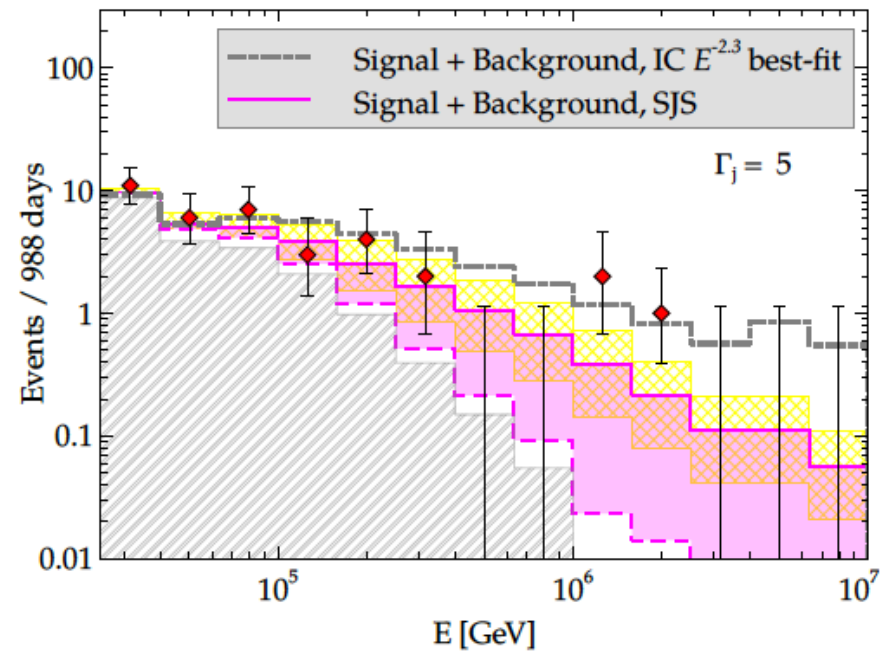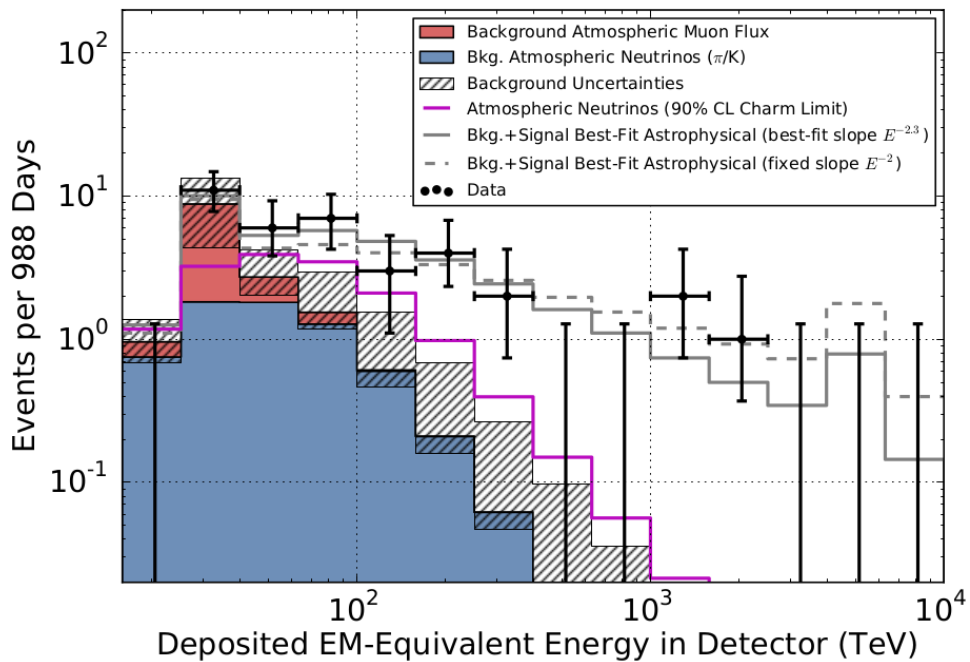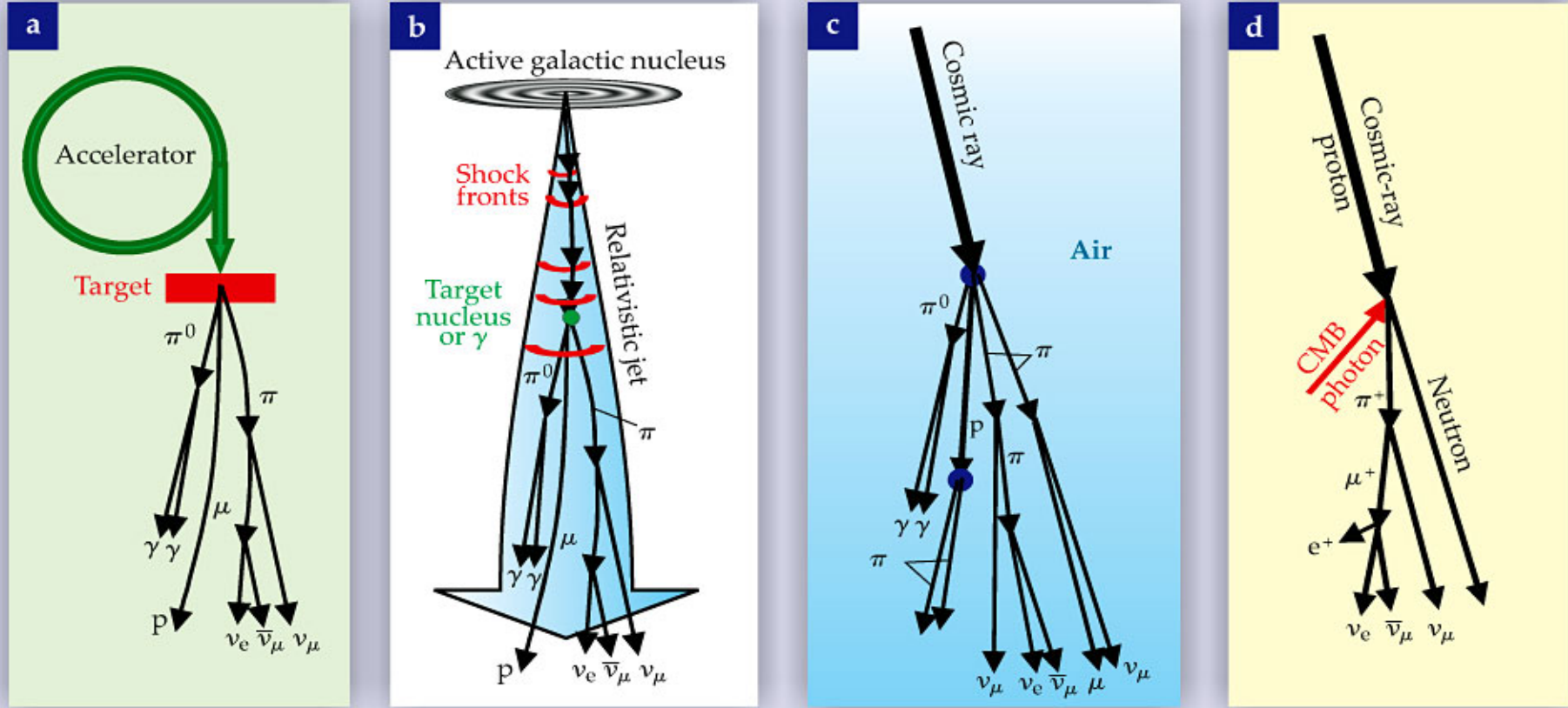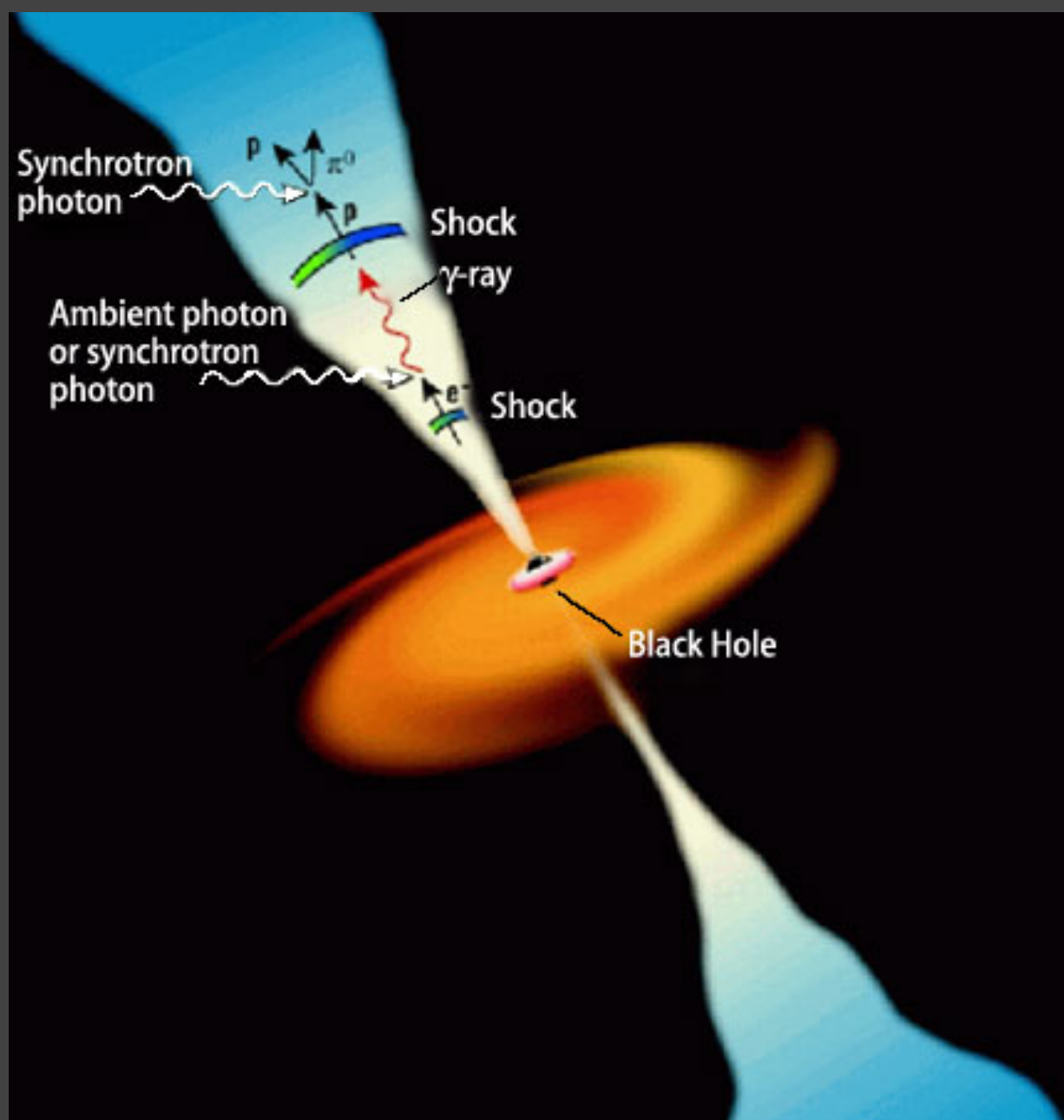# Charm Decay in Slow-Jet Supernovae as the Origin of the IceCube Ultra-High Energy Neutrino Events
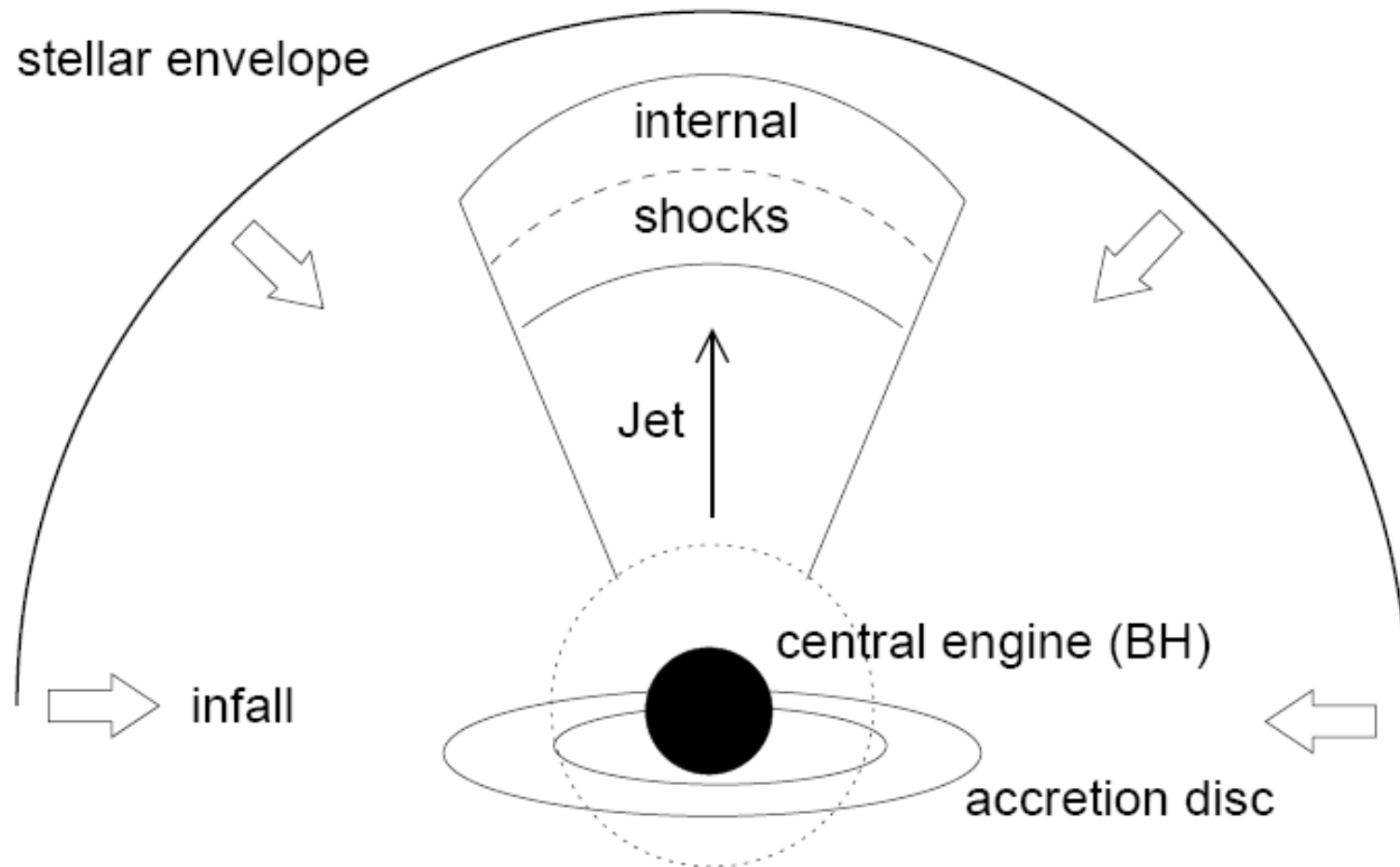
Ina Sarcevic
University of Arizona

Cosmic Accelerators

Cosmic Accelerator

Schematic picture of a relativistic jet buried inside
the envelope of a collapsing star – Slow-jet Supernovae (SJJ)

Razzaque, Meszaros and Waxman (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 gamma-rays on Earth.

- The density of electrons and protons in the jet for a slow jet SN model:

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

Proton Acceleration and Cooling Processes

- The shock acceleration time for a proton

$$t'_{\text{acc}} \simeq \frac{E'_p}{qcB'} \qquad t'_{\text{acc}} \approx 10^{-12}\left(\frac{E'_p}{\text{GeV}}\right)\ \text{s} \qquad \text{for}\ \ B = 10^9 G$$

- The maximum proton energy is limited by requiring this time not to exceed the dynamic time scale for any proton cooling process time scale (hadronic cooling, electromagnetic cooling, synchrotron and inverse Compton, Bethe-Heitler).

- Proton Hadronic Cooling Channels: Photomeson and proton-proton interactions serve as a cooling mechanism for the shock accelerated protons.

Proton Hadronic Cooling Channels

- Photomeson $(p\gamma)$ and proton-proton (pp) interactions produce high energy neutrinos. They also serve as a cooling mechanism for the shock accelerated protons.

- The average cross sections are $\sigma_{p\gamma}=5\times10^{-28}cm^2$ and $\sigma_{pp}=5\times10^{-26}cm^2$ respectively.

- The corresponding optical depths are:

$$\tau'_{p\gamma} = \frac{\sigma_{p\gamma}n'_\gamma r_j}{\Gamma_b} \qquad \tau'_{pp} = \frac{\sigma_{pp}n'_p r_j}{\Gamma_b}$$

- Hadronic cooling times are:

$$t'_{p\gamma} = \frac{E'_p}{c\sigma_{p\gamma}n'_\gamma \Delta E'_p} \approx 10^{-7.3}\ s \qquad t'_{pp} = \frac{E'_p}{c\sigma_{pp}n'_p \Delta E'_p} \approx 10^{-5.6}\ s$$

- Depending on the optical depth, in some astrophysical sources photons may be thermalized – this is the case for SJS

- First we consider single SJS with these values for Lorentz factor, proton and photon densities and magnetic field in the jet:

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}

This will give us qualitative features of the neutrino flux from a single SJS-type source

In evaluating proton cooling times we use :

★ Energy dependent hadronic interaction lengths

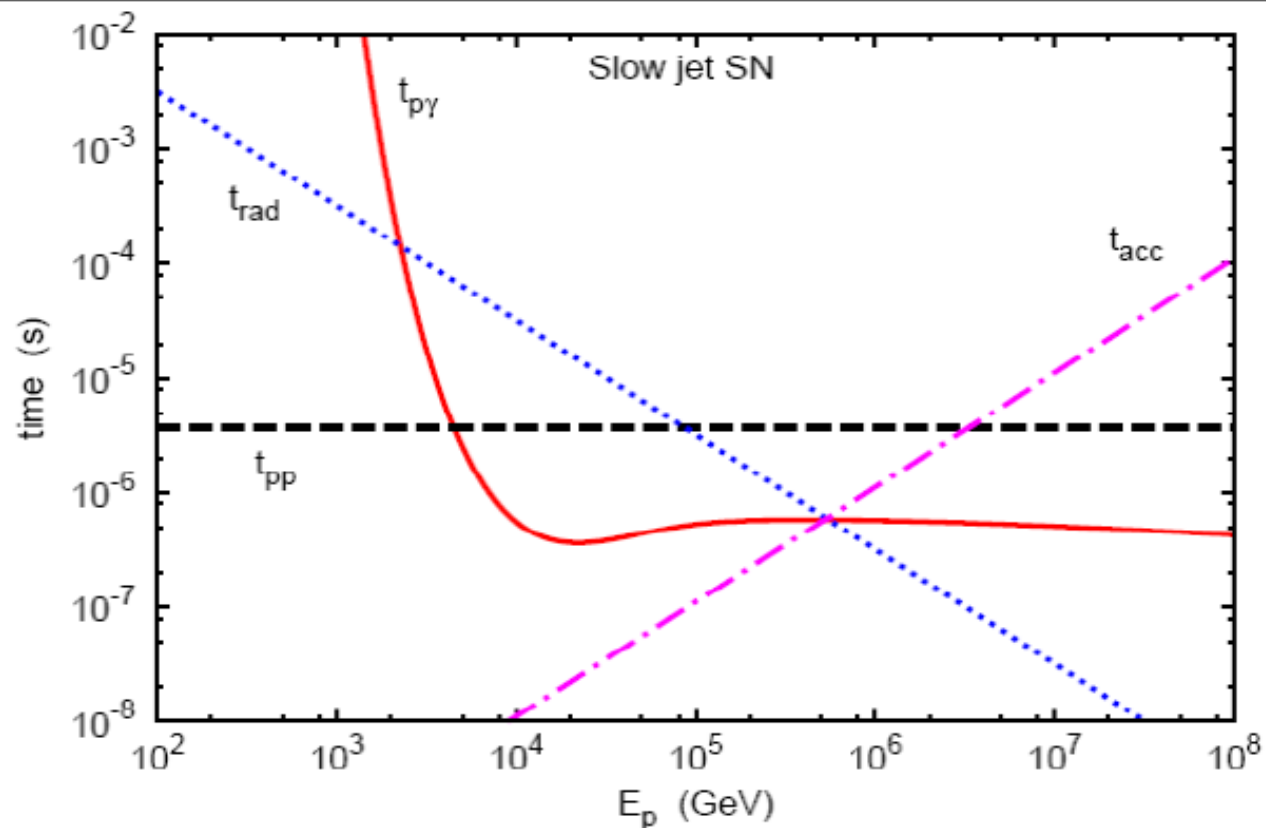★ The scattering length for inverse Compton scattering is
$L_N^{IC} = 3m_p^4 c^4 / 4\sigma_T m_e^2 E_p' E_\gamma'$. This effective scattering length
rescaled by $(m_M/m_p)^4$ for mesons .

★ The threshold energy for delta production in p-γ
interactions, for E=5 keV, is $E`_{p,th} = 2 \times 10^5$ GeV . For
p-γ scattering, the averaged reaction rate is

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

where n(E) is the photon number density (photon
distribution is thermal).We include resonance plus continuum
multiparticle production contributions

Proton cooling times for hadronic and electromagnetic processes : photomeson ($t_{p\gamma}$) , proton-proton (t_{pp}) , Inverse Compton scattering ($t_{IC}=3m^4_p c^3/(4\sigma_T m^2_e E\dot{}_p U\dot{}_\gamma))$) , and synchrotron radiation due to the magnetic field in the jet ($t_{syn}=6\pi m^4_p c^4/(\sigma_T c m^2_e E\dot{}_p B\dot{}^2))$.

Enberg, Reno and Sarcevic, Phys. Rev. D79, 053006 (2009)

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.

- In the case of $p\gamma$ interactions neutrinos are produced from charged pion (π^+) decay as

$$p\gamma \rightarrow \Delta^+ \rightarrow n\pi^+ \rightarrow \mu^+ \nu_\mu \rightarrow e^+ \nu_e \bar{\nu}_\mu \nu_\mu$$

- The pp interactions also produce charged pions , kaons , D mesons . The energy of the shock accelerated protons in the jet is expected to be distributed as $\sim 1/E^2$ following the standard shock acceleration models. Charged mesons, produced by pp and $p\gamma$ interactions, are expected to follow the proton spectrum with $\sim 20\%$ of the proton energy for each pion or kaon .

Meson Cooling Channels

- 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 eloctromagnetic energy losses and do not contribute much to high-energy neutrino production.

- Suppression factors for neutrinos from pion and kaon decay are important..

- The hadronic energy losses for mesons is similar to the proton energy losses.

Meson cooling times for the slow-jet core collapse supernovae
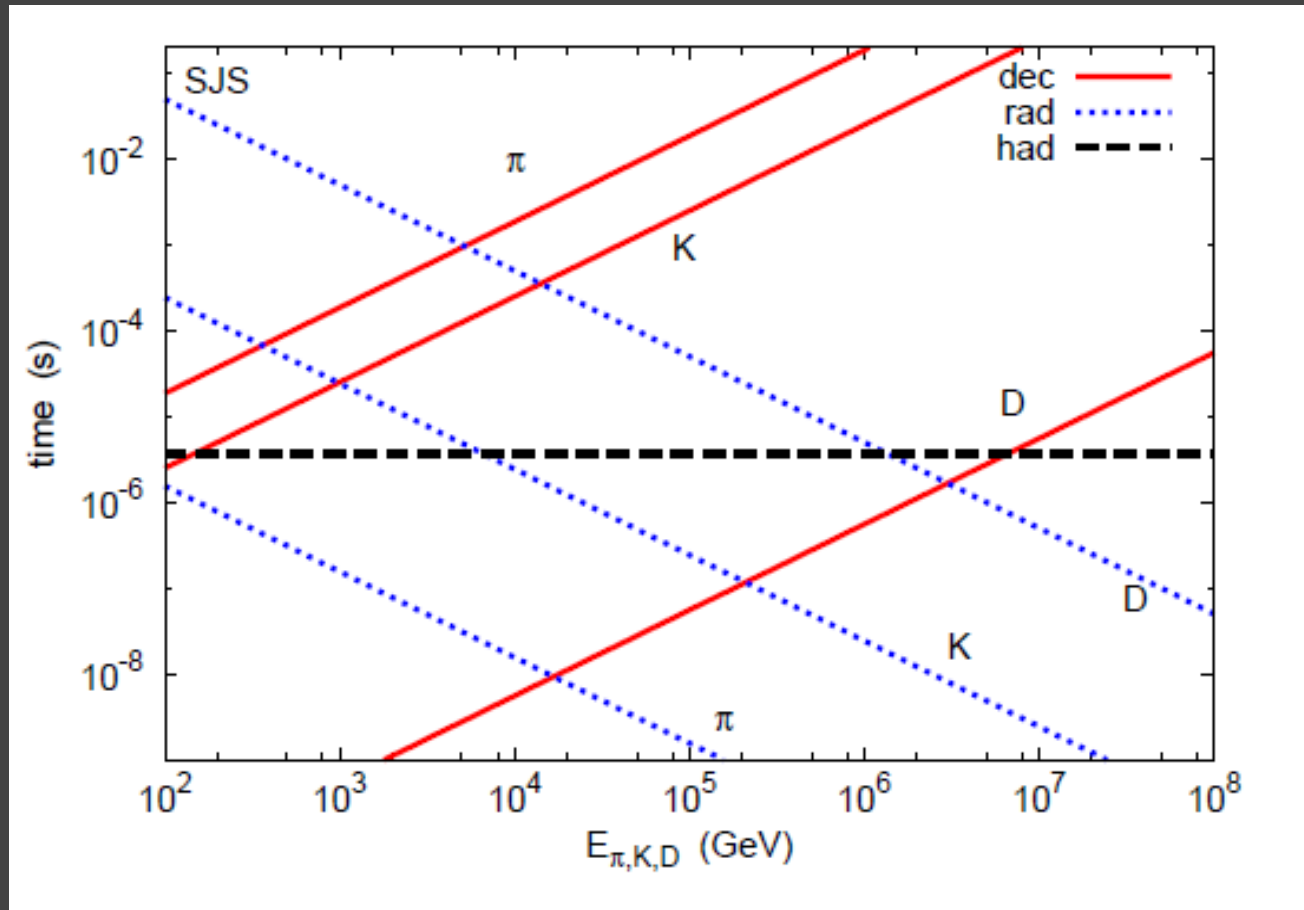
Hadronic (t_{had}) and electromagnetic (t_{rad}) cooling times and meson decay times (t_{dec}), as functions of energy in the comoving frame.

Enberg,Reno and Sarcevic, Phys. Rev. D79 (2009)

Neutrino Fluxes at Earth

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

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

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

$$\frac{d\phi_l}{dX} = \sum_M S(M \to \nu)$$

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

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

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

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

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

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

We define the Z-moments :

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

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

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

- 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 dn/dx_E is the energy distribution of the meson M produced by N (or from M decay).

- Meson flux is determined by solving the evolution equation:

$$\frac{d\phi_M}{dX} = -\frac{\phi_M}{\lambda^{dec}} - \frac{\phi_M}{\lambda^{had}} - \frac{\phi_M}{\lambda^{rad}} + Z_{MM}\frac{\phi_M}{\lambda^{had}} + Z_{NM}\frac{\phi_N}{\lambda_N}$$
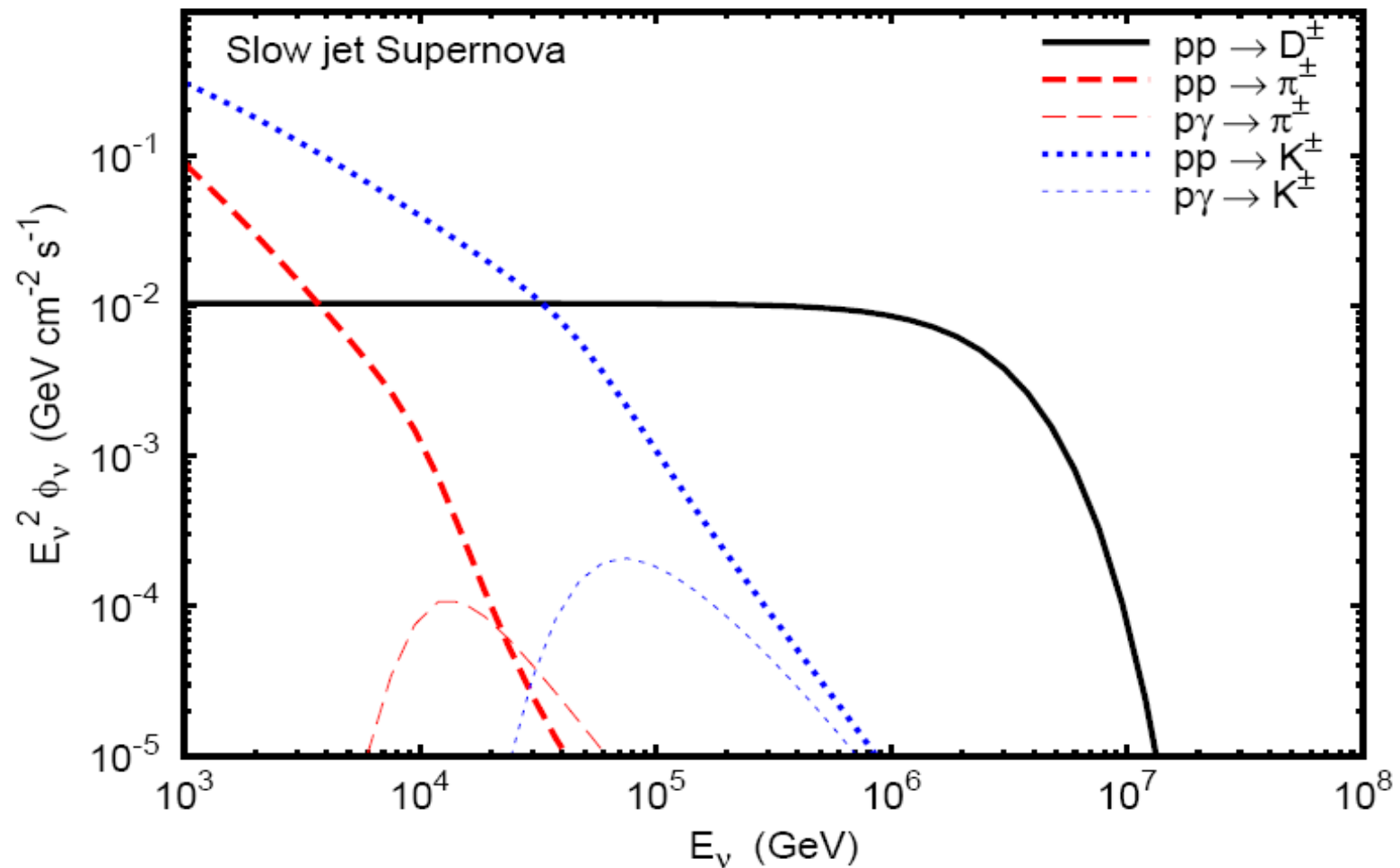
Proton flux has energy cut-off (because of the cooling) and is given by

$$f_N(E') = \left[1 + \left(\frac{E'}{E'_{\text{max}}}\right)\right] e^{-E'/E'_{\text{max}}}$$

In general Z-moments are energy-dependent and they also have energy cut-off coming from the proton flux cutt-off (but at lower energies)

$$Z_{NM} = \int_0^1 \frac{\lambda_N(E)}{\lambda_N(E/x_E)} \frac{\phi_N(E/x_E)}{\phi_N(E)} \frac{\mathrm{d}n_{N \to M}}{\mathrm{d}x_E} \frac{\mathrm{d}x_E}{x_E}$$

Neutrino Flux From Slow-Jet Core Collapse Supernova
(obtained with energy-independent Z-moments)

Slow jet Supernova

Legend:
- pp → $D^\pm$ (solid black)
- pp → $\pi^\pm$ (dashed red)
- pγ → $\pi^\pm$ (thin dashed red)
- pp → $K^\pm$ (dotted blue)
- pγ → $K^\pm$ (thin dotted blue)

Y-axis: $E_\nu^2 \phi_\nu$ (GeV cm^{-2} s^{-1})

X-axis: E_ν (GeV)

Enberg, Reno and Sarcevic, Phys. Rev. D79, 053006 (2009)

Could IceCube Excess in PeV Neutrino Flux be Due to Charm from Slow-jet Supernovae?
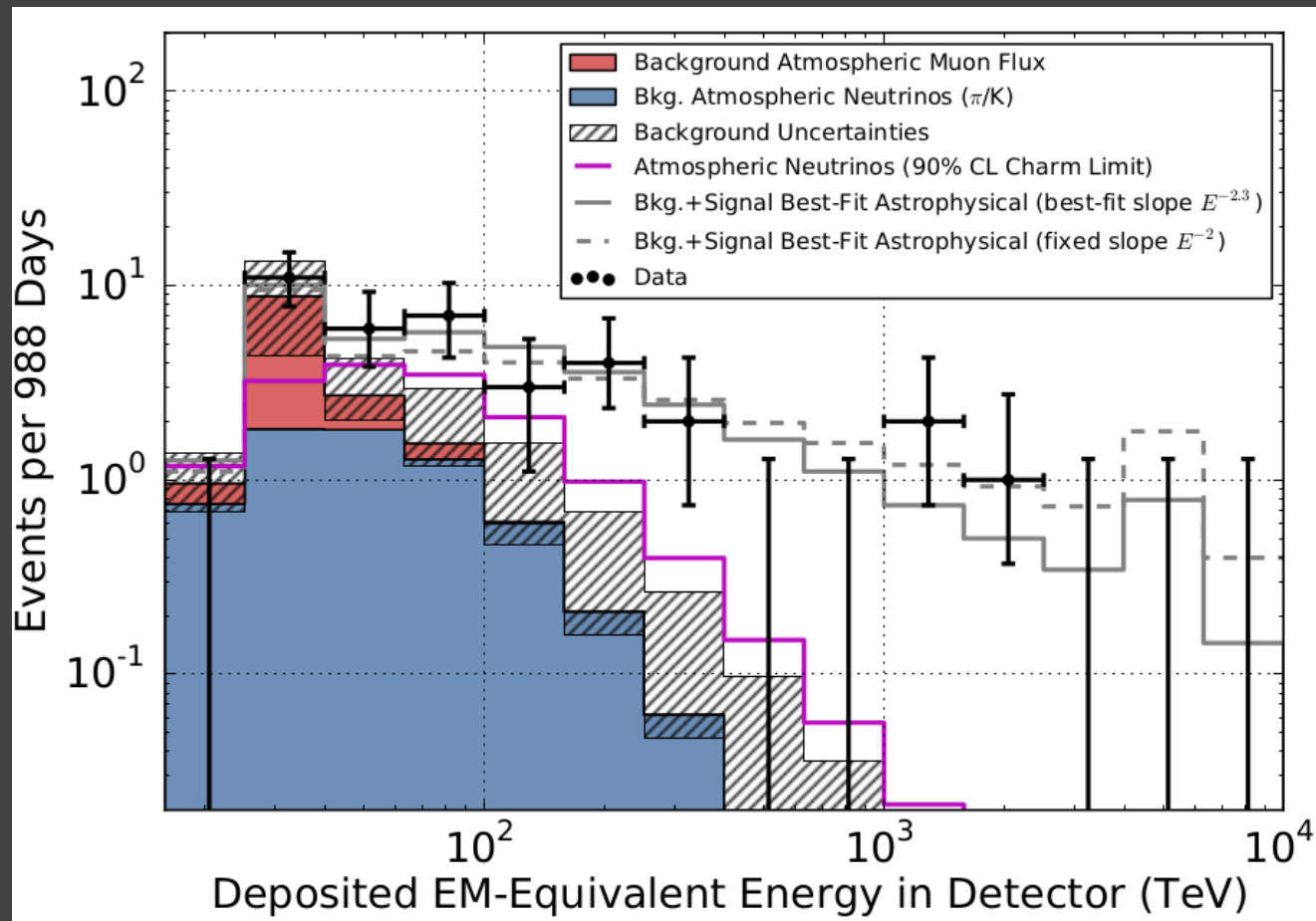
- We consider difuse flux from SJS with astrophysical parameters allowed by IceCube
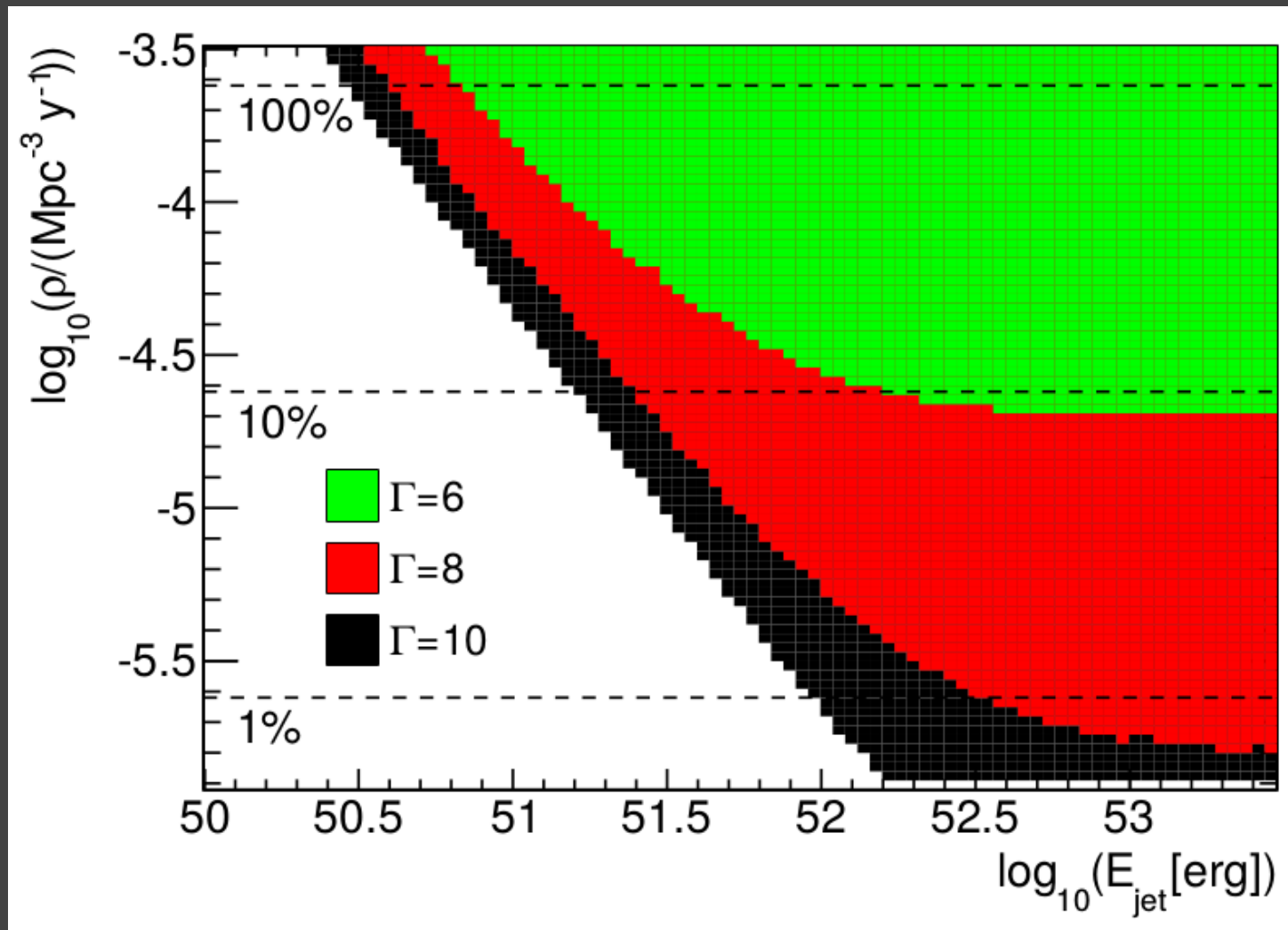
IceCube Exclusion Region

Our choice for benchmark values in evaluating neutrino flux

$$\phi_\nu(E) = Z_{M\nu} Z_{NM} \phi_N(E) \frac{L_j \Gamma_j^2}{2\pi \theta_j^2 d_L^2 \log(E'_{\max}/E'_{\min})}$$

We have chosen diffusion coeficient to be $\kappa = 1$ which gives maximum proton energy in the jet frame:

$$E'_{max} = 10.2 \text{ PeV}$$

For the bulk Lorentz factor and for jet luminosity we take:

$$\Gamma_j = 5$$

$$L_j = 10^{50} \text{ erg s}^{-1}$$
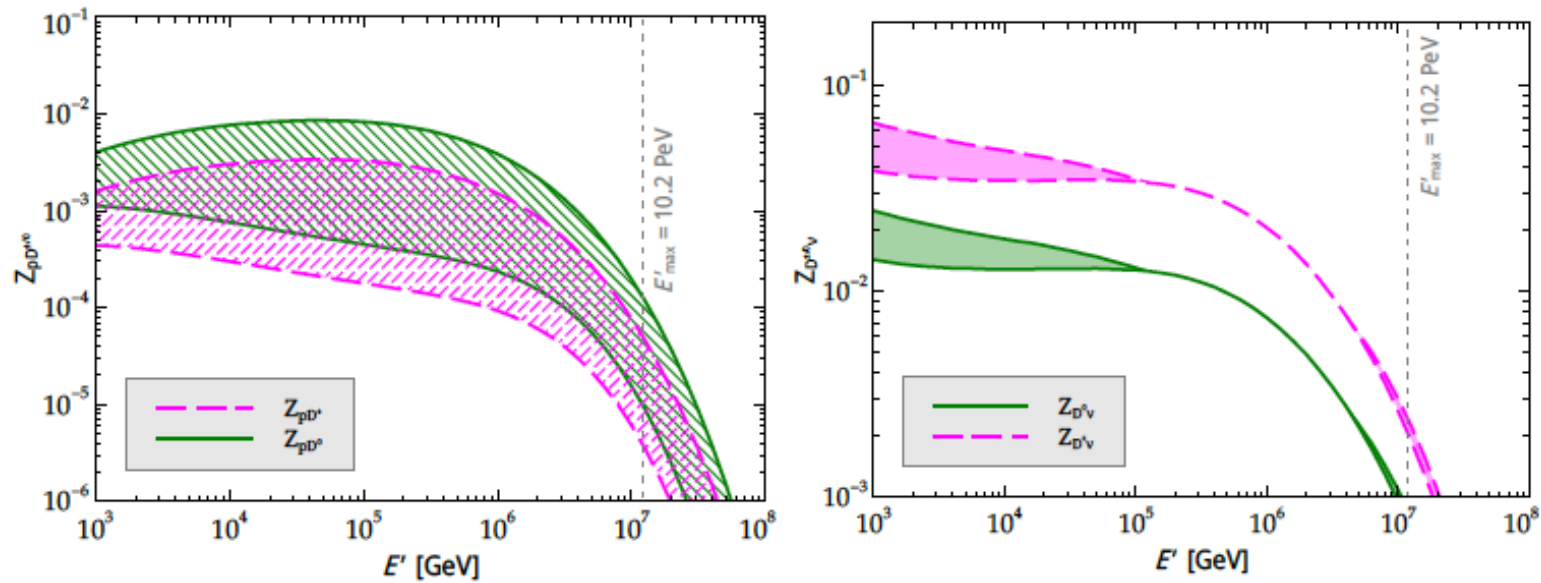
Energy-dependent Z-moments

Figure 1: Z-moments for $D^0/D^\pm$ production (left) and decay (right) in the jet-comoving frame for $m_c = 1.27$ GeV, shown with uncertainties due to variation the renormalization (μ_R) and factorization (μ_F) scales within the range $[1.71 m_c, 4.65 m_c]$ and $[1.48 m_c, 1.25 m_c]$. $\Gamma_j = 5$ is used in each case, and the dotted vertical line indicates $E'_{\max}$ for the proton flux in the source.

Diffuse Neutrino Flux from Slow-Jet Supernovae Sources

$$\Phi(E_\nu) = \frac{\xi_{\mathrm{sn}}}{2\Gamma_j^2} \int_0^\infty \frac{\dot{n}_{\mathrm{sn}}(z)d_L^2 ct_j}{(1+z)^2} \phi_\nu\left[E_\nu(1+z)\right] \left|\frac{\mathrm{d}t}{\mathrm{d}z}\right| \mathrm{d}z$$

where

$$\frac{\mathrm{d}z}{\mathrm{d}t} = H_0(1+z)\sqrt{\Omega_\Lambda + \Omega_{\mathrm{M}}(1+z)^3}.$$

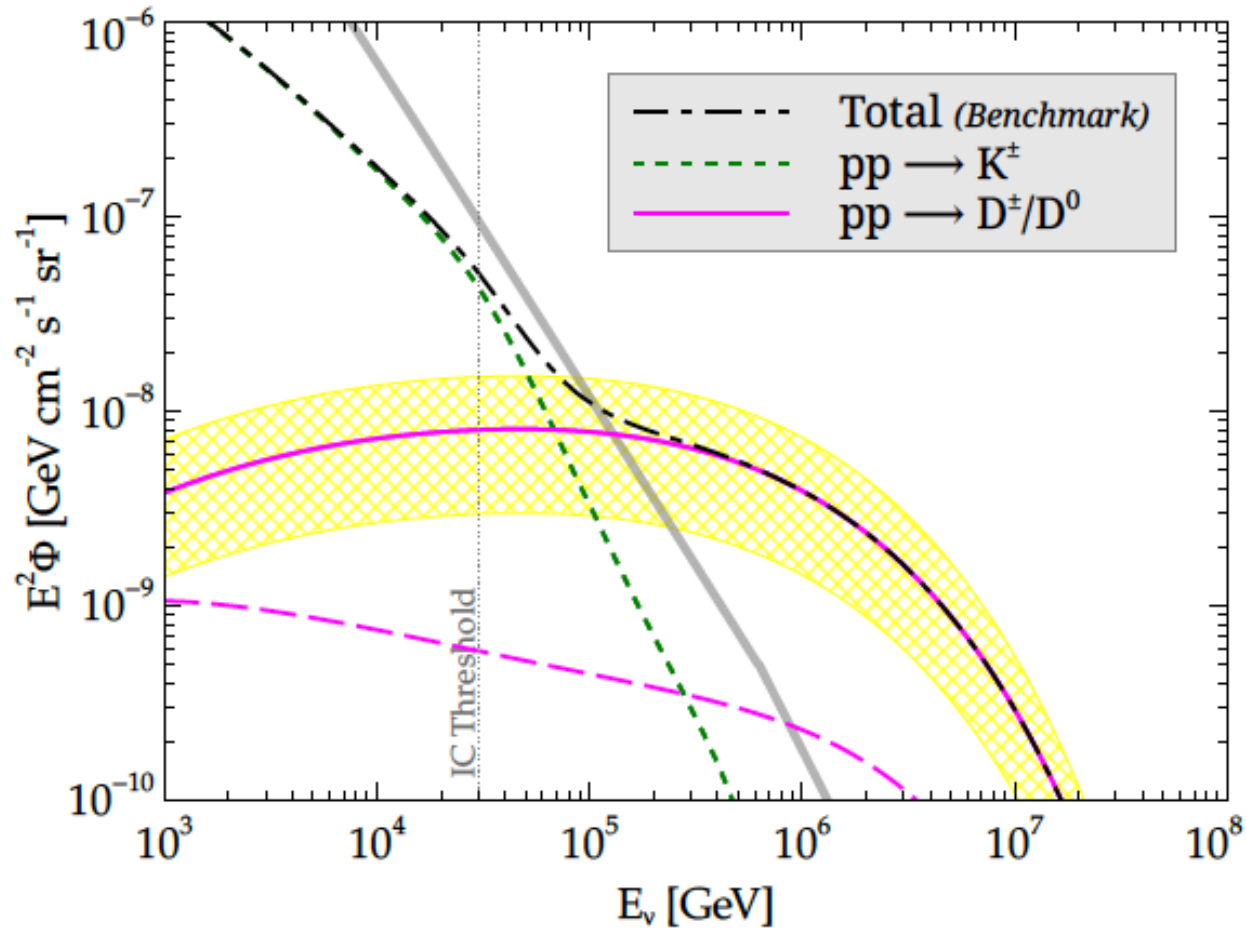We take the fraction of supernova with slow-jets to be $\xi_{sn} = 1$

Figure 2: The (unoscillated) diffuse $\nu_\mu + \bar{\nu}_\mu (= \nu_e + \bar{\nu}_e)$ flux obtained with the jet luminosity $L_j = 10^{50}$ erg s^{-1}, $\Gamma_j = 5$, $E'_{max} = 10.2$ PeV and $\xi_{sn} = 1$. The upper solid line and lower long-dashed line show the range of QCD uncertainties from the scale choices in evaluating the charm production cross section. The yellow hatched region shows the variation of the QCD upper limit flux (using $[\mu_R, \mu_F] = [1.71 m_c, 4.65 m_c]$) from uncertainties in the SN formation rate. The short-dashed lines show the kaon contributions to the diffuse neutrino flux from SJS. For comparison, the gray curve shows the vertical flux of conventional atmospheric $\nu_\mu + \bar{\nu}_\mu$ (see, *e.g.*, [46]).
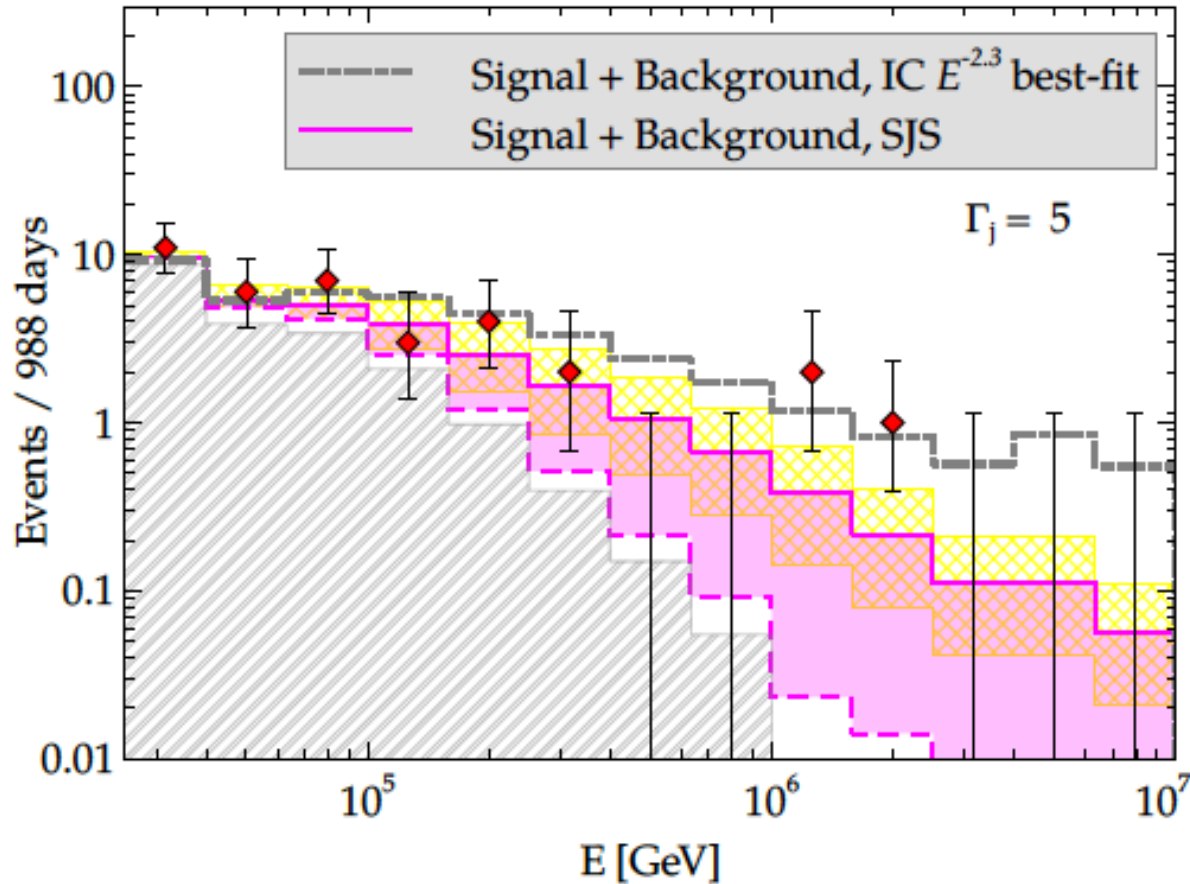
In evaluating event rates we use IceCube Effective Area
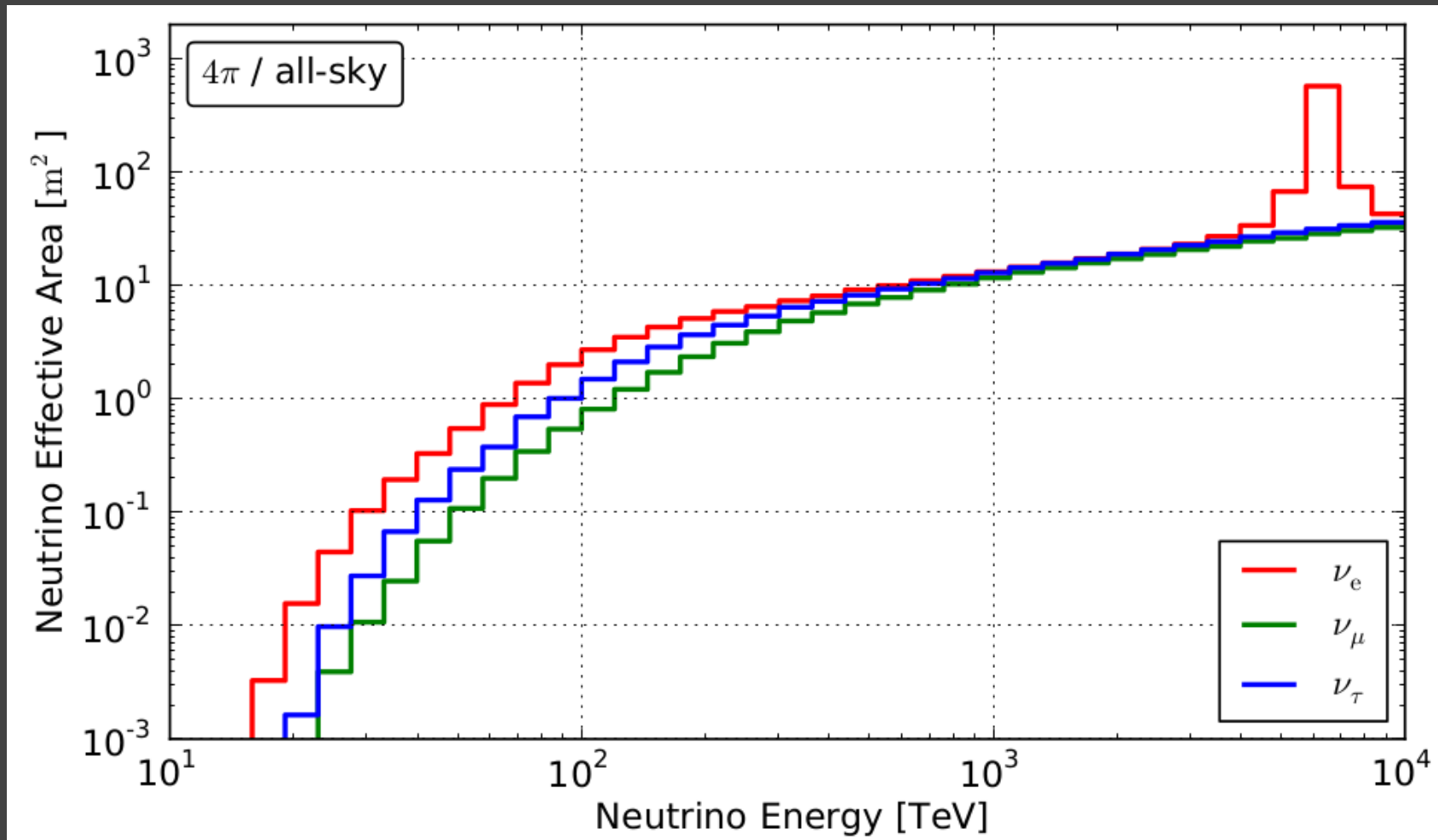
Figure 3: Predicted 988-day total (shower + track) event rates at IC from slow-jet sources for $L_j = 10^{50}$ erg s^{-1}, $\Gamma_j = 5$, $E'_{max} = 10.2$ PeV and $\xi_{sn} = 1$. The solid shaded histogram reflects the QCD scale uncertainties in the charm pair production cross section calculation, with the solid (dashed) histogram showing the upper (lower) range of the SJS diffuse plus atmospheric background number of events. The variation in event-rates relative to the solid histogram from uncertainties in the SN formation rate is shown as a yellow hatched area. Observed event-rates from [3] along with 1σ statistical error bars are shown (red diamonds), as is the total atmospheric neutrino + muon background estimated in the same reference (grey shaded region).

A. Bhattacharya, R. Enberg, M.H. Reno and I. Sarcevic, JCAP 06 (2015) 034

Summary

- We have shown that charm production in Slow-Jet Supernovae could provide explanation for the IceCube observation of excess neutrinos in energy range between 30TeV and 2 PeV with natural energy cut-off.

Our choice of astrophysical parameters (SJS luminosity, Lorentz factor, fraction of supernovae that are SJS-type, etc) and QCD parameters (charm quark mass, renormalization and factorization scale, pdfs, etc) provides specific size and the cut-off energy of the neutrino flux

Possible Additional Neutrino Flux from Heavy Dark Matter Decay

Galactic:

$$\frac{\mathrm{d}\Phi^{\mathrm{G}}}{\mathrm{d}E_\nu} = \frac{1}{4\pi\, m_{\mathrm{DM}}\, \tau_{\mathrm{DM}}} \frac{\mathrm{d}N_\nu}{\mathrm{d}E_\nu} \int_0^\infty \rho(r(s,l,b))\, \mathrm{d}s$$

Extragalactic:

$$\frac{\mathrm{d}\Phi^{\mathrm{EG}}}{\mathrm{d}E} = \frac{\Omega_{\mathrm{DM}}\, \rho_{\mathrm{c}}}{4\pi\, m_{\mathrm{DM}}\, \tau_{\mathrm{DM}}} \int_0^\infty \frac{1}{H(z)} \frac{\mathrm{d}N_\nu}{\mathrm{d}E_\nu} \left[(1+z)E_\nu\right]\, \mathrm{d}z$$

Decay modes:

$$DM \to \tau^+ \tau^-$$
$$DM \to Z^0 Z^0$$

$$DM \to \mu^+ \mu^-$$
$$DM \to W^+ W^-$$

Neutrino Energy Spectrum from Heavy Dark Matter Decay

SJS + DM + Atm. Bkg.

Signal + Background, IC $E^{2.3}$ best-fit

Signal + Background, SJS

$DM \rightarrow \tau^+\tau^-$

$\tau = 2.5 \times 10^{28}$ s

$m_{DM} = 5$ PeV