Diffusive Shock Acceleration in Astrophysics

Athina Meli

Physics Department, National University of Athens

RICAP'07, 20-22 June, Rome

Cosmic Rays Observations

- *Cosmic Rays* are subatomic particles and radiation of *extra-terrestrial* origin.
- First discovered in 1912 by German scientist *Victor Hess*, measuring radiation levels aboard a balloon at up to 17,500 feet (*without oxygen!*)
- Hess found increased radiation levels at higher altitudes: named them *Cosmic Radiation*

Cosmic Ray Spectrum – Key features…

10 decades of energy – 30 decades of flux !

$\sim E^{-2.7}$ 'knee' → 3×10^{15} eV

$\sim E^{-3.1}$ above the knee → $\sim 10^{16}$ eV

chemical transition 3×10^{18} eV

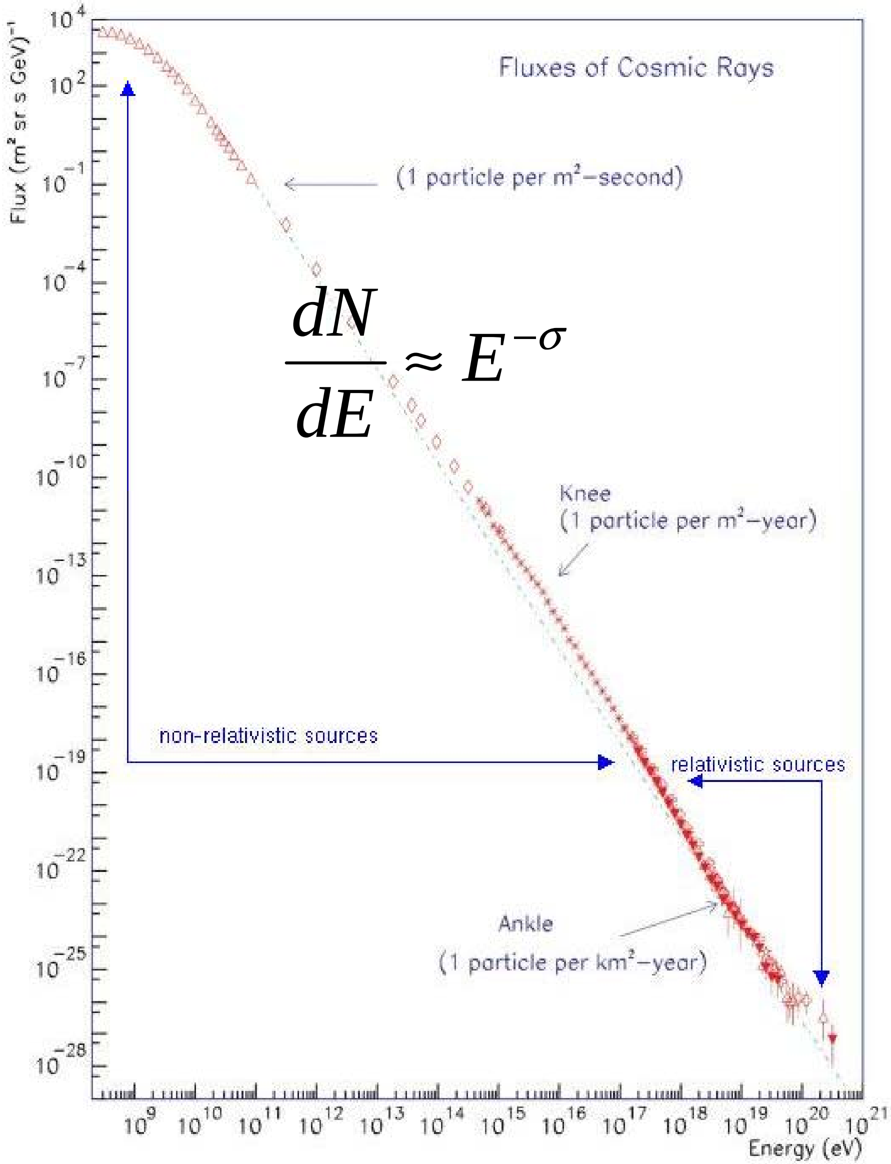
$\sim E^{-2.7}$ 'ankle' → $\sim 10^{18}$ eV – 10^{20} eV

Transitions: 1) nature of CR accelerators,

2) propagation

$>6 \times 10^{19}$ uncertainty (low flux, event st.)

GZK paradox….



$$\frac{dN}{dE} \approx E^{-\sigma}$$

Sources of cosmic ray acceleration

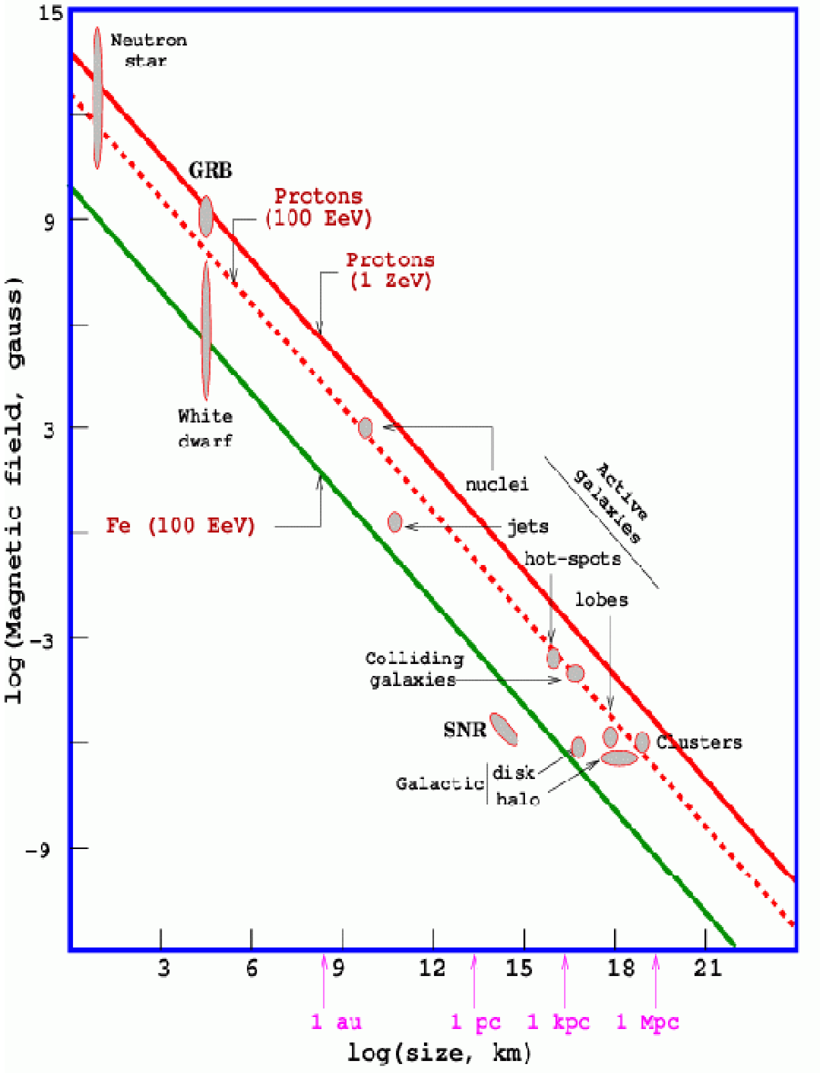
Requirements:

Magnetic field dimensions sufficient to contain the accelerating particles.

Strong fields with large-scale structure (astrophysical shocks)

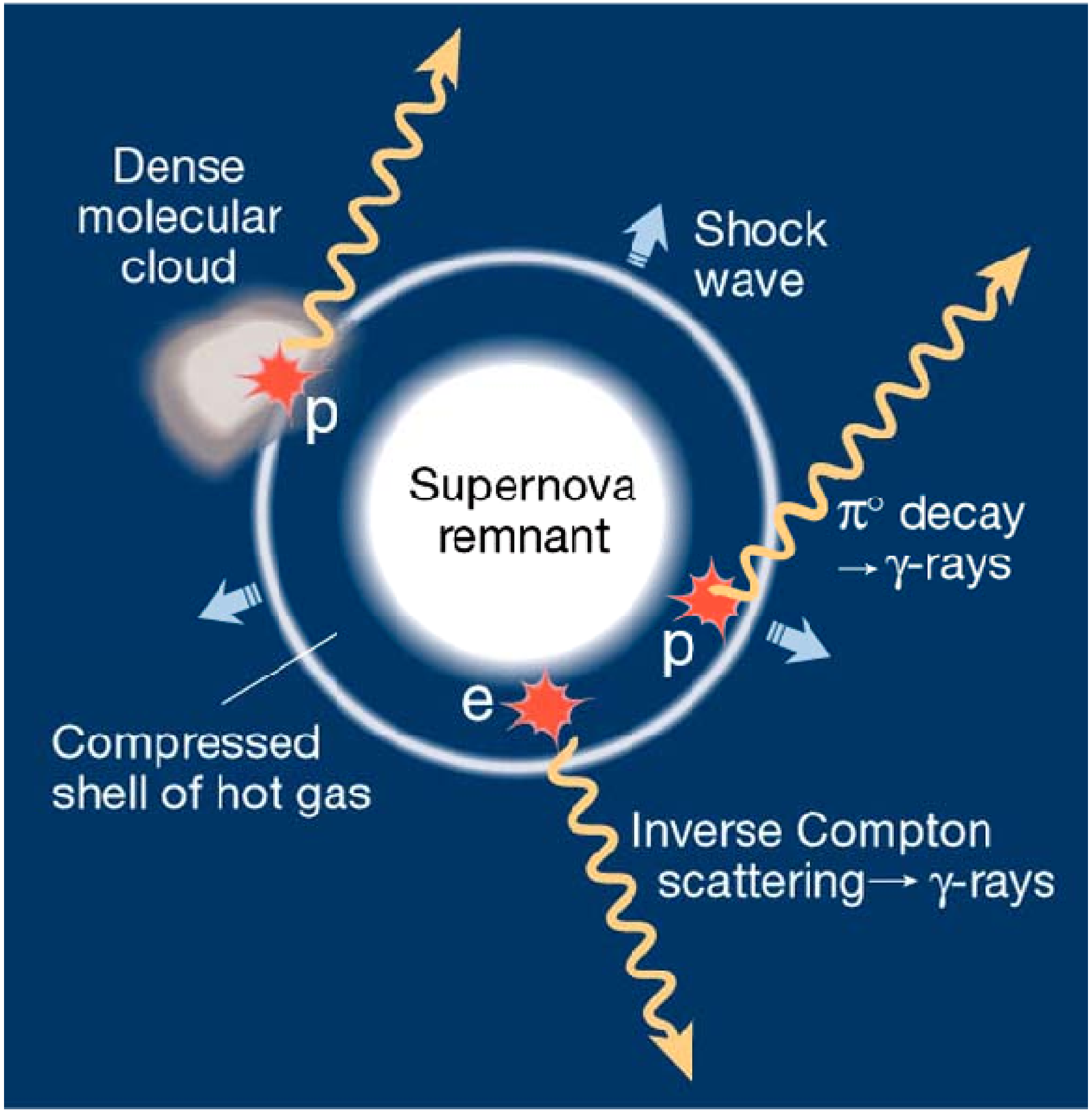
$$E_{max} \approx \beta Z (B/1\mu G)(R/1\ kpc)$$

ISM-SN: (Lagage&Cesarsky, 1983)
Wind-SN: (Biermann, 1993)
AGN radio-lobes: (Rachen&Biermann,1993)
AGN Jets or cocoon: (Norman et al.,1995)
GRB: (Meszaros&Rees, 1992,1994)
Neutron stars: (Bednarek&Protheroe,2002)
Pulsar wind shock: (Berezhko, 1994)

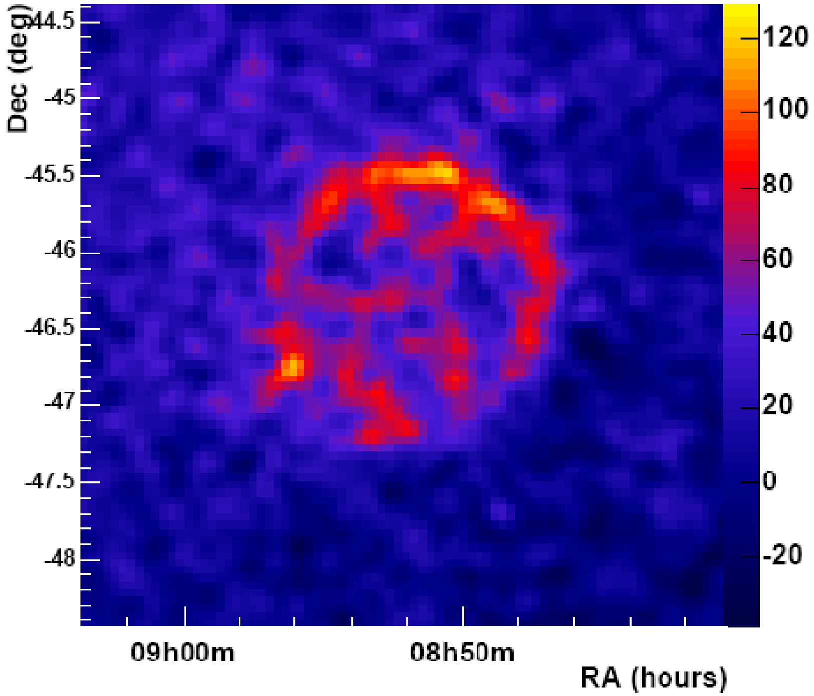


Hillas, 1984

1. Non-relativistic shocks in Supernovae (ISM-SN & WIND-SN models)



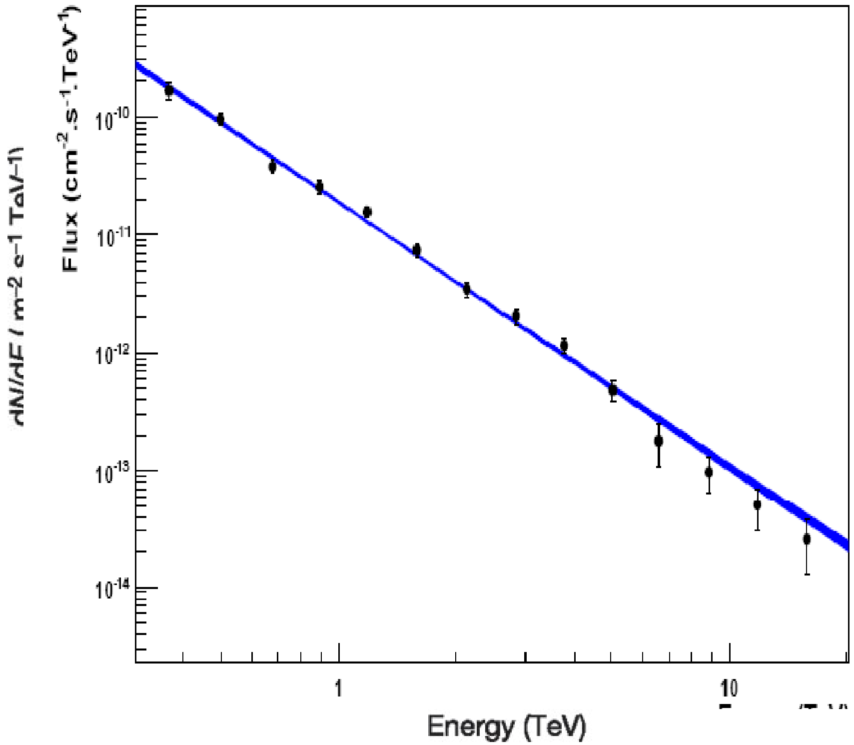
Acceleration observed *in situ*...



Gamma-ray image of the SNR RX J1713.7-3946 (G347).
Linear color scale is in units of counts.

The superimposed (linearly spaced) black contour lines show the X-ray surface brightness as seen by ASCA in the 1–3 keV range.

HESS collaboration: Aharonian et al
Nature 2004, 432, 75 – 77



Relativistic Shocks: Shock speed approaches *c* ($V_{sk} = u_0 \sim c$)

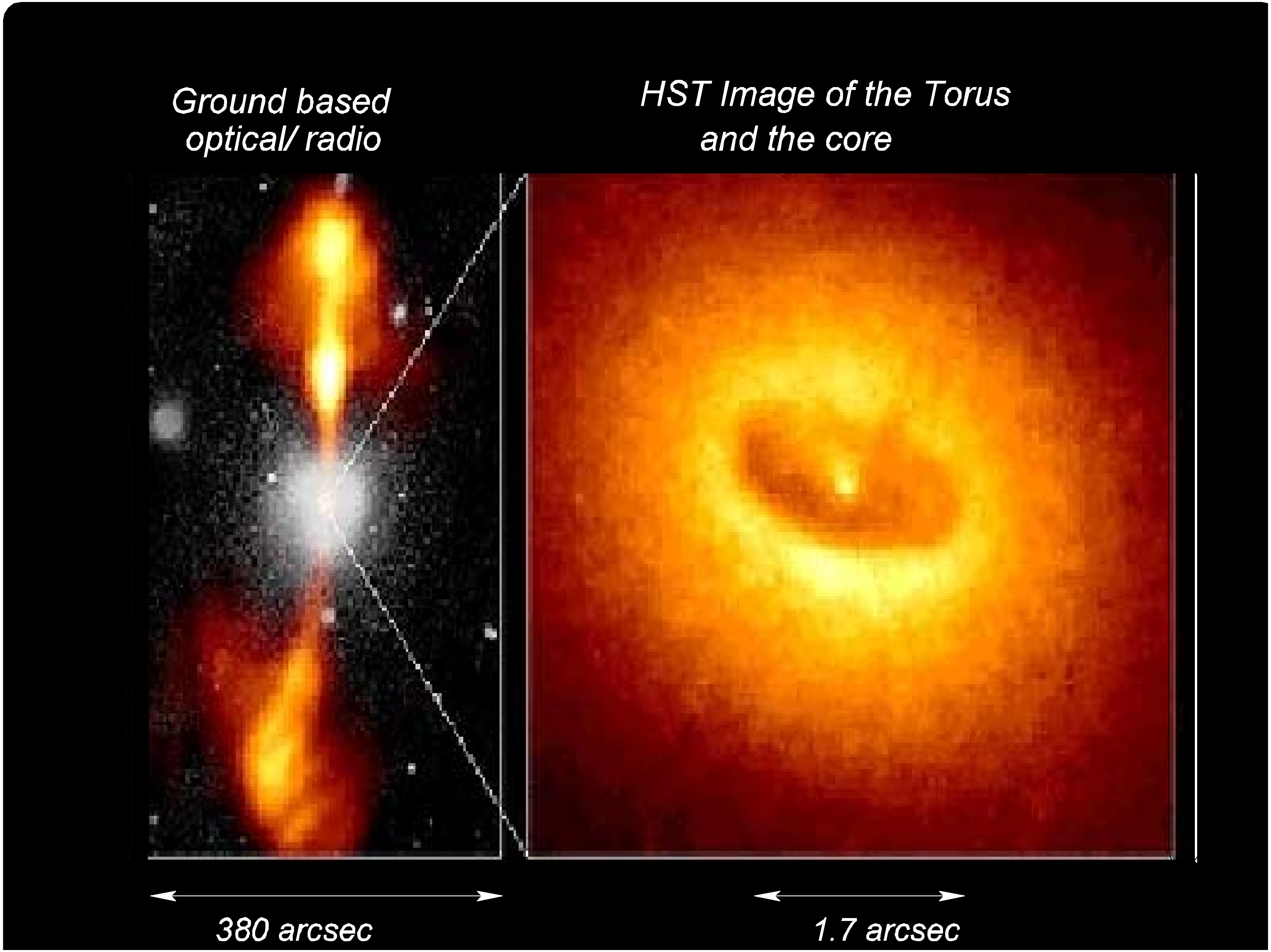
Main applications in:

1) AGN Radio jets

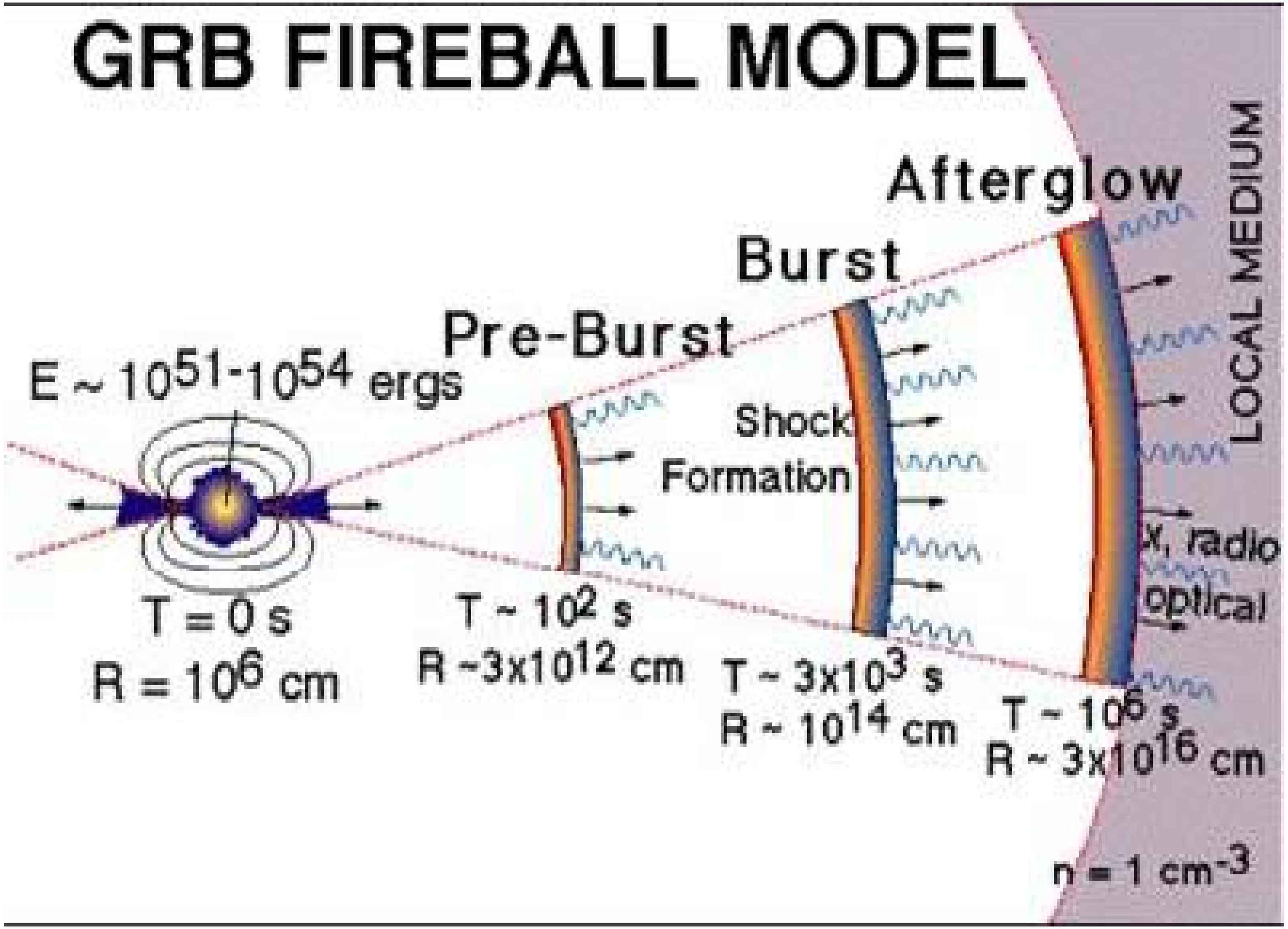
2) Gamma-Ray Bursts (fireball, internal shocks, afterglow)

More difficult to understand than non-relativistic shocks because:

- Particle speed never >> shock speed. Cannot use diffusion approximation → No simple test-particle power law derivable
- Acceleration, even in test-particle limit, depends critically on scattering properties (i.e., self-gen. B-field), which are unknown
- No direct observations of relativistic shocks. . .
- PIC simulations more difficult to run


Ground based
optical/ radio
HST Image of the Torus
and the core
380 arcsec
1.7 arcsec

3. Gamma Ray Bursts



Fermi acceleration

- Second order Fermi acceleration (Fermi, 1949)
- First order Fermi acceleration -diffusive acceleration- (Krymskii, 1977; Bell, 1978a,b; Blandford&Ostriker, 1978; Axford et al. 1978)

Transfer of the macroscopic kinetic energy of moving magnetized plasma to individual charged particles → non- thermal distribution

Second order Fermi acceleration

- Particles are reflected by ‘magnetic mirrors’ associated with irregularities in the galactic magnetic field. → *Net energy gain.*

- Cloud frame:
  1) No change in energy
     (colissionless scattering, elastic)
  2) Cosmic ray’s direction randomised

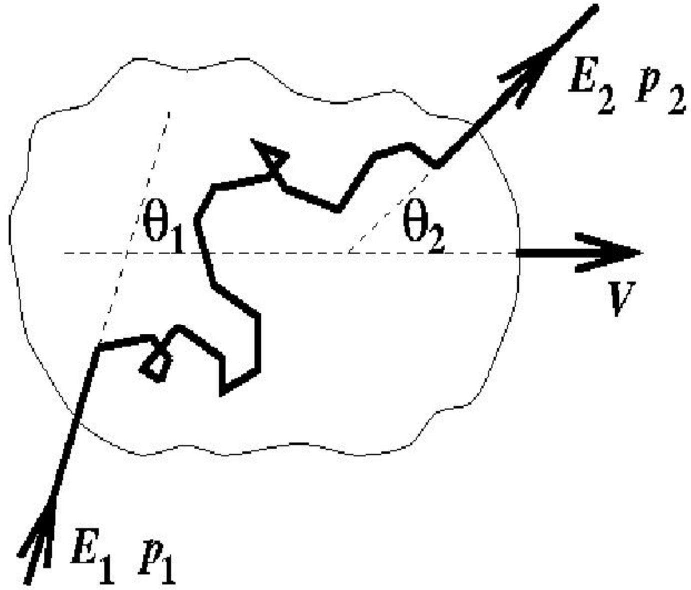
- If particles remain in the acceleration region for τ → power law distribution :

$$N(E) \propto E^{-\sigma}$$

$$\sigma = 1 + 1/\alpha\tau \quad \text{and} \quad \alpha \propto (V/c)^2$$

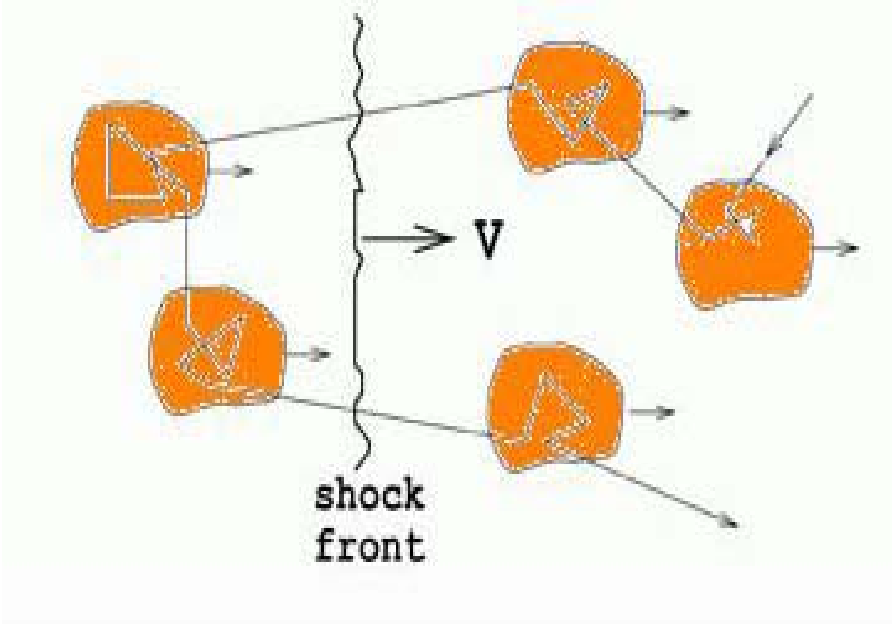
The average energy gain per collision:

$$\langle \Delta E/E \rangle = (V/c)^2$$



First order Fermi acceleration
(diffusive shock acceleration)

1970's modification of general theory: Particles undergo a process on crossing a *shock* from upstream to downstream and back again (*Supernovae shocks*)



upstream downstream

Power-law distribution depends only on compression ratio, r :

$$N(E) \propto E^{-\sigma}$$

$$\sigma=(r+2)/(r-1), \quad r=V_1/V_2=(\gamma+1)/(\gamma-1)$$

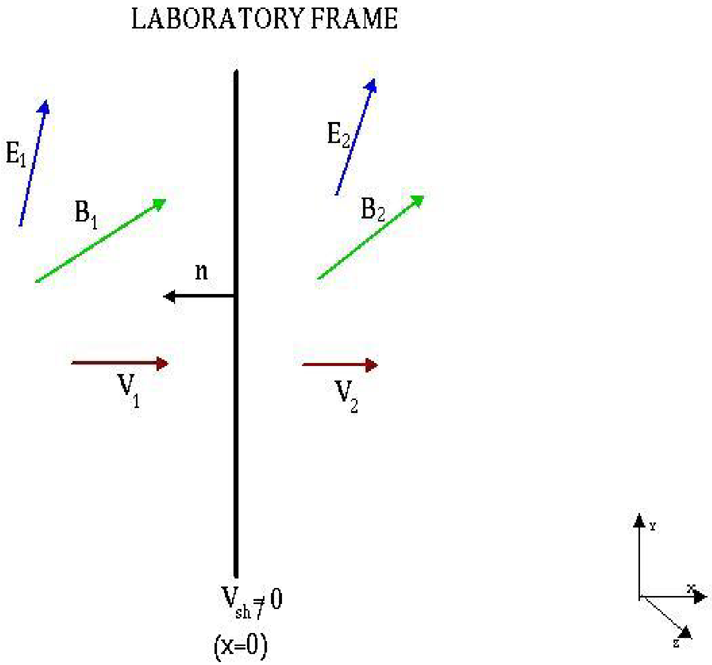
for mono-atomic gas $\gamma=5/3 \rightarrow r=4 \rightarrow E^{-2}$

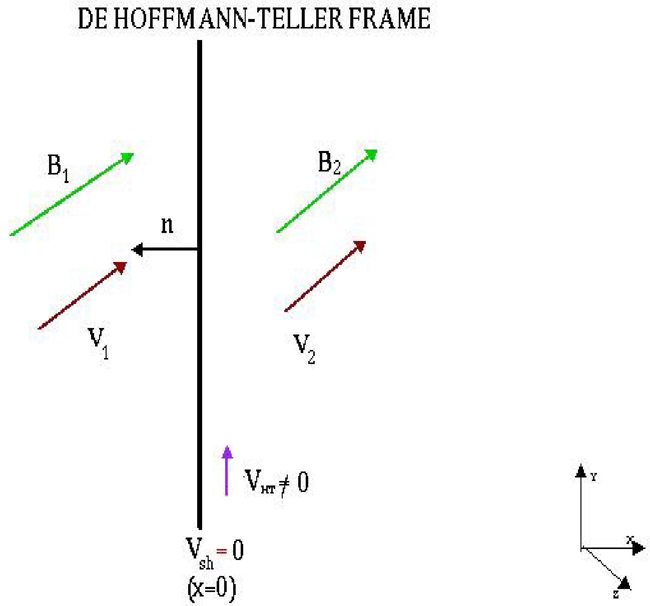
The average energy gain per collision:

$$<\Delta E/E> = V/c$$

Note: Only for non-relativistic shocks

Sub-luminal and super-luminal relativistic shocks





The Lorentz transformation is limited due to $V_{HT} \leq V_1 \tan\psi_1$

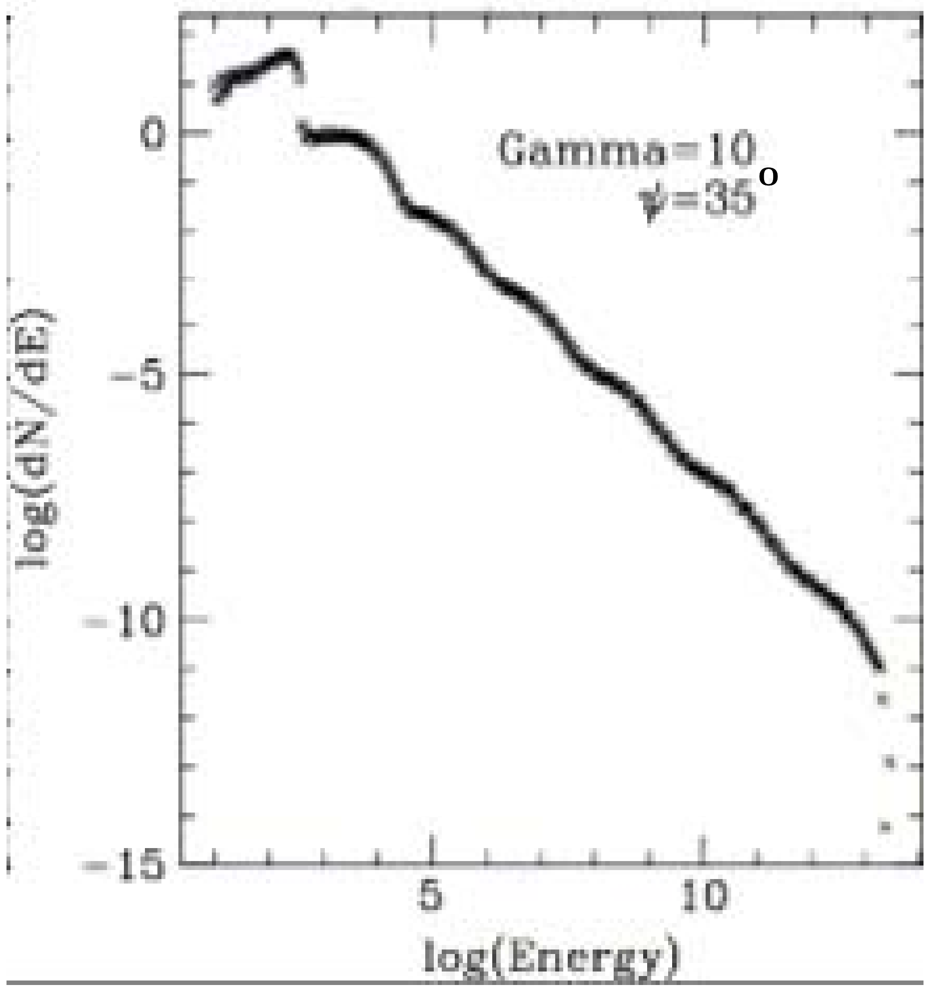
Relativistic shocks? → **Monte Carlo simulation technique**

Analytical solutions Vs *Numerical Simulations*

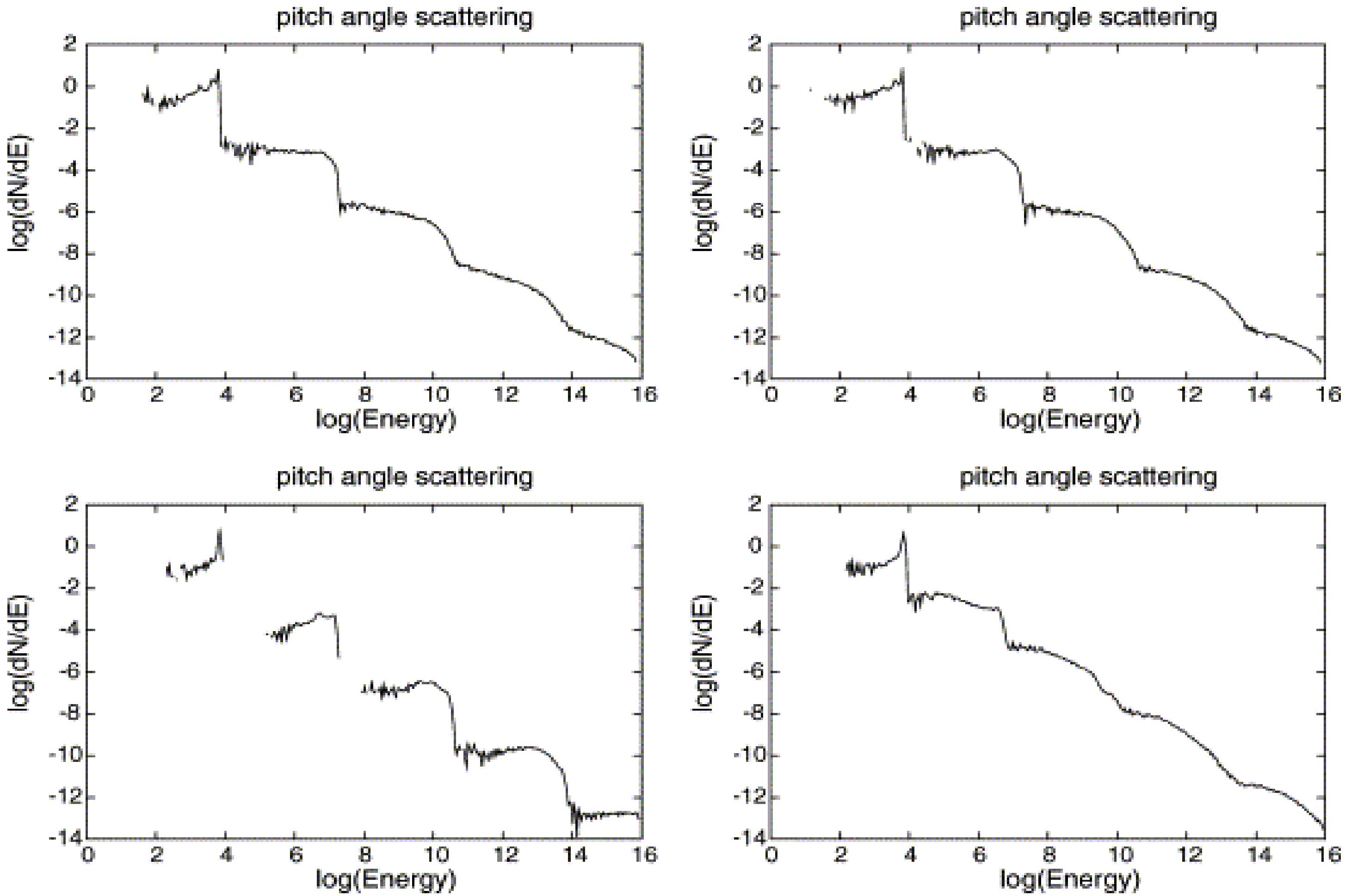
- Notion of '*test particles*' → interact with the plasma shock waves but do not react back to modify the plasma flow.
- Very efficient in describing particle '*random walks*'.
- *Random number generation* → simulation of the random nature of a physical process.
- Follow closely each particle path using a large number of particles.
- Apply *escape* (momentum and spatial) *boundaries* in the simulation box, according to certain physical conditions.

- Does the Fermi acceleration mechanism hold at relativistic speeds (*universality*?)
- Are different models of particle diffusion important?
- What is the energy gain efficiency per shock cycle?
- How the spectra look like at the source of the acceleration?
- Is the acceleration faster in relativistic shocks?
- . . . What else . . .?

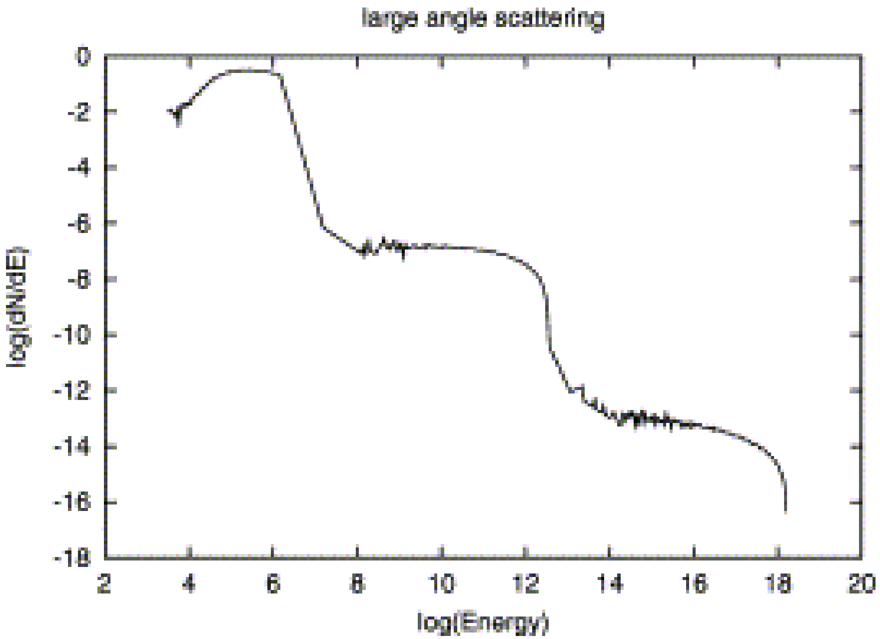
1. *Relativisitic sub-luminal* shocks

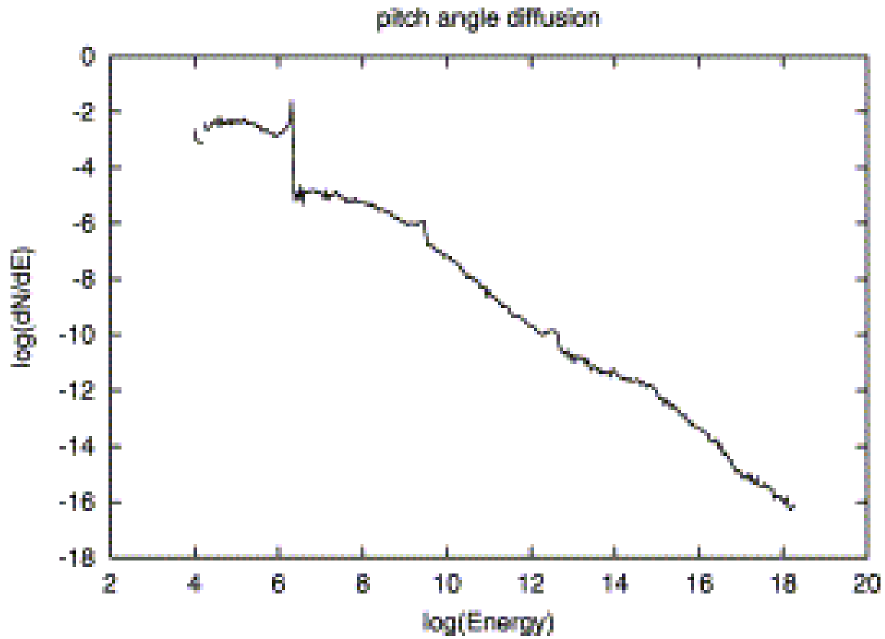


Spectral shape for upstream gamma equal to 10 and magnetic field inclination at 35 degrees. Later we will observe the smoothness of the spectral shape compared to larger upstream gammas.

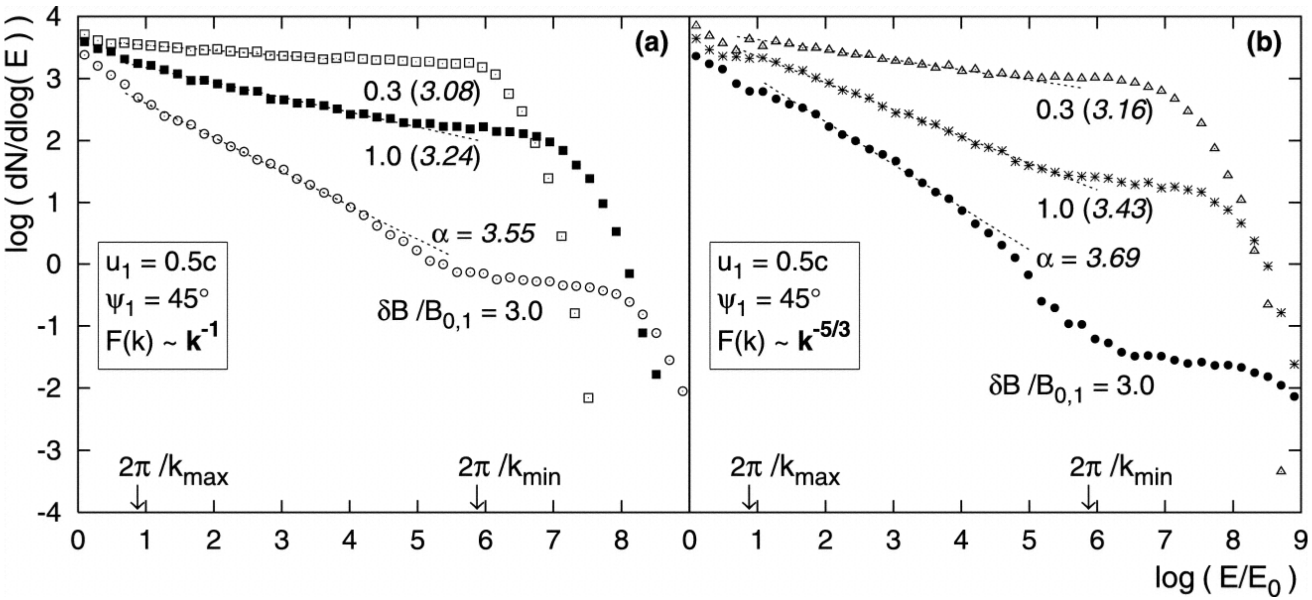


Spectral shape for gamma=500. Top plots: shock at 15^{o}, r = 3,4. Bottom plots: shock at 35^{o}, r = 3,4 respectively.





Spectral shapes for an upstream gamma = 300



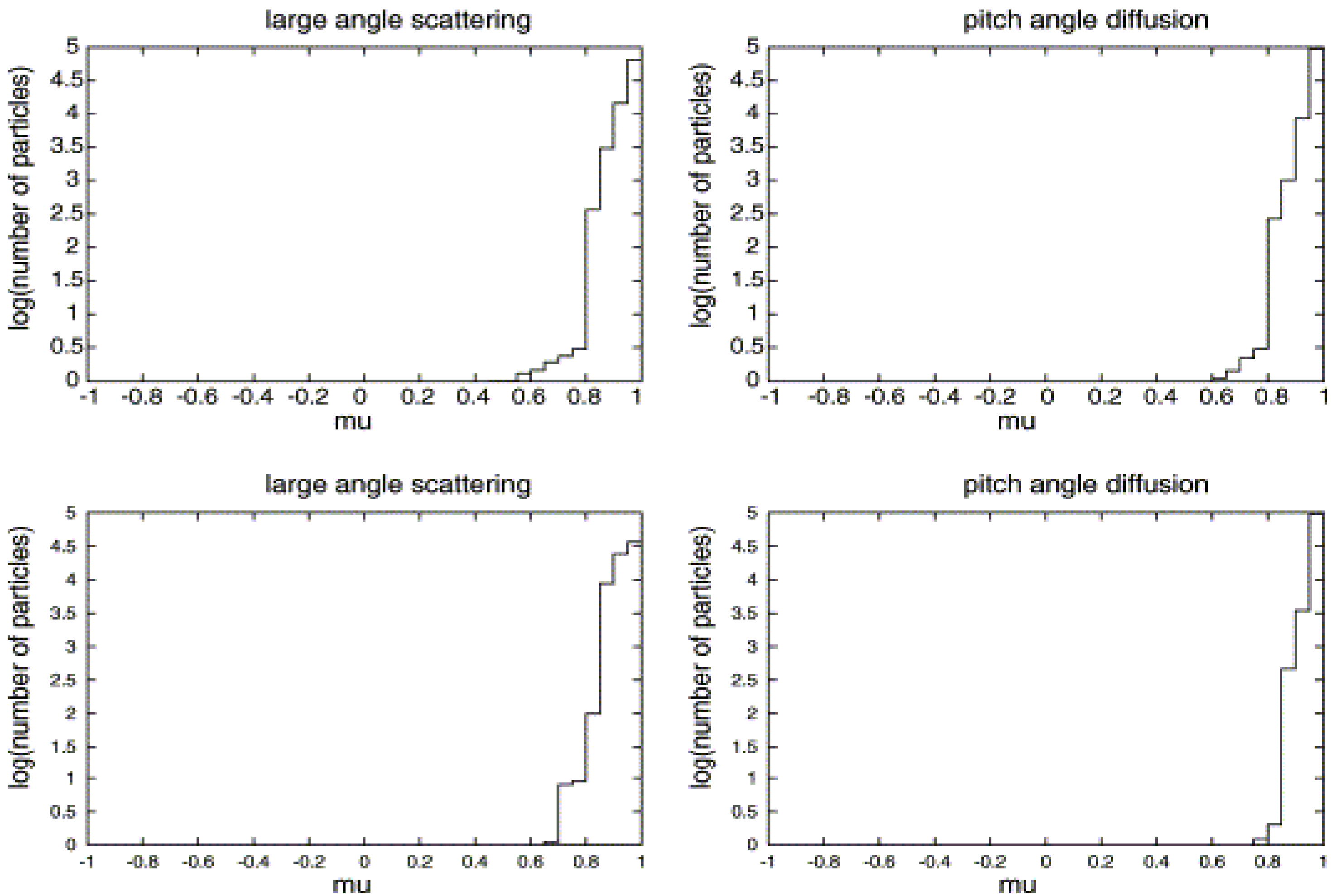
Niemiec & Ostrowski 2004

Spectrum depends on how particles scatter. Here, Niemiec & Ostrowski calculate particle trajectories in various magnetic field configurations, F(k).

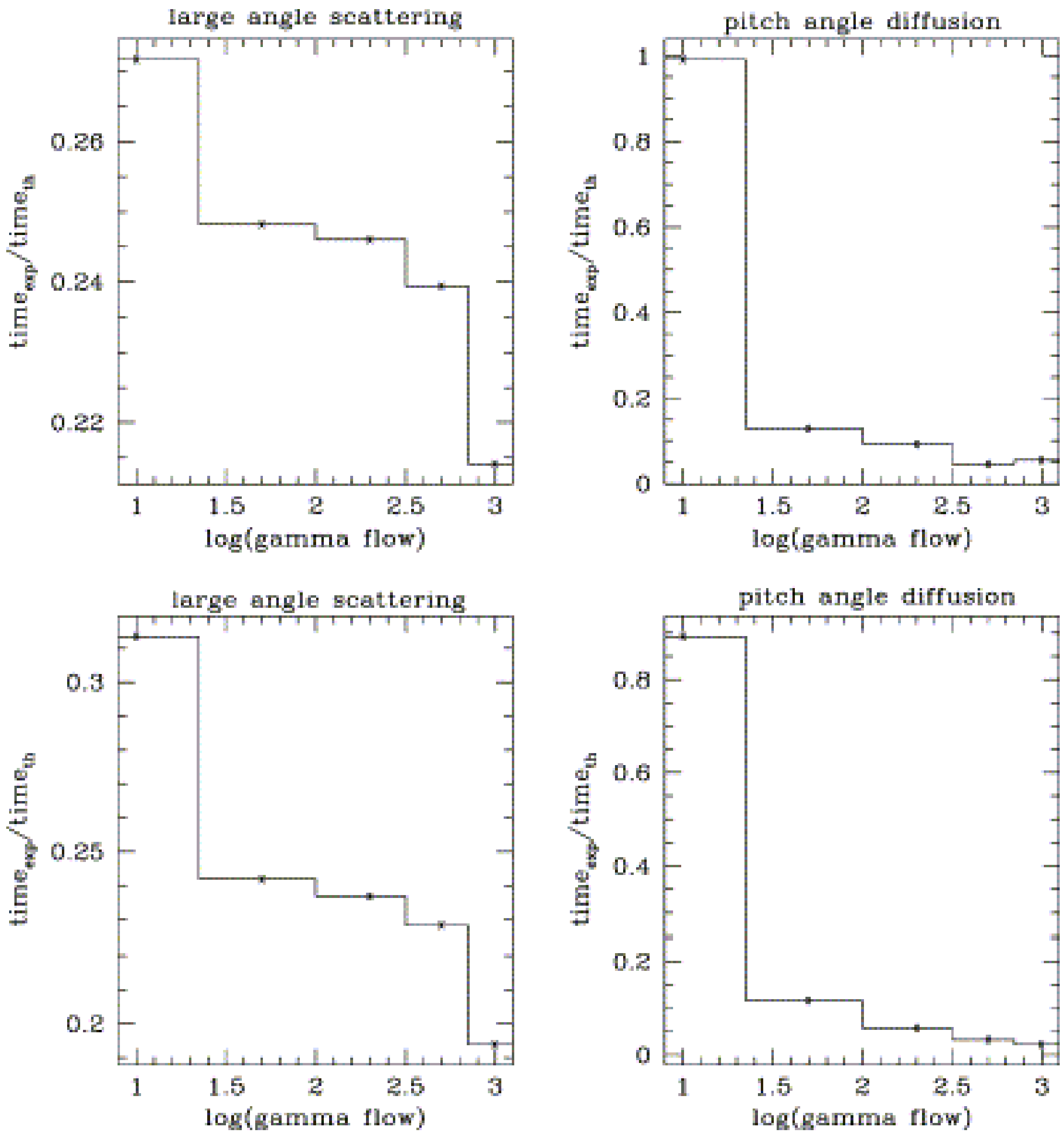
-Spectrum not necessarily a power law

-Cutoffs if no magnetic turbulence at relevant scales

Note: Acceleration in relativistic shocks depends critically on details of diffusion and details of diffusion are unknown



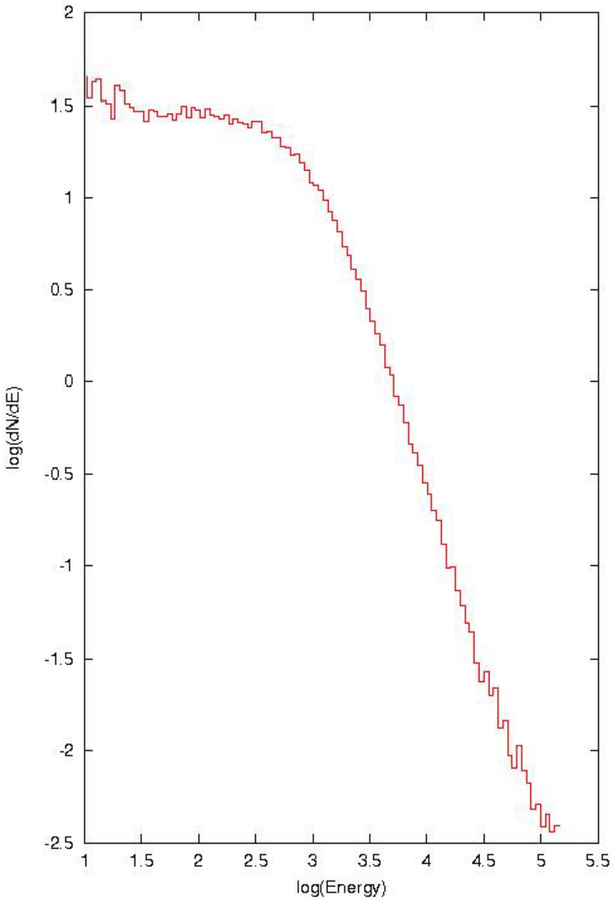
The angular distribution of the logarithm of the number of the transmitted particles versus mu= cosθ. Top plots: Gamma=200, at 15º. Bottom plots: Gamma=1000, at 35º. Strong 'beaming ' (Lieu and Quenby, 1993).



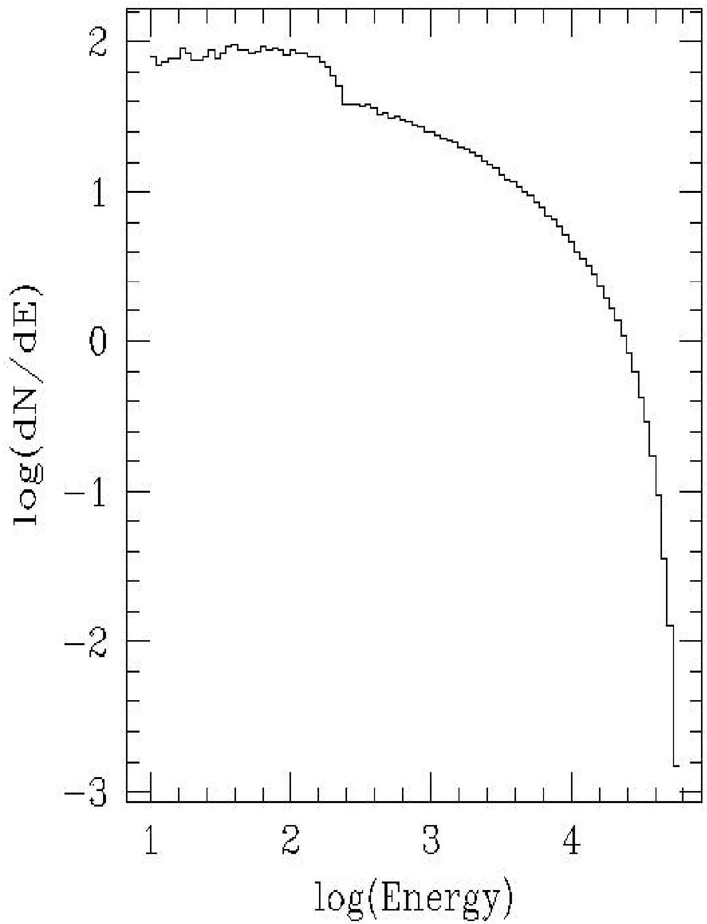
The ratio of the computational time to the theoretical acceleration time constant. Top at 15º, bottom at 35º.

2. Efficiency of Fermi acceleration at *relativistic super-luminal* shocks

pitch angle diffusion

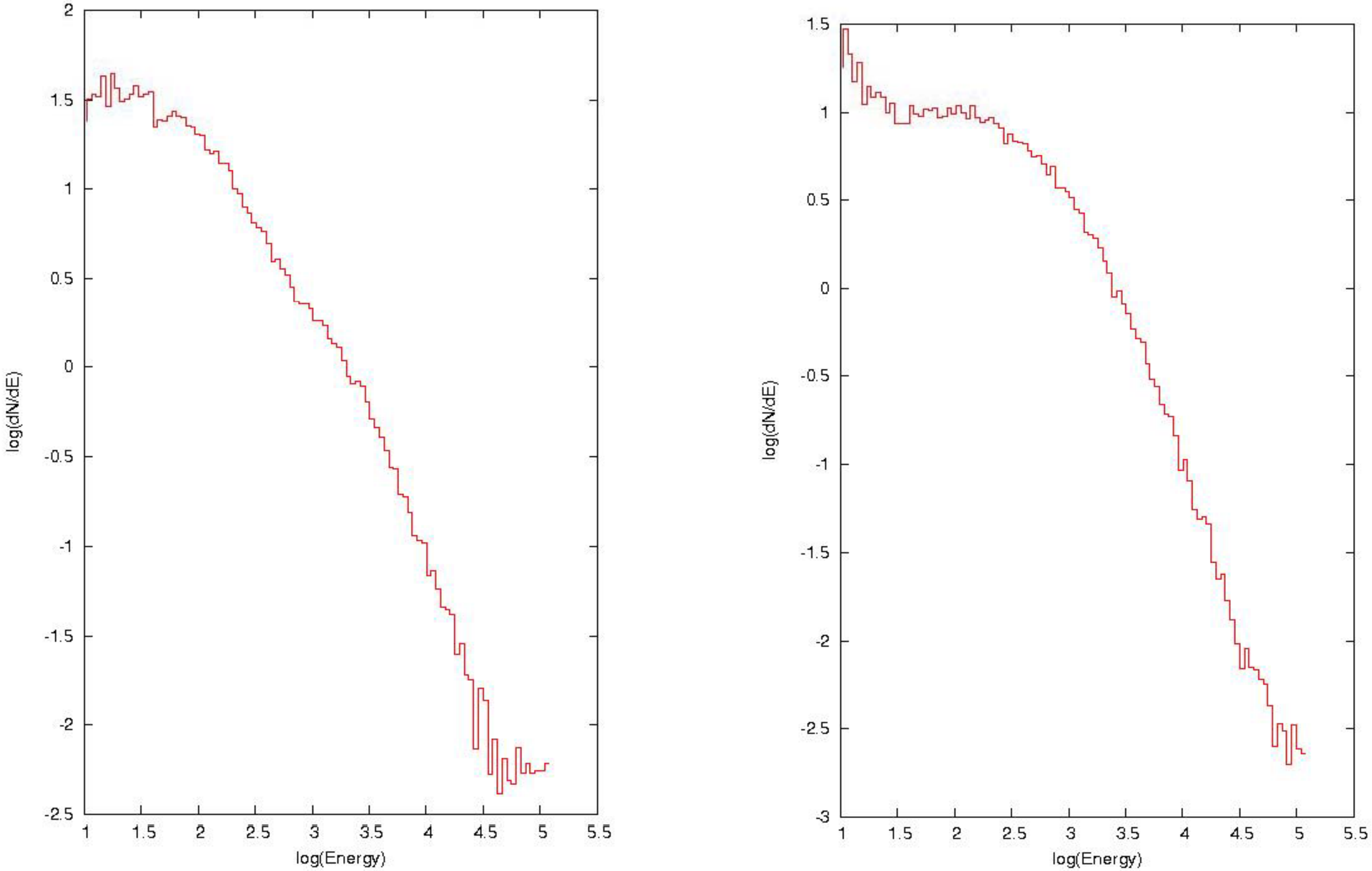


large angle scattering



Spectra for Gamma=300 and angle of 76 degrees. Left, pitch angle diffusion. Right, same values for large angle scattering. Note: in this case there is no 'structure' in the spectrum.

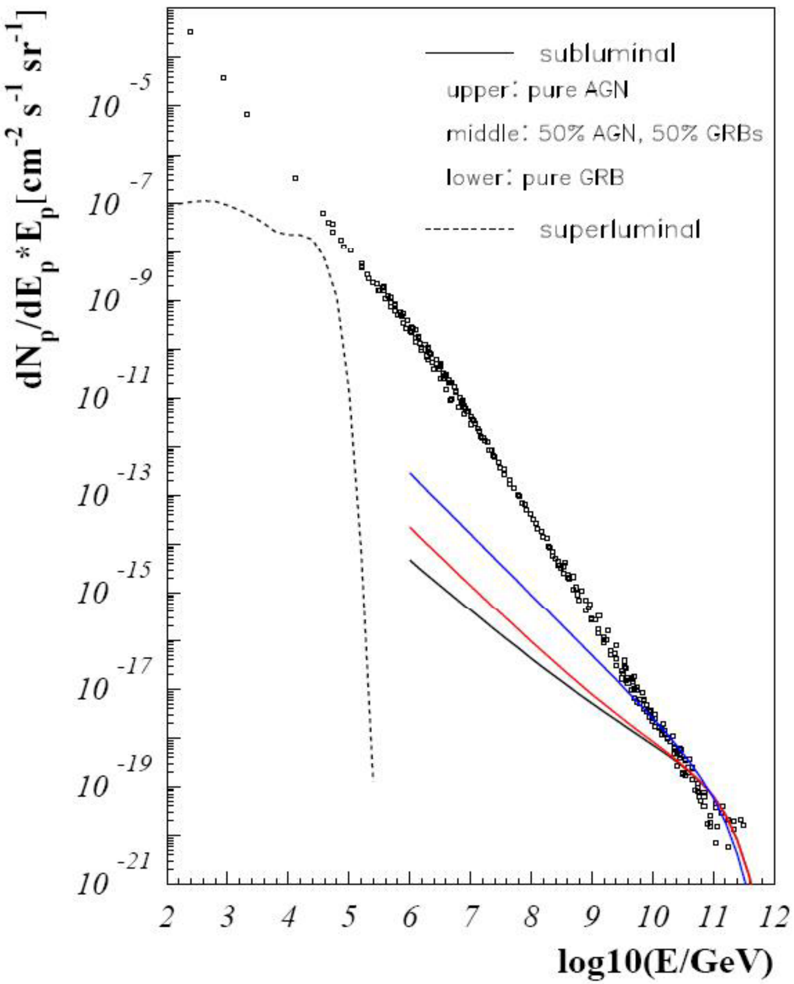
pitch angle diffusion



Left, shock lorentz factor of 500 and angle of 76 degrees. Right, shock lorentz of 900 and shock inclination angle of 89 degrees.

Findings

- Spectral shape $\leftrightarrow$ scatter model (details of diffusion)
- Highly anisotropic angular distribution ('beaming effect')
- 'Speed-up' effect (faster acceleration)
- Gamma squared energy boosting (first cycle)
- Sub-luminal shocks more efficient then Super-luminal



The diffuse energy spectrum of sources, compared
to the total diffuse spectrum (Meli, Becker & Quenby ('06 '07))

$$\frac{dN_{CR}}{dE} = \alpha \cdot \frac{dN_{AGN}}{dE} + (1-\alpha) \cdot \frac{dN_{GRB}}{dE}$$

$$0 \leq a \leq 1$$

The energy density of the observed cosmic ray spectrum J_E is then used to normalise the calculated Monte Carlo spectra

$$j_E := \int_{E_{\min}=10^{18.5}\,eV} \frac{dN}{dE} E\, dE \approx 10^{-7} \mathrm{GeV\ cm^{-2}\, s^{-1}\, sr^{-1}}.$$

Conclusions

Non-Relativistic shocks:

First-order Fermi acceleration mechanism (Diffusive shock acceleration) it is well studied → predictions for spectral shapes from earth's bow shock, planetary shocks and Supernova Remnants it works.

Relativistic Shocks :

- Important in AGN radio jets and GRBs
- Diffusive shock acceleration harder to describe (but still seems to work)
- Spectrum depends on (1) unknown scattering properties, (2) shock Lorentz factor, (3) obliquity → "Universal" power law index, $f(p) \propto p^{-4.2}$ is a special case
- Application to GRBs and AGN – still work to be done...

Thank you