A Unified Model of Stellar Collapse Origin of All Cosmic Rays upto 10^{20} eV

by

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Plan of talk

- Motivation: The Cosmic Ray spectrum, possible Galactic/ extra-galactic contributors

- Hypernovae/TRSNe $\Rightarrow$GRB associated Supernovae

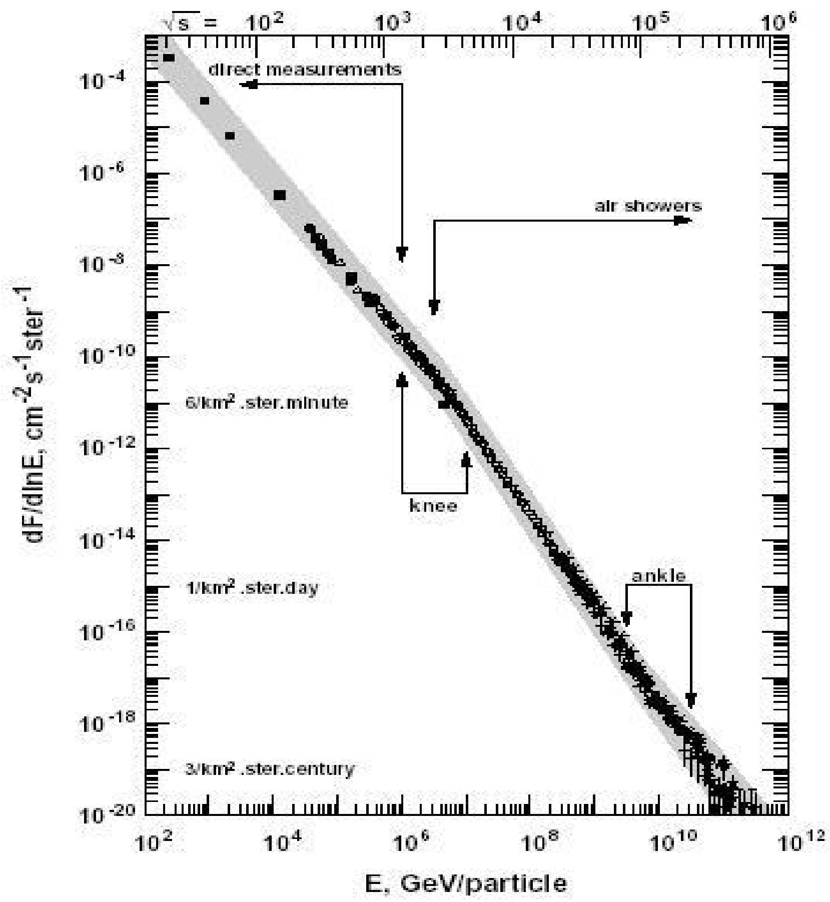
- Constraining Cosmic GRB rate using diffuse ν background $\Rightarrow f_{GRB/CCSN}$

- Particle spectra from Galactic Supernovae and Hypernovae: Solution of diffusion equation for CR number density

- Summary and discussion on future goals

MOTIVATION
FOR THE WORK

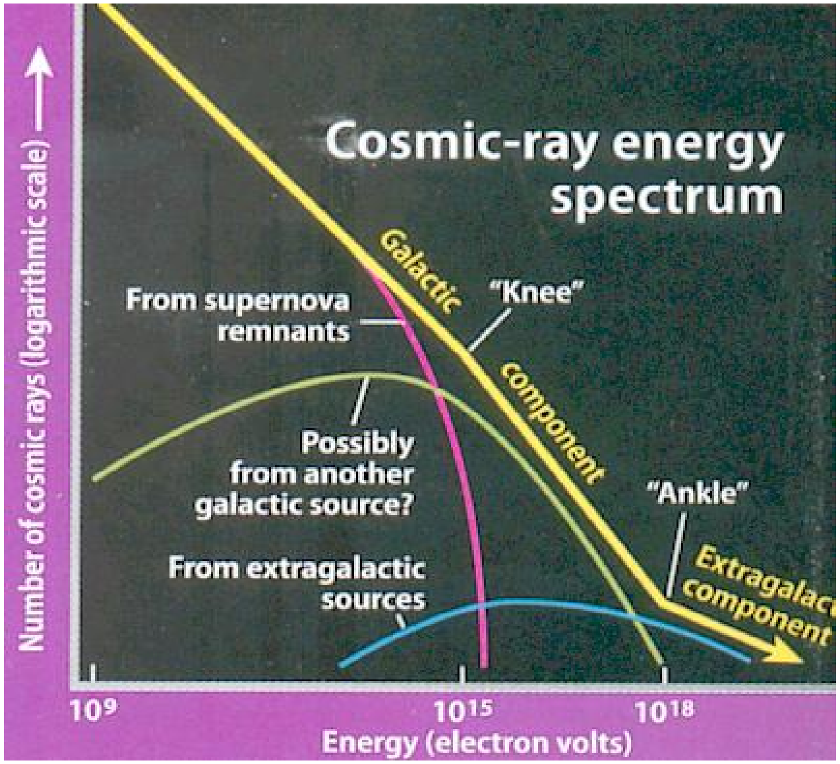
The Cosmic Ray spectrum



Power-law spectrum, with two features:

- "knee" at $\sim 10^{15}$ eV: spectrum steepens as power law index changes from ~ 2.7 to ~ 3.1
- "ankle" at $\sim 10^{18}$ eV: spectrum flattens again

Source of CRs between Knee and Ankle of spectrum



Properties of the "new" type of source:

- Most likely of Galactic origin.
- Has to be *supernova-like* in nature.
- Has to be more energetic than a typical Supernova, so that ϵ_{max} is higher.

  $\Rightarrow$ Highly energetic Supernova or, HYPERNOVA of Galactic origin

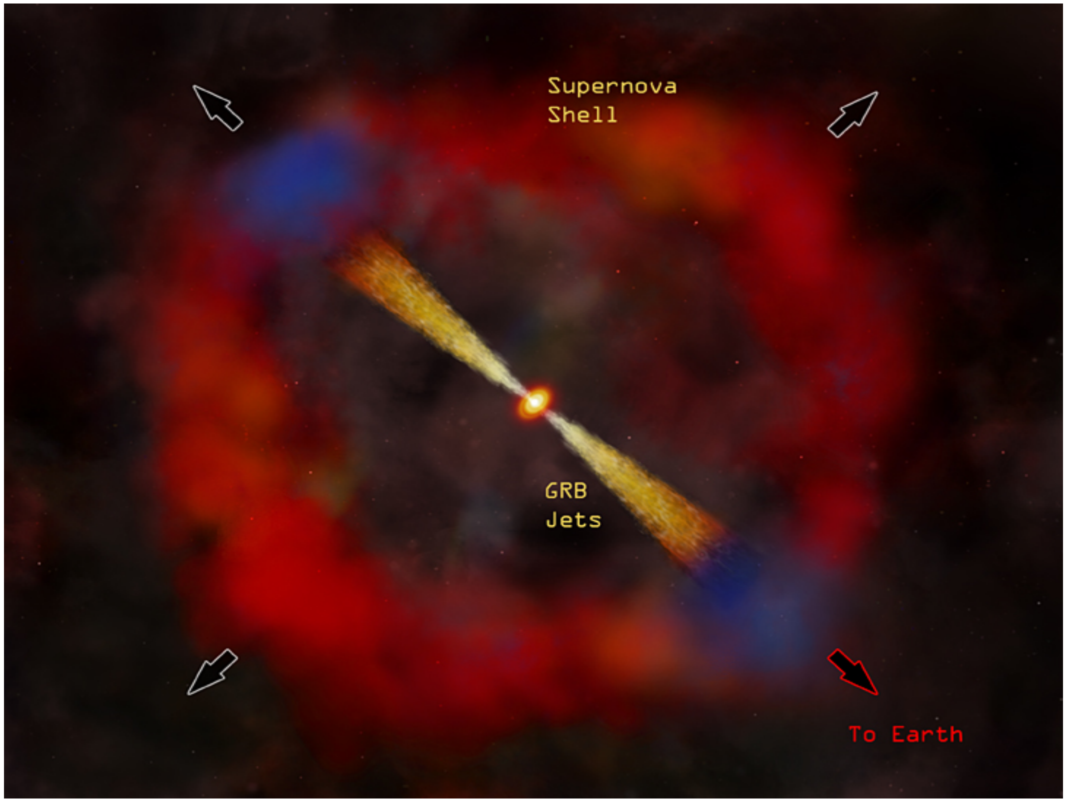
  - Uptil now all observations of such events have been extra-galactic.
  - All of them have been accompanied by GRBs.

Our objective is to explain the entire CR spectrum in terms of stellar core-collapse events.

CCSNe - GRB CONNECTION: TRSNe/HYPERNOVAE

What are Hypernovae?

Hypernovae or the **Trans-Relativistic Supernovae** are the supernovae associated with the sub-energetic Gamma Ray Bursts. They deposit a significant fraction ($> 10^{-2}$) of the explosion energy in mildly relativistic ejecta.



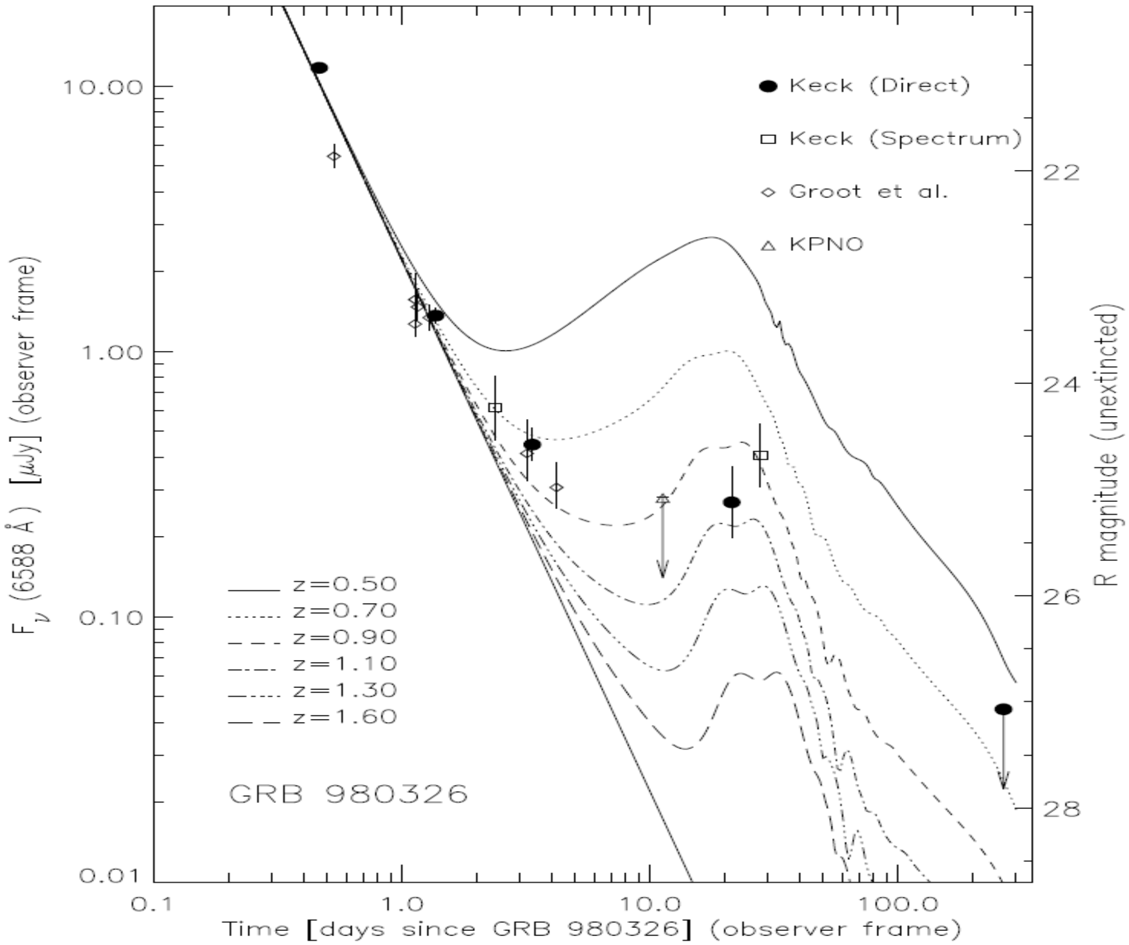
CCSN-GRB Connection: Observational Evidences

Observation of various GRBs in positional coincidence with CCSNe has indicated strong CCSN-GRB connection.

- GRB980425-SN1998bw: Observed at 40 Mpc, coincident in both time and place.
- GRB030329-SN2003dh: Observed at $z = 0.1685$, supernova features were detected in the spectra of afterglow by various groups.
- Compelling spectroscopic evidences exist for supernova associations of GRB031203 (SN2003lw) and GRB021211 (SN2002lt).
- There have also been "bumps" in optical afterglows of many GRBs, consistent in color, timing and brightness with what is expected from Type I supernovae of luminosity comparable to SN1998bw.

Difficulties in making observations make us assume the hypothesis that *all long-soft GRBs are accompanied by CCSNe*.

Optical SN-like bump superimposed on afterglow of GRB 980326



(Woosley, S.E. and Bloom, J.S. 2006, astro-ph/0609142v1)

Do all stellar collapses lead to GRBs?

Probably only $> 30M_{\odot}$ stars lead to GRBs, while $> 8M_{\odot}$ stars would give rise to a core collapse supernova.

Other factors that might prove decisive are rotation of the star, metallicity etc.

So, we introduce a fraction $f_{GRB/CCSN}$ that implies fraction of Supernovae going to GRBs (Hypernovae).

"Observed" value of fraction of Supernovae giving rise to GRBs

Methods based on astronomical observations indicate the ratio between cosmic GRB rate and cosmic Type Ib/c supernova rate, $f_{GRB/SNIbc}$, to be in the range $\sim 10^{-3} - 10^{-2}$.

[Here, a wide variety of assumption on SFR, IMF of stars,masses of Type Ib/c SNe progenitors, luminosity function of GRBs, beaming factor of GRBs have been made]

As Type II SNe probably constitute $\sim 75\%$ of all core collapse SNe,

$$f_{GRB/CCSN} \,|_{'observed'} \;=\; 2.5 \times (10^{-4} - 10^{-3})$$

UPPER BOUND ON GRB RATE USING DIFFUSE NEUTRINO BACKGROUND

Constraining $f_{GRB/CCSN}$ with Diffuse Neutrinos

In our work* we use the diffuse TeV-PeV neutrino background produced by the GRBs as a tool for determination of the upper limit on $f_{GRB/CCSN}$ along with the experimental upper limit on high energy diffuse neutrino background (DGRBNuB)given by the **AMANDA-II** experiment in the South Pole.

Advantages of using DGRBNuB:-

- All GRBs that have taken place till date are taken into account
- GRBs at very large distances (till $z \simeq 6$) can be considered
- "Failed GRBs" are automatically taken into account
- No beaming correction needed

*Bhattacharjee, P., Chakraborty, S., SDG & Kar, K., Phys.Rev.D77:043008,2008

Diffuse GRB Neutrino Background

Total differential flux of neutrinos, $\Phi(\epsilon_\nu^{ob})$, giving no. of ν's (of all flavors) crossing per unit area per unit time per unit energy per unit solid angle, due to all GRBs upto a maximum redshift z_{max}, can be written as,

$$\Phi(\epsilon_\nu^{ob}) = \frac{c}{4\pi} {H_0}^{-1} \int_0^{z_{max}} R_{GRB}(z) \left(\frac{dN_\nu(\epsilon_\nu)}{d\epsilon_\nu} \right) \frac{dz}{\sqrt{\Omega_m (1+z)^3 + \Omega_\lambda}}$$

where, $\epsilon_\nu \; = \; (1+z) \; \epsilon_\nu^{ob}$. where, $R_{GRB}(z) =$ GRB rate per comoving volume at redshift z.

$$\begin{aligned} R_{GRB}(z) &= f_{GRB/CCSN}(z) \; R_{CCSN}(z) \\ &= f_{GRB/CCSN}(0)(1+z)^\alpha \; R_{CCSN}(z) \end{aligned}$$

Neutrino spectrum due to photopion interaction of protons with photons is given by,

$$\epsilon_\nu^2 \frac{dN_\nu(\epsilon_\nu)}{d\epsilon_\nu} = \frac{3}{4} \times \frac{1}{2} \times 0.56 \times f_\pi(\epsilon_p) \left(\frac{\xi_p}{\xi_e}\right) \varepsilon_\gamma \begin{cases} 1 & \text{for } \epsilon_\nu < \epsilon_{\nu*} \\ \left(\frac{\epsilon_\nu}{\epsilon_{\nu*}}\right)^{-2} & \text{for } \epsilon_\nu > \epsilon_{\nu*} \end{cases}$$

where, $\epsilon_p = 20\epsilon_\nu$.

Here, $f_\pi(\epsilon_p)$ has the form,

$$f_\pi(\epsilon_p) = f_0 \begin{cases} 0.88 \left(\frac{\epsilon_p}{\epsilon_{pb}}\right)^{1.25} & \text{for } \epsilon_p < \epsilon_{pb} \\ 1 & \text{for } \epsilon_p > \epsilon_{pb} \end{cases}$$

where,

$$f_0 = \frac{0.09 L_{\gamma,51}}{\Gamma_{300}^4 \; t_{v,-3} \; \epsilon_{\gamma b,MeV}}$$

The source spectrum $\frac{dN_\nu(\epsilon_\nu)}{d\epsilon_\nu}$ for a single GRB is a function of various GRB parameters: L_γ, Γ, T_d , t_v ,ξ_p/ξ_e and $\epsilon_{\gamma b}$. The final diffuse neutrino flux also depends on α, the evolution index (with z) for the GRB rate.

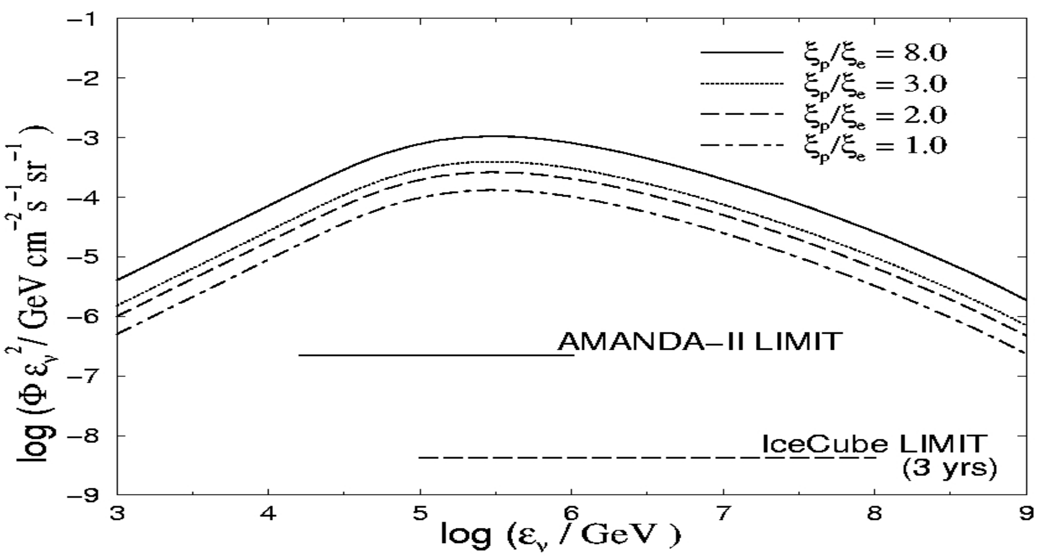
- We average over the "measurable" GRB parameters, L_γ, Γ, T_d and t_v.

- $\epsilon_{\gamma b}$ can be related to ε_γ, and thus to L_γ, through the empirical "Amati relation" given by,

$$\frac{\epsilon_{\gamma b}}{100keV} = (3.64 \pm 0.04)\left(\frac{\varepsilon_\gamma}{7.9 \times 10^{52} erg}\right)^{0.51 \pm 0.01}$$

- ξ_p/ξ_e and α remain free parameters (though according to *Kistler, M.D. et al, 2007, arXiv:0709.0381v2*, best fit to existing data seems to be for $\alpha \sim 1.5$)

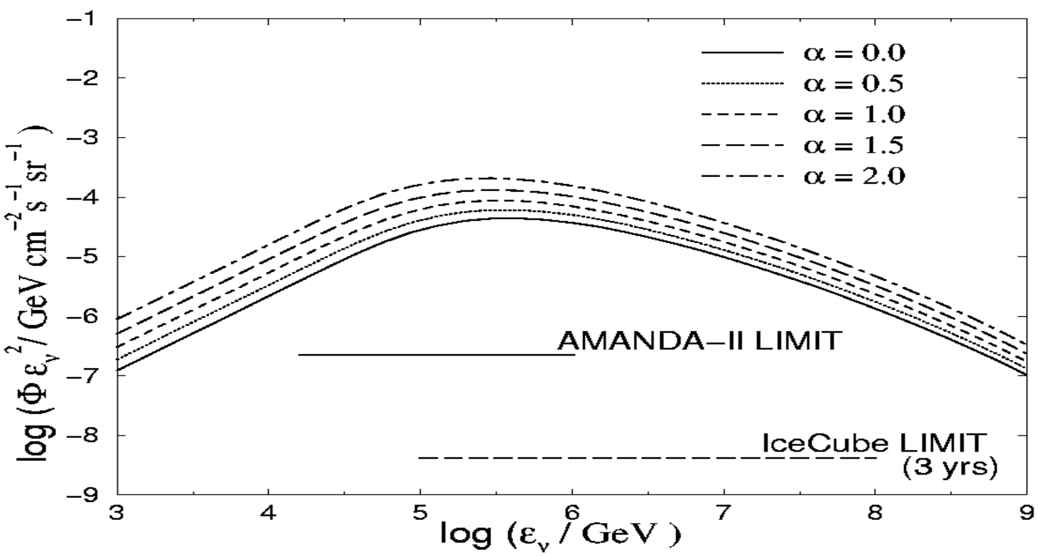
DGRBNuB spectrum variation with ξ_p/ξ_e for $f_{GRB/CCSN}(0) = 1$



Upper limit on $f_{GRB/CCSN}(0) \ll 1$; lower the efficiency of transfer of energy from protons to electrons, i.e., larger the value of ξ_p/ξ_e, tighter is the constraint on $f_{GRB/CCSN}(0)$

(PB, SC, SDG & KK, Phys.Rev.D77:043008,2008)

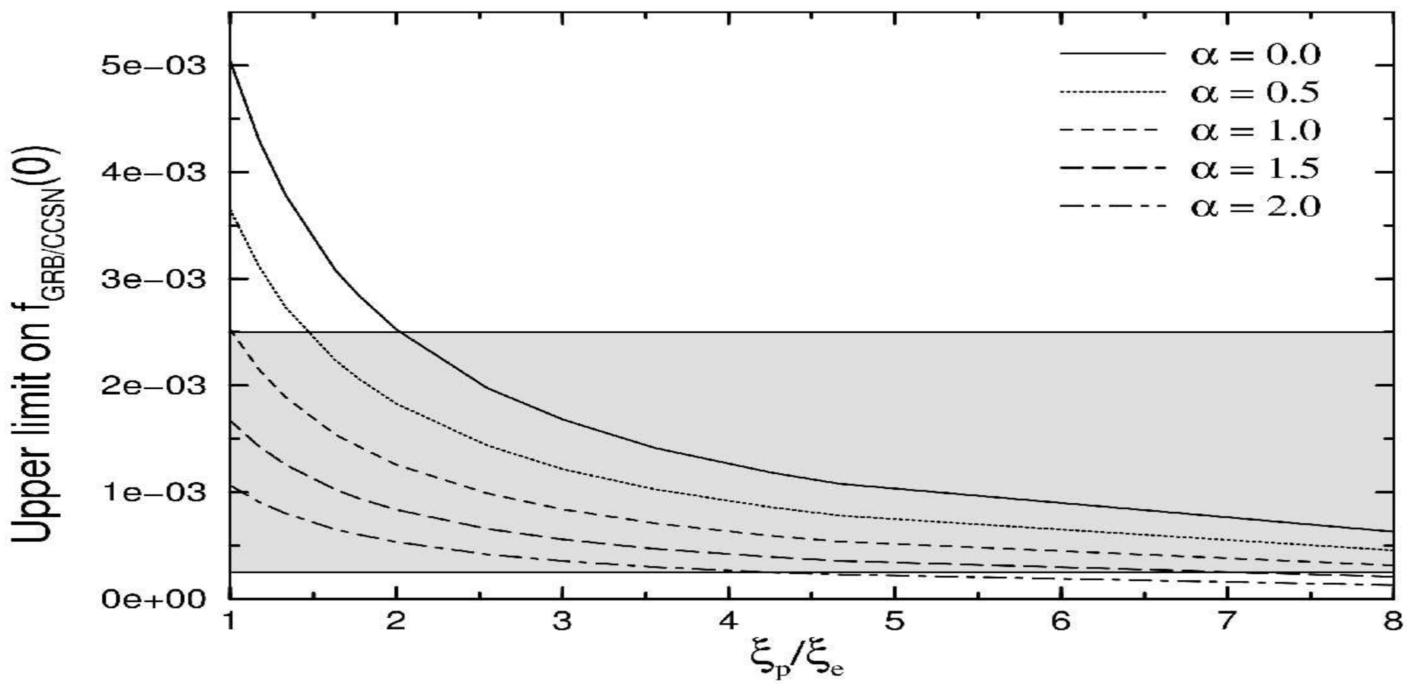
DGRBNuB spectrum variation with α for $f_{GRB/CCSN}(0) = 1$



Upper limit on $f_{GRB/CCSN}(0) \ll 1$; best constraint on $f_{GRB/CCSN}(0)$ is obtained for strongest considered relative evolution of GRB rate with respect to SFR

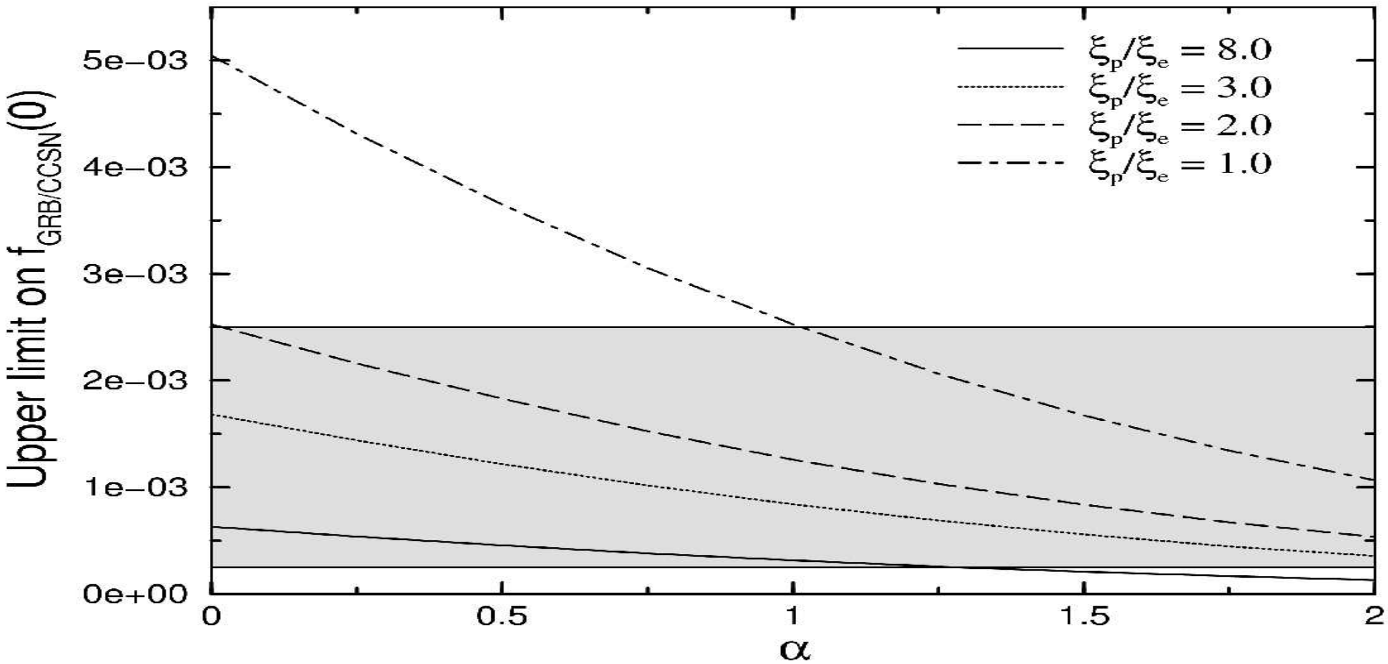
(PB, SC, SDG & KK, Phys.Rev.D77:043008,2008)

Upper limit on $f_{GRB/CCSN}(0)$ as a function of ξ_p/ξ_e for various α



(PB, SC, SDG & KK, Phys.Rev.D77:043008,2008)

Upper limit on $f_{GRB/CCSN}(0)$ as a function of α for various ξ_p/ξ_e



(PB, SC, SDG & KK, Phys.Rev.D77:043008,2008)

Implications for the Galactic Hypernova rate

- Our conservative upper limits are

$$\begin{aligned} f_{GRB/CCSN}(0) &\leq 5 \times 10^{-3} \text{for } \alpha = 0 \\ &\leq 1.1 \times 10^{-3} \text{for } \alpha = 2 \end{aligned}$$

- These limits are comparable to the current upper limit on this ratio inferred from other astronomical considerations.

- The limits are more restrictive ($\sim 10^{-4}$) for $\alpha \geq 1$, and also for $\xi_p/\xi_e > 1$.

Hence, if average SN rate in our Galaxy is 1 per 100 years, the Hypernova rate could be as low as as 1 per 10^6 years !

HIGH ENERGY PARTICLE SPECTRA FROM GALACTIC SNe and HNe

Diffusion Equation in cylindrical polar coordinates

In an attempt to obtain the CR spectrum from Galactic SNe and TRSNe, one needs to solve the diffusion equation, as Larmor radii of $10^{11} - 10^{18}$ eV nuclei are ≤ 100 pc (maximum scale of turbulence of Galactic B field), which in turn is $\ll (\sim 3$ kpc) (Galactic height).

- Time Dependent Diffusion Equation for CR density $N(E, r, \phi, z)$ is:

$$\frac{\partial N(E, r, \phi, z)}{\partial t} = \nabla_i \left(D_{ij}(r, z)\nabla_j N(E, r, \phi, z)\right) + Q(E, r, \phi, z)$$

- The diffusion tensor can be decomposed as,

$$D_{ij} = (D_{\parallel} - D_{\perp})b_i b_j + D_{\perp}\delta_{ij} + D_A \epsilon_{ijk} b_k$$

- We solve the steady state diffusion equation for diffused SN contribution, and time dependent diffusion equation for single HN contribution to the CR spectrum.

- The components of CR flux $\overrightarrow{j}$ are given by,

$$j_i(E, r, \phi, z) = -D_{ik}(r, z)\nabla_k N(E, r, \phi, z)$$

The Diffusion Coefficients

- Approximate expressions for the components of CR diffusion tensor are,

$$D_{\parallel} = lv/3, \qquad D_{\perp} = gA^4 lv/3, \qquad D_A = -r_{H_0} v/3$$

where, the mean free path l is estimated as,

$$l = A^{-2} L (r_H/L)^m, \qquad r_H \leq L; \qquad l = A^{-2} L^{-1} (r_{H_0}^2), \qquad r_H > L$$

- We have taken $A^2 = 0.1, g = 0.5$ and particle velocity $v \simeq c$.

- The value $m = 1/3$ corresponds to a Kolmogorov spectrum and $m = 1/2$ corresponds to a Kraichnan spectrum for the Galactic random magnetic field.

(Ptuskin, V. S. et al Astron. Astrophys. 268, 726-735 (1993))

Inputs for the particle spectra

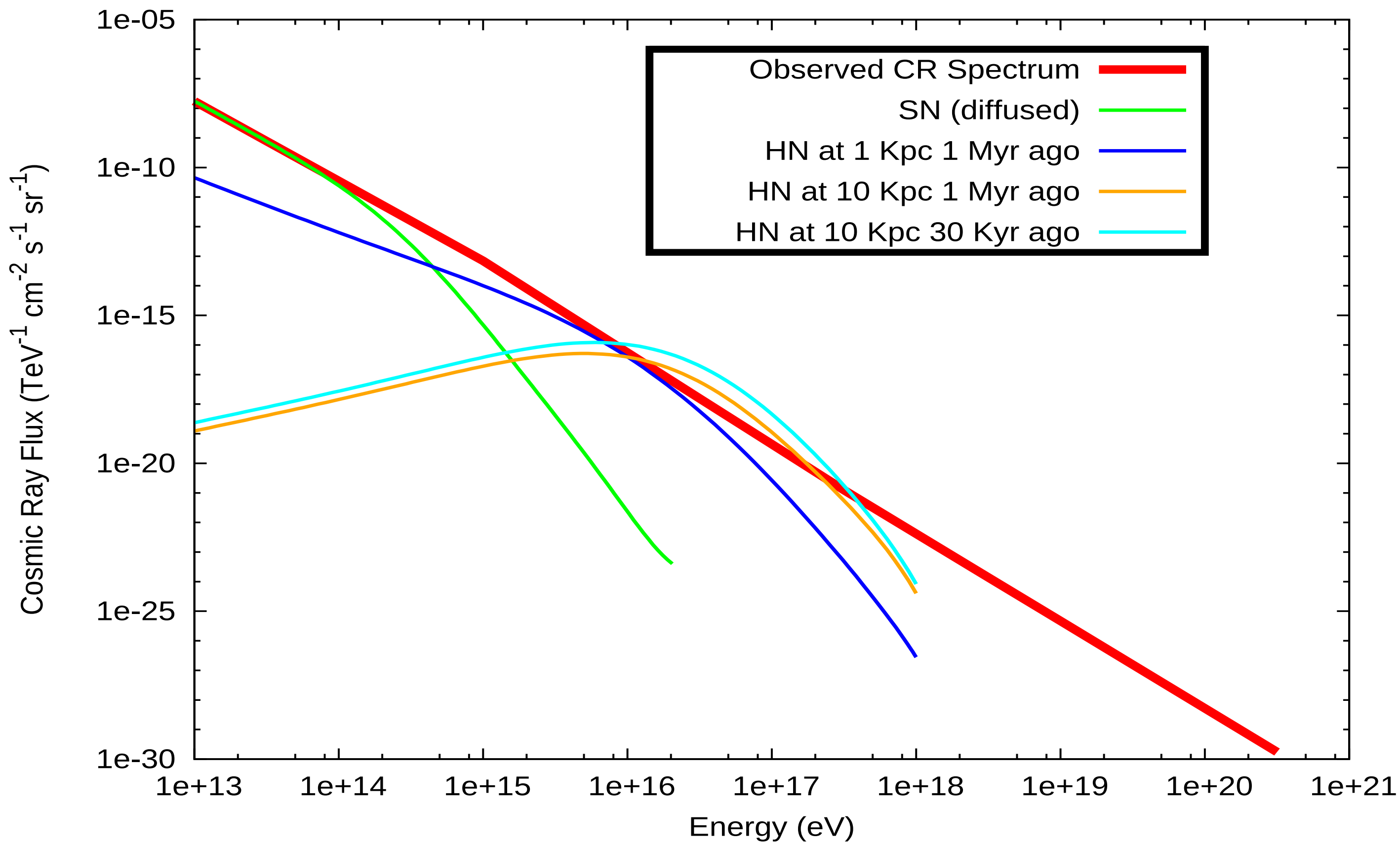
Galactic SNe

- $Q_X(E,r,z) = \xi(X) K_1 \left[\mathcal{R}_{\rm Ia}(r,z) + 7.3 \times \mathcal{R}_{\rm CC}(r,z)\right] \; E^{-\beta} \times \frac{e^{1-E/E_{max}}-1}{e-1}$
- $\beta = 2.3$
- $E_{max} = Z \times 10^{15}$ eV

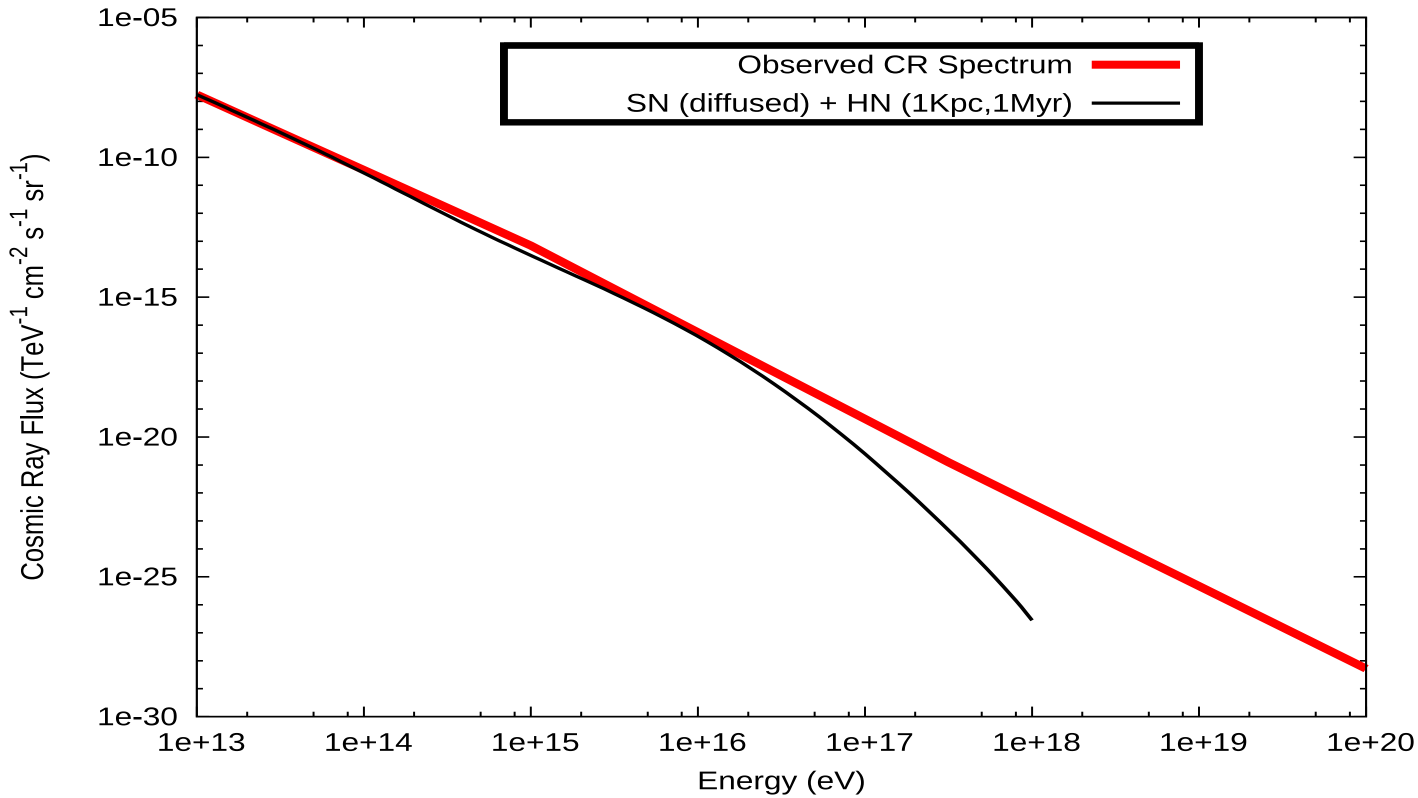
Galactic HNe

- $Q_X(E,r,z) = \xi(X) K_2 \left[7.3 \times \mathcal{R}_{\rm CC}(r,z)\right] \; E^{-\beta} \times \frac{e^{1-E/E_{max}}-1}{e-1} \delta^4(t-t_0)(r-r_0)(z-z_0)(\phi-\phi_0)$
- $\beta = 2.3$
- $E_{max} = Z \times 10^{17}$ eV

All-Particle spectra from Galactic SNe and various HNe



All-Particle spectra from Galactic SN distribution and single HN at 1 Kpc 1Myr ago



Summary and Discussion on Future Goals

- The aim of our work is to explain origin of CR spectrum in terms of stellar core-collapse events, both Galactic and extra-galactic.

- In order to explain the region of the CR spectrum between the *knee* and the *ankle* in terms of the Galactic HNe, we have studied constraints on the rates of these events, using diffuse neutrino background signal, as these neutrinos sample the entire Universe.

- As the Hypernova rate can be as low as 1 per 10^6 years, the time being comparable to the Galactic confinement time, we solve time dependent diffusion equation for various cases of "single HN burst" in order to get the HN contribution to CR spectrum.

- In future, we shall try to obtain the secondary neutrino and gamma ray spectra due to cosmic ray interaction in the Galaxy, considering the SN and HN contributions to the CR spectrum.

- If we are able to successfully bridge the gap in the CR spectrum considering the HNe contribution, this will present a unifying hypothesis that *all CRs have their origin in collapsing stars, Galactic or extragalactic...*

THANK YOU !

Origin of the Cosmic Ray spectrum

- Origin of the spectrum has to be extra-galactic beyond 10^{18} eV. Larmor radius of a high energy nucleus is given by,

$$r_L(E) \equiv \frac{E}{ZeB_{reg}} \simeq \left(\frac{E/Z}{10^{18}\text{eV}}\right)\left(\frac{B_{reg}}{1\mu\text{G}}\right)^{-1}\text{kpc}$$

  Hence, for a 10^{19} eV proton, $r_L \sim 10$ kpc, which is greater than height of the galaxy (~ 3 kpc).

- Fermi mechanism predicts a power law spectrum for shock accelerated particles with power index ~ 2. Observed CR spectrum has a power index ~ 2.7, indicating a possible power index ~ 2 at source, provided diffusion in Galaxy is considered.

Origin of the Cosmic Ray spectrum, contd.

- Galactic Supernovae could be the source of spectrum below 10^{18} eV because of the following arguement: (Baade & Zwicky, 1934)
  - A power supply of $\sim 1.5 \times 10^{41}$ erg/s required to sustain observed CR flux
  - Energy output in a typical Supernova $\sim (1-2) \times 10^{51}$ erg, a significant part of which goes into the KE of ejected material
  - Estimated average SN rate in Galaxy $\sim$ 1 per 100 years
  - Hence, power output from SNe in the Galaxy is $\sim (2 \times 10^{51} \mathrm{erg}/100 \mathrm{year}) \sim 6.6 \times 10^{41}$ erg/s !
  - Need to convert $\sim 20\%$ of KE of ejected material to KE of CR particles

Origin of the Cosmic Ray spectrum, contd.

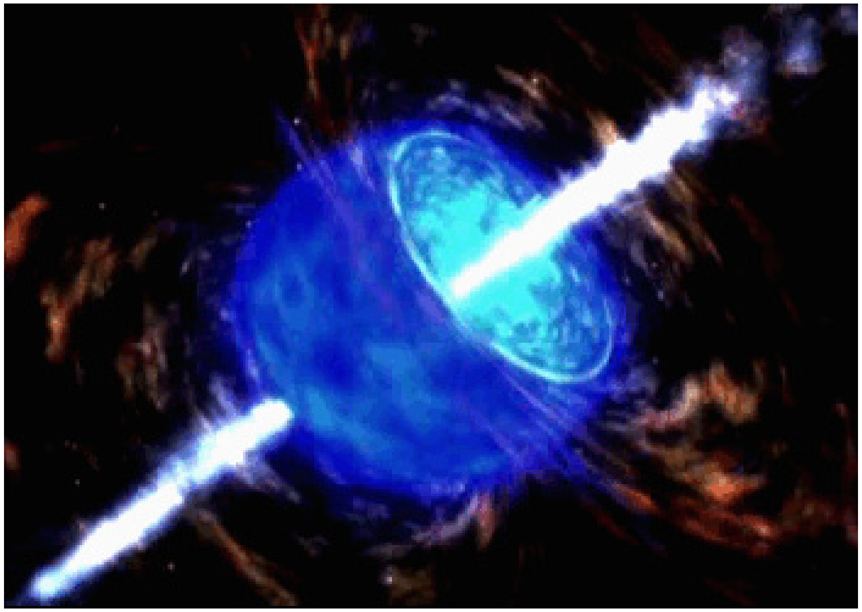
- But energetics of Supernovae suggest that acceleration of particles possible only upto 10^{15} eV, as, maximum energy to which particles can be accelerated in collisionless shocks is given by,

$$\epsilon_{max} \sim Ze\beta_s B r_s$$

- Sources of CRs between 10^{15} - 10^{18} eV: **??**

What are GRBs?

Gamma **R**ay **B**ursts are the most concentrated and brightest electro-magnetic explosions in the Universe. They are brief events occurring for periods of a few seconds to sometimes few minutes, at an average rate of a few per day throughout the Universe.



Some Properties of GRBs

1. Typical energy scale associated with GRB explosions is $\sim 10^{51-52}$ ergs.

2. The emission is in the form of ultra-relativistic jets (with $\Gamma \sim$ few 100's).

3. A GRB has two phases:

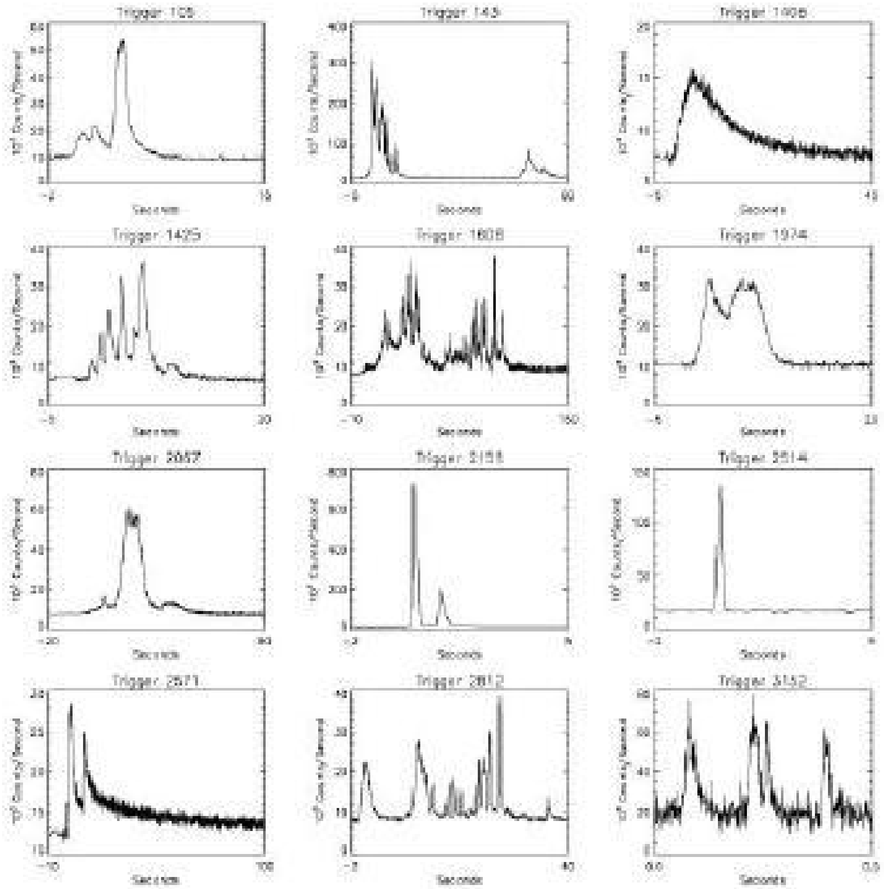
   - Prompt phase: A very brief ($\sim$ seconds or less) period of high energy gamma emission.

   - Afterglow phase: Radiation softens from X-ray to optical to radio. This phase could last for a month or more.

4. All sky survey done by BATSE on CGRO satellite showed that the burst were isotropically distributed, indicating their cosmological origin.

5. Redshift measurements of the host galaxies from afterglow studies have led to positional determination of GRBs, thus confirming that GRBs are indeed cosmological objects.

Some Examples of GRB Light Curves

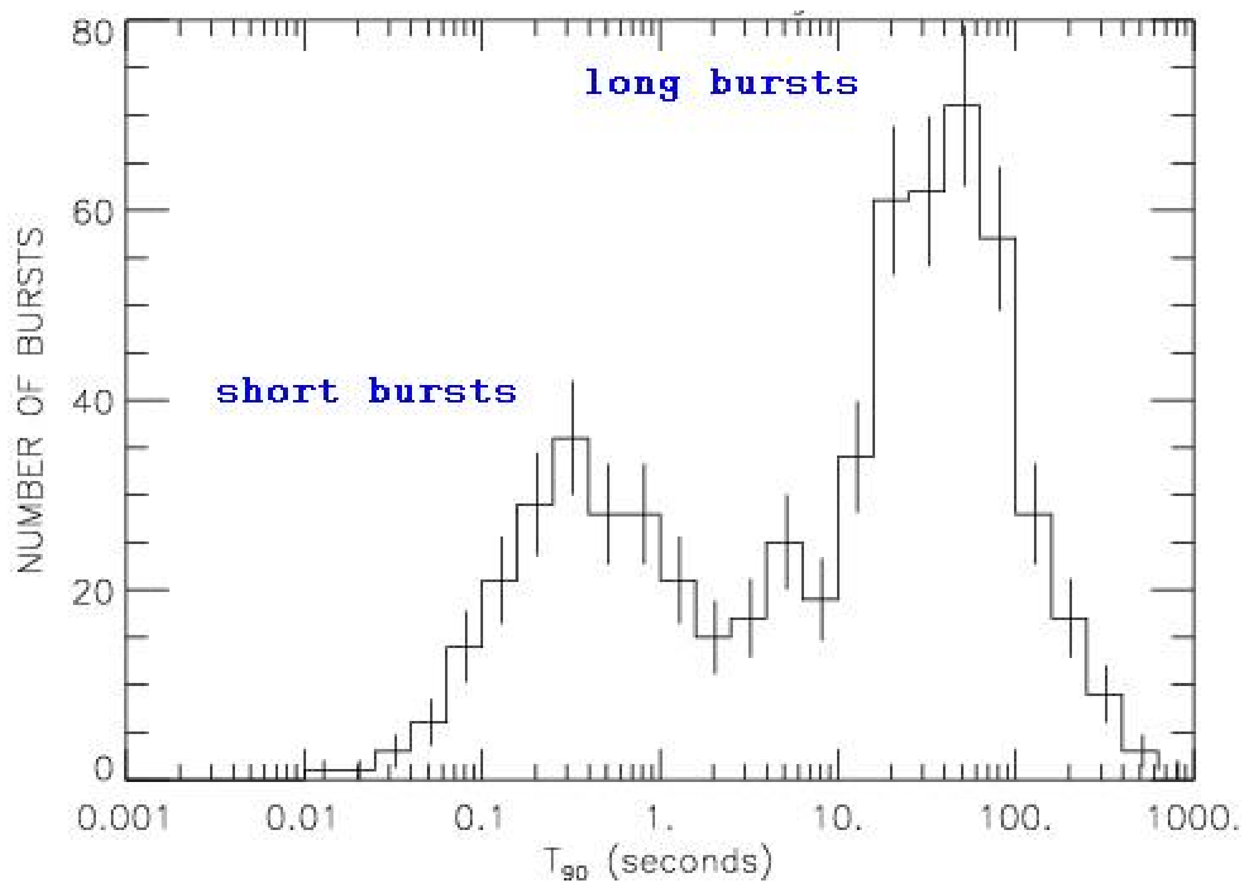


Diversity of gamma ray light curves, as observed by BATSE.

Variability time is of the order of milliseconds which implies that the GRB sources are compact, with a linear scale comparable to a light-ms.

(Mészáros,P. 2006, astro-ph/0605208v5)

Classification of GRBs: Bimodal distribution



(BATSE collaboration)

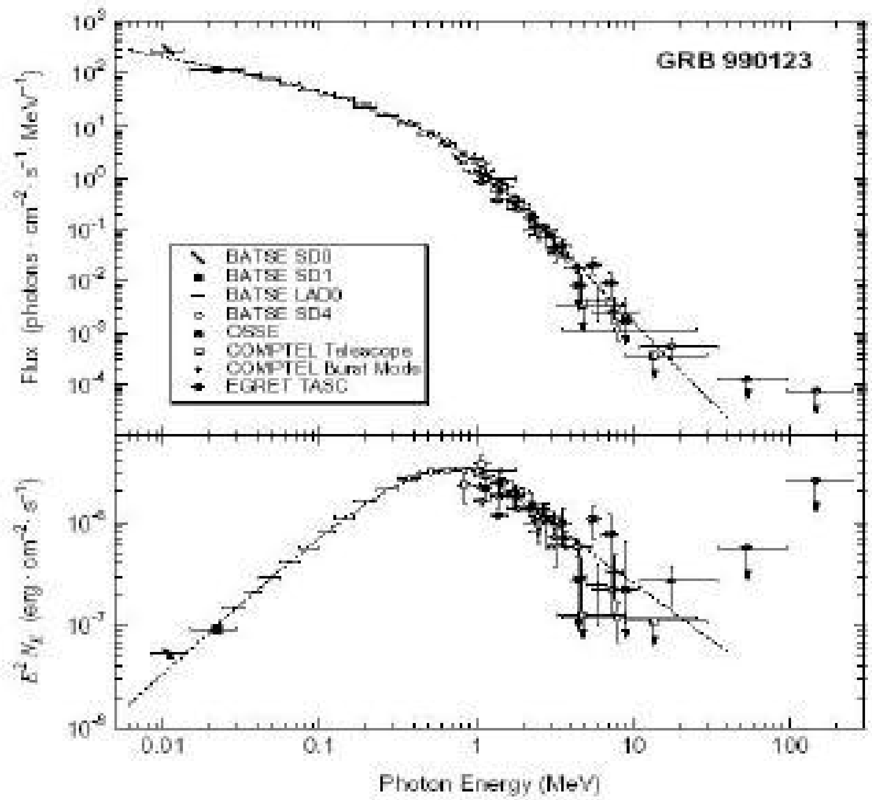
GRB spectrum

A typical GRB photon spectrum is of the form,

$$\frac{dN_\gamma}{d\epsilon_\gamma} = \text{const.} \times \epsilon_\gamma^{\alpha-1}$$

where,

$$\begin{aligned} \alpha &\approx 0 \quad \text{for} \quad \epsilon_\gamma \leq 1\text{MeV} \\ &\approx -1 \quad \text{for} \quad \epsilon_\gamma \geq 1\text{MeV} \end{aligned}$$



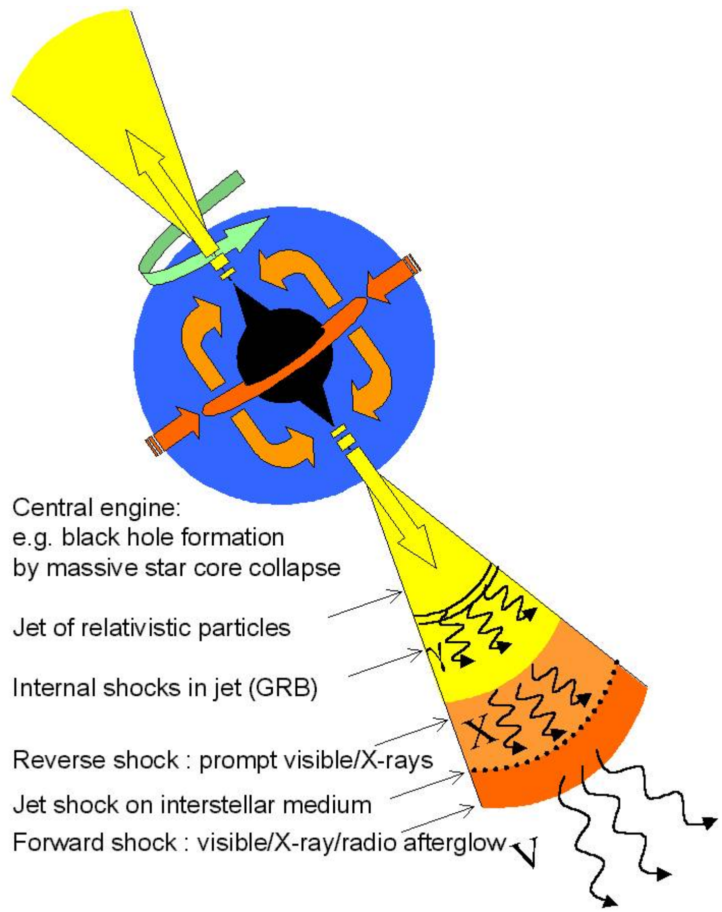
(Briggs, M. S. et al, 1999, astro-ph/9903247v1)

Modelling GRB Explosions

- Current interpretation of such tremendous energy release in GRBs is that a correspondingly large amount of gravitational energy is released in a very short span of few seconds, in a very small region ($\sim$10's of km) by a cataclysmic stellar event, possibly, the collapse of the core of a massive star $\Rightarrow$ "Collapsar" model for GRBs.

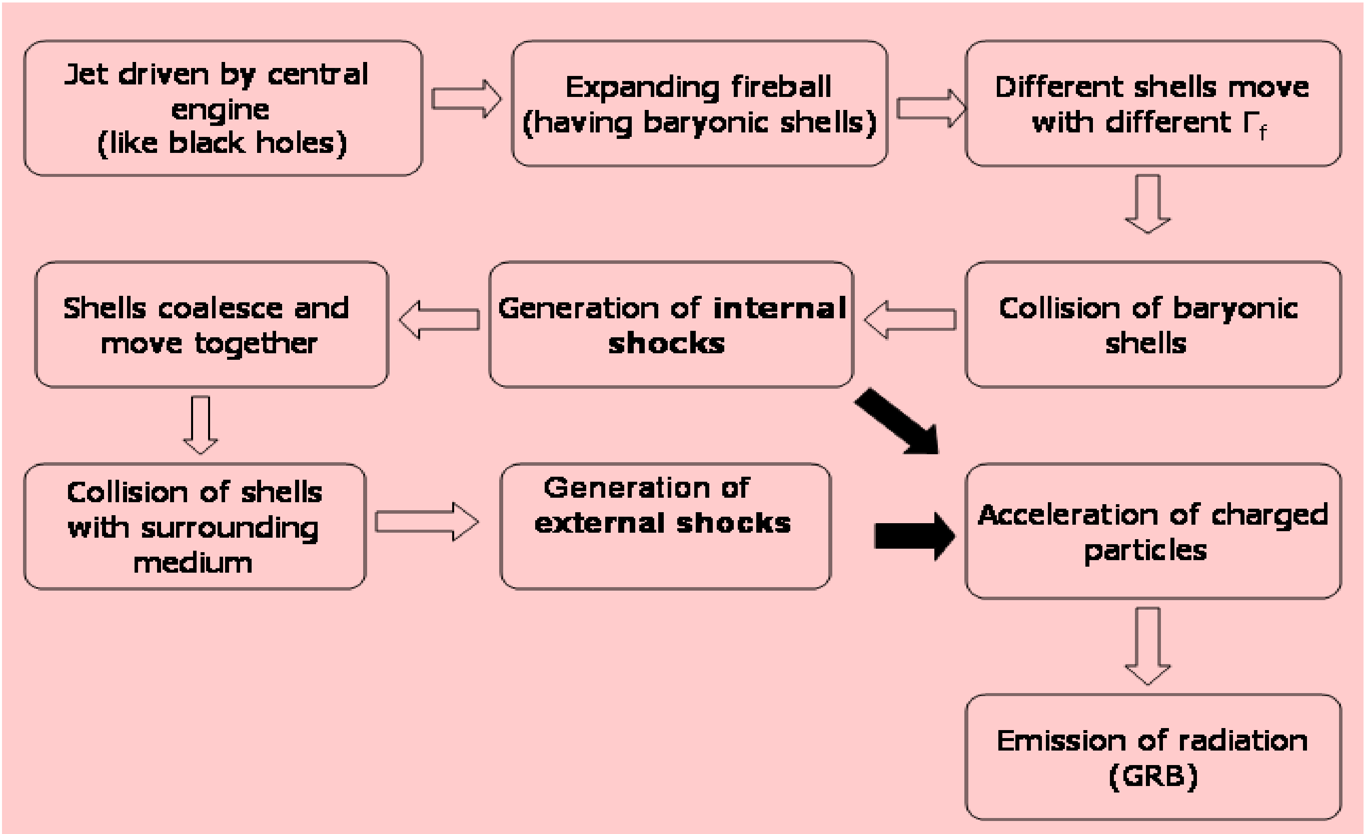
- The GRB collapsar model must be such that it allows, far away from the progenitor star, collimated jets with Lorentz factor, $\Gamma \sim$ few 100's.

- The necessary conditions to make a collapsar are black hole formation in the middle of a massive star (central engine) and sufficient angular momentum to make an accretion disk around the hole.



(Modelling GRB Explosions contd.)

- It is believed that further acceleration of charged particles in the ultra-relativistic jets takes place through diffusive shock acceleration mechanism incorporated in the **Fireball Model** as explained below.



Core-Collapse Supernovae

CCSNe are explosive deaths of massive stars that occur when their iron cores collapse to Neutron Stars or Black Holes.

- Total kinetic energy $\sim 10^{51}$ erg, roughly the same as the jet energy of a GRB.

- Last from weeks to months.

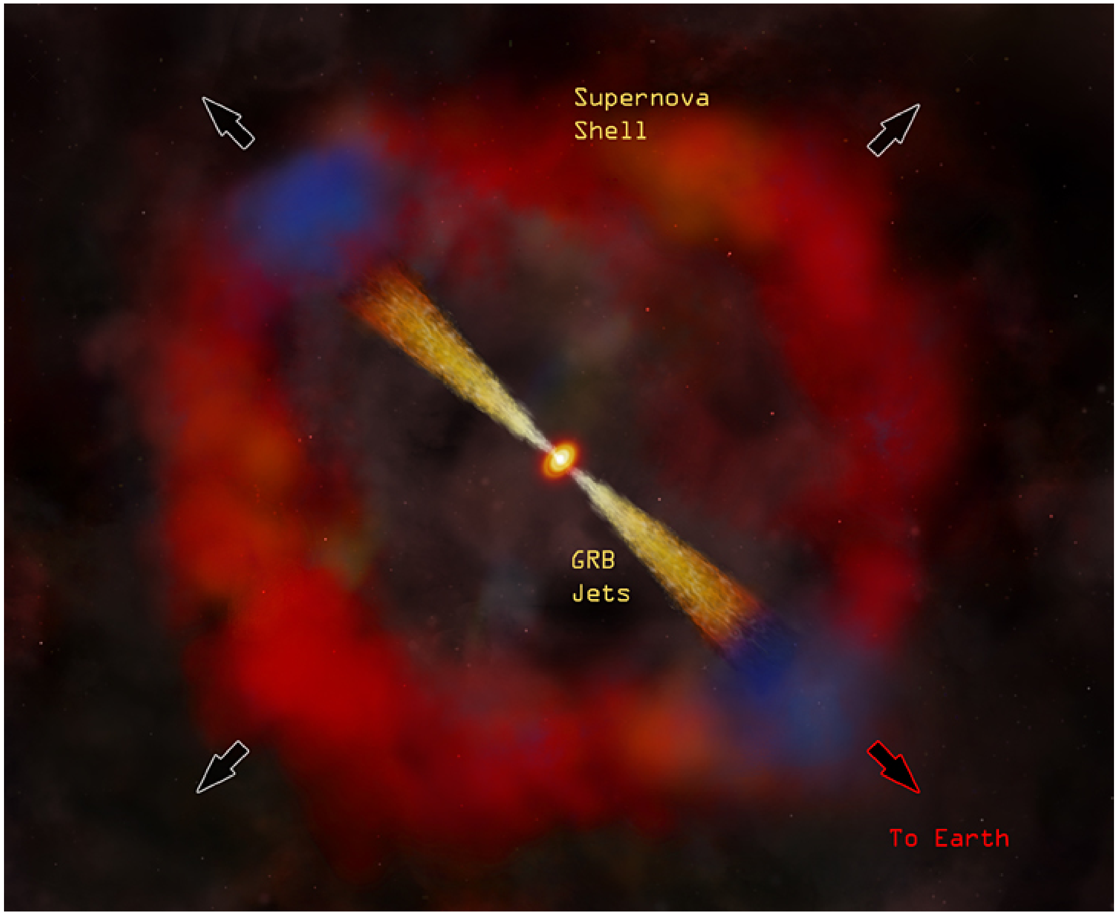
- In general, they are not accompanied by highly relativistic collimated mass ejection, hence visible from all directions.

- Roughly classified as,

  Type Ib/c: Hydrogen (and Helium in case of Ic) envelope is lost

  Type II: Hydrogen envelope present

Simultaneous SN-GRB Occurrence



Origin of High Energy (TeV-PeV) Neutrinos in GRB jet

- We assume, protons are accelerated at the internal shocks to very high energies (upto $\sim 10^{20} eV$)

- These UHE protons give rise to charged pions due to photopion interaction on the synchrotron photons in the jet. Each pion carries $\sim 20\%$ of the proton energy.

$$p + \gamma \longrightarrow \pi^+ + n$$

- A charged pion decays as

$$\pi^+ \longrightarrow \mu^+ + \nu_\mu \longrightarrow e^+ + \nu_e + \bar{\nu_\mu} + \nu_\mu$$

- Thus, a charged pion decays into 4 leptons, all carrying roughly equal energies. Therefore, each neutrino receives $\sim 5\%$ of initial proton energy.

Hence, UHE protons ($\leq 10^{20}$ eV) $\longrightarrow$ VHE neutrinos ($\leq 10^{18}$ eV)

The Core Collapse Supernova Rate, $R_{CCSN}(z)$

- We assume the "Concordance Model" of SFR (it is in concordance with recent accurate UV, optical and IR data, while at the same time in conformity with experimental upper limit on diffuse supernova neutrino background (DSNuB) flux given by the **Super-Kamiokande** experiment in Japan)

- As all stars more massive than $\sim 8M_{\odot}$ undergo core collapse and die on a timescale short compared to Hubble time, we assume

$$R_{CCSN}(z) \propto R_{SF}(z)$$

(The Core Collapse Supernova Rate, $R_{CCSN}(z)$, contd.)

- Using the appropriate IMF we obtain the proper normalization constant for the $R_{CCSN}(z)$

- Therefore,

$$R_{CCSN}(z) = (2.60\times10^{-4})\ \mathrm{yr}^{-1}\mathrm{Mpc}^{-3}\begin{cases} (1+z)^{3.44} & \text{for } z < 0.97 \\ 12.29(1+z)^{-0.26} & \text{for } 0.97 < z < 4.48 \\ 4.57\times10^{6}(1+z)^{-7.8} & \text{for } 4.48 < z \end{cases}$$

The GRB Rate, $R_{GRB}(z)$

- Stellar core collapse of GRBs, as indicated by CCSN-GRB association implies GRB rate should follow CCSN rate.

- However, recent analysis of large sample of GRBs with known redshift by the *Swift* mission, together with recent accurate determination of star formation history gives strong indication of an evolution of GRB rate w.r.t. SFR:

$$R_{GRB}(z) \propto (1+z)^{\alpha} \; R_{SF}(z)$$

- Therefore, we write,

$$\begin{aligned} R_{GRB}(z) &= f_{GRB/CCSN}(z) \; R_{CCSN}(z) \\ &= f_{GRB/CCSN}(0)(1+z)^{\alpha} \; R_{CCSN}(z) \end{aligned}$$

Certain inputs for our calculations:-

- Normalized photon spectrum in source rest frame,

$$\frac{dn_\gamma}{d\epsilon_\gamma} = 0.2\ U_\gamma\ {\epsilon_{\gamma b}}^{-1} \begin{cases} {\epsilon_\gamma}^{-1} & \text{for } \epsilon_\gamma \le \epsilon_{\gamma b} \\ {\epsilon_{\gamma b}}^{1.25} {\epsilon_\gamma}^{-2.25} & \text{for } \epsilon_\gamma > \epsilon_{\gamma b} \end{cases}$$

  where, U_γ is the total photon energy in source rest frame.

- Assumed differential spectrum for protons: $\frac{dn_p}{d\epsilon_p} \propto {\epsilon_p}^{-2}$

- Total energy in the system, ε_{total} is distributed in,

  $\varepsilon_p = \xi_p\ \varepsilon_{total},\ \varepsilon_e = \xi_e\ \varepsilon_{total},$ and $\varepsilon_B = \xi_B\ \varepsilon_{total}$

  with, $\xi_p + \xi_e + \xi_B = 1$

(Inputs for our calculations contd.)

- We assume electrons to be efficient radiators, ie,

  $\varepsilon_e \approx \varepsilon_\gamma = \xi_e \; \varepsilon_{total}$

- We assume $\xi_B \approx \xi_e$

- In general, one expects $\xi_p/\xi_e \geq 1, \;\; \xi_p = \xi_e \Rightarrow$ **equipartition case**

Neutrino Flux from Individual GRBs

Neutrino spectrum due to photopion interaction of protons with photons is given by,

$$\epsilon_\nu^2 \frac{dN_\nu(\epsilon_\nu)}{d\epsilon_\nu} = \frac{3}{8} \times 0.56 \times f_\pi(\epsilon_p) \left(\frac{\xi_p}{\xi_e}\right) \varepsilon_\gamma \begin{cases} 1 & \text{for } \epsilon_\nu < \epsilon_{\nu*} \\ \left(\frac{\epsilon_\nu}{\epsilon_{\nu*}}\right)^{-2} & \text{for } \epsilon_\nu > \epsilon_{\nu*} \end{cases}$$

where, $\epsilon_p = 20\ \epsilon_\nu$

Here, $f_\pi(\epsilon_p)$ has the form,

$$f_\pi(\epsilon_p) = f_0 \begin{cases} 0.88 \left(\frac{\epsilon_p}{\epsilon_{pb}}\right)^{1.25} & \text{for } \epsilon_p < \epsilon_{pb} \\ 1 & \text{for } \epsilon_p > \epsilon_{pb} \end{cases}$$

where,

$$f_0 = \frac{0.09 L_{\gamma,51}}{\Gamma_{300}^4\ t_{v,-3}\ \epsilon_{\gamma b,MeV}}$$

(Neutrino Flux from Individual GRBs contd.)

We notice the ν spectrum derived has two breaks:

- 1st break at $\epsilon_{\nu b} = 0.05\ \epsilon_{pb}$ is due to break in $f_\pi(\epsilon_p)$ at,

  $$\epsilon_{pb} = 1.3 \times 10^7\ \Gamma_{300}^2 \left(\epsilon_{\gamma b,MeV}\right)^{-1}\ \mathrm{GeV},$$

  which, in turn is due to the break in the photon spectrum at $\epsilon_{\gamma b}$

- 2nd break is at $\epsilon_{\nu *}$ given by,

  $$\epsilon_{\nu *}\ =\ 2.56 \times 10^6\ \xi_e{}^{1/2}\ \xi_B{}^{-1/2}\ L_{\gamma,51}^{-1/2}\ \Gamma_{300}^4\ t_{v,-3}\ \mathrm{GeV},$$

  which is due to muon cooling.