ARENA 2008 Workshop

Neutrino Fluxes from Astrophysical Sources, the Role of Charmed Meson Production and Decay

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High Energy Neutrino Interactions

- **Neutrinos are highly stable, neutral particles $\Rightarrow$ Thus cosmic neutrinos point back to astrophysical point sources and bring information from processes otherwise obscured by a few hundred gm of a material.**
- **Interaction length of a neutrino is**

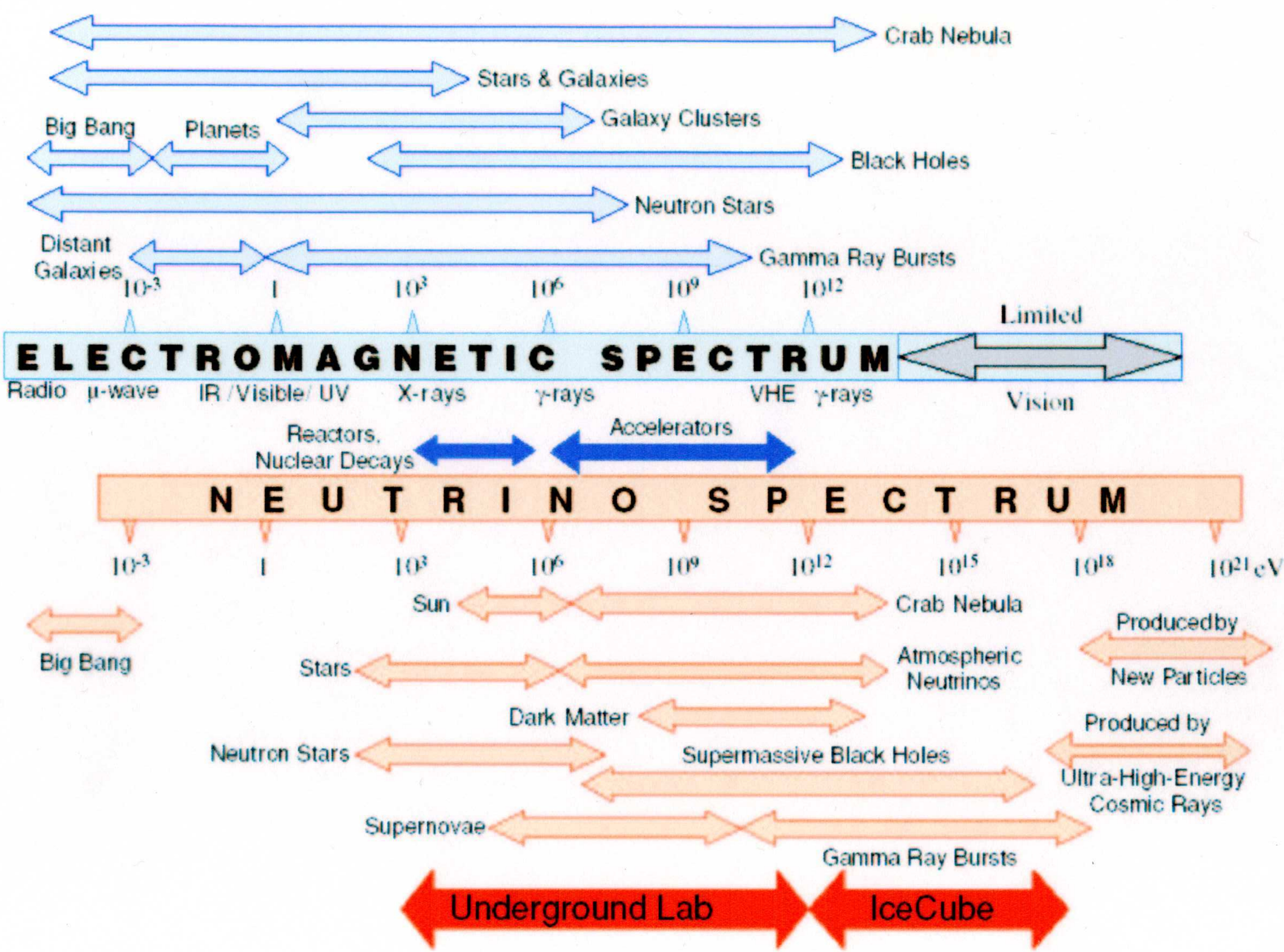
$$\mathcal{L}_{\rm int} \equiv \frac{1}{\sigma_{\nu N}(E_\nu)\cdot N_A}$$

Interaction length of 1TeV neutrino is 250 kt/cm^2 or column of water of 2.5 million km deep.

- **Neutrino astronomy $\Rightarrow$ a unique window into the deepest interiors of stars and galaxies**
  (HE photons get absorbed by a few hundred gm of a material).

Neutrinos as multi-messengers of the extreme Universe

Neutrino Facilities Assessment Committee, 2002



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, 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**

Sources of UHE Neutrinos

- Cosmogenic ("GZK") neutrinos (interactions of cosmic rays with microvawe background radiation)
- Active Galactic Nuclei (AGN)
- Gamma Ray Bursts (GRB's)
- ...

Active Galactic Nuclei (AGN)

- **Radio loud quasars in elliptical host galaxies, often have jets.**
- **Radio quiet quasars in the core of spiral galaxies.**
- **Several AGN detected γ-rays in TeV energy range:**

in the Northern Hemisphere:

⋆ **Mkn 421 (z=0.0300);** $\alpha = 2.1$

⋆ **Mkn 501 (z=0.033)**

⋆ **1ES 2344+514 (z=0.044)**

⋆ **1ES 1959+650 (z=0.048)**

⋆ **1ES 1426+428 (z=0.129)**

in the Southern Hemisphere:

⋆ **PKS 2155-304 (z=0.116);** $\alpha = 3.3$

⋆ **PKS 2005-4899 (z=0.071);** $\alpha = 4.0$

- Basic processes of neutrino production in extragalactic sources:

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

$$\hookrightarrow n + \gamma \rightarrow p + \pi^-$$

$$\hookrightarrow \pi^\pm \rightarrow \mu^\pm + \nu_\mu$$

$$\hookrightarrow \mu^\pm \rightarrow e^\pm + \nu_\mu + \nu_e$$

$$p + \gamma \rightarrow p + \pi^o$$

$$\hookrightarrow \pi^o \rightarrow \gamma\gamma$$

$$p + p \rightarrow \pi^+\pi^-\pi^o K^+ K^- D^+ D^- D^o D_s \ldots \underrightarrow{\text{decay}} \; \nu_\mu \nu_e \nu_\tau \ldots$$

- The probability for $\nu_\mu \rightarrow \nu_\tau$ oscillations is given by

$$P(\nu_\mu \rightarrow \nu_\tau; L) = \sin^2 2\theta \; \sin^2(\frac{1.27\Delta \mathrm{m}^2 \mathrm{L(Km)}}{\mathrm{E(GeV)}})$$

- For astronomical distances ($L \sim 1000 Mpc$) and large mixing angle, $P(\nu_\mu \rightarrow \nu_\tau; L) = 1/2$, i.e. $F_{\nu_\mu} = F_{\nu_\tau}$

Neutrino Flavors

- **source:** π **decays** $\Rightarrow \nu_e : \nu_\mu : \nu_\tau = 1 : 2 : 0$

- **propagation towards Earth: neutrino oscillations**
  - $\star$ ν_μ **and** ν_τ **maximally mixed** $\Rightarrow \nu_e : \nu_\mu : \nu_\tau = 1 : 1 : 1$

- **If** $F^0_{\nu_e} : F^0_{\nu_\mu} : F^0_{\nu_\tau} \neq 1 : 2 : 0$ **then three flavor mixing is relevant**

$$F_{\nu_e} = F^0_{\nu_e} - \frac{1}{4}\sin^2 2\theta_{12}(2F^0_{\nu_e} - F^0_{\nu_\mu} - F^0_{\nu_\tau})$$

$$F_{\nu_\mu} = F_{\nu_\tau} = \frac{1}{2}(F^0_{\nu_\mu} + F^0_{\nu_\tau}) + \frac{1}{8}\sin^2 2\theta_{12}(2F^0_{\nu_e} - F^0_{\nu_\mu} - F^0_{\nu_\tau})$$

Jones, Mocioiu, Reno and Sarcevic, PRD 69 (2004)

- **Detection of HE neutrinos with neutrino telescopes depends strongly on neutrino interactions and their cross section:**

- **Event rates for *downward* leptons/sleptons or hadrons from neutrino interactions:**

$$R_\nu = V \int dE_\nu \;\; \sigma_{cc}(E_\nu) \;\; F_\nu(E_\nu)$$

- **Event rates for *upward* leptons/sleptons from neutrino interactions:**

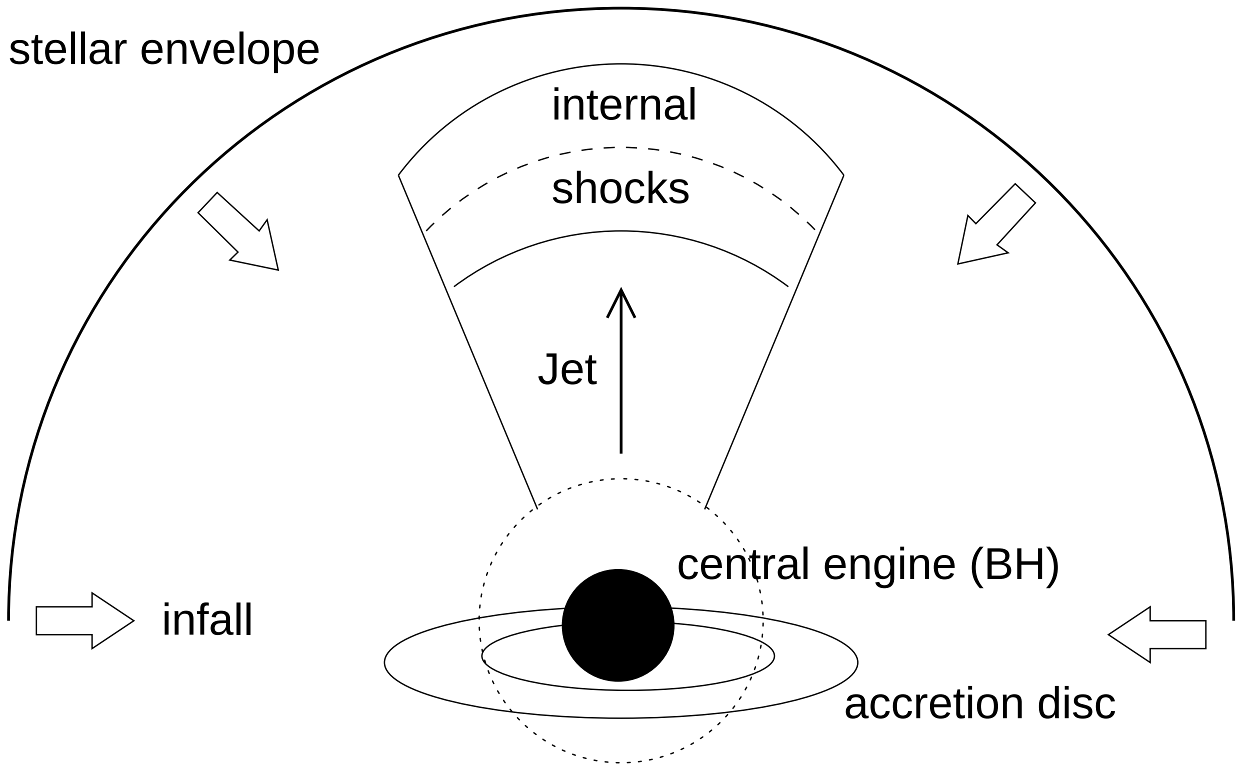
$$R_\nu = AN_A \int dE_\nu R(E_\nu, E_\mu)\sigma_{cc}(E_\nu)S(E_\nu)F_\nu(E_\nu, X)$$

where $R(E_\nu, E_\mu)$ is the lepton/slepton range and $S(E_\nu)$ is the neutrino attenuation factor.

EXPERIMENTS

- **AMANDA/ICECUBE/ICECUBE-PLUS/HYPERCUBE**
- **ANTARES, NESTOR**
- **RICE**
- **ANITA**
- **PIERRE AUGER**
- **EUSO, OWL, LOFAR, ARIANNA ...**

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. The density of these electrons and protons in the jet**

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

For GRBs:

$$n'_e \simeq n'_p \simeq\approx 10^{12} cm^{-3}$$

and for AGN:

$$n'_e \simeq n'_p \simeq\approx 10^{5} cm^{-3},$$

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.

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**

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

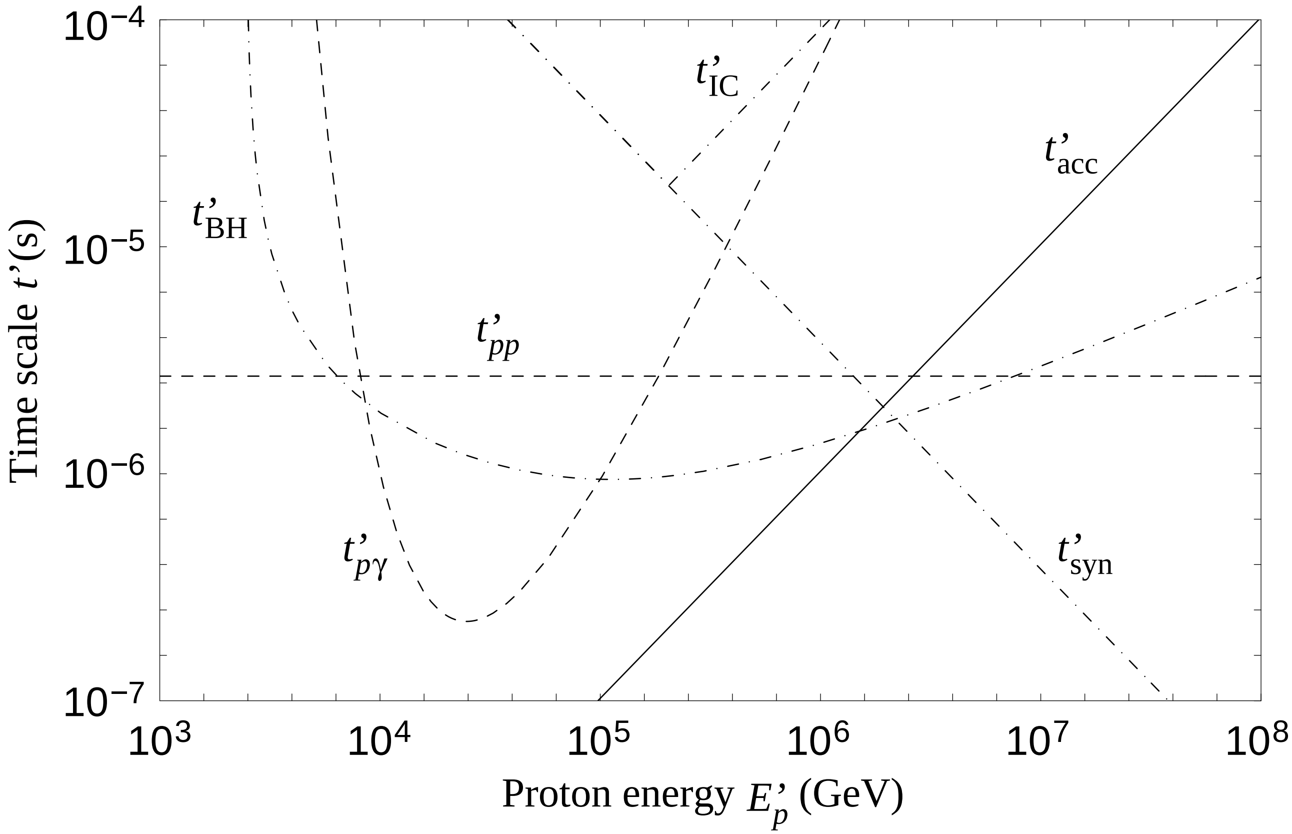
$$\tau'_{pp} = \frac{\sigma_{p\gamma} n'_p r_j}{\Gamma_b}$$

and the hadronic cooling time scales are

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

$$t'_{pp} = \frac{E'_p}{c\sigma_{pp} n'_p \Delta E'_p} \approx 10^{-5.6} \text{ s},$$

- **Proton cooling times for hadronic and electromagnetic processes: photomeson ($t'_{p\gamma}$), proton-proton (t'_{pp}), synchrotron radiation ($t'_{\rm syn}$), IC scattering ($t'_{\rm IC}$) and BH ($t'_{\rm BH}$) (comoving frame).**



Razzaque, Meszaros and Waxman, PRL 93 (2004)

- **The maximum proton energy can be roughly estimated, by equating the $t'_{\rm syn}$ to $t'_{\rm acc}$, since $t'_{\rm BH} \approx t'_{\rm syn} \approx t'_{\rm acc}$ 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 $E'_p \approx 10^4 - 10^5$ 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 $\propto 1/E'^2_p$, 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.**

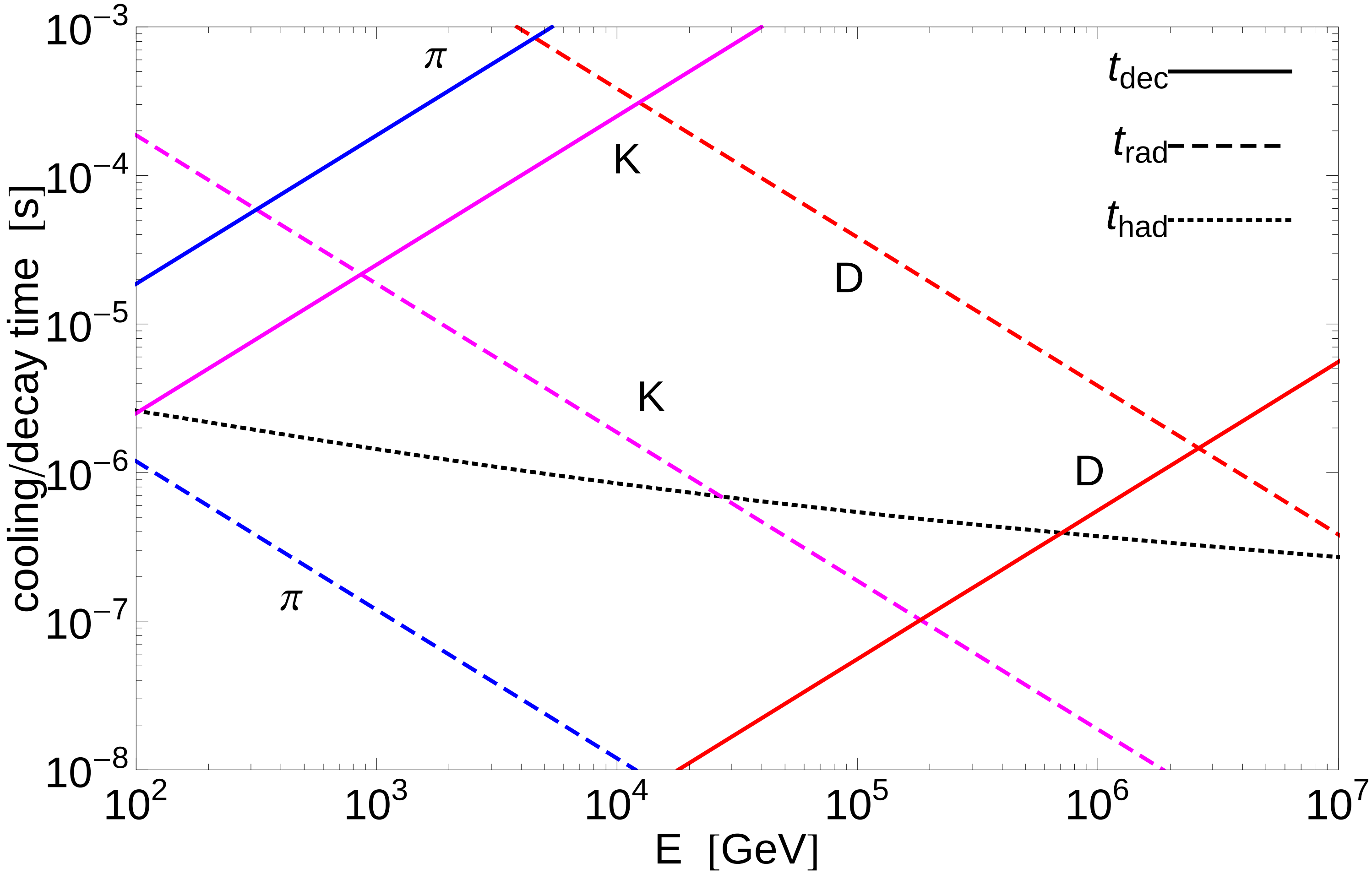
Meson Cooling Chanells

- **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 $t_{\rm em}^{\prime -1} = t_{\rm syn}^{\prime -1} + t_{\rm IC}^{\prime -1}$. 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 is similar to the proton energy losses by pp interactions.**

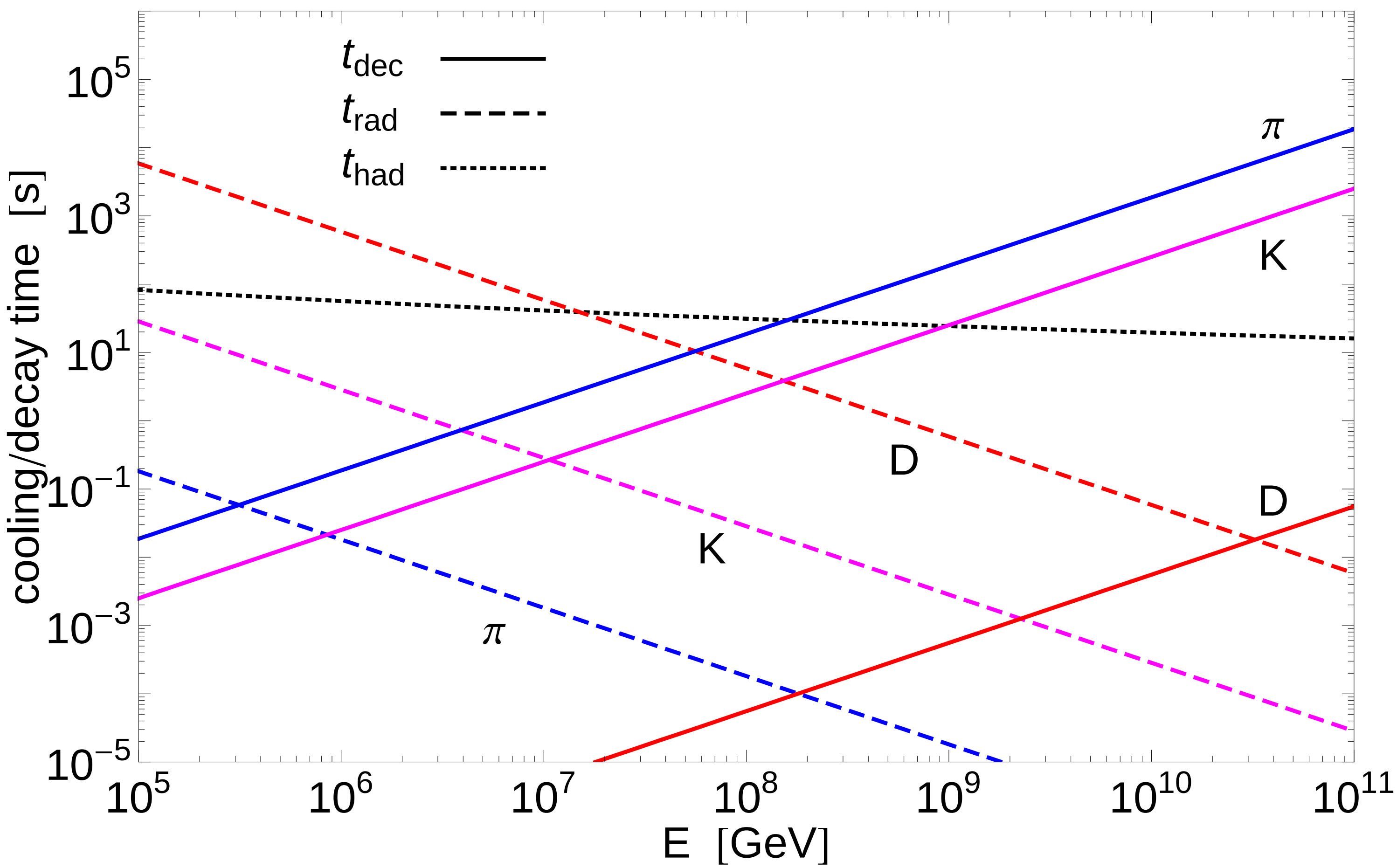
Meson cooling times for the slow-jet core collapse supernovae



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

Enberg, Reno and Sarcevic (2008)

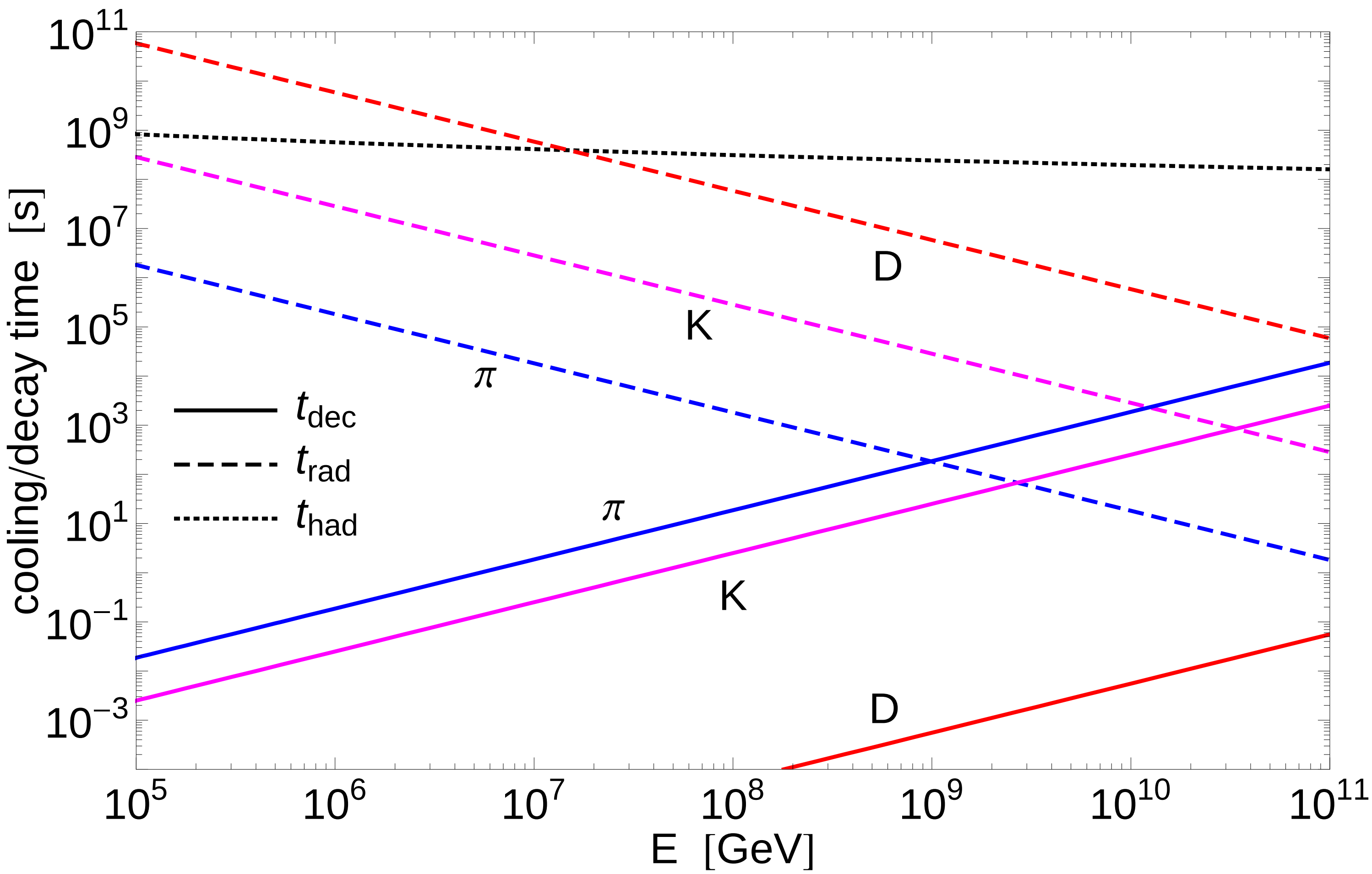
Meson cooling times for the gamma ray burst (GRB)



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

Enberg, Reno and Sarcevic (2008)

Meson cooling times for the AGN



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

Enberg, Reno and Sarcevic (2008)

Neutrino Fluxes at Earth

Enberg, Reno and Sarcevic (2008)

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

$$\frac{d\phi_N}{dX} = -\frac{\phi_N}{\lambda_N} + S(Np \to NY)$$

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

$$\frac{d\phi_\ell}{dX} = \sum_M S(M \to \ell)$$

where $\lambda_k^{\mathbf{had}}$ is the interaction length, $\lambda^{\mathbf{dec}} = \rho\, d_M \simeq \rho\, \gamma c \tau_M$ is the decay length in the comoving frame, $\lambda^{\mathbf{rad}} = \rho\, c t_{\mathbf{rad}}$, and the column depth, $X(r) = \int dr' \rho(r')$.

$S(k \to j)$ is the regeneration function, given by

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

where $\frac{dn(k \to j; E_k, E_j)}{dE_j}$ refers either to the production distribution:

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

or to the decay distribution:

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

We define the Z-moments:

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

- **The nucleon flux equation then has the solution**

$$\phi_N(X,E) = \phi(E) e^{-X/\Lambda_N(E)},$$

where $\phi(E) \propto E^{-2}$ is the incoming flux of nucleons in the jet and

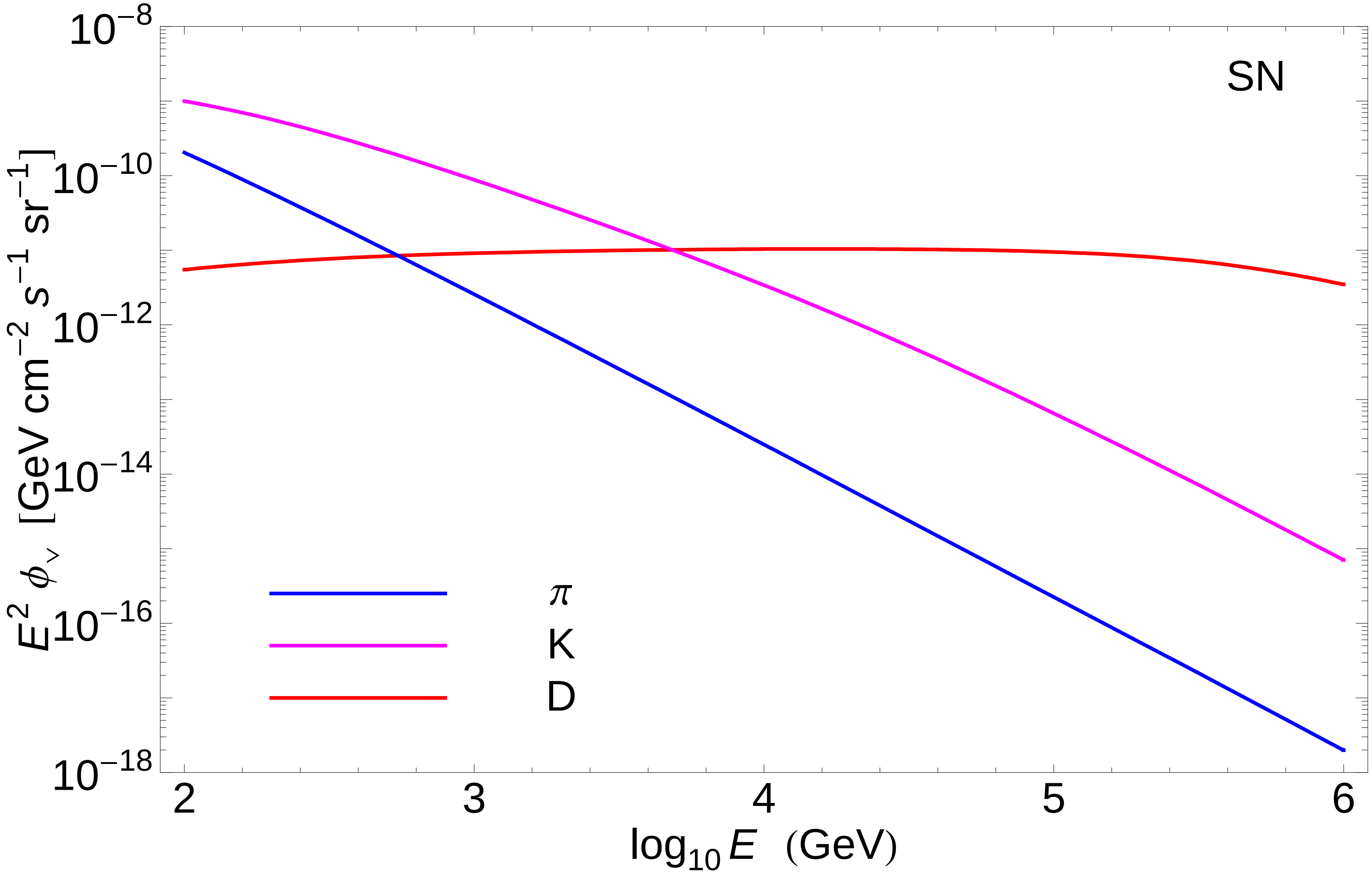
$$\Lambda_N = \frac{\lambda_N^{\mathbf{had}}}{1 - Z_{NN}}$$

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

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

- **We assume that density decreases as $\rho \sim r^{-2}$.**

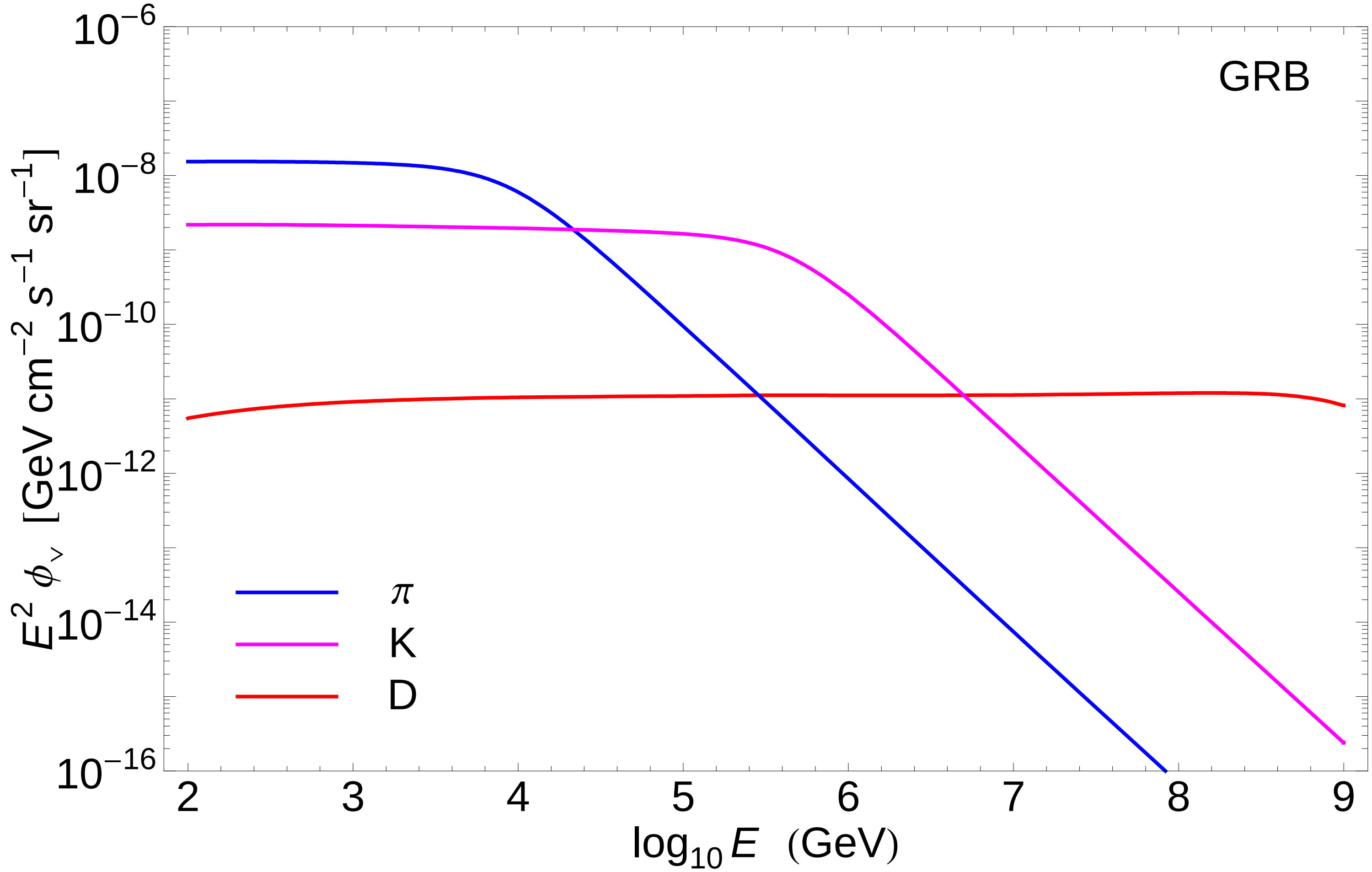
Neutrino Flux from Slow-jet Core Collapse Supernovae



Neutrino flux from decays of pions, kaons and charmed mesons.

Enberg, Reno and Sarcevic (2008)

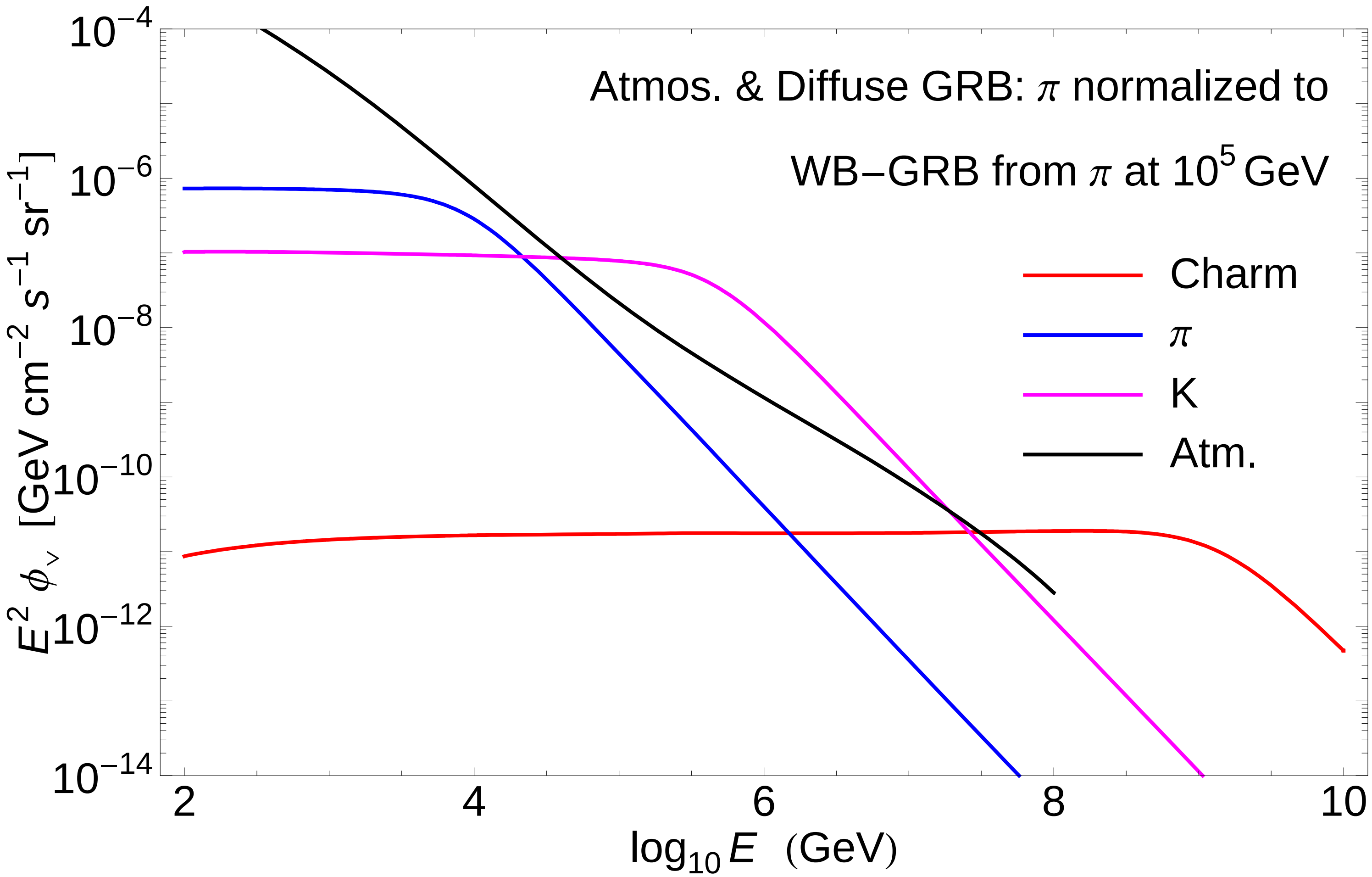
Neutrino Flux from GRBs



Neutrino flux from decays of pions, kaons and charmed mesons.

Enberg, Reno and Sarcevic (2008)

Diffuse Neutrino Flux from GRBs



Diffuse GRB neutrino flux from decays of pions, kaons and charmed mesons, compared to atmospheric neutrino flux.

Enberg, Reno and Sarcevic (2008)

Probing Particle Physics with UHE Neutrinos

- **UHE cosmic neutrinos present unique opportunity to study the interactions of elementary particles at energies beyond current or planned colliders.**

- **Cosmic neutrinos with energies E_ν above 10^{17} eV probe neutrino-nucleon scattering at center-of-mass (c.m.) energies above**

$$\sqrt{s_{\nu N}} \equiv \sqrt{2 m_N E_\nu} \simeq 14 \left(\frac{E_\nu}{10^{17}\ \mathrm{eV}} \right)^{1/2} \mathrm{TeV}$$

- **These energies are beyond the proton-proton c.m. energy $\sqrt{s_{pp}} = 14$ TeV of the LHC, and Bjorken-x values below $\simeq 2 \times 10^{-4}$**

Examples of New Particle Physics that one could probe with UHE neutrinos:

- **Microscopic black holes as predicted in TeV scale gravity models**

- **Production of charged supersymmetric particles (staus) in UHE neutrino interactions**

Measurements of neutrino interactions at extremely high energies $\Rightarrow$ powerful tests of fundamental physics at and beyond a scale of 1-10TeV.

Probing SUSY with Astrophysical Neutrinos

- **In most SUSY scenarios, particle produced in high energy collisions decay immediately into the lightest one and are thus hard to detect.**
- **In some low-scale SUSY models in which gravitino is the lightest supersymmetric particle (LSP), the next-to-lightest particle (NLSP) is the charged super-partner of the right-handed tau, the stau.**
- **The cross section for the production of staus in neutrino-nucleon scattering is several orders of magnitude smaller than neutrino charged-current or neutral-current cross section.**

I. Albuquerque, G. Burdman, Z. Chacko, PRL **92** (2004); PR **D75** (2007)
M. Ahlers, J. Kersten and A. Ringwald, JCAP **0607** (2006)

- However, due to its weak coupling to the gravitino, the stau is a long-lived particle. For the SUSY breaking scale, $\sqrt{F} > 5 \times 10^6$ GeV, the long-lived stau could potentially travel long distances before decaying into gravitino.
- Stau lifetime depends on the gravitino mass (or SUSY breaking scale) and the stau mass, i.e.

$$c\tau = \Big(\frac{\sqrt{F}}{10^7 GeV}\Big)^4 \Big(\frac{100GeV}{m}\Big)^5 10km$$

- Limits on stau mass are about 100GeV (from non-observation in accelerator experiments)
- Stau with energy of 10^6GeV and mass of 100GeV, could potentially travel 10^4 km before decaying

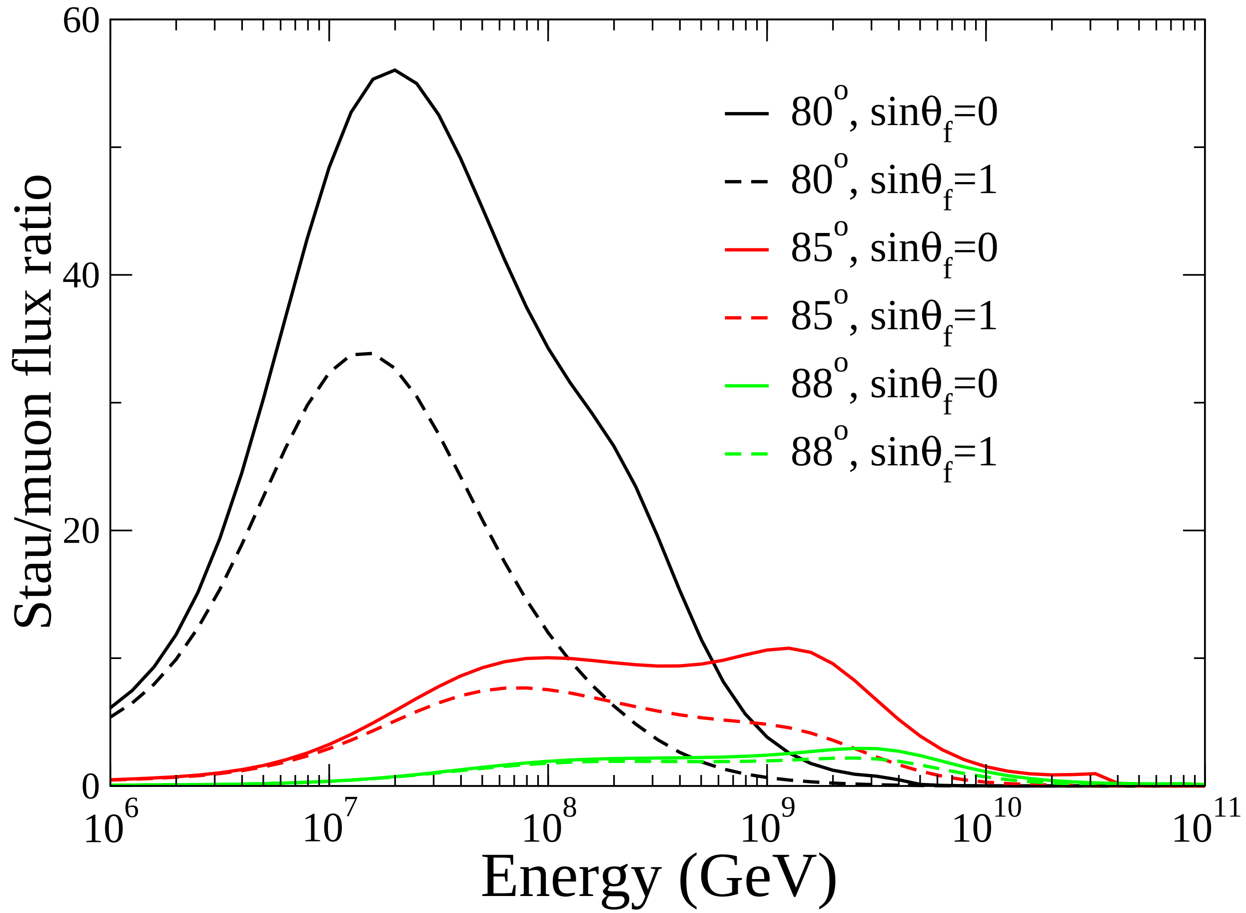
- Detection of staus depend on their initial production and on stau range (charged tracks), and on stau interactions in the detector/ice (showers).
- Stau interactions are important for detection:
  - ⋆ Stau range depends on its energy loss as it traverses the earth. Photonuclear interactions of staus is a dominant process at high energies. Weak interactions suppress the stau range, but they provide the signal for detectors which cannot detect charged tracks.

M.H. Reno, I.S. and S. Su, Astropart. Phys. 24 (2005)
M.H. Reno, I.S. and J. Uscinski, Phys. Rev. D74 (2006)
M.H. Reno, I.S. and J. Uscinski, Phys. Rev. D76 (2007)

- Neutrino telescopes (ICECUBE, ANITA, ARIANNA) have unique ability to provide the first evidence for supersymmetry at weak scale.

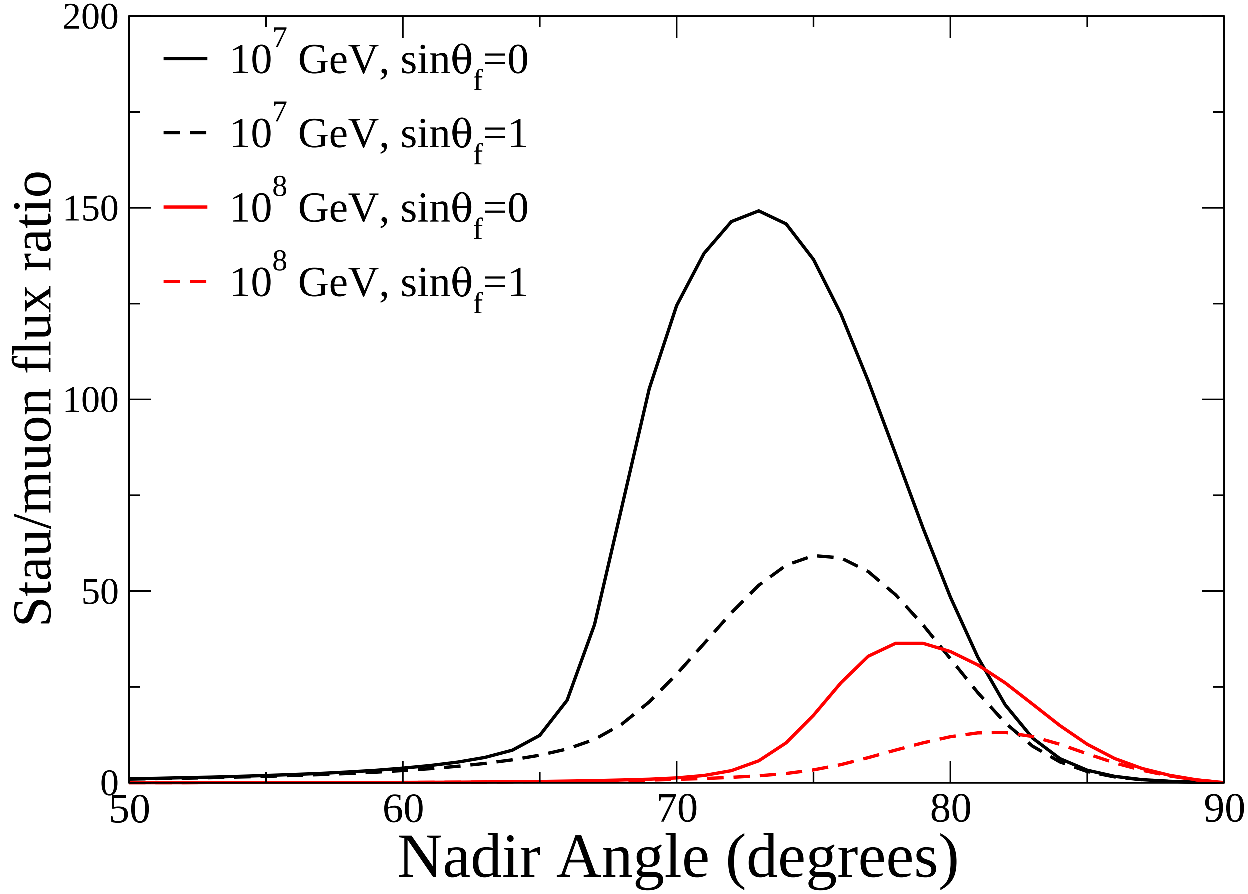
- **Stau production cross section is about three orders of magnitude smaller than the muon production cross section.**
- **Once staus are produced, they lose very little energy as they traverse the earth while muon energy loss is of the order 10^2-10^3 times greater. The stau range can be as high as 10^4 km w.e. for vanishing charged-current interactions or suppressed to about 10^3 km w.e. for maximal charged-current interactions.**
- **Neutrino attenuation has a large effect on the signals. It depletes more muons than staus, since muons must be created near the detector to be seen, whereas the staus can be produced farther away.**
- **Stau to muon ratio depends on the stau (muon) energy as well as the nadir angle. Including maximal charged-current interactions of the stau results in suppression of the signal to background ratio.**

Stau to Muon Flux Ratio for Cosmogenic Neutrinos



Reno, Sarcevic and Uscinski, Phys. Rev. D76 (2007)

Stau to Muon Flux Ratio for Cosmogenic Neutrinos

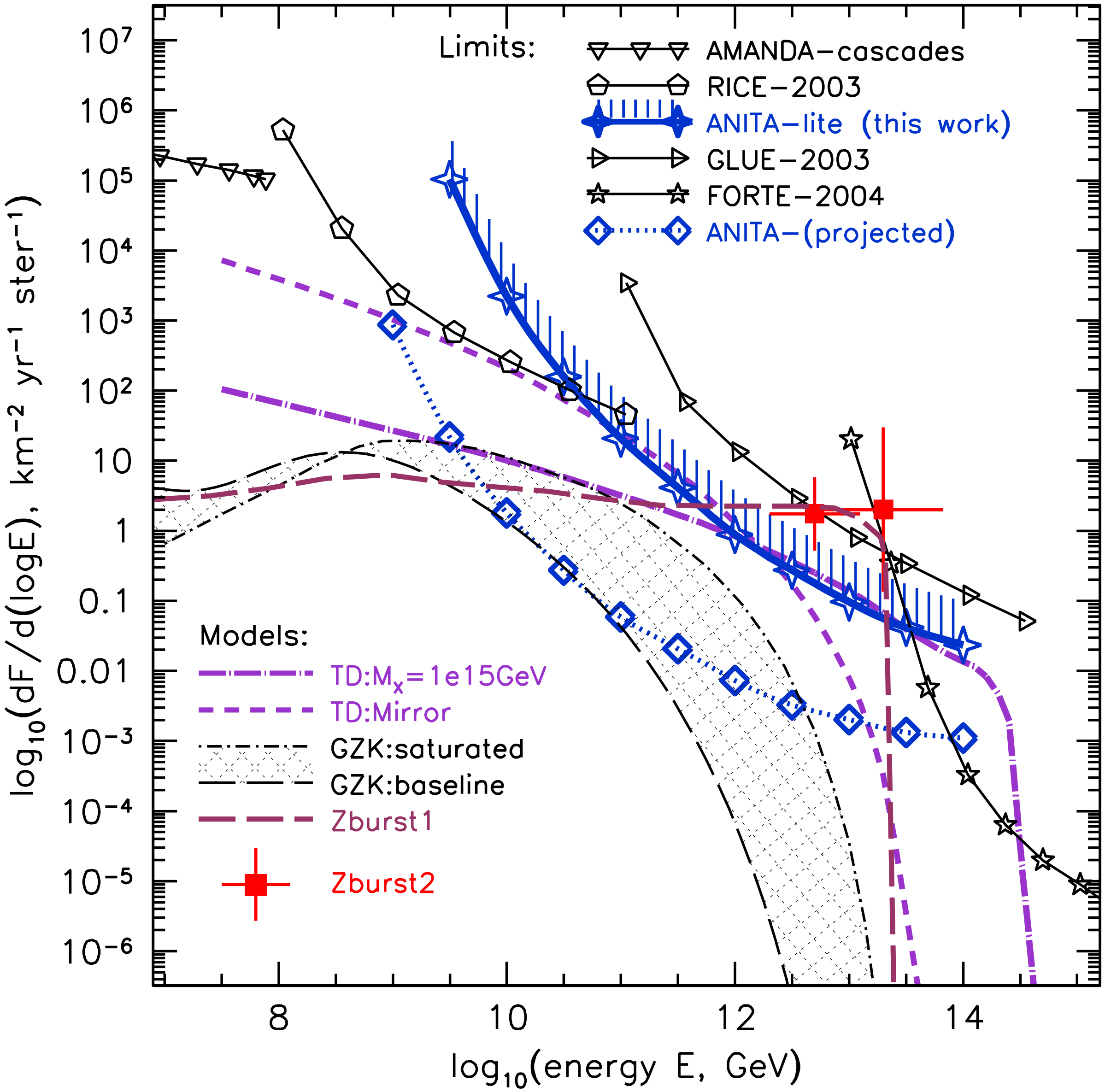


SUMMARY

- **Neutrinos from astrophysical sources originate in interactions of the shock accelerated protons with cold protons, which produce mesons (pions, kaons, charmed mesons) that decay into neutrinos.**
- **At low energy, dominant contribution to neutrino flux comes from the pion decay.**
- **As energy increase, pion cooling becomes important and dominant contributions to neutrinos come from kaon decay.**
- **At even higher energies, both pions and kaons interact either hadronically or electromagnetically, while charmed mesons decay into neutrinos. At these energies, neutrinos come from charmed meson decay.**

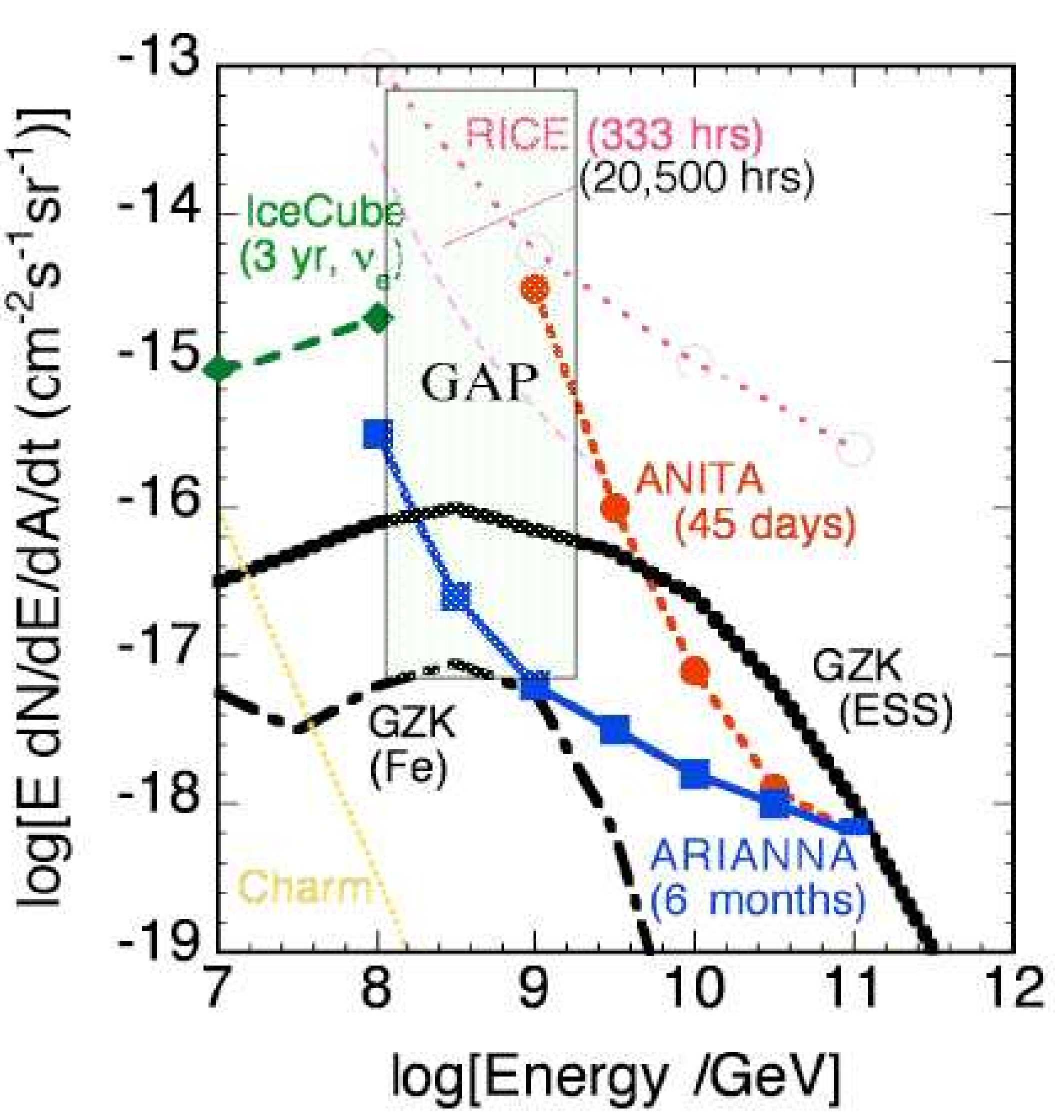
- **Astrophysical neutrinos are unique probes of the mechanism that takes place in astrophysical sources that is responsible for producing observed high energy (TeV) gamma rays from these sources**
- **In addition, high energy neutrino telescopes have unique ability to provide the first eveidence for physics beyond the standard model (low scale supersymmetry, TeV scale gravity, extra dimensions...)**

Neutrino Flux limits (ANITA and ANITA-lite)



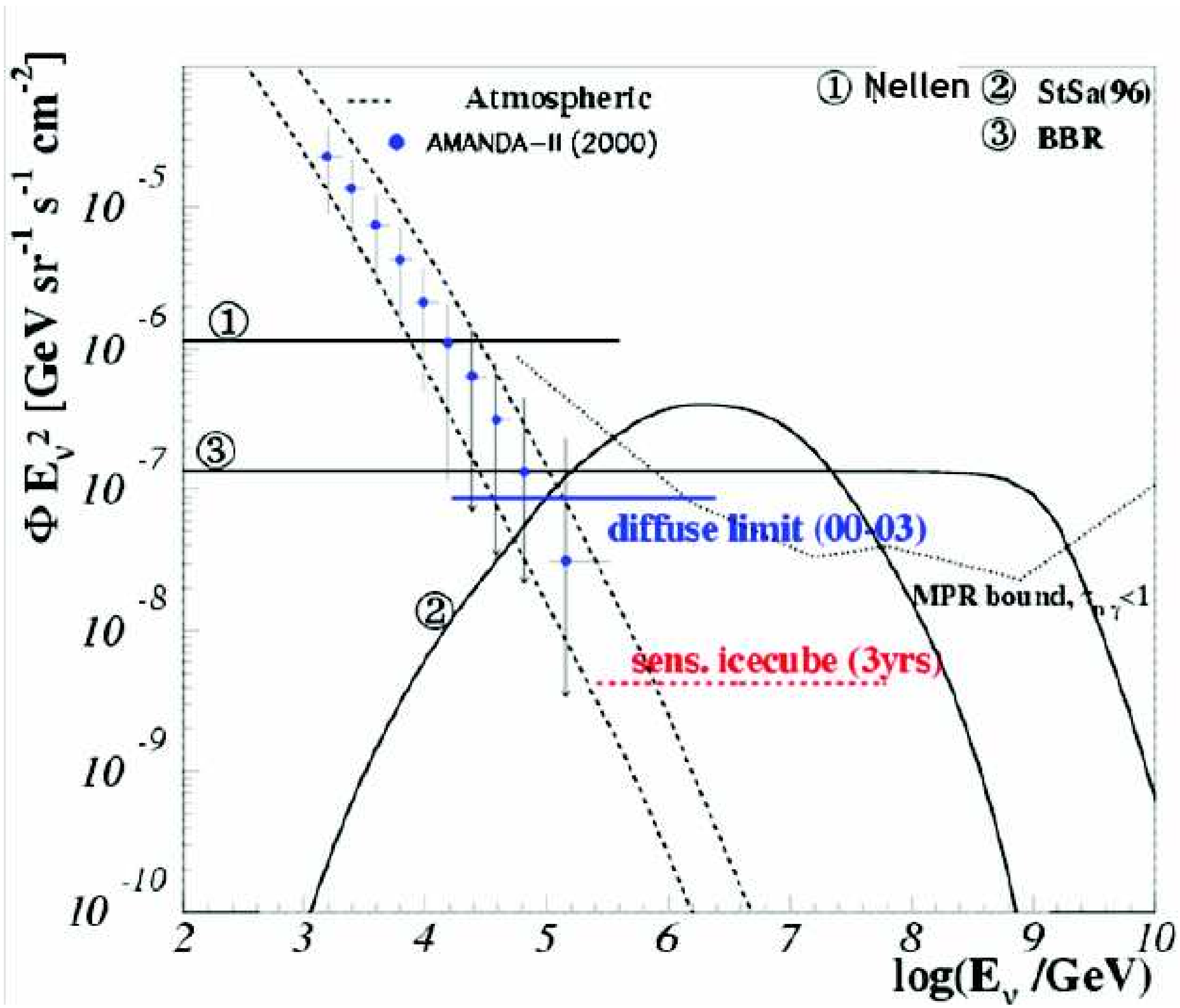
Anita Collaboration, PRL 96 (2006)

ARIANNA: Antarctic Ross Iceshelf ANtenna Neutrino Array



S. Barwick, arXiv:astro-ph/0610631

Amanda neutrino flux limit and IceCube sensitivity



IceCube Collaboration, presented at TeV Particle Astrophysics Workshop, Madison, August 2006