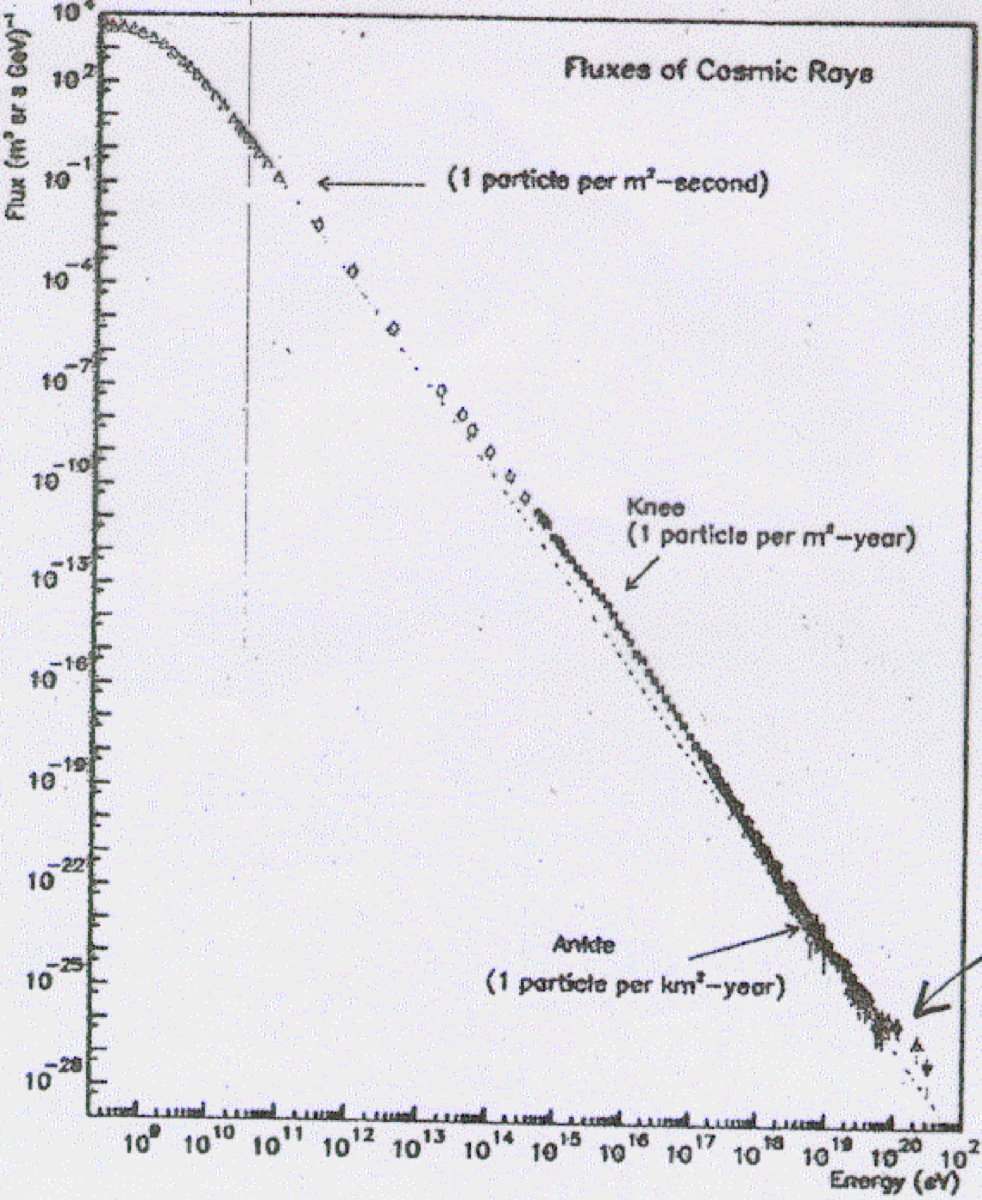
UHE NEUTRINOS:

Some Relevant Theoretical and Phenomenological Issues

NEUTRINO 2000
Sudbury, June 21

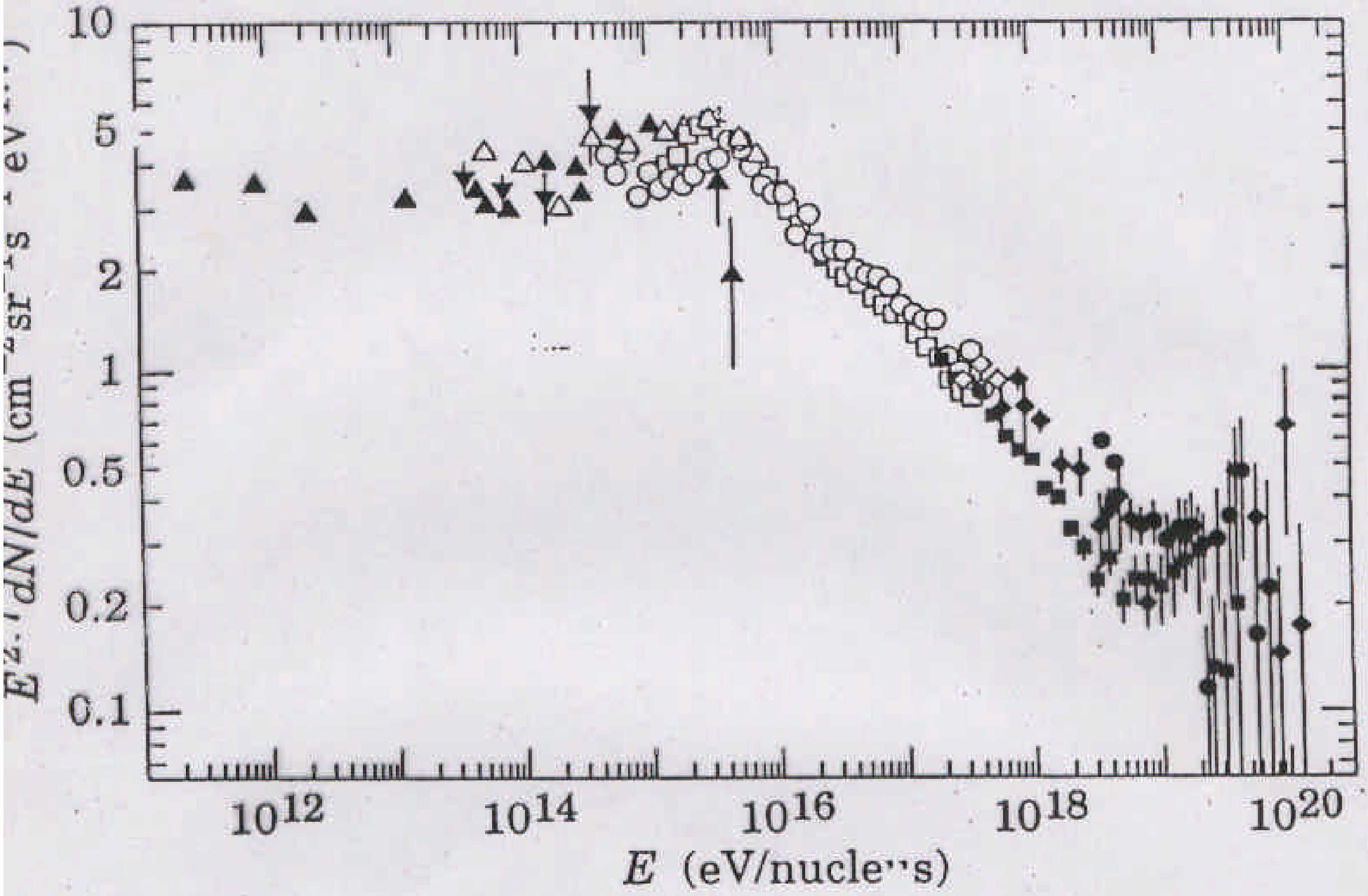
Why should we search for and expect to detect UHE Neutrinos?

- The observed cosmic ray (CR) spectrum spans 12 orders of magnitude in energy, with events observed upto 10^{20} eV.
  - Below $10^{13} - 10^{14}$ eV, the composition is fairly accurately known to be 98% hadrons, mainly protons ($\sim 84\%$), some α particles ($\sim 12\%$) and heavier nuclei (1%).
  - Although at present our knowledge of the composition around the knee is less certain, balloon, air-shower and CR tracking detector data combine to give a picture of the composition as being predominantly hadronic, with a substantial extragalactic component.
  - Very little is known about the composition above 10^{16} eV. However, even the highest energy CR events ($\sim 10^{20}$ eV) seem to have muon content and cross-sections similar to hadrons.



1 particle per km² - centur

pilation[14] of measurements of the differential energy spectrum of cosmic rays.
ows an E^{-3} power-law for comparison. Approximate integral fluxes (per stera-
vn.



From recent EGRET observations, the origin ~~and spectrum~~ upto ~ the knee is with confidence known to be galactic. The physical process involved is beleived to be SN blast shocks

- Whatever the sources and mechanisms by which hadrons are accelerated to such energies in the source, and whatever the details of the composition (i.e light vs heavy) the expected production (via pp and/or $p\gamma \to \pi^{\pm}$) and subsequent decay of accompanying pions is expected to result in neutrino fluxes.

  ($\pi \to \mu + \nu_\mu \to e + \nu_e + \nu_\mu + \nu_\mu$, leading to the familiar ratio $\nu_\mu / \nu_e = 2.$)

- Above 5×10^{19} eV, a CR proton interacts with the CMBR to photoproduce pions, and hence neutrinos.

- A diffuse galactic neutrino background should exist due to the interactions of galactic CR with interstellar matter, at energies lower than $\sim 10^{15}$ eV.

- Gamma Ray Burst (GRB) observations provide increasing support for a 'fireball' model:

  An initial merger-collapse involving either black-holes, neutron stars or other highly magnetized compact stars, to a small radius object.

  - This then undergoes rapid expansion by a factor $\sim 10^5 - 10^6$ over timescales of ~ 1 sec due to a relativistic shock.

- The GRB burst and the afterglow is a result of synchrotron emission of the shock accelerated electrons.

From the γ -ray observations ($\sim$ MeV), energy outputs of these objects are estimated to be $10^{52} - 10^{53}$ ergs. GRB's are thus associated with matter acceleration to very high energies, and may be the source of the highest energy CR if protons are also shock-accelerated along with the electrons. The $p + \gamma$ interactions are expected to produce pions, and hence UHE neutrino fluxes.

- Active Galactic Nuclei (AGN) highly compact bright objects powered presumably by black-holes causing acceleration and accretion of matter, characterised usually by jet emission. ~ 70 high confidence observations with MeV-GeV gamma rays by EGRET. Observations of TeV gamma-rays from 3 blazar sites.

  There are 2 classes of blazar models. Electron blazars predict no neutrinos and no gammas above a few TeV at most, while Proton blazars, where $p - \gamma, pp$ interactions are expected to occur result in UHE neutrino fluxes and gammas extending to energies greater than 10 TeV.

- Topological Defects (TD) where GUT scale particles decay to give fluxes of neutrinos, photons, and protons.

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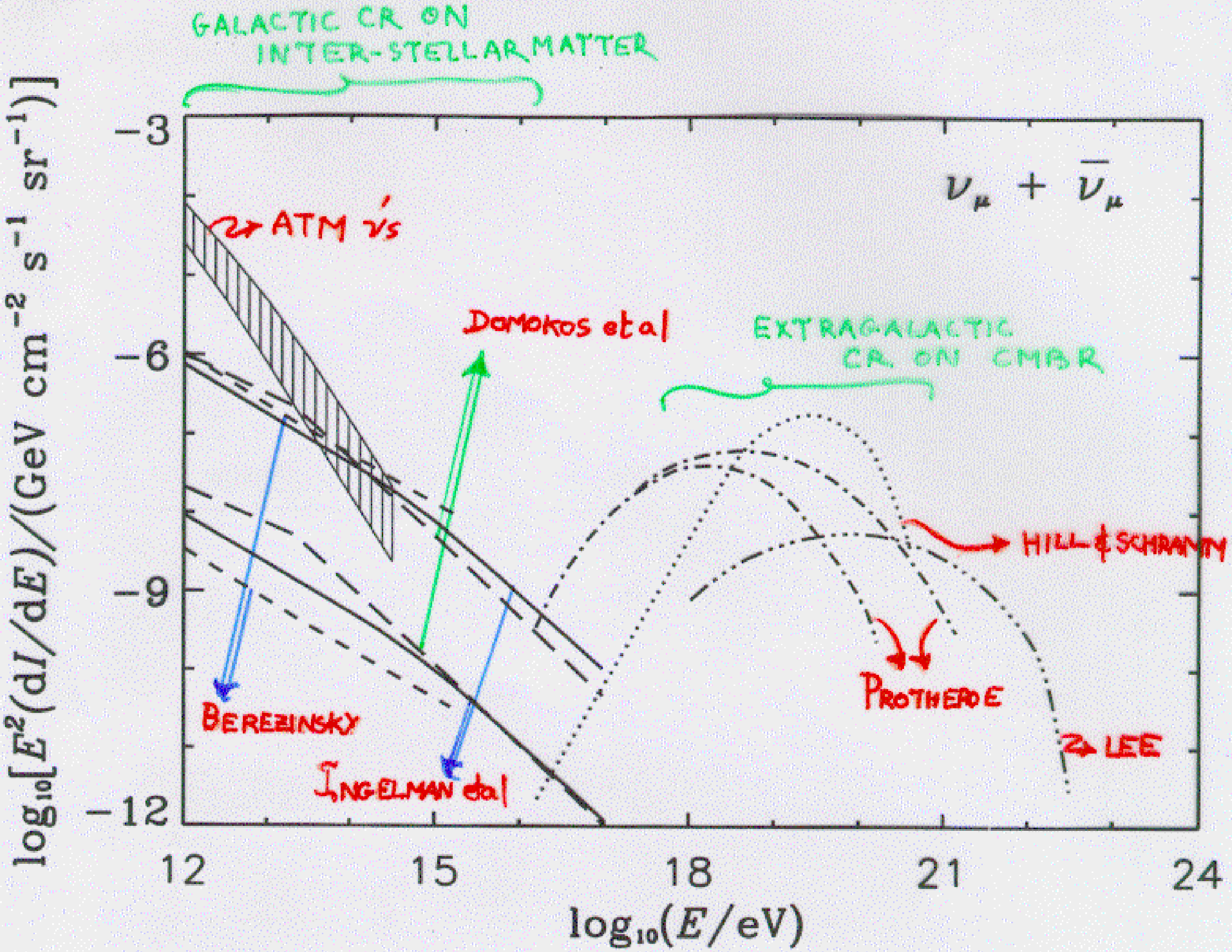
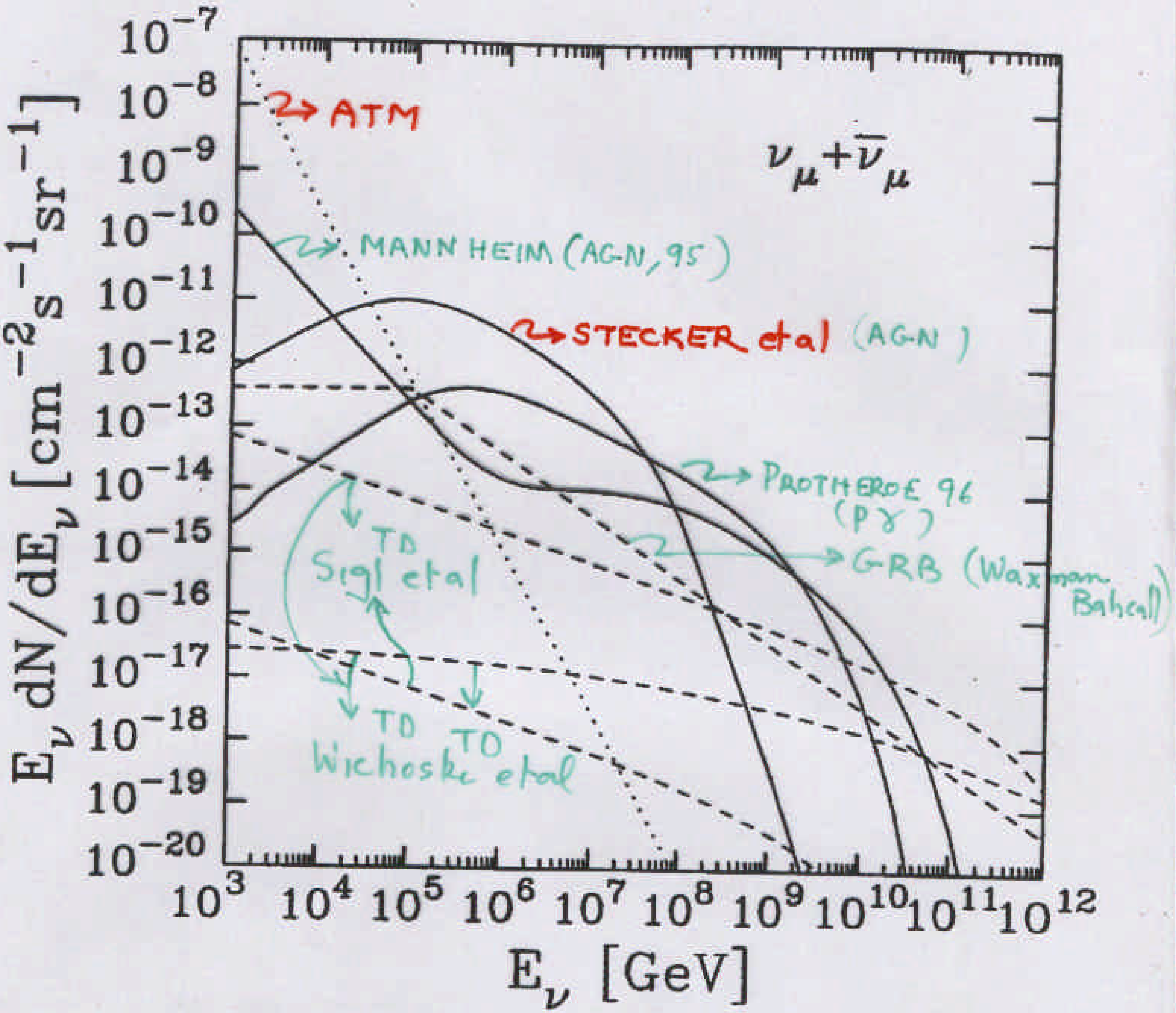


Figure 1: Neutrinos from cosmic ray interactions with the interstellar medium (upper curves for $\ell = 0^\circ$, $b = 0^\circ$, lower curves for $b = 90^\circ$): — — — Domokos et al. [9]; - - - - Berezinsky et al. [10]; ——— Ingelman and Thunman [11]. The band with vertical hatching shows the range of atmosheric neutrino background [12] as the zenith angle changes from 90° (highest) to 0° (lowest). Neutrinos from cosmic ray interactions with the microwave background: — · — · — · — Protheroe and Johnson [23] for $E_{\max} = 3 \times 10^{20}$ eV and 3×10^{21} eV; · · · · · · Hill and Schramm [24]; — · · · — · · · — · · · — assuming the highest energy cosmic rays are due to GRB according to Lee [25].

PROTHEROE

DIFFUSE FLUXES FROM POINT SOURCES



Flux Calculations for Extragalactic UHE neutrino Sources: Some Considerations

- Important! Flux calculations, especially for AGN and TD sources, are at best in a stage of "active development". For AGN's understanding of the sources and how observations can be used to constrain the astrophysics causing the acceleration is gradually emerging.

- If UHE neutrinos are produced in optically thin sources via $p-\gamma$ interactions, the protons which produce them leave the site of the source and contribute to the UHE CR flux. The observed CR spectrum then constrains the UHE neutrino flux.

  This strongly restricts several AGN models which had used the fact that the flux of neutrinos from charged pions is proportional to the gamma rays resulting from simultaeneously produced neutral pion decay and used the gamma-ray background observations for normalizing the neutrino flux. [Waxman-Bahcall]

- The above bound assumes an overall CR injection spectrum $dN/dE \propto E^{-2}$ extending to the highest observable energies. This assumption has been questioned by some authors. [Rachen- Protheroe-Mannheim]

Detection of UHE Neutrinos: General Considerations

- The main mode of detection so far has been via the observation of long-range muons in produced in charged current neutrino-nucleon interactions. Due to the low fluxes, large volume Water/Ice detectors shielded by several kmwe from the atmospheric muon background are necessary.

- Existing detectors thus look for upward moving muons produced by UHE neutrinos entering the opposite side of the earth, interacting in the rock below the detector to produce a muon which, despite losses, makes it to the detector.

- A 10 TeV muon will travel several km in rock before its energy is degraded to 1 TeV, which is a typical detector threshold. Thus, one is typically looking at an effective detector volume of $O(1\ \mathrm{km}^3)$.

- An important consideration for calculating event rates for detectors is the attenuation of neutrinos in the Earth, due to the rapid rise in the cross-section at these energies.The interaction length of a neutrino in rock equals the diameter of the earth at $E_\nu = 40$ TeV.

- One can then compute the "shadow-factor", which is an effective solid angle divided by 2π for upward muons, using the energy dependant interaction length of neutrinos in the earth's rock:

$$S(E_\nu) = \frac{1}{2\pi} \int_{-1}^{0} d\cos\theta \int d\phi \exp\left[-z(\theta)/\mathcal{L}_{int}(E_\nu)\right] . \qquad (1)$$

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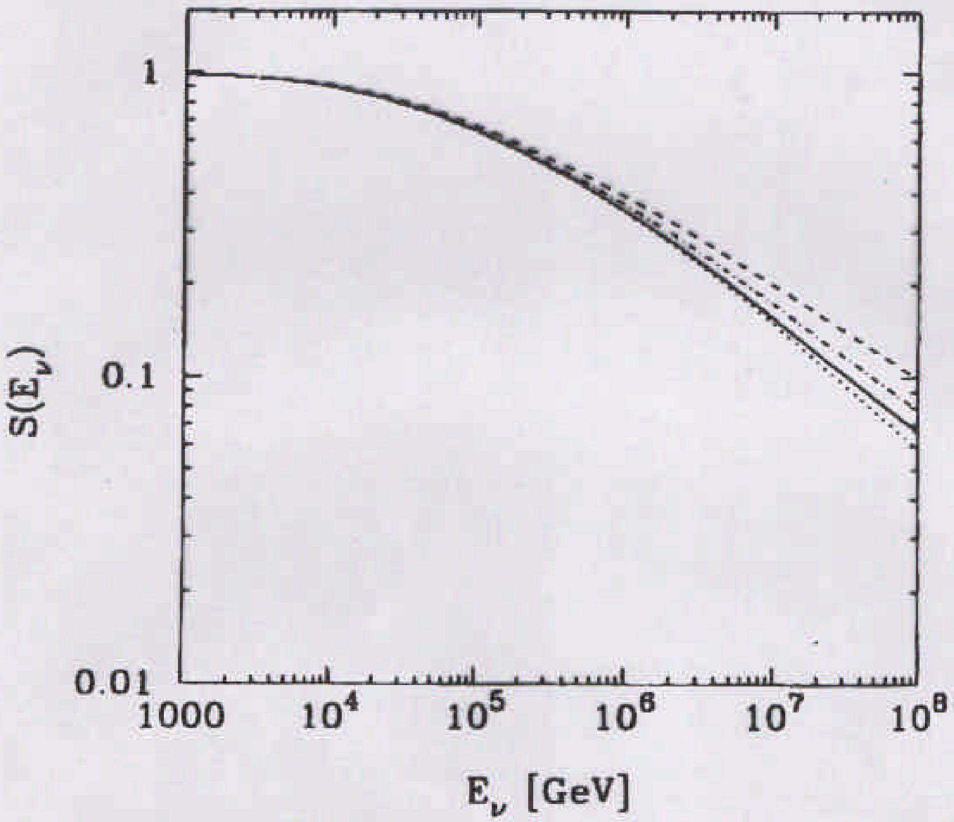


Shadowing for Tau Neutrinos is interestingly different.

- In the light of Super Kamiokande and other supporting data (Kamiokande, IMB, Soudan II, MACRO) it is crucial to test if $\nu_\mu \to \nu_\tau$ oscillations actually occur, by ν_τ appearance experiments. UHE neutrinos provide an opportunity to do this. [Learned-Pakvasa]

- Whatever the source of UHE neutrinos, their origin in hadronic interactions ensures almost no ν_τ content, and a composition $\nu_\mu : \nu_e \equiv 2 : 1$.

- However, the oscillation probability

$$\mathcal{P}_{\nu_{\mu,e} \to \nu_\tau} = \sin^2 2\theta \; \sin^2 \left[1.27 \, \Delta m^2 \, \frac{L}{E_\nu} \right] \tag{2}$$

  averages to 1/2 over the energies and distances relevant for UHE neutrinos, for Super Kamiokande oscillation parameters. One thus expects a flux entering the earth in the ratio $\nu_\mu : \nu_e : \nu_\tau \equiv 1 : 1 : 1$.

- A ν_τ interaction in the earth will produce a τ which quickly decays , producing another ν_τ with degraded energy. Hence there is practically no attenuation, but an altering of the initial ν_τ spectrum. The zenith angle dependence will thus be different compared to the attenuated ν_μ flux. [Halzen-Saltzberg]

ν_τ detection via

a) "double bang" events

(down-moving ν_τ's)

b) flattened zenith ∠ dependance

learned Pakvasa

Dutta, Reno & Sarcevic

Athar, Parente & Zas

The Neutrino-Nucleon DIS Cross-Section at UHE

- Of crucial importance to the attenuation and the event rate calculations is the UHE $\nu - N$ DIS CC and NC cross-section.

$$\frac{d^2\sigma}{dxdy} = \frac{2G_F^2 M E_\nu}{\pi} \left(\frac{M_W^2}{Q^2 + M_W^2}\right)^2 \left[xq(x,Q^2) + x\bar{q}(x,Q^2)(1-y)^2\right], \tag{3}$$

where $-Q^2$ is the invariant momentum transfer between the incident neutrino and outgoing muon, $\nu = E_\nu - E_\mu$ is the energy loss in the lab (target) frame, M and M_W are the nucleon and intermediate-boson masses, and $G_F = 1.16632 \times 10^{-5}$ GeV^{-2} is the Fermi constant. The quark distribution functions are

$$\begin{aligned} q(x,Q^2) &= \frac{u_v(x,Q^2) + d_v(x,Q^2)}{2} + \frac{u_s(x,Q^2) + d_s(x,Q^2)}{2} \\ &\quad + s_s(x,Q^2) + b_s(x,Q^2) \qquad (4) \\ \bar{q}(x,Q^2) &= \frac{u_s(x,Q^2) + d_s(x,Q^2)}{2} + c_s(x,Q^2) + t_s(x,Q^2), \end{aligned}$$

where the subscripts v and s label valence and sea contributions, and u, d, c, s, t, b denote the distributions for various quark flavors in a *proton.*

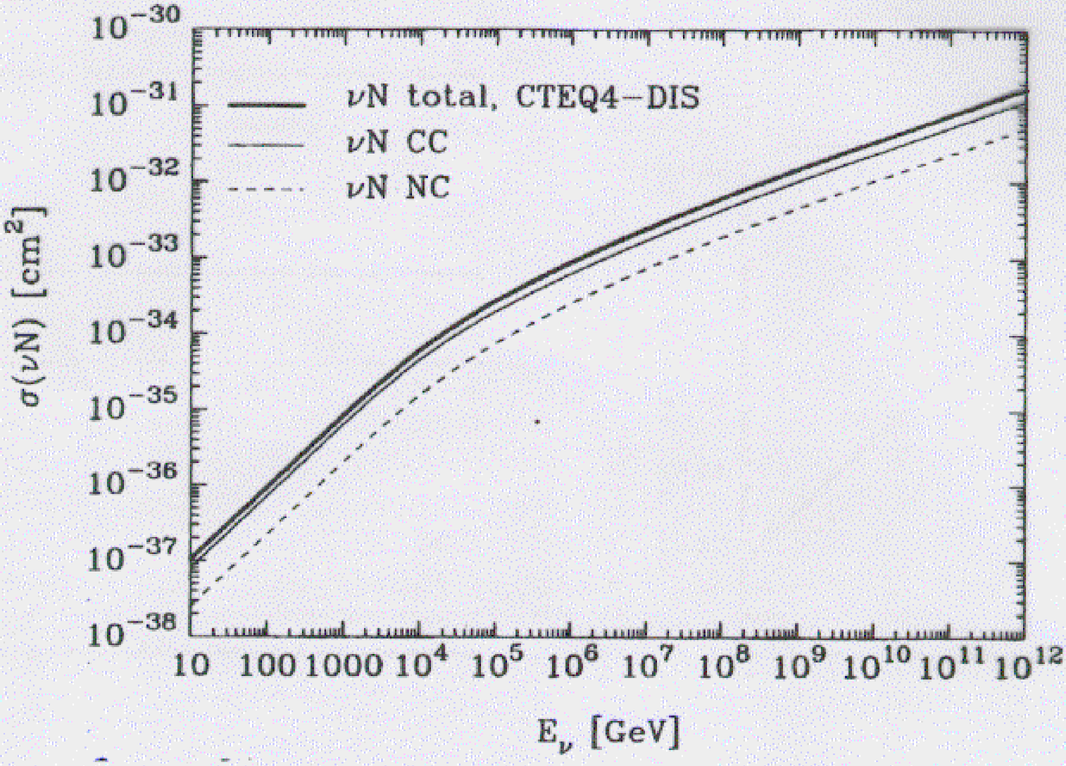
- Modern parametrizations of parton distribution functions, nourished by a variety of experimental data, have grown increasingly robust. Recent HERA data provide mappings of the structure function $F_2(x, Q^2)$ in the region $10^{-4} \leq x \leq 10^{-2}$ and 8.5 GeV$^2 \leq Q^2 \leq 15$ GeV^2.

- In the UHE domain, the most important contributions to the cross-section come from $x \sim M_W^2/(2M_n E_\nu)$. At the highest neutrino energies, this probes the parton distribution at $x \sim 10^{-6} - 10^{-8}$.

- Upto $E_\nu \approx 10^5$ GeV, the parton distributions are probed at x values constrained by experiments. Beyond these energies, one needs to evolve the distributions from some low $Q^2 = Q_0^2 =$ few GeV^2 to low x values.

- Two Approaches:
  - Solve NLO Alterelli-Parisi equations numerically. Good for not so small x and large Q^2.
  - Solve Balitskii-Fadin-Kuraev-Lipatov equation which is a leading $\alpha_s ln(1/x)$ resummation of soft gluon emissions. Good for small x but not-so-high Q^2.

FIGURES



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KWIECINSKI , MARTIN & STASTO

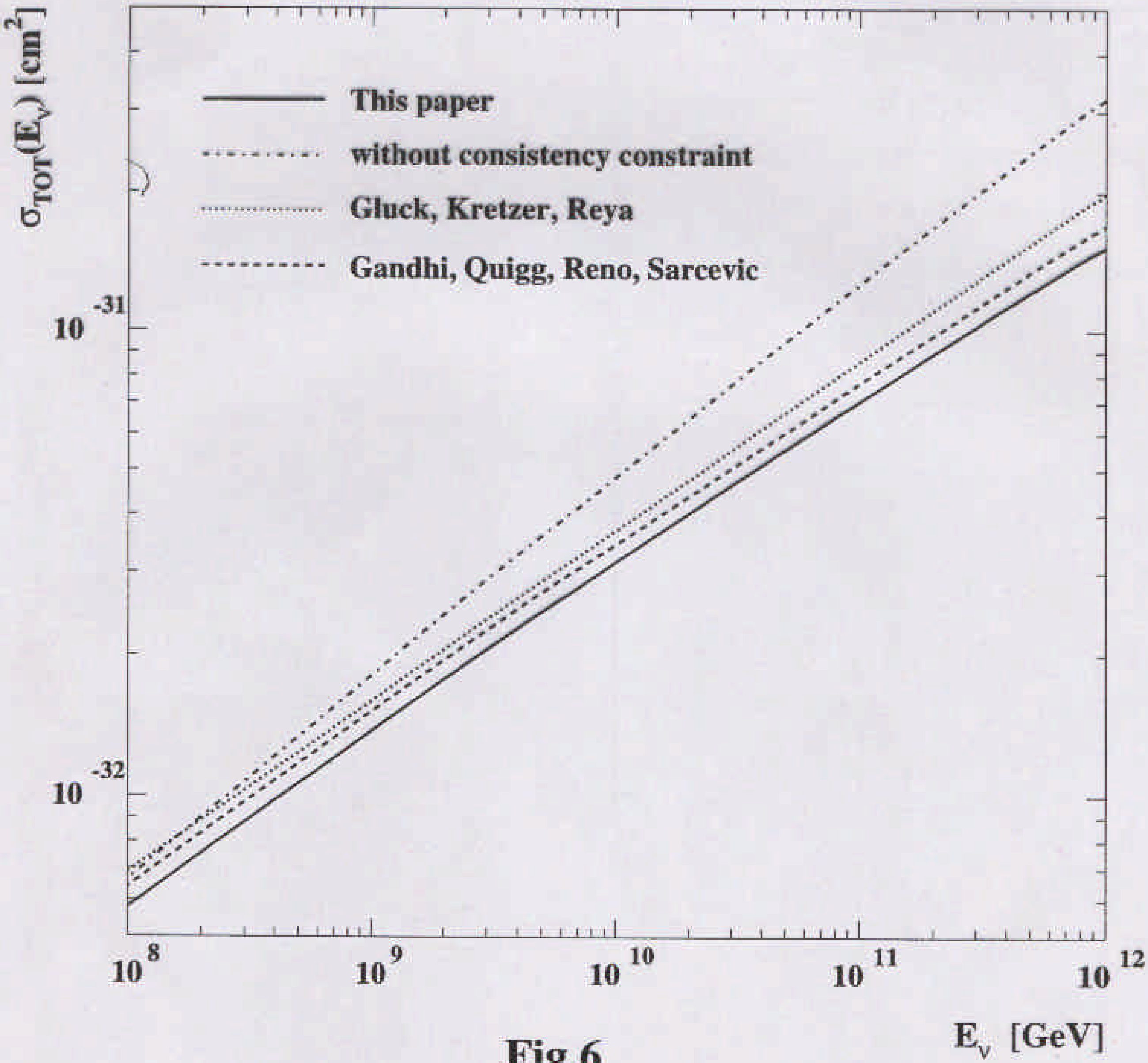

Fig.6

Predictions for Event Rates

$$\mathrm{Rate} = A \int_{E_\mu^{\rm min}}^{E^{\rm max}} dE_\nu \; P_\mu(E_\nu; E_\mu^{\rm min}) S(E_\nu) \frac{dN}{dE_\nu}. \tag{5}$$

$$P_\mu(E_\nu, E_\mu^{\rm min}) = N_{\rm A}\, \sigma_{\rm CC}(E_\nu) \langle R(E_\nu; E_\mu^{\rm min}) \rangle, \tag{6}$$

$$S(E_\nu) = \frac{1}{2\pi} \int_{-1}^{0} d\cos\theta \int d\phi \exp\left[-z(\theta)/\mathcal{L}_{int}(E_\nu)\right]. \tag{7}$$

* PRESENT GENERATION OF DETECTORS, WHEN FULLY DEPLOYED, WILL HAVE $A \sim 0.02\ km^2$

TABLE III. Upward $\mu^+ + \mu^-$ event rates per year arising from $\nu_\mu N$ and $\bar{\nu}_\mu N$ interactions in rock, for a detector with effective area $A = 0.1\ \mathrm{km}^2$ and muon energy threshold $E_\mu^{\min} = 1$ TeV. The rates are shown integrated over all angles below the horizon and restricted to "nearly horizontal" nadir angles $60° < \theta < 90°$.

	nadir angular acceptance		
Flux	$0° < \theta < 90°$		$60° < \theta < 90°$
ATM [58]	1100	11000	570
ATM [58] + charm [60]	1100	11000	570
AGN-SS91 [56]	500	5000	380
* AGN-M95 ($p\gamma$) [49]	31	310	18
* AGN-P96 ($p\gamma$) [48]	45	450	39
GRB-WB [50]	12	120	8.1
TD-SLSC [51]	0.005	0.05	0.0046
TD-WMB12 [52]	0.50	5	0.39
TD-WMB16 [52]	0.00050	0.0050	0.00039

TABLE IV. Upward $\mu^+ + \mu^-$ event rates per year arising from $\nu_\mu N$ and $\bar{\nu}_\mu N$ interactions in rock, for a detector with effective area $A = 0.1\ \mathrm{km}^2$ and muon energy threshold $E_\mu^{\min} = 10$ TeV. The rates are shown integrated over all angles below the horizon and restricted to "nearly horizontal" nadir angles $60° < \theta < 90°$.

	nadir angular acceptance		
Flux	$0° < \theta < 90°$		$60° < \theta < 90°$
ATM [58]	17	170	10
ATM [58] + charm [60]	19	190	11
AGN-SS91 [56]	270	2700	210
* AGN-M95 ($p\gamma$) [49]	5.7	57	4.3
* AGN-P96 ($p\gamma$) [48]	28	280	25
GRB-WB [50]	5.4	54	4.0

$A = 1\ km^2$

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* In conflict with bound from CR observations (Waxman - Bahcall)

$A = 1$ km^2

TABLE V. Upward $\mu^+ + \mu^-$ event rates per year arising from $\nu_\mu N$ and $\bar{\nu}_\mu N$ interactions in rock, for a detector with effective area $A = 0.1$ km^2 and muon energy threshold $E_\mu^{\min} = 100$ TeV. The rates are shown integrated over all angles below the horizon and restricted to "nearly horizontal" nadir angles $60° < \theta < 90°$.

	nadir angular acceptance		
Flux	$0° < \theta < 90°$		$60° < \theta < 90°$
ATM [58]	0.13	1.3	0.09
ATM [58] + charm [60]	0.21	2.1	0.16
AGN-SS91 [56]	85	850	73
AGN-M95 ($p\gamma$) [49] *	1.6	16	1.5
AGN-P96 ($p\gamma$) [48] *	13	130	12
GRB-WB [50]	1.2	12	1.0

TABLE VI. Downward $\mu^+ + \mu^-$ events per year arising from $\nu_\mu N$ and $\bar{\nu}_\mu N$ interactions in 1 km^3 of water.

	Muon-energy threshold, $E_\mu^{\min}$			
Flux	100 TeV		1 PeV	3 PeV
ATM [58]	0.85	8.5	0.0054	0.00047
ATM [58] + charm [60]	2.6	26	0.050	0.0076
AGN-SS91 [56]	520	5200	120	42
AGN-M95 ($p\gamma$) [49] *	16	160	11	8.7
AGN-P96 ($p\gamma$) [48] *	100	1000	50	31
GRB-WB [50]	7.7	77	1.9	0.93
TD-SLSC [51]	0.037	0.37	0.032	0.029
TD-WMB12 [52]	1.1	11	0.74	0.58
TD-WMB16 [52]	0.00087	.0087	0.00050	0.00035

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TABLE IX. Annual event rates in the Pierre Auger Cosmic Ray Observatory for horizontal showers induced by $(\nu_e, \bar{\nu}_e)N$ charged-current interactions.

Flux	Parton distributions	$E_{\text{sh}} > 10^8$ GeV	$E_{\text{sh}} > 10^9$ Ge
AGN-SS91 [56]	CTEQ4–DIS	0.15	0.00026
	CTEQ3–DLA	0.13	0.00022
	D_′	0.23	0.00051
AGN-M95 $(p\gamma)$ [49] *	CTEQ4–DIS	6.1	3.3
	CTEQ3–DLA	5.3	2.8
	D_′	12	7.5
AGN-P96 $(p\gamma)$ [48] *	CTEQ4–DIS	8.9	2.6
	CTEQ3–DLA	7.9	2.2
	D_′	16	5.4
GRB-WB [50]	CTEQ4–DIS	0.31	0.18
	CTEQ3–DLA	0.27	0.16
	D_′	0.67	0.45
TD-SLSC [51]	CTEQ4–DIS	0.068	0.061
	CTEQ3–DLA	0.056	0.051
	D_′	0.18	0.17
TD-WMB12 [52]	CTEQ4–DIS	0.85	0.71
	CTEQ3–DLA	0.72	0.60
	D_′	2.1	1.9
TD-WMB16 [52]	CTEQ4–DIS	0.00024	0.00014
	CTEQ3–DLA	0.00021	0.00012
	D_′	0.00049	0.00032

FIGURES

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CAN NEUTRINOS EXPLAIN THE HIGHEST ENERGY CR EVENTS ?

- Simple extensions of the SM (leptoquark resonances, technicolor) in which ν_s become strongly interacting above some HE threshold require cross-sections which violate unitarity
  (Burdman, Halzen & RG)

But - - - -

- Annhilation of UHE ν's ($\sim 10^{24}$ eV) on 2°K relic ν's in galactic halo may give nearby protons which evade the GKZ cutoff
  (Weiler)

- Compact dimensions @ TeV scales from low energy unification may
  (Dienes)

lead to sufficiently high ν cross-sections

(Domokos & Kovesi-Domokos)

Unitarity - - - - -

(Shrock & Nussimov)

CONCLUSIONS

- Observations of UHECR, observations of AGNs including TeV γ-ray signals from blazars, of GRBs, which may be the most energetic phenomena in the Universe, all seem to indicate that matter is accelerated to energies all the way upto 10^{20} eV. It is at least reasonable to assume that hadrons are among the particles undergoing such acceleration. If so, we expect UHE neutrino fluxes and are able to calculate them given certain assumptions about the nature of the processes occuring at these natural accelerators. Increasingly, flux predictions are incorporating constraints from the growing body of gamma-ray and CR observations.

- Event-rate calculations depend importantly on the neutrino-nucleon cross-section at UHE. Growing knowledge of parton distributions and increasingly refined calculations have reduced the uncertainties in the cross-section inspite of the low-x extrapolations required.

- At energies below 100 TeV, UHE neutrinos are primarily detectable via upward muons produced in the rock below the detector. Above these energies, as the atmospheric muon background disppears, downward detection becomes possible.

- Currently deployed detectors may not be able to see too many events above background, however, future detectors of $O(1\ \text{km}^3)$ should see UHE neutrinos.

- Some of questions UHE neutrino detection may shed light on include:

- The physics occuring at sites that accelerate matter to energies in excess of 10^{20} eV

- The nature of the primaries which are responsible for the highest energy CR events. Are they from AGN's, or GRB's or TD's or a yet unknown source?

- An opportunity to do neutrino oscillation tests via ν_τ detection. (probe Δm^2 down to 10^{-17} eV^2,) verify SK $\nu_\mu \to \nu_\tau$ ossc.)
- Extremely sensitive tests of weak equivalence & SR using GRB ν's!.
- ?????????????