High-Energy Neutrinos Produced Interactions of Relativistic Protons in Shocked Pulsar Winds

ApJ, 600, 883-904 (2004).

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§Introduction

Previous Works

Gunn and Ostriker (1969) pointed out the possibility that a rotating magnetic neutrons star may be a source of high energy cosmic rays.

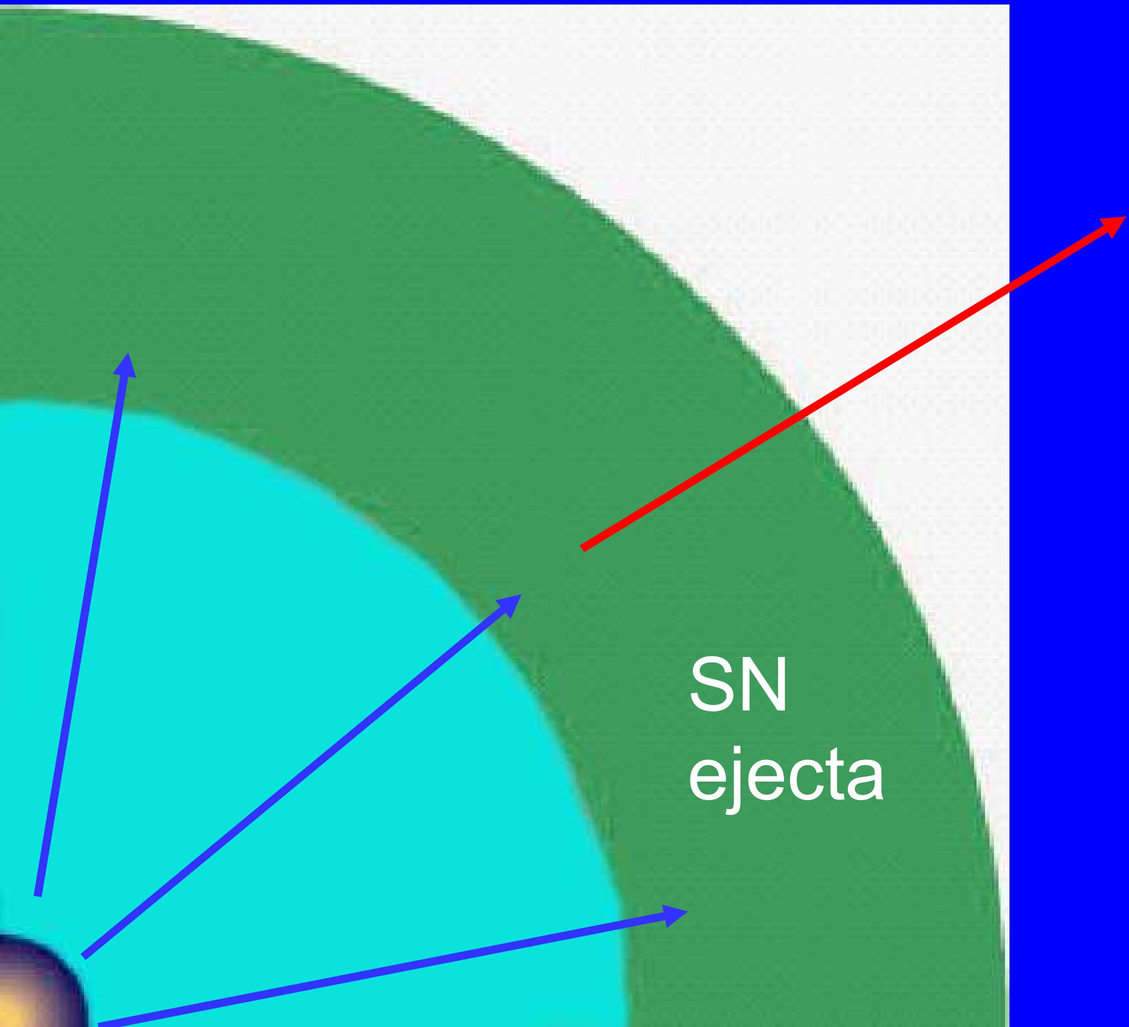
It is pointed out that hadronic component may exist in pulsar winds to Satisfy the Goldreich-Julian value in the outflow (ex. Hoshino et al. 1992).

Moreover, hadronic components may be the energetically dominant species although they are dominated by electron-positron pairs in number, because inertial masses of hadrons are much larger than that of electrons (Hoshino et al. 1992).

Based on this assumption that hadronic components are not negligible in pulsar winds, some scenarios are proposed to produce high energy neutrinos and gamma-rays generated through interactions between accelerated high energy cosmic rays and surrounding photon fields (Beal & Bednarek 2002) and/or matter (Protheroe et al. 1998; Bednarek and Bartosik 2003; Amato et al. 2003).

Location where neutrinos are produced

Blew arrow: neutron
Red arrow: neutrino



Iron is ejected from the Surface of the neutron star.

↓

Neutron is extracted by photodisintegration of iron.

↓

Neutron will intercact with supernova ejecta.

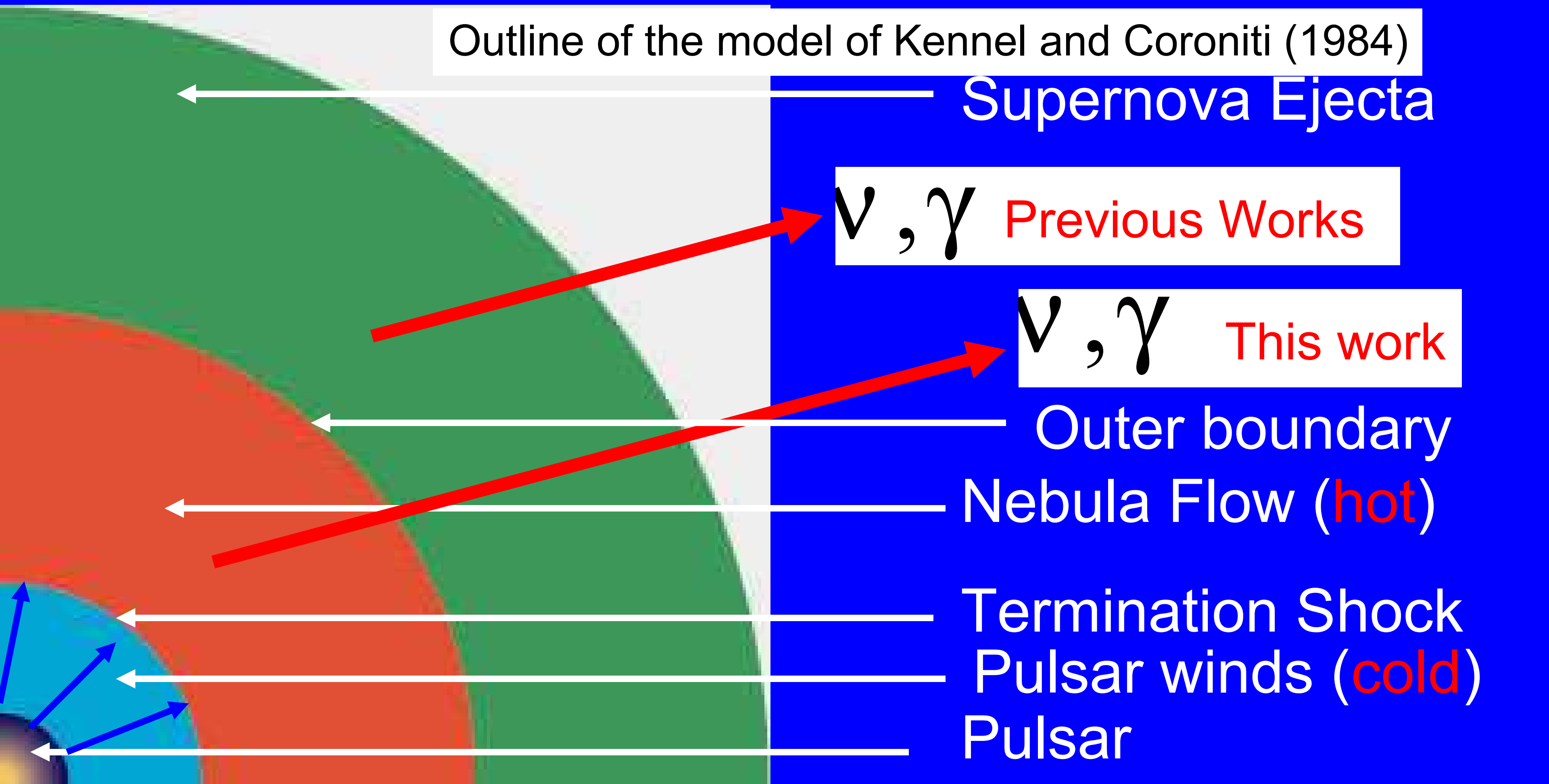
Dynamics of charged particles are neglected.

Protheroe et al. 98

What's new?

In this work, we estimate fluxes of neutrinos and gamma-rays including an effect that has not been taken into consideration, that is, interactions between high energy cosmic rays themselves in the nebula flow, which is based on the model presented by Kennel and Coroniti (1984).

Outline of the model of Kennel and Coroniti (1984)



Assumptions in This Work

In this study, we consider the case where proton is the energetically dominant component ($n_p / (n_{e+} + n_{e-}) > 10^{-3}$).

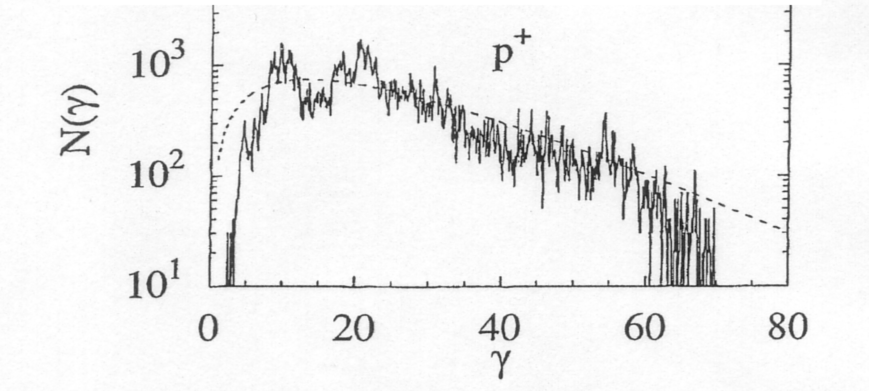
Initial bulk Lorenz factor of protons is constant and same with that of electrons.

Bulk flow is entirely randomized by passing through the termination shock and distribution functions of protons and electrons behind the termination shock obey the relativistic Maxwellians. This assump calculations by Hoshino et al.1992.

It is noted that the system is not thermalized but just randomized.

Energy distribution of protons behind the termination shock (Hoshino et al. 1992)

$$T_{p,2} / \gamma_1 m_p c^2 \approx 0.34$$



Contribution of Fermi I acceleration is not included in this study in order to avoid the uncertainty of the efficiency of the Fermi I acceleration.

§Formulation

Procedure to Estimate Fluxes of Neutrinos and Gamma-rays

1. Hydrodynamics (Kennel & Coroniti 1984)

   a. Pulsar Winds (with Monotonic Bulk Lorentz Factor)

   b. Shock Conditions

   c. Nebula Flow

   d. Outer boundary (SN ejecta)

Location of the termination shock is determined from the outer boundary condisitons.

2. Microphysics of proton-proton Interaction

Hydrodynamics (1)

Pulsar Winds

(we determine the luminosity and bulk Lorenz factor of the wind as functions of B and P)

$$L = 9.6 \times 10^{42} \left(\frac{B_p}{10^{12}\mathrm{G}}\right)^2 \left(\frac{R}{10^6\mathrm{cm}}\right)^6 \left(\frac{1\mathrm{ms}}{P}\right)^4 \mathrm{erg\ s^{-1}}.$$

Spin-down power of a pulsar

$$L = 4\pi n \gamma u r_s^2 m_p c^3 (1+\sigma),$$

$$(\gamma^2 = 1 + u^2),$$

Wind luminosity is assumed to be comparable with the spin- down power

$$\sigma = \frac{B^2}{4\pi n u \gamma m_p c^2},$$

Ratio of magnetic flux to the particle energy flux.

This is fixed by the outer boundary conditions.

$$\Delta\Phi = \frac{1}{2}\left(\frac{\Omega R}{c}\right)^2 R B_p$$

Electric potential difference between the pole and the feet of the corotating magnetosphere which is nearest to the pole.

$$\epsilon_{\max} = 3 \times 10^{18} Z \left(\frac{B_p}{10^{12}\mathrm{G}}\right) \left(\frac{1\mathrm{ms}}{P}\right)^2 \left(\frac{R}{10^6\mathrm{cm}}\right)^3 \mathrm{eV},$$

↔

$$\gamma_{\max} = 3.2 \times 10^9 \left(\frac{B_p}{10^{12}\mathrm{G}}\right) \left(\frac{1\mathrm{ms}}{P}\right)^2 \left(\frac{R}{10^6\mathrm{cm}}\right)^3.$$

Maximum energy and bulk Lorenz factor of protons

$$t_{\mathrm{spin}} \equiv 6.2 \times 10^9 \left(\frac{10^{12}\mathrm{G}}{B_p}\right)^2 \left(\frac{10^6\mathrm{cm}}{R}\right)^6 \left(\frac{P}{1\mathrm{ms}}\right)^2 \mathrm{s}.$$

Spin-down age

Hydrodynamics (2)

Shock Conditions

$$n_1 u_1 = n_2 u_2$$

$$E = \frac{u_1 B_1}{\gamma_1} = \frac{u_2 B_2}{\gamma_2}$$

$$\gamma_1 \mu_1 + \frac{E B_1}{4\pi n_1 u_1} = \gamma_2 \mu_2 + \frac{E B_2}{4\pi n_2 u_2}$$

$$\mu_1 u_1 + \frac{P_1}{n_1 u_1} + \frac{B_1^2}{8\pi n_1 u_1} = \mu_2 u_2 + \frac{P_2}{n_2 u_2} + \frac{B_2^2}{8\pi n_2 u_2}.$$

Relativistic Rankine-Hugoniot relations for perpendicular shock (μ : specific enthalpy)

Approximation (cold&relativistic)

$$\gamma_1 \sim u_1,\ P_1 \sim 0, \text{ and } \mu_1 \sim m_p c^2.$$

↓

$$u_2^2 = \frac{8\sigma^2 + 10\sigma + 1}{16(\sigma+1)} + \frac{1}{16(\sigma+1)} \left[64\sigma^2(\sigma+1)^2 + 20\sigma(\sigma+1) + 1\right]^{1/2}.$$

$$\frac{P_2}{n_1 m_p c^2 u_1^2} = \frac{1}{4 u_2 \gamma_2} \left[1 + \sigma \left(1 - \frac{\gamma_2}{u_2}\right)\right],$$

Assumption: Relativistic Maxwellian

↓

$$N(\gamma) = A\gamma \exp\left[-\frac{m_p c^2}{k_B T}(\gamma - 1)\right],$$

$$P_2 = \frac{2}{3} n_2 k_B T_2$$

Hydrodynamics (3)

Nebula Flow

$$\frac{d}{dr}(cnur^2) = 0;$$

Conservation of number flux

$$\frac{d}{dr}\left(\frac{ruB}{\gamma}\right) = 0;$$

Conservation of magnetic flux

$$\frac{d}{dr}(ur^2e) + P\frac{d}{dr}(r^2u) = 0;$$

Propagation of thermal energy

$$\frac{d}{dr}\left[nur^2\left(\gamma\mu + \frac{B^2}{4\pi n\gamma}\right)\right] = 0;$$

Conservation of total energy

Solution

$$(1+u_2^2v^2)^{1/2}\left[\delta + \Delta(vz^2)^{-1/3} + \frac{1}{v}\right] = \gamma_2(1+\delta+\Delta),$$

v is defined as $v = u/u_2$, z is defined as $z = r/r_s$, δ is defined as $\delta = 4\pi n_2\gamma_2^2 m_p c^2/B_2^2$

$\Delta = 16\pi P_2^2 \gamma_2^2 B_2^2$

$$P_{\mathrm{T}} = P + \frac{E^2+B^2}{8\pi} = \frac{L}{4\pi r_s^2 c(1+\sigma)}\left[\frac{P_2}{n_1 m_p c^2 u_1^2}(vz^2)^{-4/3} + \frac{\sigma}{z^2}\left(1+\frac{1}{2u_2^2v^2}\right)\right]$$

Functions of σ and r

r ↗ P ↘ u ↘

In particular, $u_\infty = \left(\frac{\sigma^2}{1+2\sigma}\right)^{1/2}$

Location of the termination shock and value of σ are determined so as to achieve a contact discontinuity at the outer boundary.

Hydrodynamics (4)

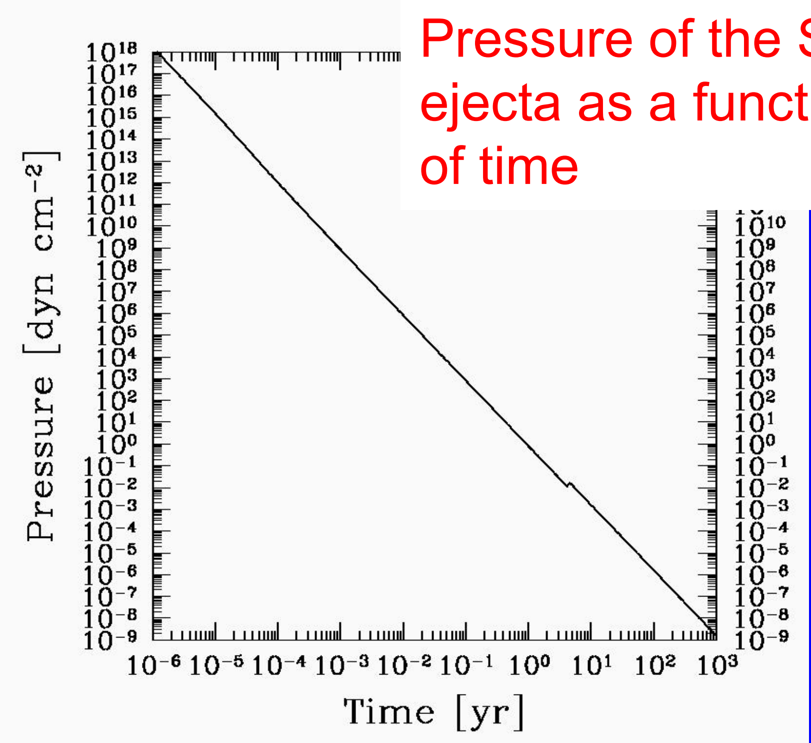
Outer boundary condistions (interface between nebula flow and supernova ejecta)

Contact discontinuity

$V_{Nebula} = V_{SNR} = 2000\text{km/s}$

$P_{Nebula} = P_{SNR}$

$\sigma = 0.0067$



Pressure of the SN ejecta as a function of time

$$E_{\rm th} = 0.02 \times 10^{51} \times \frac{6M_\odot}{20M_\odot}\,{\rm erg} = 6 \times 10^{48}\,{\rm erg},$$

Thermal energy in a He layer

$$E_{\rm th} = \frac{3}{2}(N_{\rm e} + N_{\rm He})k_B T + 3aT^4 V$$

$$V = \frac{4}{3}\pi\left[V_{\rm max}^3 - V_{\rm min}^3\right]\left(\frac{t}{1{\rm sec}}\right)^3,$$

Volume of the remnant

Vmax=3000km/s, Vmin=2000km/s

$$P = (n_{\rm e} + n_{\rm He})k_B T + aT^4,$$

Microphysics of Proton-Proton Interaction (1)

Fluid rest frame ⟶ Observer's frame

$$dR_{12} = \sigma_{pp} v_{\rm rel} \frac{p_1}{E_1}\frac{p_2}{E_2} n_1 n_2 dV\, dt$$
$$= c\sigma_{pp} n_1 n_2 \sqrt{(\vec{\beta}_1 - \vec{\beta}_2)^2 - (\vec{\beta}_1 \times \vec{\beta}_2)^2} dV\, dt,$$

Number of collisions that occur in a volume dV, for a time dt with monotonic spectrums in the momentum space.

$$\frac{F(E_\pi)}{dV} = c\int_1^\infty d\gamma_2 \int_1^{\gamma_2} d\gamma_1 \int_{-1}^{1} d\cos\theta \frac{d\sigma_{pp}(\gamma_1,\gamma_2,\cos\theta)}{dE_\pi} n(R,\gamma_1) n(R,\gamma_2)$$
$$\times \sqrt{(\vec{\beta}_1 - \vec{\beta}_2)^2 - (\vec{\beta}_1 \times \vec{\beta}_2)^2},$$

Number spectrum of pions [particles $\mathrm{cm}^{-3}\,\mathrm{s}^{-1}\,\mathrm{erg}^{-1}$]

$$\cos\theta = \vec{\beta}_1 \cdot \vec{\beta}_2 / \left|\vec{\beta}_1\right| \left|\vec{\beta}_2\right|$$

$d\sigma_{pp}(\gamma_1, \gamma_2, \cos\theta)/dE_\pi$ Differential cross section

Relativistic Maxwellian

$$\frac{dF(E_\pi)}{d\Omega} = \frac{1}{4\pi}\int_{\Delta V} \frac{F(E_\pi)}{dV} dV,$$

ΔV is the fluid element

Number spectrum of pions is unit solid angle [particles $\mathrm{cm}^{-3}\,\mathrm{s}^{-1}\,\mathrm{erg}^{-1}\,\mathrm{sr}^{-1}$]

$$\frac{dF'(E'_\pi)}{d\Omega'} = \frac{1}{\Gamma'^2(1-\beta'\cos\theta')^2}\frac{F(E_\pi)}{4\pi},$$

$$E'_\pi = \frac{1}{\Gamma'(1-\beta'\cos\theta')} E_\pi.$$

However, the bulk flow is non-relativistic in the nebula flow. Thus, number spectrum is not so deformed due to this Lorenz transformation.

Microphysics of Proton-Proton Interaction (2)

Calculation of the differential cross section $d\sigma_{pp}(\gamma_1, \gamma_2, \cos\theta)/dE_\pi$

Procedure: Fluid rest ⟶ Particle1 rest ⟶ Fluid rest

$$p'_\pi = \begin{pmatrix} \sqrt{p'^2_\pi + m^2_\pi c^2} \\ p'_\pi\{\cos\alpha'\cos\theta' - \sin\alpha'\cos\phi'\sin\theta'\} \\ -p'_\pi\{\cos\alpha'\sin\theta' + \sin\alpha'\cos\phi'\cos\theta'\} \\ p'_\pi\sin\alpha'\sin\phi' \end{pmatrix}.$$

Four momentum of a pion in the Lab frame

$$\begin{pmatrix} \gamma_1 & \gamma_1\beta_1 & 0 & 0 \\ \gamma_1\beta_1 & \gamma_1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} p'_\pi = \begin{pmatrix} \gamma_1\sqrt{p'^2_\pi + m^2_\pi c^2} + \gamma_1\beta_1 p'_\pi\{\cos\alpha'\cos\theta' - \sin\alpha'\cos\phi'\sin\theta'\} \\ \gamma_1\beta_1\sqrt{p'^2_\pi + m^2_\pi c^2} + \gamma_1 p'_\pi\{\cos\alpha'\cos\theta' - \sin\alpha'\cos\phi'\sin\theta'\} \\ -p'_\pi\{\cos\alpha'\sin\theta' + \sin\alpha'\cos\phi'\cos\theta'\} \\ p'_\pi\sin\alpha'\sin\phi' \end{pmatrix}.$$

Fluid rest frame

Since

$$\int dE_\pi \frac{d\sigma_{pp}(\gamma_1, \gamma_2, \cos\theta)}{dE_\pi} = \int dE'_\pi \frac{d\sigma_{pp}(E'_\pi, E'_2)}{dE'_\pi},$$

Result:

$$\frac{d\sigma_{pp}(\gamma_1, \gamma_2, \cos\theta)}{dE_\pi} = \frac{d}{dE_\pi}\int\int\int dE'_\pi d\phi' d\cos\alpha' \sqrt{E'^2_\pi - m^2_\pi c^4}\left(E'_\pi \frac{d^3\sigma_{pp}}{dp'^3_\pi c^3}\right)$$
$$\times H(\gamma_1\sqrt{p'^2_\pi + m^2_\pi c^2} + \gamma_1\beta_1 p'_\pi\{\cos\alpha'\cos\theta' - \sin\alpha'\cos\phi'\sin\theta'\} - E_\pi)$$
$$\times H(E_\pi + dE_\pi - \gamma_1\sqrt{p'^2_\pi + m^2_\pi c^2} + \gamma_1\beta_1 p'_\pi\{\cos\alpha'\cos\theta' - \sin\alpha'\cos\phi'\sin\theta'\})\},$$

Where

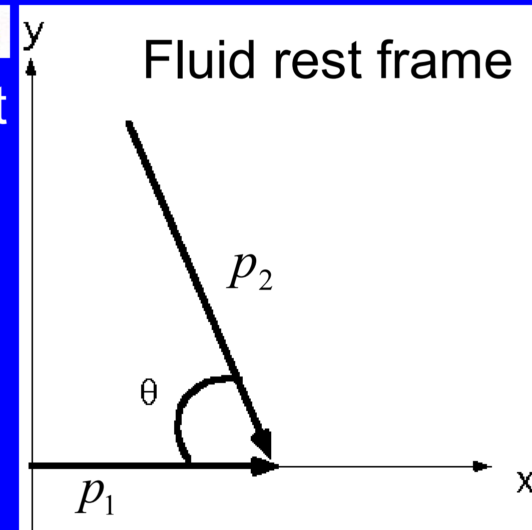
$$E^*_\pi \frac{d^3\sigma^*_\pi}{d^3p^*_\pi} = \frac{A}{(1 + 4m_p^2c^4/s)^r}(1 - \tilde{x})^q \exp\left[\frac{Bp^*_\perp}{1 + 4m_p^2c^4/s}\right],$$

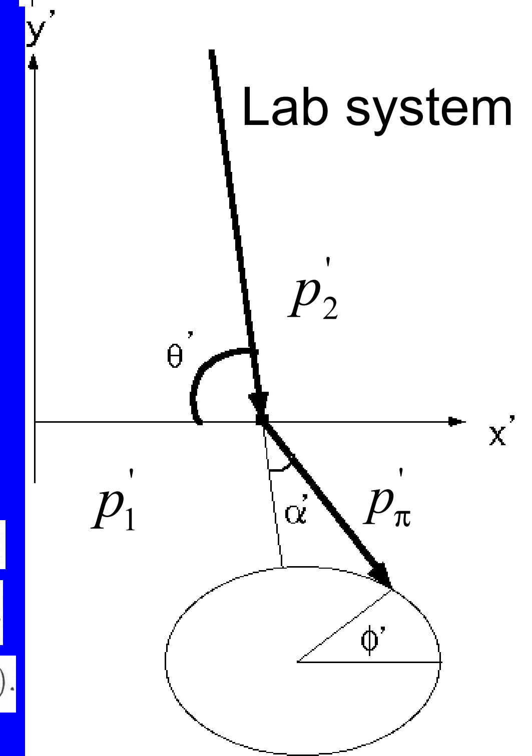
$$\tilde{x} = \{x^{*2}_\parallel + (4/s)(p^{*2}_\perp c^2 + m^2_\pi c^4)\}^{1/2}$$

$$x^*_\parallel = p^*_\parallel c/\sqrt{s/4 - m_p^2 c^4}.$$

$$q = (C_1 + C_2 p^*_\perp + C_3 p^*_\perp).$$

Scaling law model (Badhwar et al. 1977)





§Results

In this study, we have to check whether the energy spectrum of protons can be regarded to obey the Maxwellian distribution.

→ From this argument, some constraints are derived.

(i) Production rate of pions [erg/s] should be much smaller than the luminosity of the pulsar wind.

(ii) Synchrotron cooling timescale of protons should be longer than dynamical timescale and/or pp collision timescale.

(iii) Energy transfer timescale from protons to electrons should be longer than dynamical timescale and/or pp collision timescale.

$$t_{p,\text{syn}} = \left(\frac{m_p}{m_e}\right)^4 \times t_{e,\text{syn}} \sim 1.1 \times 10^{13} t_{e,\text{syn}},$$

$$t_{e,\text{syn}} = 3.9 \times 10 \, (1 \text{ GeV}/E) \left(10^2 \text{ G}/B\right)^2 \text{ s}.$$

$$t_{\text{travel}} = \frac{r}{v},$$

$$t_{\text{col}} = \frac{1}{n \sigma_{pp} c},$$

$$t_{\text{ep}} = \frac{4}{\ln \Lambda} \frac{n_e}{n_p} \left(\frac{kT_e}{m_e c^2}\right)^2 \frac{1}{n_e \sigma_T c}$$

$$\ln \Lambda = \ln \left[\frac{kT_e}{\hbar \omega_p}\right]$$

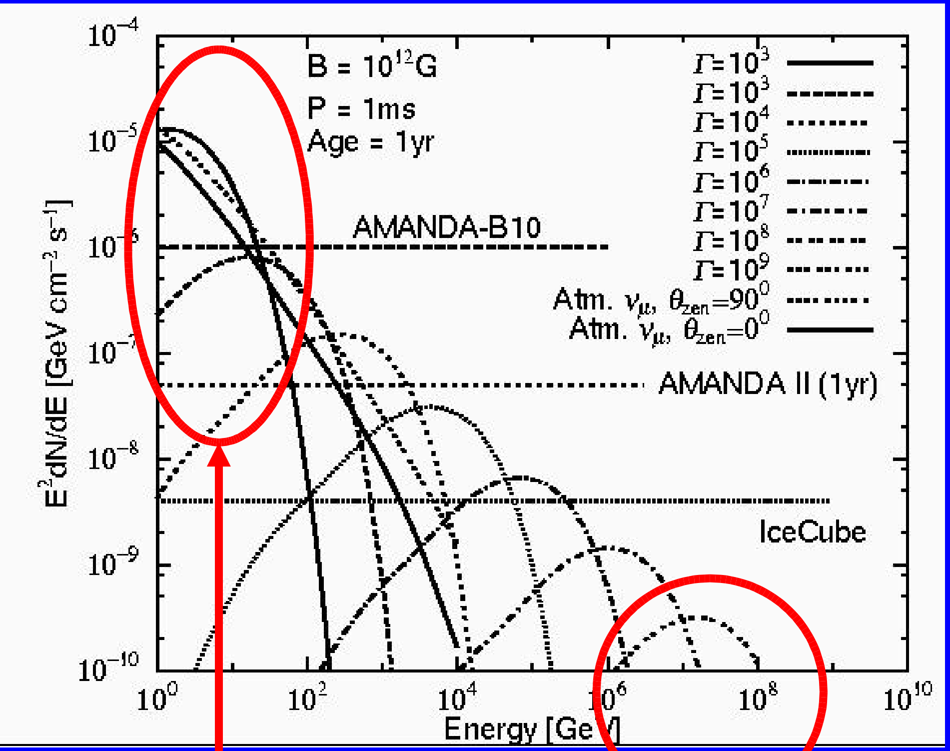
$$\omega_p = \left(\frac{4\pi e^2 c^2 n_e}{3kT_e}\right)^{1/2}$$

(t_{ad}, $t_{\mu,\text{sync}}$, t_{IC}) : Later

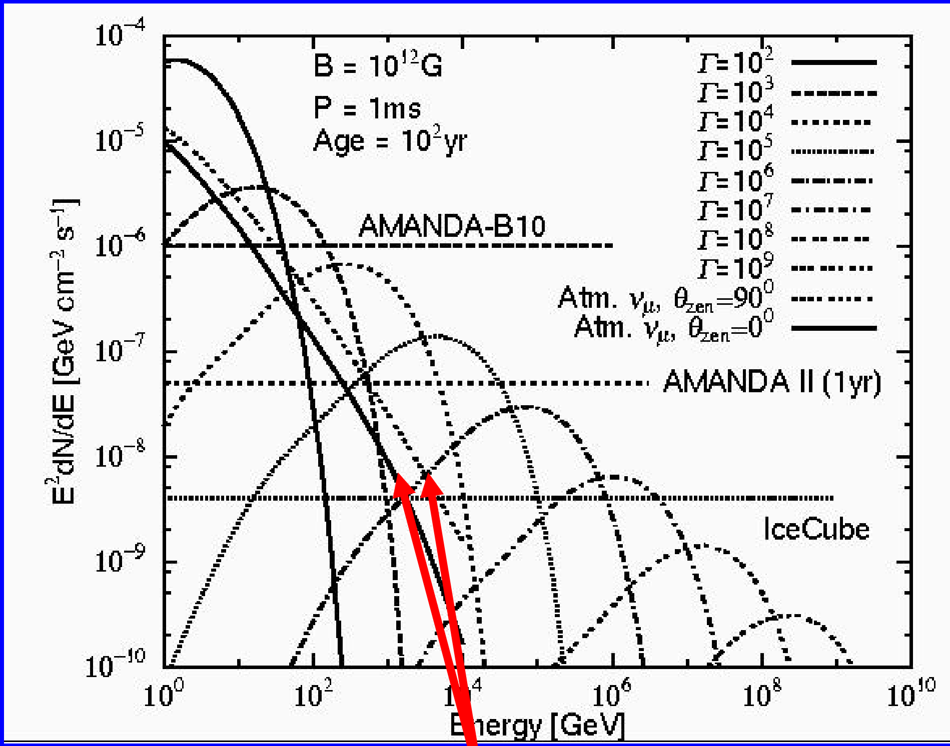
Spectrum of Energy Fluxes of Neutrinos from a Pulsar

D=10kpc

Age=1yr



Age=100yr



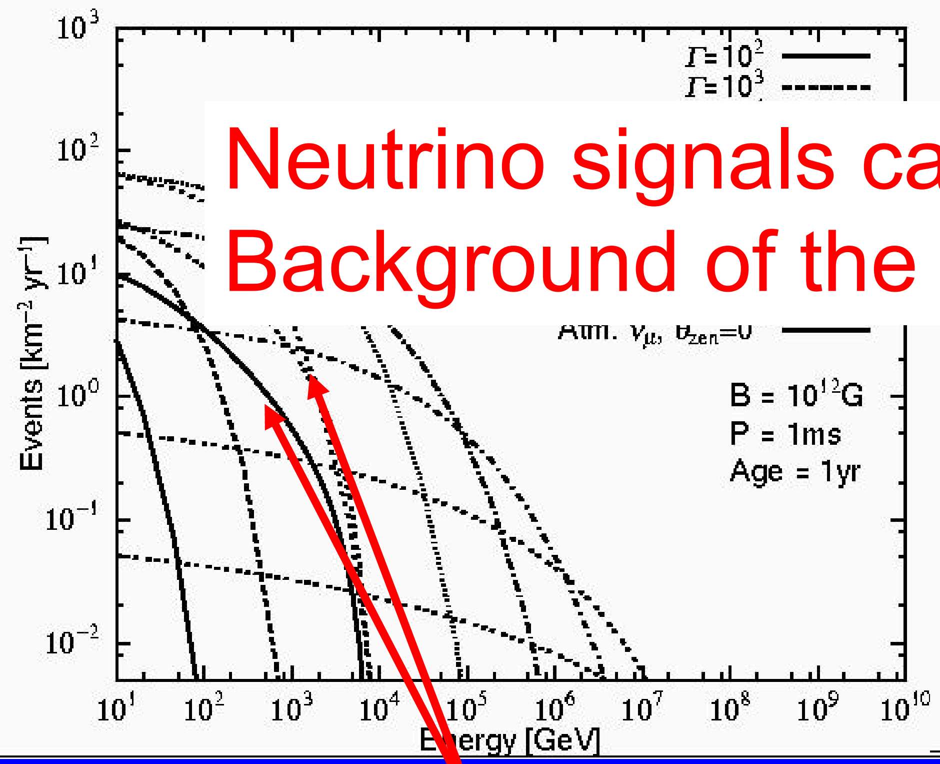
Low energy (T:small)
High flux (n:large)

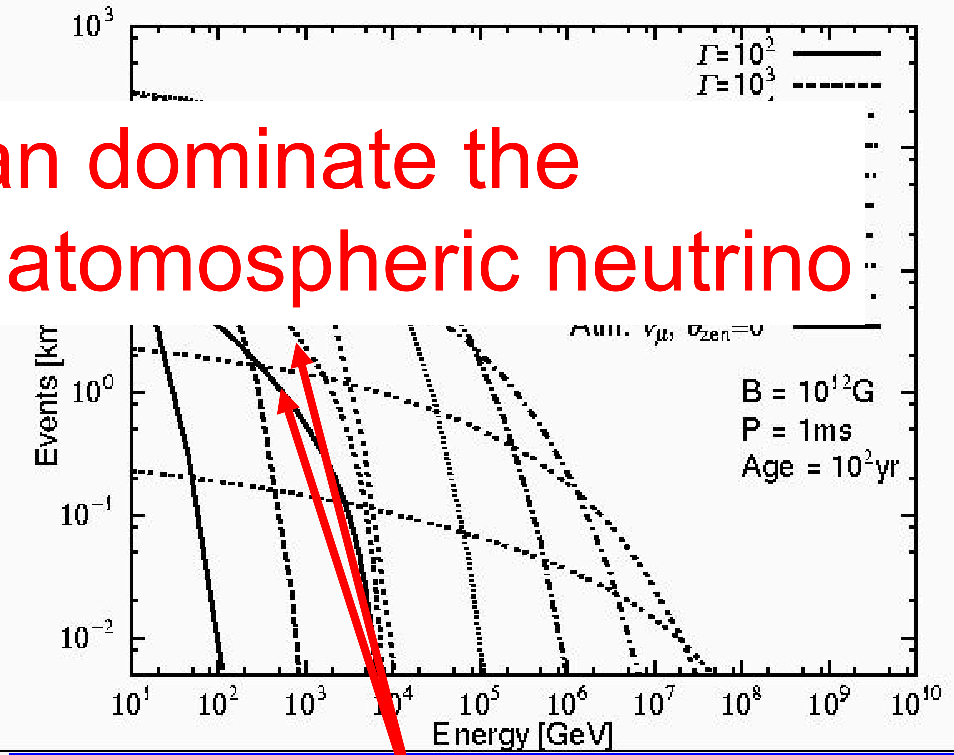
High energy (T:large)
Low flux (n:small)

Atomospheric
neutrino

Neutrino Event Rate per Year from a Pulsar as a Function of Muon Energy Threshold

Age=1yr D=10kpc Age=100yr





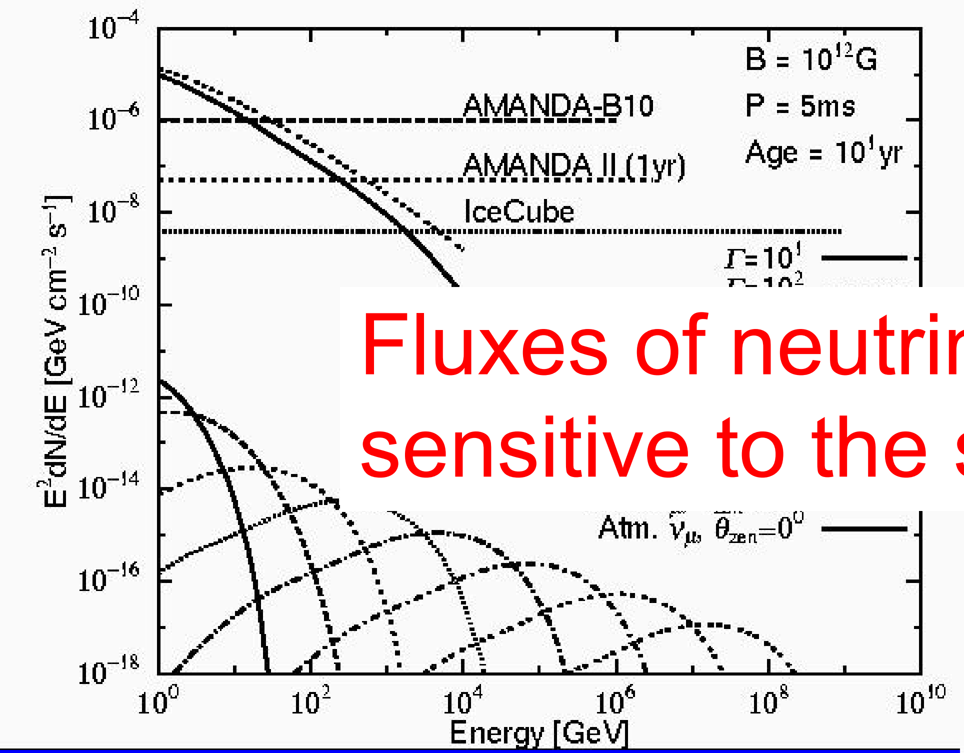
Neutrino signals can dominate the Background of the atomospheric neutrino

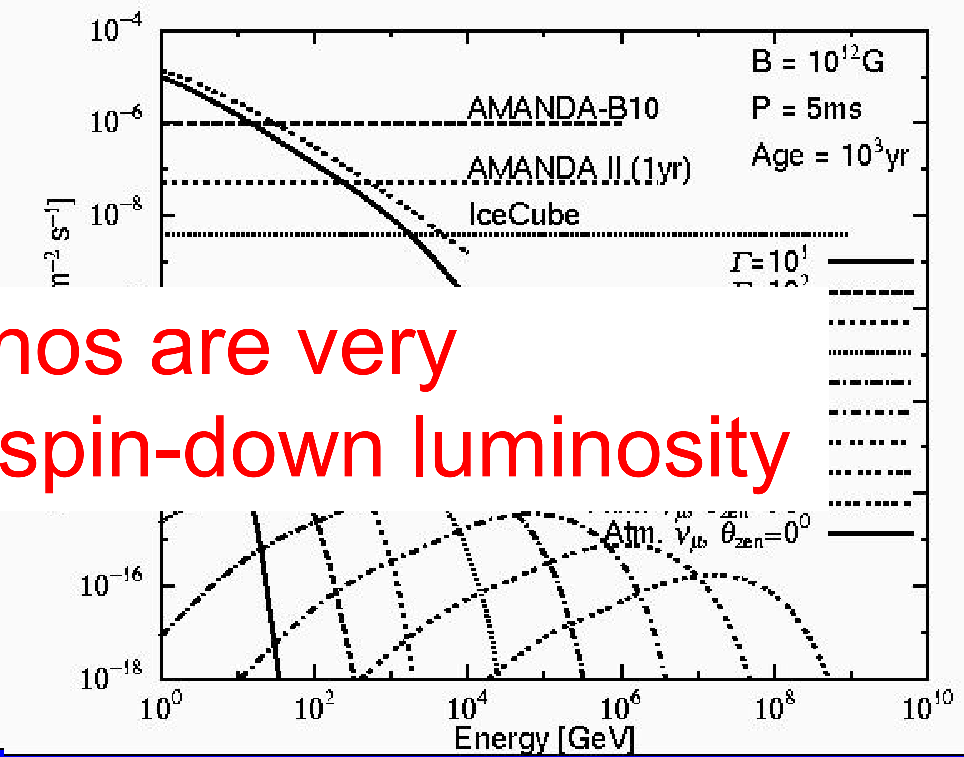
Atomospheric neutrino

Atomospheric neutrino

Spectrum of Energy Fluxes of Neutrinos from a Pulsar with P=5ms

Age=10yr D=10kpc Age=1000yr





Fluxes of neutrinos are very sensitive to the spin-down luminosity

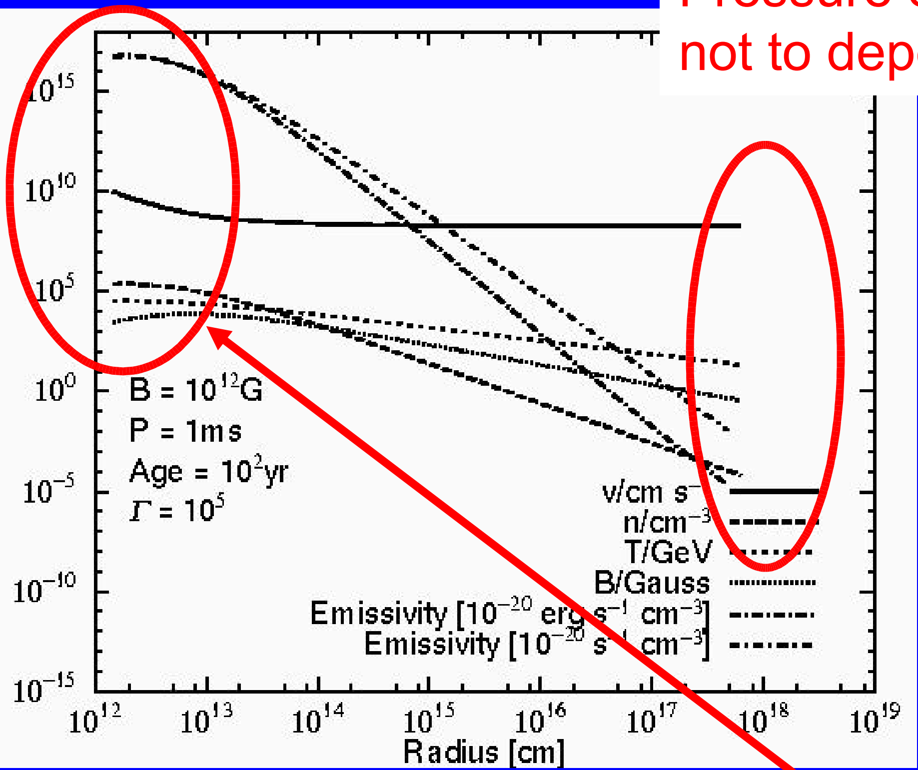
Fluxes of neutrinos are too low to be detected in the cases where $B=10^{12}$ G and P=5ms.

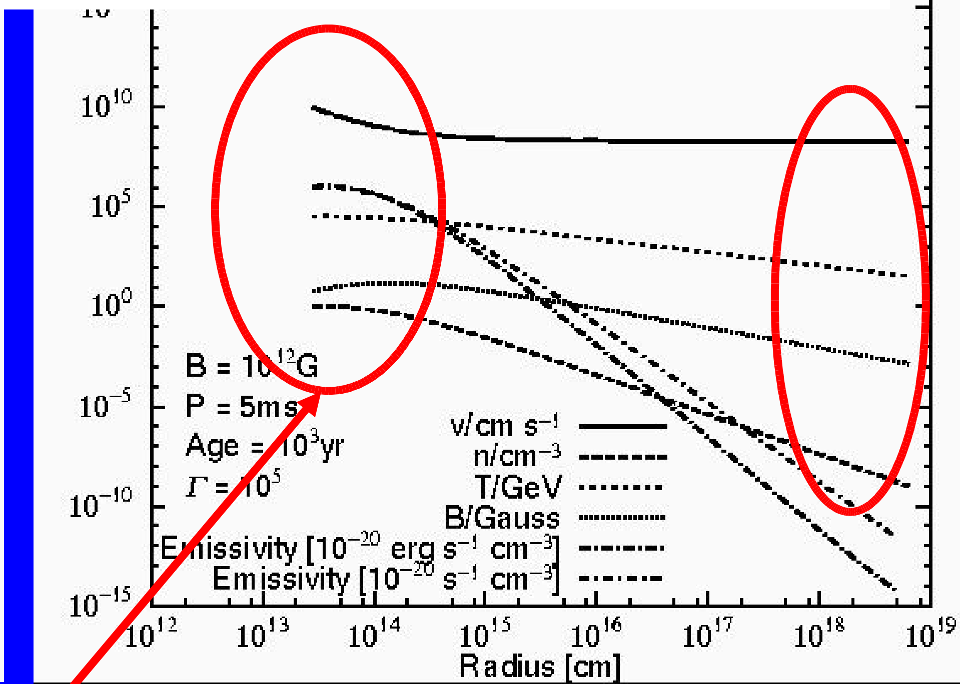
Profiles of Velocity, Number Density, Temperature, Magnetic Field, and Emissivity of Charged Pions for a Pulsar with P=5ms

P=1ms

P=5ms

Pressure of the supernova ejecta is assumed not to depend on the pulsar's activity.



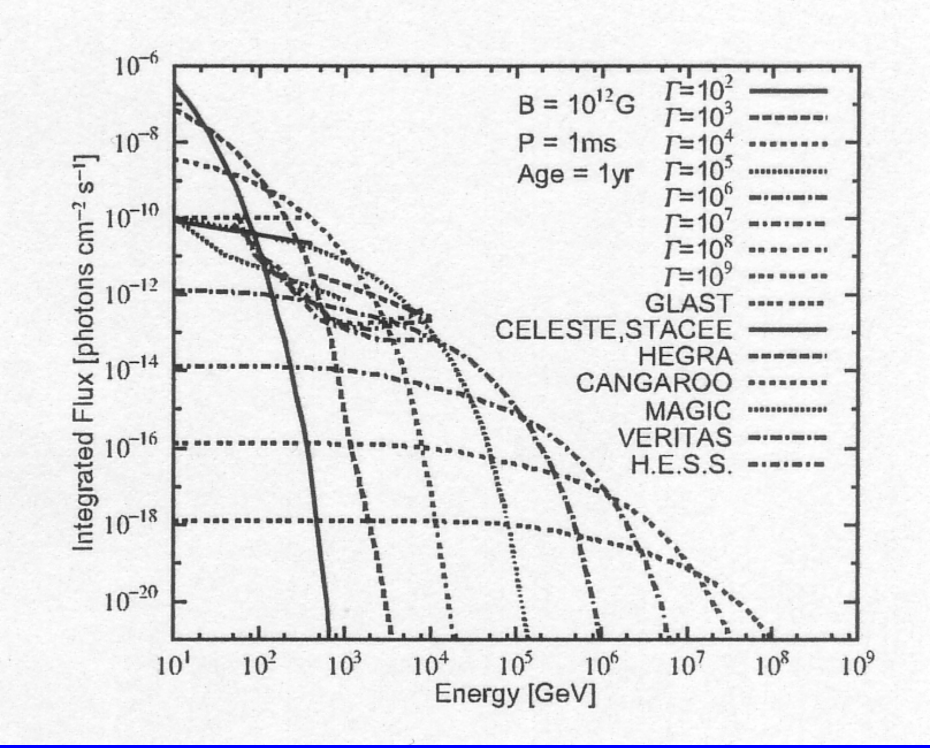


P(period) ↘ L ↗ r_s ↘ n ↗ ε ↗

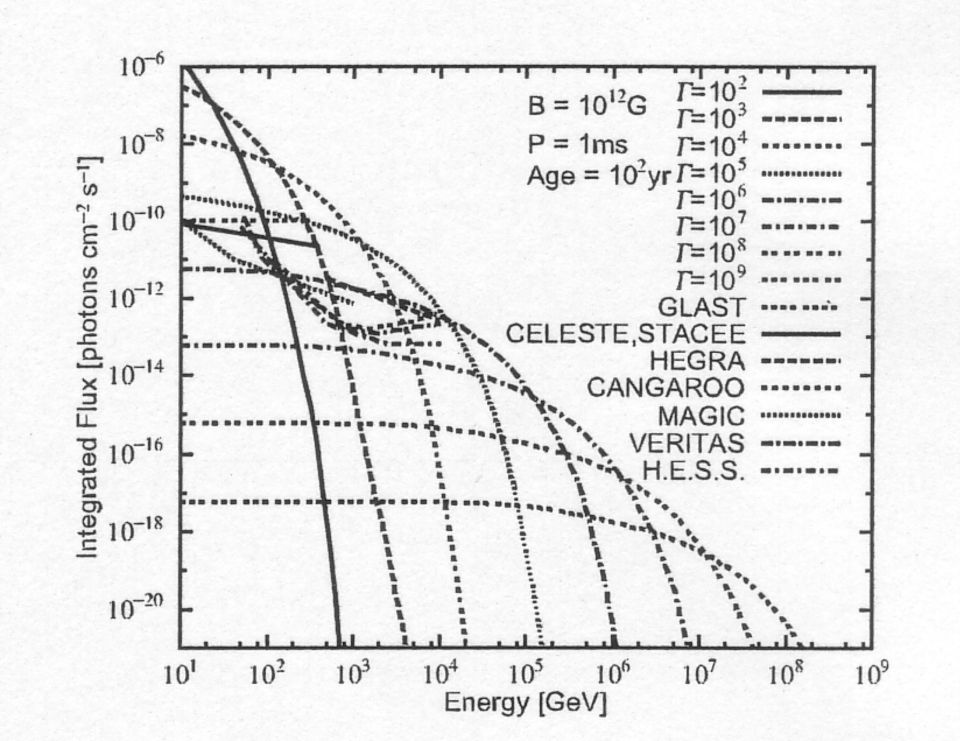
Integrated Gamma-ray Fluxes from Neutral Pion Decays

P=1ms,D=10kpc

Age=1yr



Age=100yr

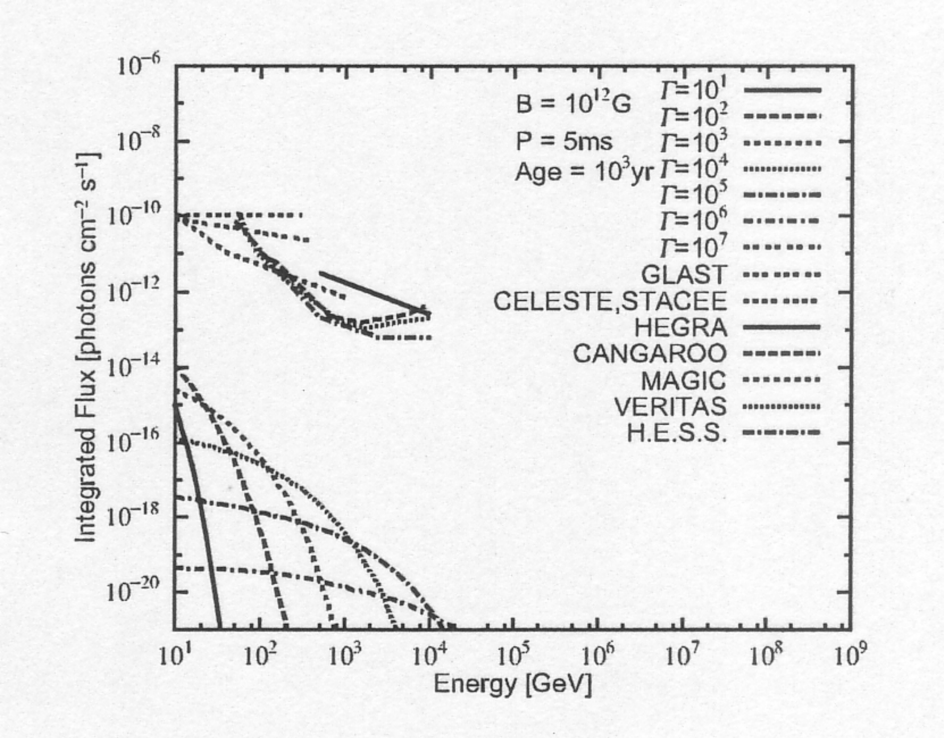


Gamma-rays will be detected by Cherenkov Detectors as well as gamma-ray satellites.

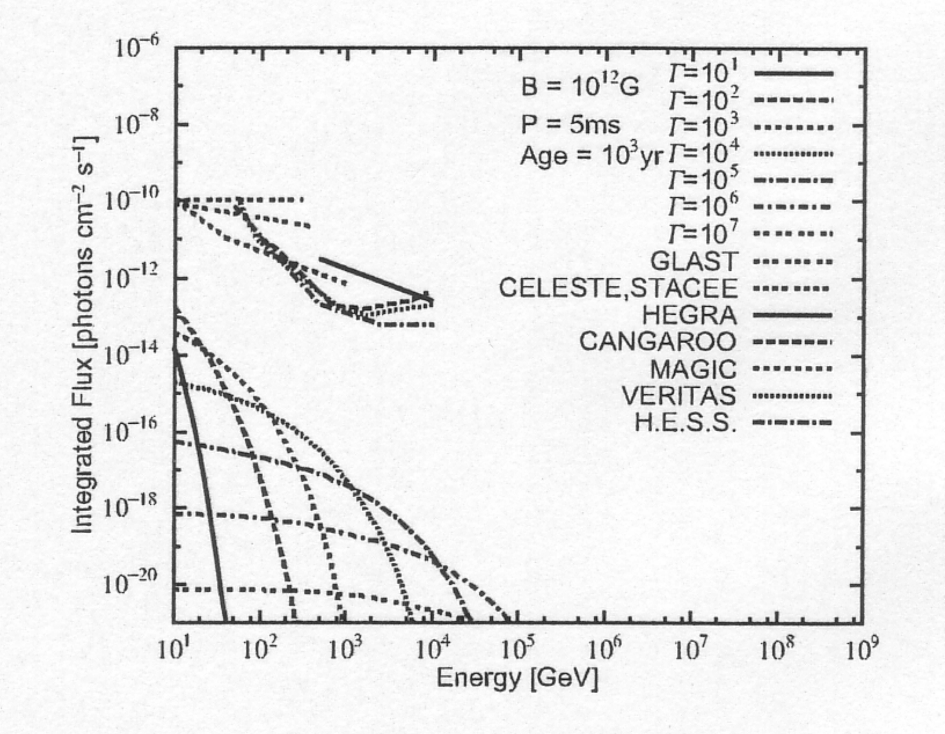
Integrated Gamma-ray Fluxes from Neutral Pion Decays from a Pulsar with P=5ms

D=10kpc

Age=10yr



Age=1000yr



Fluxes of gamma-rays are too low to be detected in the cases where $B=10^{12}$ G and P=5ms.

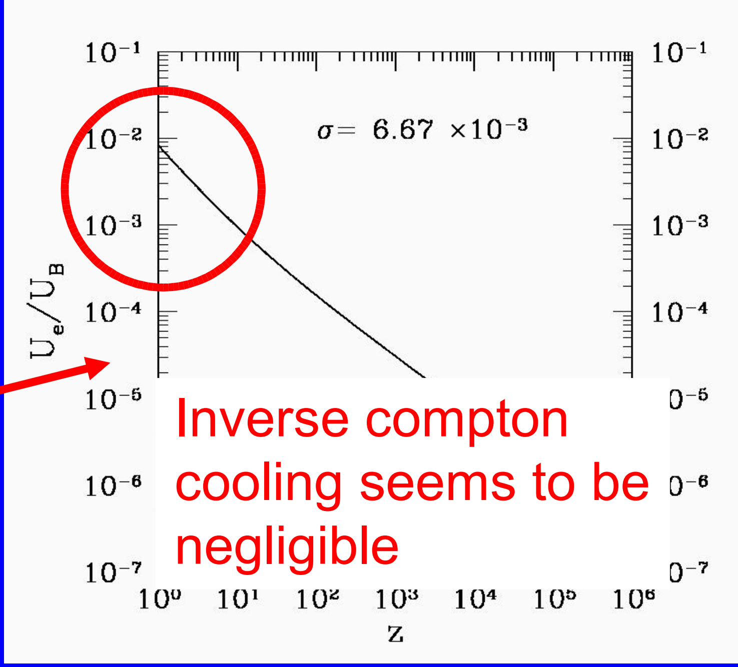
§ Discussions

Other timescales

1. Inverse compton cooling timescale

$$\frac{t_{\rm sync}}{t_{\rm IC}} = \frac{U_\gamma}{U_B},$$

$$\frac{t_{\rm sync}}{t_{\rm IC}} \le \frac{U_e}{U_B} = \frac{m_e U_p}{m_p U_B} = \frac{m_e}{m_p}\frac{z^2\{3\sigma+(3\sigma/z)^{2/3}\}^2}{\sigma\{3\sigma z^2+(3\sigma)^{2/3}z^{4/3}\}^{4/3}[4+\{3\sigma+(3\sigma/z)^{2/3}\}^2]}.$$



2. Synchrotron cooling timescale of muon

$$t_{\mu,{\rm syn}} = \left(\frac{m_\mu}{m_e}\right)^4 \times t_{e,{\rm syn}} \sim 1.82\times 10^9 t_{e,{\rm syn}}$$
$$= 7.11\times 10^{10}\,(1~{\rm GeV}/E_\mu)\,(10^2~{\rm G}/B)^2~{\rm s}.$$

When $E_\mu \ge 5.85\times 10^5\left(\frac{10^4{\rm G}}{B}\right)$ GeV. ,

mean lifetime of muon becomes longer than the synchrotron cooling time.

3. Adiabatic cooling time is taken into consideration by adopting nebula flow equations.

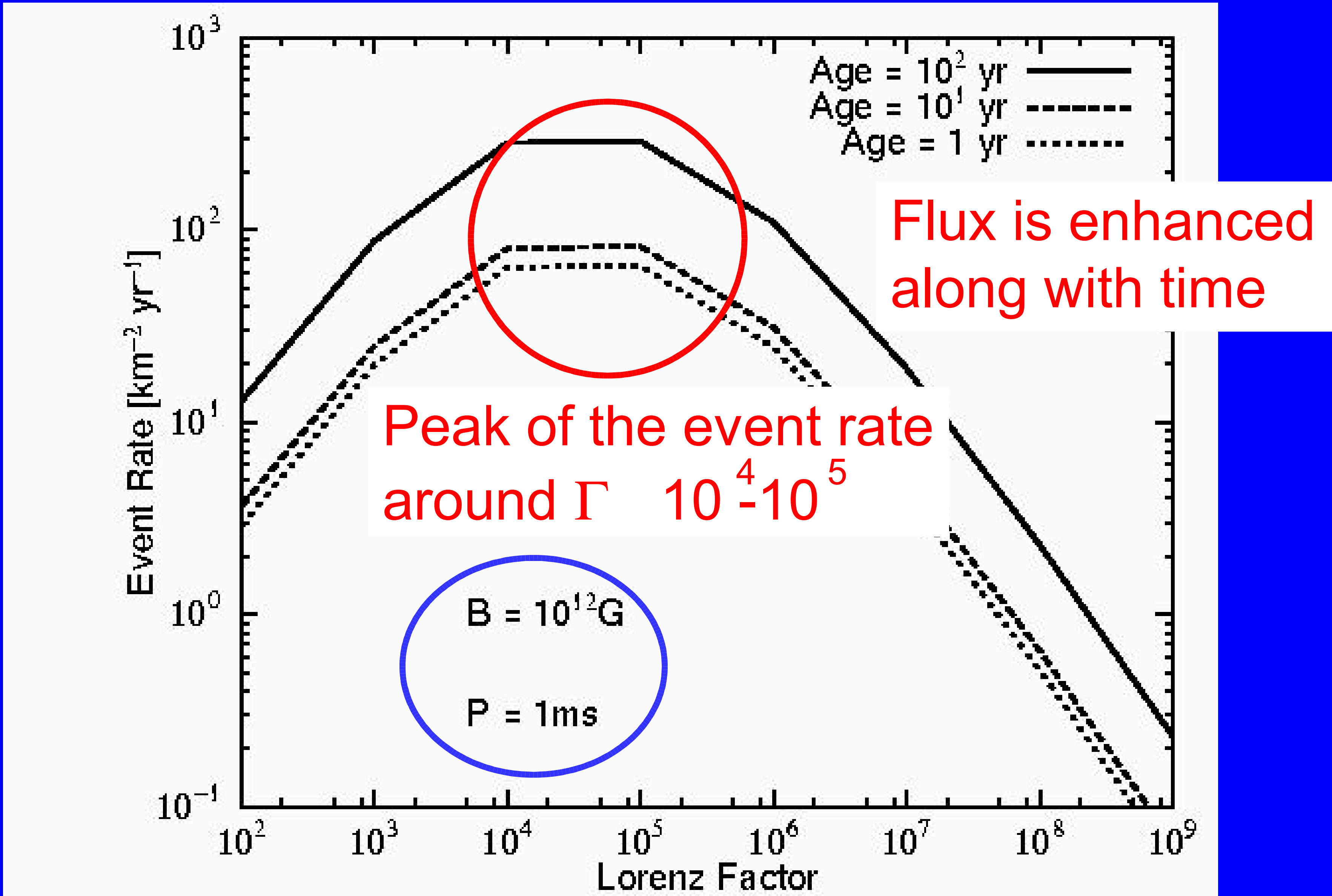
§ Conclusion

We have estimated fluxes of neutrinos and gamma-rays from a pulsar surrounded by supernova ejecta in our galaxy, including an effect that has not been taken into consideration, that is,interactions between high energy cosmic rays themselves in the nebula flow.

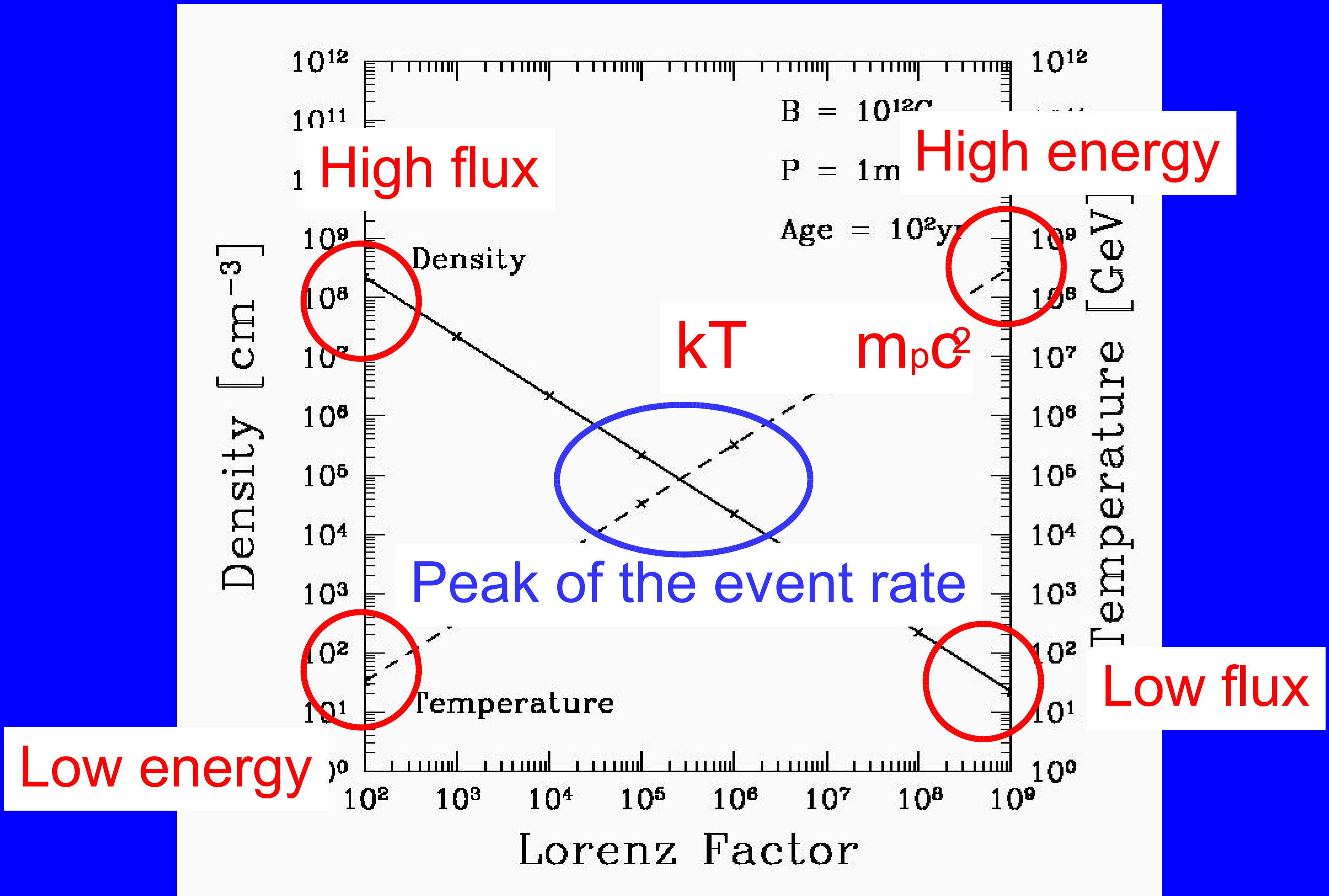
We have found that fluxes of neutrinos and gamma-rays depend very sensitively on the wind luminosity. In the case where $B=10^{12}$G and P=1ms, neutrinos should be detected by km^2 high energy neutrino detectors such as AMANDA, ANTARES, and IceCube. Also, gamma-rays should be detected by Cherenkov telescopes such as Cangaroo, MAGIC, VERITAS, and HESS as well as by GLAST satellite.

We have found that interactions between high energy cosmic rays themselves are so effective that this effect can be confirmed by future observations. Thus, we conclude that it is worth while investigating this effect further in the near future.

Event Rates of Neutrino whose energy is greater than 10GeV



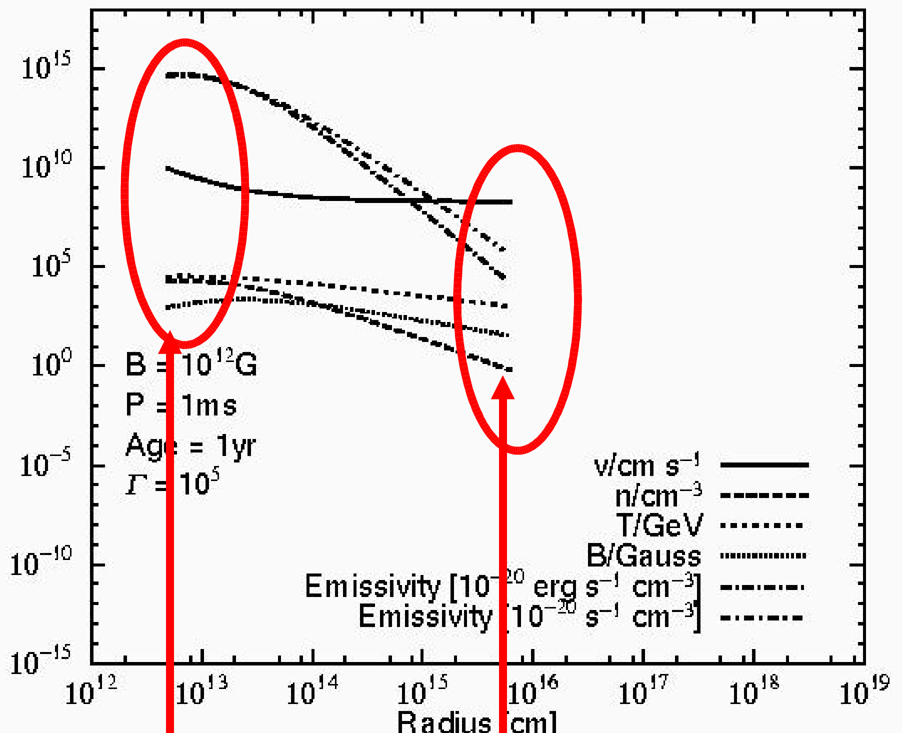
Density and Temperature behind the Termination Shock



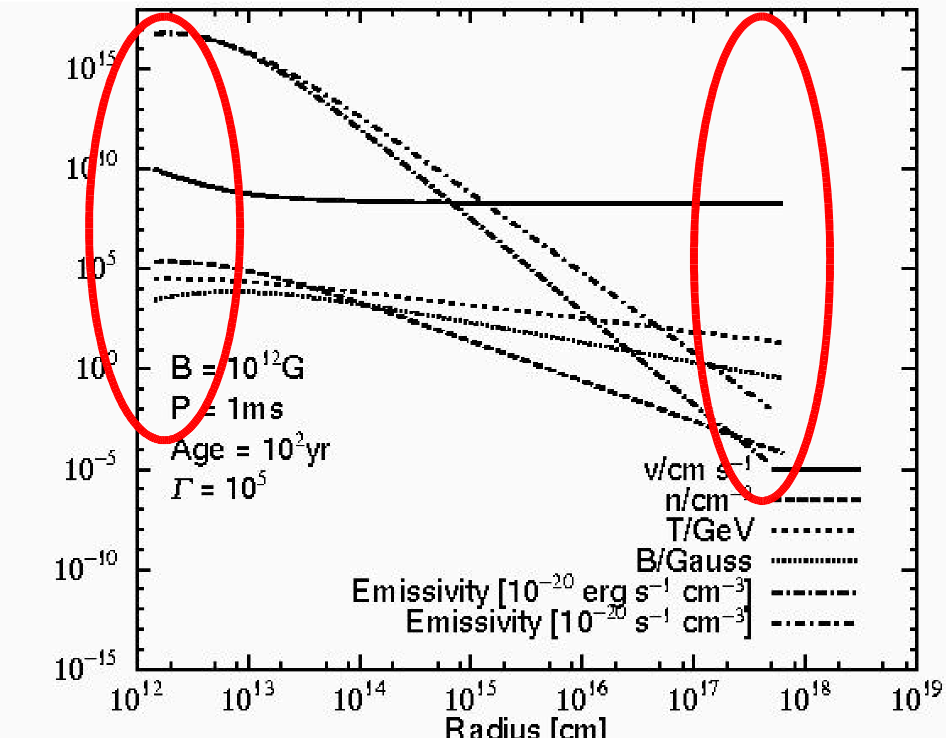
Profiles of Velocity, Number Density,Temperature, Magnetic Field, and Emissivity of Charged Pions

Location of the Termination shock moves inwardly ← Pressure Is lower

Age=1yr



Age=100yr



Location of the Termination shock

Inner-edge of the supernova ejecta

Emissivity t ↗ P ↘ r ↘ n ↗ F ↗

$$\epsilon = n^2 c\sigma_{pp} = 3 \times 10^{-5} \left(\frac{n}{10^5 \mathrm{cm}^{-3}}\right)\left(\frac{\sigma_{pp}}{100\mathrm{mb}}\right).$$