Neutrinos from charm production: atmospheric and astrophysical applications

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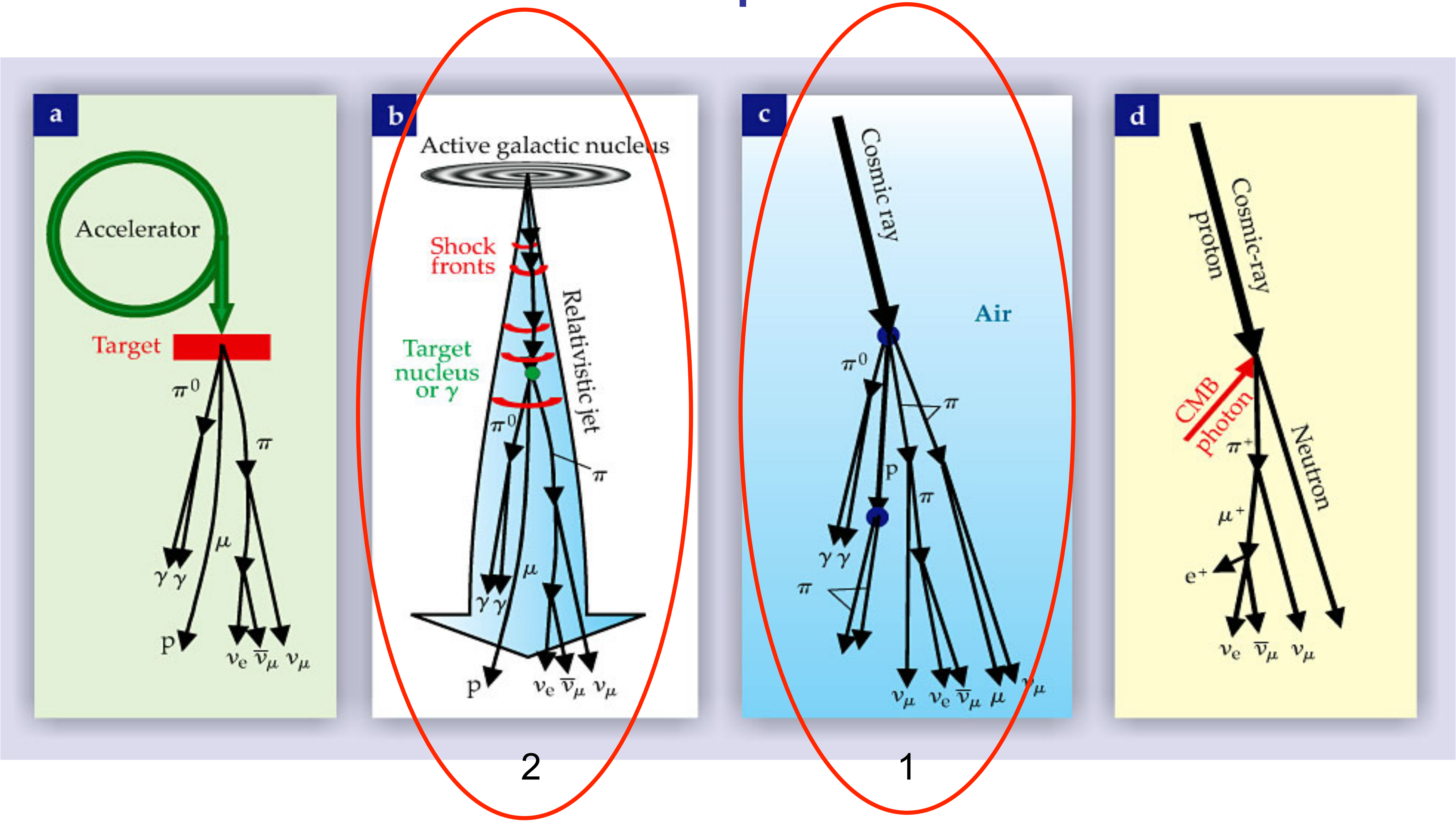
June 9, 2011

QCD in Paris

Collaborators: Ina Sarcevic and Rikard Enberg

Neutrino production



F. Halzen and S. Klein, Physics Today, May 2008

Plan

- Back of envelope evaluation of atmospheric lepton flux
- Standard model physics at energies above accelerator energies: results on high energy lepton contribution from charm production and decay in the atmosphere.
- Similar evaluation in context to astrophysical sources

http://www.particlezoo.net/shop.html

Collaborators: Rikard Enberg & Ina Sarcevic

Some References

- Cosmic Rays and Particle Physics, T. Gaisser, Cambridge U Press
- Gaisser & Honda, Ann. Rev. Nucl. Part. Sci. 52 (2002) 153 and references therein. (GH label below)
- L. V. Volkova, Sov. J. Nucl. Phys. 31 (1980)
- P. Lipari, Astropart. Phys. 1 (1993)
- Thunman, Ingelman and Gondolo, Astropart. Phys. 5 (1996) (TIG label below)

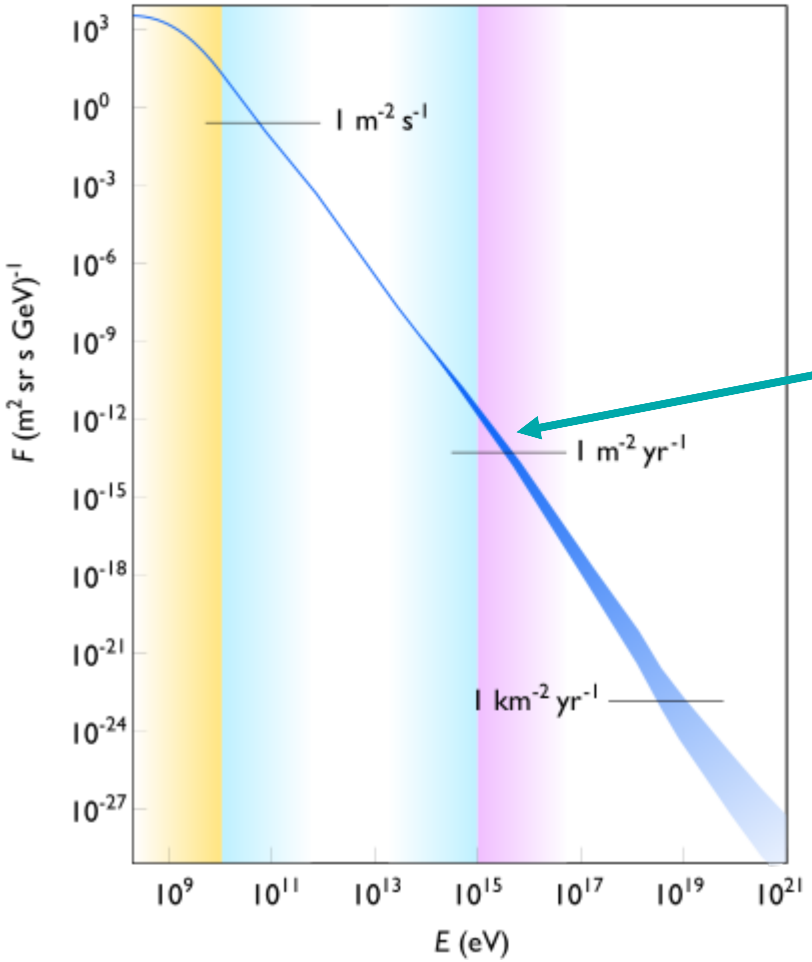
Our work on lepton fluxes from charm decays:

- Pasquali, Reno & Sarcevic, Phys. Rev. D 59 (1999)
- Enberg, Reno & Sarcevic, Phys. Rev. D 78 (2008)
- Enberg, Reno & Sarcevic, Phys. Rev. D 79 (2009)

Ingredients for atmospheric lepton flux

- Cosmic ray flux – energy spectrum and composition
- CR interaction cross section with air nuclei (A = 14.5)
  - Regeneration of CRs
  - Production of mesons, including the energy distributions
- Decays of meson, including energy distribution of leptons
- Coupled transport equations of CRs, mesons and leptons

Cosmic ray flux

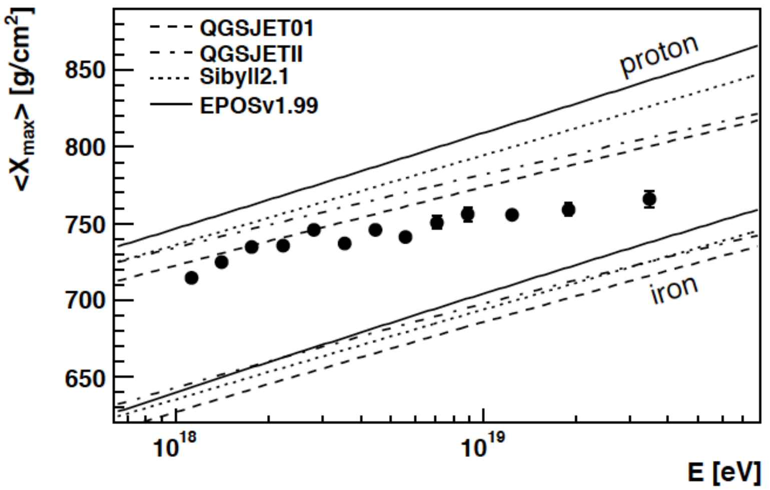


S. Lafebre, http://en.wikipedia.org/wiki/Cosmic_rays
following S. Swordy.

$$\phi \sim \frac{1.7}{E_{\mathrm{GeV}}^{2.7}} \frac{1}{\mathrm{cm}^2 \mathrm{s}\,\mathrm{sr}\,\mathrm{GeV}}$$

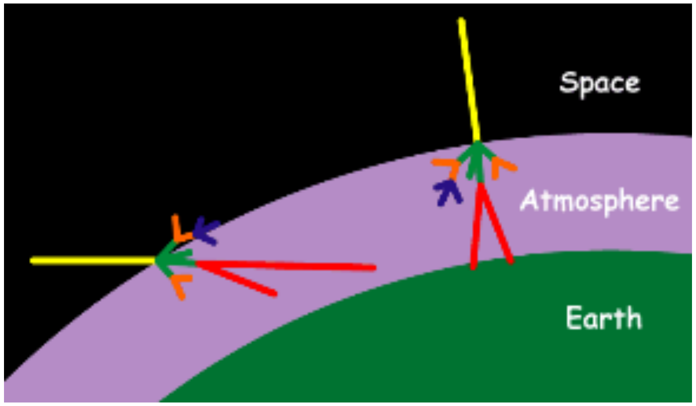
approximately isotropic above 30 GeV,
(I will call them protons or N)

“knee”, change in energy behavior



Auger Collab, arXiv:1002.0699

Distance scales and column depth



Different from most particle physics experiments: exponential atmosphere:

$$\rho = \rho_0 e^{-h/h_0} \quad \rho_0 \simeq 2 \times 10^{-3}\ \mathrm{g/cm^3},\ h_0 \simeq 6.4\ \mathrm{km}$$

$$\frac{1}{\ell_N} = \sigma_{N\,\mathrm{air}} \times \frac{N_A}{A} \times \rho \longrightarrow \qquad \frac{1}{\lambda_N} = \sigma_{N\,\mathrm{air}} \times \frac{N_A}{A}$$

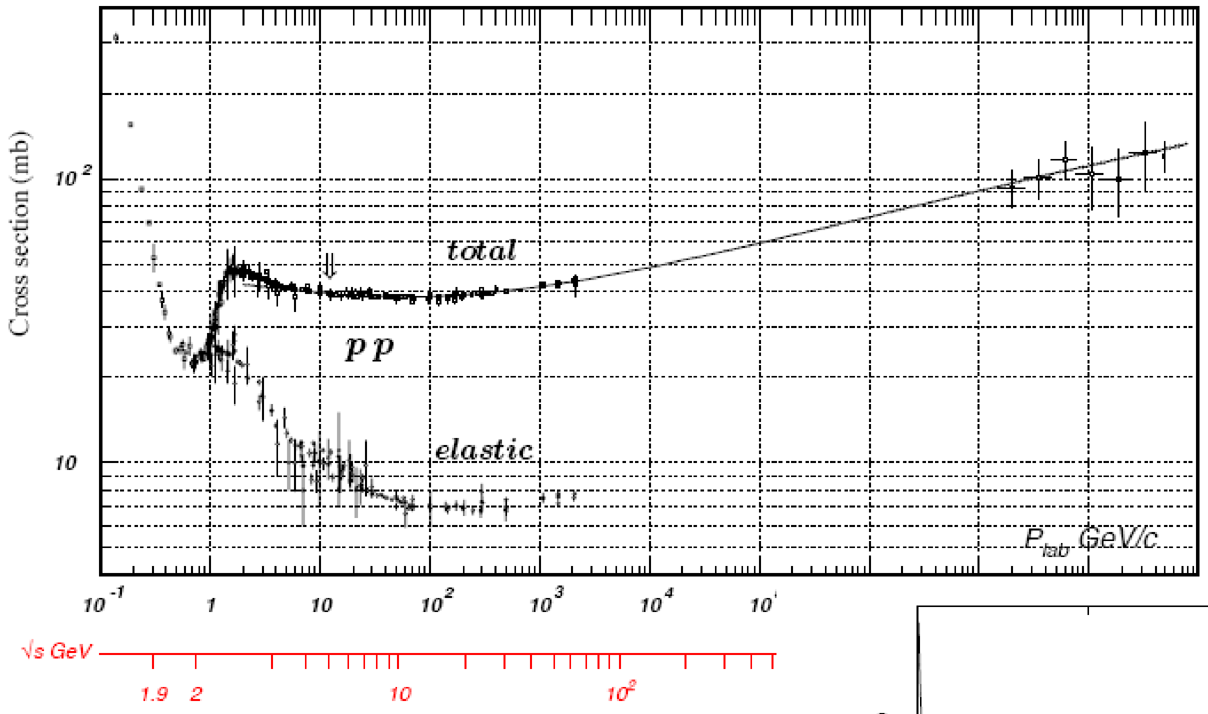
$$X_v = \int_h^\infty \rho(h')\, dh'$$

Vertical column depth

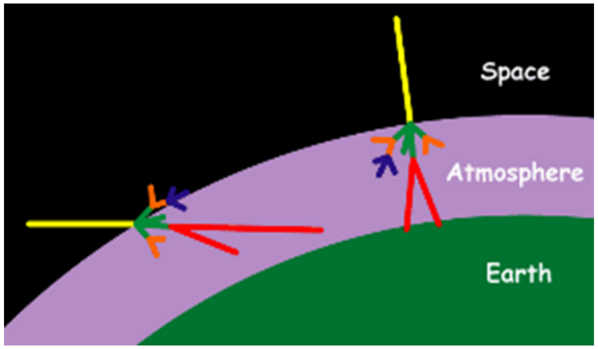
$$\gamma c\tau \to \gamma c\tau\rho$$

Decay length, depends on depth in these units

Figure from: http://www2.slac.stanford.edu/vvc/cosmic_rays.html

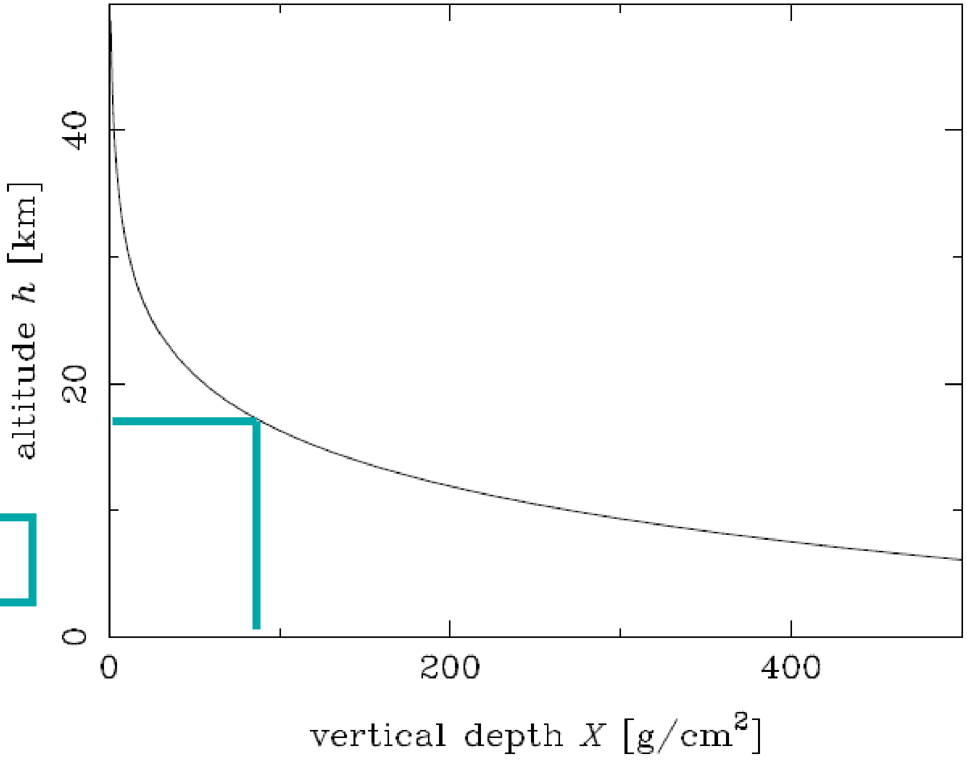


pdg.lbl.gov



$$\sigma_{N\,\mathrm{air}} = 300\ \mathrm{mb}$$

$$\lambda_N \simeq 80\ \mathrm{g/cm}^2$$



Altitude of interaction: approx. 15 km

pA collisions produce hadrons and eventually leptons (etc)

$$
\begin{aligned}
pA &\to \pi^{\pm} \\
&\to \pi^{0} \\
&\to K^{\pm} \\
&\to K_L,\ K_S \\
&\to D^{\pm} \ldots
\end{aligned}
$$

Electron neutrinos, muon neutrinos and muons.

$$
\begin{aligned}
\pi^- &\to \mu \bar{\nu}_\mu \quad B = 100\% \\
\pi^0 &\to \gamma\gamma \quad B = 98.8\% \\
K^- &\to \mu \bar{\nu}_\mu \quad B = 63.5\% \\
K_L &\to \pi \ell \bar{\nu}_\ell \quad B(K_{e3}) = 38\%,\ B(K_{\mu 3}) = 27.2\% \\
&\ldots
\end{aligned}
$$

“conventional atmospheric flux” from pions and kaons

Conventional and prompt

	$c\tau_0$ [cm]		$c\tau_0$ [cm]
$\pi^\pm$	730	$D^\pm$	0.028
$K^\pm$	371	D^0	0.013
μ	30,000		

Decay lengths for relativistic particles

	$\gamma c\tau_0$ [m]		$\gamma c\tau_0$ [m]
$\pi^\pm$	$52\ E/\mathrm{GeV}$	$D^\pm$	$1.5 \times 10^{-4}\ E/\mathrm{GeV}$
$K^\pm$	$7.5\ E/\mathrm{GeV}$	D^0	$7 \times 10^{-5}\ E/\mathrm{GeV}$

Here decay length=h0

"Critical energies" for vertical mesons: decay lengths=15 km

$E_c^\pi = 290$ GeV

$E_c^K = 2$ TeV

$E_c^{D^\pm} = 10^8$ GeV

$E_c^{D^0} = 2 \times 10^8$ GeV

$\epsilon_c^\pi = 115$ GeV

$\epsilon_c^K = 850$ GeV

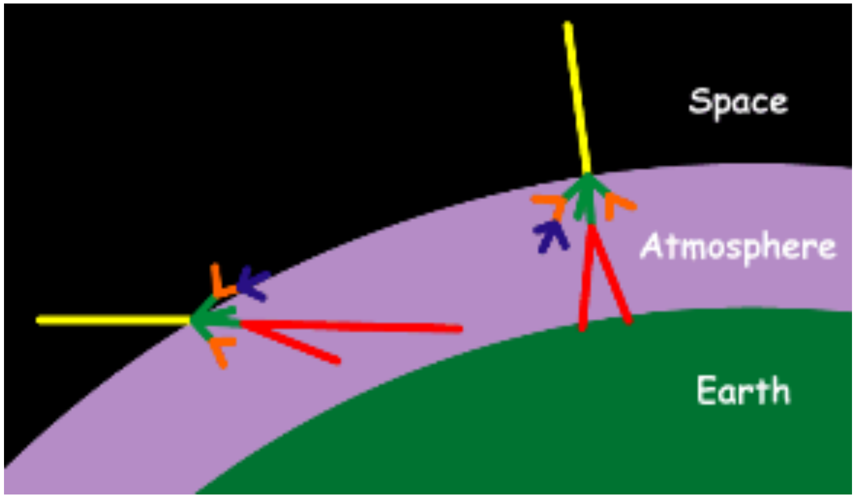
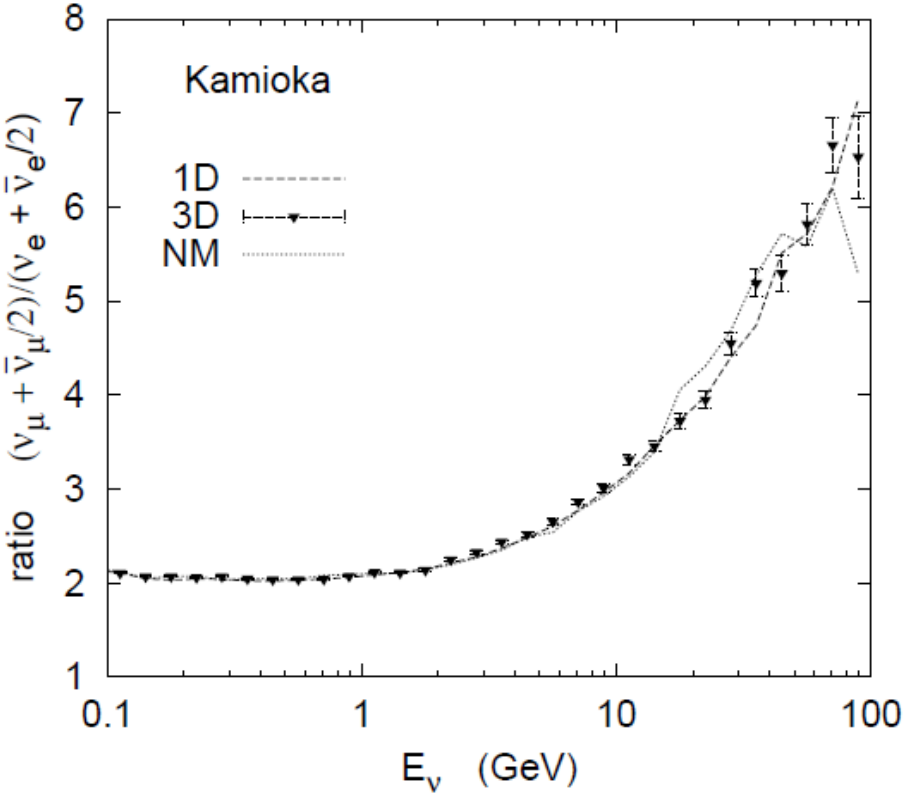


Figure from: http://www2.slac.stanford.edu/vvc/cosmic_rays.html

Critical energies depend on incident angles:

$$\sim \epsilon_c^i / \cos\theta$$



2:1 ratio when muons decay

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

$$\mu^+ \rightarrow \bar{\nu}_\mu e^+ \nu_e$$

Ratio doesn't go to infinity because some electron neutrinos produced in kaon decays.

Transport equations

$$\frac{d\phi_j}{dX} = -\frac{\phi_j}{\lambda_j} - \frac{\phi_j}{\lambda_j^{\mathrm{dec}}} + \sum S(k \to j)$$

For which particles? High enough energies that muons are "stable".

$$S(k \to j) = \int_E^\infty dE' \frac{\phi_k(E')}{\lambda_k(E')} \frac{dn(k \to j; E',\ E)}{dE}$$

$$j = N,\ \pi,\ K,\ D,\ \nu_i,\ \mu$$

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

Production

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

Decay

Need cross section and energy distribution of the final state particle.

Conventional lepton flux

$$\frac{d\phi_j}{dX} = -\frac{\phi_j}{\lambda_j} - \frac{\phi_j}{\lambda_j^{\rm dec}} + \sum S(k \to j)$$

$$S(k \to j) = \int_E^\infty dE' \frac{\phi_k(E')}{\lambda_k(E')} \frac{dn(k \to j; E',\ E)}{dE}$$

Example: proton to proton

$$S(k \to j) = Z_{kj}(E) \frac{\phi_k(E)}{\lambda_k(E)}$$

Z-factor approximately independent of *X*

$$\phi_N(E, X) = \exp(-X(1 - Z_{NN})/\lambda_N)\phi_N(E, 0), \quad Z_{NN} \simeq 0.4$$

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

Another example:

$$\phi_\pi \simeq Z_{N\pi} \times \text{factor} \times \phi_N(E, 0)$$

$$\phi_\nu \simeq P_{\pi \to \nu}^{\rm dec} Z_{\pi\nu} \times \text{factor} \times \phi_\pi$$

High energy: $P_{\pi \to \nu}^{\rm dec} = 1 - \exp(-ct/\gamma c\tau) \simeq E_c^\pi / E$

Low energy: $P_{\pi \to \nu}^{\rm dec} \simeq 1$

$$Z_{N\pi} = 0.1$$

$$Z_{\pi\nu} = 0.06$$

$$E_c^\pi = 290 \text{ GeV}$$

$$E_c^D = 2 \text{ TeV}$$

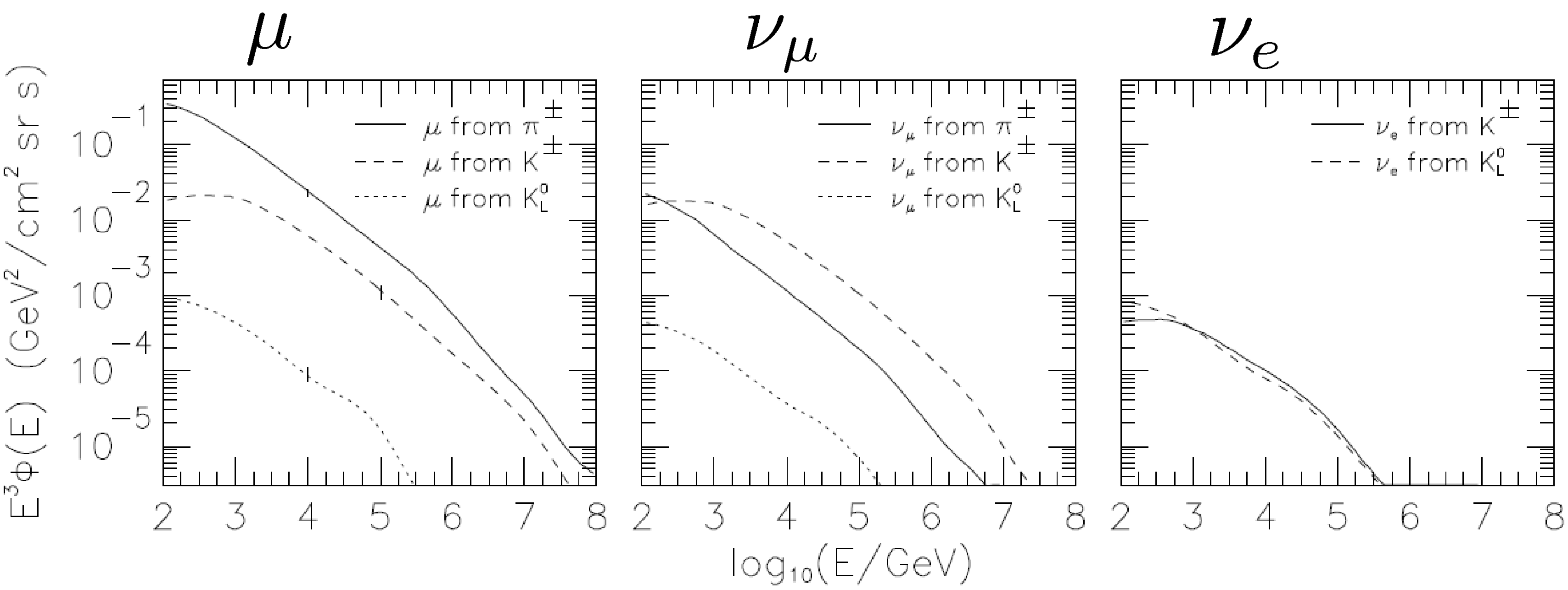
Approximate formulae

$$\phi_\ell^{low} = \frac{Z_{NM} Z_{M\ell}}{1 - Z_{NN}} \phi_N$$

$$\phi_\ell^{high} = \frac{Z_{NM} Z_{M\ell}}{1 - Z_{NN}} \frac{\ln(\Lambda_M/\Lambda_N)}{1 - \Lambda_N/\Lambda_M} \frac{\epsilon_c^M}{E} \phi_N$$

Exponential atmosphere, 1D, approximate factorization of depth dependence.

Conventional lepton fluxes (vertical)



$$\phi_N \sim E^{-2.7}$$

$$\phi_\nu^{\mathrm{low}} \sim E^{-2.7}$$

$$\phi_\nu^{\mathrm{high}} \sim E^{-3.7}$$

Fig. from Thunman, Ingelman and Gondolo, (TIG) Astropart. Phys. 5 (1996)
Used PYTHIA and JETSET.

Prompt neutrinos: charm contributions using parton distribution functions

PDF = parton distribution function

$$\sigma(pp\to c\bar{c}X)\simeq\int dx_1\,dx_2\,G(x_1,\mu)G(x_2,\mu)\hat{\sigma}_{GG\to c\bar{c}}(x_1x_2s)$$

One approach, pQCD with PDFs.

$$x_1,\ x_2:$$

$$x_F=x_1-x_2$$

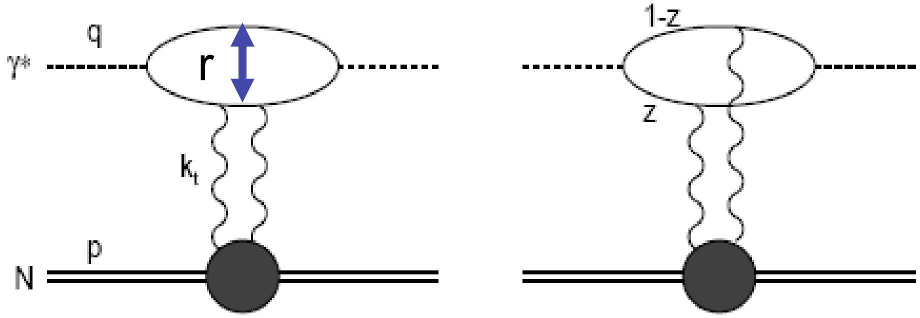
$$x_F\simeq x_E=E/E'$$

$$x_{1,2}=\frac{1}{2}\left(\sqrt{x_F^2+\frac{4M_{c\bar{c}}}{s}}\pm x_F\right)\qquad x_1\simeq x_F\sim 0.1,\quad x_2\ll 1$$

Disadvantage: need gluon PDF in low x, not very big Q range.

Charm contributions: dipole approach

Advantage: don’t need small x gluon PDF



$$\begin{aligned}\gamma^* &\rightarrow q\bar{q}\\ q\bar{q}\,N &\rightarrow X\end{aligned}$$

heavy quarks:

$$\begin{aligned}\gamma^* &\rightarrow c\bar{c}\\ c\bar{c}\,N &\rightarrow c\bar{c}X'\end{aligned}$$

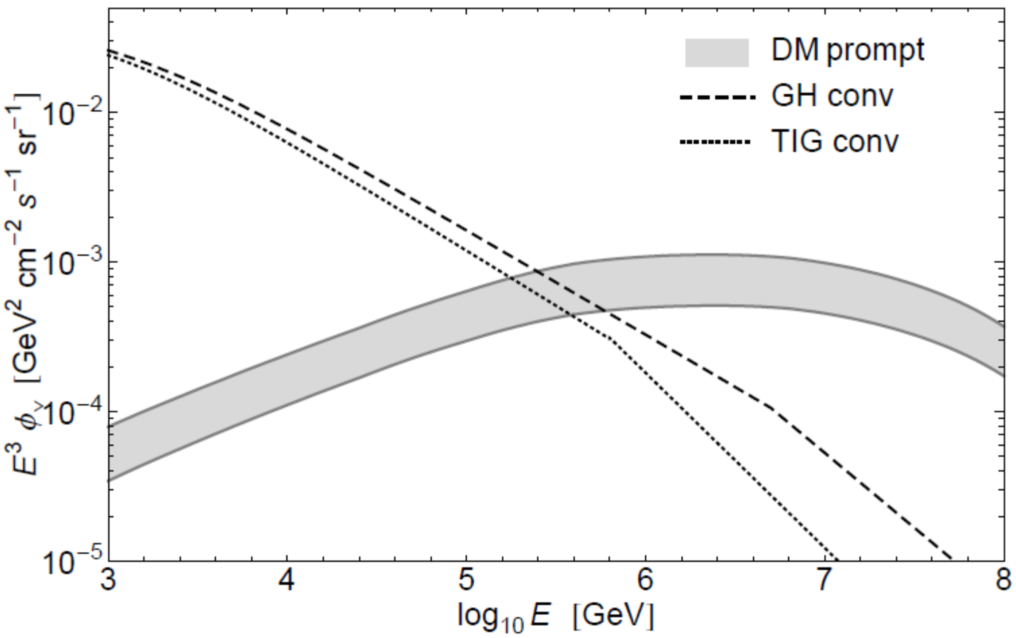
$$\sigma_T(\gamma^* N) \quad = \quad \int_0^1 dz \int d^2 r \mid \Psi_T(z,\mathbf{r},Q^2) \mid^2 \sigma_{dN}(x,\mathbf{r})$$

- Golec-Biernat & Wusthoff (GBW, PRD 59 (1999))
- Data show as small x that the [illegible] proton cross section scales: dipole model inclu[illegible]ing (Stasto, Golec-Biernat & Kwiecinski, PRL 86 (200[illegible]

SEE RIKARD ENBERG’s TALK THIS AFTERNOON

- Improved QCD motivated form – Balitsky-Kovchegov (BK) evolution
- Modified for gluon -> charm anticharm pair

Results for prompt lepton flux (vertical)



DM=dipole model

GH=Gaisser-Honda

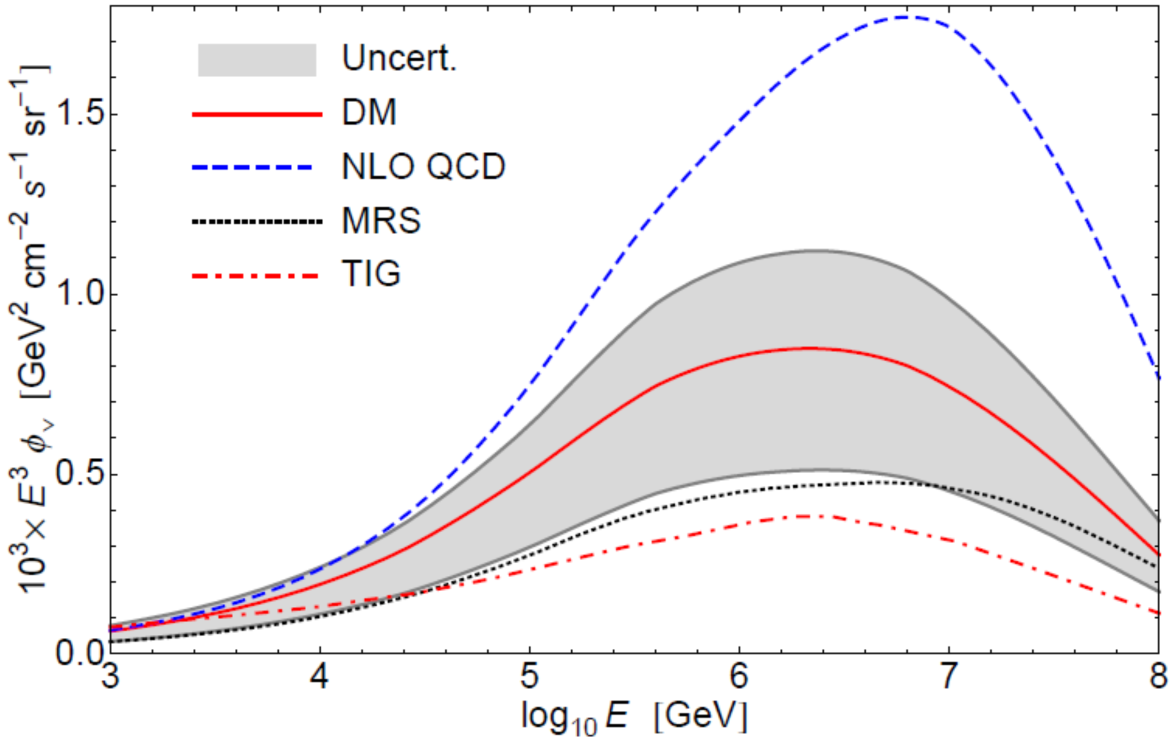
TIG=Thunman et al. (PDF + pythia, small x extrapolation)

Uncertainties: charm mass, gluon PDF, dipole parameters, scales

Enberg, Reno, Sarcevic, Phys. Rev. D 78 (2008) 043005

Using dipole model parameterization of Soyez, Phys. Lett. B 655 (2007) fit to the IMM approximate solution to the BK equations, (Iancu, Itakura, Munier PLB 590 (2004)), prescription for hadronic scattering by Nikolaev, Piller & Zakharov, ZPA 354 (1996), incl. fragmentation.

Prompt flux



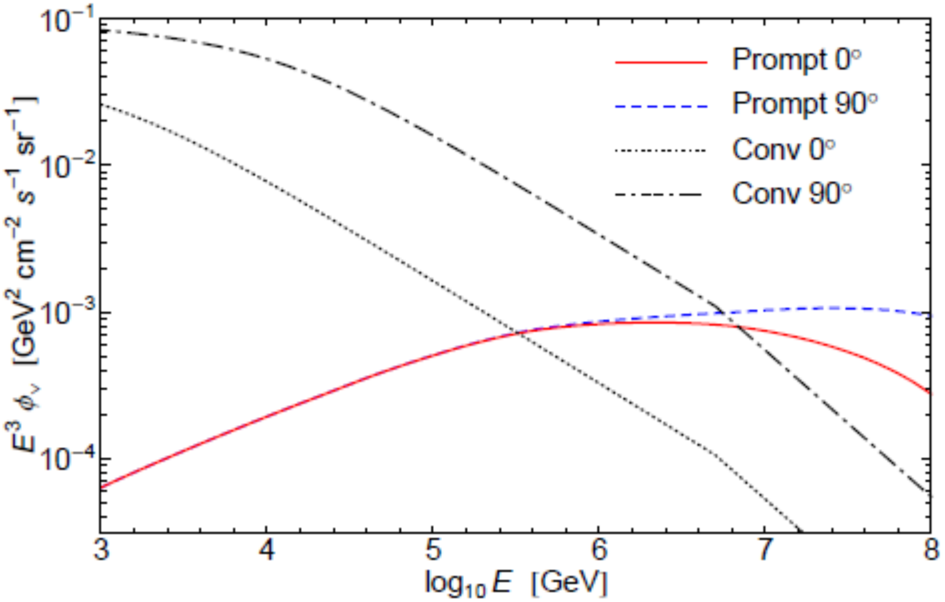
Range of predictions

DM=our dipole model

MRS=Martin, Roberts, Stasto, Acta Phys. Polon. B34 (2003), uses a simpler form for dipole model cross section.

Enberg, Reno, Sarcevic, Phys. Rev. D 78 (2008) 043005

Atmospheric neutrinos-angular dependence

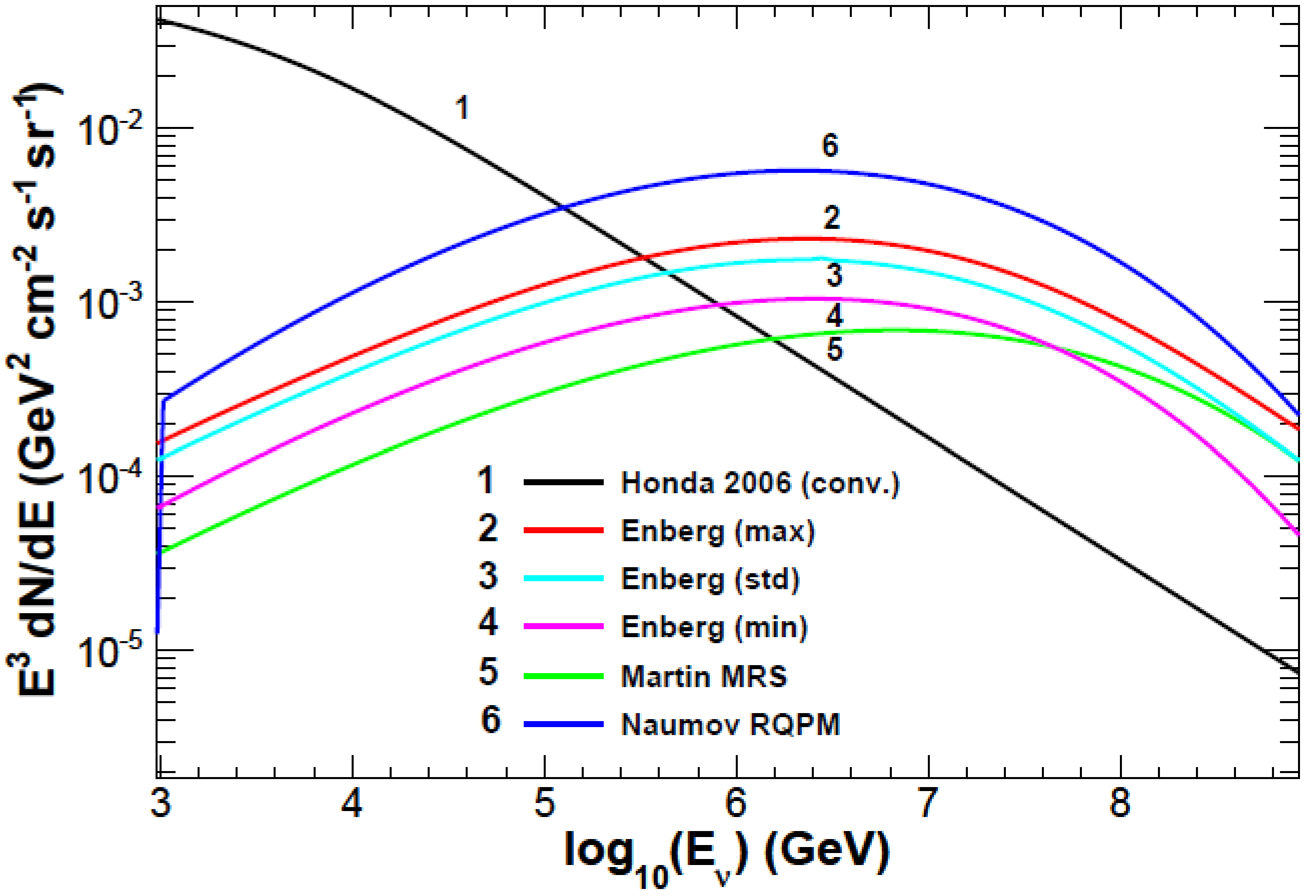


Muon neutrino plus antineutrino flux, from our dipole model "prompt" calculation.

Conventional flux from Gaisser-Honda.

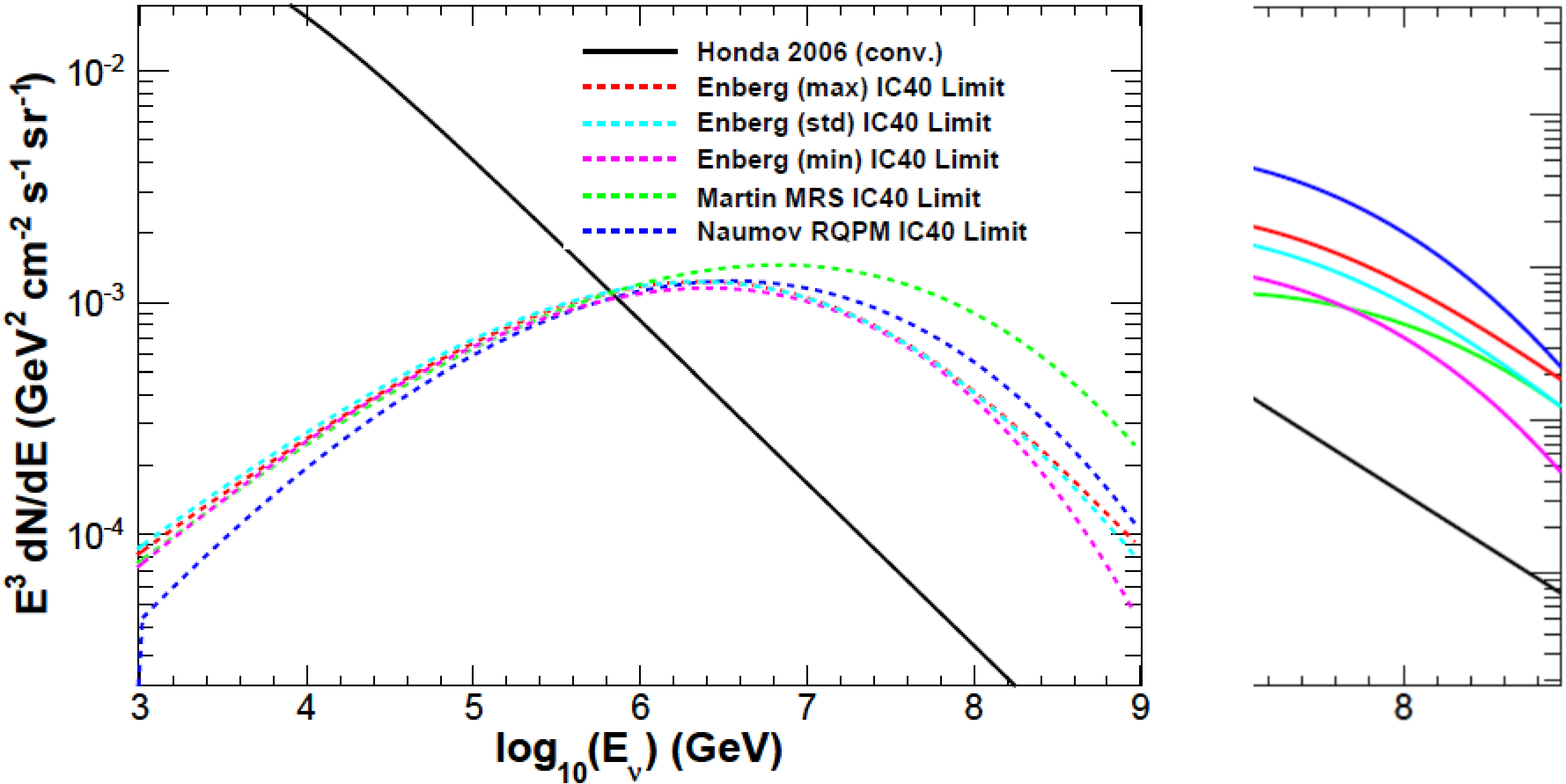
Enberg, Reno, Sarcevic, Phys. Rev. D 78 (2008) 043005

Predictions of the prompt muon neutrino flux



IceCube Collab., arXiv:1104.5187

Limits on prompt muon neutrino flux



IceCube Collab., arXiv:1104.5187

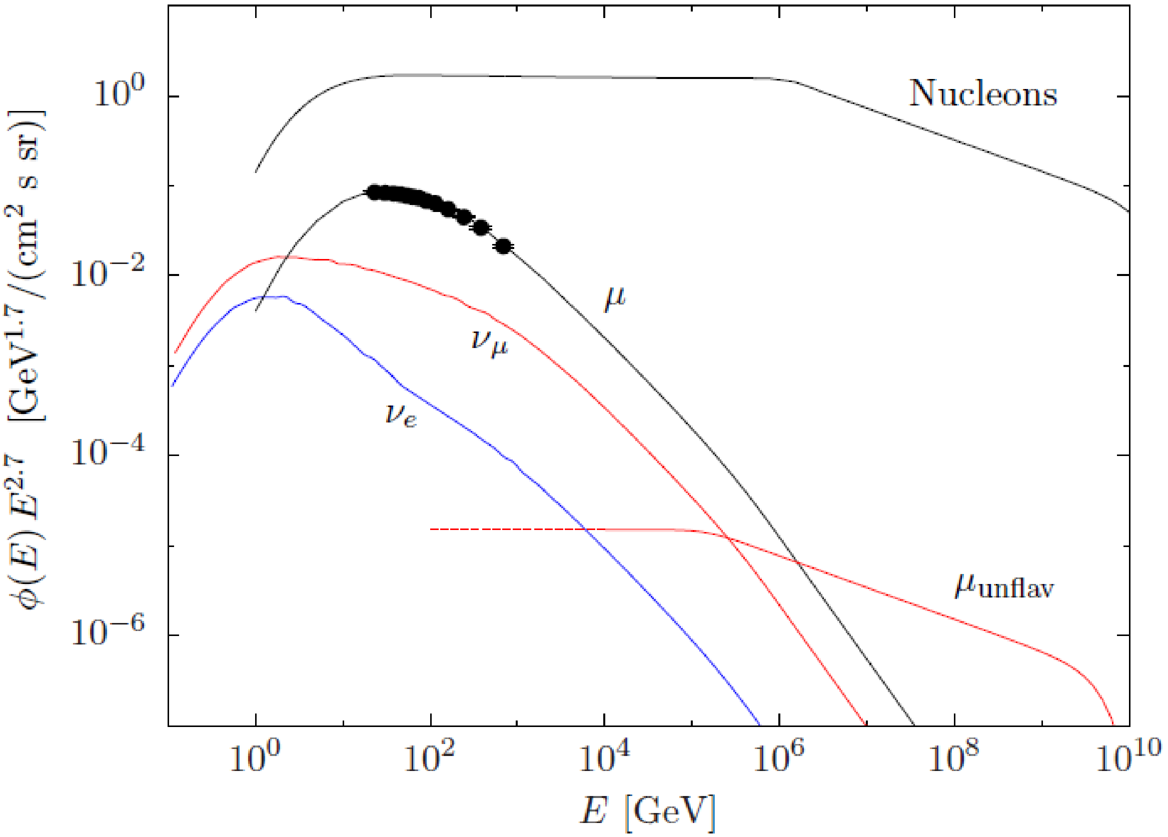
Caveats

- IceCube used extrapolated conventional spectrum of Honda et al.
- Expect a steepening of the incident CR spectrum, which will be reflected in steeper conventional neutrino fluxes
- CR composition comes into play
- Expect some relaxation of the constraints on the prompt models…stay tuned!

IceCube Collab., arXiv:1104.5187

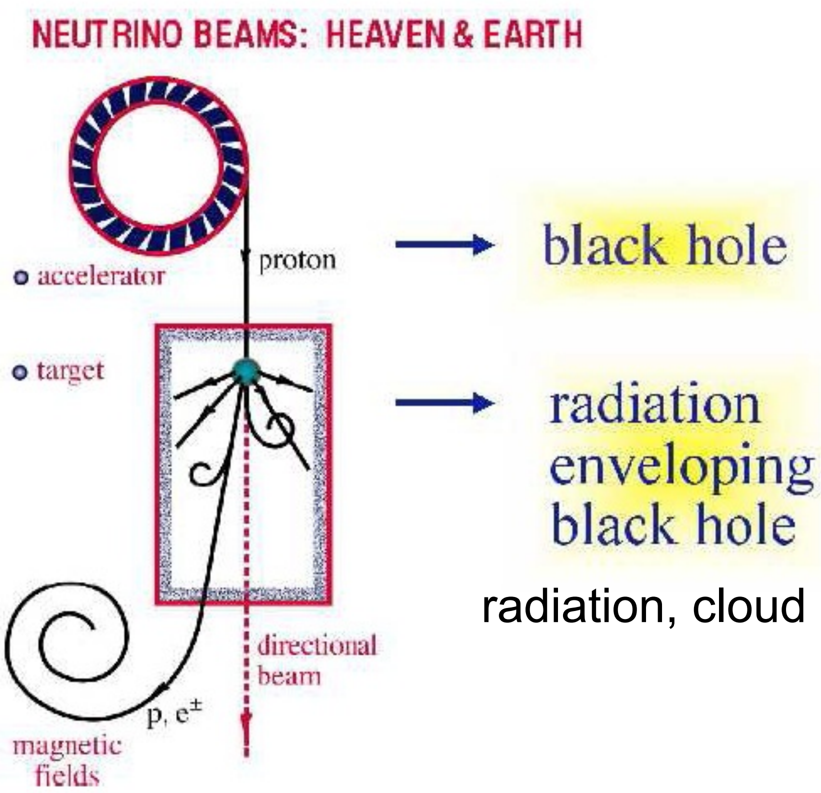
Unflavored – prompt – electromagnetic decays to muons

$\eta,\ \eta',\ \rho^0, \omega\ldots$



Illana, Lipari, Masip and Meloni, arXiv:10105084

b.) Astrophysical sources



radiation, cloud of gas

- hidden source (neutrinos only, not even cosmic rays!)
- transparent source (cosmic rays, photons and neutrinos)
- in-between source

Halzen, astro-ph/0506248

Basic processes to yield neutrinos

- need CR acceleration (Fermi shock) $\phi_p \sim E_p^{-2}$

- need targets

Photon target:

$$p\gamma \rightarrow \Delta^+ \rightarrow n\pi^+, \quad \pi^+ \rightarrow \mu^+\nu_\mu, \quad n \rightarrow pe\bar{\nu}_e, \quad \mu \text{ decay}$$

Proton target:

$pp \rightarrow \pi^0,\ \pi^\pm,\ K^\pm$ followed by decays

- account for interactions (cooling, hadronic or radiative) (affects energy dependence of decaying mesons, therefore neutrinos)

- normalization

Some candidate neutrino sources

- Gamma ray bursts (GRB): relativistic fireball expanding which eventually allows release of photons (non-thermal spectrum), some baryons in with photons and leptons, extends to interstellar medium.
- Some GRBs may be beamed – jet features.
- Active Galactic Nuclei (AGN), Blazars, accretion on supermassive black holes, jets with shocked protons

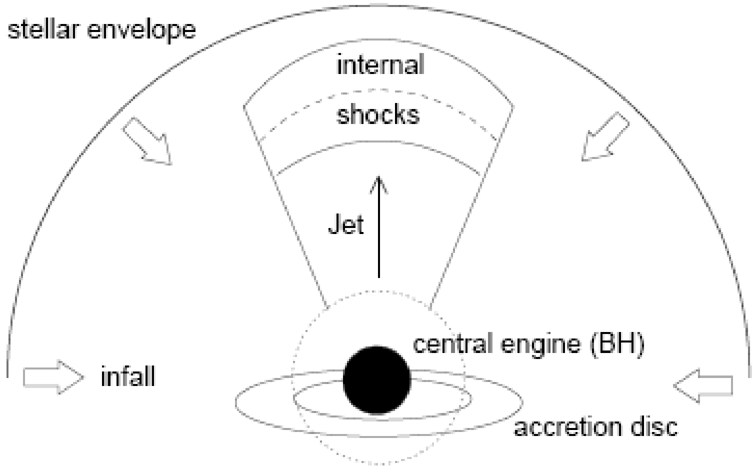


Fig from Razzaque, Meszaros and Waxman, Mod. Phys. Lett. A20 (2005)

A source calculation, with an interest in charm contributions

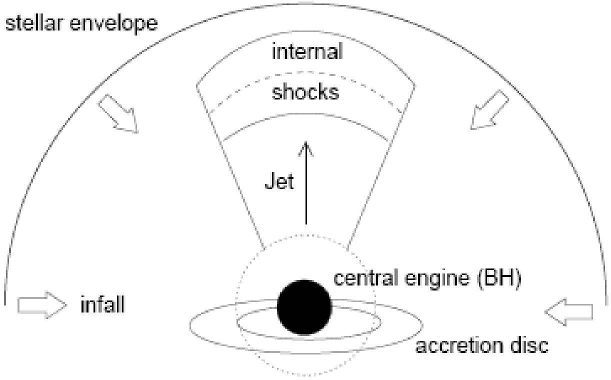


Fig from Razzaque, Meszaros and Waxman, Mod. Phys. Lett. A20 (2005), basis for Slow Jet Supernova model below.

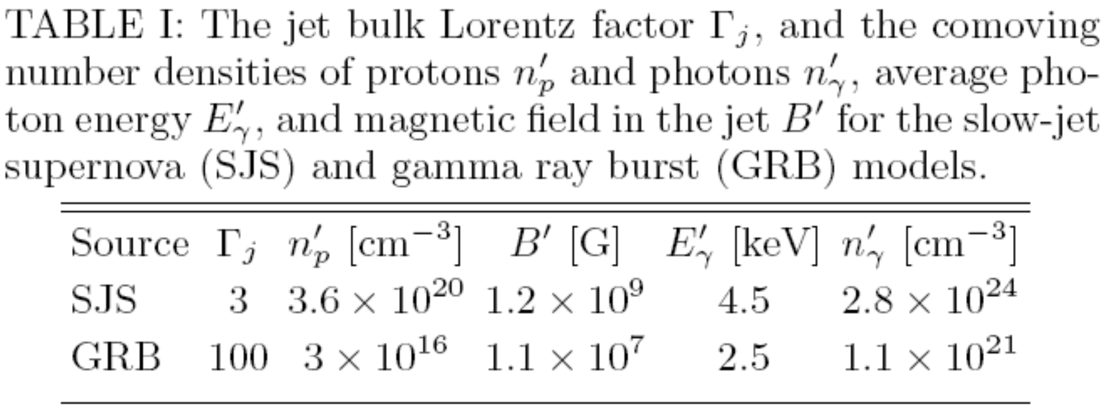
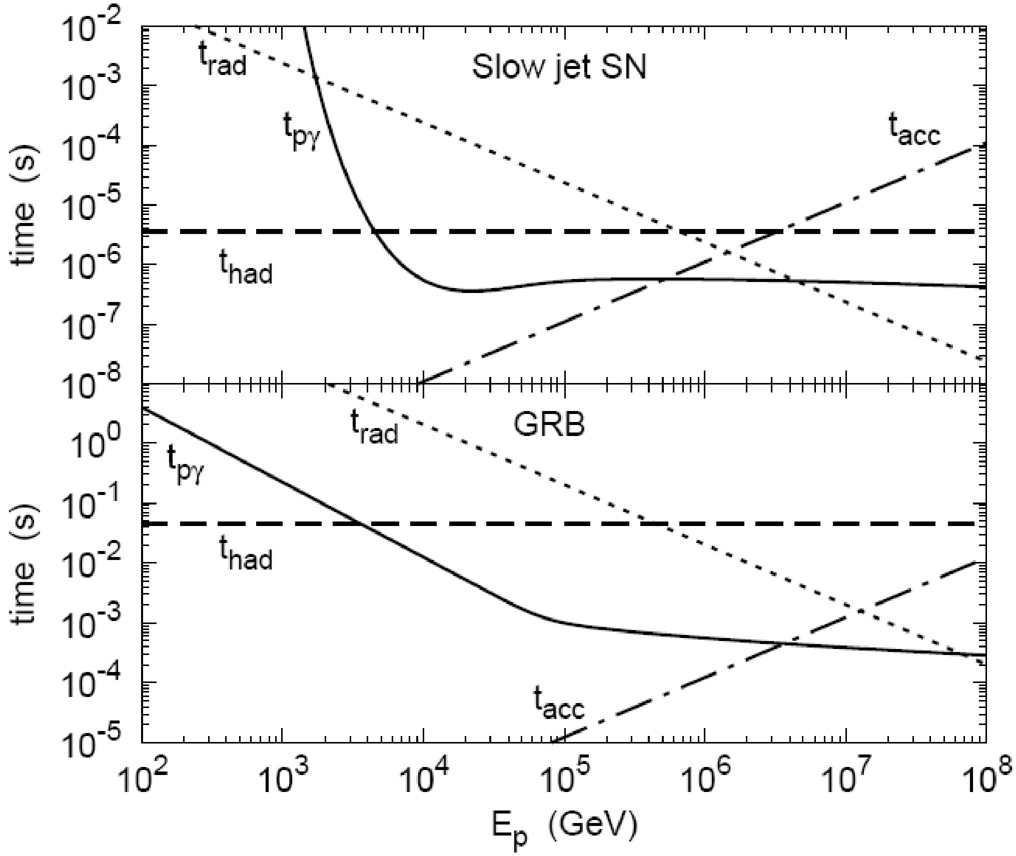


TABLE I: The jet bulk Lorentz factor Γ_j, and the comoving number densities of protons n'_p and photons n'_γ, average photon energy E'_γ, and magnetic field in the jet B' for the slow-jet supernova (SJS) and gamma ray burst (GRB) models.

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}

Enberg, Reno and Sarcevic, (PRD 79 (2009)), see also Beacom and Ando, PRL 95 (2005), Horiuchi and Ando, PRD 77 (2008), Wang and Dai, arXiv 0807.0290, Kachelriess and Tomas, PRD 74 (2006), adding to get diffuse flux: Gandhi, Samanta, Watanabe,arXiv:0905.2483

Characteristic times for protons in the astrophysical jet



Times in the frame co-moving with the jet.

Depends on environment: B, number densities, etc.

The shortest time gives the most important process. When the acceleration time crosses a cooling time, end of proton acceleration:

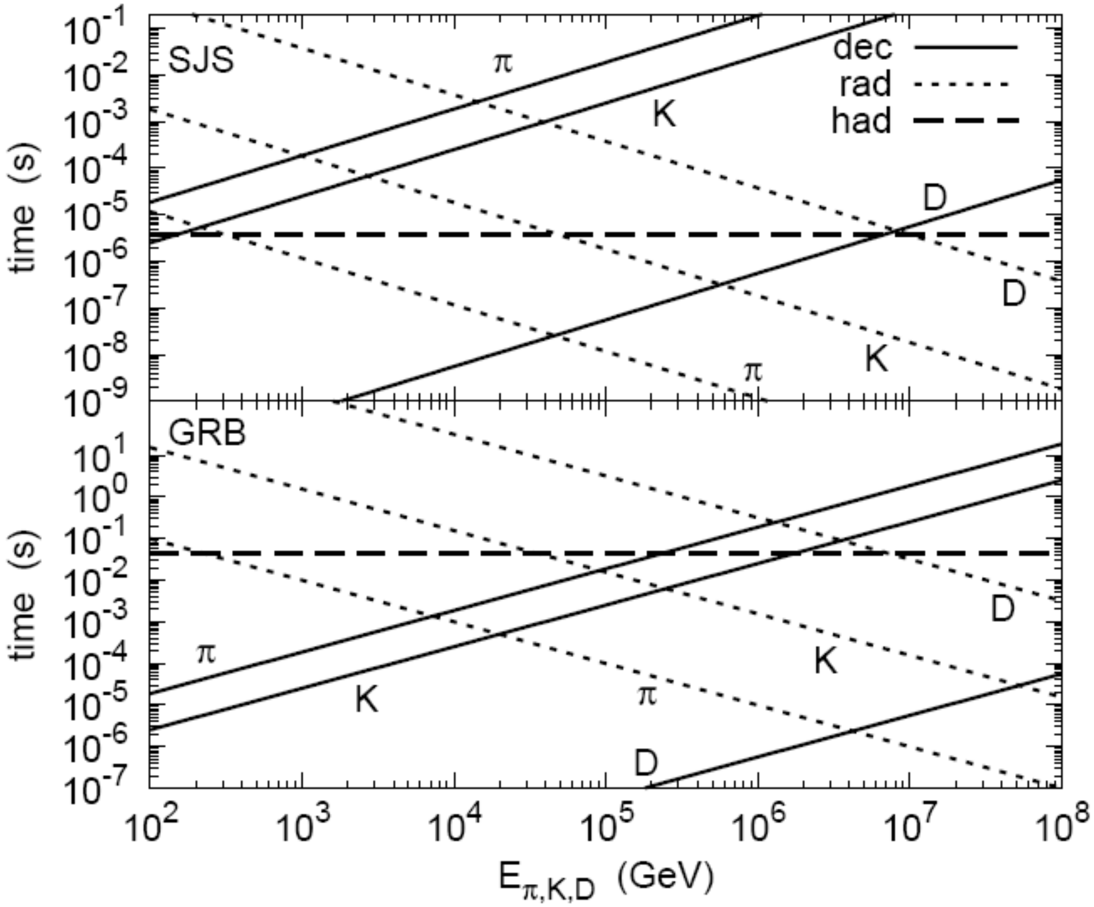
proton energy cutoff.

rad=inverse compton and synchrotron radiation

had=hadronic scattering

Pgamma= Delta production

Characteristic times for mesons in jet



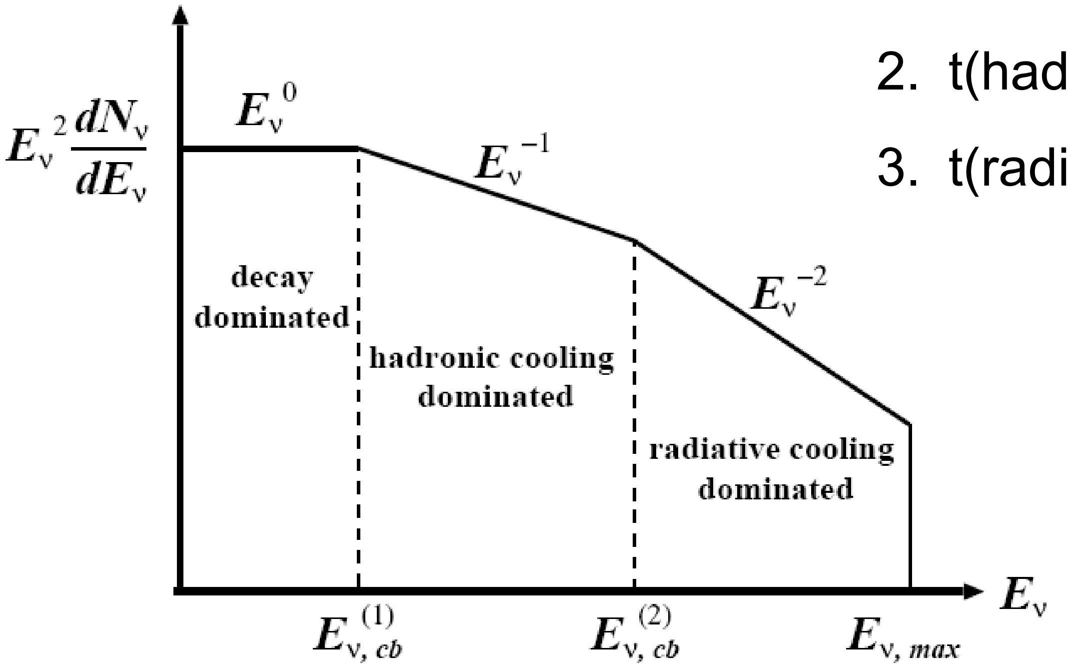
The shortest time gives the most important process.

rad=inverse compton and synchrotron radiation

had=hadronic scattering

Pgamma= Delta production

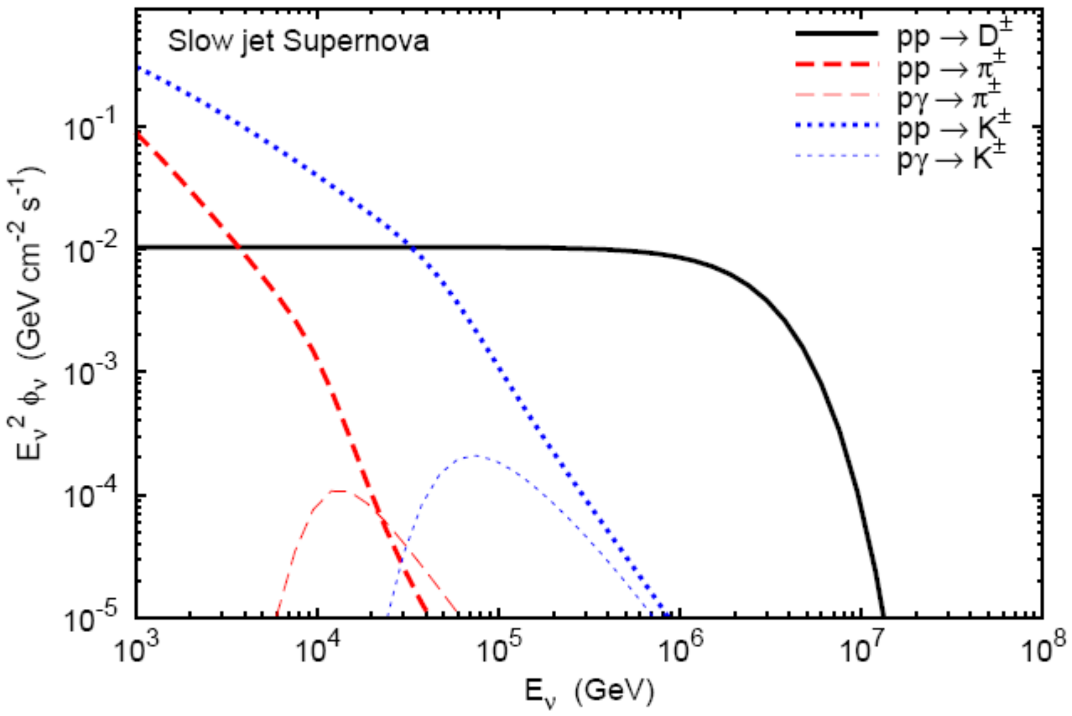
Sources – neutrino energy dependence for pp interactions



1. Mesons decay right away
2. t(hadronic)/t(decay) ~ 1/E
3. t(radiative)/t(decay) ~ 1/E^2

Schematic energy dependence, Fig. from Ando & Beacom

Slow jet supernova example



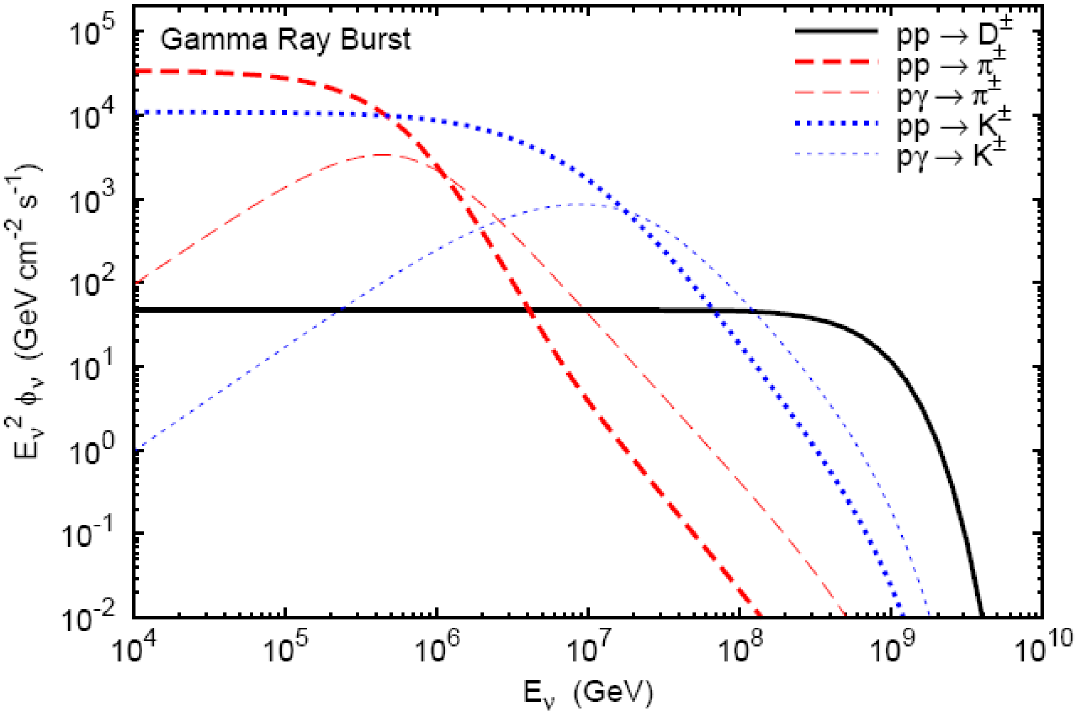
Normalized to a source at 20 Mpc with jet luminosity of log10(L) =50.5.

We have used a Z-moment method, smoother transitions between energy regimes.

$$
\begin{aligned}
\phi_\nu(E) = & Z_{M\nu} \frac{L_M^{\mathrm{eff}}}{L_M^{\mathrm{dec}}(\ell_n^{\mathrm{had}} + \ell_N^\gamma)} \\
& \times (Z_{NM}\ell_N^\gamma + Z_{NM}^\gamma \ell_N^{\mathrm{had}}) \\
& \times \frac{L_j \Gamma_j^2}{2\pi\theta_j^2 d_L^2 \ln(E'_{\mathrm{max}}/E'_{\mathrm{min}})} E^{-2}
\end{aligned}
$$

Enberg, Reno and Sarcevic, PRD 79 (2009)

GRB example



Smaller B-field, more energetic, non-thermal distribution of photons.

Enberg, Reno and Sarcevic, PRD 79 (2009)

Discussion of composition and neutrino fluxes also include: Anchordoqui et al. PRD 76 (2007); Kampert, Nucl. Phys. Proc. Suppl. 188 (2009); Ahlers, Anchordoqui, Sarkar, PRD 79 (2009)

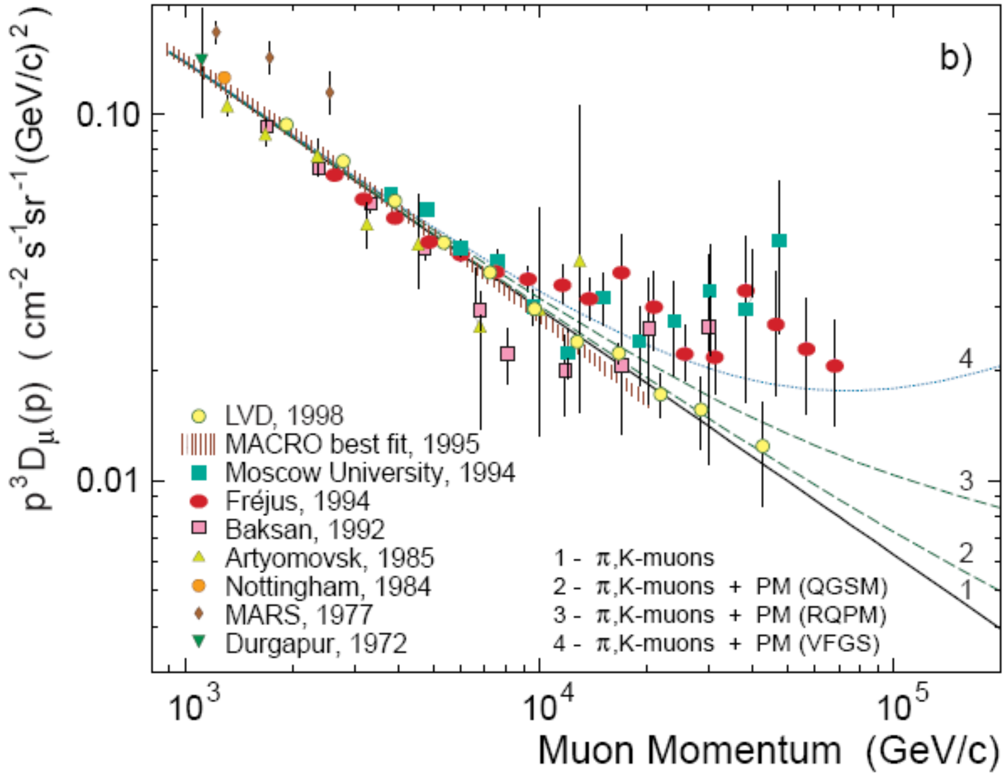
Conclusions:

by Roz Chast, from Symmetry publication, May 2007

- Atmospheric neutrinos (and muons) are intrinsically interesting – input is hadronic physics at high energies. Could we constrain this physics from e.g. prompt neutrinos?

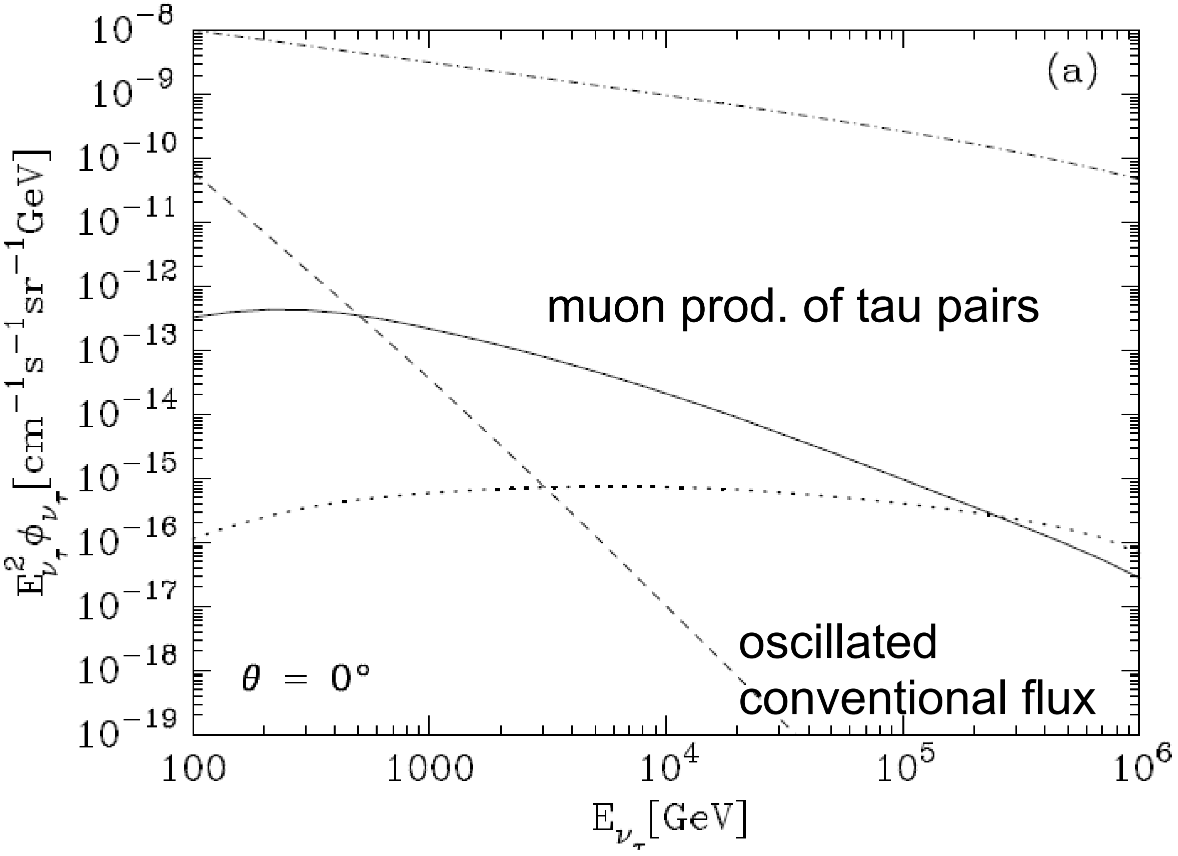
- Astrophysical neutrino fluxes on more speculative standing – expect neutrinos associated with sources of cosmic rays (the “where there is smoke, there is fire” theory). We may be able to learn about CR sources from the neutrino flux, including prompt.

Measurements-vertical muon flux at sea level



Bugaev et al, Phys Rev D 58 (1998)

Atmospheric tau neutrino flux



prompt tau neutrino flux

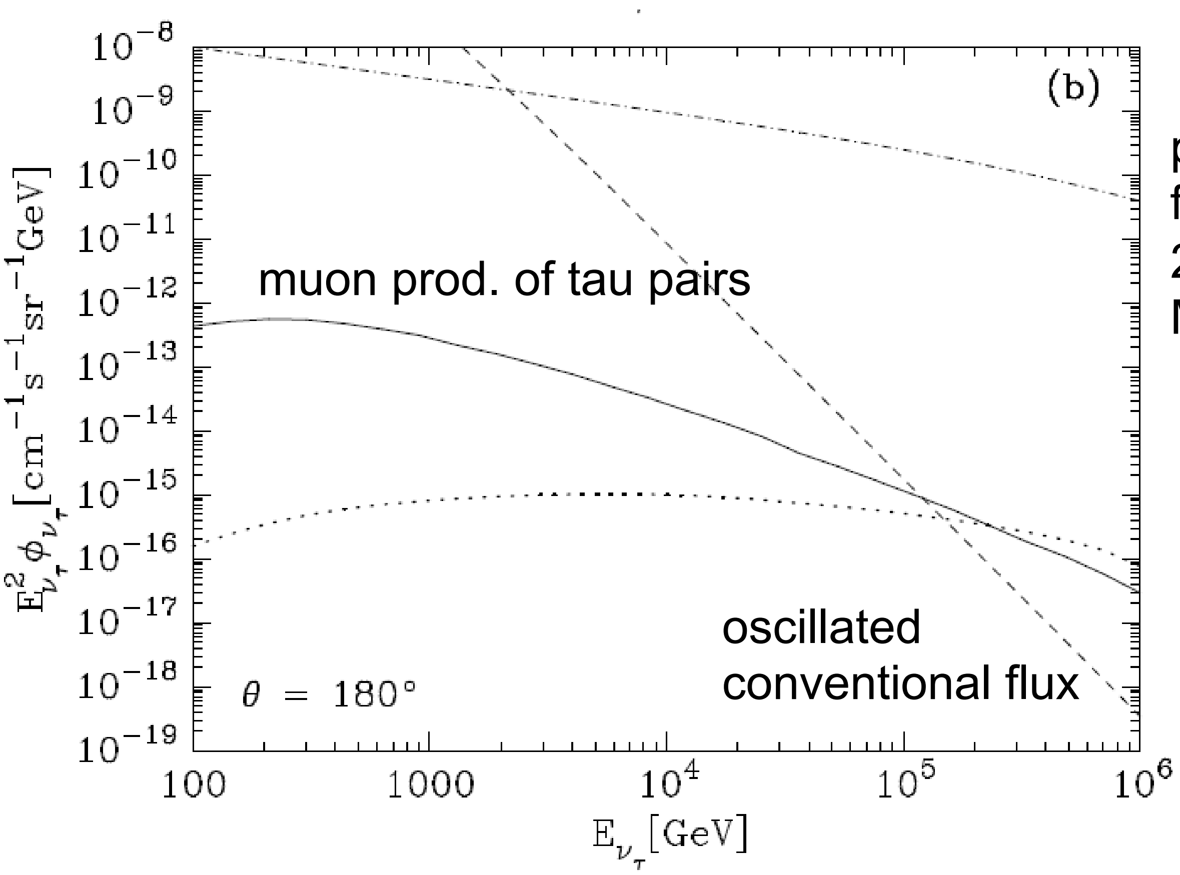
muon prod. of tau pairs

oscillated conventional flux

Downward vertical tau neutrino flux

A. Bulmahn and MHR, Phys. Rev. D 82 (2010) 057302 ; see also PRD 81 (2010) 053003.

Atmospheric tau neutrino flux



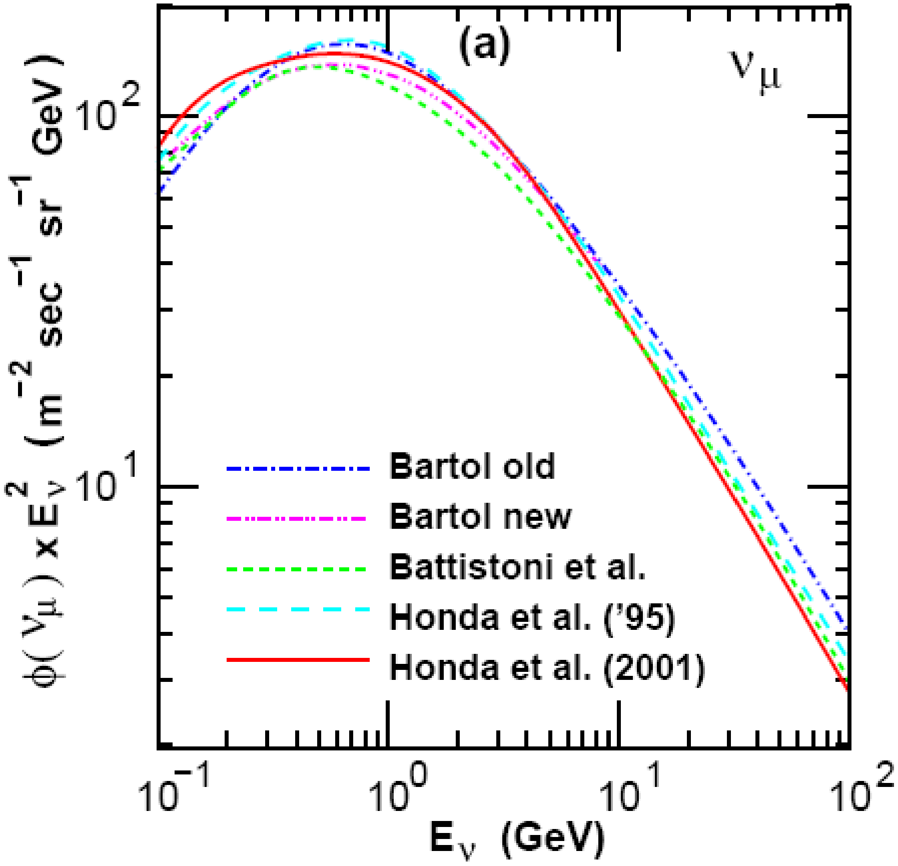
prompt tau neutrino flux (Stasto et al 2003, Pasquali & MHR 1999)

muon prod. of tau pairs

oscillated conventional flux

Upward vertical tau neutrino flux
A. Bulmahn and MHR, Phys. Rev. D 82 (2010) 057302 ; see also PRD 81 (2010) 053003.

Conventional flux



Refinements:

geomagnetic effects

3-D vs 1-D

charge ratios

(see, e.g., Schreiner, Reichenbacher & Goodman, Astropart. Phys. 32 (2009))

Fig. from Gaisser Honda Ann. Rev. Nucl. Part. Sci.