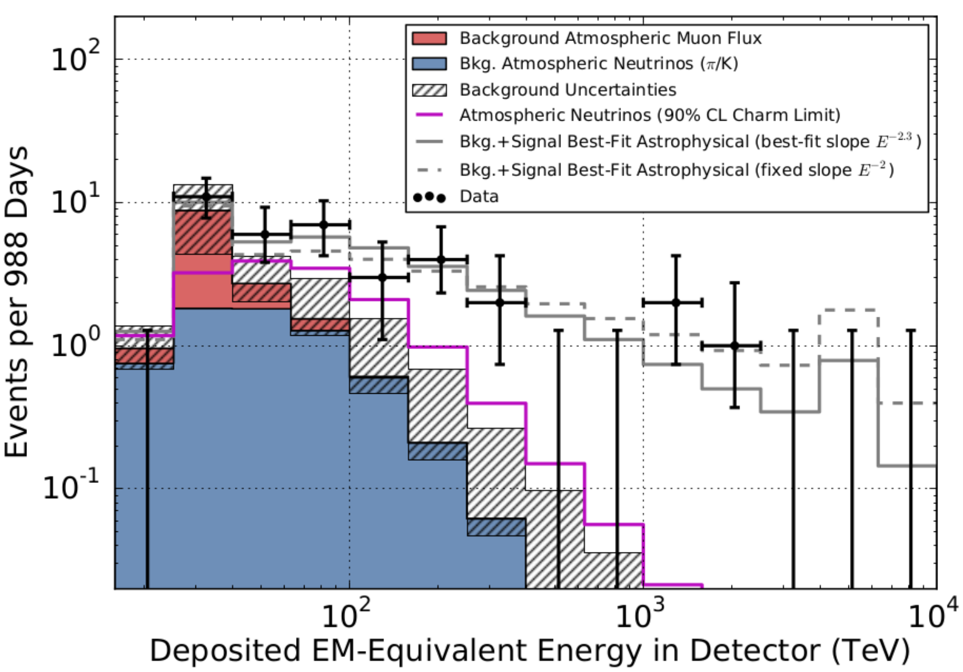
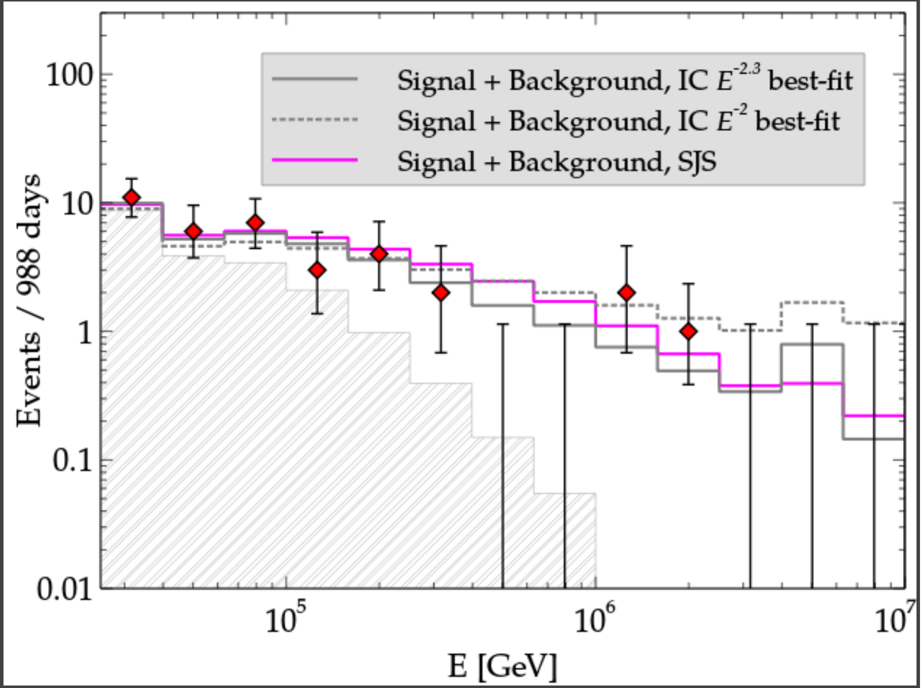
Charm Decay in Slow-Jet Supernovae as the Origin of the IceCube Ultra-High Energy Neutrino Events

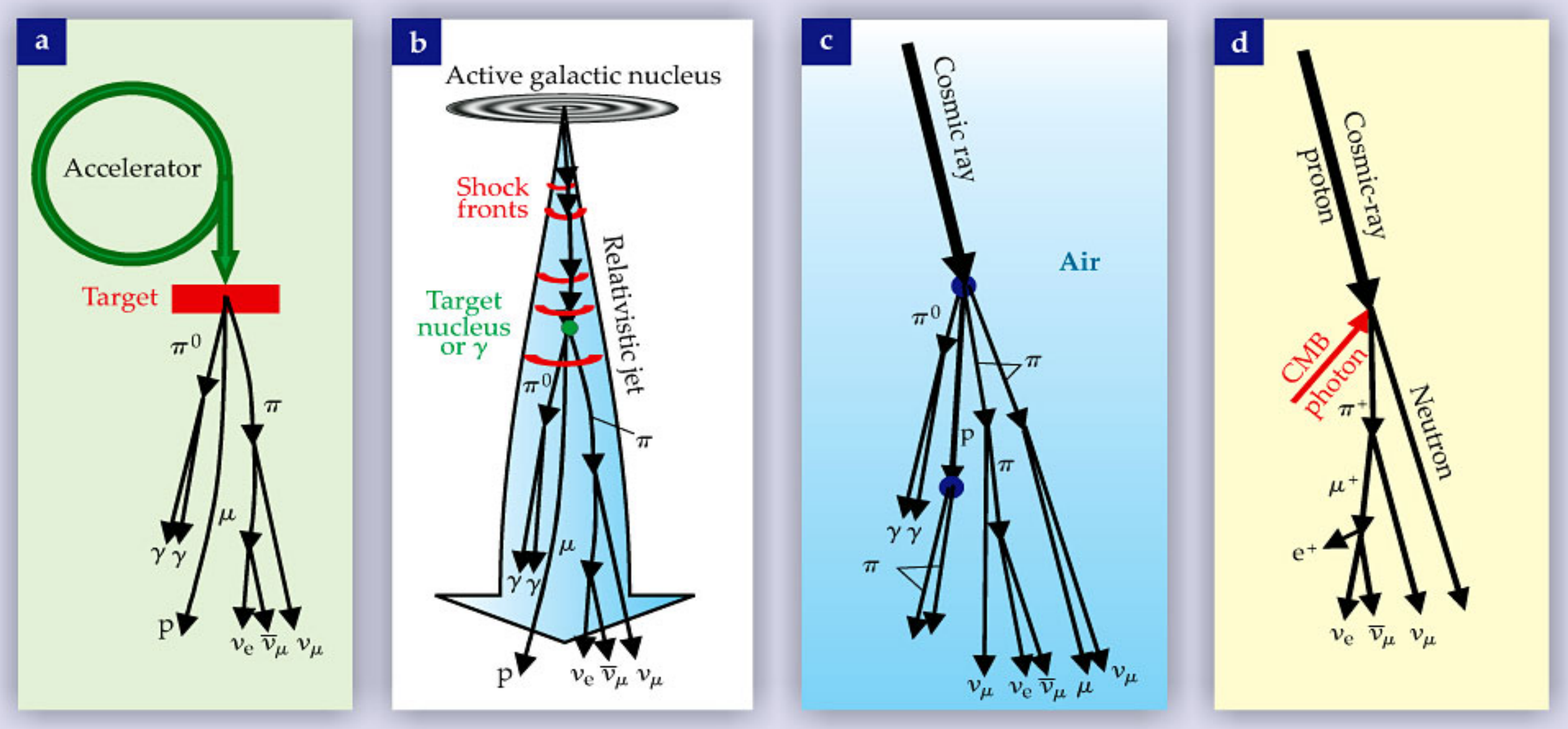
Ina Sarcevic
University of Arizona





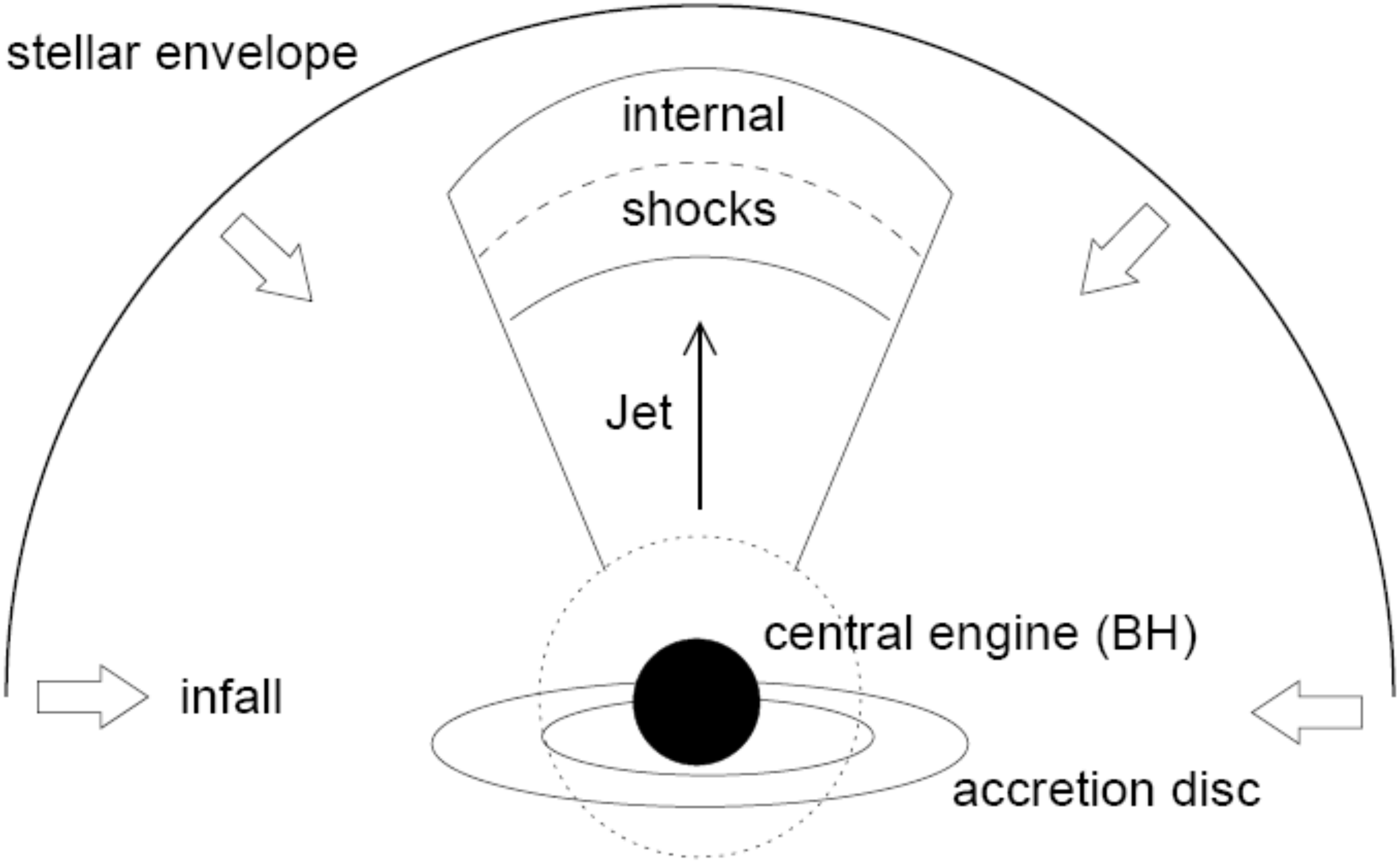
A. Bhattacharya, M.H. Reno and I. Sarcevic,
arXiv: 1407.2985, submitted to PRL

Cosmic Accelerators



Physics Today 2009

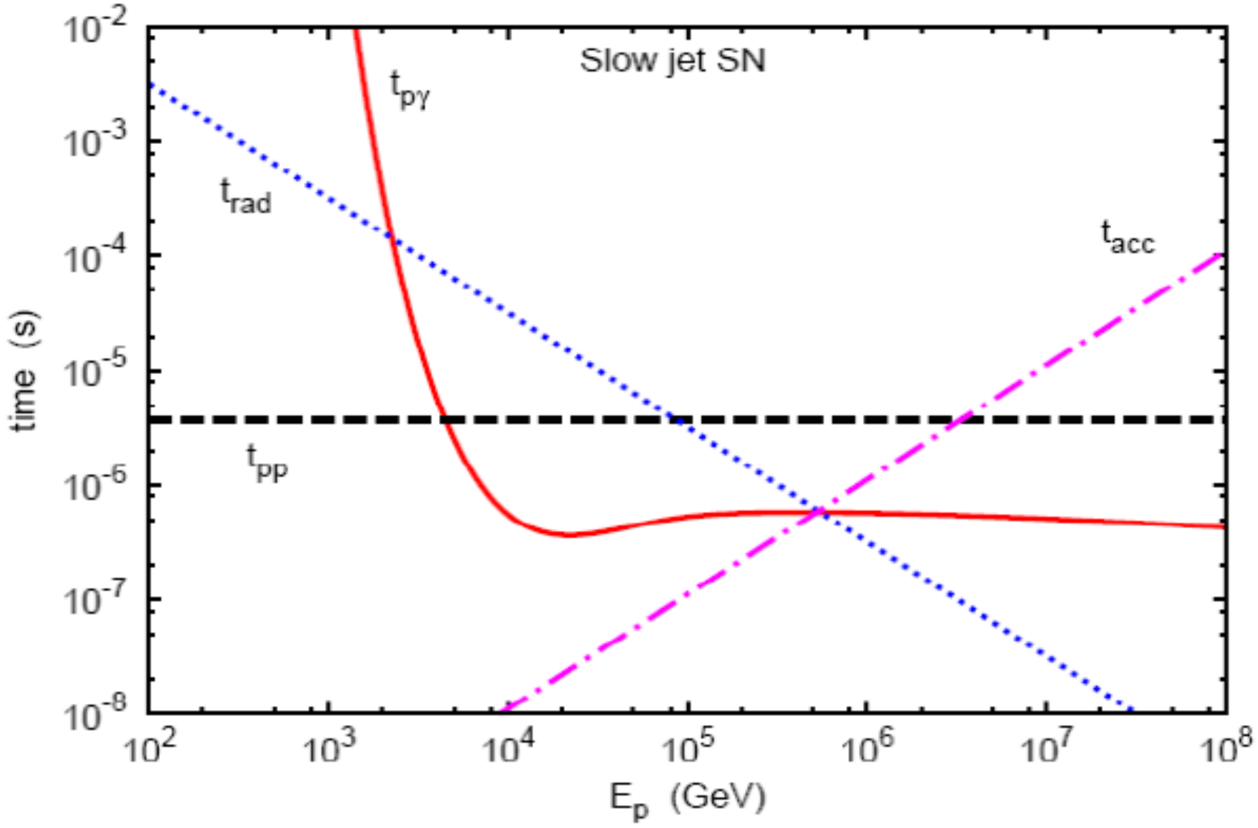
Cosmic Accelerator



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

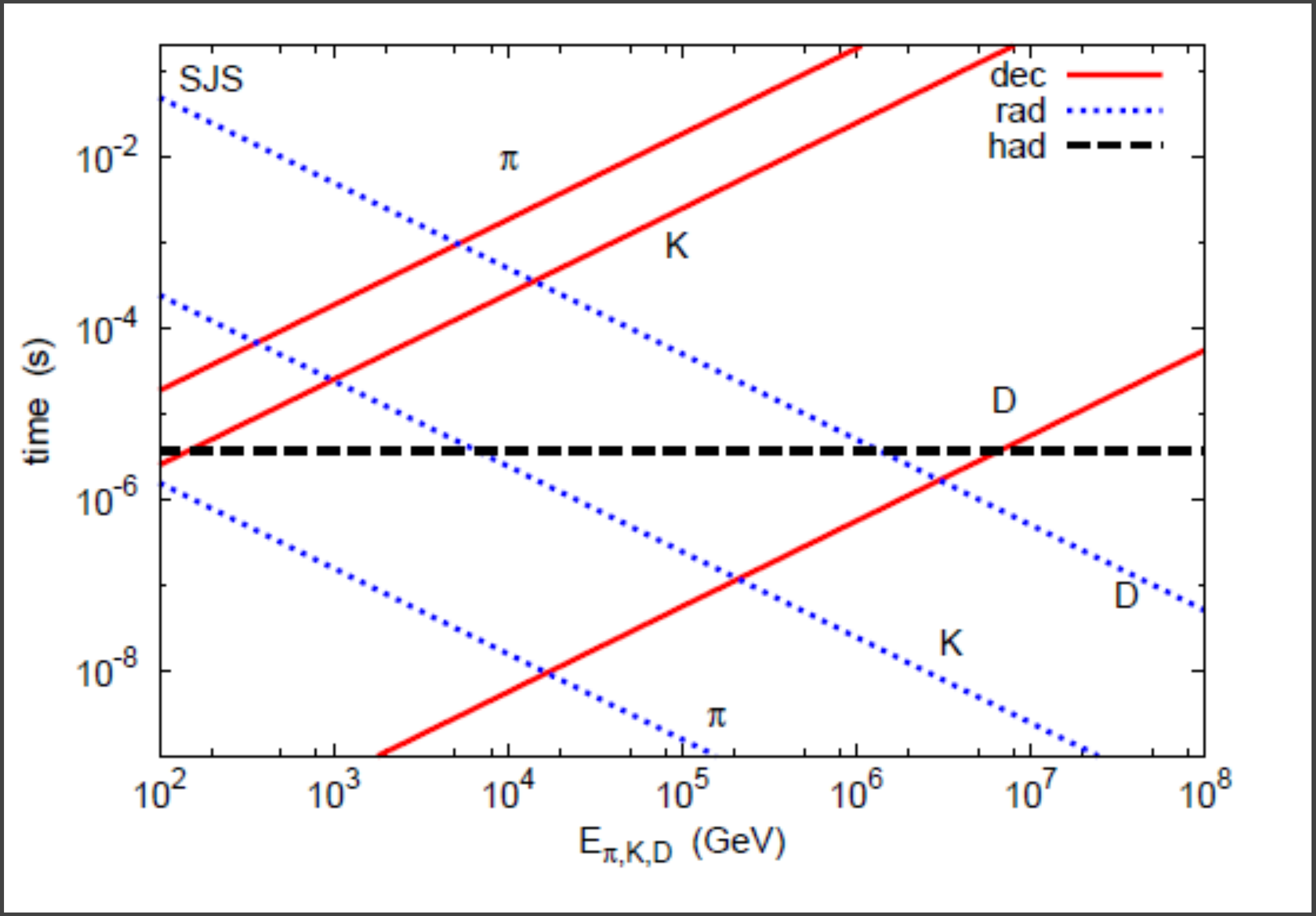
Razzaque, Meszaros and Waxman (2004)

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



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

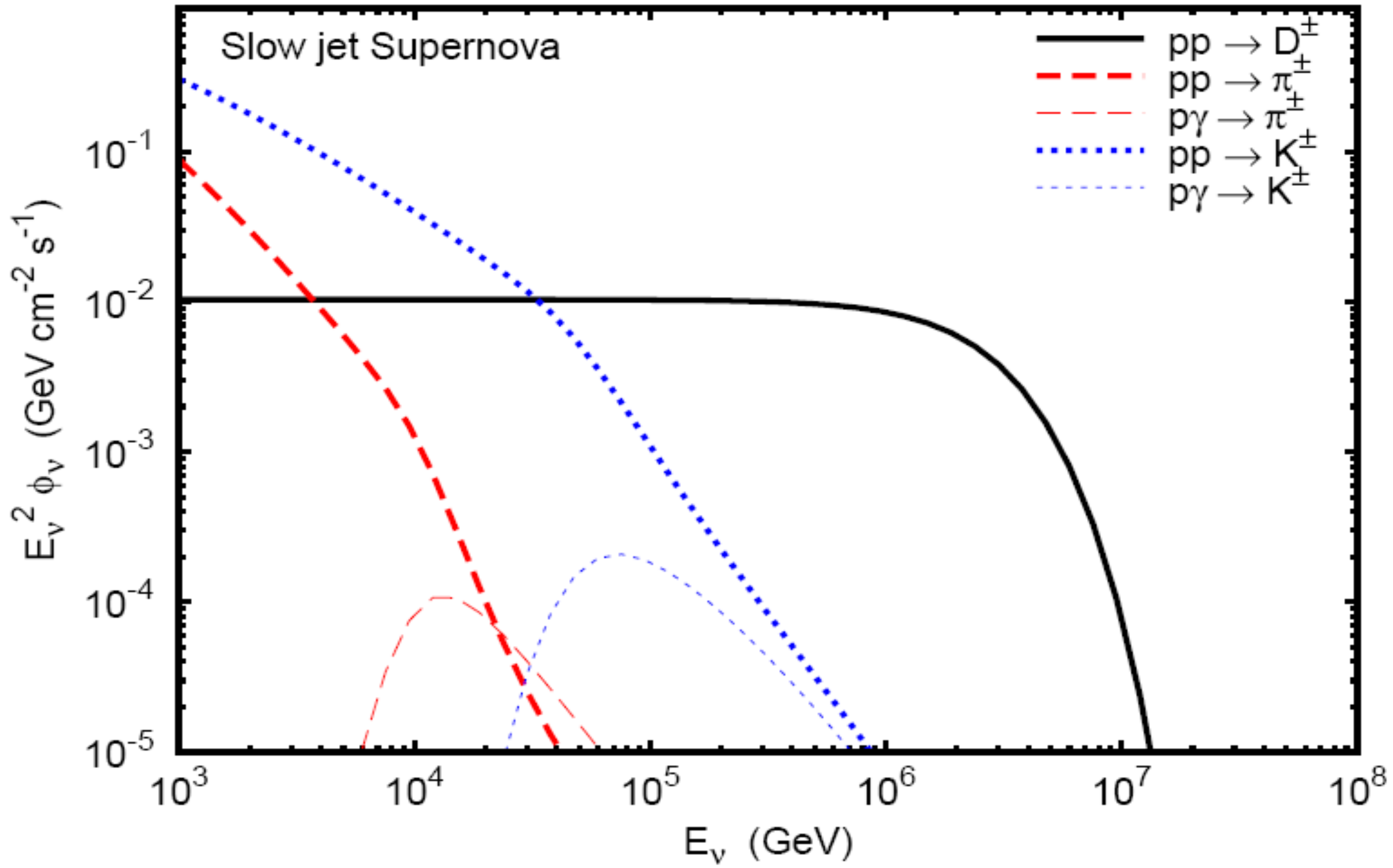
Meson cooling times for the slow-jet core collapse supernovae



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

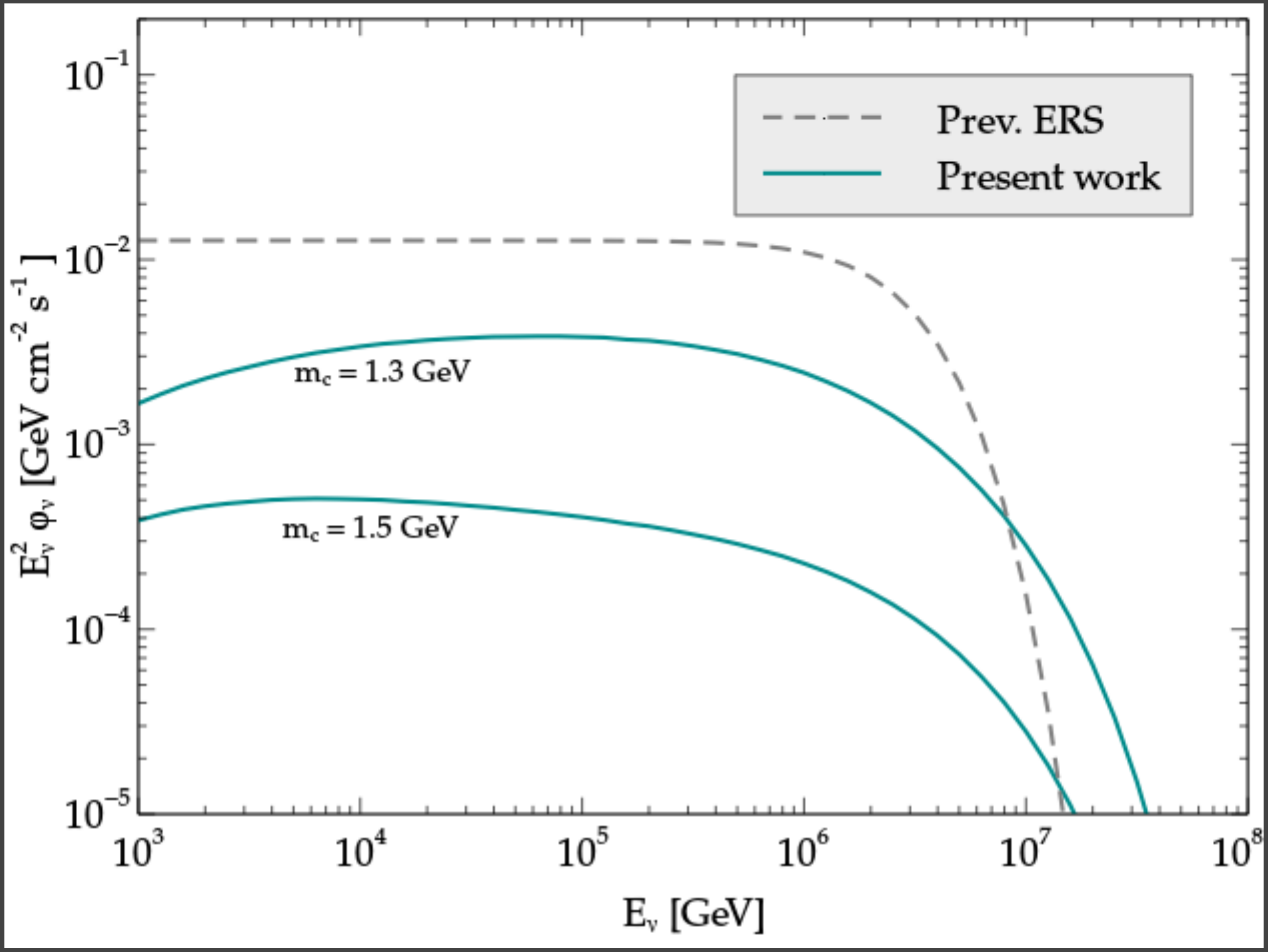
Enberg,Reno and Sarcevic, Phys. Rev. D79 (2009)

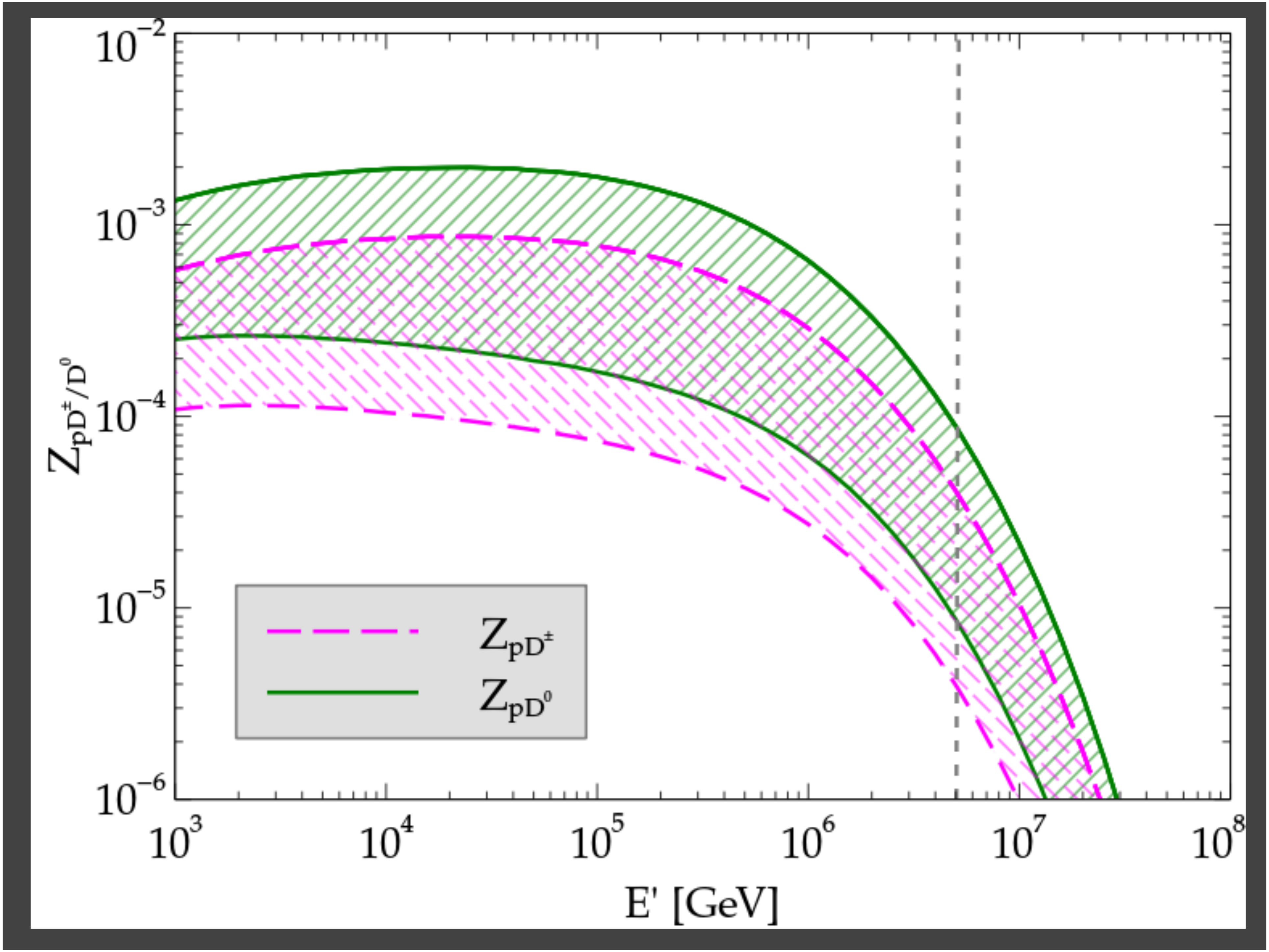
Neutrino Flux From Slow-Jet Core Collapse Supernovae

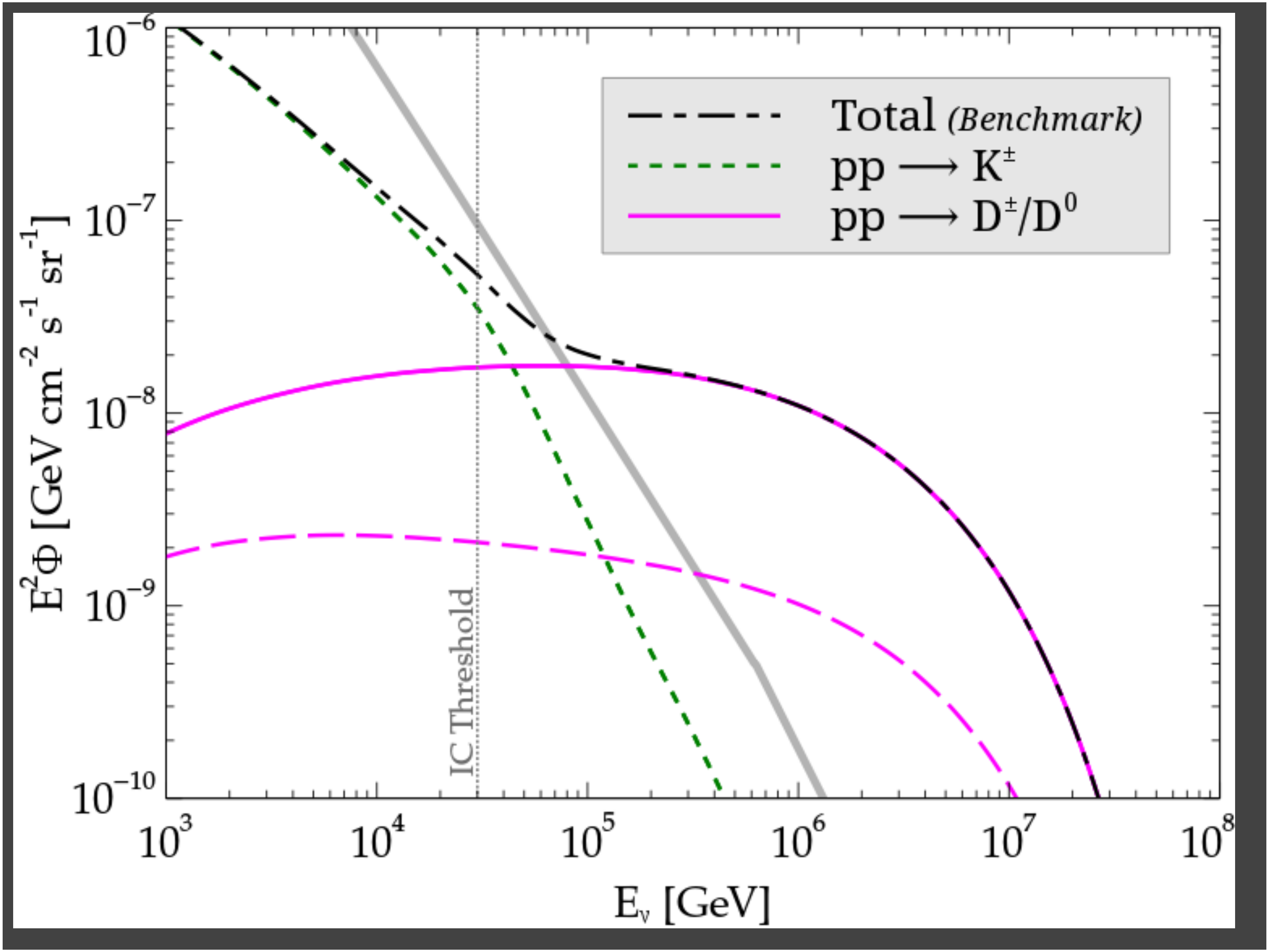


Enberg, Reno and Sarcevic, Phys. Rev. D79, 053006 (2009)

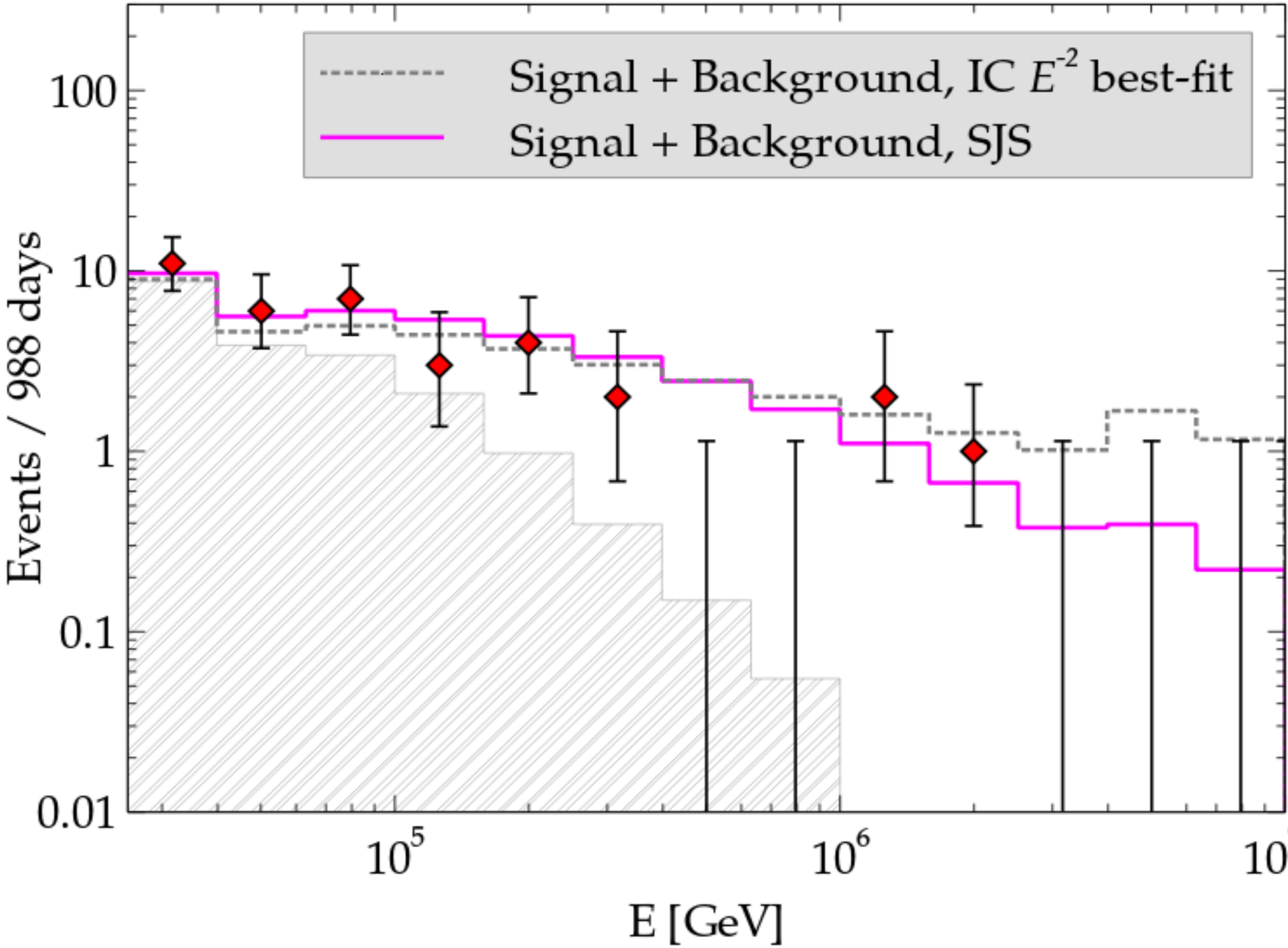
Neutrino Flux with Energy-Dependent Z-moments




10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
$Z_{pD^{\pm}/D^{0}}$
10^{3}
10^{4}
10^{5}
10^{6}
10^{7}
10^{8}
E' [GeV]
$Z_{pD^{\pm}}$
$Z_{pD^{0}}$



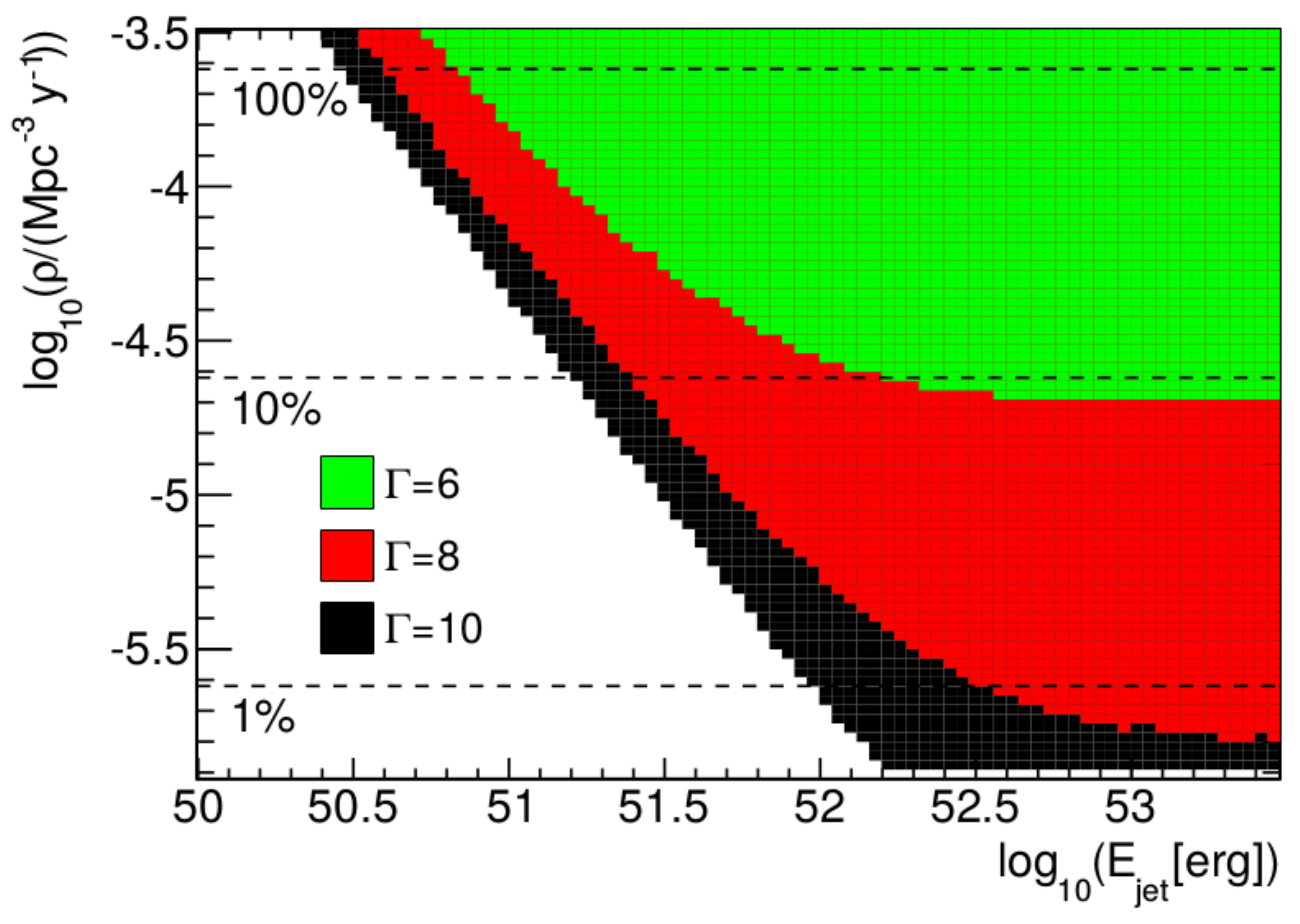
Total (Benchmark)
pp ⟶ K±
pp ⟶ D±/D0
IC Threshold
$E^2\Phi$ [GeV cm^{-2} s^{-1} sr^{-1}]
E_ν [GeV]
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{3}
10^{4}
10^{5}
10^{6}
10^{7}
10^{8}



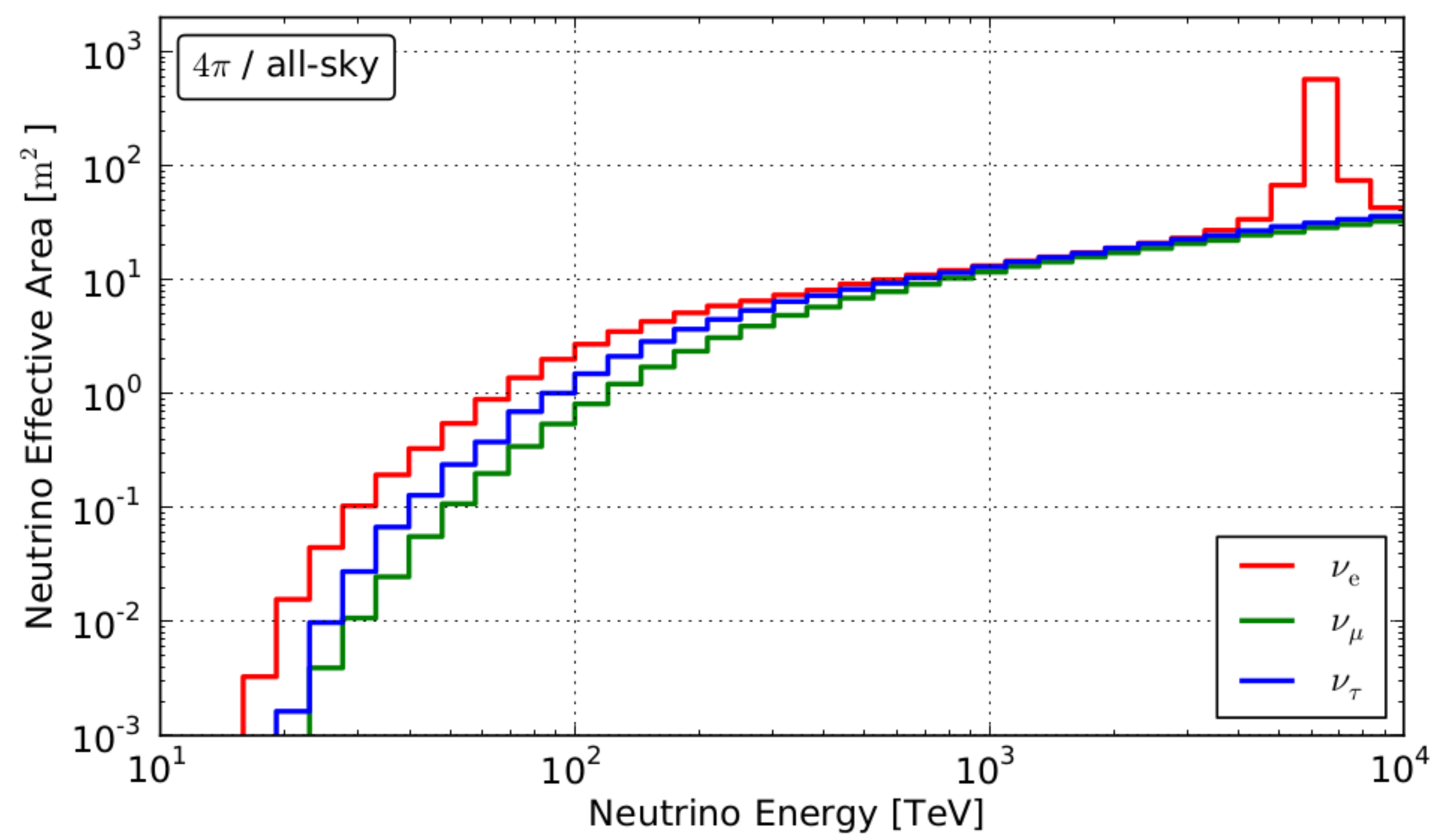
Signal + Background, IC E^{-2} best-fit
Signal + Background, SJS
Events / 988 days
100
10
1
0.1
0.01
10^5
10^6
10^7
E [GeV]

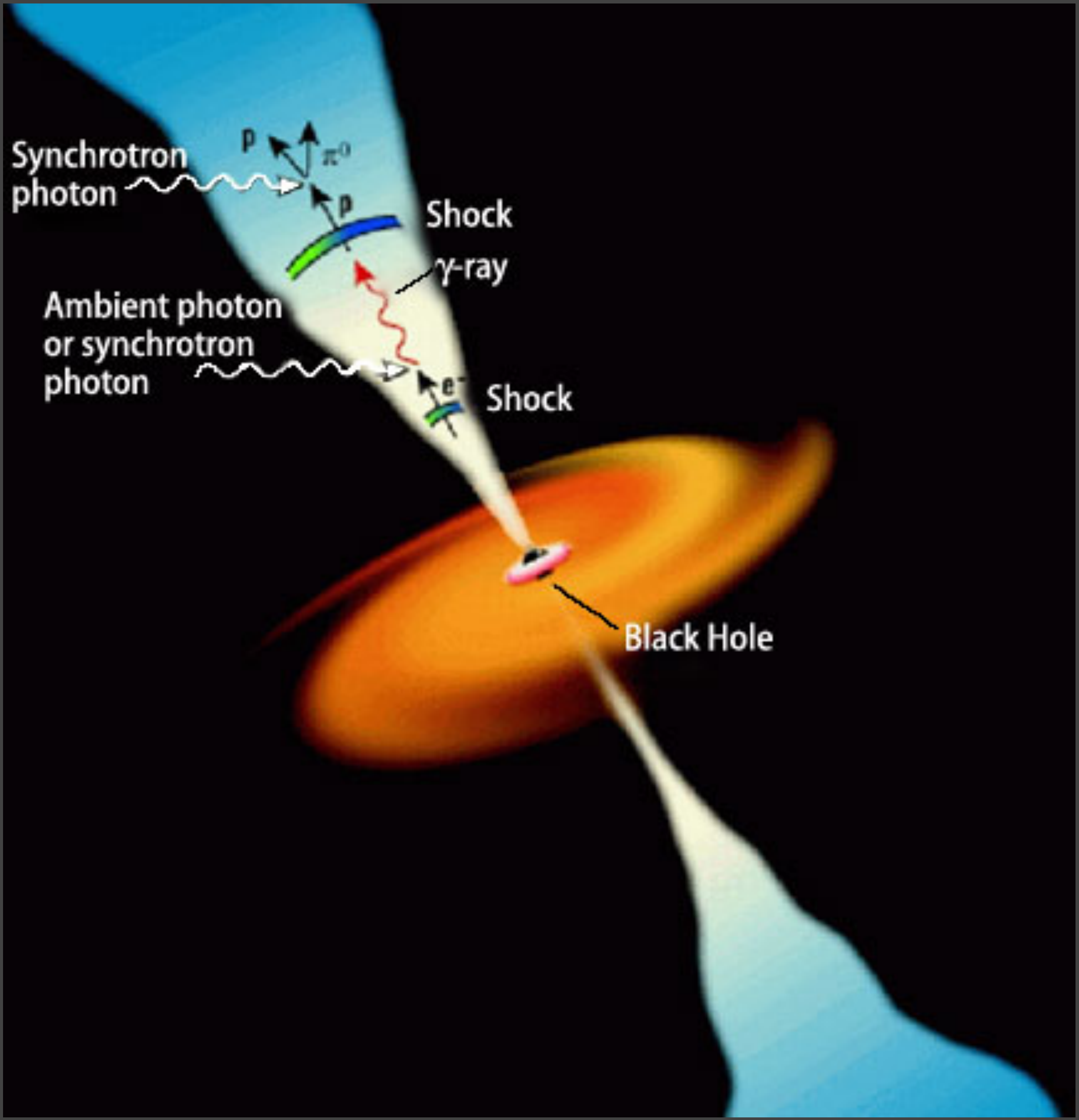
Back-up Slides

IceCube Exclusion Region



IceCube Effective Area




Synchrotron photon
p
π0
p
Shock
γ-ray
Ambient photon or synchrotron photon
e−
Shock
Black Hole

Proton Acceleration and Cooling Processes

- The shock acceleration time for a proton

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

- 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.

- 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 Hadronic Cooling Channels

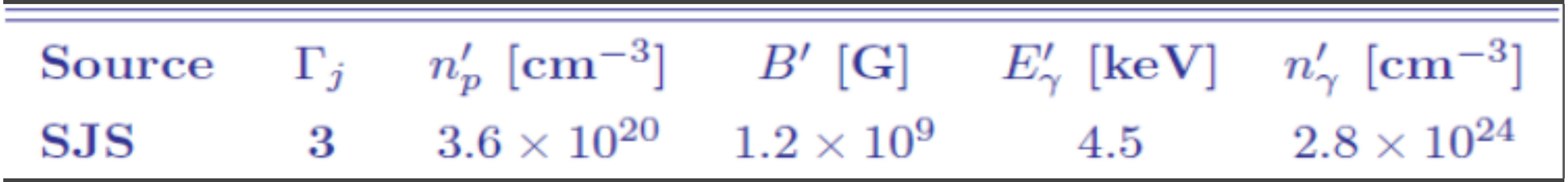
- Photomeson $(\mathrm{p}\gamma)$ and proton-proton (pp) interactions produce high energy neutrinos. They also serve as a cooling mechanism for the shock accelerated protons.
- The average cross sections are $\sigma_{\mathrm{p}\gamma}=5\times10^{-28}\mathrm{cm}^2$ and $\sigma_{\mathrm{pp}}=5\times10^{-26}\mathrm{cm}^2$ 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



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}

Neutrino Production and Flux on Earth

- Shock accelerated protons in the jet can produce non-thermal neutrinos by photomeson $(\mathrm{p}\gamma)$ interactions with thermal synchrotron photons and/or by proton-proton (pp) interactions with cold protons present in the shock region.

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

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

- 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 pγ 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 ($(\pi p$ 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.

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

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

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

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

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

We define the Z-moments :

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

- 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:

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

★ To evaluate hadronic interaction lengths, we use energy dependent hadronic cross sections.

★ The scattering length for inverse Compton scattering is $L^{IC}_{N}=3m^{4}_{p}c^{4}/(4\text{¾}_{T}m^{2}_{e}E\text{`}_{p}U\text{`}_{\circ})$. This effective scattering length is rescaled by $(m_{M}/m_{p})^{4}$ for mesons .

★ The threshold energy for delta production in p-gamma interactions, for E=5 keV, is $E\text{`}_{p,th}=2\ \ 10^{5}$ GeV . For p-gamma 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, we include resonance plus continuum multiparticle production contributions. Photon distribution is thermal