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Neutrinos as a new tracer of the gas distribution in the Milky Way Centre

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The centre of the Milky Way hosts the most massive and dense clouds of molecular hydrogen gas in our Galaxy. The inferred star formation efficiency at the Galactic Centre is however surprisingly low, given the large gas reservoir. Uncertainties in the measurement of gas density makes the comparison between observations and theories difficult. Measurements of the gas density based on different mass tracers yield inconsistent results, even when using conventional probes such as CS and dust. We propose using neutrinos as an alternative, independent gas tracer to resolve this ambiguity. Neutrinos are produced when cosmic rays interact with the cloud gas, with their surface brightness directly proportional to the cloud's density integrated along the line of sight. We quantify the impact of future neutrino data from the next generation of telescopes—KM3NeT, Baikal-GVD, and P-ONE—which offer angular resolutions close to a tenth of a degree for detecting muon neutrinos from the Galactic Centre. We show how neutrinos will improve the measurement of the gas density, allowing for more robust tests of star formation theories.

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1. Introduction

The Centre of the Milky Way, or the Galactic Centre (GC), emits bright gamma-rays up to 100 TeV [1–4]. The diffuse high-energy gamma-rays ($\gtrsim$ 1 TeV) from the GC are believed to be the result of decays of neutral pions, which are products of hadronic interactions. Hadronic interactions require two ingredients. These are high-energy cosmic-rays (CRs), and target baryons. The GC hosts the most massive and dense molecular clouds (MCs) in the Milky Way, and this collection of MCs comprises a region known as the Central Molecular Zone (CMZ). The CMZ provides numerous target baryons for the CRs to collide with. Although the origin of the GC CRs is still unclear [2, 5, 6], it is almost certain that a strong particle accelerator resides in the GC region. The spatial coincidence of the CMZ and the gamma-ray emission strongly supports the scenario described above [2].

Although gamma-rays are a good tool to study hadronic interactions in the CMZ, its validity is based on two assumptions. The first is that the leptonic contribution to the gamma-ray emission is negligible. Besides neutral pion decays, gamma-rays can also be emitted in other processes such as Compton scattering. While some studies argued that this leptonic contribution can hardly contribute significantly at such high energies [2], other studies have explained the TeV emission with a pure leptonic model [6]. The second assumption is that the gamma-rays are unabsorbed during their propagation from the emission site to the Earth. Gamma-rays could be attenuated during their propagation when interacting with the cosmic microwave background photons or stellar photons. This absorption is usually negligible within the Milky Way, but the unique environment of the GC and the unexpected energy cut-off of Sgr A* has led to consideration of such a possibility [2].

Besides neutral pions, hadronic interactions also result in charged pions that decay into electrons, positrons, and neutrinos. Neutrinos, unlike with gamma-rays, do not suffer from attenuation, and their production channel is predominately hadronic at high energies. They are often disregarded due to the difficulty in detecting them at high angular resolutions. Nevertheless, the advancement of neutrino observatories will soon provide the opportunity to conduct observations at resolutions close to a tenth of a degree [7]. IceCube has shown us the capability of a neutrino observatory by identifying neutrino sources, including TXS 0506+056, NGC 1068, and our Milky Way [8–10]. The field of view of IceCube high-resolution events is limited to the Northern Sky because of its geographical location. Several neutrino telescopes capable of observing the Southern Sky with high angular resolution are being constructed or proposed worldwide. Among them, KM3NeT/ARCA in the Mediterranean Sea [11] and Baikal-GVD in Lake Baikal [12] are in an advanced construction phase and are expected to begin operations at their full capacity within the next few years. Other proposed telescopes include P-ONE [13], located offshore of Vancouver Island, as well as TRIDENT [14] and NEON [15] in the South China Sea, and HUNT in Lake Baikal or the South China Sea [16]. Tentative timelines suggest that P-ONE will come online at the beginning of the next decade, followed by TRIDENT, NEON, and HUNT in the subsequent decade. This rapidly growing network of neutrino telescopes will dramatically enhance our neutrino detection capabilities in the near future and expand the field of view for high-angular-resolution neutrinos [7].

Detecting neutrinos coming from the GC will help us to understand the low star-formation rate of the CMZ. Despite having the most massive clouds in the Milky Way, their star formation rate is below theoretical expectations [17]. One reason could be the high uncertainty in measuring

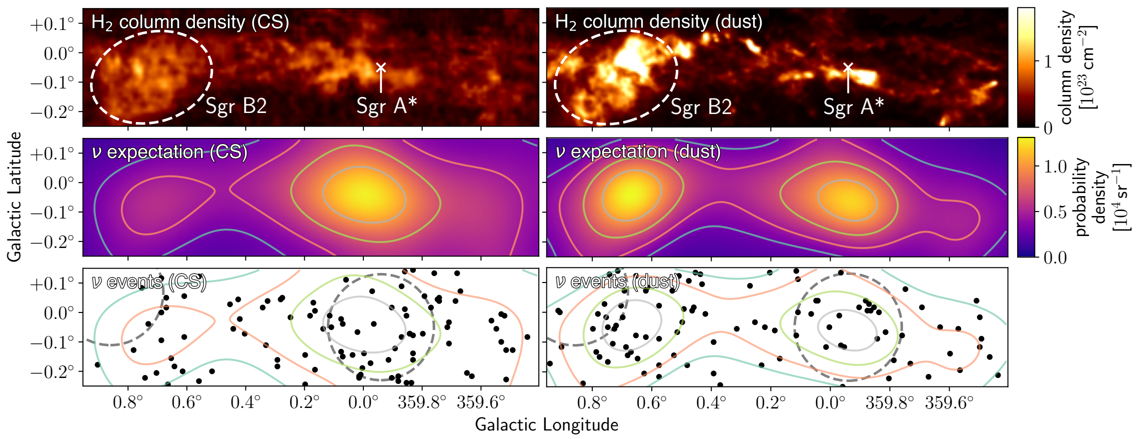

Figure 1: *Top panels*: hydrogen column density in the CMZ inferred from the CS [18] and dust [19] mass tracers, normalised to an integrated mass of $\sim 10^7$ $M_\odot$ in the displayed Galactic longitude and latitude ranges. *Middle panels*: probability of neutrino emission, assuming the column densities in the respective top panels and a cosmic-ray density that decreases as the inverse of the distance from Sgr A*. The plot has been smoothed with a Gaussian kernel to emulate an angular resolution of 0.09°, which is our reference value for next-generation experiments. The contours delineate iso-probability levels. *Bottom panels*: a possible picture in neutrinos containing 100 events, which is the expected number to be collect by combining data from a future network of neutrino telescopes with ten times the exposure that IceCube has accumulated so far. The gray dashed circles show regions centered around two gamma-ray point sources, HESS J1745−290 and G0.9+0.1, with a radius of 2σ of our reference angular resolution of 0.09°. These regions are not usable for our proposed analysis.

the gas mass. If the total gas mass is overestimated, the predicted star formation rate will also be overestimated which makes the measured star formation rate appear to be lower than expected. Indeed, the gas mass estimated by different mass tracers are not always consistent. For example, CS vs. dust [18, 19], two of the most commonly used tracers, yield the most divergent gas distributions of the CMZ among all mass tracers. Figure 1 top panels show the CMZ gas distribution each of these tracers predict, which show clear differences. However, at present, there is no reliable means to determine which tracer gives a more reliable view. We propose that neutrinos can work as a calibrator of the gas mass tracers, and determine which one gives a more accurate description.

Below, we model the neutrino spectrum based on gamma-ray observations, and discuss how neutrinos can function as a calibrator for the mass tracers by considering the future global network of neutrino telescopes.

2. Neutrino emission from the CMZ

The resulting energy spectra of neutrinos and gamma-rays from hadronic interactions differ by less than 20% [20, 21]. Assuming that all the diffuse gamma-ray emission of the CMZ has a hadronic origin, we take the modelled neutrino spectrum to be the same as the measured gamma-ray spectrum as our baseline model. Many gamma-ray telescopes have observed the GC before and they all yield similar results. In this work, we construct our neutrino spectrum based on the HESS measurement of the diffuse Galactic Ridge emission from the CMZ [2]. With the best-fit parameters

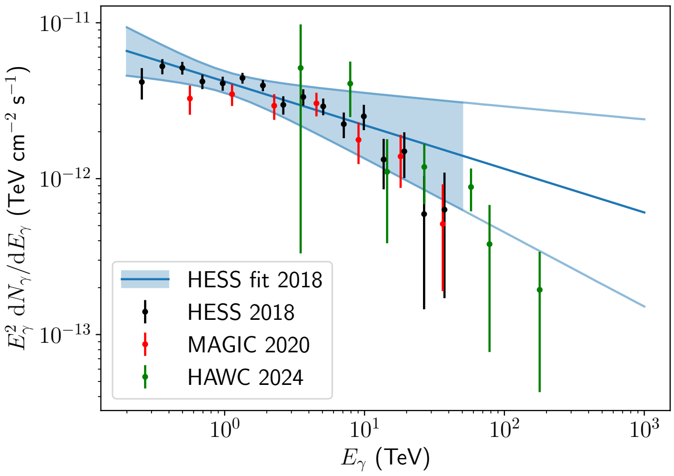

Figure 2: The Central Molecular Zone gamma-ray flux measured by HESS [2], MAGIC [3], and HAWC [4], i.e. the diffuse flux from the Galactic Centre ridge. The blue straight line shows the best fit of the HESS data [2], while the blue shaded areas represent our reconstructed 1σ probability intervals, obtained by sampling the central values and uncertainties of the fit parameters.

of a power law and its uncertainty, we construct the 1σ probability intervals, as shown in Figure 2. This 1σ band sufficiently encompasses all the gamma-ray measurements of the CMZ. As we are only interested in the track events induced by muon neutrinos that can be reconstructed with high angular resolutions, the muon neutrino spectral flux is only a third of the all-favour spectral flux due to neutrino oscillations [22].

The spatial morphology of the neutrino map depends on the gas mass distribution and the CR profile. We use CS and dust as two illustrative tracers for the reasons we discussed above. We assume the CR density decreases as the inverse of the distance from Sgr A*, which is the result of a steady particle injection point (Sgr A* in this case) and CR diffusion [1, 2]. The modelled neutrino map is shown in Figure 1 middle panels. In principle, two different gas distribution models with the same CR model should yield different neutrino fluxes. Instead, we scale the neutrino flux of the two models such that they have the same neutrino flux that we modelled above.

3. Prospects of neutrino observations

With the modelled neutrino spectrum and morphology of the CMZ, we calculate the expected number of events that will be detected by the neutrino observatories. All of our calculations are based on an IceCube-like detector located at the site of KM3NeT. The event rate and the resulting reconstructed energies are calculated following the methodology and inputs detailed in Ref. [7]. The event rates against the reconstructed muon energy are shown in Figure 3. We estimate a detection rate of CMZ muon neutrinos with energy above 100 GeV of 0.8 events per year for the HESS best-fit flux value. The background contribution is expected to be 1.4 events per IceCube-equivalent-year for the same area of interest, which is significant but can be mitigated due to its distinct energy and angular distribution. Events above 10 TeV will be particularly useful as they mostly originate from the CMZ.

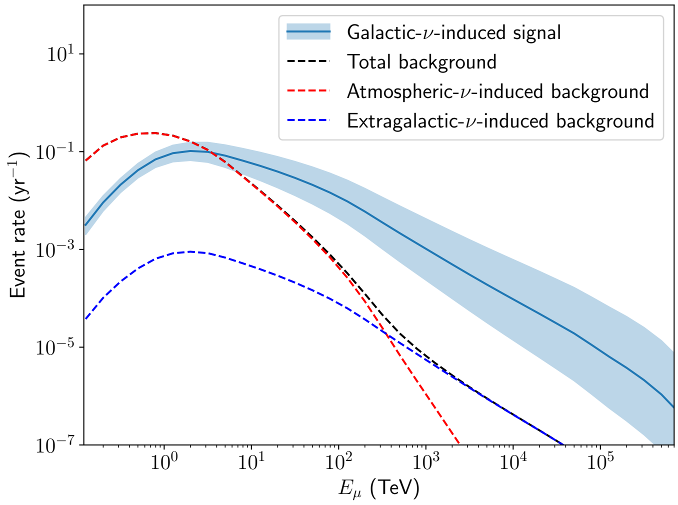

Figure 3: Expected annual detection rate of muon neutrino events from the CMZ. This rate is shown assuming an all-flavour neutrino flux equal to the gamma-ray best-fit flux of HESS and our reconstructed 1σ probability intervals (see Fig. 2).

Given this event rate, neutrinos cannot be an independent mass tracer for the CMZ in the immediate future. Instead, we try to formulate a different question: how much exposure is needed to discriminate between two gas distribution models to a certain significance level? We frame this statistical problem as a hypothesis test, where the null hypothesis assumes that the gas distribution in the CMZ follows that inferred from CS, while the alternative hypothesis assumes it follows that traced by dust. In contrast, the atmospheric and diffuse astrophysical neutrino backgrounds are modelled to be uniform across longitude and latitude. Similarly, the reconstructed energy spectra are based on the earlier discussion and are illustrated in Figure 3.

We evaluate the significance of model discrimination using a likelihood-ratio test statistic derived from an unbinned likelihood approach. This likelihood is built by taking the product of the probabilities for individual events, where each probability is defined by a three-dimensional distribution over energy, latitude, and longitude. This distribution is composed of contributions from both the signal (CMZ neutrinos) and background sources (atmospheric and diffuse astrophysical neutrinos). The signal and background rates used to scale the probability distributions are treated as nuisance parameters and varied in the test statistics to maximise the likelihood of each model. The three-dimensional probability distributions are generated using the previously described event distributions, assuming energy is uncorrelated with spatial coordinates. To minimise contamination from gamma-ray point sources that are unrelated to the diffuse emission, we mask out circular areas on the latitude-longitude plane corresponding to their locations.

To keep the discussion general, we present our sensitivity studies for a future network of telescopes in terms of *IceCube-equivalent-years*, i.e. the effective exposure that a single detector with the efficiency of IceCube would need to achieve the combined sensitivity of the network. For instance, two telescopes with twice the detection efficiency of IceCube would collectively accumulate 4 IceCube-equivalent-years per year.

Due to the low neutrino event rate, we apply a parametric bootstrapping method to construct the

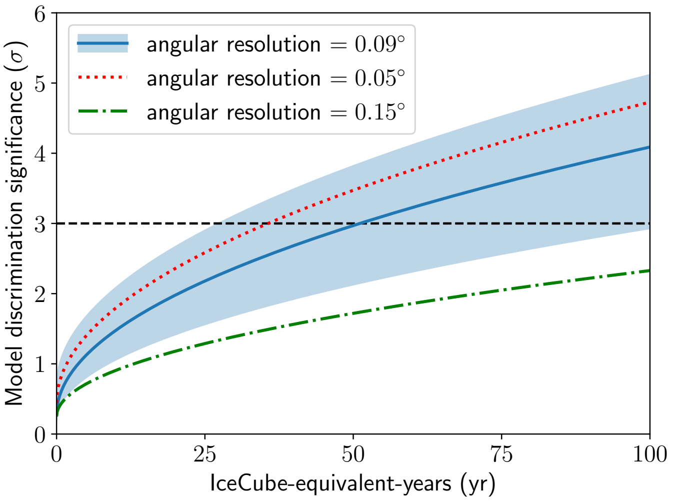

Figure 4: Discrimination significance between gas distribution models built from the CS and dust mass tracers. The dotted, solid, and dash-dotted lines correspond to different angular resolutions. The blue line and band correspond to calculations assuming the best-fit HESS flux or its 1σ uncertainty envelope as input.

probability distribution of the test statistic for both hypotheses. This involves generating synthetic datasets under each hypothesis by drawing signal and background events from the same three-dimensional probability distributions used in the likelihood calculation. We then evaluate the test statistic for each of these datasets. To determine the model-discrimination significance, we locate the quantile in the alternative hypothesis distribution that aligns with the median value of the test statistic under the null hypothesis. This bootstrapping process is repeated across various IceCube-equivalent-year exposures to map out how the discrimination significance evolves with increasing observation time.

The outcomes of our analysis are presented in Figure 4. Using a baseline angular resolution of 0.09°, we can achieve a 3σ level of model discrimination for the best-fit HESS energy spectrum by accumulating 50 IceCube-equivalent years of data. This level of exposure is anticipated within the next twenty years [7]. The figure also highlights the influence of angular resolution, which—alongside exposure—is one of the critical detector characteristics.

4. Conclusion

Our study demonstrates that neutrino observations can provide important information about the gas distribution within the CMZ. Although achieving statistically significant model separation may require exposure levels not expected for another twenty years, neutrino detectors will eventually offer a completely independent means of verifying gas densities derived from mass tracers, providing the most reliable constraints in terms of systematic errors. Enhanced understanding of gas properties will support the refinement of star formation models within the CMZ, with these insights potentially extending to systems with comparable conditions, including extragalactic environments.

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