Constraints on Extragalactic Point Source Flux from Diffuse Neutrino Limits

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***Abstract*. We constrain the maximum flux from extragalactic neutrino point sources by using diffuse neutrino flux limits. We show that the maximum flux from extragalactic point sources is $\mathrm{E}^2(\mathrm{dN}_\nu/\mathrm{dE}) \leq \mathbf{5.1 \times 10^{-9}}$ $(\mathbf{L}_\nu/\mathbf{10^{45}}\ \mathrm{erg/s})^{\mathbf{1/3}}$ GeV cm^{-2} s^{-1} from an ensemble of sources with average neutrino luminosity per decade, $\mathbf{L}_\nu$. It depends only slightly on factors such as the inhomogeneous matter density distribution in the local universe, the luminosity distribution, and the assumed spectral index.**

***Keywords*: Extragalactic sources, diffuse and point sources, high energy neutrinos**

I. Introduction

The origin of ultra high energy cosmic rays (UHECR), is still unknown. AGN, GRB's, or processes beyond the standard model have been hypothesized to be the sources of UHECR's, and may originate from regions of the sky correlated with AGN sources [1]. Therefore, if nearby AGN are the sources of the highest energy CR's, and if AGN emit ν's in addition to photons, protons and other charged particles, then the fluxes from individual AGN may be observable by current generation of neutrino detectors. Several models predict a diffuse neutrino flux from AGN, in particular ν-production has been predicted from the core of radio-quite AGN as presented in [2], [3], and from AGN jets and radio lobes as suggested in [4], [5], [6]. There are good but speculative reasons to expect a correlation between sources of cosmic rays and sources of neutrinos. Direct searches for diffuse [7] and point flux [8] by current telescopes have set the most stringent upper limits, but generally have not reached the sensitivity required, and the models suggest that challenges exist even for next generation telescopes.

Of course, one of the primary motivations for the construction of ν-telescopes is to search for unexpected sources with no obvious connection to the power emitted in the electromagnetic (EM) band. However, we show in this paper that the ν-flux from EG point sources can be constrained by the measured diffuse ν-flux limits. We also test models from individual sources with the constraints.

II. Analysis

If the diffuse ν-flux is generated by an ensemble of extragalactic (EG) sources, then only the nearest of the diffusely distributed sources would be detectable as point sources. Point sources of neutrinos are observed when several neutrinos originate from the same direction, and in the context of this study, only the very nearest of the uniformly distributed sources are detectable as point sources. The number of detectable (or resolvable) point sources, N_s, first proposed in [9], is determined for a given diffuse ν-flux limit and point source sensitivity. The N_s calculation is based on three general assumptions: (1) the sources are extragalactic and uniformly distributed in space; (2) the ν-luminosity follows a power law or broken power law distribution; (3) the sources are assumed to emit neutrinos with an E^{-2} energy spectrum. Later, we discuss the robustness of the constraint by investigating the validity and caveats of the assumptions.

The number of resolvable sources N_s for a distribution of luminosities L_ν per decade in energy is given by:

$$N_s \simeq \frac{\sqrt{4\pi}}{3} \frac{1}{\sqrt{\ln\left(\frac{E_{max}}{E_{min}}\right)}} \frac{H_0}{c} \frac{K_\nu^{diff}}{(C_{point})^{3/2}} \frac{\langle L_\nu^{3/2}\rangle}{\langle L_\nu \rangle} \frac{1}{\xi} \quad (1)$$

where the parameter ξ depends on cosmology and source evolution as described in [9]. The ν-luminosity of the source, L_ν has units of (erg/s), and (E_{min}, E_{max}) defines the energy range of the flux sensitivity, where $E_{max} = 10^3 E_{min}$ for a typical experimental condition. For canonical energy spectrum proportional to E^{-2}, we use the results for all-flavor diffuse flux limits presented in [7] to obtain the ν_μ-diffuse flux: $K_\nu^{diff} \equiv \mathrm{E}^2\Phi_{\nu_\mu} = (1/3) * \mathrm{E}^2\Phi_{\nu_{all}} = (1/3) * 8.4 \times 10^{-8}$ GeV cm^{-2}s^{-1}sr^{-1} $= 2.8 \times 10^{-8}$ GeV cm^{-2}s^{-1}sr^{-1} valid for the energy interval of 1.6 PeV < E < 6.3 EeV. This is the energy interval of interest for CR interaction with energies above the ankle. Below PeV energies K_ν^{diff} can be obtained from [10], $K_\nu^{diff} < 7.4 \times 10^{-8}$ GeV cm^{-2} s^{-1} sr^{-1}, valid between 16 TeV to 2.5 PeV. So, similar diffuse flux limits, K_ν^{diff}, exist for the entire interval from TeV to EeV energies. C_{point} is the experimental sensitivity to ν-fluxes from point sources for an E^{-2} spectrum, and we used $C_{point} = \mathrm{E}^2(\mathrm{dN}_\nu/\mathrm{dE}) < 2.5 \times 10^{-8}$ GeV cm^{-2} s^{-1} [8].

The diffuse flux K_ν^{diff} and the point flux sensitivity C_{point} are linearly correlated by the following equation:

$$4\pi K_\nu^{diff} = \left[3 \left(\frac{c}{H_0}\right) \frac{1}{r_{max}}\ N_s\right] \times C_{point} \quad (2)$$

where (c/H_0) represents the Hubble distance given by $c/H_0 = 3 \times 10^5$ (km s^{-1})/77 (km s^{-1} Mpc^{-1}) ~ 4

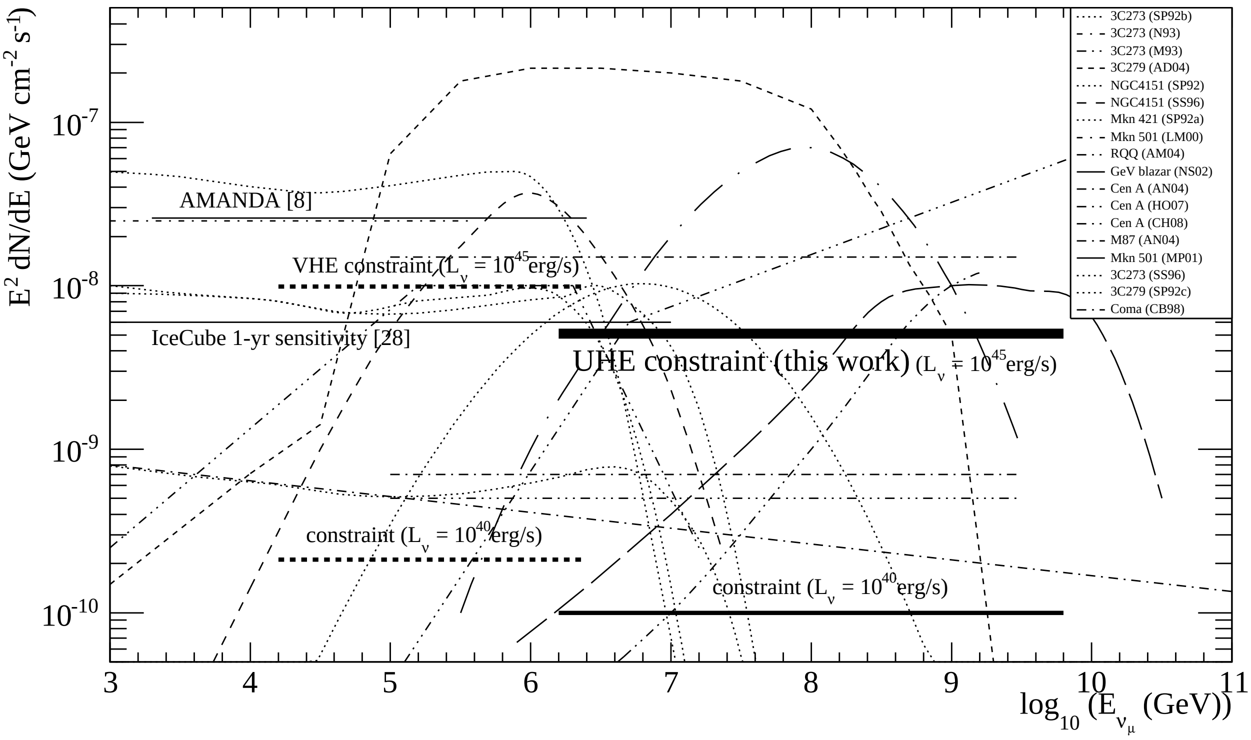

Fig. 1. Constraints on neutrino point fluxes derived from the UHE diffuse ν-flux limit [7], and from VHE limit [10], and assuming a range of neutrino luminosities $L_\nu = (10^{40} - 10^{45})$ erg/s. Current AMANDA limit [8] and IceCube sensitivity [28] to ν-point fluxes are also shown (thin solid lines). Model predictions for ν_μ-point flux from EG sources are displayed in thin dotted-dashed lines: emission from 3C273 predicted by $[3C273\ (SP92)]$ [13], core emission due to pp interactions $[3C273\ (N93)]$ [14], including pp and $p\gamma$ interactions $[3C273\ (M93)]$ [15]; core emission due to $p\gamma$ interaction $[3C273\ (SS96)]$ [24]; AGN jet, calculated for a 3C279 flare of 1 day period $[3C279\ (AD04)]$ [16] and continuous emission $[3C279\ (SP92)]$ [13]; emission from NGC4151 by $[NGC4151\ (SP92)]$ [13] and core emission from NGC4151 due to $p\gamma$ interaction $[NGC4151\ (SS96)]$ [2]; Spectra predicted for Mkn 421 $[Mkn\ 421\ (SP92)]$ [13], and for Mkn 501 during the outburst in 1997 $[Mkn\ 501\ (LM00)]$ [17] and blazar flaring Mkn 501 $[Mkn\ 501\ (MP01)]$ [23]; radio-quiet AGN $[RQQ\ (AM04)]$ [18] and GeV-loud blazars $[GeV\ blazar\ (NS02)]$ [19]; emission from Cen A as described in $[Cen\ A\ (AN04)]$ [20], $[Cen\ A\ (HO07)]$ [21] and $[Cen\ A\ (CH08)]$ [22]; emission from M87 $[M87\ (AN04)]$ [20], and emission from Coma galaxy cluster $[Coma\ (CB98)]$ [25].

Gpc, and r_{max} defines the maximum observable distance for a point source of luminosity L_ν, which is given by:

$$r_{max} = \left[\frac{L_\nu}{4\pi\ \ln(E_{max}/E_{min})\ C_{point}}\right]^{1/2} \quad (3)$$

The constraint also holds for time variable sources, since it depends only on the observed luminosity and is independent of the duration of the variability [11]. Similarly, it holds for beamed sources, such as GRB's. However for luminosities of the order of 10^{51} erg/s typical of GRB emission, we found that a dedicated search for GRB's leads to more restrictive limits [12].

III. Results

We can now estimate a numerical value for N_s by incorporating the ν-diffuse flux limit and the sensitivity to point sources in Eq. 1: $N_s \simeq (3.7 \cdot 10^{-29}\mathrm{cm}^{-1}) \times (K_\nu^{diff}) \times (C_{point})^{-3/2} \times (L_{45})^{1/2} \times 1/\xi \simeq 0.07$ computed assuming $L_{45} = 10^{45}$ erg/s, and $\xi = \xi_{AGN} \simeq 2.2$ which defines the effects due to cosmology and source evolution that follows AGN [9]. The estimate for $N_s \simeq 0.07$, which is compatible with the non-detection of any point sources.

The constraint on ν-flux is determined by setting $N_s = 1$ and inverting Eq. 1 to solve for C_{point}:

$$\mathrm{E}^2\frac{\mathrm{dN}_\nu}{\mathrm{dE}} \leq \left[\frac{\sqrt{4\pi}}{3}\frac{1}{\sqrt{\ln\left(\frac{E_{max}}{E_{min}}\right)}}\frac{H_0}{c}\cdot K_\nu^{diff}\sqrt{L_\nu}\cdot\frac{1}{\xi}\right]^{2/3}$$

$$\mathrm{E}^2\frac{\mathrm{dN}_\nu}{\mathrm{dE}} \leq 5.1\times 10^{-9}\left(\frac{L_\nu}{10^{45}\ \mathrm{erg/s}}\right)^{1/3}\left(\frac{\mathrm{GeV}}{\mathrm{cm}^2\ \mathrm{s}}\right) \quad (4)$$

valid for the same energy range 1.6 PeV $<$ E $<$ 6.3 EeV of the diffuse flux limit K_ν^{diff}. This result defines a benchmark flux constraint $\Phi_C \equiv \mathrm{E}^2(\mathrm{dN}_\nu/\mathrm{dE}) \leq 5.1 \times 10^{-9}$ GeV cm^{-2} s^{-1} on neutrino fluxes from bright ($L_\nu = 10^{45}$ erg/s) extragalactic point sources, which is a factor five lower than present experimental limits from direct searches. Note from Eq. 2, that for the case of $N_s < 1$ the distance ratio $(c/H_0)/r_{max} > 1$, which occurs for sources well within the Hubble distance.

Fig. 1 shows these results represented by the constraint derived from the Ultra High Energy (UHE) diffuse ν-flux limit for energies above PeV (thick solid line), and from the Very High Energy (VHE) limit in the TeV-PeV range (thick dotted line). Model predictions for ν_μ-point flux from EG sources (dotted/dashed lines),

TABLE I

SUMMARY OF MODELS FOR ν_μ POINT FLUX FROM EXTRAGALACTIC SOURCES CONSTRAINED BY THE RESULTS FROM THIS WORK. MODELS ARE ORDERED ACCORDING TO THE TYPE OF THE NEUTRINO SOURCE. THE PARAMETER BAND$_\gamma$ REPRESENTS THE PHOTON ENERGY-BAND ASSUMED IN THE GIVEN MODEL. THE NEUTRINO FLUX PREDICTED BY A GIVEN MODEL FOR AN E^{-2} SPECTRUM IS DENOTED BY Φ_ν^{model} AND NEUTRINO FLUXES FOR MODELS WHICH ARE ALMOST CONSTANT TO AN E^{-2} SPECTRUM FOR A LARGE ENERGY RANGE. THE CORRESPONDING FLUX CONSTRAINED FOR AN E^{-2} SPECTRUM IS DEFINED BY THE BENCHMARK FLUX Φ_C. IF THE SOURCE IS COMMONLY REPLICATED IN THE UNIVERSE WITH OUR ASSUMPTIONS, THEN THE RATIO $R_{flux} = \Phi_C/\Phi_\nu^{model} < 1$ DETERMINES A MODEL CONSTRAINED BY THIS WORK.

Model	Band$_\gamma$	Φ_ν^{model} (GeV/cm^2 s)	R_{flux}	Reference
$[3C273\ (SP92)]$	IR/x-ray	1.0×10^{-8}	0.51	[13]
$[3C273\ (N93)]$	x-ray	2.5×10^{-8}	0.20	[14]
$[3C273\ (M93)]$	γ-ray/IR	1.0×10^{-8}	0.51	[15]
$[3C279\ (AD04)]$	GeV	2.0×10^{-7}	0.03	[16]
$[NGC4151\ (SP92)]$	IR/x-ray	3.5×10^{-8}	0.14	[13]
$[Mkn\ 421\ (SP92)]$	IR/x-ray	9.0×10^{-9}	0.10	[13]
$[Mkn\ 501\ (LM00)]$	TeV	2.5×10^{-8}	0.57	[17]
$[RQQ\ (AM04)]$	x-ray/UV	1.0×10^{-8}	0.51	[18]
$[Cen\ A\ (AN04)]$	TeV	1.5×10^{-8}	0.34	[20]
$[Cen\ A\ (CH08)]$	TeV	6.0×10^{-9}	0.85	[22]

have been tested by this analysis and are summarized in Tab. I.

Tab. I summarizes the results from the constraint Φ_C compared to a number of models of neutrino point fluxes from extragalactic sources. The fluxes Φ_ν^{model} predicted from these models can be directly compared to Φ_C since either follow an E^{-2} spectrum, or do cover a large energy range almost constant to an E^{-2} spectrum. These models are constrained since their predicted fluxes exceed the benchmark flux set by Φ_C. If the source is commonly replicated in the universe with the assumptions defined in Sec II, then the ratio $R_{flux} = \Phi_C/\Phi_\nu^{model} < 1$ determines a model constrained by this analysis.

Models have also been presented which predict ν-fluxes from nearby AGNs [20], [21], [22], such as Centaurus A (Cen A) and M87 at a distance of 3.4 Mpc and 16 Mpc, respectively. We note these predictions lie below the upper value of the constraint Φ_C, and are compatible with our results.

A few other models, as shown in Fig. 1, present flux predictions which strongly deviate from an E^{-2} spectrum and in this class of models a direct comparison with the benchmark flux Φ_C is less straightforward. In these cases, the predicted energy spectra should be integrated over the energy interval that defines the constraint to obtain the total neutrino event rate, N_ν^{model}. This result should be compared to the integrated neutrino event rate N_C determined by the constraint and by the given neutrino detector characteristics.

IV. DISCUSSION

The thick dark horizontal line in Fig. 1 indicates our primary constraint Φ_C. It was derived for a mean neutrino luminosity that characterizes the brightest AGN in the EM band. The constraint is even stronger for less luminous classes of sources. In this section we address the robustness of the constraint by focusing the discussion on the three assumptions listed in Sec. II.

A. Homogeneity of source distribution

The matter distribution within 50 Mpc of the Milky Way is far from uniform, which suggests the possibility that the number density of neutrino sources, n_s, may be higher than the universal average if n_s is correlated with matter density. We argue that, in practice, the local inhomogeneity affects only the class of sources characterised by low luminosities. The bright sources are too rare to be affected by local matter density variation - the likelihood of finding a bright neutrino source within 50 Mpc is small to begin with (if EM luminosity and neutrino luminosity are comparable), and the local enhancements in matter density insufficient to change the probability of detection.

On the other hand, low luminosity sources are more likely to be within 50 Mpc, and their density could be affected by fluctuations (e.g. by a factor of 15 [26] at 5 Mpc) in the local matter density. In this case, the flux constraint (Eq. 4) should be adjusted to account for the higher density of local matter, $\Phi' = \Phi * (n_{local}/\langle n_s\rangle)^{2/3}$ (Tab II). However, the adjusted fluxes are below the benchmark flux constraint Φ_C.

To exceed Φ_C a source of a given luminosity L_ν must be within a distance $d_l = (4\pi/3)^{1/3} \cdot r_{max} * (\Phi'/\Phi_C)^{1/2}$. However, we found no counterparts in the EM band within a distance d_l that would violate the constraint Φ_C.

TABLE II

ADJUSTED Φ' TO ACCOUNT FOR LOCAL n_s ENHANCEMENT.

L_ν erg/s	Φ GeV/^{2}s	$n_l/\langle n_s\rangle$ [26]	Φ' GeV/cm^{2}s	d_l Mpc
8×10^{41}	0.5×10^{-9}	15	2.8×10^{-9}	3.7
1×10^{43}	1.1×10^{-9}	5	3.1×10^{-9}	16
1×10^{44}	2.4×10^{-9}	2.5	4.3×10^{-9}	55

B. Distribution function of ν-luminosity

The number of detectable sources N_s depends on $\langle L_\nu^{3/2}\rangle / \langle L_\nu\rangle$, but the luminosity distribution for neutrino sources is not known. However, if the distribution function follows a broken power law, which is measured for several class of energetic sources in various electromagnetic bands, then the estimate for N_s based on a full distribution agrees with an estimate using the mean luminosity of the distribution to within few percent, as shown in [11]. So, to an excellent approximation, the mean value of the luminosity distribution is sufficient to predict $N_s \sim \langle L_\nu \rangle^{1/2}$ for power law or broken power law distributions. The most common distribution of luminosities can only be observed at relatively small distances, so source evolution and cosmological effects are negligible. Larger values of luminosity are too rare to contribute significantly.

C. Energy spectrum of the source

The constraint can be extended to energy spectra that differ from the assumed E^{-2} dependence, but the constraint applies over a restricted energy interval that matches the energy interval of the diffuse neutrino limits. Experimental diffuse limits span two different energy regions, VHE and UHE, and either limit can be inserted into Eq. 4. The restriction in energy range is required to avoid extrapolating the energy spectrum to unphysical values. In other words, for power law indices far from 2, the spectrum must cut-off at high energies for indices $\gamma < 2$, or at low energies for indices $\gamma > 2$. Subject to this restriction, we find that the constraint depends weakly on the assumed spectral index. For example, the constraints improve by a factor 2 for hard spectra $(\gamma = 1)$ and weaken by roughly the same factor for soft spectra $(\gamma = 3)$ [11].

On the other hand, it could be argued that the energy spectrum dN_ν/dE is completely unknown. In this case, instead of relying on the power law of neutrino luminosity L_ν, one could derive the constraints by examining the measured number density n_s, $(n_s \propto 1/L_\nu)$ for a given class of sources [27].

V. Conclusion

The constraint on neutrino fluxes from extragalactic point sources is $\mathrm{E}^2(\mathrm{dN}_\nu/\mathrm{dE}) \leq 5.1 \times 10^{-9}\ (L_\nu/10^{45}\ \mathrm{erg/s})^{1/3}\ \ \mathrm{GeV\ cm^{-2}\ s^{-1}}$, which is a factor 5 below current experimental limits from direct searches if the average L_ν distribution is comparable to the EM luminosity that characterizes the brightest AGN. We tested a number of model predictions for ν-point fluxes, and models which predict fluxes higher than the constraint have been restricted by this analysis. The constraint is strengthened for less luminous sources, and noncompetitive with direct searches for highly luminous explosive sources, such as GRB. We found that the constraint is robust when accounting for the non-uniform distribution of matter that surrounds our galaxy, or considering energy spectra that deviate from E^{-2}, or various models of cosmological evolution. The constraint suggests that the observation of EG neutrino sources will be a challenge for kilometer scale detectors unless the source is much closer than the characteristic distance between sources, d_l, after accounting for local enhancement of the matter density. Although the constraint cannot rule out the existence of a unique, nearby EG neutrino sources, we note that we found no counterparts in the EM band with the required luminosity and distance to violate the constraint, assuming $L_\nu \sim L_\gamma$.

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