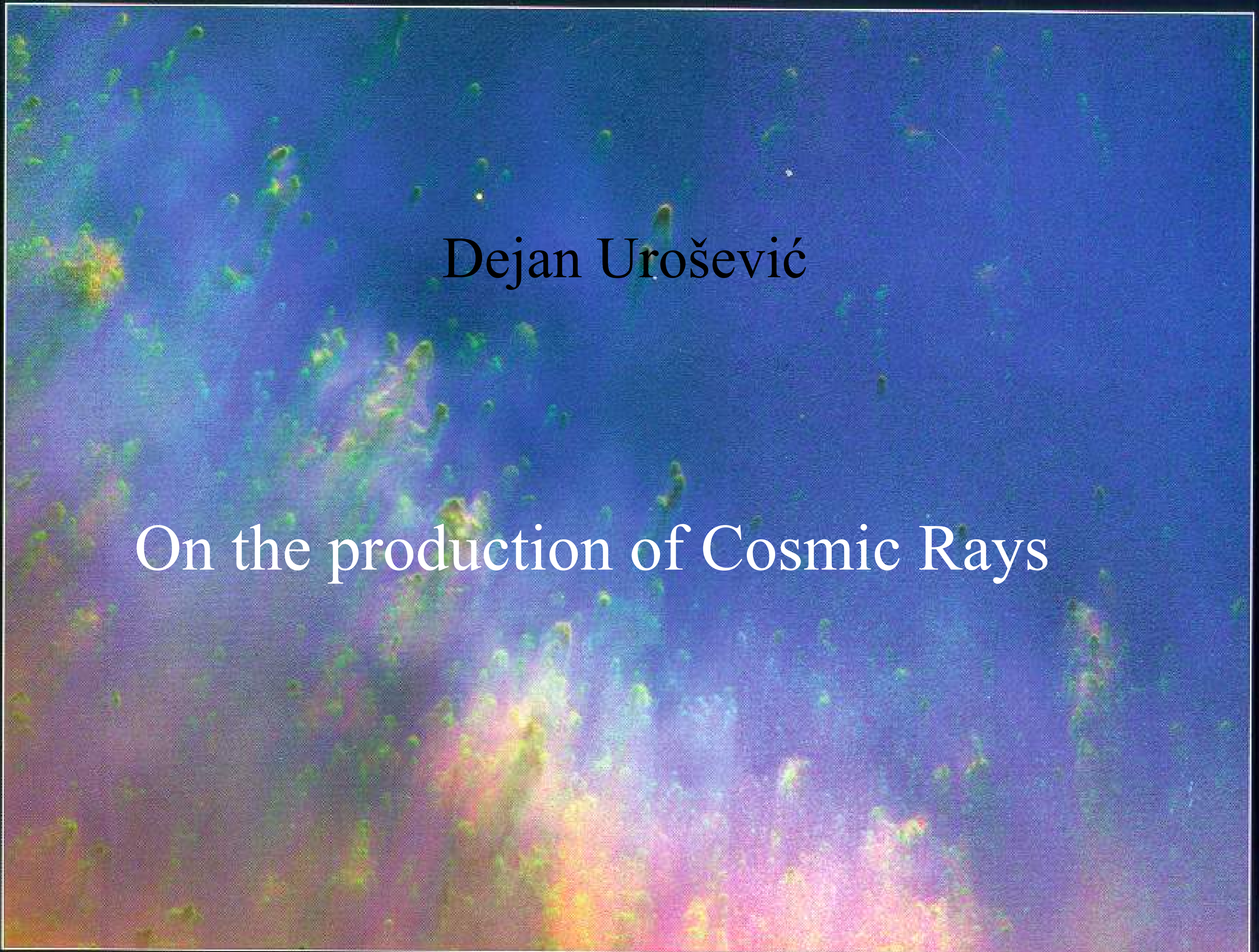
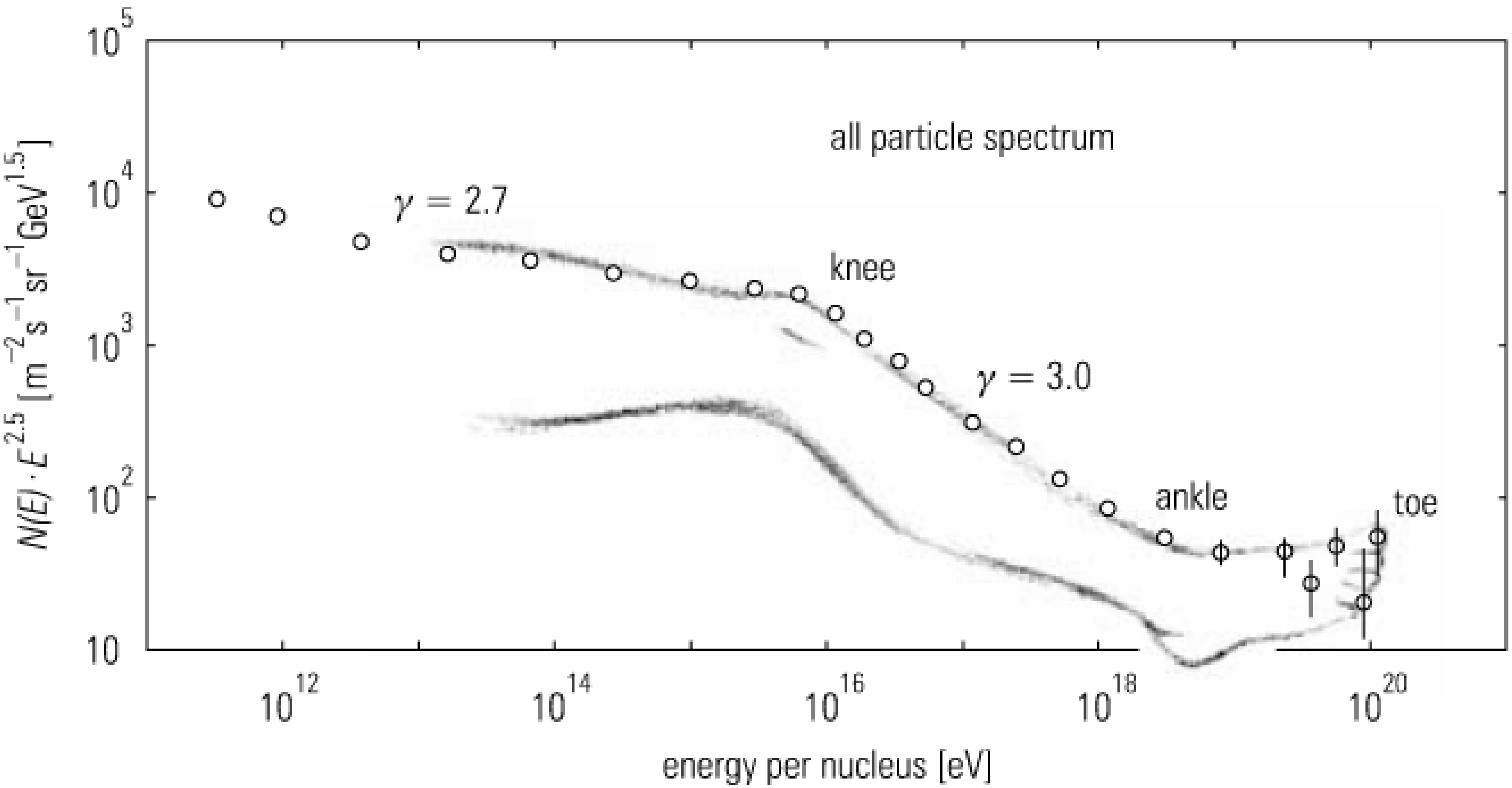

Dejan Urošević
On the production of Cosmic Rays

Cosmic Rays (CRs)

- Victor Hess discovered CRs (1912)
- Nobel Prize in Physics (1936)

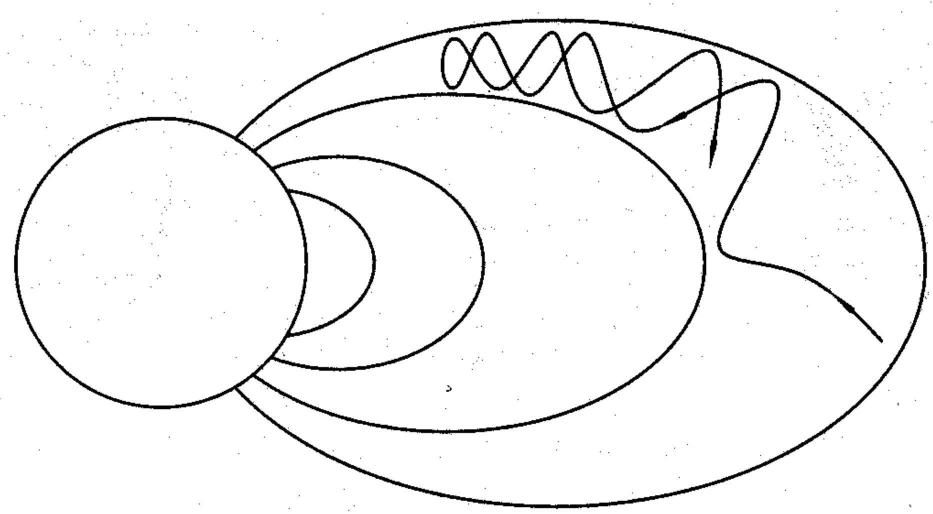


all particle spectrum
$\gamma = 2.7$
knee
$\gamma = 3.0$
ankle
toe
$N(E) \cdot E^{2.5}$ [$m^{-2}s^{-1}sr^{-1}GeV^{1.5}$]
10^5
10^4
10^3
10^2
10
10^{12}
10^{14}
10^{16}
10^{18}
10^{20}
energy per nucleus [eV]

- transverse adiabatic invariant (magnetic mirror)

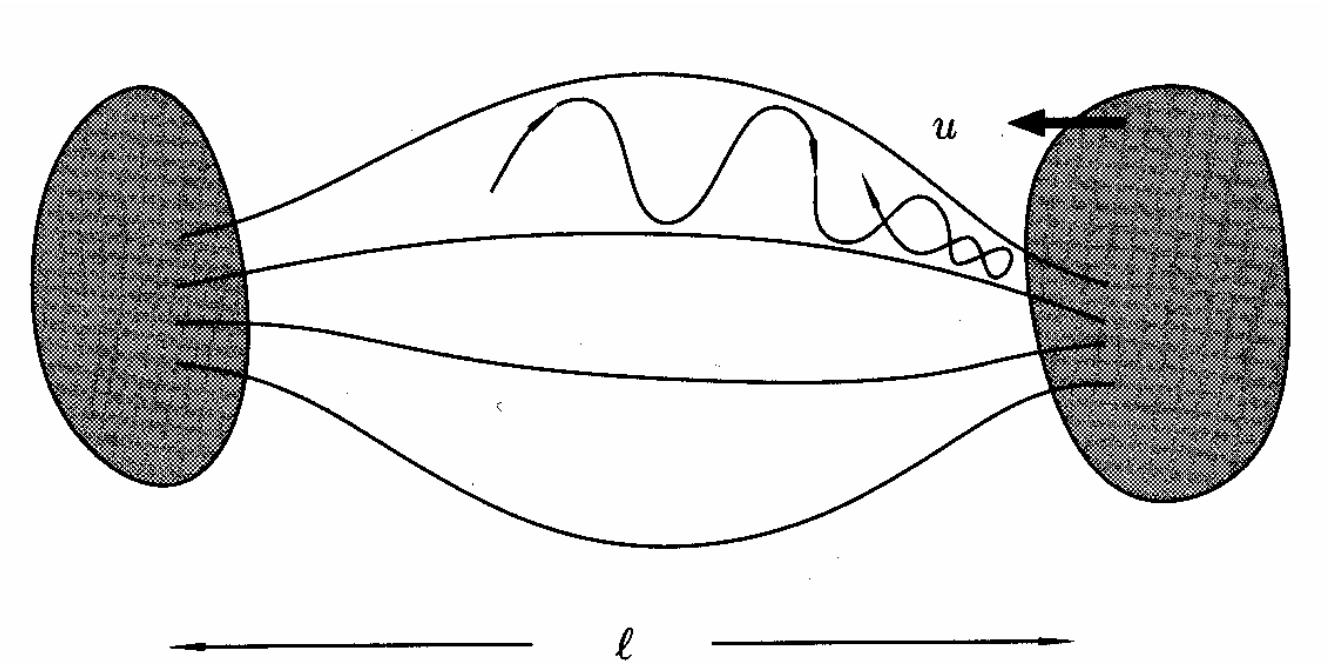
$$p_\perp^2 / B = \text{const.}$$

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



- longitudinal adiabatic invariant

$$J \equiv 1/(2\pi)\int p_{\parallel}\, dl \sim p_{\parallel} l = \text{const.}$$



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.

- The energy and momentum of the CR particle with respect to the reference frame of the magnetic perturbation that moving at velocity *U*:

$$E' = \gamma_U (E + U p_x)$$

$$\gamma_U = \sqrt{1 - U^2/c^2}$$

$$p'_x = \gamma_U (p_x + UE/c^2)$$

- The energy of a particle is conserved in an encounter ($E'_{\text{before}} = E'_{\text{after}}$), while momentum has opposite direction after collision!

- In the frame of reference of an observer:

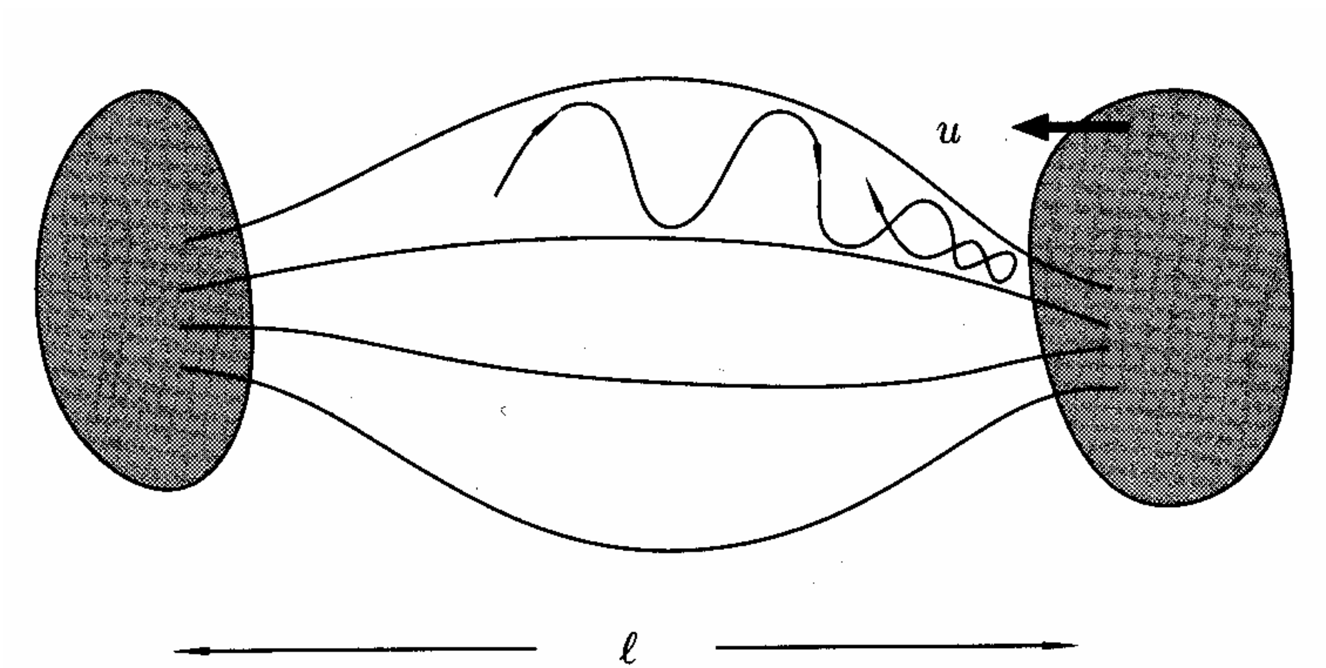
$$E'' = \gamma_U^2(E \pm 2U p_x + U^2) E/c^2)$$

- Using $p_x/E = p\cos\theta/E = v\cos\theta/c^2$

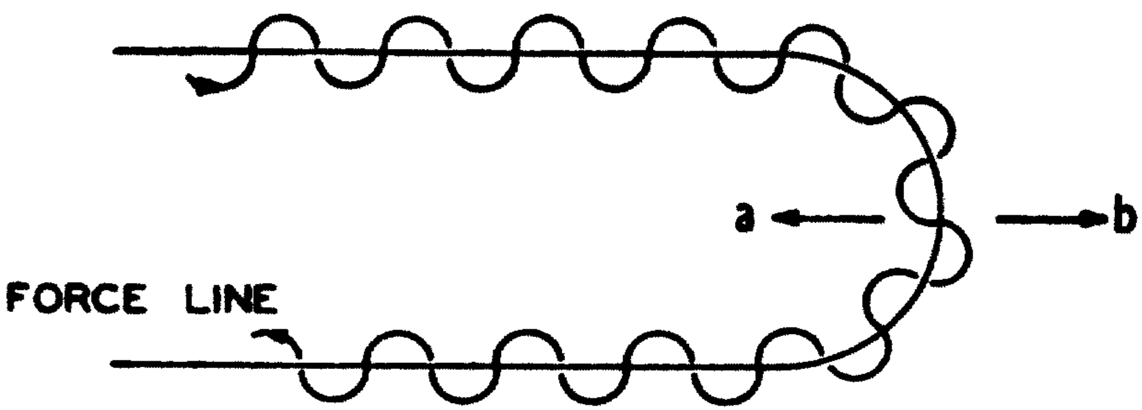
- The energy change is:

$$\frac{E''}{E} = \frac{(1 \pm 2(U/c)(v/c)\cos\theta + (U/c)^2}{1-(U/c)^2}$$

- Fermi acceleration (“Type A” in Fermi (1949))



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

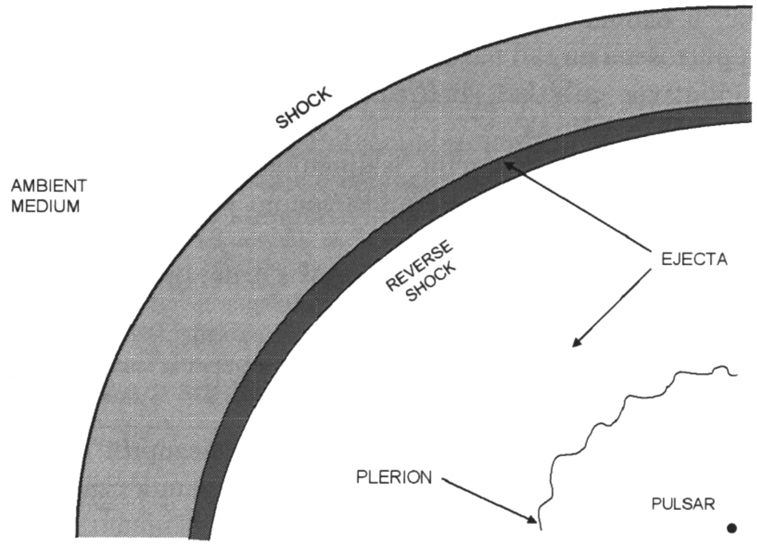


- In both cases

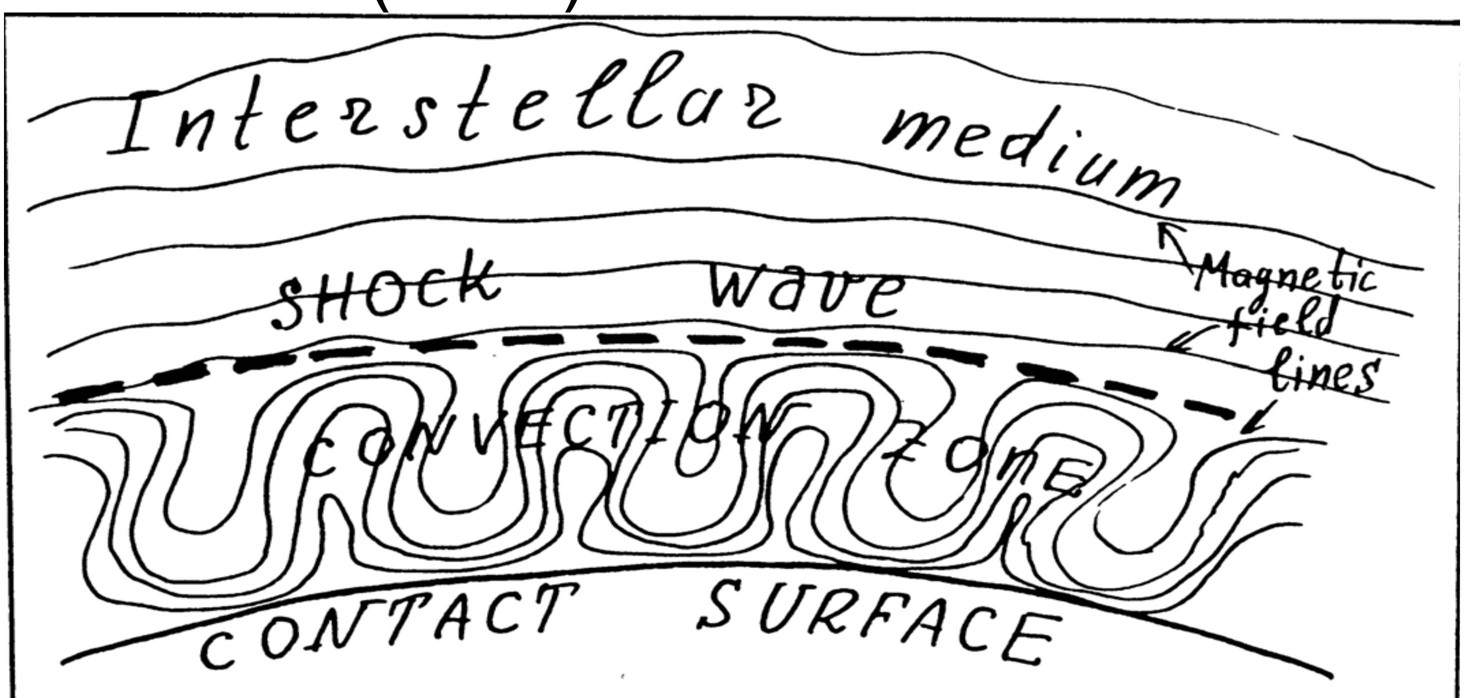
$$\Delta E / E \sim (v / c)^2$$

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

- diffuse shock acceleration – first order Fermi acceleration $\Delta E / E \sim v / c$
- Bell (1978a,b), Blandford & Ostriker (1978, 1980), Drury (1983a,b), Malkov & Drury (2001)

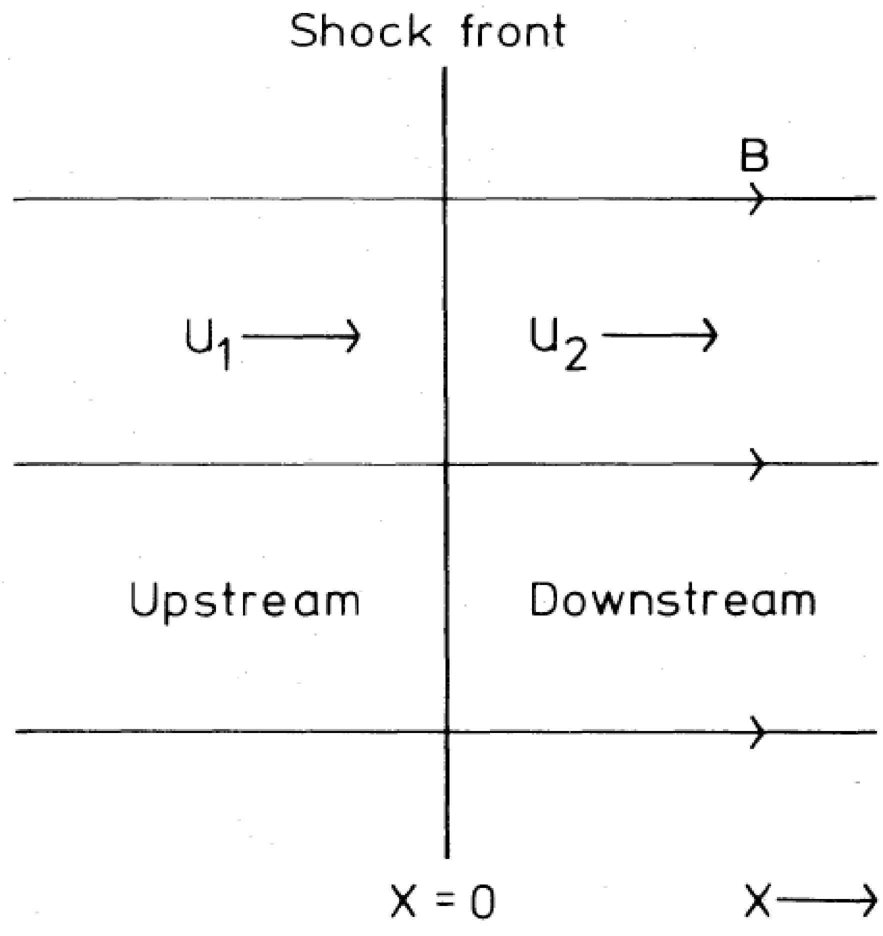


- second order Fermi acceleration – turbulences in downstream region
- Scott & Chevalier (1975), Galinsky & Shevchenko (2007)

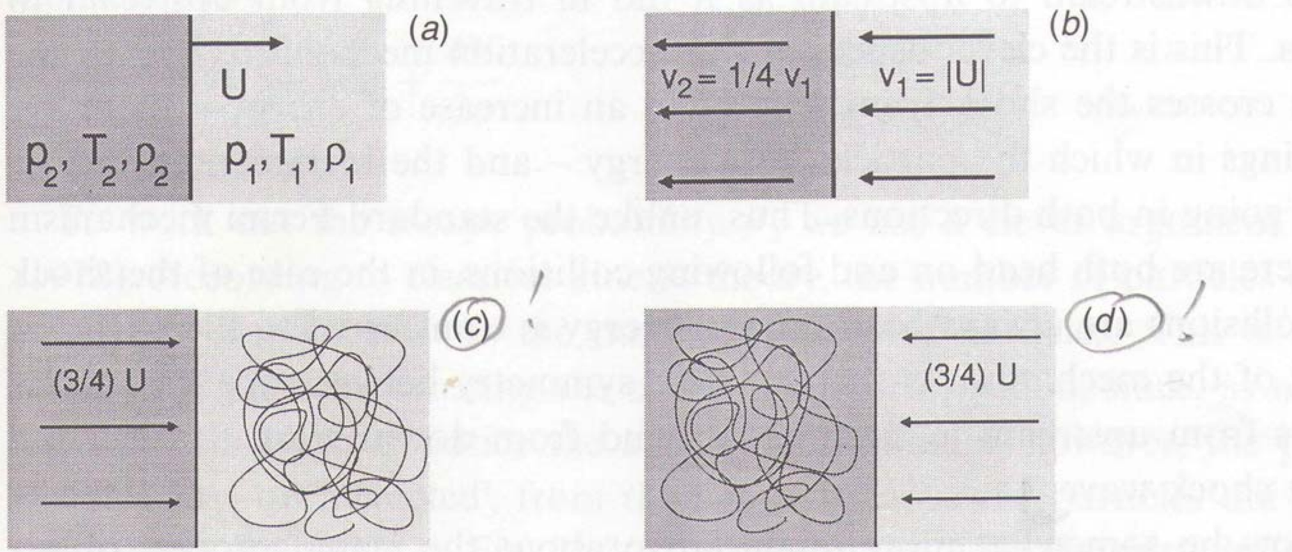


DSA – diffuse shock acceleration

Microscopic approach (Bell 1978a)



DSA – diffuse shock acceleration



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)

↓↓

RECROSSING FROM UPSTREAM TO DOWNSTREM

DSA – diffuse shock acceleration

After N cycles particle is

“diffuse shocked”

Particle “loses memory” about its initial spectrum

- If a particle goes from region 1 to region 2 its energy is:

$$E_2 = \gamma_U [E_k + (v_1 - v_2) p_{k1} \cos\theta_{k1}] = \gamma_U E_k \left[1 + (v_1 - v_2)\frac{v_{k1}\cos\theta_{k1}}{c^2}\right]$$

- When re-crosses the shock:

$$\frac{E_{k+1}}{E_k} = \gamma_U^2 \left[1 + (v_2 - v_1)\frac{v_{k2}\cos\theta_{k2}}{c^2}\right]\left[1 + (v_2 - v_1)\frac{v_{k1}\cos\theta_{k1}}{c^2}\right]$$

- After l cycles: $$\frac{E_l}{E_0} = \prod_{k=0}^{l-1} \frac{E_{k+1}}{E_k}$$ =>

$$\ln\left(\frac{E_l}{E_0}\right) = \ln\left\{\frac{1}{1-[(v_1-v_2)/c]^2}\right\}^l + \sum_{k=1}^{l-1} \ln\left(1+\frac{v_1-v_2}{c}\cos\theta_{k1}\right) + \sum_{k=1}^{l-1} \ln\left(1+\frac{v_2-v_1}{c}\cos\theta_{k2}\right).$$

- $l \sim c/(v_1-v_2)$ =>

$$l = O\left(\frac{c}{v_1-v_2}\right) = \frac{c}{v_1-v_2}\left[1+1/O\left(\frac{c}{v_1-v_2}\right)\right] = \frac{c}{v_1-v_2}\left[1+O\left(\frac{v_1-v_2}{c}\right)\right],$$

- The energy gain in each cycle is approximately the same =>

$$\ln\left(\frac{E_1}{E_0}\right) = l\,\ln\left\{\frac{1}{1-[(v_1-v_2)/c]^2}\right\}$$
$$+l\left\langle \ln\left(1+\frac{v_1-v_2}{c}\cos\theta_{k1}\right)\right\rangle + l\left\langle \ln\left(1+\frac{v_1-v_2}{c}\cos\theta_{k2}\right)\right\rangle.$$

- Averaging over angles 0 to *π*/2 for index 1, and from *π* to *π*/2 for index 2 =>

$$\ln\left(\frac{E_l}{E_0}\right) = \frac{4}{3}\,l\,\frac{v_1-v_2}{c}\left[1+O\left(\frac{v_1-v_2}{c}\right)\right]$$

- The probability P_l of a particle completing at least l cycles, and therefore of reaching an energy E_l:

$$P_l = \ln(1-\eta) = \ln\left(1 - \frac{4v_2}{c}\right)$$
$$= \frac{3v_2}{v_1 - v_2} \ln\left(\frac{E_l}{E_0}\right)\left[1 + O\left(\frac{v_1 - v_2}{c}\right)\right].$$

- When $l \rightarrow \infty$ => $\int_{E_0}^{\infty} P(E)dE = C\,E_0 \int_{E_0}^{\infty} \left(\frac{E}{E_0}\right)^{-\mu} \frac{dE}{E_0} = 1$

- Finally:

$$N(E) \propto \left(\frac{\mu - 1}{E_0}\right)\left(\frac{E}{E_0}\right)^{-\mu},$$

$$\mu = \frac{2v_2 + v_1}{v_1 - v_2}\left[1 + O\left(\frac{v_1 - v_2}{c}\right)\right]$$

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 ($v_1=4v_2$)

$$\mu=2$$

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 $M \rightarrow \infty$

$$\downarrow\downarrow$$

$$N(p)dp = 4\pi p^2 f(p)dp$$

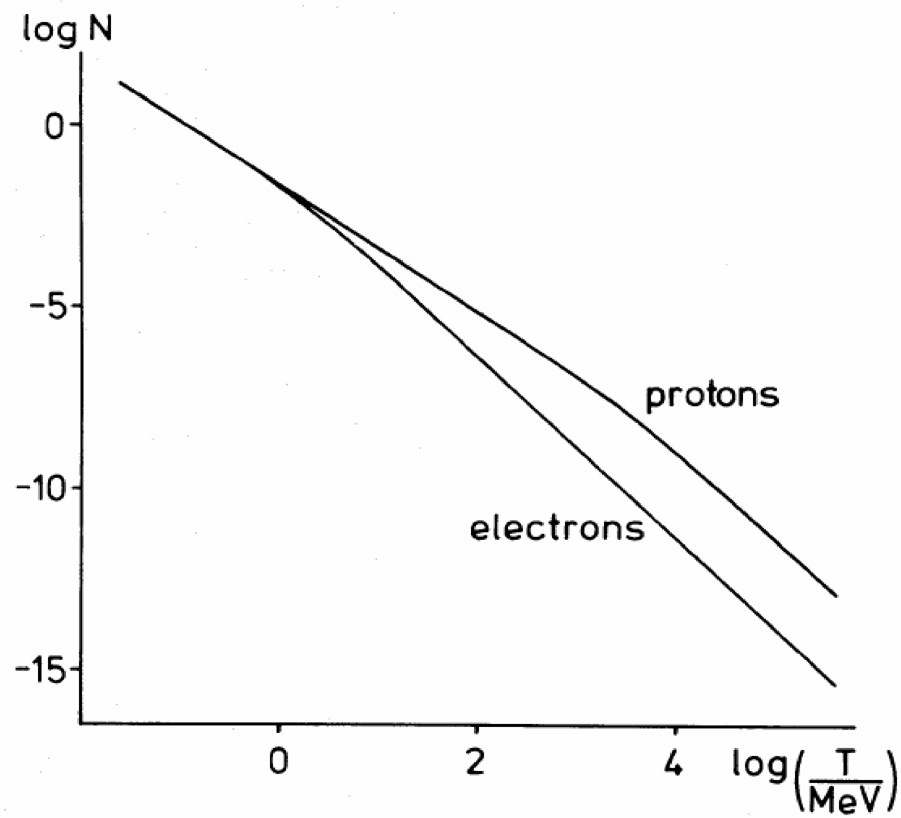
DSA - SNRs

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

(Blandford & Ostriker 1978)

* Still, the particle injection stays as an open problem

Injection (Bell 1978b) → $E_{inj} = 4(1/2 m_p v_s^2)$



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

MODIFIED SHOCKS

Non-linear effects

Including of cosmic ray (CR) pressure

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

In early phases of SNR evolution non-linear DSA provides more efficient acceleration and therefore increase in object brightness!!!

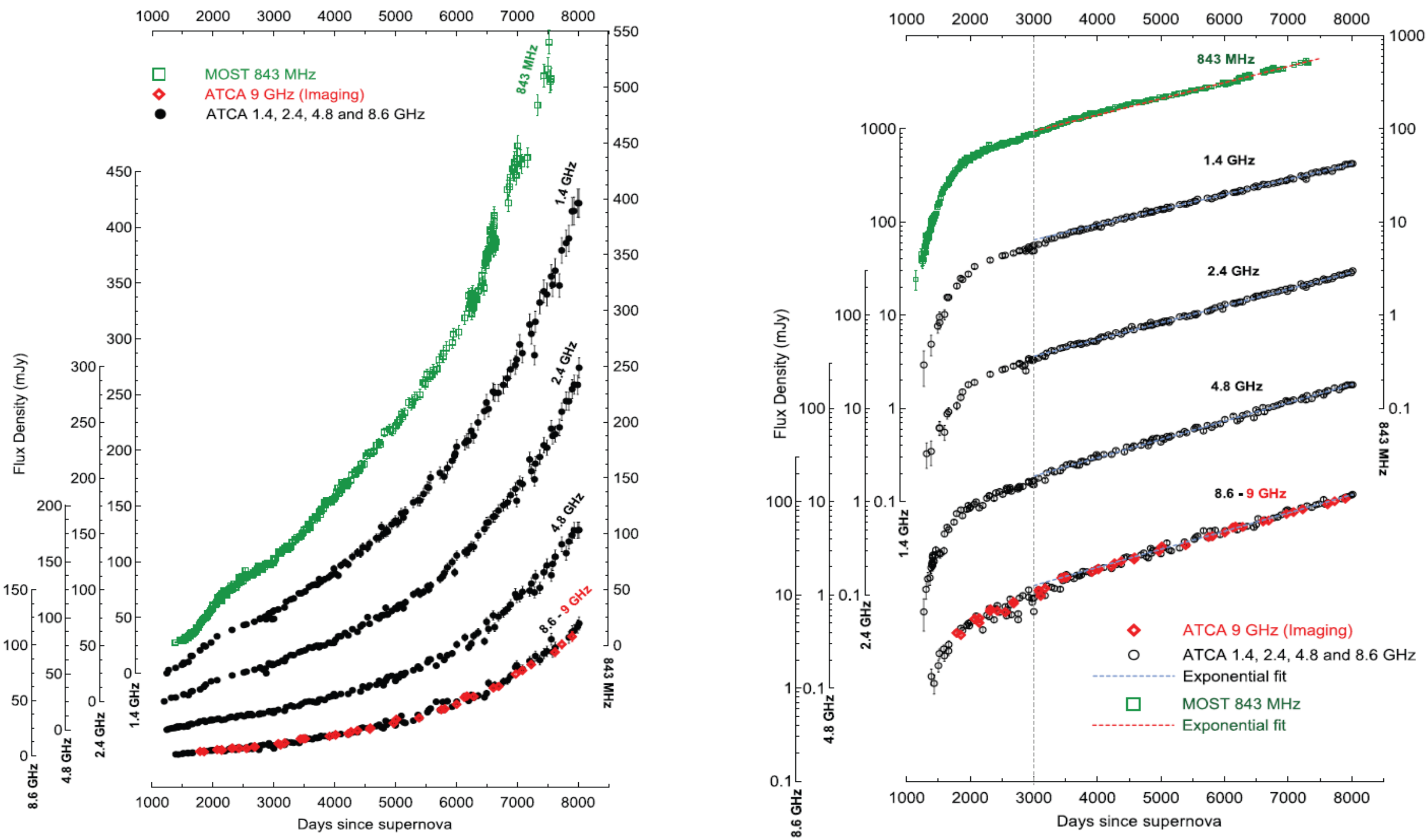
Bell’s (2004) instabilities produces
(in the early free expansion phase)

↓↓

amplification of the magnetic field ~ 100 times, by the non-linear effects!!!

SURFACE BRIGHTNESS OF AN VERY YOUNG SNR INCREASES WITH TIME!!!

SNR 1987A (Zanardo et al. 2010)



- Summary for DSA:

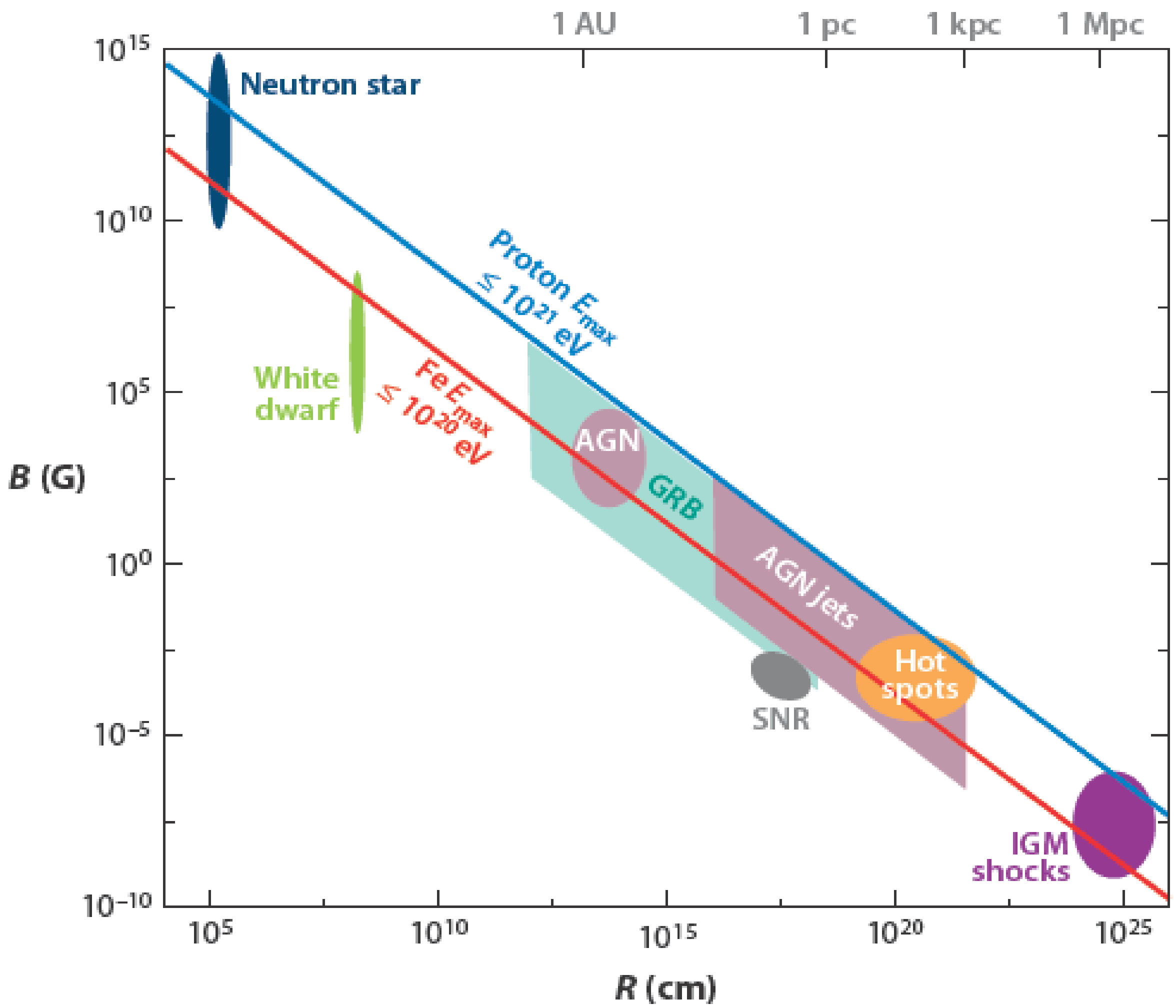
  - in SNR blast wave, DSA mechanism can provide energy/particle → 10^{15} eV

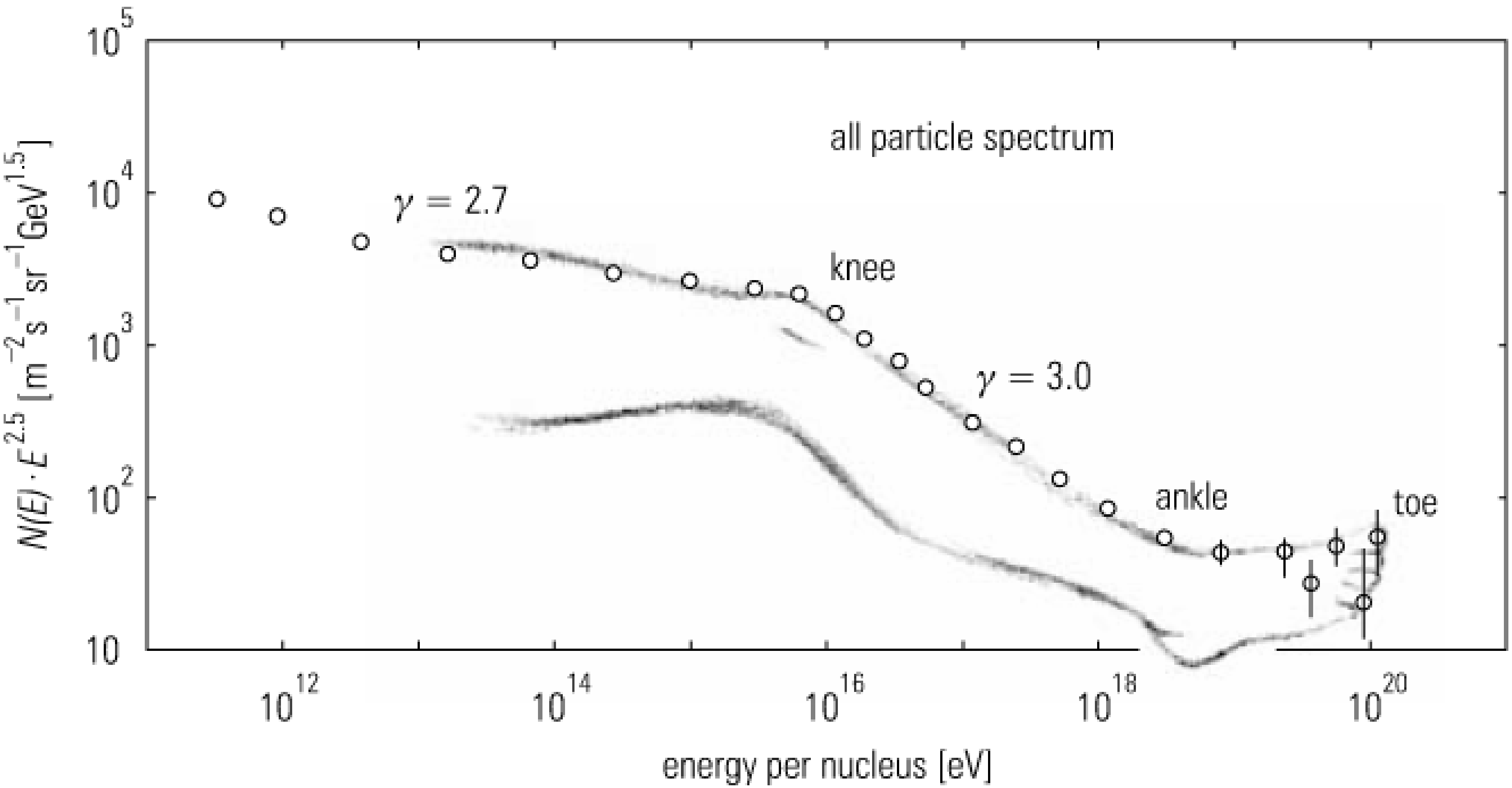
  - non-linear DSA → $10^{17} – 10^{18}$ eV

  - detected CR particles at ~ 10^{21} eV

  (LHC ~ 10^{12} eV)

Candidate sources for UHECRs





all particle spectrum
$\gamma = 2.7$
knee
$\gamma = 3.0$
ankle
toe
$N(E) \cdot E^{2.5}$ [$m^{-2}s^{-1}sr^{-1}GeV^{1.5}$]
energy per nucleus [eV]
10^5
10^4
10^3
10^2
10
10^{12}
10^{14}
10^{16}
10^{18}
10^{20}

THANK YOU VERY MUCH FOR YOUR ATTENTION!!!