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Charmed Galaxies

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Abstract. The quest for finding the origins of cosmic rays has been going on for many decades. Cosmic rays as charged particles react to cosmic magnetic fields and typically travel in diffusive motion through the Universe. Their imprint on Earth therefore holds little information on their origin, and finding the sources of cosmic rays is a major challenge. The question of their origins has been a leading questions in physics and astrophysics in the past decades. To solve this riddle, a multimessenger approach is used, including cosmic-ray interaction products in the searches, specifically gamma-rays and neutrinos produced in the resulting particle showers. In this multimessenger picture, the detection of high-energy neutrinos from the cosmos by IceCube - as a unique tracer of cosmic rays - is an important piece of the puzzle. First evidence for neutrino emission from the active galaxies TXS0506+056 and NGC1068 indicates that a significant fraction comes from such sources. In this paper, the intriguing fact that gamma-rays seem to be absorbed in these sources discussed. The possibility of neutrinos being produced in regions of high photon or gas densities, together with the possibility of in the future revealing neutrinos from the decay of charmed particles, will be investigated, possibly opening a window to *Charmed Galaxies*.

1 Introduction

The existence of high-energy cosmic rays is still one of the biggest riddles in physics and astrophysics. More than 100 years after their first detection, it is still mostly unclear how the Universe can manage to accelerate particles up to 10^{20} eV energies. The search for the specific acceleration mechanism is complicated by the fact that the origin of cosmic rays is not deducible from their arrival directions at Earth: these charged particles react to large- and small-scale magnetic fields in extragalactic space and in the Milky Way, leaving a close-to isotropic arrival pattern as their imprint at Earth. A way around this problem is the search for neutral particles that are produced in cosmic-ray interactions in the sources. Hadronic interactions lead to the production of high-energy gamma-rays and neutrinos, dominantly from pion and Kaon decays:

$$p\,p \quad \rightarrow \quad \#(\pi^{\pm}/\pi^{0}) + \#(K^{\pm}/K_L^{0}) + X \tag{1}$$

$$p\,\gamma \quad \rightarrow \quad \begin{cases} \Delta^{+} \rightarrow n\pi^{+}/p\pi^{0} \\ \#(\pi^{\pm}/\pi^{0}) + \#(K^{\pm}/K_L^{0}) + X \end{cases}, \tag{2}$$

Here, multi-pion and multi-Kaon production is leading the production of high-energy neutrinos and gamma-rays, X stands for everything else that is produced in the particle showers. The decay processes of pions and Kaons are given in Table 1 and lead to the production of gamma-rays and neutrinos as shown. Rare processes from the decay of charmed mesons like $D^{\pm}/D^{0}$ are typically subdominant, but could become important in regions of extreme densities as will be discussed below.

The above equations are formulated for protons, which make up around 90% of the cosmic-ray spectrum at GeV energies. Significant contributions from helium up to iron are present at higher energies, see e.g. [11] for a review.The proton-proton cross-section can in principle be used to estimate the cross sections of the heavier nuclei (mass-number times the proton cross-section at 1/mass-number of the total energy per nucleus). Alternatively, the interactions can be treated in more detail by including the full interaction networks, as it is done for instance in [8, 16, 22, 24, 26]. Effects of rare particle decays can be taken into account by using event generators like SYBILL, EPOS, or QGSJET, as we will see that these can play a role in the dense cores of galaxies (see Section 3.2). At this point, more than 150 astrophysical sources have been detected in TeV gamma-rays [14]. These are, however, ambiguous signs of particle acceleration, as these photons can arise from the acceration of electrons as well, via bremsstrahlung or inverse Compton scattering. A clear sign of hadronic acceleration are neutrinos, as these are not produced by electrons. These, on the other hand, are difficult to detect. With the instrumentation of one cubic kilometer of Antarctic Ice, it was possible for the first time to establish the existence of a diffuse flux of high-energy

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Table 1. Processes relevant in cosmic-ray air showers, after [18]. The mean life time in the rest frame of the particle is given as $\overline{\tau}_0$. Data from [28].

decay channel	valence quark contribution	branching ratio	$\overline{\tau}_0$/s
$\mu^\pm \to e^\mp + \overline{\nu}_e/\nu_e + \nu_\mu$	-	100%	$2.2 \cdot 10^{-6}$
$\pi^\pm \to \mu^\pm + \nu_\mu/\overline{\nu_\mu}$	u/d	99.99%	$2.6 \cdot 10^{-8}$
$\pi^0 \to \gamma\gamma$	u/d	98.8%	$8.4 \cdot 10^{-17}$
$K^\pm\mu^\pm + \nu_\mu/\overline{\nu}_\mu$	u/s	63.55%	$1.2 \cdot 10^{-8}$
$K_L^0 \to (\pi^+ + e^- + \overline{\nu}_e)/(\pi^- + e^+ + \nu_e)$	d/s	40.55%	$5.1 \cdot 10^{-8}$
$K_L^0 \to (\pi^+ + \mu^- + \overline{\nu}_\mu)/(\pi^- + \mu^+ + \nu_\mu)$	d/s	27.04%	$5.1 \cdot 10^{-8}$
$K^\pm \to \pi^0 + e^\pm + \nu_e/\overline{\nu}_e$	u/s	5.07%	$1.2 \cdot 10^{-8}$
$K^\pm \to \pi^0 + \mu^\pm + \nu_\mu/\overline{\nu}_\mu$	u/s	3.35%	$1.2 \cdot 10^{-8}$
$D^\pm \to \overline{K}^0 + \mu^{+/-} + \nu_\mu/\overline{\nu}_\mu$	d/c	9.2%	$1.0 \cdot 10^{-12}$
$D^0 \to \overline{K}^- + \mu^+ + \nu_\mu$	u/c	3.3%	$4.1 \cdot 10^{-13}$
$D_s^{+/-} \to \tau^\pm + \nu_\tau/\overline{\nu}_\tau$	s/c	5.5%	$5.0 \cdot 10^{-13}$
$\tau^\pm \to (e^+ + \nu_e + \nu_\tau)/(e^- + \overline{\nu}_e + \overline{\nu}_\tau)$	-	17.83%	$2.9 \cdot 10^{-13}$
$\tau^\pm \to (\mu^+ + \nu_\mu + \nu_\tau)/(\mu^- + \overline{\nu}_\mu + \overline{\nu}_\tau)$	-	17.41%	$2.9 \cdot 10^{-13}$
$\eta \to \mu^+\mu^+\gamma$	u/d	0.031%	$5.0 \cdot 10^{-19}$

neutrinos from the cosmos [1]. More recent measurements show first evidence that active galaxies are among the sources, with concrete evidence of emission from the blazar TXS 0506+056 [2] and the Seyfert-Starburst composite NGC 1068 [4]. Here, the current knowledge on these galaxies and their features of hadronic emission will be summarized, and prospects will be given to study rare particle decays in dense cores of active galaxies.

2 Neutrino and gamma-ray emission from active galaxies

The class of active galaxies describes all galaxies that host an active core, very abstractly meaning that there is activity connected to the supermassive black hole (SMBH) in the center. This very general class is subdivided into different sub-catagories and the objects can look very different to the observer at Earth. Very distinct features are an accretion disk around the black hole, a torus of dust that is at a few tens of parsecs distance from the SMBH, and a jet of relativistic plasma that can reach up to Megaparsec in scale and typically radiates brightly at radio wavelengths. This description of active Galaxies is very simplistic, as there are many more features that divide up this general class in an entire zoo of subclasses. In the context of cosmic-ray acceleration and interaction, active Galaxies represent interesting candidates to reach particle energies up to the highest energies of 10^{20} eV observed at Earth. There is a simple argument that sources have to fulfill the Hillas criterion [20],

$$E_{\max} = 10^{18}\ \text{eV} \cdot Z \cdot (B/\mu\text{G}) \cdot (R/\text{kpc})\,. \quad (3)$$

This equation is valid for nuclei of charge Z and velocity $v \sim c$, in a magnetic field B that is present in a source with radius R, see [11] for a review. There are only a few object classes in the Universe who can provide conditions to reach $E_{\max} = 10^{20}$ eV, among them are the cores of active Galaxies with their extreme magnetic fields of up to several Gauss at radii on parsec-scale, as well as their jets with strong magnetic fields and hundreds of parsec extension in the inner jet, and lower fields (μG to mG), but significantly larger extensions (R up to kpc-Mpc) in the outer jets. But what is the mechanism to accelerate particles in these environments? As large-scale electric fields that are needed for linear acceleration cannot be created on longer time scales in natural conditions (the plasma would try to go back to neutrality), stochastic acceleration via fluctuations in the magnetic field, called Fermi acceleration, is a possibility. This can happen at shock fronts, with an efficiency of first order with respect to the shock velocity, or otherwise on moving magnetic turbulence, which is a second order effect in terms of the velocity of the magnetic turbulence. Strong shock fronts do exist in jets of active galaxies, and when the jet is pointed directly toward Earth, the relativistic plasma is boosted by the Lorentz factor γ, even boosting the particle energies. These objects are called blazars. The variability time scales of the emission points to the existence of small (parsec-scale) plasmoids that move along the jet axis with relativistic speed. One possibility for particle accelaration is thus via second order Fermi acceleration in which the plasmoids work as the moving magnetic turbulence needed for this process. All of these scenarios, however, do not solve the so-called *injection problem*: in simulations, particles are not picked up by the process of Fermi acceleration unless they are already out of equilibrium, so they must be pre-accelerated somewhere. In active Galaxies, one option to pre-accelerate particles is in events of magnetic reconnection that happen at the launching site of the jet and/or on the accretion disk that surrounds the black hole [27]. With such a scenario at hand, even galaxies that do not host strong radio jets - so-called Seyfert galaxies - can be sources of cosmic rays and neutrinos. Here, the total electromagnetic luminosity is rather dominated by the emissions connected to the accretion disk. While these might not be able to accelerate all the way up to 10^{20} eV, they could be a source of PeV cosmic-rays and this way even TeV-PeV neutrinos. This idea has started to become interesting since the first strong evidence of neutrino emission from the Seyfert-starburst composite galaxy NGC1068. Evidence for a neutrino signal was observed in 9 years of data (2011-2020) in the TeV energy range, with an indication of a steep neutrino spectrum, i.e. around E^{-3} [4]. The most fascinating fact about this measurement is that the estimated neutrino luminosity is significantly larger than the measured gamma-ray luminosity. This is to first order in strong contradiction to the fact that the production of gamma-rays and neutrinos via pion decay happens at about the same flux level. The only way to reduce gamma-rays to the level observed at GeV-TeV energies is to absorb these gamma-rays. Cores of active galaxies are ideal places for such absorption: the strong Corona that is produced in connection with the accretion disk in fact leaves little room for gamma-ray emission above GeV energies [23]. In fact, other emission regions from farther outside are needed to fully explain the Fermi observations. One possibility is the starburst ring aound the black hole at around 1 kpc distance [15], or an ultra-fast outflow launched from the core of these galaxies [25].

The fact that NGC1068 seems to be a gamma-ray absorbed neutrino source does not come as a surprise: the luminosity of the diffuse neutrino flux is also significantly higher than one of the diffuse gamma-ray flux, so that this flux in general must be dominated by gamma-ray absorbed sources [6]. Another piece of evidence that fits well into this scheme is the potential correlation of high-energy neutrinos with the position of blazars. In the sample of 9 years of data, the blazars TXS 0506+056 and PKS 1424+240 show local significances above 3σ [4]. It is interesting to note that these two sources are even correlated to events that are made public via the IceCube alert system. A high-energy neutrino event from TXS 0506+056 in particular was seen in coincidence with a gamma-ray flare (Fermi), giving a 3σ significance of evidence that this is a source of high-energy neutrinos on its own [2]. In [21], four neutrinos with high probability of being of astrophysical origin and are at the same time in spatial coincidence with blazars. This concerns the blazars PKS B1424-418, TXS 0506+056 and PKS 1502+106. Fig. 1 shows the lightcurve of the Fermi emission at GeV photon energy at the time of the neutrino arrival, which are indicated for each panel as purple, vertical lines. What has been shown in [21] is that the gamma-ray blazars show a local (TSX0506+056) or even global (PKS B1424) minimum in their gamma-ray light-curves at the time of neutrino detection. This can imply that even in the case of blazars, the neutrinos are emitted preferably when the emission region is opaque to high-energy gamma-rays. Since the same target that absorbs the gamma-rays creates the neutrinos to begin with, such a scenario is in fact quite plausible. For TXS 0506+056, the interaction of two jets has been discussed [13], and would correspond to an environment that all of the sudden becomes opaque to the gamma-rays through the enhanced density present during the interaction of the jets, which at the same time would enhance the neutrino production.

So, to summarize, to produce sources of high-energy neutrinos and at the same time reduce the gamma-ray flux at above GeV energies significantly, very dense environments are needed that host a cosmic-ray acceleration region. In the following chapter, we discuss how high gas densities could be an alternative explanation to the scenario of high photon fields that is discussed above, and what effects this could have on the neutrino flux.

3 Charmed galaxies

In this section, the possibility of hadronic interactions in dense cores of galaxies is discussed and how these could contribute to the flux of high-energy neutrinos in the Universe. We will first discuss in more detail how hadronic and photohadronic interactions can take place in cores and jets of galaxies (Section 3.1), then discuss the details of the particle showers and how rare decays could emerge toward high energies (Section 3.2), and finally, where such signatures of Charmed Galaxies could be revealed in the future (Section 3.3)

3.1 Hadronic interactions in dense cores of galaxies

In general, hadron-hadron interactions are well-suited for the production of neutrinos as discussed in Section 1. In fact, the production of neutrinos in hadron-hadron interactions has a quite low kinematic threshold close to the mass of the respective pions that are responsible for their production, so the spectra rise at a few tens of MeV. As the proton-proton cross section is almost constant at $\sigma_{\rm pp} \sim 3 \cdot 10^{-26}$ cm^{-2}, the secondary spectra basically follow the one of the initial protons above this threshold, i.e. E^{-p}, see e.g. [10] for a discussion. Photohadronic interactions, on the other hand, have a threshold that is determined by the production of the mass of the Δ^+ resonance, so 1.232 GeV beam energy which translates to a threshold that depends on the average energy of particles in the target photon field $< \epsilon >$ (see e.g. [9]) as

$$E^p_{\rm th} = \frac{m_\Delta^2 - m_p^2}{4 < \epsilon >} \,. \tag{4}$$

Taking for instance the Corona of an AGN like NGC1068 as a target photon field, results in a threshold of

$$E^p_{\rm th} \approx 14\,{\rm TeV} \left(\frac{< \epsilon_{\rm photon} >}{0.01\ {\rm MeV}} \right)^{-1} \,. \tag{5}$$

Thus, an interaction with the coronal X-ray field - which has a temperature of around 0.01 MeV - only happens above TeV cosmic-ray energies. Around 1/20th of the proton energy is transferred to neutrinos and thus, the neutrino spectra will exist at around a few hundred GeV upward only. The same is true for the gamma-rays without considering absorption. Thus, proton-proton interactions will happen at significantly lower energies already, where the flux of cosmic rays is significantly higher, at least when assuming a power-law shape of the energy spectrum.

In the environment of an accretion disk of an active Galaxy, the neutrinos can be produced by hadron-hadron interactions with the Coronal gas, which is expected to

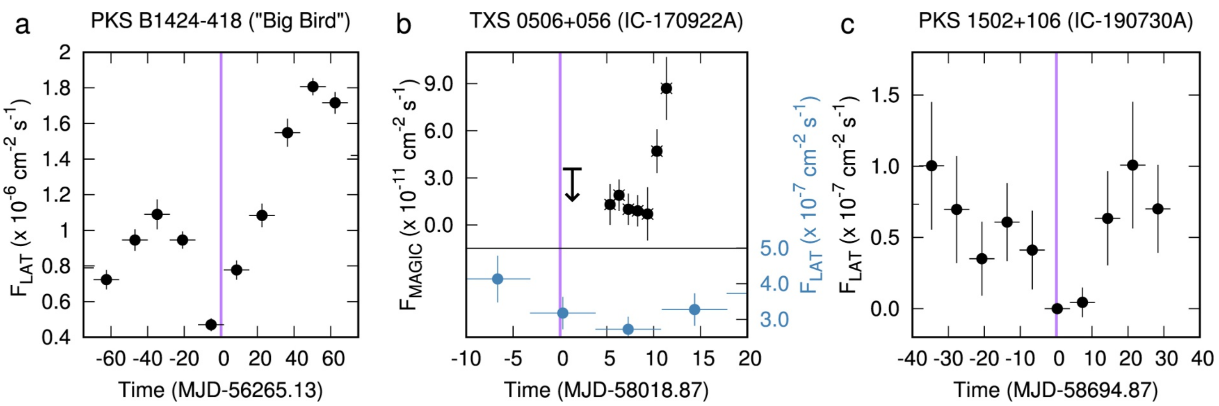

Figure 1. Fermi lightcurves of three gamma-ray blazars (from left: PKS B1424-418, TXS 0506+056, and PKS 1502+106) Neutrinos from the direction of gamma-ray blazars. The arrival of a high-energy neutrino from the direction of these is indicated by the purpel, vertical line in each of the panels. For TXS 0506+056, MAGIC data are shown in black (left y-axis), Fermi data in blue/grey (right y-axis). Figure from [21], reproduced with permission of the authors and IOP Publishing.

have a density of $n \sim 10^{9\pm1}$ cm^{-3} with an extesion of a few tens Schwarzschild-radii (max $100\,r_s$). Another option is that the interaction happens with the photon field of the Corona, but this process would only start to work efficiently above TeV energy.

Now, this is a very interesting environment for shower production from the perspective of particle physics: at high densities, the charged pions will start to interact before they can decay, possibly revealing the neutrino flux from promptly-decaying neutrinos as we discuss below.

3.2 Charmed neutrinos

The observation of rare decays in particle showers opens the window to studying the fundamental properties of matter in the form of the strong and weak interactions, it helps to make precision measurements in particle physics, as well as it provides clues of how to move to beyond-standard-model physics. Earth-bound accelerators like CERN can study the interaction directly at the vertex and have increased our understanding of the standard model of particle physics and beyond significantly. But even the observation of particle showers in the Earth's atmosphere has contributed to our understanding of the microsopic world of particle physics. It is the result of its roughly exponentially increasing density toward the ground that makes the Earth's atmosphere a most interesting test laboratory for studying the evolution of particle showers in dense targets. At a height of approximately ~ 30 km above ground, cosmic-ray nuclei hit atmospheric ones up to the highest energies at $\sim 10^{20}$ eV. In these nucleus-nucleus interactions, an energy-dependent multiplicity of mesons of different masses is produced. Their interaction and decay products are detected (among others) by the detectors of astroparticle physics. In underground experiments like the IceCube Neutrino Observatory, the predominant signal consists of muons from the first interaction above the detector and from all meson decays below ground. The Pierre Auger Observatory also detects muons from secondary interactions, but with a lower energy threshold. In order to draw solid conclusions from the measured signal about the primary cosmic rays, these interactions must be known. Previous studies could be used to quantify the proton-air cross section with Auger [5], and the neutrino-nucleon cross section with IceCube [3]. In the current discussion of these processes, two relevant problems arise in the general context of astrophysical interaction setups. On the one hand, there are tensions between the measured multiplicity of the final generated muons and the current theoretical predictions, also indicating uncertainties in the calculation of the neutrino flux created in interactions in the Earth's atmosphere [7]. On the other hand, high-density environments that are tested by measurements in the Earth's atmosphere reveal a change in the energy spectra of muons and neutrinos: low-energetic and heavy mesons decay before they interact and therefore inherit the primary cosmic-ray power-law energy spectrum. Light or high-energetic mesons, however, interact before they decay, because of their signifiantly longer life times. Table 1 show those processes relevant for neutrino and muon production in an air shower, and thus also in particle showers in astrophysical environments. Pions and Kaons in their rest frames decay after around 10^{-8} s, while heavy measons like D^{+} decay after 10^{-12} s already. Thus, if the density of a target is increased at constant energy and the limit is reached at which the interaction length of the light mesons becomes shorter than the decay length, the decay products of the heavy mesons are filtered out. The condition needed for the pions (and Kaons) to interact before decay is an optical depth for pion-gas (Kaon-gas) interactions that is larger than one:

$$\tau_{\pi+p/K+p} = \frac{L}{\lambda_{\mathrm{mfp}}^{\pi/K}} \geq 1\,. \qquad (6)$$

Here, the mean free path of the pions/Kaons is determined as $\lambda_{\mathrm{mfp}} = (\rho\,\sigma_{\pi p/Kp})^{-1}$ and the propagation length is given by the decay length in the observer's frame, $L = c \cdot \gamma \cdot \tau^{0}_{\pi/K}$. Using $\gamma = E/(m\,c^2)$, we receive a relation between the density of the source and the energy of the neutrinos resulting from the decaying pions and Kaons (we assume that $E_\nu = E_\pi/4$):

$$E_\nu \gtrsim 10^5\,\mathrm{PeV}\left(\frac{\rho}{10^{10}\mathrm{cm}^{-3}}\right)^{-1}. \quad (7)$$

This is a limit for the production of neutrinos via pion and Kaon decay. This shows that at the highest energies, this flux will disappear and the flux of promptly decaying particles is predicted to emerge. It is interesting that it is the absolute density that is relevant for this effect rather than the column depth. So, inhomogenieties in the plasma might enhance the effect and shift it toward lower energies. The effect of charm production has been discussed previously in astrophysical sources [19] and more specifically in supernova explosions with slow jets [12]. Here, we argue that even the dense cores of galaxies might how this effect.

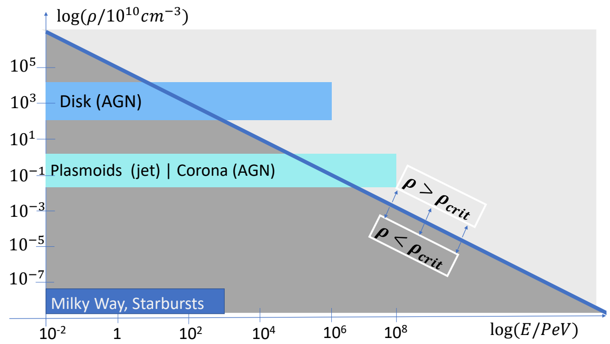

Figure 2. Regions of gas density (ρ) and cosmic-ray energies (E) of the different astrophysical systems. The solid black line shows the case where the decay length of the charged pions equals the time scale for interactions of pions with the gas, assuming a constant density medium.

3.3 Neutrino emission from Compact Obscured Nuclei (CONs)

The fact that the detection of the diffuse flux of neutrinos by IceCube must be connected to gamma-ray absorbed sources together with the strong evidence that NGC1068 is among the sources shows that neutrino production must happen in very dense environments as discussed above. This specifically makes galaxies with a dense and active core outstanding candidates. The production of high-energy protons in this scenario is believed to happen very close to the black hole, possibly via magnetic reconnection in connection to the accretion disk, or via a combination of reconnection and the plasmoid-instability at the foot of an AGN jet. Interaction can then happen with the local gas target in the Corona or jet, or with the photon field. The absorption of gamma-rays is then typically discussed as being due to interactions of the high-energy photons from hadronic interactions with the Coronal photon field. Another option would be the interaction via Bethe-Heitler pair production, i.e. $p\gamma \rightarrow pe^+e^-$, or more generally the interaction of photons in the field of the nuclei of the gas. This type of absorption could also happen outside of the Corona and no strong background photon fields for interaction are needed to absorb the photons. The existence of compact obscured nuclei (CONs) has been established in recent year, see e.g.[17] for a review. Compact obscured nuclei (CONs) have been shown to be present in close to 40% of ULIRGs and more than 20% of LIRGs [17]. While the existence of CONs in lower luminosity galaxies is still unclear, these measurements reveal that there is a large number of (active) core out in the Universe that have extreme densities. Due to their huge column densities of $10^{25} - 10^{26}$ cm^2, these are ideal environments for the production of neutrinos. At the same time, these compact structures are more extended than the very innermost region of the active galaxy, i.e. typically have a size of 10 – 100 pc, thus leaving a larger radius for particle acceleration to happen.

4 Summary, Conclusion & Outlook

The measurements of high-energy neutrinos with IceCube in the past decades has taught us quite a lot concerning the properties of potential neutrino emitters: the detection of a diffuse flux from the cosmos shows that there is no obvious correlation with the Galactic Plane, implying that a large fraction of the flux must be of extragalactic nature. As the neutrino flux is significantly larger than the signal detected in gamma-rays, this means that we are looking at gamma-ray absorbed sources. First pieces of evidence point to emission from the blazars TXS 0506+056 and PKS 1424+240, as well as the Seyfert-starburst composite NGC1068. These potential sources match well with the idea of gamma-ray absorbed sources and start to establish dense cores of galaxies as neutrino emitters. Such a scenario also opens the window to with the next generation neutrino telescopes IceCube-Gen2 and KM3NeT search for a contribution from charmed neutrinos, thus opening the window to studying *Charmed Galaxies*.

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