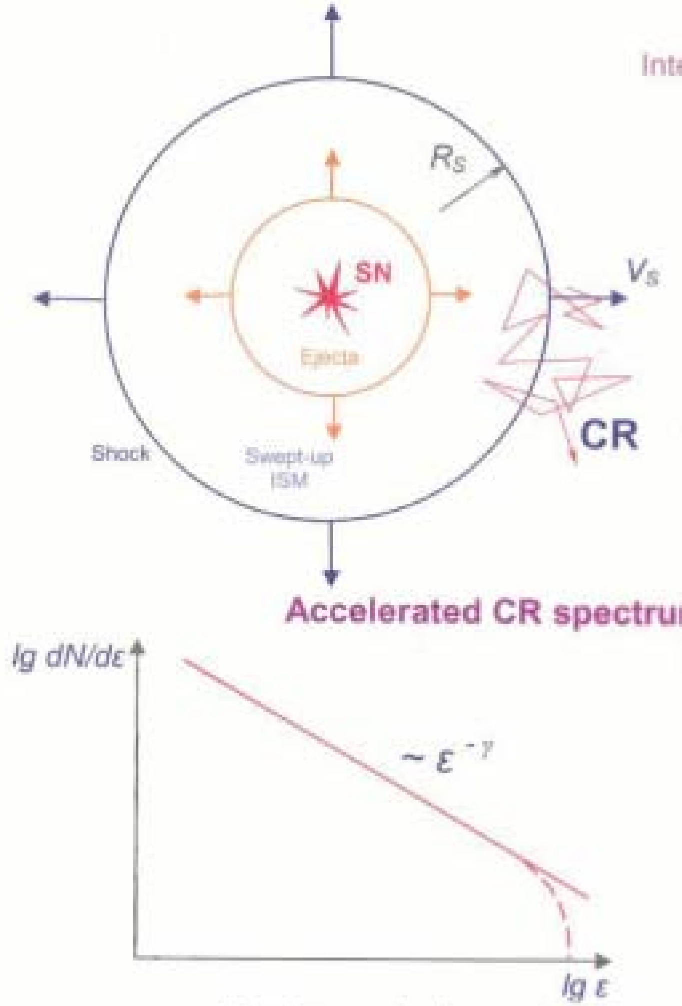
Gamma-ray emission expected from young supernova remnants

E. G. Berezhko

Institute of Cosmophysical Research & Aeronomy
Yakutsk, Russia

- Introduction
- Kinetic model for CR acceleration in SNRs
- Individual SNRs:
  theoretical prediction of emission produced by accelerated CRs and comparison with experimental data
  - SN 1006
  - Tycho's
  - Cassiopeia A
- Conclusions

Cosmic Ray Acceleration in Supernova Remnants



Krymsky (1977)

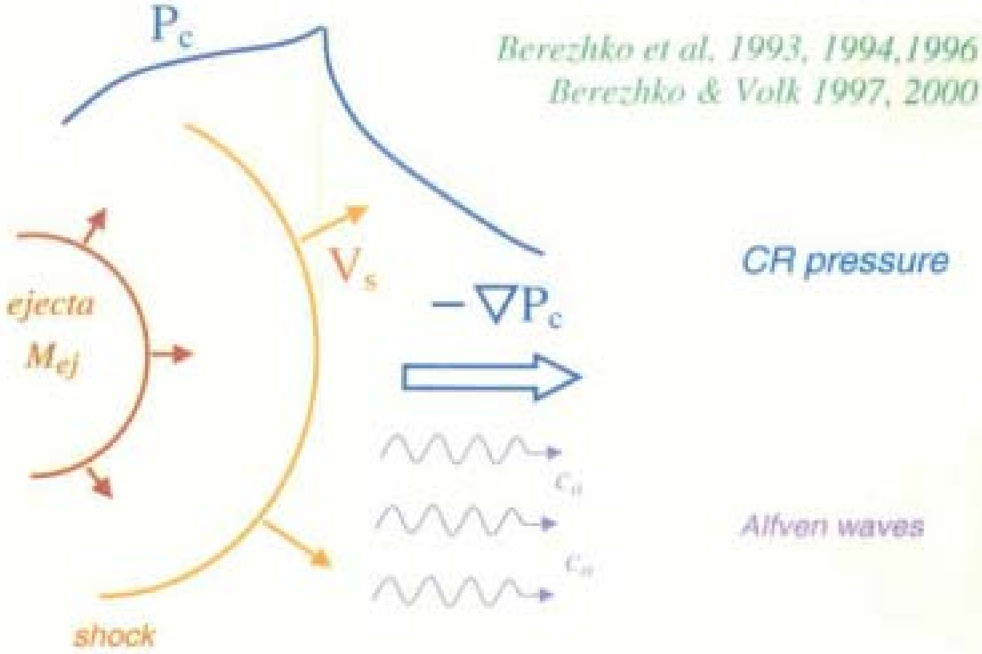
$$\gamma = \frac{\sigma + 2}{\sigma - 1}$$

σ – shock compression ratio

For strong shock: $\sigma = 4 \implies \gamma = 2$

Nonlinear kinetic theory of CR acceleration in SNRs

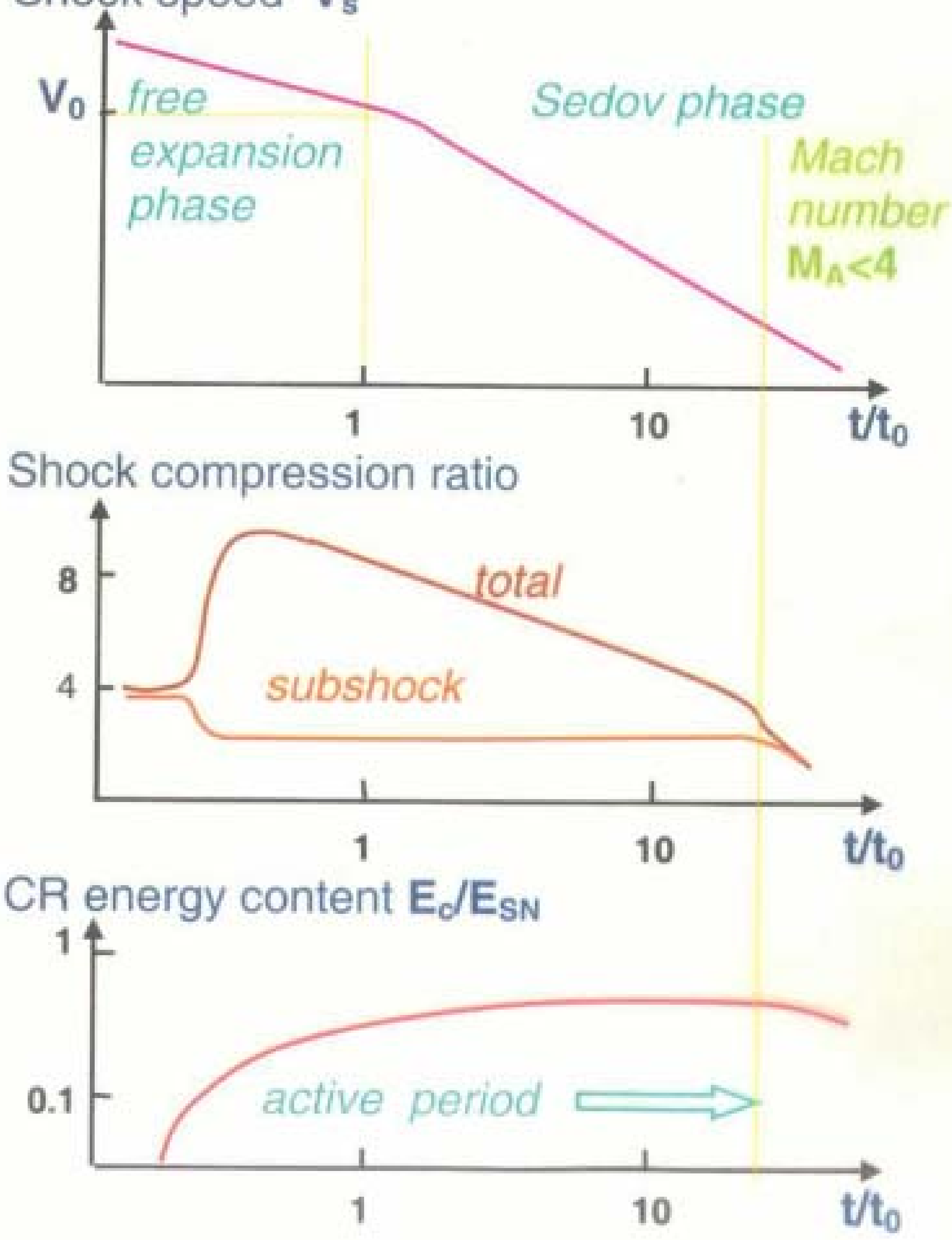
Berezhko et al. 1993, 1994, 1996
Berezhko & Volk 1997, 2000



- Gas dynamic equations
- CR transport equation
- Suprathermal particle injection
- Gas heating due to Alfven wave dissipation

Institute of Cosmophysical Research
and Aeronomy
Yakutsk, Russia

CR content inside SNR



SN shock scales

$$V_0 = \sqrt{\frac{2E_{SN}}{M_{ej}}}$$ *mean ejecta speed*

$$R_0 = \left(\frac{3M_{ej}}{4\pi\rho_0}\right)^{\frac{1}{3}}$$ *sweepup radius*

$$t_0 = \frac{R_0}{V_0}$$ *sweepup time*

$$\rho_0 = 1.4 m_p N_H$$ *ISM density*

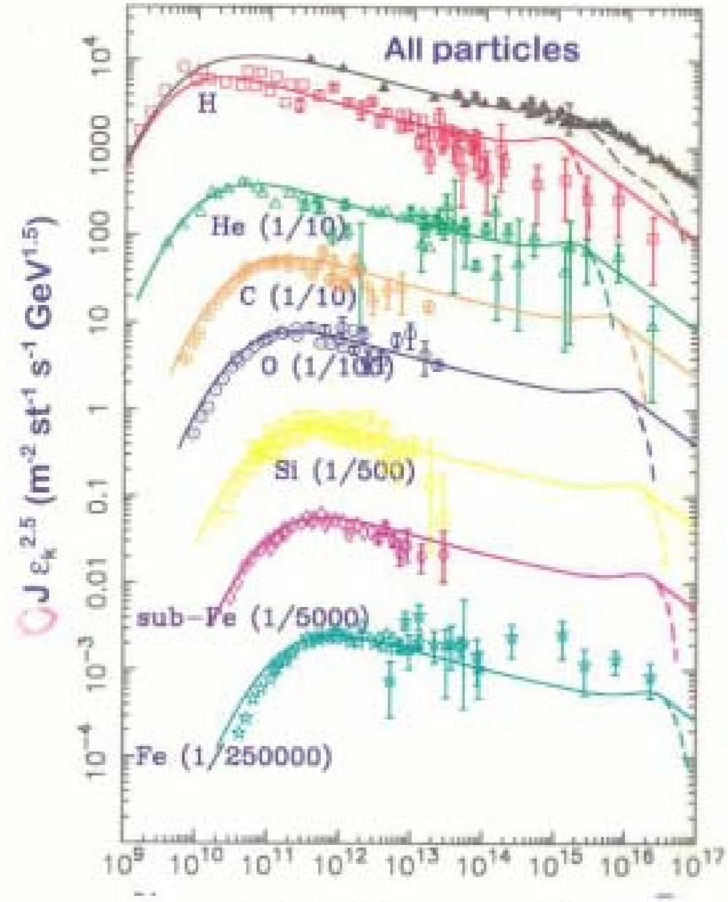
for $M_{ej}=1.4M_\odot$ (SN Ia) $N_H=0.3\ cm^{-3}$

$R_0 \approx 3$ pc $t_0 \approx 370$ yr

Institute of Cosmophysical Research
and Aeronomy
Yakutsk, Russia

Experiment: Shibata (1995)
Theory: Berezhko, Ksenofontov (1999), JETPh

CR Flux

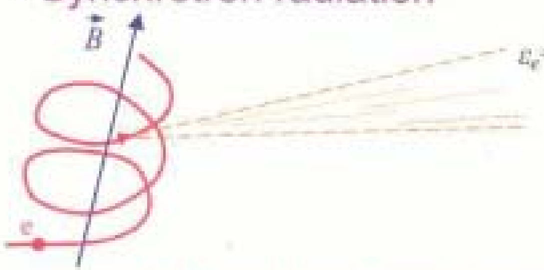


Institute of Cosmophysical Research
and Aeronomy
Yakutsk, Russia

Emission Produced by Cosmic Rays
(How one can "see" CR sources)

- Synchrotron radiation (radio–, X-ray)

ε_e = 0.1–10 GeV ε_e=1–100 TeV

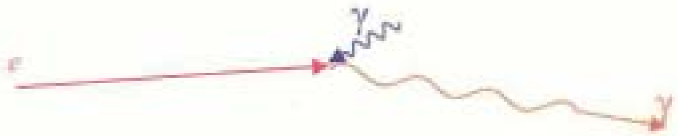


$S_\nu \propto \nu^{-\alpha}$

$\alpha = \frac{\gamma - 1}{2}$

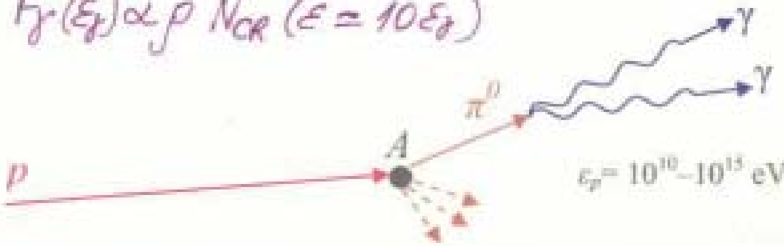
- Inverse Compton scattering (γ - rays)

ε_e= 1–100 TeV



- Nuclear collisions (γ - rays)

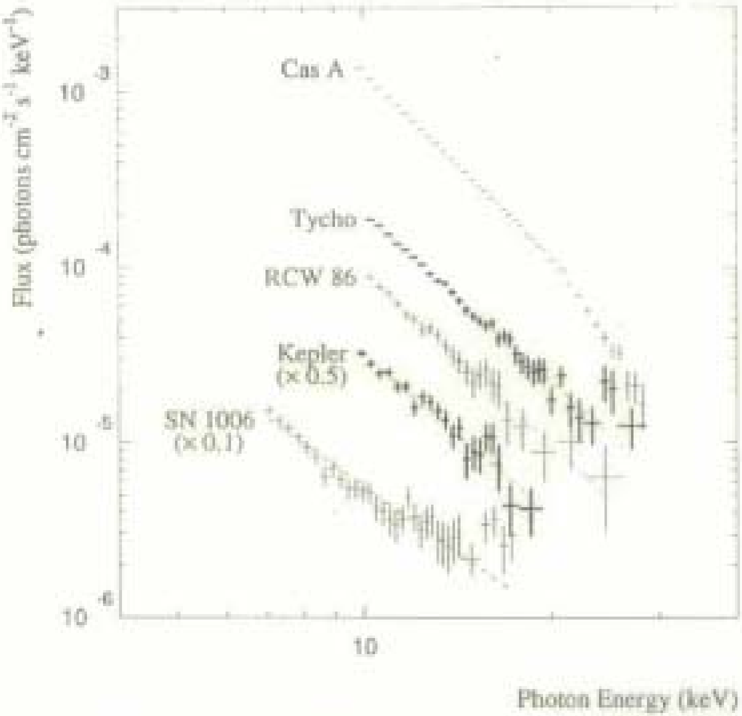
$F_\gamma(\varepsilon_\gamma) \propto \rho N_{CR}(\varepsilon = 10\varepsilon_\gamma)$



ε_p= 10^{10}–10^{15} eV

Institute of Cosmophysical Research
and Aeronomy
Yakutsk, Russia

Evidence of 10-100 TeV electrons in SNRs
G.E. Allen et al

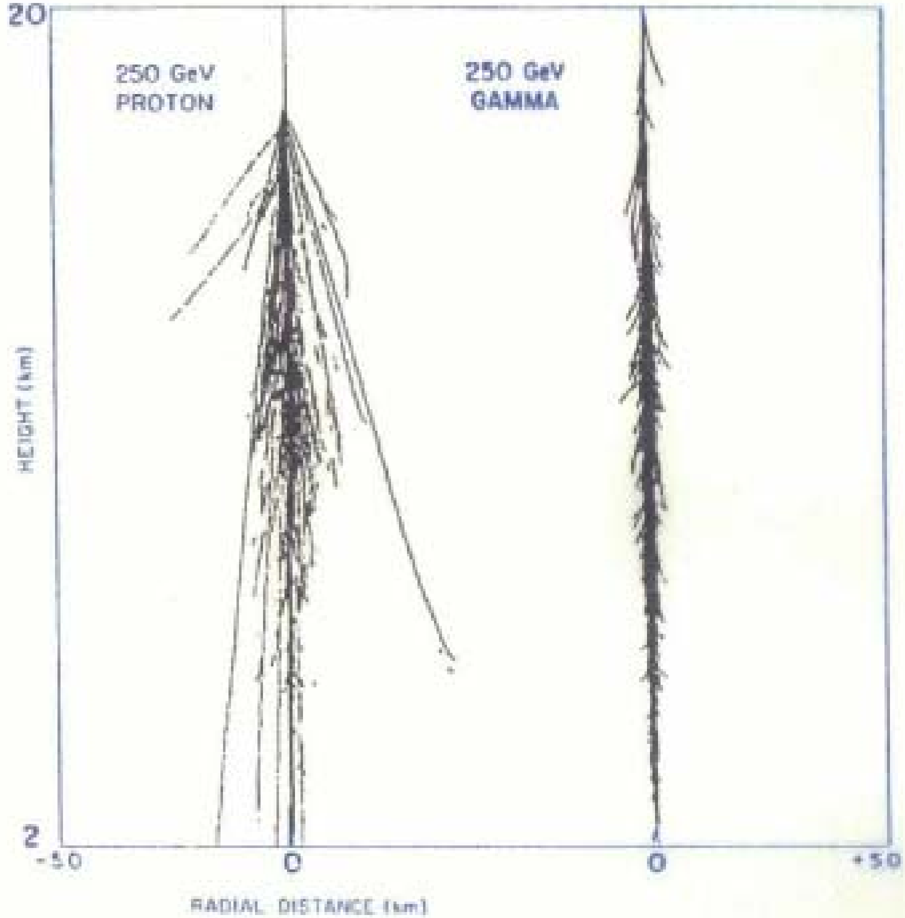


$\varepsilon_{max} \sim 10$ TeV

	Cas A	Kepler	Tycho	SN1006	RCW86
$E_c/(10^{49}$ erg)	5.2	2	1	2	1
$B/(10^{-6}G)$	10^3	10^2	10^2	10	10^2

Proton and gamma-ray initiated air shower in the atmosphere

Weekes, 1996



Institute of Cosmophysical Research
and Aeronomy
Yakutsk, Russia

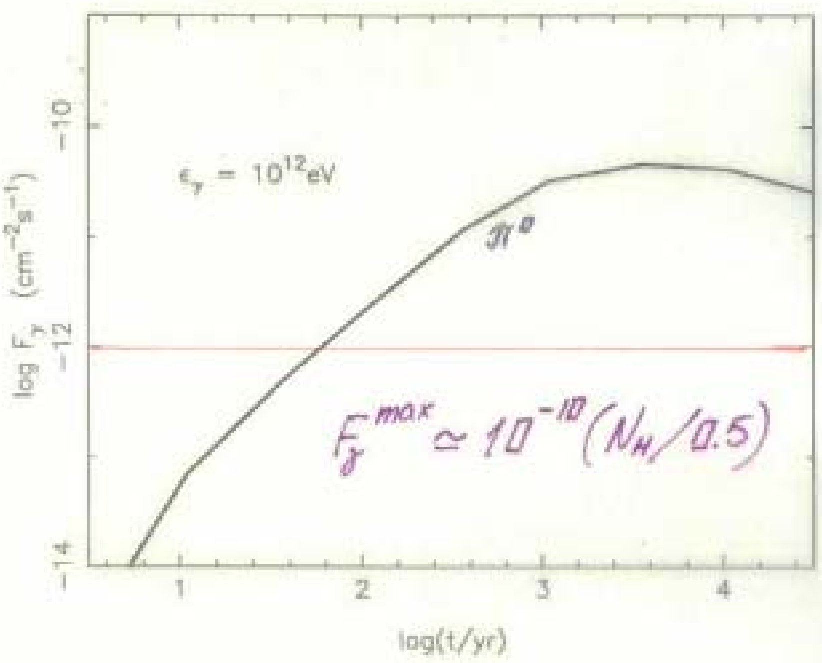
Cherenkov Telescope at the **HEGRA** experiment

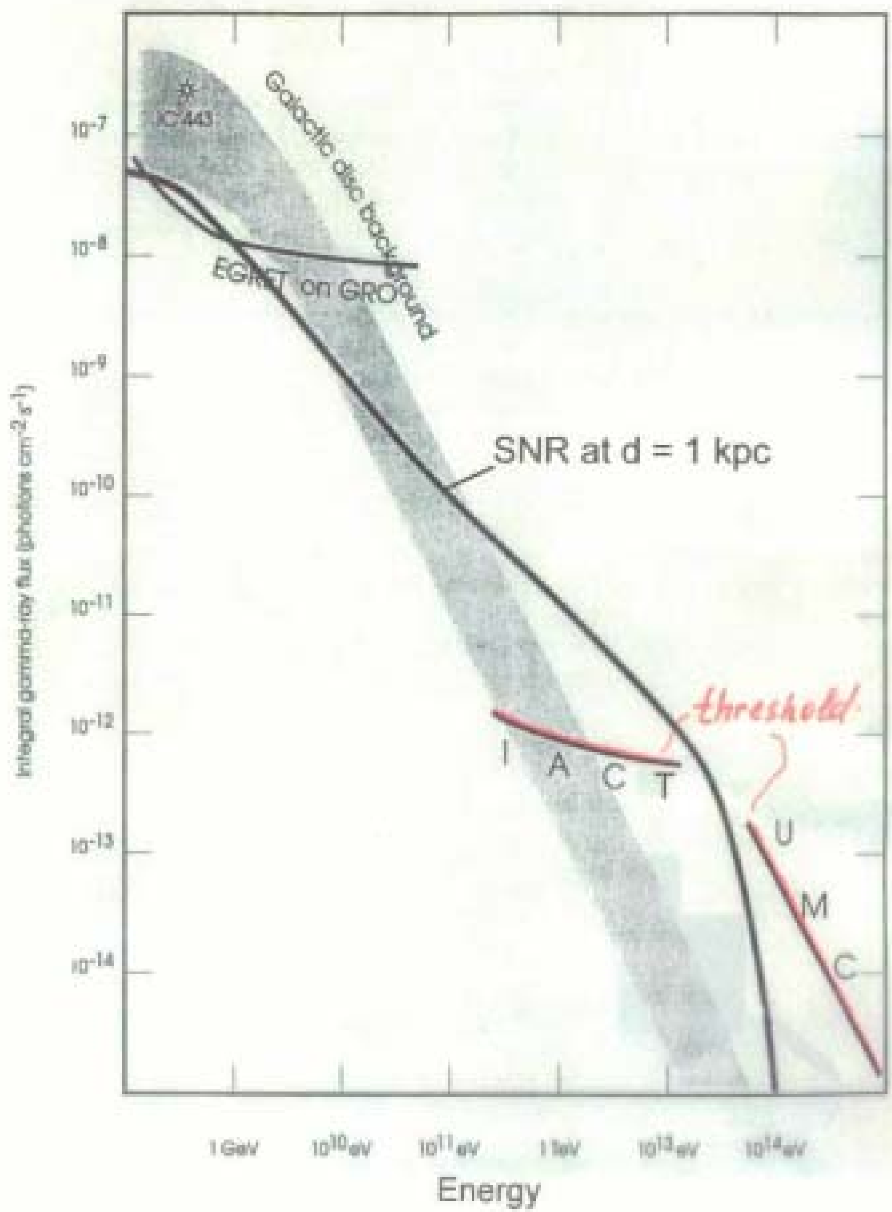
The **H.E.S.S.** project
an Array of Imaging Atmospheric Cherenkov Telescopes

Berezhko & Völk, 199?

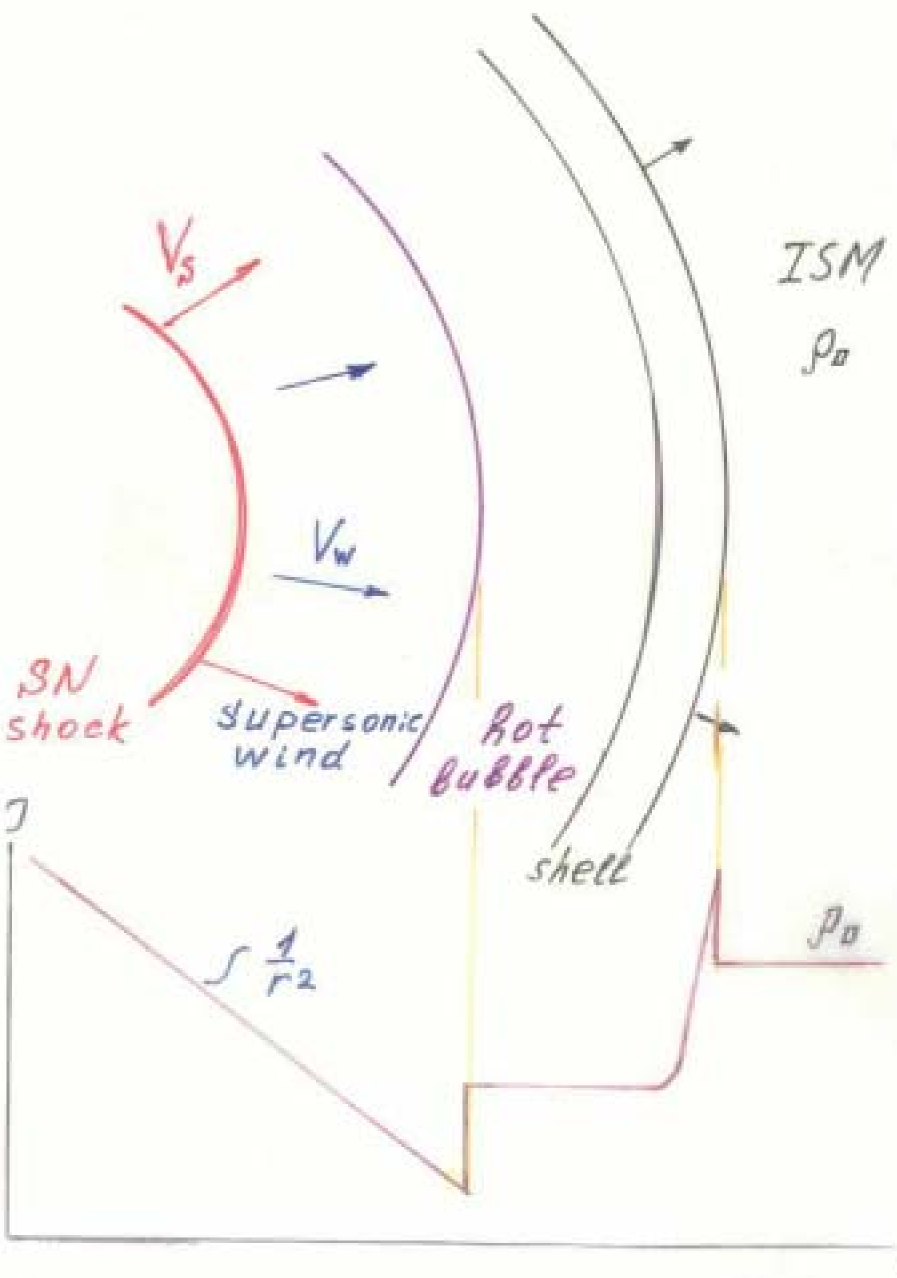
SN Ia, uniform ISM

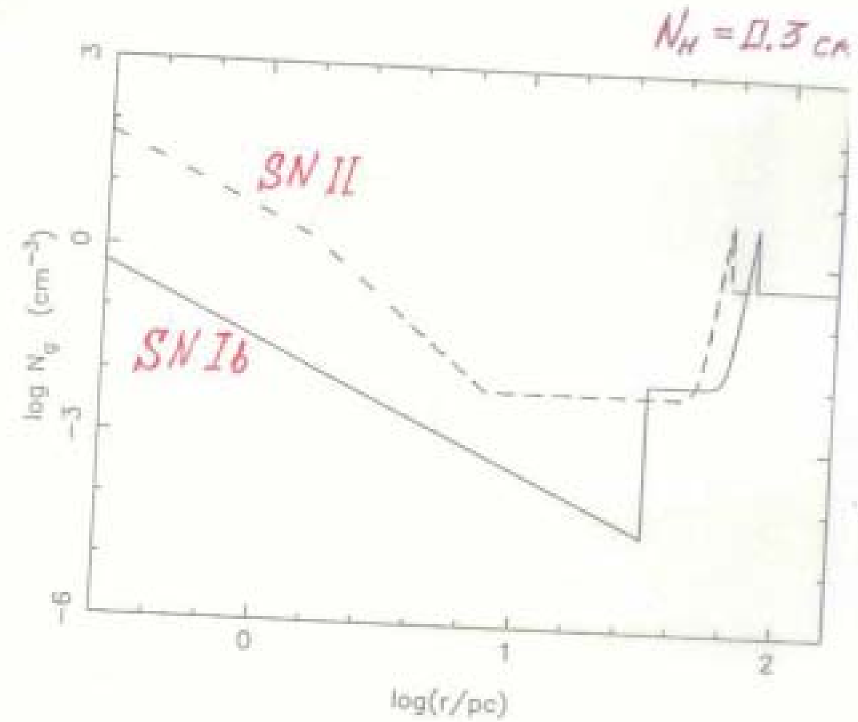
$N_H = 0.3\,cm^{-3}$ $B_0 \doteq 5\,\mu G$ $M_{ej} = 1.4\,M_\odot$





Wind bubbles around SNIb, SNII



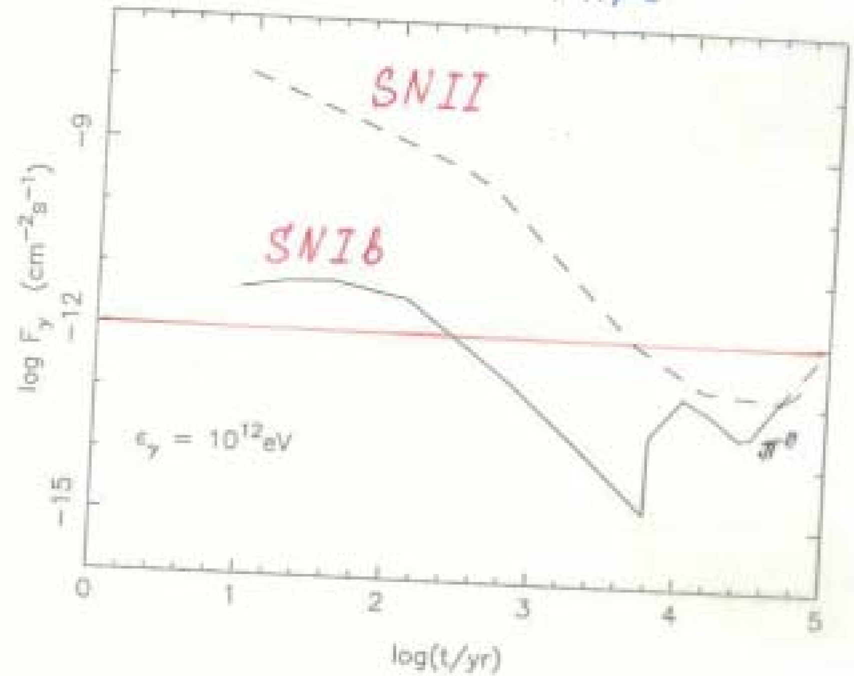


SN Ib ($35 M_\odot$): MS → RSG → WR

SN II ($15 M_\odot$): MS → RSG

Berezhko, Völk 2000

distance $d = 1$ kpc



In the bubble ($t \gtrsim 10^4$ yr)

$F_\gamma \sim 10^{-2} F_\gamma^{Ia}$ (the same N_H)

Number of SNRs, visible in TeV gamma-rays

$$d_{max} = \sqrt{\frac{F_\gamma(d = 1\ kpc)}{F_l}}\ kpc$$ maximum distance

$$N_{SN}^\gamma = \nu_{SN} T_{SN}(F_\gamma) \times \begin{cases} \dfrac{d_{max}^2}{R_{Gal}^2} & \text{if } d_{max} < R_{Gal} \\ 1 & \text{if } d_{max} > R_{Gal} \end{cases}$$

For $N_H = 1\ cm^{-3}$ and $F_l = 10^{-12}\ cm^{-2}s^{-1}$:

SN type	ν_{SN}, yr^{-1}	T_{SN}, yr	N_{SN}^γ
Ia	2/500	10^4-10^5	2-20
Ib	3/500	10^2	1
II	1/100	10^3	10
total	1/50		10-30

Institute of Cosmophysical Research
and Aeronomy
Yakutsk, Russia

Individual SNRs

- Efficient CR acceleration, consistent with requirments for Galactic CR sources !

Physical parameters

distance d → size R_s, speed V_s

X-ray emission L_x → N_H (background gas density) → E_{SN} (SN explosion energy)

magnetic field B ↔ $S_\nu(\nu)$ synchrotron emission

↕

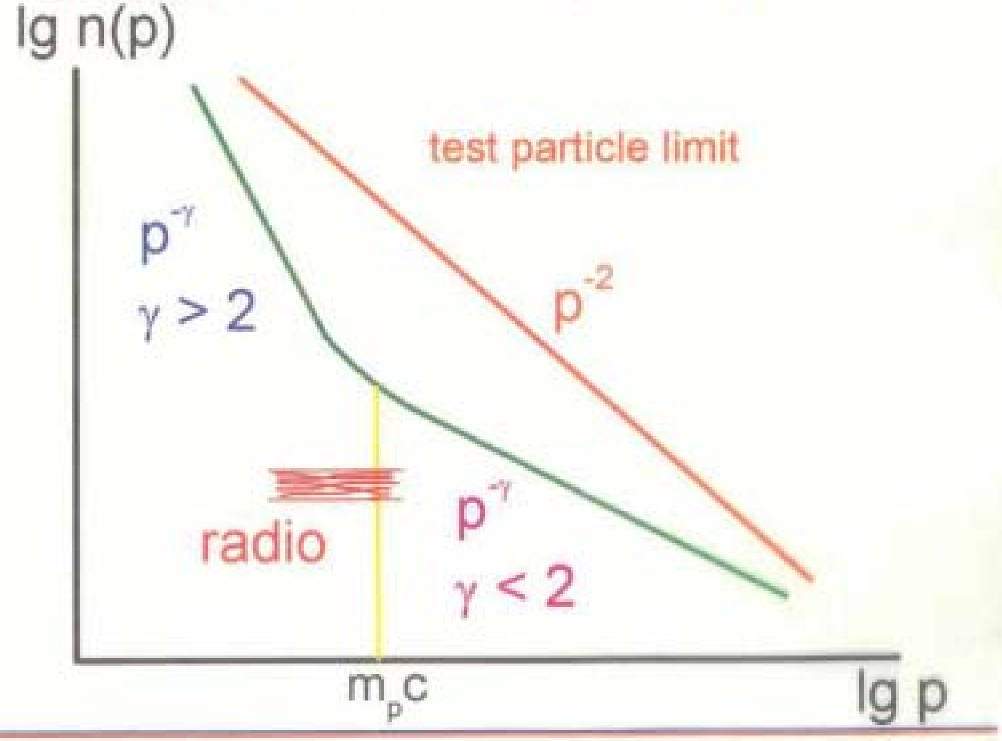
CR injection/acceleration efficiency

↕

$F_\gamma(\varepsilon_\gamma)$ γ-ray emission

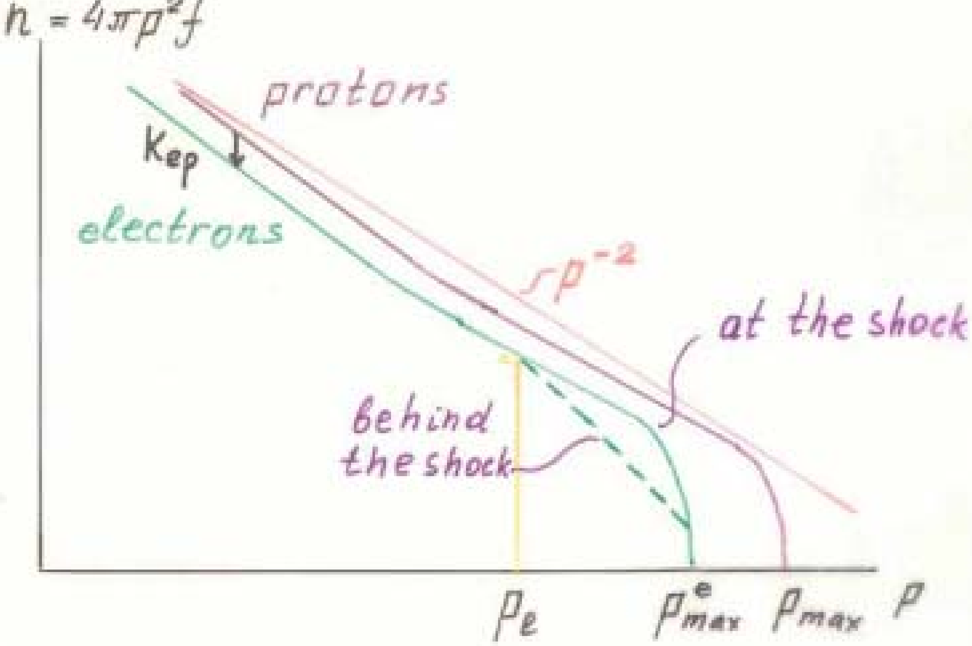
Shock modification due to CR backreaction

⇓	⇓
shock transition broadening	increase of shock compression
⇓	⇓
less transparent shock for low energy CRs	stronger acceleration of high energy CRs
⇓	⇓
steepening of CR spectrum at $p \le m_p c$	hardening of CR spectrum at $p \gg m_p c$



Institute of Cosmophysical Research
and Aeronomy
Yakutsk, Russia

CR maximum momentum



$$\varkappa(p_{max}) = \frac{R_s V_s}{A} \qquad A \simeq 10$$

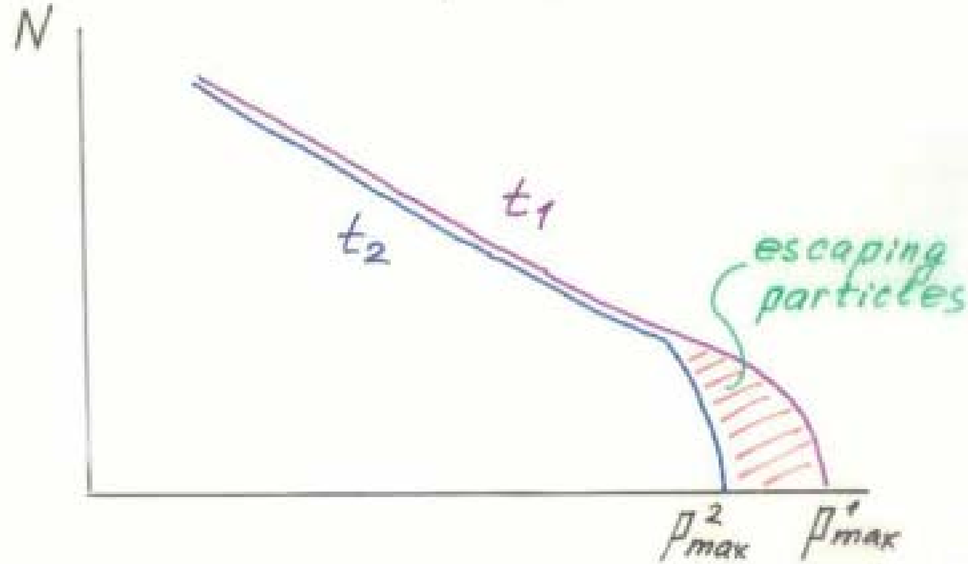
$$\varkappa \propto 1/B \Rightarrow p_{max} \propto R_s V_s B_0$$

$$\tau_{acc} \propto \frac{\varkappa}{V_s^2} \qquad \tau_e \propto \frac{1}{pB^2}$$

$$\Rightarrow p^e_{max} \propto V_s / \sqrt{B_0(r=R_s)}$$

$$\frac{p_e}{mc} = \left(\frac{10^8\,yr}{t}\right)\left(\frac{10\,\mu G}{B_d}\right)^2$$

Particle escape from SNR



$$p_{max} \propto R_s V_s B_0(R_s)$$

$$p_{max}(t_2) \ll p_{max}(t_1) \text{ if } (V_s B_0)_2 \ll (V_s B_0)_1$$

$\Rightarrow$ essential increase of $\varkappa(p > p^2_{max})$

$\Rightarrow$ escape of particles with $p > p^2_{max}$

Synchrotron emission

$$S_\nu \propto \nu^{-\alpha} \qquad \alpha = \frac{\gamma-1}{2}$$

$\gamma = 2 \rightarrow \alpha = 0.5$

$\gamma > 2 \rightarrow \alpha > 0.5$

$$\varepsilon_e(\nu) \simeq 4\sqrt{\frac{\nu/1\,GHz}{B/10\,\mu G}}\ GeV$$

- efficient proton acceleration ⇒
  ⇒ shock modification
- steep synchrotron spectrum ($\alpha > 0.5$) is inderect evidence of efficient proton acceleration
+ large magnetic field strength $B \gtrsim 10^{-4}$ G

Phenomenological approach

assumption: the whole emission of SN 1006 is due to electrons proton CR component plays no role

Mastichiadis & de Jager (1996)
Pohl (1996)
Yoshida & Yanagita (1997)

$$N_e(\varepsilon) = N_0\left(\frac{\varepsilon}{m_e c^2}\right)^{-\gamma} \exp\left(-\frac{\varepsilon}{\varepsilon_{max}}\right)$$

$\gamma = 2.2 \qquad B_d = 4\,\mu G \qquad \varepsilon_{max} = 50$ TeV

Naito et al. 1999

Inconsistent with the shock acceleration!

Inefficient proton acceleration model

low efficiency of proton injection

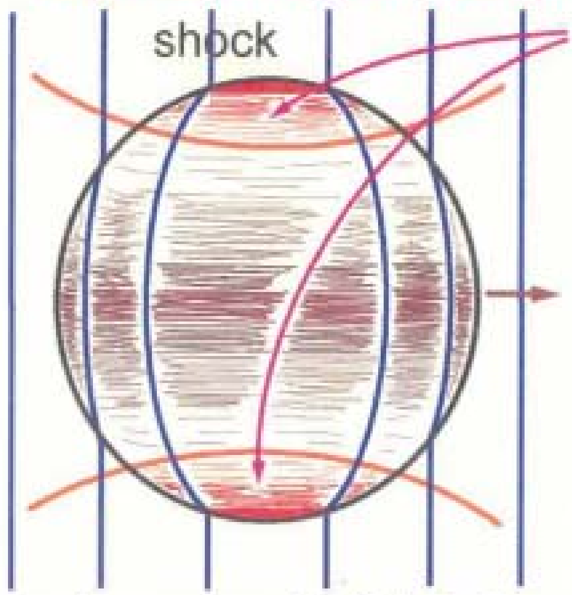
$$N_e \propto \varepsilon^{-2} \exp\left(-\frac{\varepsilon}{\varepsilon_{max}}\right)$$

$B_d \gtrsim 13\,\mu G$

$\gamma = 2$ — radio data need $\gamma = 2.2$

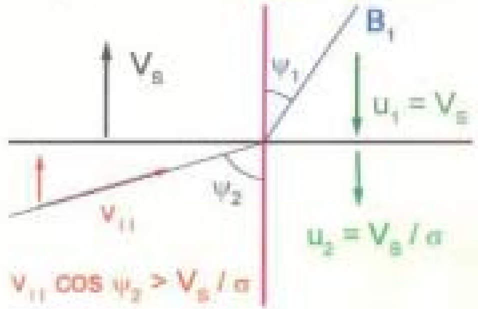
$K_{ep} \geq 0.2$ — much larger then in GCRs

Correction for the lack of spherical symmetry



quasiparallel shock
efficient
injection/acceleration

quasiperpendicular
shock
inefficient
injection/acceleration



$f_{re} = S_{||} / (S_{||} + S_{\perp}) < 1$ renormalization factor

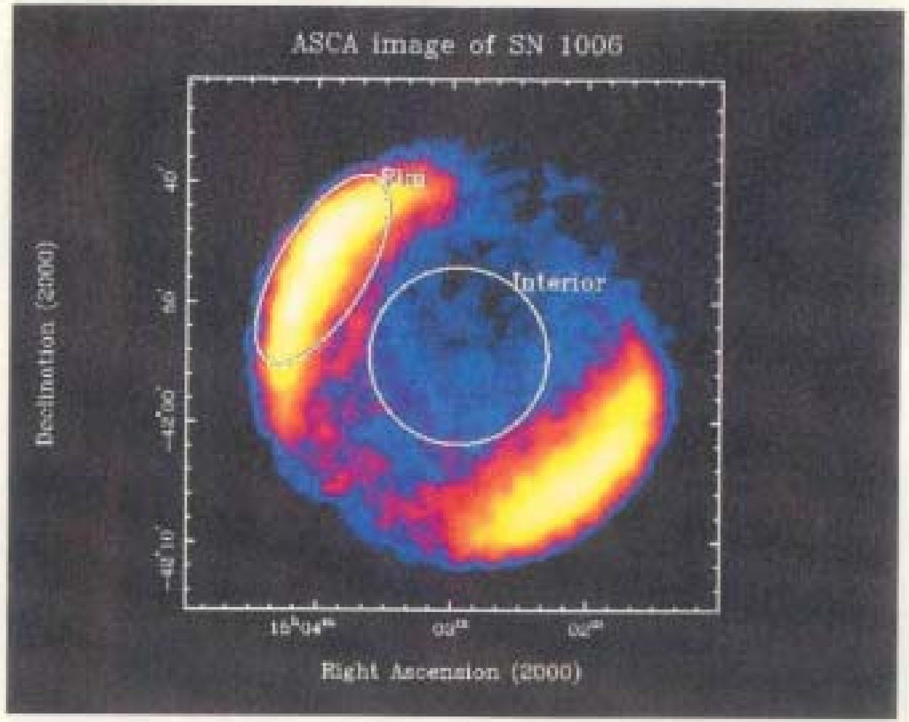
$E_c^{re} = f_{re} E_c$

$E_c / E_{SN} = 0.4 \div 0.6$ model prediction

$E_c^{re} / E_{SN} \simeq 0.1$ required for GCRs

$$f_{re} = 0.15 \div 0.25$$

Institute of Cosmophysical Research
and Aeronomy
Yakutsk, Russia



SN 1006

We know:

Age T ≈ 1000 yr

Distance d ≈ 1.8 kpc

SNR (shock) size and expansion speed

The SN type (SN Ia)

Synchrotron flux in radio and X-ray bands

Gamma-ray flux at 1 TeV and upper limit at 1 GeV

We'd like to know:

- How CRs (e and p) are produced
- Whether standard CR acceleration theory fits the data

SN 1006

Berezhko, Ksenofontov, Völk 2001, 2002

$M_{ej} = 1.4\ M_\odot$ ejecta mass

$\frac{dM_{ej}}{dv} \propto v^{2-k}$ $k = 7$

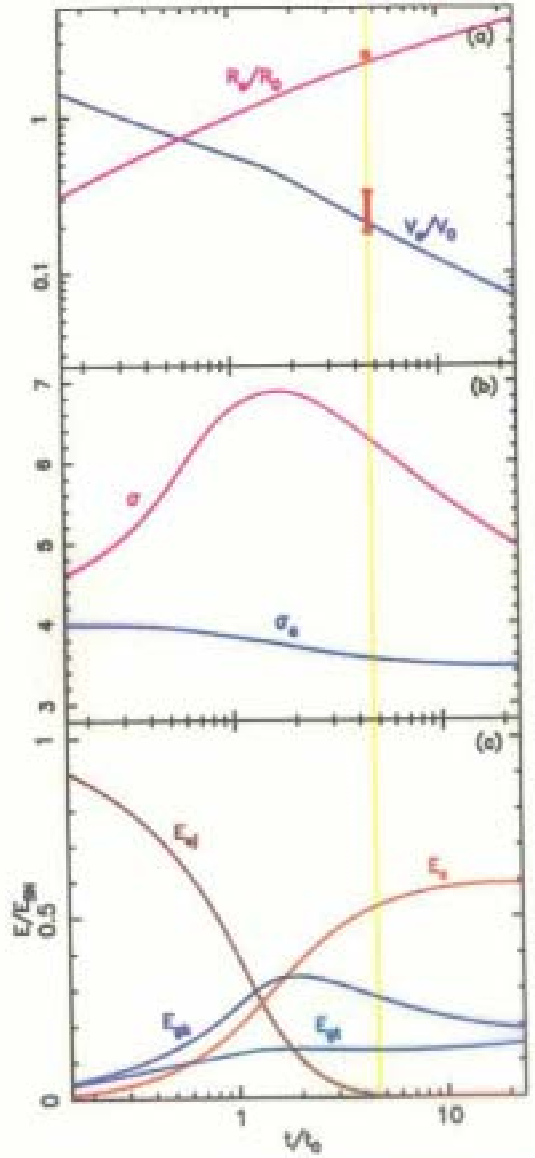
$N_H = 0.3\ cm^{-3}$ ISM number density

$E_{SN} = 3 \cdot 10^{51}\ erg$

$d = 1.8\ kpc$

$B_d \simeq 100\ \mu G$ required magnetic feild

Evolution of SN 1006



R_s – shock size
V_s – shock speed

R_0=3.2 pc – sweep-u radius
V_0=14675 km/s – m ejecta speed

σ – shock compressio ratio
σ_s – subshock compr ratio

Energy components:
E_{ej} – ejecta
E_c – CRs
E_{gk} – gas kinetic
E_{gt} – gas thermal

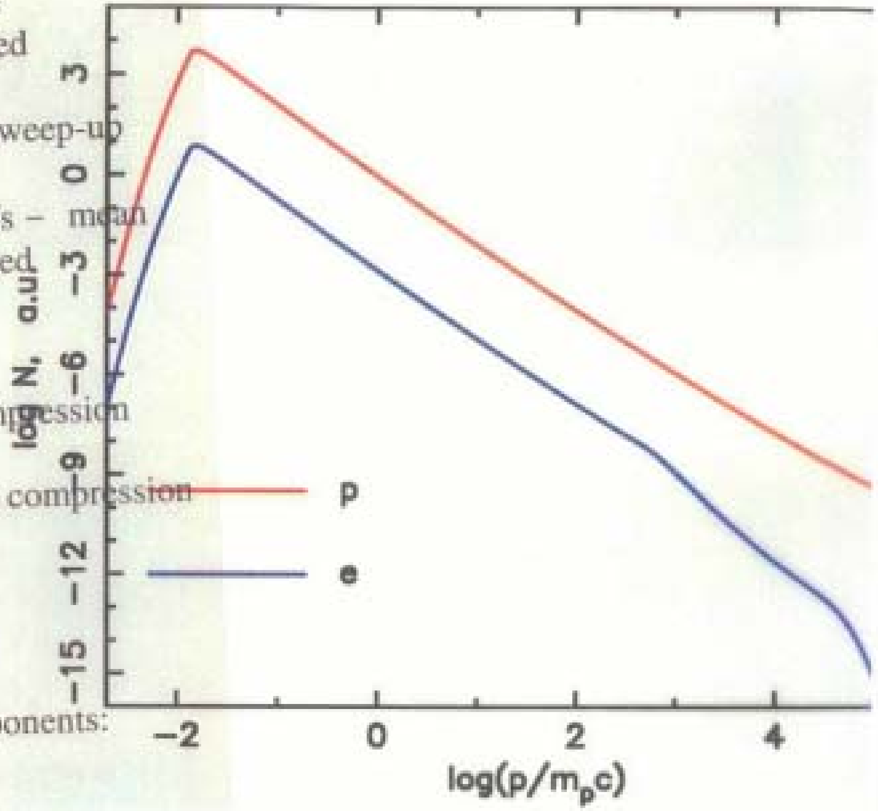
t_0=212 yr – sweep-u time

Institute of Cosmophysical Research and Aeronomy Yakutsk, Russia

006

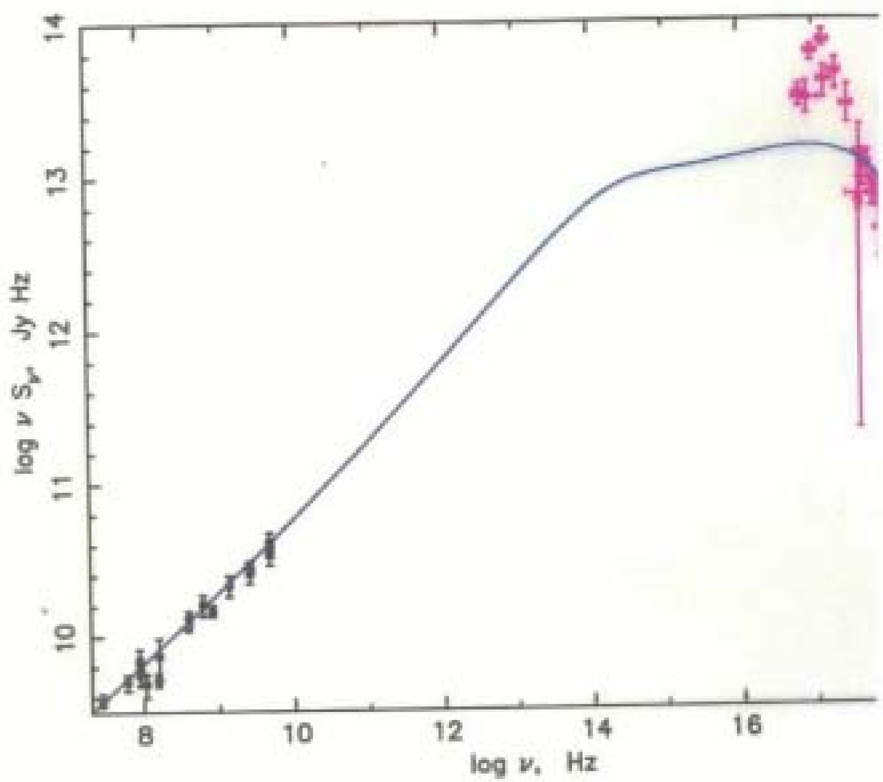
Overall CR spectrum in SN 1006

– shock size
– shock speed
$_0$=3.2 pc – sweep-up radius
$_0$=14675 km/s – mean ejecta speed
– shock compression ratio
$_s$ – subshock compression ratio
Energy components:
E_{ej} – ejecta
E_c – CRs
E_{gk} – gas kinetic
E_{gt} – gas thermal
t_0=212 yr – sweep-up time
esearch



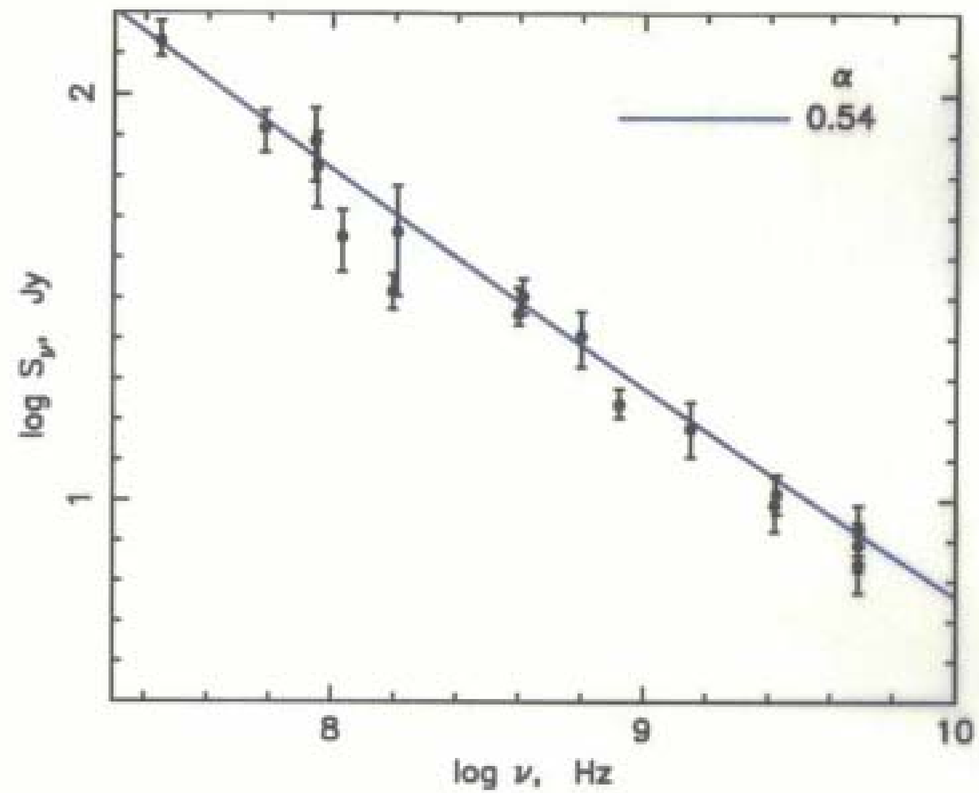
Institute of Cosmophysical Research and Aeronomy Yakutsk, Russia

Synchrotron emission flux from SN 100



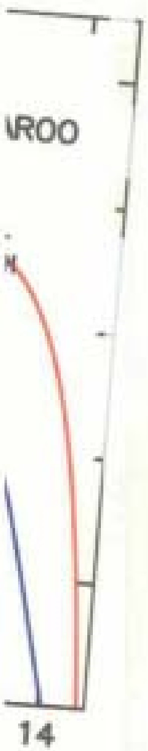
Institute of Cosmophysical Research
and Aeronomy
Yakutsk, Russia

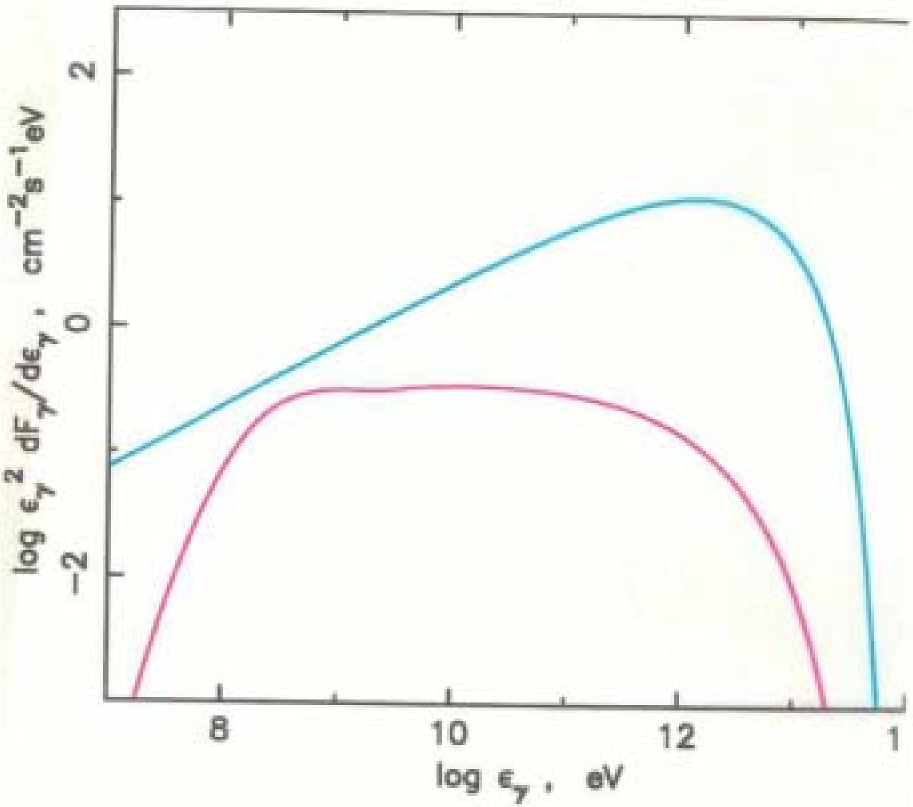
Total radio flux from SN 1006



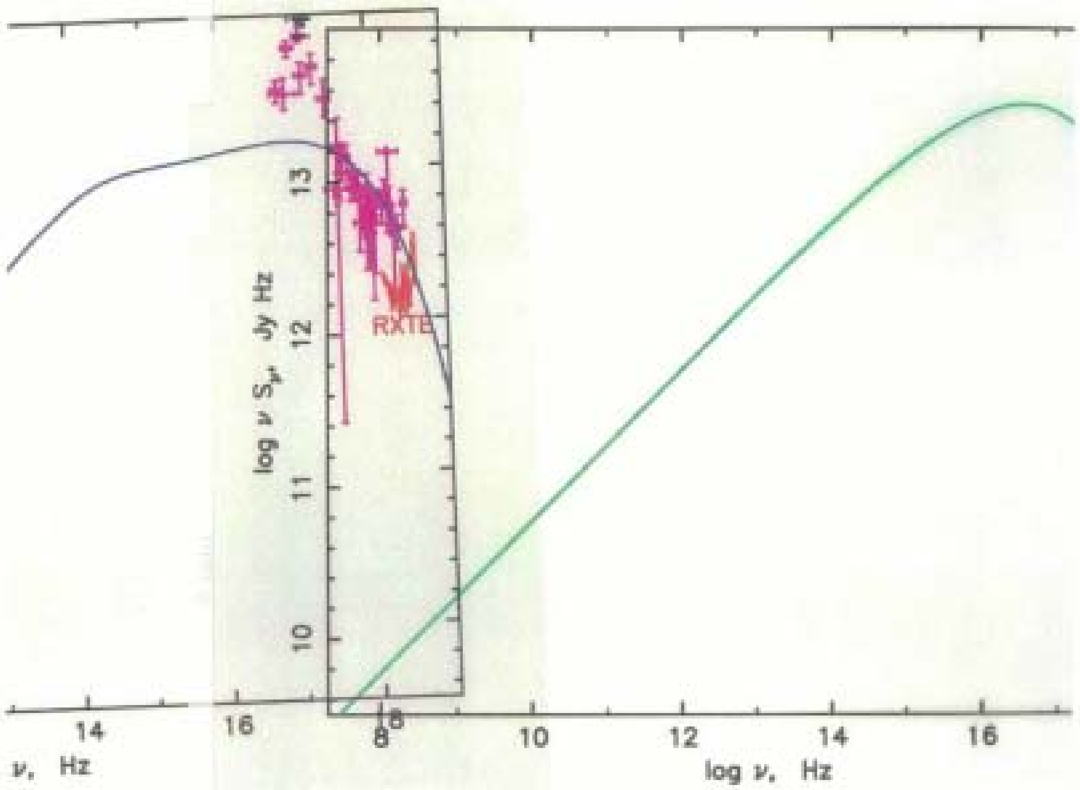
Institute of Cosmophysical Research
and Aeronomy
Yakutsk, Russia

N 1006

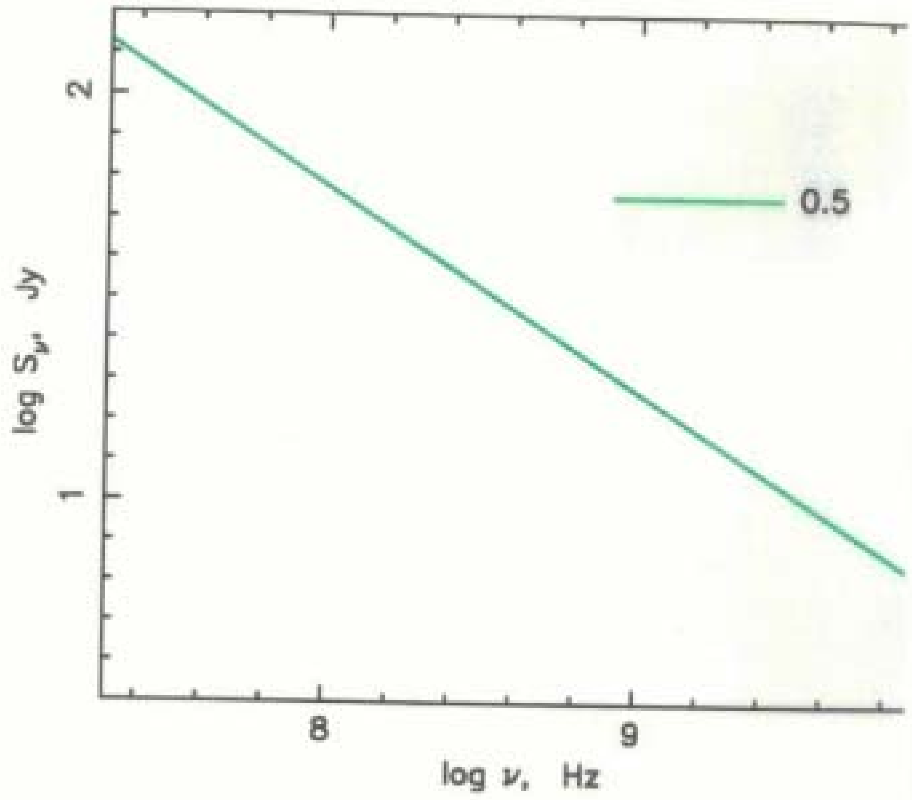




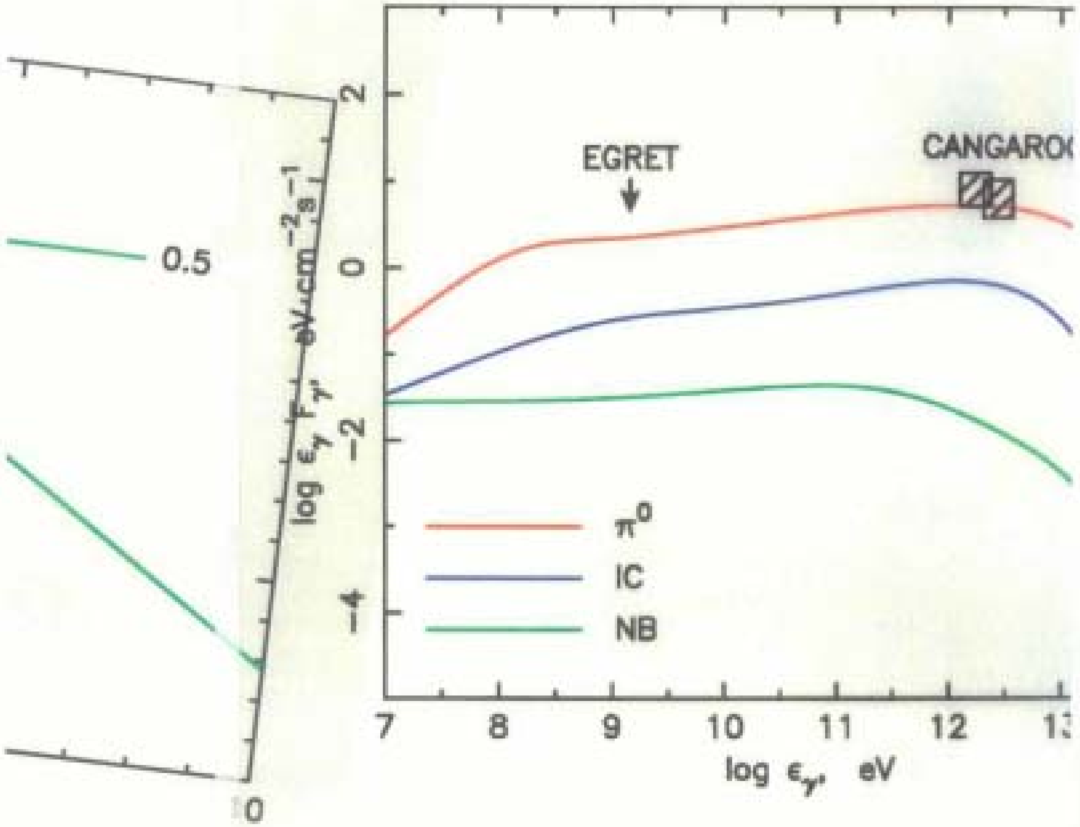
flux from SN 1006



ysical Research
nomy
Russia

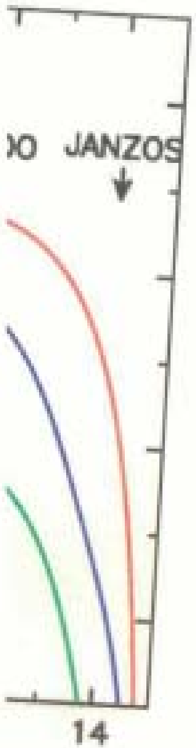


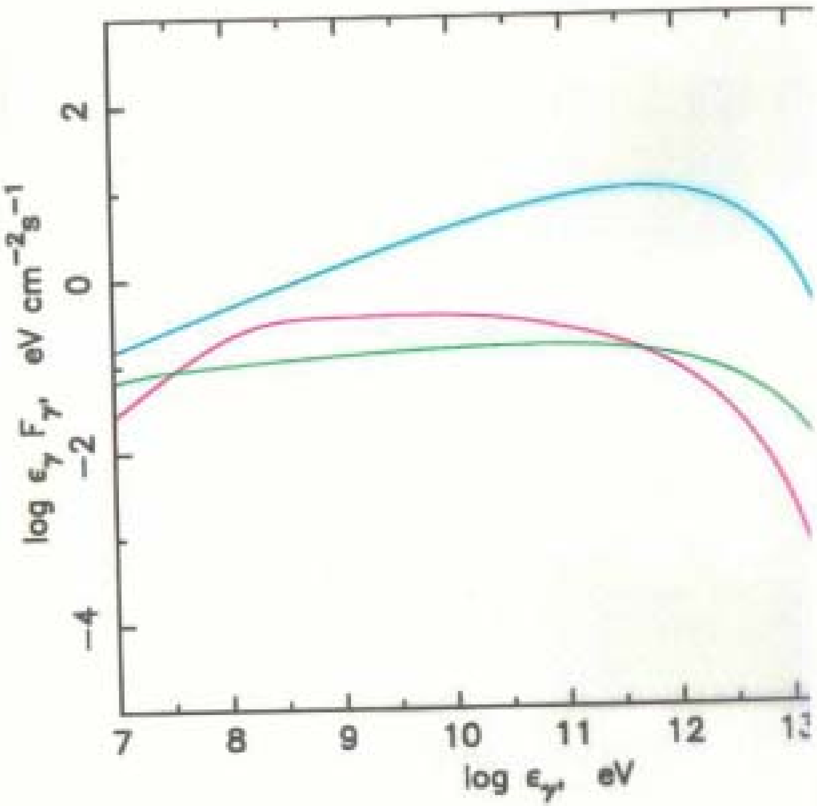
Gamma-ray energy fluxes from SN



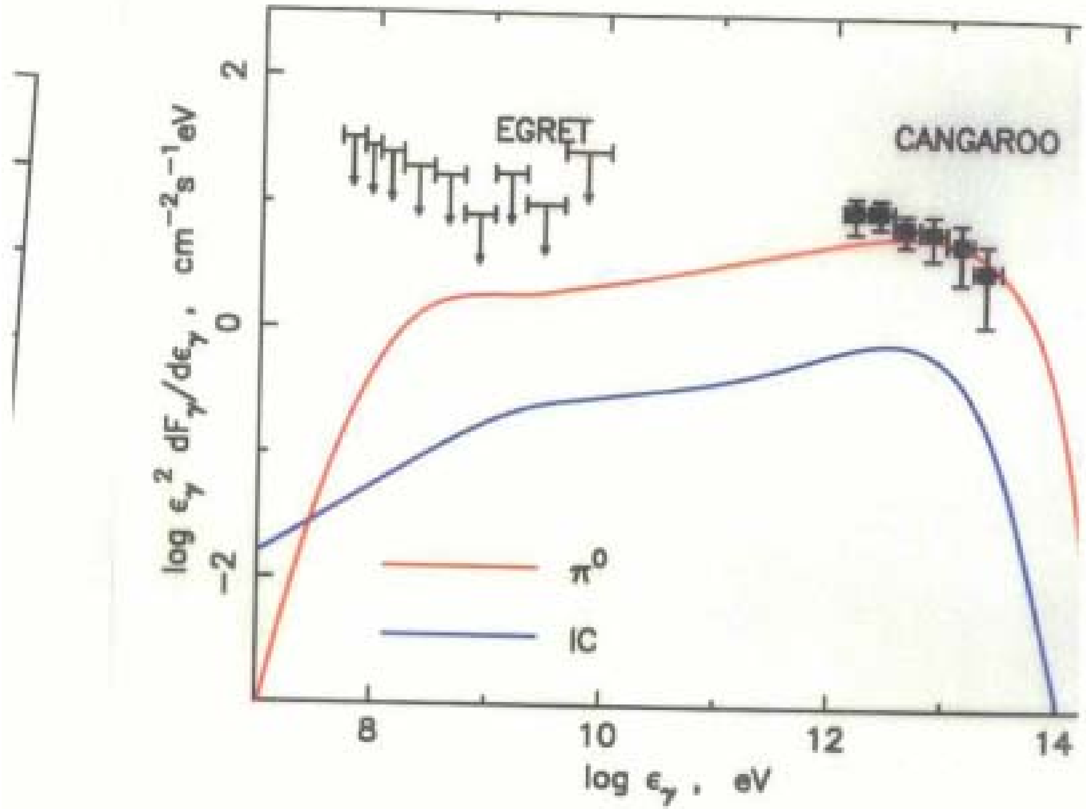
Institute of Cosmophysical Research
and Aeronomy
Yakutsk, Russia

N 1006

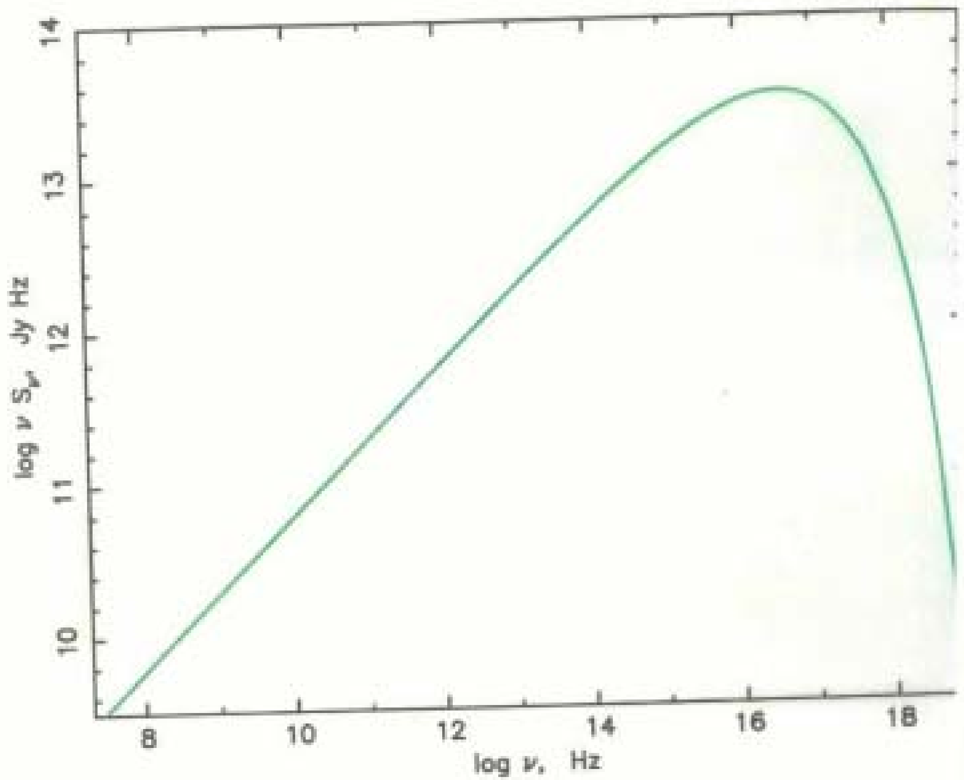




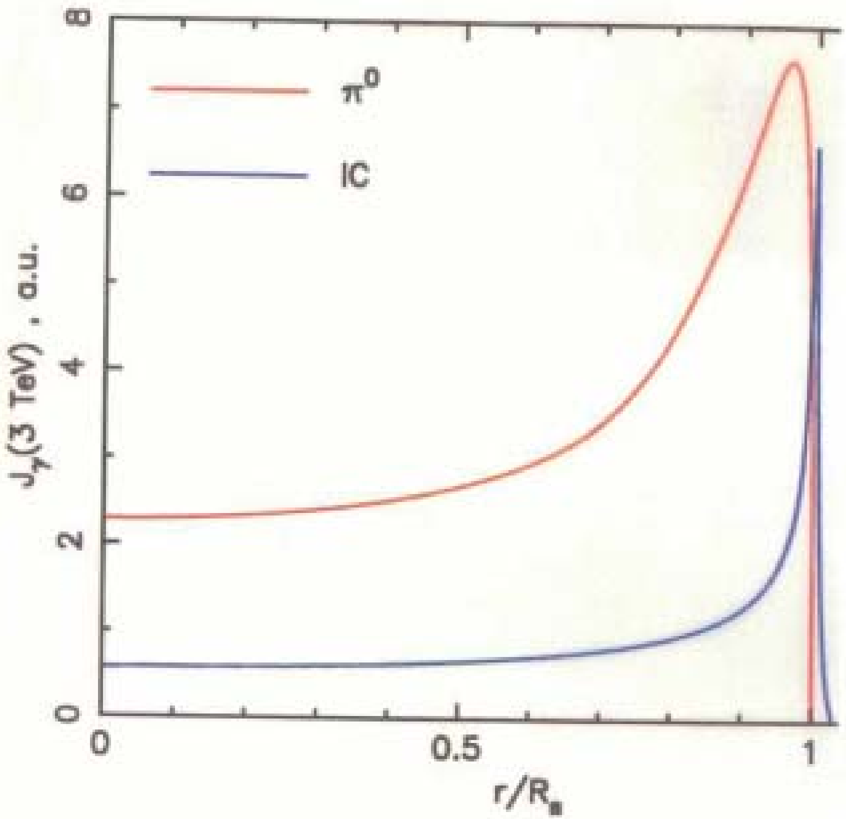
Differential gamma-ray fluxes from SN 100



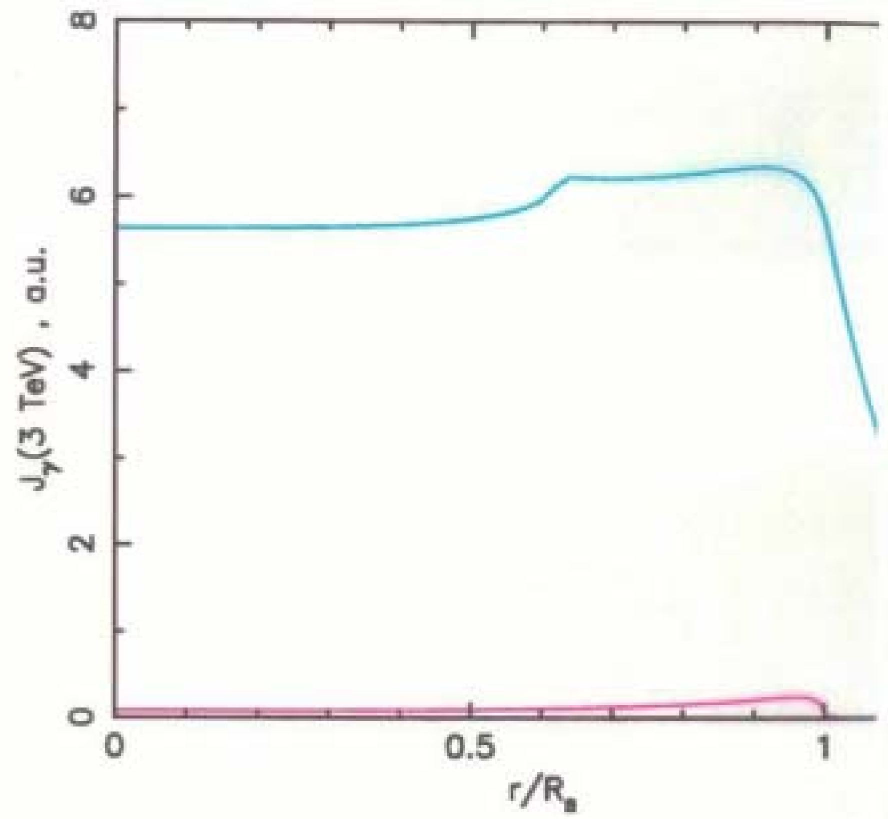
Institute of Cosmophysical Research
and Aeronomy
Yakutsk, Russia



Gamma-ray brightness of SN 1006



Institute of Cosmophysical Research
and Aeronomy
Yakutsk, Russia



Völk, Berezhko, Ksenofont… Rowell … 2…

Tycho's SNR

$t \simeq 430$ yr — age

SN Ia — type

↓

$M_{ej} = 1.4$

$\frac{dM_{ej}}{dv} \propto v^{2-k}$ — $k = 7$

$d = 2.3$ kpc — distance

$N_H = 0.5$ cm^{-3} — ISM number de…

↓

$E_{SN} = 0.3 \times 10^{51}$ erg — explosion en…

$S_\nu \propto \nu^{-\alpha}$ — $\alpha = 0.607 \pm 0.007$

↓

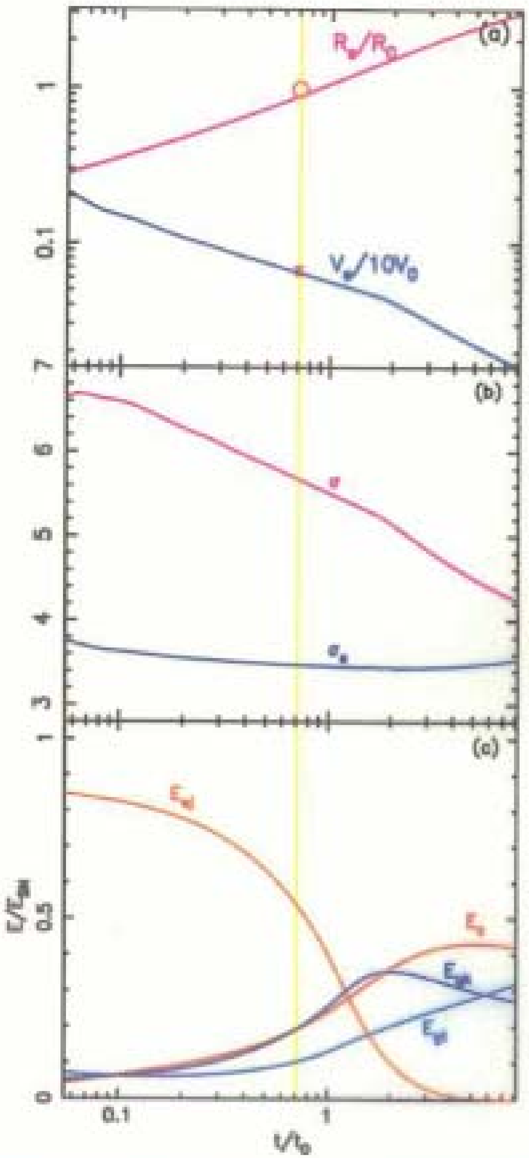
$B_0 = 40\ \mu G$

$B_\perp \simeq 140\ \mu G$

$K_{ep}^{re} = 2 \times 10^{-2}$

$f_{re} = 0.2$

Evolution of Tycho's SNR



R_s – shock siz
V_s – shock spe

R_0=2.7 pc – s
radius
V_0=4402 km/s
ejecta spe

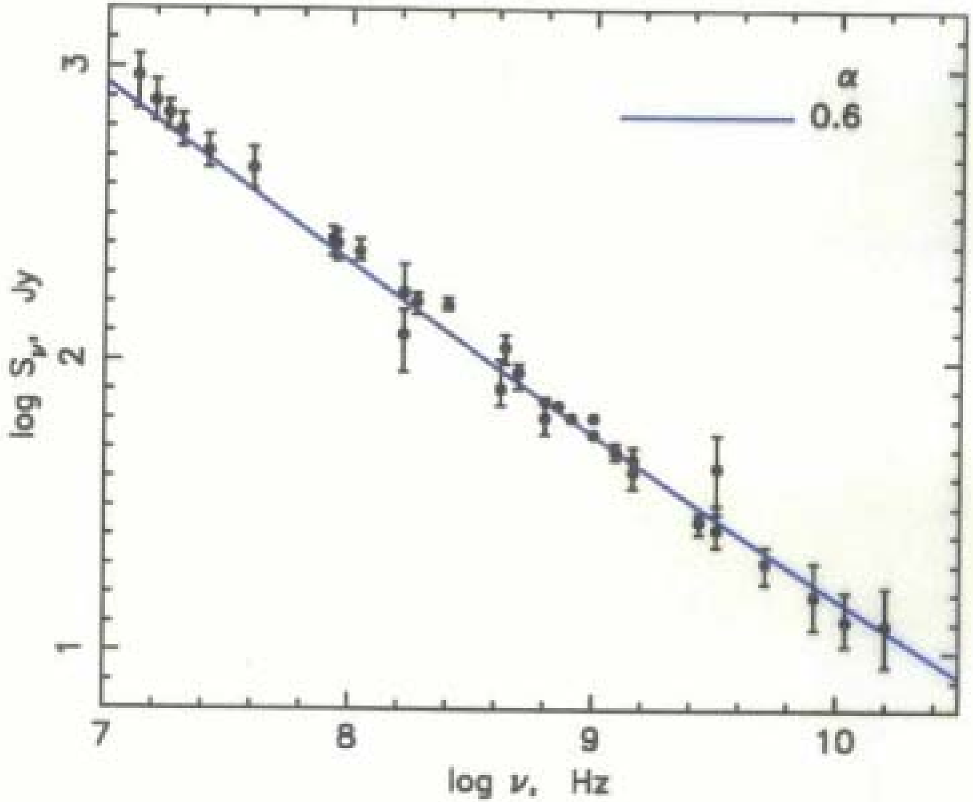
σ – shock com
ratio
σ_s – subshock
ratio

Energy compo
E_{ej} – ejecta
E_c – CRs
E_{gk} – gas kine
E_{gt} – gas therm

t_0=605 yr – sw
time

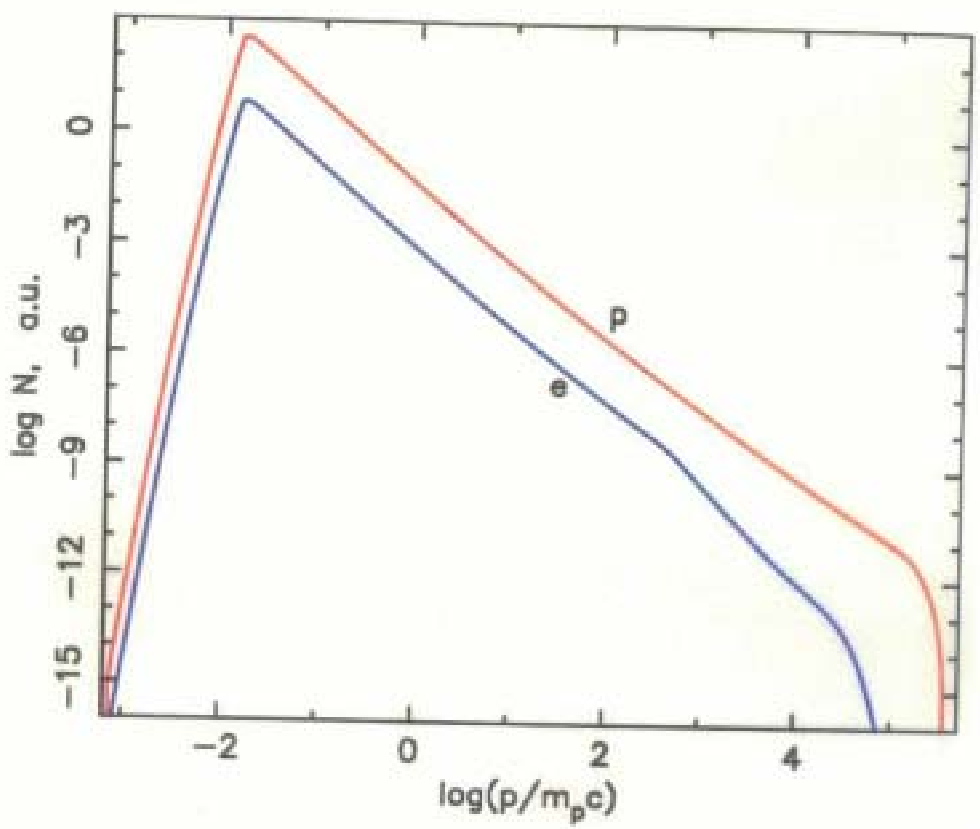
Institute of Cosmophysical Research
and Aeronomy
Yakutsk, Russia

Total radio flux from Tycho's SNR

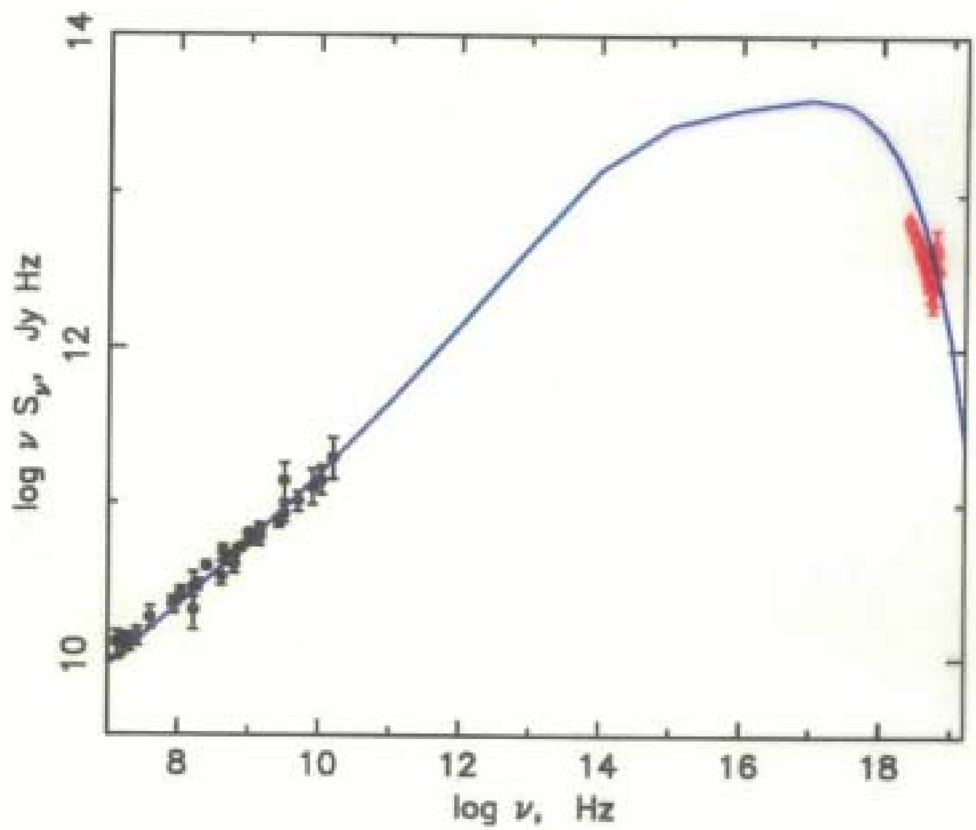


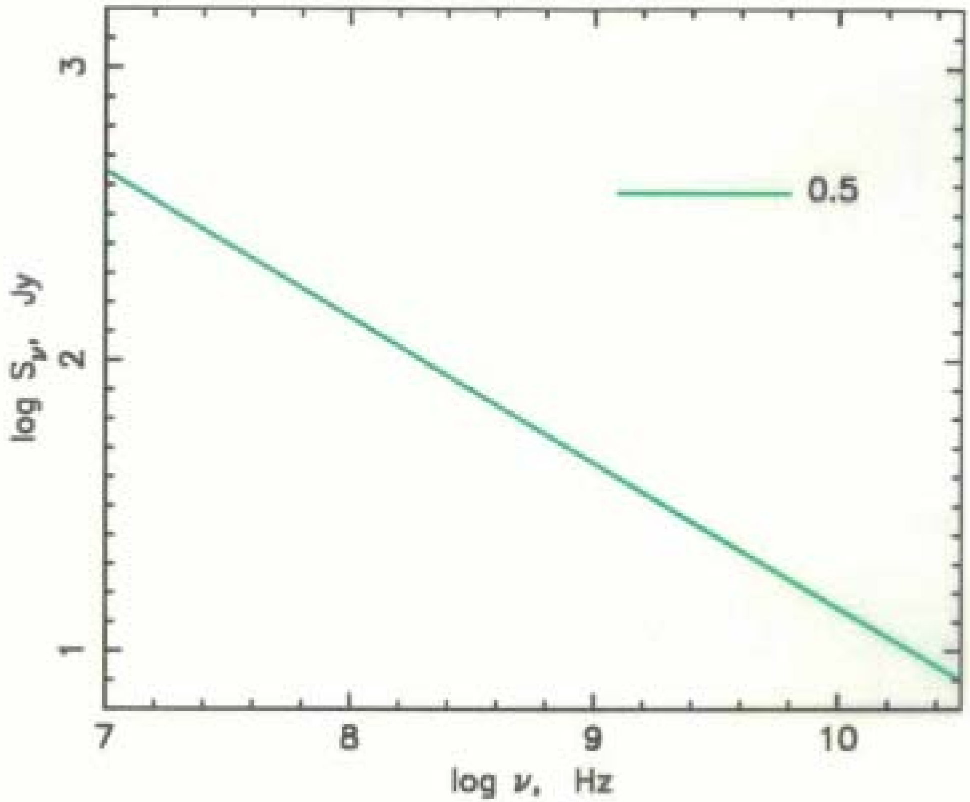
Institute of Cosmophysical Research
and Aeronomy
Yakutsk, Russia

Overall CR spectrum in Tycho's SNR

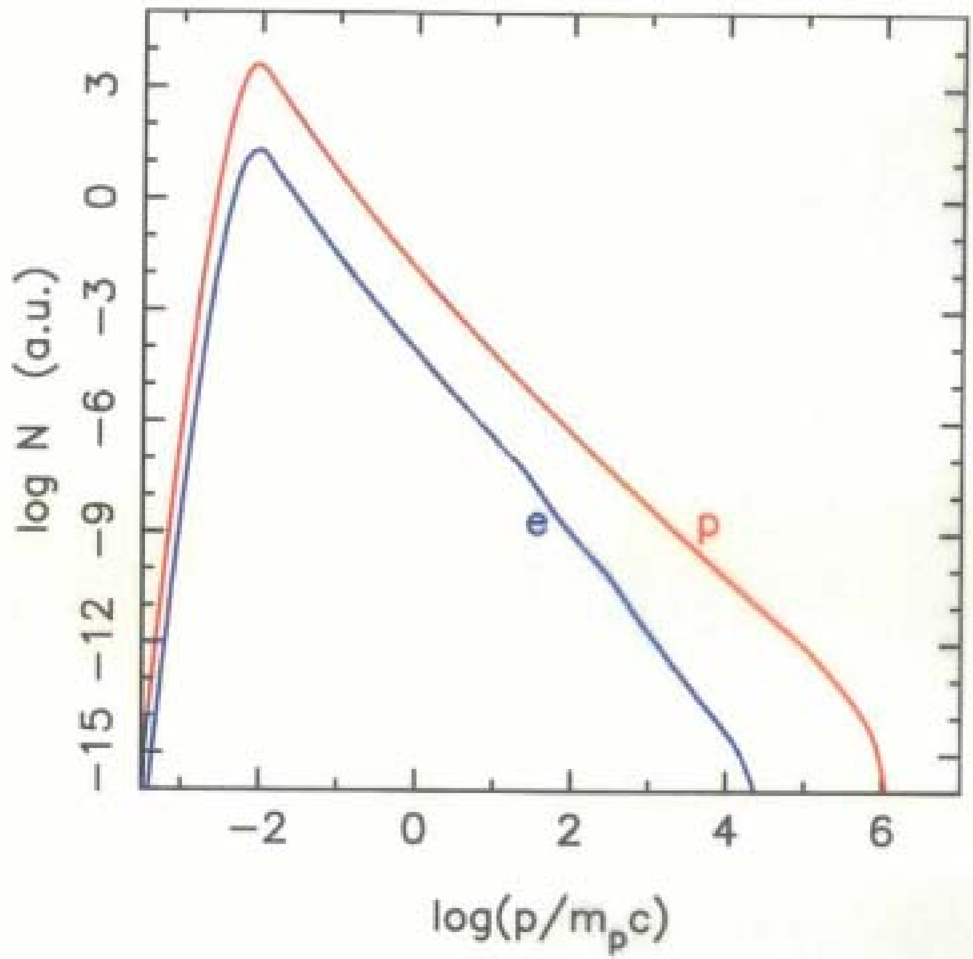


Synchrotron emission flux from Tycho's SNR



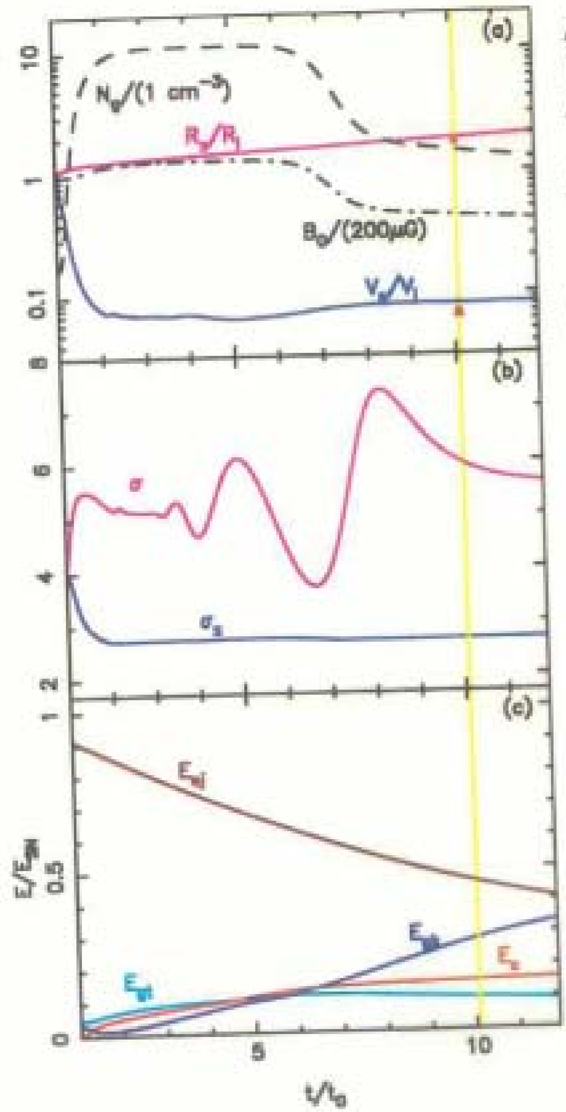


Overall CR spectrum in Cas A



Institute of Cosmophysical Research
and Aeronomy
Yakutsk, Russia

Evolution of Cas A SNR



R_s – shock size
V_s – shock speed
N_g – circumstellar number density
B_0 – background magnetic field

R_i=1 pc
V_i=30000 km/s

σ – shock compression rati
σ_s – subshock compressior ratio

Energy components:
E_{ej} – ejecta
E_c – CRs
E_{gk} – gas kinetic
E_{gt} – gas thermal

t_0=31.7 yr

Institute of Cosmophysical Research
and Aeronomy
Yakutsk, Russia

Cas A

Berezhko, Pühlhofer, Völk 2001,2

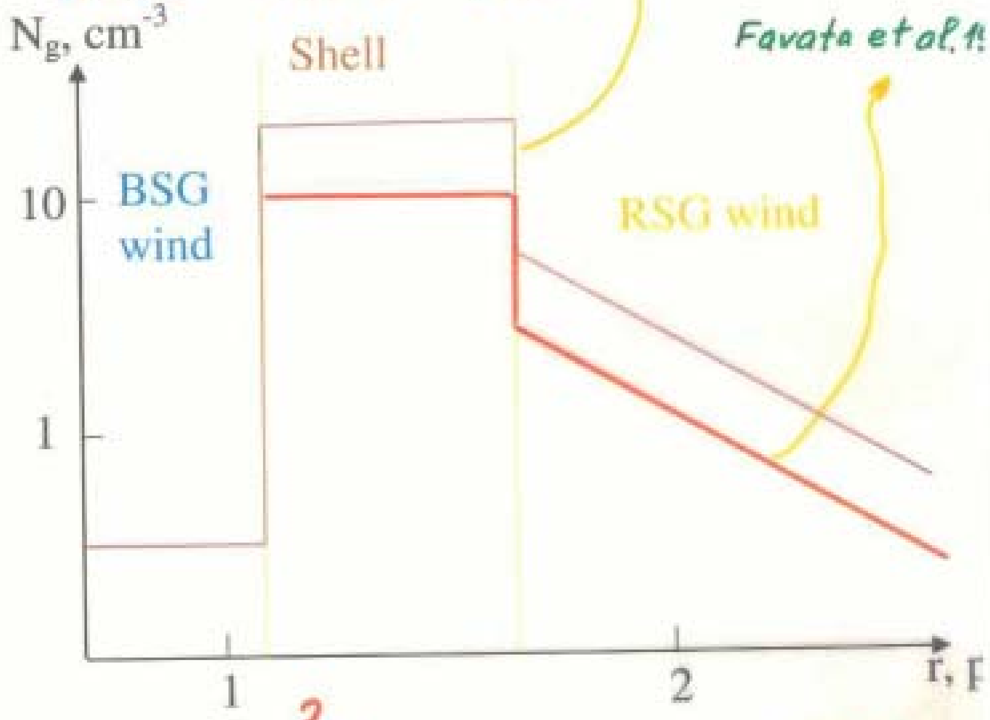
d=3.4 kpc

Circumstellar medium

Borkowski et al., 1996

RSG → BSG → SN

Favata et al. 1!



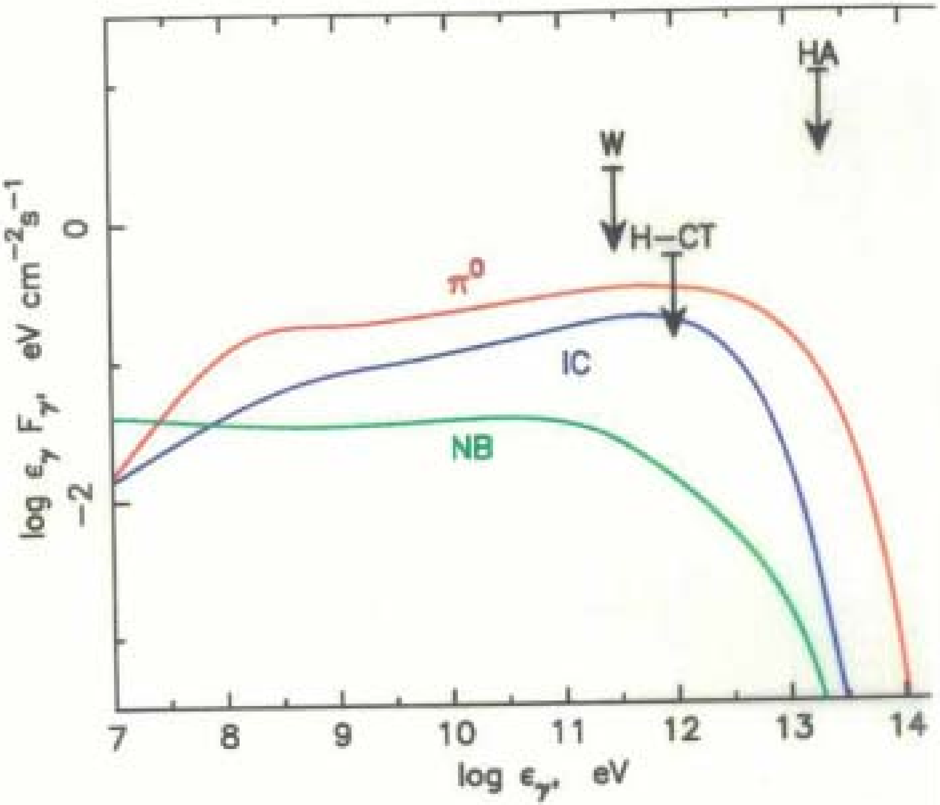
$M_{ej} = \cancel{3}\,2\,M_{Sun}$

$E_{SN} = \cancel{1}\,0.4 \cdot 10^{51}$ e

$\frac{dM_{ej}}{dv} \propto v^{2-k}$

$k=6$

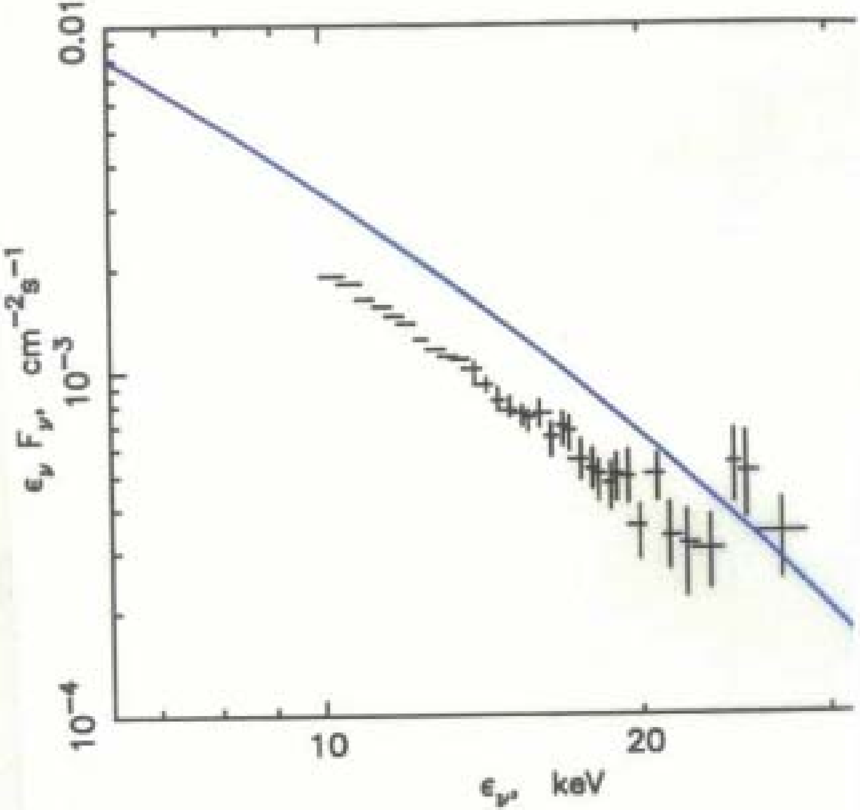
Gamma-ray energy fluxes from Tycho's SNF



SNR

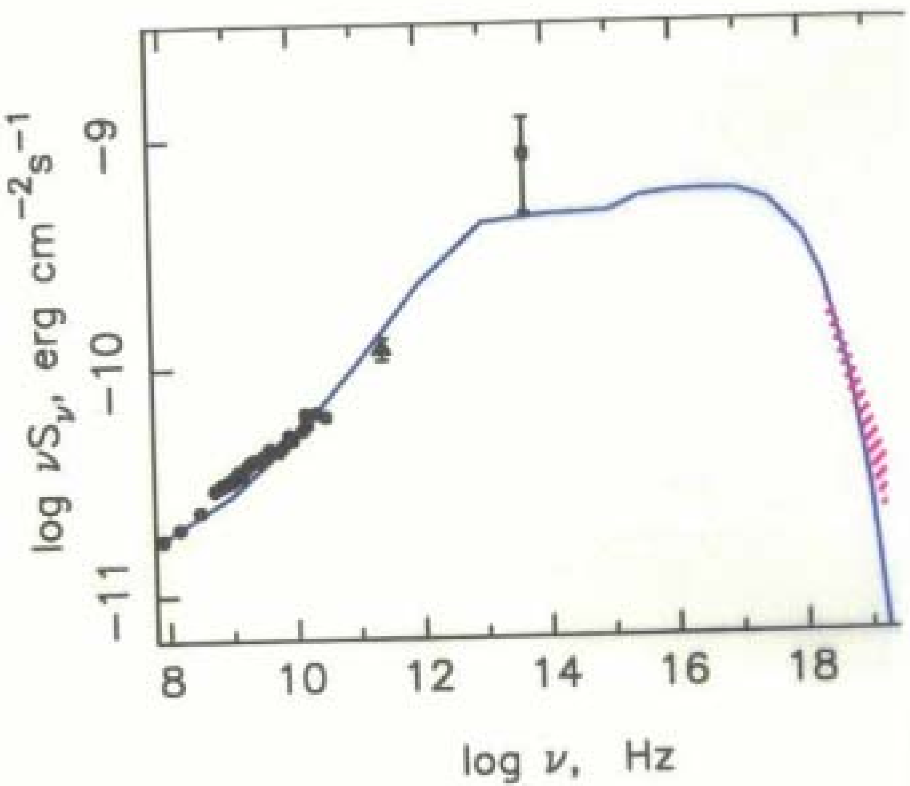
Institute of Cosmophysical Research
and Aeronomy
Yakutsk, Russia

X-ray flux from Tycho's SNR



Institute of Cosmophysical Research
and Aeronomy
Yakutsk, Russia

Synchrotron emission flux from Cas A



Institute of Cosmophysical Research
and Aeronomy
Yakutsk, Russia

Secular synchrotron flux variation

$$N_e \propto N_0 p^{-\gamma}$$

$$S_\nu \propto B^{\frac{\gamma+1}{2}} N_0 \nu^{-\frac{\gamma-1}{2}}$$

For young SNR ($t \lesssim 10^3$ yr) in uniform ISM

$B(t) \sim const \quad \frac{dN_0}{dt} > 0$

$$\Rightarrow \quad \frac{dS_\nu}{dt} > 0$$

Cas A :

$\frac{dS_\nu}{dt} < 0 \Rightarrow$ nonuniform ISM

a) Free wind

$N_g \propto R_s^{-2}$

$B(t) \propto B_0(R_s) \propto R_s^{-1}$

$N_0 \propto R_s^3 N_g(R_s) \propto R_s$

$$\frac{d\lg S_\nu}{dt} = -\frac{\gamma-1}{2}\frac{V_s}{R_s}$$

Cas A: $-\frac{d\lg S_\nu}{dt} \simeq 0.1\,\%/yr \ll$ obs.

b) Dense shell + free wind

emission is dominated by electrons produced in the shell at $t_i < t$

$f(t,p) = f_i(t_i, ap)$

$a = \left(\frac{\rho_i}{\rho}\right)^{1/3}$ adiabatic factor

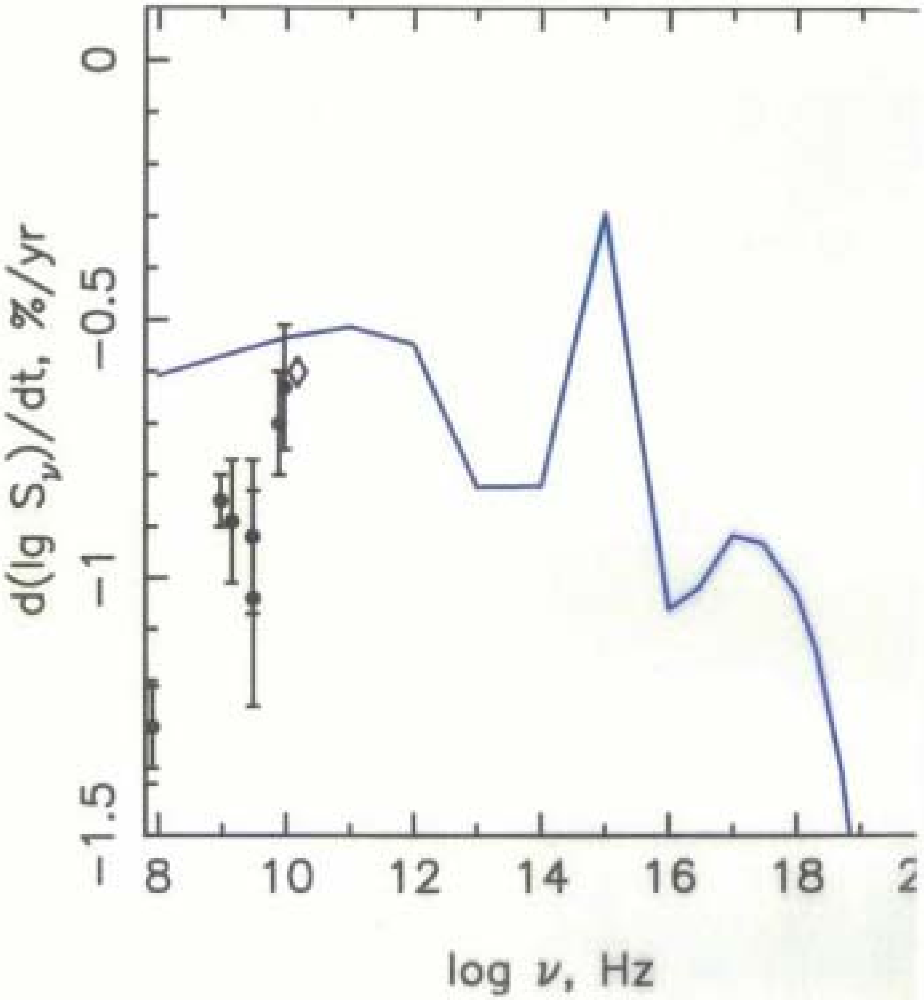
$\rho \propto R_s^{-3} \rightarrow a \propto R_s$

$B_d \propto a^{-2} \propto R_s^{-2}$

$$\frac{d\lg S_\nu}{dt} = -(2\gamma+3)\frac{V_s}{R_s}$$

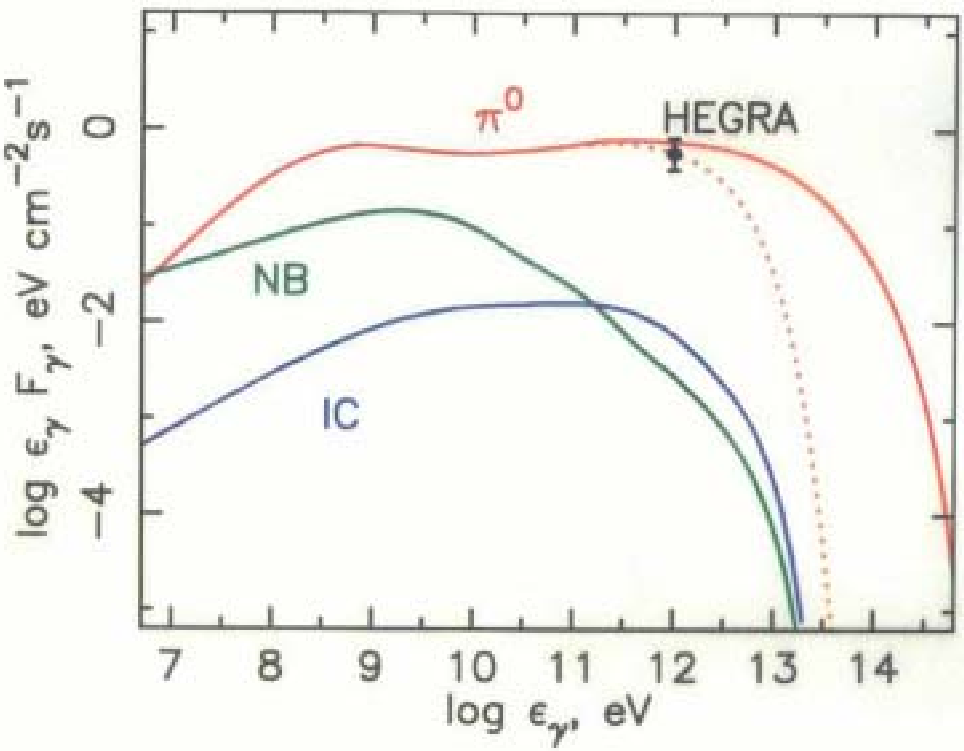
Cas A: $-\frac{d\lg S_\nu}{dt} \simeq 0.8\,\%/yr \simeq$ obs.

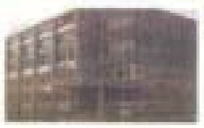
Secular decline of the synchrotron emissio from Cas A



Institute of Cosmophysical Research
and Aeronomy
Yakutsk, Russia

Gamma-ray energy fluxes from Cas A





Institute of Cosmophysical Research
and Aeronomy
Yakutsk, Russia

Conclusions

- Existing data (radio, x-ray, γ-ray) are consistent with the efficient CR acceleration in SNRs providing

  $E_C / E_{SN} \cong 0.1 \quad \varepsilon_{\max} \sim 3\times10^{14} eV \quad Kep \sim 10^{-2}$

  that is required for Galactic CR sources

In particular:

- Efficient nuclear CR production leading to strong shock modification and a large downstream magnetic field

  $B_d \sim 100\mu G\,(SN1006, Tycho) \div 1\mu G\,(Cassiopeia\ A)$

  are required to reproduce the observed synchrotron emission from radio to x-ray frequencies

- γ-ray flux is dominated by π^0-decay γ-rays generated by CR nuclear component.
  Integral γ-ray flux

  $$F_\gamma \propto \varepsilon_\gamma^{-1}$$

  extends up to $\varepsilon_\gamma \sim 50\ TeV$ if CR diffusion is as strong as the Bohm limit

Institute of Cosmophysical Research
and Aeronomy
Yakutsk, Russia