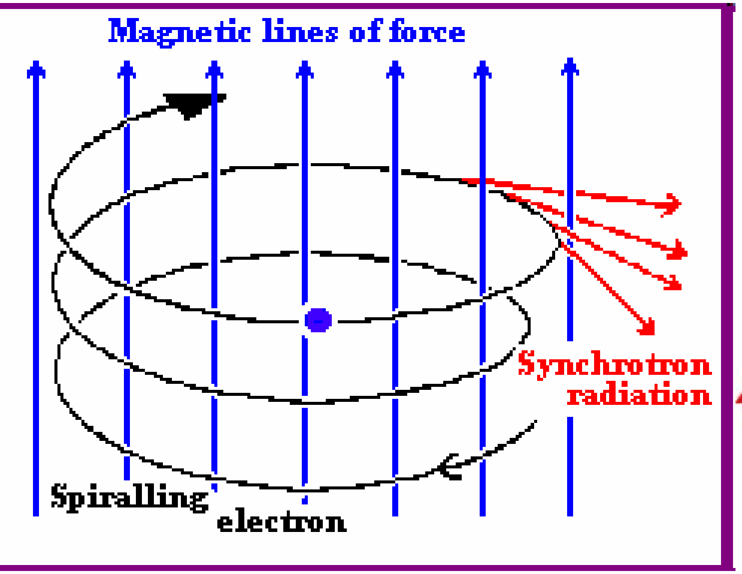
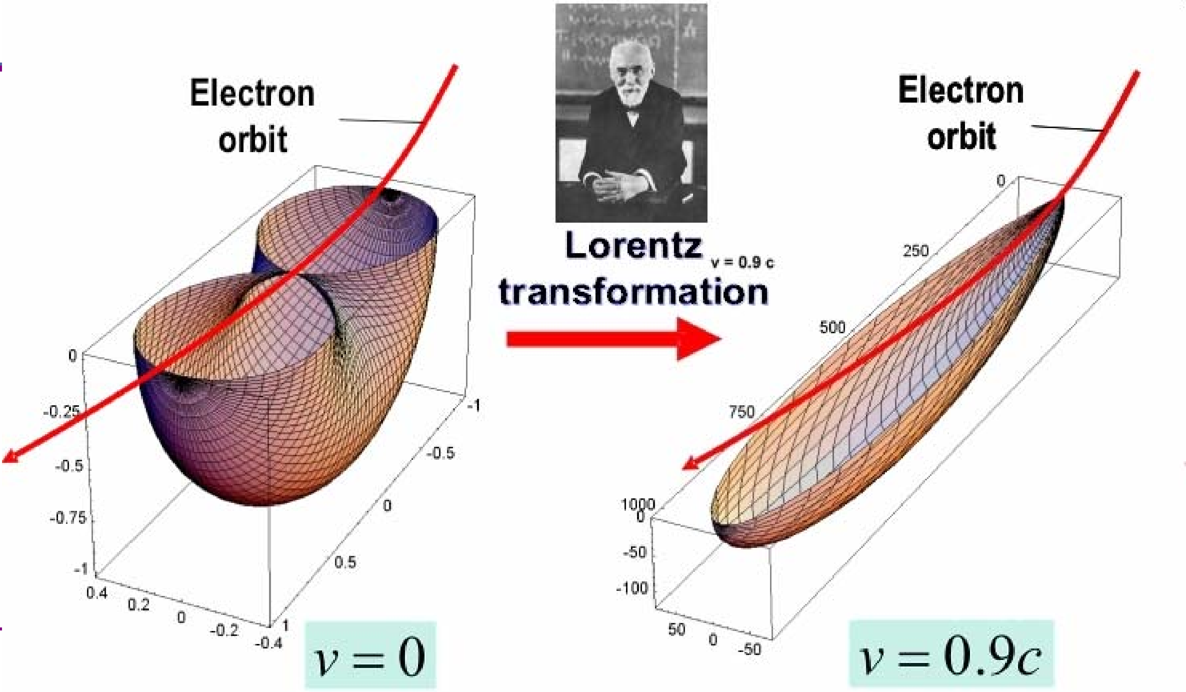
Radio Spectra of Supernova Remnants

Dejan Urošević

Synchrotron radiation

- The ultra-relativistic electron in the magnetic field



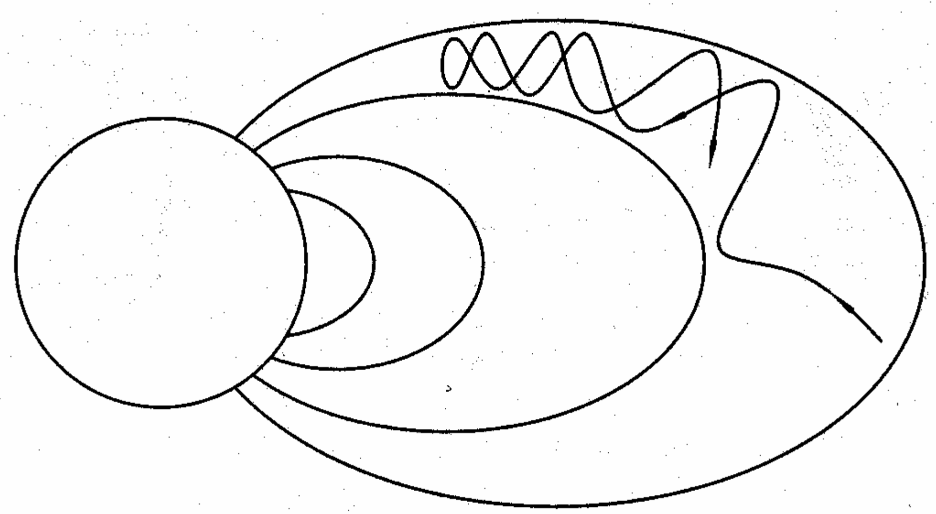


Particle acceleration

- transverse adiabatic invariant

$$p_\perp^2 / B = \text{const.}$$

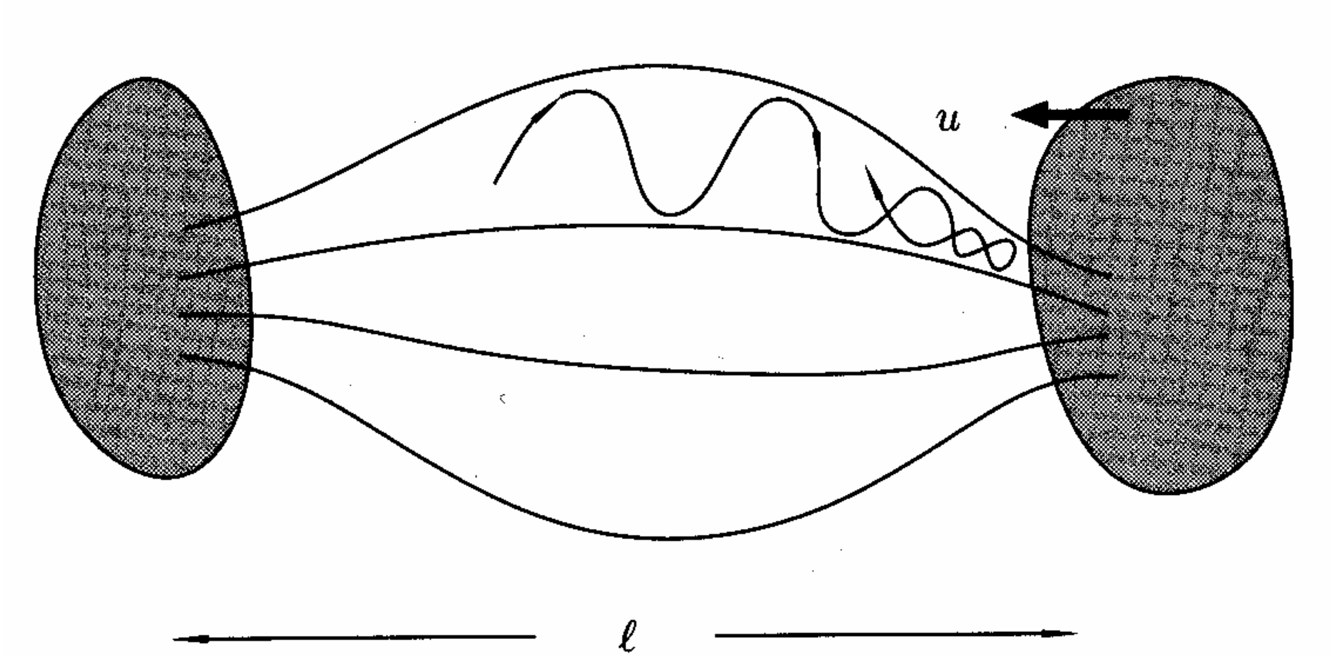
$$p_\perp^2 + p_\parallel^2 = \text{const.}$$



Particle acceleration

- longitudinal adiabatic invariant

$$p_{\parallel} l = \text{const.}$$



Particle acceleration

PHYSICAL REVIEW VOLUME 75, NUMBER 8 APRIL 15, 1949

On the Origin of the Cosmic Radiation

ENRICO FERMI
Institute for Nuclear Studies, University of Chicago, Chicago, Illinois
(Received January 3, 1949)

A theory of the origin of cosmic radiation is proposed according to which cosmic rays are originated and accelerated primarily in the interstellar space of the galaxy by collisions against moving magmetic fields. One of the features of the theory is that it yields naturally an inverse power law for the spectral distribution of the cosmic rays. The chief difficulty is that it fails to explain in a straightforward way the heavy nuclei observed in the primary radiation.

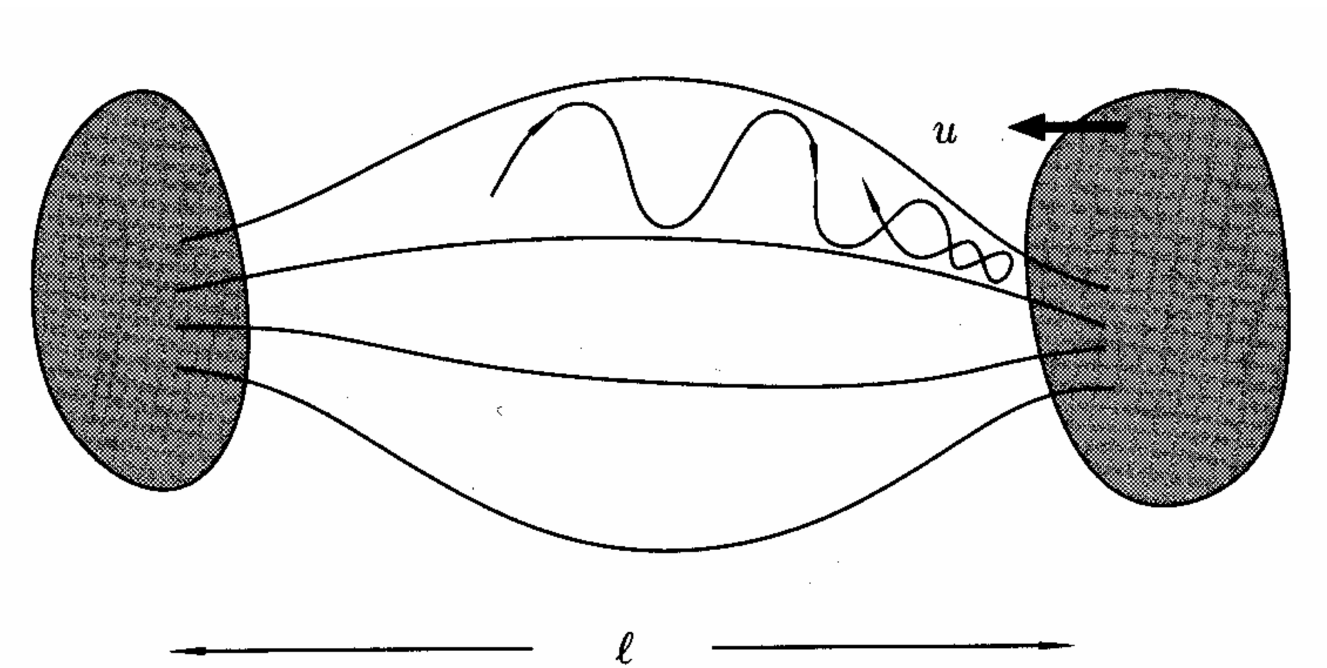
I. INTRODUCTION

IN recent discussions on the origin of the cosmic radiation E. Teller[1] has advocated the view that cosmic rays are of solar origin and are kept relatively near the sun by the action of magnetic fields. These views are amplified by Alfvén, Richtmyer, and Teller.[2] The argument against the conventional view that cosmic radiation may extend at least to all the galactic space is the very large amount of energy that should be present in form of cosmic radiation if it were to extend to such a huge space. Indeed, if this were the case, the mechanism of acceleration of the cosmic radiation should be extremely efficient.

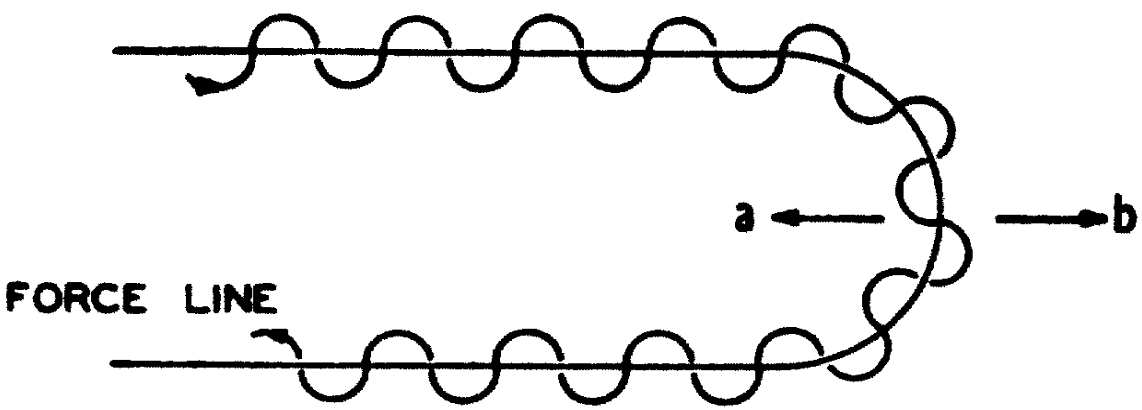
where H is the intensity of the magnetic field and ρ is the density of the interstellar matter.

One finds according to the present theory that a particle that is projected into the interstellar medium with energy above a certain injection threshold gains energy by collisions against the moving irregularities of the interstellar magnetic field. The rate of gain is very slow but appears capable of building up the energy to the maximum values observed. Indeed one finds quite naturally an inverse power law for the energy spectrum of the protons. The experimentally observed exponent of this law appears to be well within the range of the possibilities.

- Fermi acceleration ("Type A" in Fermi (1949))



- Fermi acceleration ("Type B" in Fermi (1949)) – affirmed in this paper



- In both cases

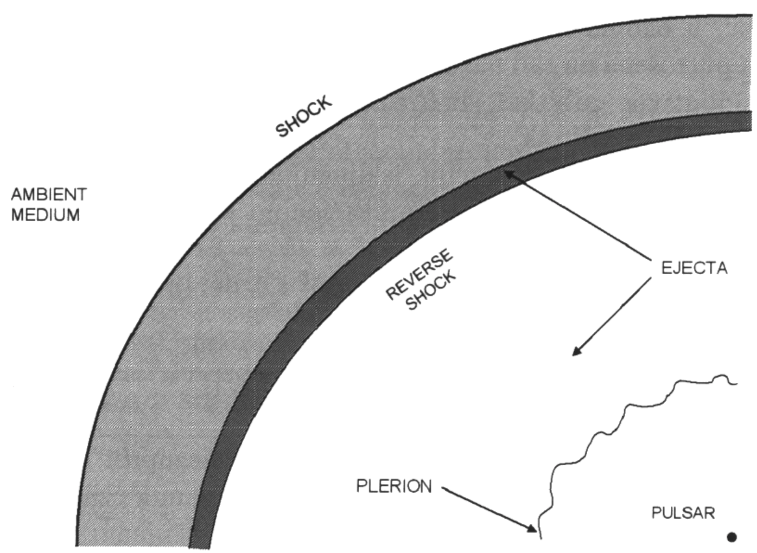
$$\Delta E / E \sim (v / c)^2$$

Particle acceleration

- Cosmic rays
- Ultra-relativistic electrons
- Synchrotron emission, gamma-ray emission by inverse Compton scattering and pion decay
- SNRs, AGNs

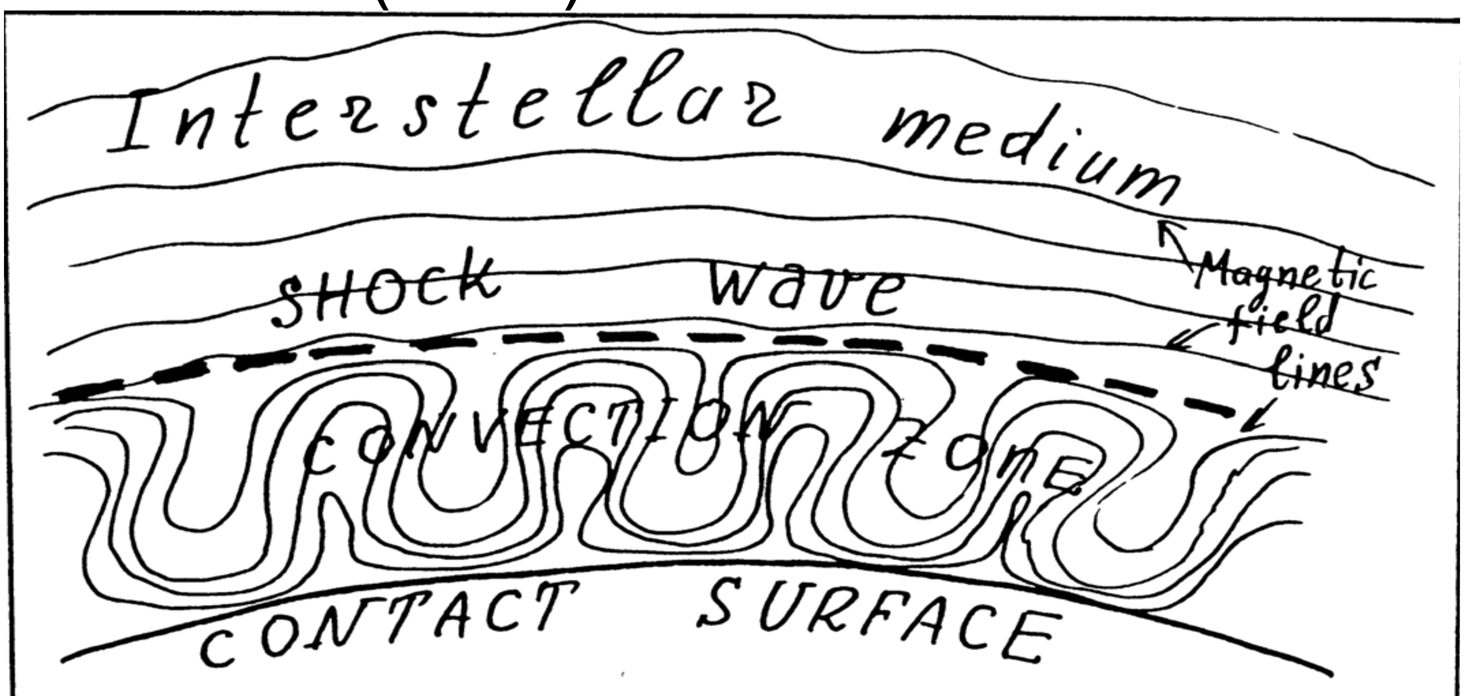
SNRs – particle acceleration

- diffuse shock acceleration – first order Fermi acceleration
- Bell (1978a,b), Blandford & Ostriker (1978, 1980), Drury (1983a,b), Malkov & Drury (2001)



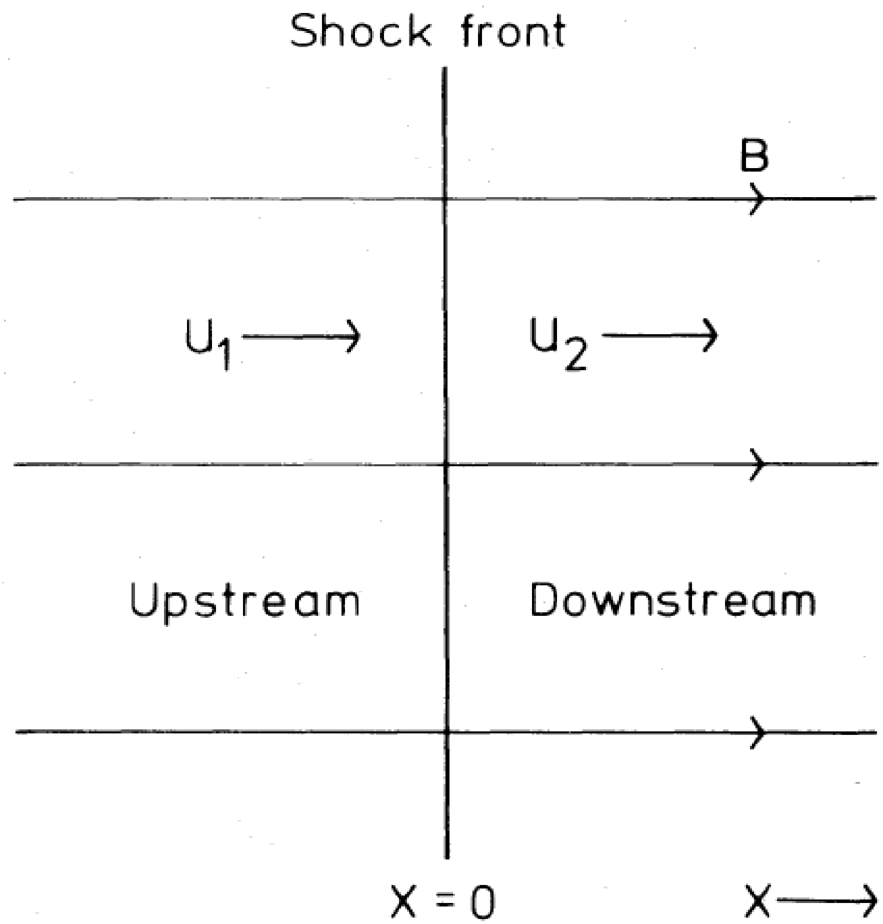
SNRs – particle acceleration

- second order Fermi acceleration – turbulences in downstream region
- Scott & Chevalier (1975), Galinsky & Shevchenko (2007)

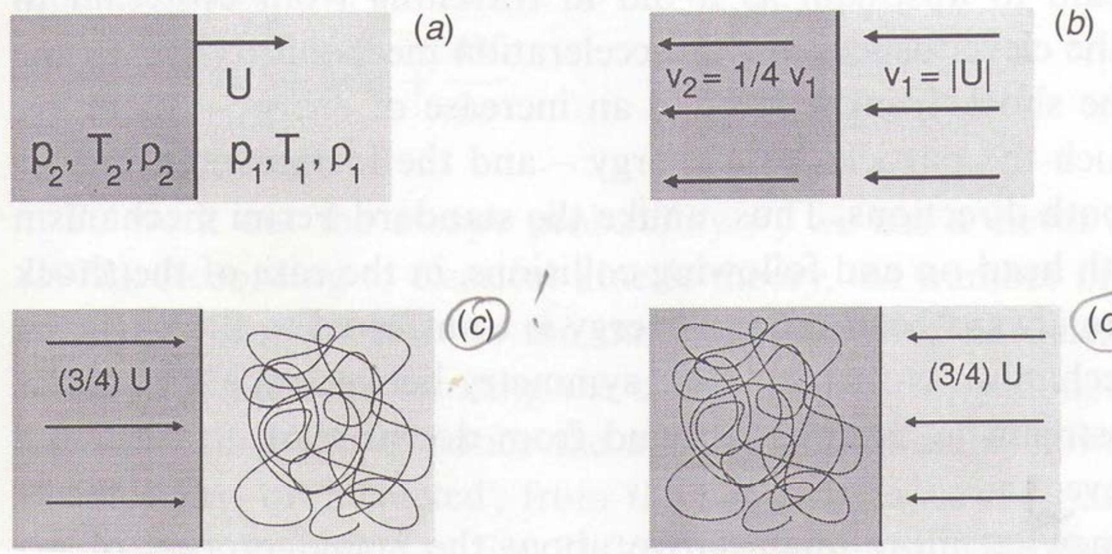


DSA (Diffuse Shock Acceleration)

Microscopic approach (Bell 1978a)



DSA – test particle case



DSA – diffuse shock acceleration

- Probability of escape at a large distance downstream

$$\eta = 4\, v_2 / v$$

v – test particle velocity ($v \approx c$)

$$\downarrow\downarrow$$

PROBABLE RECROSSING FROM DOWNSTREM TO UPSTREAM

scattering induced by magnetic turbulence in downstream region

DSA – diffuse shock acceleration

- Scattering in upstream region is induced by turbulence in the form of Alfven waves excited by energetic particles which pass through the shock and attempt to escape upstream

  (quasi-non-linear effect)

$\downarrow\downarrow$

RECROSSING FROM UPSTREAM TO DOWNSTREM

DSA – diffuse shock acceleration

After N cycles particle is

“diffuse shocked”

Particle “loses memory” about its initial spectrum

DSA – test particle case

Resulting spectrum of the cosmic ray particles in DSA theory is power law:

$$N(E)\, dE \sim E^{-\mu}\, dE,$$

where $\mu=(2v_2+v_1)/(v_1-v_2)$,

for strong non-modified shocks ($v_1=4v_2$)

$$\mu=2$$

DSA – test particle case

Macroscopic approach

(Krymsky 1977, Axford et al. 1977, Blandford & Ostriker 1978)

$f(t,x,p)$ - distribution function of the phase space density

again the power-law form $f(p) \sim p^{-4}$

for the ideal gas (γ = 5/3), and Mach number $M \to \infty$

$\downarrow\downarrow$

$$N(p)\mathrm{d}p = 4\pi p^2 f(p)\mathrm{d}p$$

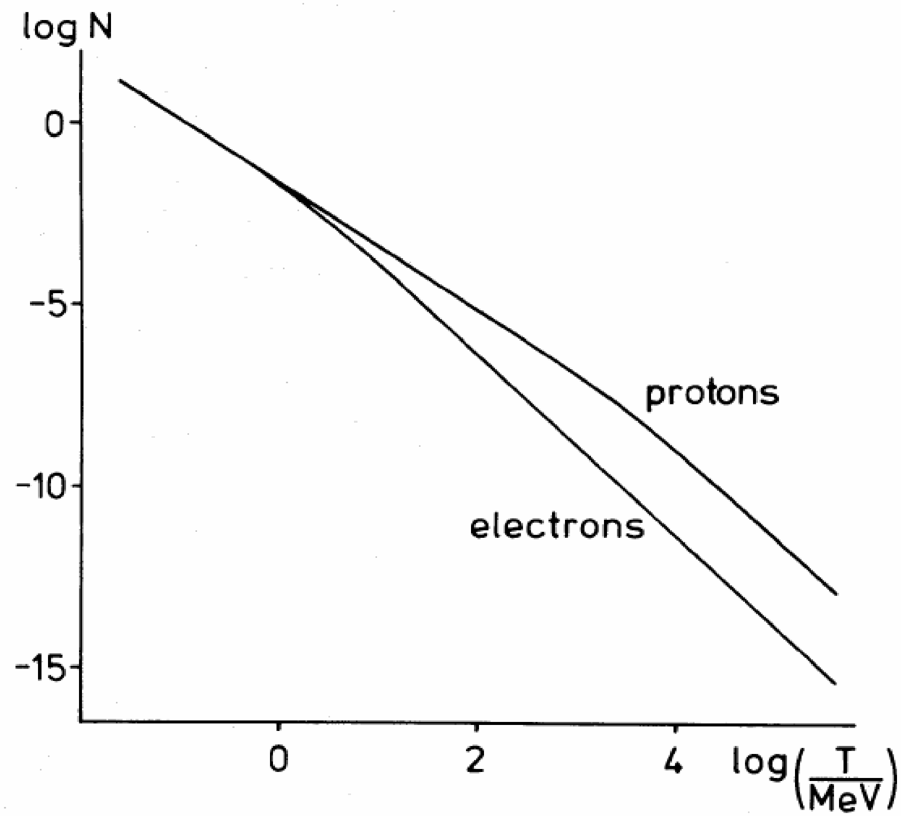
DSA - SNRs

* SNRs are energetically capable to accelerate CRs by DSA mechanism!!!

(Blandford & Ostriker 1978)

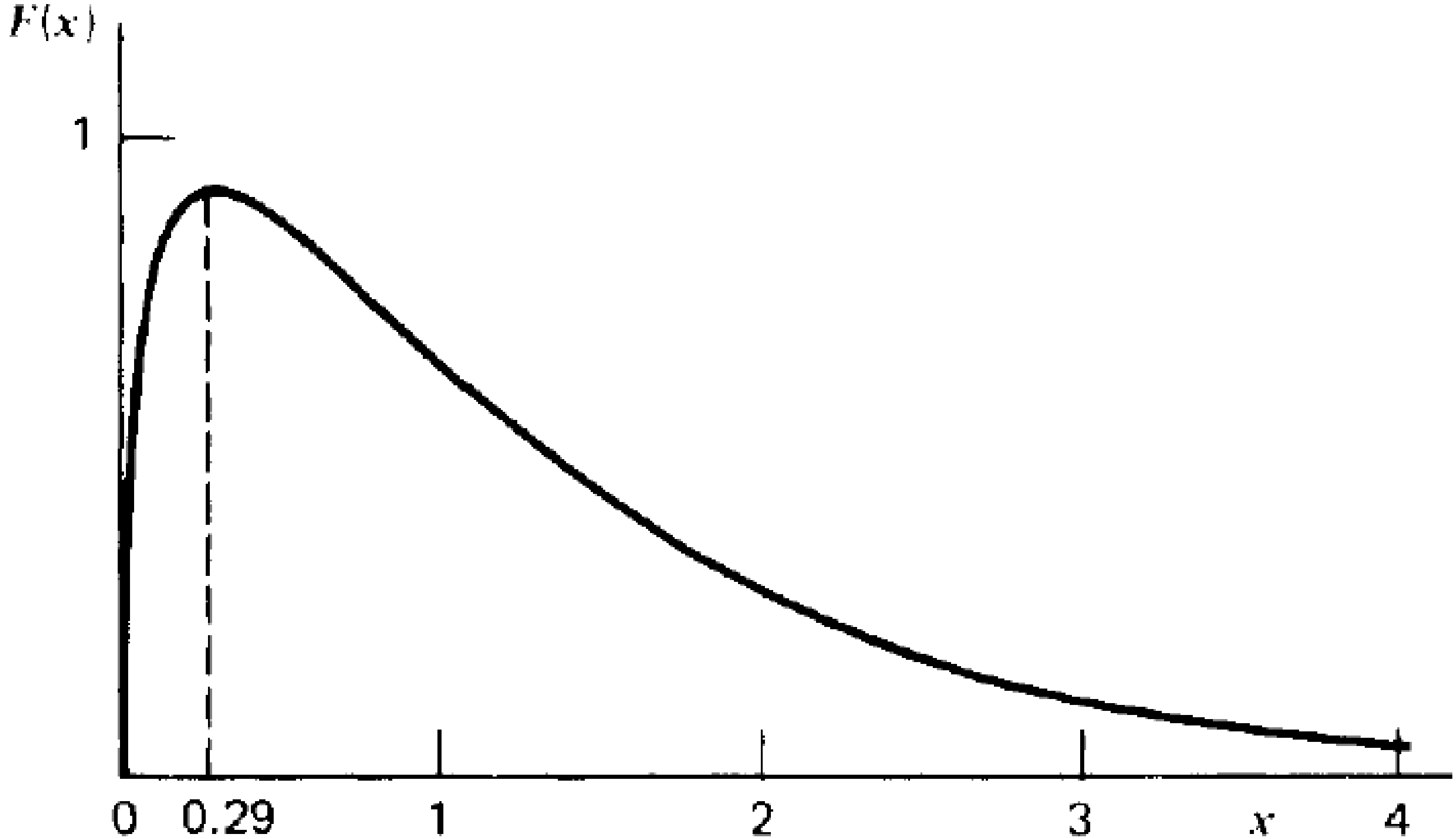
DSA - SNRs

Energy spectra for CR protons and electrons (Bell 1978b)



The energy spectra of protons and electrons injected at an energy $T_0 = 10\,\text{keV}$.

Spectrum of one synchrotron electron



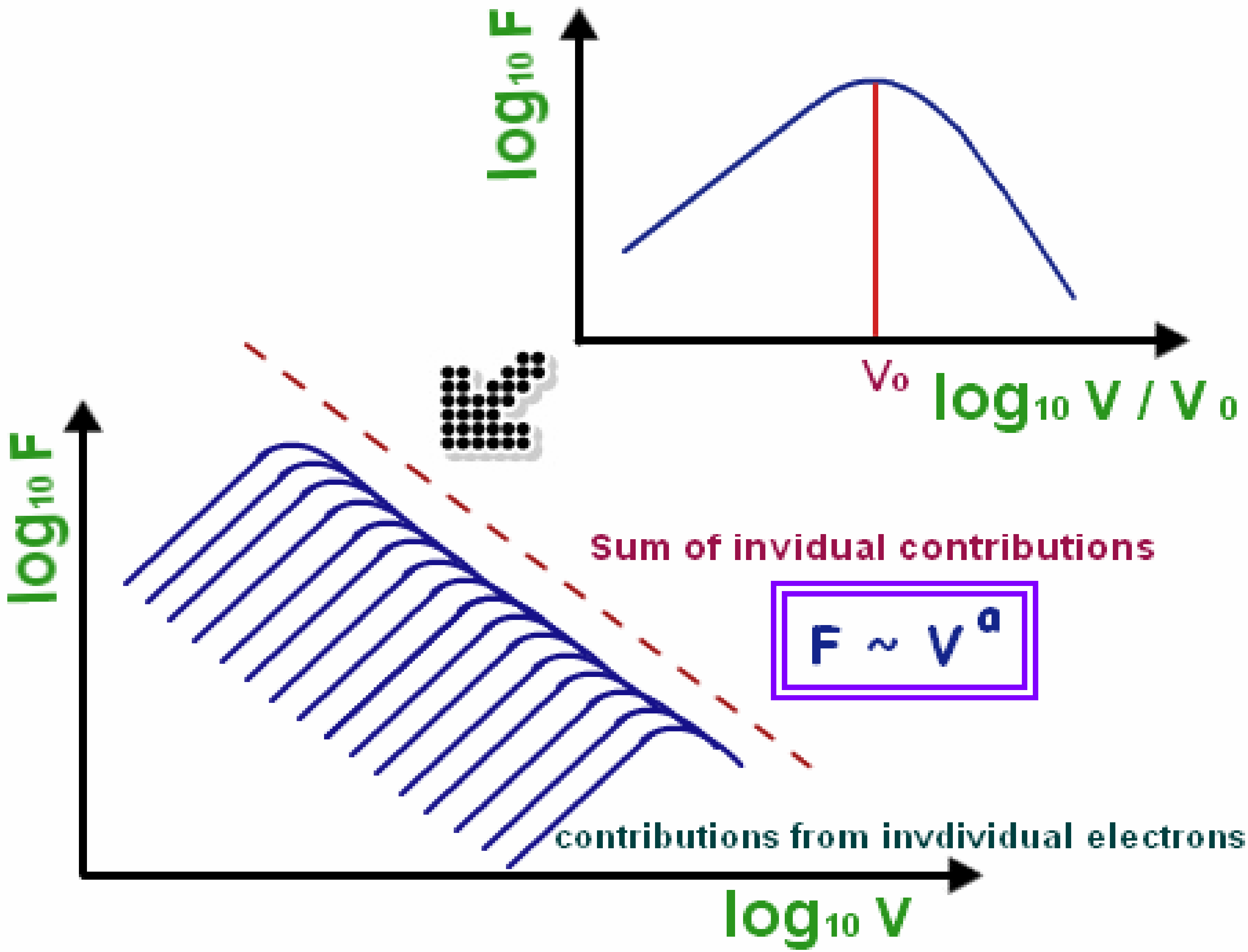
$$\nu_{\rm crit} = c_1 E^2 B_\perp = 16.08\,\mathrm{MHz}\,(E/\mathrm{GeV})^2 (B_\perp/\mu\mathrm{G})$$

$$\nu_{\rm crit} = c_1 E^2 B_\perp = 16.08 \mathrm{MHz} \, (E/\mathrm{GeV})^2 (B_\perp/\mu\mathrm{G})$$

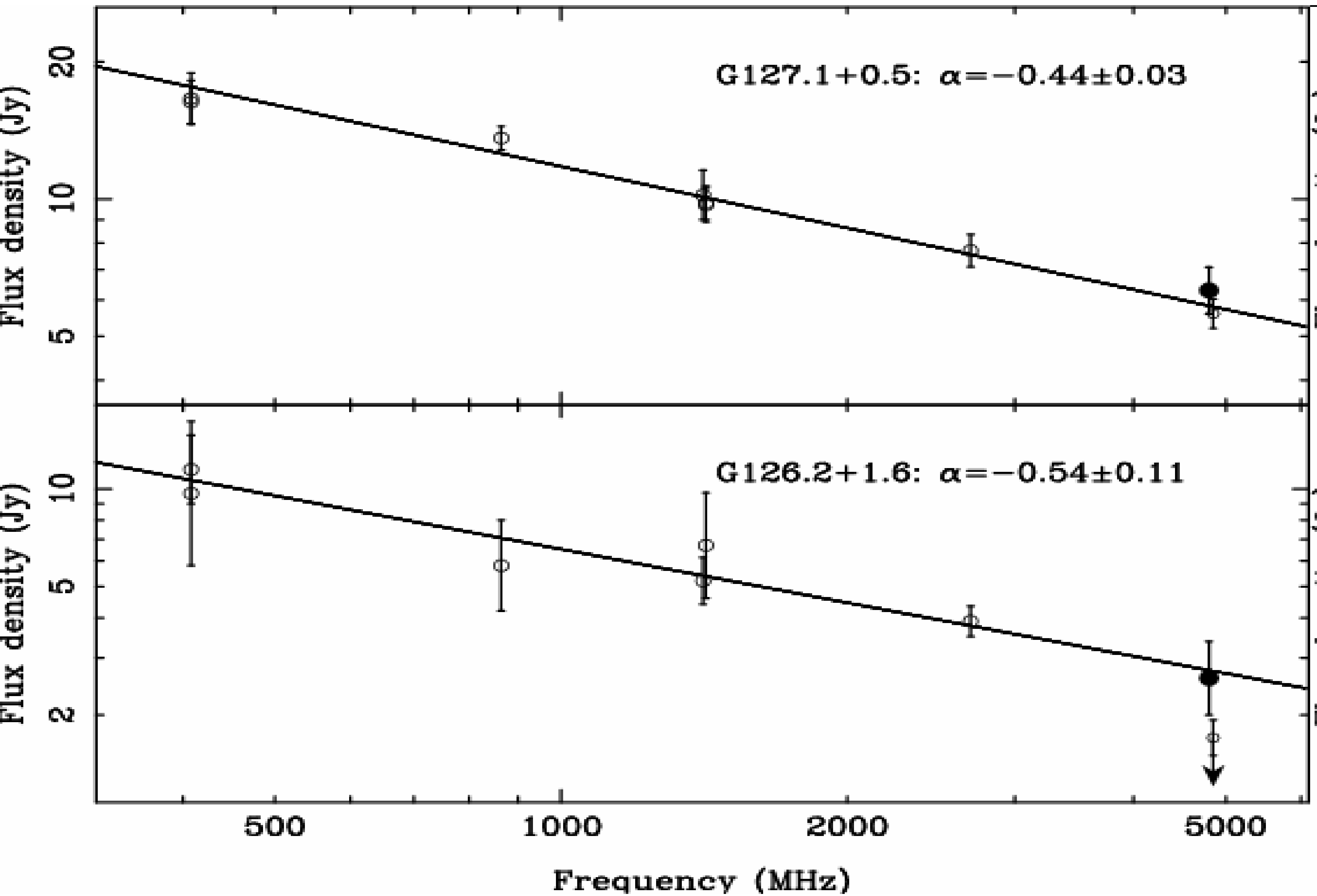
- the limiting frequencies of the radio domain,
  10MHz - 100GHz

- the corresponding energies of electrons:
  800MeV (at 10 MHz)
  80GeV (at 100 GHz)
  for $B = 1\mu$G - the characteristic value of ISM magnetic field.

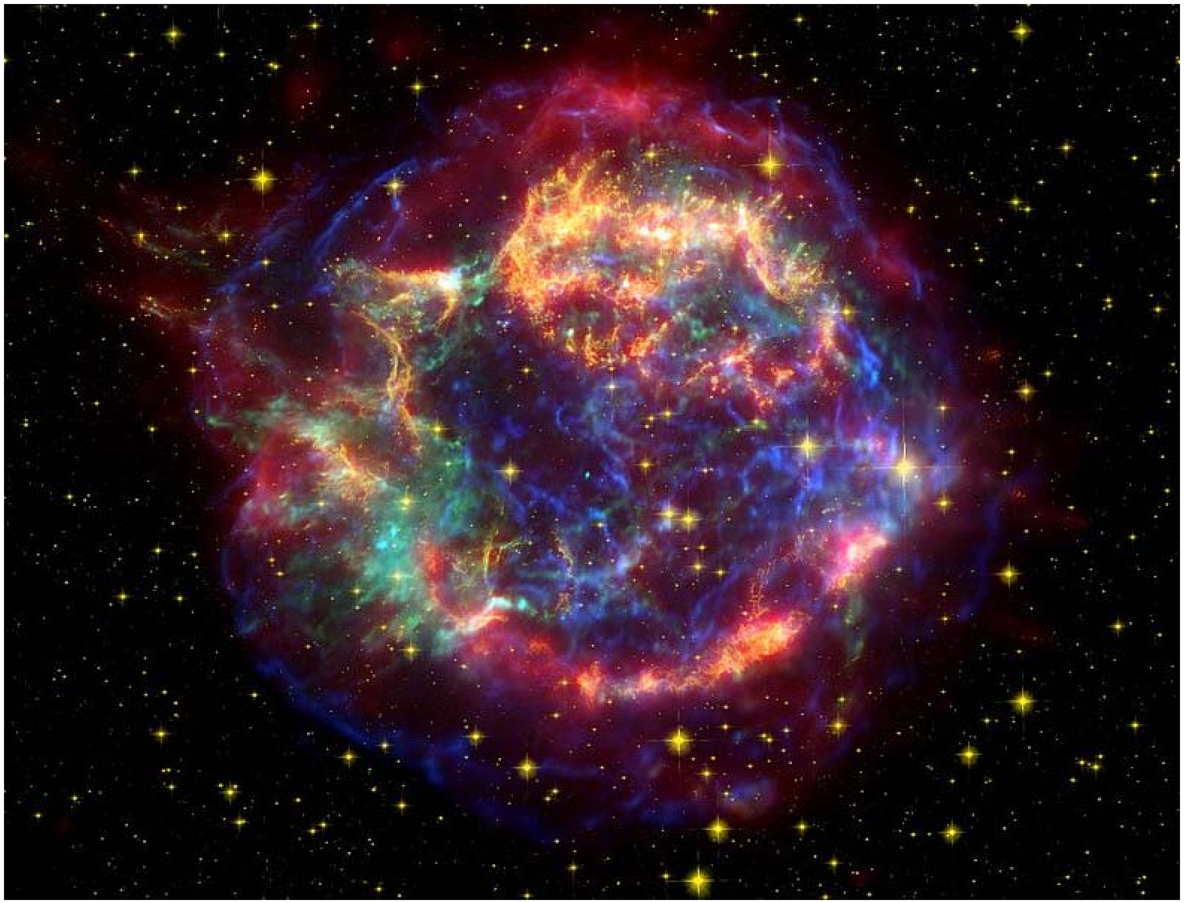
- electron energies $\sim$ TeV $\rightarrow$ X-ray synchrotron emission



$\log_{10} F$
V_0
$\log_{10} V / V_0$
Sum of invidual contributions
$F \sim V^a$
$\log_{10} F$
contributions from invdividual electrons
$\log_{10} V$


G127.1+0.5: α=−0.44±0.03
G126.2+1.6: α=−0.54±0.11
Flux density (Jy)
Flux density (Jy)
20
10
5
10
5
2
500
1000
2000
5000
Frequency (MHz)

Young SNRs



- Observations – steeper than α=0.5 spectral indices!

Non-linear DSA

MODIFIED SHOCKS

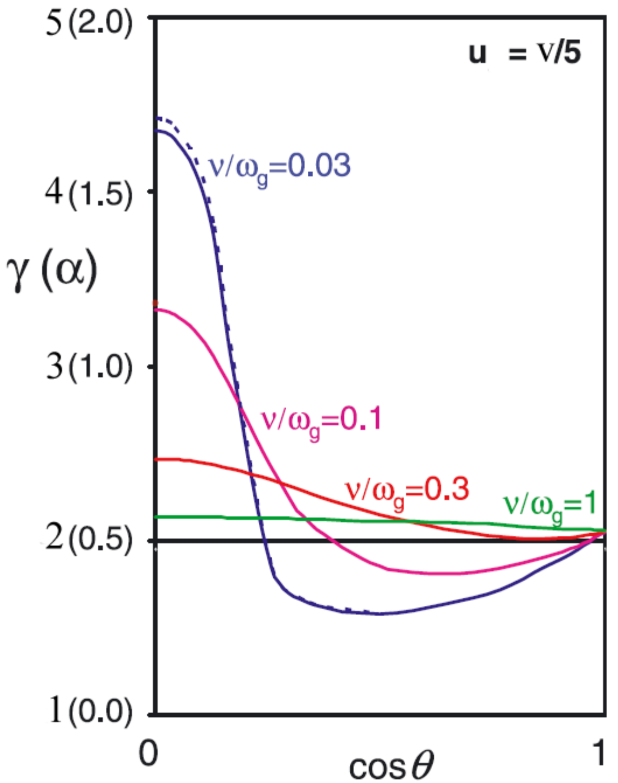
Non-linear effects

Including of cosmic ray (CR) pressure

$\gamma = 4/3 \rightarrow$ compression ratio $r = 7$!!!

Young SNRs (linear spectra)

- Bell et al. (2011) – quasiperpendicular orientation of the magnetic field!



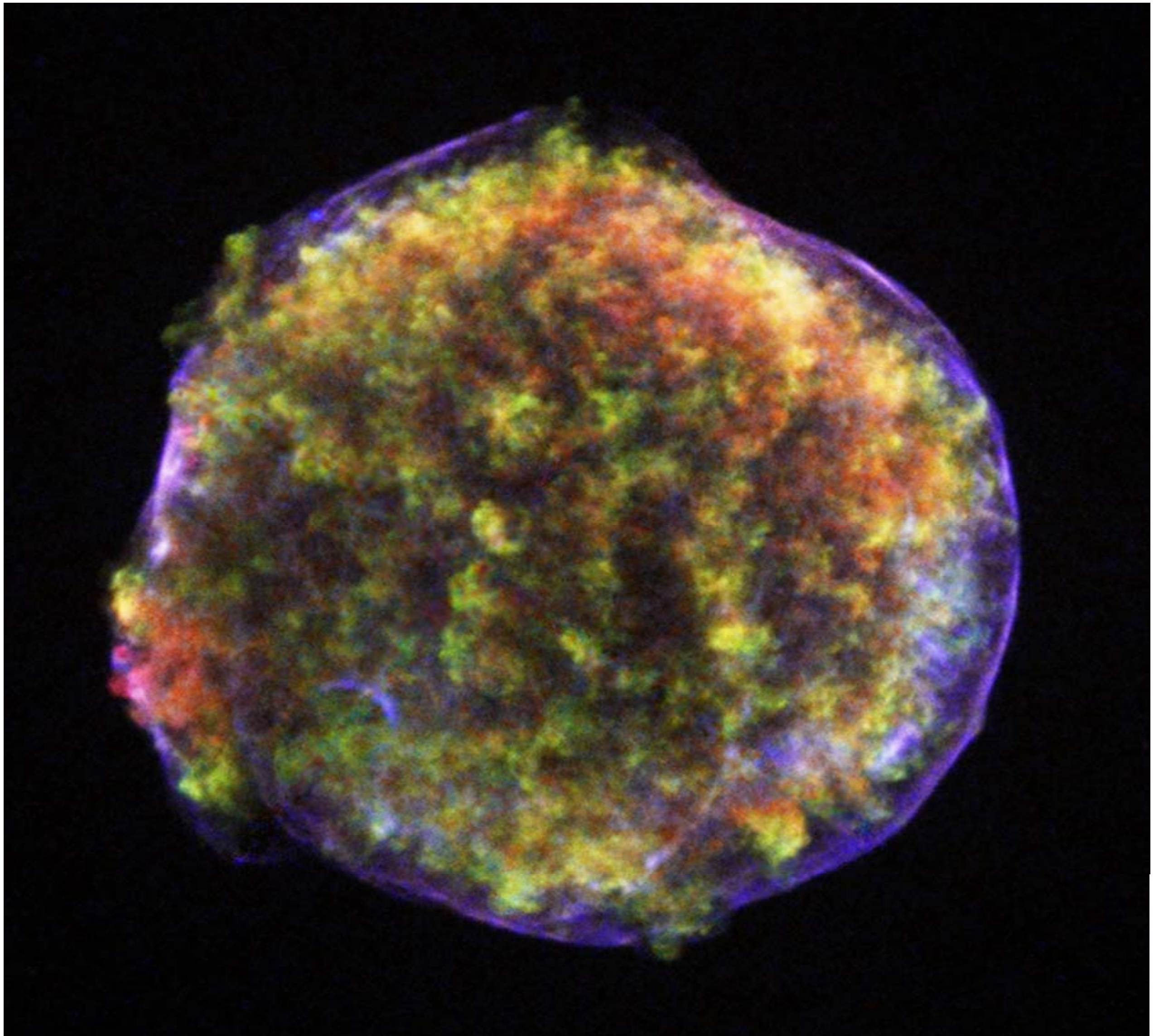
Young SNRs (linear spectra)

- Jiang et al. (2013) - Alfvenic drift effect can make softer spectra (steeper spectral indices)

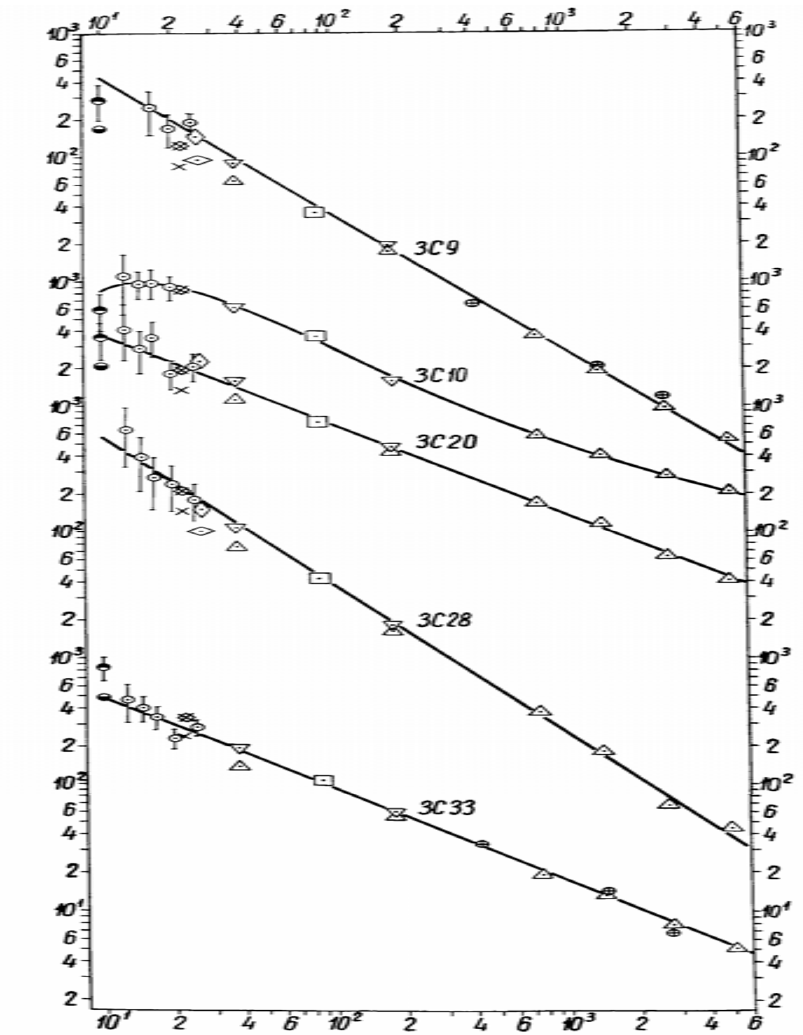
$$M_{\mathrm{A}} = u_1/v_{\mathrm{A}} = 1/B$$

- Problem: model assumes the test particle case in the non-linear DSA approach…

Young SNRs (curved spectra)



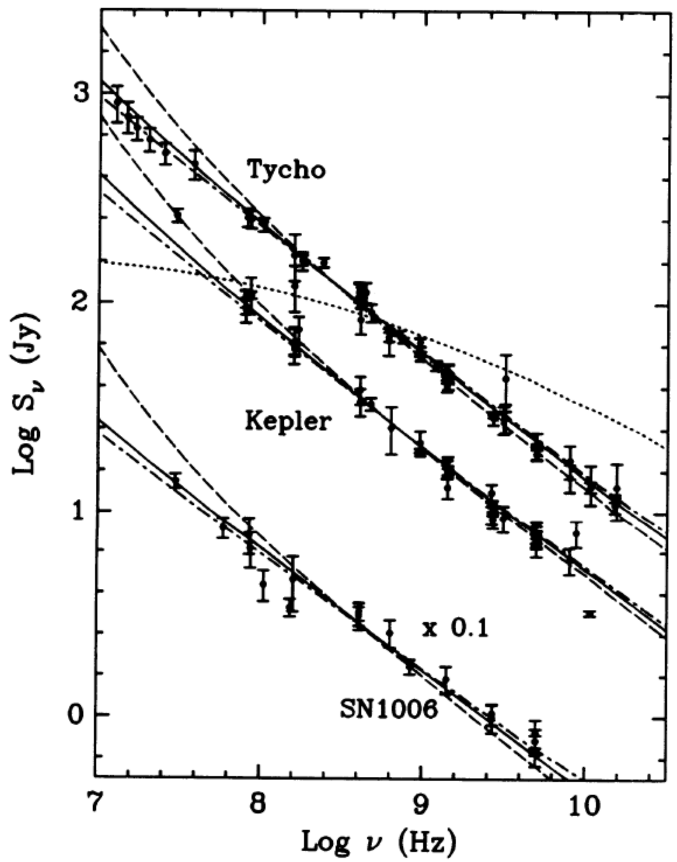
Young SNRs (curved spectra)



- Braude et al. (1970)

Young SNRs (curved spectra)

- Reynolds and Ellison (1992)



- Pure non-linear effect!

Evolved SNRs (linear spectra)

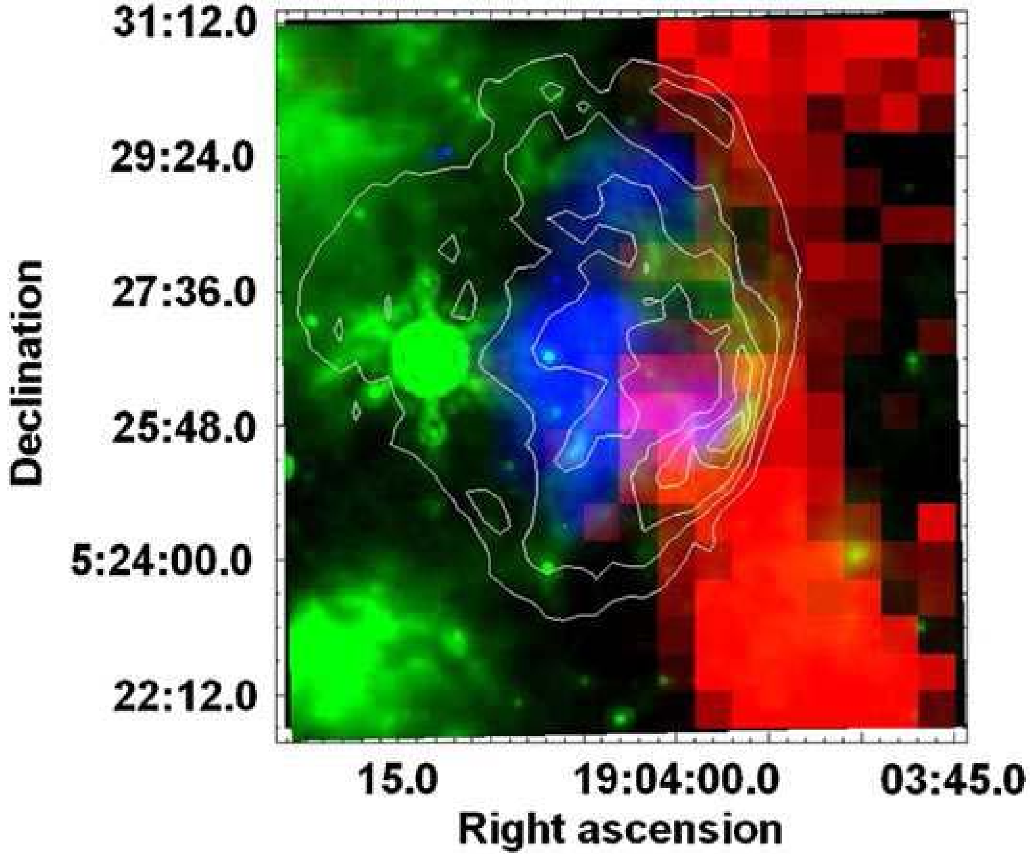
- Linear DSA predictions $\alpha=0.5$
- For older SNRs steeper than $\alpha=0.5$ (Bell 1978)
- Observations $0.5 < \alpha < 0.6$.

- Some SNRs with $\alpha < 0.5$
- Coupling of DSA and Fermi 2 acceleration

in turbulent downstream plasma near the shock (velocity diffusion)

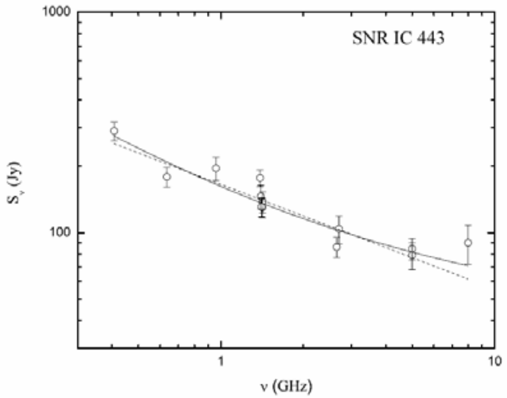
Schlickeiser and Furst (1989), Ostrowski (1999)

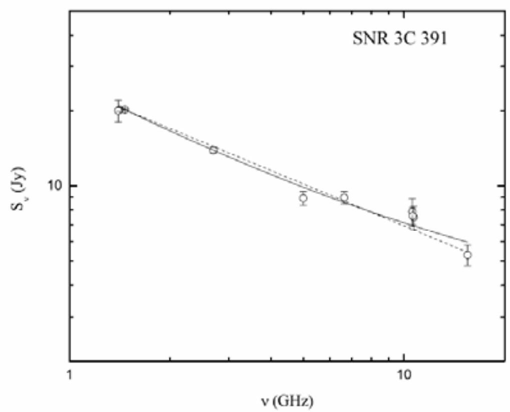
Evolved SNRs - curved (concave-up) spectra

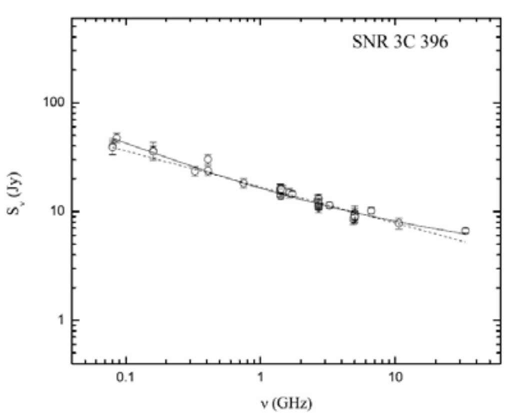


- Mixed-morphology and ”radio thermally active” SNR 3C 396 (Su et al. 2011)

Evolved SNRs - curved (concave-up) spectra







SYNCHROTRON

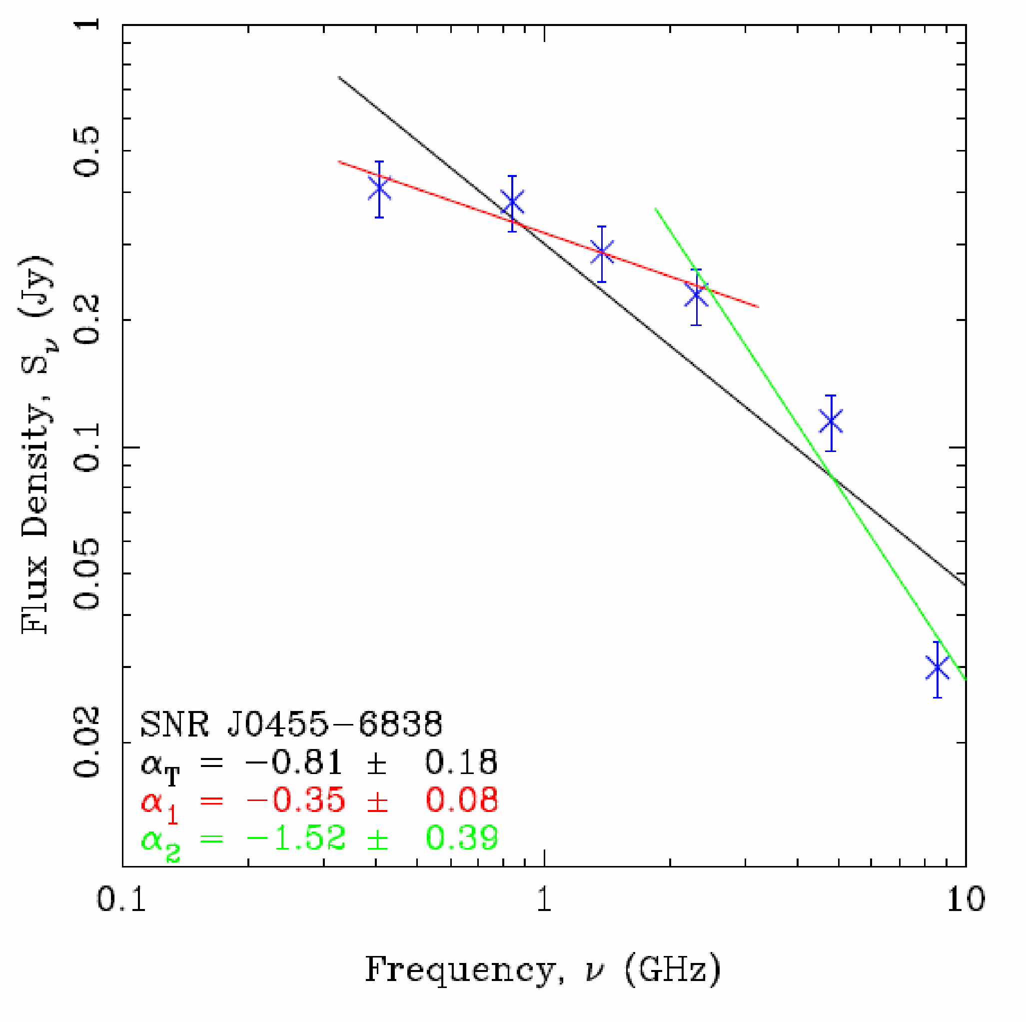
+

BREMSSTRAHLUNG

EMISSION

- Onić et al. (2012)
- Onić (2013a,b)

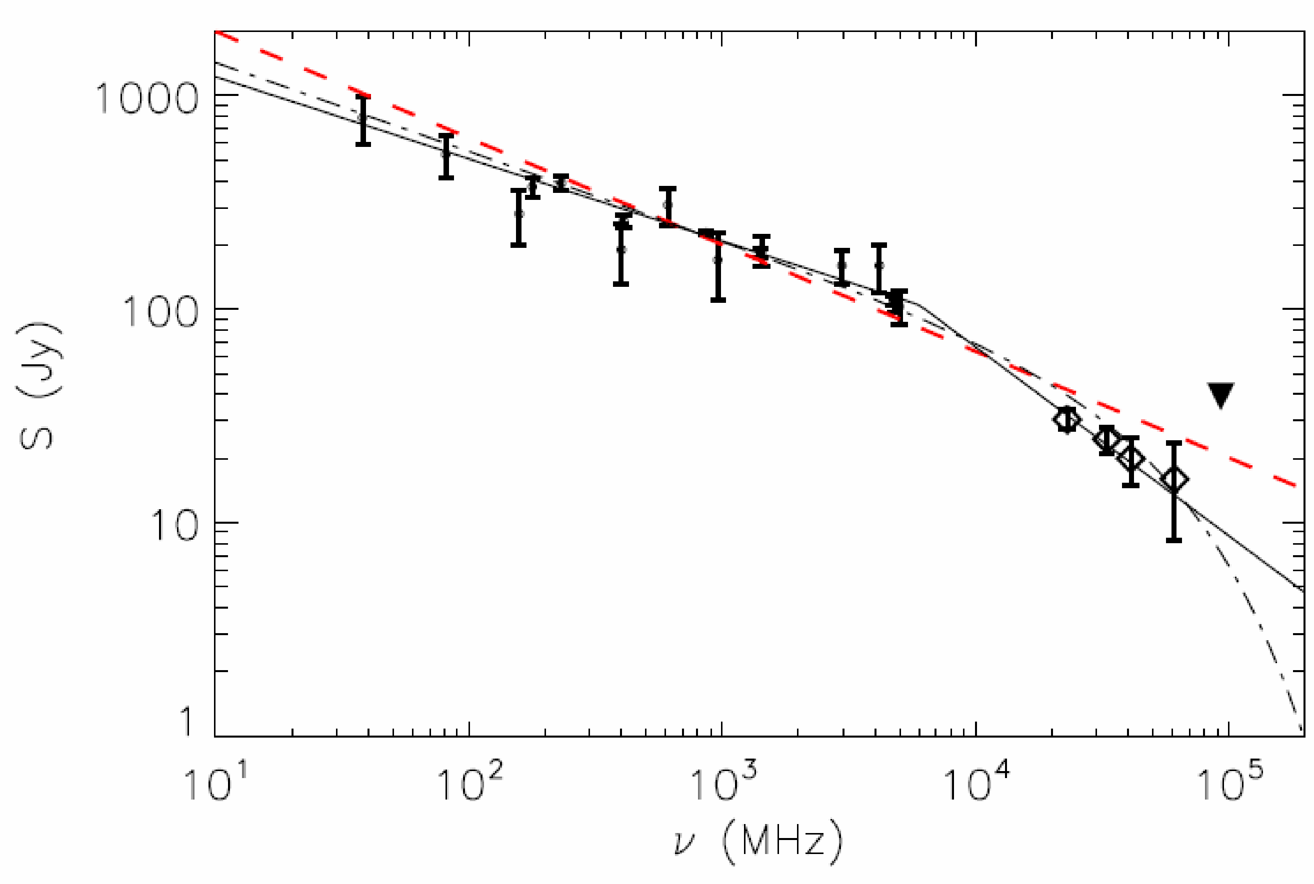
Evolved SNRs - curved (concave-down) spectra



- DSA theory with the effect of synchrotron losses within the finite emission region

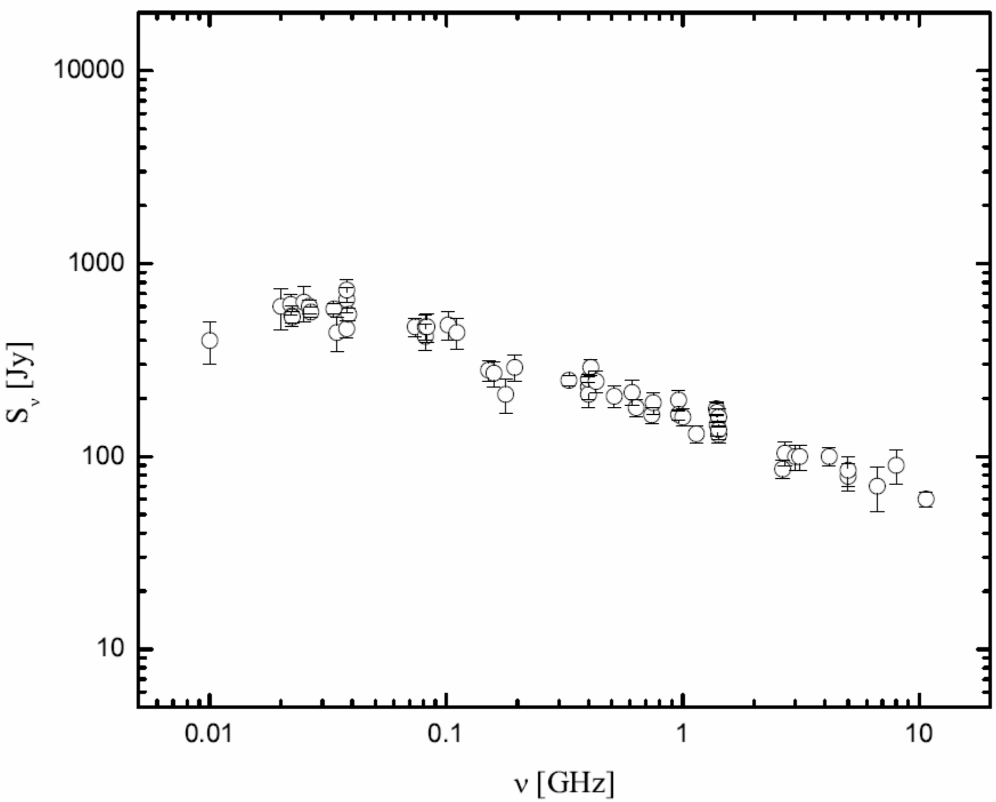
→ The radio spectrum of LMC SNR J0455-6838 (Crawford et al. 2008).

Evolved SNRs - curved (concave-down) spectra



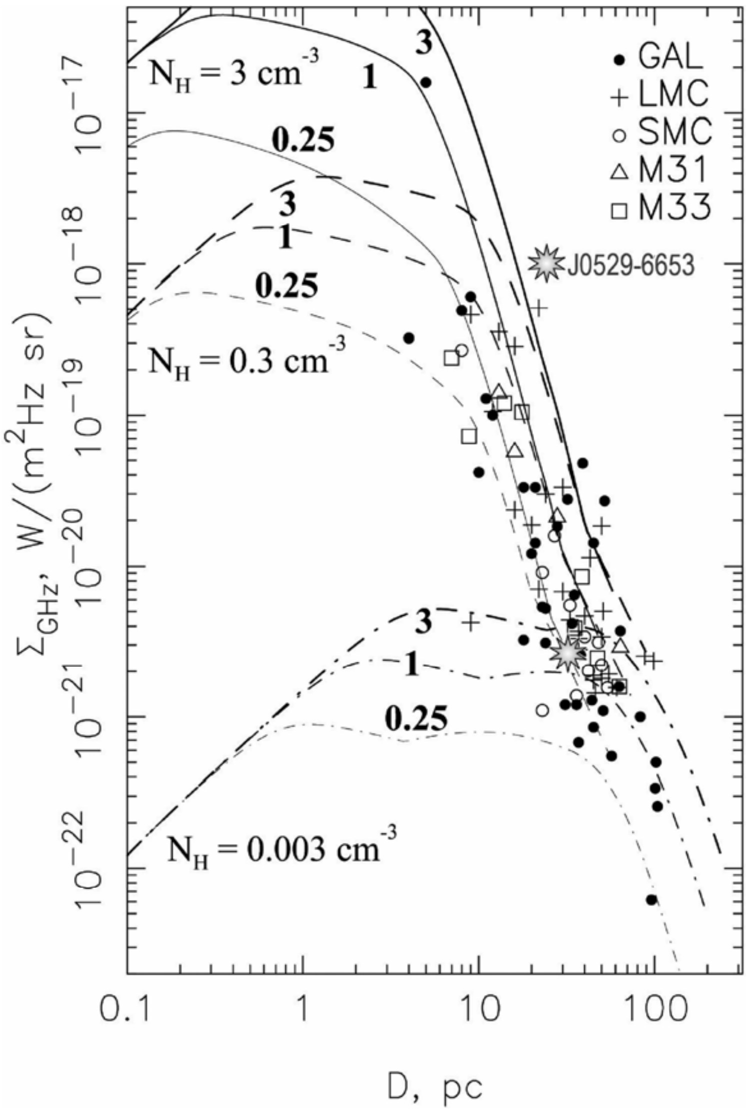
- Radio spectrum of HB21 (Pivato et al. 2013)

Evolved SNRs - curved (low-frequency absorption) spectra



The radio spectrum with the low-frequency turnover of SNR IC443 (Onić 2013a)

Σ-D relation; B from equipartition



http://poincare.matf.bg.ac.rs/~arbo/eqp/index.php

Summary

theoretical predictions					
	linear radio spectra			curved radio spectra	
	$\alpha = 0.5$	steep ($\alpha > 0.5$)	flat ($\alpha < 0.5$)	concave-up	concave-down
young SNRs	test particle DSA	ampl. mag. field + quasi-perp. shocks	DSA + Fermi 2	non-linear DSA	obs. effects + DSA effects
evolved SNRs	DSA	test particle DSA	DSA + Fermi 2	synch. + brem. or spin. dust	obs. effects + DSA effects

from observations					
	linear radio spectra			curved radio spectra	
	$\alpha = 0.5$	steep ($\alpha > 0.5$)	flat ($\alpha < 0.5$)	concave-up	concave-down
young SNRs	/	e.g. Cas A, G1.9+0.3	/	e.g. Tycho, Kepler, SN1006	/
evolved SNRs	e.g. Monoceros and Lupus loops	e.g. HB3, HB9	e.g. W28, Kes67, 3C434.1	e.g. IC443, 3C391, 3C396	e.g. S147, HB21, J0455-6838

THANK YOU VERY MUCH FOR YOUR ATTENTION!!!