COSMO 2008 Workshop

Neutrino fluxes from astrophysical sources: the role of the charmed meson production and decay

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Rikard Enberg, Mary Hall Reno and Ina Sarcevic, arXiv:0808.2807

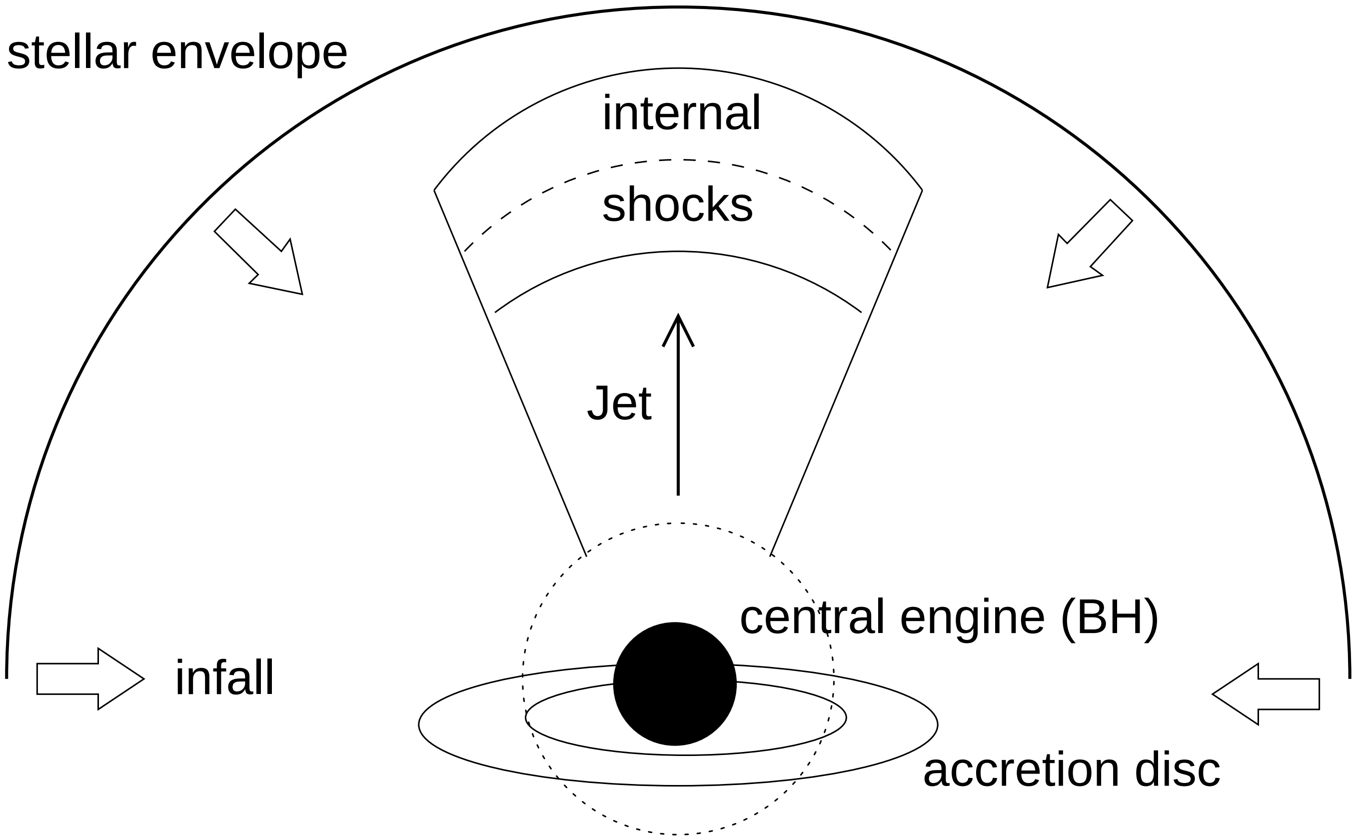
Cosmic Neutrinos

- ⋆ **Cosmic Neutrino Background** ($T \sim 1.9K$, **i.e.** $E_\nu \sim 10^{-4} eV$)
- ⋆ **Solar Neutrinos (MeV energies)**
- ⋆ **SN 1987A (MeV energies)**
- ⋆ **Atmospheric Neutrinos (GeV to TeV energies)**
- ⋆ **Extragalactic Neutrinos (Cosmogenic, AGN, GRB, Slow-jet Core Collapse SNe, etc; GeV to EeV energies)**

UHE Astrophysical Neutrinos: probes of Astrophysics and Particle Physics

- Escape from Extreme Environments
- Point Back to Sources
- Probe Particle Production Mechanism in Astrophysical Sources
- Energy Much Higher than Available in Colliders

Cosmic Accelerators



Schematic picture of a relativistic jet buried inside the envelope of a collapsing star.

Razzaque, Meszaros and Waxman, PRL 93 (2004)

- **Electrons and protons are accelerated to high energies in the internal shocks, via the Fermi mechanism. Electrons cool down rapidly by synchrotron radiation in the presence of the magnetic field. In an optically thin environment, these relativistic electrons emit synchrotron photons which are observed as γ-rays on Earth.**
- **In an optically thick environment, protons interact with embient protons and photons. Density of electrons and protons in the jet**

$$n'_e \simeq n'_p \simeq \frac{L_{\mathrm{kin}}}{4\pi r_j^2 \Gamma_b^2 m_p c^3} \simeq \frac{E_j}{2\pi r_j^2 m_p c^3 t_j}$$

For a slow jet SN model:

$$n'_e \simeq n'_p \simeq 3.6 \times \approx 10^{20} cm^{-3}$$

while for GRB:

$$n'_e \simeq n'_p \simeq 3 \times 10^{16} cm^{-3},$$

in the comoving jet frame. Here r_j is the radius where shock occurs in the jet, L_j is the total jet power, Γ_b is the Lorentz factor and t_j is the variability time scale.

- **Depending on the optical depth, in some astrophysical sources photons may be thermalized**
- **In the astrophysical enviroments when photons are not thermalized, their energy distribution is a power law, characterized by some break energy E_γ^b**

Source	Γ_j	n'_p **[cm^{-3}]**	B' **[G]**	E'_γ **[keV]**	n'_γ **[cm^{-3}]**
SJS	**3**	3.6×10^{20}	1.2×10^9	4.5	2.8×10^{24}
GRB	**100**	3×10^{16}	1.1×10^7	2.5	1.1×10^{21}

Table 1: The jet bulk Lorentz factor Γ_j, and the comoving number densities of protons n'_p and photons n'_γ, average photon energy E'_γ (or break energy for GRB), and magnetic field in the jet B' ($B' = [4\epsilon_B L_j/(\theta_j^2 r_j^2 \Gamma_j^2 c)]^{1/2}$) for the slow-jet core collapse supernova (SJS) and gamma ray burst (GRB) models. Comoving energy density of photons in the jet is $U'_\gamma = \epsilon_e L_j/(2\pi\theta_j^2 r_j^2 \Gamma_j^2 c)$ and $\epsilon_{b,e}$ is the fraction of kinetic jet energy converted into magnetic field or radiated into photons.

Proton Acceleration and Cooling Processes

- **The shock acceleration time for a proton of energy E'_p is proportional to its Larmor's radius and may be estimated as**

$$t'_{\rm acc} \simeq \frac{AE'_p}{qcB'} \approx 10^{-12}\left(\frac{E'_p}{\rm GeV}\right)\ {\rm s},$$

- **The maximum proton energy is limited by requiring this time not to exceed the dynamic time scale for the shock to cross plasma material, or any other possible proton cooling process time scale (electromagnetic cooling, synchrotron and inverse Compton, Bethe-Heitler).**

- **Because of a high density of thermal photons in the jet, protons may produce e^+e^- pairs by interacting with them, a process known as Bethe-Heitler (BH), i.e. $p\gamma \to pe^+e^-$. The energy loss rate of the proton is proportional to the BH scattering rate.**

Proton Hadronic Cooling Channels

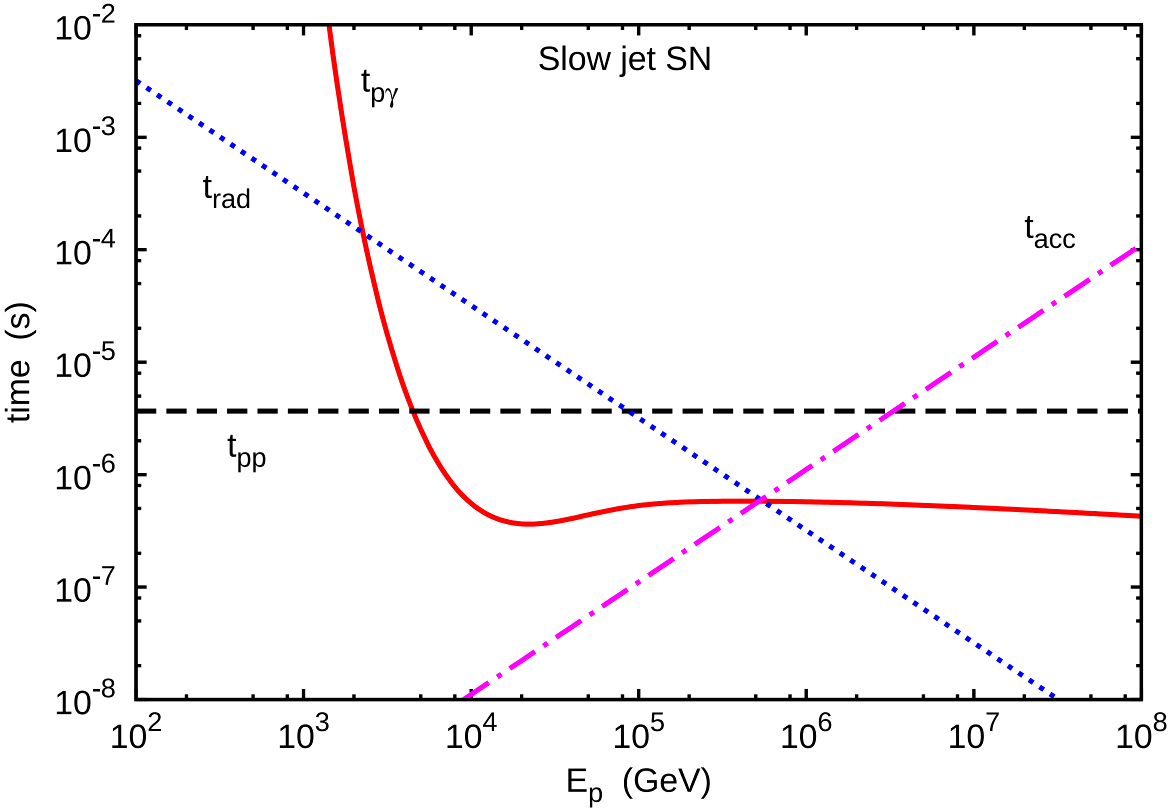
- **Photomeson ($p\gamma$) and proton-proton (pp) interactions which are responsible for producing high energy neutrinos may also serve as a cooling mechanism for the shock accelerated protons. The average pp cross-sections are $\sigma_{p\gamma} = 5 \times 10^{-28}$ cm^2 and $\sigma_{pp} \approx 5 \times 10^{-26}$ cm^2 respectively. The corresponding optical depths, given by**

$$\begin{aligned} \tau'_{p\gamma} &= \frac{\sigma_{p\gamma} n'_\gamma r_j}{\Gamma_b} \\ \tau'_{pp} &= \frac{\sigma_{p\gamma} n'_p r_j}{\Gamma_b} \end{aligned}$$

and the hadronic cooling time scales are

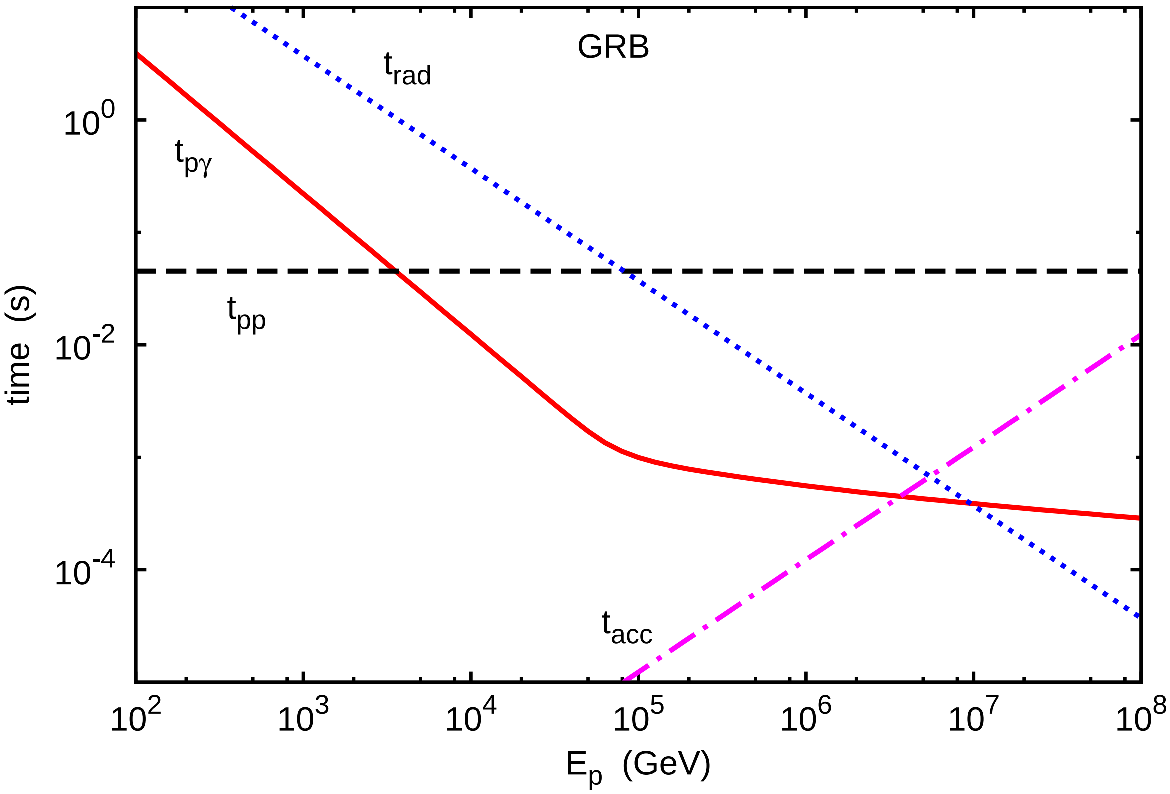
$$\begin{aligned} t'_{p\gamma} &= \frac{E'_p}{c\sigma_{p\gamma} n'_\gamma \Delta E'_p} \approx 10^{-7.3} \text{ s} \\ t'_{pp} &= \frac{E'_p}{c\sigma_{pp} n'_p \Delta E'_p} \approx 10^{-5.6} \text{ s}, \end{aligned}$$

- **Proton cooling times for hadronic and electromagnetic processes: photomeson ($t_{p\gamma}$), proton-proton (t_{pp}), Inverse Compton scattering ($t_{IC} = 3m_p^4c^3/(4\sigma_T m_e^2 E'_p U'_\gamma)$), and synchrotron radiation due to the magnetic field in the jet ($t_{syn} = 6\pi m_p^4 c^4/(\sigma_T c m_e^2 E'_p B'^2)$). Radiate cooling time is $(t_{\mathrm{rad}})^{-1} = (t_{\mathrm{IC}})^{-1} + (t_{\mathrm{syn}})^{-1}$.**



Enberg, Reno and Sarcevic, arXiv:0808.2807

- **Proton cooling times for hadronic and electromagnetic processes: photomeson ($t'_{p\gamma}$), proton-proton (t'_{pp}), and radiative cooling due to synchrotron and IC scattering (t'_{rad}).**



- **The maximum proton energy can be roughly estimated, by equating the t'_{syn} to $t'_{\mathrm{p}\gamma}$, since $t'_{\mathrm{rad}} \approx t'_{\mathrm{p}\gamma}$ at this energy.**

Neutrino Production and Flux on Earth

- **Shock accelerated protons in the jet can produce non-thermal neutrinos by photomeson ($p\gamma$) interactions with thermal synchrotron photons and/or by proton-proton (pp) interactions with cold protons present in the shock region. The $p\gamma$ process is dominant in the energy range $E'_p \approx 10^4$ GeV and the pp process is dominant at higher energies.**

- **In the case of $p\gamma$ interactions neutrinos are produced from charged pion (π^+) decay as $p\gamma \to \Delta^+ \to n\pi^+ \to \mu^+\nu_\mu \to e^+\nu_e\bar{\nu}_\mu\nu_\mu$. The pp interactions also produce charged pions ($\pi^\pm$), kaons ($K^\pm$), D-mesons (D). The energy of the shock accelerated protons in the jet is expected to be distributed as $\propto 1/E_p^{'2}$, following the standard shock acceleration models. If there is no cooling, charged mesons produced by pp and $p\gamma$ interactions are expected to follow the proton spectrum.**

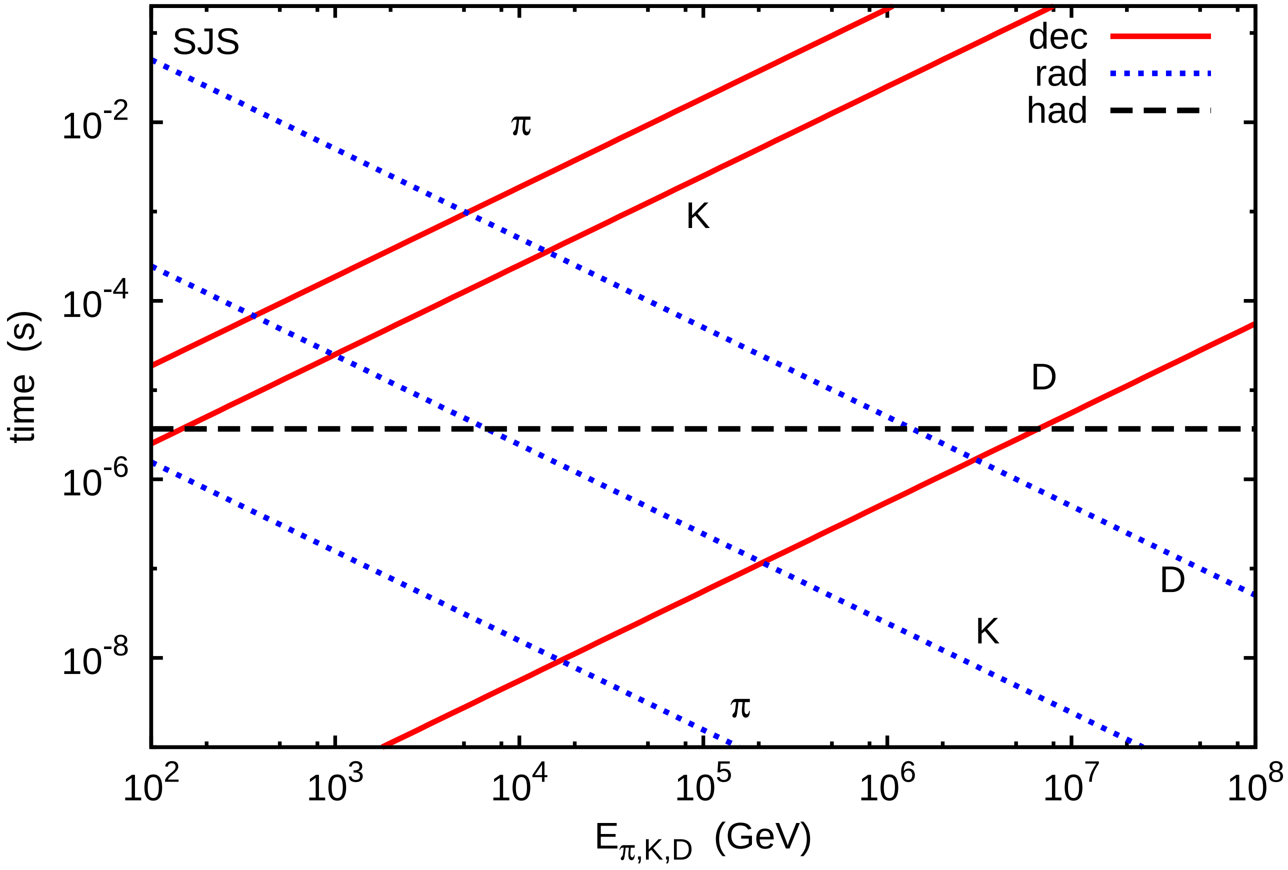
Meson Cooling Chanells

- **High-energy pions, kaons, D-mesons and muons produced by $p\gamma$ and pp interactions do not all decay to neutrinos as electromagnetic (synchrotron radiation and IC scattering) and hadronic (πp and Kp interactions) cooling mechanisms reduce their energy. Muons are severely suppressed by electromagnetic energy losses and do not contribute much to high-energy neutrino production. Suppression factors for pion and kaon decay neutrinos are important.**

- **The synchrotron and IC cooling times may be combined into a single electromagnetic cooling rate as $t_{\rm rad}^{\prime -1} = t_{\rm syn}^{\prime -1} + t_{\rm IC}^{\prime -1}$. For IC cooling in the Thomson regime $t'_{\rm IC} \approx t'_{\rm syn}$ and in the KN regime $t'_{\rm IC} \gg t'_{\rm syn}$.**

- **The hadronic energy losses for mesons are similar to the proton energy losses by pp interactions.**

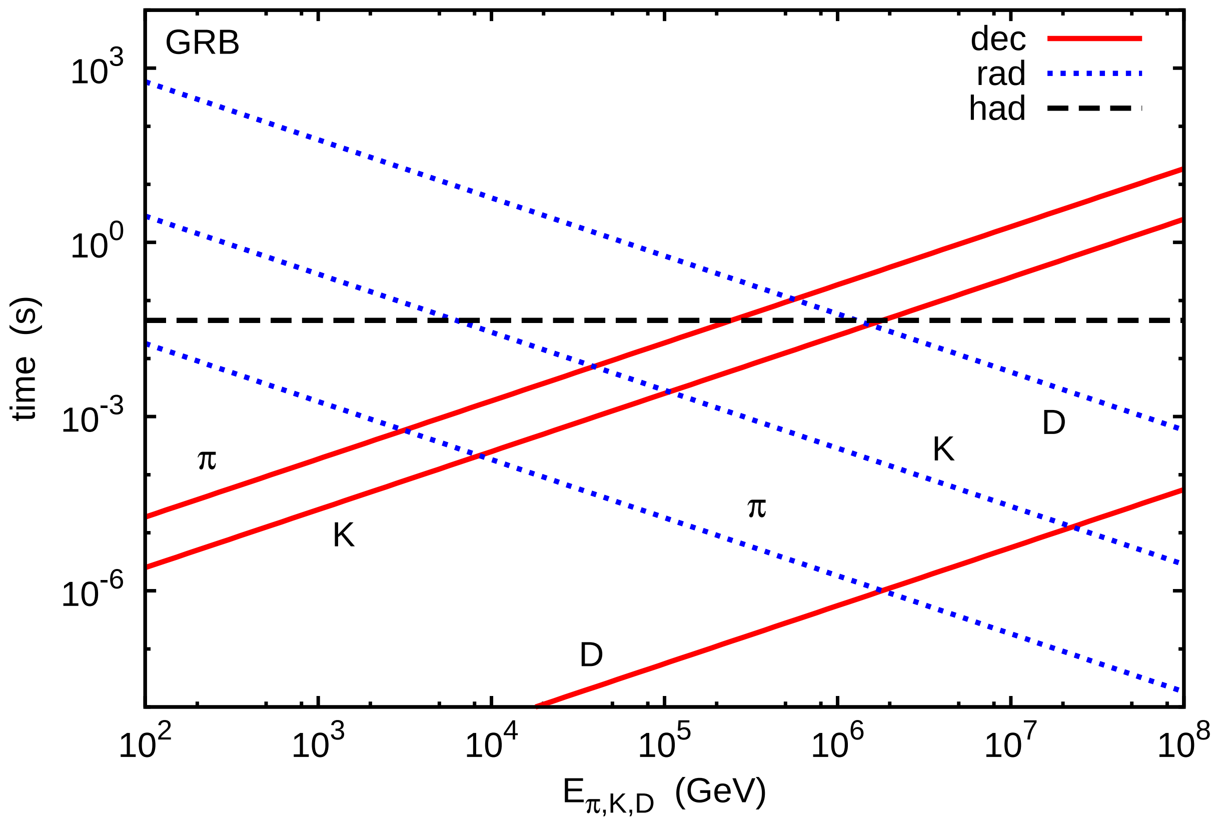
Meson cooling times for the slow-jet core collapse supernovae



Hadronic (t_{had}) and electromagnetic (t_{rad}) cooling times and meson decay times (t_{dec}), as a functions of energy in the comoving frame.

Enberg, Reno and Sarcevic, arXiv:0808.2807

Meson cooling times for the gamma ray burst (GRB)



Hadronic (t_{had}) and electromagnetic (t_{rad}) cooling times and meson decay times (t_{dec}), as a functions of energy in the comoving frame.

Enberg, Reno and Sarcevic, arXiv:0808.2807

Neutrino Fluxes at Earth

Enberg, Reno and Sarcevic, arXiv:0808.2807

- Astrophysical neutrino flux is obtained by solving the evolution equations for nucleon, meson, and neutrino fluxes, which are given by

$$\frac{d\phi_N}{dX} = -\frac{\phi_N}{\lambda_N} + S^{\rm had}(Np \to NY) - \frac{\phi_N}{\lambda_{\rm rad}} + S^{\rm EM}(Np \to NY)$$

$$\frac{d\phi_M}{dX} = -\frac{\phi_M}{\lambda^{\bf dec}} - \frac{\phi_M}{\lambda^{\bf had}} - \frac{\phi_M}{\lambda^{\bf rad}} + S^{\rm had}(Np \to MY) + S^{\rm had}(Mp \to M$$

$$\frac{d\phi_\ell}{dX} = \sum\nolimits_M S(M \to \nu)$$

where $\lambda^{\rm had}_{N,M}$ is the interaction length ($\lambda_N = 1/n_p\sigma_{pp}$), $\lambda^{\bf dec} = \gamma c\tau_M$ is the decay length in the comoving frame and $\lambda^{\bf rad} = ct_{\bf rad}$ is the radiative interaction length.

$S(k \to j)$ is the regeneration function for $k = p, \pi^{\pm}, K^{\pm}, D^{\pm}, D^0$,

$$S(k \to j) = \int_E^{\infty} \frac{\phi_k(E_k)}{\lambda_k(E_k)} \frac{dn(k \to j; E_k, E_j)}{dE_j} dE_k$$

$\frac{dn(k \to j; E_k, E_j)}{dE_j}$ is the meson $(\pi^{\pm}, K^{\pm}, D^{\pm}, D^0)$ production or decay distribution:

$$\frac{dn(k \to j; E_k, E_j)}{dE_j} = \frac{1}{\sigma_{kA}(E_k)} \frac{d\sigma(kp \to jY, E_k, E_j)}{dE_j}$$

and

$$\frac{dn(k \to j; E_k, E_j)}{dE_k} = \frac{1}{\Gamma_k} \frac{d\Gamma(k \to jY, E_j)}{dE_j}.$$

We define the Z-moments:

$$Z_{kj} = \int_E^\infty dE' \frac{\phi_k(E', X)}{\phi_k(E, X)} \frac{\lambda_k^{\mathbf{had}}(E)}{\lambda_k^{\mathbf{had}}(E')} \frac{dn(kp \to jY; E', E)}{dE}.$$

- **For proton flux (ϕ_N) the propagation over distance X in the co-moving jet frame is given by**

$$\left.\frac{d\phi_N}{dX}\right|_{\mathrm{cool}} = -\frac{\phi_N}{\lambda_N^{\mathrm{had}}} + Z_{NN}^{\mathrm{had}} \frac{\phi_N}{\lambda_N^{\mathrm{had}}} - \frac{\phi_N}{\lambda_N^{\mathrm{EM}}} + Z_{NN}^{\mathrm{EM}} \frac{\phi_N}{\lambda_N^{\mathrm{EM}}}$$

- **The Z-moment is defined by**

$$Z_{NM} = \int_0^1 dx_E x_E^{\alpha-1} \frac{dn_{N\to M}}{dx_E}$$

where $\phi_N \sim (E)^{-\alpha}$, $x_E \equiv E_M/E_N$ and dn/dx_E is the energy distribution of the meson M produced by N (or from N decay).

- **Meson flux is determined by solving the evolution equation:**

$$\frac{d\phi_M}{dX} = -\frac{\phi_M}{\lambda^{\mathbf{dec}}} - \frac{\phi_M}{\lambda^{\mathbf{had}}} - \frac{\phi_M}{\lambda^{\mathbf{rad}}} + Z_{MM} \frac{\phi_M}{\lambda^{\mathbf{had}}} + Z_{NM} \frac{\phi_N}{\lambda_N}$$

- **To evaluate hadronic interaction lengths, we use energy dependent cross hadronic cross sections, σ_{pp} and $\sigma_{p\gamma}$.**
- **For example, $\lambda_N^{\rm had}(pp) = (\sigma_{pp} n'_p)^{-1} \simeq 5.5 \times 10^4$ cm for the SJS model, and $\lambda_N^{\rm had} \simeq 6.8 \times 10^8$ cm for the GRB (with $\sigma_{pp} \simeq 5 \times 10^{-26}$ cm^2).**
- **The scattering length for inverse Compton scattering is $L_N^{IC} = 3m_p^4 c^4/(4\sigma_T m_e^2 E'_p U'_\gamma)$. This effective scattering length is rescaled by $(m_M/m_p)^4$ for mesons.**
- **The threshold energy for Δ^+ production in $p\gamma$ interactions, for $E'_\gamma = 5$ keV, is $E'_{p,\mathbf{th}} = 2 \times 10^5$ GeV. For $p\gamma$ scattering, the averaged reaction rate is given by,**

$$\langle n'\sigma v\rangle = \frac{c}{8\beta'_p E'^2_p} \int dE'_\gamma \frac{\hat{n}_\gamma(E'_\gamma)}{E'^2_\gamma} \int ds (s - m_p^2) \sigma_{p\gamma}(s),$$

where $\hat{n}_\gamma(E'_\gamma)$ is the photon number density, $\sigma_{p\gamma}$ has the resonance plus continuum multiparticle production contributions. Photon distribution $\hat{n}_\gamma$ is thermal for the SJS and a power law for the GRB.

- **We calculate the Z-moments for charm production taking into account the effects of parton saturation at high energies.**

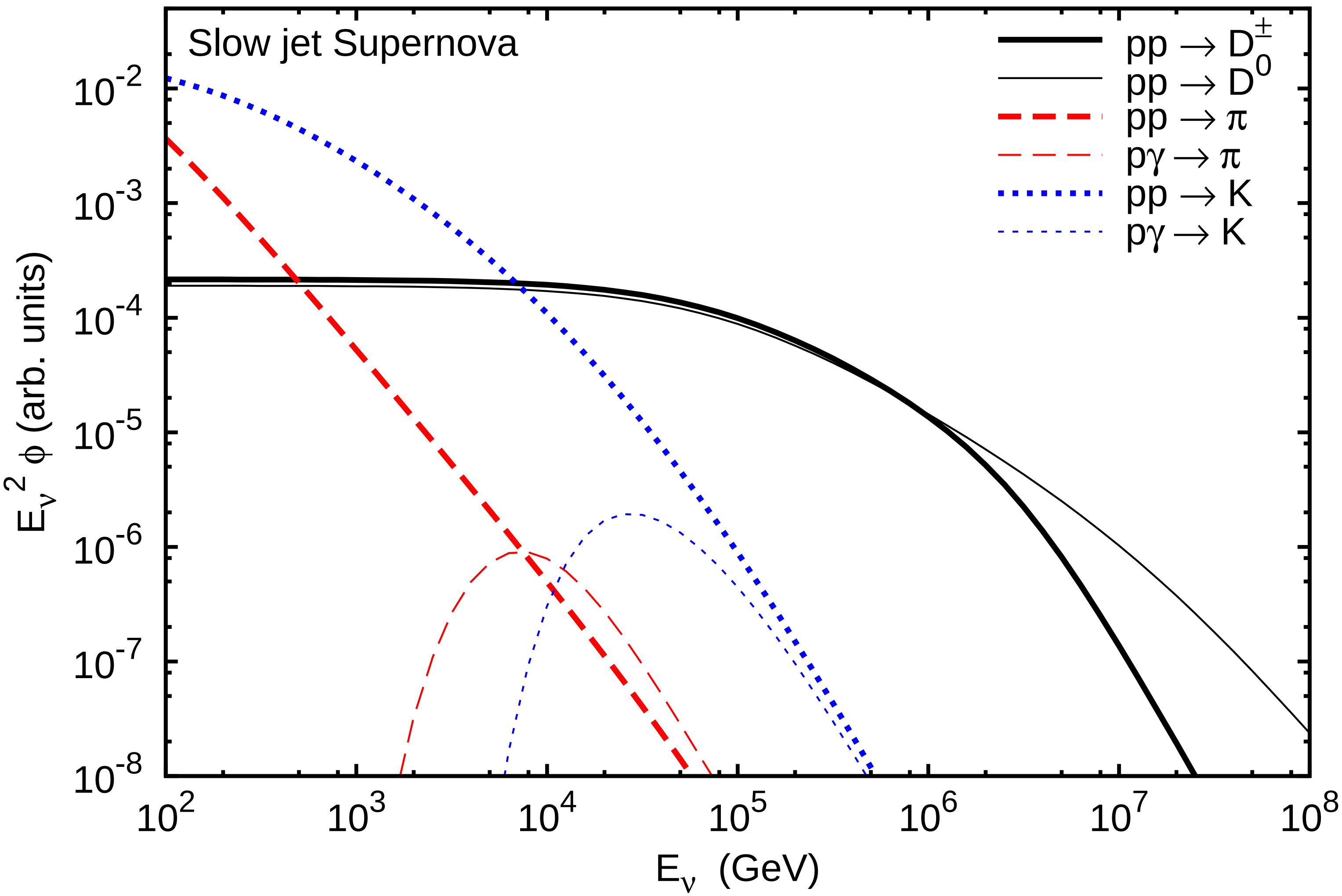
Enberg, Reno and Sarcevic, Phys. Rev. D78, 043005 (2008)

- **To compute the Z-moments for pp we use the parametrization of the rapidity distribution, $dN_\pi/dx_E = 0.12(1-x_E)^{2.6}x_E^{-2}$ where $x_E = E_\pi/E_p$, and for $p\gamma$ we fit this form to the data for π^0 production. For $K^\pm$ we take the $\pi^\pm$ result rescaled by 0.1.**

Z-moments and decay lengths

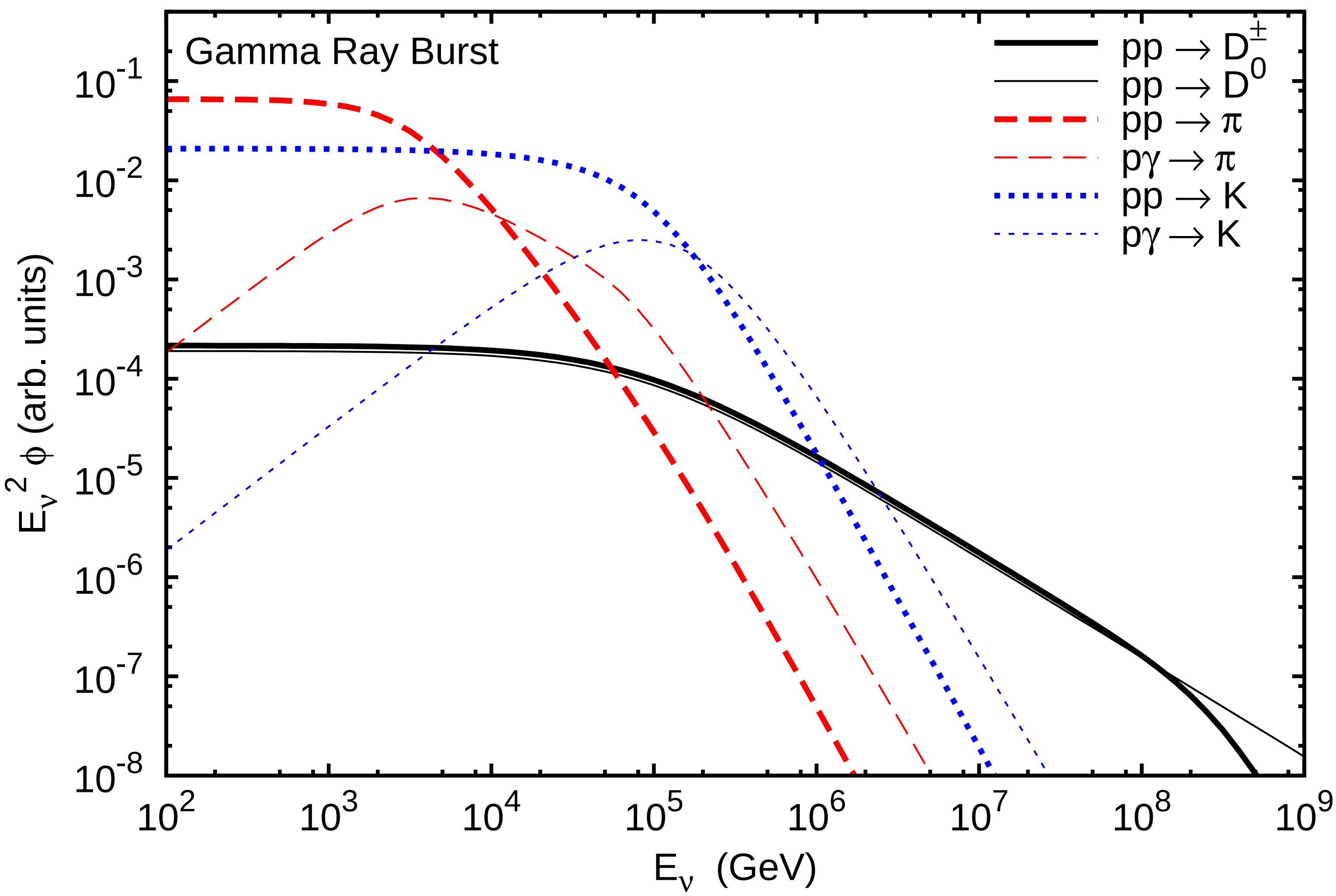
M	$Z_{M\nu}$	Z_{NM}	Z^γ_{NM}	$c\tau$ [cm]
$\pi^\pm$	**0.061**	**0.55**	**0.13**	**780**
$K^\pm$	**0.19**	**0.055**	**0.0065**	**370**
$D^\pm$	**0.045**	2.4×10^{-3}	–	3.2×10^{-2}
D^0	**0.017**	5.6×10^{-3}	–	1.2×10^{-2}

Neutrino Flux from Slow-jet Core Collapse Supernovae



Enberg, Reno and Sarcevic, arXiv:0808.2807

Neutrino Flux from GRBs



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SUMMARY

- **Astrophysical sources, such as core collapse supernovae triggered by mildly relativistic jets, Gamma Ray Bursts (GRBs), Active Galactic Nuclei (AGN), etc. are potential astrophysical sources of high energy neutrinos**

- **In these astrophysical sources protons are excelerated to high energies via Fermi shock acceleration. Proton energy spectrum due to shock acceleration, $\Phi \sim E^{-2}$, becomes steeper at higher energies where cooling processes, such as synchrotron radiation and scatterings with surrounding protons and photons become important.**

- **High energy protons interact with surrounding protons and photons producing charged pions, kaons and charmed mesons. These mesons interact or decay, depending on their cooling times due to hadronic and electromagnetic interactions, relative to their decay time.**

- At low energies, neutrinos primarely come from pions decay. For intermediate energies, kaons start playing a role. At very high energies, D-mesons give dominant contribution.

- In contrast to pions and kaons, charmed mesons give equal amounts of $\nu_e + \bar{\nu}_e$ and $\nu_\mu + \bar{\nu}_\mu$ at the source since the neutrino are coming from semileptonic deays. This gives flavor ratios of neutrinos that deviate from the "standard" $1:2:0$ ratio (from pion decay) in neutrino telescopes at very high energies.

- Since many properties of astrophysical sources are not well understood, neutrino measurements may hold the key to understanding the environments in which they were produced. Charm production in astrophysical jets provides important enchancement of the neutrino flux at very high energies.