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Searching for High-Energy Neutrinos from Ultra-Luminous Infrared Galaxies with IceCube

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Ultra-luminous infrared galaxies (ULIRGs) have total infrared luminosities that exceed 10^{12} solar luminosities, making them the most luminous objects in the infrared sky. They are mainly powered by starbursts with star-formation rates exceeding 100 solar masses per year, with a possible secondary contribution from an active galactic nucleus (AGN). Both starburst regions and AGN are environments in which hadronic acceleration, and hence neutrino production, is plausible. In this work we present the results of a stacking search for high-energy neutrinos from a representative sample of 75 local ULIRGs using 7.5 years of IceCube data. No significant neutrino excess is found. We therefore report upper limits on the neutrino flux originating from these 75 ULIRGs, and extrapolate these to limits on the full ULIRG source population. We also compare these results with model predictions.

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1. Introduction

Since 2013, a diffuse flux of high-energy astrophysical neutrinos is observed by the IceCube Neutrino Observatory at the South Pole [1]. Various studies have been performed searching for the origin of these astrophysical neutrinos (see [2] for a current overview), but apart from the blazar TXS 0506+056 [3, 4] no neutrino sources have been identified to date. Current constraints imply that if a single source population is responsible for the diffuse IceCube observations, it should be relatively numerous and consist of low-luminosity neutrino sources [5].

Ultra-luminous infrared galaxies (ULIRGs; see [6] for a review) are the brightest infrared (IR) objects on the sky, with total IR luminosities $L_{\mathrm{IR}} \geq 10^{12} L_{\odot}$ between 8–1000 μm. ULIRGs are relatively abundant, with a local number density of roughly 10^{-7}–10^{-6} Mpc^{-3} which increases strongly up to a redshift $z \sim 1$. These dusty spiral-galaxy mergers are mainly powered by regions of enhanced starburst activity, where star-formation rates exceed 100 $M_{\odot}$ yr^{-1}. In addition, ULIRGs can host an active galactic nucleus (AGN), which can also provide a secondary contribution to the total IR luminosity. Both starbursts and AGN are sites where hadronic acceleration, and hence neutrino production, could take place [7, 8]. As such, ULIRGs are candidate neutrino sources that could be responsible for a fraction of the diffuse flux observed by IceCube [9–11].

In the following we present the results of an IceCube stacking search for high-energy neutrinos from ULIRGs. Further details on the study presented in this work can be found in a recently submitted publication [12].

2. ULIRG Stacking Analysis

2.1 Object Selection

We start with an initial selection of 189 unique ULIRGs obtained from three catalogs that are mainly based on data of the Infrared Astronomical Satellite (*IRAS*) [13–15]. In order to obtain a representative sample of the local ULIRG population, defined as a sample of ULIRGs that is complete up to a certain redhift, we perform a redshift cut on our initial ULIRG selection. For this purpose, we find the redshift up to which the least luminous ULIRGs ($L_{\mathrm{IR}} = 10^{12} L_{\odot}$) can be observed given a conservative *IRAS* sensitivity $f_{60} = 1$ Jy at 60 μm. Our final representative selection of ULIRGs consists of 75 objects within $z \leq 0.13$.

2.2 Detector and Data Set

The 1 km^3 IceCube Neutrino Observatory, located at the geographic South Pole, contains 5160 optical modules which detect the optical Cherenkov radiation emitted by secondary charged particles produced in the interactions of neutrinos[1] in the surrounding ice or the nearby bedrock. Using the detected Cherenkov light, the direction, energy and flavor of the neutrino can be reconstructed [16].

For this analysis, we use 7.5 years of the gamma-ray follow-up (GFU) data sample [17], which was collected using the full 86-string IceCube configuration between 2011–2018. This sample consists of well-reconstructed muon tracks, which have an angular resolution $\lesssim 1^{\circ}$ above

[1]Since IceCube can in general not distinguish between neutrinos and antineutrinos, we use the term neutrino for both in these proceedings.

1 TeV. Such tracks are signatures of secondary muons produced in charged-current interactions of astrophysical muon neutrinos, which are expected to occur at a rate of several μHz. The rate of track signatures in the detector is dominated by background, namely atmospheric muons (at the kHz level; only in the Southern hemisphere) and atmospheric neutrinos (at the mHz level; over the full sky) produced in cosmic-ray air showers. Quality and neutrino selection cuts reduce the GFU sample to an all-sky rate of 6.6 mHz, which is at the level of the atmospheric-neutrino background.

2.3 Sensitivity and Discovery Potential

To search for astrophysical neutrinos that are spatially correlated with our selection of ULIRGs, we perform a maximum-likelihood analysis [18] where we stack the sources in order to enhance the sensitivity of our search [19]. For the stacking, we weight the ULIRGs according to their total IR flux $F_{\mathrm{IR}} = L_{\mathrm{IR}}/4\pi d_L^2$, with d_L the luminosity distance determined from redshift measurements.

Figure 1 shows the performance of our stacking analysis for a simulated astrophysical signal that follows an unbroken power-law spectrum, $\Phi_{\nu_\mu+\bar{\nu}_\mu}(E_\nu) = \Phi_{\nu_\mu+\bar{\nu}_\mu}(E_0)(E_\nu/E_0)^{-\gamma}$, normalized at $E_0 = 10$ TeV. The analysis performance is given in terms of the sensitivity at 90% confidence level (CL), and the potential for a 3σ and a 5σ discovery. From the right panel of Fig. 1 we find that the analysis is more sensitive for harder spectra, since such a signal would be easier to distinguish from the atmospheric background, which follows an $E^{-3.7}$ power-law spectrum.

3. Results and Interpretation

The ULIRG stacking analysis yields a p-value = 1.0, indicating that the data is compatible with atmospheric background without any evidence for astrophysical neutrinos originating from our representative sample of 75 local ULIRGs within $z \leq 0.13$. We therefore set upper limits at 90% CL on the diffuse flux of these ULIRGs, $\Phi^{z\leq 0.13}_{\nu_\mu+\bar{\nu}_\mu}$, which correspond to the 90% sensitivity shown in Fig. 1. We can extrapolate these upper limits to the flux of all ULIRGs up to a certain maximum redshift z_{max},

$$\Phi^{z\leq z_{\mathrm{max}}}_{\nu_\mu+\bar{\nu}_\mu} = \frac{\xi_{z=z_{\mathrm{max}}}}{\xi_{z=0.13}} \Phi^{z\leq 0.13}_{\nu_\mu+\bar{\nu}_\mu}. \tag{1}$$

Here we make the assumption that our selection is representative for the full ULIRG population, and that over cosmic history, ULIRGs have identical properties of hadronic acceleration and neutrino production. The factor ξ_z effectively integrates the redshift evolution of the ULIRGs up to a given redshift [20]. We parameterize the ULIRG source evolution according to [11], $\mathcal{H}(z) = (1+z)^m$, with $m = 4$ for $0 \leq z < 1$ and $m = 0$ for $z \geq 1$.

Figure 2 shows the upper limits on the diffuse flux of the ULIRG population up to a redshift $z_{\mathrm{max}} = 4.0$. The left panel of Fig. 2 shows the integral limits for unbroken $E^{-2.0}$, $E^{-2.5}$, and $E^{-3.0}$ power-law spectra. We find that the $E^{-2.0}$ and $E^{-2.5}$ limits constrain the contribution of the ULIRG population to the diffuse observations of [21, 22] up to ~3 PeV and ~600 TeV, respectively. The right panel of Fig. 2 shows the quasi-differential limits, which are determined by computing the $E^{-2.0}$ limit in each decade of energy. The differential limits constrain the contribution of ULIRGs to the diffuse observations between 10–100 TeV and 0.1–1 PeV.

Next, we compare our upper limits on the ULIRG source population to predictions of starburst reservoir models. The left panel of Fig. 3 considers the model by He et al. [9], in which hypernovae

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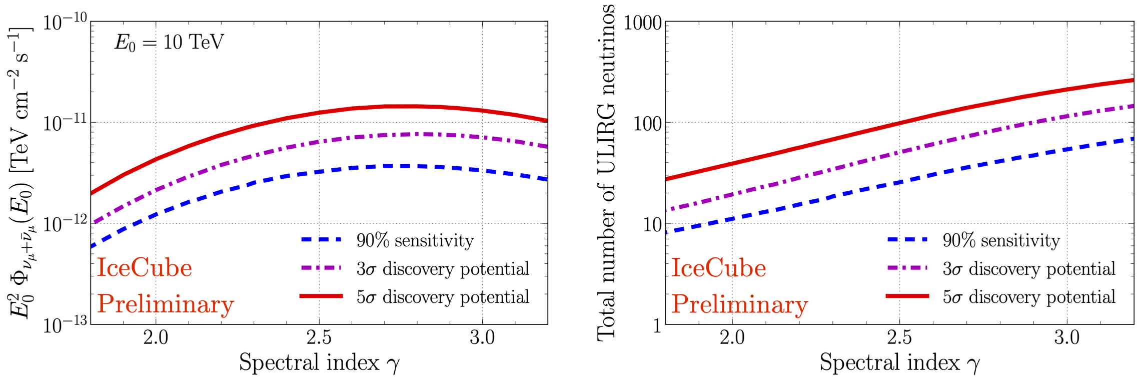

Figure 1: Sensitivity, 3σ, and 5σ discovery potentials for an unbroken $E^{-\gamma}$ power-law spectrum. *Left*: Shown in terms of the flux at the normalization energy $E_0 = 10$ TeV. *Right*: Shown in terms of the total number of ULIRG neutrinos.

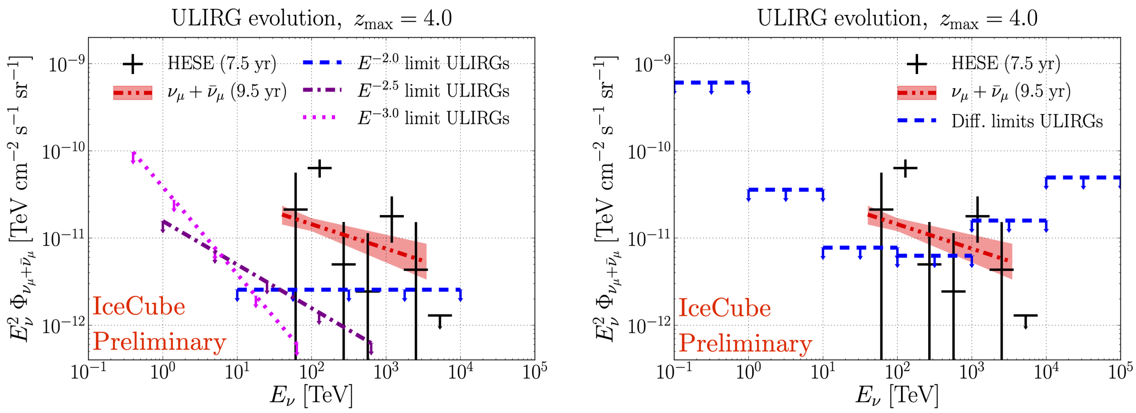

Figure 2: Upper limits (90% CL) on the contribution of the ULIRG source population up to a redshift $z_{\max} = 4.0$ to the diffuse IceCube observations (black data points and red band). *Left*: Integral limits are shown for unbroken $E^{-2.0}$ (dashed blue line), $E^{-2.5}$ (dash-dotted dark magenta line), and $E^{-3.0}$ (dotted light magenta line) power-law spectra, within the respective 90% central energy ranges that contribute to the upper limits. *Right*: Quasi-differential limits (dashed blue lines) are obtained by computing the $E^{-2.0}$ limit in each bin of energy decade.

are responsible for the hadronic acceleration in ULIRGs. We compare their prediction to our $E^{-2.0}$ upper limit, where we integrate the ULIRG source evolution up to a redshift $z_{\max} = 2.3$. The prediction by He et al. lies at the level of our upper limit. A follow-up analysis with additional years of data is therefore required in order to validate or exclude this model.

The right panel of Fig. 3 considers the generic model by Palladino et al. [10], who consider ULIRGs as a candidate population of hadronically-powered gamma-ray galaxies (HAGS). Such HAGS could be responsible for the bulk of the diffuse neutrino observations. We compare their prediction to our $E^{-2.12}$ upper limit, where in this case we follow Palladino et al. and parameterize the source evolution according to the star-formation rate [23], $\mathcal{H}(z) = (1+z)^m$ with $m = 3.4$ for $0 \leq z < 1$ and $m = -0.3$ for $1 < z \leq 4$, which we integrate up to a redshift $z_{\max} = 4.0$. Our limit

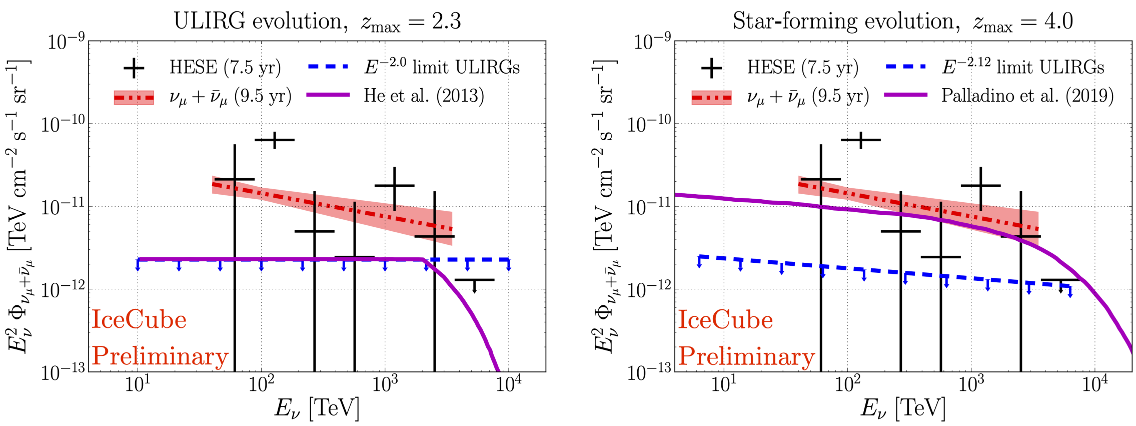

Figure 3: Comparison of our ULIRG upper limits (90% CL; dashed blue lines) to two model predictions (full magenta lines). *Left*: Comparison with the model of He et al. [9], where for the upper limit we assume an ULIRG source evolution integrated up to a redshift $z_{\max} = 2.3$. *Right*: Comparison with the model of Palladino et al. [10], where for the upper limit we assume a source evolution according to the star-formation rate integrated up to a redshift $z_{\max} = 4.0$.

excludes ULIRGs as the sole population of HAGS responsible for the diffuse neutrino observations.

Lastly, we compare our results to the beam-dump model by Vereecken & de Vries [11]. They consider the AGN component of ULIRGs as the main source of high-energy neutrinos. The model strongly depends on the electron-to-proton luminosity ratio, f_e. By fitting the model to our $E^{-2.0}$ upper limit, we obtain an order-of-magnitude estimation of a lower limit on this electron-to-proton luminosity ratio, $f_e \gtrsim 10^{-3}$. This value is consistent with previously reported lower limits in the context of obscured AGN studied with IceCube [24, 25].

4. Conclusions

This work reports the results of an IceCube stacking search for high-energy neutrinos from a representative sample of 75 local ULIRGs. We find no excess of astrophysical neutrinos from these ULIRGs in 7.5 years of data. We therefore report upper limits on the stacked neutrino flux of our representative ULIRG sample, and extrapolate these to upper limits on the diffuse flux of the full ULIRG source population. The integral limits for unbroken $E^{-2.0}$ and $E^{-2.5}$ power-law spectra constrain the contribution of ULIRGs to the diffuse neutrino observations up to energies of ~3 PeV and ~600 TeV, respectively. The quasi-differential limits constrain the contribution of ULIRGs between 10–100 TeV and 0.1–1 PeV.

We also compared our results with model predictions. The reservoir model by He et al. [9] predicts a ULIRG neutrino flux at the level of our upper limit. More data is required in order to validate or exclude this model. In the context of the reservoir model by Palladino et al. [10], we exclude ULIRGs as the sole population of HAGS that is responsible for the diffuse neutrino observations. Finally, we fit the AGN beam-dump model of Vereecken & de Vries [11] to our upper limit. As such, we obtain an order-of-magnitude estimation of a lower limit on the electron-to-proton luminosity ratio of ULIRGs, $f_e \gtrsim 10^{-3}$.

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