Evolution of Supernova Remnants and Particle Acceleration

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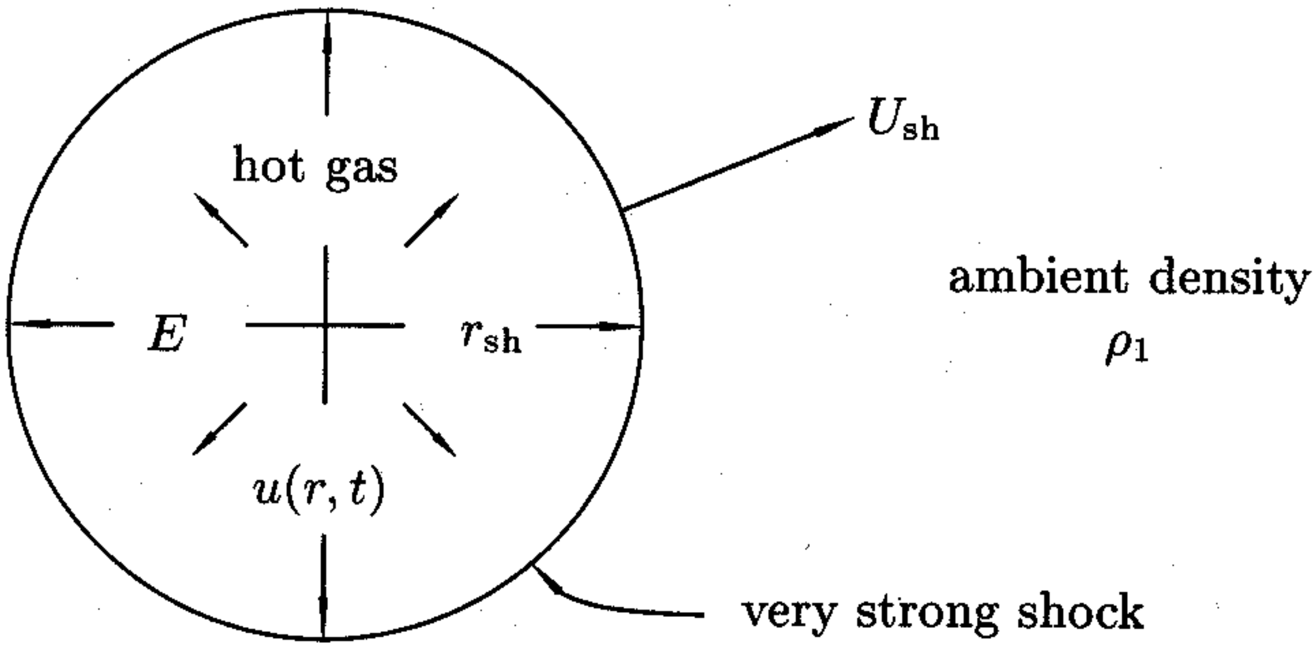
Workshop „Interstellar Medium in the Nearby Universe“, Bamberg, 26-28 March, 2018

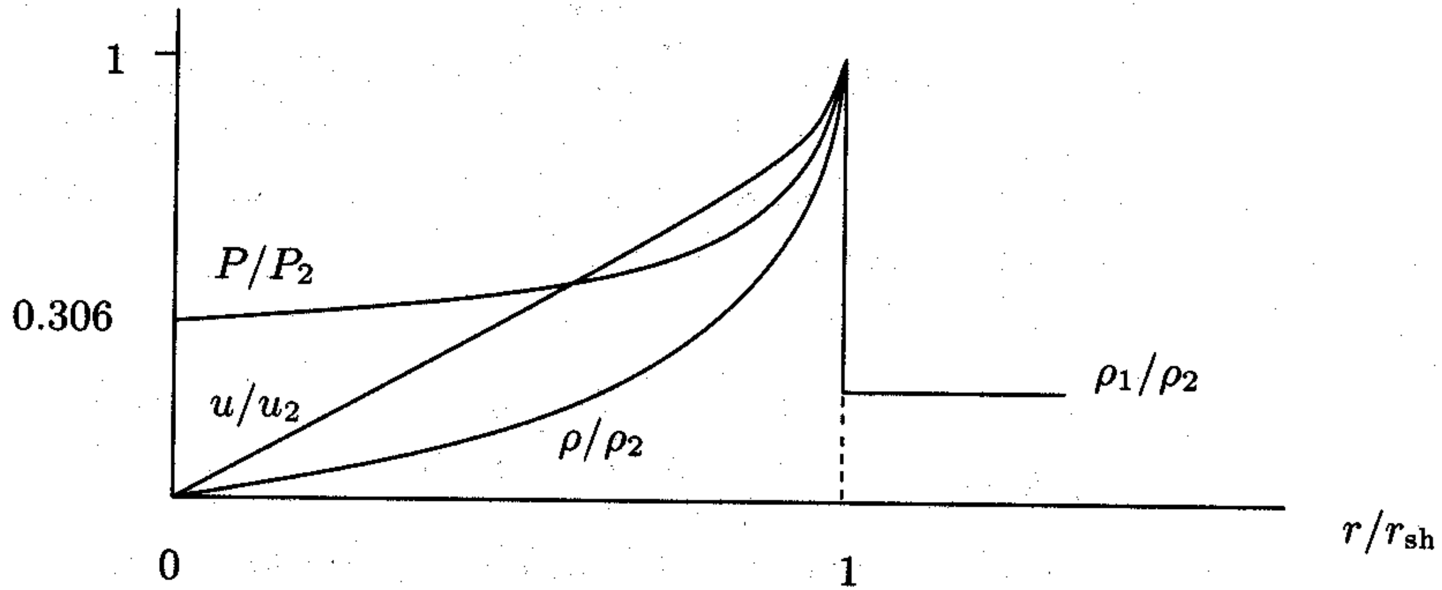
Blast Waves and Supernova remnants

- the point release of a large amount of energy creates a spherical blast wave



Blast Waves and Supernova remnants

- the blast wave solution - Sedov and Taylor
  $r \sim t^{2/5}$

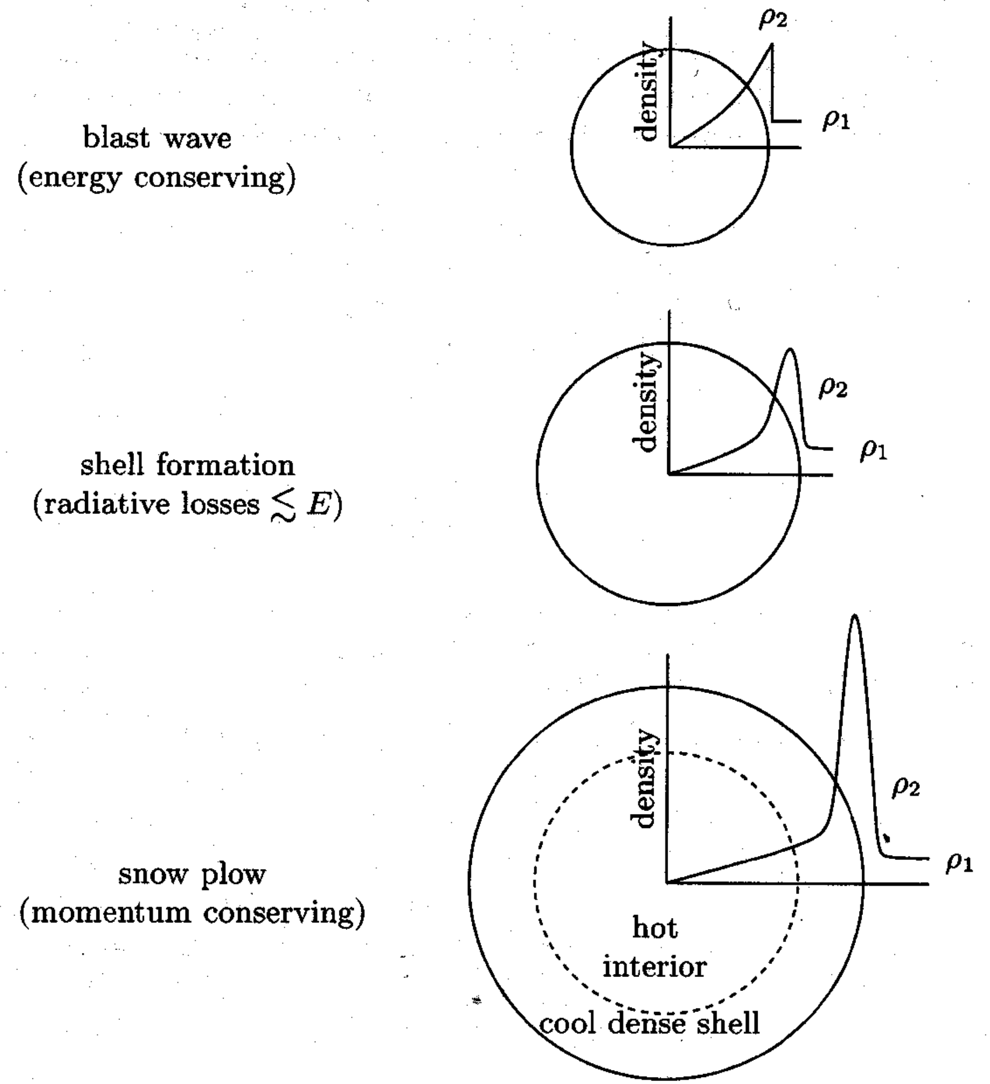


Blast Waves and Supernova remnants

- compression:

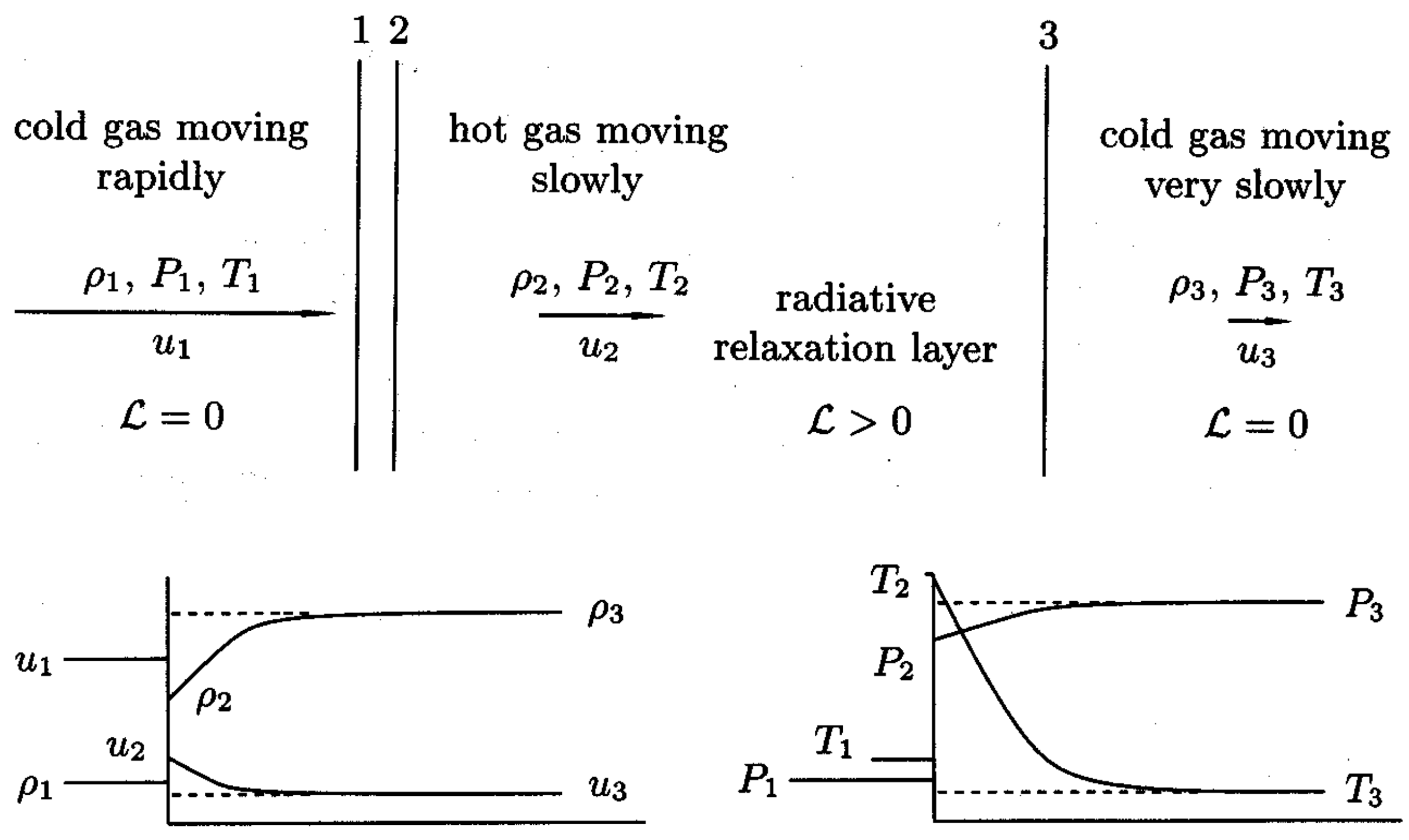
$$\rho_2/\rho_1=4$$

HD phases of an SNR evolution



HD phases of SNR evolution

- radiative shocks



HD phases of SNR evolution

- isothermal shock

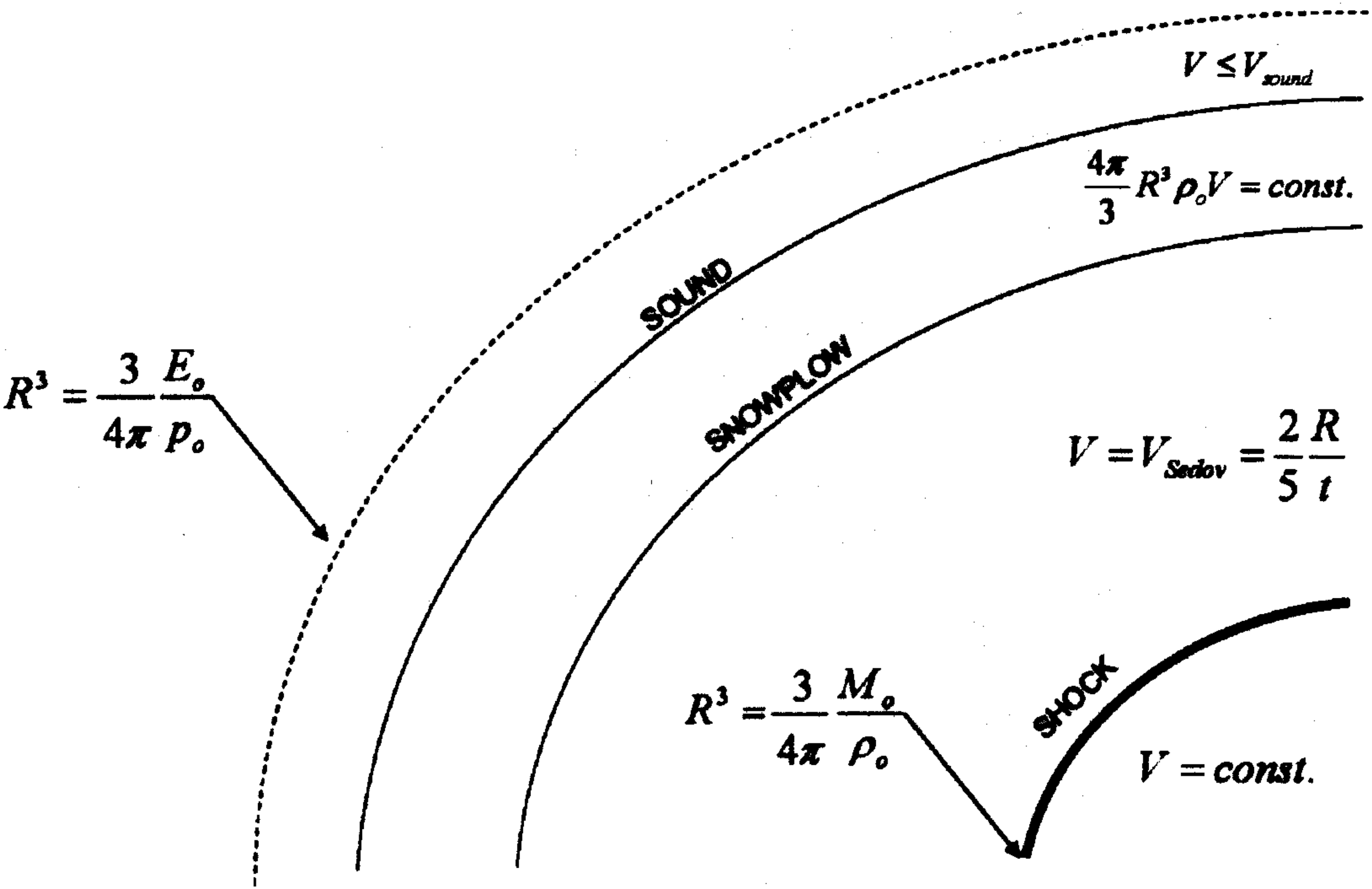
  compression:

$$\rho_2 / \rho_1 \sim (\text{Mach number})^2$$

$$\text{Mach number} = u_1 / v_{s,T}$$

HD phases of SNR evolution

- First phase – free expansion phase ($M_s < M_e$), till 3/4$E_k \rightarrow U$ ($M_s \approx 3M_e$), (for 1/2$E_k \rightarrow U$, $M_s \approx M_e$).
- Second phase – Sedov (energy conserving) phase ($M_s >> M_e$) till 1/2$E_k \rightarrow$ radiation
- Third phase – radiative (isothermal) phase – formation of thick shell
- Forth phase – dissipation into ISM



$V \le V_{sound}$
$\frac{4\pi}{3} R^3 \rho_o V = const.$
SOUND
SNOWPLOW
$R^3 = \frac{3}{4\pi} \frac{E_o}{p_o}$
$V = V_{Sedov} = \frac{2}{5} \frac{R}{t}$
SHOCK
$R^3 = \frac{3}{4\pi} \frac{M_o}{\rho_o}$
$V = const.$

Cosmic Rays (CRs)

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

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 magnetic 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.

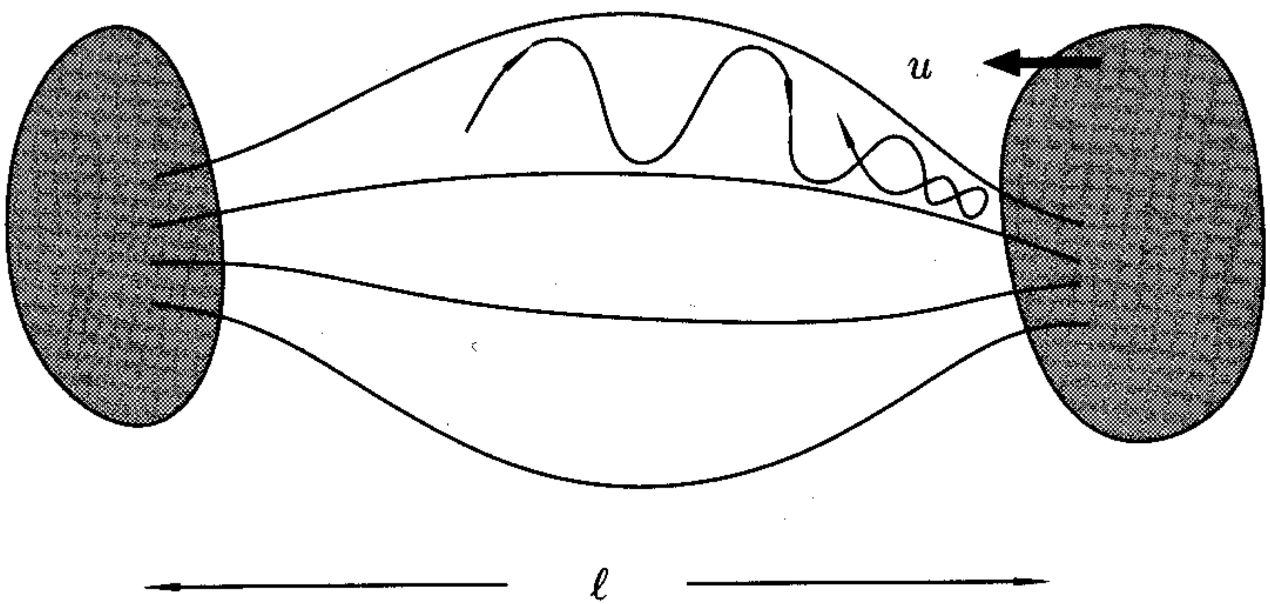
I. INTRODUCTION

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.

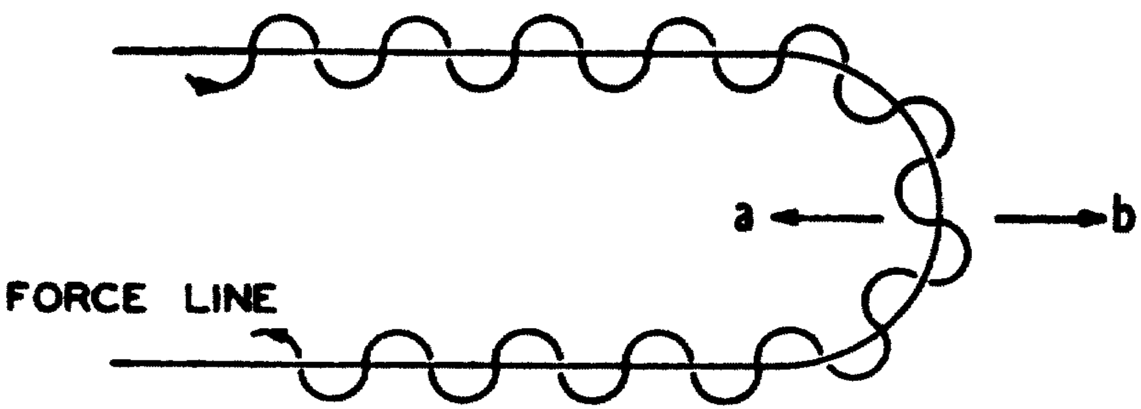
where H is the intensity of the magnetic field and ρ is the density of the interstellar matter.

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

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

Diffuse Shock Acceleration (DSA)

- first order Fermi acceleration

$$\Delta E / E \sim v / c$$

- Bell (1978a,b), Blandford & Ostriker (1978, 1980), Drury (1983a,b), Malkov & Drury (2001)

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 ($v_1=4v_2$)

$$\mu=2 \Leftrightarrow \alpha=0.5$$

It is way for creation of:

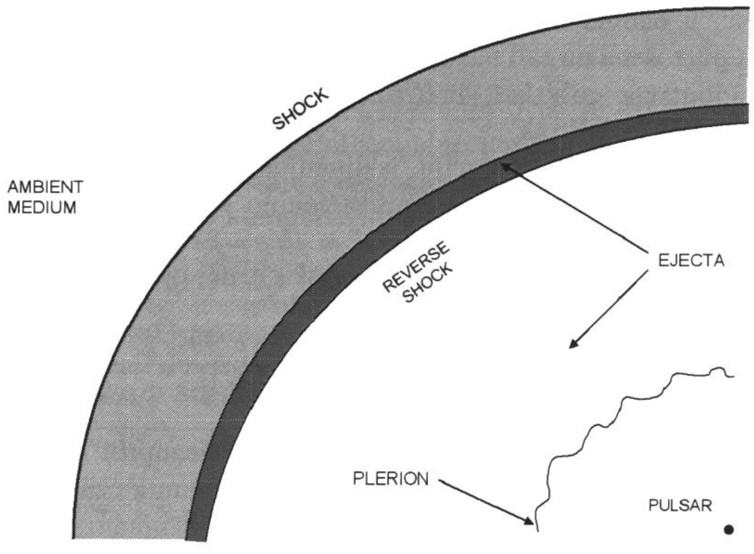
CRs (ultra-relativistic electrons)

↓

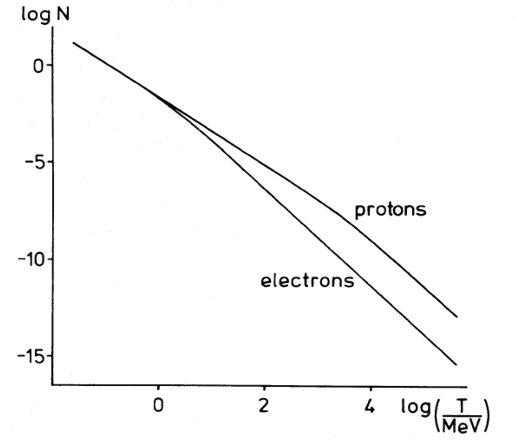
radio and X-ray synchrotron emission, gamma-ray emission by: inverse Compton scattering, non-thermal bremsstrahlung and pion decay

(SNRs, AGN, PSRs, PWN…)

DSA - SNRs



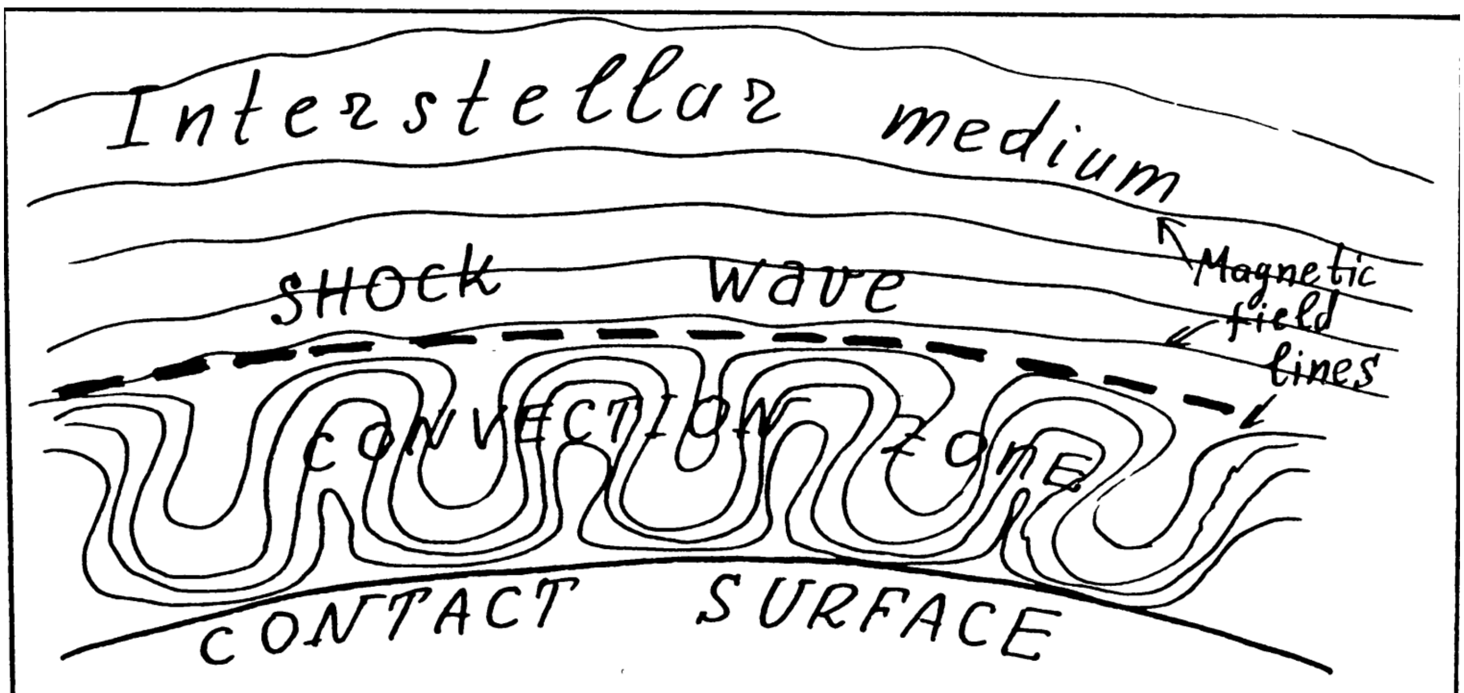
Energy spectra for CR protons and electrons
(Bell 1978b)



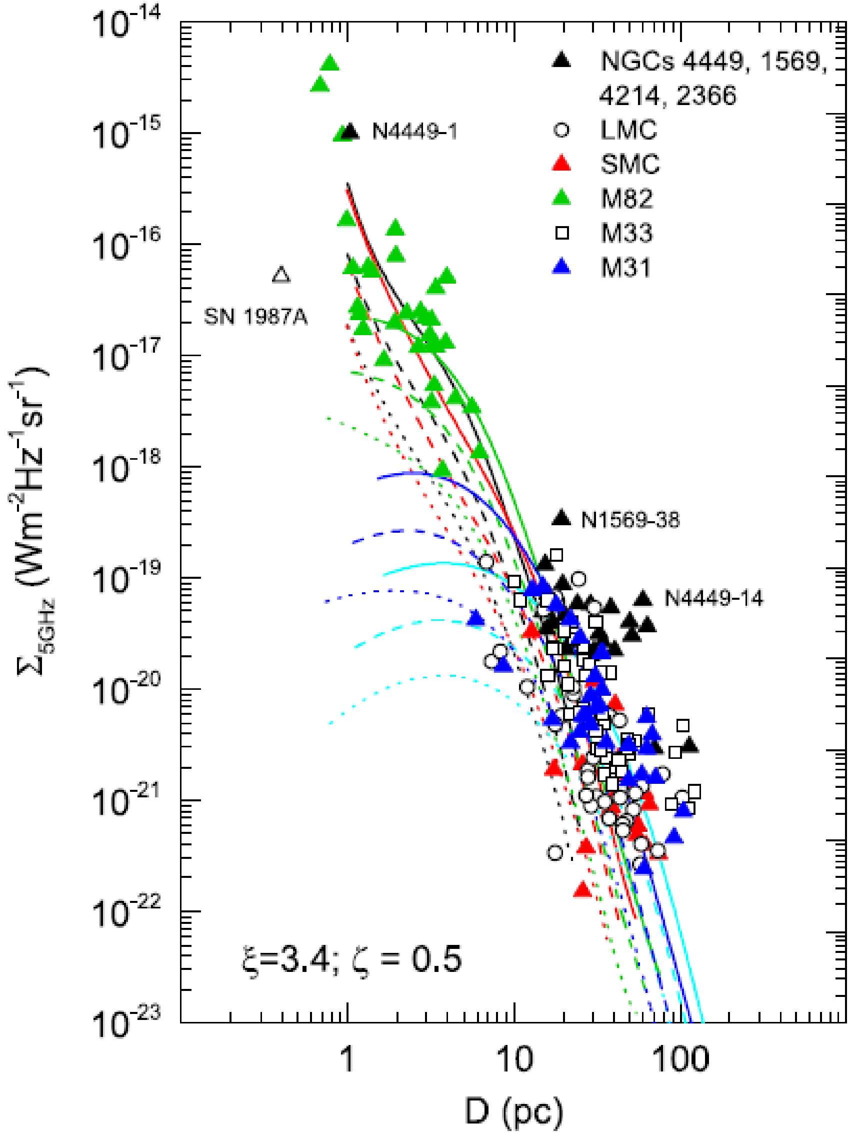
The energy spectra of protons and electrons injected at an energy $T_0 = 10\,\text{keV}$.

SNRs – second order Fermi acceleration

- turbulences in downstream region
- Scott & Chevalier (1975), Galinsky & Shevchenko (2007)



Evolution of SNRs in radio and particle acceleration



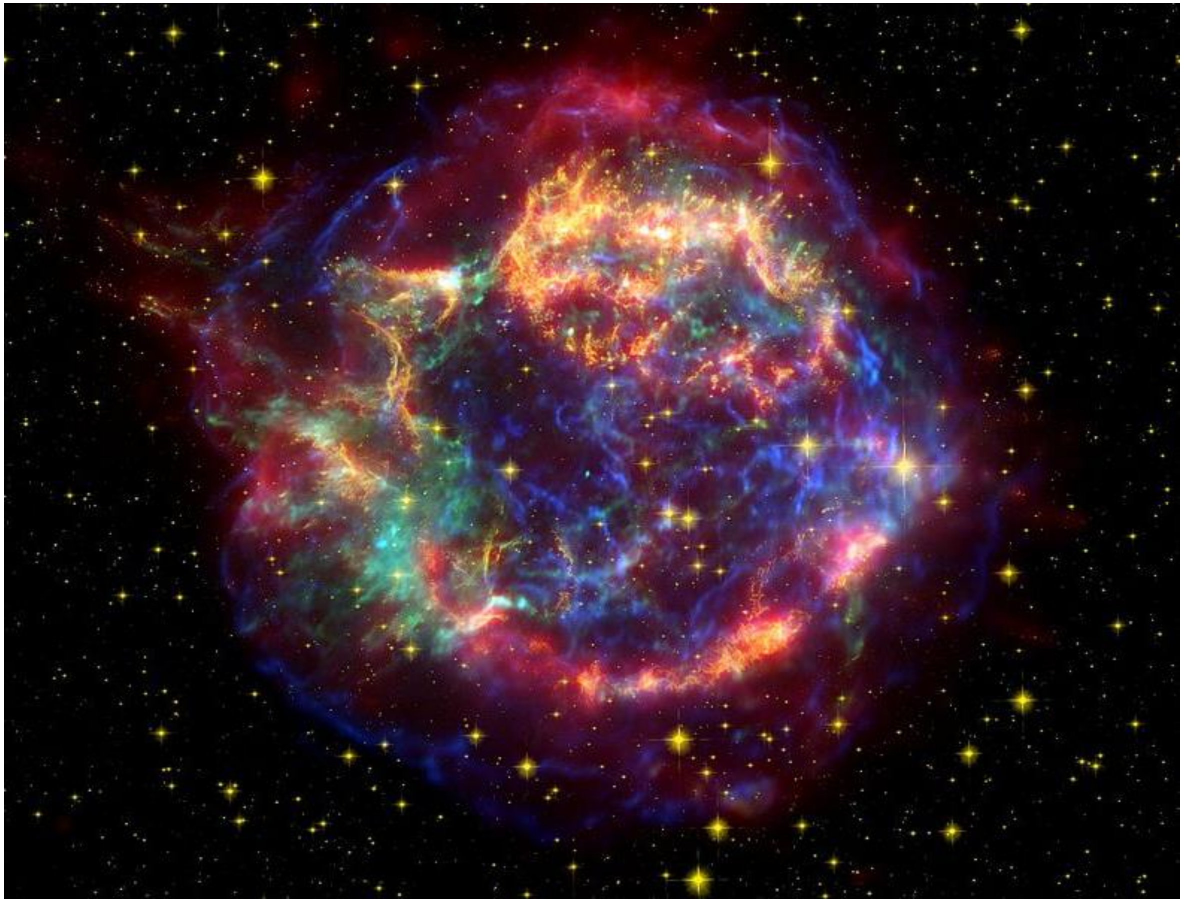
Pavlović et al. (2018)

Evolution of SNRs in radio and particle acceleration

More details in today talk of Marko Pavlović – this session (11:40)

Radio spectra of SNRs and particle acceleration

Young SNRs



- Observations – steeper than $\alpha=0.5$ spectral indices!

Non-linear DSA

MODIFIED SHOCKS

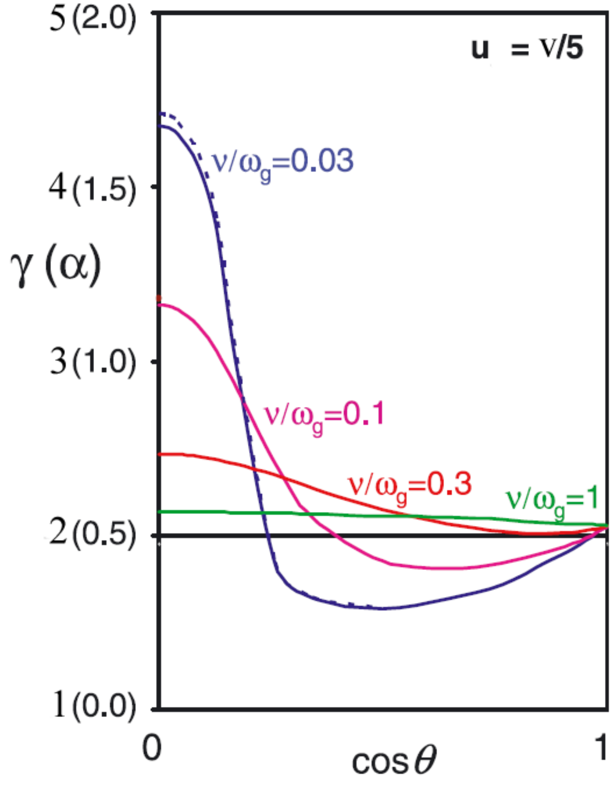
Non-linear effects

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)

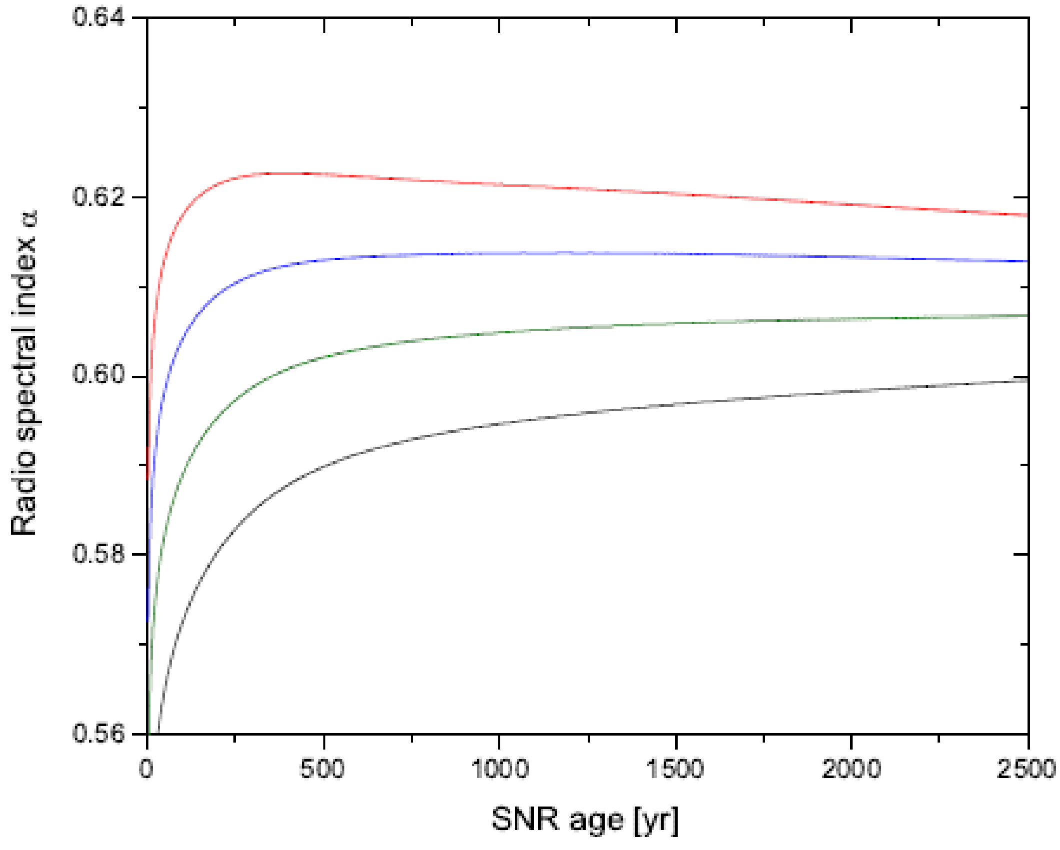
$$M_{\mathrm{A}} = u_1/v_{\mathrm{A}} = 1/B$$

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

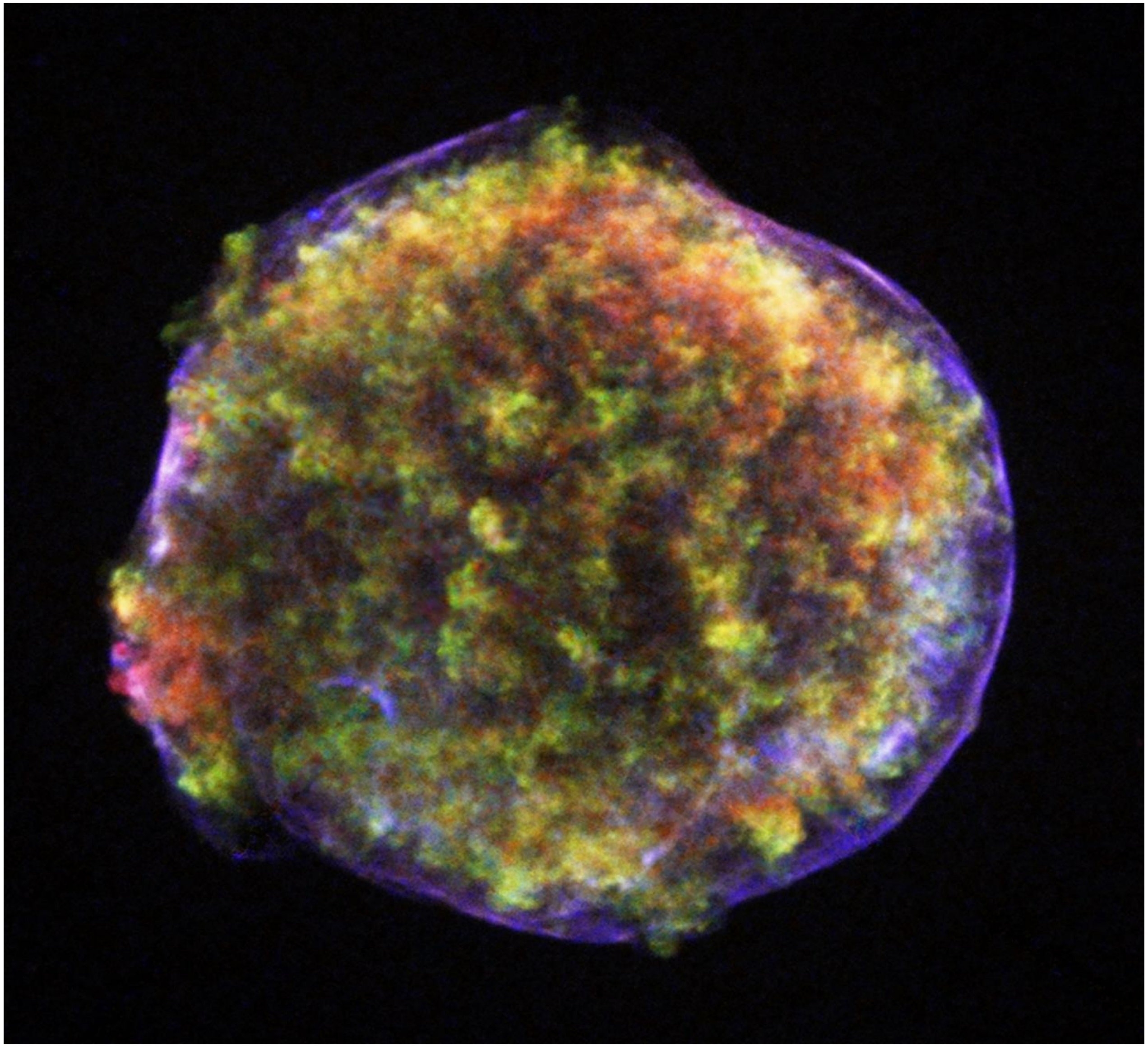
Young SNRs (linear spectra)

steeper spectra:

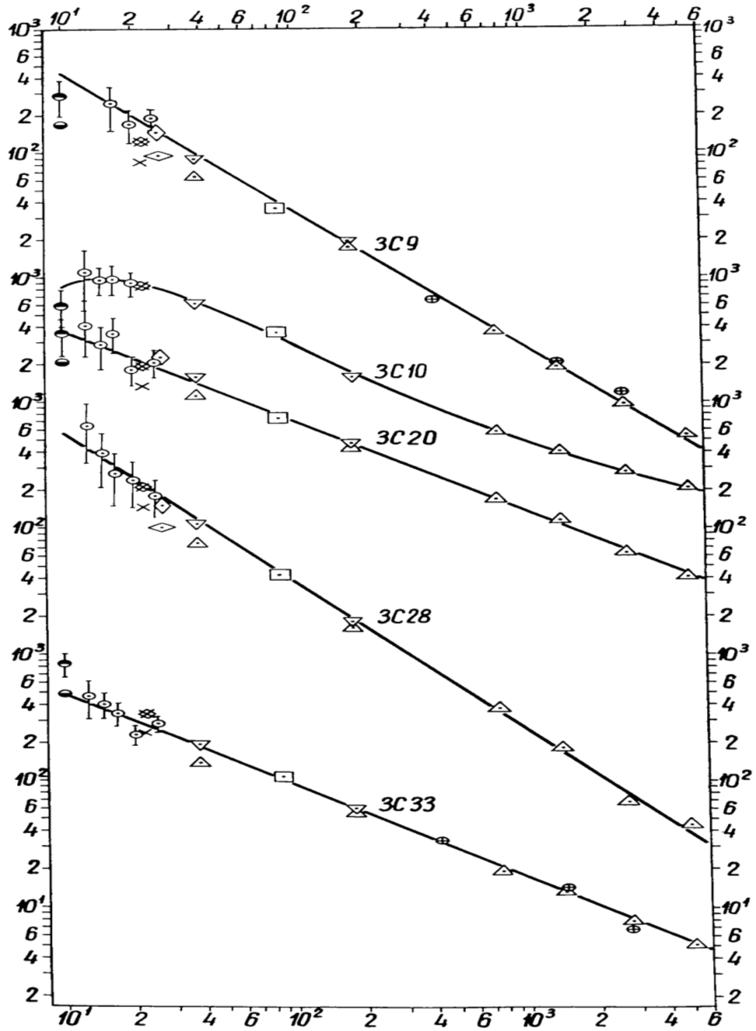
efficient non-linear DSA and accompanying strong magnetic field amplification (Pavlović 2017)



Young SNRs (curved spectra)



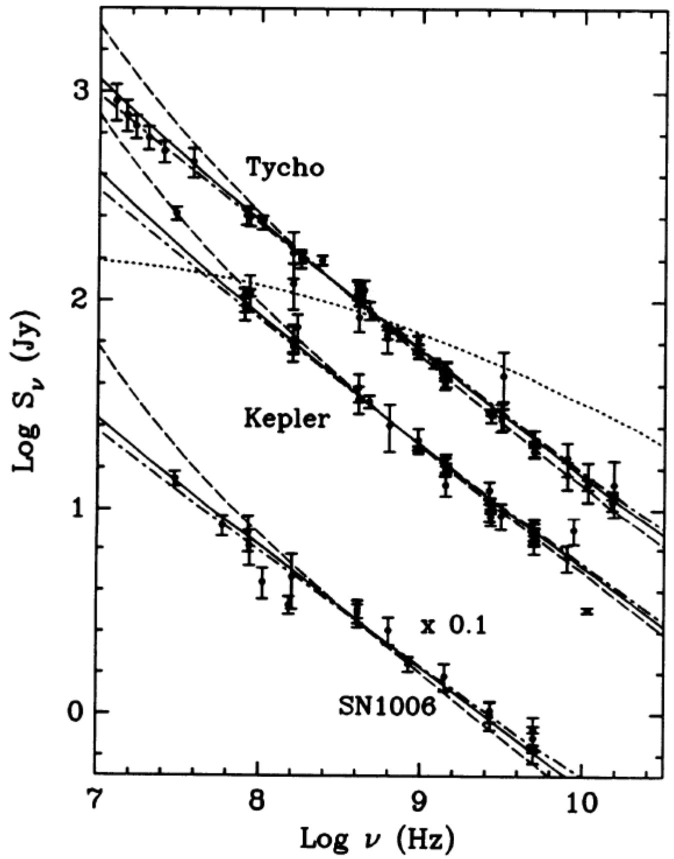
Young SNRs (curved spectra)



- Braude et al. (1970)

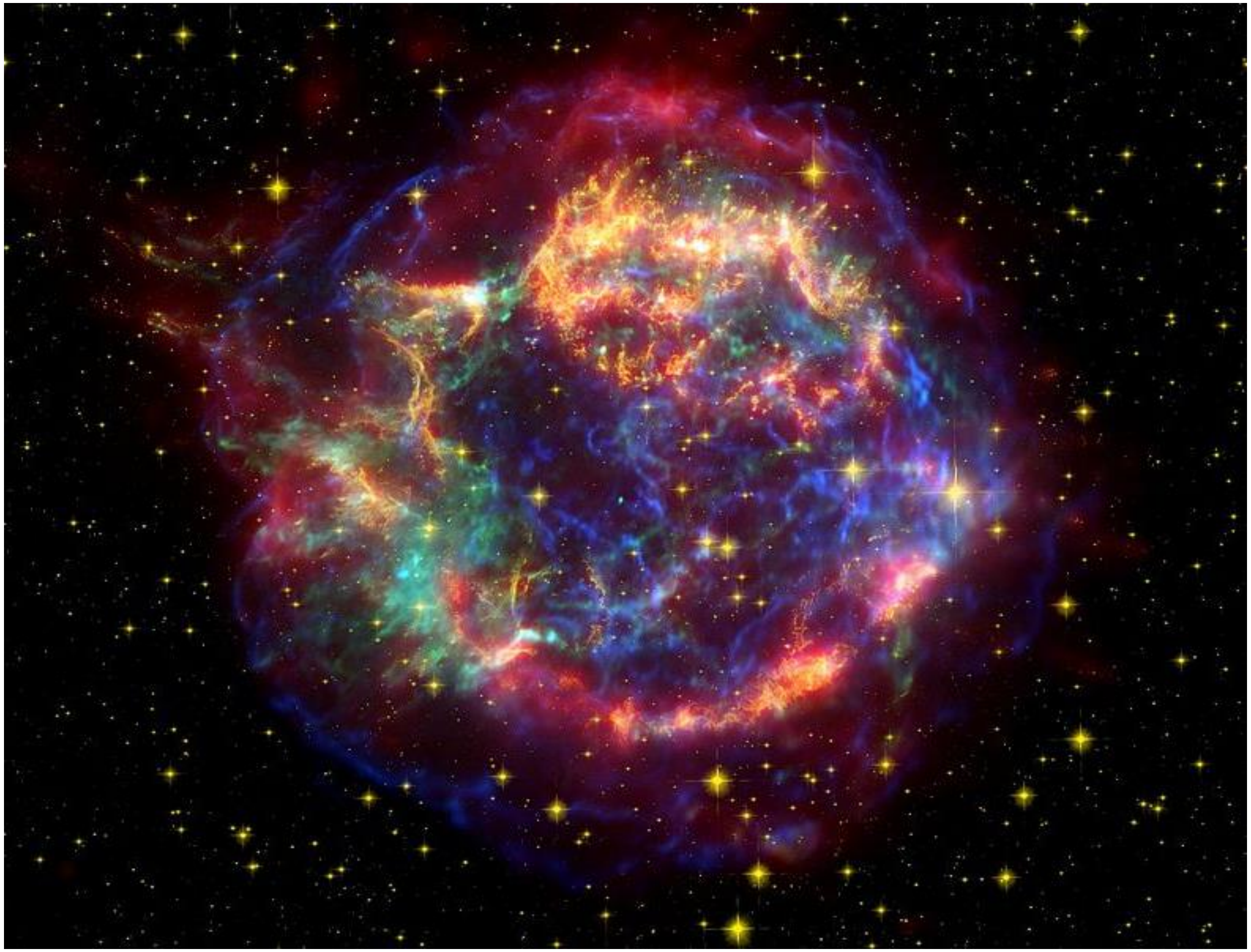
Young SNRs (curved spectra)

- Reynolds and Ellison (1992)

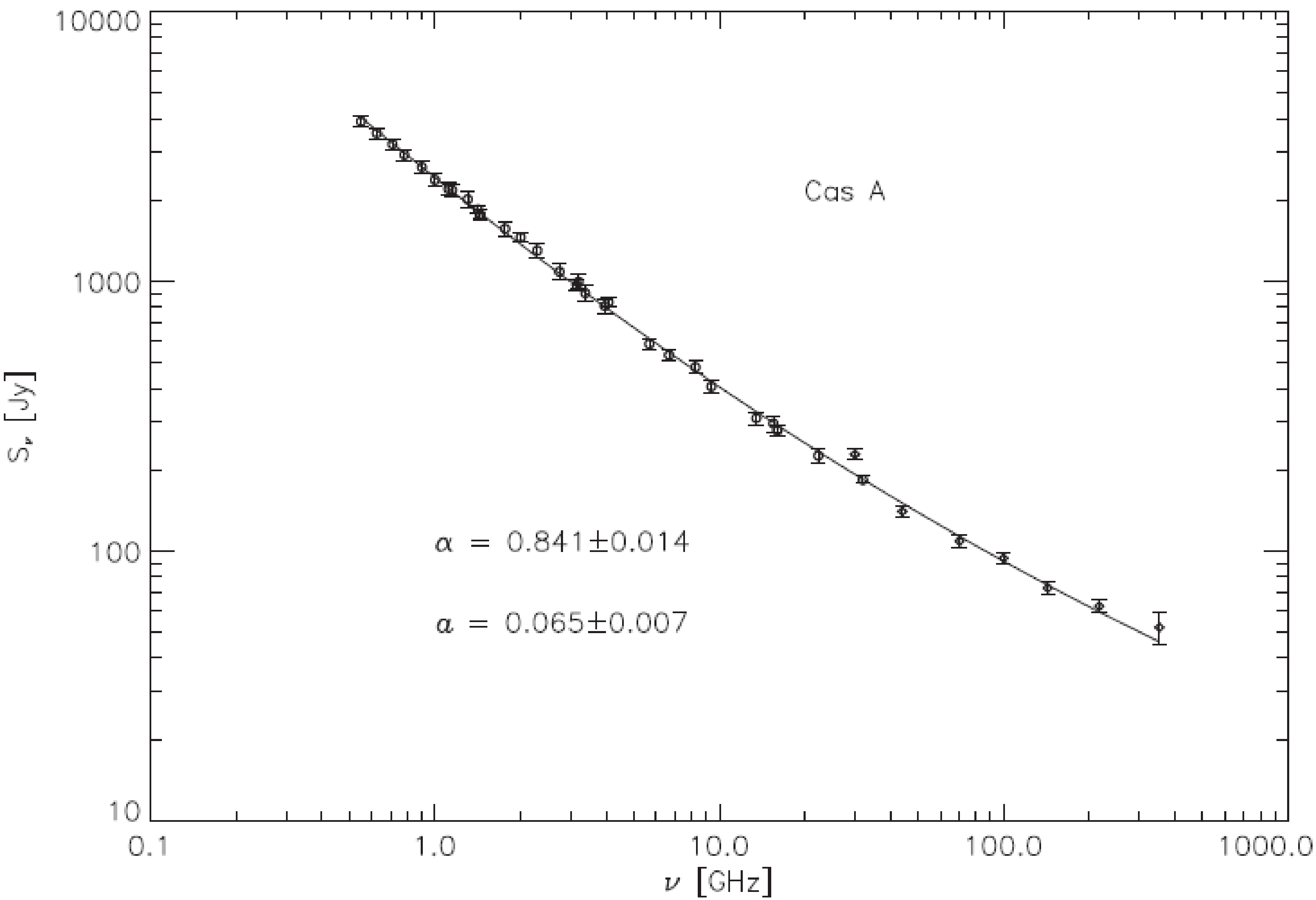


- Pure non-linear effect!

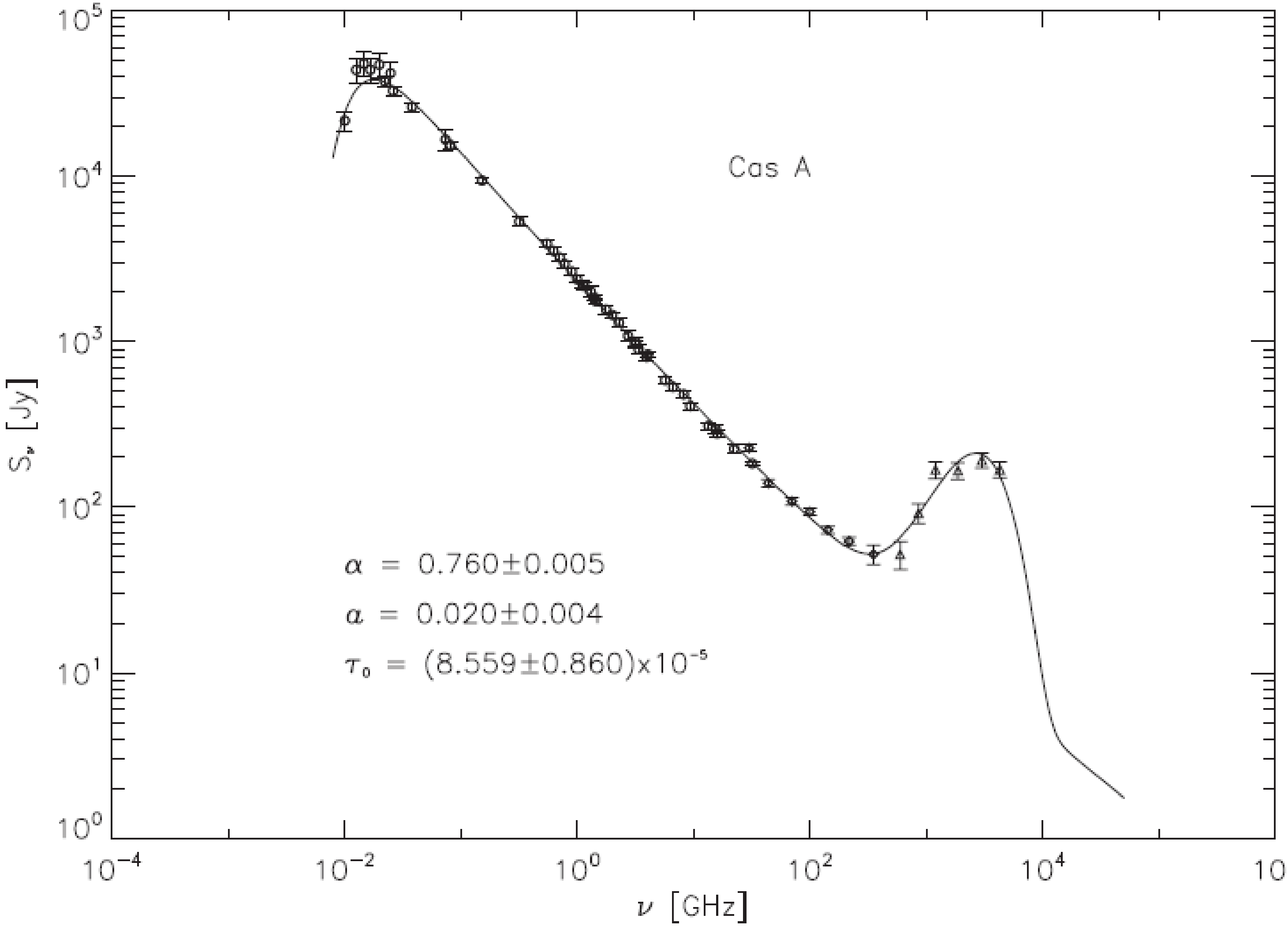
Cas A



Onić & Urošević (2015)



nonlinear particle acceleration + thermal absorption + dust emission



Evolved SNRs (linear spectra)

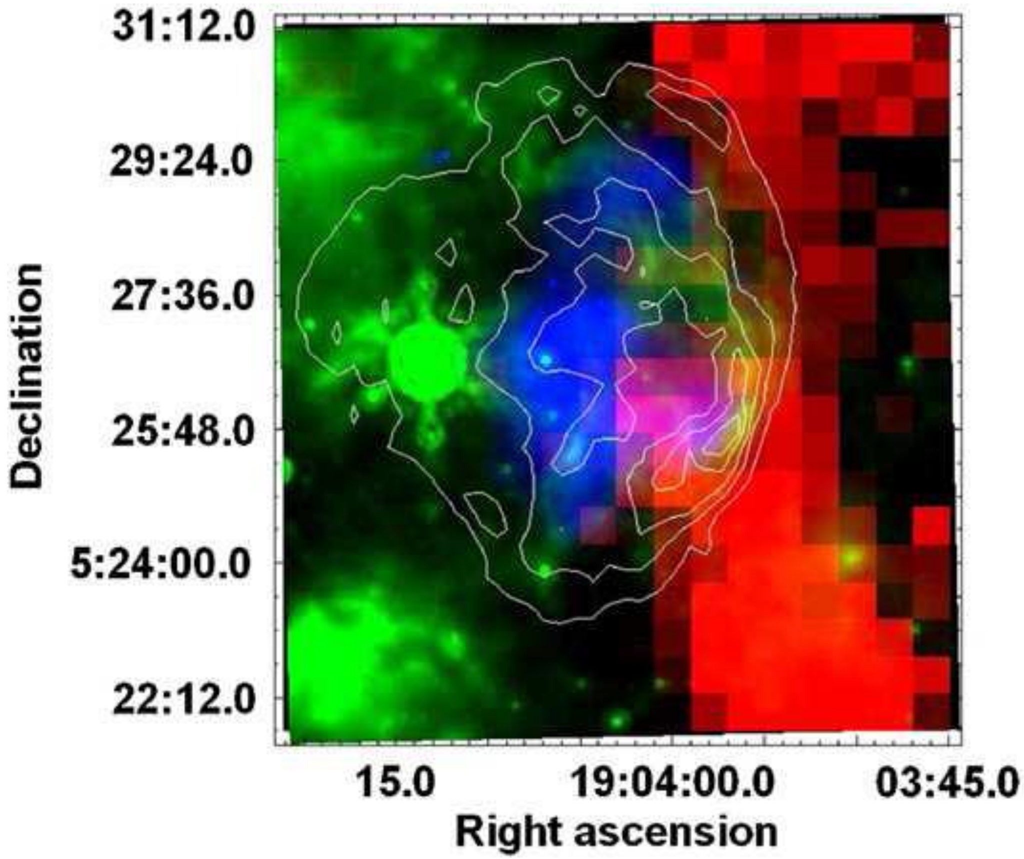
- Linear DSA predicts $\alpha=0.5$
- For older SNRs, steeper than $\alpha=0.5$ (Bell 1978)
- Observations $0.5 < \alpha < 0.6$.

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

in turbulent downstream plasma near the shock (velocity diffusion)

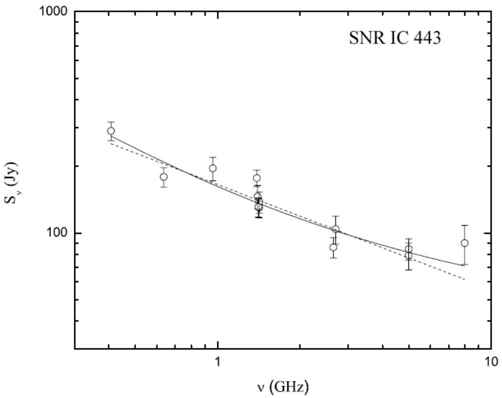
Schlickeiser and Furst (1989), Ostrowski (1999)

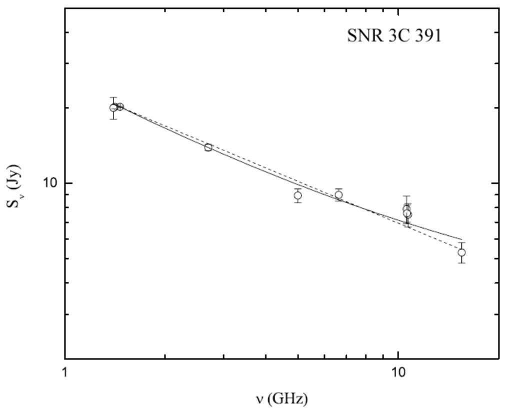
Evolved SNRs - curved (concave-up) spectra

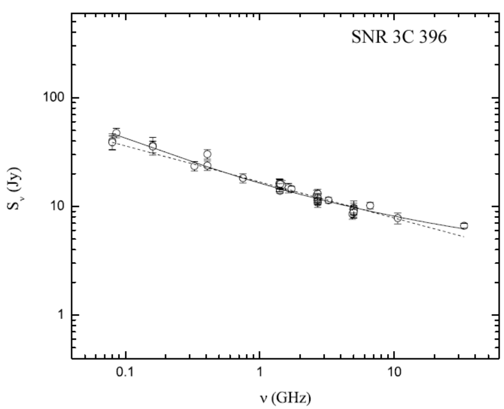


- Mixed-morphology and ”radio thermally active” SNR 3C 396 (Su et al. 2011)

Evolved SNRs - curved (concave-up) spectra







SYNCHROTRON

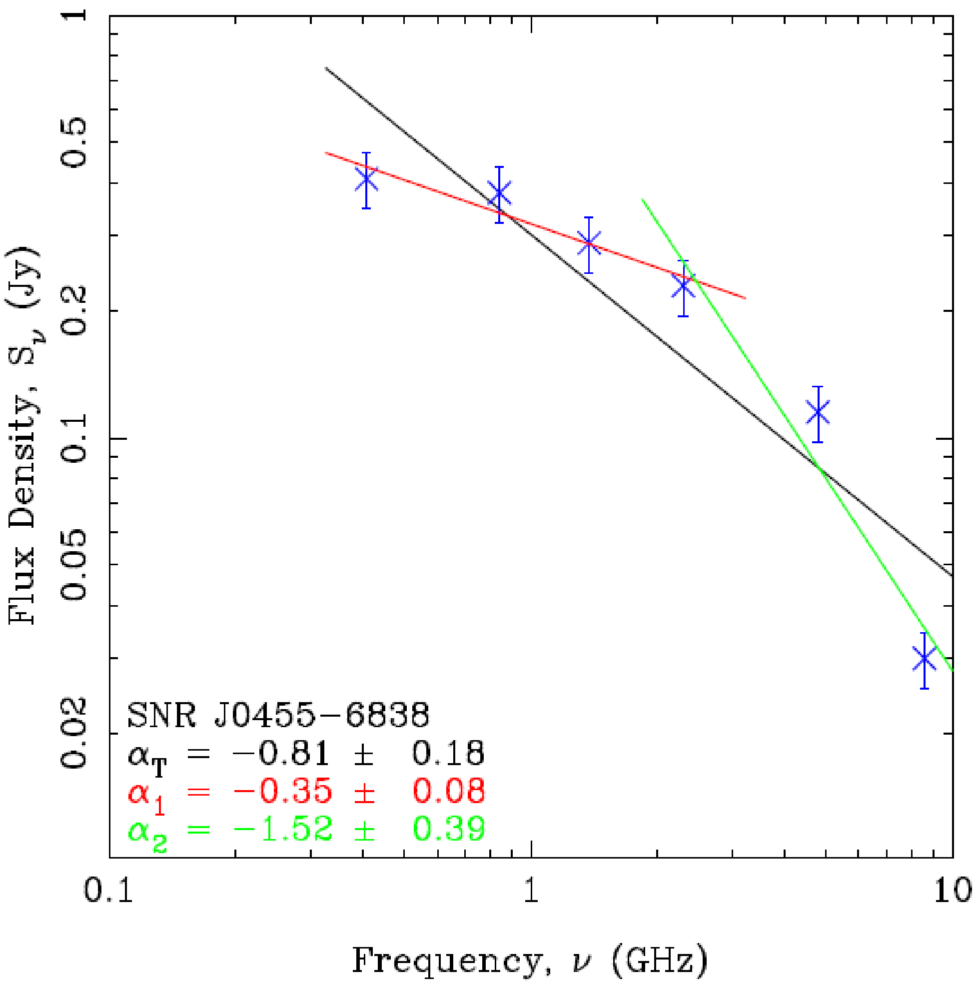
\+

BREMSSTRAHLUNG

EMISSION

- Onić et al. (2012)
- Onić (2013a,b)

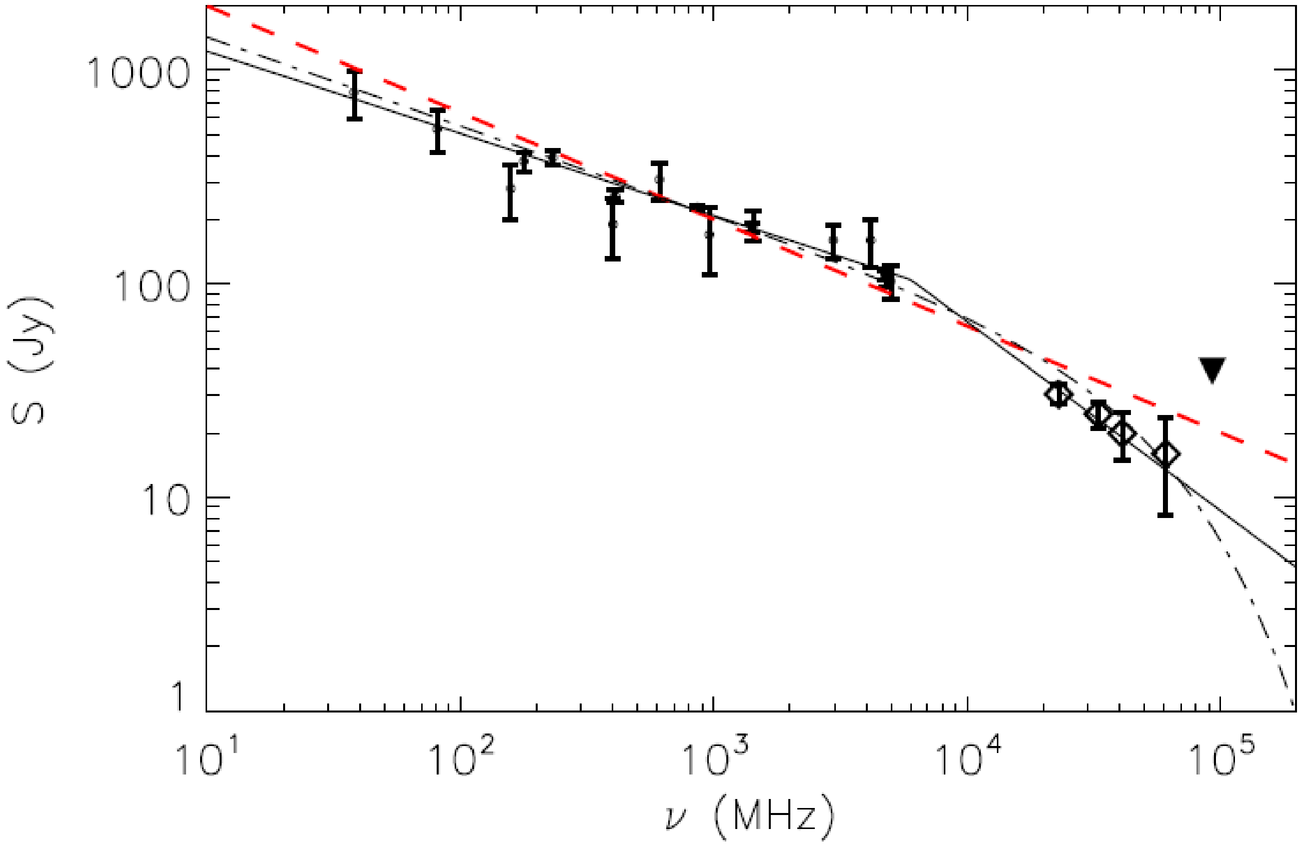
Evolved SNRs - curved (concave-down) spectra



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

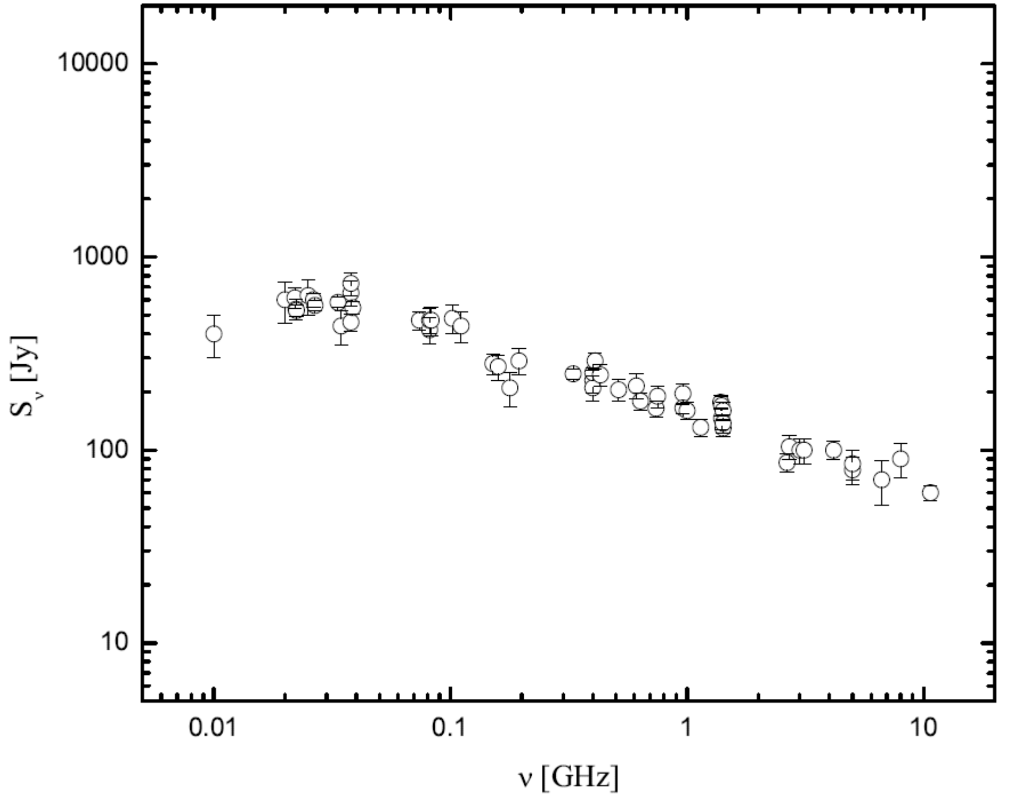
→ The radio spectrum of LMC SNR J0455-6838 (Crawford et al. 2008).

Evolved SNRs - curved (concave-down) spectra



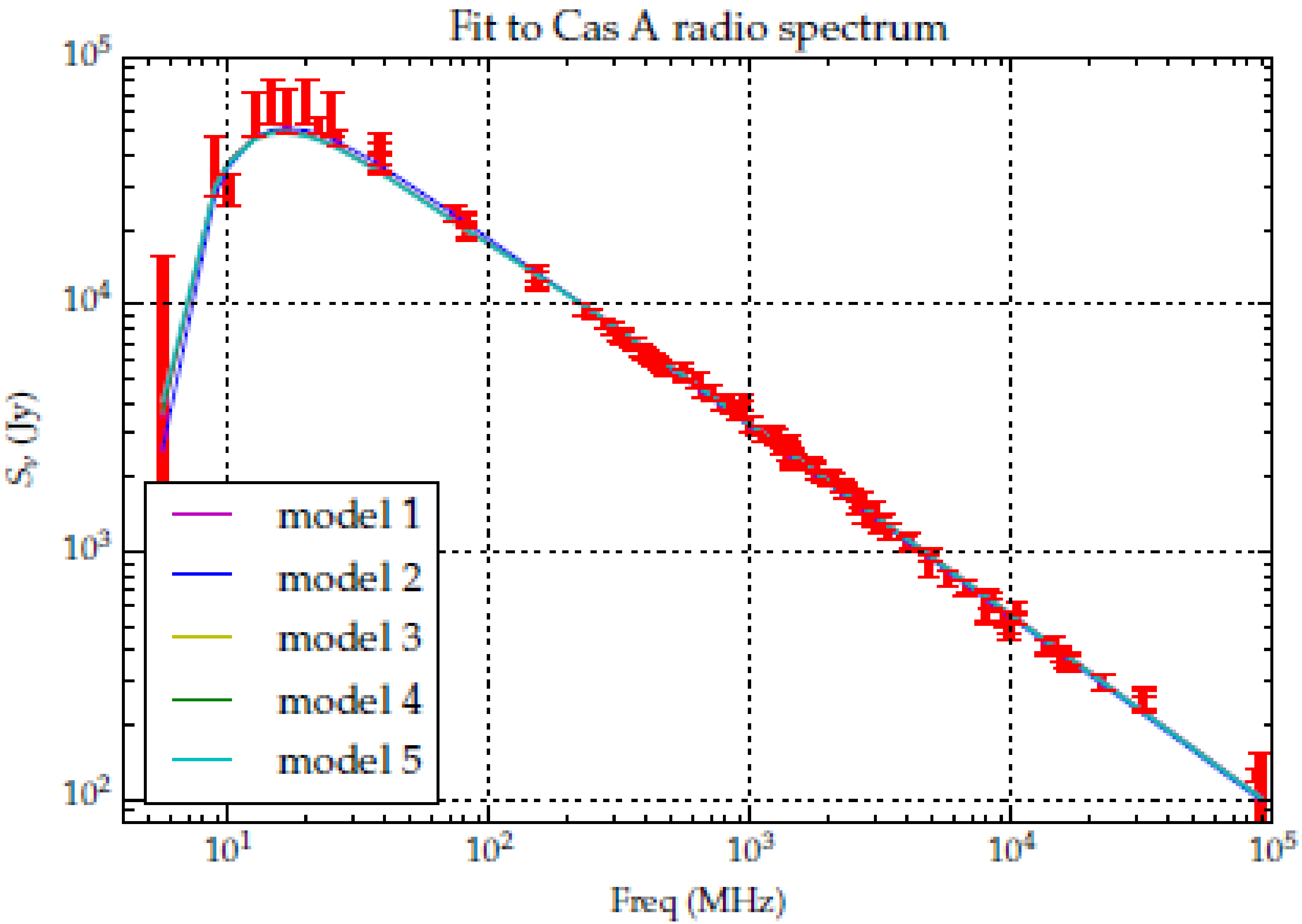
- Radio spectrum of HB21 (Pivato et al. 2013)

Evolved SNRs - curved (low-frequency absorption) spectra

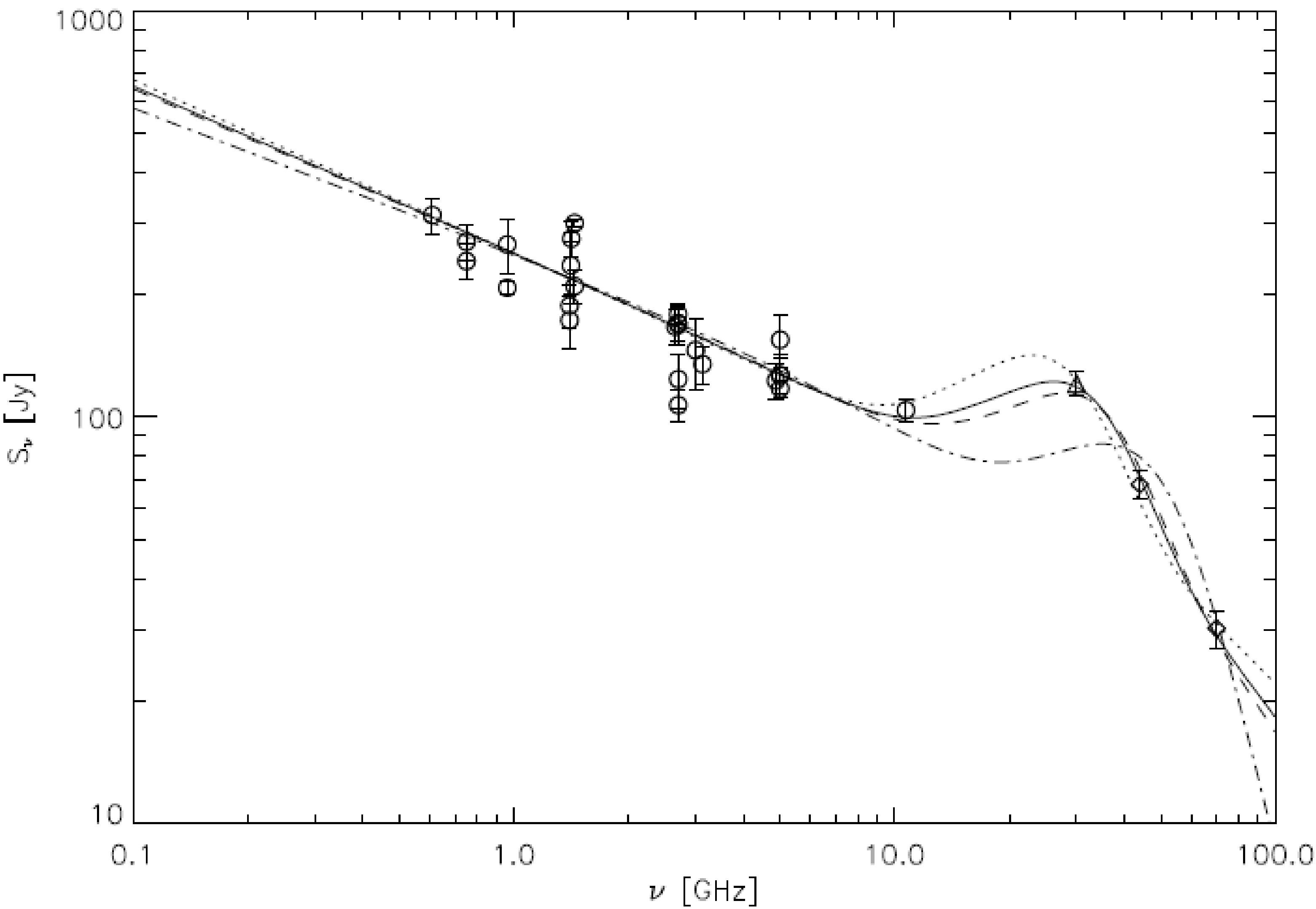


The radio spectrum with the low-frequency turnover of SNR IC443 (Onić 2013a)

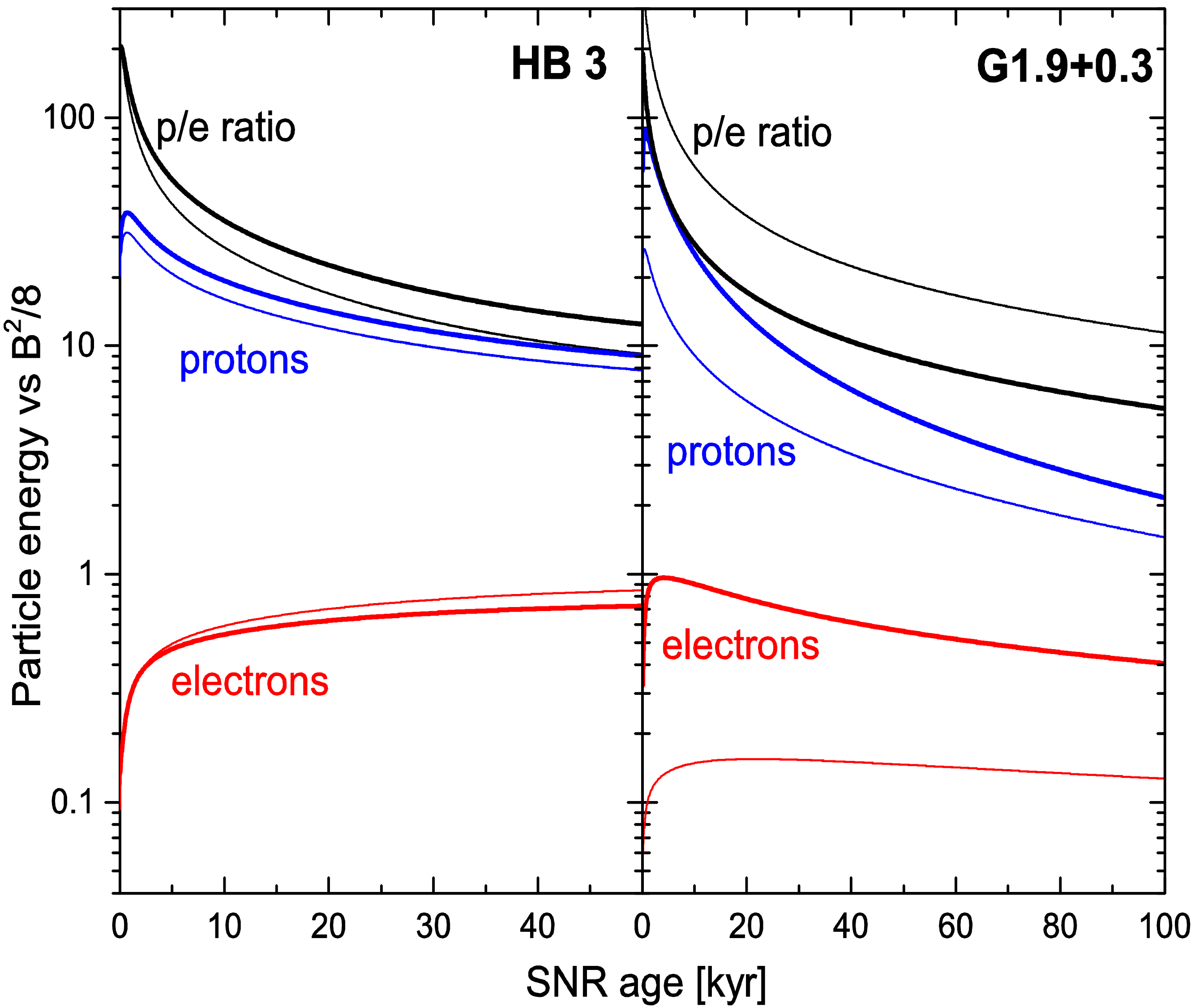
Cas A (Arias et al. 2018)



W44 (Onić 2015)



Equipartition through SNR evolution



Urošević et al. (2018)

Equipartition through SNR evolution

More details in today talk of Dušan Onić – this session (14:40)

Belgrade SNR group

Better part…

THANK YOU VERY MUCH FOR YOUR ATTENTION!!!