

# Tracing Cosmic Accelerators with Decaying Neutrons

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- **Introduction**
- **Gamma-Ray Bursts (GRBs)**
- **Neutrinos from Gamma-Ray Bursts**
  - \* **Neutrinos from pion decay.**
  - \* **Anti-neutrinos from neutron decay.**
- **Conclusion**



# Introduction

Ultrahigh energy cosmic rays (UHECRs) are, cosmic rays with energy  $> 10^{18}$  eV.

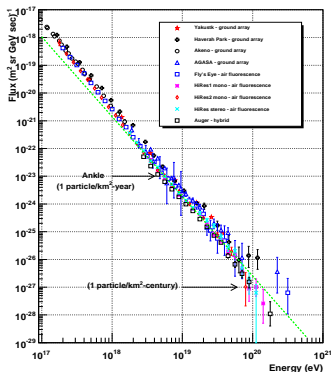
Extensive air showers (EAS) are detected by,

- \* Direct detection by surface detectors
- \* Fluorescence light by large mirrors.

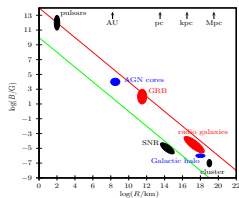
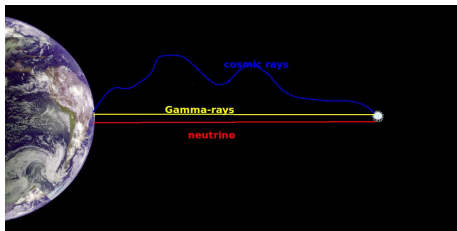
Basic questions regarding UHECRs with a flux of 1 particle/  $km^2$  Century.

- \* Composition. (Protons/Fe)
- \* Origin.
- \* Acceleration Mechanism.
- \* Propagation through galactic and extragalactic medium (IR/UV, CMBR radiation and magnetic fields.)

Cosmic Ray Spectra of Various Experiments



# Motivation



$$\bullet E_{max} \sim 2cZeBr_L$$

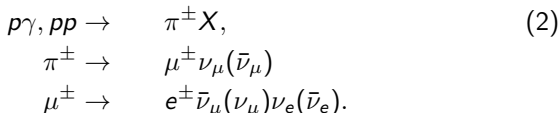
- Hillas criteria: Supernovae remnants(SNRs), Active galactic nuclei(AGNs), Gammarray bursts (GRBs).
- UHECRs get deflected by galactic and extra galactic magnetic fields.
- Secondary gamma-rays and neutrinos from cosmic rays, help in tracing the source of cosmic rays.



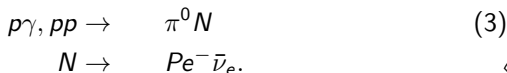
- VHE gamma-rays from cosmic rays (if they are protons).



- Relativistic electrons get inverse compton scattering by the magnetic field.
- UHE neutrinos from cosmic rays (if they are protons).



- 5% of proton energy goes to neutrinos.



- $\sim 10^{-3}$  energy of proton goes to antineutrinos.

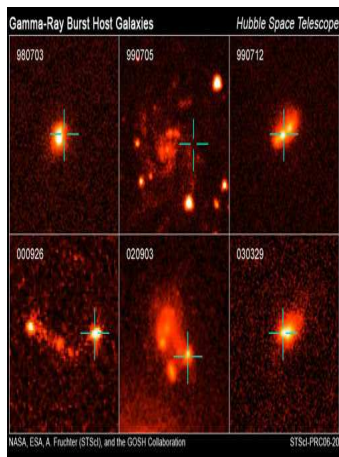


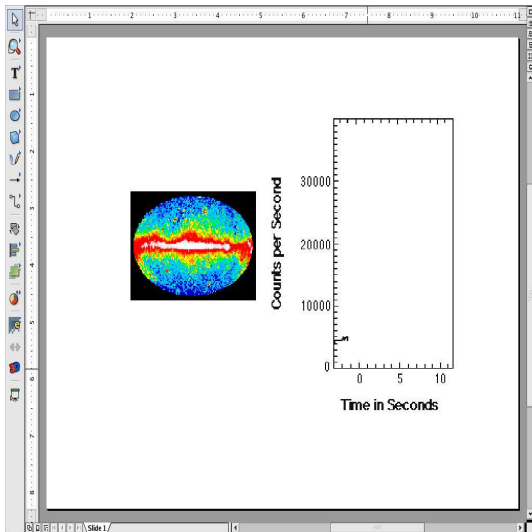
- Charged pion lose energy by synchrotron radiation in the magnetic field of the source at high energies.
- But for neutral neutrons, this effect is not affecting.
- Neutrinos from pion decay will be less than neutron decay neutrinos at higher energy, depending on the magnetic field, and other intrinsic properties of the source.

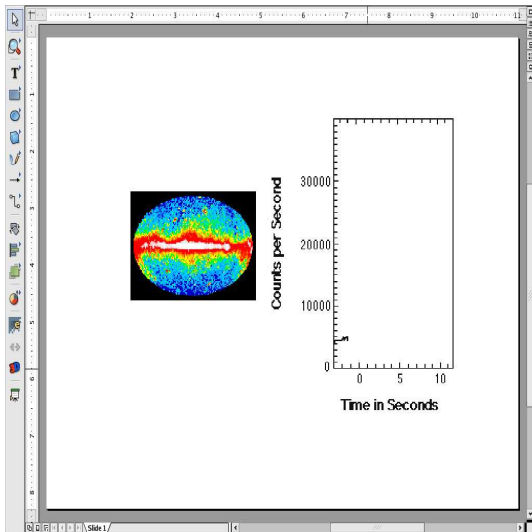


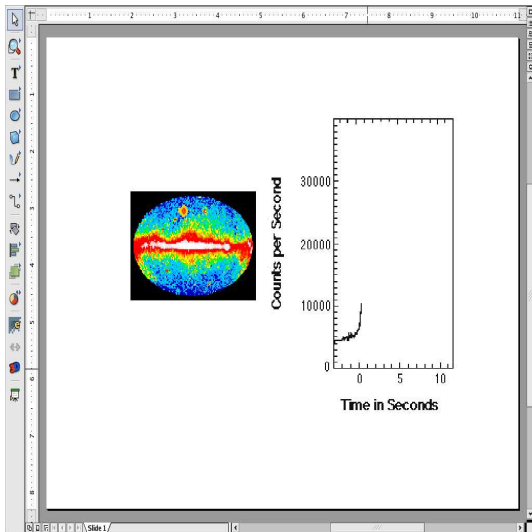
# Gamma-ray Bursts (GRBs)

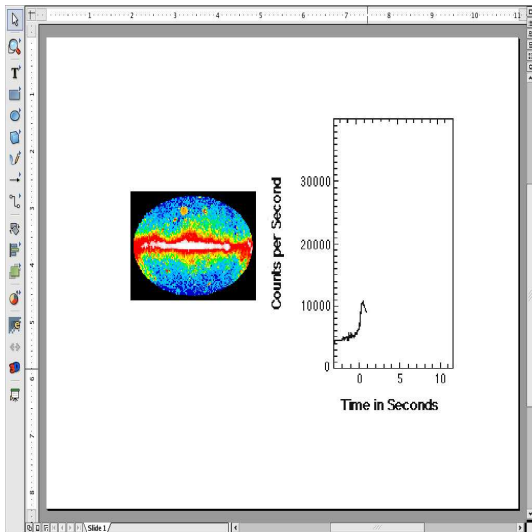
- GRBs were detected for the first time in late 1960's by U.S military satellites and announced in 1973
- BURST and Transient Experiment (BATSE) on CGRO launched in 1991, detected 2704 GRBs in keV and MeV range.
- Hard gamma-ray detection from EGRET experiment, OSSEL and Comptel.
- Most luminous  $\sim 10^{52}$  ergs explosions in the Universe.

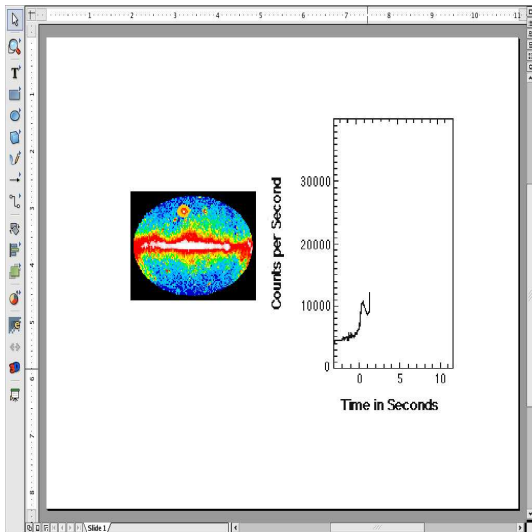


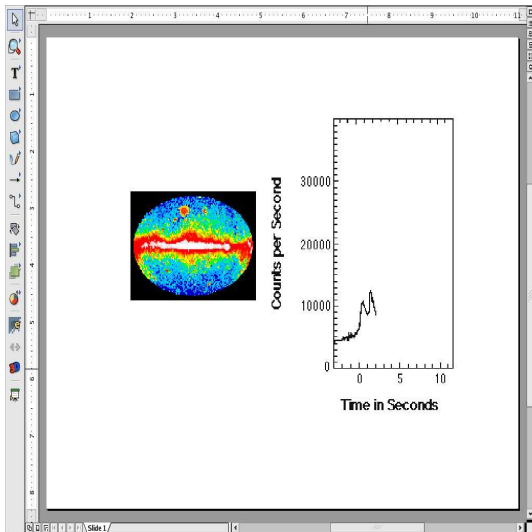


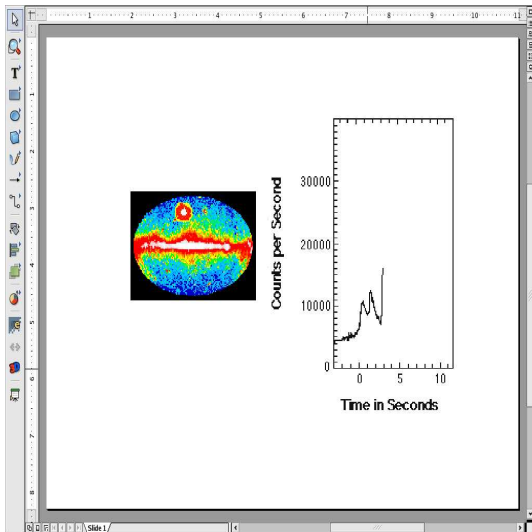


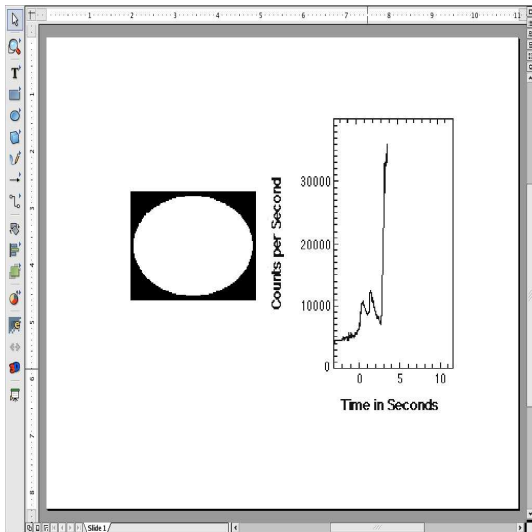


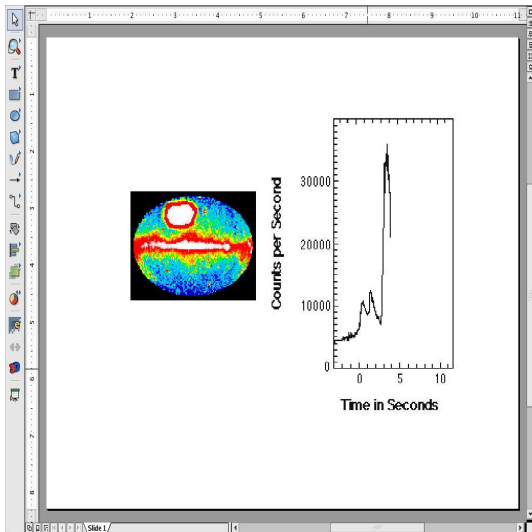


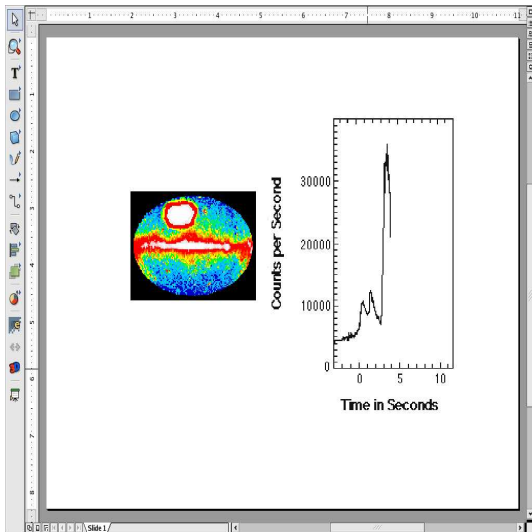


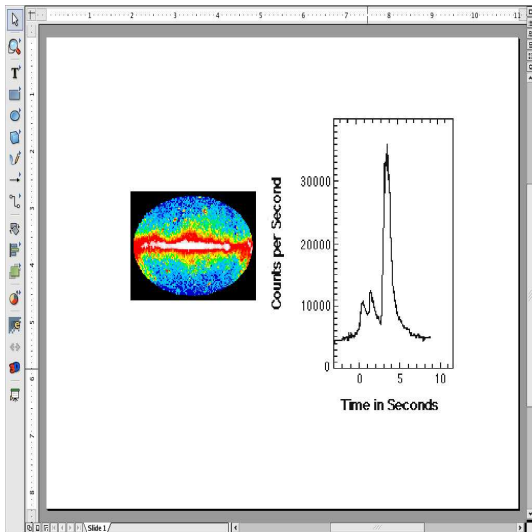


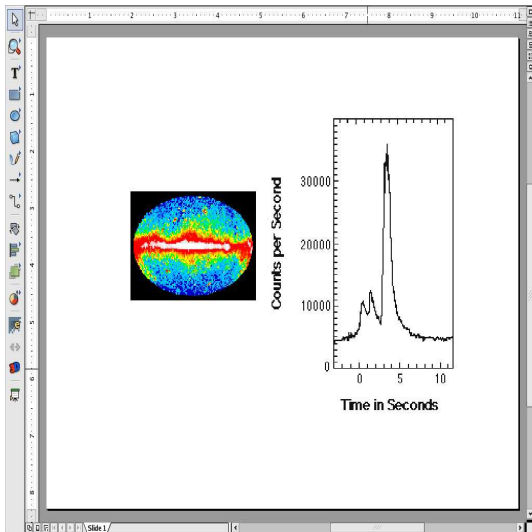












- Prompt emission lasts for few seconds.
- Photon energy spectrum of GRB in its comoving-frame.

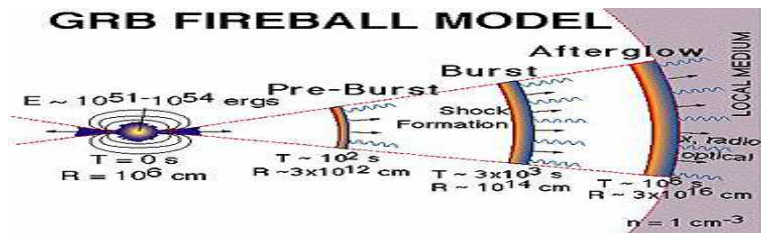
$$\frac{dn_\gamma}{d\epsilon_\gamma} = A \begin{cases} \epsilon_\gamma^{-\gamma_1} & \epsilon_\gamma < \epsilon_{br,c} \\ \epsilon_{br,c}^{\gamma_2-\gamma_1} \epsilon_\gamma^{-\gamma_2} & \epsilon_\gamma > \epsilon_{br,c} \end{cases} \quad (4)$$

- $\epsilon_{br,c}$  the break energy in the comoving frame.  $\sim 0.5 \text{ MeV}$
- $\gamma_1 < 2$ , and  $\gamma_2 > 2$ .

$$A = \frac{U_\gamma \epsilon_{br,c}^{\gamma_1-2}}{[\frac{1}{\gamma_2-2} - \frac{1}{\gamma_1-2}]}$$

- Internal photon energy density  $U_\gamma = L_\gamma / (4\pi r_d^2 \Gamma^2 c)$
- Afterglow phases- emission at wavelengths of X-ray, ultraviolet, optical, infrared and radio.





- Prompt emission- due to collision of ultra-relativistic shells during expansion , producing internal shocks
- Electrons and protons get accelerated by Fermi mechanism
- Afterglow- external shocks as a result of shells passing through interstellar medium.



- X-ray afterglow from GRB 970228 was detected by Beppo-SAX in 1997.
- GRB 970508 and GRB 971214 were detected at redshifts of 0.835 and 3.418 respectively.
- NASA launched *Swift* (with three detectors BAT, XRT and UVOT) satellite experiment in 2004.
- GRB 090423, the farthest GRB known so far, at  $z=8.1^{+0.1}_{-0.3}$  was detected by *Swift* in 2009 .
- Gamma-ray Large Area Space Telescope (GLAST) or *Fermi* was launched in 11 June 2008.
  - LAT (Large Area Telescope), with a energy range  $< 20$  MeV to  $>300$  GeV. Detects 14 GRBs or  $\approx 9$  GRB/yr at a redshifts of  $\approx 0.7$  to 4.35.
  - GBM (Gamma ray Burst Monitor) energy range 10 KeV - 25 MeV.  $\approx 500$  GRB/yr with full-sky
- Their origin, prompt emission, afterglow mechanisms and classification



# Neutrinos from pion decay at GRBs

- Fractional energy loss rate of proton due to pion production in wind rest frame.

$$t_{\pi}^{-1}(E_p) \equiv -\frac{1}{E_p} \frac{dE_p}{dt} \\ = \frac{1}{2\Gamma_p^2} c \int_{\epsilon_{th}}^{\infty} d\epsilon \sigma_{\pi}(\epsilon) \xi(\epsilon) \epsilon \int_{\epsilon/2\Gamma_p}^{\infty} dx x^{-2} \frac{dn(x)}{dx} (x = \epsilon_{\gamma}) \quad (5)$$

- $\Gamma_p = \epsilon_p/m_p c^2$ ,  $\sigma_{\pi}(\epsilon)$ , cross section for pion production in the proton rest frame.
- $\xi(\epsilon)$  is the average fraction of energy lost to the pion.
- Doing the integration at the  $\Delta$  resonance peak. With values
  - \*  $\epsilon_{peak} = 0.3 \text{ GeV}$ ,  $\sigma_{peak} \simeq 5 \times 10^{-28} \text{ cm}^2$
  - \*  $\xi_{peak} \simeq 0.2$ , and peak width  $\Delta\epsilon \simeq 0.2$



- Fraction of energy lost by protons to pions is  $f_\pi \simeq t_d/t_\pi$ .

$$f_\pi(E_p) = 0.2f_0 \begin{cases} \frac{1.34\gamma_1^{-1}}{\gamma_1+1} (E_p/E_p^b)^{\gamma_1-1} & E_p > E_p^b \\ \frac{1.34\gamma_2^{-1}}{\gamma_2+1} (E_p/E_p^b)^{\gamma_2-1} & E_p < E_p^b \end{cases} \quad (6)$$

- $f_0 = \frac{0.45L_{\gamma,51}}{\Gamma_{300}^4 t_{v,-3}\epsilon_{br,MeV}} \frac{1}{\left[\frac{1}{\gamma_2-2} - \frac{1}{\gamma_1-2}\right]}$ .
- The fireball Lorentz factor  $\Gamma_{300} = \Gamma/300$ , photon luminosity  $L_{\gamma,51} = L_\gamma/(10^{51} \text{ ergs/sec})$ , variability time  $t_{v,-3} = (t_v/10^{-3} \text{ sec})$ .
- Break in proton spectrum due to break in photon spectrum,

$$E_{pb} = 1.3 \times 10^7 \Gamma_{300}^2 (\epsilon_{br,MeV})^{-1}$$

- Wind expansion time measured in wind rest frame ( $t_d \sim r_d/(\Gamma c)$ ).  $r_d \sim \Gamma^2 ct_v$   
N.Gupta, B.Zhang *Astropart.Phys*(2007)



- Total energy emitted by neutrinos of energy  $E_\nu$

$$E_\nu^2 \frac{dN_\nu(E_\nu)}{dE_\nu} \approx \frac{3f_\pi}{8} \frac{1}{\kappa} \frac{(1 - \epsilon_e - \epsilon_B)}{\epsilon_e} E_\gamma^{iso} \quad (7)$$

- factor 3, as three neutrinos produced in each interaction and factor 1/8 for, charged and neutral pions are produced with equal probabilities and each neutrino takes 1/4 of the pion energy.
- $E_\gamma^{iso}$ , total isotropic energy of the emitted gamma-ray photons in the energy range of 1keV to 10MeV *Swift*.
- $\epsilon_e, \epsilon_B \sim 0.3$  are the energy fractions carried by electrons and the magnetic field.
- $\kappa$  normalization factor, assuming photon fluence proportional to neutrino luminosity.
- Lower limit on  $\Gamma$  is,

$$\Gamma \geq 250 \left[ L_{\gamma,52} \left( \frac{\epsilon_t}{100 \text{ MeV}} \right) \Delta t_{-2}^{-1} \right]^{1/6}$$

$\epsilon_t$  is high energy test photon



# Synchrotron loss of pion/muon energy

- The charged pion and muon, lose energy due to synchrotron radiation.
  - \* Synchrotron loss time of pion in magnetic field energy density ( $U_B$ ) in CM frame,

$$t'_{\text{syn}} = \frac{3m_{\pi}^4 c^3}{4\sigma_T m_e^2 \epsilon_{\pi} U_B}.$$

- \* pion lifetime for decay,

$$\tau'_{\pi} \approx 2.6 \times 10^{-8} \epsilon'_{\pi} / (m_{\pi} c^2) \text{ s}$$

- Comparing two, the break energy in neutrino spectrum due to synchrotron loss of muon energy, (as pion loss is 10 times of muon loss due to synchrotron radiation).

$$E_{\nu}^s = 2.56 \times 10^6 \epsilon_e^{1/2} \epsilon_B^{-1/2} L_{\gamma, 51}^{-1/2} \Gamma_{300}^4 t_{\nu, -3} \text{ GeV}$$



$$E_\nu^2 \frac{dN_\nu(E_\nu)}{dE_\nu} \approx \frac{3f_\pi}{14.4} \frac{(1 - \epsilon_e - \epsilon_B)}{\epsilon_e} E_\gamma^{iso} \begin{cases} 1 & E_\nu < E_\nu^s \\ (\frac{E_\nu}{E_\nu^s})^{-2} & E_\nu > E_\nu^s \end{cases} \quad (8)$$

- Normalization is done for spectral index of 2.5 of electron, and considering *Swift* energy range 1keV to 10MeV.

\* corresponding  $\kappa = 1.8$ .

- The spectrum decreases with index 2 as the energy is proportional to  $-2$ . The maximum proton energy attained inside GRBs,

$$E_{p,max}^2 = \Gamma^2 \frac{6\pi m_p^4 c^4 e}{\sigma_t m_e^2 B_c}$$

Magnetic field in the comoving frame,

$$B_c \sim 1.56 \times 10^4 L_{\gamma,51300}^{1/2-3} t_{v,-3}^{-1}$$



# Neutrinos from neutron decay

- Fractional energy of fireball proton lost to neutron production,

$$f_n(E_p) = 0.8f_0 \begin{cases} \frac{1.34^{\gamma_1-1}}{\gamma_1+1} (E_p/E_p^b)^{\gamma_1-1} & E_p > E_p^b \\ \frac{1.34^{\gamma_2-1}}{\gamma_2+1} (E_p/E_p^b)^{\gamma_2-1} & E_p < E_p^b \end{cases} \quad (9)$$

- Fraction of energy transfer to neutron from proton is,  $\langle x_{p \rightarrow n} \rangle = 0.8$ .

- The neutron spectrum,

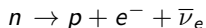
$$E_n^2 \frac{dN_n}{dE_n} = \frac{f_n}{2\kappa} \frac{1 - \epsilon_e - \epsilon_B}{\epsilon_e} E_\gamma^{iso} \quad (10)$$

- $\frac{1}{2}$  corresponds to the assumption that charged and neutral pions are produced with equal probabilities.

R. Moharana, N. Gupta PRD (2010)



# Anti-neutrino flux from neutron decay



\* Decay mean free path  $c\Gamma_n\bar{\tau}_n = 10(E_n/GeV)$  Kpc where  $\bar{\tau}_n = 886$  seconds, the rest frame lifetime.

- $\bar{\nu}_e$  flux with lab frame energy  $E_{\bar{\nu}}$  on earth relates to the neutrons flux ( $dN_n/dE_n$ ) as,

$$\frac{dN_{\bar{\nu}}}{dE_{\bar{\nu}}}(E_{\bar{\nu}}) = \int dE_n \frac{dN_n}{dE_n}(E_n) \left(1 - e^{-\frac{D_s m_n}{E_n \bar{\tau}_n}}\right) \int_0^Q d\epsilon_{\bar{\nu}} \frac{dP}{d\epsilon_{\bar{\nu}}}(\epsilon_{\bar{\nu}}) \times \int_{-1}^1 \frac{d\cos\bar{\theta}_{\bar{\nu}}}{2} \delta [E_{\bar{\nu}} - E_n\epsilon_{\bar{\nu}}(1 + \cos\bar{\theta}_{\bar{\nu}})/m_n]$$

\*  $\epsilon_{\bar{\nu}}$  energy of  $\bar{\nu}_e$ ,  $\bar{\theta}_{\bar{\nu}}$  antineutrino angle with respect to the direction of the neutron momentum in neutron rest frame.

\*  $\frac{dP}{d\epsilon_{\bar{\nu}}}(\epsilon_{\bar{\nu}})$  is the normalized probability that the decaying neutron in its rest-frame produces a  $\bar{\nu}_e$  with energy  $\epsilon_{\bar{\nu}}$  and  $Q = m_n - m_p - m_e = 0.71$  MeV.



- \* Comoving radial distance of the GRB,  $D_s$

$$D_s = \int_0^z \frac{c}{H_0} \frac{dz'}{\sqrt{\Omega_\Lambda + \Omega_m(1+z')^3}}$$

- \*  $\Omega_\Lambda = 0.73$ ,  $\Omega_m = 0.27$  and the Hubble constant  $H_0 = 71 \text{ km sec}^{-1} \text{ Mpc}^{-1}$ .

- Anti-neutrino flux at the source,

$$\frac{dN_{\bar{\nu}}}{dE_{\bar{\nu}}}(E_{\bar{\nu}}) = \frac{m_n}{2\epsilon_0} \int_{\frac{m_n E_{\bar{\nu}}}{2\epsilon_0}}^{E_{n, \max}} \frac{dE_n}{E_n} \frac{dN_n}{dE_n}(E_n) \left(1 - e^{-\frac{D_s m_n}{E_n \tau_n}}\right)$$

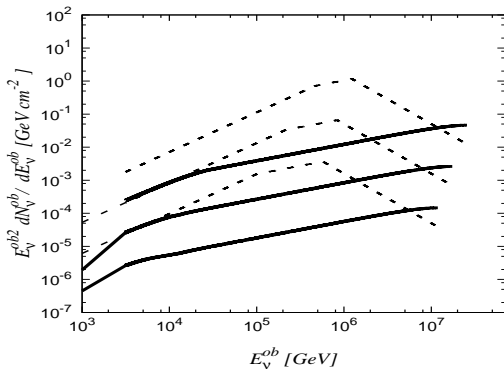
L. Anchordoqui et al., *Astropart. Phys.* (2004)

- Observed anti-neutrino flux at earth

$$\frac{dN_{\bar{\nu}}^{\text{ob}}(E_{\bar{\nu}}^{\text{ob}})}{dE_{\bar{\nu}}^{\text{ob}}} = \frac{dN_{\bar{\nu}}(E_{\bar{\nu}})}{dE_{\bar{\nu}}} \frac{1+z}{4\pi D_s^2}$$

- $\epsilon_0$  is the mean energy of neutrino.





- Neutrino flux from neutron decay (black line), pion decay channel (dashed lines).
- $L_\gamma$  varying from  $10^{53}$ ,  $10^{52}$  and  $10^{51}$  erg/sec from top to bottom with variable time  $t_\nu = 10$  ms.



# Conclusion

- UHE neutrinos are expected from astrophysical UHECR sources by CR- $\gamma$ /CR-matter interactions.
- Charged pions/muons lose energy by synchrotron radiation in the magnetic field of GRBs.
- The antineutrino flux produced in decay of ultrahigh-energy neutrons may become more important than the neutrino flux from photopion decay depending on the luminosity, Lorentz boost factor, variability time of a GRB at very high energy.



Thank you



# Detection of neutrino events

- Neutrinos are detected by its interaction with the nucleons of the detector.

- Muon-neutrino event rate by  $Km^2$  area detector,

$$\text{Rate} = A \int_{E_\mu^{\min}}^{E_\mu^{\max}} dE_\nu P_\mu(E_\nu; E_\mu^{\min}) S(E_\nu) \frac{dN_\nu}{dE_\nu}(E_\nu).$$

- \* The probability that a muon is produced by charged-current interaction of neutrino (energy above  $E_\mu^{\min}$ ) with the detector,

$$P_\mu(E_\nu, E_\mu^{\min}) = N_A \sigma_{CC}(E_\nu) \langle R(E_\nu; E_\mu^{\min}) \rangle,$$

- \*  $\langle R(E_\nu; E_\mu^{\min}) \rangle$  is the average range of a muon in ice.
- \* Interaction length in ice,

$$\mathcal{L}_{\text{int}} = \frac{1}{\sigma_{\nu N}(E_\nu) N_A},$$

- \* Showing factor, attenuation while traversing earth,

$$S(E_\nu) = \frac{1}{2\pi} \int_{-1}^0 d \cos \theta \int d\phi \exp[-z(\theta)/\mathcal{L}_{\text{int}}(E_\nu)].$$

Raj Gandhi et al., Phys. Rev. D (1998)



- Neutrino event detected inside effective volume of  $2 \text{ km}^3$

$$\mathcal{N} = N_A \rho V_{\text{eff}} \int_{E_{\text{th}}}^{+\infty} dE_\nu \sigma_{\nu N}^{CC} \frac{dN_\nu}{dE_\nu}(E_\nu)$$

\*  $\rho$  the density of ice.

A Cuoco et al., Phys. Rev. D (2008)

- Neutrino event from neutron decay channel above 1 TeV from GRB at 0.8 redshift, with luminosity  $L_\gamma = 10^{51} \text{ erg/sec}$ , Lorentz factor  $\Gamma = 300$ , duration 5sec, and variability time  $t_v = 10 \text{ ms}$ . The GRB has been assumed to occur at a zenith angle,  $\theta$  of  $120^\circ$  with respect to an observer at the south pole, is  $10^{-5}$
- Neutrino event from pion decay channel  $10^{-4}$



