Neutrinos from Gamma-ray Burst

Yu-Ting Chou

Institute of Physics
National Chiao-Tung University

4 April, 2011

Outline

Purpose of this research

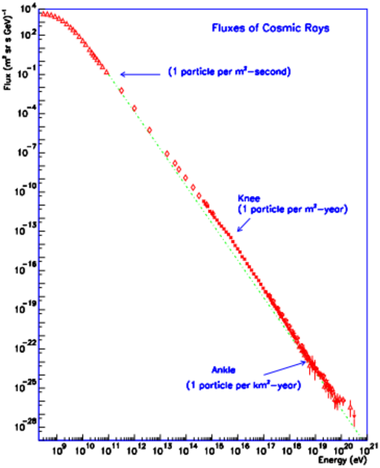
Predict the neutrino flux...

The flavor composition...

Searching for a pure neutron beam source...

- From typical gamma-ray bursts
- The magnetic field effects
- The dependence on measured photon spectrum

Ultra high energy cosmic rays (UHECR)



[Olinto (2005)]

- Power law spectrum $\frac{dI_{ob}}{d\mathcal{E}} \propto \mathcal{E}^{-2.7}$
- Energy up to $\mathcal{E} > 10^{20}$ eV
- A cut-off at $\mathcal{E} \approx 5 \times 10^{19}$ eV
- Fermi (shock) acceleration model:
  Initially: $\frac{dI}{d\mathcal{E}} \propto \mathcal{E}^{-\alpha}$, $\alpha = 2.0 - 2.4$

Production of neutrinos

$$p + \gamma \to \Delta^+ \to p + \pi^0 \qquad (1)$$

$$p + \gamma \to \Delta^+ \to n + \pi^+ \qquad (2)$$

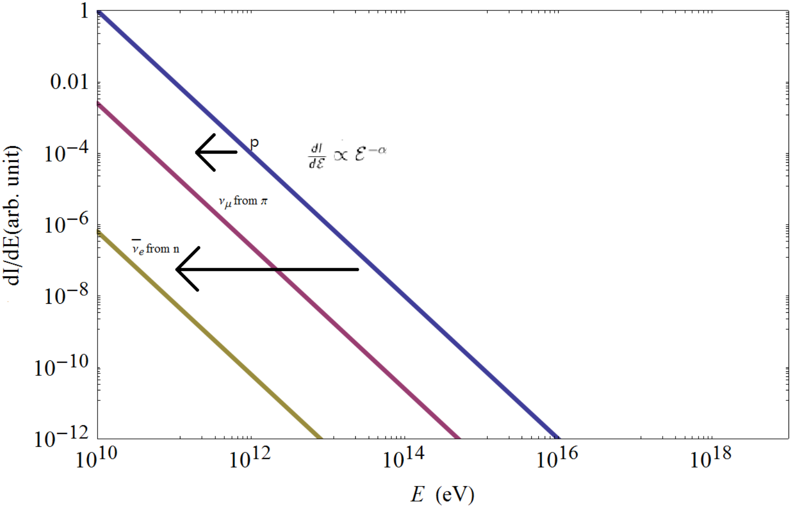
$$\pi^+ \to \mu^+ + \nu_\mu \qquad (3)$$

$$\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu \qquad (4)$$

$$\mathcal{E}_{\nu_\mu} \approx 0.05\mathcal{E}_p$$

$$n \to p + e^- + \bar{\nu}_e \qquad (5)$$

$$\mathcal{E}_{\nu_e} \approx 0.0008\mathcal{E}_p$$


dI/dE(arb. unit)
1
0.01
10−4
10−6
10−8
10−10
10−12
p
$\frac{dI}{d\mathcal{E}} \propto \mathcal{E}^{-\alpha}$
ν_μ from π
$\overline{\nu}_e$ from n
1010
1012
1014
1016
1018
E (eV)

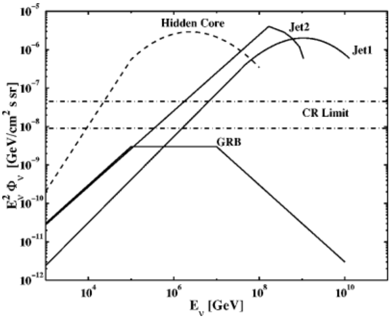
Possible source candidates of UHECR

- Gamma-ray Burst (GRB)
- Active Galactic Nucleus (AGN)

Gamma-ray burst

- Gamma-ray burst (GRB): a possible astrophysical source of UHECR
- (Internal) shock: $\Gamma \gtrsim 100$
- Protons(nuclei) are accelerated in the shock
- Photons from synchrotron emission by $e^{\pm}$

The cosmic ray limit



[Waxman and Bahcall (1999)]

- Normalization from UHECR flux
- AGN-jets model: disfavored
- Gamma-ray burst: a more probable source

Relativistic Fireball Shock model

Gamma-ray burst:

- Massive objects collapse or merger
- Particles ejected relativistically
- (Internal) shock: $\Gamma \gtrsim 100$
- Protons(nuclei) are accelerated in the shock
- Photon from synchrotron emission by $e^{\pm}$

Total energy of internal shock

To determine B'....

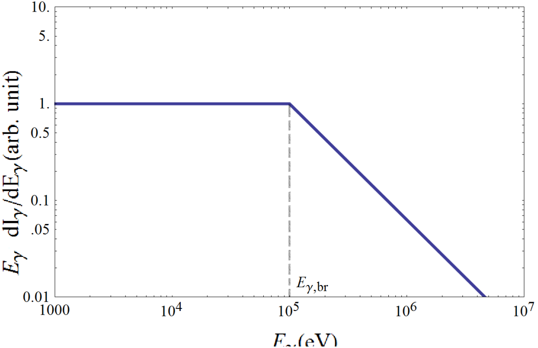
- $L_\gamma\ :\ 10^{50} - 10^{54}$ erg/s
- $L_\gamma = \xi_e L_{int}$,
- $\frac{2\pi r_i^2 c \Gamma^2 B'^2}{\mu_0} = \xi_B L_{int} = \frac{\xi_B L_\gamma}{\xi_e}$
- $\xi_e = \xi_B = 0.3$
- $r_i \sim 2\Gamma^2 c t_v$

The effects by magnetic field

- The proton (or nuclei) acceleration
- The synchrotron effects on charged particles
- The photon characteristic energy

$$\mathcal{E}_{\gamma,ch} = \frac{\Gamma \hbar \Gamma_e^2 e B'}{m_e}$$

The photon spectrum of GRB



- $p + \gamma \to \Delta^+ \to n + \pi^+$
- $\mathcal{E}_\gamma \frac{dI_\gamma}{d\mathcal{E}_\gamma} \propto \mathcal{E}_\gamma^{-\alpha_1}$ if $\mathcal{E}_\gamma \leq \mathcal{E}_{\gamma,br}$
- $\mathcal{E}_\gamma \frac{dI_\gamma}{d\mathcal{E}_\gamma} \propto \mathcal{E}_\gamma^{-\alpha_2}$ if $\mathcal{E}_\gamma \geq \mathcal{E}_{\gamma,br}$
- $\alpha_1 \approx 0,\ \alpha_2 \approx 1 - 4$
- $\mathcal{E}_{\gamma,br} = \mathcal{E}_{\gamma,ch}$

To determine the neutrino spectrum...

Take proton as the primary cosmic ray

1. Consider the magnetic field effect by comparing time scales:
2. Pions may lose enegy before decay in magnetic field, Neutrons do not.
3. Comparing time scales

   $t_{acc,p} == t_{sync,p} => \mathcal{E}_{p,max}$

   $t_{sync,\pi} == t_{decay,\pi} => \mathcal{E}_{\pi,sync}$
4. Consider the photon spectrum indices

Production of neutrinos

$$p + \gamma \rightarrow \Delta^+ \rightarrow p + \pi^0 \tag{6}$$

$$p + \gamma \rightarrow \Delta^+ \rightarrow n + \pi^+ \tag{7}$$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu \tag{8}$$

$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu \tag{9}$$

$$\mathcal{E}_{\nu_\mu} \approx 0.05\mathcal{E}_p$$

$$n \rightarrow p + e^- + \bar{\nu}_e \tag{10}$$

$$\mathcal{E}_{\nu_e} \approx 0.0008\mathcal{E}_p$$

Time scales related to B'

Consider a charged particle (mass m, charge q) in a uniform magnetic field B'(in GRB shock frame):

- $$t'_{acc} = \frac{\mathcal{E}'}{c^2 q B'}$$
- $$t'_{sync} = \frac{9\pi\epsilon_0 m^4 c^5}{q^4 B'^2 \mathcal{E}'}$$
- $$t'_{deacy} = \mathcal{E}'\tau/\mathcal{E}_0$$

$dI_p/d\mathcal{E}_p \propto \mathcal{E}_p^{-2}$ if $\mathcal{E}_p < \mathcal{E}_{p,max}$

The proton spectrum

$$\frac{dI_p}{d\mathcal{E}_p}(\mathcal{E}_p) \propto \begin{cases} \mathcal{E}_p^{-2} & \text{if } \mathcal{E}_p \leq \mathcal{E}_{p,max} \\ \exp(-\frac{\mathcal{E}_p}{\mathcal{E}_{p,max}}) & \text{if } \mathcal{E}_p \geq \mathcal{E}_{p,max} \end{cases}$$

- By Fermi acceleration:
- The maximal energy is derived by comparing time-scales
- $\mathcal{E}_{p,max} \propto B'^{-1}$

The pion source spectrum

$$p + \gamma \rightarrow \Delta^+ \rightarrow n + \pi^+$$

$$\mathcal{E}_{\gamma,br} = \frac{\Gamma \hbar \Gamma_e^2 e B'}{m_e}$$

$$\mathcal{E}_{p,br} = \Gamma^2 \frac{m_\Delta^2 c^4 - m_p^2 c^4}{4\mathcal{E}_{\gamma,br}}$$

$$\mathcal{E}_{\pi,br} \approx 0.2\mathcal{E}_{p,br}$$

The pion source spectrum

$$\phi_\pi(\mathcal{E}_\pi) \propto \begin{cases} \mathcal{E}_\pi^{\alpha_2}\mathcal{E}_\pi^{-2} & \text{if } \mathcal{E}_\pi \leq \mathcal{E}_{\pi,br} \\ \mathcal{E}_\pi^{\alpha_1}\mathcal{E}_\pi^{-2} & \text{if } \mathcal{E}_{\pi,br} \leq \mathcal{E}_\pi \leq \mathcal{E}_{\pi,max} \\ \exp(-\frac{\mathcal{E}_\pi}{\mathcal{E}_{\pi,max}}) & \text{if } \mathcal{E}_\pi \geq \mathcal{E}_{\pi,max} \end{cases}$$

Muon-neutrino from pion:

$$\frac{dI_{\nu_\mu}}{d\mathcal{E}_{\nu_\mu}}(\mathcal{E}_{\nu_\mu}) = -\frac{\partial}{\partial \mathcal{E}_{\nu_\mu}} \int_{4\mathcal{E}_{\nu_\mu}}^{\infty} d\mathcal{E}_i \phi_\pi(\mathcal{E}_i) P_\pi(\mathcal{E}_i, 4\mathcal{E}_{\nu_\mu})$$

where

$$P(\mathcal{E}_i, \mathcal{E}_f) = 1 - \exp\left(-\mathcal{E}_{\pi,sync}^2 \frac{(\mathcal{E}_f^{-2} - \mathcal{E}_i^{-2})}{2}\right)$$

$$\mathcal{E}_{\pi,sync}^2 \propto B'^{-2}$$

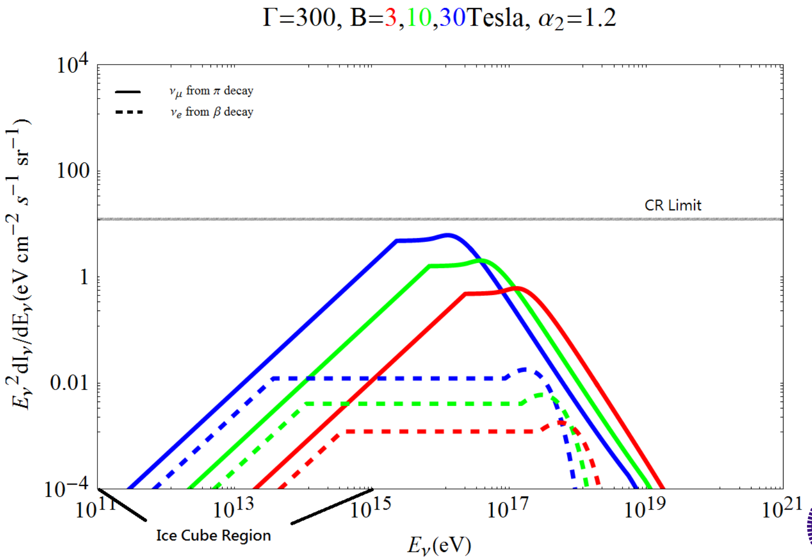
The neutron source spectrum

$$p + \gamma \rightarrow \Delta^+ \rightarrow n + \pi^+$$

- Neutron not affected by B'
- Constrained by $\mathcal{E}_{p,max}$

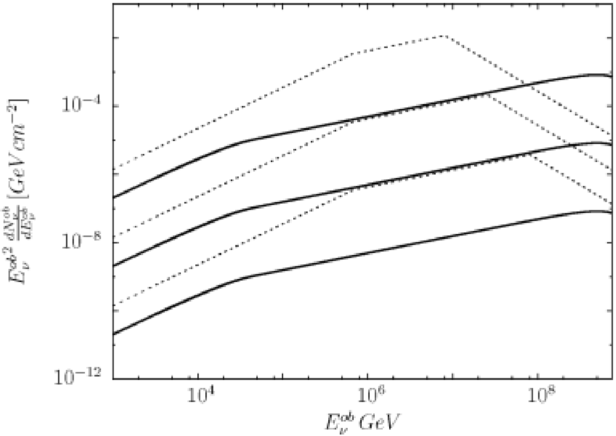
$$\phi_{\nu_e} = \frac{dI_{\nu_e}}{d\mathcal{E}_{\nu_e}} \propto \begin{cases} \mathcal{E}_{\nu_e}^{\alpha_2}\mathcal{E}_{\nu_e}^{-2} & \text{if } \mathcal{E}_{\nu_e} \leq \mathcal{E}_{\nu_e,br} \\ \mathcal{E}_{\nu_e}^{\alpha_1}\mathcal{E}_{\nu_e}^{-2} & \text{if } \mathcal{E}_{\nu_e,br} \leq \mathcal{E}_{\nu_e} \leq \mathcal{E}_{\nu_e,max} \\ \exp(-\frac{\mathcal{E}_{\nu_e}}{\mathcal{E}_{\nu_e,max}}) & \text{if } \mathcal{E}_{\nu_e} \geq \mathcal{E}_{\nu_e,max} \end{cases}$$

Typical GRB


Γ=300, B=3,10,30Tesla, α2=1.2
νμ from π decay
νe from β decay
CR Limit
10^4
100
1
0.01
10^−4
10^11
10^13
10^15
10^17
10^19
10^21
Eν(eV)
Eν^2dIν/dEν(eV cm^−2 s^−1 sr^−1)
Ice Cube Region

Typical GRB: a comparison

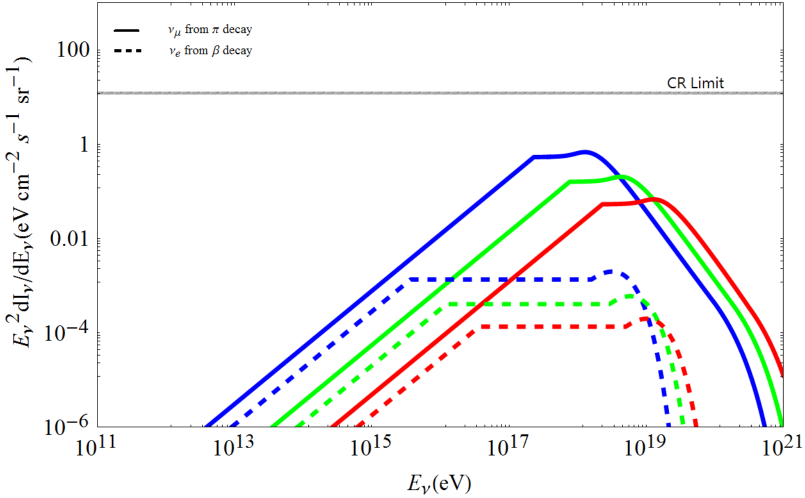
•



[Moharana and Gupta (2010)]

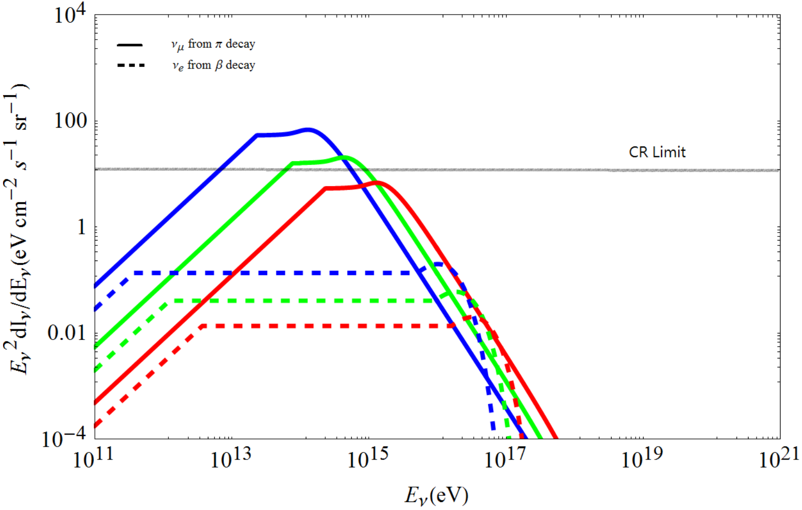
Weak Magnetic field

Γ=1000, B'=0.1,0.3,1Tesla, α_2=1.2

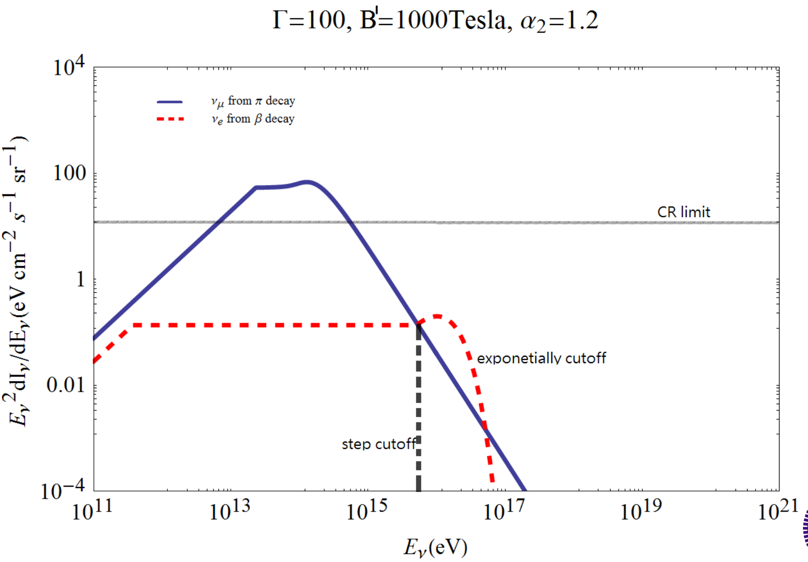


Strong Magnetic field

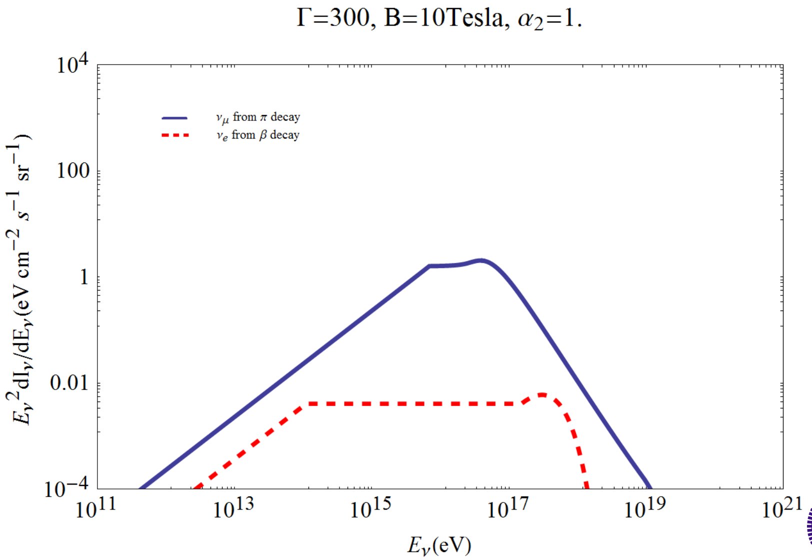
$\Gamma=100$, $B'=100, 300, 1000$ Tesla, $\alpha_2=1.2$



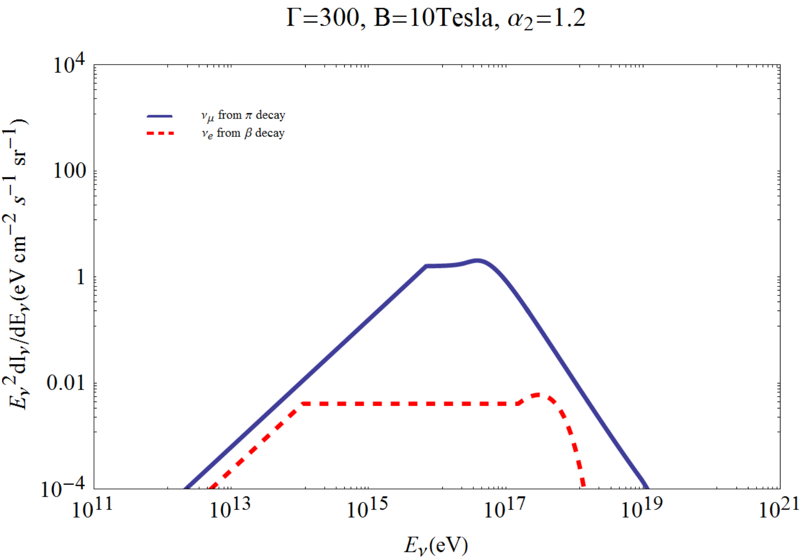
Cut-off form


Γ=100, B'=1000Tesla, α2=1.2
νμ from π decay
νe from β decay
CR limit
exponetially cutoff
step cutoff
10^4
100
1
0.01
10^-4
10^11
10^13
10^15
10^17
10^19
10^21
Eν(eV)
Eν^2dIν/dEν(eV cm^-2 s^-1 sr^-1)

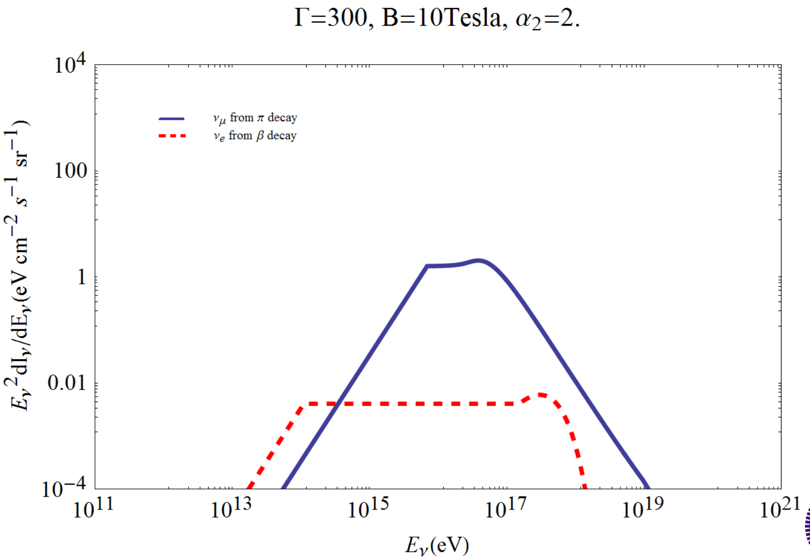
Dependence on α_2



Dependence on α_2

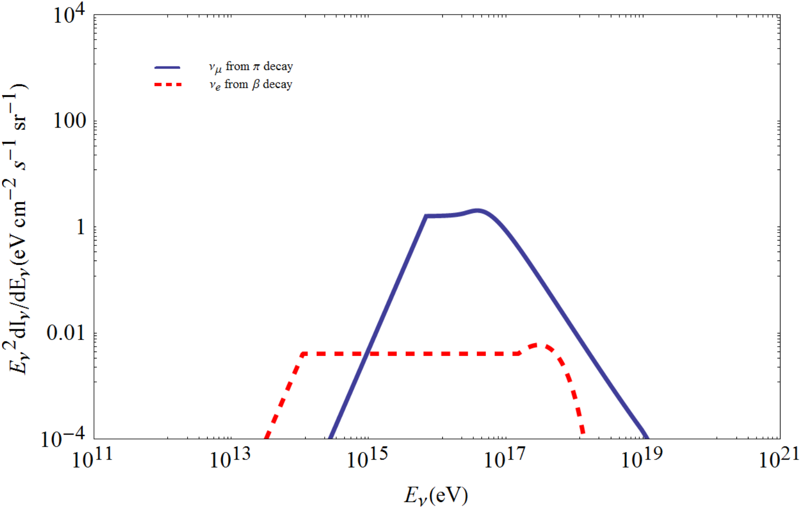


Dependence on α_2



Dependence on α_2

Γ=300, B=10Tesla, α_2=3.



Summary

- The expected flux:(Handout)
- Typical GRB: A different result with [Moharana and Gupta](Does neutron beam exist?)
- GRB with Strong magnetic field:
  1. Depends on the cut-off form
  2. Exceed the cosmic-ray limit
- Flavor dependence on α_2...

Conclusion

1. The pure neutron beam ($\phi_{\nu_e} : \phi_{\nu_\mu} : \phi_{\nu_\tau} = 1 : 0 : 0$)...
   - Not from Typical GRB.
   - Not likely from a GRB with Strong magnetic field too
   - In the low energy region for some gamma-ray burst, depending on the photon-spectrum index α_2
2. Neutrino flavor composition before oscillation from typical GRB: $\phi_{\nu_e} : \phi_{\nu_\mu} : \phi_{\nu_\tau} \approx 1 : 1.5 : 0$ in IceCube region (10^{11} eV $\leq \mathcal{E}_\nu \leq 10^{15}$ eV)

Future works

1. The red-shift correction
2. Synchrotron effect on muons
3. Nuclei dominance of UHECR origin

Thank you for your attention