On the relation between the neutrino flux from Centaurus A and the associated diffuse neutrino flux

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Based on recent results obtained by the Pierre Auger Observatory (PAO), it has been hypothesized that Centaurus A (Cen A) is a source of ultra-high-energy cosmic rays (UHECRs) and associated neutrinos. We point out that the diffuse neutrino flux may be used to constrain the source model if one assumes that the ratio between the UHECR and neutrino fluxes outputted by Cen A is representative for other sources. Under this assumption we investigate the relation between the neutrino flux from Cen A and the diffuse neutrino flux. Assuming furthermore that Cen A is the source of two UHECR events observed by PAO, we estimate the all-sky diffuse neutrino flux to be \( \sim 200 - 5000 \) times larger than the neutrino flux from Cen A. As a result, the diffuse neutrino fluxes associated with some of the recently proposed models of UHECR-related neutrino production in Cen A are above existing limits. Regardless of the underlying source model, our results indicate that the detection of neutrinos from Cen A without the accompanying diffuse flux would mean that Cen A is an exceptionally efficient neutrino source.

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I. INTRODUCTION

The Pierre Auger Observatory (PAO) has recently reported new results \cite{1,2} on the arrival directions of the highest-energy cosmic rays (CRs). The data show strong evidence for anisotropy of these CRs, which suggests that at least some sources of ultra-high-energy cosmic rays (UHECRs) are relatively close. The cosmic-ray anisotropy has been confirmed by other studies using different statistical methods and source catalogs \cite{3,4,5}. The correlation between the arrival directions of these CRs and the positions of known active galactic nuclei (AGNs) has lead the PAO to suggest that nearby AGNs, or astrophysical objects with a similar spatial distribution, are the sources of UHECRs \cite{1}. However, the observed deficit of UHECRs from the nearby Virgo cluster appears to be incompatible with such a source distribution \cite{6}. Therefore the origin of UHECRs remains unclear at present.

Independent of a possible general connection between UHECRs and AGNs, the PAO data raise the possibility that Centaurus A (Cen A) is a source of UHECRs. The PAO analysis \cite{1,2} associates two events with Cen A, but it has been pointed out that at least four events can be associated with Cen A if one takes account of its morphology \cite{7}. At a distance of \( \sim 3.5 \) Mpc, Cen A (NGC 5128) is the nearest active galaxy (see Ref. \cite{8} for a review). It is classified as a Fanaroff-Riley type I radio galaxy, possibly harboring a misdirected BL Lac nucleus. The galaxy is believed to be powered by accretion on a \( \sim 10^8 M_\odot \) central black hole \cite{9}. It has a very compact nucleus, a pronounced northern jet, a dimmer southern jet, and giant radio lobes extending out to \( \sim 250 \) kpc. We likely observe the jets from the side, under a viewing angle of \( 50^\circ - 80^\circ \) \cite{10} (see, however, Ref. \cite{11}). Due to its proximity, it has been suggested long ago that this galaxy may be the source of UHECR events observed at Earth \cite{12,13,14}.

A general prediction of models of UHECR acceleration is the production of neutrinos through the interaction of accelerated protons (or nuclei) with the ambient photon field or with target protons in the source. Hence, for a given acceleration mechanism the neutrino and UHECR fluxes are related. Detection of neutrinos from Cen A or limits on their flux may therefore translate into constraints on the underlying acceleration models.

Neutrino production in AGNs has been studied by many authors, see e.g. Refs. \cite{15,16,17,18,19,20,21,22,23,24,25}. More recently, the authors of Refs. \cite{26,27} have presented estimates on the neutrino flux from Cen A under the assumption that two out of the 27 UHECR events in the PAO analysis can be attributed to this galaxy. These authors have however not considered the diffuse flux due to all (unresolved) neutrino sources within their models. Assuming that the environment in Cen A is somehow representative for all sources of UHECRs and accompanying neutrinos, the diffuse neutrino flux may also constrain the source model. In this work we investigate the connection between the UHECR-related neutrino flux from Cen A and the associated diffuse neutrino flux.

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In relating the diffuse flux to that from Cen A, we assume (as a working hypothesis) that Cen A is a ‘typical’ source of UHECRs and neutrinos, i.e. we assume universal UHECR and neutrino injection spectra with a fixed relative strength. We do not make any assumptions on the intrinsic luminosity or on the distance of the UHECR sources. Within the assumption of typicality, the diffuse neutrino flux can be estimated by upscaling the neutrino flux from Cen A using CR data. The scaling factor is the product of a trivial factor standing for the fraction of observed UHECR events that is attributed to Cen A, and a non-trivial factor that accounts for the difference in CR and neutrino mean free paths: as the UHECR flux from far-away sources is strongly attenuated by interactions with the cosmic microwave background, the ratio of the diffuse neutrino flux to the Cen-A neutrino flux will be much larger than the observed ratio of the diffuse UHECR flux to the Cen-A UHECR flux. In this study we estimate this scaling factor without relying on any specific source model. For definiteness we assume that the UHECRs are protons, the composition of UHECRs still being under debate [28].

We find that the all-sky diffuse neutrino flux is expected to be \( \sim 200 - 5000 \) times larger than the neutrino flux from Cen A, depending most strongly on the assumed source evolution. As a consequence, diffuse neutrino fluxes associated with some of the recently proposed models of UHECR-related neutrino production in Cen A overshoot existing bounds by the AMANDA-II [24, 30] and PAO [31] experiments. Regardless of the underlying production model, our results indicate that the detection of neutrinos from Cen A without the accompanying diffuse flux would imply that Cen A is an exceptionally strong neutrino source.

This paper is organized as follows. In section II we discuss attenuation of the UHECR proton and neutrino fluxes and estimate the ratio of the diffuse neutrino flux to the Cen-A neutrino flux. In section III we apply these results to models that were recently proposed in Refs. [26, 27]. We summarize and discuss our work in section IV. The appendices contain additional information on the computer code used to calculate attenuation of the cosmic proton flux, and an estimate of the neutrino effective area of the IceCube experiment.

II. RELATING THE DIFFUSE PROTON AND NEUTRINO FLUXES

The flux of high-energy protons from a cosmic source is attenuated by redshift and by interactions with CMB photons. As a result, the observed flux of UHECR protons is significantly smaller than the flux that is injected by all sources. Neutrinos, on the other hand, only suffer redshift energy losses, which is of far lesser importance. This difference boosts the diffuse neutrino flux reaching Earth compared to the diffuse flux of UHECRs, an effect that should be taken into account when normalizing the diffuse neutrino flux to the observed UHECR flux. Under the assumption of a universal relation between the outputted neutrino and proton fluxes, this effect may be parameterized by a parameter \( H \) that we introduce in this section.

A. The neutrino boost factor

The observed differential flux \( \phi \) from a single source at proper distance \( D \) (redshift \( z \)) can be expressed as

\[
\phi(E) = \frac{j^0(E_0)}{4\pi D^2 (1+z)} \frac{dE_0}{dE},
\]

where \( E \) is the observed energy, \( E_0 = E_0(E, z) \) is the energy at the source, and \( j^0 \) denotes the differential spectrum at the source. Integrating over a cosmological distribution of sources, the diffuse flux is equal to (see, e.g., Ref. [32])

\[
\phi^{\text{diff}}(E) = \frac{c n_0}{4\pi} \int_0^\infty dz \left| \frac{dt}{dz} \right| \frac{dE_0}{dE} \epsilon(z) j^0(E_0),
\]

where \( n_0 \) is the present source density and \( \epsilon(z) \) parameterizes source evolution (no evolution corresponds to \( \epsilon(z) \equiv 1 \)). In this expression we assume that all sources are identical. Within the \( \Lambda \)CDM concordance model that we adopt,

\[
\left| \frac{dt}{dz} \right| = \frac{1}{H_0 (1+z) \sqrt{\Omega_m (1+z)^3 + \Omega_\Lambda}},
\]

where \( H_0 = 73 \text{ km s}^{-1} \text{ Mpc}^{-1} \) denotes the present Hubble constant, \( \Omega_m = 0.24 \) is the present matter density parameter, and \( \Omega_\Lambda = 0.76 \) is the present vacuum energy density parameter [33].

Since we assume a universal neutrino injection spectrum in this work, we approximate the observed diffuse neutrino flux by \( \phi_\nu^{\text{diff}}(E) \propto j_\nu^0(E) \). (In the case of spectral breaks this neglects smearing due to different source redshifts. We
will come back to this issue in the next section.) We normalize the diffuse neutrino flux to the integral UHECR flux \( \Phi_p^{\text{diff}} \) above a threshold energy \( E_{\text{th}} \), and define a constant of proportionality \( H \) as follows:

\[
\frac{\Phi_p^{\text{diff}}(E)}{\int_0^E \Phi_p^{\text{diff}}(E)} = H(E_{\text{th}}) \frac{\Phi_p^{\text{diff}}(E_{\text{th}})}{\int_0^{E_{\text{th}}} \Phi_p^{\text{diff}}(E_{\text{th}})},
\]

(4)

where \( J_p^0 \) is the differential neutrino spectrum at the source, and \( J_p^0 \) is the integral UHECR proton spectrum at the source (we will use capital symbols to refer to integral spectra and fluxes, and lower-case symbols for differential ones). The effect of the different UHECR proton and neutrino mean free path lengths is now contained in the scaling factor \( H \), which we will refer to as the neutrino boost factor. It can be determined for any neutrino and any proton injection spectrum from eq. (2), together with a formula for \( E_0(E, z) \). Note that \( H \) depends on the threshold energy \( E_{\text{th}} \) but not on the neutrino energy \( E \).

We have computed the parameter \( H \) numerically for power-law proton and neutrino injection spectra, \( J_p^0(E) \propto E^{-p_p} \) and \( J_p^0(E) \propto E^{-p_\nu} \), respectively. This is done with the help of a computer code that solves eq. (2) for protons and neutrinos and then determines \( H \) from eq. (4). Proton energy losses are taken into account in the continuous loss approximation using expressions for the energy-loss time that are given in appendix A. In this process we integrate over a cosmological distribution of sources up to redshift \( z = 5 \). Because we do not know the redshift evolution of UHECR sources, we consider as limiting cases both no evolution and strong evolution tracing the AGN luminosity density evolution given in Ref. [34], i.e. \( \epsilon(z) \propto (1+z)^{1.4} \) up to \( z = 1.9 \), a constant \( \epsilon \) up to \( z = 3 \), and negative evolution \( \epsilon(z) \propto (z-3)^{-0.33} \) beyond \( z = 3 \). We have not explicitly considered milder source evolution models, but the results for \( H \) will be numerically intermediate between the two cases considered.

In figure 1 we show the neutrino boost factor \( H \) as a function of proton power-law index \( p_p \) for different neutrino power-law indices \( p_\nu \). In producing this figure, we have taken the detector threshold energy equal to \( E_{\text{th}} = 57 \) EeV (the energy threshold used in the PAO analysis [1, 2]), and we have assumed that the maximum proton energy is much larger than this. As can be seen in the figure, the boost factor increases mildly as the neutrino injection spectrum becomes harder compared to the proton injection spectrum, which can be understood from the scaling of energy spectra with redshift. Including source evolution is a more dramatic effect, increasing \( H \) by an order of magnitude. This of course reflects the fact that, with strong source evolution, the fraction of sources that can be in high-energy neutrinos but not in UHECRs increases substantially.

The systematic uncertainty of \( \sim 20\% \) in energy determination by PAO [33] introduces some uncertainty in our results on the neutrino boost factor \( H \). If the actual threshold energy is lower than 57 EeV, the effect of UHECR flux attenuation is less severe and hence the neutrino boost factor \( H \) is smaller than the results presented in figure 1. We have found that, for the parameters used in figure 1, this effect is well approximated by the simple formula

\[
H(E_{\text{th}}) = 10^{\frac{E_{\text{th}} - E_0}{57}} H(E_0),
\]

(5)

where \( E_{\text{th}} \) now denotes the actual threshold energy and \( E_0 = 57 \) EeV. As this equation shows, the neutrino boost factor \( H \) becomes smaller (larger) by a factor \( \sim 1.6 \) in case the energy is systematically overestimated (underestimated) by \( 20\% \).

### B. Scaling the neutrino flux from Cen A

We now specialize the discussion to the recent PAO data. The number of events with energy above \( E_{\text{th}} \) from a point source at declination \( \delta_s \) can be expressed as \( N^\text{pt} = \Phi^\text{pt}(E_{\text{th}})TA(\delta_s) \), where \( \Phi^\text{pt}(E_{\text{th}}) \) is the integral flux above \( E_{\text{th}} \), \( T \) is the observation time, and \( A(\delta_s) \) denotes the experiment’s effective area for a source at declination \( \delta_s \). The number of events due to the diffuse flux is then \( N^\text{diff} = \Phi^\text{diff}\Xi \), where \( \Phi^\text{diff} \) is the integral diffuse flux per sterad, and \( \Xi \equiv \int_T A(\delta_s)d\Omega \) denotes the exposure. With these expressions, we estimate the diffuse UHECR flux \( \Phi_p^\text{diff} \) and the UHECR flux from Cen A \( \Phi_p^\text{Cen A} \) above \( E_{\text{th}} = 57 \) EeV to be:

\[
\Phi_p^\text{diff}(E_{\text{th}}) = \frac{N_{\text{tot}} - N_{\text{Cen A}}}{\Xi} \Xi = 9 \times 10^{-21} \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1};
\]

(6)

\[
\Phi_p^\text{Cen A}(E_{\text{th}}) = \frac{N_{\text{Cen A}} \int A(\delta_s)d\Omega}{\Xi} \Xi = 5 \times 10^{-21} \text{cm}^{-2} \text{s}^{-1},
\]

(7)

where \( \Xi = 9000 \text{ km}^2 \text{ yr}^{-1} \) is the total Auger exposure, \( \delta_s = -43^\circ \) is the declination of Cen A, \( N_{\text{tot}} = 27 \) is the total number of observed UHECR events, and \( N_{\text{Cen A}} \) is the number of events from Cen A. Following the PAO analysis [1, 2] we attribute \( N_{\text{Cen A}} = 2 \) events to Cen A (note however that the actual number may be larger [7]).
where (cf. eqs. (B6) and (B9)) source evolution.

is a factor of order unity that accounts for the angular dependence of the detector. Here we took the IceCube field-of-view equal to $\Omega = 0$. From top to bottom the neutrino spectrum becomes progressively softer compared to the proton spectrum: $p_\nu = p_\nu - 1.0$ (dashed line), $p_\nu = p_\nu - 0.5$ (dash-dash-dotted), $p_\nu = p_\nu$ (solid), $p_\nu = p_\nu + 0.5$ (dot-dot-dashed), and $p_\nu = p_\nu + 1.0$ (dotted). In the left panel we assumed no source evolution; in the right panel we assumed that the sources follow AGN evolution.

In eq. (7) we used the relation $A(\delta_s) \propto \omega(\delta_s)$, where $\omega$ is the relative PAO exposure given in Ref. [36], to estimate $A(\delta_s)/\int A(\delta_s)d\Omega = 0.15$ sr$^{-1}$.

Using the definition (3) of the neutrino boost factor $H$, we now express the ratio of the neutrino flux from Cen A to the associated diffuse flux as follows:

$$\frac{\phi_\nu^{\text{diff}}(E)}{\phi_\nu^{\text{Cen A}}(E)} = \frac{H(E_{\text{th}})\Phi_\nu^{\text{diff}}(E_{\text{th}})}{\Phi_\nu^{\text{Cen A}}(E_{\text{th}})} = \frac{H(E_{\text{th}})(N_{\text{tot}} - N_{\text{Cen A}}) A(\delta_s)}{N_{\text{Cen A}} \int A(\delta_s)d\Omega} = 1.9 H(E_{\text{th}}) \text{sr}^{-1}, \tag{8}$$

where we have used the fact that protons from Cen A reach Earth virtually without energy loss. This equation is the main result of this paper. Together with the results presented in figure 11 it allows to estimate the diffuse neutrino flux from Cen A, under the assumption that the physical environment in Cen A is representative for all UHECR and neutrino sources. Within the parameter range shown in figure 11 we thus find that the all-sky diffuse neutrino flux is $\sim 200 - 500 \, (800 - 5000)$ times larger than the neutrino flux from Cen A in the case of no (strong) source evolution.

We now compare the expected event rate in a neutrino detector for neutrinos from Cen A to the event rate for the diffuse neutrino flux. In this work we focus on neutrino detection with IceCube for definiteness. Neutrino detection with IceCube is discussed in appendix 13. Neutrinos from Cen A are downgoing for IceCube. Hence, for a fair comparison between Cen A and the diffuse flux, we consider both upgoing and downgoing diffuse neutrinos although detection of the latter is complicated by the atmospheric muon background. From eqs. (8), (16), and (18) we find that the ratio of events associated with the diffuse downgoing neutrino flux to events associated with Cen A is

$$\frac{N_{\nu}^{\text{diff, dn}}}{N_{\nu}^{Cen A}} \simeq 11H(E_{\text{th}}), \tag{9}$$

where we took the IceCube field-of-view equal to $\Omega_f = 5.7$ (up to $5^\circ$ from the horizon). In this expression we approximated the effective area for downgoing neutrinos as angle-independent. The ratio of events associated with the diffuse upgoing neutrino flux to events associated with Cen A is

$$\frac{N_{\nu}^{\text{diff, up}}}{N_{\nu}^{Cen A}} \simeq 11\chi H(E_{\text{th}}), \tag{10}$$

where (cf. eqs. [16] and [19])

$$\chi := \frac{\int dE \phi_\nu(E) A_{\nu, \text{eff}}^{\text{up}}(E)}{\int dE \phi_\nu(E) A_{\nu, \text{eff}}^{\text{dn}}(E)} \tag{11}$$

is a factor of order unity that accounts for the angular dependence of the detector. Here $A_{\nu, \text{eff}}^{\text{up}} (A_{\nu, \text{eff}}^{\text{dn}})$ denotes the (average) effective area for downgoing (upgoing) diffuse neutrinos. Using estimates for the effective areas of the IceCube detector given in eqs. [17] and [10], respectively, we have verified that $1 \lesssim \chi \lesssim 2$ for neutrino test spectra $\phi_\nu \propto E^{-p}$, where $1 \leq p \leq 3$ and $10^8 \text{ GeV} < E_\nu < 10^8 \text{ GeV}$.

FIG. 1: Neutrino boost factor $H$ as a function of proton power-law index $p_p$ for five neutrino power-law indices $p_\nu$ and for $E_{\text{th}} = 57$ EeV. From top to bottom the neutrino spectrum becomes progressively softer compared to the proton spectrum: $p_\nu = p_\nu - 1.0$ (dashed line), $p_\nu = p_\nu - 0.5$ (dash-dash-dotted), $p_\nu = p_\nu$ (solid), $p_\nu = p_\nu + 0.5$ (dot-dot-dashed), and $p_\nu = p_\nu + 1.0$ (dotted). In the left panel we assumed no source evolution; in the right panel we assumed that the sources follow AGN evolution.
III. SOURCE MODEL EXAMPLE

Following the hypothesis that 2 of the 27 UHECR events detected by PAO are from Cen A, different models for ultra-high-energy (UHE) proton and neutrino production in Cen A were proposed in Refs. [26, 27]. For reasons of space we focus on the model adopted in Ref. [26], hereafter referred to as the CH model, which is based on earlier work in Ref. [18]. For this model, we estimate the associated diffuse neutrino flux and compare its detection prospects to those of the neutrinos from Cen A using the general results obtained in the previous section. In the last part of this section we comment on the detection prospects of the models that were recently proposed in Ref. [27].

A. The model

An attractive feature of the model adopted in Ref. [26] is that the neutrino flux at high energies is harder than the flux of UHECR protons. To achieve this, the model requires that a population of high-energy seed protons (accelerated through e.g. shock acceleration) is confined to a region close to the source. These protons create neutrons and neutrinos in photopion interactions with the ambient photon field. The neutrons escape from the source, decay, and give rise to UHECR protons. In this process the neutrons lose energy in interactions with the photon field before decay, thus softening the spectrum of UHE protons. Neutrinos, on the other hand, trace the neutron energy spectrum upon production (i.e. without energy loss).

The model predicts two spectral breaks in the cosmic-ray injection spectrum at the energies where the optical depths for proton and neutron photopion production become unity (see Ref. [18] for a thorough discussion). Since these energies are generally similar, one may assume a single break energy $E_{br}$. Below this break energy both the cosmic-ray injection spectrum and the neutrino spectrum are harder than the seed proton spectrum by one power of the energy (assuming photopion production on a $n_{\gamma}(\epsilon_{\gamma}) \propto \epsilon_{\gamma}^{-2}$ photon field). Above the break energy the cosmic-ray injection spectrum is softer than the seed proton spectrum by one power of the energy (assuming the same photon field), while the neutrino spectrum follows the initial seed proton spectrum. Identifying the high-energy part of the injected cosmic-ray spectrum with the observed UHECR flux $\phi_p$, we can express the all-flavor neutrino flux $\phi_{\nu}$ as:

$$\phi_{\nu}(E) = \frac{\xi_{\nu}}{\xi_{n}\eta_{en}} \min \left( \frac{E}{\eta_{en}E_{br}}, \frac{E^2}{\eta_{en}^2 E_{br}^2} \right) \phi_p \left( \frac{E}{\eta_{en}} \right),$$

where $\xi_{i}$ is the energy fraction of the proton that is transferred to species $i$ (neutron or neutrino) in photopion interactions, and $\eta_{en}$ is the ratio of the average neutrino energy to the average neutron energy. The values of these quantities depend on the spectral distribution of the photon field and can be estimated numerically. The authors of Ref. [26] take $\xi_{\nu}/\xi_{n} = 0.2$ and $\eta_{en} = 0.04$ for interactions in the nucleus of Cen A. The break energy, being due to a change in photopion production efficiency, is determined by the ambient photon distribution. Although its value cannot be directly inferred from observations, it may be estimated from the observed gamma-ray spectrum because interactions between gamma rays and the ambient photons also give rise to a spectral break in the gamma-ray flux. In this way the break energy in the UHECR spectrum can be estimated as $E_{br} \simeq 3 \times 10^{8} E_{\gamma, br}$, where $E_{\gamma, br}$ denotes the gamma-ray break energy [18, 26]. The authors of Ref. [26] conservatively take $E_{\gamma, br} \simeq 200$ MeV for Cen A, so that $E_{br} \simeq 10^{8}$ GeV.

In this work we only consider detection of muon neutrinos for definiteness, and hence we should take account of the neutrino flavor ratios. In the CH model, the source is optically thin and the effect of meson synchrotron energy loss is neglected. Under these conditions, the neutrino flux from proton-photon interactions is dominated by neutrinos from pion decay at all energies [37]. This implies that the neutrino flavor ratio (electron : muon : tau) at the source is approximately 1 : 2 : 0, as is also indicated in fig. 1 of Ref. [26]. In this case neutrino oscillations lead to a flavor ratio close to 1 : 1 : 1 at Earth [38]. Hence the expected muon-neutrino flux from Cen A, in the CH model, is:

$$\phi_{\nu}^{\text{Cen A}}(E) = \frac{\Phi_{p}^{\text{Cen A}}(E_{th})}{3} \frac{\xi_{n}E_{th}^{-2}(p-1)}{\xi_{n}} \left( \frac{E}{E_{th}} \right)^{-p} \left( \frac{E}{E_{\nu, br}} \right) \min \left( 1, \frac{E}{E_{\nu, br}} \right),$$

$$= 3 \times 10^{-11} \left( \frac{E}{1 \text{GeV}} \right)^{-1.7} \min \left( 1, \frac{E}{E_{\nu, br}} \right) \text{GeV}^{-1} \text{cm}^{-2} \text{s}^{-1},$$

where $E_{\nu, br} \equiv \eta_{en}E_{br} = 4 \times 10^{6}$ GeV.
FIG. 2: Diffuse muon-neutrino flux obtained by scaling (thick solid line) and by numerical computation (solid), together with the diffuse UHECR flux obtained numerically (dotted) and the atmospheric muon-neutrino background (dashed) as a function of neutrino energy. Also shown are existing upper limits from AMANDA-II and PAO, the projected upper limit for IceCube (3 years), and UHECR data from PAO (diamonds). Left panel: no source evolution; right panel: strong source evolution.

B. Diffuse neutrino flux

The neutrino boost factor for a proton power-law spectrum with index $p = 2.7$ and a neutrino power-law spectrum with index $p = 1.7$, with and without source evolution, is $H = 19$ and $H = 159$, respectively (see fig. [1]). Scaling the model neutrino flux from Cen A from eq. (13), we find the following estimates for the diffuse muon-neutrino flux within the CH model:

$$\phi_{\nu}^{\text{diff}}(E) \simeq 10^{-9} \left(\frac{E}{1 \text{ GeV}}\right)^{-1.7} \min\left(1, \frac{E}{E_{\nu,br}}\right) \text{GeV}^{-1} \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$$  

(14)

in the case of no source evolution, and a factor of 10 larger in the case of strong evolution. These fluxes are shown in figure [2]. Also shown are numerical results (obtained by the method described in section [11]) for the diffuse UHECR and neutrino fluxes after propagation, the preliminary AMANDA-II UHE limit [30], the PAO limit [31], the projected limit for IceCube [39] after three years of data-taking, PAO data on the UHECR proton flux [41], and the atmospheric neutrino background. The AMANDA-II, PAO, and IceCube detection limits are the 90% confidence level upper limits for a $\phi_{\nu} \propto E_{\nu}^{-2}$ diffuse muon-neutrino flux, where we have assumed a 1 : 1 : 1 flavor ratio at Earth. The atmospheric muon-neutrino background flux is parameterized as follows:

$$\phi_{\nu}^{\text{bg}}(E_{\nu}) = \begin{cases} 
8.4 \times 10^{-2}(E_{\nu}/1 \text{ GeV})^{-2.74} \text{GeV}^{-1} \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1} & (E_{\nu} < 10^{5.3} \text{ GeV}) \\
5.7 \times 10^{-3}(E_{\nu}/1 \text{ GeV})^{-3.01} \text{GeV}^{-1} \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1} & (E_{\nu} > 10^{5.3} \text{ GeV}) 
\end{cases}$$  

(15)

where the high-energy contribution is due to prompt charm decay. This parameterization is, by construction, close to the maximum background indicated in figure 11 of Ref. [39].

We observe from figure [2] that the scaled neutrino flux is an excellent approximation to the numerical results in the high-energy regime, where the energy spectrum follows a single power-law. The spectral break in the scaled neutrino flux is however much sharper than in the numerical results, where it is smoothened due to an averaging over redshift. As a result, the approximation obtained by scaling underestimates the resulting diffuse neutrino flux at lower energies. We have verified that this does not strongly affect the expected number of neutrino events in IceCube. (In principle, the diffuse flux at energies below and above the break can be estimated independently from the results obtained in section [1] which would give a better estimate. Given the other uncertainties we are faced with, we will not pursue this though.) In producing this figure, we have assumed that the maximum neutrino energy is larger than $10^{11} \text{ GeV}$. The exact value is not very important for our estimates, as the interaction rate in IceCube is dominated by neutrinos of energy below $10^{8} \text{ GeV}$.

We note from the figure that the UHECR flux follows the PAO data above $57 \text{ EeV}$, which is a consistency check of our numerical method. The model flux for strong evolution is marginally consistent with the PAO data at lower energies, given the large uncertainties in energy calibration.

The estimated diffuse neutrino flux for the CH model is well above AMANDA-II and PAO limits in the case of strong evolution. This implies that either the CH model (when applied to strongly evolving sources) is too optimistic, Cen A is intrinsically exceptional, or that significantly more than two of the UHECR events observed by PAO are
from Cen A. In the case of no evolution, the diffuse flux is only marginally above these limits. (Note that the limits are based on a neutrino flux $\phi_\nu \propto E^{-2}$, so that a more accurate comparison requires further analysis.) The flux is however well above the projected IceCube upper limit. At energies larger than $\sim 10^6$ GeV, the atmospheric neutrino background is strongly suppressed and hence detection should pose no difficulties.

C. Event rates

Using estimates for the neutrino effective area presented in appendix B (see fig. 3), we can now estimate the neutrino event rate of the diffuse neutrino flux and that from Cen A in the IceCube neutrino detector. Since Cen A is in the southern hemisphere, neutrinos from this galaxy are downgoing for IceCube. This makes detection challenging, and only possible at very high energies. To eliminate the background we consider the flux of neutrinos with energy $10^6$ GeV $< E_\nu < 10^8$ GeV (cf. fig. 2). For a fair comparison between the neutrino interaction rates for Cen A and the diffuse flux, we consider both up- and downgoing diffuse neutrinos. We find that $\chi = 1.4$ for the CH model, where $\chi$ is the factor that enters the scaling relation eq. (10). We adopt a field of view $\Omega_I = 5.7$, corresponding to cutting at $5^\circ$ below or above the horizon.

From eq. (13), we find 0.08 events per year for Cen A with an expected background of 0.004 $(\theta/5^\circ)^2$, where $\theta$ is the angular resolution. This is in reasonable agreement with results obtained in Ref. [26], where an event rate of 0.35 per year is found for neutrinos of all flavors (assuming equal detection probabilities). Using the scaling relations eqs. (9) and (10), we directly obtain our estimate of 17 (24) neutrino events per year due to downgoing (upgoing) diffuse neutrinos per year in the case if no source evolution. Including source evolution, we find 145 (203) downgoing (upgoing) events per year. In this energy range the number of background events for the downgoing (upgoing) diffuse neutrino flux is roughly 0.4 (1) per year, and hence detection is virtually background-free.

Our results for the event rate due to the diffuse flux of upgoing neutrinos in the CH model are larger than recent estimates in Ref. [41], who estimate $\sim$5 events per year for this model. This result is to be compared with our no-evolution estimate of 24 events per year. The authors of Ref. [41] attribute the diffuse neutrino and UHECR flux to Fanaroff-Riley I (FRI) radio galaxies, of which Cen A is an example. They estimate the diffuse neutrino flux by adding the contribution of sources up to $z = 0.5$ using the inferred FRI source density. In contrast, our estimates are normalized to the UHECR flux and we consider sources up to $z = 5$. It is reassuring that these results, which are obtained in a different manner, are within a factor few. The fact that our estimates are somewhat larger may be attributed to the larger maximum redshift that we have adopted (see also the comment at the end of section III of Ref. [41]).

D. Comparison with other models

In the above we have focused on a model for Cen A that was put forward in Ref. [26]. More recently, the authors of Ref. [27] have also discussed UHE proton and neutrino production in Cen A. The authors consider three different spectra for the accelerated protons: (i) a straight power-law spectrum with index $p = 2.0$, (ii) a broken power-law spectrum with $p = 2.0$ before and $p = 2.7$ after the break energy, and (iii) a straight power-law spectrum with index $p = 1.2$. The first two spectra may be the result of stochastic shock acceleration, the last spectrum of linear acceleration in a regular electric field. In case of acceleration near the core neutrinos are produced predominantly in the interaction of the accelerated protons with UV photons while low-energy protons provide the dominant target for neutrino production if the protons are accelerated in the jet [27]. The authors obtain neutrino spectra for the three acceleration mechanisms, applied to both the core and the jets, numerically. We do not attempt to reproduce these here, but rather estimate the associated diffuse neutrino flux and the event rates from their results.

For the three acceleration models (i), (ii) and (iii), we find that $H = 14, 13,$ and 14, respectively, in the case of no evolution (see also fig. 1). Including source evolution, we find $H = 101, 69,$ and 136, respectively. In deriving these estimates we have approximated the neutrino spectra as tracing the proton spectra; for softer spectra the results are somewhat lower. Scaling the neutrino fluxes presented in fig. 1 of Ref. [27] with these values, we find that the diffuse neutrino fluxes corresponding to model (ii) are well above the existing AMANDA-II limits [24, 30] in the case of strong source evolution. For all models except the linear accelerator (iii) the expected event rates in IceCube (obtained by scaling the results presented in table 1 of Ref. [27]) are $\gg 1$ per year, even in the case of no source evolution. Hence IceCube should be able to put strong constraints on these models.
In this work we have considered the relation between the diffuse neutrino flux and the neutrino flux from Cen A under the hypothesis that Cen A is a characteristic source of UHECR protons and UHECR-related neutrinos. This is motivated by recent results from PAO [1, 2] which suggest that Cen A may be a source of UHECRs. If it is also a source of neutrinos, as proposed in Refs. [26, 27], and if the environment in Cen A is representative for other sources, we argue that the diffuse neutrino flux may also constrain the source model. The diffuse neutrino flux can easily be estimated by scaling a model Cen-A neutrino flux (see eq. 8) if one assumes that Cen A is a ‘typical’ source, i.e. under the assumption of universal UHECR and neutrino injection spectra with a fixed relative strength. We stress that we make no assumptions on the intrinsic luminosity or distance of the sources. We have derived estimates for the corresponding scaling factor in section II without relying on a particular source model (see fig. 1). The scaling factor depends mildly on both the assumed proton and neutrino energy spectra, but very strongly on the assumed model of source evolution. This suggests that constraints related to the diffuse neutrino flux may be especially useful in constraining the evolution of UHECR sources.

Regardless of the source model, we find that the estimated neutrino event rate in IceCube due to the diffuse neutrino flux is expected to be at least two orders of magnitude larger than the event rate of neutrinos from Cen A, as may be seen from eqs. (9) and (10). When sources follow strong AGN evolution as parameterized in Ref. [34], the rate is even three orders of magnitude higher. Therefore we conclude that the detection of neutrinos with IceCube, without the detection of the associated diffuse neutrino flux, would imply that Cen A is an exceptionally efficient neutrino source. Here we assume that the neutrino flux extends to energies above $10^9$ GeV, so that neutrino detection is not limited by background rejection.

We have applied our results to models recently proposed in the literature in section III. We find that the diffuse neutrino flux associated with the model adopted in Ref. [26] is well above the (preliminary) AMANDA-II UHE limit [30] and the PAO limit [31] when the sources follow strong evolution. This implies that either the model (when applied to strongly evolving sources) overpredicts the neutrino flux, Cen A is intrinsically exceptional, or that considerably more than two of the UHECR events observed by PAO are produced by Cen A. Similarly, we find that the diffuse flux associated with the most optimistic models considered in Ref. [27] is also above AMANDA-II limits [29, 30] for strong source evolution. The expected event rate in IceCube is much larger than 1 yr$^{-1}$ for all models considered in Ref. [27] except for the linear acceleration (both in the case of no source evolution and of strong source evolution). IceCube should thus be able to put strong constraints on these models.

Several comments are in order. First of all, it is presently unknown to which extent UHECR source are similar in nature, and whether or not Cen A is a typical cosmic-ray source (recall that we use ‘typical’ only as a statement on the ratio of outputted neutrino flux to cosmic-ray flux; it bears no meaning to the intrinsic luminosity or the distance). We have found no a priori reason to suppose that Cen A is an atypical cosmic-ray source. Cen A is quite representative of the local population of radio-loud AGNs [42], which, although constituting a subdominant fraction of 15 – 20% of all AGNs [42], are commonly (though not uniquely) considered as the dominant cosmic-ray sources because of their powerful jets. Notwithstanding this plausibility argument, the question whether or not Cen A is indeed a typical UHECR source can only be resolved by further observations. Our results address this question by placing constraints on the simplest scenario, namely that Cen A is a typical source, representative of a universal class of cosmic-ray sources. In this context we reiterate our conclusion that the detection of neutrinos from Cen A, without the detection of the diffuse neutrino flux, would rule out Cen A as a typical cosmic-ray source on the ground of its exceptionally high neutrino production efficiency.

A second comment regards the number of UHECR events attributed to Cen A. In our numerical estimates we have followed the PAO analysis, which associates two events with Cen A as the angles between their arrival directions and the nucleus of Cen A are smaller than 3.1$^\circ$. It has been pointed out in Ref. [2] that at least four events can be associated with Cen A if one takes account of its extended structure (the radio lobes subtend $\sim 9^\circ$ on the sky). On the other hand, it is also possible that the observed UHECR events are not from Cen A but rather from sources in the more distant Centaurus supercluster, as suggested in Ref. [2]. In both cases our estimates on the neutrino boost factor would be reduced by a factor $\sim 2$. This would not qualitatively affect the conclusions for the models studied in this work. Future data from PAO will increase the rather limited statistics and will very likely shed more light on the UHECR production rate of Cen A.

Thirdly, the relation between the produced neutrino and UHECR fluxes may be complicated when neutrinos and protons are emitted within cones of different opening angle (as in the model discussed in Ref. [43]), or when the source luminosity varies in time. These effects will average out for diffuse fluxes but may affect the emission from Cen A. Any collimation in the direction of the jet will reduce the visibility on Earth as Cen A is viewed off-axis. Because the opening angle of the neutrino emission cone is expected to be smaller than that of the proton emission cone, this further decreases the expected neutrino flux from Cen A compared to the diffuse neutrino flux. Radio and X-ray measurements of Cen A show variability on a time scale shorter than a year [8]. The arrival times of protons
and neutrinos produced during a flaring phase will however not be correlated as the proton path length is increased by its motion in the galactic magnetic field. Hence a strong flare may in principle lead to an increased neutrino flux without an increase in the observed UHE proton flux from Cen A.

Finally, we note that the diffuse gamma-ray flux produced by sources similar to Cen A may also constrain the source model, in a fashion very similar to the diffuse neutrino flux that was considered here. Gamma-ray emission by Cen A was considered in Refs. [27, 44] but these authors have not considered the associated diffuse gamma-ray flux.

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APPENDIX A: PROTON ENERGY LOSS APPROXIMATION

Proton energy loss during propagation from a source at redshift $z$ can be described by the differential equation (see, e.g., Ref. [32])

$$\frac{1}{E} \frac{dE}{dz} = \frac{1}{1 + z} + \frac{(1 + z)\beta_0((1 + z)E)}{H(z)},$$  \hspace{1cm} (A1)

where the first term accounts for redshift energy loss and the second for particle interactions. The function $\beta_0$ gives the inverse energy-loss time (at present epoch) for interactions between protons and CMB photons.

In this work we determine the energy at the source $E_0$ as a function of observed energy $E$ and redshift $z$ by solving eq. (A1) numerically. To do this, we split $\beta_0 = \beta^\pi_0 + \beta^{ee}_0$ into two parts corresponding to energy loss due to pion photoproduction and electron-positron pair production, which we approximate by:

$$\log \beta^\pi_0 = \sum_{n=1}^{5} a_n X^{n-1};$$  \hspace{1cm} (A2)

$$\log \beta^{ee}_0 = \sum_{n=1}^{5} b_n X^{n-1},$$  \hspace{1cm} (A3)

where $X = \log(E/1\, \text{eV})$, and $\beta_0$ is expressed in units of $\text{yr}^{-1}$. For $10^{10.5}$ GeV < $E$ < $10^{12}$ GeV, $\bar{a} = (-1.2 \times 10^5, 2.3 \times 10^4, -1.7 \times 10^3, 52, -0.62)$; for higher energies $a_1 = -7.6$ is the only non-zero coefficient; for lower energies $\beta^\pi_0 = 0$. For $10^{8.5}$ GeV < $E$ < $10^{12}$ GeV, $\bar{b} = (-1.3 \times 10^4, 2.6 \times 10^3, -2.0 \times 10^2, 6.6, -0.082)$; at lower or higher energies $\beta^{ee}_0 = 0$.

APPENDIX B: NEUTRINO DETECTION WITH ICECUBE

In this section we estimate the effective area for the detection of muon-neutrinos with IceCube. The word ‘neutrino’ refers to muon-neutrino throughout this section.

1. Neutrino interaction and muon track length

The expected number of neutrino events in IceCube for a neutrino source with differential flux $\phi^\nu (E_\nu)$ at an angle $\theta$ with respect to the nadir (i.e., $\theta = 0$ points towards the North Pole) can be written as follows:

$$N = T \int dE_\nu \phi^\nu (E_\nu) P_\nu(E_\nu, \theta) \int dE_\mu n(E_\nu, E_\mu) P_\mu(E_\mu) A_{\mu, \text{eff}}(E_\mu),$$  \hspace{1cm} (B1)

where $T$ is the observation time; $E_\nu$ the neutrino energy; $E_\mu$ the muon energy; $P_\nu$ the probability that a neutrino reaches the vicinity of the detector; $P_\mu$ the probability that a muon is created that reaches the detector with sufficient energy for detection; $A_{\mu, \text{eff}}$ the detector’s muon effective area (which is close to the geometrical surface for high-energy
for upgoing (downgoing) events equal to $5^\circ$

$I$, where $\Omega$ consequently our estimates for the detection rate of downgoing neutrinos may be too optimistic.

For simplicity we take the muon effective area for downgoing neutrinos equal to the geometrical area, for downgoing neutrinos:

$$A_{\mu,\text{eff}}(E_\mu) = \frac{1}{b} \ln \left( \frac{a + b E_\mu}{a + b E_{\mu,\text{min}}} \right),$$

where $a = 2.0 \times 10^{-3}$ GeV cm$^{-1}$ (w.e.) accounts for ionization and $b = 3.9 \times 10^{-6}$ cm$^{-1}$ (w.e.) for radiation losses [43]. In this work we adopt $E_{\mu,\text{min}} = 10^2$ GeV. For simplicity we assume that a neutrino interaction leads to a single muon with energy $E_\mu = y_{\text{CC}}(E_\nu) E_\nu$, i.e.

$$n(E_\nu, E_\mu) = \delta(E_\mu - y_{\text{CC}}(E_\nu) E_\nu),$$

where the charged-current inelasticity $y_{\text{CC}}$ is tabulated in Ref. [42]. Lastly, we use the IceCube muon effective area given in Ref. [39]. This is the only quantity in our estimates that accounts for detector efficiency.

### 2. Effective area for downgoing neutrinos

Since downgoing neutrinos reach the detector virtually unhindered, we may approximate $\mathcal{P}_\nu \simeq 1$ and $\mathcal{P}_\mu \simeq N_A \sigma_{\nu,N}^{\text{CC}}(E_\nu) \min (R_\mu, R_d)$, where $R_d \simeq 2 \times 10^5$ cm denotes the detector depth. At the energies where downgoing muons are detectable the interaction length is determined by the detector depth (i.e., $R_d < R_\mu$). With these simplifications, we express the expected number of neutrino interactions for a single point source above IceCube as

$$N_{\nu,\text{pt}} = T \int dE_\nu \phi_\nu^{\text{pt}}(E_\nu) A_{\nu,\text{eff}}^{\text{dn}}(E_\nu),$$

where $T$ is the observation time, $\phi_\nu^{\text{pt}}$ is the neutrino flux from the source and $A_{\nu,\text{eff}}^{\text{dn}}$ denotes the neutrino effective area for downgoing neutrinos:

$$A_{\nu,\text{eff}}^{\text{dn}}(E_\nu) = T R_d N_A \sigma_{\nu,N}^{\text{CC}}(E_\nu) A_{\mu,\text{eff}}(E_\mu).$$

For simplicity we take the muon effective area for downgoing neutrinos equal to the geometrical area, $A_{\mu,\text{eff}} = 10^{10}$ cm$^2$, so that the corresponding neutrino effective area is angle-independent. In this case we may express the number of events due to the diffuse flux of downgoing neutrinos as follows:

$$N_{\nu,\text{diff}} = T \Omega_1 \int dE_\nu \phi_\nu^{\text{diff}}(E_\nu) A_{\nu,\text{eff}}^{\text{dn}}(E_\nu),$$

where $\Omega_1$ is the detector’s opening angle and $\phi_\nu^{\text{diff}}$ is the diffuse neutrino flux. We take the maximum viewing angle for upgoing (downgoing) events equal to $5^\circ$ below (above) the horizon, so that $\Omega_1 = 5.7$.

We note that the detection of downgoing neutrinos is challenging and requires special analysis techniques. Consequently our estimates for the detection rate of downgoing neutrinos may be too optimistic.
FIG. 3: Estimated neutrino effective area for the detection of upgoing and downgoing muon neutrinos with IceCube. For upgoing neutrinos, we have chosen \( E_{\mu}^{\text{min}} = 10^2 \) GeV. For downgoing neutrinos, we adopt the geometrical muon effective area \( A_{\mu,\text{eff}} = 10^{10} \) cm\(^2\).

3. Effective area for diffuse upgoing neutrinos

For upgoing neutrinos the event rate in angle-dependent because the neutrino survival probability depends on the incident angle. We compute the number of neutrino events for the diffuse flux of upgoing neutrinos by integrating eq. (B1) over the angle \( \theta \). We express the result as follows:

\[
N_{\text{diff},\text{up}} = T \Omega_1 \int dE_{\nu} \phi_{\nu}^{\text{diff}}(E_{\nu}) A_{\nu,\text{eff}}^{\text{up}}(E_{\nu}).
\]  

Here the average effective area for diffuse up-going neutrinos, using the simplifying assumptions described above, is given by:

\[
A_{\nu,\text{eff}}^{\text{up}}(E_{\nu}) = S(E_{\nu}) P_\mu(E_{\mu}) A_{\mu,\text{eff}}(E_{\mu}),
\]

where we adopt values for \( A_{\mu,\text{eff}}(E_{\mu}) \) from Ref. [39], and the shadowing factor \( S \) is:

\[
S(E_{\nu}) \equiv \frac{1}{1 - \cos \theta_{\text{max}}} \int_0^{\theta_{\text{max}}} d\theta \sin \theta P_\nu(E_{\nu}, \theta).
\]

Here \( \theta_{\text{max}} = 85^\circ \), i.e. \( 5^\circ \) below the horizon.

In figure 3 we show our estimates of the IceCube effective area for downgoing and upgoing neutrinos, given in eqs. (B7) and (B10), respectively. The initial increase of the effective area for upgoing neutrinos with energy is due to the increased muon path length, whereas the subsequent decrease is due to the fact that the Earth becomes opaque to neutrinos. These effects play no role for downgoing neutrinos; here the energy dependence of the effective area follows the energy dependence of the neutrino interaction cross section. We stress that the effective area for downgoing neutrinos corresponds to a muon effective area \( A_{\mu,\text{eff}} = 10^{10} \) cm\(^2\). Given the difficulty in detecting downgoing neutrinos, this is very optimistic and may be considered as an upper limit.

We have verified that our estimates on the neutrino effective area for the upgoing diffuse flux agree with the estimate presented in Ref. [46] within a factor two (for energies below \( 10^7 \) GeV) to three (at \( 10^8 \) GeV). Furthermore, the corresponding event rates for a fiducial \( \phi_{\nu} \propto E^{-2} \) source spectrum are within a factor 2 of results presented in Ref. [39].

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