Neutrinos from SNR and Pulsars

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Neutrino Production in SNR (pion decay)

$$p + p \rightarrow p + p + a\,\pi^0 + b(\pi^+ + \pi^-)$$

$$\pi^0 \rightarrow 2\gamma \quad ; \quad \pi^+ \rightarrow \mu^+ + \nu_\mu \quad ; \quad \pi^- \rightarrow \mu^- + \nu_\mu{}^*$$

$$\mu^+ \rightarrow e^+ + \nu_e + \nu_\mu{}^* \quad ; \quad \mu^- \rightarrow e^- + \nu_e{}^* + \nu_\mu$$

To compute fluxes from pion decay, it is required

(*) Cosmic Rays – Total Energy and Spectrum

(*) Gas density in the shocked shell

(*) neutrinos should be produced in amounts nearly equal to γ's

Synchrotron Emission from SNR

information about the spectral index $S_\nu \propto \nu^{-(\gamma - 1)/2}$

total energy on CR electrons (if <H> is known)

shock theory $W_p/W_e \approx (m_p/m_e)^{(\gamma - 1)/2}$

non-thermal X-rays (SN 1006, Cas A, G347.3-0.5, IC443)

if synchrotron $E \sim 10 – 100$ TeV (for electrons)

’’Classical’’ Expansion Phases of SNR

Phase I – ’’free-expansion’’ $t < (3/4\pi\rho_i)^{1/3} M^{5/6} (2E_k)^{½}$

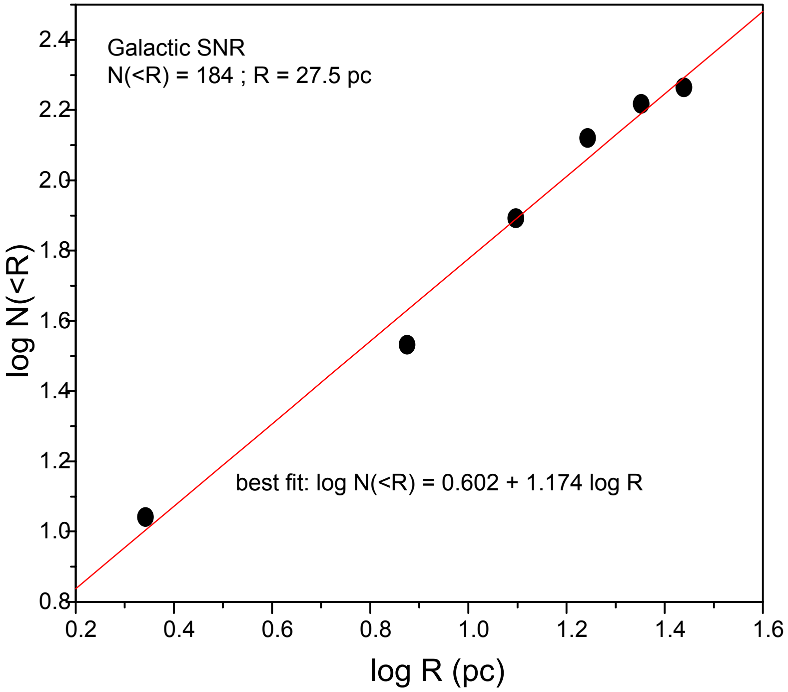
Phase II – adiabatic or Sedov phase $R \propto t^{2/5}$

Phase III – constant momentum $R \propto t^{¼}$

If most of the remnants are in the Sedov phase $N(<R) \propto R^{5/2}$

Problem : in the LMC $R \propto t$ up to radii of the order 20 pc !

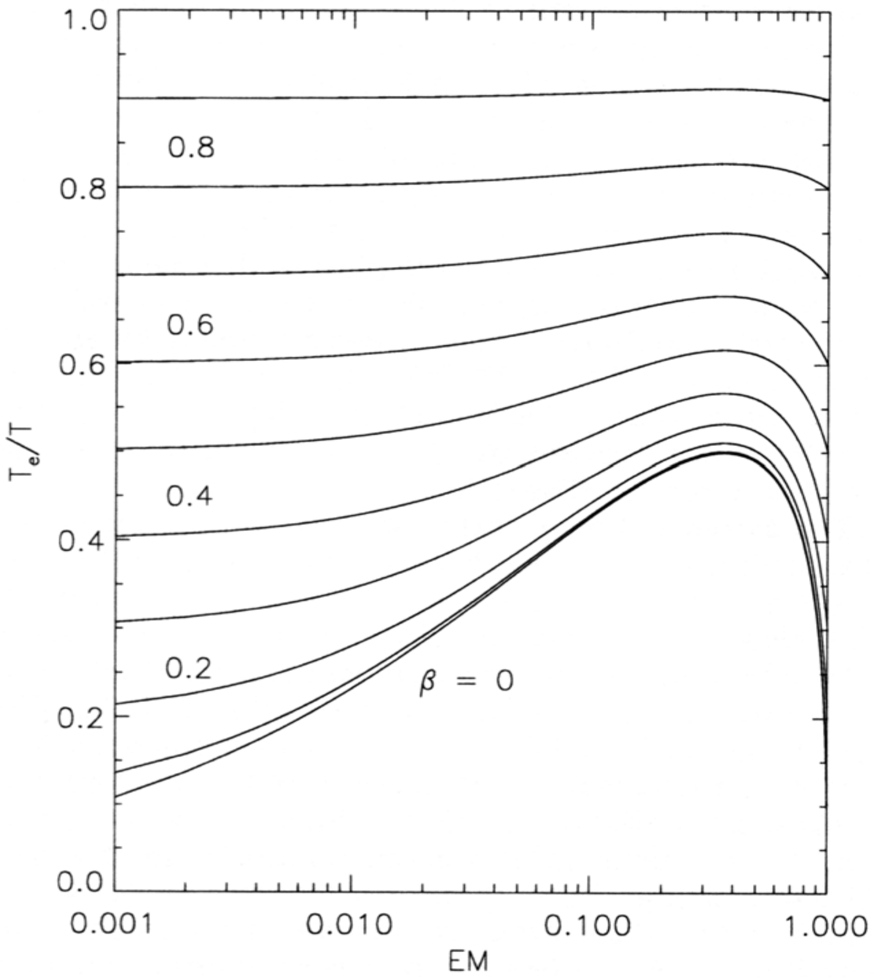
Galactic SNR : distribution of radii



- **Distrbution differs from expected (Sedov)**
- **Inhomogeneities in the ISM produce a flatter distribution of radii (but not the only reason)**

Numerical Simulations (Sedov phase)

(Borkowski et al. 2001)

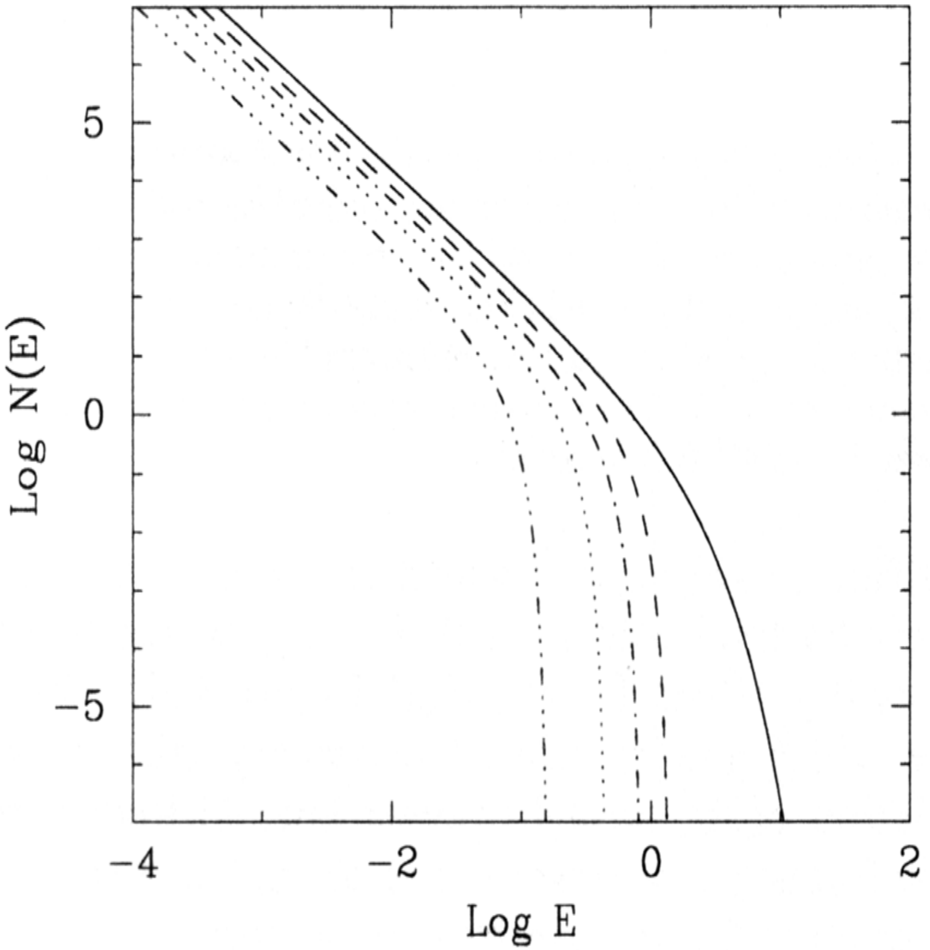


Ratio of the electron temperature to the mean gas temperature as a function of the emission measure EM of the shell.

β characterizes the efficiency of the heating transfer between ions and electrons

Numerical Simulations (Sedov phase)

(Reynolds 1998)



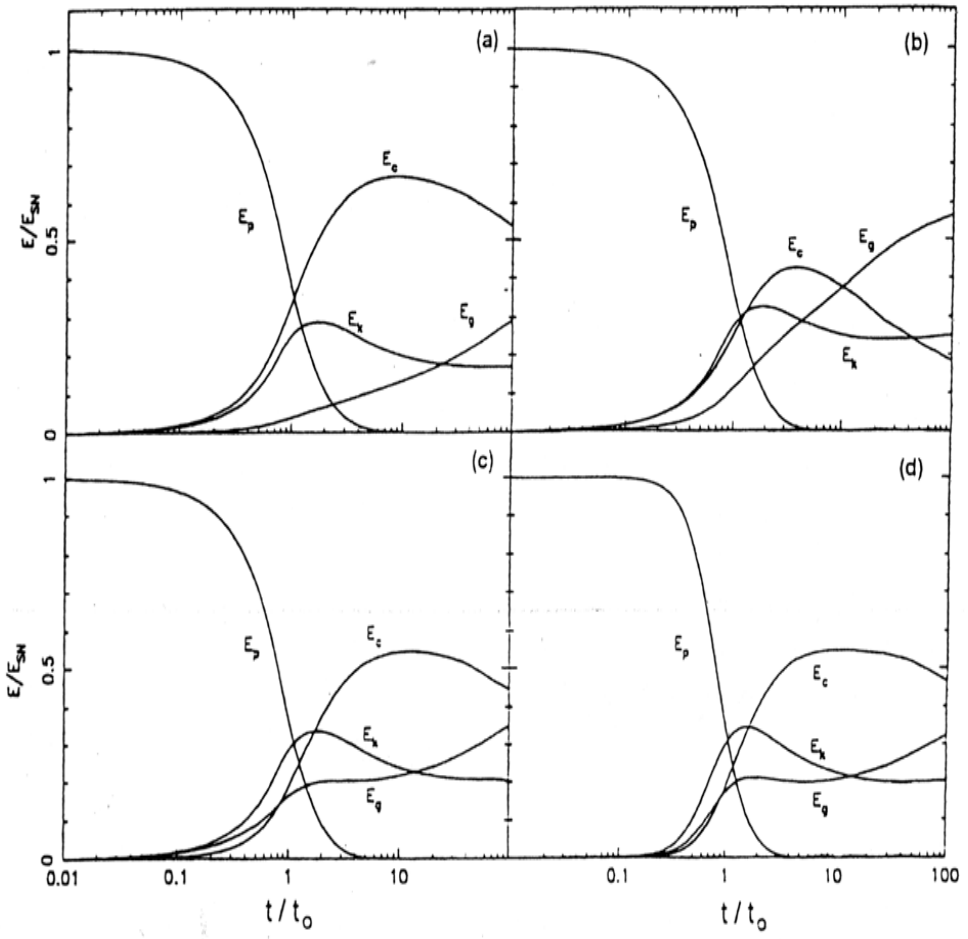
Cosmic Rays – Electron component

Variation of the CR electron density per energy interval at different distances of the shock radius

solid curve = Rs
others = (0.8, 0.6, 0.4, 0.2) x Rs

Numerical Simulations (Cosmic Ray Kinetics)

(Berezhko & Völk 1997)



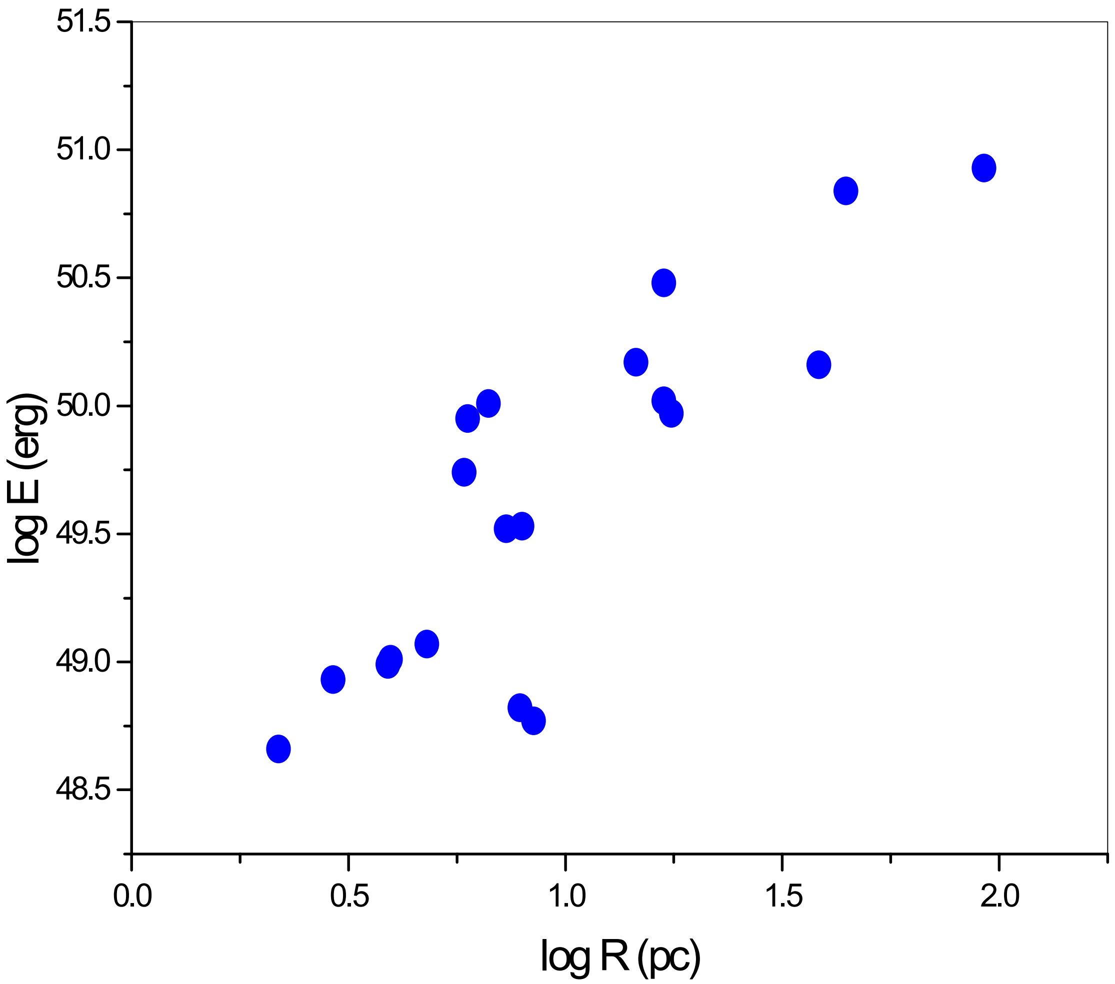
$H = 5 \mu G$ (a, c, d); $H = 30 \mu G$ (b)

$\eta = 10^{-3}$ (a, b) ; $\eta = 10^{-4}$ (c, d)

$n_o = 0.3\ cm^{-3}$

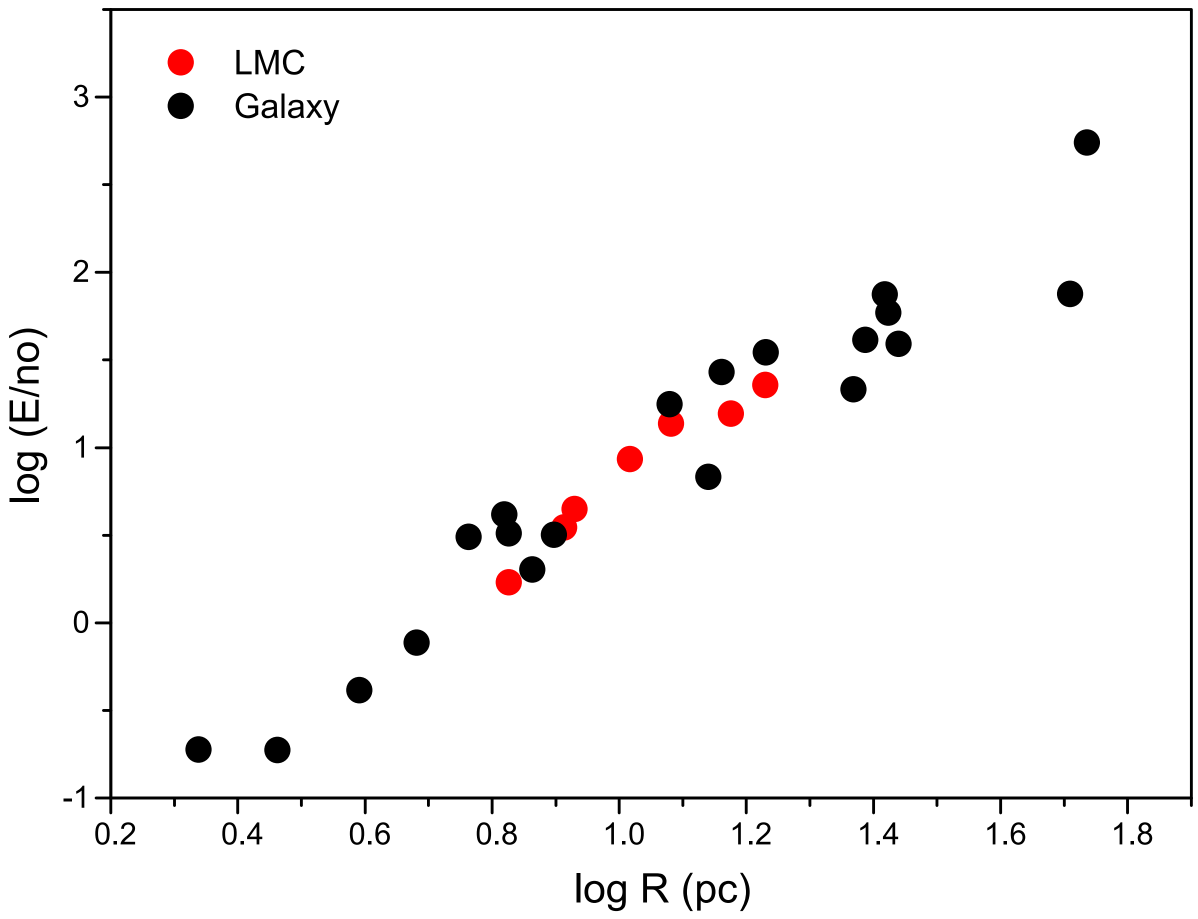
$t_o = 1890$ yr

Cosmic Ray Energy vs Shell Radius

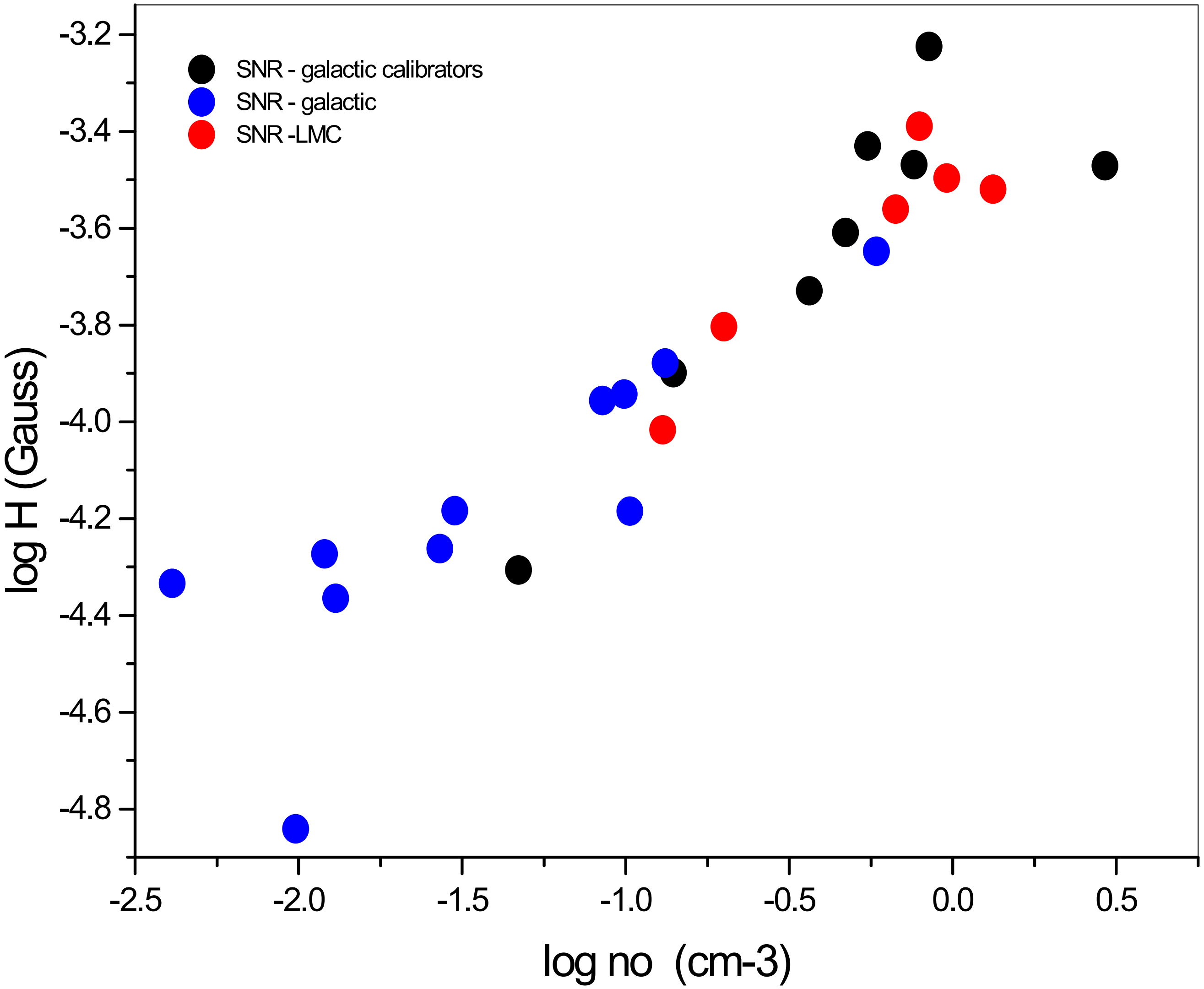


Thermal Energy x Shell Radius

(E in units of 10^{50} erg)



Interstellar Medium Density vs Magnetic Field



Some SNR Parameters

SNR	D(kpc)	R(pc)	$E_{RC}(10^{49}$ erg)	$E_{th}(10^{49}$ erg)	$n_0(\text{cm}^{-3})$	H(μ G)
Kepler	5.0	2.2	0.46	2.34	0.84	520
11.2-0.3	5.0	2.9	0.85	3.57	2.92	440
27.4+00	6.7	3.9	0.98	1.93	0.55	320
29.7-0.3	13.4	5.8	5.49	0.74	0.11	420
31.0+00	8.5	7.3	3.31	6.30	0.48	220
33.6+0.1	10.0	14.5	14.8	37.4	0.14	160
39.2-0.3	7.9	8.0	3.39	12.4	0.58	200
43.3-0.2	13	6.5	9.77	31.3	0.76	440
53.6-22	6.0	26.5	25.1	28.8	0.085	93

Expected Neutrino Fluxes from SNR

SNR	F_γ (> 100 MeV) (cm^{-2} s^{-1})	F_γ (> 1 TeV) (cm^{-2} s^{-1})	F_ν(>100 GeV) (cm^{-2} s^{-1})
G11.2-0.3	1.4×10^{-9}	1.3×10^{-14}	2.9×10^{-14}
G43.3-0.2	6.1×10^{-10}	5.9×10^{-15}	1.3×10^{-14}
G332.4-0.4	5.5×10^{-10}	5.3×10^{-15}	1.1×10^{-14}
G31.0+0.0	3.1×10^{-10}	2.9×10^{-15}	6.3×10^{-15}
G33.6+0.1	2.9×10^{-10}	2.8×10^{-15}	6.1×10^{-15}
Kepler	2.2×10^{-10}	2.1×10^{-15}	4.5×10^{-15}
G27.4+0.0	1.7×10^{-10}	1.6×10^{-15}	3.5×10^{-15}

SNR suspected to be associated with Egret sources

(also having nearby pulsars)

SNR	**F_γ(>100MeV)** (cm^{-2} s^{-1})	**3EG**	**Pulsar** (PSR)	**P** (ms)
W28	8.2×10^{-7}	J1800-2338	1758-23	415
W44	9.9×10^{-7}	J1856+0114	1853+0.1	267
G180.0-1.7	3.5×10^{-7}	J0542+2610	J0538+28	143
G290.1-0.8	4.2×10^{-7}	J1102-6103	J1105-61	63
Kes67	9.7×10^{-7}	J1823-1314	B1823-13	101
G106.6+2.9	5.7×10^{-7}	J2227+6122	J2229+61	51.6

SNR detected at keV (Synchrotron) & TeV Energies

SNR 1006 (G327.6+14.6)

$f_x(0.1\text{-}3.0\ \mathrm{keV}) = 2.0 \times 10^{-10}\ \mathrm{erg.cm^{-2}.s^{-1}}$ (ASCA + ROSAT)

$f_\gamma(>1.7\ \mathrm{TeV}) = 4.6 \times 10^{-12}\ \mathrm{photons.cm^{-2}.s^{-1}}$ (CANGAROO)

SNR J1713.7-3946 (G347.3-0.5)

$f_\gamma(>1.8\ \mathrm{TeV}) = 5.3 \times 10^{-12}\ \mathrm{photons.cm^{-2}.s^{-1}}$ (CANGAROO)

$f_x(0.5\text{-}10\ \mathrm{keV}) = 2.0 \times 10^{-10}\ \mathrm{erg.cm^{-2}s^{-1}}$ (ROSAT)

Cas A

$f_x(>20\mathrm{keV}) = 8.0 \times 10^{-11}\ \mathrm{erg.cm^{-2}.s^{-1}}$ (ROSSI)

$f_\gamma(>1\ \mathrm{TeV}) = 5.8 \times 10^{-13}\ \mathrm{photons.cm^{-2}.s^{-1}}$ (HEGRA)

SNR J1713.7-3946 (G347.3-0.5)

If TeV photons are IC and keV photons are synchrotron $H = 8.4\ \mu G$

predicted IC $f_\gamma(> 100\ \mathrm{MeV}) = 4.8 \times 10^{-6}\ \mathrm{ph.cm^{-2}.s^{-1}}$

nearby 3EG 1714-3857 $f_\gamma(>100\ \mathrm{MeV}) = 6.8 \times 10^{-7}\ \mathrm{ph.cm^{-2}.s^{-1}}$

Assume TeV photons are from pion decay:

required CR energy 8×10^{50} erg (acceptable!)

predicted $f_\gamma(>100\ \mathrm{MeV}) = 5.5 \times 10^{-7}\ \mathrm{ph.cm^{-2}.s^{-1}}$ (OK!)

predicted $f_\nu(>0.1\ \mathrm{TeV}) = 1.1 \times 10^{-11}\ \mathrm{cm^{-2}.s^{-1}}$ (important ν-source)

Note: a larger distance has been claimed – 6.0 kpc instead of 1.0 kpc. In this case, the pion-decay scenario will no longer be true!

SNR 1006 (G327.6+14.6)

If TeV photons are IC (same electrons producing keV synchrotron ph)

Then interstellar magnetic field $H = 6.5\ \mu G$

This field implies a CR energy to explain radio emission of 5.4×10^{50} erg

Then: pion decay contributes to 10% of the observed TeV emission

$f_{\gamma}(> 100\ \mathrm{MeV}) = 1.4 \times 10^{-7}\ \mathrm{ph.cm^{-2}.s^{-1}}$ (43% pion decay + 57% IC)

$f_{\nu}(> 0.1\ \mathrm{TeV}) = 1.2 \times 10^{-12}\ \mathrm{cm^{-2}.s^{-1}}$

Cas A

Difficulties with IC to explain TeV photons

$f_{IC}(>100\text{ MeV}) = 8.3 \times 10^{-5}\text{ ph.cm}^{-2}\text{.s}^{-1}$ and $W_e(>10\text{ TeV}) \approx 0.012 W_{e,T}$

Radio and X-rays (<15 KeV) same power-law, requiring

$H = 1.5 \times 10^{-3}\text{ G}$ and $E_{RC} = 3.4 \times 10^{50}\text{ erg}$

Predictions

$f_{\gamma}(>100\text{ MeV}) = 6.0 \times 10^{-8}\text{ ph.cm}^{-2}\text{.s}^{-1}$

$f_{\gamma}(>1\text{ TeV}) = 6.3 \times 10^{-13}\text{ ph.cm}^{-2}\text{.s}^{-1}$

$f_{\nu}(>0.1\text{ TeV}) = 1.4 \times 10^{-12}\text{ cm}^{-2}\text{.s}^{-1}$

The Unruh Effect

Minkowski	**Rindler**	**Hawking's Effect**
inertial observer	accelerated observer	black hole
$T = 0$	$kT = \nabla a/2\pi c$	$kT = \nabla g/2\pi c$

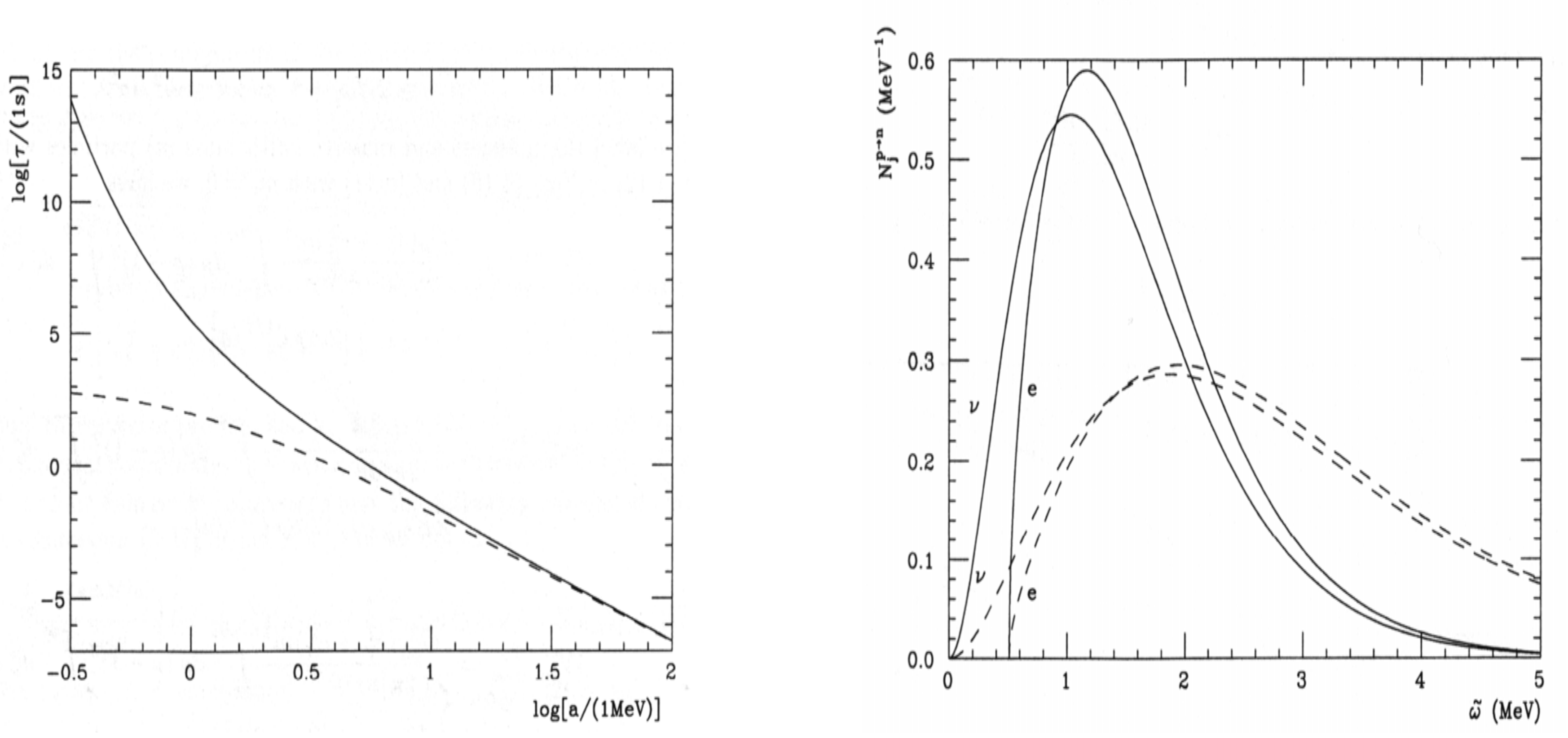
Decay of an accelerated proton — Ginzburg & Syrovatskii (1965)

Vanzella & Matsas (2000;2001)

Inertial observer $\mathbf{p \quad ne^+ \nu_e}$

accelerated observer $\mathbf{pe^- \quad n\nu_e , p\nu_e^* \quad ne^+ \text{ or } pe^-\nu_e^* \quad n}$

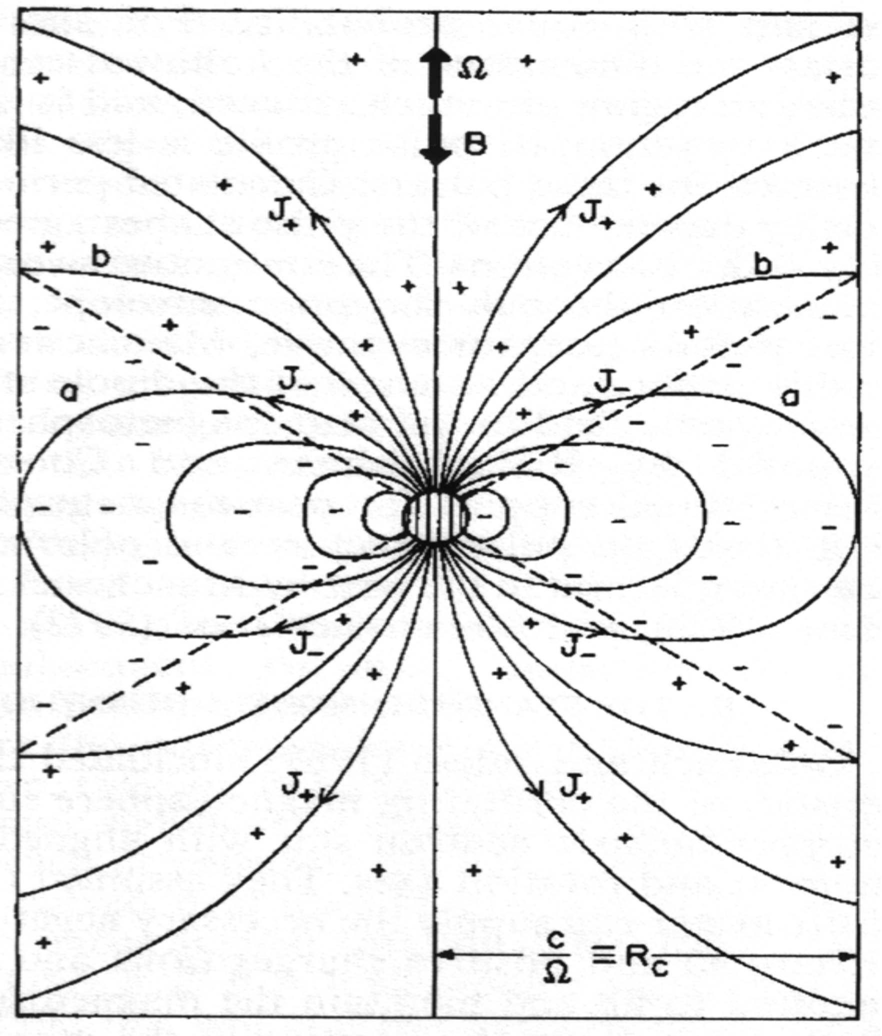
(e^- and ν_e* are ‘’’Rindler’’ particles)



left: proton lifetime (—) neutron lifetime (---)

right: spectra of secondaries $(e^- \nu_e)$

The Pulsar Magnetosphere



Dashed lines separate positive and negative charge regions

Force lines inside a are closed

Open lines between a and b pass through regions of positive and negative charges

Protons in Strong Magnetic Fields

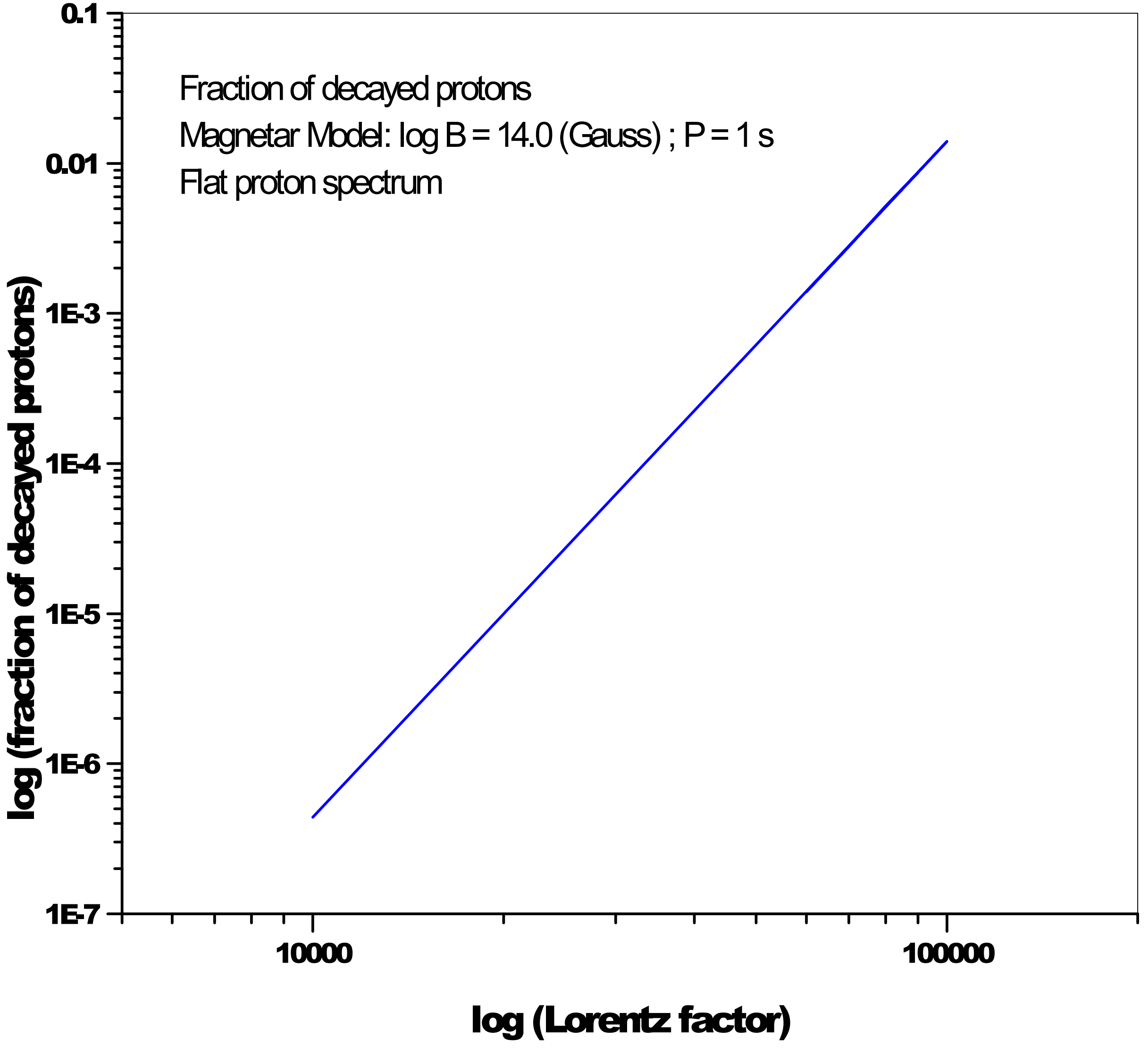
Proper acceleration $a_H = \gamma c \omega_H$ **where** $\omega_H = eH/m_p c$

Typical neutrino energy $E_\nu \sim \gamma \nabla \omega_H$

$$d^2N_\nu/dE_\nu dt = (d^2N_p/dE_p dt)(dE_p/dE_\nu) f(E_p \to E_\nu)$$

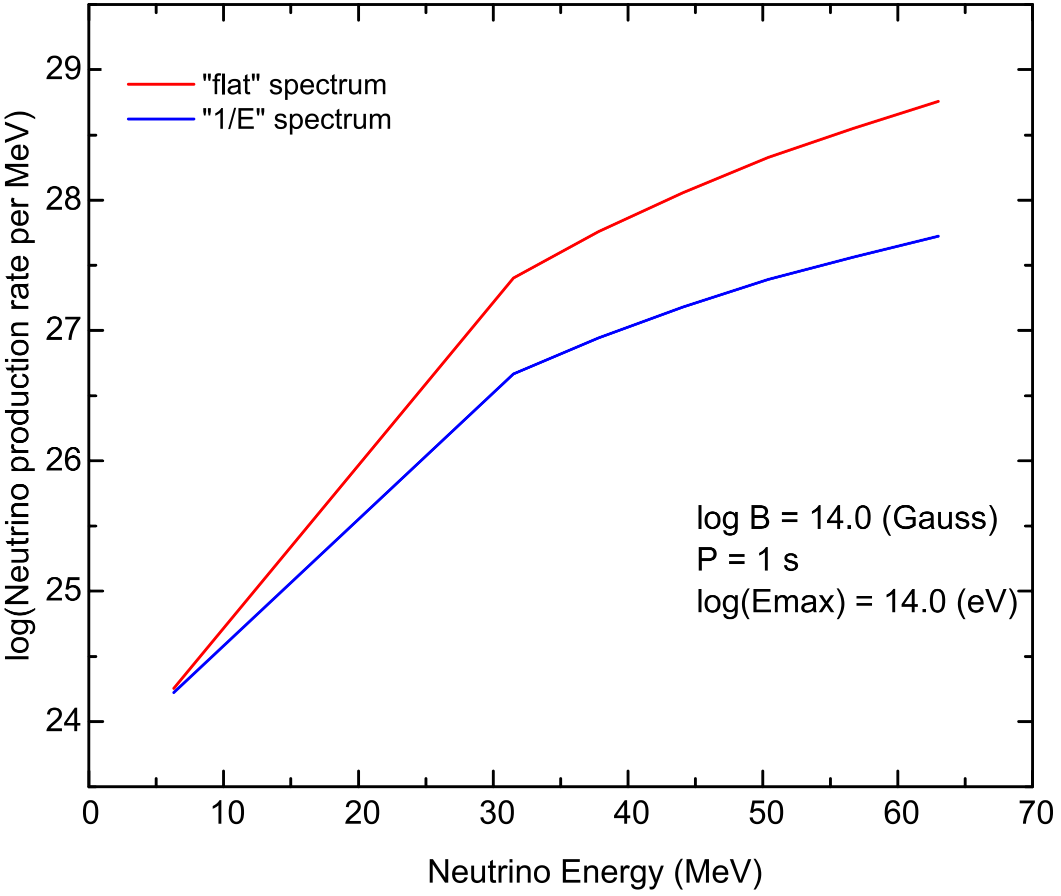
$$\int d^2N_p/dE_p dt = 2.74 \text{ x } 10^{32} H_{14} (R/10\text{km})^3 P^{-2} \text{ s-1}$$

$$E_{max} \approx 1.6 \text{ x } 10^{14} H_{14} (R/10\text{km})^3 P^{-2} \text{ eV}$$

Fraction of decayed protons
Magnetar Model: log B = 14.0 (Gauss) ; P = 1 s
Flat proton spectrum
0.1
0.01
1E-3
1E-4
1E-5
1E-6
1E-7
10000
100000
log (fraction of decayed protons)
log (Lorentz factor)

Predicted spectrum of Unruh neutrinos

(Magnetar : B = 10^{14} G and P = 1 s)



Flux in the range

6-70 MeV

for D = 1 kpc

10^{-14} cm^{-2}s^{-1}

Summary

- SNR have typical predicted neutrino fluxes (above 0.1 TeV) of about **$f_\nu \sim 10^{-14}$-10^{-15} $cm^{-2}.s^{-1}$**
- These SNR are expected to be in the Sedov phase, but predictions of the distribution of radii are not in agreement with data
- SNR associated with TeV radiation may have higher fluxes: Cas A SN 1006 **($f_\nu \sim 10^{-12}$ $cm^{-2}.s^{-1}$)** and G347.3-0.5 **($f_\nu \sim 10^{-11}$ $cm^{-2}.s^{-1}$)**