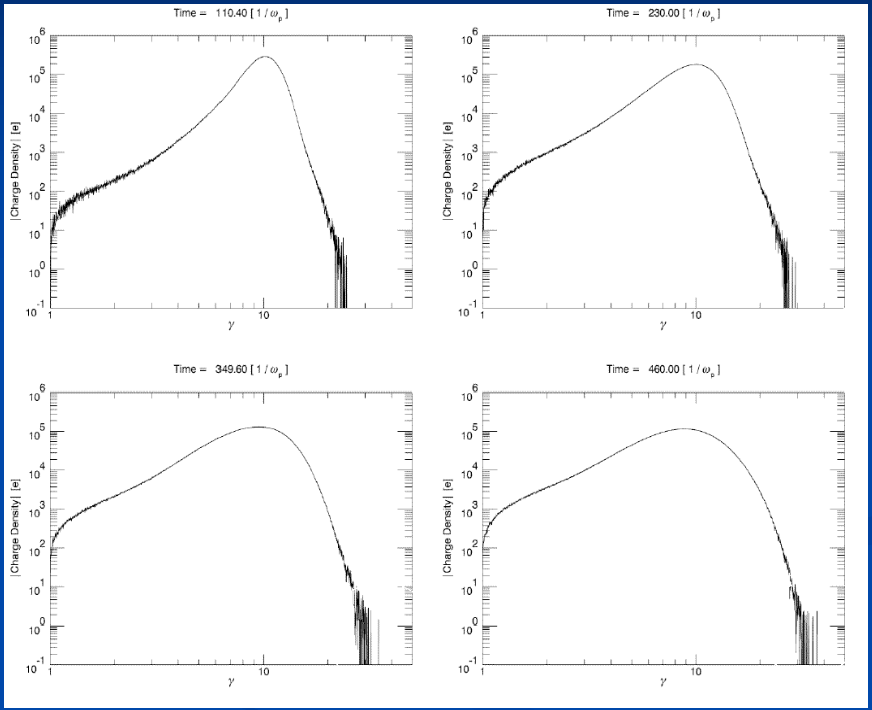
- Synchrotron radiation (preferred paradigm) fits most burst spectra - index below 100 keV is key (Preece et al. 1998 "line of death") issue;
- But, underlying electron distribution is predominantly non-thermal, i.e. unlike a variety of shock acceleration predictions (e.g. PIC codes, hybrid codes, Monte 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.*

Shock Acceleration, Sources & CRs: What do we know?

- *Maximum Energy*: the key parameter is the magnetic field strength in the (diffusive) shock environs -
  - Active galaxies (jets and radio lobes), gamma-ray bursts and magnetars are best candidates;
- *Global Energetics*: population supply for UHECRs OK for gamma-ray bursts, a little harder for AGNs -
  - Source space density and CR production efficiency relative to neutrinos and radiation are key unknowns;
- *Spectral Issues*: relativistic shocks in GRBs and AGN can only generate $\sim E^{-3}$ CR distribution if either quasi-parallel or possessing strong field turbulence -
  - GRB and AGN non-thermal radiation are consistent with $\sim E^{-3}$ electron (and therefore CR?) distributions.

Shock Acceleration, Sources & CRs: Where are we going next?

- Need to see evidence of ions in discrete sources, either SNRs, AGNs, GRBs or all;
- Need to fully understand relationship between electron acceleration (probed by radiation) and ion energization (i.e. injection);
- Need to understand character of relativistic shocks in more detail (e.g. do non-linear effects operate?);
- Need to ascertain under what conditions magnetic field amplification occurs;
- GLAST and TeV-band Cherenkov telescopes will provide huge advances on individual sources;
- Auger and other CR arrays will propel the UHECR database, while ICECUBE, etc probe neutrinos.

Shocks in the Heliosphere: Testing Grounds for Acceleration Theory

- *Planetary bow shocks*: usually strong, with nonlinear acceleration being important.
- *Interplanetary travelling shocks*: usually low Mach number, with a big contribution from interstellar pick-up ions;
- *Solar wind termination shock*: site of anomalous cosmic ray generation [Voyager I was there, 2005?].