HIGH ENERGY NEUTRINOS
Fluxes & Detection

Todor Stanev, Bartol Research Institute
University of Delaware, Newark, DE19716, U.S.A.

NEUTRINO ASTRONOMY WHAT, WHY & HOW
It is the general question of the role of hadronic processes in the Universe. Obsevrationally, neutrinos would let us see the central engines of powerful systems that are otherwise hidden. The price is in the huge detectors needed. The window above the atmospheric background opens above a TeV.

SOURCES
We will distinguish betweeb three types of potential neutrino sources:
- galactic
- extragalactic
- related to the UHE cosmic rays

'SCIENCE NEWS'
I will briefly review several recent developments that have strengthen our ability to understand the emission of high energy radiation and its detection: gamma ray observations, theoretical developments in astrophysics and particle physics.

EVENT RATES
Expected event rates will give ideas of the chances for detection of different candidate sources and define the detector size required for neutrino astronomy.

QUESTIONS
Can we ever see the highest energy neutrinos in the Universe ? ... and how ? Could we do particle physics with EeV neutrinos ?

WE SHALL KNOW SOME ANSWERS SOON

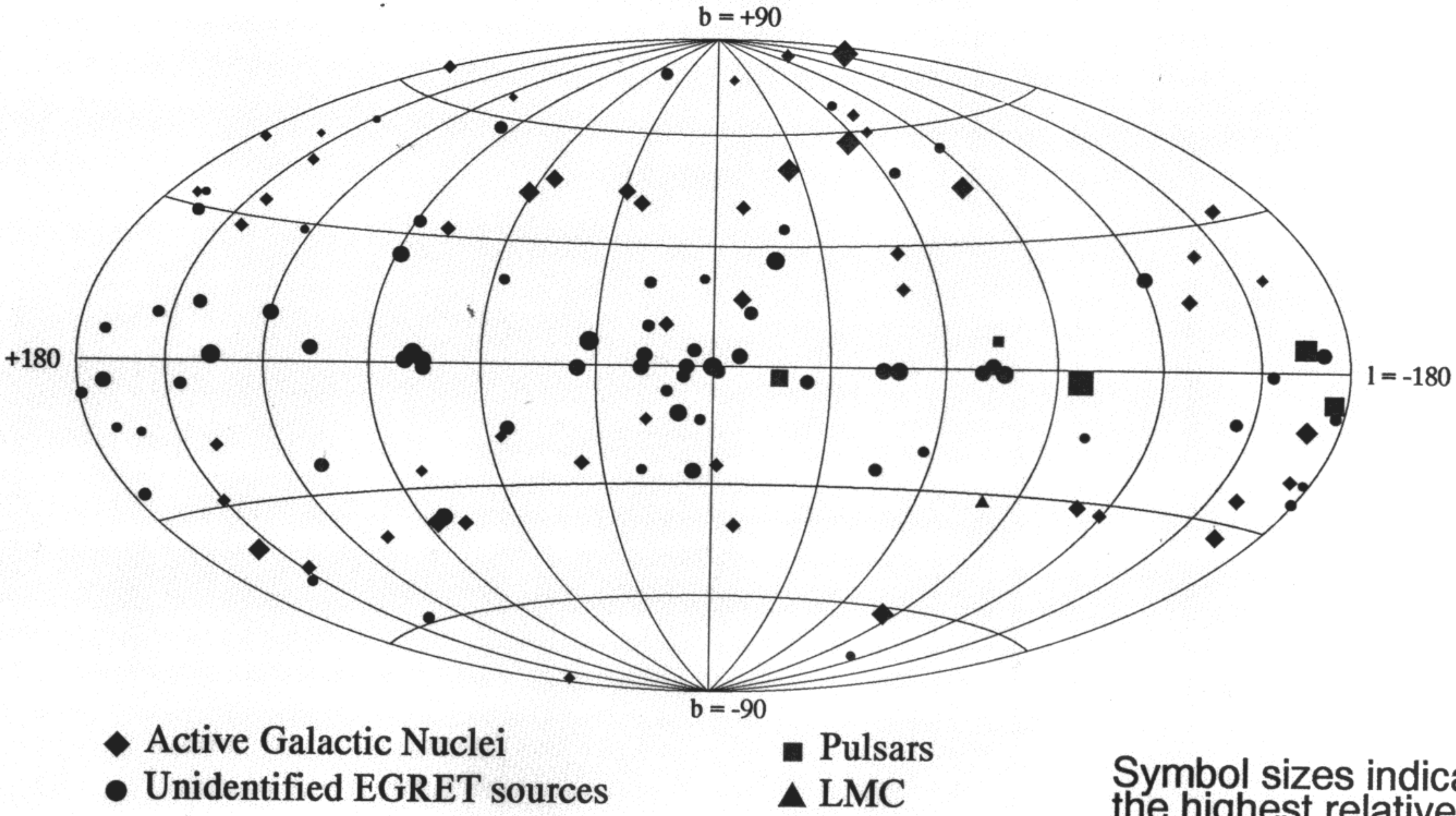
GALACTIC NEUTRINO SOURCES include all energetic astrophysical systems, where we suspect cosmic ray acceleration, i.e.supernova remnants, binary systems, etc. EGRET has detected GeV gamma ray emission associated with several remnants. TeV emission has also been detected from SN1006. It is not yet obvious if these signals are related to proton acceleration and interactions - they could also be explained in terms of electron energy loss.

The expectations are that in our galaxy neutrinos come from proton-proton interactions. It is possible that the matter density in the vicinity of cosmic ray acceleration sites is very low and the photon and neutrino signals from point sources are low. The GeV signals from SNR also show energy spectra that are steeper than the theoretically favored flat ones.

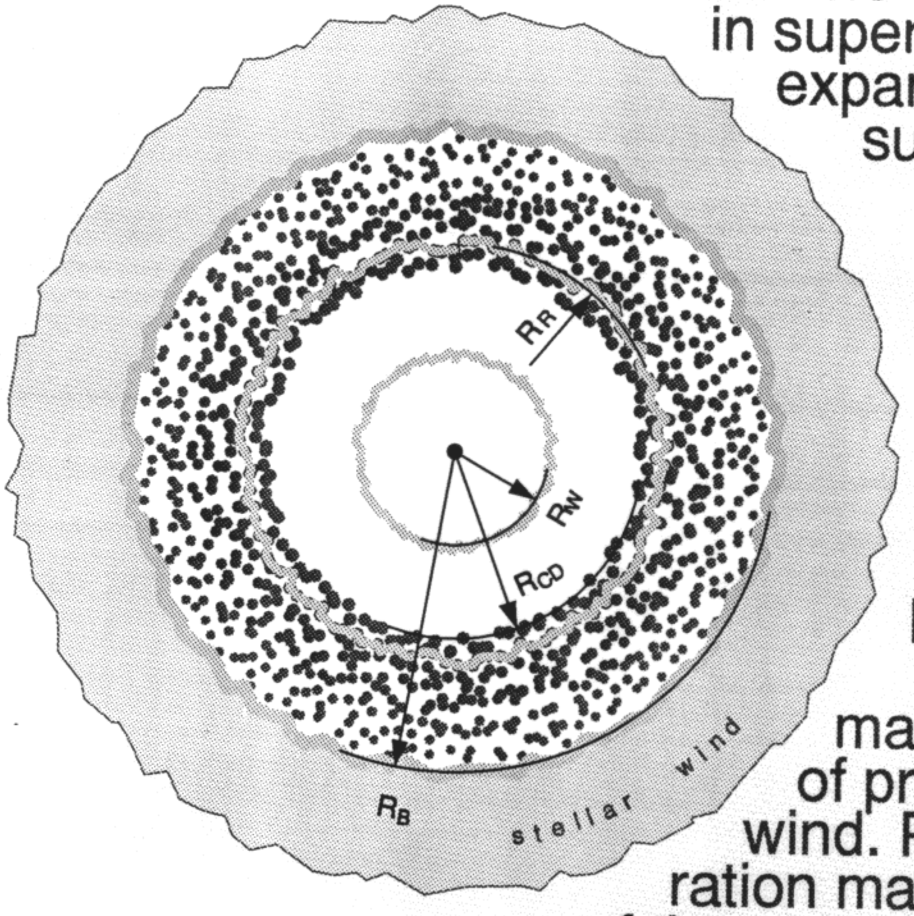
On the other hand, cosmic rays propagating in the Galaxy will necessarily interact on galactic matter and generate diffuse galactic neutrinos, similar to the gamma rays detected in the GeV range. The good news is that the diffuse galactic radiation has an energy spectrum similar to those of individual Supernova remnants.

Second EGRET Catalog

E > 100 MeV



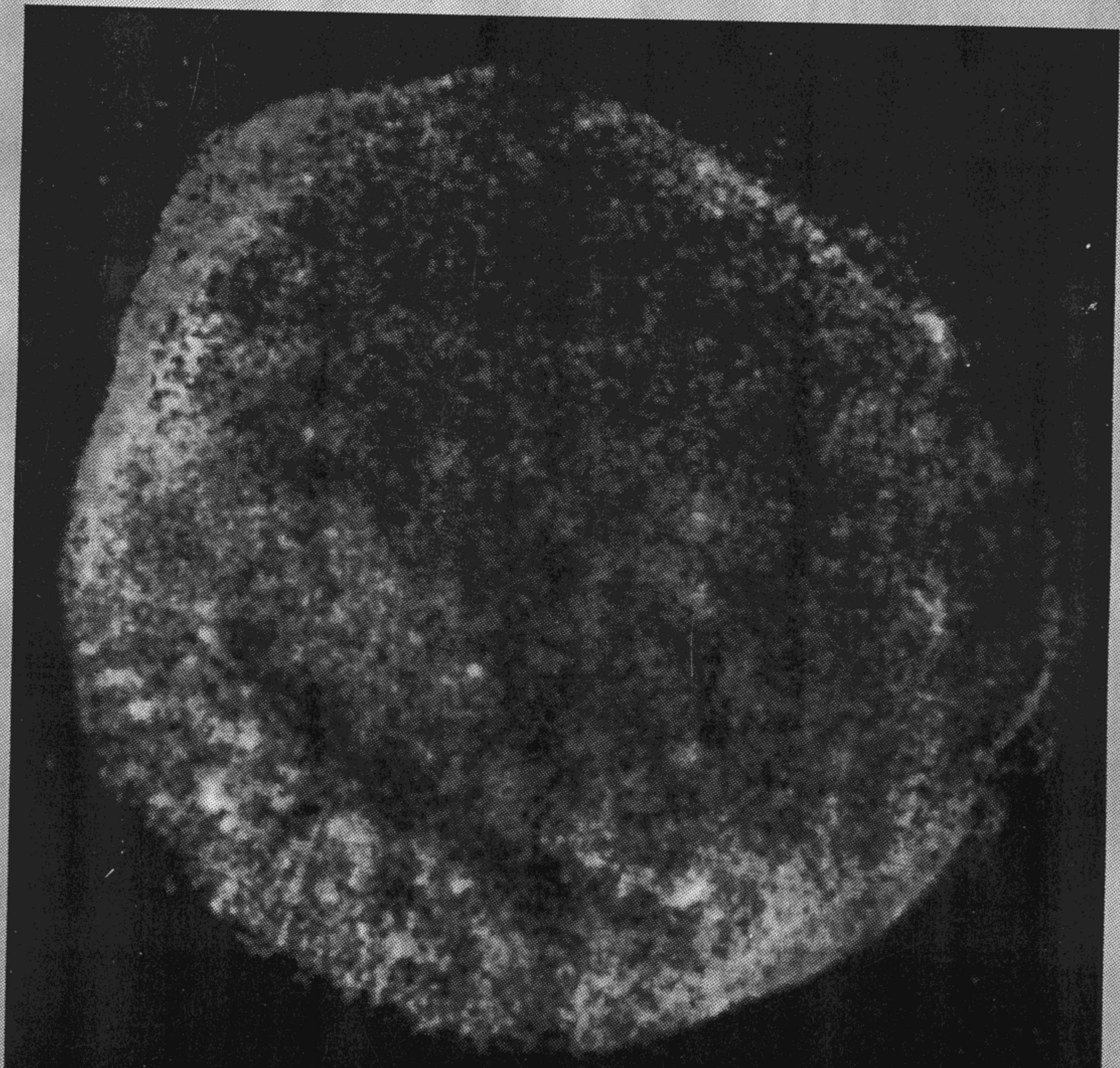
Symbol sizes indicate the highest relative intensity observed from the source.



Possible shock locations in supernova remnants expanding in the pre supernova stellar environment. From inside out: Pulsar wind shock; Reverse shock; Supernova blast shock. Exact positions depend on the mass and velocity of progenitor stellar wind. Particle acceleration may occur on any of these shocks.

Accelerated nuclei are contained in the shock region by magnetic fields and only slowly diffuse out. Total amount of matter for injection and as interaction target is several solar masses. GeV gamma rays and non-thermal X-rays are observed from several supernova remnants.

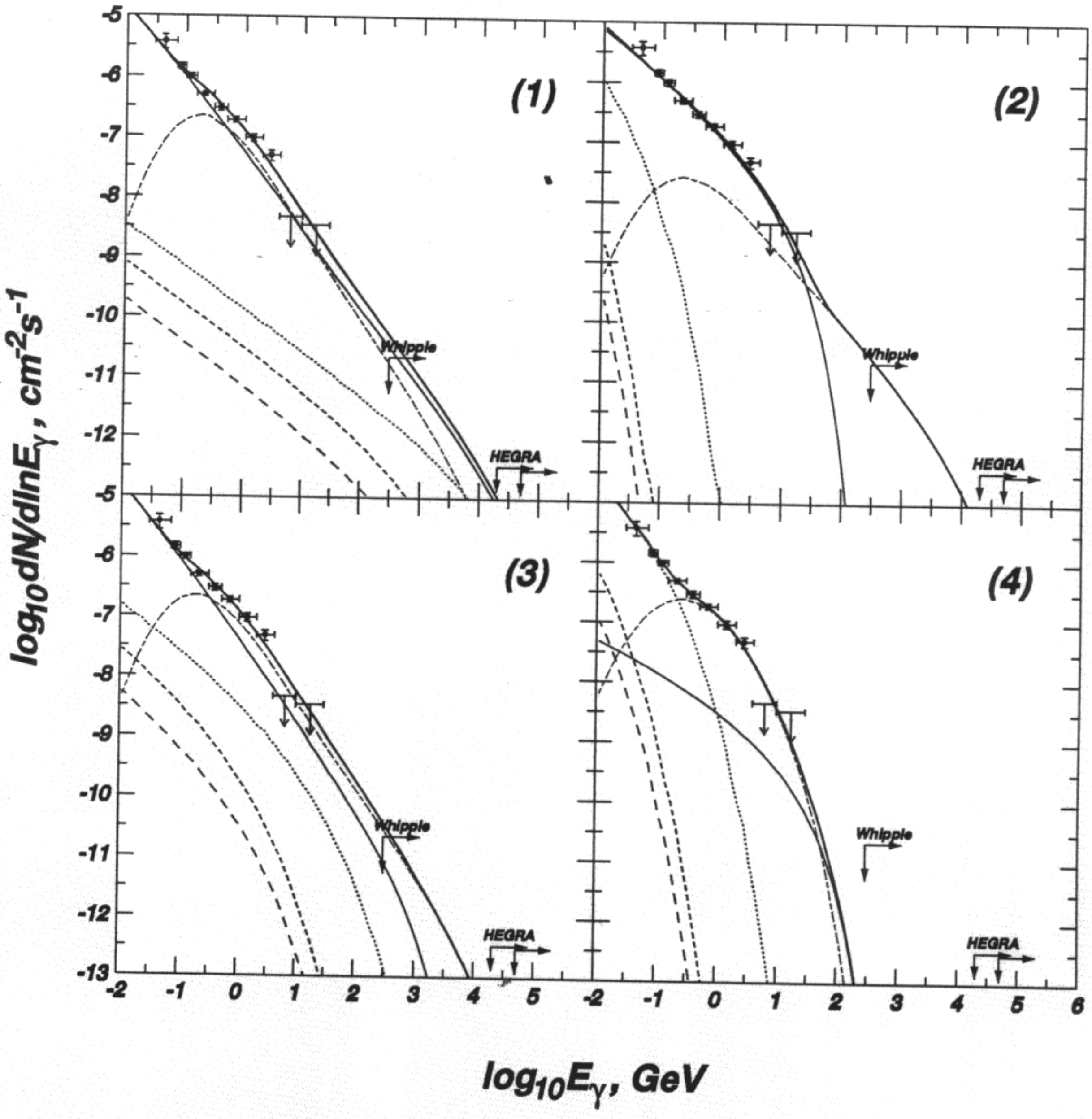
The main energy source is the kinetic energy of the expanding supernova shell, which is of order 10^{51} *ergs. Only 1/100 of this energy could supply the total amount of cosmic rays in the Galaxy if there are 3–5 supernova explosions per century. Shock acceleration calculations show that 5–10% of the energy could be released in the form of accelerated particles. Pulsar radiation could also be important if young pulsars are already spinning fast.*



SN 1006 ROSAT HRI Image

University of Leicester

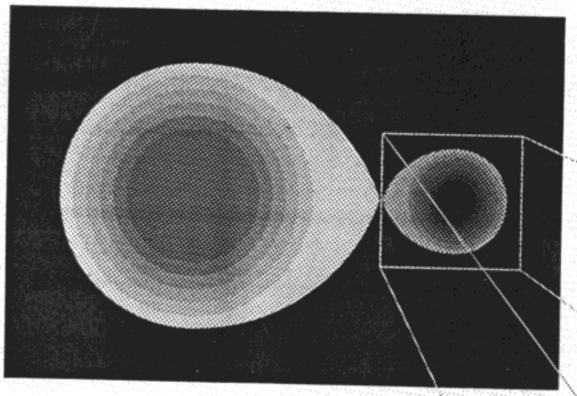
Fits of the gamma ray emission of g_Gygni

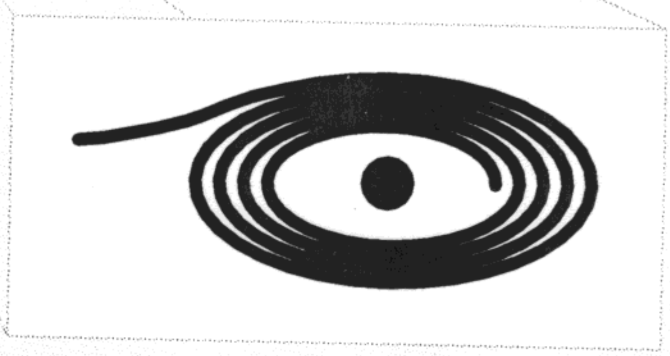


(1) proton, electron spectra parallel to 100 TeV
(2) spectra parallel, electrons cut off
(3) different spectra for protons & electrons
(4) spectra parallel, both cut off at the same energy

Compact X-ray Binary systems

Energy sources: mass transfer through Roche lobe overflow, pulsar spindown. Multiple targets for particle interactions: the matter of the accretion disk or/and of the companion star; the radiation fields of both; the pulsar magnetic fields.



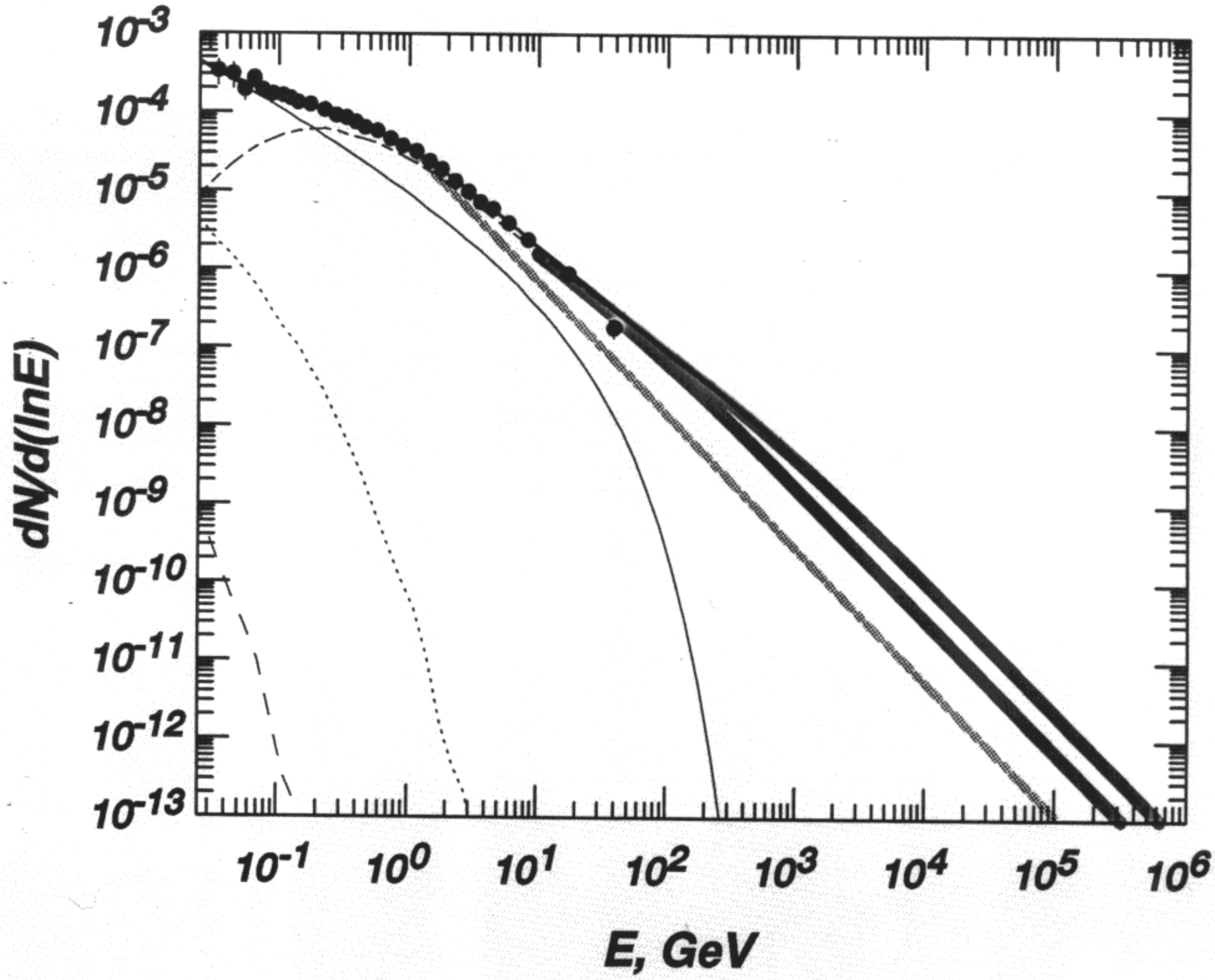


If only electrons are accelerated at such objects, there will be no neutrinos. Accretion, however, supplies a large number of ionized nuclei for injection and acceleration. Once protons are accelerated they could generate both gamma rays and neutrinos. No statistically significant observations of TeV gamma rays from X-ray binary systems.

Accretion driven luminosity is limited by the Eddington luminosity $\mathrm{L_{edd}} = 4\pi \mathrm{GMm_p}/\sigma_\mathrm{T} < 1.4 \times 10^{38} \mathrm{M/M_\odot}$ erg/s *for X–ray emission.*

Magnetic dipole luminosity is $\mathrm{L_{MD}} = 4 \times 10^{43}\ \mathrm{B_{12}^2}\ \mathrm{P_{ms}^{-4}}$ erg/s, *where* $\mathrm{B_{12}}$ *is the pulsar surface magnetic field in* 10^{12} *G and* $\mathrm{P_{ms}}$ *is the pulsar period in milliseconds.*

DIFFUSE RADIATION FROM THE INNER GALAXY



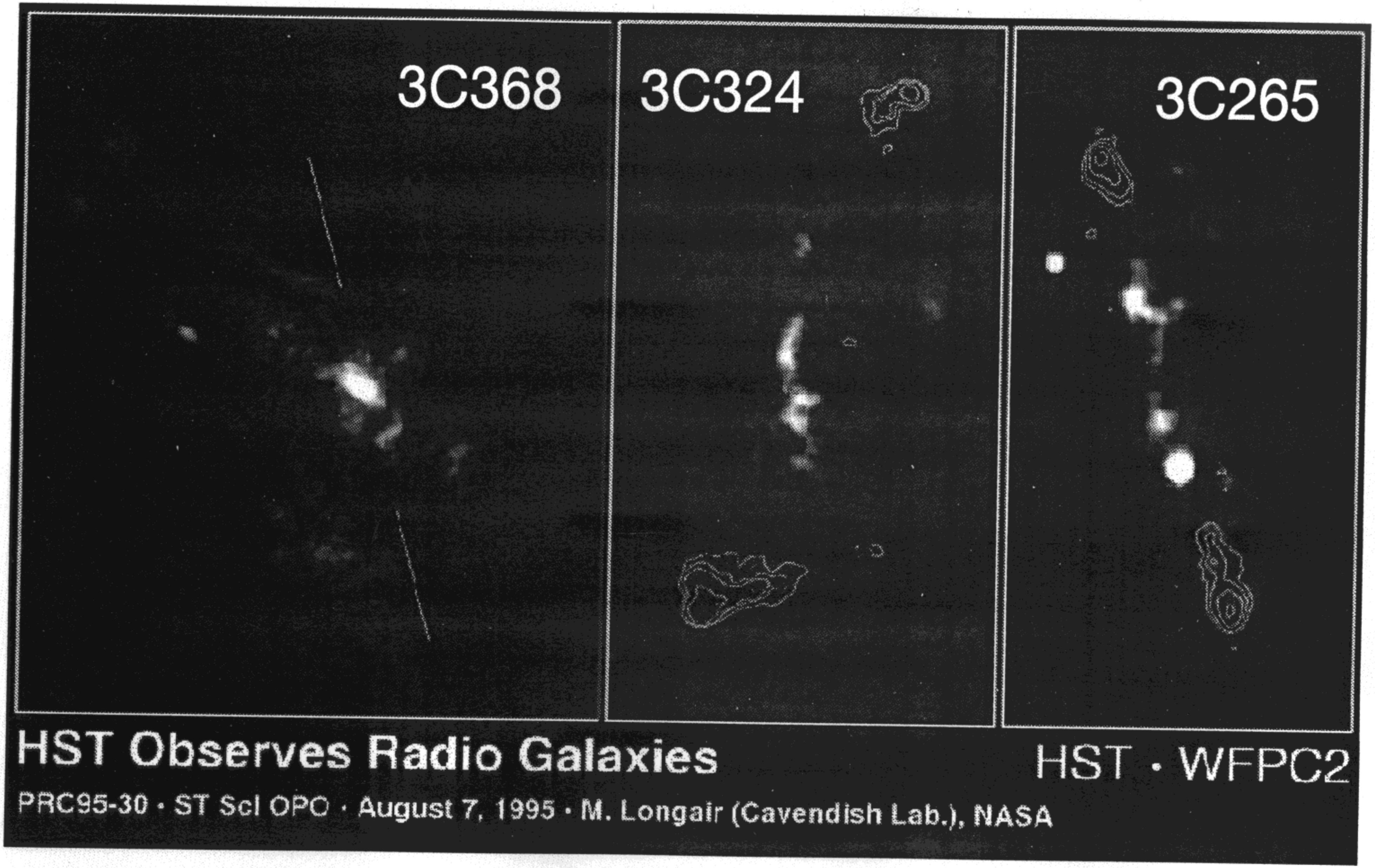
EGRET shows a very flat gamma ray spectrum from the inner galaxy. If it is produced by a collection of supernova remnants it requires a filling factor of 10.

It is likely that the primary proton spectrum steepens at some energy above 100 GeV (because of diffusion) to become similar to the local galactic cosmic ray The blue lines show the neutrino spectrum that would result from such steepening. It is significantly higher than what would follow from a $E^{-2.7}$ spectrum, shown with a purple dash-dot line.

***EXTRAGALACTIC NEUTRINO SOURCES** are most likely based on different type of physics: interactions of the accelerated cosmic rays on the ambient photon fields. The photoproduction cross section is lower than pp one by a factor of 30 and the threshold energy for pion production on the soft ambient photon fields is high -- more than 50 EeV on the microwave background. On the other hand, excatly because of the low energy of the photons their target density is very high.*

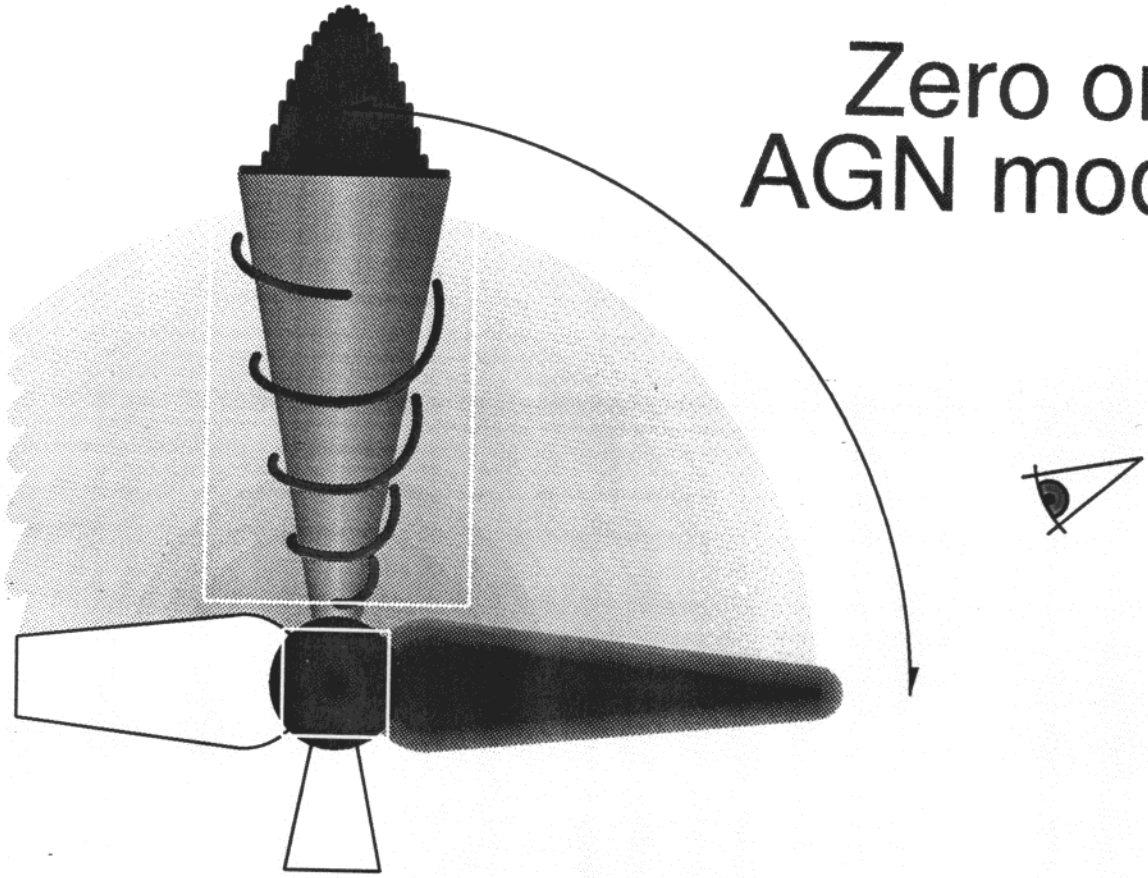
Suspected sources are the most luminous ones: the Active Galactic Nuclei. Neutrinos could be produced either close to the central AGN engine (black hole?) or in the AGN Jets. Jets have the advantage of their superluminal motion, which increases the neutrino energy by the Dopler factor of the jet. Jets may also be a better environment for proton acceleration. AGN neutrino spectra extend to extremely high energy

Diffuse extragalactic neutrino background is expected from the neutrino emission of all unresolved AGN The cosmological and luminosity evolution of the active galactic nuclei is very important for the estimate of the diffuse neutrino background. Other types of diffuse backgrounds set strong limits on the expectations. Although isotropic, this background radiation should be easily identifiable by its ultra high energy.


3C368
3C324
3C265
HST Observes Radio Galaxies
HST • WFPC2
PRC95-30 • ST ScI OPO • August 7, 1995 • M. Longair (Cavendish Lab.), NASA

Moriond, March '97

Zero order AGN models



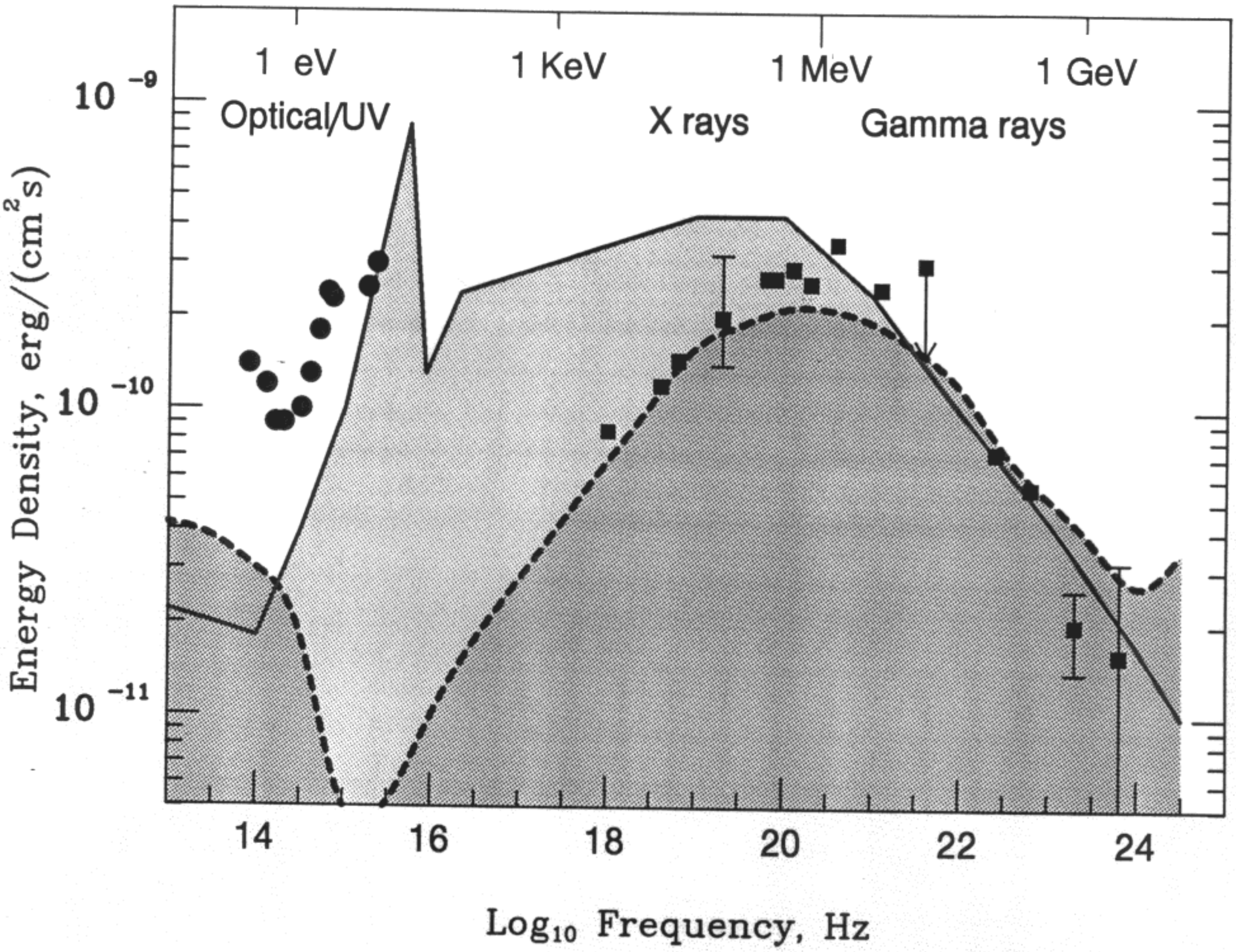
Active galactic nuclei are the same and consist of a central engine (massive black hole), accretion disk and jets. Appearent differences are due to the position of the observer.
Jets carry about 10% of the AGN luminosity, and may appear brighter because of the motion of the emitting matter toward the observer.

The mass of the black hole

$$\mathrm{M_{BH}} = \mathrm{L_{AGN}}/\mathrm{L_{Edd}} = (10^6 - 10^8) \times \mathrm{M_\odot}$$

For observers looking along the jet axis

$$\mathrm{E_{obs}} = \Gamma_\mathrm{j} \times \mathrm{E_{jf}} \quad \text{and} \quad \mathrm{L_{obs}} = \Gamma_\mathrm{j}^4 \times \mathrm{L_{jf}}$$



Quasi-simultaneous observations of 3C273 compared to purely electromagnetic gamma ray production model [Dermer et al] and the proton induced cascading model of Mannheim, in purple. The latter fits better the X-ray to gamma ray range although the radiation in the optical is not predicted well.

An outstanding problem for all models is the very fast variability of AGN gamma rays detected by EGRET, at the timescale of days.

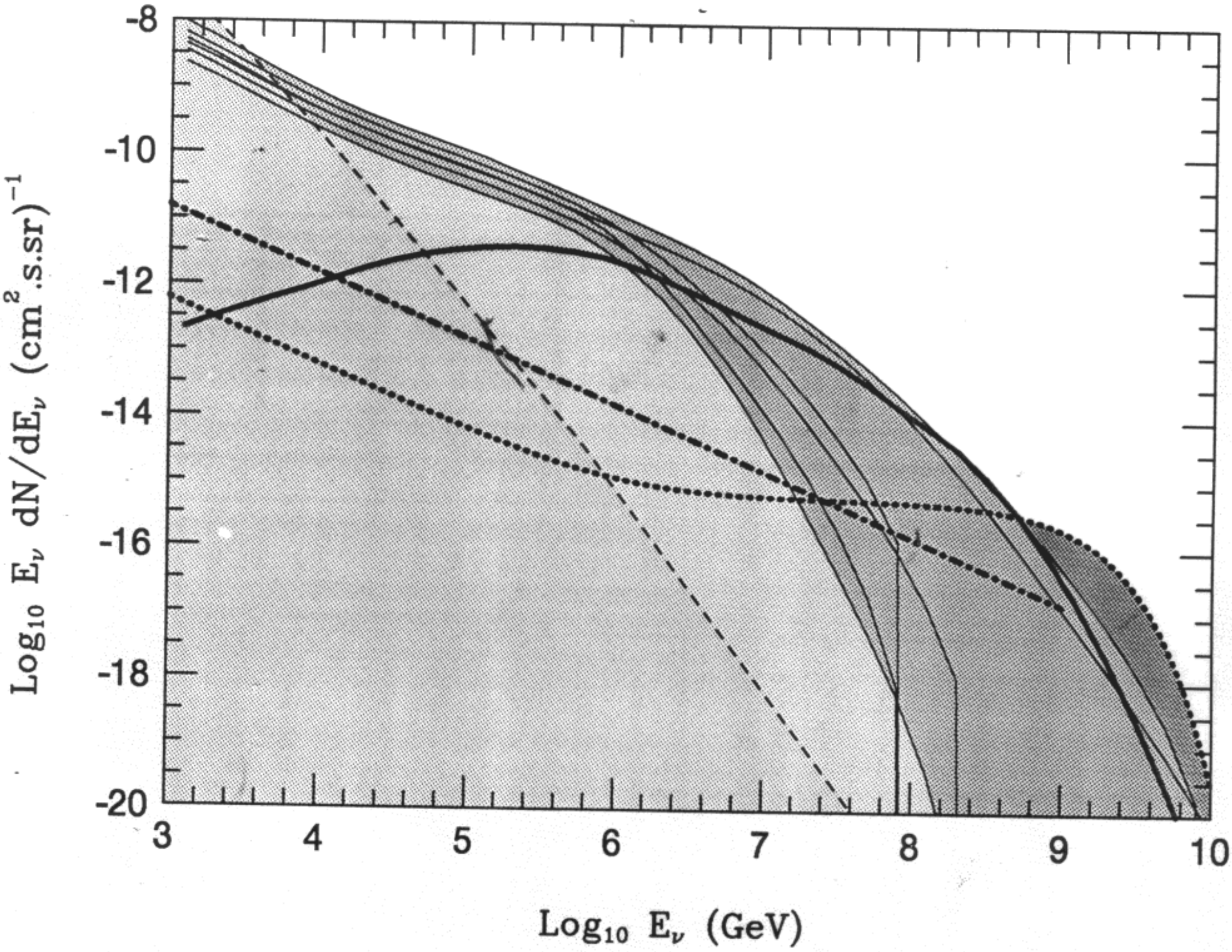
POWERFUL OUTBURSTS IN TeV γ RAS DETECTED IN 97/98 FROM MRK 501 AND MRK 421

ENERGY SPECTRUM MEASURED TO ~30 TeV

VARIABILITY TIMESCALE $\lesssim$ 1 hR

(Whipple, HEGRA, CAT)

SIMULTANEOUS MULTIWAVE LENGT OBSERVATION



INTEGRATED ν LUMINOSITY (ISOTROPIC) FROM AGN
NORMALIZED TO ISOTROPIC XRAY FLUX

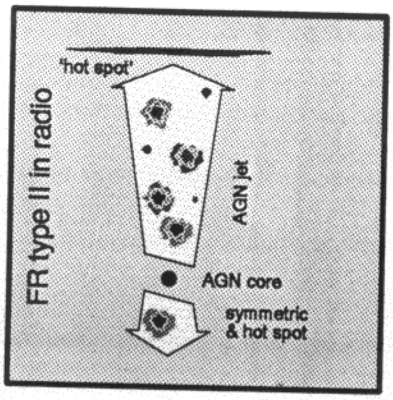
$$\frac{dI}{dE} = \frac{1}{4\pi}\frac{c}{H_0}\frac{1}{E R_0^3}\int dL_x \int_0^{z_{max}} dz\, \rho(L_x, z)(1+z)^{-5/2}\frac{dL}{dE}\left[E(1+z), L_x\right]$$

$$\rho(L_x, z) = \ell_0^3 \frac{g(z)}{f(z)}\rho_0\left(\frac{L_x}{f(z)}\right)$$

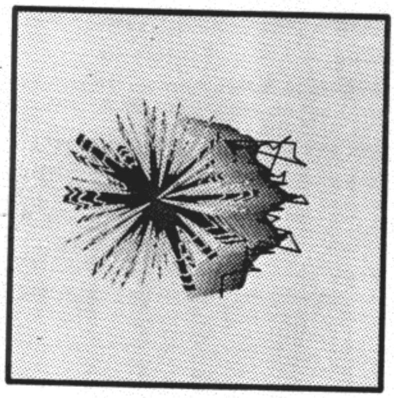
THE SOURCES OF THE HIGHEST ENERGY COSMIC RAYS are suspected of being also neutrino sources. For some models, such as the topological defects, in which UHECR are the products of the evolution of ultra massive X particles, neutrino emission is much stronger than the nucleon emission. Gamma rays are the most likely UHECR in such models.

In other, more conventional models, neutrinos are always secondary particles, generated in photohadronic interactions. This sets the end of the neutrino energy spectrum at relatively modest energies, about one order magnitude lower than the cosmic ray spectrum. It is not yet obvious that any acceleration model would necessarily generate UHE neutrino fluxes. This is however unavoidable in the GRB and AGN Jet models.

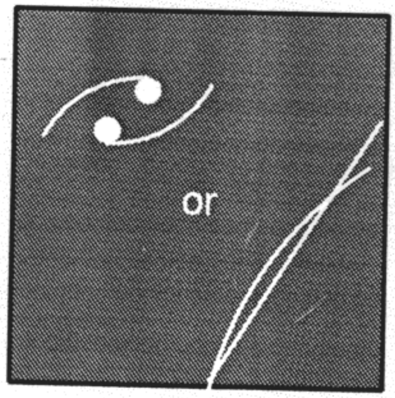
Cosmic rays of energy above 50 EeV interact on the microwave background in their propagation to us. This is a certain source of diffuse UHE neutrinos. The magnitude of the flux depends on the CR source distribution and the maximum proton energy at acceleration.



Radiogalaxies may accelerate HECR at the huge termination shocks of the the jet flow - hot spots. Neutrinos could be produced by the HECR during propagation, a la Hill&Schramm. Magnitude of these UHE neutrino fluxes depends on the HECR source distribution. Far away sources generate the highest fluxes.



Gamma ray bursts have been suggested as also sources of HECR. Both signals are generated in a fireball expanding with Lorentz factor > 100. Accelerated protons photoproduce in the plasma frame and and generate neutrinos that peak at 100 TeV. In the Lab frame the signal duration is 1-100 sec for neutrinos as well. GRB and neutrino burst are coincidental.



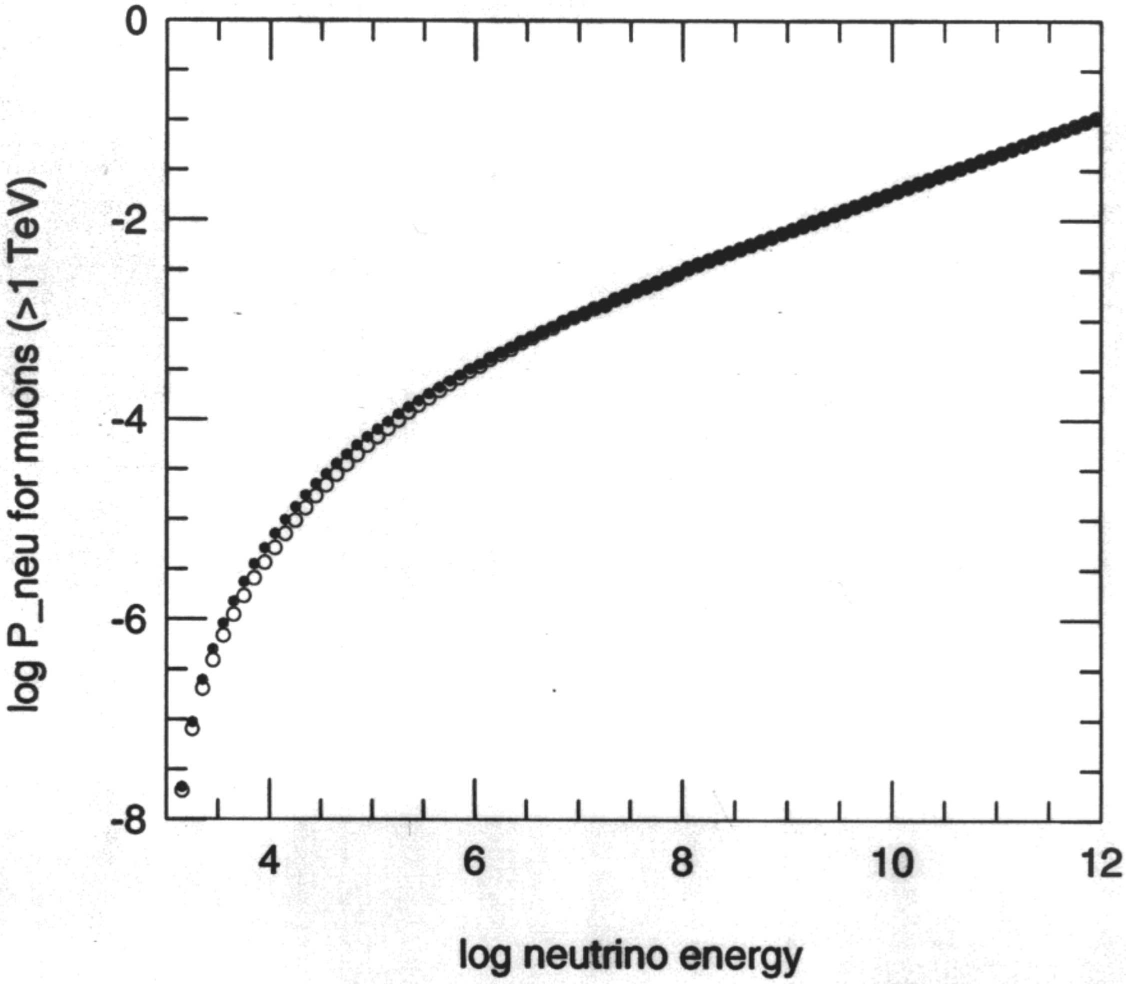
Topological defects, cosmic strings or annihilating monopoles, could emit GUT scale particles that eventually decay into nucleons, gamma rays and neutrinos. Neutrino flux extends to the GUT scale and contains 1/2 of the energy. Energy spectrum is very flat (~E^4/3). Special techniques should be used for detection of such neutrinos.

PROTONS INTERACT ON THE MICROWAVE BACKGROUND ($n = 400\ cm^{-3}$) TO PRODUCE Δ^+ at

$$E_p \approx \frac{\Delta^2 - m_p^2}{2(1-\cos\theta)\epsilon} \approx \frac{5\times 10^{20}}{1-\cos\theta}\,eV \times \frac{1}{1+z}$$

$\epsilon = 6.6\times 10^{-4}\ eV$

ACTUAL THRESHOLD IS 3×10^{19} eV



NEUTRINO INDUCED MUONS (UPWARD)

$$P_{\nu\to\mu} = \int_{E_\mu}^{E_\nu} \sigma(E_\nu, E'_\mu) R(E'_\mu, E_\mu) dE'_\mu$$

$$\text{Signal} = \int_{E_\mu}^{E_\nu^{max}} F_\nu(E_\nu) P_{\nu\to\mu} dE_\nu$$

NOTE: $P_{\nu/\mu}$ GROWS FASTER THAN σ_{cc} FOR $E_\nu > 10^7$ GeV

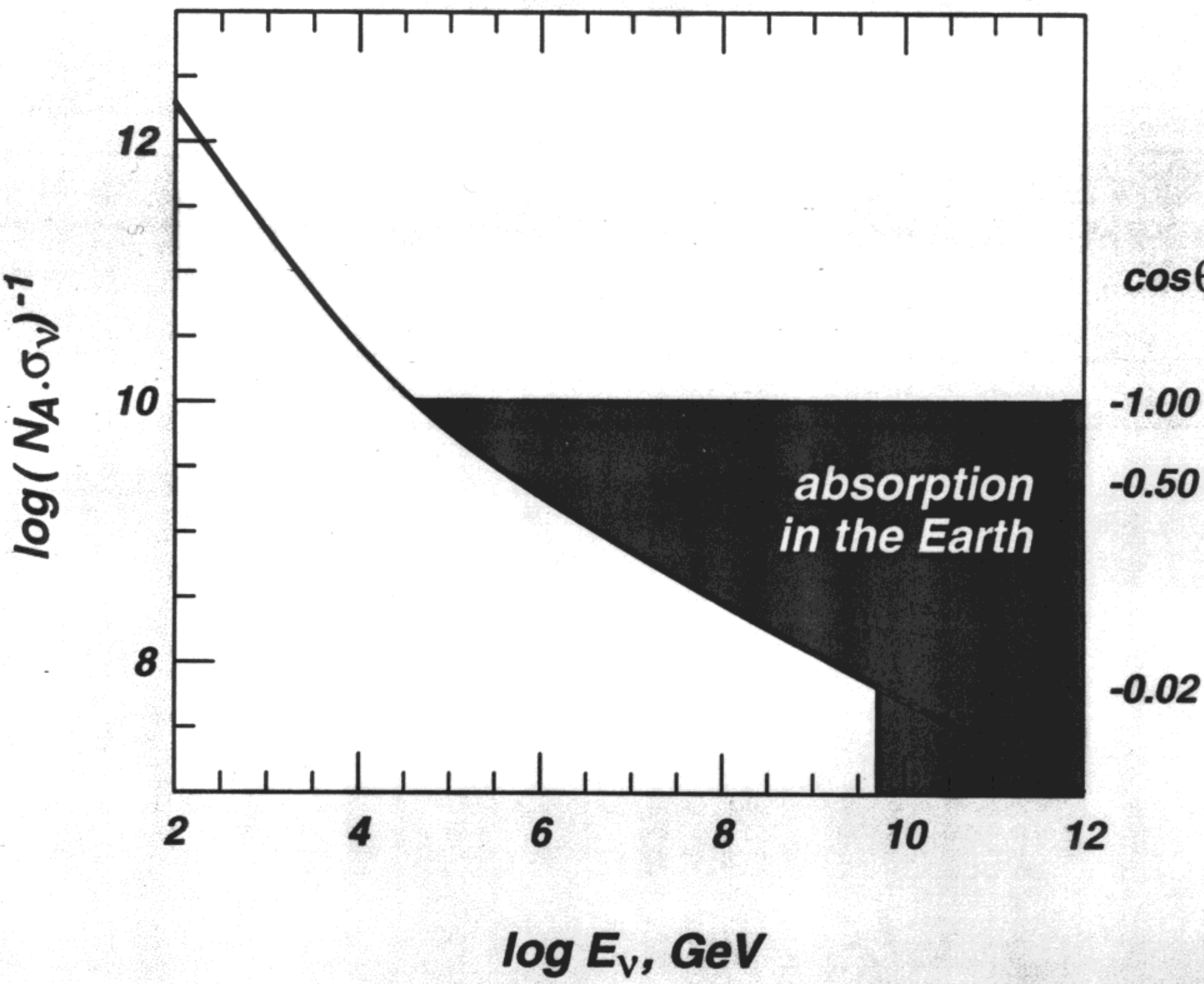
ULTRA HIGH ENERGY NEUTRINO CROSS SECTIONS

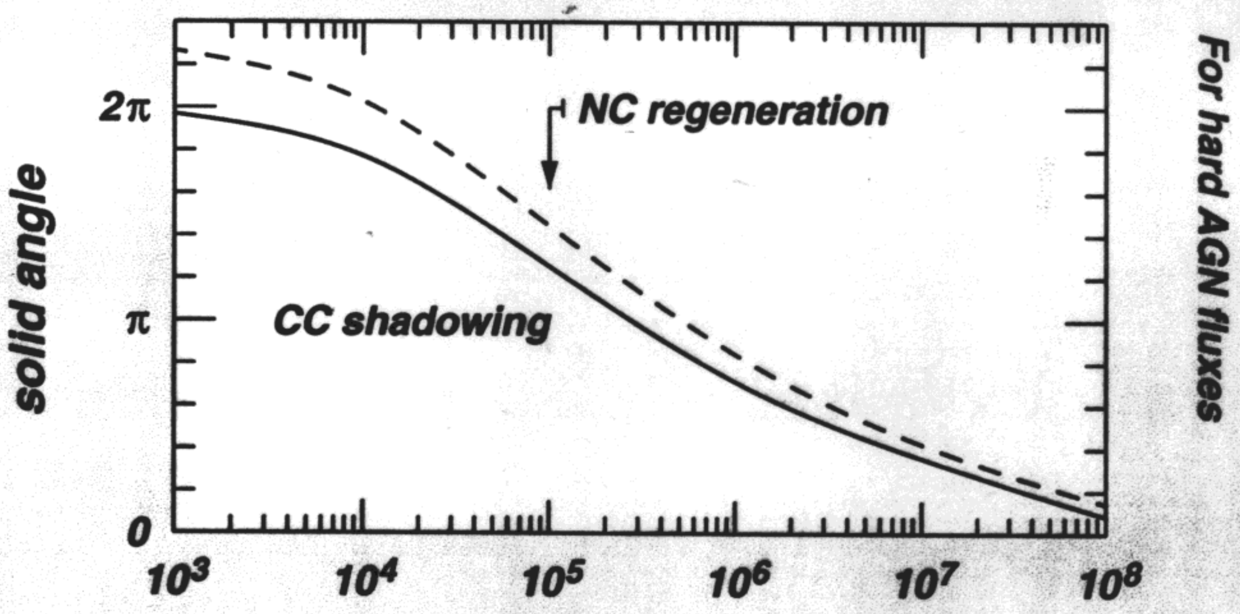
- the measurements of the structure functions at HERA have lead to stable estimates of the neutrino cross sections at very high energy. A recent preprint of the Durham group agrees with the earlier CTEQ calculation better than 20% at 100 EeV.

- muon to tau neutrino oscillations may have an interesting effect, because tau mesons have a very short lifetime (decay length of 50 km at 10 PeV). Tau neutrinos will thus not be absorbed in the Earth, just lose energy until the Earth becomes transparent (H&A). This will not affect much the prospects for neutrino observations because even the flattest energy spectrum is quite steep.

- the same will happen with all neutrinos because of neutral current interactions (KM&S). A fraction of the absorbed neutrinos will be recovered at lower energy. The effect is however at the 20% level even for very flat neutrino fluxes.

Kwiecinski, Martin & Stasto. '98





WAXMAN&BAHCALL NEUTRINO LIMIT
(derived from the flux of the UHE cosmic rays)

1. $\frac{dN_{CR}}{dE} \propto E^{-2}$ in $10^{19} - 10^{21}$eV range

$\dot{\varepsilon} \sim 5 \times 10^{44}$ erg $\mathrm{Mpc}^{-3}\mathrm{yr}^{-1}$

$E_\nu^2 \frac{dN_\nu}{dE_\nu} \simeq \frac{t_H}{4} \varepsilon E^2 \frac{d\dot{N}}{dE}$

2. $\begin{cases} \varepsilon < 1 \text{ is assumed energy independent} \\ E_\nu \text{ assumed } 1/20 \text{ of } E_p \end{cases}$

I_{max} is achieved for $\varepsilon = 1$

$I_{max} \simeq \frac{t_H}{4} \xi_Z \frac{c}{4\pi} E^2 \frac{d\dot{N}}{dE}$

$\simeq 1.5 \times 10^{-8} \xi_Z$ GeV.$\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$, i.e.

$E_\nu^2 \Phi(\nu_\mu + \bar{\nu}_\mu) = \varepsilon \times I_{max}$

MANNHEIM, PROTHEROE & RACHEN :

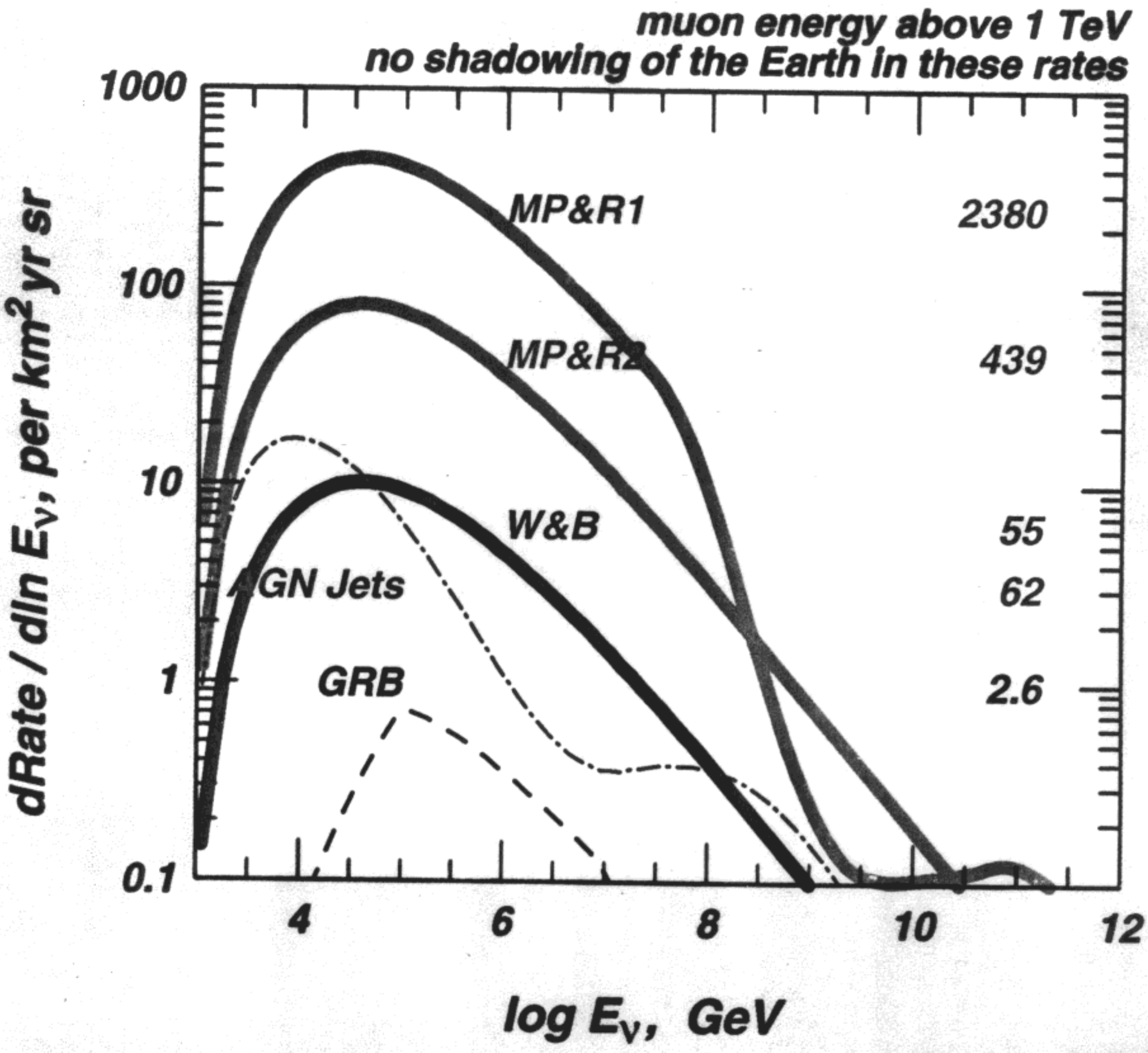
Waxman&Bahcall have not accounted for:

- the difference in the protons and neutrinos energy loss horizon: $\lambda_p^{-1} = \lambda_z^{-1} + \lambda_{p,BH}^{-1} + \lambda_{p,\pi}^{-1}$

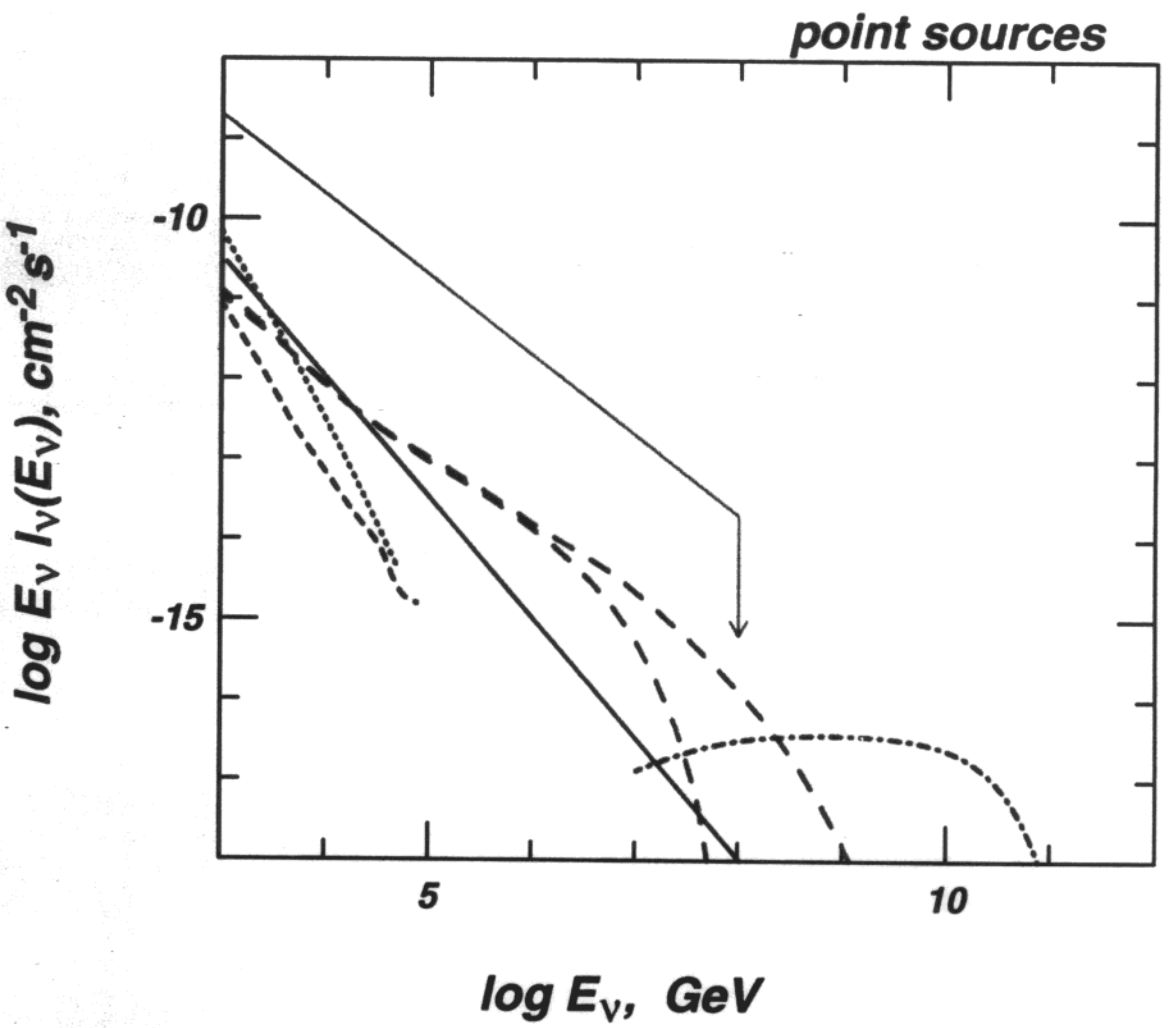
$\lambda_{p,\pi} = (n_{bg}\langle K_p \sigma_{p\gamma}\rangle)^{-1} = (400 \times 2.5 \times 10^{-29})^{-1} = 10^{26}$ cm $\sim$ 30 Mpc, while $\lambda_\nu = \lambda_z$, which is the energy loss due to the expansion of the Universe. This distorts the account for the cosmological evolution of the proton and neutrino fluxes.

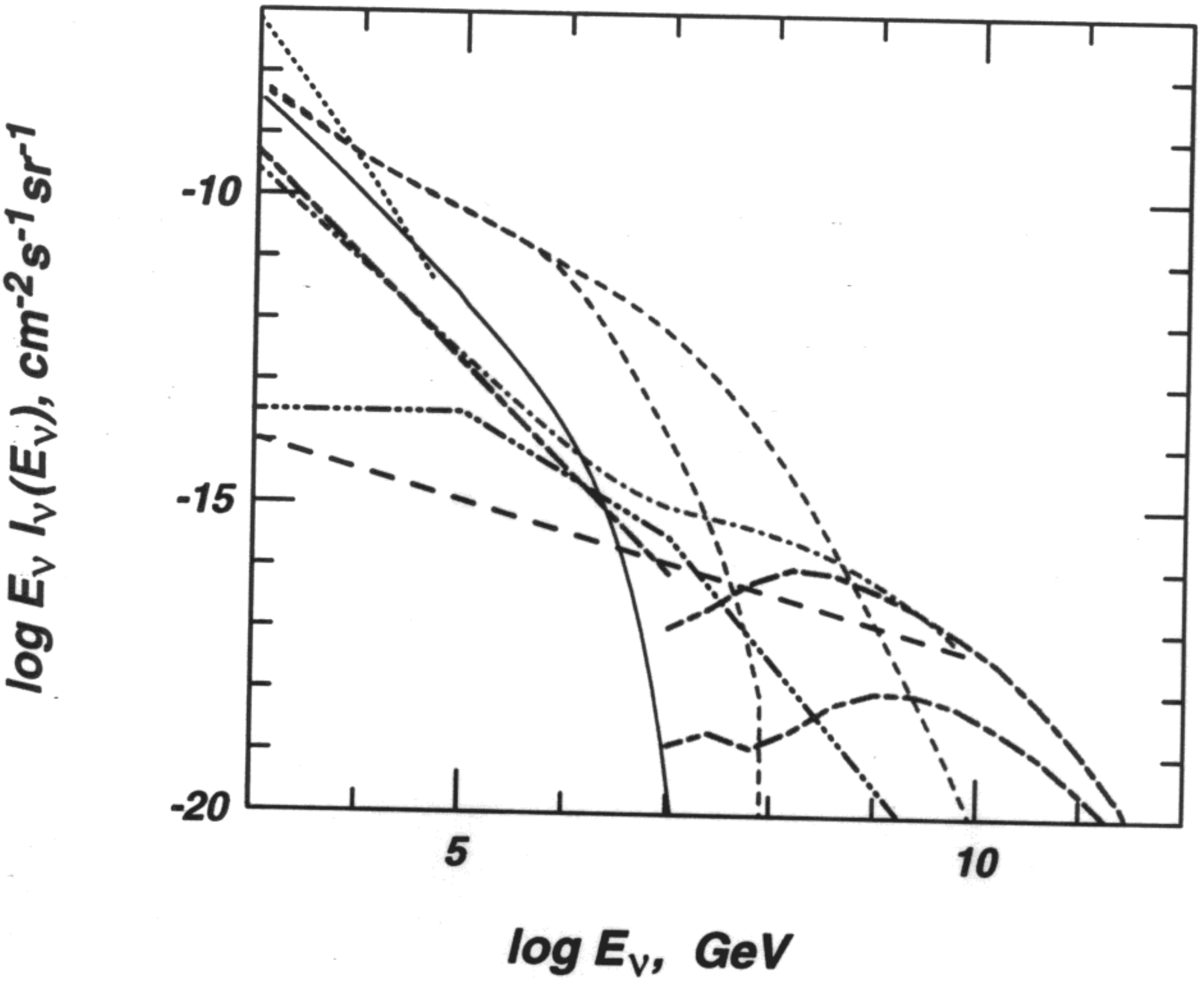
- have not accounted correctly for the actual energy spectrum of the cosmic rays (assuming E^{-2}) and have neglected the adiabatic losses for the protons possibly accelerated at gamma ray bursts.

- MP&R limit agree with W&B only at 10^{19} eV, where that latter calculation is normalized.



muon energy above 1 TeV
no shadowing of the Earth in these rates
1000
100
10
1
0.1
MP&R1
2380
MP&R2
439
W&B
55
AGN Jets
62
GRB
2.6
4
6
8
10
12
dRate / dln E_ν, per km^2 yr sr
log E_ν, GeV


point sources
-10
-15
5
10
log E_ν $I_\nu(E_\nu)$, $cm^{-2}s^{-1}$
log E_ν, GeV



log E_ν $I_\nu(E_\nu)$, $cm^{-2}s^{-1}sr^{-1}$
-10
-15
-20
5
10
log E_ν, GeV

SUMMARY OF EVENT RATES[$] IN KM^3 DETECTOR

- **DIFFUSE FLUX (per steradian)**

muon energy	atm. ν's	AGN	AGN jets
> 10 GeV	43000	600 – 800	188
> 1 TeV	1040	400 – 800	45
also $\nu_e\,(6.3\,\text{PeV}) + e \rightarrow W^-$		300 per km^3	
		1	

- **INNER GALAXY (0.73 ster)**

muon energy	atm. ν's	inner galaxy	gal plane
> 10 GeV	31400	880 – 2000	120 – 200
> 1 TeV	760	160 – 470	15 – 30

- **ATMOSPHERIC ν's IN 1° BIN**

muon energy	$\cos\theta = 0.05$	$\cos\theta = 0.95$
> 10 GeV	79	29
> 1 TeV	2.1	0.5

- **POINT SOURCES**

	muon energy >1 TeV
(Sources of galactic CR)/100	26
Supernova remnants (γCygni)	3
Extragalactic source (3C273)	1 – 100
GRB source of UHECR(B&W)	3 per burst
Topological defects (UHECR)	5*

- **LIMITS FROM UHECR (per sr)**

	muon energy >1 TeV
(Waxman & Bahcall)	36
Mannheim, Protheroe&Rachen 1	1590
Mannheim, Protheroe&Rachen 2	289